Dark matter direct detection

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KIAA Workshop on Astroparticle Physics

Beijing, 28-29 September 2015

Nature of dark matter ?

From **astrophysics** and searches for **new particles**:

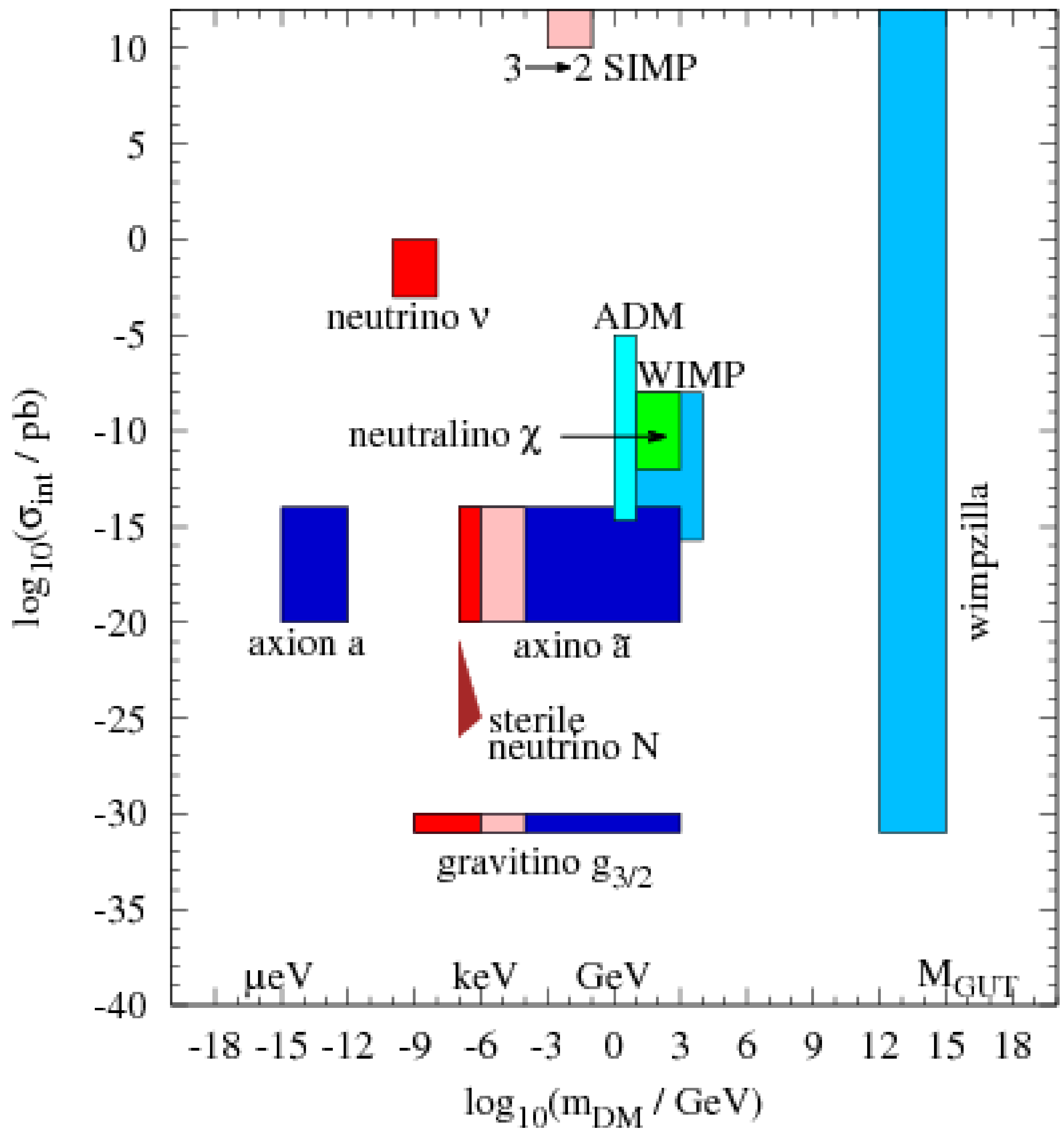
- no strong self-interaction
- no colour charge
- no electric charge

Stable or long lived

The cross-sections and masses of candidates span many orders of magnitude!

This talk: two classes of well motivated candidates:

- **WIMPs**
- **Axions**



Baer *et al*. ArXiv 1407.0017

Direct detection of WIMPs

Search for **elastic collisions** of the WIMP with atomic **nucleus** in a low background detector

$$\frac{dR}{dE_R} = N_T \frac{\rho_{DM}}{m_W} \int_{v_{min}}^{v_{max}} d\vec{v} f(\vec{v}) v \frac{d\sigma}{dE_R}$$

N_T number of target nuclei
ρ_{DM} DM density (gal. halo)
$d\sigma/dE_R$ WIMP-nucleus diff. cross section
$f(v)$ WIMP vel. distribution function in Earth frame

$$E_R = \frac{m_r^2 v^2}{m_N}(1 - \cos\theta)$$

$$v_{min} = \left(\frac{m_N E_{th}}{2m_r^2}\right)^{\frac{1}{2}}$$

θ scattering angle in CM
m_N nuclear mass
m_r reduced mass

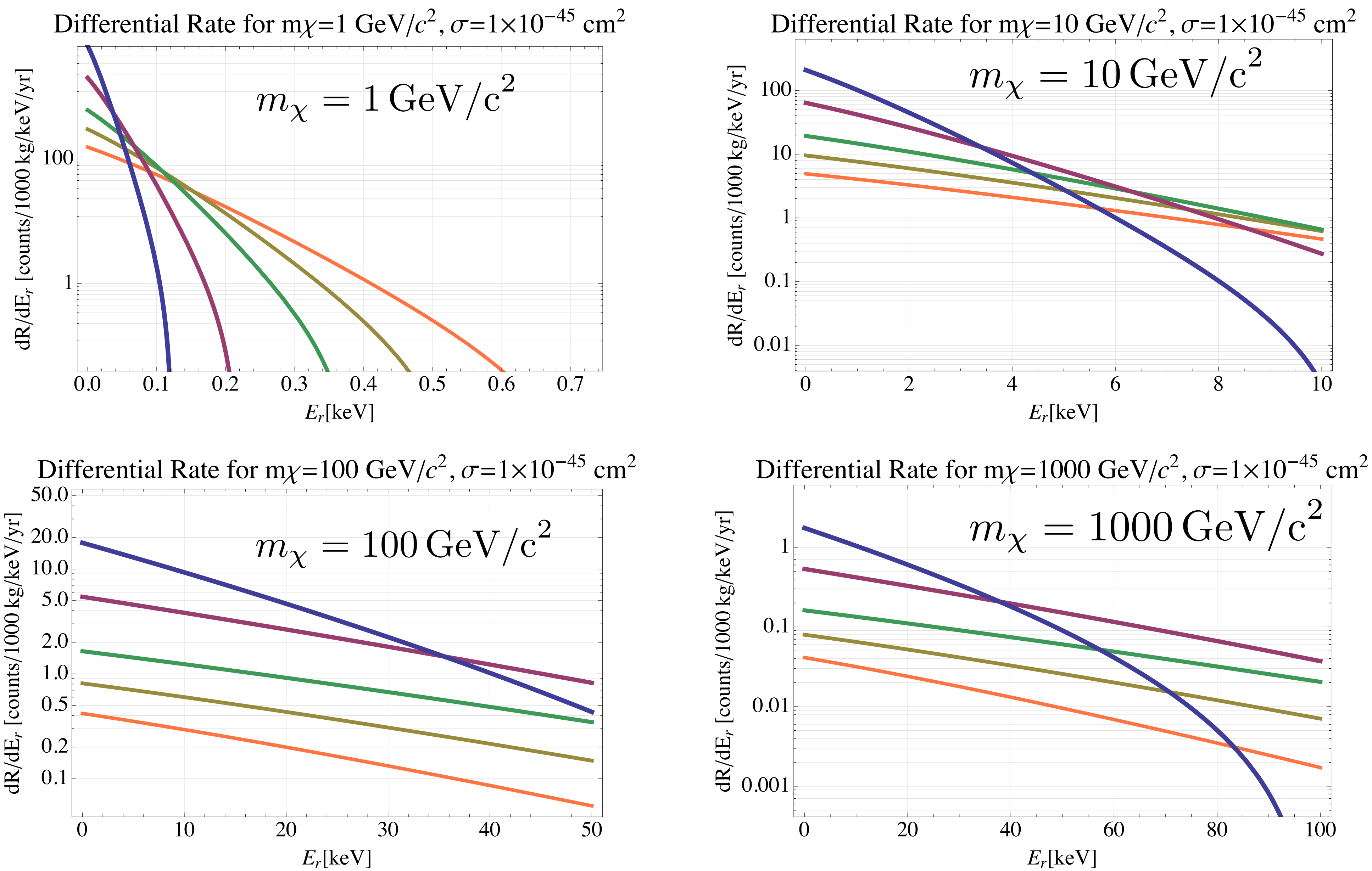
E_{th} energy threshold in the detector

Simplest galactic model: Maxwell-Boltzmann distribution for the WIMP in the gal. rest frame, dispersion $\approx$ 220 km.s^{-1}, $v_{esc} \approx$ 544 km.s^{-1}

$$\frac{d\sigma}{dE_R} \propto \sigma_{SI}^0 F_{SI}^2(E_R) + \sigma_{SD}^0 F_{SD}^2(E_R)$$

Diff. cross section split in leading components
F_{SI} nuclear form factor

Differential rate x nuclear recoil



$\sigma_0^{SI} = 10^{-45}\,\mathrm{cm}^2$

Xenon A=131

Germanium A=73

Argon A=40

Silicon A=28

Neon A=20

Deposited energy from **0.1 to 100 keV** (measured by ionization, phonon or scintillation signals)

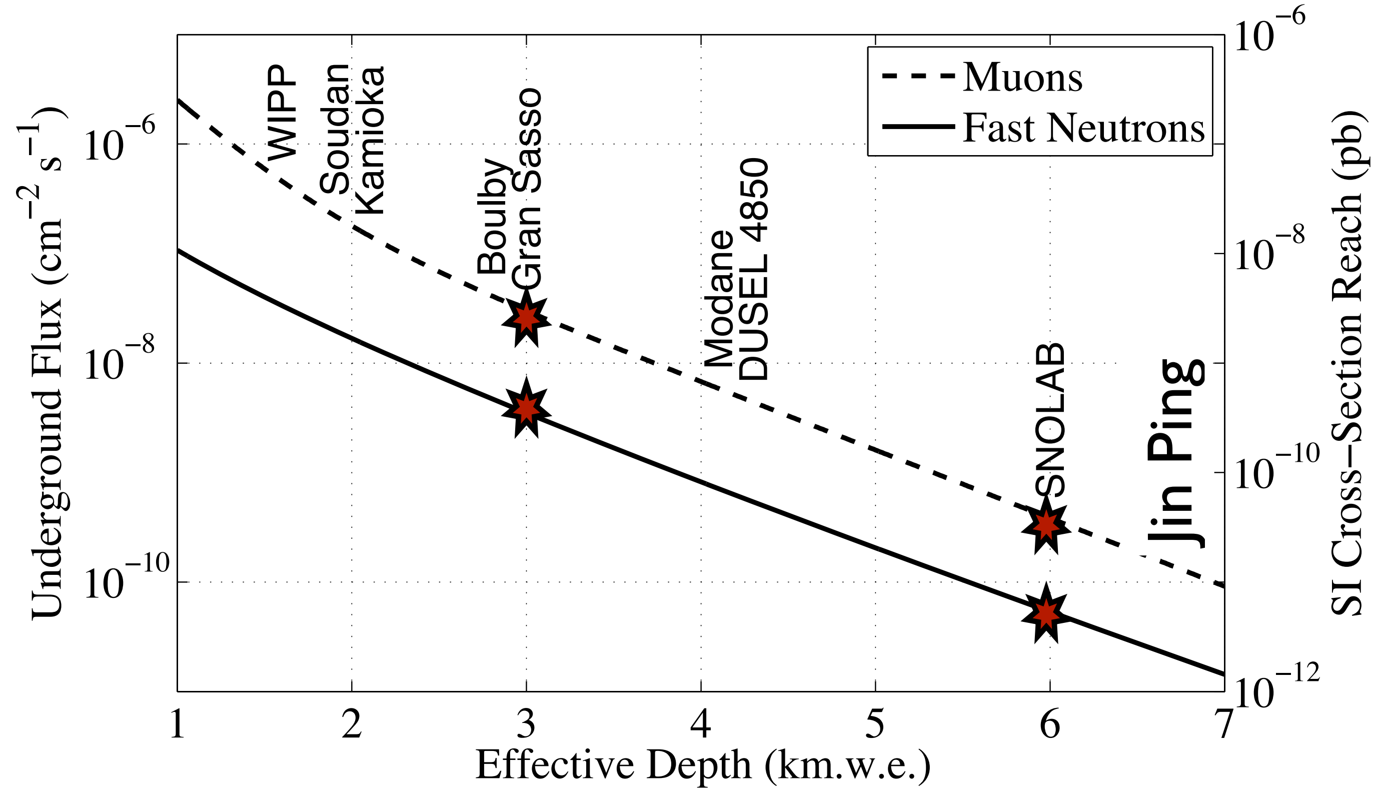
Lower **threshold**, larger sensitivity: spectrum rises exponentially towards low energy

Most evident for **heavy target** isotopes, more important for **low mass WIMPS**

Snowmass CF1 Arxiv 1310.8327

Backgrounds

- Cosmic rays and their secondaries
- Cosmic activation of detector materials at Earth's surface
- Natural radioactivity: ^{238}U, ^{232}Th, ^{222}Rn, ^{40}K
- Antropogenic sources: ^{85}Kr, ^{137}Cs



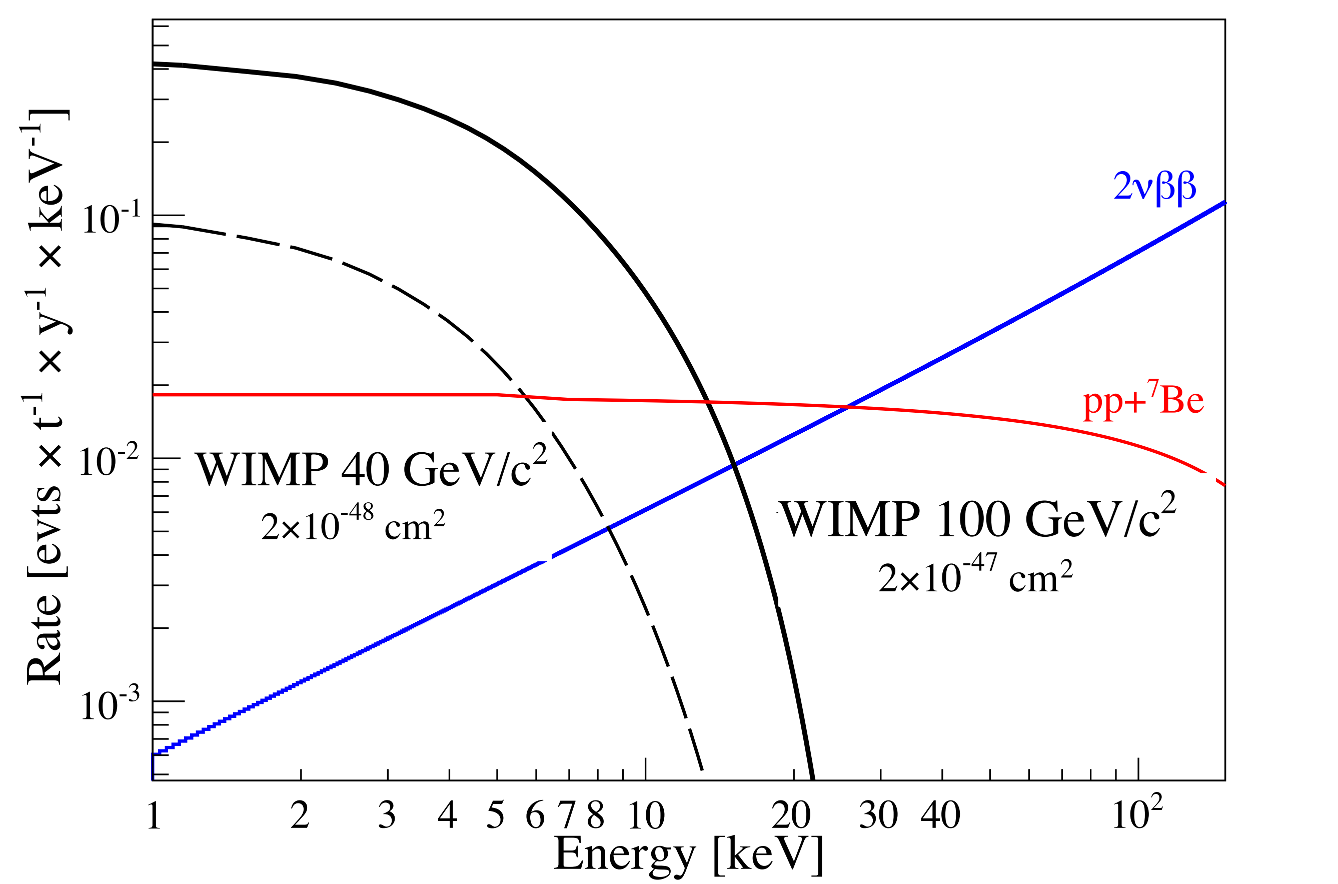
Schnee ArXiv 1101.5205

Ultimate background: **neutrinos**

Ex: Xenon liquid detector
Summed differential spectrum for pp and ^{7}Be
double beta decay of ^{136}Xe

