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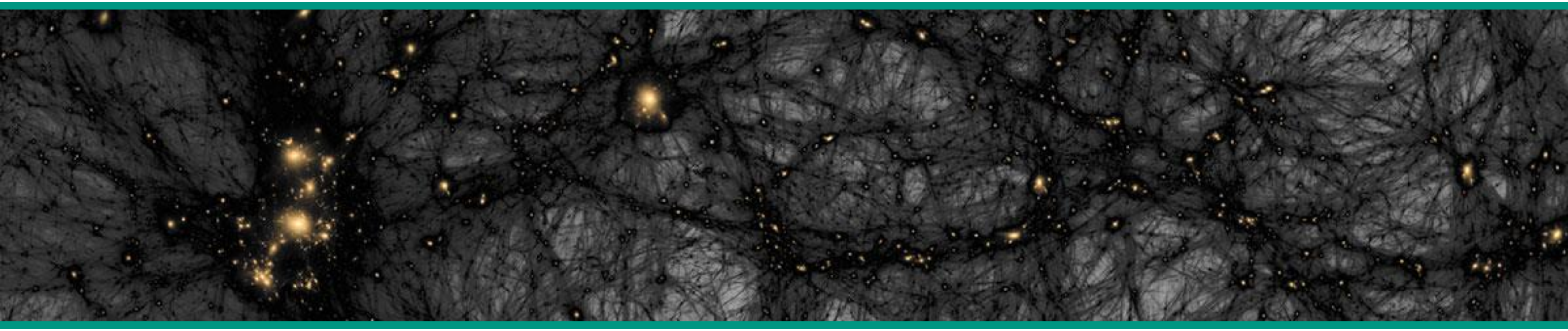
Astroparticle physics *I* – Dark Matter

Winter term 23/24 Lecture 16 Jan. 17, 2024



Recap of Lecture 15

- **Indirect and direct searches for $CDM - neutralinos$**

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

  - $WIMP -$ burning stars: a few close to galactic center?

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

  - $WIMP$ interactions: σ_{SI}: via scalar Higgs (mass) h, H ⇔ σ_{SD}: via spin-1 Z^0

  - cross section: $d\sigma_{SI}/dq^2 \sim A^2 \cdot F(q^2)$ ⇨ large nucleus, low–momentum transfer **coherent interaction** ⇨ long ***de–Broglie*** wavelength

Direct detection of $WIMPs$: form factor $F(q^2)$

- $\boldsymbol{Neutralino}$ **interactions: the important condition for** $\boldsymbol{coherent\ scattering}$

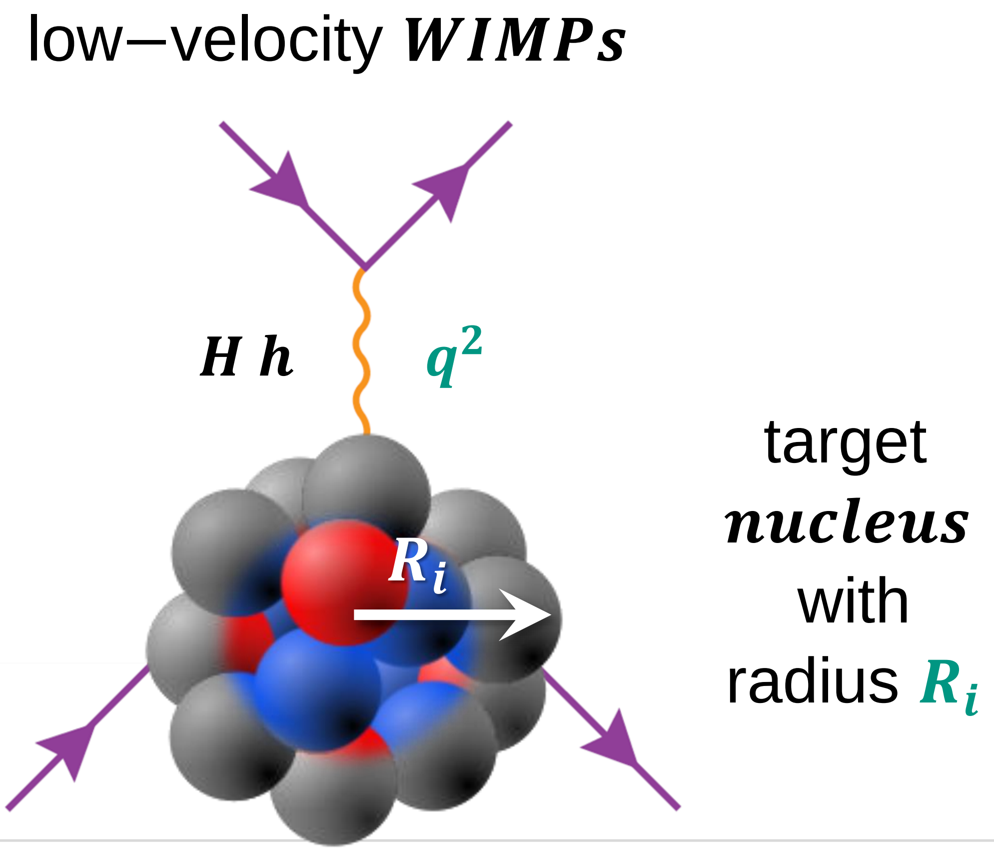
$$\boxed{\frac{d\sigma_{SI}}{dq^2} \sim A^2 \cdot F(q^2)}$$

- scattering amplitudes only add $\boldsymbol{coherently}$,
in case the **following condition** is fulfilled:

$$\boxed{q \cdot R_i \ll 1}$$ (typcially only for $A < 50$)

momentum transfer $q \sim A \cdot 10^{-3}\ GeV$

$\boldsymbol{nuclear}$ radius $R_i \sim A^{1/3} \cdot 7\ GeV^{-1}$



$WIMP$ scattering: impact of form factor $F(q^2)$

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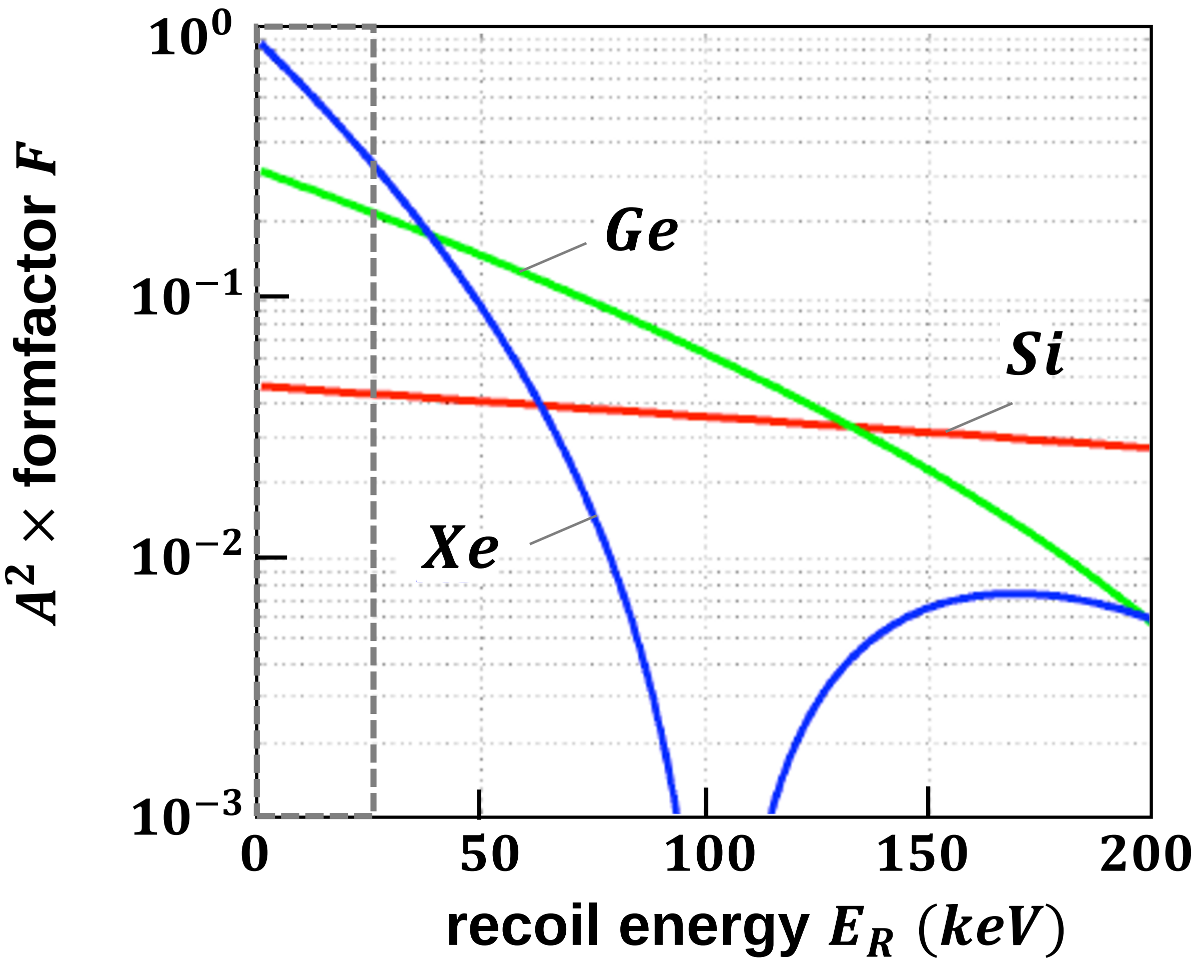
- **high recoil energies E_R: implications of the loss of coherence**

- we aim for heavy nuclei with **large A** & large nuclear radius R_i (⇨ $Xenon$)

- **challenge**: the loss of coherence already starts at rather small values of the momentum transfer q^2 (or nuclear recoil energy E_R)

$$\frac{d\sigma_{SI}}{dq^2} \sim A^2 \cdot F(q^2)$$

extremely low energy threshold required



$WIMP$ scattering off nuclei: interaction via Z^0

- $Neutralinos$ **can also interact via a different exchange particle:** Z^0

  - **spin–dependent** interaction

    ⇩

    σ_{SD}: Spin Dependent

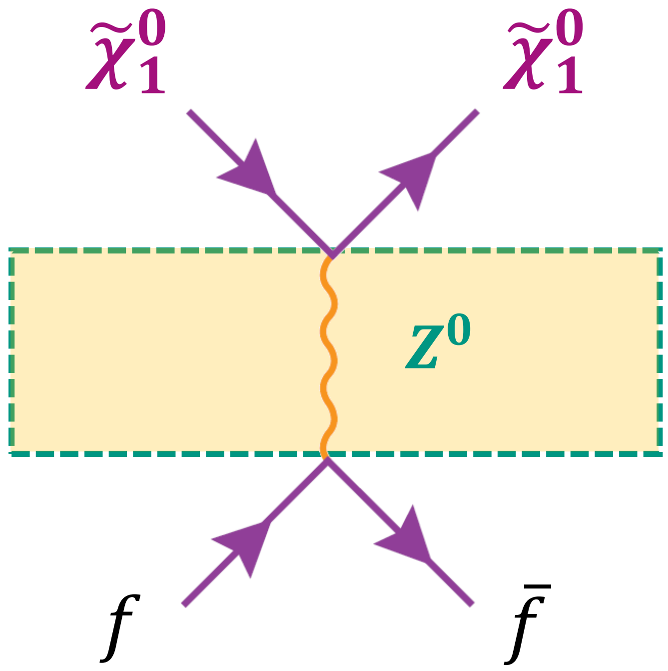
  - exchange of an intermediate **vector boson Z^0** with **spin $S = 1$**

  - many $SUSY$ models ´favour´ Z^0 :

    ⇨ we expect rather ´large´ couplings

$neutralinos$

$S = 1$



collision kinematics

$WIMP$ scattering off nuclei: spin–dependent

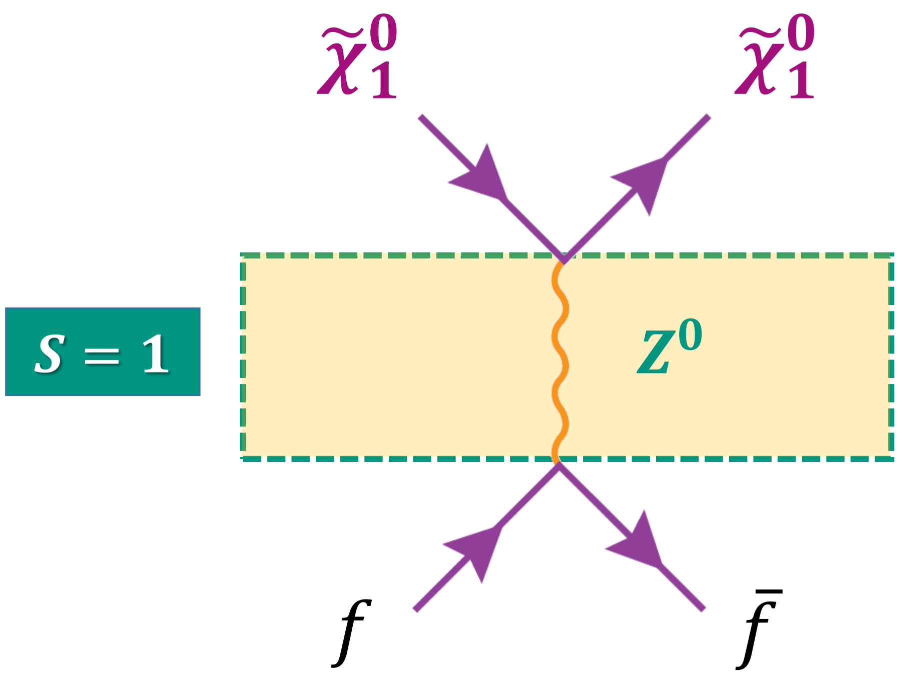
- $Neutralinos$ **can couple to the overall spin J of a nucleus via Z^0 exchange**

  - **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 $SUSY$ models ´favouring´ Z^0 : we expect **small contributions** of σ_{SD} to total elastic $WIMP$ – scattering $xsec$

$neutralinos$

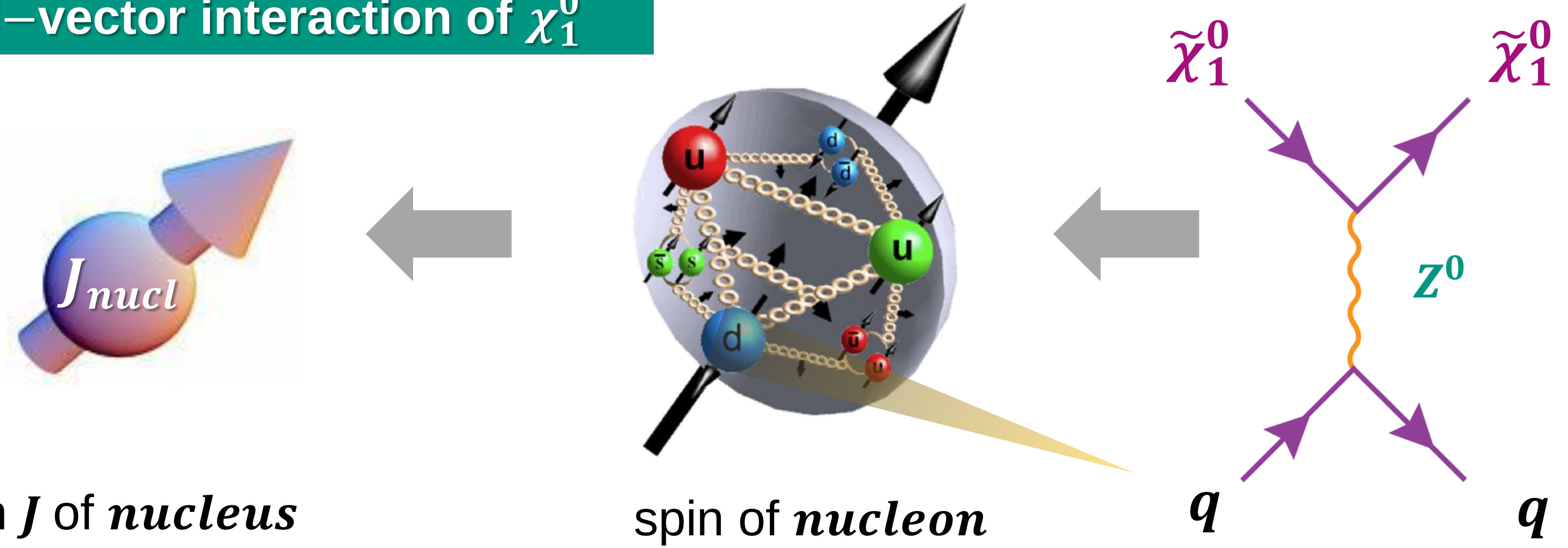


collision kinematics

$WIMP$ 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



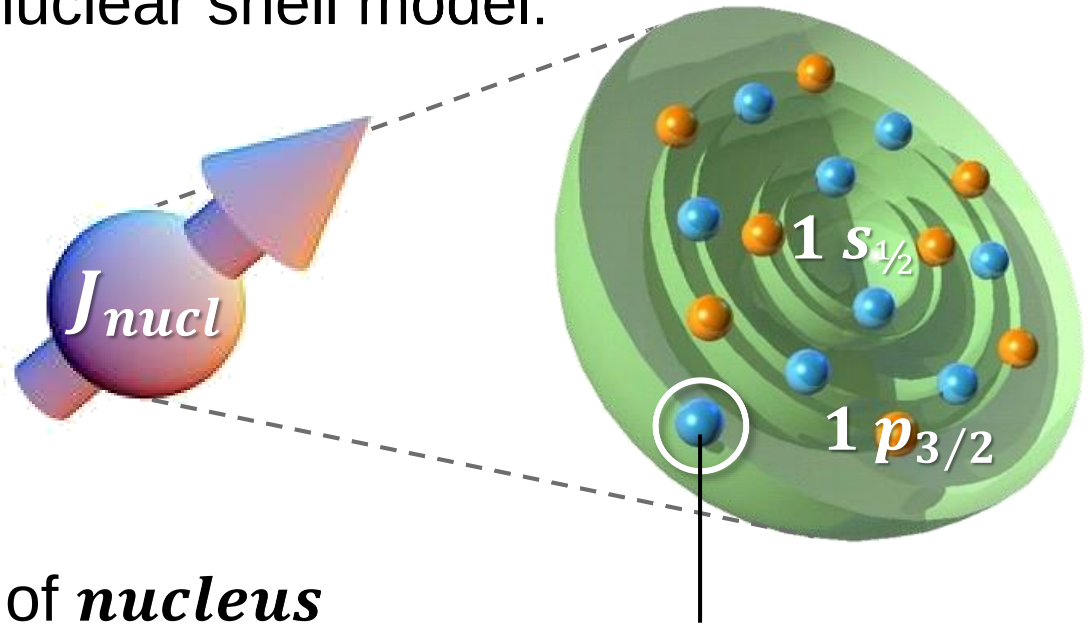
spin J of $nucleus$ ($nucleons$)

spin of $nucleon$ ($quarks$)

RECAP: Spin J of a nucleus & nucleon spins

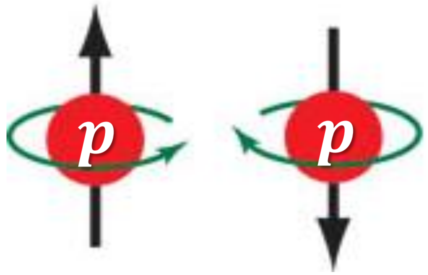
- ***Nucleons*** **inside a *nucleus* are paired: nuclear spin from *unpaired nucleon***
  - nuclear spin J arises from total angular momentum L of ***unpaired nucleon***

nuclear shell model:



spin J of ***nucleus***
(nucleons)

unpaired nucleon



coupling to
$J = 0$

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

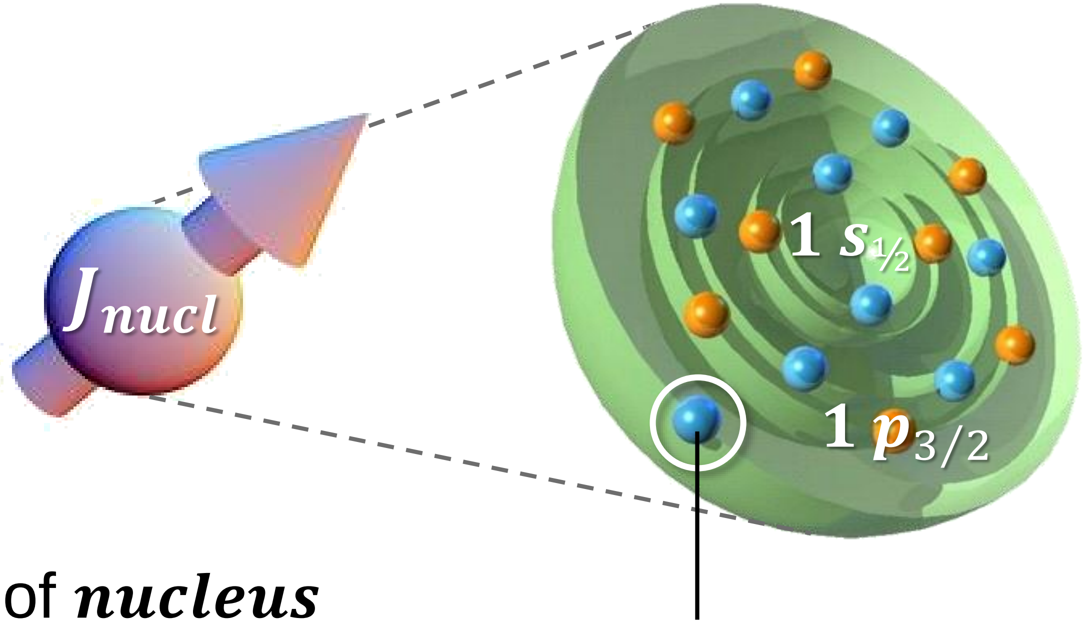
two p, n couple ($\Delta E \sim 2\ MeV$)
⇨ $gg/ug/uu$ – nuclei

Suitable detector materials for σ_{SD}

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

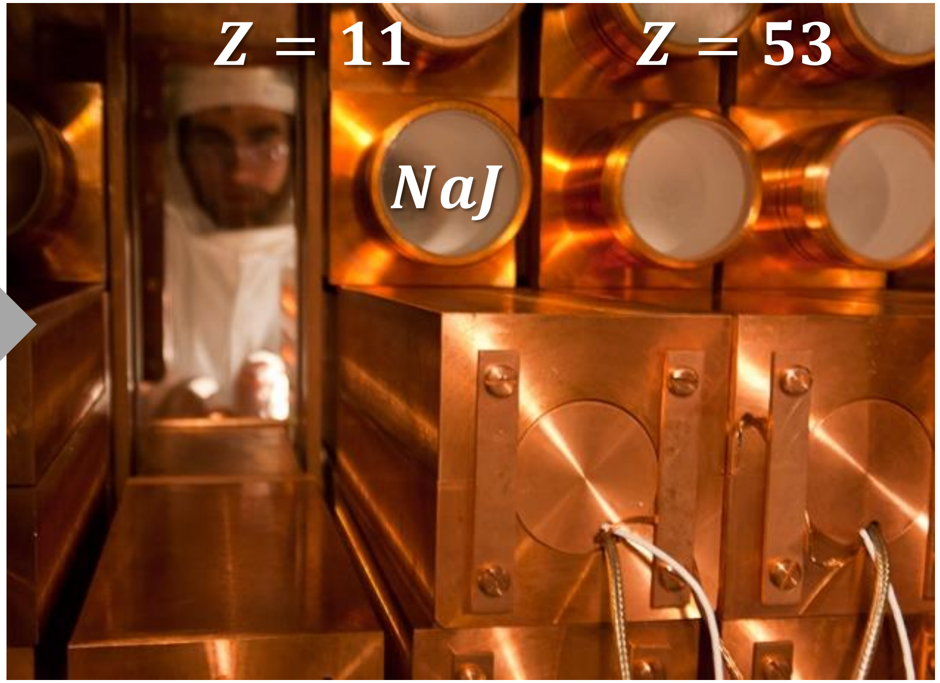
  - **nuclear spin J** due to ***unpaired nucleon***

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



spin J of ***nucleus***
(nucleons)

unpaired nucleon



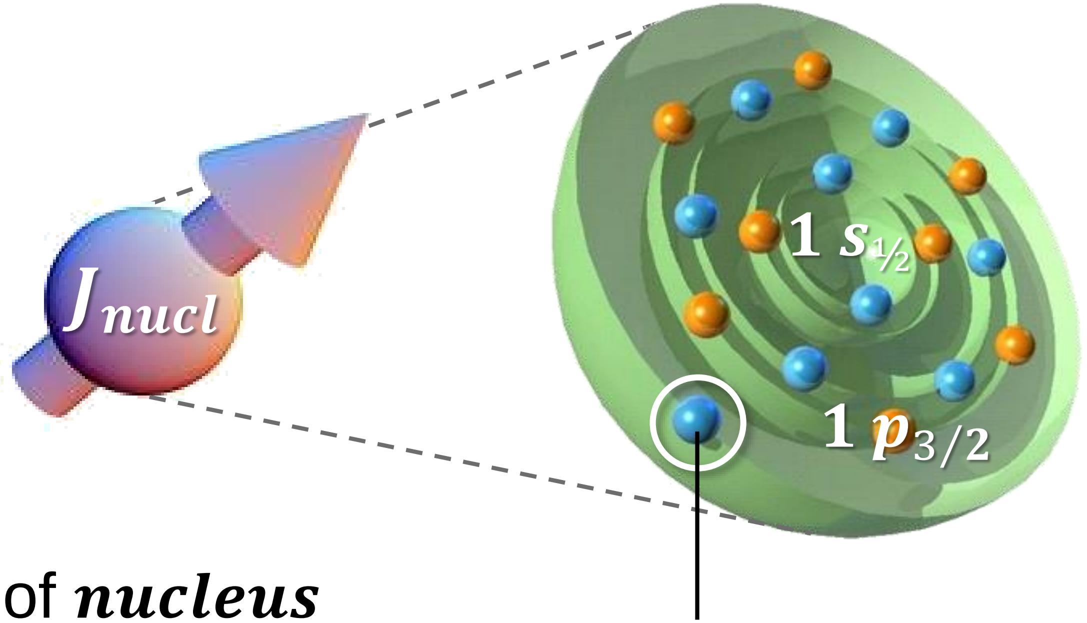
anorganic scintillators (***DAMA – Libra***)

Suitable detector materials for σ_{SD}

- **Nuclei with $\mathit{unpaired\ nucleon}$ that can be used as $WIMP$ detector**

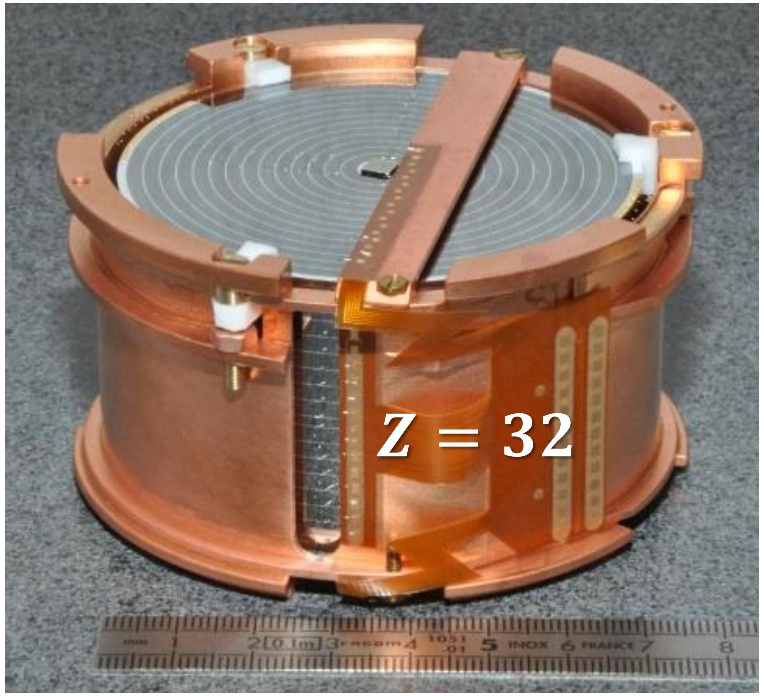
  - nuclear spin J due to $\mathit{unpaired\ nucleon}$

$^{73}Ge\ \ (7.76\%)$



spin J of $\mathit{nucleus}$
(nucleons)

$\mathit{unpaired\ nucleon}$

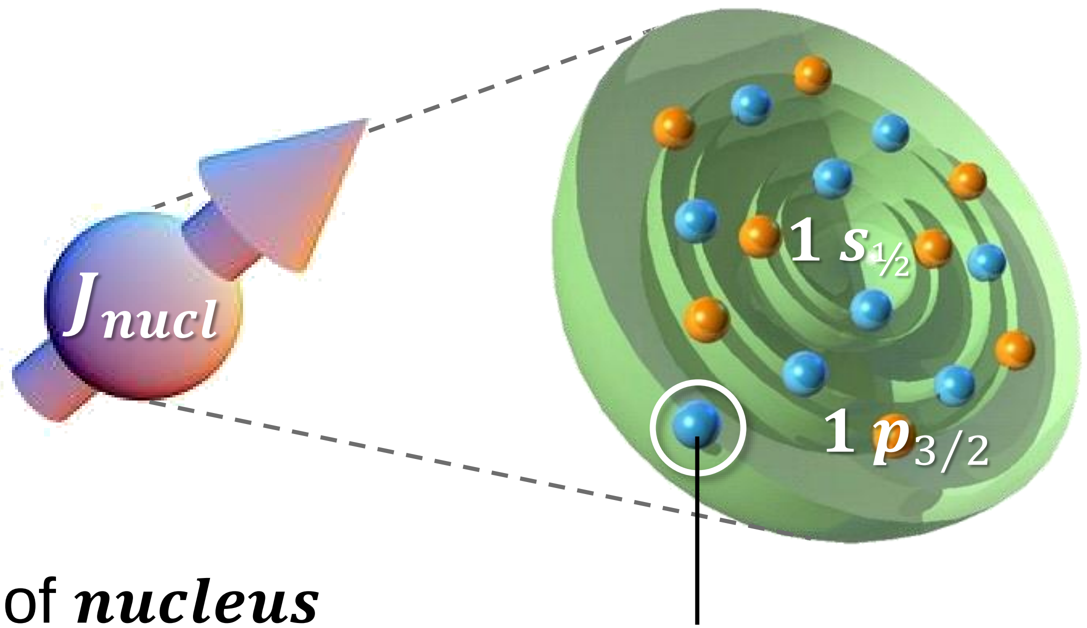


solid−state detector ($\mathit{Edelweiss}$)

Suitable detector materials for σ_{SD}

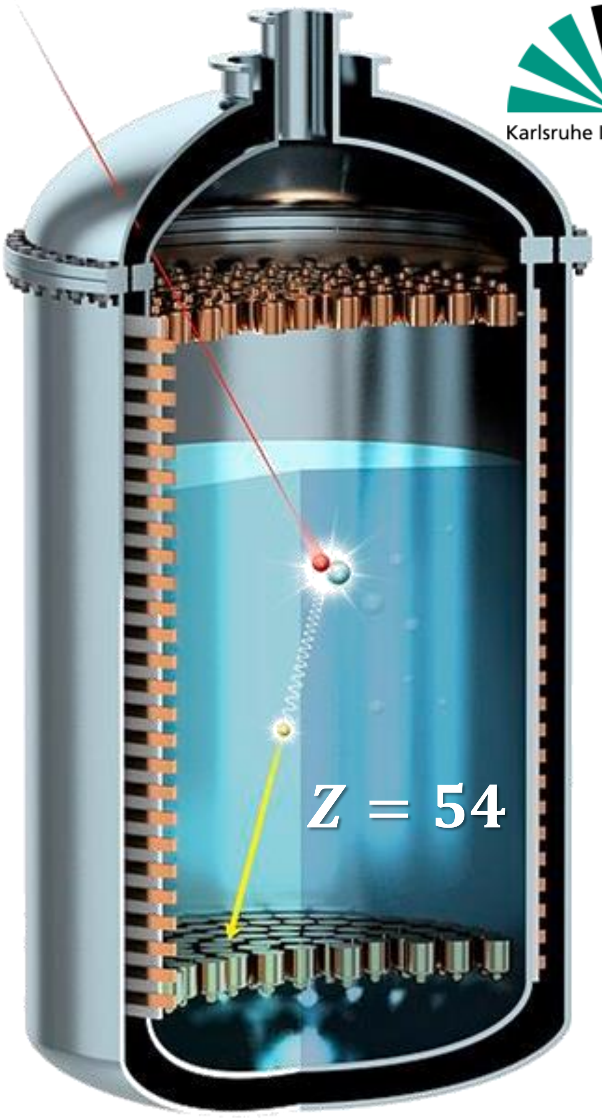
- **Nuclei with $\boldsymbol{unpaired\ nucleon}$ that can be used**

  - **nuclear spin J** due to $\boldsymbol{unpaired\ nucleon}$



spin J of $\boldsymbol{nucleus}$
(nucleons)

$\boldsymbol{unpaired\ nucleon}$



^{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)

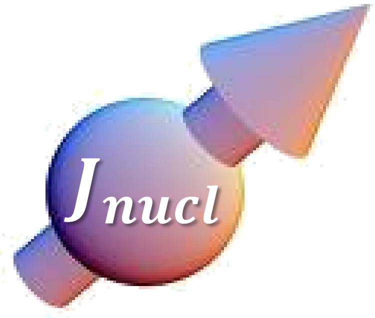
detector type	isotope	fraction	protons	neutrons	spin J	coupling
NaJ	^{23}Na	100%	11	12	$3/2$	a_p
(scintillator)	^{127}I	100%	53	74	$5/2$	a_p
LXe	^{131}Xe	21.2%	54	77	$3/2$	a_n
(liquid TPC)	^{129}Xe	26.4%	54	75	$1/2$	a_n
Ge (bolometer)	^{73}Ge	7.8%	32	41	$9/2$	a_n

Spin−dependent $WIMP$ scattering cross section

- **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



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

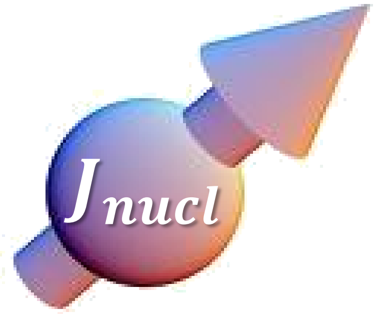
⇨ **spin ´enhancement´ factor** (typcially $\mathbf{0.2 \ldots 0.5}$)

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

The spin ´enhancement´ factor C_{spin}

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

$a_{p,n}$: $WIMP$ – 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)



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

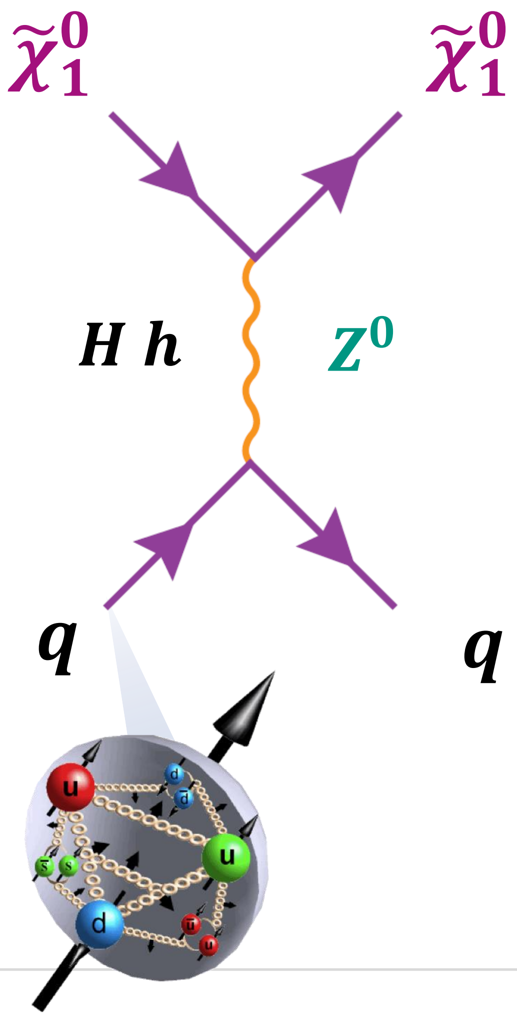
$\langle S_{p,n} \rangle$: **expectation values** for p, n – spin in a target nucleus
(follows from detailed shell model calculations)

J : nuclear 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 $\boldsymbol{parton}$ level to $\boldsymbol{nucleons}$ then to the $\boldsymbol{nucleus}$



1 – level of $\boldsymbol{partons}$: q, g

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

2 – level of $\boldsymbol{nucleons}$: p, n

kinematics & spin within a $\boldsymbol{nucleon\ p, n}$ determined via $\boldsymbol{parton}$ – 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 $\boldsymbol{parton}$ level to $\boldsymbol{nucleons}$
    then to the $\boldsymbol{nucleus}$

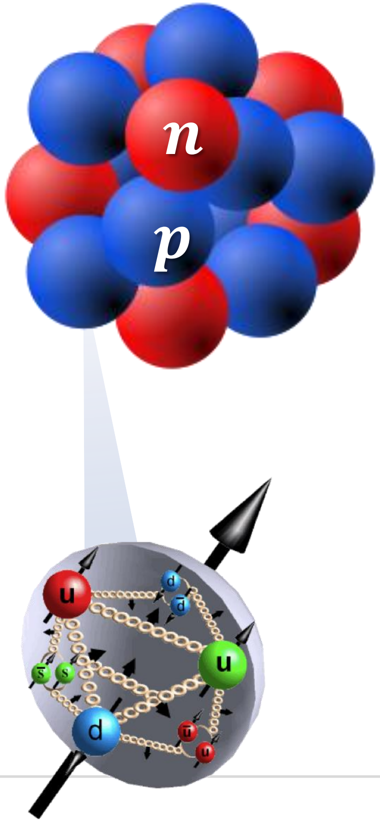
3 – level of $\boldsymbol{nuclear}$ structure: $\boldsymbol{Ar, Ge, Xe, \ldots}$

χ^0 – interaction with $\boldsymbol{nucleus}$

⇨ nuclear wave function
using nuclear shell model

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

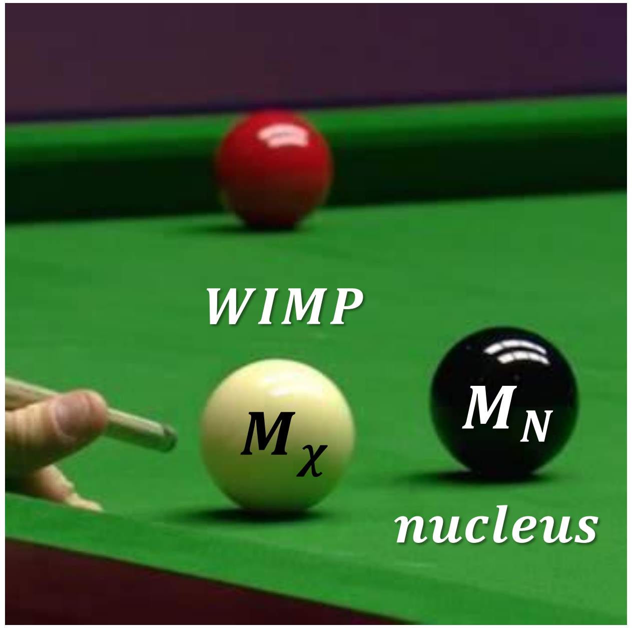
- kinematics of process – **coherent nuclear recoil**



More details on the elastic nuclear recoil

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

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

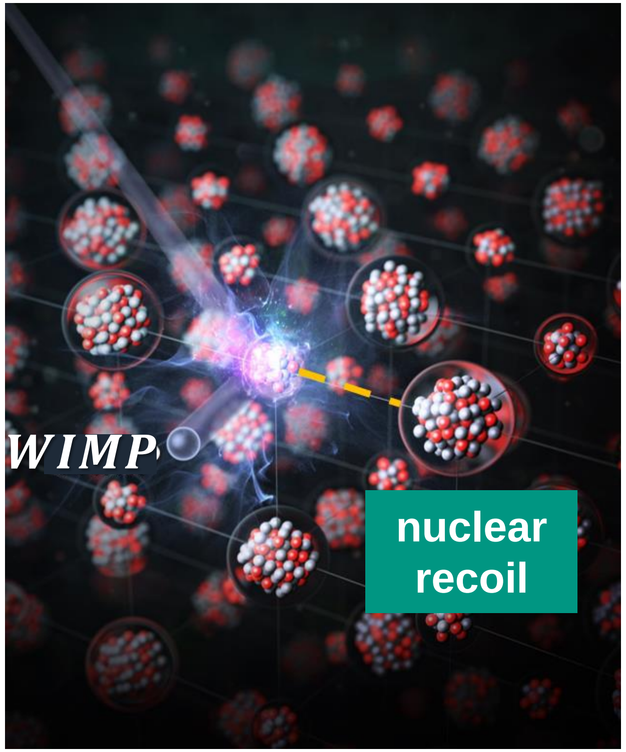


- **parameters**:

  $\boldsymbol{a}$) relative velocities

  $\boldsymbol{b}$) masses $\boldsymbol{M_\chi}$ and $\boldsymbol{M_N}$

  $\boldsymbol{c}$) scattering angle $\boldsymbol{\theta}$



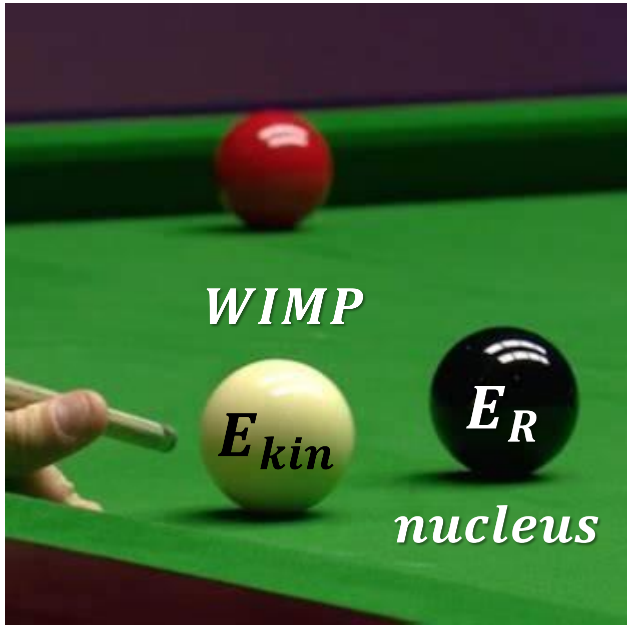
* see Classical Exp. Phys. $\boldsymbol{I}$

Reaction kinematics of $WIMP$ scattering

- We can use non–relativistic kinematics due to rather small $WIMP$ velocities

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

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**

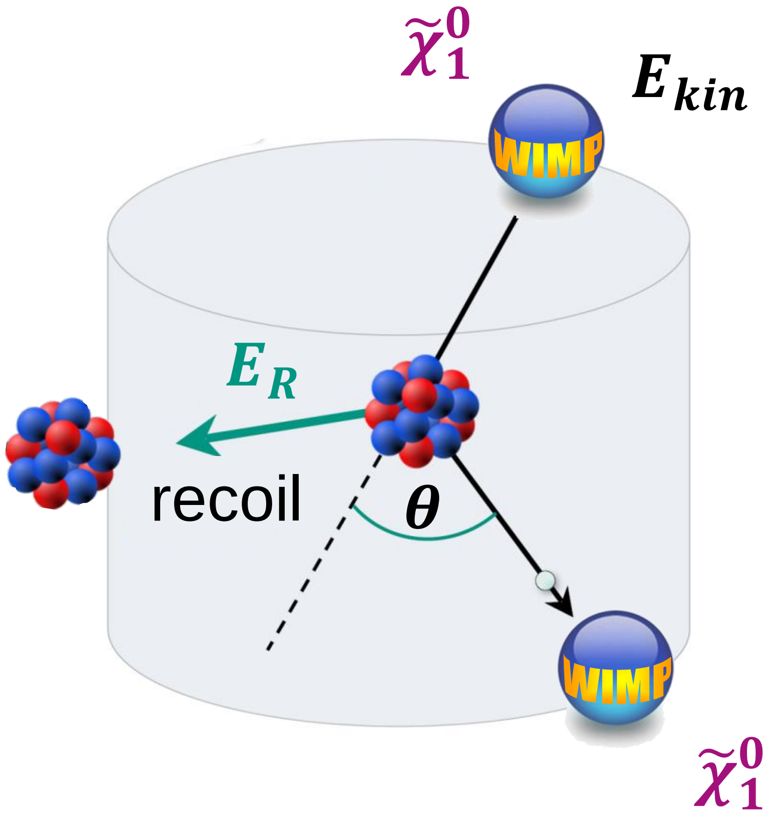
$$\boxed{E_R = 2 \cdot \frac{\mu}{M_\chi + M_N} \cdot E_{kin} \cdot (1 - cos\theta)}$$

E_R: recoil energy of $nucleus$ (usually in keV)

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

μ: reduced mass of $WIMP - nucleus$ system

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



Reaction kinematics: equal masses

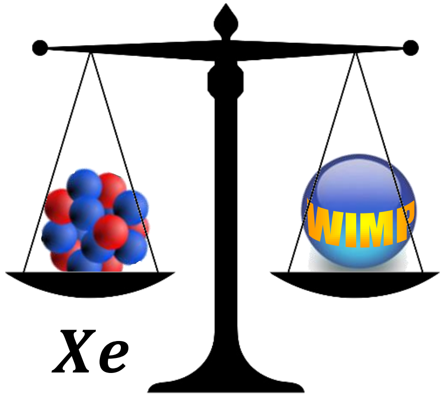
- **Optimum transfer of energy & momentum which maximises E_R for given E_{kin}**

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

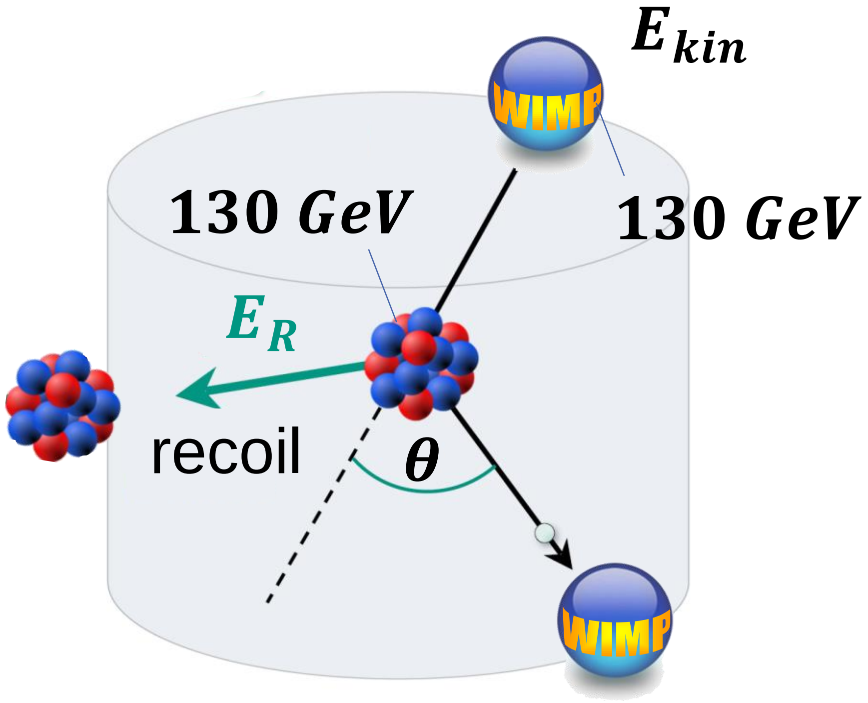
\- **identical** mass scale

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

⇨ 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

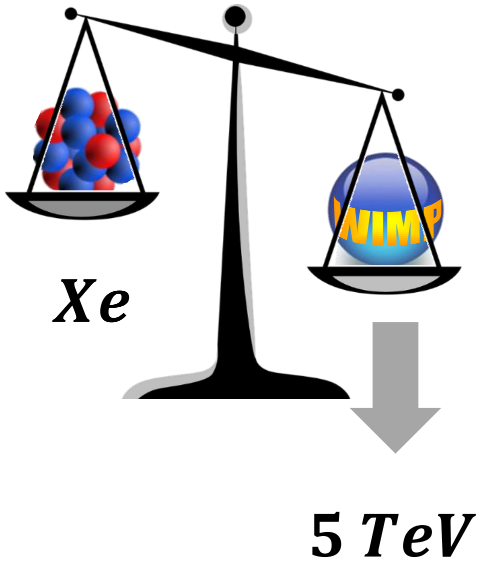
$$\boxed{E_{R,max} = 2 \cdot M_N \cdot \beta^2}$$

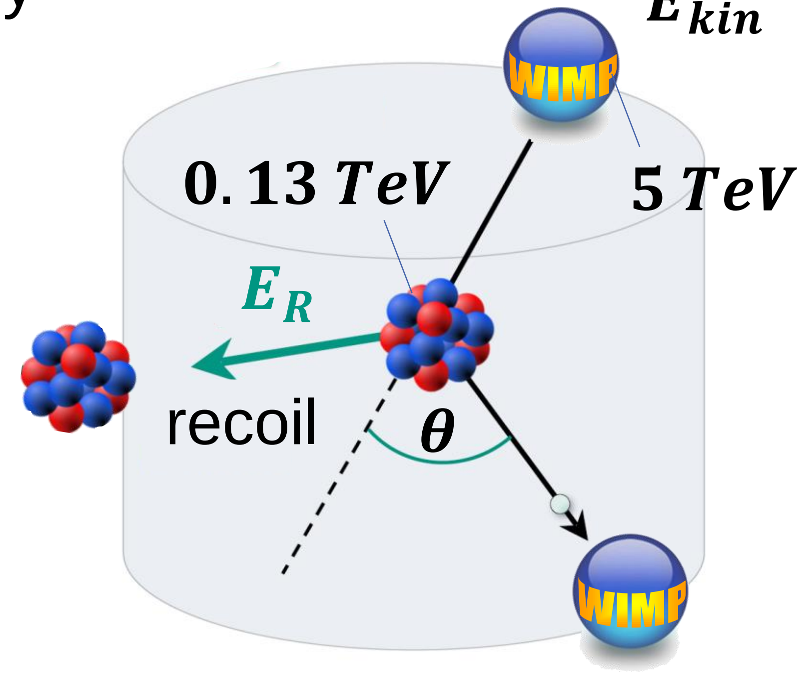
- **non−identical** mass scale

$$M_\chi \gg M_N : \ \mu = M_N$$

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

only $4 \times$ larger energy





χ^0 – scattering off electrons: is it relevant?

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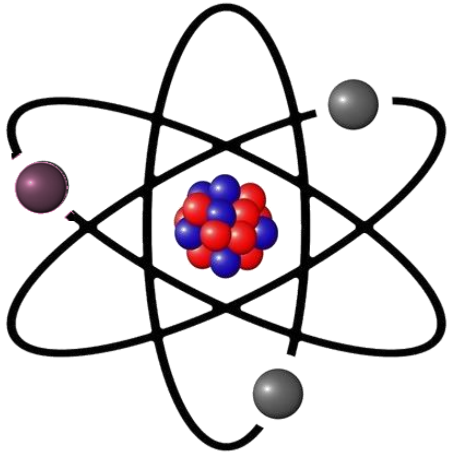
- **Why can´t we simply use electrons as target for $WIMP$ scatterings?**

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

M_e



- **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)

$WIMP$ 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: what 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?

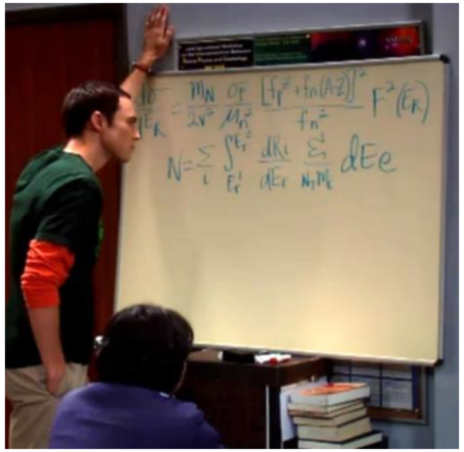
c) how **many $WIMP$ scatterings** will my detector see?

$WIMP$ scattering in an actual DM – detector

- **We first calculate the rate R of elastic $WIMP$ scatterings**

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

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



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

(or $\boldsymbol{DM}$ – halo velocity v)

cross section as function of kinetic energy E_{kin}

averaged values

$WIMP$ scatterings as function of recoil energy E_R

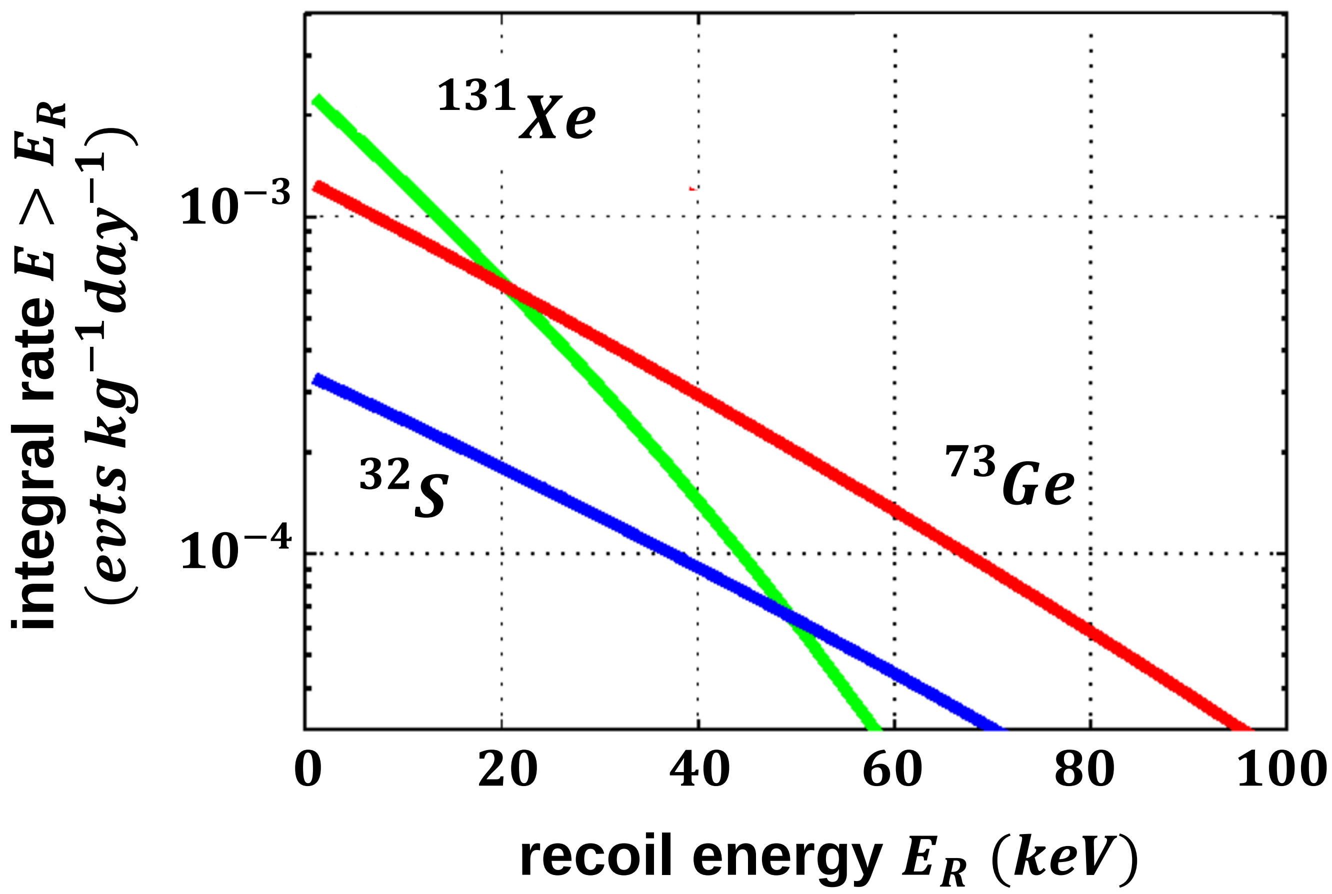
- **We now focus on integrated rate of events above a specific threshold $E > E_R$**

- 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 employ a flux−averaged value $\sigma_{SD} = 3.6 \cdot 10^{-45}\ cm^2$

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



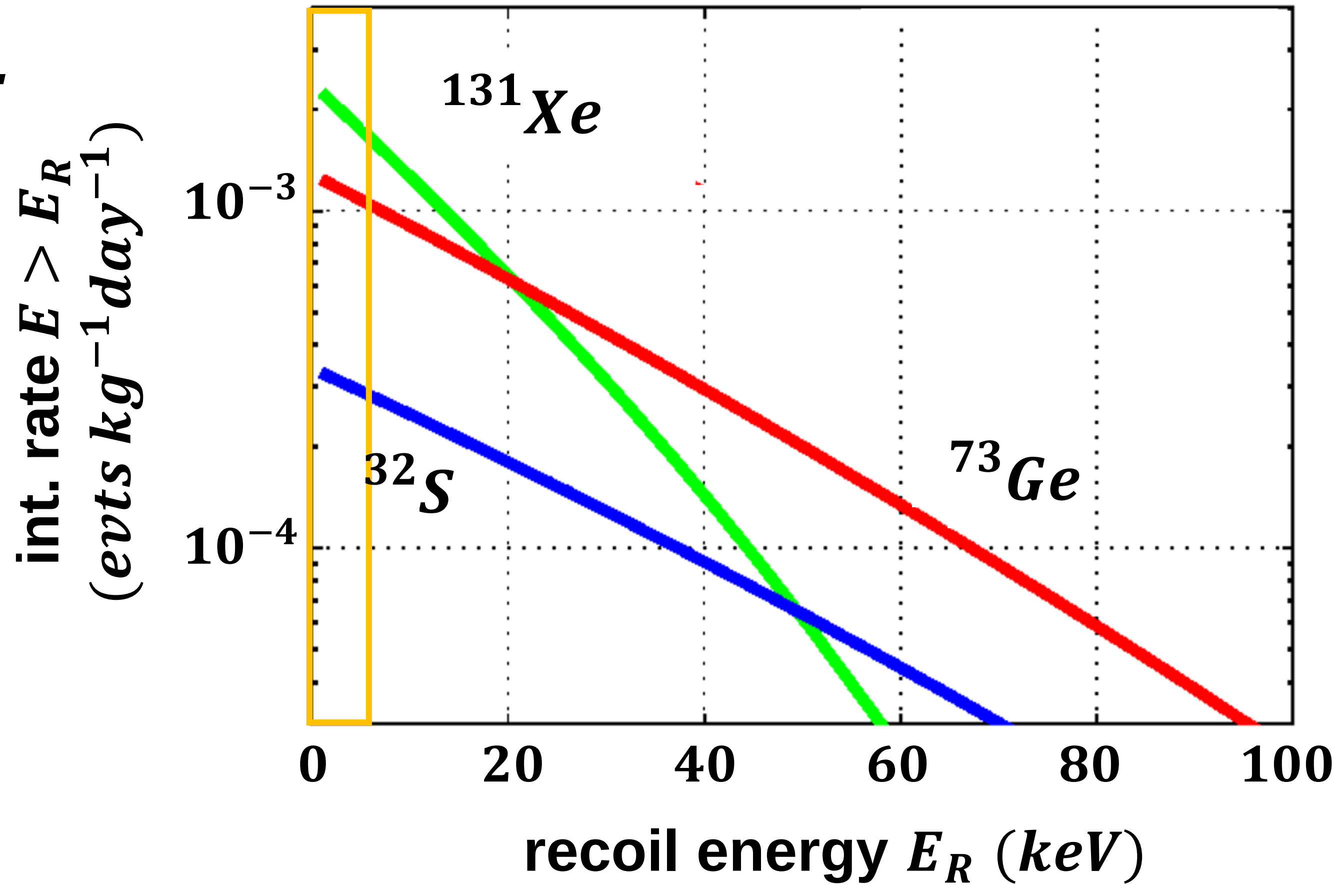
$WIMP$ scatterings: lowest threshold desirable

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

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

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

$WIMP$ – detectors with target masses of $\boxed{1 \ldots 10\ t}$



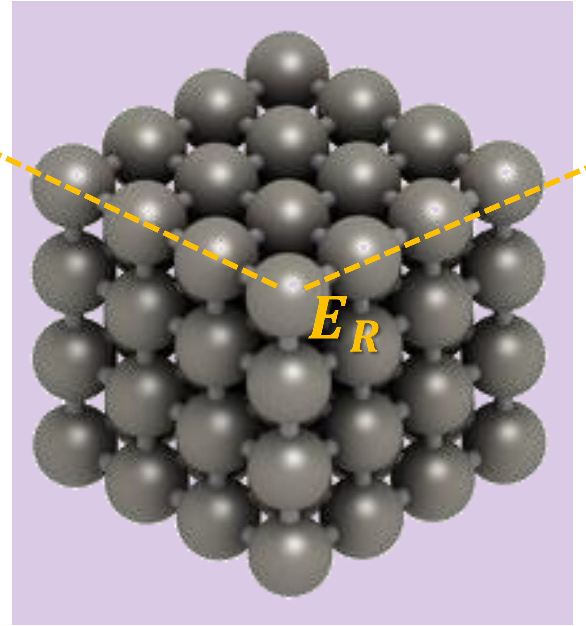
Solid state response to E_R from the nuclear recoil

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

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

$\tilde{\chi}_1^0$ $\tilde{\chi}_1^0$

ions & **electrons**



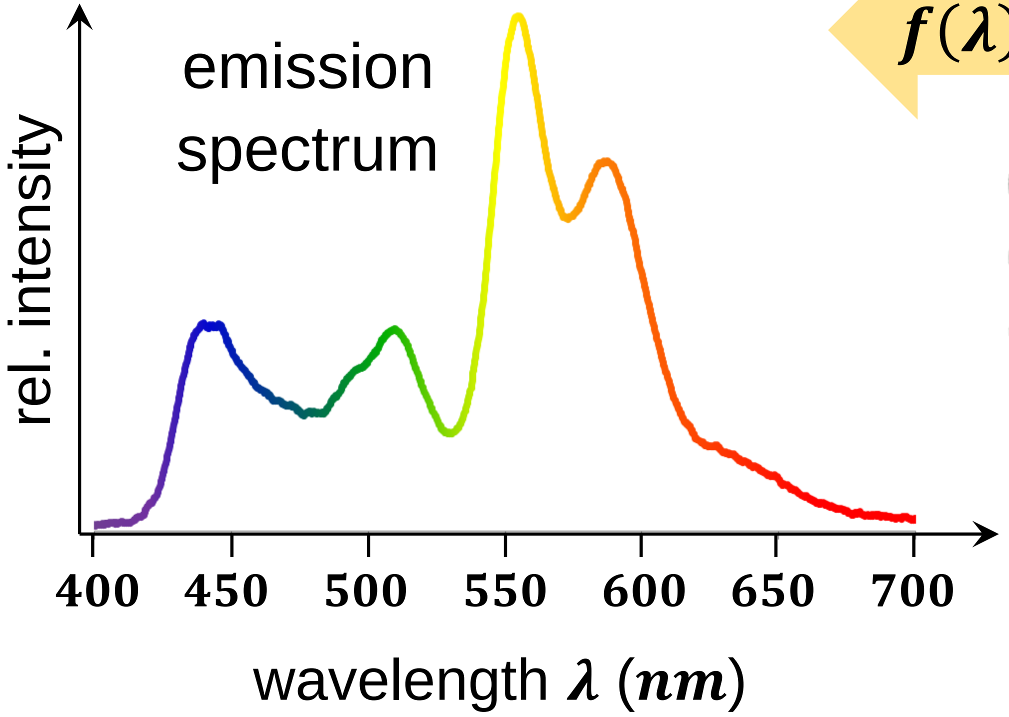
scintillation – **photons**

phonons

Solid state response part – I: scintillation

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

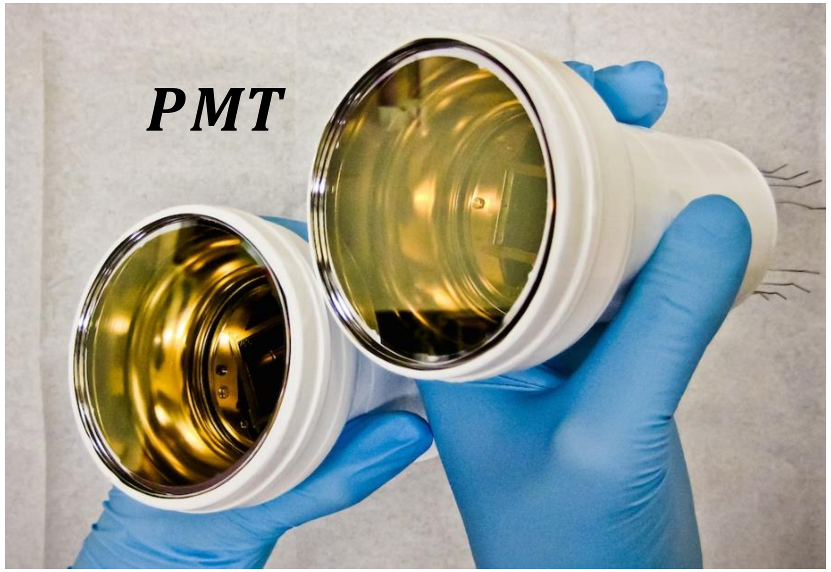
  - **effective energy** for detection of scintillation light: $\Delta E \sim 100\ eV$ per photon



$f(\lambda)$ SHOULD MATCH

organic &
anorganic
scintillators

spectral sensitivity of
PMT photocathode



Solid state response part – I: scintillation

- DM – **detectors based purely on scintillation light:** $DAMA - Libra$, $SABRE$, ...

  - NaJ / CsJ / CaF_2 – **crystals** with optical readout by $PMTs$

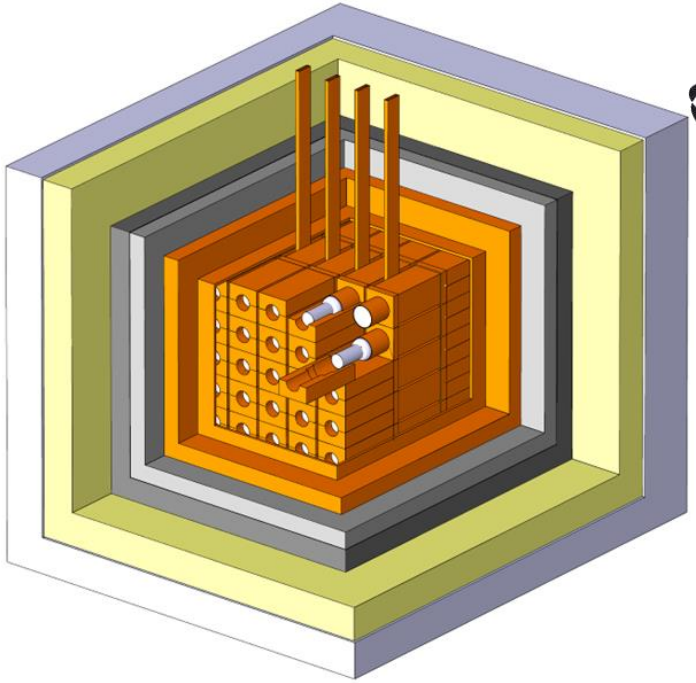
  - each **scintillation material** has its specific emission properties: we aim for **large light yield**, **fast decay** time & optimum λ_m – **match** to PMT

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

Solid state response part – I: scintillation

- **DM – detectors based purely on scintillation light: $DAMA$ – $Libra$, $SABRE$, ...**

  - NaJ / CsJ / CaF_2 – **crystals** with optical readout by $PMTs$

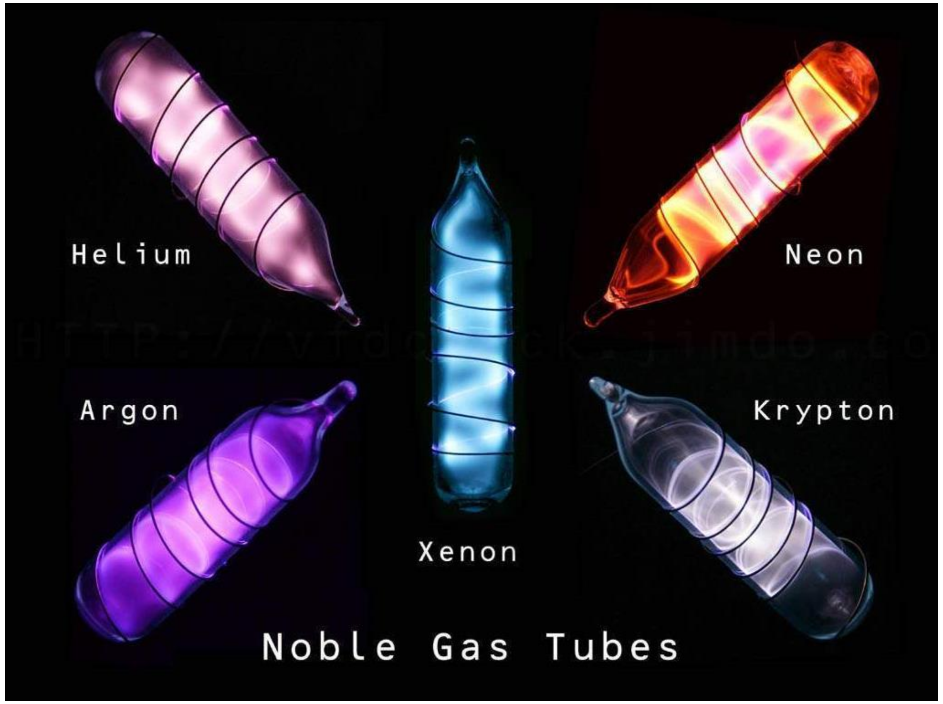


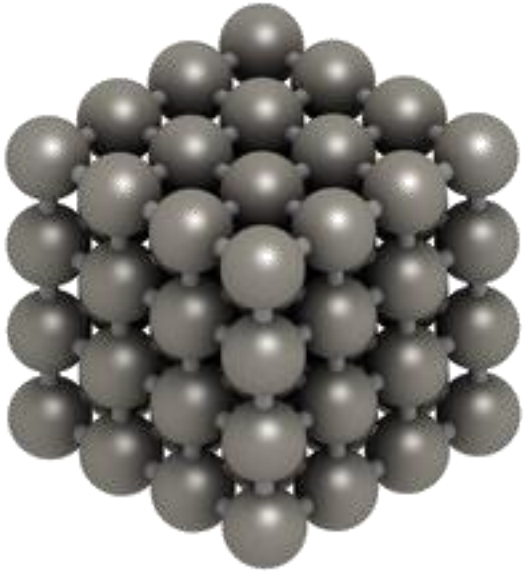
$COSINE$ – 100 detector

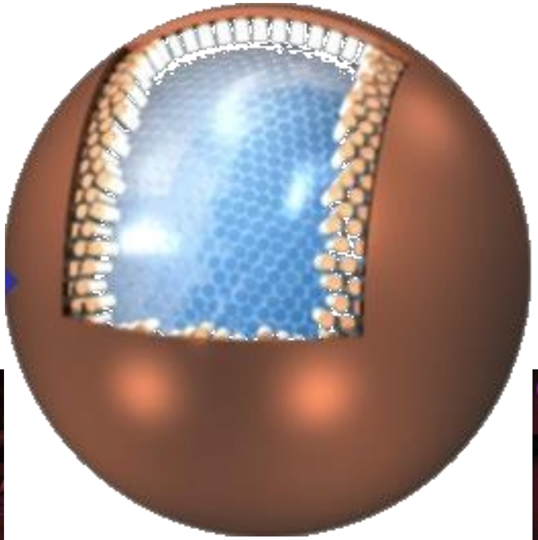
Scintillation light in liquid noble gas detectors

- **Emission of scintillation light in the VUV (Vacuum Ultra$-V$iolet) band**

  - later: large LXe / LAr – based $TPCs$, where VUV – **scintillation** occurs





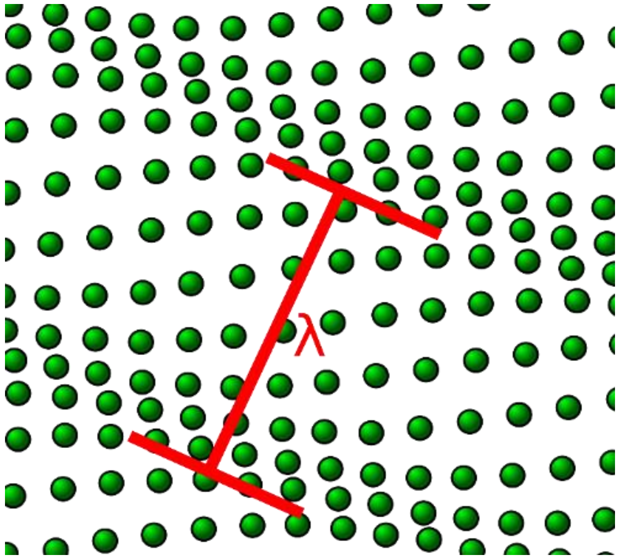


discharge tubes: ionized **noble gases** (which is ***not*** based on a scintillation process!)

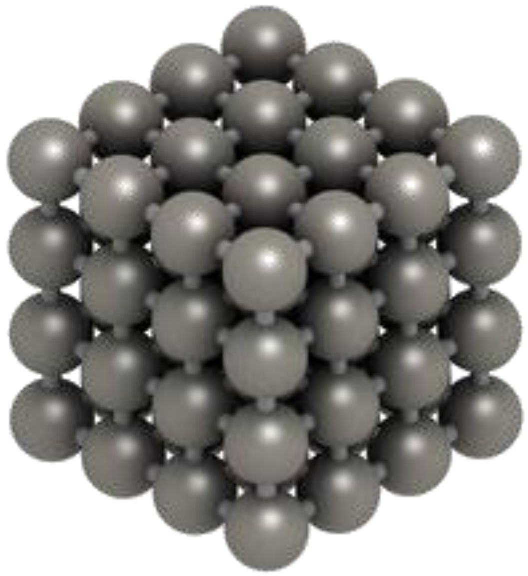
Solid state response part – II: phonons

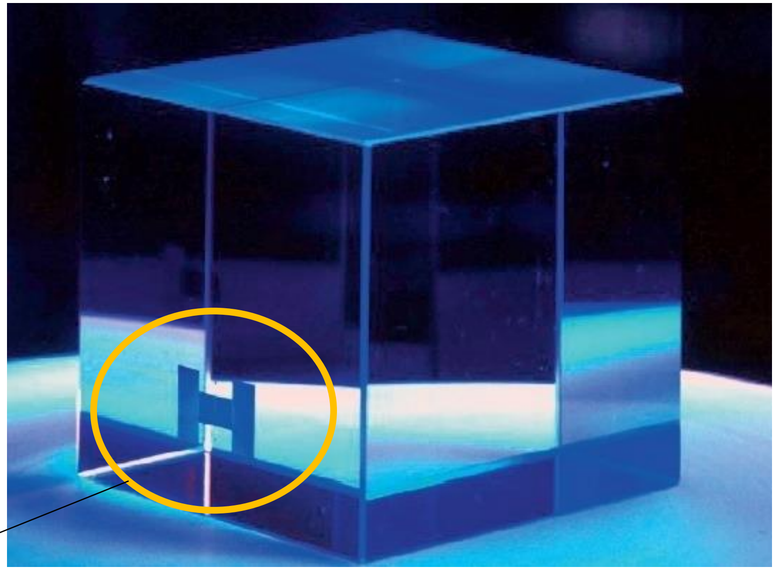
- **Nuclear recoil results in the emission of a spherical phonon wave**

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



phonon wave propagating





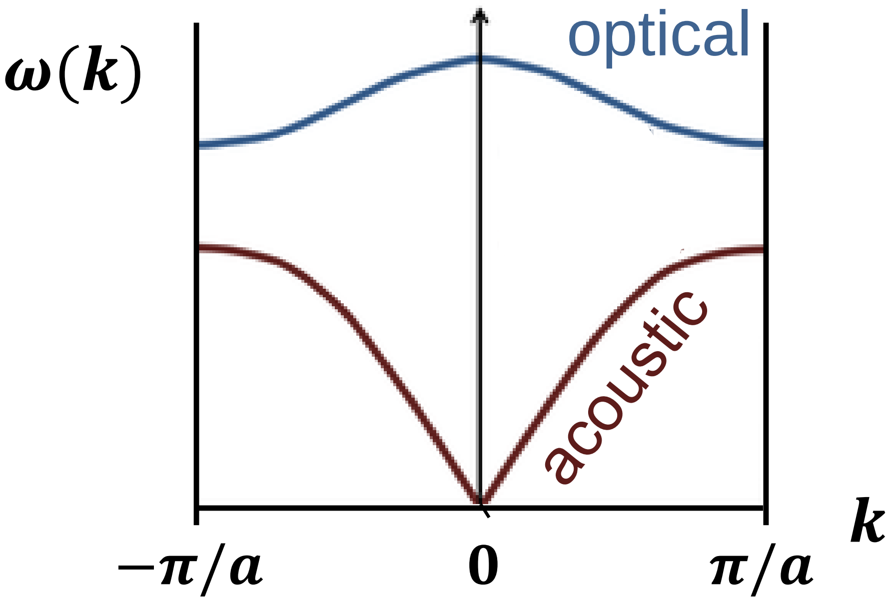
thermistor

$CaWO_4$ – **crystal**

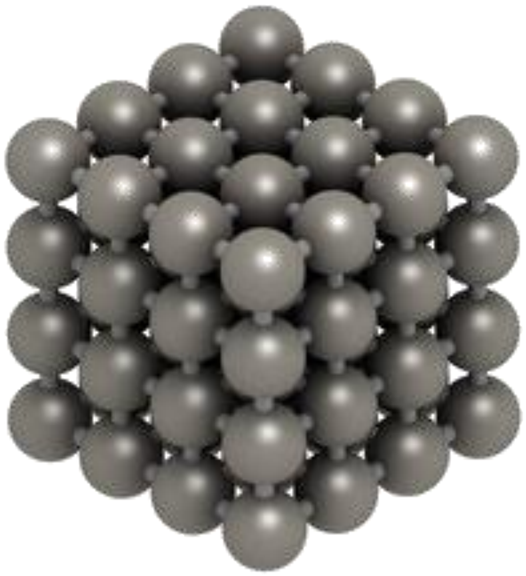
Solid state response part – II: phonons

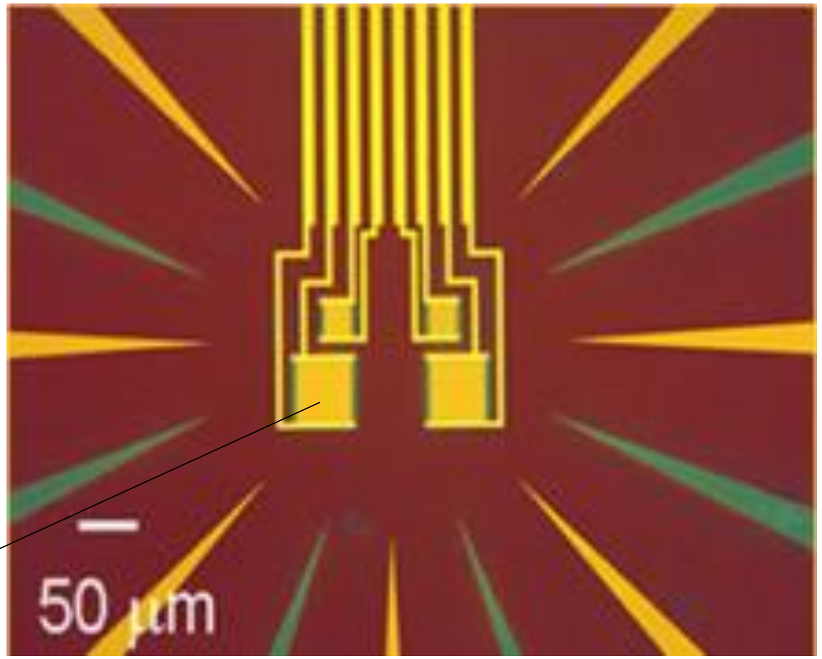
- **Nuclear recoil results in the emission of a spherical phonon wave**

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



phonon dispersion relation



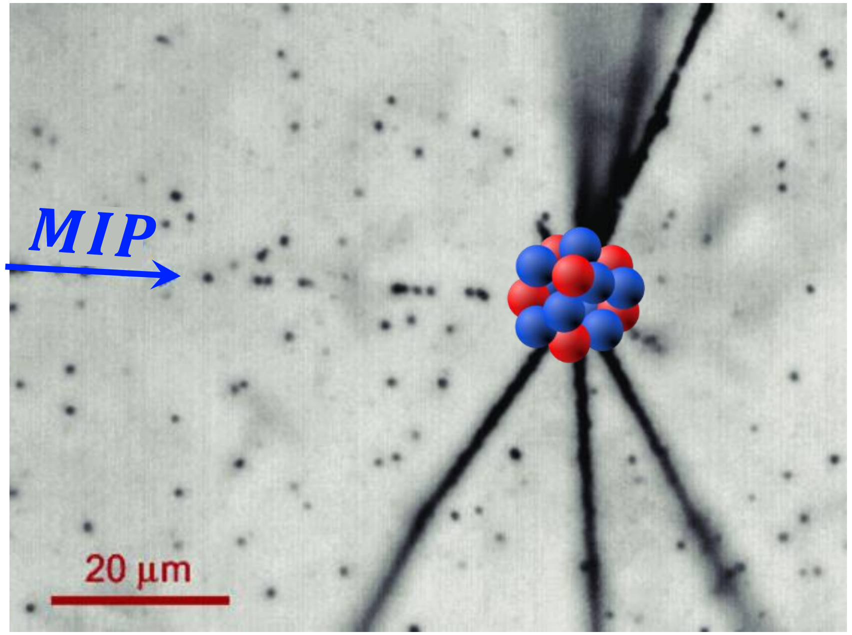


thermistor

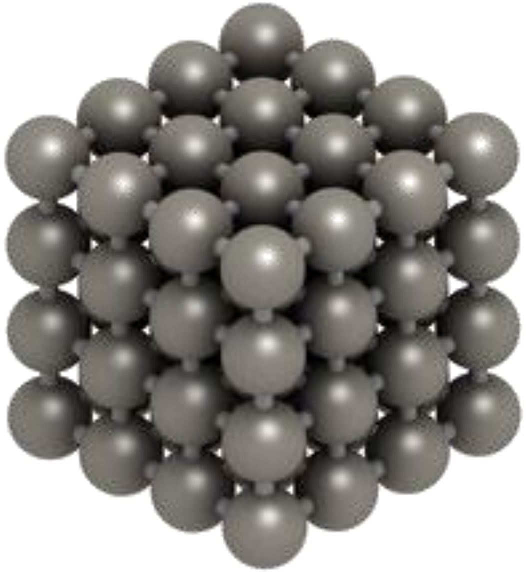
Solid state response part – III: electrons

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

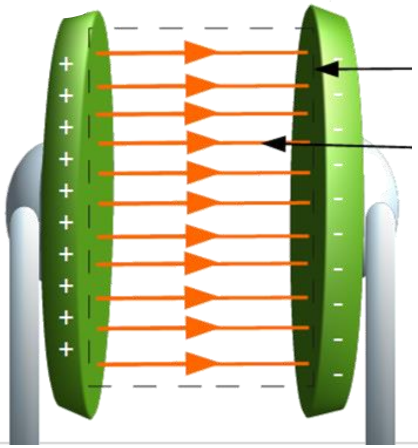
  - **recoil nucleus** has a very **large stopping power dE/dx** ⇨ short recoil track
  - **high density** of electrons & ions along the track: **recombination**



low–energy nuclear tracks vs. MIP*



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



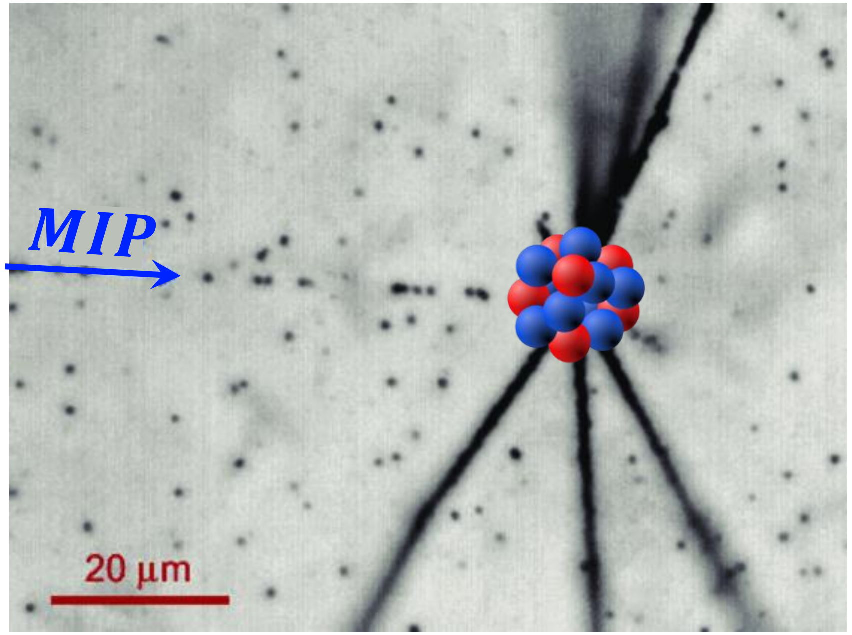
*Minimum Ionizing Particle

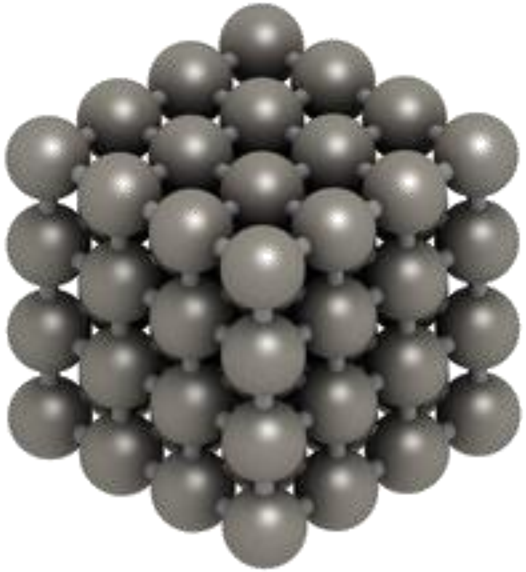
Read–out of ionization signal: strong drift fields

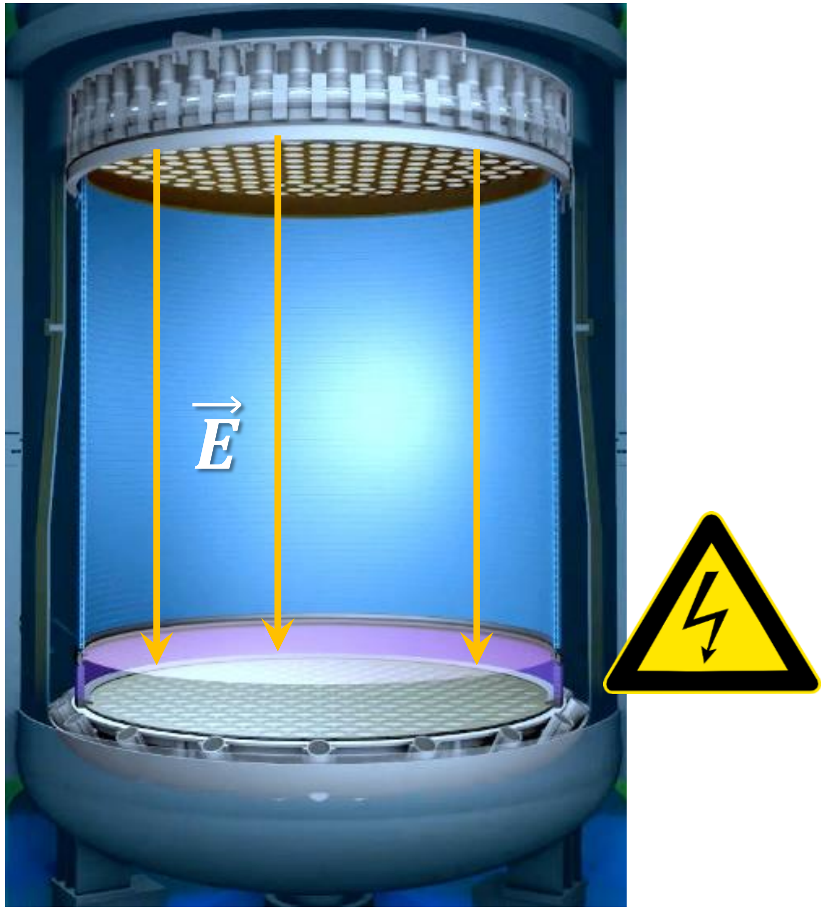
- **Nuclear recoil results in the generation of electron–ion pairs (ionization)**

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

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







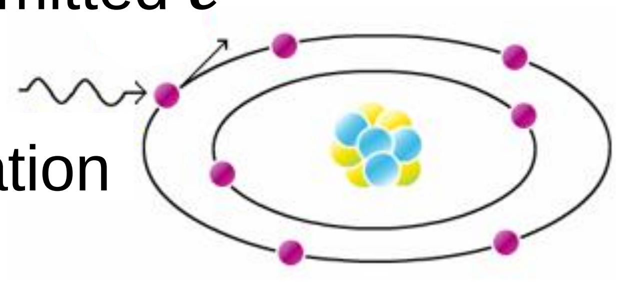
nuclear tracks vs. MIP: use **range** to discriminate!!

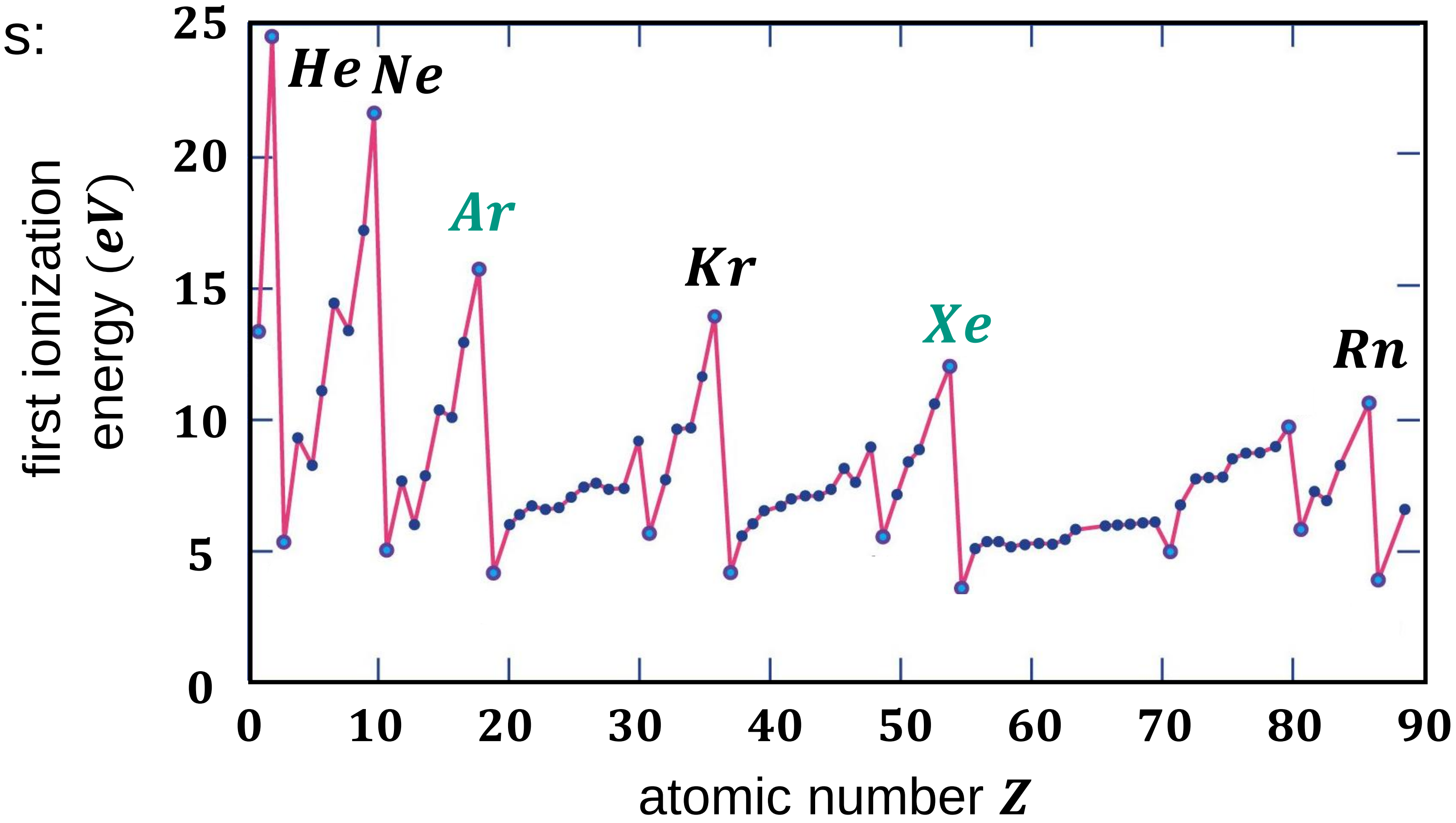
Energy required to generate an e^- / ion (hole) pair

- **Ionization energies of different elements: characteristic atomic structure**

- we will use these materials:

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





High–Tech required for $WIMP$ – detection

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

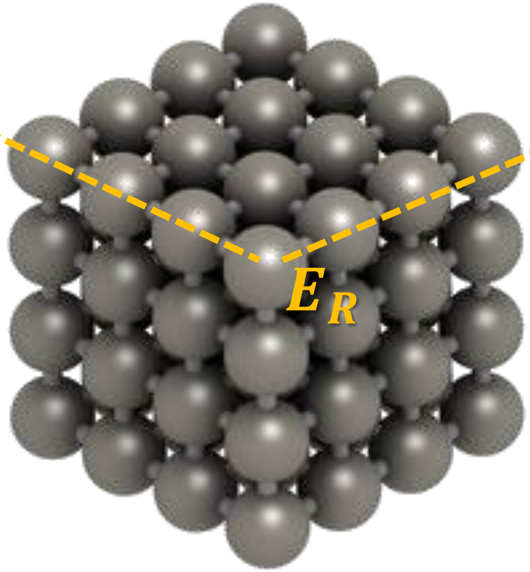
  - **only** by **combining two methods** we can achieve background discrimination

low–noise electronics
cryogenics
precision drift fields
novel optical sensors

$\tilde{\chi}_1^0$

$IONIZATION$

$10\ eV$ / electron



$\tilde{\chi}_1^0$

$SCINTILLATION$

$100\ eV$ / photon

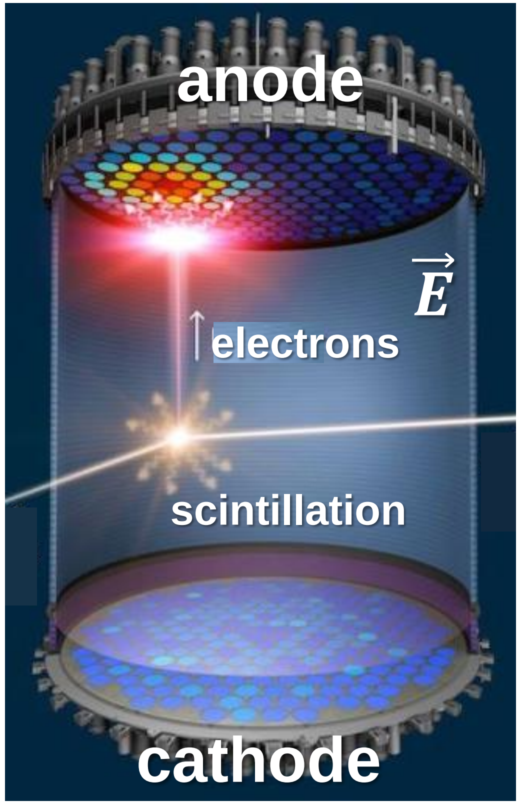
$VIBRATION$

$10\ meV$ / phonon

$WIMP$ – detection via ionization & scintillation

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

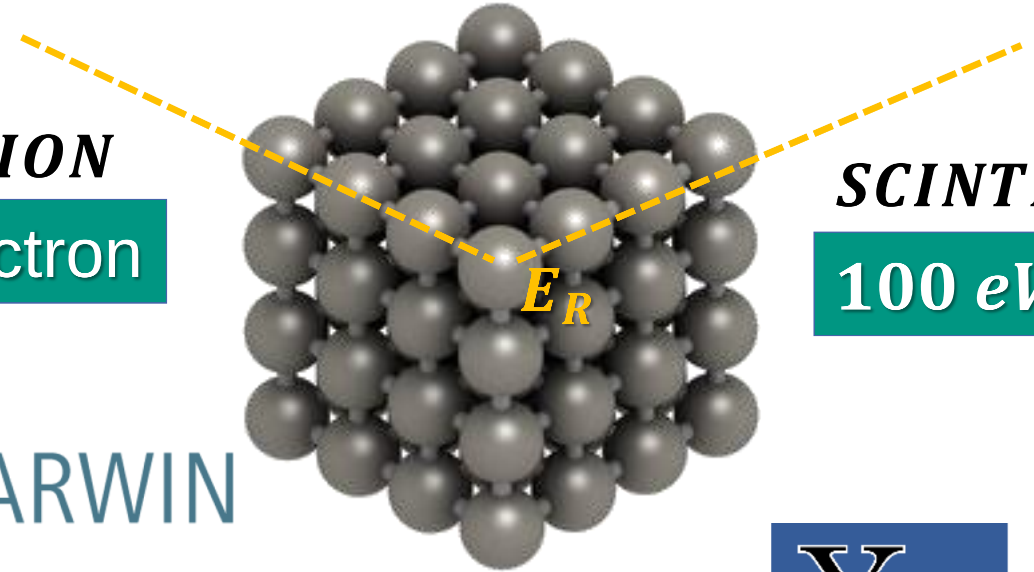
  - **ratio of scintillation light / electrons**: excellent background discrimination



$\tilde{\chi}_1^0$ $\tilde{\chi}_1^0$

IONIZATION

10 eV / electron



$\tilde{\chi}_1^0$ $\tilde{\chi}_1^0$

SCINTILLATION

100 eV / photon

DARWIN

darkside
two-phase argon TPC for Dark Matter Direct Detection

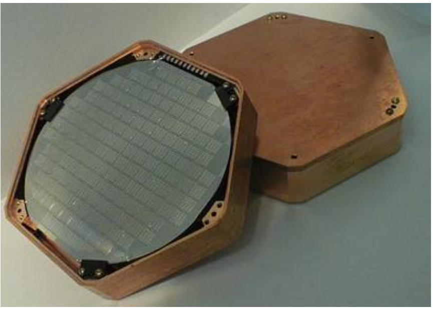
Xe
XENON
Dark Matter Project

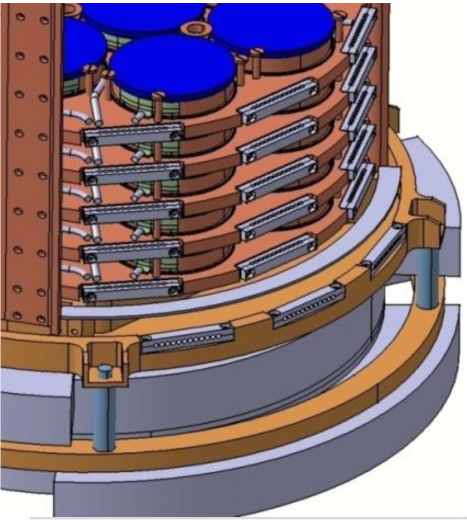
*Time Projection Chamber

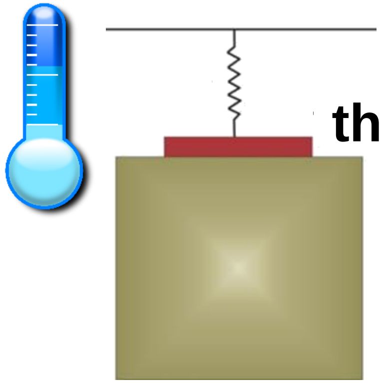
$WIMP$ – detection via ionization & phonons

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

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

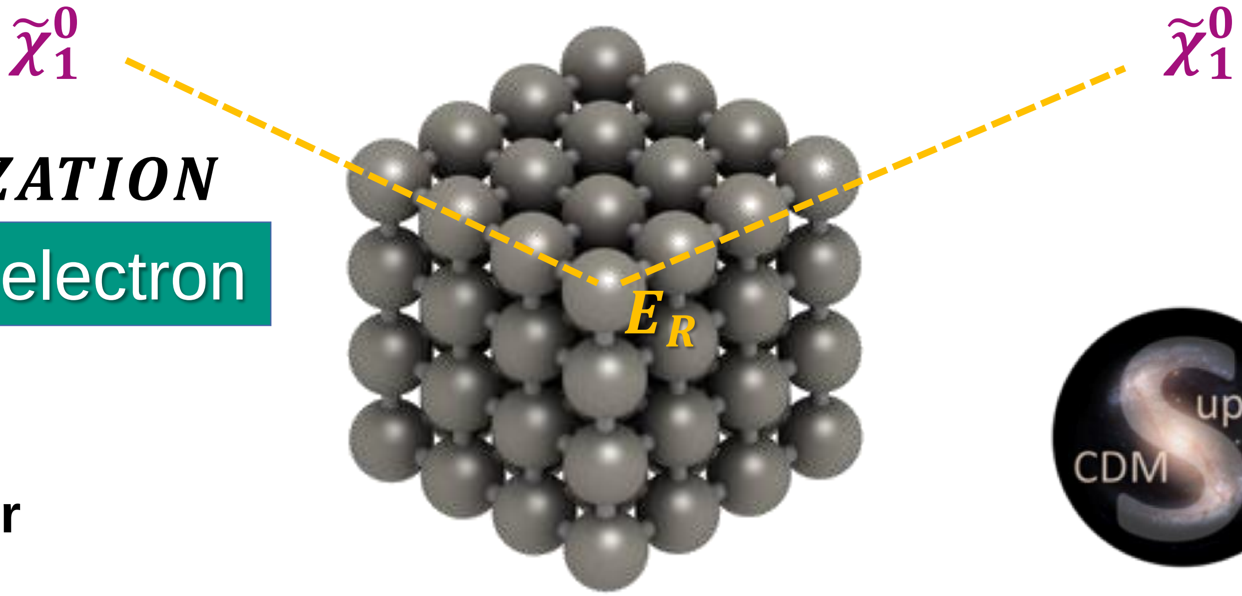






IONIZATION

10 eV / electron



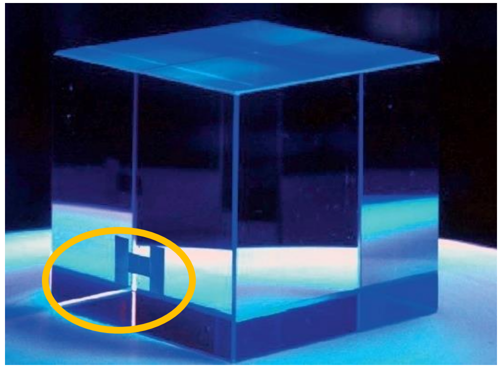
VIBRATION

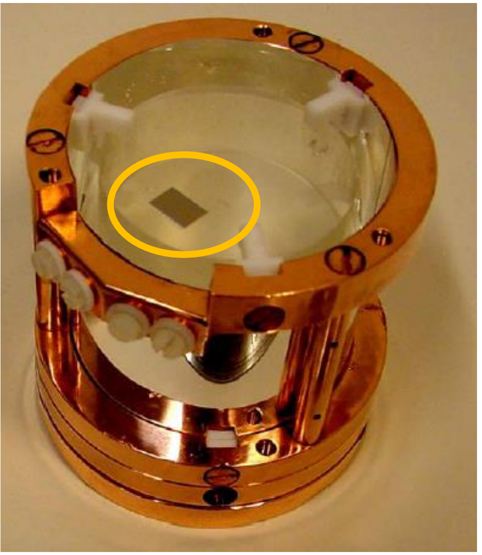
10 meV / phonon

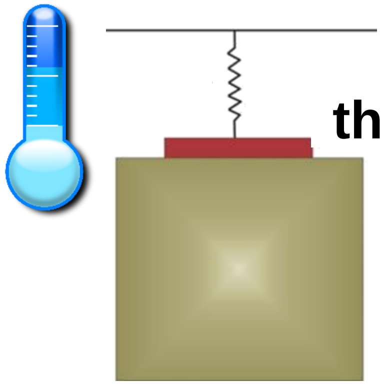
$WIMP$ – detection via scintillation & phonons

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

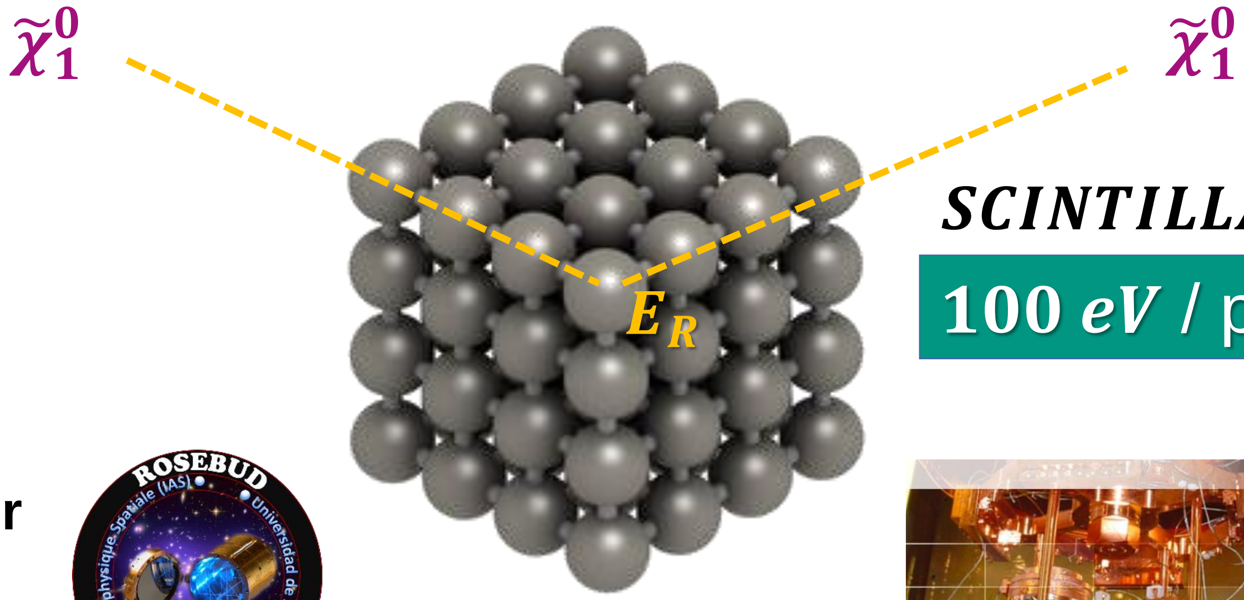
  - ratio of photons / phonons: excellent background discrimination







thermistor



SCINTILLATION

100 eV / photon

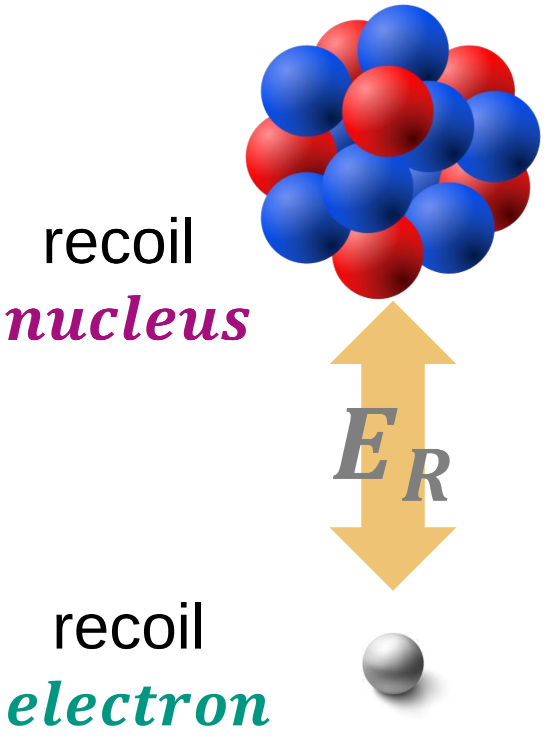
VIBRATION

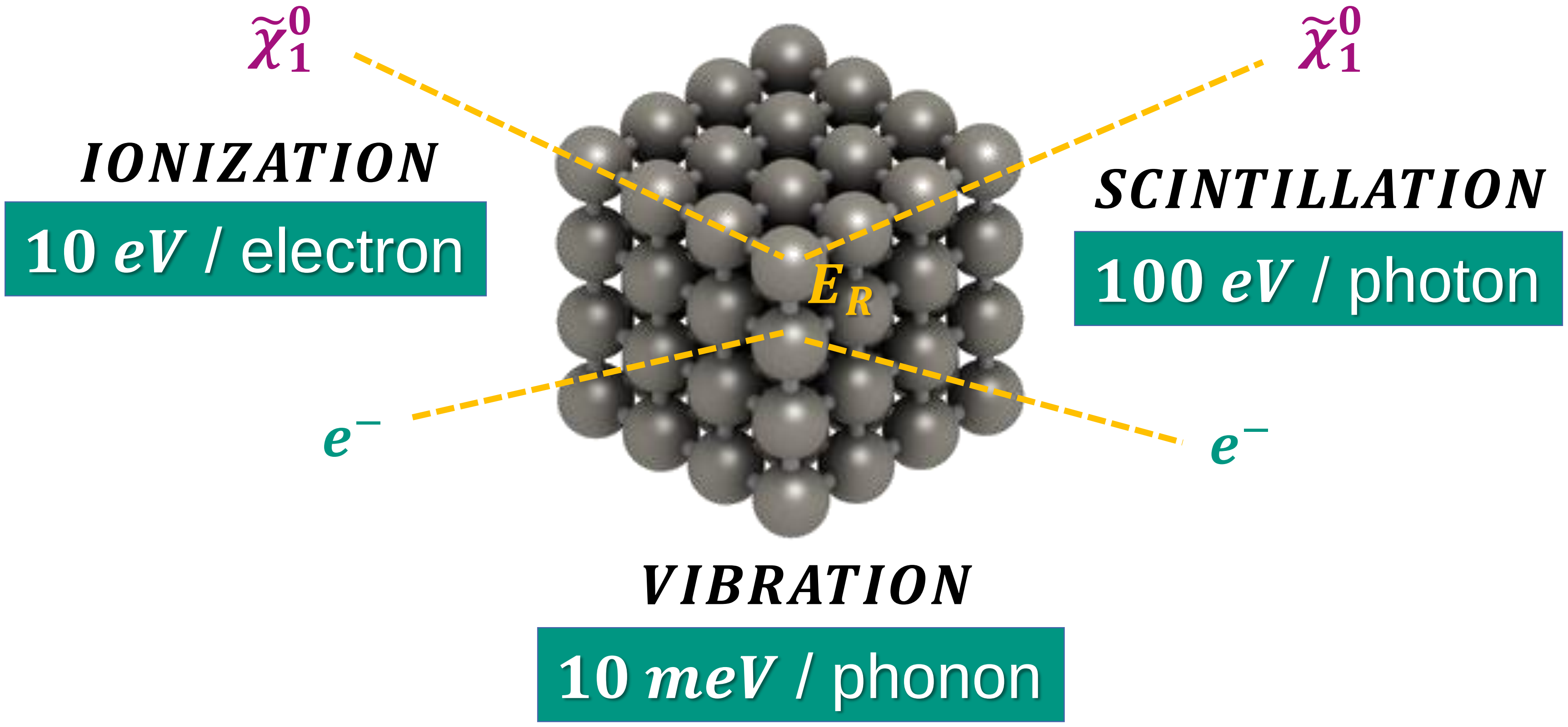
10 meV / phonon

Discriminating nuclear recoils from electrons

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

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

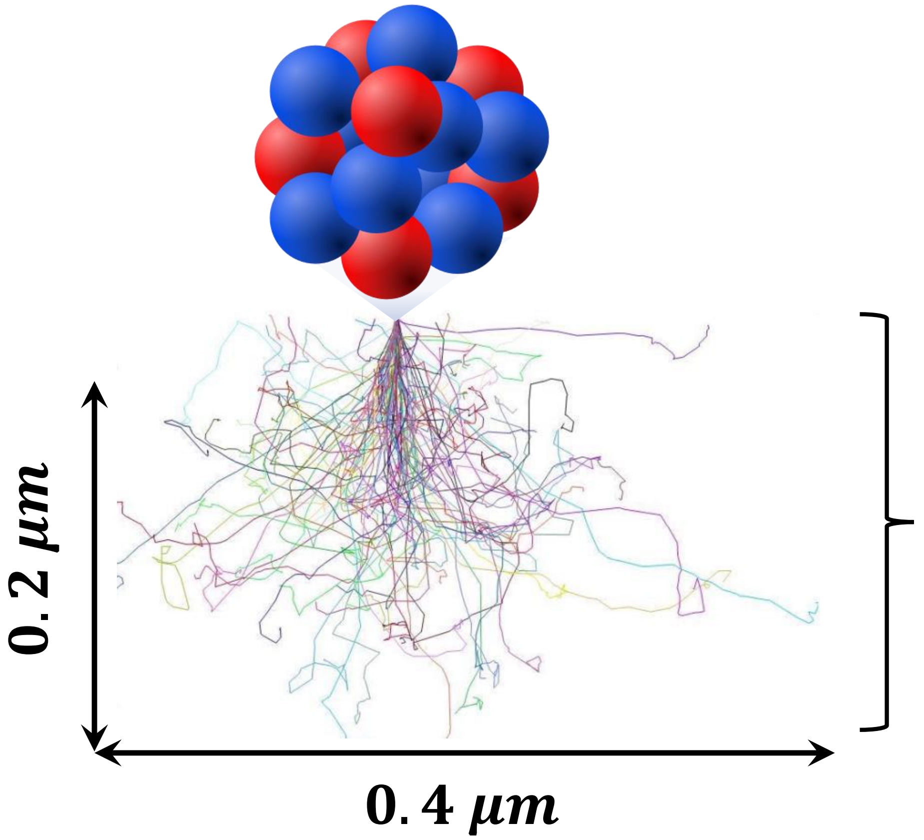




nuclear recoils: a closer look at their tracks

- **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**

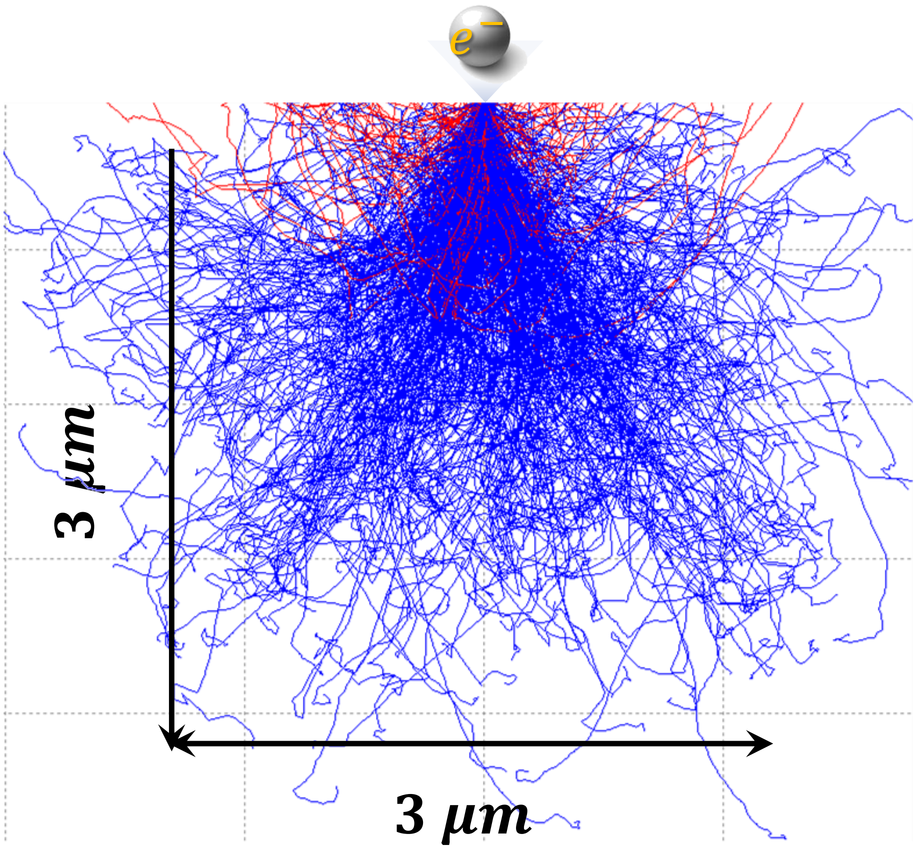
⇨ **recombination of charges (quenching)**

⇨ **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**

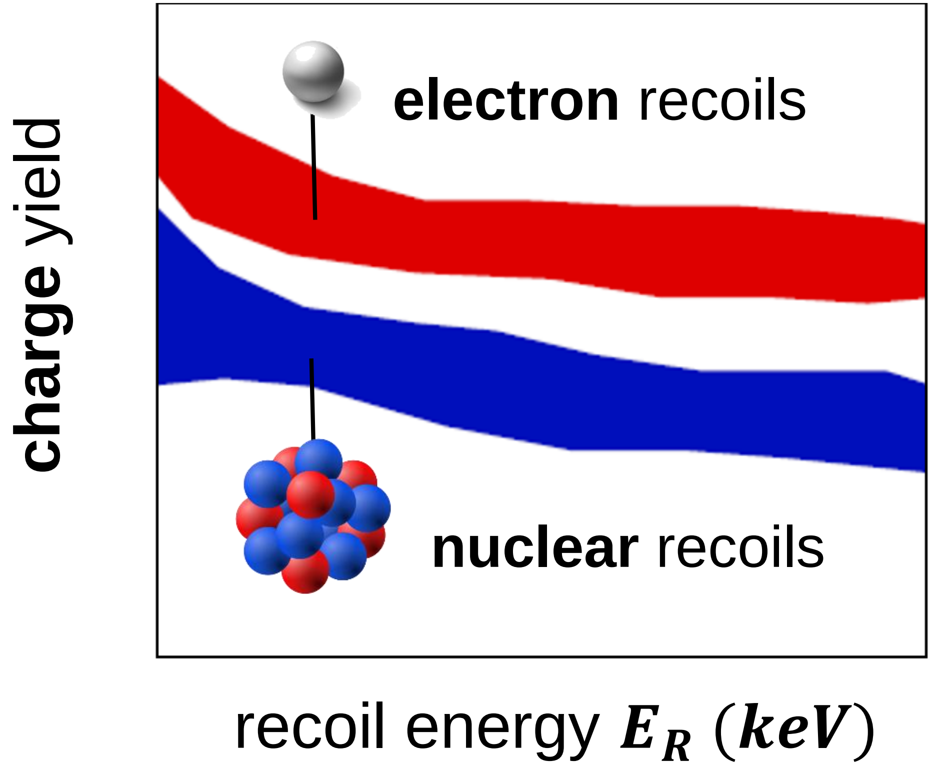
⇨ **no charge recombination (no quenching)**

⇨ **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**

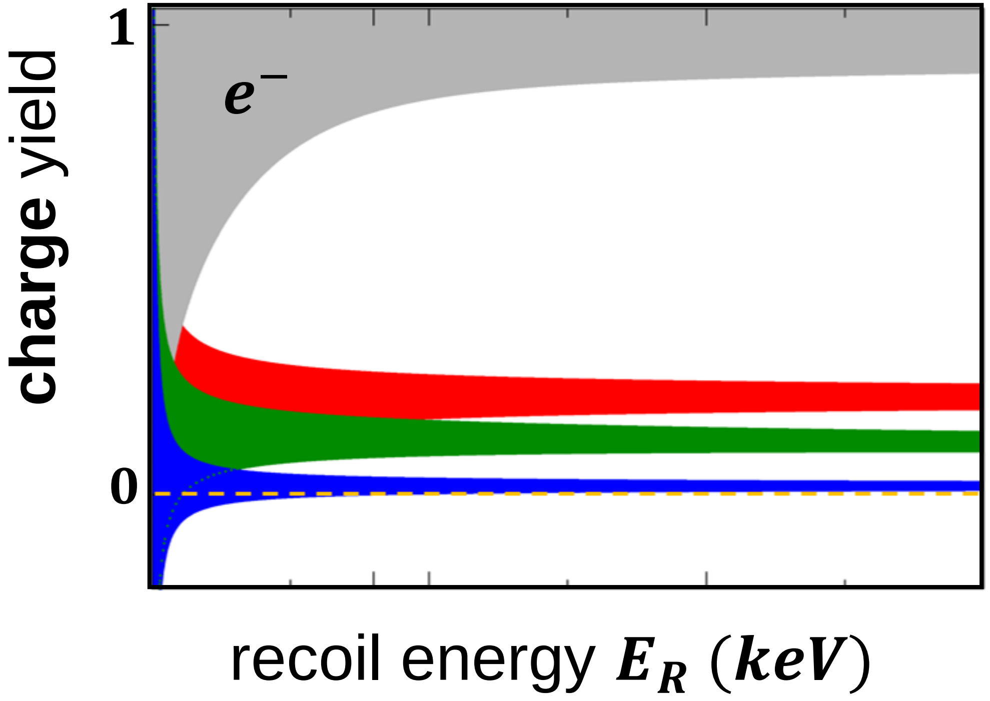
* ***P**article **ID**entification*

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)

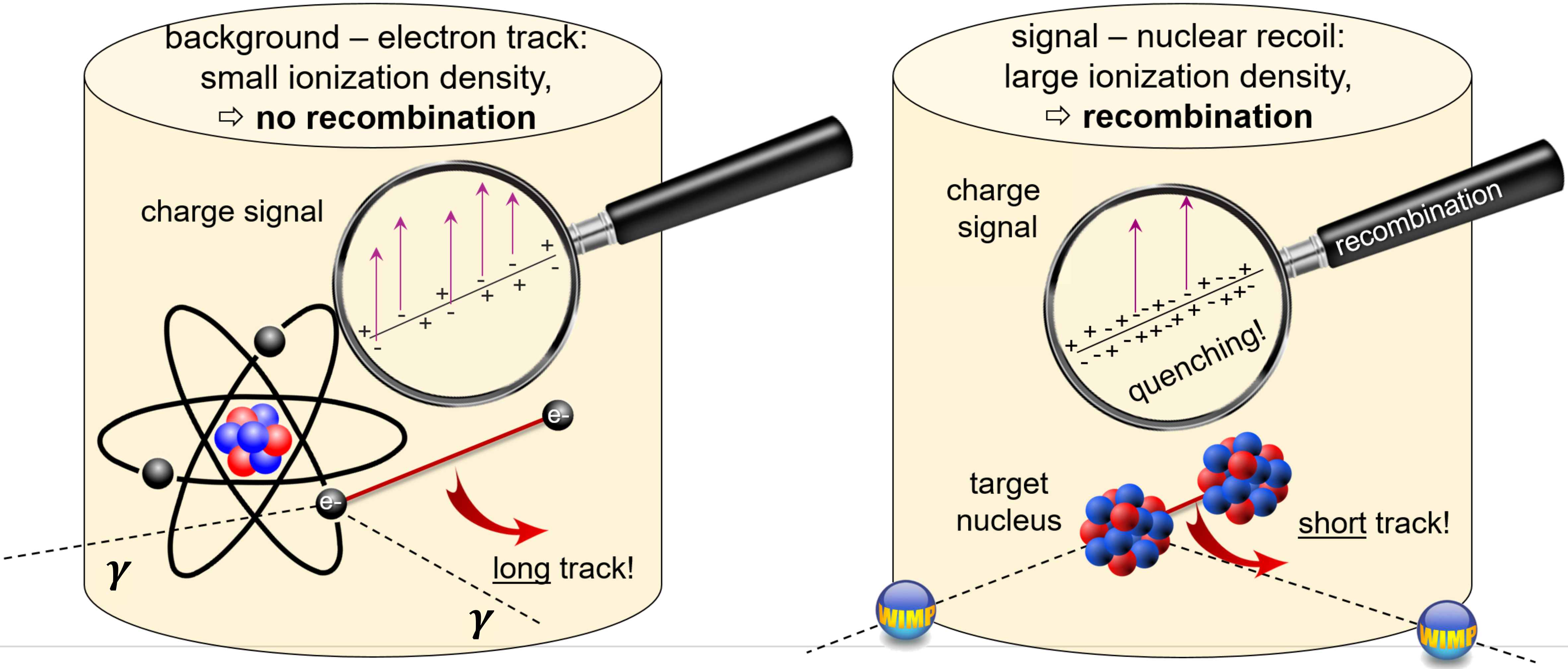
  - **quenching** of charge signal: typically **factor** $\mathbf{3 \ldots 4}$



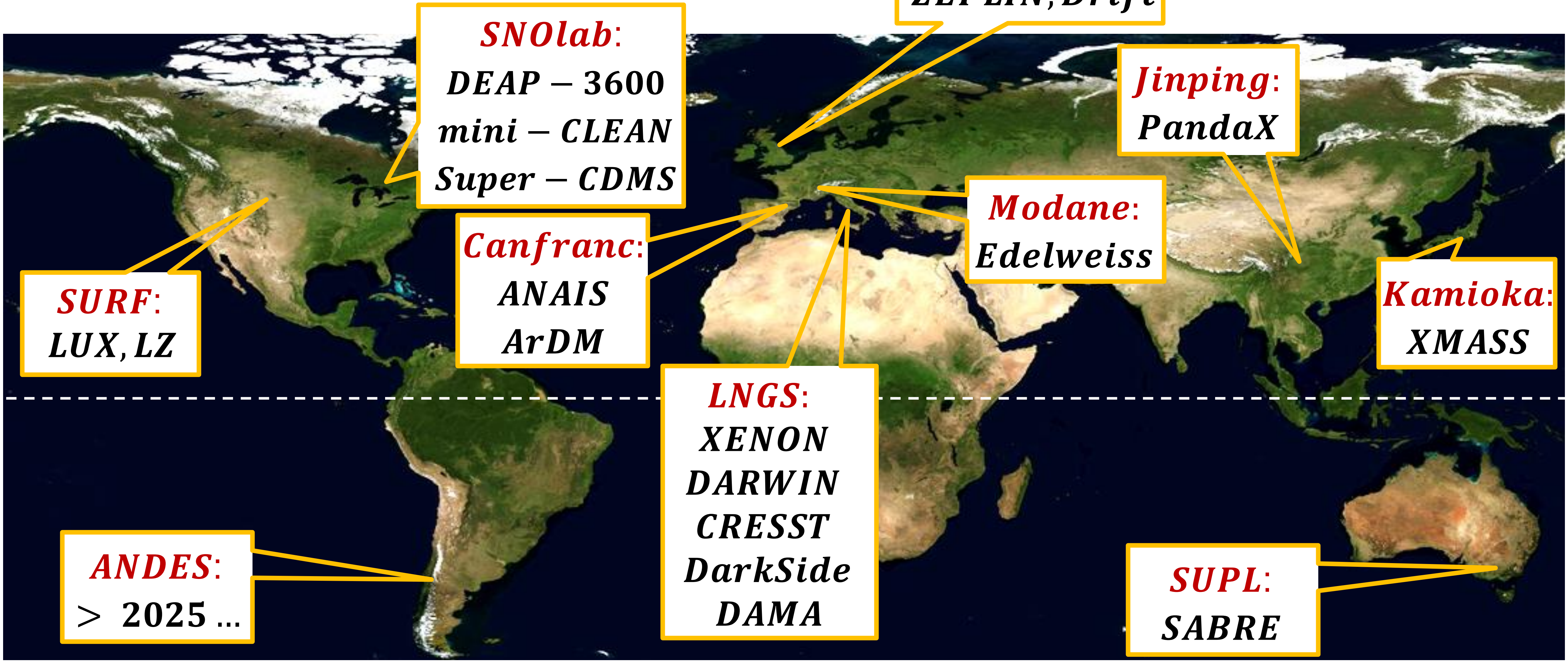
$\left.\begin{array}{l}\boldsymbol{\alpha}\\ \boldsymbol{light}\\ \boldsymbol{heavy}\end{array}\right\}$ for **heavy nuclei** the quenching becomes **stronger** due to their larger $\boldsymbol{dE/dx}$ & **very small range**

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

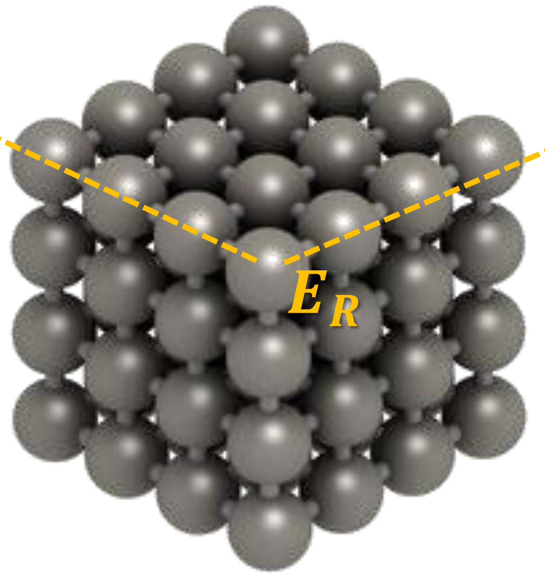
- **Many different technologies & detectors have been & are being developed**

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

$\tilde{\chi}_1^0$ $\tilde{\chi}_1^0$

electrons

scintillation – **photons**



E_R

phonons