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Direct Dark Matter Searches

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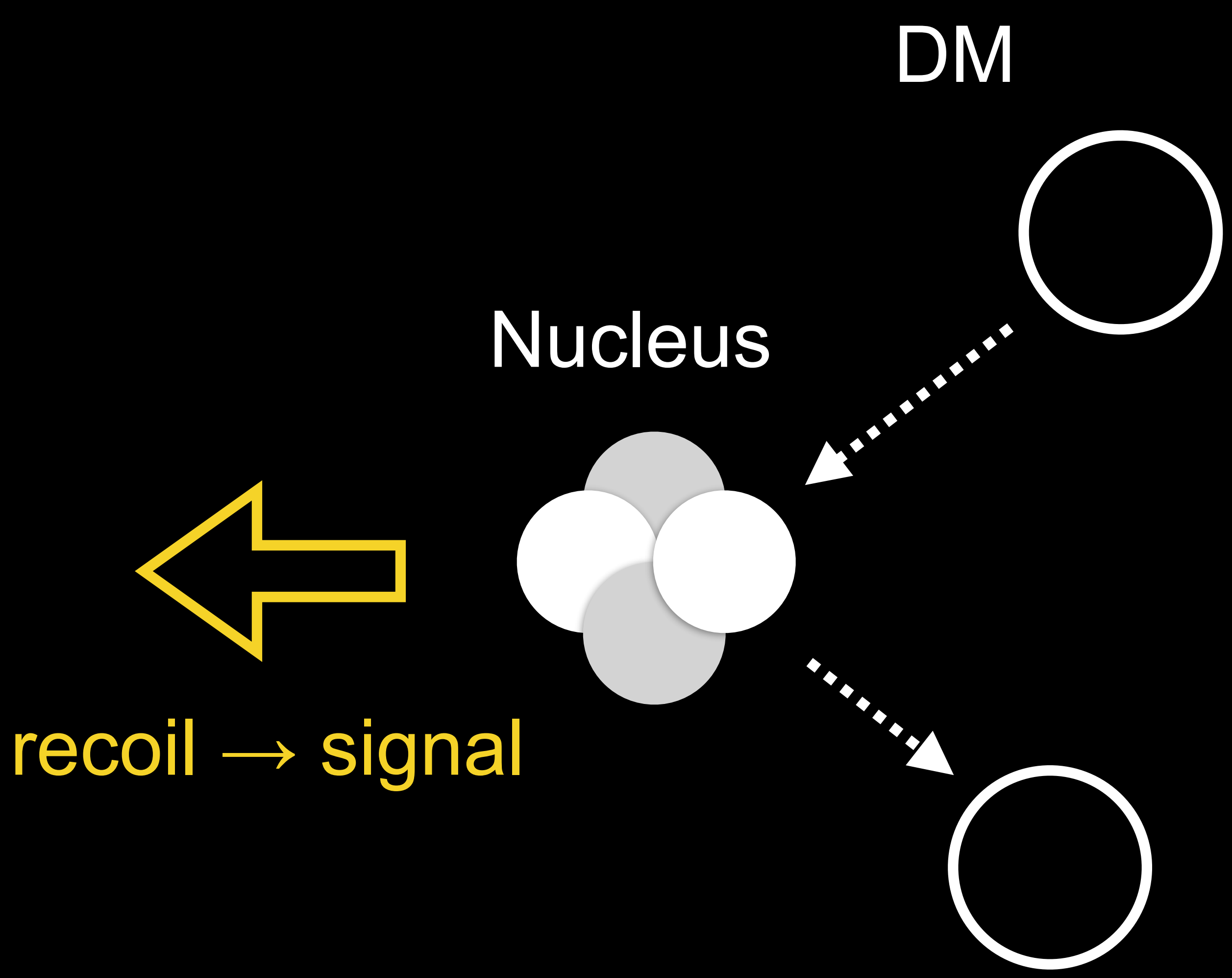
Overview

- Direct dark-matter searches
- Astrophysical aspects & signatures
- Backgrounds
- Technologies and status of direct searches
    - Scintillating crystals at room temperature
    - Cryogenic bolometers
    - Liquid noble gas detectors
    - Super-heated liquids
    - Directional detectors
- Summary

Direct Detection Overview

- Look for DM as our solar system passes through the galactic halo
- Direct Searches look for halo DM interacting with the nuclei of a target material
- Interactions are expected to happen rarely and at low energies
- Roughly 1 interaction per kg per year
- Detected by recoils off ultra - sensitive detectors placed deep underground
- Very active field with exciting physics prospects and technical challenges

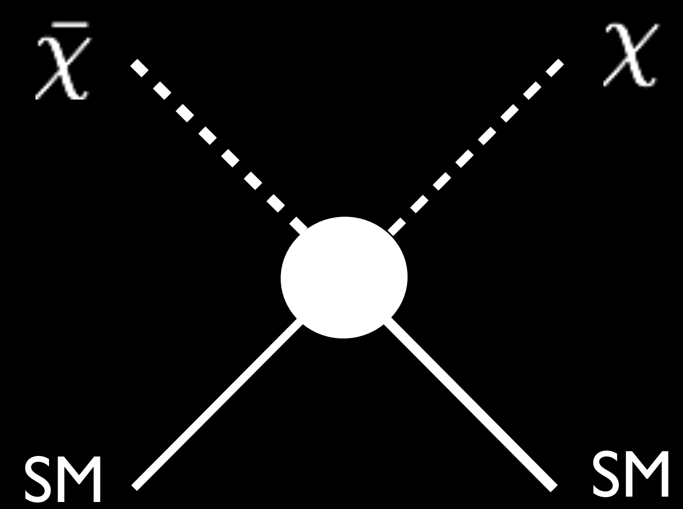


The particle physics picture

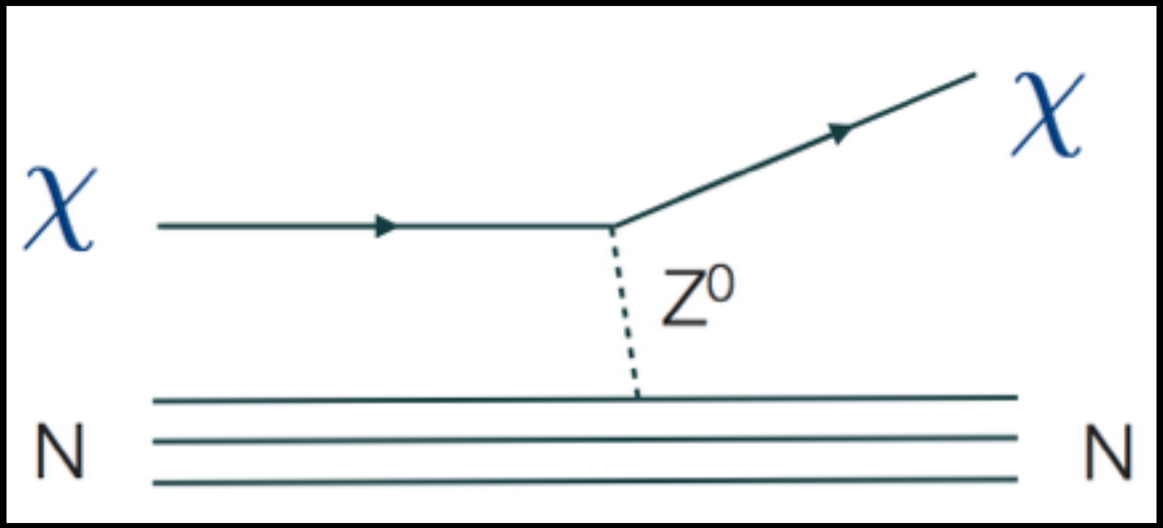
- Effective operators used to describe WIMP-quark interactions (always valid at DD)

$$\mathcal{L}_{\chi}^{\rm eff} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$

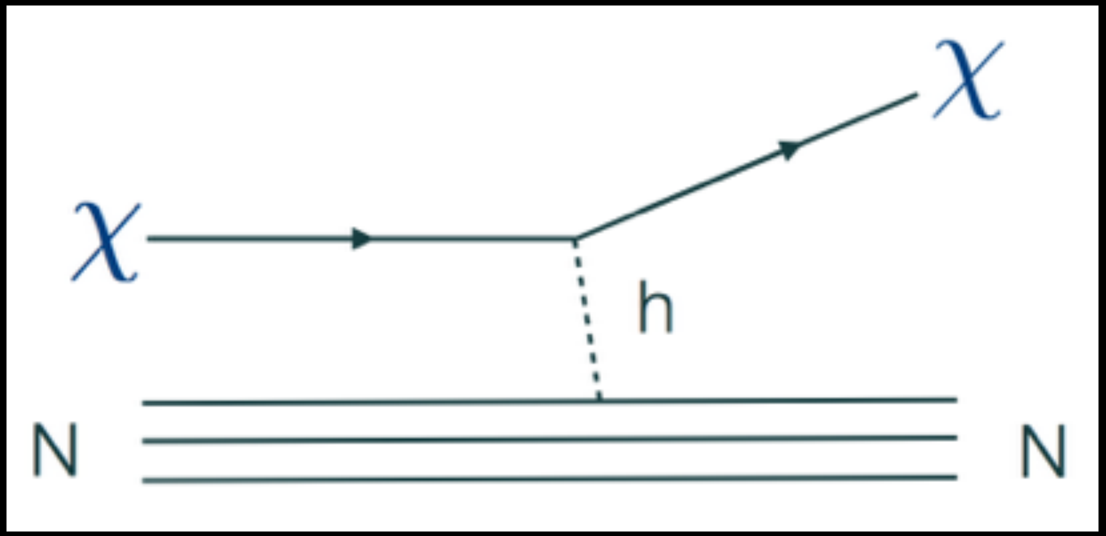
$$\Lambda = m_R/\sqrt{g_q g_\chi}$$



- Example (more exist):
  - Vector couplings→ Spin-independent
  - Axial couplings → Spin-dependent



$$\sigma_0 \sim 10^{-39} cm^2$$



$$\sigma_0 \sim 10^{-45} cm^2$$

DM-Nucleus Interactions

arXiv:1509.0876

- Spin-independent interactions:
  - Same couplings to proton/neutron (isospin conservation)
  - Scattering amplitude for each nucleon adds in phase and results in a coherent process (e.g. coupling to nuclear mass, for low q)
  - If $f^p=f^n$, then $\sigma \sim A^2$

$$\sigma_0^{SI} = \sigma_p \cdot \frac{\mu_A^2}{\mu_p^2} \cdot [Z \cdot f^p + (A - Z) \cdot f^n]^2$$

μ=reduced DM-nucleus mass, $f^{p,n}$=coupling constants

DM-Nucleus Interactions

arXiv:1509.0876

- Spin-dependent interactions: coupling to nuclear spin
  - Only unpaired nucleons contribute to scattering
    e.g. only nuclei with an odd number of protons or neutrons
  - Cross section related to the quark spin content of the nucleon with components from both proton and neutron couplings
- Experiments typical a few orders of magnitude less sensitive

$$\sigma_0^{\mathrm{SD}} = \frac{32}{\pi}\mu_A^2 \cdot G_F^2 \cdot [a_p \cdot \langle S^p \rangle + a_n \cdot \langle S^n \rangle]^2 \cdot \frac{J+1}{J}.$$

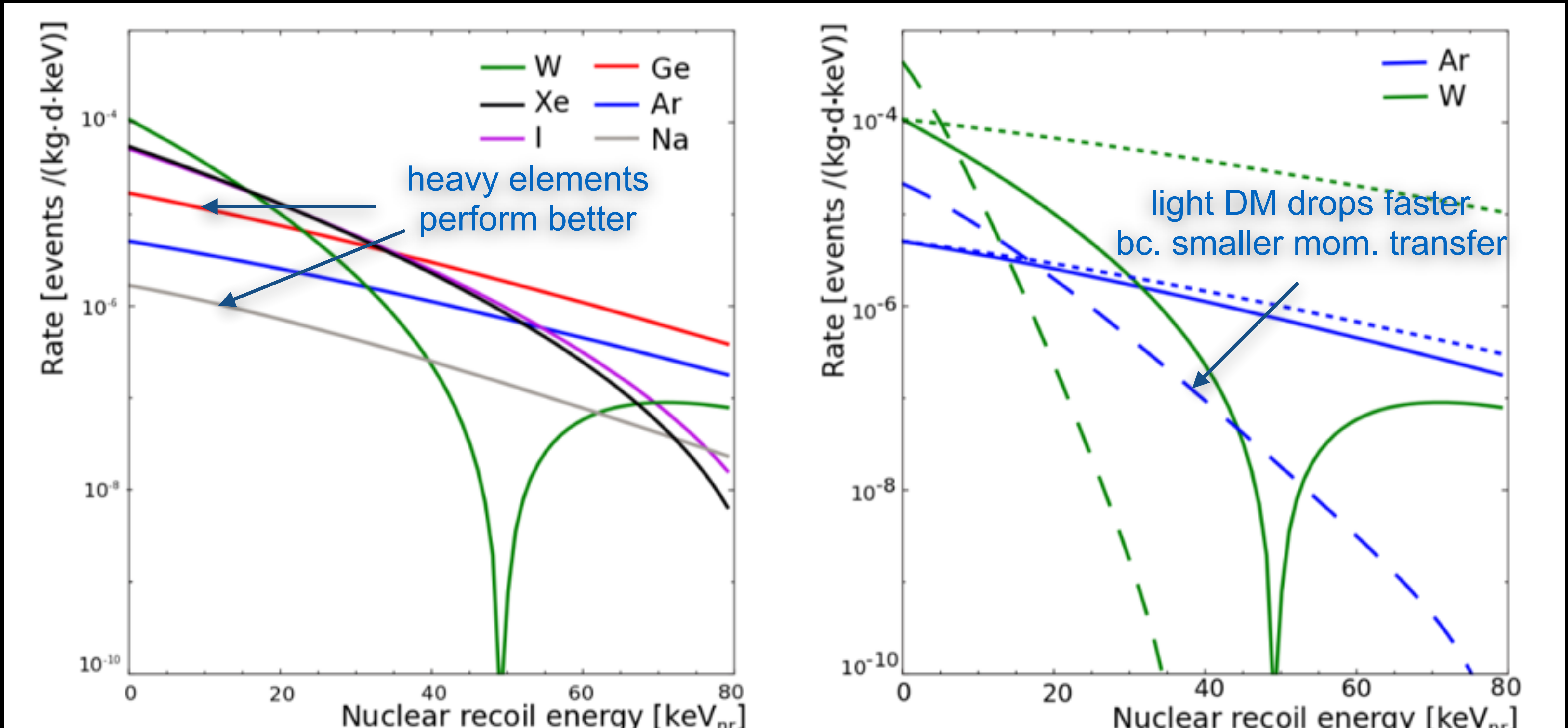
⟨Sp,n⟩: expectation of the spin content of the p, n in the target nuclei
ap,n: effective couplings to p and n.

Expected Detection Rates

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v)\ \mathrm{d}^3 v,$$

- Astrophysical parameters:
  - ρ_0 = local density of the dark matter in the Milky Way
  - f (v, t) = WIMP velocity distribution
- Parameters of interest:
  - m_χ = WIMP mass (~100 GeV)
  - σ = WIMP-nucleus elastic scattering cross section

Event Rates



Differential rates for 100 GeV DM particle

- Event rates as function of nuclear recoil energy for different targets
  - Dotted line: no form factor correction
  - Dashed line: for a 25 GeV WIMP mass
- Energy transfer is largest for WIMP and target with identical mass.

The energy scale

- Energy of recoils is tens of keV
- Entirely driven by kinematics, elastic scattering of things with approximately similar masses (100 GeV) and v ~ 0.001c

$$\frac{1}{2} m_N v_N^2 = \frac{1}{2} \times 100\,\mathrm{GeV} \times 10^{-6} = 50\,\mathrm{keV}$$

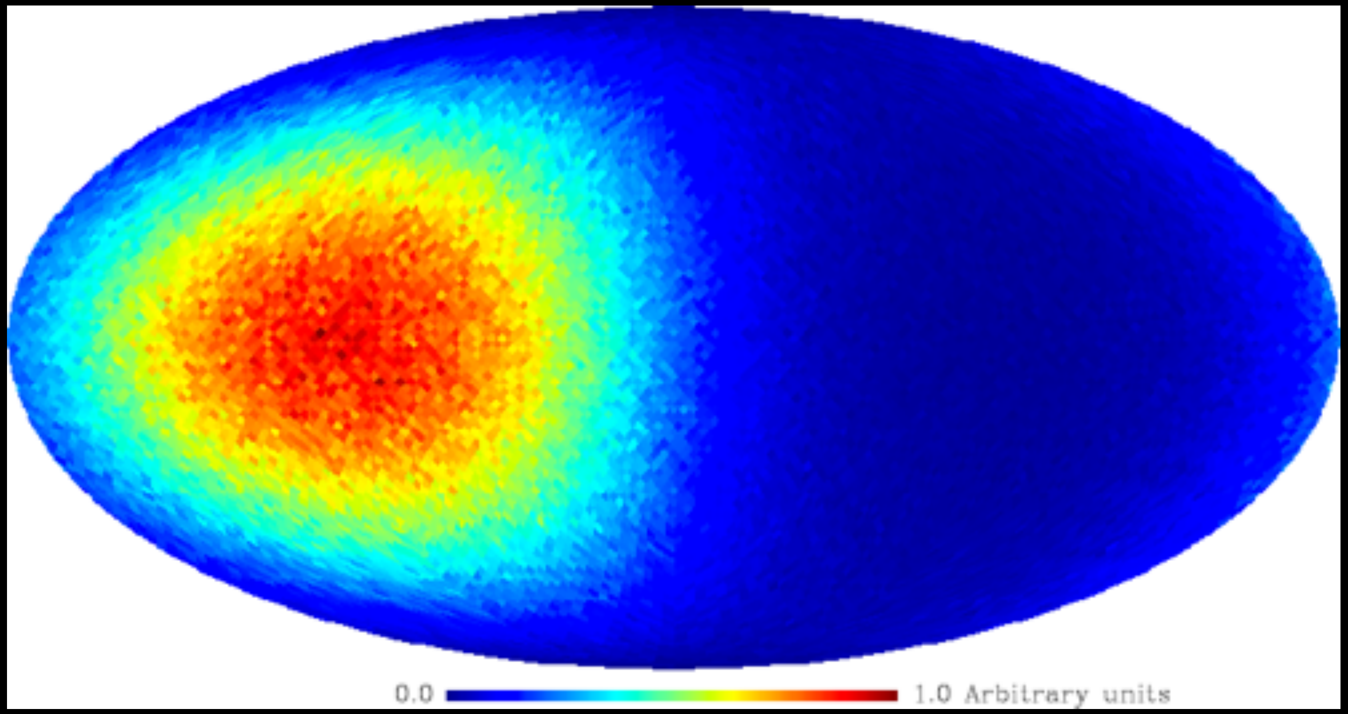
The standard halo model

arXiv:1001.2983
arXiv:1406.6896

- Isotropic, isothermal sphere with a Maxwellian velocity distribution

$$f(\mathbf{v}) = \frac{1}{\sqrt{2\pi\sigma}} \cdot \exp\left(-\frac{|\mathbf{v}|^2}{2\sigma^2}\right)$$

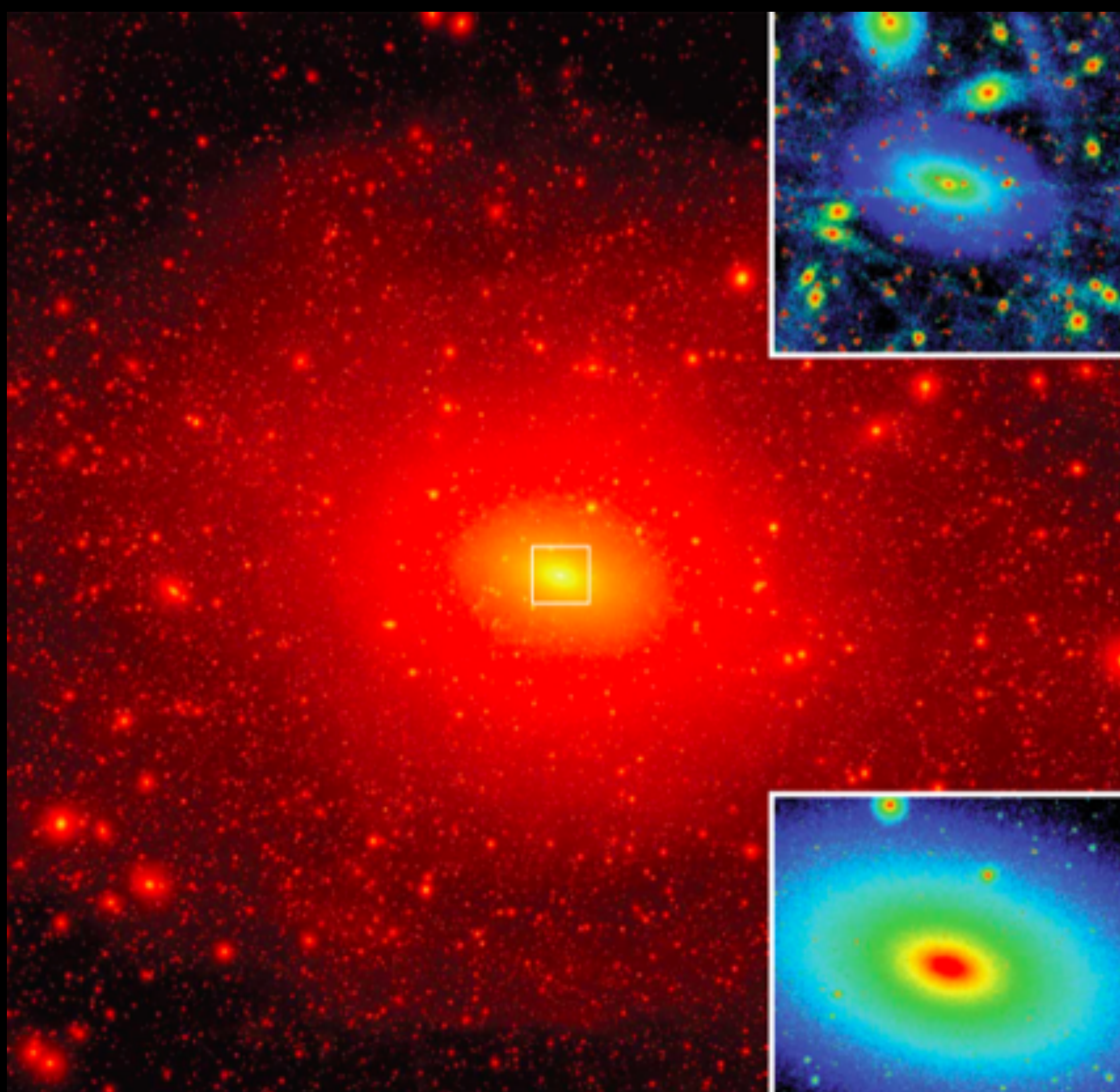
- Local density:
  ρ_0 = 0.3 GeV/cm^3 = 0.008 $M_\odot$/pc^3 = 5x10^{-23} g/cm^3
- Circular velocity v = 220 km/s, radial dispersion $\sigma_r = v_c/\sqrt{2}$
- Escape velocity:
  v_{esc}=544km/s



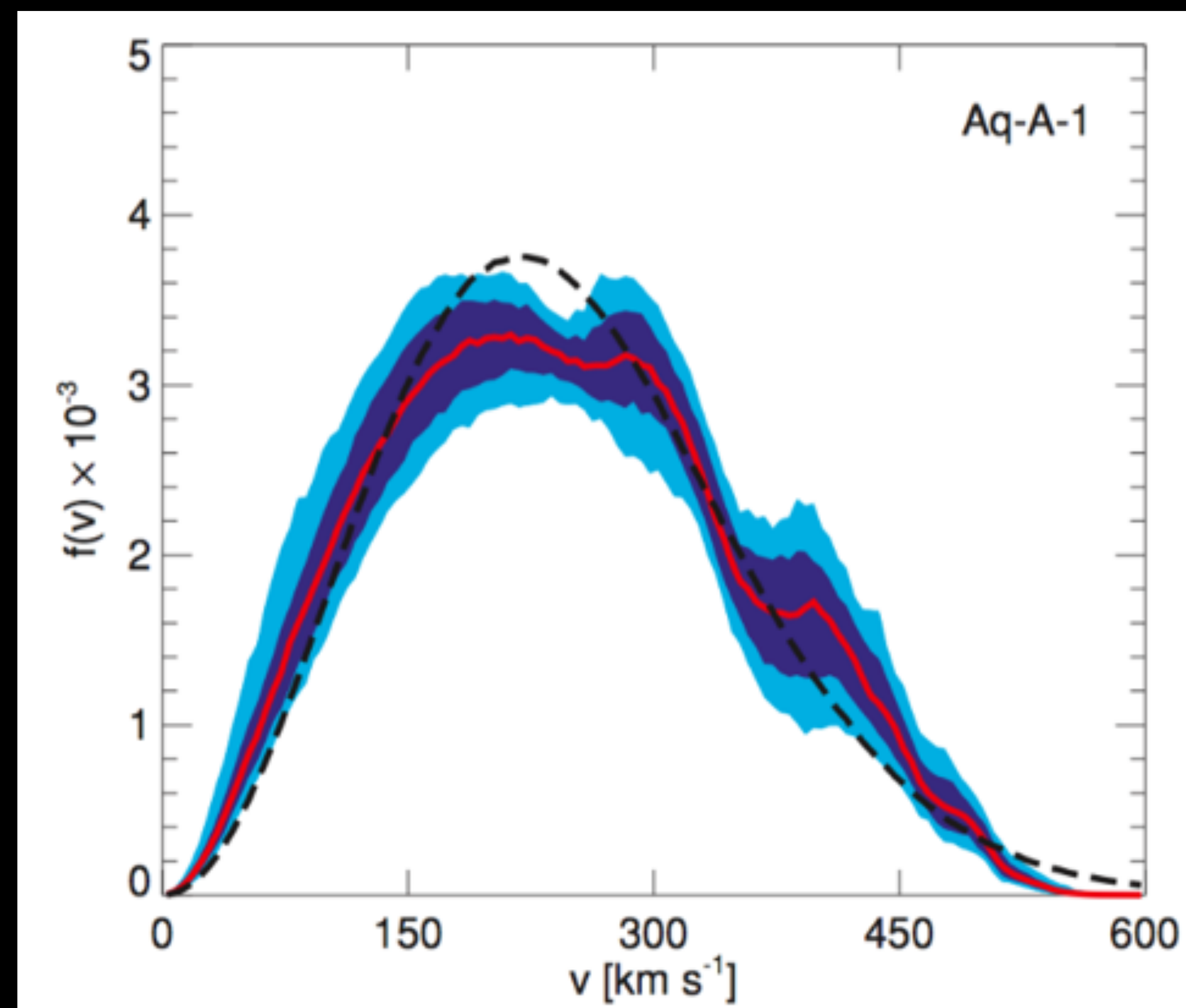
Dark Matter Distribution

R. Astron. Soc. 395 (2009) 797

- Rates depend on velocity & density distributions:
  - Standard model: isotropic Maxwellian
  - Simulations: triaxial and with non-smooth |v|, sub-structure, sub-halos



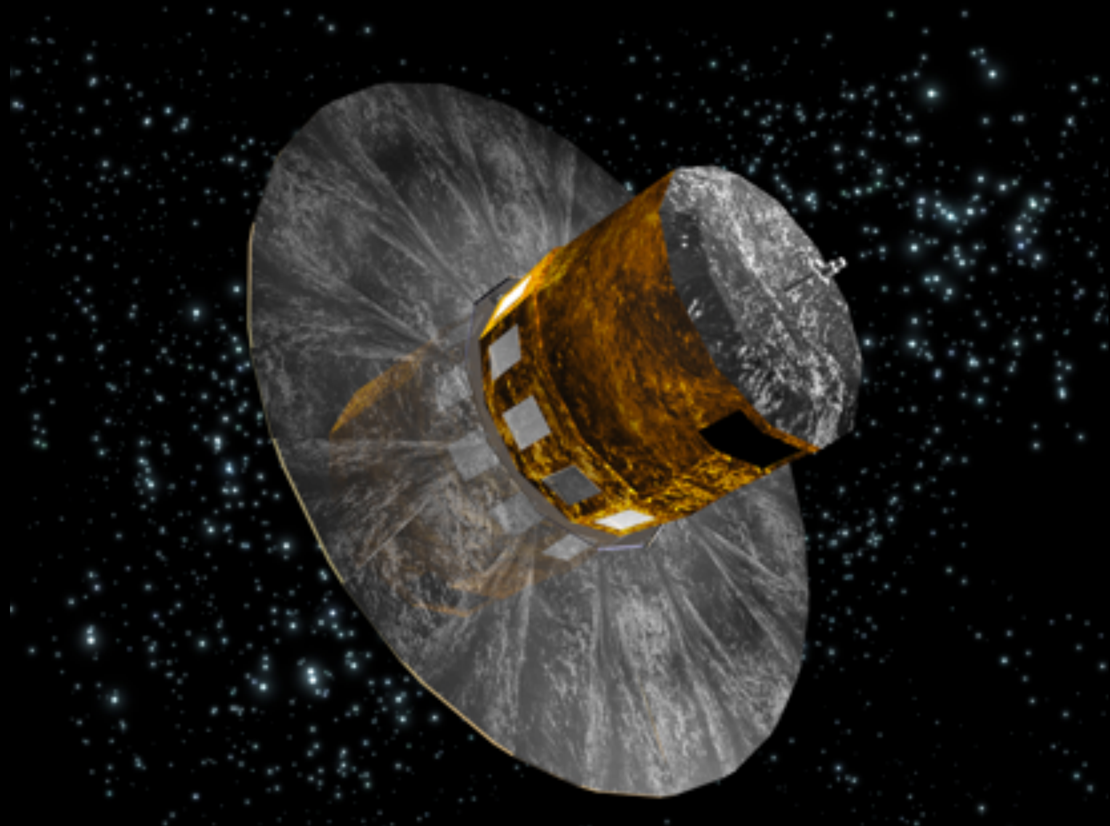
DM density of a galaxy similar to ours

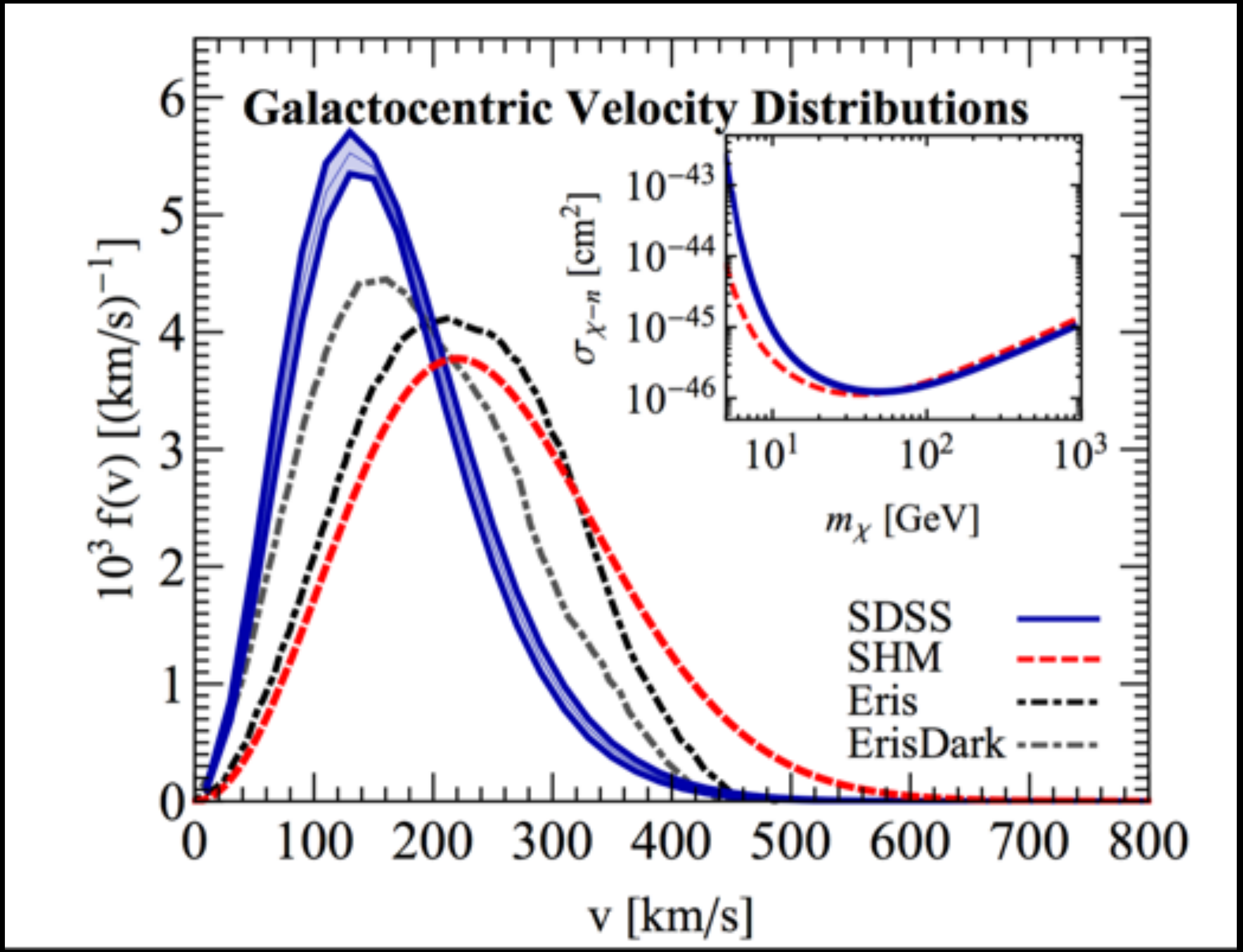


Velocity modulus distribution a simulated halo

Dark Matter Distribution

arXiv:1704.04499





- Measured differences can have up to 0(10) effect!
- GAIA satellite will measure 1B stars in our Galaxy precisely
  - produce 3D dynamic ap

