Experimental Search for Dark Matter

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Part 2: Dark Matter Direct Detection

Introduction

Review of DM evidence and properties

Galaxy Clusters
Galactic Rotation Curves
Gravitational Lensing and X-ray surveys
Structure Formation
DM Candidates

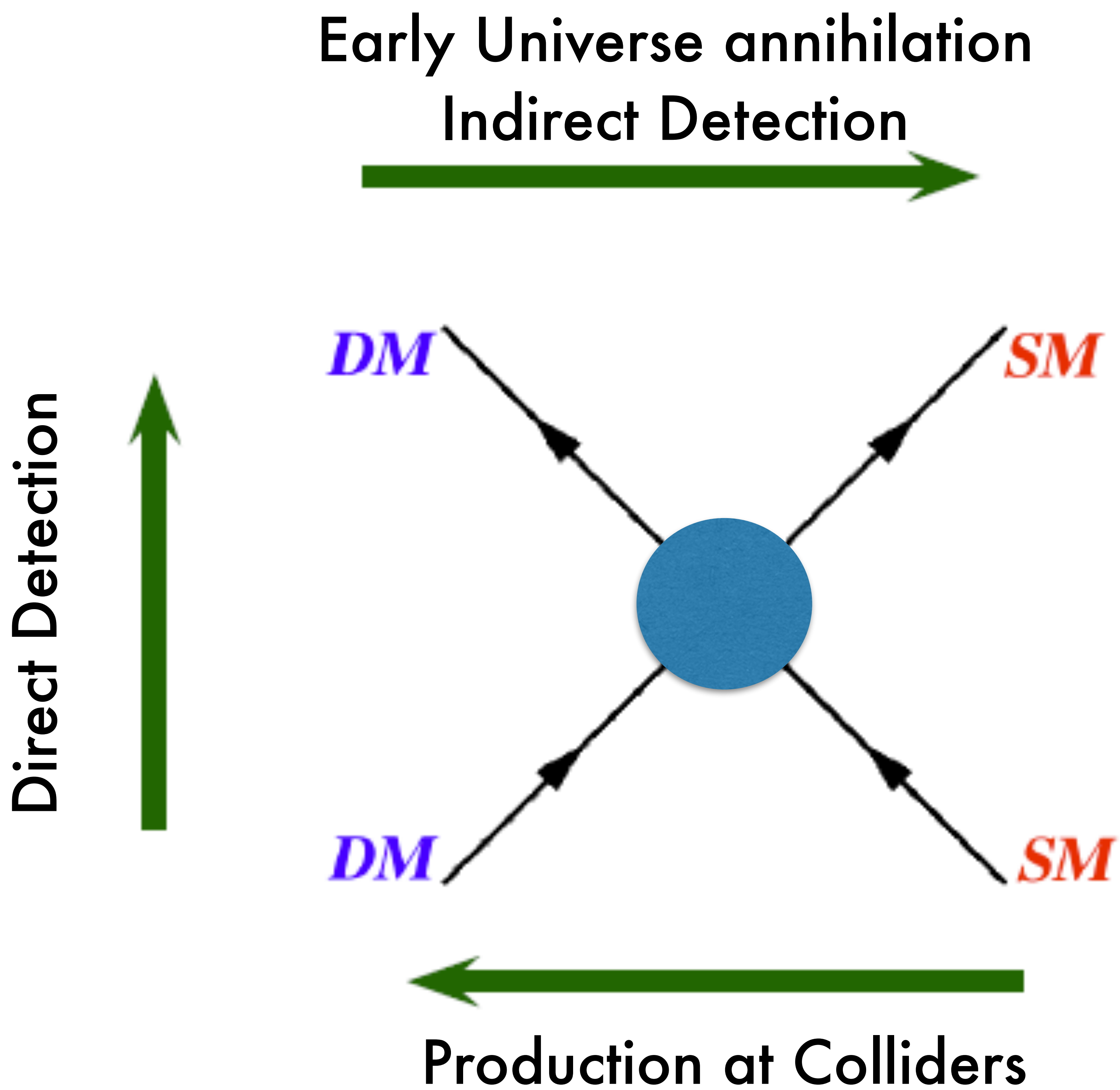
Basic Principles of Direct Detection

Scattering Rates
Corrections
Spin Dependence

Experimental Techniques

Overview of the detection principles
Current experimental activity
Noble liquids, cryogenic detectors, bubble chambers
Accelerator-based DM production and detection

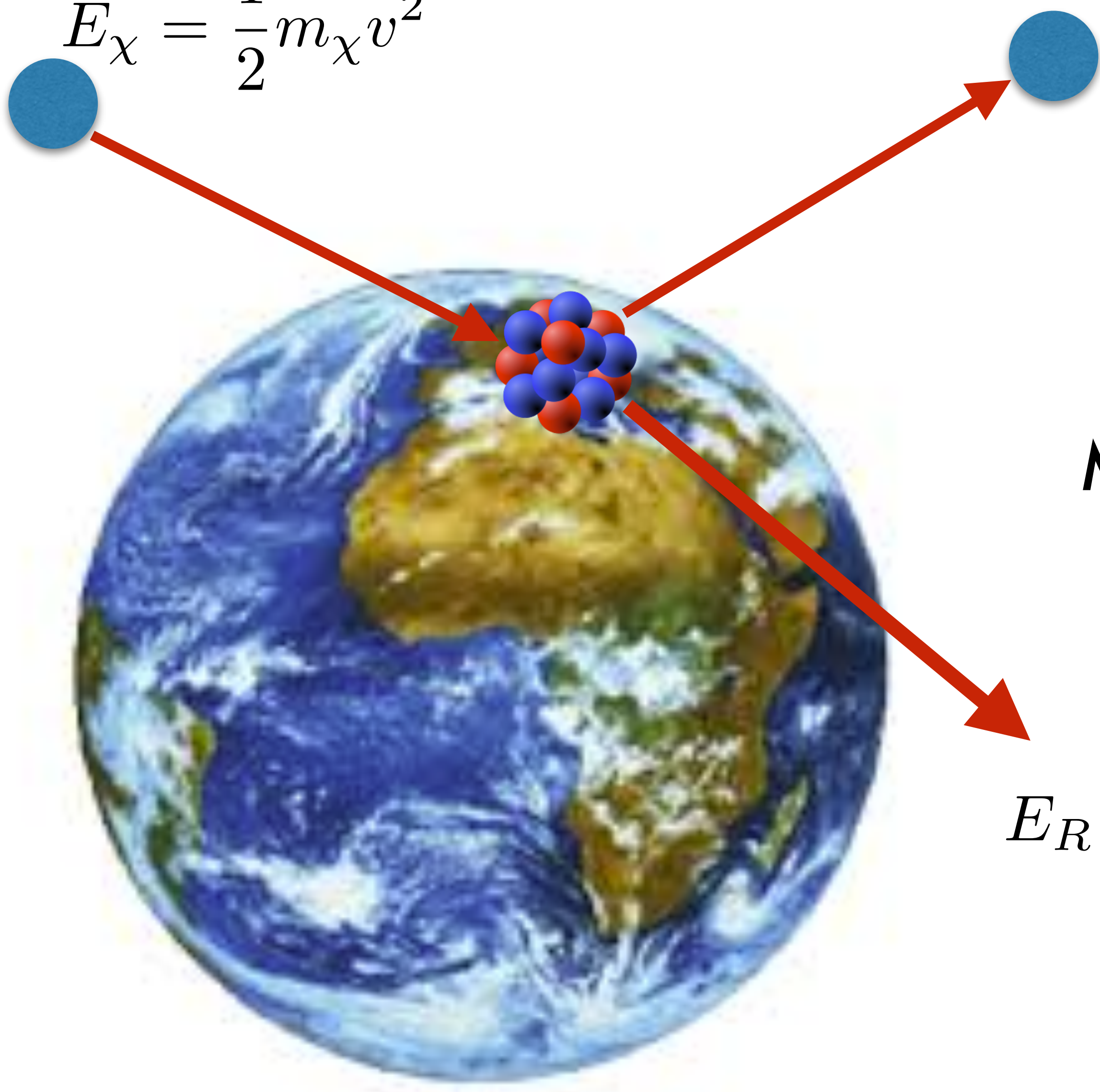
Dark Matter Detection Methods



Direct Detection

The Principle of Direct Detection

$$E_\chi = \frac{1}{2} m_\chi v^2$$



Basic idea: elastic DM-Nucleus collision

Momentum transfer $|\bar{q}|^2 = 2\mu^2 v^2 (1 - \cos\theta)$

Reduced mass $\nu = \dfrac{m_\chi m_N}{m_\chi + m_N}$

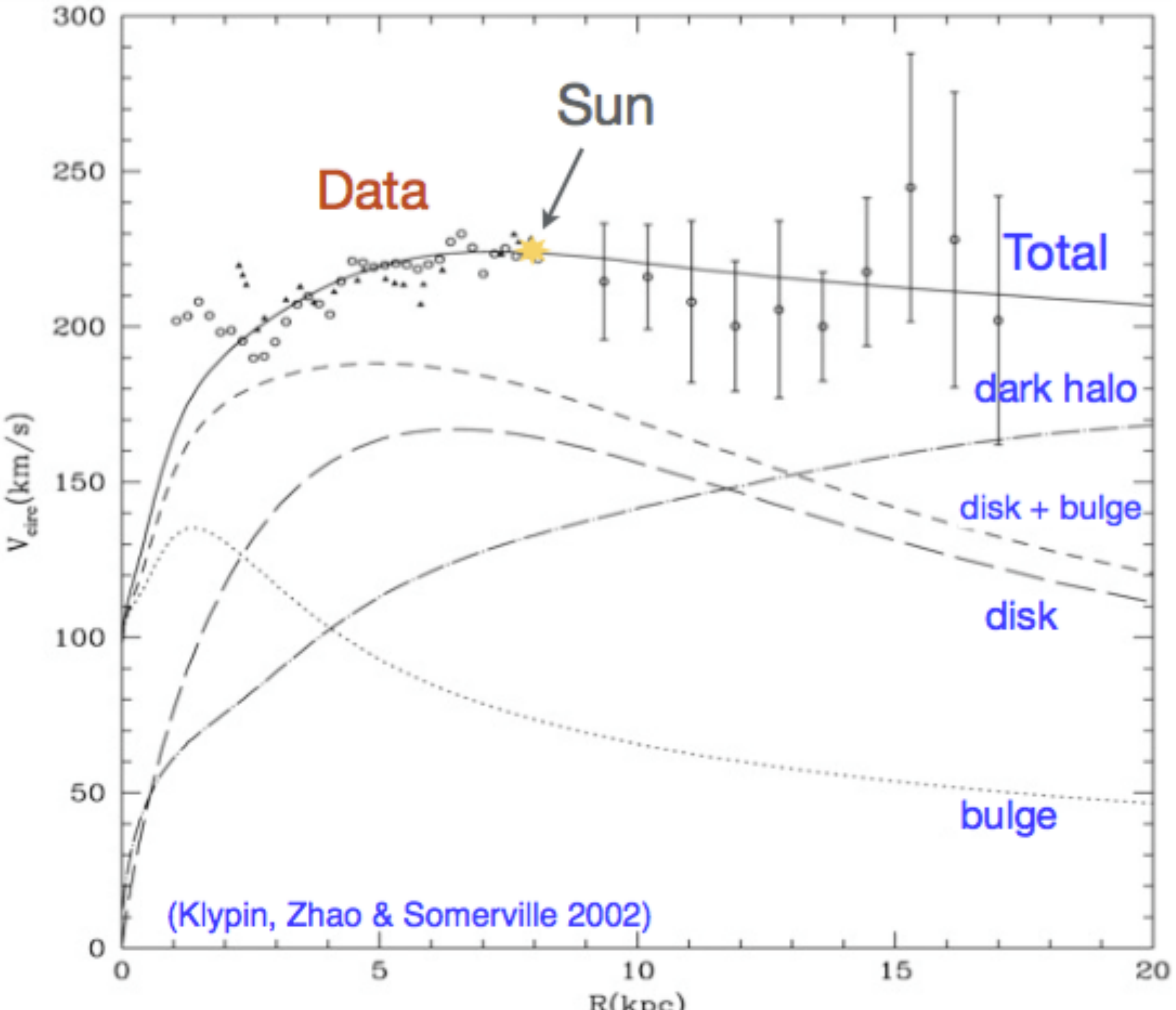
$$E_R = \frac{|\bar{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta)$$

CM scattering angle

Key issue: Backgrounds

$\gamma e \to \gamma e$	Need to separate N-recoils from e-recoils
$nNe \to nN$	Same signature as the signal
$N \to N' + \alpha\ ,\ e^{\pm}$	Nuclear decays / natural or induced radioactivity
$\nu N \to \nu N$	Very small but it depends on your sensitivity

What to Expect



$$\rho_{Halo} \sim 0.1 - 0.7\ \mathrm{GeV/cm^3}$$

$$\rho_{Disk} \sim 2 - 7\ \mathrm{GeV/cm^3}$$

$$\rho_\chi \sim 0.3\ \mathrm{GeV/cm^3} \Rightarrow 3000\ \mathrm{WIMPs/m^3}\ \text{for}\ m_\chi = 100\ \mathrm{GeV/c^2}$$ (typical standard values)

WIMP flux on Earth $\sim 10^5 \mathrm{cm^{-2} s^{-1}}$

Approximate rate:

$$R \sim N \rho_\chi \frac{\sigma_{\chi N}}{m_\chi} \langle v \rangle$$

- Input from astrophysics
- Particle Physics

N : # of nuclei in the detector

ρ_χ : local DM density in the Milky Way

$\langle v \rangle$: mean WIMP velocity wrt target

m_χ : WIMP mass

$\sigma_{\chi N}$:WIMP-Nucleus cross section: SI/SD

Rate Calculation

Rate/E_R = # of targets N_T X Dark Matter Flux

$n_\chi = \rho_\chi / m_\chi$

Average DM number density n X velocity v X d(cross section)/dE_R

$$\frac{dR}{dE_R} = N_T n_\chi \langle v_\chi \frac{d\sigma}{dE_R} \rangle$$

From the kinematics

$$dE_R = (d\cos\theta)\frac{\mu^2 v^2}{m_N}$$

The cross-section might in general depend on the velocity, which has a certain distribution function on which we have to average.

