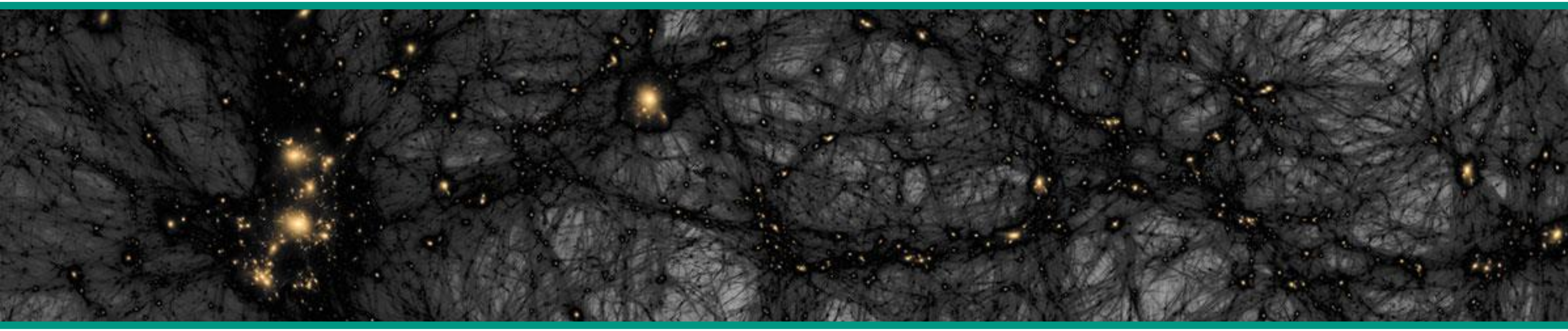
Astroparticle physics *I* – Dark Matter

Winter term 23/24 Lecture 17 Jan. 18, 2024



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**)

  - scattering 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

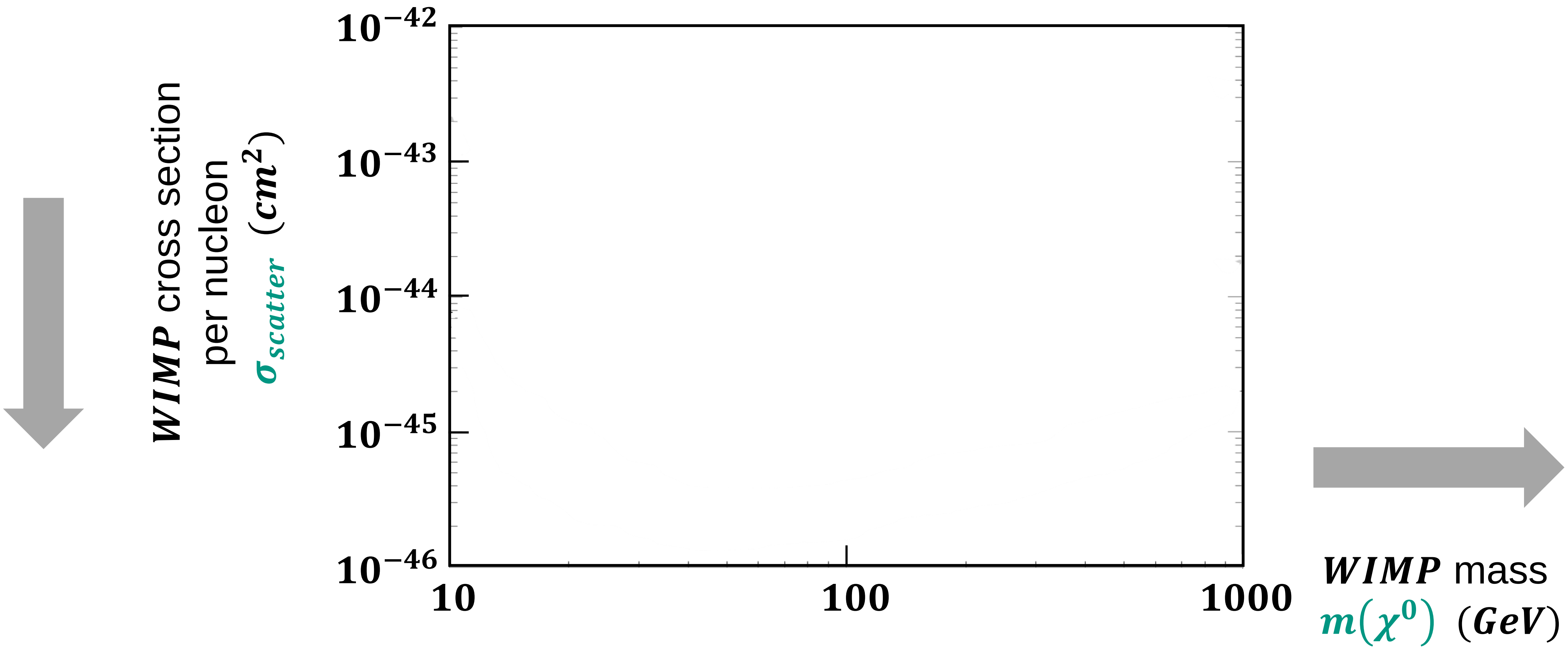
  - solid–state answer **to recoil nucleus**:
    - **phonons** ($few\ meV$)
    - **scintillation** ($100 \ldots 200\ eV$)
    - **ionisation** ($< 20\ eV$)

    phonons + scintillation } **energy E_R**

    ionisation ⇨ PID **via quenching**

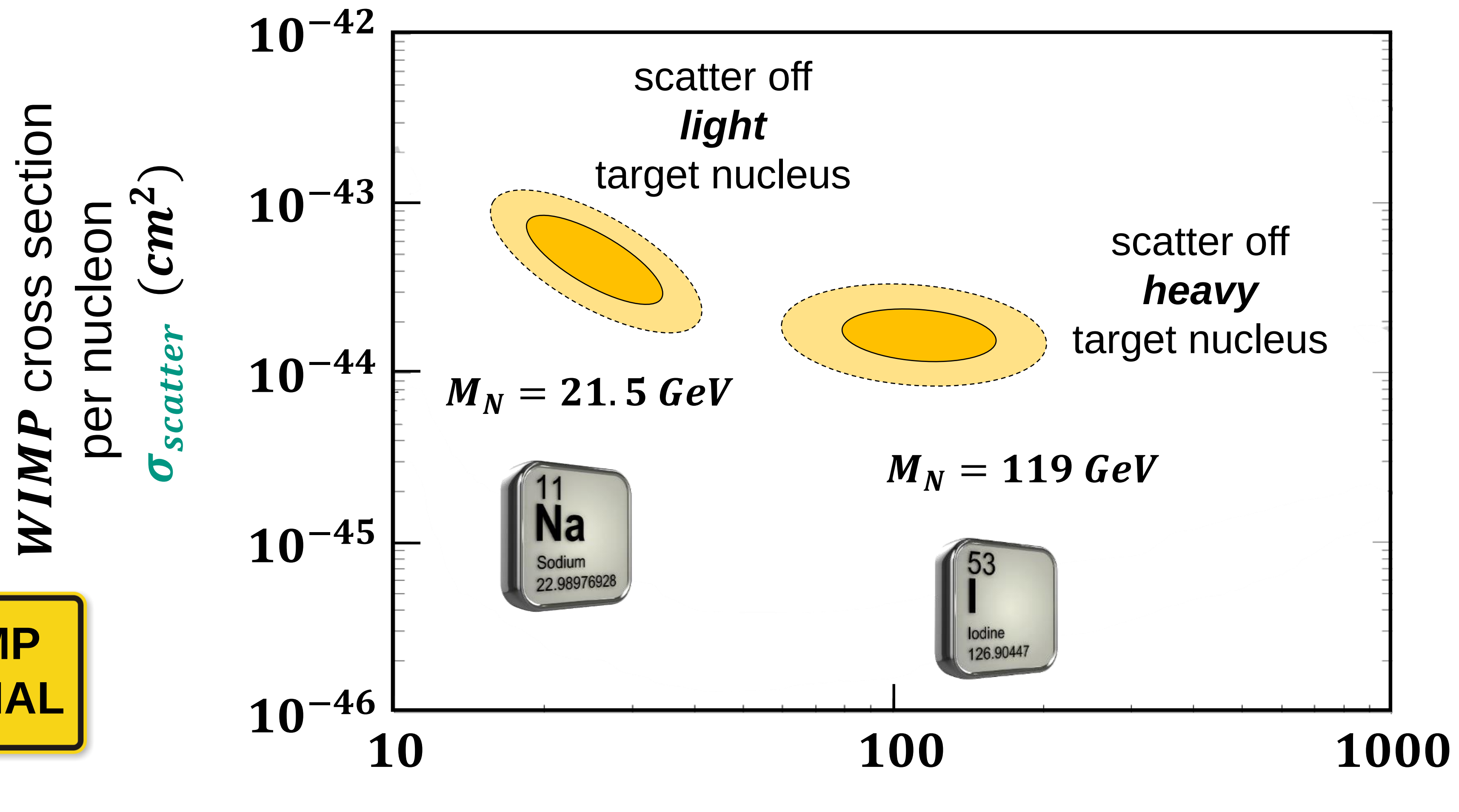
Introducing the famous ´$WIMP$´ plot

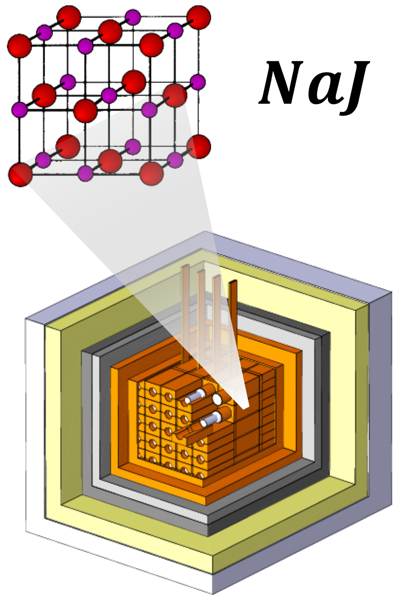
- Comparing different experiments in a $2-$ parameter plot:



$WIMP$ plot in case of a signal (claim)

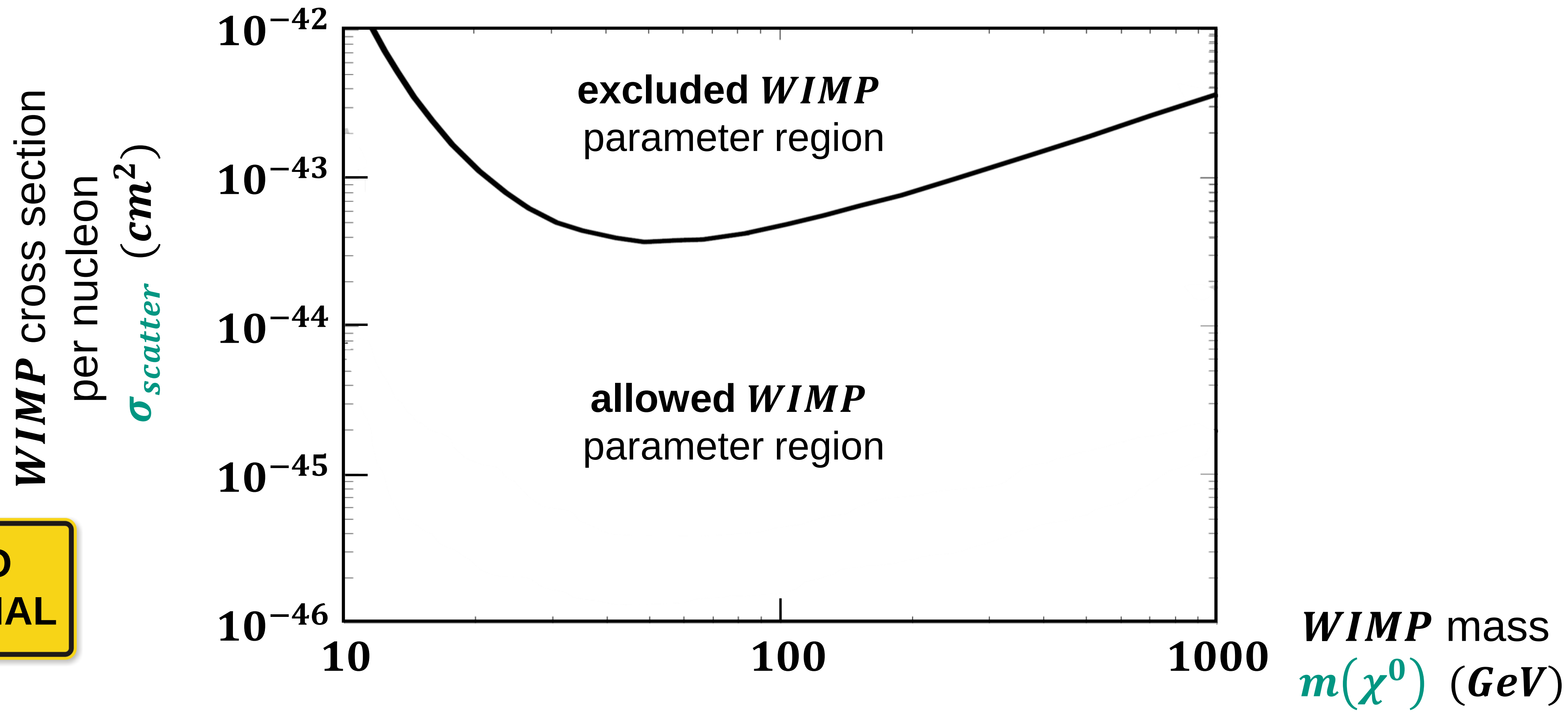
- Claiming an evidence for a DM −signal: error ellipses for $m(\chi^0)$, $\sigma_{scatter}$





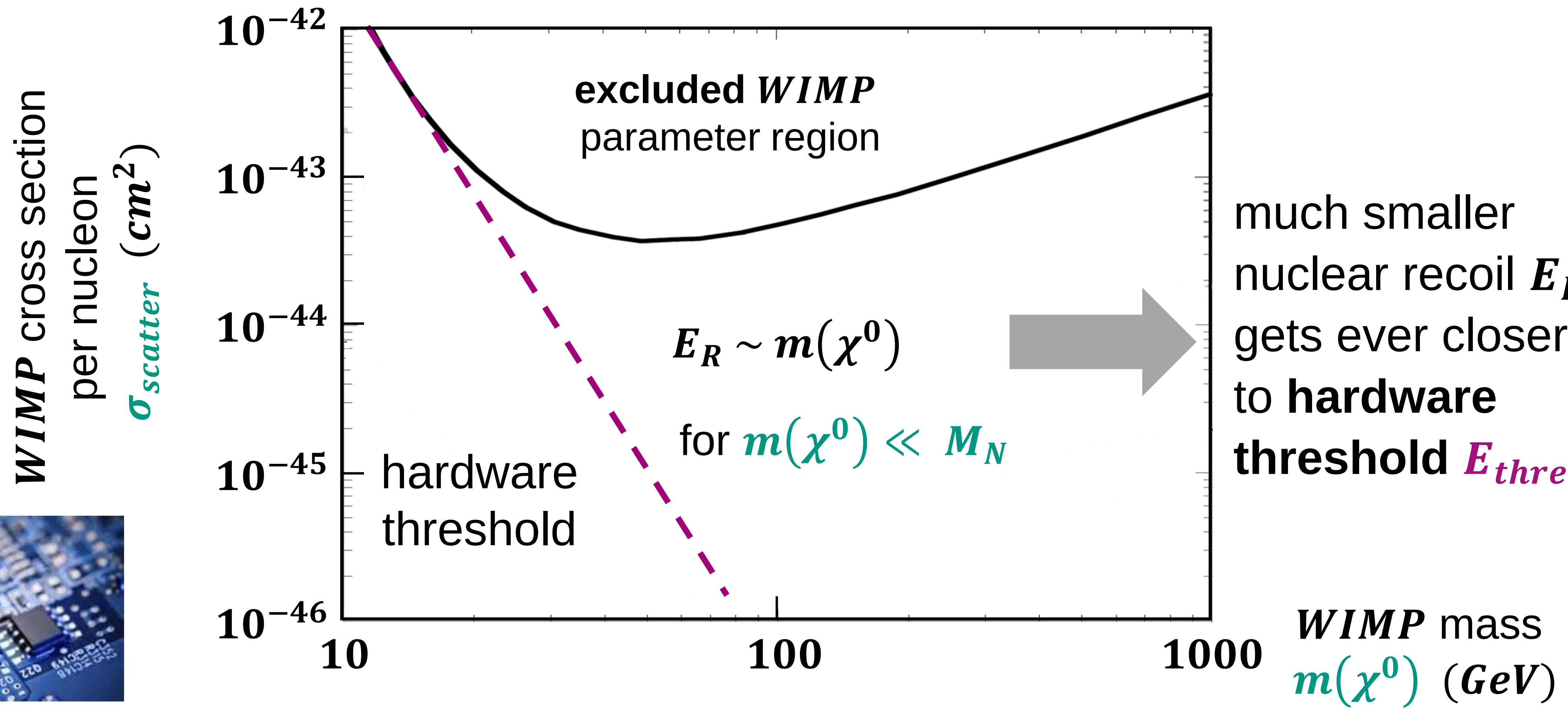
$WIMP$ plot in case of no signal

- **We see no signal above background and draw an exclusion curve ($90\%\ CL$)**



$WIMP$ plot in case of no signal: light $WIMPs$

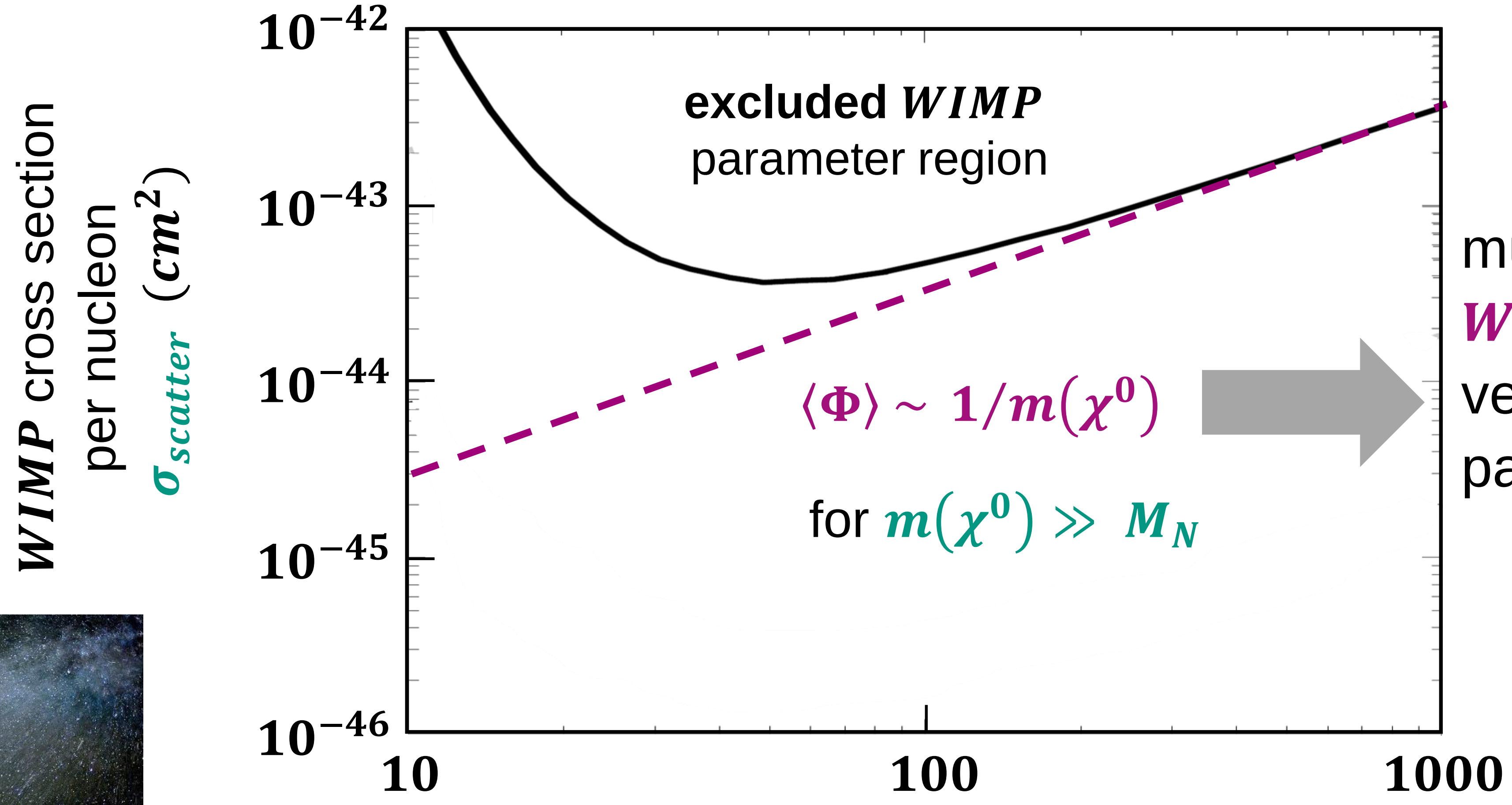
- For very light $WIMPs$ our sensitivity decreases: an effect of the threshold



much smaller nuclear recoil E_R gets ever closer to **hardware threshold** E_{thres}

