A Southern Hemisphere prospective on Dark Matter

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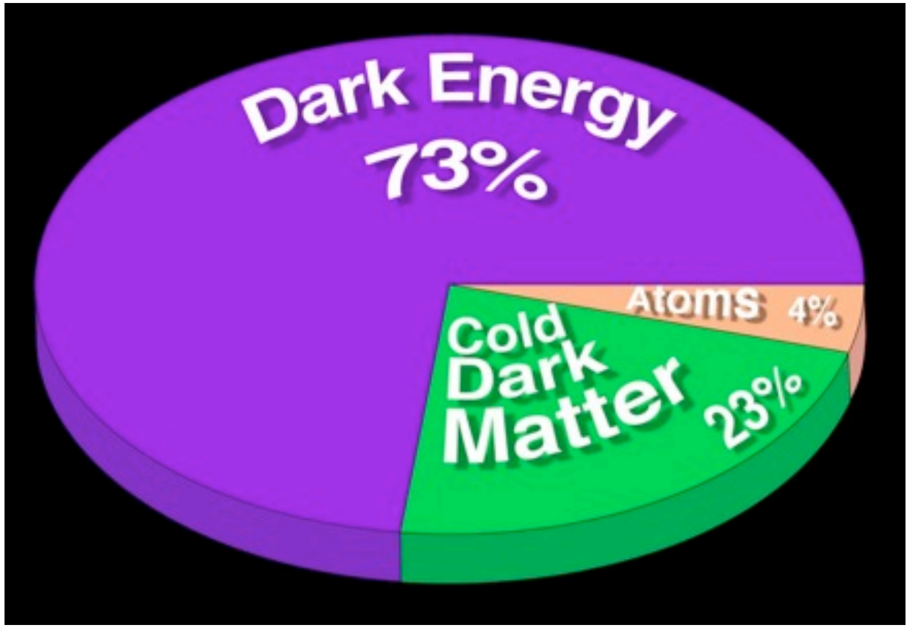
CoEPP

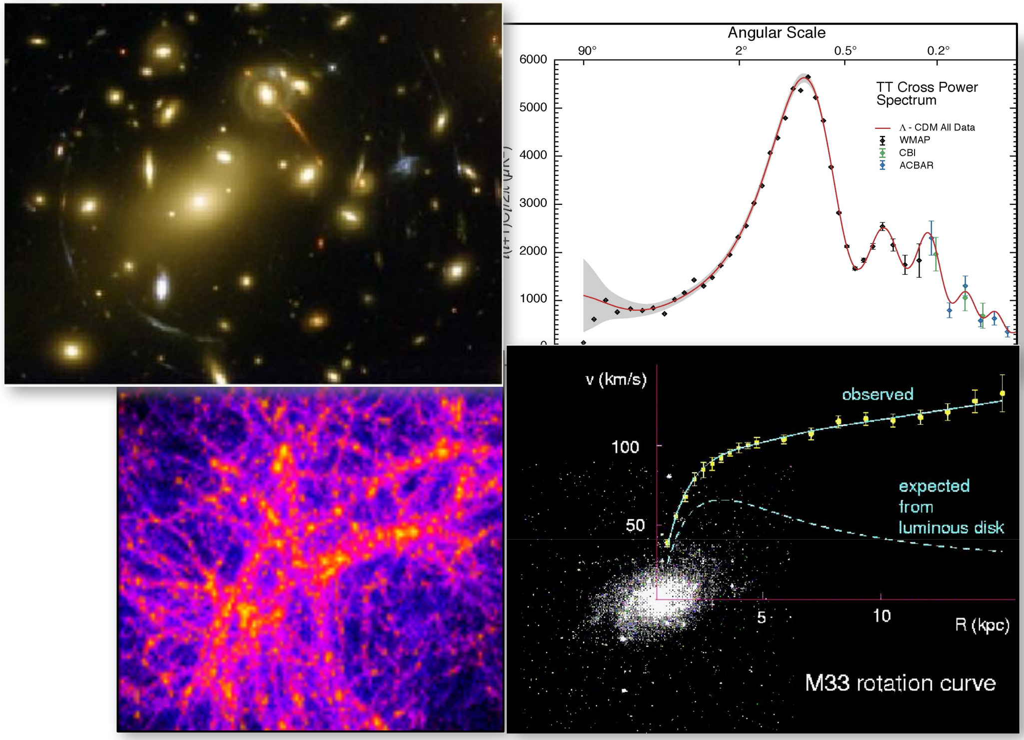
ARC Centre of Excellence for Particle Physics at the Terascale

Universe's Energy Density Budget

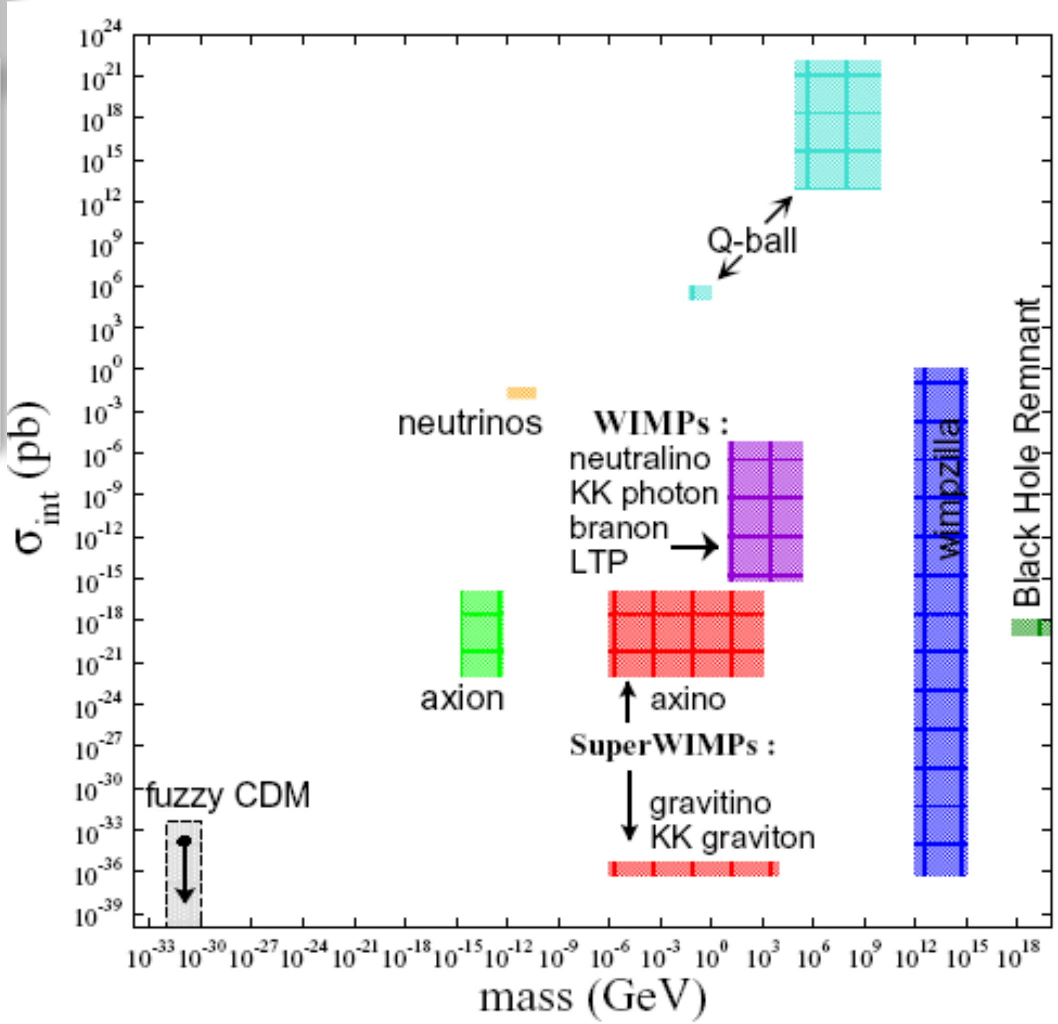


- There exists a wide variety of independent indications that dark matter exists
- Each of these observations infer dark matter's presence through its gravitational influence
- Without observations of dark matter's non-gravitational interactions, we are unable to determine its particle nature

Nature dark matter



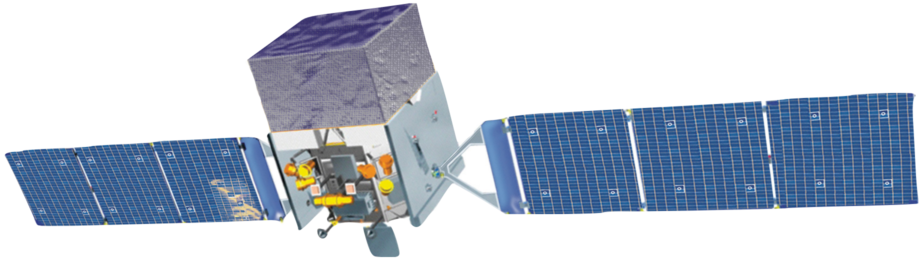
Observational constraints are no match for the creativity of theorists

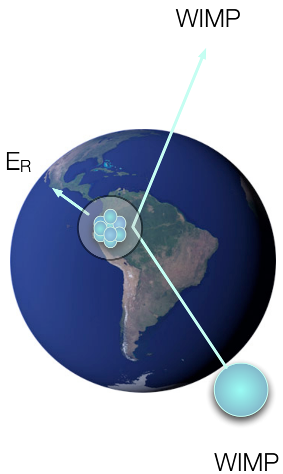


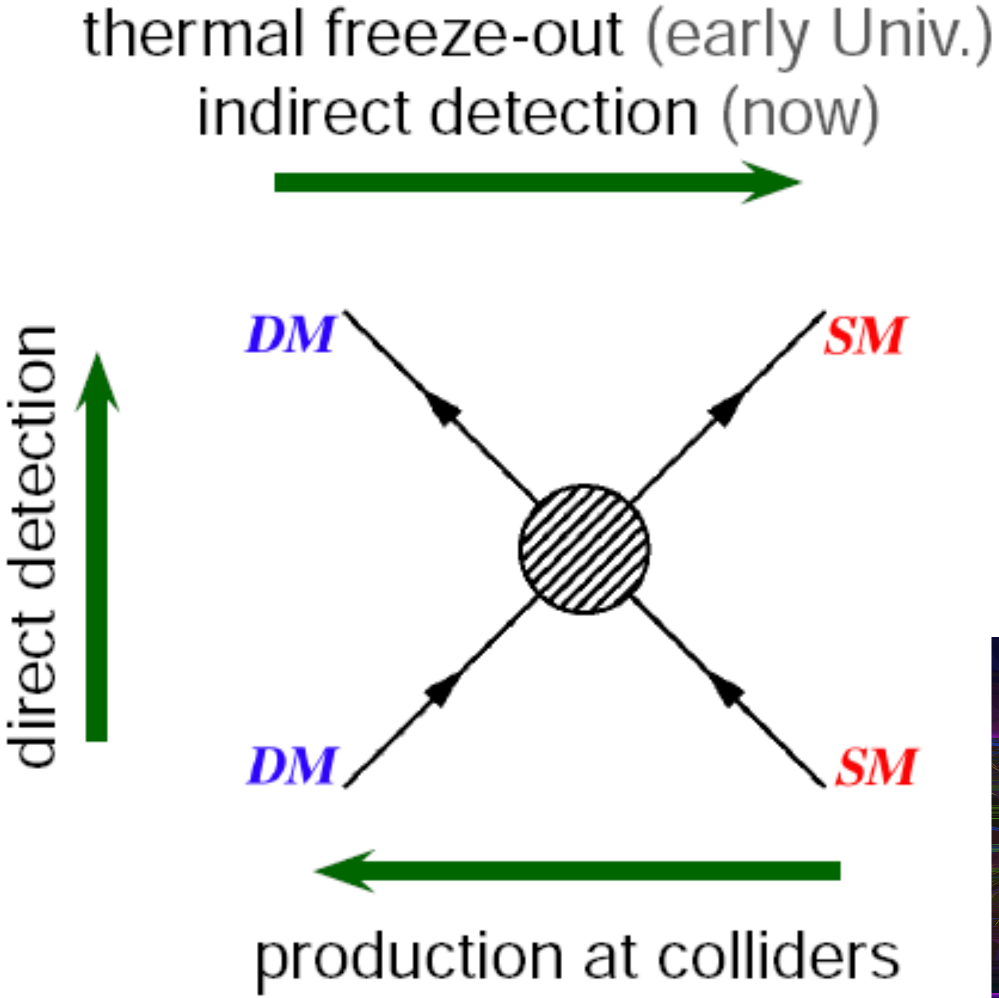
In this talk, we assume that the dark matter particle is a

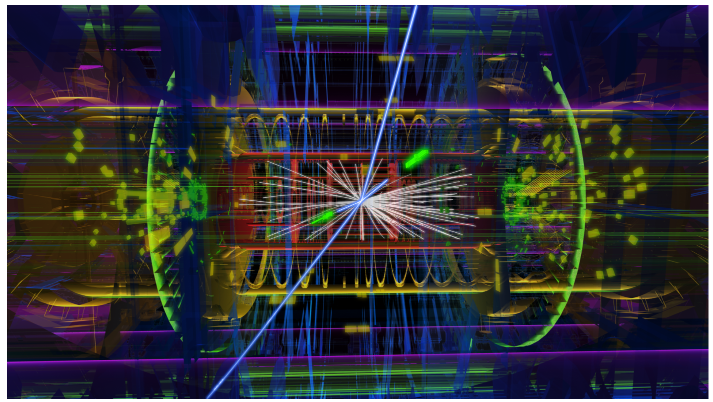
WIMP = weakly interacting massive particle

DM Interactions

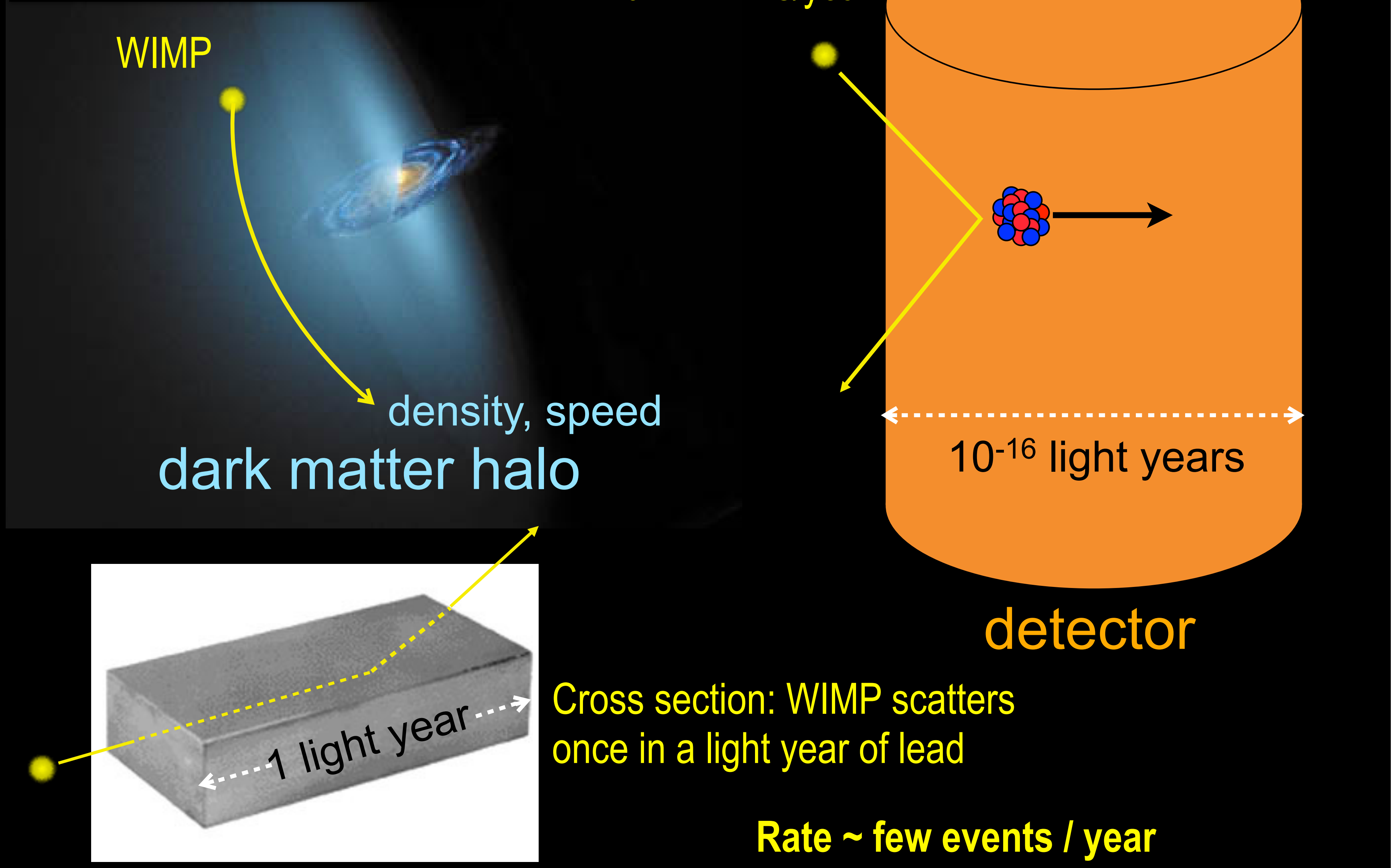








Direct detection



Expected Rates in a Detector

Astrophysics

$$R \propto N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \cdot \langle v \rangle$$

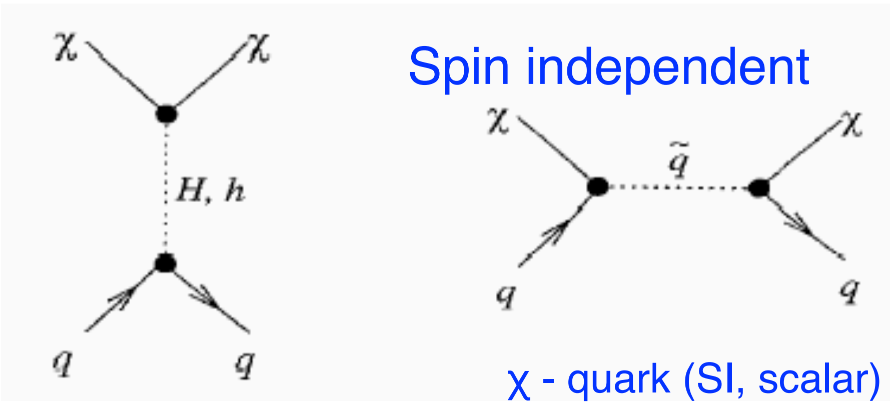
Particle physics

- N = number of target nuclei in a detector
- ρ_χ = local density of the dark matter in the Milky Way
- <v> = mean WIMP velocity relative to the target
- m_χ = Dark matter (WIMP)-mass
- $\sigma_{\chi N}$ =cross section for WIMP-nucleus elastic scattering

WIMP-Nucleon Interactions

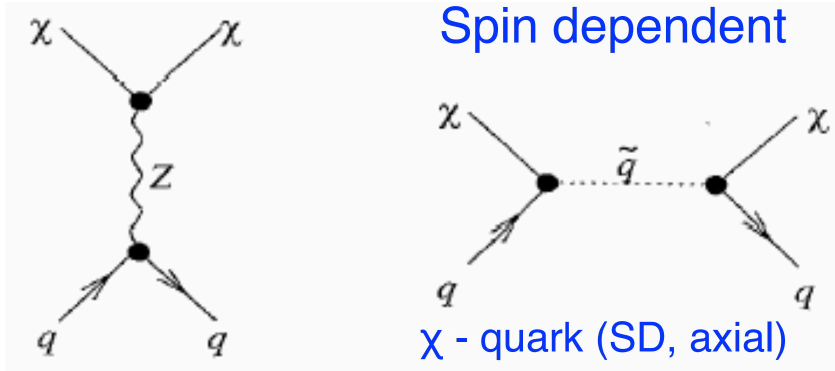
A priori, we do not know how dark matter WIMPs interact with ordinary matter (detector, Sun, ...)