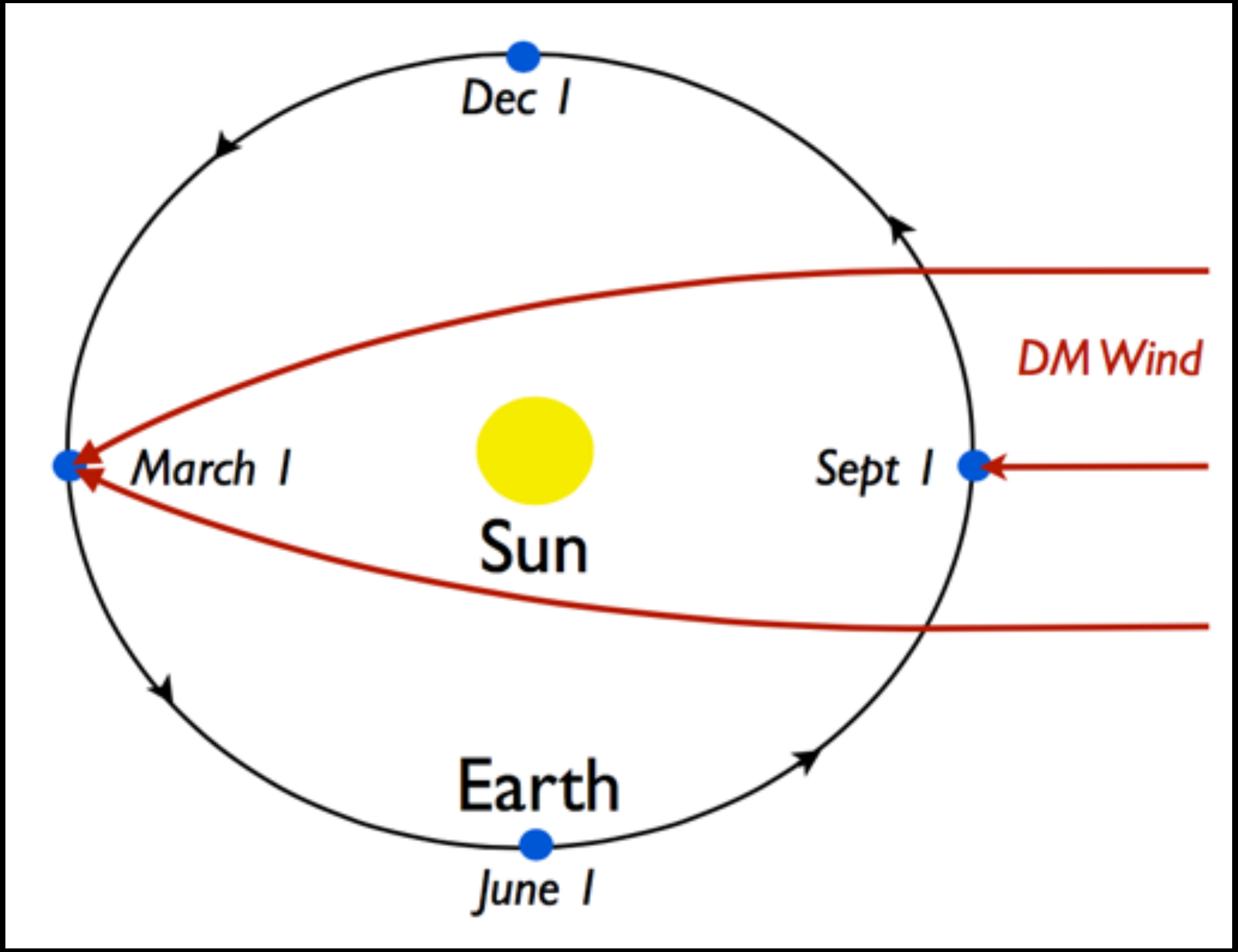
Velocity modulus distribution a simulated halo

Signatures: Annual Modulation

arXiv:1308.1953

$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E) \cdot \cos\left(\frac{2\pi(t-t_0)}{T}\right)$$

- DM 'wind' from rotation of Sun around Galactic center.
- Earth rotation around the Sun
- Relative velocity of DM particles relative to Earth largest in summer (June 2)
- E.g. larger number of nuclear recoils above threshold
- Potentially modulation due to gravitational lensing



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Signatures: Directionality

- Nuclear recoil (NR) direction has an angular dependence
- Mostly low-pressure gases used for directional searches

$$\frac{dR}{dE\ d\cos\gamma} \propto \exp\left[\frac{-[(v_E + v_\odot)\cos\gamma - v_{min}]^2}{v_c^2}\right]$$

- γ: NR direction relative to the mean direction of solar motion
- v_E and $v_\odot$: the Earth and Sun motions
- vc = sqrt(3/2$v_\odot$): halo circular velocity

Directionality visualisation

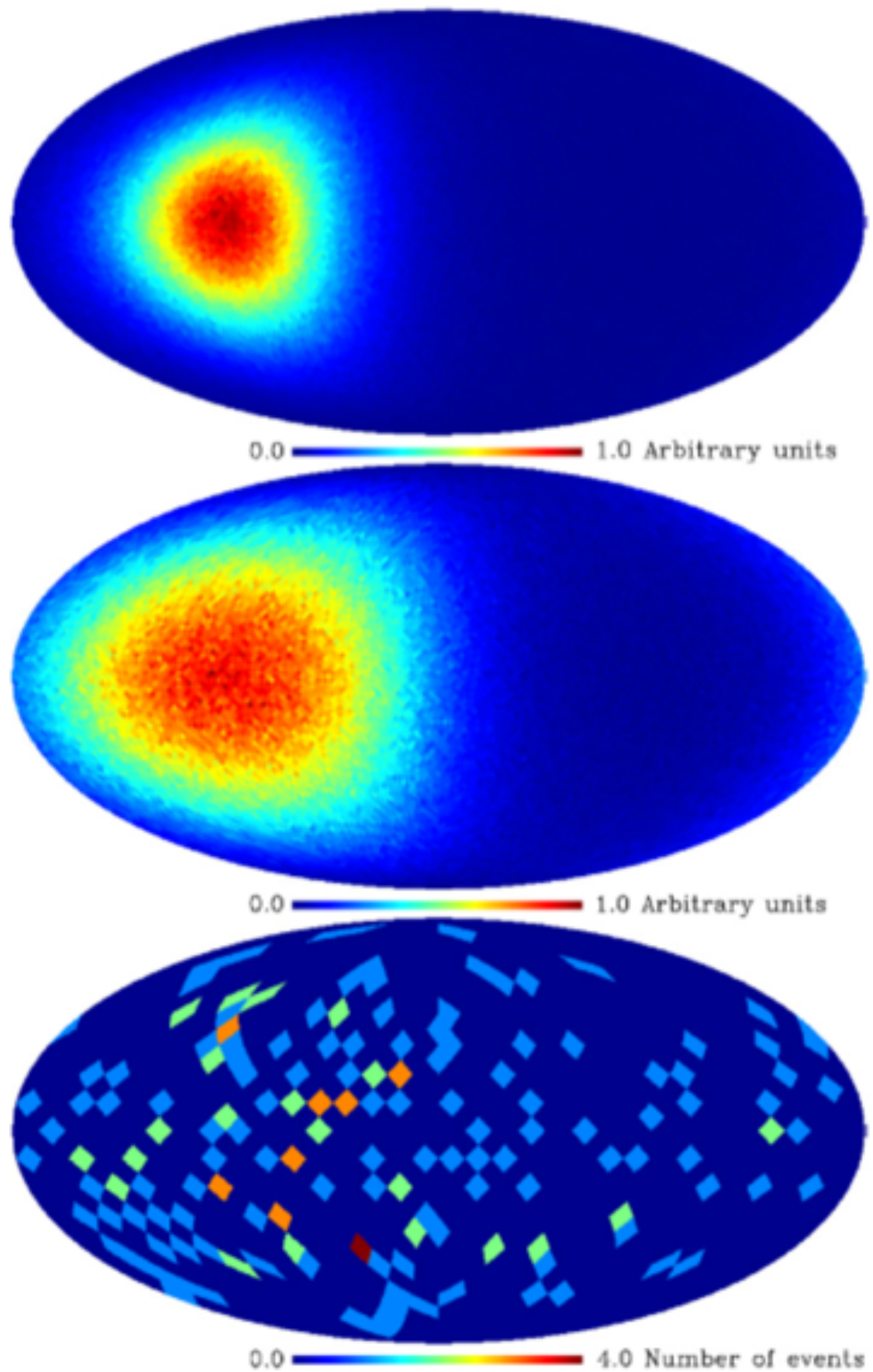

Figure from J. Billard *et al.* 2010

- WIMP flux in the case of an isothermal spherical halo
- WIMP-induced recoil distribution
- A typical simulated measurement:
  100 WIMP recoils and 100 background events (low angular resolution)

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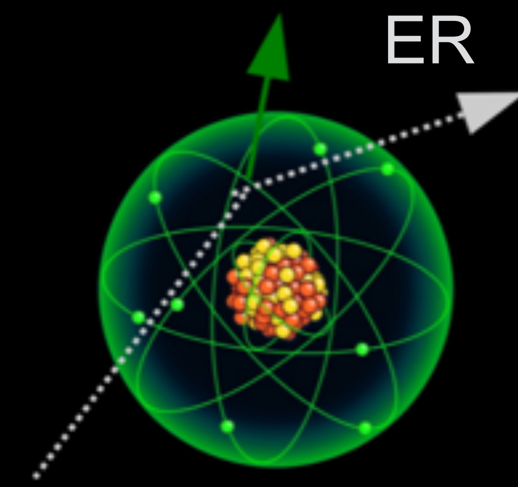
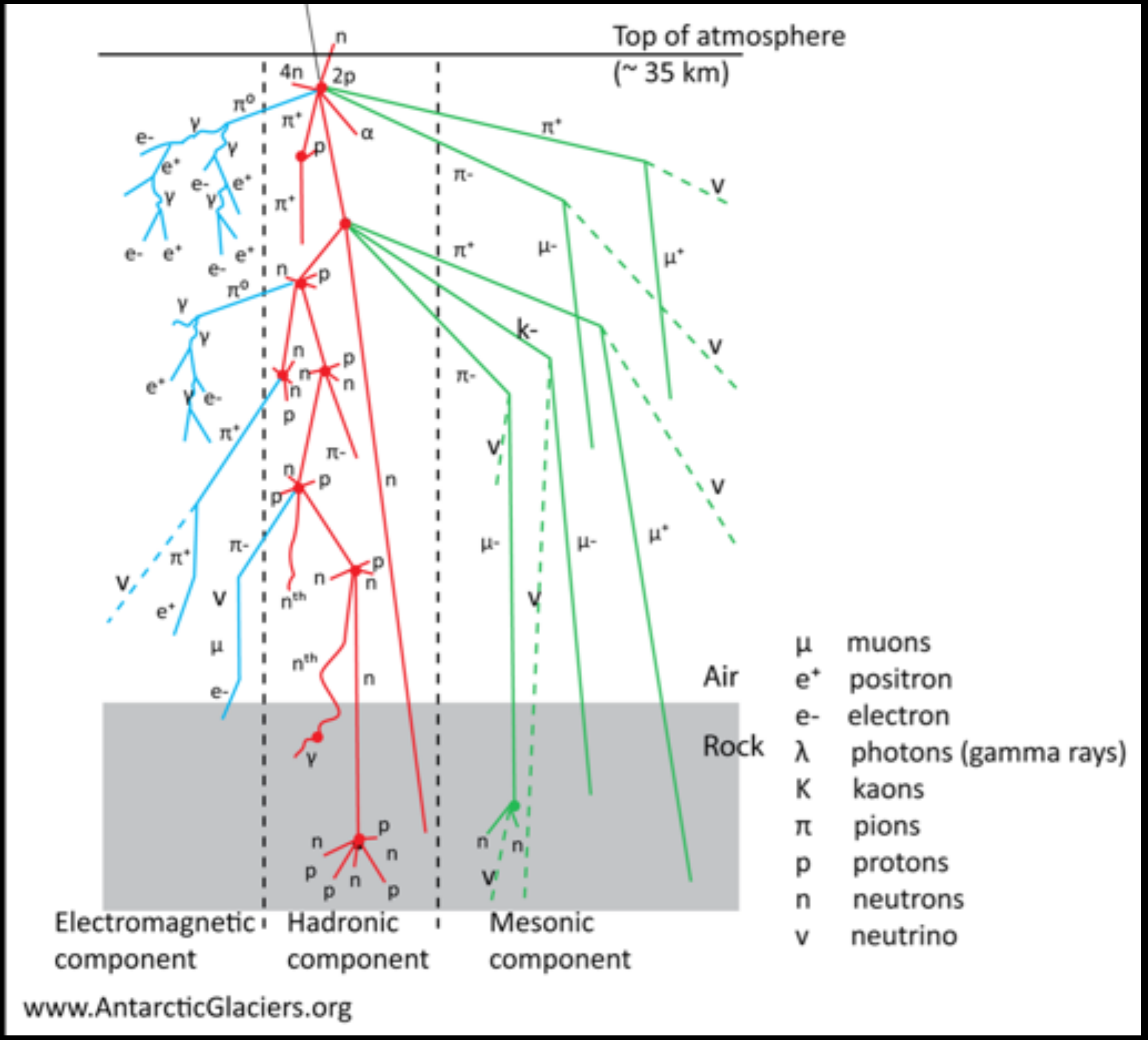
Background Sources

- Cosmic rays are constantly streaming through
  - All experiments have to go underground to get away from cosmic rays
- Radioactive contaminants - rock, radon in air, impurities
  - Emphasis on purification and shielding
- The detector itself - steel, glass, detector components
  - Self-shielding to leave a clean inner region
- Discrimination - can you tell signal from background (gamma rays, alphas, neutrons, etc)?

External Backgrounds



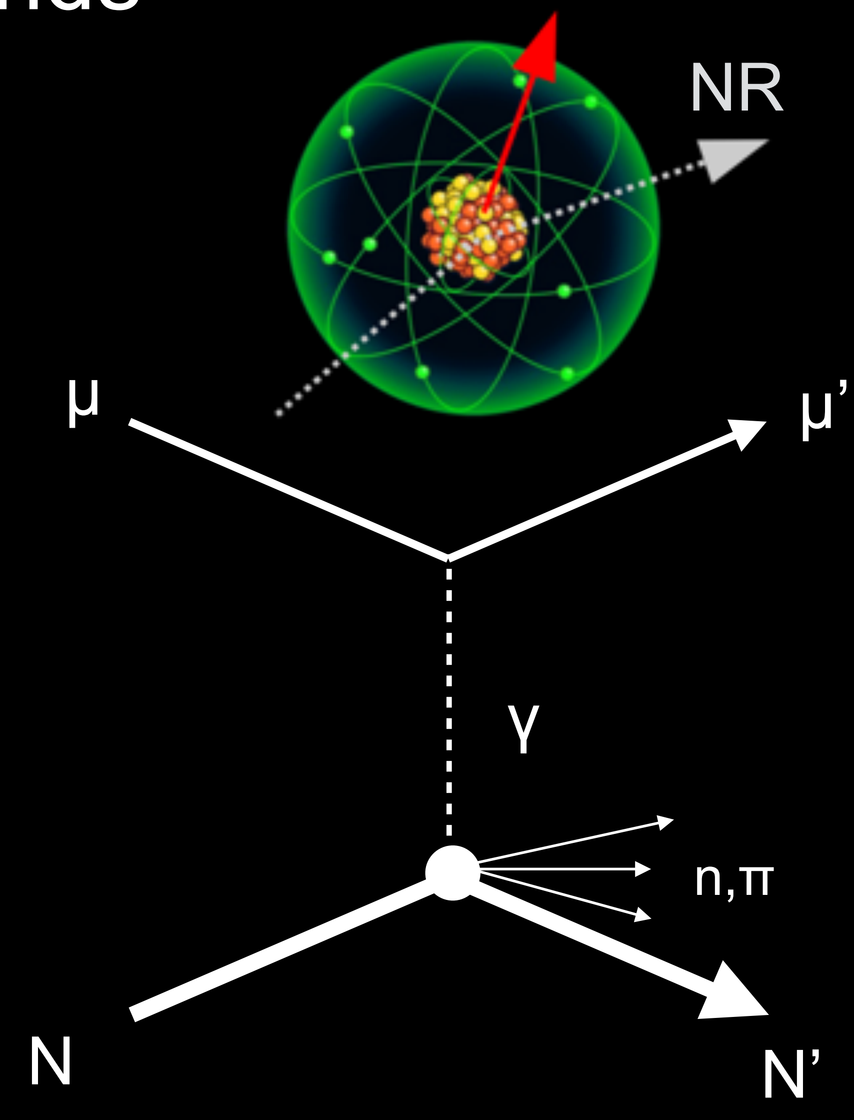
- γ-rays
- Decay of natural uranium and thorium (α,β)
    - E_γ~O(10 keV -2.6 MeV)
- Radon, etc
- Subsequent interactions with matter (phoelectric effect, compton scat., e+e-) cause electrons with energy in target: O(keV)
- Reduce using
    - Active and passive shielding
    - Material screening and selection
    - Rejection of multiple scatters & discrimination

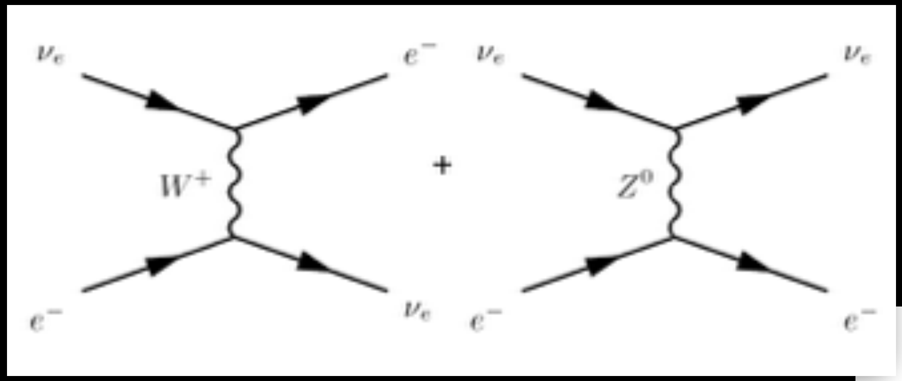


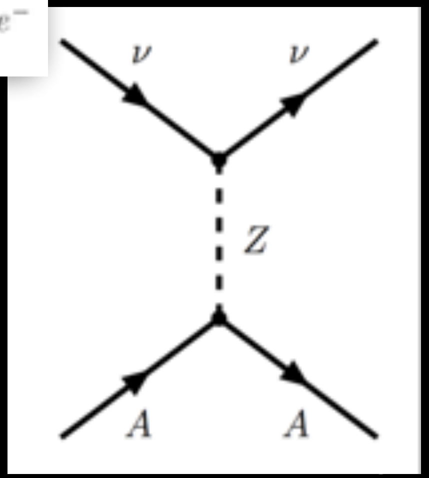
External Backgrounds

arXiv:340911

- External neutrons:
  - Create nuclear recoils via elastic scattering (WIMP-y!)
  - Produced from μ induced spallation, (α, n)- and spontaneous fission
  - From natural occurring U, Th
  - Go underground!
    - Shield: passive (polyethylene) or active (water/scintillator vetoes)
    - Use low U and Th det. material
- Neutrinos:
  - from the Sun, atmospheric and from supernovae
  - Elastic neutrino-electron scattering
  - Coherent neutrino-nucleus scattering (not yet measures)



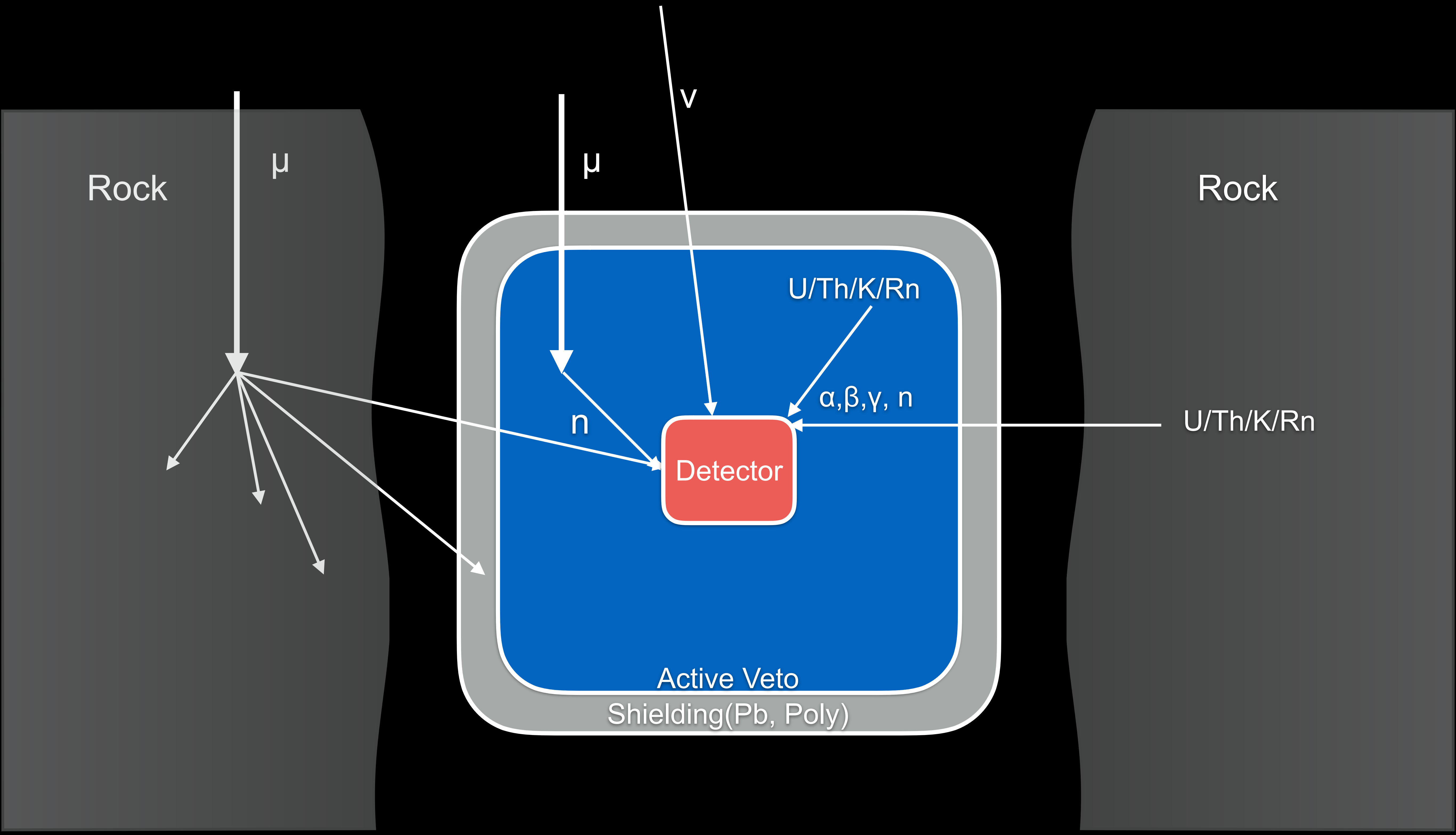




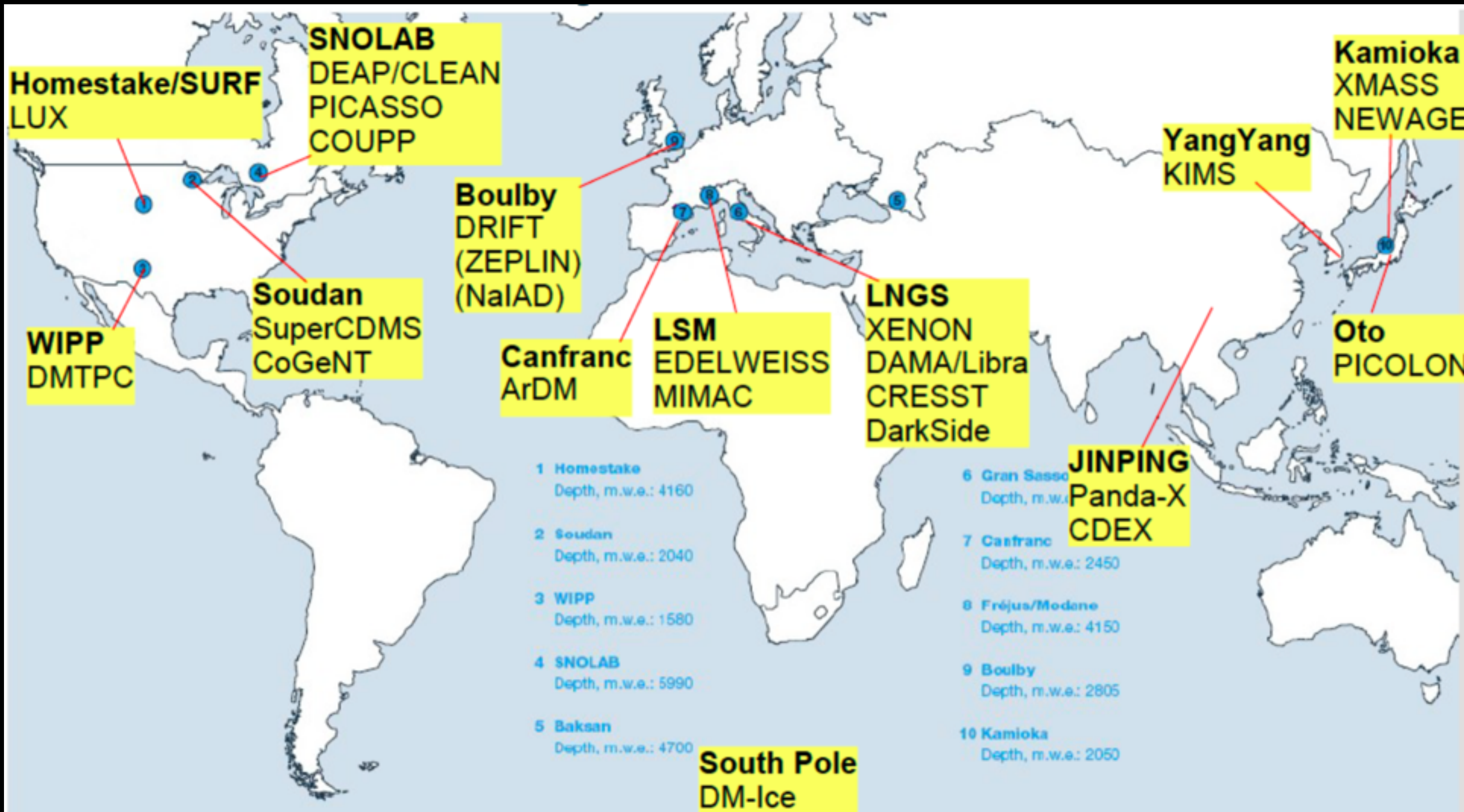
Internal & Surface Backgrounds

- Solid detectors:
  - Germanium detectors and solid scintillators grown from high purity materials → low intrinsic background
  - Surface contamination from radon decay products (α, β decay), K, Rb
  - Cosmic activation
- Liquid detectors:
  - Cosmogenic-activated radioactive isotopes contained in the target nuclei
  - Radon emanated from materials containing U, TH, diffuses into target
  - Remove using cryogenic distillation/chromatography/centrifuges

Background Overview



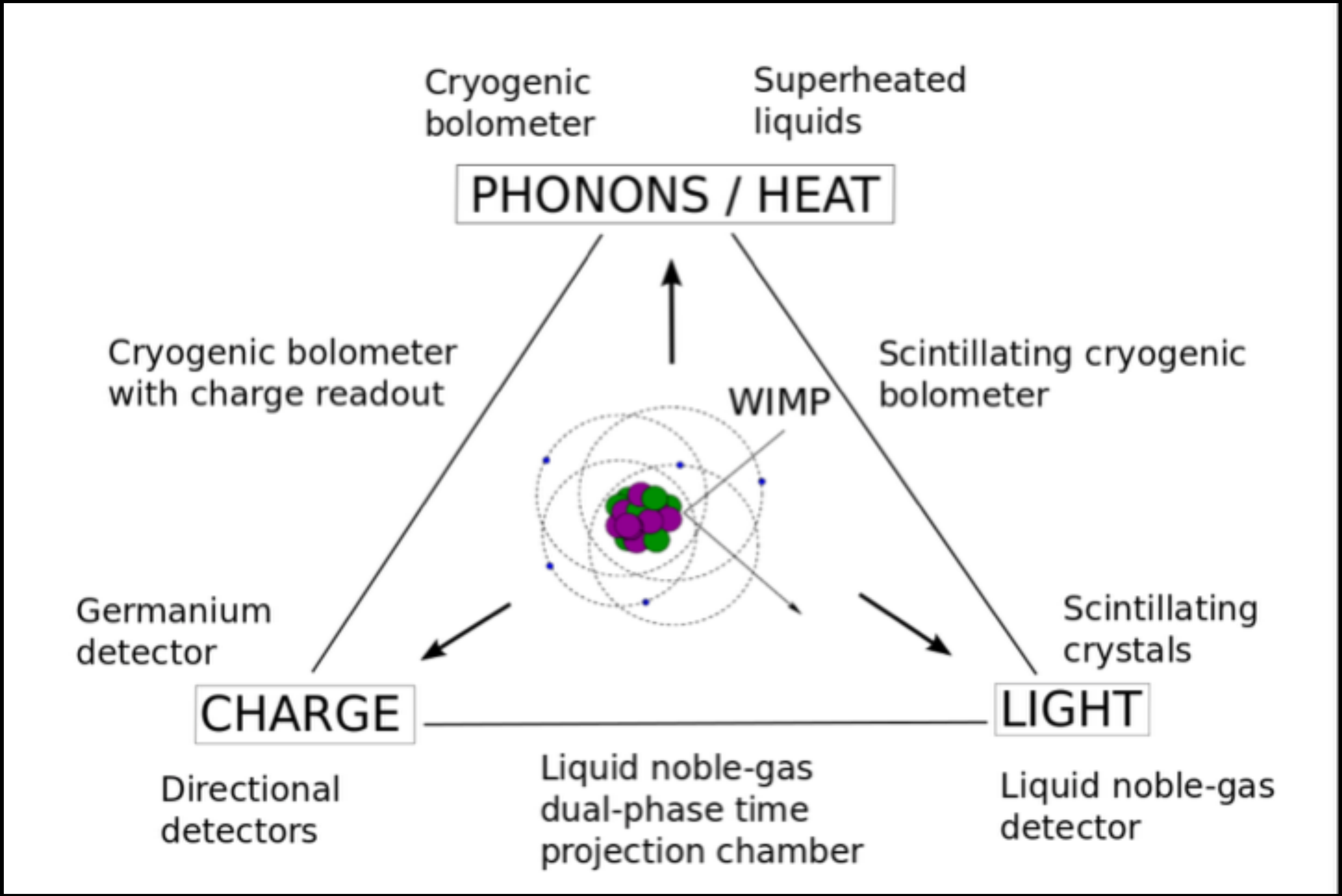
Underground Laboratories



Reduce muon/CR flux underground

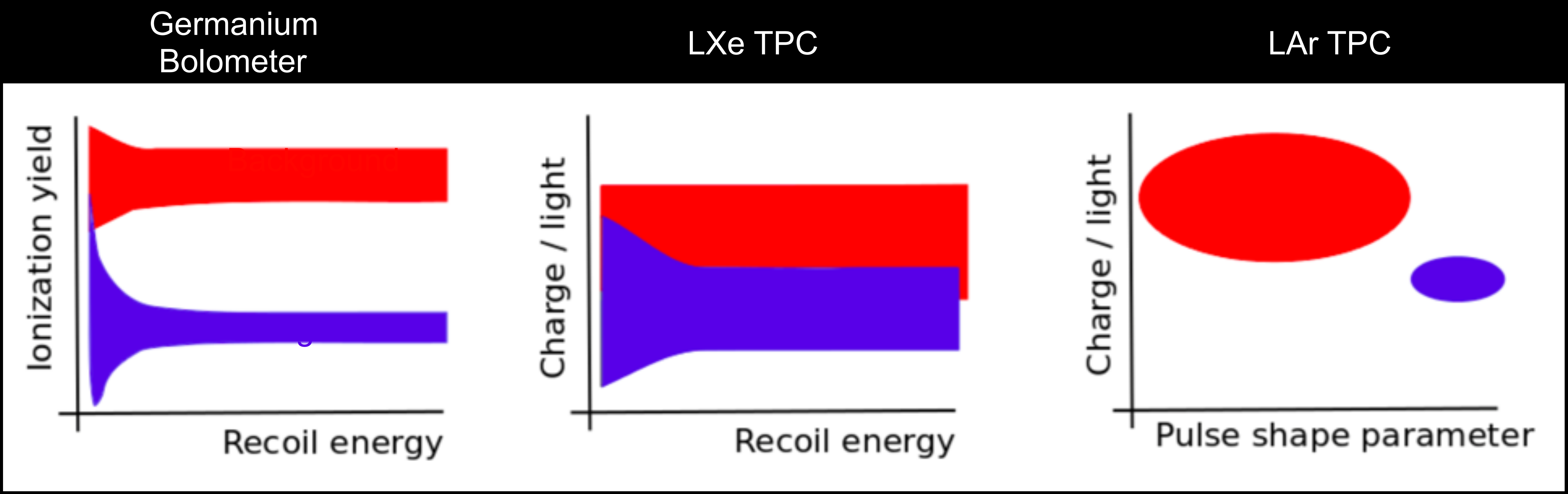
Experimental Approaches

Direct detection experiments



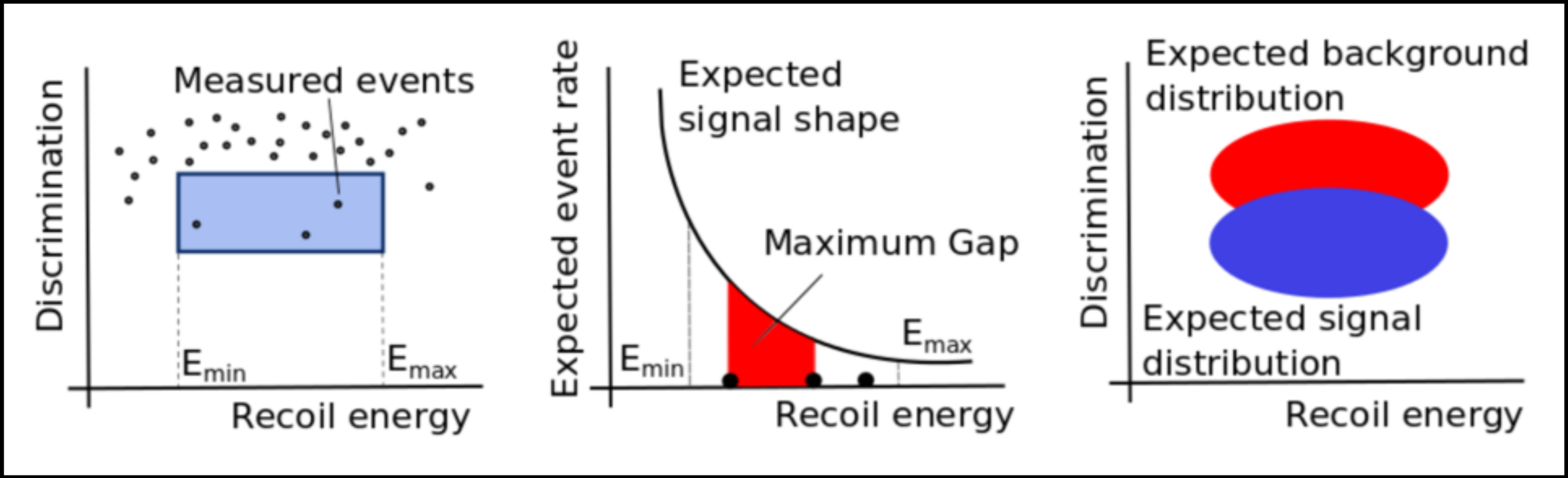
- DM energy transfer to nuclei
- Combination of two channels allows to identify particle

