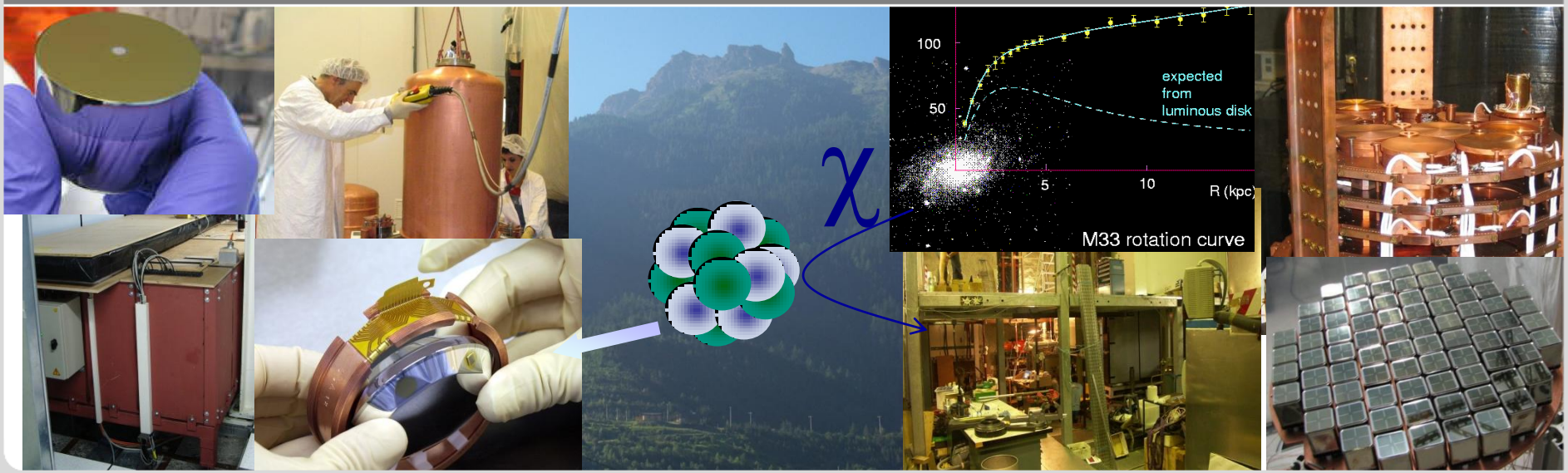
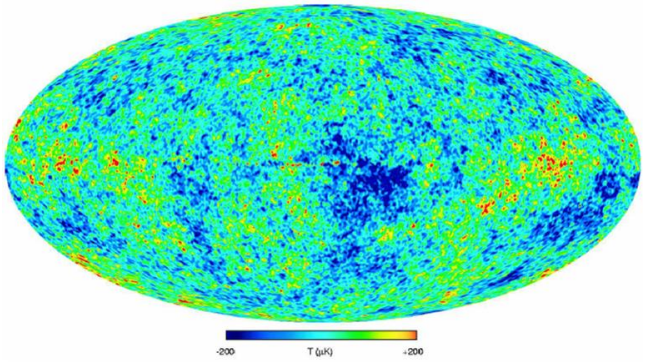
# Direct search for cosmological Dark Matter

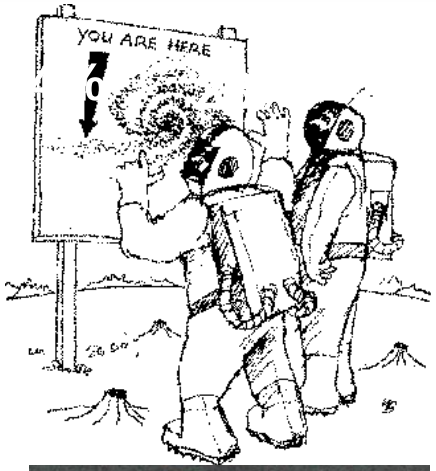
KIT Centrum Elementarteilchen- und Astroteilchen-Physik (KCETA), Institut für Kernphysik



# Content of the lecture

- DM evidences from astrophysics
- our cosmological model and DM
- DM candidates, the case for a WIMP
- DM in our galaxy
- kinematics and structure of direct detection of DM
- methods to detect DM directly
- ... using Germanium crystals
  - as PPC detectors (CoGeNT)
  - as cryogenic bolometers (EDELWEISS)
- ... using liquid noble gas (XENON)
- results & conclusions



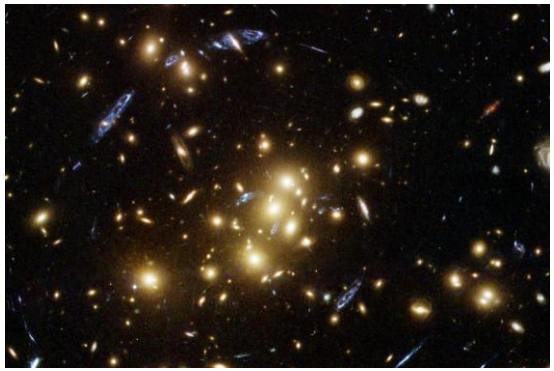




# Astronomical evidences for DM

collision of “bullet cluster”: galaxies, gravitational wells and excited baryons

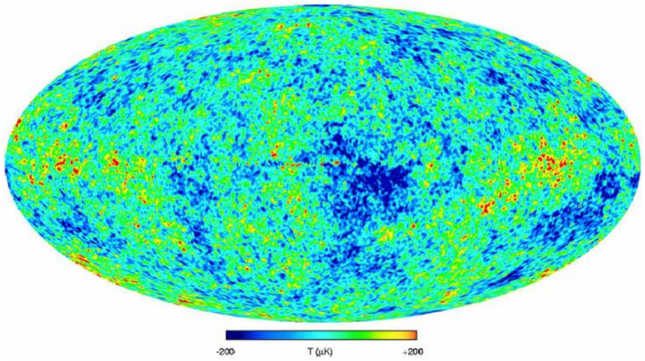
0.7 Mpc

galaxy cluster as gravitational lenses



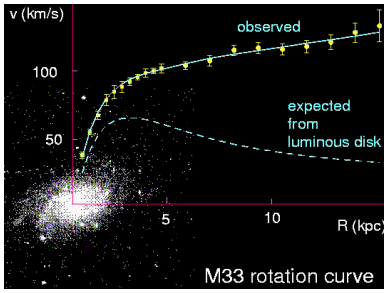
10-100Mpc

anisotropies in the cosmic microwave bg rad. (CMBR)



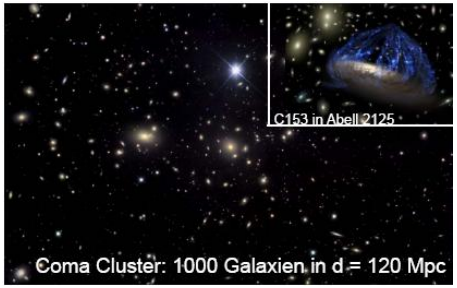

100Mpc- ~Gpc

0.1Mpc



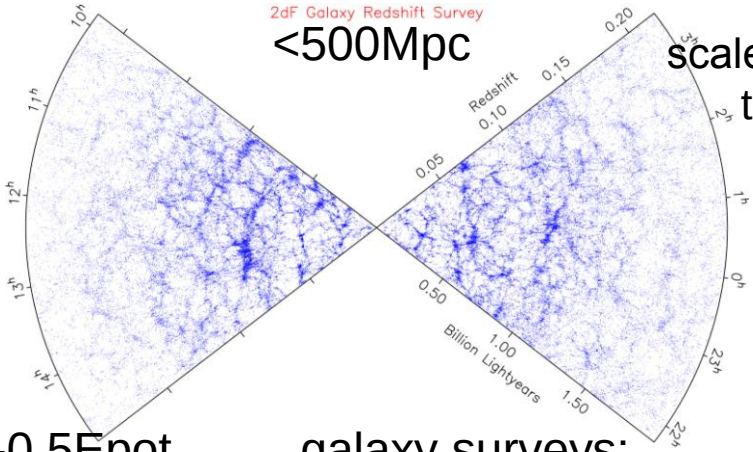

rotation curves of galaxies: DM halo needed

3-5 Mpc




Coma galaxy cluster: virial theorem Ekin = -0.5Epot brings F Zwicky to “Dark Matter”

<500Mpc

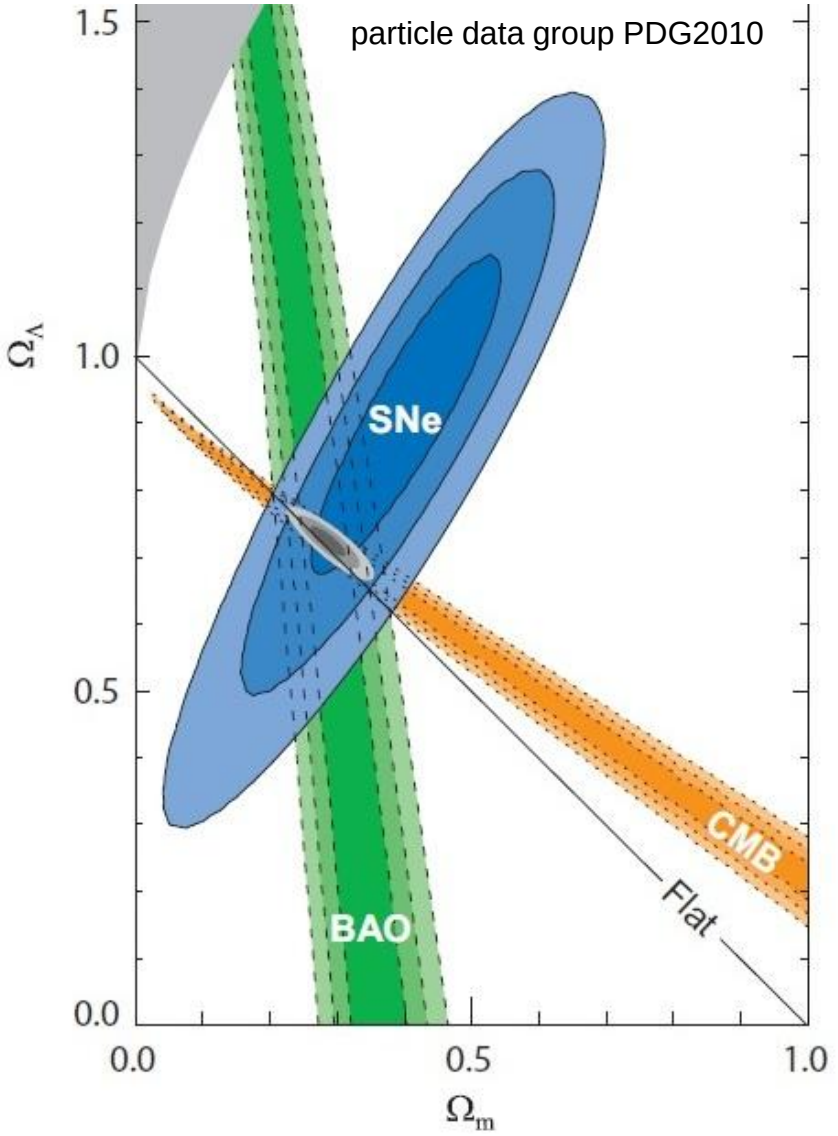



galaxy surveys: filaments and voids

scale (“view back towards early Universe”)

1 parsec = 3.26ly

# Dark Matter – particle candidates




**WIMP neutralino $\chi$:**
lightest (neutral) SUSY particle
$\sigma \sim 1 \ldots 10^{-2}\ \sigma_{electroweak}$

**axion:**
light WIMP produced
non-thermally (to solve
CP violation via Peccei-Quinn)

**axino:**
SUSY partner of axion,
produced via decays of sparticles

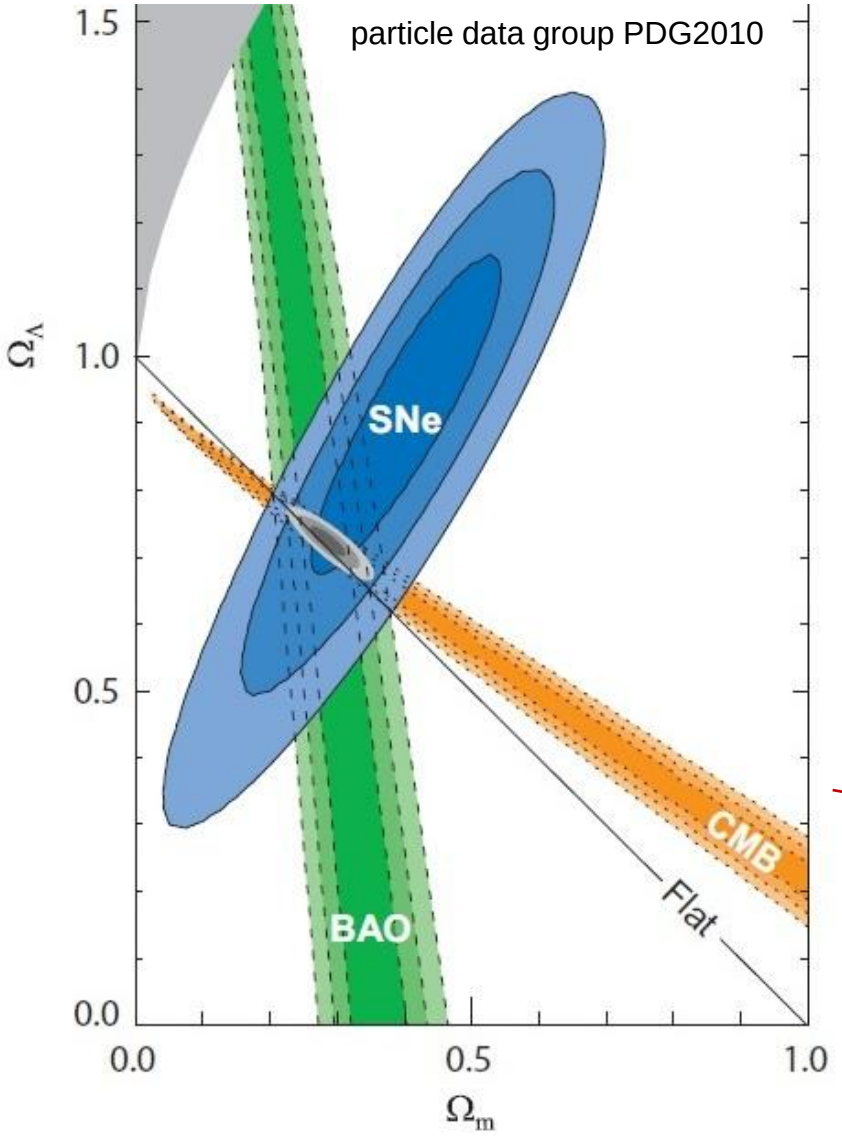
CDM

**neutrino:**
known neutral, non-baryonic
massive particle, weakly-interacting

HDM

**... many more...**

# Dark Matter – particle candidates

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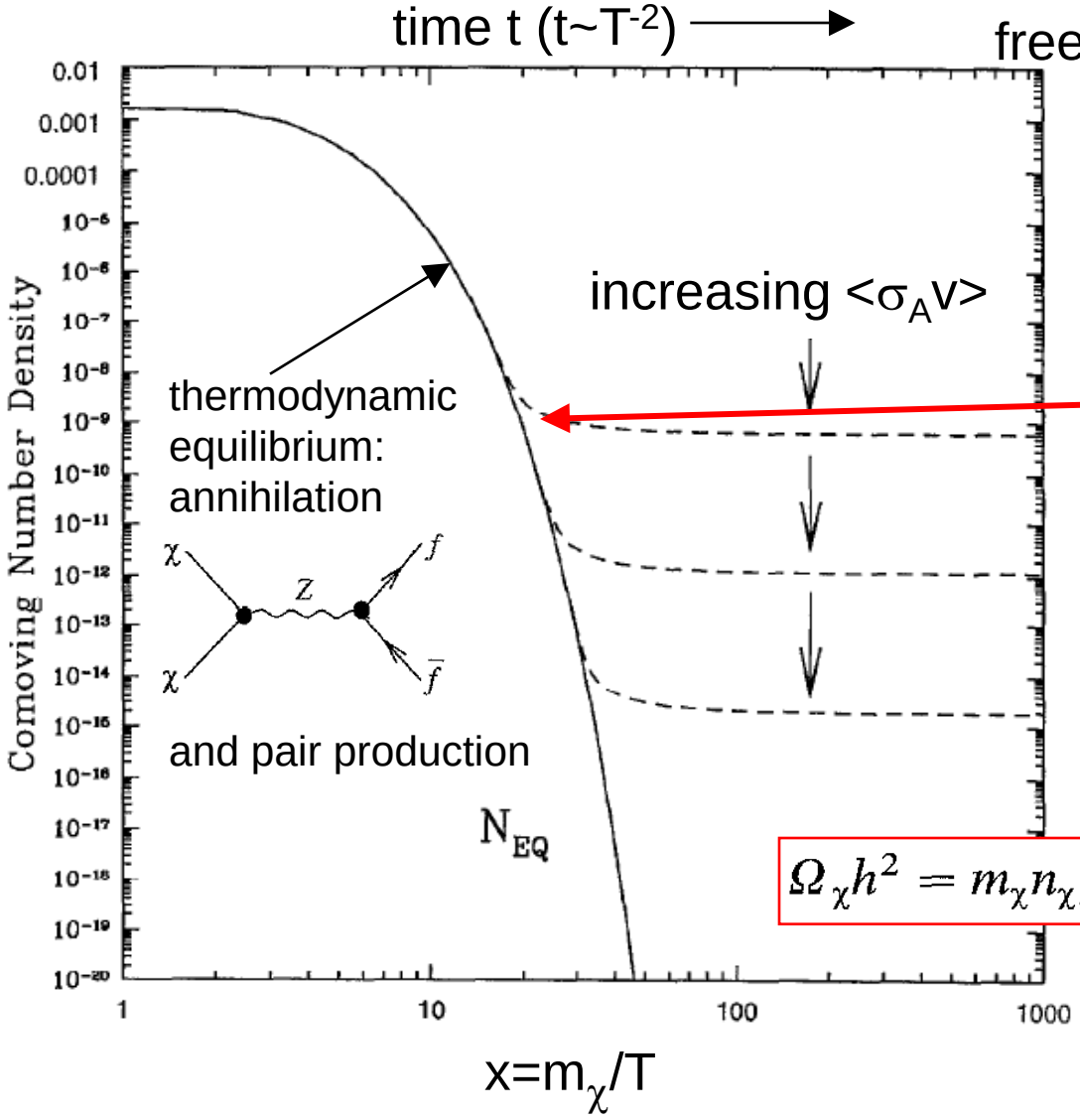
~~HDM~~

**... many more...**

# WIMP DM as the SUSY LSP




freeze-out of a weakly interacting massive particle (WIMP $\chi$)

$T_{freeze\text{-}out}$~ 1/20 m(WIMP)