$WIMP$ plot in case of no signal: heavy $WIMPs$

- **For heavy $WIMPs$ our sensitivity decreases: an effect of the $WIMP$ – flux**

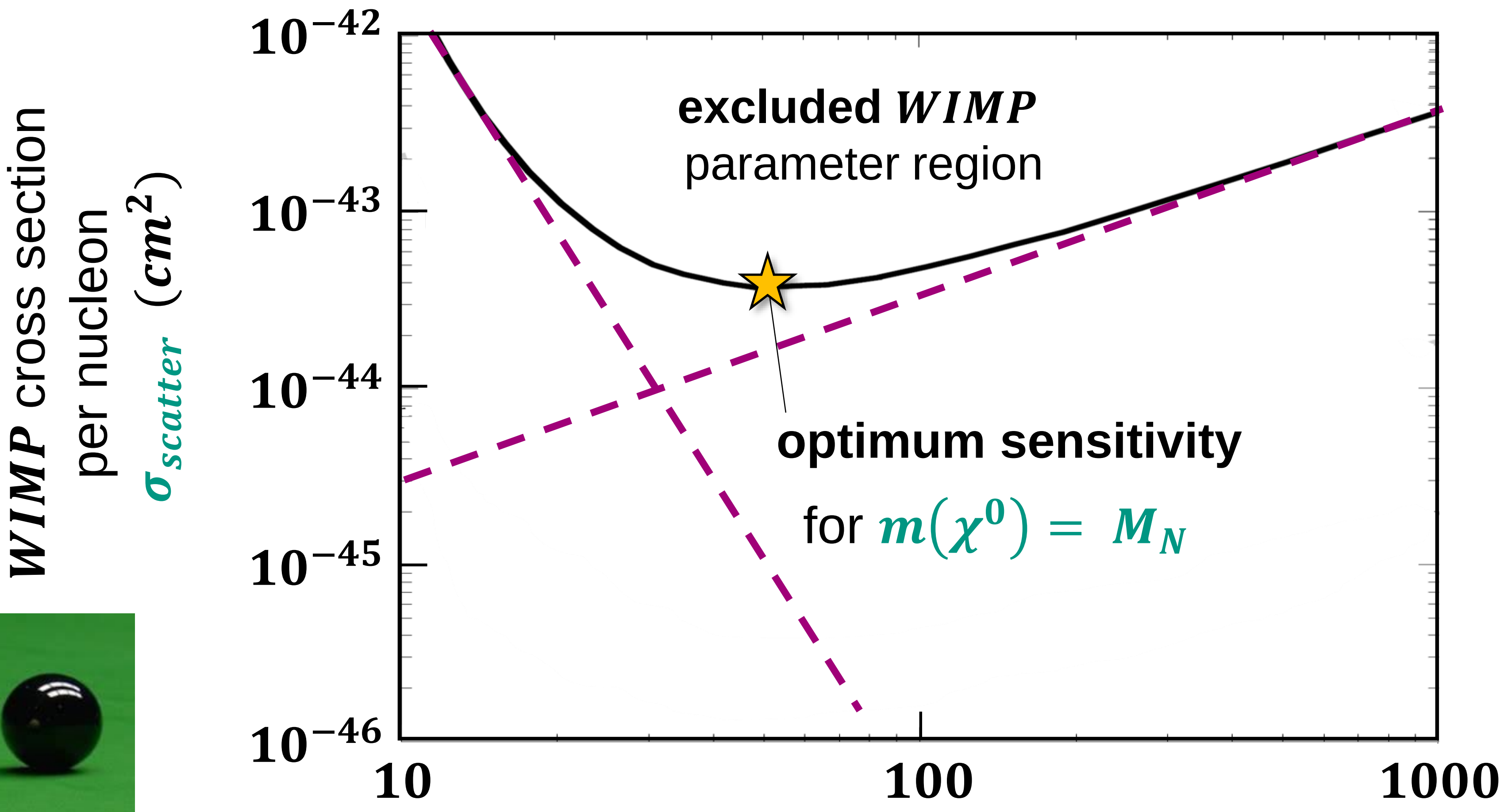


much smaller $WIMP$ flux for very heavy DM – particles

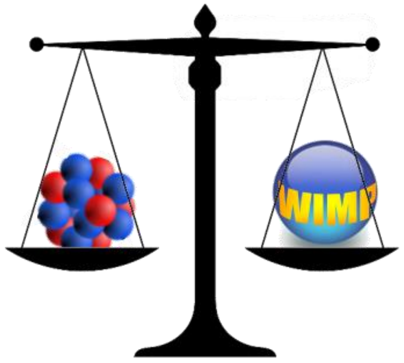
$WIMP$ mass $m(\chi^0)$ (GeV)

$WIMP$ plot in case of no signal: all $WIMP$ masses

- For optimum sensitivity the masses of $WIMP$ & target should be identical

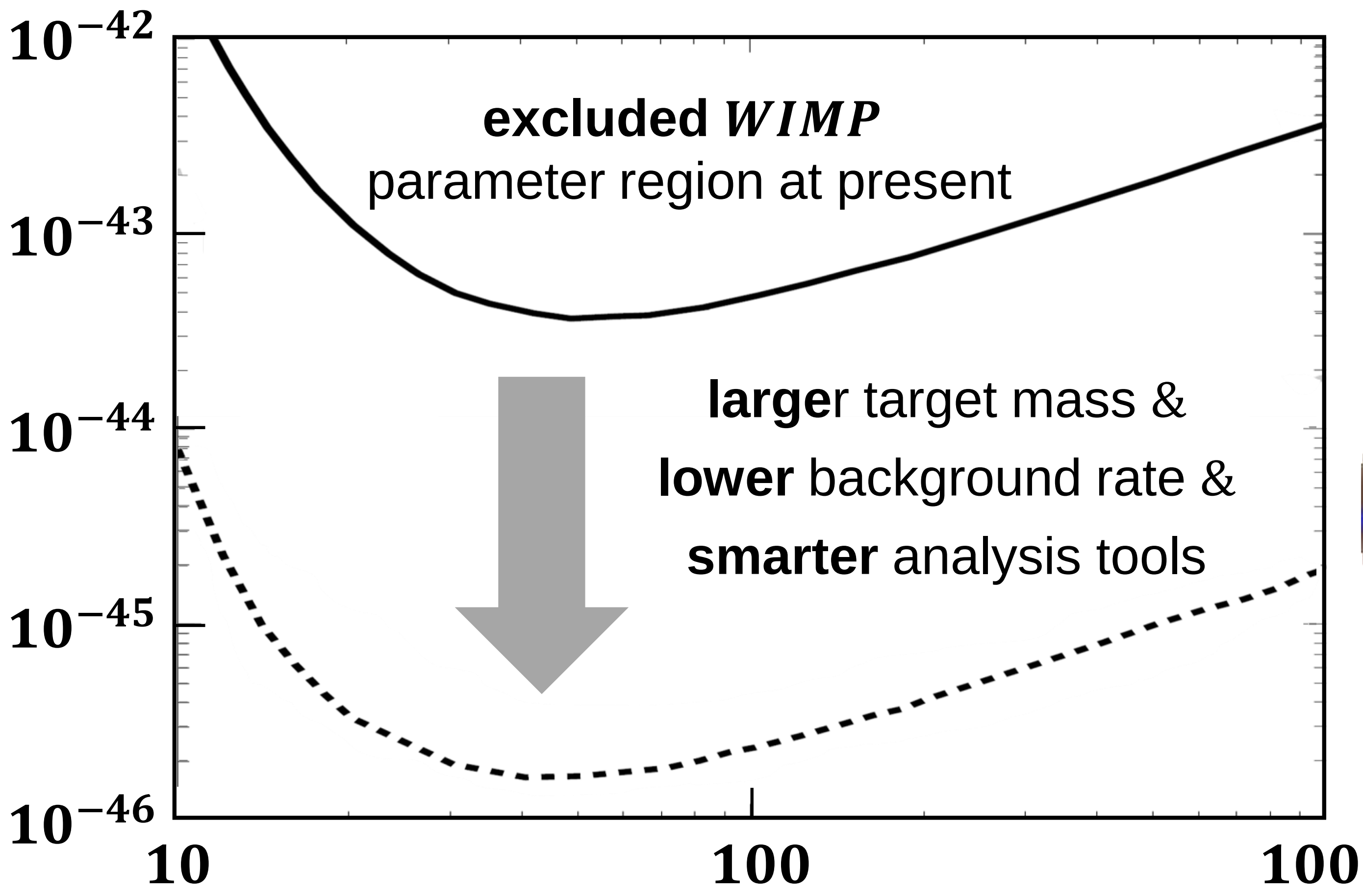


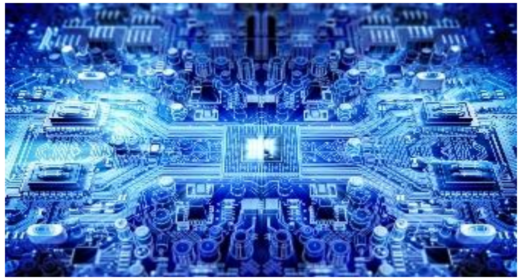
$WIMP$ mass $m(\chi^0)$ (GeV)

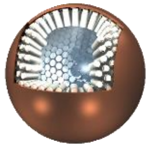


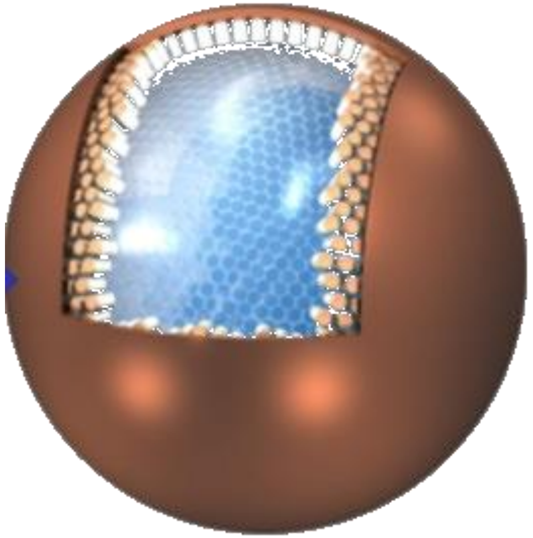
WIMP plot in case of no signal: better sensitivity

- **Better sensitivity: *DM* detector should be larger & background smaller**



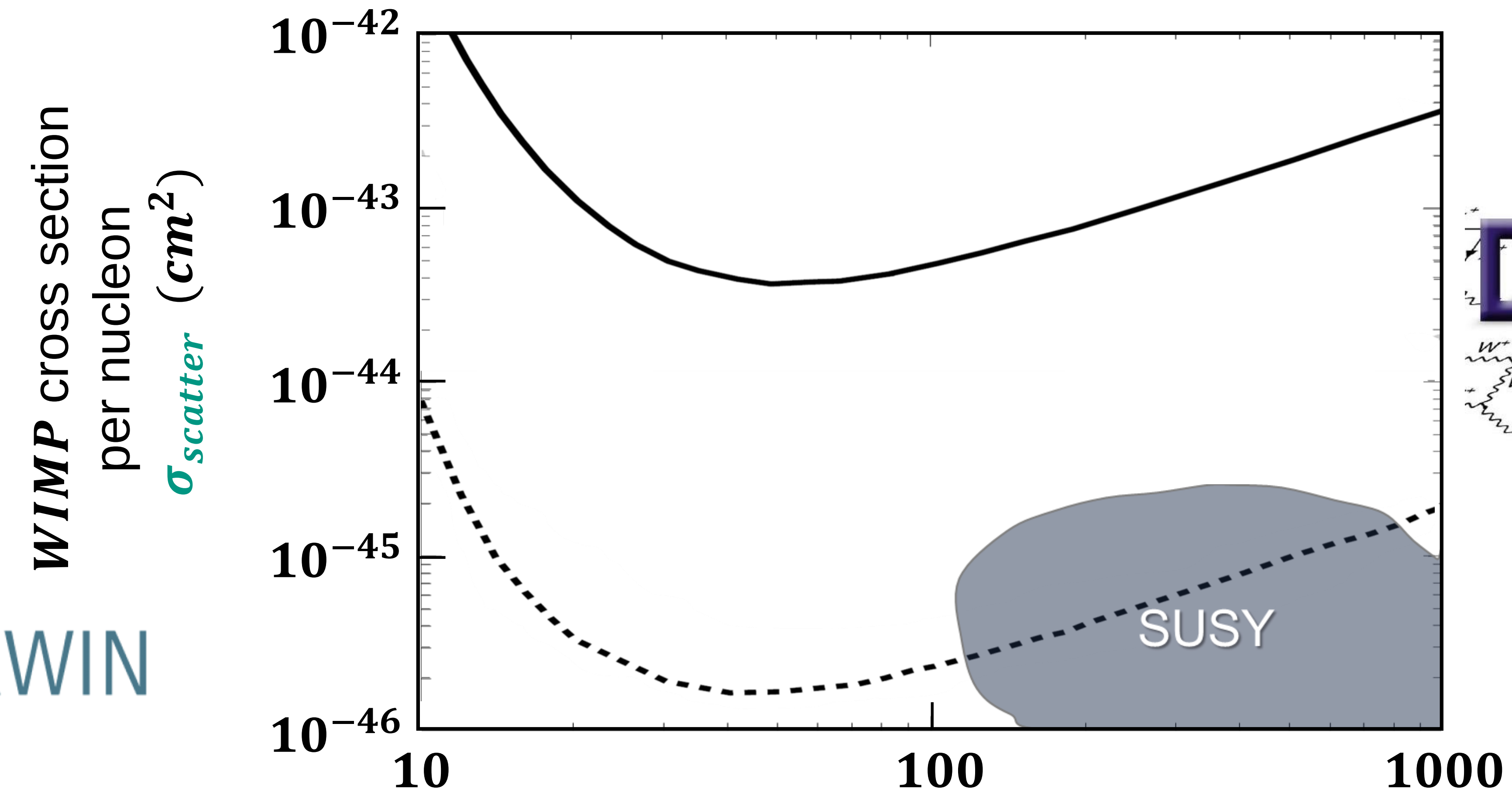


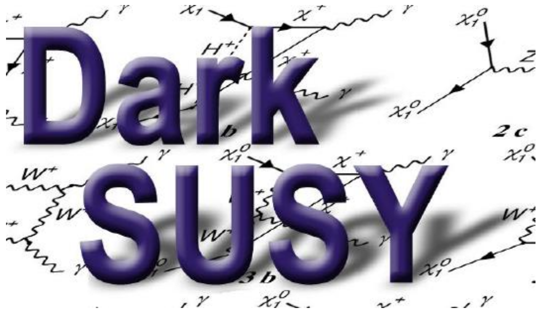




$WIMP$ plot in case of no signal: theory responds

- The ´preferred´ $SUSY$ – parameter space is ´re–adjusted´ from time to time ...