Spin independent



χ - quark (SI, scalar)

Spin dependent



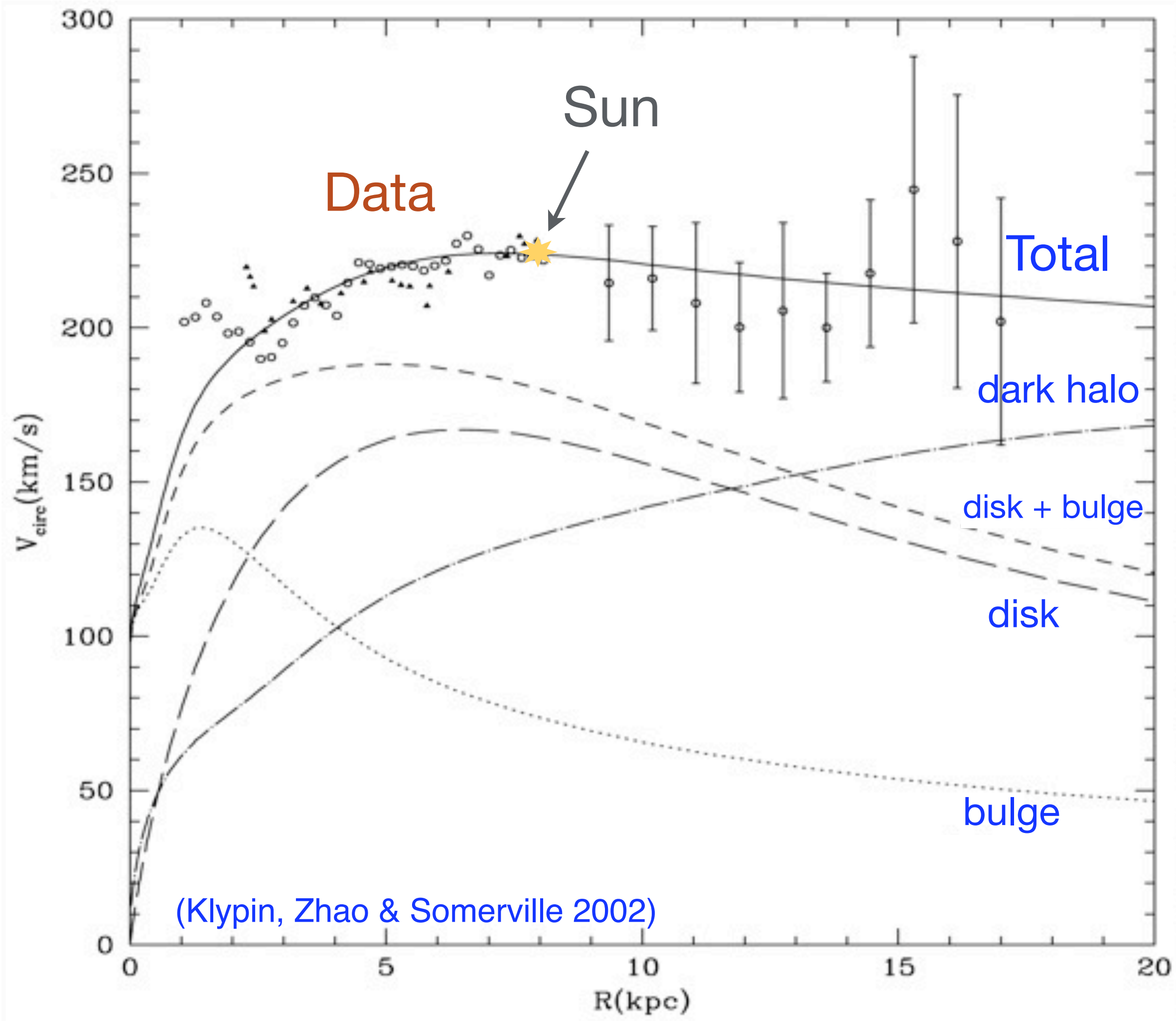
χ - quark (SD, axial)

$$\frac{d\sigma}{d|\mathbf{q}|^2} = \frac{C_{spin}}{v^2} G_F^2 \frac{S(|\mathbf{q}|)}{S(0)} \qquad C_{spin} = \frac{8}{\pi}[a_p \langle S_p \rangle + a_n \langle S_n \rangle]^2 \frac{J+1}{J}$$

often express in proton-on or neutron-only

Spin ind. standard assumption $\sigma_{\chi N} \sim 10^{-44}$ cm^{-2}

Local Density in the Milky Way



Particle data group:

$$\rho_{halo} = 0.1 - 0.7\ GeVcm^{-3}$$
$$\rho_{disk} = 2 - 7\ GeVcm^{-3}$$

'Standard' value:

$$\rho_{\chi} \simeq 0.3\ GeVcm^{-3}$$

$$\rho_{\chi} \simeq 3000\ \mathrm{WIMPs} \cdot m^{-3}$$
$$(M_{WIMP} = 100\ \mathrm{GeV})$$

WIMP flux on Earth:
~ 10^5 $cm^{-2}s^{-1}$

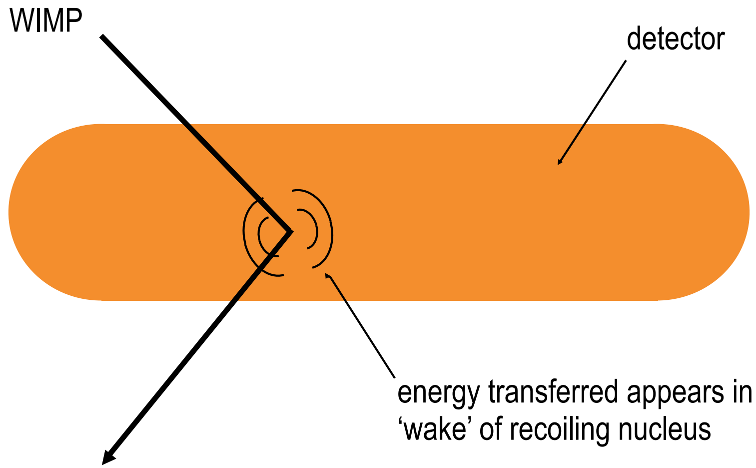
WIMPs in the Galactic Halo

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-\frac{E_R}{E_0 r}}$$

- **R =** event rate per unit mass
- **E_R =** nuclear recoil energy
- **R_0 =** total event rate
- **E_0 =** most probable energy of WIMPs

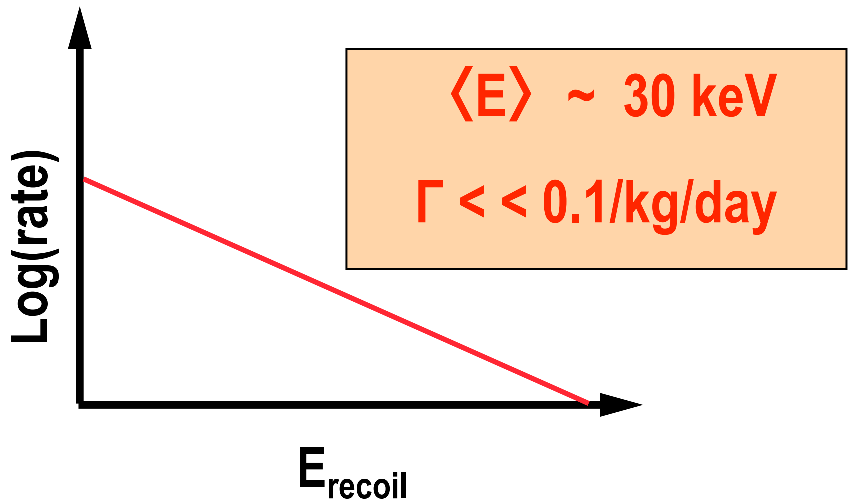
  (Maxwell-Boltzmann distribution)
- **r =** kinematic factor

$$r = \frac{4 m_\chi m_N}{(m_\chi + m_N)^2}$$



WIMP-Nucleus Scattering

Scatter from a Nucleus in a Terrestrial Particle Detector



Some Typical Numbers

$$m_\chi = m_N = 100\ GeV \cdot c^{-2}$$

$$\Rightarrow r = \frac{4 m_\chi m_N}{(m_\chi + m_N)^2} = 1$$

kinematic factor

$$\mathrm{v} \sim 220\ \mathrm{km\ s^{-1}} = 0.75 \times 10^{-3} c$$

mean WIMP velocity relative to target
(halo is stationary, Sun moves through halo)

$$\langle E_R \rangle = E_0 = \frac{1}{2} m_\chi \mathrm{v}^2$$

$$\langle E_R \rangle = \frac{1}{2} 100 \frac{GeV}{c^2} (0.75 \times 10^{-3} c)^2$$

$$\langle E_R \rangle \approx 30\ \mathrm{keV}$$

mean recoil energy deposited in a detector

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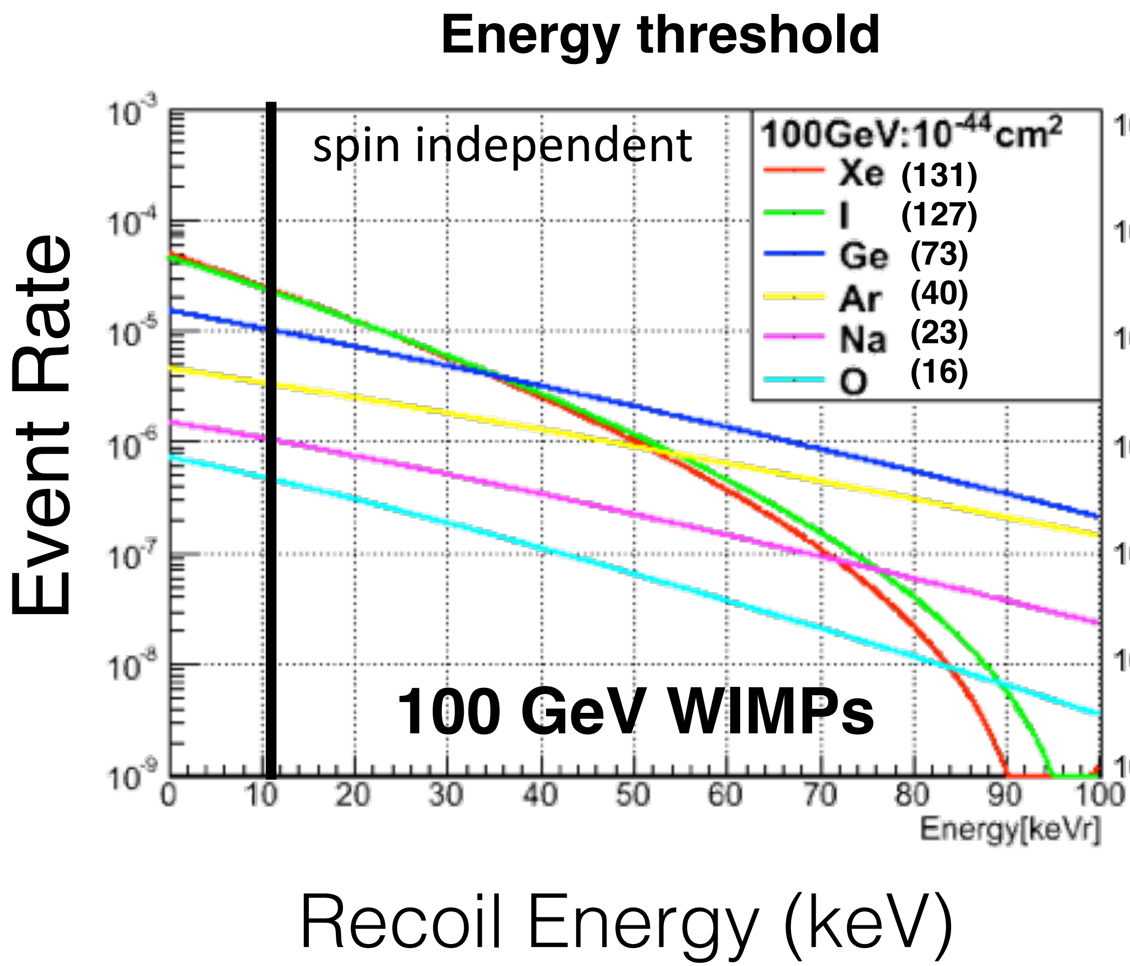
Energy spectrum ($f_n = f_p$)



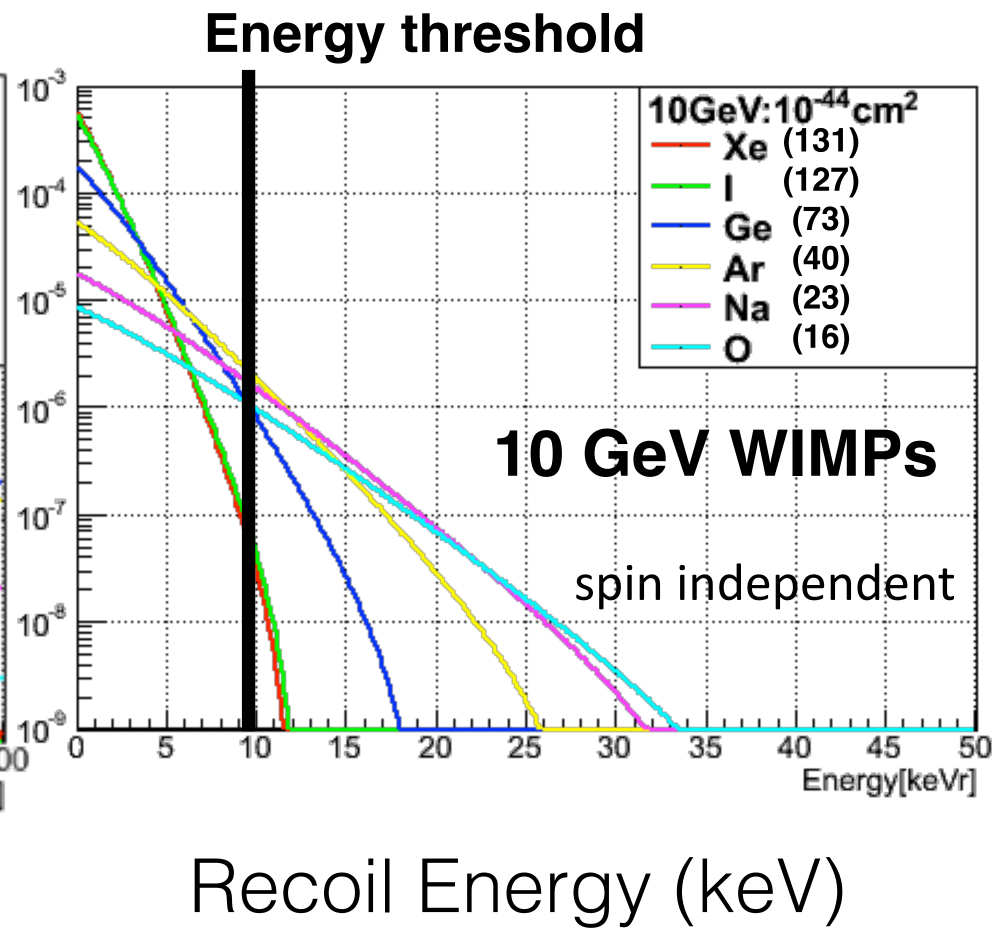
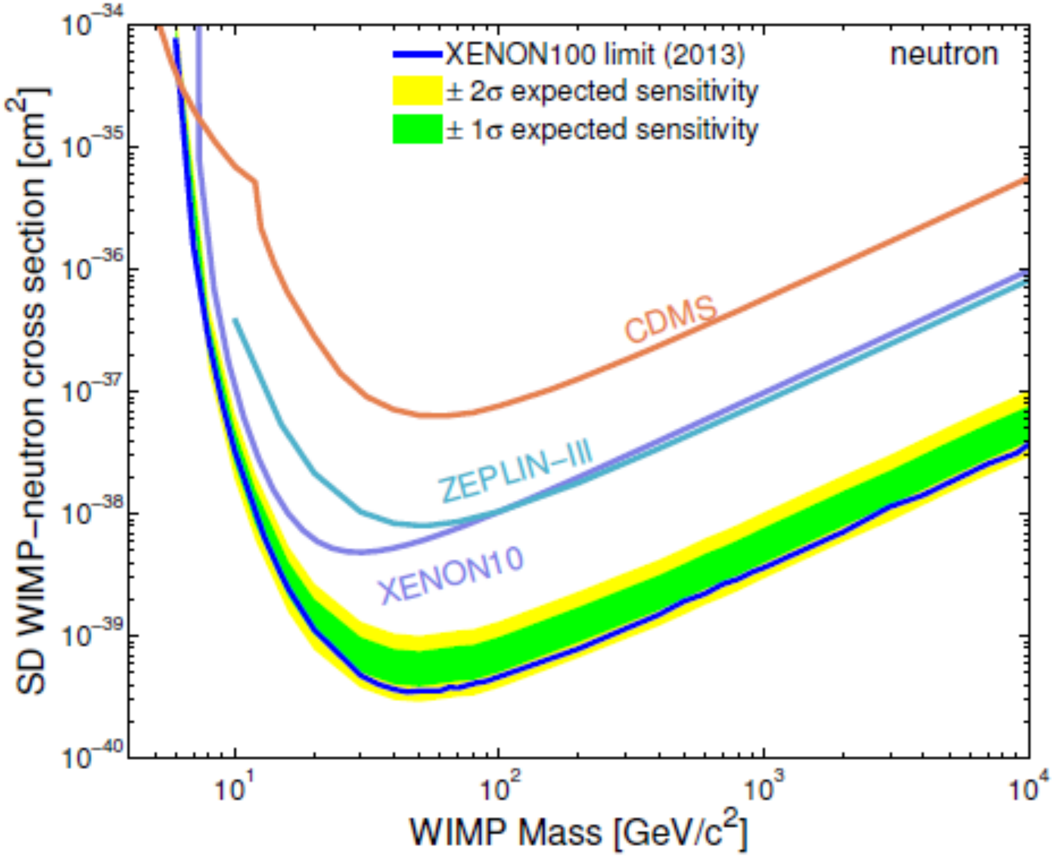


