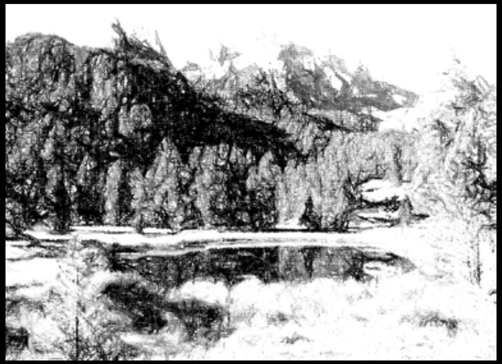
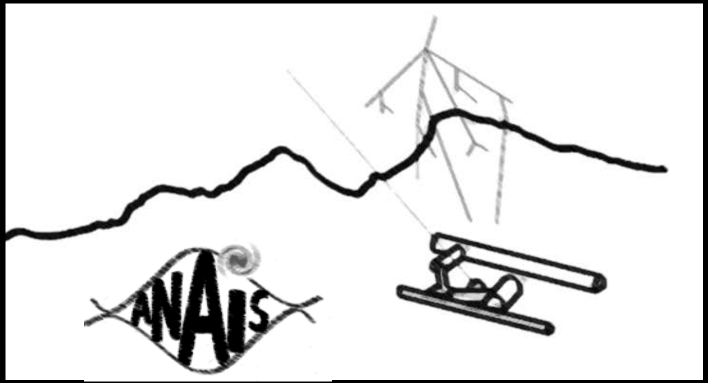
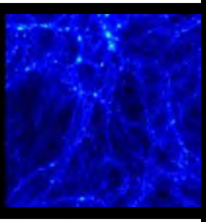


Dark Matter Review - II

M.L. Sarsa
Centro de Astropartículas y Física de Altas Energías, UNIVERSIDAD DE ZARAGOZA



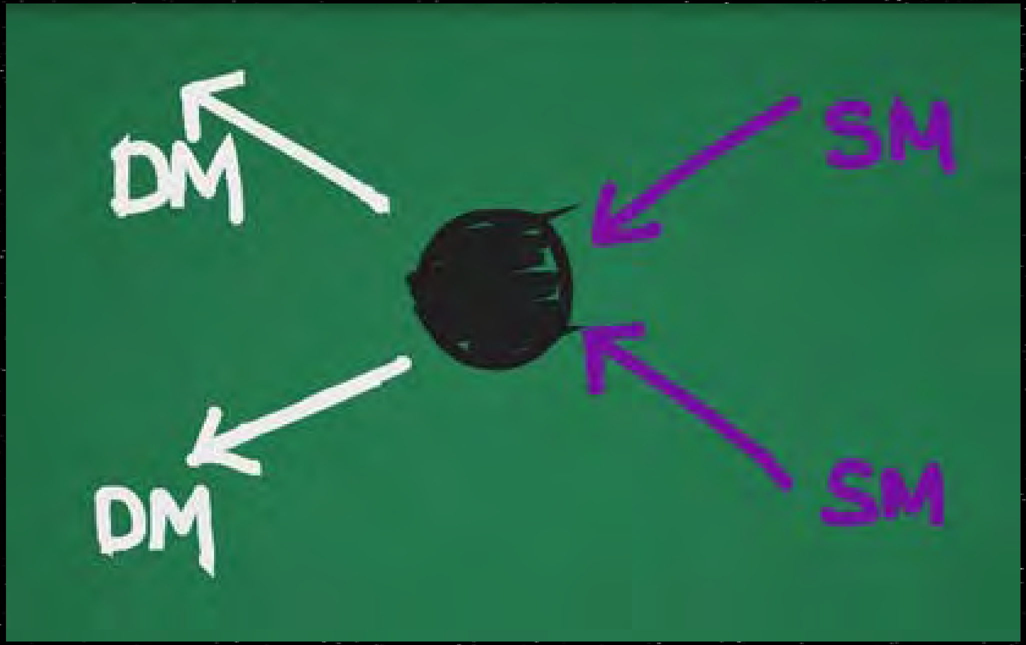
MultiDark
Multimessenger Approach for Dark Matter Detection



XLVIII International Meeting on Fundamental Physics
BENASQUE, 8 September 2021

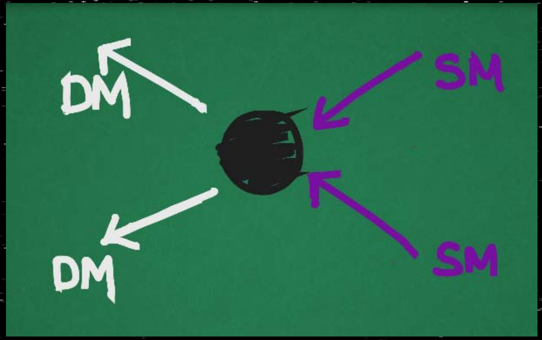
LSC Laboratorio Subterráneo de Canfranc
CAPA Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

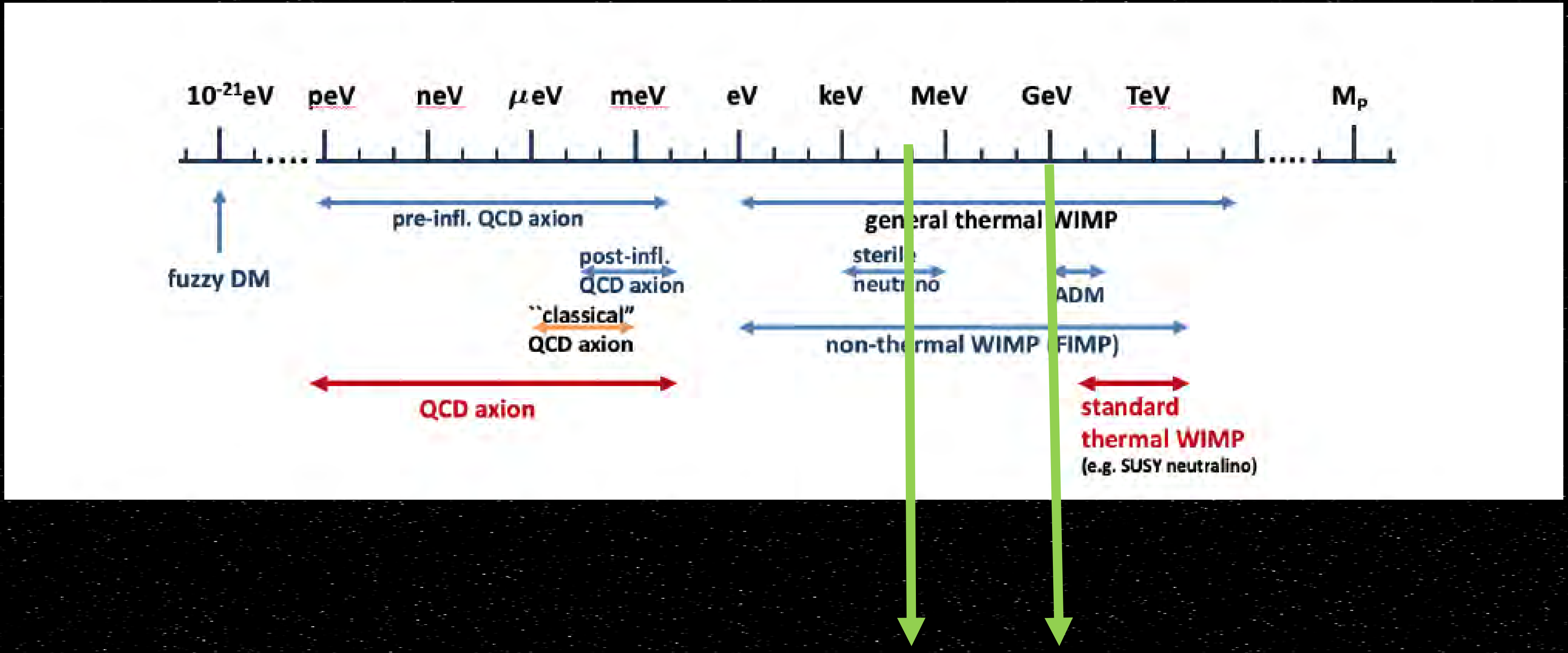
DM Searches in Accelerators



Almost any hint pointing at new Physics has a DM-related consequence

DM Searches in Accelerators

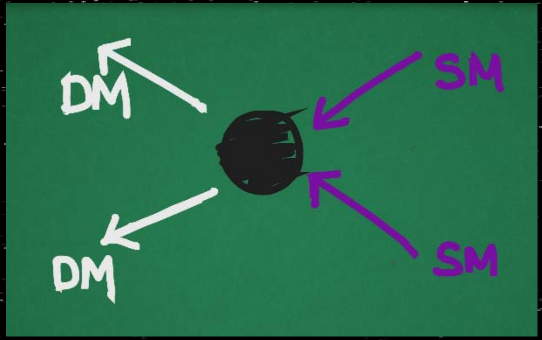




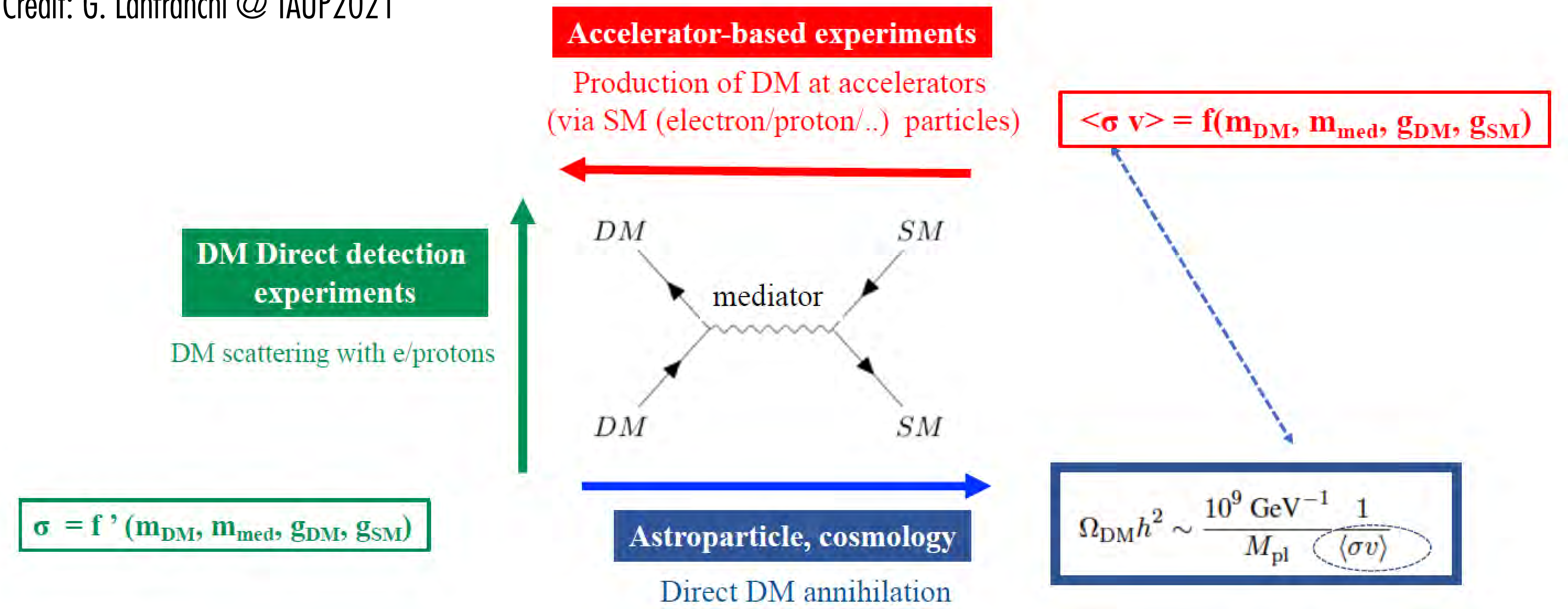
Light DM (thermal relic)

G. Lanfranchi @ TAUP2021

A theoretical framework is key to interpret results and compare them
IMPORTANT COMPLEMENTARITY



Credit: G. Lanfranchi @ TAUP2021



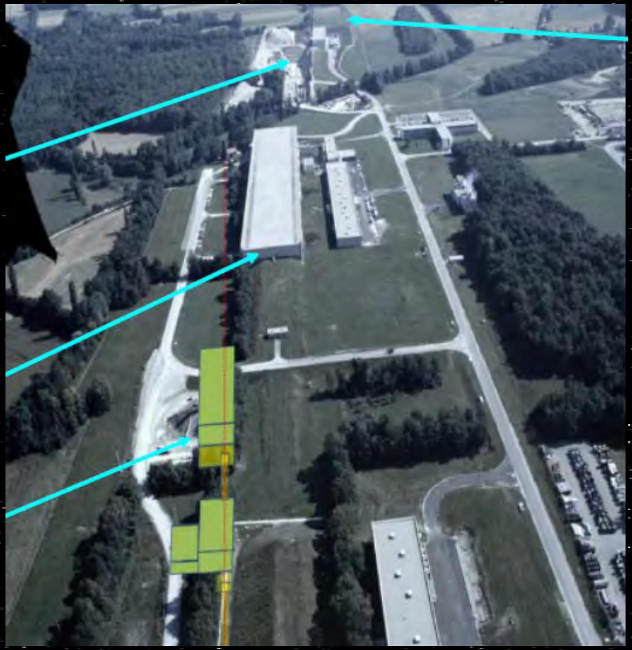
A theoretical framework is key to interpret results and compare them
IMPORTANT COMPLEMENTARITY

In accelerator searches momentum transfer is large ($q > m_{DM}$) and process are less sensitive to the details of the microscopic interaction/mediator. If assuming thermal origin -> competitive sensitivity

ECN3
400 GeV, p-beam

EHN1
100 GeV, e-beam

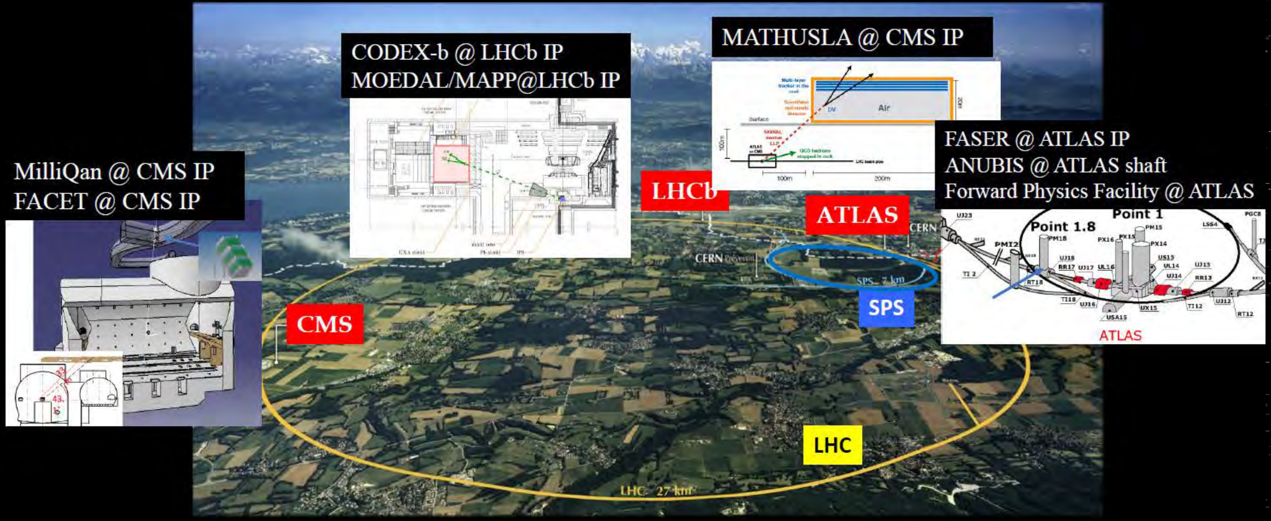
Medium @ long-term projects
SHiP @ BDF



EHN2
100-16

CERN-North Area

Long-Lived Particle detectors at LHC IPs



Credit: G. Lanfranchi @ TAUP2021

A theoretical framework is key to interpret results and compare them

IMPORTANT COMPLEMENTARITY

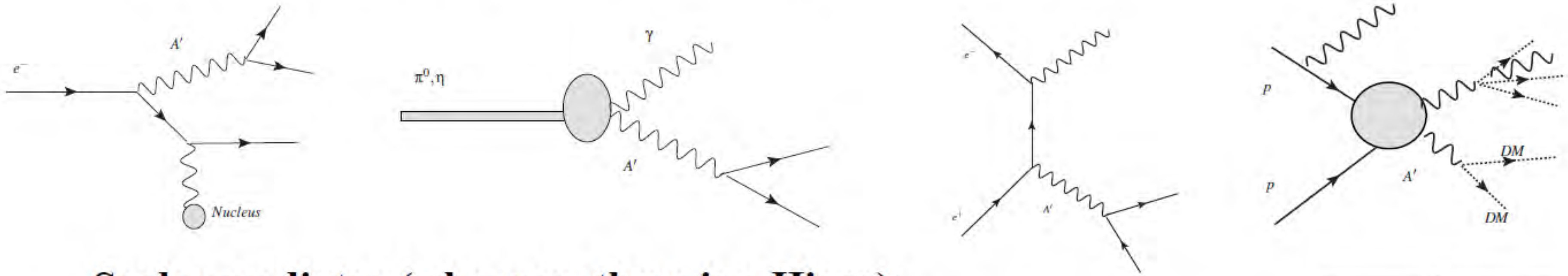
Effort to establish BENCHMARK MODELS

MEDIATORS CAN BE PRODUCED AT ACCELERATORS

Credit: G. Lanfranchi @ TAUP2021

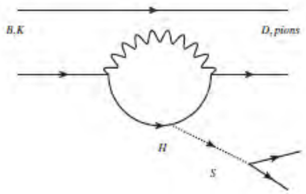
Vector mediator (wherever there is a photon):

- Dark Bremsstrahlung (p and electron beam dump)
- Annihilation ($e^+ e^- \rightarrow A' \gamma$) (positron beam dump or e+ e- collider)
- Light meson decays (eg: $\pi^0 \rightarrow A' \gamma$) (proton/e beam dump, e+ e-/pp colliders)



Scalar mediator (wherever there is a Higgs):

1) K, B decays: b,s → S X (virtual Higgs): p beam dump, K factory, pp collider
2) Higgs → SS (Higgs on shell): LHC



A theoretical framework is key to interpret results and compare them

IMPORTANT COMPLEMENTARITY

Effort to establish BENCHMARK MODELS

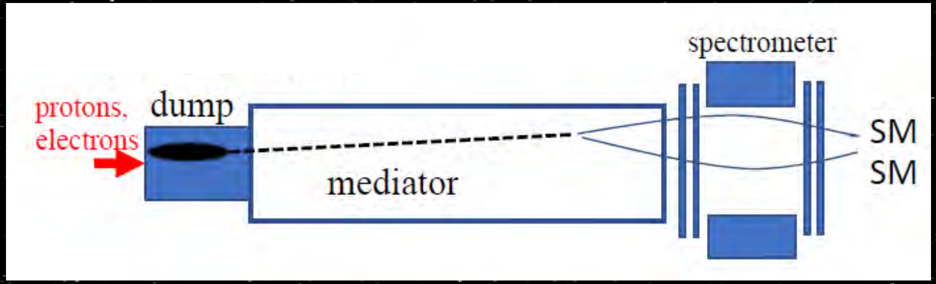
MEDIATORS CAN BE PRODUCED AT ACCELERATORS

At beam lines

Signatures dependent on the mediator mass

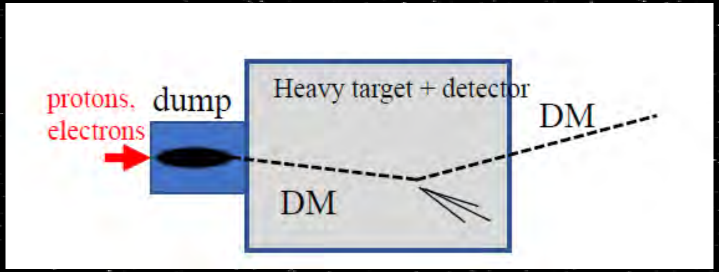
-Mediators produce visible final states

M(med) < 2 M(DM)

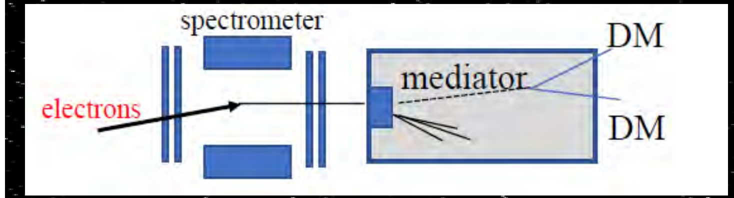


-Mediators produce invisible final states

M(med) > 2 M(DM)



DM scattering in the detector



Missing energy/momentum

Credit: G. Lanfranchi @ TAUP2021

A theoretical framework is key to interpret results and compare them

IMPORTANT COMPLEMENTARITY

Effort to establish BENCHMARK MODELS

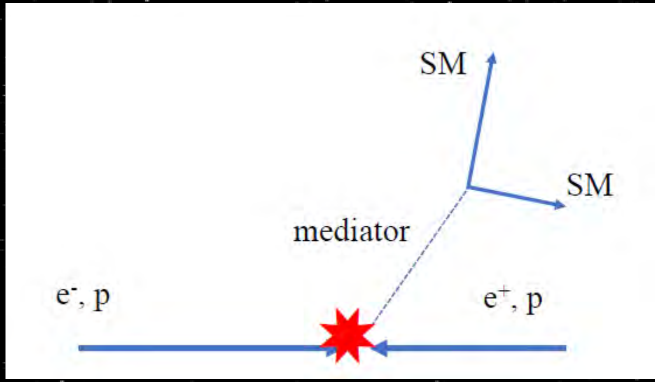
MEDIATORS CAN BE PRODUCED AT ACCELERATORS

At colliders

Signatures dependent on the mediator mass

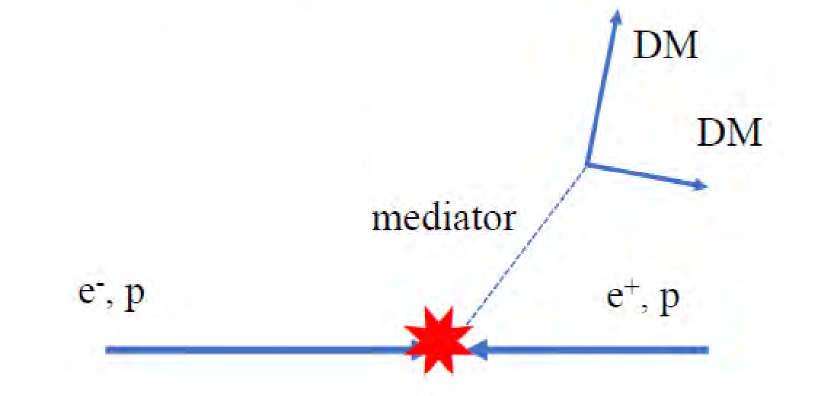
-Mediators produce visible final states

M(med) < 2 M(DM)



-Mediators produce invisible final states

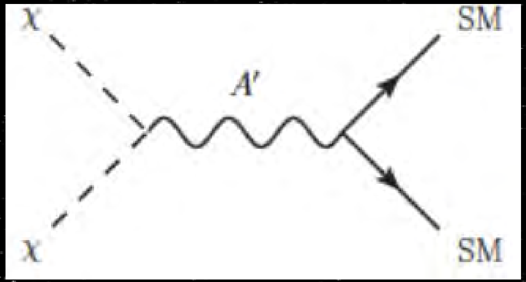
M(med) > 2 M(DM)

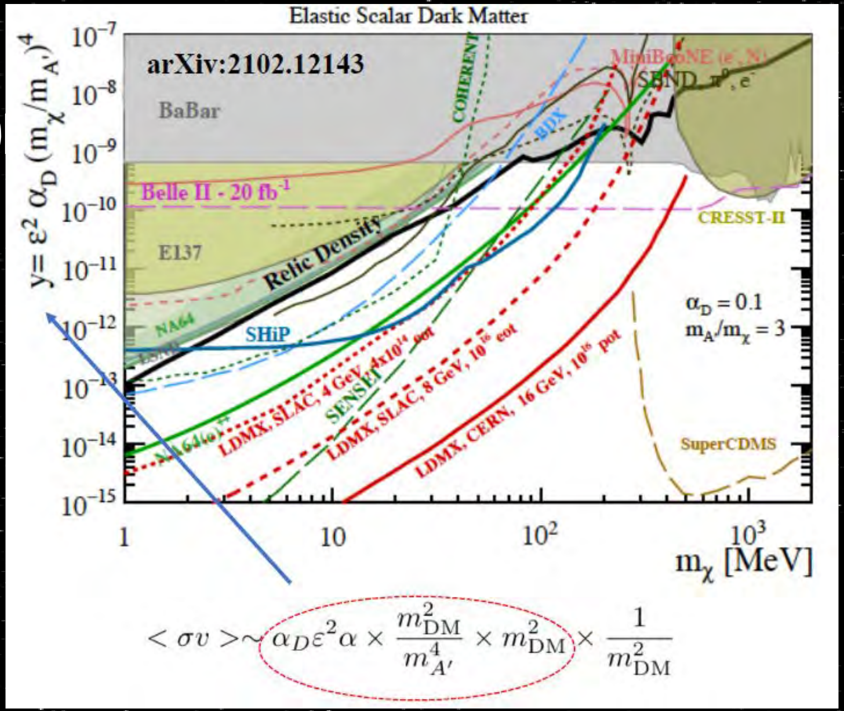


Credit: G. Lanfranchi @ TAUP2021

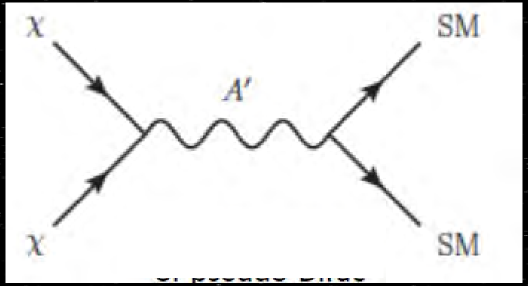
A theoretical framework is key to interpret results and co
IMPORTANT COMPLEMENTARITY

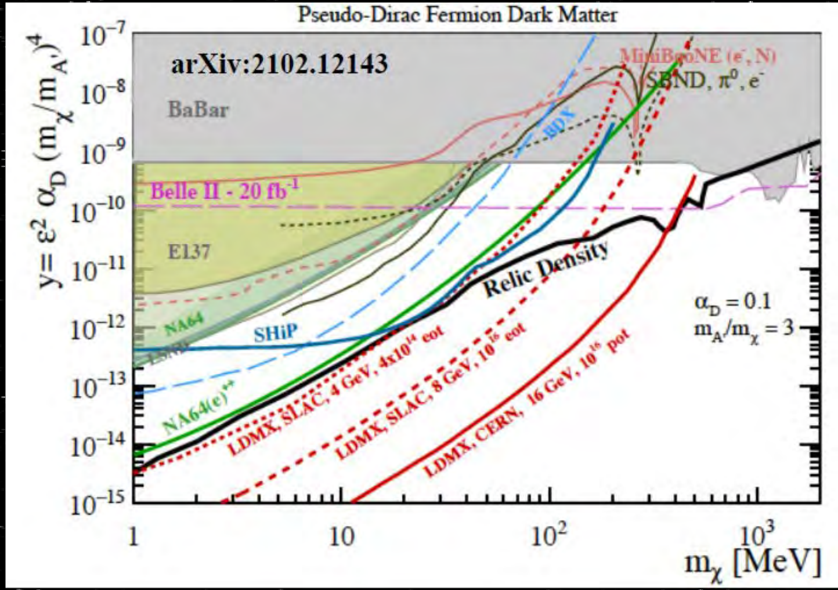
For SCALAR DM with VECTOR mediator





For Pseudo-Dirac DM with VECTOR mediator



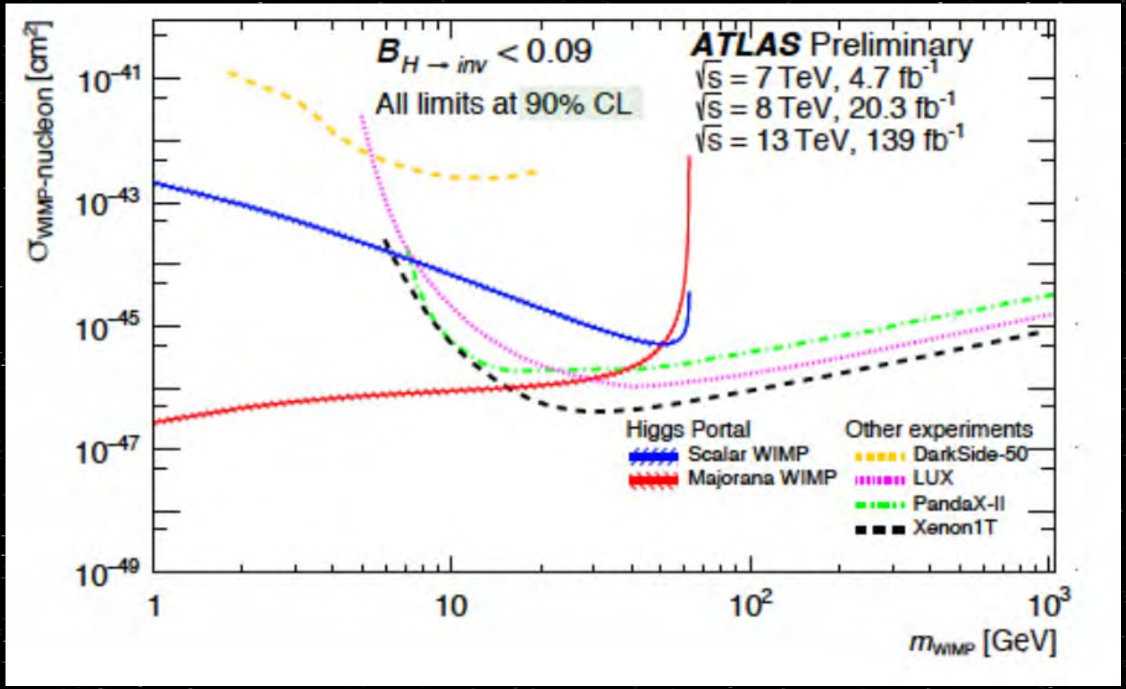


No signal in Direct Detection experiments (Kinematically Suppressed)

Credit: G. Lanfranchi @ TAUP2021

A theoretical framework is key to interpret results and compare them
IMPORTANT COMPLEMENTARITY

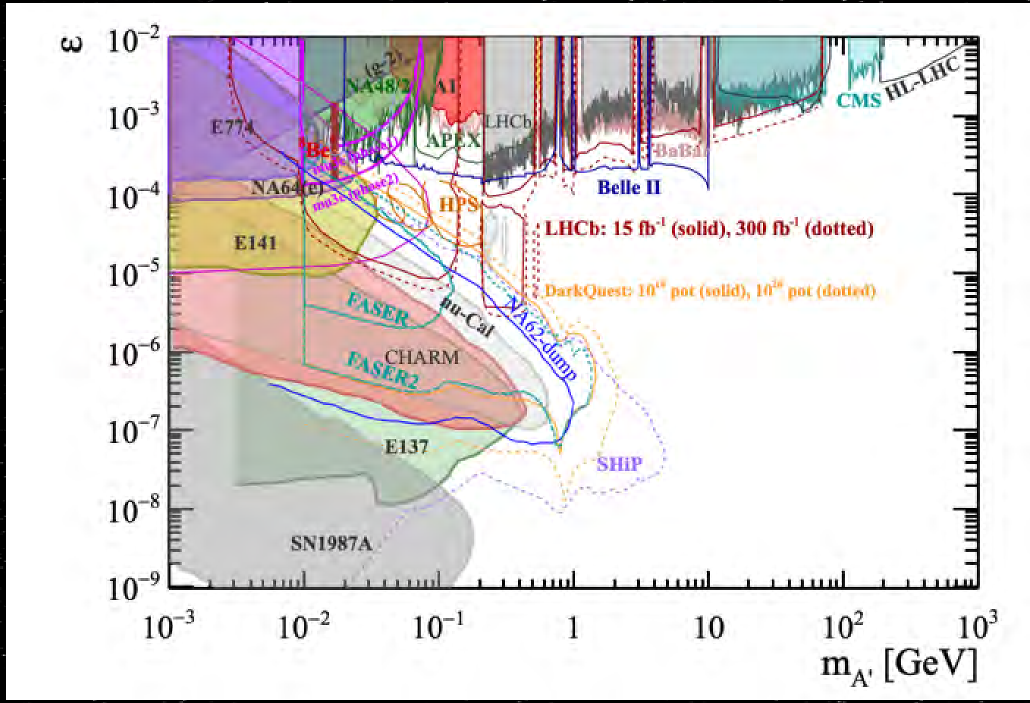
DM searches through invisible Higgs width (if DM is Higgs-mediated)



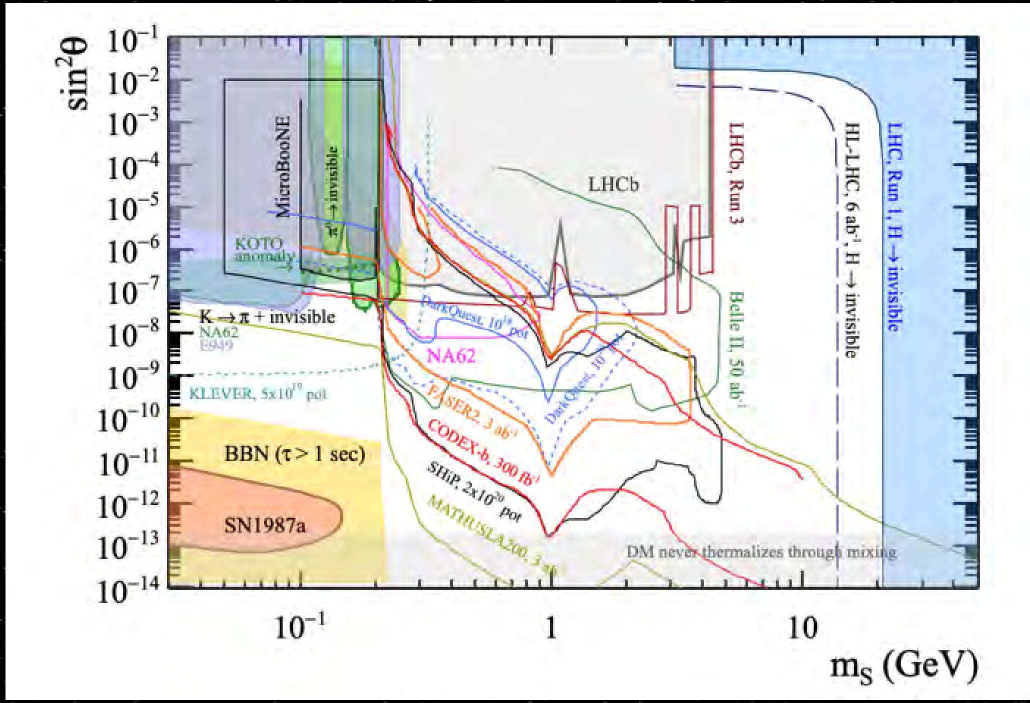
Competitive with Direct Detection

A theoretical framework is key to interpret results and compare them
IMPORTANT COMPLEMENTARITY

Vector Portal: Dark photon into visible final states

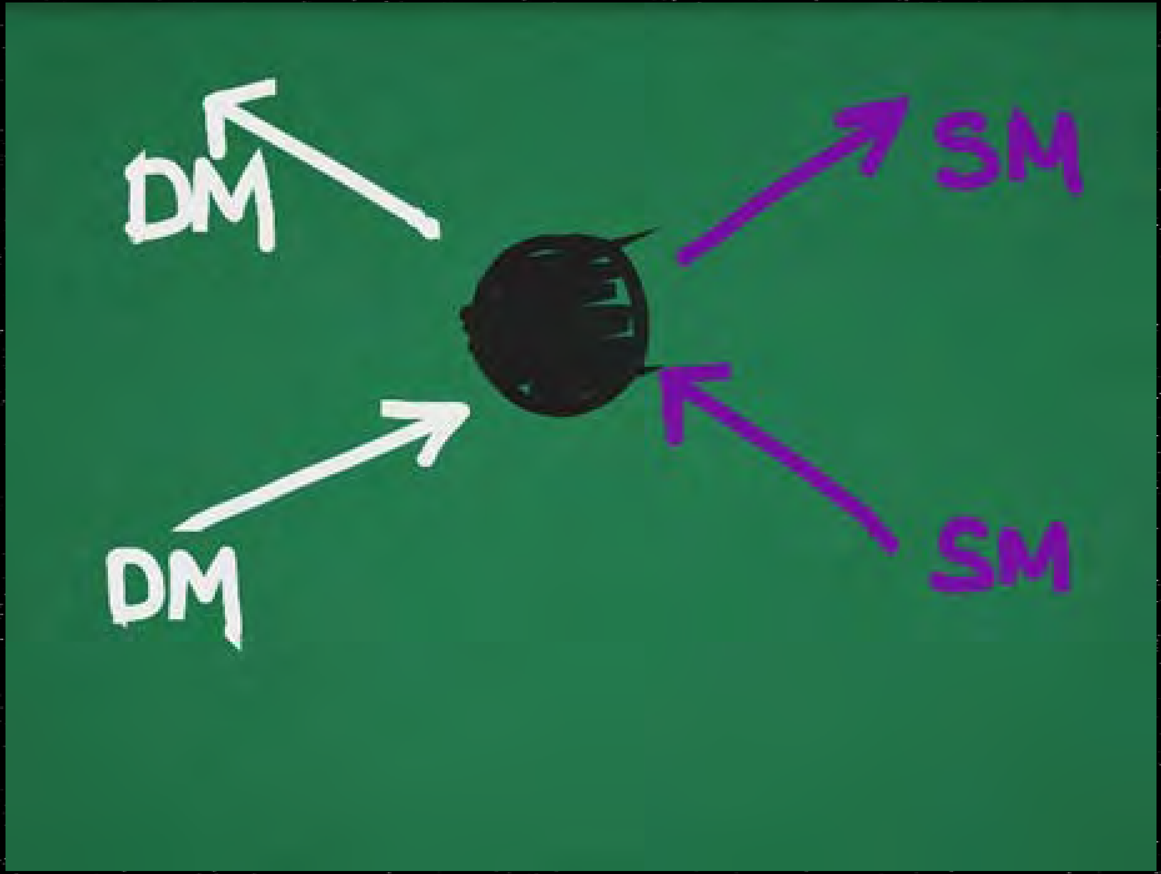


Scalar Portal: Dark scalar mixing with Higgs and decaying to visible final states

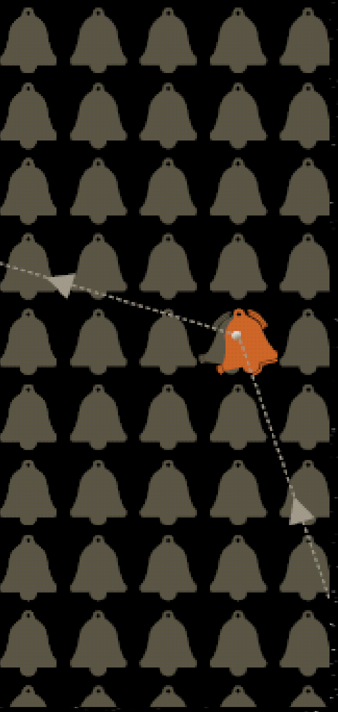


Feebly Interacting Particles Physics Centre (https://pbc.web.cern.ch/fpc-mandate)

DIRECT DETECTION OF DARK MATTER

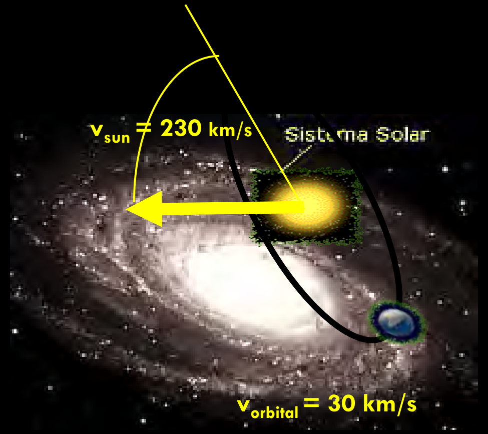


DIRECT DETECTION OF DARK MATTER

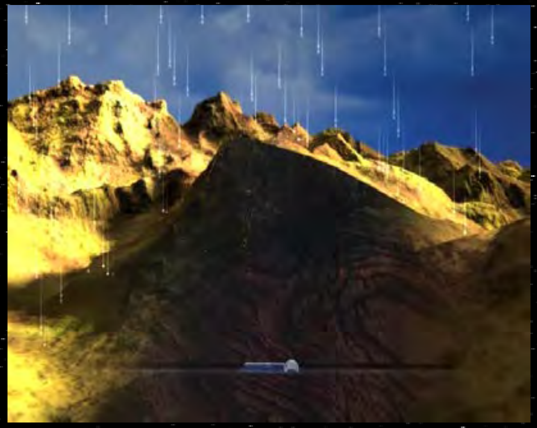


Availability of very sensitive and radiopure particle detectors

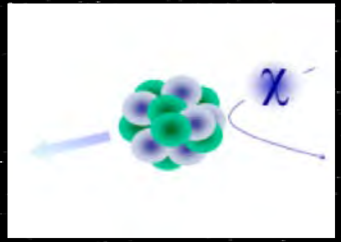
Signatures of a Dark Matter interaction are very convenient for a positive result



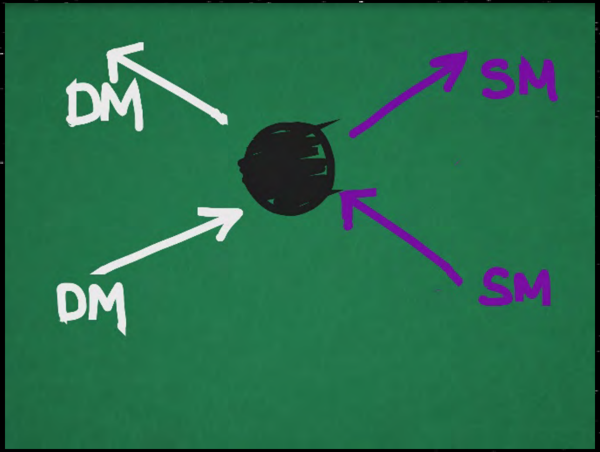
Experiments have to be shielded against all possible backgrounds and profit from active background rejection techniques

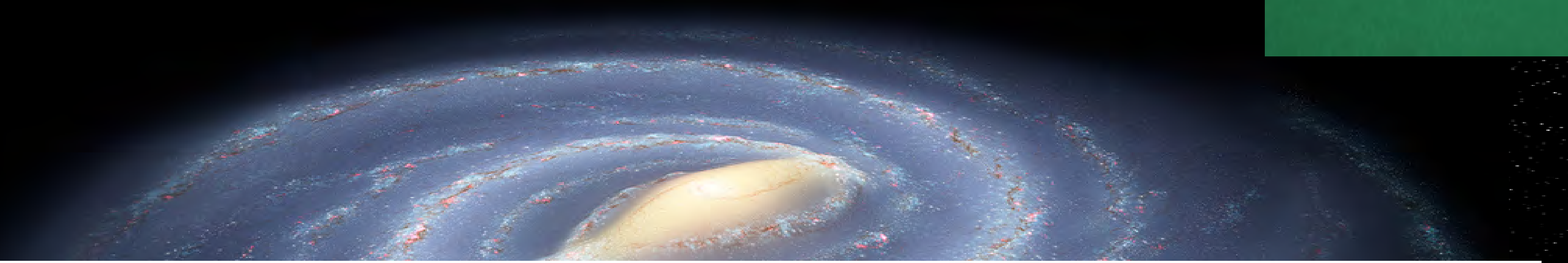


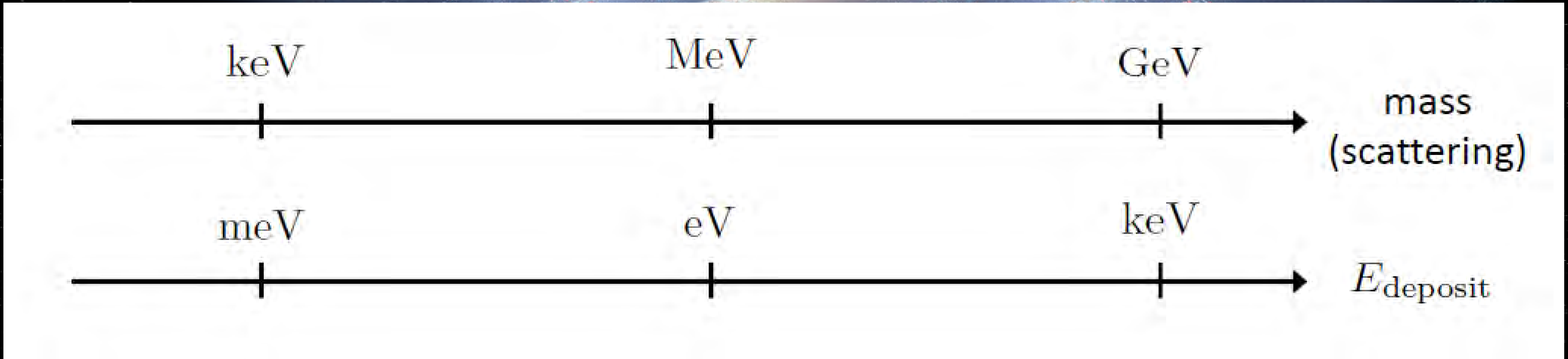
WIMPs interact (although weakly) with ordinary matter



