MultiDark
Multimessenger Approach for Dark Matter Detection

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FUNDACIÓN AGENCIA ARAGONESA PARA LA INVESTIGACIÓN Y EL DESARROLLO

Dark Matter searches via direct detection

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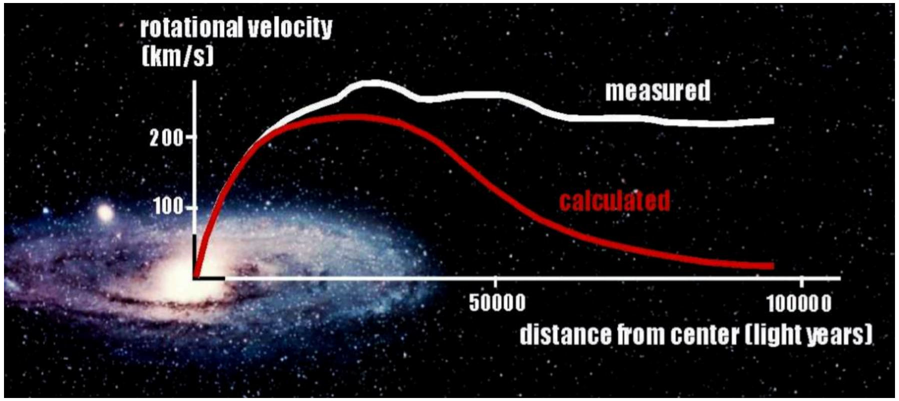
Workshop on the Standard Model and Beyond
Corfu, Aug 31 – Sep 09 2018

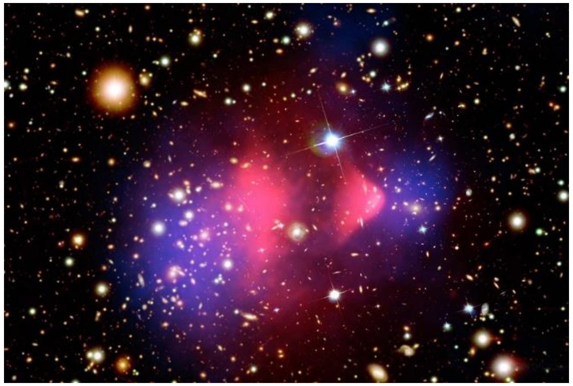
OUTLINE

- INTRO
- Direct detection status @ 2018
- DM Annual Modulation & DAMA signal
- Checking the DAMA signal: ANAIS experiment

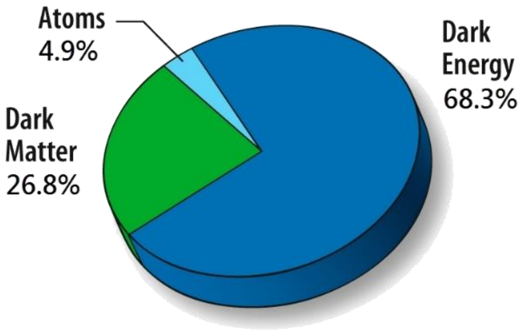
Intro: DM

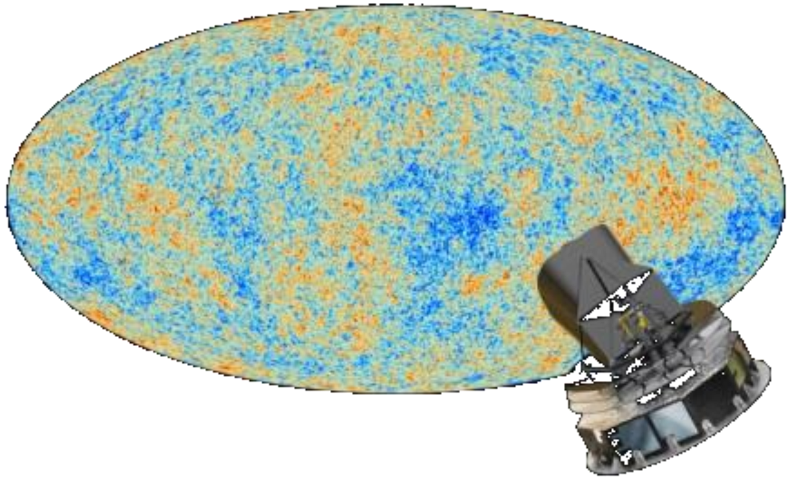
The evidence for DM in the Universe is beyond question





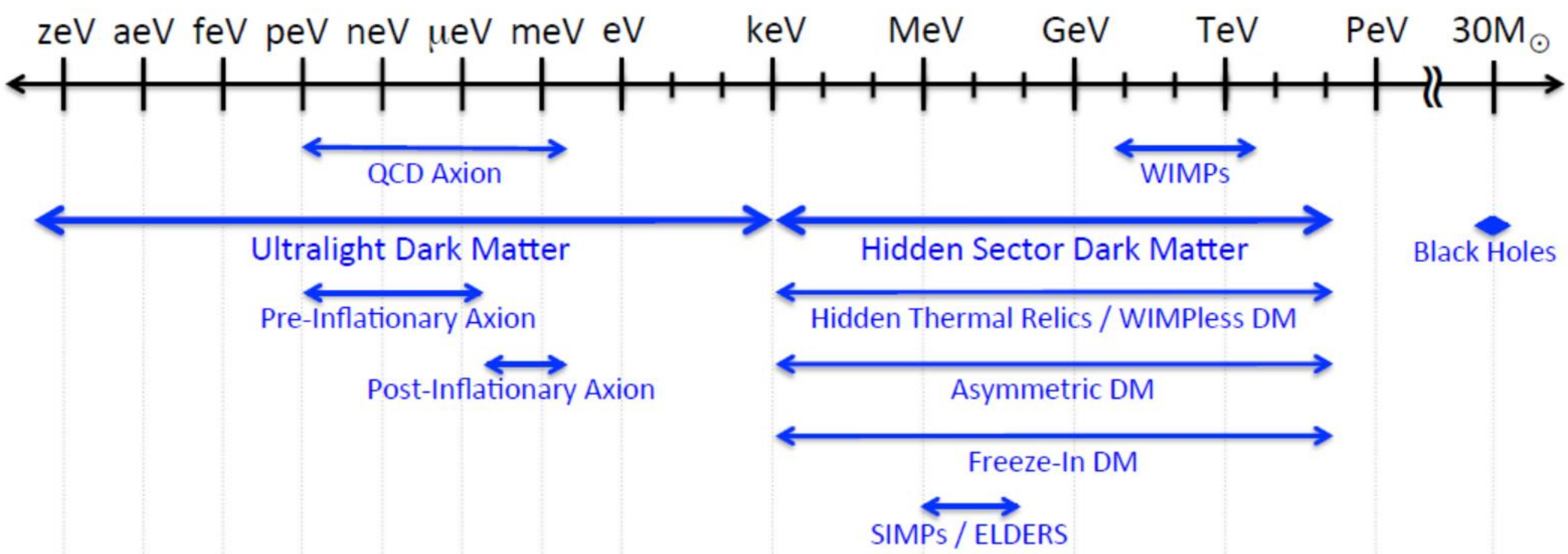
We know how much there is:





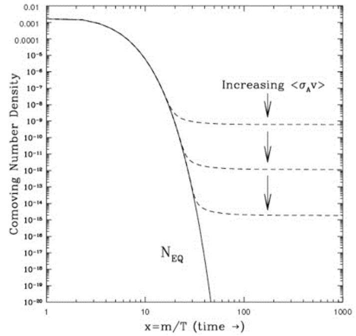
But we don't know what it is DM made of !!

DM Candidates



From “US Cosmic Visions: New Ideas in Dark Matter 2017:Community Report”, arXiv:1707.04591

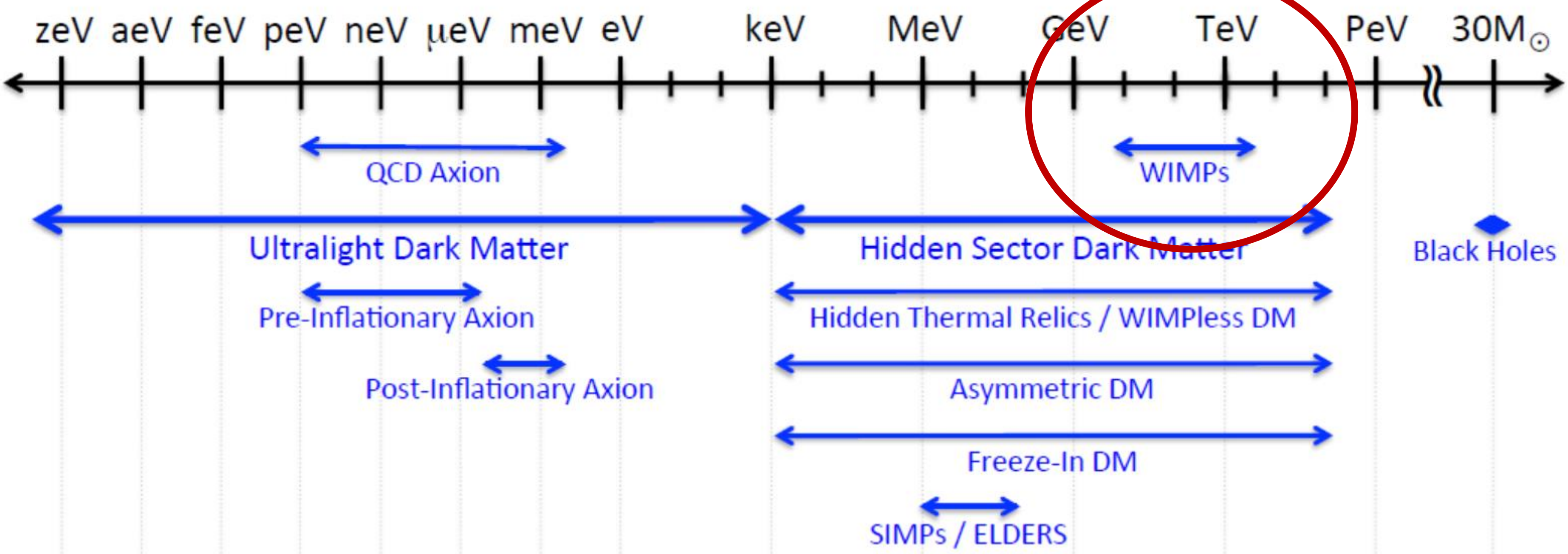
WIMPS



Jungman *et al* hep-ph/9506380

Abundance of a termal relic $\sim \frac{0.1\ pb}{<\sigma_A\ v/c>}$

- For the observed DM density, σ corresponds to the one expected for a new weak-interacting particle (WIMPs)
- WIMPs predicted in many extensions of the Standard Model such as SUSY



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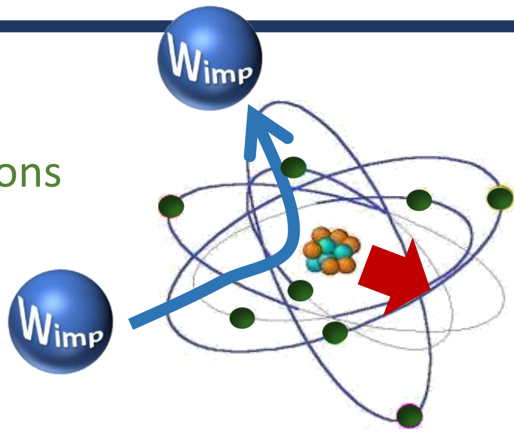
DM direct detection

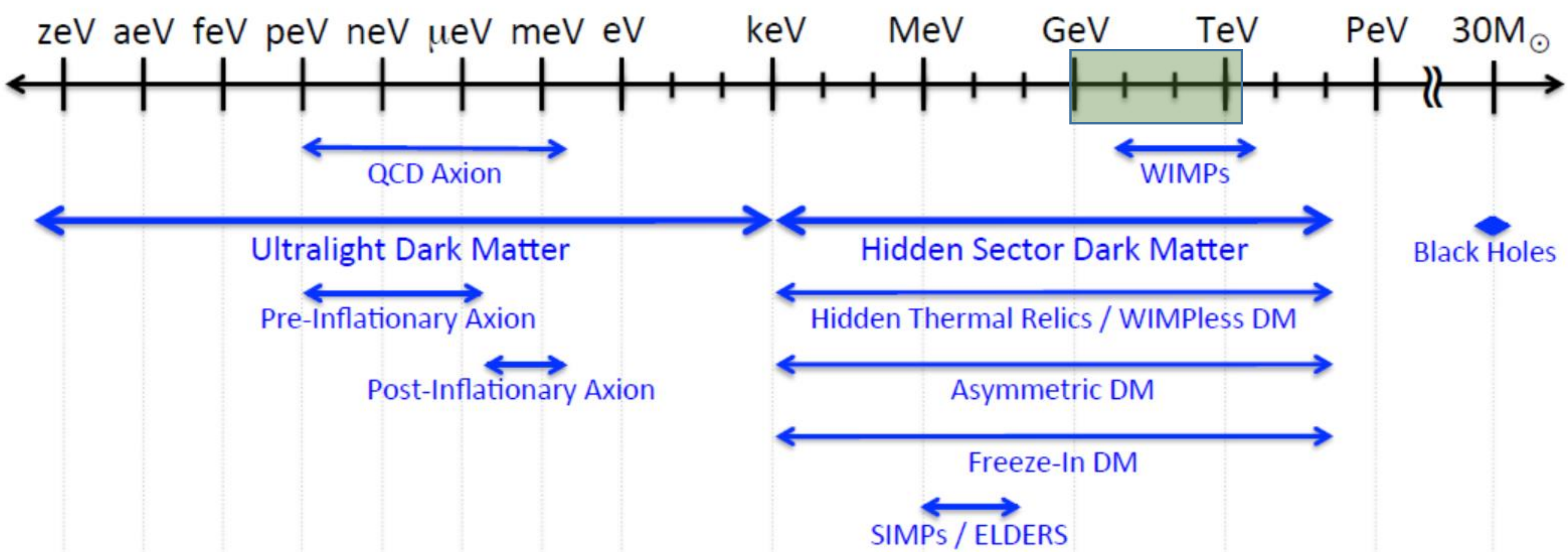
Look for
WIMP collisions
With atomic
nuclei



The nuclear
recoil produces a
detectable signal

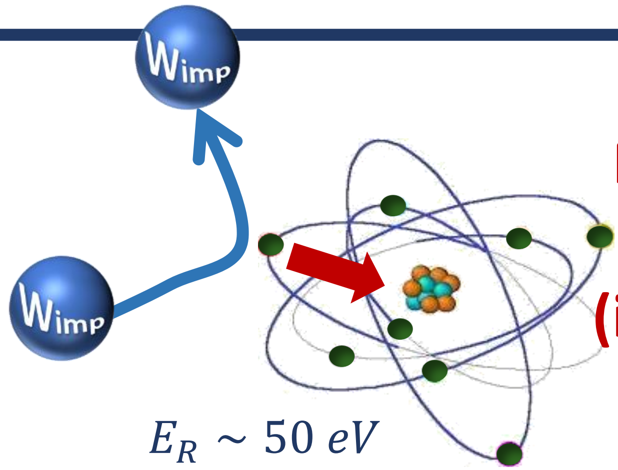
$$E_R = \frac{q^2}{2m_N} \leq 30\ keV$$

“standard”
Direct detection
(DM-nucleon
elastic scattering)



From “US Cosmic Visions: New Ideas in Dark Matter 2017:Community Report”, arXiv:1707.04591