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi m_N}{m_\chi \mu^2} \int_{v_{min}}^{v_e} d^3v \frac{f(v)}{v} \frac{d\sigma}{d\cos\theta}$$

$$v_{min} = \frac{m_N E_R}{2\mu^2} = \frac{q}{2\mu}$$

Nuclear Recoils

If we set up a detector for the detection of DM via nuclear recoils, what is the energy scale of those?

Consider the (WIMP) case $m_\chi \sim m_M \sim 100 GeV/c^2$

and the average DM halo velocity $v \sim 220 km/s = 0.75 \times 10^{-3} c$

The average nuclear recoil energy is then $\langle E_R \rangle = \frac{1}{2} m_\chi v^2 = 30 keV$

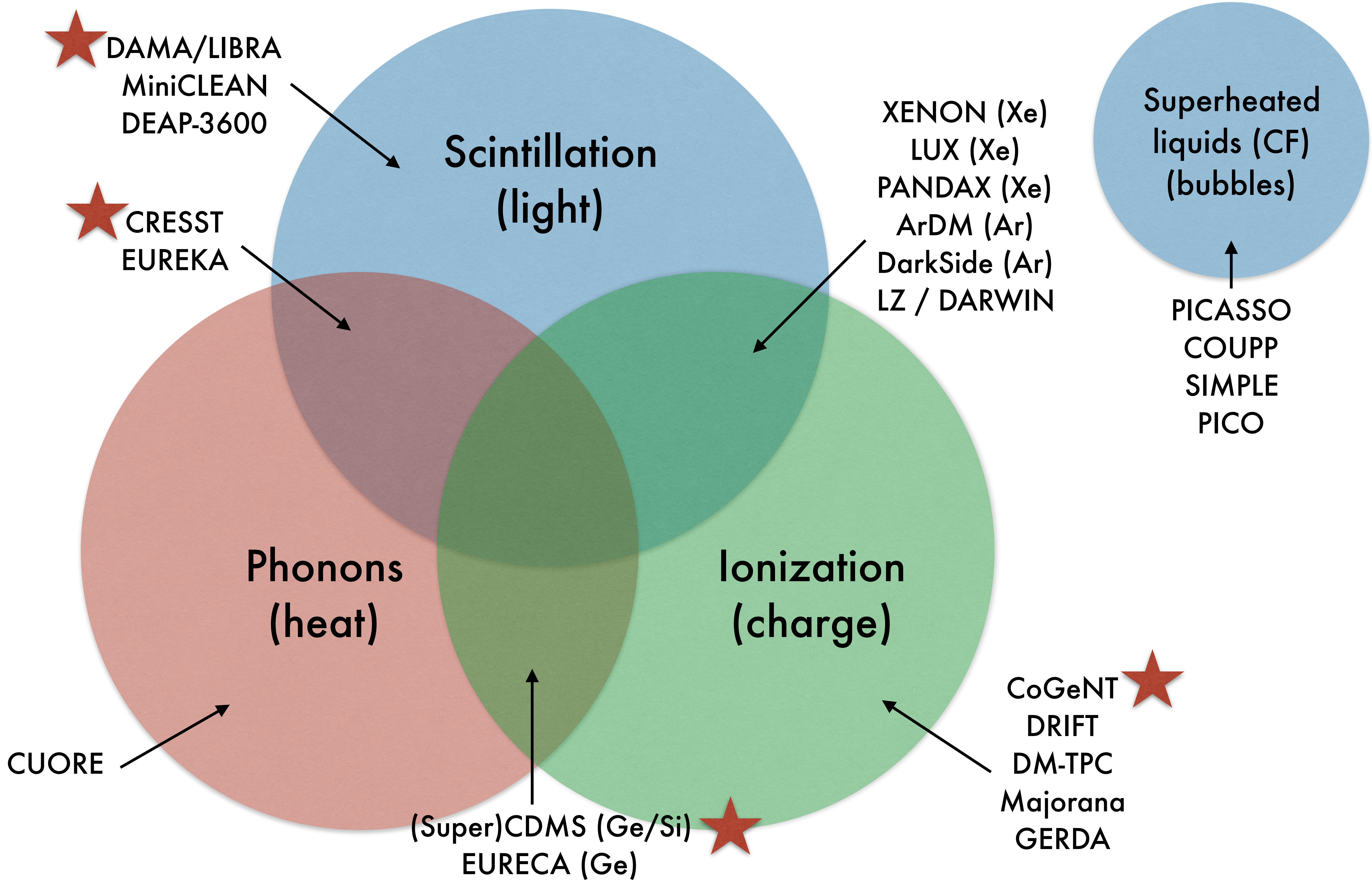
We need quite sensitive detectors with very low backgrounds!

Rate Calculation

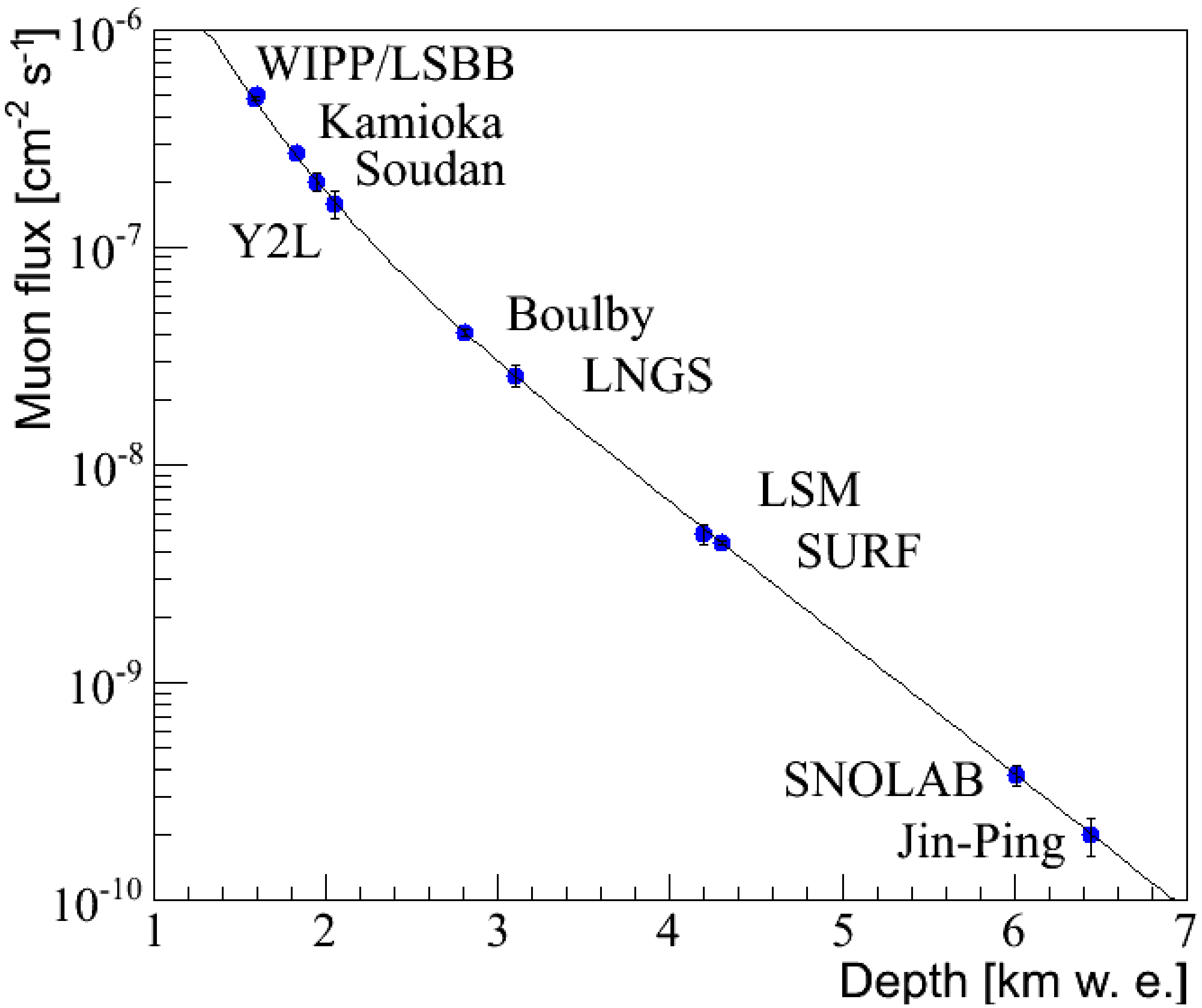
In order to calculate the expected DM rate in our detector, we have to take into account the DM characteristics, and those of the detector.
For referring to a concrete case, we consider WIMP DM here.

1) WIMPS have a velocity distribution inside the Milky Way f(v).
2) The detector moves with the Earth/Sun system wrt to the galaxy.
3) The cross-section depends on the type of interaction (spin-dependent or not)
4) DM scatters on nuclei which have a finite size —> Form Factors
5) We have to take into account the detector inefficiency in converting the recoil energy in visible energy (quenching).
6) Detectors have a finite energy resolution

Direct Detection Techniques



Deep Underground Labs



WIPP in USA (DMTPC)

LSBB in France (SIMPLE)

Kamioka in Japan (XMASS, NEWAGE)

Soudan in USA (SuperCDMS, GoGeNT)

Y2L in Corea (KIMS)

Boulby in UK (DRIFT, ZEPLIN)

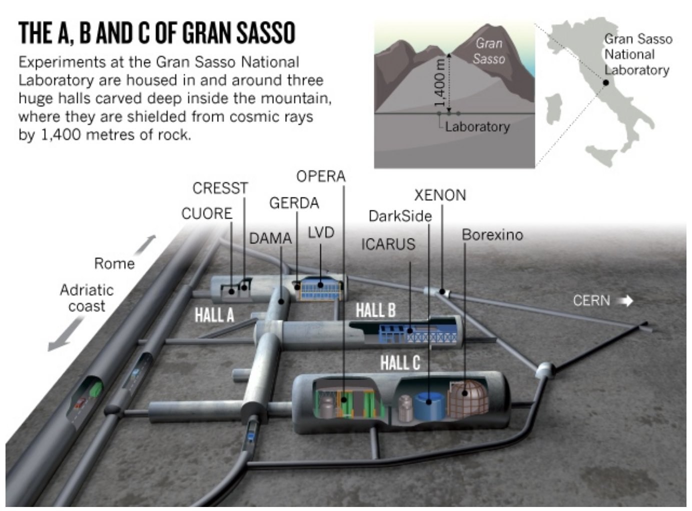
LNGS in Italy (XENON, DAMA, Cresst, DarkSide)

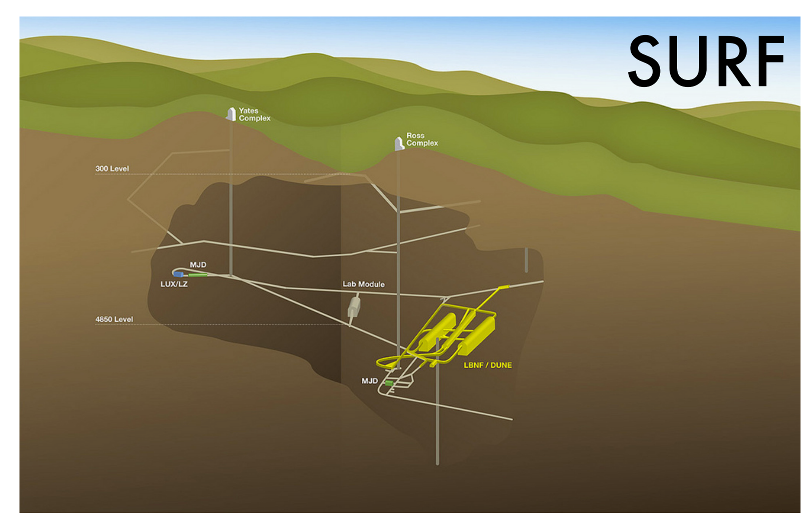
LSM in France (Edelweiss, MIMAC)

SURF in USA (LUX)

SNOLAB in Canada (DEAP/CLEAN, PICASSO, COUPP)

Jin-Ping in China (PandaX, CDEX)





External Backgrounds and Shielding

Gamma rays from natural radioactivity:

- Target self-shielding
- Selected materials
- Discrimination and multiple-scattering detection

Neutrons (cosmics-induced or from natural fission)

- Deep underground labs
- Passive shielding / active shielding
- Selected Materials

Neutrinos (from the Sun, atmosphere, supernovae)

- Elastic neutrino-electron scattering
- Coherent neutrino-nucleus scattering

Backgrounds from materials

Internal Backgrounds (from the target itself)

- ^{85}Kr
- Radon (Rn)
- In Argon: ^{39}Ar (565 keV endpoint, 1Bq/kg), ^{42}Ar
- In Xenon: ^{136}Xe (double beta decay with $T_{1/2}=2.2\times10^{21}$yr)

Surface Backgrounds (in the containing materials)

- Cosmic activation (underground construction)
- Germanium/Silicon (high-purity powders/melts)
- Surface events from alpha/beta decays

Scintillation (only)

- DM searches using only scintillating materials use inorganic crystals, in particular NaI(Tl) and CsI(Tl).

