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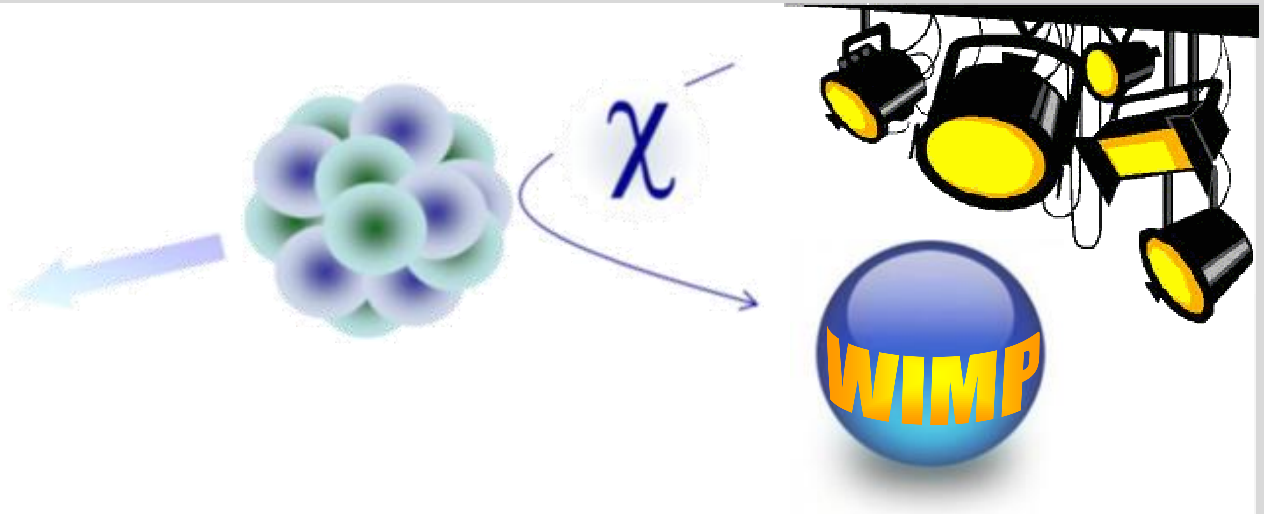


Dark Matter - III

GRK 1694: Elementarteilchenphysik bei höchster Energie und höchster Präzision

Workshop Freudenstadt 2015

September 30, 2015

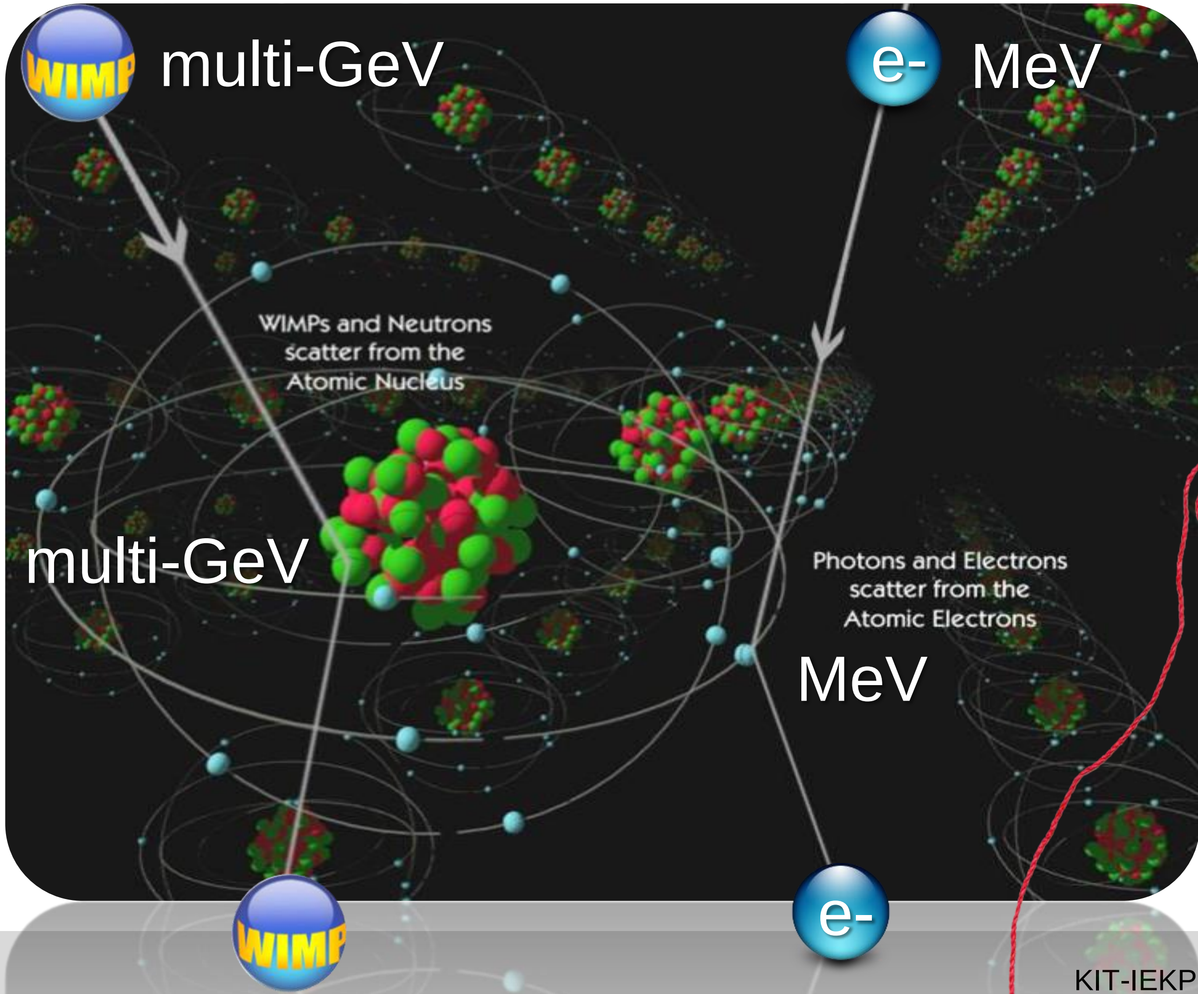
Guido Drexlin, Institut für Experimentelle Kernphysik

outline of today´s final afternoon lecture

Dark Matter – 3: direct detection of dark matter

- expected WIMP rates: SUSY (M_χ, σ_{SI},SD) and astrophysics (Φ, v)
- detection methods: 1- & 2- parameter experiments
- underground experiments & background
- DAMA´s annual modulation
- bolometers vs. LXe detectors
- 2-phase liquid noble gas detectors: XENON100/1T/ DARWIN
- conclusion

elastic WIMP-nucleus scattering in keV-range



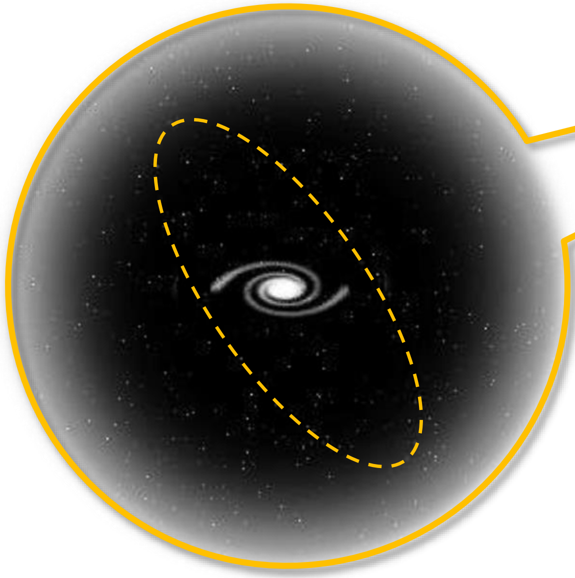
WIMP detection

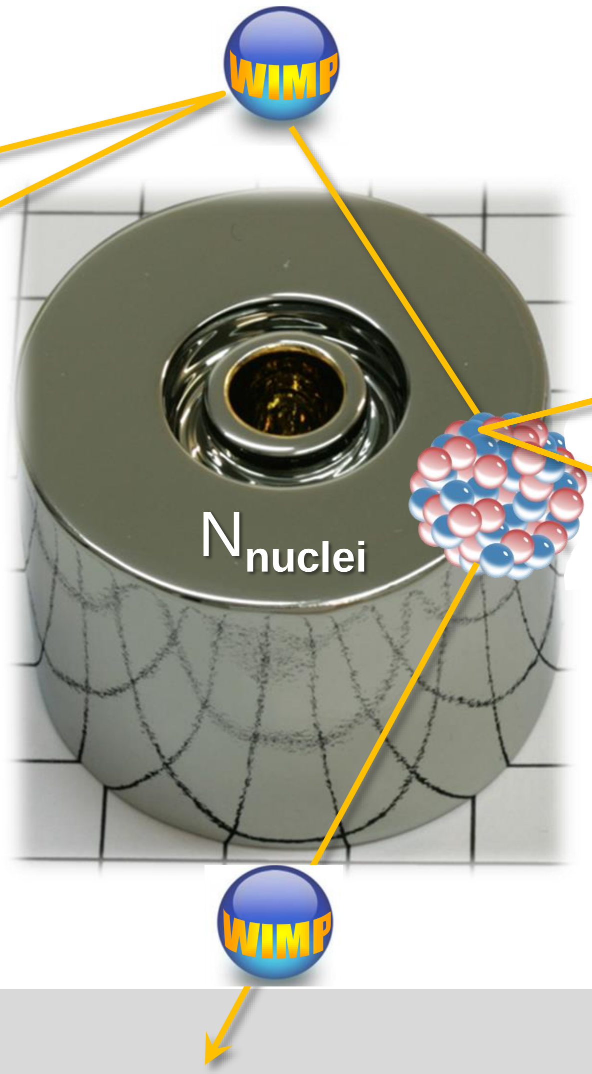
- **reaction kinematics: input from astrophysics & SUSY**

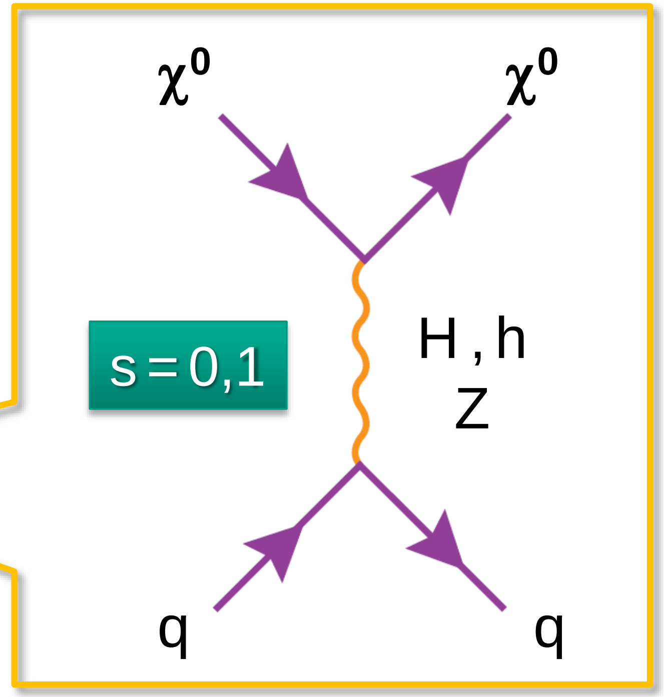
$$R = N_{nuclei}\cdot\langle\Phi\rangle\cdot\langle\sigma_{SI/SD}\rangle = N_{nuclei}\cdot\frac{\rho_{DM,\,local}}{M(\chi^0)}\cdot\langle\sigma_{SI/SD}\cdot \mathrm{v}\rangle$$

SUSY

ASTRO







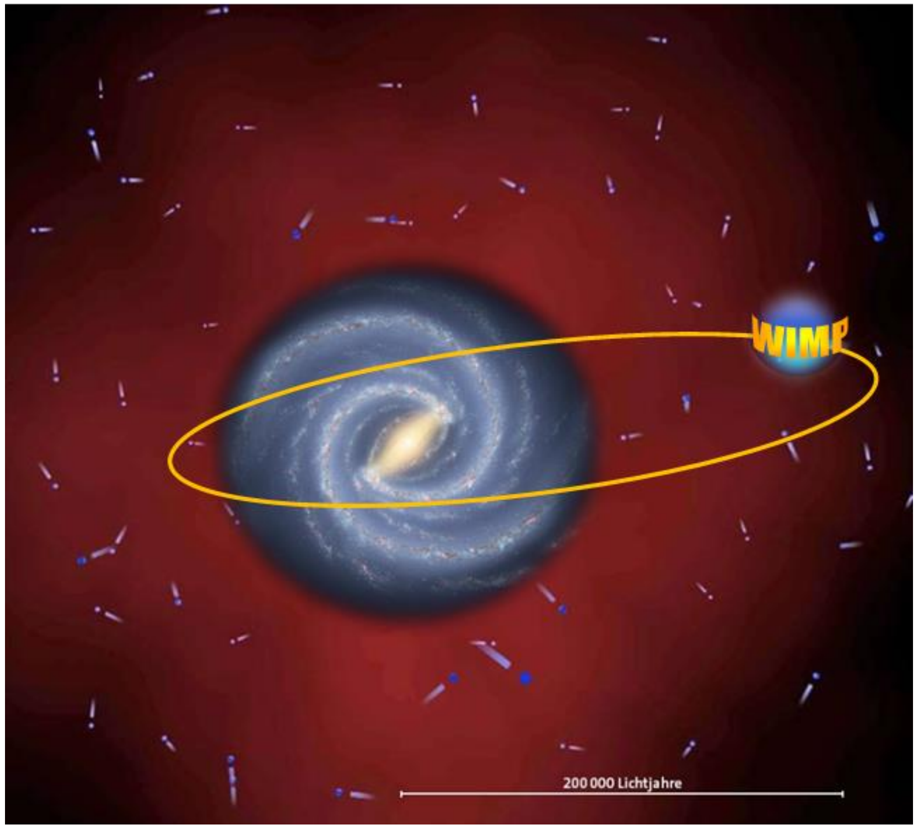
WIMP properties:
- kinetic energy (v)
- local density $\rho_{DM,local}$
- flux Φ (from v & $\rho_{DM,local}$)

WIMP properties:
- cross sections scalar σ_{SI} / axial σ_{SD}
- mass $M(\chi^0)$

WIMP velocity profile

- **WIMP energies from DM-halo**
  - ‹v› ~ 10^{-3} c
  - $E_{kin} = ½ M_χ \cdot v^2$
  - $M_χ$ = 100 GeV ⇨ **E_{kin} < 100 keV**

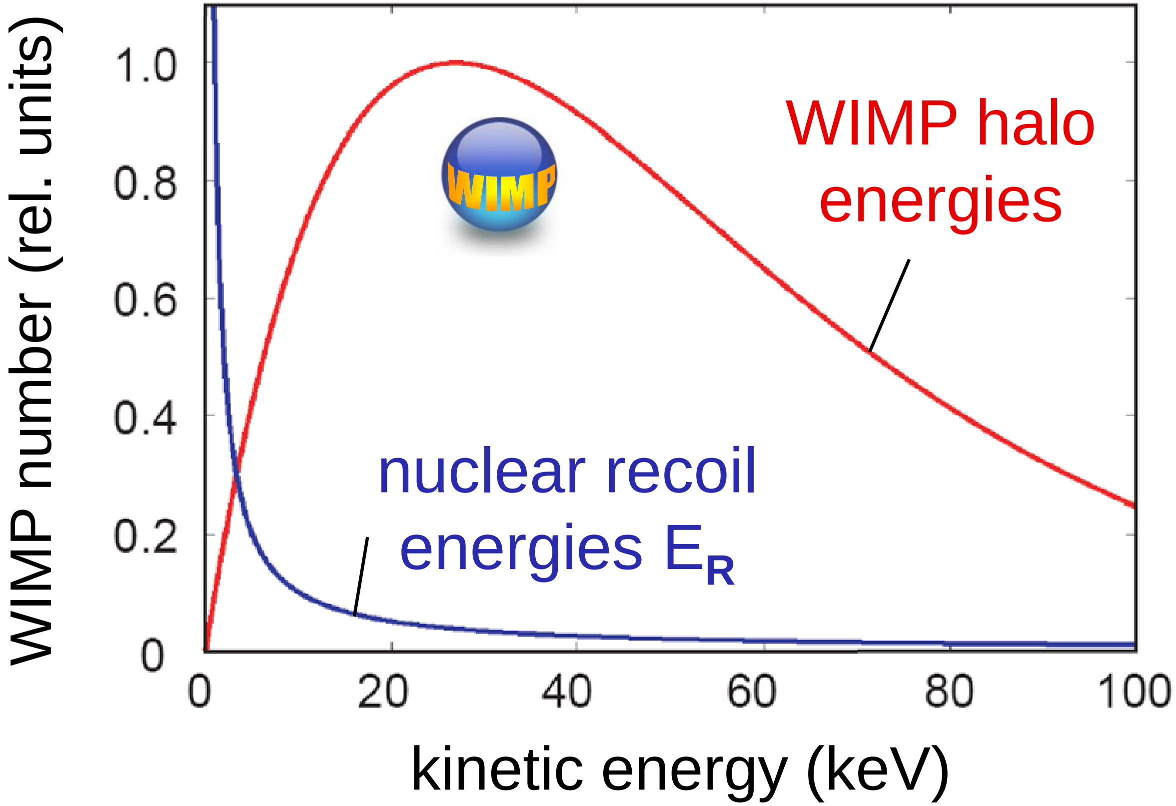
  $E_{kin} \ll M_χ$



- **isothermal WIMP velocity profile f(v)**

$$f(\mathrm{v})\,dv = \frac{4\mathrm{v}^2}{\mathrm{v}_0^3\sqrt{\pi}} e^{\left(-\mathrm{v}^2/\mathrm{v}_0^2\right)} d^3\mathrm{v}$$

Maxwell-Boltzmann-velocity distribution

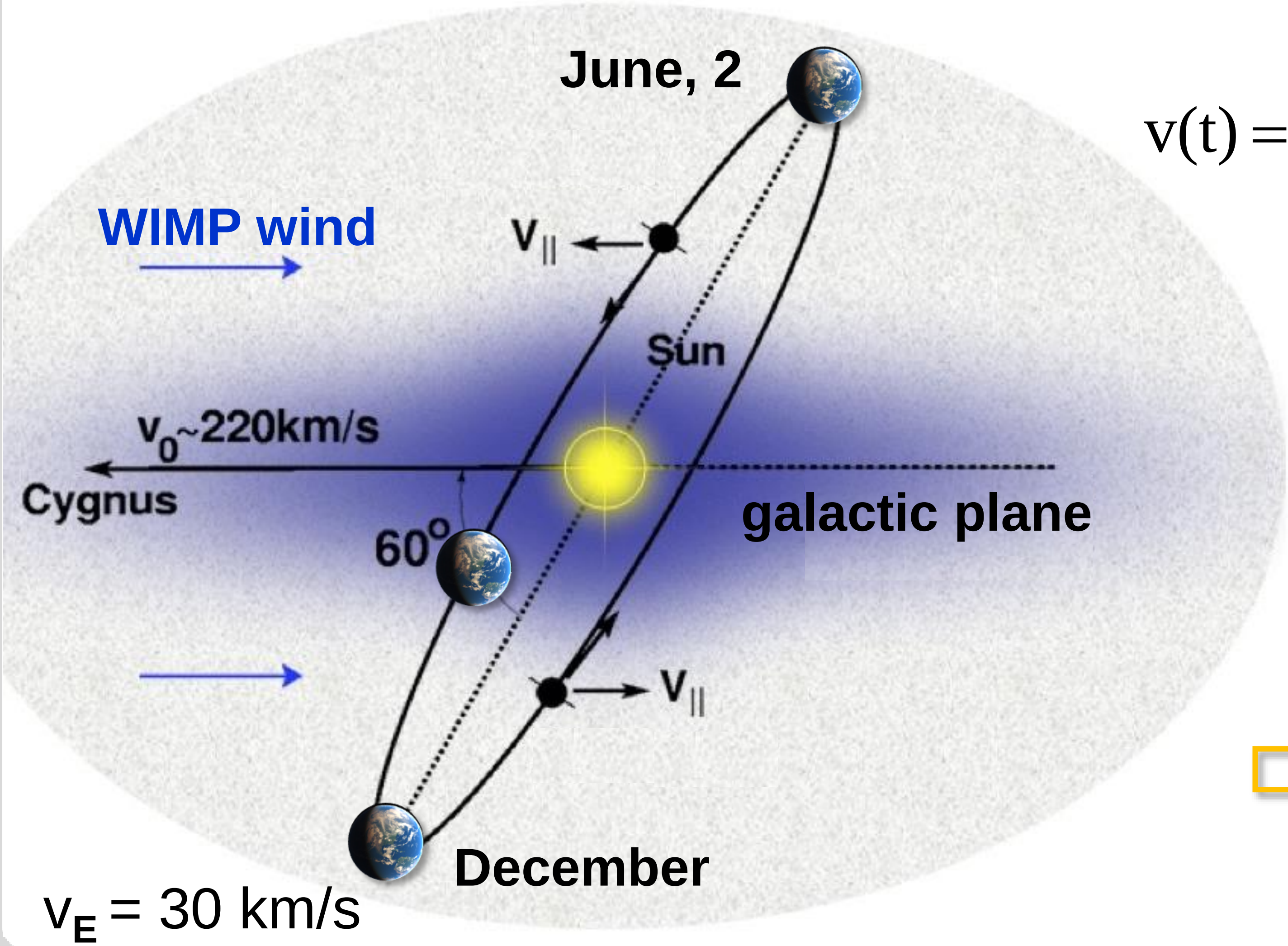


WIMP scattering – annual modulation

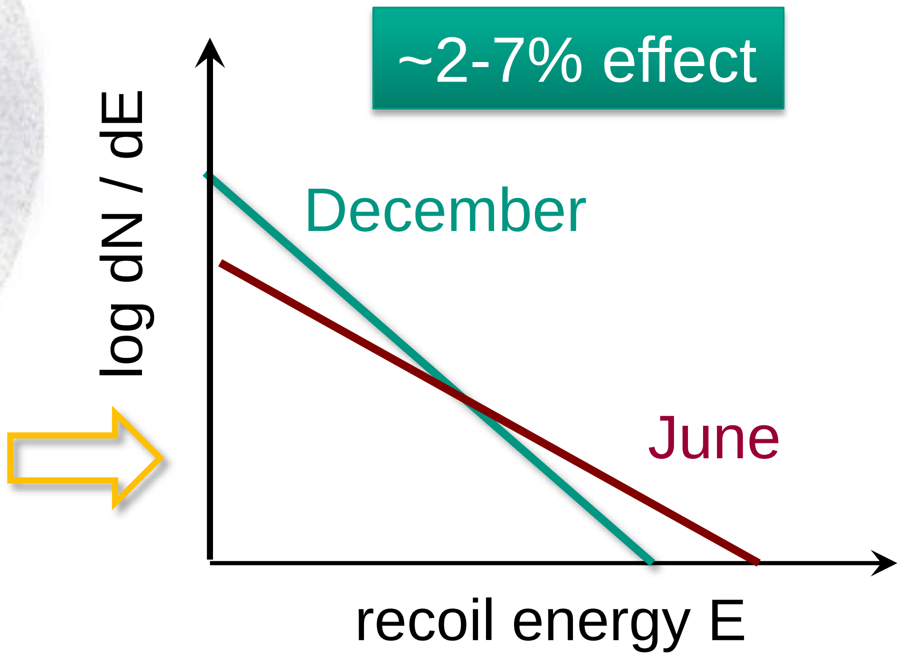
modulation of WIMP recoil spectrum

- superposition of velocity vectors v_S (sun) & v_E (earth)