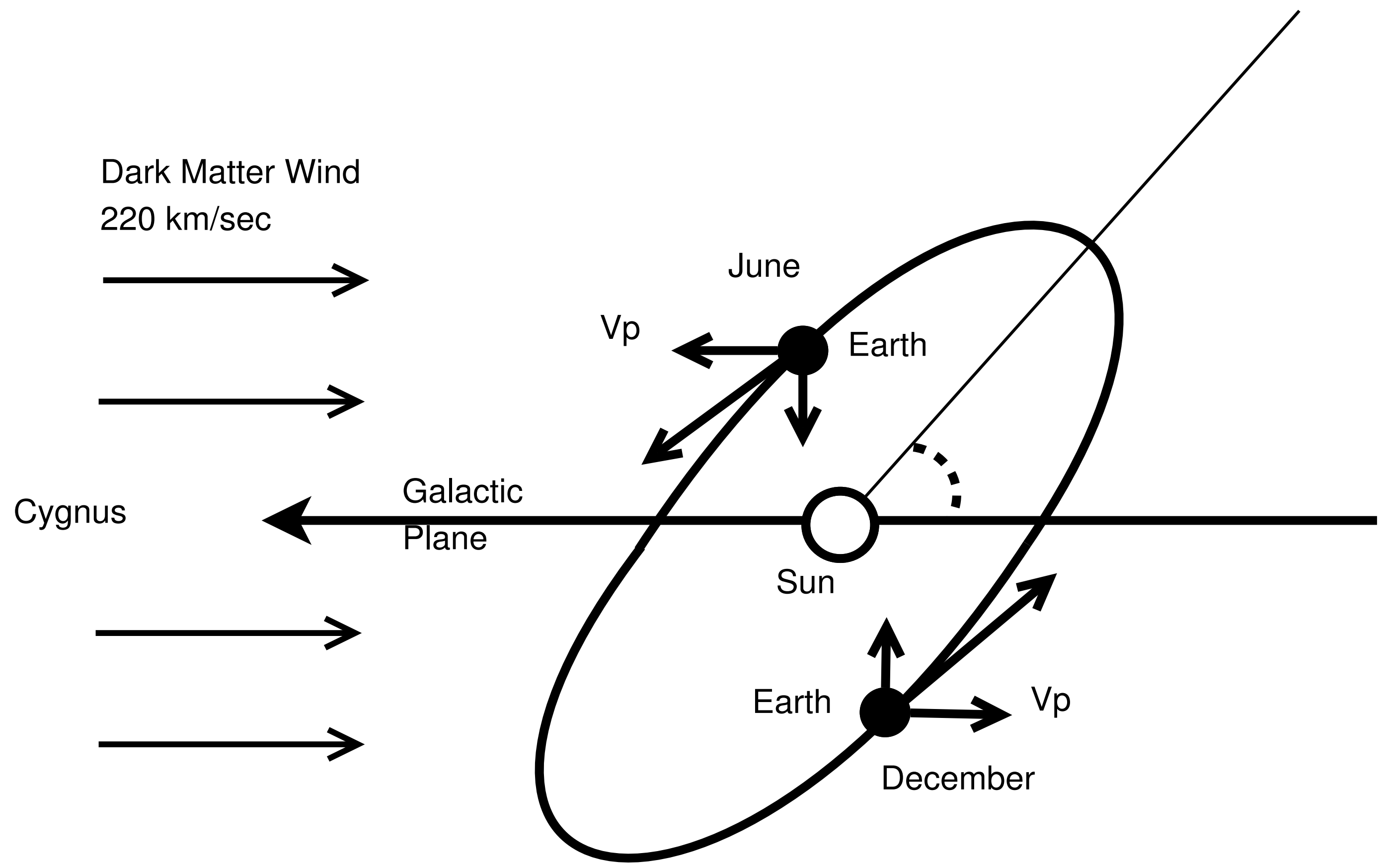
WIMP 40 GeV, $2\text{x}10^{-48}$ cm^2

WIMP 100 GeV, $2\text{x}10^{-47}$ cm^2



Baudis et al. ArXiv 1309.7024

WIMP modulation



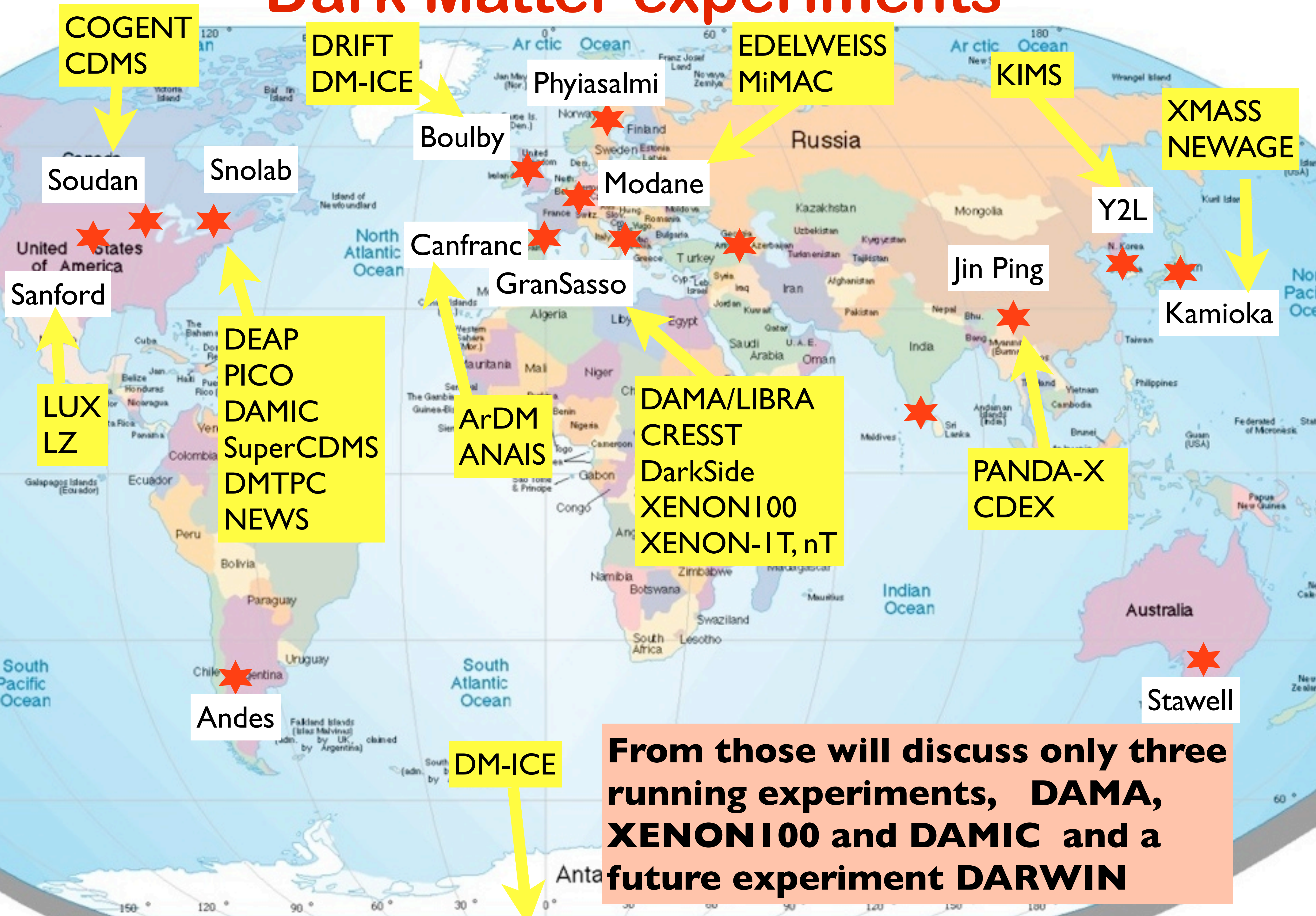
Earth's orbit around the sun:

- the relative velocity between DM particles in galactic halo and detectors varies over the year
- approximately sinusoidal **modulation** for the recoil rate of DM at keV energies
- peaks in early June

Underground labs

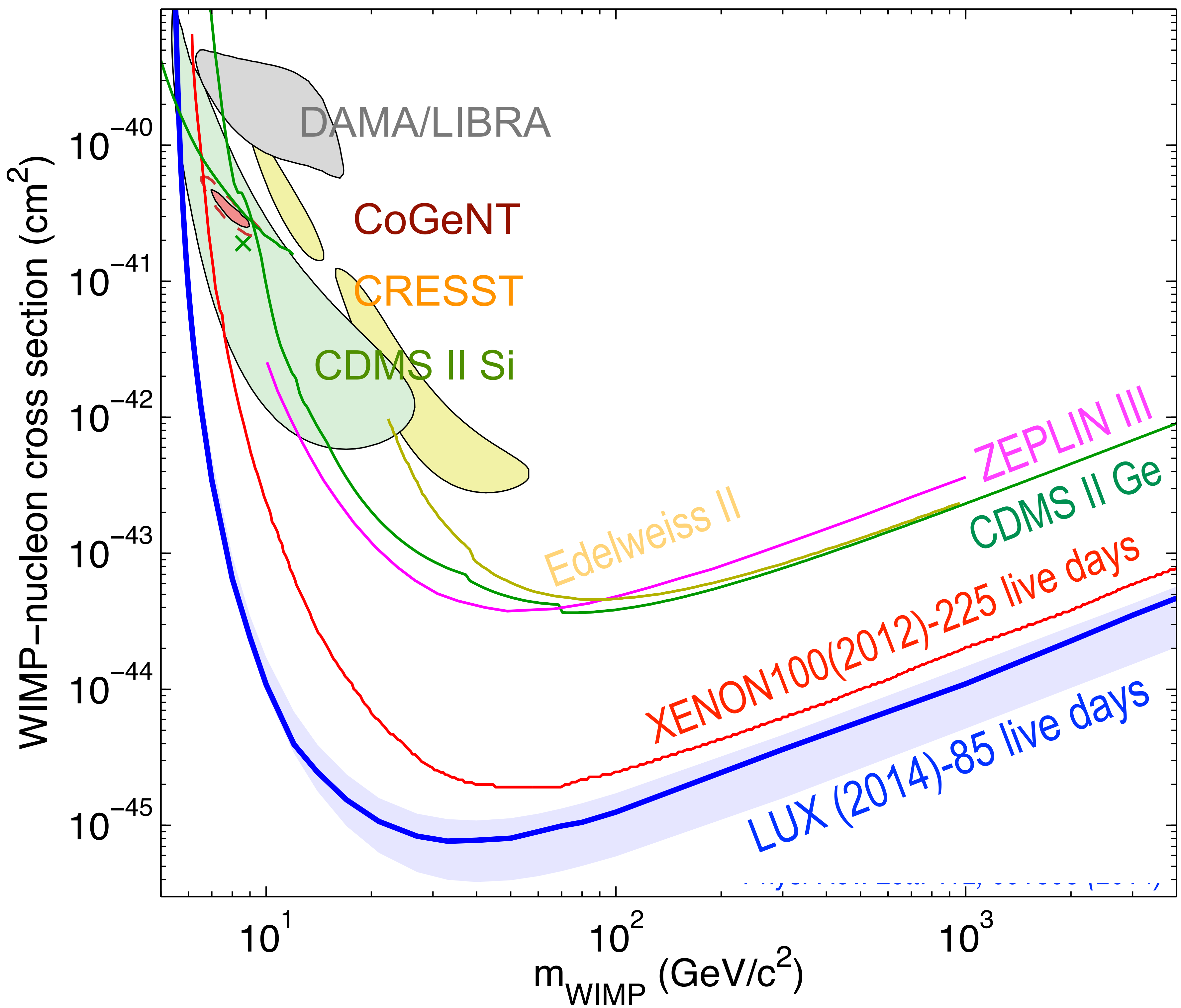
Dark Matter experiments

Dark Matter experiments



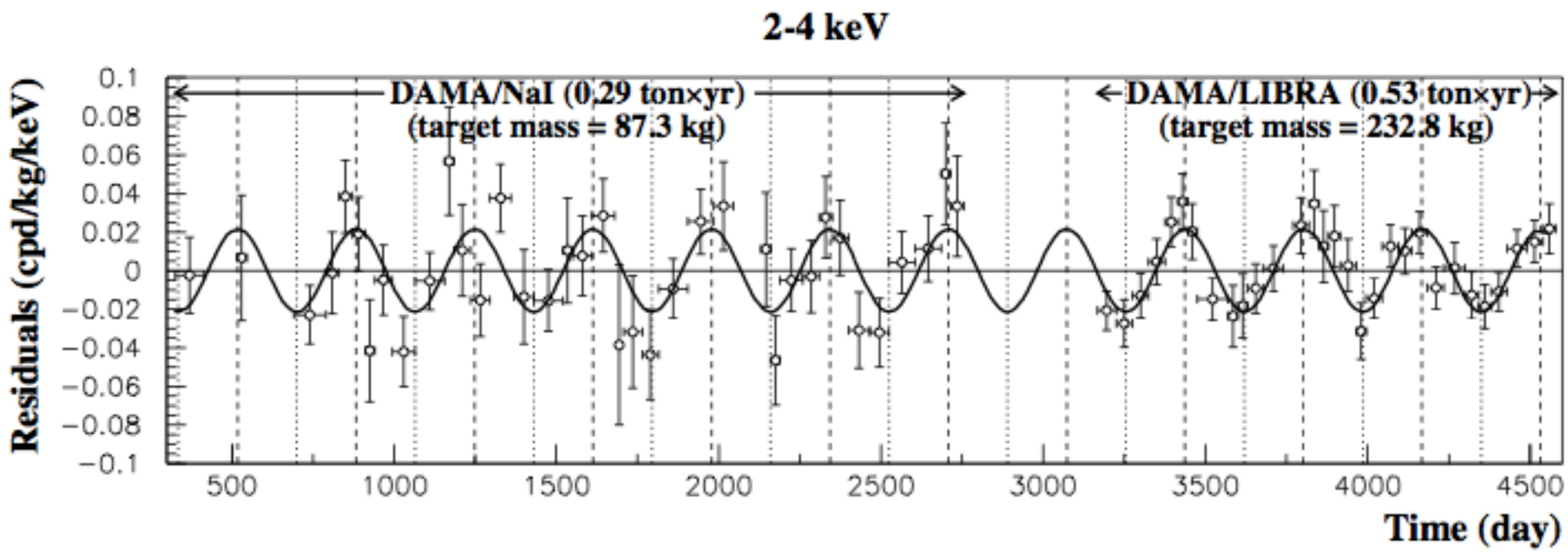
From those will discuss only three running experiments, DAMA, XENON100 and DAMIC and a future experiment DARWIN

WIMP spin independent measurements



Lux Collab., PRL 2014

DAMA/LIBRA modulation signal



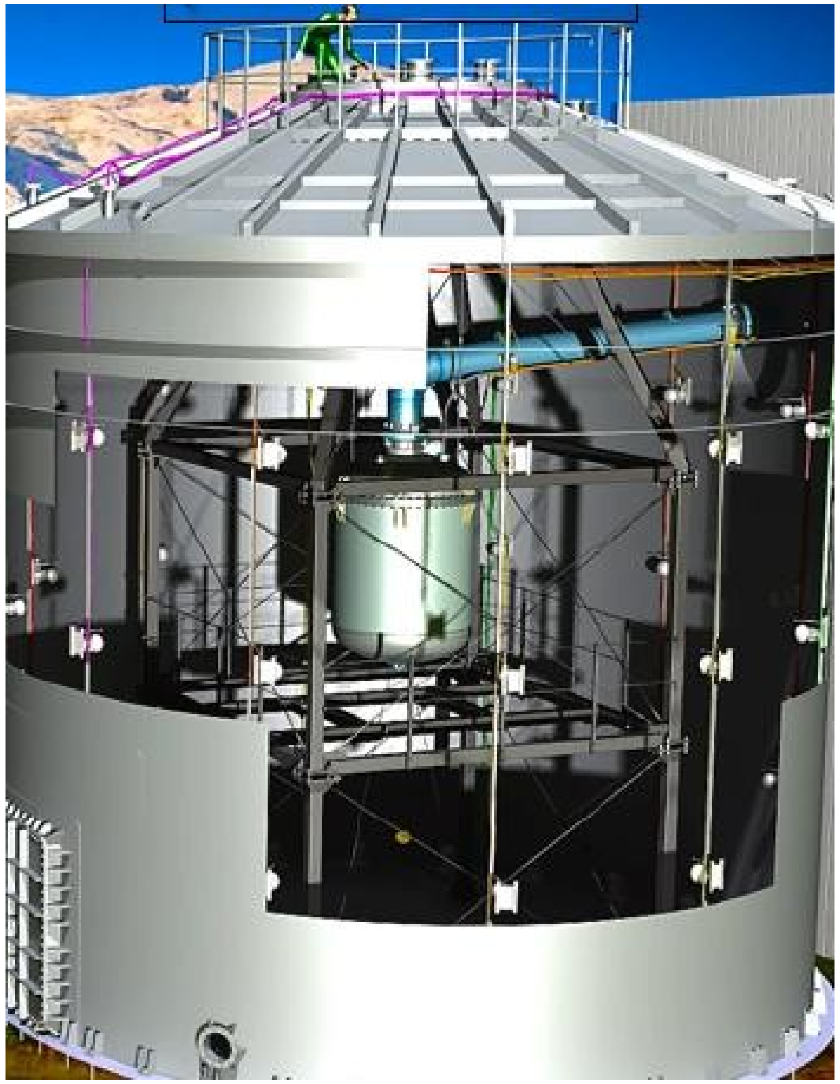
DAMA Coll, Arxiv 1003.1028

- Array of **NaI** (sodium iodide) **crystals** in 1995
- Operating the current DAMA/LIBRA setup of 250 kg of NaI since 2003.
- Observed an **annual modulation** in their data (**9σ significance**) with a **phase consistent** with that expected from galactic dark matter interactions.
- If signal is interpreted as evidence of scattering of WIMP dark matter: strong **tension** with results from many other searches.
- No successful experimental or theoretical **explanation** for the annual modulation signal.

Xenon100

XENON10
2005 – 2007
15 cm
25 kg
> 8.8 x 10^{-44} cm^2

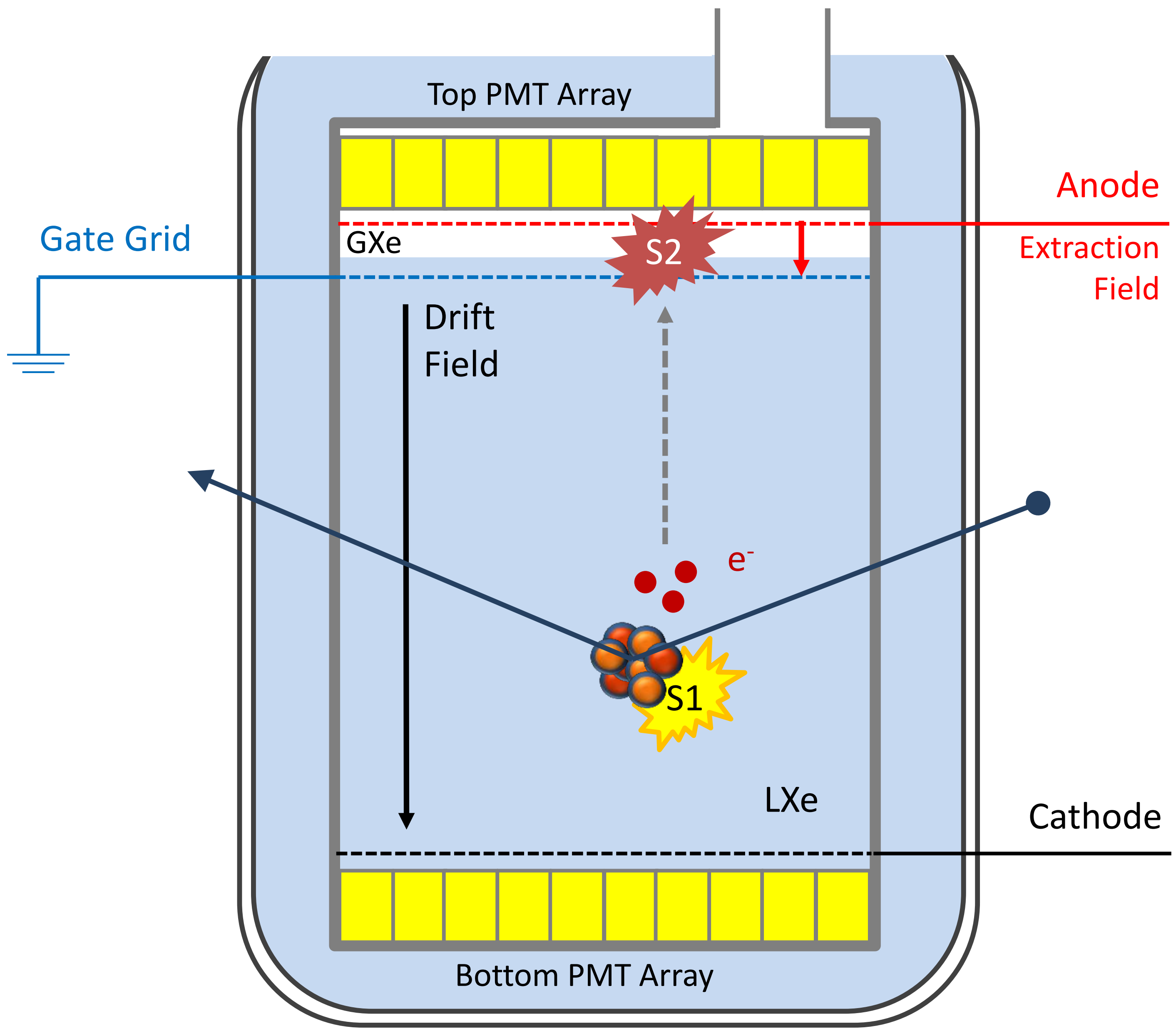
XENON100
2008 –
30 cm
161 kg
> 2 x 10^{-45} cm^2



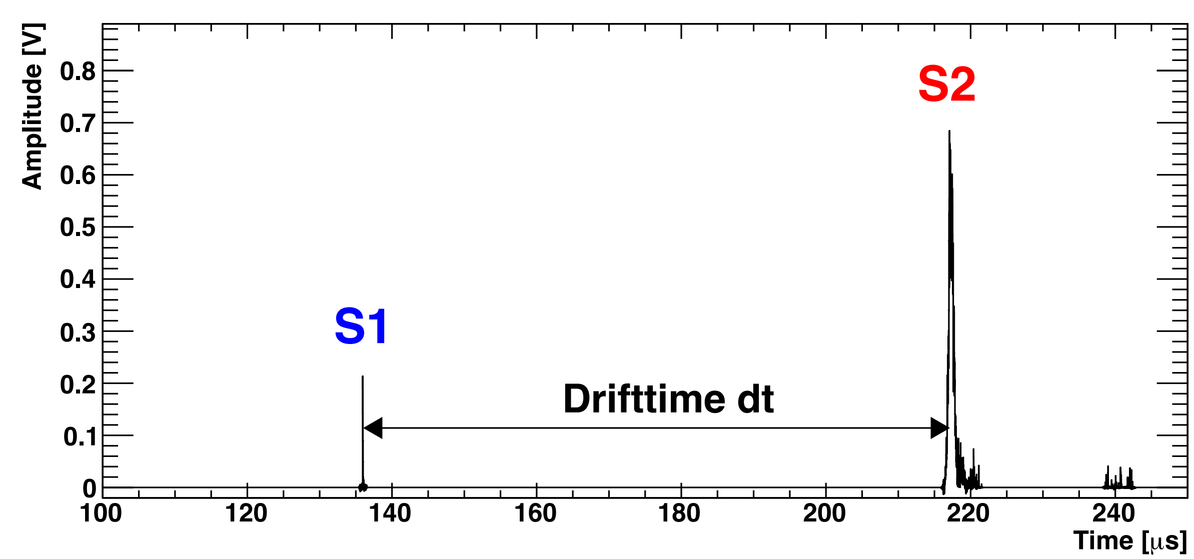
XENON1T
2015 –
100 cm
3300 kg
~2 x 10^{-47} cm^2