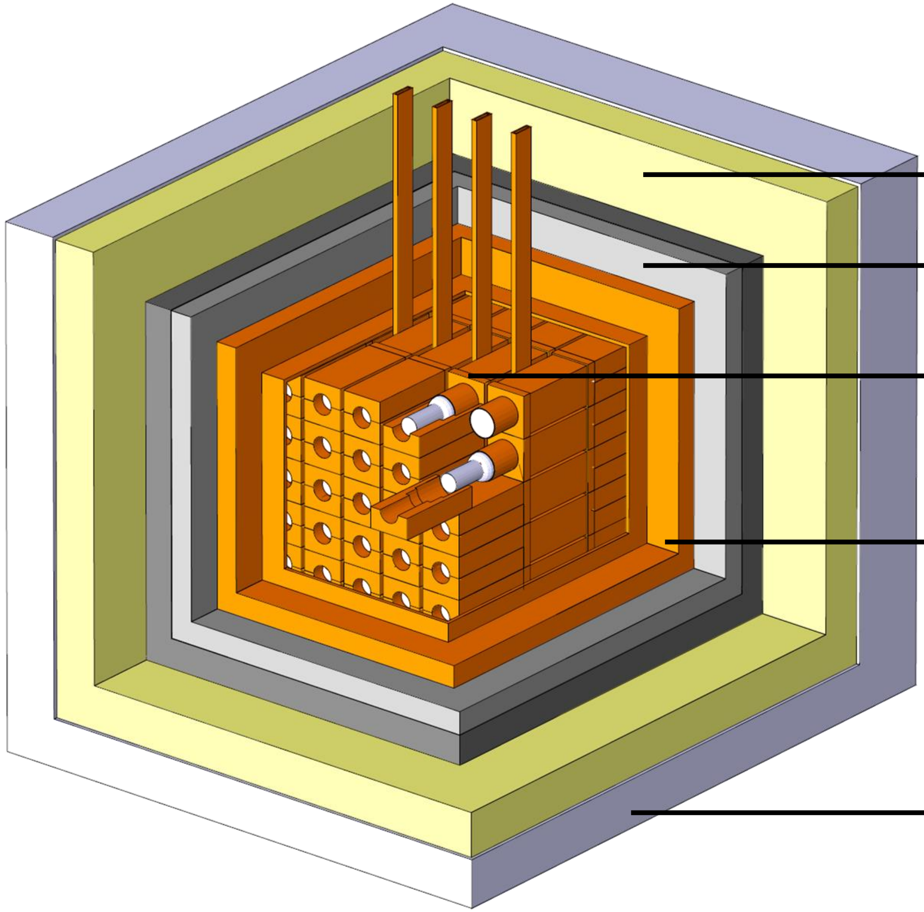




$WIMP$ mass
$m(\chi^0)$ (GeV)

Direct $WIMP$ searches: $DAMA$*/$LIBRA$

- **A scintillator−based DM – experiment yielding a highly controversial result**



polyethylene / paraffine−shielding

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

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

$\boldsymbol{Cu}$ – shielding ($\mathbf{10}\ \boldsymbol{cm}$) & flushed with high−purity, dry $\boldsymbol{N_2}$ – gas to reduce $\boldsymbol{Rn}$ – emanation & humidity

concrete – shielding ($\mathbf{1}\ \boldsymbol{m}$)

*$\boldsymbol{DA}$rk $\boldsymbol{MA}$tter experiment

Direct $WIMP$ searches: $DAMA/LIBRA$*

Karlsruhe Institute of Technology

- **A scintillator optimized for low−energy events (measurements 1995 … today)**
  - ☑ **large target** mass: $m = 250\ kg\ NaJ$ scintillating crystals
  - ☑ read−out of scintillating crystals via **2** $PMTs$: light yield ~ $5 \ldots 7\ p.e./keV$
  - ☒ 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 $WIMPs$

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

*Large Sodium Iodide Bulk for RAre processes

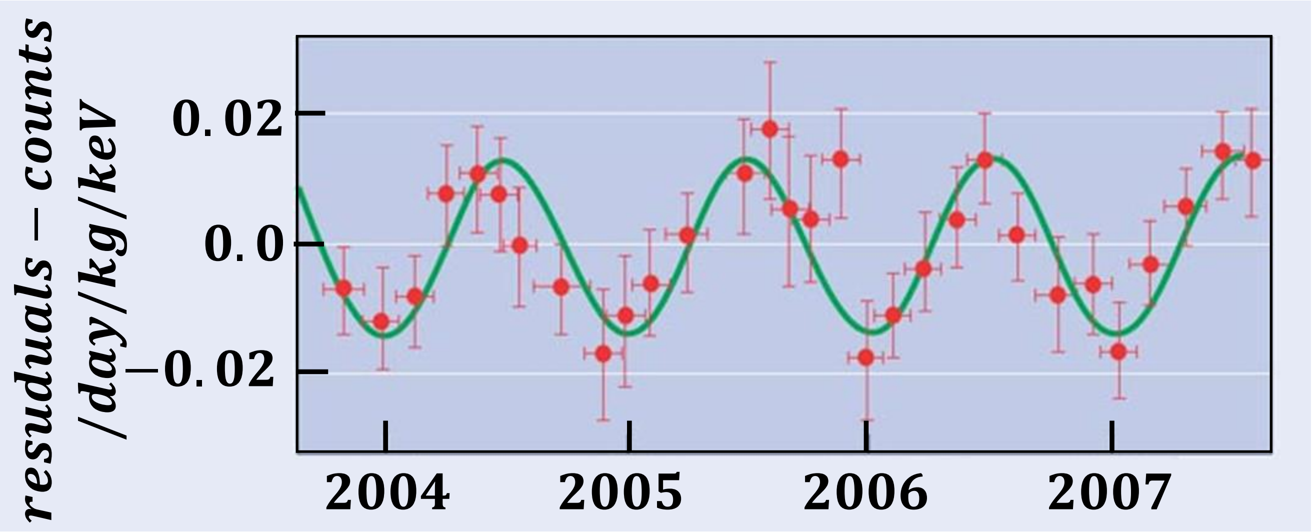
Results from $DAMA/LIBRA$: annual modulation

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

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

- **phase t_0** of the **modulation**:

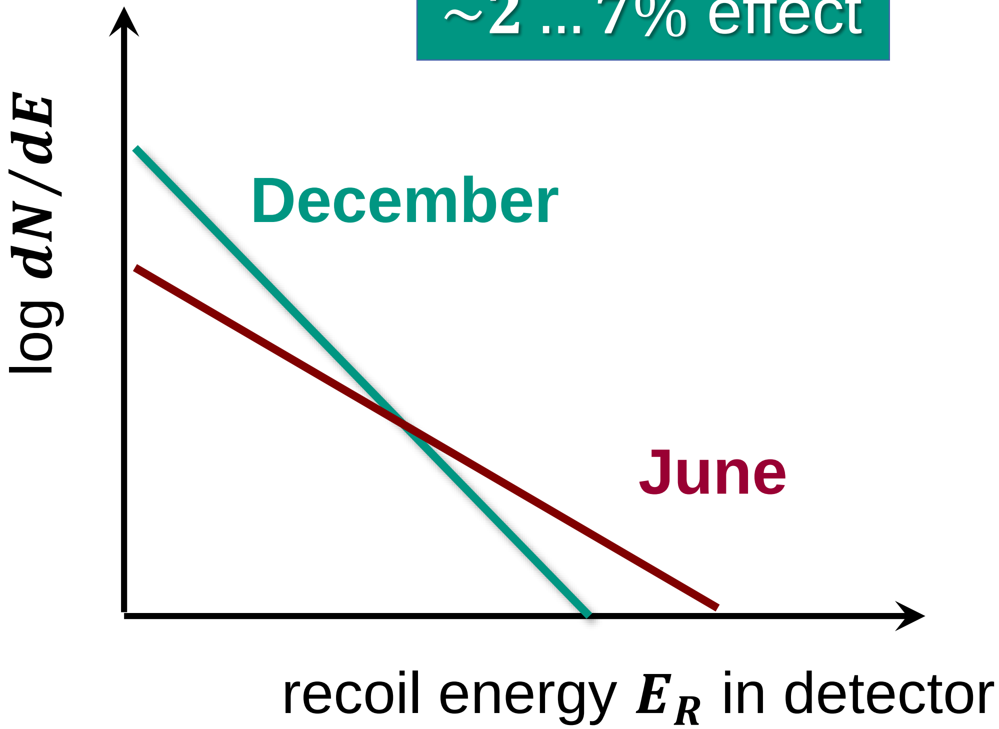
$t_0(expected)$ = **June**, **2**

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

variation of detector ´speed´ over one year

$t_0(observed)$ = May, **17** (± 7 days)

~2 ... 7% effect



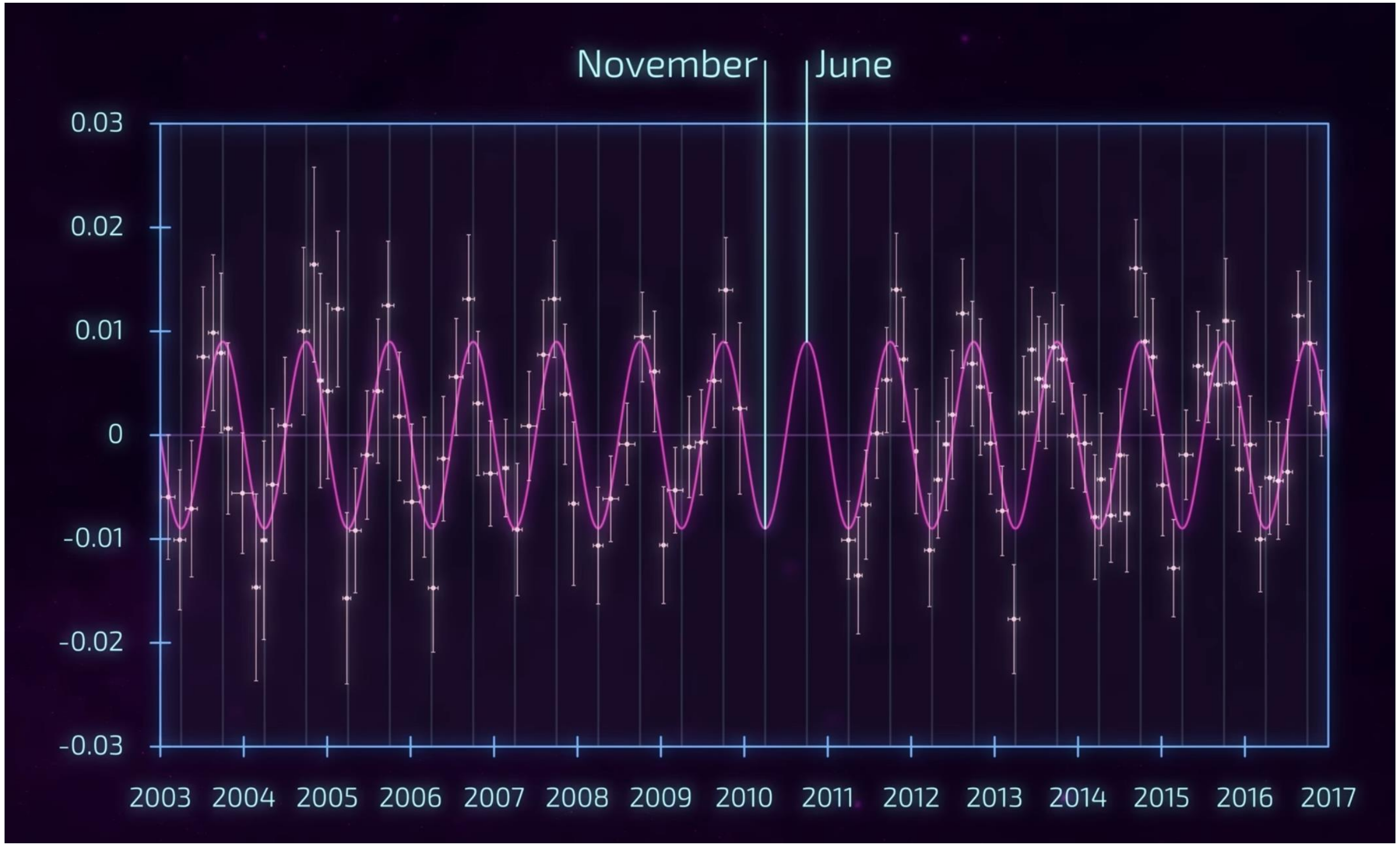
$DAMA/LIBRA$: updated results – $2003 \ldots 2017$

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

- modulation is only seen in low–energy interval from $\mathbf{1 \ldots 6\ keV}$ (above E_{thres})

- evidence for modulation: but is it really induced by $\boldsymbol{WIMP}$ – interactions?

$resuduals - counts\ /day/kg/keV$

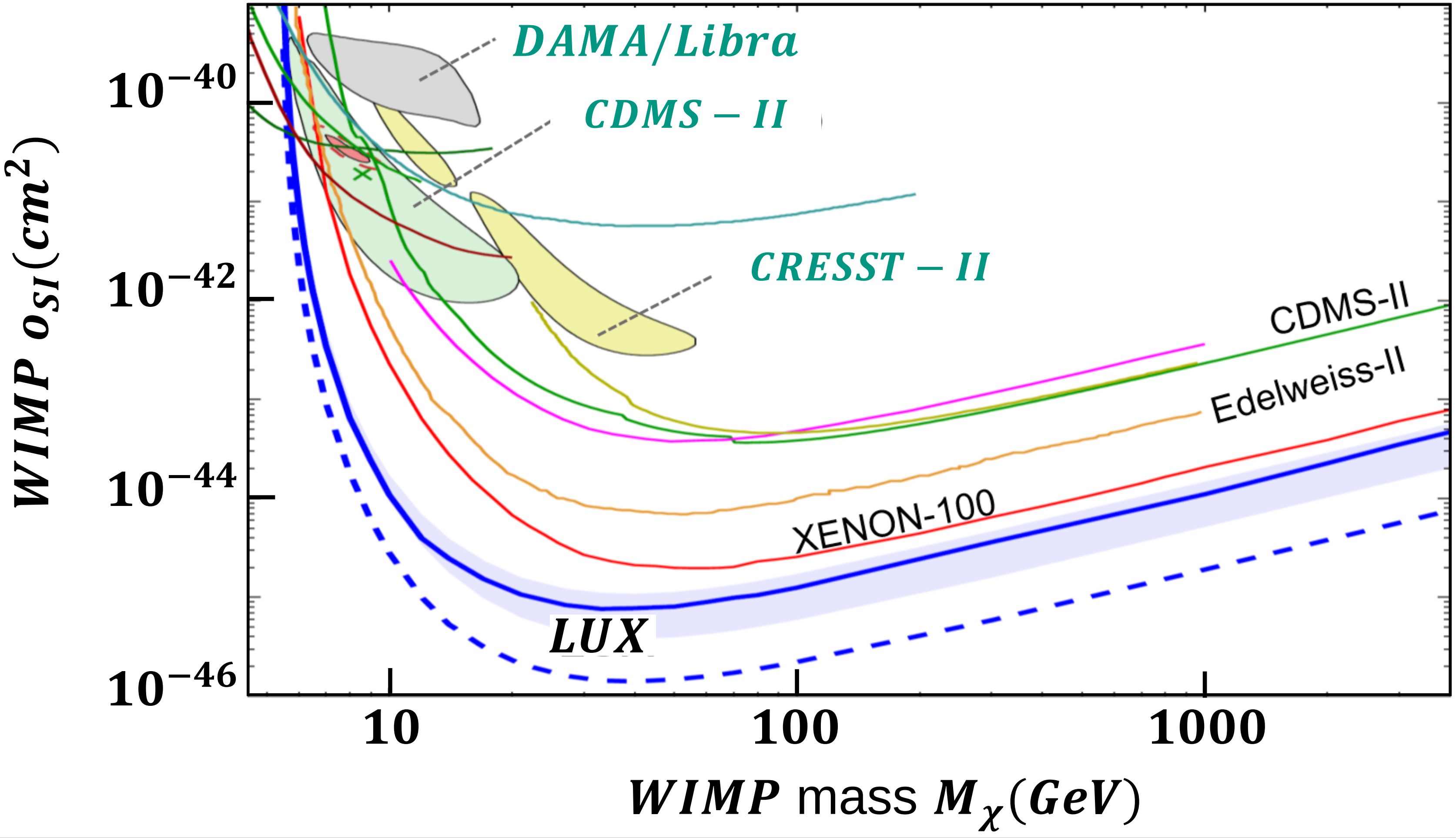


$DAMA/LIBRA$: $WIMP$ signal region & exclusions

- $DAMA/Libra$ favoured signal region & results 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 low–mass region** of $DAMA/Libra$!

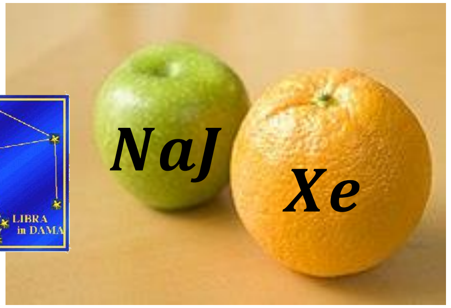


$DAMA/LIBRA$: $WIMP$ signal region & exclusions

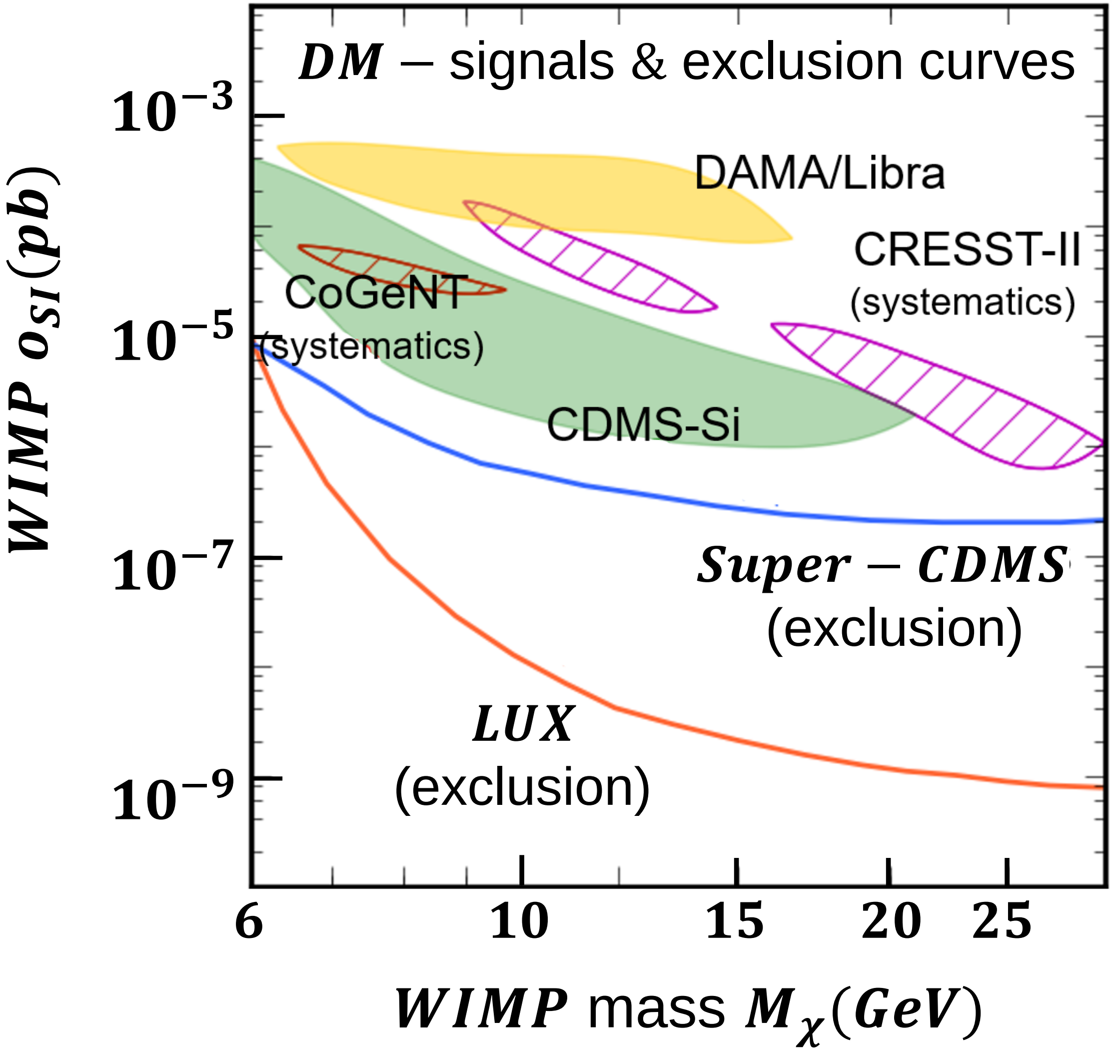
- **Many other ´DM – signals´ were due to systematic effects: $DAMA$ remains…**

  - comparison is somewhat model–dependent due to different DM – halo assumptions of each experiment

  - systematics: detector response at E_{thres} ?