⇨ period: T = 1.00 year   phase: φ_0 = June, 2



$$v(t) = v_0 + v_E \cos(60°) \cdot \cos \omega (t - t_0)$$



WIMP detection

■ reaction kinematics: input from SUSY

$$R = N_{nuclei} \cdot \langle \Phi \rangle \cdot \langle \sigma_{SI/SD} \rangle = N_{nuclei} \cdot \frac{\rho_{DM,\,local}}{M(\chi^0)} \cdot \langle \sigma_{SI/SD} \cdot v \rangle$$

1 – level of **partons**: q, g

χ^0 - interaction with ***quarks, gluons***

χ^0 – coupling strength from SUSY model

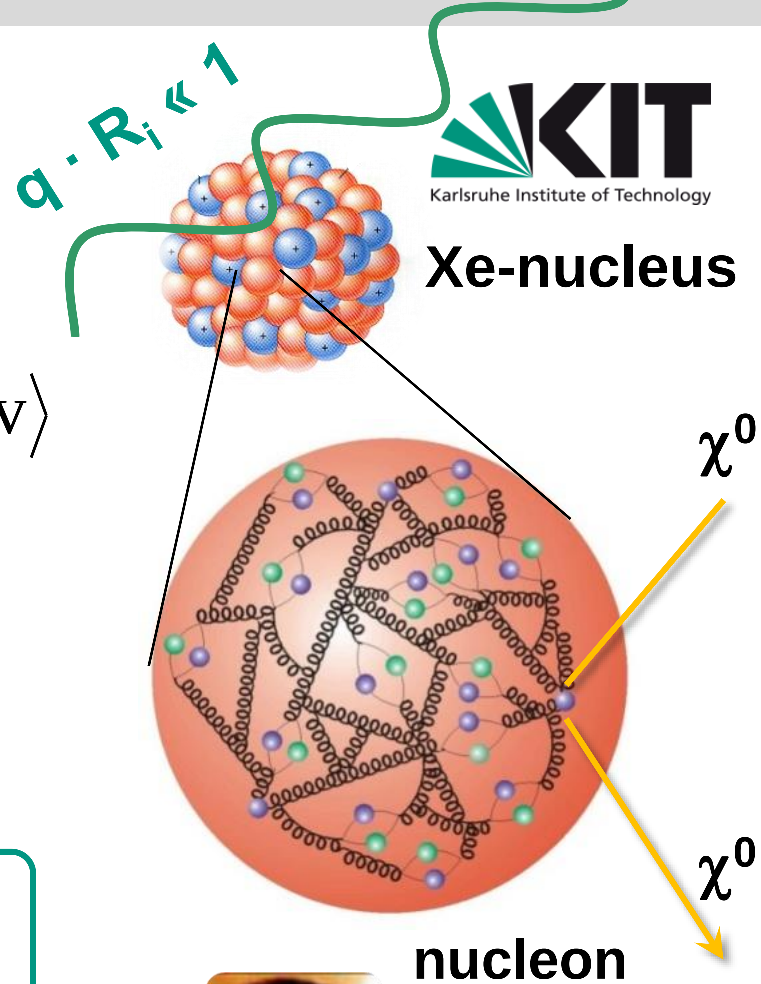
2 – level of **nucleons**: p, n

q, g kinematics within the ***nucleons*** is determined by parton distributions (valence- & sea quarks)

3 – level of **nuclear** structure: Ar, Ge, Xe,…

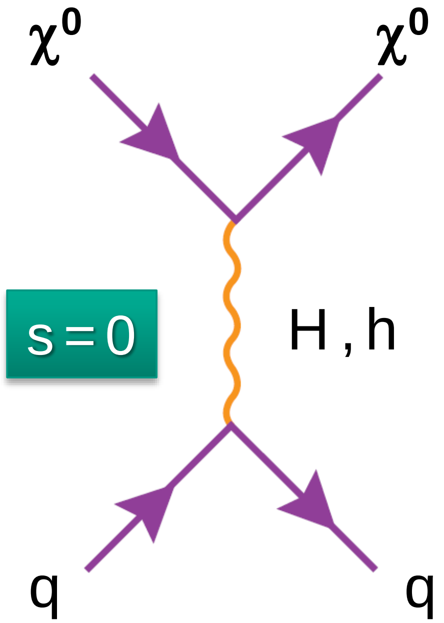
χ^0 - interaction on scale of ***nucleus*** (nuclear wave function)

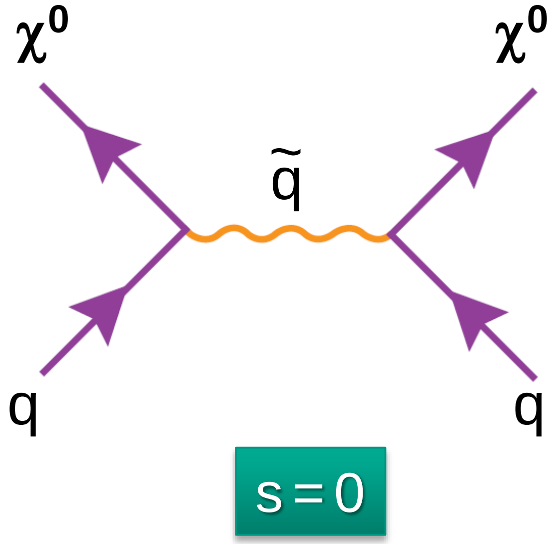
- reaction kinematics – **coherent nuclear recoil**



neutralino scattering: scalar interaction

scalar interaction: neutralino couples to mass distribution of the nucleus





- mechanism:
  - exchange of a light or a heavy higgs boson H, h
  - annihilation into squark ($\tilde{q}$-mixing)
  - also loop diagrams with (massless) gluons

- **scalar χ^0 – interaction** with a quark (σ_{SI}: **s**pin **i**ndependent)
  - quark- & gluon functions in nucleon: also heavy quarks contribute
  - **coherent interaction ~ A^2**
  - σ_{SI} dominates the elastic χ^0-cross section in many SUSY models

neutralino scattering: spin-dependent

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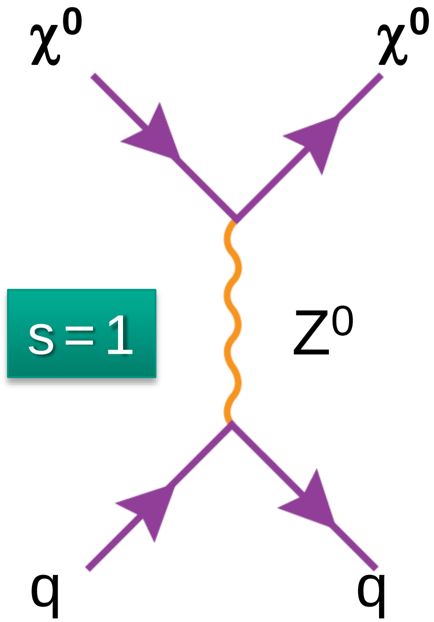
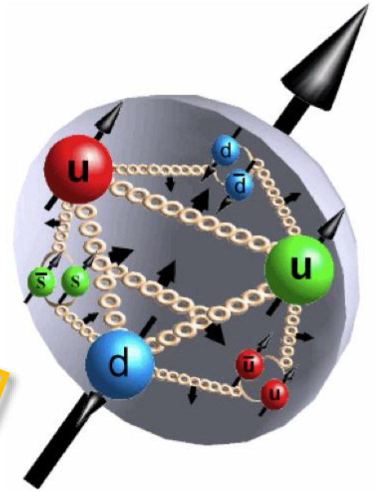
axial-vector interaction: spin of neutralino couples to spin of nucleus





important: target nucleus with $J \neq 0$

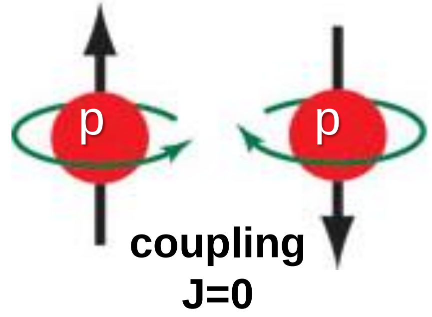
- **spin-dependent χ^0-interaction** (σ_{SD}: **s**pin **d**ependent)
  - spin structure functions: nucleon spin (p,n) from partons
  - spin matrix elements: nucleons in nucleus (´mean´ p/n-spin in nucleus)
  - nuclear shell model: nuclear spin from coupled nucleons in shells

neutralino scattering: spin-dependent

$$\sigma_{SD} \sim \sigma_0 \cdot \left(a_p \langle S_p \rangle + a_n \langle S_n \rangle \right)^2 \cdot \frac{J+1}{J}$$

$a_{p,n}$: WIMP-proton/neutron couplings (SUSY-model-dependent)

J : spin of nucelus via unpaired nucleon (proton / neutron) due to pairing term (Bethe-Weizsäcker)



$\langle S_{p,n} \rangle$: expectation value of proton/neutron spin (e.g. 5/2, 1/2) within nulcear shell model

- **only J ≠ 0 targets are sensitive to spin-dependent WIMP-scattering**

  examples of important target nuclei for σ_{SD} (sensitive to a_p or a_n):

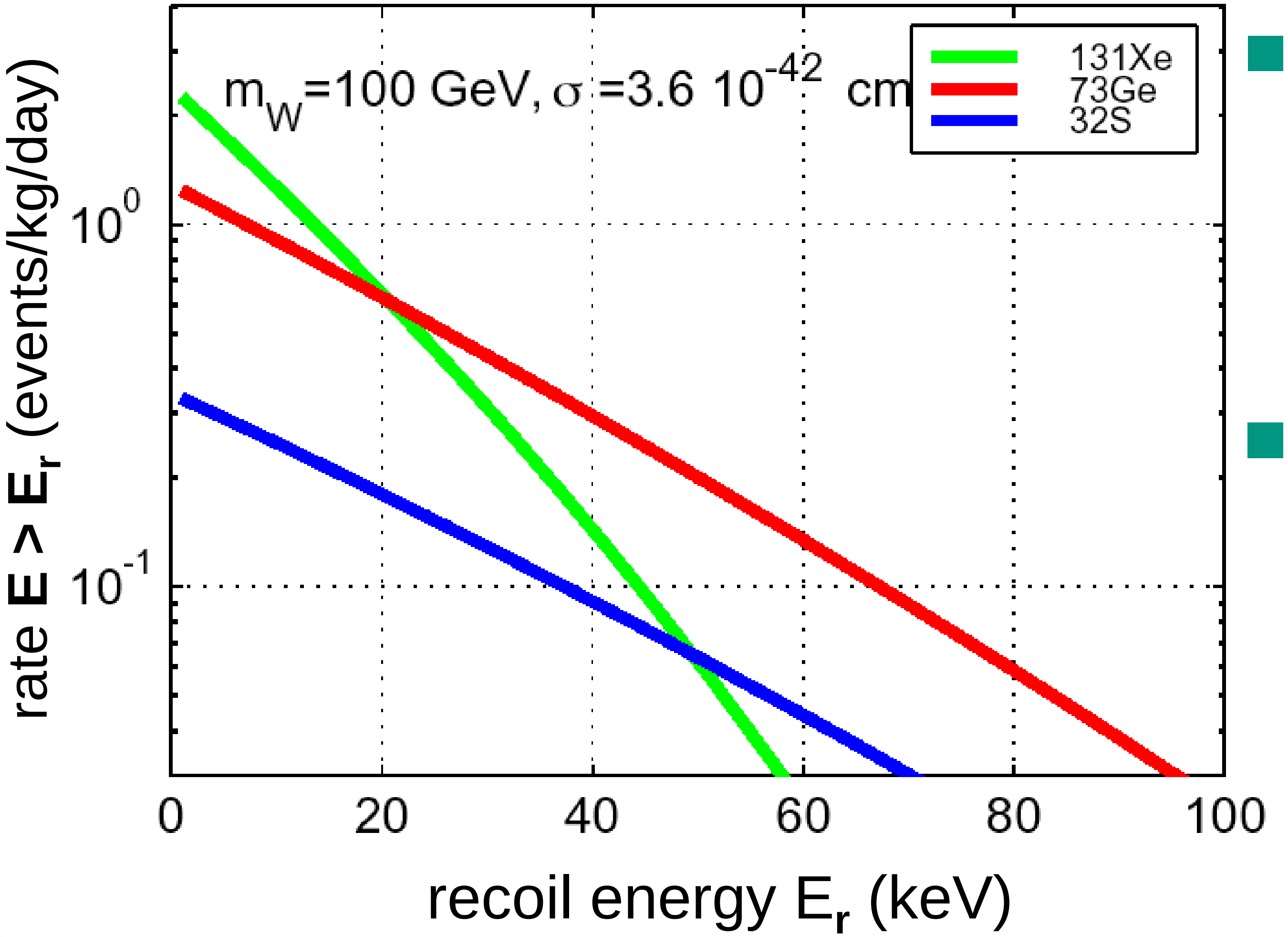
detector type	isotope	fraction	protons	neutrons	nucl. spin J	coupling
NaJ (scintillator)	^{23}Na		**11**	12	3/2	a_p
	^{127}I		**53**	74	5/2	a_p
LXe (TPC/scint.)	^{131}Xe	21.2 %	54	**77**	3/2	a_n
	^{129}Xe	26.4 %	54	**75**	1/2	a_n
Ge (bolometer)	^{73}Ge	7.8 %	32	**41**	9/2	a_n

WIMP – recoil spectra

- **recoil spectrum** for scalar interaction (coherent, form factor)

$$\frac{dR}{dE_R} \sim \int \frac{d\sigma}{dE_R} \mathrm{v} \cdot f(\mathrm{v})\, d\mathrm{v}$$

recoil energies of nuclei on keV-scale

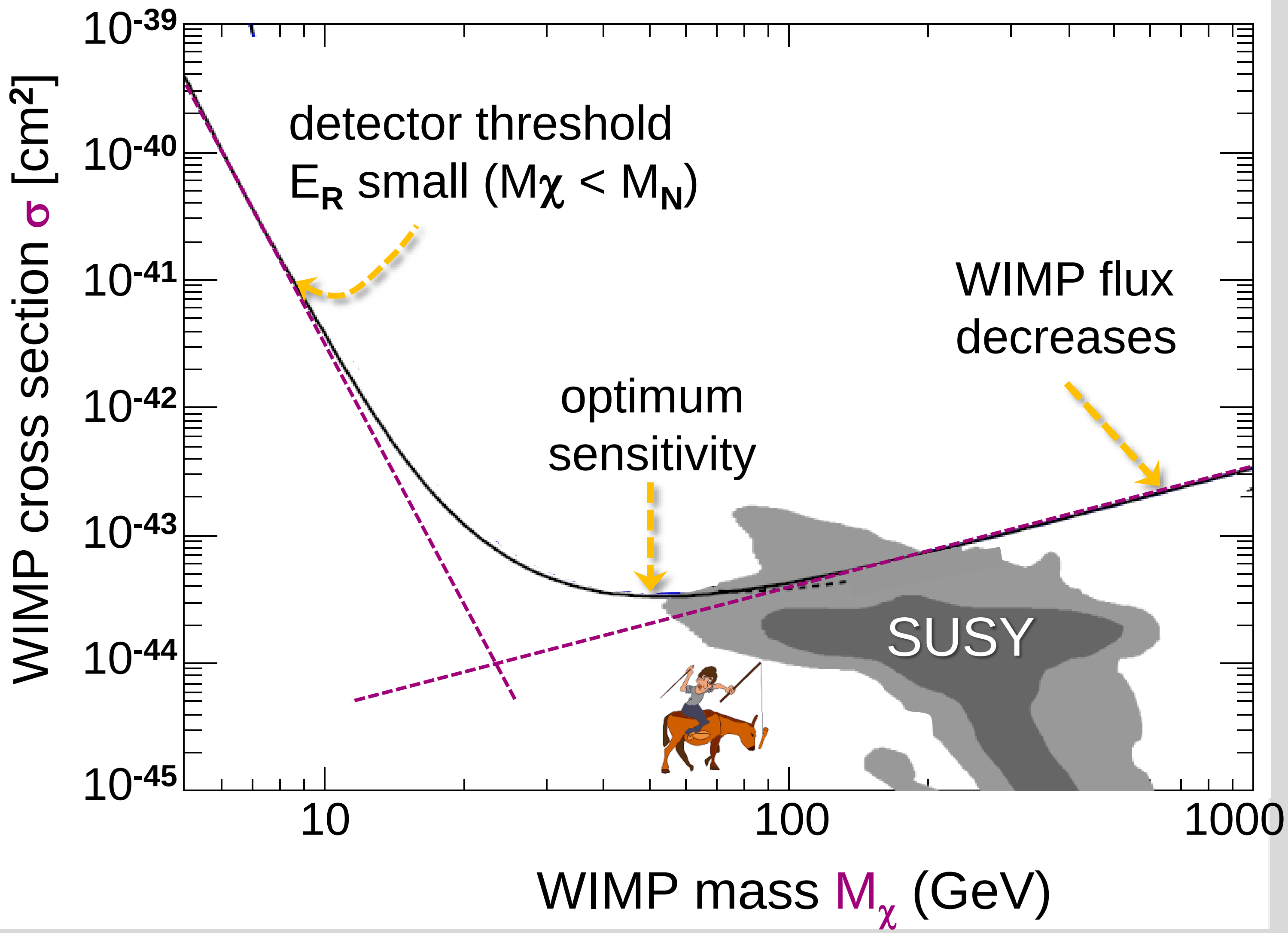


- **astrophysics**
  - WIMP-halo model (ρ_{CDM}, v_0) :
    the larger v_0, the larger the rate
  - neutralino mass M_χ
- **detector properties**
  - nuclear target mass M_N
  - nuclear structure (formfaktor F)
  - **very low threshold (few keV)**
    for heay target nuclei (Xe, J)

WIMP plots – comparison of results

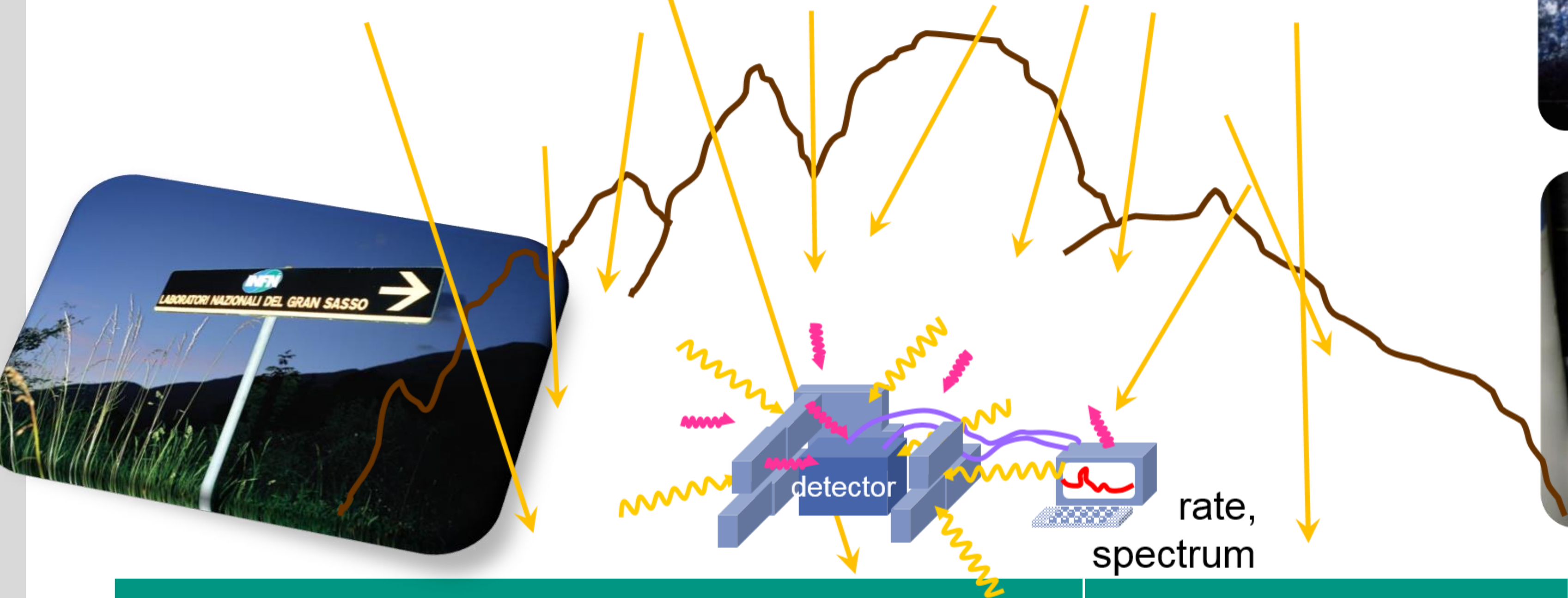
$$R = N_{nuclei} \cdot \langle \Phi \rangle \cdot \langle \sigma_{SI/SD} \rangle = N_{nuclei} \cdot \frac{\rho_{DM,local}}{M(\chi^0)} \cdot \langle \sigma_{SI/SD} \, v \rangle$$

- **light WIMPs**:
  nuclear recoil energy below threshold
- **heavy WIMPs**:
  $\Omega_{CDM} = 0.22$ is fixed
  for large M_χ the WIMP fluss Φ decreases, less signal events
- **SUSY region**:
  to cover larger fraction: larger mass & smaller background