Generic Results



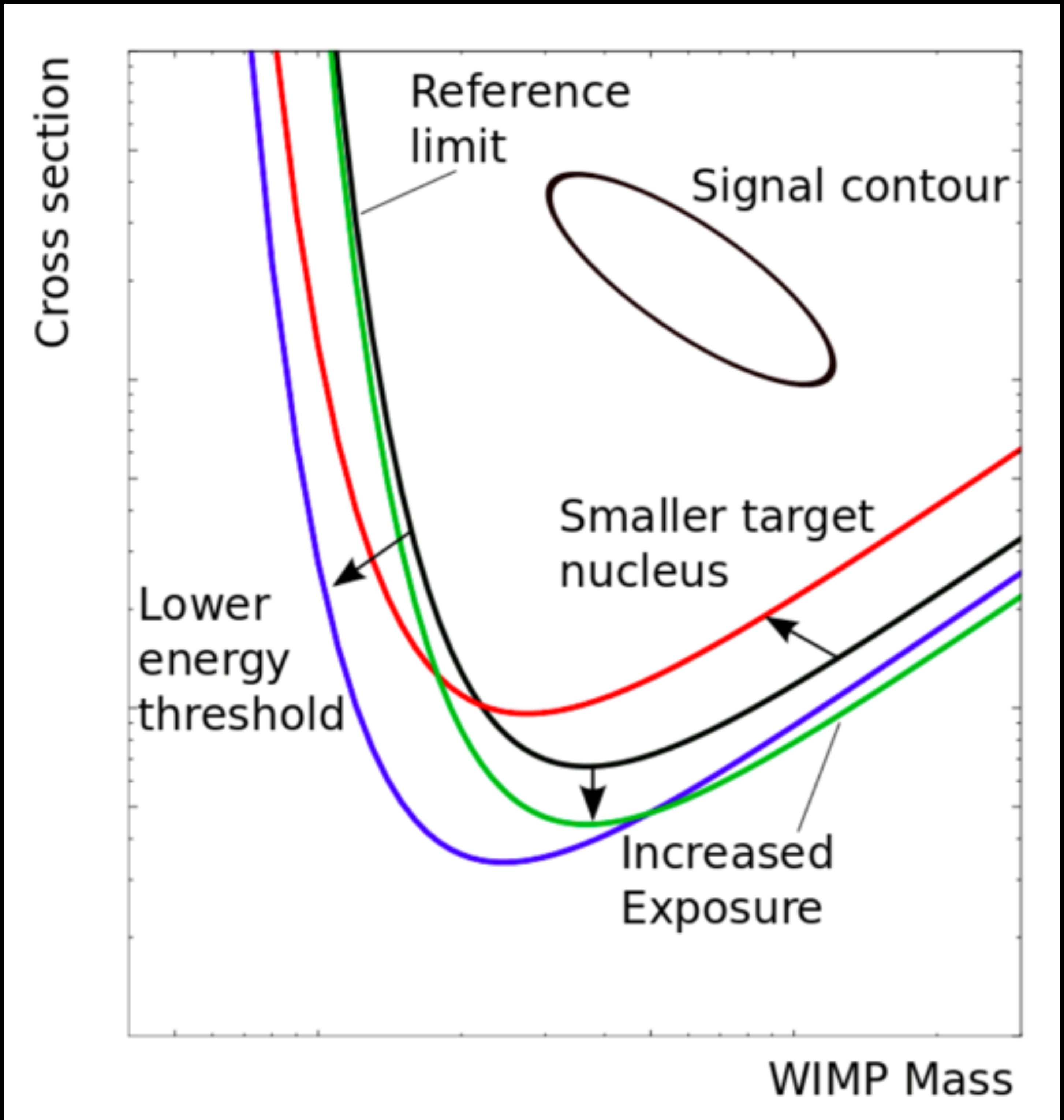
- Left: Cryogenic germanium detector
  - Best separation, ~10^6 rejection of electronic recoils
- Middle: Liquid xenon
  - Less discriminating, ~$5x10^3$ electronic recoil
- Right: Liquid argon detector (right):
  - Also use pulse shape of scintillation signal to separate signal and background
- Real world of course things might change

Interpretation of Results



- Statistical interpretations:
  - Simple counting-experiment, Poison statistics
  - Max Gap: Calculate upper limit because of absence of events (no discovery possible)
  - Maximum likelihood method: Details of background distribution are used to calculate two sides confidence limits:

Result of a direct detection experiment



- Positive signal
  - Region in σ_χ versus m_χ
- No signal:
  - Exclusion limits
  - Low mass: kinematic threshold
  - High mass: Suppressed event rate because of density, exposure important

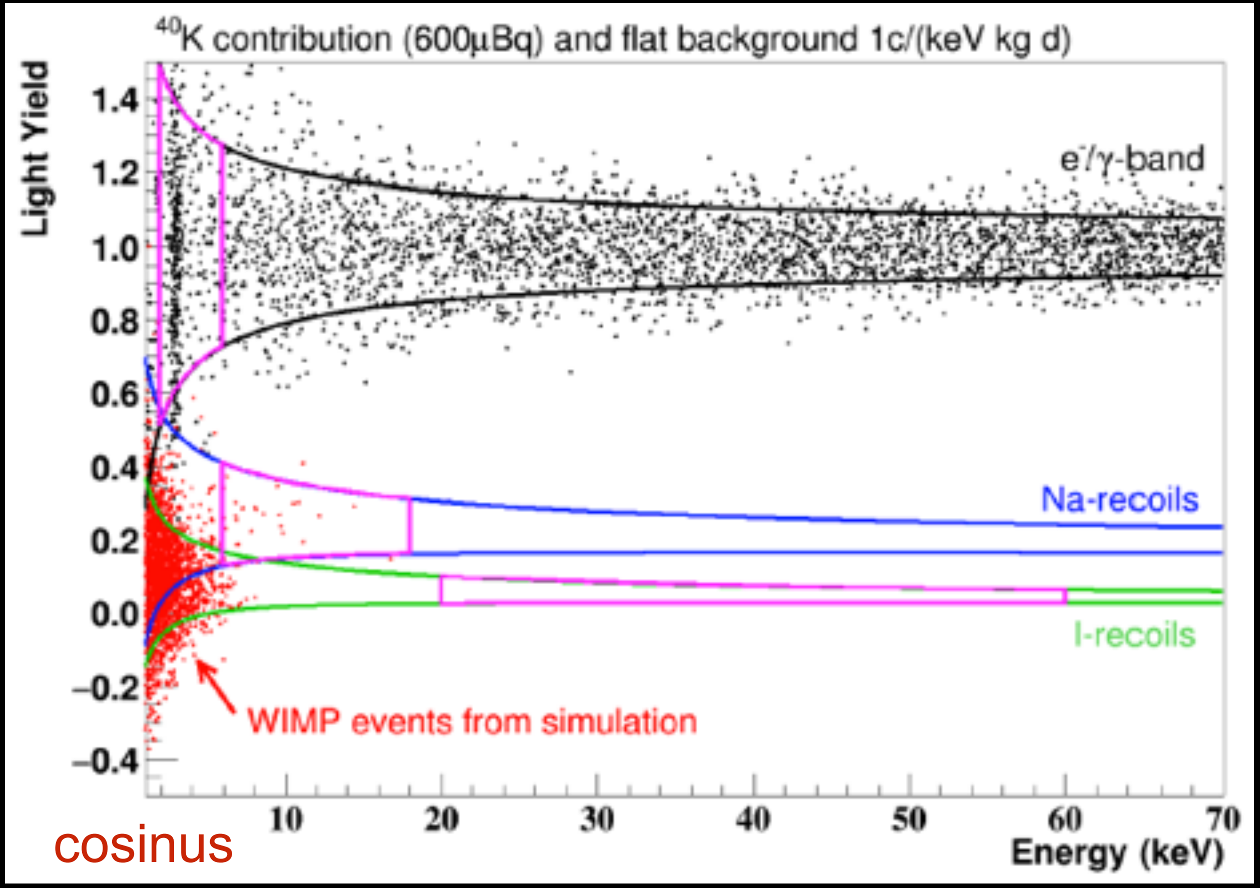
Detectors

- Crystals -

Scintillating crystals (Warm)

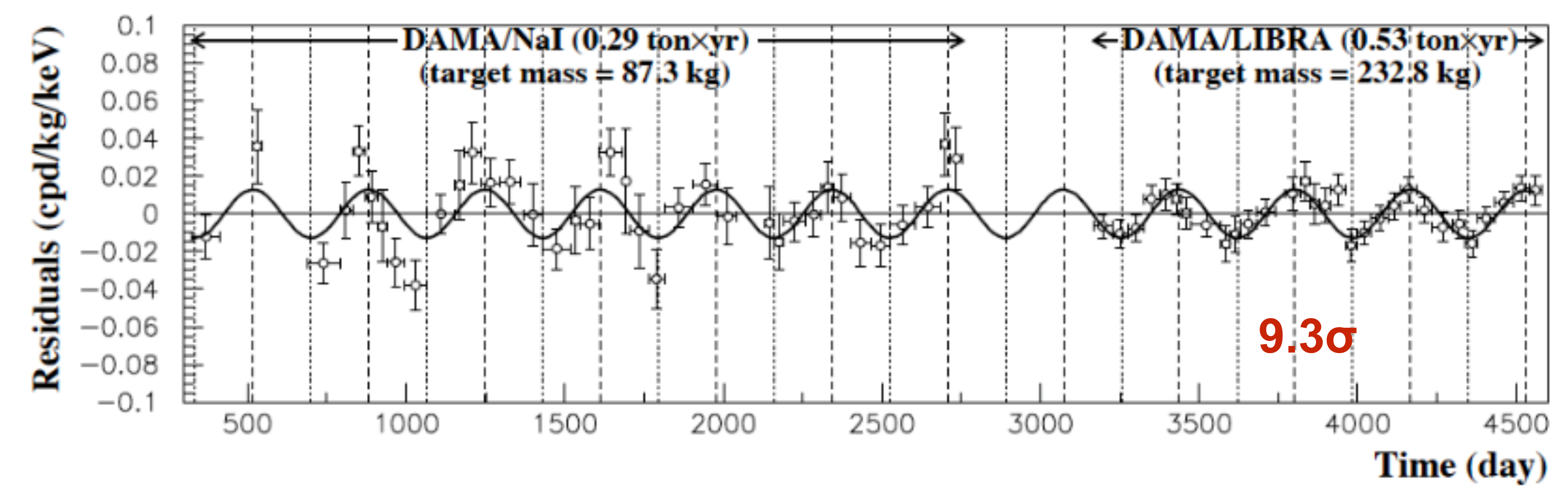
- NaI(Tl) and CsI(Tl) often used for DM searches
  - Na,Cs, I provide WIMP recoil
  - Thallium for scintillations
- High density and light yield
- Combine crystals for larger target masses
- At room temperature:
  - Only scintillation signal
  - No particle discrimination → annual modulation signal
  - "Simple" long term stable operations
  - But Na very hygroscopic

DAMA/LIBRA



Annual Modulation Experiments

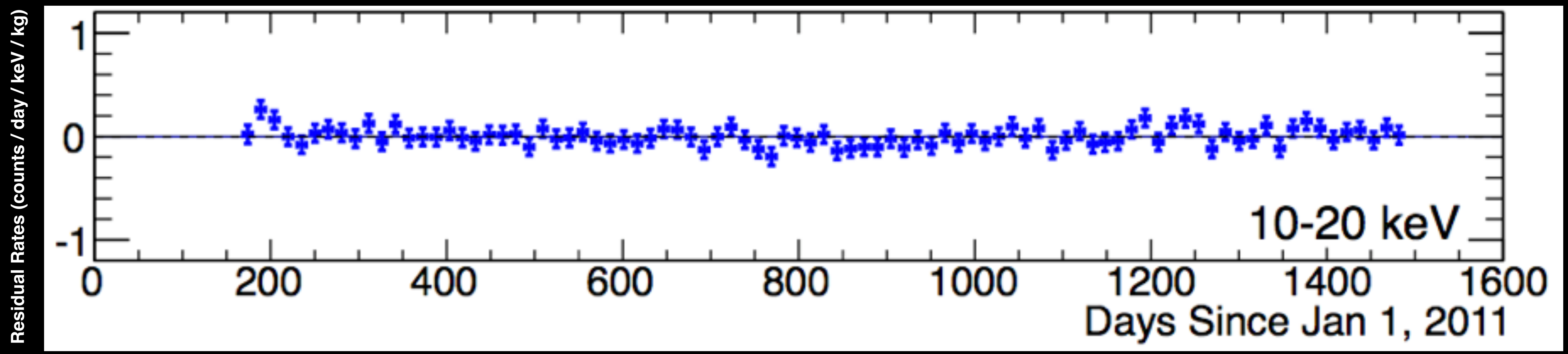
arXiv:1308.5109



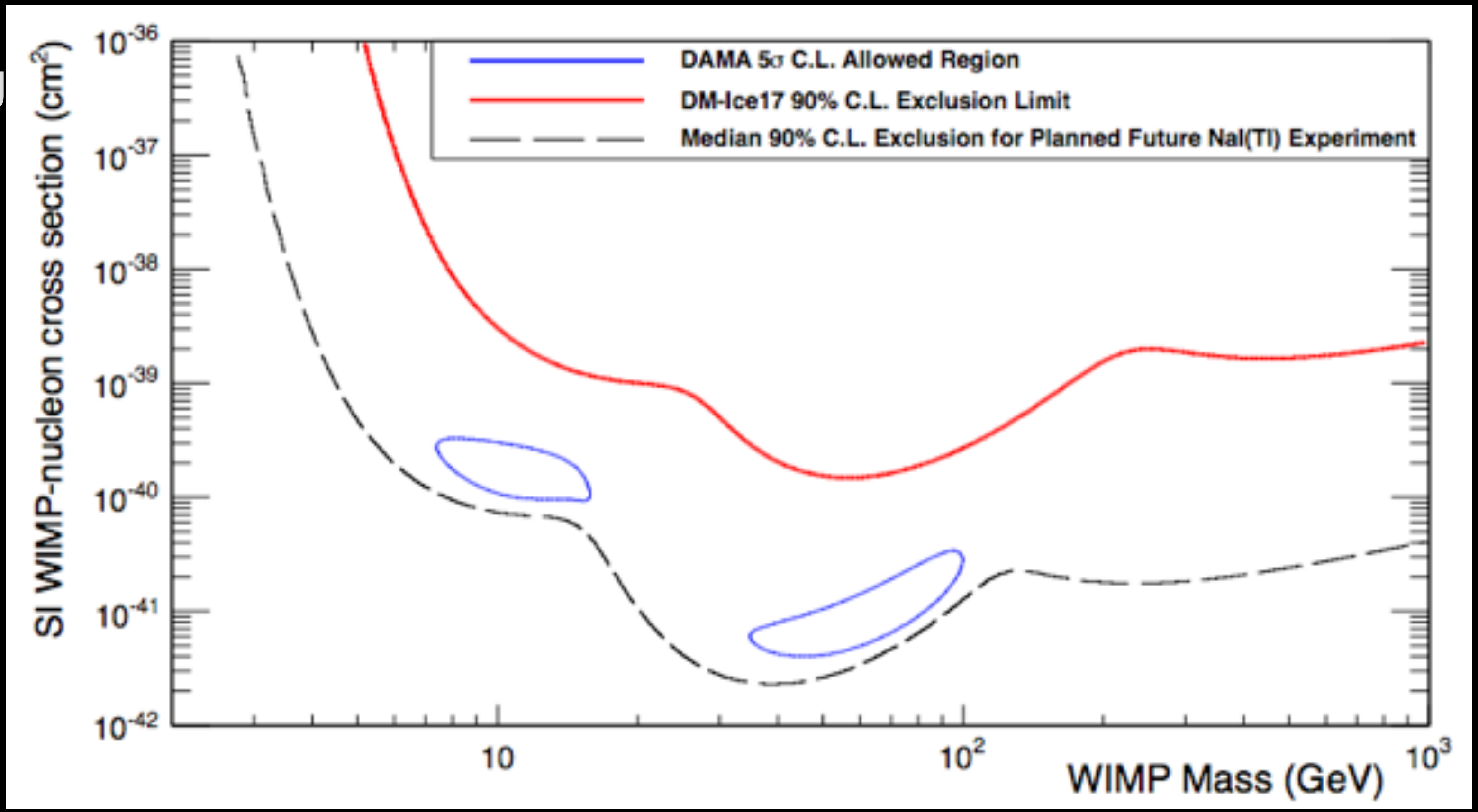
- DAMA/Libra at LNGS running for many years
- Ultra radio-pure NaI crystals
- Annual modulation of the background rate in the energy region (2 − 6) keV → 9.3σ significance!

Tests of annual modulation

arXiv:1602.05939



- Other exp. using NaI
  - ANAIS @ Canfranc running with 25 kg
  - SABRE @ LNGS, SUPL; both hemispheres
  - PICO-LON @ Japan, 250kg
  - DM-Ice @ south Pole with 17 kg NaI running since June 2011
  - KIMs @ Yangyang Lab in Korea, running!
  - DM-Ice+KIMs = Cosine, @YYL, run
- Challenge: radio-purity of the crystals and components!

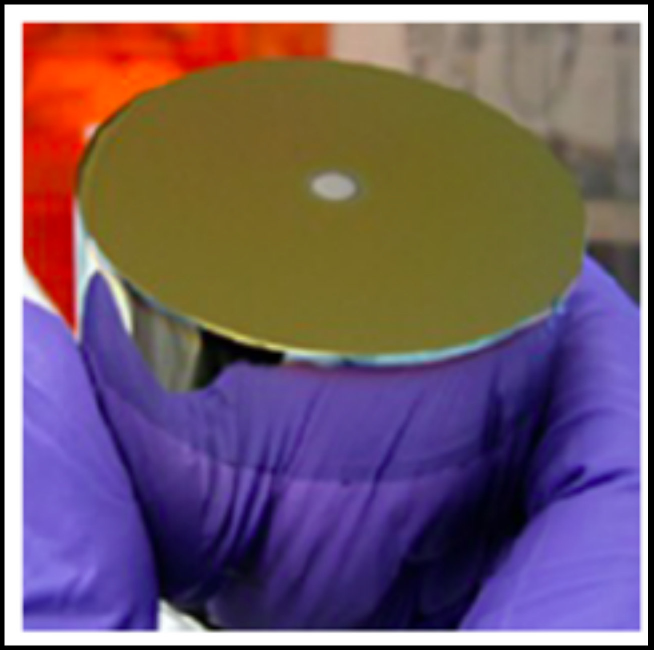


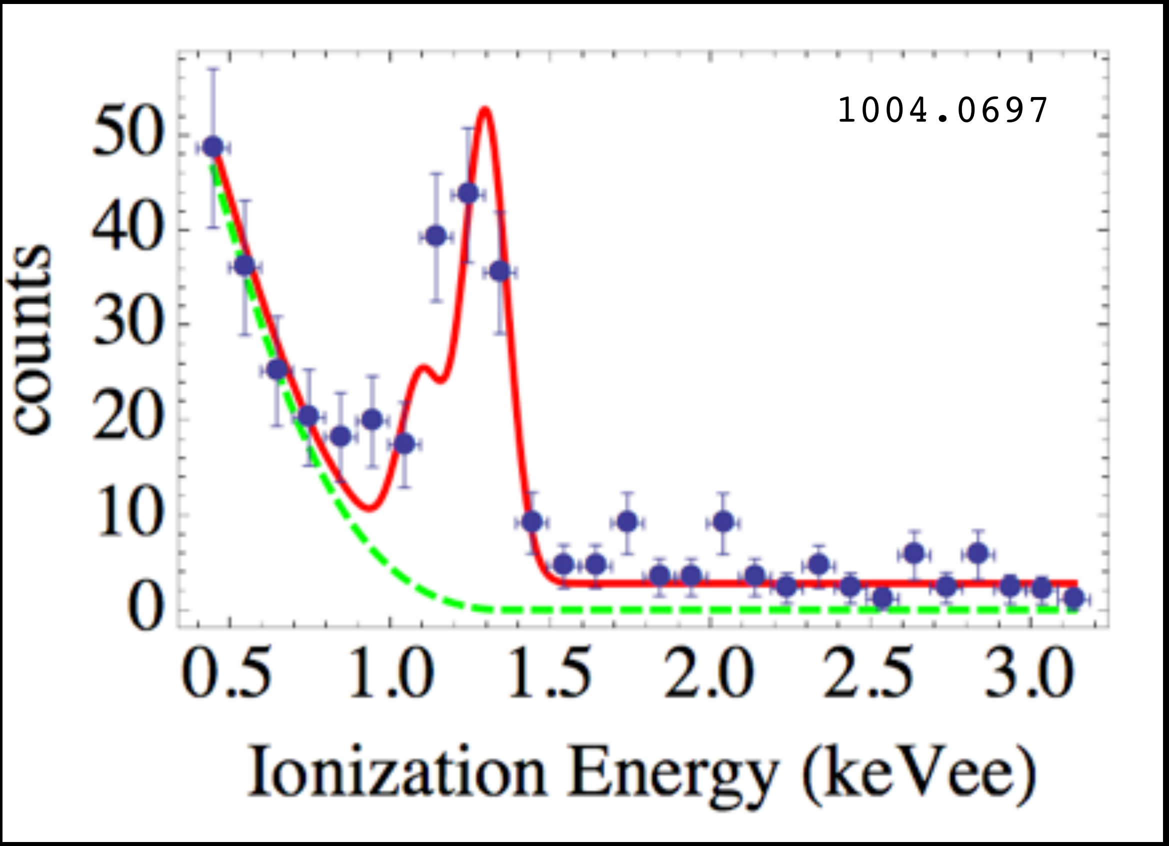
What might cause the DAMA signal?

- Muon-flux modulates due to the changing temperature of the atmosphere: muon-induced signal? Blum, arXiv:1110.0857 → wrong phase phase
- Neutrinos also modulate (due to the varying Sun-Earth distance) → Combination of muon-induced and neutrino flux? Davis, arXiv:1407.1052
- Varying rates of background neutrons? Ralston, arXiv: 1006.5255
- Experimental effect?

Ionizing (Ge) detectors (cold)

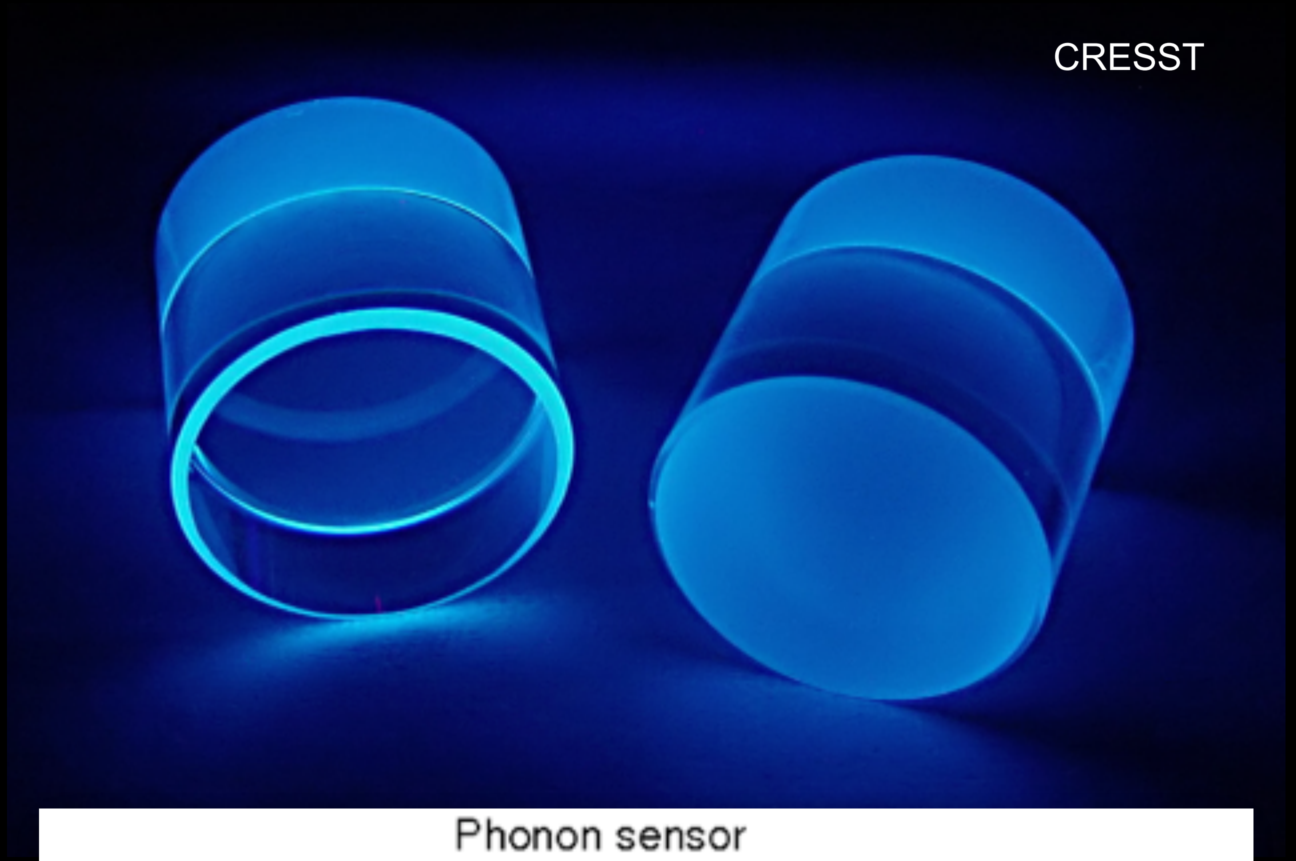
- Combine radio-purity with very low threshold (~0.5 keV)
- Cooled down to LN temperature, i.e. relatively easy, to reduce noise
- Very good energy resolution (0.15 % at 1.3 MeV) to understand backgrounds
- No separation between electronic/ nuclear recoil
- CoGeNT: Excess of events at low energies and annual modulation of the rate,
- Tests with Ge detectors: CDEX (China) and TEXONO (Taiwan) → no indication of dark matter

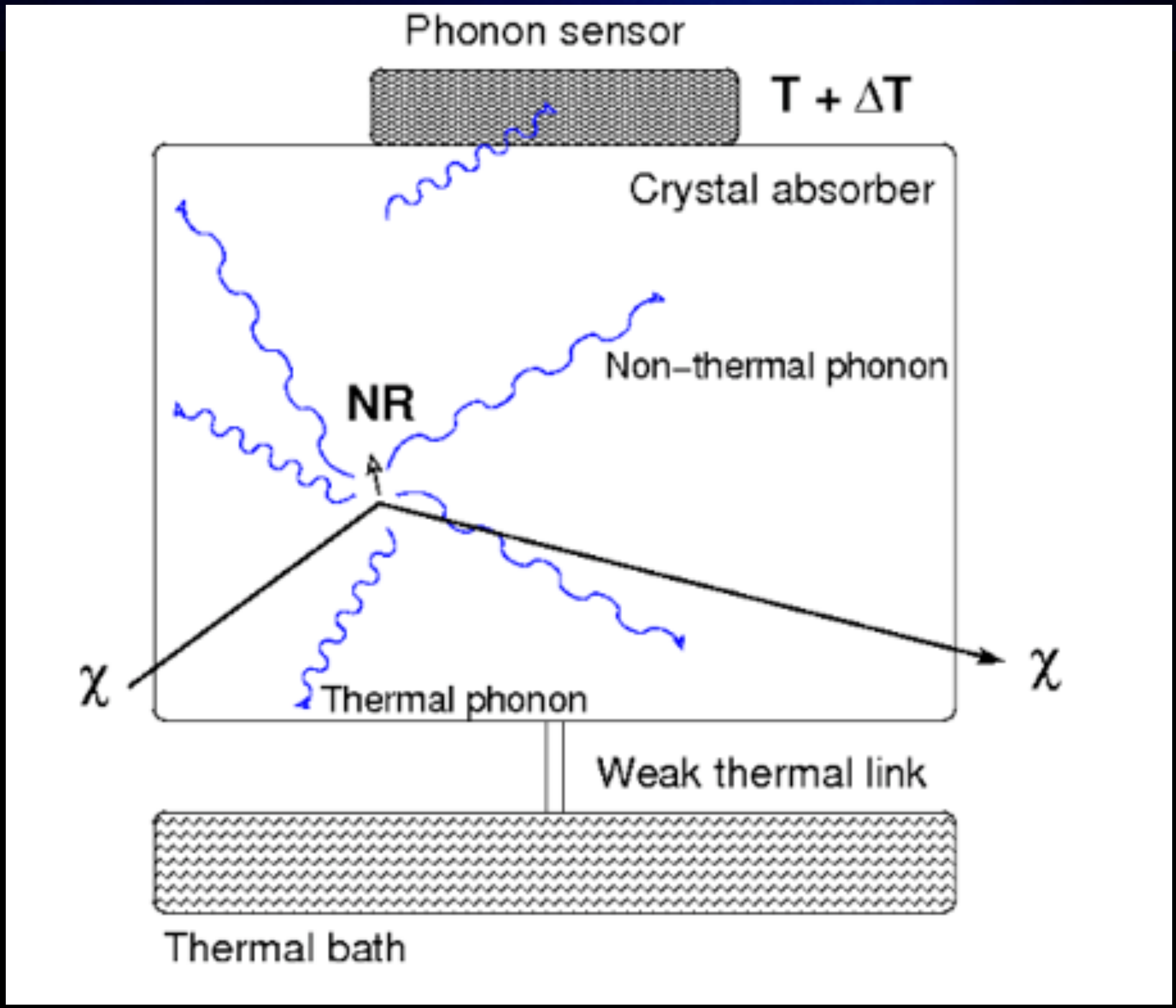




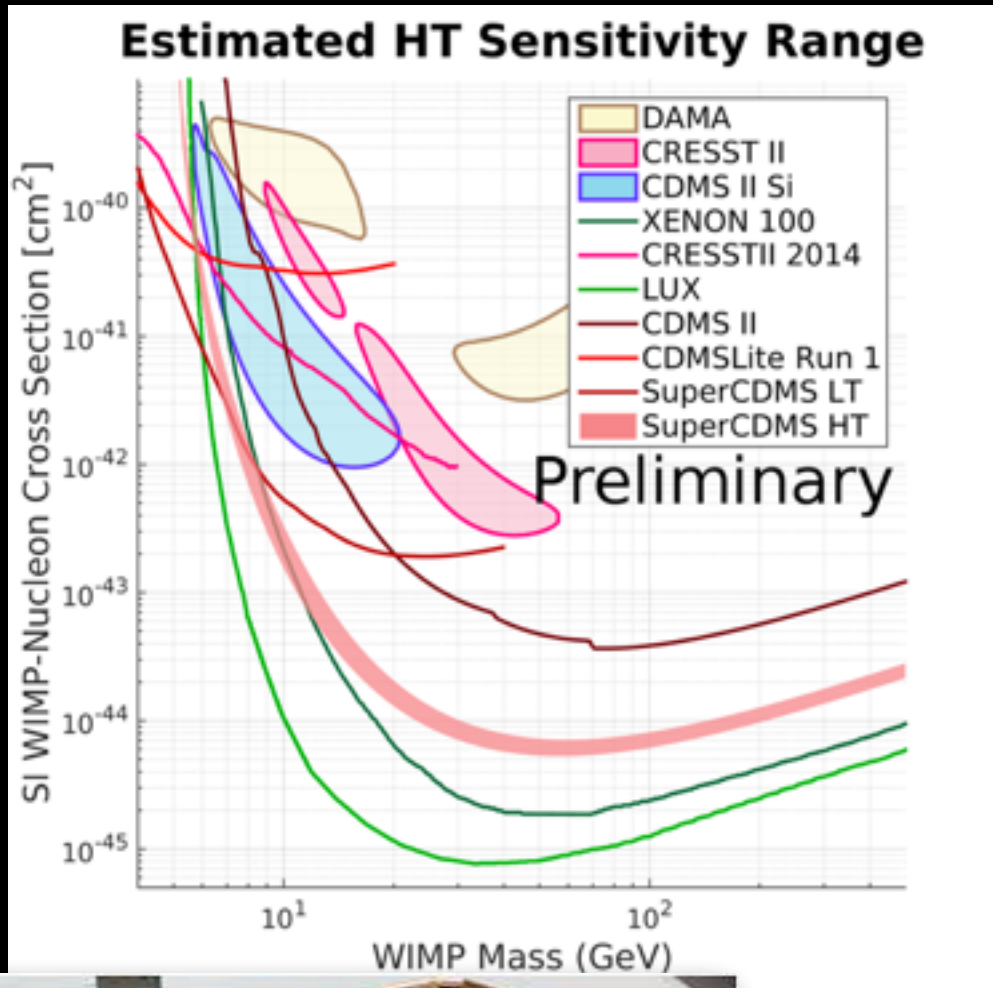
Cryogenic Detectors

- Thermal and athermal phonons can be used to obtain energy and location
- Produce more phonons by applying drift field
- Recording in addition to phonon signal also scintillation light for recoil discr.
- Limited crystal size (like Ge)
- Crystals at (10-100) mK
- Temp. rise: $\Delta T \sim O(20\mu K)$ for few keV recoil
- Measurements of ΔT:
  - Neutron transmutation-doped Ge sensors (NTD)
  - Transition edge sensors (TES)