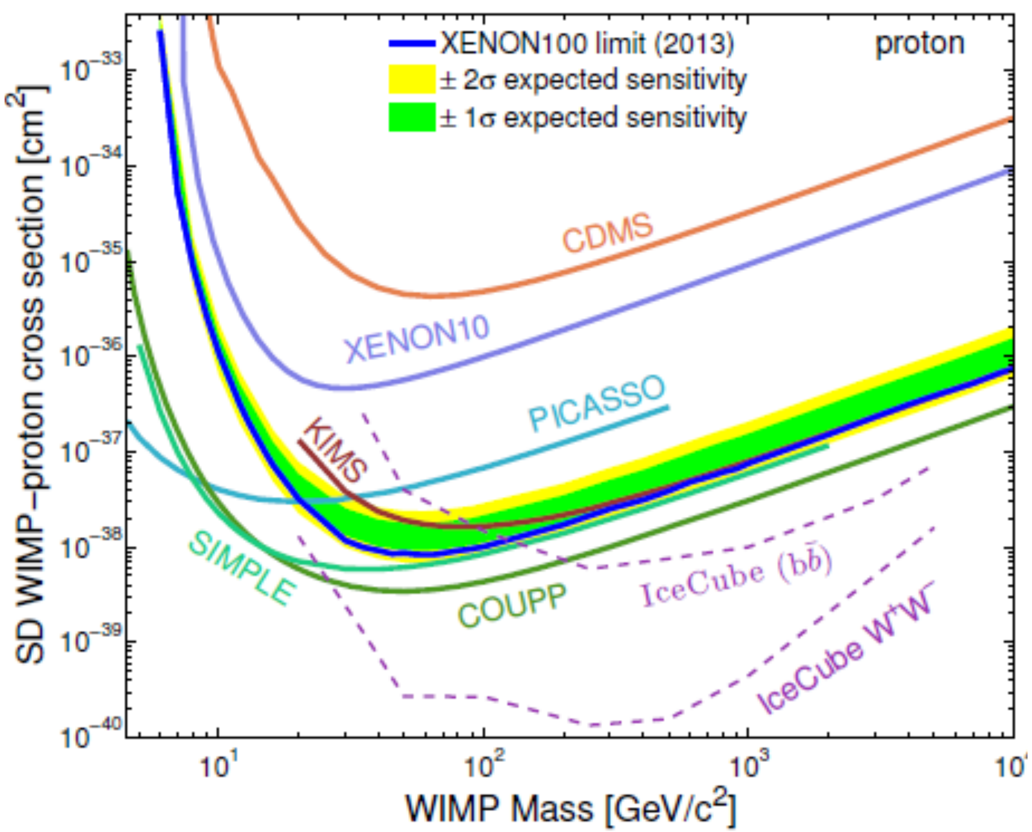
Fig. from M. Yamashita

Low mass WIMP better to have a small Atomic Mass

Spin-dependent Sensitivity

spin-dependent, elastic interactions

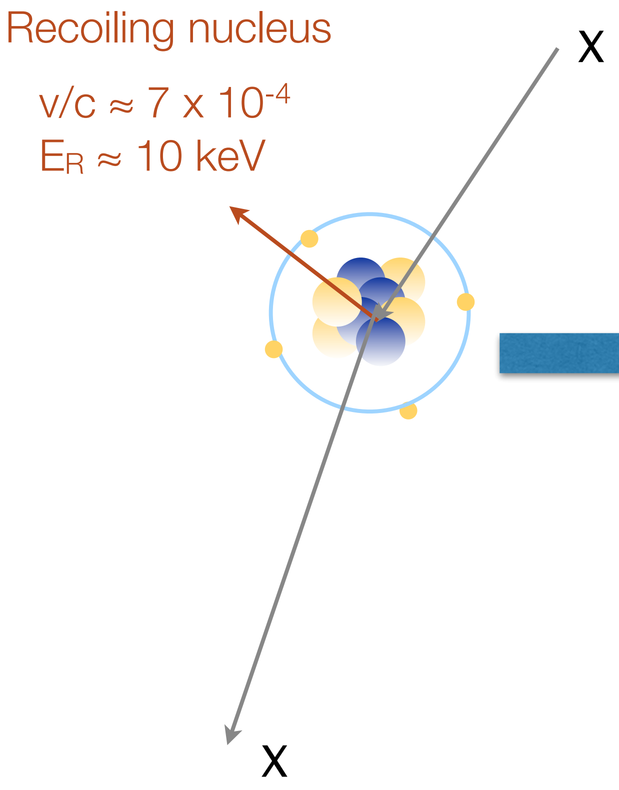


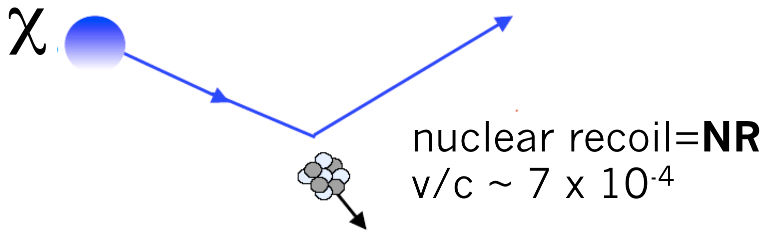


The isotopic composition of the material matters

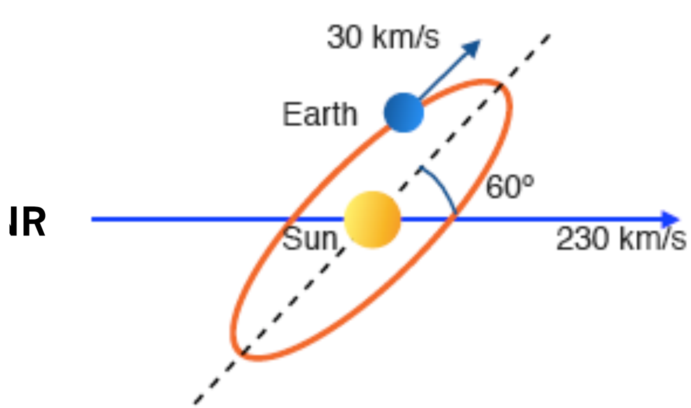
PRL 111, 021301 (2013)

Strategies for Direct Detection

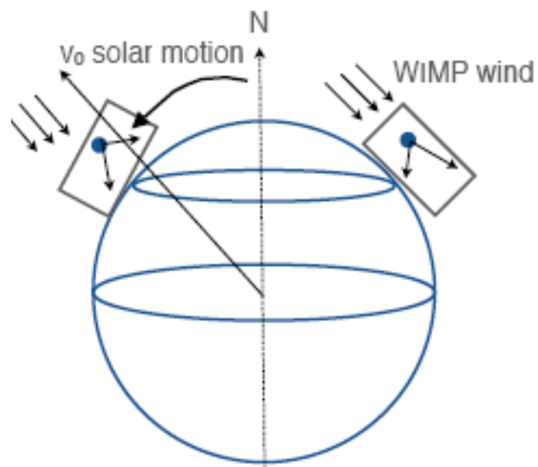




Count nuclear recoils



annual flux variation

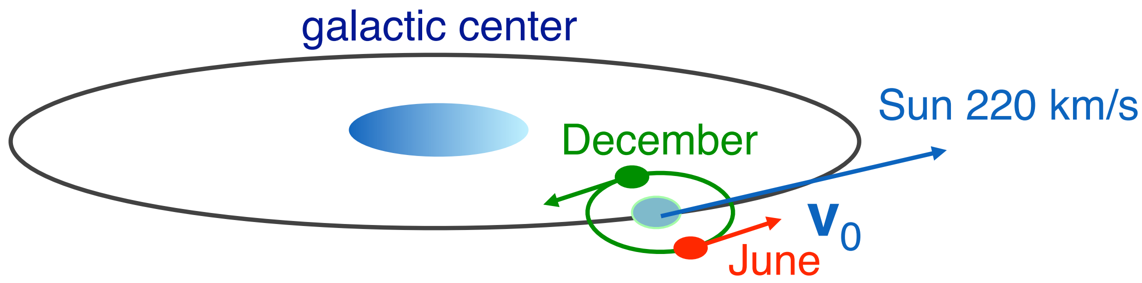


diurnal directional modulation

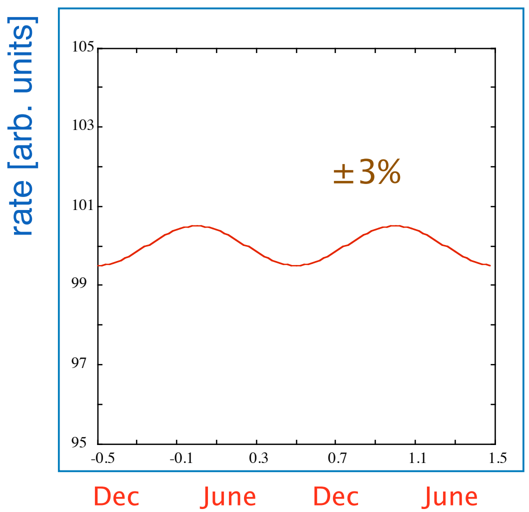
WIMPs in the Galactic Halo

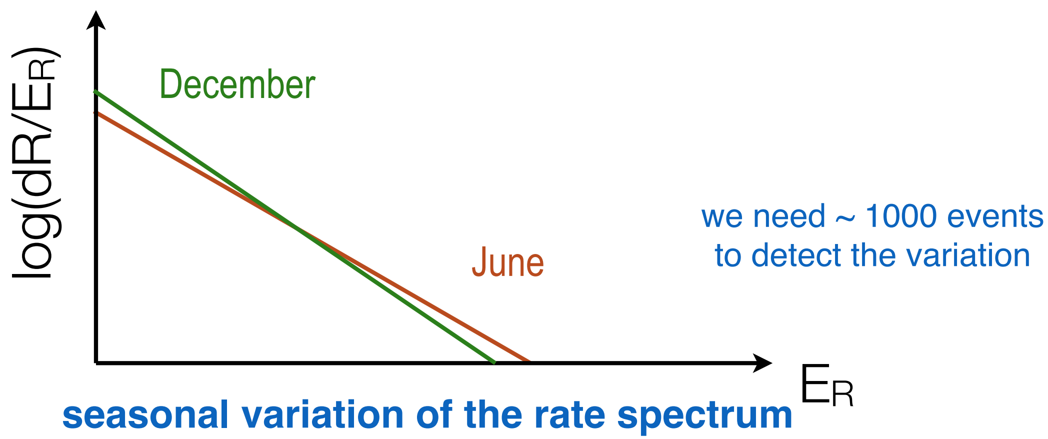
- Exploit movements of the Earth and Sun through the WIMP halo
  - Direction of recoil -- most events should be opposite Earth/Sun direction
  - Annual modulation -- harder spectrum when Earth travels with sun

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



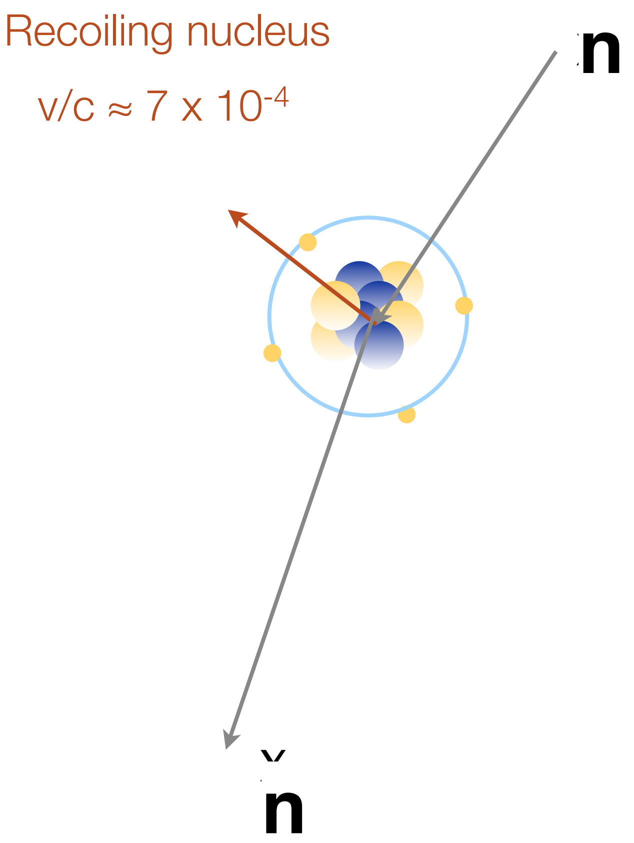
- t = days since January 1st
- t_p = 2. June (152.5 d) ± 1.3 d; 1 yr = 362.25 d



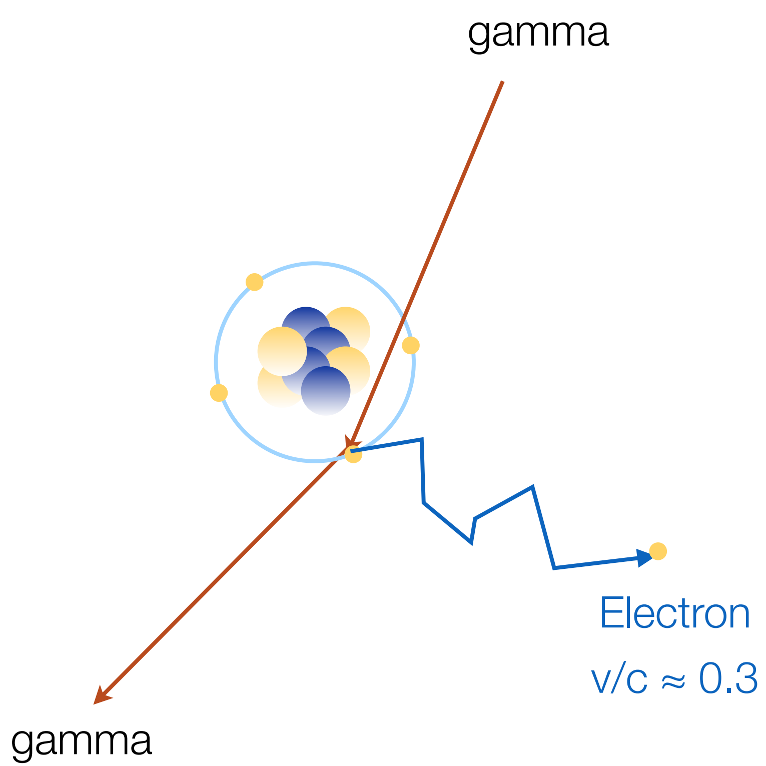


Background

n recoil (cosmogenic muon, surrounding material)



e recoil (γ,β radiation)



Backgrounds: cosmic rays and natural radioactivity

WIMP scattering (<1 evts /10kg/day)

- Remember: activity of a source

$$A = \frac{dN}{dt} = -\lambda N$$

N = number of radioactive nuclei
λ = decay constant, $T_{1/2} = \ln 2/\lambda = \ln 2\ \tau$
[A] = Bq = 1 decay/s (1Ci = 3.7 x 10^{10} decays/s = A [1g pure ^{226}Ra])

- **Do you know?**

1. how much radioactivity (in Bq) is in your body? where from?

1. 4000 Bq from ^{14}C, 4000 Bq from ^{40}K (e^- + 400 1.4 MeV γ + 8000 ν_e)

2. how many radon atoms escape per 1 m^2 of ground, per s?

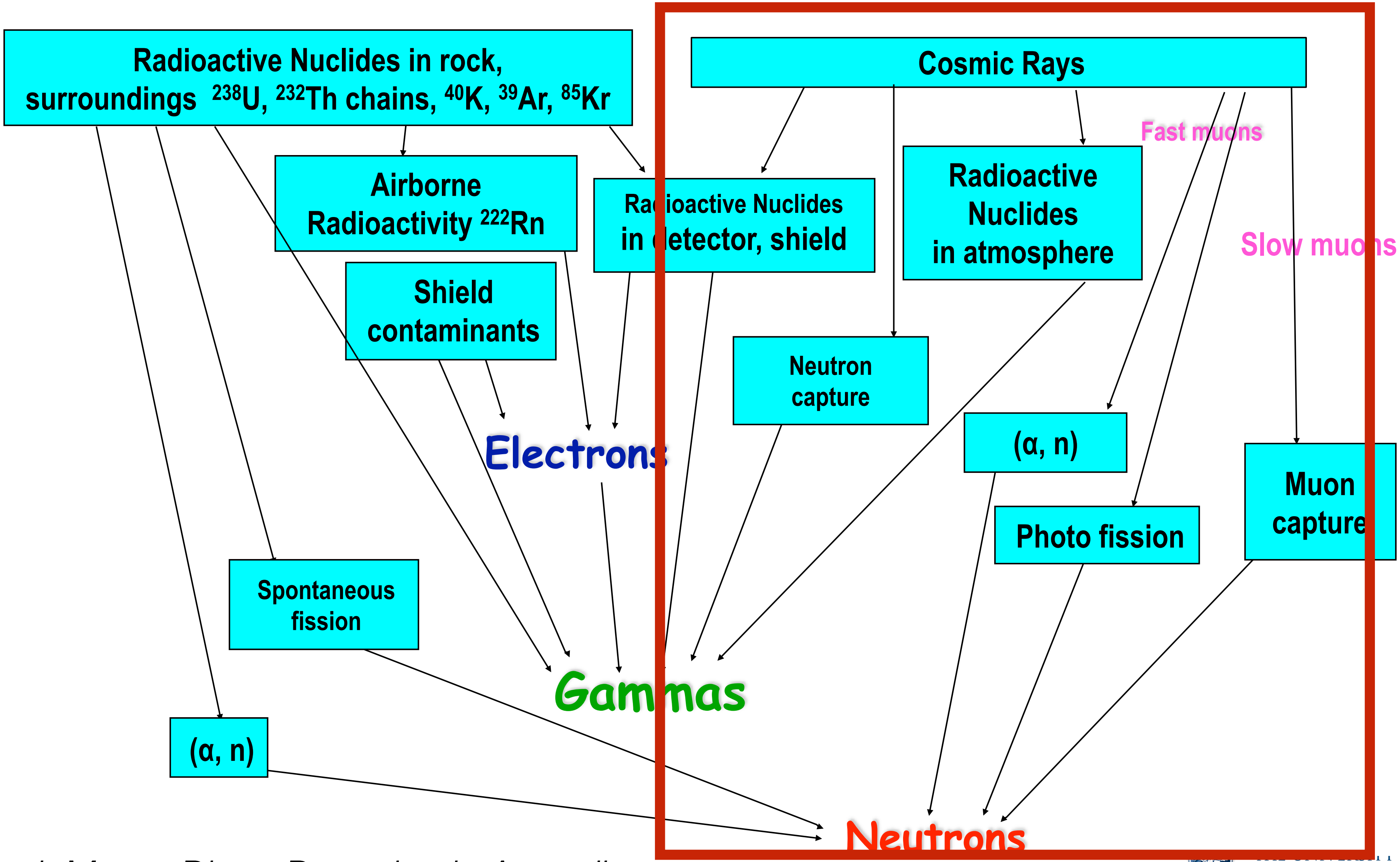
2. 7000 atoms/m^2 s

3. how many plutonium atoms you find in 1 kg of soil?

3. 10 millions (transmutation of ^{238}U by fast CR neutrons), soil: 1 - 3 mg U per kg

Background: cosmic rays and natural radioactivity

WIMP scattering (<1 evts /10kg/day) swamped by background (>10^{6-7} evts/kg/d)



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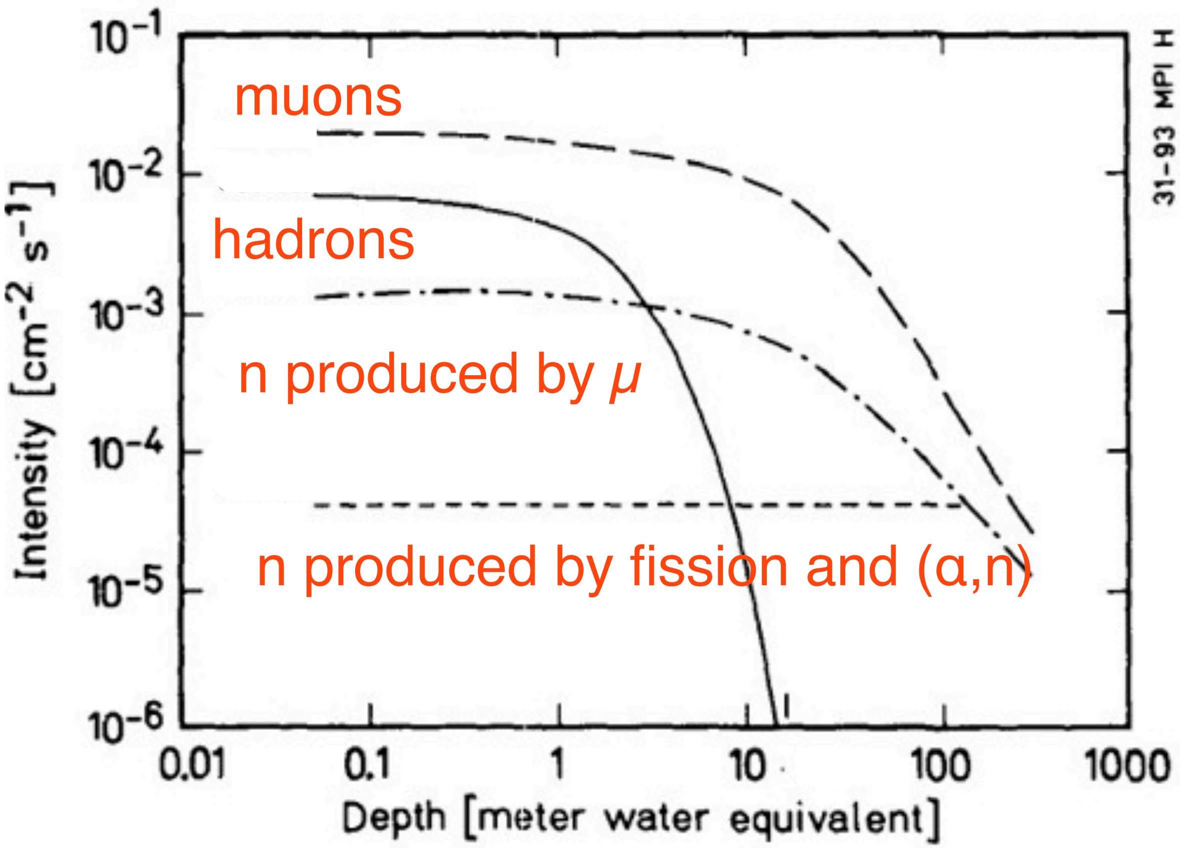
Background Flux

Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shield vs shielding depth
Gerd Heusser, 1995



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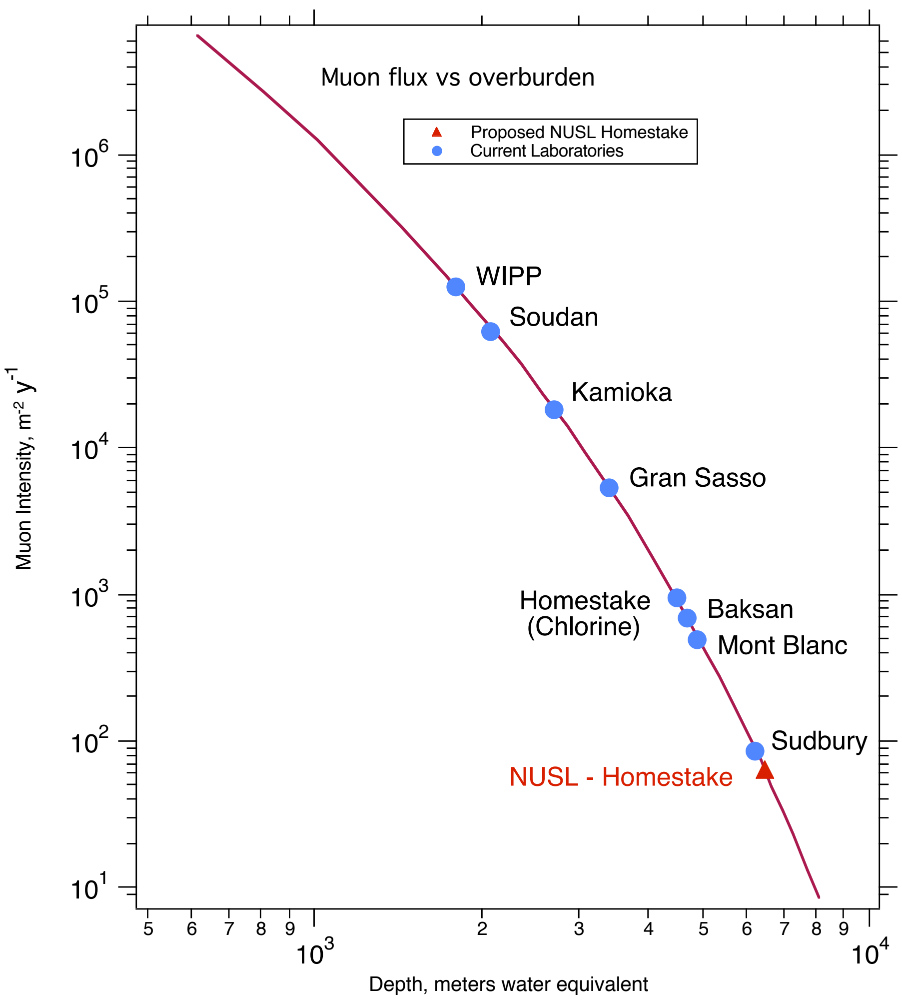
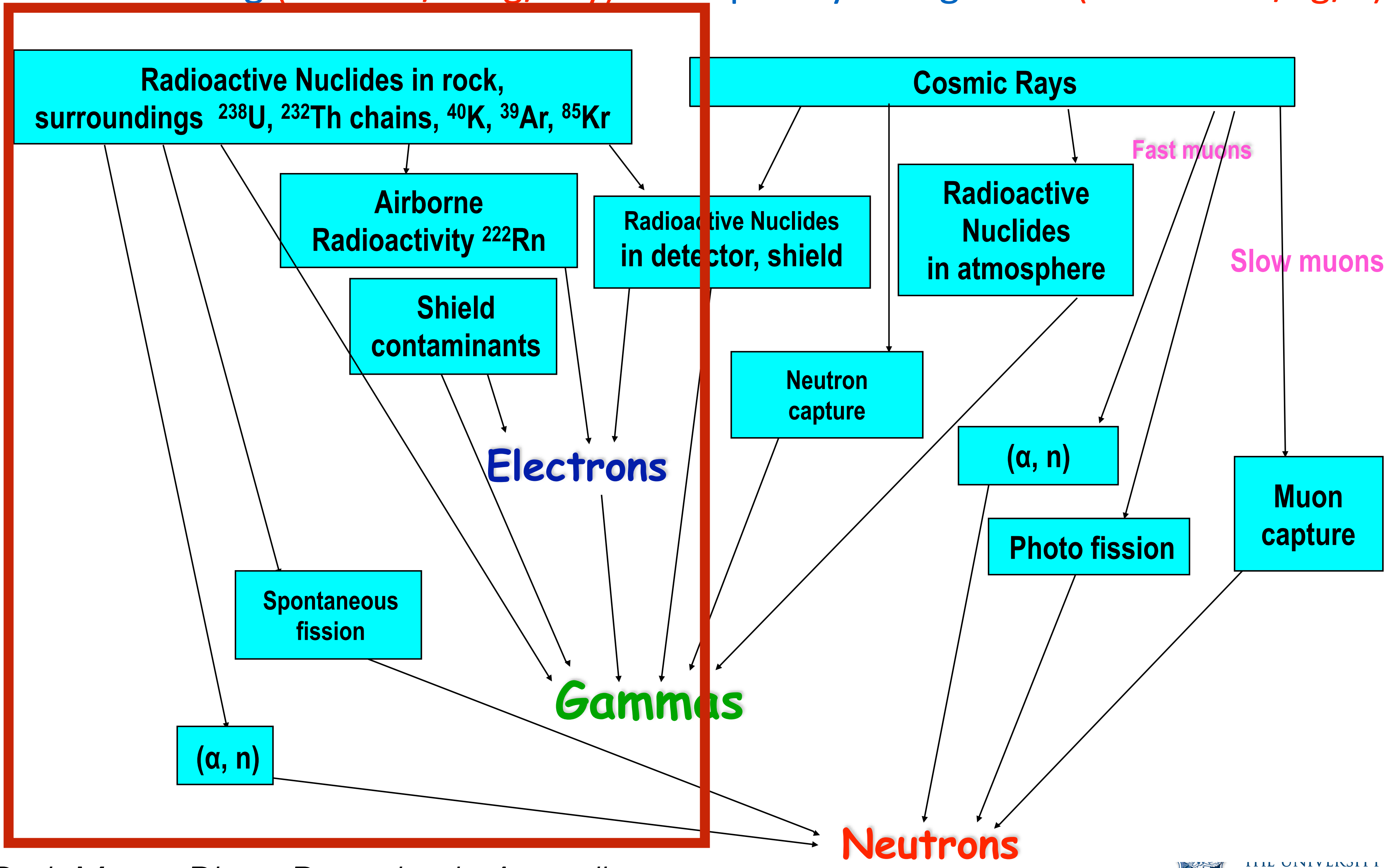


Site (multiple levels given in ft)	Relative muon flux	Relative neutron flux T > 10 MeV
WIPP (2130 ft) (1500 mwe)	$\times 65$	$\times 45$
Soudan (2070 mwe)	$\times 30$	$\times 25$
Kamioke	$\times 12$	$\times 11$
Boulby	$\times 4$	$\times 4$
Gran Sasso (3700 mwe)		
Frejus (4000 mwe)	$\times 1$	$\times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

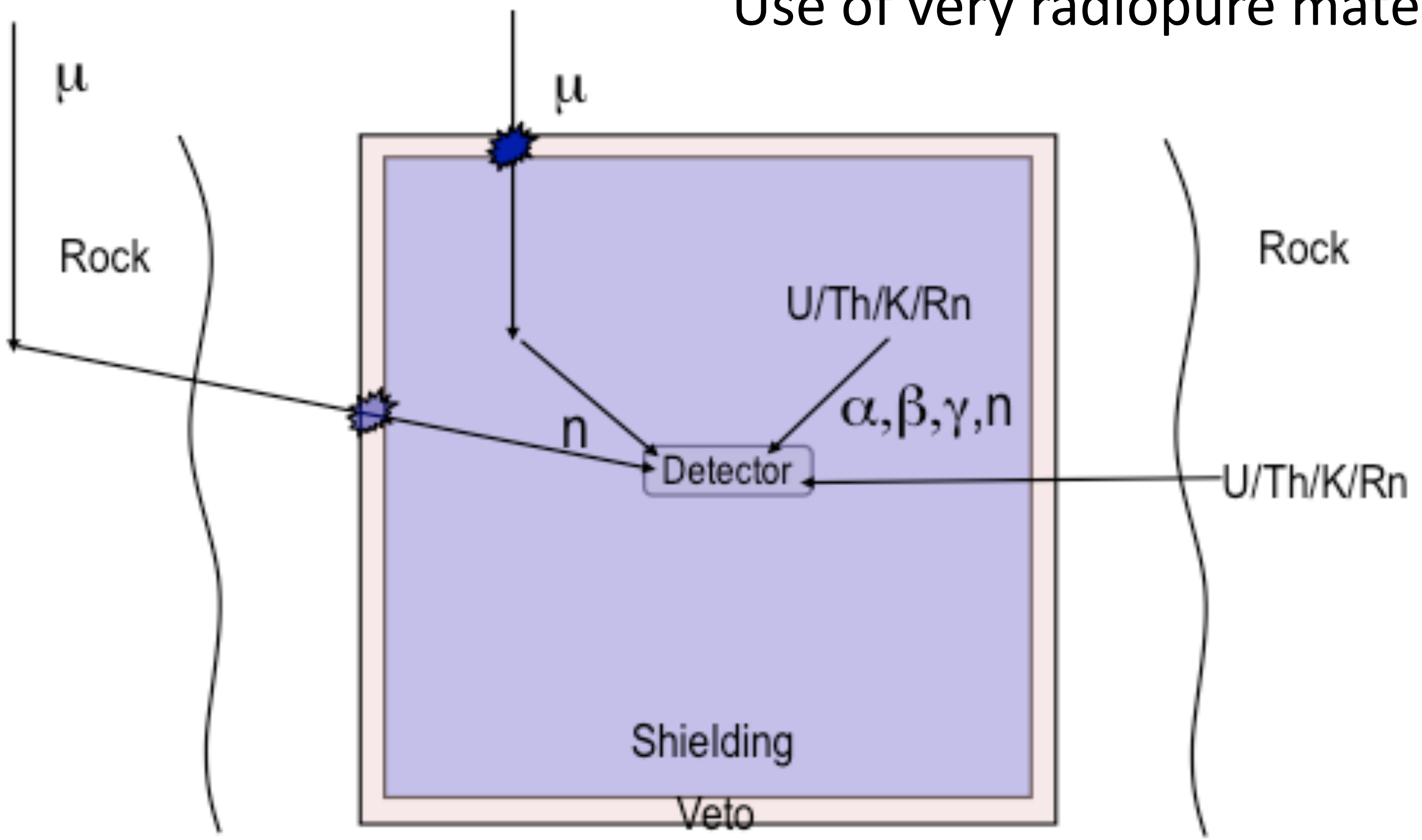
Background: cosmic rays and natural radioactivity

WIMP scattering (<1 evts /10kg/day) swamped by background (>10^{6-7} evts/kg/d)



Remaining Background

Use of very radiopure materials



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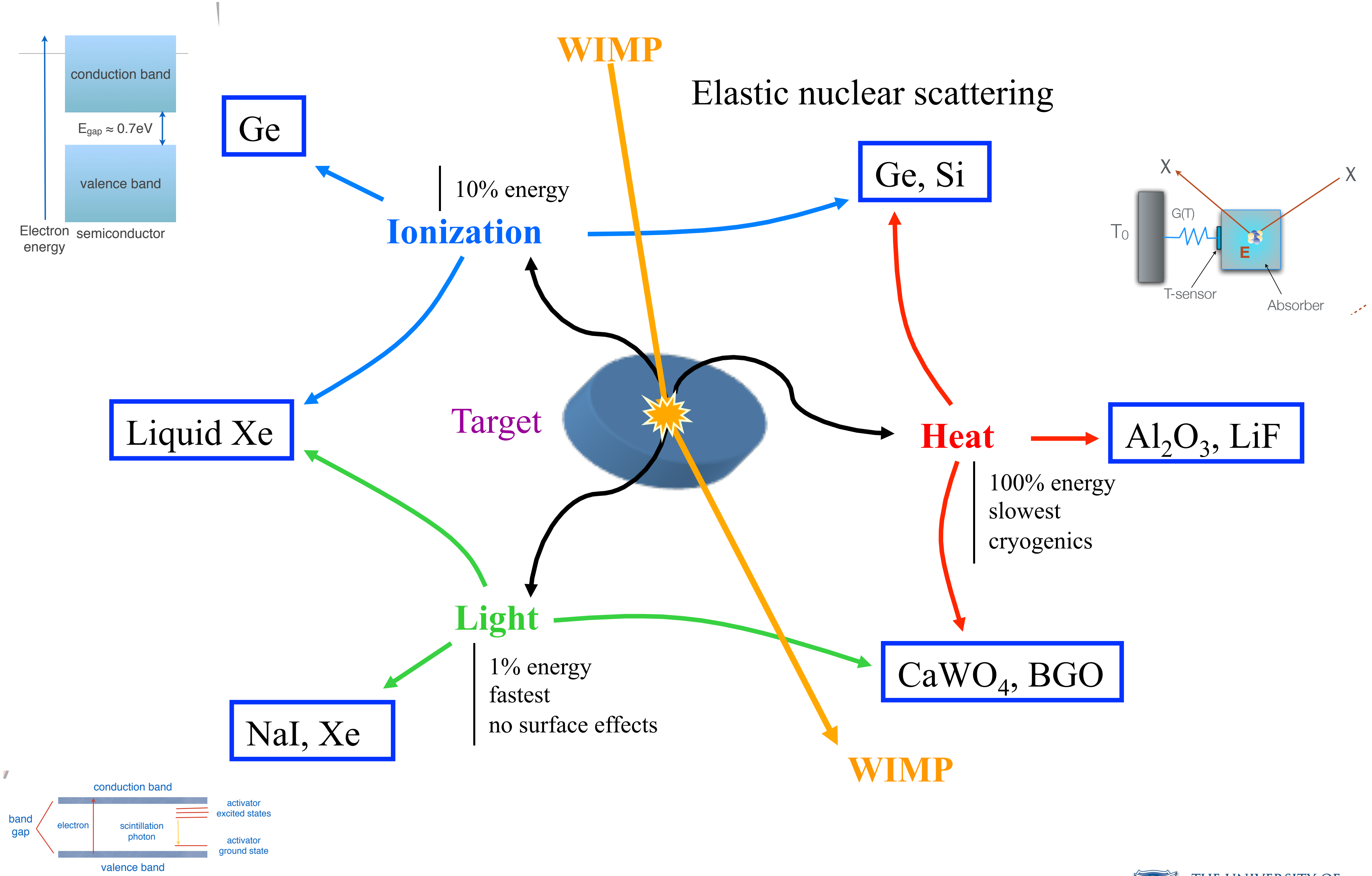
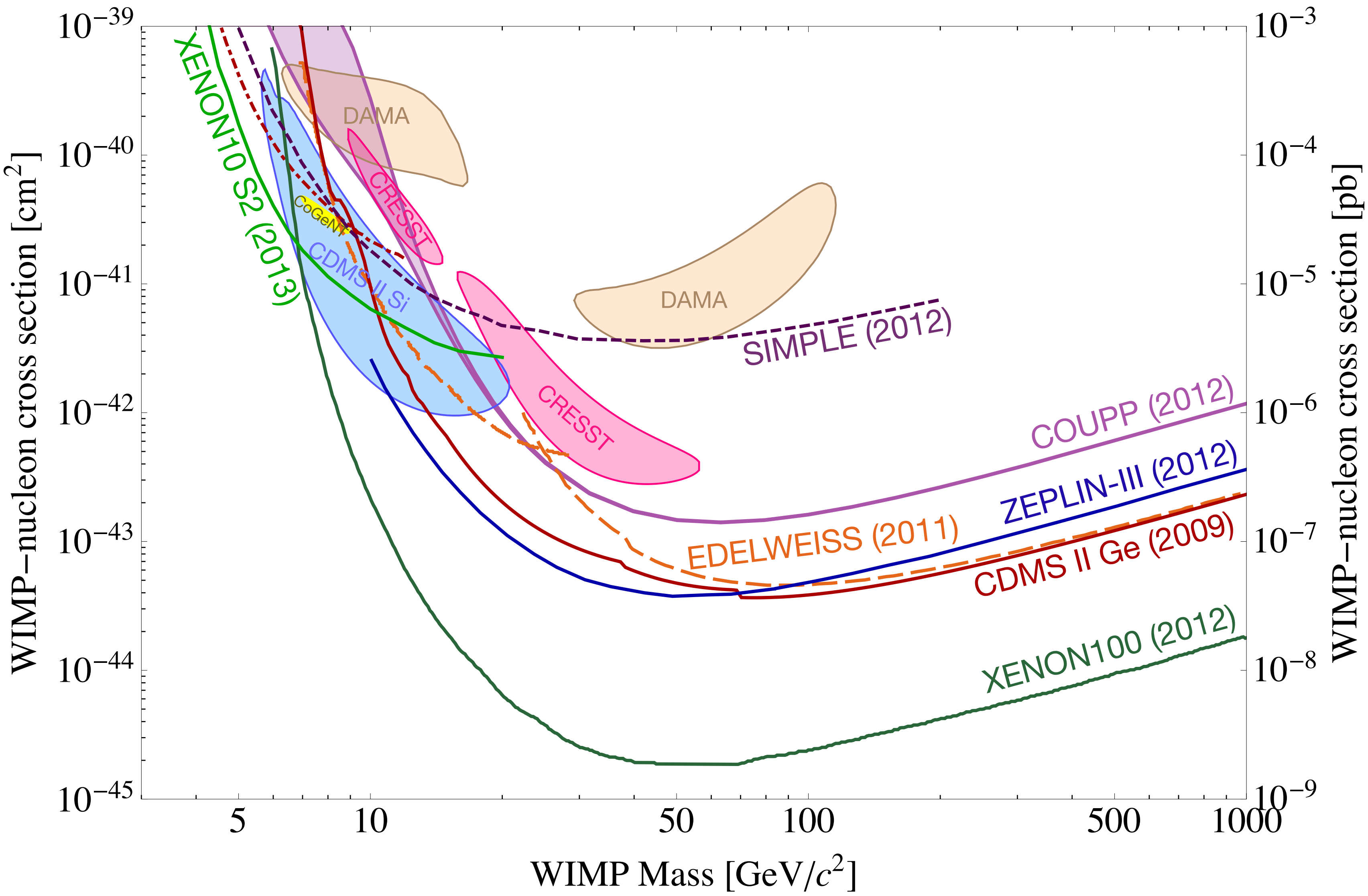
Detection Methods



Combined Results



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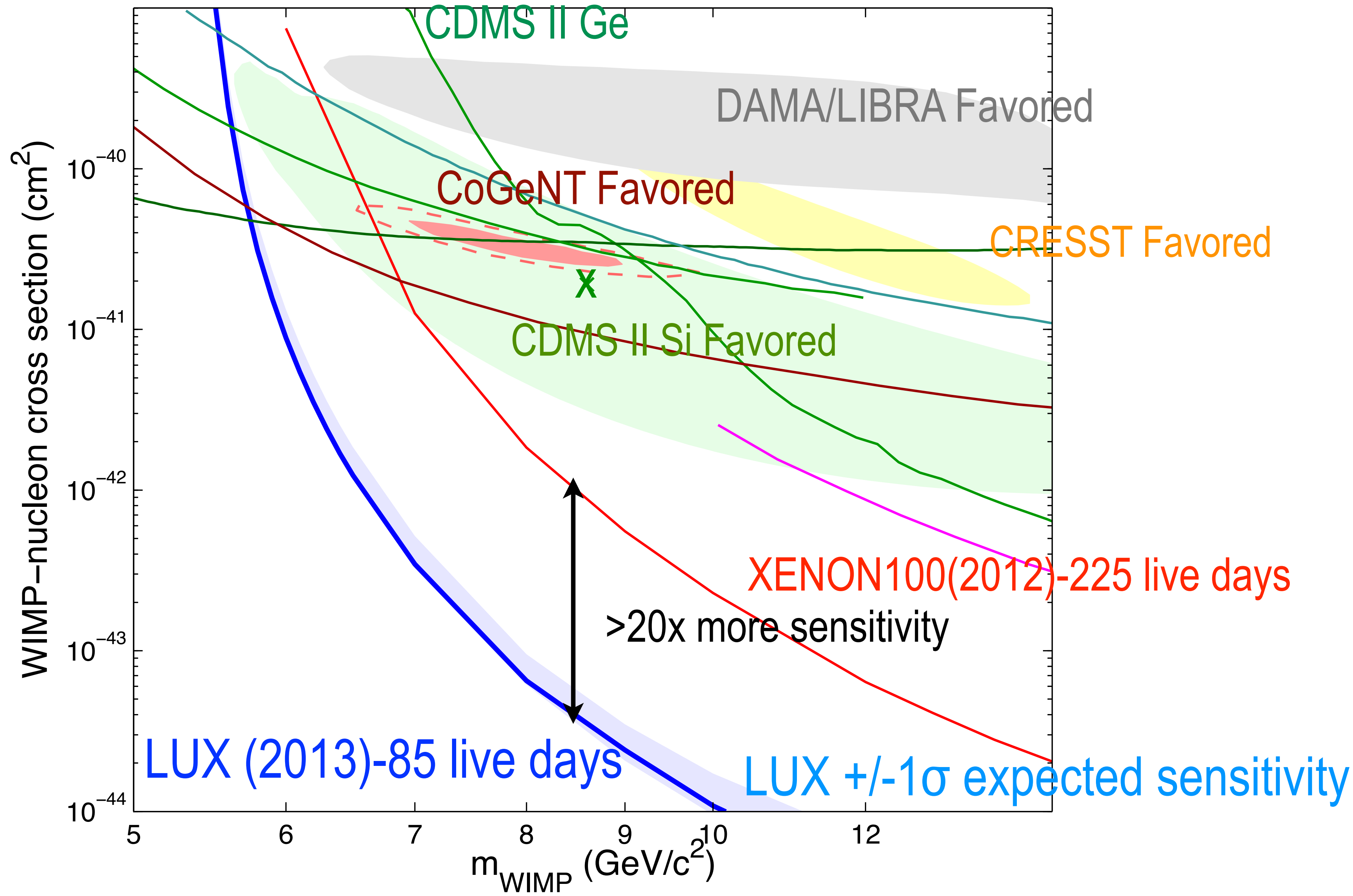
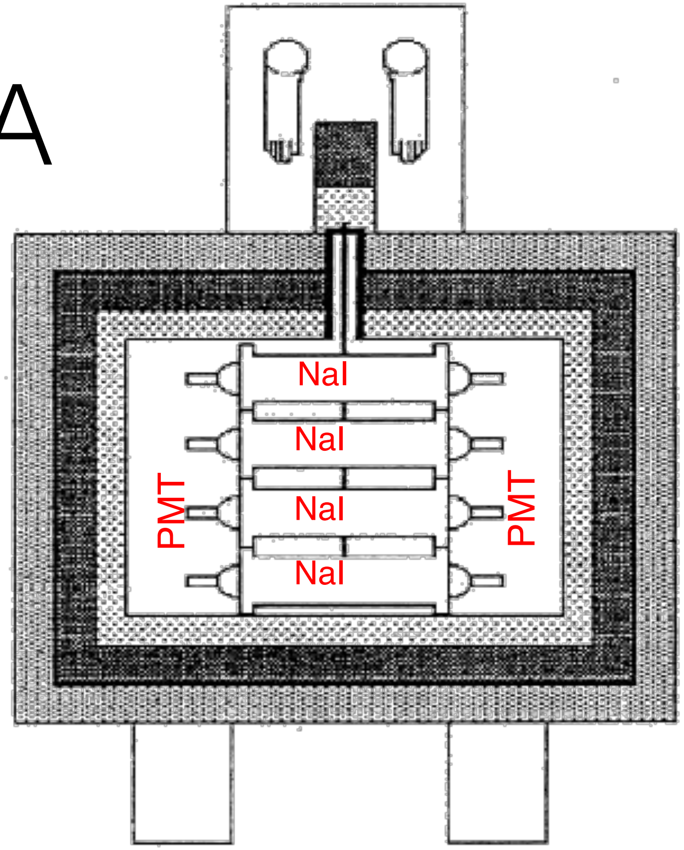
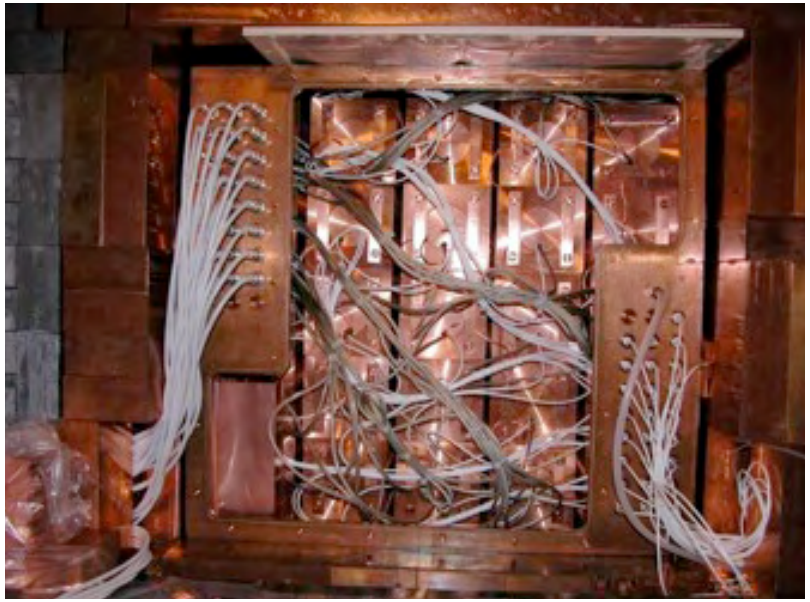
Low Mass WIMPs



DAMA-LIBRA

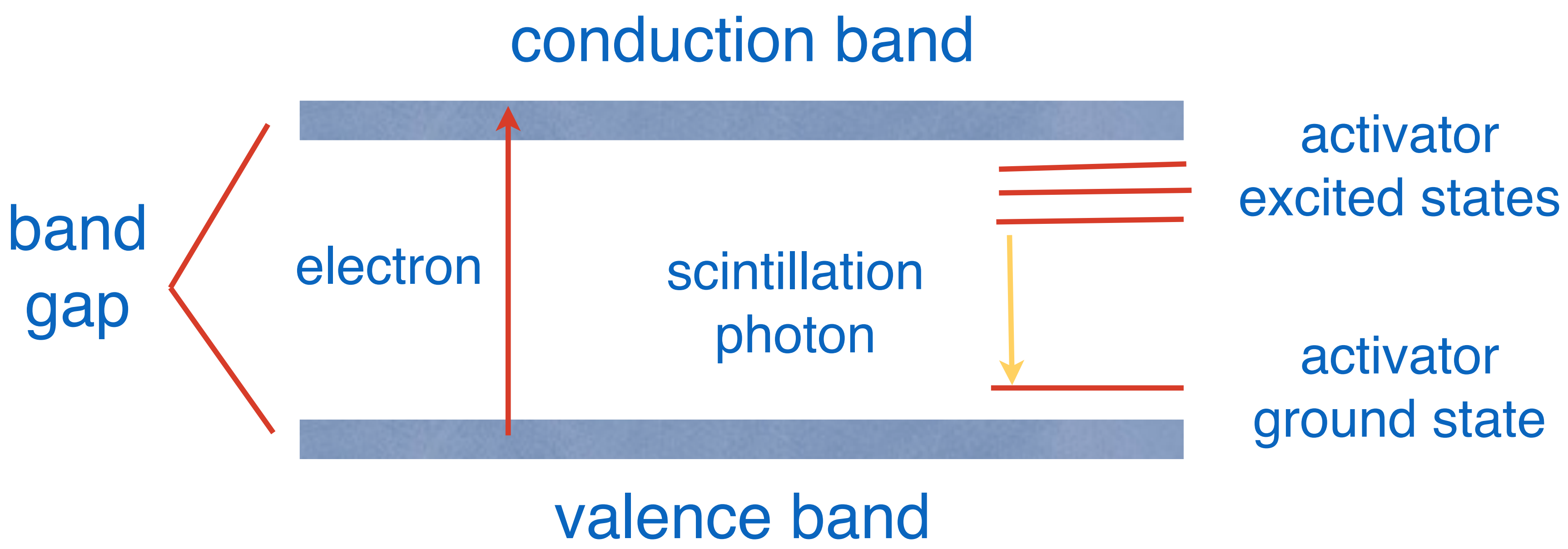


Based in Gran Sasso lab (3500 mwe)
250Kg of NaI Crystals.



Human radioactivity can contaminate the measurement - require clean room environments.

Room Temperature Scintillation Experiment

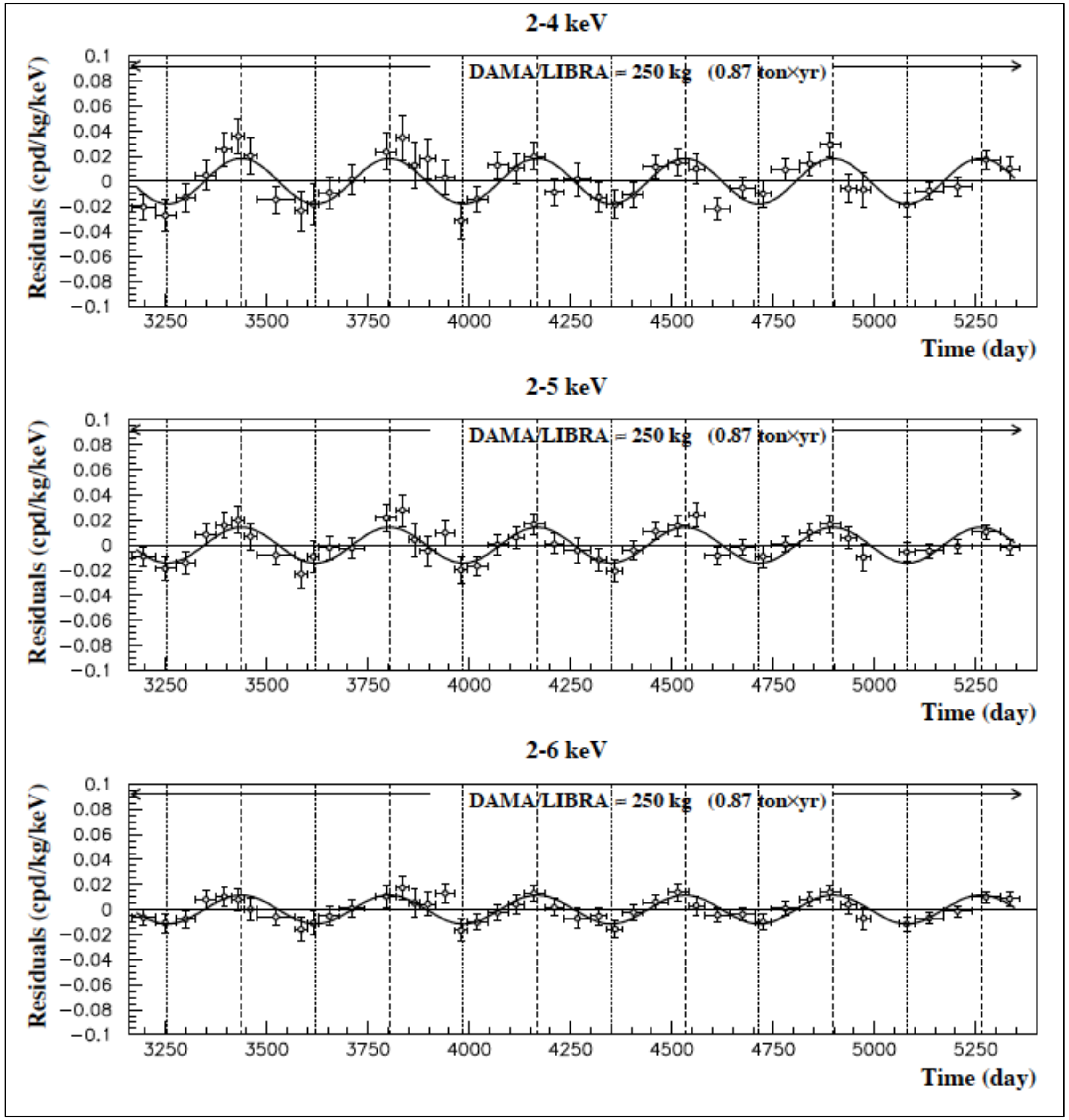


NaI (Tl): 20 eV to create e^--hole pair, scintillation efficiency ~ 12%

➡ 1 MeV yields 4 x 10^4 photons, with average energy of 3 eV

➡ dominant decay time of the scintillation pulse: 230 ns, λ_{max} = 415 nm

DAMA-LIBRA



- 9 σ evidence of DM-like signature.

DAMA/LIBRA modulation is 0.0112±0.0012 cpd/kg/keVee in 2-6 keV

Signal ~ 0.15 cpd/kg/keVee in [2,6] keVee for 10 GeV/c^2 10^{-41} cm^2

New DAMA/LIBRA run:

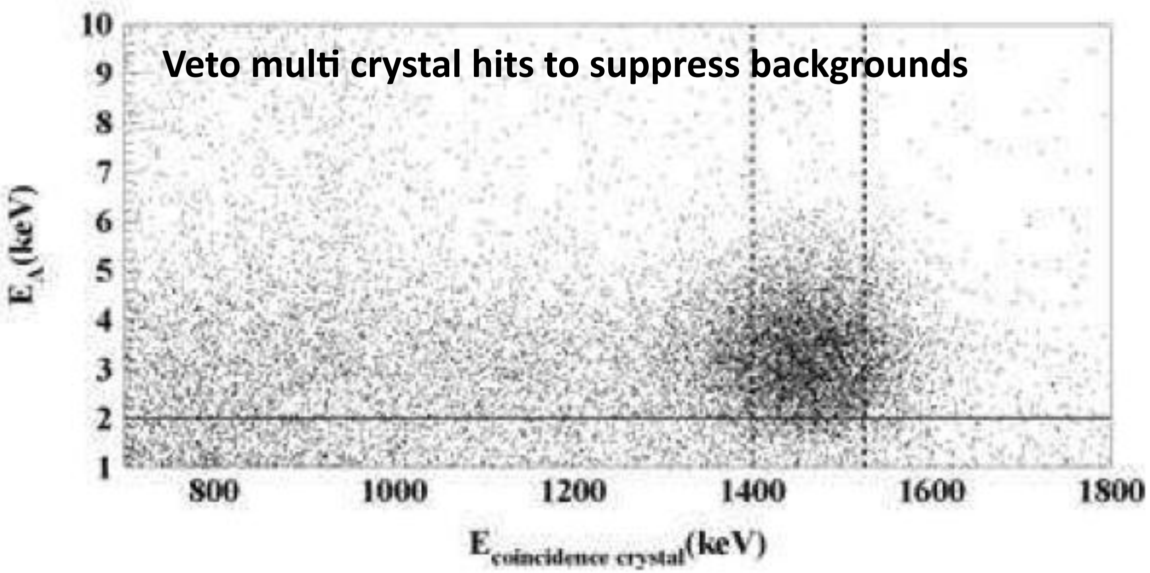
- New Hi-QE PMTs
- Taking data again since Dec 2010, first results…. in few years

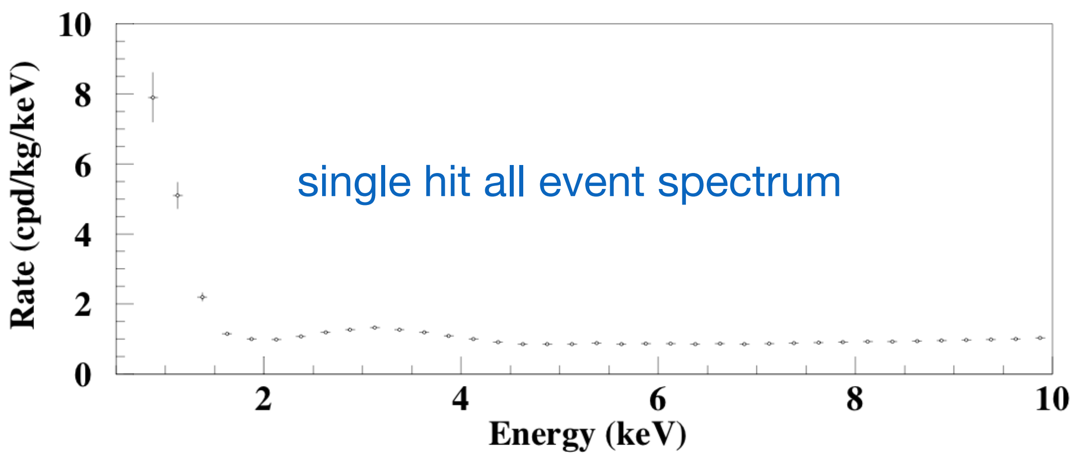
2012 JINST 7 P03009

DAMA background studies

WIMPs interact only once → single scatter selection require some position resolution.

No distinction between dark matter interaction through e⁻ or nuclear recoil.





No systematics effect or background reaction is able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature.

What’s Next?

- DAMA/LIBRA finds a robust modulation signal that may be interpreted as dark matter. This WIMP signal is excluded by Xe detectors (e.g. LUX)

- Resolving the DAMA/LIBRA modulation puzzle: Hidden detector effect? Non WIMP dark matter? Electron recoil?