XENONnT
2018 –
130 cm
7000 kg
~2 x 10^{-48} cm^2

Two-phase time projection chamber

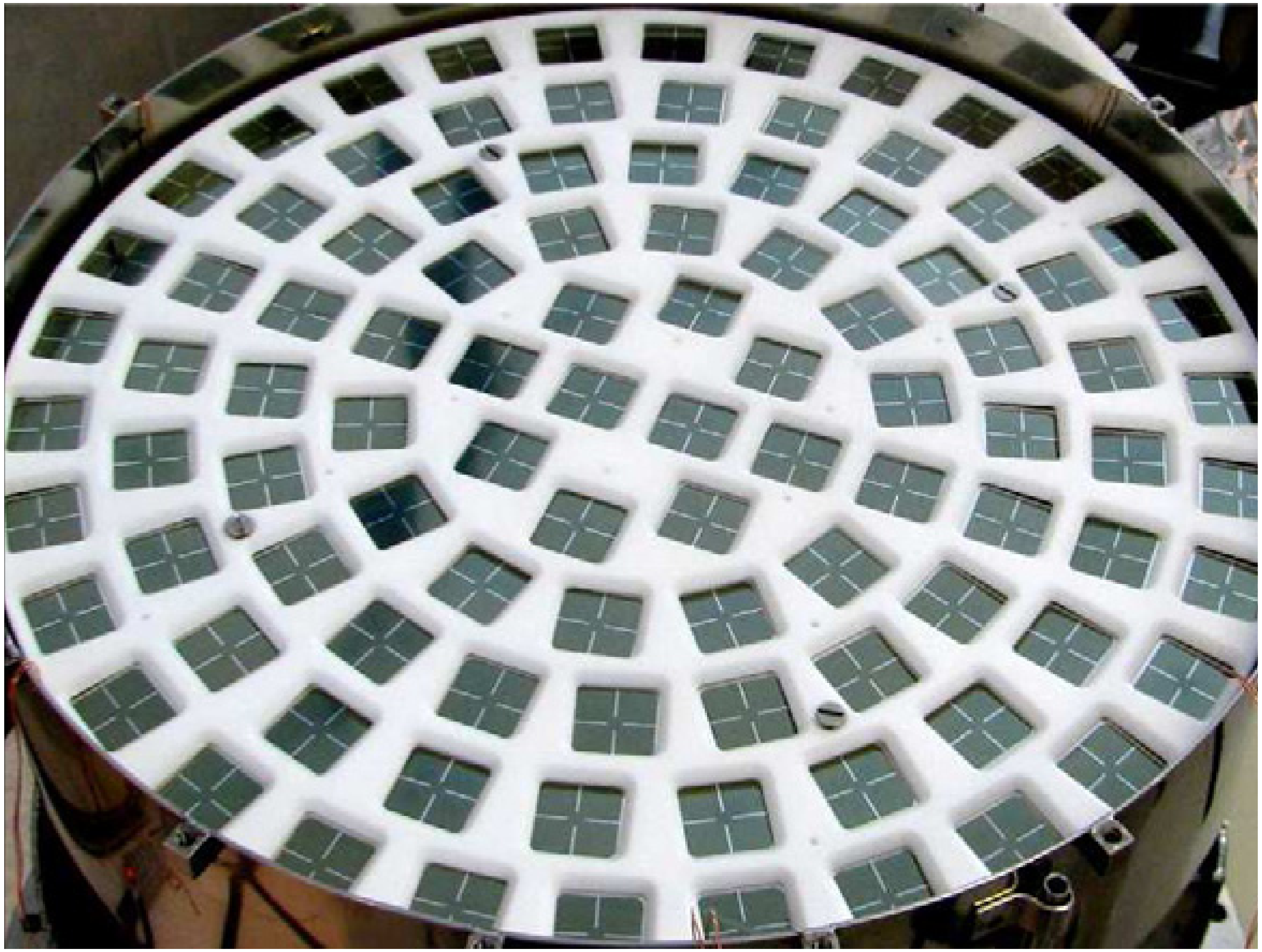


- Interactions in LXe: prompt scintillation light (S1) and ionization electrons
- Electrons drift in applied electric field until liquid/gas interface
- Extracted into the GXe by a much stronger field: generate secondary amplified scintilation signal (S2)
- The time difference between S1 and S2: height of the vertical event position



XENON100, Astrop. Part. 2011

Hamamatsu R8520 PMTs



Top of the TPC:

arranged in concentric circles to improve the reconstruction of the radial event position

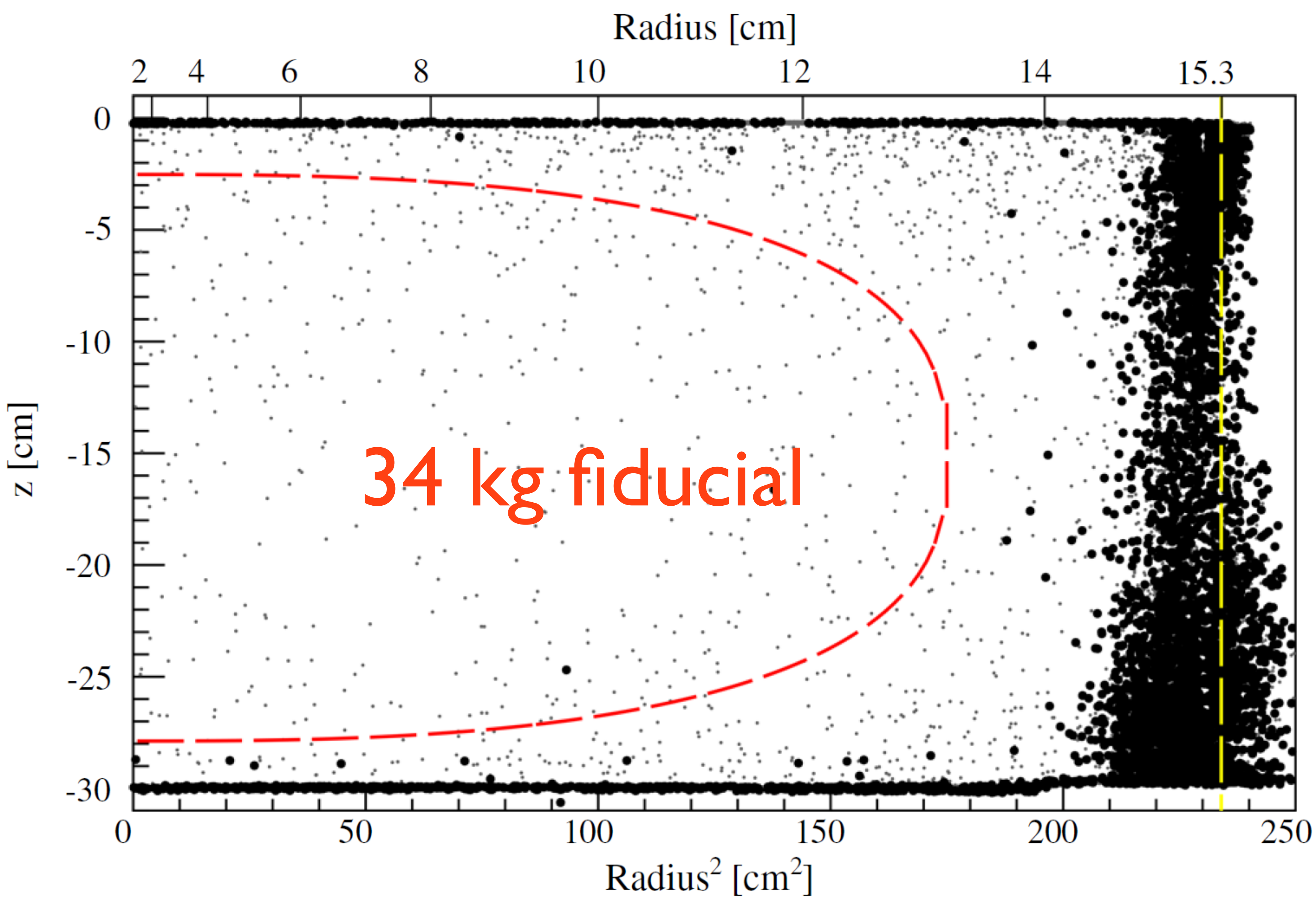
Bottom of the TPC:

arranged as closely as possible in order to achieve high light collection (low threshold detector)

position reconstruction based on S2 hit pattern:
$\Delta r < 3mm$, $\Delta z < 2mm$

XENON100, Astrop. Part. 2011

Spatial events distribution in TPC



single scattering events, 225 live days, 2011/2012

powerful background suppression

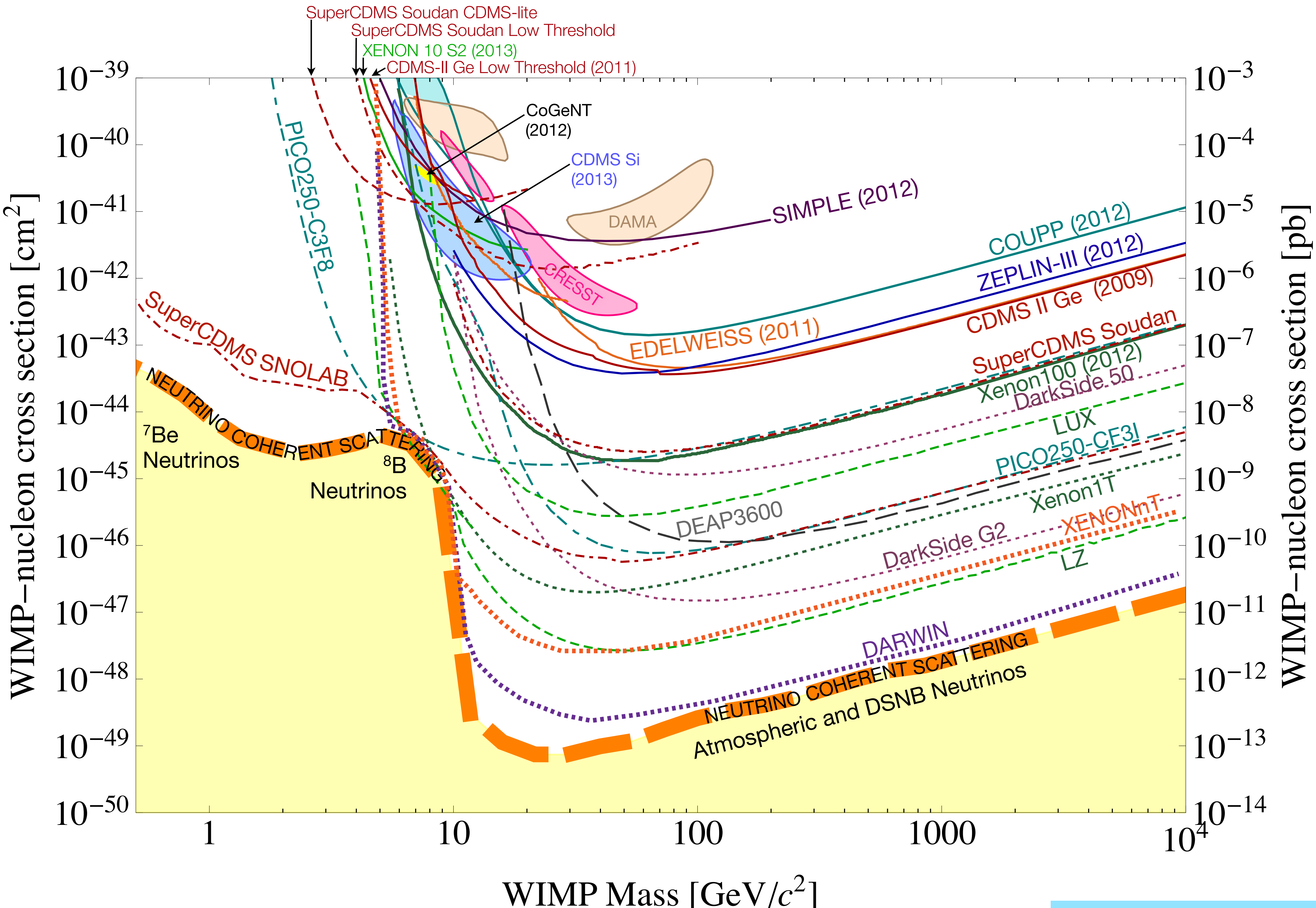
- fiducialization
- event multiplicity

black dots: events below 97.5% rejection cut

low background experiment: ~5 x 10^{-3} evts/kg/keV/day after veto cut and before S2/S1 discrimination

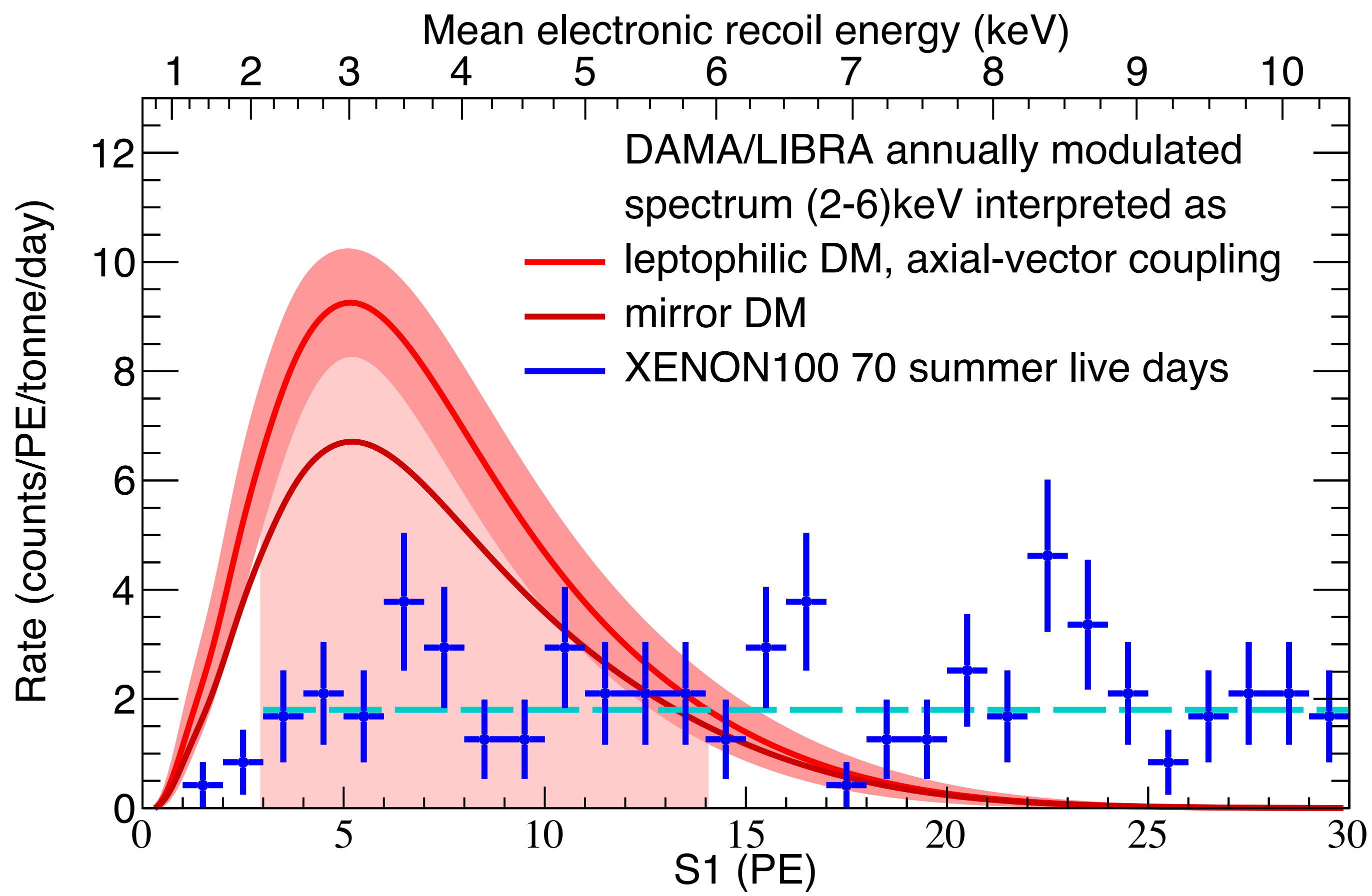
XENON100, Astrop. Part. 2011

WIMP landscape and prospects



Arkerib, TAUP2015

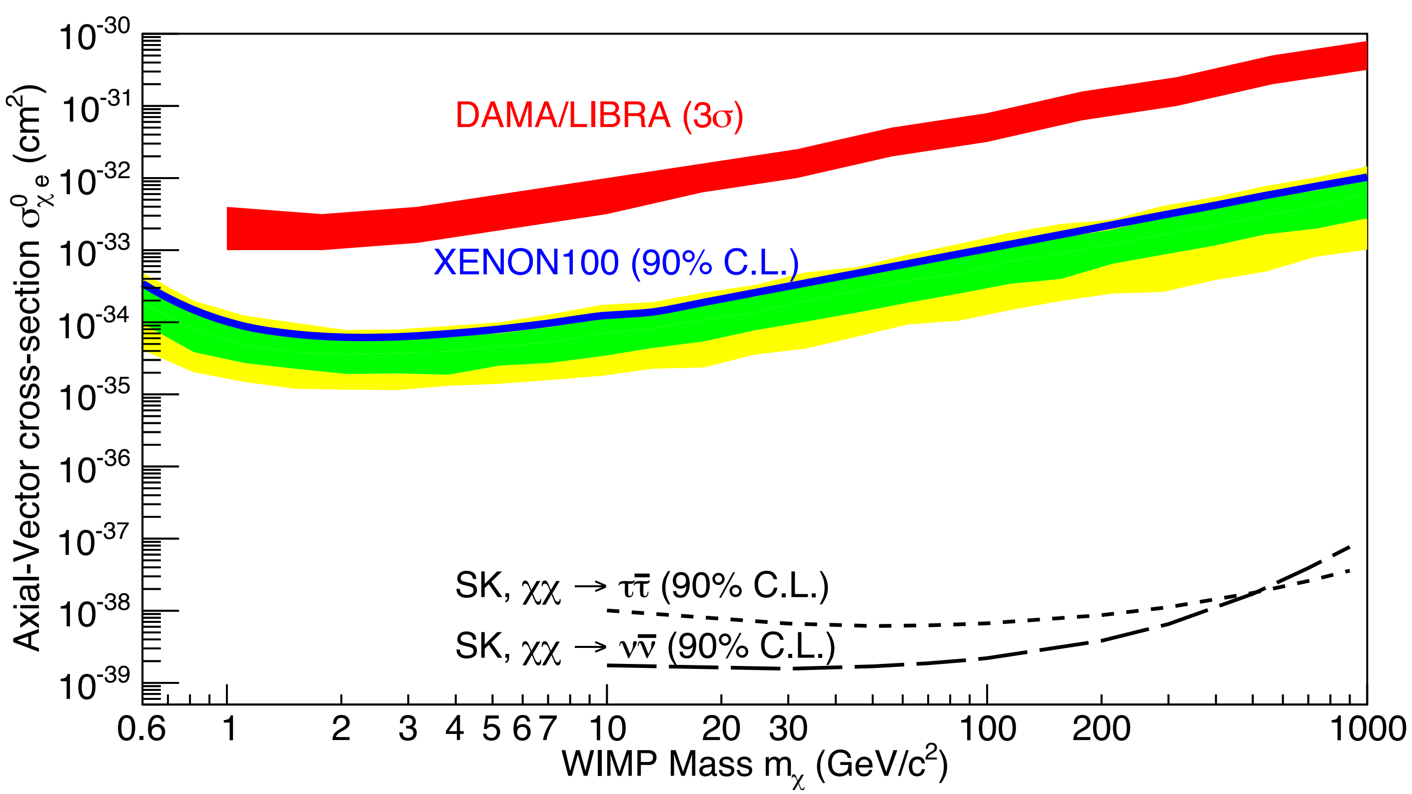
Exclusion of Leptophilic Dark Matter Models



Search interaction DM - electrons.
This interaction could reconcile DAMA and null results from nuclear recoils

Electron recoil events selected around expected peak of modulation (70 days around Jun, 2nd.)