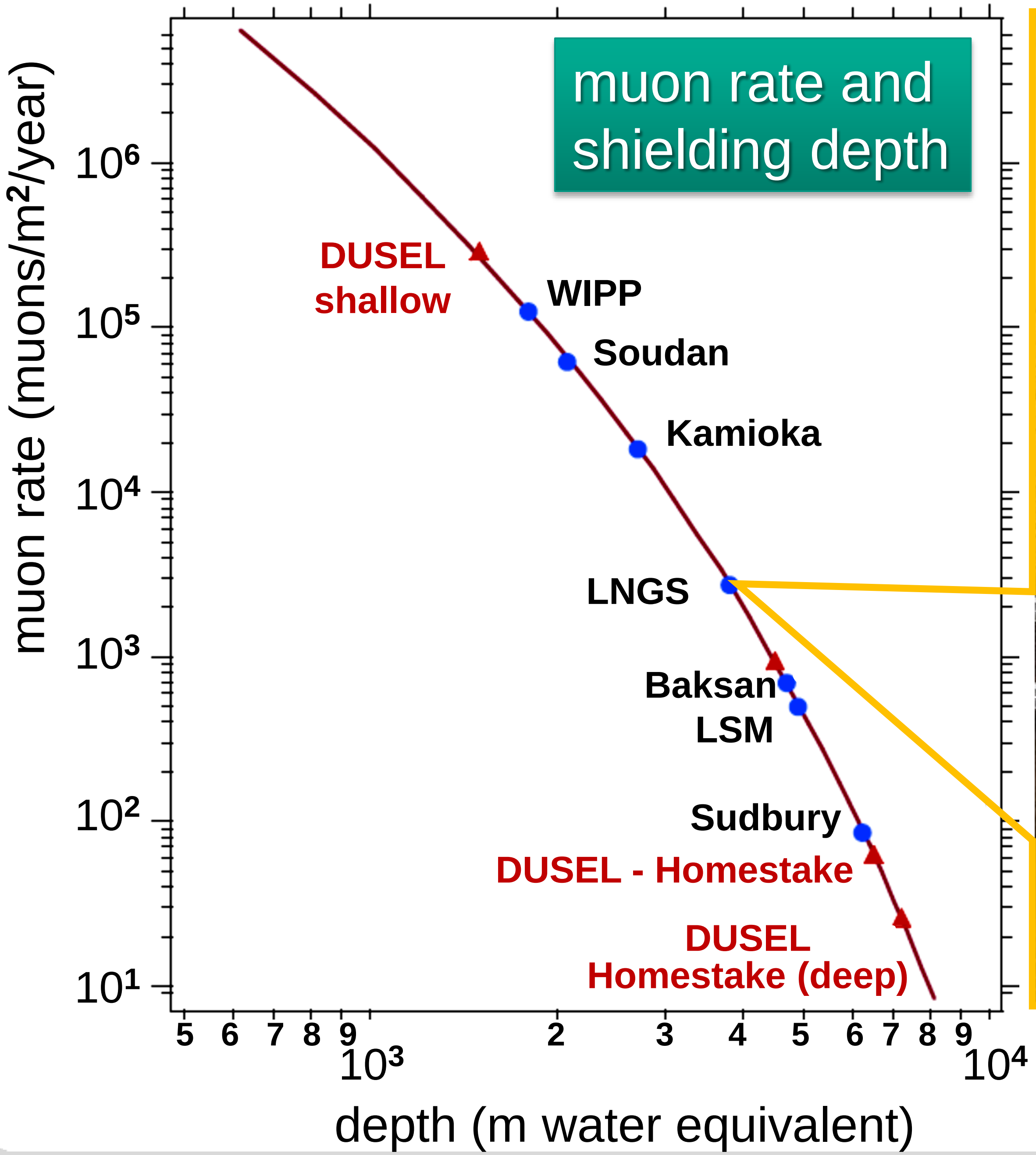
WIMP signal & background rate

$$R = N_{nuclei} \cdot \langle \Phi \rangle \cdot \langle \sigma_{SI/SD} \rangle = N_{nuclei} \cdot \frac{\rho_{DM,\,local}}{M(\chi^0)} \cdot \langle \sigma_{SI/SD} \cdot v \rangle$$



source and shielding	events/kg/s	events/kg/day
natural gamma activity	100	**10^7**
after passive shielding		**10^2**
cosmic muons at surface of earth	0.1	**10^4**
expected CDM detection rate		**$< 10^{-2}$**

underground labs – muon rate & depth



direct dark matter experiments

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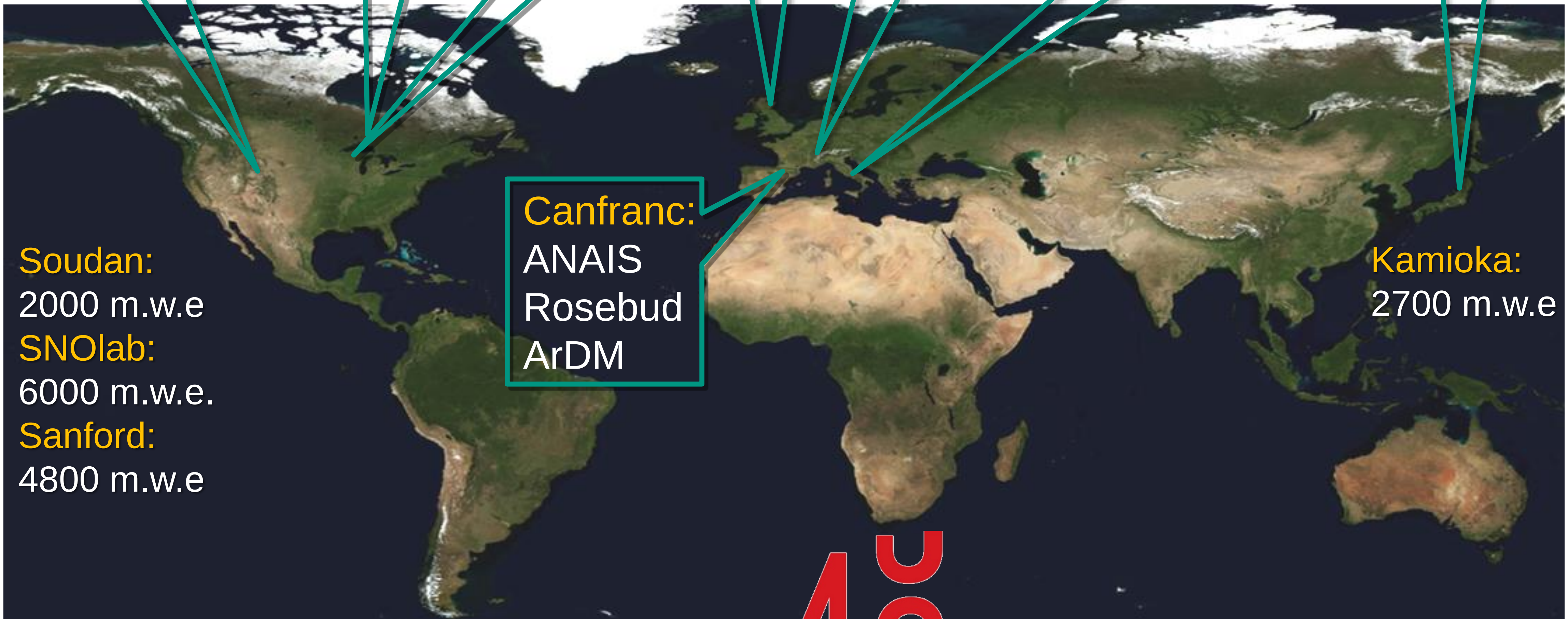
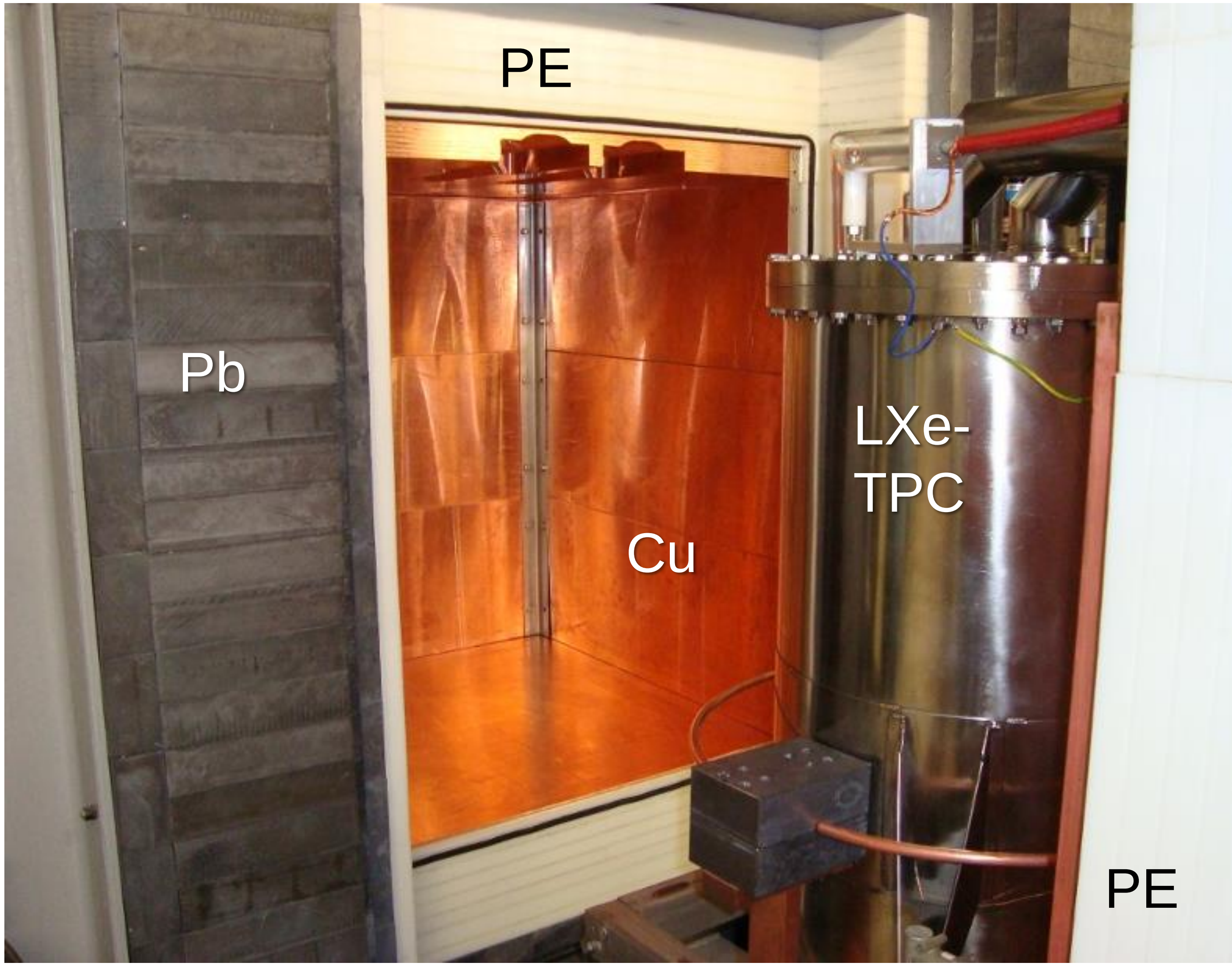
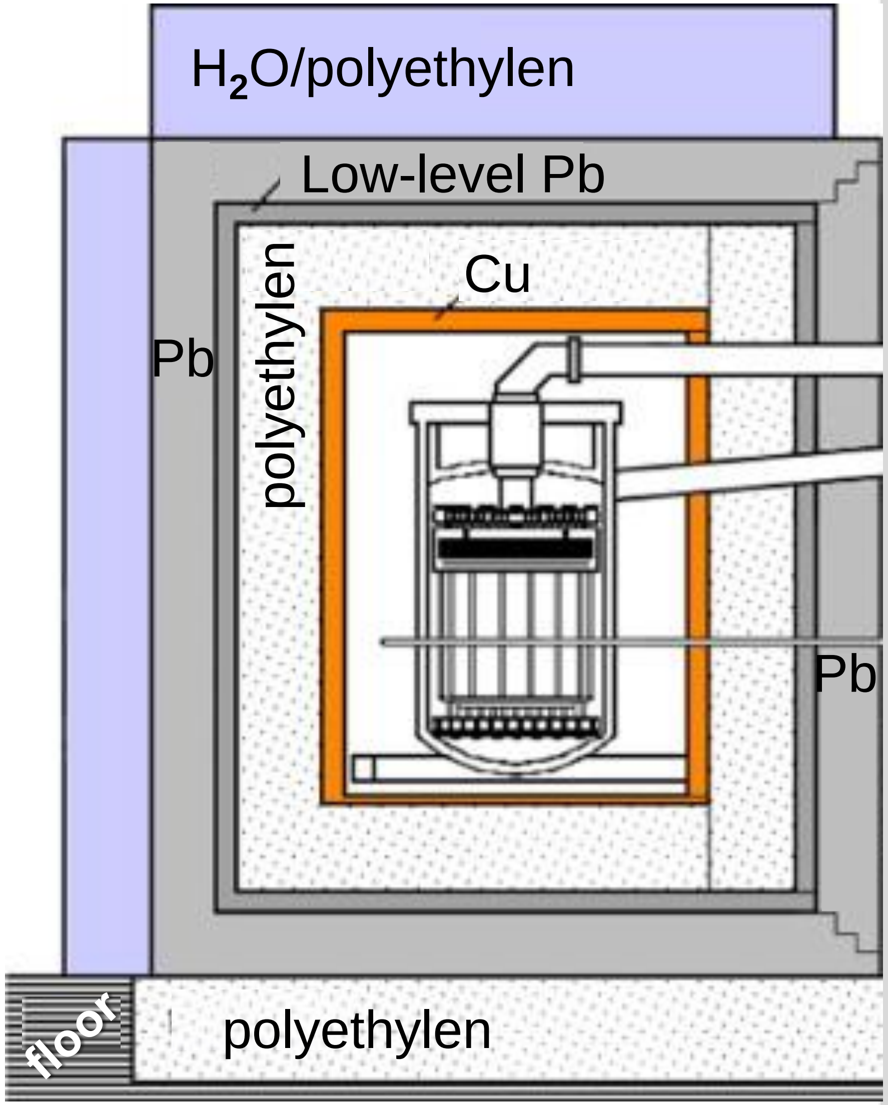


Where are the detectors?

extensive shielding – example XENON100

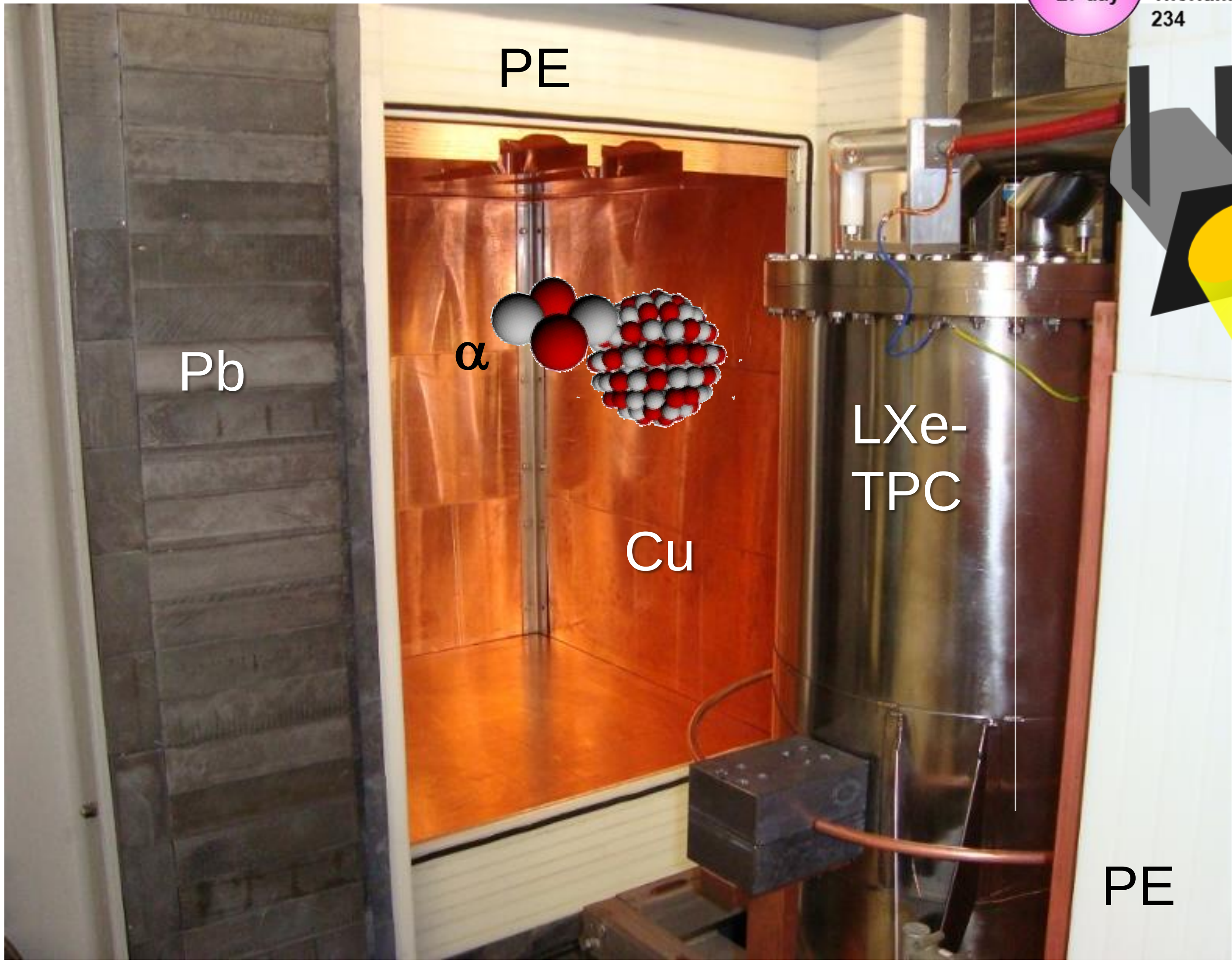
- Pb- & Cu-shielding in the **XENON100** experiment
  - against gammas (^{235}U, ^{238}U, ^{232}Th, ^{237}Np, ^{40}K,…), neutrons (μ-induced)

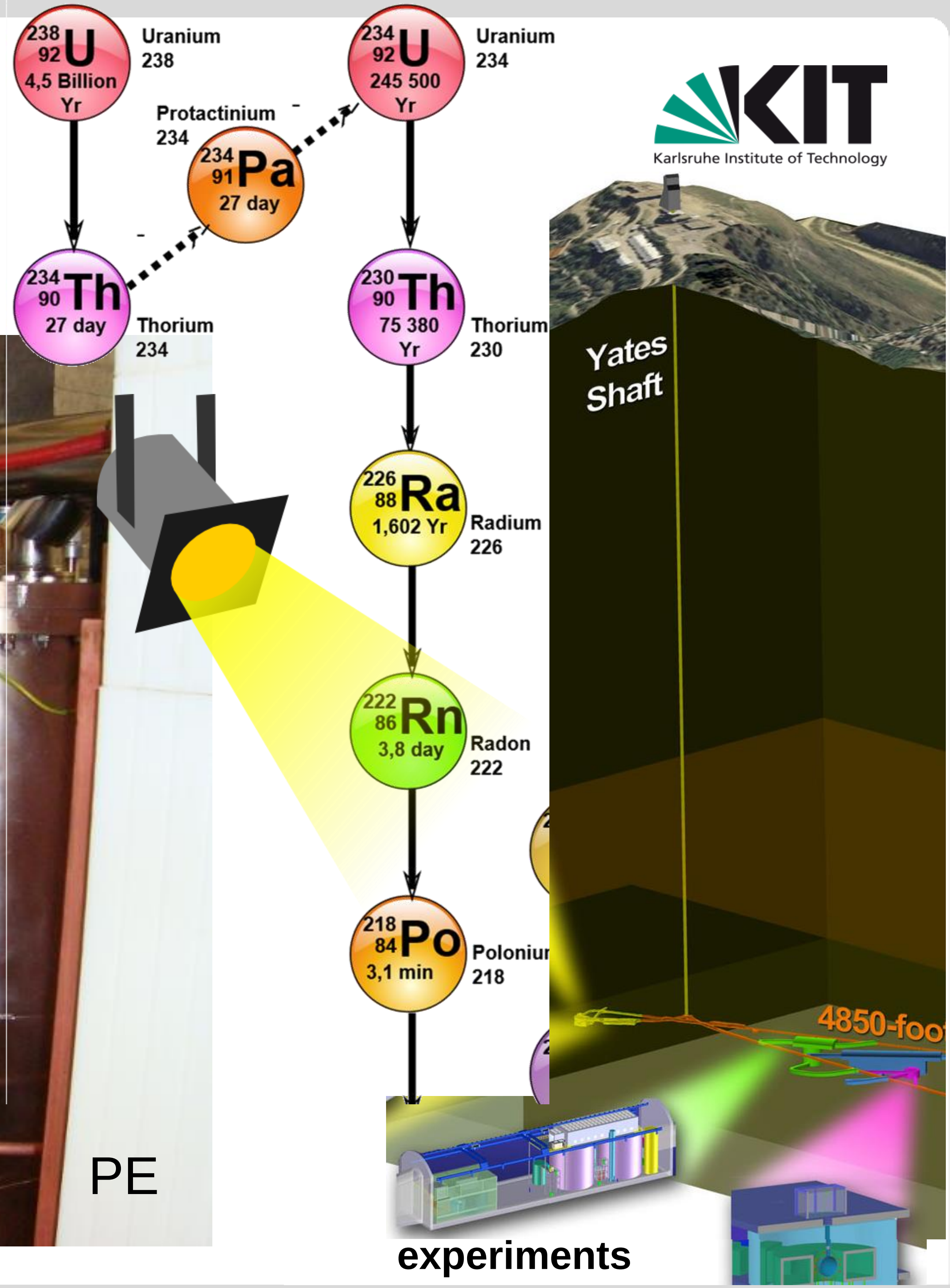




Radon background

- **radon emanation** in underground laboratories is substantial





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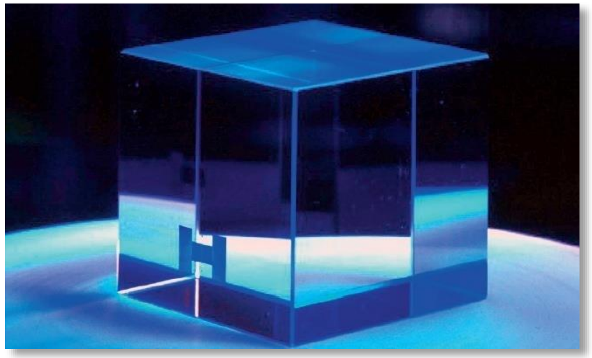
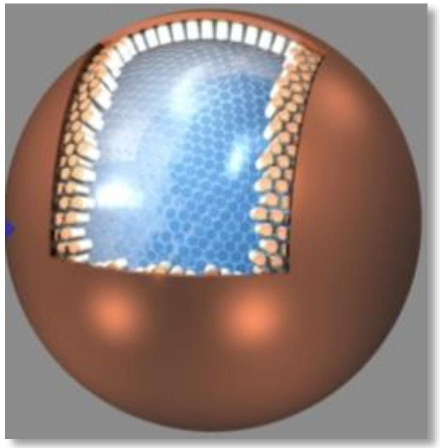
WIMP detection methods – 1 parameter