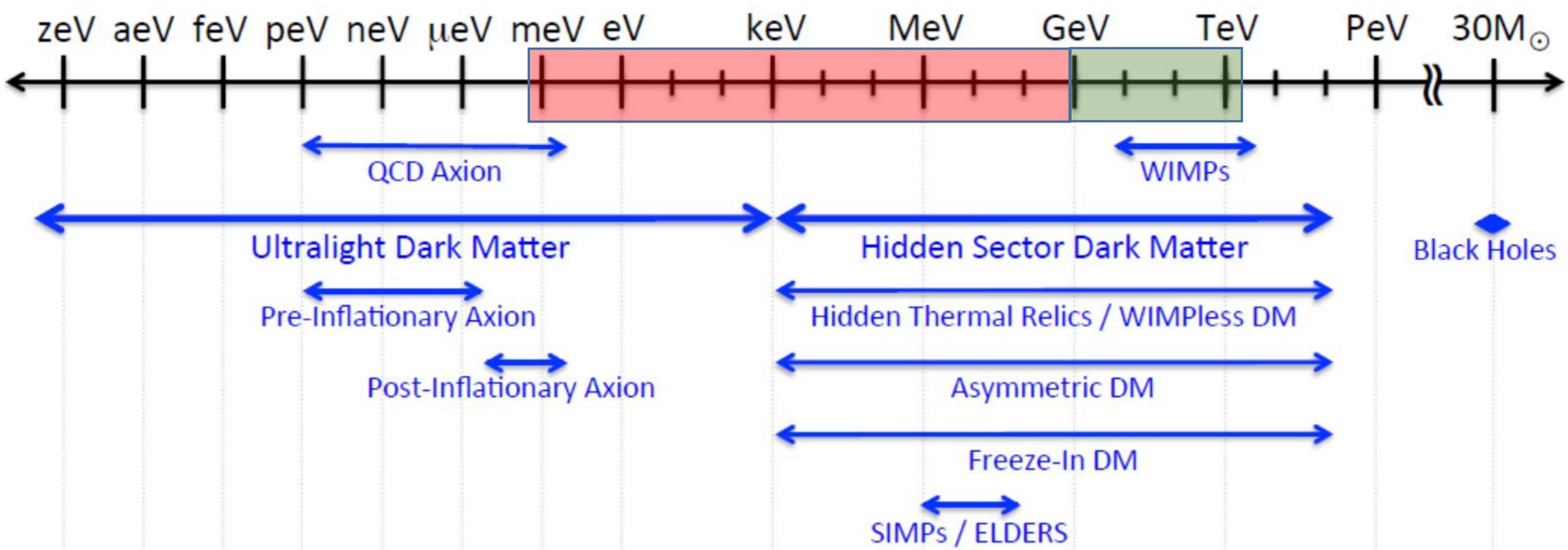
DM direct detection



$E_R \sim 50\ eV$

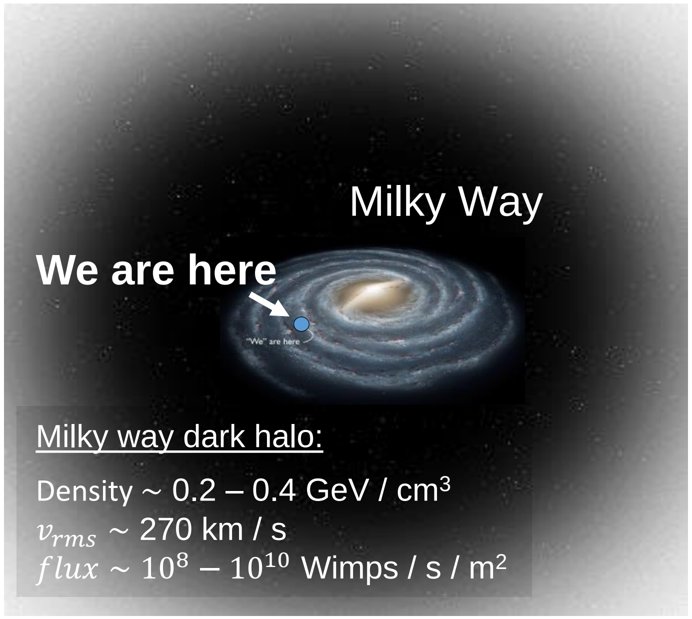
New ideas for sub-GeV Direct detection (including DM-electron scattering)

"standard" Direct detection (DM-nucleon elastic scattering)



From "US Cosmic Visions: New Ideas in Dark Matter 2017:Community Report", arXiv:1707.04591

Expected WIMP rate

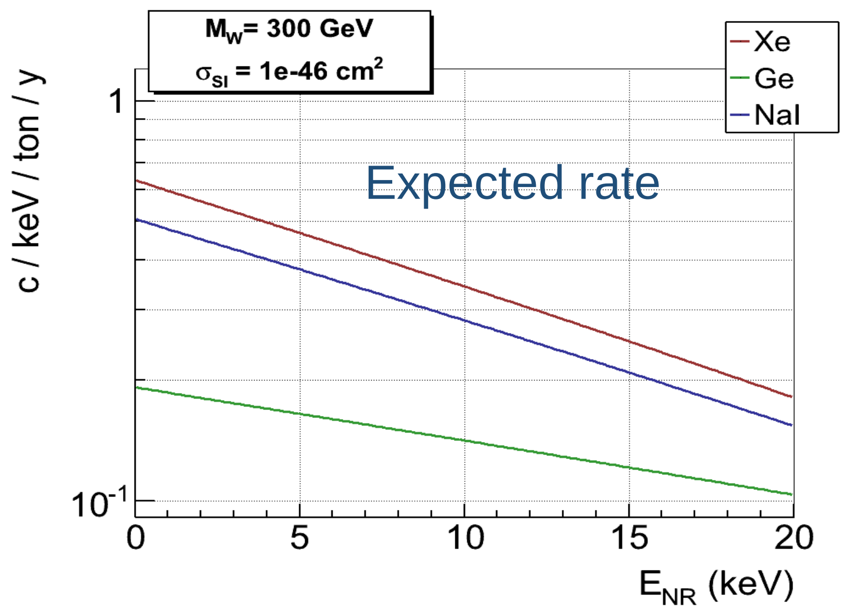


Expected rate @ Earth:

$$\frac{dR}{dE_R} = \frac{\rho_0 M_{Det}}{2 m_W m_{WN}^2} \sigma_{WN} \int_{vmin}^{vmax} \frac{f(v)}{v} dv^3$$

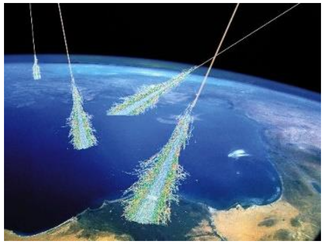
(depend on WIMP & Halo Model!)

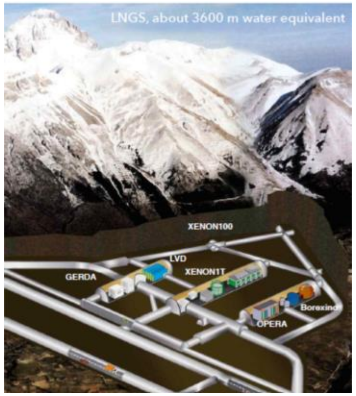
Extremely low and without characteristic signatures (no peaks!)



Beating the background

- Cosmic rays-induced muons, cosmogenic activation

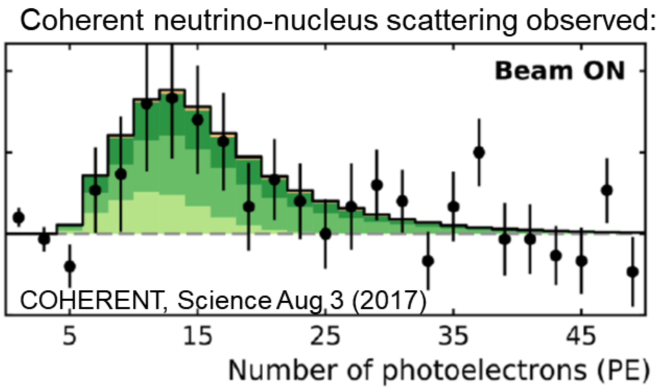


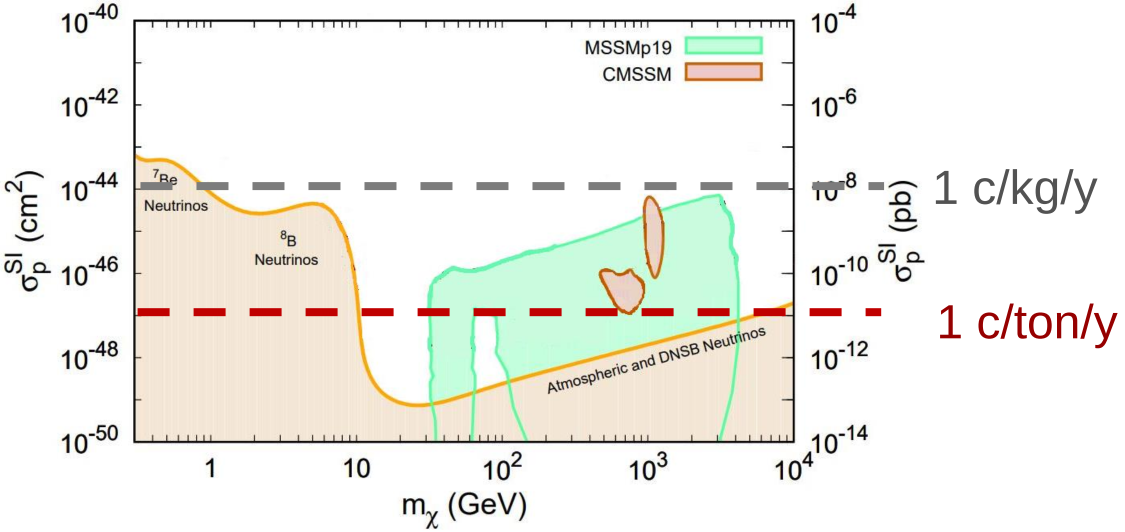


Underground experiments

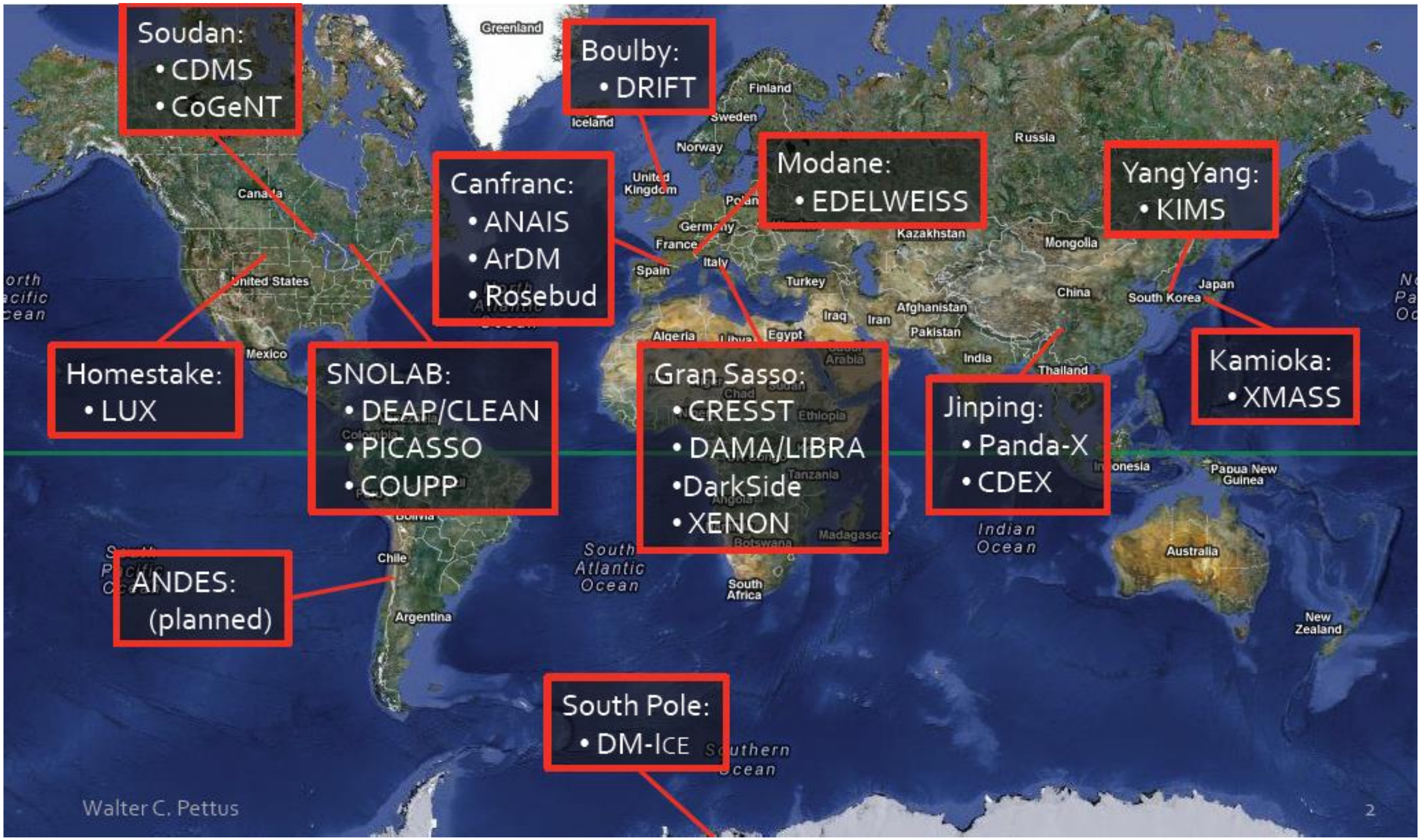
- Natural radioactivity
  - Shieldings
  - Fiducialization
  - Particle discrimination

- Neutrinos!





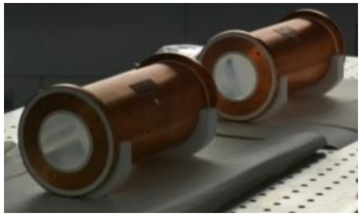
Underground laboratorios around the World



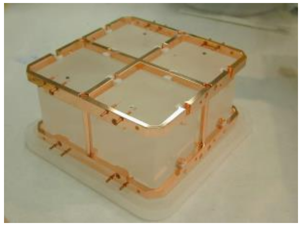
The DM race

1990 - 2000

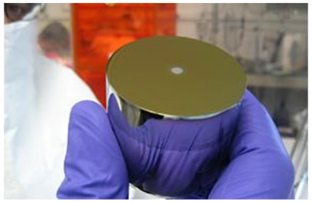
Scintillators

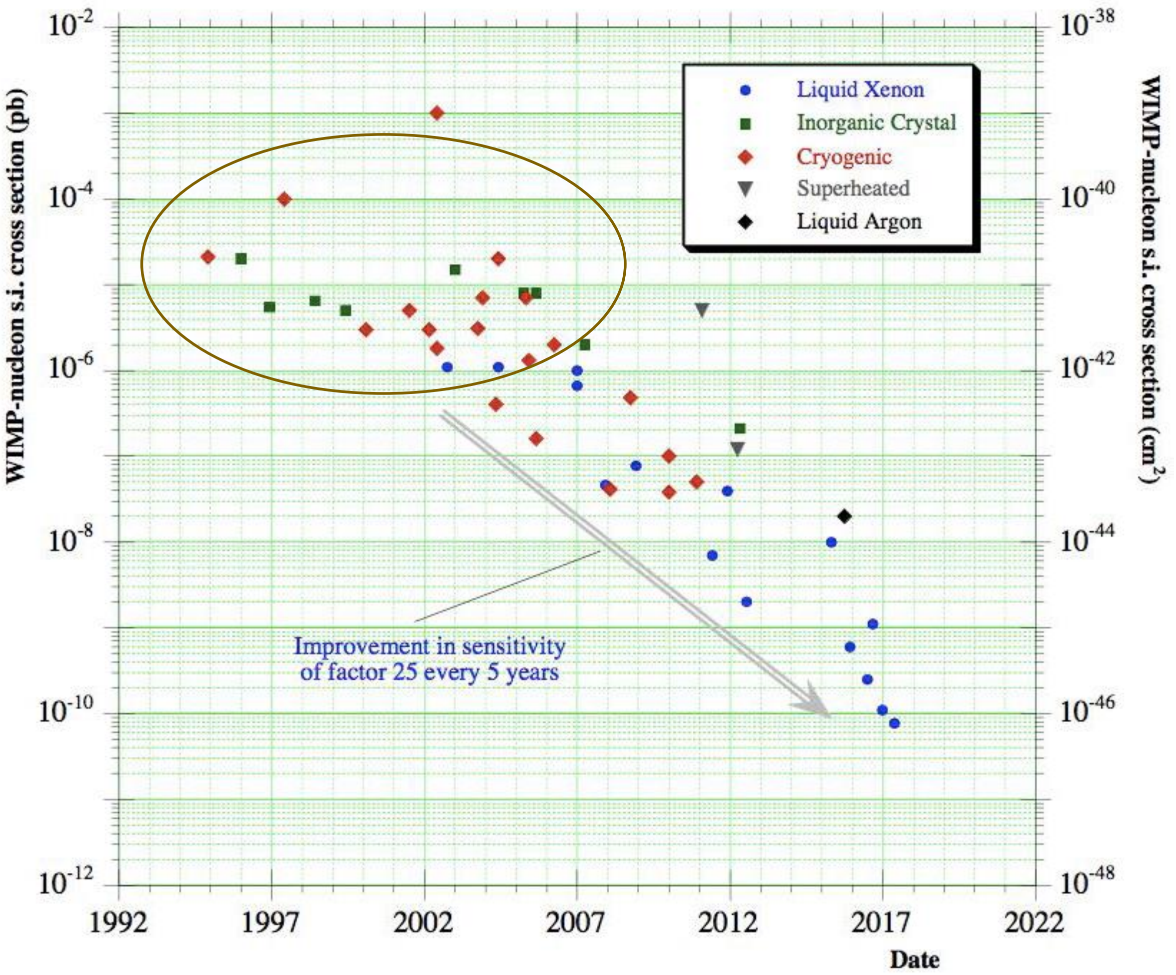


Cryogenic detectors



HPGe

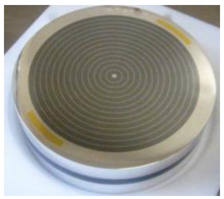




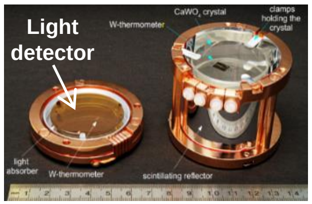
The DM race

2000 -

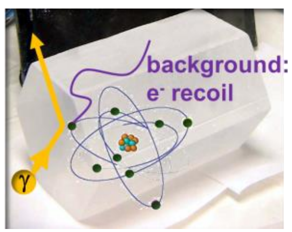
Double readout detectors!