For 3 models of WIMP coupling to e^- expected signal and exclusion curves were calculated.



DAMA signal excluded as being induced by WIMPS interacting with e^- according to

- Axial vector coupling 4.4 σ
- Mirror DM at 3.6 σ
- Luminous DM at 4.6 σ

XENON100, Science, 2015

"Anomalies"

DAMA/LIBRA: 9.2σ excess in 2-6 keV, 1.33 ton-yr NaI data set, with modulation

COGENT: excess in 0.5-3 keVee in 145 kg-day data set with Ge detector

SuperCDMS: CDMS Si reported excess, SuperCDMS Ge excludes it in 577 kg-day, 1.6 keVr threshold run
This analysis strongly disfavors a WIMP-nucleon scattering interpretation of the excess reported by CoGeNT, which also uses a germanium target.

CRESST-II: excess reported in phase-1, phase-2 excludes it 29.4 kg-day, 0.6 keV threshold run

DArk matter Wimp search with Noble liquids DARWIN

- Ultimate, multi-ton (~50 tons!) dark matter detector at LNGS.
- Primary goal: to probe the spin-independent WIMP-nucleon cross section down to the 10^{-49} cm^2 region for ~50 GeV WIMPs.
- Explore the experimentally accessible parameter space, finally limited by irreducible neutrino backgrounds.
- WIMPs discovered DARWIN:
  - measure WIMP-induced nuclear recoil spectra with high-statistics
  - constrain the mass and the scattering cross section
- First real-time detection of solar pp-neutrinos (high stats)
- Search for the neutrinoless double beta decay (neutrino is its own anti-particle?)
  - ^{136}Xe has a natural abundance of 8.9% in xenon.
- 99.98% discrimination, 30% NR acceptance,
- LY = 8 pe/keV at 122 keV

arXiv:1506.08309

DAMIC - Dark Matter In CCDs

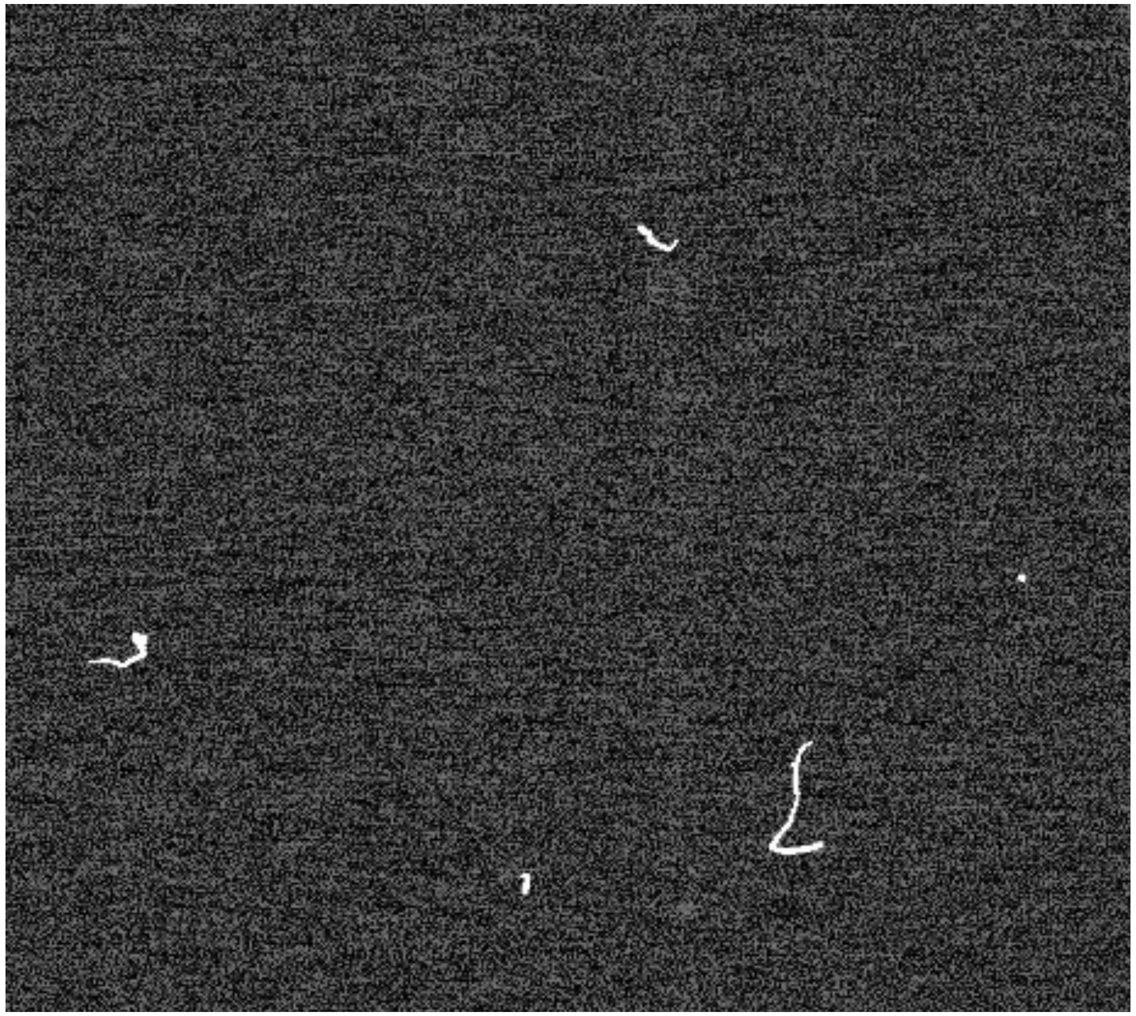
DAMIC: bulk silicon of scientific-grade CDDs as targets

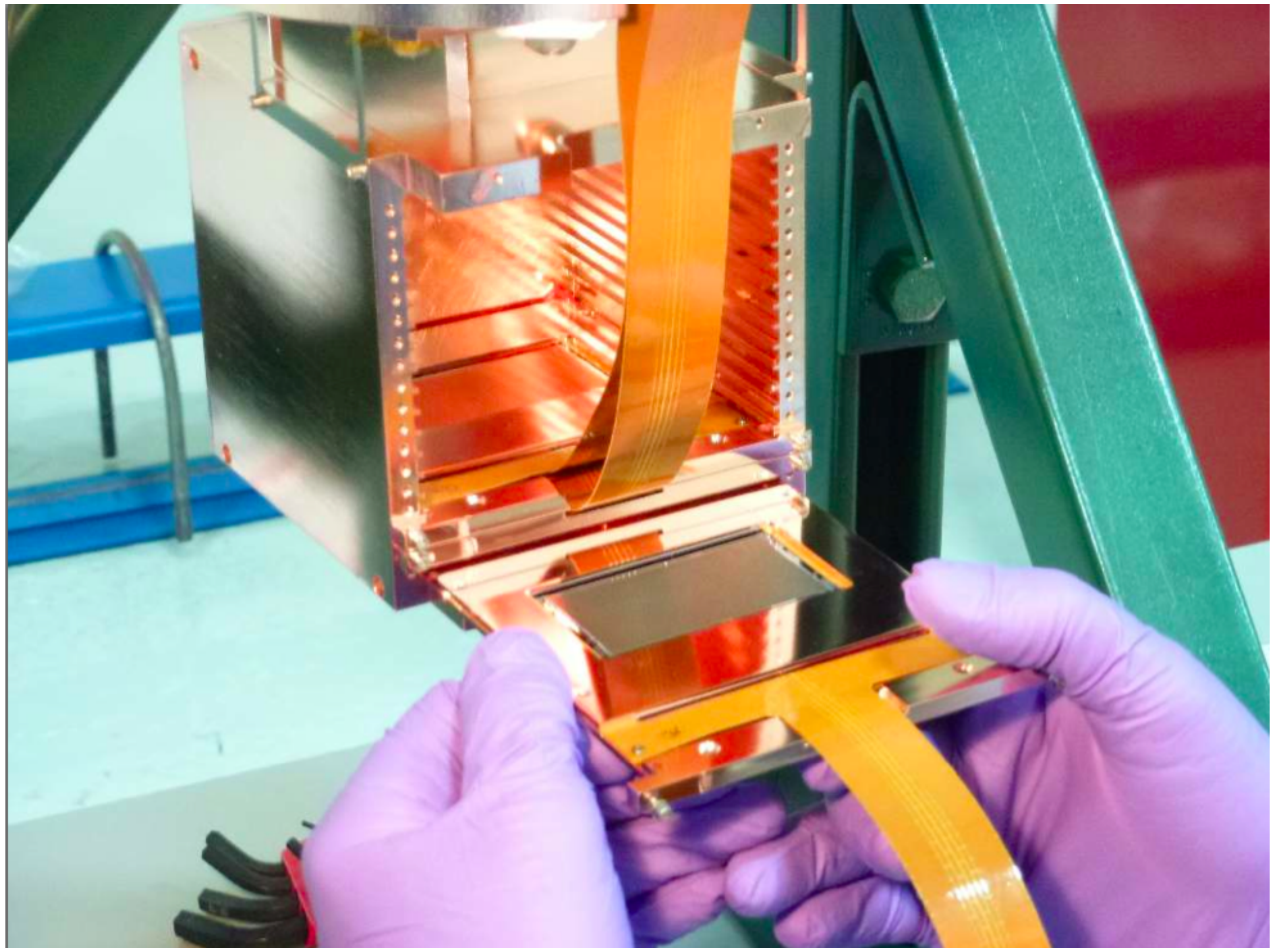
★ Low readout noise of CCDs

★ Relatively low mass of the silicon nucleus

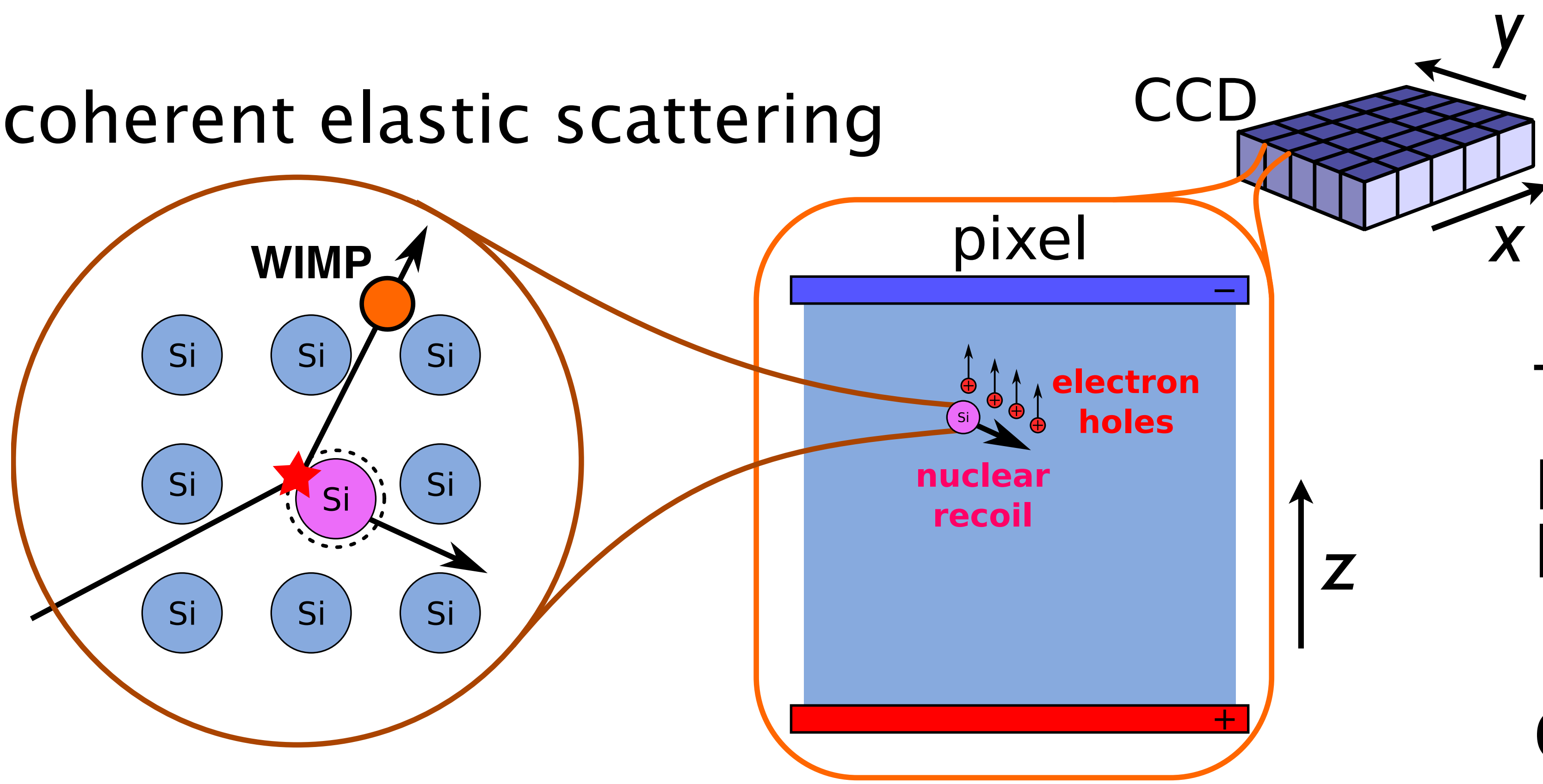
CCDS are ideal instruments for the identification of nuclear recoils from WIMPs < 10 Gev/c^2

Damic Collab., Phys Letters, 2012

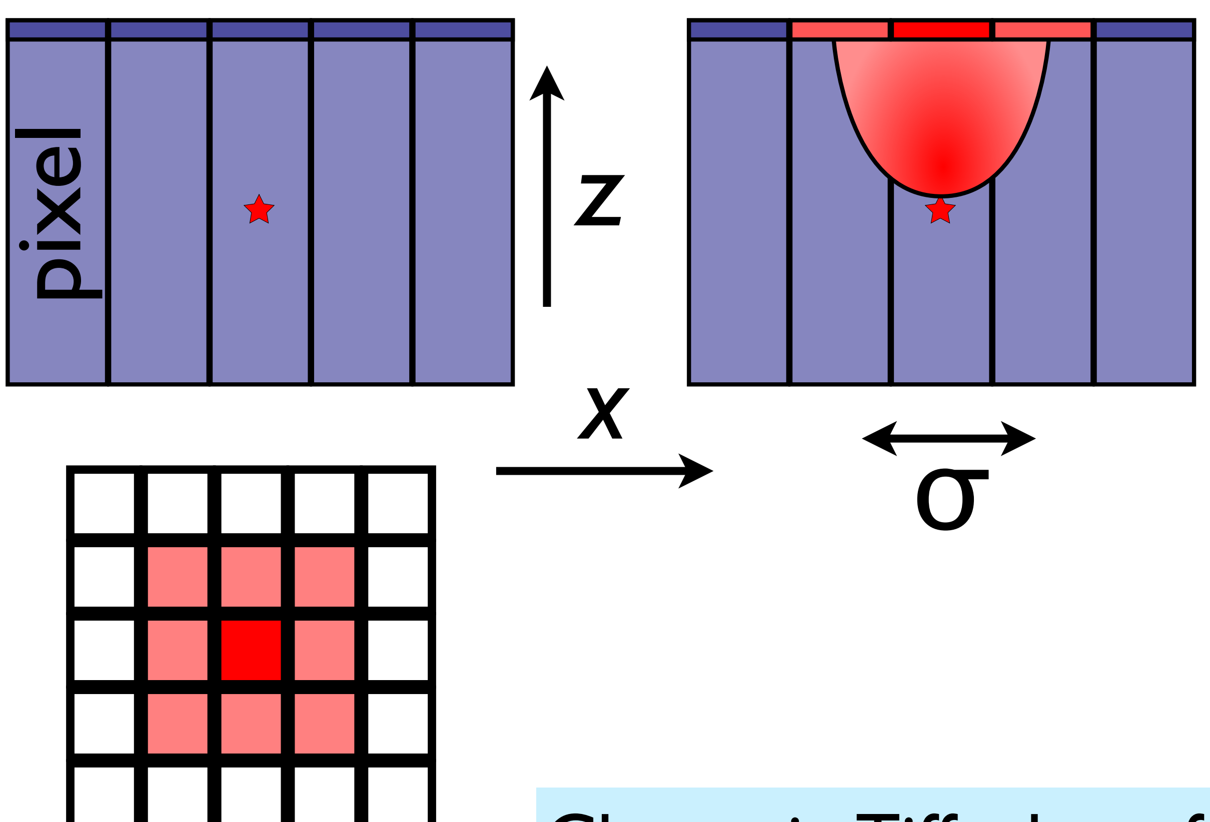




CCDs as WIMP detectors



The **scattering** of a DM particle with a SI nucleus leads to **ionization**



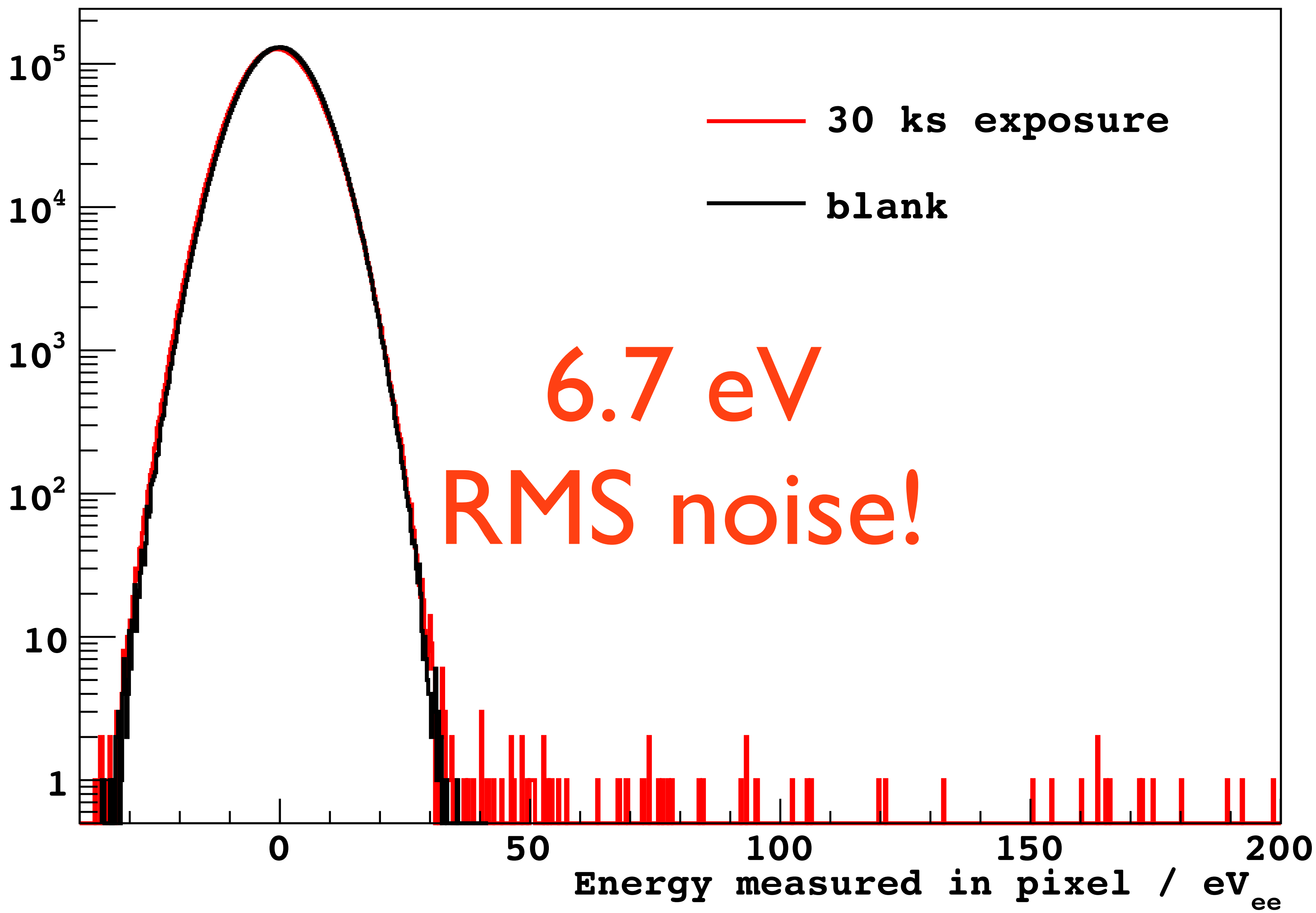
Charge carriers are **drifted** along z direction and collected at CCD gates