- Testing DAMA results is challenging:
  - ➡ requires complementary tests in the Southern Hemisphere
  - ➡ crystals purities < 1 ct/keV/day —> New R&D on NaI purity

worldwide effort to check DAMA:

- ➡ South Pole —> DM ice
- ➡ Australia, Stawell and Italy, Gran Sasso —> SABRE
- ➡ Another Northern Hemisphere site —> KIMS (different Crystals)

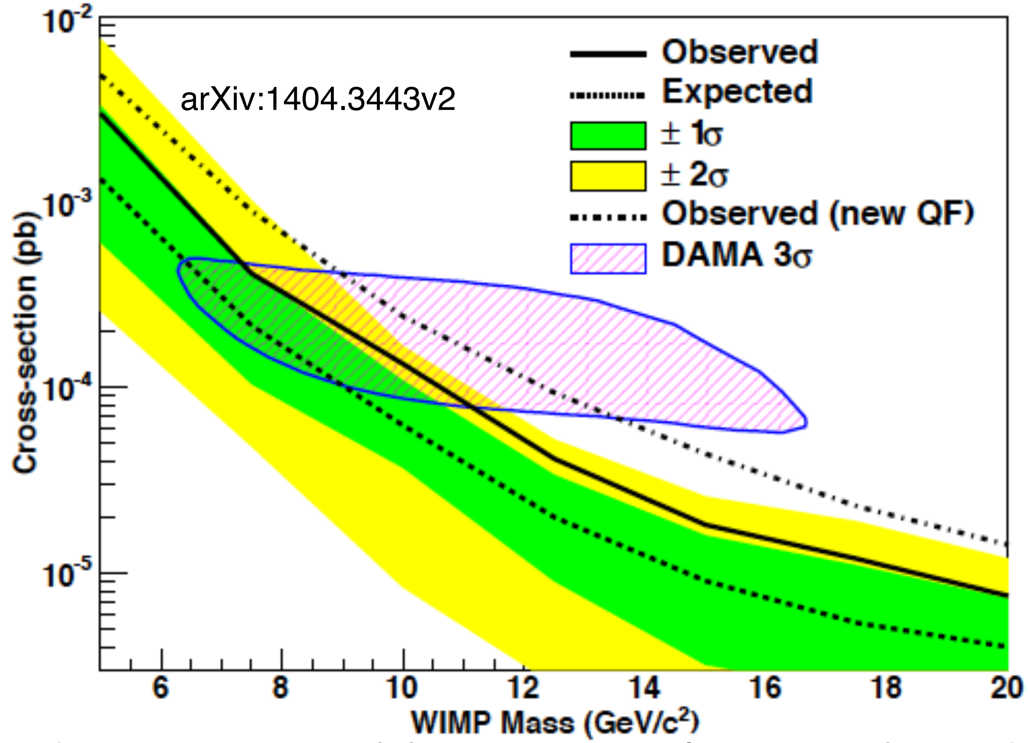
Kims

KIMS (Yangyang Lab, Korea - 2400 mwe)

H.S. Lee,[1,*] H. Bhang,[2] J.H. Choi,[2] S. Choi,[2] I.S. Hahn,[3] E.J. Jeon,[4] H.W. Joo,[2] W.G. Kang,[4] B.H. Kim,[2] G.B. Kim,[2] H.J. Kim,[5] J.H. Kim,[2] K.W. Kim,[2] S.C. Kim,[2] S.K. Kim,[2] Y.D. Kim,[4,6] Y.H. Kim,[4,7] J.H. Lee,[2] J.K. Lee,[2] S.J. Lee,[2] D.S. Leonard,[8] J. Li,[4] J. Li,[9] Y.J. Li,[9] X.R. Li,[10] S.S. Myung,[2] S.L. Olsen,[2] J.W. Park,[2] I.S. Seong,[2] J.H. So,[4] and Q. Yue[9]

Results from 67 kg-y (2009-2010) are consistent with null, incl. the exp. decay of ^{134}Cs.

Note they hey are discriminating against electron recoils



The 90% upper limit of KIMS amplitude is comparable to DAMA's annual modulation (0.0189 cpd/kg/keV), newer very preliminary result exclude more... but it's a PhD thesis

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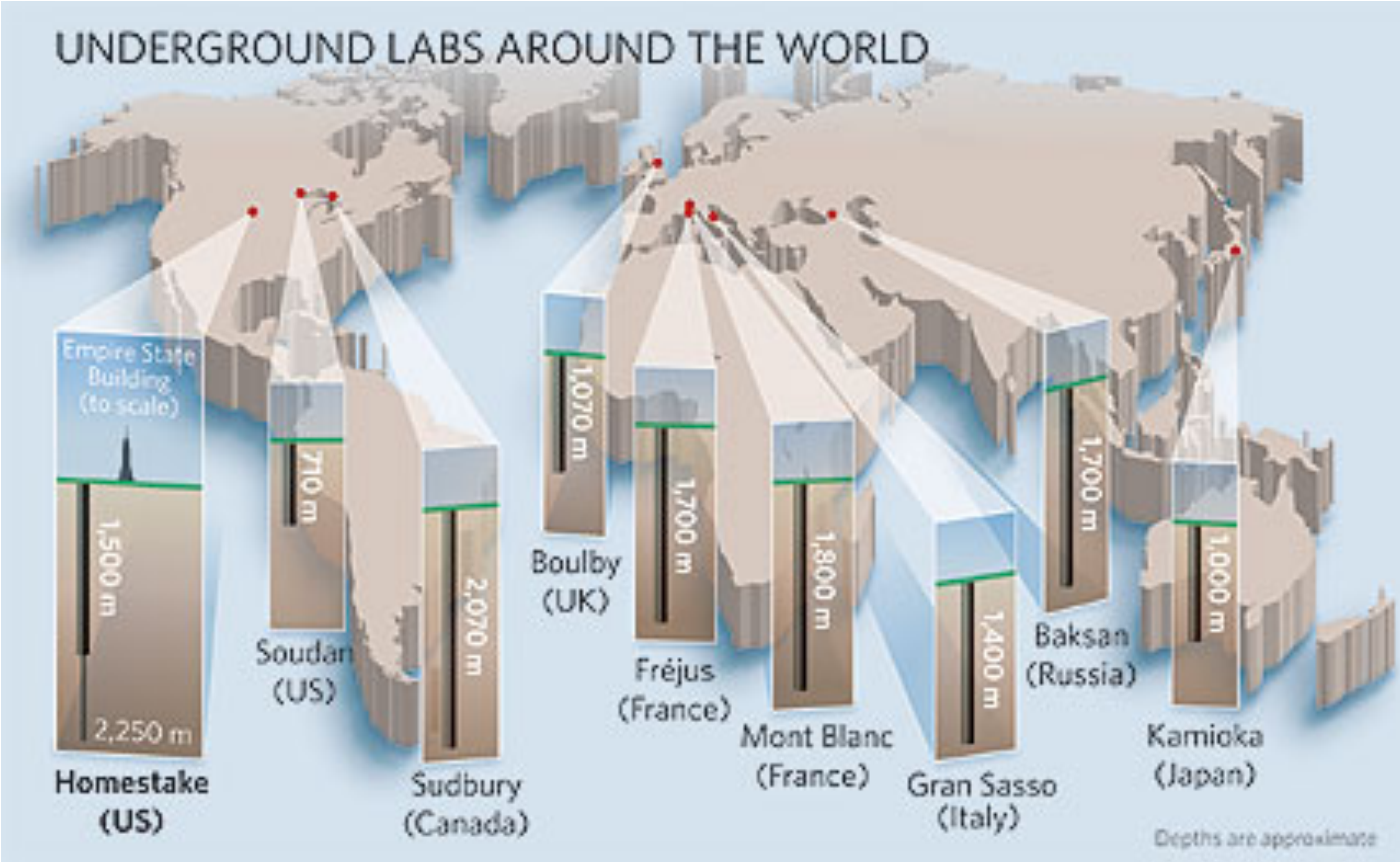
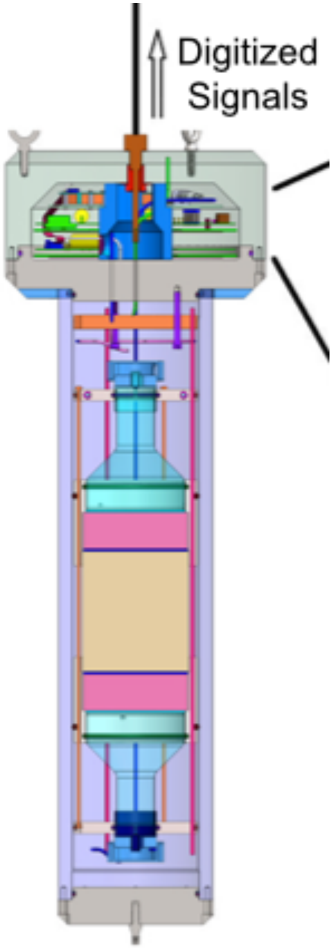
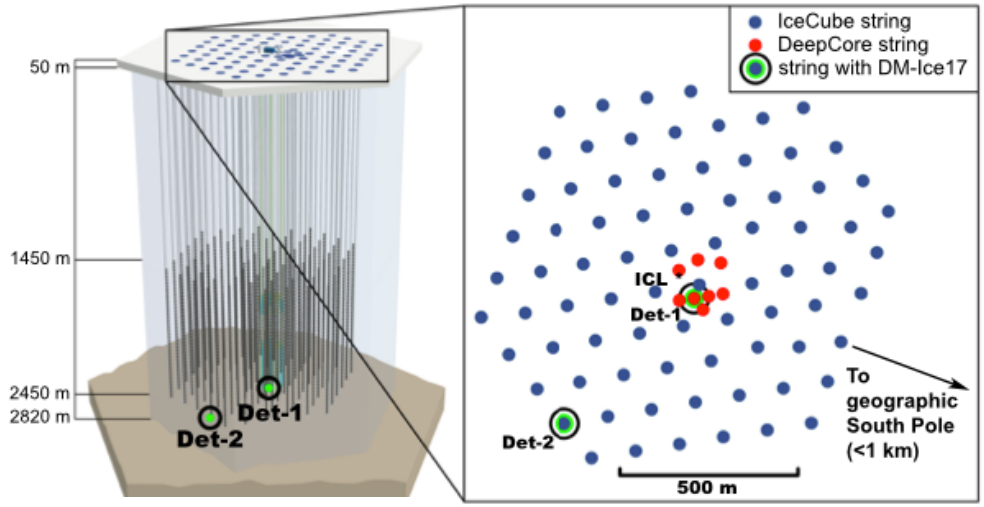
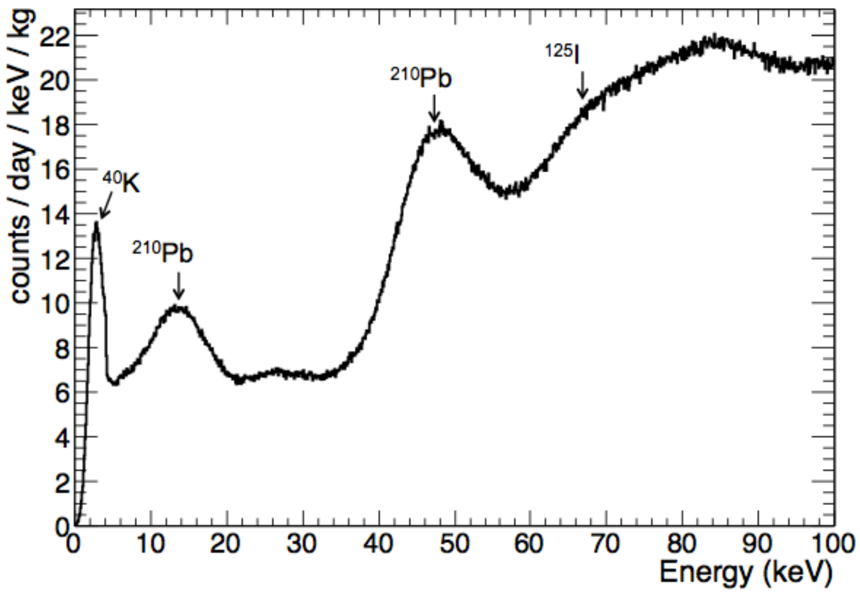


DM-Ice

17kg operating since 2011







6.5 – 8.0 keVee region is measured to be 7.9 ± 0.4 counts/day/keV/kg."
Dominated by assembly housing and PMT - no ice contribution

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DM-Ice

Prototype: 8.5 kg NAIAD crystals (~8 cts/keV/d) at the bottom of two IceCube strings (Dec 2010)

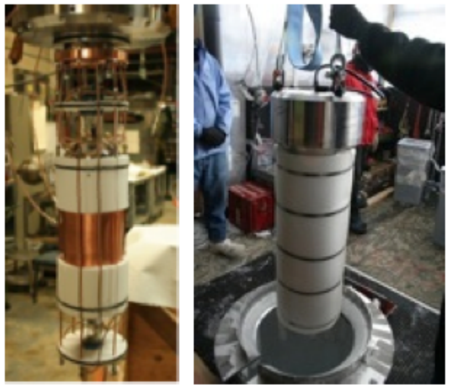
To test DAMA requires crystals purities < 1 ct/keV/day

New R&D on NaI purity ongoing

10 m_χ [GeV/c^2] 10

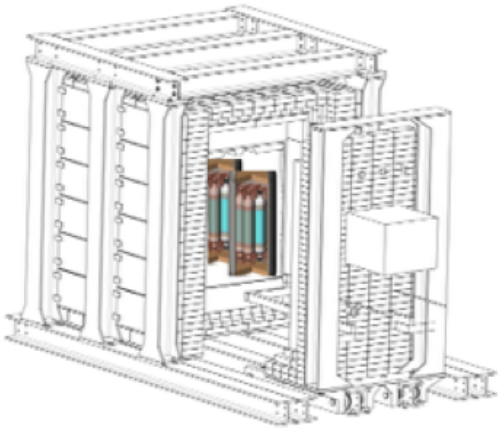
A Phased Experimental Program

DM-Ice17



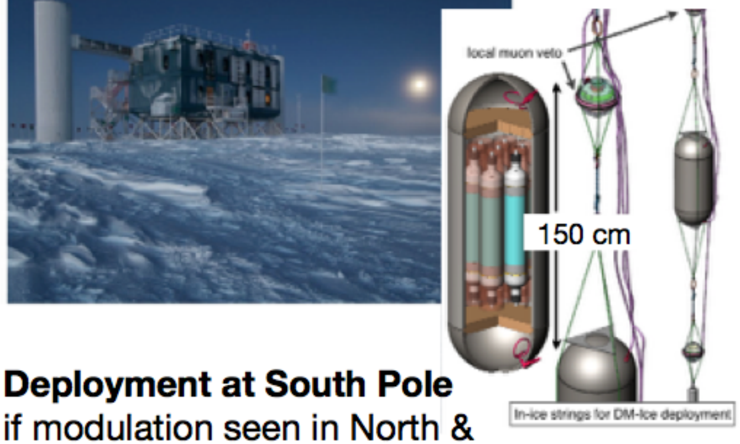
Operating since 2011
17 kg of NaI(Tl) at 2450m depth at South Pole

DM-Ice 250 North



Northern Hemisphere Run
portable 250 kg NaI(Tl) detector, first deployment in the Northern Hemisphere

DM-Ice 250 South



Deployment at South Pole
if modulation seen in North & ice drilling becomes available

SABRE: Sodium iodide with Active Background REjection

- **Dual-linked experiment**: one part in Gran Sasso (Italy) and one in Stawell (Australia)

- Developing and testing low background NaI(Tl) scintillating crystals that exceed the radio-purity of DAMA/LIBRA (driven by F. Calaprice - Princeton). —> NO ONE SUCCEEDED TO DO THIS.

- A well-shielded active veto to reduce internal and external background

- New low background and high QE PMTs and low radioactivity copper housing U, Th < μBq/kg

SABRE

Current SABRE Collaboration

Princeton University (Led by Frank Calarice) main driver; University of Houston, PNNL, Gran Sasso National Lab, Milano University; Roma la Sapienza University, University of Melbourne, Australian National University and University of Adelaide.

SABRE Status – NaI Powder

Princeton R&D with Sigma-Aldrich resulted in radiopure NaI powder similar to Dama crystals

Element	Seastar-MV Lab (ppb)	Sigma-Aldrich (ppb)	DAMA Powder (ppb)	DAMA Crystal (ppb)
[K]	12	3.5 (18)*	100	~13
[Rb]	14	0.2	n.a.	<0.35
[U]	<0.2 (0.003.5)**	<1.7 (<0.001)**	~0.020	0.0005-0.0075
[Th]	<0.1 (<0.001)**	<0.5 (<0.001)**	~0.020	0.0007-0.010

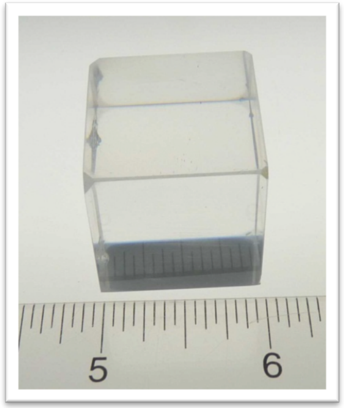
Chemical purification research started at Princeton with J. Benziger, F. Calaprice, A. Wright. Efforts transitioned to collaborations with commercial companies.

* Denotes measurement by Seastar.

** Denotes measurement at PNNL by E. Hoppe and company.

SABRE Status – Crystal Growth

Princeton is working with RDM in Watertown, Massachusetts to develop methods to grow, cut, and polish crystals with high radiopurity.



Crucible/ Ampoule	Cleaning Procedure	K	Rb	Th	U
		(Impurities in ppb)			
#1 with NaI	Normal	65 (10)	N.A	0.2-0.4	0.1-0.2
#2 with NaI	Precision	41 (10)	N.A.	N.A.	N.A.
#3 with NaI	Precision	63 (10)	N.A.	N.A.	N.A.
#4 with NaI	Precision	6 (10)	N.A	N.A.	N.A.
4 Heat w/o NaI Before heat Blank	Precision “ “	1.5 0.025 0.0010	0.0040 <0.001 <0.0001	0.0004 <0.001 <0.0001	0.00014 <0.0004 <0.00005

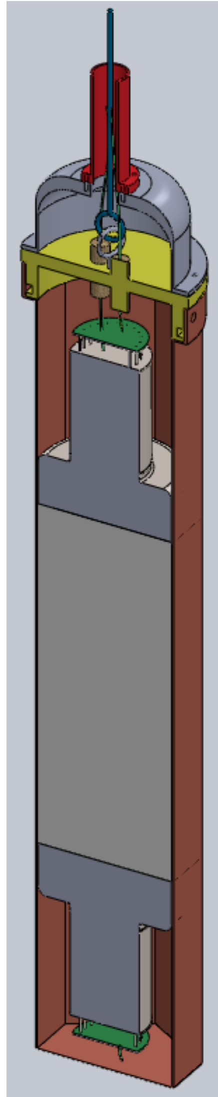
Maximum contaminations due to crystal growth are

[K] < 0.4 ppb, [Rb] < 1 ppt, [U] and [Th] < 0.1 ppt.

Excellent Results in #4 (synthetic material)

SABRE PMT

Low radioactivity PMT



- Hamamatsu R11065-series PMT
  - ~30-35% Q.E.
  - ~1 mBq U and Th (lower chain activity)
  - ~1 mBq Co, ~10 mBq K
- High light collection efficiency without light guide
- Minimal background due to low radioactivity & veto
- Light yield from NaI(Tl) as high as 19 p.e./kev observed.
- LNGS pre-amp to reduce PMT noise (dark rate & light)
- Low energy threshold with high L.Y. and low Noise.

