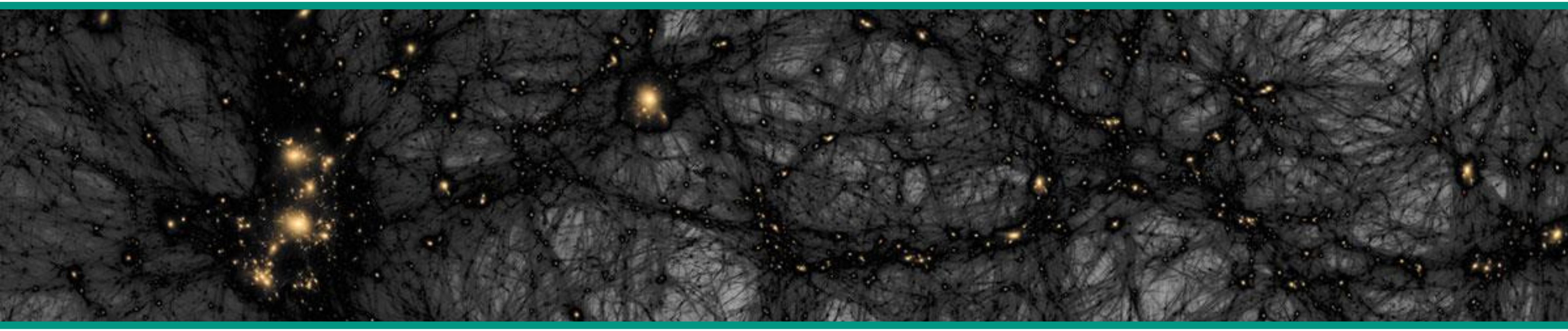
Astroparticle physics I – Dark Matter

WS22/23 Lecture 16 Jan. 19, 2023



Recap of Lecture 15

Indirect and direct searches for CDM neutralinos

- positrons: **clear excess** $(\boldsymbol{E = 10 \dots 1000\ GeV})$ compared to ´classical´ models
  origin: a) CDM annihilation in local DM-halo   b) emission of nearby pulsars

- WIMP-burning stars close to galactic center?

- direct searches for CDM: **elastic nuclear recoils** with typical recoil energy
  $\boldsymbol{E_R \approx few\ keV}$ (WIMP wind from Cygnus, small yearly modifcation of v)

- WIMP interaction $\boldsymbol{\sigma_{SI}}$: $\boldsymbol{S}$pin $\boldsymbol{I}$ndependent via Higgs $\boldsymbol{h, H}$ $\boldsymbol{\sigma_{SD}}$: via $\boldsymbol{Z^0}$

- cross section: $\boldsymbol{d\sigma/dq^2 \sim A^2 \cdot F(q^2)}$ ⇨ large nucleus, low momentum transter
  coherent interaction ⇨ large de-Broglie wavelength

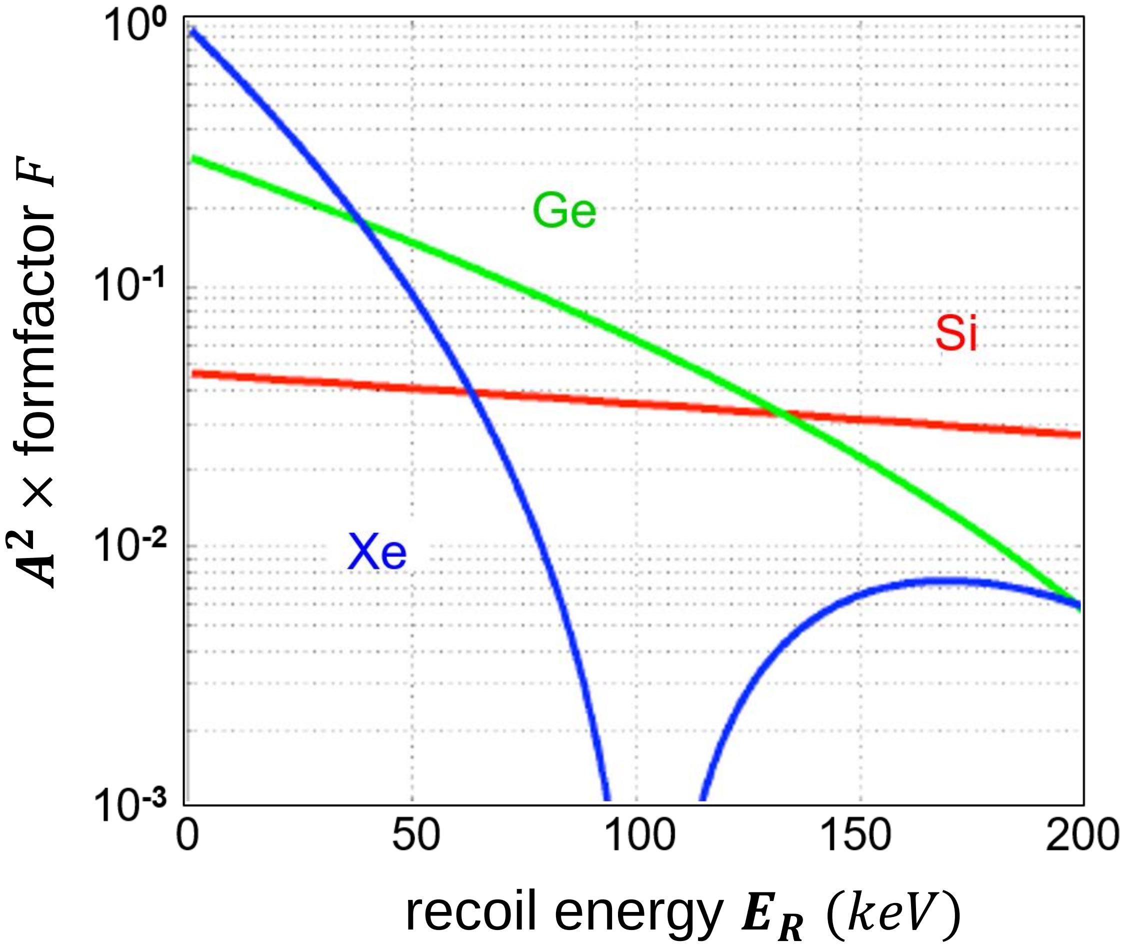
WIMP scattering off nuclei: form factor – $F(q^2)$

Implications of the loss of coherence at high recoil energies

- we aim for heavy nuclei with **large A** & large nuclear radius R_i (⇨ **xenon**)
- **challenge**: the loss of coherence already starts for smaller values of the momentum transfer q^2 or nuclear recoil energy E_R

$$\sim A^2 \cdot F(q^2)$$

extremely low energy threshold required



WIMP scattering off nuclei: types of interaction

- **Neutralinos can interact via two types of exchange particles: $\boldsymbol{H\ h} \Leftrightarrow \boldsymbol{Z^0}$**

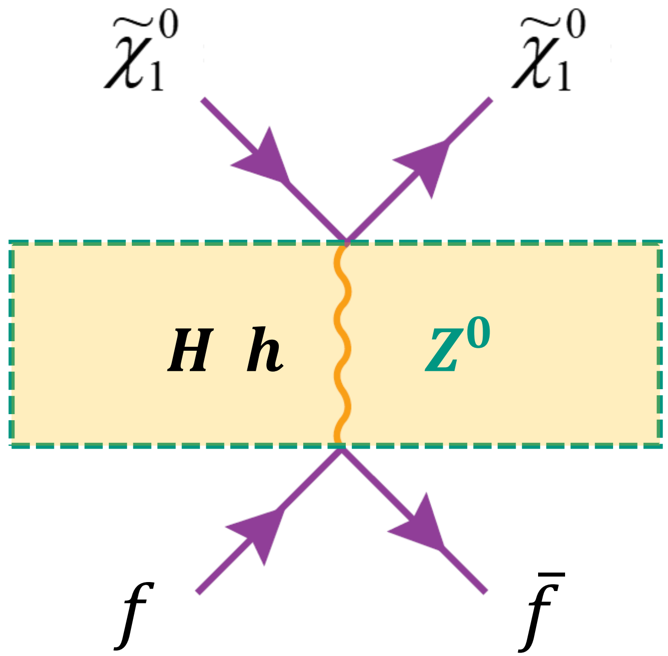
  - **spin-dependent** interaction via $\boldsymbol{Z^0}$ **– boson**

σ_{SD}: Spin Dependent

  - exchange of an intermediate **vector boson Z^0 with spin $S = 1$**

  - many SUSY models ´favour´ Z^0 : we expect rather ´large´ couplings

$S = 1$



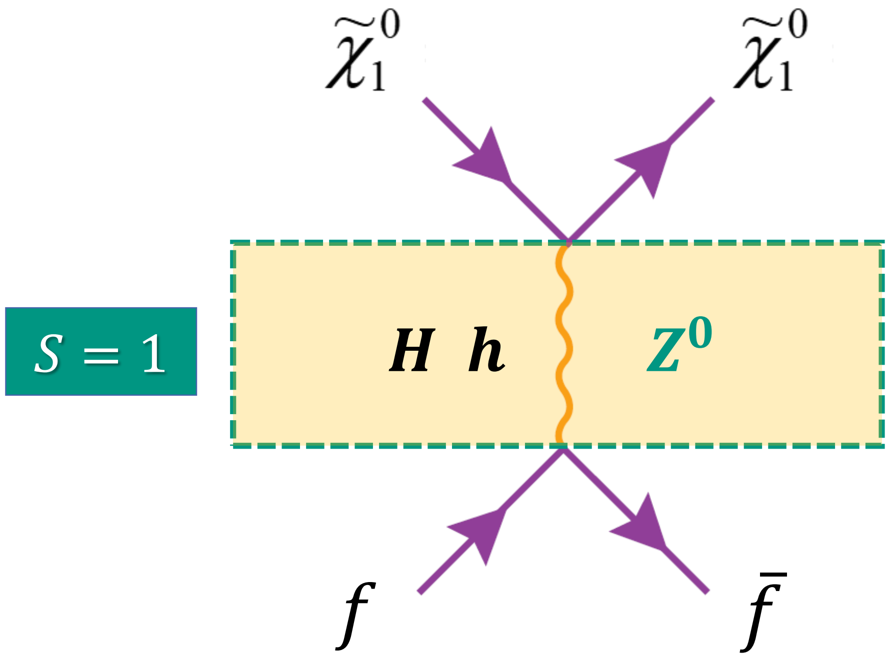
WIMP scattering off nuclei: spin-dependent

- **Neutralinos can couple to the overall spin J of a nucleus via Z^0 exchange**

  - **Scattering amplitude** depends on the **spin orientation**

  - for σ_{SD} there is no increase in the interaction rate due to coherence, as Z^0 couples to the total nuclear spin J

  - despite the SUSY models ´favouring´ Z^0 : we expect rather small contributions of σ_{SD} to total elastic WIMP-scattering cross section



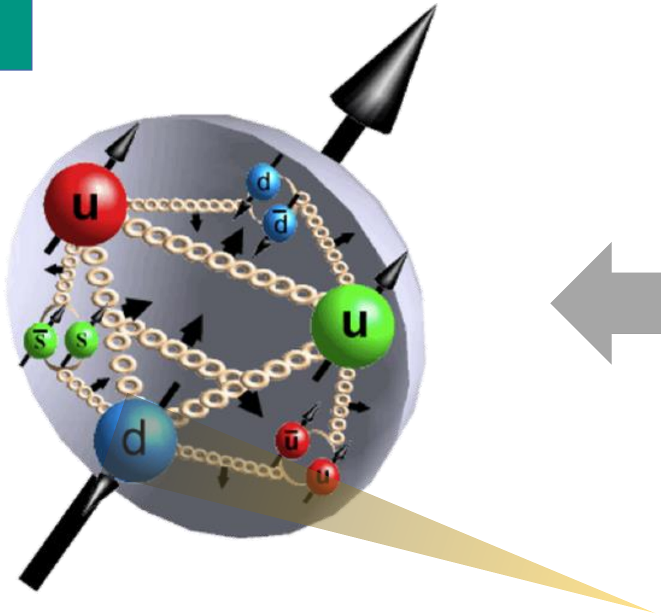
WIMP scattering off nuclei: spin-dependent

- Neutralinos can couple to the **overall spin J** of a nucleus via Z^0 exchange

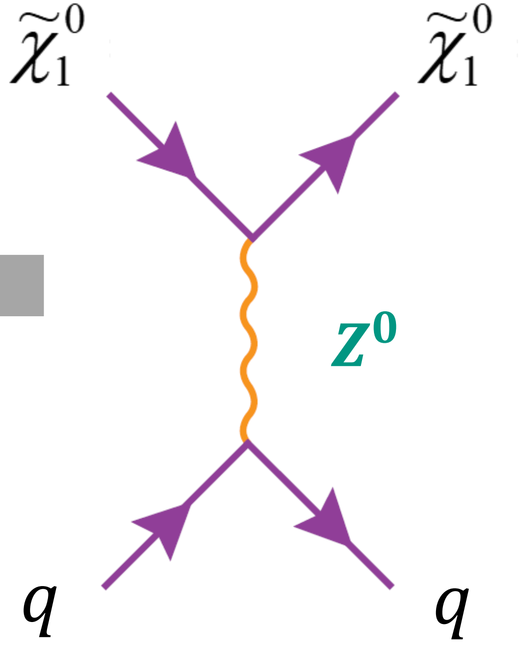
  ⇨ **the target nucleus must possess $J \neq 0$**

axial-vector interaction of χ_1^0

spin J of nucleus
(nucleons)



spin of nucleon
(quarks)

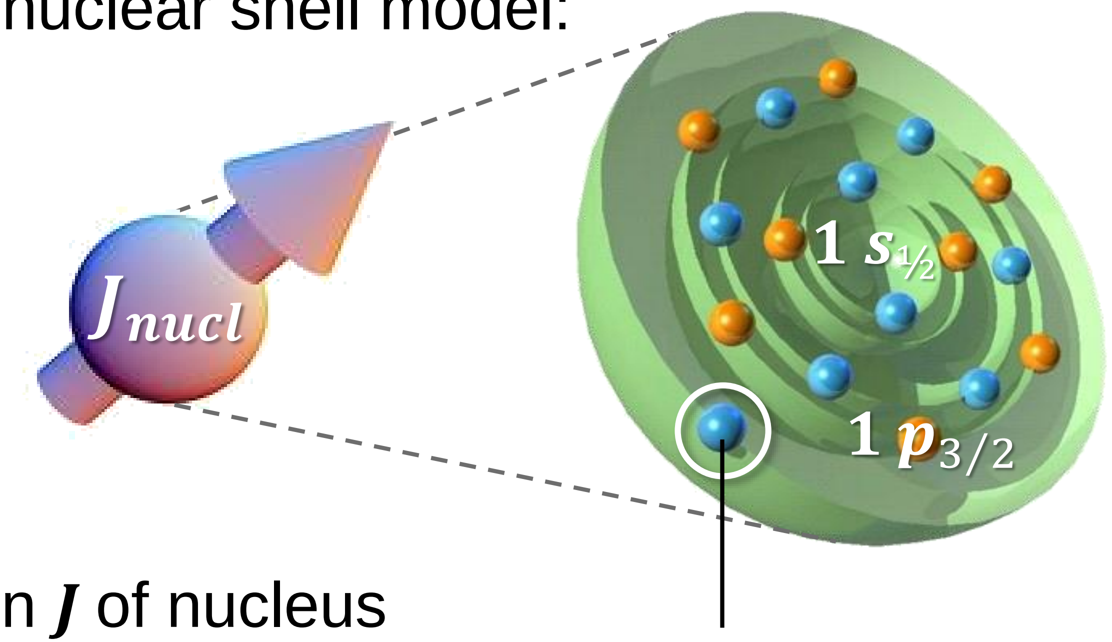


RECAP: Spin J of a nucleus & nucleon spins

- **Nucleons inside a nucleus are paired: nuclear spin from unpaired nucleon**

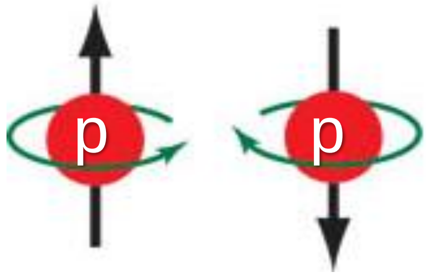
  - **nuclear spin J** arises from total angular momentum L of unpaired nucleon

nuclear shell model:



spin J of nucleus
(nucleons)

unpaired nucleon



coupling to
$J = 0$

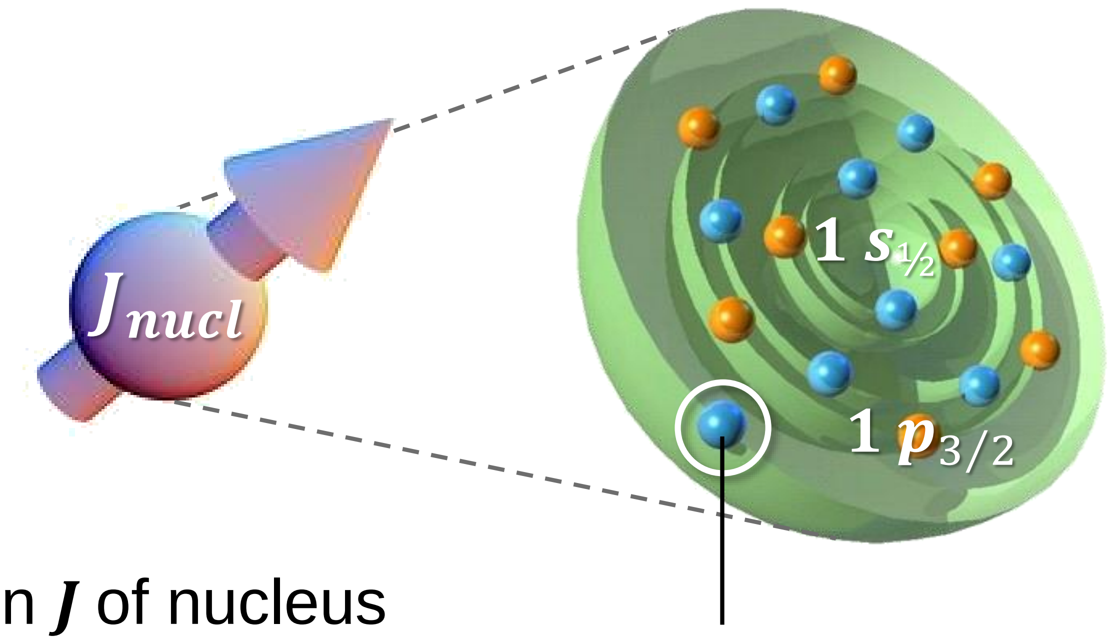
two p, n couple ($\Delta E \sim 2\ MeV$)
⇨ $gg / ug / uu$ – nuclei

important for σ_{SD}:
target nucleus must have an unpaired p or n

Suitable detector materials for σ_{SD}

- **Nuclei with unpaired nucleon that can also be used as WIMP detector**

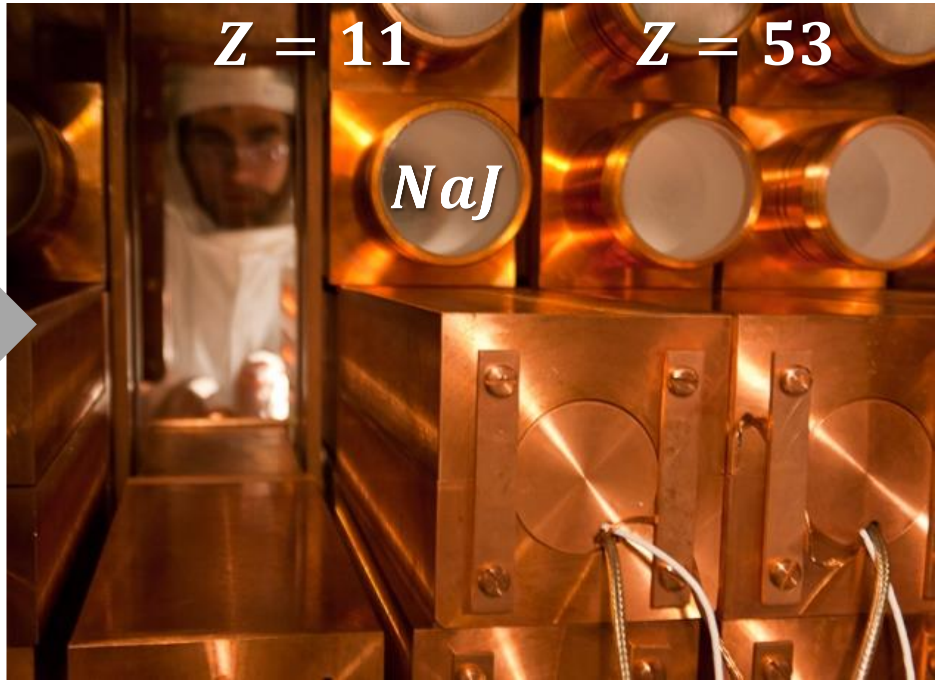
  - **nuclear spin J** due to unpaired nucleon



spin J of nucleus
(nucleons)

unpaired nucleon

^{23}Na (100%) ^{127}J (100%)

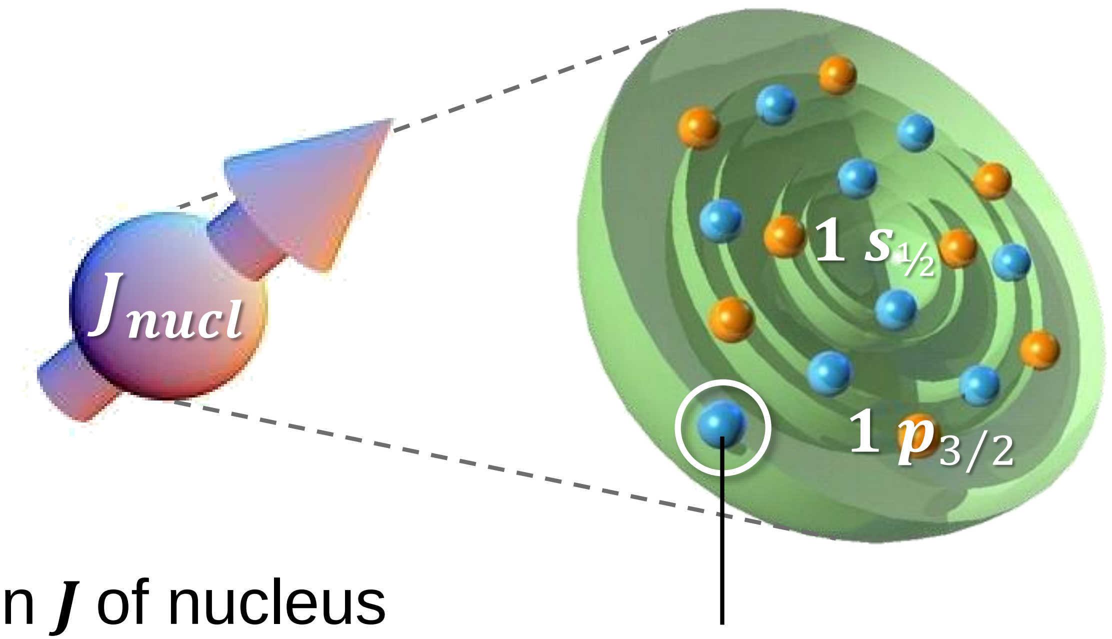


anorganic scintillators (DAMA-Libra)

Suitable detector materials for σ_{SD}

- **Nuclei with unpaired nucleon that can be used as WIMP detector**

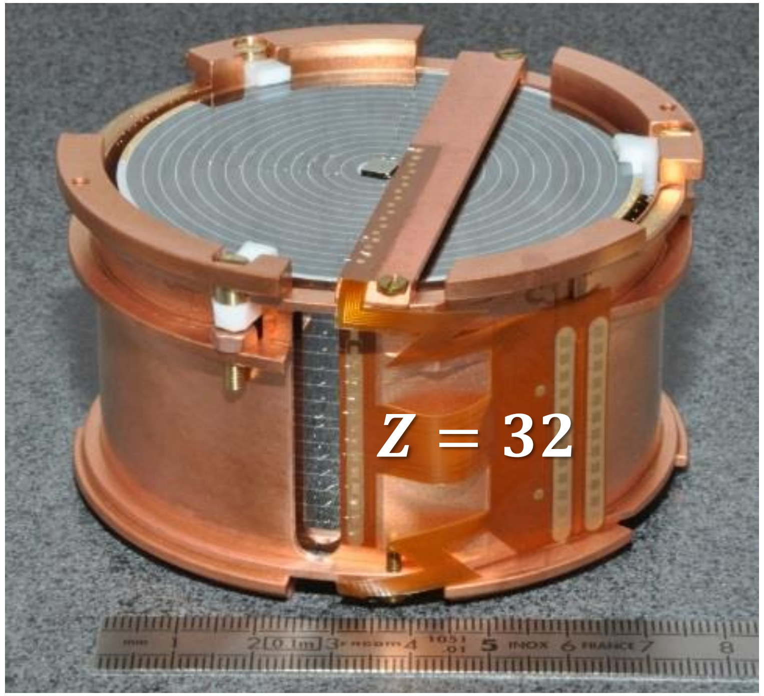
  \- **nuclear spin J** due to unpaired nucleon



spin J of nucleus (nucleons)

unpaired nucleon

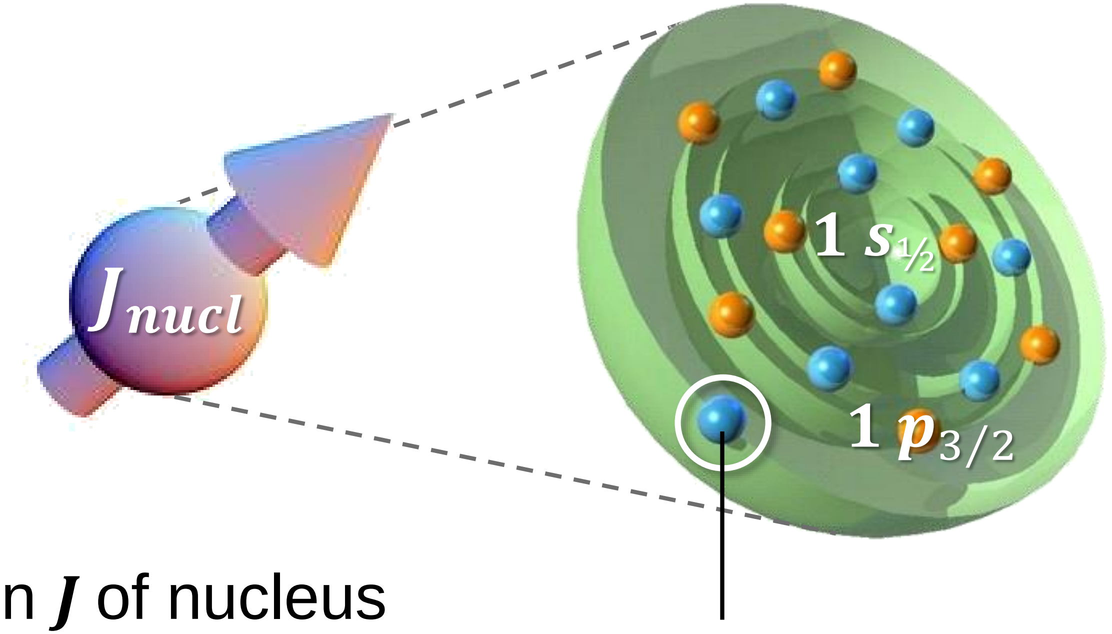
^{73}Ge (7.76%)



solid-state detector (Edelweiss)

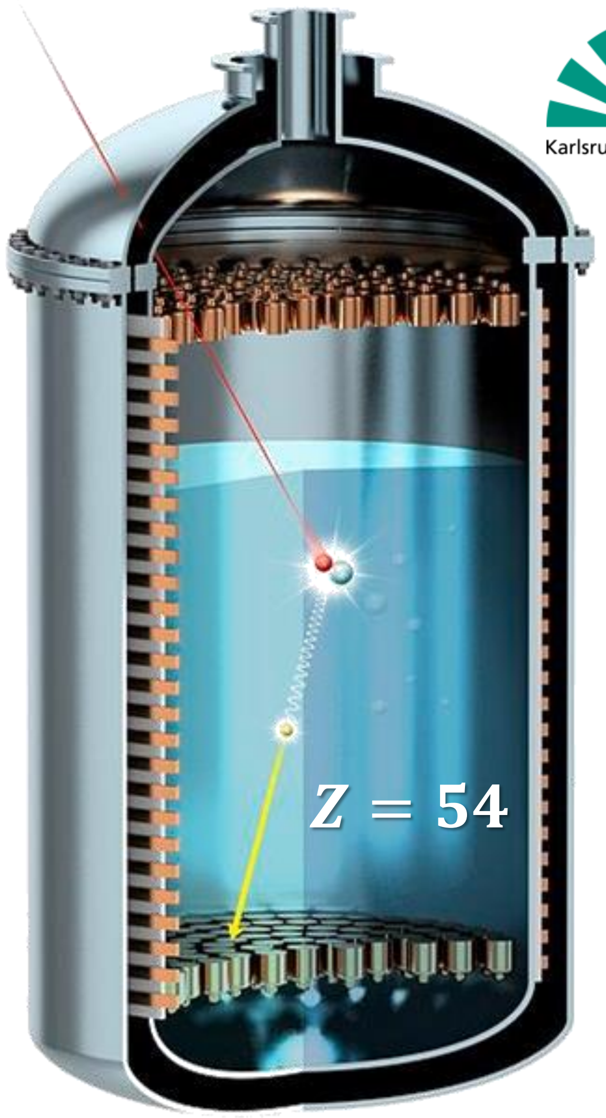
Suitable detector materials for σ_{SD}

- Nuclei with unpaired nucleon that can be used
  - **nuclear spin J** due to unpaired nucleon



spin J of nucleus (nucleons)

unpaired nucleon



^{129}Xe 26.4%

^{131}Xe 21.2%

liquid TPC (Xenon-nT)

Suitable detector materials for σ_{SD}

- **Nuclei with unpaired nucleon p, n that can be used for DM-searches**

  - spin-dependent coupling to unpaired proton (a_p) or neutron (a_n)

detector type	isotope	fraction	protons	neutrons	spin J	coupling
NaJ	^{23}Na	100%	11	12	$3/2$	a_p
(scintillator)	^{127}I	100%	53	74	$5/2$	a_p
LXe	^{131}Xe	21.2%	54	77	$3/2$	a_n
(liquid TPC)	^{129}Xe	26.4%	54	75	$1/2$	a_n
Ge (bolometer)	^{73}Ge	7.8%	32	41	$9/2$	a_n

Cross section of spin-dependent WIMP scattering

- **We can calculate the spin-dependent interaction rate of WIMPs via Z^0**

  - WIMPs moving with velocity v in the galactic DM-halo undergo an elastic scattering event with momentum transfer q^2

Fermi coupling constant

$$\frac{d\sigma_{SD}}{dq^2} \sim \frac{G_F^2}{v^2} \cdot C_{Spin} \cdot \frac{S(q)}{S(0)}$$

⇨ **Spin ´enhancement´ factor** (typcially $0.2 \ldots 0.5$)

Spin structure function $S(q)$: spatial distribution of spin inside the nucleus for different q

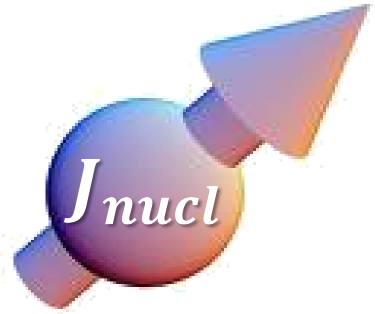
The Spin ´enhancement´ factor C_{spin}

- **We now consider in detail how the WIMP couples to the spin of the target**

$\boldsymbol{a_{p,n}}$: WIMP-coupling factor to p, n

takes into account the spin distribution on the quark level

(strength strongly depends on WIMP-flavour composition of $SUSY$ – model)



$$C_{Spin} = \frac{8}{\pi} \cdot \left(a_p \langle S_p \rangle + a_n \langle S_n \rangle \right)^2 \cdot \frac{J+1}{J}$$

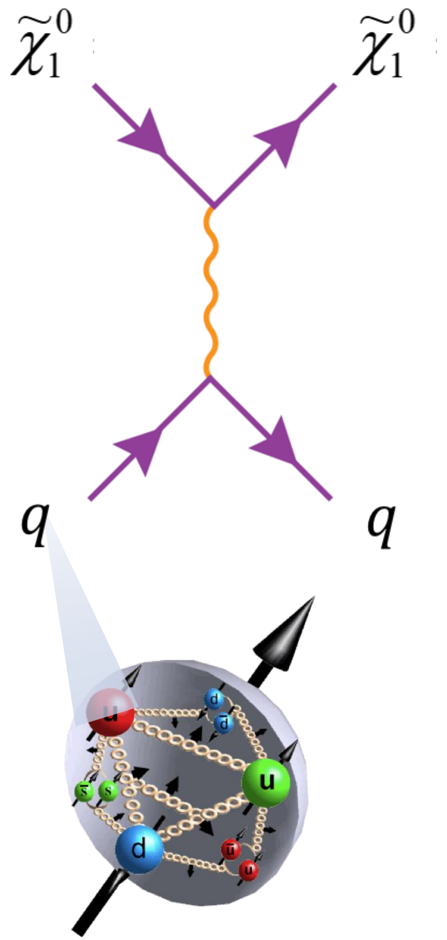
$\boldsymbol{\langle S_{p,n} \rangle}$: expectation values for p, n – spin in target nucleus (follows from detailed shell model calculations)

$\boldsymbol{J}$: nucelar spin due to the unpaired nucleon (proton / neutron)

WIMPs: how do they couple to the nucleus?

- **We now compare again the scalar (σ_{SI}) to spin-dependent (σ_{SD}) scattering**

  - we ´zoom out´ from the **parton level** to **nucleons** then to the nucleus



1 – level of partons: q, g

χ^0 – interaction with ***quarks, gluons***
χ^0 – coupling from specific $SUSY$ – **model**

2 – level of nucleons: p, n

kinematics & spin within a ***nucleon*** p, n determined via parton-distributions (valence/sea-quarks, gluons)

WIMPs: how do they couple to the nucleus?

- **We now compare again the scalar (σ_{SI}) to spin-dependent (σ_{SD}) scattering**

  - we ´zoom out´ from the parton level to nucleons then to the **nucleus**

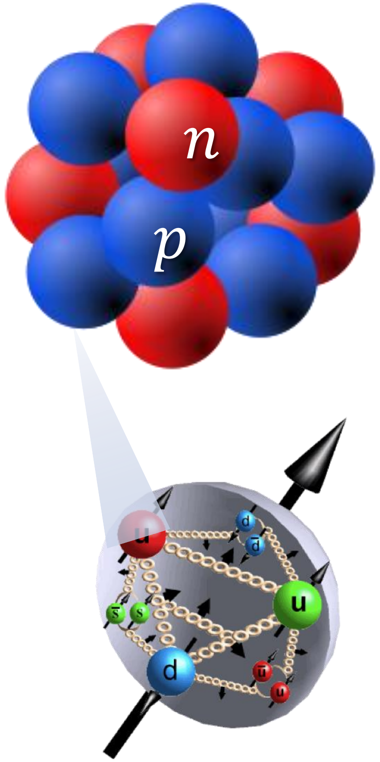
3 – level of nucelar structure: $Ar, Ge, Xe, \ldots$

χ^0 – interaction with nucleus

⇨ nuclear wave function using nuclear shell model

⇨ **form factors** to describe the mass / spin distributions within the nucleus

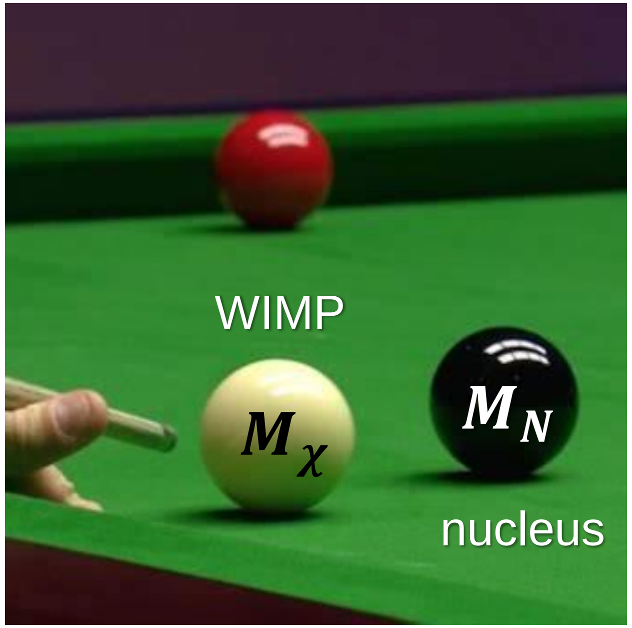
- kinematics of process – **coherent nuclear recoil**



More details on the elastic nuclear recoil

- **We now look in more detail at the WIMP signal due to the elastic scattering**

  - due to the low energy transfer involved in a WIMP scattering off a nucleus: we do not have to consider nuclear excitations A^* (even for uu – nuclei)
  ⇨ purely **elastic reaction kinematics***

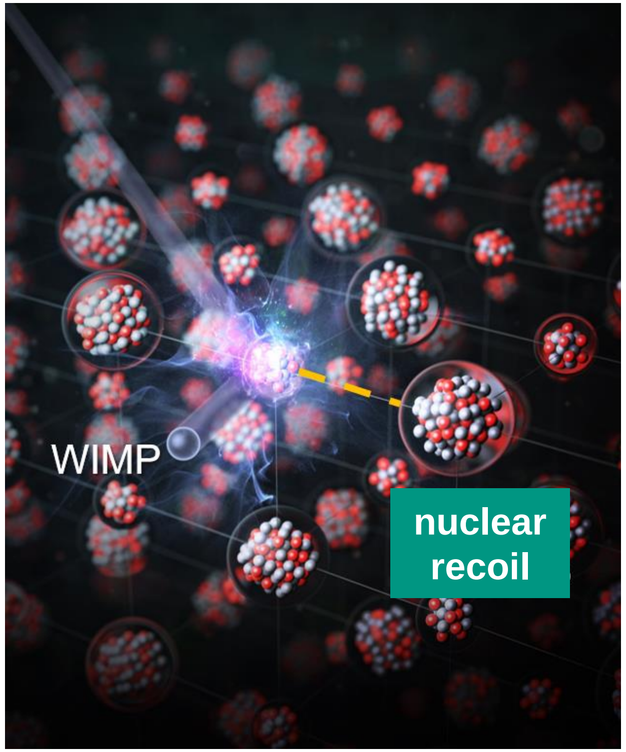


- **parameters**:

  a) relative velocities

  b) masses M_χ and M_N

  c) scattering angle θ



* see Class. Exp. Phys. I

Reaction kinematics of WIMP scattering

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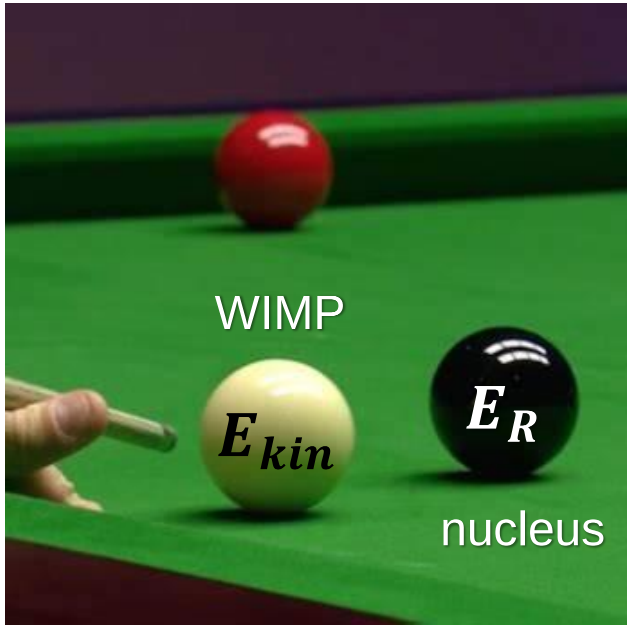
- **We can use non-relativistic kinematics due to rather low WIMP velocities**

$$E_{kin} = \frac{1}{2} \cdot M(\chi^0) \cdot \beta^2 \Rightarrow E_R < 100\ keV$$

small nuclear recoil energy E_R:
few tens of keV at maximum



- **parameters**:

a) relative velocities: $v \approx 10^{-3} \cdot c$ (WIMP in DM-halo)

b) masses M_χ and M_N: $M_{\chi,N} \approx 100\ GeV$

c) scattering angle θ: $\theta = 0° \ldots 180°$ (forward / backward)

Reaction kinematics of WIMP scattering

- We now describe WIMP scattering off a target nucleus which is at rest

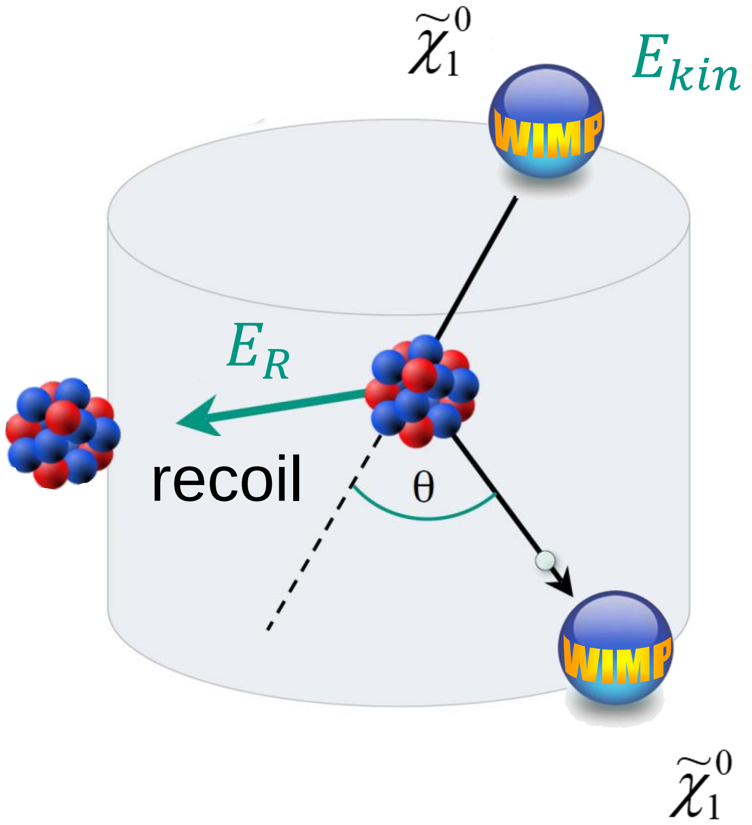
$$E_R = 2 \cdot \frac{\mu}{M_\chi + M_N} \cdot E_{kin} \cdot (1 - \cos\theta)$$

$\boldsymbol{E_R}$: recoil energy of nucleus (usually in $\boldsymbol{keV}$)

$\boldsymbol{E_{kin}}$: kinetic energy of WIMP (usually in $\boldsymbol{keV}$)

$\boldsymbol{\mu}$: reduced mass of WIMP-nucleus system

$$= {M_\chi \cdot M_N} / {M_\chi + M_N}$$



Reaction kinematics: equal masses

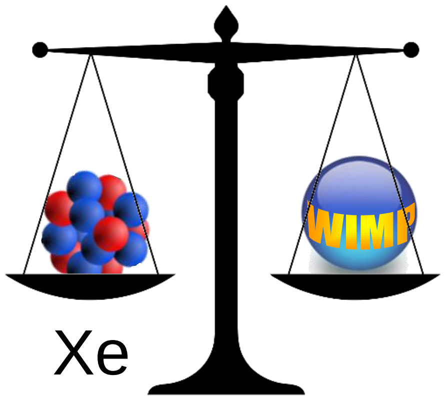
- **Optimum transfer of energy & momentum which maximises E_R for given E_{kin}**

$$E_{R,max} = \frac{1}{2} \cdot M_N \cdot \beta^2$$

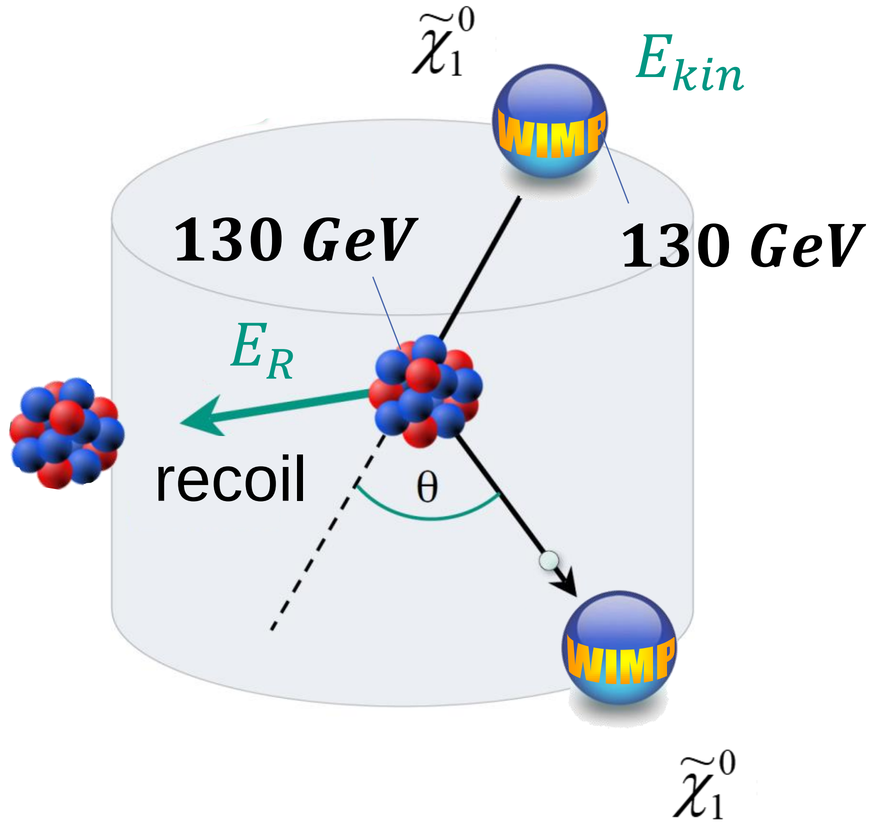
- identical mass scale

$$M_\chi = M_N \; : \; \mu = \frac{M_N}{2}$$

⇨ recoil nucleus receives full kinetic energy E_{kin} of incoming WIMP



$130\ GeV$ WIMP scatters off xenon



Reaction kinematics: non-equal masses

- **non-optimum transfer of energy & momentum which impacts E_R**

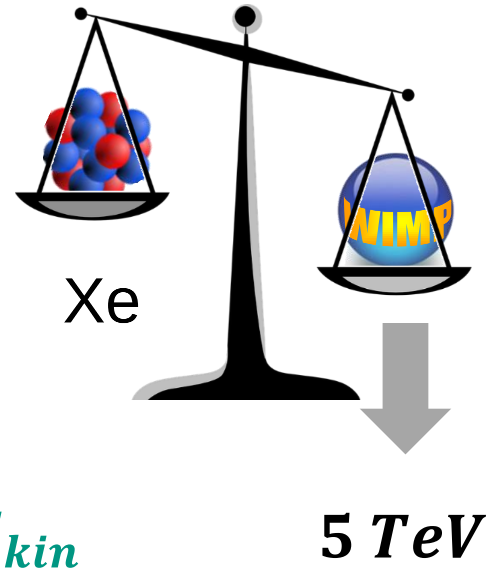
$$\boldsymbol{E_{R,max} = 2 \cdot M_N \cdot \beta^2}$$

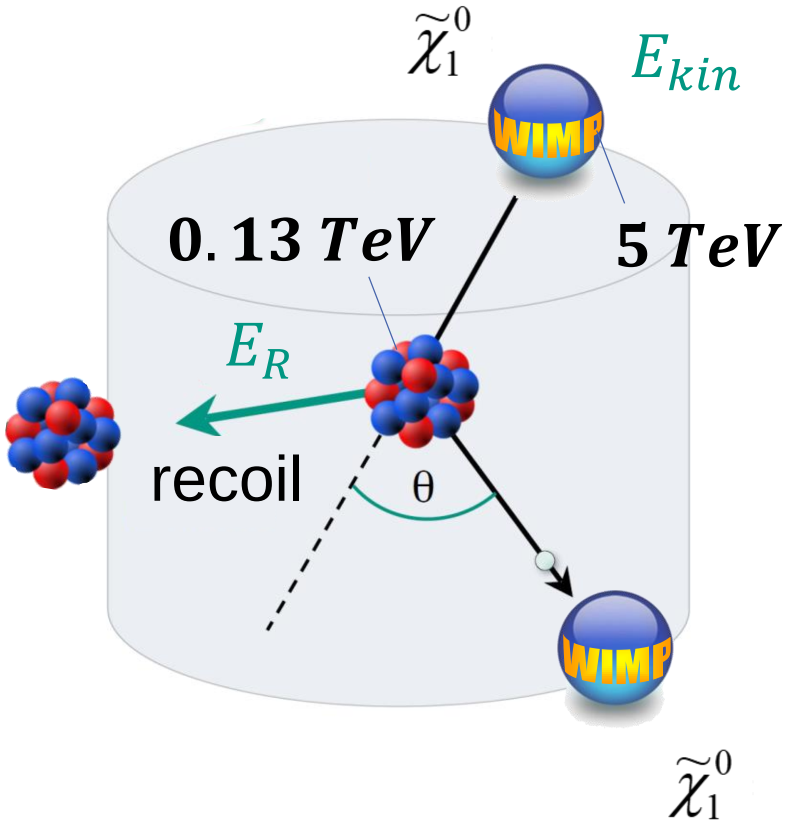
only $4 \times$ larger energy

- non-identical mass scale

$$M_\chi \gg M_N \; : \; \boldsymbol{\mu = M_N}$$

⇨ recoil nucleus receives
only part of kinetic energy $\boldsymbol{E_{kin}}$
of incoming WIMP, but now:
much smaller WIMP flux





INSERTION: χ^0 – SCATTERING OFF ELECTRONS?

- **Why can´t we use electrons as target for WIMP scatterings?**

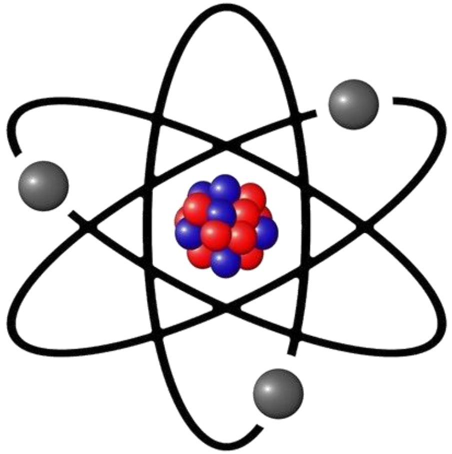
$$E_{R,max} = 2 \cdot M_e \cdot \beta^2$$

- non-identical mass scale

$$M_\chi \gg M_e \; : \; \mu = M_e$$

⇨ recoil electron receives
only part of kinetic energy E_{kin}
of incoming WIMP
$E_{R,max}$ is on the eV-scale (undetectable)

M_e



WIMP scattering in an actual DM-detector

- **How do I optimize my detector to observe elastic WIMP scattering?**

  - now that we have analysed the kinematics of elastic WIMP scattering, which are the most **important detector parameters** to observe it?

  a) how large should the **target mass** of my detector be?

  b) how low should the **energy threshold** of my detector be?

  c) how many **WIMP scatterings** will my detector see?

WIMP scattering in an actual DM-detector

- **We first calculate the expected number of elastic WIMP scatterings**

  - expected DM-event rate $\boldsymbol{R}$ in a detector with number N_{nucl} of target nuclei

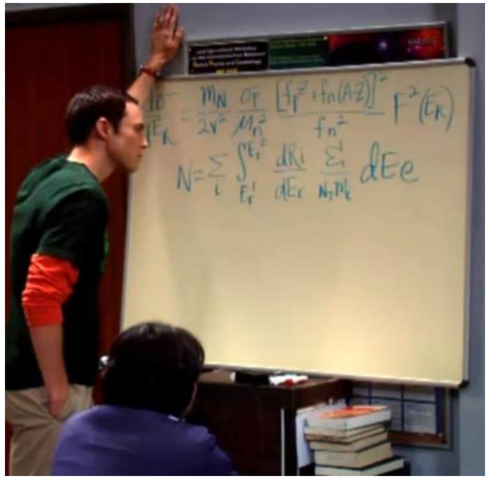
$$R = N_{nucl} \int_{E_{kin,\min}}^{E_{kin,\max}} \Phi(E) \cdot \sigma_{SI/SD}(E)\, dE \approx N_{nucl} \cdot \langle \Phi \rangle \cdot \langle \sigma_{SI/SD} \rangle$$

WIMP flux as function of kinetic energy $\boldsymbol{E_{kin}}$

cross section as function of kinetic energy $\boldsymbol{E_{kin}}$

averaged values

(or DM-halo velocity v)



WIMP scatterings as function of recoil energy E_R

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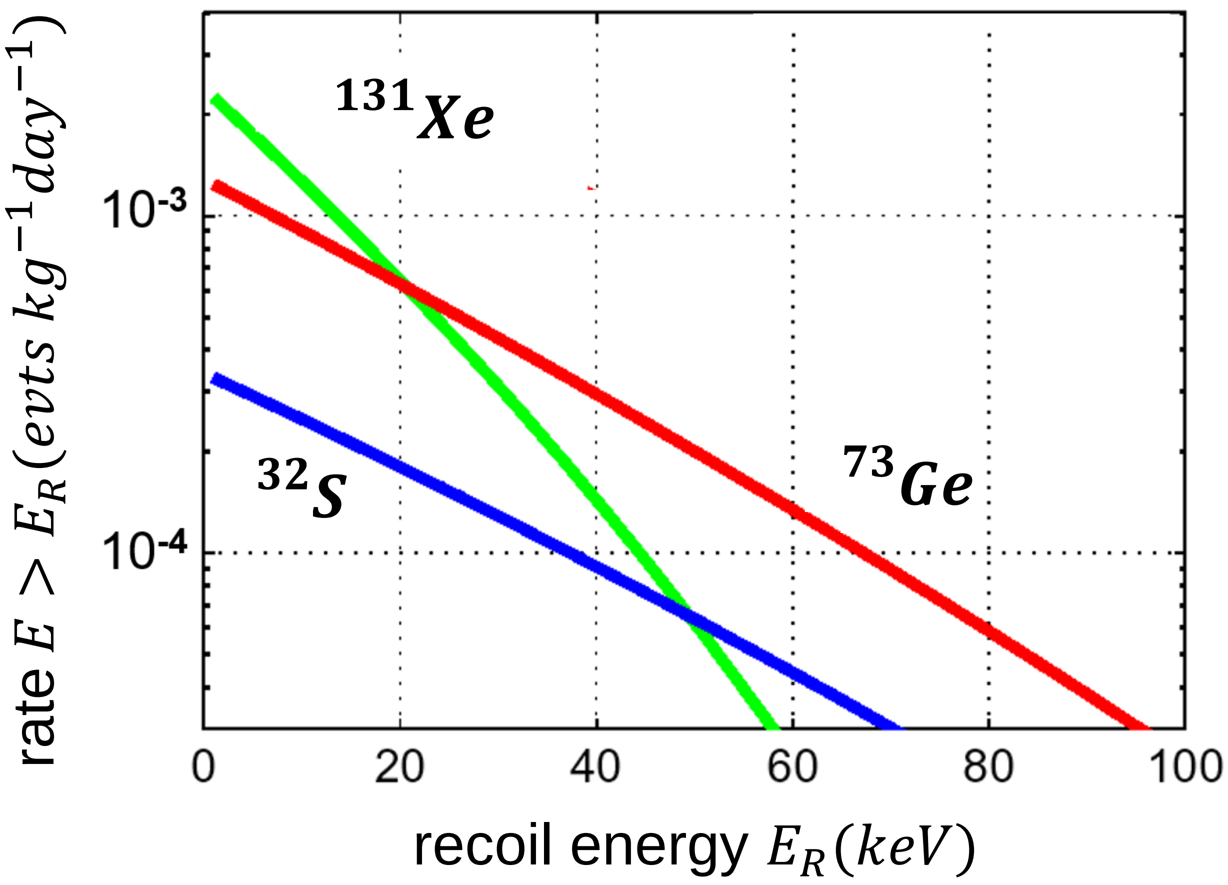
- **We now investigate the number of events above a specific threshold $E > E_R$**

- here we display the integrated number of events **above** a specific recoil energy E_R

- equivalent to an **integrated recoil energy spectrum** above threshold

- here we use a flux-averaged value $\boldsymbol{\sigma_{SD} = 3.6 \cdot 10^{-45}\ cm^2}$

- visualizes impact of nuclear mass M_N via kinematics & form factor F



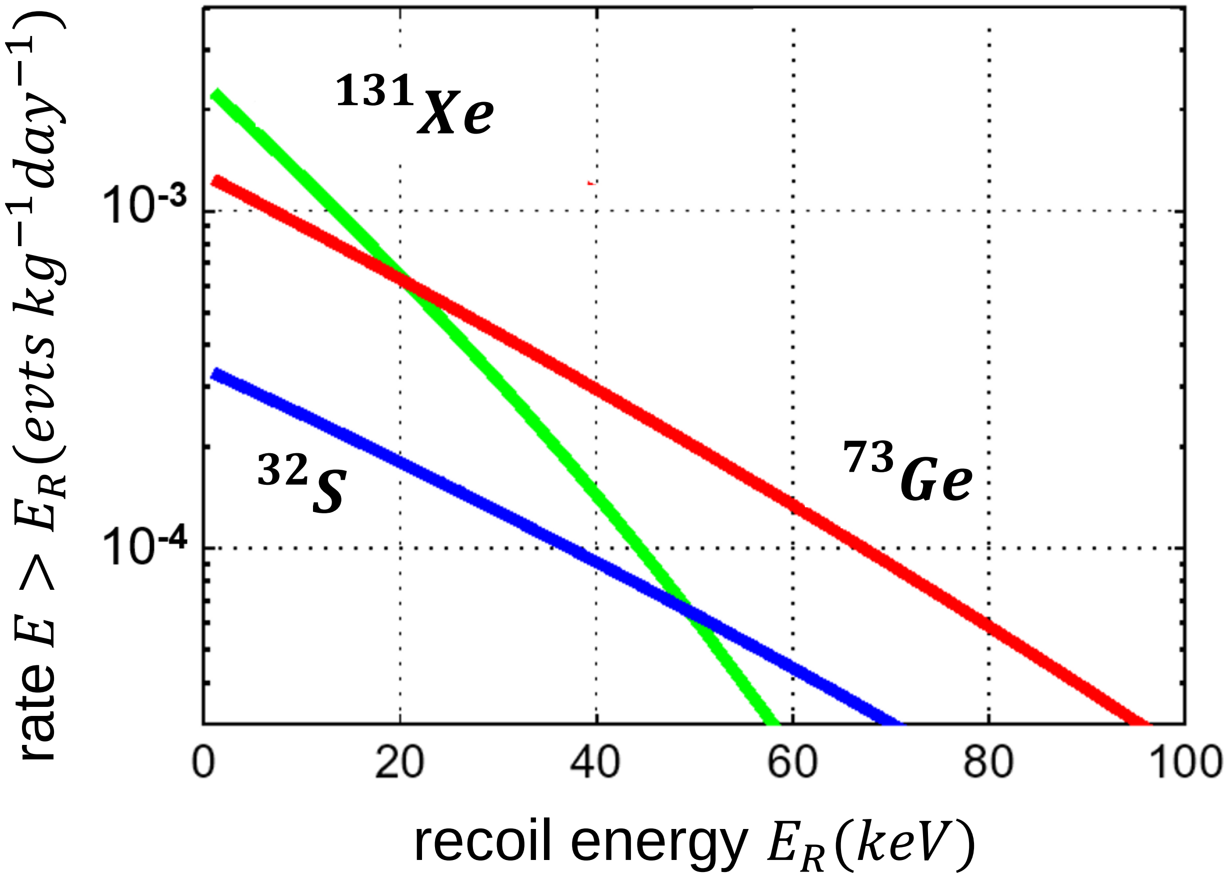
WIMP scatterings: recoil energy spectrum

- **Conclusion from the integrated spectrum above a specific threshold $E > E_R$**

$$R = N_{nucl} \int_{E_{kin,\min}}^{E_{kin,\max}} \Phi(E) \cdot \sigma_{SI/SD}(E)\, dE$$

it is of paramount importance to reach an energy threshold of $\boldsymbol{E_{thres} = 1 \ldots 2\ keV}$ for

WIMP-detectors with target masses of $\boldsymbol{1 \ldots 10\ t}$

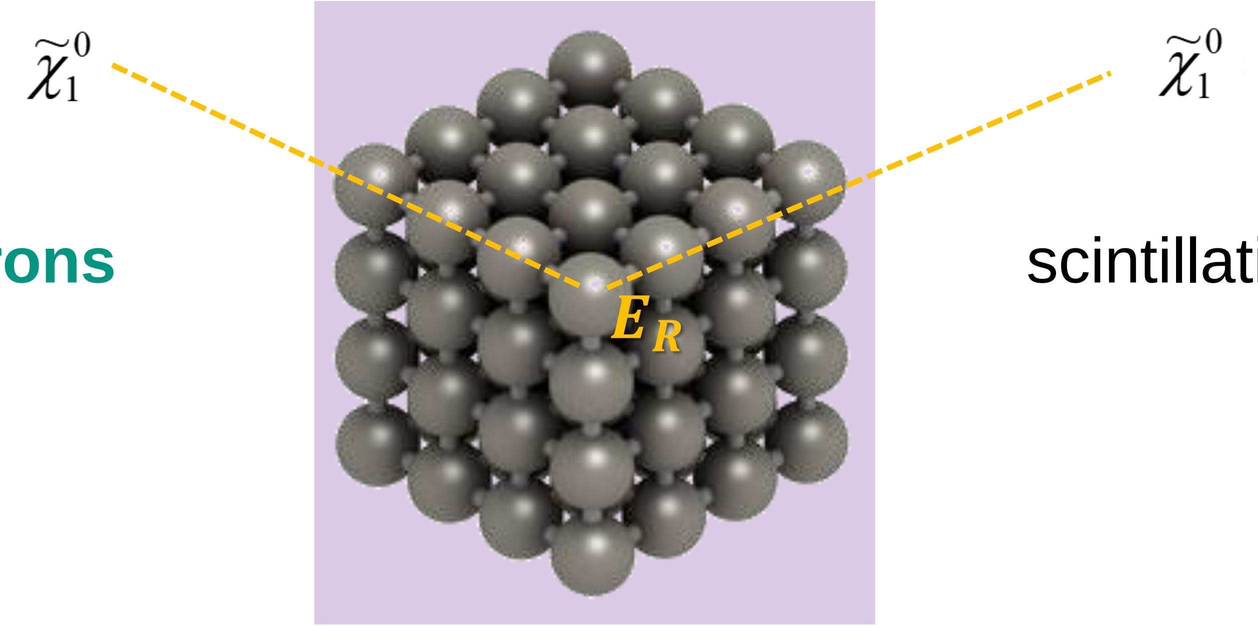


Solid state response to E_R from the nuclear recoil

- **What happens in my solid-state detector after a WIMP interaction?**

  - nuclear recoil can be detected via **three solid-state responses**

ions & **electrons**



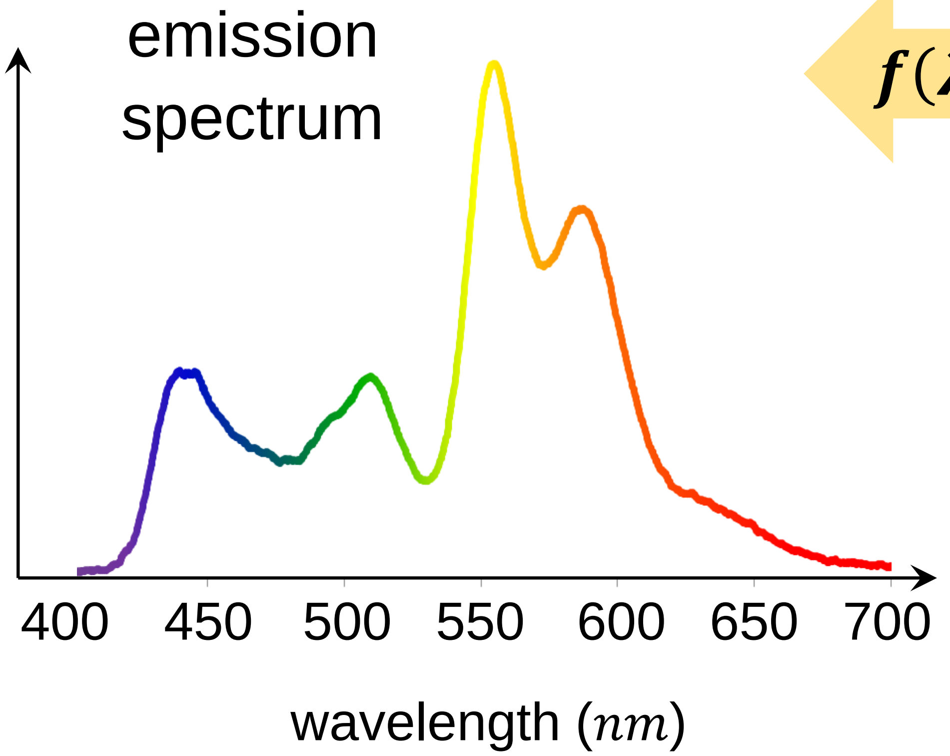
scintillation - **photons**

phonons

Solid state response part$-I$: scintillation

- **Emission and subsequent detection of scintillation photons**

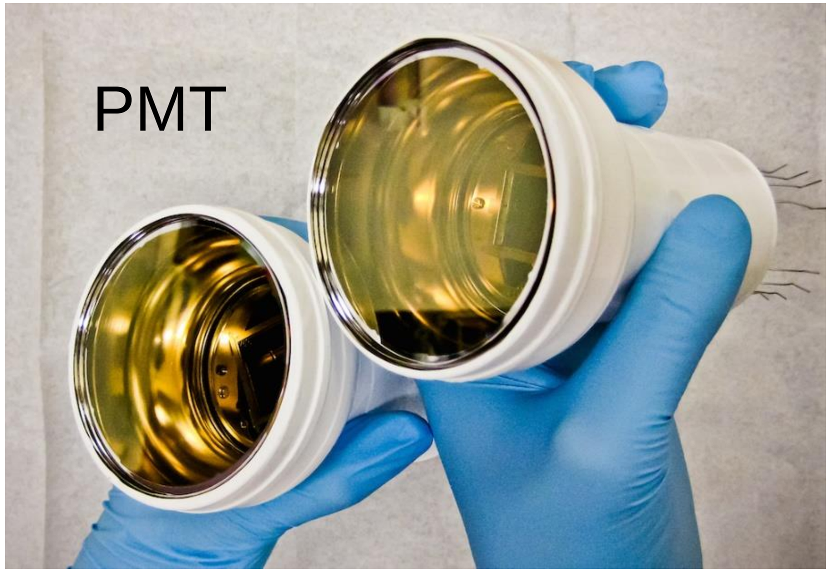
  - effective energy for the detection of the scintillation light:
    $\Delta E \sim 100\ eV$ per photon



$f(\lambda)$ **SHOULD MATCH**

organic &
anorganic
scintillators

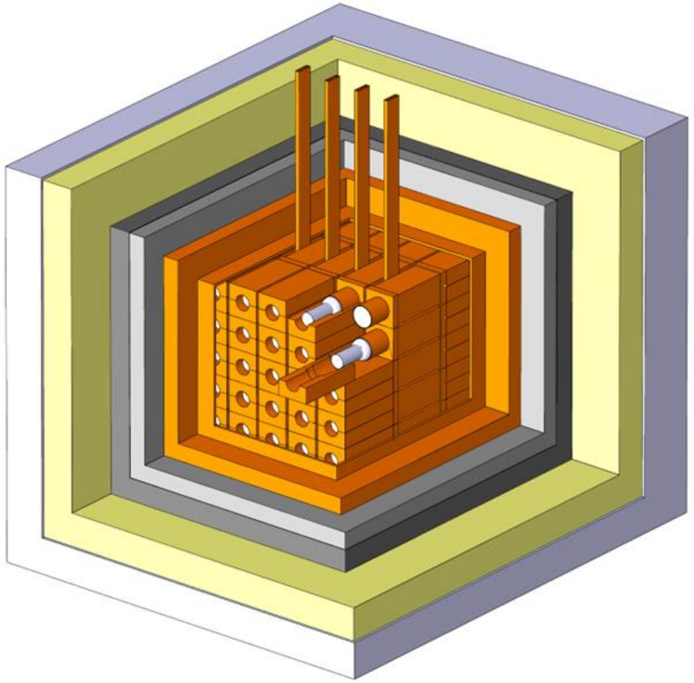
spectral sensitivity of
PMT photocathode



Solid state response part–I: scintillation

- **Examples of DM-detectors based on scintillation: DAMA-Libra, SABRE,…**

  - **NaJ / CsJ / CaF2 - crystals** with readout by PMTs



COSINE-100 detector

Solid state response part $-I$: scintillation

- **Examples of DM-detectors based on scintillation: DAMA-Libra, SABRE,…**

  - **NaJ / CsJ / CaF2 - crystals** with readout by PMTs

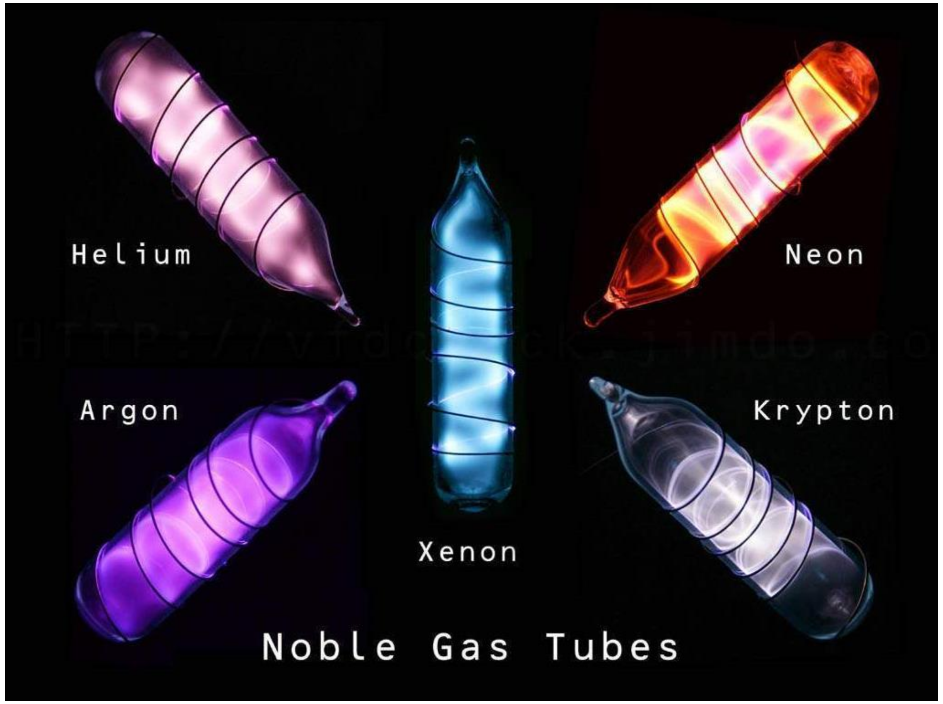
  - each scintillation material has its specific properties,
    we aim for large light yield, fast decay time & optimum λ – match to PMT

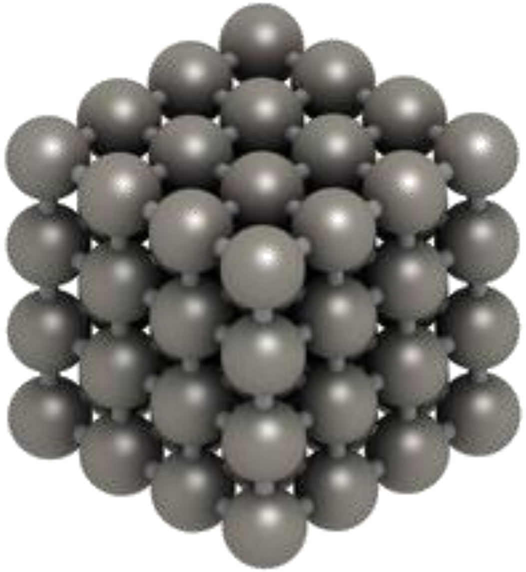
scintillator	light yield (photons keV^{-1})	decay time τ_f (ns)	mean wave-length λ_m (nm)	n
$NaJ\ (Tl)$	38	230	415	1.85
$CsJ\ (Tl)$	65	800	540	1.86
$CaF_2\ (Eu)$	19	940	424	1.44

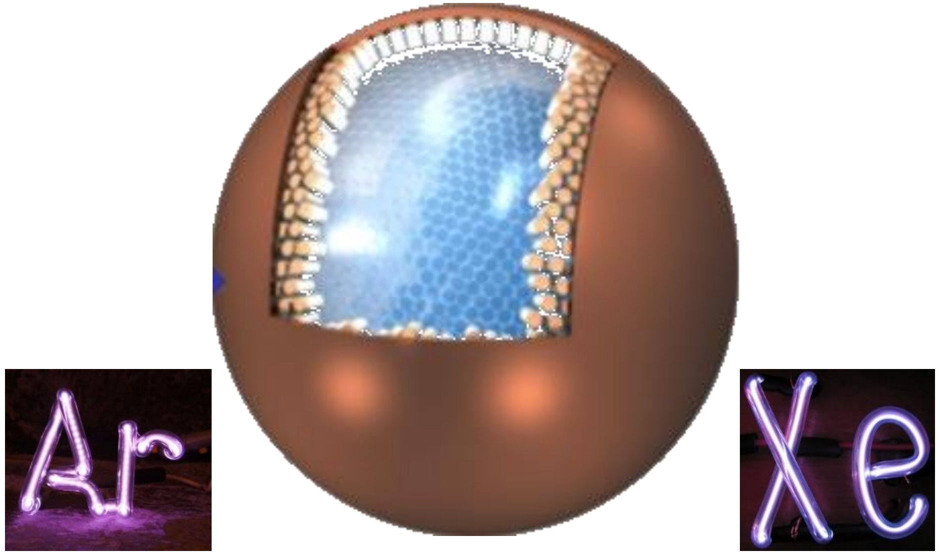
Scintillation light in liquid noble gas detectors

- **Emission of scintillation light in the VUV (Vacuum Ultra-Violet) band**

- we will later discuss large LXe / LAr – based TPCs, where **VUV-scintillation** occurs





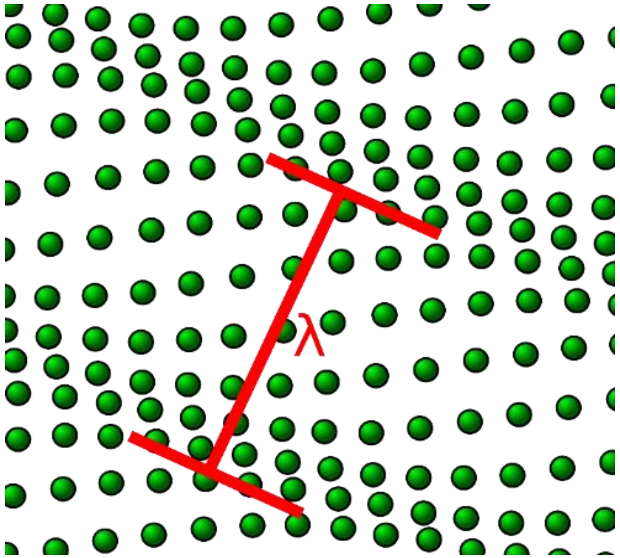


discharge tubes: ionized noble gases (which is not a scintillation process!)

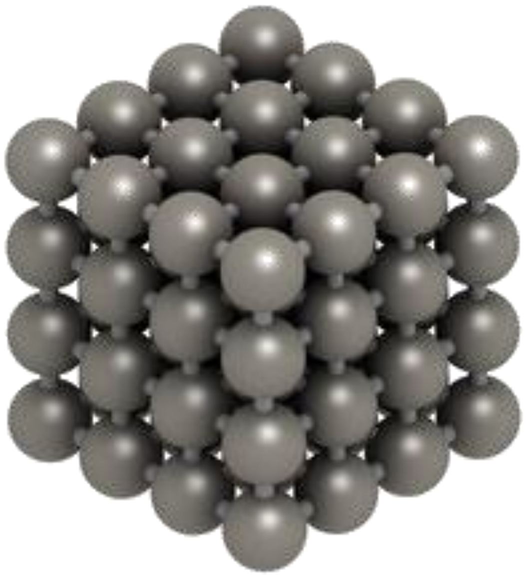
Solid state response part$-II$: phonons

- **Nuclear recoil results in the emission of a spherical phonon wave**

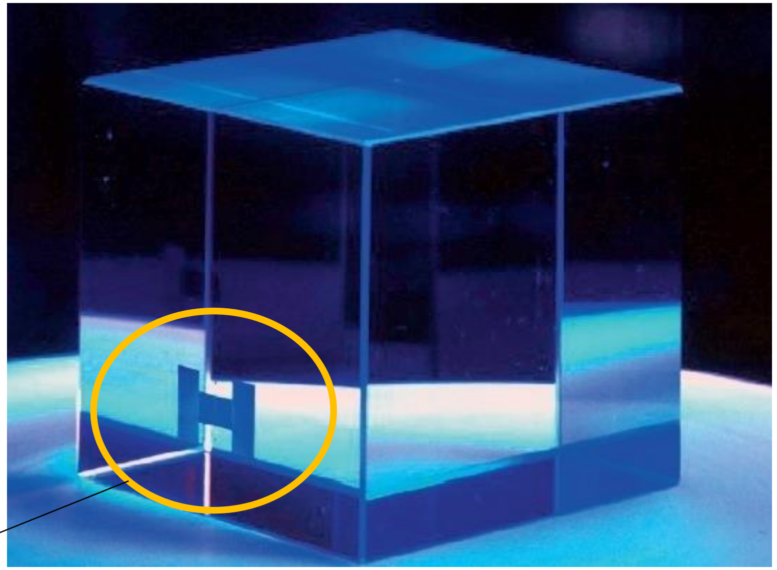
  - phonon: quasi-particle, corresponds to a ´quantized sound wave´
  - detection of phonons requires detector operation at the $\boldsymbol{mK-}$ **scale**



phonon wave propagaiting



thermistor

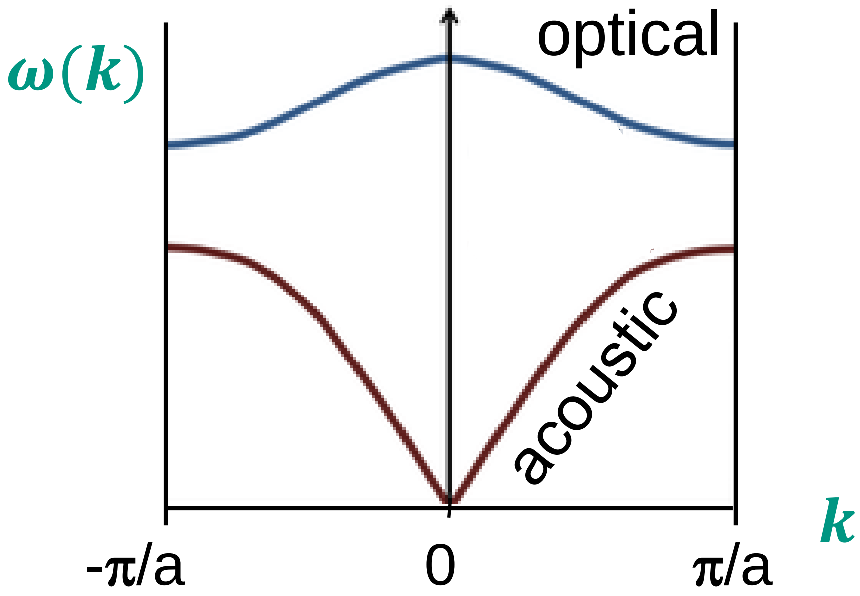


$CaWO_4$ – crystal

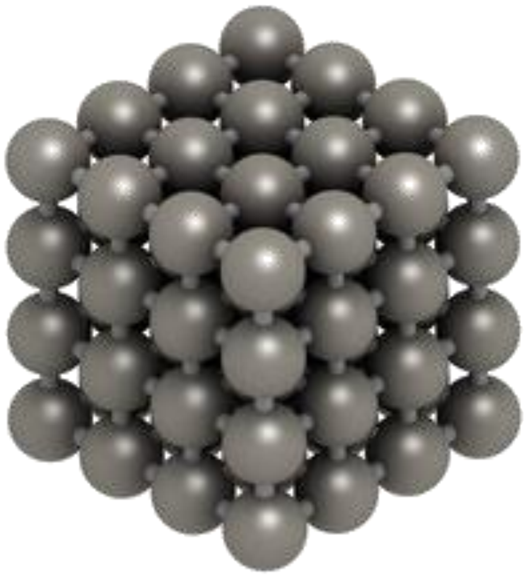
Solid state response part$-II$: phonons

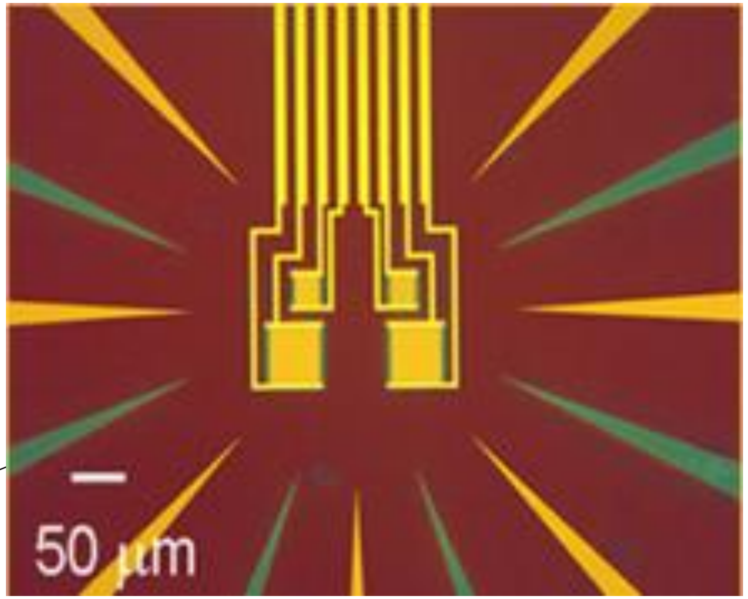
- **Nuclear recoil results in the emission of a spherical phonon wave**

  - phonon: quasi-particles with very small energies on the meV − scale
  - detection of recoil energy E_R via **thermistor** ($\Delta T \rightarrow \Delta R$)



phonon dispersion relation





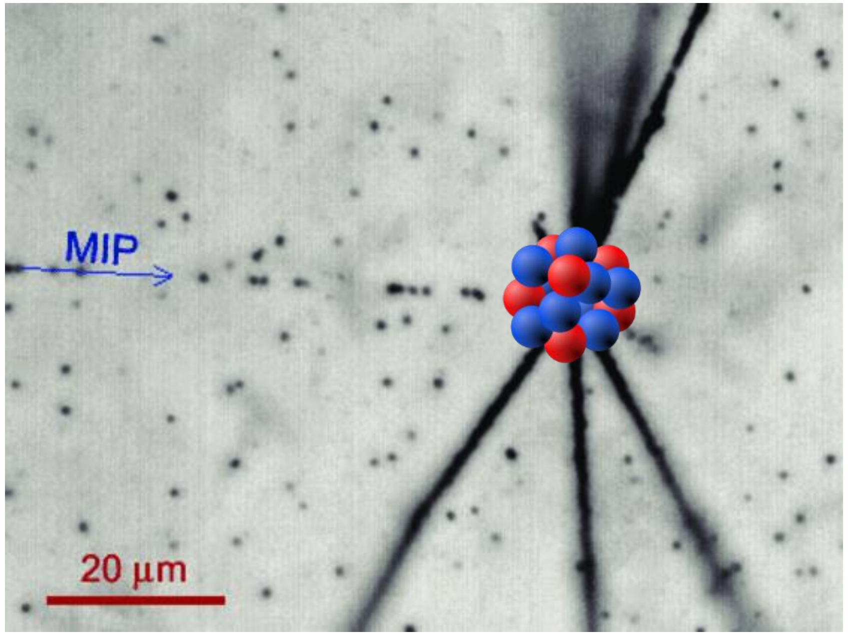
thermistor

Solid state response part–III: electrons

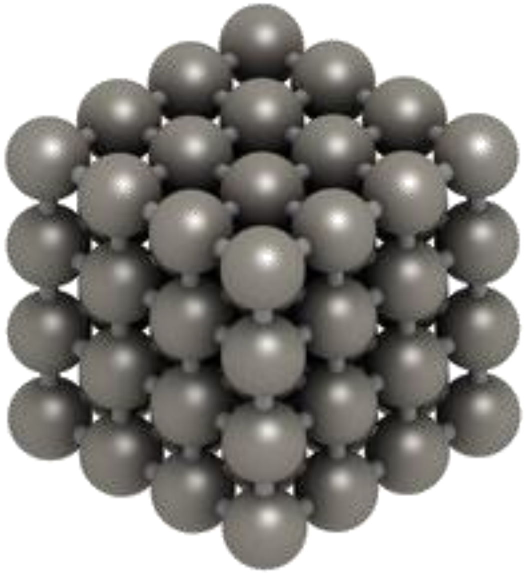
- **Nuclear recoil results in the generation of electron-ion pairs (ionization)**

  - recoil nucleus has a very **large stopping power dE/dx** ⇨ short recoil track

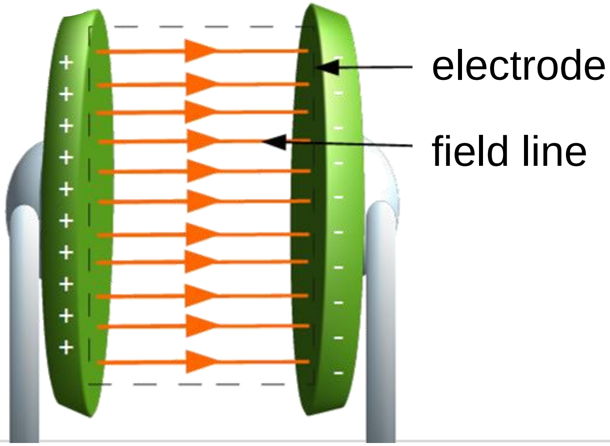
  - high density of electrons & ions along the track: recombination



low-energy nuclear tracks vs. MIP*



- we have to drift the electrons using strong electric drift fields to detector´s anode for read-out



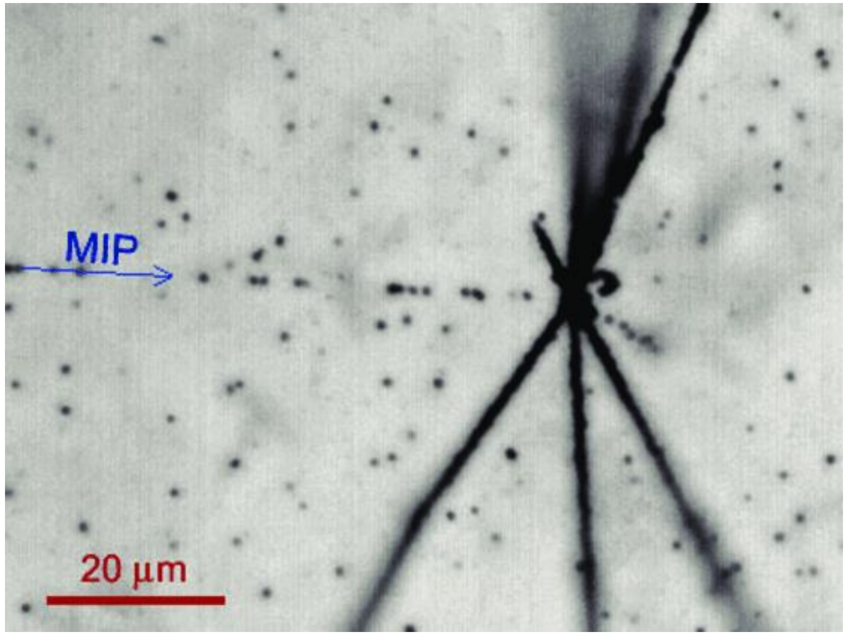
*minimum ionizing particle

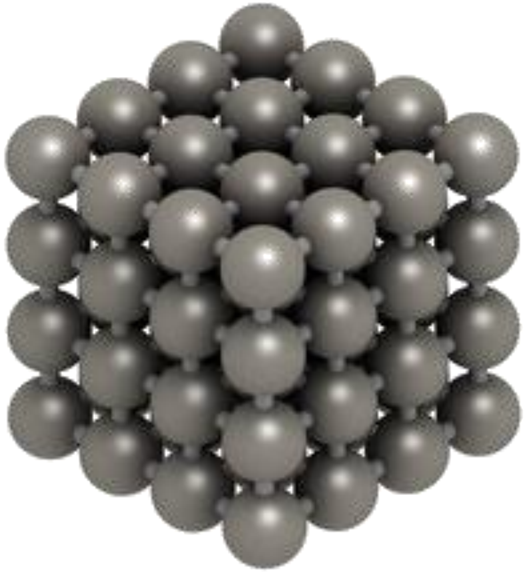
Read-out of ionization signal via drift fields

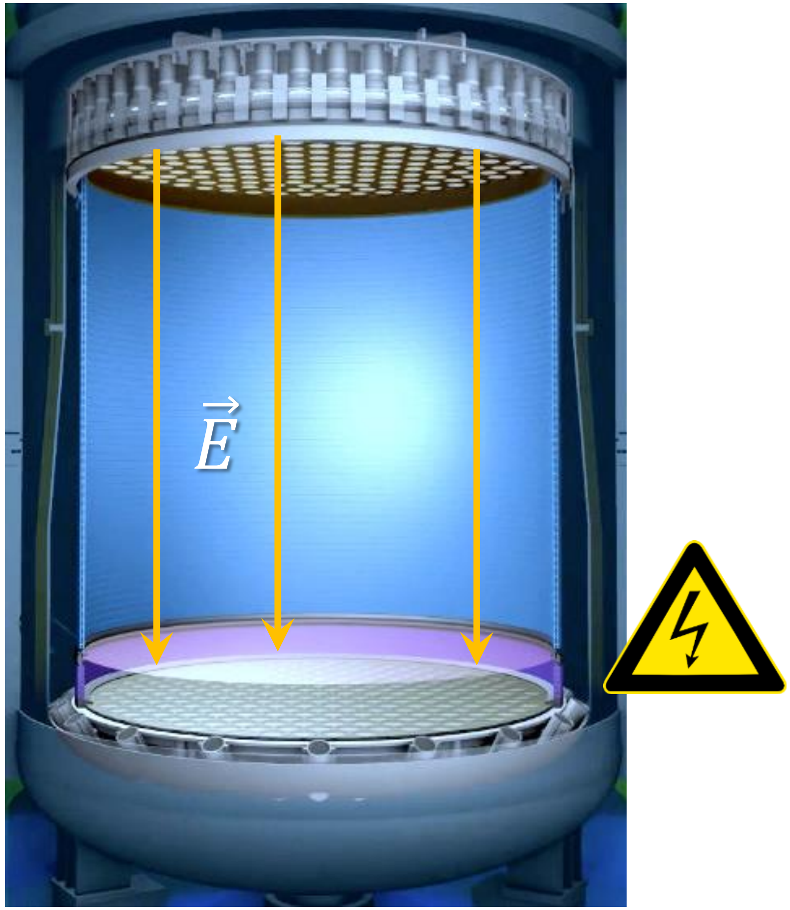
- **Nuclear recoil results in the generation of electron-ion pairs (ionization)**

  - to generate an e^- & ion – pair: $\mathbf{10 \ldots 20\ eV}$

  - separate e^- & ions via **strong uniform $\vec{E}$ – field**







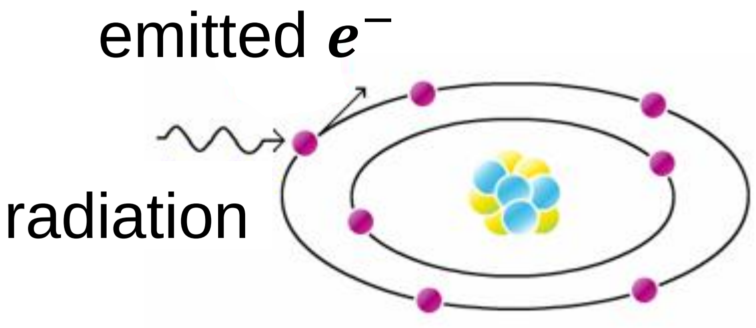
nuclear tracks vs. MIP: use range to discriminate!!

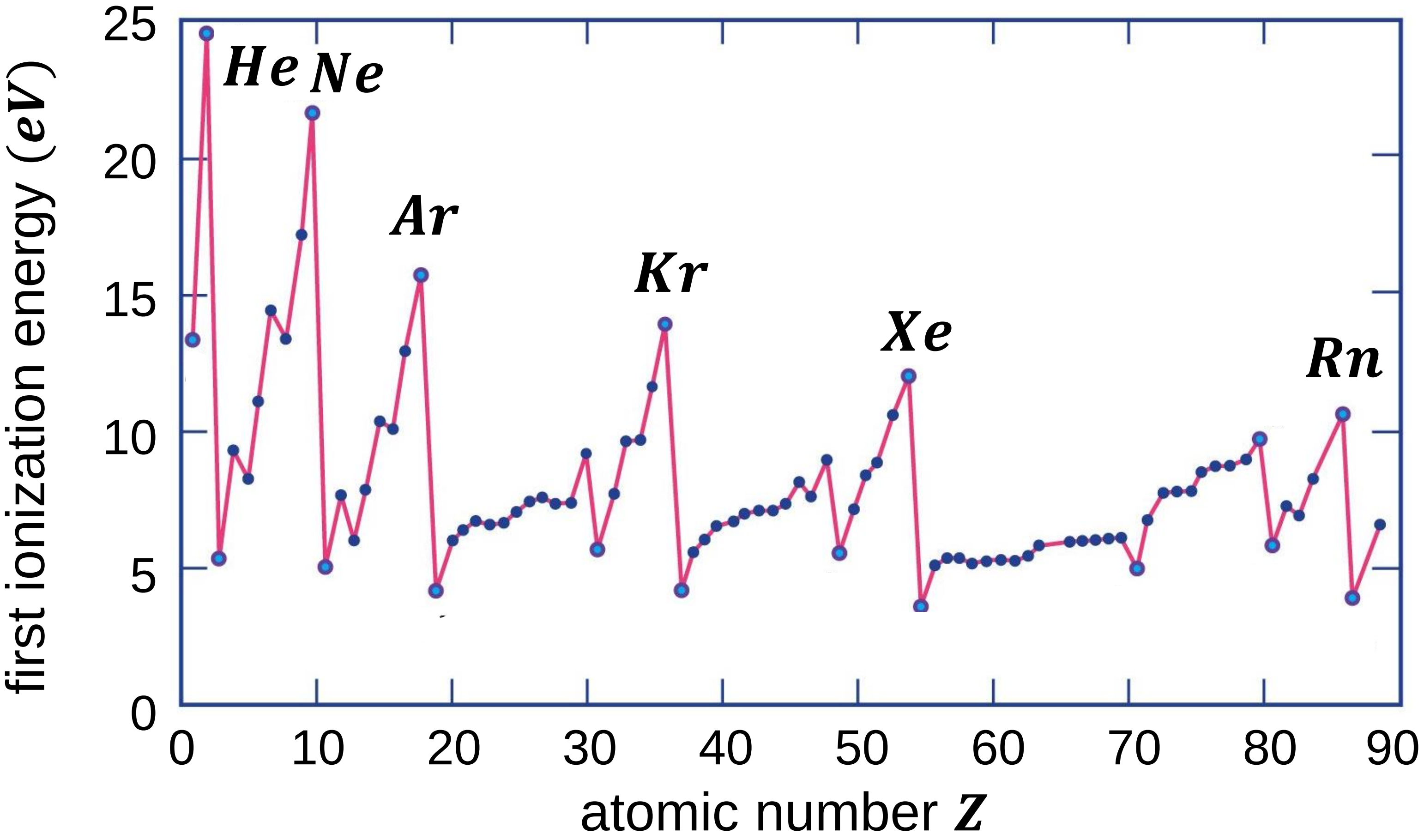
Energy required to generate an e^- / ion (hole) pair

- Ionization energy of elements shows atomic structure

  - we will use detectors:

$$Si:\ \Delta E = 3.6\ eV$$
$$Ge:\ \Delta E = 2.9\ eV$$
$$Ar:\ \Delta E = 15.76\ eV$$
$$Xe:\ \Delta E = 12.13\ eV$$



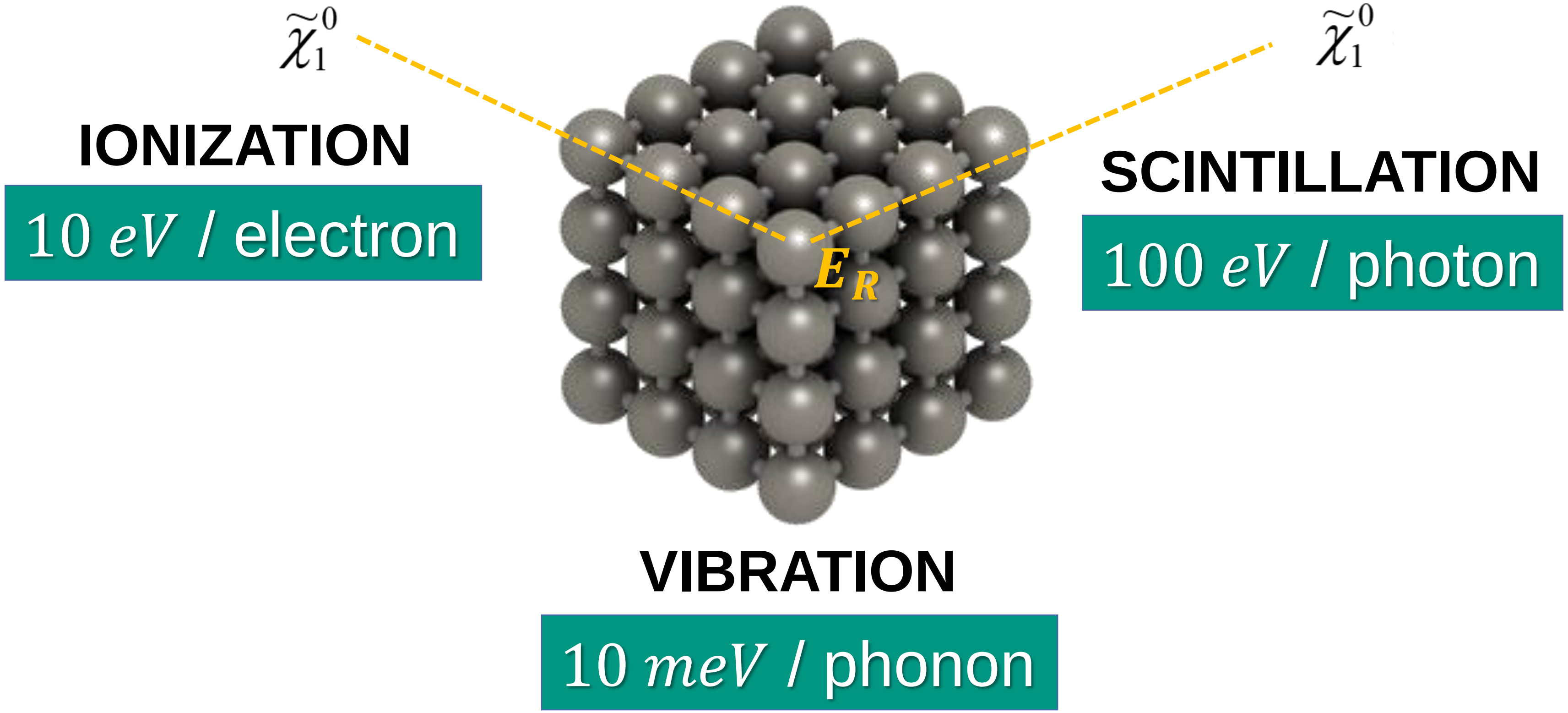


High-Tech required for WIMP-detection

- **We will combine 2 out of the 3 detection methods to get best sensitivity!**

  - only by **combining two methods** we can achieve background discrimination

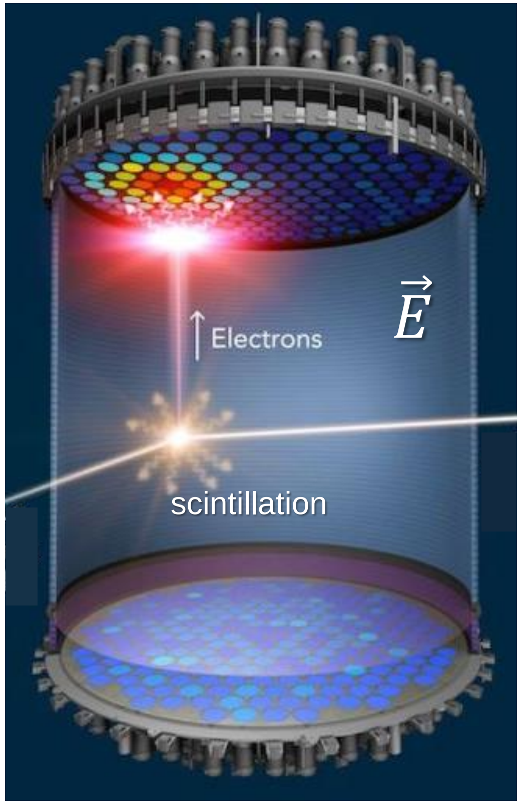
low-noise electronics
cryogenics
precision drift fields
novel optical sensors



WIMP-detection via ionization & scintillation

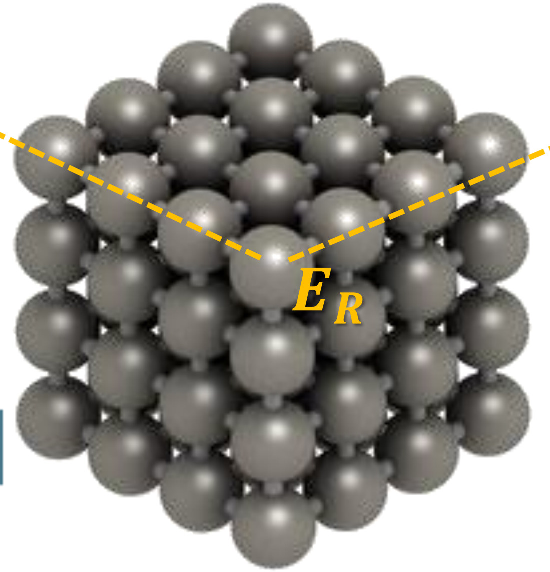
- **large-scale TPCs* with liquid noble gases: *LXe* & *LAr***

  - **ratio of scintillation light / electrons**: excellent background discrimination



IONIZATION

10 eV / electron



SCINTILLATION

100 eV / photon

DARWIN

darkside
two-phase argon TPC for Dark Matter Direct Detection

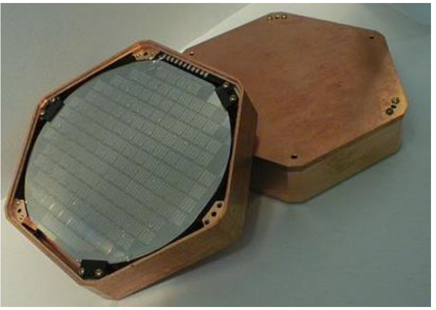
Xe
XENON
Dark Matter Project

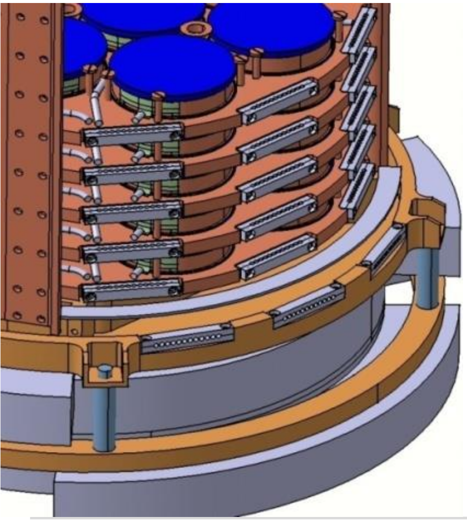
*Time Projection Chamber

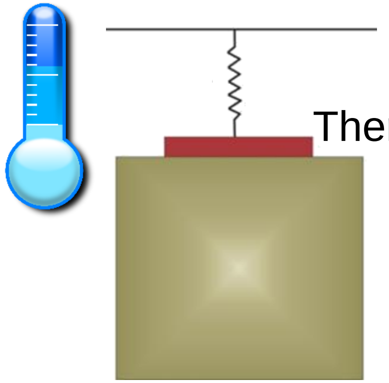
WIMP-detection via ionization & phonons

- **solid-state Ge- (Si-) detectors at the mK –scale with thermistor read-out**

  - **ratio of electrons / phonons signal**: excellent background discrimination

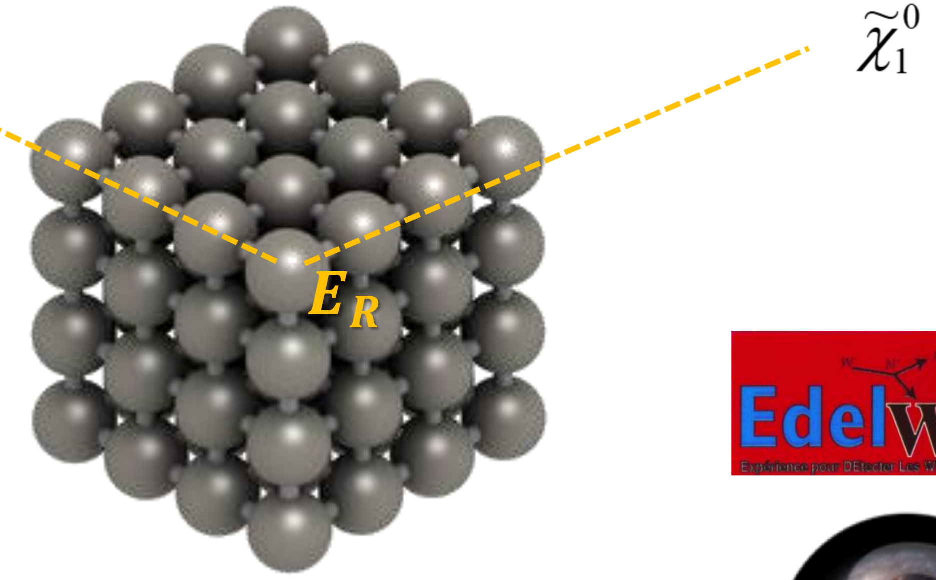






IONIZATION

10 eV / electron



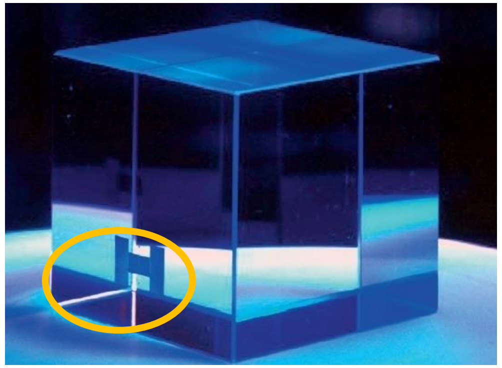
VIBRATION

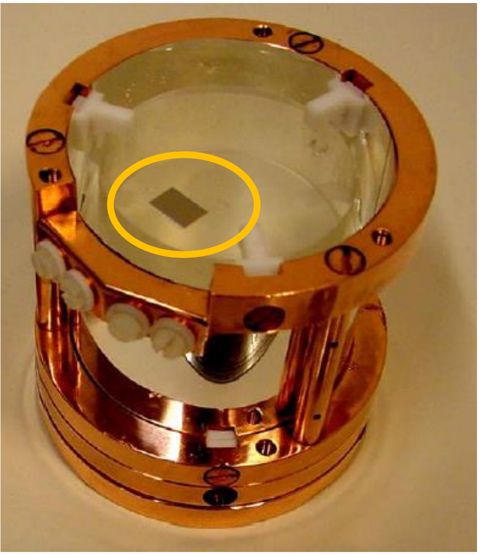
10 meV / phonon

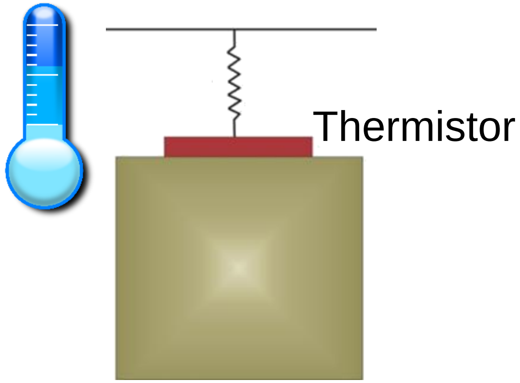
WIMP-detection via scintillation & phonons

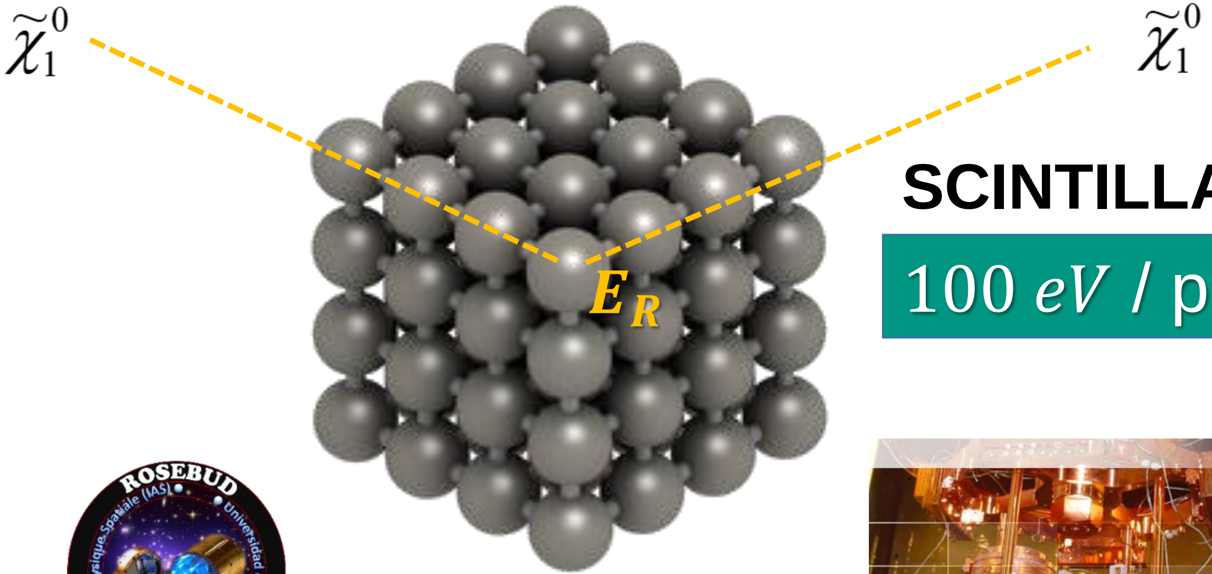
- **Scintillating crystals ($CaWO_4$) at the mK –scale with thermistor read-out**

  - **ratio of photons / phonons signal**: excellent background discrimination









SCINTILLATION

100 eV / photon

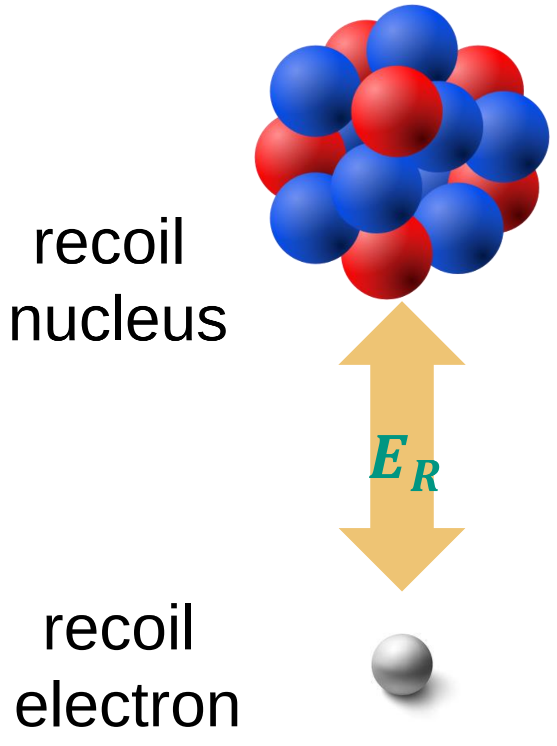
VIBRATION

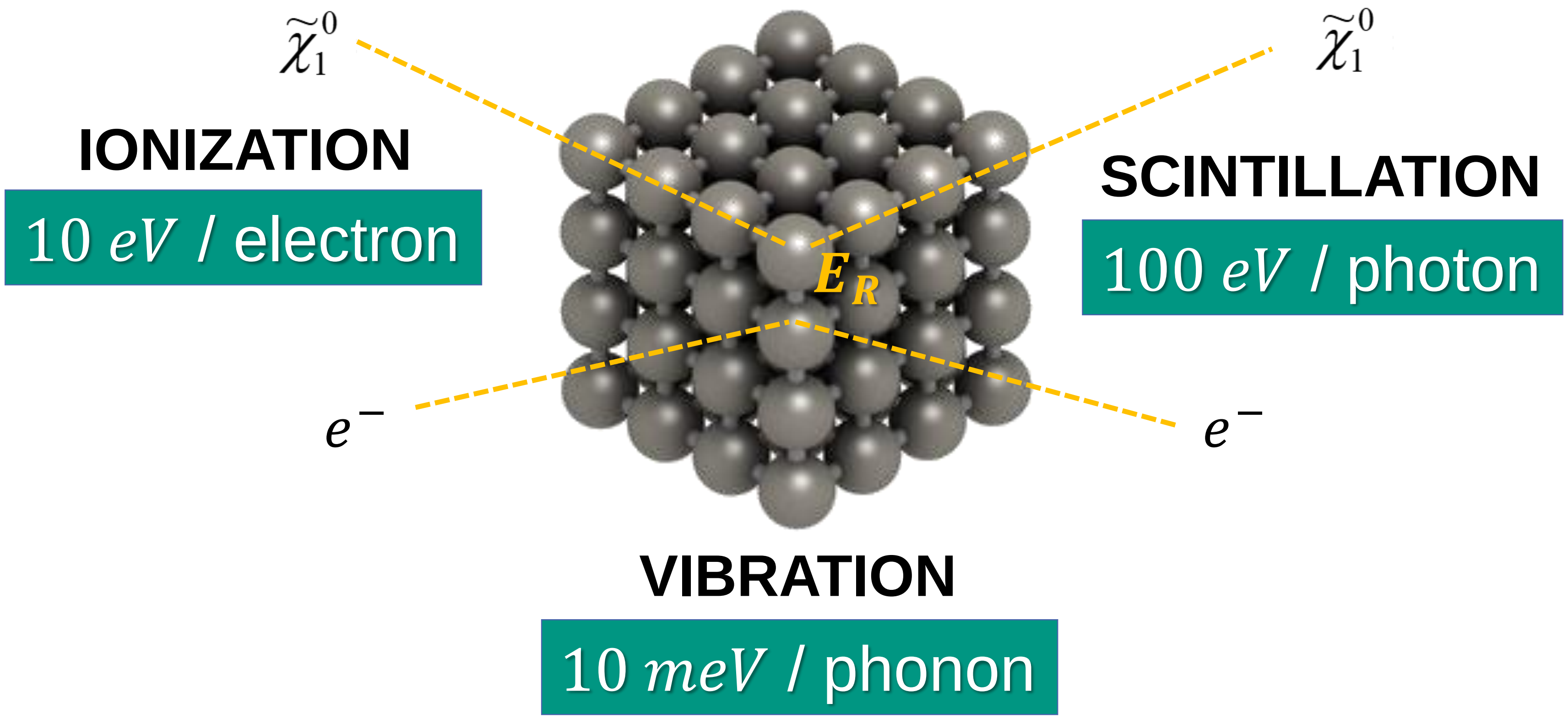
10 meV / phonon

Dicriminating nuclear recoils from electrons

- **Why do we need 2 parameters to discriminate signal from background?**

- a comparison of **nuclar recoils** vs. **electron tracks** (from γ – background)

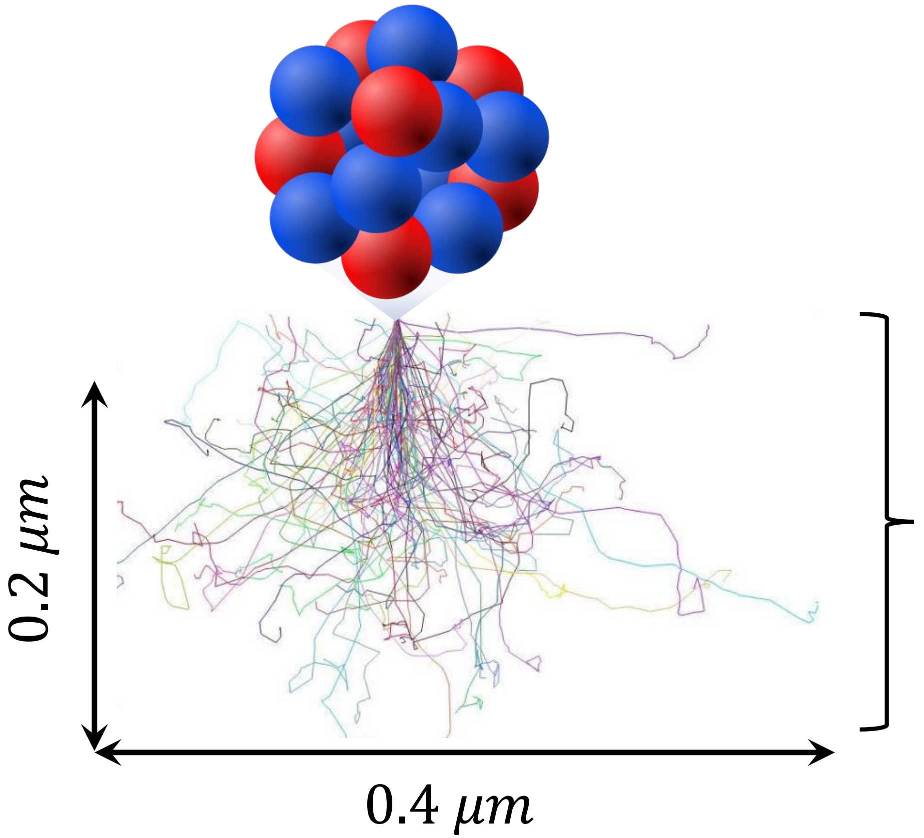




nuclear recoils: a closer look at their tracks

- **The value of dE/dx is key to the particle discrimination**

  - recoil nucleus with $E_R \sim keV$ – scale: extremely **small range $R < 1\ \mu m$**



nuclear recoil in an emulsion

⇨ **high ionization density**

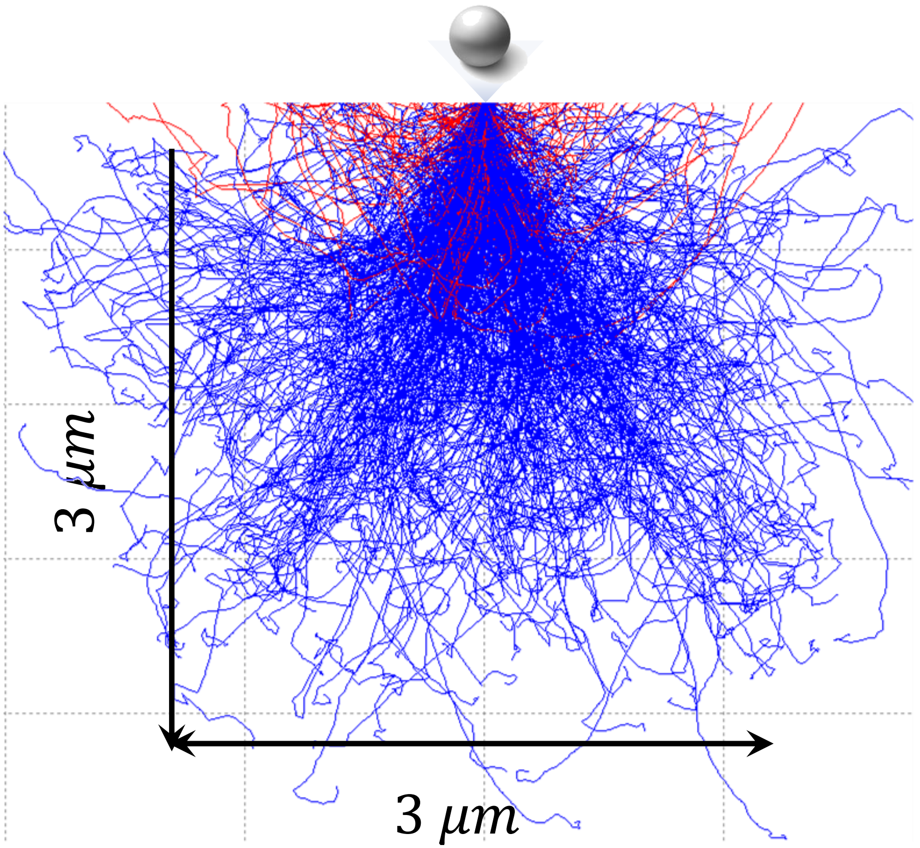
⇨ **recombination of charges (quenching)**

⇨ **smaller charge signal for WIMP scattering**

electron recoils: a closer look at their tracks

- The value of dE/dx is key to the particle discrimination

  - electron recoil with $E_R \sim keV$ – scale: rather **large range $R \approx several\ \mu m$**



electron recoil in an emulsion

⇨ **low ionization density**

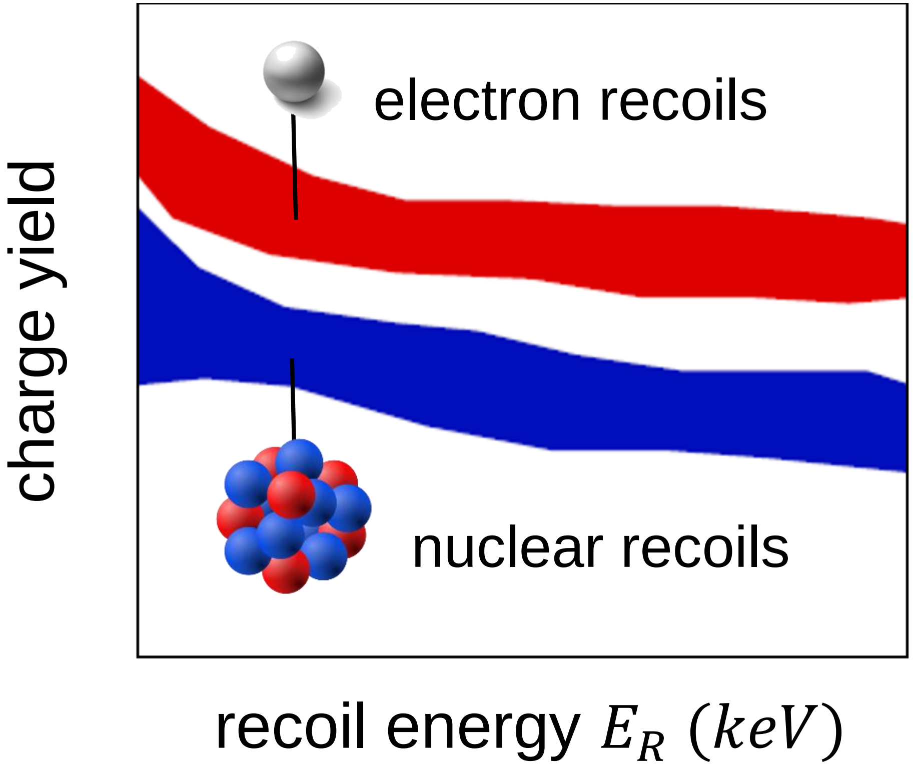
⇨ **no charge recombination (no quenching)**

⇨ **larger charge signal for electron recoils**

Particle discrimination via quenching

- **The quenching effect due to different dE/dx is key to successful PID***

  - quenching observed for charge signal (scintillation light treated separately)



- quenching of charge signal: typically **factor 3 … 4**

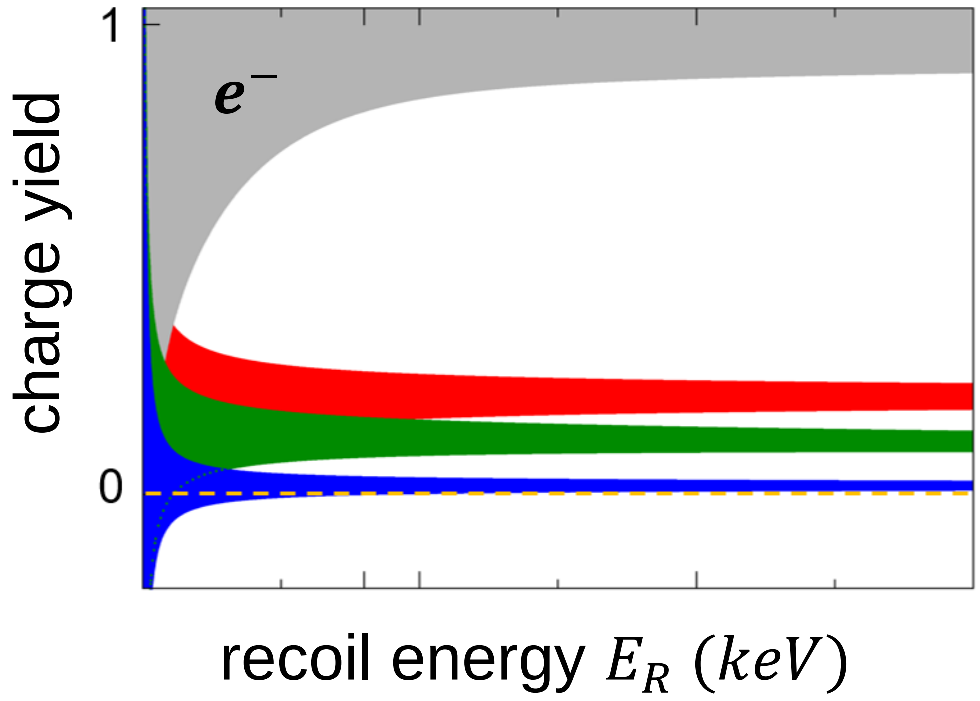
- **IMPORTANT**: the **phonon signal** remains ´**unquenched**´ for all particle species $(p, {}^{A}Z, e^{-})$, ⇨ this allows to **determine recoil energy** E_R

* Particle IDentification

Particle discrimination via quenching

- **The quenching effect due to different dE/dx is key to successful PID**

  - quenching observed for charge signal (scintillation light treated separately)



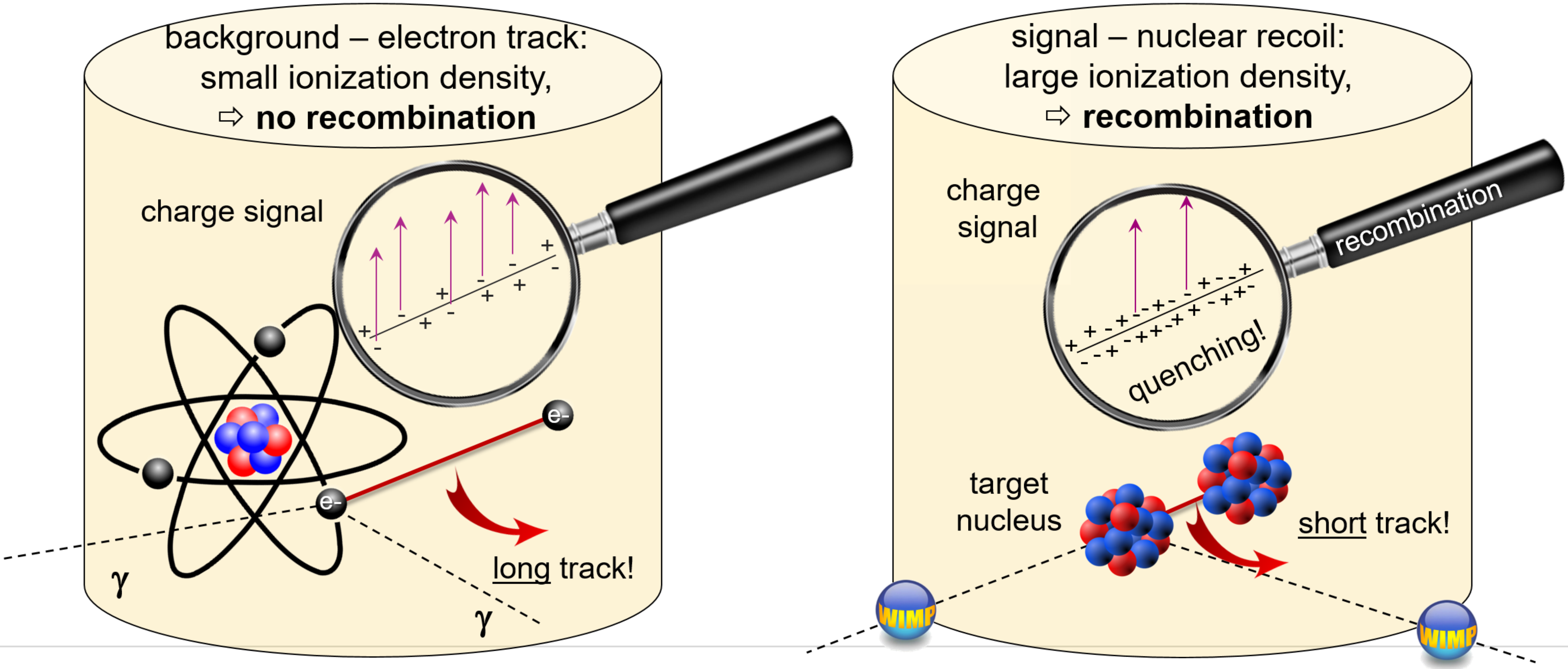
- quenching of charge signal: typically **factor 3 … 4**

α
light
heavy

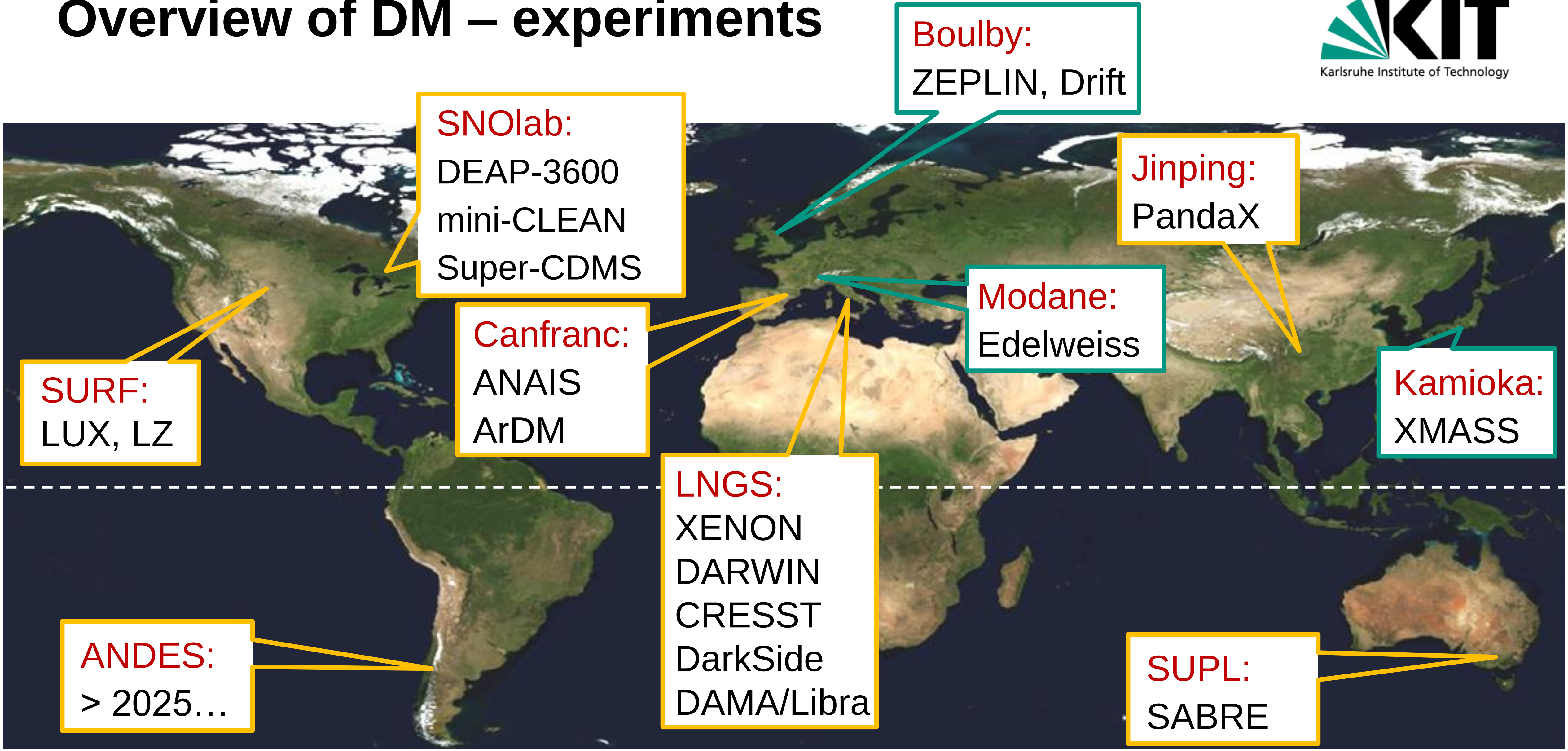
for **heavy nuclei** the quenching becomes stronger due to their larger dE/dx **& very small range**

Particle discrimination via quenching

- **The quenching effect due to different dE/dx is key to successful PID**



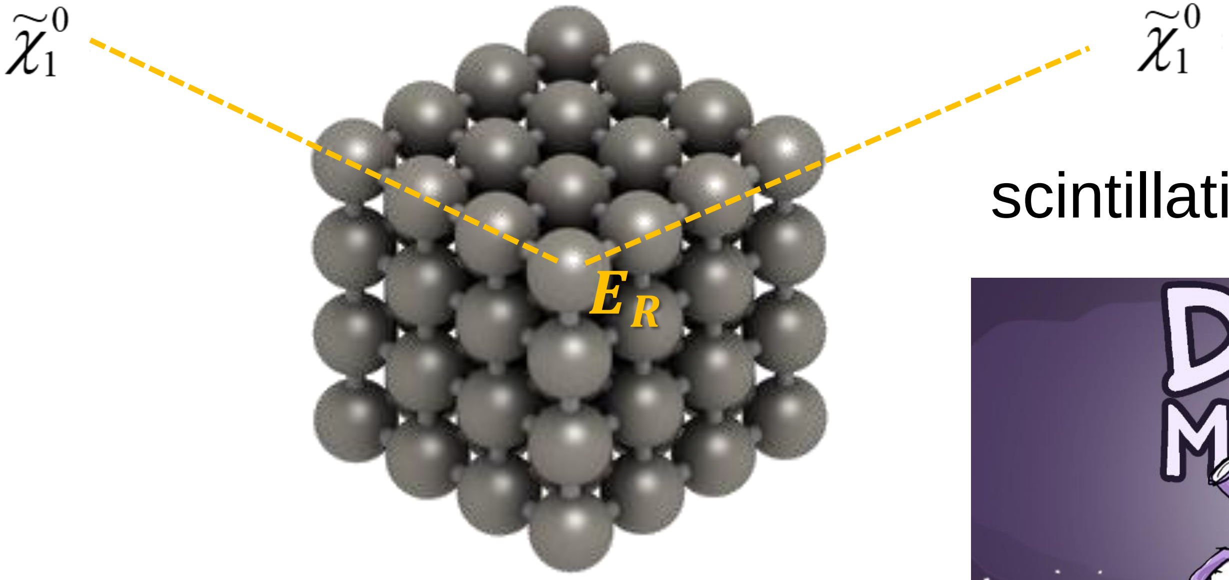
Overview of DM – experiments



Search for DM: a competitive field worldwide

- **Many different technologies & detectors have been & will be developed**

  - how can we best compare the sensitivities of different experiments?



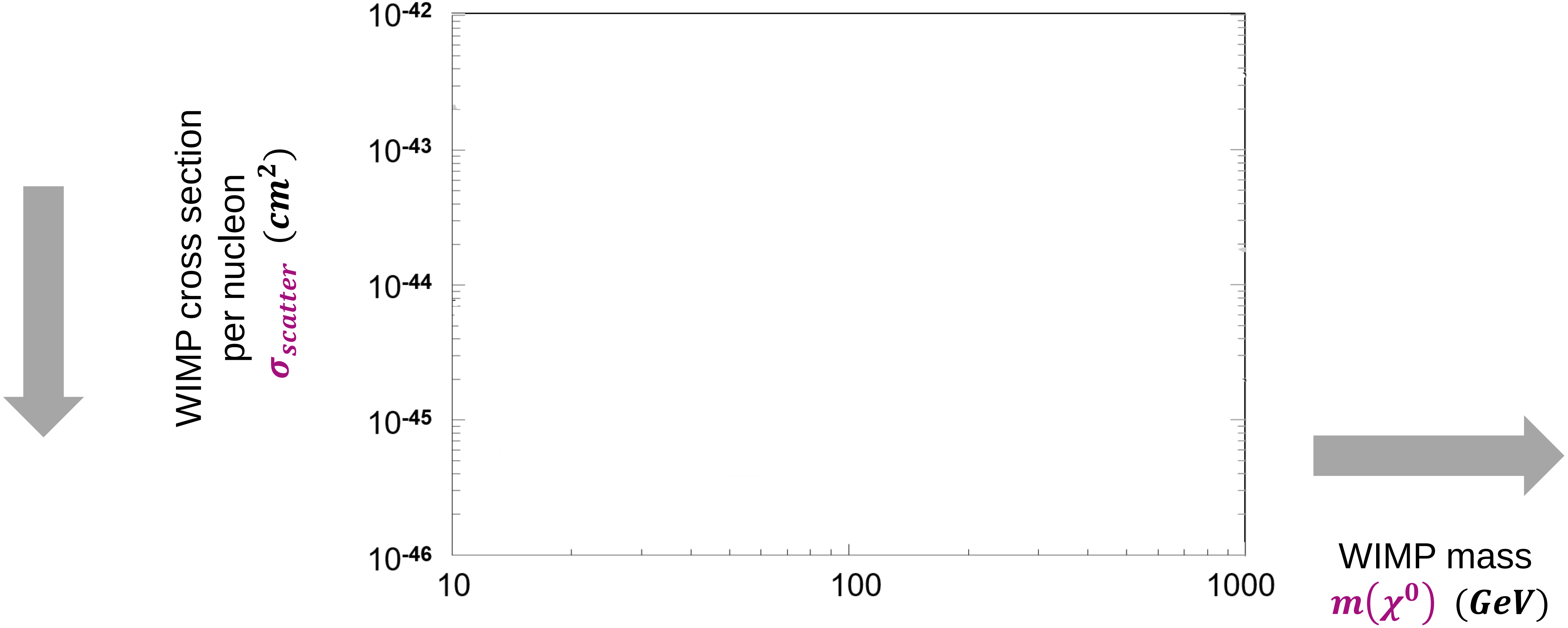
electrons

phonons

scintillation - **photons**

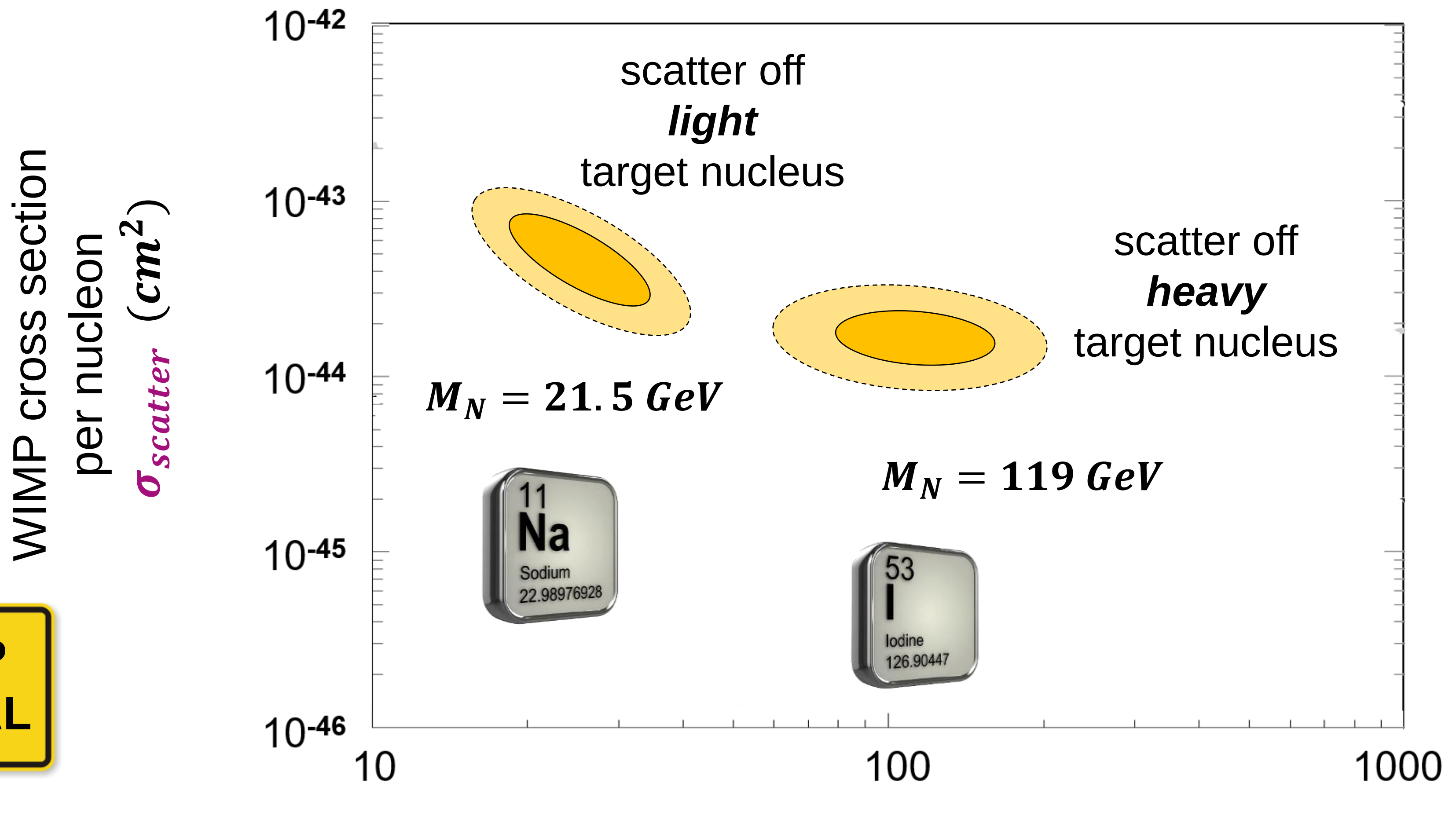
Introducing the famous ´WIMP´ plot

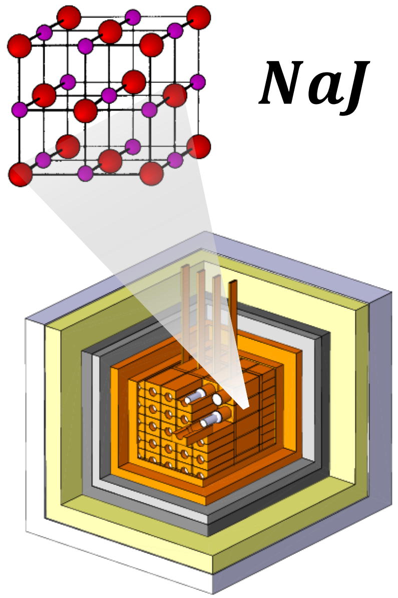
- Comparing different experiments in a 2-parameter plot:



WIMP plot in case of a signal (claim)

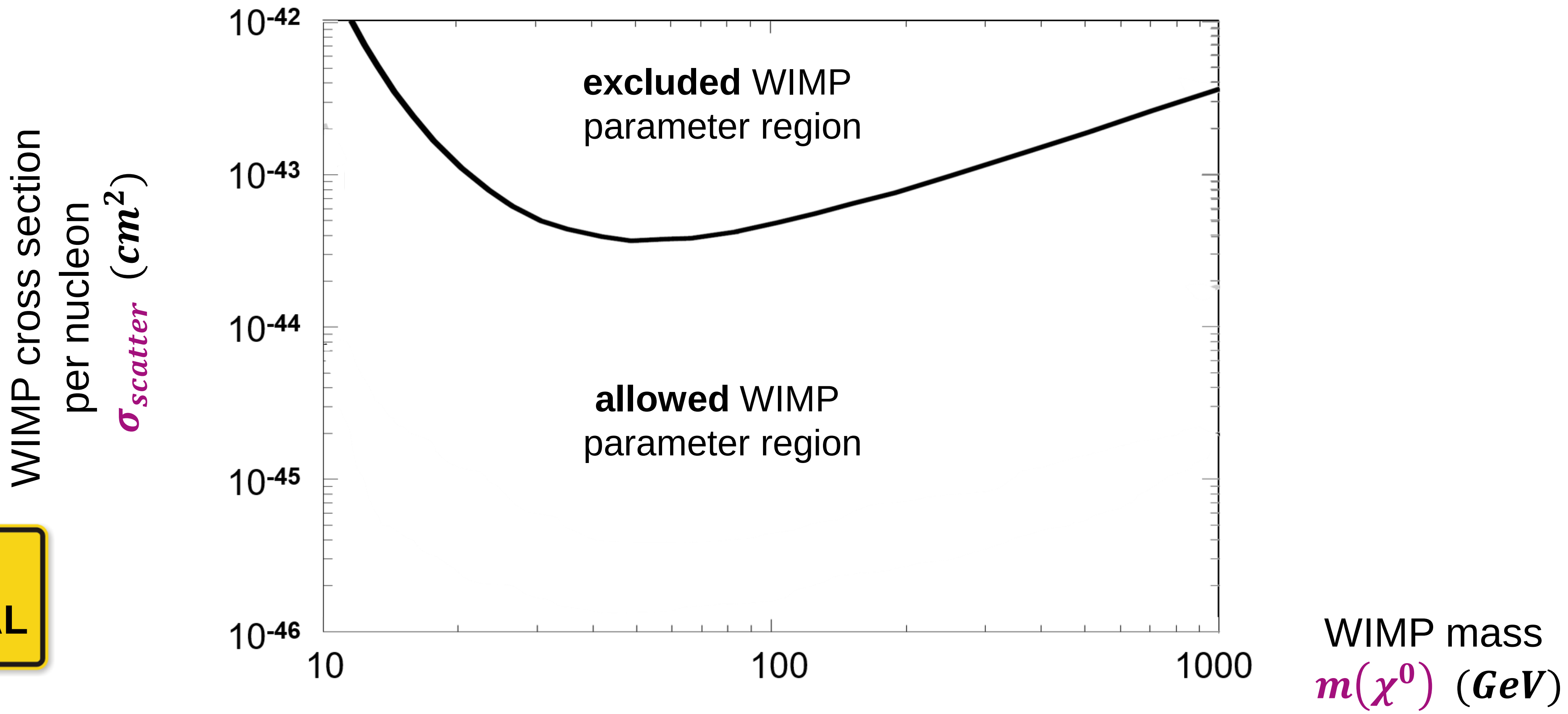
- **We are claiming an evidence for a DM-signal: error ellipses for $m(\chi^0), \sigma_{scatter}$**





WIMP plot in case of no signal

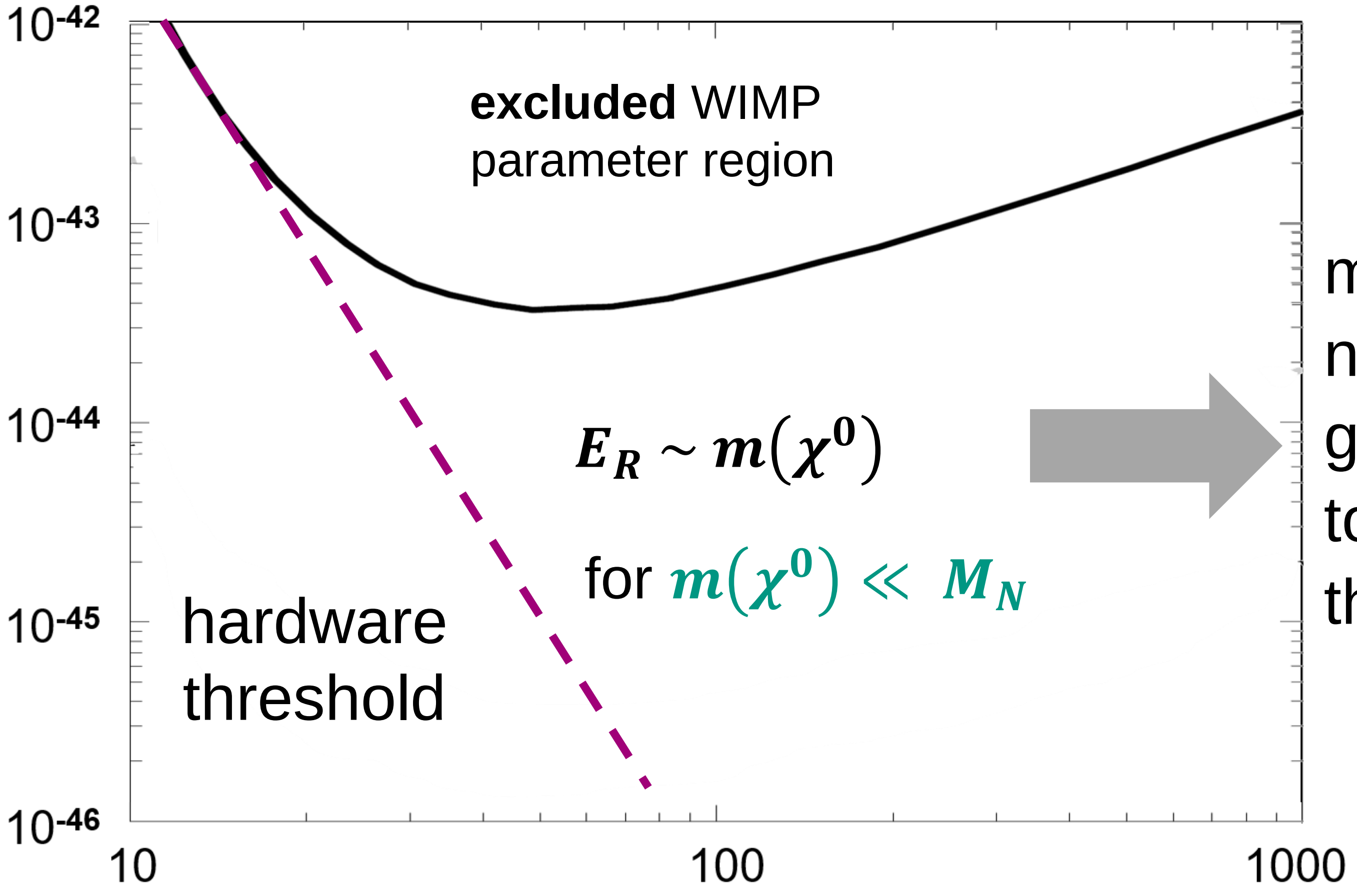
- **We see no signal above background and draw an exclusion curve $(90\% CL)$**



WIMP plot in case of no signal: light WIMPs

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

WIMP cross section per nucleon $\sigma_{scatter}$ (cm^2)

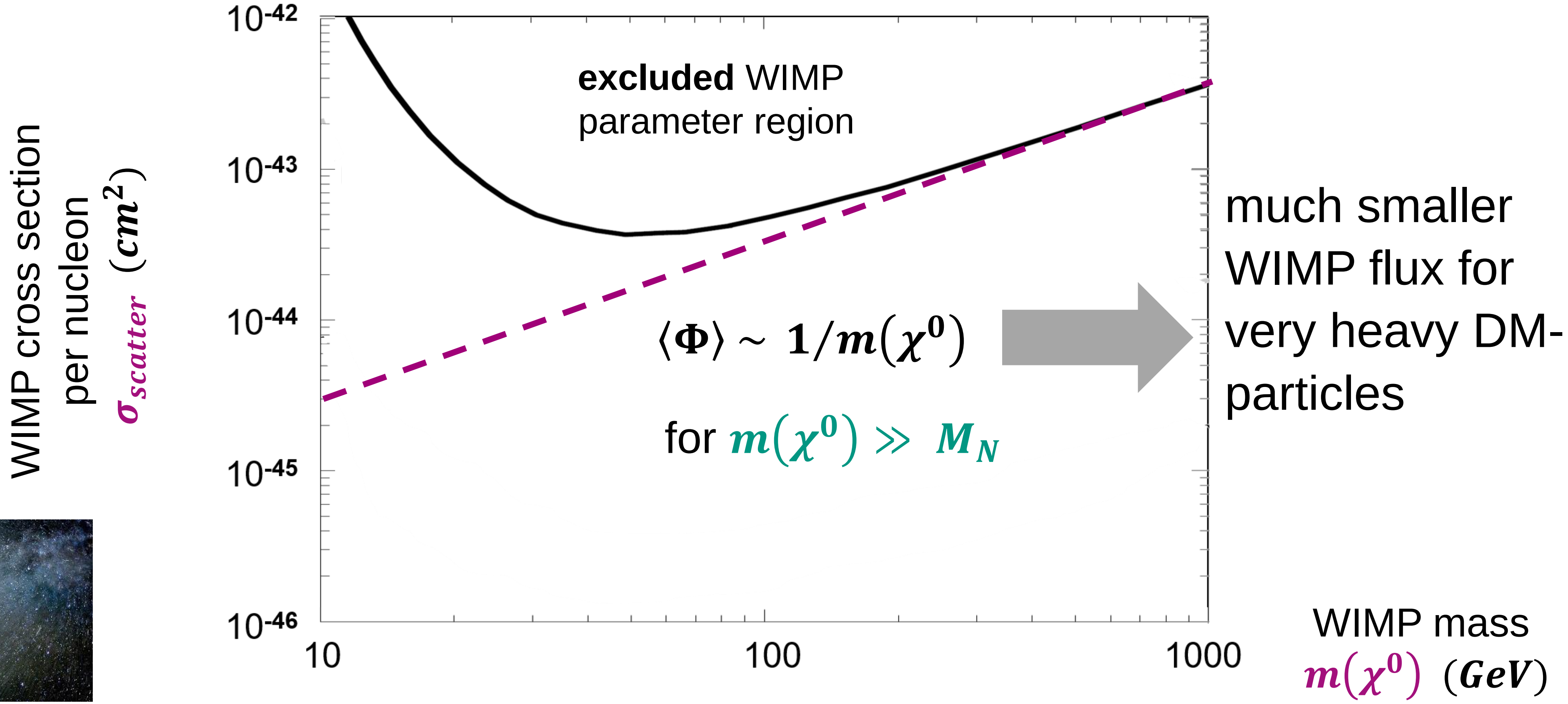


much smaller nuclear recoil E_R gets ever closer to hardware threshold E_{thres}

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

WIMP plot in case of no signal: heavy WIMPs

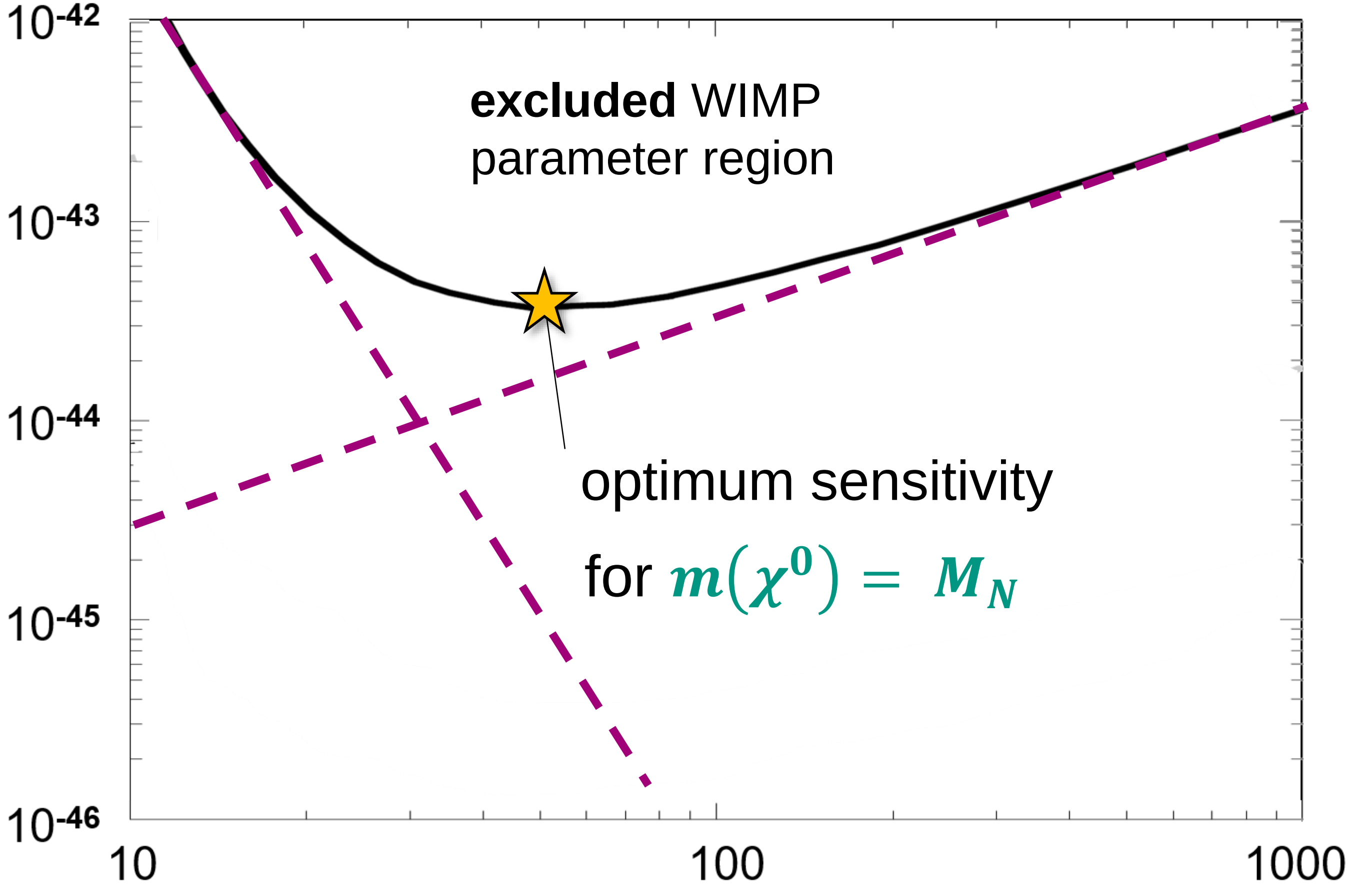
- **For very heavy WIMPs our sensitivity decreases: an effect of the WIMP-flux**

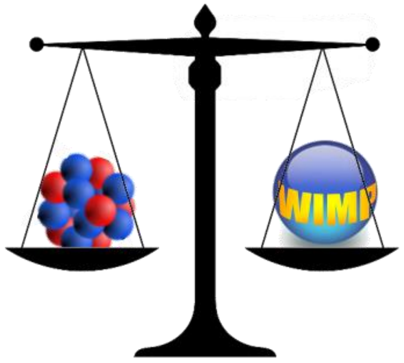


WIMP plot in case of no signal: all WIMP masses

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

WIMP cross section per nucleon $\sigma_{scatter}$ (cm^2)

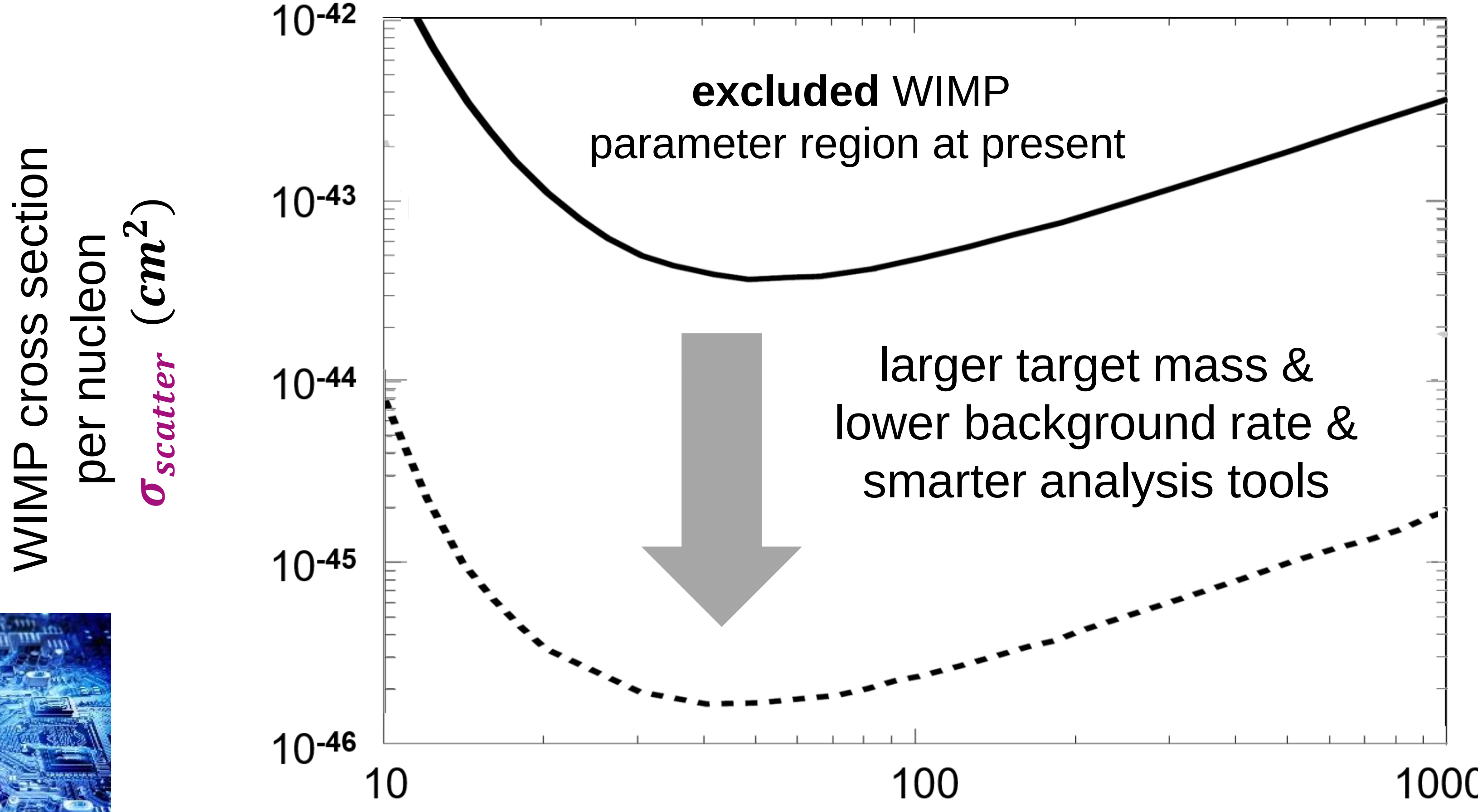


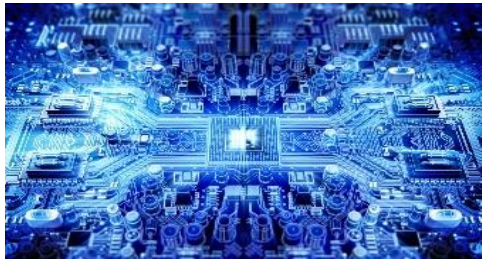


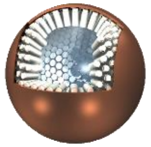
WIMP mass $m(\chi^0)$ (GeV)

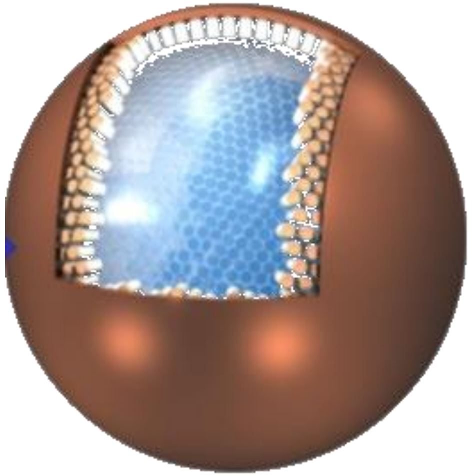
WIMP plot in case of no signal: better sensitivity

- **For better sensitivity the DM detector should be larger & background smaller**



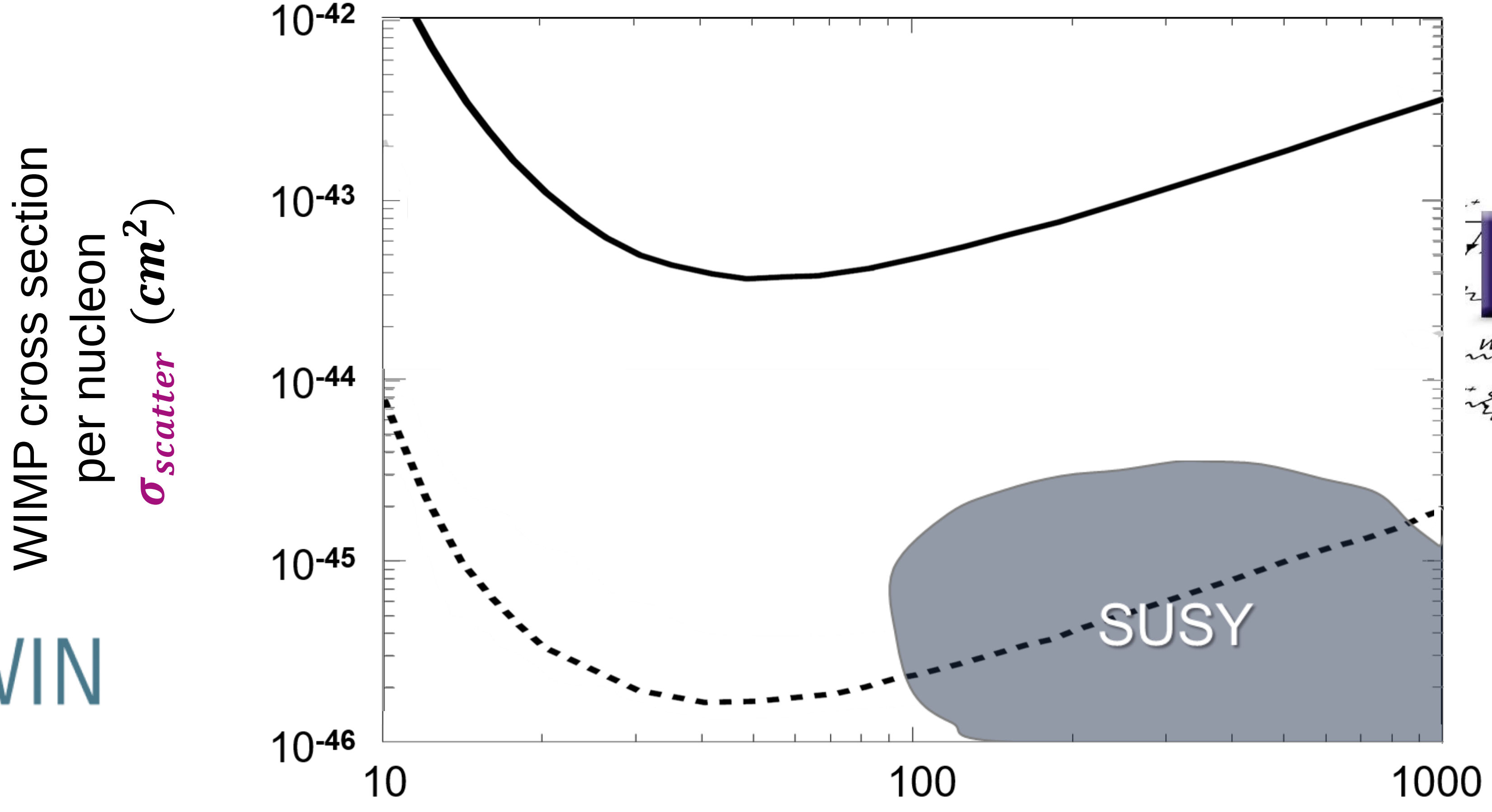


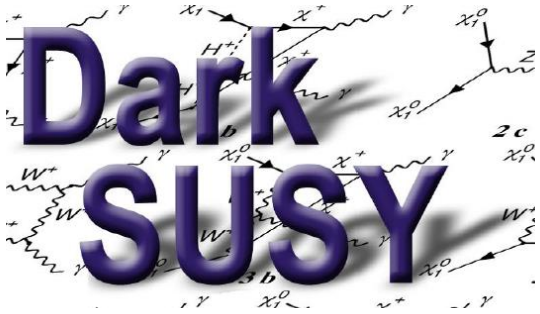




WIMP plot in case of no signal: theory responds

- The ´preferred´ $SUSY$ – parameter space is ´readjusted´ from time to time





DARWIN