Cryogenic Detectors



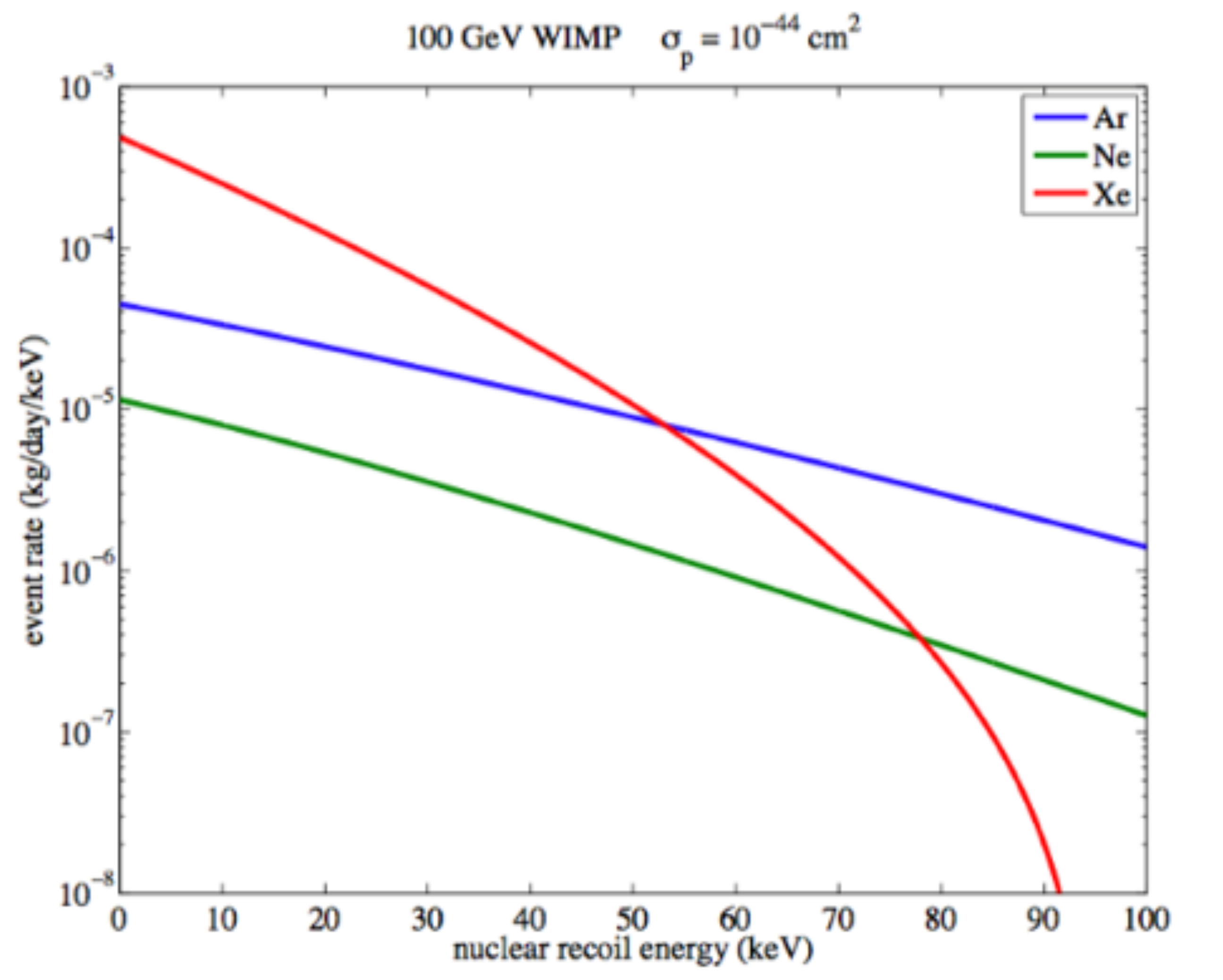
- Cryogenic detectors offer best sensitivities at low WIMP masses
- SuperCDMS
  - Germanium bolometers at Soudan
  - No significant signal with respect to the expected background
- CRESST
  - Scintillating CaWO4 crystals in LNGS
  - 2014: low-threshold analysis with an upgraded detector TUM-40
  - Previous signal indication rejected for most WIMP masses
  - CRESST-III exp. 2017
- Others: EDELWEISS, ROSEBUD, EURECA

Detectors

- Liquid -

Noble liquid gases

- Large masses and homogeneous targets (LXe, LAr, (LNe))
- Two detector concepts: single & double phase
- 3D position reconstruction → fiducial volme
- Transparent to their own scintillation light
- Distinguish ER and NR by using pulse-shape discrimination or charge-to-light ratio



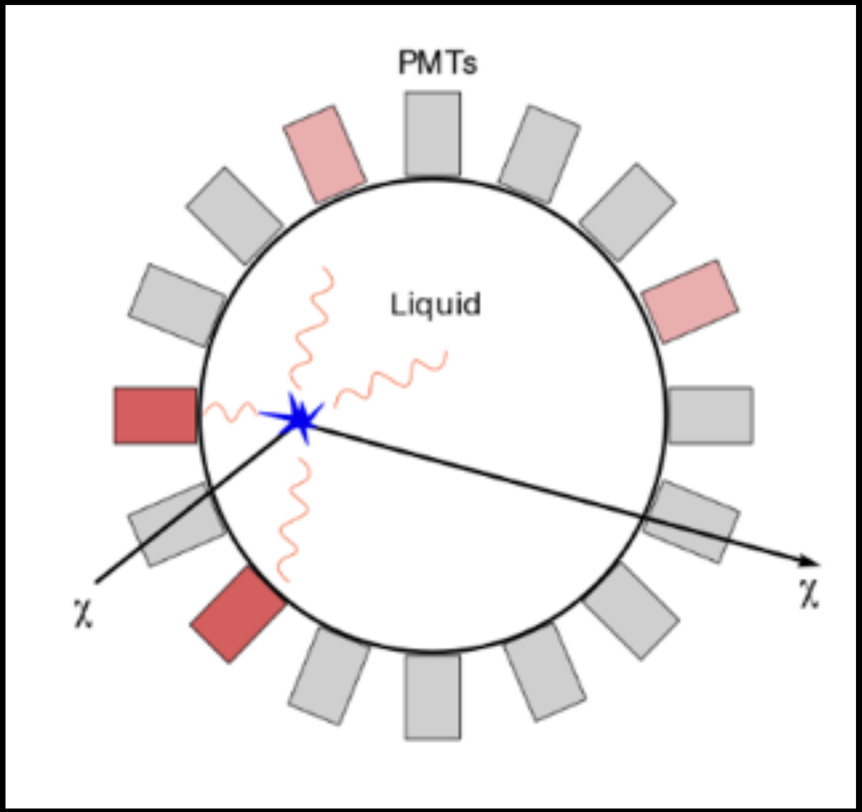
	LNe	LAr	LXe
Z (A)	10 (20)	18 (40)	54 (131)
Density [g/cm^3]	1.2	1.4	3.0
Scintillation λ	78 nm	125 nm	178 nm
BP [K] at 1 atm	27	87	165
Ioniz. [e^-/keV]*	46	42	64
Scint. [γ/keV]*	7	40	46

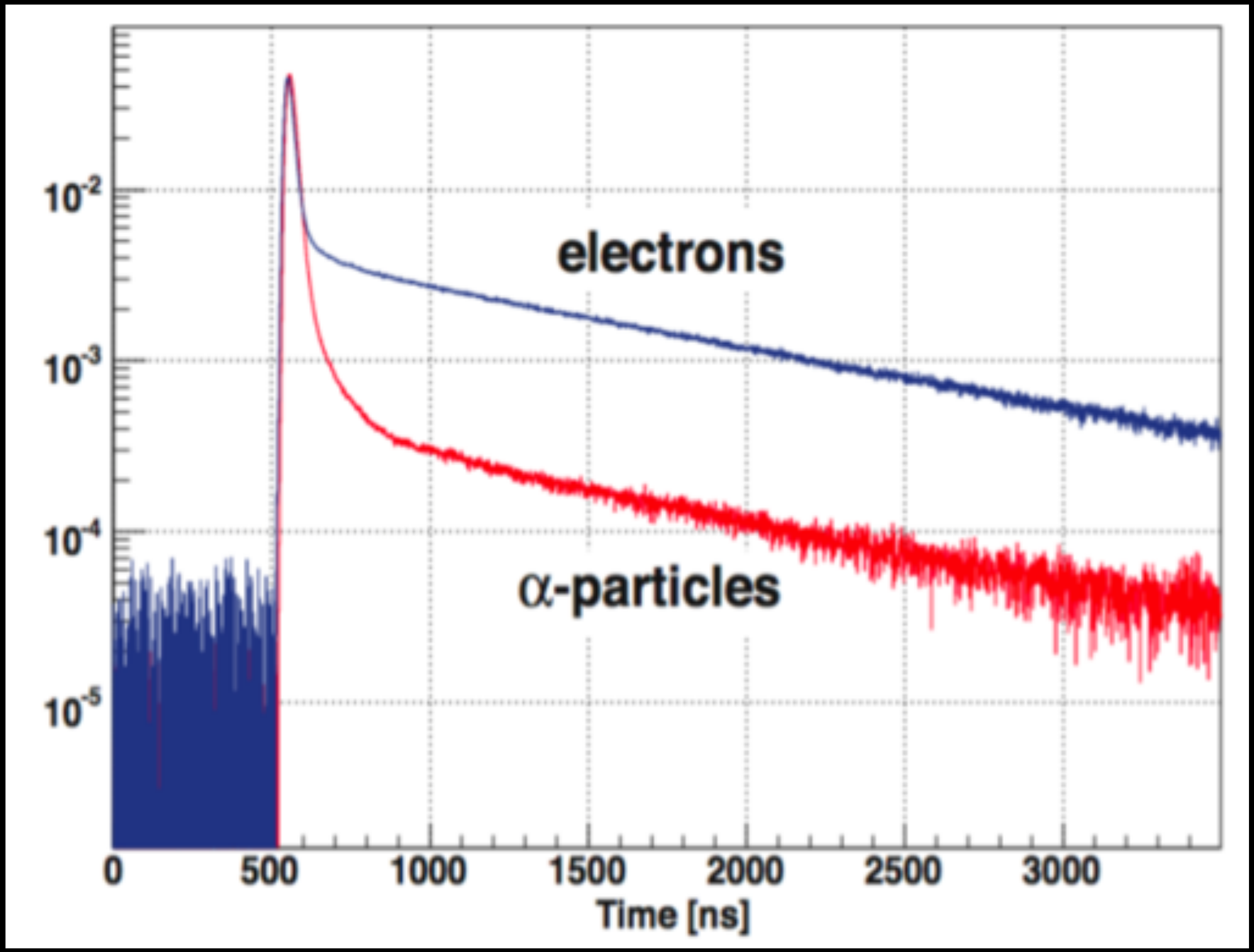
* for electronic recoils

Single phase (liquid) detectors

arXiv:0904.2930

- 4π photosensor coverage → high light yield
- Use distribution and timing of the photons for the position of the interaction: ~O(cm)
- Pulse shape discrimination (PSD) used as main discriminator

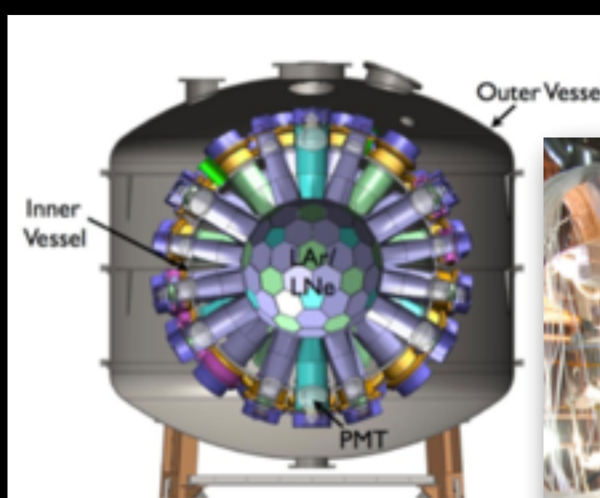




Scintillation decay constants of Ar by ArDM

- Very different singlet and triplet lifetimes in argon & neon
- Discrimination DEAP-I obtained 10^8 discrimination in LAr above 25 keVee (50% acceptance)
- PSD less powerful in LXe: similar decay constants
- Detectors: DEAP, CLEAN, XMAss

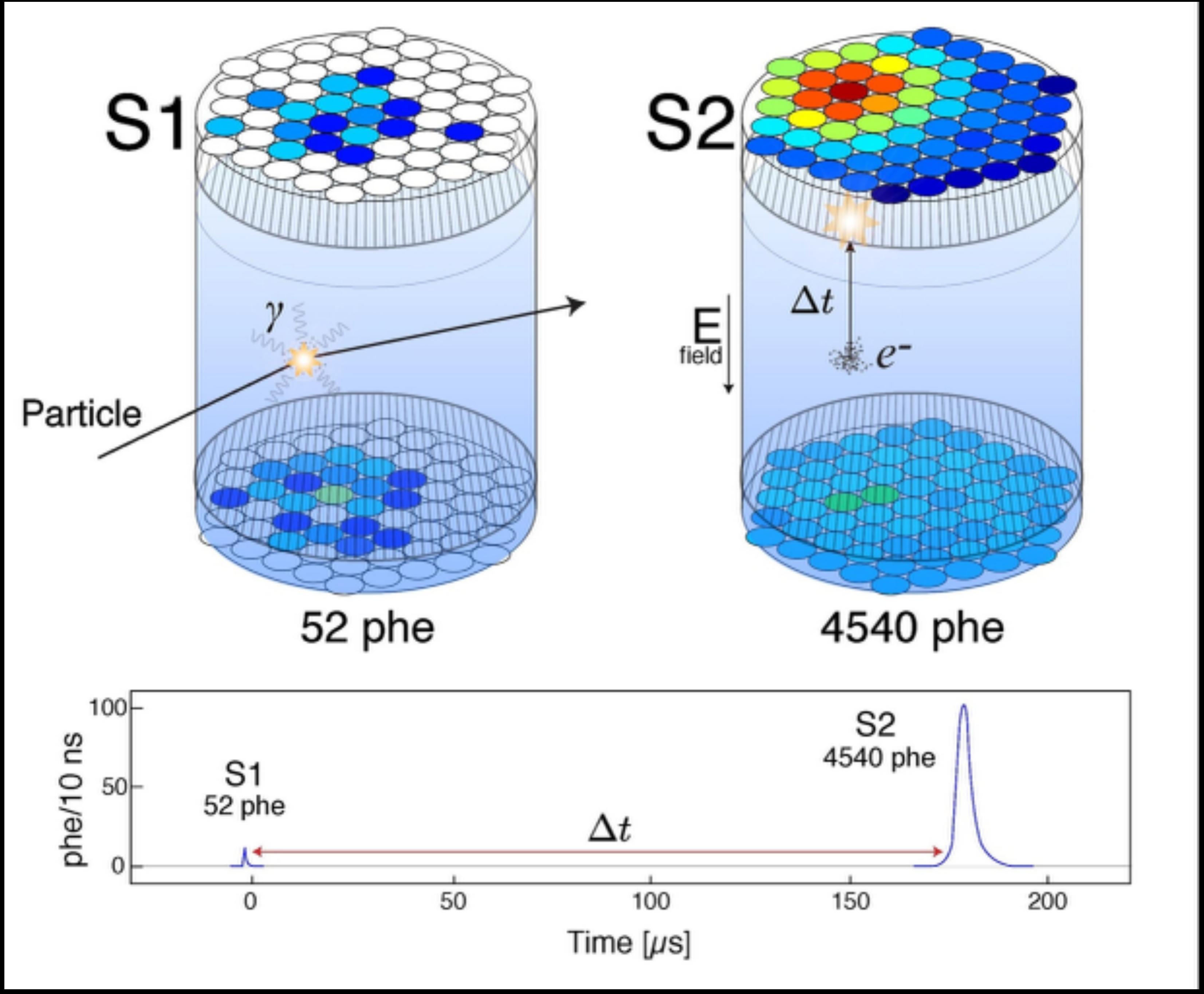
Single Phase Detectors



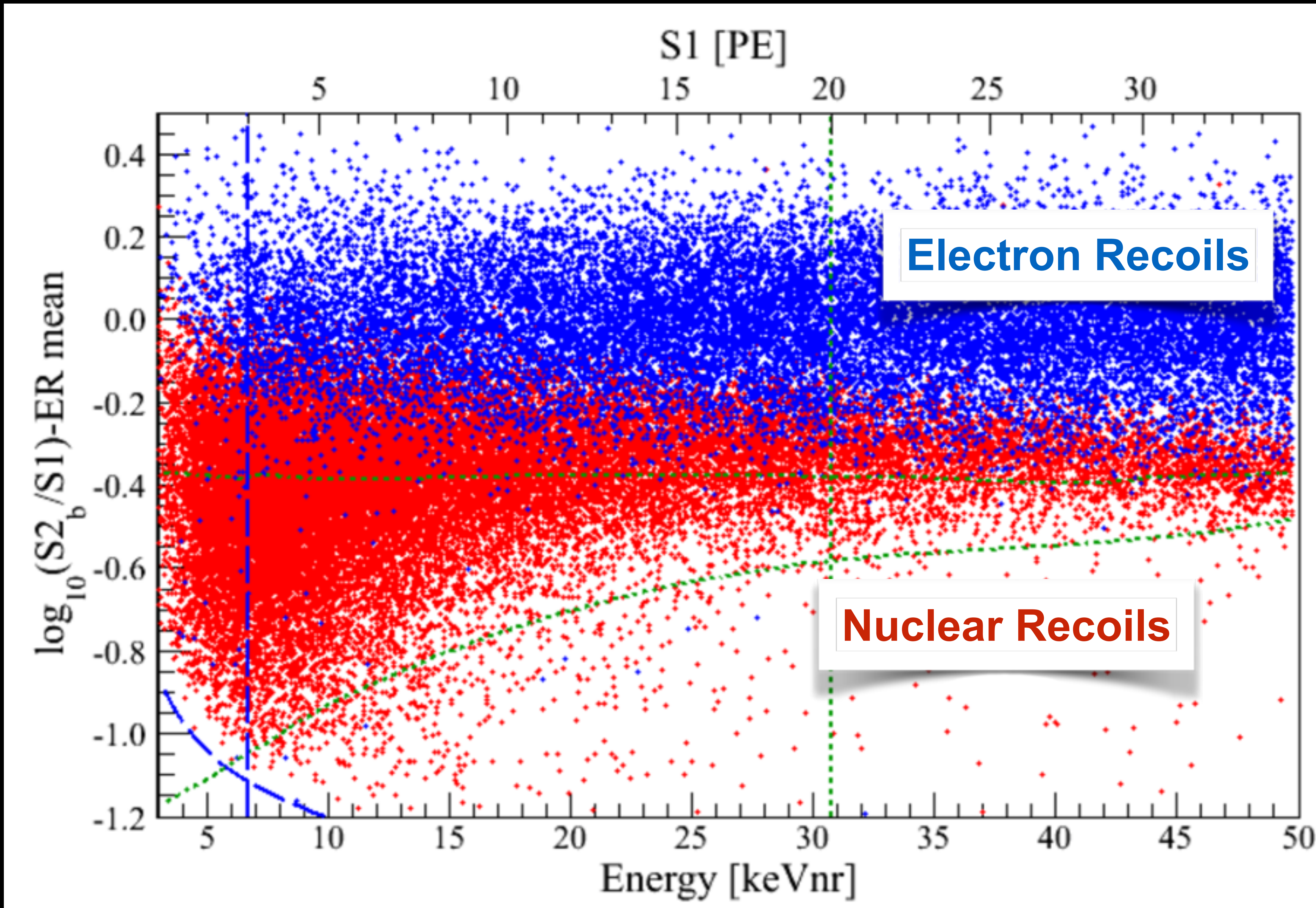
- DEAP (Dark matter Experiment with Argon and Pulse shape discrimination)
  - 3 600 kg LAr
  - Results imminent
  - Heroic surface cleaning
- CLEAN (Cryogenic Low Energy Astrophysics with Noble gases)
  - 150 kg FV with LAr/LNe MiniCLEAN cool down just started
  - DEAP & CLEAN at SNOlab, Canada
- XMASS
  - 800 kg FV LXe (at Kamioka, Japan)
  - Ultra-low background required + Self-shielding
  - High light yield Detector refurbished, resumed data-taking in Nov. 2013,
  - Currently designing XMASS-1.5

Two Phase TPCs

- Detect two signals
  - Prompt scintillation light (S1)
  - Prop. charge signal amplified in gas (S2)
- Ratio allows to discriminate particle
- Depths from drift time between S1/S2 and light pattern in (x, y): O(mm) resolution



Double phase LAr & LXe experiments



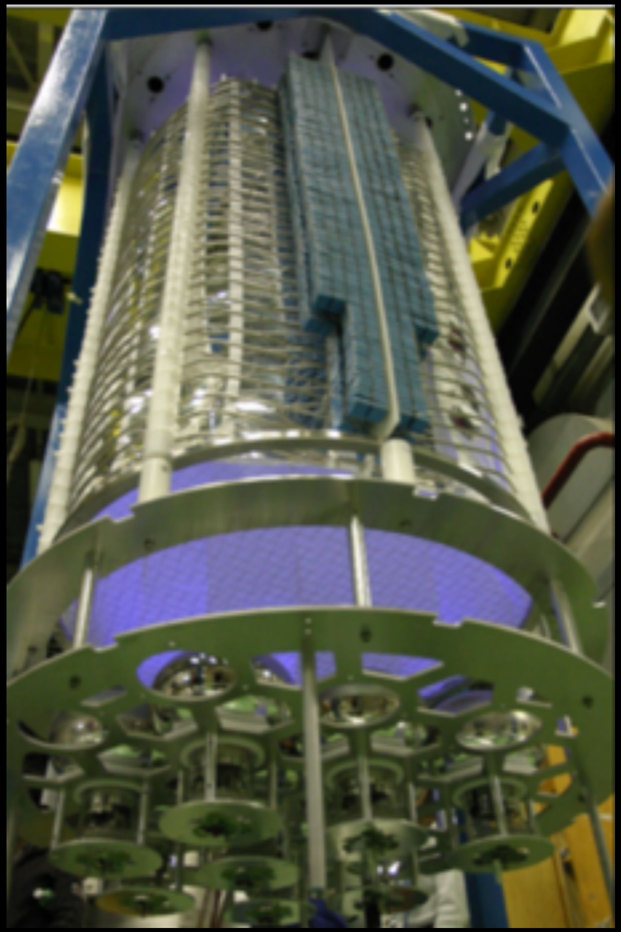
LAr double-phase TPCs

DarkSide-50:

- Detector inside Borexino counting facility, LNGS
- 50 kg depleted argon from underground sources, > 100 reduction in ^{39}Ar level
- Running since 2015, 3 yr. run ongoing
- DarksSide-20T in preparatin, using also SiPMs

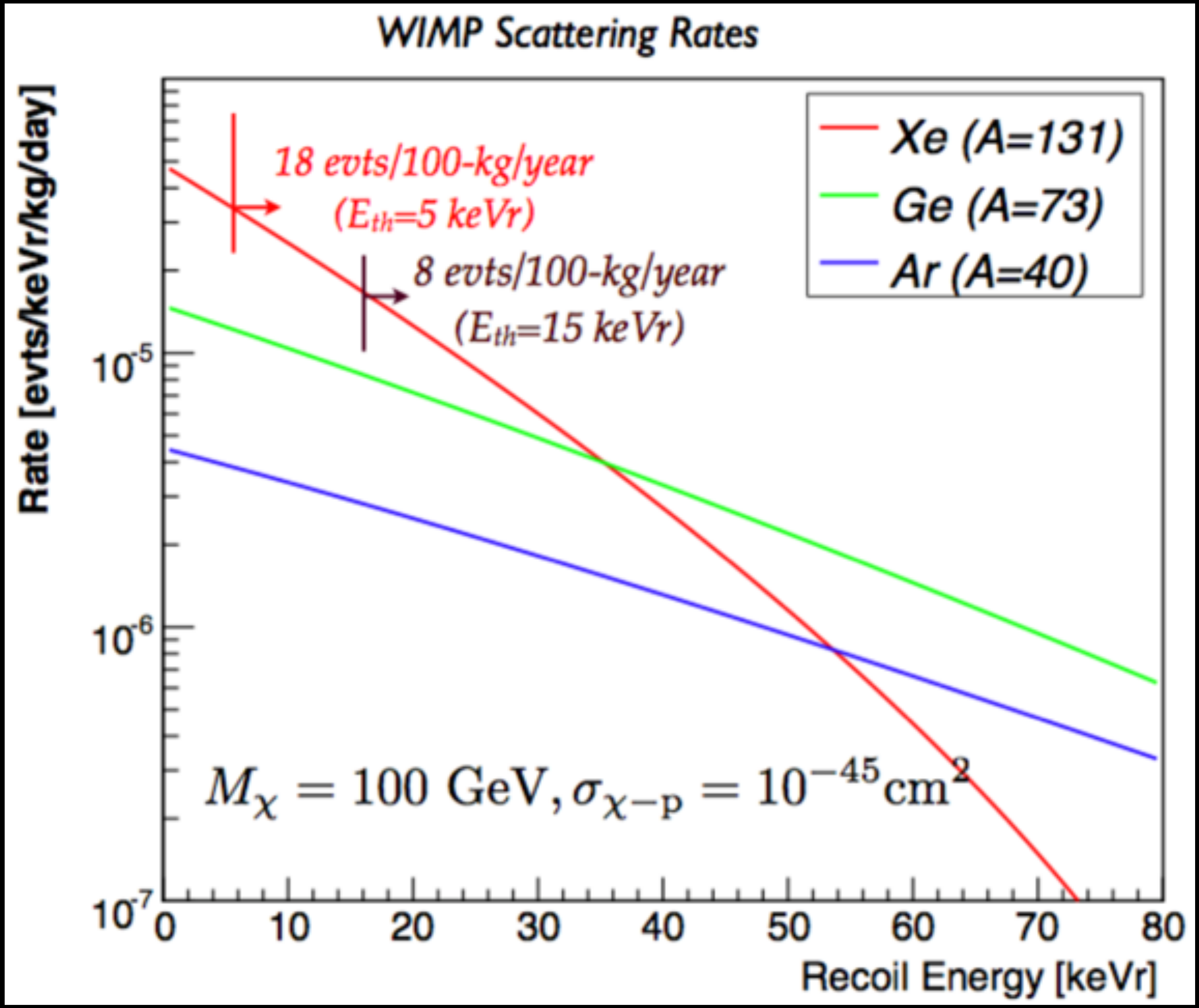
ArDM:

- 1T liquid argon
- Technology demonstrator
- A year long operation of 2 tons of LAr in single phase
- Installed at Canfranc (Spain)
- Run 2: plan to install TPC instrumented with SiPMs

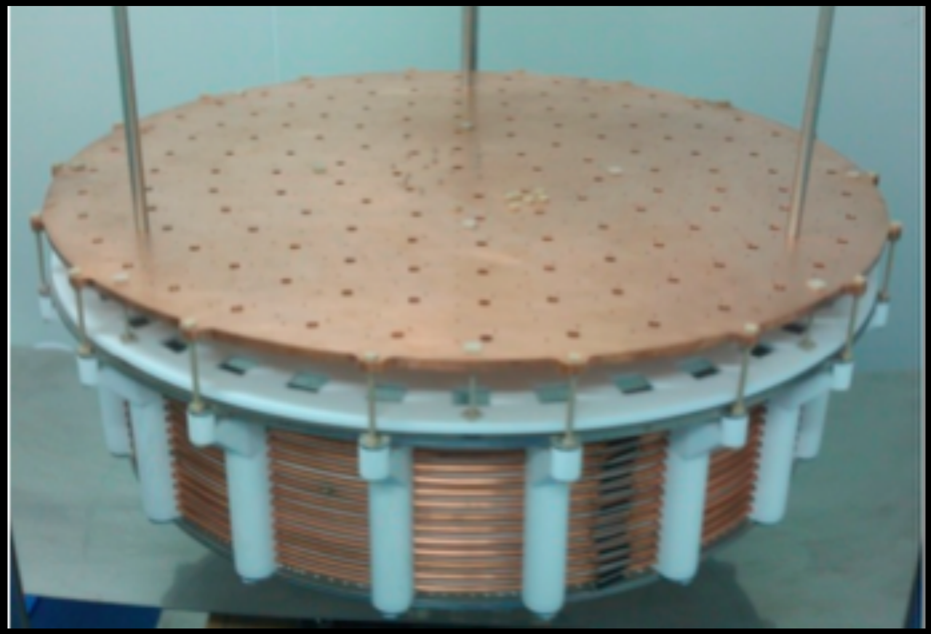


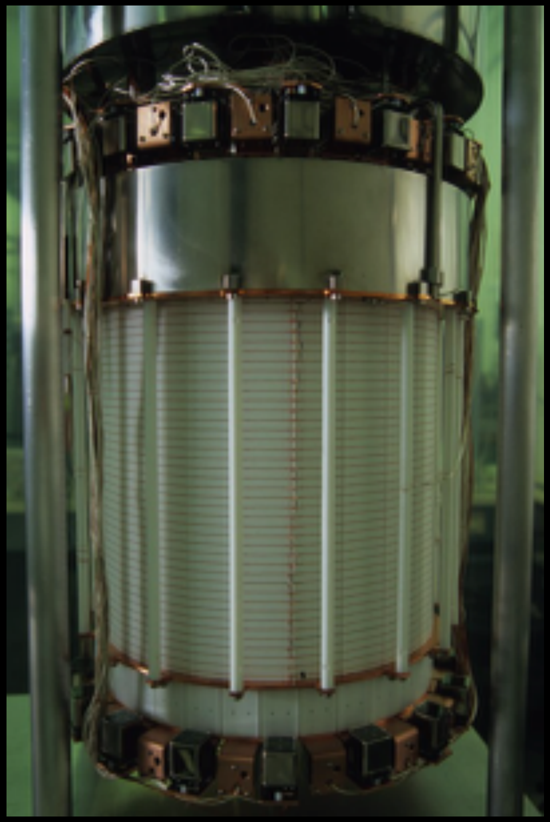
Xenon targets

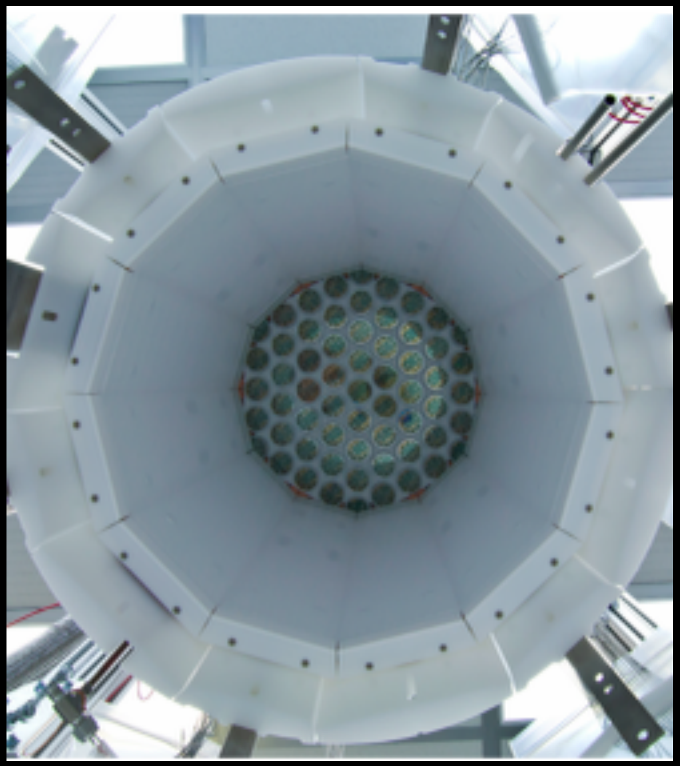
- Large homogeneous targets (kg-tons)
- Self-shielding
  → High stopping power
- 178 nm UV photons
  → no wavelength-shifter
- High atomic mass: ~131
  → spin-indep. interactions
- 129Xe and 131Xe
  → spin-dep. interactions



LXe double-phase TPCs







Panda-X:

- Stage I: 54 kg fiducial mass (450 kg total)
- Stage II: 300 kg fiducial mass
- Recent full dataset

arXiv:1607.07400

XENON 1T:

- 1T fiducial mass (3.3 total)
- Running since 2016
- Currently most sensitive dataset

arXiv:1705.06655

LUX:

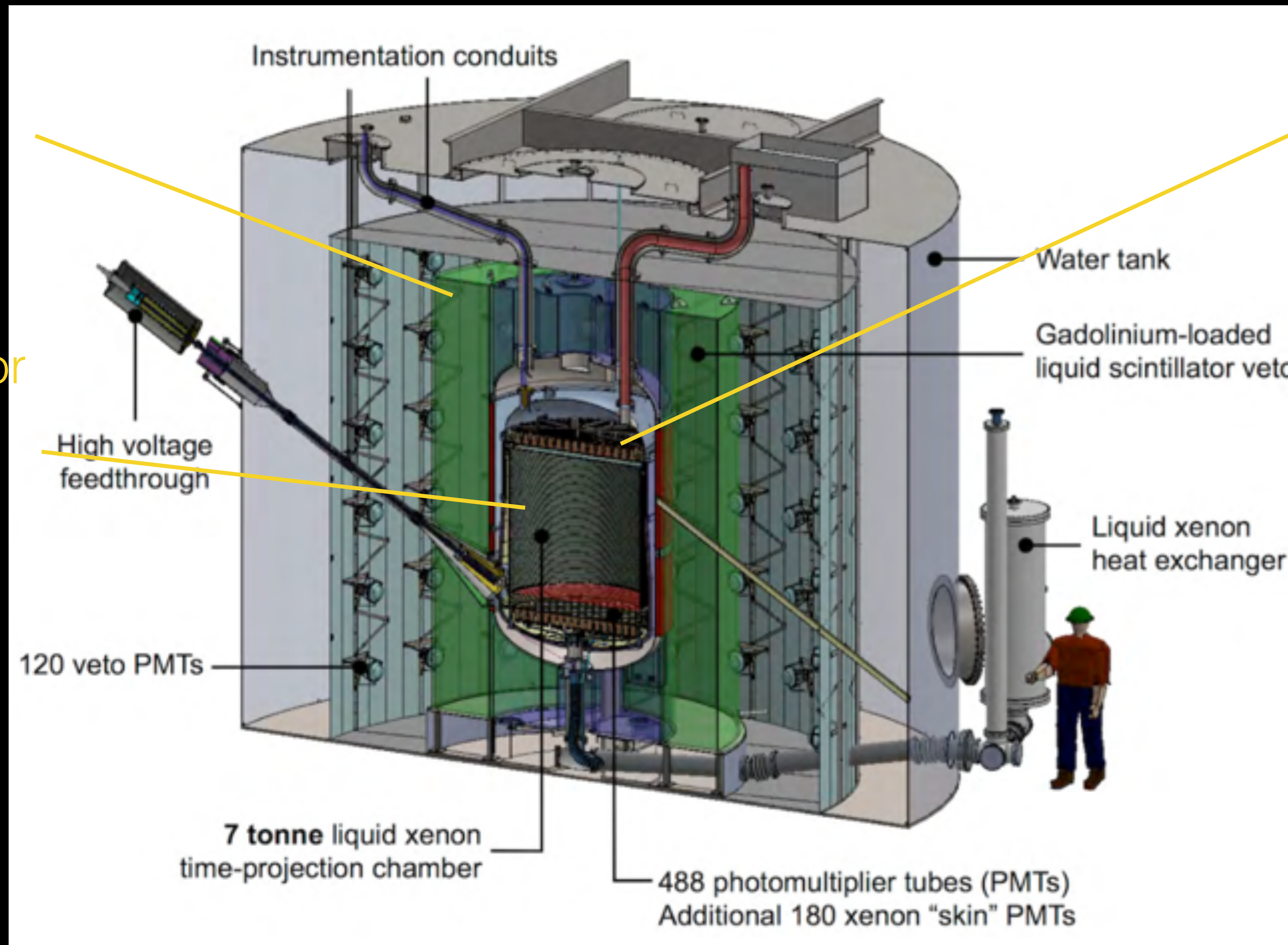
- 118 kg fiducial mass
- First results in 2013,
- Just finished data taking
- Under construction: LZ (Lux-Zeplin)
- 7T Fiducial Mass

arXiv:1608.07648

LZ experiment

ultra-pure water shield

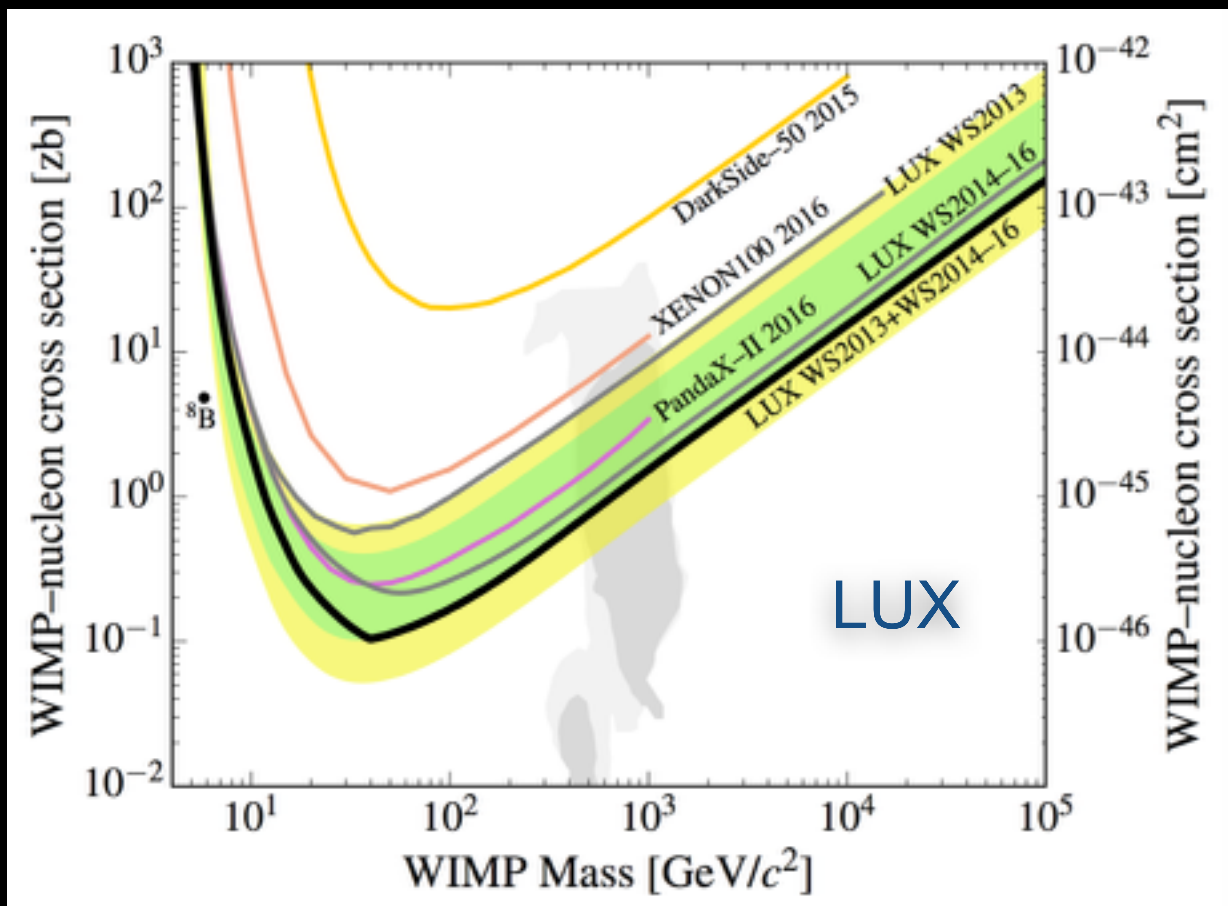
20t lq. scintillator outer detector

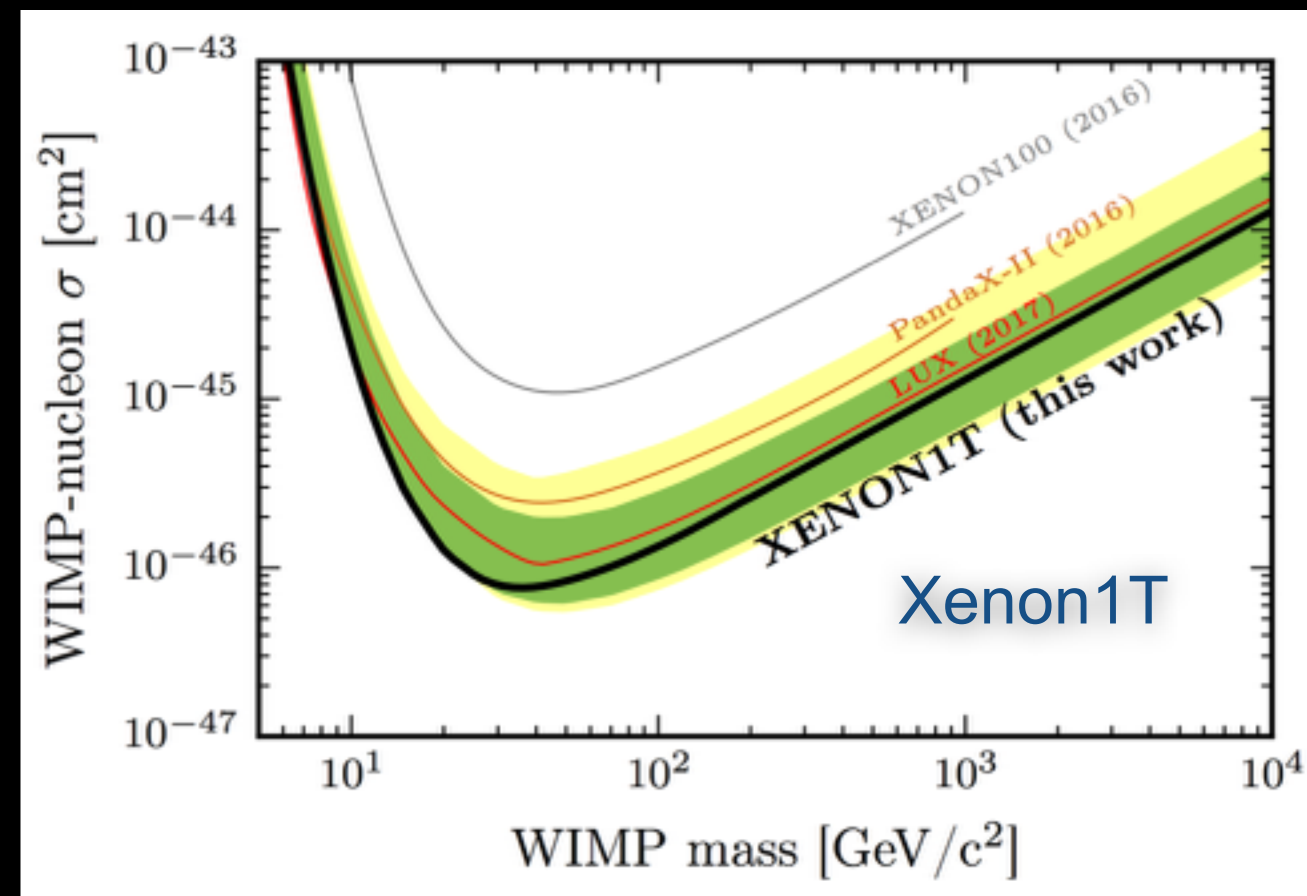


7t LXe TPC
494 PMTs
131 'skin' PMTs

- LZ is 7t LXe target mass surrounded by 20t liquid scintillator outer detector
- Operations start in 2019
- Outer detector allows doubling of sensitive volume

Xe Detector Results



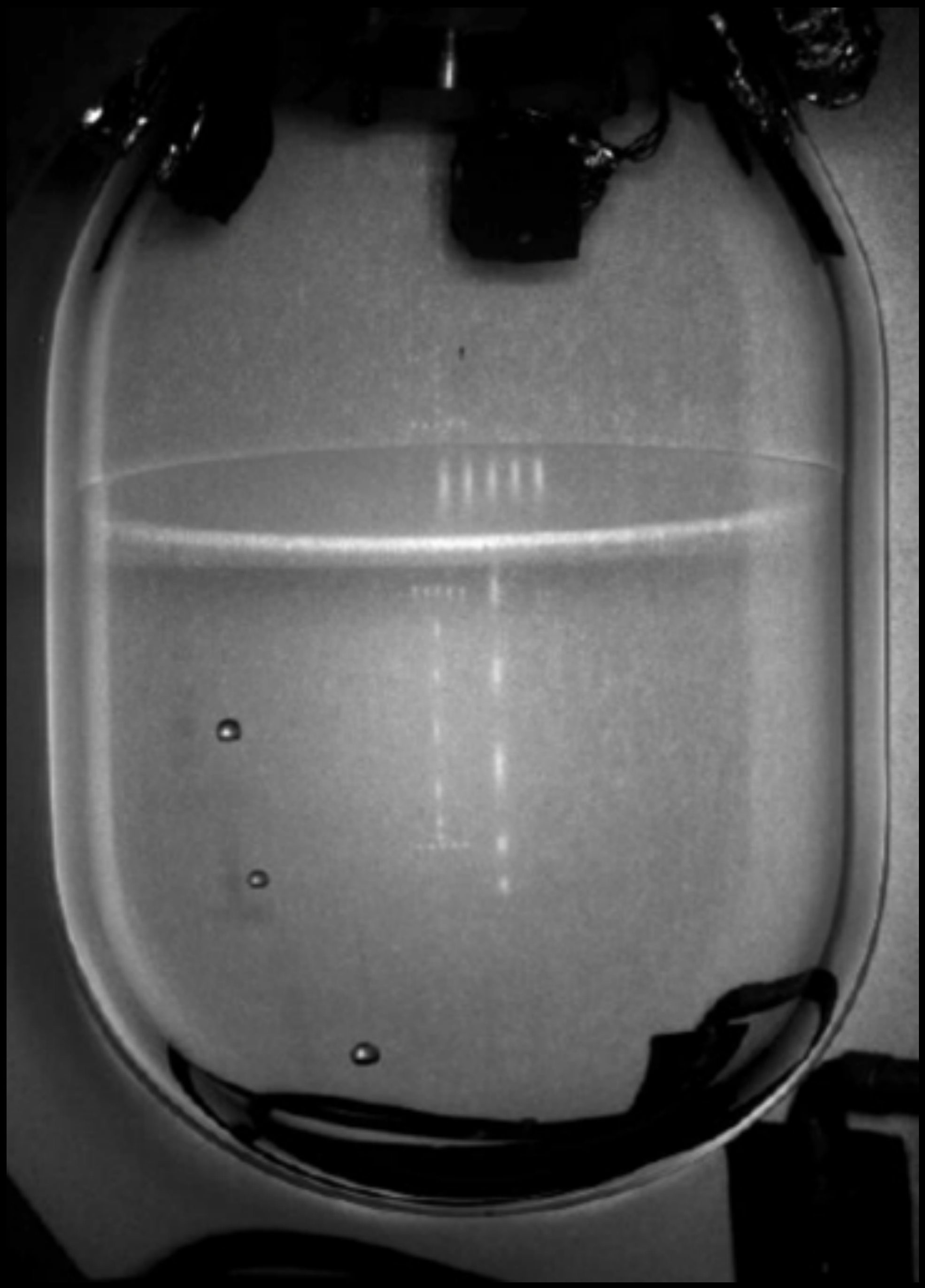


- Several recent results with comparable sensitivity
- Many future developments ongoing

Other Detectors

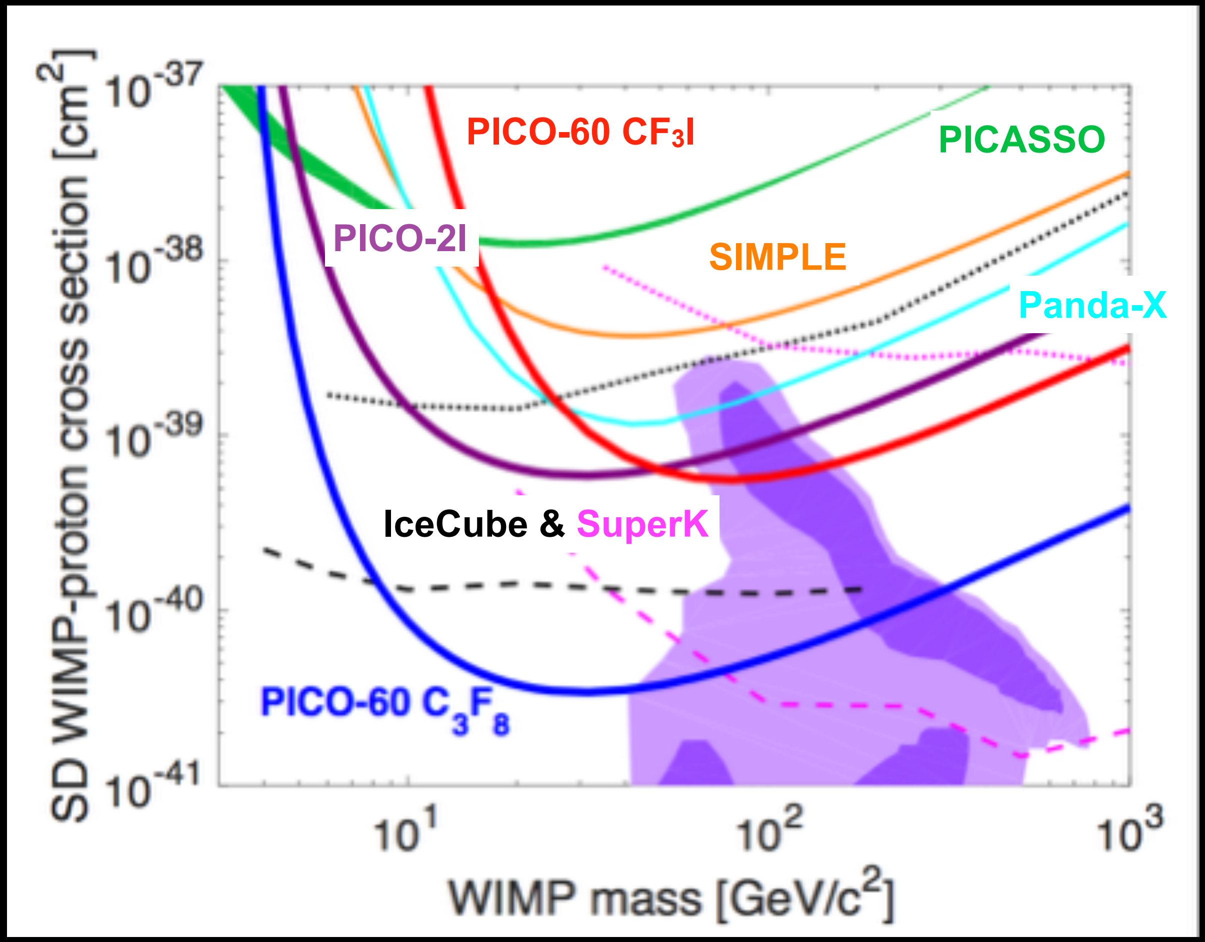
Superheated fluid detectors

arXiv:1702.07666



COUPP/PICO

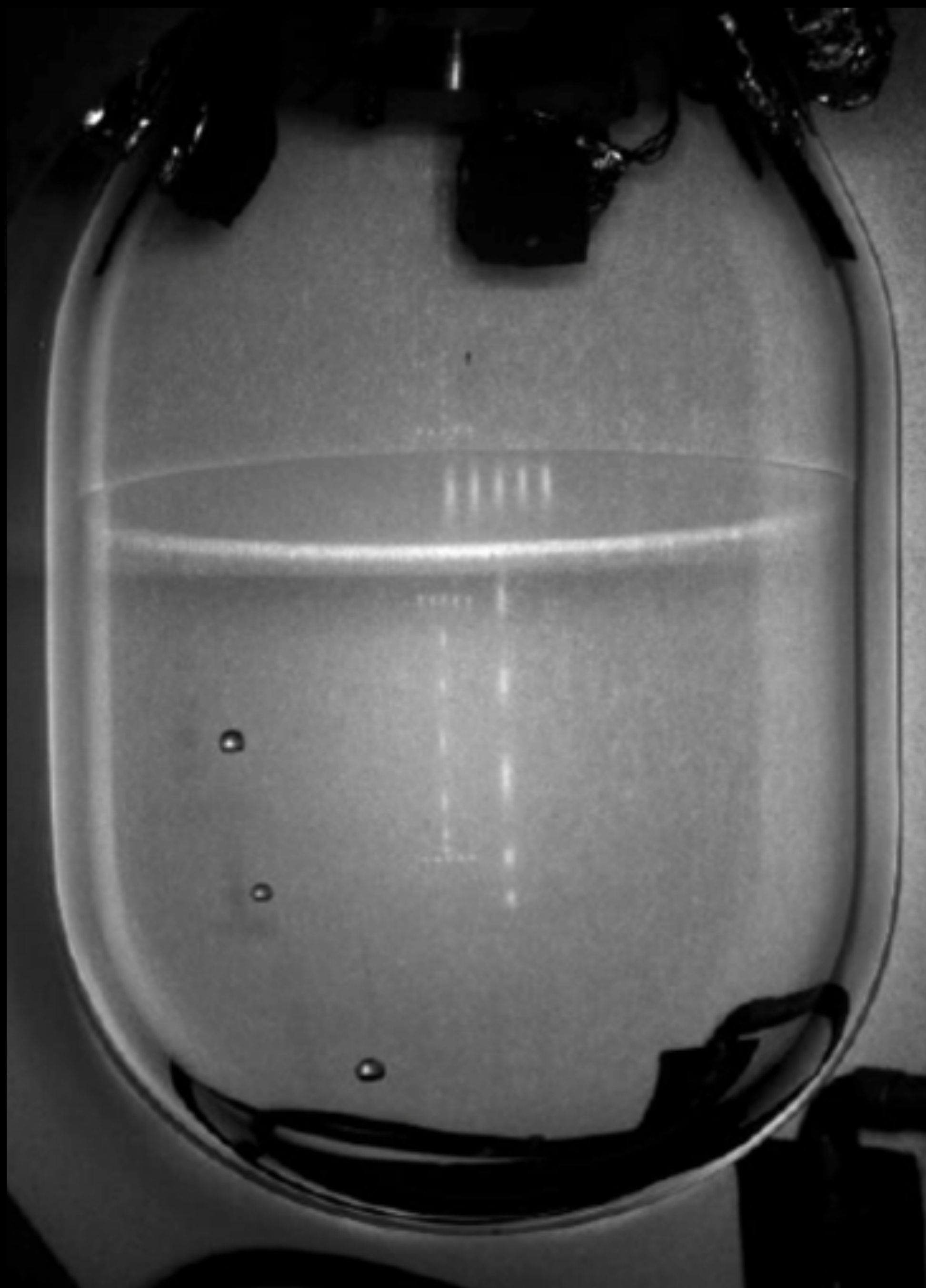
- Bubble chamber filled with superheated fluid (C_3F_8) in meta-stable state
- Energy depositions → Bubble expands → detected via cameras % piezo-acoustic sensors
  - https://www.youtube.com/watch?v=Y4kPhBsu4L8
- Also: COUPP, Picasso, Simple



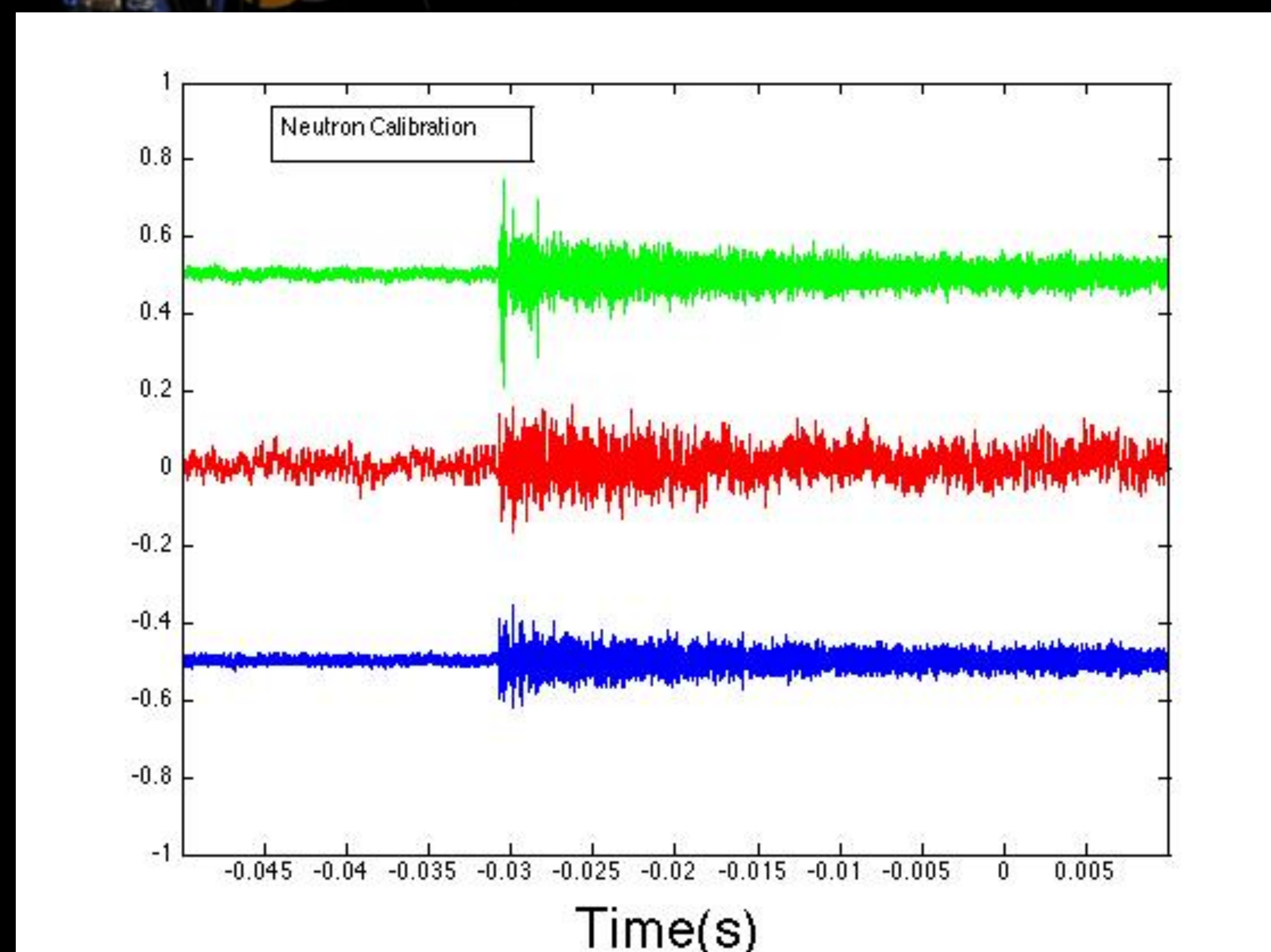
PICO: Best proton-coupling SD sensitivity

This is what DM would sound like

Hello darkness my old friend,
I've come to talk with you again.
Because a vision softly creeping,
left its seeds while I was sleeping.

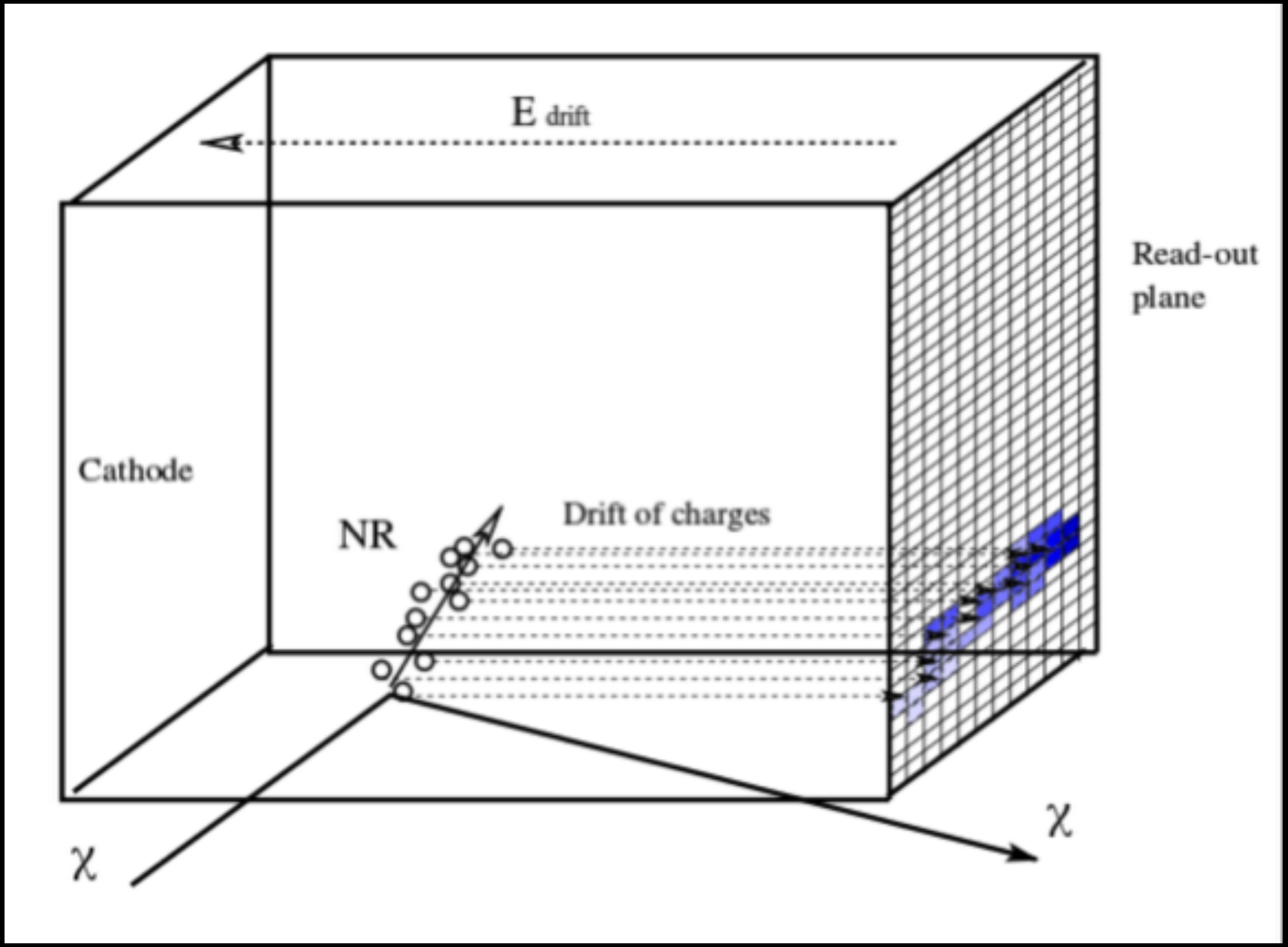


COUPP/PICO



Directional Searches

- Solids or liquids: O(keV) recoil is short (<100 nm)
- Low pressure-gas ($p < 100$ Torr): The range is ~O(10) mm
- Most projects use low pressure TPCs with CF_4 (^{19}F) as target

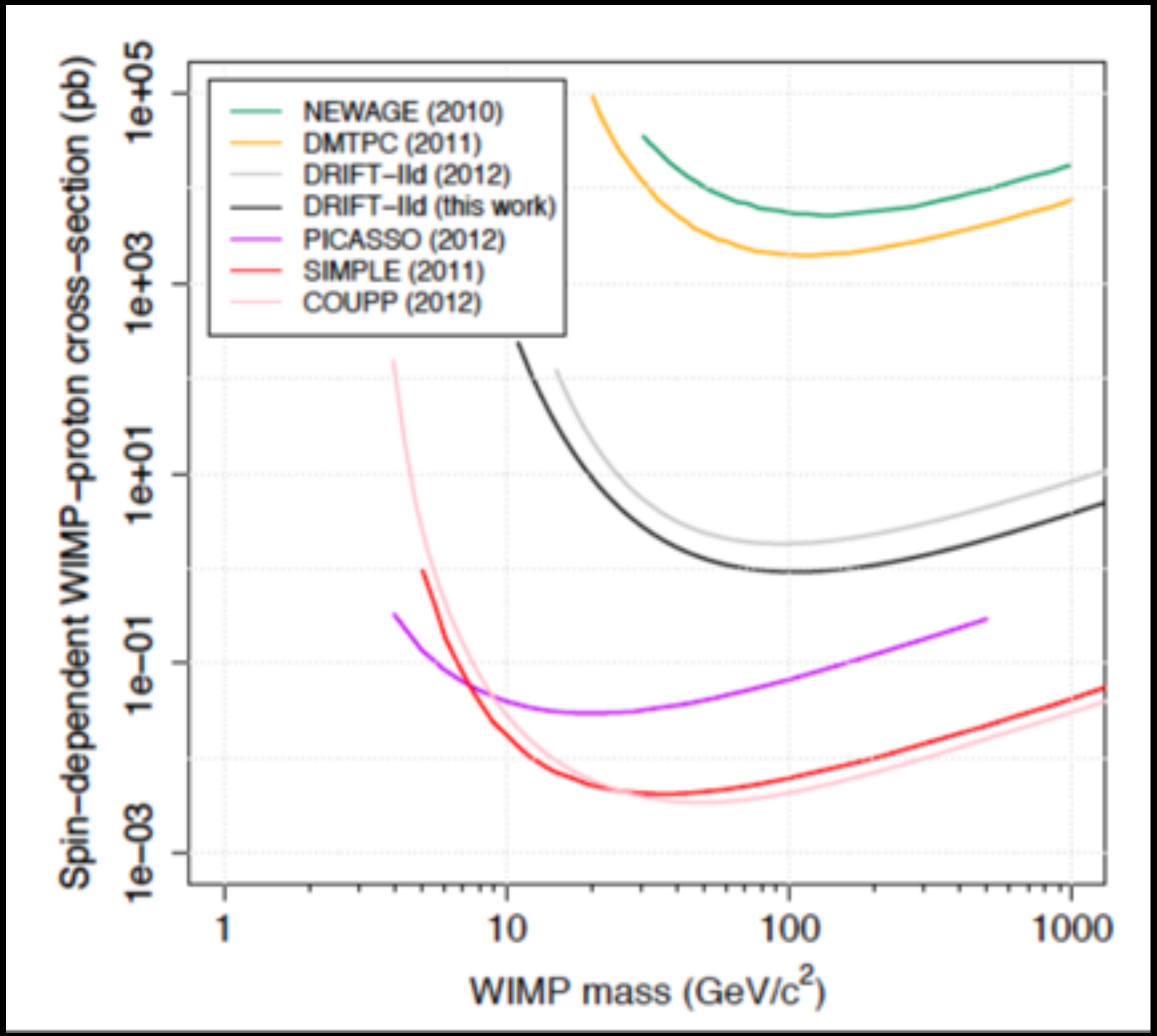


Directional Searches

arXiv:1410.7821 (2014)

- Key parameter angular resolution: Tracking ionisation detectors → Not competitive with liquids or solids bc. of mass but important confirmation in case of a WIMP detection
- Might be best way to overcome 'neutrino floor' but long way to go