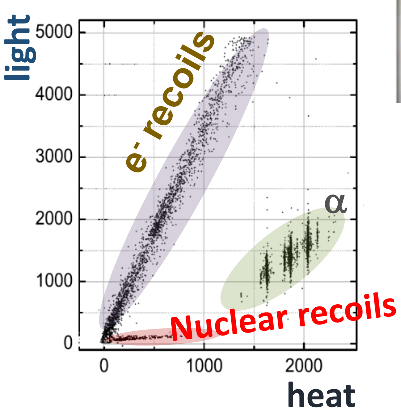


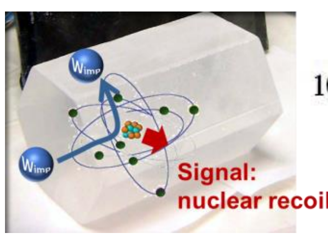
Heat/charge

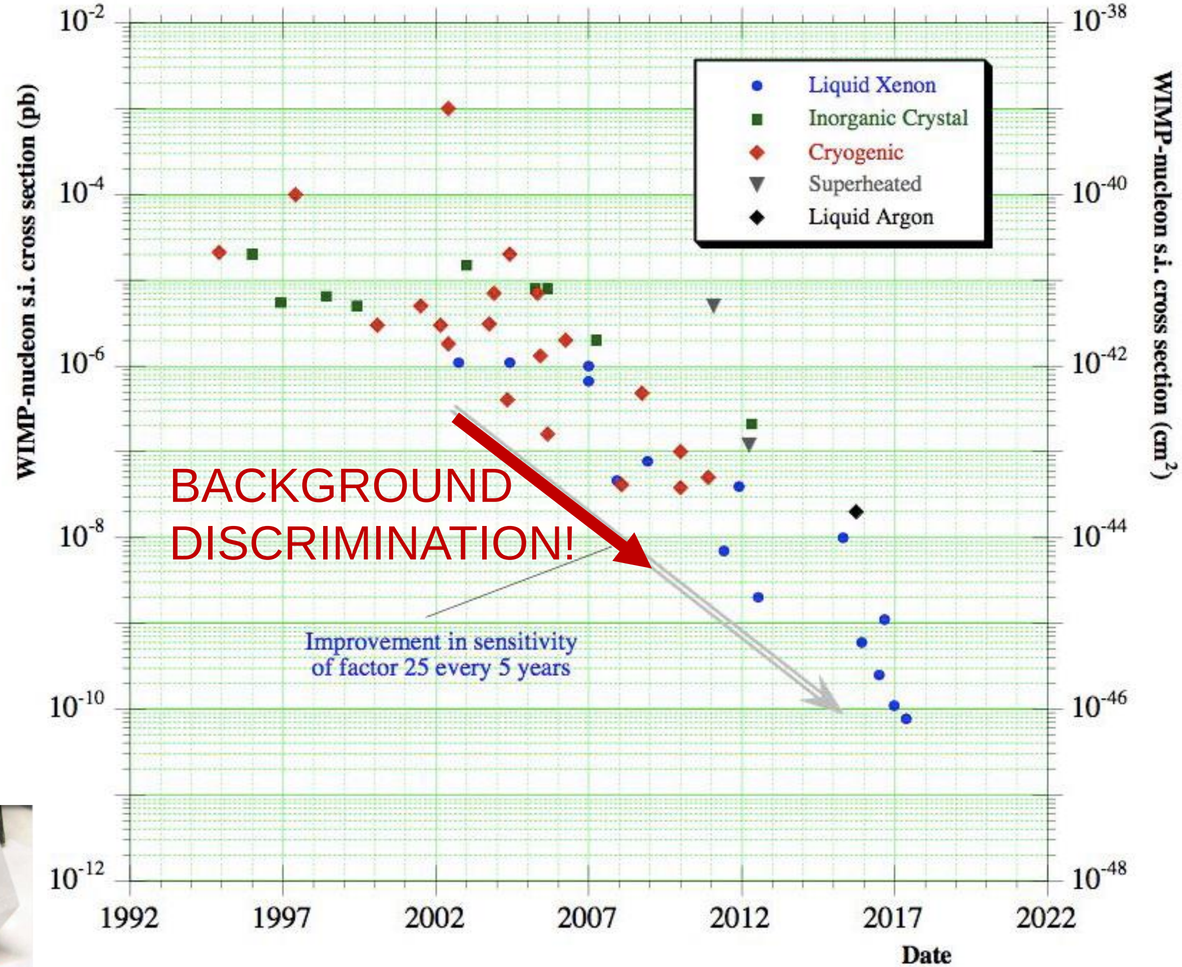


Heat/light





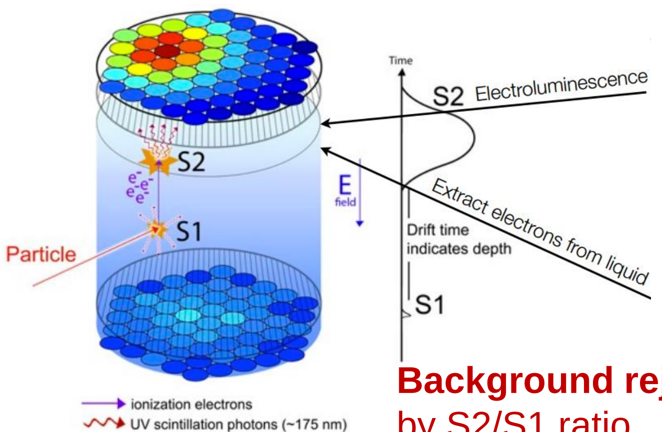




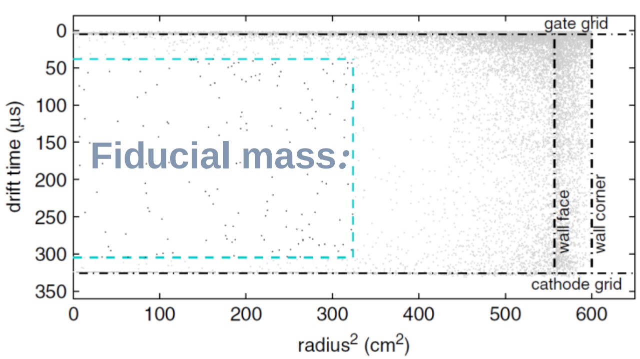
The DM race

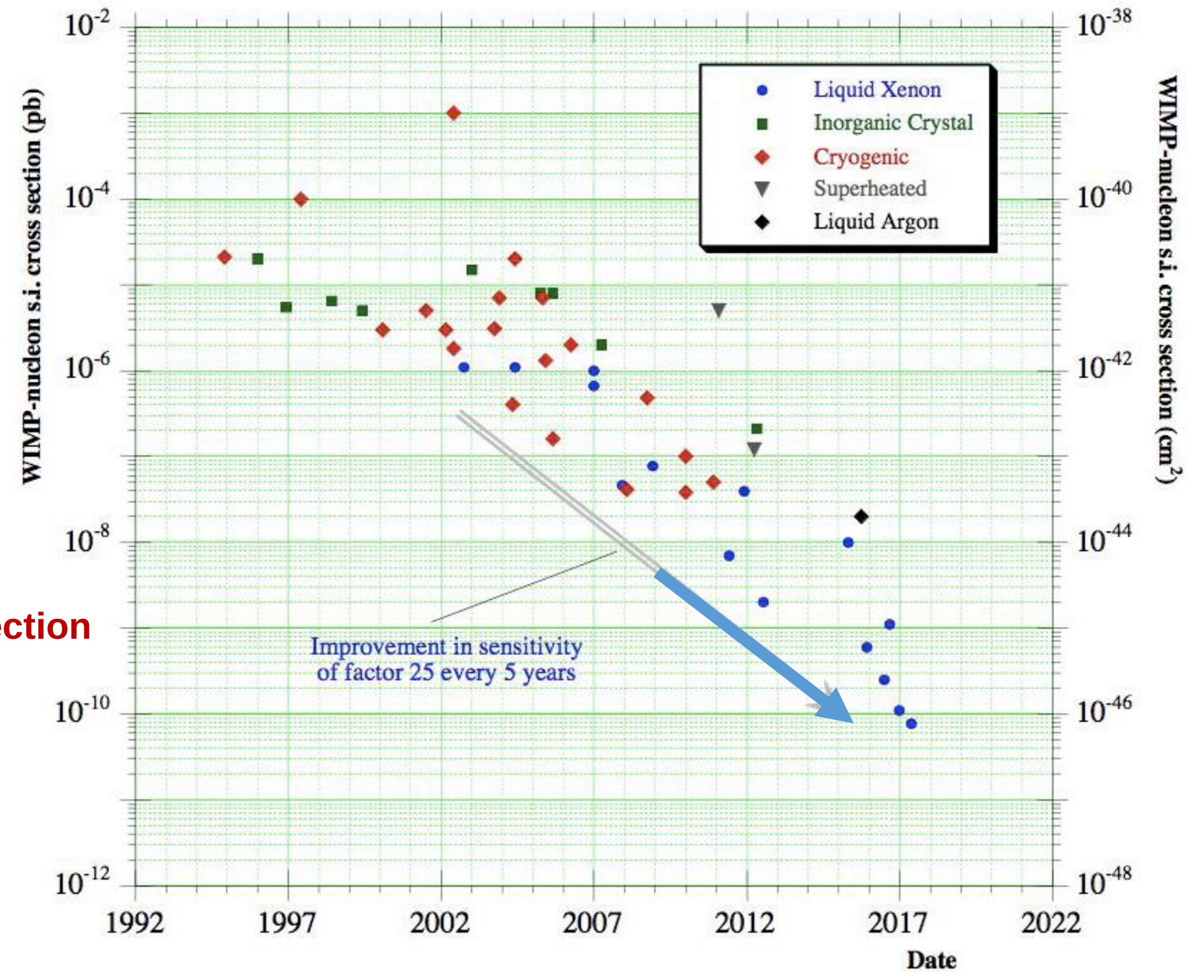
2010 -

Noble liquids TPCs
(light & ionization)



Background rejection
by S2/S1 ratio

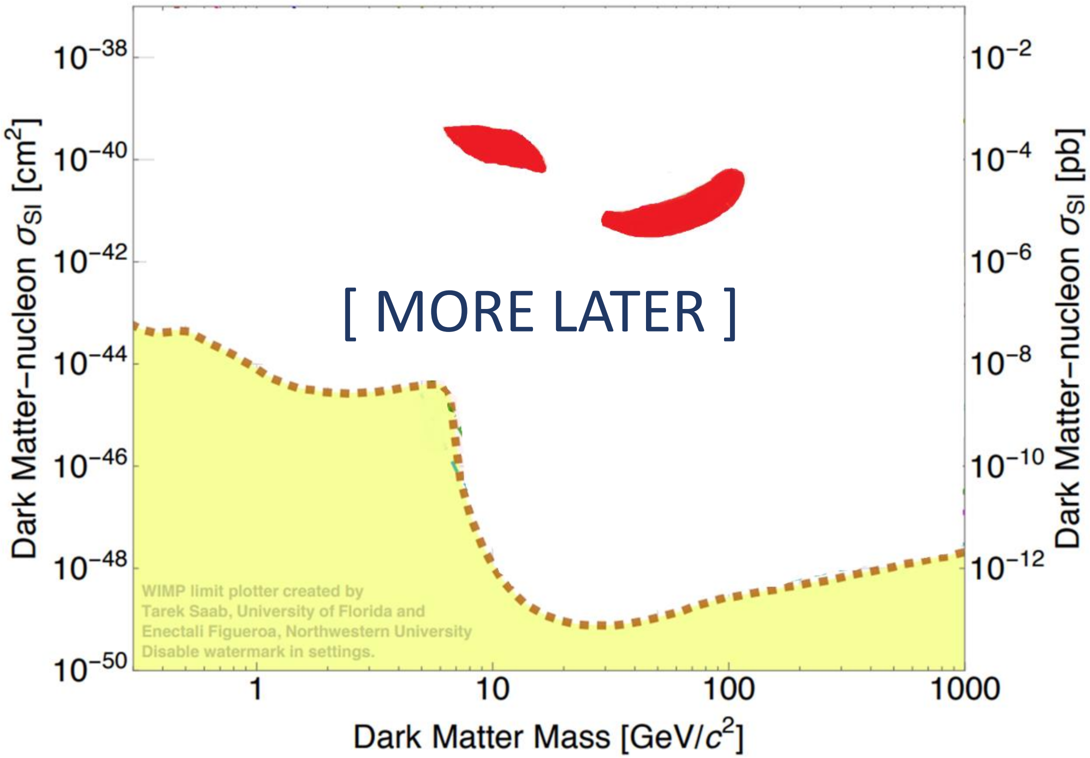




Direct detection status @ 2018

Direct detection status @ 2018

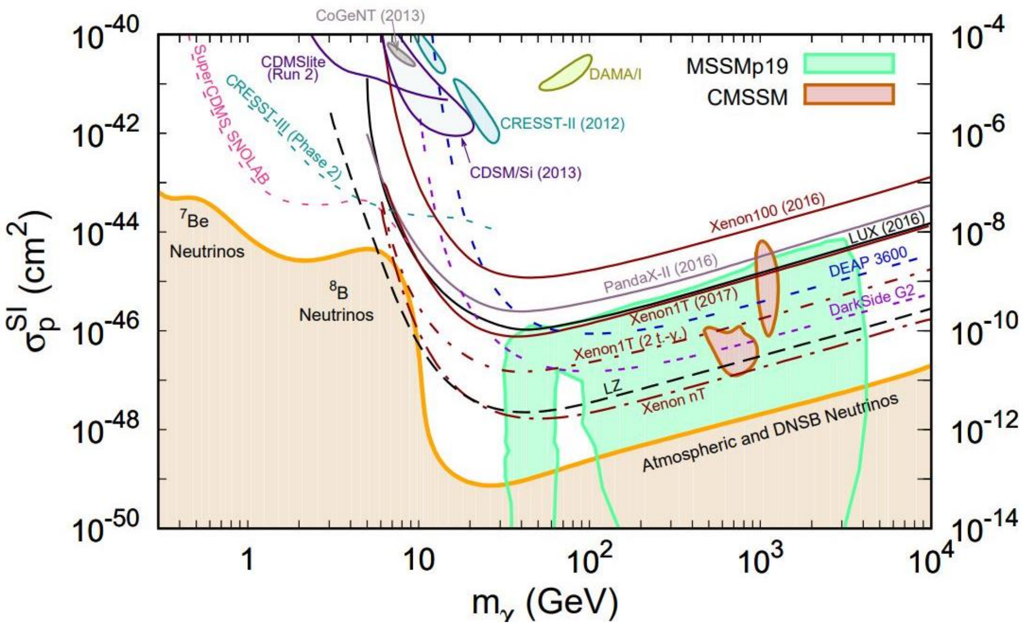
- One positive signal:
  DAMA/LIBRA (NaI(Tl) scintillators)



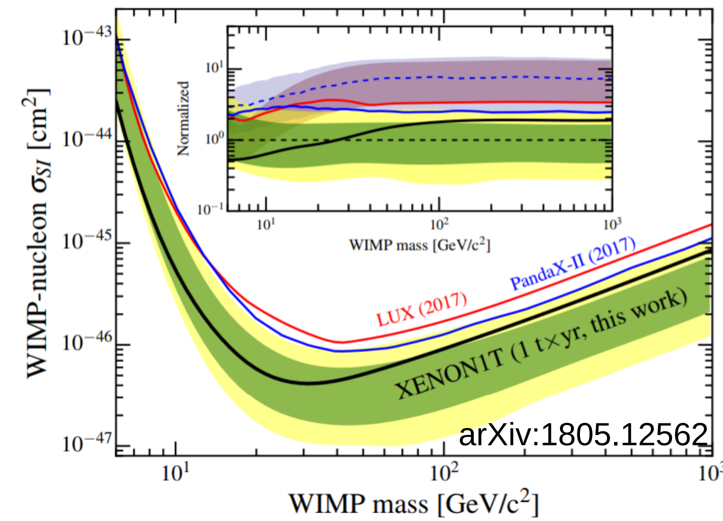
Direct detection status @ 2018

- High mass region (>10 GeV) **Spin independent**

Dominated by liquified noble gases (Xe/Ar)

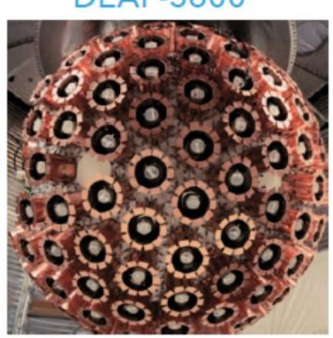


PRESENT BEST SENSITIVITY:



XMASS

DEAP-3600



XENON1T

LUX

DarkSide-50

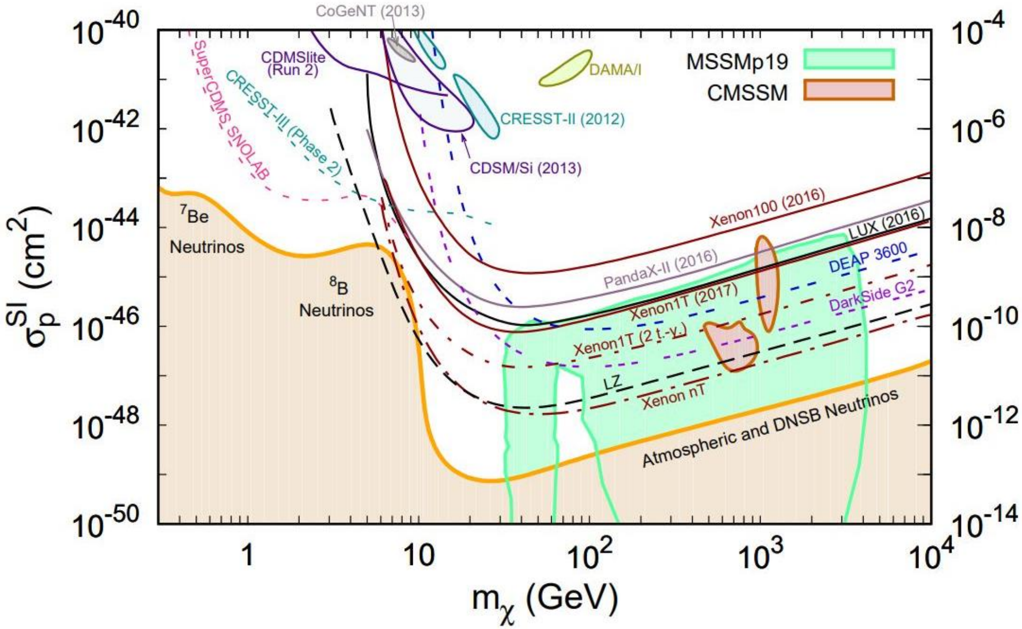
PandaX-II

(from L. Baudis, SUSY18)