**Cold** Dark Matter:

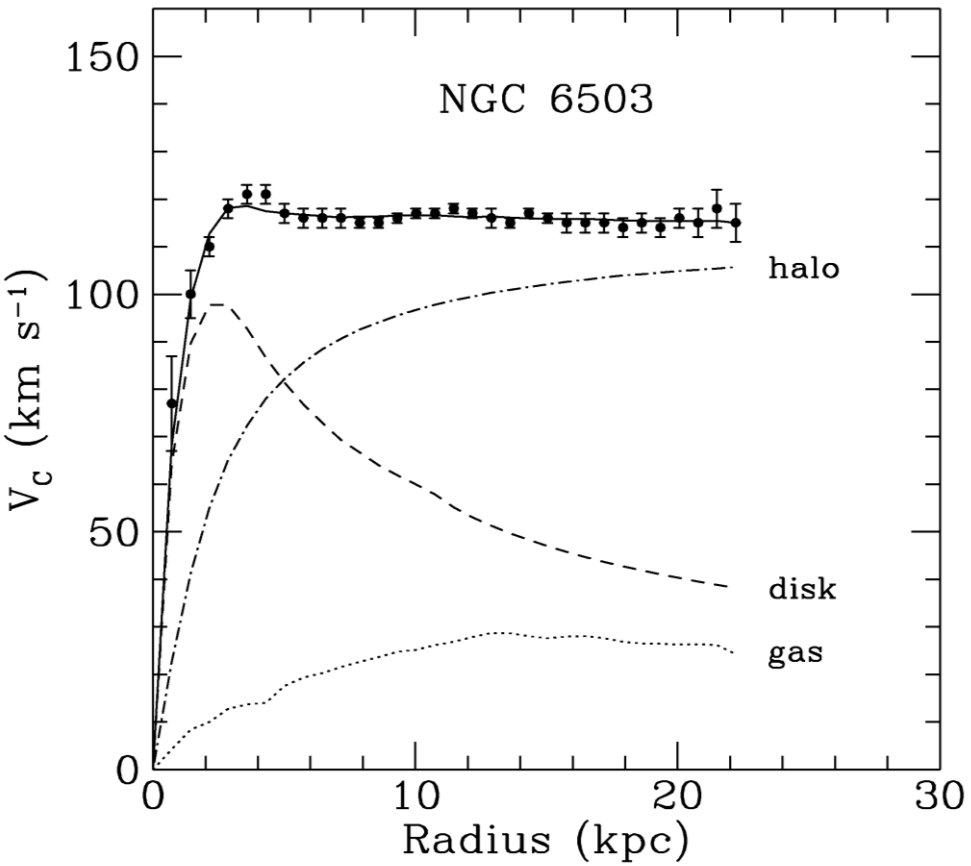
- non-relativistic
- no “free streaming”

“survival of the weakest”

$$\Omega_\chi h^2 = m_\chi n_\chi/\rho_c \simeq (3\times 10^{-27}\ \mathrm{cm^3\,s^{-1}}/\langle\sigma_A v\rangle)$$

Jungman, Kamionkowski, Griest (1995)

# DM distribution in galaxies:




**Kepler´s law:**
rotation velocity $v_{rot}$ of a star of mass m around a central inner mass $M_r$ :

$$F = \frac{G M_r m}{r^2} = m \cdot a$$

$$a = \frac{v_{rot}^2}{r} = \frac{G M_r}{r^2}$$

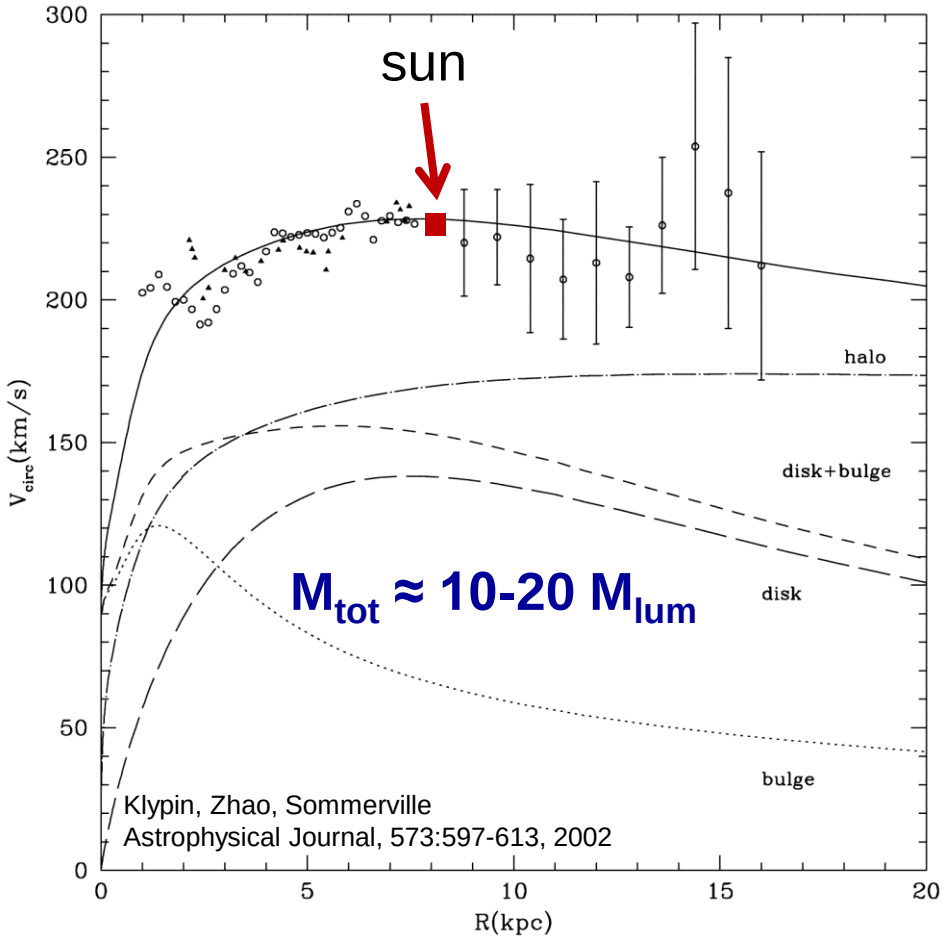
$$\Rightarrow v_{rot}(r) = \sqrt{\frac{G M_r}{r}}$$

$$M_r = \int \rho(r) dV$$

(galactic bulge: $\rho(r)=\rho_0$=const. r<5kpc
outside: $\rho(r)\sim 0$ → $M_r$=const. → $v_{rot} \sim r^{-1/2}$)

$v_{rot}$ ~ const. → $\rho(r) \sim r^{-2}$ outside bulge

# DM in our galaxy: the Milky Way halo




**ρ(DM, 8kpc) ≈ 0.3GeV/cm³**
**$\sqrt{\langle v^2 \rangle}$ ~ 270km/s**
**with Maxw-Boltzm distrib.**

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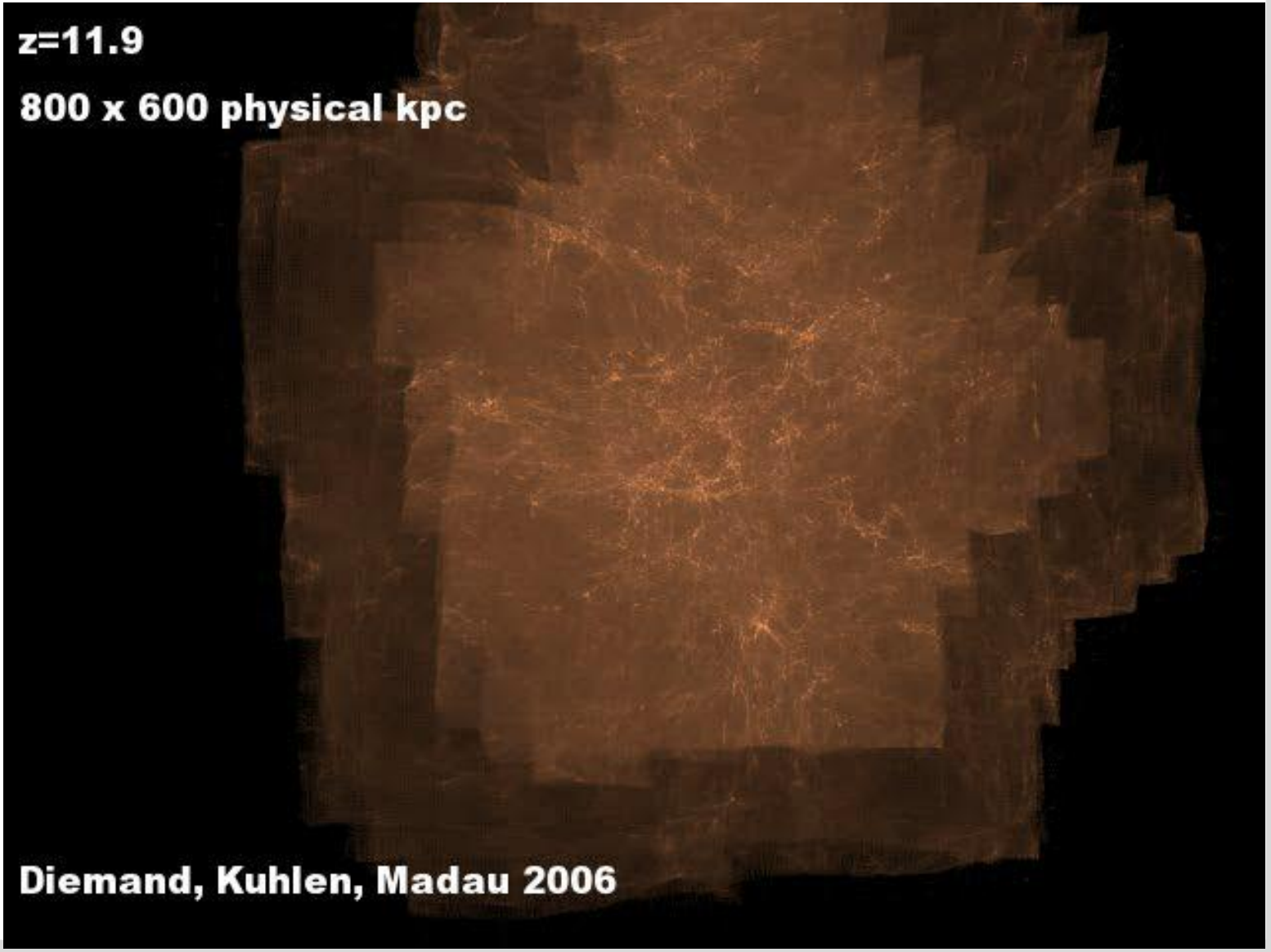
# Dark Matter halo model

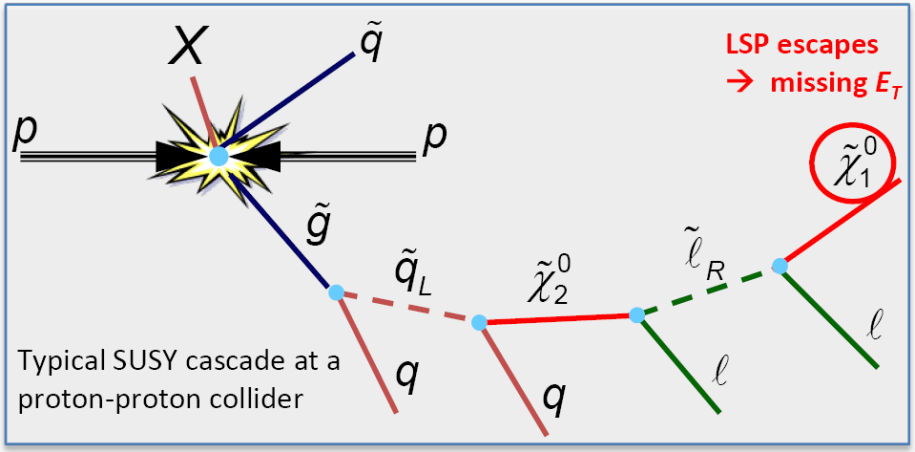
N-body simulations: evolution of a DM halo

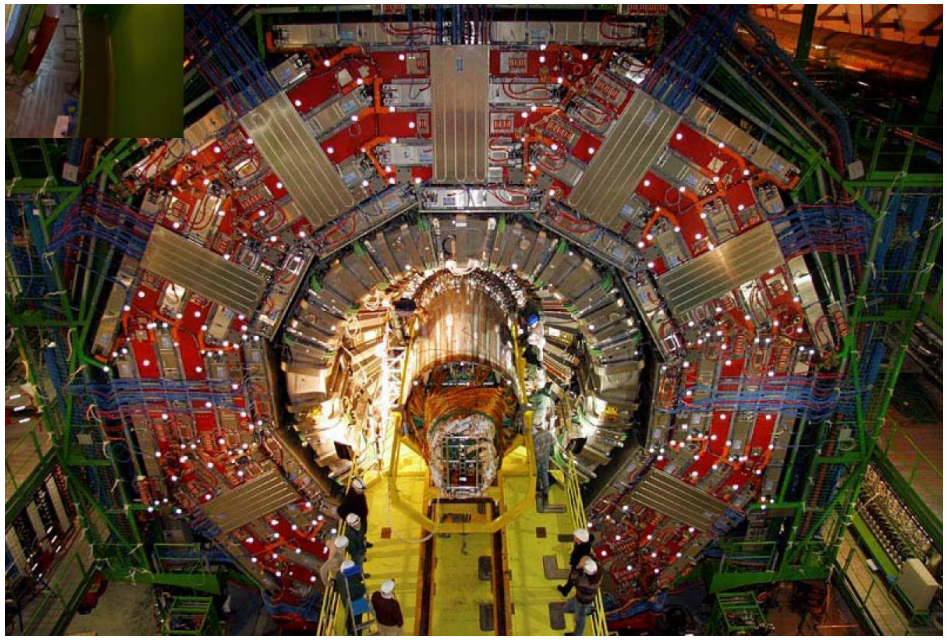
B. Moore et al. ETH Zürich



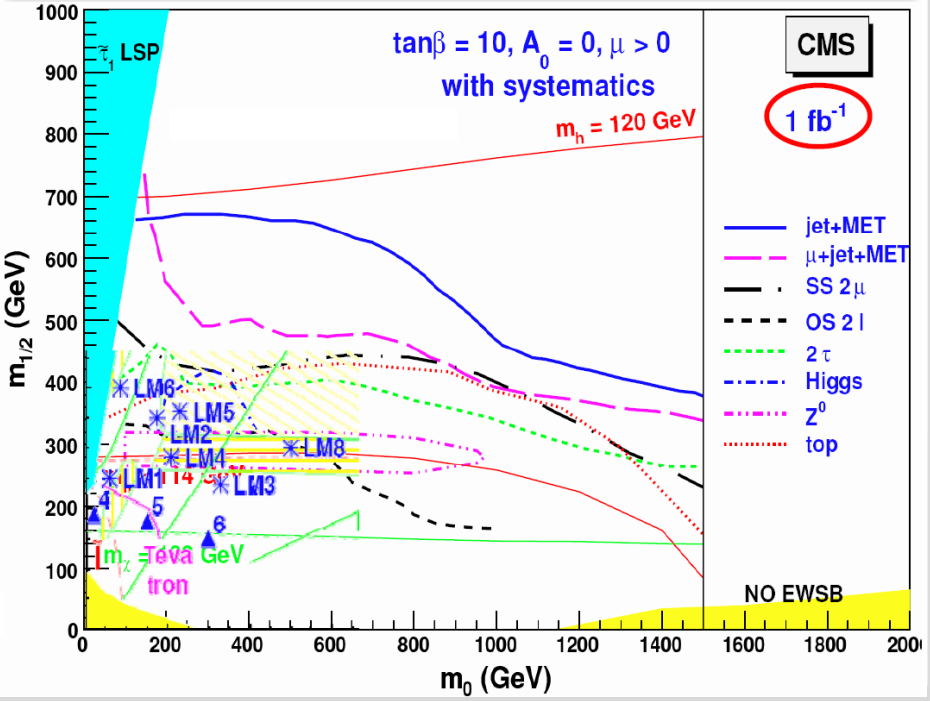
# Production of SUSY particles at LHC

**DM signature:**
production of squarks with subsequent decay chain leading to a neutralino escape
→ missing “transverse energy”



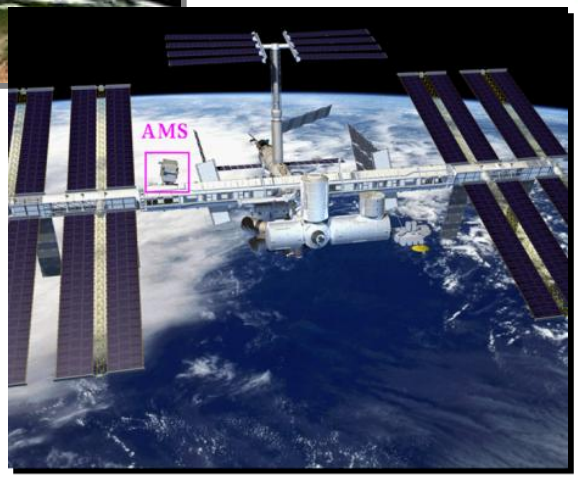
CMS at LHC



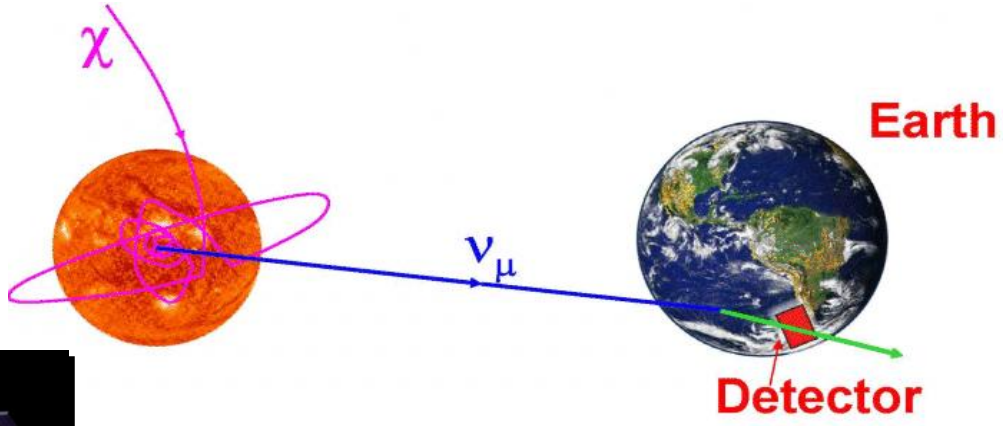
# “indirect” DM search ($\chi\chi$ annihilation)

$\chi\chi \rightarrow f\bar{f}$ needs astrophysical overdensities:

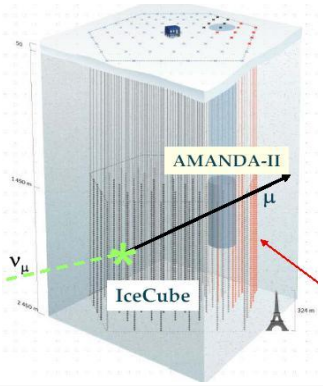
1. galactic center → excess of cosmic rays ($\gamma$´s & antimatter)
2. the sun → energetic “solar” neutrinos ($\bar{\nu}_e$, $\nu_\mu$, $\bar{\nu}_\mu$)
3. the earth → “upward-going” muons from ($\nu_\mu$, $\bar{\nu}_\mu$)