- Other experiments: DMTPC, NewAge, Emulsion detectors



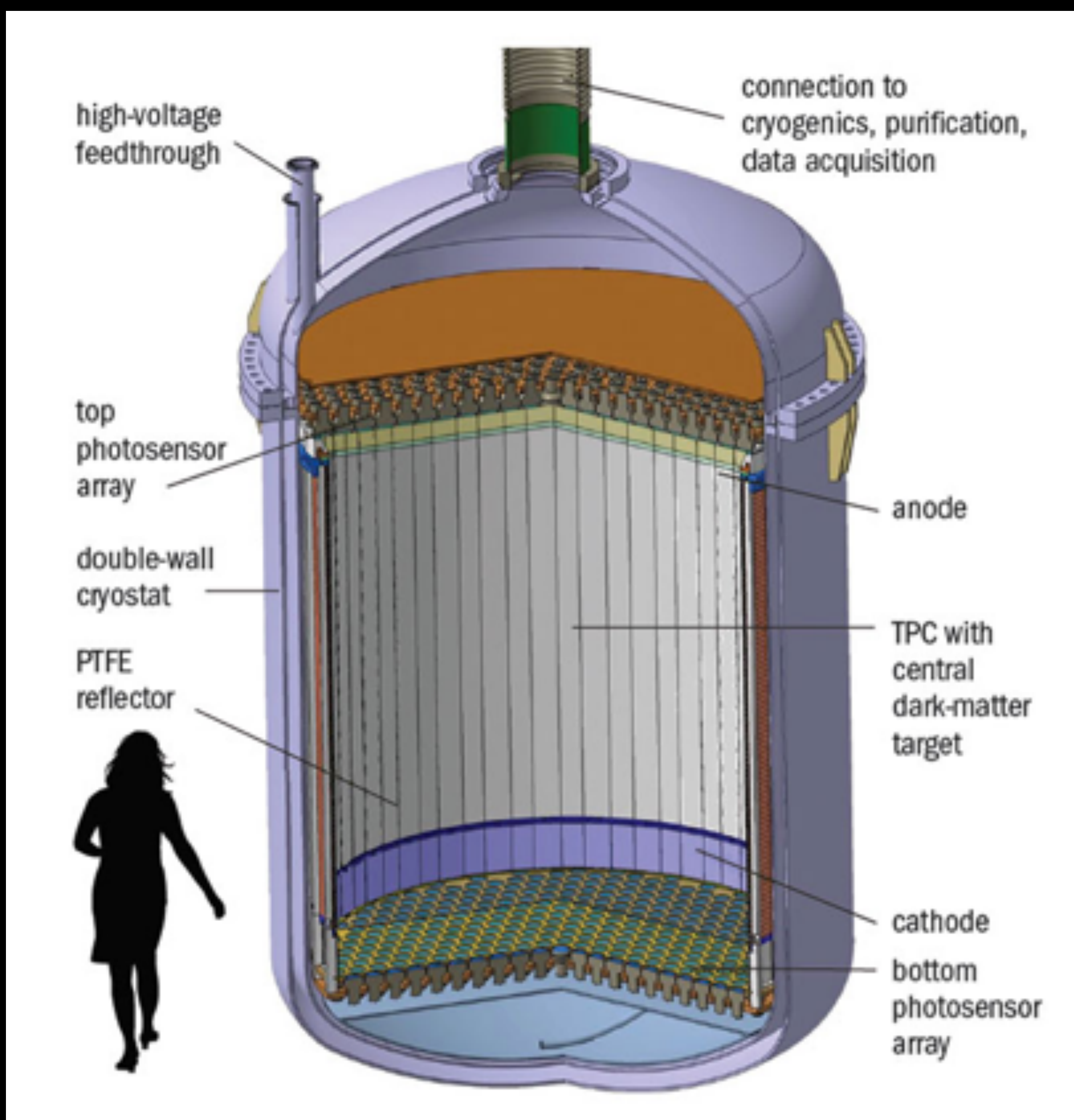
DRIFT collaboration

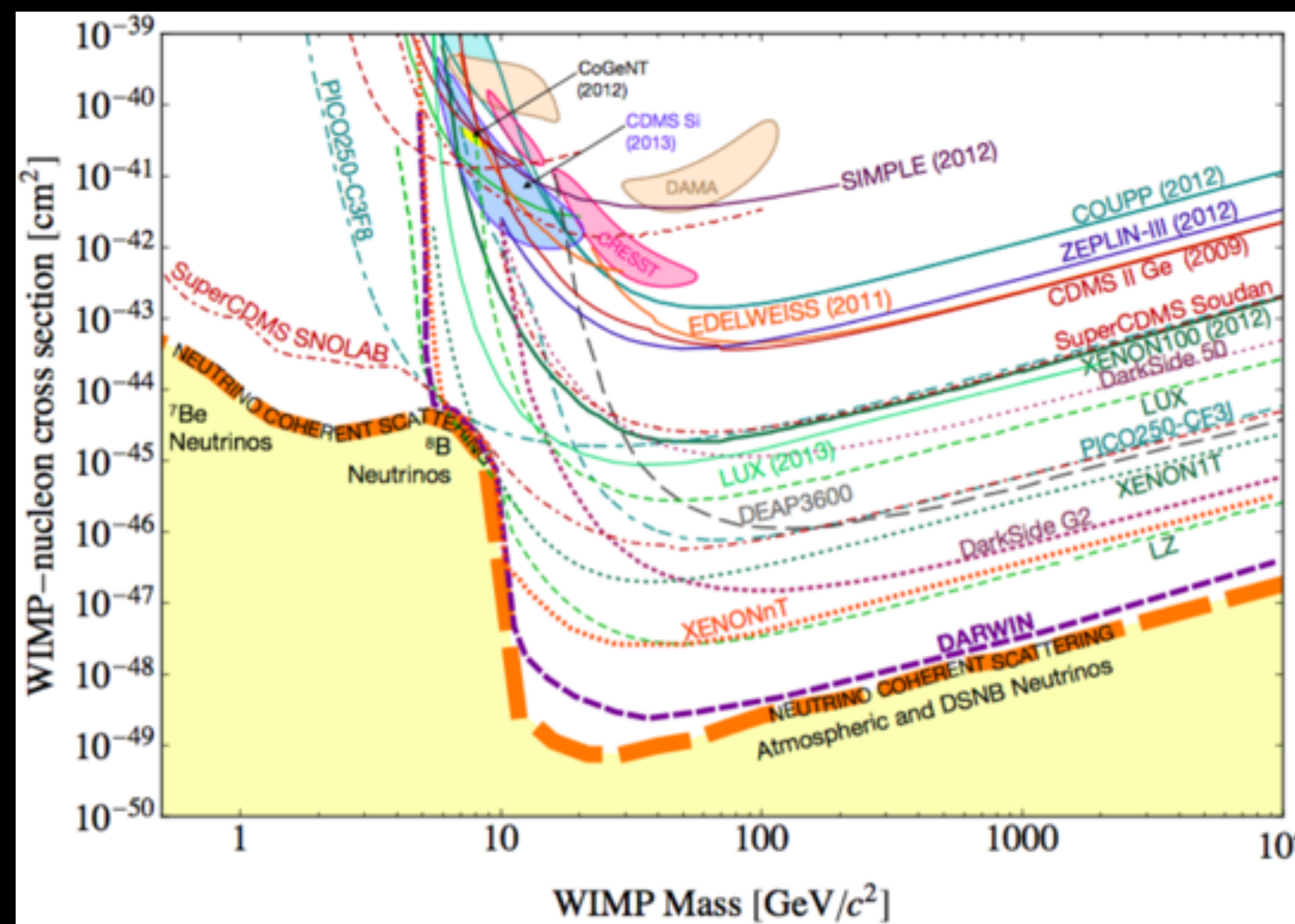
University of BRISTOL

DARWIN: 3rd Gen. WIMP detector

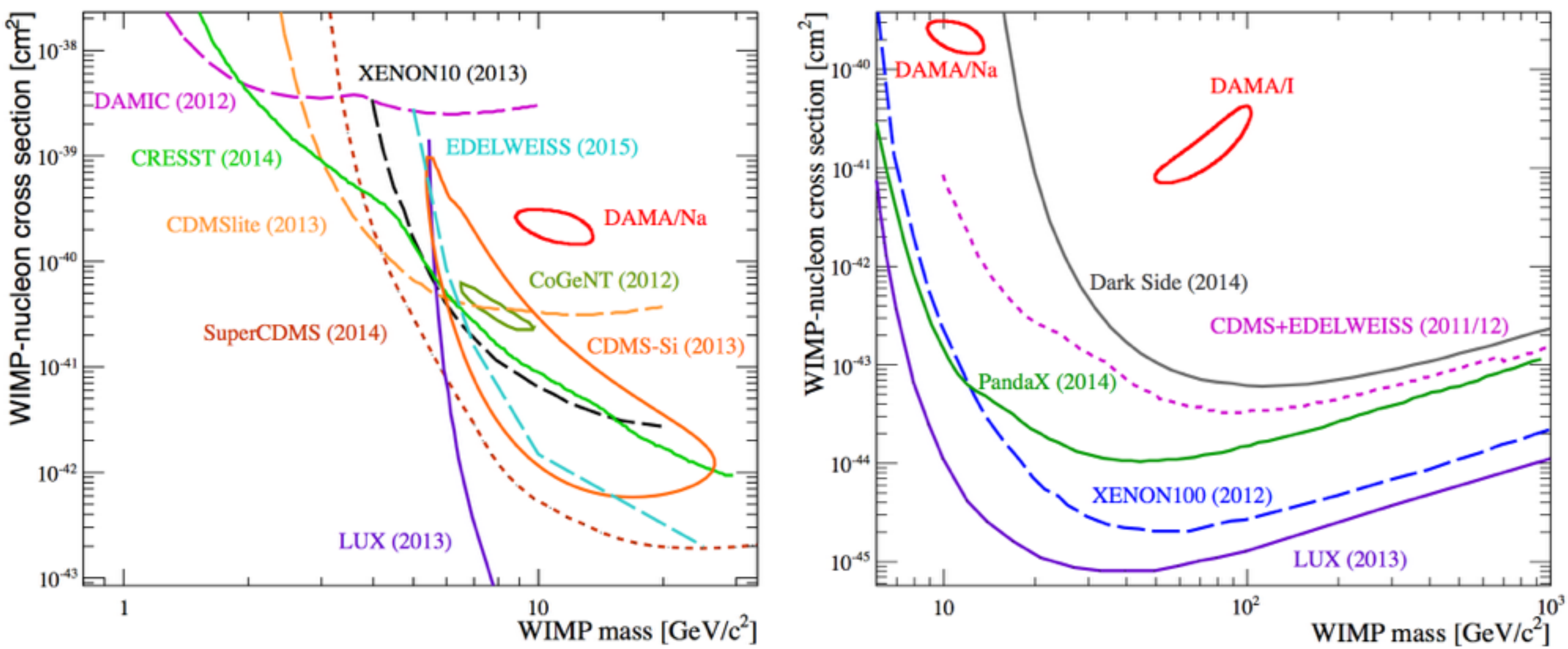
DARWIN

- R&D and design study for a noble liquid facility in Europe
- LAr and LXe communities involved
- 28 groups from 10 countries
- Construction: mid 2020s?

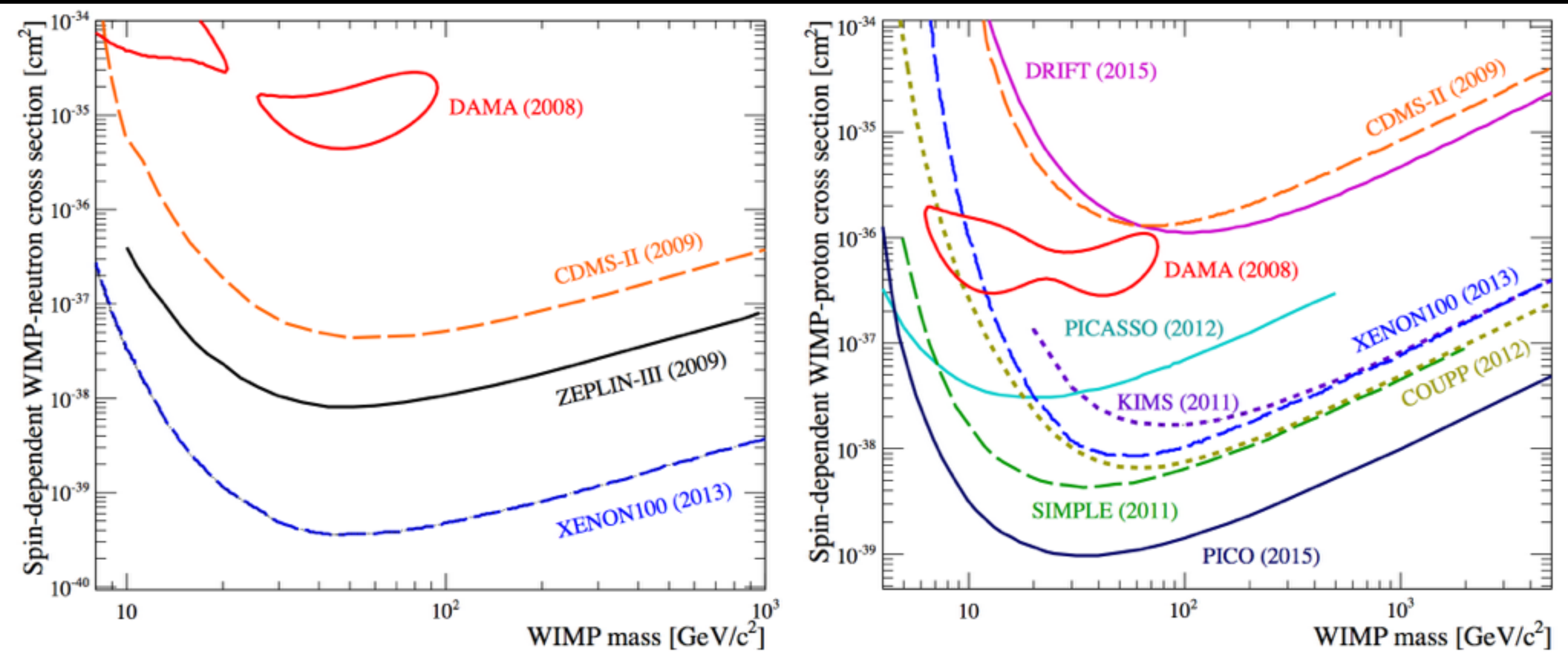




Summary of Direct Searches: SI

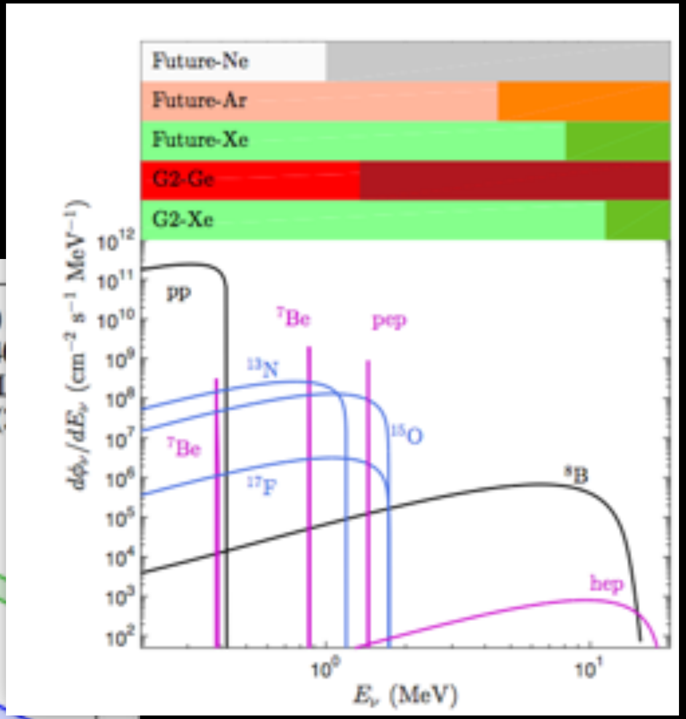


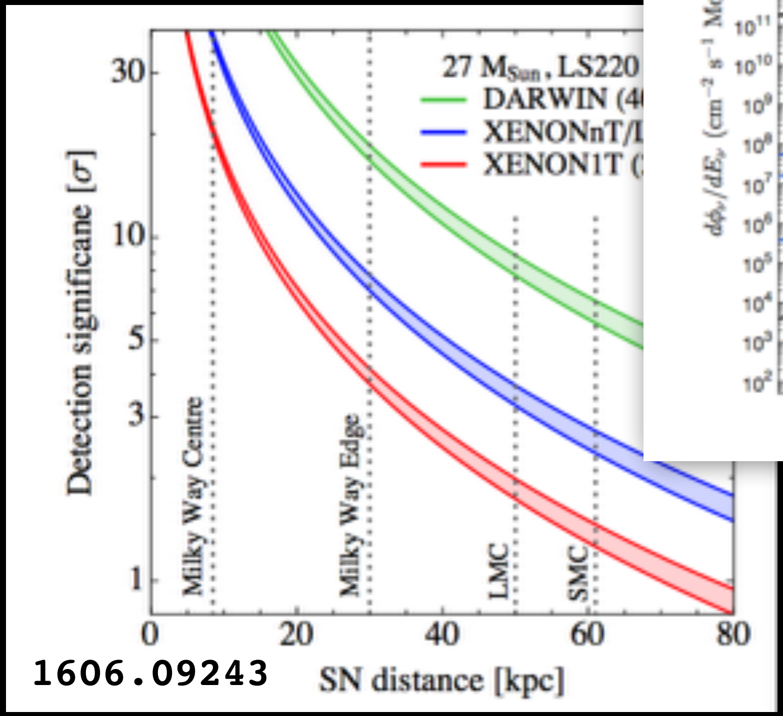
Summary of Direct Searches: SD



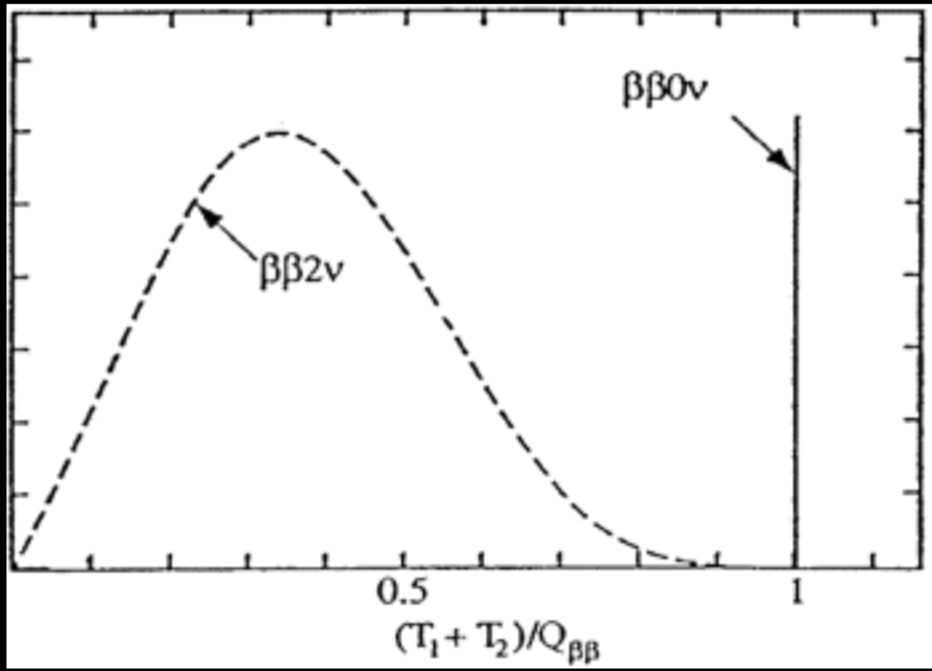
No only DM…

- Modern DD experiments are 'physics laboratories', not only DM
- Neutrino/Supernovae physics with LZ:
  - Sensitive up to 35kpc out
  - Observe full ν envelope w.r.t T2K etc
  - Lower energy thresholds
  - Determine $\sin\Theta_W$ using solar ν





- Also search for 0νbb:



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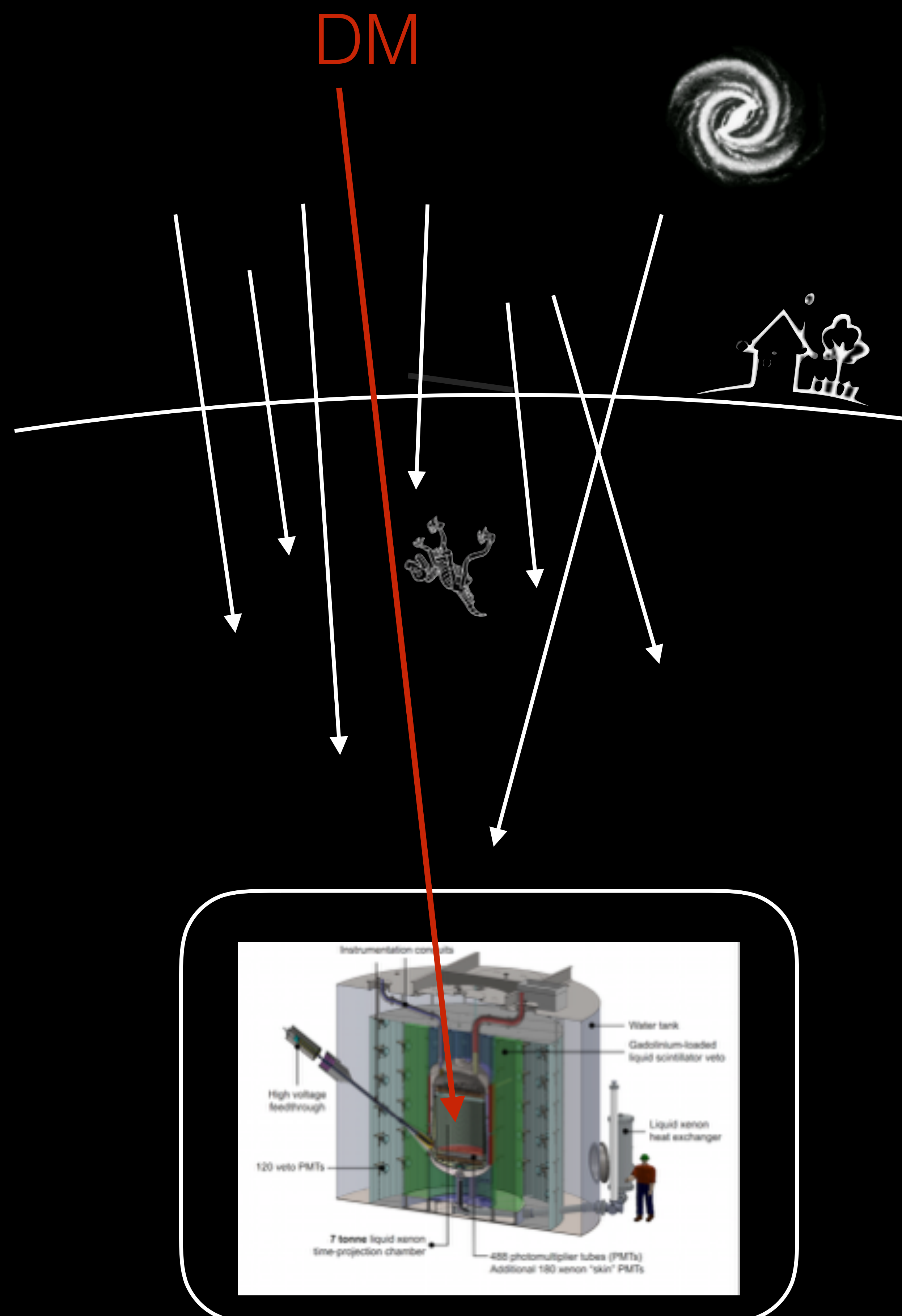
Summary

- Requirements for a dark matter detector
  - Large detector mass
  - Low energy threshold ~ keV
  - Ultra low background rates
- Possible signatures of dark matter
  - Spectral shape of the recoil spectrum
  - Annual modulated rate
  - Directional dependance
- Second generation of DD detectors starting now
- Wide range of physics probed



Backup

Effective Field Theory

- Detailed description of WIMP couplings to matter
  Fitzpatrick et al., arXiv:1211.2818 and arXiv:1203.3542
  Anand et al., arXiv:1308.6288
- Composite nature of the nucleus is reflected
- EFT operators are composed by 4 three-vectors: $i\frac{\vec{q}}{m_N}$, $\vec{v}^{\perp}$, $\vec{S}_N$ and $\vec{S}_\chi$

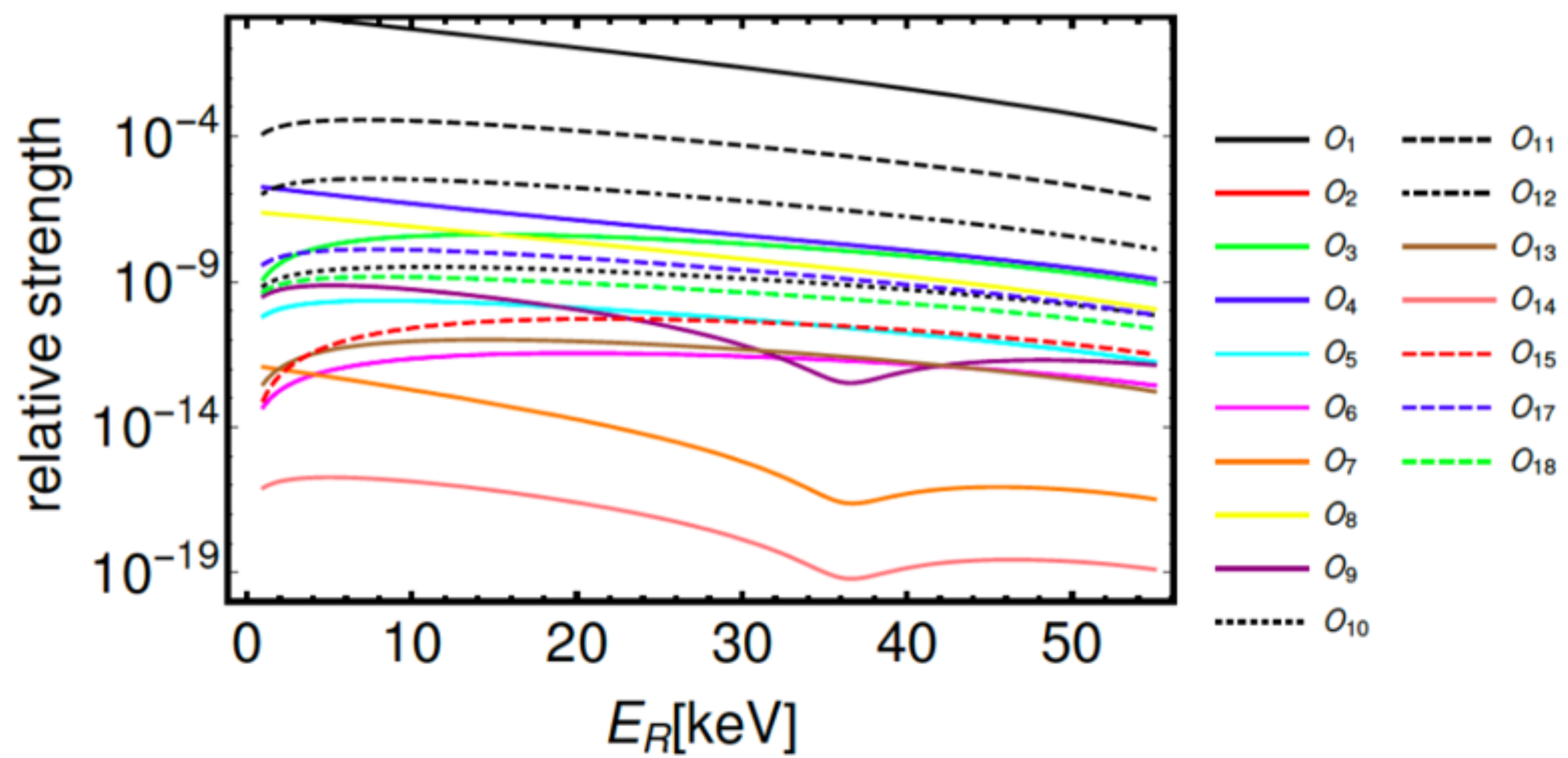


Figure from Dent *et al*., arXiv:1505.03117

Annual Modulation Effects

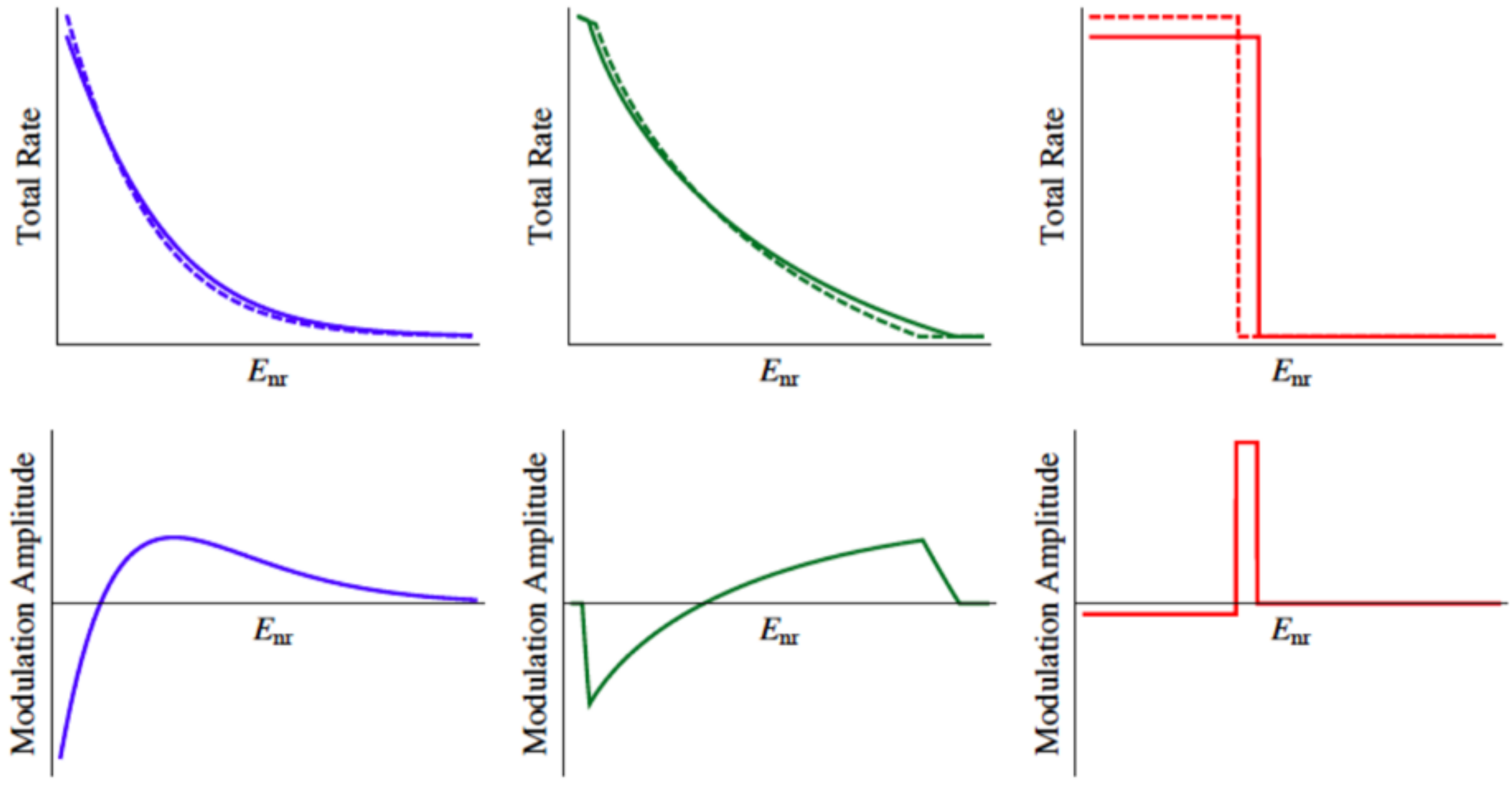


Figure from K. Freeze *al.* arXiv:1209.3339

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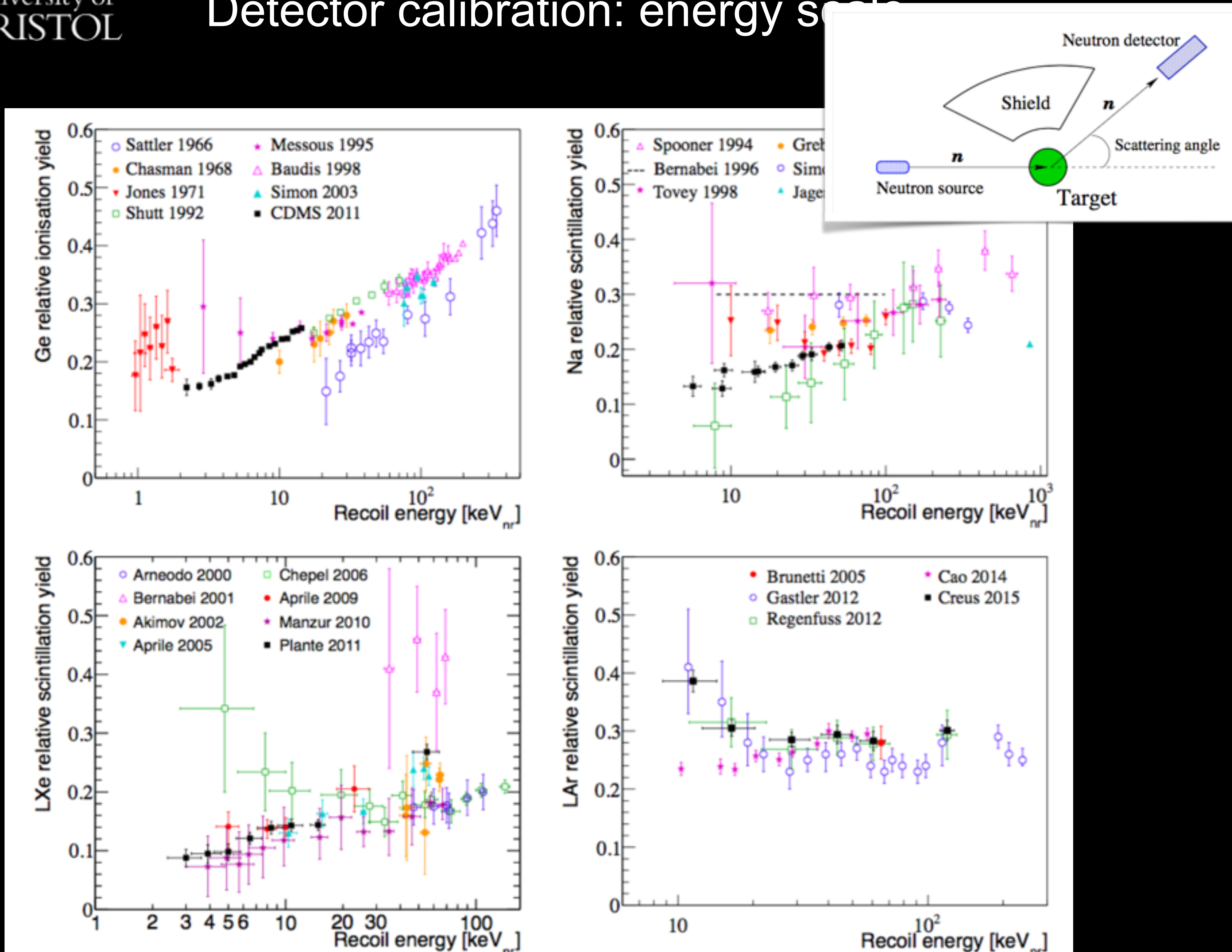
Detector calibration