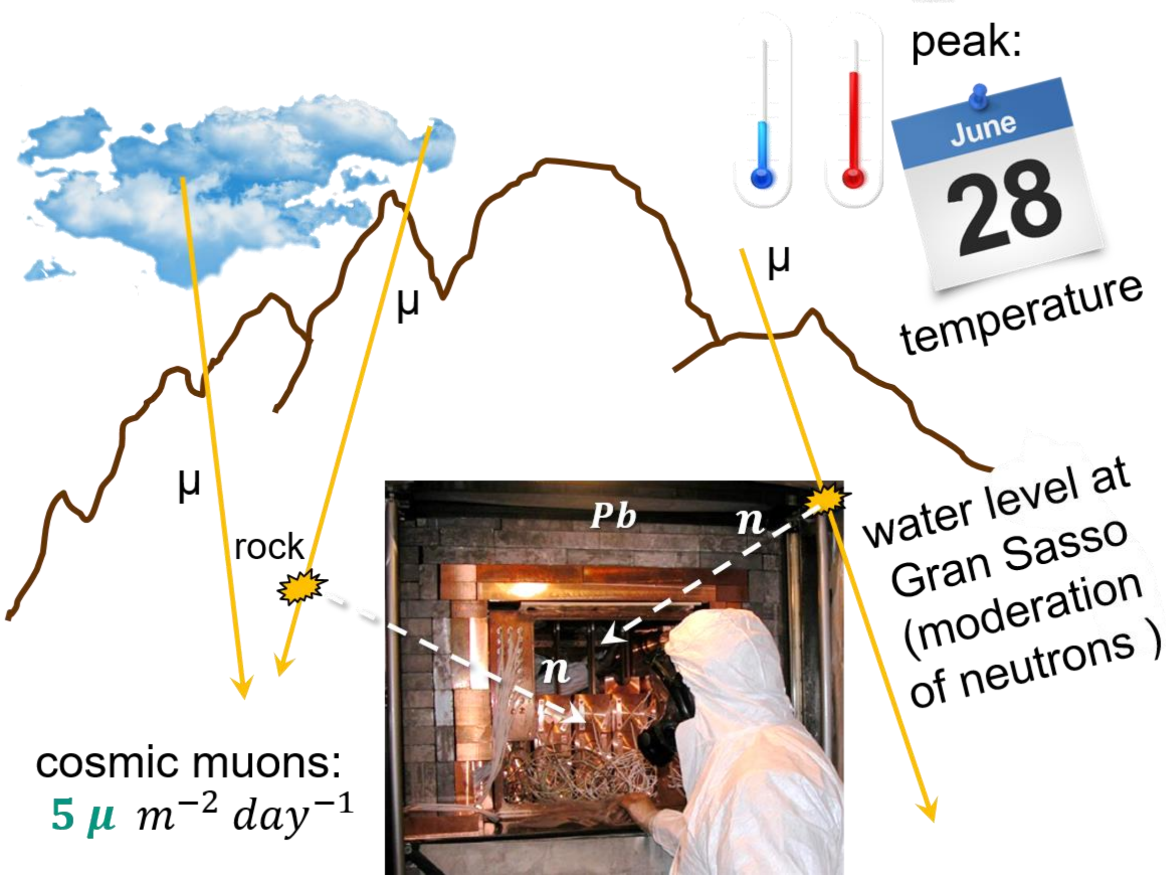


comparing ´apples & oranges´ ??



$DAMA/LIBRA$: explaining the 1 yr modulation

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



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 the $1\ yr$ 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**

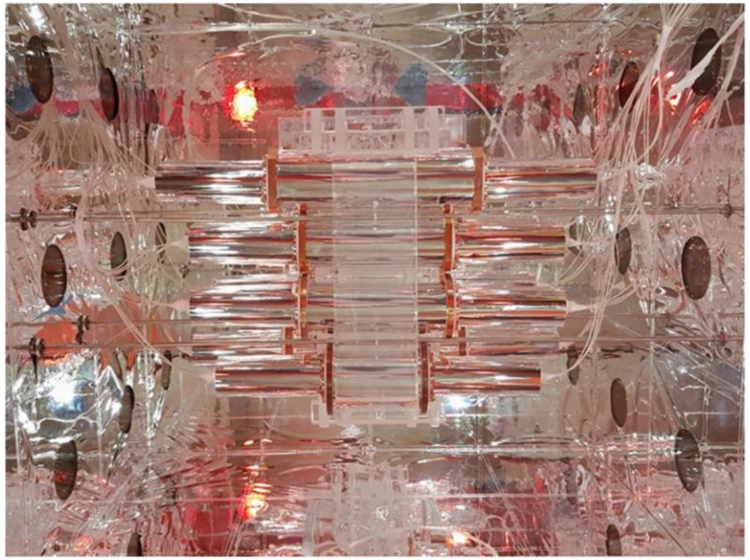
NEWS | 16 August 2022

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

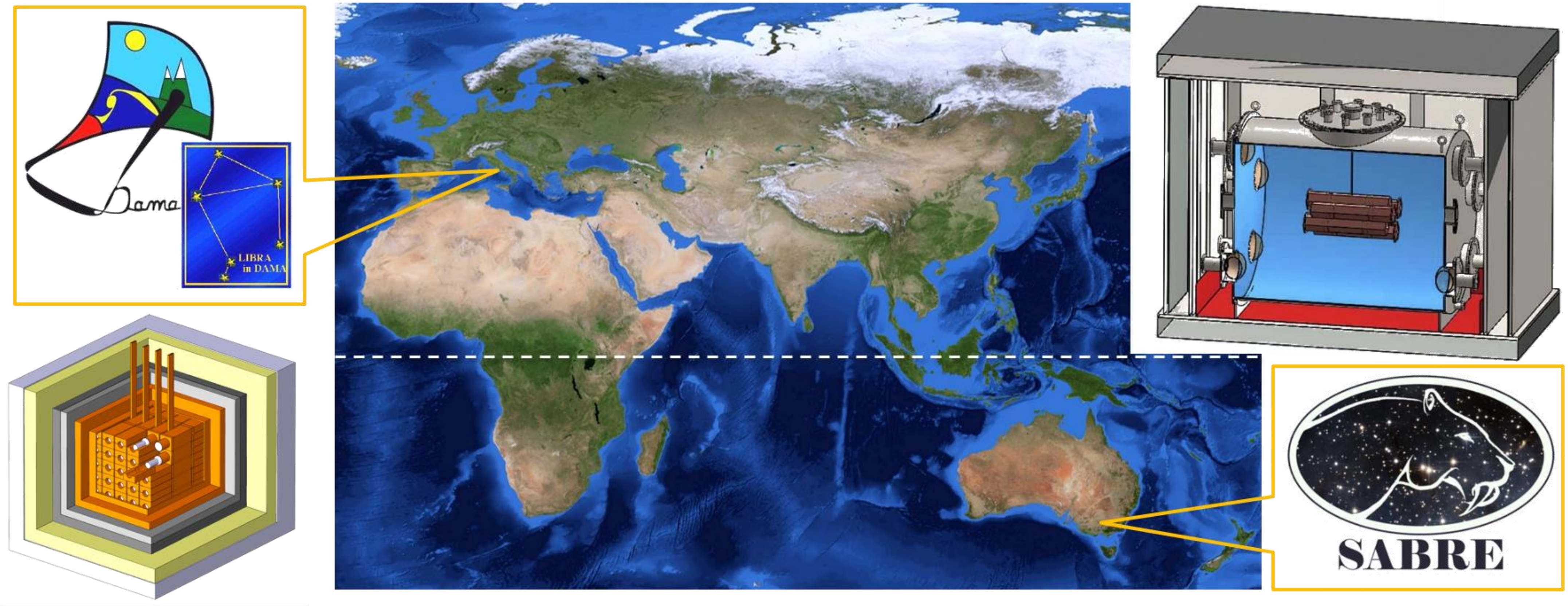
Physicists have shown that an underground experiment in South Korea can 'see' dark matter streaming through Earth – or not, depending on how its data are

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

$DAMA/LIBRA$: new tests by NaJ detectors

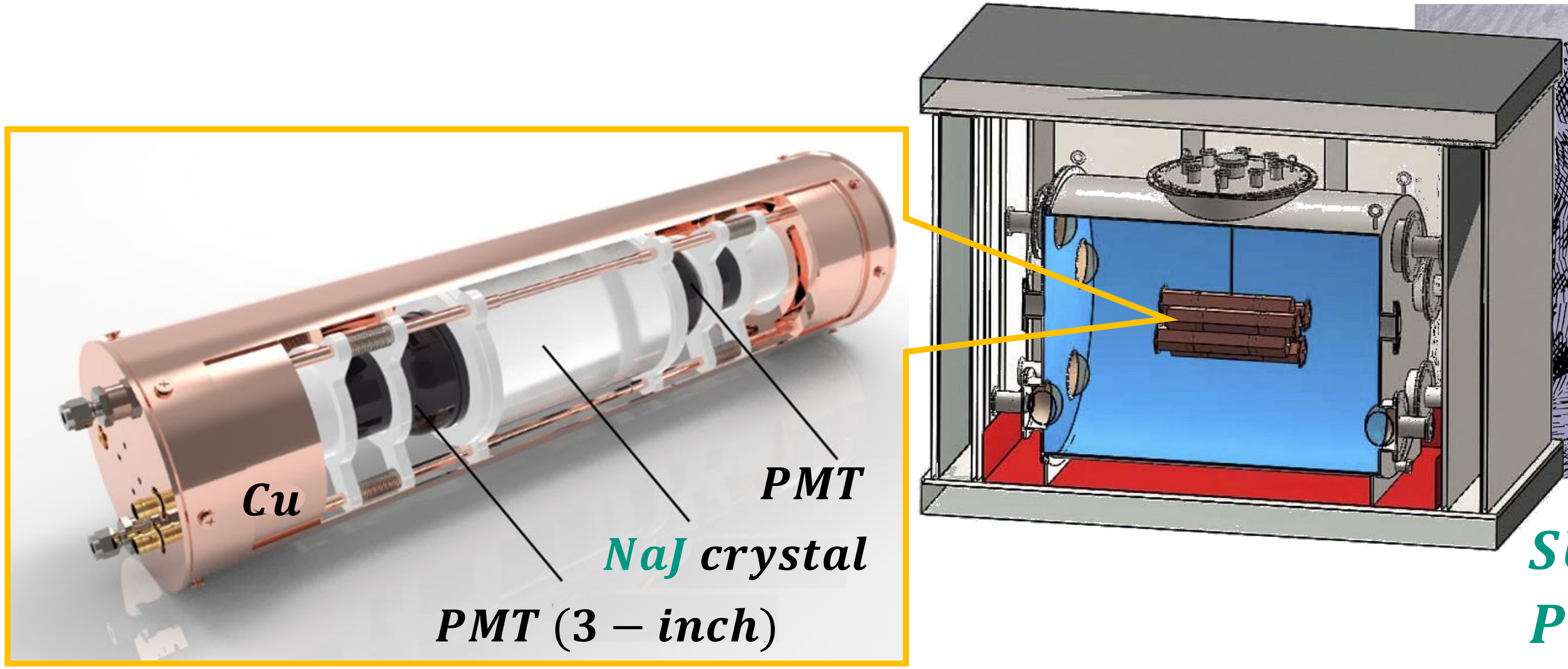
- $SABRE$, $COSINE-100$ & $ANAIS$: **can we reproduce the results from $DAMA$?**

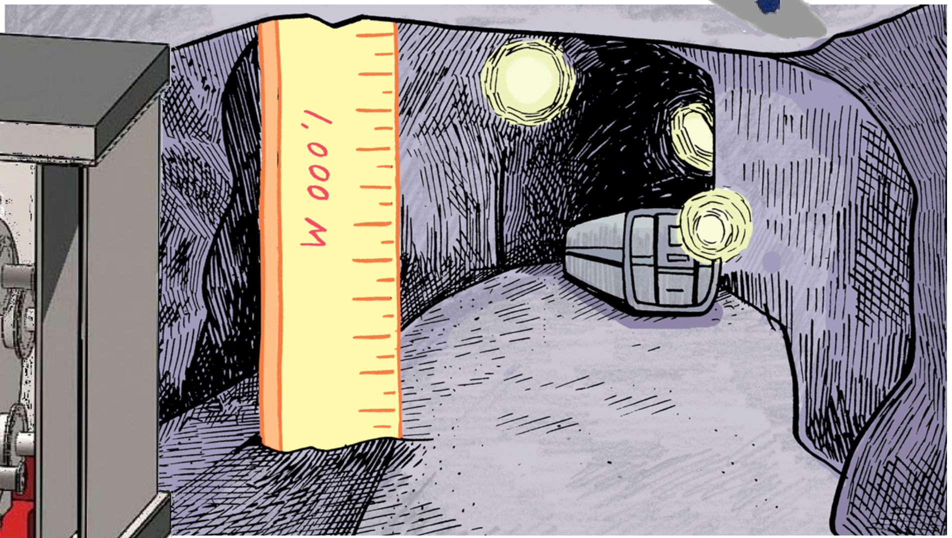
- experiment also in **Southern** Hemisphere: same $WIMPs$, but different background



*SABRE** experiment in both hemispheres

- **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 – ***S***tawell ***U***nderground ***P***hysics ***L***ab (**2900 *m.w.e.***)

**S*odium–iodide with *A*ctive *B*ackground *RE*jection

$COSINE - 100$ experiment in South Korea

- A NaJ detector $(106\ kg)$ like $DAMA/LIBRA$ at $YangYan\ L$aboratory ($Y2L$)

- start of measurements in $9/2016$
- publication of first results in $12/2018$, $11/2021$ full results: **no modulation**, rules out $WIMP$ – interactions claimed by $DAMA/Libra$


PHYSICS

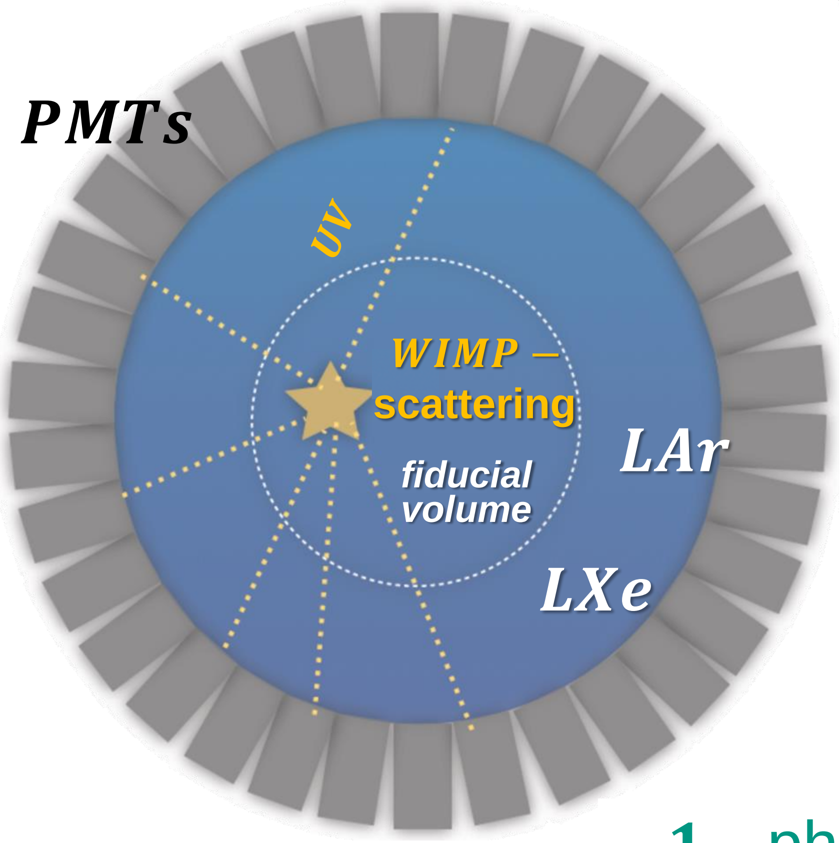
A Famous Dark Matter Signal Is Probably Coming From Something Else

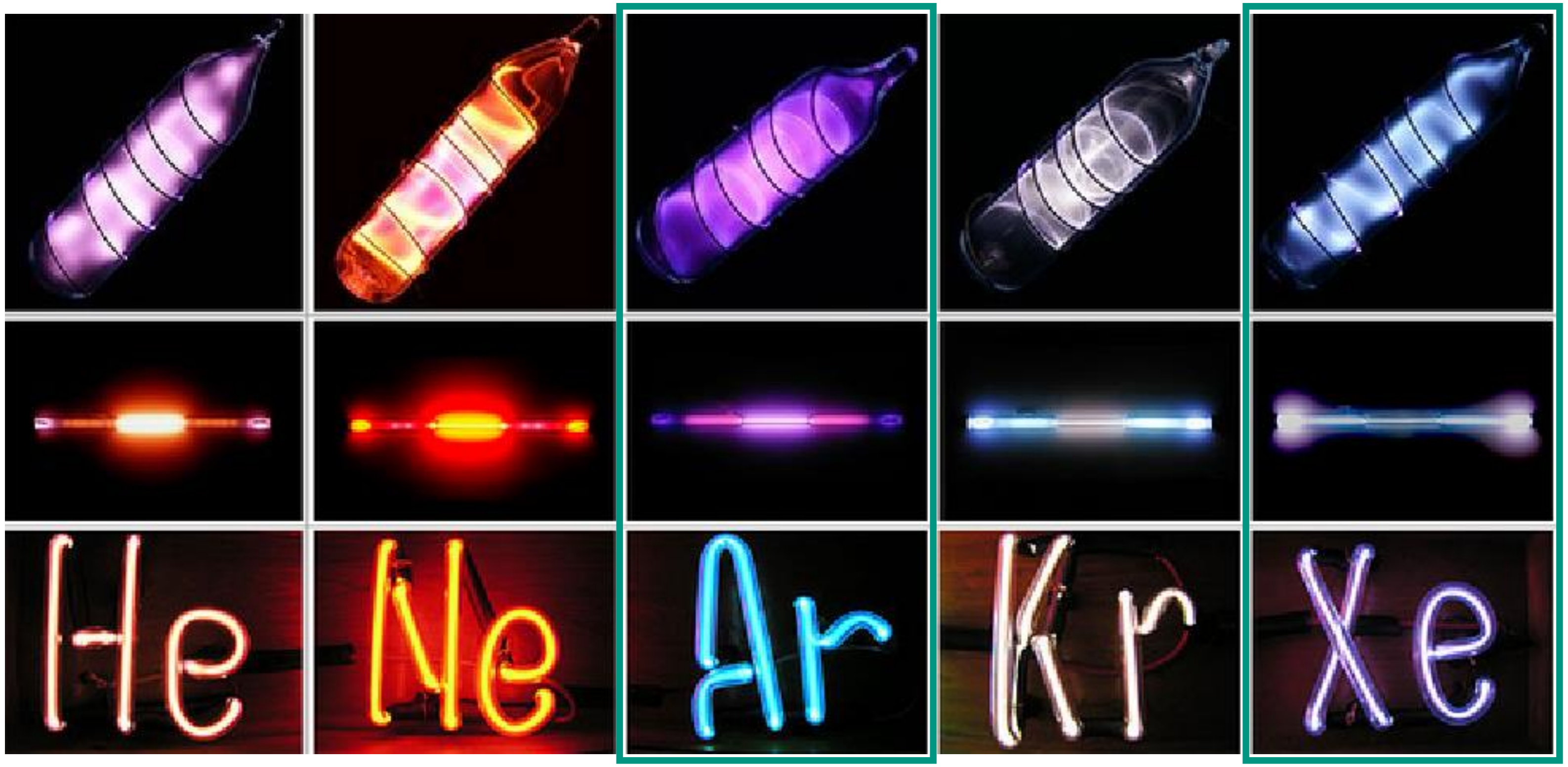
An underground experiment in South Korea has turned up nothing, suggesting an intriguing observation from 2017 was a red herring.