EGRET,
Fermi-LAT,
PAMELA,
ATIC,
AMS-02

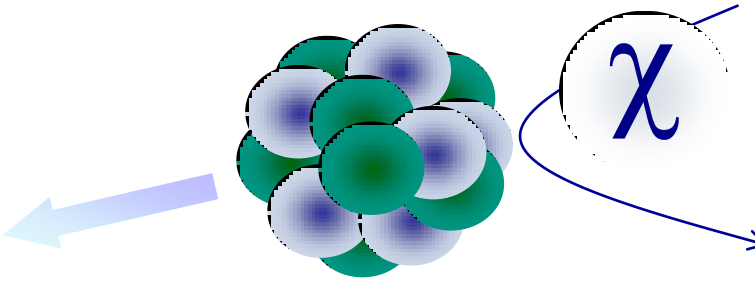



e.g. SuperK, IceCube

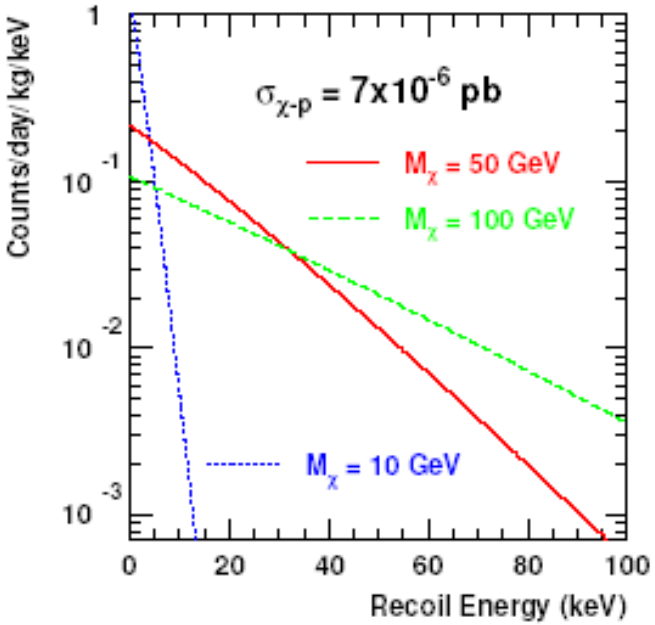


# direct (WIMP) DM search

elastic scattering on a nucleus




$^{72}$Ge




- nuclear recoils:
  - mass *~10 GeV to ~ 1000 GeV*
  - relative speed *o(300 km/s)*

  *(~ our orbital velocity around galactic center)*

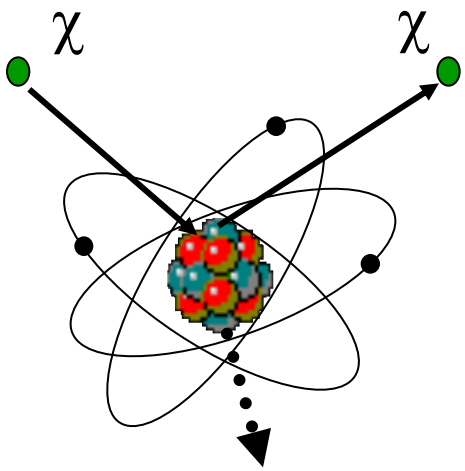
$$E_{recoil} = E_{WIMP}\frac{4M_{nucleus}M_{WIMP}}{(M_{nucleus}+M_{WIMP})^2}\cos^2\theta_{recoil}$$

⇒ only a few keV of recoil energy

- cross section $\sigma_\chi < 10^{-42} cm^2$
- local WIMP-density $\rho_\chi = 0.3\ GeV/cm^3$

⇒ very very rare scattering events
(< 1 / year / kg)

# direct (WIMP) DM search




## spin-independent interaction (SI):

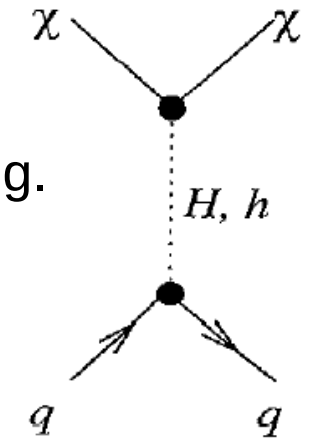
coherent scattering of $\chi$ off nucleus with A nucleon wave functions

$$\sigma_{W-A} = \frac{\mu_A^2}{\mu_p^2}\left(Z + (A-Z)\frac{f_n}{f_p}\right)^2 \sigma_{W-p} = A^2 \frac{\mu_A^2}{\mu_p^2}\sigma_{W-p}$$

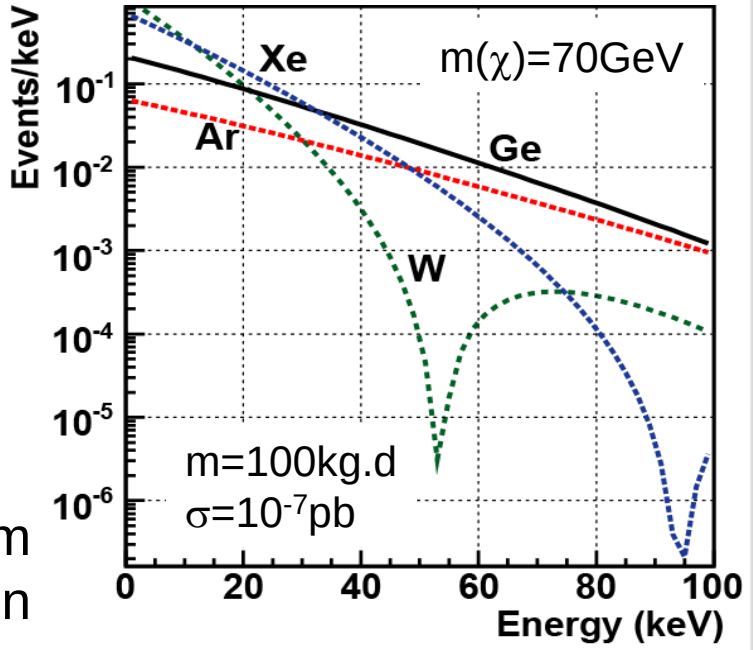
$\chi$-A reduced mass

effective $\chi$-p(n) coupling

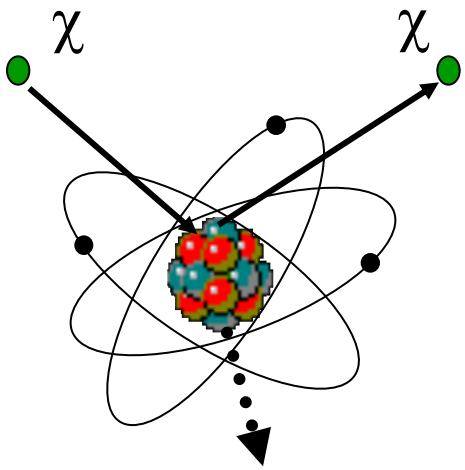
e.g.

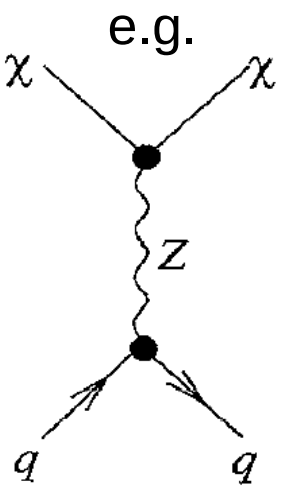



form factor from nuclear calculation



# direct (WIMP) DM search




$\chi$-p reduced mass

spin structure function

effective $\chi$-p(n) coupling

$$\sigma_{W-A} = \frac{\mu_A^2}{\mu_p^2} \frac{4}{3} \frac{J+1}{J} \left( \langle S_p \rangle + \langle S_n \rangle \frac{a_n}{a_p} \right)^2 \sigma_{W-p}$$

total nuclear spin

**spin-dependent interaction (SD):**

different amplitudes a(p), a(n) depending on nucleon carrying nuclear spin J

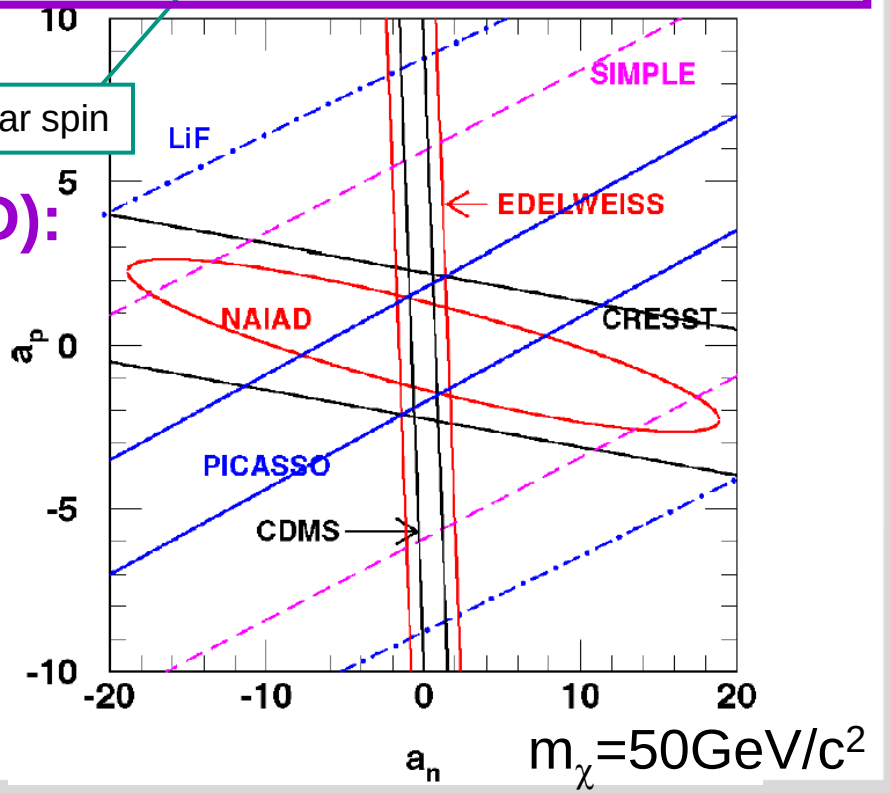
$^{73}$Ge: J=9/2 (Z=32,A-Z=41)→a(n)

$^{27}$Al: J=5/2 (Z=13,A-Z=14)→a(p)

$^{7}$Li: J=3/2

$^{127}$I: J=5/2

$^{19}$F: J=1/2

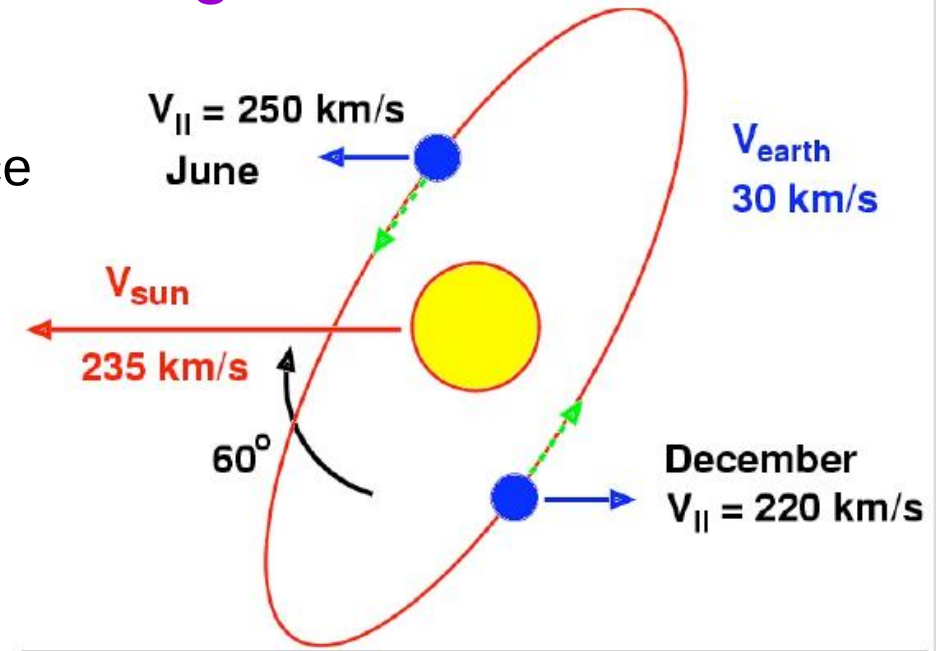


# direct (WIMP) DM search

## features of elastic WIMP-scattering:

SI or SD ??
SI enhanced by $A^2$ due to coherence
→ use different targets

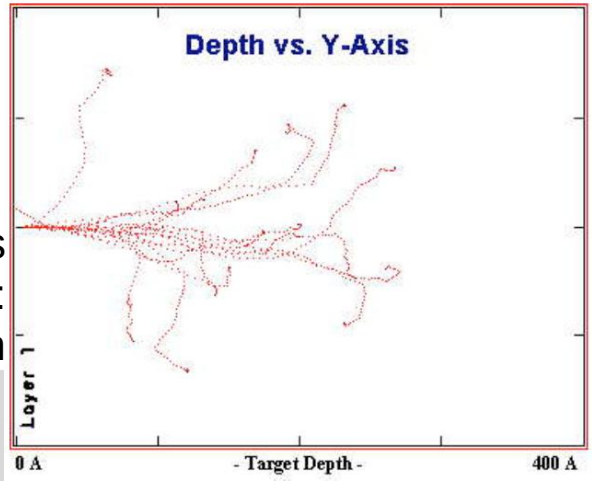
seasonal modulation
→ long term measurements



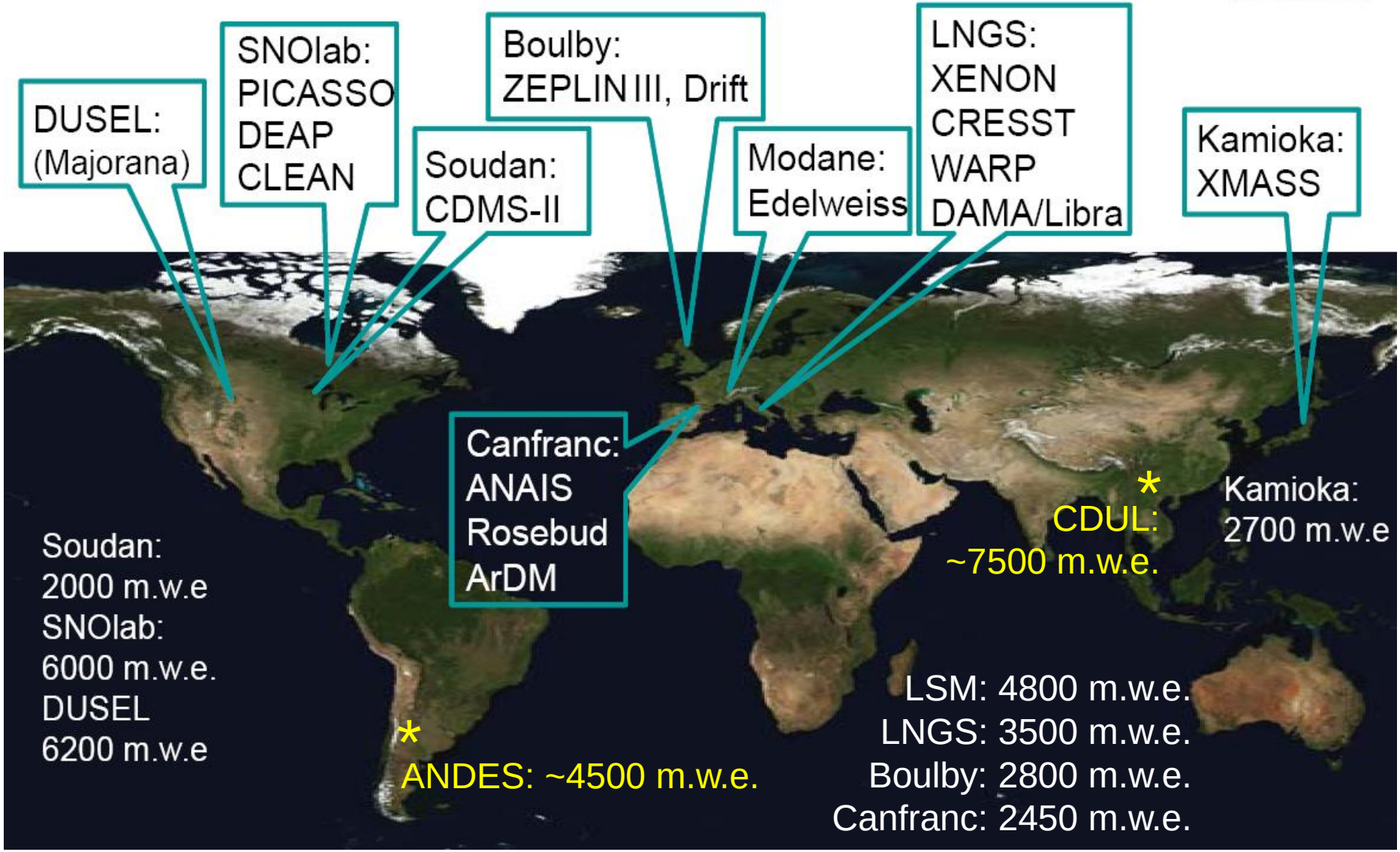

rare events, low energy deposit ~ 1-100keV
exponentially falling spectrum
→ suppress radioactive & cosmic bg

directional signature
→ track reconstruction

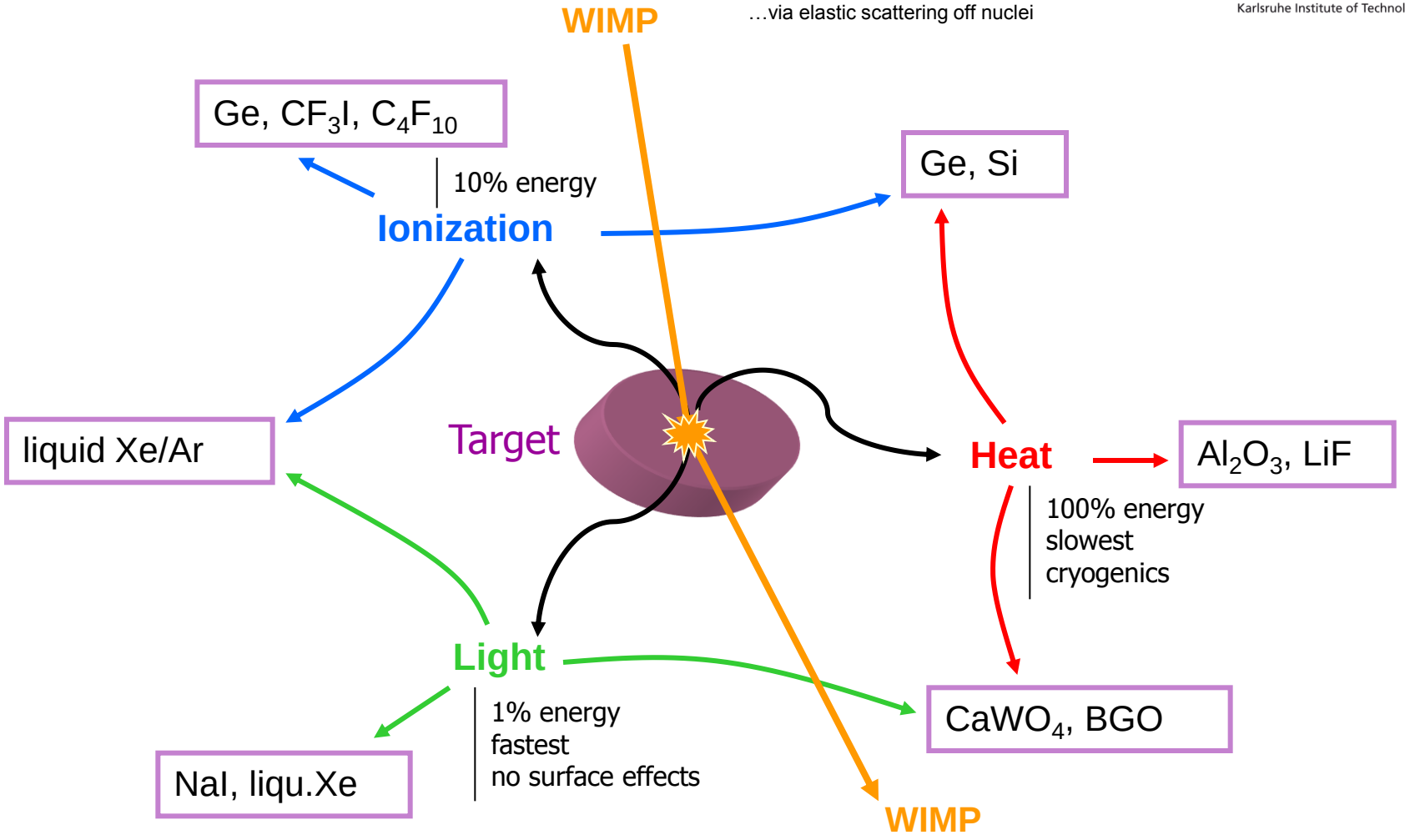
20 keV Ge recoils in crystalline Ge: range ~20 nm