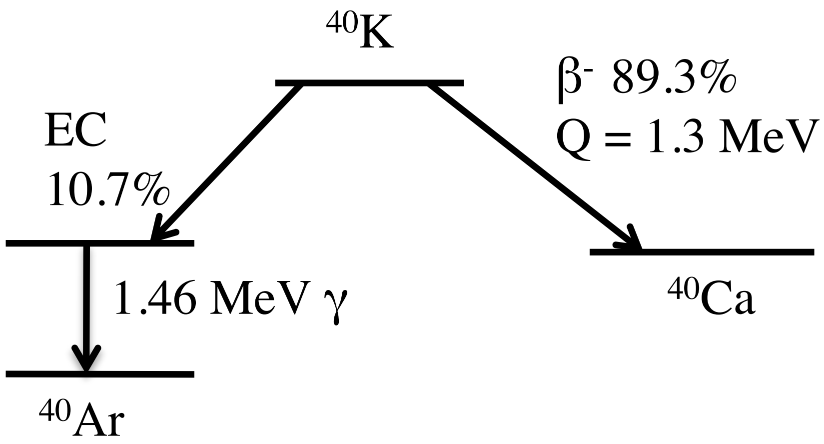
PNNL electroformed copper for enclosure

- ~µBq/kg U, Th radioactivity
- Same as used in the Majorana 0νββ decay experiment

DAMA/LIBRA Energy spectrum

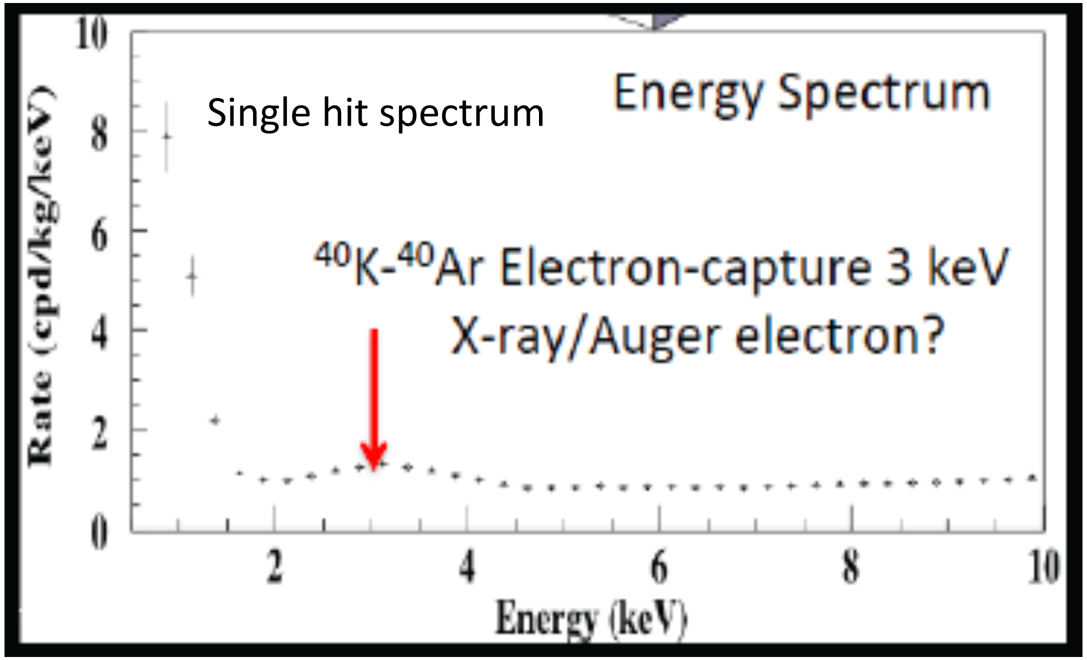
DAMA/LIBRA signal region: 2-6 keV.

Background from ^{40}K decay? 13 ppb K in DAMA crystals.



$^{40}K \rightarrow {}^{40}Ar$, ~11% branch ratio

- 3 keV K shell X-ray, Auger e^-
- Background at ~3 keV if γ escapes



Eur. Phs. C56 333 (2008)

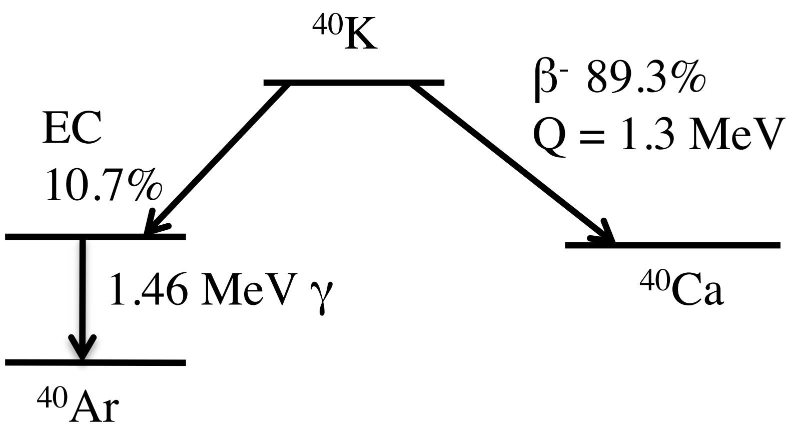
ACTIVE VETO

Goal: lower background, lower threshold, and higher sensitivity than DAMA.

DAMA/LIBRA signal region: 2-6 keV.

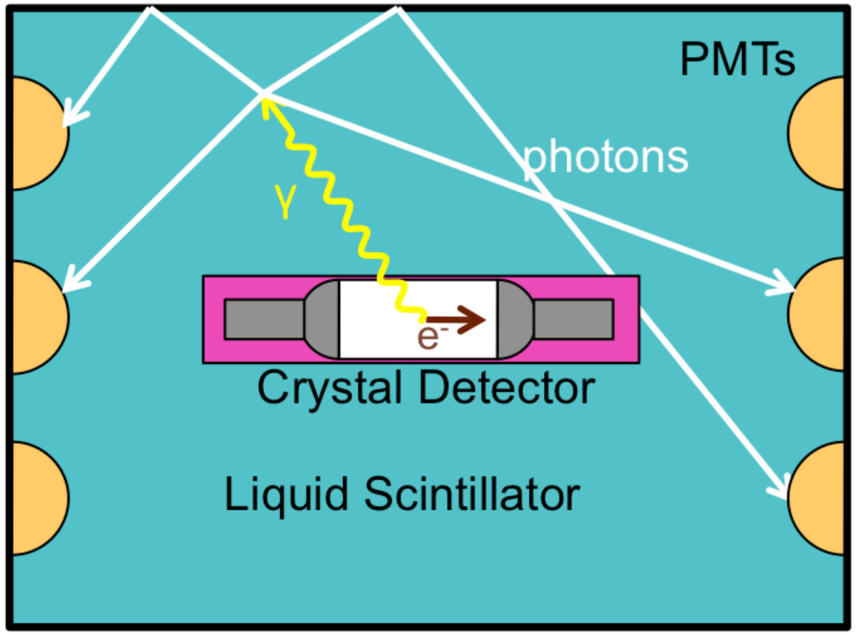
Background from ^{40}K decay? 13 ppb K in DAMA crystals.

Ultra-high purity NaI(Tl) detector + Active veto detector



$^{40}K \rightarrow ^{40}Ar$, ~11% branch ratio

- 3 keV K shell X-ray, Auger e^-
- Background at ~3 keV if γ escapes



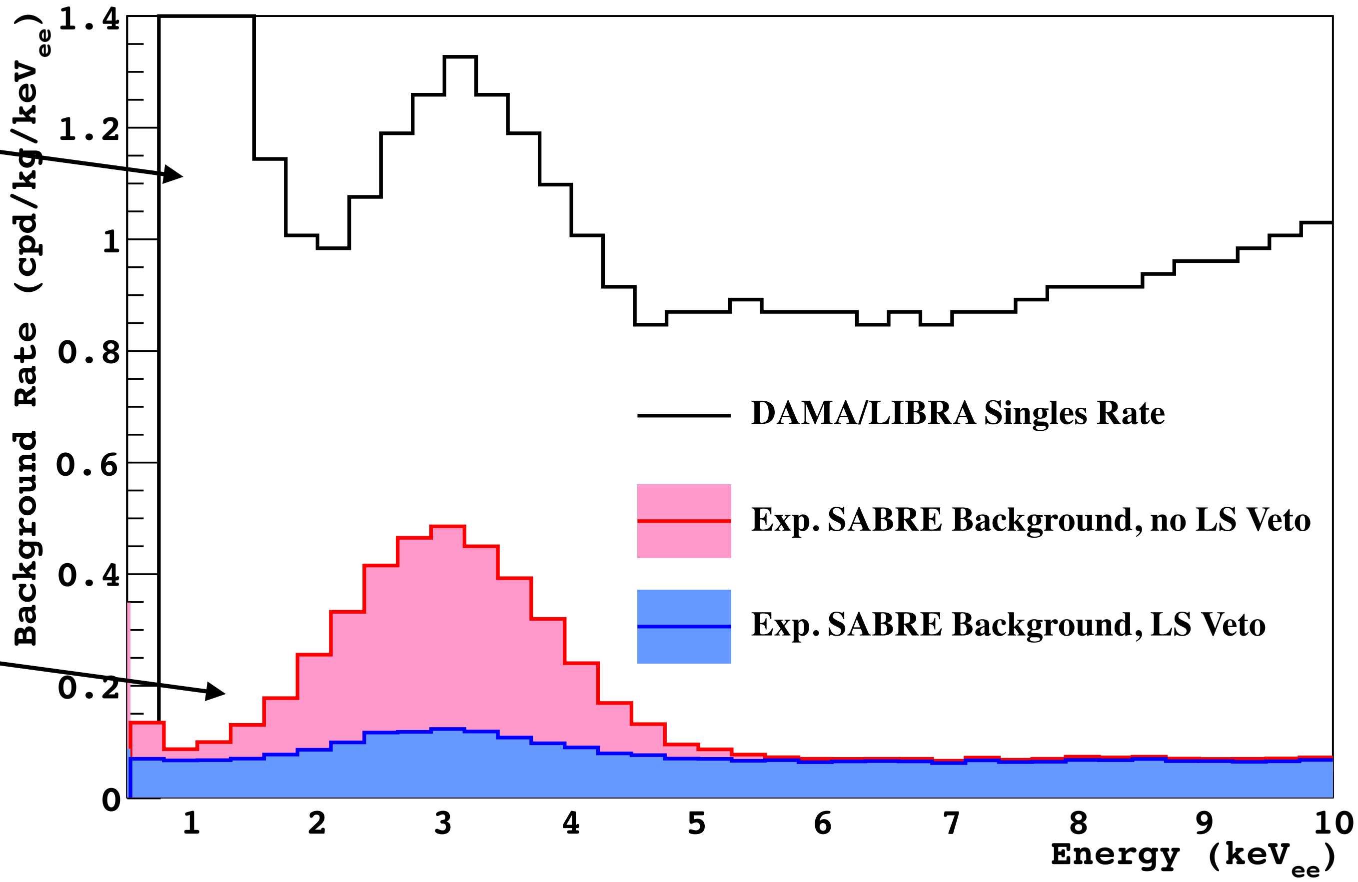
1.46MeV γ can be detected by a veto. ^{40}K background can be rejected.

Expected background

Photomultiplier, we will use new radio pure photomultipliers (as DarkSide)

Simulation, without Photomultiplier

Frank Calaprice



Assume the K level is the same as the powder (~10 ppb K);
U (<1 ppt), Th (<1ppt), Rb (0.2 ppb) levels are measurements in recent crystal tests.
External background is estimated to be relatively small compared to internal.

Testing Dama

DAMA/LIBRA modulation is 0.0112±0.0012 cpd/kg/keVee in 2-6 keV

Signal ~ 0.15 cpd/kg/keVee in [2,6] keVee for 10 GeV/c^2 10^{-41} cm^2

Amplitude [cpd/kg/keVee]:

~ 0.030 10 GeV/c^2 10^{-41} cm^2

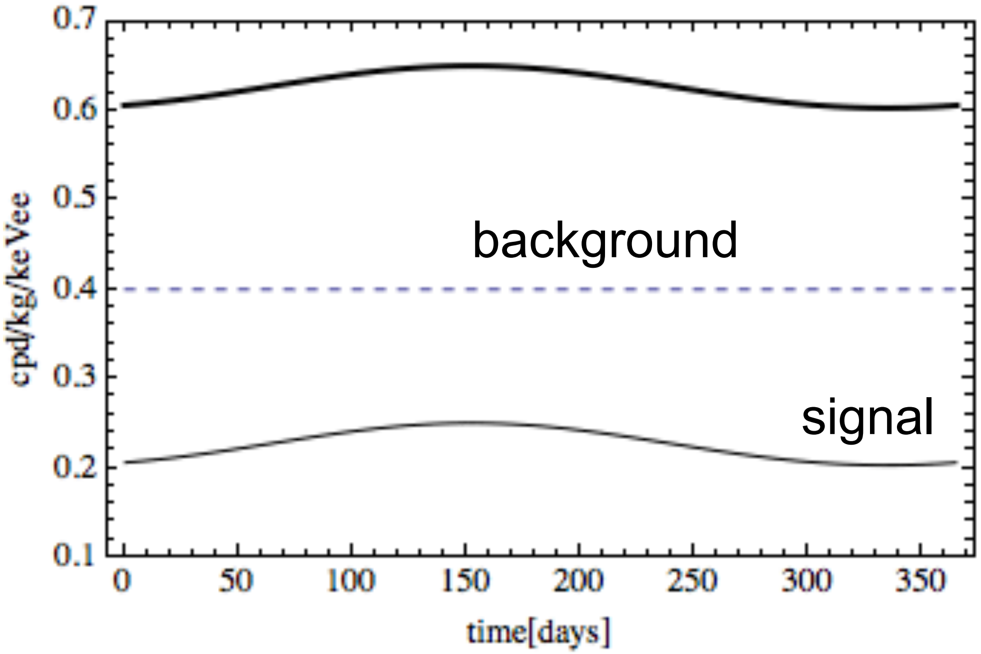
~ 0.015 8 GeV/c^2 10^{-41} cm^2

For 50 kg x 3 year

S/√B ~ 9.5 10 GeV/c^2 10^{-41} cm^2

S/√B ~ 5.2 8 GeV/c^2 10^{-41} cm^2

3 keVee, 10 GeV/c^2 , 10^{-41} cm^2



25 Kg of these new crystals+active veto can test DAMA/Libra in 3 years

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Dedicated 2-ton SABRE Veto Detector

Possible configuration of Sabre veto with Shielding

Cylinder: 1.5 m x 1.5 m

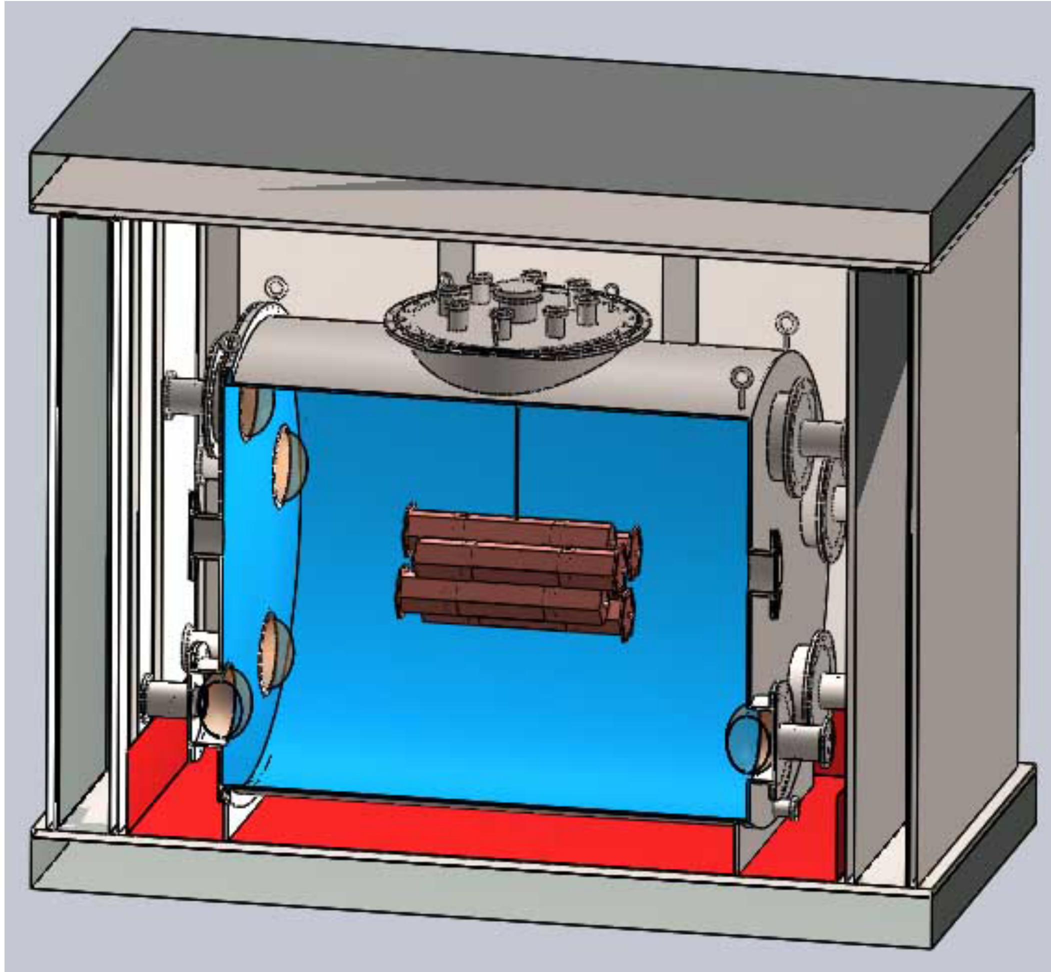
~2 tons LAB scintillator

10 8-inch PMTs

Reflector in inner surface

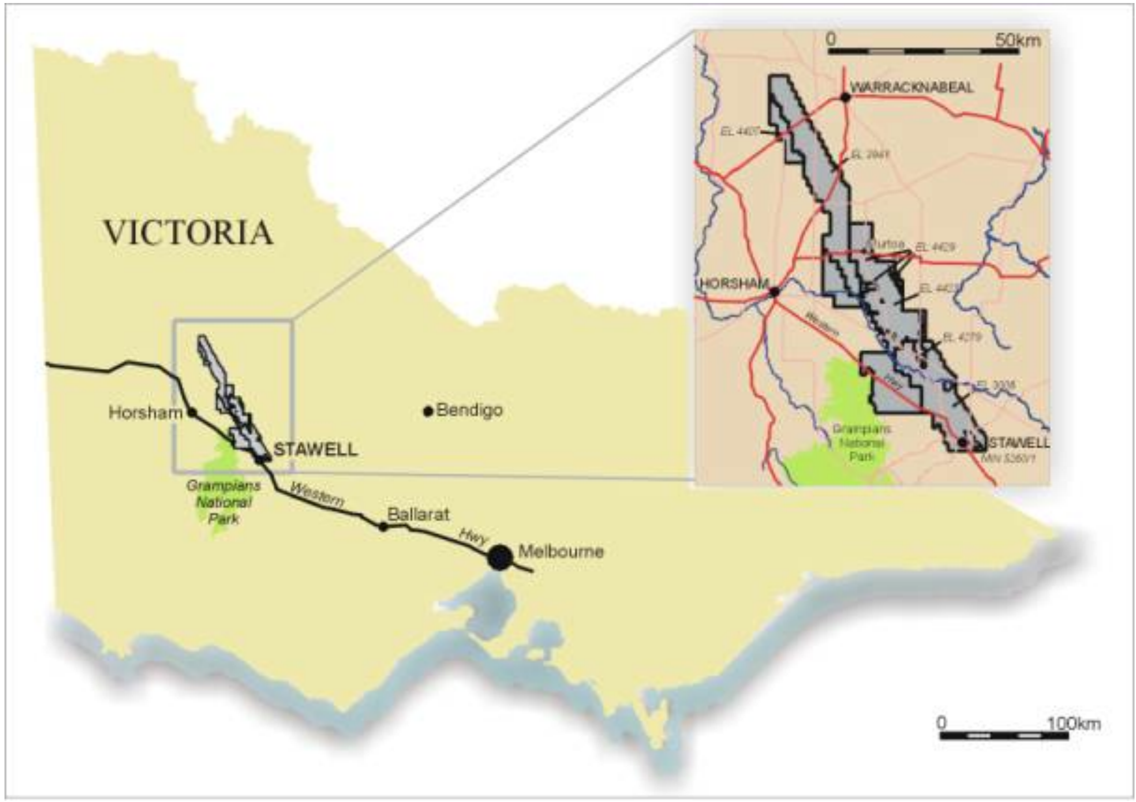
Expected: 0.22 p.e./keV

Shielding:
- 20-25cm steel
- Water filled chamber.