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**

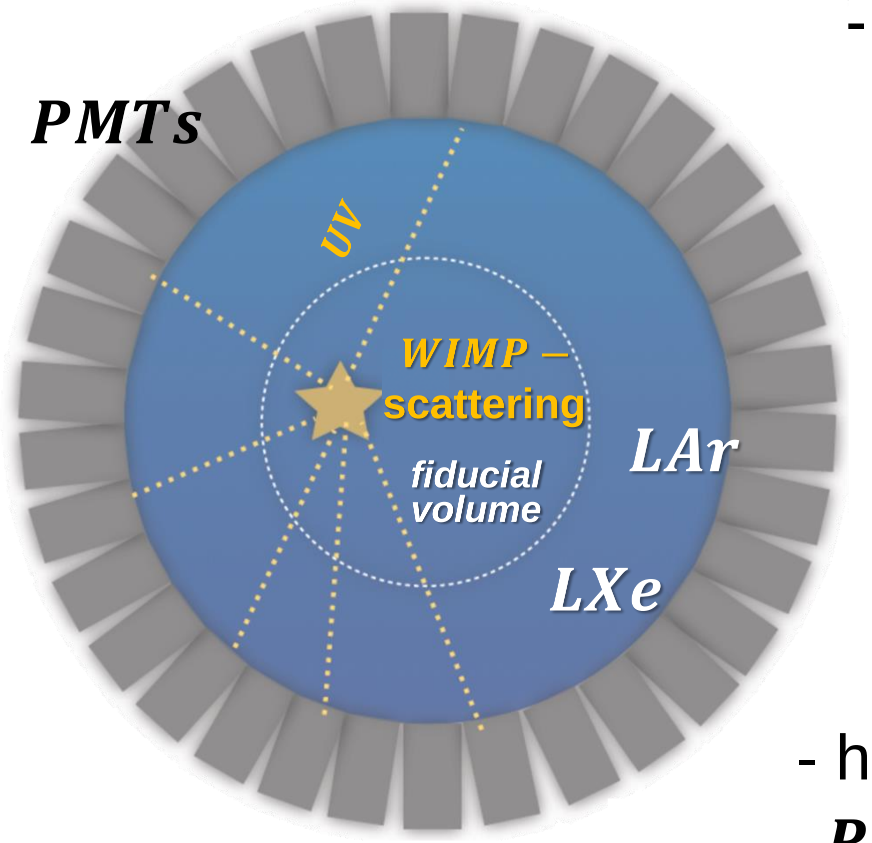




1 –phase layout: spherical geometry with 4π PMT – **coverage**

Liquid noble gases: scintillation & ionisation

LAr & LXe detectors: 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

Karlsruhe Institute of Technology

- **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	$54\ (129 \dots 131)$	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 $PMTs$

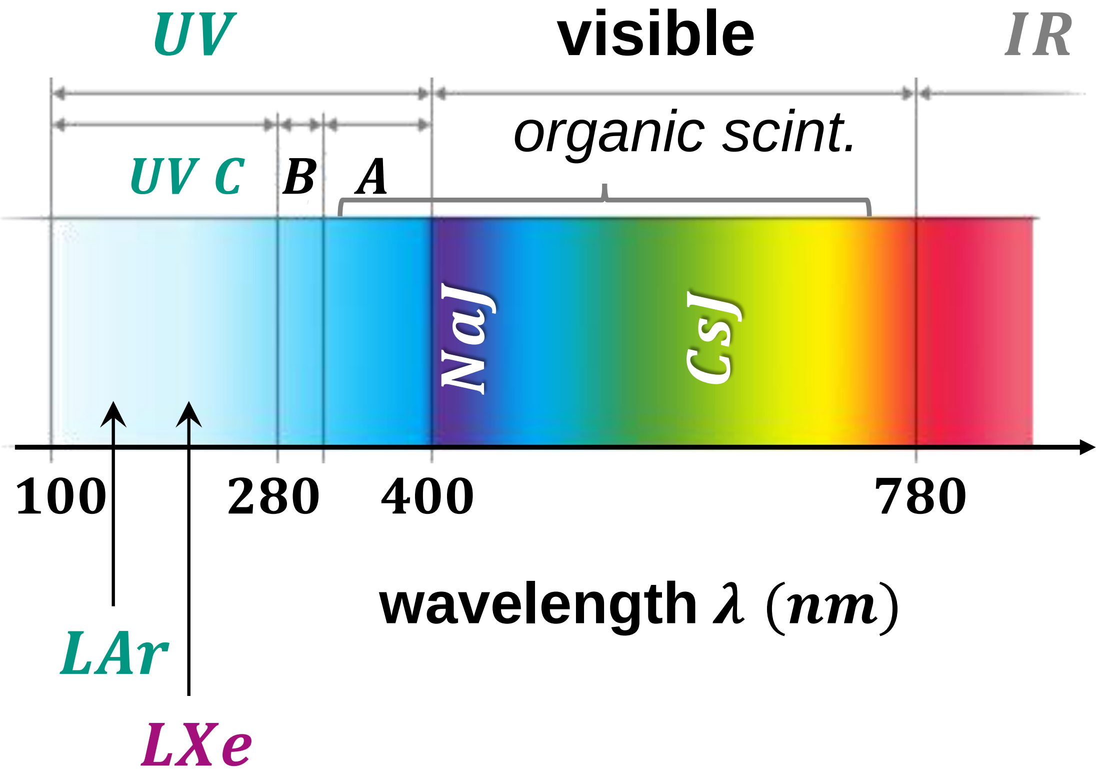
*WLS = Wave–Length–Shifter

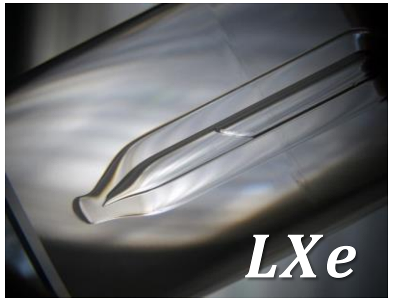
Liquid noble gases: scintillation

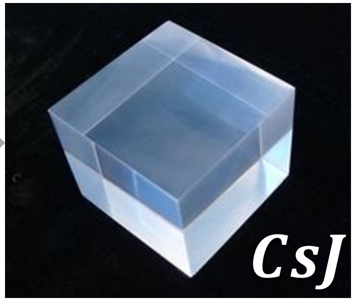
- **Scintillation processes in liquid noble gases: emission of short–wave light**

  - **Liquid noble gases** emit scintillating light in the VUV (Vacuum Ultra–Violet) range with $\lambda < 200\ nm$

  - for comparison: anorganic scintillators like NaJ, CsJ emit **long–wave light** with $\lambda_{max} \sim 400 \dots 500\ nm$



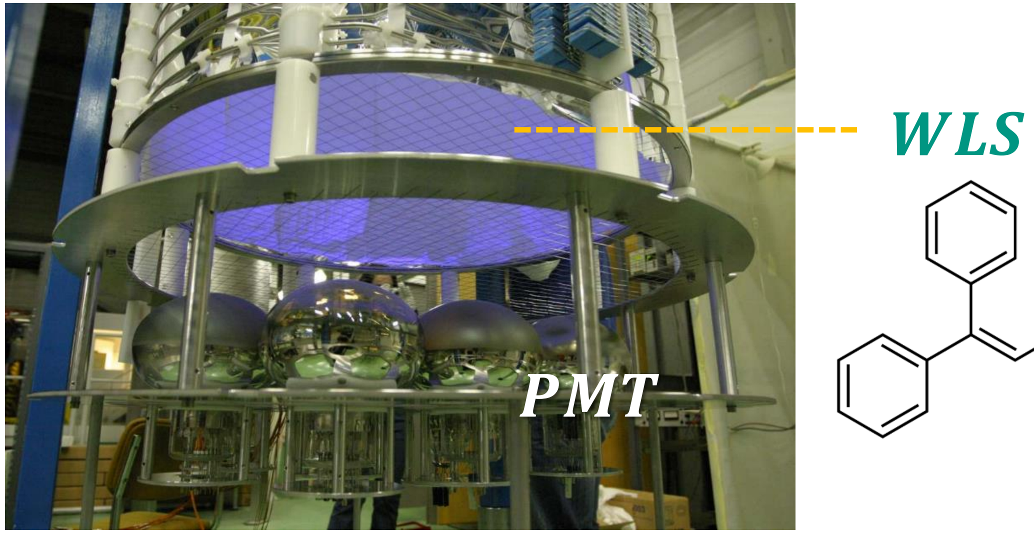


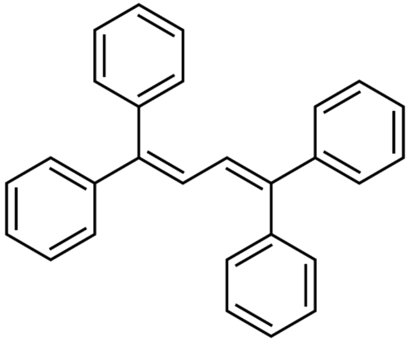


Liquid noble gases: scintillation of LAr

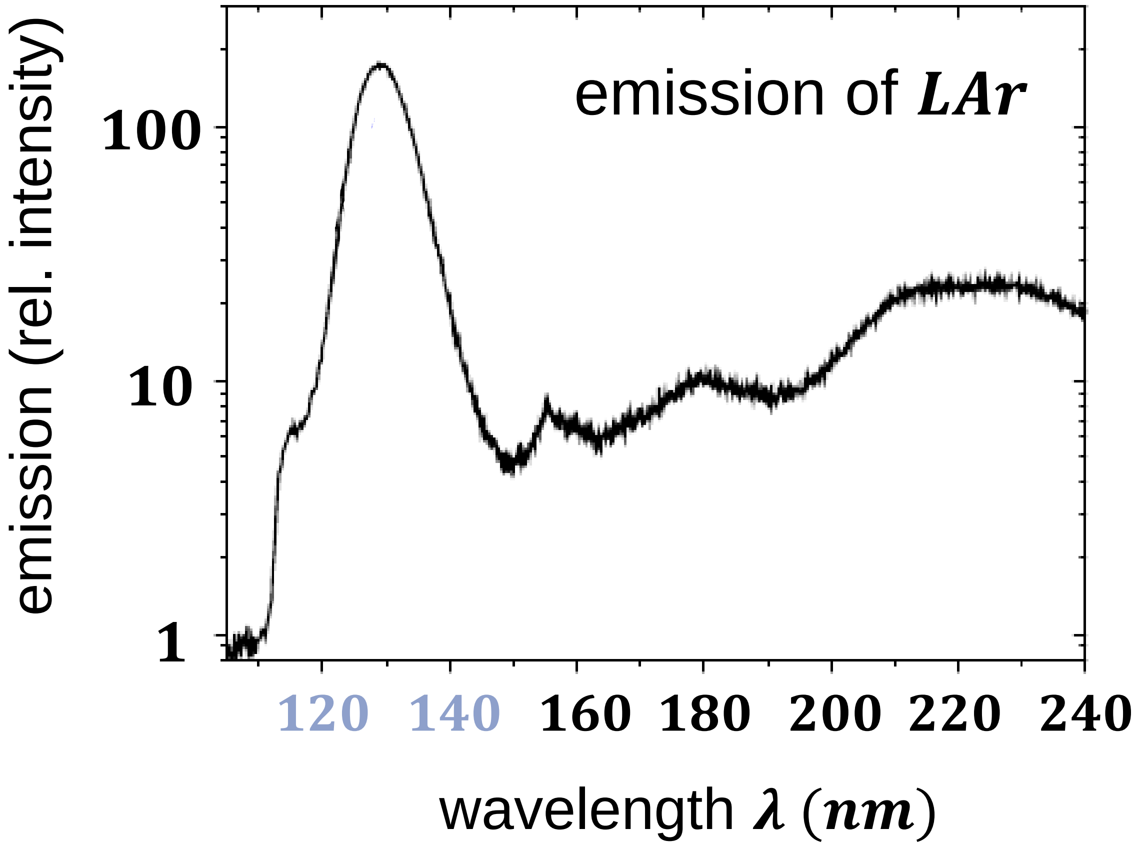
- **Liquid argon emission of ultra short–wave light with $\lambda \approx 120 \ldots 130\ nm$**

- requires **wavelength shifter** (photo–fluorescent material) in front of $PMTs$ with bialkali photo–cathode





TPB (TetraPhenyl–Butadiene)

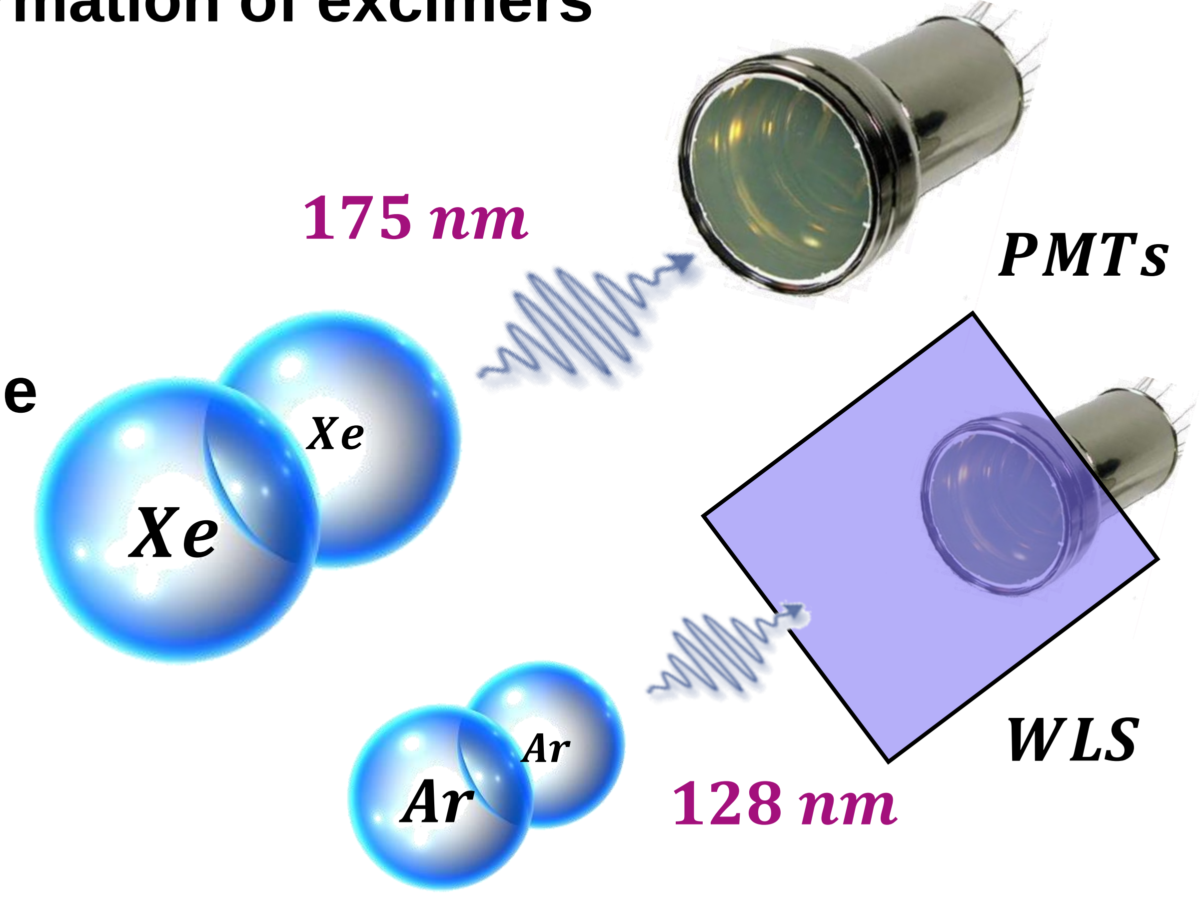


Liquid noble gases: scintillation light detection

- **Scintillation light in the VUV due to formation of 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 $E \sim \mathbf{10\ eV}$
  ⇨ decay of the excimer after a few ns, resulting in VUV scintillation light

- LXe: special class of $PMTs$ required which are sensitive in the VUV – range



$(Ar_2^*, Xe_2^*) =$ ´**excimer**´

Liquid noble gases: gas–kinetic processes

- **Scintillation of LAr**

scattering process

excitation

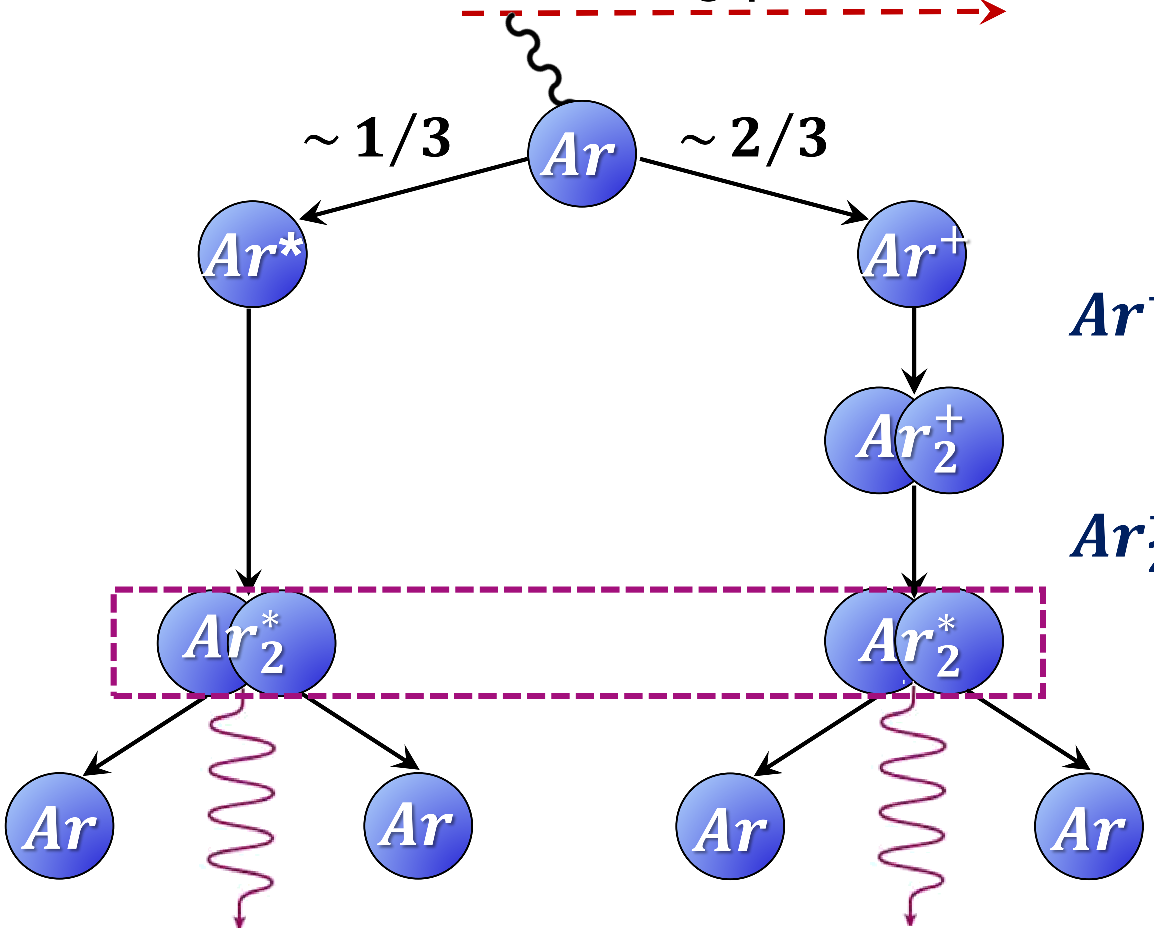
$$Ar^* + Ar \rightarrow Ar_2^*$$

ionisation

$$Ar^+ + Ar + Ar \rightarrow Ar_2^+ + Ar$$

ionised molecule

$$Ar_2^+ + e^- \rightarrow Ar_2^* + \textbf{heat}$$



excited molecule

decay & dissociation

scintillation light VUV

Liquid noble gases: gas–kinetic processes – LAr

- **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**

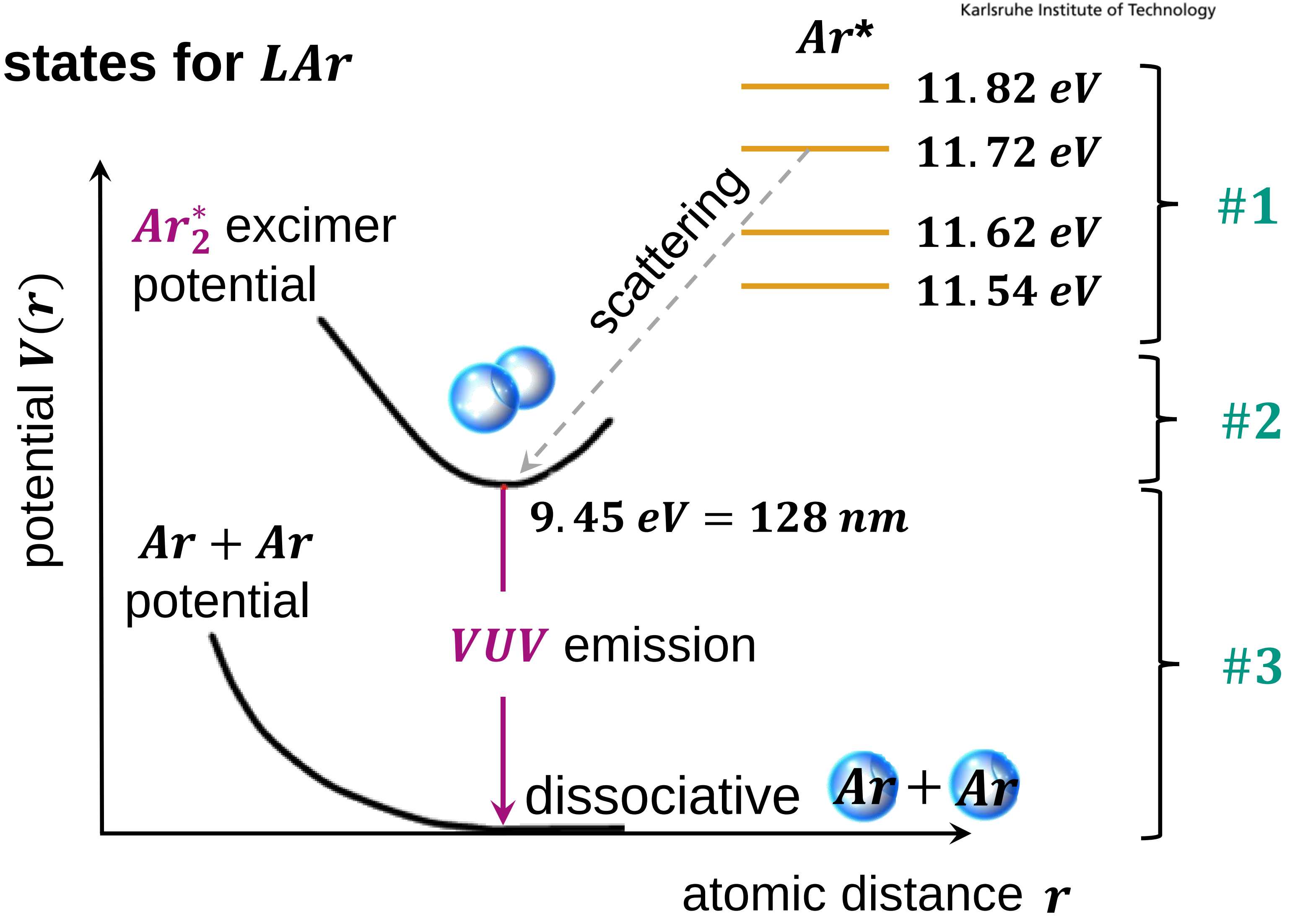
Liquid noble gases: formation of excimers

■ **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**:
  $Ar_2^* \rightarrow Ar + Ar + VUV$

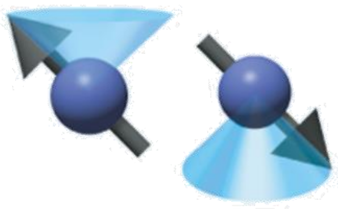


RECAP: *singlet* & *triplet* states

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

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

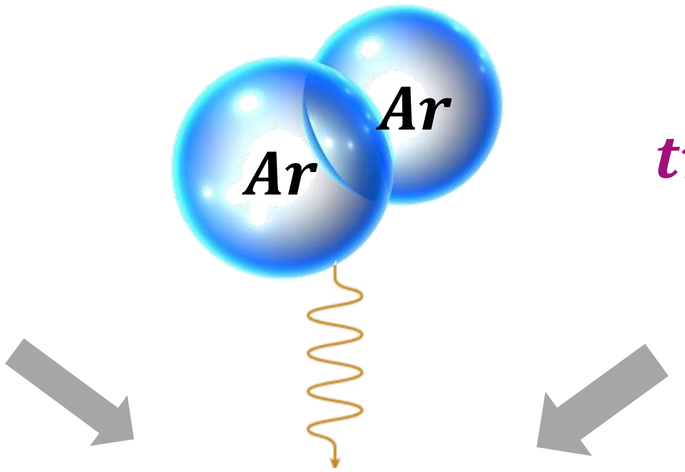
    ⇨ **different decay times of *singlet* / *triplet* states**



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

singlet

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

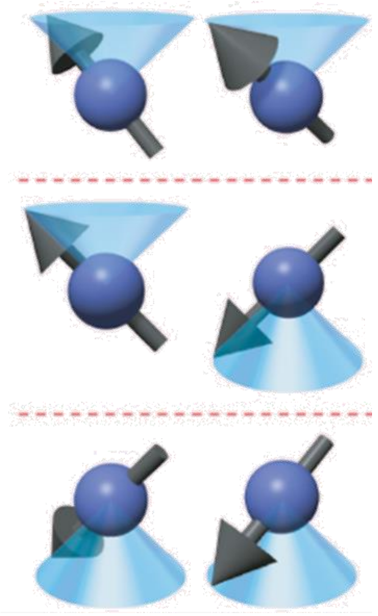


$$^{1}\Sigma_g^+$$

repulsive ***ground state***

triplet

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



$$|\Uparrow\Uparrow\rangle$$

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

$$|\Downarrow\Downarrow\rangle$$

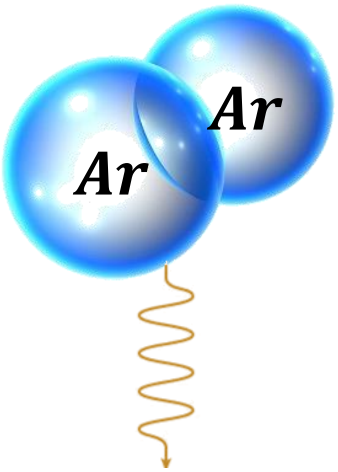
Decay of argon: $\boldsymbol{singlet}$ & $\boldsymbol{triplet}$ states

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

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

$\boldsymbol{singlet}$

$^1\Sigma_u^+$



$\boldsymbol{triplet}$

$^3\Sigma_u^+$

$^1\Sigma_g^+$

τ_S **(singlet)** $= 6\ ns$

repulsive $\boldsymbol{ground\ state}$

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

Decay of argon: *singlet* & *triplet* states

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

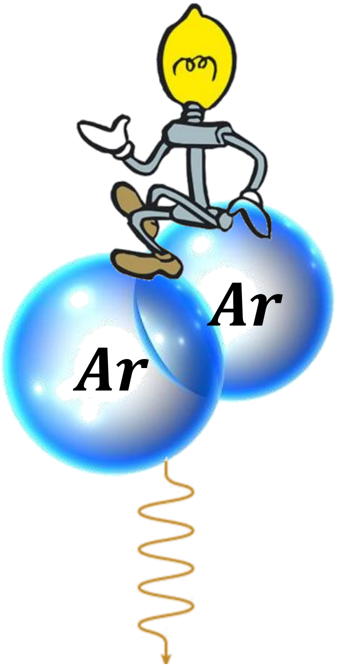
$WIMP$ recoil nucleus

~70 % of excimers in *singlet* states

singlet

$^1\Sigma_u^+$

´$WIMP$ sprinter´



$^1\Sigma_g^+$

repulsive *ground state*

background electron

80 … 90 % of excimers in *triplet* states

triplet

$^3\Sigma_u^+$

´background walker´

DM – searches with LAr – detectors

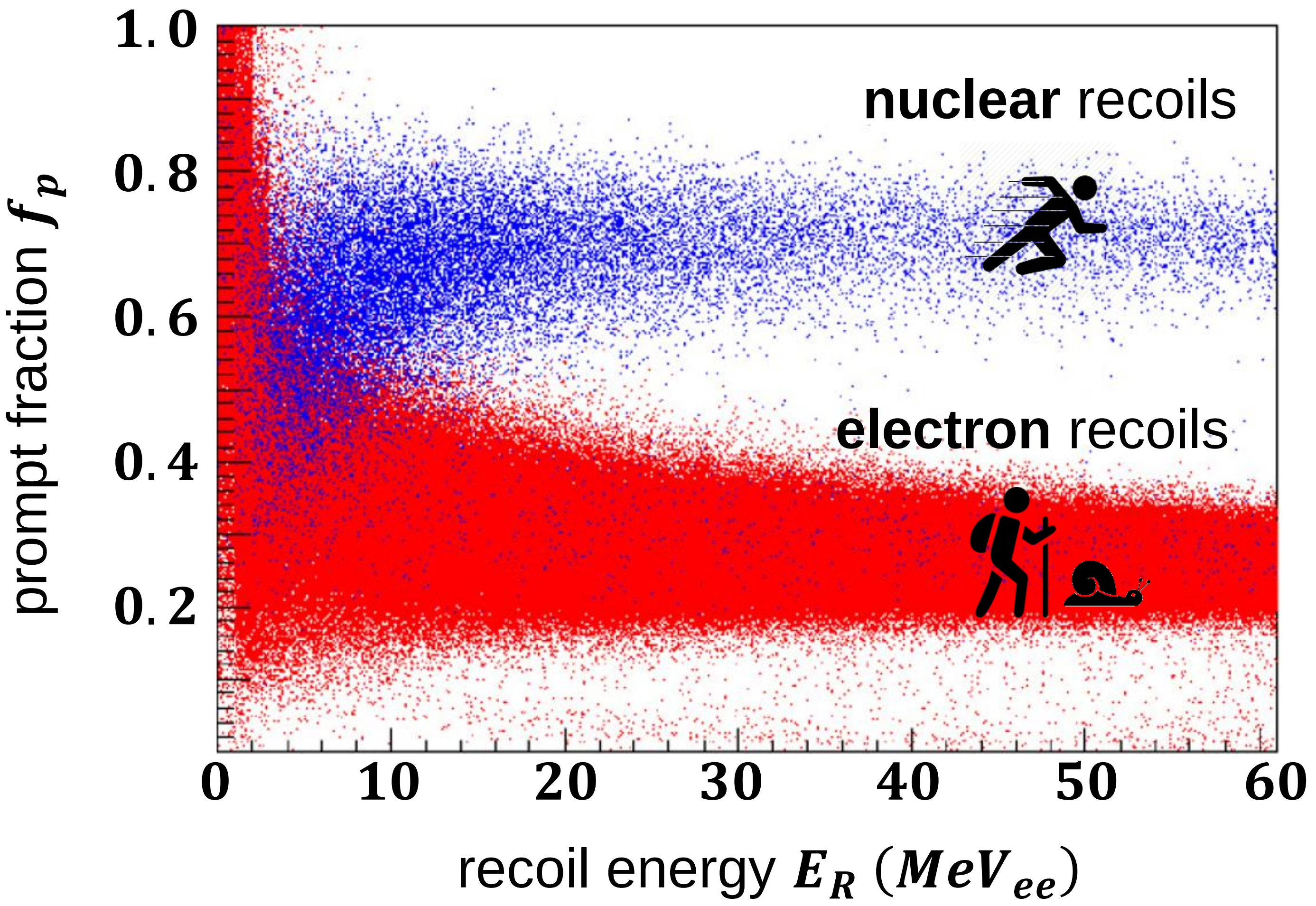
- **$Pulse\ Shape\ Discrimination$ (PSD): prompt fraction f_p of light seen by $PMTs$**

- **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^-)

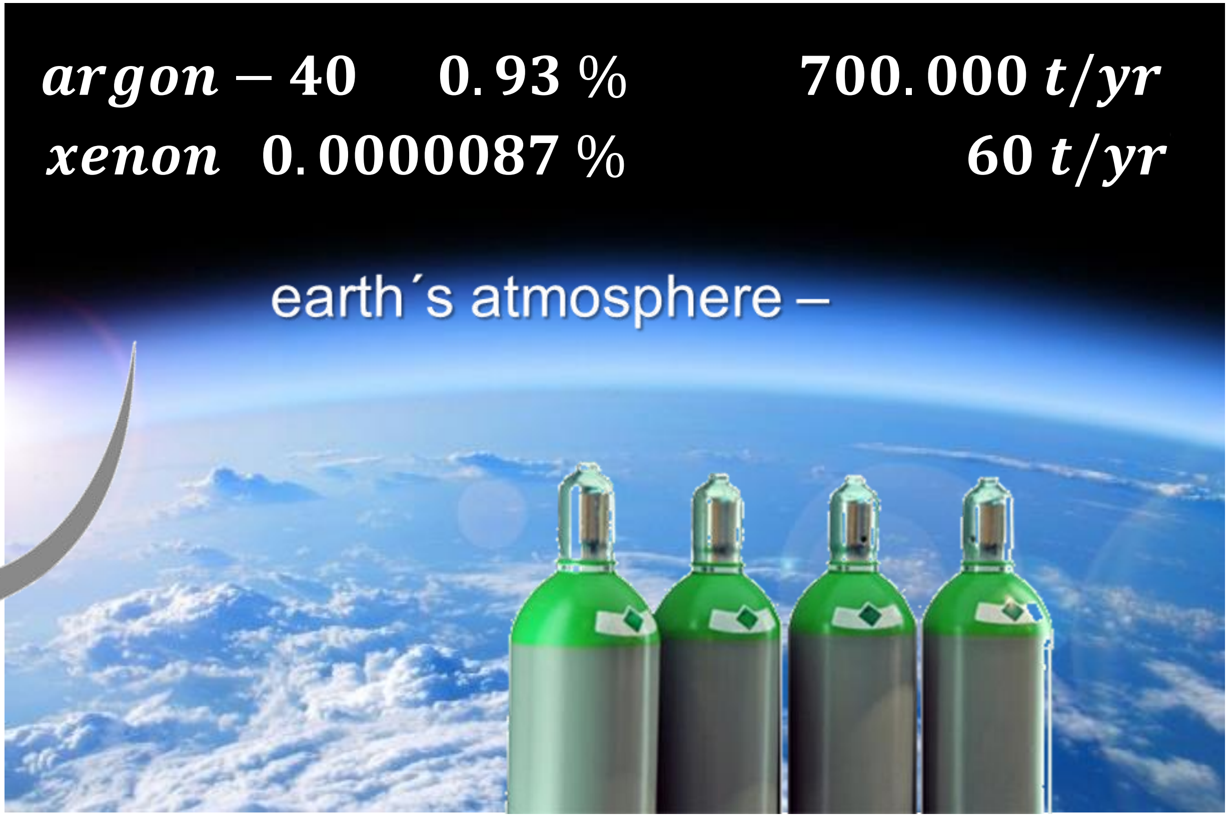
  ⇨ **large** for $singlet$ states (^AZ)



HANDS–ON: MARKET RESEARCH INTO LXE/LAR

- **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 ($60\ t\ yr^{-1}$)
    ⇨ significant **cost factor** in direct DM – searches ($DARWIN\ 50\ t$)



HANDS–ON: PRODUCTION OF LXE

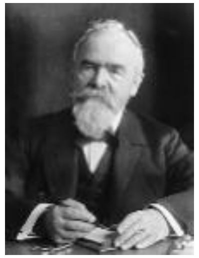
- **xenon: a precious by–product of commercial air liquefication**

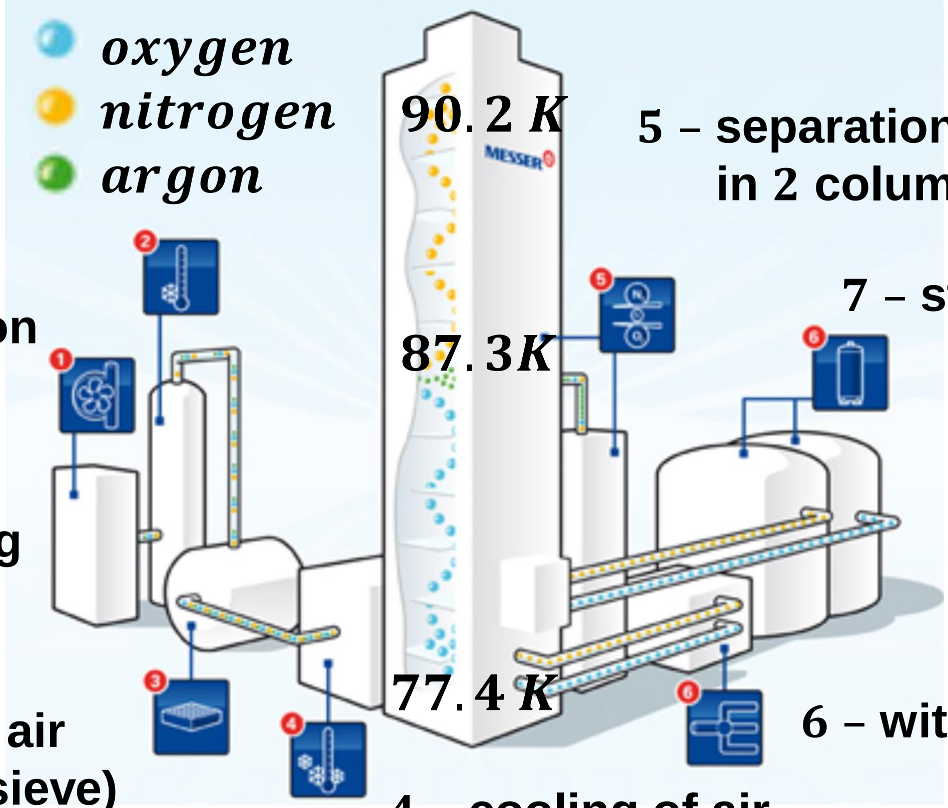
- **xenon**: generated in several large–scale commercial *A*ir *S*eparation *U*nits (*ASU*s)
  goal: production of **oxygen** for **steel mills**

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

- **cryodestillation** allows to separate **xenon** from $argon$

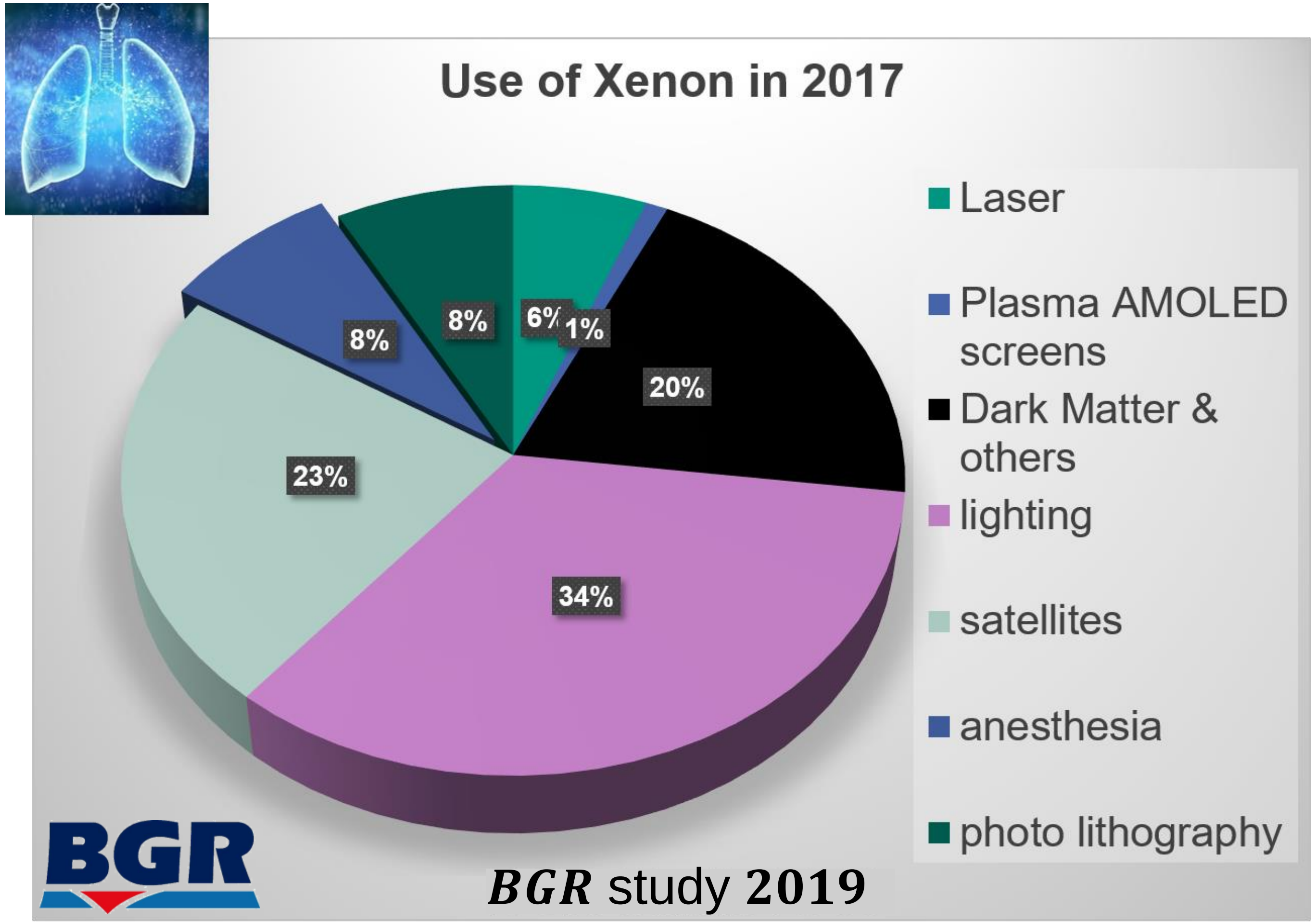
Q: Messer-Griesheim





HANDS–ON: PRODUCTION OF LXE

- DM – consumption compared to others



BGR study 2019

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 background

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

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

we need to purify our xenon from this $\boldsymbol{krypton}$ – again by $\boldsymbol{cryodestillation}$!

LXe-experiments: isotope Kr-85

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

  - anthropogenic origin (from nuclear fission with 0.3% yield)

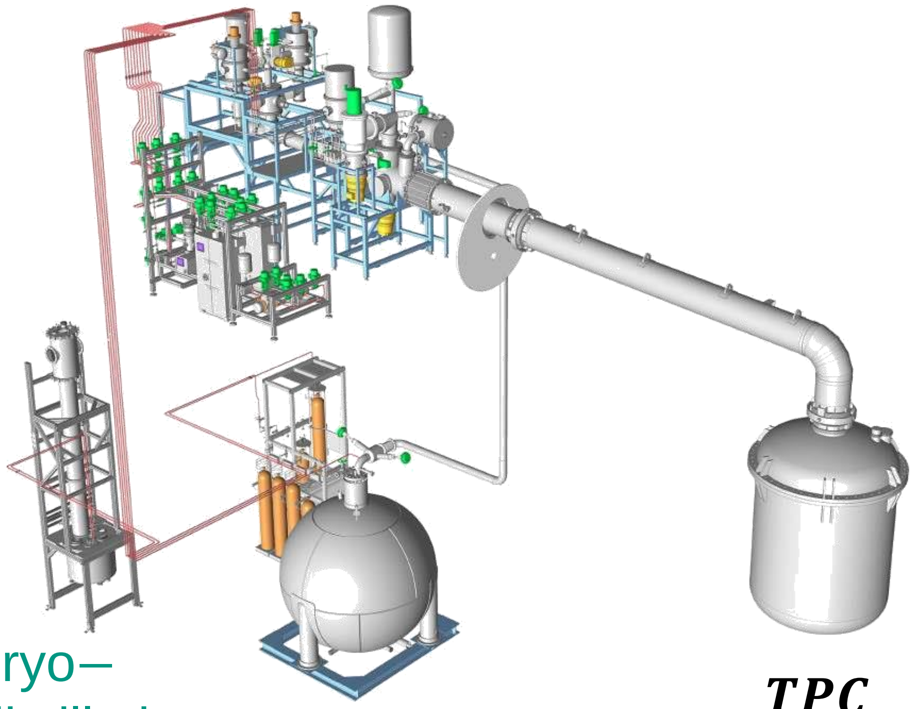
  - worldwide inventory: $\boldsymbol{A \sim 5.5\ TBq}$
    $\boldsymbol{\sim 1.3\ Bq\ m^{-3}}$

^{85}Kr
$t_{1/2}$ = 10.6 a

Liquid noble gases – fighting intrinsic background

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

  - $\boldsymbol{xenon}$ 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!)

  - installation of a column for dedicated cryodistillation

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

^{85}Kr
$t_{1/2}$ = 10.6 a

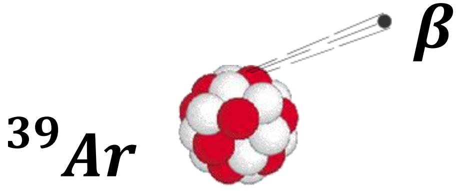
Liquid noble gases – fighting intrinsic background

- **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

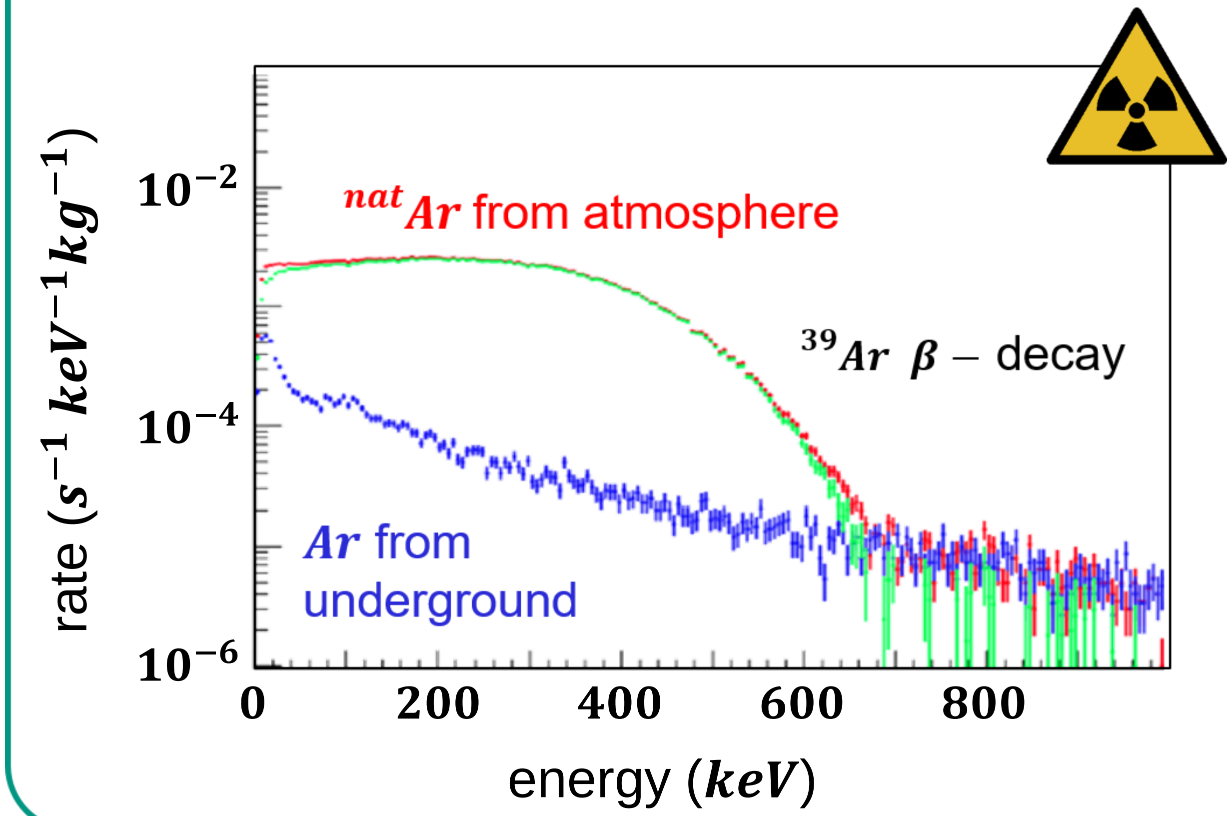
β – decay with $Q = 565\ keV$

$t_{½} = 269\ y$



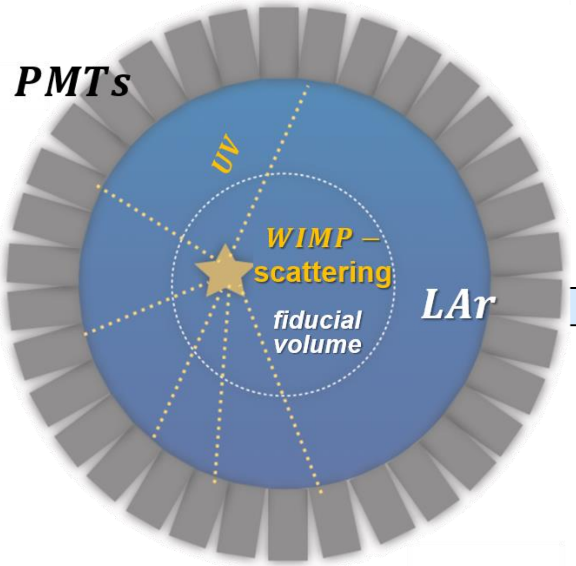
⇨ very high β – activity:
$\sim 1\ Bq$ per $kg\ Ar$

LAr –experiments: isotope Ar-39



Liquid noble gases – fighting intrinsic background

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



LAr –experiments: isotope Ar-39

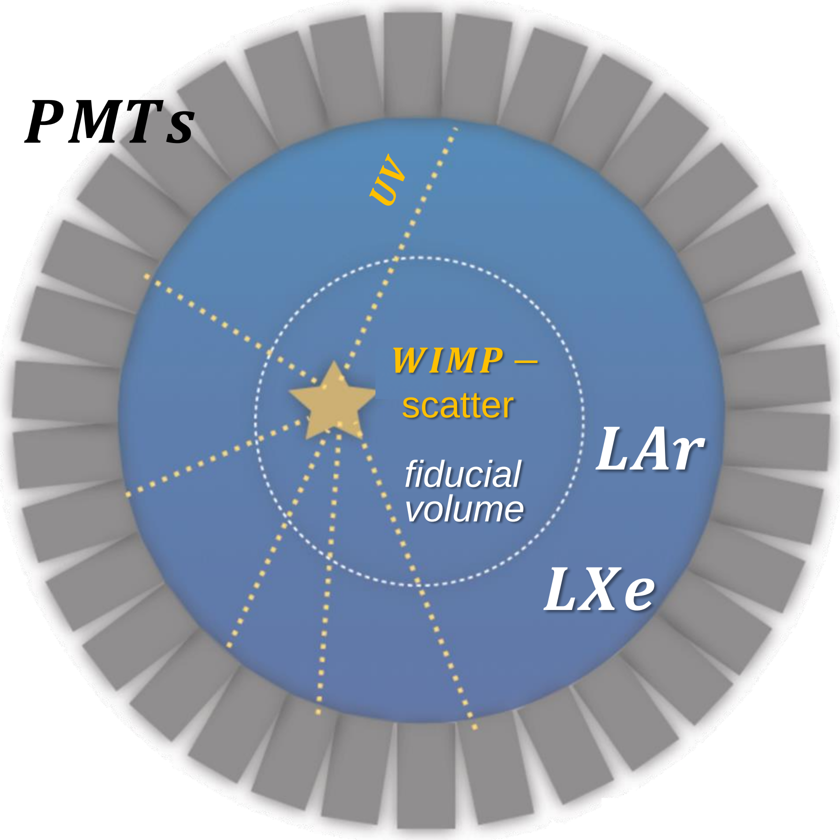
extraction of underground argon

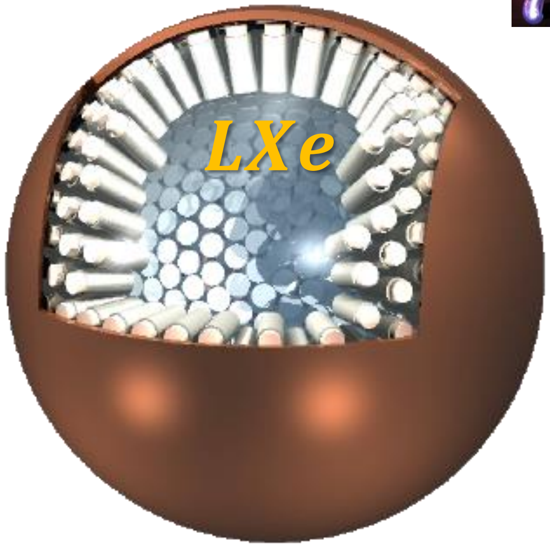
Liquid noble gases: single phase experiments

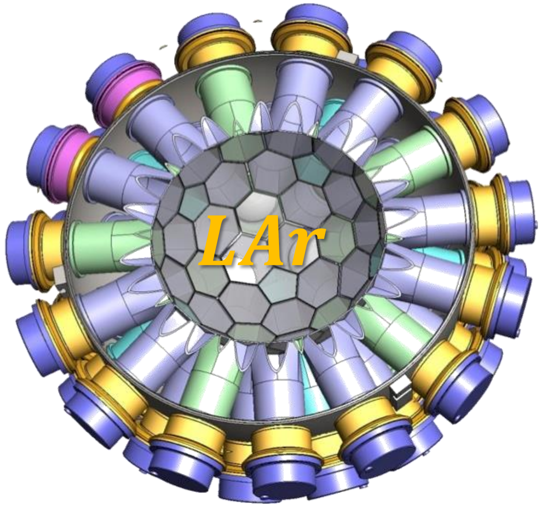
- **Early DM – experiments focused only on 1 parameter: scintillation light**

spherical geometry

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







Liquid Argon experiments: *MiniCLEAN*

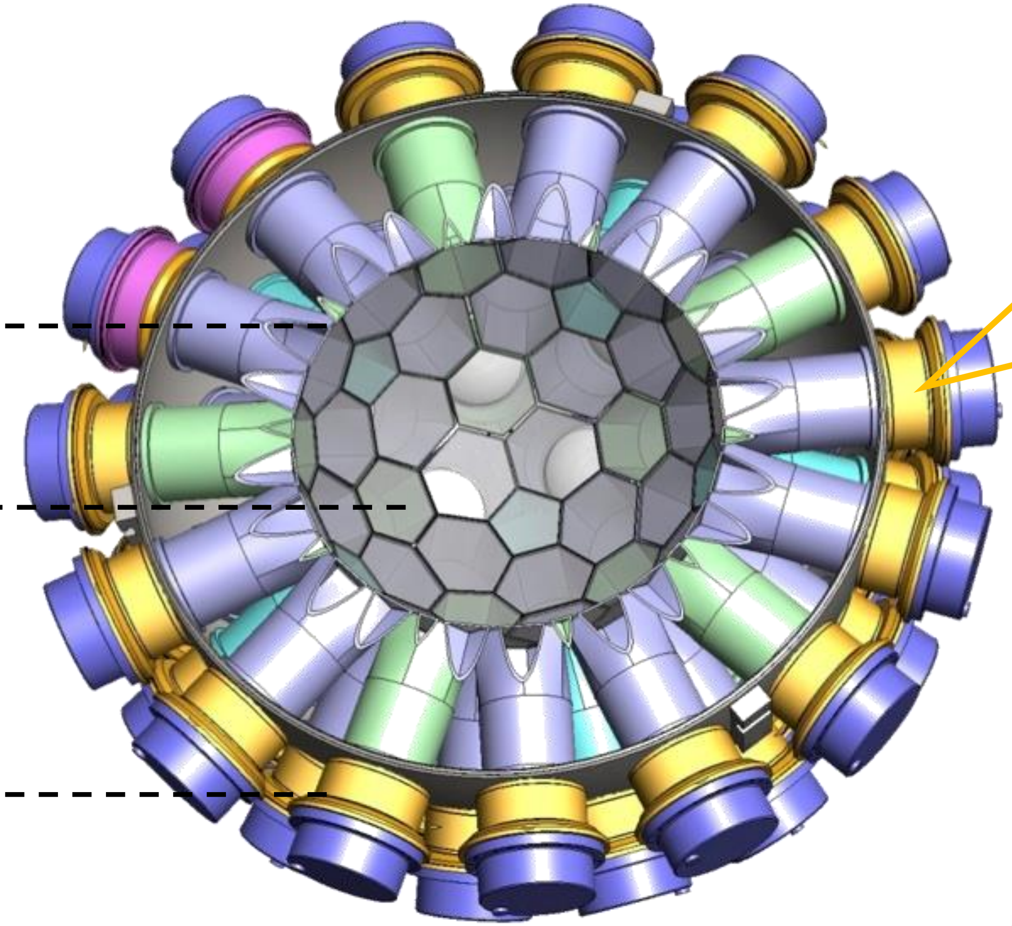
- *R & D* prototype for a (planned) larger detector (*CLEAN*) with 1 parameter

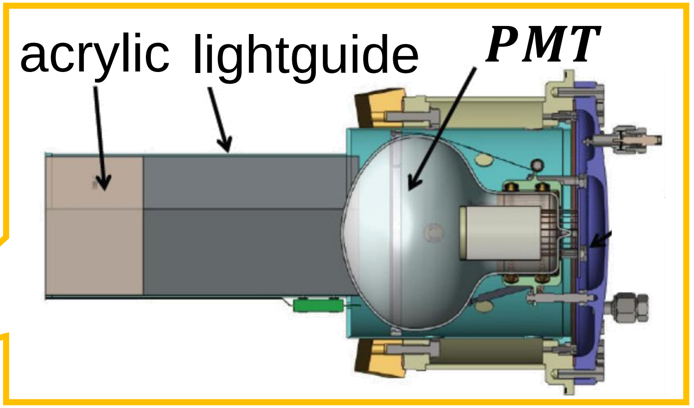
$\varnothing = 45\ cm$

$500\ kg\ argon$

($150\ kg$ 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*

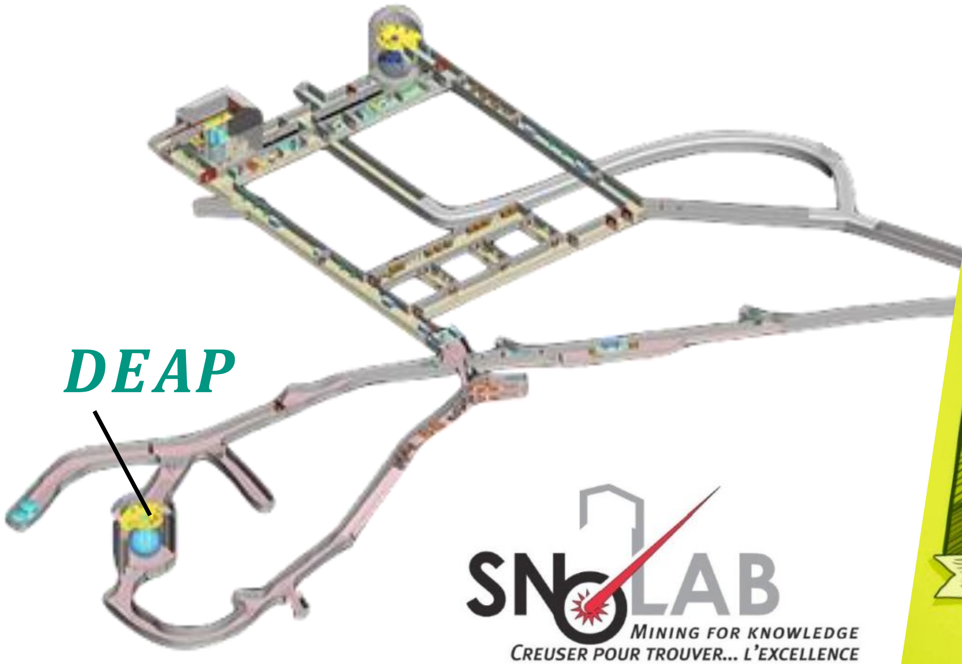
SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

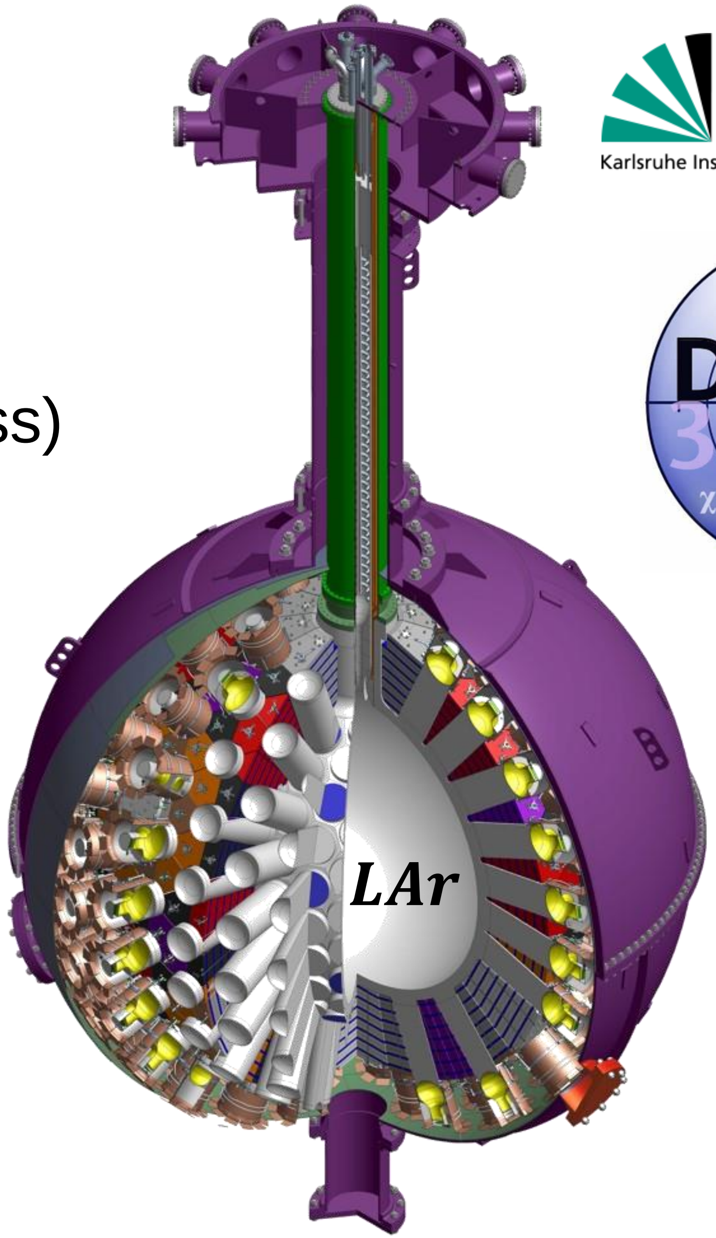
Liquid Argon experiments: $DEAP$

- ***D***ark Matter ***E***xperiment using ***A***rgon ***P***ulse shape discrimination

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

ee: ***e***lectron ***e***quivalent
NR: ***N***uclear ***R***ecoil





Liquid Argon experiments: *DEAP*

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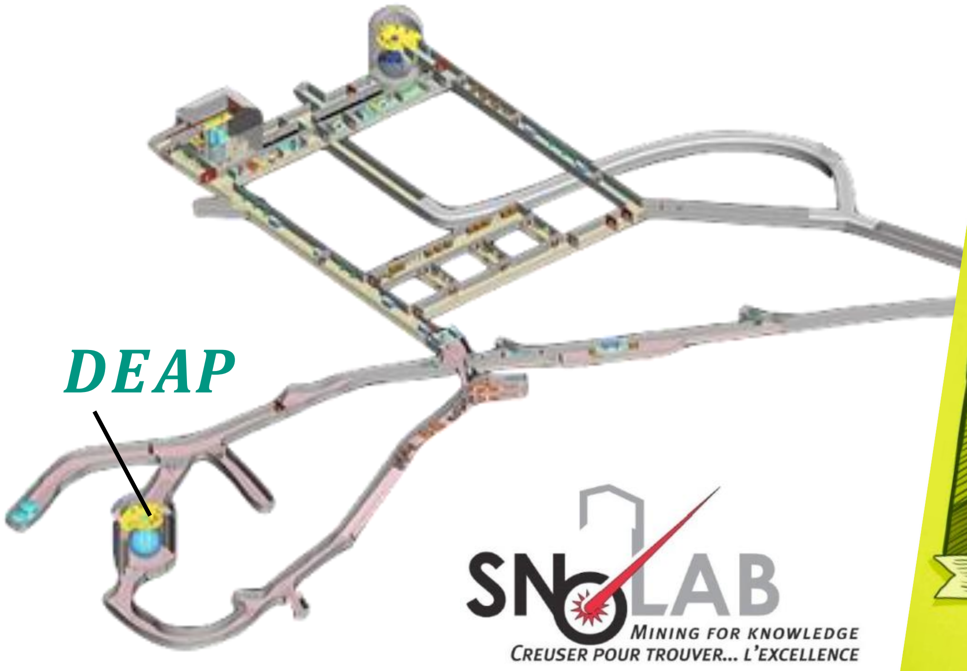
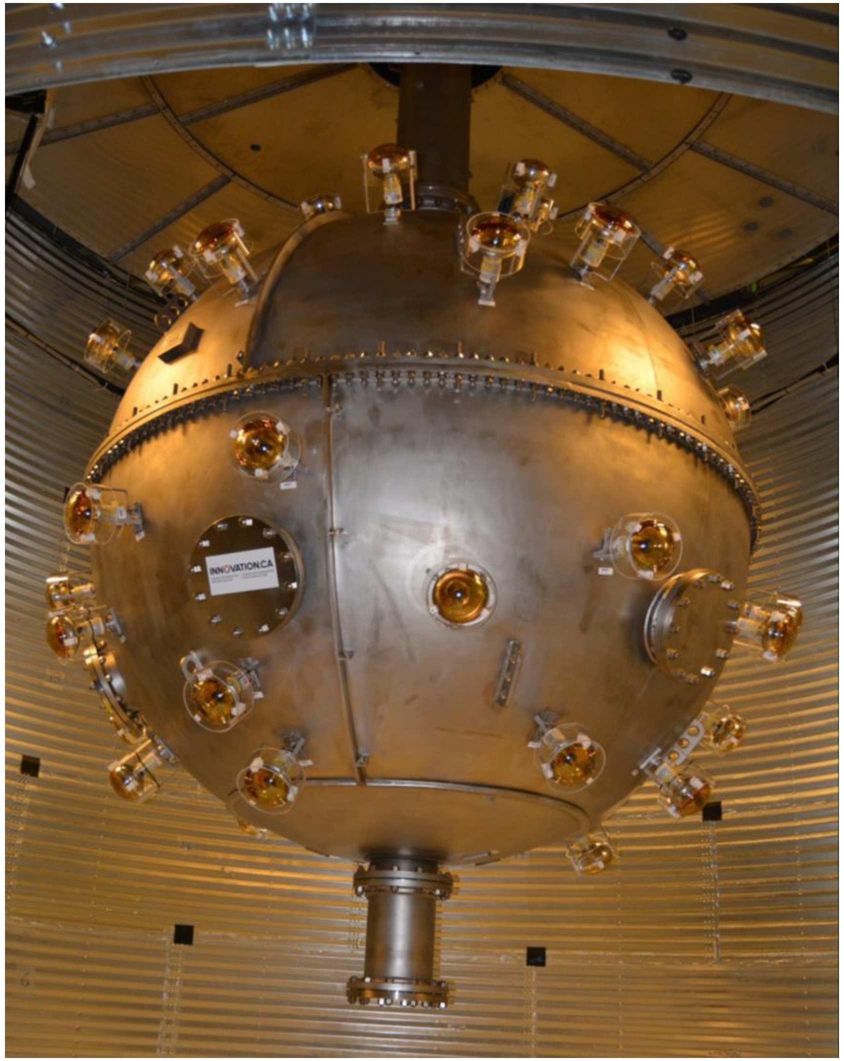
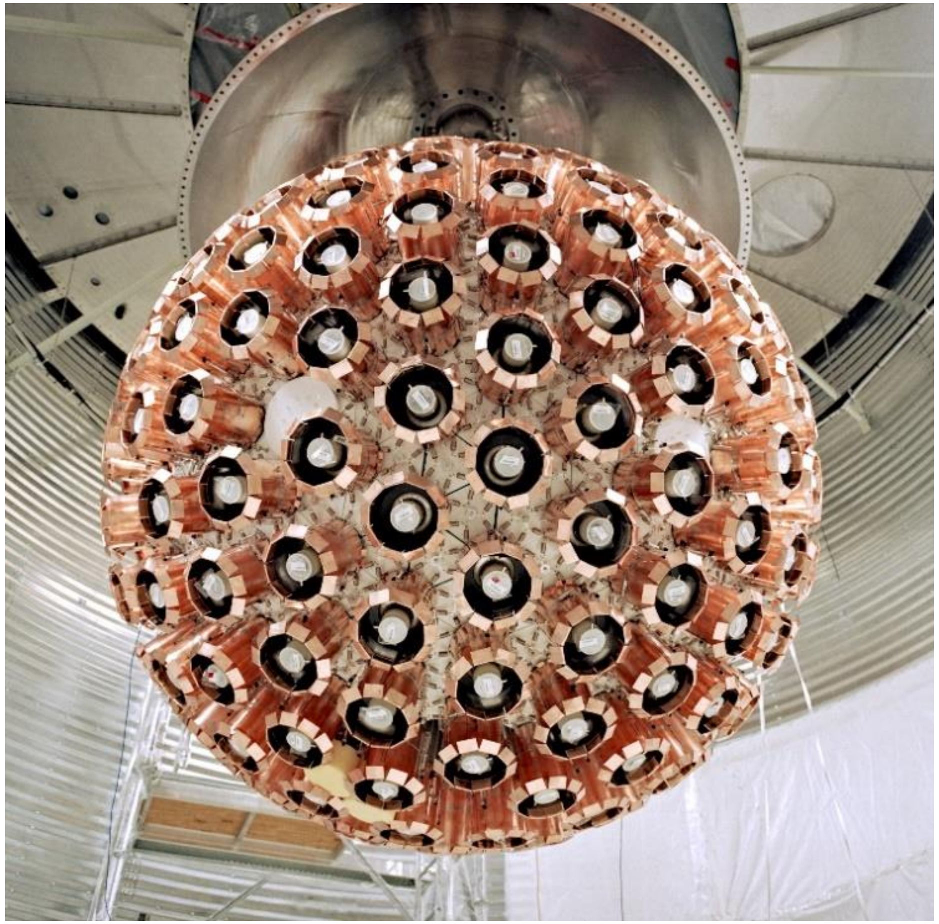
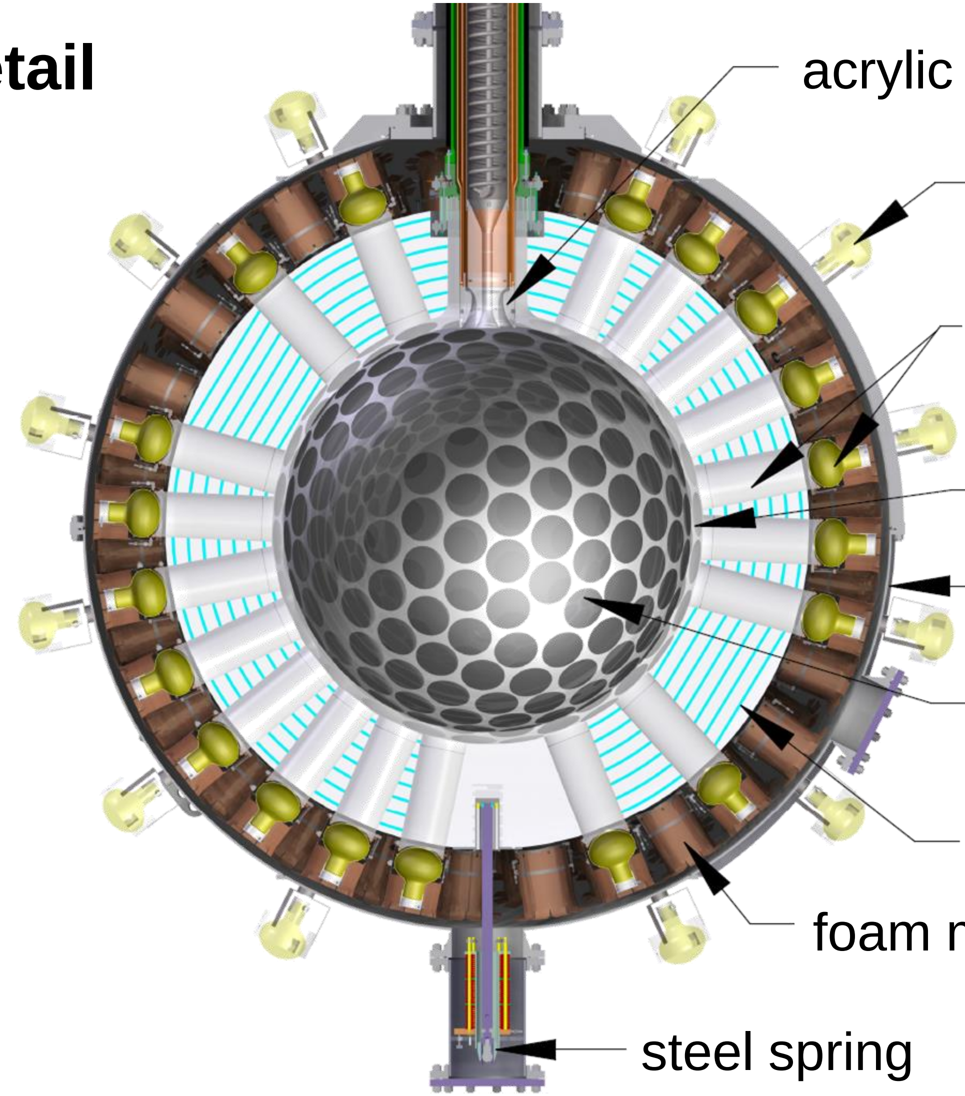




Liquid Argon experiments: $\boldsymbol{DEAP}$

- $\boldsymbol{DEAP}$ **detector setup in detail**

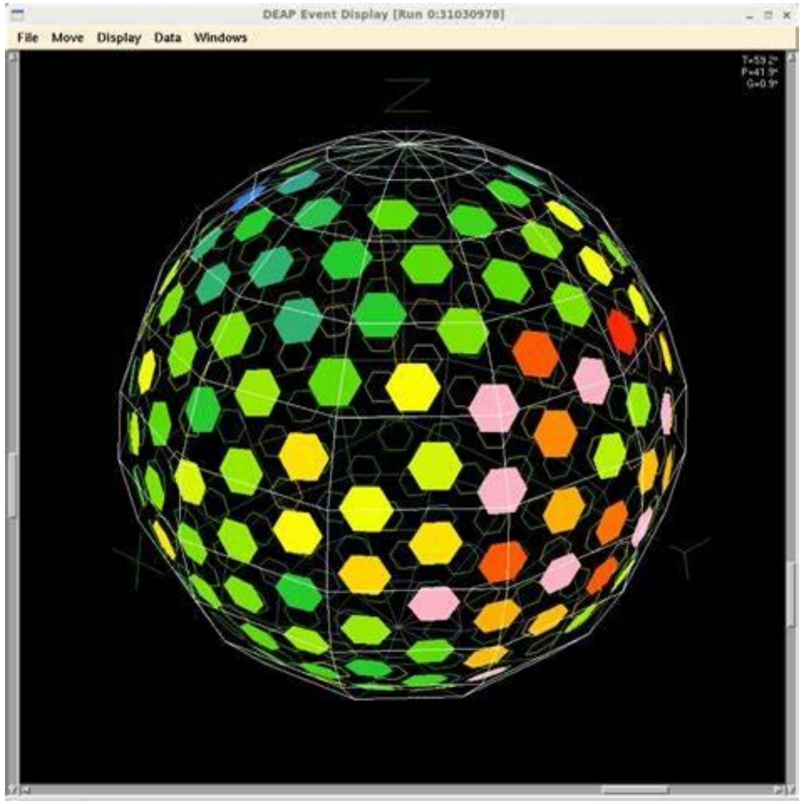




Liquid Argon experiments: $DEAP$

■ **Measurements and results**

- $DEAP$ event



- measurements & data taking since $\mathbf{2016}$

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

- DM – results $\mathbf{2019}$

  - $\mathbf{231}$ days measurement time

  - **no $WIMP$ signal**

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