# direct DM search - locations



# direct DM search – detection schemes



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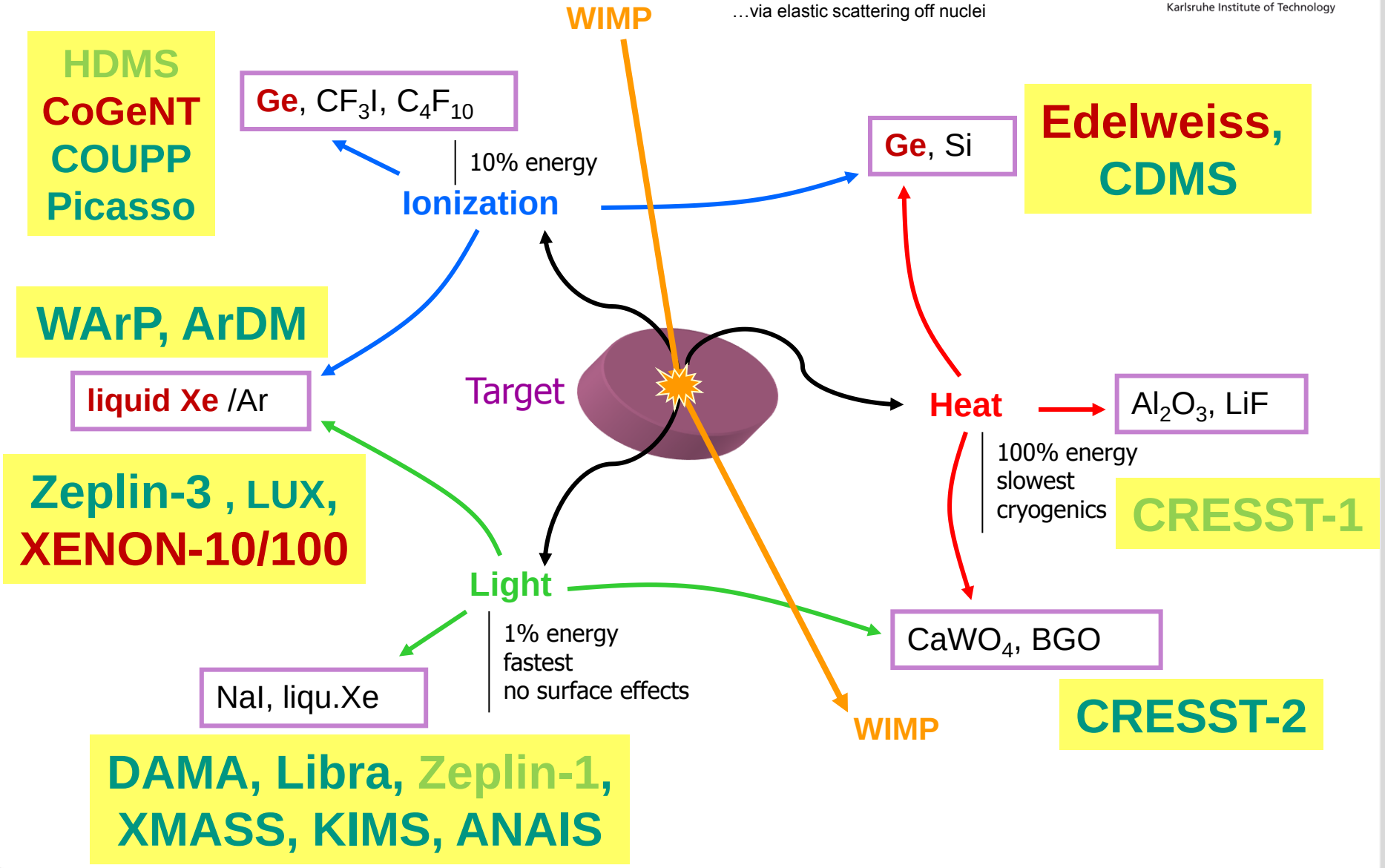
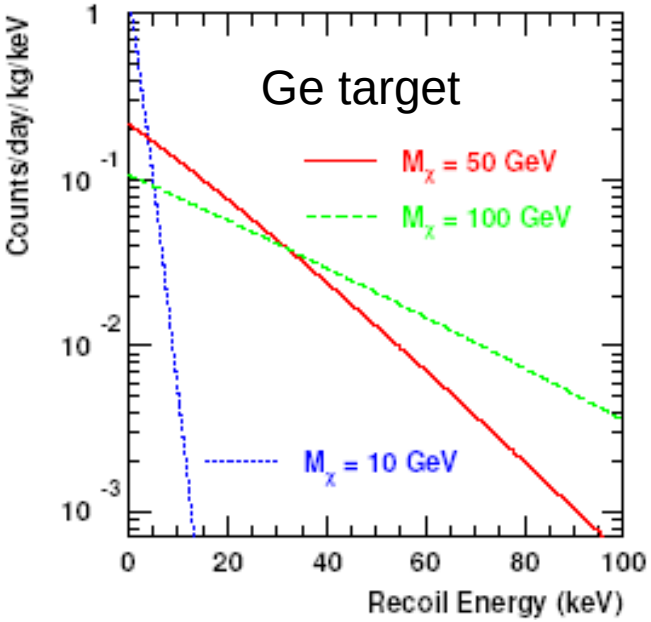
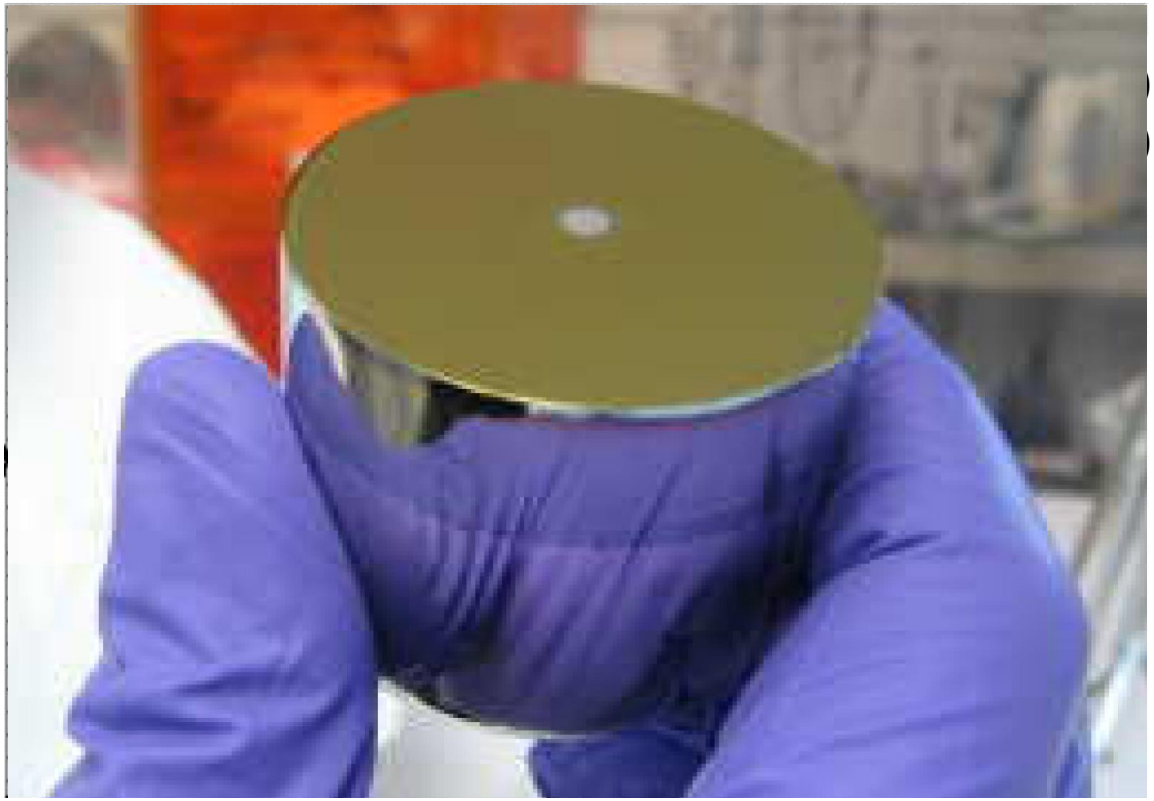


# direct DM search with ultralow noise ionization detectors – CoGeNT

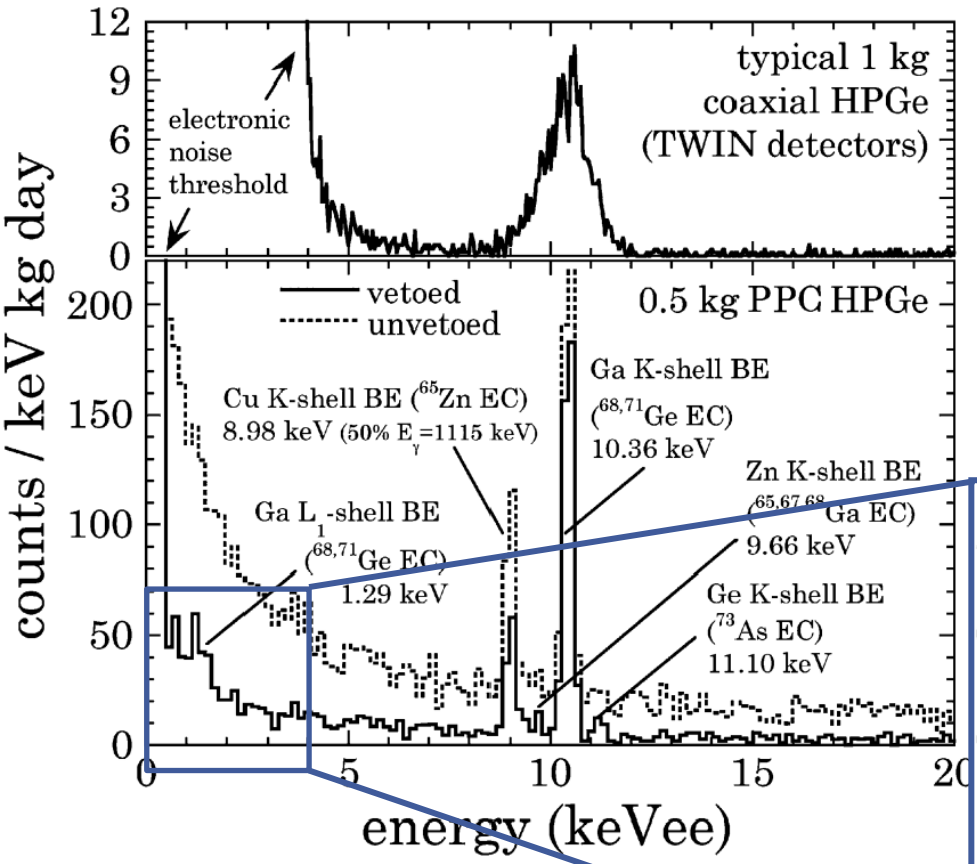



to investigate low m$\chi$
→ low threshold
→ small target mass
(475g)
(330 m.w.e., part of
Chicago's Tunnel
And Reservoir Plan)



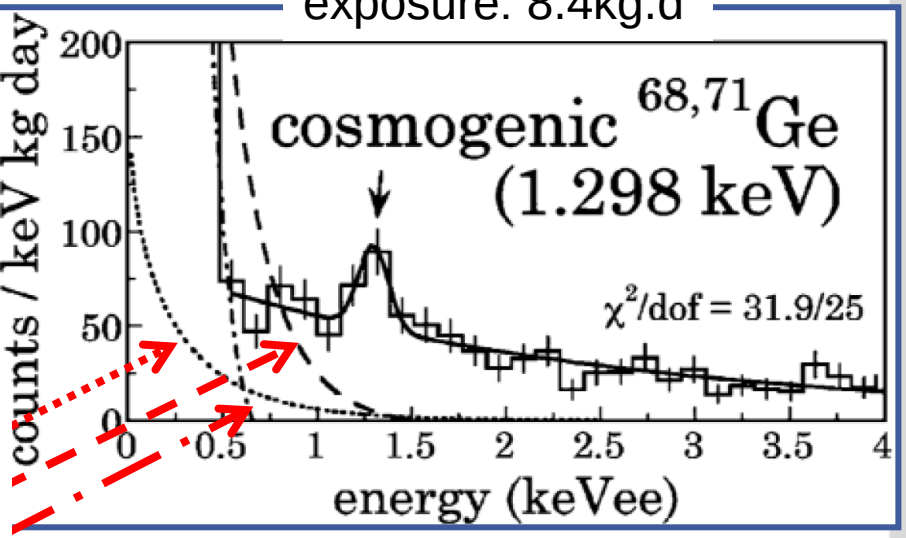
p-type point contact (PPC)
Germanium detector (HPGe)

# direct DM search with ultralow noise ionization detectors – CoGeNT




(i) a low-bg NaI[Tl] anti-Compton veto,
(ii) 5 cm of low-background lead,
(iii) 15 cm of standard lead,
(iv) 0.5 cm of borated neutron absorber,
(v) a >99:9% efficient muon veto,
(vi) 30 cm of polyethylene,
(vii) a low-effic. large-area external μ veto

exposure: 8.4kg.d

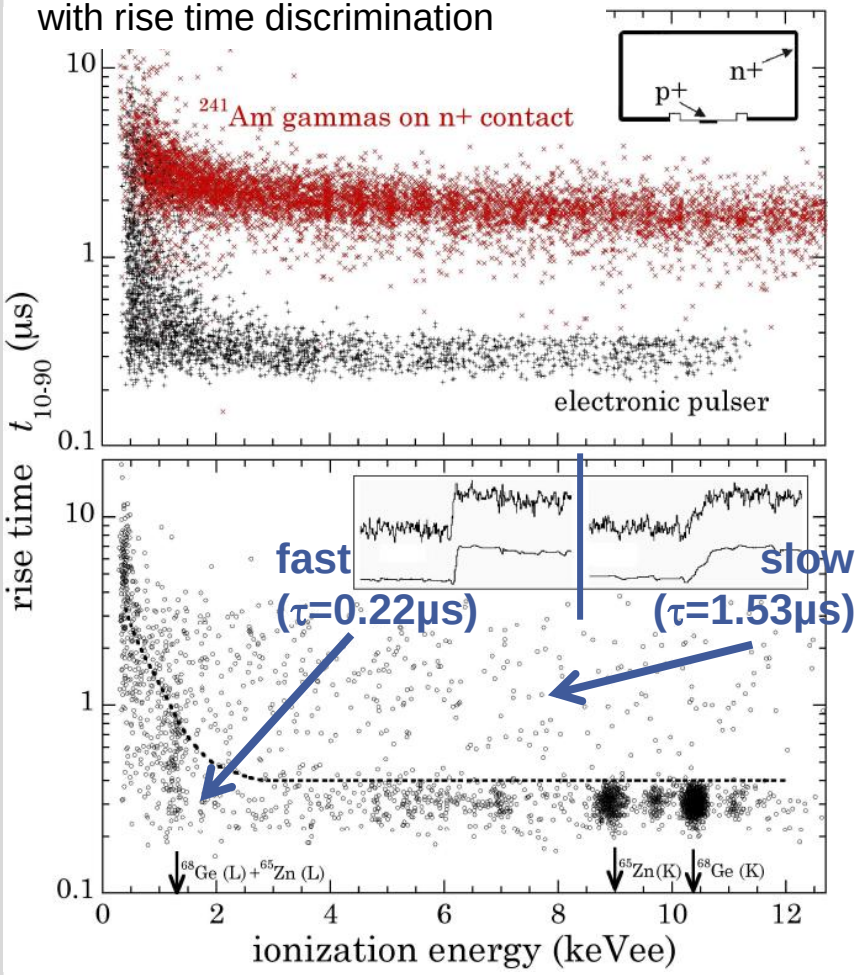



mχ=8GeV, $\sigma_{SI}=10^{-4}$pb
mχ=6GeV, $\sigma_{SI}=2\times10^{-3}$pb
mχ=4GeV, $\sigma_{SI}=10^{-2}$pb

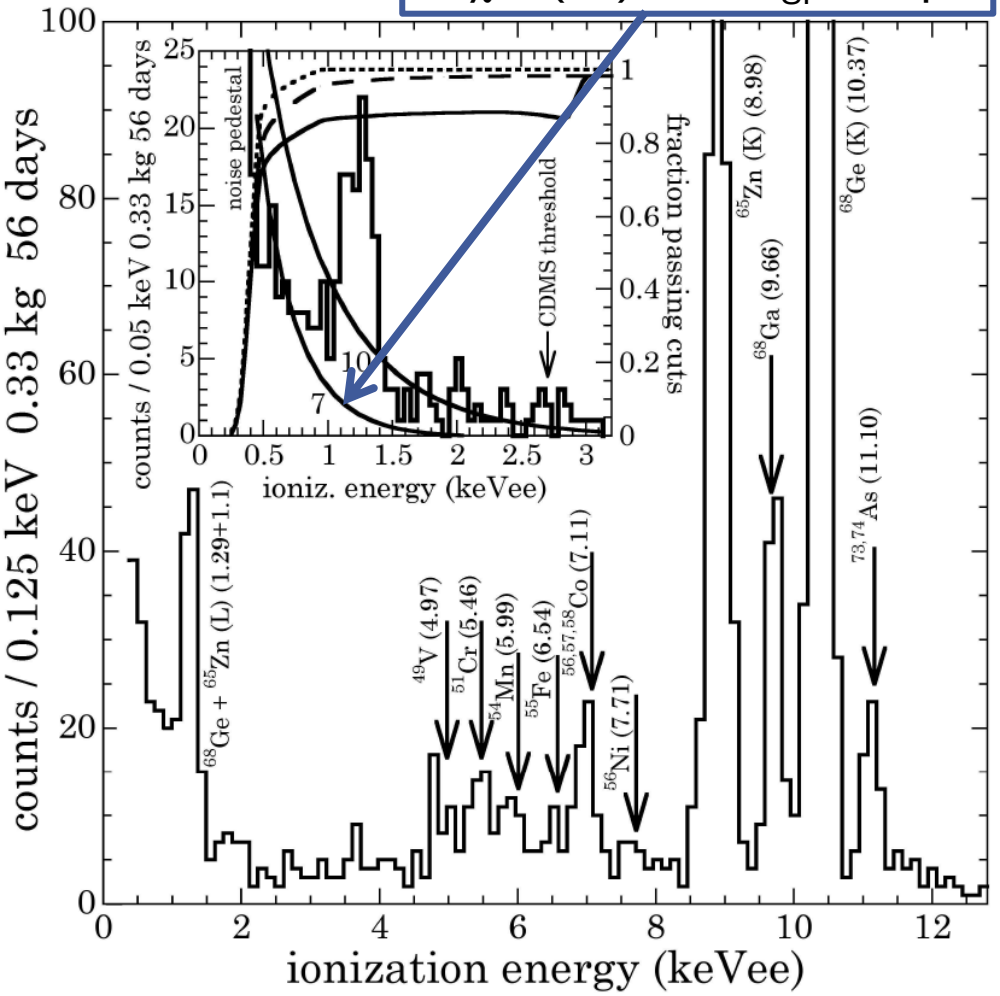
PRL 101, 251301 (2008)