Australian Site

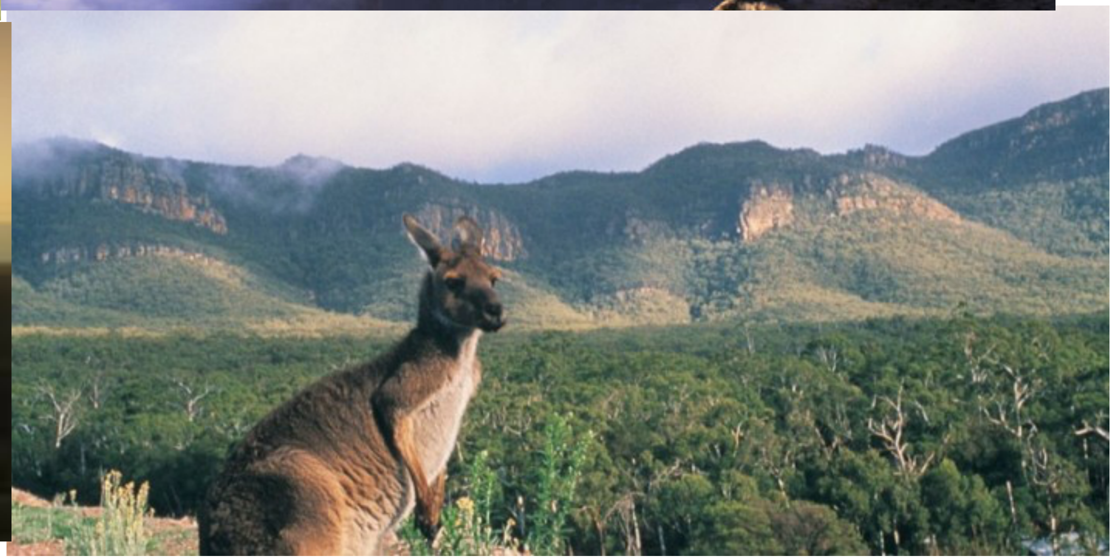
Stawell gold mine ~240 km west of Melbourne, will host the first ready to be used underground laboratory in the Southern hemisphere.



Australian Site

Near the Grampians National Park



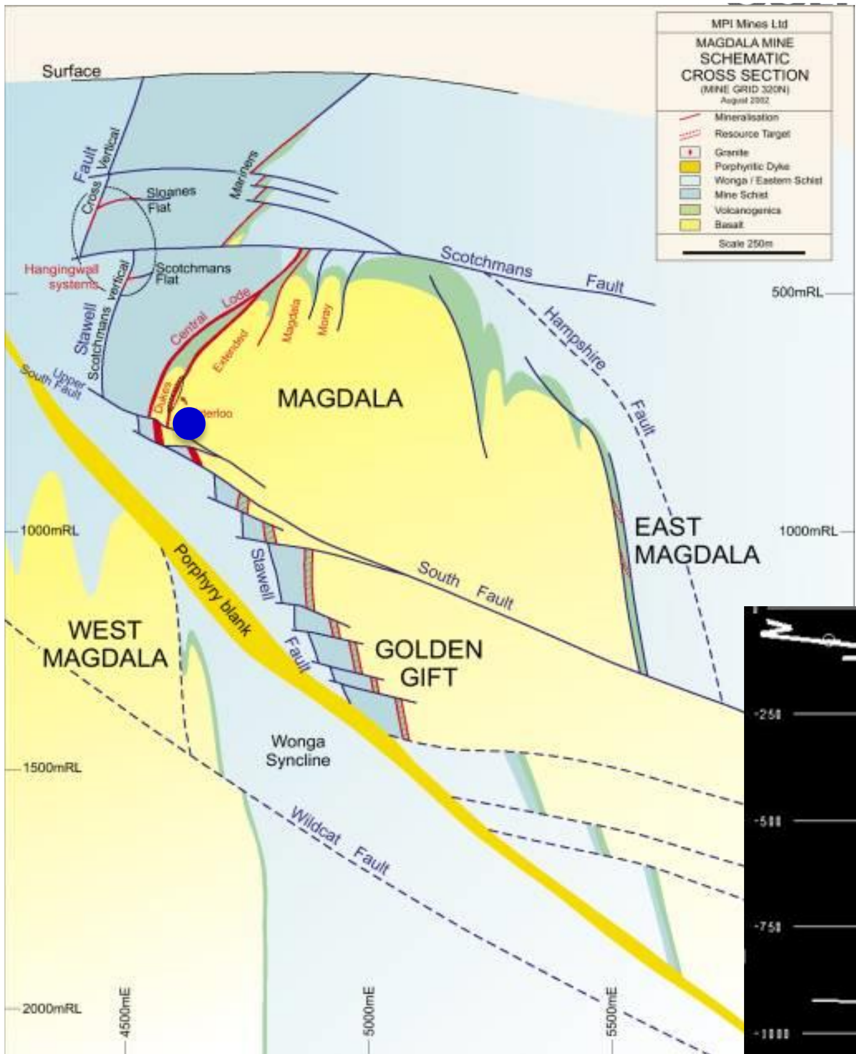
Stawell Gold Mine

Decline gold mine mine, 1.6 km deep, with many caverns. All sites served with electricity, optical fibre, reached by car/truck.

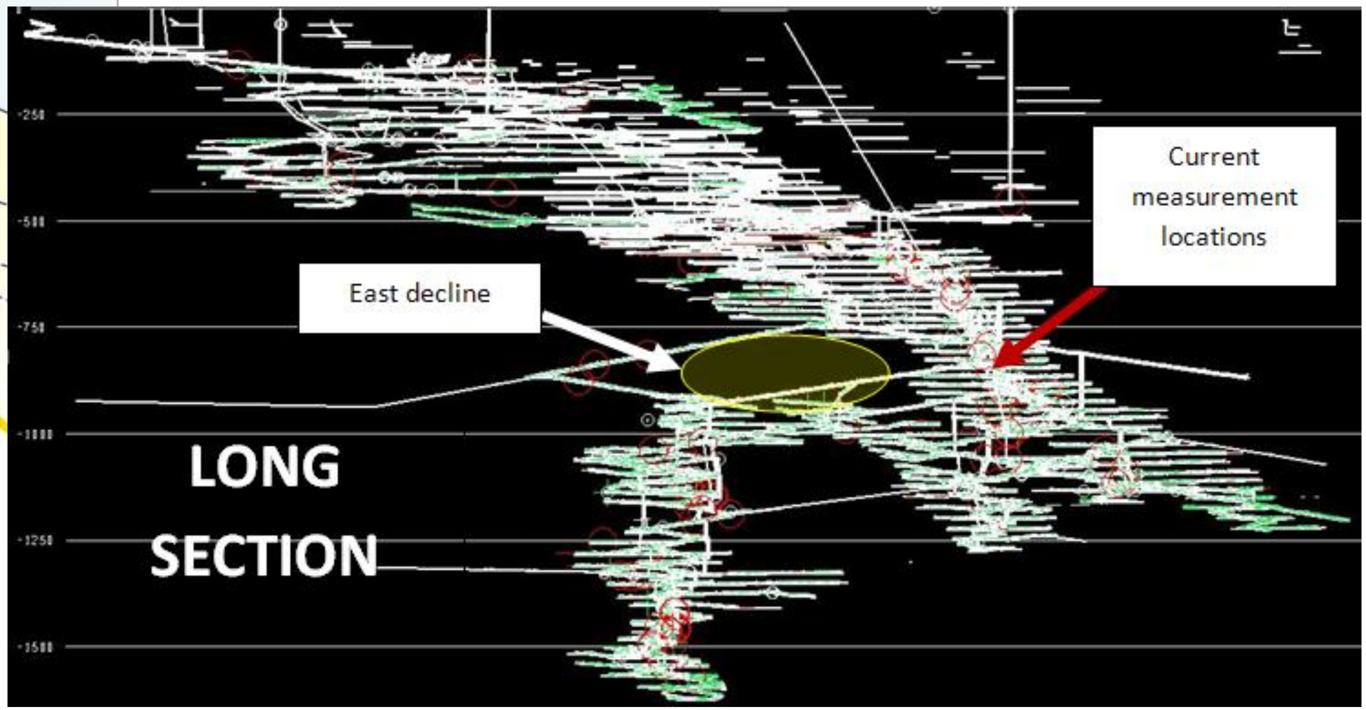
Stawell Gold Mine

The measurements are preformed in 2 different locations that can be ventilated, at 730 m , 880 m and 1.02 km

Stawell Mine ↓ 1km



We chose a site at 1.02km underground, ~3 km water equivalent (similar to Gran Sasso).



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Stawell Mine ↓ 1km

THE UNIVERSITY OF MELBOURNE

Measurements of the environment so far

	Gran Sasso Lab.	Stawell
Neutron Flux	4 x 10^{-6} n/s/cm^2	7 x 10^{-6} n/s/cm^2 UL
Gamma-ray flux below 3 MeV	0.73 γ/s/cm^2	2.5 γ/s/cm^2 UL
Radioactivity levels of rock		
Rock Hall ^{238}U (ppm) @ 880m	2.63	0.64
Rock Hall ^{232}Th (ppm) @ 880m	0.72	1.63
Refuge Radon Bq/m^3 (12 day accumulation)		36±5 21°C, 1056 kPa, 21% humidity

- These measurements have been made with the help of ANSTO
- We also thank Crocodile Gold Corp. and the Stawell gold mine staff for their help

Rock analysis

- Rock composition and concrete on walls contribute to the radioactive background

Banana dose 100 Bq/Kg

Client ID	^{40}K activity Bq/kg	^{210}Pb activity Bq/kg	^{226}Ra activity Bq/kg	^{228}Ra activity Bq/kg	^{228}Th activity Bq/kg	^{238}U activity Bq/kg
1. Basalt - 596/597	505 ± 27	79 ± 7	55 ± 4	34 ± 2	33 ± 3	53 ± 8
2. Quartz - 596/597	246 ± 14	14 ± 4	3 ± 1	3 ± 1	< 6	< 11
3. Basalt - 729	228 ± 13	8 ± 3	2 ± 1	< 2	7 ± 1	< 9
4. Concrete - 729 [Wall]	317 ± 19	37 ± 8	14 ± 2	23 ± 2	25 ± 7	< 23
5. Basalt - 729	902 ± 49	77 ± 8	44 ± 3	67 ± 4	63 ± 8	57 ± 10
6. Concrete - 729 [Wall]	99 ± 6	< 17	8 ± 1	13 ± 1	8 ± 3	< 13
7. Concrete - 729 [Floor]	339 ± 20	< 31	10 ± 2	17 ± 2	15 ± 6	< 27
8. Quartz - 729	24 ± 3	< 18	< 3	< 2	< 6	< 12
9. Basalt - 729	22 ± 4	< 9	6 ± 1	< 2	< 6	8 ± 3
10. Concrete - 729 [Wall]	96 ± 9	< 15	12 ± 2	10 ± 1	10 ± 4	< 14
11. Basalt - 880	22 ± 5	24 ± 4	30 ± 2	3 ± 1	< 7	19 ± 4
12. Concrete - 880	308 ± 18	< 16	17 ± 2	25 ± 2	24 ± 5	< 16
13. Concrete - 880	104 ± 10	< 21	65 ± 5	30 ± 2	30 ± 6	61 ± 9
14. Mud + Concrete - 880 tunnel	96 ± 8	< 13	13 ± 2	4 ± 1	< 7	< 11

Muon and neutron spectra measurements are in progress.

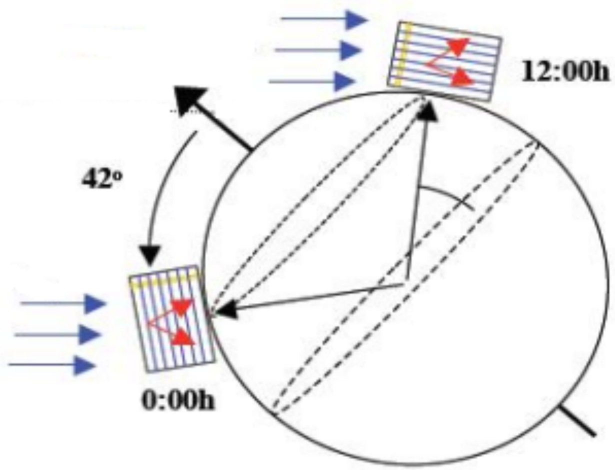
Underground lab

A delegation of Italian scientists, including Antonio Masiero (INFN Vice President) & Stefano Ragazzi (LNGS Director) visited the site.
The new lab will also house scientific experiments from different fields e.g. astrophysics, biology, geosciences and engineering. It will be very similar to Boulby or Canfranc in size. The design is ongoing with the help of Gran Sasso and Boulby.

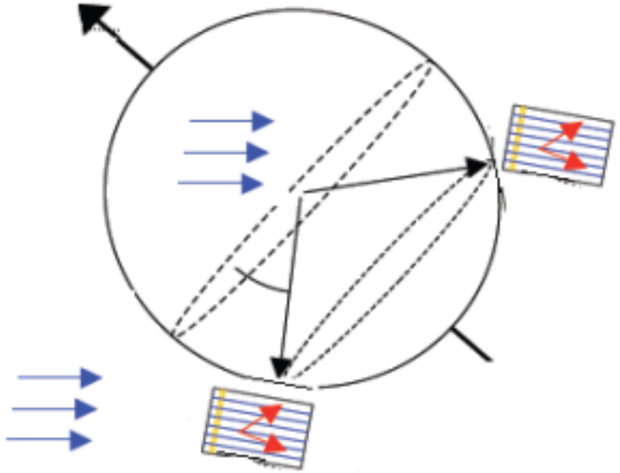
Funding from the Sate Government of Victoria have been secured, the construction will start later this year, to be completed end 12016. We may have more funding from the federal government.

Bonus of the site: Diurnal Modulation

North Hemisphere

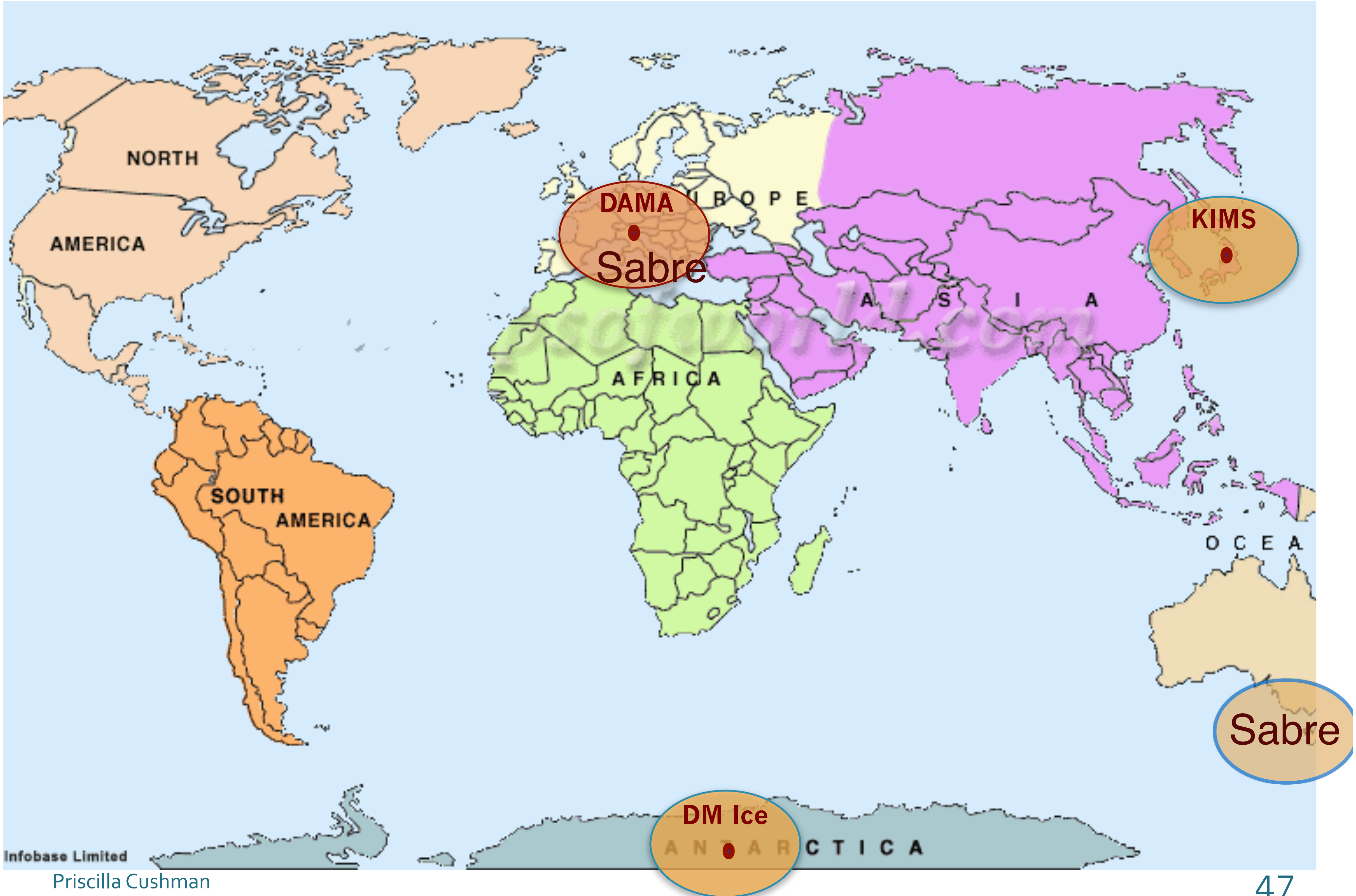


South Hemisphere



Stawell is in the ideal position to measure diurnal
modulation, as predicted by many models with self iteration dark matter for example
R.Foot, S.Vagnozi, arXiv:1409.7174

Underground labs with Crystals



Time line

	Stawell	**Sabre**
2014	Lab proposed	NaI(Tl) crystal growth study (small crystal)
2015	Funding secured (Jan) Possible extra finding (Apr) Start construction (Jun-Jul)	Veto tests (Gran Sasso) R&D on crystal growth
2016	Facility ready (Nov-Dec)	Large NaI(Tl) crystal growth Large crystal detector tested/ operated in DS veto SABRE veto vessel (Melbourne)
2017	Detector goes in	Large Array (>50kg) of NaI(Tl) detectors in operation

Outlook

Hunting for Dark Matter is difficult

Direct detection experiment are challenging and many results are contradictory, depending on the technology

The DAMA/LIBRA modulation is still a mystery,

A new dual North-South Hemisphere crystal experiment may settle the issue.

End of 2016 the first operating underground lab in the Southern Hemisphere will be operational

After that…