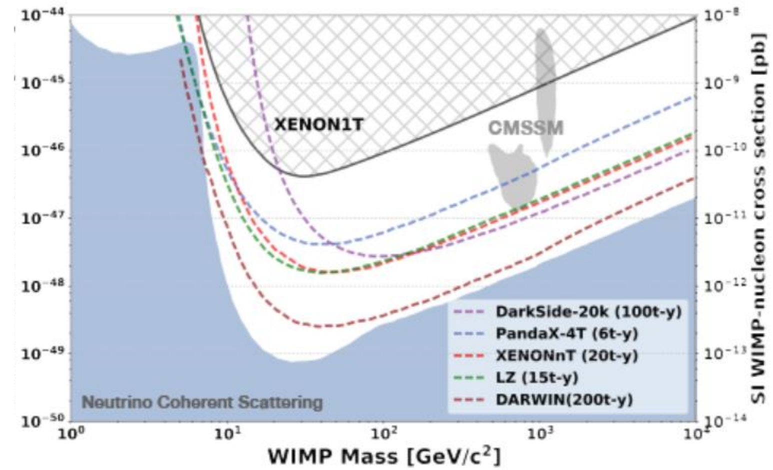
Direct detection status @ 2018

- High mass region (>10 GeV) **Spin independent**

Dominated by liquified noble gases (Xe/Ar)

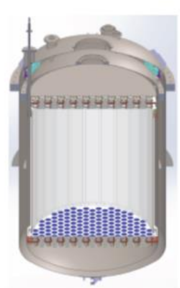


PROJECTED SENSITIVITY IN 5-10 years:

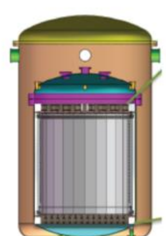


Planned experiments:

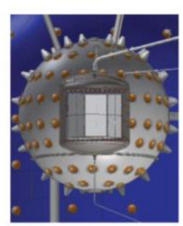
(from L. Baudis, SUSY18)



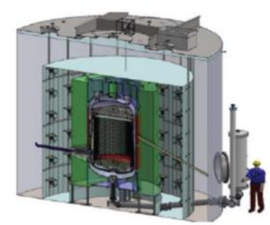
XENONnT: 8t LXe
Data taking 2019



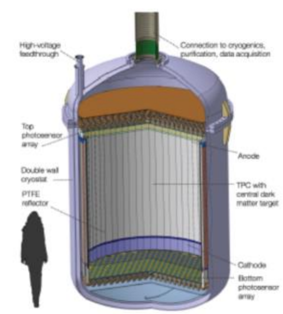
PandaX-4t LXe
Data taking 2019



DarkSide: 20 t LAr
Data taking 2021



LUX-ZEPLIN: 8 t LXe
Data taking 2020



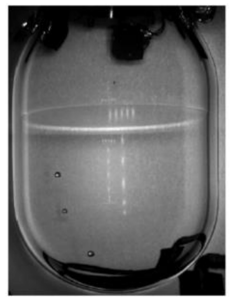
DARWIN: 50 t LXe
Data taking ~2026

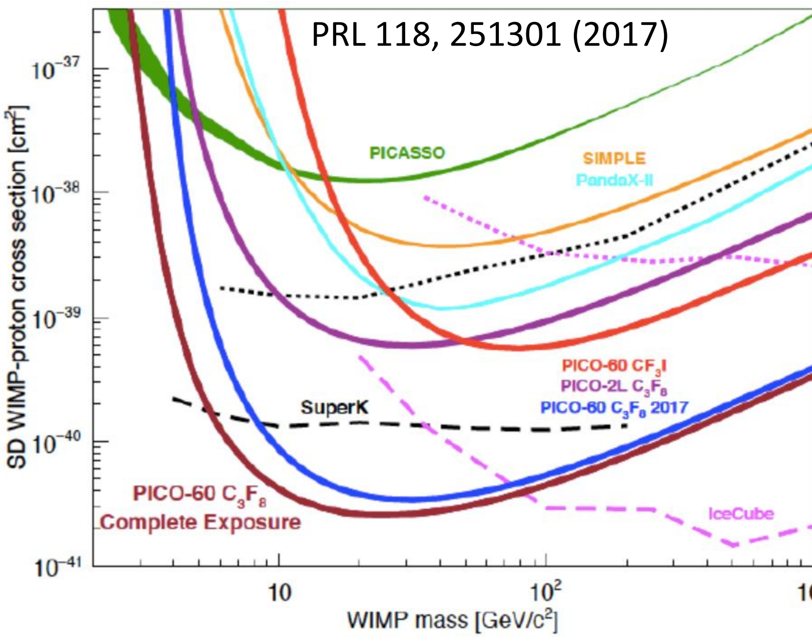
Direct detection status @ 2018

- High mass region (>10 GeV) **Spin dependent**

WIMP-proton

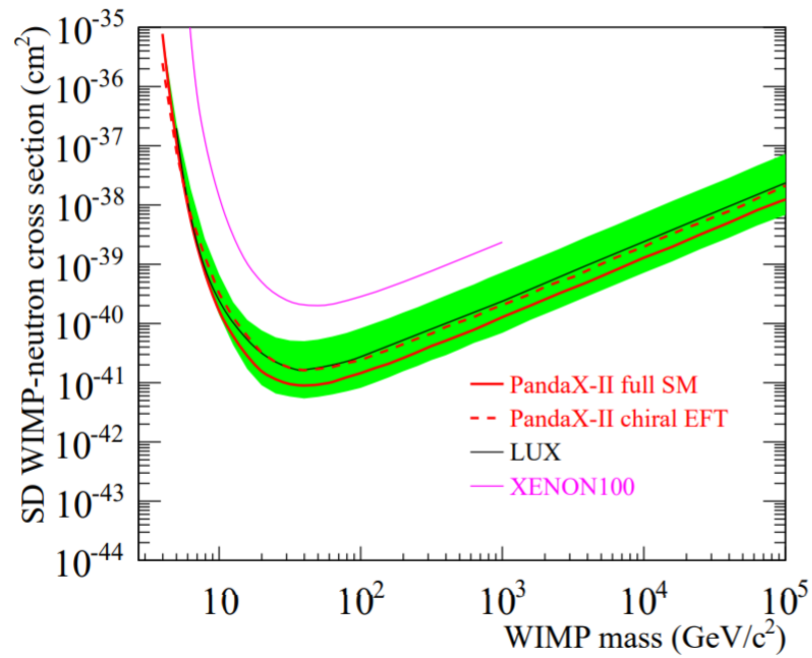
Bubble chambers (PICO)
superheated
CF_3I, C_3F_8, C_4F_{10}





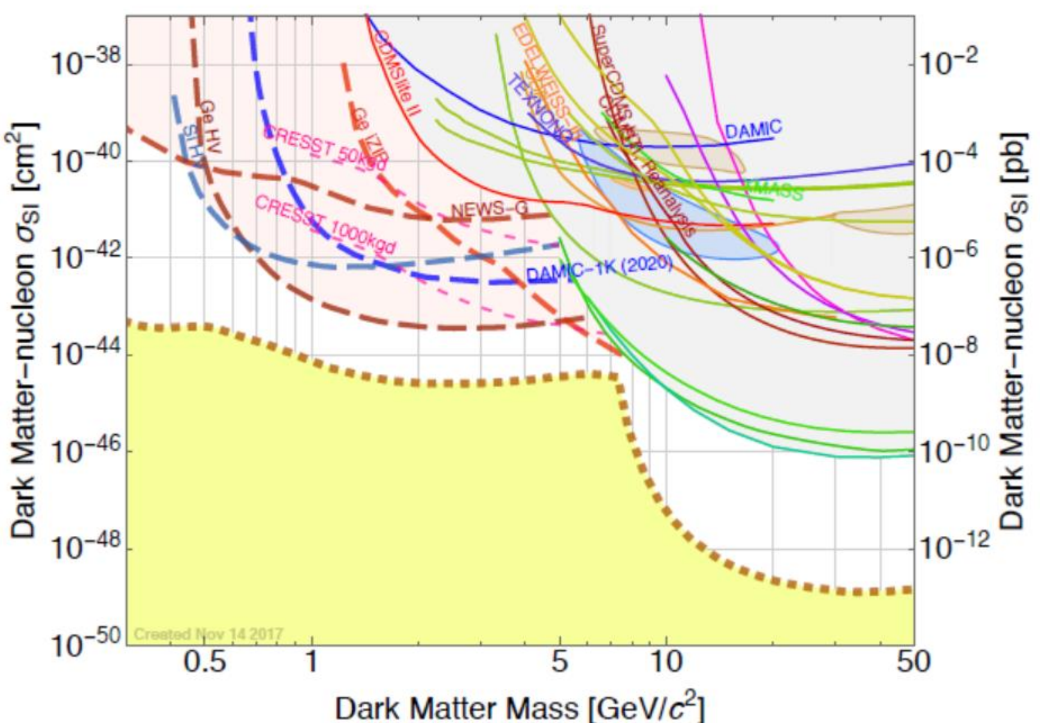
WIMP-neutron

Xe experiments



Direct detection status @ 2018

- Low mass region (<10 GeV):
  - **- Cryogenic experiments with sub-keV threshold** (CRESST, SuperCDMS, EDELWEISS)
  - **- New ideas:** CCDs (DAMIC, SENSEI), TPCs (NEWS, TREX), graphene & carbon nanotubes, superconductors, superfluid He…



See K. Nikolopoulos talk on Sat 08

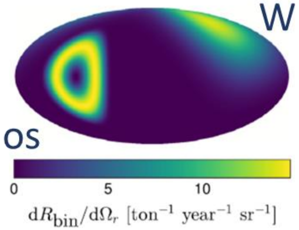
Beyond neutrino floor

Phys. Rep. 627 (2016) 1

Directionality

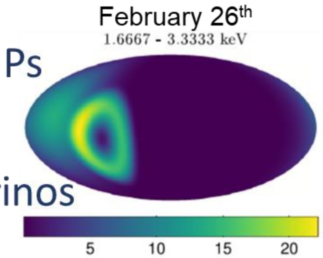
WIMPs

^{8}B neutrinos



WIMPs

^{8}B neutrinos



(from L. Baudis, SUSY18)

Cygnus: coordination of R&D efforts for gas detectors, one common technology in 2019

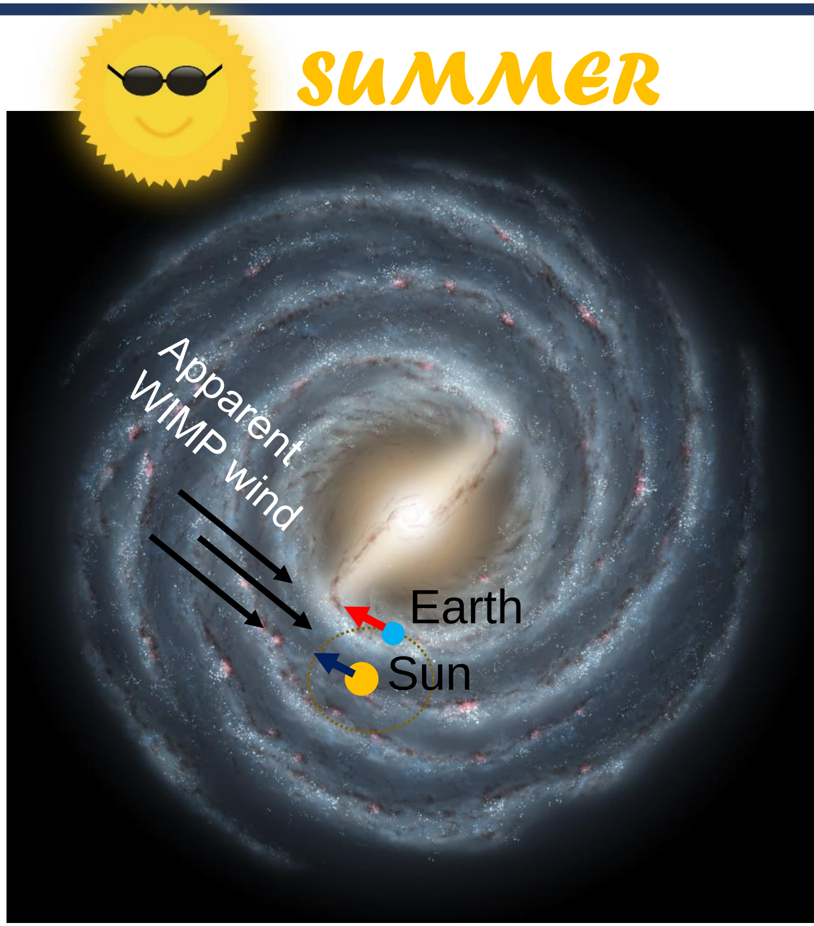
But also: annual modulation, complementarity among targets, energy dependence..

Looking for a distinctive signal:

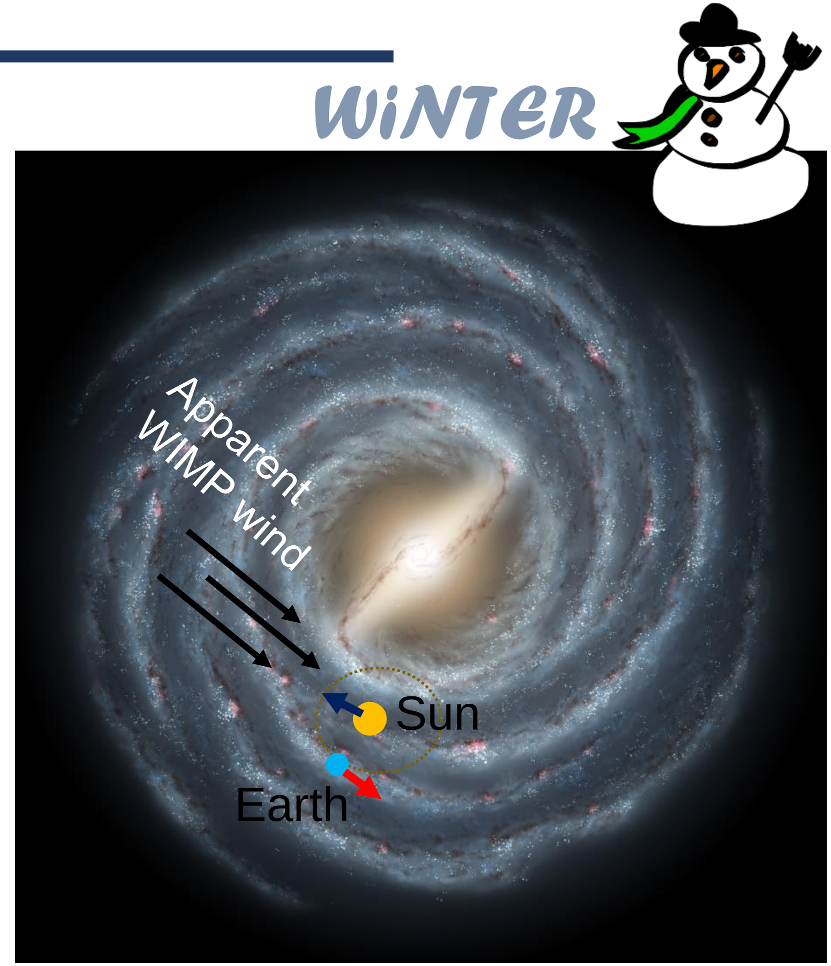
Annual Modulation

Annual modulation

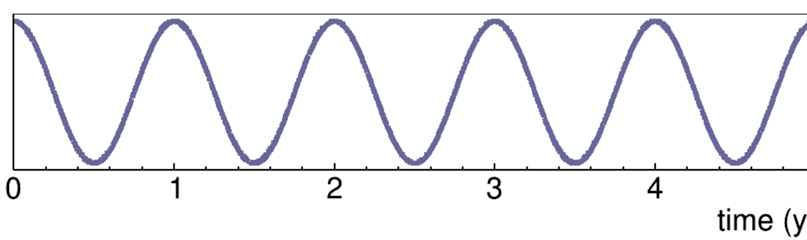
SUMMER



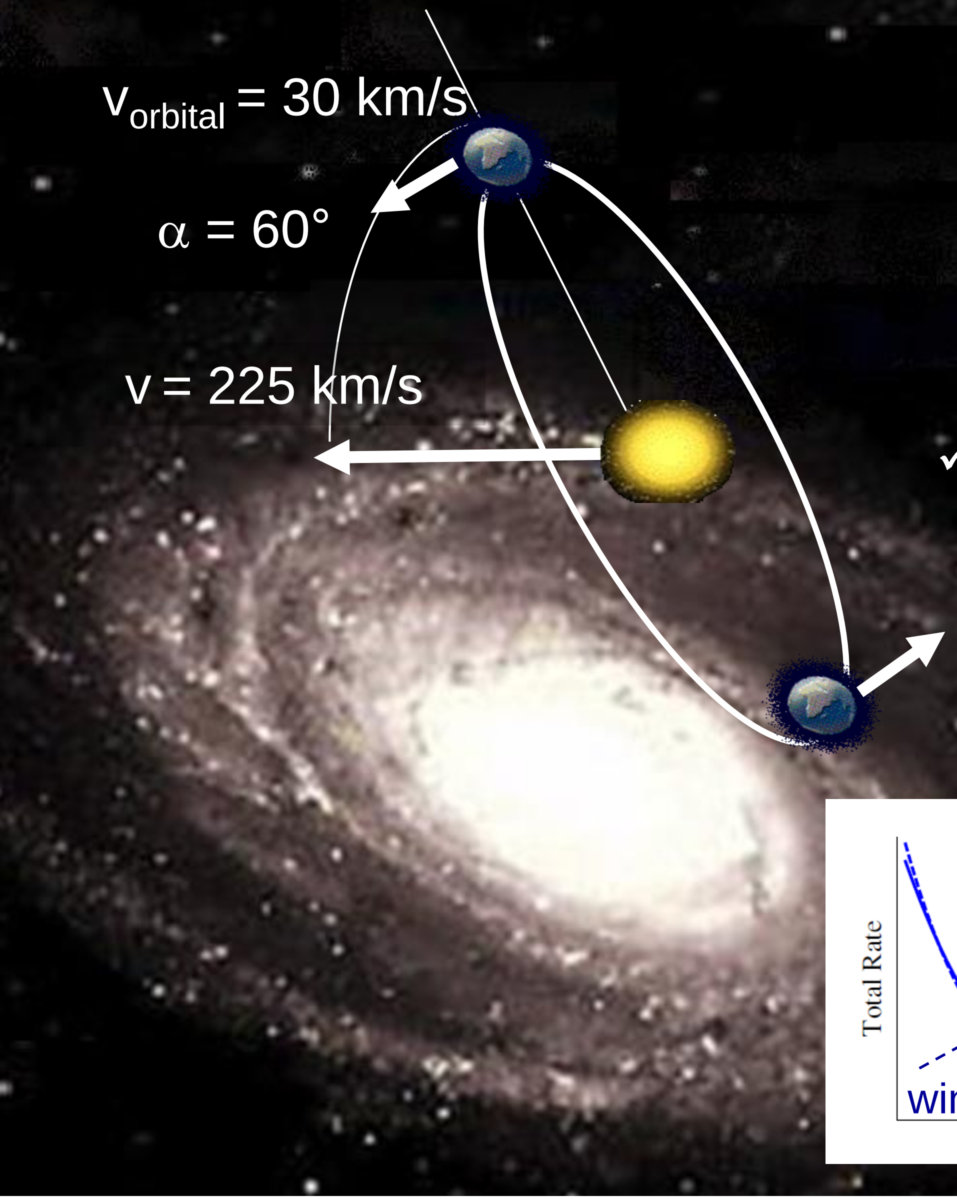
WINTER



We expect a modulated rate with 1 year period

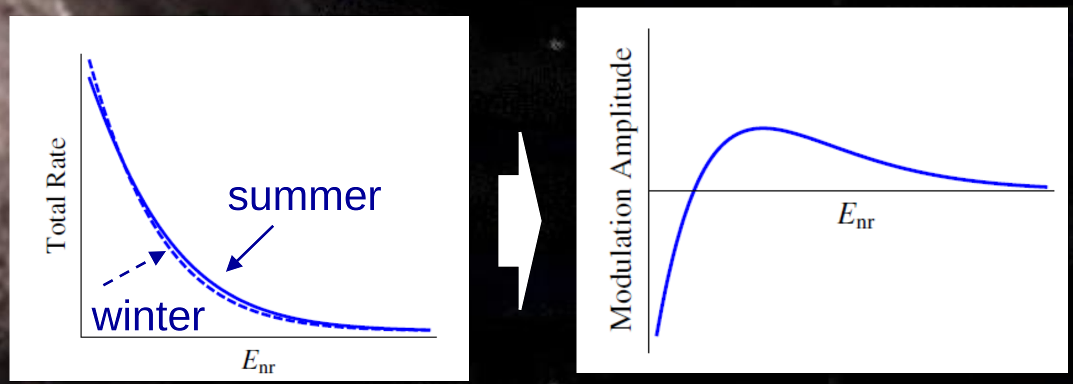


Annual modulation: a disctintive signal

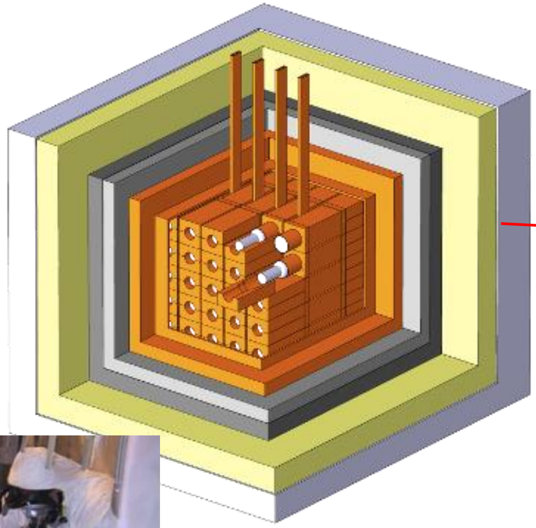


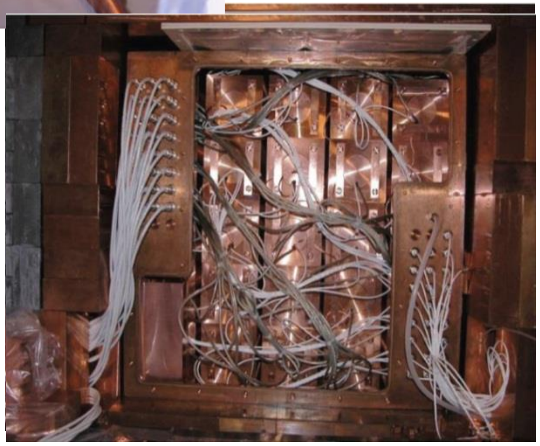
- ✓ Cosine behaviour
- ✓ 1 year period
- ✓ Maximum around June 2nd
- ✓ Weak effect (1-10%)
- ✓ Only noticeable at low energy
- ✓ Should have a phase reversal at low E

→ **Very hard to mimic by bkg!!**



DAMA/LIBRA @ LNGS

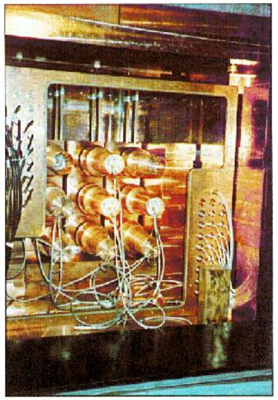




- 20 ultrapure NaI(Tl) scintillating crystals (250 kg total mass) in a 5x5 matrix
- Each crystal coupled to two PMT for light readout
- First setup (DAMA/NaI, 115 kg) started in ~1995
- Expusure so far: 2.17 ton × y (!!)

DAMA/NaI & DAMA/LIBRA (phase 1)

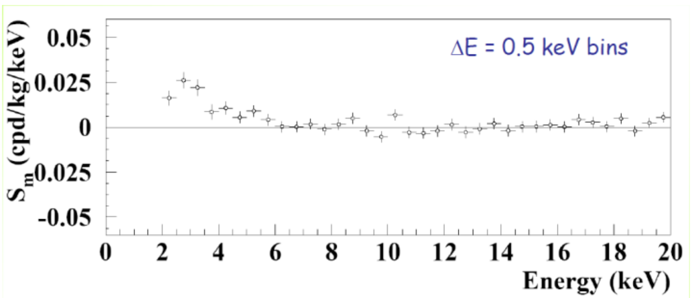
DAMA / NaI (1995-2002)

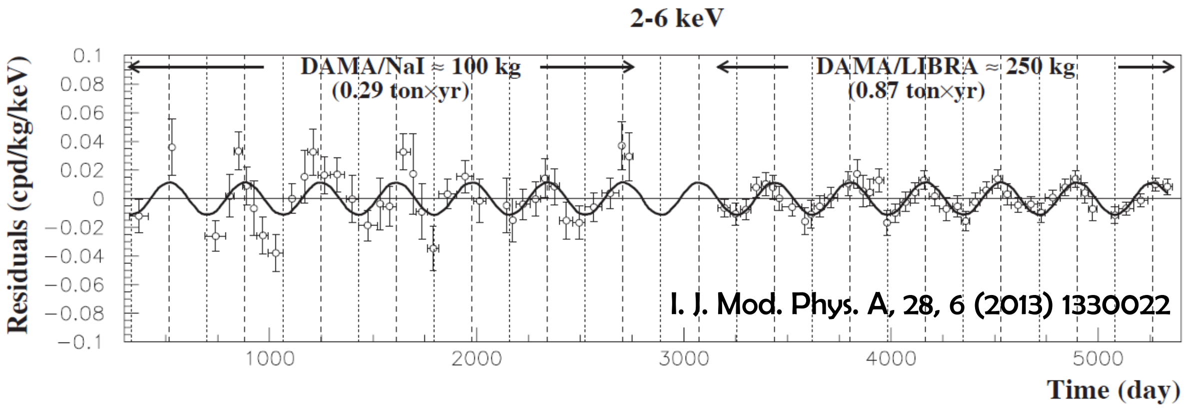


- 10 × 9.7 kg NaI(Tl) (3x3 matrix)
- 7 anual cycles
- Exposure : 0.29 ton × y

DAMA / LIBRA (2003-2010)

- 25 × 9.7 kg NaI(Tl) (5x5 matrix)
- 7 anual cycles
- Exposure : 1.17 ton × y

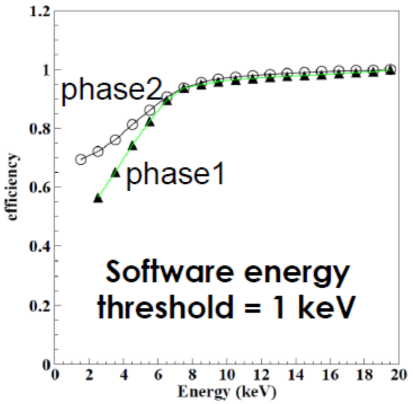




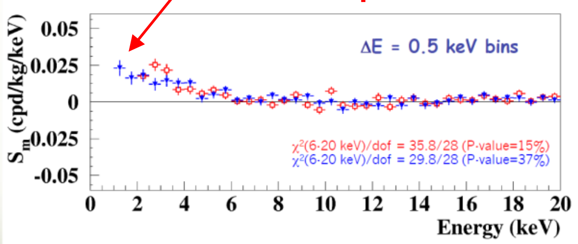
Solid line: $Cos\omega(t - t_0)$, with period 1 year and phase on June 2[nd]

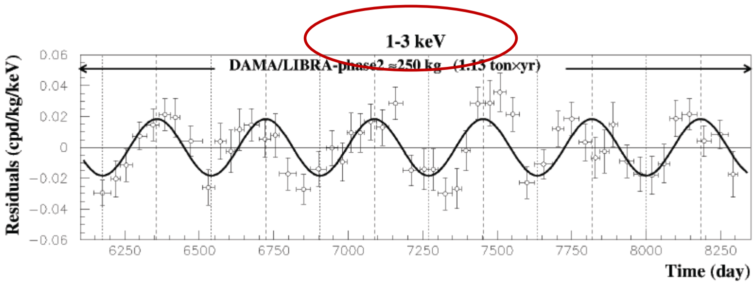
DAMA/LIBRA phase2 (2011-2018)

all PMTs replaced with new ones of higher Q.E.

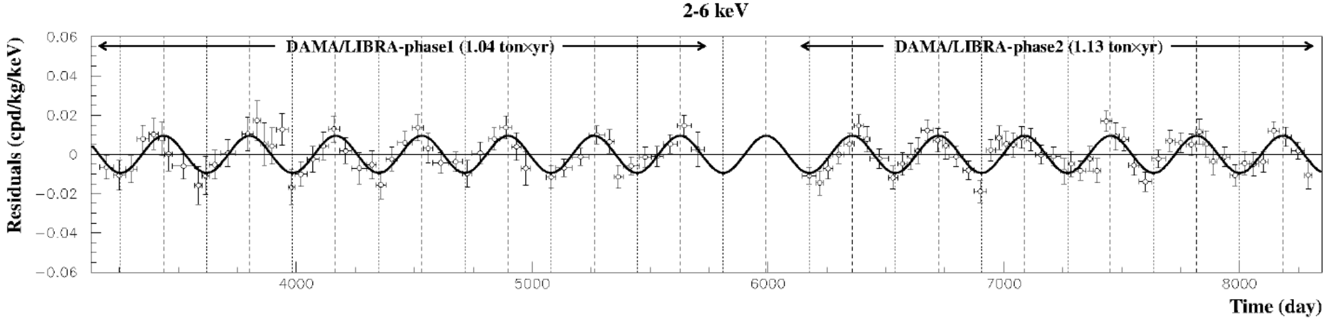


2 more points





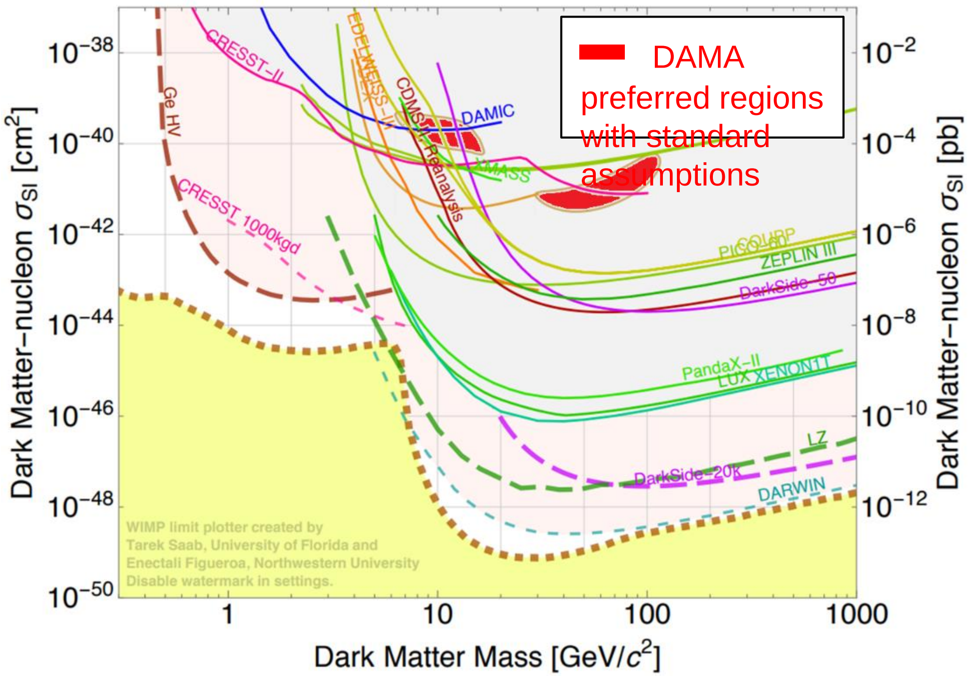
- 6 anual cycles
- Exposure: 1.13 ton × y



The data of DAMA/LIBRA phase1+phase2 favor the presence of a modulation with proper features at **11.9σ CL** (2.17 ton × yr)

arXiv:1805.10486

Interpreting DAMA/LIBRA ph1 as DM

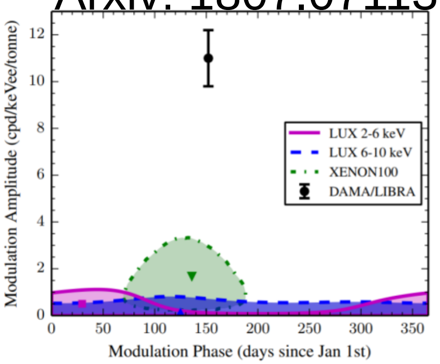


Strong tensión even assuming more general halo/interaction models!

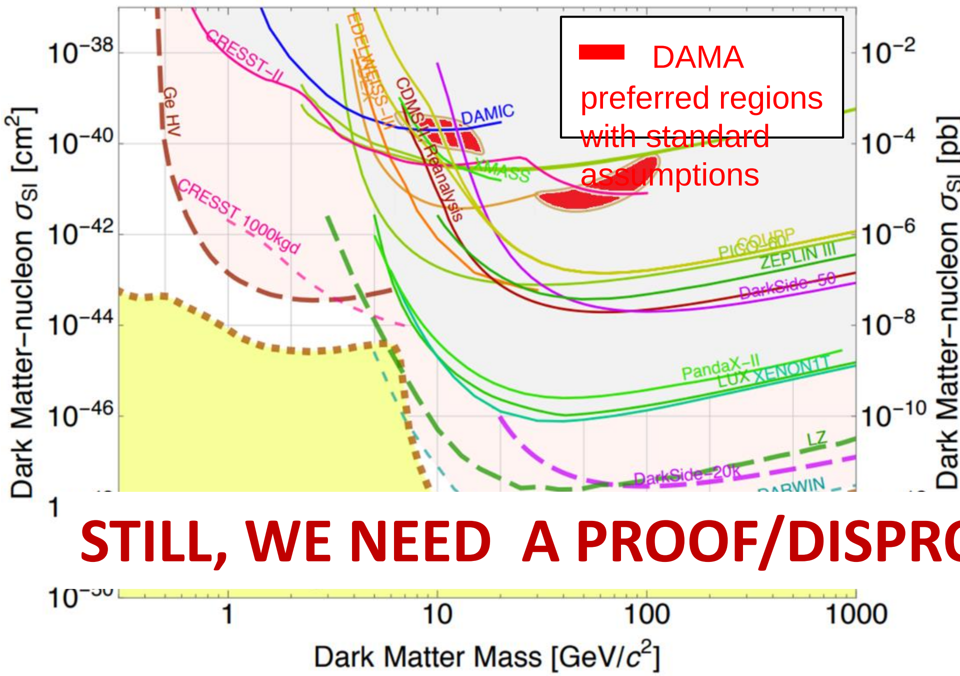
+ No anual modulation signal in some experiments (when bkg discrimination is turned off)

- LUX: arXiv:1807.07113
- XMASS : arXiv:1801.10096
- XENON100 : PRL118, 101101 (2017)
- CDMS-II: arXiv:1203.1309

Arxiv: 1807.07113



Interpreting DAMA/LIBRA ph1 as DM



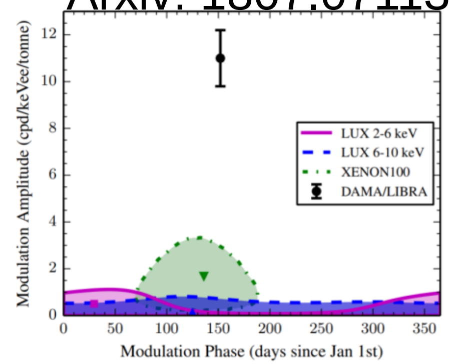
Strong tensión even assuming more general halo/interaction models!