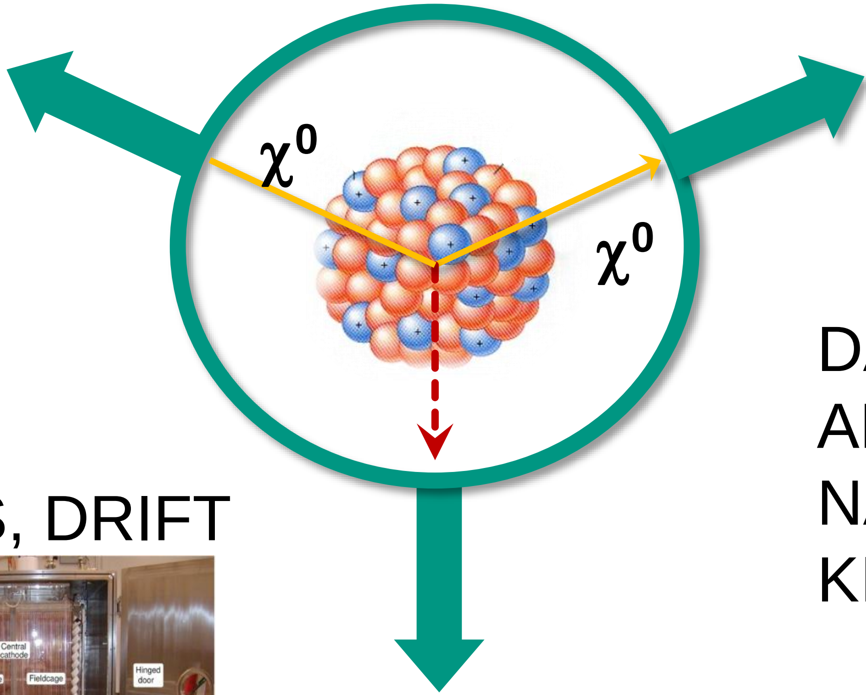


CRESST-I

XMASS
CLEAN
Zeplin I

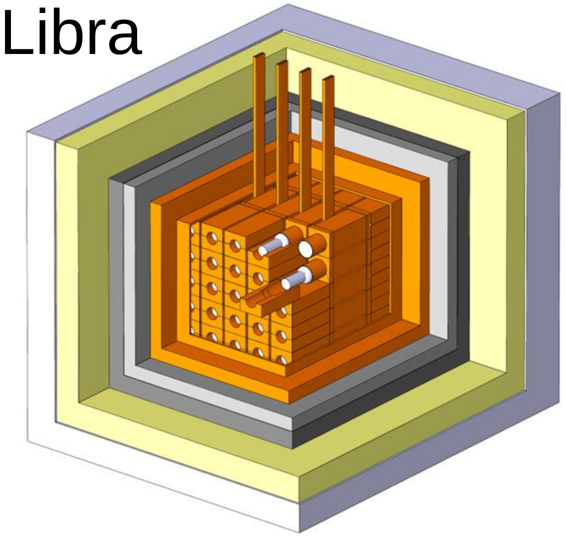


phonons

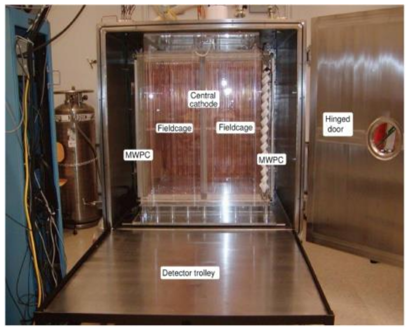


scintillation

DAMA/Libra
ANAIS
NAIAD
KIMS

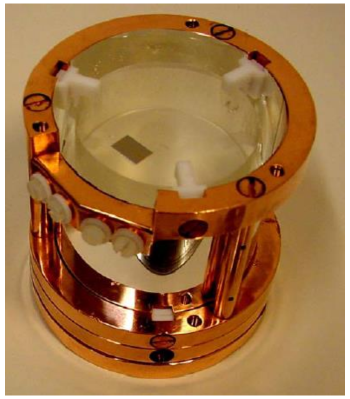


HDMS, DRIFT



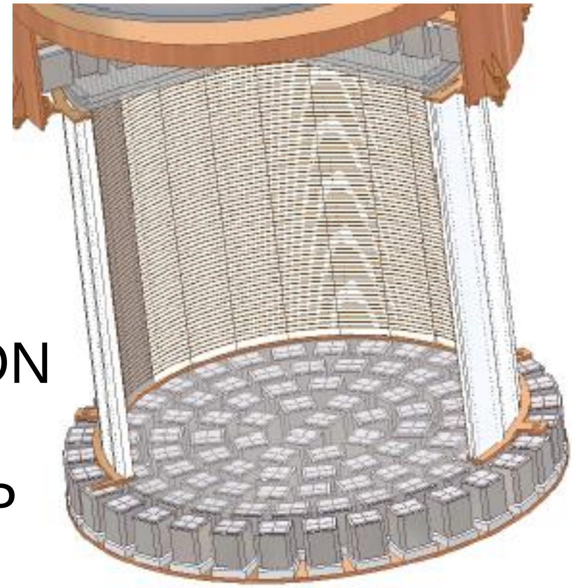
ionization

WIMP detection methods – 2 parameters

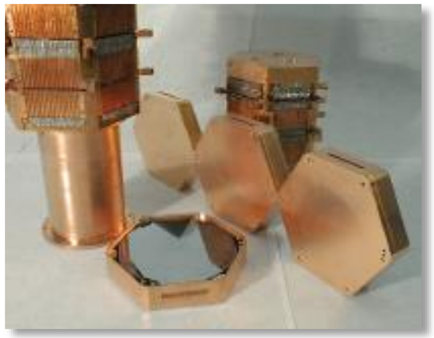


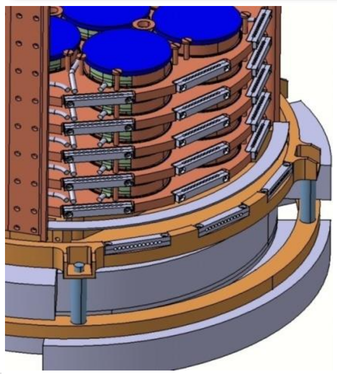
CRESST-II
ROSEBUD

scintillation & phonons

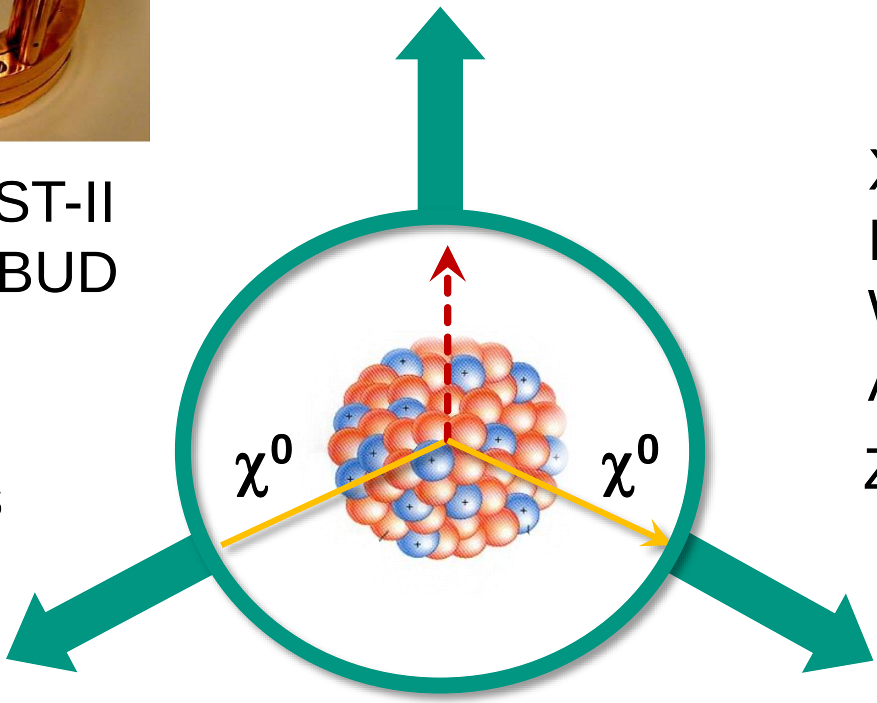


XENON
LUX
WARP
ArDM
ZEPLIN II,III





CDMS
Edelweiss



phonons & ionization

ionization & scintillation

DAMA/LIBRA

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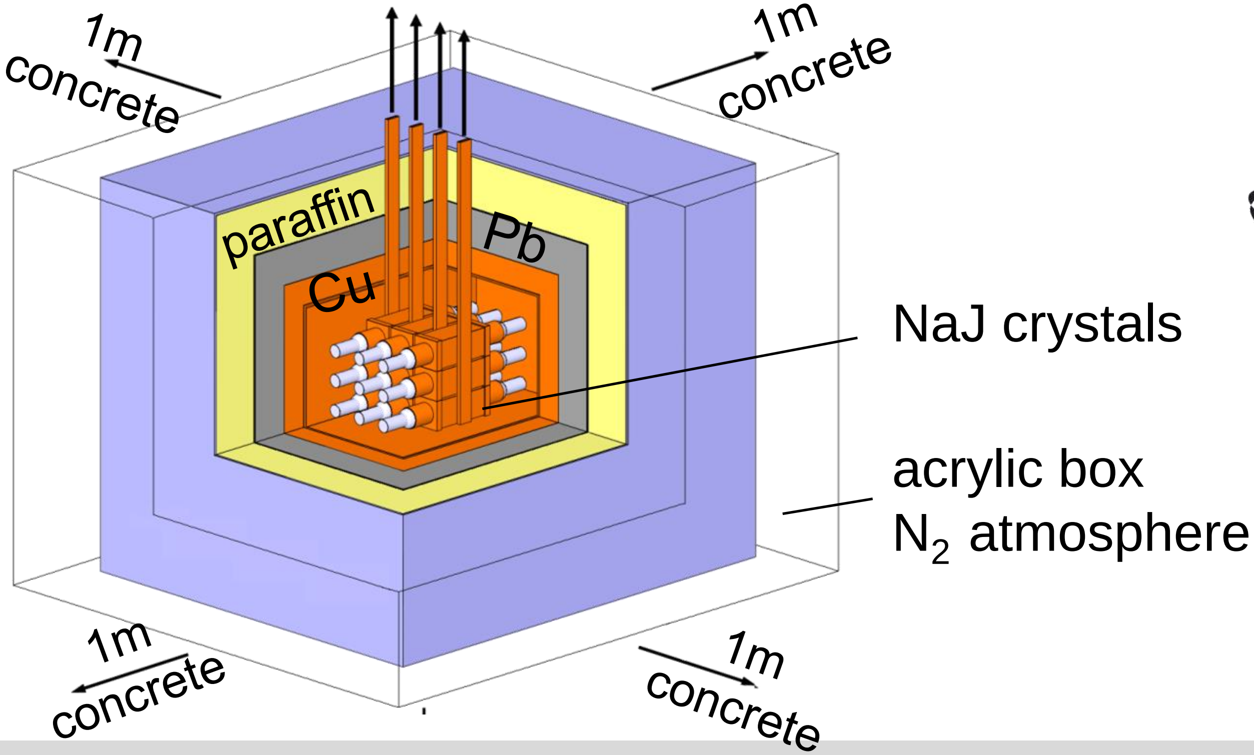
- **DA**rk **MA**tter experiment: **NaJ scintillation detector array**

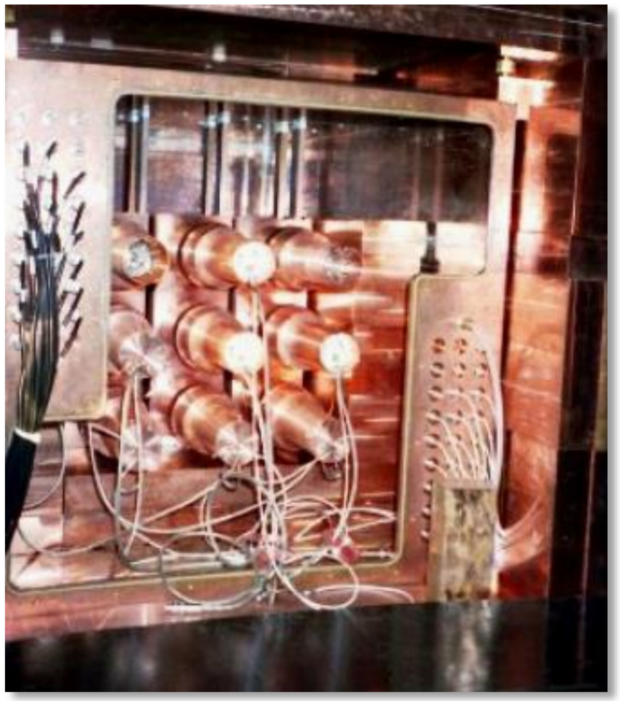
target: 9×9.7 kg high-purity NaJ crystals (scintillators)

$E_{thres} = 2\ keV_{ee}$ (≡ 20 keV recoil energy of ^{23}Na nucleus)

Read-out: 2 PMT´s / crystal, light yield 5-7 p.e. / keV

background: sehr geringe NaJ Eigenaktivität, shielding : concrete, paraffin, 15 cm „Boliden-Pb“, 10 cm Cu, ↳ 1-2 events/keV/kg/day





DAMA set-up at LNGS

DAMA – annual modulation

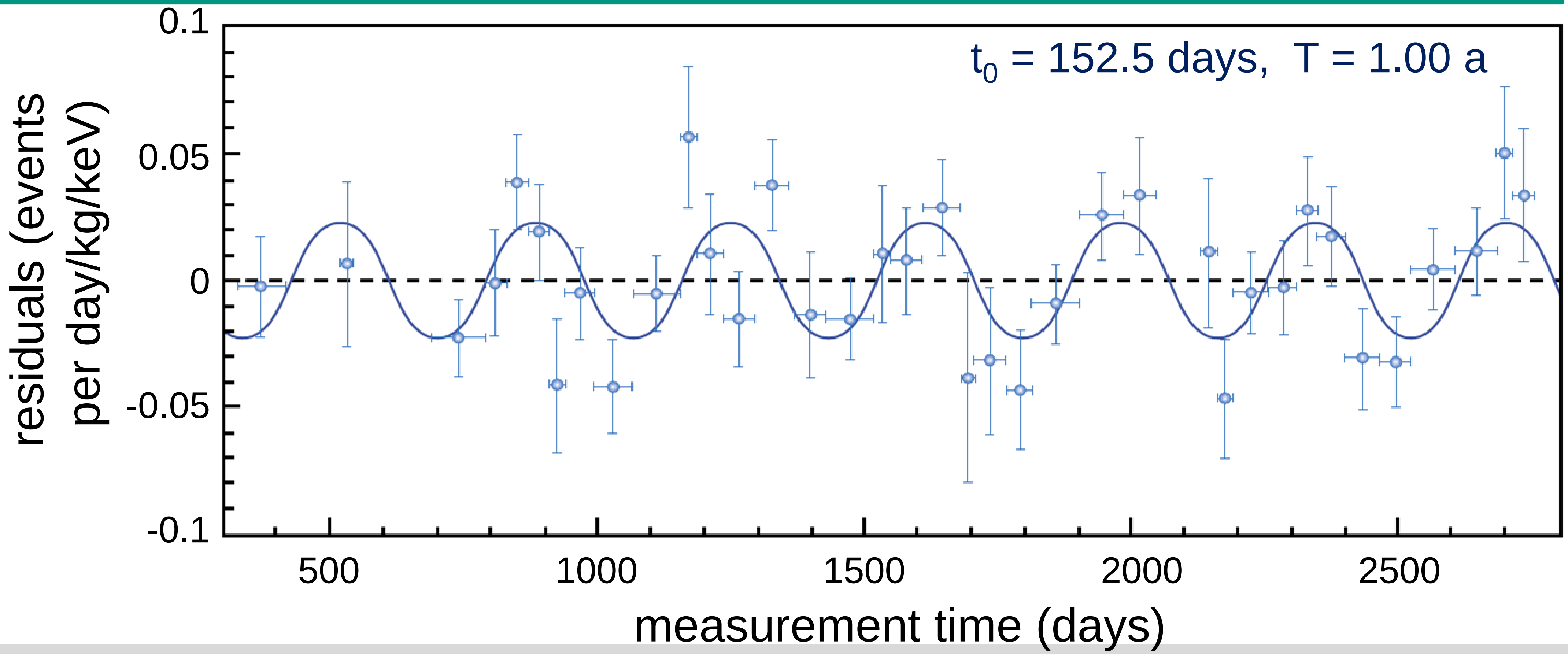
- **7 years data taking** (107 731 kg-days) from January 1995 – July 2002

  modulation of event rate with T = 1a & expected phase (t_0 = June, 2)

  - signal directly above *hardware* threshold in region E = 2 - 6 keV

  - no modulation for E = 6-14 keV, statistical significance (CL) = 6.3 σ

  - interpreted by DAMA as **evidence for direct WIMP-detection** (??)

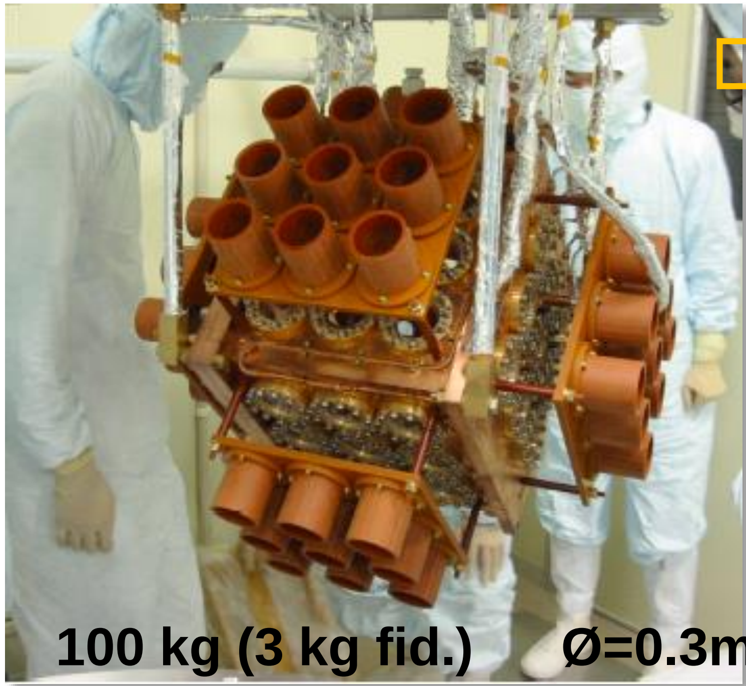


XMASS - overview

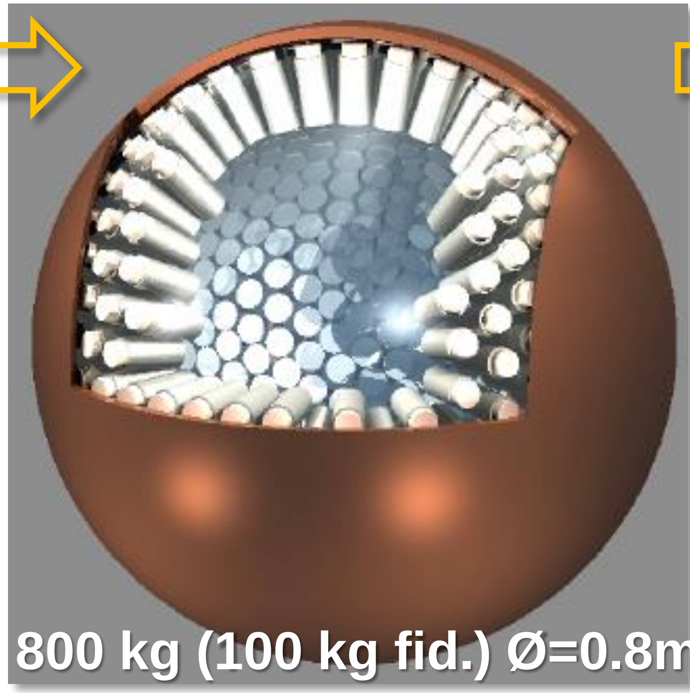
- **XMASS:** **X**enon detector for Weakly Interacting **MASS**ive Particles operated in Kamioka mine in the Japanese alps

  strategy: gradual increase of Xe target mass ⇨ improved self absorption of background via LXe (10^{-4} events/kg/keV/day)

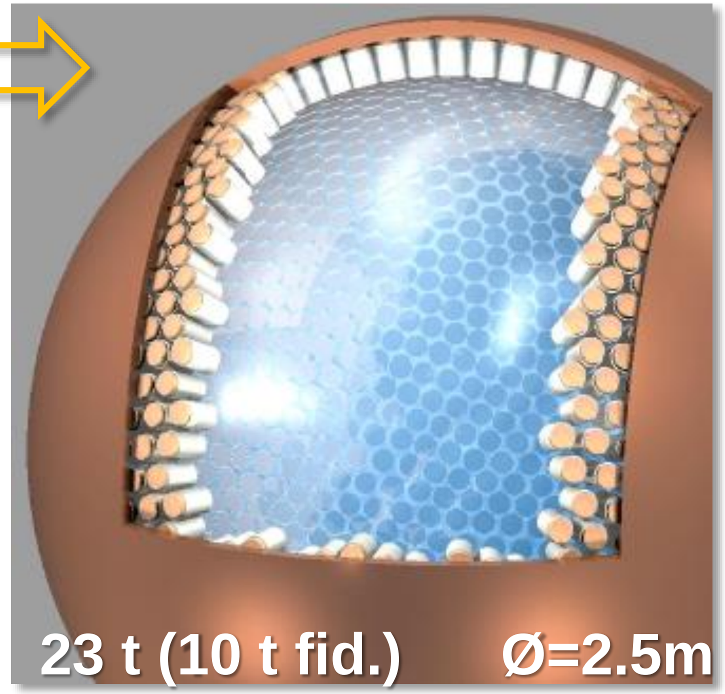
  method: UV-scintillation light in **liquid-Xenon (LXe)** (T = 165 K) at λ = 175 nm, but: Rayleigh scattering limits position resolution