# direct DM search – CoGeNT(2010) → light WIMP signal?

440g PPC @Soudan (2100mwe)
with rise time discrimination




mχ=7(10)GeV, $\sigma_{SI}=10^{-4}$pb



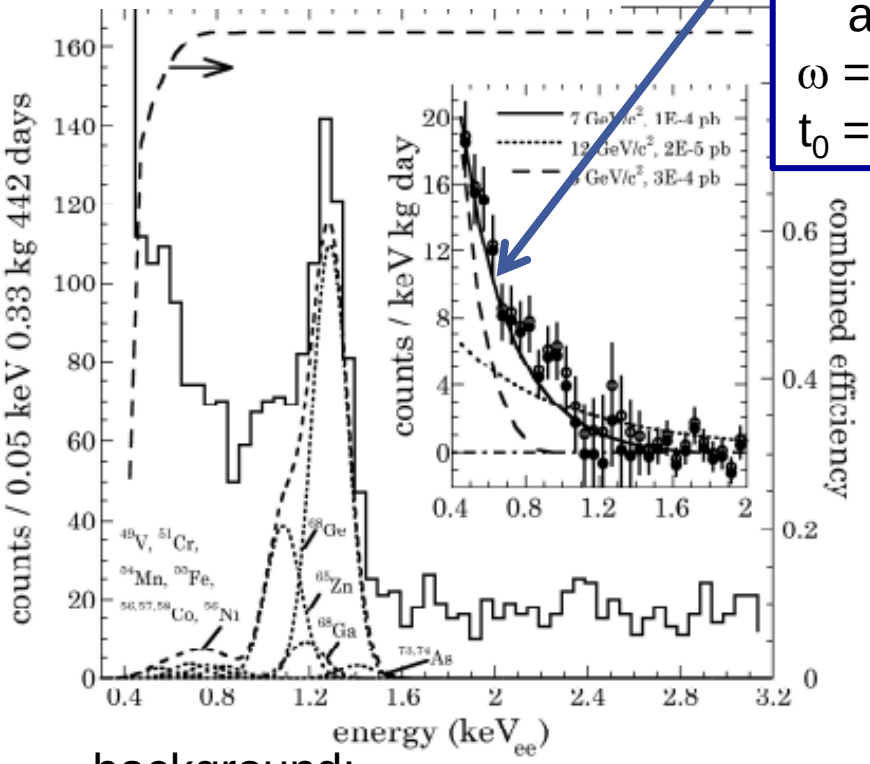

C. Aalseth etal., PRL106:131301,2011 18.4kg.d exposure

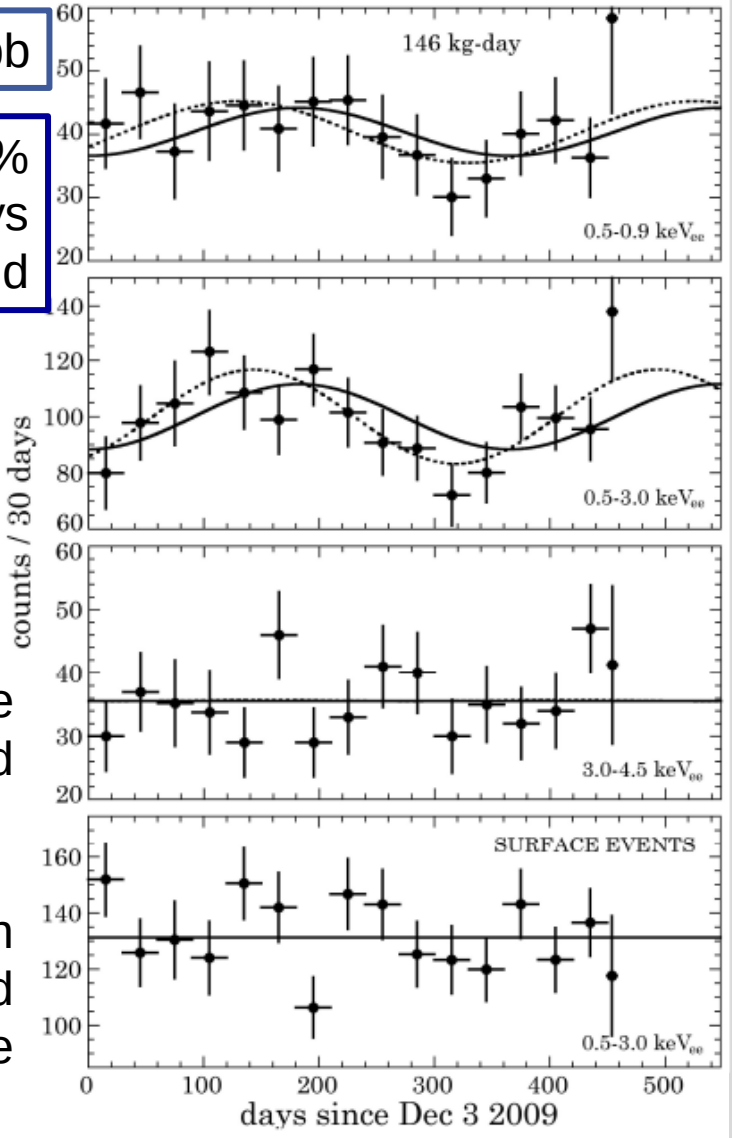
# direct DM search – CoGeNT(2011)
# → light WIMP signal + annual modulation?

440g PPC @Soudan (2100mwe)
Dec 2009 – March 2011
C. Aalseth etal., arXiv:1106.0650v1

$m\chi$=7GeV, $\sigma_{SI}=10^{-4}$pb

$a_m$=16.6±3.8%
$\omega$ = 347±29 days
$t_0$ = Oct.16 ± 12d



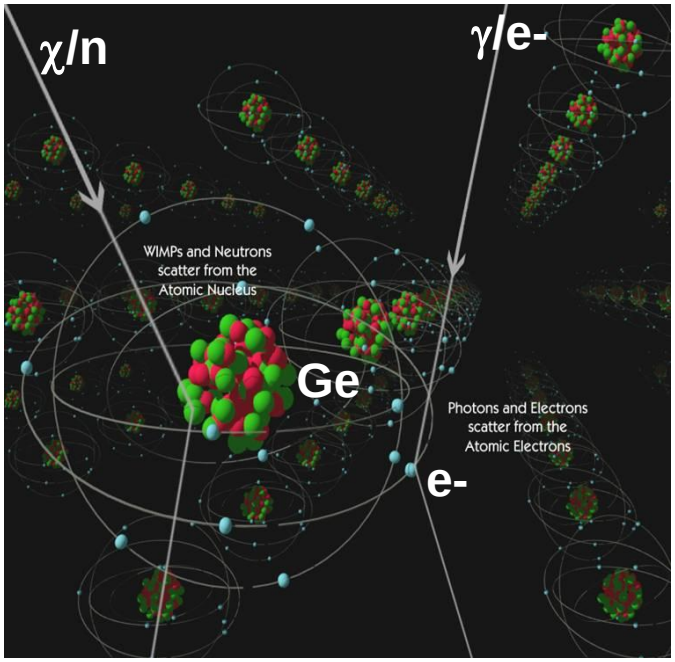

exposure
145 kg.d

background:
cosmogenic $\gamma$ lines
+ flat bg ~2.7cnts/kg/d/keV

no modulation
in background
E>3keV; surface

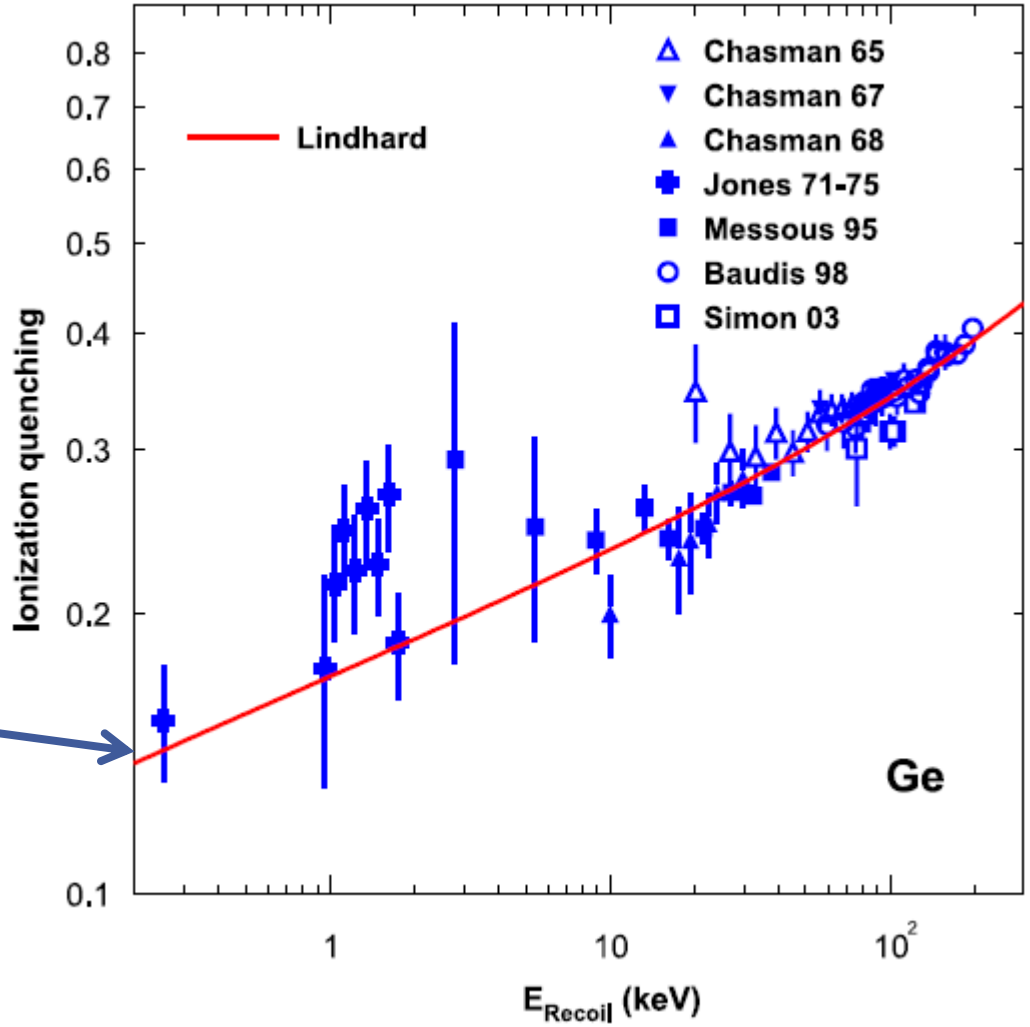
# quenched ionisation signal for recoiling Ge nuclei

A. Benoit et al.
NIMA 577 (2007) 558




ionisation signal relative to equivalent electronic signal

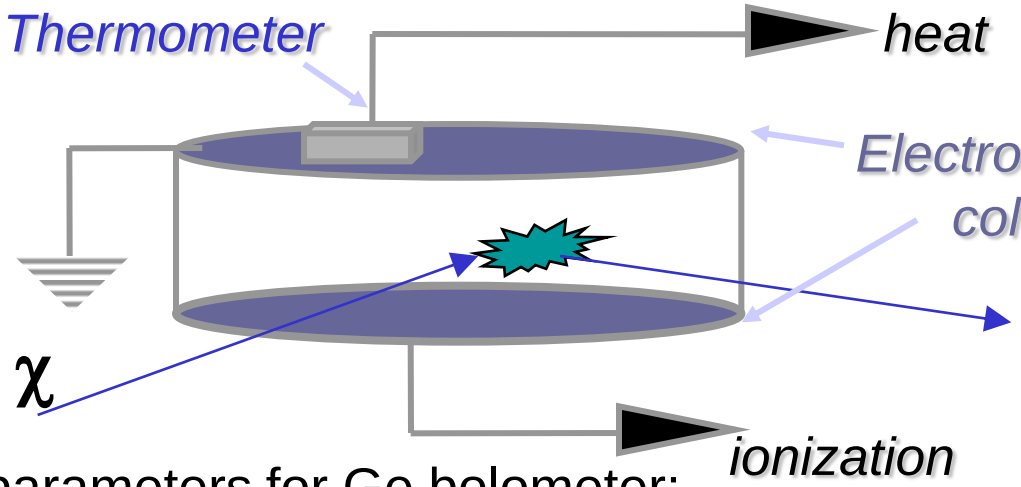
$q=E_{nr}/E_{ee}$



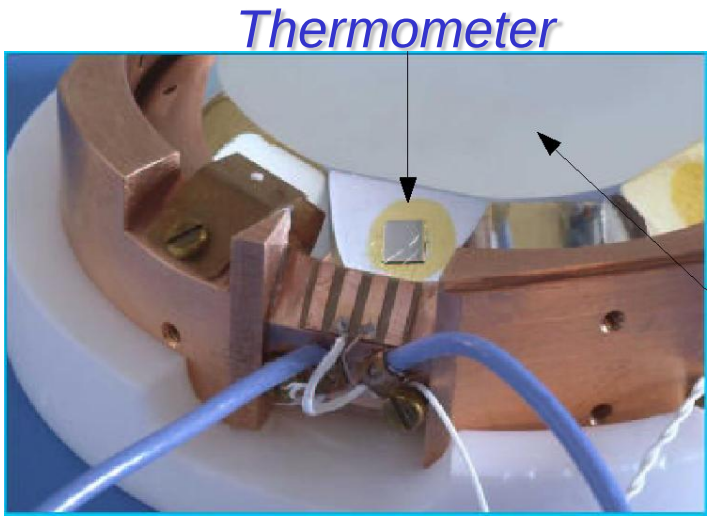
# EDELWEISS – using cryo-crystals

measuring principle:
$\chi$ scattering with energy deposit $E_R$ leads to $\Delta T$ which can be read out via thermometer → detector with small $V \cdot C_V$ needed

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




parameters for Ge bolometer:
E = 3V/cm
$T_{op}$ = 20mK
m = 300g (d=20mm; r=35mm)
$VC_V$ ~ 1nJ/K @ $T_{op}$
G ~ 5nW/K thermal link to heat bath



# Ionisation&heat: pulses & signals

Karlsruhe Institute of Technology

<u>Ge-NTD detector in EDELWEISS:</u>

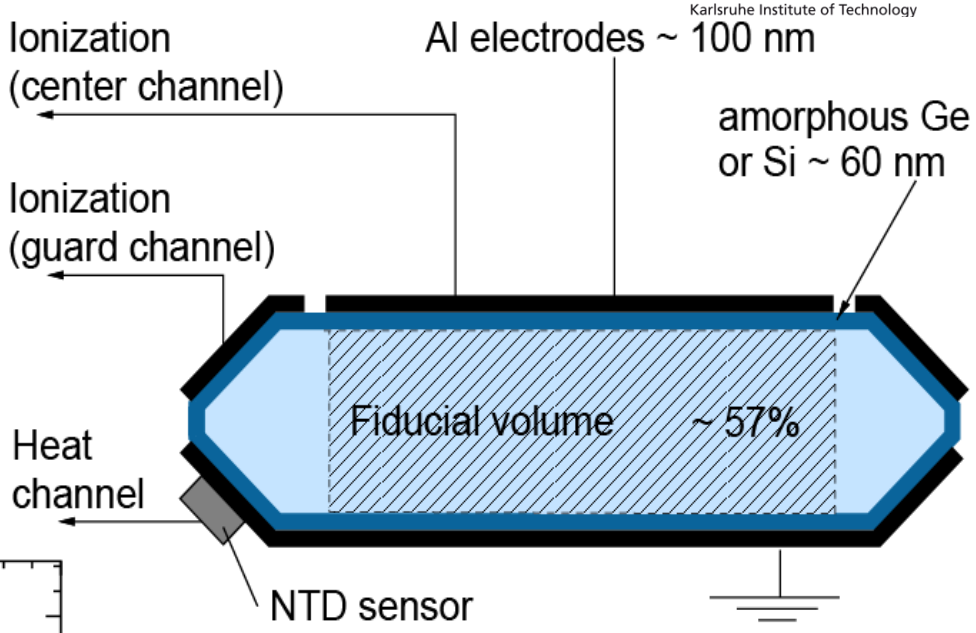
E ~ 10 $keV_{ee}$

heat: $\Delta T=1.3\mu K$; $\Delta U=1\mu V$

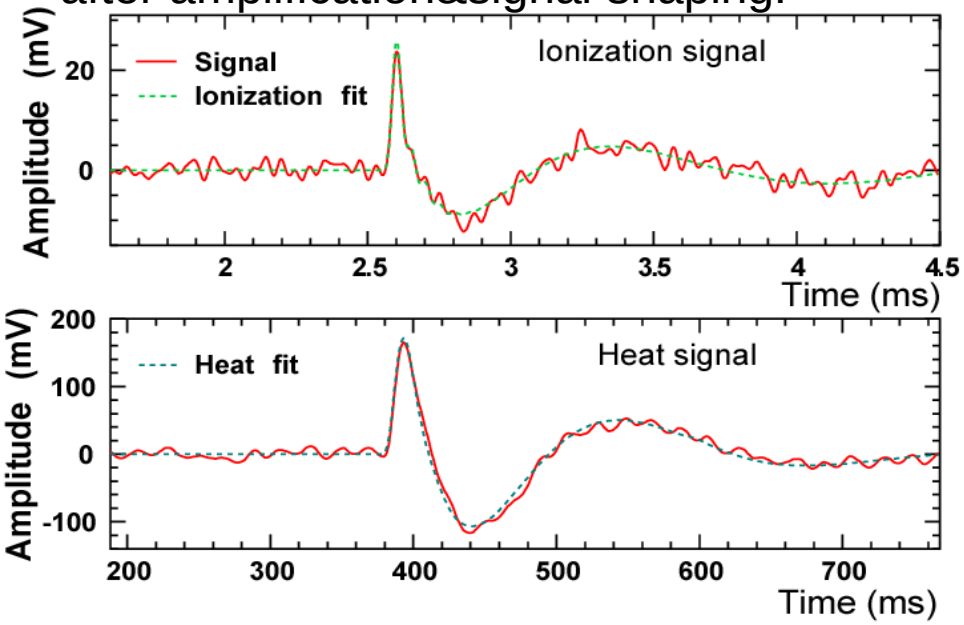
$t_{rise}$~10µs-10ms; $t_{fall}$~100ms

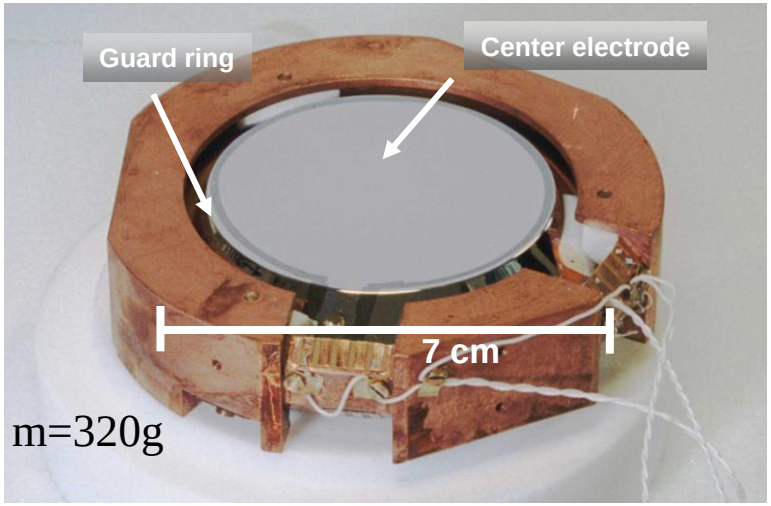
ionisation: $\Delta U=0.5mV$

$t_{rise}$~100ns-1µs; $t_{fall}$~100µs




after amplification&signal shaping:



# EDELWEISS – discrimination power

PRD 71, 122002 (2005)