DIRECT DETECTION OF DARK MATTER







DM particles in the galactic halo have velocities of the order of 200-300 km/s -> DM kinetic energy ~ $m_{DM} \times 10^{-6}$
Small energy depositions in the target

DARK MATTER INTERACTION RATE

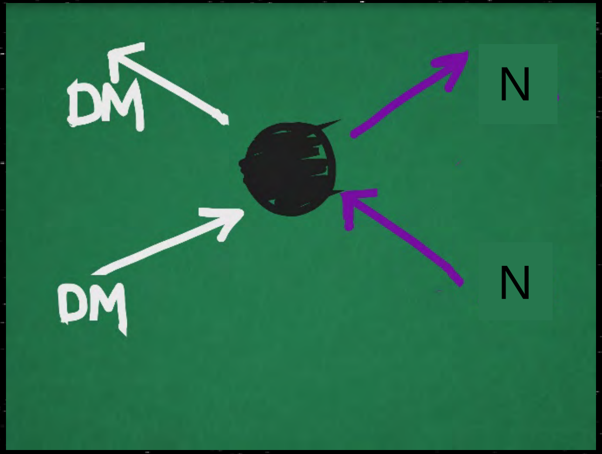
MODEL DEPENDENCIES ENTER INTO THE GAME FROM BEGINNING

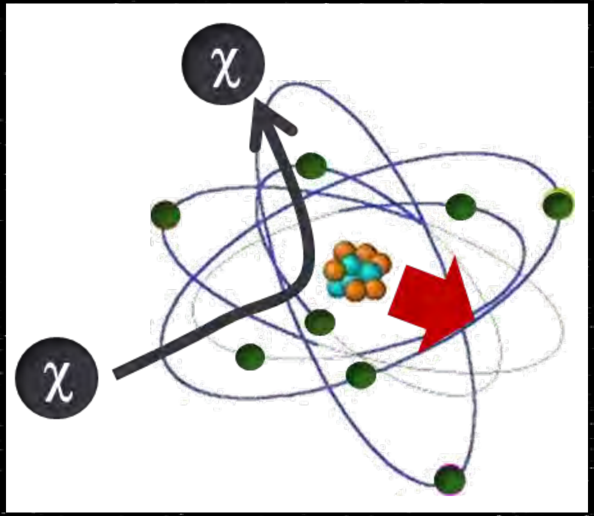
WEAK INTERACTING PARTICLES ON:
- ELECTRONS
- NUCLEI

$$\frac{dR}{dE} = n_{DM} N_N \int f(\vec{v}) v \frac{d\sigma_{DM-N}}{dE} d\vec{v}$$

Dark Matter Halo model

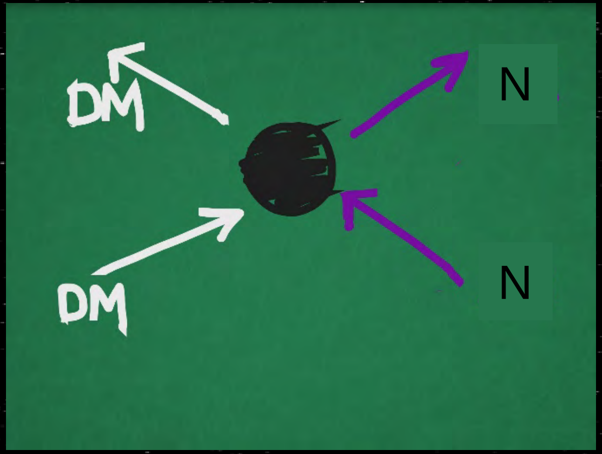
DM-Particle model
(Nuclear effects)





Typical Thermal WIMP models asume interactions by elastically scattering target nuclei and producing NUCLEAR RECOILS

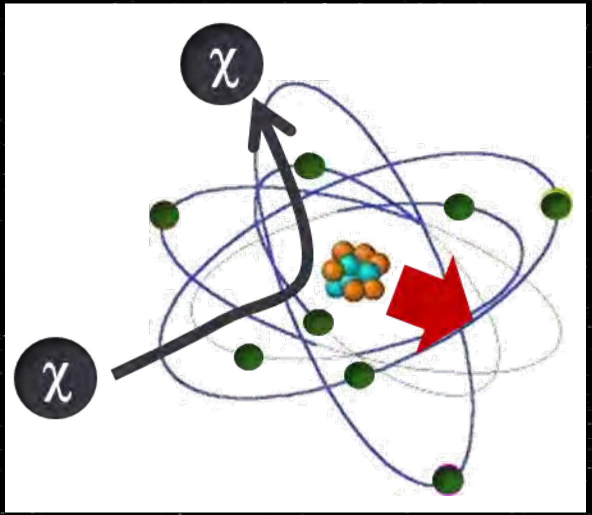
DARK MATTER INTERACTION RATE



Extreme non-relativistic limit
Isotropic scattering in the CM reference frame can be assumed
Kinematics determines maximum energy transfer for a given initial WIMP energy and target mass

$$T_{recoil} = E_0 - E^f_{WIMP} = \frac{m_W{}^2 M_N}{(m_W + M_N)^2} v^2 (1 - \cos\theta)$$

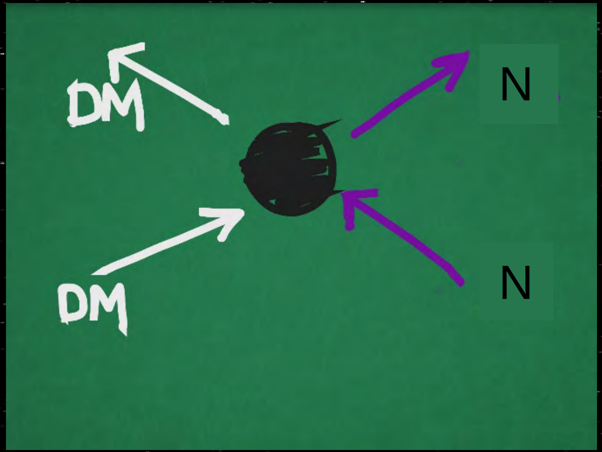
$$\Rightarrow \quad T_{\max} = \frac{2 m_W{}^2 M_N}{(m_W + M_N)^2} v^2$$



Interaction rate depends on the specific WIMP (m_W and σ_{WN}) and halo model (dark halo mass density ρ, WIMP velocity distribution at the Solar System position)

$$S(E_{NR}) = \frac{dR}{dE_{NR}} = \frac{\rho\, M_{det}}{2 m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v}\, \sigma_{WN}\, dv^3$$

DARK MATTER INTERACTION RATE



Halo model relevance

Milky Way Rotation Velocity Curve determines halo mass density but not particle number density or mass of DM particle

$$n_W = \frac{\rho_0}{m_W}$$

$\rho_0 \approx 0.2\text{-}0.4\ \text{GeV/cm}^3$

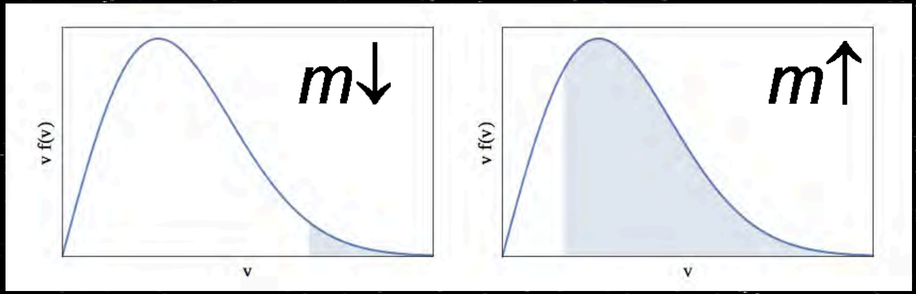
The most simple model isotropic and spherical thermal distribution of non relativistic WIMPs (SHM)

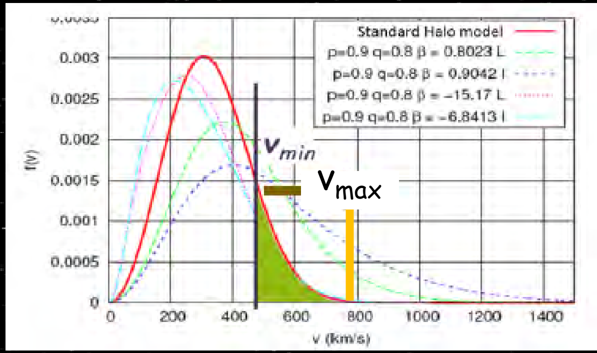
$$f(\vec{v}_{gal})d^3\vec{v}_{gal} = \frac{1}{v_0^3\pi^{3/2}} e^{-\frac{|\vec{v}_{gal}|^2}{v_0^2}} d^3\vec{v}_{gal}$$

$v_{rms} \approx 270\text{km/s}–300\text{km/s}$

$v_{esc} \approx 544\ \text{km/s}$

$$v_{\min}^{\ 2} = \frac{(m_W + M_N)^2}{2m_W^{\ 2} M_N} T_{threshold}$$



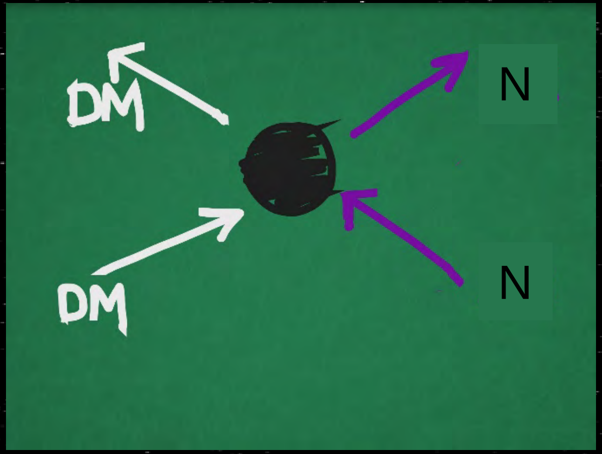


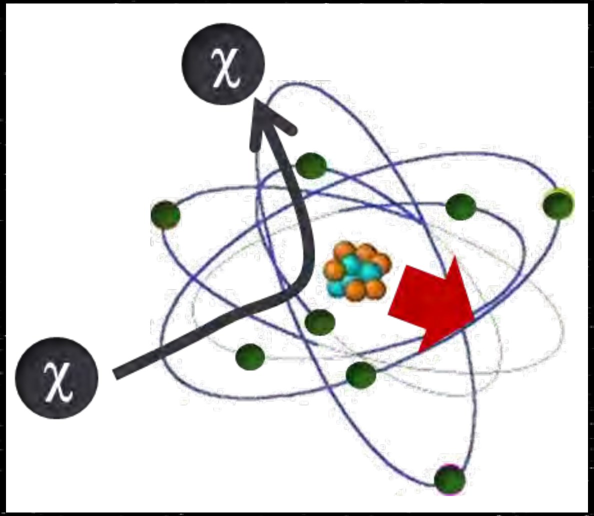
The whole WIMP phase space cannot be accesible

Energy threshold of the experiment is very important for low mass WIMPs

$$S(E_{NR}) = \frac{dR}{dE_{NR}} = \frac{\rho\, M_{det}}{2m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v}\, \sigma_{WN}\, dv^3$$

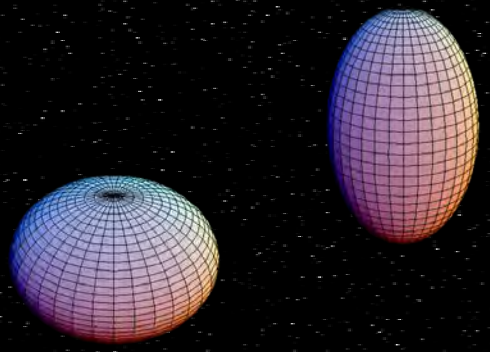
DARK MATTER INTERACTION RATE





Halo model relevance

Haloes can be quite different from SHM



Haloes can be non-spherical

Haloes can have sub-structure:

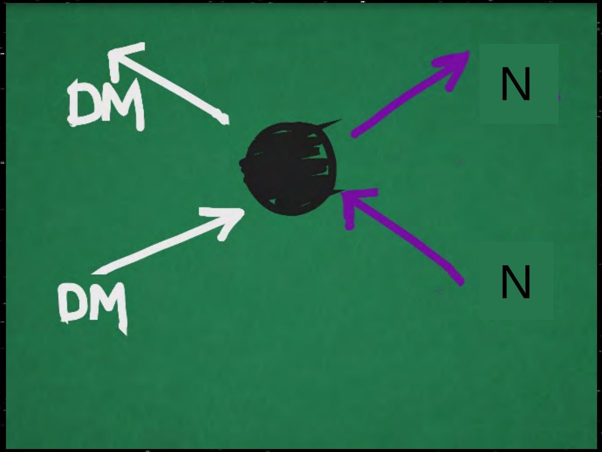
- -Sub-haloes
- -Dark Disk
- -Satellites producing directional fluxes

The whole WIMP phase space cannot be accesible

Energy threshold of the experiment is very important for low mass WIMPs

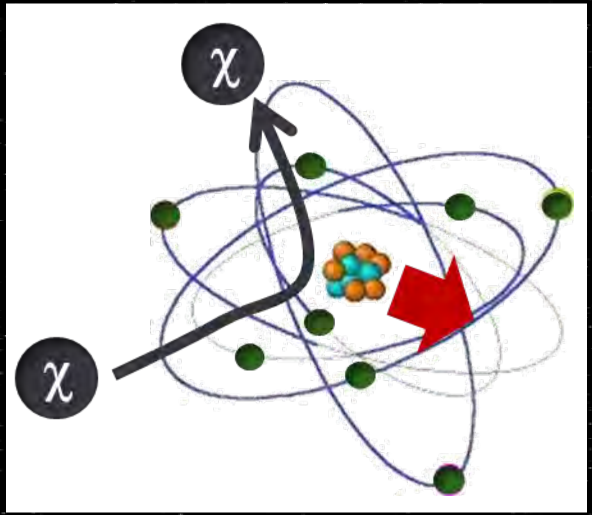
$$S(E_{NR}) = \frac{dR}{dE_{NR}} = \frac{\rho \, M_{det}}{2m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} \, \sigma_{WN} \, dv^3$$

DARK MATTER INTERACTION RATE



DM Particle model relevance

The scattering cross section σ_{WN} is completely unknown and contains details from DM particle model and target nuclear structure



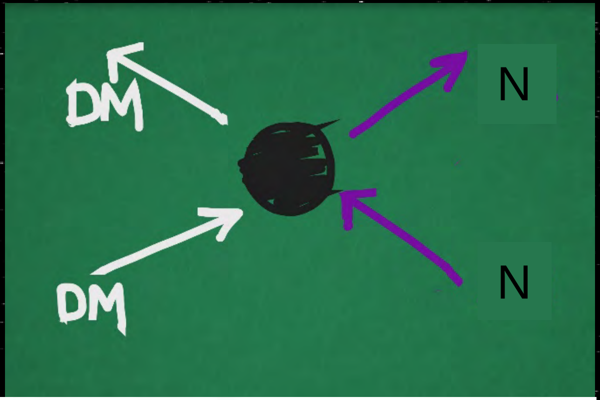
Effective WIMP couplings to neutrons and protons can be calculated for every theoretical model from the Lagrangian

Nuclear models allow to build the total cross-section with the target nuclei (form factors are required)

Experiments provide limits on σ_{WN} while comparison between different target experiments should be done on σ_{Wn}

$$S(E_{NR}) = \frac{dR}{dE_{NR}} = \frac{\rho\, M_{det}}{2 m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v}\, \sigma_{WN}\, dv^3$$

DARK MATTER INTERACTION RATE



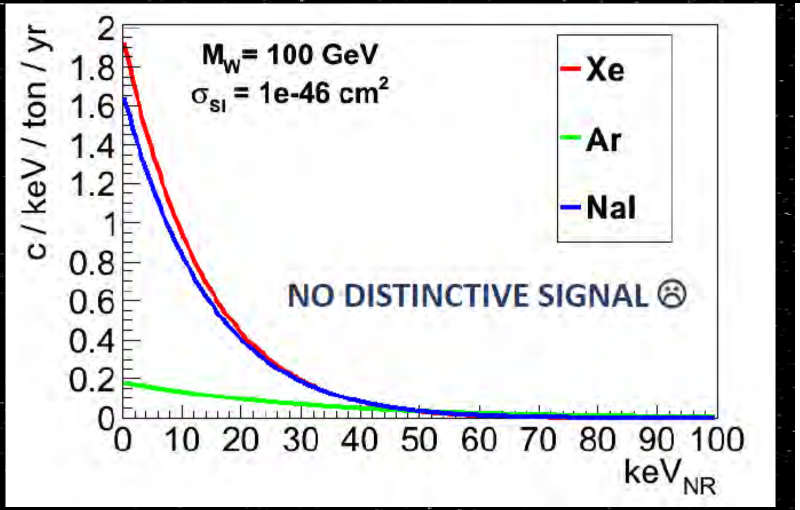
DM Particle model relevance

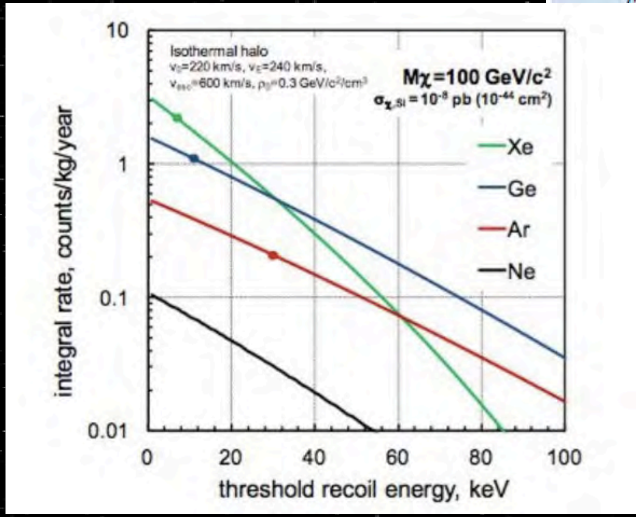
The scattering cross section σ_{WN} is completely unknown and contains details from DM particle model and target nuclear structure

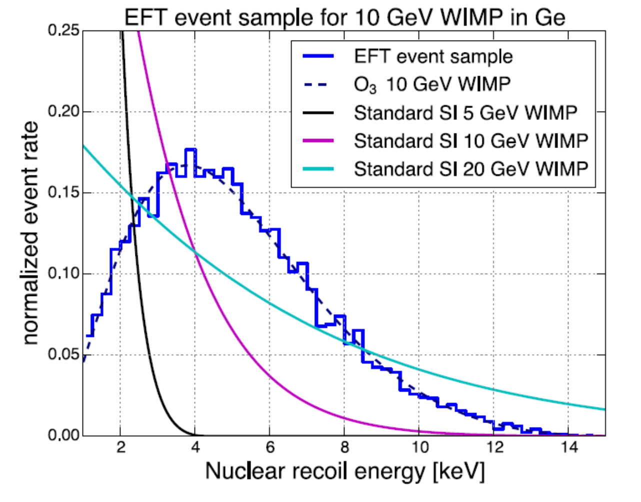
For the Direct Detection approach, effective operators are the most convenient option to explore all the posible interaction mechanisms

$$\mathcal{L}_{\text{int}} = \sum_{i=1,15} c_i \chi^* \mathcal{O}_\chi \chi \Psi^*_N \mathcal{O}_i \Psi_N$$

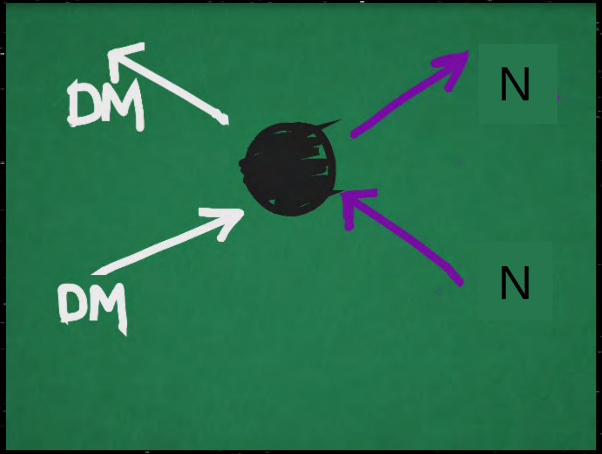
$$\mathcal{O}_1 = 1_\chi 1_N$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$
$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$$







DARK MATTER INTERACTION RATE



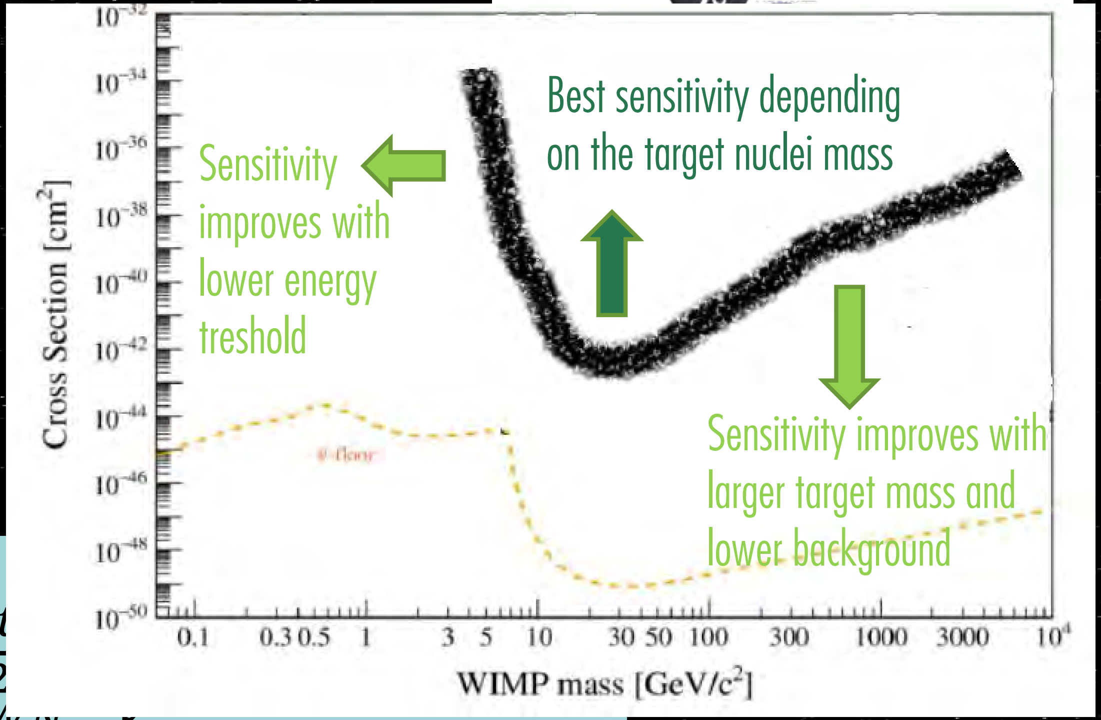
DM Particle model relevance

$$\sigma_{SI} \propto \frac{m_{WN}^2}{m_{Wn}^2} A^2 F^2 \sigma_{SI\ -nucleon}^0$$

- For SI interacting WIMPs
  - -rate scales with A^2
  - -no distinctive energy spectrum is expected
- Easy to scale
- Usually adopted to compare experiments using different target

$$\mathcal{O}_1 = 1_\chi 1_N$$

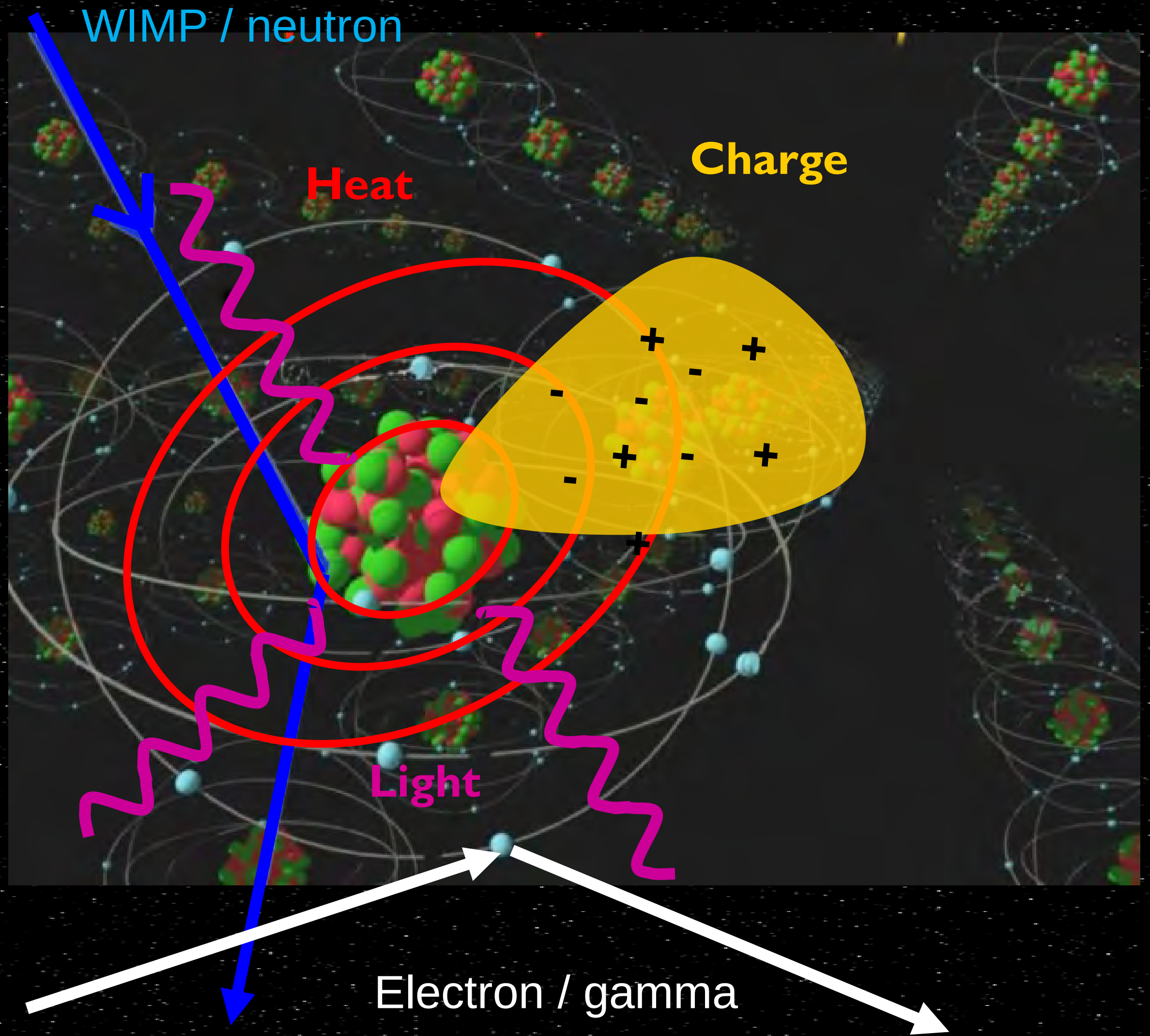
MODEL DEPENDENT COMPARISON BETWEEN EXPERIMENTS USING DIFFERENT NUCLEI AS TARGET!



Experiments provide limits on σ_{WN} while comparison between different should be done on σ_{Wn}

$$S(E_{NR}) = \frac{dR}{dE_{NR}} = \frac{\rho\, M_{det} \ldots}{2 m_W m_{WN}^2 \ldots} \ldots_{v_{min}}$$

DETECTION TECHNIQUES AND REVIEW OF THE EXPERIMENTAL STATUS



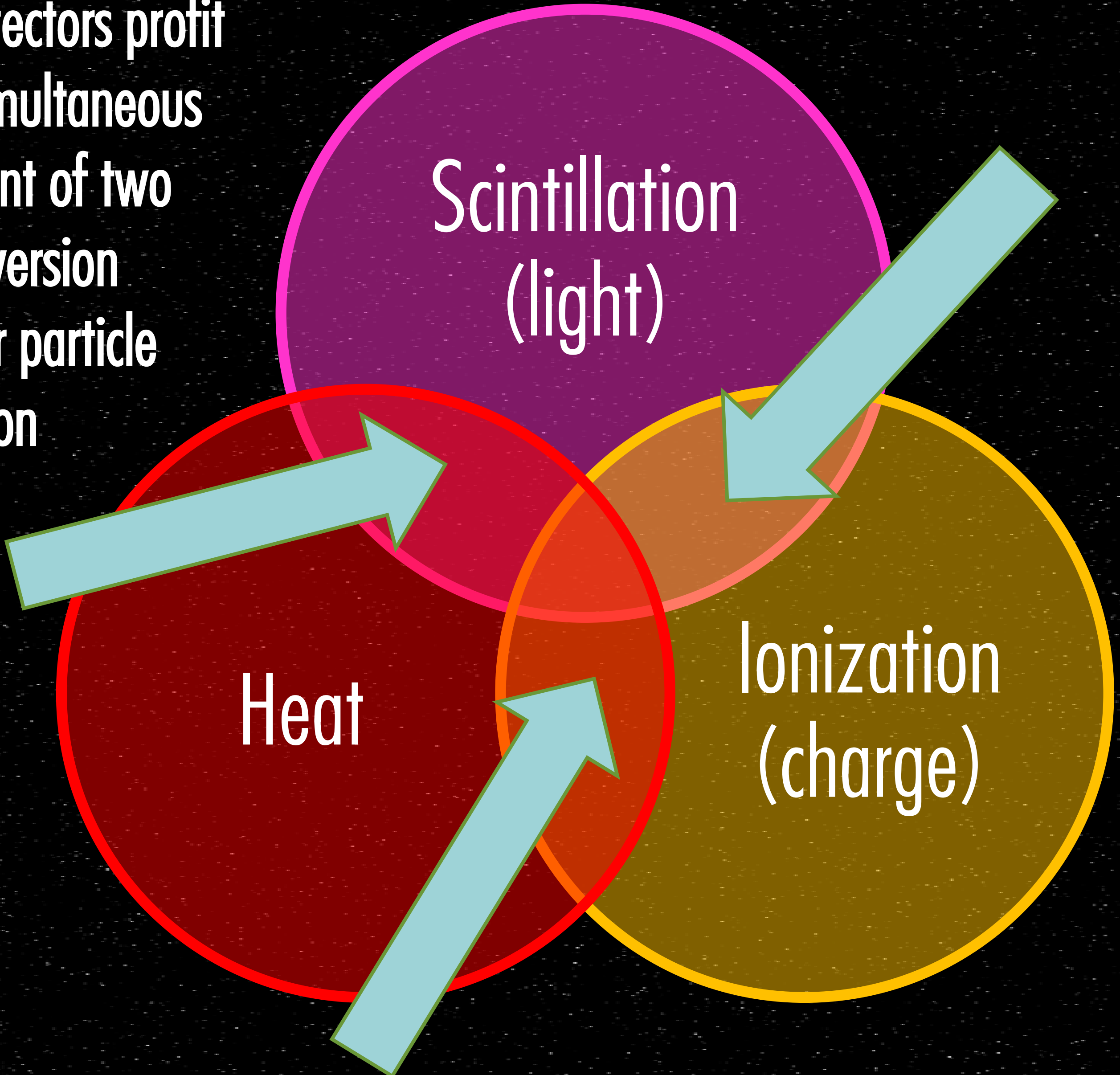
Energy conversion into VISIBLE signal is strongly dependent on the interaction mechanism, incident particle and target

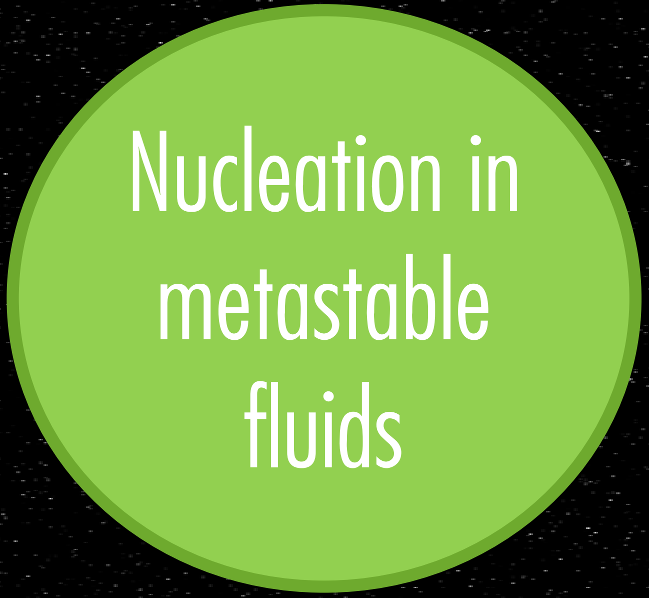
"VISIBLE Energy" is what defines the detection technique

Precise conversion between visible energy and deposited energy in the detector is mandatory!

DETECTION TECHNIQUES AND REVIEW OF THE EXPERIMENTAL STATUS

HYBRID Detectors profit from the simultaneous measurement of two energy conversion channels for particle discrimination





DETECTION TECHNIQUES AND REVIEW OF THE EXPERIMENTAL STATUS

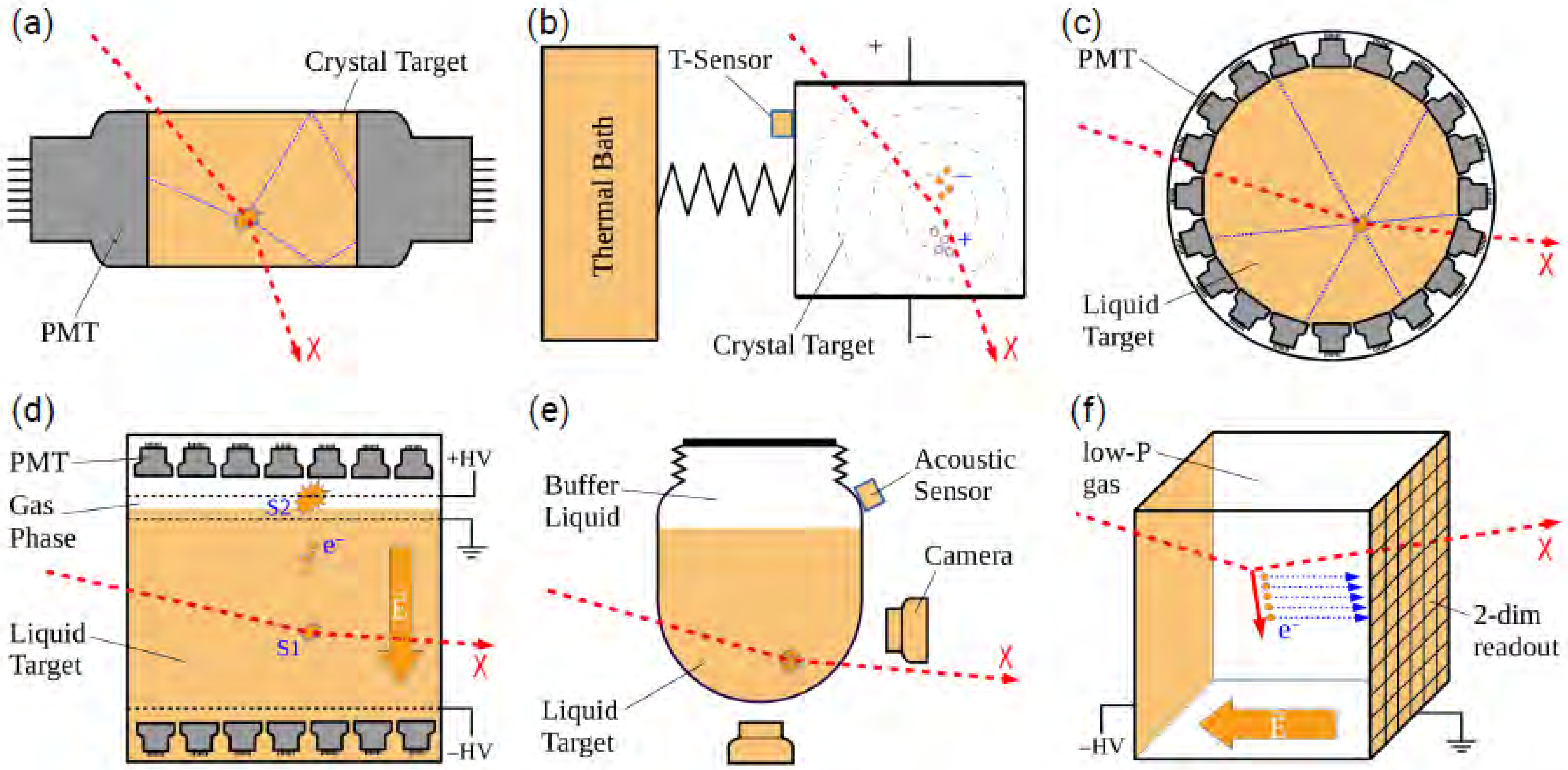


Figure 2: Working principle of common detector types for the direct WIMP search: (a) scintillating crystal, (b) bolometer (here with additional charge-readout), (c) single-phase and (d) dual-phase liquid noble gas detectors, (e) bubble chamber, (e) directional detector. Images adapted from [113].

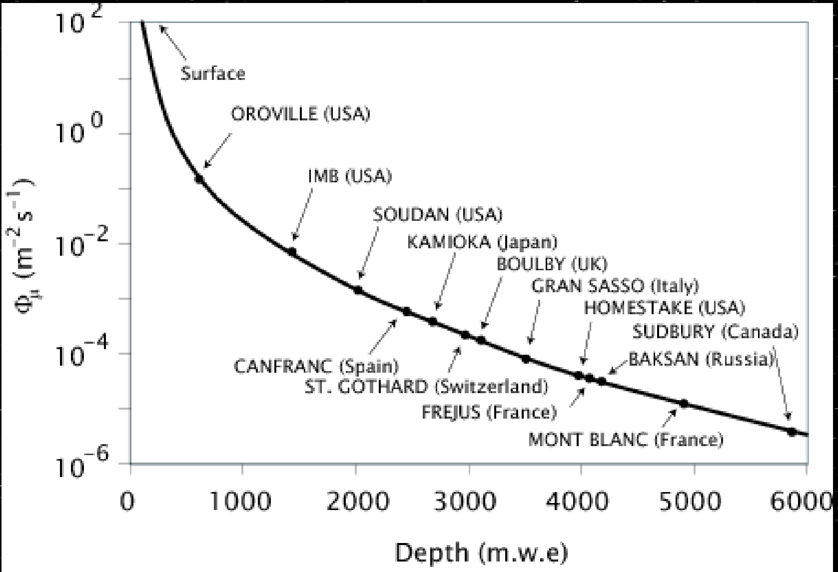
APPEC Report 2021

DIRECT DETECTION OF DARK MATTER

Background signals interferring with WIMP detection come from

-COSMIC Rays

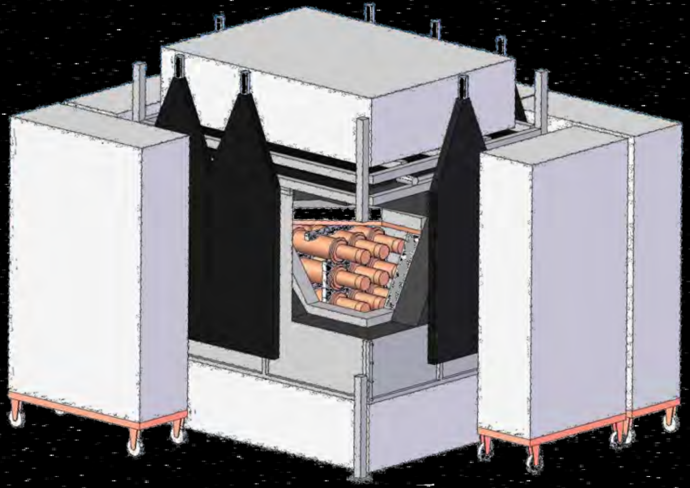
Most of the experiments are carried out in underground laboratories



DIRECT DETECTION OF DARK MATTER

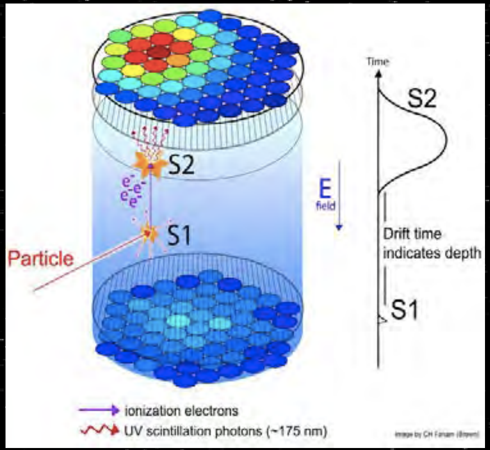
Background signals interferring with WIMP detection come from
- -COSMIC Rays
- -Environmental Radioactivity

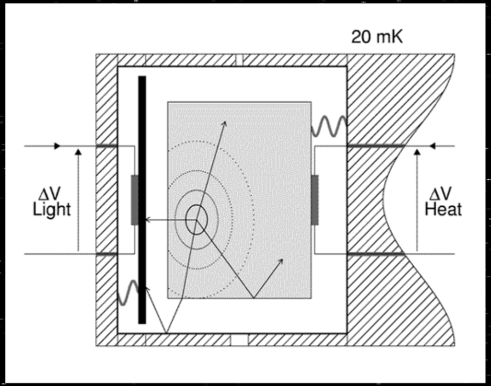
Strong Passive and Active Shielding Strategies have to be applied

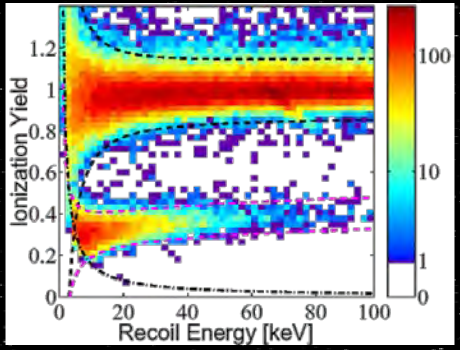


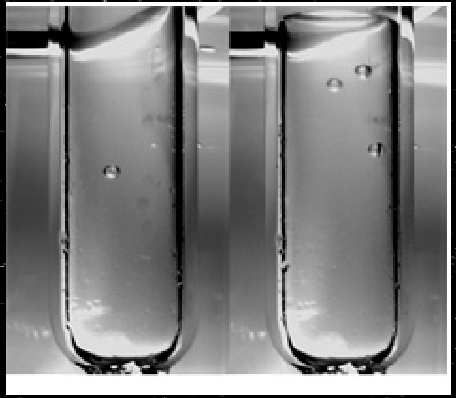
Convenient shieldings against gamma radiation, fast neutrons, muon residual flux, and Radon intrusión

But utlimate sensitivity requires other techniques for active background suppresion:
- Nuclear Recoil / Electron Recoil Discrimination
- Neutrons identified by multiple scattering