- Purposes of detector calibration:
- Data stability:
  monitoring of detector parameters (amplification of signals, slow control parameters, ..) and of the related electronics
- Determination of energy scale:
  detector signals are photoelectrons, charges or heat → need to convert to keVnr
- Determination of signal and background regions:
  description of nuclear and electronic recoil regions

Detector calibration: energy s



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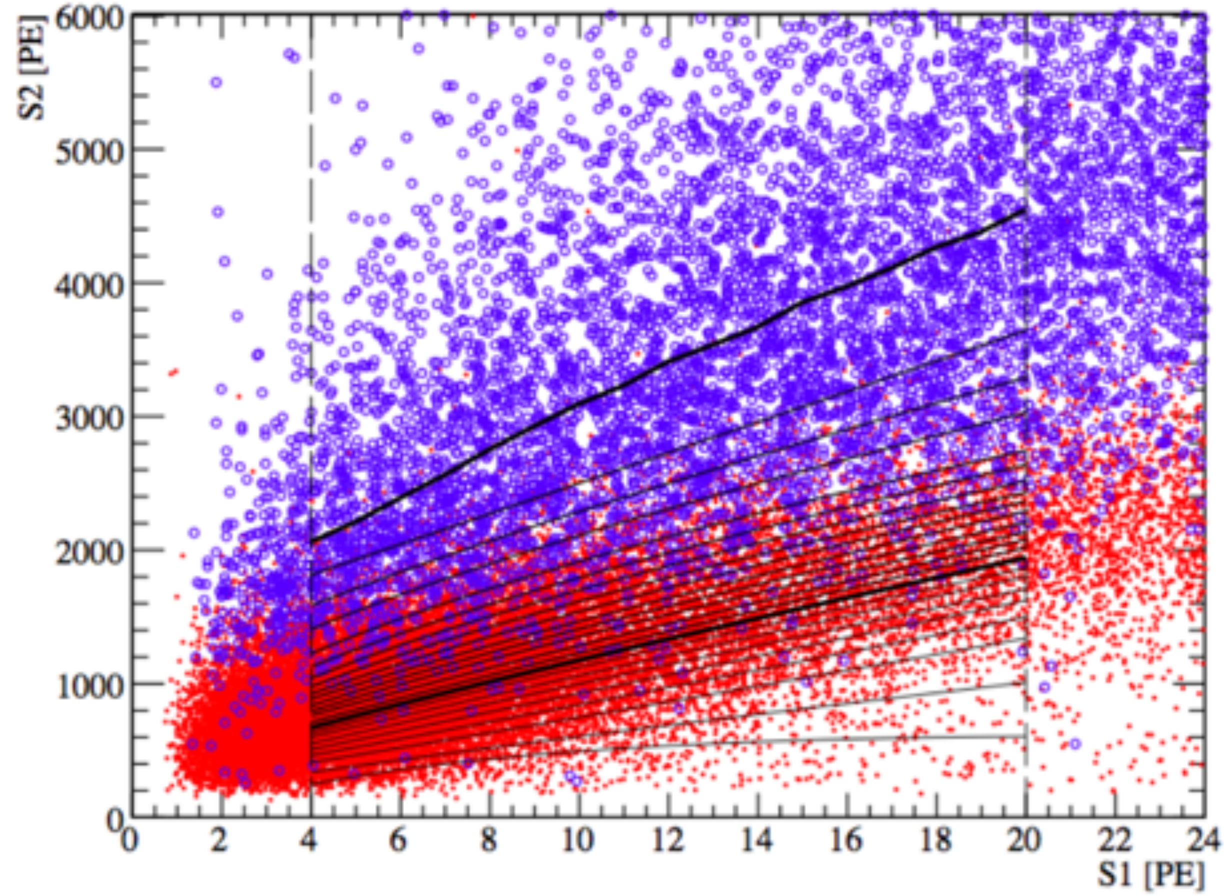
Title



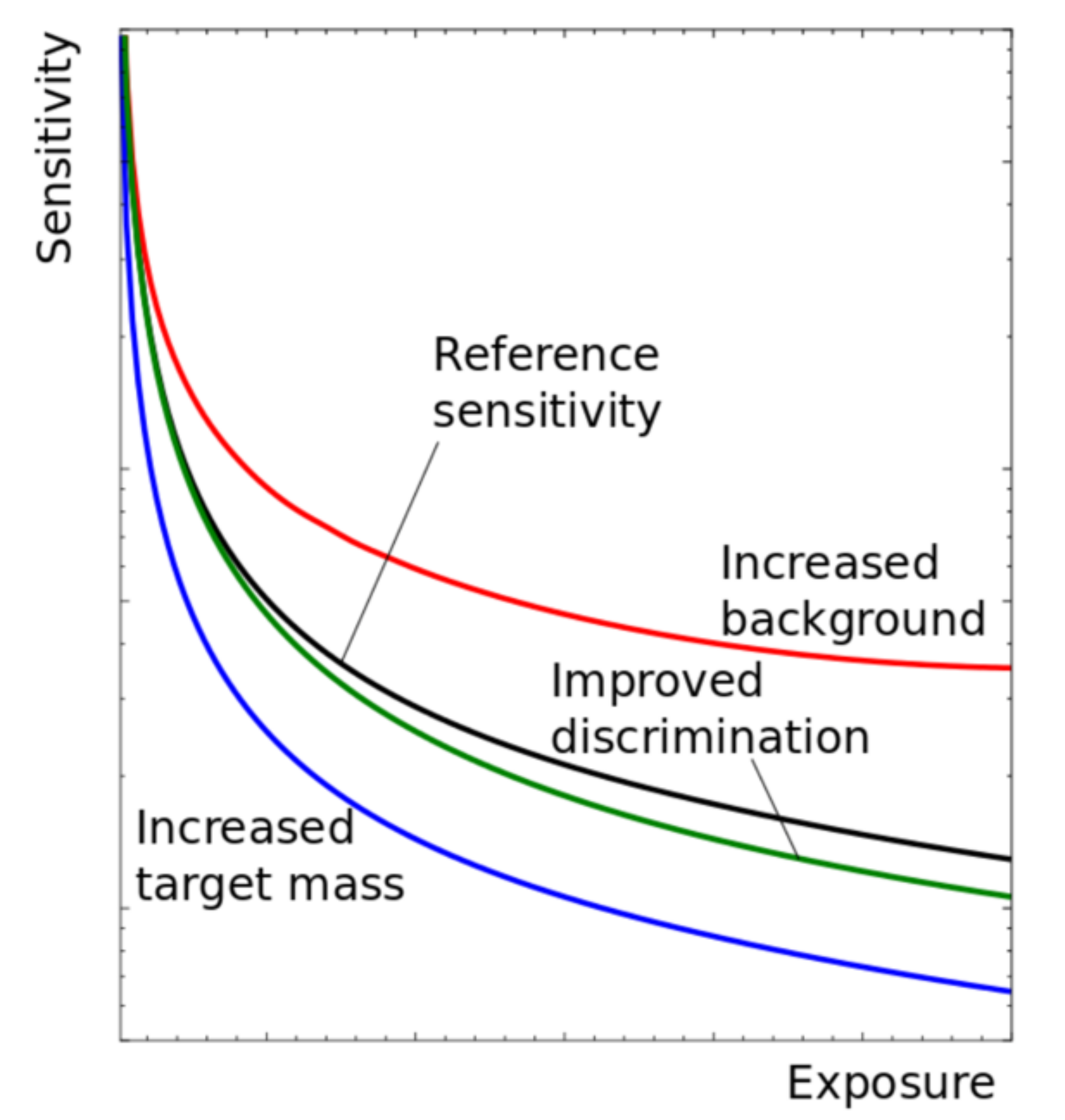
XENON100, Phys. Rev. Lett. 109 (2012) 181301

$$\mathscr{L} = \prod_{j=1}^{K} \mathrm{Poiss}(n^j|\epsilon_s^j N_s + \epsilon_b^j N_b)$$
$$\times \prod_{i=1}^{n^j} \frac{\epsilon_s^j N_s f_s(S1) + \epsilon_b^j N_b f_b(S1)}{\epsilon_s^j N_s + \epsilon_b^j N_b}$$
$$\times \mathrm{Poiss}(m_b^j|\epsilon_b^j M_b) \times \mathrm{Poiss}(m_s^j|\epsilon_s^j M_s)$$
$$\times e^{-(t-t^{\mathrm{obs}})^2/2} \times f_v(v_{\mathrm{obs}}|v_{\mathrm{esc}}).$$

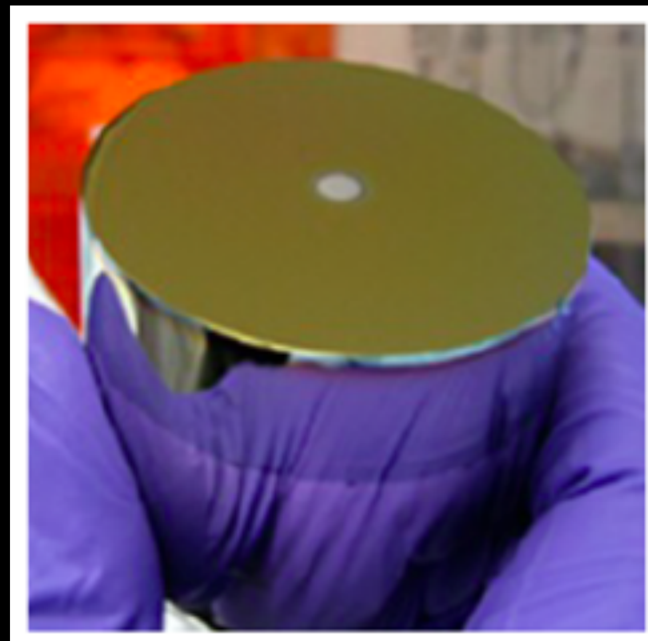
- Likelihood function:
  - Poisson on data for each band
  - Event distribution per band
  - Poisson on calibration data
  - Penalty term for energy scale parametrisation

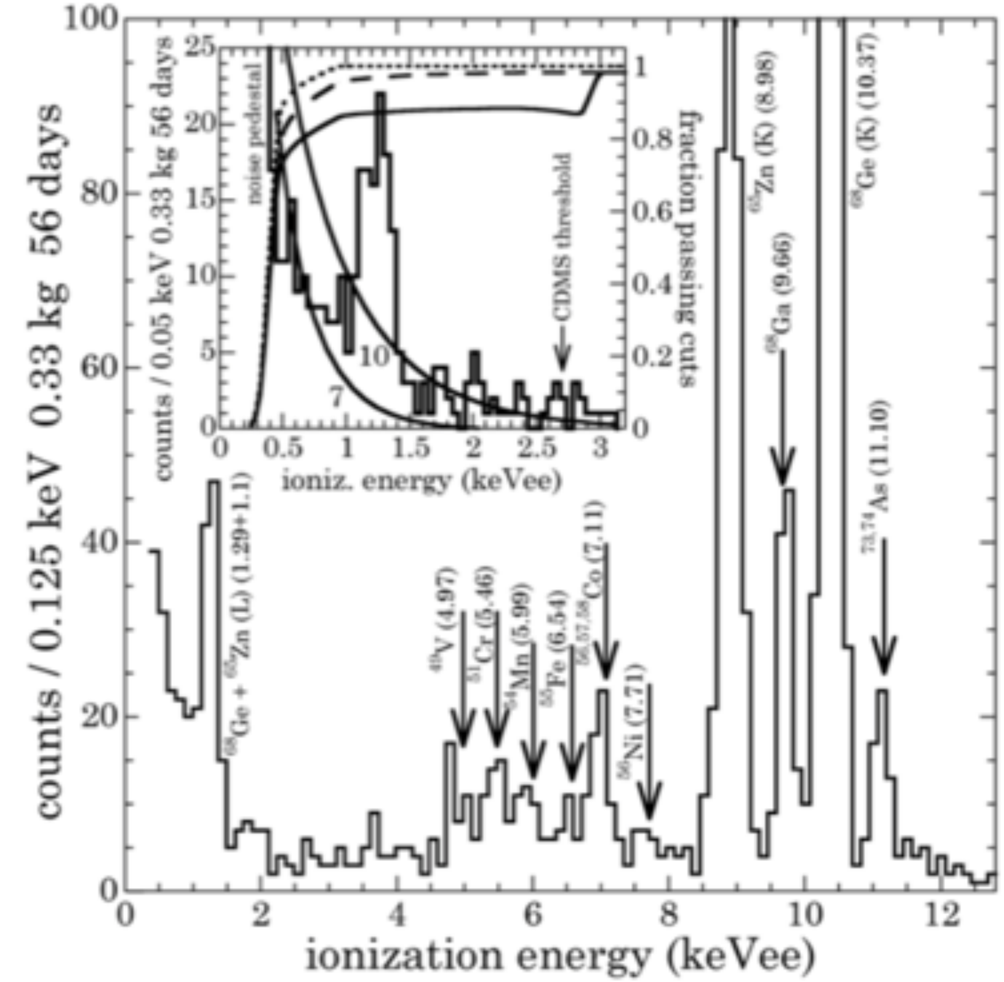
- Calibration data:
  background ER from γ-sources
  signal NR from a neutron source
- Bands defined with equal number of signal events

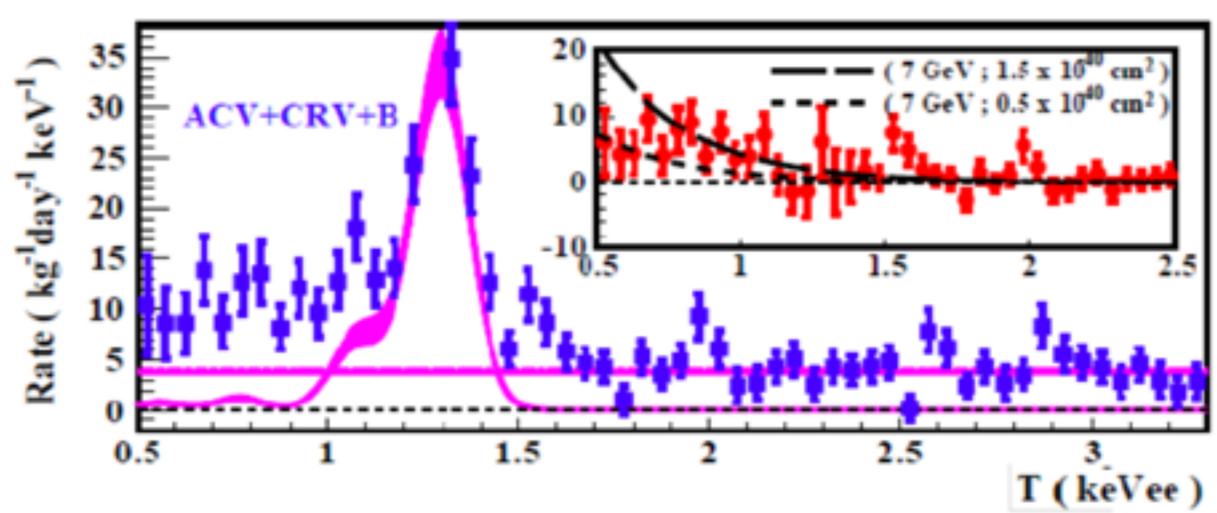
Sensitivity evolution with measuring time



The CoGeNT experiment



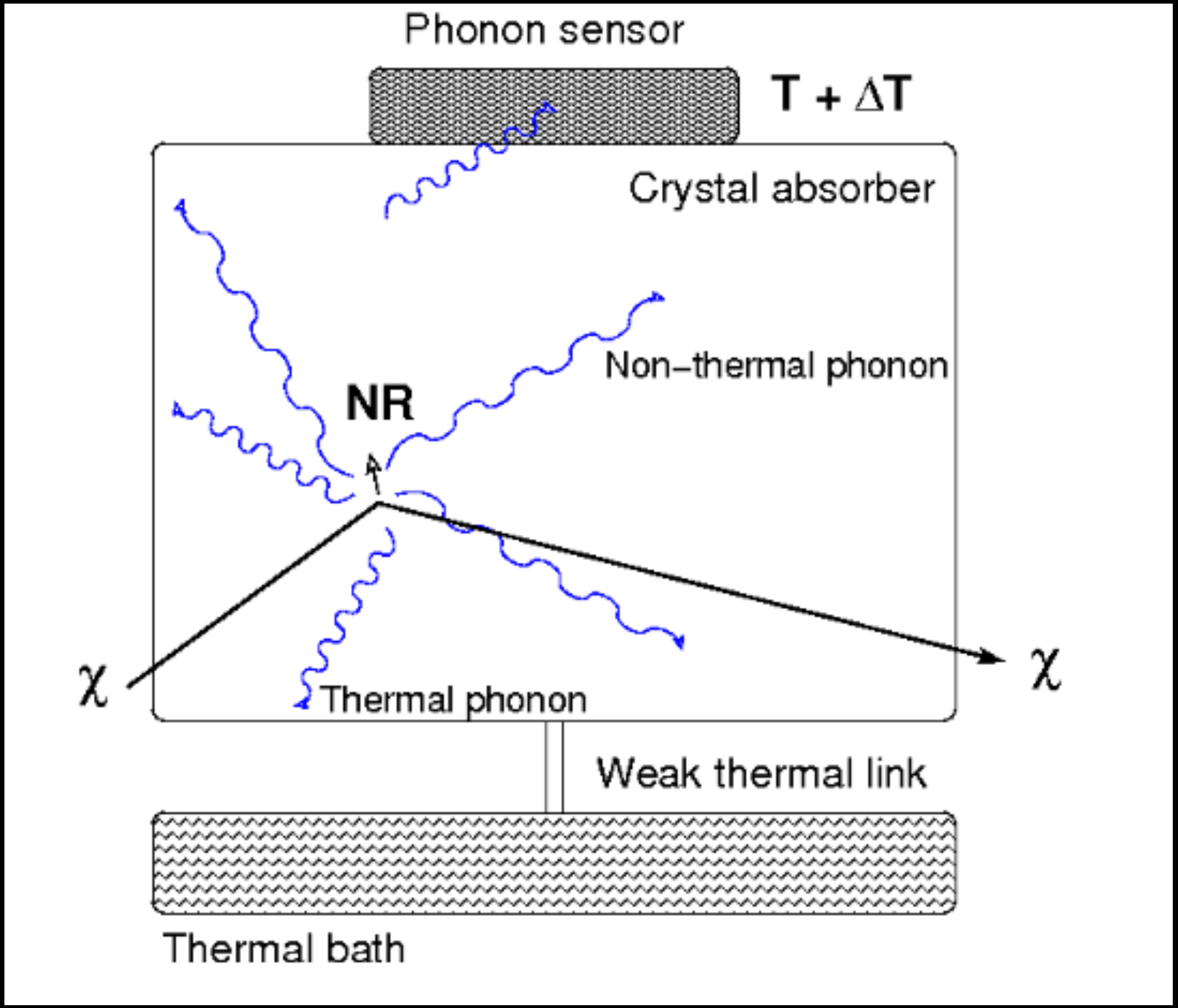




TEXONO, Phys. Rev. Lett. 110, 261301 (2013)

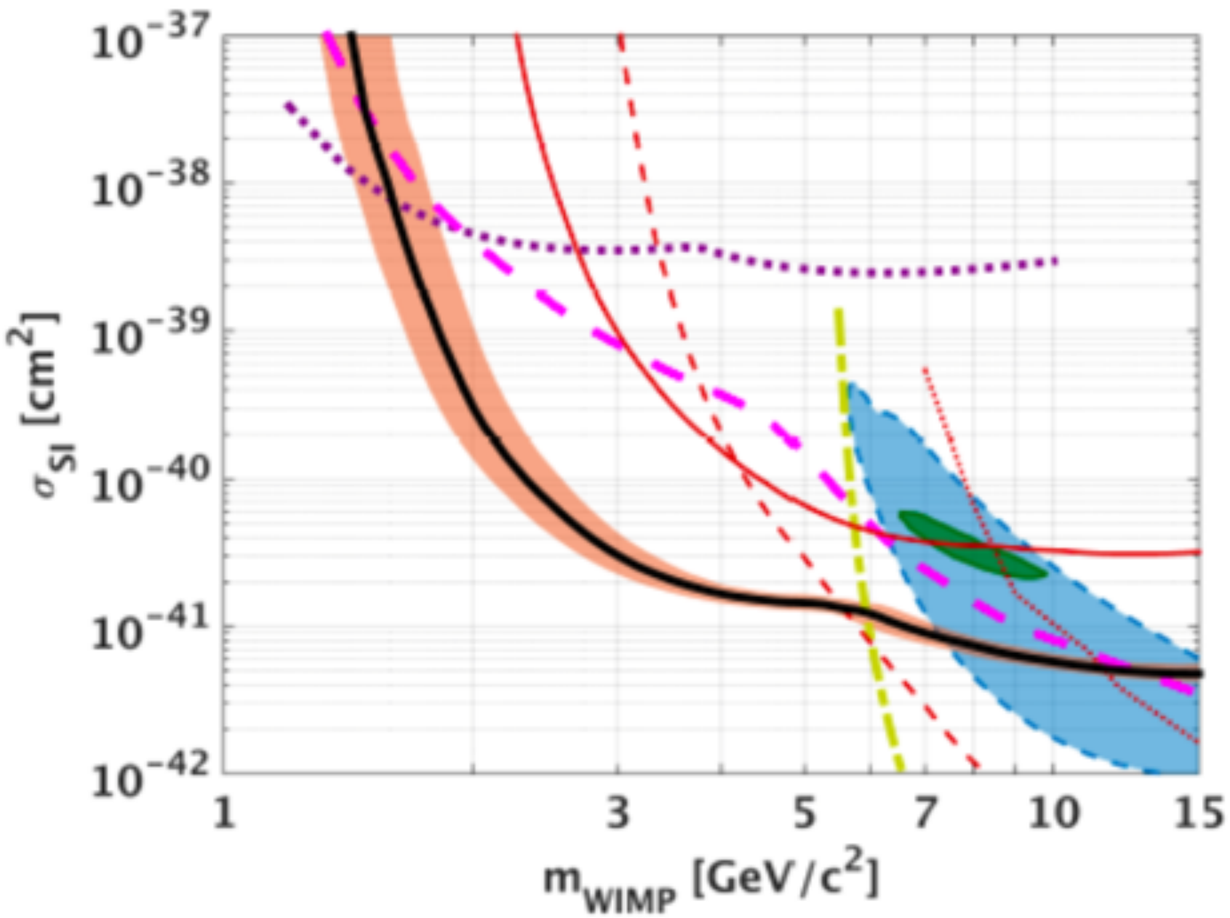
- Excess of events at low energies and annual modulation of the rate CoGeNT,
  `Phys. Rev. Lett. 106 131301 (2011)`
- Independent analysis of the data find no significant modulation
  `Davis, 1405.0495 & Aalseth et al., 1401.6234`
- Tests with Ge detectors:
  CDEX (China) and
  TEXONO (Taiwan)
  → no indication of dark matter

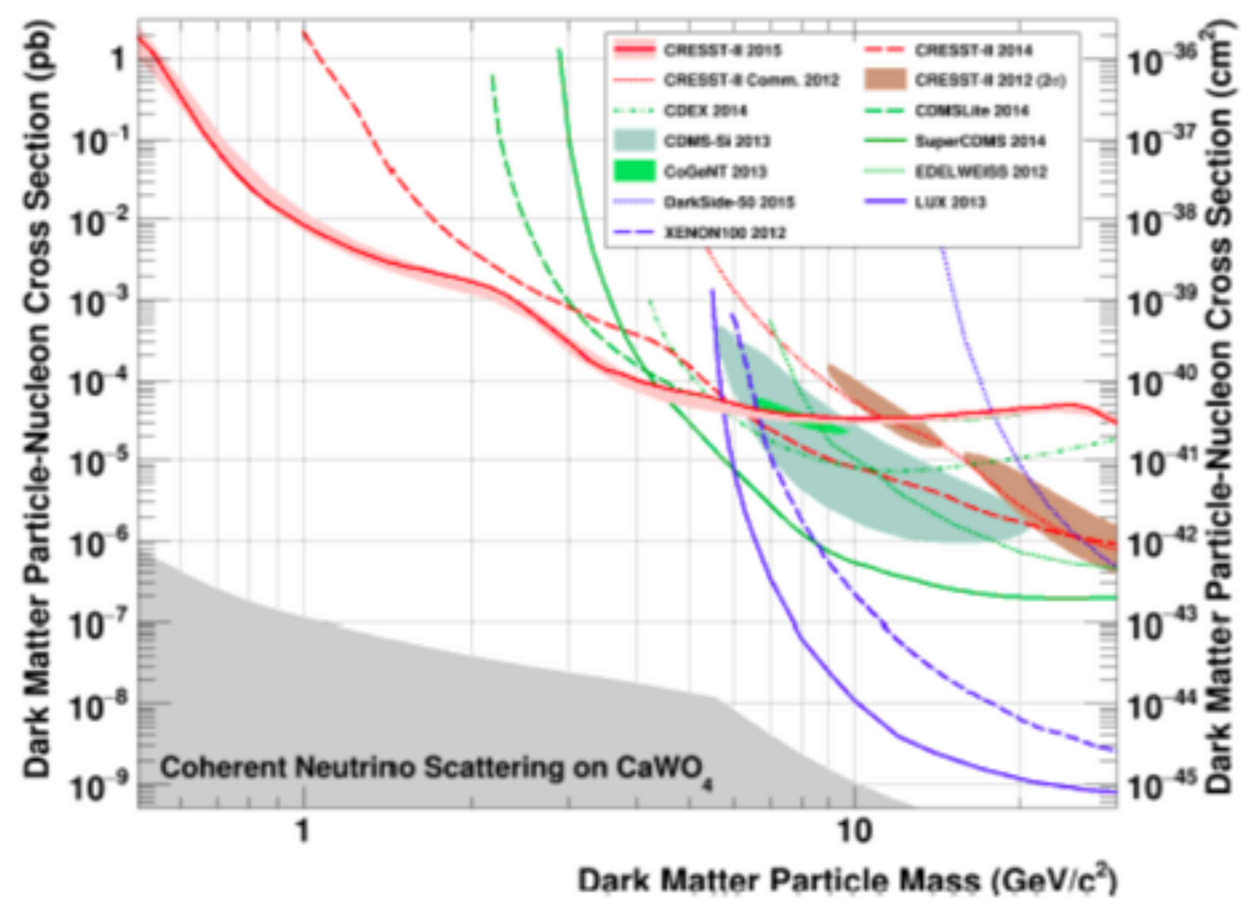
Cryogenic bolometers



- Crystals at (10 − 100) mK
- Temperature rise:
  $\Delta T = E/C(T)$
  E.g. Ge at 20mK, ΔT = 20μK for few keV recoil
- Measurements of ΔT:
  - Neutron transmutation-doped Ge sensors (NTD)
  - Transition edge sensors (TES)
- Discrimination: combination with light or charge read-out

Cryogenic bolometers: recent results

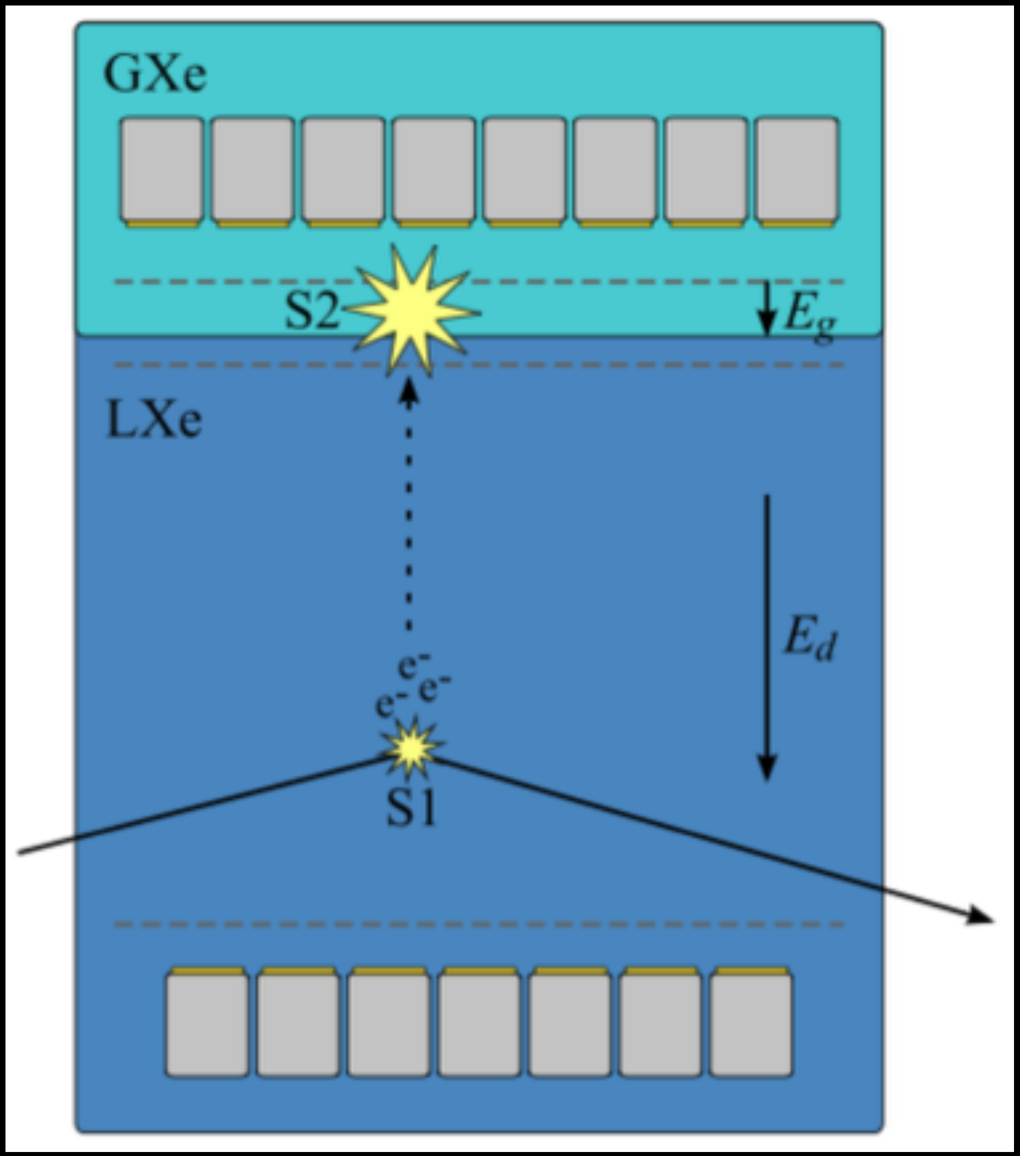


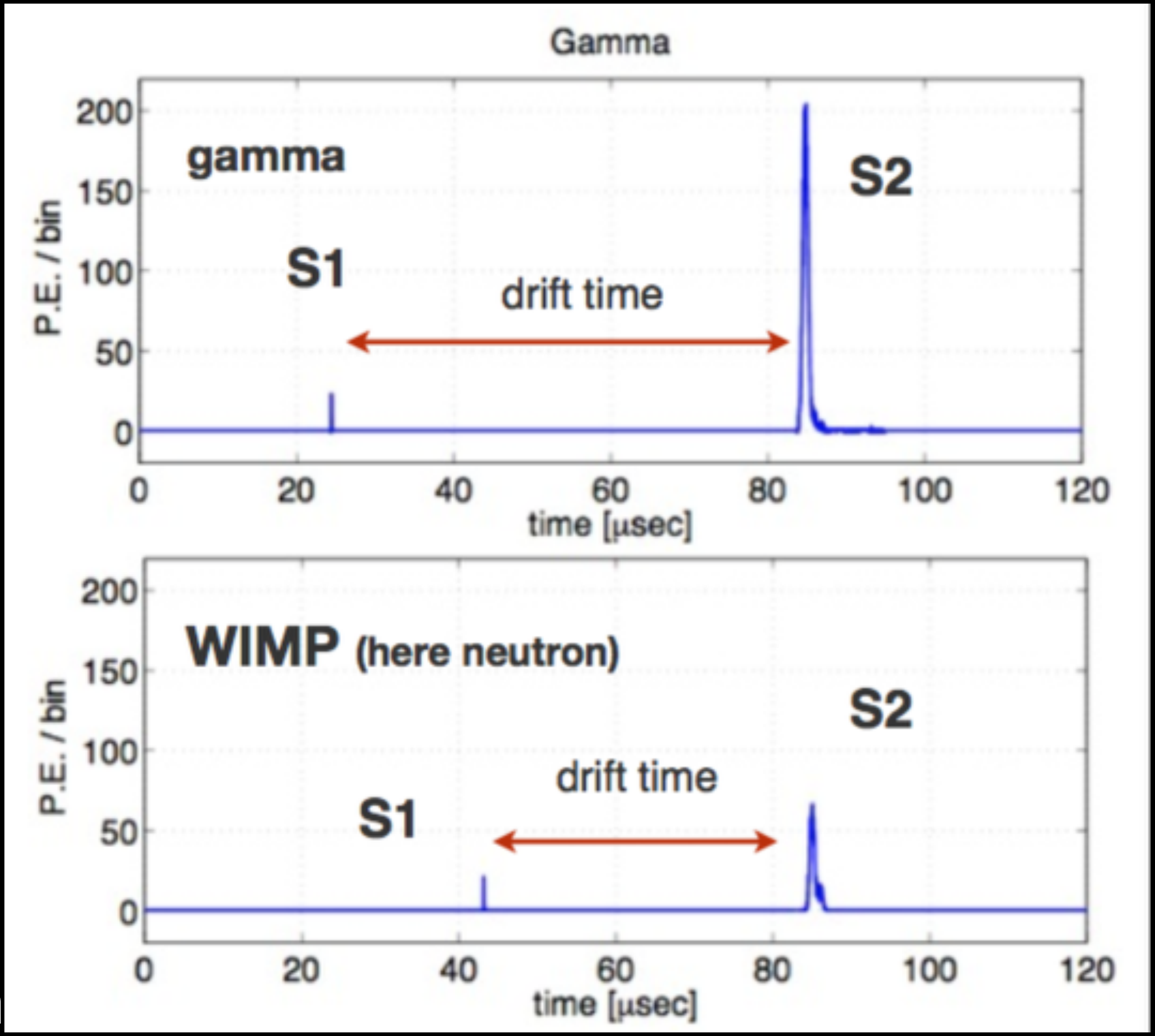


- Low WIMP mass results in September
  - CDMSlite, arXiv:1509.02448
  - CRESST-II, arXiv:1509.01515

