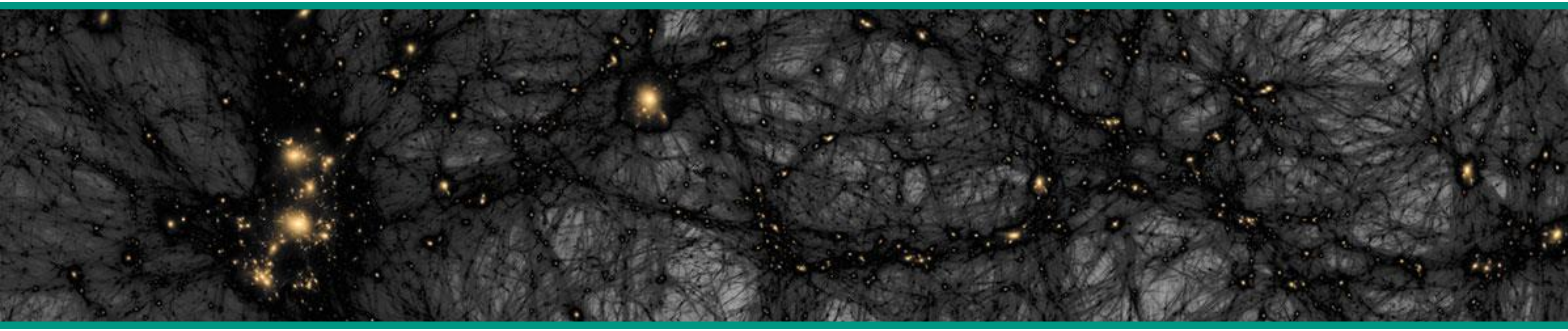
Astroparticle physics I – Dark Matter

WS22/23 Lecture 17 Jan. 26, 2023



Recap of Lecture 16

- **Detecting WIMP recoils on the keV – energy scale**

  - **spin-dependent** WIMP interaction via Z^0 – boson: $\sigma_{SD} \sim (J+1)\,/\,J$
    coupling to distribution of spin inside a nucleus (**unpaired nucleon** p, n)

  - reaction kinematics of WIMP $m(\chi^0)$ & nucleus $m(N)$ via reduced mass μ

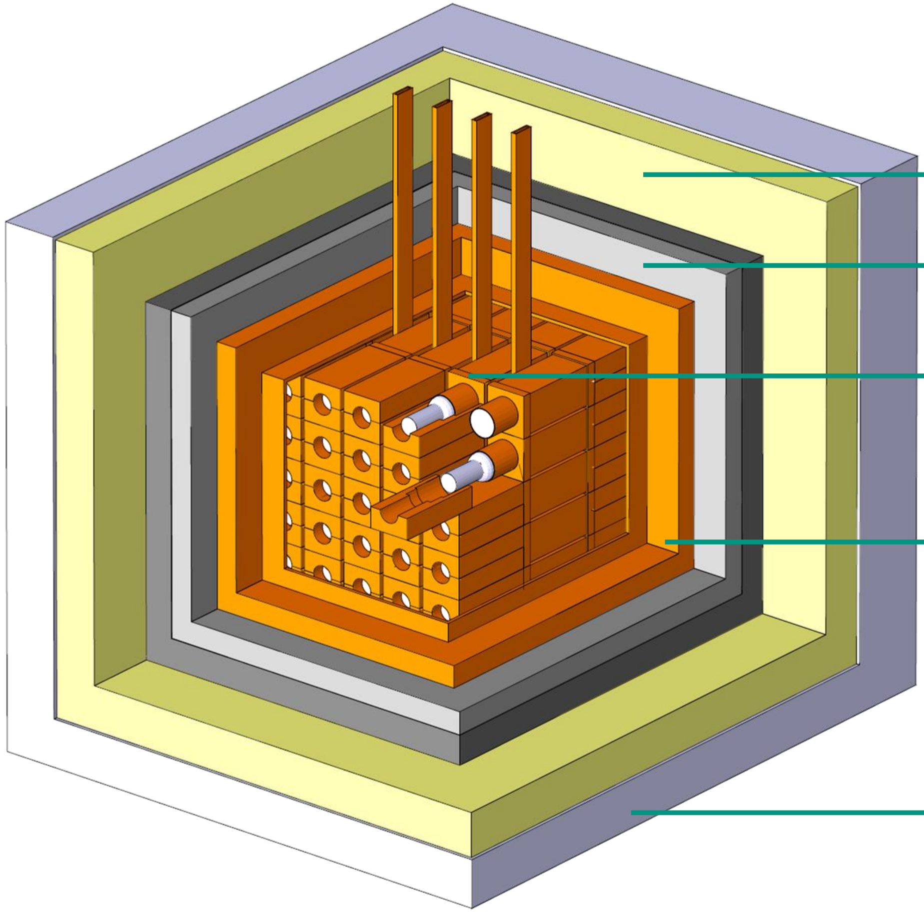
  - mass ratio $m(\chi^0)$ / $m(N)$ determines recoil energy E_R of nucleus with ´optimum´ case for equal masses

  - solid-state answer to recoil nucleus: **phonons** ($few\ meV$) ⇨ **energy** E_R
    ionisation ($< 20\ eV$) **/ scintillation** ($100 \ldots 200\ eV$) ⇨ **PID via quenching**

  - WIMP-plot: parameters $m(\chi^0)$ & $\sigma_{SI,SD}(\chi^0)$ – exclusion limit vs. DM-evidence

Direct WIMP searches: DAMA*/LIBRA

- **A scintillator-based DM-experiment with a highly controversial result**



polyethylene / paraffine-shielding

Boliden-$\boldsymbol{Pb}$ –shielding ($15\ cm$)

$\boldsymbol{NaJ}$ **crystals** (in a 5×5 matrix), read-out via 2 low-background PMTs

Cu – shielding ($10\ cm$), flushed with high-purity, dry N_2 – gas to reduce emanation of radon & humidity

concrete - shielding ($1\ m$)

*DArk MAtter experiment

Direct WIMP searches: DAMA/LIBRA*

Karlsruhe Institute of Technology

- **A scintillator optimized for low-energy events (measurements 1995 … today)**
  - ☑ large target mass: $\boldsymbol{m = 250\ kg\ NaJ}$ scintillating crystals
  - ☑ light read-out of scintillating crystals via 2 PMTs: light yield $\sim \boldsymbol{5 \ldots 7\ p.e./keV}$
  - ☒ detection based only on 1 parameter: scintillation light only (⇨ no PID)

- ☑ scintillating crystals formed from special **low-activity** materials with bg-rate R

$$R = 1 \ldots 2\ events\ keV^{-1} kg^{-1} day^{-1}$$

- ☒ rather high energy threshold for WIMPS

$$\boldsymbol{E_{thres}} = \ \ 2\ keV \text{ (for electron recoils)}$$
$$= 20\ keV \text{ (for nuclear recoils of } {}^{23}\boldsymbol{Na}\text{)}$$

*Large Sodium Iodide Bulk for RAre processes

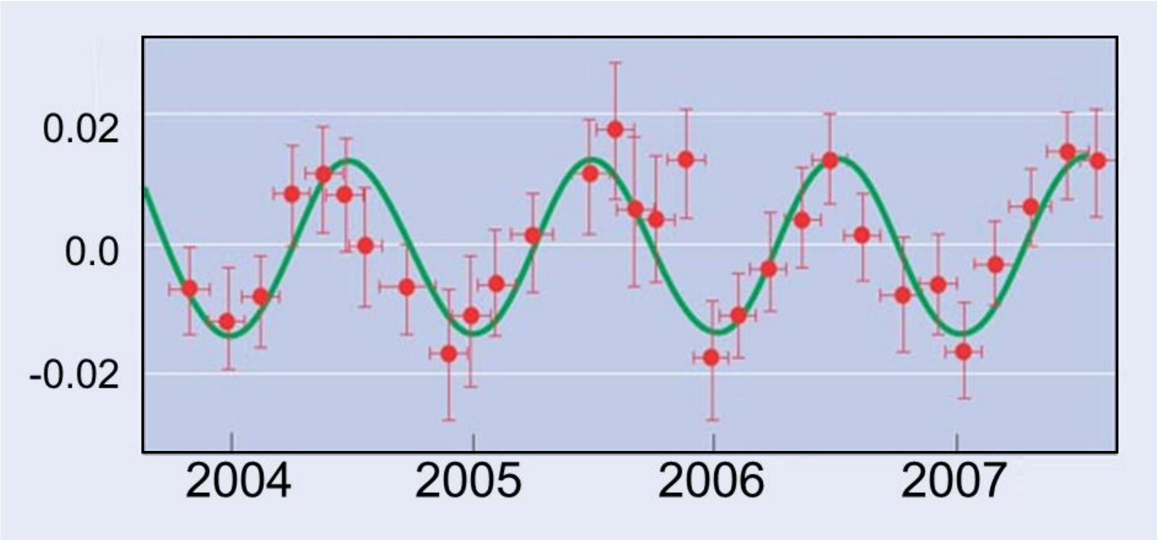
Results from DAMA/LIBRA: annual modulation

- **Since 1995: the event rate is modulated with period of $T = 1\ year$!**

- observed event rate (above threshold): small variation over many years (decades)

- phase t_0 of the modulation:

$t_0(expected)$ = June, 2



DAMA/LIBRA: mass = $250\ kg$

data: $0.87\ ton \cdot years$

$t_0(observed)$ = May, 17 (± 7 days)

Results from DAMA/LIBRA: annual modulation

- **Since 1995: the event rate is modulated with period of $T = 1\ year$!**

- observed event rate (above threshold): small variation over many years (decades)

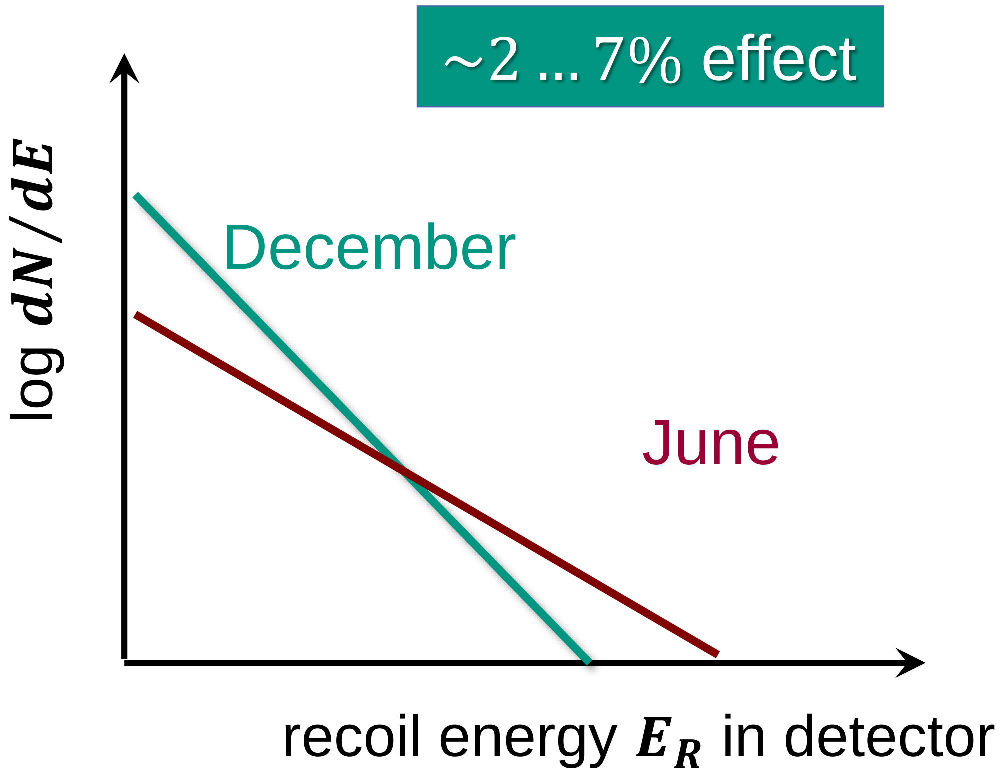
- phase t_0 of the modulation:

$t_0(expected)$ = June, 2

$$\boxed{v(t) = v_S + v_E \cdot \cos(60°) \cdot \cos\omega(t - t_0)}$$

variation of detector speed over one year

$t_0(observed)$ = May, 17 (± 7 days)

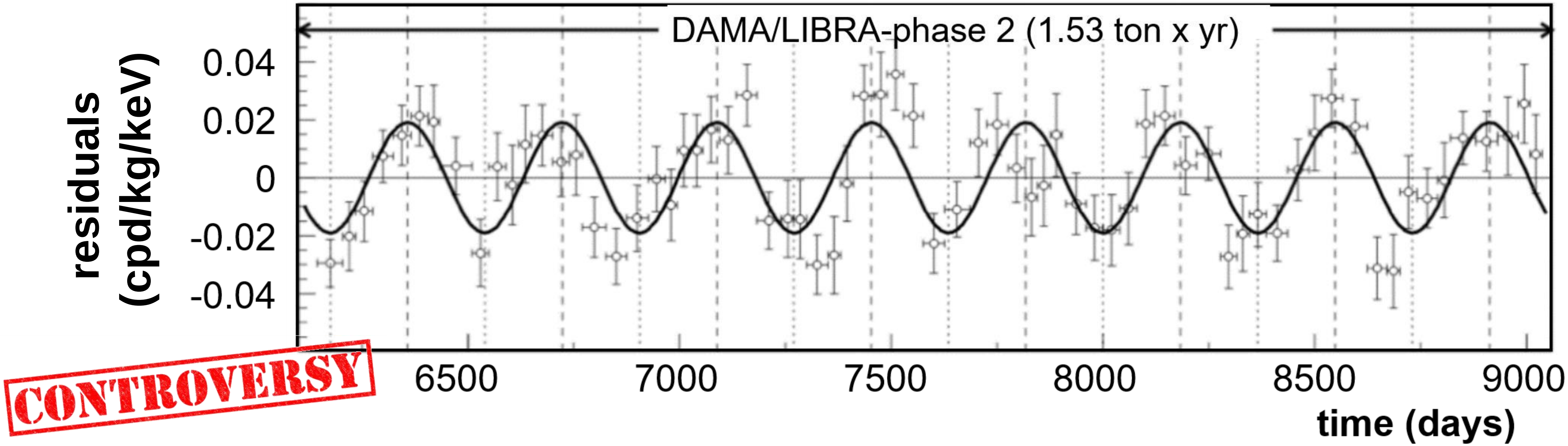


DAMA/LIBRA: updated results for further 8 years

- **Total exposure** $M \cdot t = 2.86\ ton \times years$, **evidence for modulation** $= 13.7\ \sigma$

  - modulation signal is only seen in low-energy interval from 1-6 keV (above E_{thres})

  - clear evidencce for modulation: but is it really induced by WIMP-interactions?

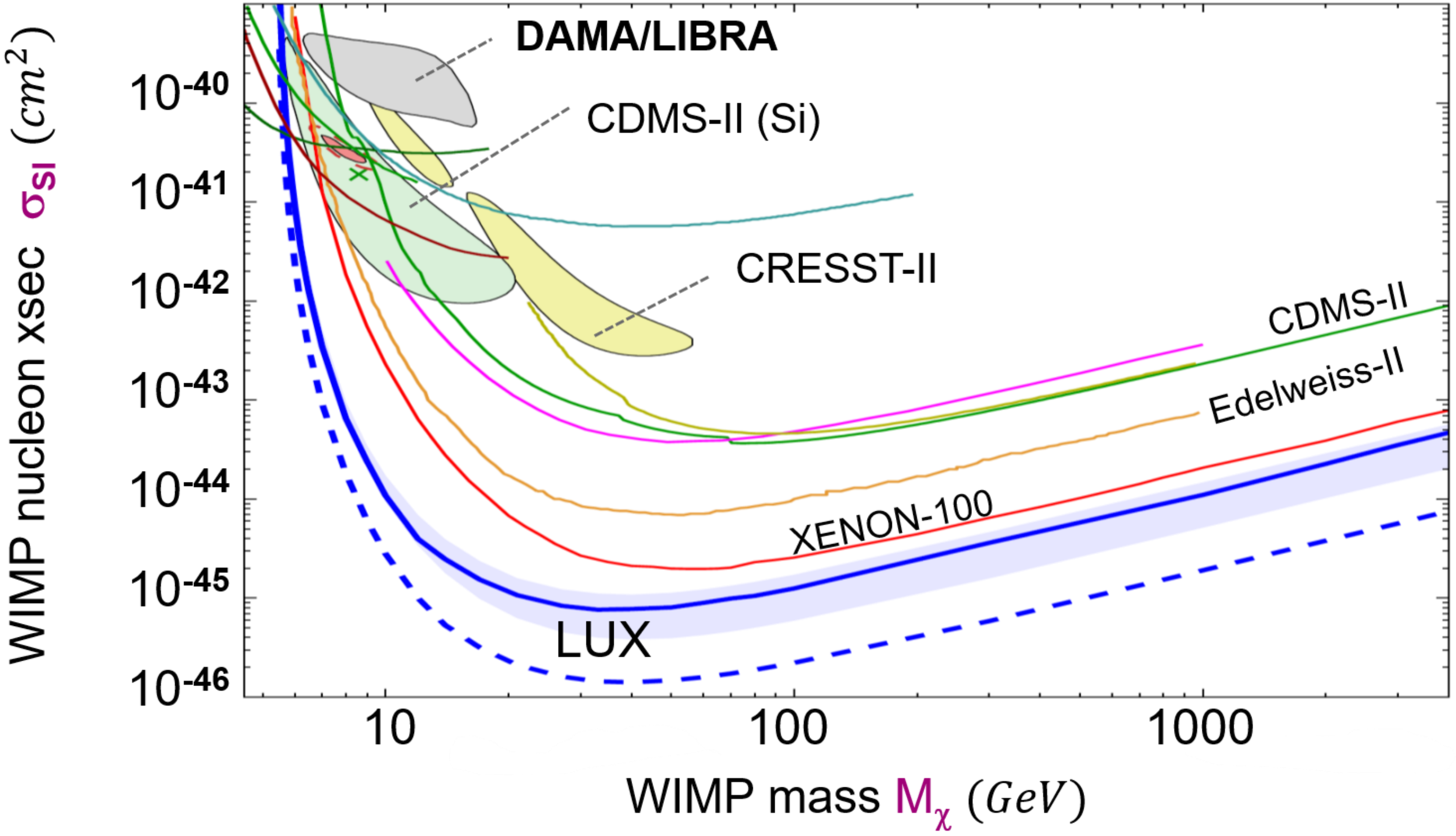


DAMA/LIBRA: WIMP signal region & exclusions

DAMA/Libra favoured signal region & exclusion limits by other experiments

- DAMA/LIBRA favours **low mass WIMPs:** a region initially also favoured by other early experiments as well

- modern experiments (XENON, LUX,…) however **exclude the low mass region** of DAMA/Libra!

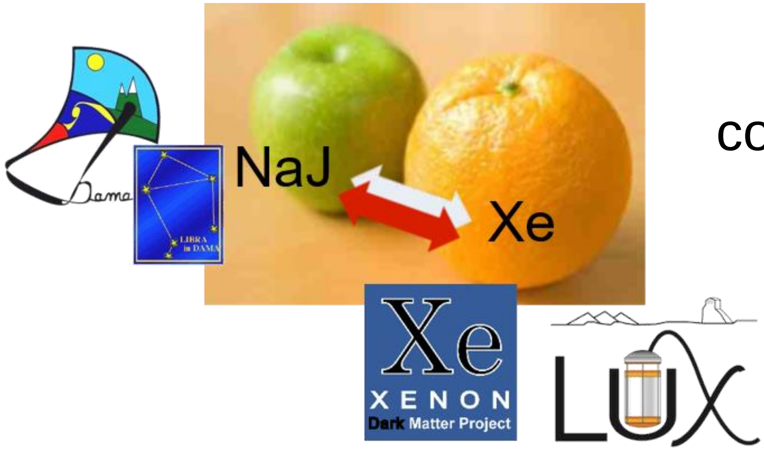


DAMA/LIBRA: WIMP signal region & exclusions

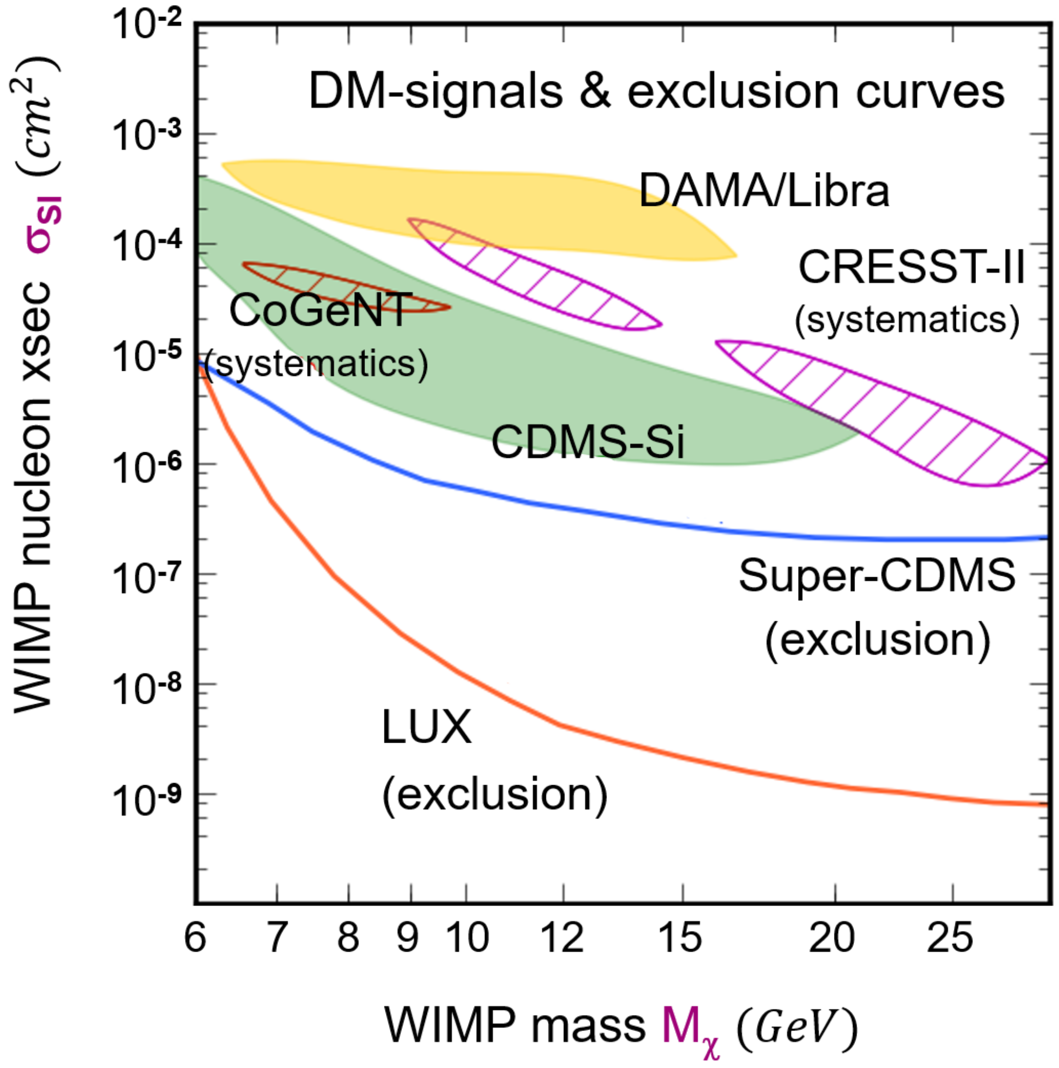
- **Many other ´DM-signal´ were due to systematic effects: DAMA remains…**

- comparison is somewhat model-dependent due to different DM-halo assumptions of the experiments

- systematics: detector response at E_{thres} ?



comparing ´apples & oranges´ ??



DAMA/LIBRA: explaining a $1\ yr$ modulation

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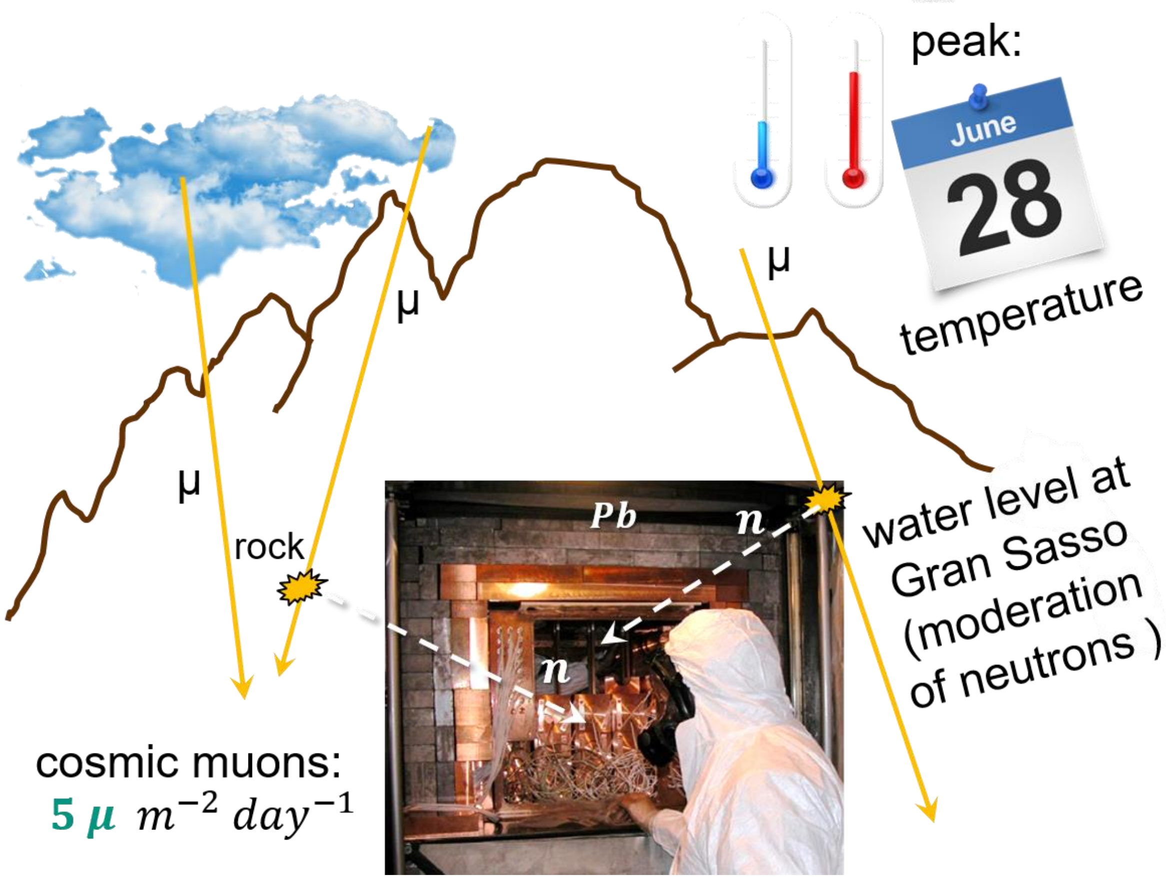
- **Combining neutrons & neutrinos may give rise to an annual modulation of events in DAMA**



cosmic muons:
$5\ \mu\ m^{-2}\ day^{-1}$

physicsworld.com

Scattered neutrons could mimic DAMA-LIBRA's 'dark matter' modulation

Jul 17, 2014

On a high: do muons and neutrinos mimic DAMA's signal?

For the last 16 years, researchers at the DAMA/LIBRA experiment in Italy have seen a controversial annual oscillation in the signal from their dark-matter detector. This type of variation would be seen if the Milky Way galaxy was wreathed in a "halo" of dark matter. But apart from the CoGENT dark-matter experiment in the US, no other dark-matter searches have seen a similar effect. Now, a physicist at Durham University in the UK has proposed an alternative source for the modulation in the form of neutrons, which are knocked out of atoms by muons and neutrinos scattering in the rock or shielding material around DAMA/LIBRA.

DAMA/LIBRA: explaining a $1\ yr$ modulation

- **Modulation due to the specific DAMA/Libra analysis method?!**

  - if the background in DAMA/Libra is slowly increasing over the years (slow migration of radon or other impurities) this could **mimic a DM-signal**!

  - problem: DAMA/Libra does NOT reveal the full data (missing transparency)

  - other collaborations showed that a non-constant background is dangerous

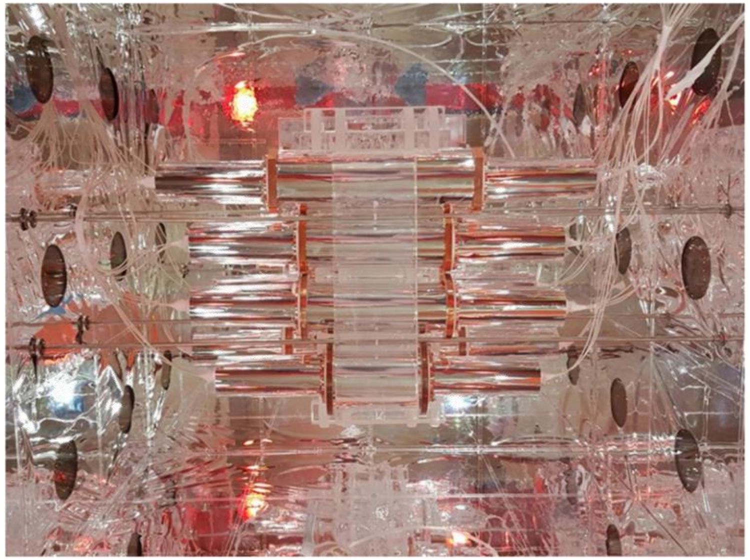
NEWS | 16 August 2022

Notorious dark-matter signal could be due to analysis error

Observations that physicists have so far failed to replicate could be the result of misinterpreted data.

nature

Davide Castelvecchi



To catch dark matter, modules containing sodium-iodide crystals sit inside the COSINE-100 detector in South Korea. The experiment started running in 2016. Credit: COSINE-100 collaboration

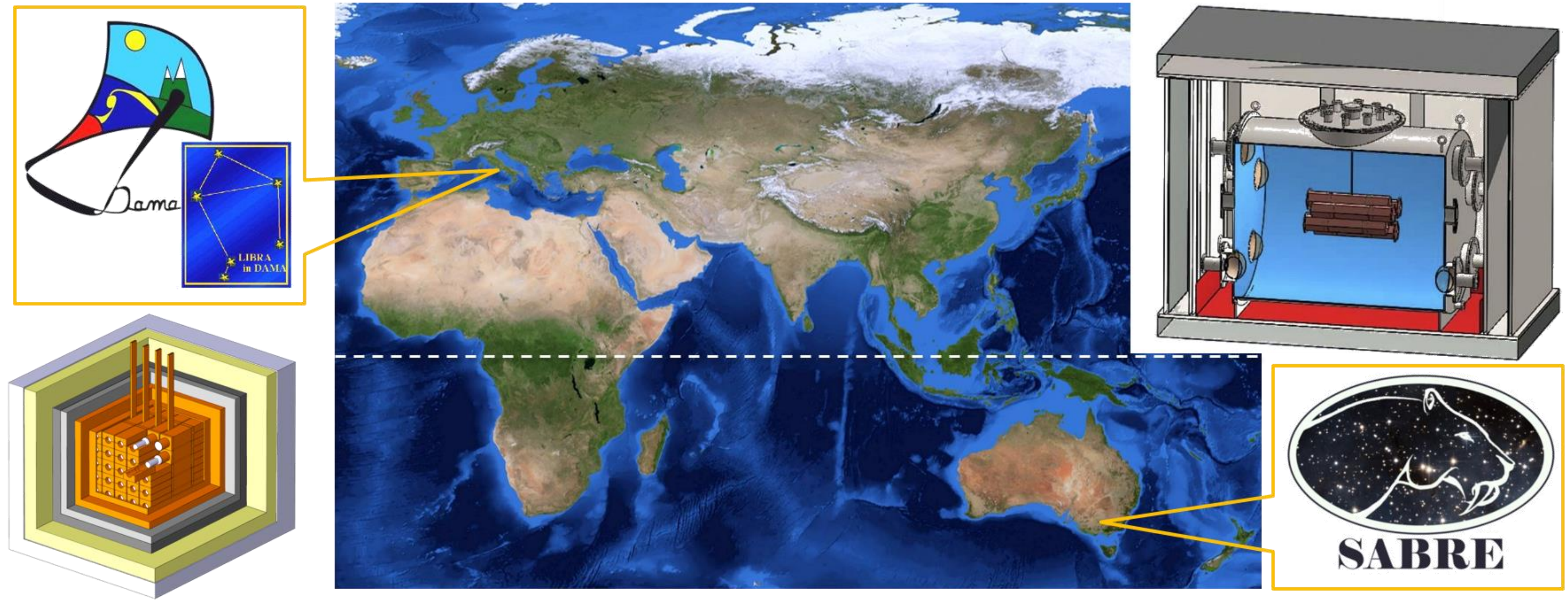
Physicists have shown that an underground experiment in South Korea can 'see' dark matter streaming through Earth – or not, depending on how its data are

[Notorious dark-matter signal could be due to analysis error (nature.com)]

DAMA/LIBRA: new tests by NaJ detectors

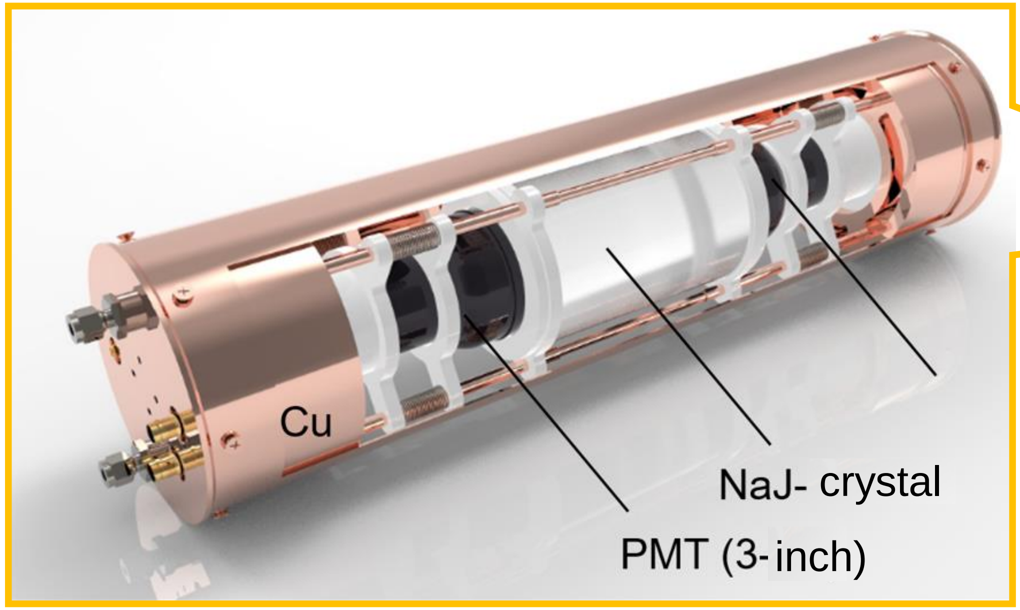
- **SABRE, COSINE-100 and ANAIS aim to reproduce the data from DAMA**

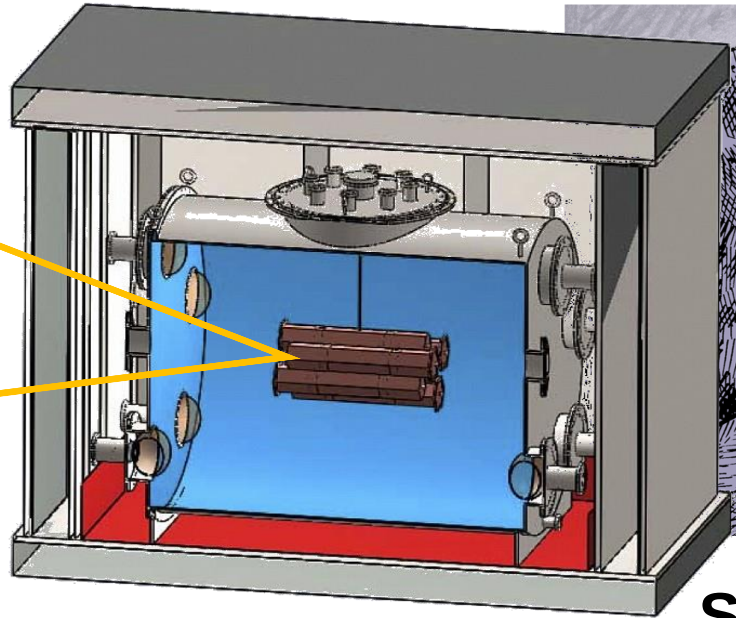
- experiment also in Southern Hemisphere: same WIMPs, but different background

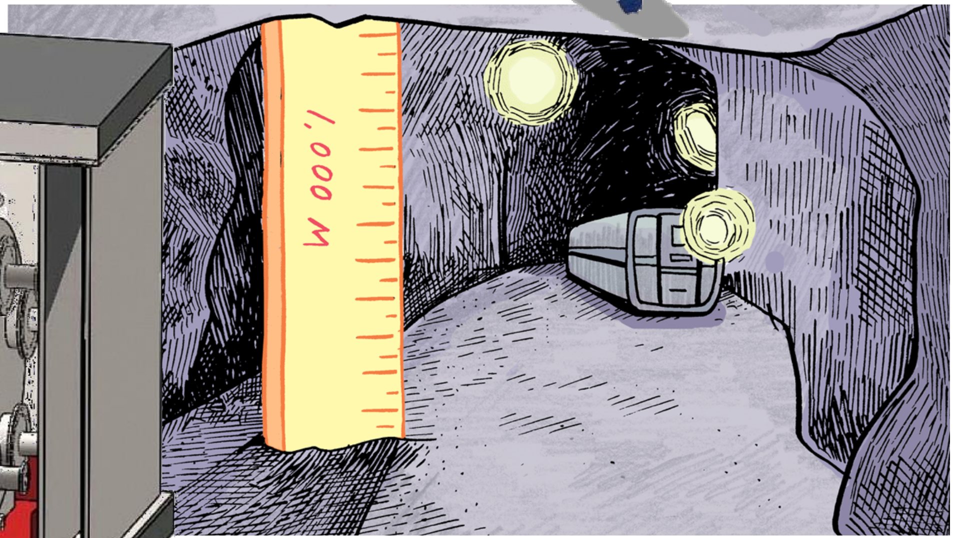


SABRE* experiment

- **Test with NaJ detectors at LNGS & SUPL**
  - 2 identical set-ups at Southern & Northern Hemispheres
  - high-purity – crystals $(5\ kg)$ with active scintillator veto







SUPL- Stawell Underground Physics Lab $(2900\ m.w.e.)$

*Sodium-iodide with Active Background REjection

COSINE-100 experiment in South Korea

- A NaJ detector $(106\ kg)$ like DAMA/LIBRA at Yangyan Laboratory (Y2L)

  - start of measurements in 9/2016

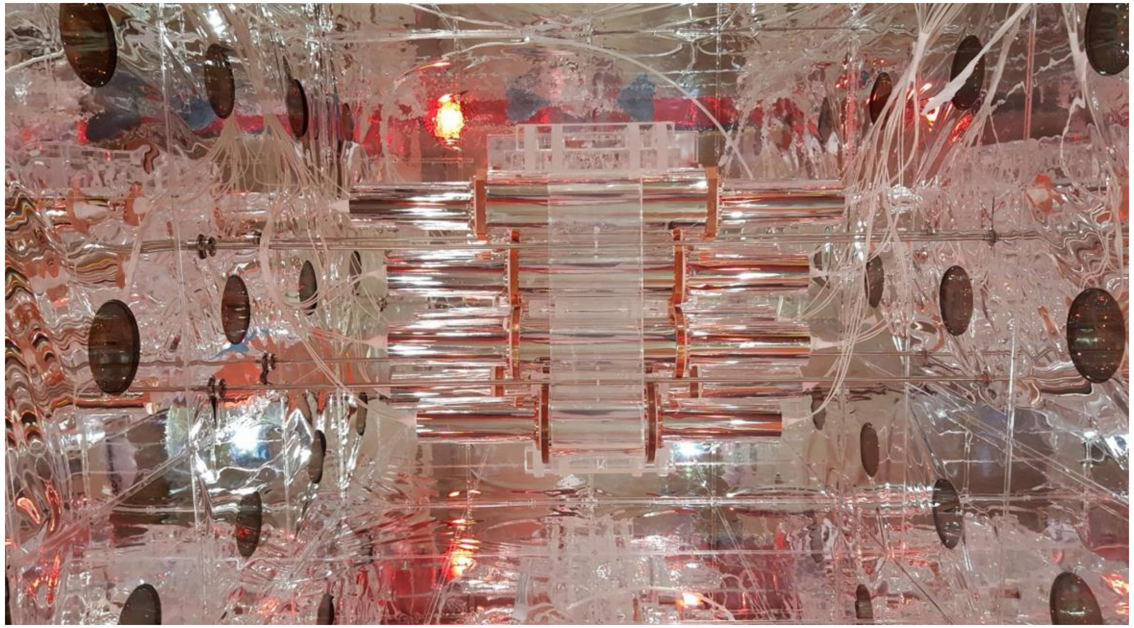
  - publication of first results in 12/2018, 11/2021 full results: **no modulation**, **rules out WIMP-nucleon** interactions claimed by DAMA

PHYSICS

A Famous Dark Matter Signal Is Probably Coming From Something Else

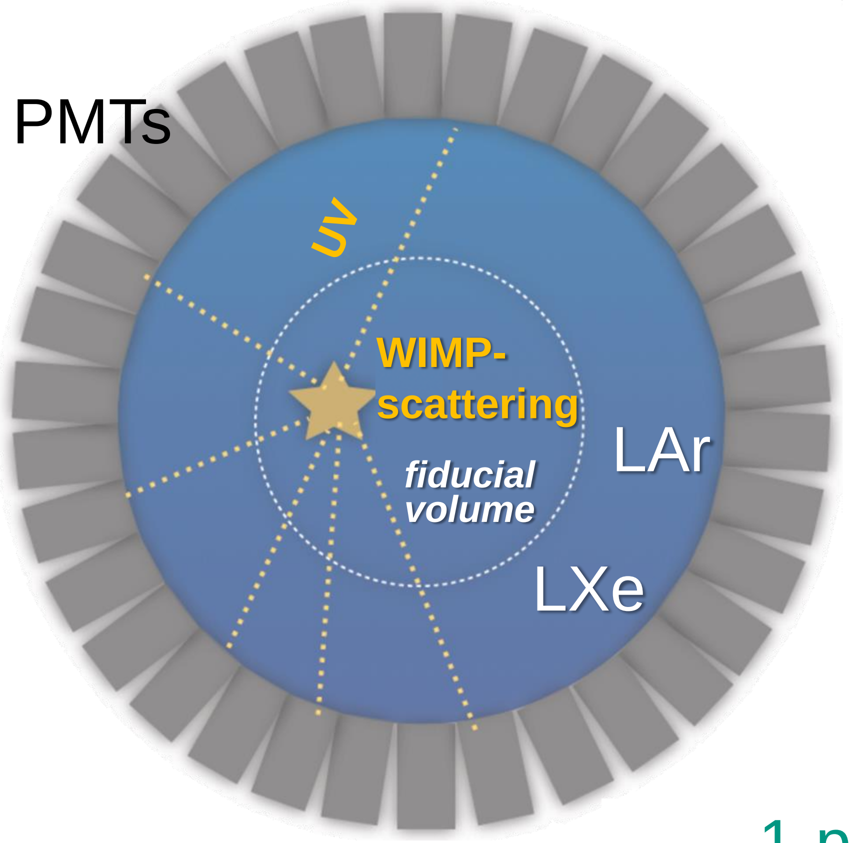
An underground experiment in South Korea has turned up nothing, suggesting an intriguing observation from 2017 was a red herring.

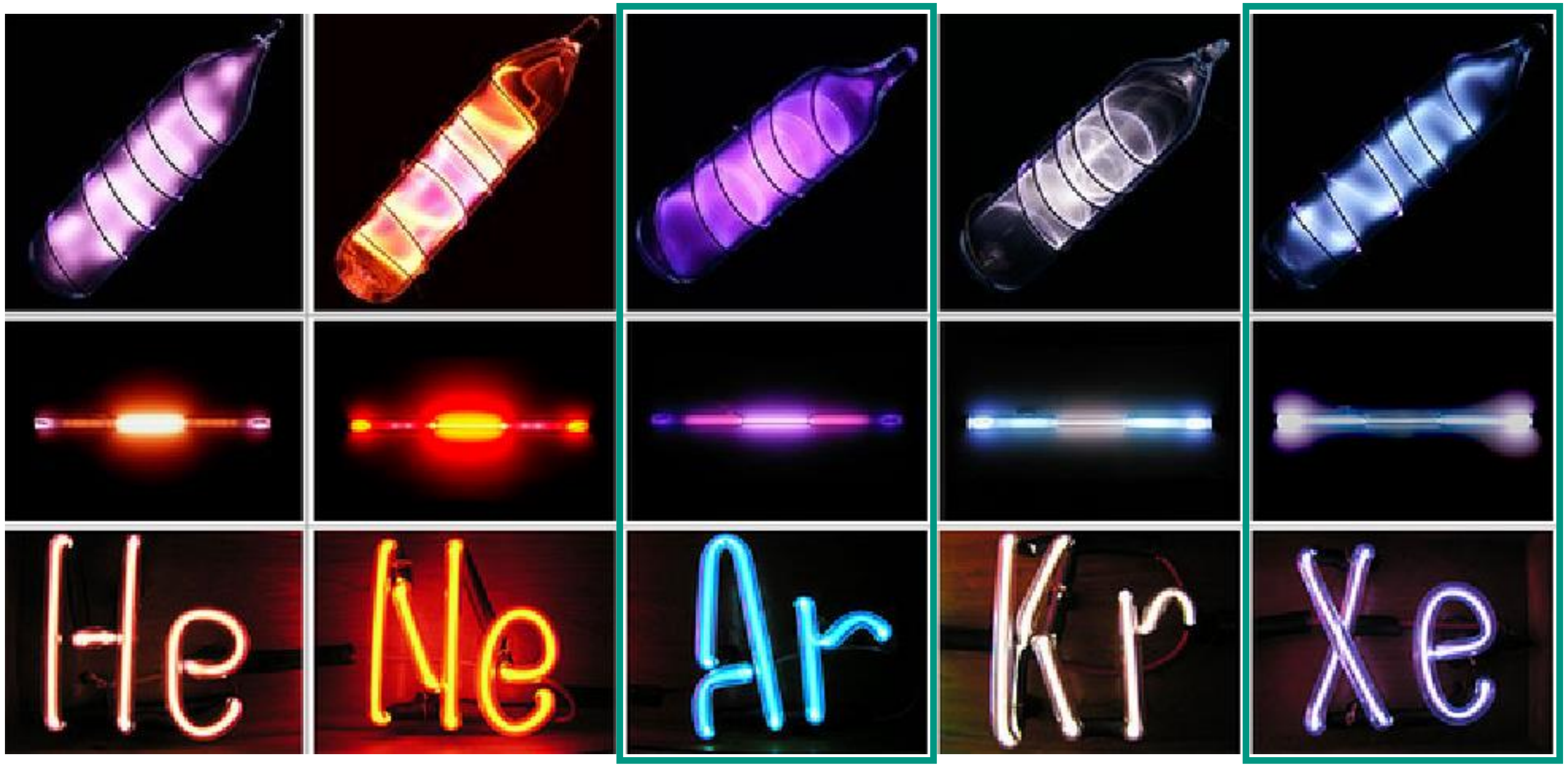
By Isaac Schultz | 11/10/21 4:00PM | Comments (5) | Alerts



4.5.2 Liquid noble gas detectors

- **The leading technology to directly observe very rare WIMP interactions**

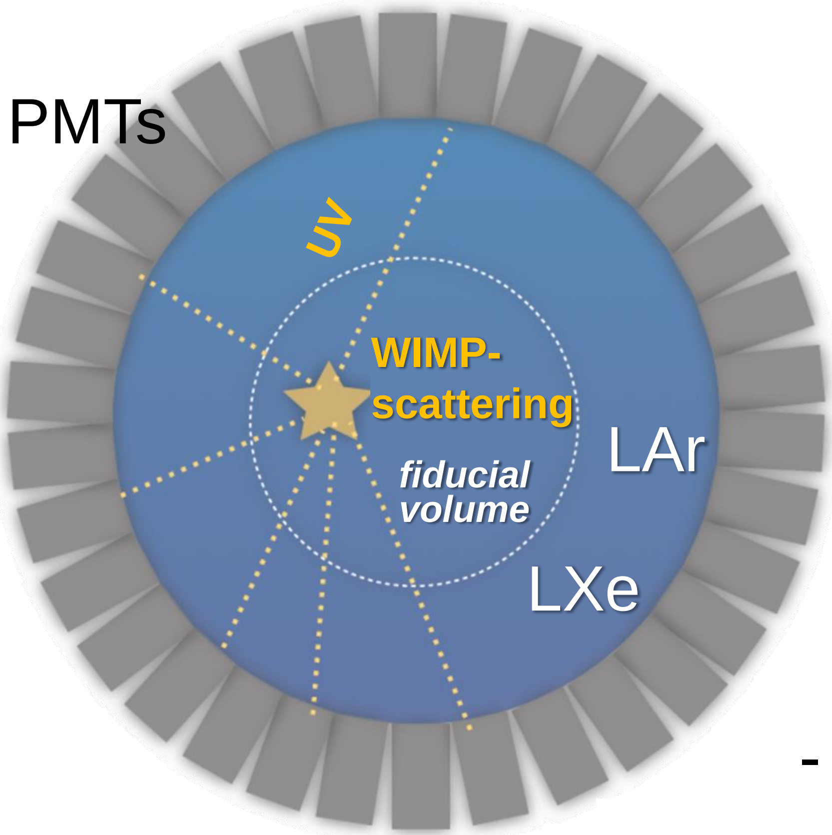




1-phase layout: spherical geometry with 4π PMT-coverage

Liquid noble gases: scintillation & ionisation

- LAr & LXe **detectors: an overview of their major advantages in DM-searches**



- large **target masses**: $m = 1 \dots 10\ t$ ($50\ t$ in future)

- large **stopping power** (large dE/dx for m.i.p.),
  ⇨ good self-absorption of external background

- good **particle discrimination** in **2-phase layout**
  liquid + gaseous noble gas TPC

- high **scintillation light yield** ($40 \dots 50\ p.e.\ keV^{-1}$)

- high **position resolution** (on the cm – scale) via
  PMT-timing, also important to define fiducial volume

Liquid noble gases: scintillation & ionisation yields

- **Comparing different noble gases as to their key performance parameters**

  - **xenon** offers the distinct advantages of highest charge & light yields

liquid noble gas detectors: properties relevant for DM-searches				
	$Z(A)$	ionisation ($e^- \, keV^{-1}$)	scintillation yield (photons keV^{-1})	scintillation light λ (nm)
neon	$10\ (20)$	46	7	85 (WLS)
argon	$18\ (40)$	42	40	128 (WLS)
xenon	$54\ (129 \ldots 131)$	64	46	175

- neon & argon scintillation produces short-wave light which is too short in λ to be detected by PMTs ⇨ requires to install **WLS* elements** in front of PMTs

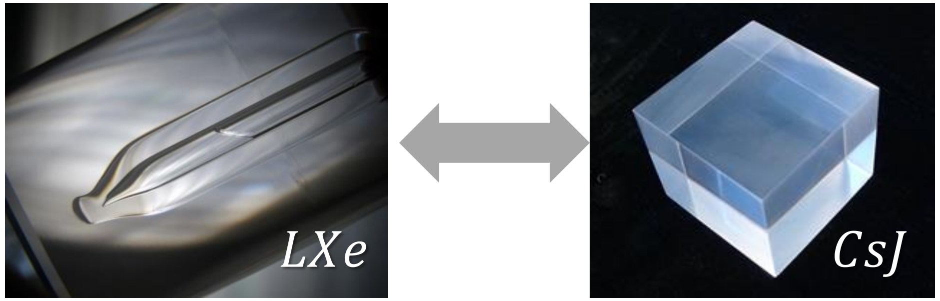
***WLS = Wave-Length-Shifter**

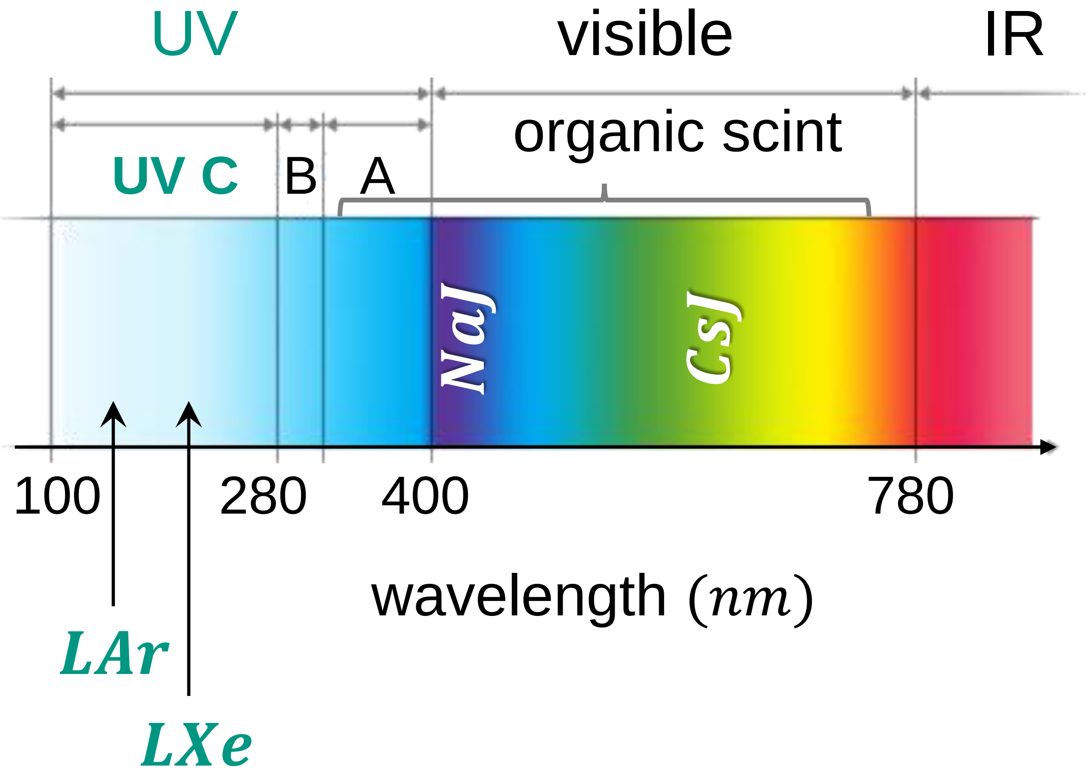
Liquid noble gases: scintillation

- **Scintillation processes in liquid noble gases: emission of short-wave light**

- Liquid noble gases emit scintillating light in the **VUV** (**V**acuum **U**ltra-**V**iolet) range with $\boldsymbol{\lambda < 200\ nm}$

- for comparison: anorganic scintillators like $\boldsymbol{NaJ, CsJ}$ emit long-wave light with λ_{max} ~ 400…500 nm

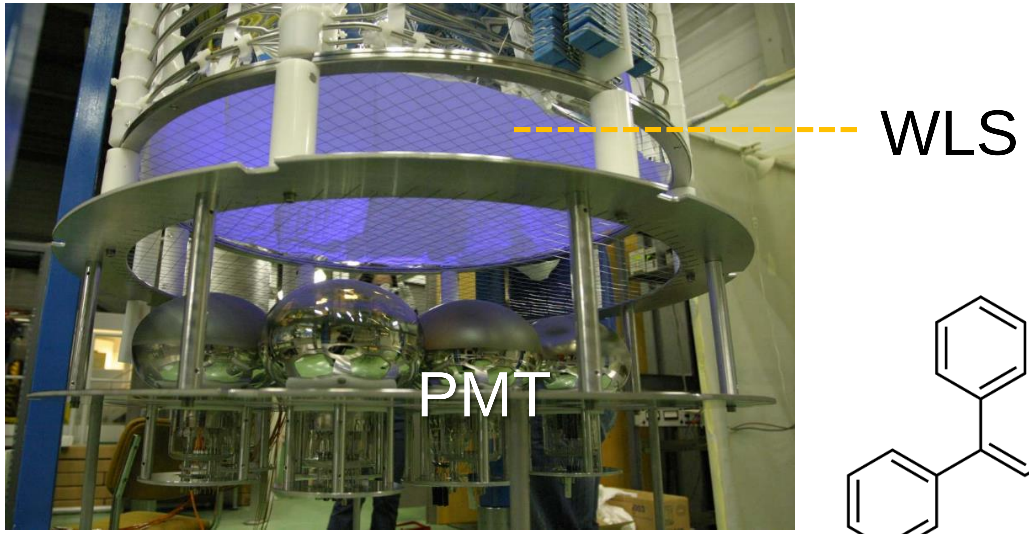


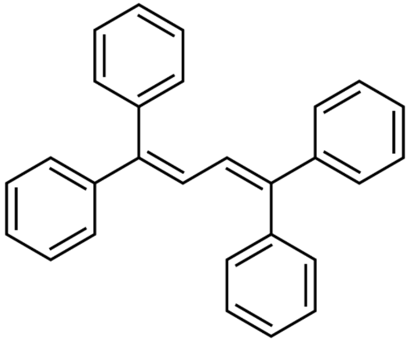


Liquid noble gases: scintillation of LAr

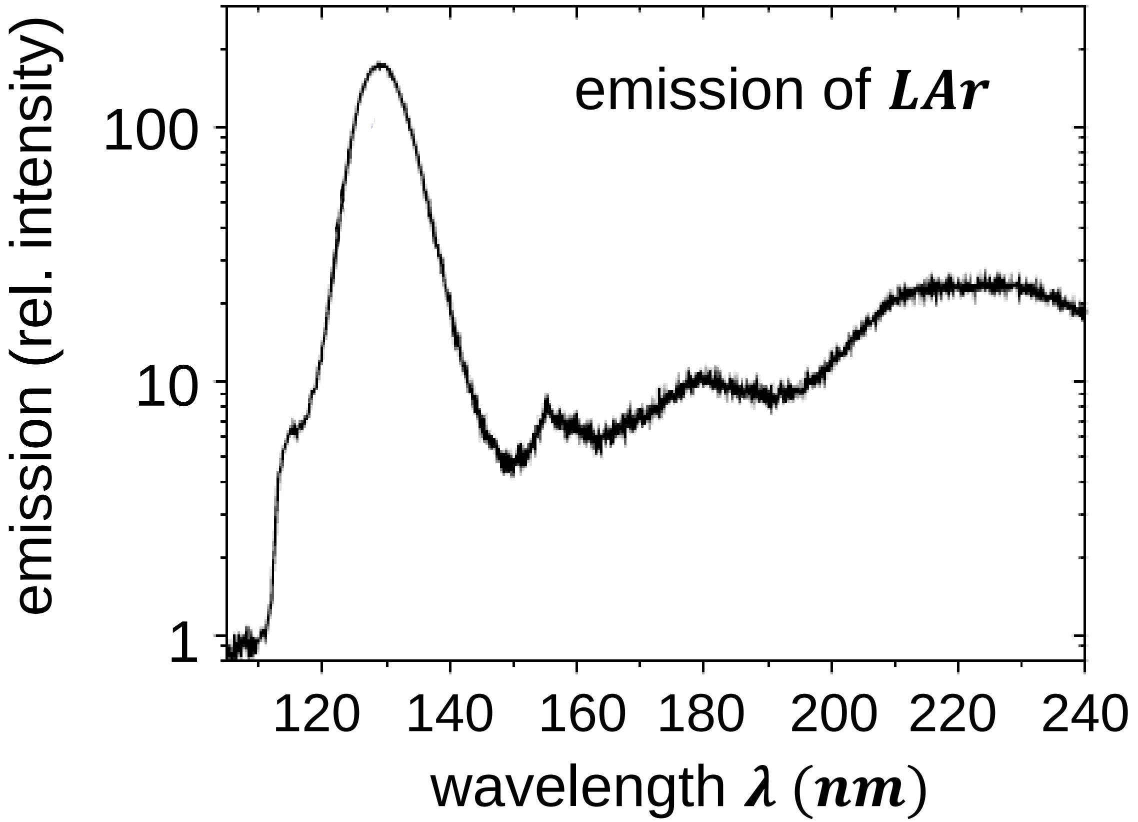
- **Liquid argon emission of ultra short-wave light with $\lambda \approx 120 \ldots 130\ nm$**

  - requires wavelenght shifter (photo-fluorescent material) in front of PMTs with bialkali photo-cathode





TPB (tetraphenyl-butadiene)



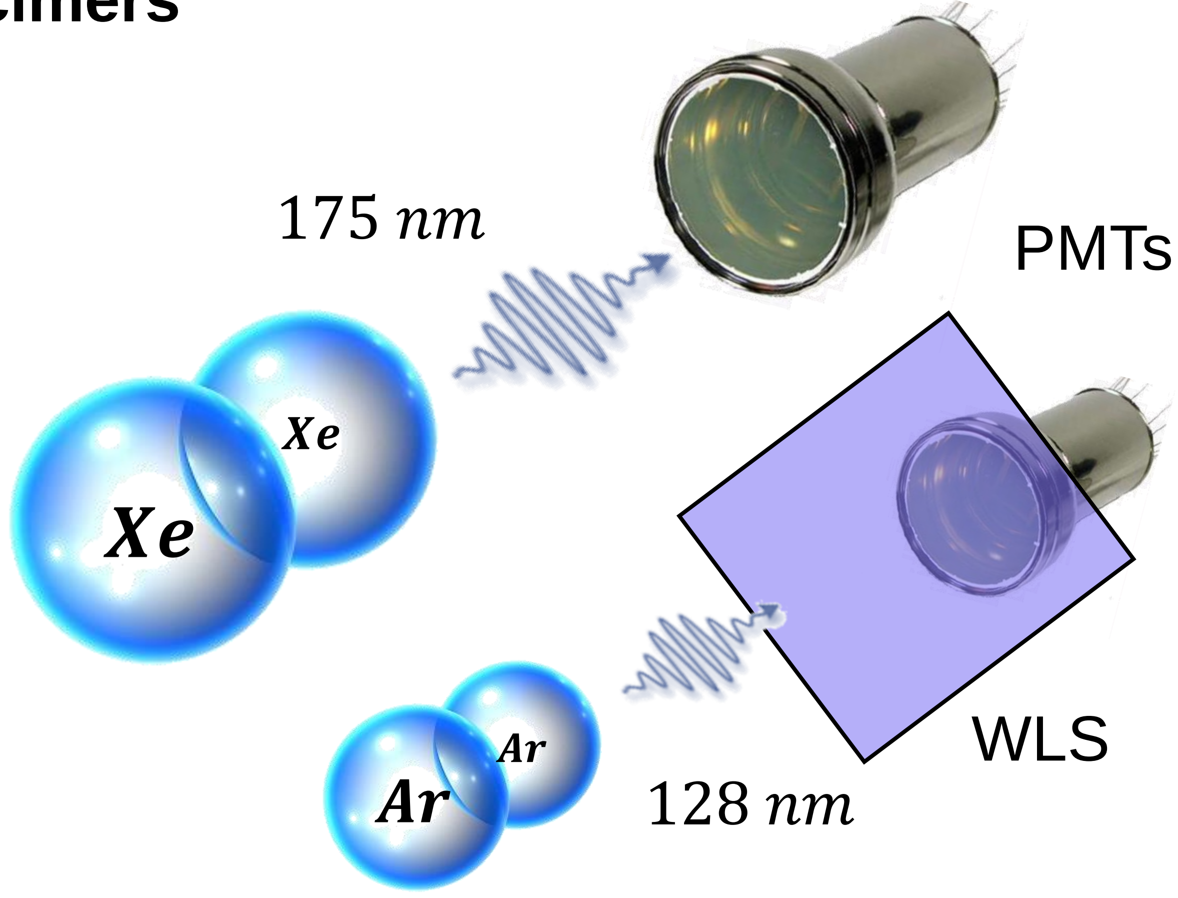
Liquid noble gases: scintillation light detection

Karlsruhe Institute of Technology

- **Scintillation light in the VUV due to excimers**

  - along the very short track of the recoiling nucleus: **excited dimers** (´**excimers**´) are formed
    ⇨ formation (very short-lived) of a noble gas ´molecule´ requires a large excitation energy of $E \sim 10\ \mathrm{eV}$
    ⇨ decay of the excimer after a few $\boldsymbol{ns}$, resulting in VUV scintillation light

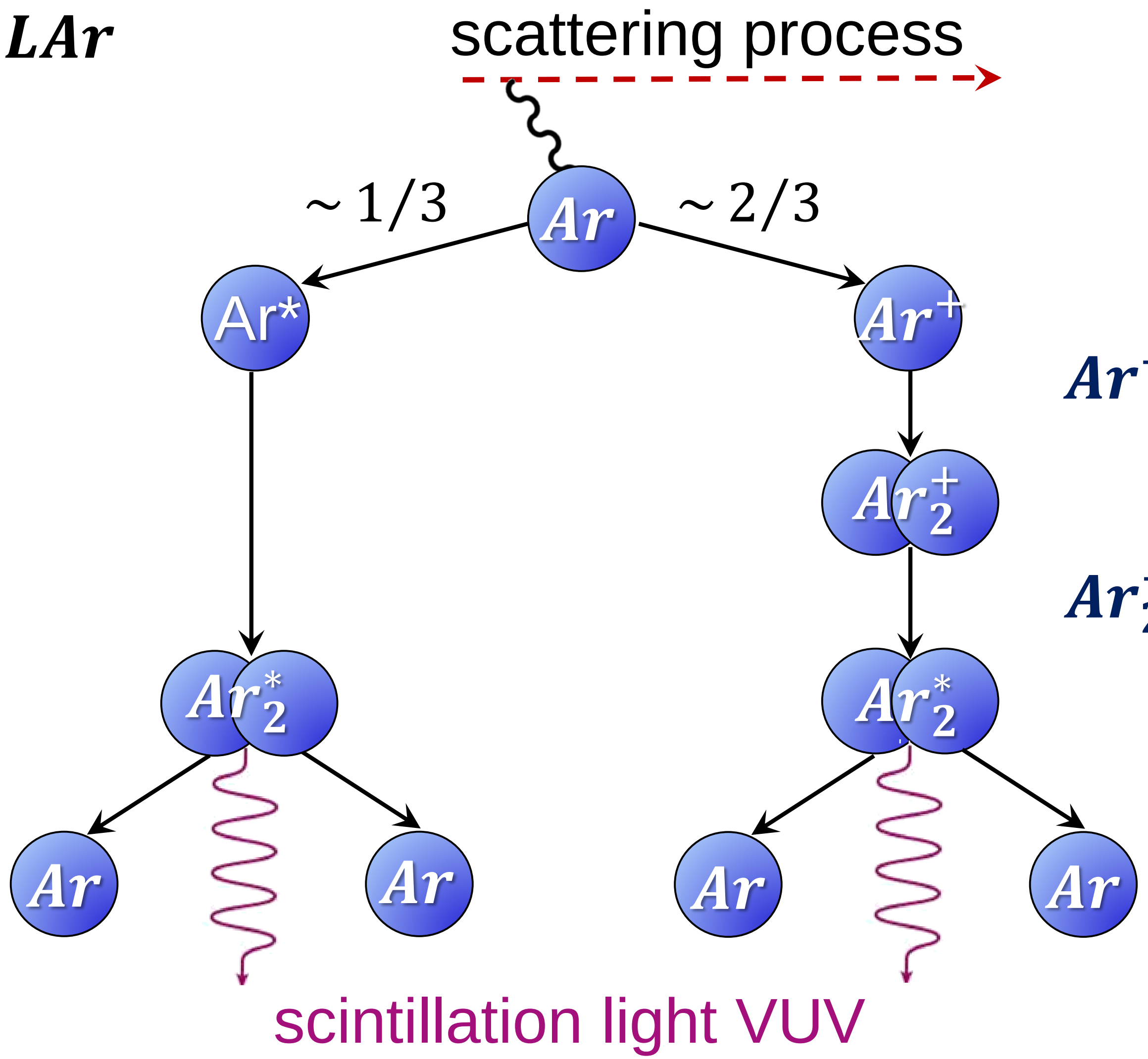
  - $\boldsymbol{LXe}$: special class of PMTs required which are sensitive in the VUV-range



$(\boldsymbol{Ar_2^*}, \boldsymbol{Xe_2^*})$ „**excimer**“

Liquid noble gases: gas-kinetic processes

- **Scintillation of LAr**



excitation

$Ar^* + Ar \to Ar_2^*$

excited molecule

decay & dissociation

ionisation

$Ar^+ + Ar + Ar \to Ar_2^+ + Ar$

ionised molecule

$Ar_2^+ + e^- \to Ar_2^*$ + heat

Liquid noble gases: gas-kinetic processes - LAr

Karlsruhe Institute of Technology

- **Different steps in the scintillation process using LAr as an example**

  - ionising radiation in liquid noble gas: **nuclear recoil of ^{40}Ar** or electron track

  - dE/dx along track: formation of ions (Ar^+) & excited atoms (Ar^*)

  - in both cases: formation of a short-lived **excited molecule** (Ar_2^*)

  - de-excitation of excited dimer / excimer (Ar_2^*)
    ⇨ **emission of scintillation light in the VUV-range**

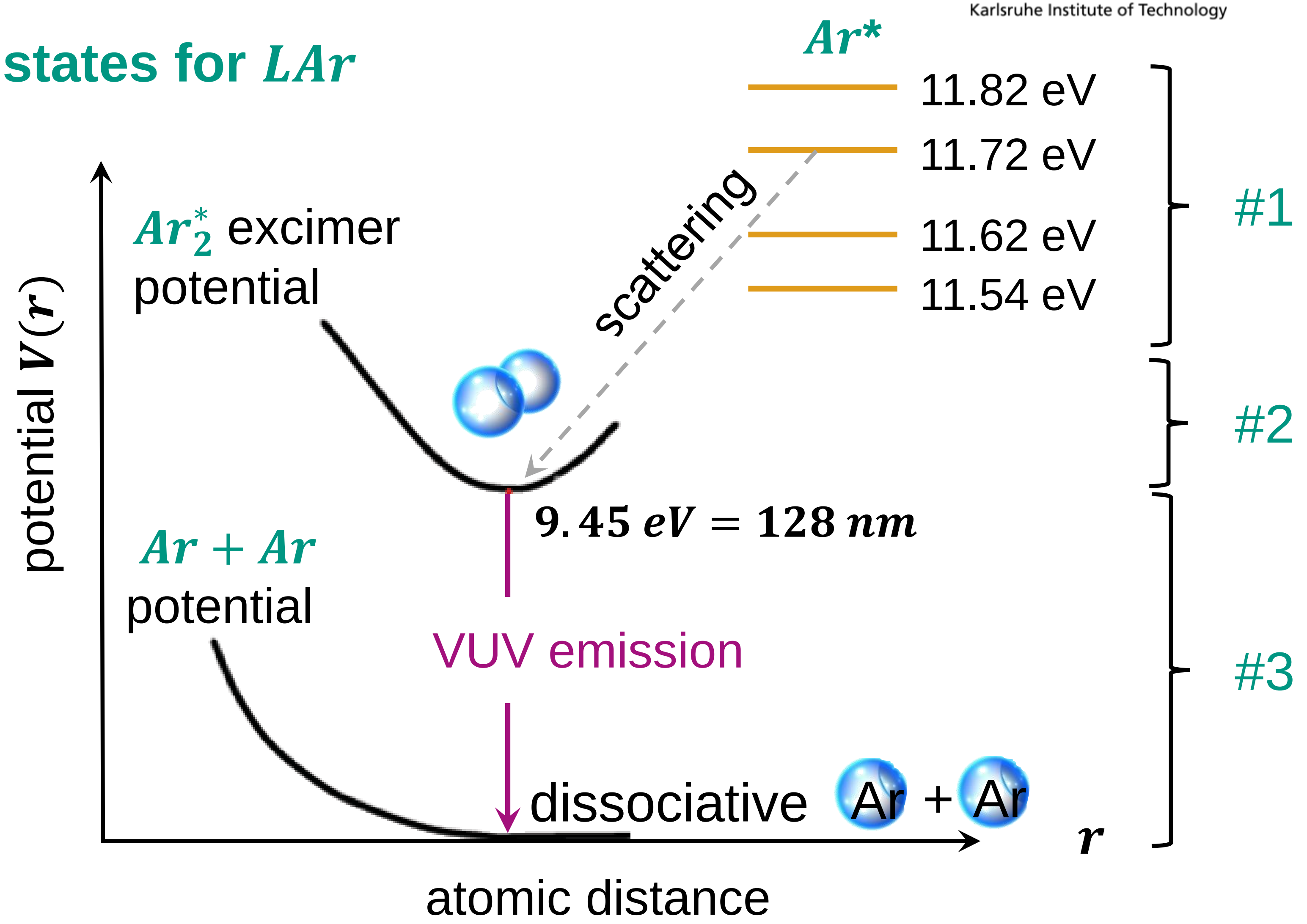
Liquid noble gases: formation of excimers

- A closer look at electronic states for LAr

- #1 **primary excitation**:
  low-lying atomic states Ar^*
  with $\Delta E_{exc} = 11.5 \ldots 11.8\ eV$

- #2 **scattering process**:
  $Ar^* + Ar \rightarrow Ar_2^*$
  formation of an excimer state ($9.45\ eV$) is allowed energetically

- #3 **excimer decay**:
  $Ar_2^* \rightarrow Ar + Ar$ + VUV

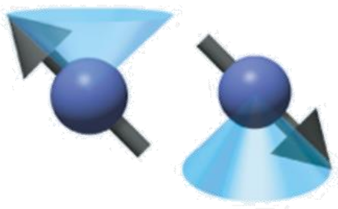


RECAP: singlet & triplet states

- **An important property of DM-detection with LAr: singlet/triplet states**

  - important: selection rules for de-excitation of excimer to g.s. atoms

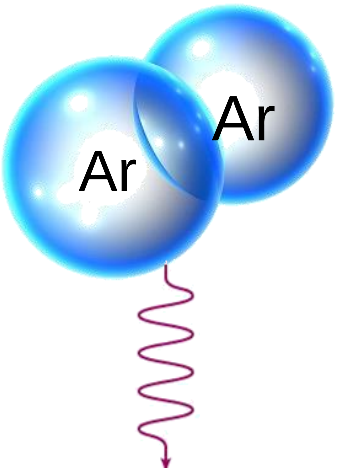
    ⇨ **different decay times of singlet/triplet states**



$$\frac{|\Uparrow\Downarrow\rangle - |\Downarrow\Uparrow\rangle}{\sqrt{2}}$$

singlet

$${}^{1}\Sigma_u^+$$

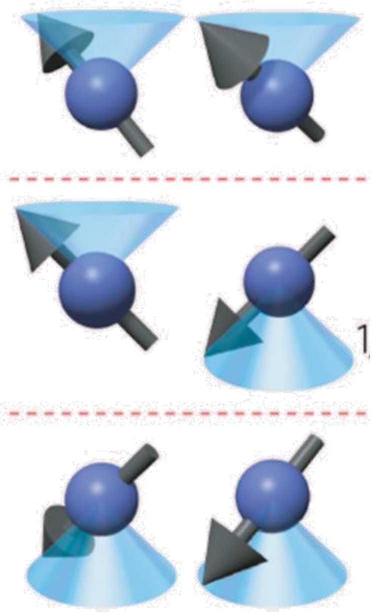


triplet

$${}^{3}\Sigma_u^+$$

$${}^{1}\Sigma_g^+$$

repulsive ground state



$$|\Uparrow\Uparrow\rangle$$

$$\frac{|\Uparrow\Downarrow\rangle + |\Downarrow\Uparrow\rangle}{\sqrt{2}}$$

$$|\Downarrow\Downarrow\rangle$$

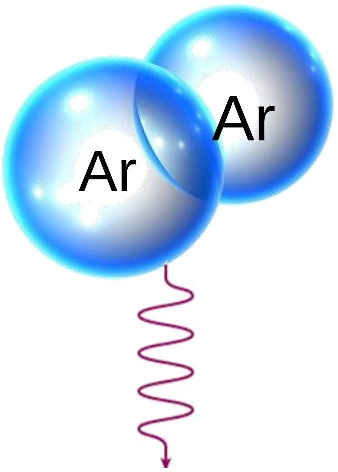
Decay of argon: singlet & triplet states

- **DM-search with LAr: decay time of the excimer is an important tool**

  - decay of excimer: the singlet & triplet **decay times differ significantly**
  can this be used for background discrimination between WIMPs & e^-?

singlet

$^1\Sigma_u^+$



triplet

$^3\Sigma_u^+$

$^1\Sigma_g^+$

τ_S (singlet) $=$ **$6\ ns$**

repulsive ground state

τ_T (triplet) $\approx$ **$1.6\ \mu s$**

Decay of argon: singlet & triplet states

- **DM-search with LAr**: decay time of the excimer ⇨ particle discrimination

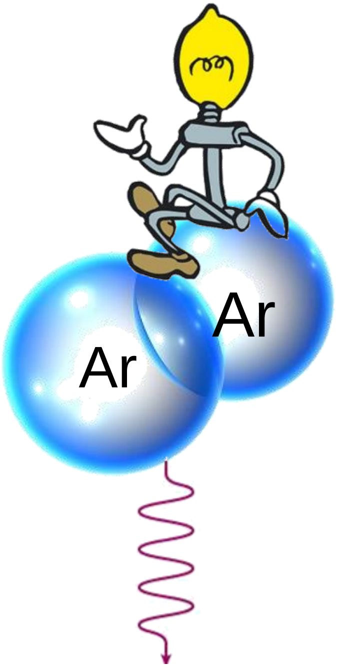
WIMP recoil nucleus

~70% of excimers in singlet states

´WIMP sprinter´

singlet

$^1\Sigma_u^+$



$^1\Sigma_g^+$

repulsive ground state

triplet

$^3\Sigma_u^+$

background electron

80…90% of excimers in triplet states

´background walker´

DM-searches with LAr – detectors

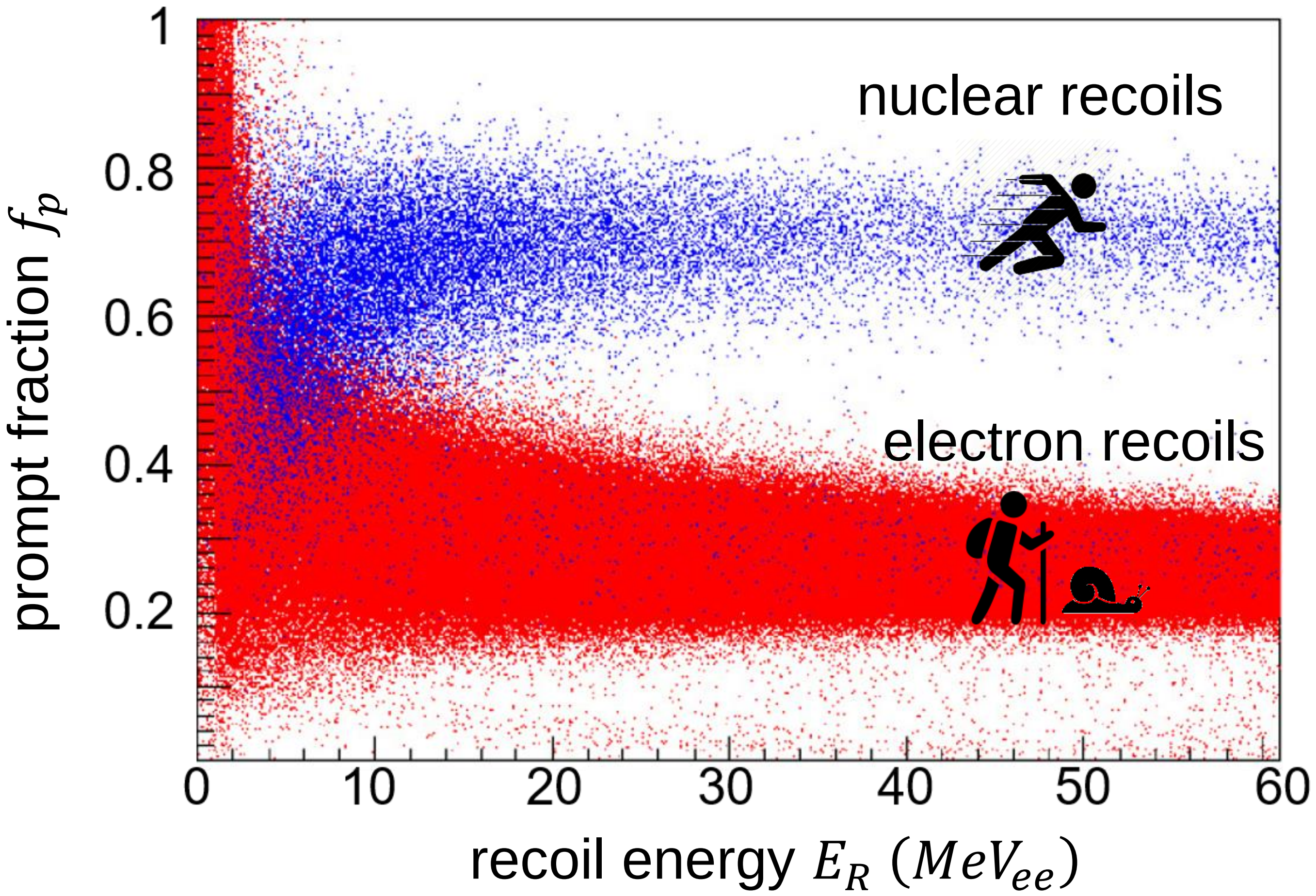
- **Pulse Shape Discrimination (PSD): prompt fraction f_p of light seen by PMTs**

- particle discrimination between WIMP-recoils & bg-electrons: different fraction of excimers in singlet / triplet state

- PID-parameter f_p: fraction of ´early´ light in the **first 100 ns**

⇨ **small** for triplet states (e^-)

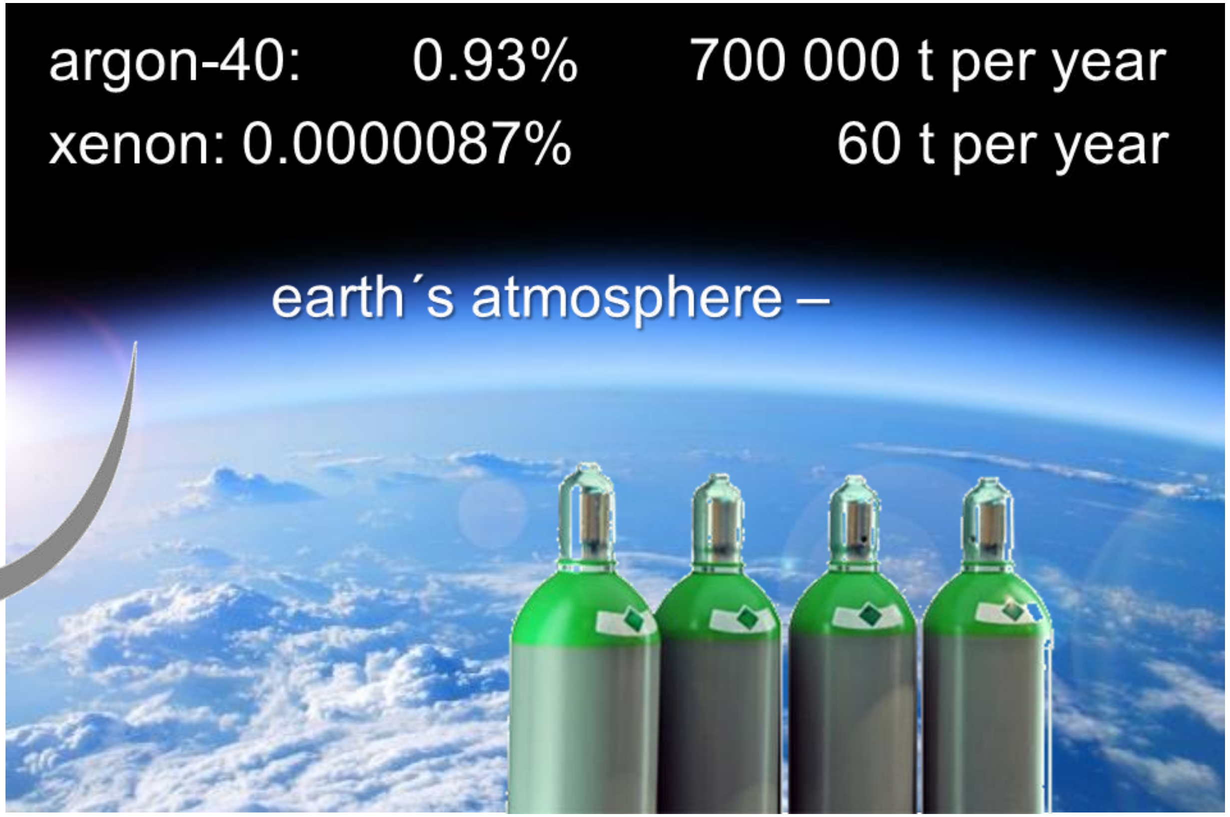
⇨ **large** for singlet states (^AZ)



EXTRA: MARKET RESEARCH INTO LXE/LAR

Karlsruhe Institute of Technology

- **Direct DM-searches: we need large detector masses – is this possible?**
  - LAr – experiments: argon is available in huge quantities due to ^{40}Ar – content
  - LXe – experiments: rather limited xenon world production ($\mathbf{60\ t\ yr^{-1}}$)
    ⇨ significant cost factor in direct DM-searches (**DARWIN $\mathbf{50\ t}$**)



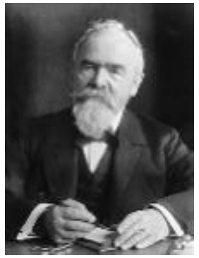
EXTRA: PRODUCTION OF LXE

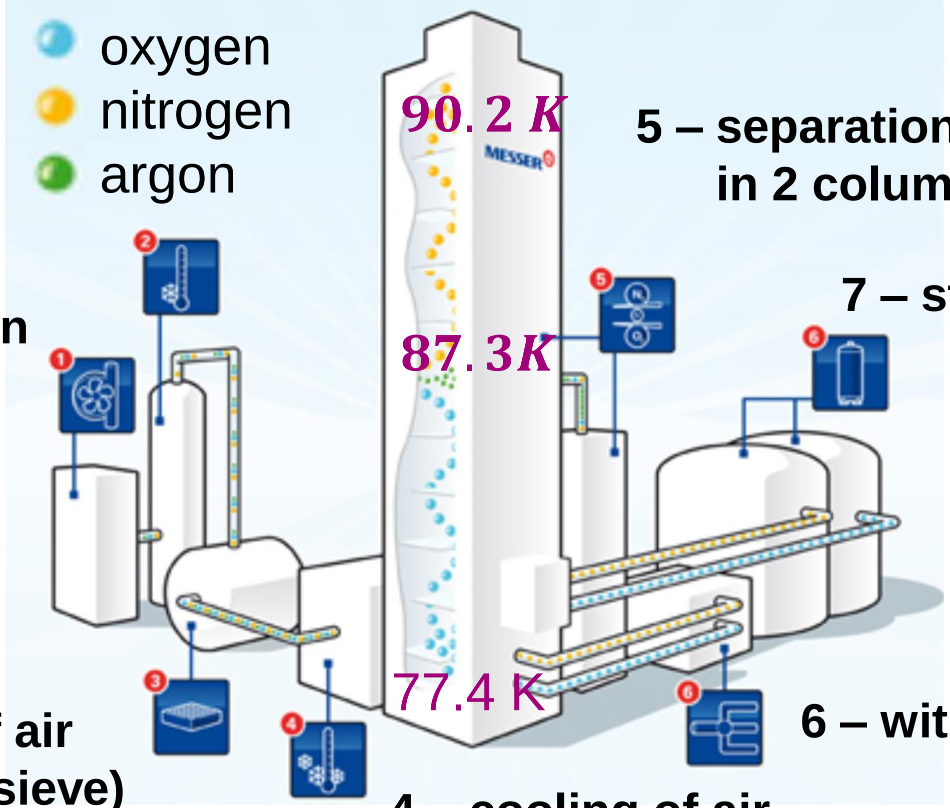
■ xenon: a precious by-product of commercial air liquefication

- **xenon**: generated in several large-scale commercial **a**ir **s**eparation **u**nits (**ASU**s) goal: production of oxygen for steel mills

- global ASU throughput: $\sim 100\ km^3/year$

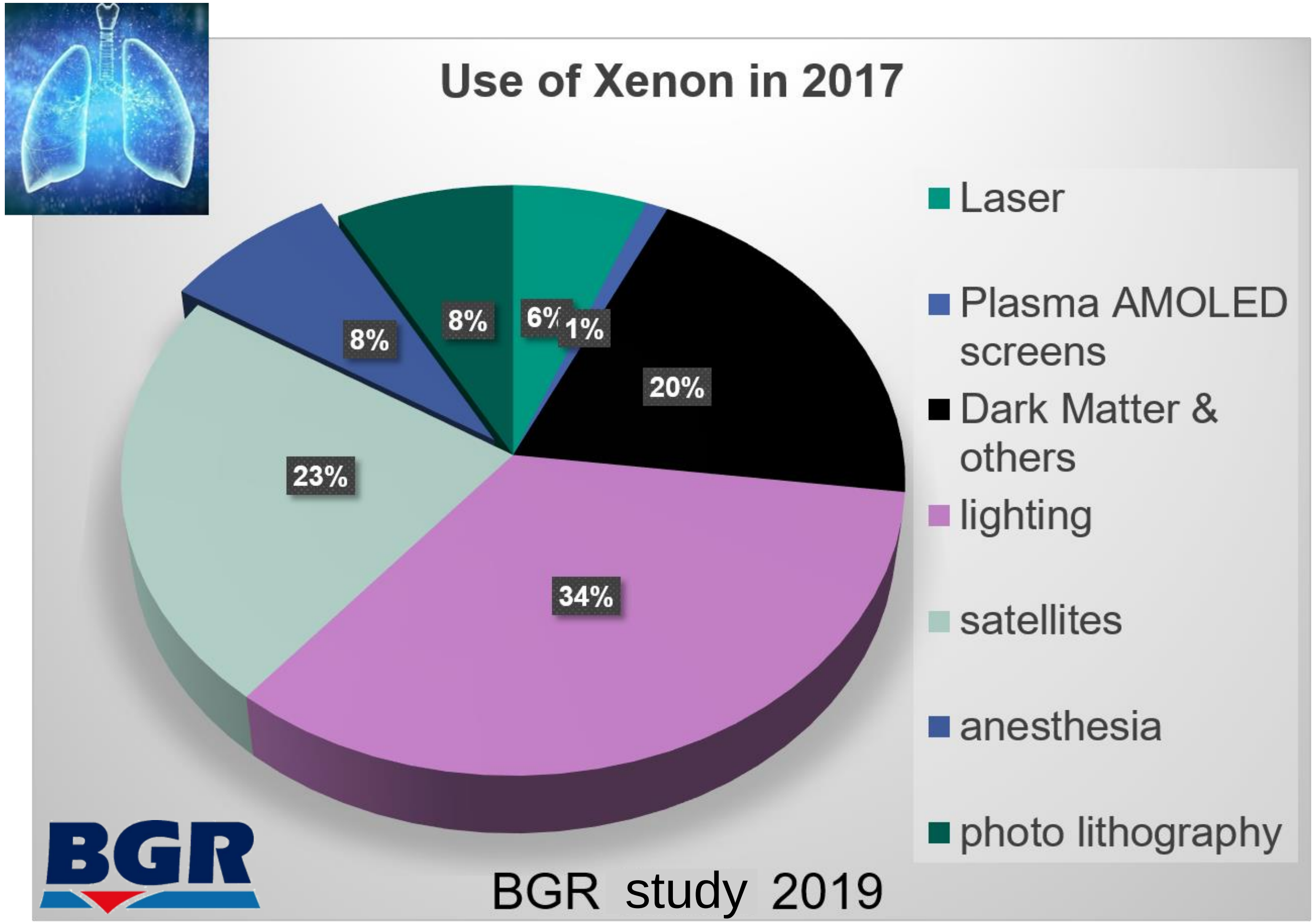
- cryodestillation allows to separate xenon from argon





EXTRA: PRODUCTION OF LXE

- DM-consumption compared to others



SOPHIA CHEN SCIENCE 01.11.18 08:00 AM

HOW DARK MATTER PHYSICISTS SCORE DEALS ON LIQUID XENON

Researchers assemble a prototype for their dark matter detector's core, known as a time projection chamber. CHRISTOPHER SMITH/SLAC NATIONAL ACCELERATOR LABORATORY

Liquid noble gases: intrinsic bacckground

- **Xenon as cryogenic fluid contains $^{85}\boldsymbol{Kr}$ – a source of background**

  - krypton & its isotope $^{85}\boldsymbol{Kr}$ – an unwanted admixture due to similiar boiling points

we need to purify our xenon from this krypton – again by cryodestillation!

LXe-experiments: isotope Kr-85

- $^{85}\boldsymbol{Kr}$: β –decay with $Q = 687.4\ keV$ & $t_{½} = 10.6$ years (long-lived!)

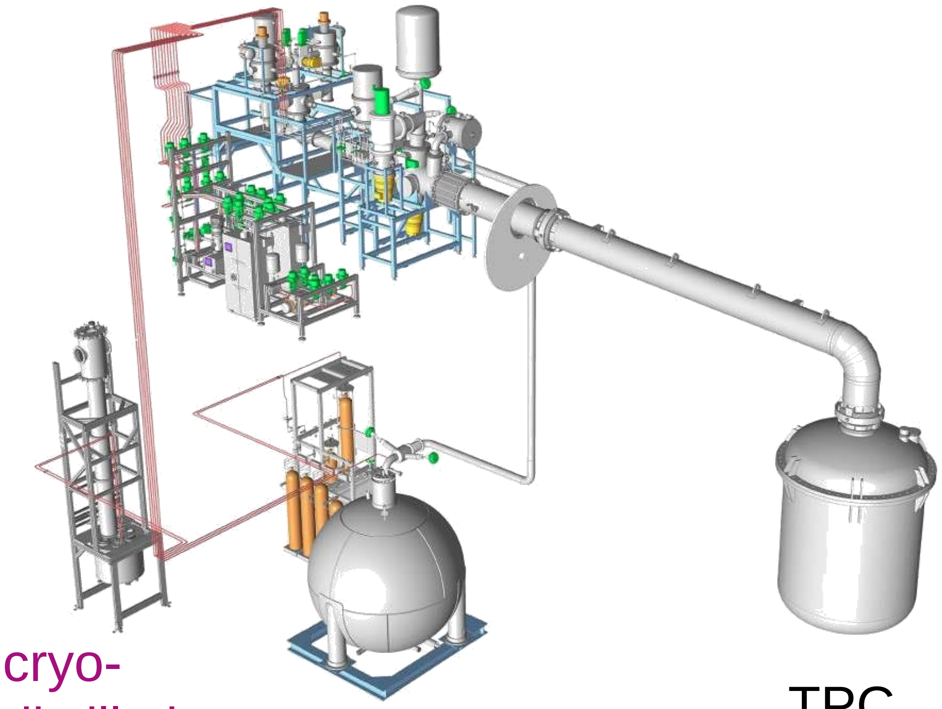
  - anthropogenic origin (from nuclear fission with 0.3% yield)
  - worldwide inventory: $\boldsymbol{A \sim 5.5\ TBq}$
    $\boldsymbol{\sim 1.3\ Bq\ m^{-3}}$

^{85}Kr
$t_{½}$ = 10.6 a

Liquid noble gases – fighting intrinsic background

- **Example: large-scale cryodestillation of xenon to remove ^{85}Kr**

  - xenon target successfully purified: no traces of $^{85}\boldsymbol{Kr}$ detected



LXe-experiments: isotope Kr-85

- $^{85}\boldsymbol{Kr}$: β –decay with $Q = 687.4\ keV$ & $t_{1/2} = 10.6$ years (long-lived!)

  ^{85}Kr

  $t_{1/2}$ = 10.6 a

  - installation of a column for dedicated cryodistillation
  - result: fraction of ^{85}Kr is reduced to a (immeasurable) level of $< \boldsymbol{0.3\ ppt}$

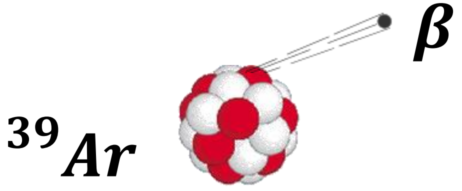
Liquid noble gases – fighting intrinsic background

- **Example: large-scale removal of isotope ^{39}Ar is required in LAr detectors**

- β – emitting isotope ^{39}Ar : trace amounts are part of the atmospheric argon inventory

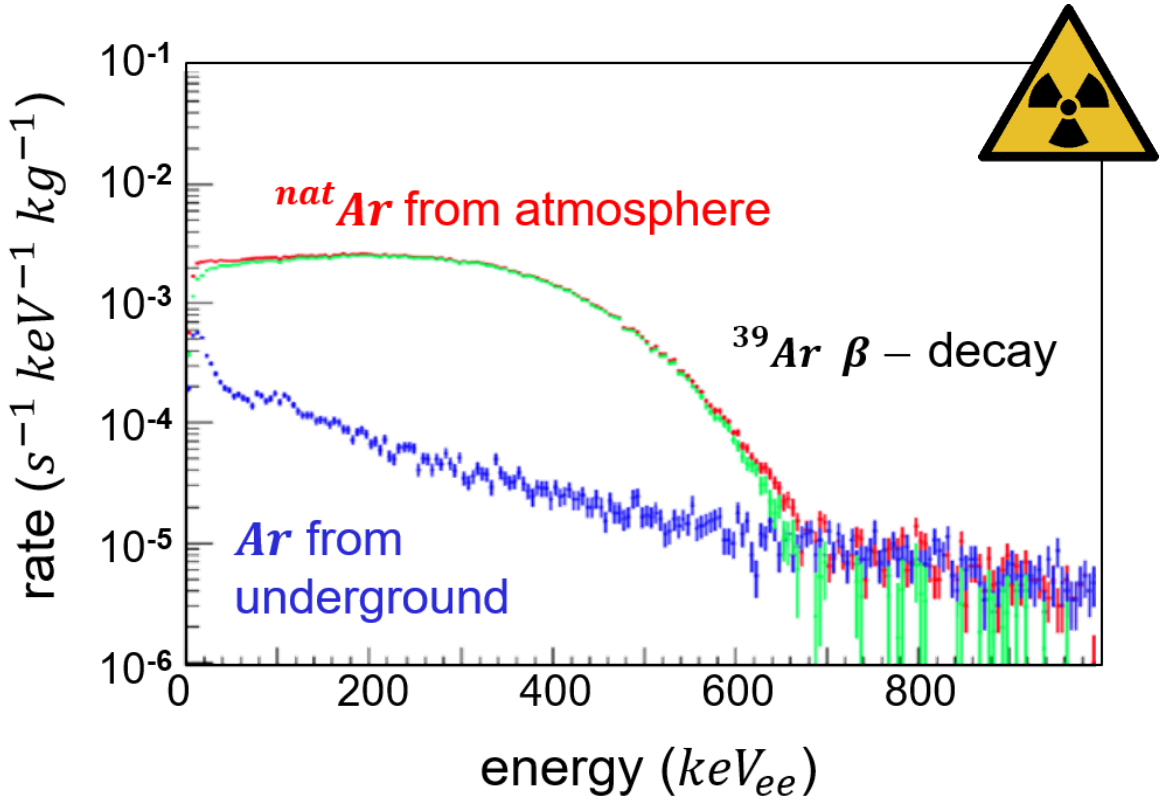
β – decay with $Q = 565\ keV$

$t_{½} = 269\ y$



⇨ very high β – activity: $\sim 1\ Bq$ **per** $kg\ Ar$

LAr –experiments: isotope Ar-39

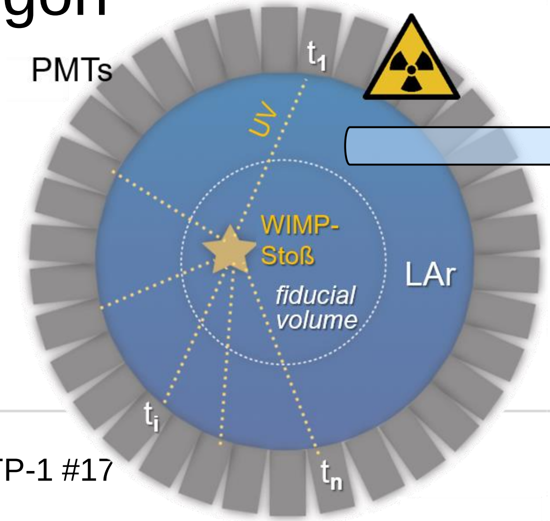


Liquid noble gases – fighting intrinsic background

- **Example:** **underground Ar**

- β – emitting isotope ${}^{39}\boldsymbol{Ar}$: produced by $(n, 2n)$ – reactions of cosmic ray muons in the atmosphere off ${}^{40}\boldsymbol{Ar}$

⇨ extract & use ´shielded´ underground argon



LAr –experiments: isotope Ar-39

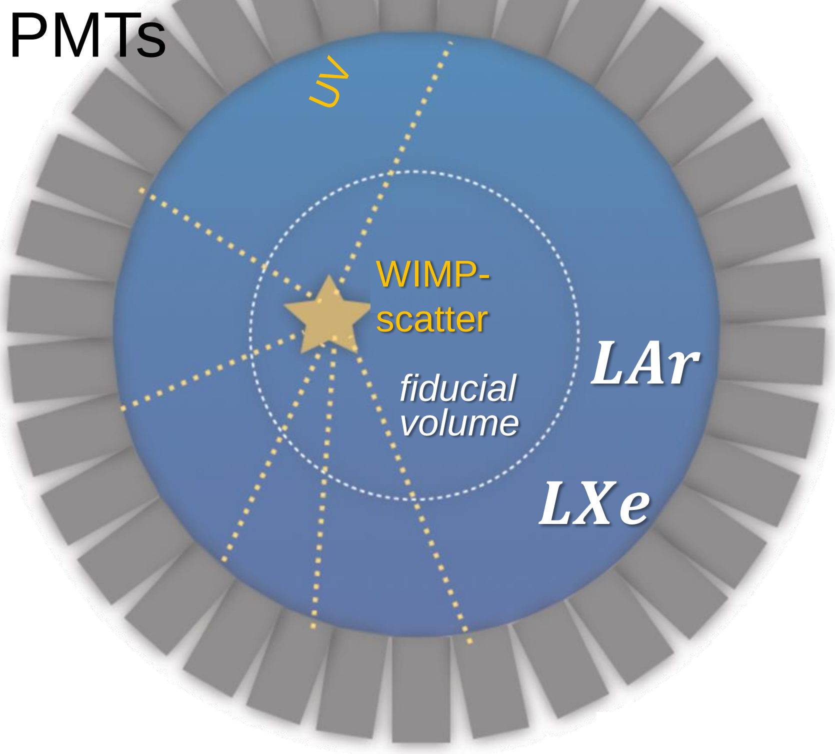
extraction of underground argon

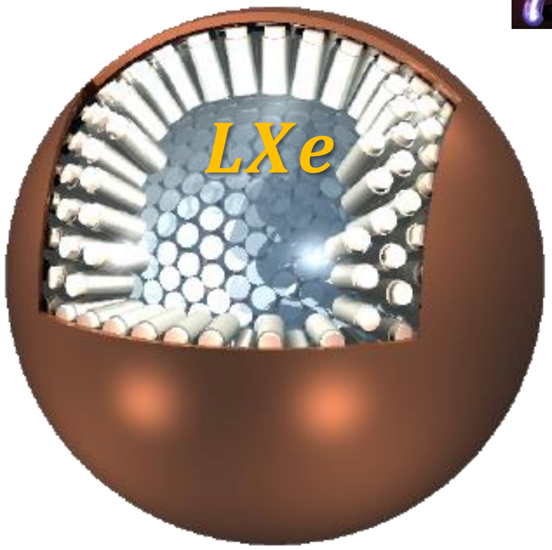
Liquid noble gases: single phase experiments

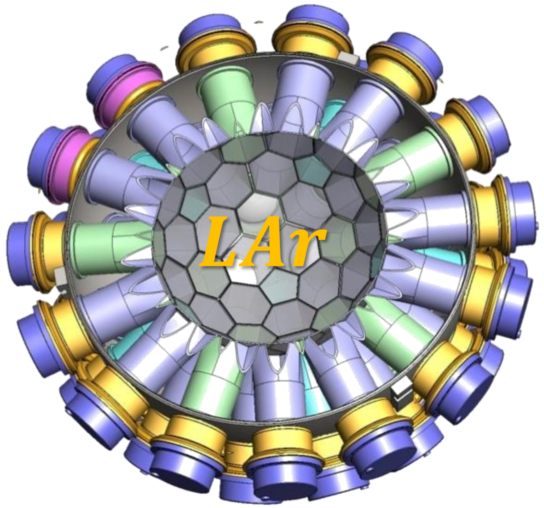
- **Early DM-experiments focusing only on 1 parameter: scintillation light**

spherical geometry

- **1 phase experiments**: entire target mass in form of a liquid noble gas – LXe or LAr







Liquid Argon experiments: MiniCLEAN

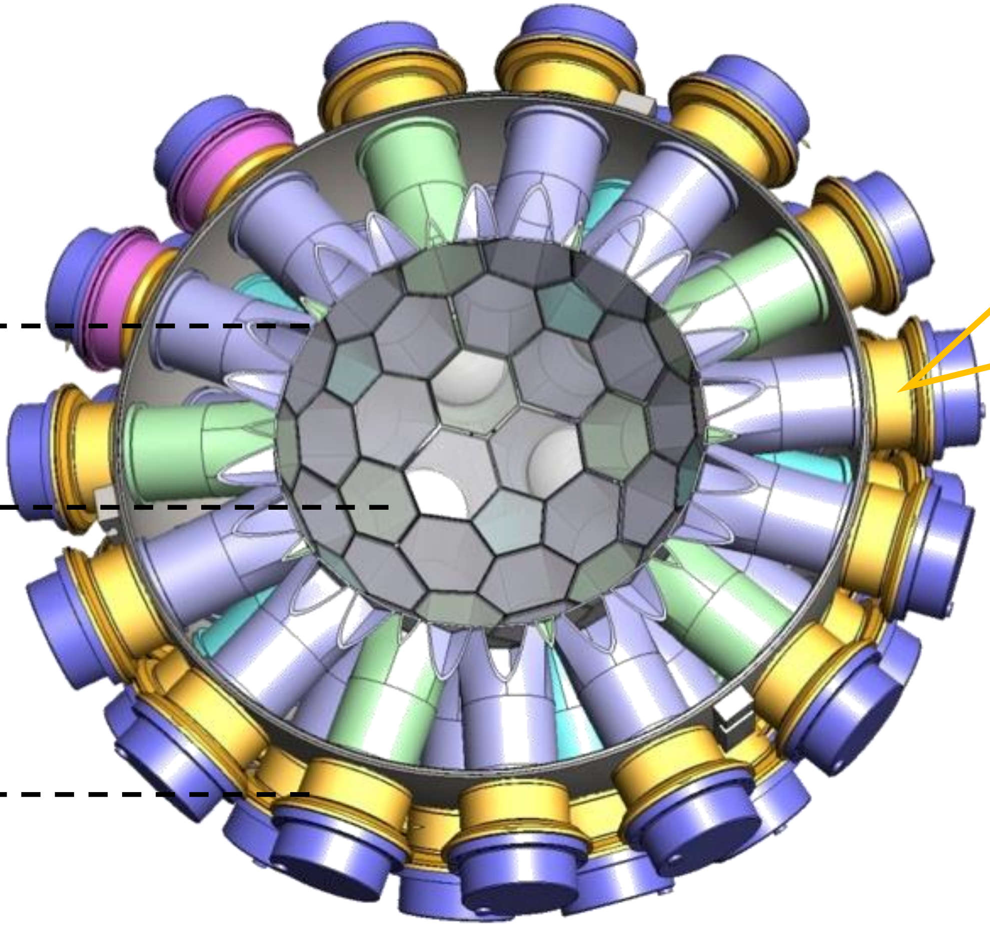
- R&D prototype for a (planned) larger detector (CLEAN) with 1 parameter

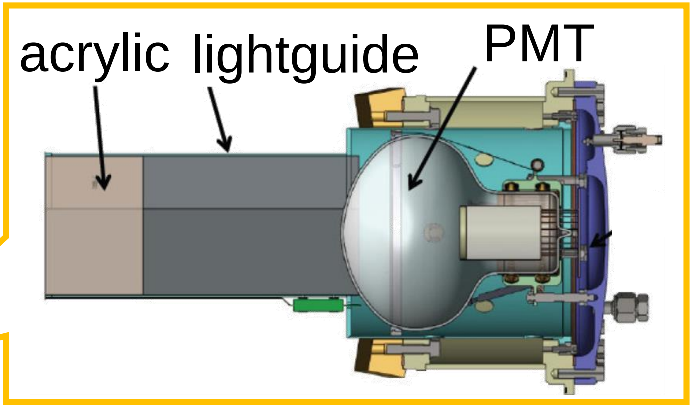
Ø = 45 cm

500 kg argon

(150 kg fiducial mass)

92 PMTs





Liquid Argon experiments: MiniCLEAN

- **R&D prototype for a (planned) larger detector (CLEAN) with 1 parameter**

  - **P**ulse **S**hape **D**iscrimination (PSD) to separate nuclear recoils from electrons

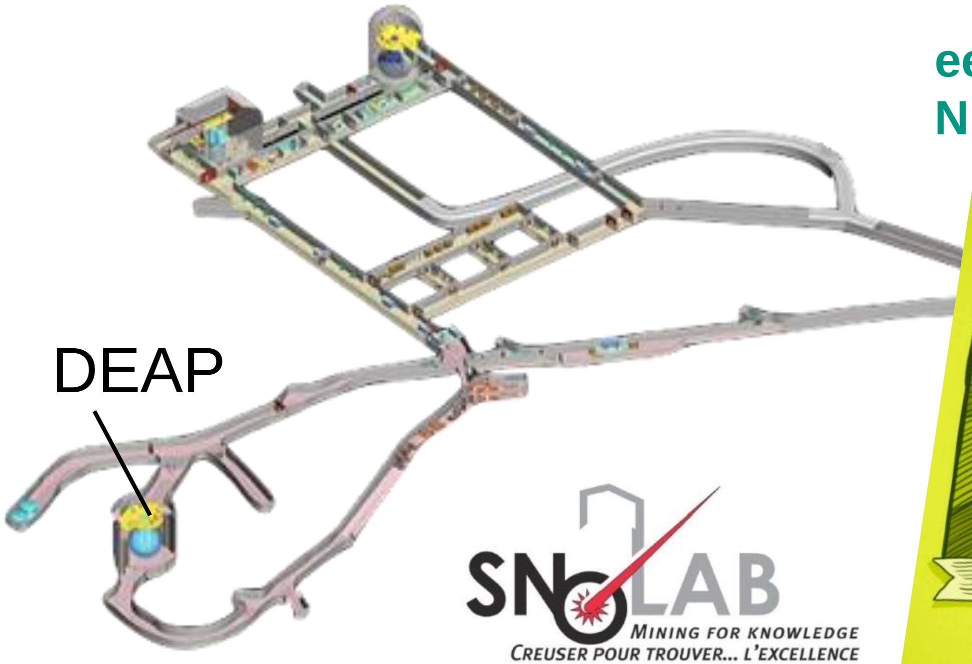
SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

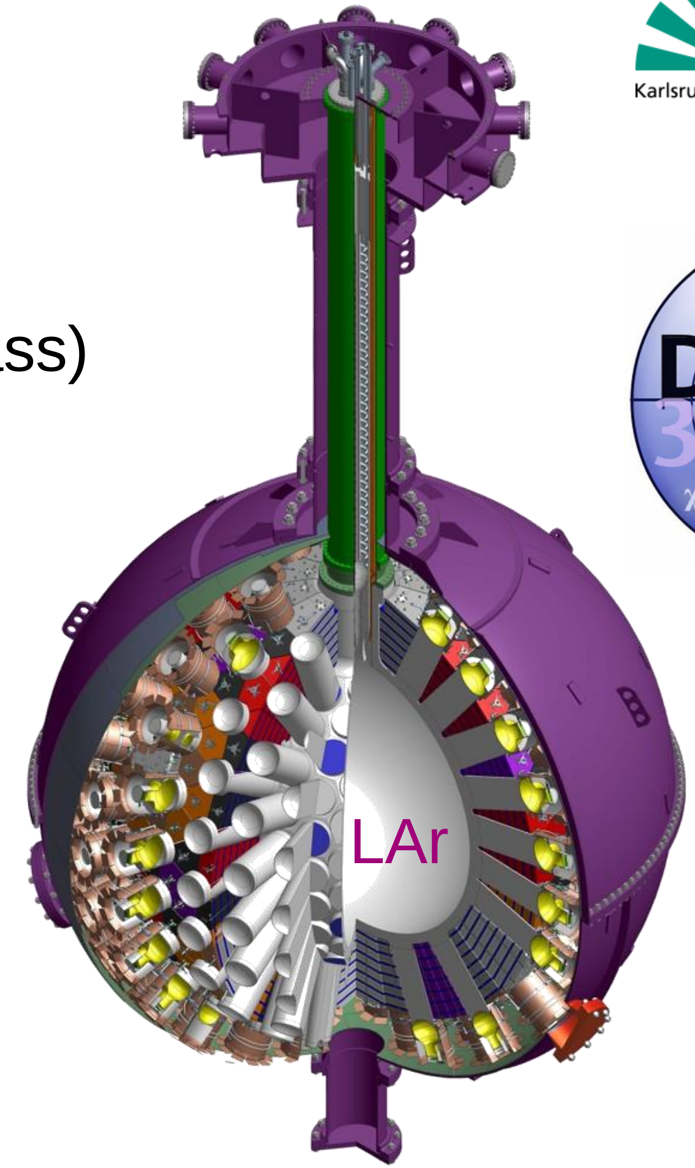
Liquid Argon experiments: DEAP

- **Dark Matter Experiment using Argon Pulse shape discrimination**

  - target mass: $\mathbf{3.6\ t}$ liquid argon (1 t fiducial mass)
  - threshold: $\mathbf{15\ keV_{ee} = 60\ keV_{NR}}$

ee: electron equivalent
NR: Nuclear Recoil





Liquid Argon experiments: DEAP

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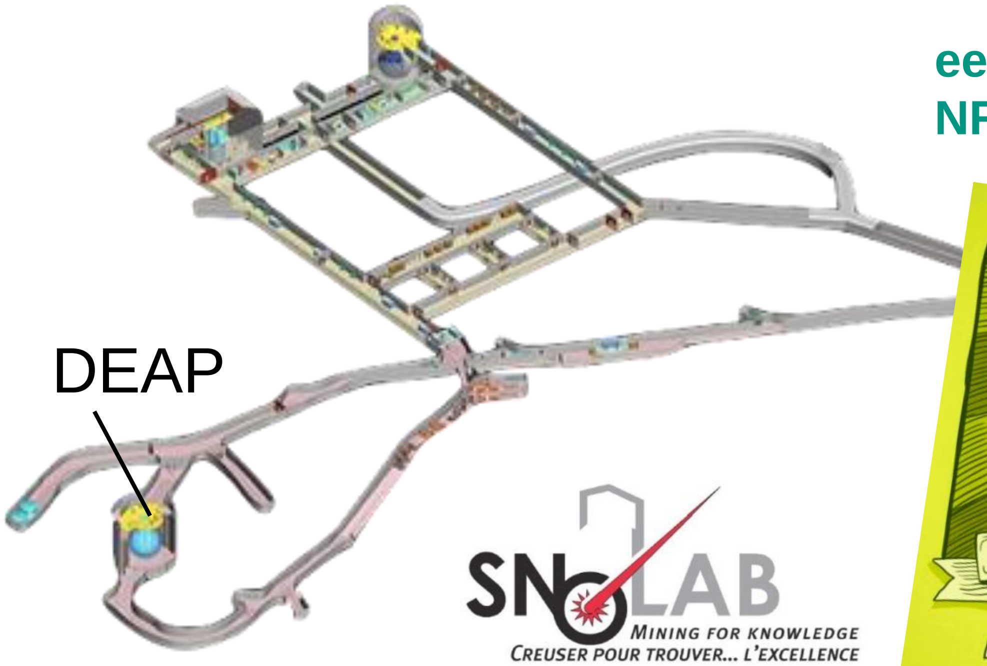

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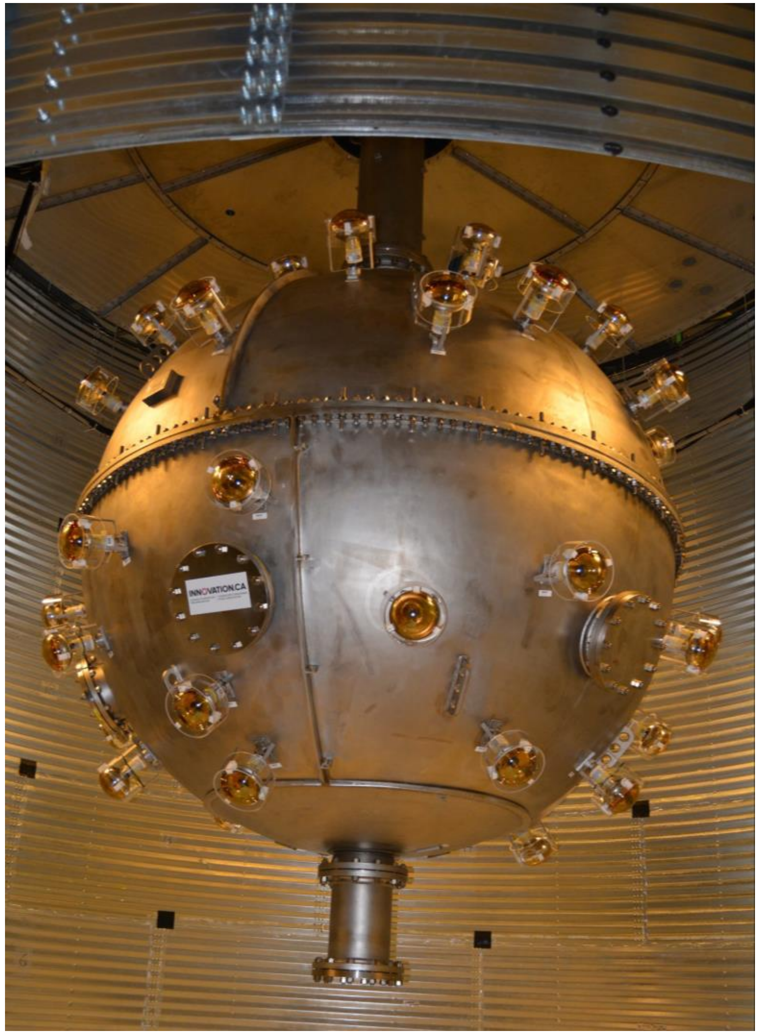
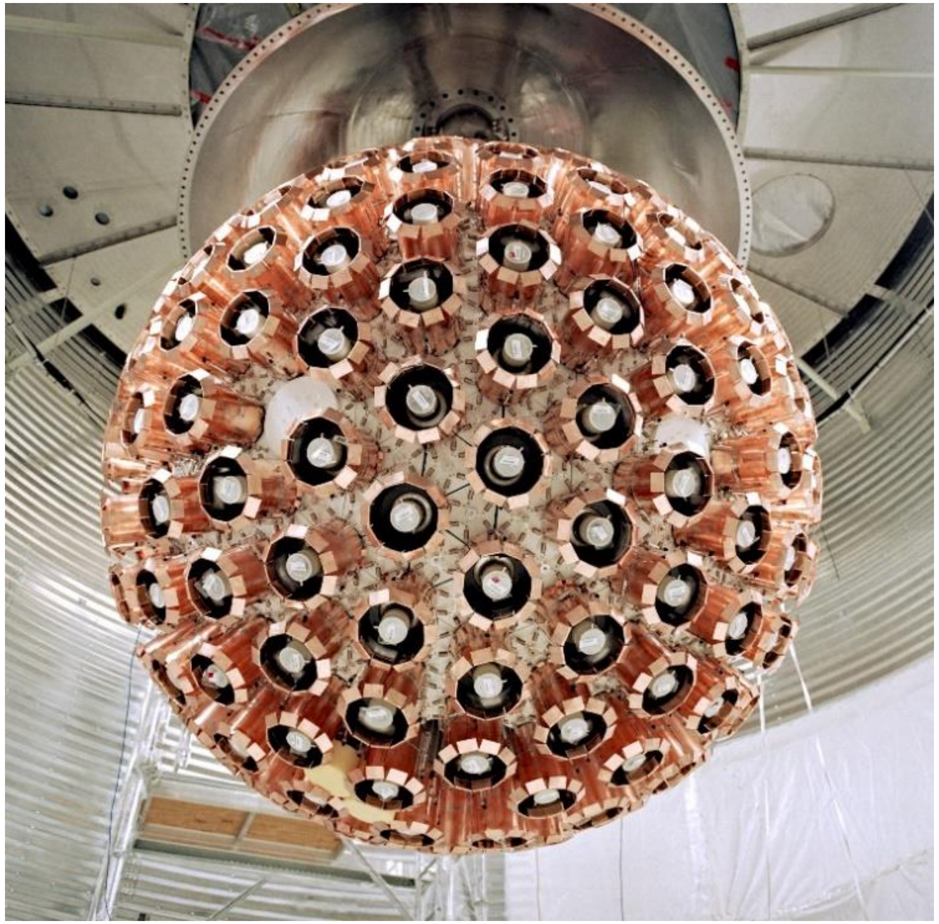
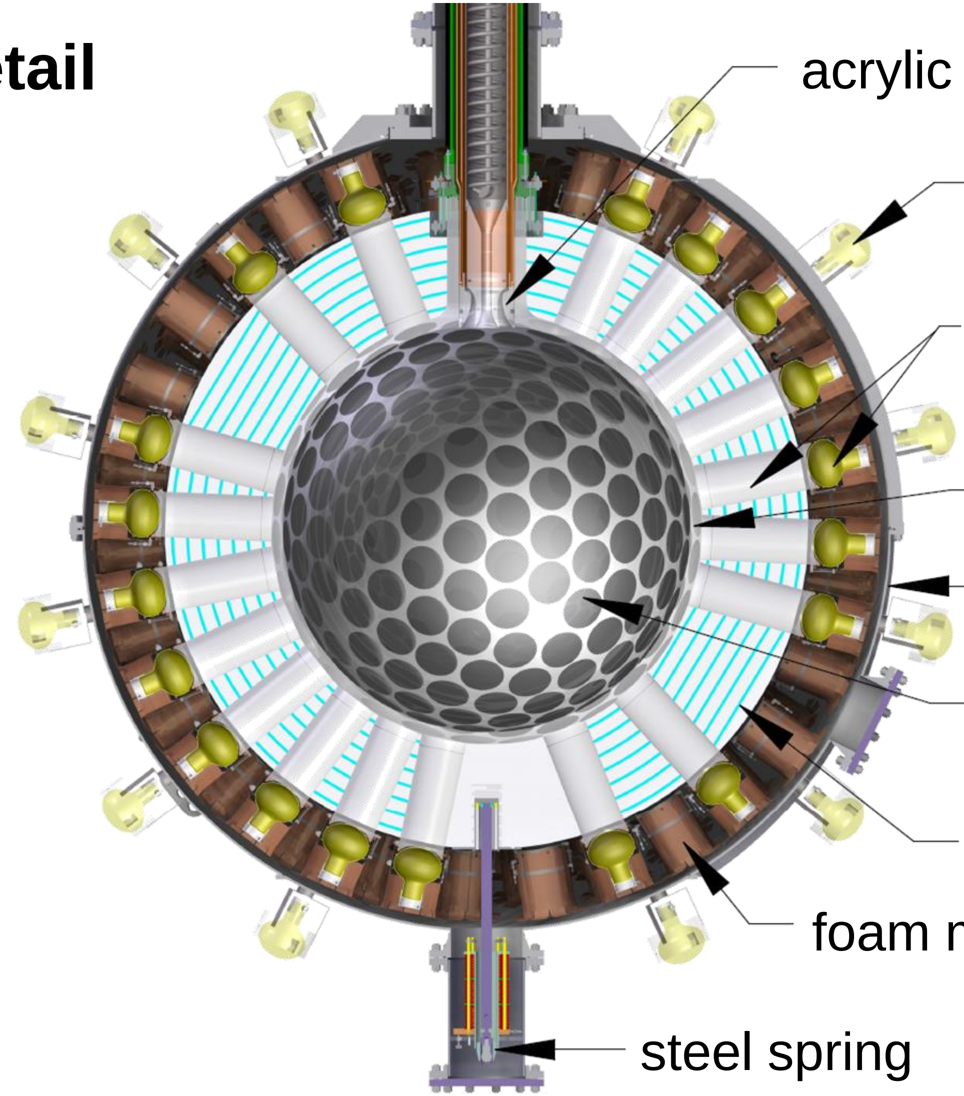


Liquid Argon experiments: DEAP

■ **DEAP detector setup in detail**

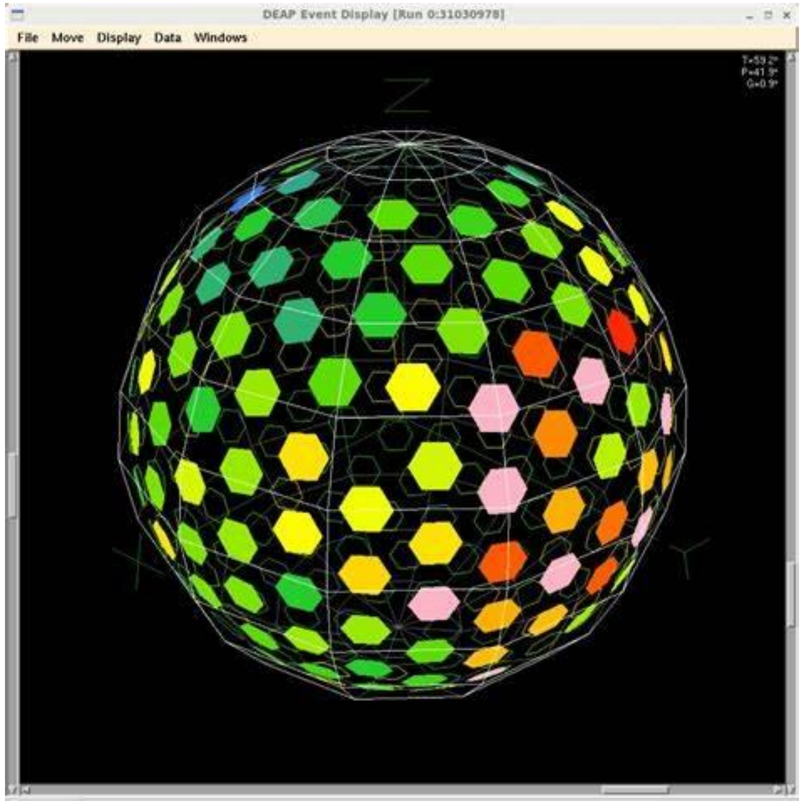




Liquid Argon experiments: DEAP

Measurements and results

- DEAP event



- measurements & data taking since 2016

- optimised for extreme **radio purity** of all detector components

- DM-results 2019

  - 231 days measurement time

  - no WIMP signal

  - $\boldsymbol{\sigma_{SI} < 3.9 \times 10^{-45}\ cm^2}$ ($\boldsymbol{100\ GeV}$ WIMPs)

Liquid Argon experiments: DEAP-50 t

- **A (planned) very large 1-phase $LAr-$ experiment**

  - 50 t *fiducial mass* =
    150 t in acrylic vessel

  - expected WIMP-sensitivity
    $\boldsymbol{\sigma_{SI} \sim 2 \cdot 10^{-48}\ cm^2}$

  - argon target planned with **depletion factor of 200** for ^{39}Ar - on an „industrial scale“

´only´ 1-phase-layout

CANCELLED