DIRECT DETECTION OF DARK MATTER

Background signals interferring with WIMP detection come from

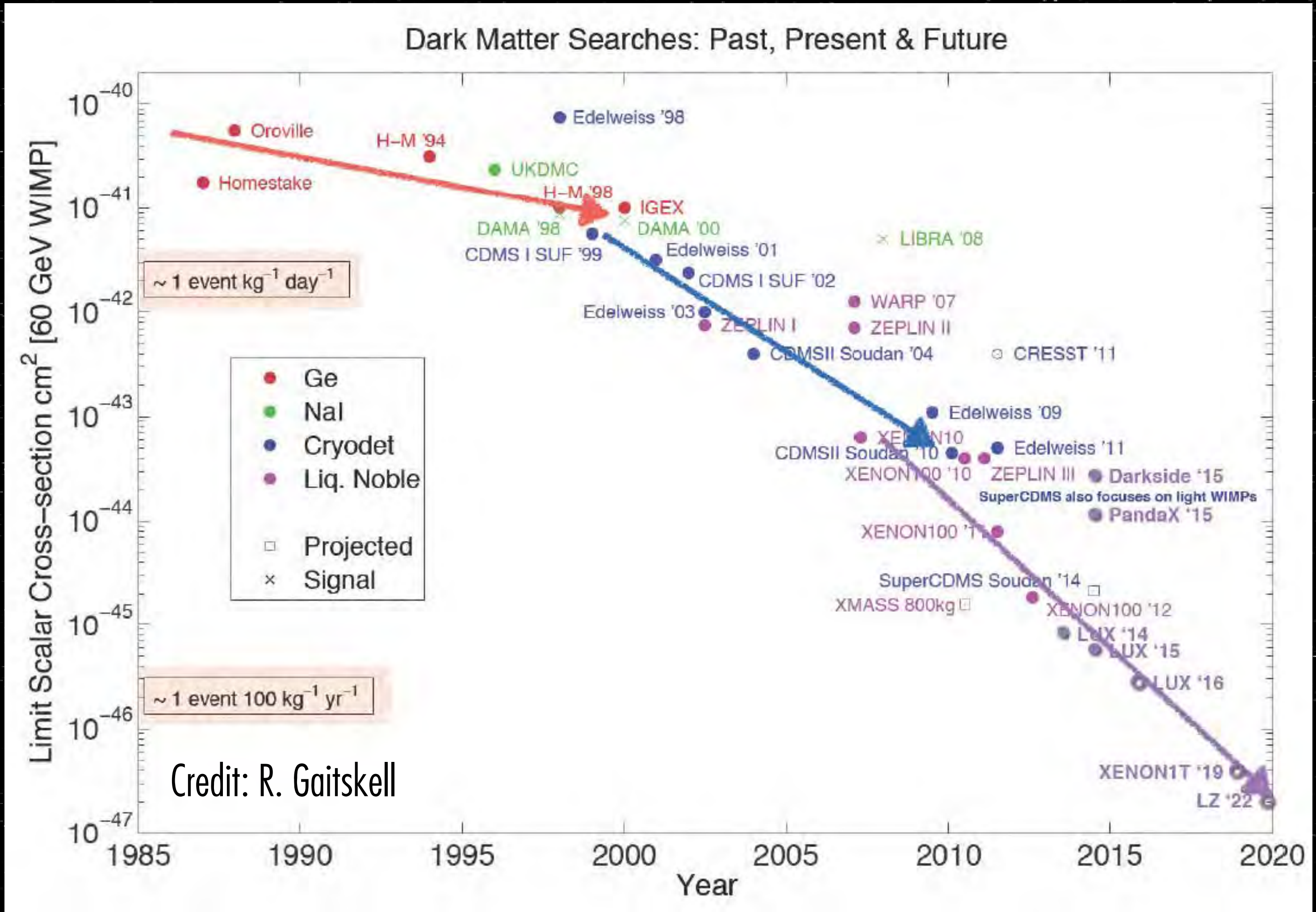
-COSMIC Rays

-Environmental Radioactivity

Strong Passive and Active Shielding Strategies have to be applied

Impressive improvement in sensitivity from 1985

- Much larger detector masses
- Better background



Credit: R. Gaitskell

DIRECT DETECTION OF DARK MATTER

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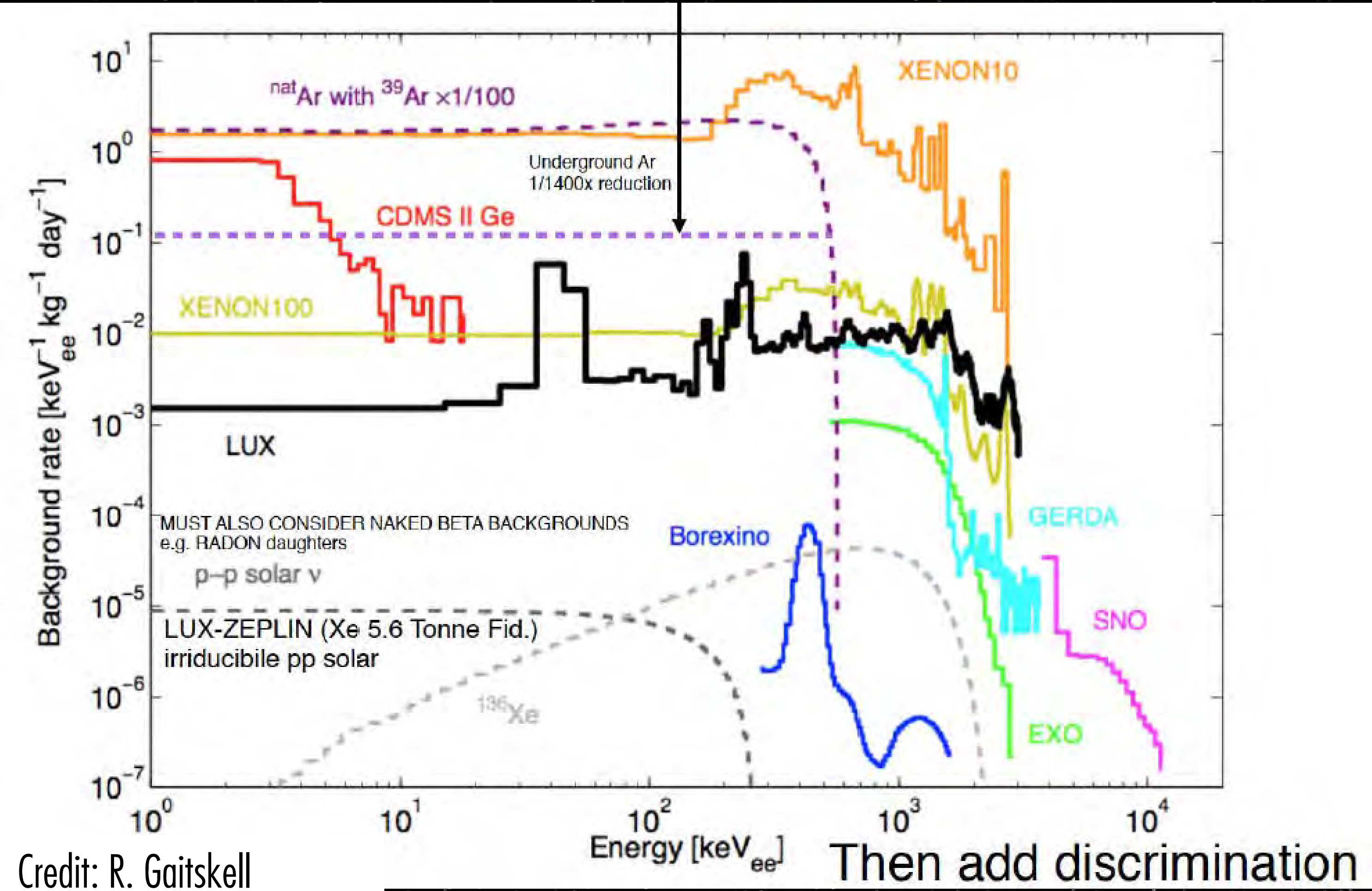
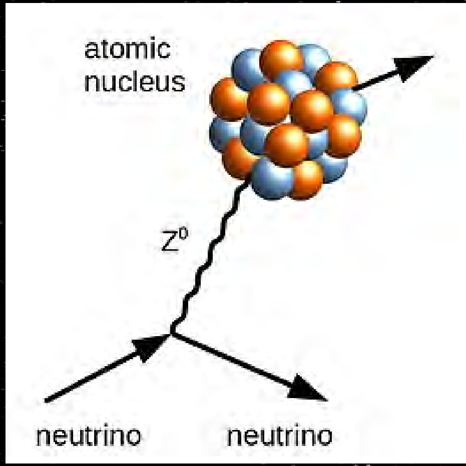


Credit: R. Gaitskell

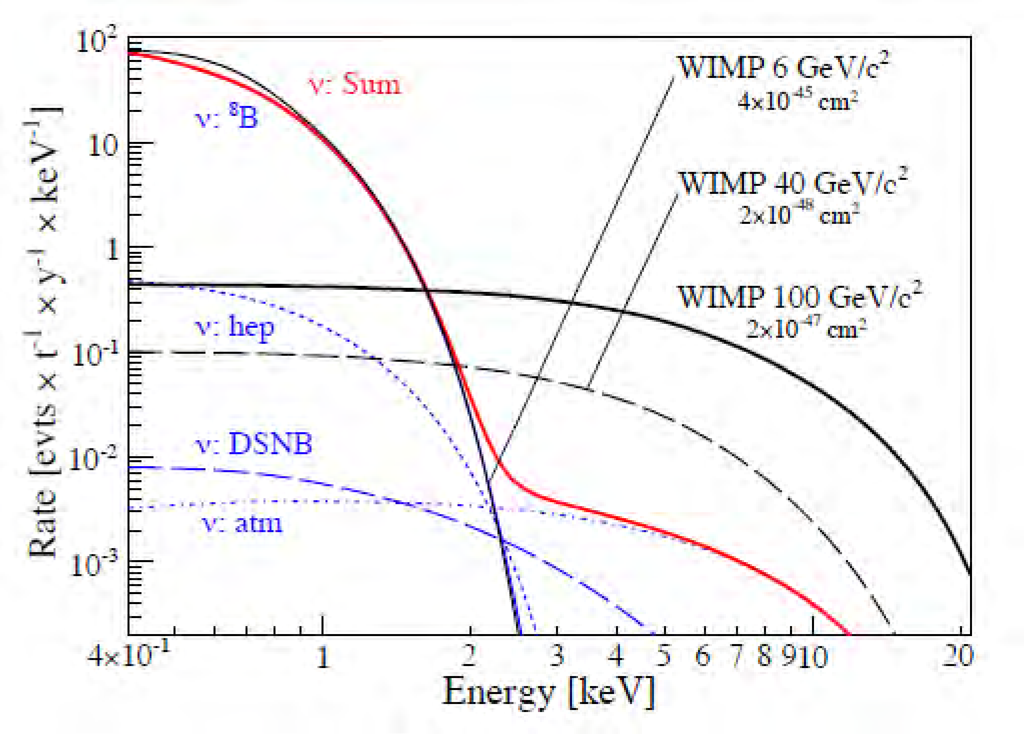
DIRECT DETECTION OF DARK MATTER

Background signals interferring with WIMP detection come from

- -COSMIC Rays
- -Environmental Radioactivity
- -Neutrinos (solar, atmospheric and supernovae)

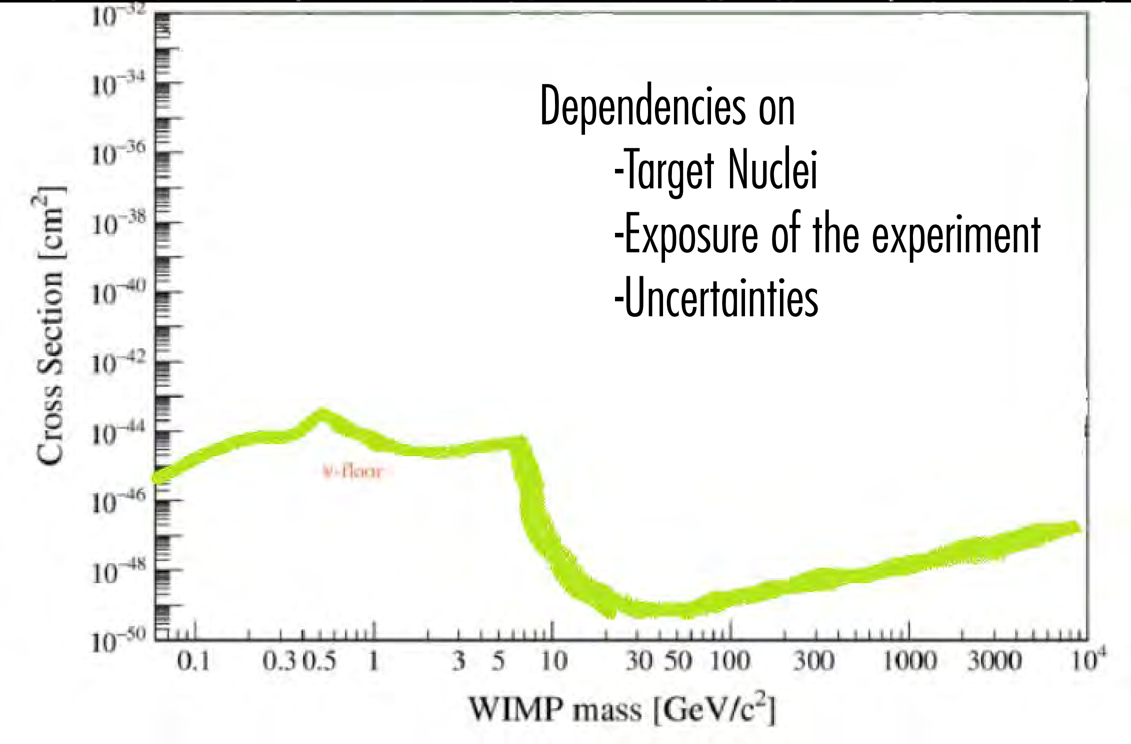


Xe as target



L. Baudis et al., JCAP 2014

Neutrino Floor
Or ….
Neutrino Fog



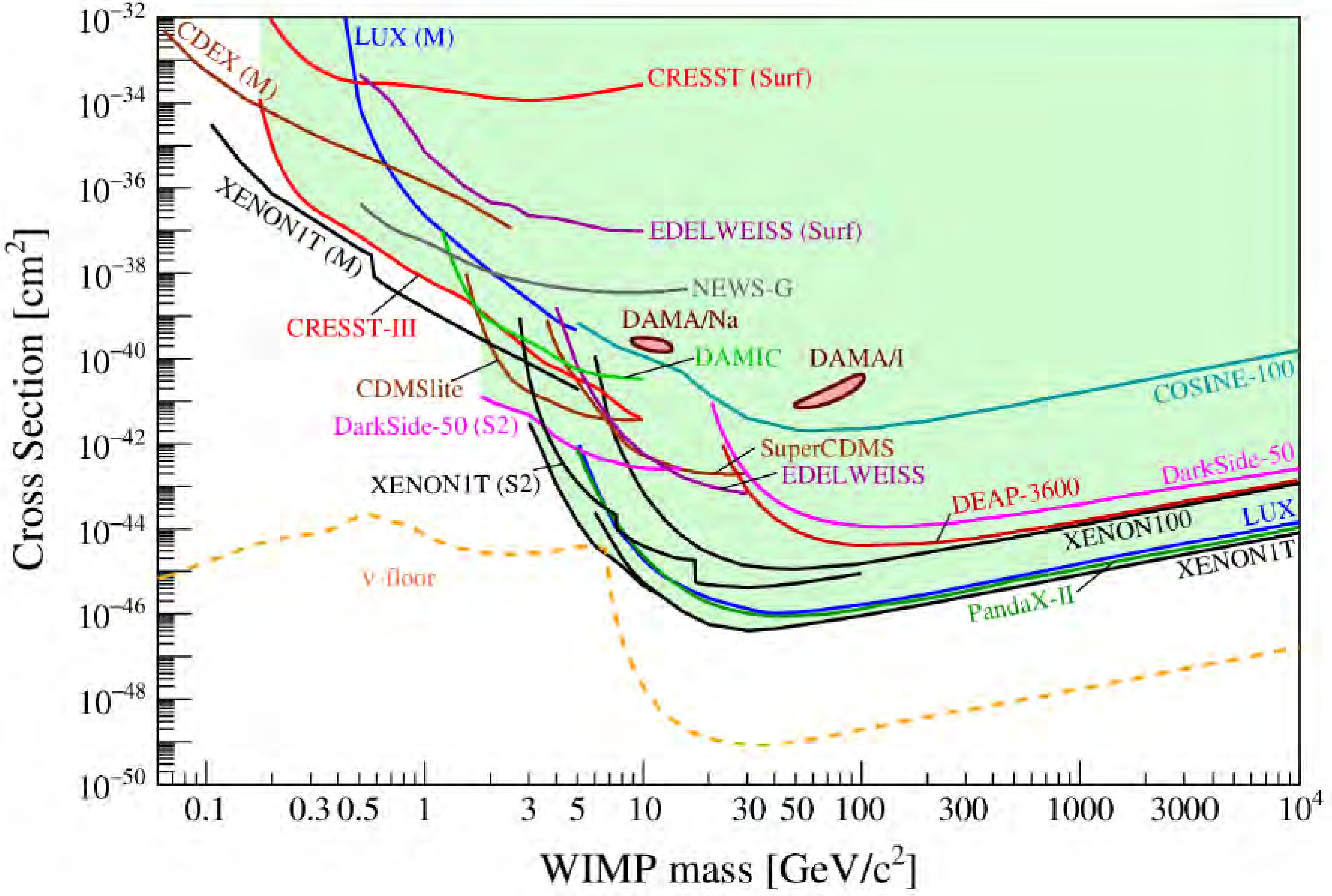
Dependencies on

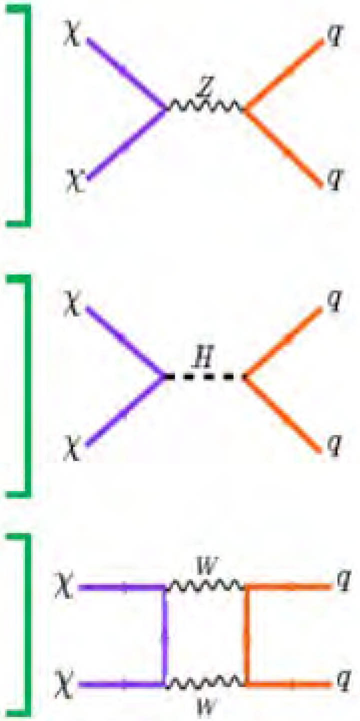
- -Target Nuclei
- -Exposure of the experiment
- -Uncertainties

REVIEW OF THE WIMP SEARCHES BY DIRECT DETECTION: EXPERIMENTAL STATUS AND RECENT DEVELOPMENTS

- EXPERIMENTS WHICH DO NOT OBSERVE SIGNAL EXCESS OVER BACKGROUNDS
- EXPERIMENTS OBSERVING POSSIBLE DARK MATTER SIGNALS

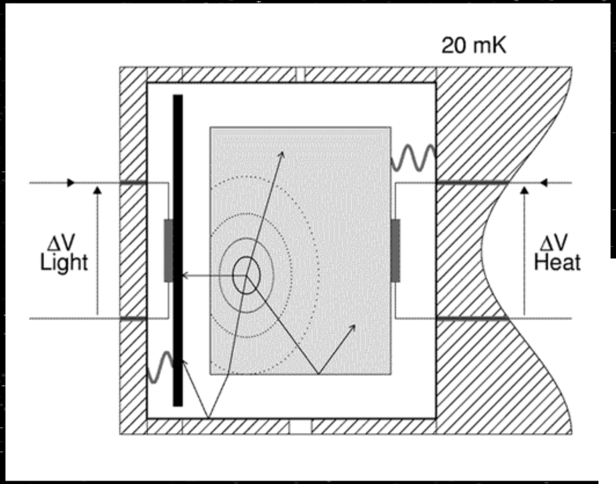
Current status of searches for SI elastic WIMP-nucleus scattering for SHM parameters – APPEC report





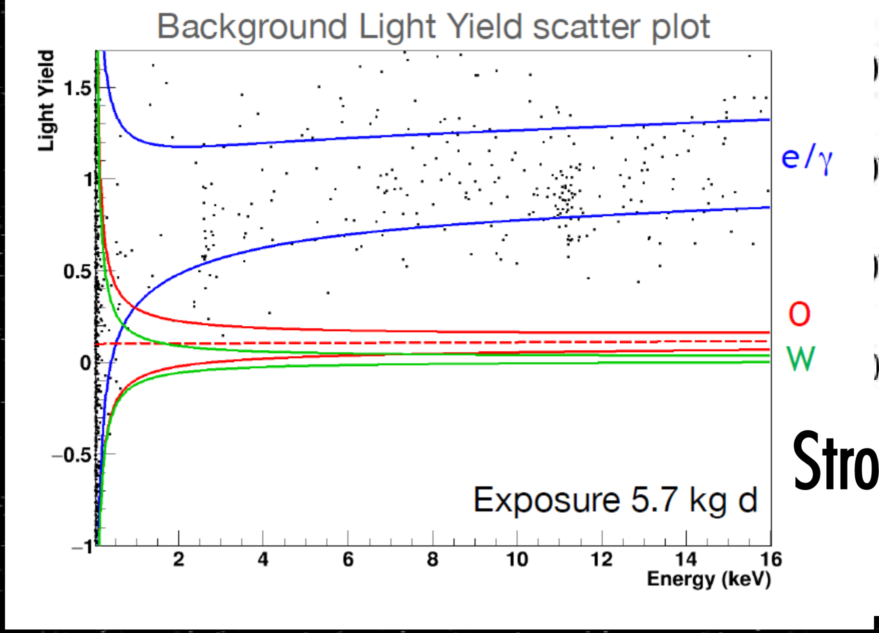
SCINTILLATING BOLOMETERS

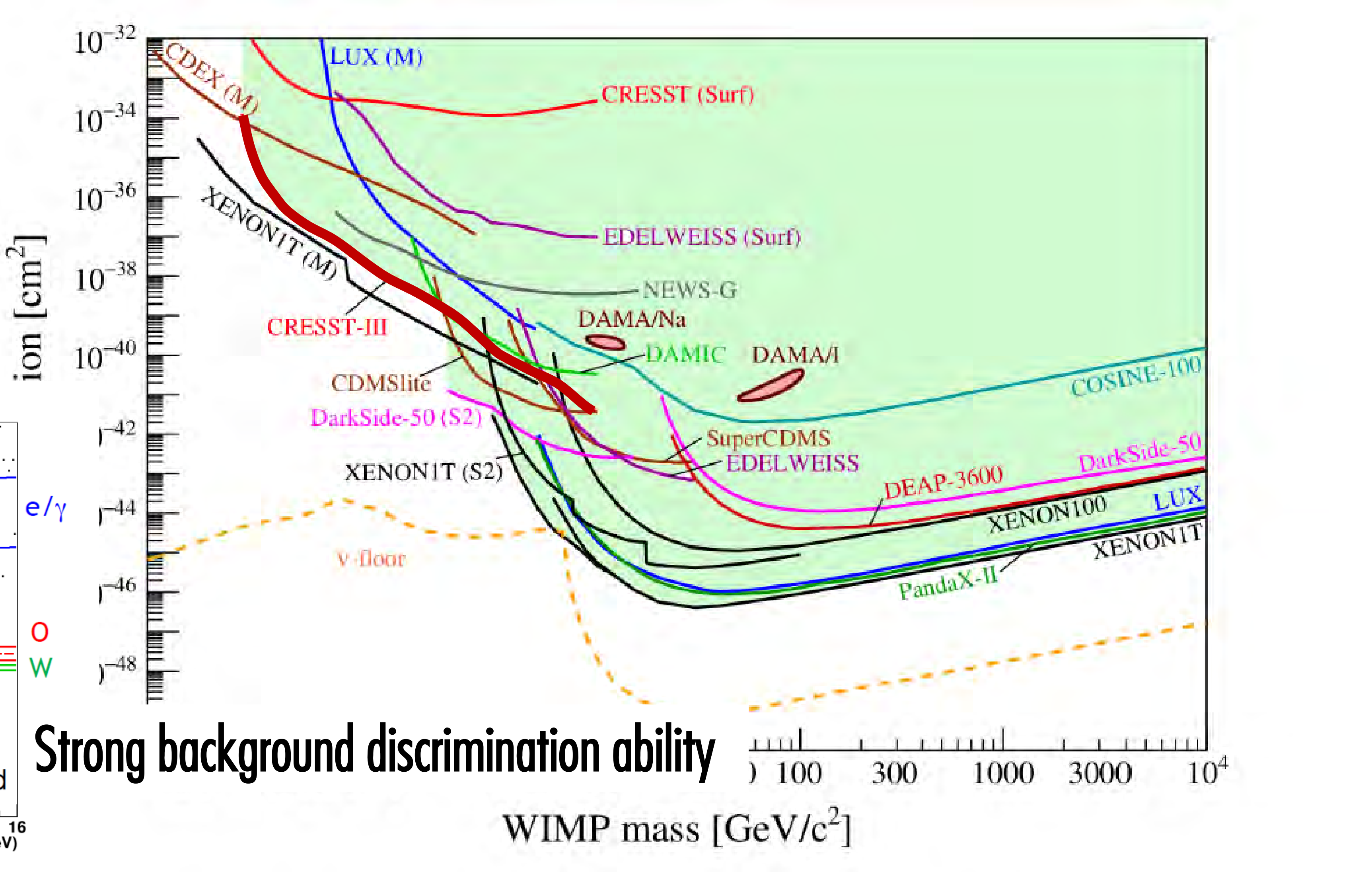
CRESST-III



24 grams of $CaWO_4$

$E_{th} = 30\ eV_{nr}$

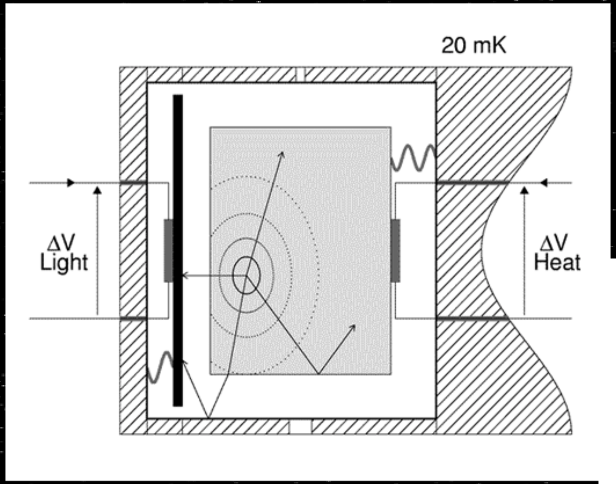




Strong background discrimination ability

SCINTILLATING BOLOMETERS

CRESST-III



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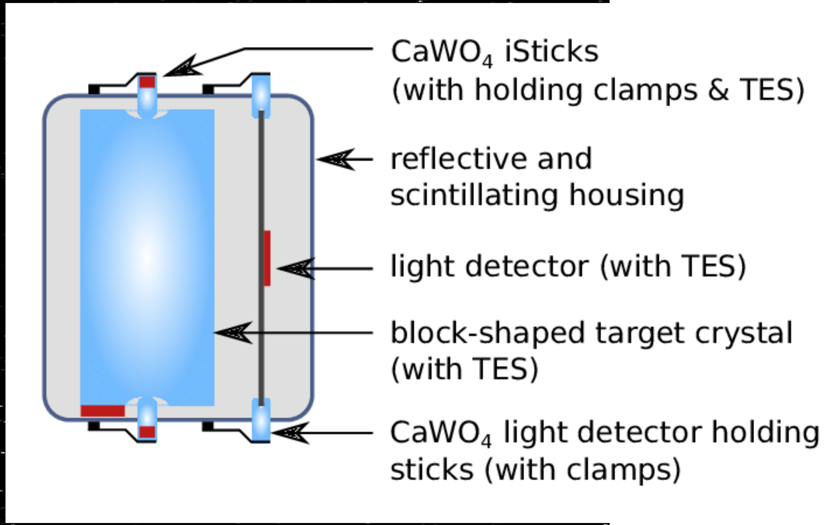
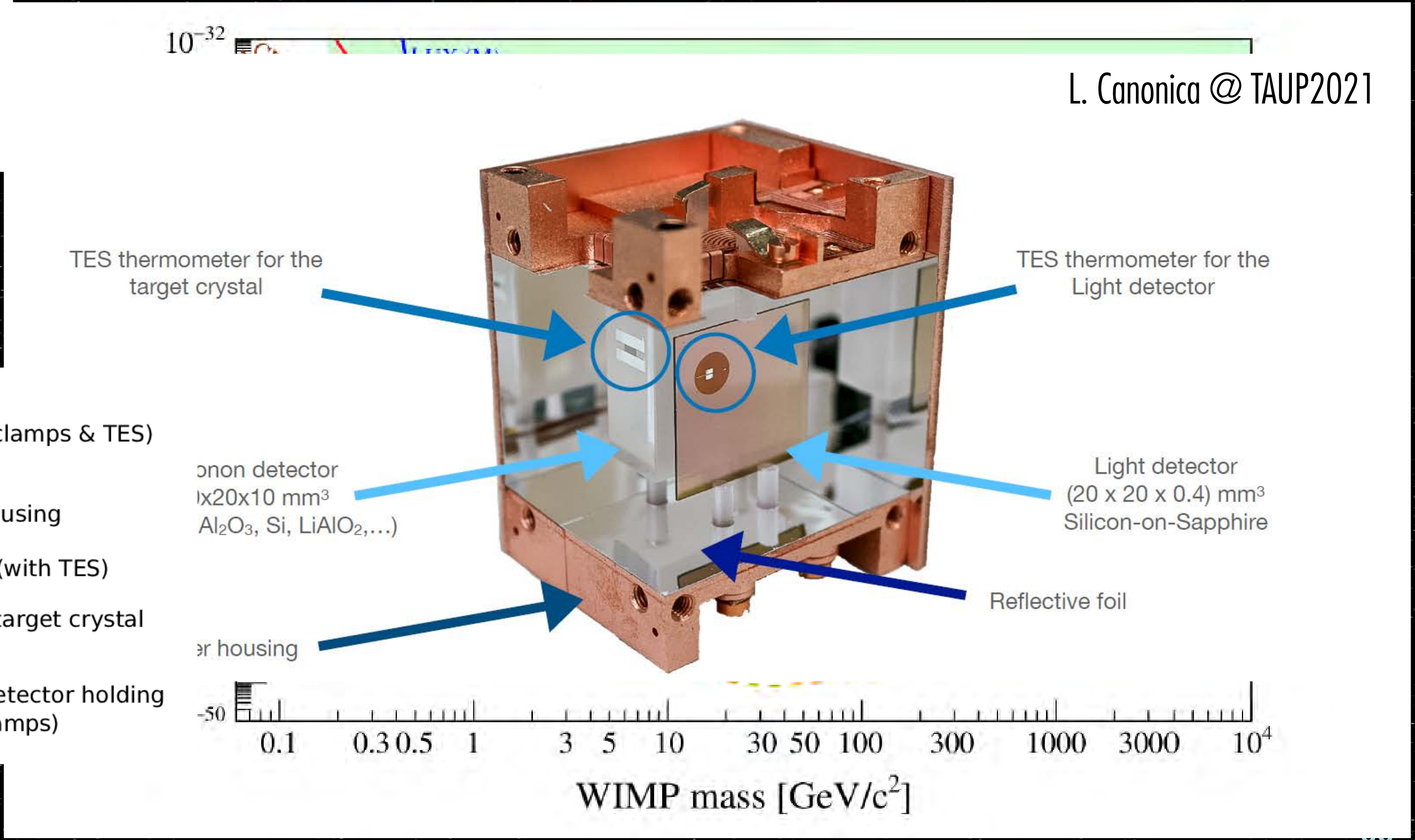
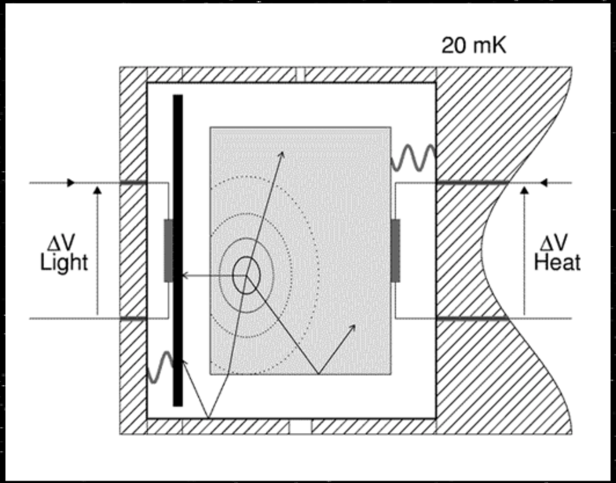
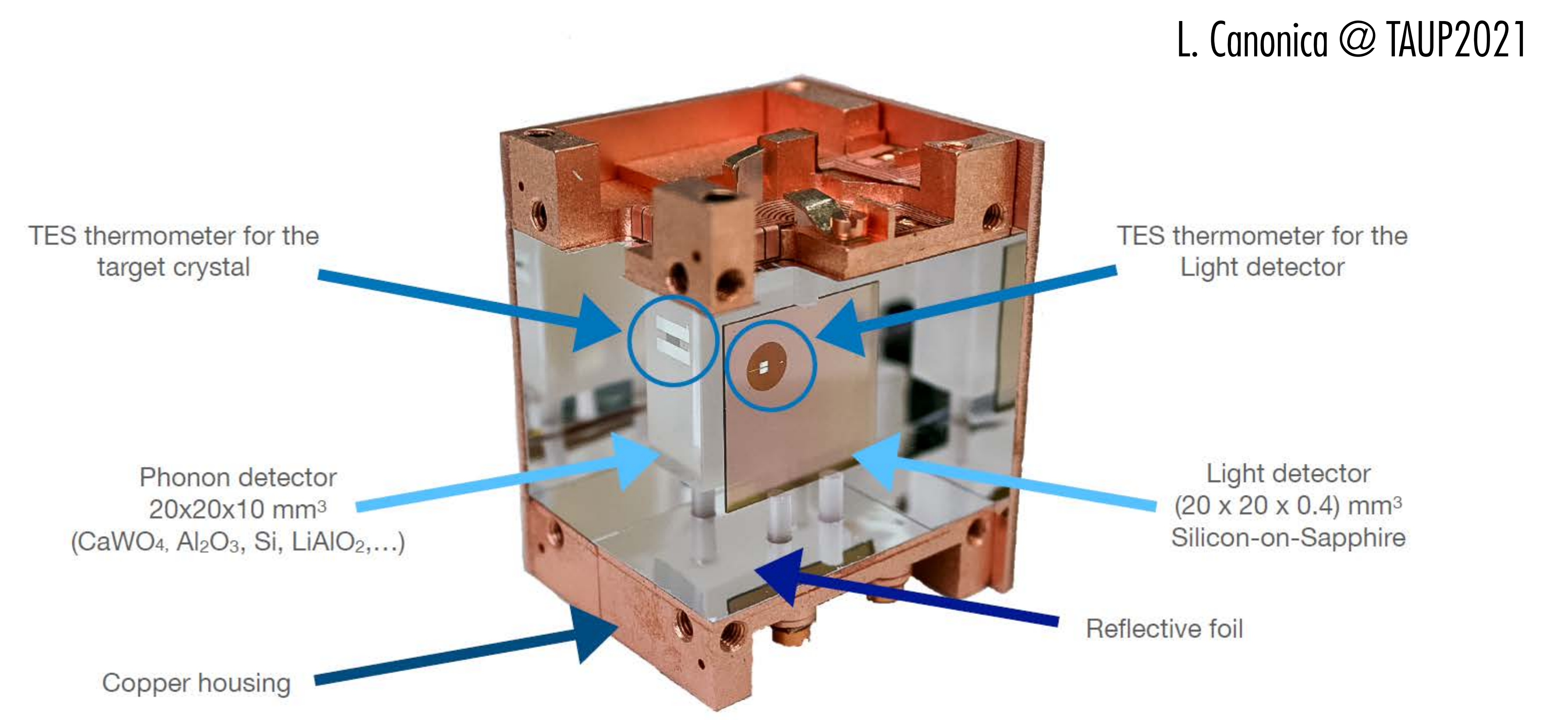






SCINTILLATING BOLOMETERS

CRESST-III

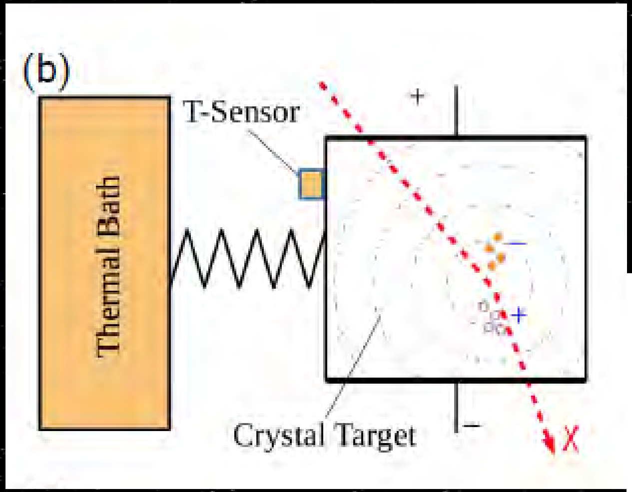


Different target materials program very interesting
Now taking data with Si, Al_2O_3, $LiAlO_2$, $CaWO_4$

Versatility – sensitivity to SD/SI interacting particles

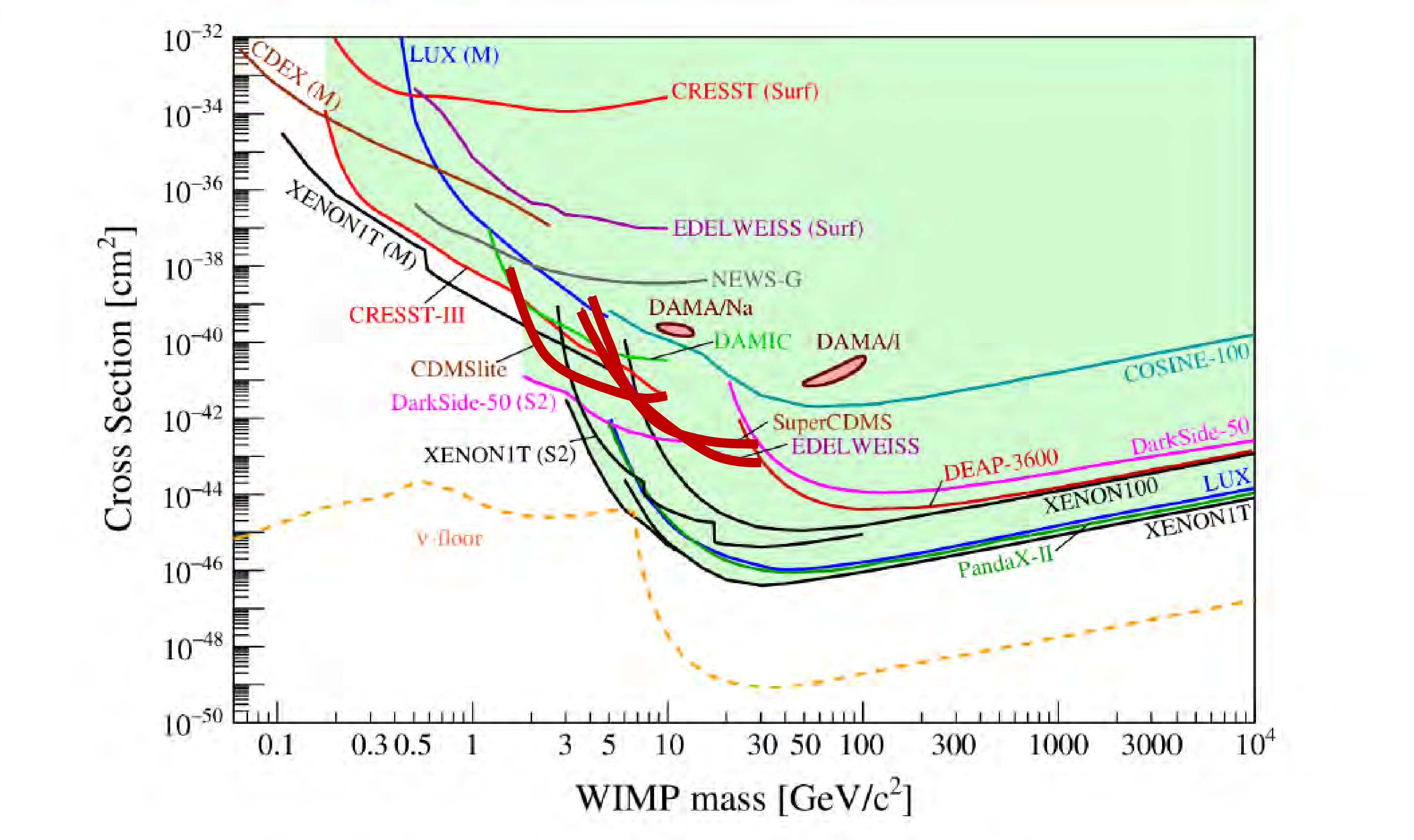
IONIZATION Ge BOLOMETERS

EDELWEISS
SuperCDMS
CDMSlite



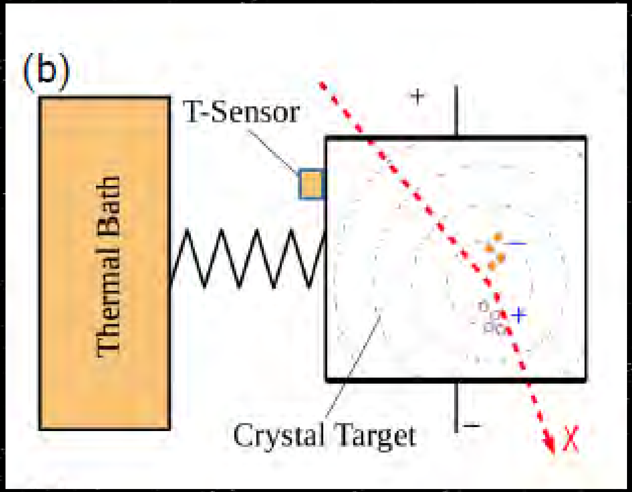
CDMSlite
600 g Ge, $E_{th} = 70\ eV_{nr}$

Charge signal is amplified and converted into heat (Luke-Neganov effect) to reduce E_{th} losing bkg discrimination ability



IONIZATION Ge BOLOMETERS

EDELWEISS
SuperCDMS
CDMSlite



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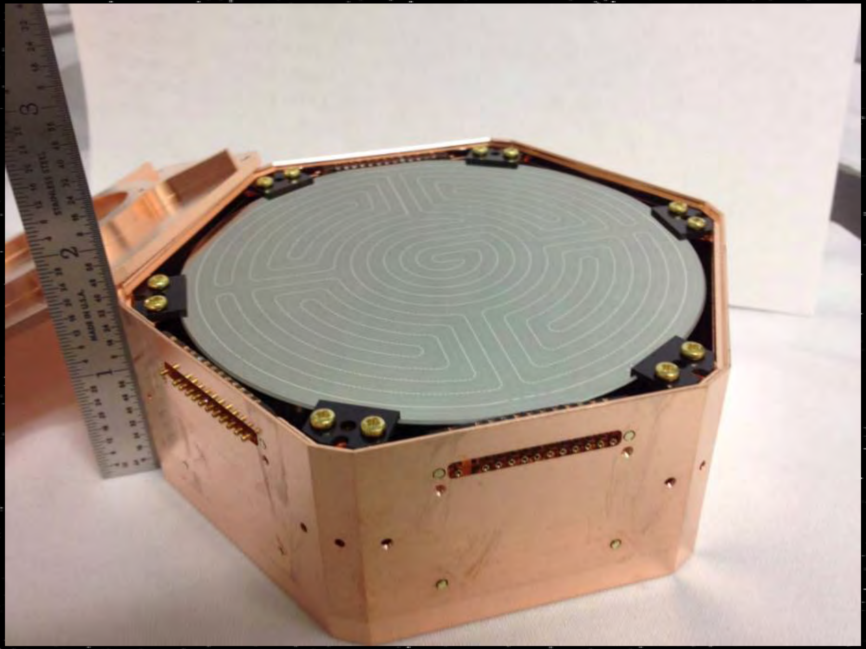
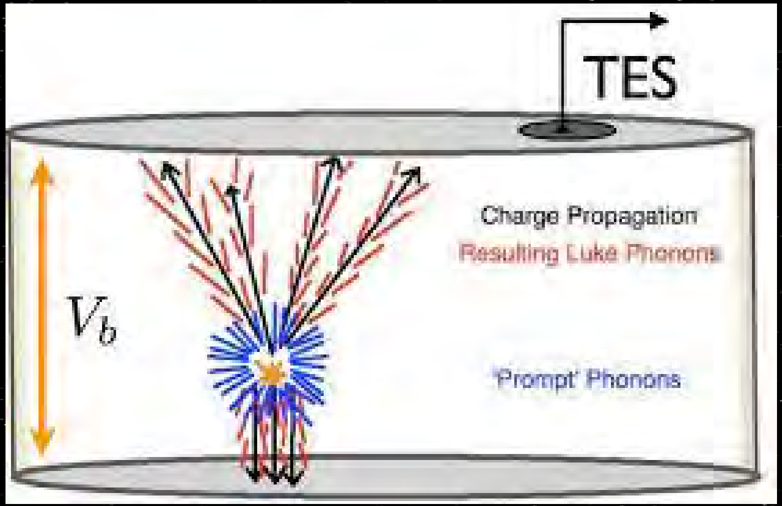
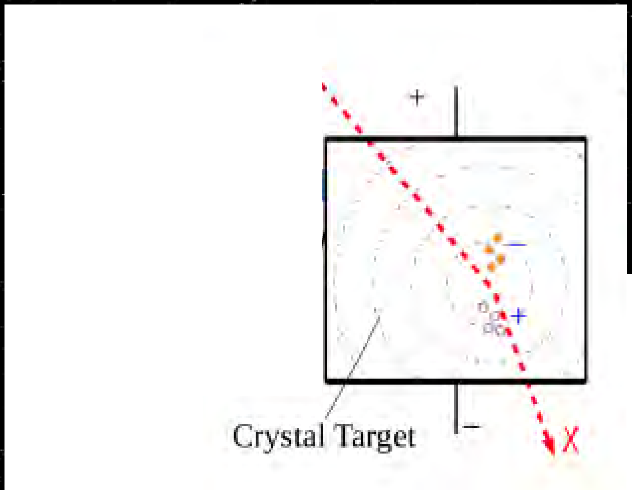