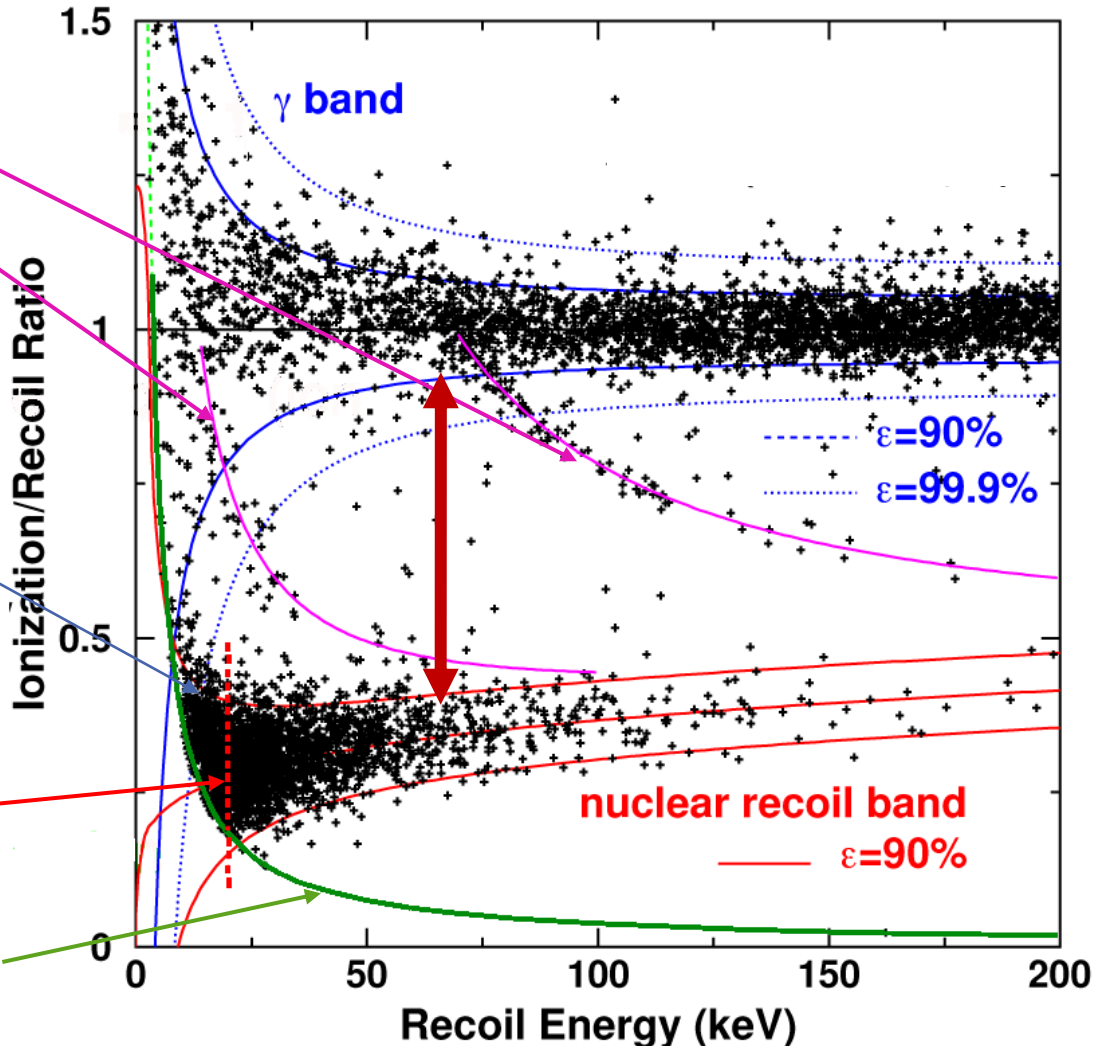
calibration of a 320g Ge bolometer with $^{252}$Cf

**$^{73}$Ge(n,n'γ) 68.8 keV**
**13.3 keV**

**n/γ discrimination**
**> 99.9%**
**for $E_r$ >15 keV**

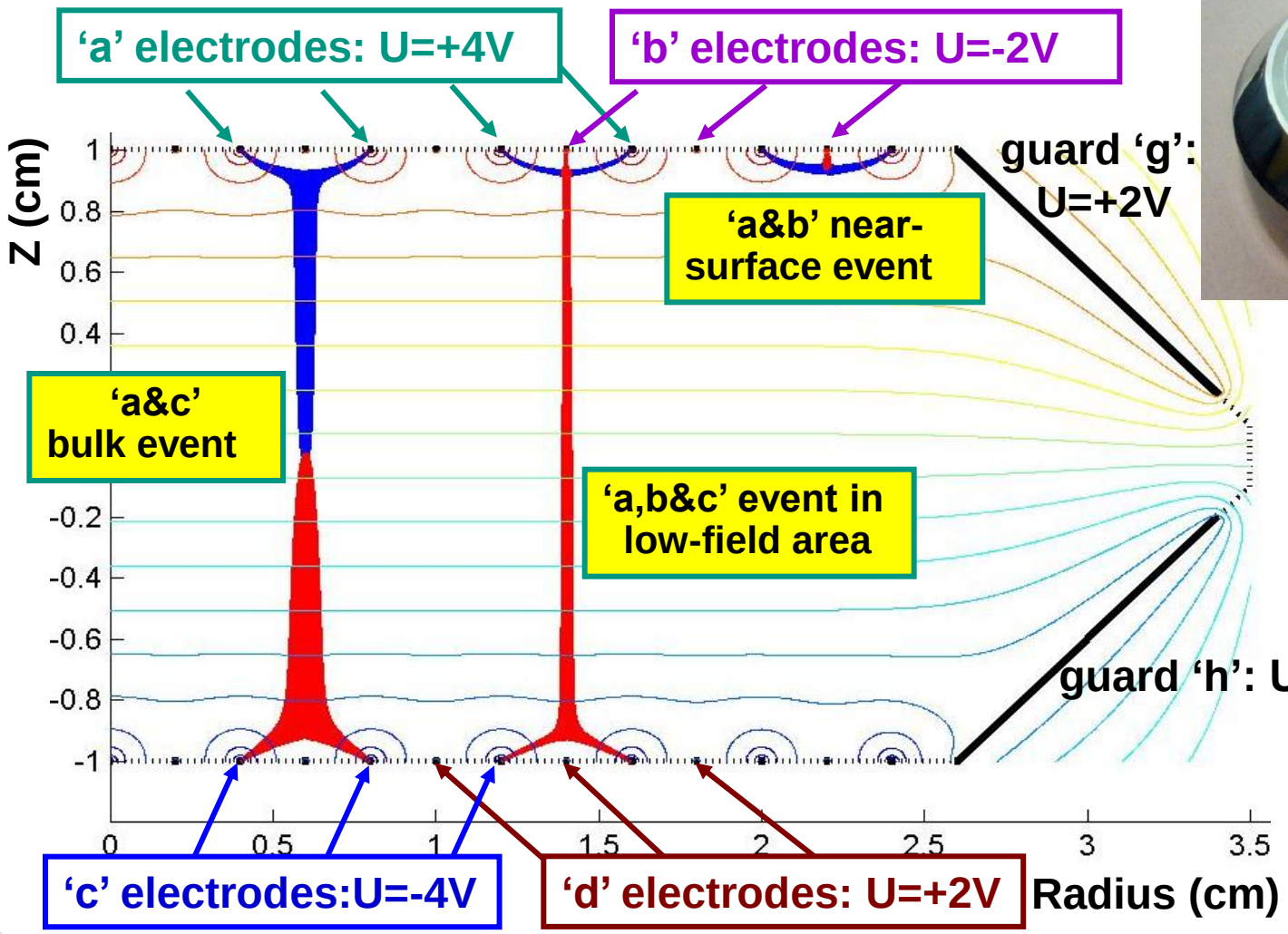
**Recoil threshold**
**20 keV**

**Ionization threshold**
**3.7 keV**



# EDELWEISS-2 – detector technology

interleaved electrodes (width: 200µm; gap 2mm)

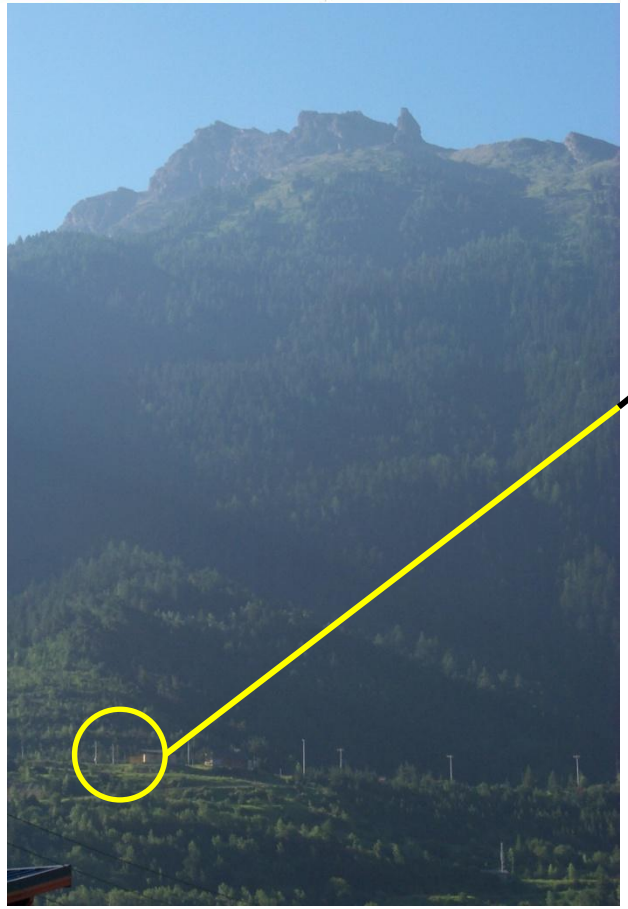


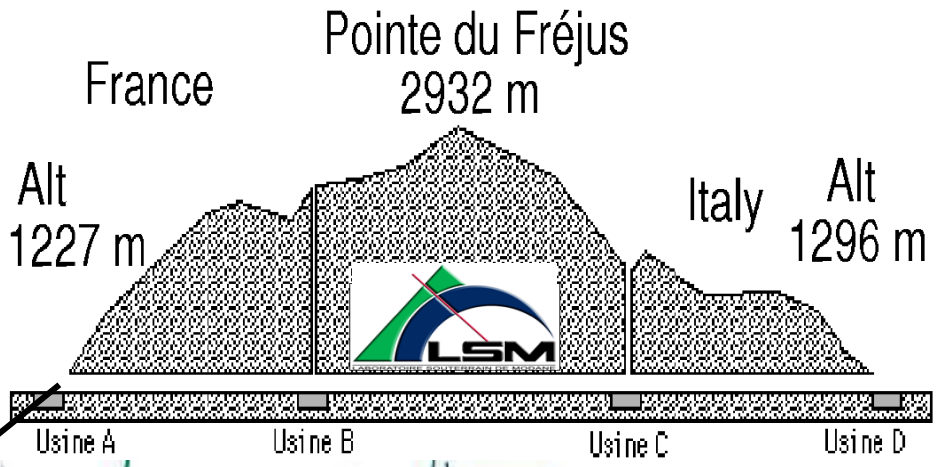

electron trajectories

hole trajectories

PLB681(2009)305

# Edelweiss @ Laboratoire Souterrain de Modane



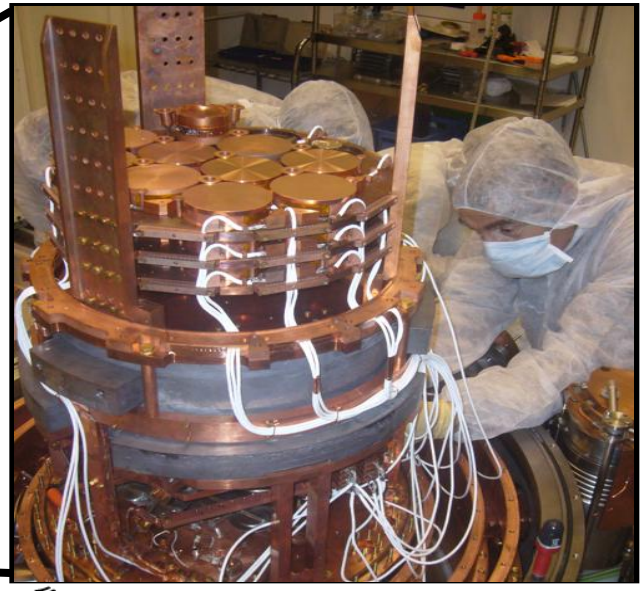



# Edelweiss experimental setup

Polyethelene shield

Pb shield

cryostat

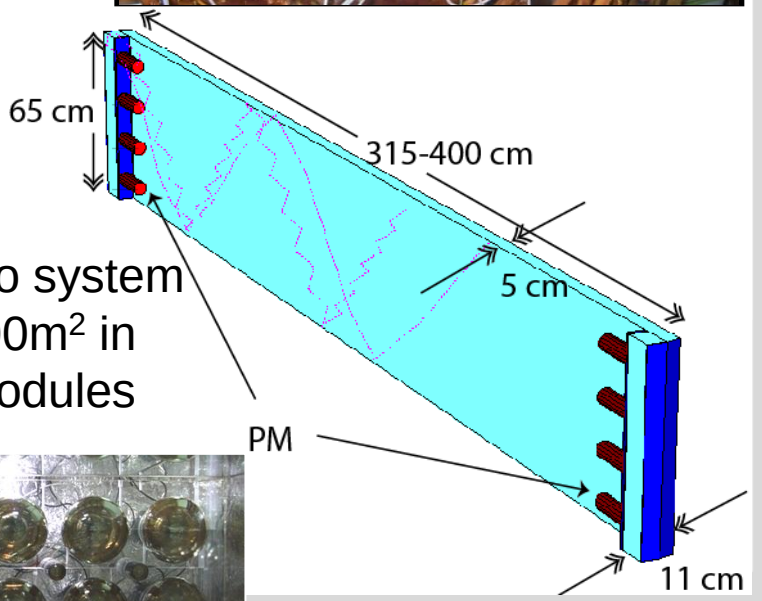




Muon Vet

1t Gd-loaded
Liquid scintillator
for μ-n coincidences

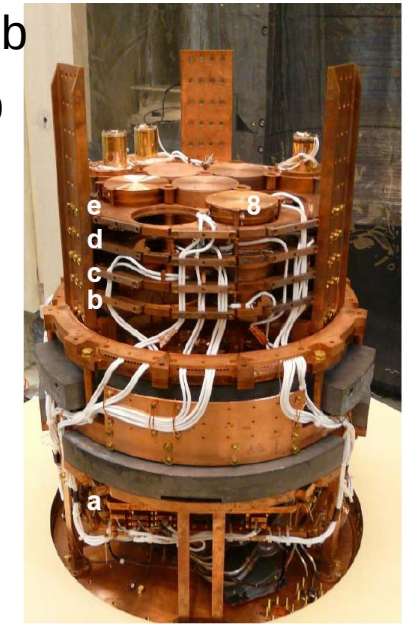
μ veto system
A=100m$^2$ in
42 modules

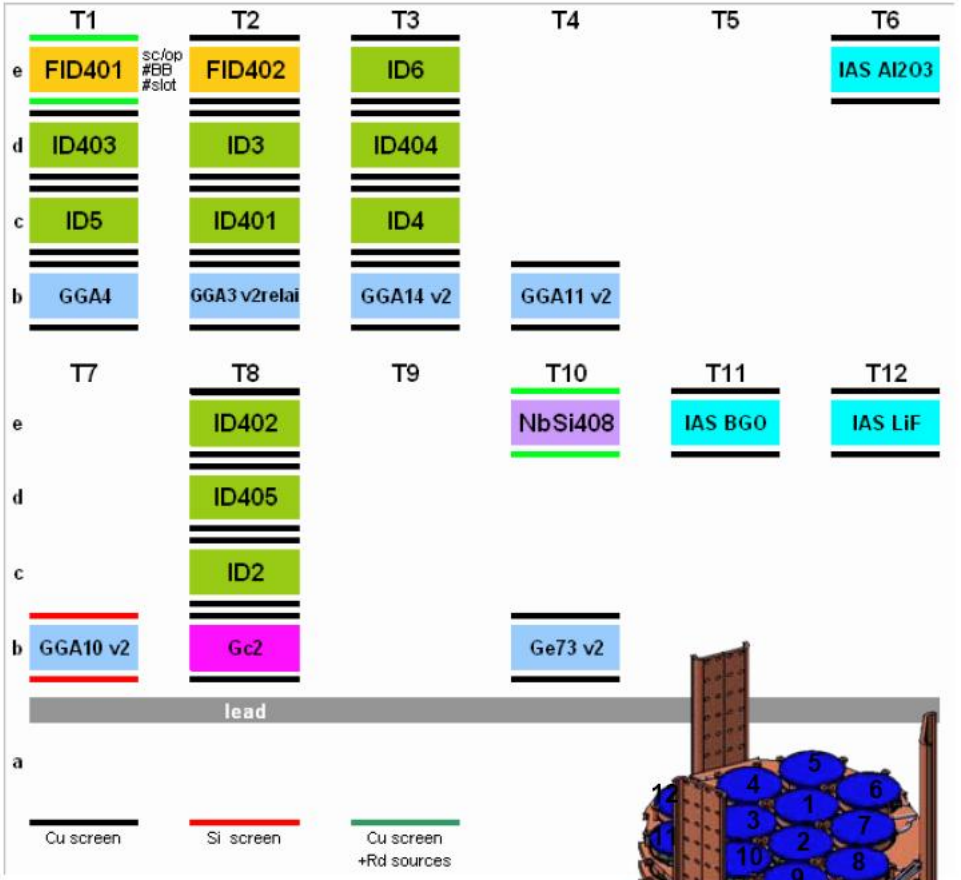


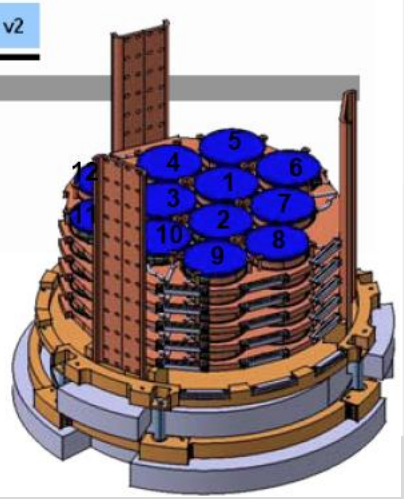
# WIMP search with ID detectors : «run 12»

**Data collected from April 1st 2009 to May 20th 2010**

- 418 d total
- 355 d data (85% of 418)
- 325 d WIMP search (78% of 418)
- All detectors working
- 90% electronics channels ok
- 9/10 bolometers for physics
- 10.1 d gamma calib
- 6.4 d neutron calib

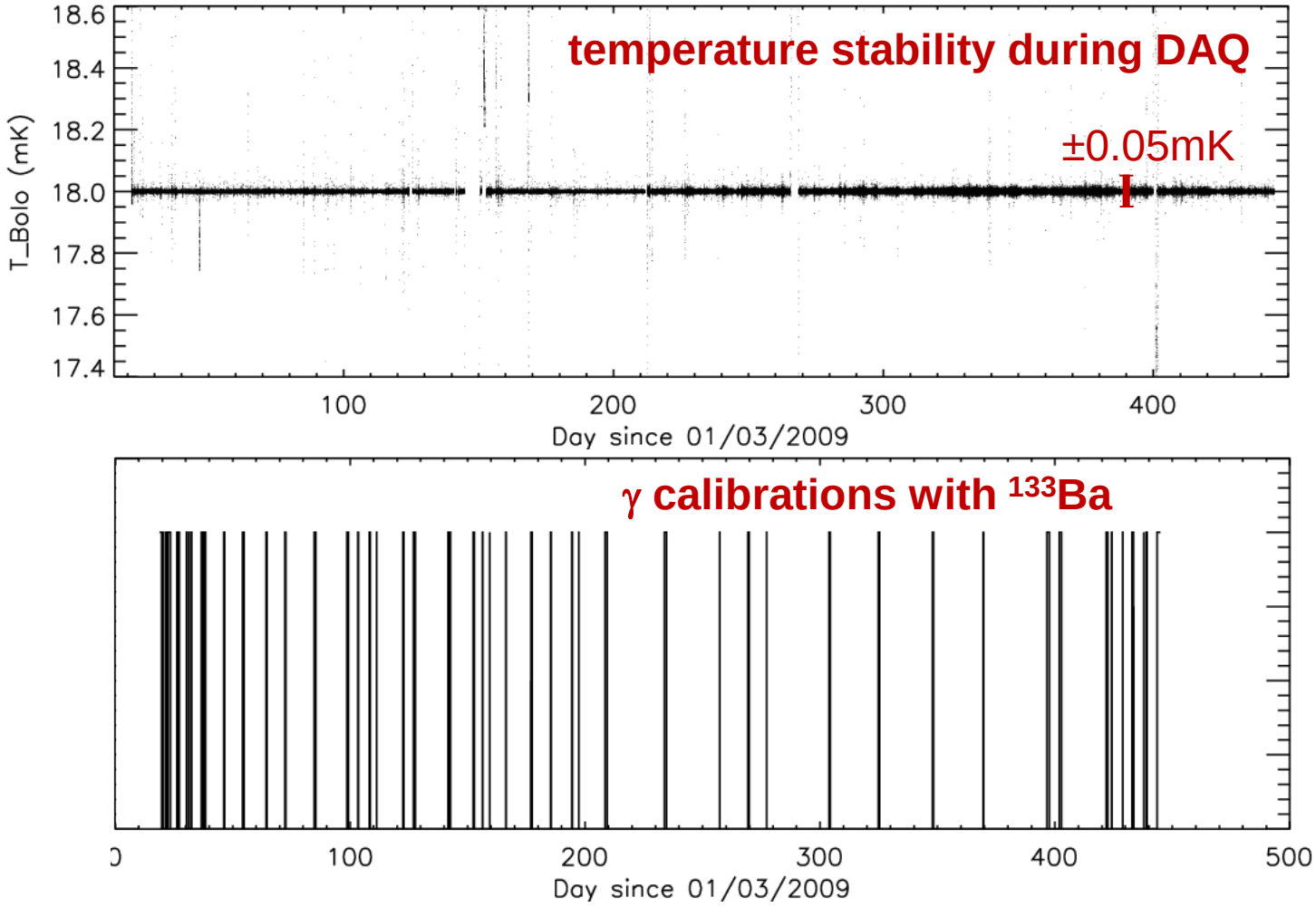


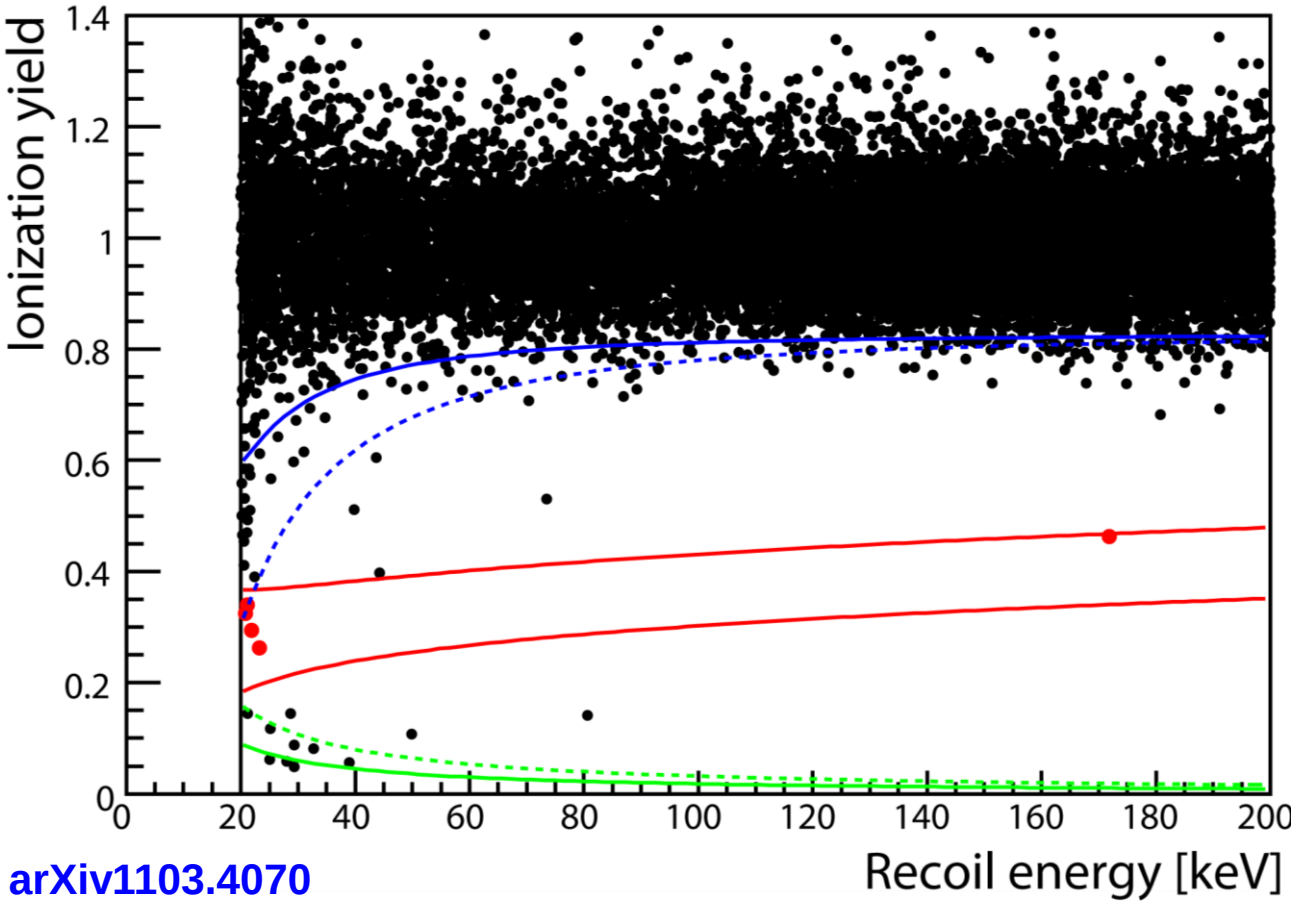



# WIMP search with ID detectors : «run 12»

**Data collected from April 1st 2009 to May 20th 2010**



# EDELWEISS WIMP search : final result (2008+2009+2010)




arXiv1103.4070

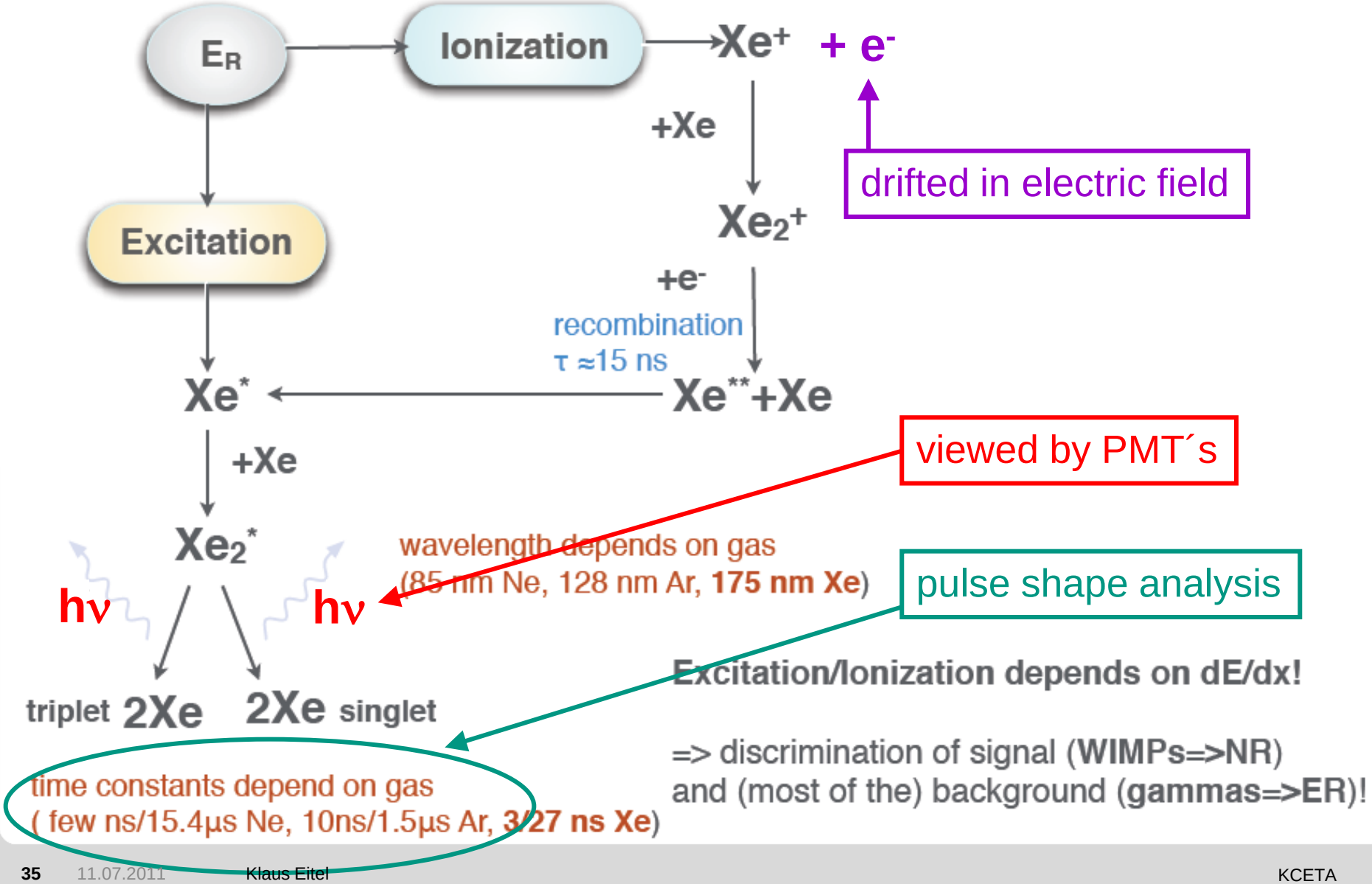
**total exposure of 427kg.d →384kg.d in 90% NR band (WIMP RoI)**

**<3 evts bg expected**
**5 events observed**
**(4 with E<22.5keV;**
**1 with E=172keV)**

**no indication for a WIMP signal**

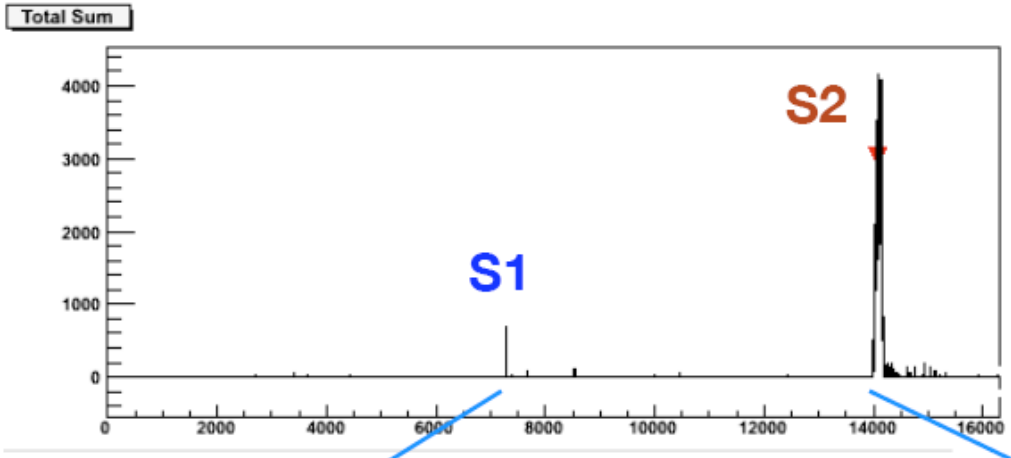
(almost) same technique used by the CDMS experiment (Soudan mine)
→ *combination of Ge ionisation&heat experiments:* ***Phys. Rev. D 84, 011102(R) (2011)***

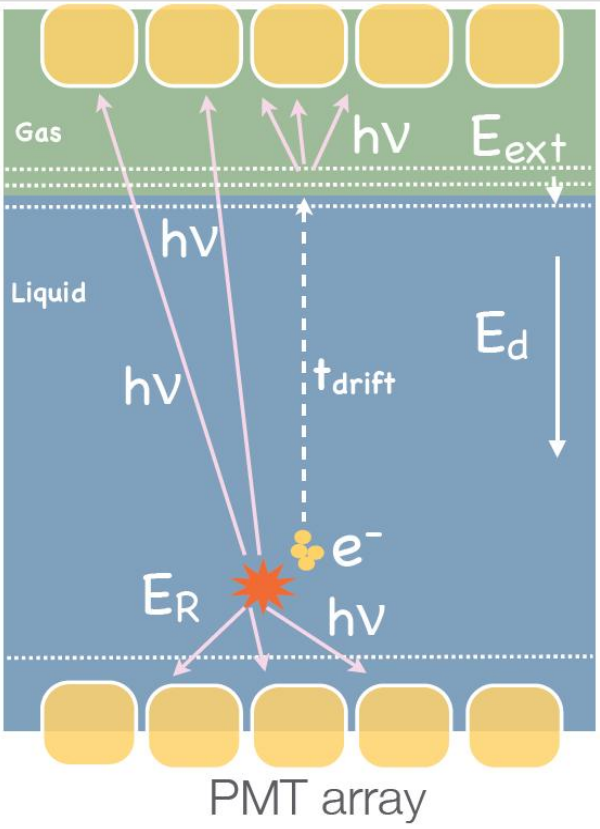
# direct DM search – using liquid Xe

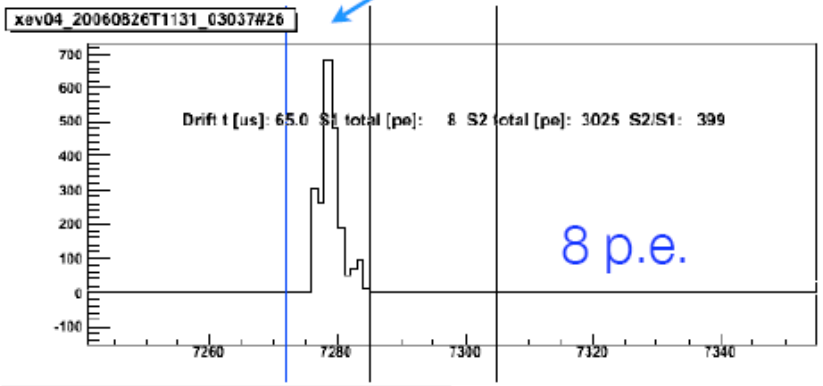


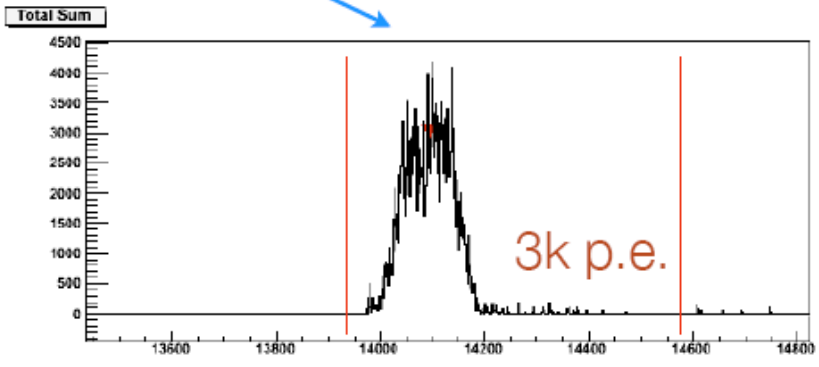
# direct DM search – using liquid Xe

typical low energy event:
4keV$_{ee}$ → S1: 8 p.e. → sc. light yield 2p.e./keV



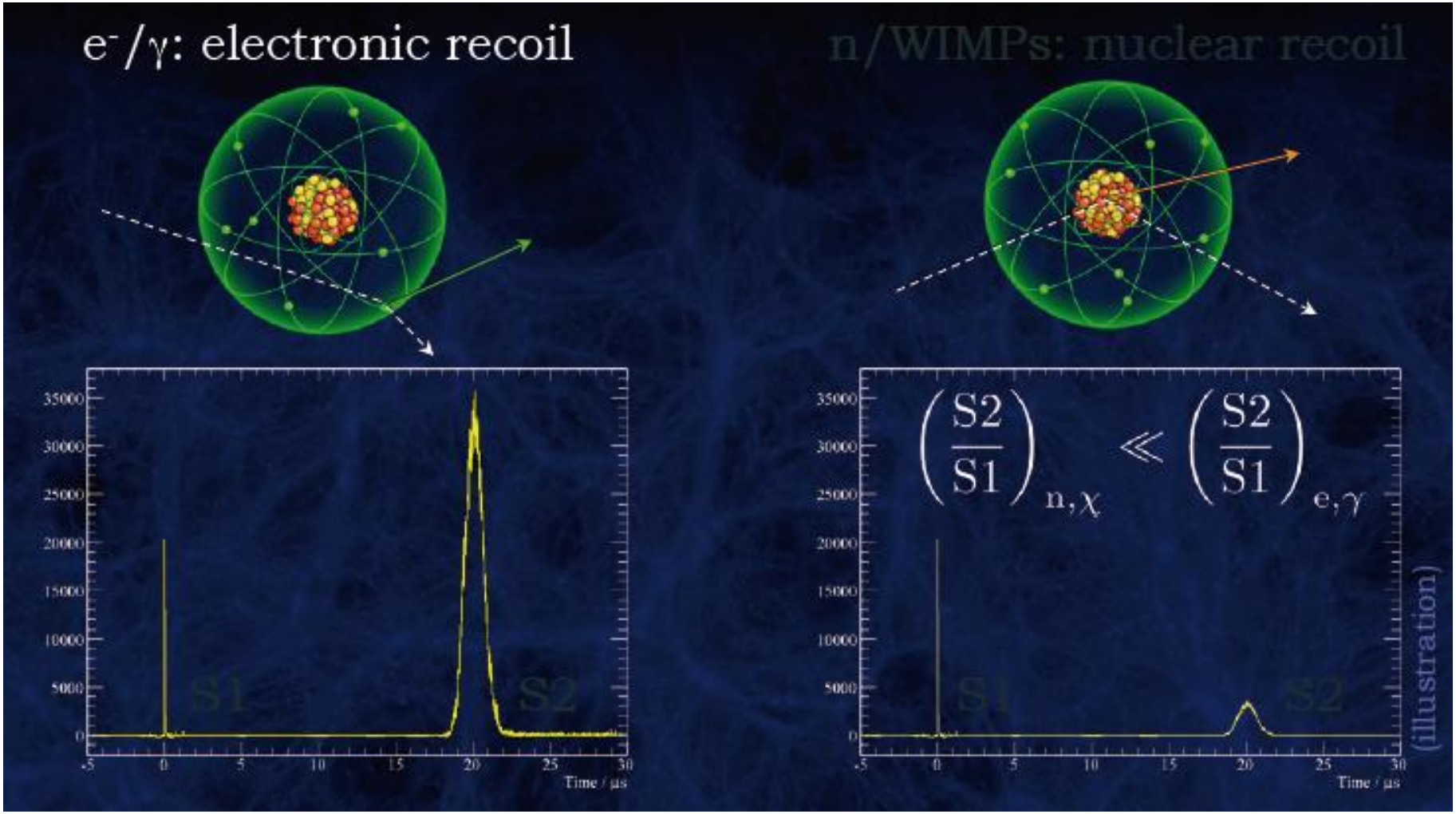



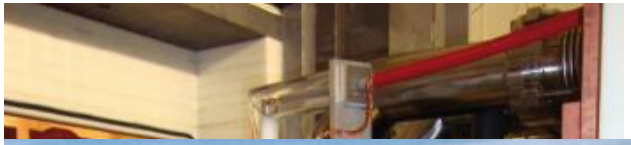

S1 S2

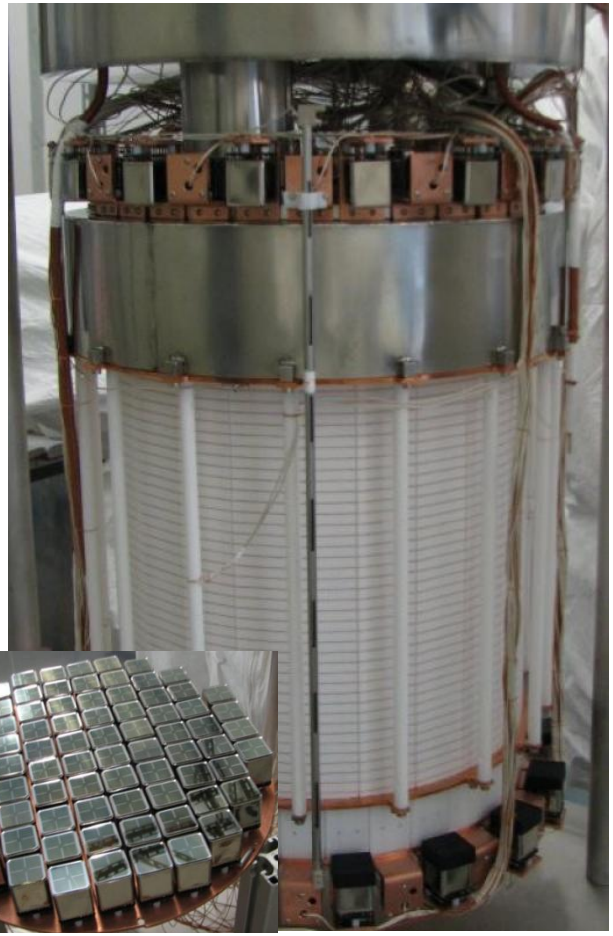
# discrimination power – using liquid Xe