Charge **diffuses** as it travels

We fit to the radial spread of the cluster to estimate its **position in z** within the CCD bulk

Chavarria, Tiffenberg for Damic Collab., Phys. Procedia, 2014

CCD performance



Readout noise:
~2 e⁻ (3.6 eV e–h)

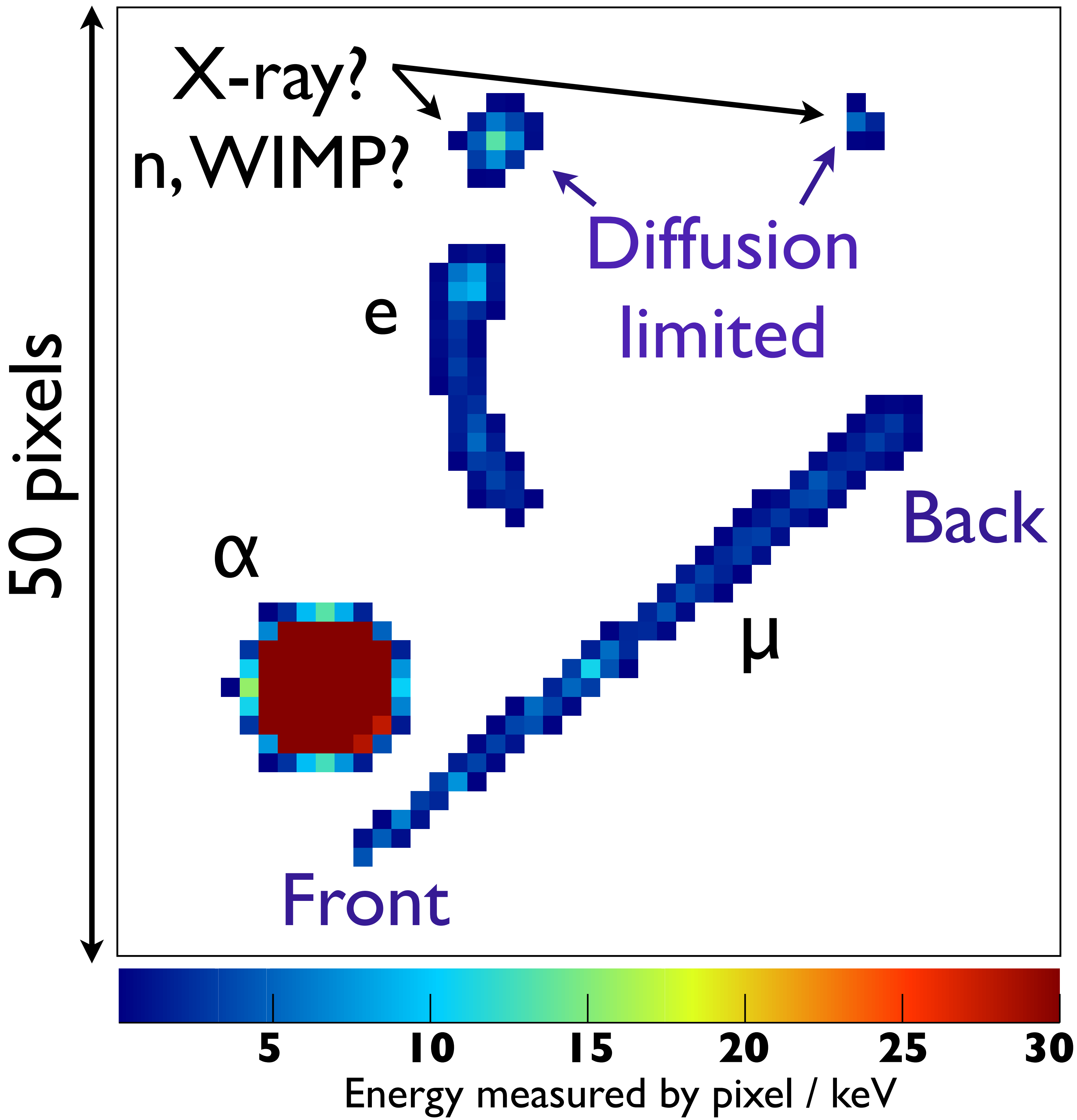
CCDs: very high **resistivity** silicon

- Low **radioactive** backg.
- Low **dark current** (0.1 e^- /pix/ day)
- Very few (if any) **defects** in silicon lattice

Histogram of all the pixel values in an image after the **median pixel** value over many images has been **subtracted.**

Blank exposure: zero-length exposures read out right after every data exposure, with **true readout noise patterns** but no physical tracks.

Particles detected (at ground level)



Low energy electrons and nuclear recoils: **diffusion limited clusters**

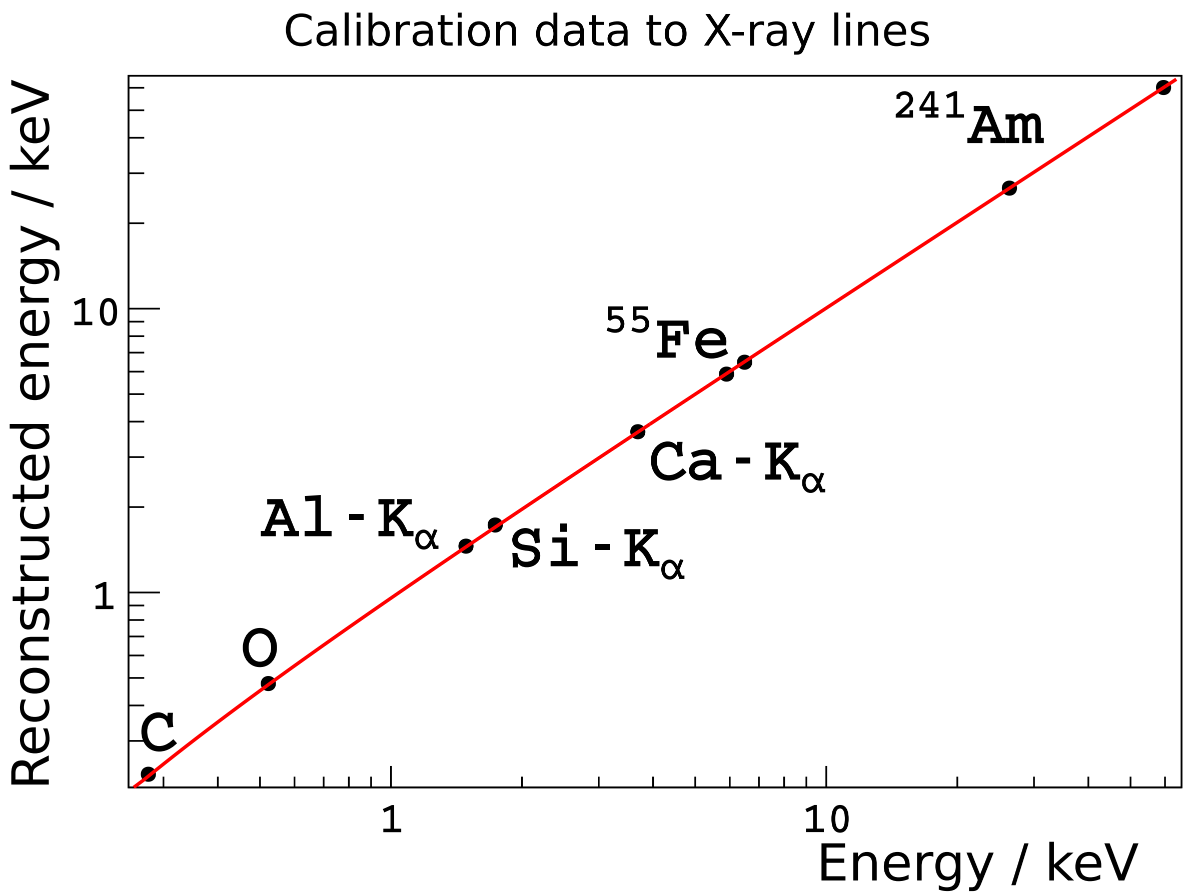
(their spatial extension is dominated by charge diffusion)

Higher energy **electrons** (Compton, β decay): extended tracks

α particles in the bulk or from the back: large round structures

cosmic **muons**: orientation of the track is evident

Calibration and energy resolution



Reconstructed x true energy

Kα fluorescence lines from Kapton target and other materials in the CCD setup

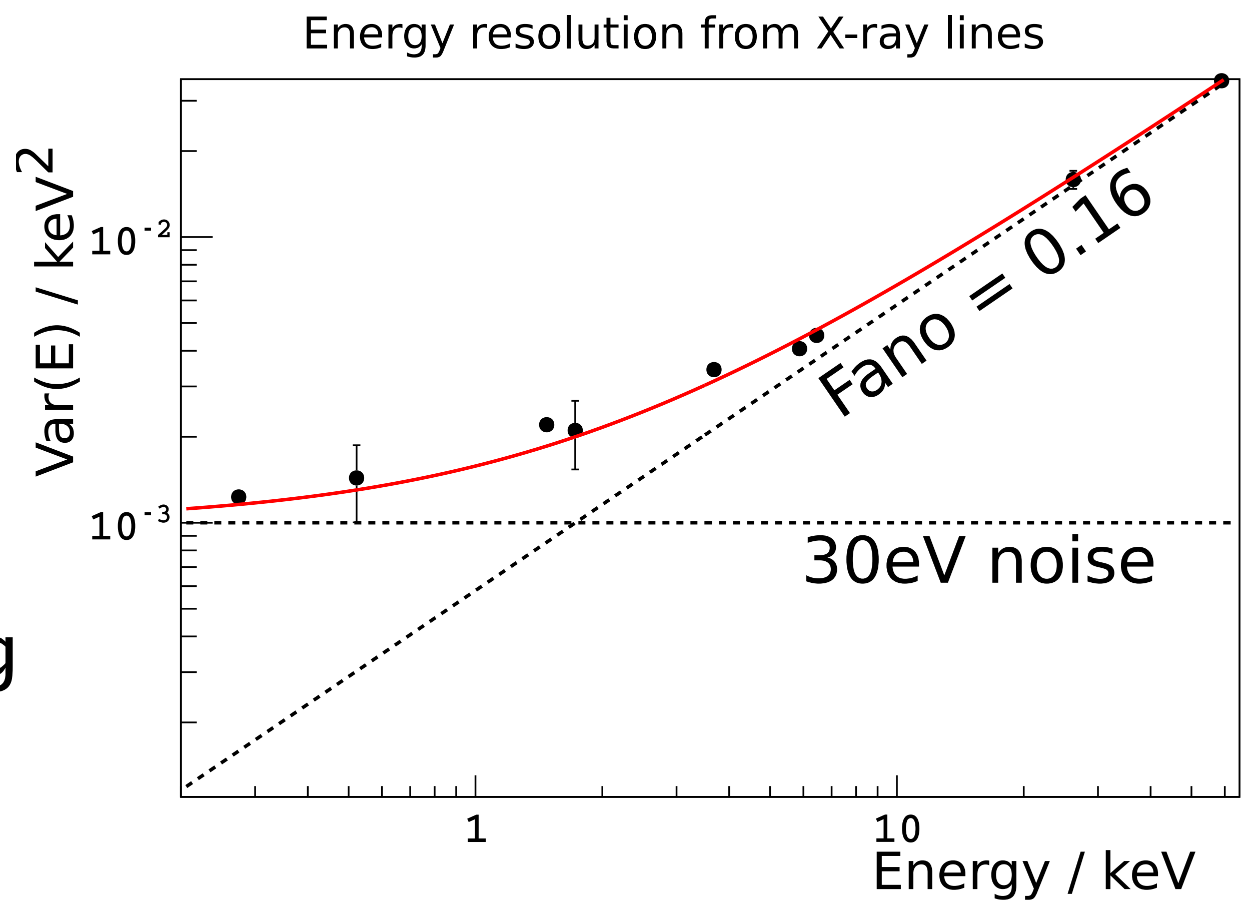
^{55}Fe and ^{241}Am X-rays by the radioactive sources

Linearity from 0.3 to 60 keVee

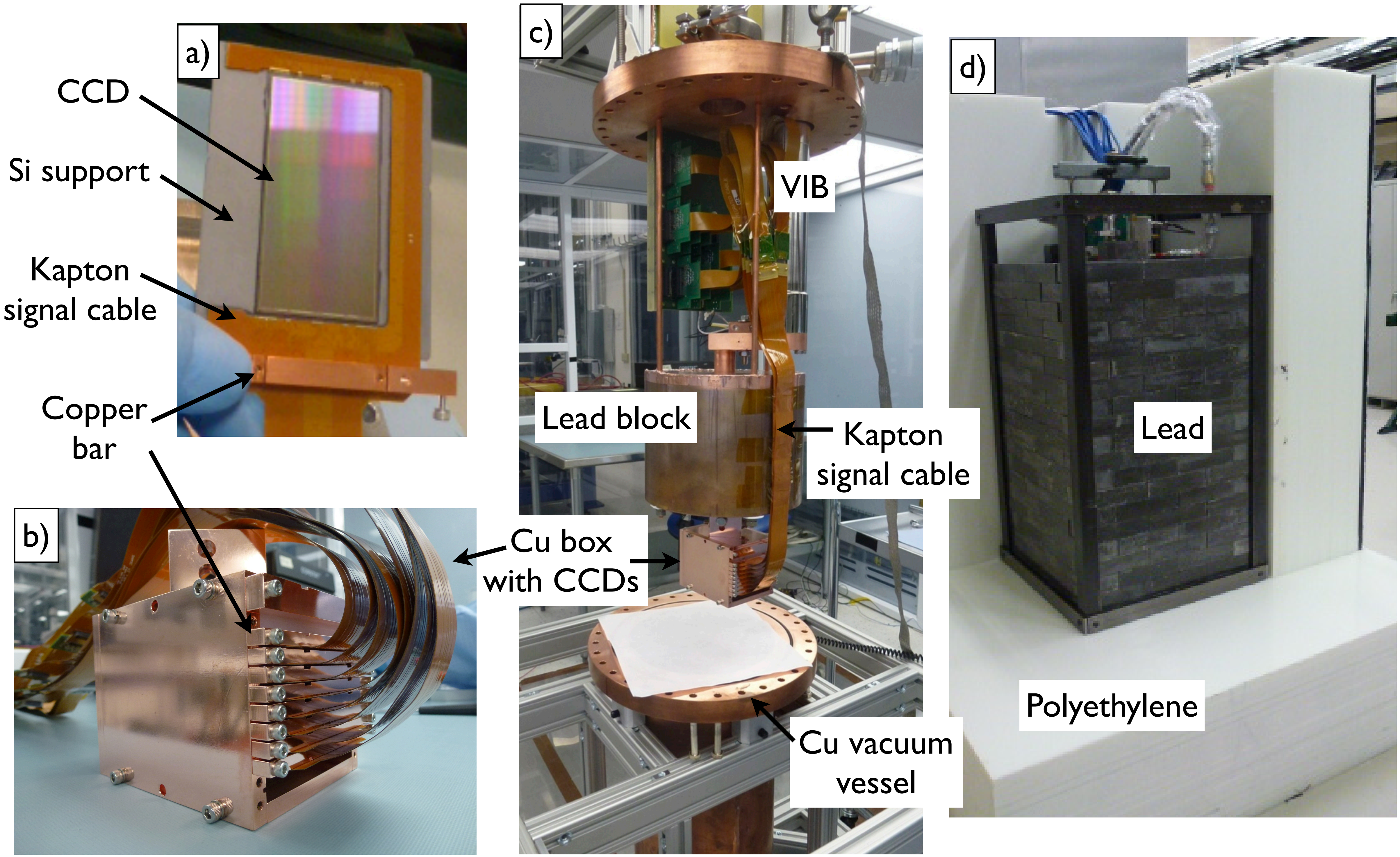
Energy resolution

Ilumination from backside, many pixels

Readout noise leads to a limiting resolution of 30 eVee.



DAMIC at SNOLAB



β - β coincidences

★ Ultimate **sensitivity** of the experiment: rate of the **radioactive background** that mimics the nuclear recoil signal from the WIMPs

★ The measurement of the **intrinsic contamination** of the detector is fundamental

★ For silicon-based experiments the **cosmogenic isotope ^{32}Si** is particularly relevant, its decay spectrum extends to the lowest energies and may become an irreducible background

$$^{210}\mathrm{Pb} \xrightarrow[64\,\mathrm{keV}]{\beta^-} {}^{210}\mathrm{Bi} \xrightarrow[1.2\,\mathrm{MeV}]{\beta^-} {}^{210}\mathrm{Po}$$

$$\tau_{1/2} = 5\,\mathrm{d}$$

$$^{32}\mathrm{Si} \xrightarrow[227\,\mathrm{keV}]{\beta^-} {}^{32}\mathrm{P} \xrightarrow[1.7\,\mathrm{MeV}]{\beta^-} {}^{32}\mathrm{S}$$

$$\tau_{1/2} = 14\,\mathrm{d}$$

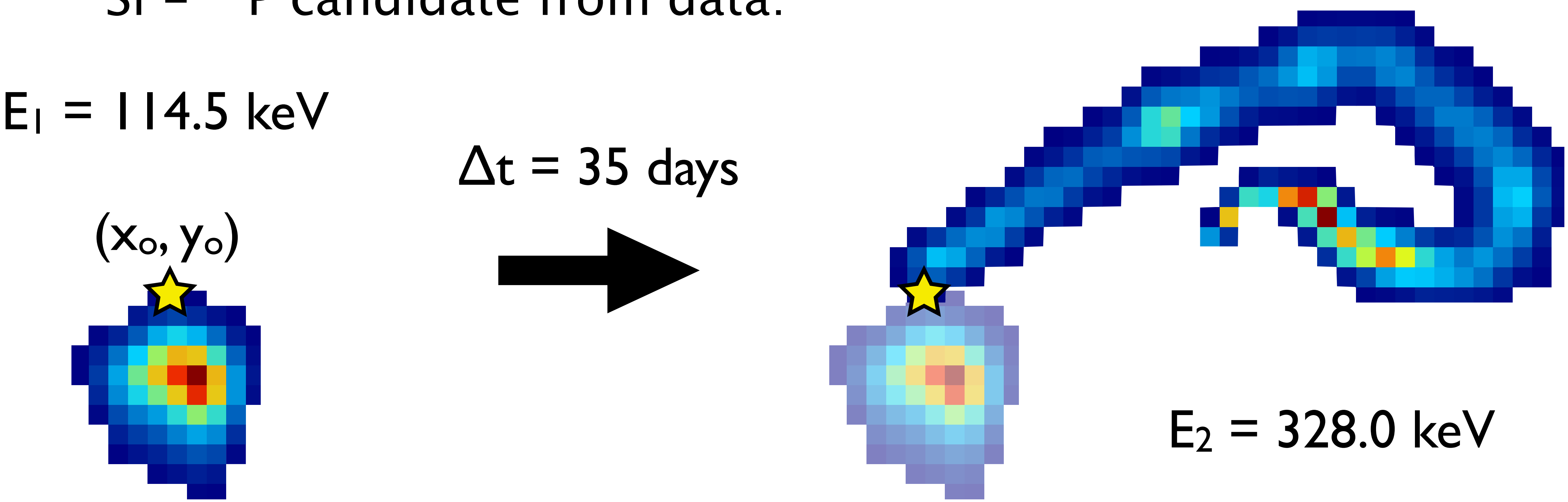
Sequence of βs starting in the **same pixel** of the CCD in **different images**

Damic Collab., JINST, 2015

β - β coincidences

We have performed a search for ^{32}Si and ^{210}Pb in 57 days of data

^{32}Si – ^{32}P candidate from data:



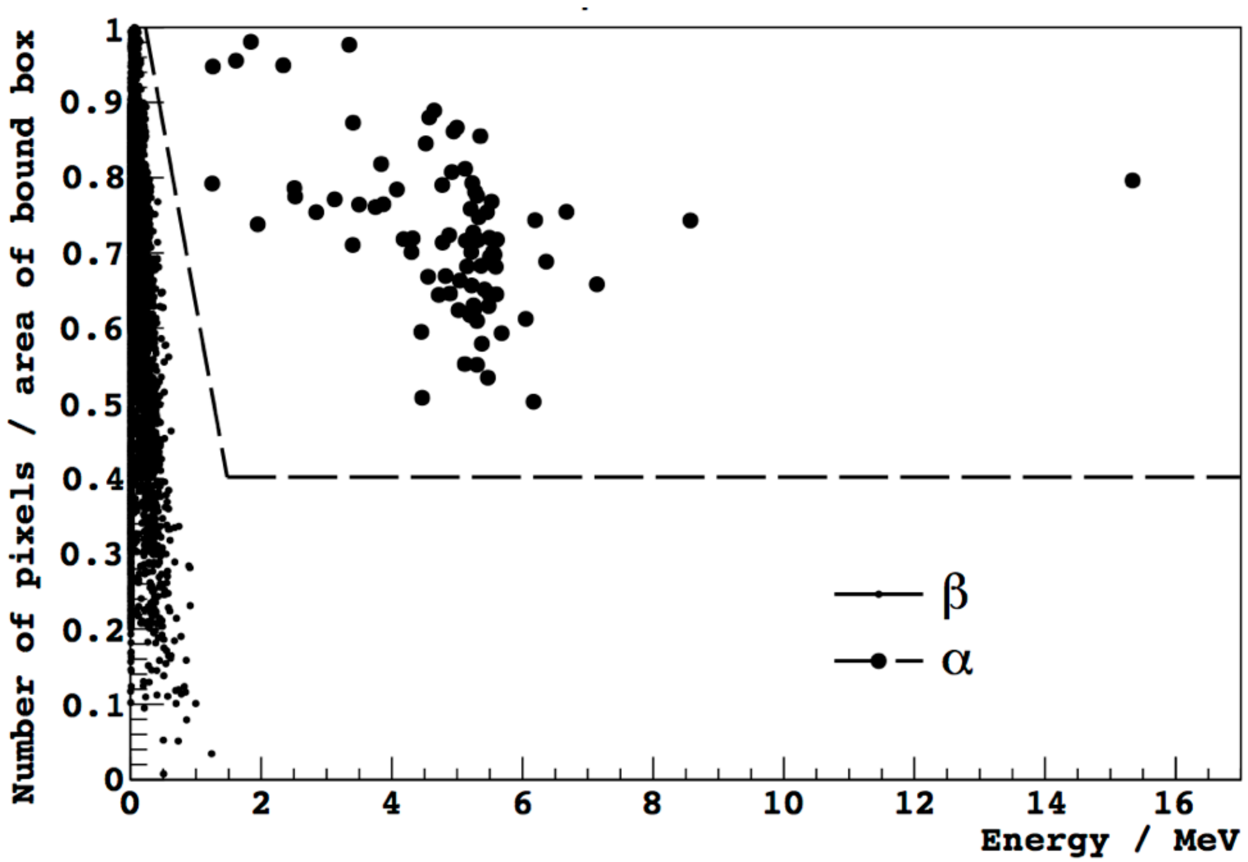
★ Efficiency and acidental pairs: detailed Monte Carlo simulations

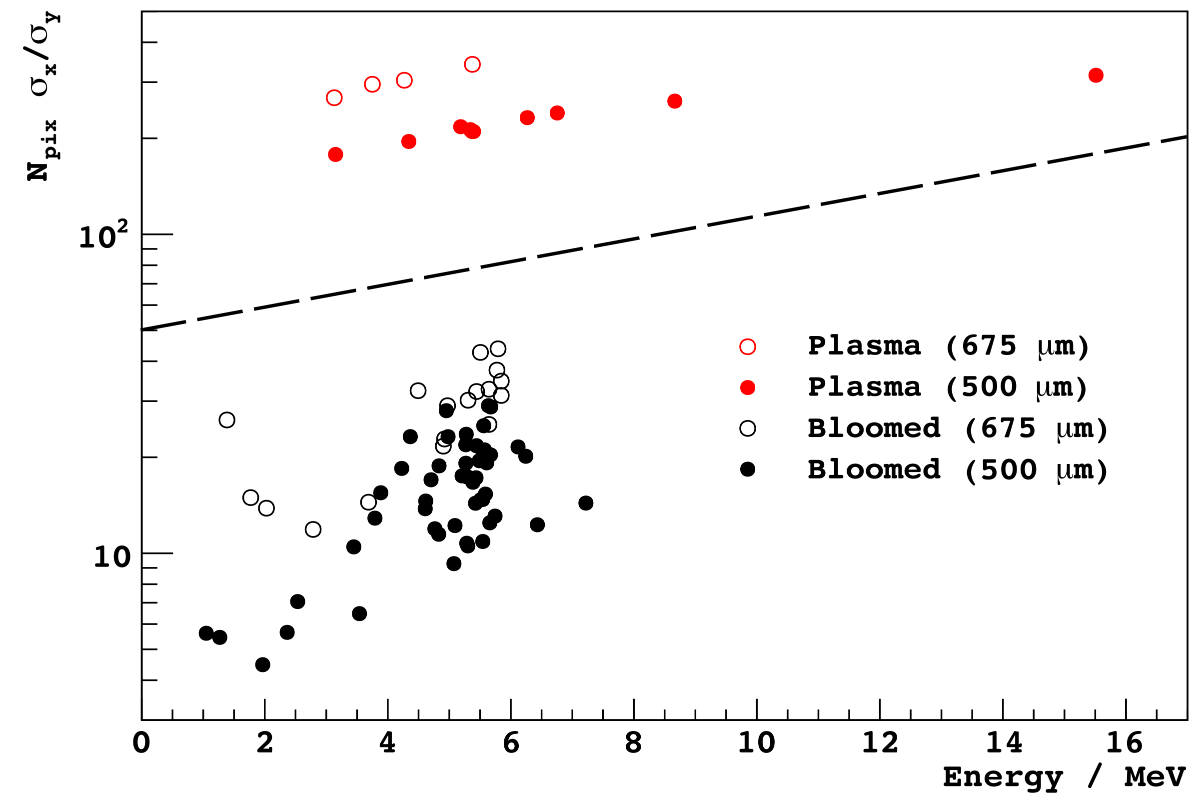
★ ^{32}**Si** decay rate was estimated to be $80^{+110}_{-65}\ \mathrm{kg}^{-1}\mathrm{d}^{-1}$ (95% CL)

★ Similar procedure: upper limit on the ^{210}**Pb** decay rate

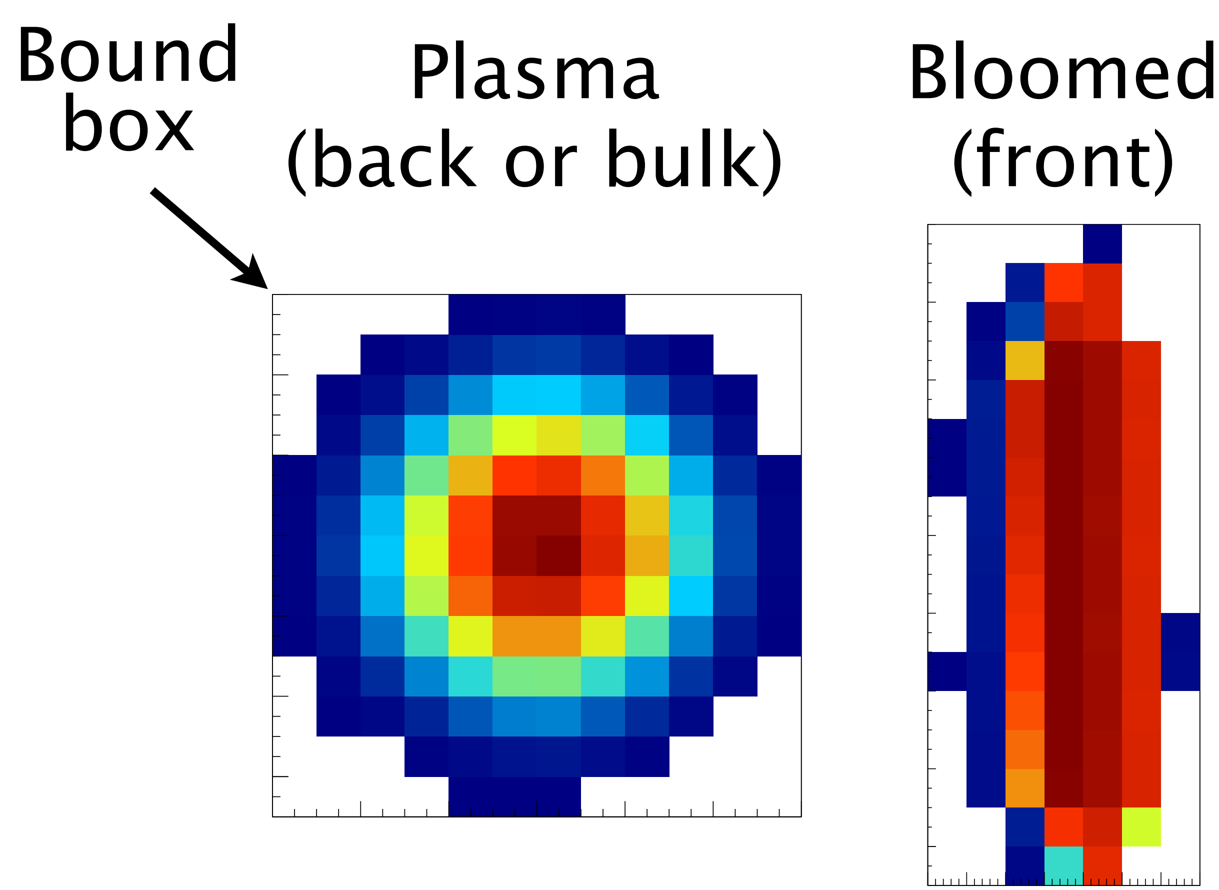
$33\ \mathrm{kg}^{-1}\mathrm{d}^{-1}$ (95% CL)

α particles





α–β **discrimination** based on shape of track.



Limits on contamination:

^{238}U < 5 kg^{-1} d^{-1} = 4 ppt
^{232}Th < 15 kg^{-1} d^{-1} = 43 ppt

Damic Collab., JINST, 2015

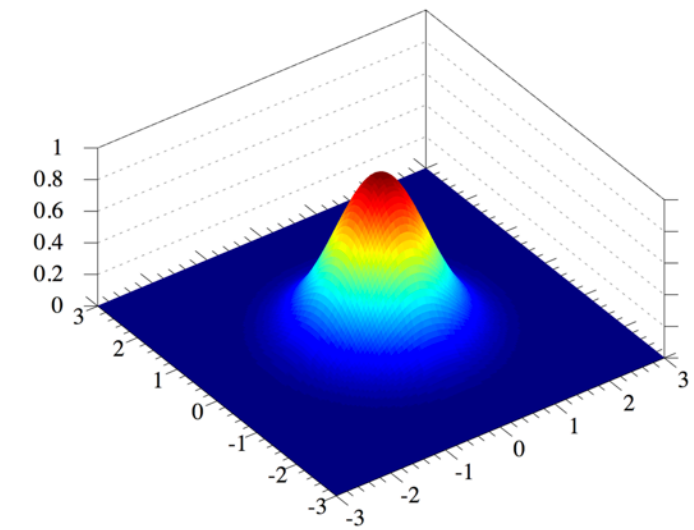
Dark Matter search analysis

$$\underbrace{N_e(E)}_{\text{Number of ionized e-}} \times \texttt{Gaus}(x, y, \underbrace{\mu_x, \mu_y}_{\text{position of energy deposition}}, \underbrace{\sigma(z)}_{\text{lateral spread}}))$$

Number of ionized e-

position of energy deposition

lateral spread



★ Fit 2D Gaussian in a moving 7x7 pixel window (baseline + peak)

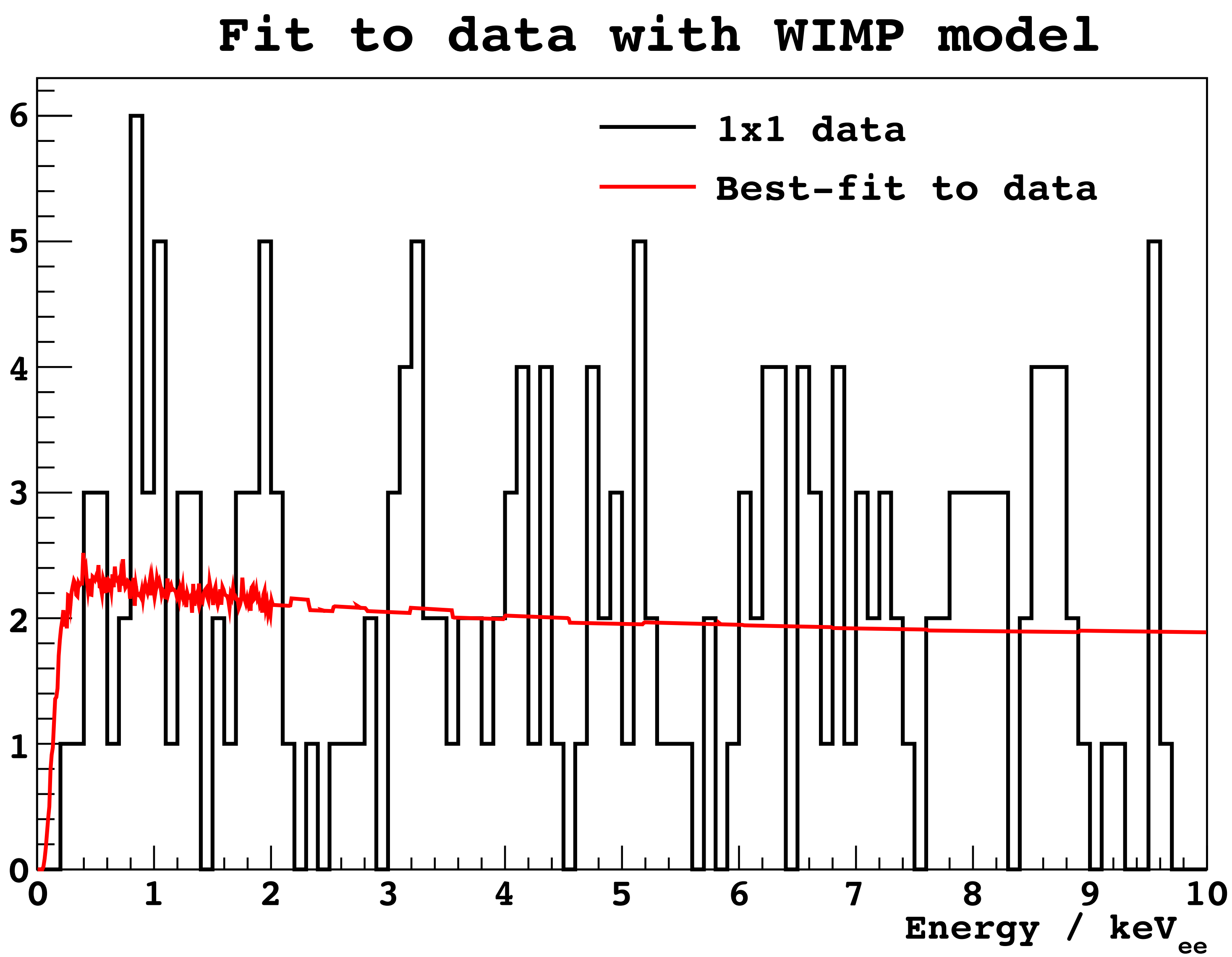
★ Get LL of of best fit

★ Compare to fit to constant pixel values (null hypothesis)

★ Calculate $\Delta LL = LL_{BF} - LL_{const\text{-}pix}$

★ Good candidates: large negative values of ΔLL

Dark Matter search analysis



Data used:
36 days with 3 CCDs
- 2 x 500 μm (2.2 g),
- 1 x 675 μm (2.9 g)

7 more days with 675 μm

Total exposure: ~0.3 kg.d

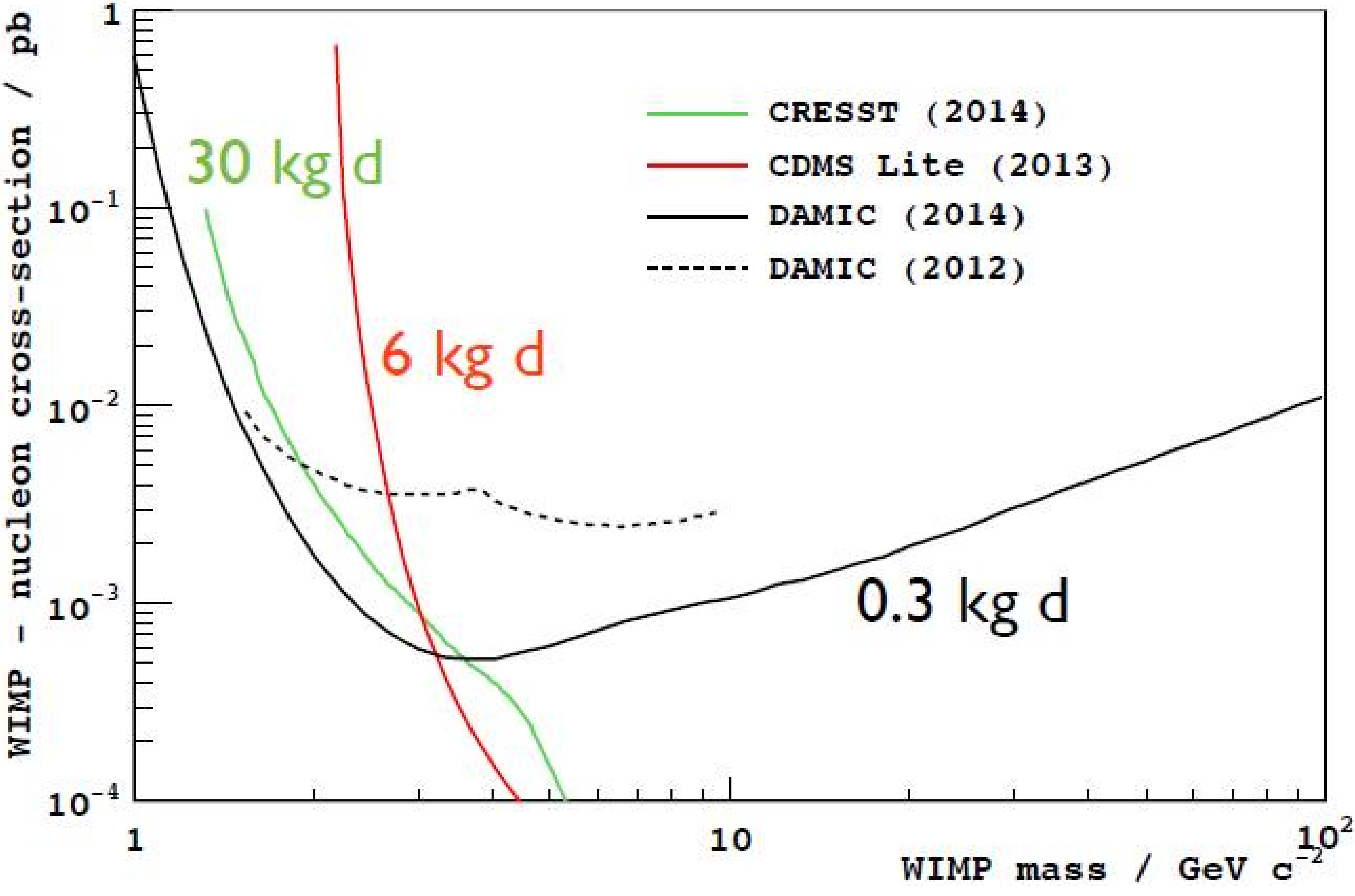
Best fit:

m_{WIMP} = 26 ± 46 GeV/c^2
σ_{WIMP} = (7 ± 16) x 10^{-4} pb
c_{bkg} = 67 ± 13 dru
min(−logL) = −396.5

Null hypothesis
c_{bkg} = 74 ± 5 dru
min(−logL)= −396.1

Dark Matter signal model;
Lindhard ionization efficiency: k=0.15
v_0 = 220 km s^{-1} v_{Earth} = 232 km s^{-1}
v_{esc} = 544 km s^{-1} ρ = 0.3 GeV c^{-2} cm^{-3}