IONIZATION DETECTORS

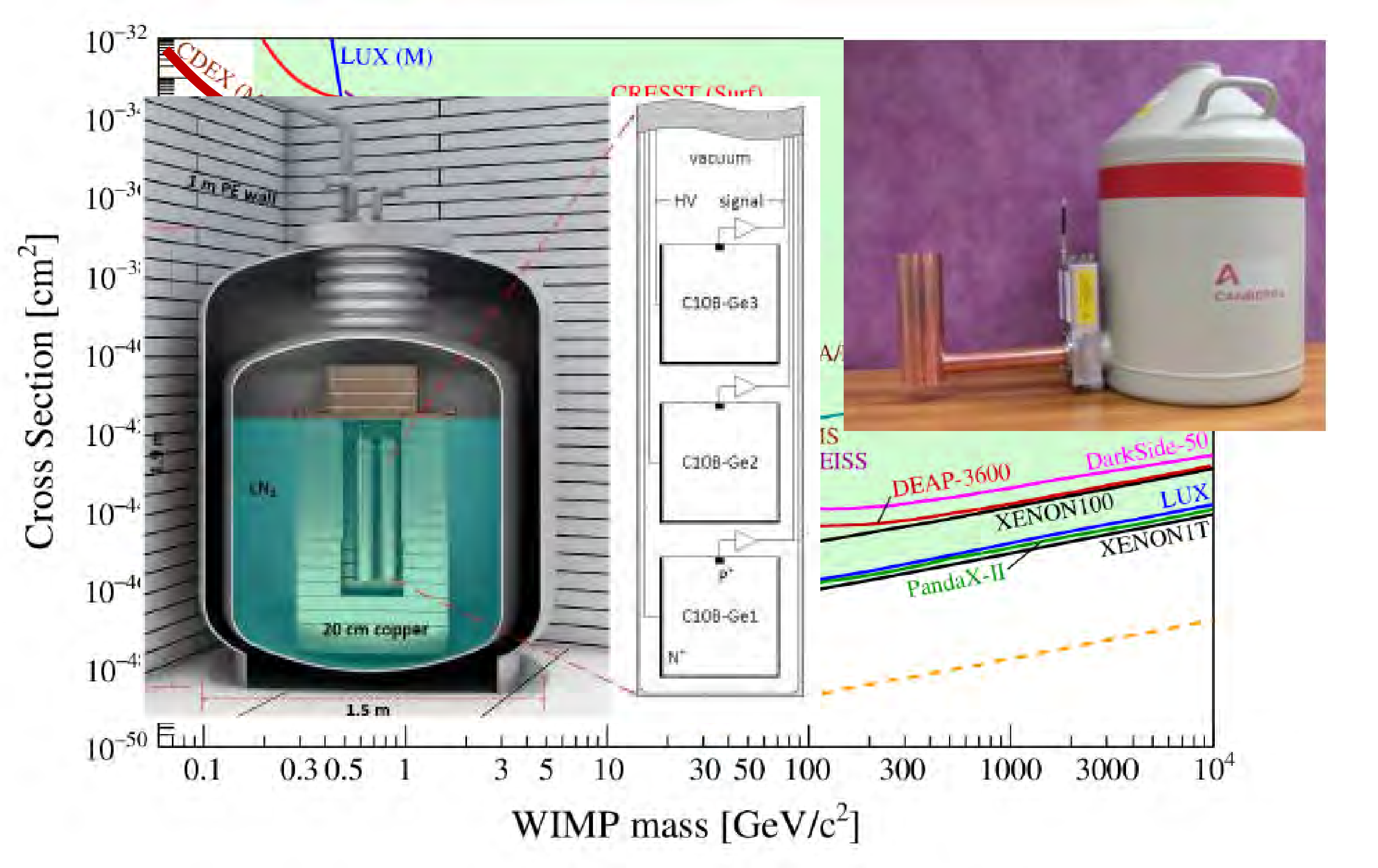
CDEX

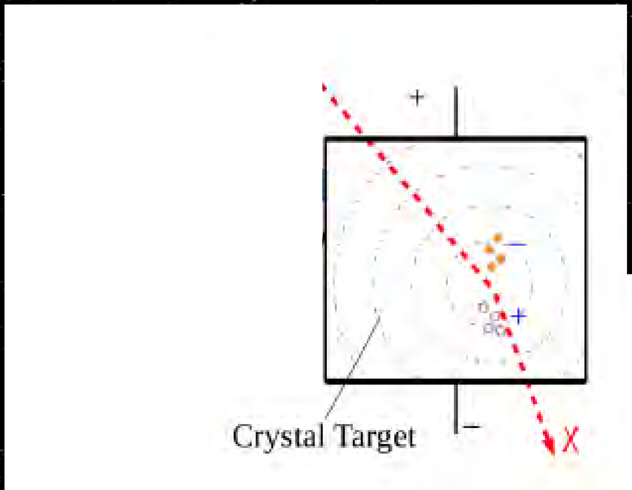


p-type point contact Ge

939g Ge modules
Eth =160 eV
Results assumes Migdal effect

Scalable to ton-scale, presently 10kg



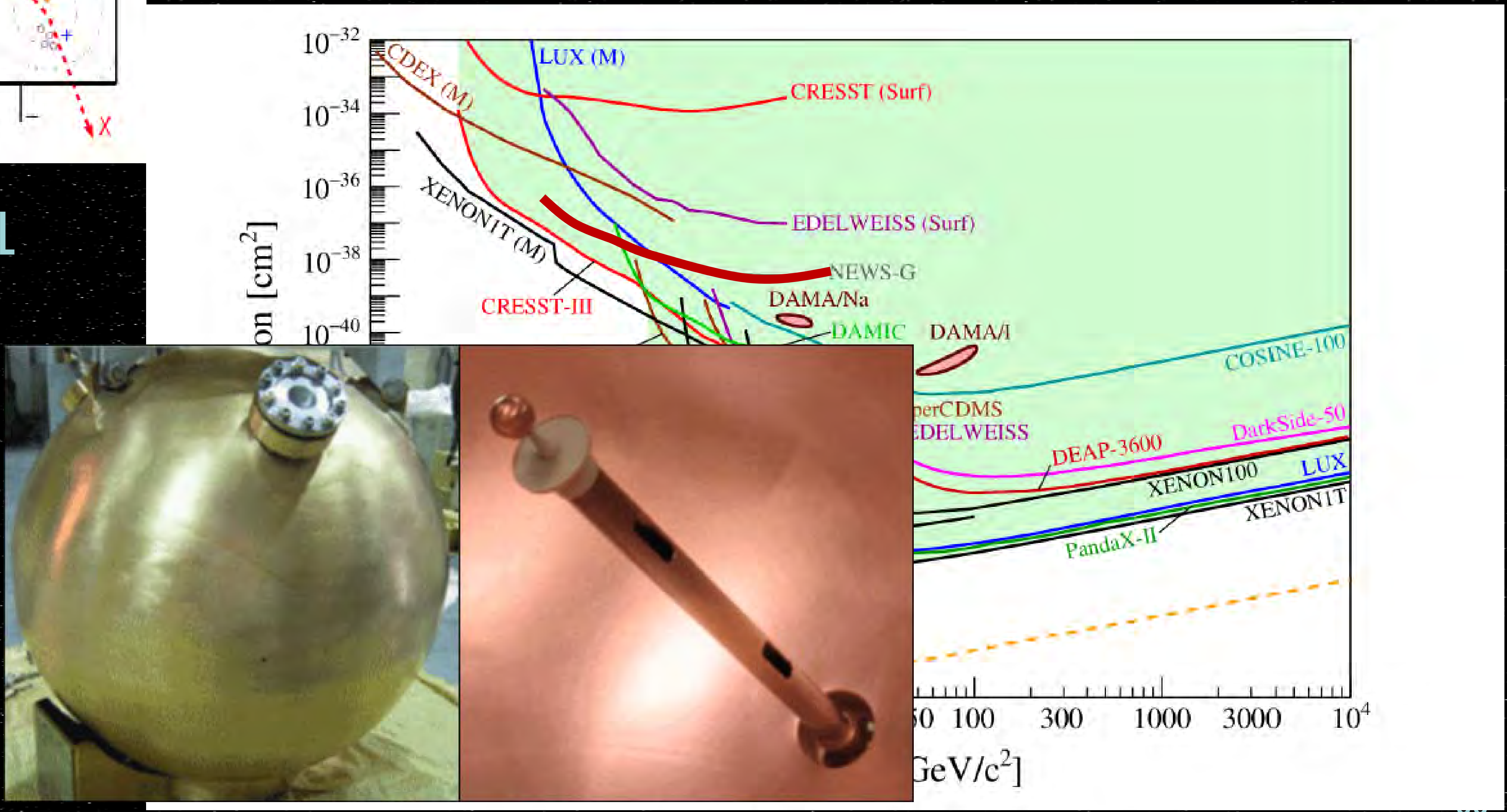


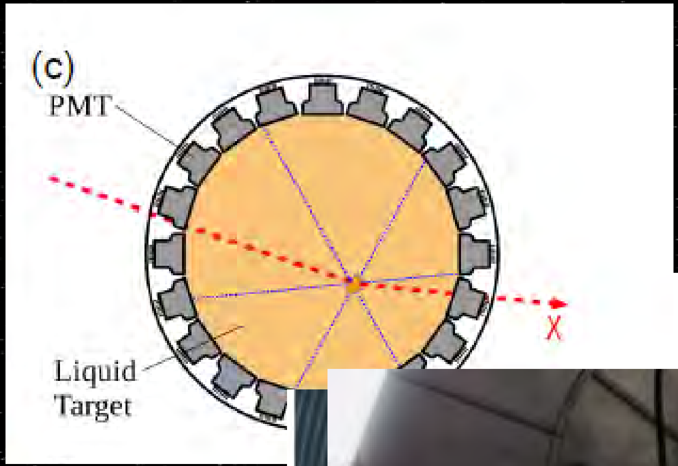
IONIZATION DETECTORS

NEWS-G

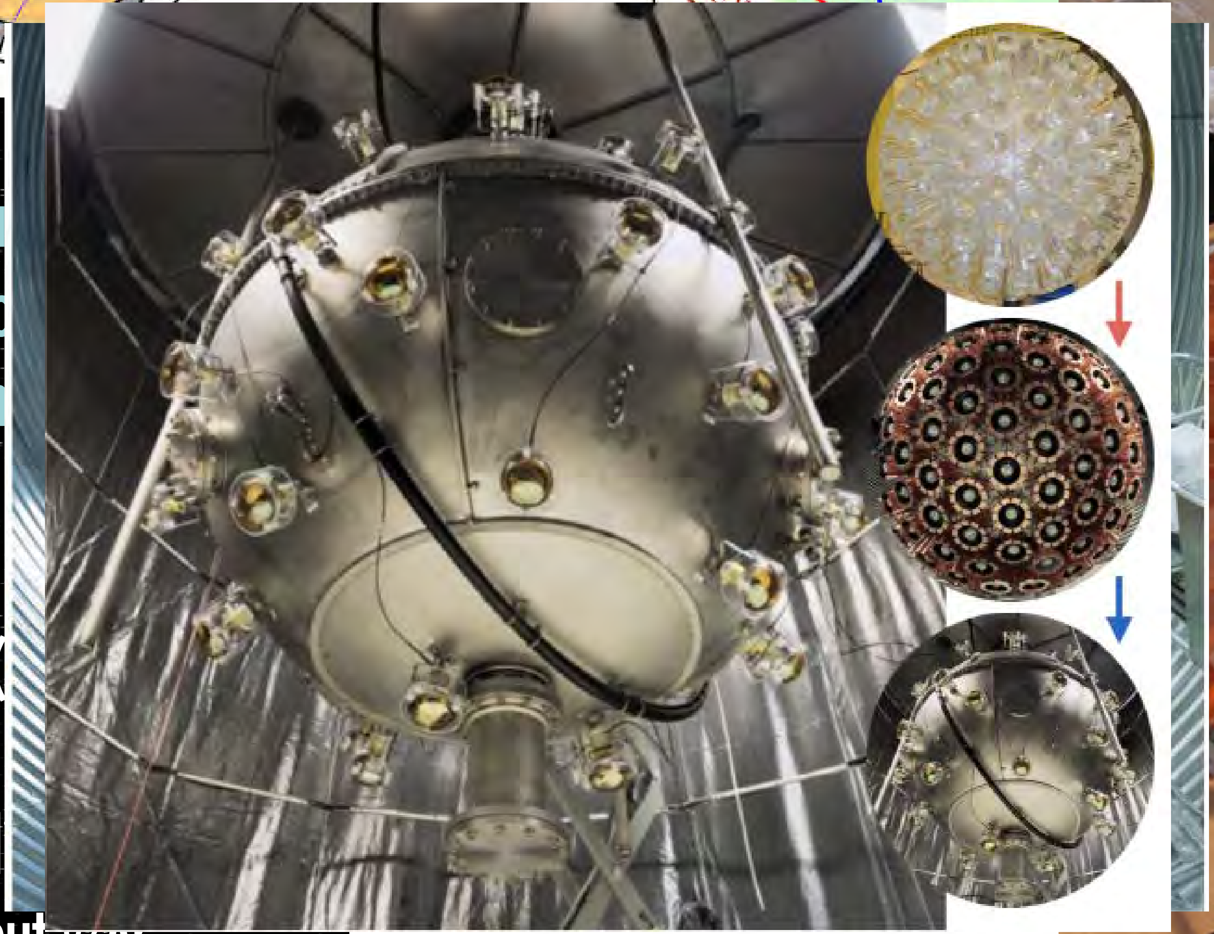
GAS PROPORTIONAL COUNTER

283g Ne+CH_4
Eth =36 eVee





SINGLE-PHASE NOB

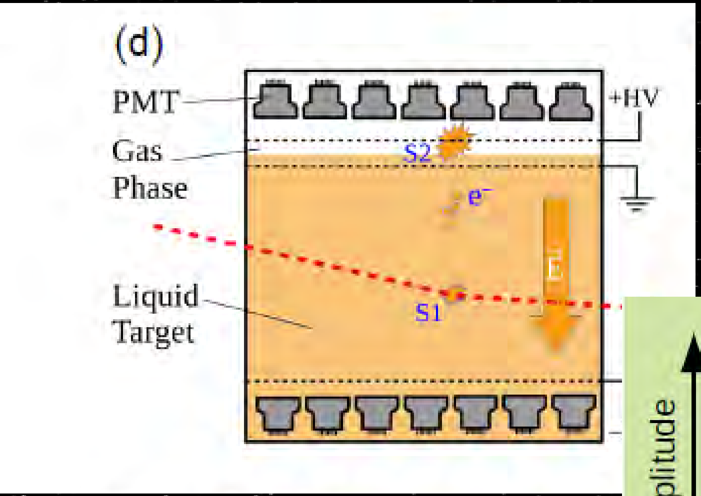


Only scintilla
Xe and Ar ga
Very large m
Background

832 kg Xe (
3280 kg Ar
able to d
NR/ER but ^{39}Ar...

DOUBLE-PHASE NOBLE LIQUIDS TPC

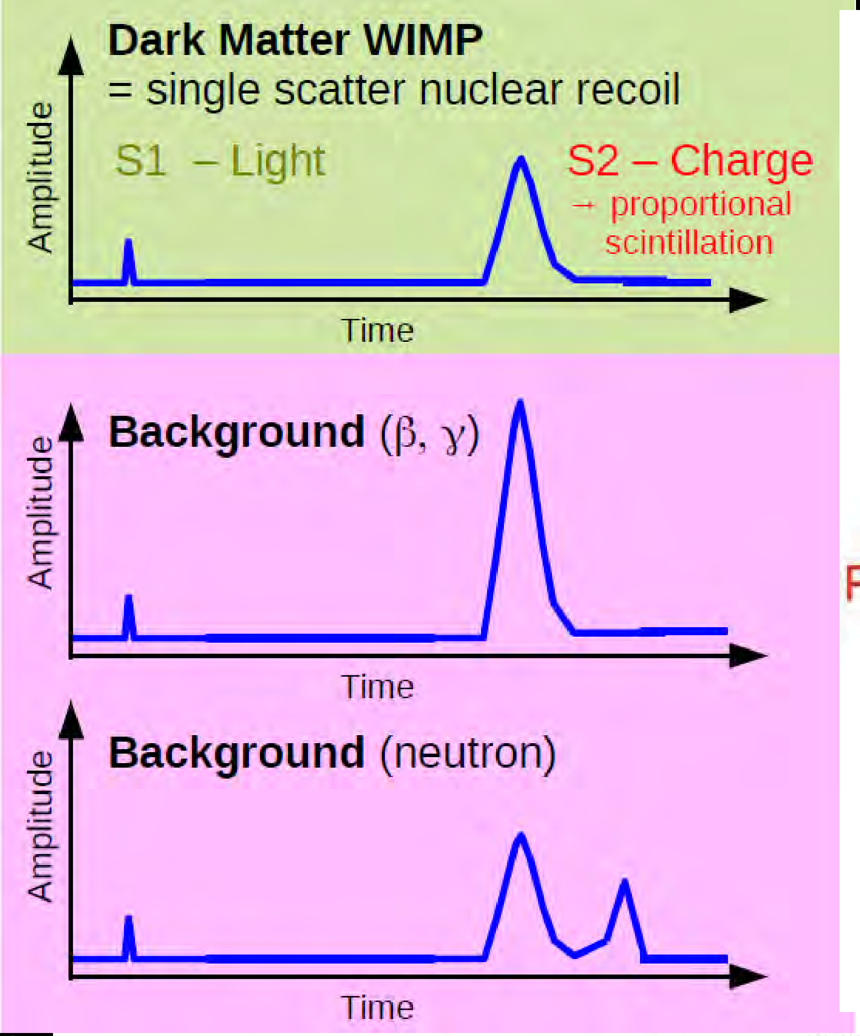
XENON PANDAX
LUX DarkSide-50

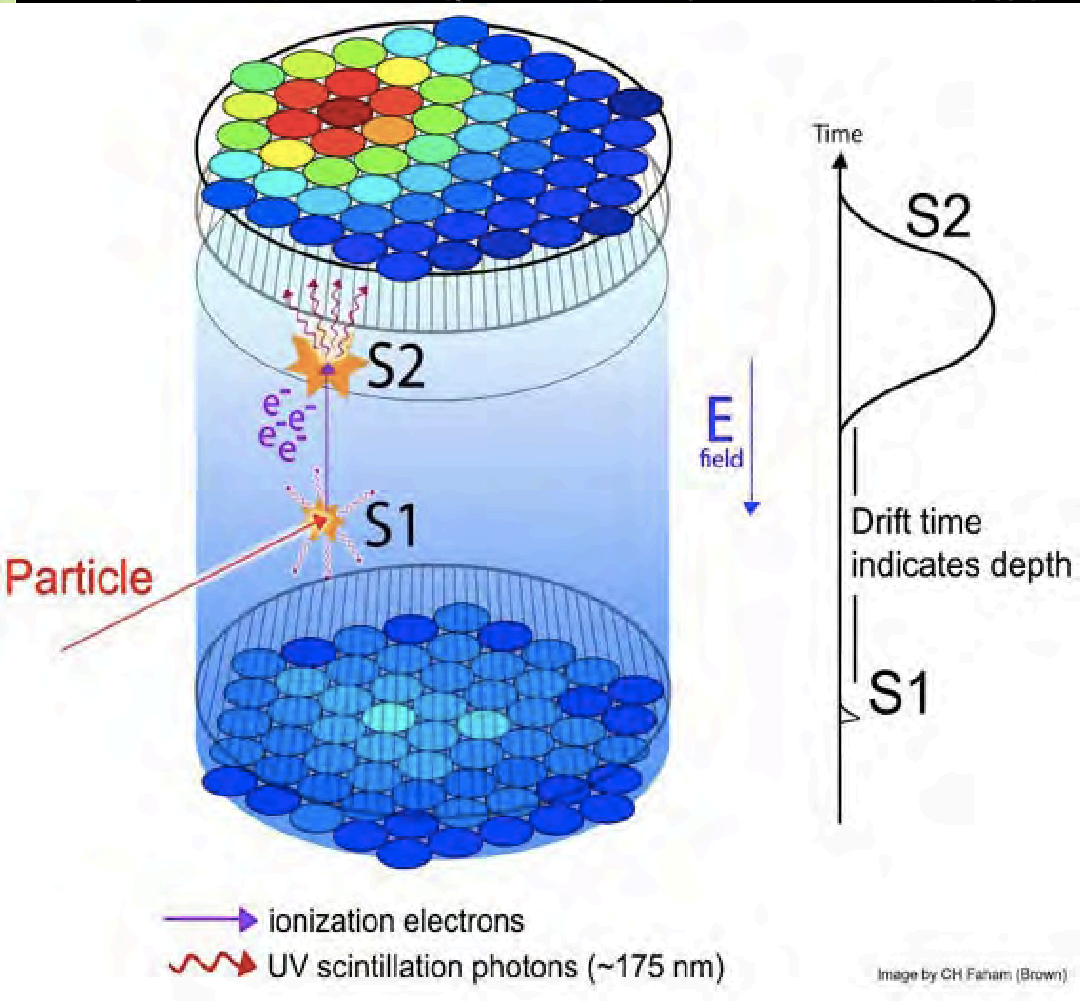


Xe and Ar good scintillators
And easily ionized

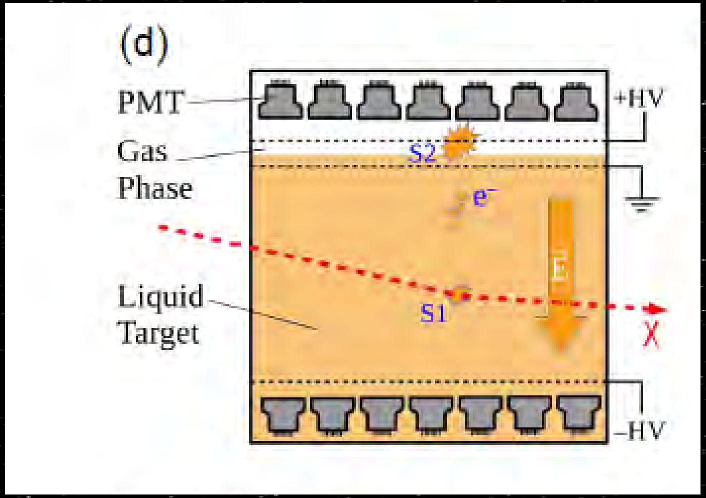
Scalability to large mass

3D reconstruction
NR/ER discrimination





WIMP mass [GeV/c^2]

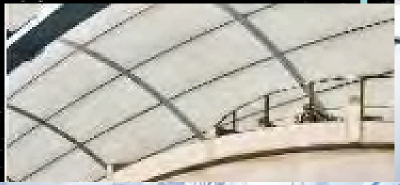


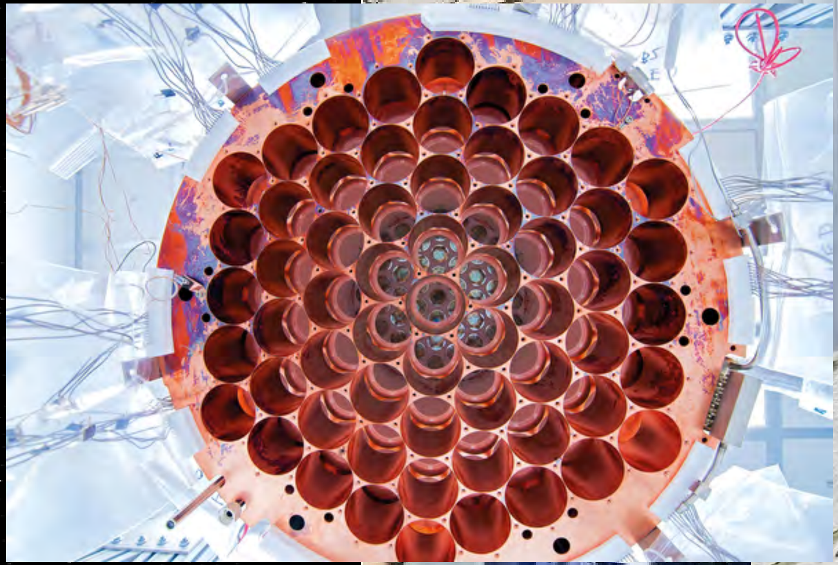
DOUBLE-PHASE NOBLE L

DarkSide-50

46kg Ar

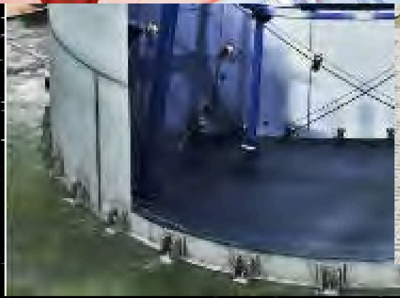
XENON-n





PANDAX-4T

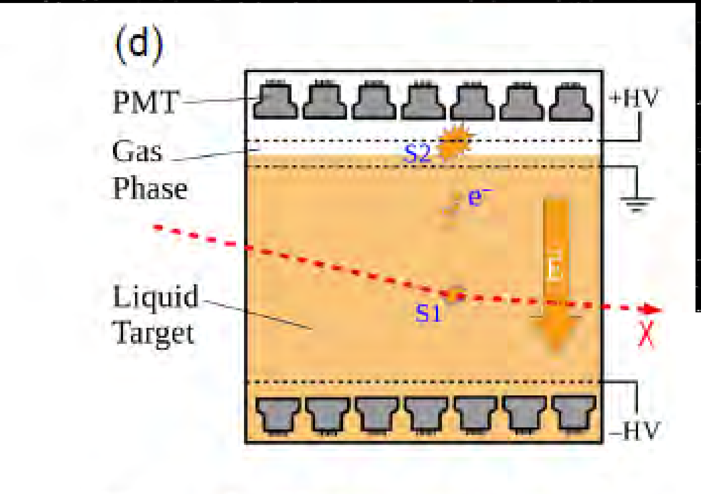
3700 kg Xe



Xe and Ar good scintillators
And easily ionized

Scalability to large mass

3D reconstruction
NR/ER discrimination



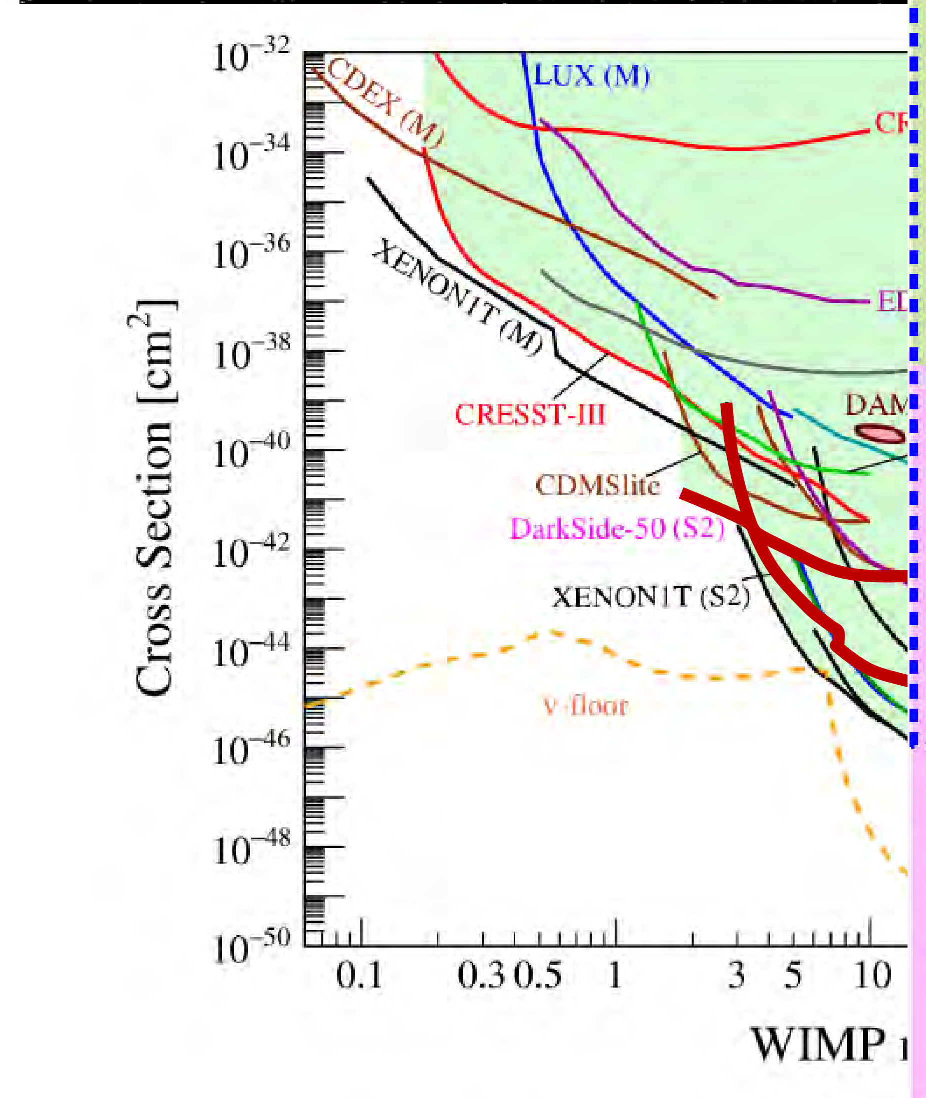
DOUBLE-PHASE NOBLE LIQUIDS TPC

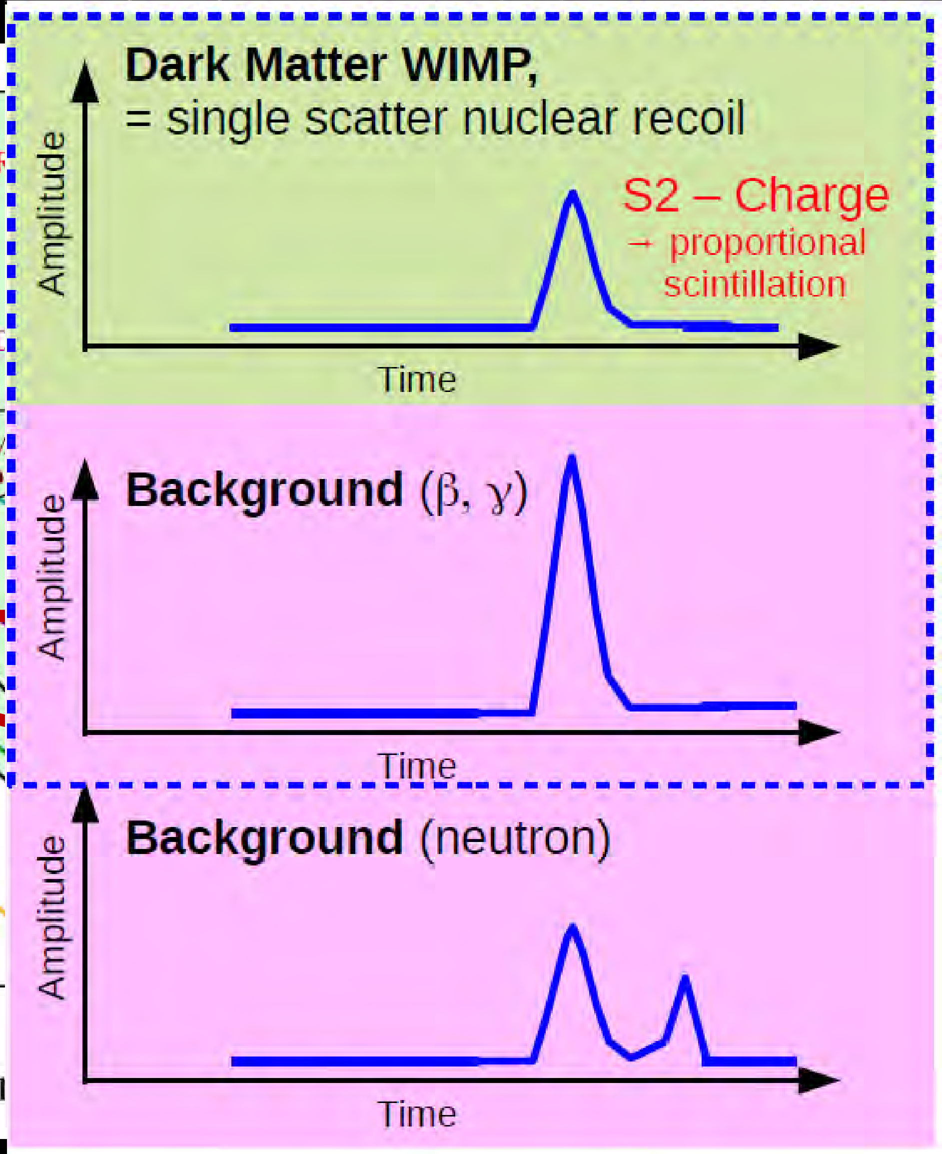
XENON1T
DarkSide-50

Using only S2 signal

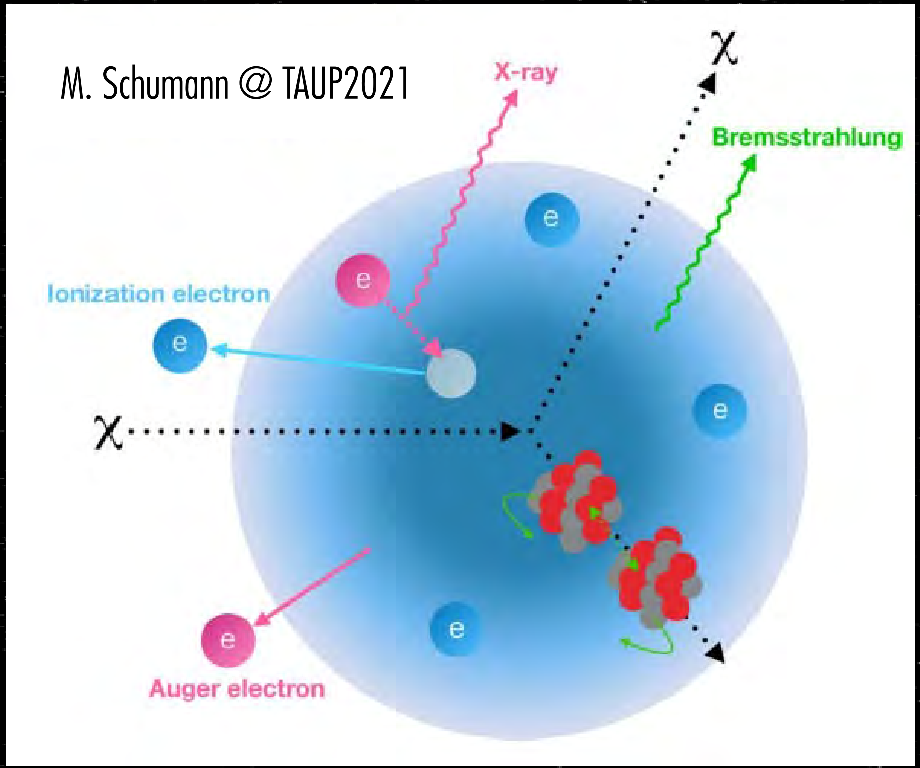
-NR/ER discrimination is lost
-only 2D reconstruction
-E_{th} is much reduced

Improves sensitivity for light WIMPs





MIGDAL EFFECT



The nucleus recoiling inside the electron cloud can transfer energy to the electrons

"electron shakeoff"

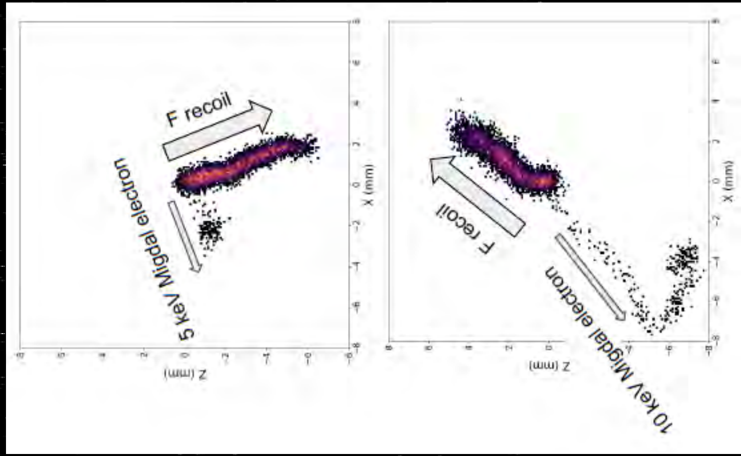
Not yet observed in calibration

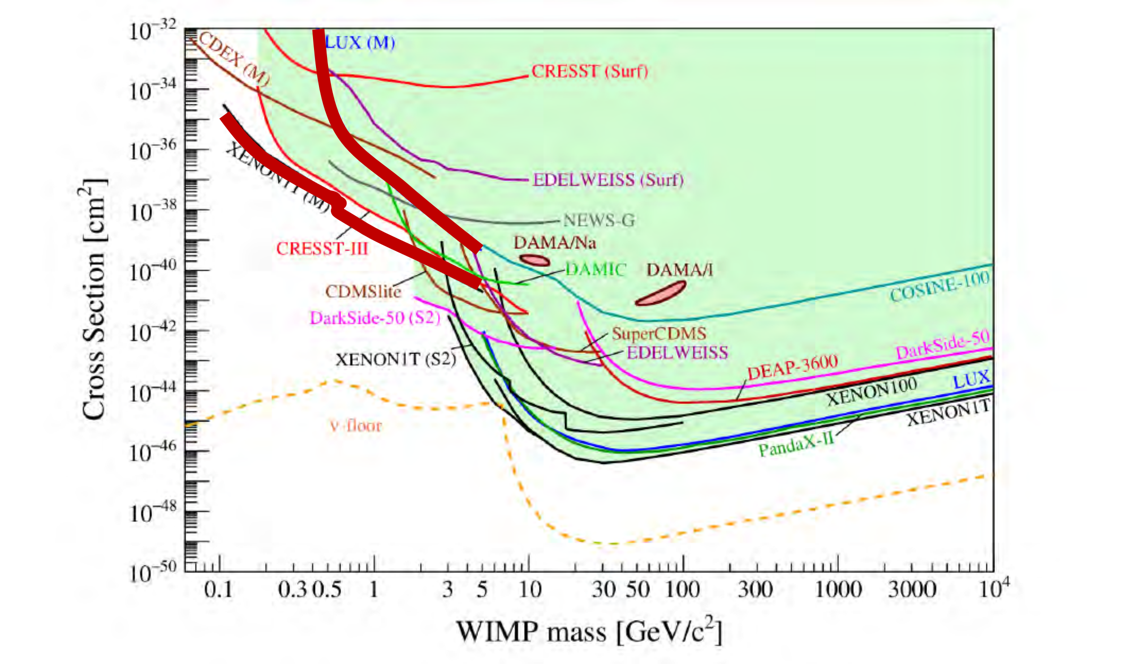
It will naturally extend down to lower energies the reach of many DM searches by increasing the ionization signal

Prospects to carry out experiments to observe Migdal electrons:

- -gaseous TPC
- -tracking ability

MIGDAL Collaboration

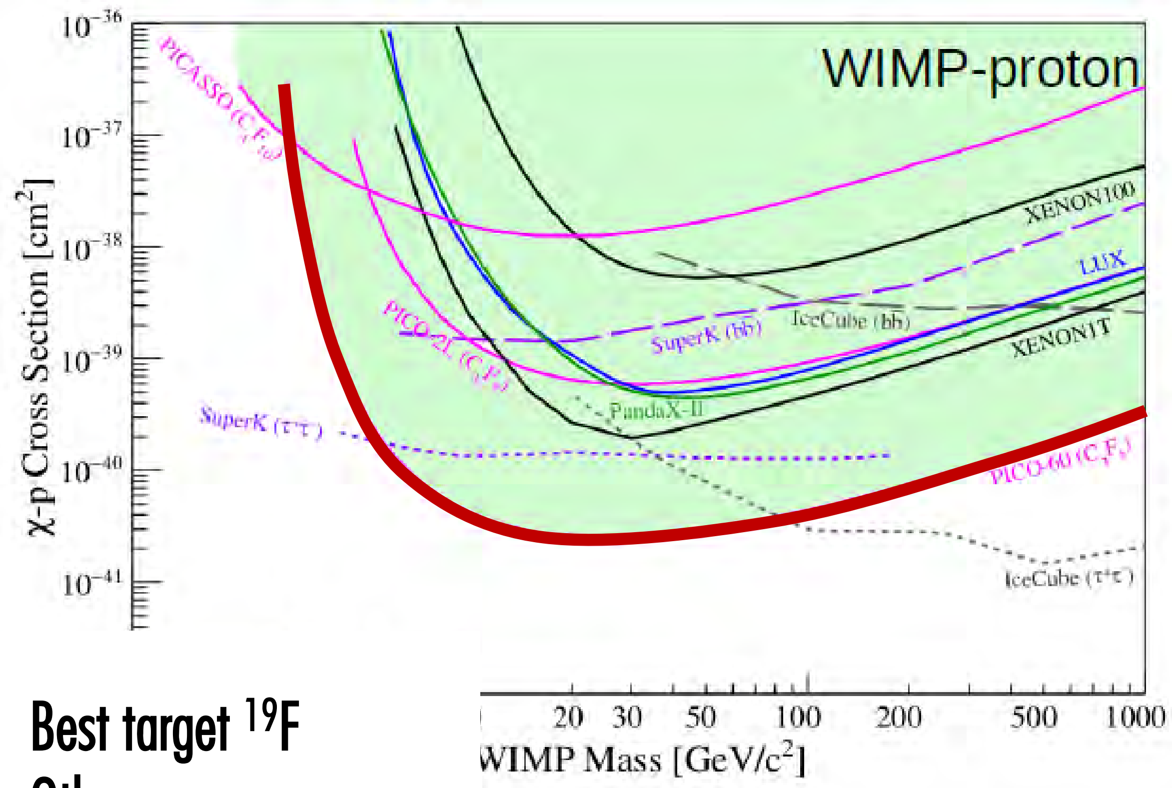




Current status of searches for SD elastic WIMP-nucleus scattering for SHM parameters

Strongly dependent on the nuclear spin and unpaired-nucleon -> Limits are shown separately for coupling to proton / neutron

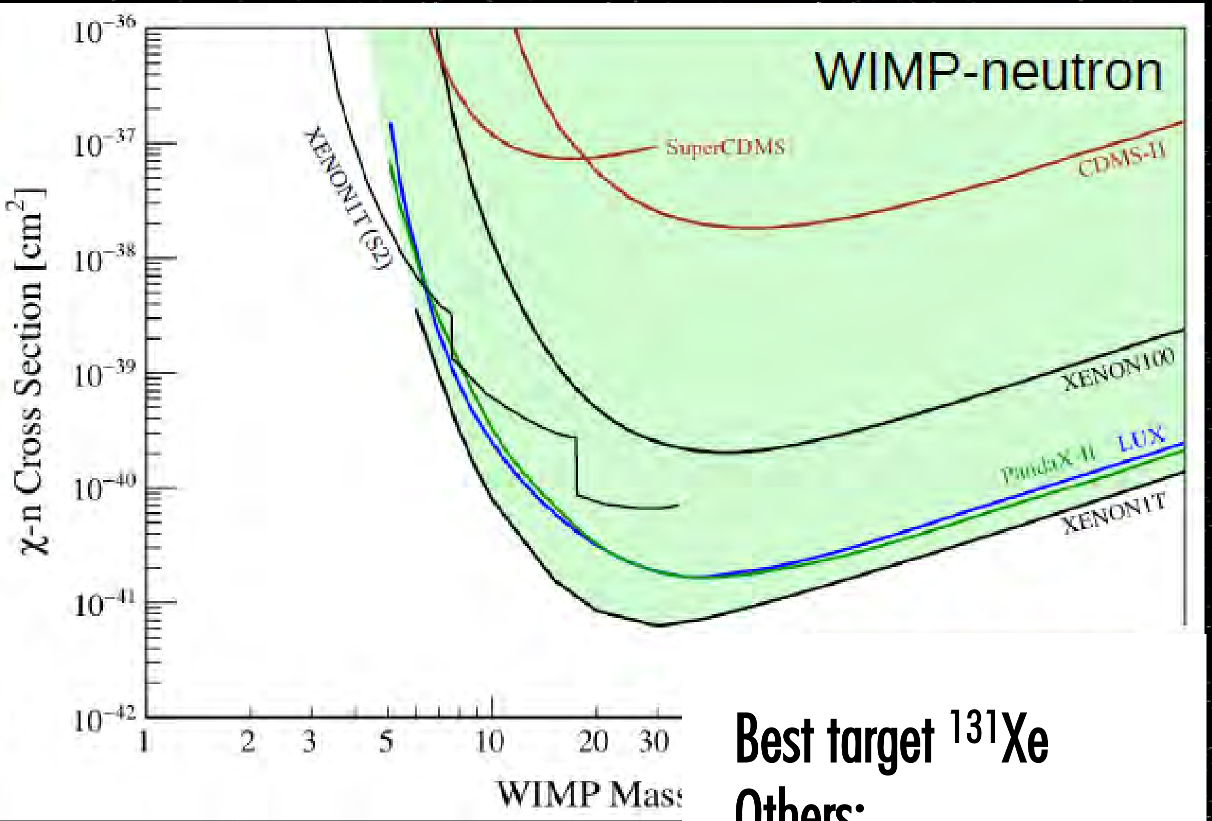
Sensitivity in cross-section worse than for SI coupling (x1000)



Best target ^{19}F

Others:

^{23}Na, ^{127}I, ^{7}Li



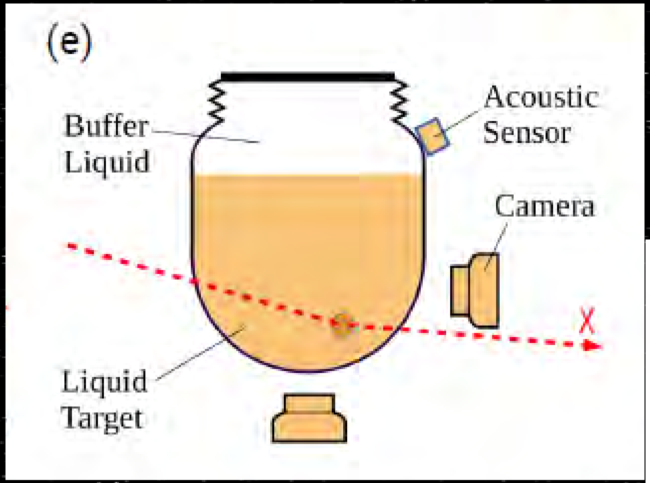
Best target ^{131}Xe

Others:

^{73}Ge, ^{29}Si

BUBBLE CHAMBERS

PICO



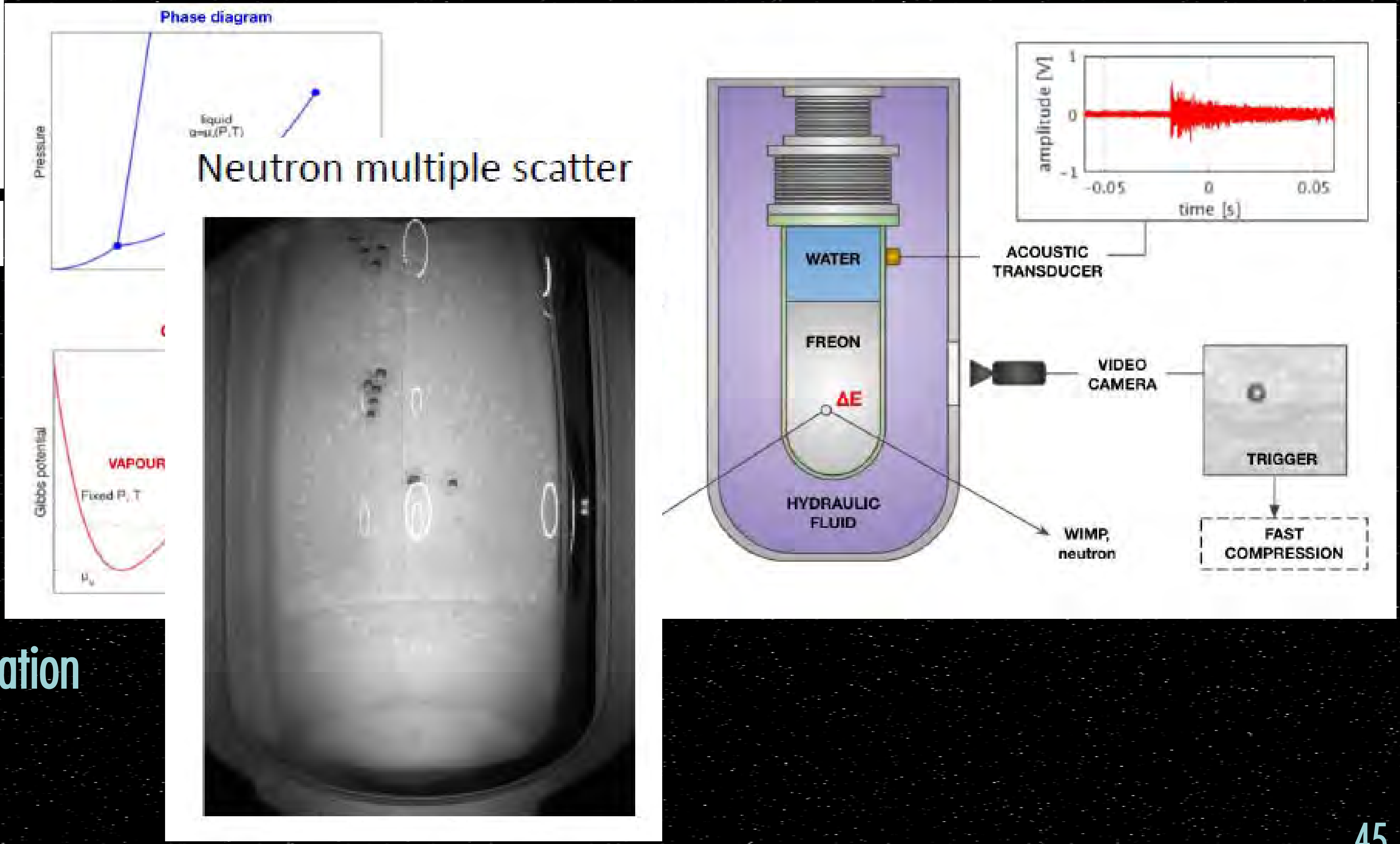
G. Giroux @ TAUP2021

~3 keVnr Eth

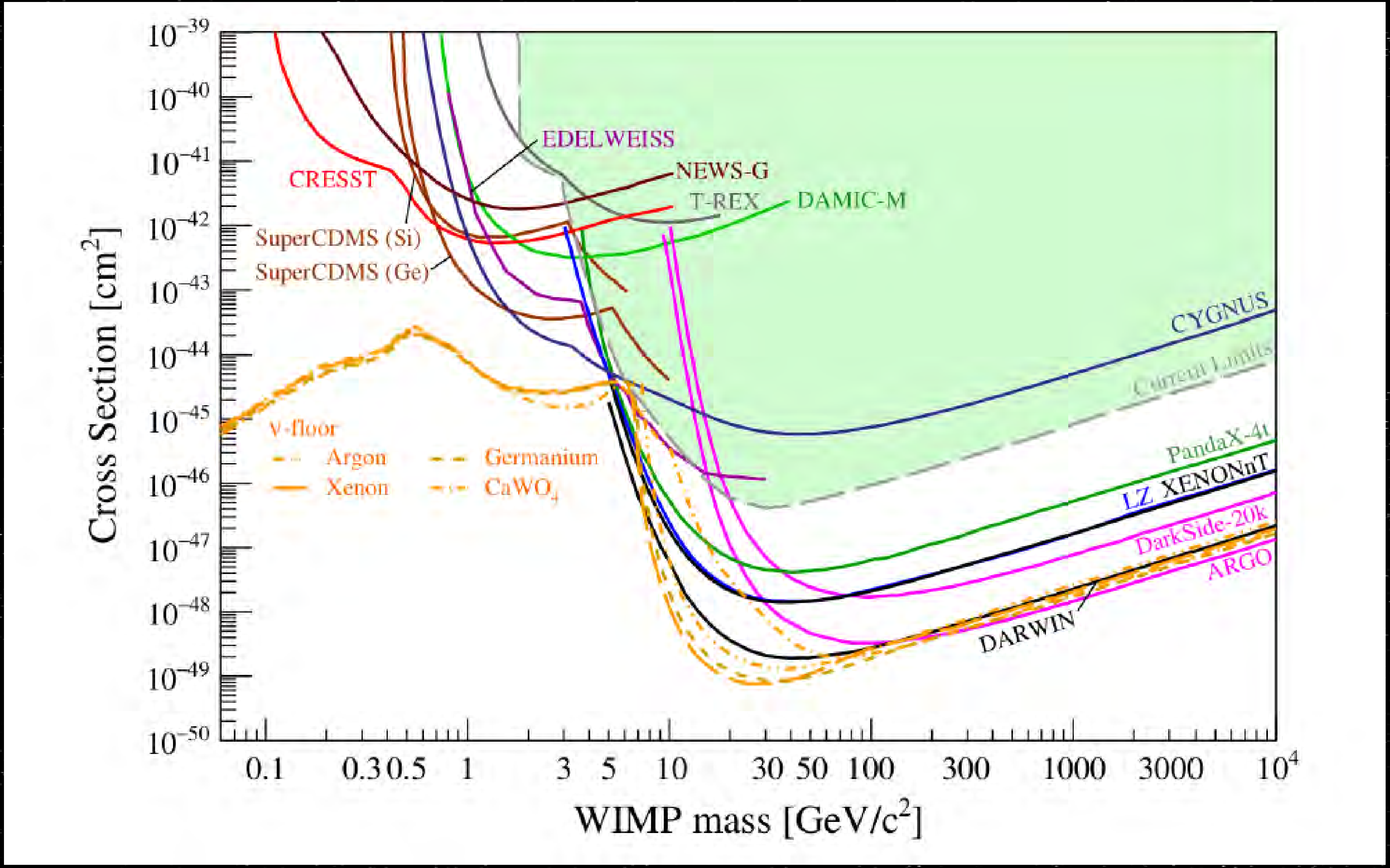
52.2 kg C_3F_8 @ SNOLAB

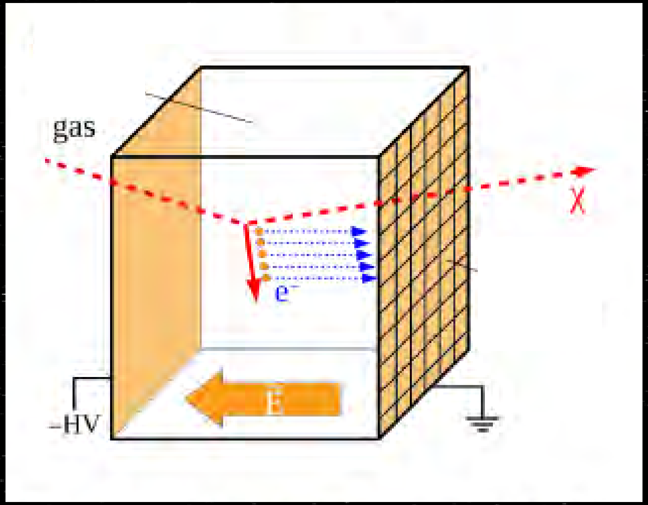
Strong reduction of bkg

- -n by multiple scattering
- -alphas by acoustic discrimination
- -e/gammas do not nucleate



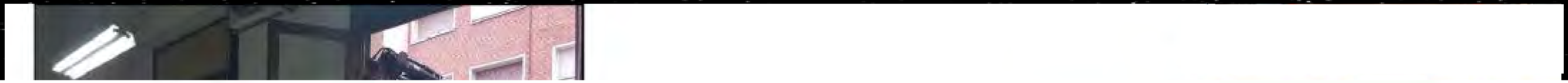
Sensitivity projections 90%C.L. for SI interacting WIMP-nucleon scattering – APPEC report

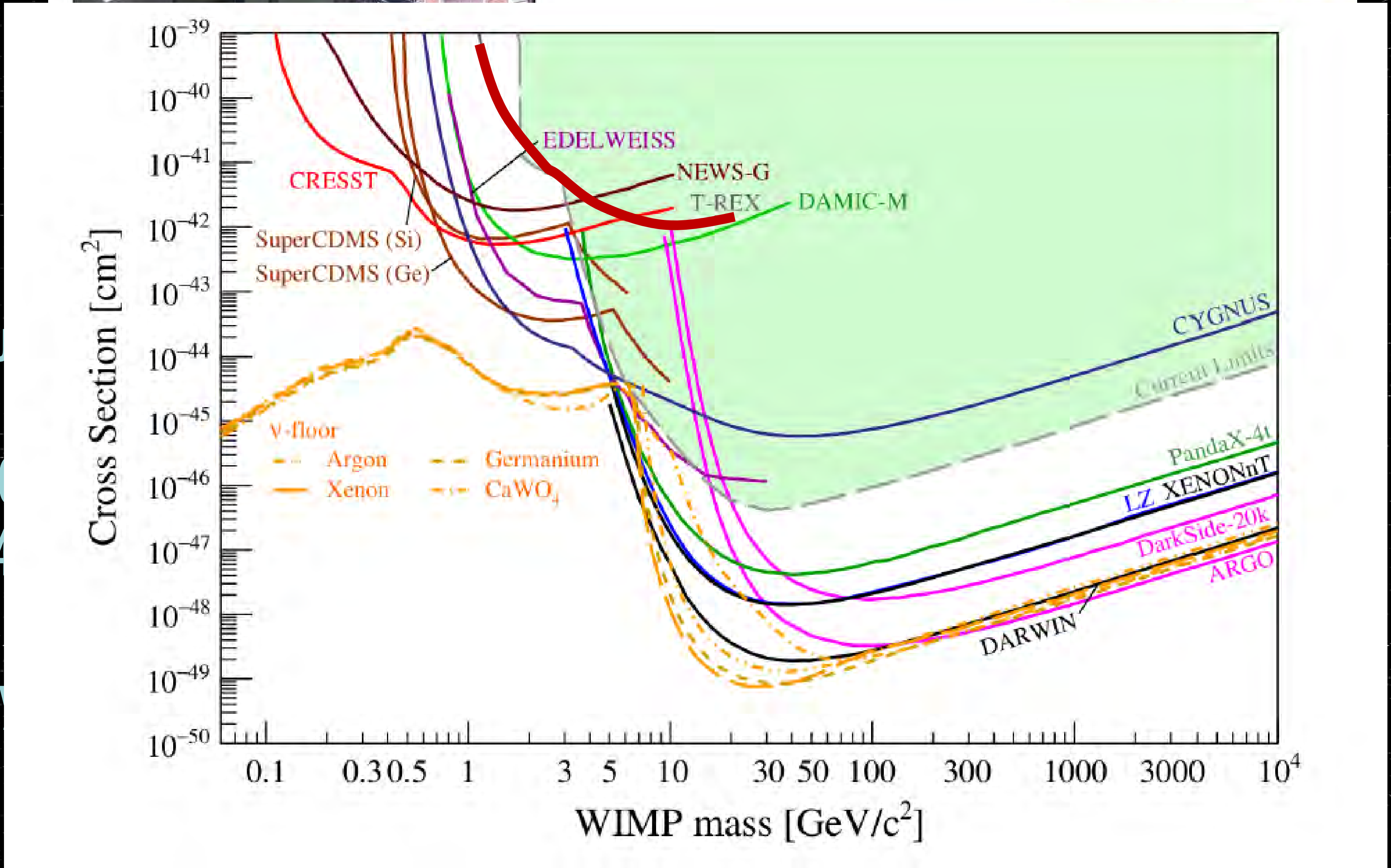




GAS High-pressure TPC

T-REX





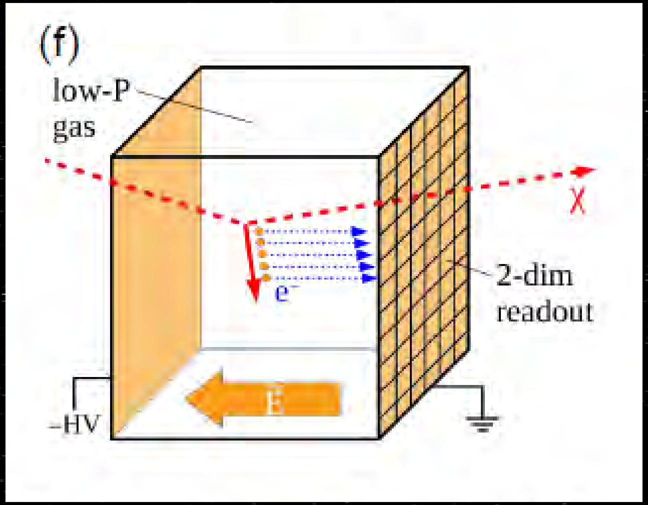
-New Microbulk Micromegas readou

-up to10 bars design

-different gas as target (0.3 kg Ar, (

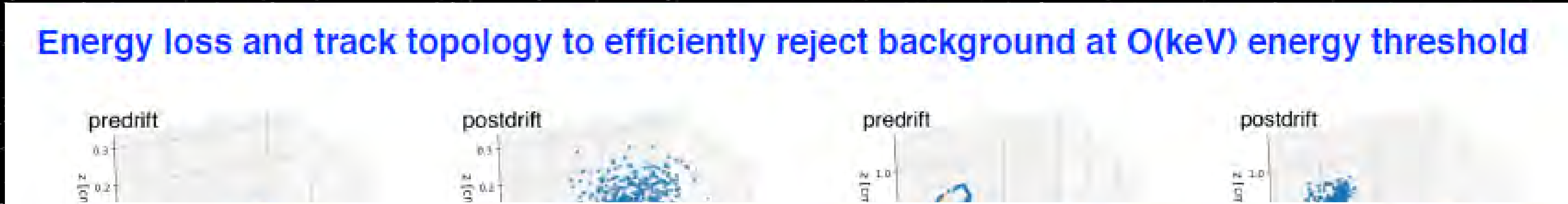
-aim at sub-keV threshold (100 – 4

@Canfranc Underground Laborator



atmospheric-pressure TPC

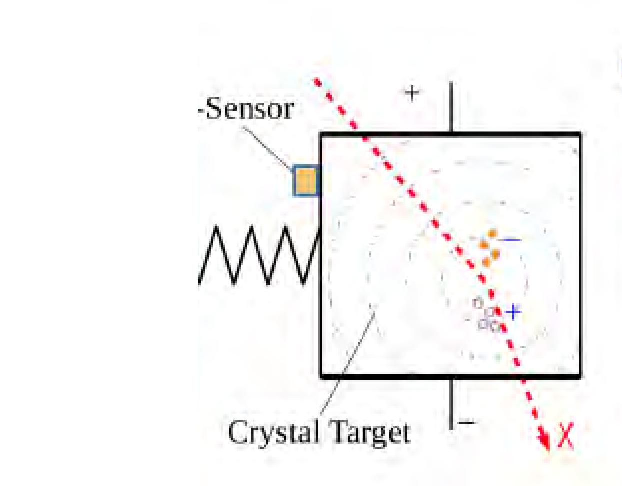
CYGNO



3D detector

Identify directionality of the energy deposition -> SIGNATURE

Not competitive with other techniques in terms of sensitivity



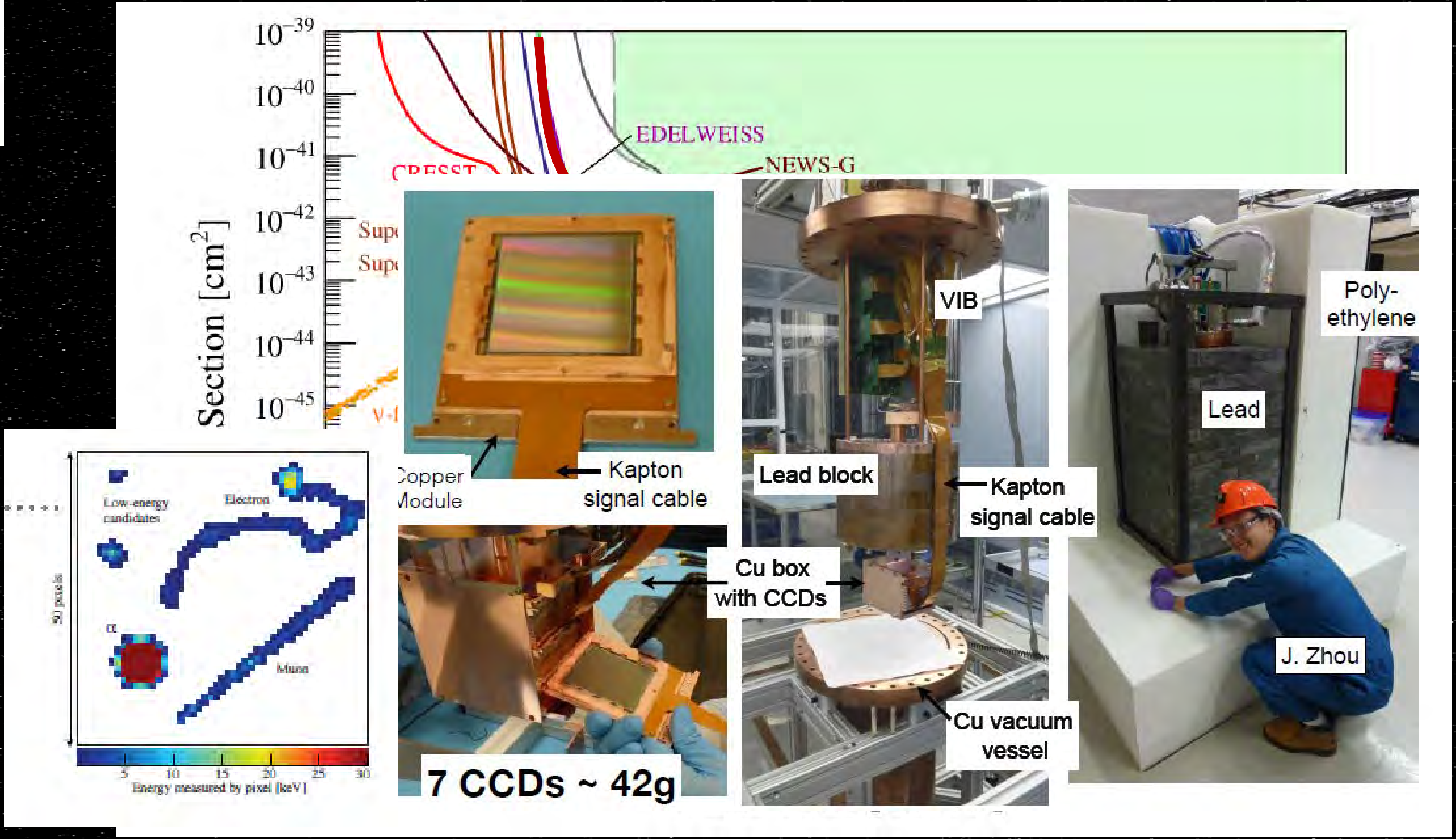
IONIZATION DETECTORS

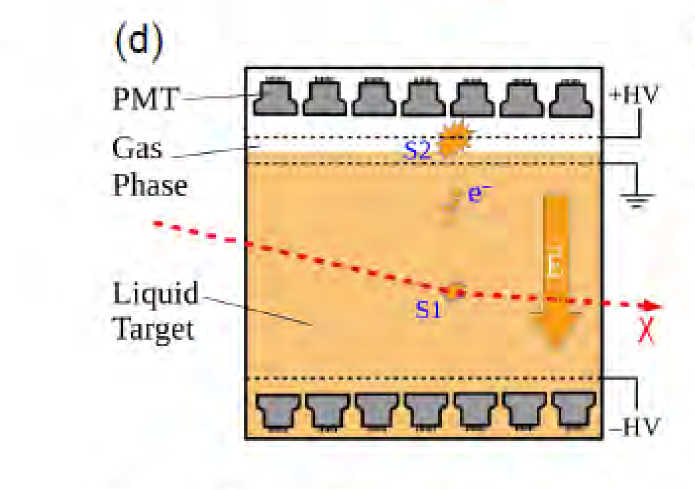
SENSEI
DAMIC-M

CCDs

42g Si -> 1kg in DAMIC-M
E_{th} = 50 eV ->1.2 eV

Good background control





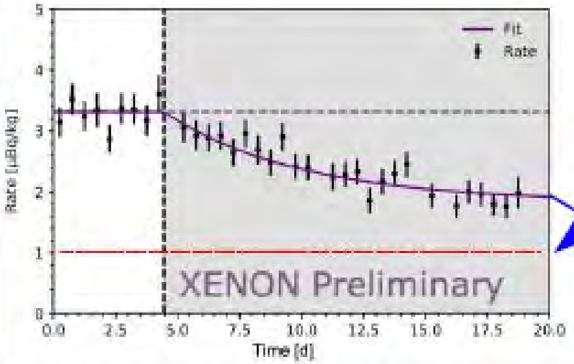
DOUBLE-PHASE NOBLE LIQUIDS TPC

XENON-nT
LZ

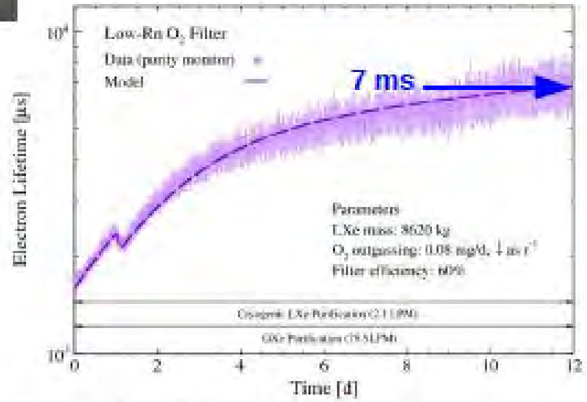
LXe future program - DARWIN

World-Wide Effort

XENONnT @ LNGS
– 5.9 t LXe target
– Rn activity (goal): 1 µBq/kg
– in data taking phase



LXe cleaning yields factor ~2

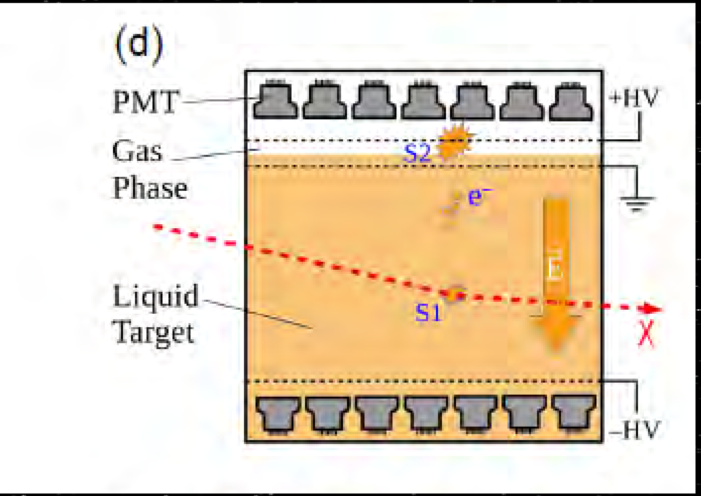


LZ @ SURF
– 7.0 t LXe target
– Rn activity (goal): 2 µBq/kg
– in commissioning phase
– expect first data later this year

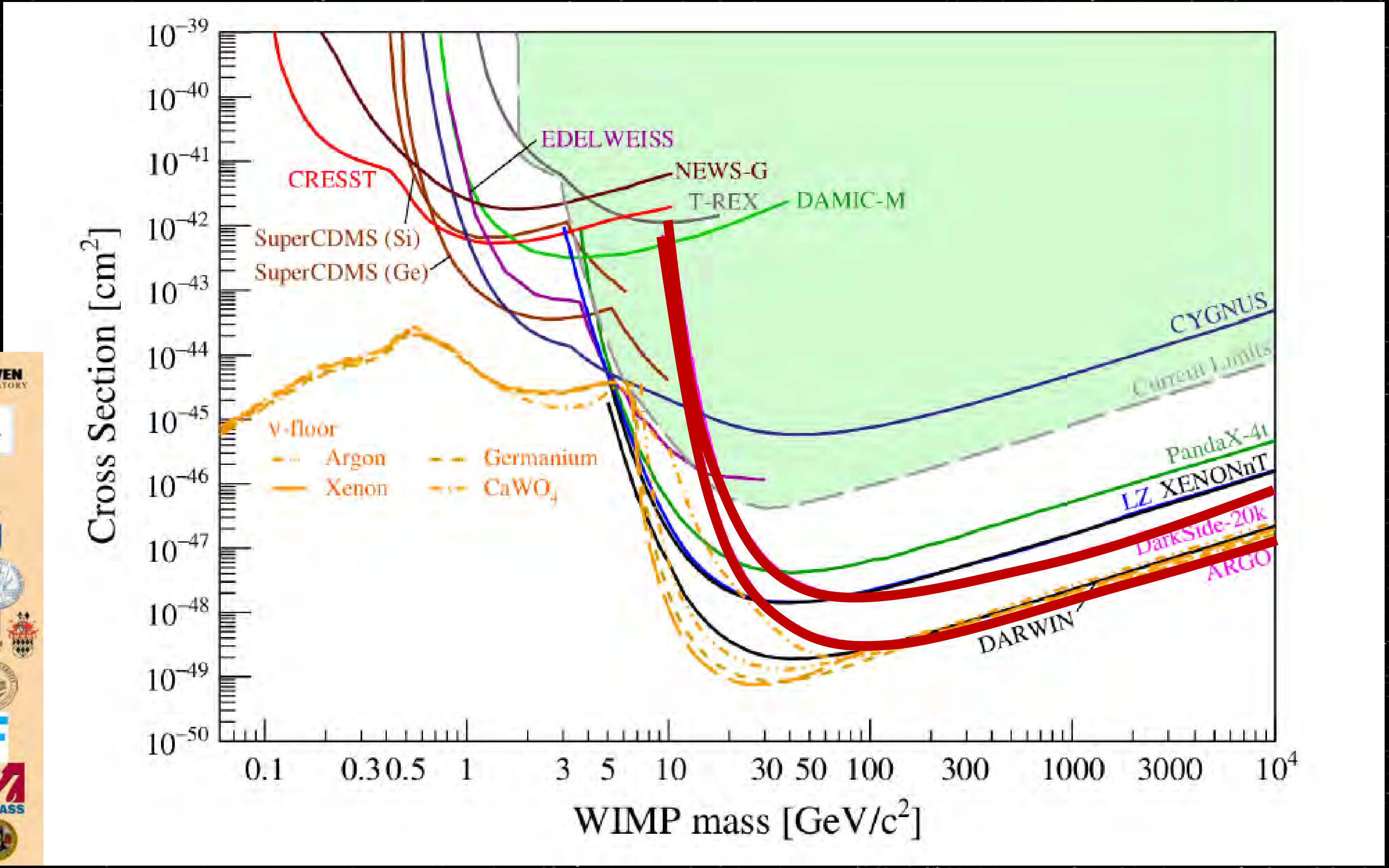
M. Schumann @ TAUP20

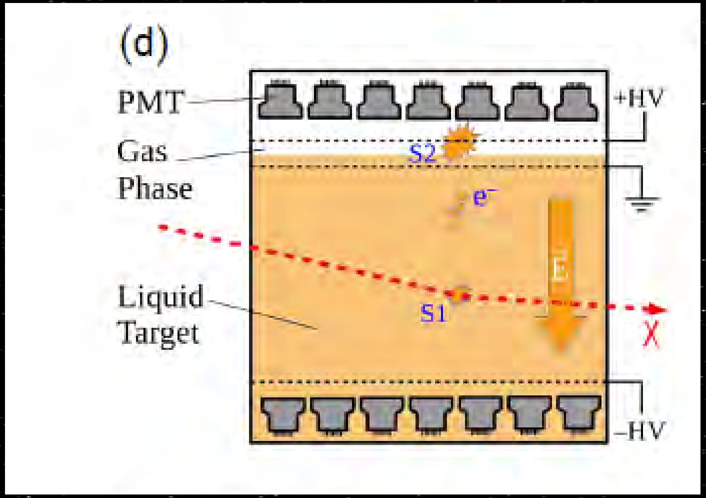
DOUBLE-PHASE NOBLE LIQUIDS TPC

GADM Collaboration



LAr program
World-Wide Effort





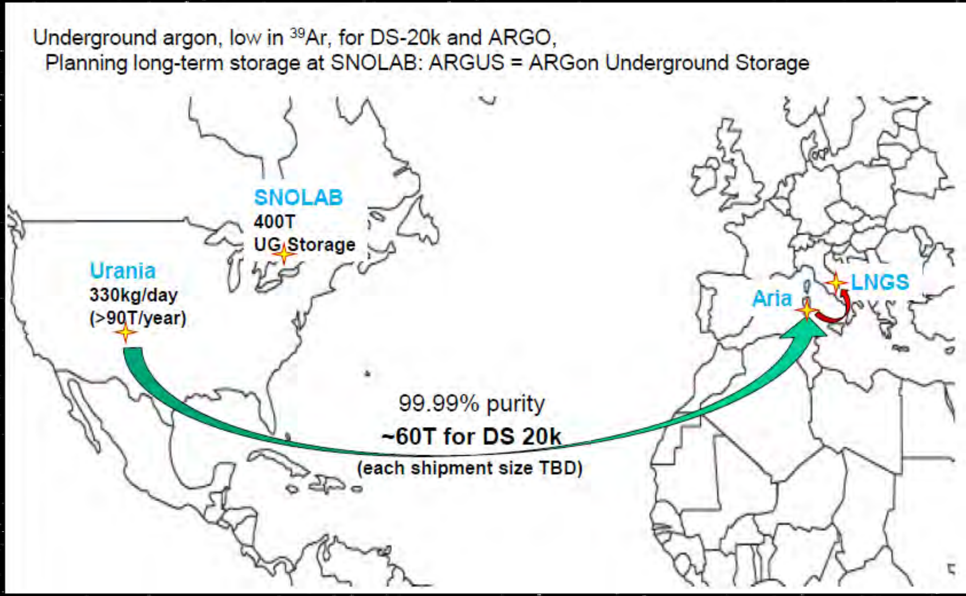
DOUBLE-PHASE NOBLE LIQUIDS TPC

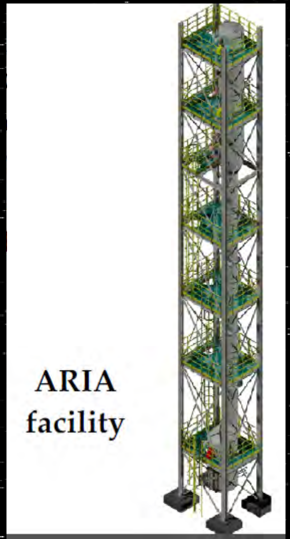
GADM Collaboration

Several key developments required:

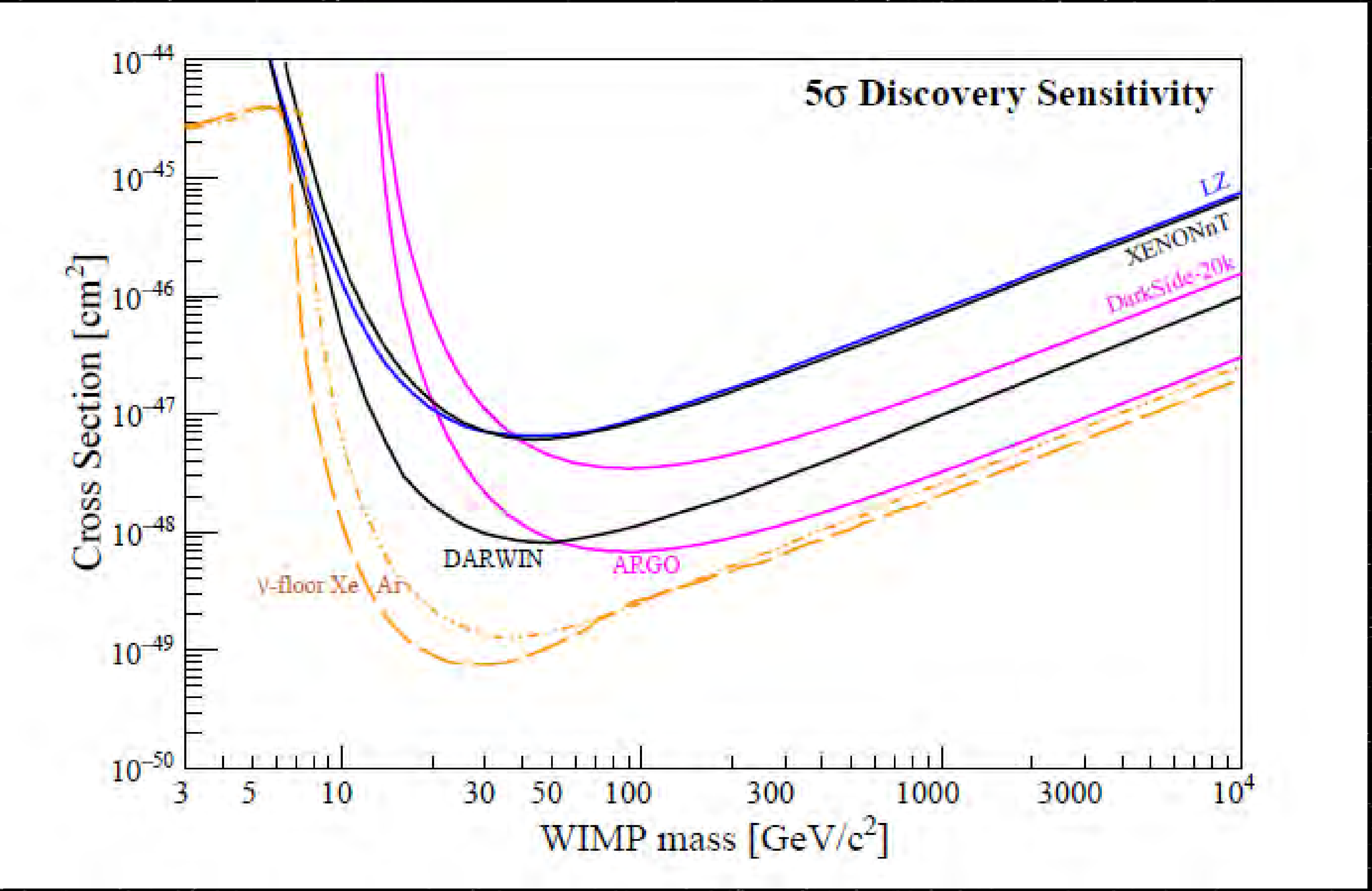
-SiPMs for the light readout replacing PMTs
-Underground Ar – low in ^{39}Ar – extracted in URANIA – US and further purified in ARIA (Italy)
-Measurement of Ar-depletion factor in DArTinArDM @ LSC

LAr program
World-Wide Effort





5 sigma discovery potential for some future projects – APPEC report



ARGO unifies all the community working with LAr technology

DARWIN unifies all the community working with LXe technology

But still, there are new proposals, new techniques, other parameter space regions to explore …

PALEODETECTORS

Solid State (Nuclear) Track Detectors (SSTDs)

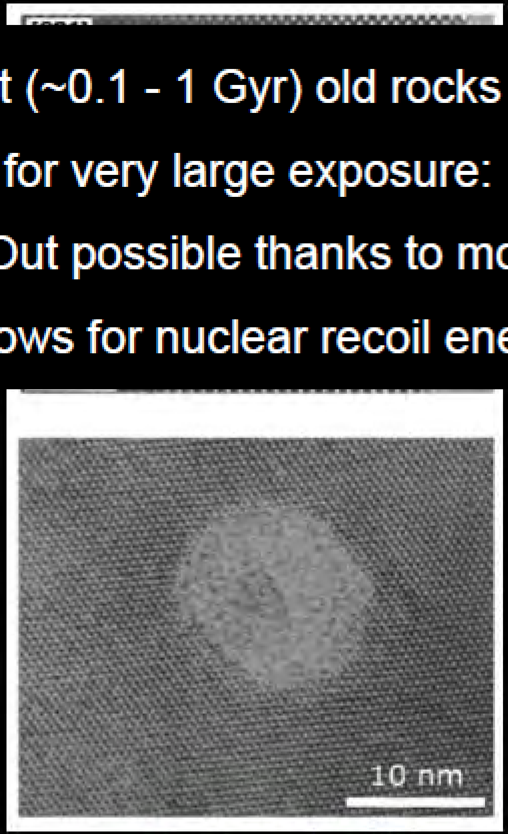
Fission fragment tracks in synthetic Mica, TEM

[Price&Walker '63]

Fossil Tracks in Phlogopite; optical microscopy after chemical et

[Price&Walker '63]

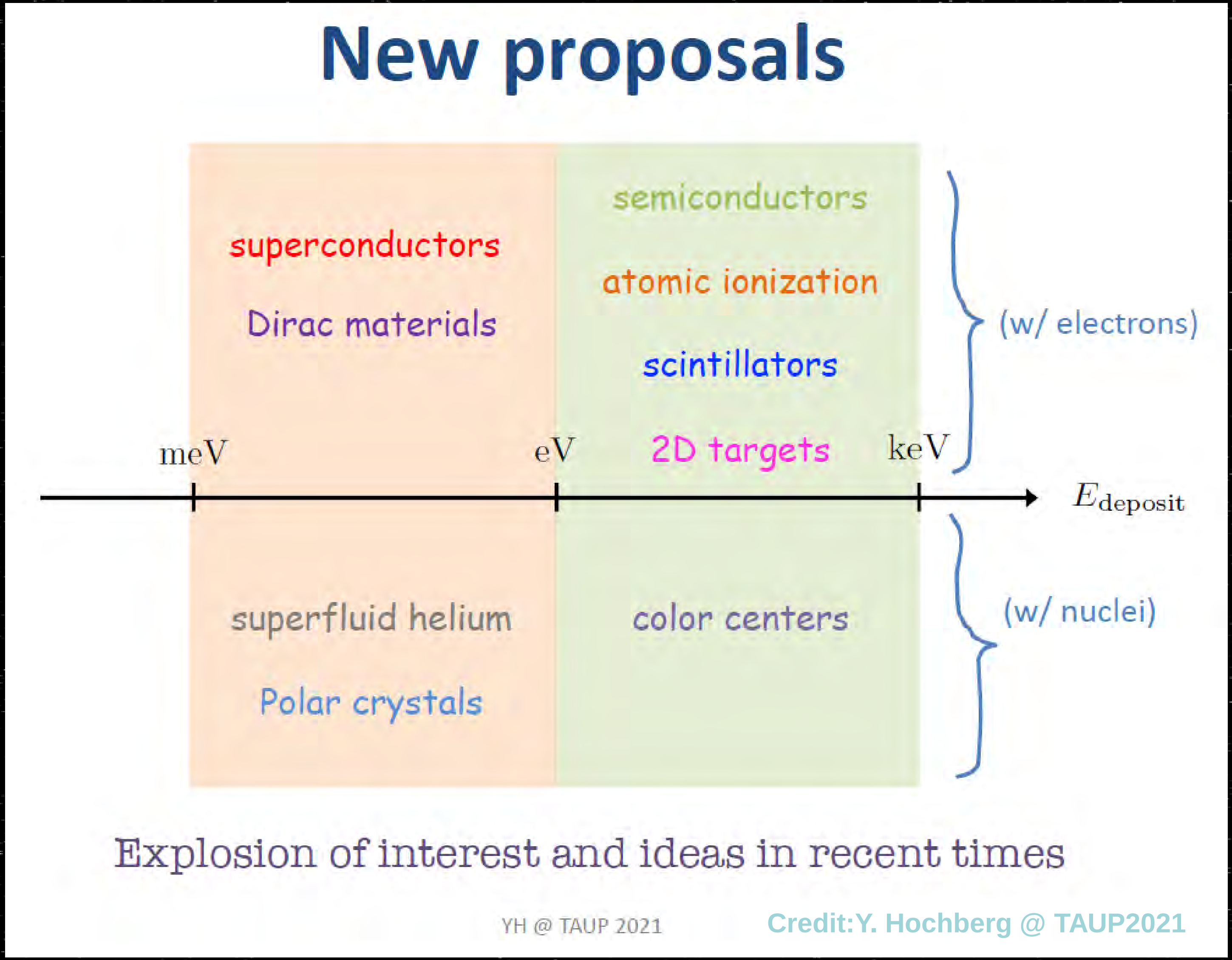
High-resolution TEM

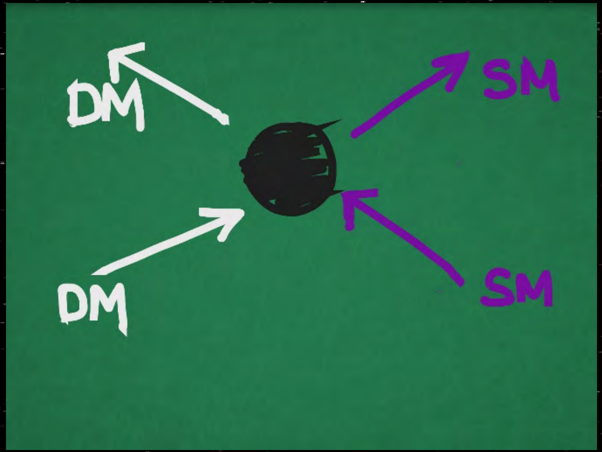


[Toulemonde+ '06]

- Ancient (~0.1 - 1 Gyr) old rocks store information about nuclear recoils
- Allows for very large exposure: 100 g × 1 Gyr = 100 kt yr!
- Read-Out possible thanks to modern nano-technology
  - Allows for nuclear recoil energy thresholds of 0.1 - 1 keV!