100 kg (3 kg fid.) Ø=0.3m



800 kg (100 kg fid.) Ø=0.8m



23 t (10 t fid.) Ø=2.5m

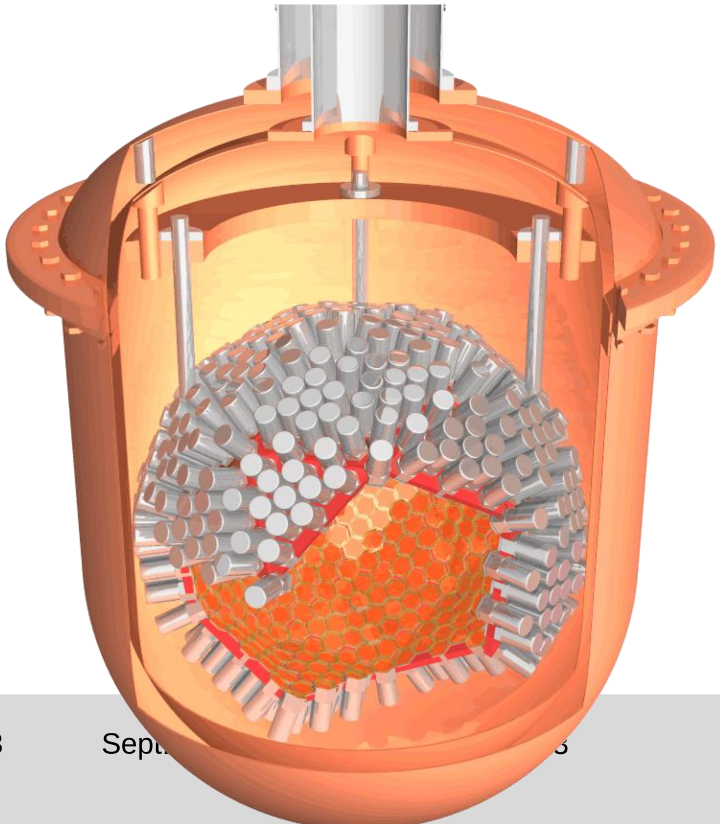
XMASS - results

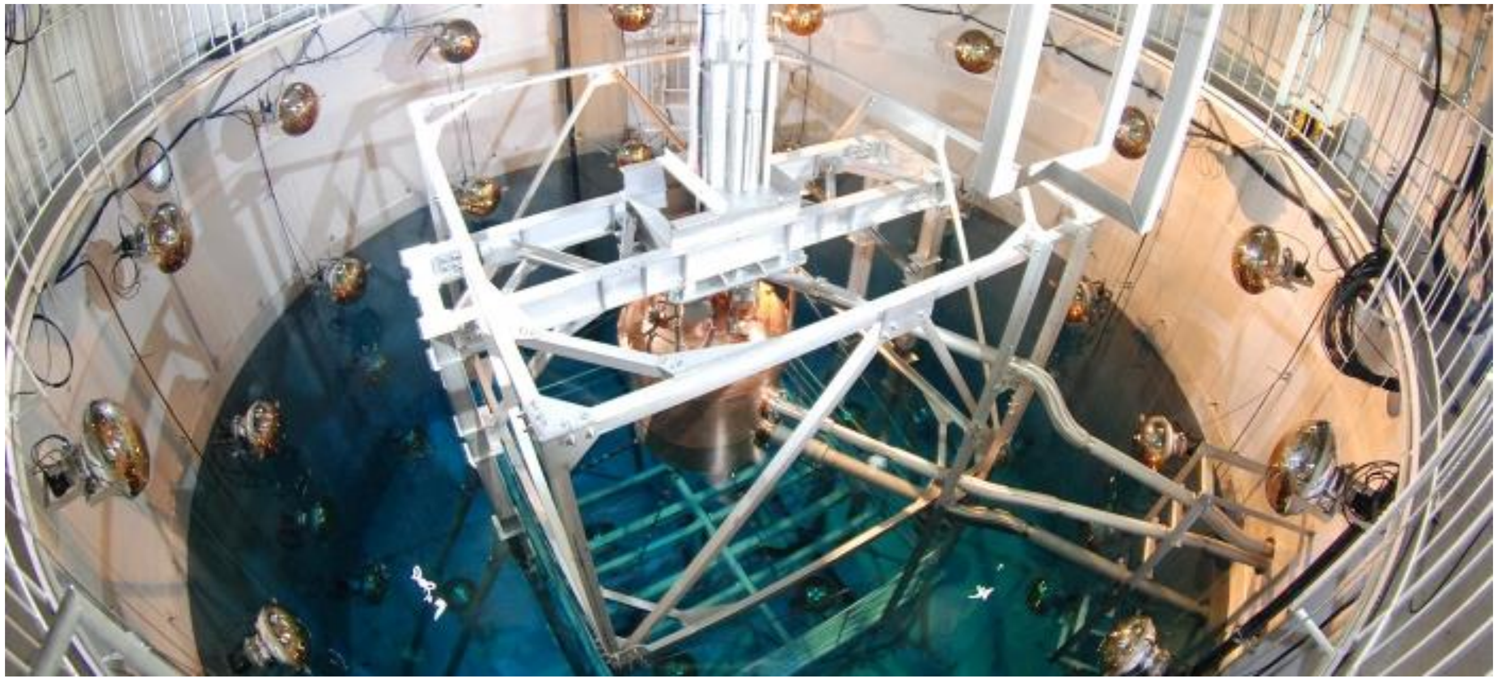
- **XMASS:** **X**enon detector for Weakly Interacting **MASS**ive Particles operated in Kamioka mine in the Japanese alps

  strategy: gradual increase of Xe target mass ⇨ improved self absorption of background via LXe (10^{-4} events/kg/keV/day)

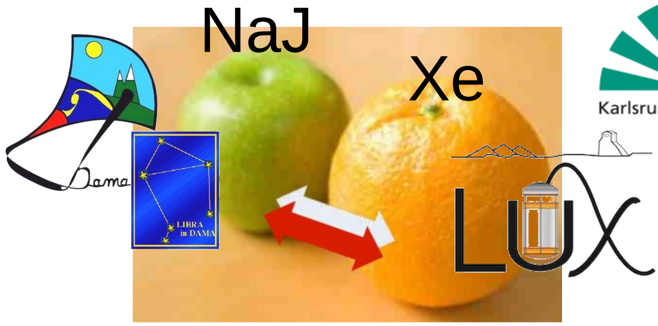
  method: UV-scintillation light in **liquid-Xenon (LXe)** (T = 165 K) at λ = 175 nm, but: Rayleigh scattering limits position resolution

  status: new 2015 results with 832 kg x 16 months exclude DAMA/Libra

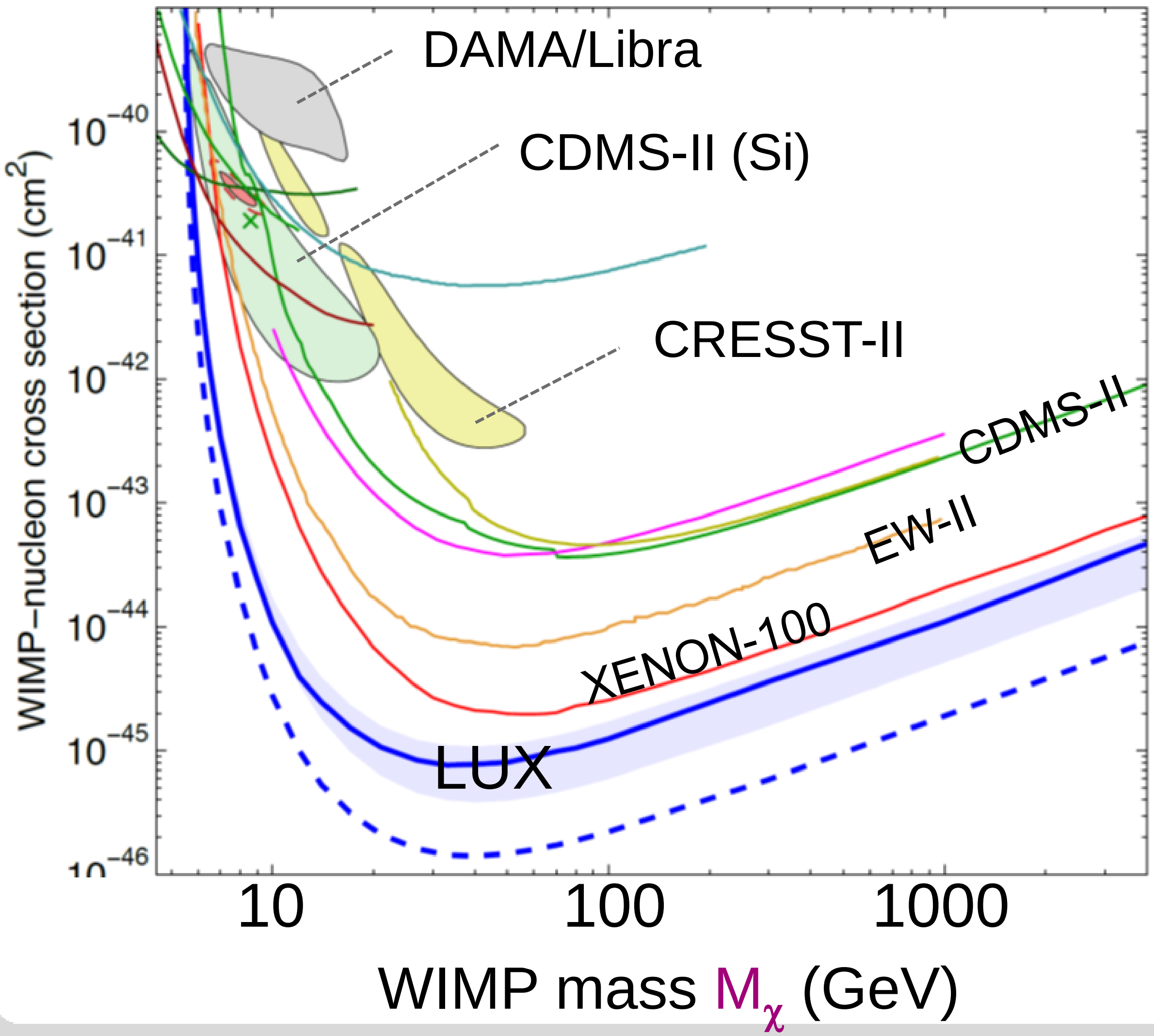


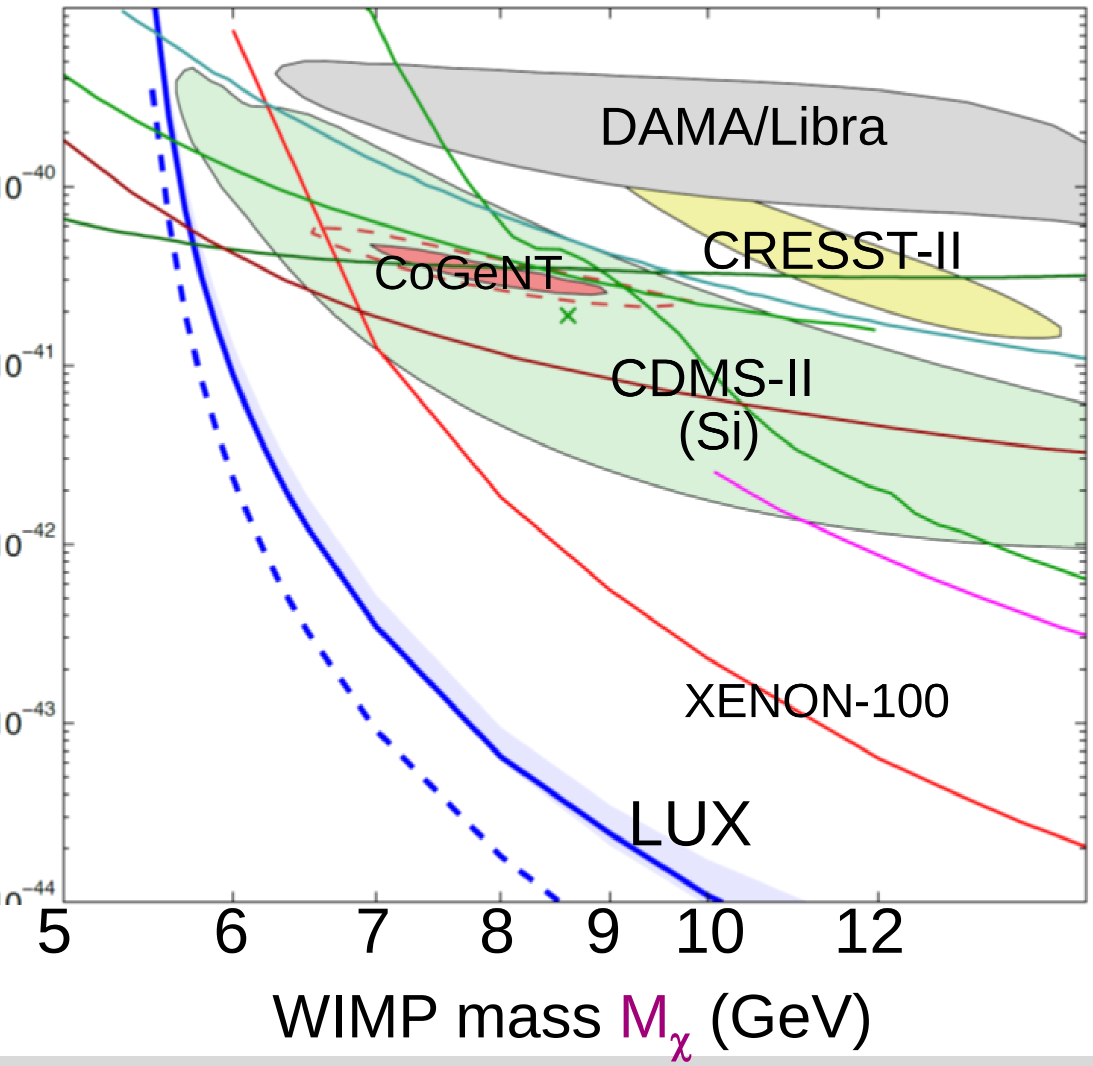


DAMA/Libra results excluded



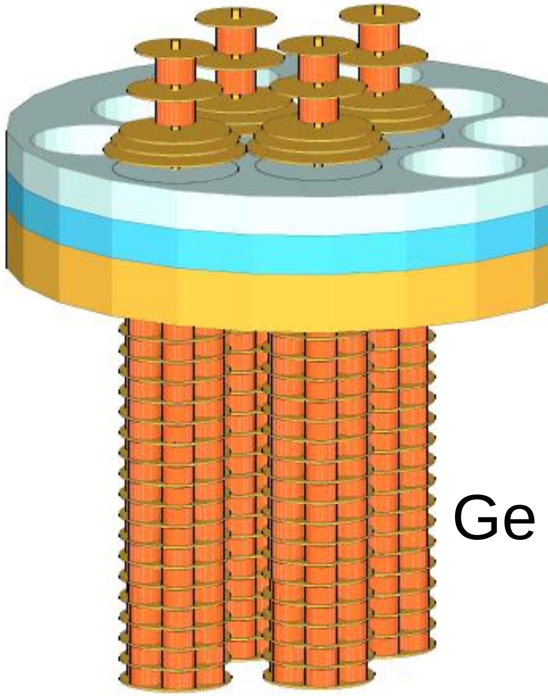
- DAMA/Libra data (favoured regions) and exclusion limits from Xe-experiments (spin-independent iinteraction)





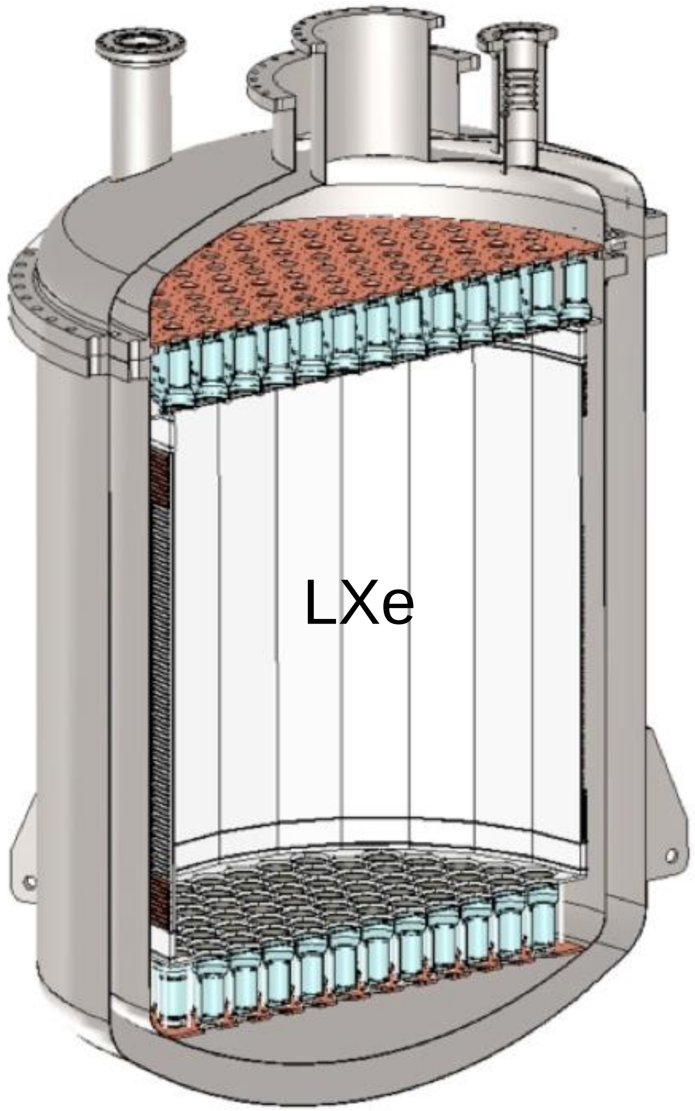
2-phase detectors: mass vs. surface

- **bolometers**: only few kg, very low threshold
  large surface, good discrimination
- **noble gases**: leading technology for WIMPs
  deploy multi-ton detectors



„sensitivity of a dark matter experiment scales with its **mass**“

„systematics & bg of a dark matter experiment scales with its **surface**“



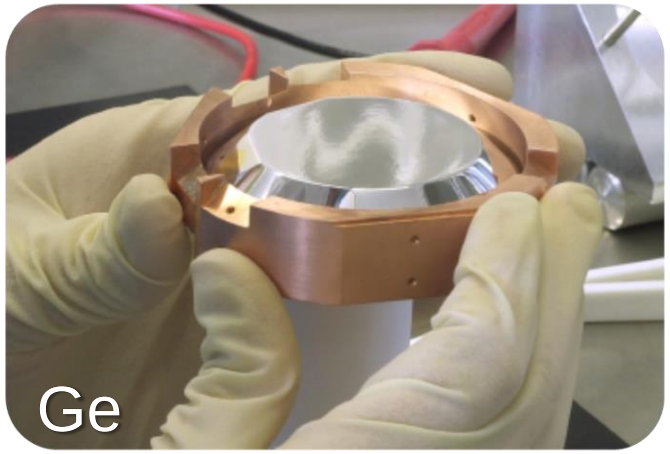
bolometers

liquid noble gases

cryogenic bolometers

■ **cryo-bolometer at low temperature in mK regime** (CRESST, CDMS,…)

advantages:
- good sensitivity to nuclear recoils (phonons)
- very low energy threshold
- good energy resolution (~150 eV @ 6 keV)
- **different target materials** (Ge, Si, $CaWO_4$)
- combine phonons with ionisation & scintillation: very good separation of gammas & electrons
- modular set-up (↳ scalable & sequentiel extension replace sub-optimal single detectors, new detectors)



disadvantages:
- extensive mK-cryotechnology (long runs)
- limited target mass (**~ 30 kg so far**)
- **modular setup** (↳ large inner surface)

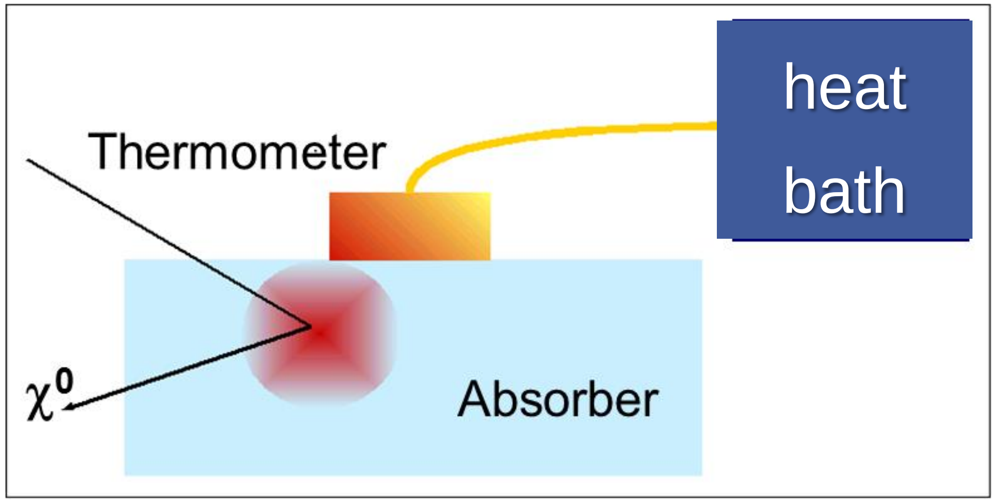
Cryo-bolometers – measurement principle

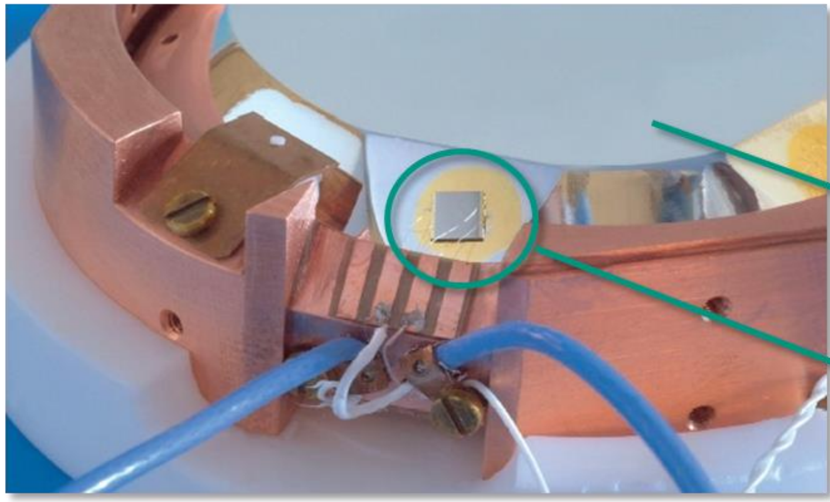
- **principle of a cryogenic bolometer** (µ-calorimeter):
  - energy deposition E_R of recoil of target nucleus from χ^0-scattering leads to small, but measurable temperature increase ΔT in absorber
  - **absorber** (Ge, Si, $CaWO_4$) with masse M ~ 300-800 g at T_0 = 10-20 mK
  - **thermometer** to measure temperature increase ΔT in absorber
  - heat bath (weak couplinng) to decrease T(bolometer) to T_0