Two phase noble gas TPC

- Scintillation signal (S1)
- Charges drift to the liquid-gas surface
- Proportional signal (S2)
  ->Electron- /nuclear recoil discrimination

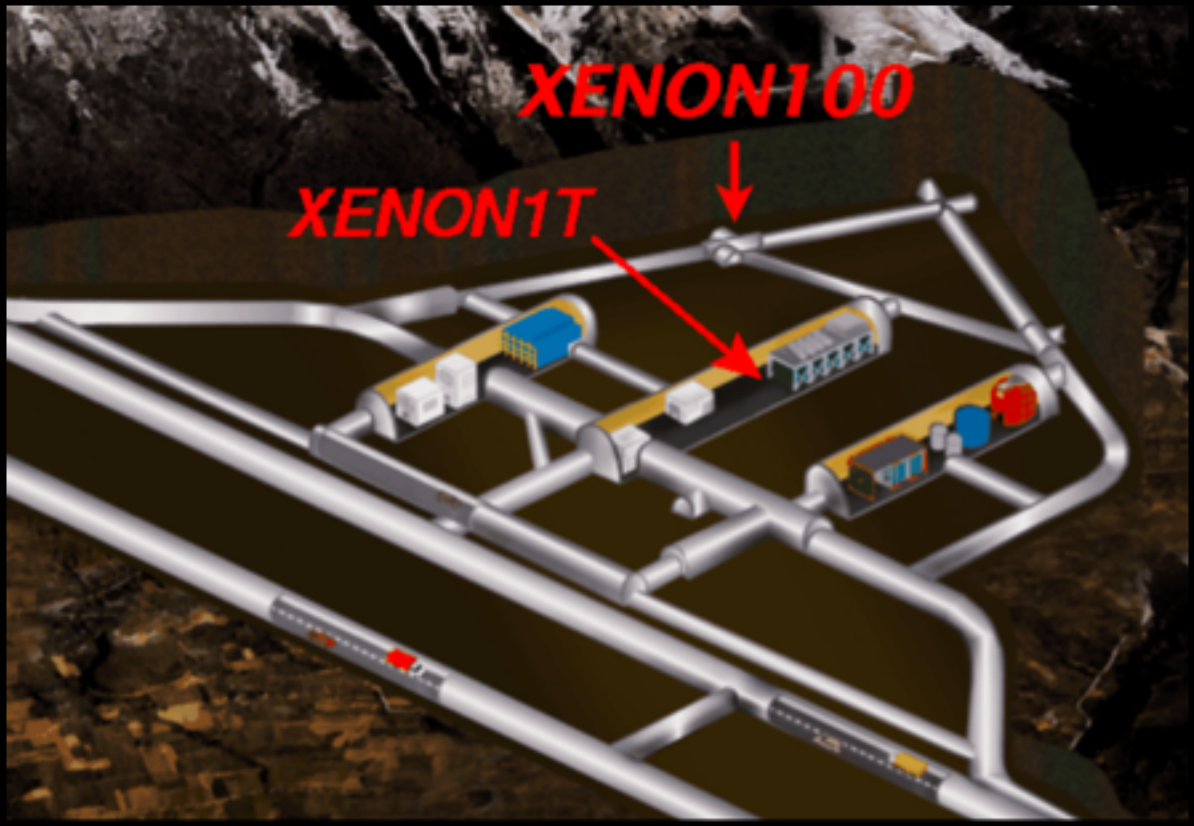




- Drift field necessary
- Electronegative purity required
- 3D position resolution in mm

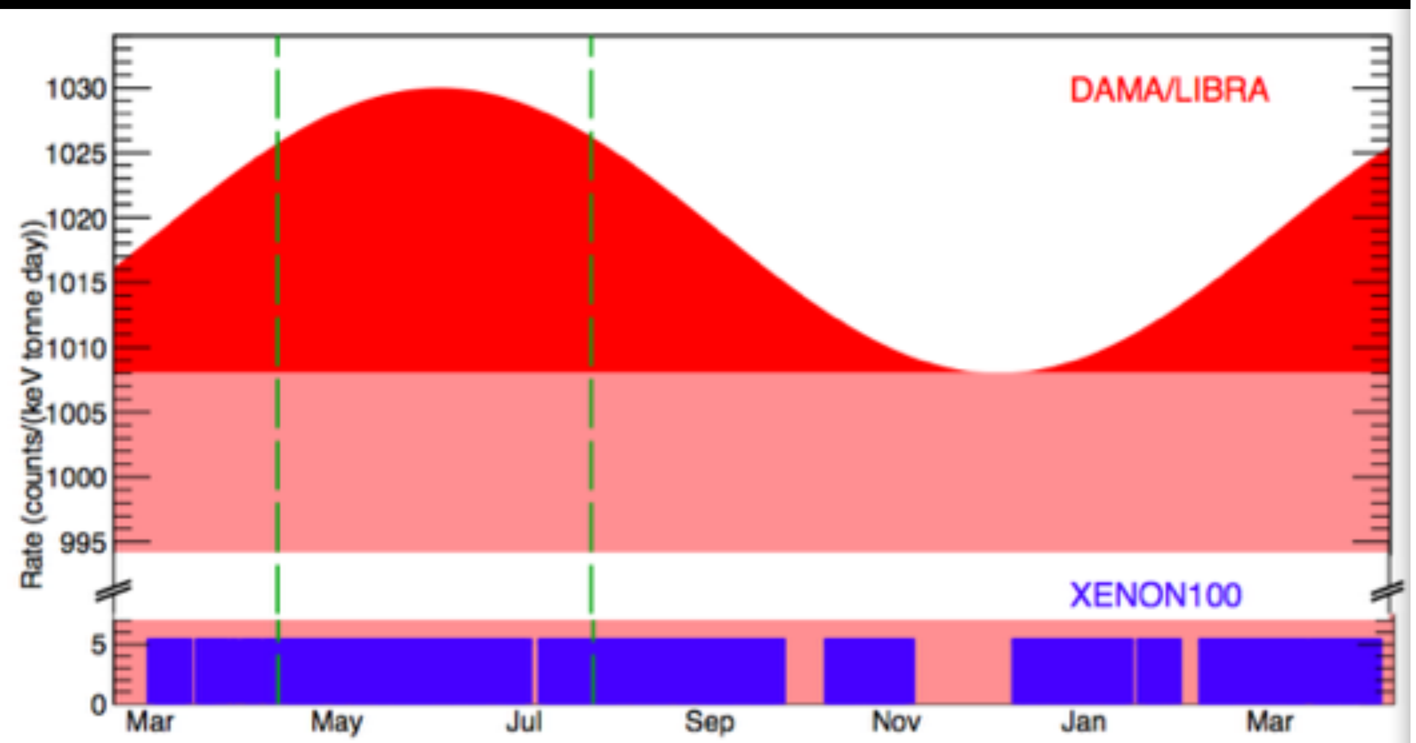
XENON experiment

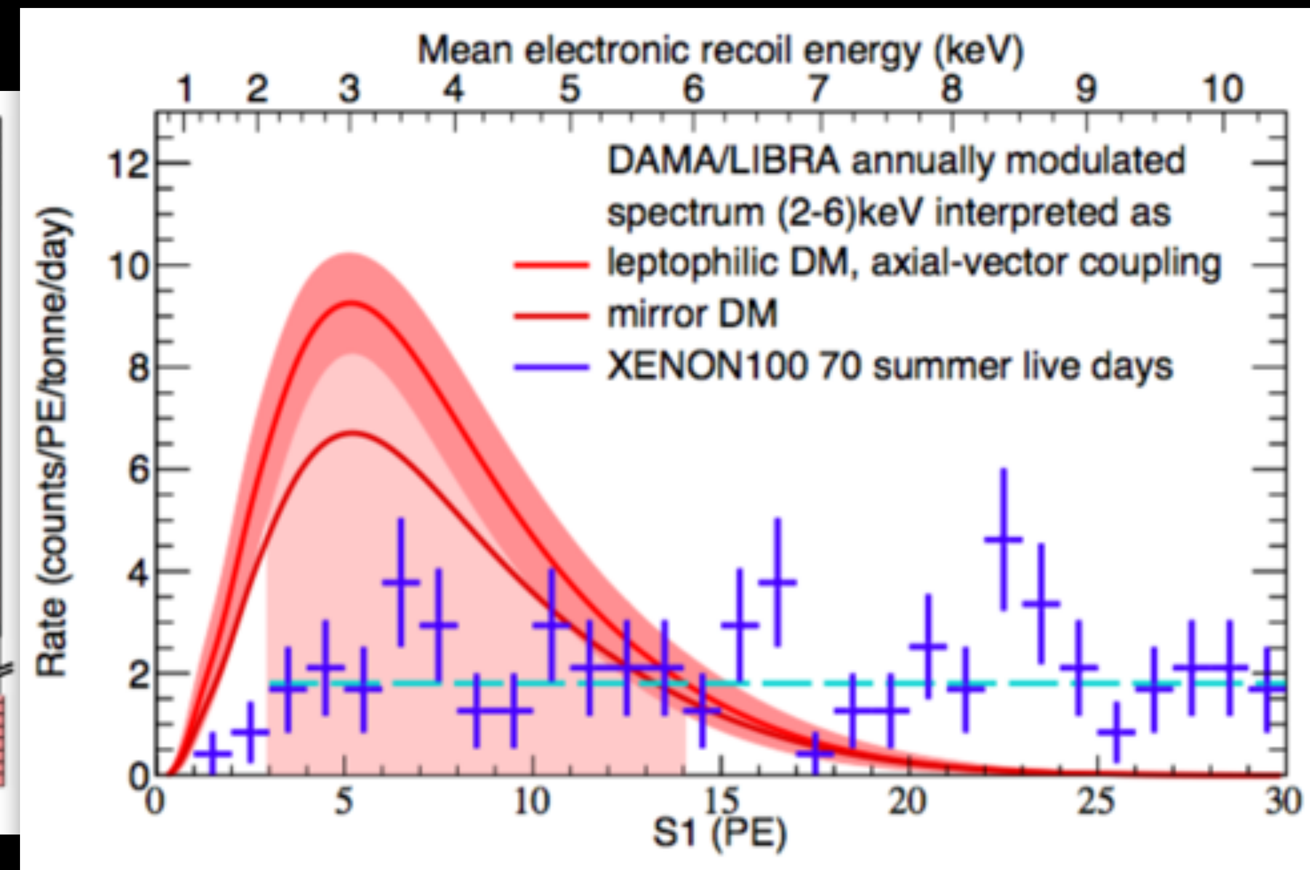
- XENON10: 15 kg active mass
- XENON100: 62 kg active mass
- XENON1T: 1T active mass, running



- Laboratori Nazionali del Gran Sasso (Italy)
- ~ 3 650 m.w.e. shielding

Excluding models producing ER signals

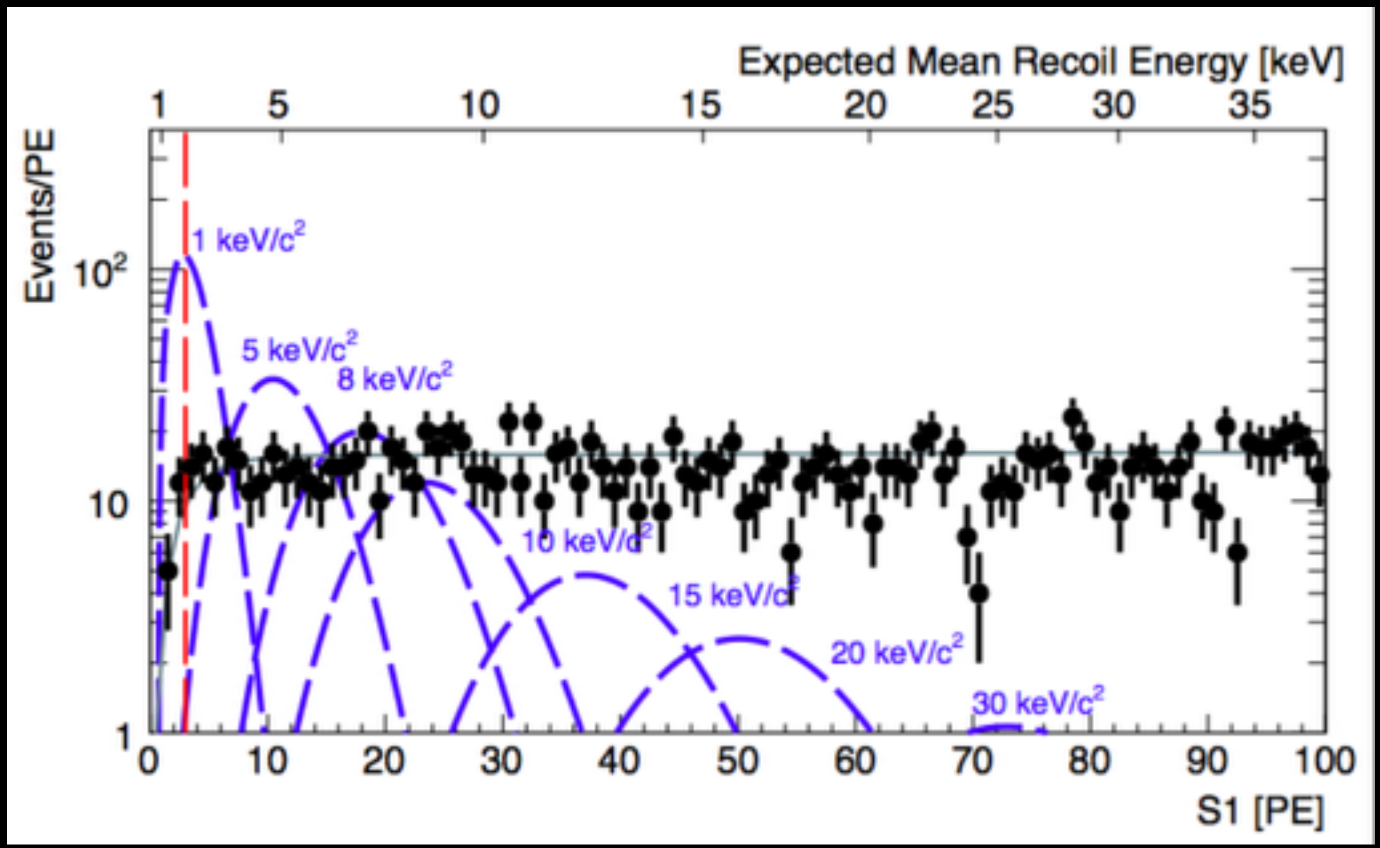


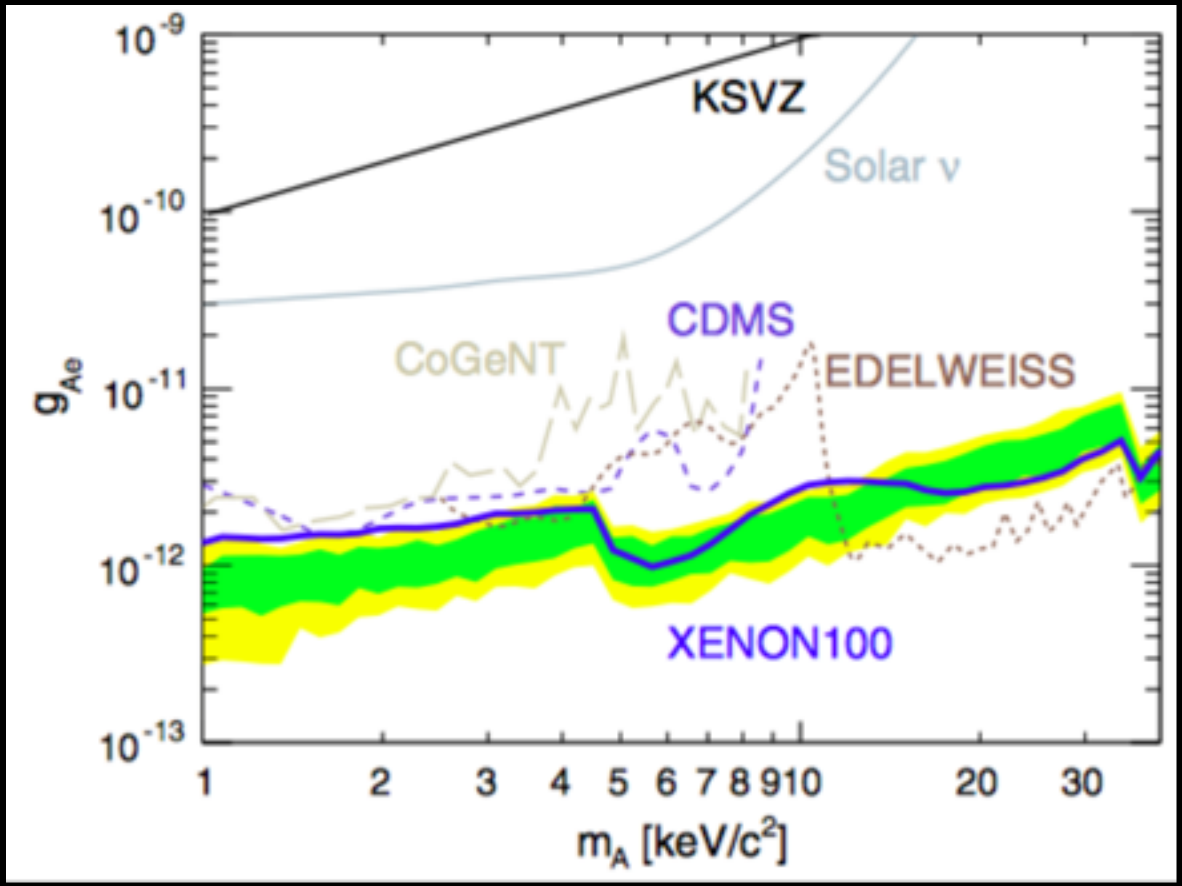


- Testing further possible interpretations of DAMA signal
- XENON100 background rate ~ 2 orders of magnitude below DAMA
- Conservative assumptions: DAMA signal is 100% modulated
    - Leptophilic models with axial-vector interactions ruled out at 4.4
    - Mirror dark matter ruled out at 3.6
    - Luminous dark matter ruled out at 4.6

XENON, Science 21 (2015), arXiv:1507.07747

Axion Search results

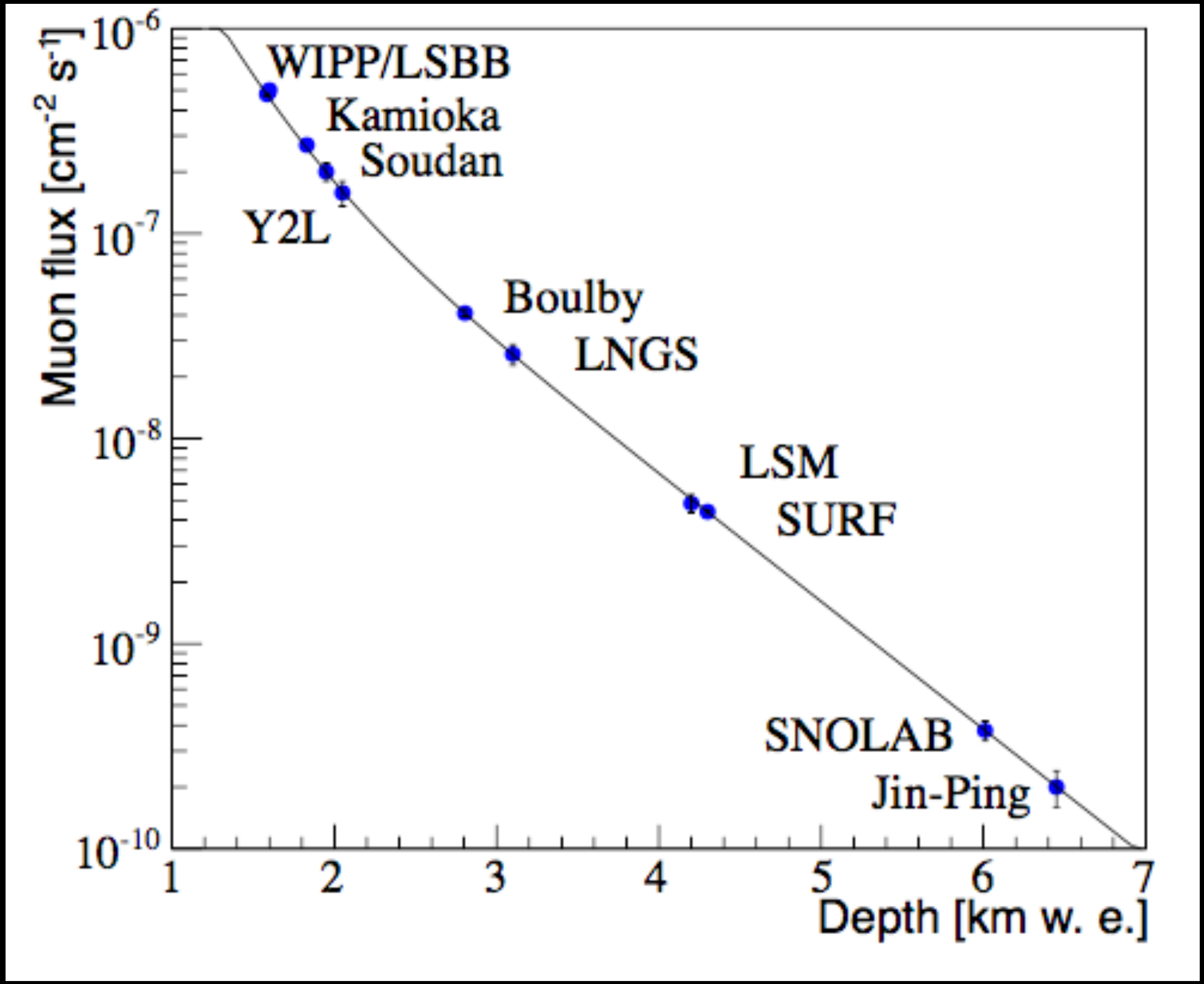




- Axions can couple to electrons gAe in a detector target
- Axio-electric effect (similar to photoelectric)
- Signal consist of electronic recoil events

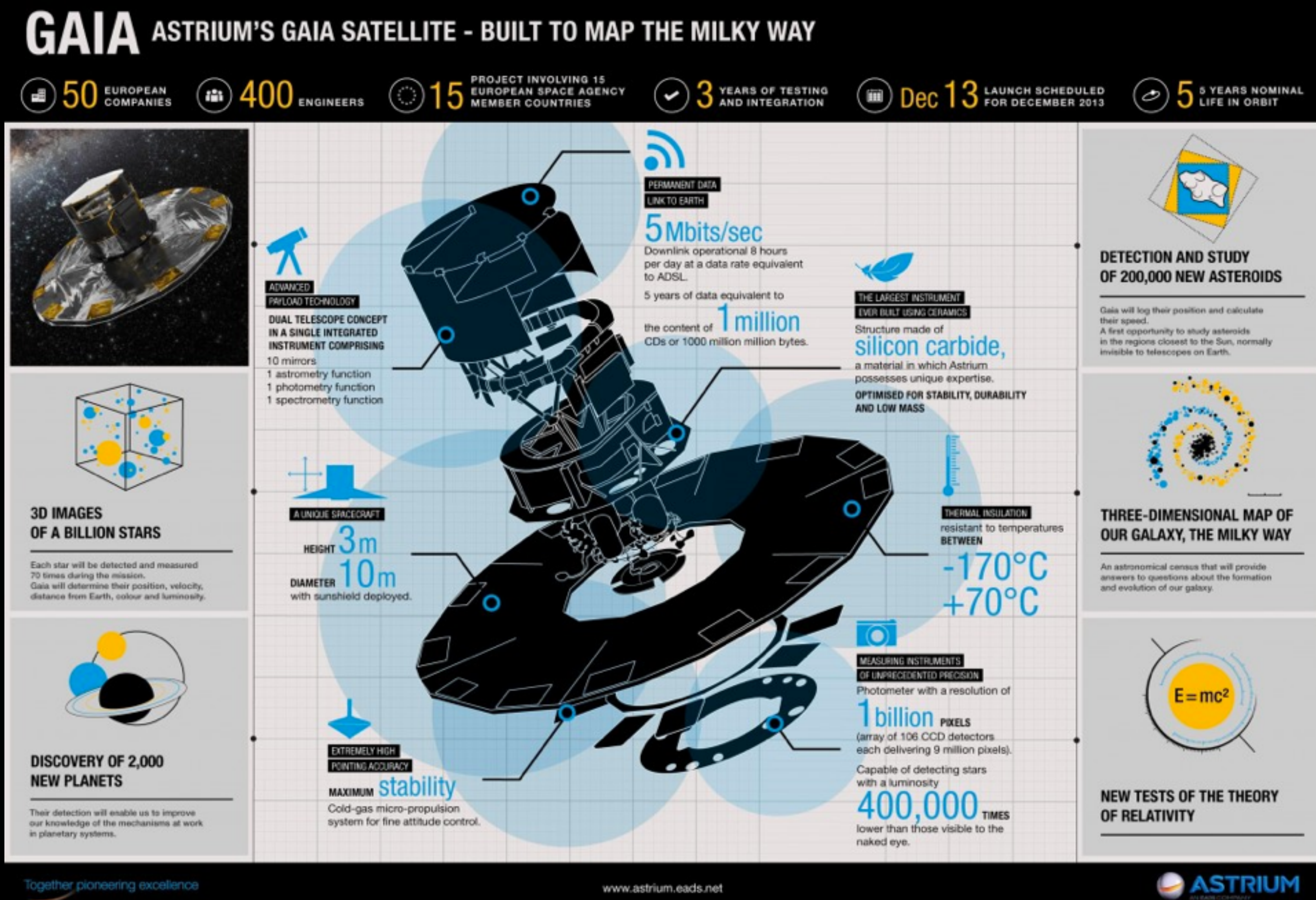
Underground Laboratories

arXiv:0512.125



- WIPP in USA (DMTPC)
- LSBB in France (SIMPLE)
- Kamioka in Japan (XMASS, NEWAGE)
- Soudan in USA (SuperCDMS, GoGeNT)
- Y2L in Korea (KIMS)
- Boulby in UK (DRIFT, ZEPLIN)
- LNGS in Italy (XENON, DAMA, Cresst, DarkSide)
- LSM in France (Edelweiss, MIMAC)
- SURF in USA (LUX, LZ, DAMIC)
- SNOLAB in Canada (DEAP/CLEAN, PICASSO, COUPP)
- Jin-Ping in China (PandaX, CDEX)

GAIA


GAIA ASTRIUM'S GAIA SATELLITE - BUILT TO MAP THE MILKY WAY
50 EUROPEAN COMPANIES
400 ENGINEERS
15 PROJECT INVOLVING 15 EUROPEAN SPACE AGENCY MEMBER COUNTRIES
3 YEARS OF TESTING AND INTEGRATION
Dec 13 LAUNCH SCHEDULED FOR DECEMBER 2013
5 5 YEARS NOMINAL LIFE IN ORBIT
ADVANCED PAYLOAD TECHNOLOGY
DUAL TELESCOPE CONCEPT IN A SINGLE INTEGRATED INSTRUMENT COMPRISING
10 mirrors
1 astrometry function
1 photometry function
1 spectrometry function
PERMANENT DATA LINK TO EARTH
5 Mbits/sec
Downlink operational 8 hours per day at a data rate equivalent to ADSL.
5 years of data equivalent to the content of 1 million CDs or 1000 million million bytes.
THE LARGEST INSTRUMENT EVER BUILT USING CERAMICS
Structure made of silicon carbide, a material in which Astrium possesses unique expertise.
OPTIMISED FOR STABILITY, DURABILITY AND LOW MASS
A UNIQUE SPACECRAFT
HEIGHT 3m
DIAMETER 10m with sunshield deployed.
THERMAL INSULATION
resistant to temperatures BETWEEN
-170°C
+70°C
MEASURING INSTRUMENTS OF UNPRECEDENTED PRECISION
Photometer with a resolution of 1 billion PIXELS (array of 106 CCD detectors each delivering 9 million pixels).
Capable of detecting stars with a luminosity 400,000 TIMES lower than those visible to the naked eye.
EXTREMELY HIGH POINTING ACCURACY
MAXIMUM stability
Cold-gas micro-propulsion system for fine attitude control.
3D IMAGES OF A BILLION STARS
Each star will be detected and measured 70 times during the mission.
Gaia will determine their position, velocity, distance from Earth, colour and luminosity.
DISCOVERY OF 2,000 NEW PLANETS
Their detection will enable us to improve our knowledge of the mechanisms at work in planetary systems.
DETECTION AND STUDY OF 200,000 NEW ASTEROIDS
Gaia will log their position and calculate their speed.
A first opportunity to study asteroids in the regions closest to the Sun, normally invisible to telescopes on Earth.
THREE-DIMENSIONAL MAP OF OUR GALAXY, THE MILKY WAY
An astronomical census that will provide answers to questions about the formation and evolution of our galaxy.
E=mc²
NEW TESTS OF THE THEORY OF RELATIVITY
Together pioneering excellence
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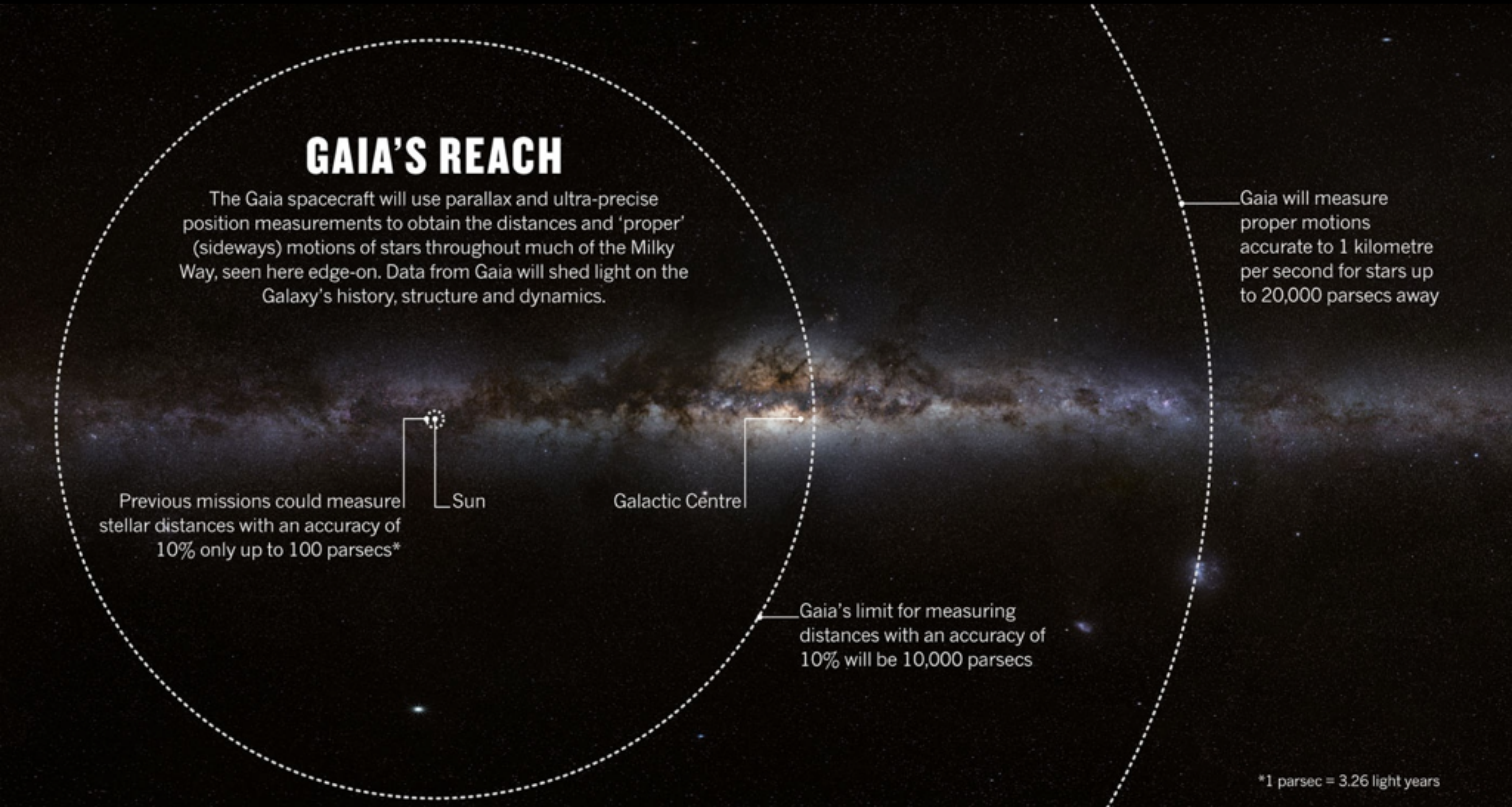
GAIA


GAIA'S REACH
The Gaia spacecraft will use parallax and ultra-precise position measurements to obtain the distances and 'proper' (sideways) motions of stars throughout much of the Milky Way, seen here edge-on. Data from Gaia will shed light on the Galaxy's history, structure and dynamics.
Gaia will measure proper motions accurate to 1 kilometre per second for stars up to 20,000 parsecs away
Previous missions could measure stellar distances with an accuracy of 10% only up to 100 parsecs*
Sun
Galactic Centre
Gaia's limit for measuring distances with an accuracy of 10% will be 10,000 parsecs
*1 parsec = 3.26 light years

Internal & Surface Backgrounds

- Solid detectors:
  - Germanium detectors and solid scintillators grown from high purity materials → low intrinsic background
  - Surface contamination from radon decay products (α, β decay), K, Rb
  - Cosmic activation

- Liquid detectors:
  - Cosmogenic-activated radioactive isotopes contained in the target nuclei
    - Argon: ^{39}Ar (565 keV endpoint, 1 Bq/kg), ^{42}Ar
    - Xenon: ^{127}Xe (short lived), ^{136}Xe ββ decay ($T1/2 = 2.2x10^{21}$ yr) long lifetime
    - Rn, ^{85}Kr (nuclear power plants, weapons) contamination of targets
  - Radon emanated from materials containing U, TH, diffuses into target
  - Remove using cryogenic distillation/chromatography/centrifuges

Spin-independent Results