DIRECT DETECTION OF DARK MATTER

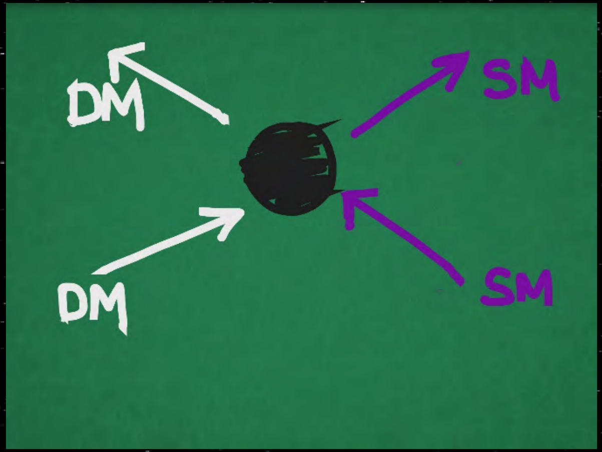




Light DM particles deposit small energy into the target

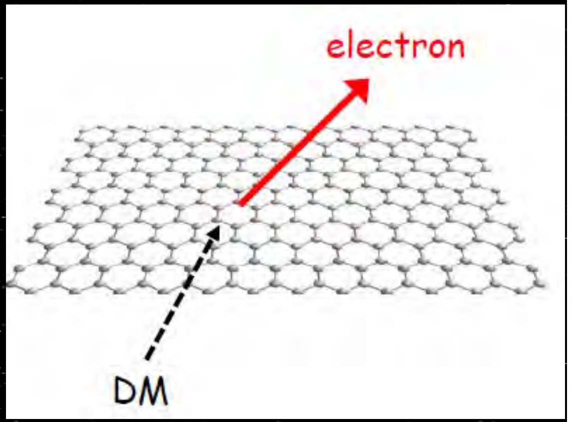
Going at sub-keV energies requires new ideas / detection techniques

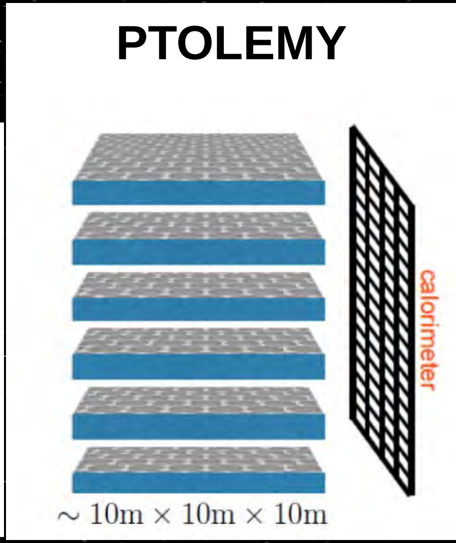
DIRECT DETECTION OF DARK MATTER



Just a few ideas:

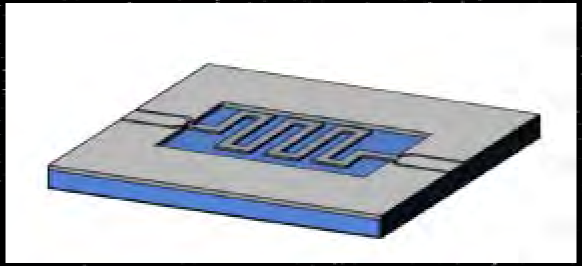
-Semiconductors – single e





-2D targets, like graphene

-Superconducting nanowires single-photon detectors

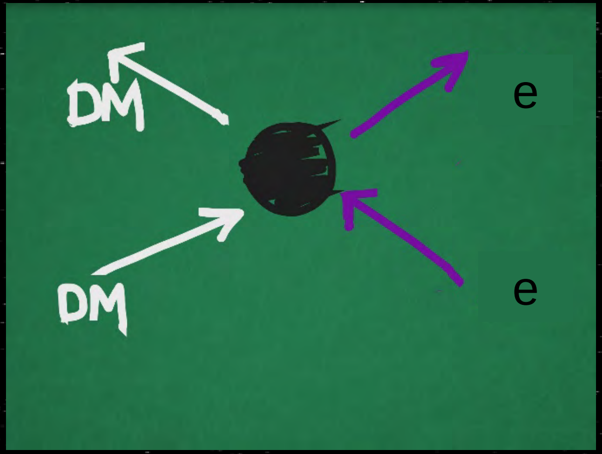


-Plasmons in heavy-fermion systems

Light DM particles deposit small energy into the target

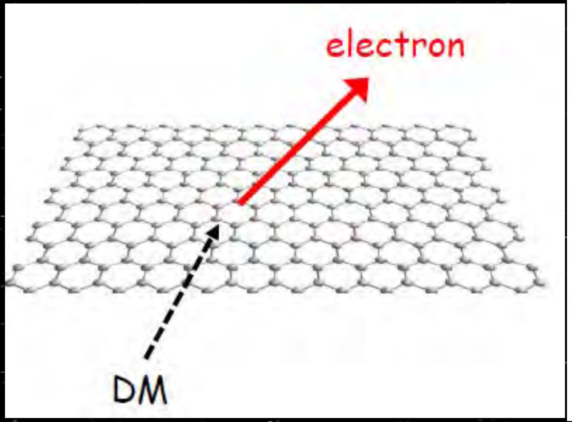
Going at sub-keV energies requires new ideas / detection techniques

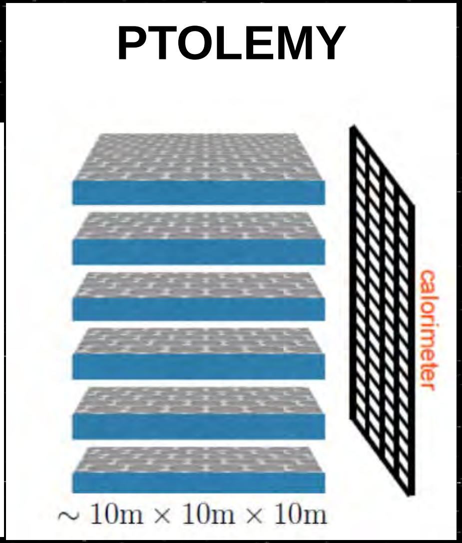
DIRECT DETECTION OF DARK MATTER



Just a few ideas:

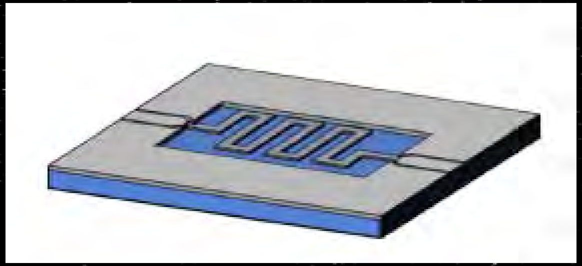
-Semiconductors – single e



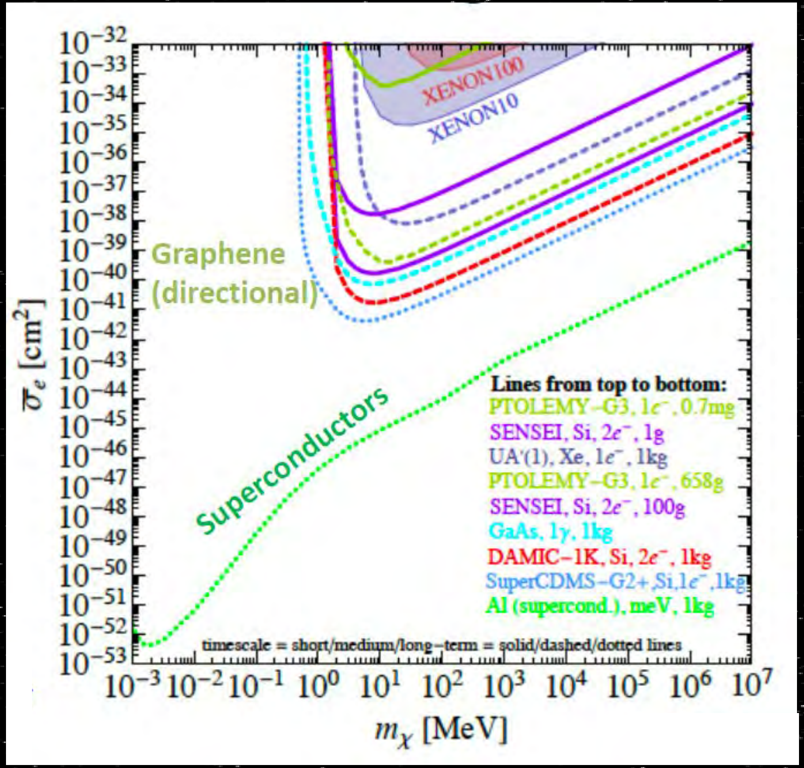


-2D targets, like graphene

-Superconducting nanowires single-photon detectors

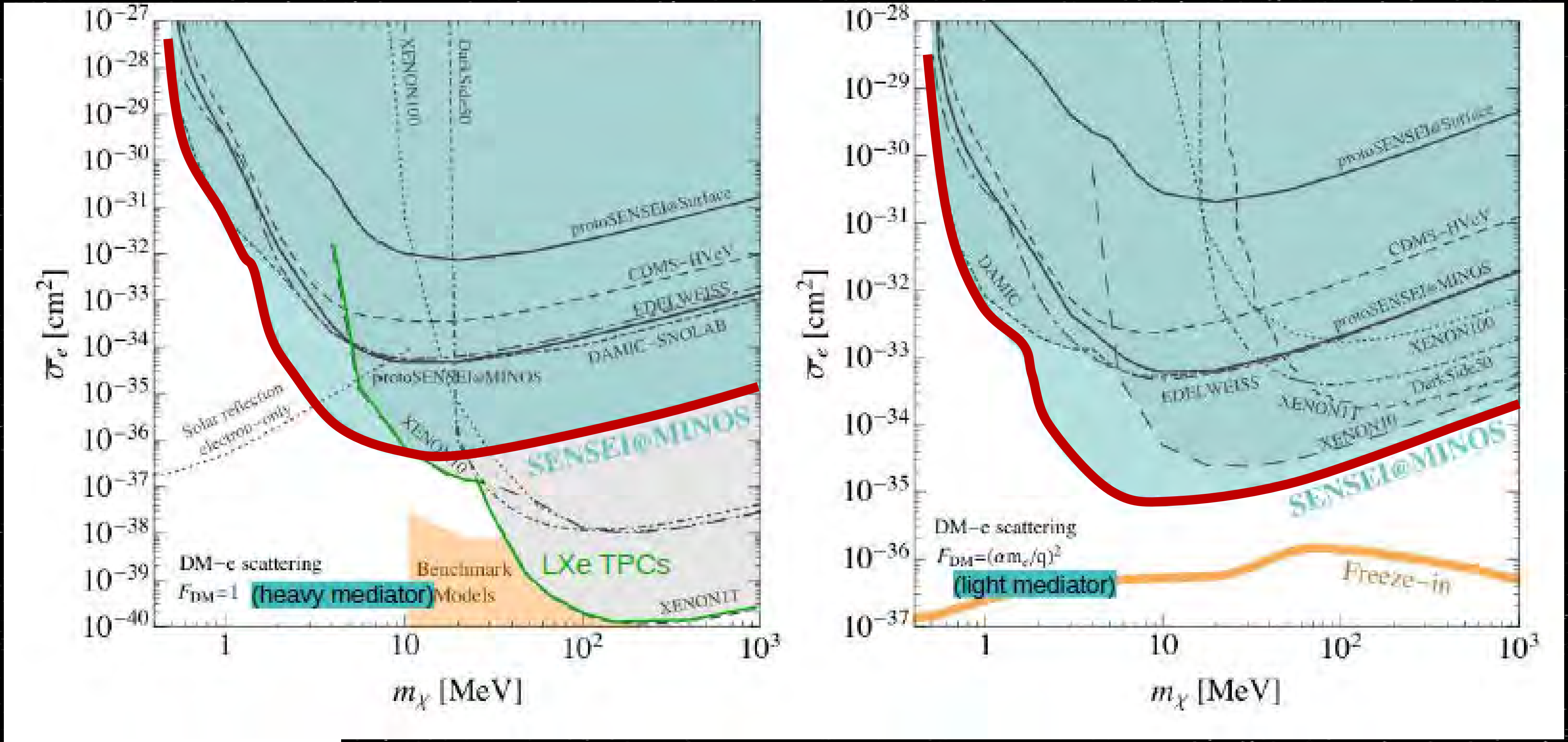


-Plasmons in heavy-fermion systems



Current status of searches for WIMP-electron scattering for SHM parameters

Present limits dominated by SENSEI -> 2g CCD Si



M. Schumann @ TAUP2021

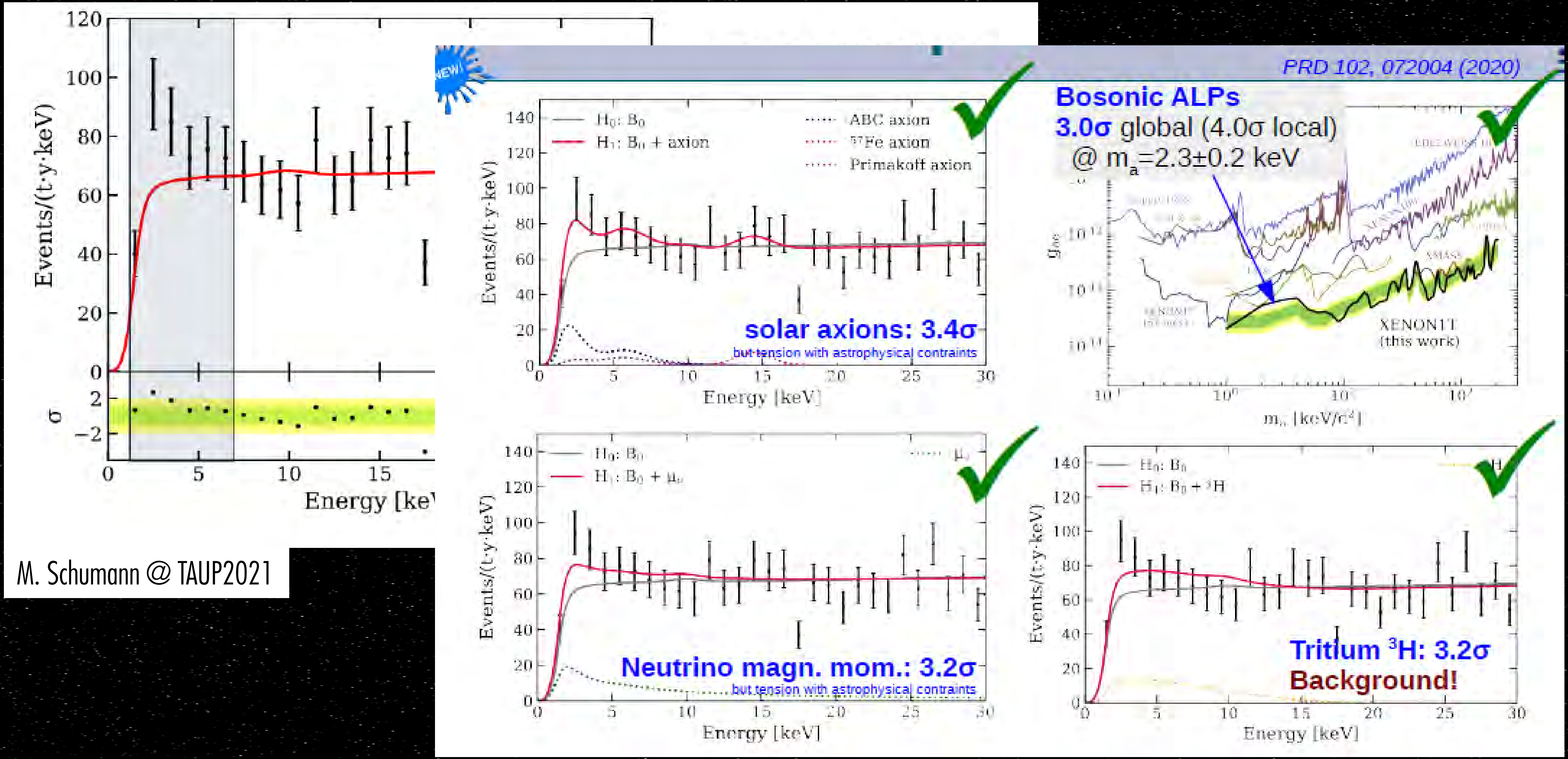
Some anomalies in the DM searches landscape…

Several excesses of events along the years, but most of them disappeared with more statistics or reanalysis or found a background origin

Only one of these "strange" results compatible with DM is still "live", accumulating more than 20 years of data

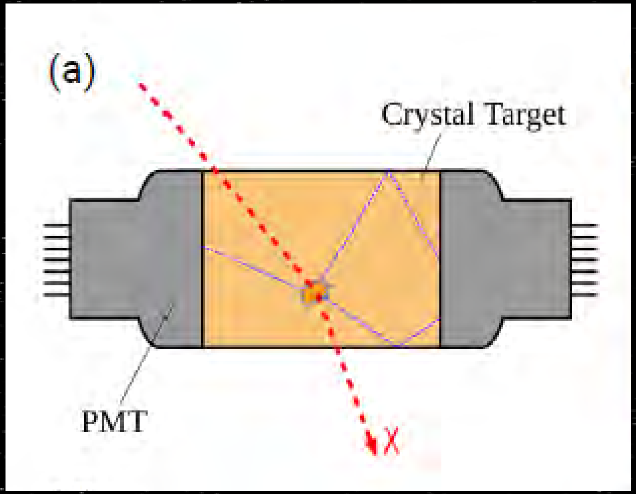
The most recent one…

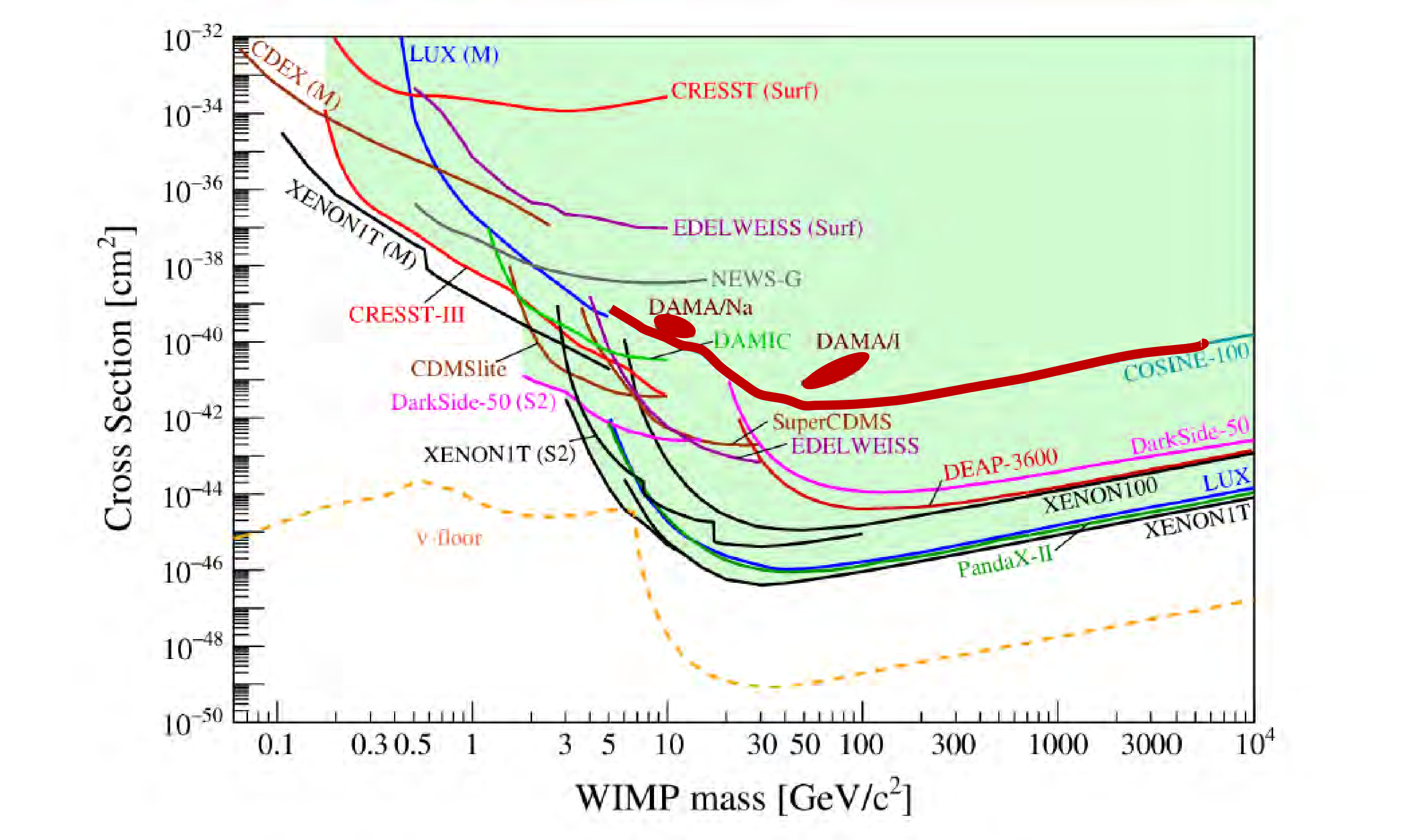
The XENON-1T "excess"



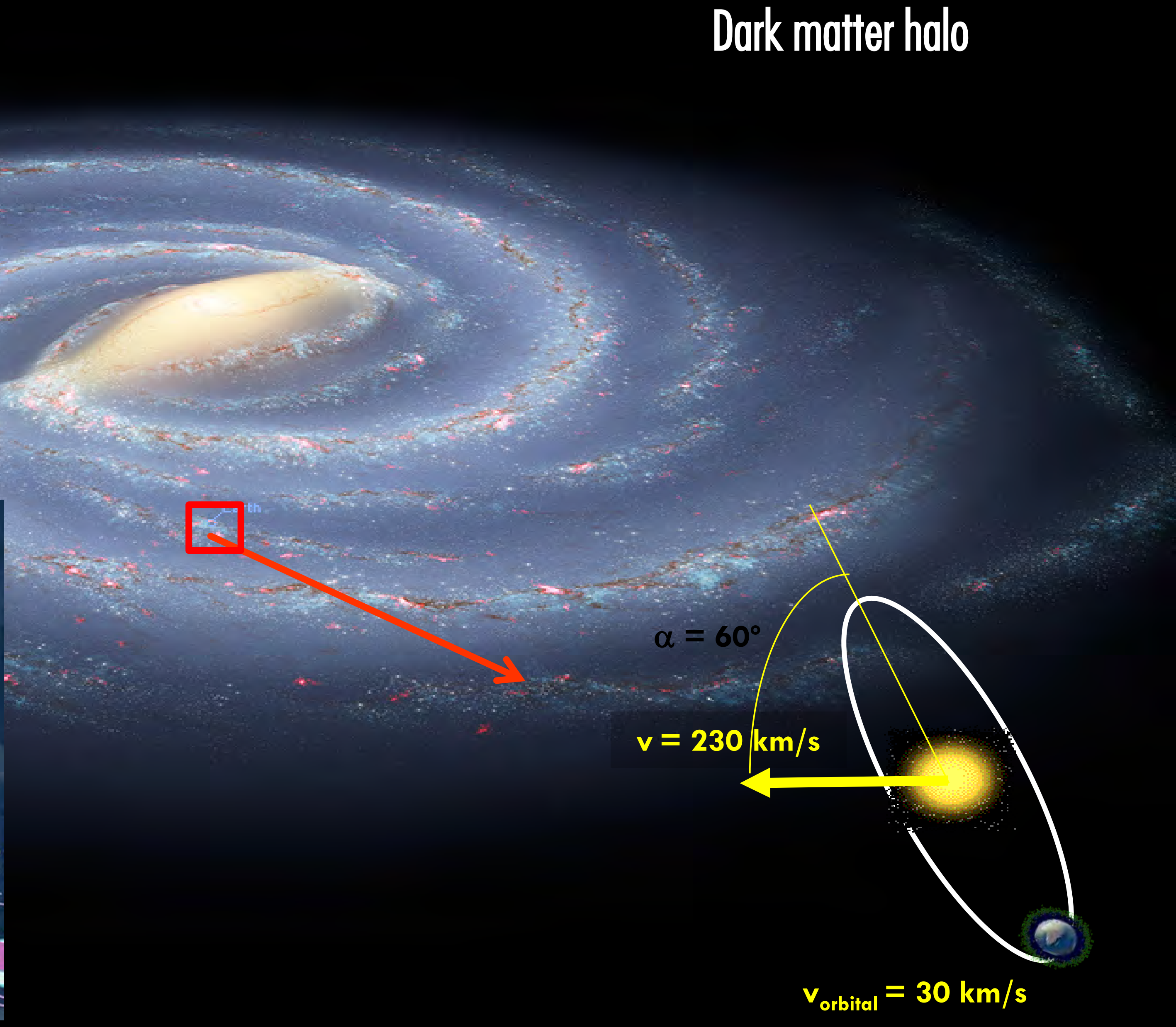
M. Schumann @ TAUP2021

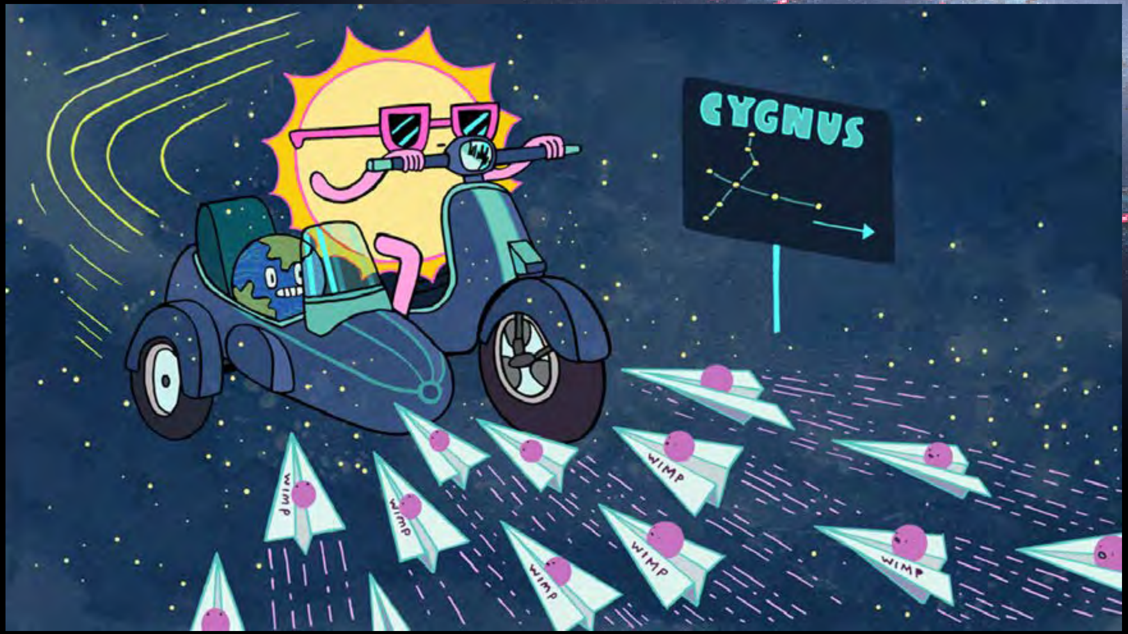
NaI SCINTILLATORS





ANNUAL MODULATION IN THE DARK MATTER SIGNAL





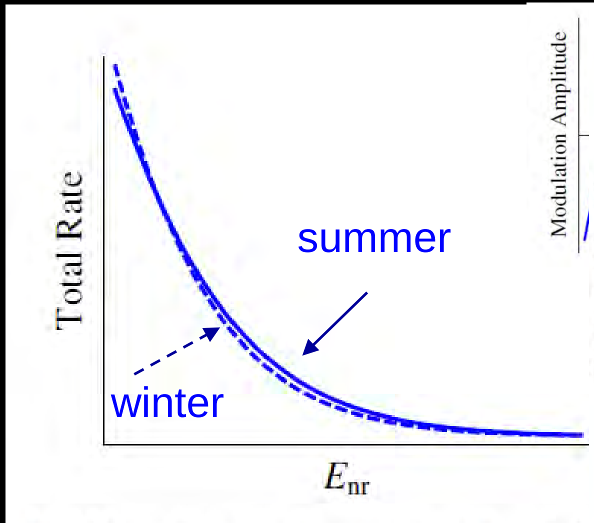
Artwork by Sandbox Studio, Chicago with Corinne Mucha

ANNUAL MODULATION IN THE DARK MATTER SIGNAL

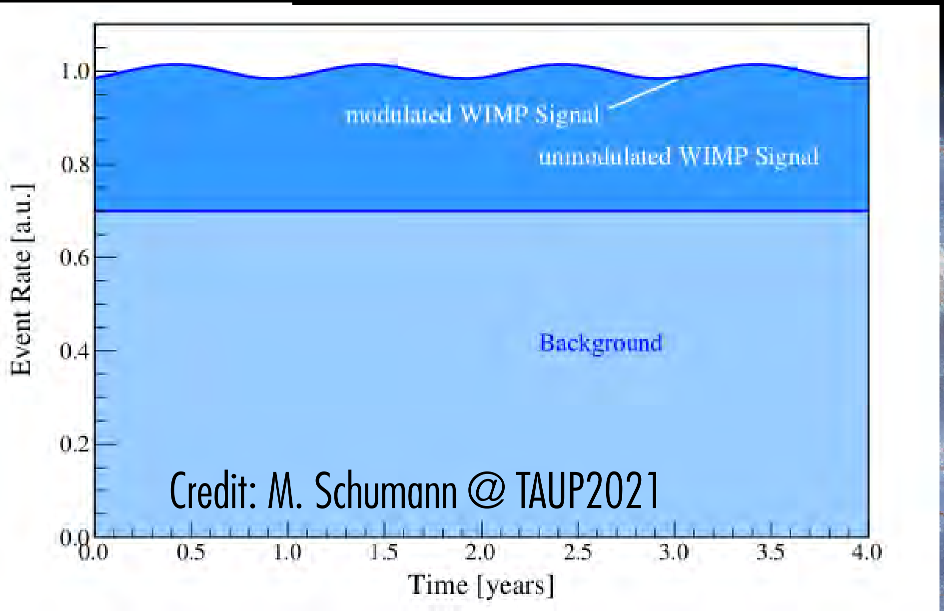
Small effect

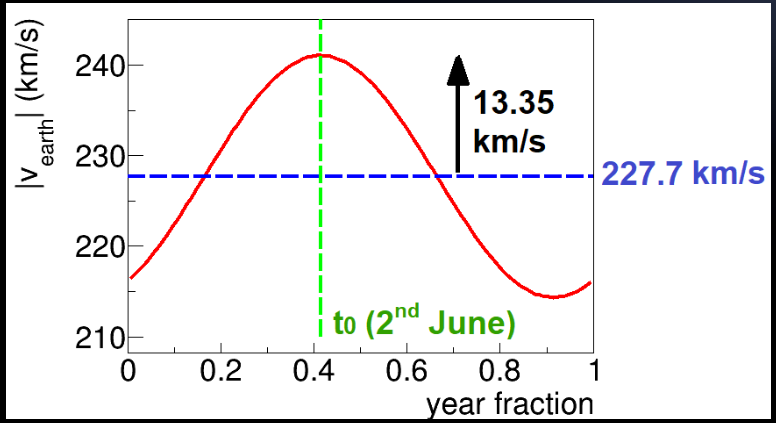
Inverse modulation at very low energies

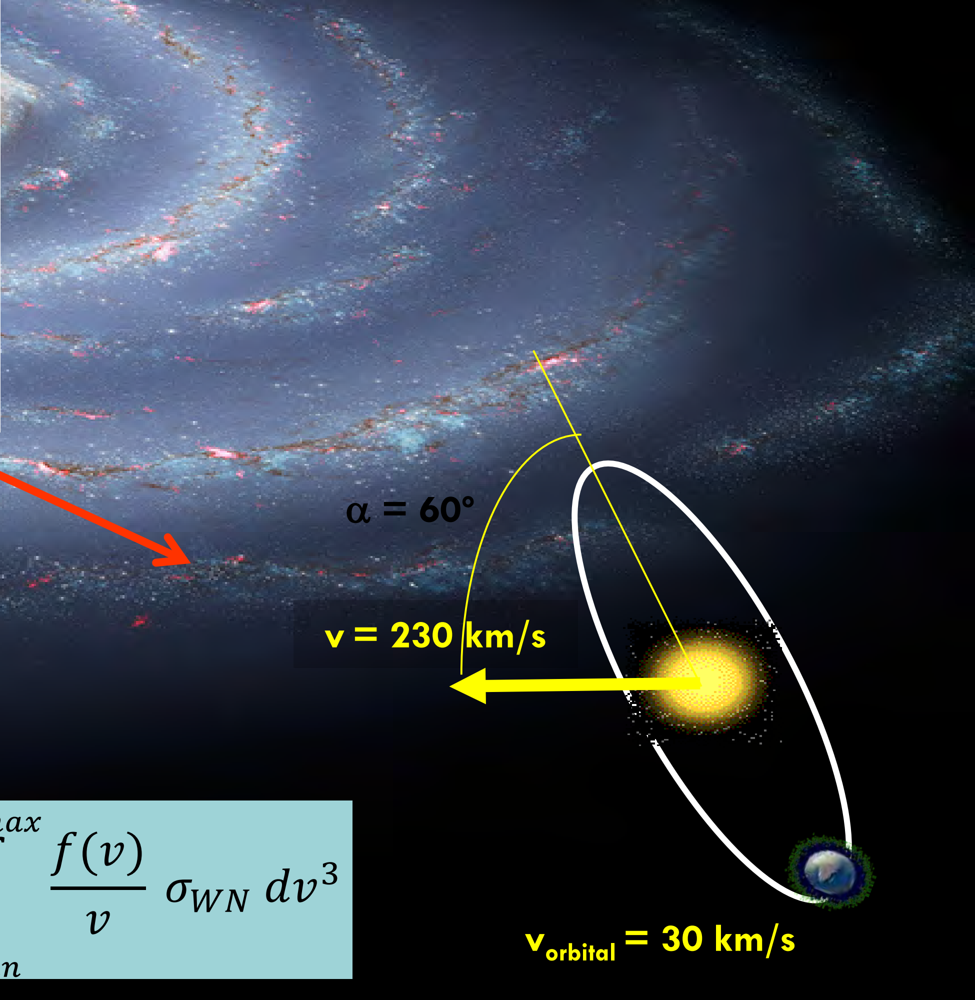
It depends strongly on the halo model



$$S_k(t) = S_{0,k} + S_{m,k} cos\omega(t - t_0)$$

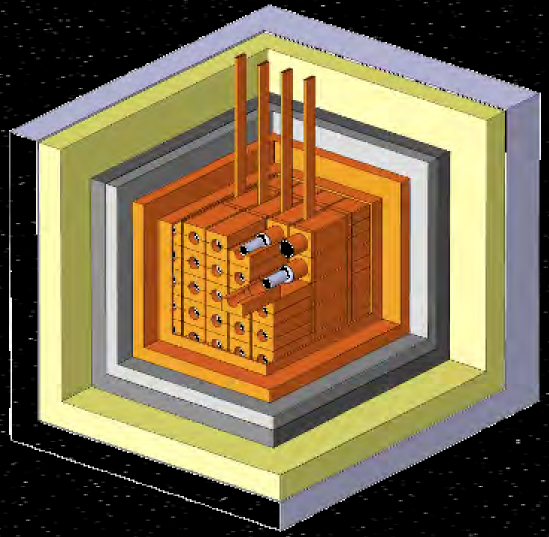






$$S(E_{NR},t) = \frac{dR}{dE_{NR}} = \frac{\rho\, M_{det}}{2m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v}\, \sigma_{WN}\, dv^3$$

DAMA/LIBRA EXPERIMENT



@ LNGS, Laboratori Nazionali del Gran Sasso, Italy

DAMA / NaI (1995-2002)

- 9 × 9.7 kg NaI(Tl) (3x3 matrix)
- 7 annual cycles
- Exposure : 0.29 ton × y

DAMA / LIBRA (2003-2010)

- 25 × 9.7 kg NaI(Tl) (5x5 matrix)
- 7 annual cycles
- Exposure : 1.04 ton × y

DAMA / LIBRA – phase2 (2011-2018)

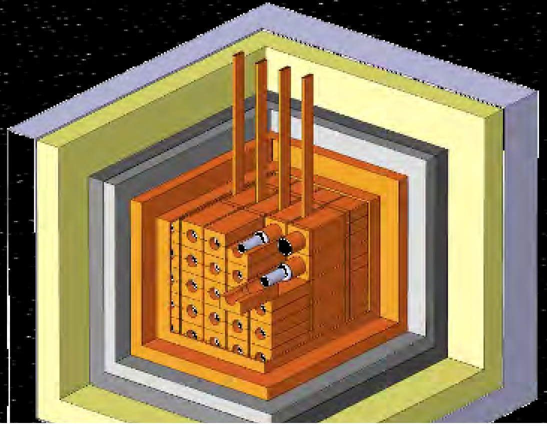
- 25 × 9.7 kg NaI(Tl) (5x5 matrix)
- 7 annual cycles
- Exposure : 1.13 ton × y

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

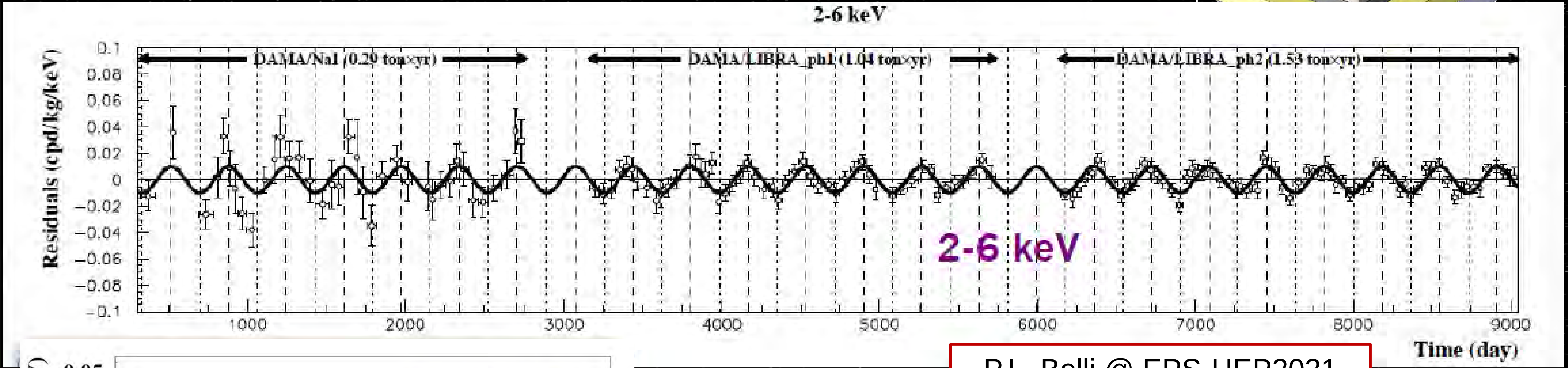
Universe 4, 116 (2018), 1805.10486

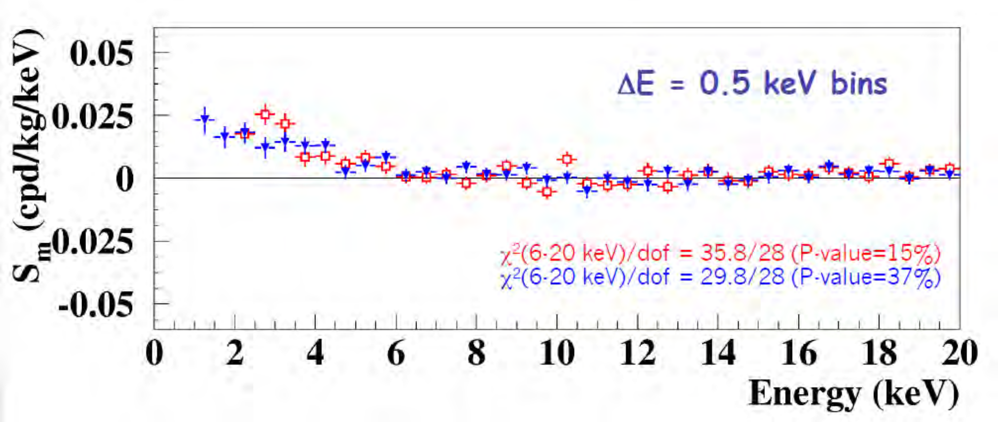
DAMA/LIBRA EXPERIMENT

@ LNGS, Laboratori Nazionali del Gran Sasso, Italy



New data release in July 2021 @ EPS-HEP



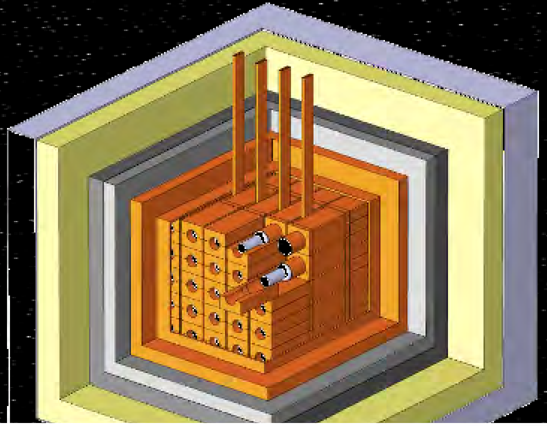


P.L. Belli @ EPS-HEP2021

The data of DAMA/LIBRA favor the presence of a modulation with proper features at 13.4 σ CL (2.86 ton × yr) in the 2-6 keV energy region

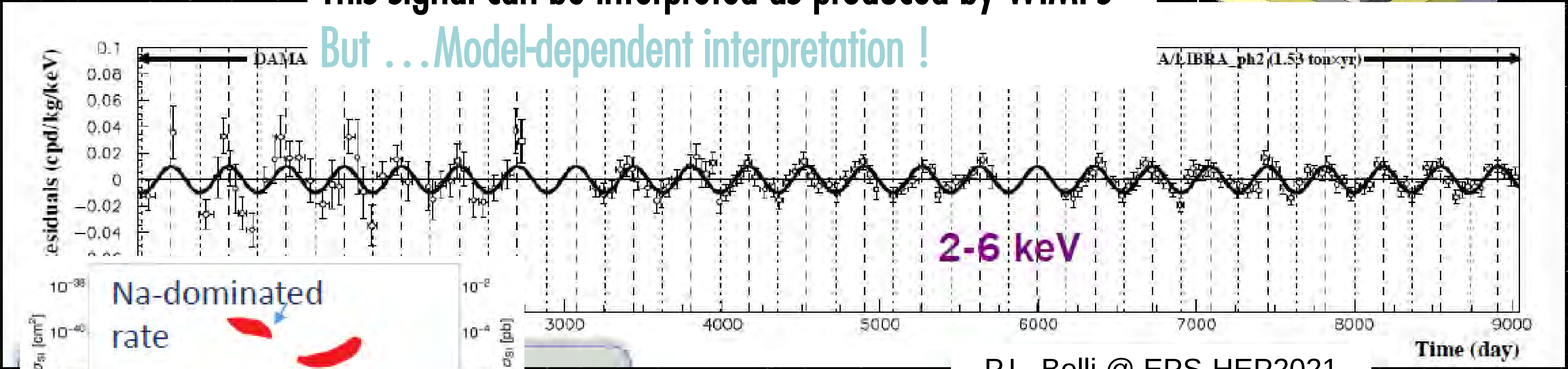
DAMA/LIBRA EXPERIMENT

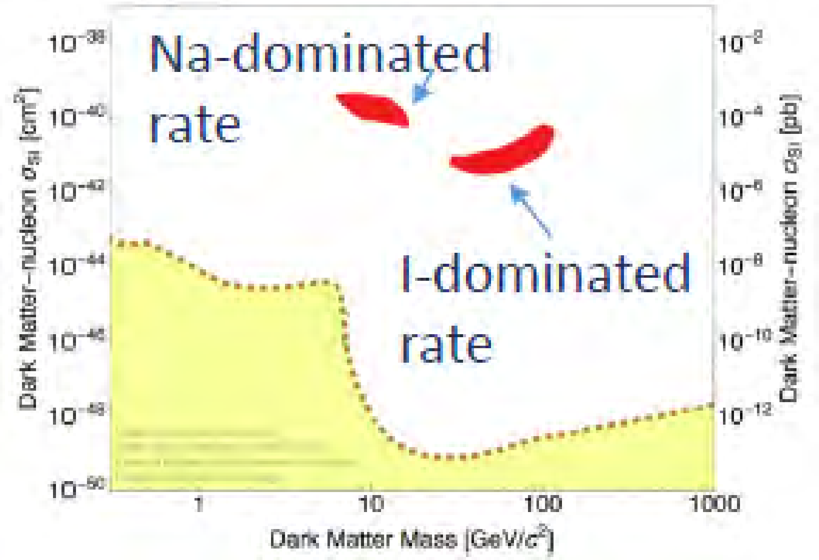
@ LNGS, Laboratori Nazionali del Gran Sasso, Italy



This signal can be interpreted as produced by WIMPs

But …Model-dependent interpretation !



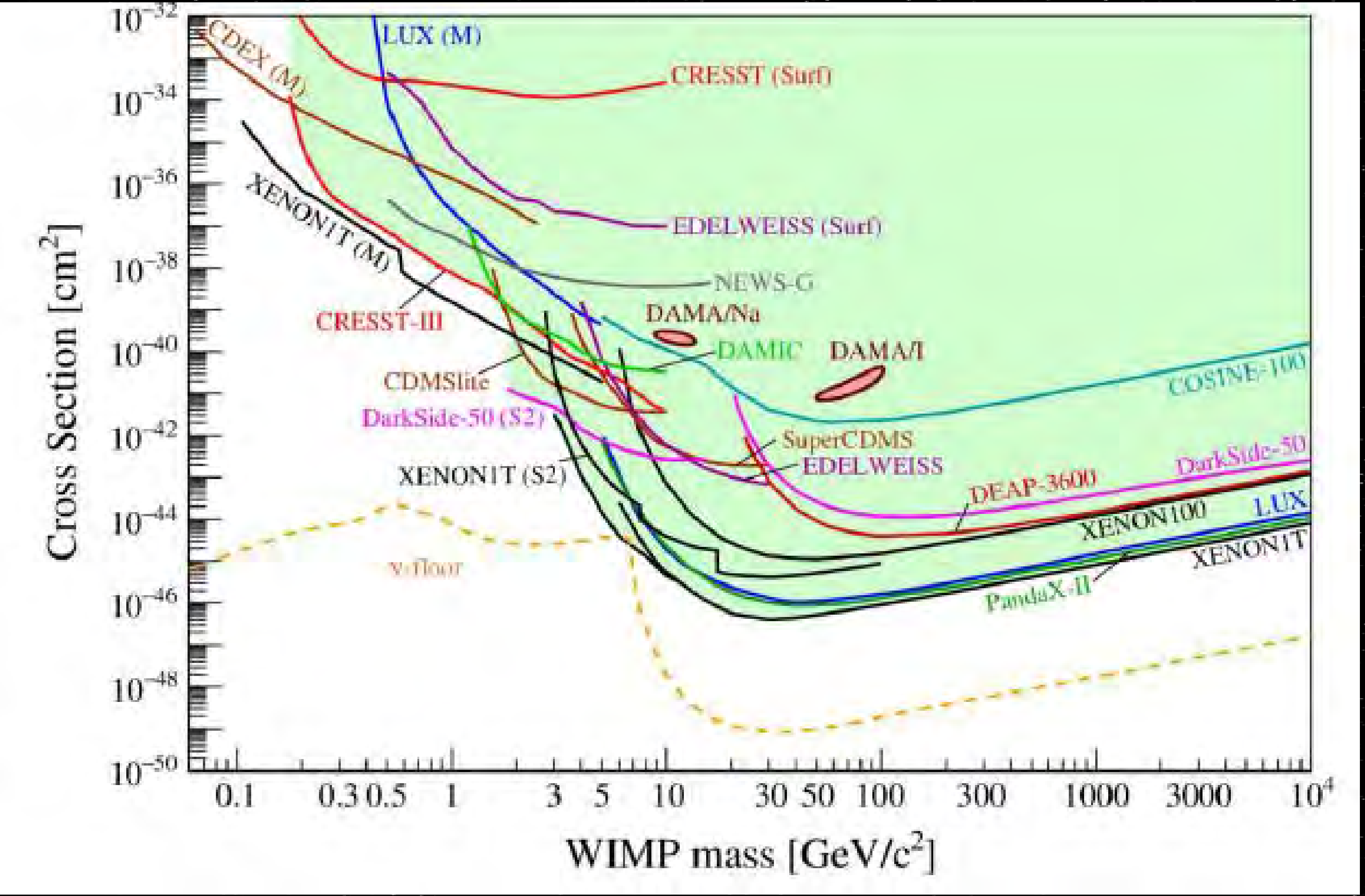


P.L. Belli @ EPS-HEP2021

Only for the [2-6] keV data
SI - isospin conserving interacting WIMPs and standard halo
do not provide a solution compatible with [1-6] keV data

ANNUAL MODULATION RESULT PUZZLE

Other much sensitive experiments do not have any hint -> Strong tension even assuming more general halo/interaction models, BUT MODEL – DEPENDENT



Same target would reduce most of the uncertainties and model dependencies !

Direct Detection of Dark Matter – APPEC Committee Report arXiv:2104.07634

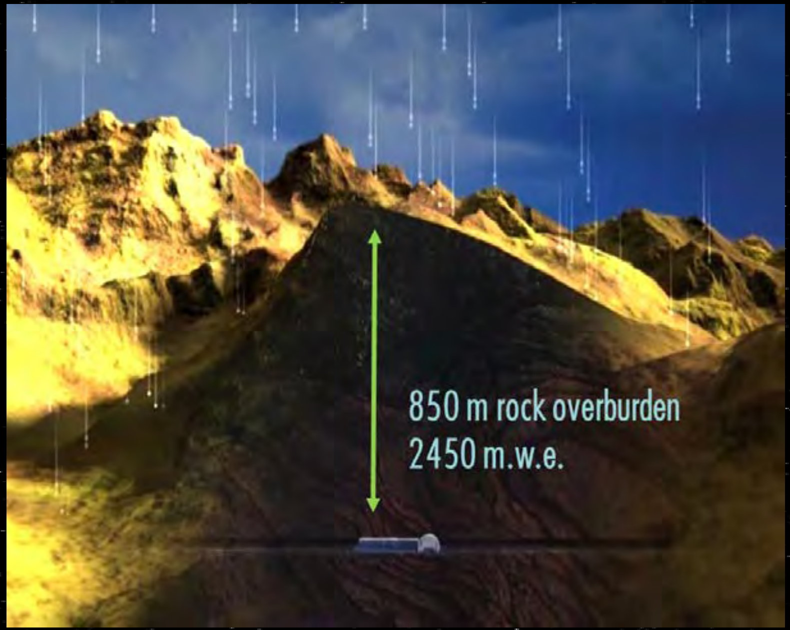
IN DATA-TAKING
112,5 kg
Since Aug 17

IN DATA-TAKING
61,3 kg (effective mass)
Since Sept 16

IN DATA-TAKING
~250 kg
Since Sept 2003 phase -1 / since Dec 2010 phase-2

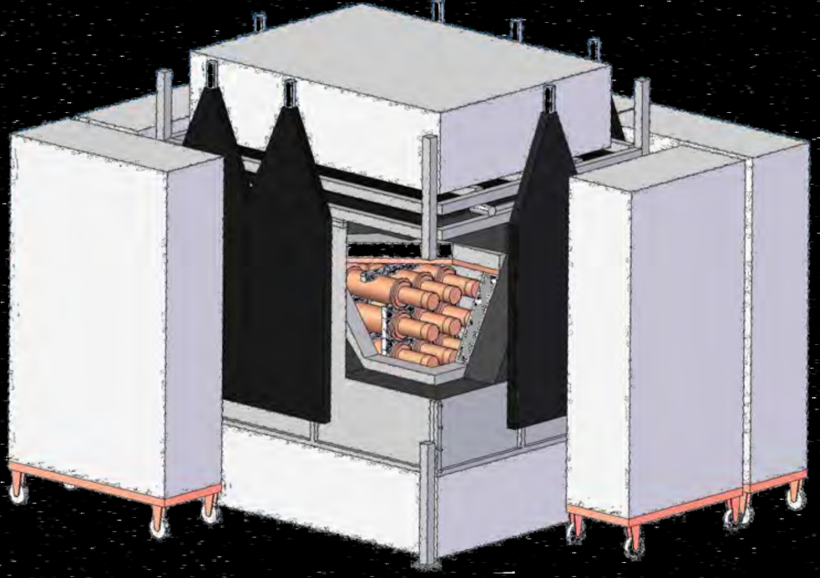
Experiment	Laboratory	Technology	Target	Size	Status
DAMA/LIBRA	LNGS	Scintillator	NaI(Tl)	~250 kg	Running
ANAIS-112	LSC	Scintillator	NaI(Tl)	112.5 kg	Running
COSINE-100	Yangyang	Scintillator	NaI(Tl)	106 kg	Running
SABRE	LNGS,Stawell	Scintillator	NaI(Tl)	~50 kg	In preparation
PICOLON	Kamioka	Scintillator	NaI(Tl)	23.4 kg	In preparation
COSINUS	LNGS	Bolometer	NaI, NaI(Tl)	~1 kg	In preparation

Direct Detection of Dark Matter – APPEC Committee Report
arXiv:2104.07634



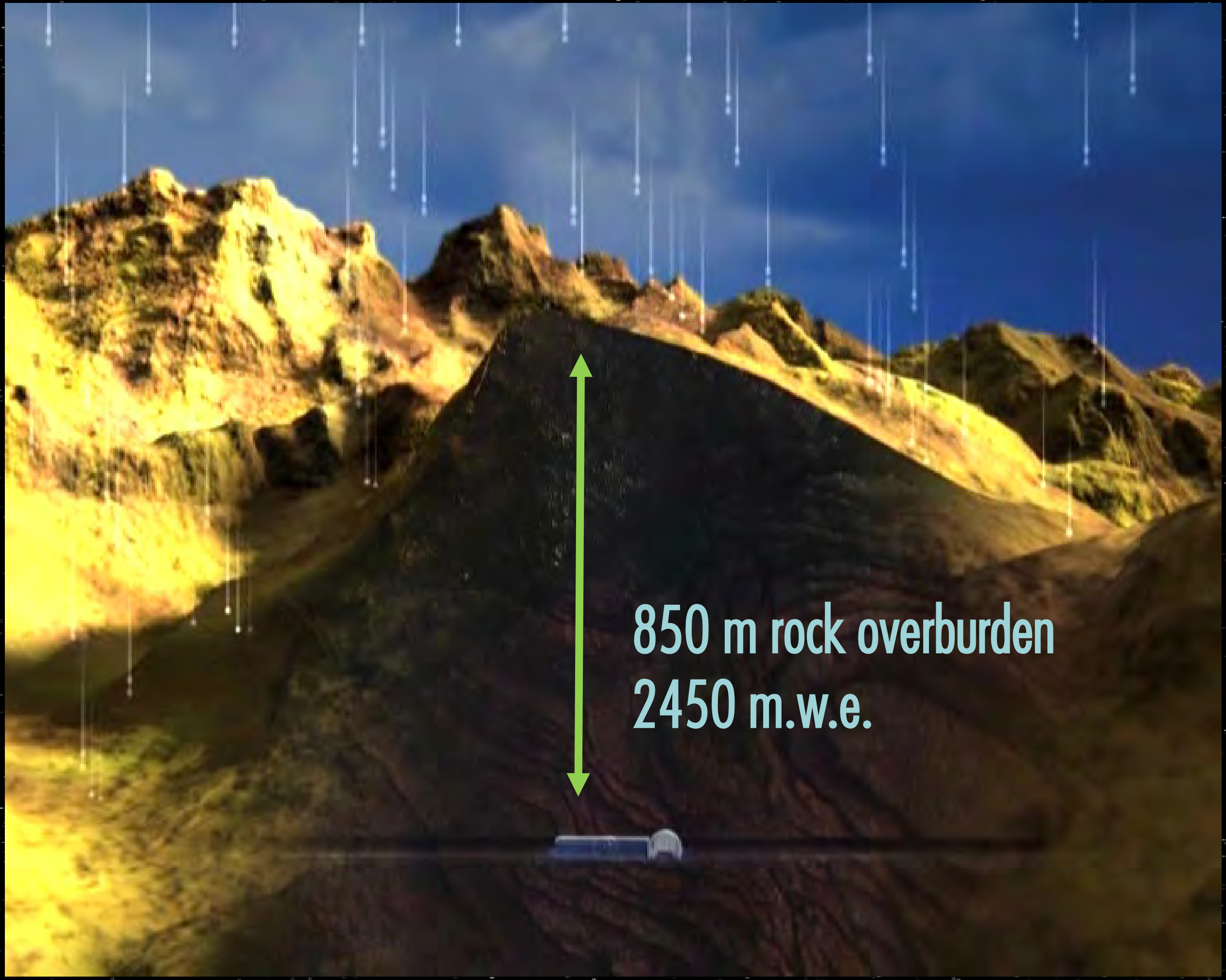
Annual modulation with NaI Scintillators

- Confirmation of DAMA-LIBRA modulation signal -> **same target and technique** / **different** experimental approach / **different** environmental conditions affecting **systematics**
- At Canfranc Underground Laboratory, @ SPAIN (under 2450 m.w.e.) taking data since August 2017
- 3x3 matrix of 12.5 kg NaI(Tl) cylindrical modules = 112.5 kg of active mass grown @ Alpha Spectra, Inc.
- HQE PMTs coupled at LSC clean room
- DATA ANALYSIS: ROI BLINDED

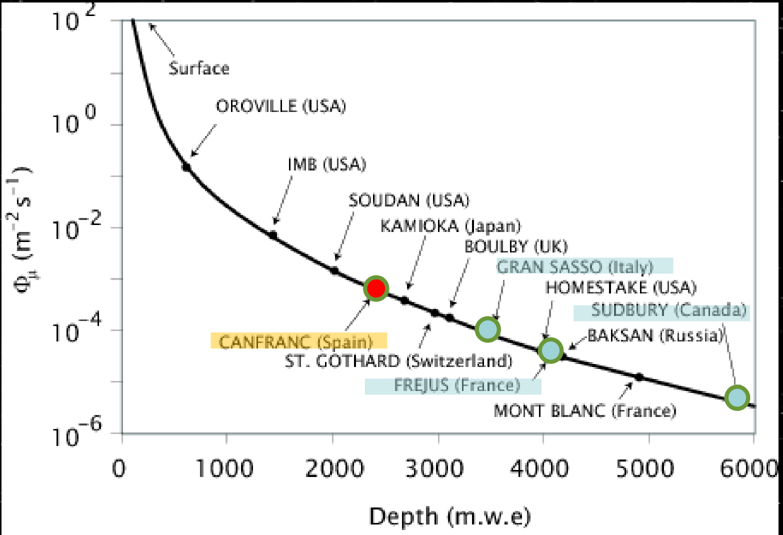


Canfranc Underground Laboratory (SPAIN)

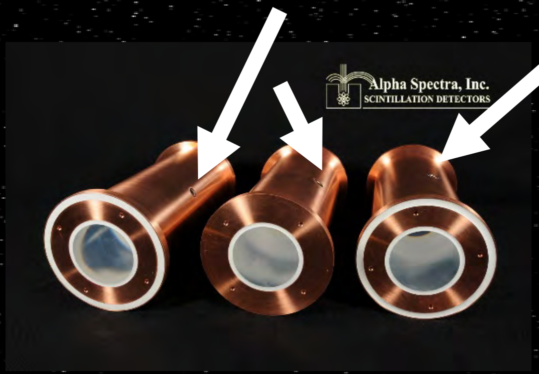
under the Pyrenees, at the Somport tunnel connecting France and Spain



Reduces muon flux in a factor 10^5 with respect to surface



Relevant experimental features



- **Mylar windows built-in, allowing for low energy calibration**
- **^{109}Cd sources on flexibles wires** in Radon-free calibration system for simultaneous calibration of the nine modules

- **Excellent light collection in all the nine modules ~ 15 p.e./keV (12.7-15.8 p.e./keV) → 7/9 modules between 14.0 and 15.0 p.e./keV**
  Larger and more homogeneous than that of DAMA/LIBRA modules
  Under continuous monitoring along data taking

Relevant experimental features

ANAIS-112 set-up

- 10 cm archaeological lead
- 20 cm low activity lead
- Tight box preventing Radon entrance
- 16 plastic scintillators acting as muon veto system
- 40 cm polyethylene / water

Setting-up ANAIS-112 at LSC
Commissioning March-June 2017

Data Taking started 3 August 2017

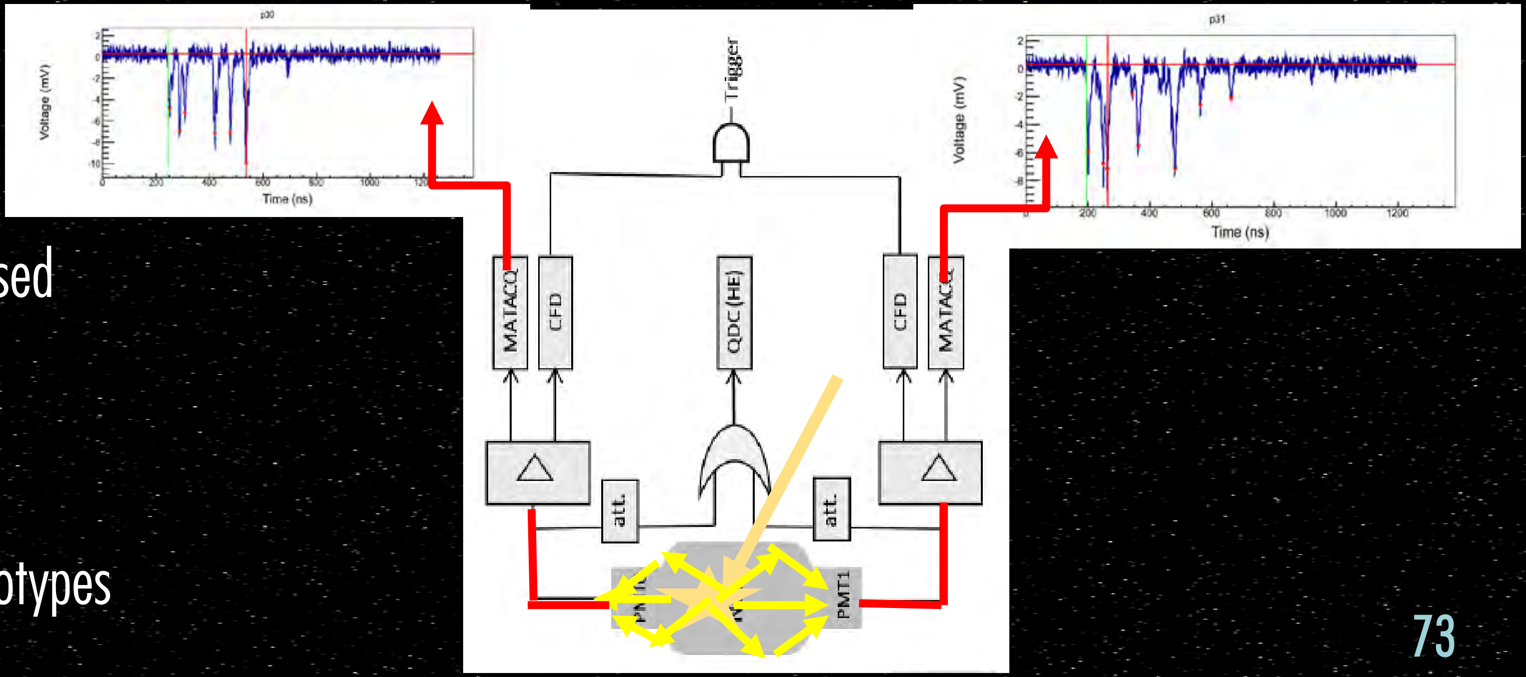
Relevant experimental features

ANAIS-112 set-up

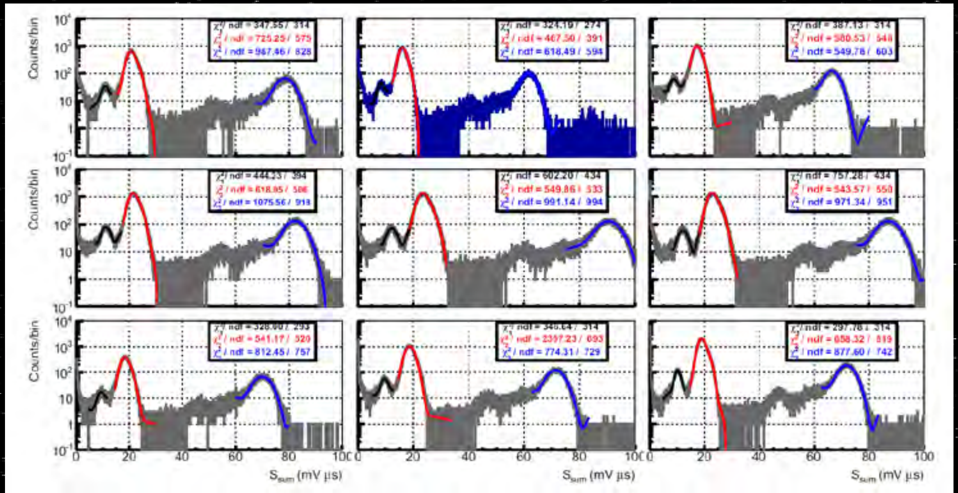
- 10 cm archaeological lead
- 20 cm low activity lead
- Tight box preventing Radon entrance
- 16 plastic scintillators acting as muon veto system
- 40 cm polyethylene / water

ANAIS-112 DAQ

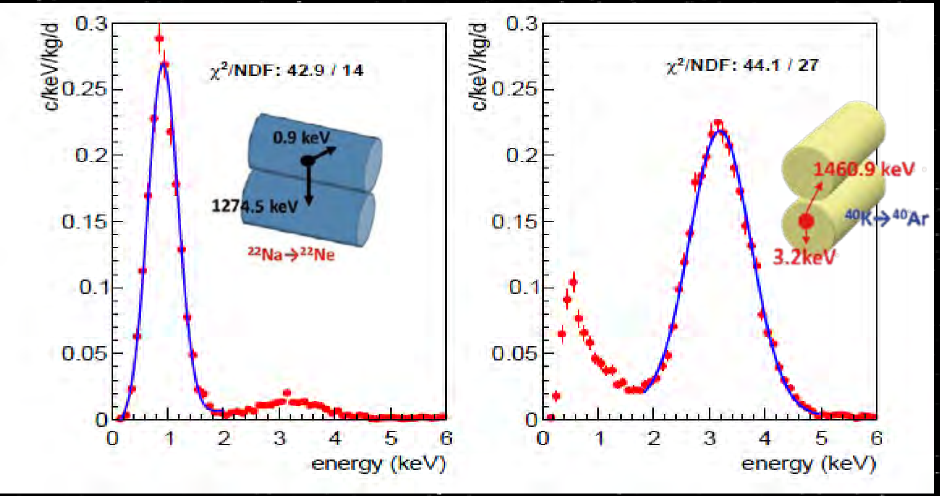
- Individual PMT signals digitized and fully processed (14 bits / 2 GS/s)
- Trigger at p.e. level for each PMT + Logical AND coincidence in 200ns window
- Robust / Low noise / tested with previous prototypes

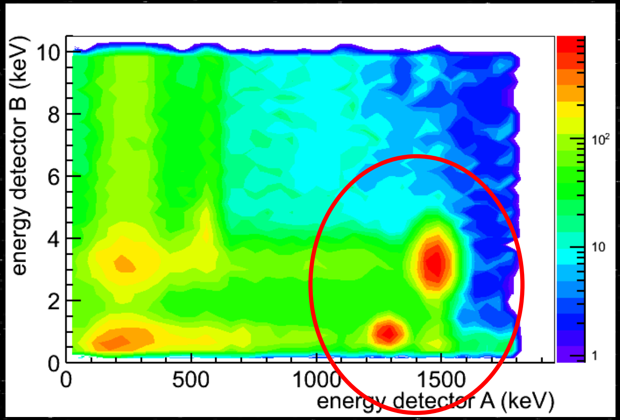


Calibrating the ROI with high accuracy



- Combination of periodical external calibration using ^{109}Cd (88.0, 22.6 and 11.9 keV) every two weeks and ^{40}K and ^{22}Na internal contamination background lines (3.2 and 0.9 keV) every 1.5 months
- ROI calibrated with 22.6, 11.9, 3.2 and 0.9 keV





Events @ROI from ^{40}K and ^{22}Na selected by the coincidence with a HE gamma in a second module

Demonstration of triggering below 1 keV

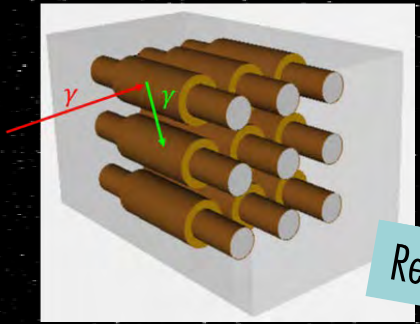
BLIND ANALYSIS STRATEGY

- M1 (single hit) events in the ROI (1-6 keV) BLINDED from beginning
- M2 in the ROI and Cd - calibration events used for fine-tuning analysis and determination of efficiencies along the first year
- Unblinding 10% (30 days randomly chosen) of the first year for background assessment

ANAIS general performance:
J. Amaré et al., EPJC79 (2019) 228

EVENTS SELECTION CRITERIA from the first year analysis are kept for subsequent analysis UPDATING EFFICIENCIES

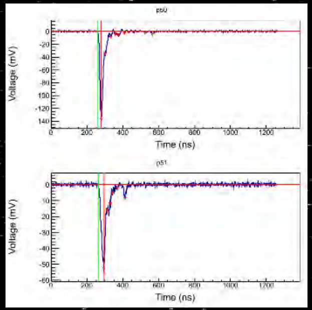
Events selection procedure developed before unblinding

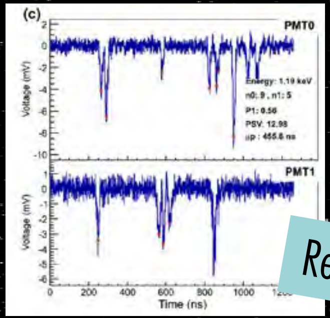


Rejected event

- Single hit events
- Events arriving more than 1 second after a muon interacting in the veto system

Our trigger rate is dominated by non-compatible with bulk scintillation events

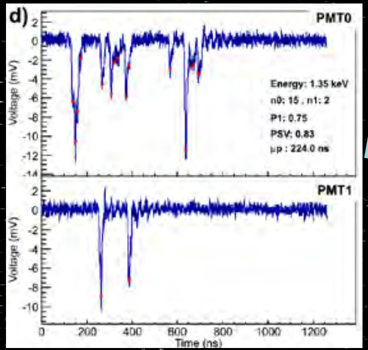




Rejected events

- Time behavior compatible with NaI scintillation constant: biparametric cut

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



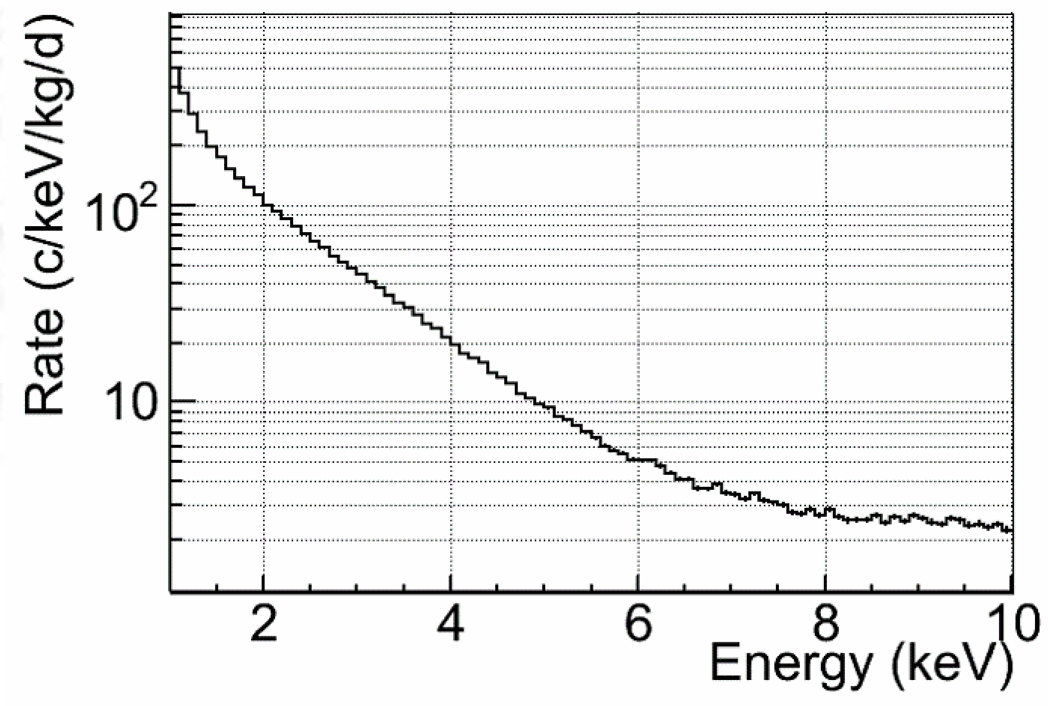
Rejected event

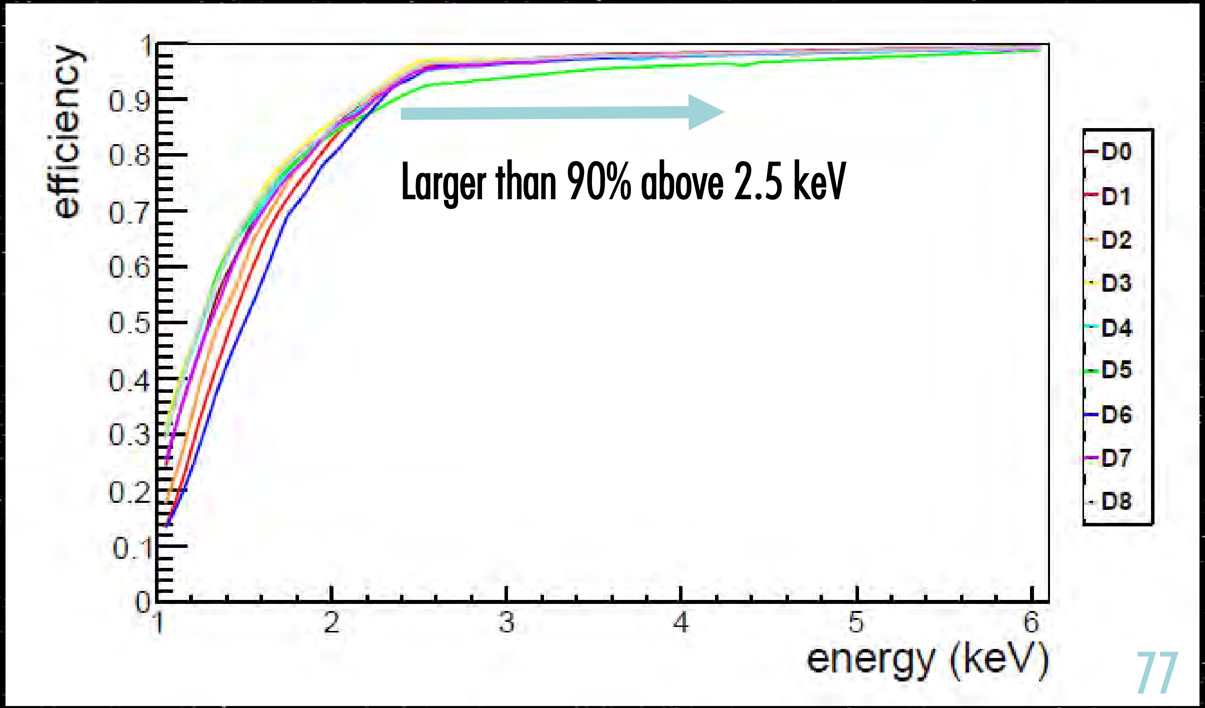
- Light sharing between the 2 PMTs compatible with bulk scintillation, number of p.e. >4 at each PMT

Events selection procedure developed before unblinding

ANAIS general performance:
J. Amaré et al., EPJC79 (2019) 228

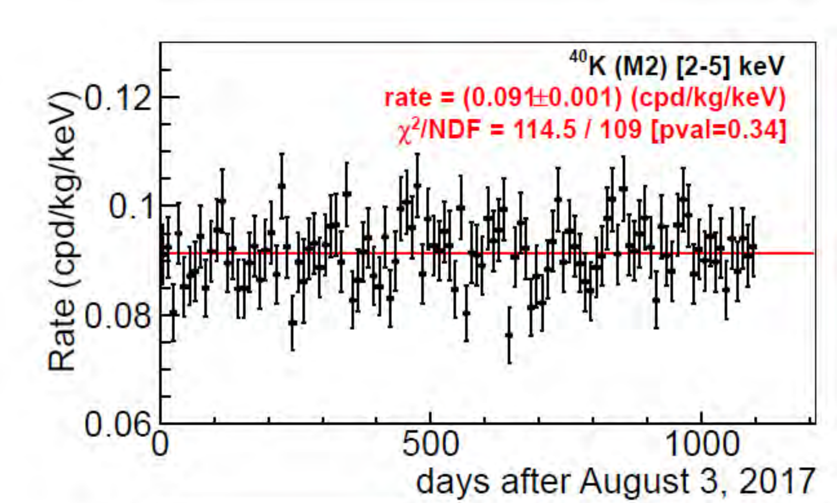
- Robust estimate of the efficiencies using ^{109}Cd / ^{22}Na and ^{40}K events BEFORE UNBLINDING / updated for the three years analysis
- Choice of analysis threshold → 1 keV

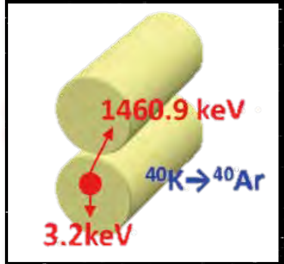




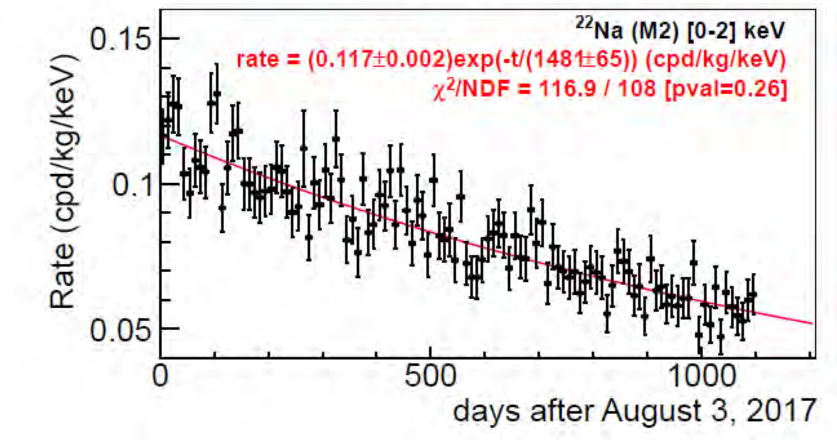
Events selection procedure developed before unblinding

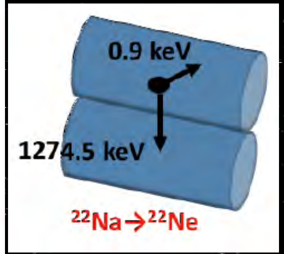
Efficiency and calibration stability checks using ^{40}K and ^{22}Na populations (M2 with a HE gamma of the right enegy in a second module)





- Constant for ^{40}K (vs $\tau = 1.8\ 10^9$ y)

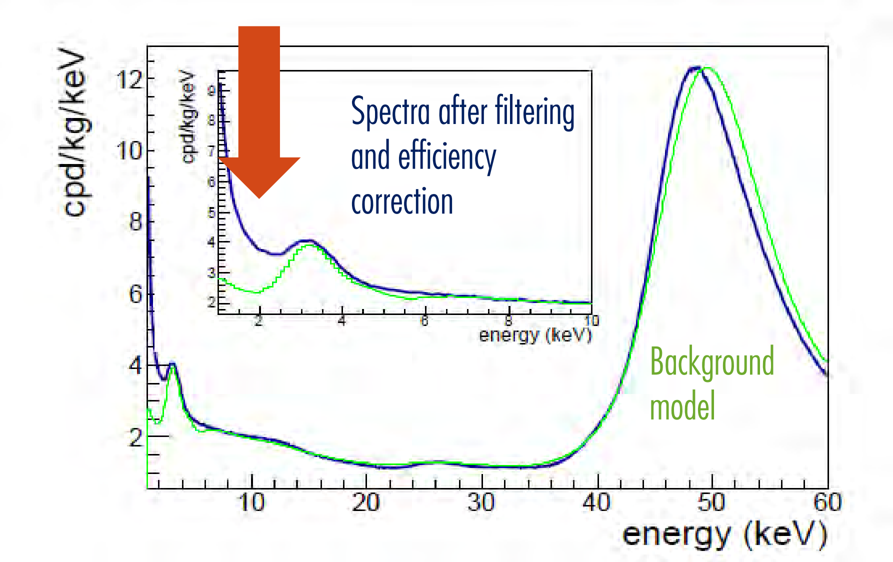




- Exponential decay for ^{22}Na -> $\tau_{exp} = 1481 \pm 65$ d (vs $\tau = 1370$ d)

Robust background model

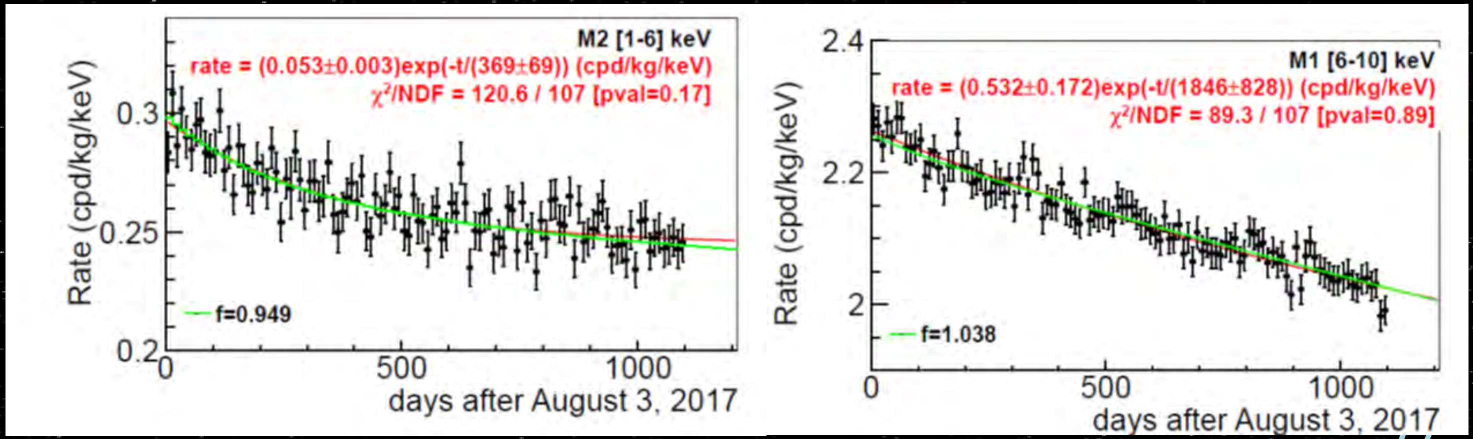
J. Amaré et al., EPJC79 (2019) 412



Comparison after unblinding three years data
Background model was established before unblinding

- ROI background dominated by ^{210}Pb, ^{40}K and cosmogenic isotopes, as ^{3}H -> higher than DAMA/LIBRA
- Good agreement in all energy regions, but underestimate in 1-2 keV energy region / Work in progress

- Our model predicts time evolution of the background detector by detector and reproduce satisfactorily the time evolution outside the ROI



ANAIS-112 three year results – annual modulation analysis

PHYSICAL REVIEW D **103**, 102005 (2021)

Editors' Suggestion | Featured in Physics

Annual modulation results from three-year exposure of ANAIS-112

J. Amaré,[1,2] S. Cebrián,[1,2] D. Cintas,[1,2] I. Coarasa,[1,2] E. García,[1,2] M. Martínez,[1,2,3,*] M. A. Oliván,[1,2,4] Y. Ortigoza,[1,2] A. Ortiz de Solórzano,[1,2] J. Puimedón,[1,2] A. Salinas,[1,2] M. L. Sarsa,[1,2] and P. Villar[1]

[1]*Centro de Astropartículas y Física de Altas Energías (CAPA), Universidad de Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Spain*
[2]*Laboratorio Subterráneo de Canfranc, Paseo de los Ayerbe s.n., 22880 Canfranc Estación, Huesca, Spain*
[3]*Fundación ARAID, Avenida de Ranillas 1D, 50018 Zaragoza, Spain*
[4]*Fundación CIRCE, Avenida de Ranillas 3D, 50018 Zaragoza, Spain*

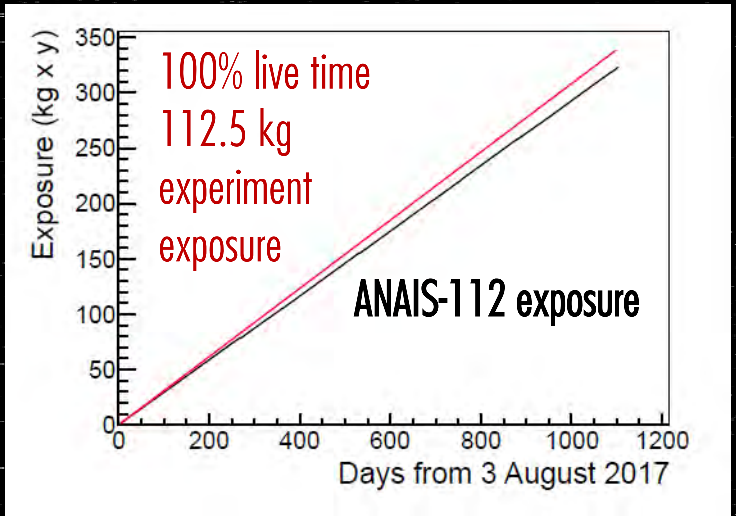
(Received 2 March 2021; accepted 15 April 2021; published 27 May 2021)

https://link.aps.org/doi/10.1103/PhysRevD.103.102005

https://arxiv.org/abs/2103.01175

First results analysis was published in 2019: Phys. Rev. Lett. 123 (2019) 031301

313.95 kg x y (95% live time for the first three years operation)



- Excellent duty cycle, 95% live time
- Down time (2.6%) mostly due to periodical calibration (every two weeks)
- Dead time (2.4%)
- Three year results: 1049.8 days live time raw / 1018.6 days after removing muon-tagged events

ANAIS-112 three year results – annual modulation analysis

PHYSICAL REVIEW D **103,** 102005 (2021)

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313.95 kg x y (95% live time for the first three years operation)

- Improved background modelling
- Checking of systematics and consistency of the results
  - Simulation of MC pseudo-experiments to analyze bias and checking sensitivity

Minimizing:

$$\chi^2 = \sum_i \frac{(n_i - \mu_i)^2}{\sigma_i^2}$$

$$\mu_i = [R_0\phi_{bkg}(t_i) + S_m cos(\omega(t_i - t_0))]M\Delta E\Delta t$$

n_i, σ_i are number of events (and Poisson uncertainty) in 10d bins corrected by live time and efficiency

ANAIS-112 three year results – annual modulation analysis

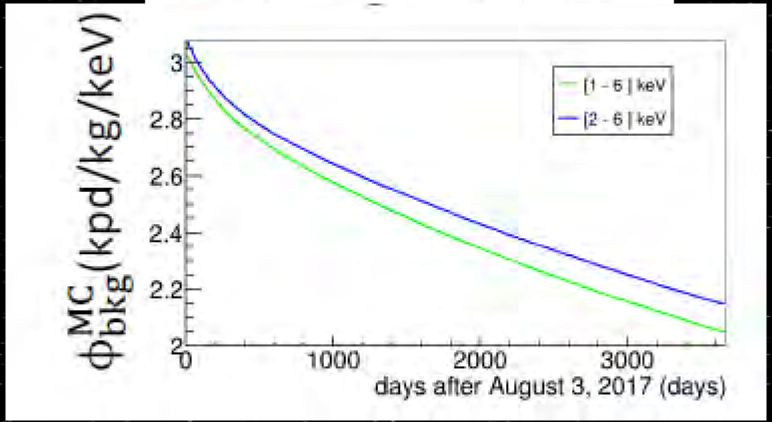
Three independent background modelling procedures

1. Exponentially decaying background -> τ ,f, R_0 free param.

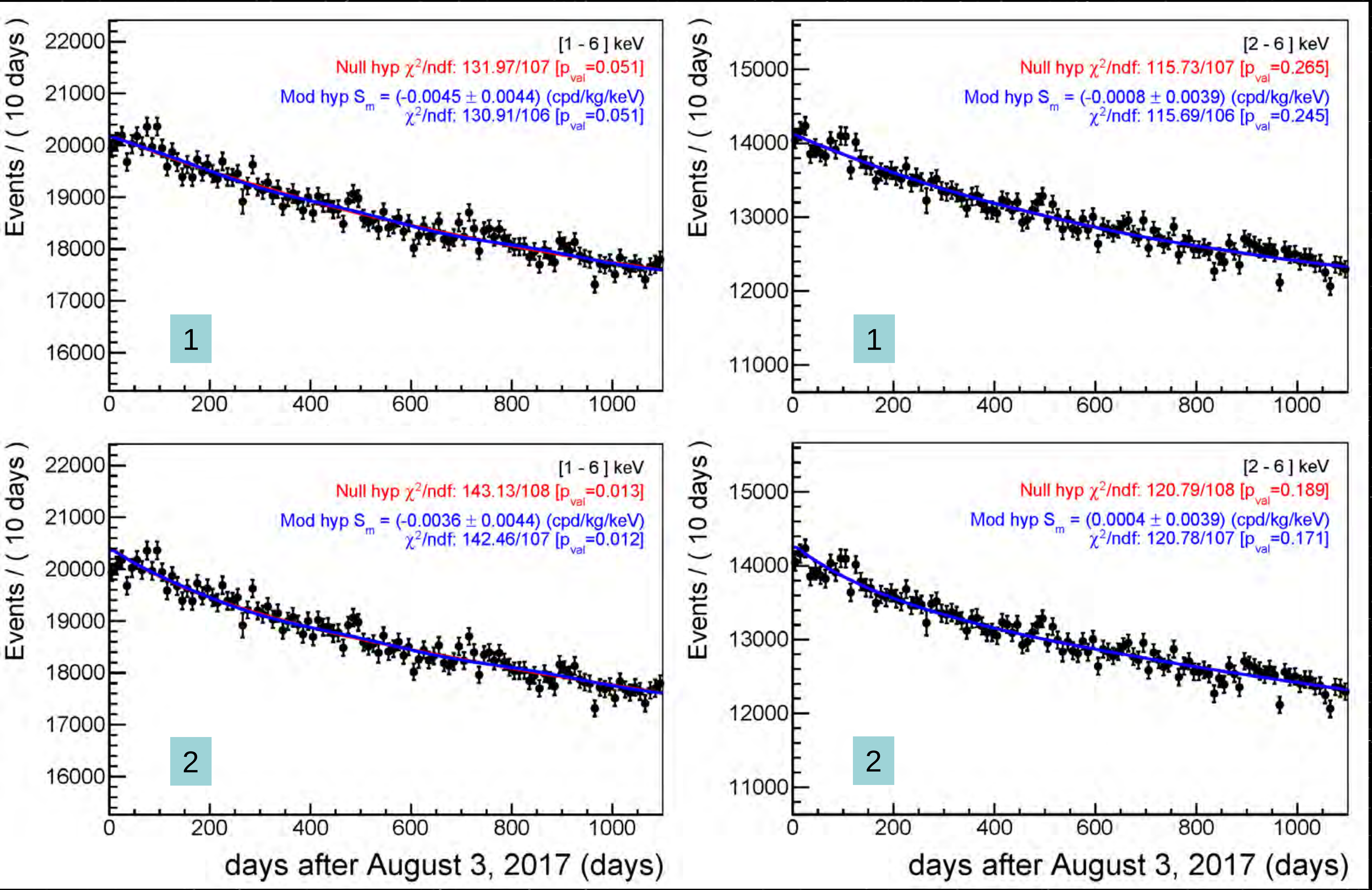
$$\phi_{bkg}(t_i) = 1 + f e^{-t_i/\tau}$$