- Room-temperature operation.

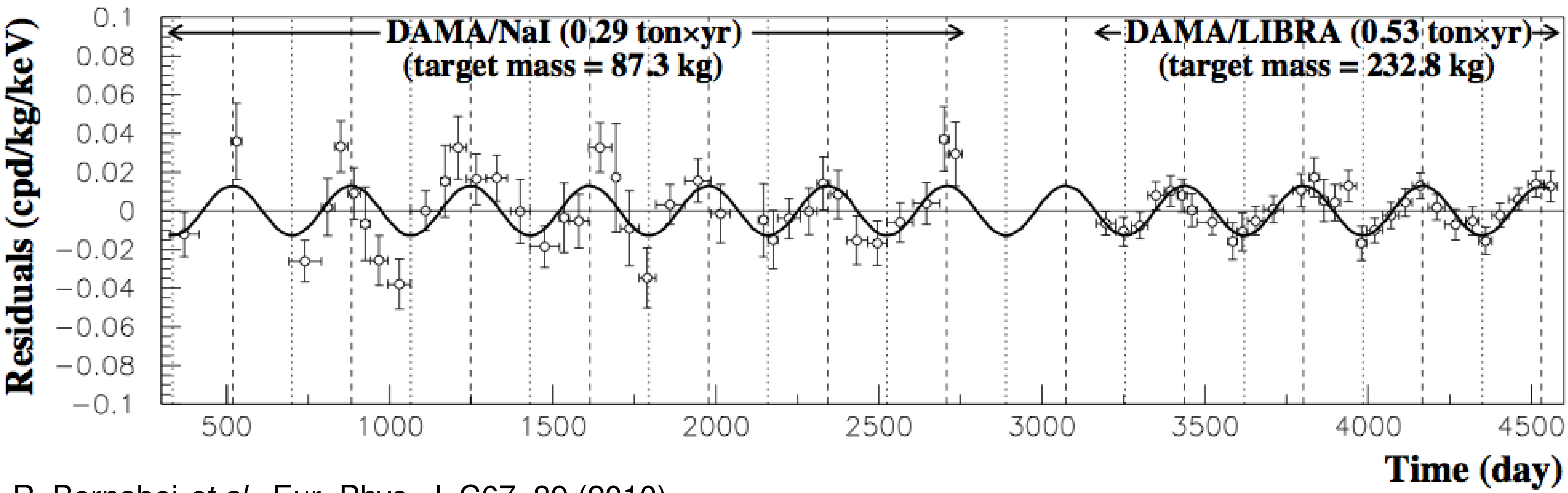
- Operated in arrays of many crystals.

- Very high stability.

- Low intrinsic radioactivity.

Famous Example: DAMA

- High-purity NaI crystals
- No ability to discriminate nuclear recoils from electron recoils.
- Detected an annual modulation signal in the 2%6 keV region with very high significance (>9sigma): what is it?

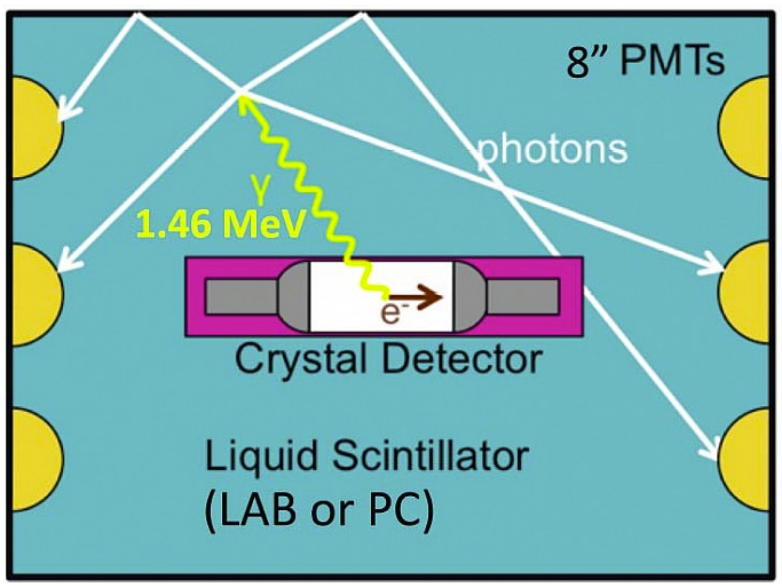


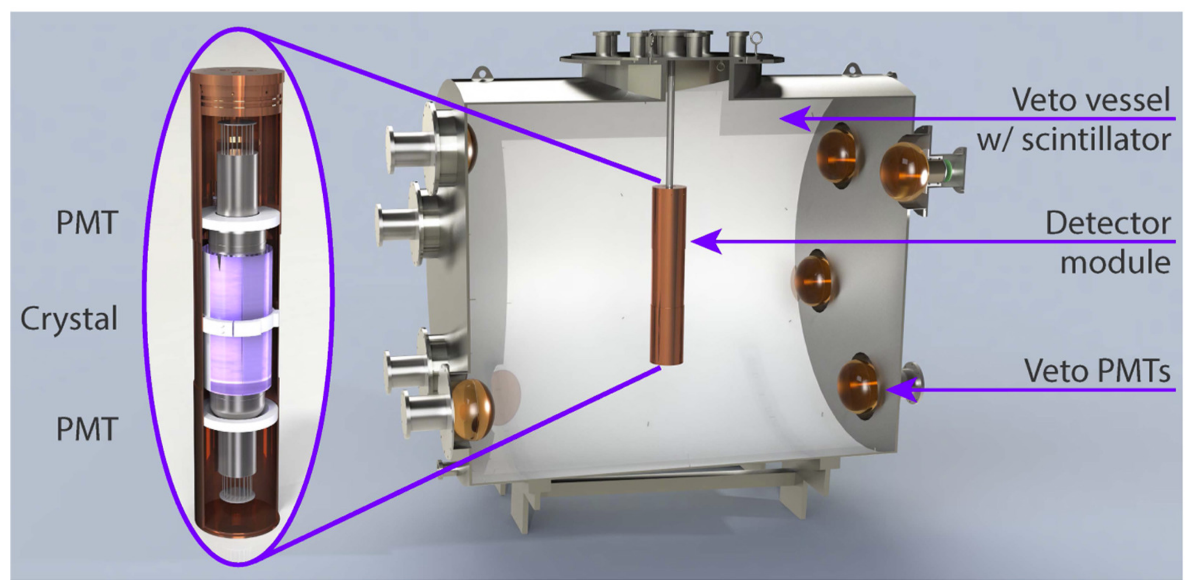
R. Bernabei *et al.*, Eur. Phys. J. C67, 39 (2010)

Challenging the DAMA result

- A CsI-based experiment (KIMS at YangyanLab, Corea) does not see the DAMA signal.
- A new NaI-based experiment is ramping up: SABRE

Experimental Concept





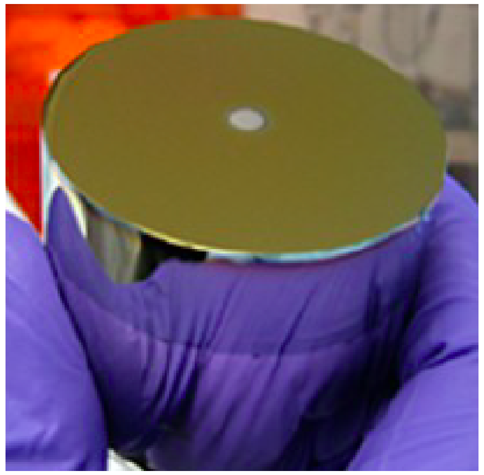
Based at Gran Sasso AND Australia (Stawell Gold mine, 1km deep).
Detectors in both hemispheres.
Can disentangle seasonal effects.

Ionization (only)

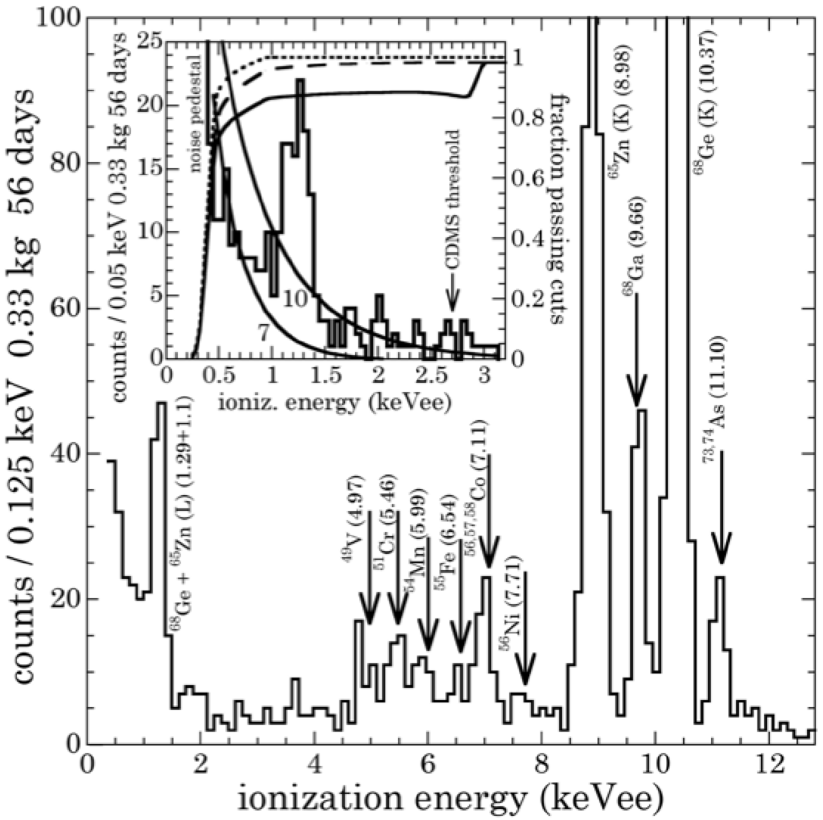
- The case of Germanium detectors

Cryogenic operation at LN temperatures
Very high energy resolution (<1% at 1 MeV)
No PID
Pulse-shape for rejecting multiple scatters.

The CoGeNT signal (2011)



Detected an excess + annual modulation
Independent analysis did not find it
Other Ge detectors did not find it
- CDEX (China)
- TEXONO (Taiwan)



CoGeNT, Phys. Rev. Lett. 106 131301 (2011)
Davis, 1405.0495 & Aalseth et al., 1401.6234
TEXONO, Phys. Rev. Lett. 110, 261301 (2013)

Cryogenic Bolometers

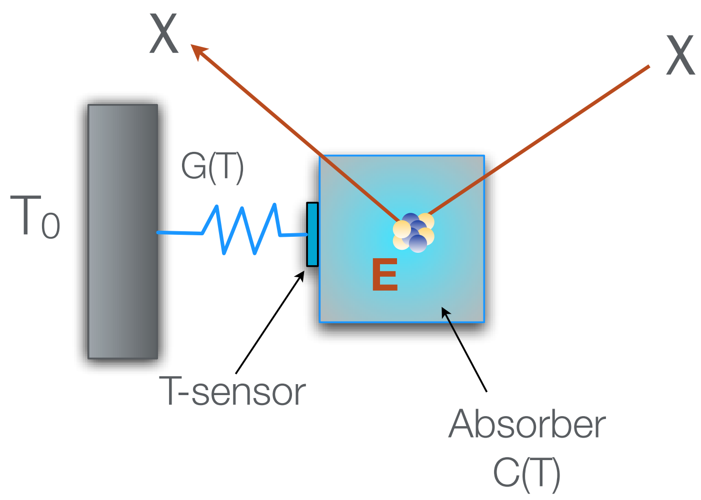
The idea is to detect phonons (quanta of lattice vibrations).
Cryogenic temperatures needed.
Energy resolution in semiconductor detectors $\frac{\sigma(E)}{E} = \sqrt{\frac{F\epsilon}{E}}$

F: Fano factor (~0.1 in Si), ϵ in Si is 3.6 eV/eh pair, band-gap ~1.2 eV.

Since the maximum phonon energy in Silicon is ~60 meV, many phonons are created per e/h pair.

In detectors for DM searches:

- Measurement of thermal phonons (temperature increase)
- Measurement of a-thermal phonons (from non-equilibrium processes)
- Use of superconductors (s.c. energy gap ~ meV).



The energy deposit produces an increase in temperature.

$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}}$$ with time constant $$\tau = \frac{C(T)}{G(T)}$$

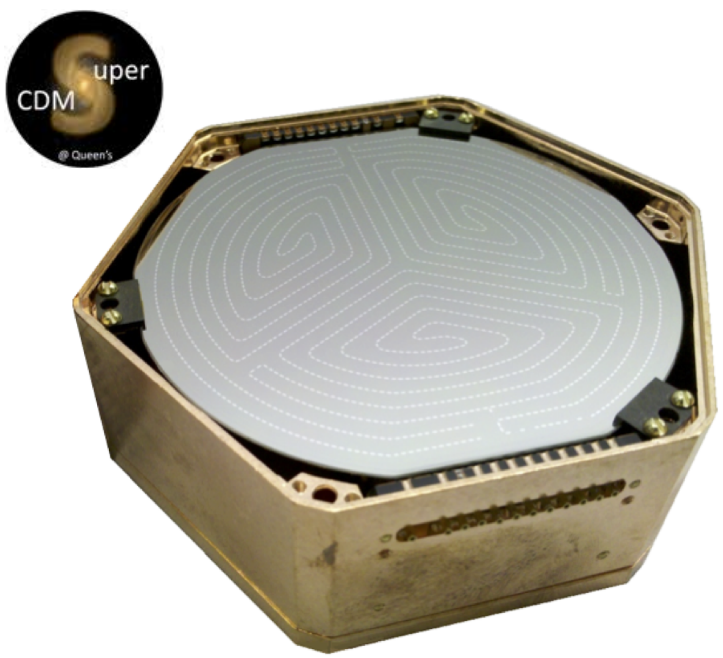
where C is the heat capacity and G the thermal conductance of the channel between the absorber and the heat bath at T_0.

For dielectric crystals $$C(T) \sim \frac{m}{M}\left(\frac{T}{\Theta_D}\right)^3 JK^{-1}$$

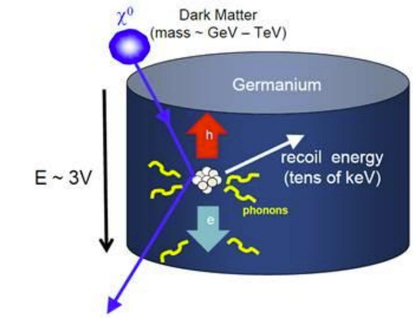
m=detector mass
M = molecular weight of the detector
theta0 = Debye temperature

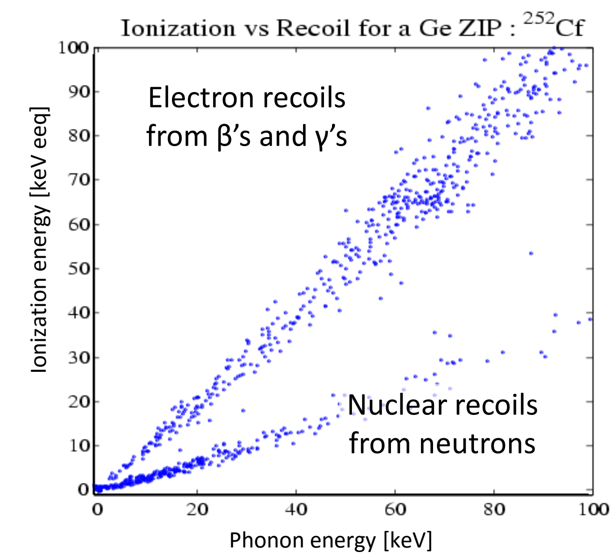
For example, at T=10mK, an energy deposit of 1keV on a 100g detector gives 1 microK temp increase.
Measuring increases in the microK range is possible, e.g. with superconductor-based detectors.

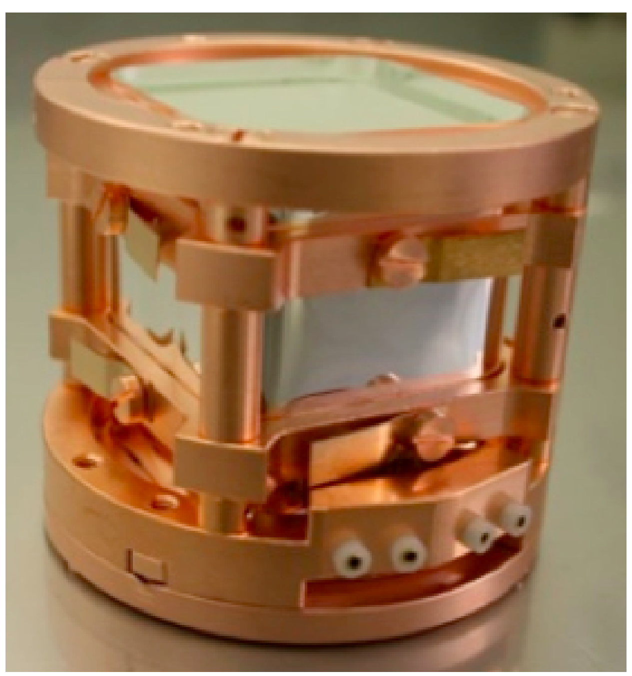
Cryogenic Bolometers



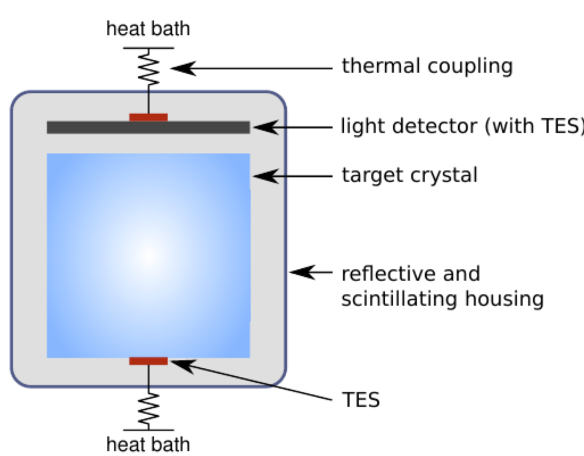
Silicon and Germanium Detectors
Located at Sudan and soon at SNOLab
Ionization + Phonons (TES)
Two detector types:
- iZIP: threshold<1keV
- HV: LN phonons, threshold<0.1keV

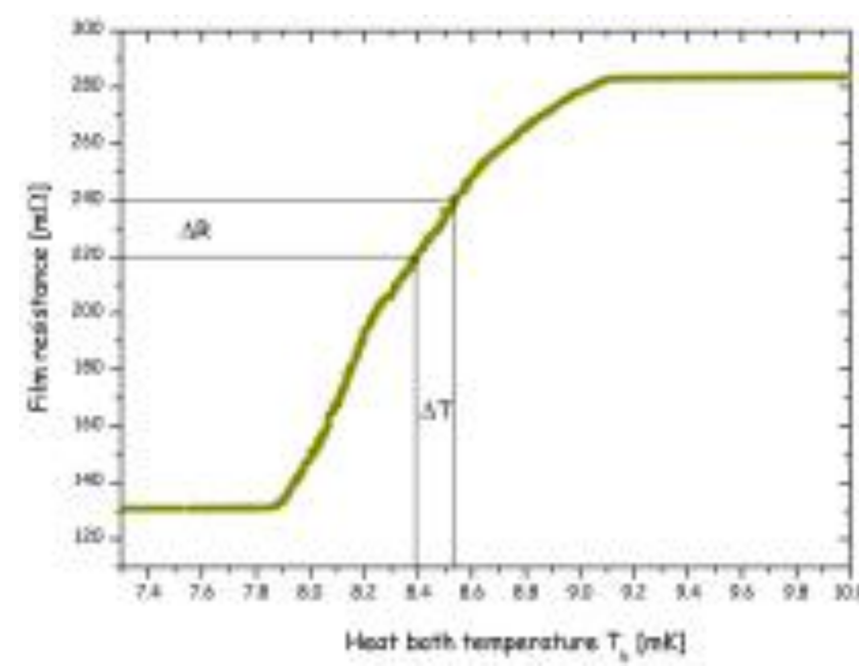






CaWO$_4$ Crystals at
Located at Gran Sasso Labs
Scintillation + Phonons (TES)





Liquid Noble Gases Detectors

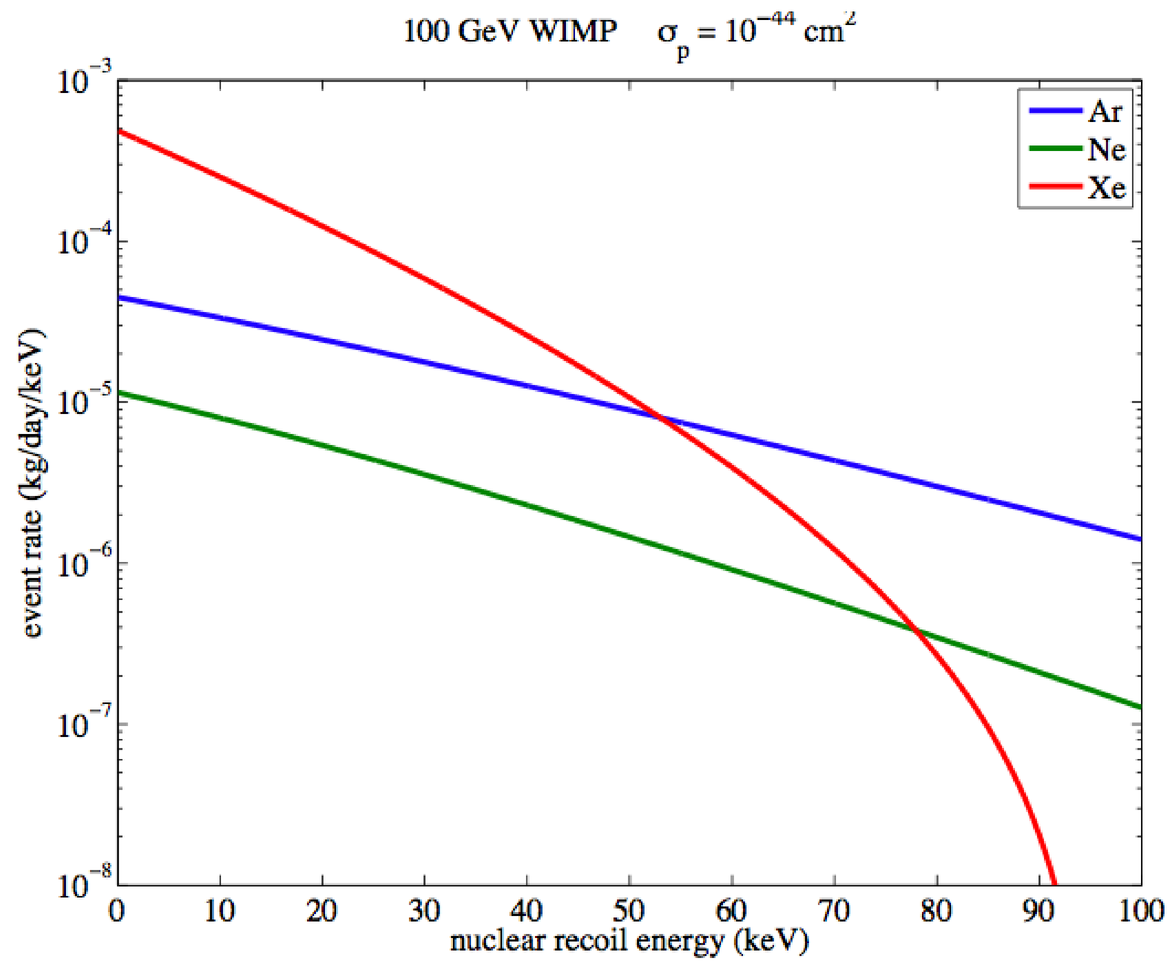
Advantages:

- Possibility to build large targets (ton-scale)
- Single and Double phase detectors
- 3D positon reconstruction —> Fiducialization
- Transparent to their own scintillation light
- High stopping power (high Z and density)
- Efficient and fast scintillators
- Good ionization yield
- Small quenching factor

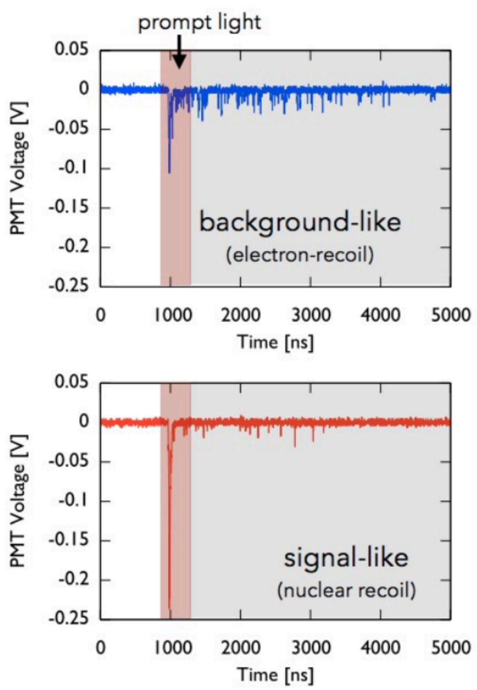
High background rejection capability:

- Fiducialization
- PDS or light/ionization correlation
- Coupling with active veto detectors

	LNe	LAr	LXe
Z (A)	10 (20)	18 (40)	54 (131)
Density [g/cm^3]	1.2	1.4	3.0
Scintillation λ	78 nm	125 nm	178 nm
BP [K] at 1 atm	27	87	165
Ioniz. [e^-/keV]*	46	42	64
Scint. [γ/keV]*	7	40	46



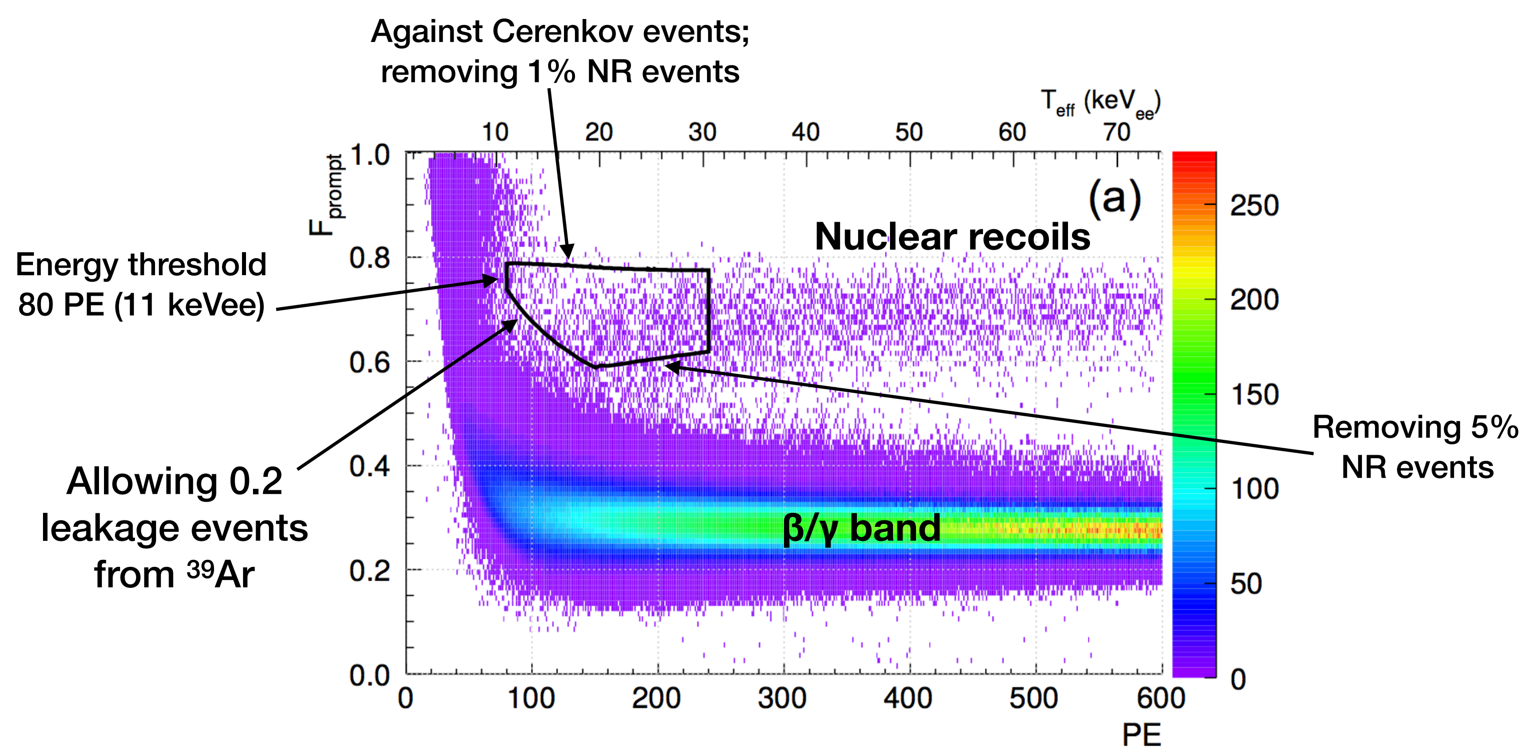
Main Example: the DEAP-3600 detector

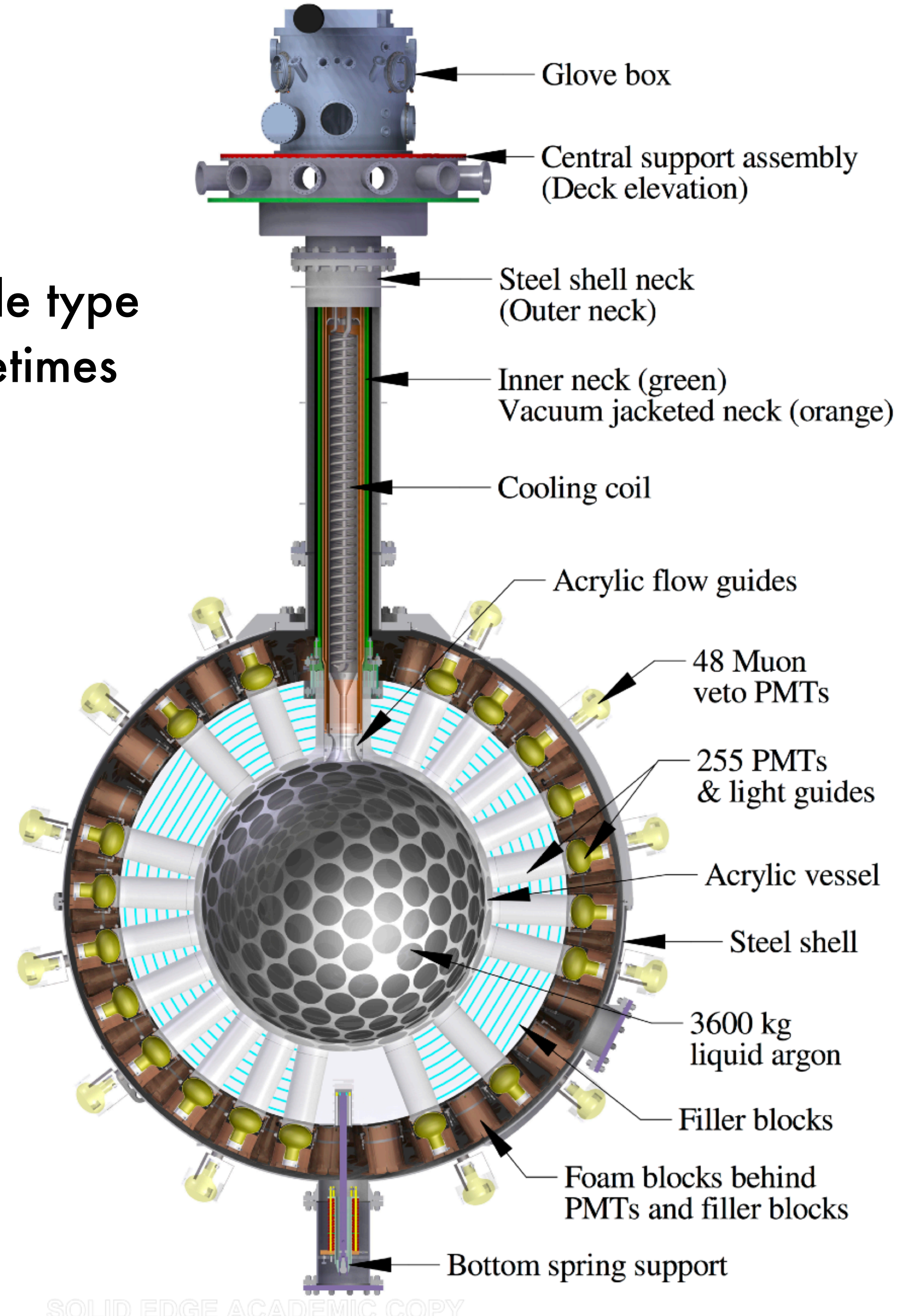


Liquid Argon, 3.6 Tons

Pulse-shape discrimination:

- Very different singlet/triplet lifetime
- Relative amplitudes depend on particle type
- PDF not good in Xenon: similar s/t lifetimes



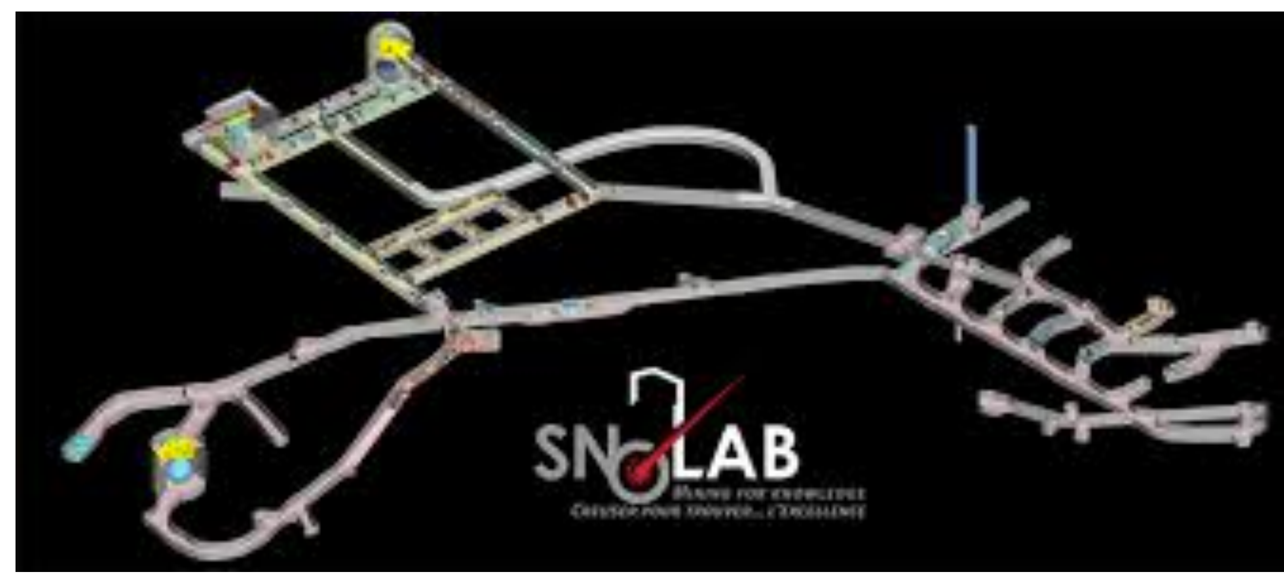


DEAP-3600



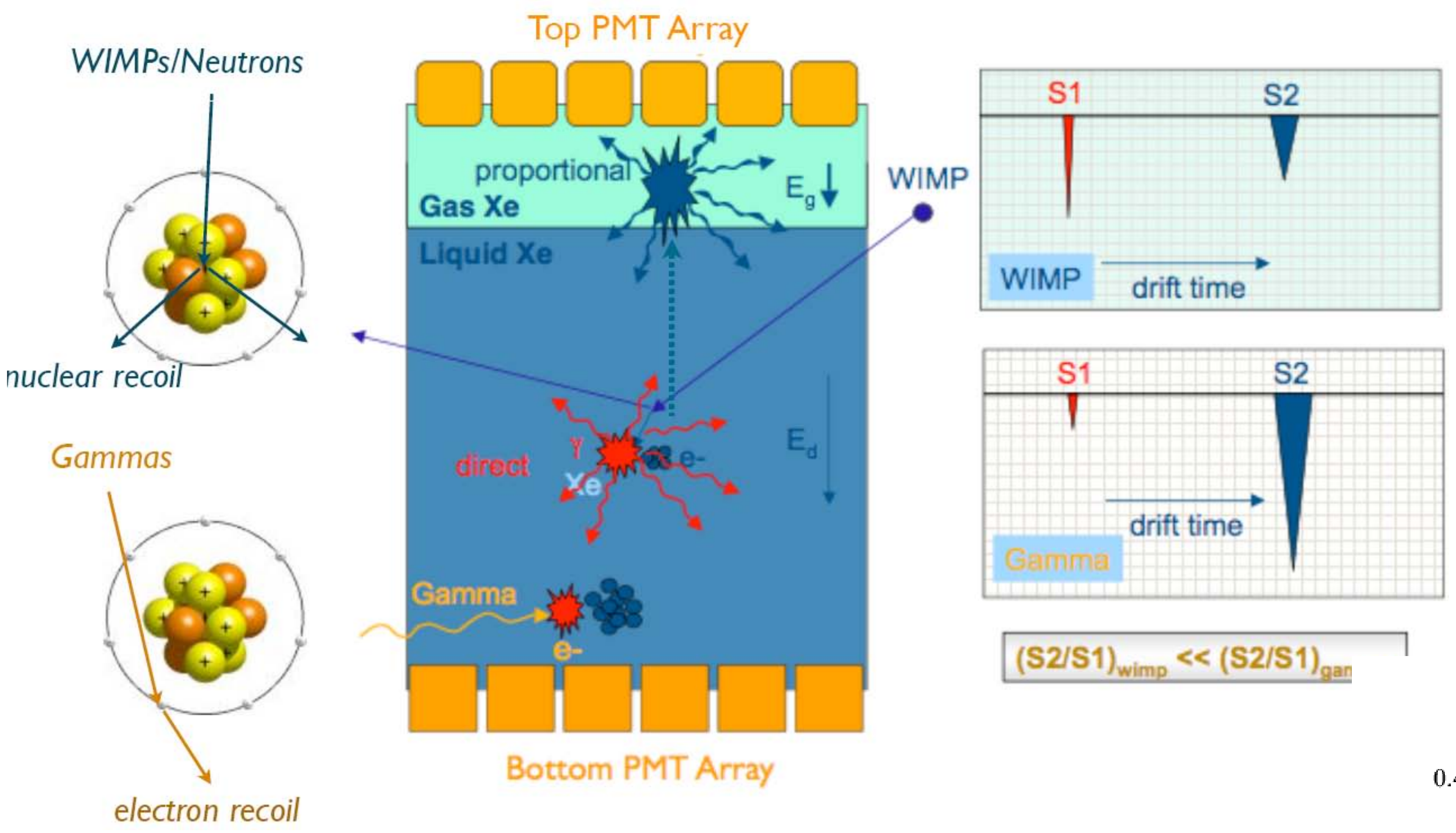




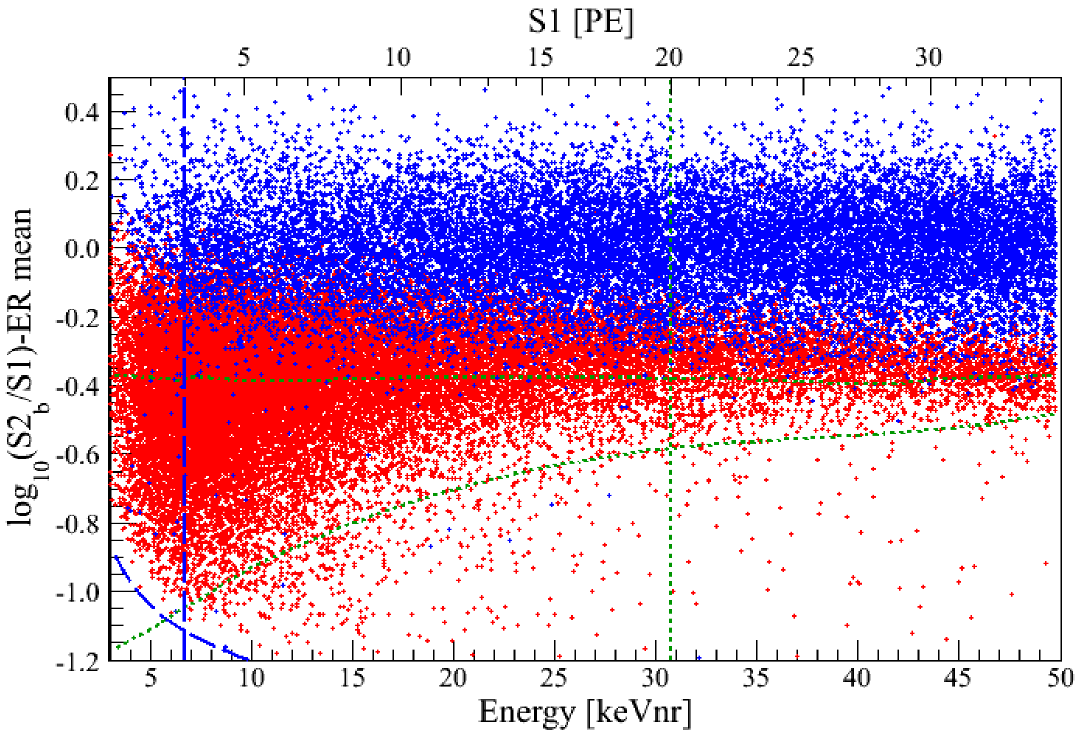


Two-Phase Detectors (Ar/Xe)

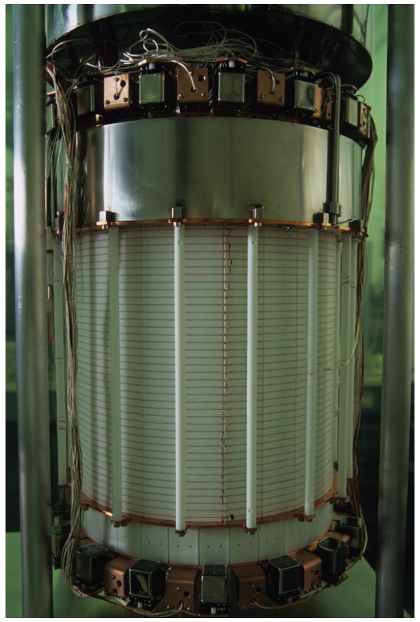
Concept:



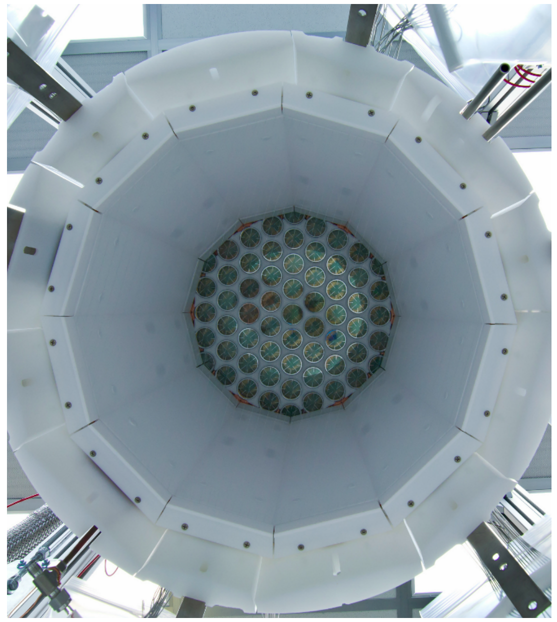
ER/NR Discrimination



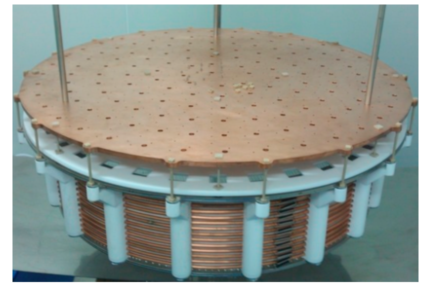
Xe/Ar Dual-phase Detectors



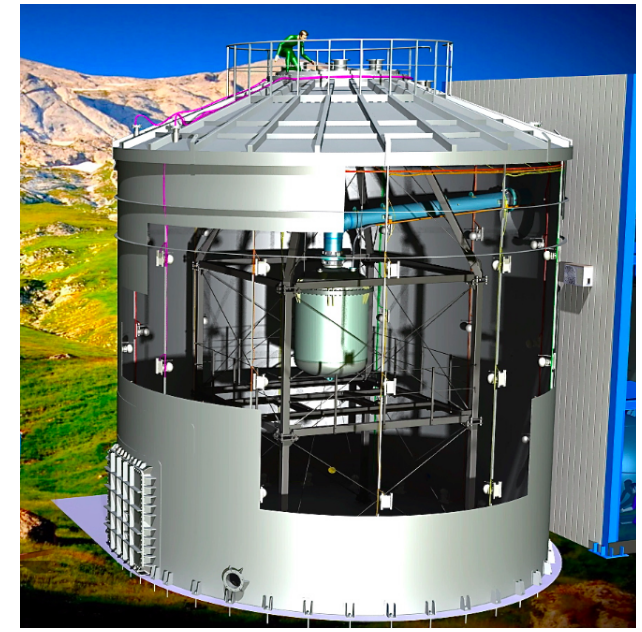
XENON100
Located at LNGS
161 kg mass
34 kg fiducial



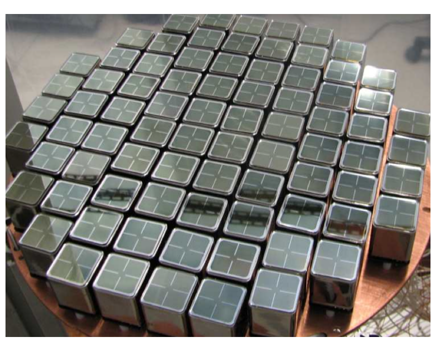
LUX
Located at SURF, SD
370 kg Xe mass
118 kg fiducial



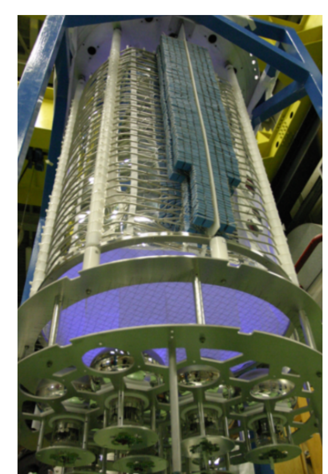
Panda-X
Located in China
450 kg Xe mass
300 kg fiducial
Similar to LUX



XENON-1T
Located at LNGS
Goal ~10^{-47} cm^2

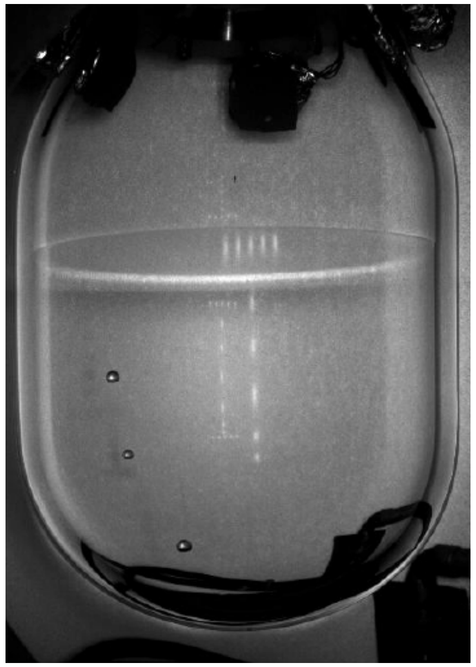


DarkSide-50
Located at LNGS
Mass 50kg depl. Argon
PSD+S1+S2
Goal ~10^{-45} cm^2



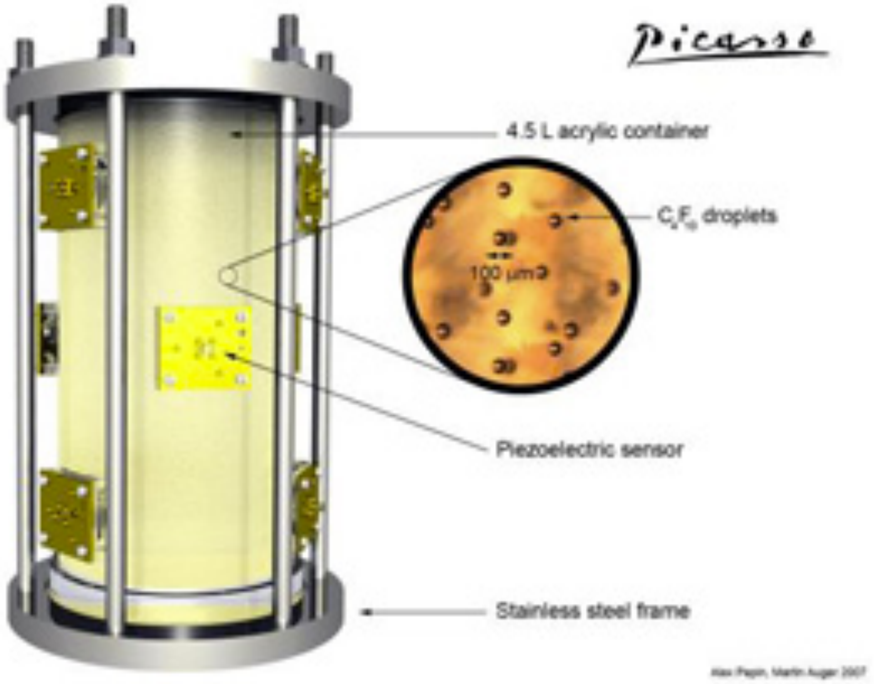
ArDM
Located at Canfranc (Spain)
Mass 2ton Argon
Tech. Demonstrator
TPC with siMs

Superheated Fluid Detectors



COUPP

PICO

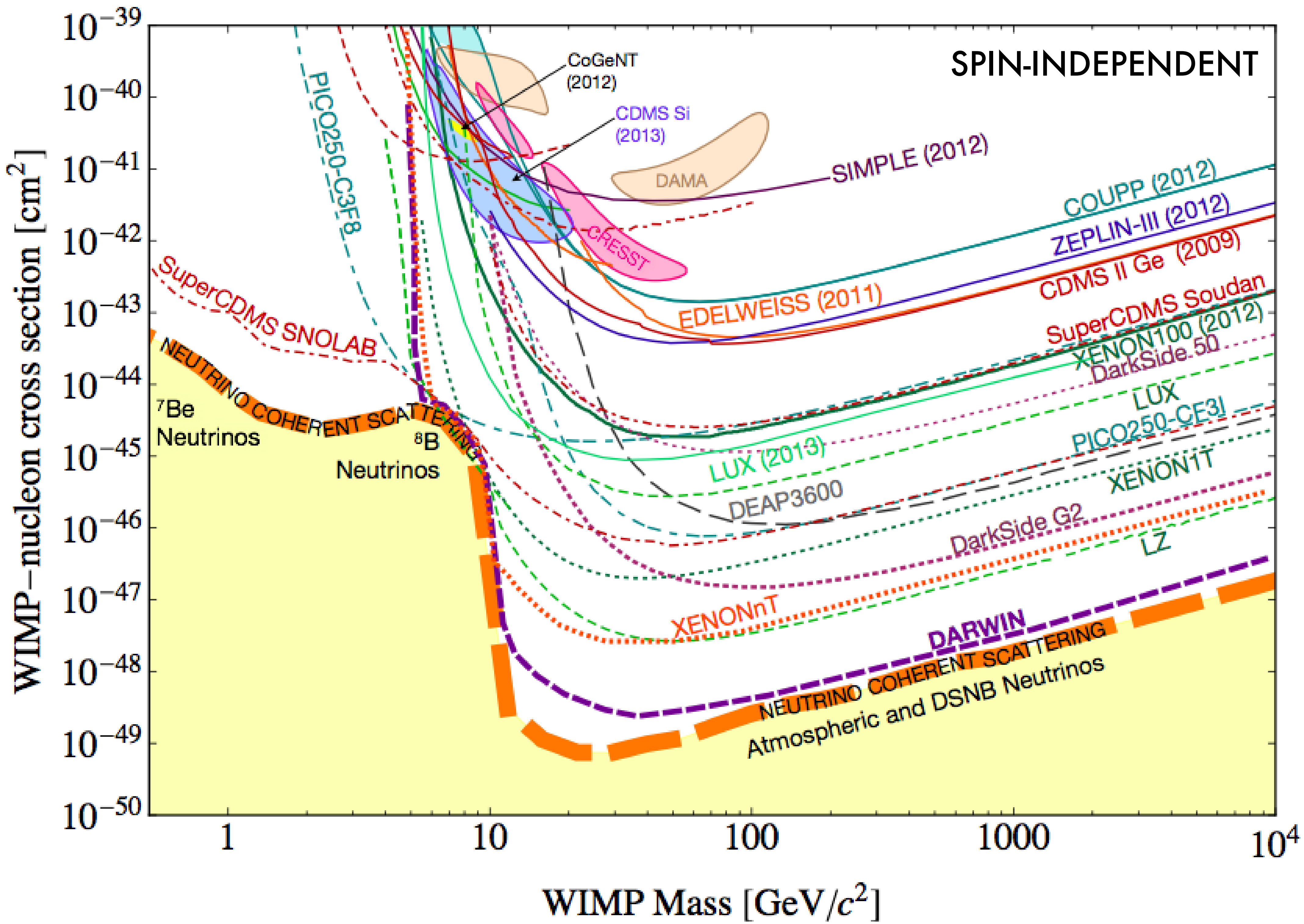


PICASSO

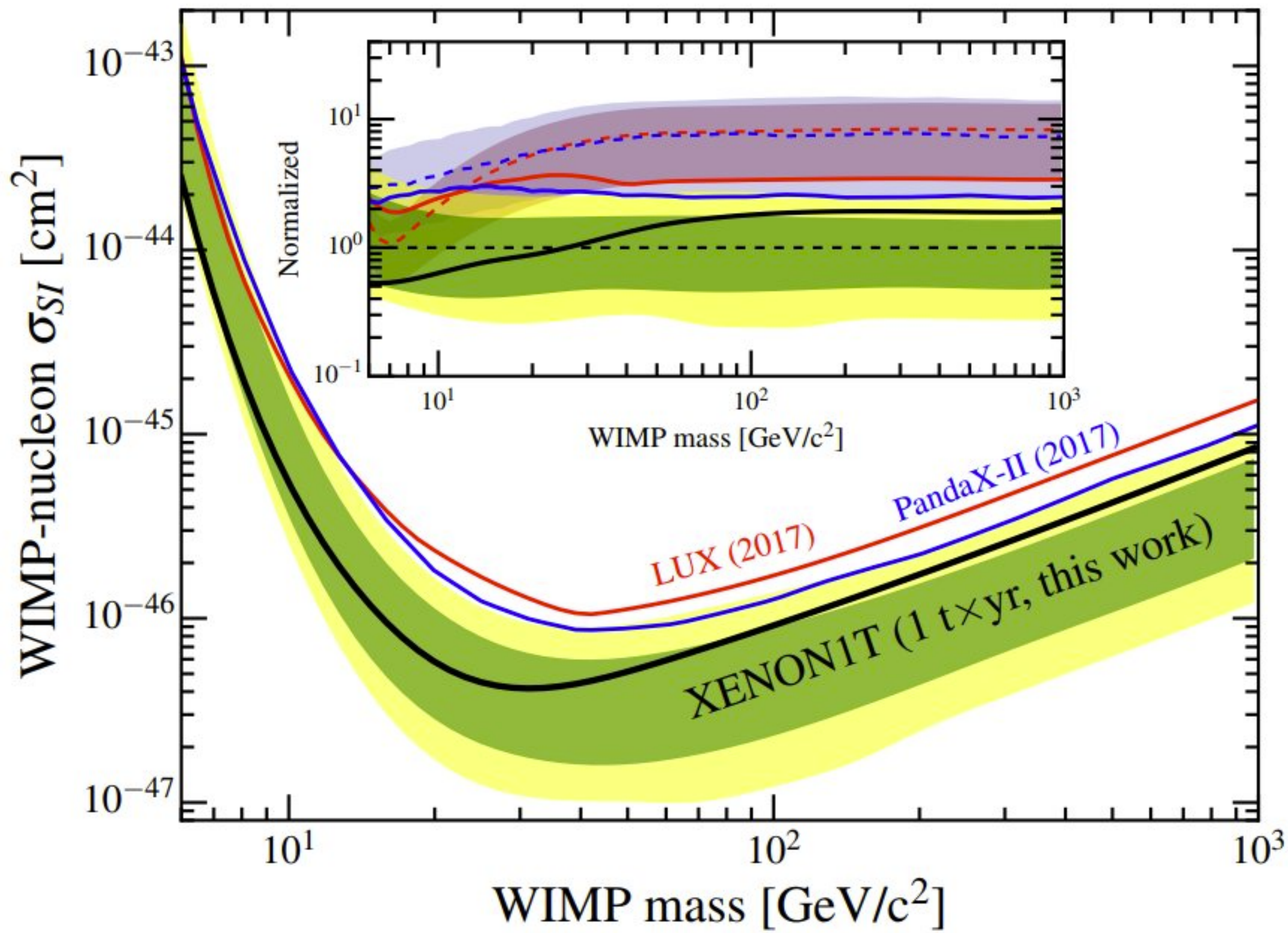
Bubble chambers filled with a superheated fluid (e.g. C_3F_8) kept in a metastable state.

If the energy deposited exceeds a threshold, an expanding bubble is detected by cameras and piezo-acustic sensors.

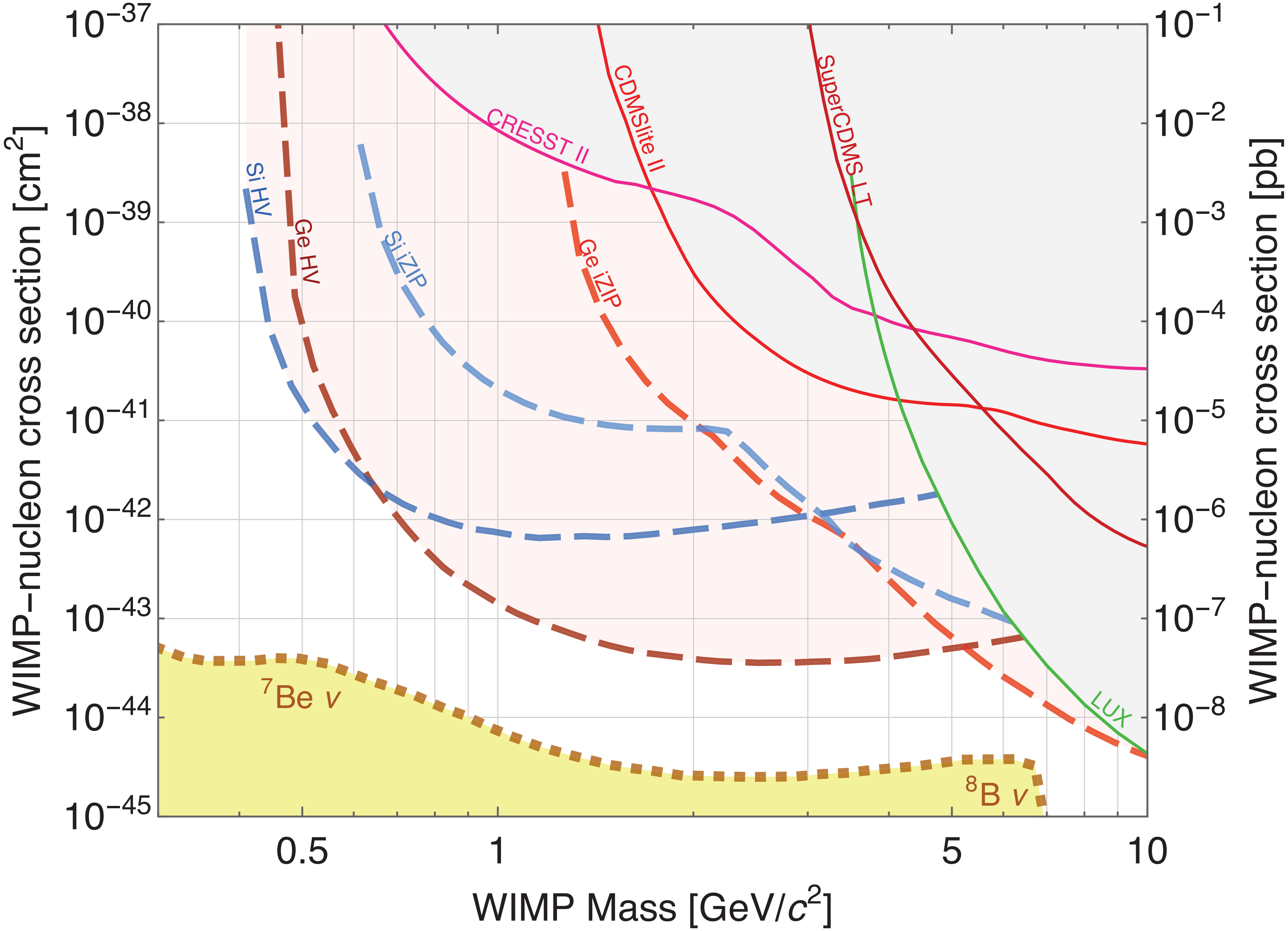
WIMP Search Status & Projections



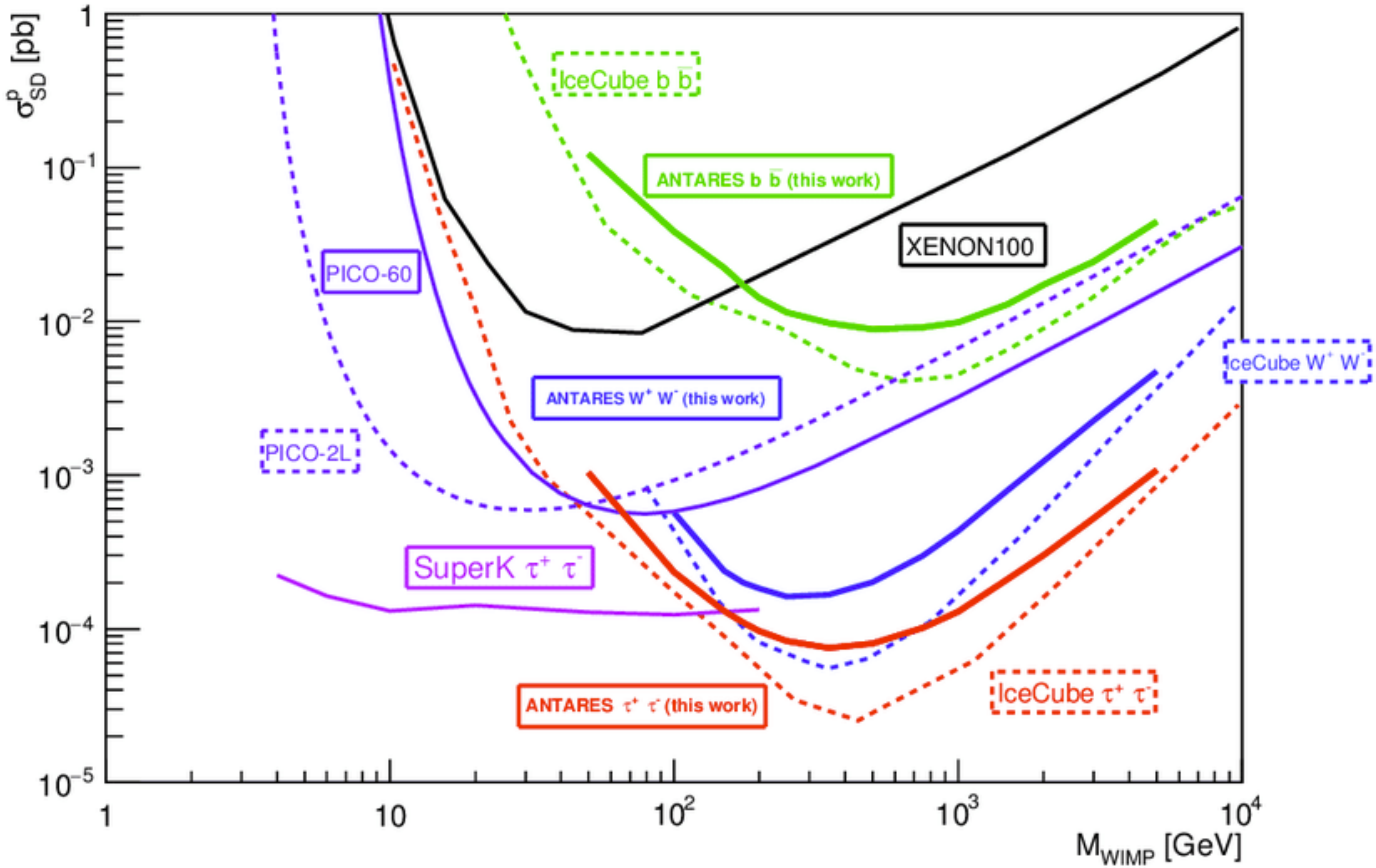
2018 Best Limit from XENON-1T



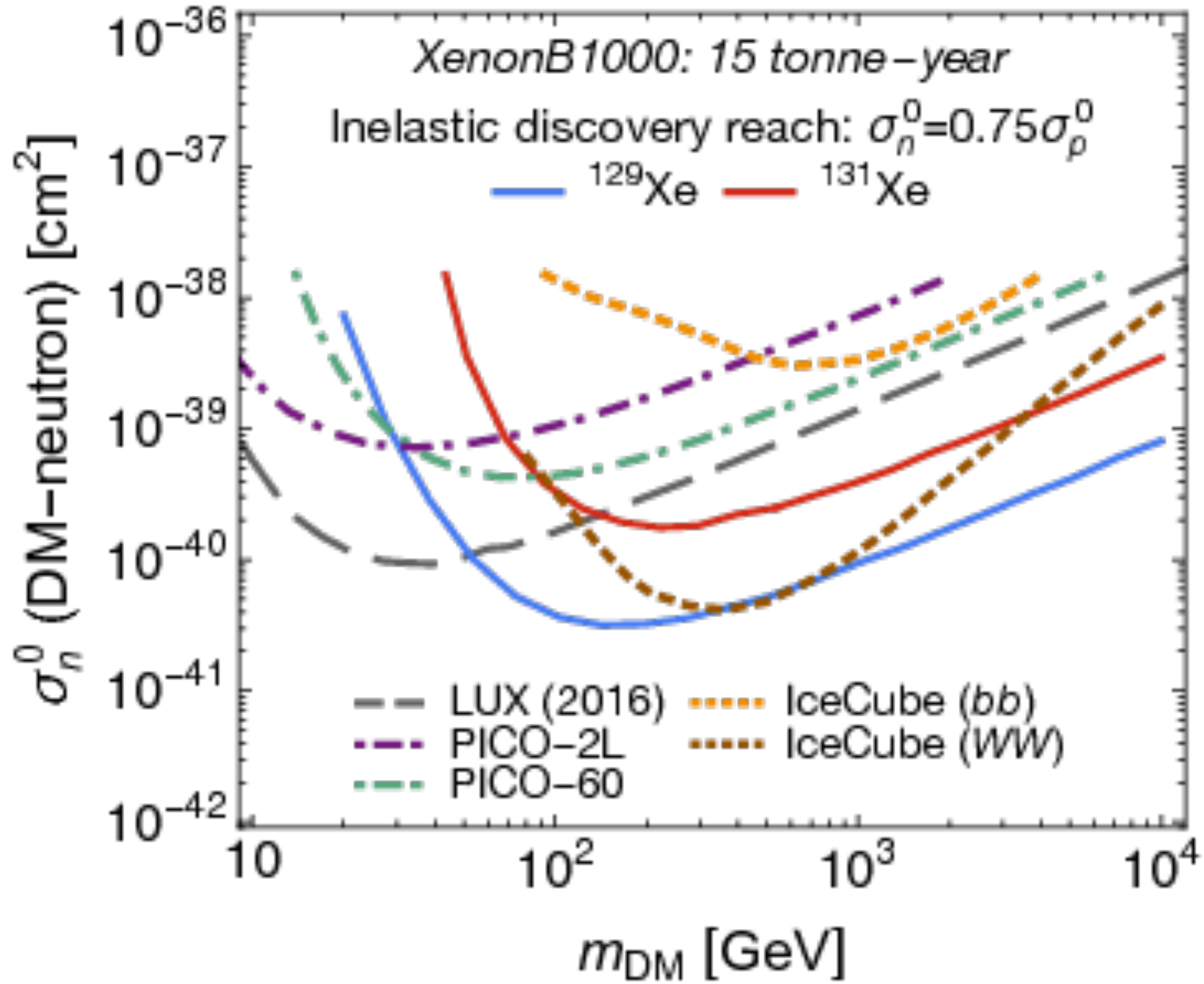
Status at "Low" Masses



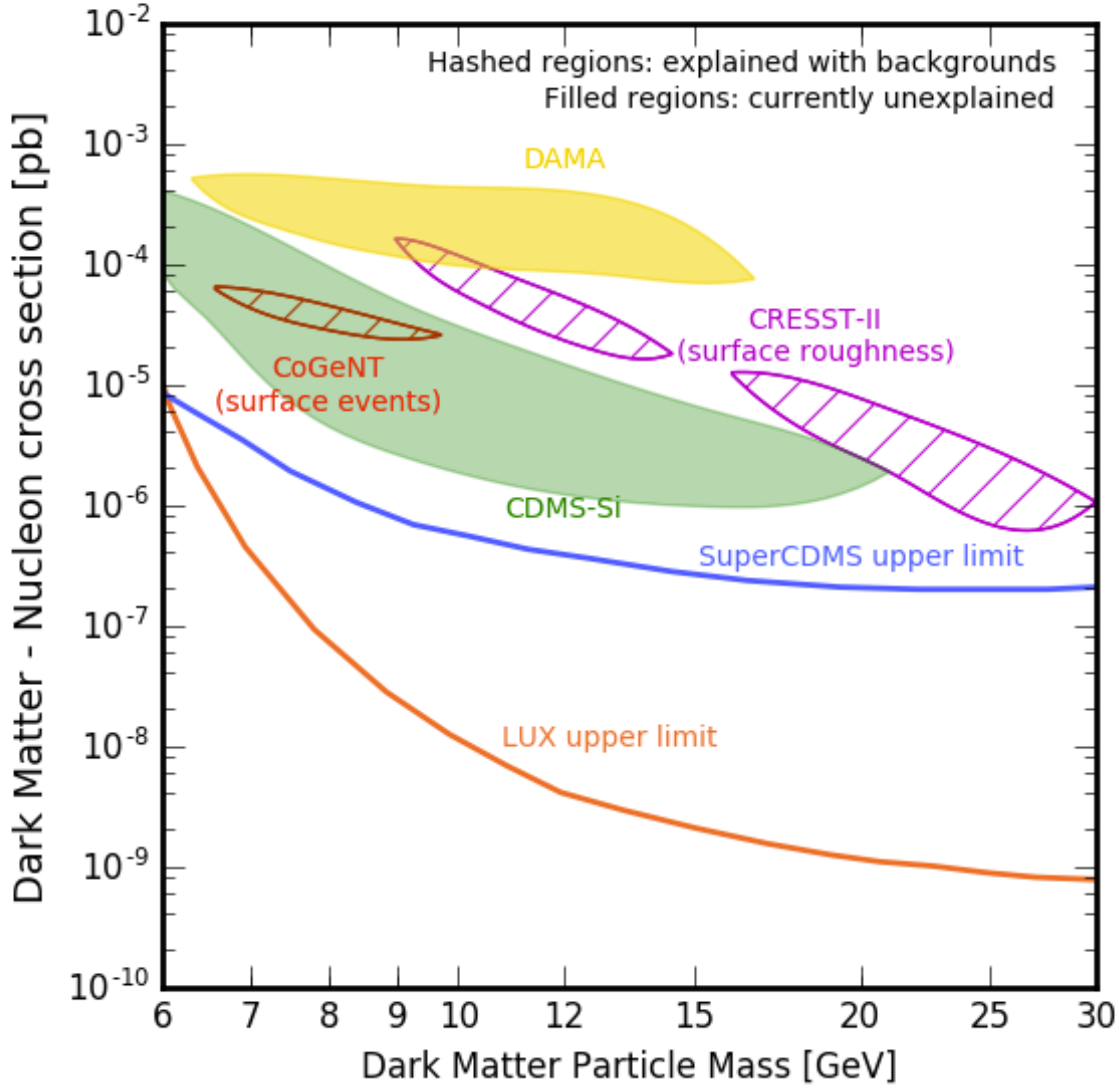
Spin-Dependent Limits



DM-Neutron Limits

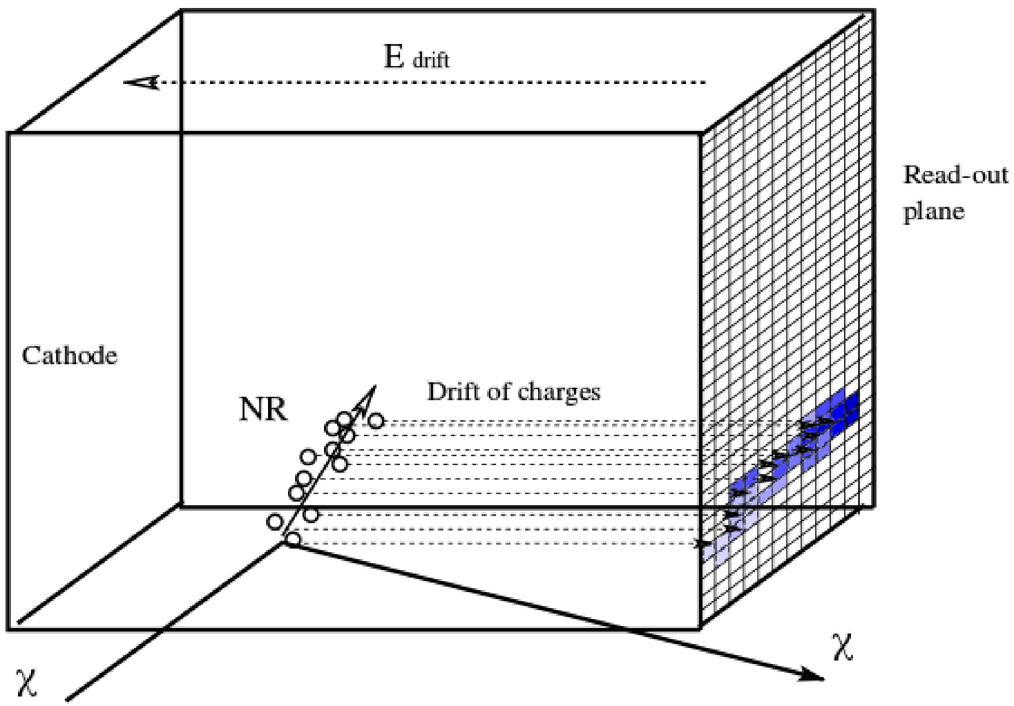


False Signals?



Beyond the Neutrino Floor

The ultimate background for direct detection experiments are neutrinos.
Possible solution to reject this background: directional search.
In gases with P<100 Torr, the range of recoils goes into the mm range
Detector technology: TPC



DRIFT - m^3 experiment

Other experiments: MAMIC, DMTPC, NEWAGE
Other technology: emulsion detectors

Summary

Accelerators and Direct Detection experiments are producing increasingly stringent limits.

DD experiments ultimately limited by neutrino background: new techniques needed (directionality?)

LXe technology the most sensitive so far.

LAr is a cheaper solution for scaling to multi-ton detectors

Many projects for the future reaching the neutrino floor.

Cryogenic bolometers are best suited for low-mass WIMPS (lower threshold)

WIMPS do not exhaust the possible DM models!

Stronger activity towards considering electron recoils.

Not discussed here: indirect detection techniques (cosmic rays/neutrinos, satellites, ...).