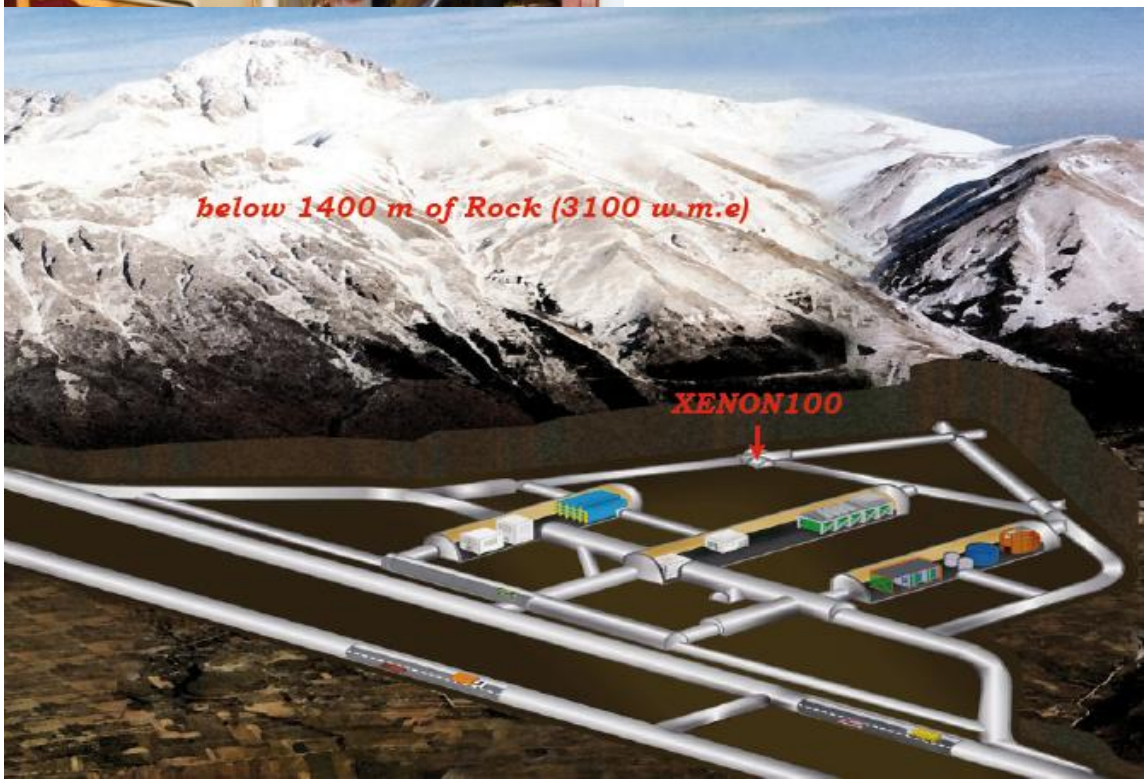
# direct DM search – Xenon100 @ LNGS

installed in 2008
commissioning&calibration 2009
data taking since 2010










- 161 kg LXe TPC (mass: 10 × Xe10 )
- 62 kg in target vol.
- 242 PMTs
- active LXe veto (≥4 cm)
- improved Xe10 shield (Pb, Poly, Cu, $H_2O$, $N_2$ purge)

# XENON100 results

arXiv:1104.2549v1

100.9 live days

3 remaining events

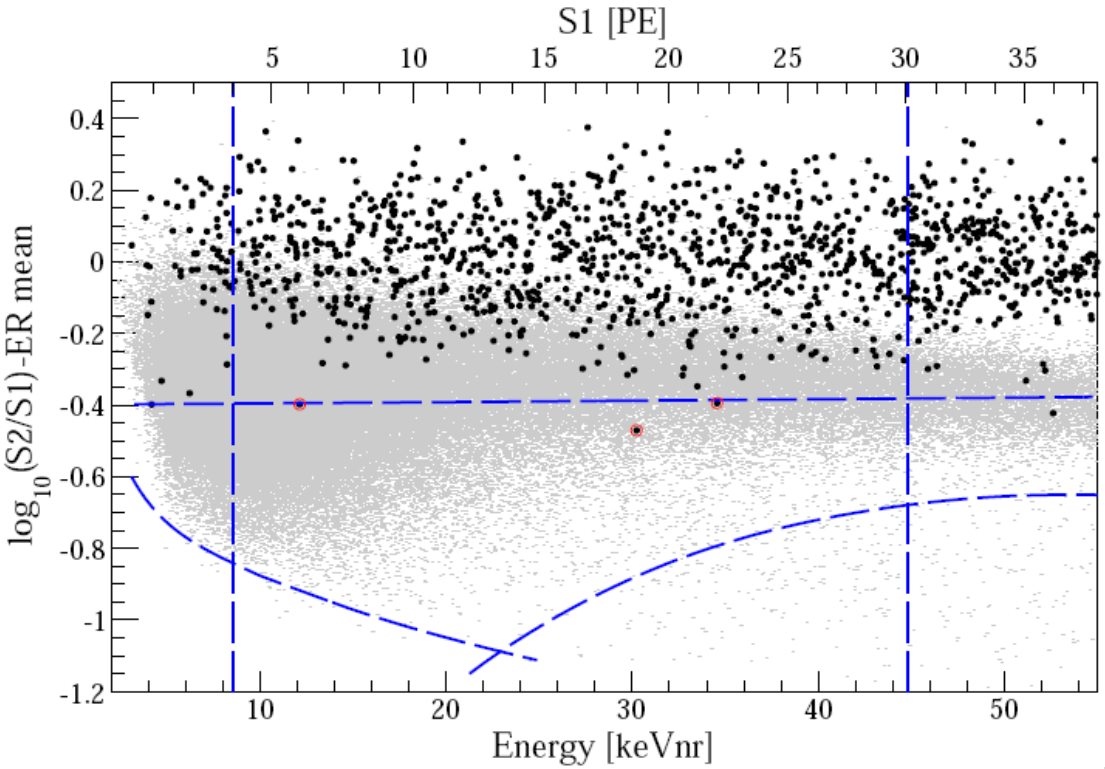
1.8 ± 0.6 bg expected

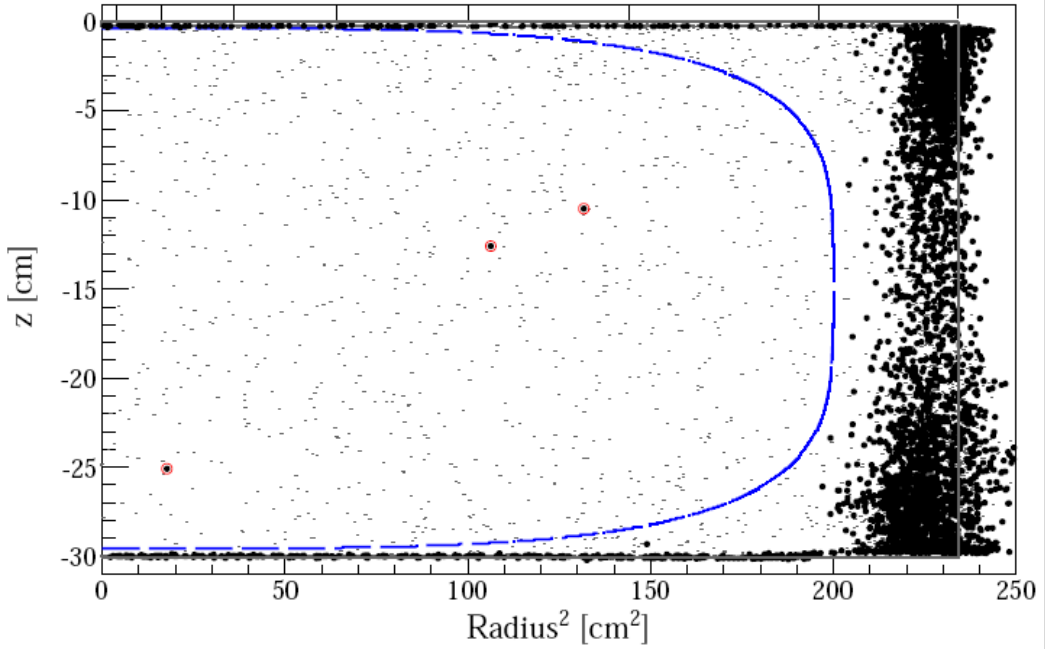
1471 kg.d exposure

**no indication for a WIMP signal**

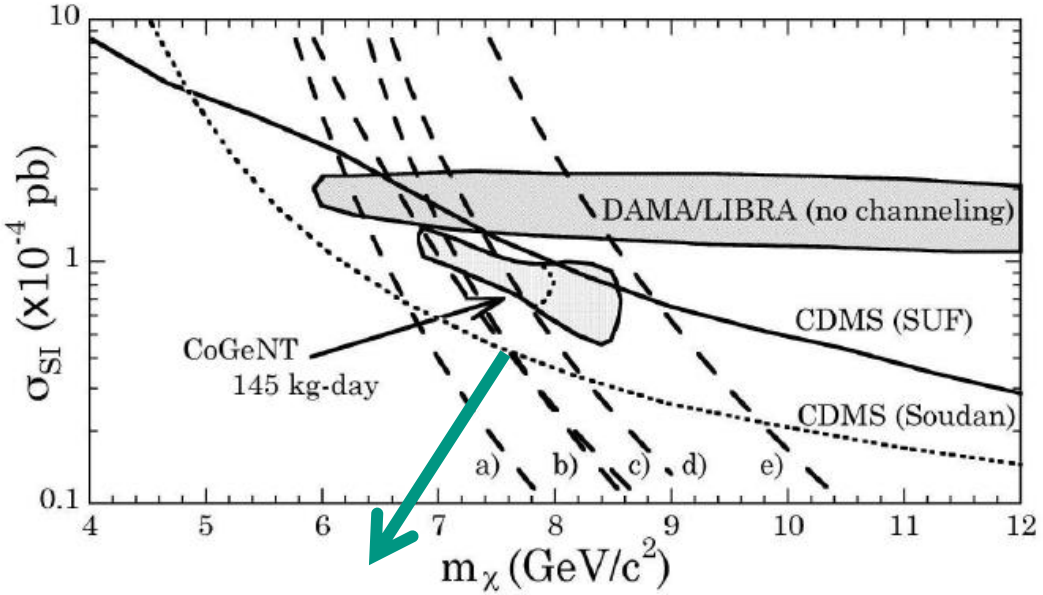
WIMP search region:

8.4 – 44.6 keVnr (4 - 30 PE)
lower bound from the S2;
median of the software threshold
S2 > 300PE (4 - 13 PE).

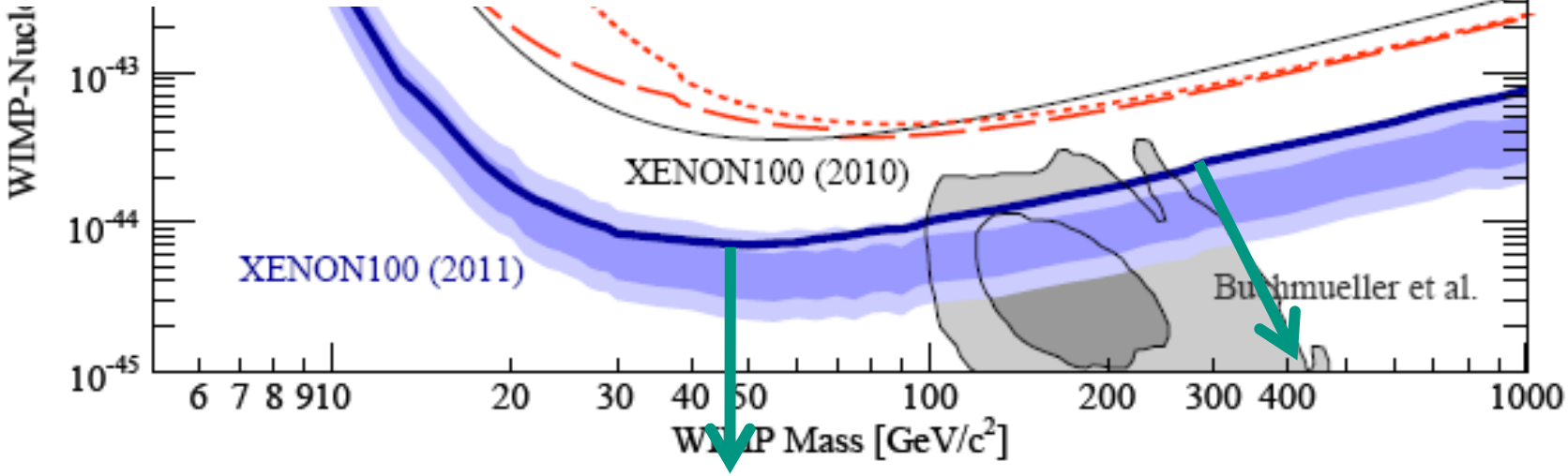


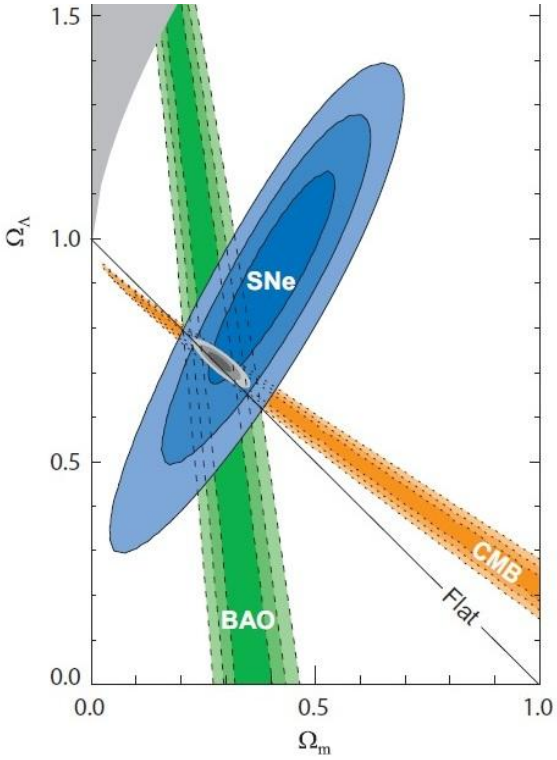
# results in the DM parameter space



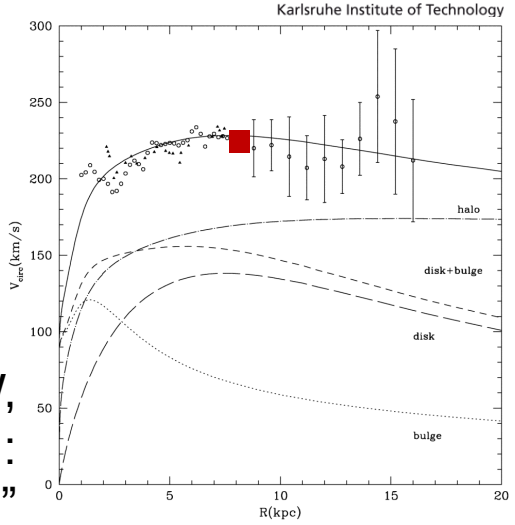

**strategy**



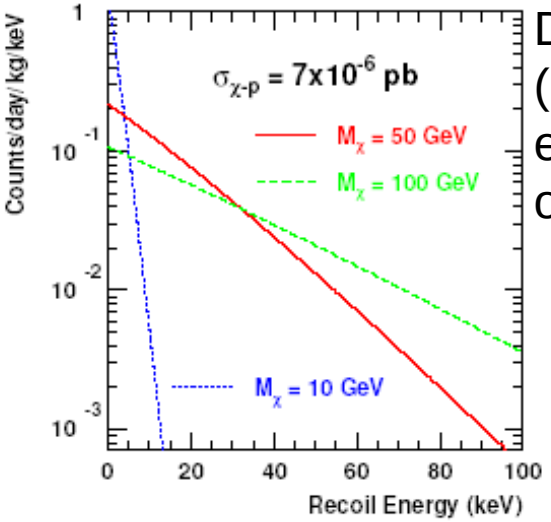
# Conclusions



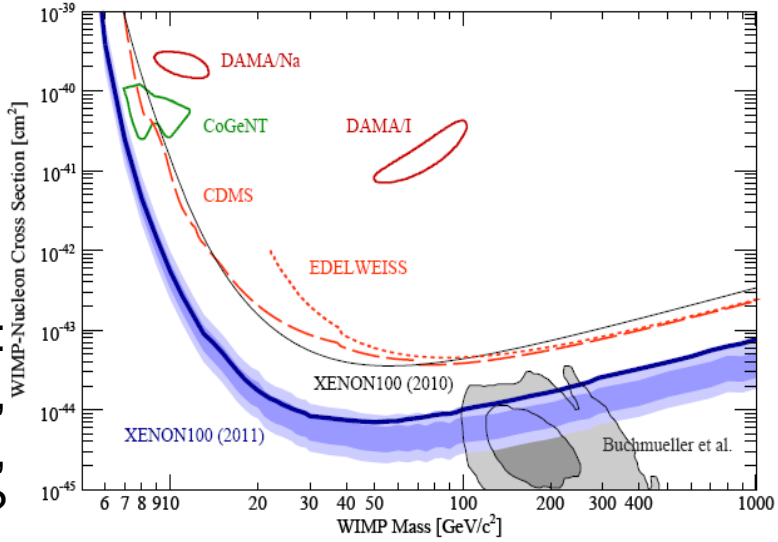

consistent cosmological model with nonbaryonic DM on all scales → ΛCDM




rotation curve of MW, N-body simulations of DM: DM in our "neighborhood"




DM as WIMP (SUSY): elastic scattering off nuclei




experimental results: evidences vs. exclusion, new results, new DM models?