STILL, WE NEED A PROOF/DISPROOF WITH THE SAME TARGET

+ No anual modulation signal in some experiments (when bkg discrimination is turned off)

- LUX: arXiv:1807.07113
- XMASS : arXiv:1801.10096
- XENON100 : PRL118, 101101 (2017)
- CDMS-II: arXiv:1203.1309

Arxiv: 1807.07113



NaI experiments around the World

Borrowed from Yeongduk Kim @ RENATA meeting, Canfranc February 2018

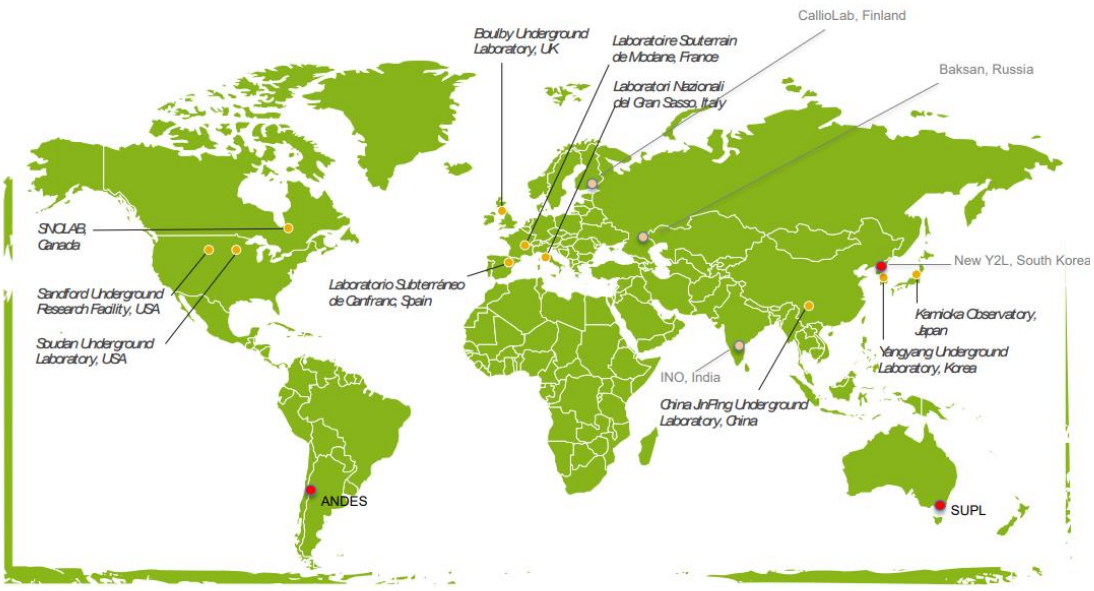
NaI experiments around the World

Borrowed from Yeongduk Kim @ RENATA meeting, Canfranc February 2018

Go south

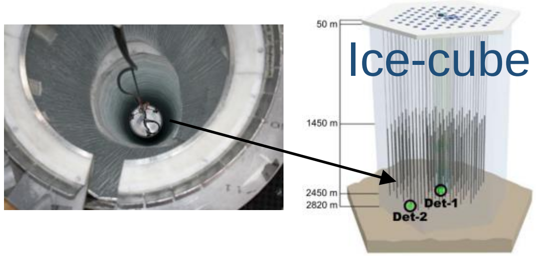
Same WIMP signal, but different seasonal-related backgrounds

But only two (not yet ready) underground labs in the southern hemisphere!!



- ANDES (Chile/Argentina)
  ready by 2027
- SUPL (Australia)
  should be ready soon → Second phase of SABRE experiment
- DM-ICE (south pole)
  NaI crystals in Ice-cube (but many technical problems!)

Borrowed from Aldo Ianni @ TAUP 2017



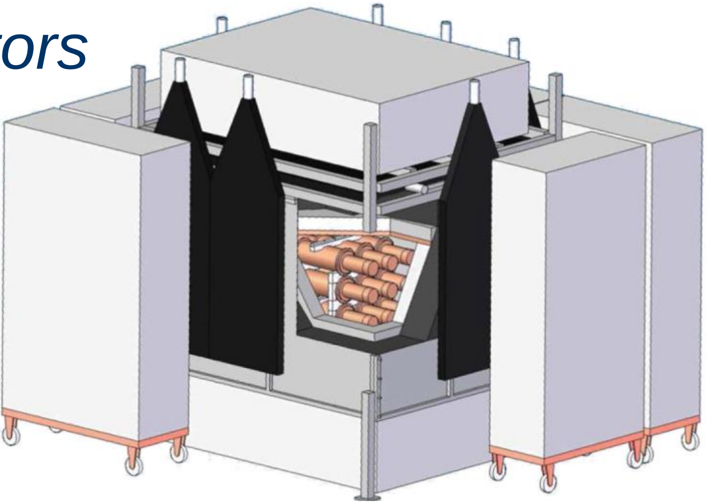
ANAIS-112


MultiDark
Multimessenger Approach
for Dark Matter Detection
LSC
Laboratorio Subterráneo de Canfranc
Universidad
Zaragoza
1542
ANAIS

The ANAIS program

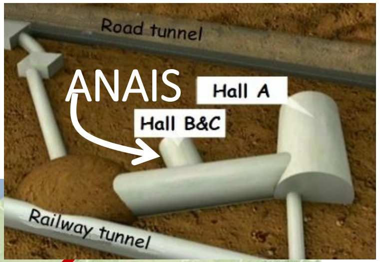
Annual modulation with NAI Scintillators

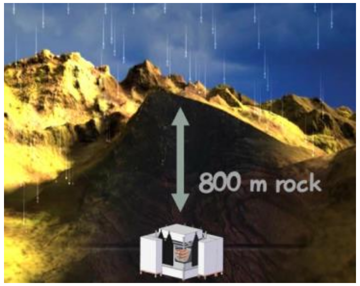
GOAL: confirm the **DAMA/LIBRA** modulation signal using the **same target and technique** in a different environment at the **Canfranc Underground Laboratory** (LSC, Spain)



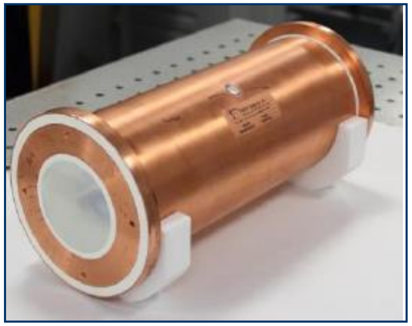
ANAIS-112

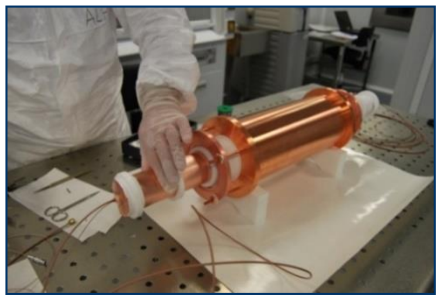
- 112 kg NaI(Tl) scintillators
- Commissioning in March-April 2017
- Calibration and general assessment from April to July 2017
- **Dark matter run** is underway since **3rd, August 2017: first year of data taking successfully completed**





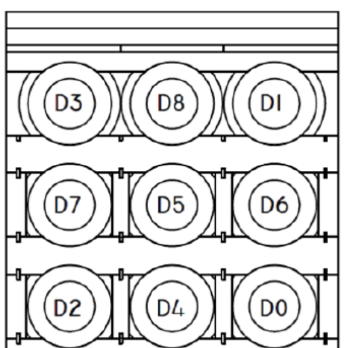
ANAIS-112: Detectors





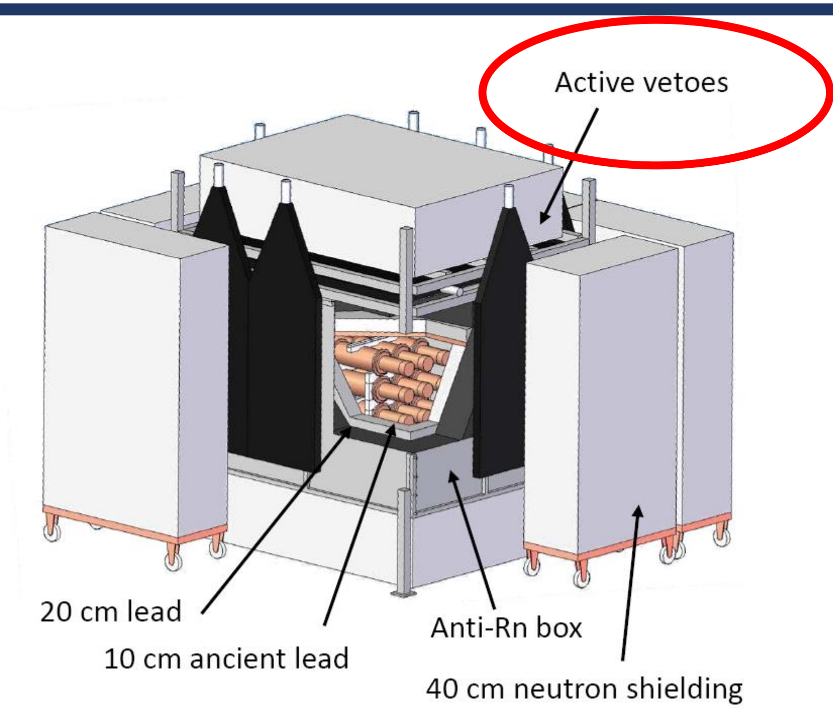
Housing made at LSC of electroformed copper

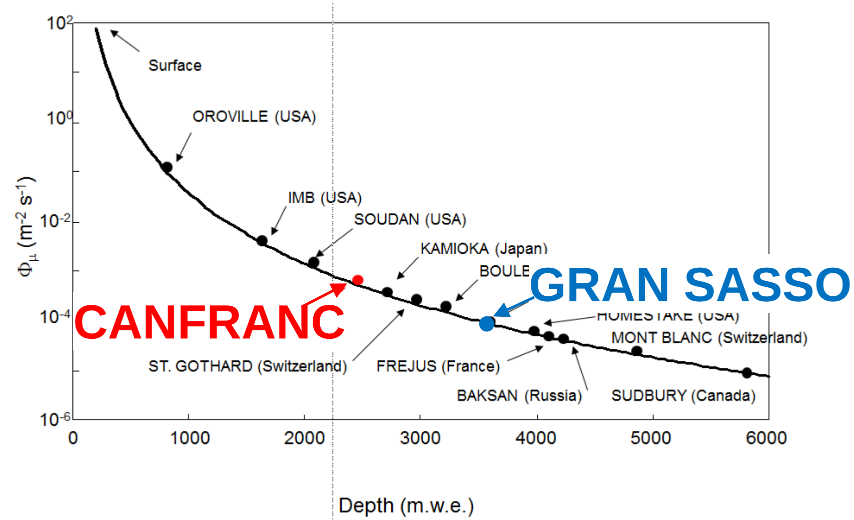
- **9 NaI(Tl) crystals** 12.3 kg each grown from selected ultrapure NaI powder (Alpha Spectra Inc)
- Housed in OFE copper
- Two Hamamatsu R12669SEL2 PMT
  - coupled to each crystal at LSC clean room
  - low background
  - high QE (~40%)



Detector	*Quality powder*	*Received at LSC:*
D0, D1	<90 ppb K	December 2012
D2	WIMPScint-II	March 2015
D3	WIMPScint-III	March 2016
D4, D5	WIMPScint-III	November 2016
D6, D7, D8	WIMPScint-III	March 2017

ANAIS-112: Shielding





Flujo μ @ Canfranc
= **10**× Flujo μ @ Gran Sasso

Anti-Rn box

16 plastic scintillators

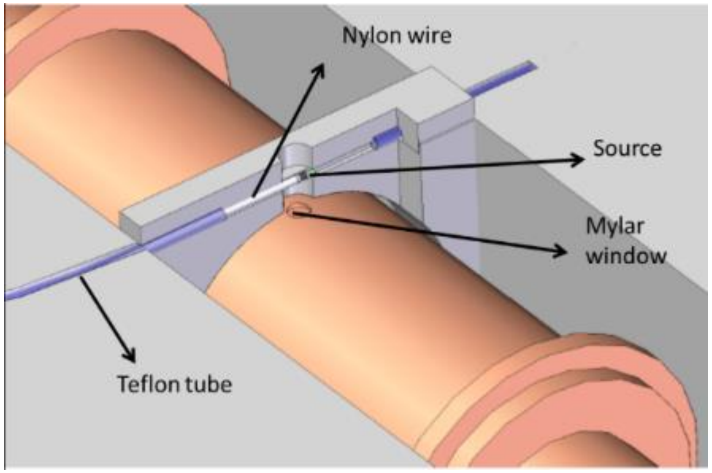
Neutron shielding

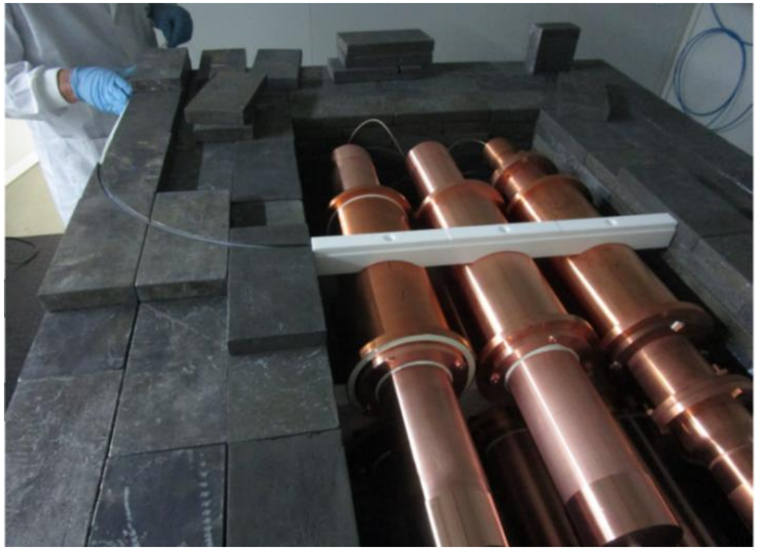
ANAIS-112: Low energy calibration

Detectors equipped with a **Mylar window**!