$$\Delta T = \frac{E_R}{V \cdot C_V}$$

important: **small specific heat capacity C_V** of asorber

⇘ limits mass M of a cryogenic bolometer to ~ 1kg



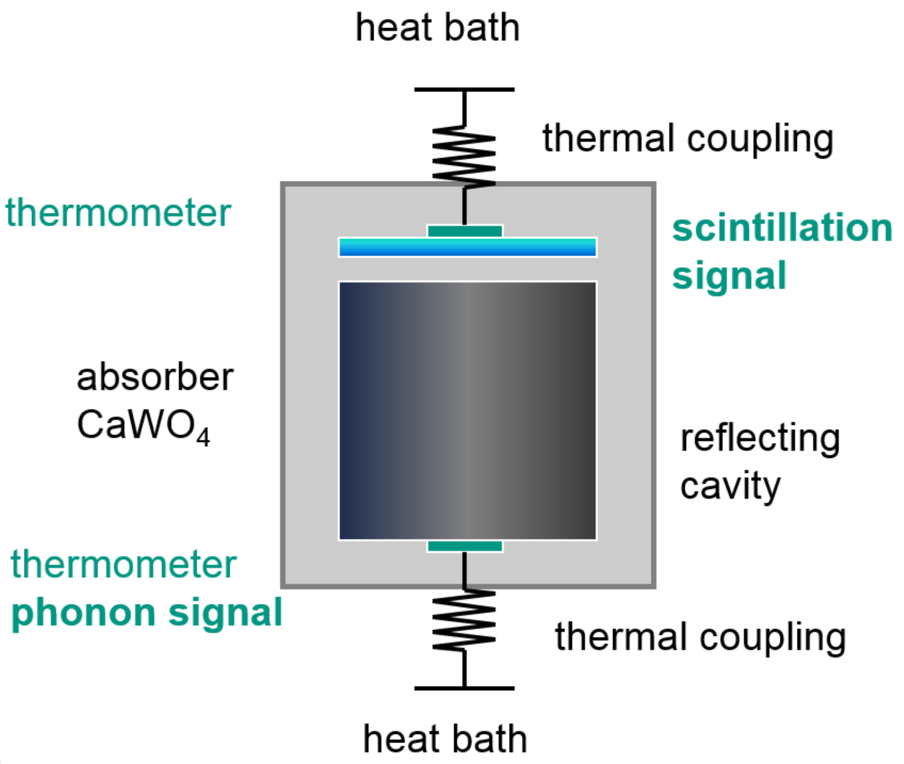


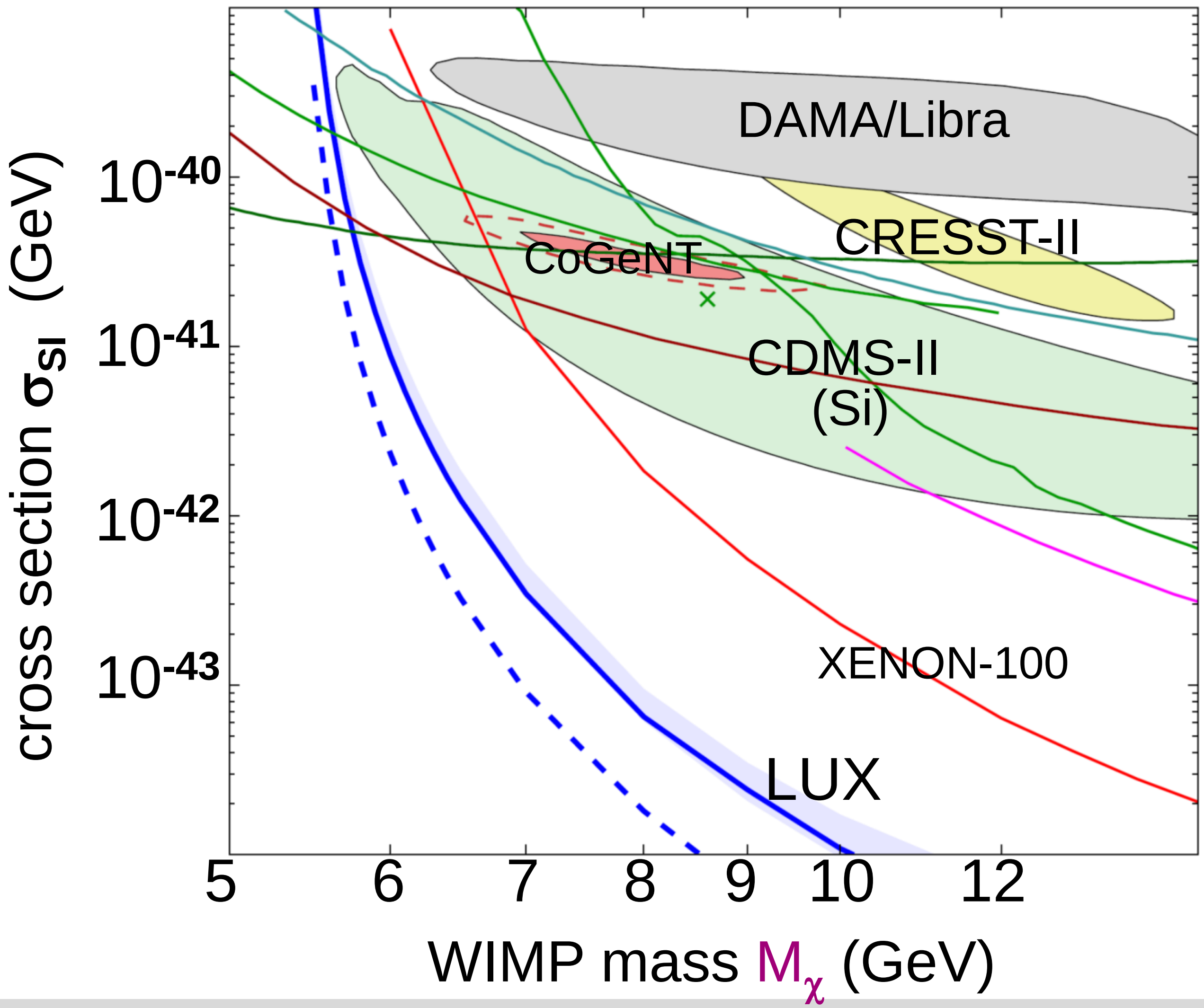
Bolometers for low-mass region

- future bolometer experiments (Super-CDMS, CRESST) will use few kg of detectors (Ge, Si) with low threshold to explore low-mass WIMP region

scintillation & phonons: CRESST

~1% of the energy is detected as light



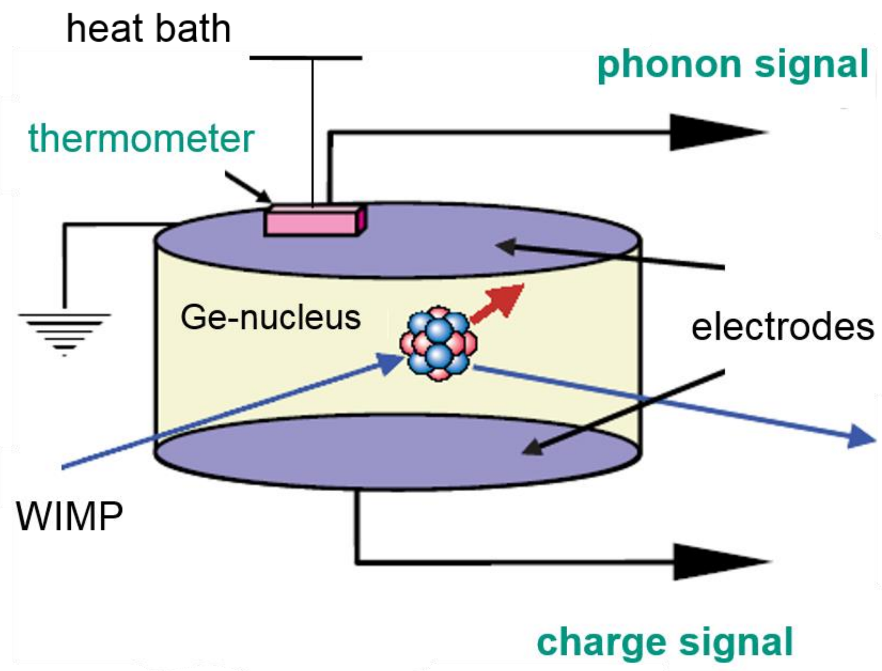


Bolometers for low-mass region

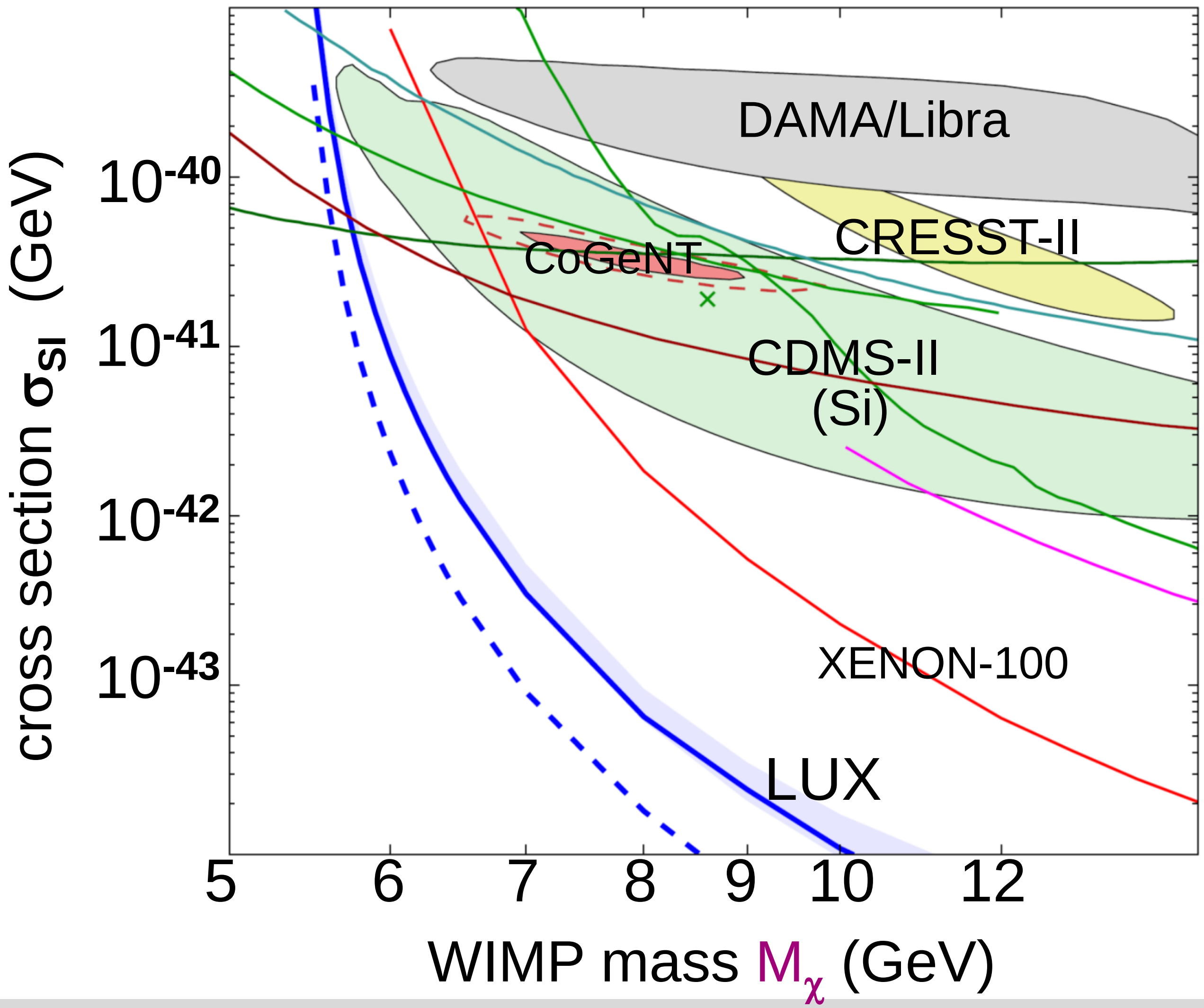
- future bolometer experiments (Super-CDMS, CRESST) will use few kg of detectors (Ge, Si) with low threshold to explore low-mass WIMP region

ionisation and phonons: CDMS, EW

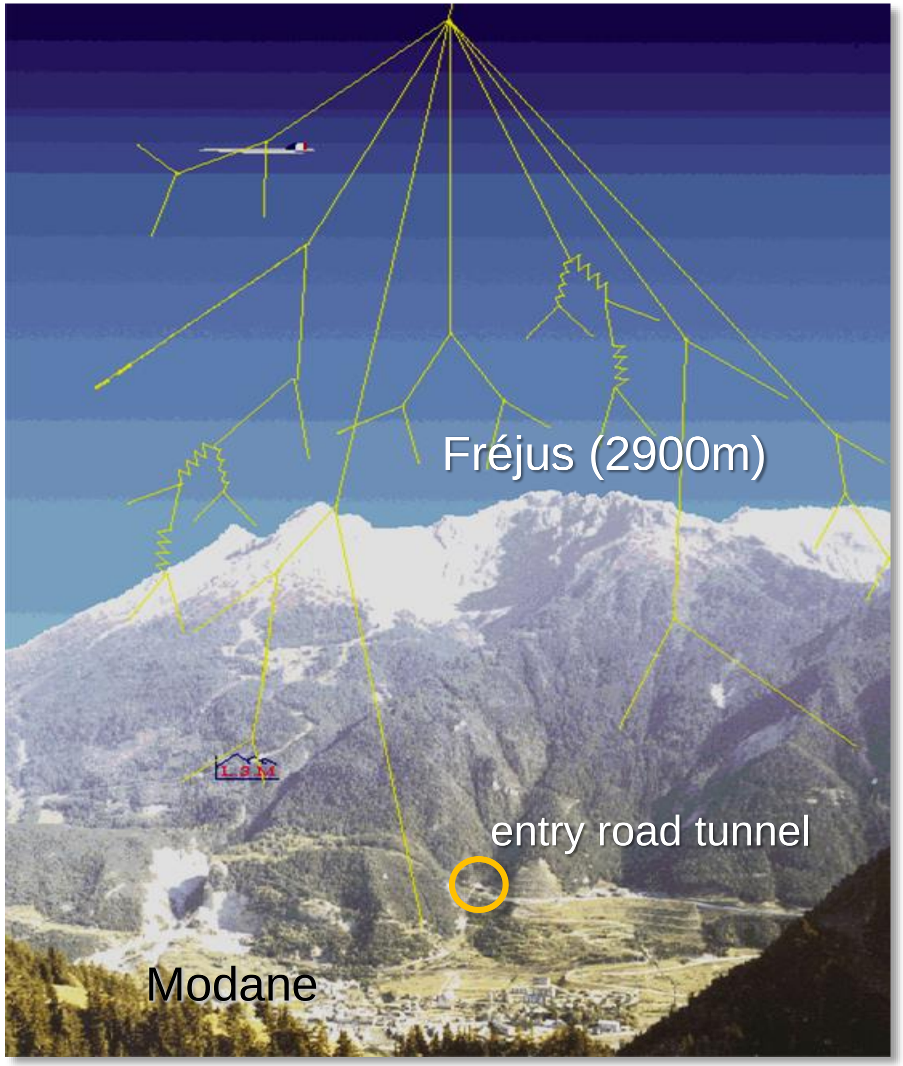
~10-20% of the energy as ionisation

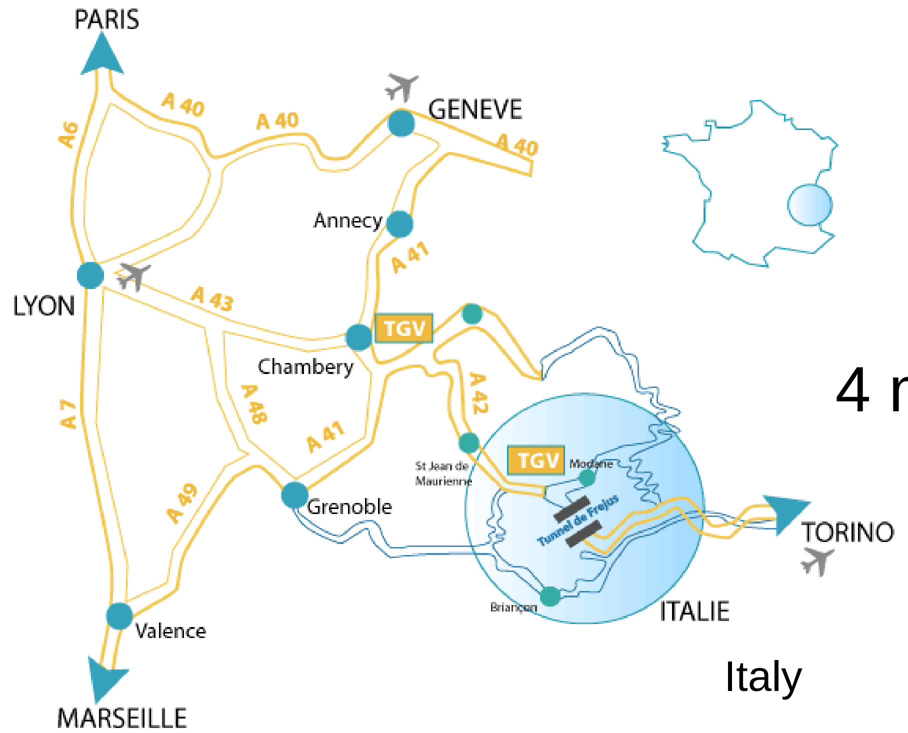


avoid surface effects during chage collection!



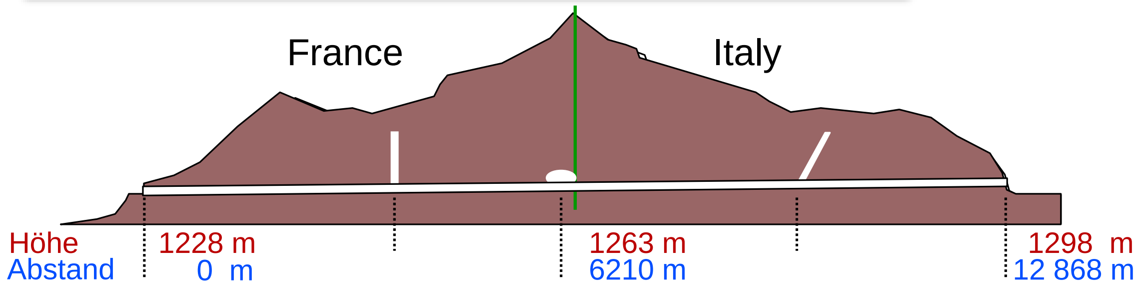
LSM – Laboratoire Souterrain de Modane

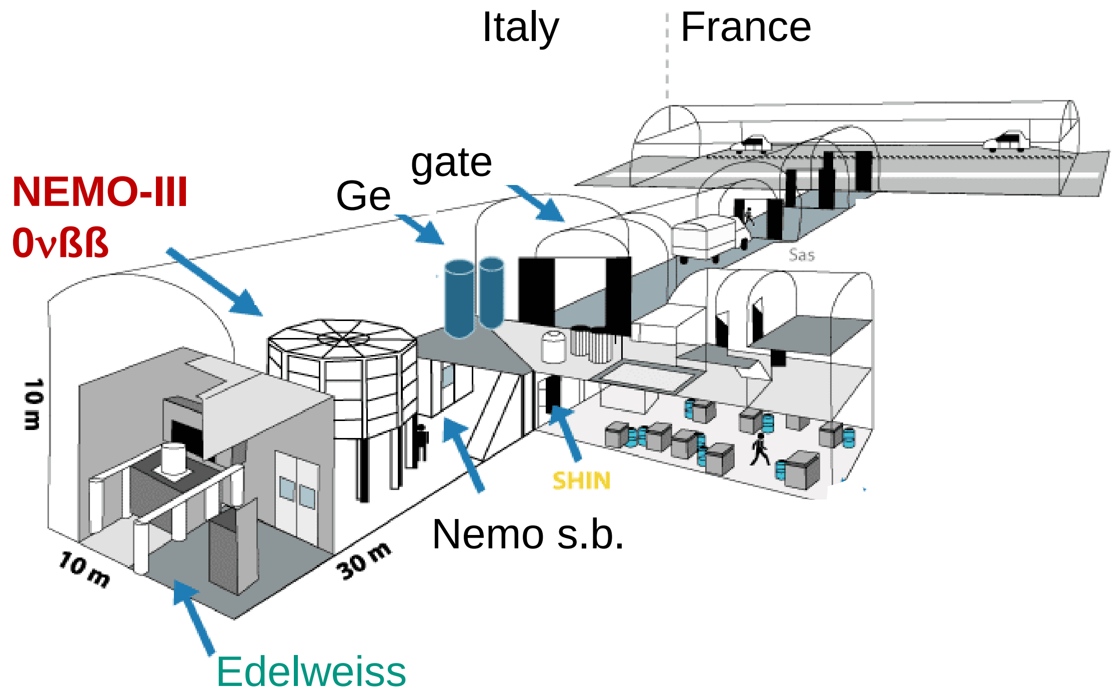




4800 m.w.e.

4 muons/m²/day



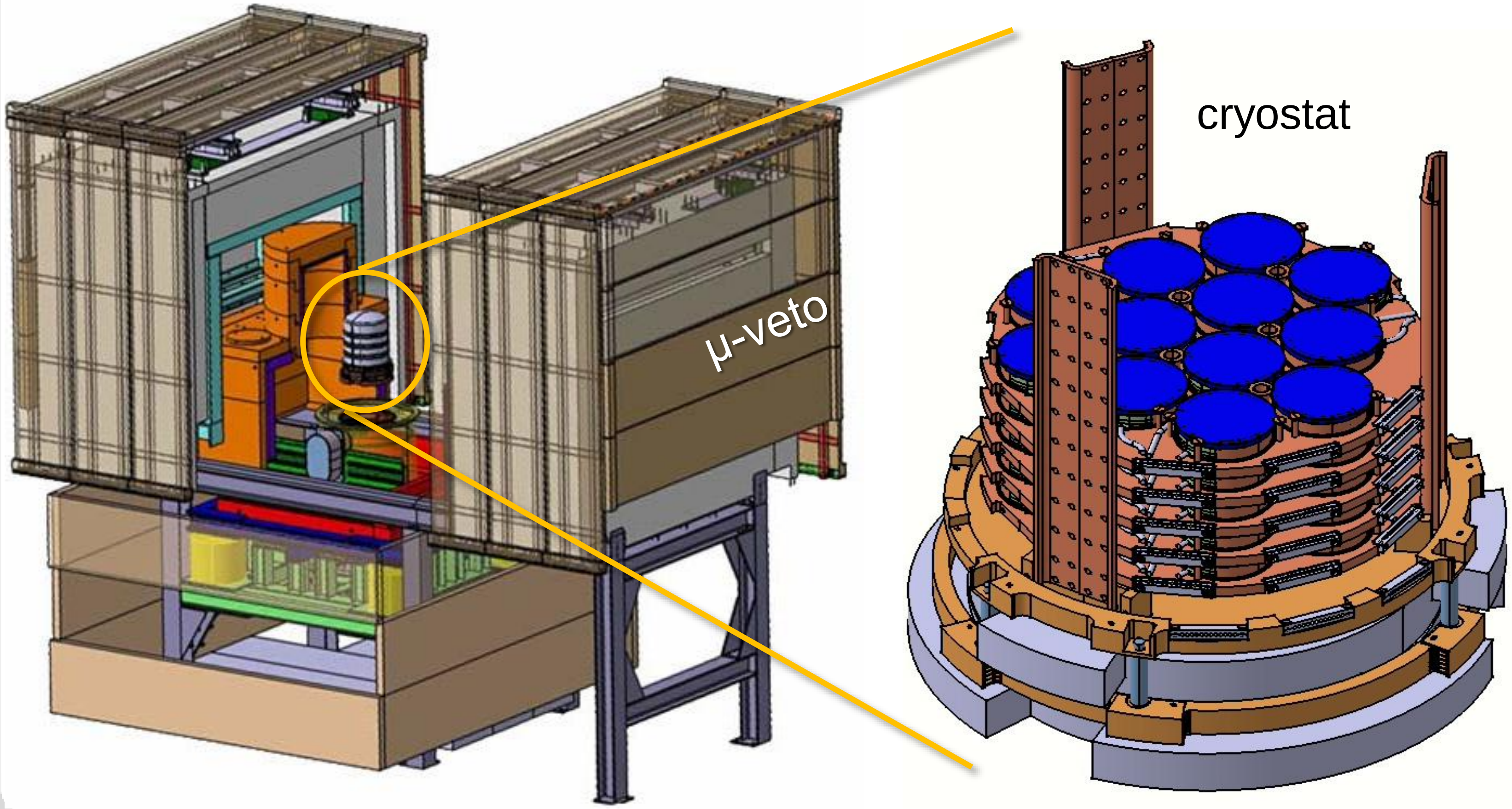


EDELWEISS – Experiment

- **Expérience pour détecter les WIMPs en Site Souterrain**

  French-German experiment at LSM with Ge-/Si-bolometers

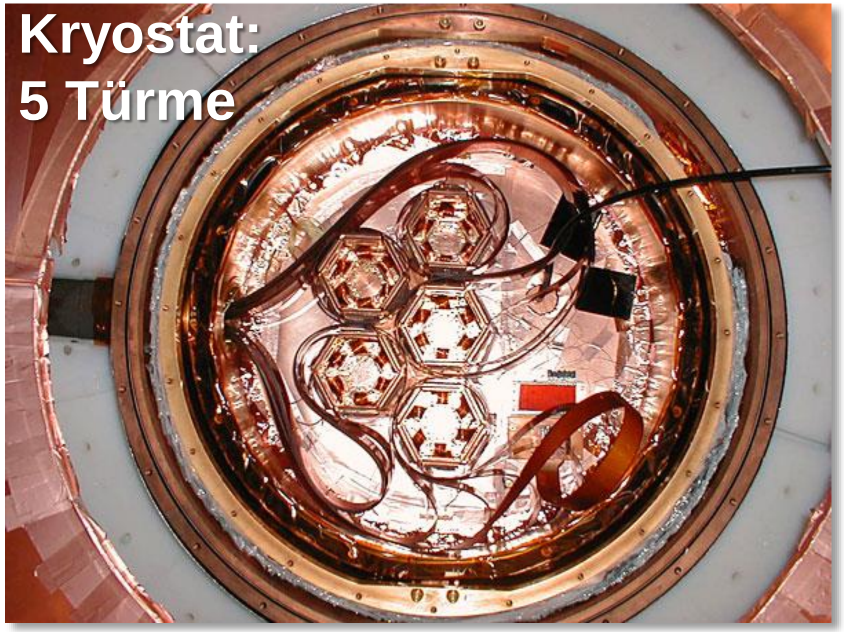
  - 2000-2003: Edelweiss-I M = 1 kg 3 detectors
  - 2008-2010: Edelweiss-II M = 4 kg 10 detectors 400 g each
  - 2011-2015: Edelweiss-III M = 32 kg 40 detectors 800 g each

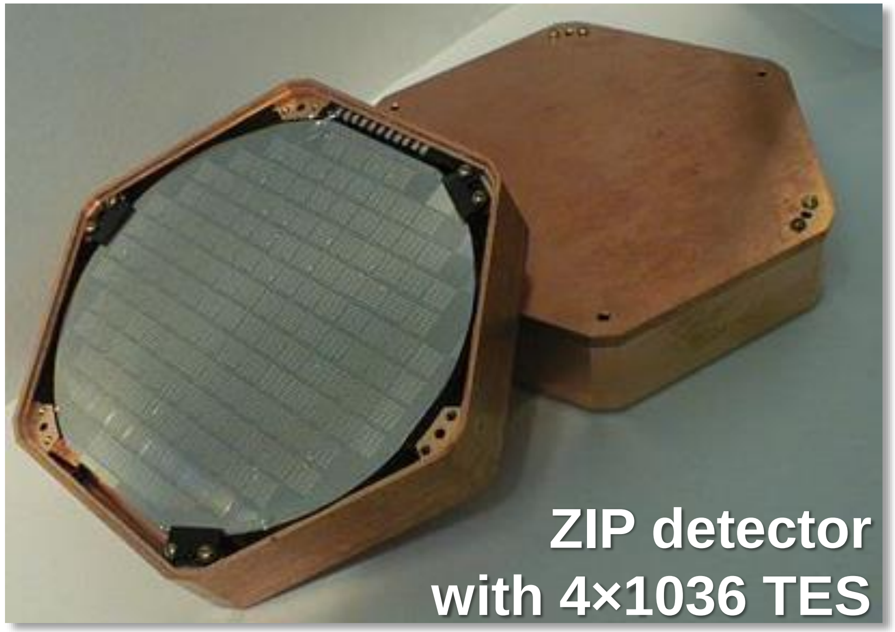


CDMS – Cryogenic Dark Matter Search

- **cryo-bolometers** in the Soudan mine in North-Minnesota (2000 m.w.e)
  absorber: 250 g germanium (Ø = 7.5 cm, h = 1 cm) and 100 g Si-crystals

  ZIP-detector technology:
  Z-sensitive **I**onisation and **P**honon mediated detector
  signals: ´ballistic´ phonons (4 × 1036 TES: Al and W)
  use phonon-timing to discriminate against surface events





Liquid noble gas detectors

- **LXe & LAr detectors** based on ultra-pure liquid noble gases
  - operated as 2-phase detectors: liquid & gaseous phase

  advantages:
  - large detector volumina (10 kg → 100 kg → 1 t → 50 t …)
  - particle identification: chage & scintillation, pulse shape

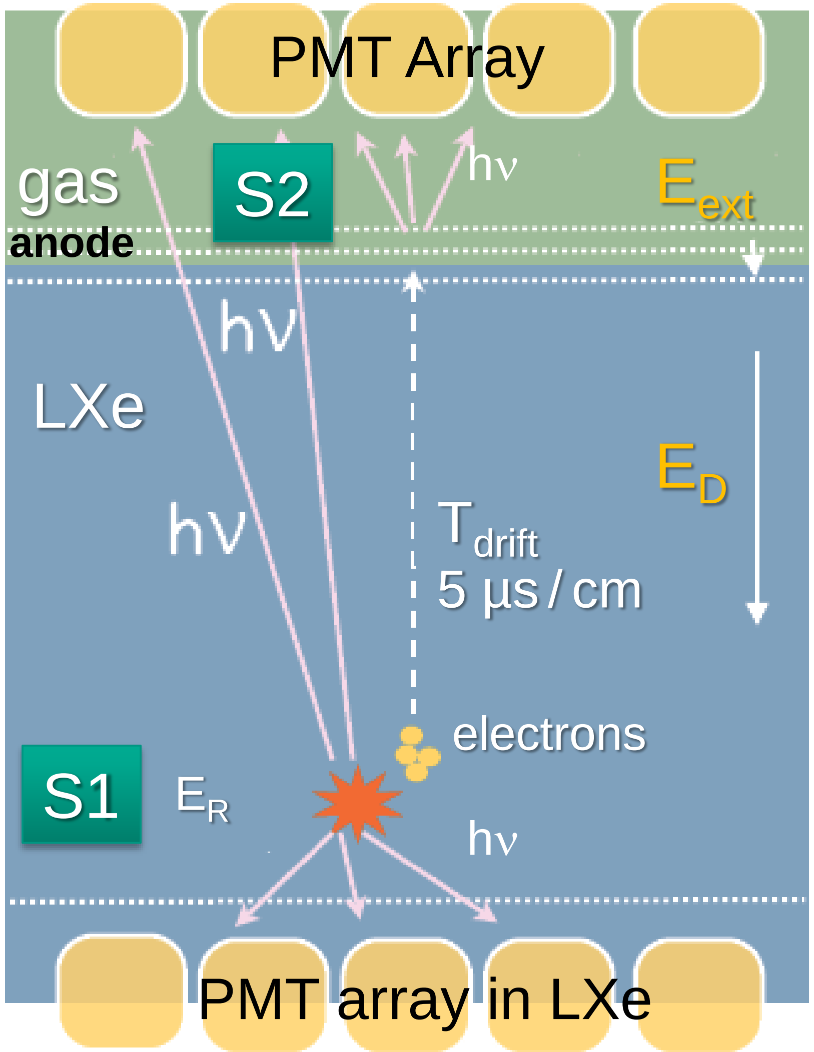
  challenges:
  - low threshold, further reduction of background rate

properties of liquid noble gases as DM-detectors

	Z (A)	boiling T_s [K] at p = 1 bar	density at T_s [g/cm³]	ionisation [e-/keV]	scintillation [photons/ keV]	scintillation light [λ in nm] λ-shifter
Neon	10 (20)	27.1	1.21	46	7	85 (WLS)
Argon	18 (40)	87.3	1.40	42	40	128 (WLS)
Xenon	54 (129/131)	**165.0**	**3.06**	64	46	175

2-phase LXe-experiments

- **principles of LXe 2-phase-detectors:**
  - **scintillation light**: detection via PMTs in LXe
  - **ionisation signal**: drift of electrons in E-field to Xe gas phase



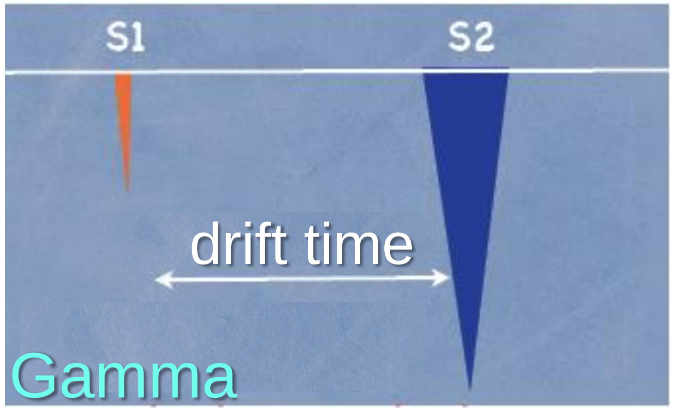
- **signals S1 (prompt) & S2 (delayed):**
  - **S1**: primary Xe-excitation due to recoiling nucleus (prompt scintillation light)
  - **S2**: detection of drifting electrons via extraction to gas phase, there acceleration of e^- in strong field electro-luminescence via scattering processes of fast electrons off gas
    ⇒ delayed light detection in upper PMT

- **coincidence of S1 and S2:**
  - **S1 + S2: particle-ID & point of interaction**

particle identification (PID)

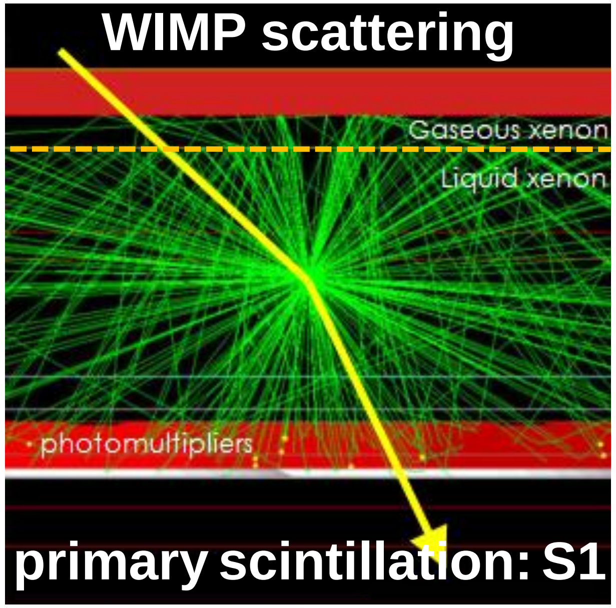
- **discrimination among WIMP-recoils of Xe-nuclei & electron/gamma-bg**

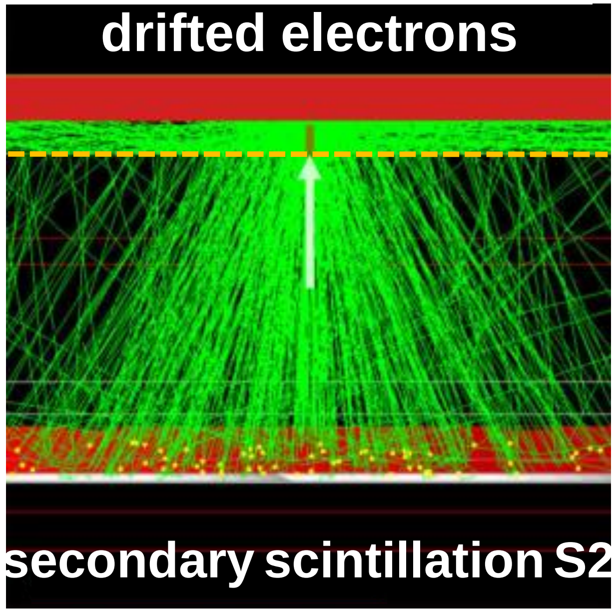
particle identification:	electron:	S2/S1 is large (no quenching)
	WIMP:	S2/S1 is small (less ionisation)
energy of Xe-recoil:	intensity S1 (primary excitation)	
position reconstruction:	PMTs (x,y), drift time (z)	



- **ratio S2/S1 used for PID**

MC-simulation of light signales



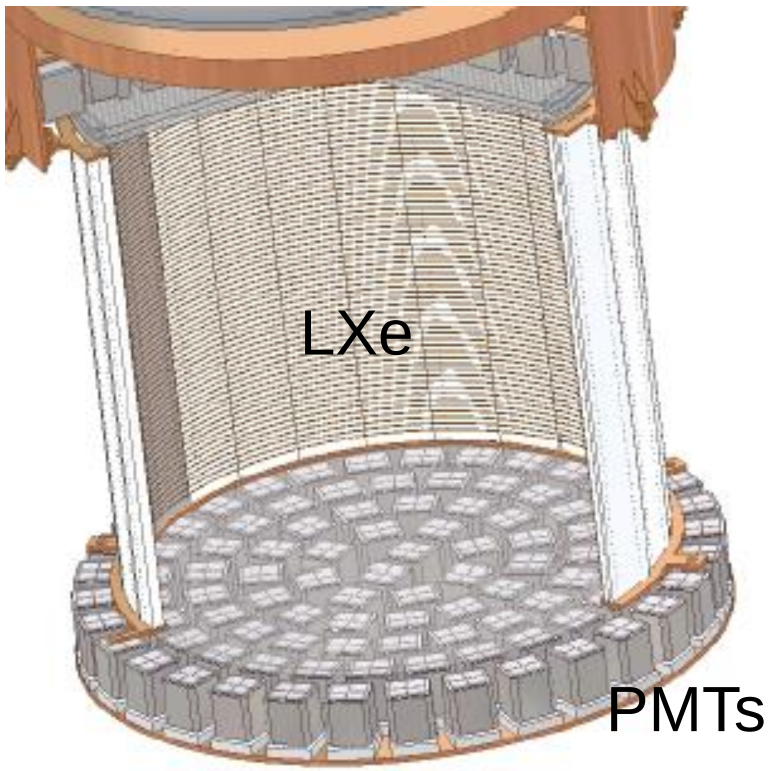


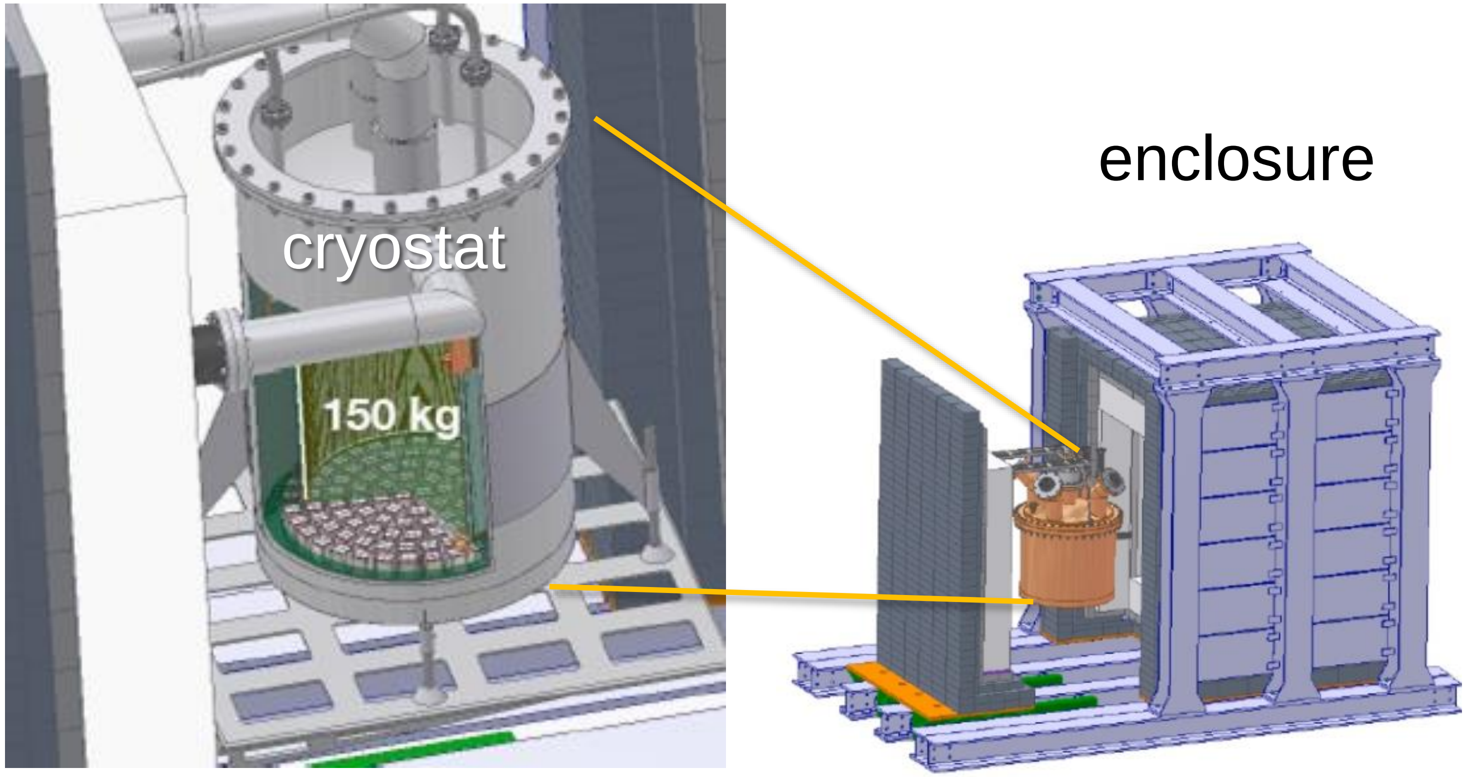
XENON100 experiment

XENON-100: at LNGS

LXe-detector with **161 kg mass** (~99 kg as veto, **62 kg as target**)
- detector: Ø = 30 cm, h = 30 cm (maximum drift distance for electrons)
- 242 PMT for read-out of scintillation- & electro-luminescence- light
- factor 100 less background (selection, cleaning, self absorption)

factor 10 more mass than predecessor XENON10

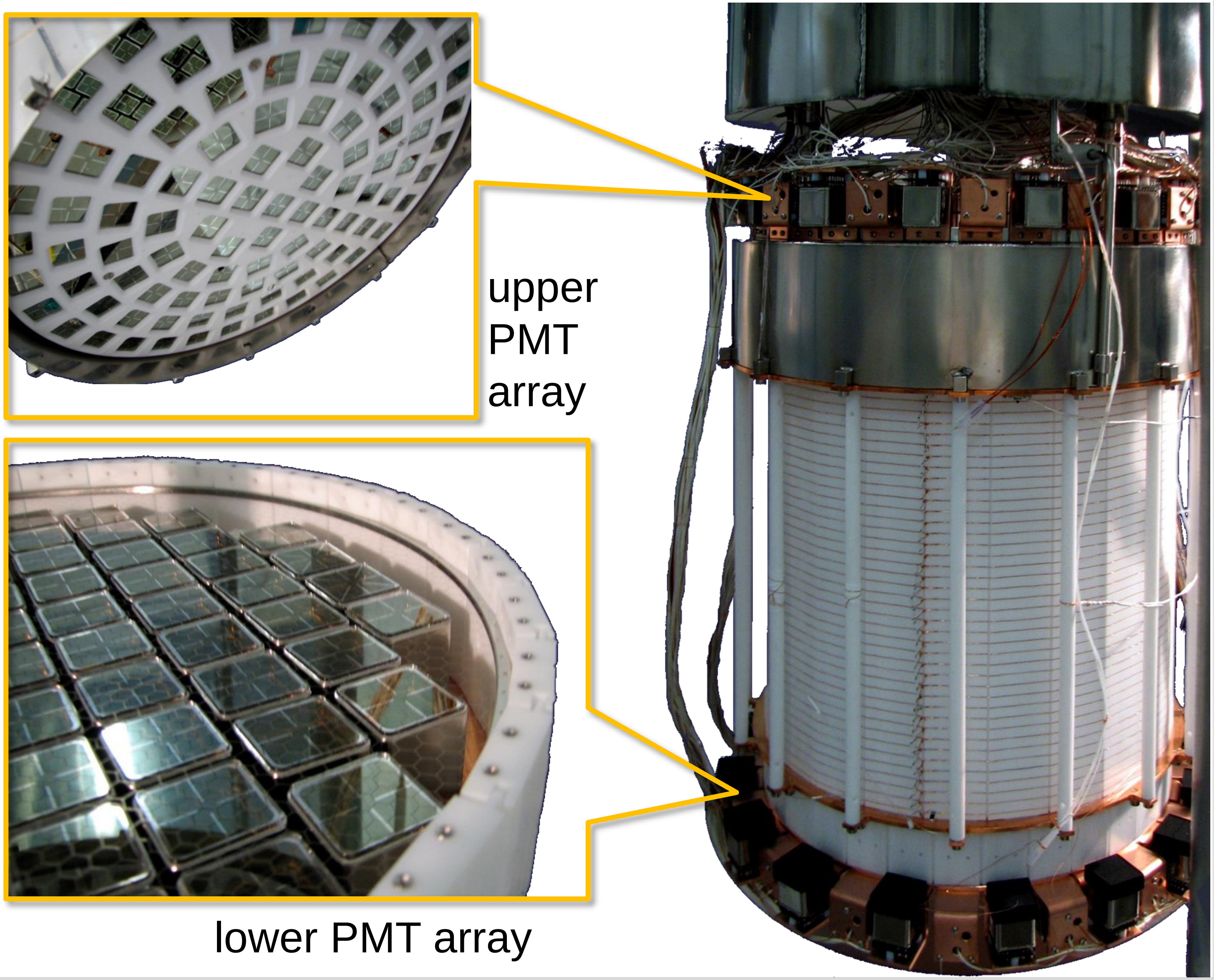




XENON100 experiment

XENON-100:

measurements at LNGS



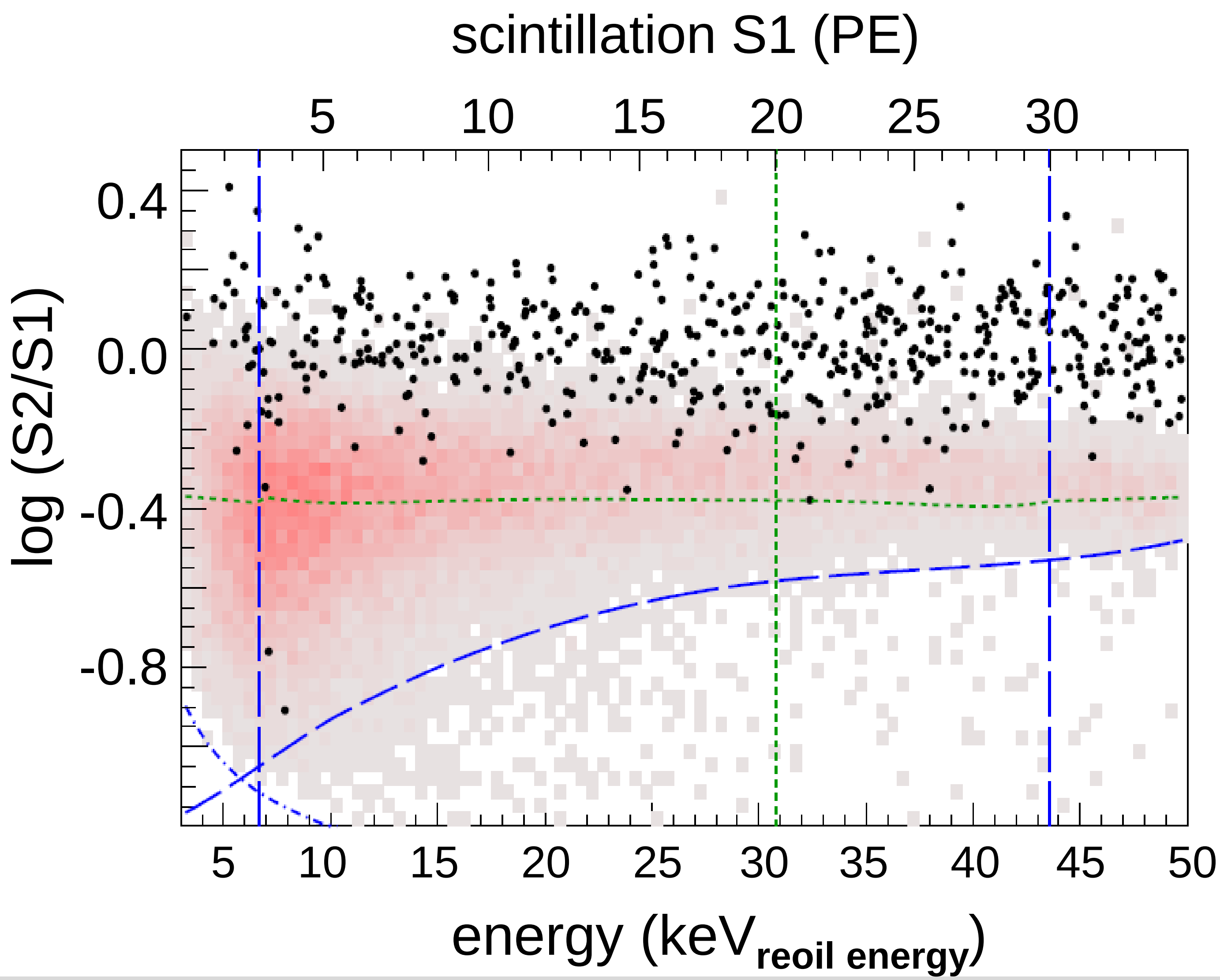
XENON100 experiment: results

- **Inital results from XENON100**:
  - 224.6 days of data taking: 2323.7 kg · days

- energy window for WIMP-search:
  6.6 – 43.3 keV
  (Xe-recoil energy)

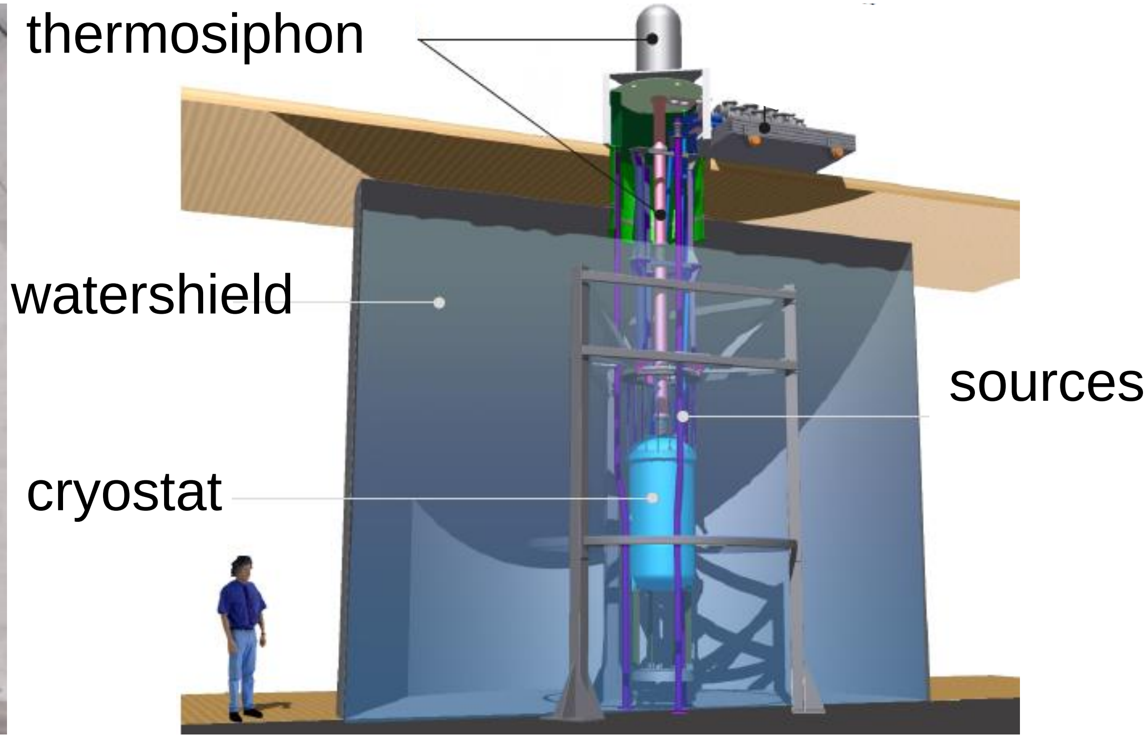
- **2 events** observed
  background expectation
  $N_{bg} = (1.0 \pm 0.2)$ events

- $\sigma_{SI} < 2.0 \times 10^{-45}$ cm^2
  at WIMP-mass
  $M_\chi = 55$ GeV

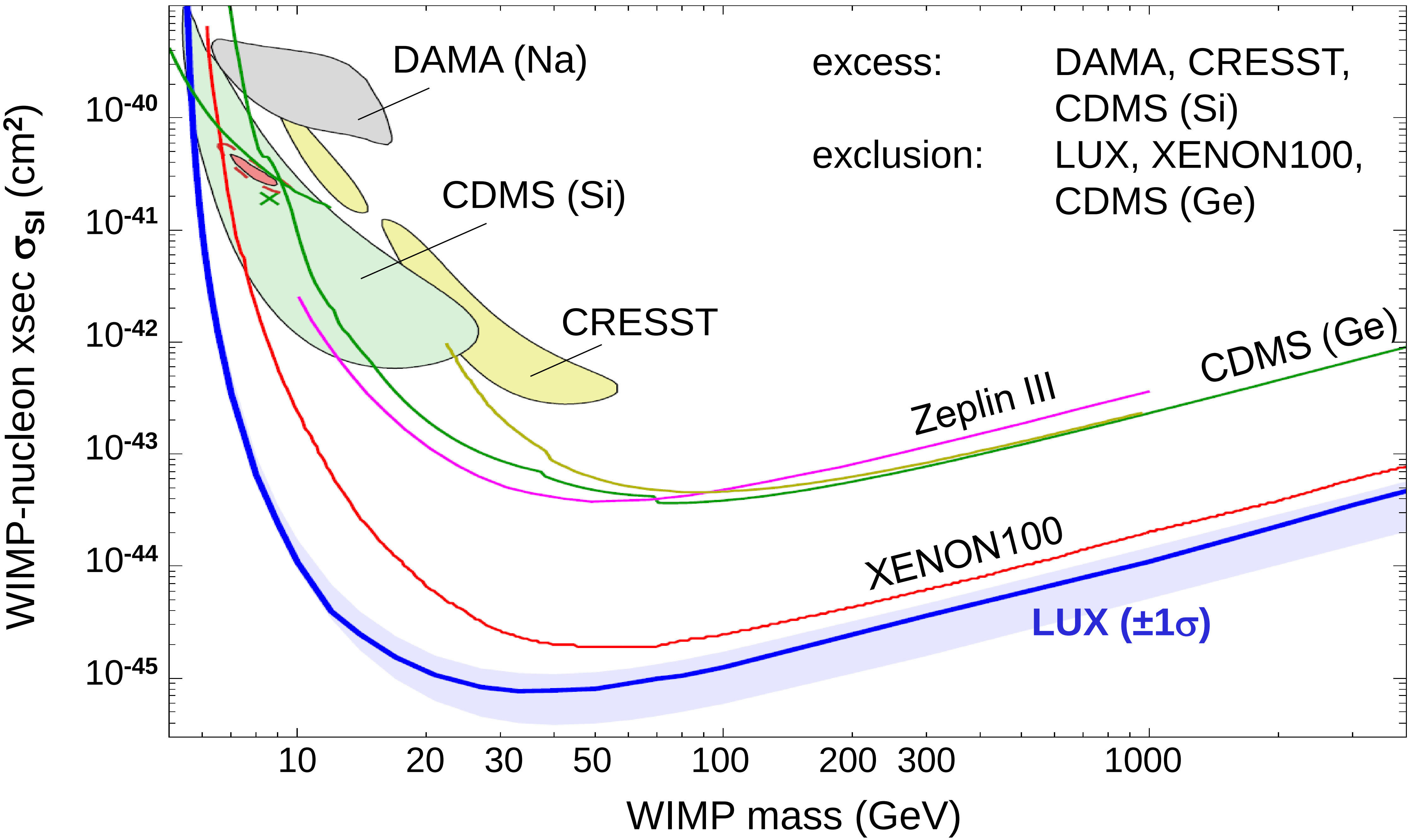


Large Underground Xenon (LUX) experiment

- **2-Phase-Xenon experiment at Sanford Lab**:
  - similar technology as in XENON (S1-S2)
    H_2O shielding instrumented as muon veto
  - detector with 370 kg mass (**100 kg ´fiducial volume´**)
  - expected initial WIMP-sensitivity:
    $\sigma_{SI} = 2 \times 10^{-46}\ cm^2$ (for R_{bg} = 0.5 events/month/100 kg)



WIMP results: actual status



XENON1T experiment

- **next-generation-Xenon experiment at LNGS**:
  - construction period: autumn 2013 – autumn 2015
  - total (active) LXe mass: 3.3 t (2.0 t), 1 m electron drift, 248 3-inch PMTs
  - bg-goal: 100 x lower than XENON100 ($\sim 5 \cdot 10^{-2}$ evts to.$^{-1}$ d^{-1} keV^{-1})

DARWIN R&D and design study

- **DARWIN: Dar**k matter **W**imp search **i**n **N**oble liquids
  - goal: ´ultimate´ DM-experiment: **30-50 tons LXe**
  - reach sensitivity where bg is dominated by neutrinos

$\sigma_{SI} \sim 10^{-48}\ \mathrm{cm}^2$

- **Experimental design parameters**
  - TPC diameter > 2 m
  - electron drift length > 2 m
  - few x 10^3 photosensors

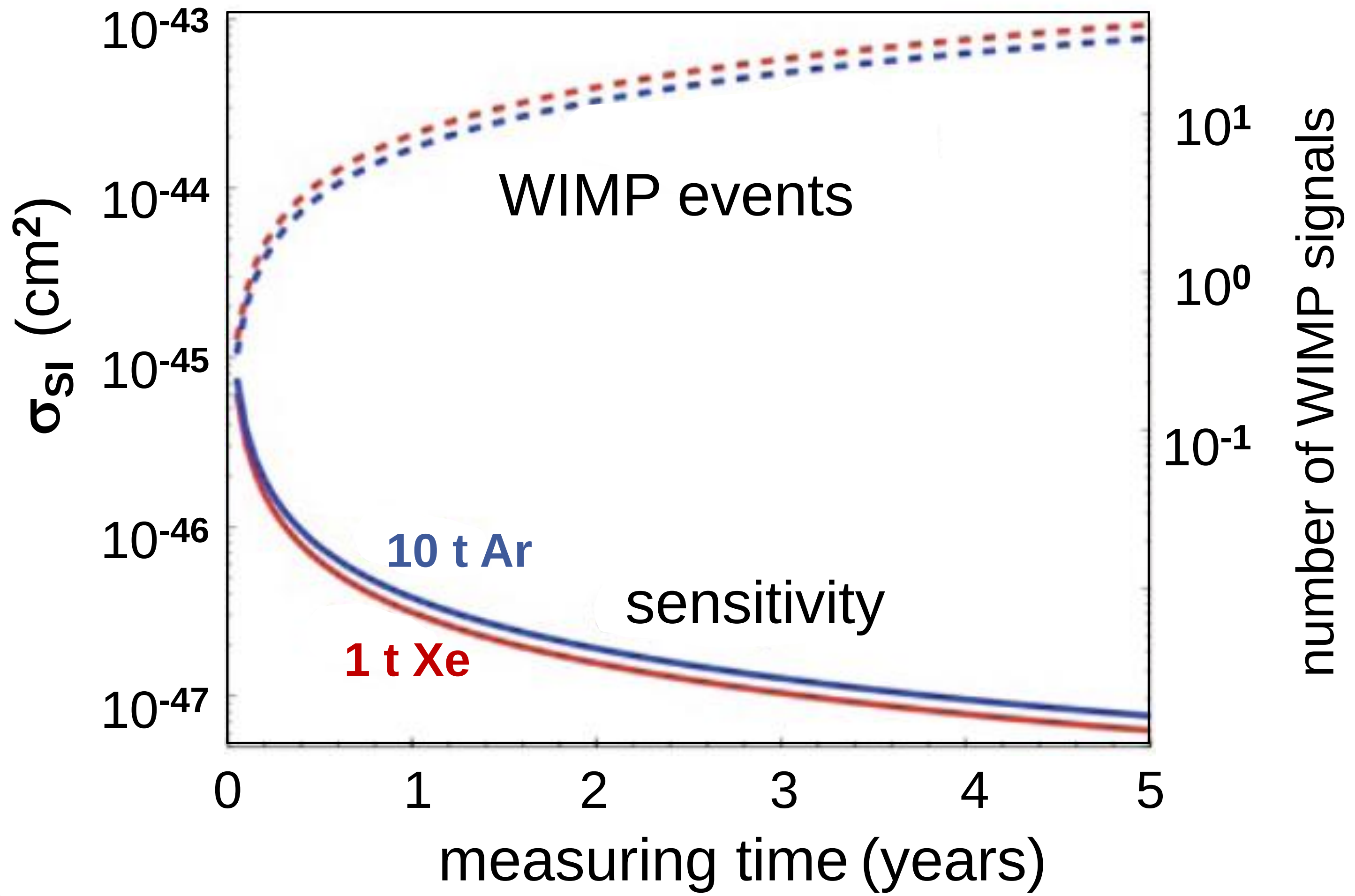
- **Physics goals**
  - WIMP spectroscopy: mass and cross section
  - others: pp-neutrinos, 0νßß of ^{136}Xe,
    axions and ALPs, bosonic SuperWIMPs

DARWIN R&D and design study

Karlsruhe Institute of Technology

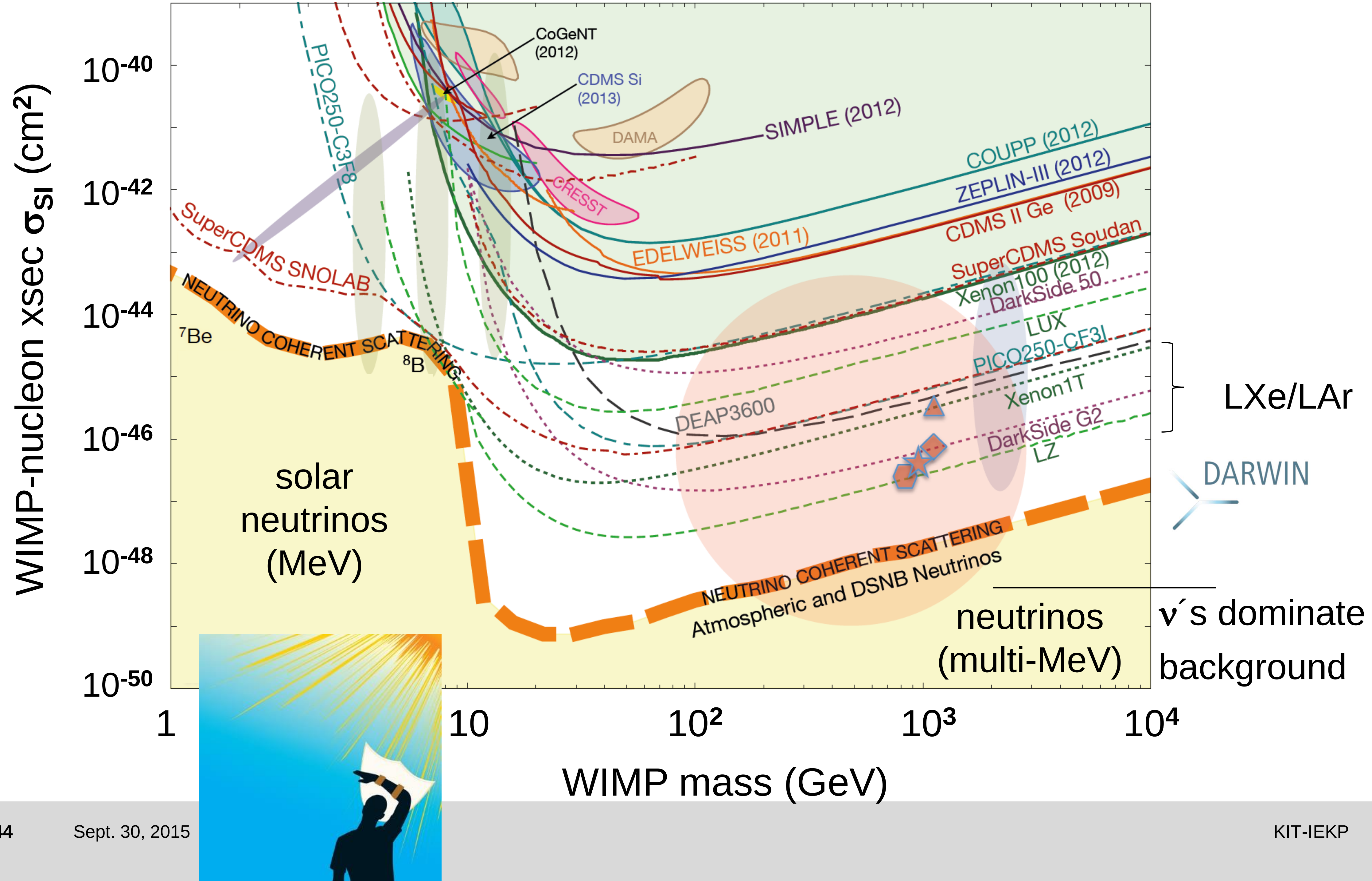
- **DARWIN: Dar**k matter **W**imp search **i**n **N**oble liquids
  - goal: ´ultimate´ DM-experiment: **30-50 tons LXe**
  - reach sensitivity where bg is dominated by neutrinos

DARWIN

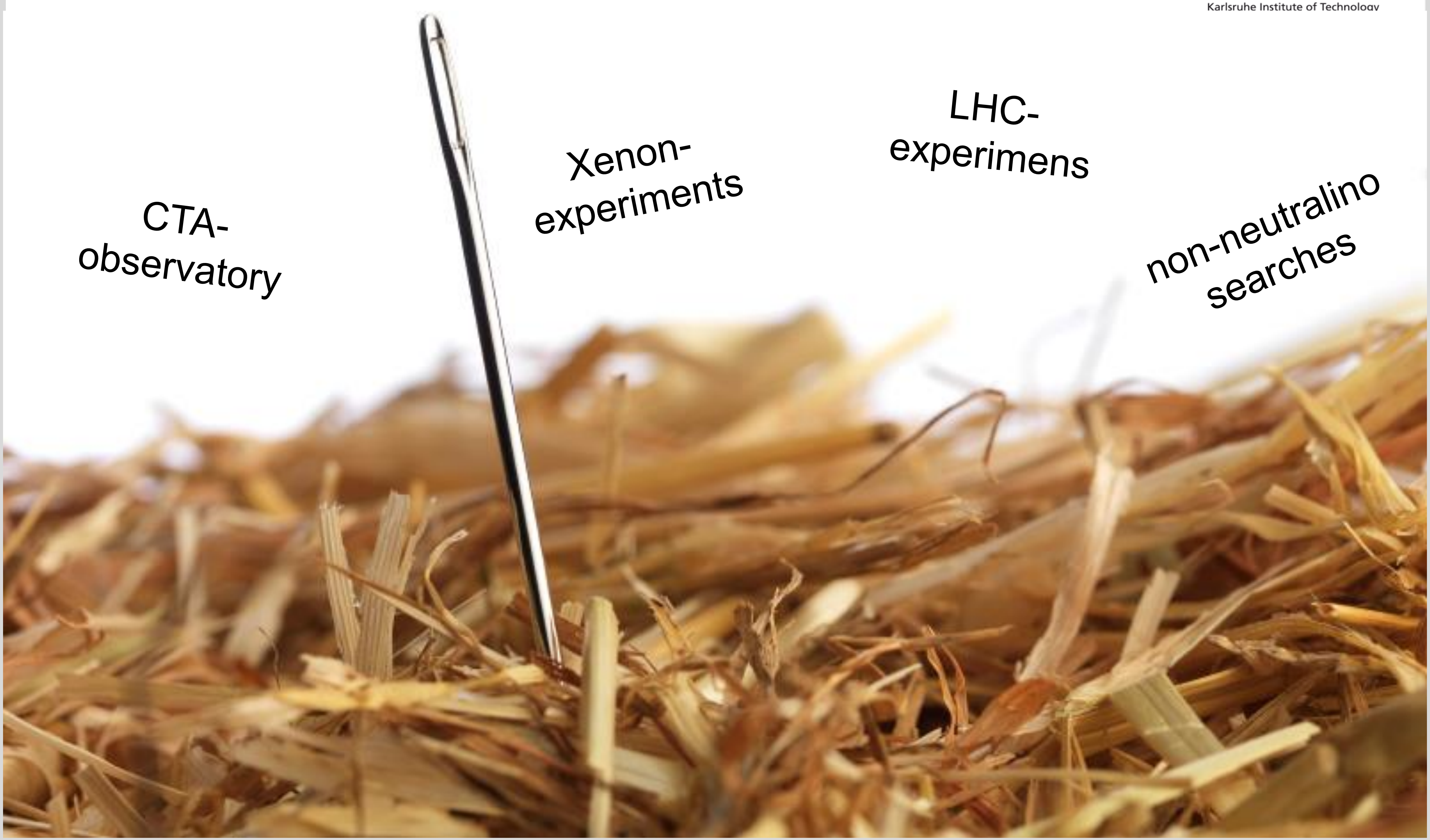


for M_W = 100 GeV
$\sigma_{SI} = 10^{-46}$ cm²

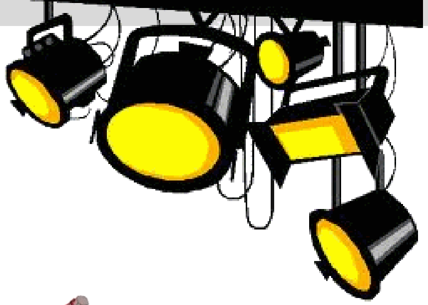
actual & future WIMP sensitivities



Searching for dark matter – a needle in a haystack



Conclusion



THANK YOU FOR YOUR ATTENTION

KIT Karlsruhe Institute of Technology