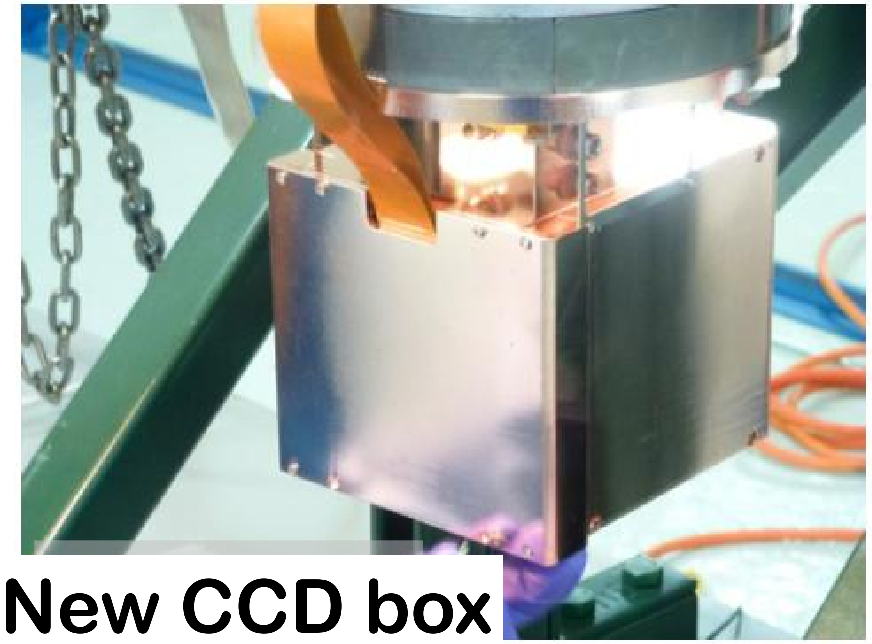
Dark Matter search analysis



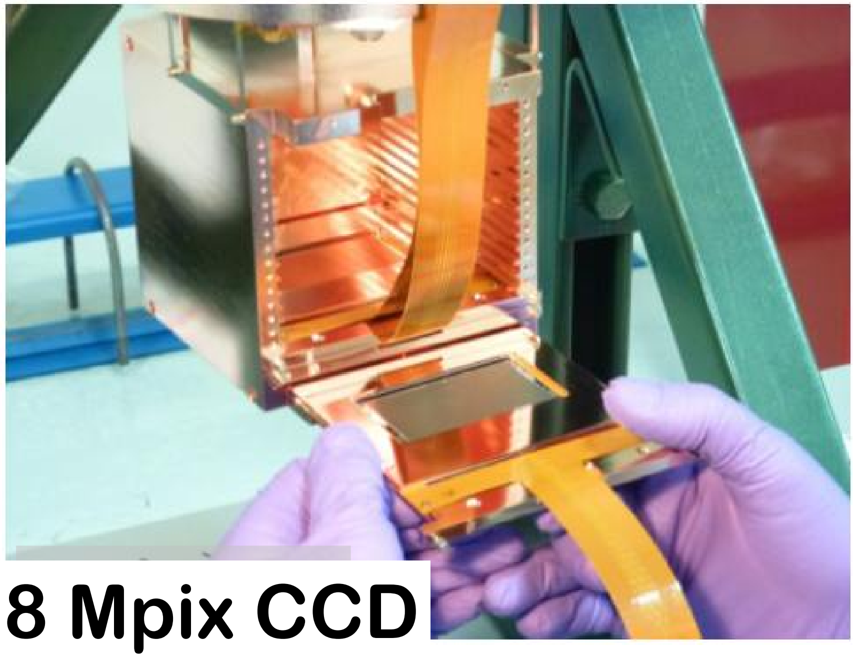
Towards DAMIC100

DAMIC100: 100g of active Si in low-noise package inside existent installation at SNOLAB

- ★ We have 24, 16 Mpix CCD's (675 μm, 5.9 g each)
- ★ **Dec 2014**: installation of the final DAMIC100 Cu box
  - new box fits 18 CCD in current vessel
  - Installed three 8 Mpix CCD's (675 μm) to study backgrounds
- ★ **Feb 2015**: Added N_2 box to remove radon. Cu vessel etching.
- ★ **Mar/Apr/May 2015**: +1 CCD (tot 4), modifications to internal CCD array to study backgrounds.
- ★ **July 2015**: first 16 Mpix DAMIC sensor packaged and tested

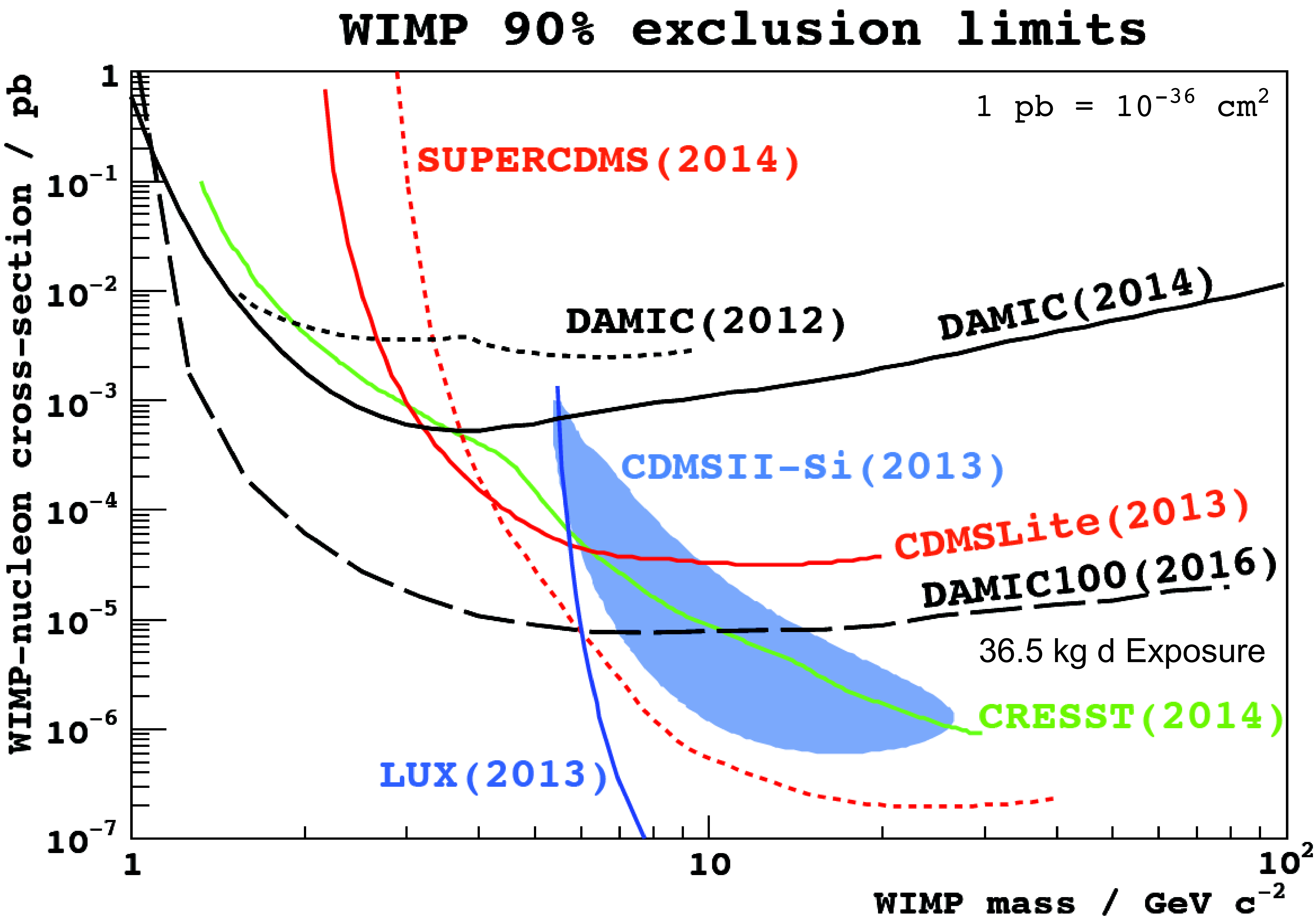


New CCD box



8 Mpix CCD

DAMIC100 sensitiviy



Axions

Another **promising** hypothetical **particle** to solve the dark matter problem

Peccei and Quinn - solution to the strong CP problem in QCD

Postulated global $U(1)_{PQ}$ symmetry spontaneously broken below **energy scale** f_a

Axion mass and decay constant f_a related to the pion: $m_a f_a \approx m_\pi f_\pi$

More precisely: $$m_a \approx 0.6\,\mathrm{eV}\,\frac{10^7\,\mathrm{GeV}}{f_a}$$

All **couplings** to the axion are inversely proportional to f_a $$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a}$$

f_a **unprescribed** in theory, g_γ dimensionless **model-dependent** parameter

f_a close to eletroweak symmetry breaking soon excluded

More general **axion-like** particle (ALP) models mass and decay constant are independent

K. Olive et al, 2014 (PDG)

Two classes of models

KSVZ (Kim-Shifman-Vainshtein-Zakharov)

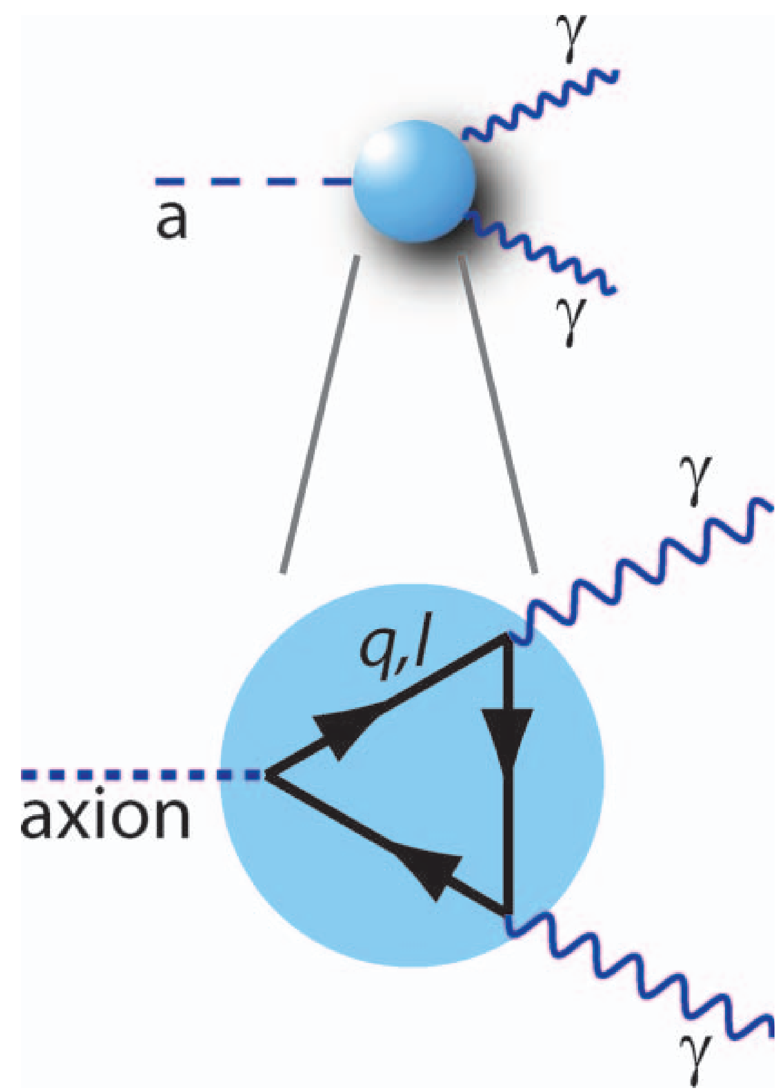
"hadronic" class of models

$$g_\gamma \approx -0.97$$

DFSZ (Dine-Fischler-Srednicki-Zhitnitskii)

more generic GUT inspired class of model

$$g_\gamma \approx 0.36$$



The axion has a model-dependent coupling to two photons, through a triangle diagram.

$$\Gamma_{a\to\gamma\gamma} = \frac{g^2_{a\gamma\gamma} m_a^3}{64\pi}$$
$$= 1.1 \times 10^{-24}\,\mathrm{s}^{-1} \left(\frac{m_a}{\mathrm{eV}}\right)^5$$

Decay life-time greater than age of universe, unless $m_a \geqq 20$ eV

The Axion Dark Matter eXperiment

$$P = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B_0^2 V C \min(Q_L, Q_a)$$

$$= 4 \times 10^{-26} \mathrm{W} \left(\frac{g_\gamma}{0.97}\right)^2 \frac{\rho_a}{0.5 \times 10^{-24} \mathrm{g\,cm^{-3}}} \frac{m_a}{2\pi(\mathrm{GHz})} \times \left(\frac{B_0}{8.5\,\mathrm{T}}\right)^2 \frac{V}{0.22\,\mathrm{m}^3} C \min(Q_L, Q_a),$$

ρ_a local axion density, B_0 strenth of static magnetic field, V cavity volume, C mode-dependent cavity factor, min(Q_L, Q_a) smaller of either the cavity or axion quality factors.

The axion signal quality factor is $Q_a = 10^6$, the ratio of their energy to energy spread

Signal **power** is expected to be **very weak**.

Cavity and amplifiers cooled to very **low temperature** to minimize **thermal noise**

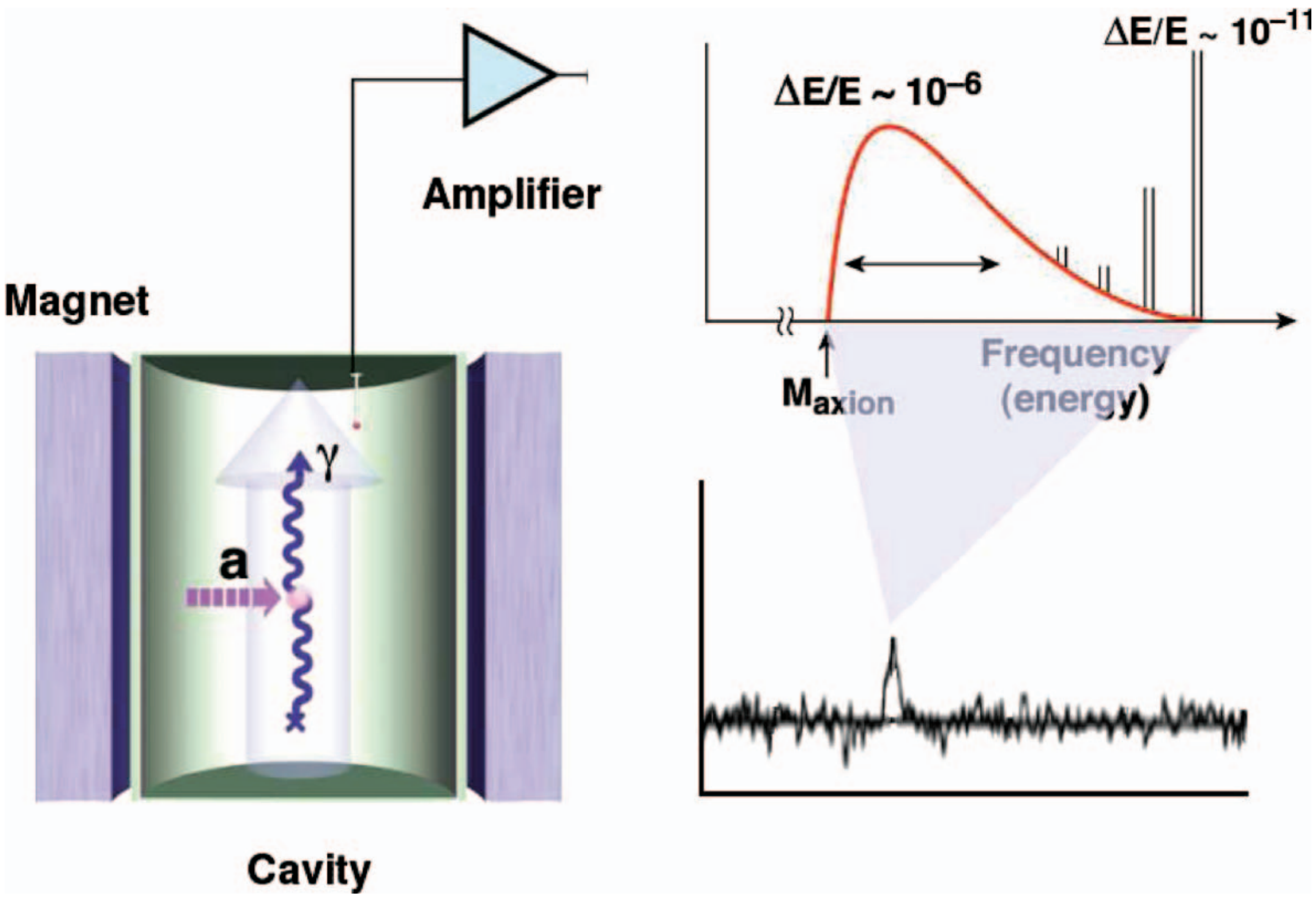
The microwave cavity technique

Pierre Sikivie (1983) proposed an elegant experiment to detect dark matter axions utilizing a resonant microwave cavity immersed in a strong magnetic field.

Through the Primakoff interaction, axions could resonantly convert to a monochromatic microwave signal and be detected in a sensitive radio receiver when the cavity was tuned to the frequency corresponding to the axion's mass:

$$h\nu = E_{\mathrm{a}} = m_{\mathrm{a}} c^2 \left(1 + \frac{1}{2}\beta_{\mathrm{a}}^2\right)$$

$$= m_{\mathrm{a}} c^2 (1 + O(10^{-6}))$$

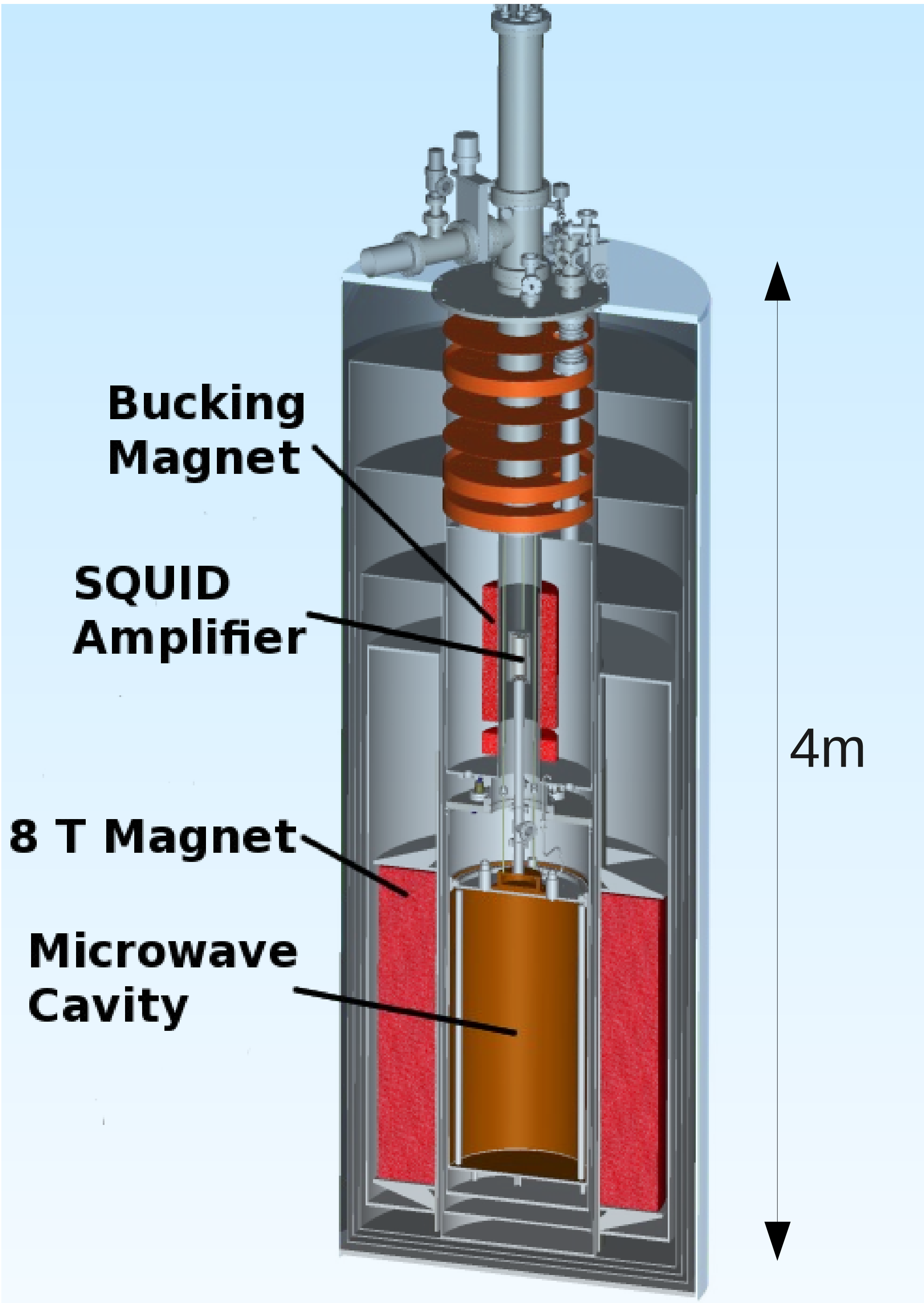


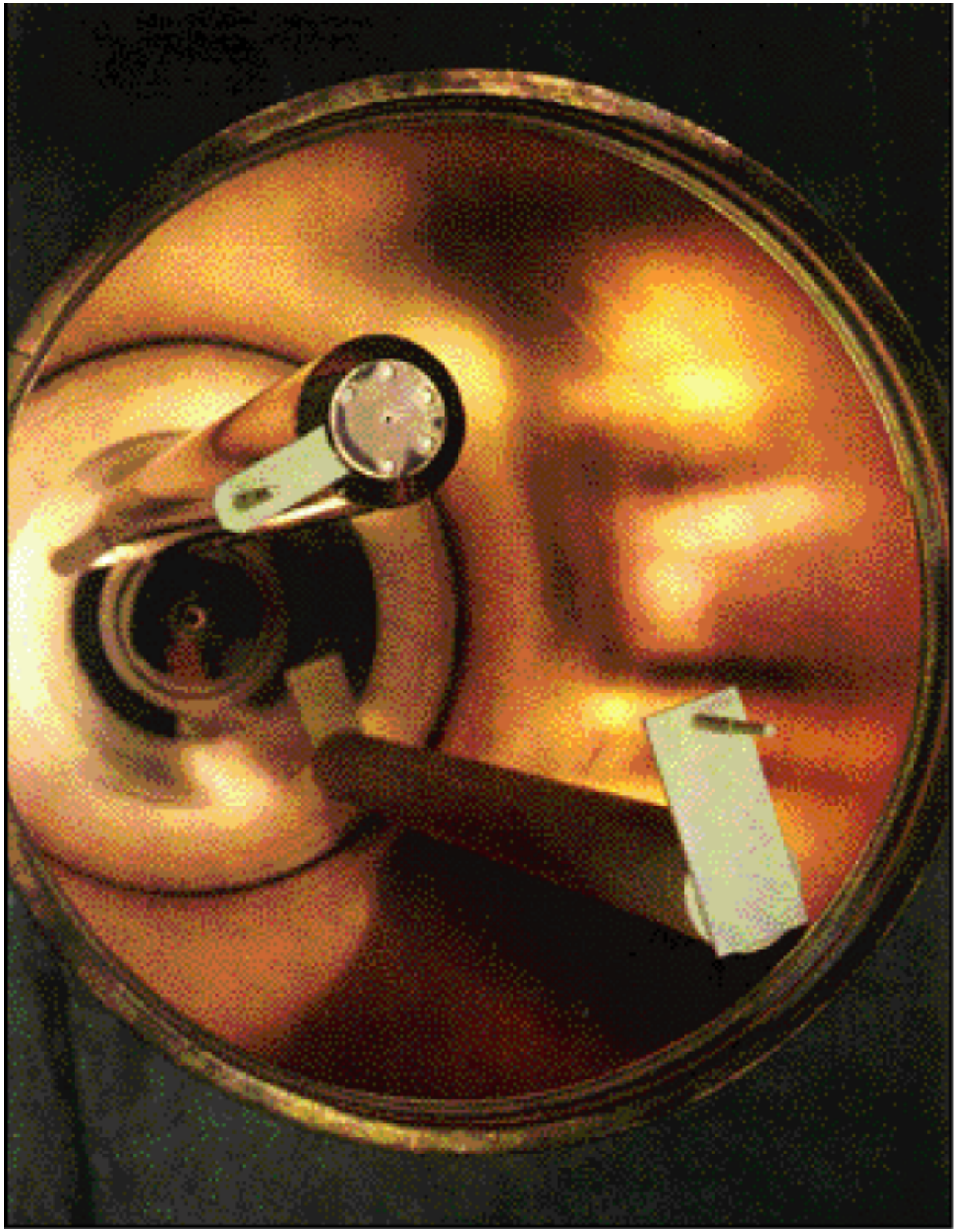
$\beta_a = v_a / c$ is the velocity of the axion in the galactic gravitational potential

$$m_a = 5\mu\mathrm{eV} \quad \Delta\beta \approx 10^{-3}$$

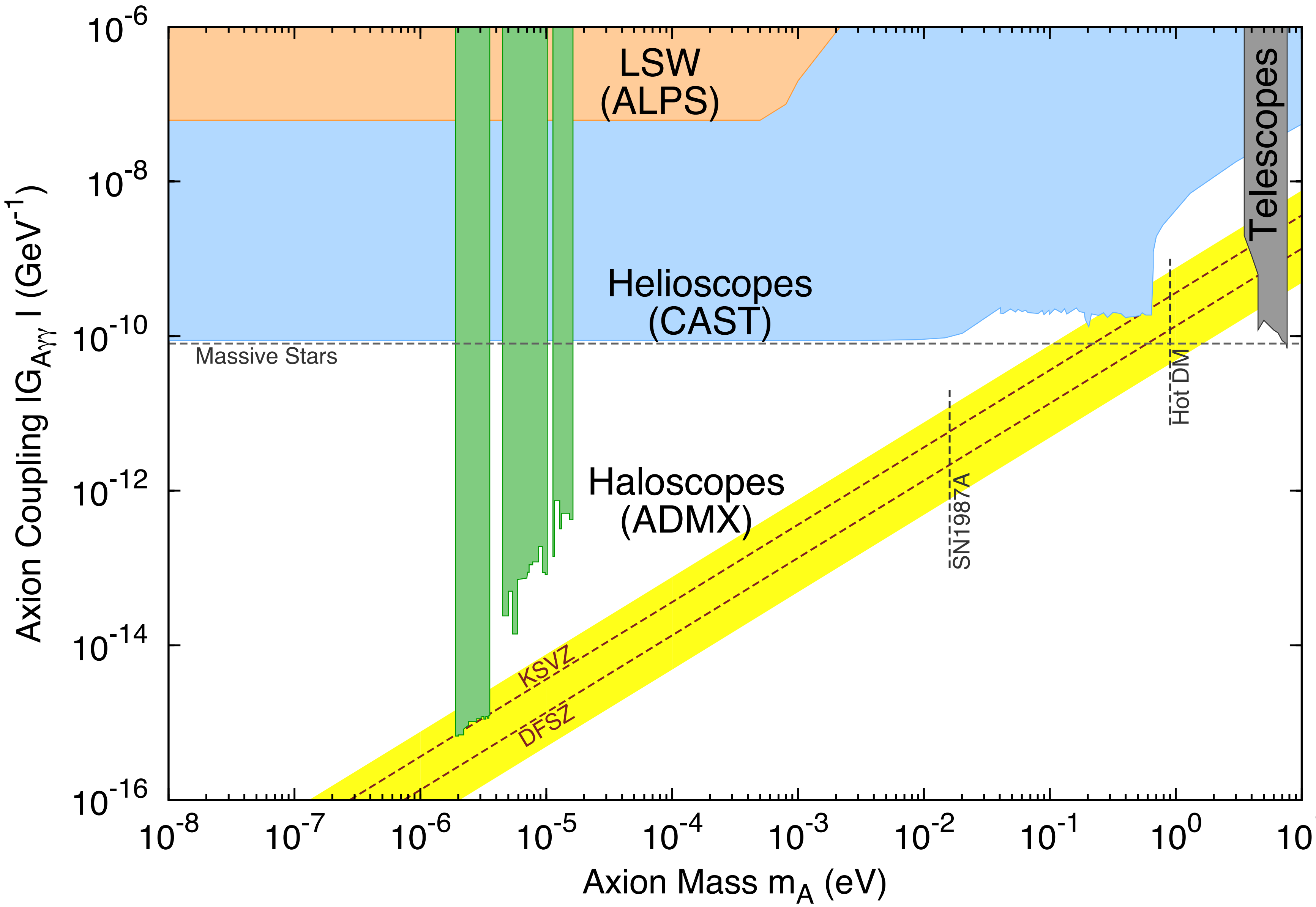
$$\Delta E/E \approx 10^{-6} \ (\approx 1.2\mathrm{kHz})$$

The Axion Dark Matter eXperiment





Exclusion plot for axion like particles



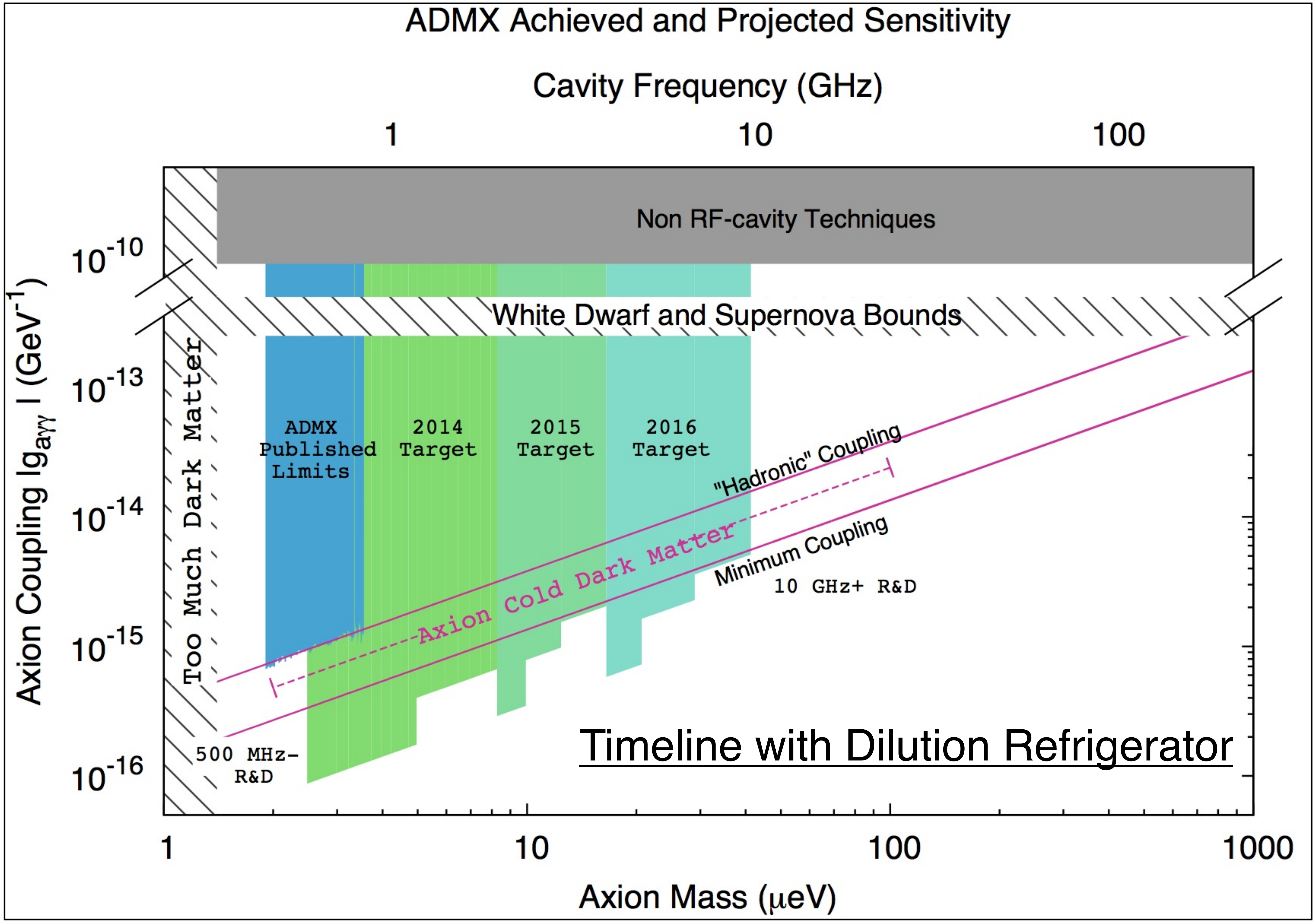
mass range ~1 μeV - 10 meV

upper: axions can be produced in astrophysical bodies and escape, new sources of energy loss

lower: relic density of the axion is smaller or equal to the observed dark matter density Ω_{dm}

K. Olive et al, 2014 (PDG)

The ADMX-Gen2 science prospects



Summary

★ Intense experimental efforts in **direct detection** of dark matter.

★ In spite of observed "anomalies" that could be interpreted as WIMPs, **no convincing evidence** of direct detection

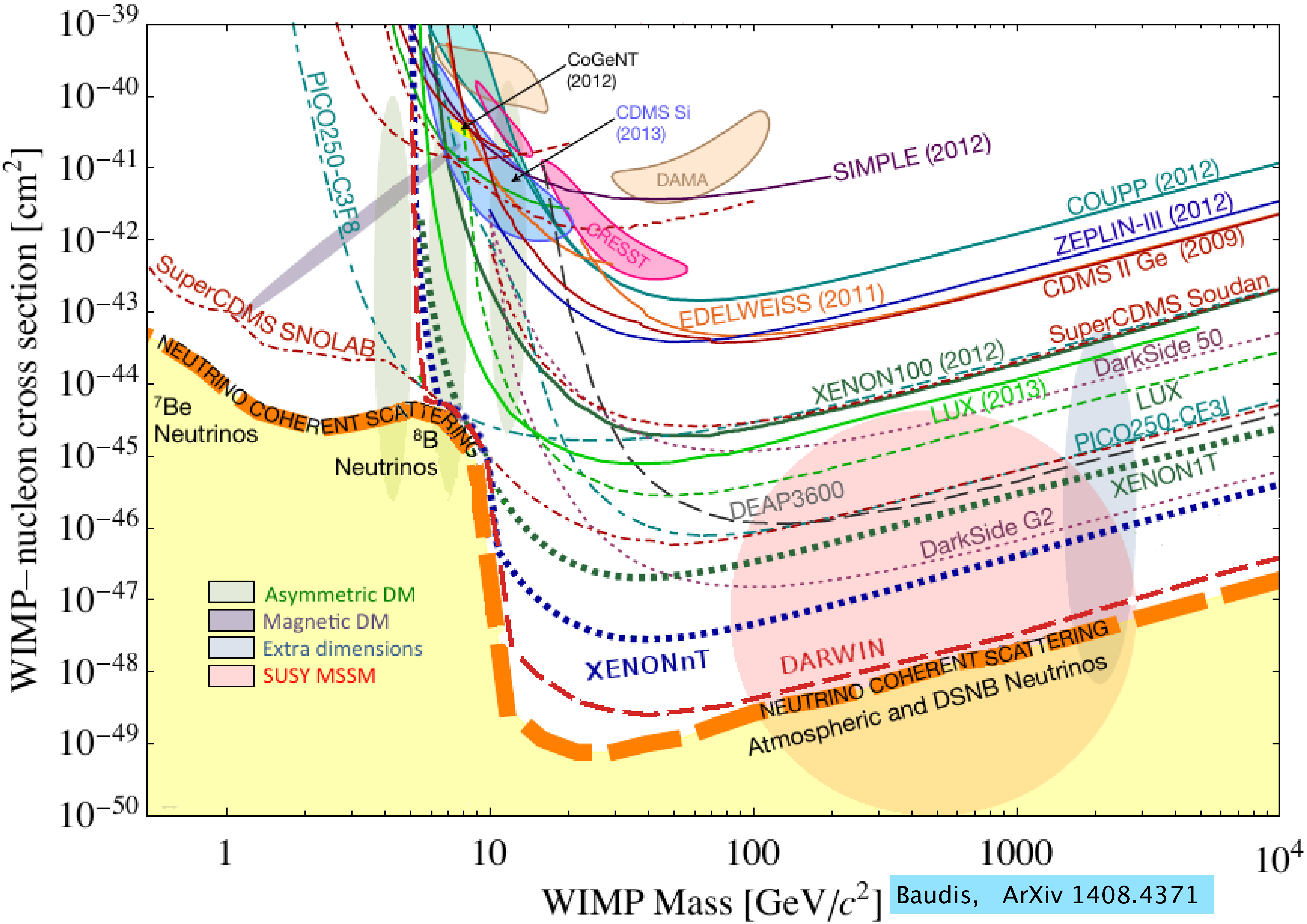
★ Direct detection searches are **progressing**: lower cross sections, lower and higher mass

★ New **particle** candidates (axions, etc..)

★ New **technologies** expanding the physics reach

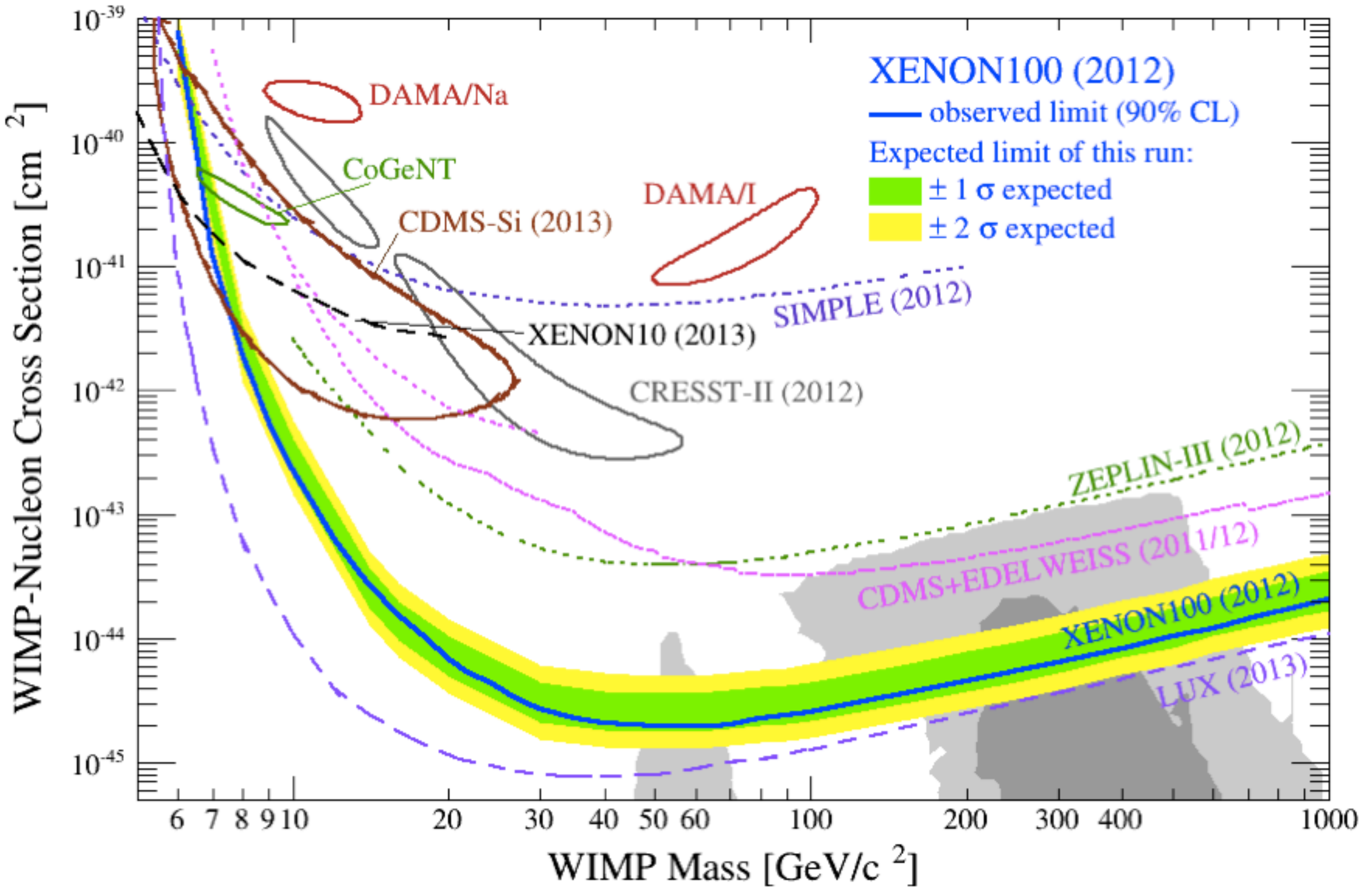
★ Experiments running now or under construction: improve **sensitivity** reach by 1 or 2 orders of magnitude in next years

★ Planned experiments to reach the **neutrino bound** within one decade



CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
CRESST
PICO250-C3F8
SuperCDMS SNOLAB
SuperCDMS Soudan
XENON100 (2012)
DarkSide 50
LUX (2013)
LUX
PICO250-CF3I
XENON1T
DEAP3600
DarkSide G2
XENONnT
DARWIN
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
⁷Be Neutrinos
⁸B Neutrinos
Asymmetric DM
Magnetic DM
Extra dimensions
SUSY MSSM
WIMP–nucleon cross section [cm²]
WIMP Mass [GeV/c²]
Baudis, ArXiv 1408.4371

XENON100 spin independent limit



XENON100, Phys. Rev. Lett. 2012