Radon-free system for low energy calibration:

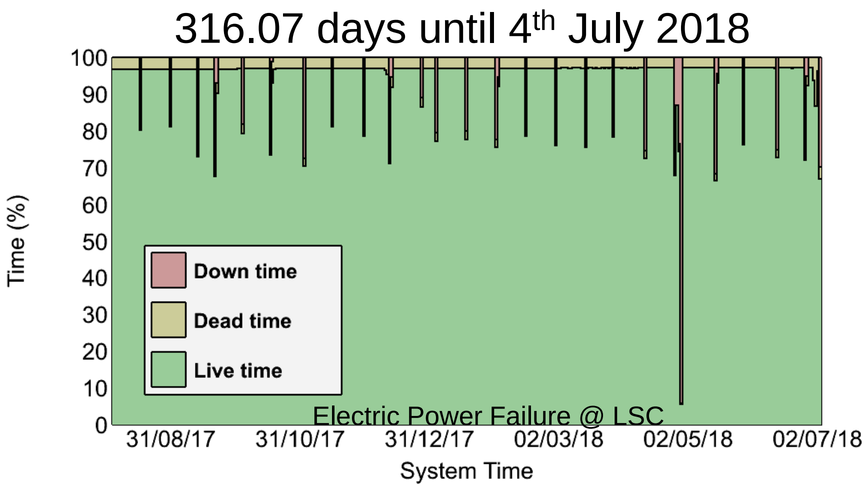
- **^{109}Cd sources** on flexible wires (radon-free)
- Energies: 11.9, 22.6 and 88.0 keV
- Simultaneous calibration of the nine modules
- Performed every two weeks

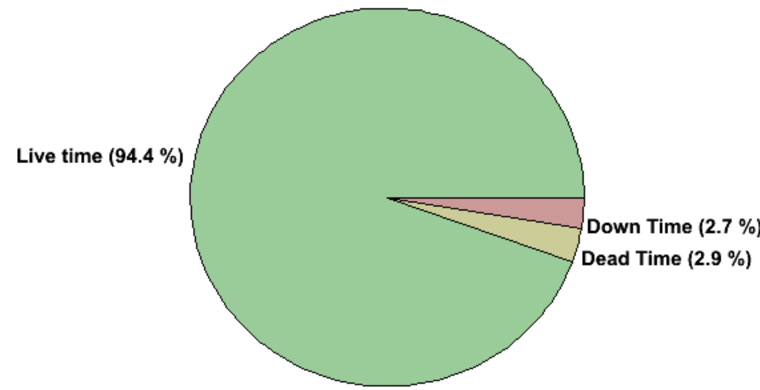




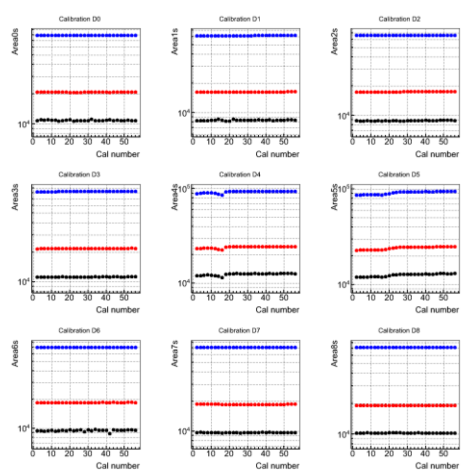
Detector Response: duty cycle & stability

- Excellent **duty cycle**





- Good **total rate and gain stability**

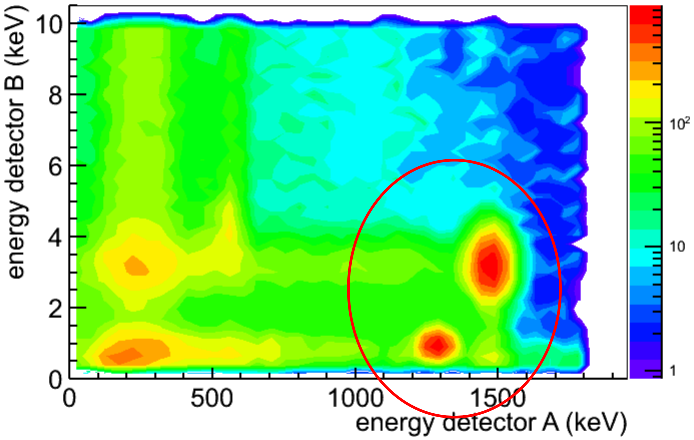


Evolution of ^{109}Cd lines from calibrations along the whole data-taking (~ 1 year)

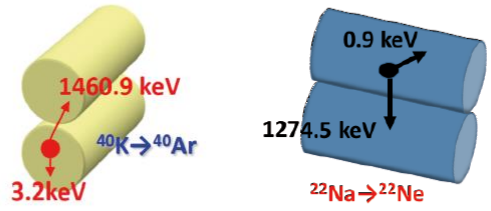
Detector respose: threshold

Outstanding **light collection** of **~15 phe/keV**

- Effectively **triggering below 1 keV_{ee}**



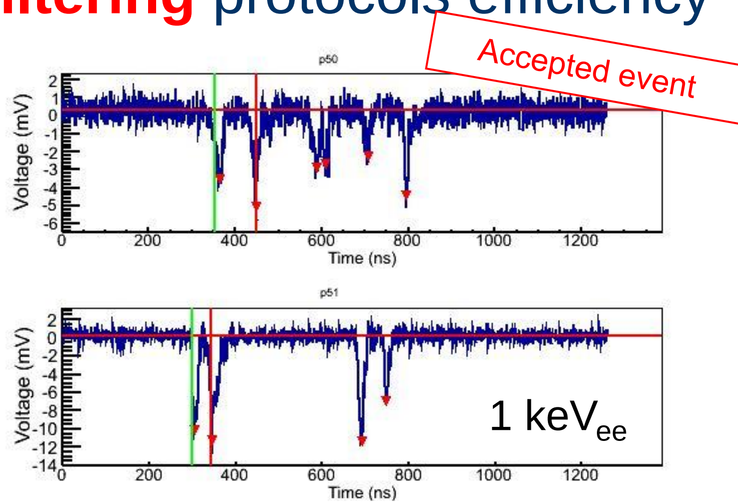
bulk ^{22}Na and ^{40}K events identified by coincidences with high energy gammas



- Energy threshold limited by PMT noise **filtering** protocols efficiency

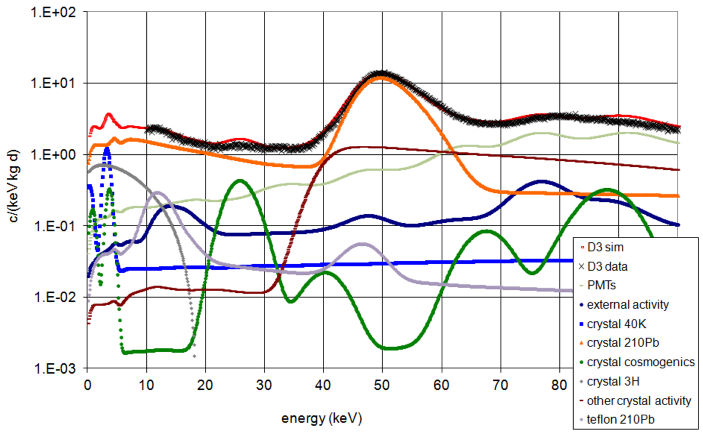
- **Multiparametric cuts** to properly select events with pulse shapes from NaI(Tl) scintillation (efficiency computed on **^{109}Cd calibration and ^{22}Na and ^{40}K** coincidence populations)

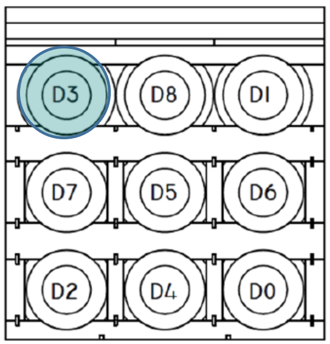
Improved algorithm for peak identification, detecting ~ 75% of the phe



Backgrond model

Comparison for low energy (<100 keV) (3 August 2017 to 30 March 2018)

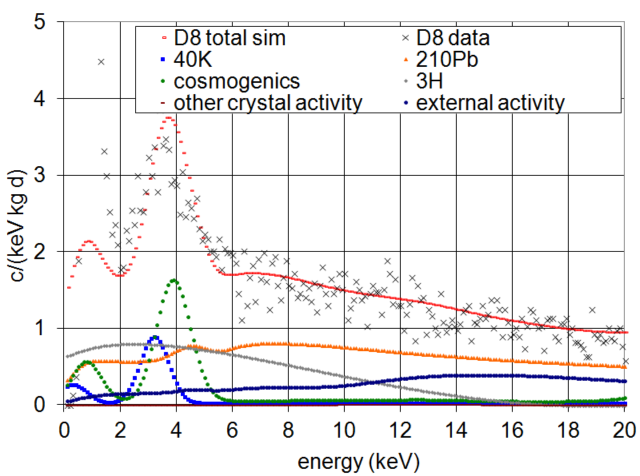


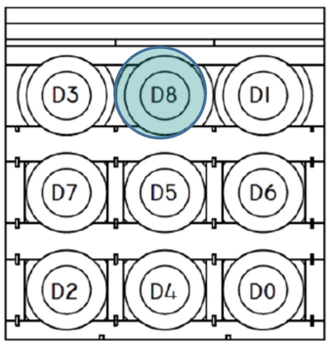


Comparison for very low energy (<20 keV) (Commissioning run, June-July 2017)

Most significant contributions:

- ^{40}**K** and ^{22}**Na** peaks
- ^{210}**Pb** (bulk+surface)
- ^{3}**H**



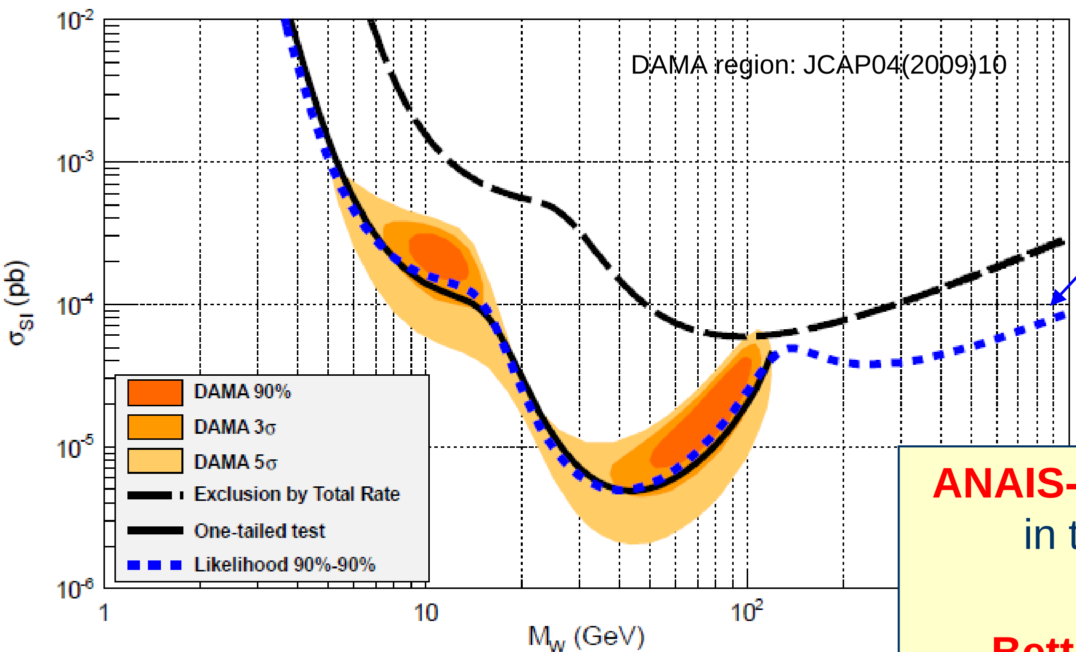


ANAIS-112 annual Modulation sensitiviy

Detection limit at 90% C.L. for a critical limit at 90% C.L. for ANAIS-112

- Conservative estimate of **background** from measured, efficiency corrected levels
- 2-6 keV_{ee} region
- 5 years

Dark matter hypothesis



90% probability of detecting an annual modulation signal at 90% C.L.

ANAIS-112 can detect the annual modulation in the 3σ region compatible with the DAMA/LIBRA result.

Better prospects if good acceptance efficiency is achieved at 1 keV_{ee}

I. Coarasa et al, arXiv:1704.06861v1

OUTLOOK

- Enormous progress in sensitivity in the last two decades
- Xe/Ar future experiments sensitivity approaching neutrino floor in next decade, ideas to go beyond
- Many new ideas for light and ultra-light DM
- DAMA/LIBRA signal still alive, needs for proof/disproof with same target
- ANAIS-112, COSINE-100 can give an answer soon (combined analysis also agreed)

OUTLOOK

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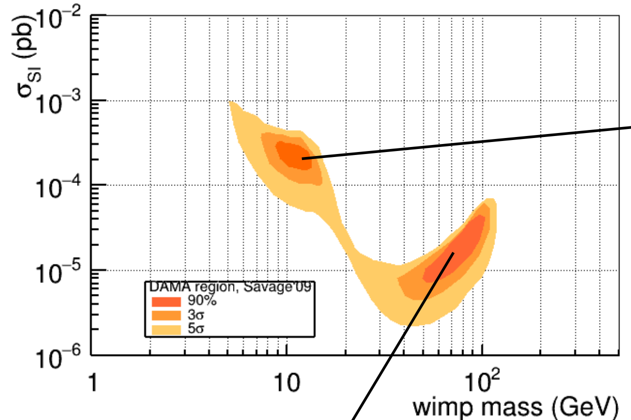
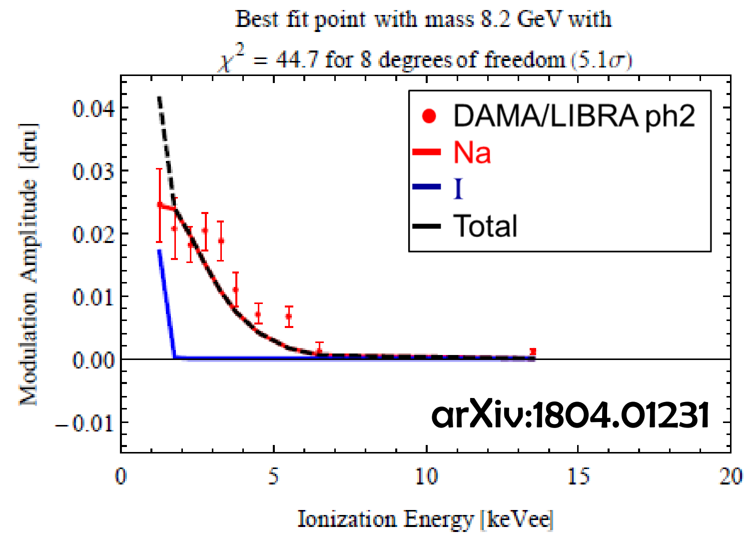
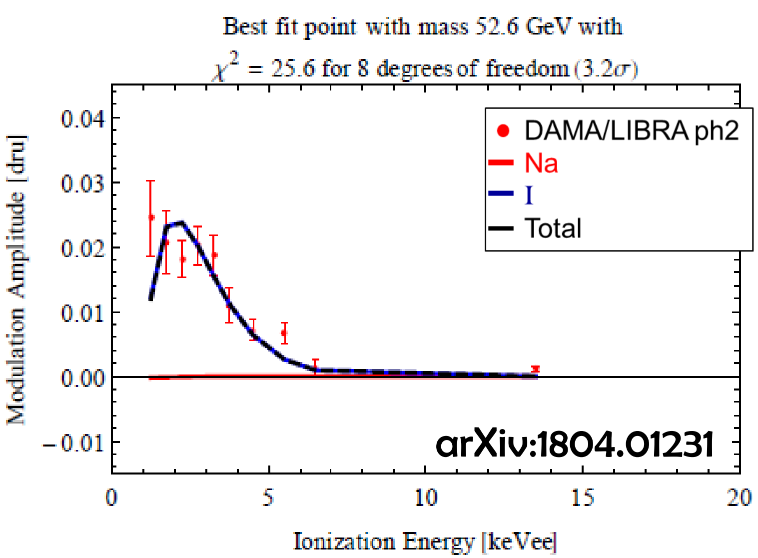
THANKS!!

Spare

Interpretation of the 1 keV point







The point @ 1 keV is hard to explain with standard models:

"the observed annual modulation signal is no longer well fitted by canonical (isospin conserving) spin-independent WIMP nucleon couplings"

New ideas for ultra-light DM

Superconductors

- material with zero electrical resistance below a critical temperature
- DM interaction breaks cooper pairs, which releases energy
- sensitive to ~meV energy depositions

optical phonons

- DM interacts with optical phonons through dipole moment
- sensitive to ~ 30-100 meV energy depositions
- optical phonons exist in polar materials, i.e. GaAs, sapphire

superfluid helium

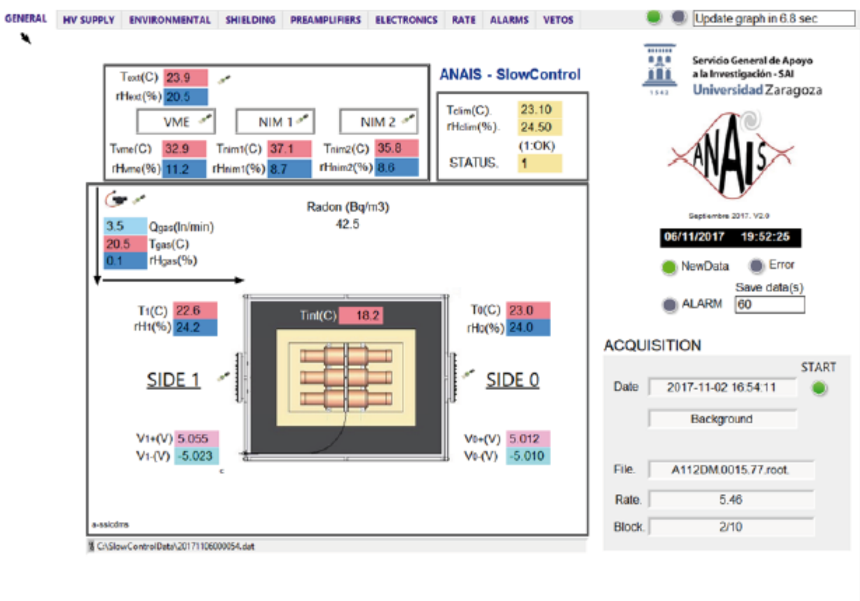
- DM couples to collective quasiparticle modes (phonons, rotons..)
- sensitive to meV-eV energy depositions

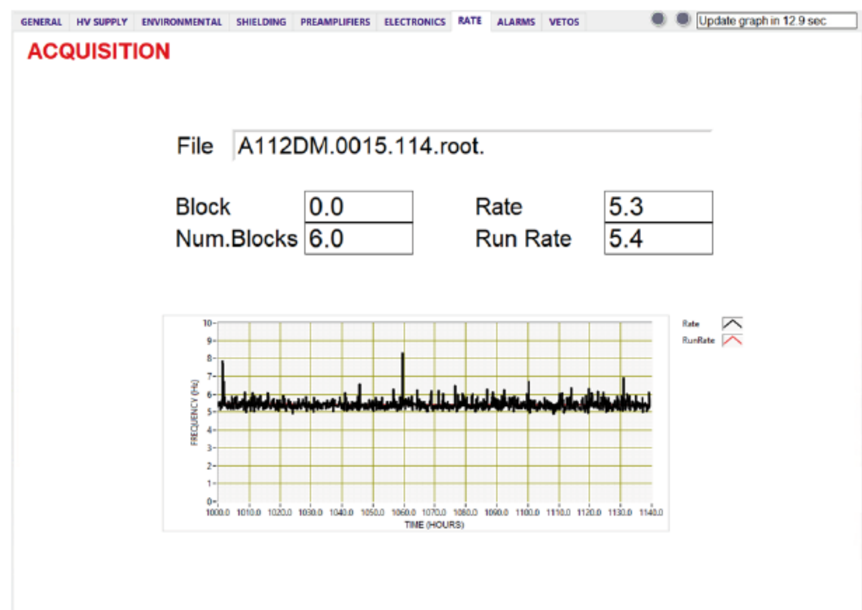
Graphene and carbon nanotubes

- Work function 4.3 eV = minimum energy to eject an electron
- has directional sensitivity!