2. Probability distribution function derived from background model corrected by a factor f, and R_0 both free

$$\phi_{bkg}(t_i) = 1 + f \phi_{bkg}^{MC}(t_i)$$

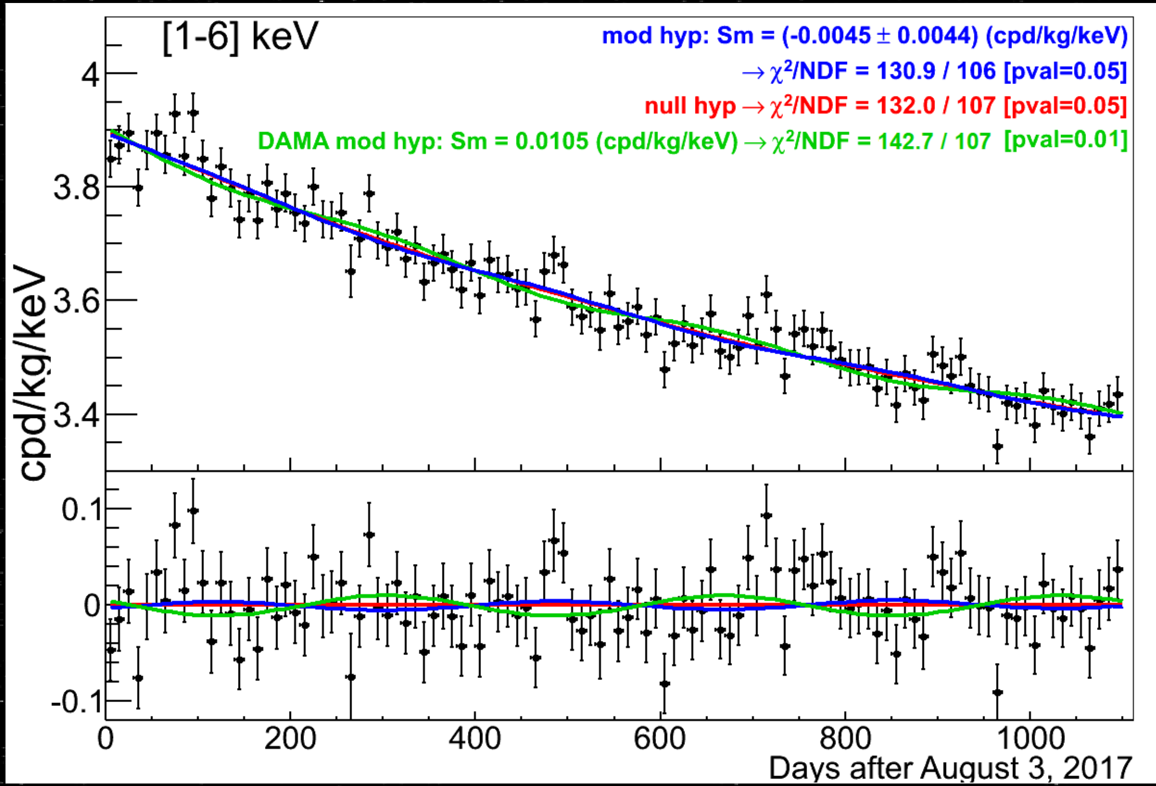


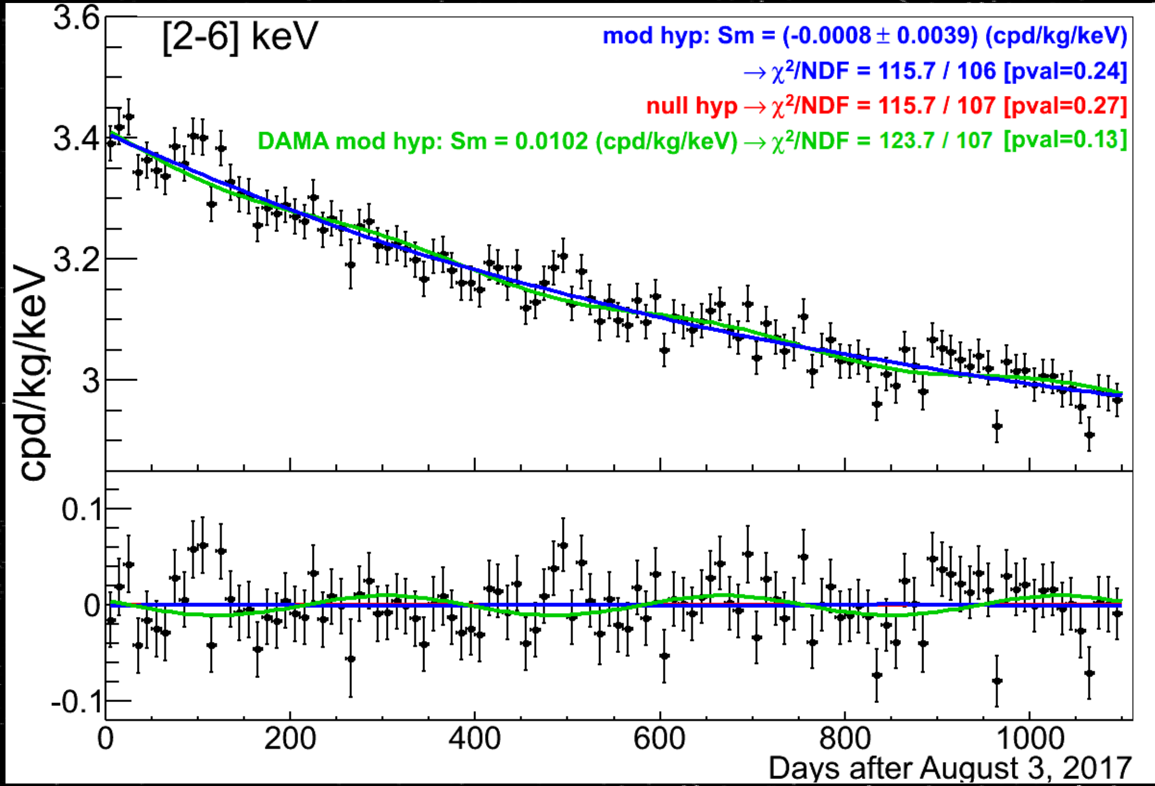
$$\mu_i = [R_0 \phi_{bkg}(t_i) + S_m cos(\omega(t_i - t_0))] M \Delta E \Delta t$$



[1 - 6] keV
Null hyp χ2/ndf: 131.97/107 [pval=0.051]
Mod hyp Sm = (-0.0045 ± 0.0044) (cpd/kg/keV)
χ2/ndf: 130.91/106 [pval=0.051]
1
[2 - 6] keV
Null hyp χ2/ndf: 115.73/107 [pval=0.265]
Mod hyp Sm = (-0.0008 ± 0.0039) (cpd/kg/keV)
χ2/ndf: 115.69/106 [pval=0.245]
1
[1 - 6] keV
Null hyp χ2/ndf: 143.13/108 [pval=0.013]
Mod hyp Sm = (-0.0036 ± 0.0044) (cpd/kg/keV)
χ2/ndf: 142.46/107 [pval=0.012]
2
[2 - 6] keV
Null hyp χ2/ndf: 120.79/108 [pval=0.189]
Mod hyp Sm = (0.0004 ± 0.0039) (cpd/kg/keV)
χ2/ndf: 120.78/107 [pval=0.171]
2
Events / (10 days)
days after August 3, 2017 (days)

ANAIS-112 vs DAMA/LIBRA





ANAIS-112 three year results – annual modulation analysis

Three independent background modelling procedures

1. Exponentially decaying background -> τ ,f, R_0 free param.

$$\phi_{bkg}(t_i) = 1 + f e^{-t_i/\tau}$$

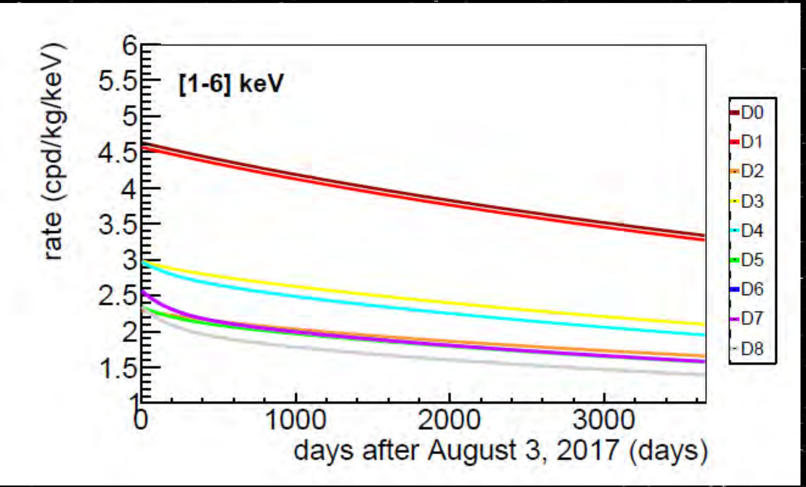
2. Probability distribution function derived from background model corrected by a factor f, and R_0 both free

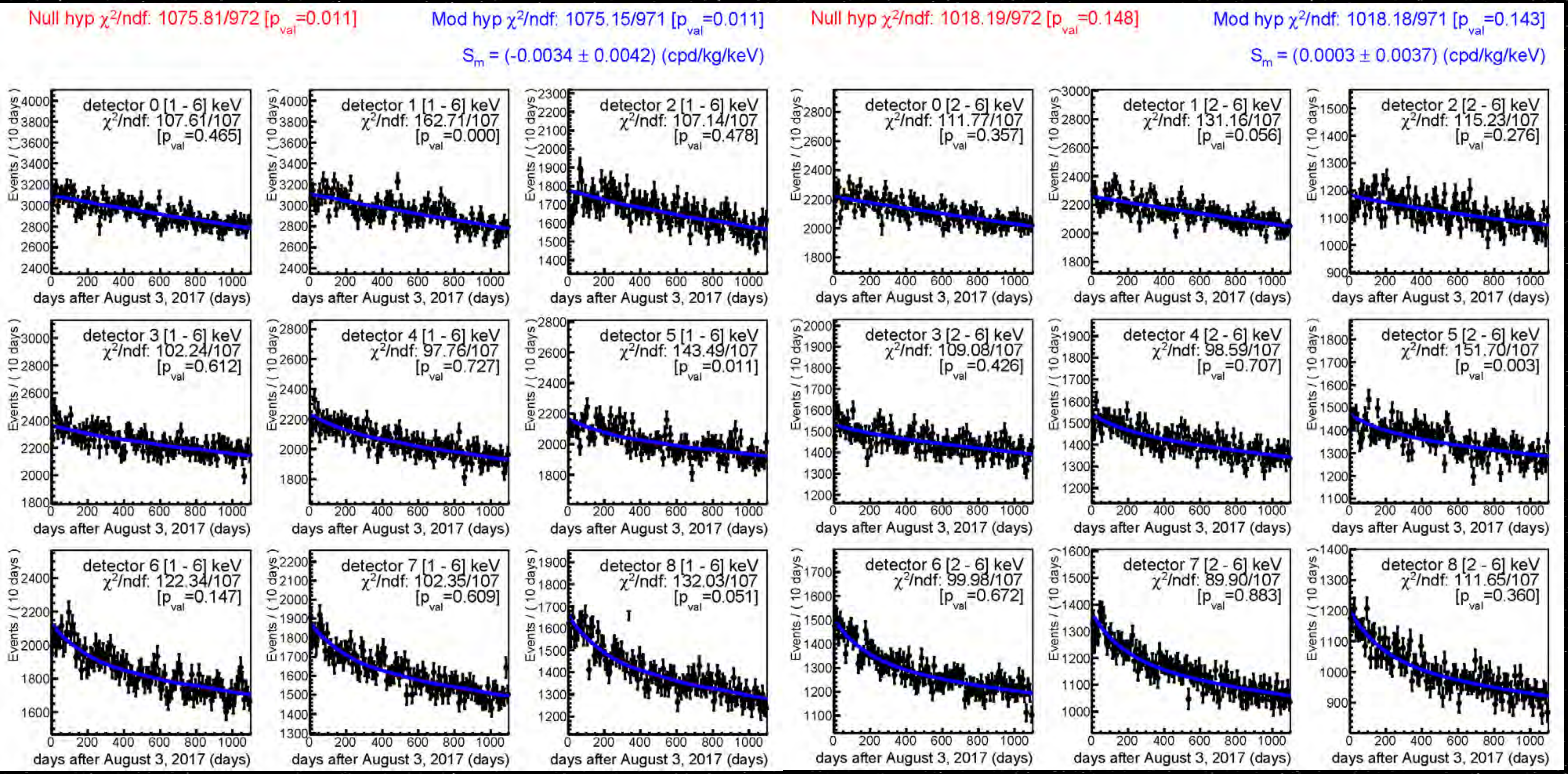
$$\phi_{bkg}(t_i) = 1 + f \phi_{bkg}^{MC}(t_i)$$

$$\mu_i = [R_0 \phi_{bkg}(t_i) + S_m cos(\omega(t_i - t_0))] M \Delta E \Delta t$$

3. Probability distribution function for every detector individually to account for possible systematic effects related with the different backgrounds and efficiencies of the different modules

$$\mu_{i,d} = [R_{0,d}(1 + f_d \phi_{bkg,d}^{MC}(t_i)) + S_m cos(\omega(t_i - t_0))] M_d \Delta E \Delta t,$$





Null hyp χ²/ndf: 1075.81/972 [p_val=0.011]
Mod hyp χ²/ndf: 1075.15/971 [p_val=0.011]
S_m = (-0.0034 ± 0.0042) (cpd/kg/keV)
detector 0 [1 - 6] keV χ²/ndf: 107.61/107 [p_val=0.465]
detector 1 [1 - 6] keV χ²/ndf: 162.71/107 [p_val=0.000]
detector 2 [1 - 6] keV χ²/ndf: 107.14/107 [p_val=0.478]
detector 3 [1 - 6] keV χ²/ndf: 102.24/107 [p_val=0.612]
detector 4 [1 - 6] keV χ²/ndf: 97.76/107 [p_val=0.727]
detector 5 [1 - 6] keV χ²/ndf: 143.49/107 [p_val=0.011]
detector 6 [1 - 6] keV χ²/ndf: 122.34/107 [p_val=0.147]
detector 7 [1 - 6] keV χ²/ndf: 102.35/107 [p_val=0.609]
detector 8 [1 - 6] keV χ²/ndf: 132.03/107 [p_val=0.051]
Null hyp χ²/ndf: 1018.19/972 [p_val=0.148]
Mod hyp χ²/ndf: 1018.18/971 [p_val=0.143]
S_m = (0.0003 ± 0.0037) (cpd/kg/keV)
detector 0 [2 - 6] keV χ²/ndf: 111.77/107 [p_val=0.357]
detector 1 [2 - 6] keV χ²/ndf: 131.16/107 [p_val=0.056]
detector 2 [2 - 6] keV χ²/ndf: 115.23/107 [p_val=0.276]
detector 3 [2 - 6] keV χ²/ndf: 109.08/107 [p_val=0.426]
detector 4 [2 - 6] keV χ²/ndf: 98.59/107 [p_val=0.707]
detector 5 [2 - 6] keV χ²/ndf: 151.70/107 [p_val=0.003]
detector 6 [2 - 6] keV χ²/ndf: 99.98/107 [p_val=0.672]
detector 7 [2 - 6] keV χ²/ndf: 89.90/107 [p_val=0.883]
detector 8 [2 - 6] keV χ²/ndf: 111.65/107 [p_val=0.360]
Events / (10 days)
days after August 3, 2017 (days)

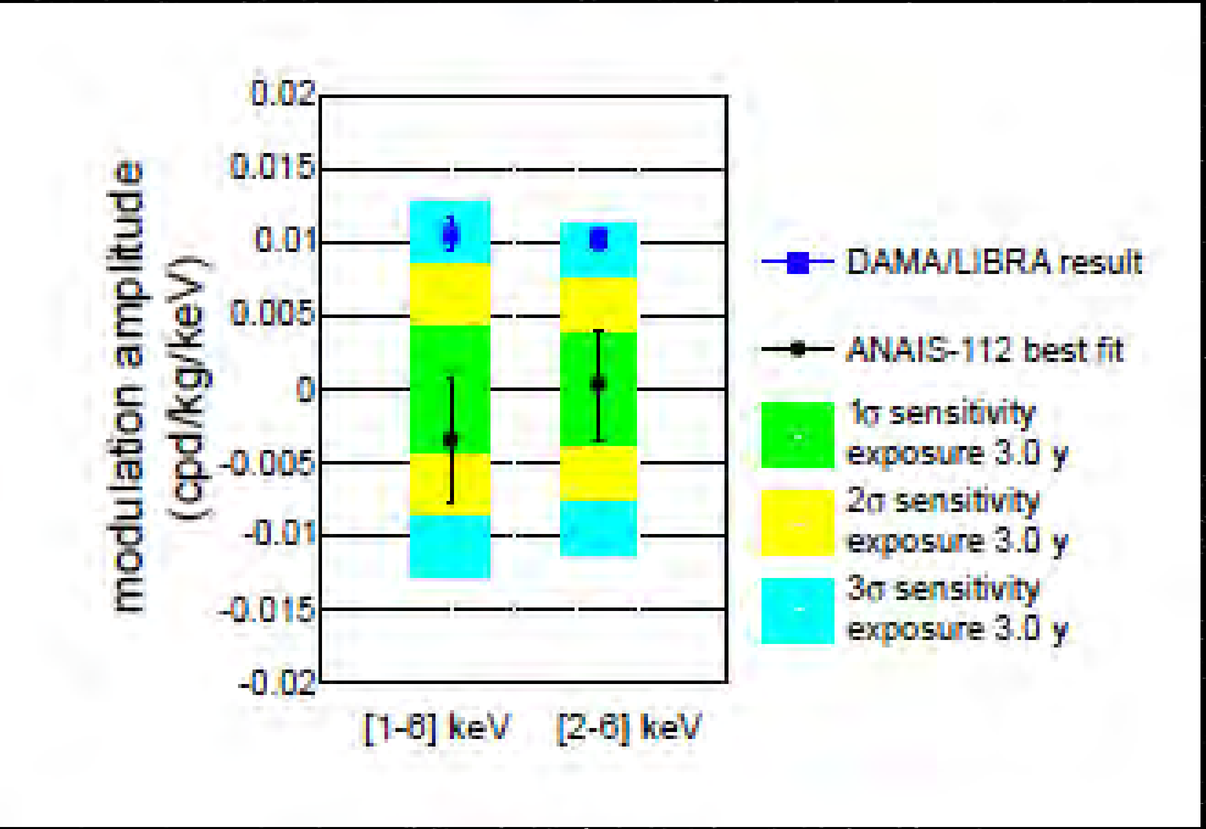
ANAIS-112 three year results – annual modulation analysis

- Data support the absence of modulation in both energy regions and three background models (all of them provide compatible results)

Energy region	Model	χ^2/NDF null hyp	nuisance params	S_m cpd/kg/keV	p-value mod	p-value null
[1-6] keV	eq. 4	132 / 107	3	-0.0045±0.0044	0.051	0.051
	eq. 5	143.1 / 108	2	-0.0036±0.0044	0.012	0.013
	eq. 6	1076 / 972	18	-0.0034±0.0042	0.011	0.011
[2-6] keV	eq. 4	115.7 / 107	3	-0.0008±0.0039	0.25	0.27
	eq. 5	120.8 / 108	2	0.0004±0.0039	0.17	0.19
	eq. 6	1018 / 972	18	0.0003±0.0037	0.14	0.15

- Results of the third approach for bckg modelling show slightly lower σ(Sm) as expected, and is taken for the comparison with DAMA/LIBRA

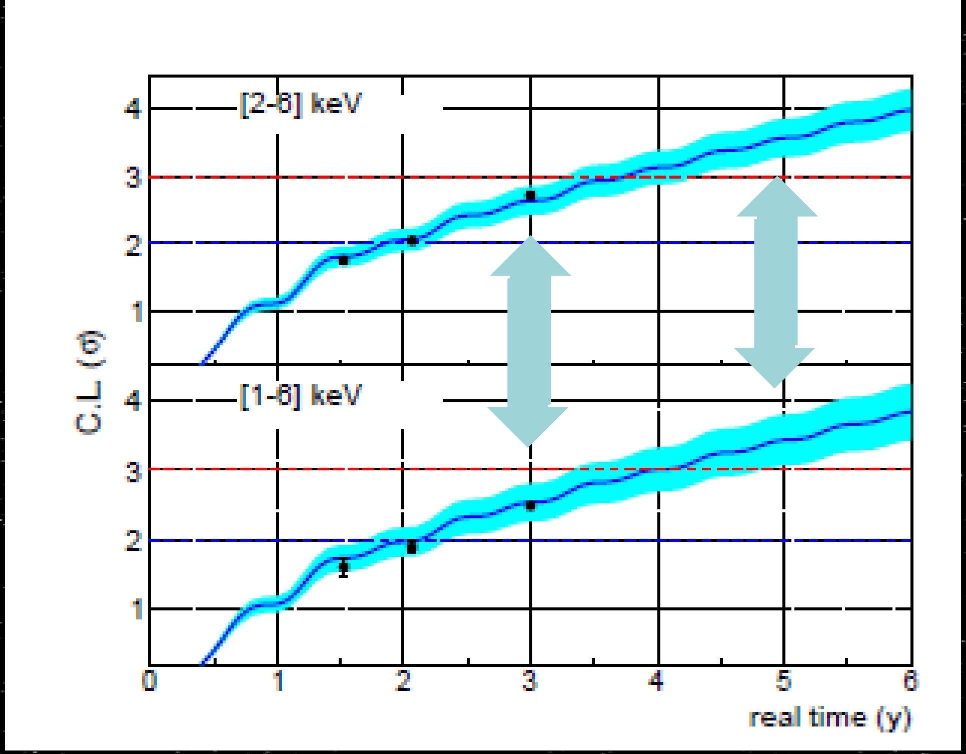
ANAIS-112 three year results – annual modulation analysis



- Best fits are incompatible with DAMA/LIBRA result at 3.3 and 2.6 σ in [1-6] and [2-6] keV energy regions
- Sensitivity is at 2.5 and 2.7 σ in [1-6] and [2-6] keV energy regions

ANAIS-112 three year results – annual modulation analysis

Sensitivity prospects:
I. Coarasa et al., EPJC79 (2019) 233



- Full agreement with our "a priori" sensitivity estimates
- We should be well at 3σ from DAMA/LIBRA result within the scheduled 5 years of data taking

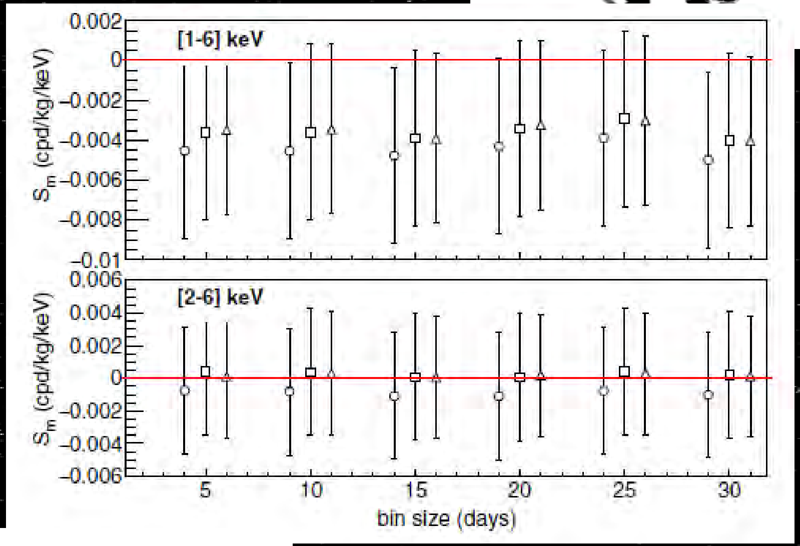
Statistical significance of our result is determined by the standard deviation of the modulation amplitude distribution, $\sigma(Sm)$

We quote our sensitivity to DAMA/LIBRA result as the ratio $S_m^{DAMA} / \sigma(Sm)$

We project our sensitivity with our updated background, efficiency estimates and its errors and live time distribution

ANAIS-112 three year results – annual modulation analysis

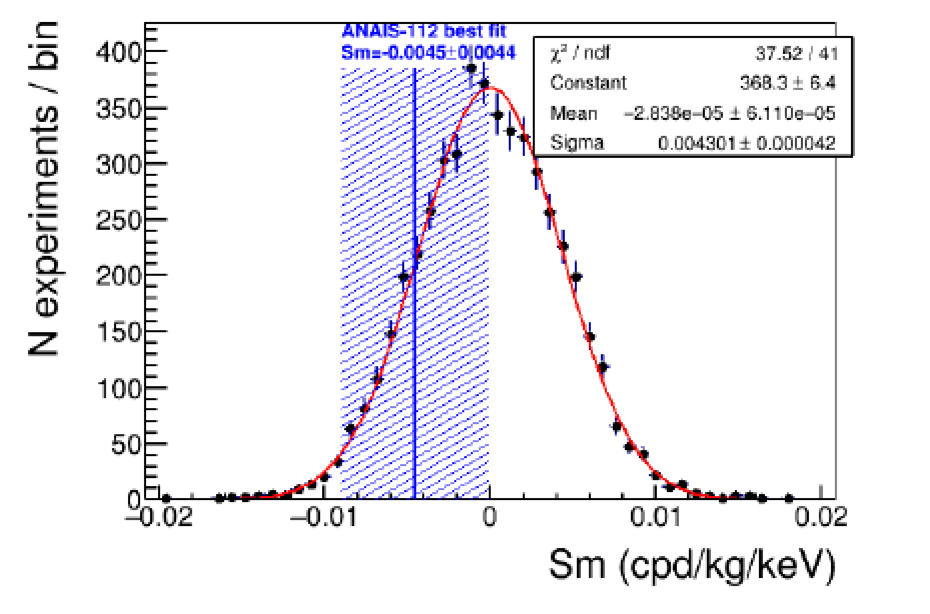
- Consistency checks of our analysis
  - Time binning -> checked bin sizes from 5 to 30 days



Negligible effect

  - Toy MC to check possible bias

No bias

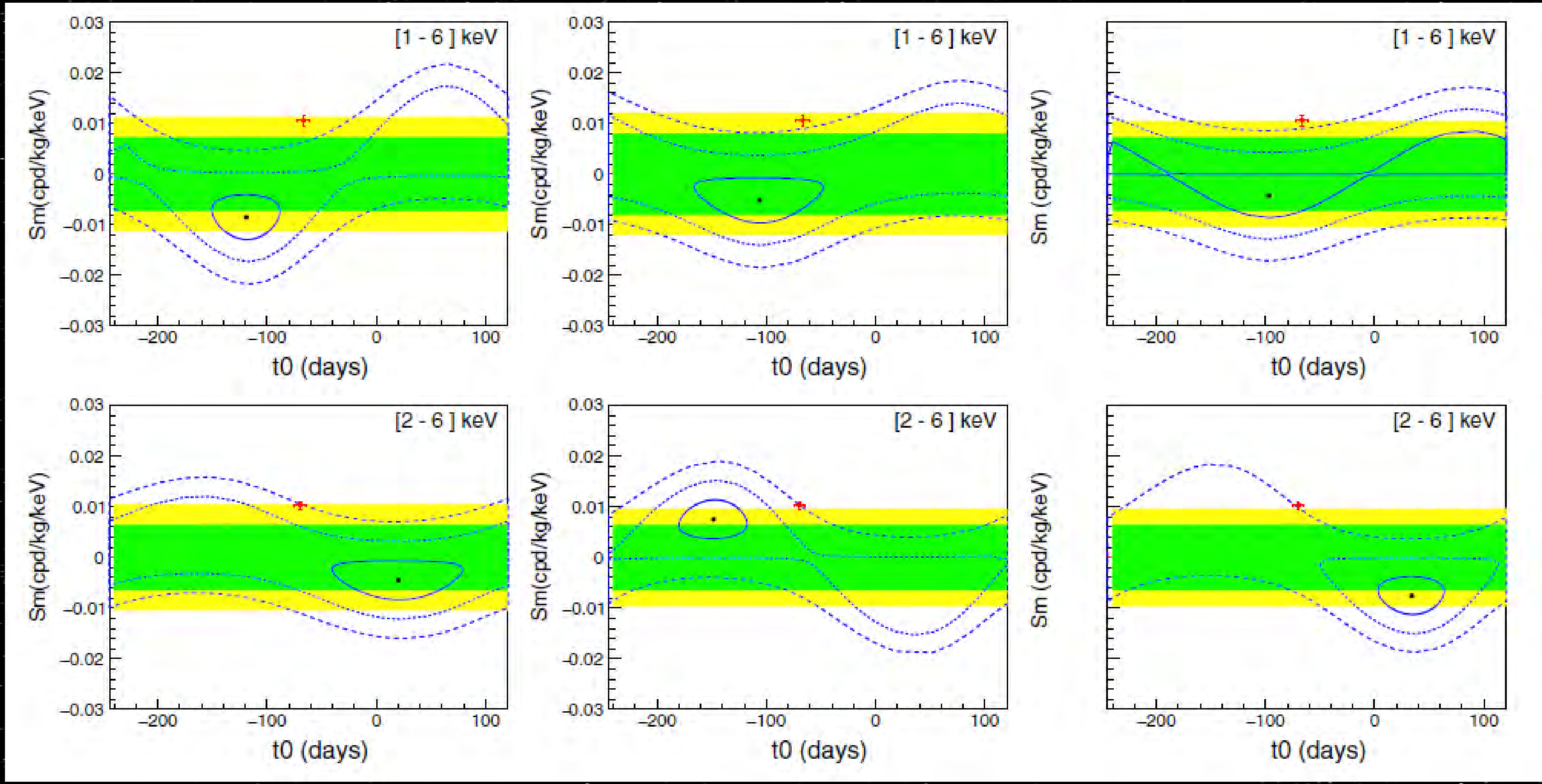


  - 1-2 years / 2-3 years

Compatible results

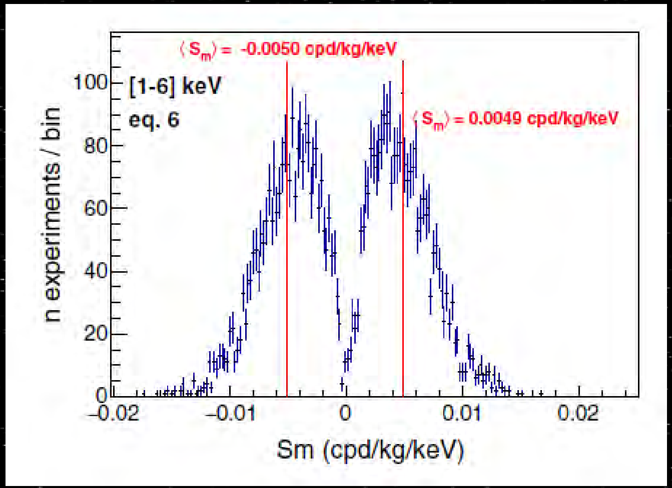
ANAIS-112 three year results – annual modulation analysis

- Phase free analysis



DAMA
ANAIS

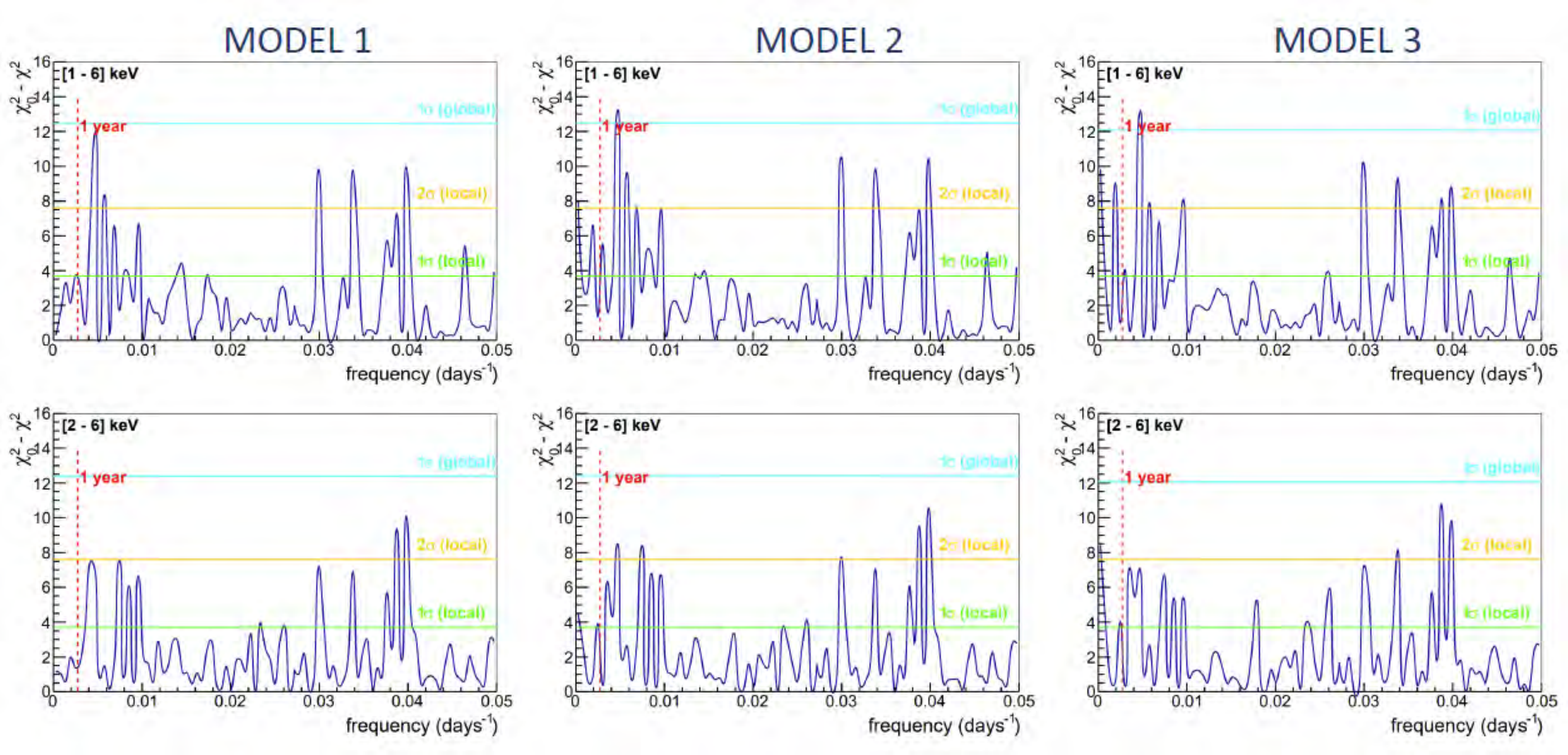
Biased fit …



Considering the bias, compatibility at 1 σ with absence of modulation

ANAIS-112 three year results – annual modulation analysis

- Frequency analysis



No statistically significant modulation at any frequency

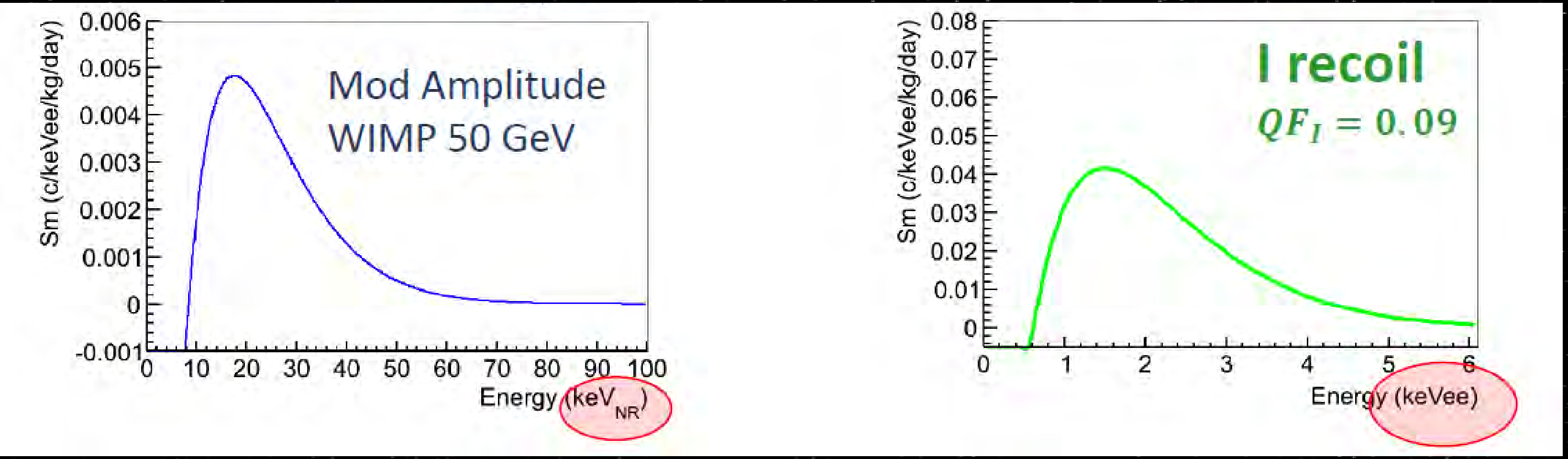
Is this a “MODEL INDEPENDENT” testing of DAMA/LIBRA result?

Using same target material the comparison between DAMA/LIBRA and ANAIS results is DIRECT

However, response of both detectors to the energy depositions from dark matter particles could be different -> improve knowledge on RESPONSE FUNCTION, specially for nuclear recoils

- Possible different response of detectors to nuclear recoils ?

Scintillation produced by nuclear recoils is quenched with respect to electron recoils (used for calibration)



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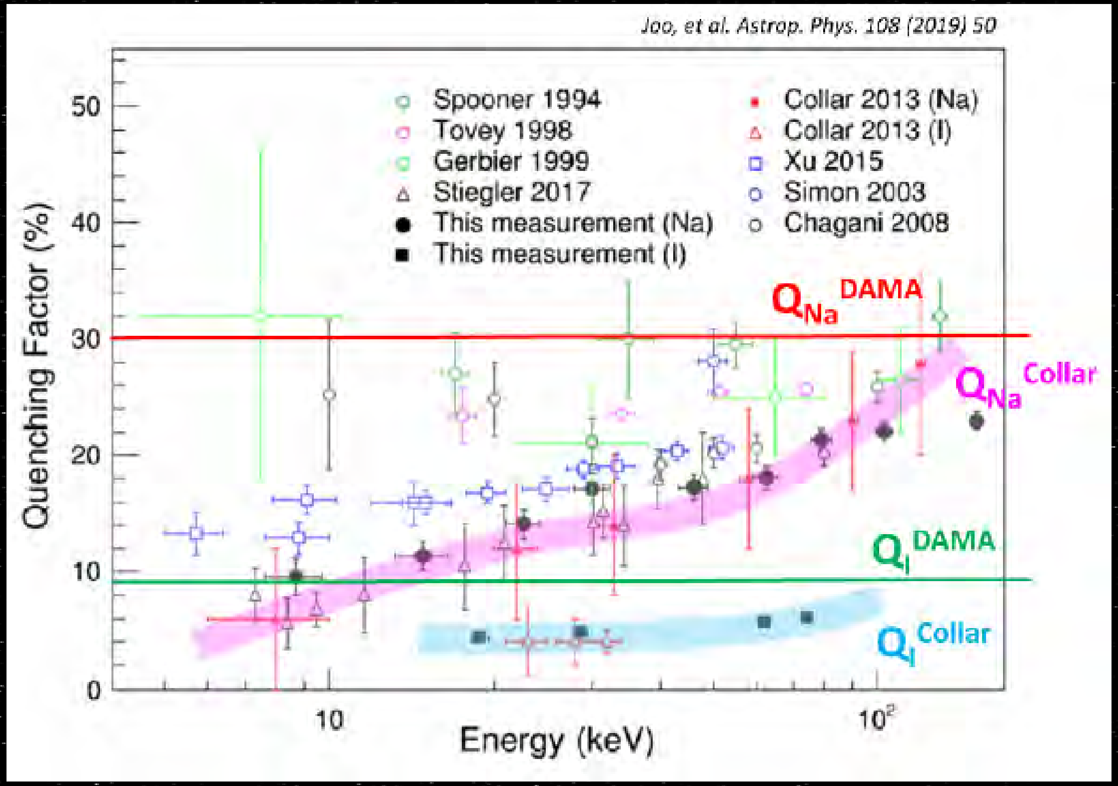
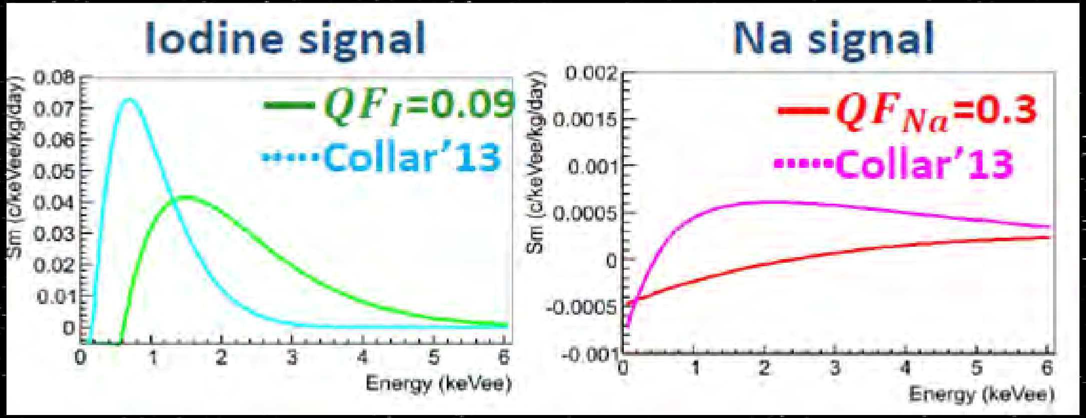




High dispersion of experimental results

Still too many uncertainties in the QF values and dependences for NaI

We have measured QF for different quality crystals in collaboration with Yale (from COSINE collaboration) and Duke researchers at the Triangle Univ. Nuclear Laboratory. Results coming soon.

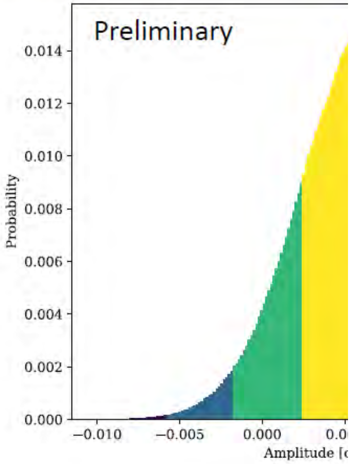
Measurement with a neutron source onsite has been recently performed with ANAIS-112 set-up. Analysis is ongoing.

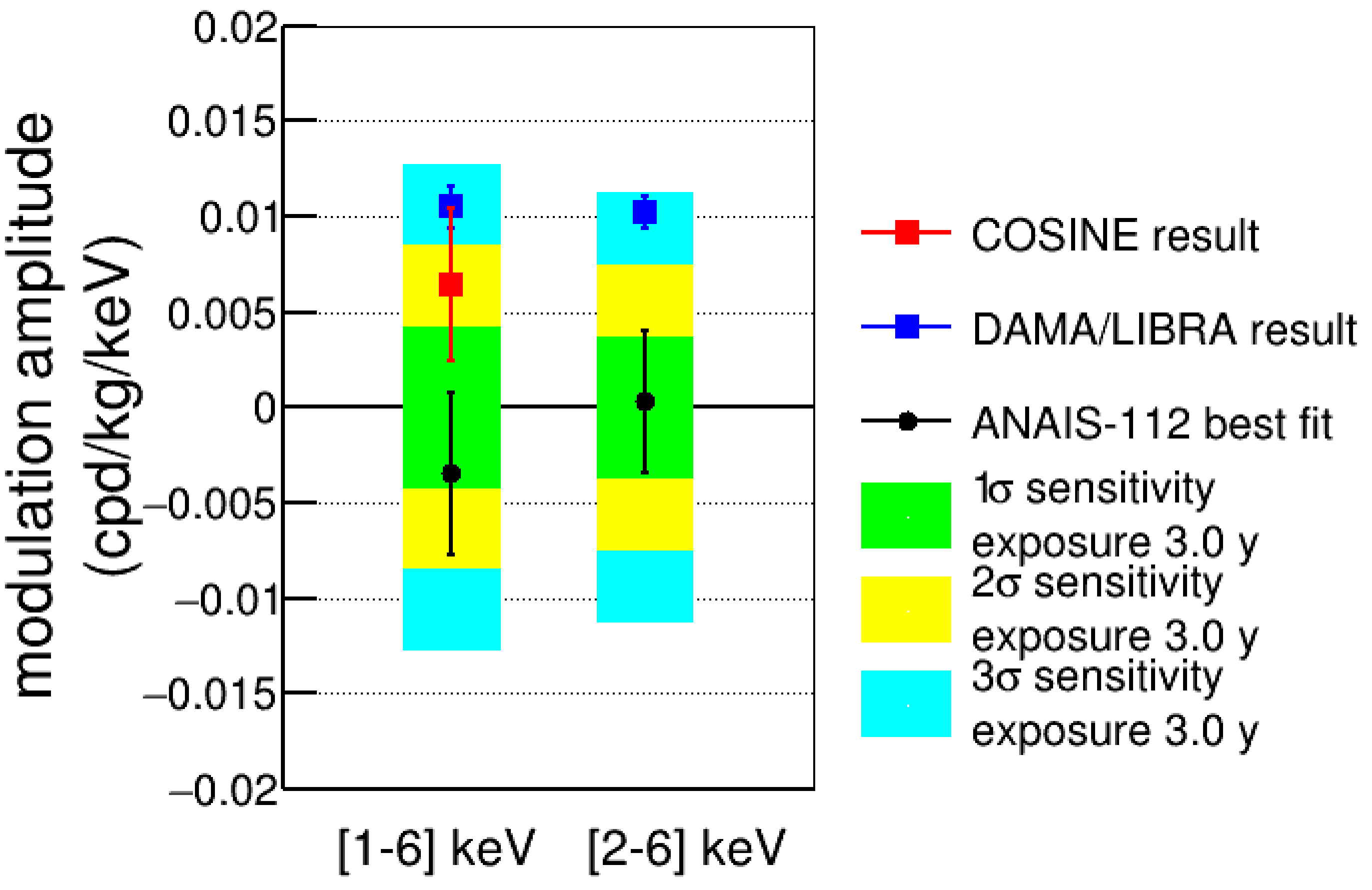
COSINE-100 thr

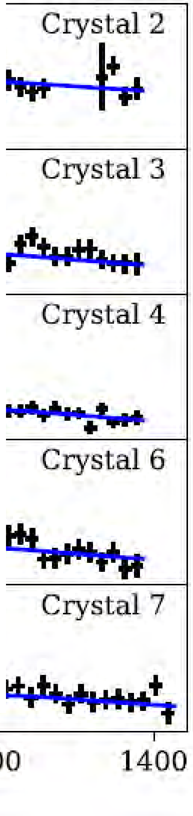
$$R(t) = \sum_i \left[C^i + \sum_{j=1}^{8} A^i_j e^{-\lambda_j t} \right] +$$

Three-Year Mod

- Five dete
  - Consta
  - Expon cosmo
  - Modu phase







- Best-fit modulation amplitude of 0.0064 ± 0.0040 cpd/kg/keV at 1-6 keV
- COSINE-100 consistent with both DAMA and no modulation with 3 years of data
- Lack of modulation in sidebands certifies analysis procedure

Yale Will Thompson - TAUP 2021 12

W. Thompson @ TAUP2021

SUMMARY

A lot of effort has been devoted to understanding the nature of DM
Both, from theory and experiment/observation

However, we do not much about.

We should keep on searching in all the possible ways

Hopefully we will find something, may be pointing at a new direction…

"Science progresses best when observations force us to alter our preconceptions."

Vera Rubin