ANAIS-112: Slow control

- Monitoring **environmental parameters** since the start of DM run
  - Monitoring:
    Rn content, humidity, pressure, different temperatures, N_2 flux, PMT HV, muon rate, …
    Data saved every few minutes and alarm messages implemented
  - Stability checks:
    gain, trigger rate, …





Detector response: light collection

- Outstanding **light collection** of **~15 phe/keV**

  - all modules
  - at different set-ups
  - checked to be stable over time

Detector	PMT/set-up	Total Light Collection (phe/keV)
D0	Ham R12669 / ANAIS112	14.6± 0.1
D1	Ham R12669 / ANAIS112	14.8 ± 0.1
D2	Ham R12669 / ANAIS112	14.6 ± 0.1
D3	Ham R12669 / ANAIS112	14.5 ± 0.1
D4	Ham R12669 / ANAIS112	14.5 ± 0.1
D5	Ham R12669 / ANAIS112	14.5 ± 0.1
D6	Ham R12669 / ANAIS112	12.7 ± 0.1
D7	Ham R12669 / ANAIS112	14.8 ± 0.1
D8	Ham R12669 / ANAIS112	16.0 ± 0.1

M.A. Oliván et al, Astropart. Phys. 93 (2017) 86

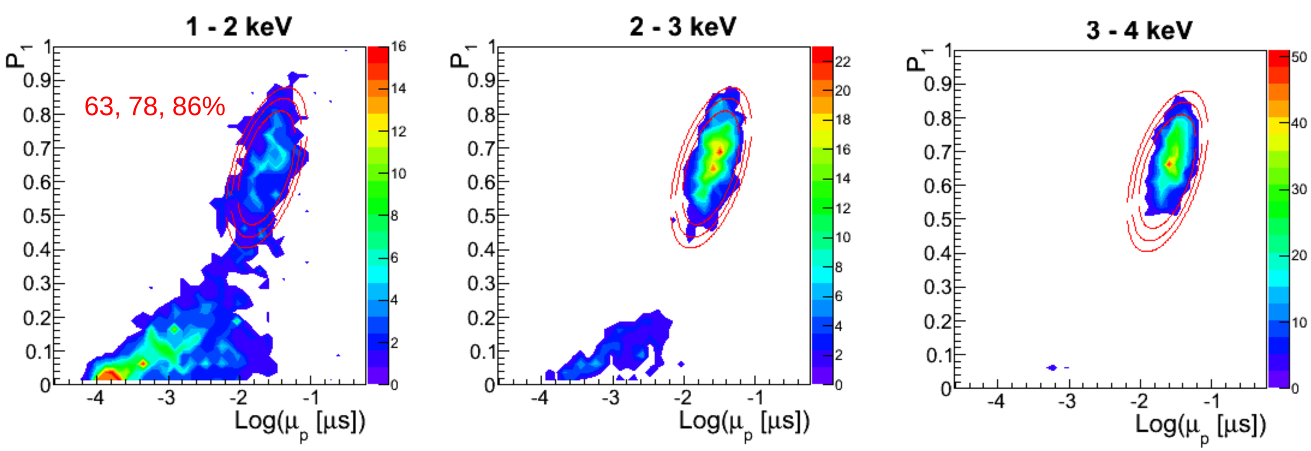
Larger and more homogeneous than the reported light collection for DAMA/LIBRA detectors:
Phase 1: **5.5-7.5 phe/keV**
Phase 2: **6-10 phe/keV**

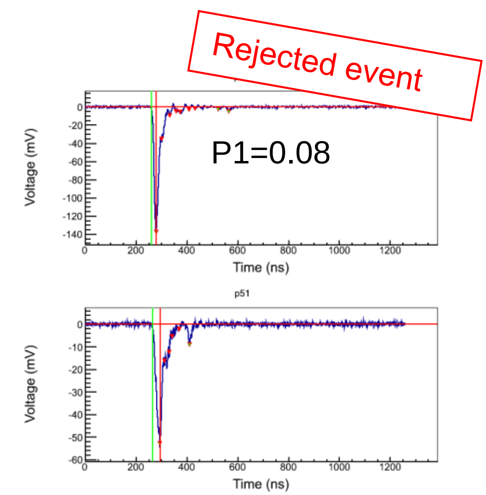
Detector response: noise rejection

- Effective **filtering** protocols for PMT noise limitig the energy threshold

1.- Biparametric cut to properly select events with pulse shapes from NaI(Tl) scintillation

$$P_1 = \frac{\int_{100\,ns}^{600\,ns} A(t)dt}{\int_{0}^{600\,ns} A(t)dt} \qquad \mu_p = \frac{\sum A_p t_p}{\sum A_p}$$



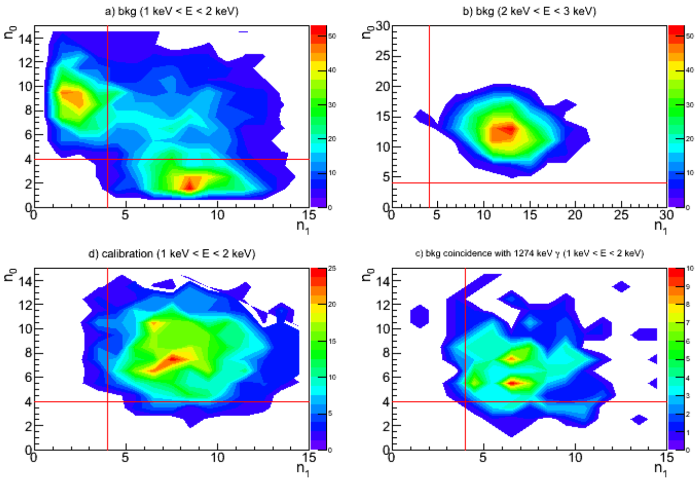


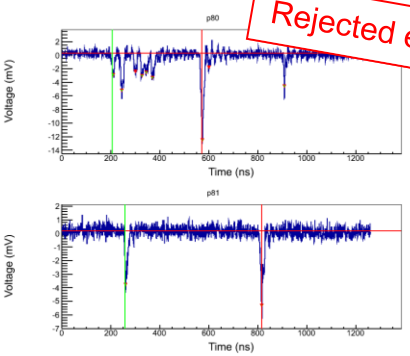
Temporal parameters of the pulse region of 78% acceptance from ^{22}Na and ^{40}K populations

Detector response: noise rejection

- Effective **filtering** protocols for PMT noise limitig the energy threshold

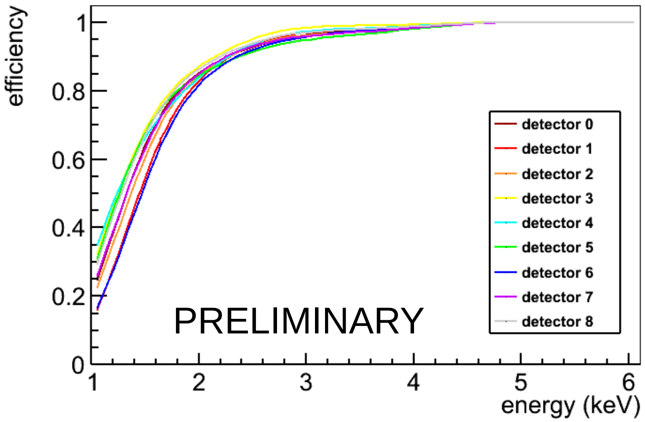
1.-Asymmetric events (<2 keVee): accept events with number_of_peaks > 4 @ every PMT





A **blank module** will be set-up to monitor non NaI(Tl) scintillation events along the second year of operation

- **Acceptance efficiency curves** after two cuts:

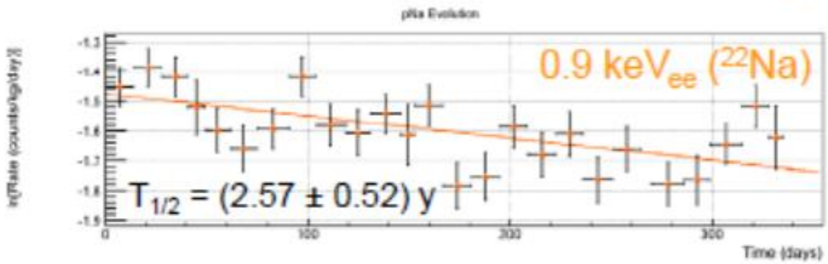


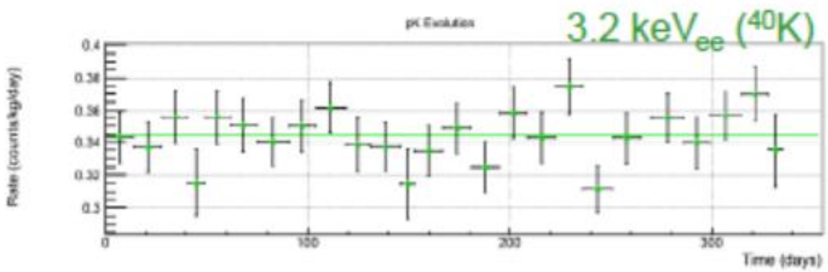
Still working on final tuning,
before unblinding the low energy data.

Expected **analysis** down to **1 keV_{ee}**

Detector response: noise rejection

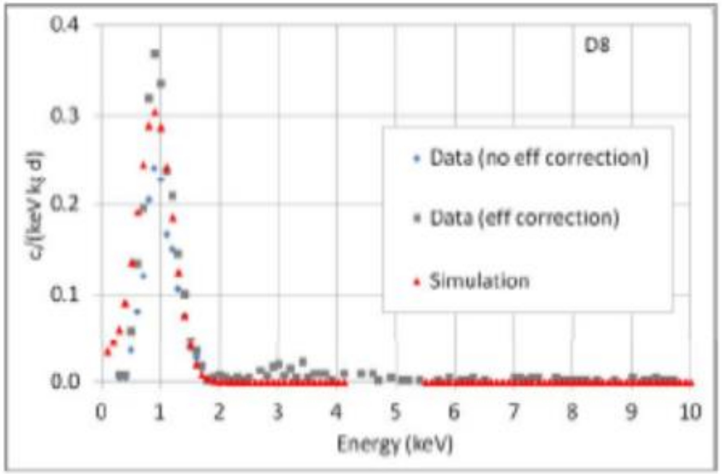
- Effective **filtering** protocols for PMT noise limitig the energy threshold
  - **- Consistent analysis of populations from ^{22}Na and ^{40}K selected by the coincidence with a high energy gamma**
    - Time evolution of the rate at low energy peaks





Still working on final tuning, before unblinding the low energy data.
Expected **analysis** down to **1 keV$_{ee}$**

- Measured rate (after filtering and efficiency correction) at 0.9 keV well reproduced by simulation using the ^{22}Na activity quantified independently

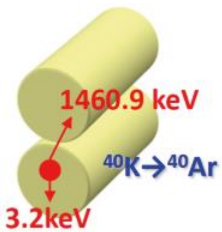


Background model: bkg sources

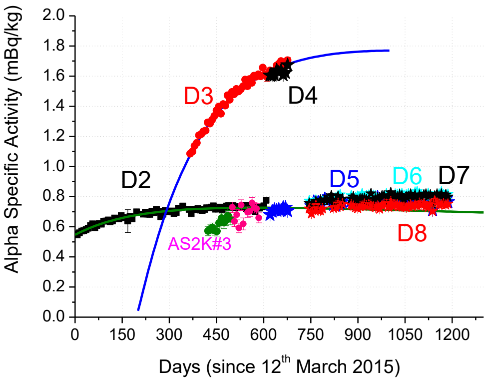
- Detailed **background models** for each detector
  - Geant4 Monte Carlo simulation
  - accurate quantification of **background sources**
    - **Activity from external components** measured with HPGe detectors at Canfranc
    - **Internal activity** directly assessed: mainly ^{40}K, ^{210}Pb

Module	^{40}K (mBq/kg)	^{210}Pb (mBq/kg)
D0	1.4 ± 0.2	3.15 ± 0.10
D1	1.1 ± 0.2	3.15 ± 0.10
D2	1.1 ± 0.2	0.7 ± 0.1
D3	0.60 ± 0.06	1.8 ± 0.1
D4	0.5 ± 0.2	1.8 ± 0.1
D5	0.8 ± 0.2	0.78 ± 0.01
D6	0.8 ± 0.2	0.81 ± 0.01
D7	0.9 ± 0.2	0.80 ± 0.01
D8	0.6 ± 0.2	0.74 ± 0.01

C. Cuesta et al., Int. J. Mod. Phys. A. 29 (2014) 1443010
J. Amaré et al, Eur. Phys. J. C 76 (2016) 429



^{40}K: by identifying coincidences



^{232}Th, ^{238}U: determined by alpha rate following PSA and analysis of BiPo sequences at a level of a few μBq/kg, but **^{210}Pb out of equilibrium**

Background model: bkg sources

- Detailed **background models** for each detector
  - Geant4 Monte Carlo simulation
  - accurate quantification of **background sources**
    - **Activity from external components** measured with HPGe detectors at Canfranc
    - **Internal activity** directly assessed: mainly ^{40}K, ^{210}Pb
    - **Cosmogenic activity:** short-lived Te and I isotopes, ^{3}H, ^{22}Na, ^{109}Cd, ^{113}Sn

^{22}Na: from analysis of coincidences

Same order of activity measured using HPGe by SABRE on AstroGrade powder: 0.8 mB/kg = 69 kg^{-1}d^{-1}

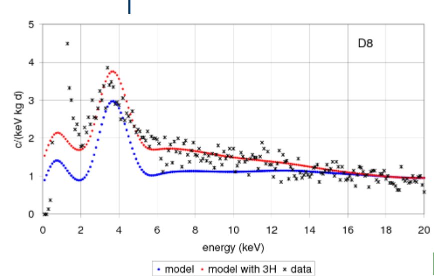
SABRE Colaboration, arXiv:1806.09344v1

^{3}H: additional background source contributing only in the very low energy region required, which could be tritium

D0-D1: 0.20 mBq/kg
D2-D8: 0.09 mBq/kg (upper limit DAMA/LIBRA)

Same order of ^{3}H activity fitted by COSINE-100

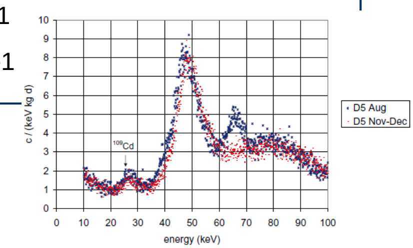
P. Adhikari et al, Eur. Phys. J. C (2018) 78:490



^{109}Cd, ^{113}Sn: from peaks at binding energies of K-shell electrons (after EC)

Preliminary estimate of production rates:

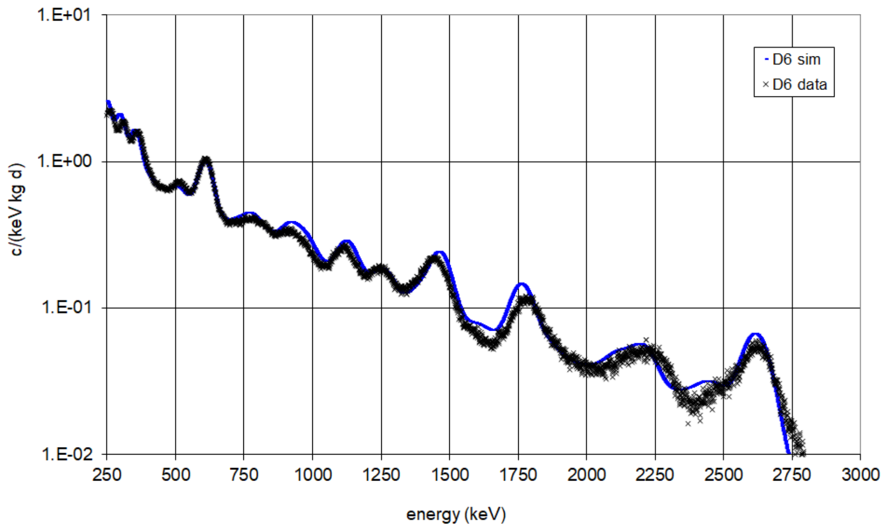
^{109}Cd (2.38±0.20) kg^{-1}d^{-1}
^{113}Sn (4.53±0.40) kg^{-1}d^{-1}

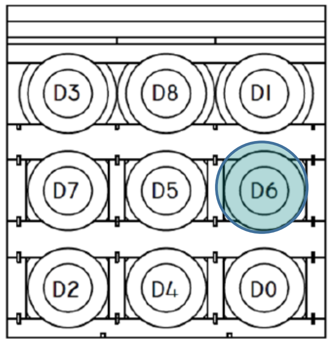


JCAP 02 (2015) 046
Astropart. Phys.97 (2018) 96
Int. J. Mod. Phys. A 33 (2018) 1843006

Backgrond model : comparison with data

Comparison for high energy (>250 keV) (3 August 2017 to 30 March 2018)





Individual contributions: