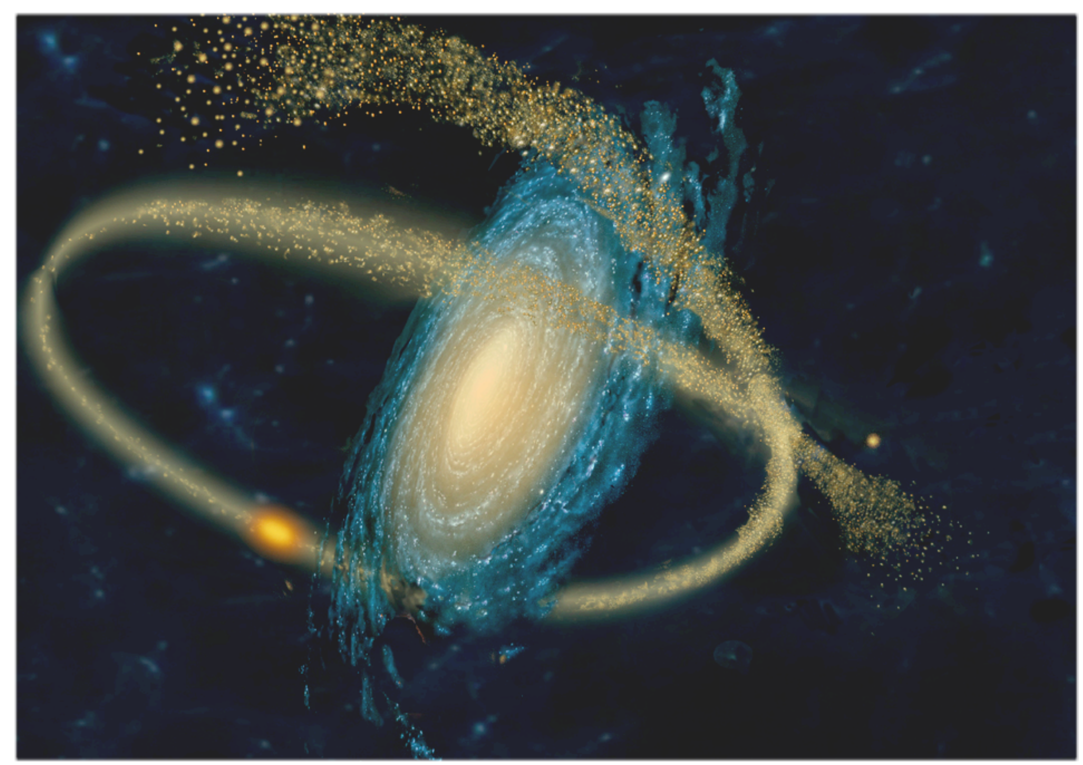
Direct dark matter detection experiments: an overview

Laura Baudis
University of Zurich

Solvay-Francqui workshop on neutrinos
Brussels, May 27-29, 2015

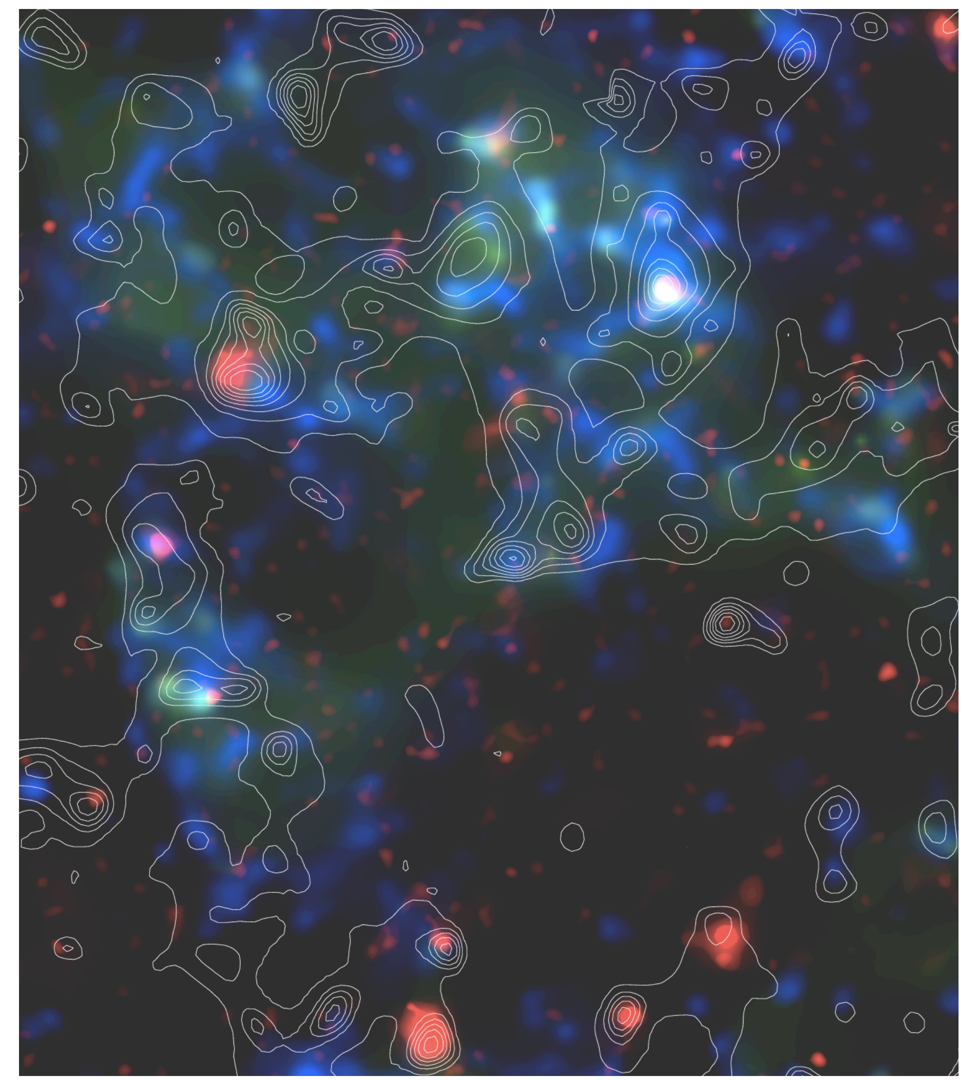


The dark matter puzzle

The dark matter puzzle is *fundamental*: dark matter leads to the formation of structure and galaxies in our universe

We have a standard model of CDM, from 'precision cosmology' (CMB, LSS): however, *measurement ≠ understanding*

For ~85% of matter in the universe is of unknown nature



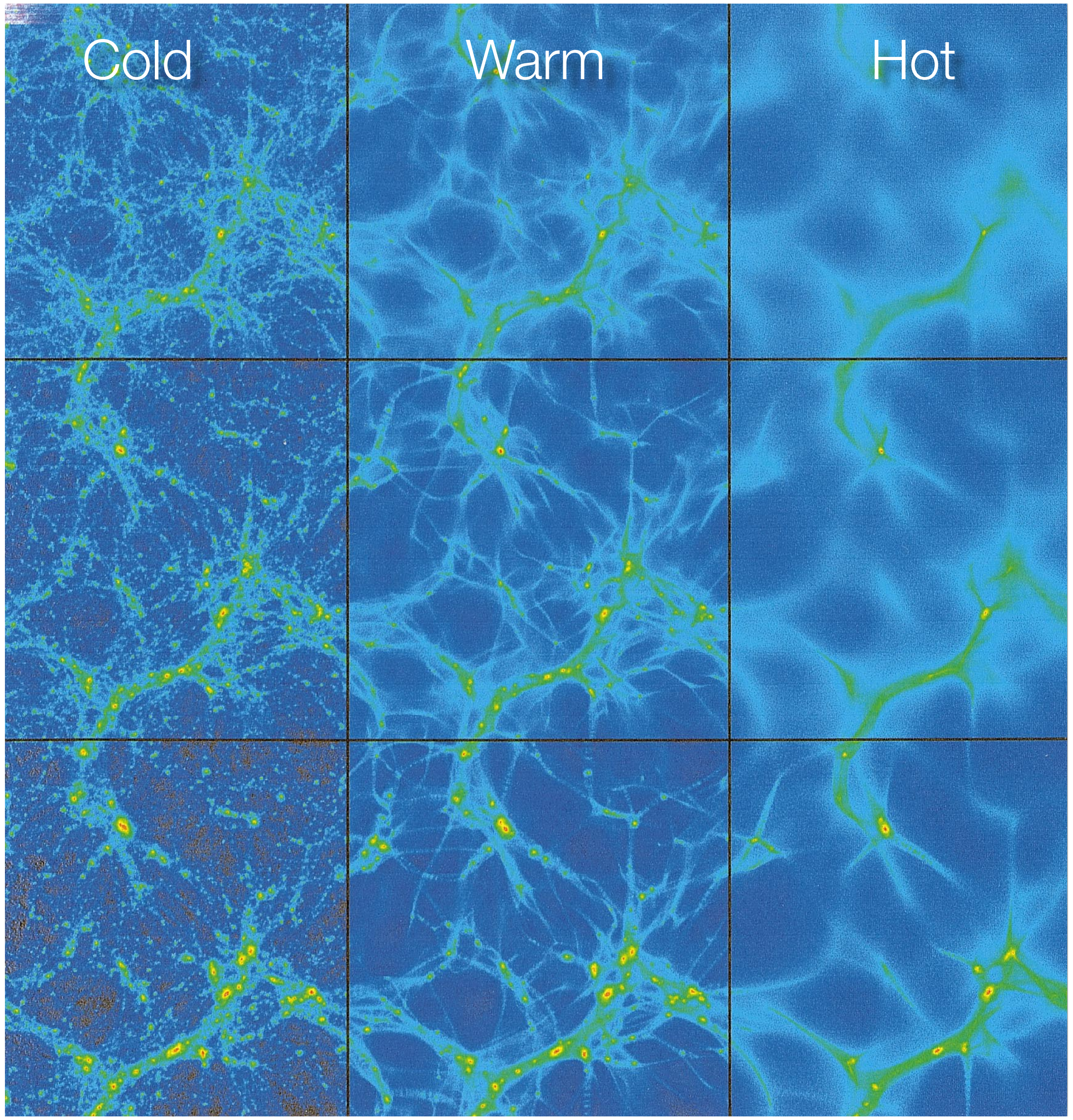
What do we know about the dark matter?

So far, we mostly have “negative” information

Constraints from astrophysics and searches for new particles:

- No colour charge
- No electric charge
- No strong self-interaction

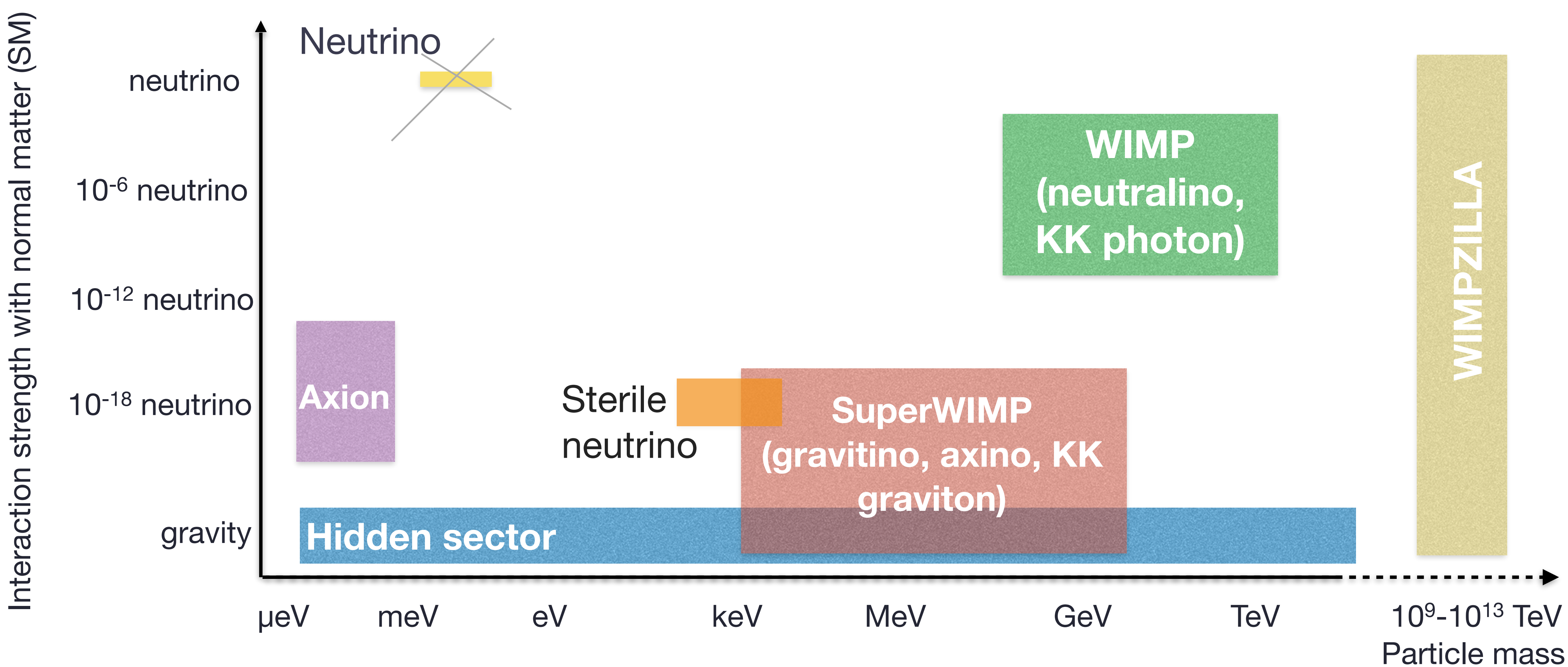
Stable, or very long-lived



Probing dark matter through gravity

What do we know about the dark matter?

- The mass and cross section span many orders of magnitude



How to detect Weakly Interacting Massive Particles

Direct detection

nuclear recoils from elastic scattering

dependance on A, J; annual modulation, directionality

local density and v-distribution

Indirect detection

high-energy neutrinos, gammas, charged CRs

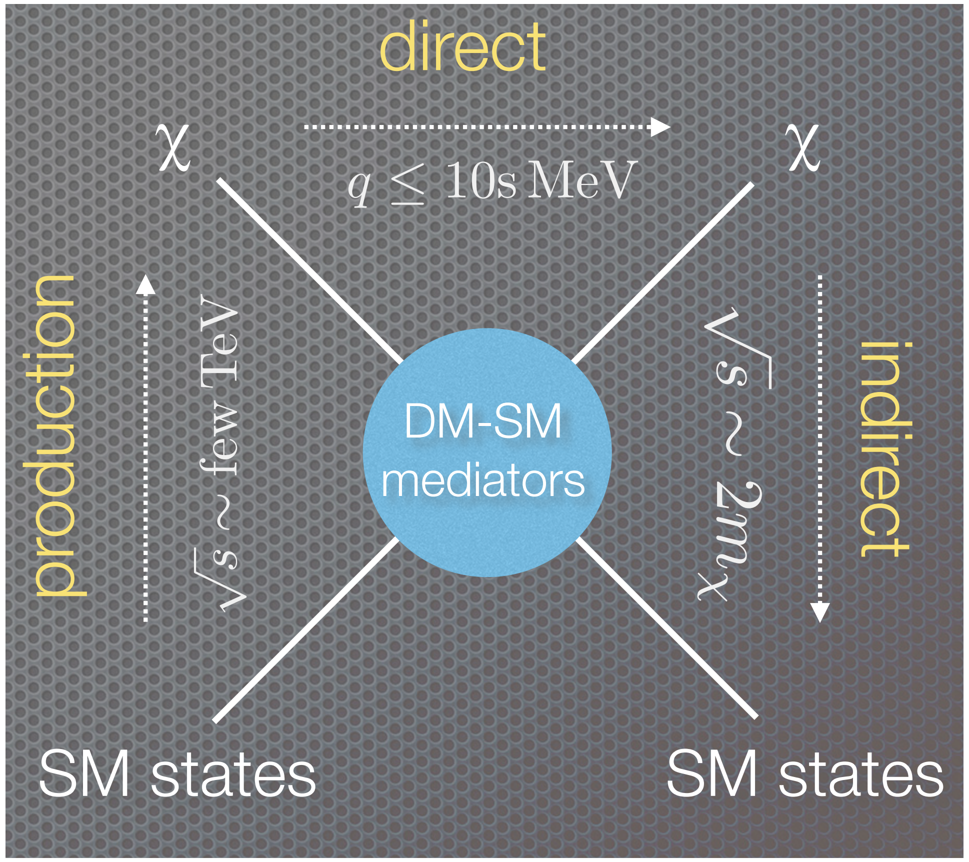
look at over-dense regions in the sky

astrophysics backgrounds difficult

Accelerator searches

missing E_T, mono-‘objects’, etc

can it establish that the new particle is the DM?



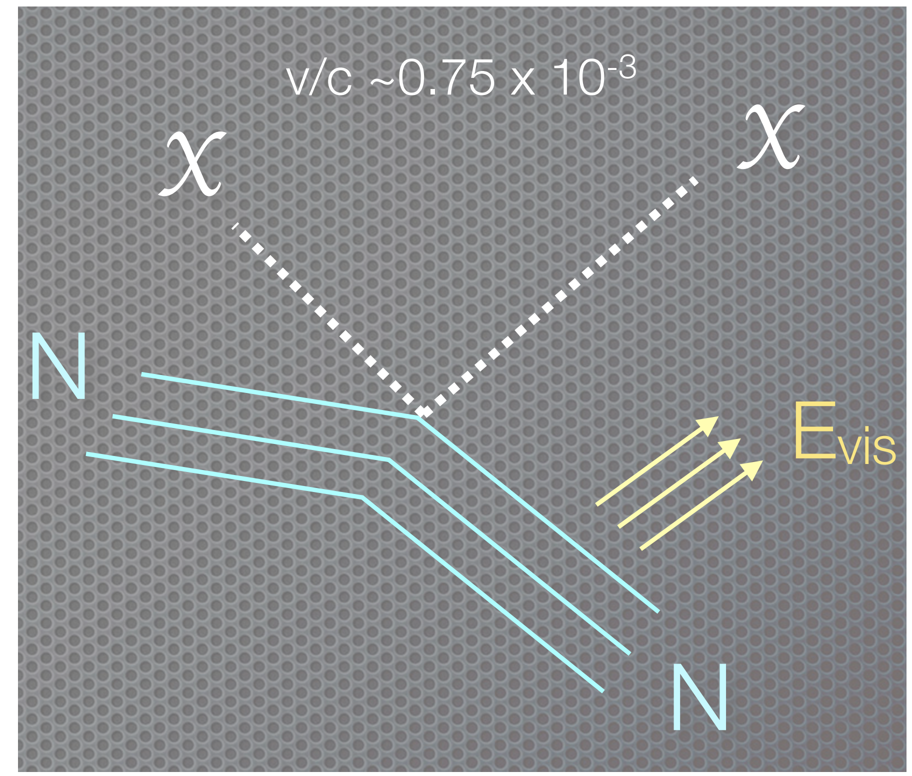
WIMP detection in the laboratory

By searching for collisions of invisibles particles with atomic nuclei => E_{vis} (q ~ tens of MeV)

Need *very low energy thresholds*

Need *ultra-low backgrounds*, good background understanding (no “beam off” data collection mode) and discrimination

Need *large detector masses*



$$E_R = \frac{q^2}{2m_N} < 30\,\mathrm{keV}$$

REVIEW D VOLUME 31, NUMBER 12

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

What do we expect in a terrestrial detector?

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{\sqrt{(m_N E_{th})/(2\mu^2)}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$

Astrophysics

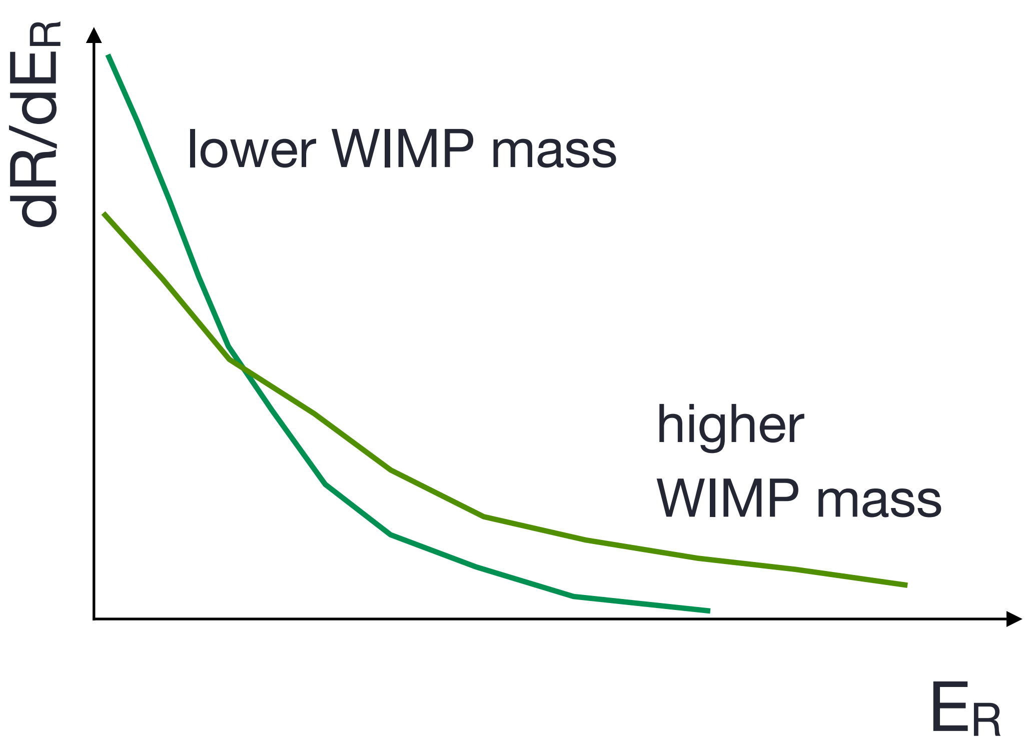
$\rho_0, f(v)$

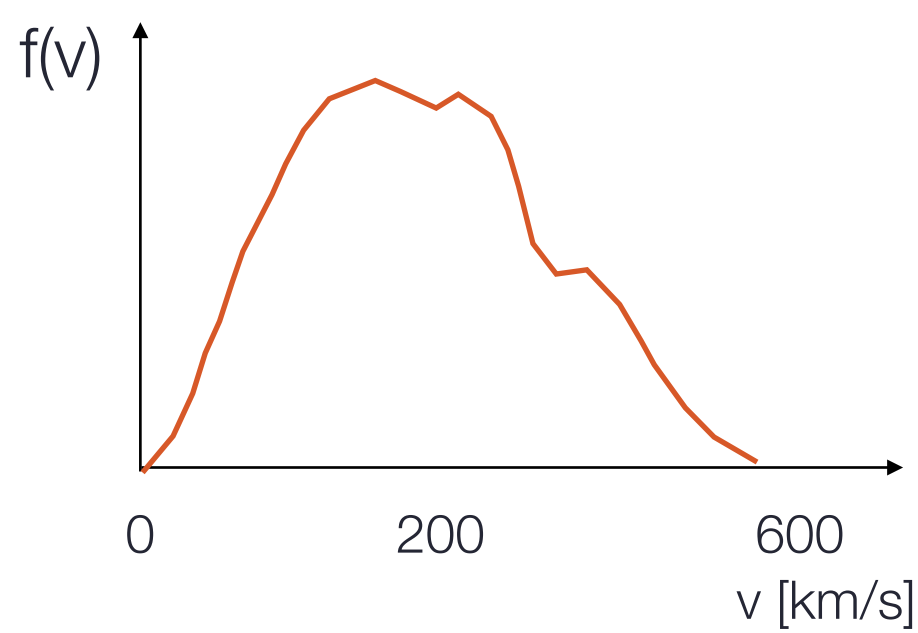
Particle/nuclear physics

$m_W, d\sigma/dE_R$

Detector physics

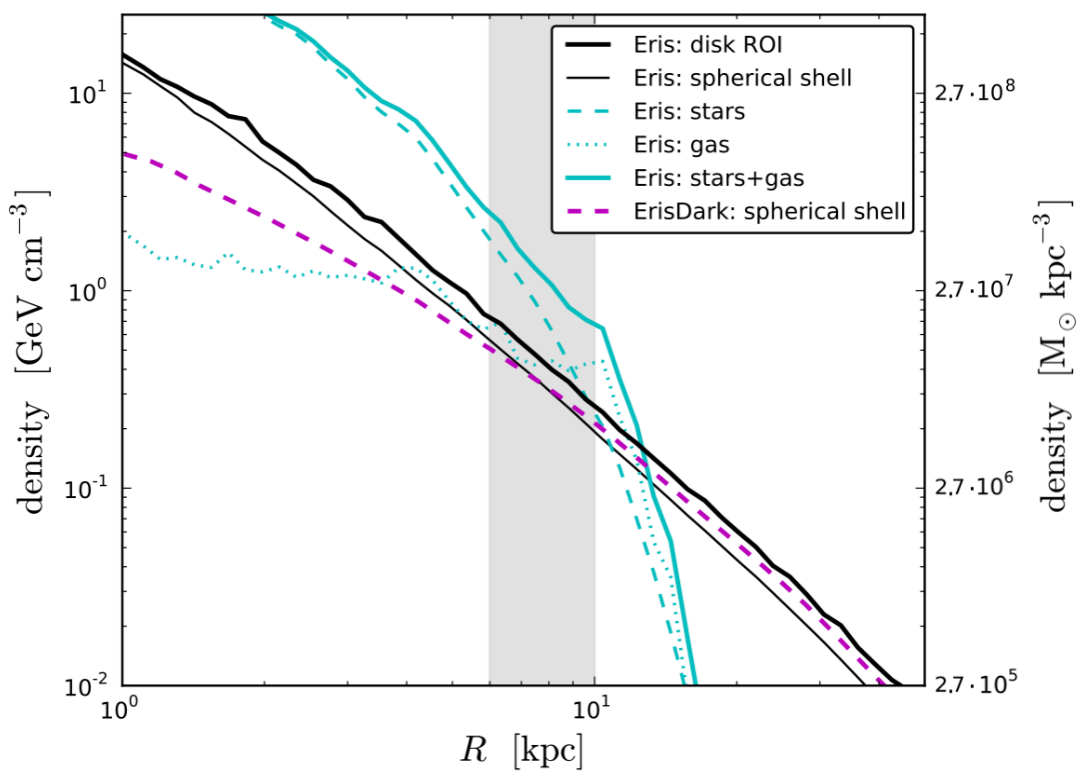
N_N, E_{th}





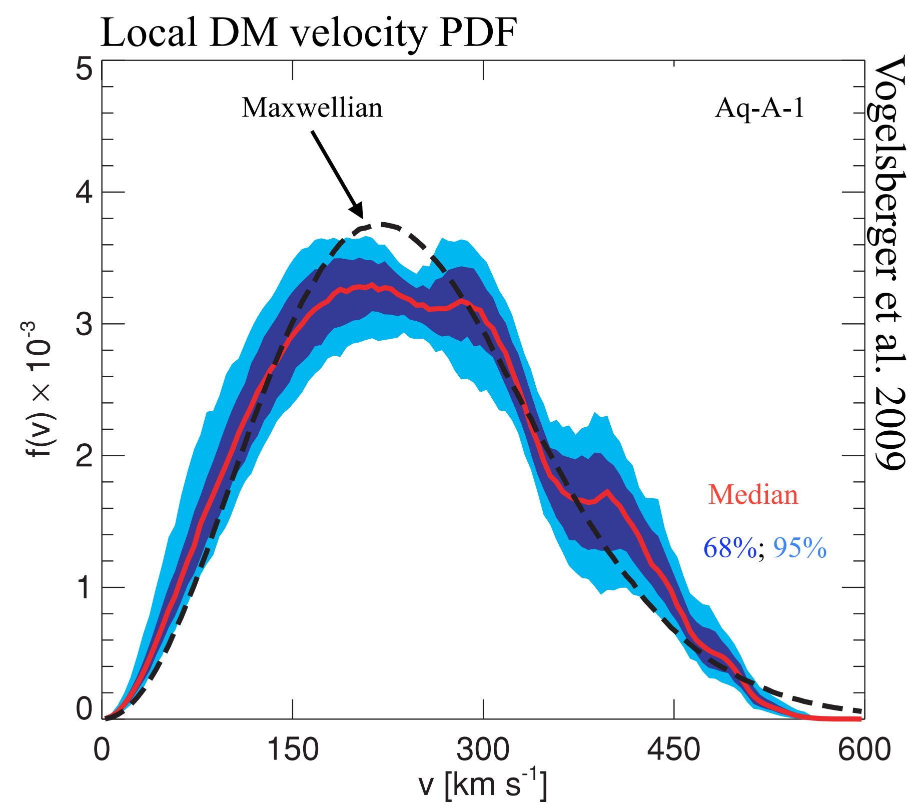
Astrophysics

Dark matter density profile in cosmological MW-like galaxy simulations with baryons (Eris) and DM only (ErisDark)



Pillepich, Kuhlen, Guedes, Madau, The Astrophysical Journal 784, 2014

Velocity distribution of WIMPs in the galaxy



From cosmological simulations of (DM only) galaxy formation: departures from the simplest case of a Maxwell-Boltzmann distribution

$$\rho(R_0) = 0.2 - 0.56\,\mathrm{GeV\,cm^{-3}} = 0.005 - 0.015\,\mathrm{M_\odot\,pc^{-3}}$$

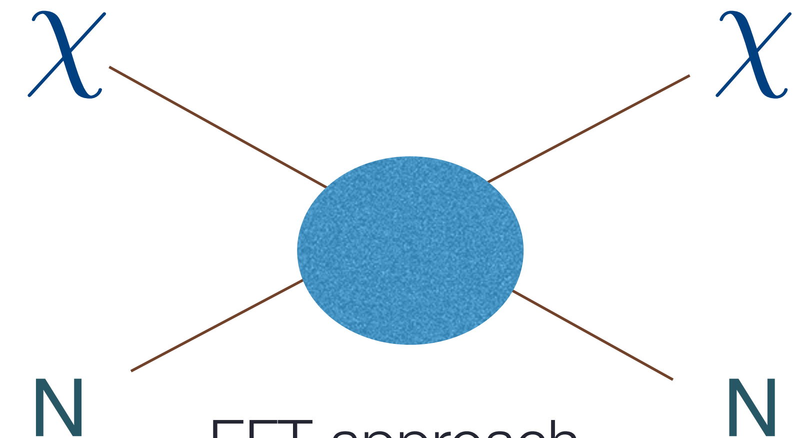
Survey by J. Read, J.Phys. G41 (2014) 063101

=> WIMP flux on Earth: ~10^5 cm^{-2}s^{-1} (M_W=100 GeV, for 0.3 GeV/cm^3)

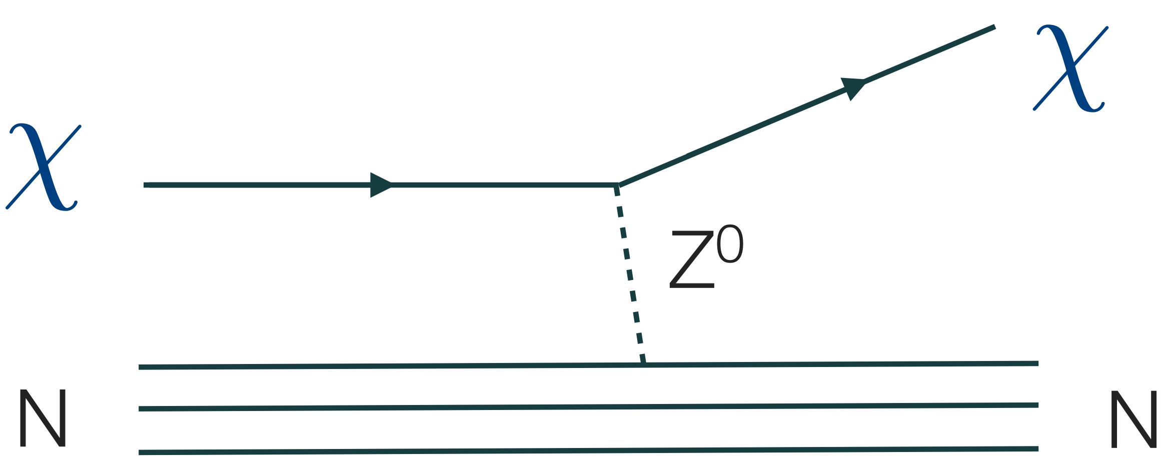
Particle Physics

- Use effective operators to describe WIMP-quark interactions
- Example: vector mediator $\mathcal{L}_{\chi}^{\text{eff}} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$
- The effective operator arises from integrating out the mediator with mass M and couplings g_q and g_χ to the quark and the WIMP:

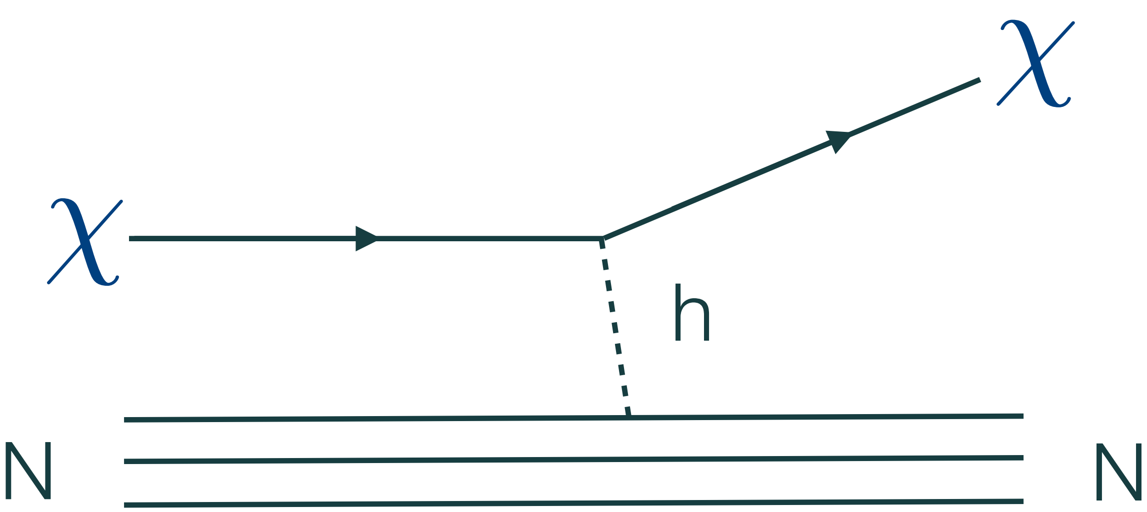
$$\Lambda = \frac{M}{\sqrt{g_q g_\chi}} \quad \Rightarrow \sigma_{\text{tot}} \propto \Lambda^{-4}$$



EFT approach (always valid for direct detection)



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



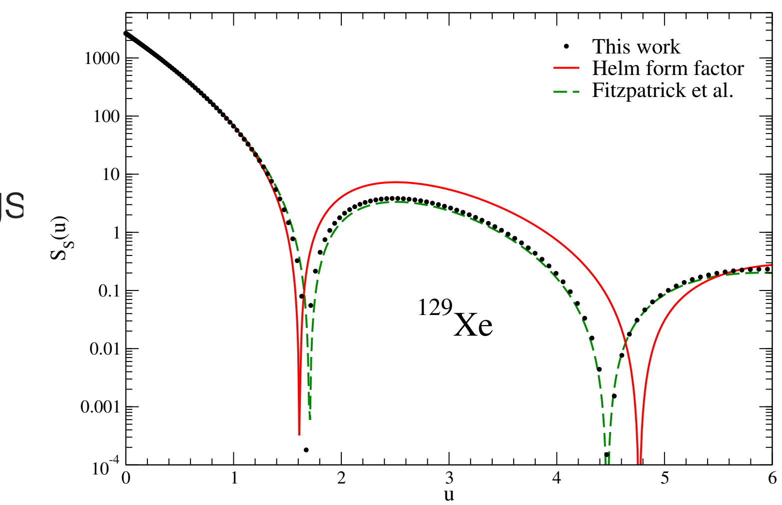
$$\sigma_0 \sim 10^{-45}\text{cm}^2$$

Scattering cross section

- In general, interactions leading to WIMP-nucleus scattering are parameterized as:
  - scalar interactions (coupling to WIMP mass, from scalar, vector, tensor part of L)

$$\sigma_{SI} \sim \frac{\mu^2}{m_\chi^2}\left[Z f_p + (A-Z) f_n\right]^2$$

f_p, f_n: scalar 4-fermion couplings to p and n



A. Schwenk et al., arXiv 1412.6091

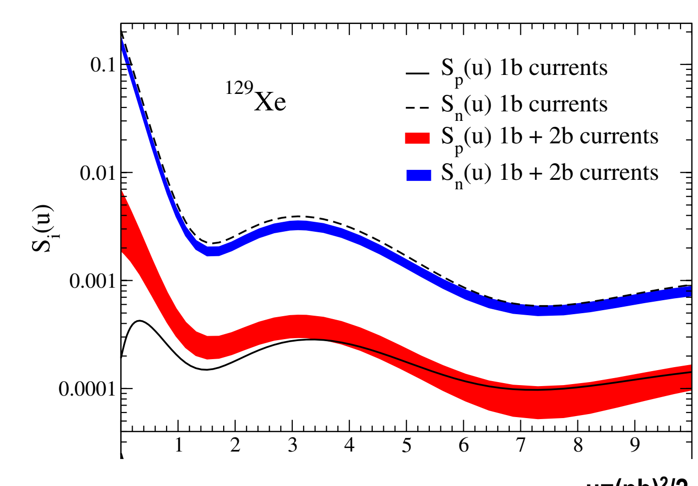
=> nuclei with large A - but nuclear form factor corrections

  - spin-spin interactions (coupling to the nuclear spin JN, from axial-vector part of L)

$$\sigma_{SD} \sim \mu^2 \frac{J_N+1}{J_N}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2$$

a_p, a_n: effective couplings to p and n; $\langle S_p\rangle$ and $\langle S_n\rangle$ expectation values of the p and n spins within the nucleus

=> nuclei with non-zero angular momentum - corrections due to spin structure functions

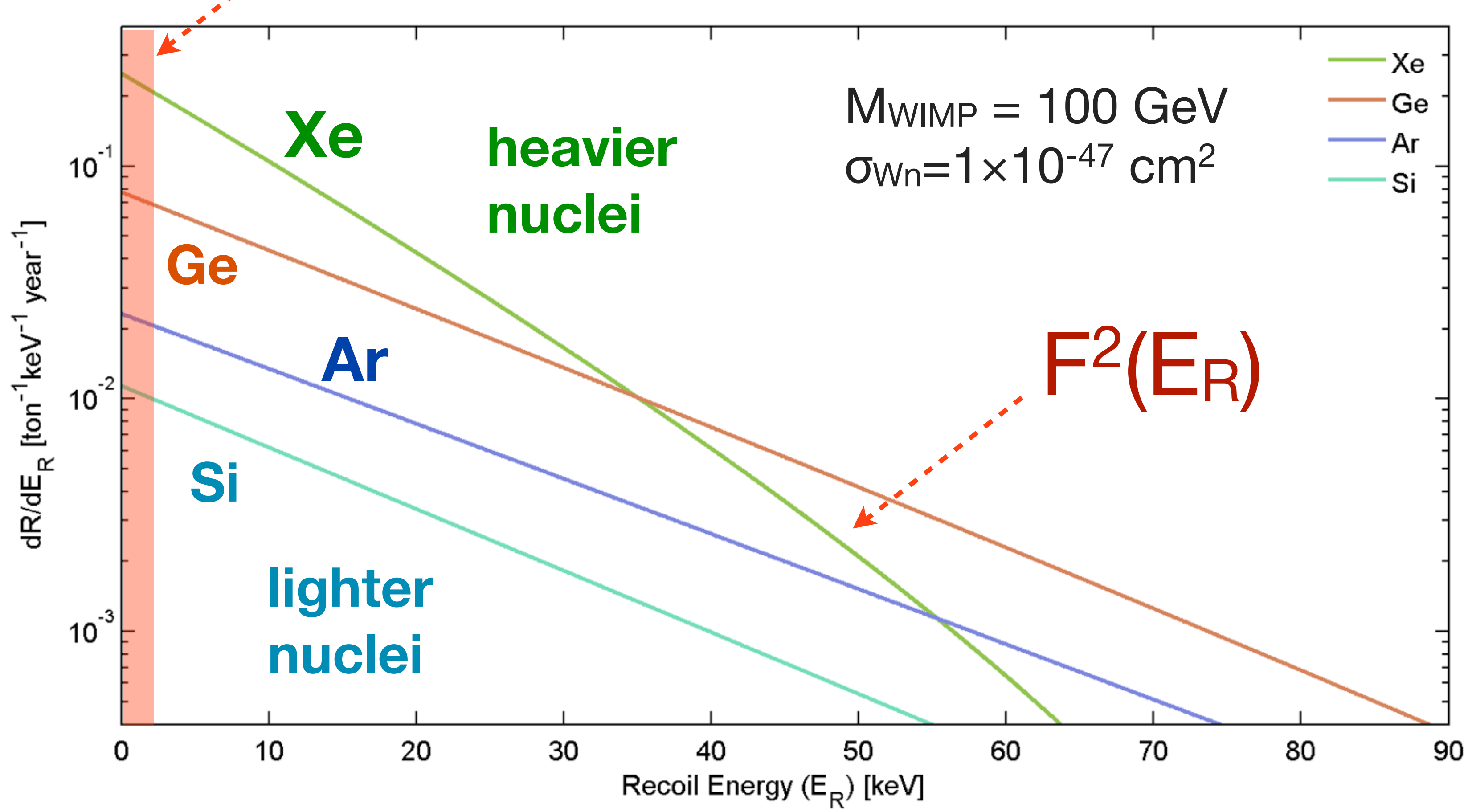


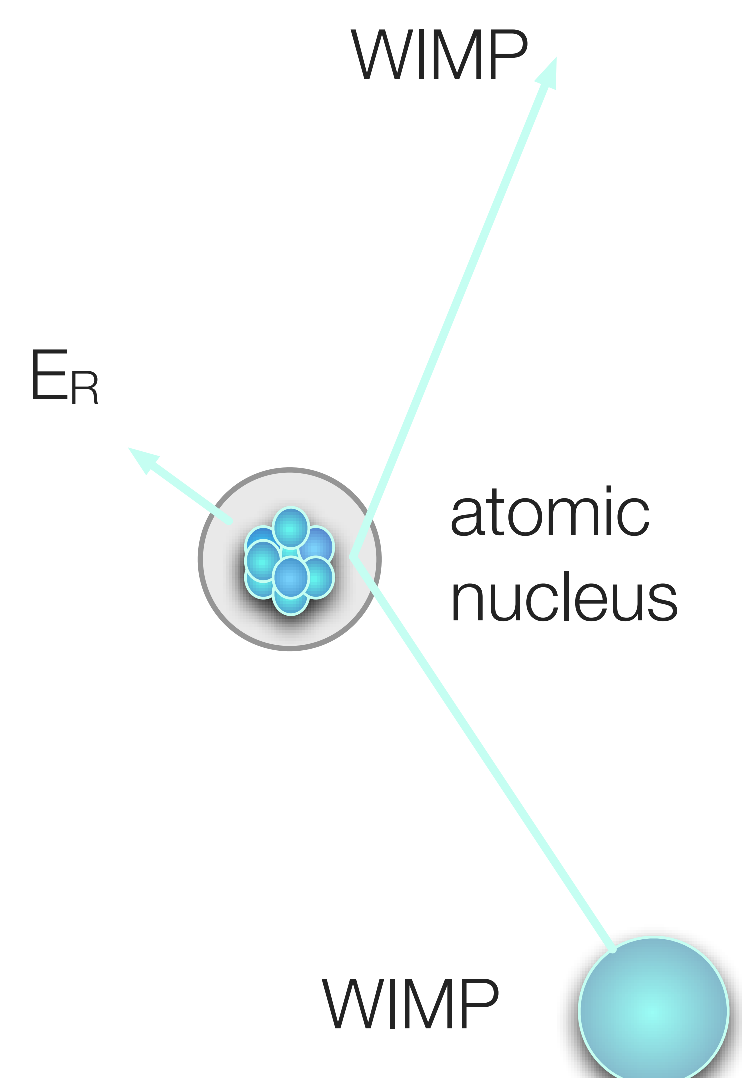
A. Schwenk et al., PRD 88 (2013)

Expected interaction rates

$$R \sim 0.13 \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$

$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu^2}}$$

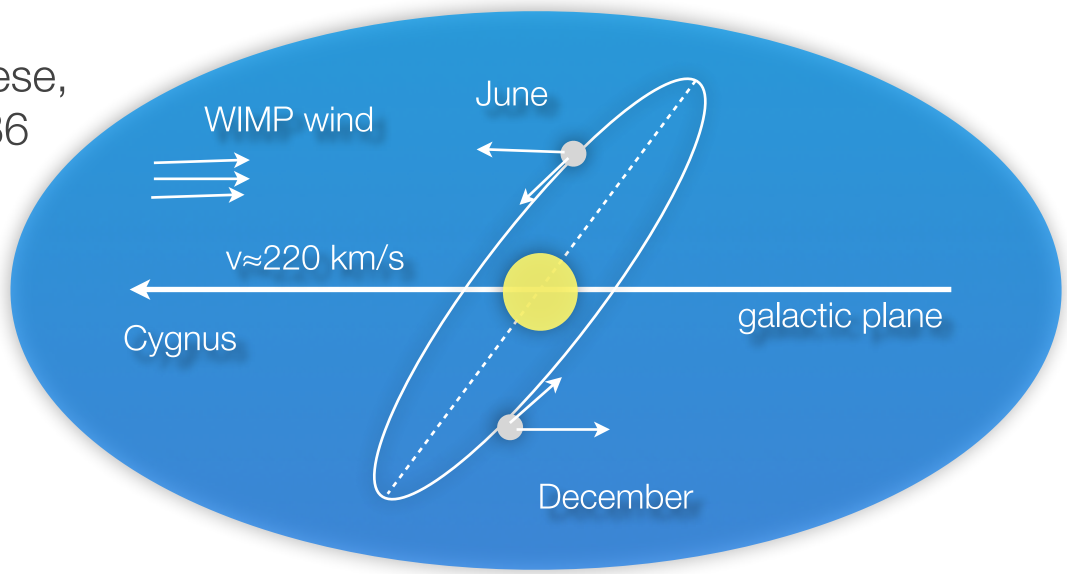


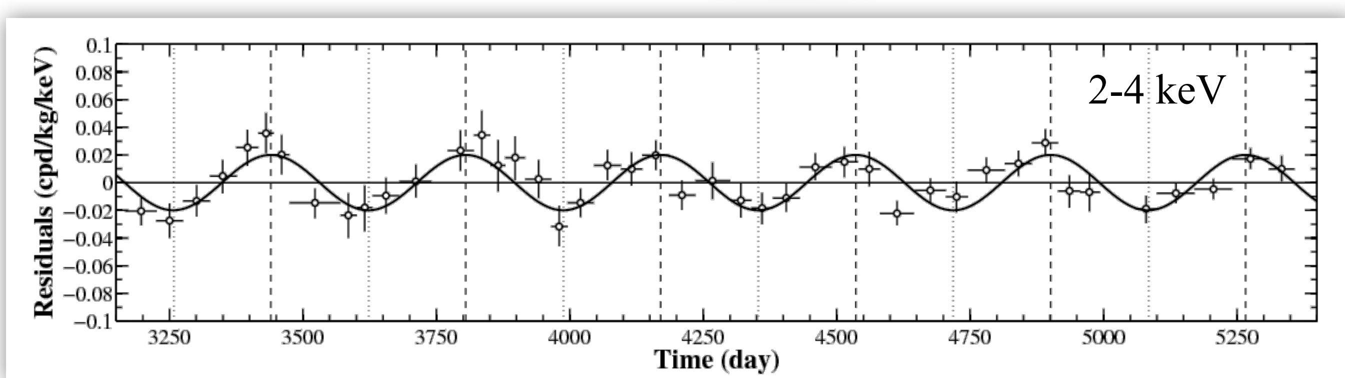


Dark matter signatures

- Rate and shape of recoil spectrum depend on target material
- Motion of the Earth causes:
  - temporal variation in rate: June - December ~ 2-10%
  - directional modulation asymmetry: ~20-100% in forward-backward event rate

Drukier, Freese, Spergel 1986





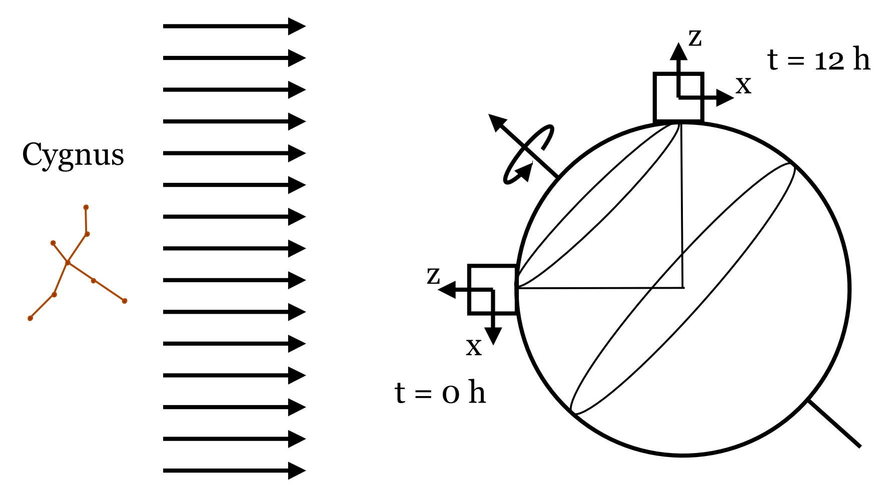
R. Bernabei et al, EPJ-C67 (2010)

D. Spergel 1988

Motion of the Earth and the detection of weakly interacting massive particles

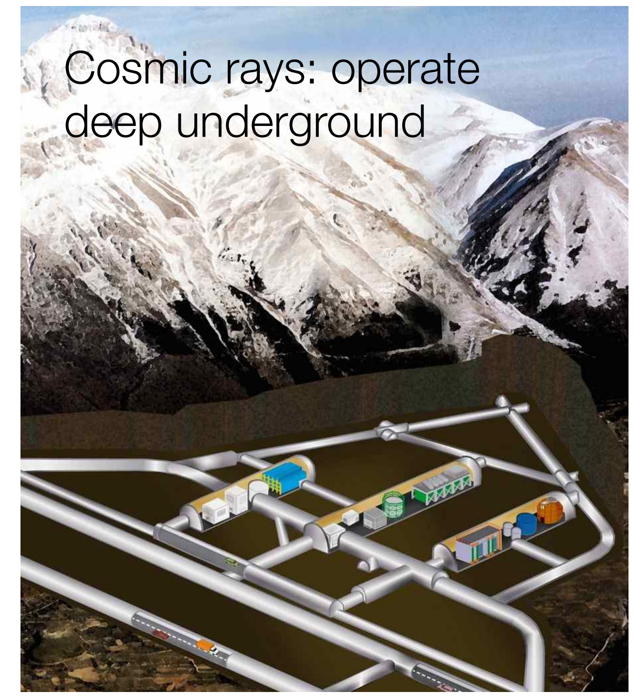
David N. Spergel*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 21 September 1987)

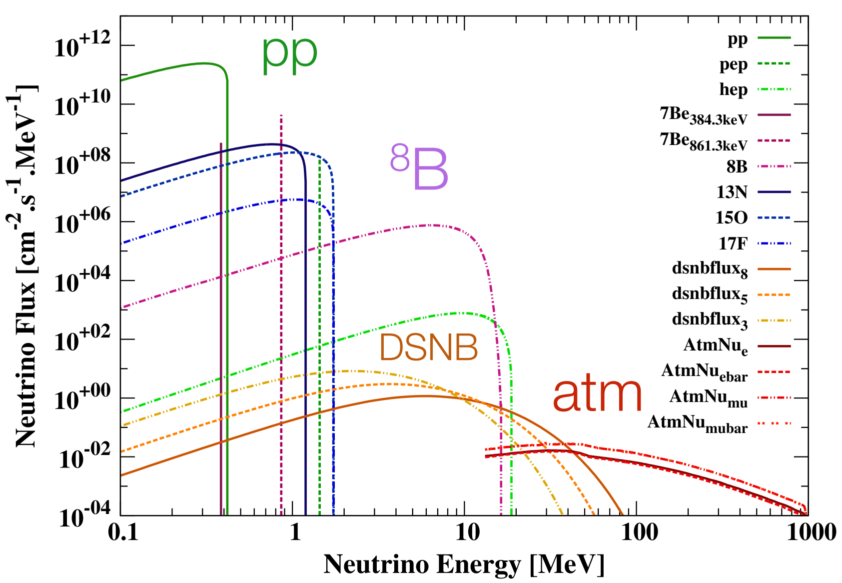
If the galactic halo is composed of weakly interacting massive particles (WIMP's), then cryogenic experiments may be capable of detecting the recoil of nuclei struck by the WIMP's. Earth's motion relative to the galactic halo produces a seasonal modulation in the expected event rate. The direction of nuclear recoil has a strong angular dependence that also can be used to confirm the detection of WIMP's. I calculate the angular dependence and the amplitude of the seasonal modulation for an isothermal halo model.

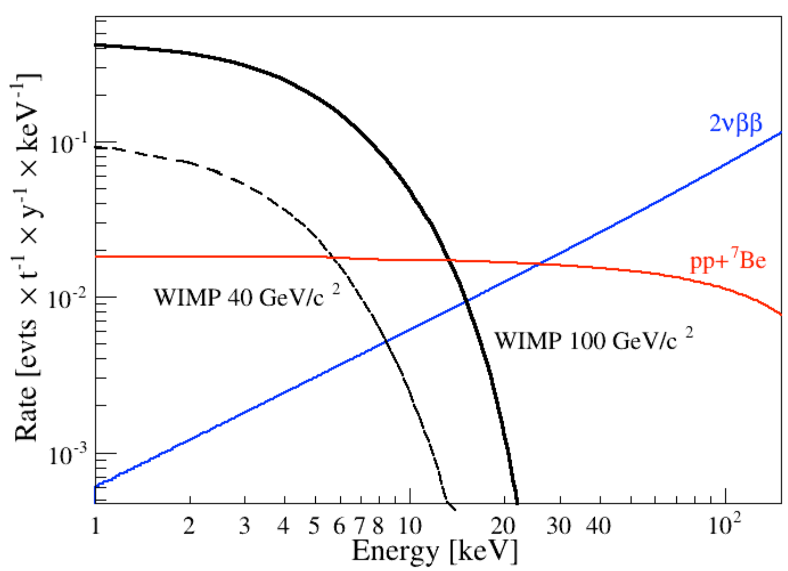


Expected backgrounds

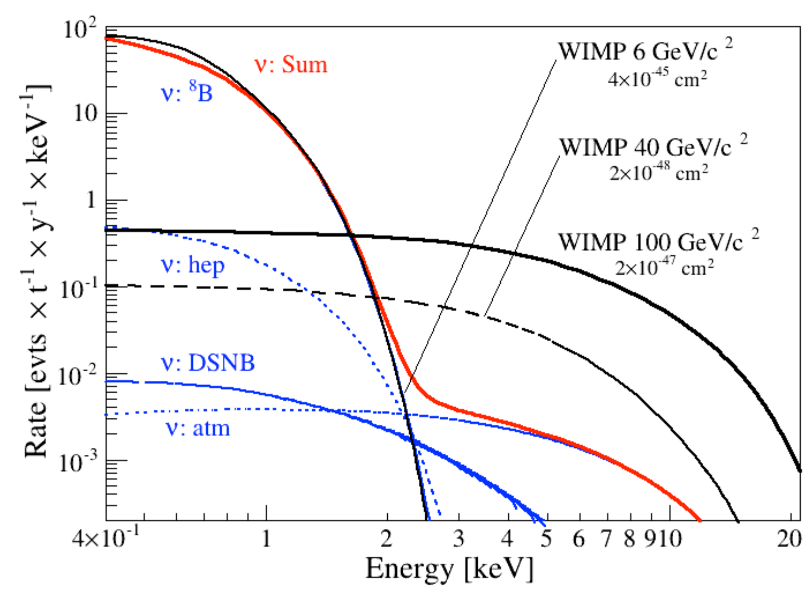
- Cosmic rays & cosmic activation of detector materials
- Natural (^{238}U, ^{232}Th, ^{40}K) & anthropogenic (^{85}Kr, ^{137}Cs) radioactivity
- Ultimately: solar, atmospheric and supernovae neutrinos







$$\nu + e^- \to \nu + e^-$$

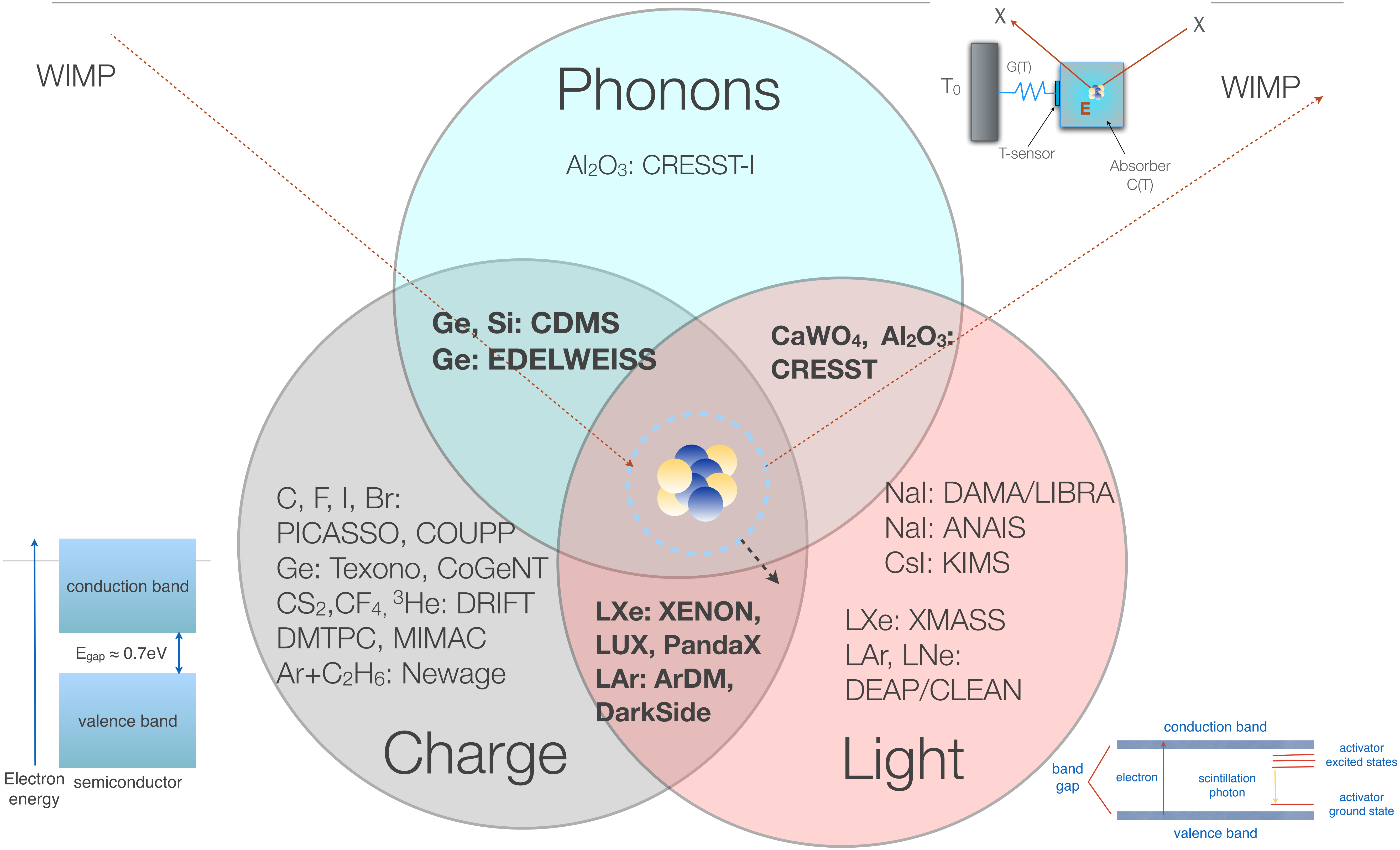


$$\nu + N \to \nu + N$$

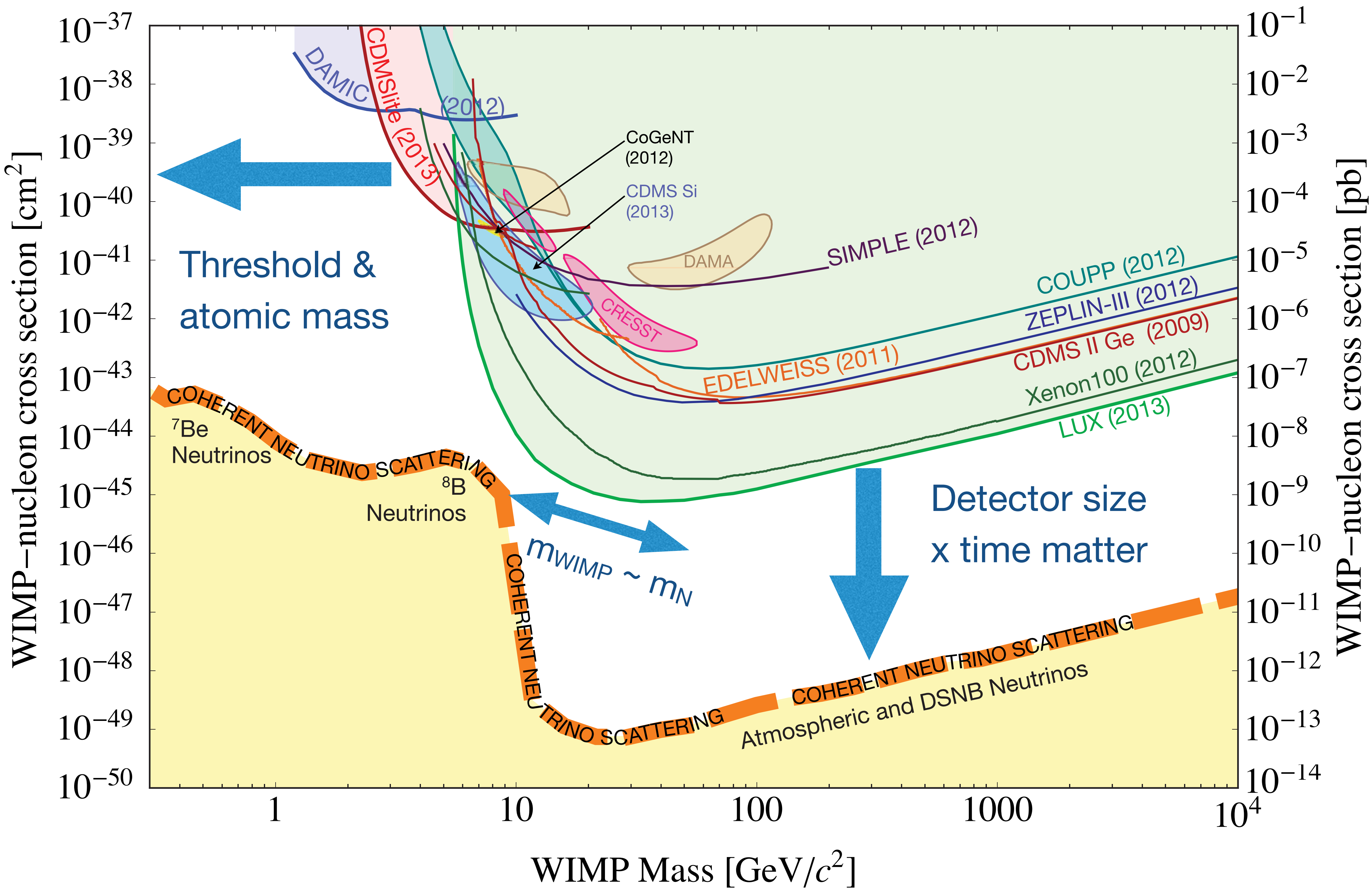
F. Ruppin et al., 1408.3581

LB et al., JCAP01 (2014) 044

Direct Detection Techniques

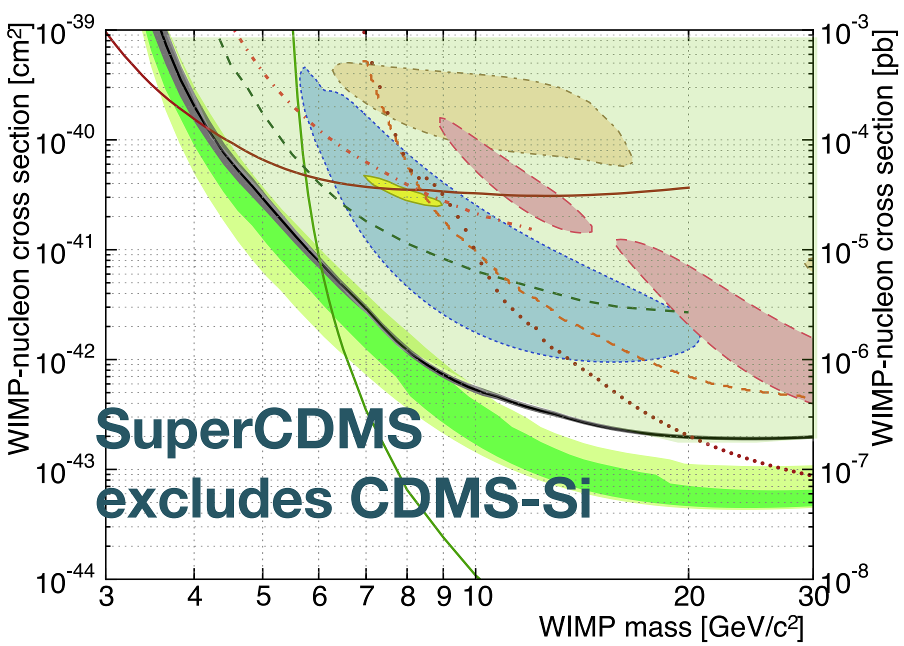


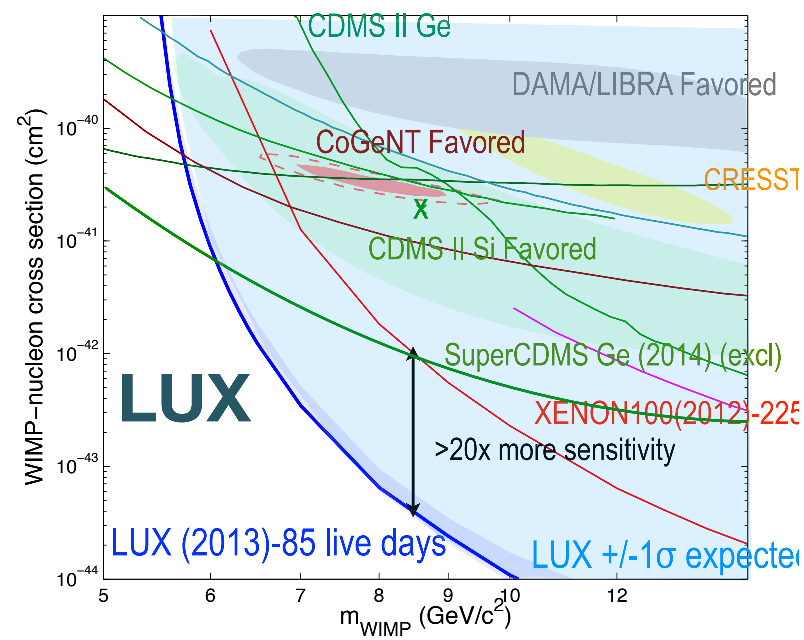
The WIMP landscape in 2015

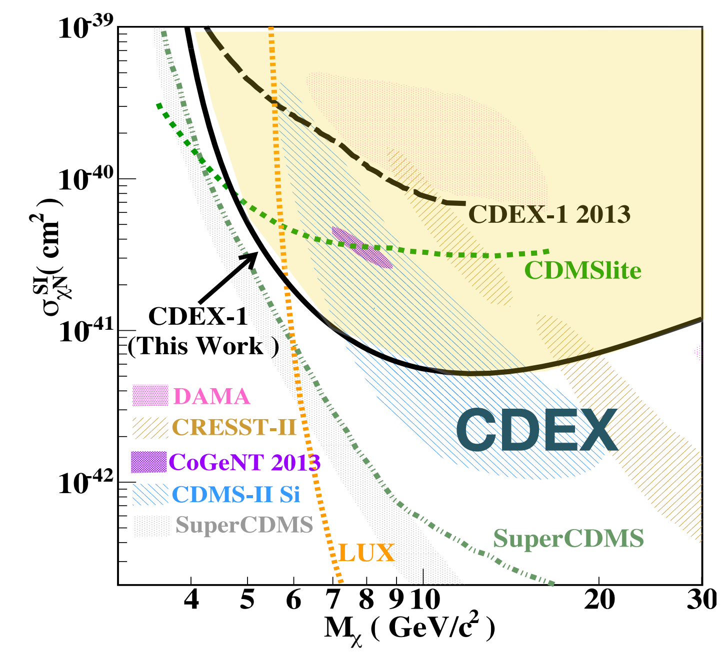


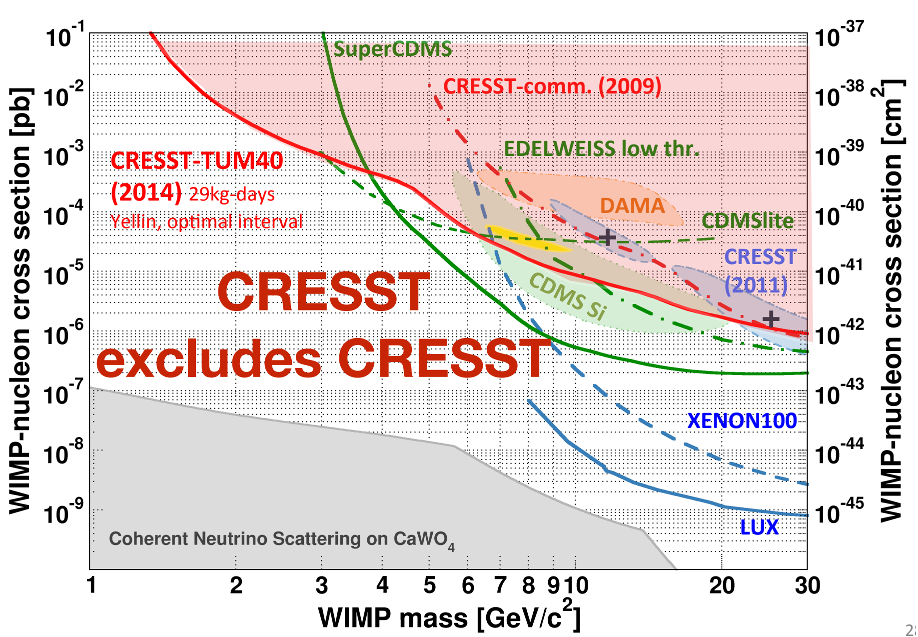
Low mass region

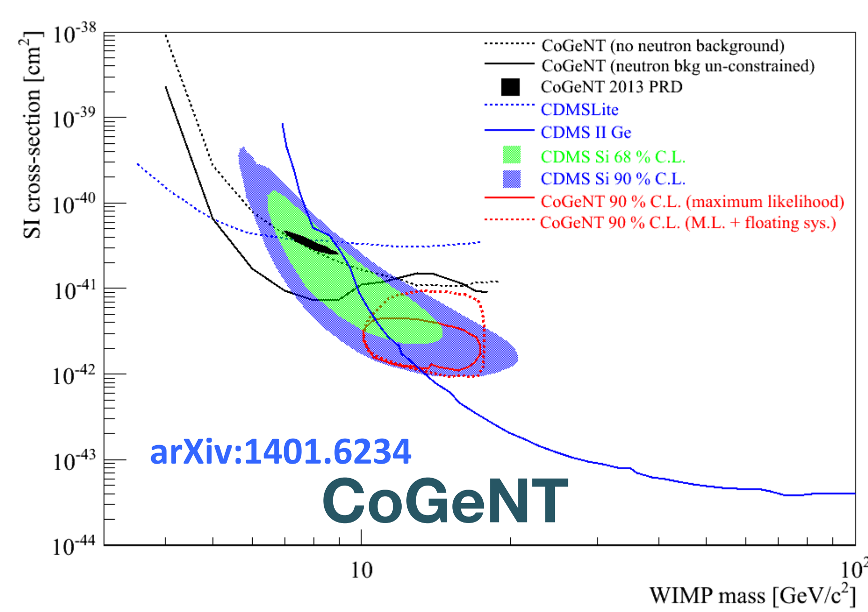
- “Anomalies” heavily constrained by many experiments & techniques

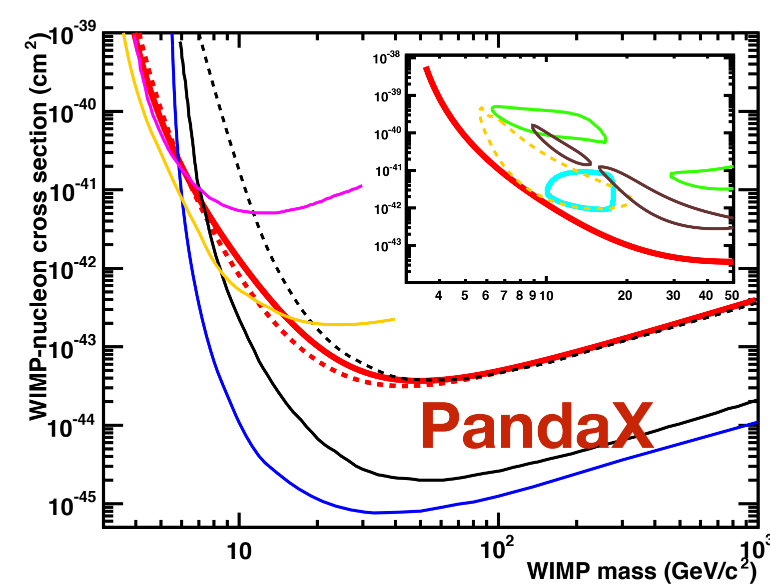






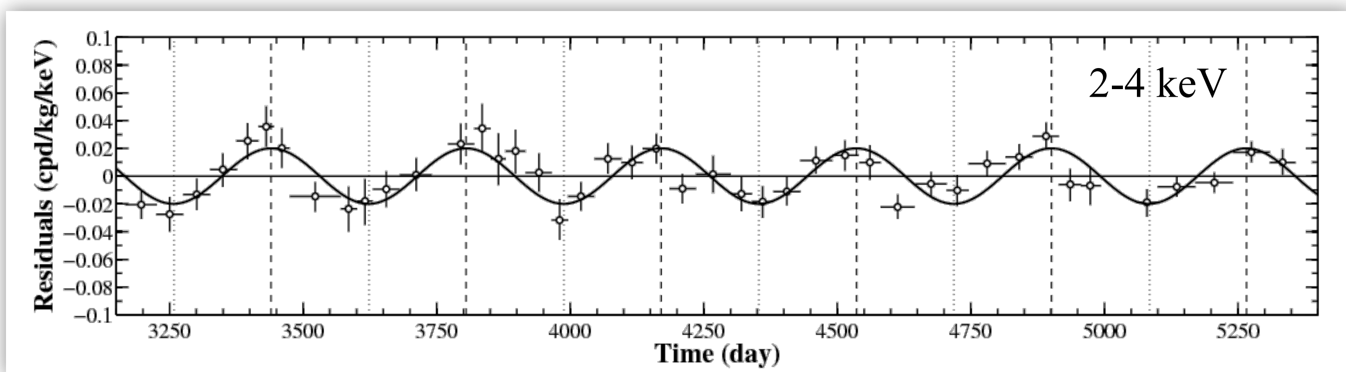




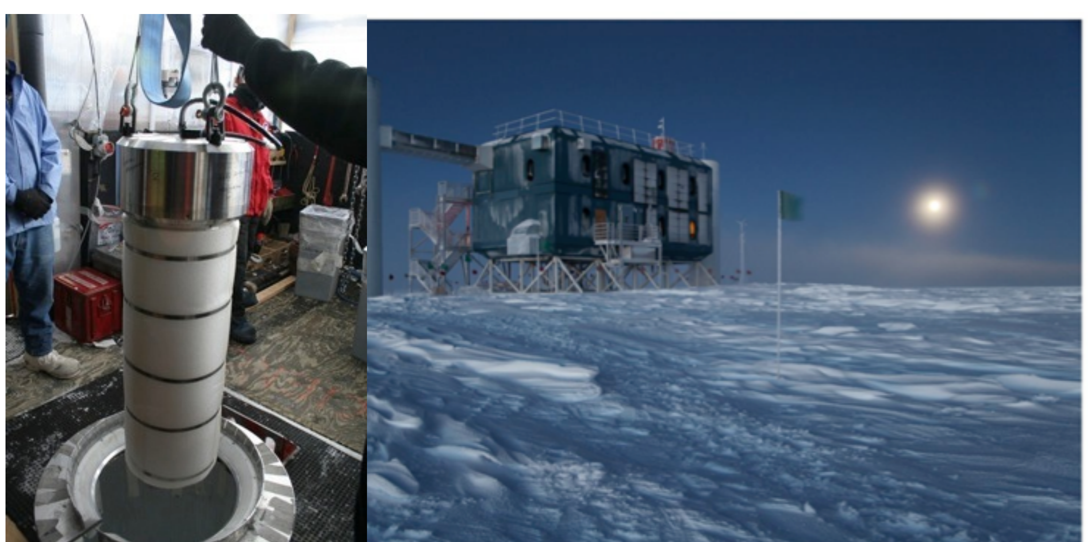


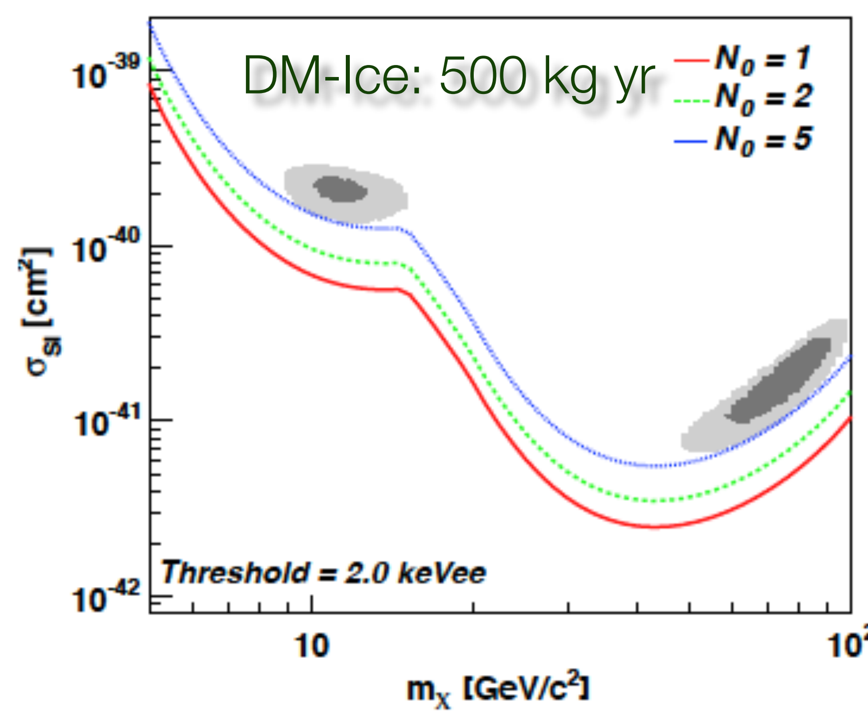
DAMA/LIBRA annual modulation signal

- Period = 1 year, phase = June 2 ± 7 days
- Several experiments to directly probe the modulation signal with similar detectors (NaI, CsI): SABRE, ANAIS, DM-Ice, KIMS



R. Bernabei et al, EPJ-C67 (2010)



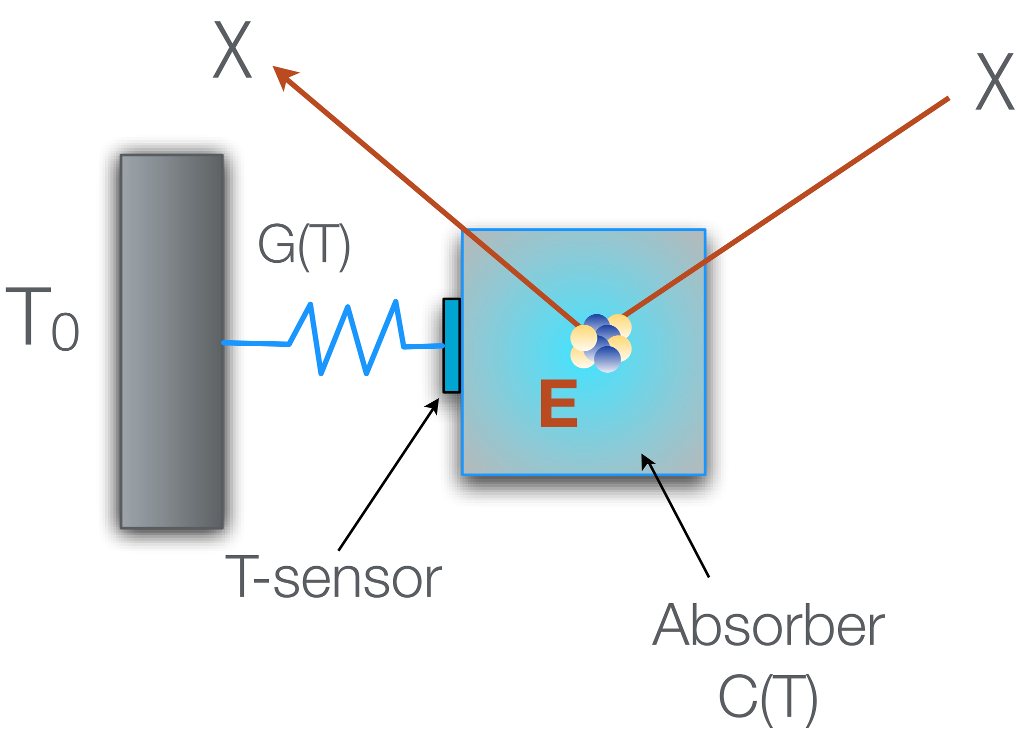


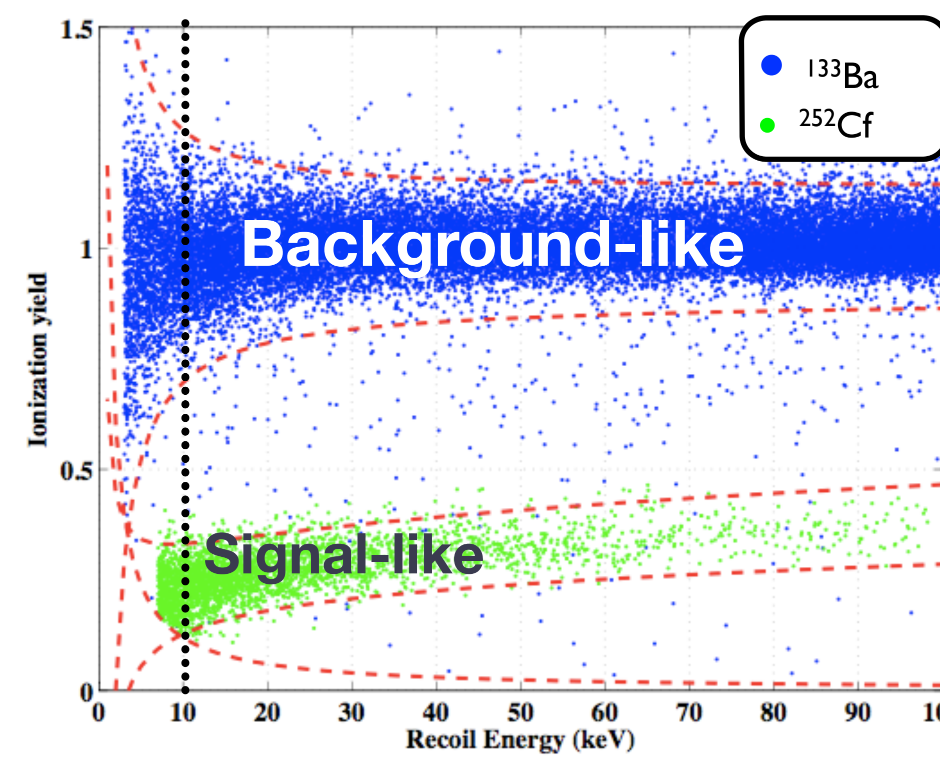
Definitive (5σ) detection or exclusion with 500 kg-yr NaI(Tl) (DAMA x 2 yrs) and same or lower threshold (< 2 keV_{ee})

Cryogenic Detectors at T ~ mK

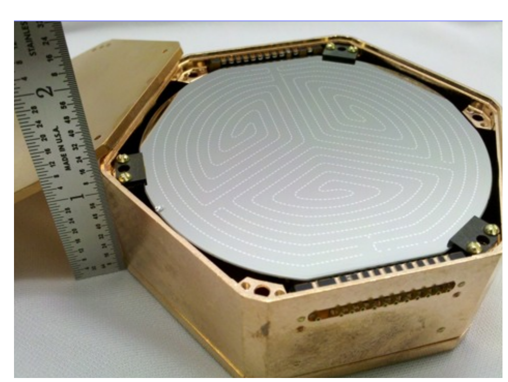
- Absorber masses from ~100 g to 1.4 kg; TES read out small T changes

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

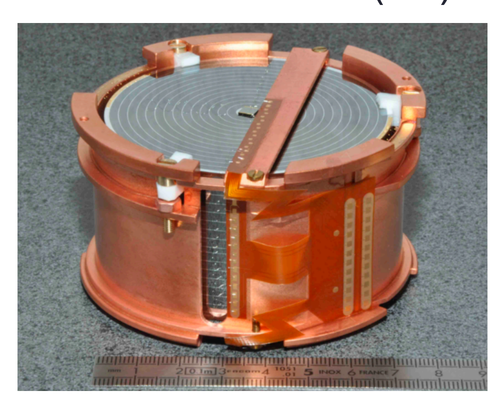




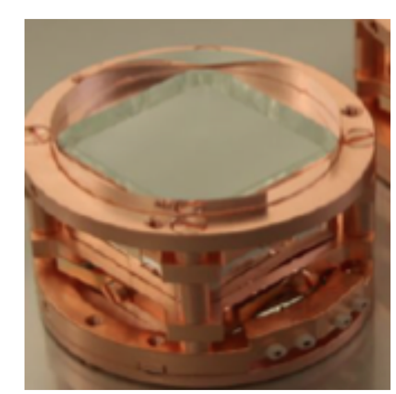
SuperCDMS: Ge, Si



EDELWEISS-III (Ge)

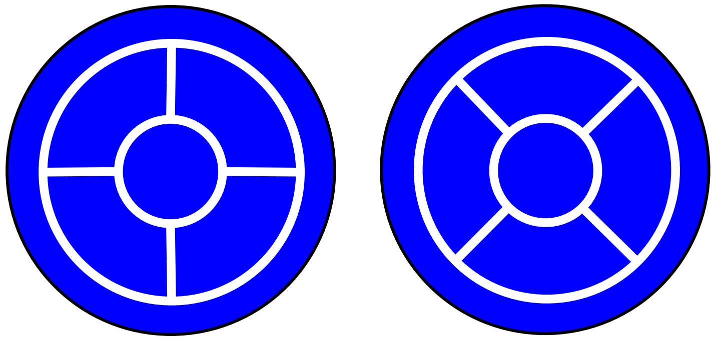


CRESST ($CaWO_4$)

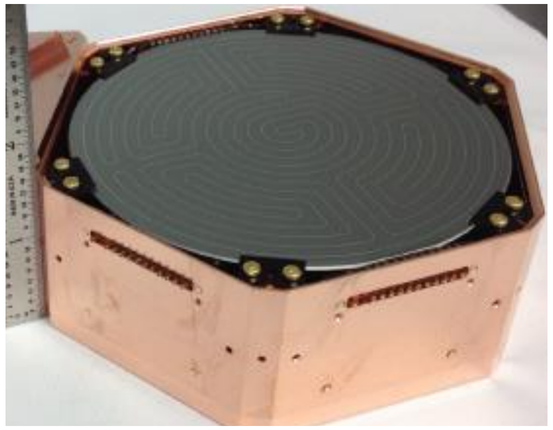


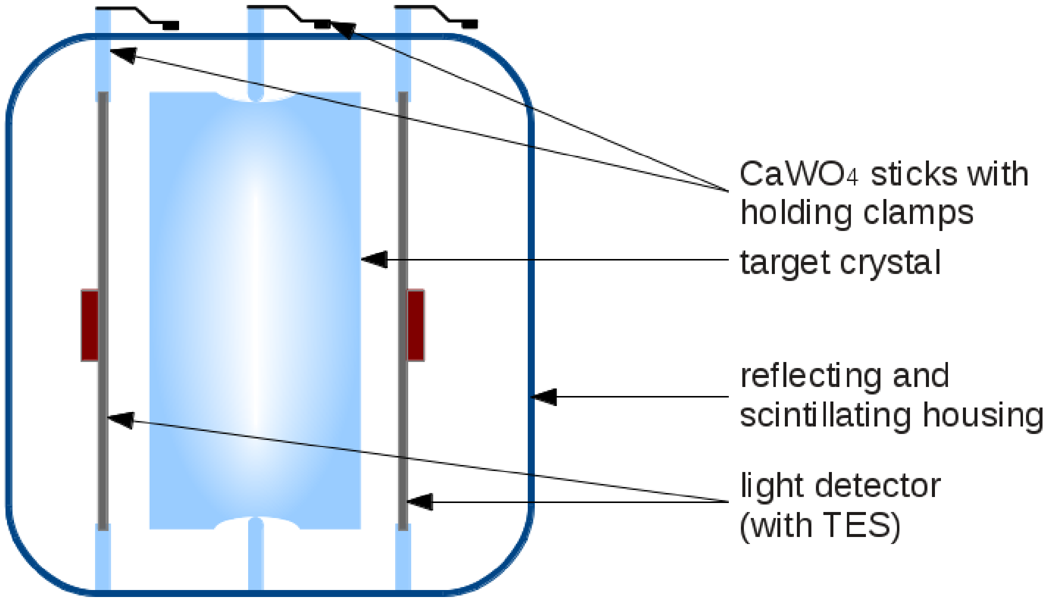
Phonon & ionisation/scintillation sensors

- SuperCDMS: iZIPs (1.4 kg Ge, 615 g Si), interleaved ionisation and phonon sensors: 2 x (6 phonon, 6 ionisation)
- EDELWEISS-III: operates new fully inter-digitised FID800 sensors
- CRESST: strategy change -> reduce volume of the target crystal (24 g) and optimise detector layout => gain sensitivity for low WIMP masses (1 - 6 GeV)



SuperCDMS: Ge, Si iZIPs





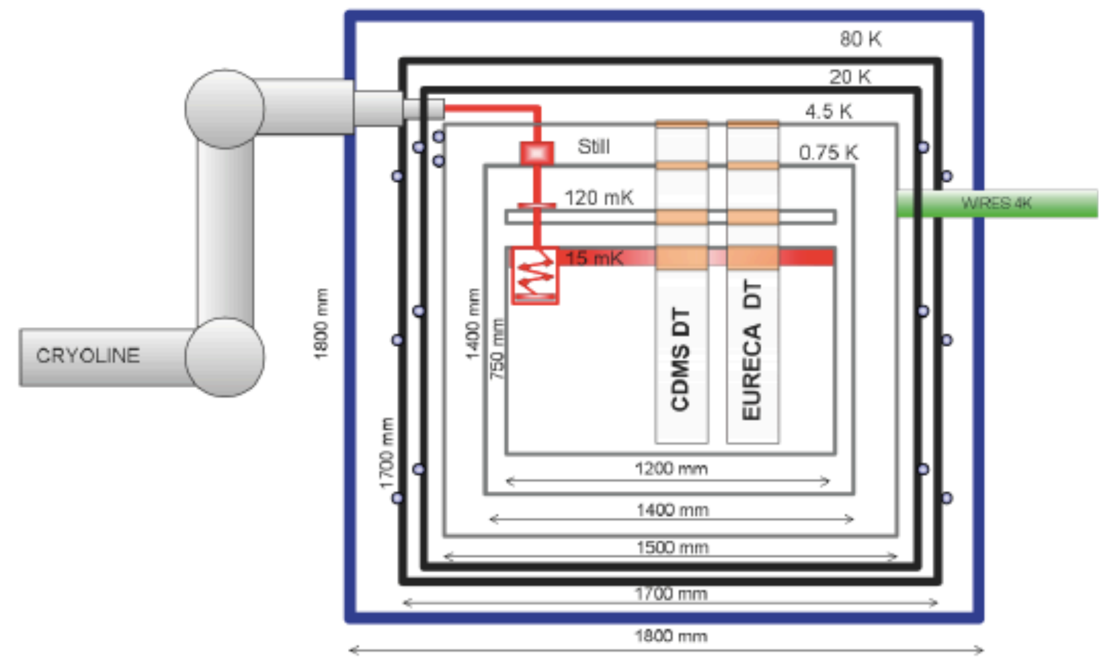
arXiv:1503.08065 [astro-ph.IM]

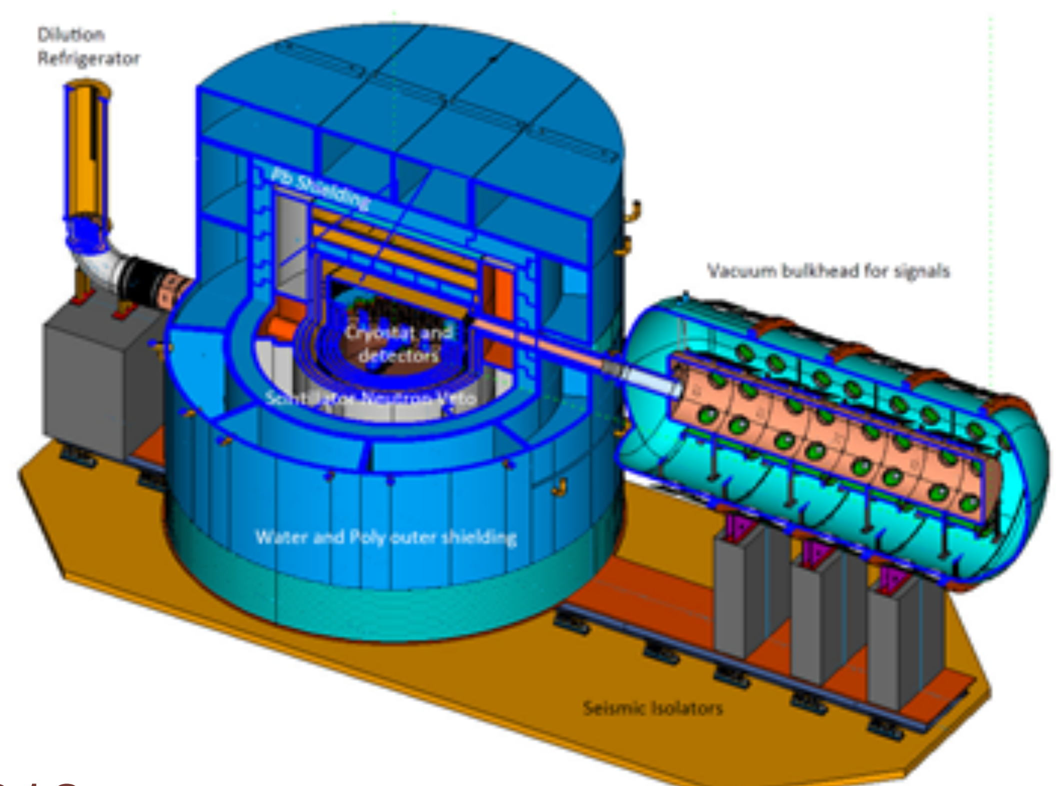
CRESST: $CaWO_4$

Edelweiss: Ge FID

SNOLAB cryostat and shield design

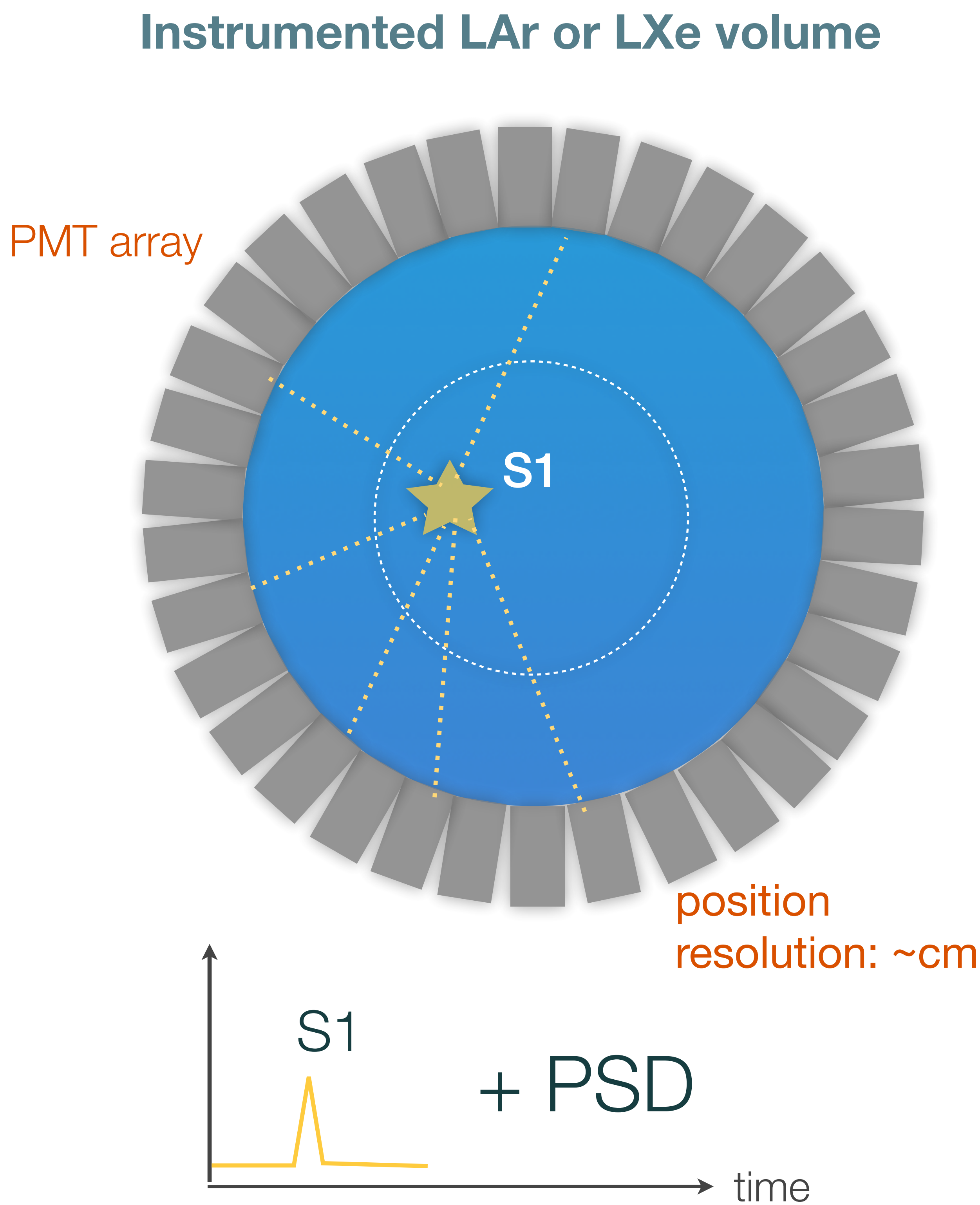
- Experience based on CRESST/EDELWEISS/ CDMS cryostats & shields
- SuperCDMS shield: to include neutron veto scintillator detector
- SuperCDMS cryostat payload: initially 50 kg, up to 400 kg
- Cooperation between SuperCDM and EURECA (CRESST+EDELWEISS):
    - cryogenic design (T ≤ 15 mK, cooling power 5 μW)
    - shielding concept
    - tower design and prototype (must be compatible with SuperCDMS concept)

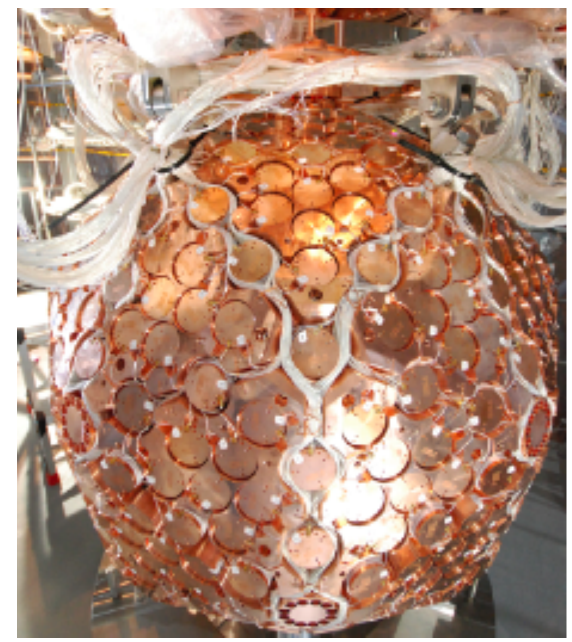




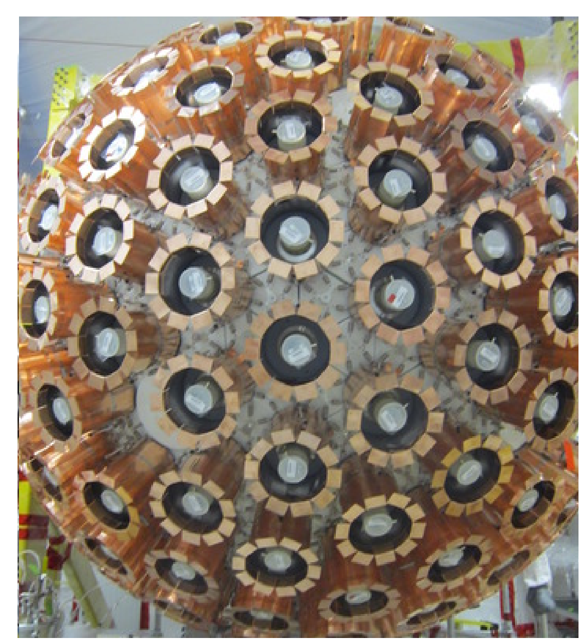
Start data taking in 2018

Single-phase noble liquid detectors



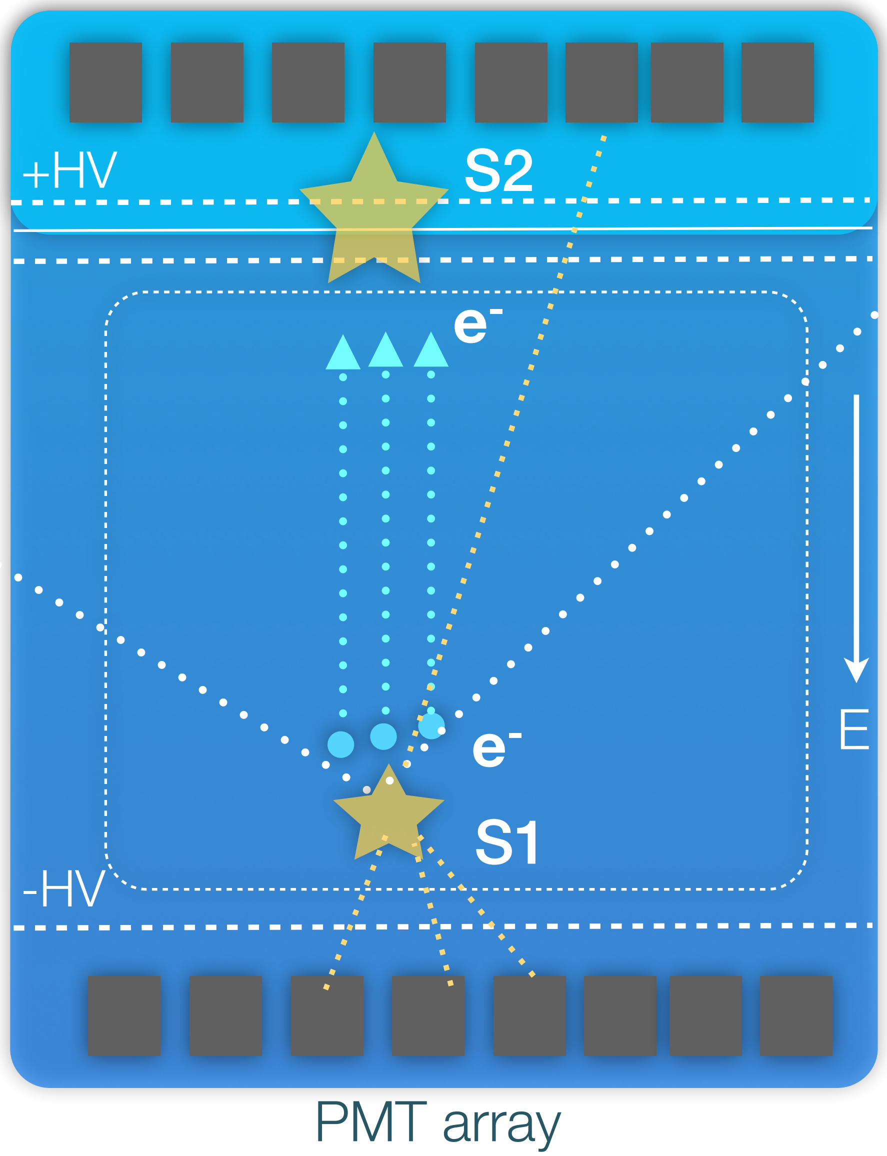


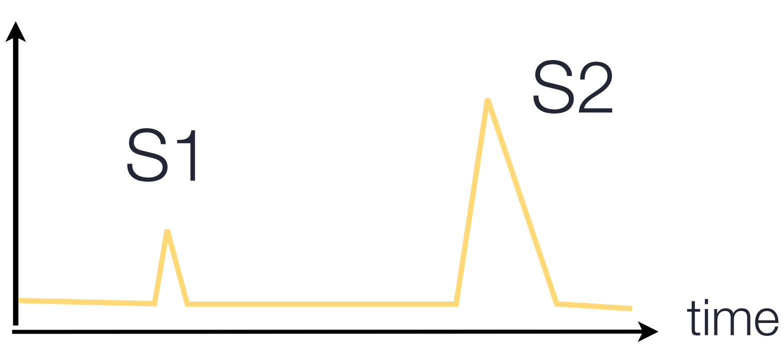
LXe: XMASS at Kamioka
New dark matter run with "refurbished" detector



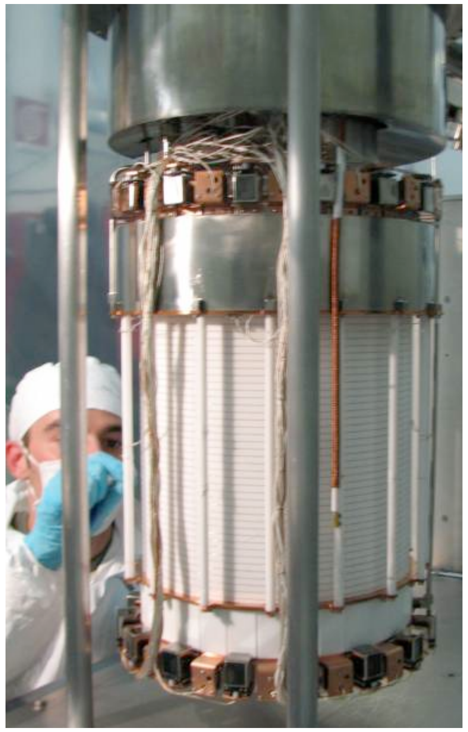
LAr: DEAP-3600 at SNOLAB
In commissioning
First results in late 2015

Dual-phase noble liquid detectors





LXe: XENON100



LXe: LUX

LAr: DarkSide

XENON100 (LXe) and DarkSide (LAr) at LNGS

LUX (LXe) at SURF, PandaX (LXe) at CJPL

ArDM (LAr) at Canfranc

Target masses between ~ 50 kg - 1 ton

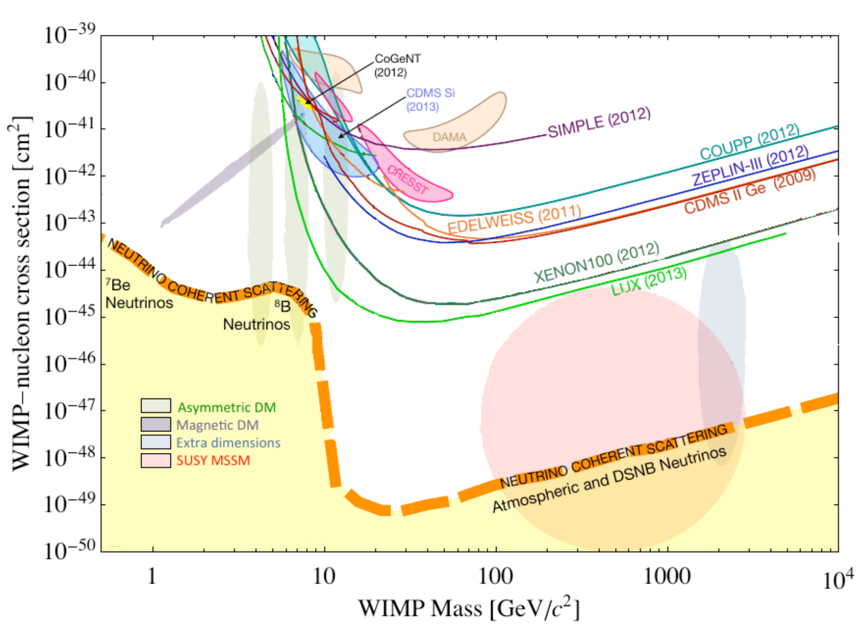
WIMP physics with xenon detectors

Probe WIMP-nucleus interactions via:

- spin-independent elastic scattering: ^{124}Xe, ^{126}Xe, ^{128}Xe, ^{129}Xe, ^{130}Xe, ^{131}Xe, ^{132}Xe (26.9%), ^{134}Xe (10.4%), ^{136}Xe (8.9%)
- spin-dependent elastic scattering: ^{129}Xe (26.4%), ^{131}Xe (21.2%)
- inelastic WIMP-^{129}Xe and WIMP-^{131}Xe scatters $\chi + {}^{129,131}Xe \rightarrow \chi + {}^{129,131}Xe^{*} \rightarrow \chi + {}^{129,131}Xe + \gamma$

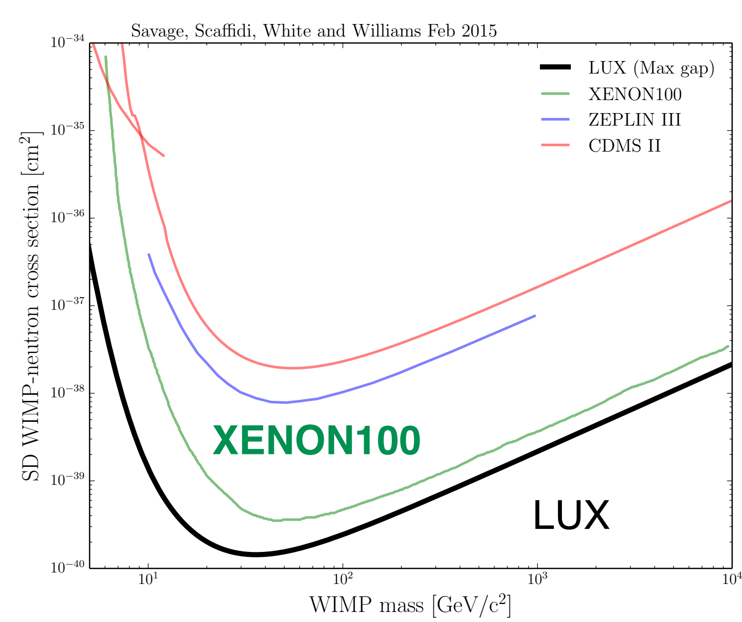
1 ns, 0.5 ns 40 keV, 80 keV

SI, elastic WIMP-nucleus



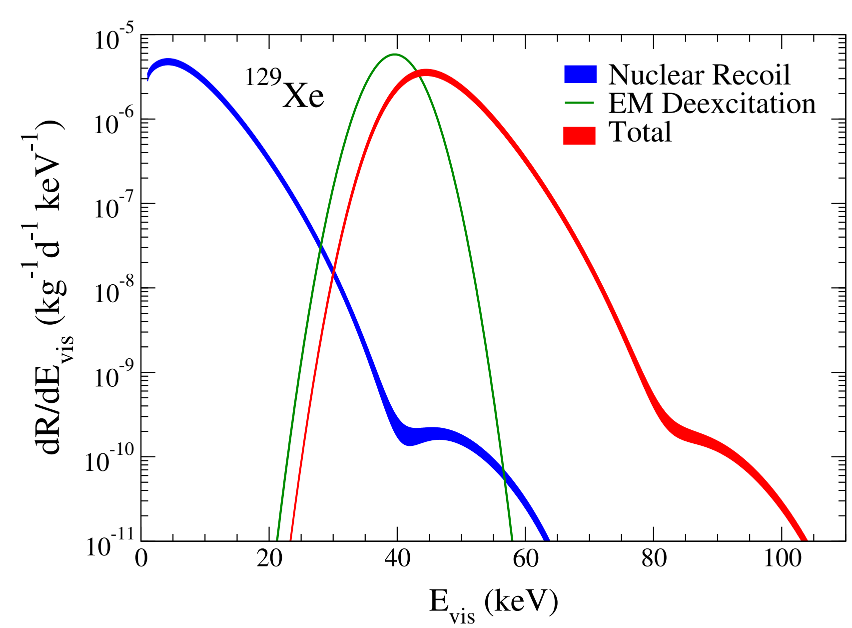
arXiv:1310.8327

SD, elastic WIMP-nucleus



C. Savage et al, arXiv:1502.02667

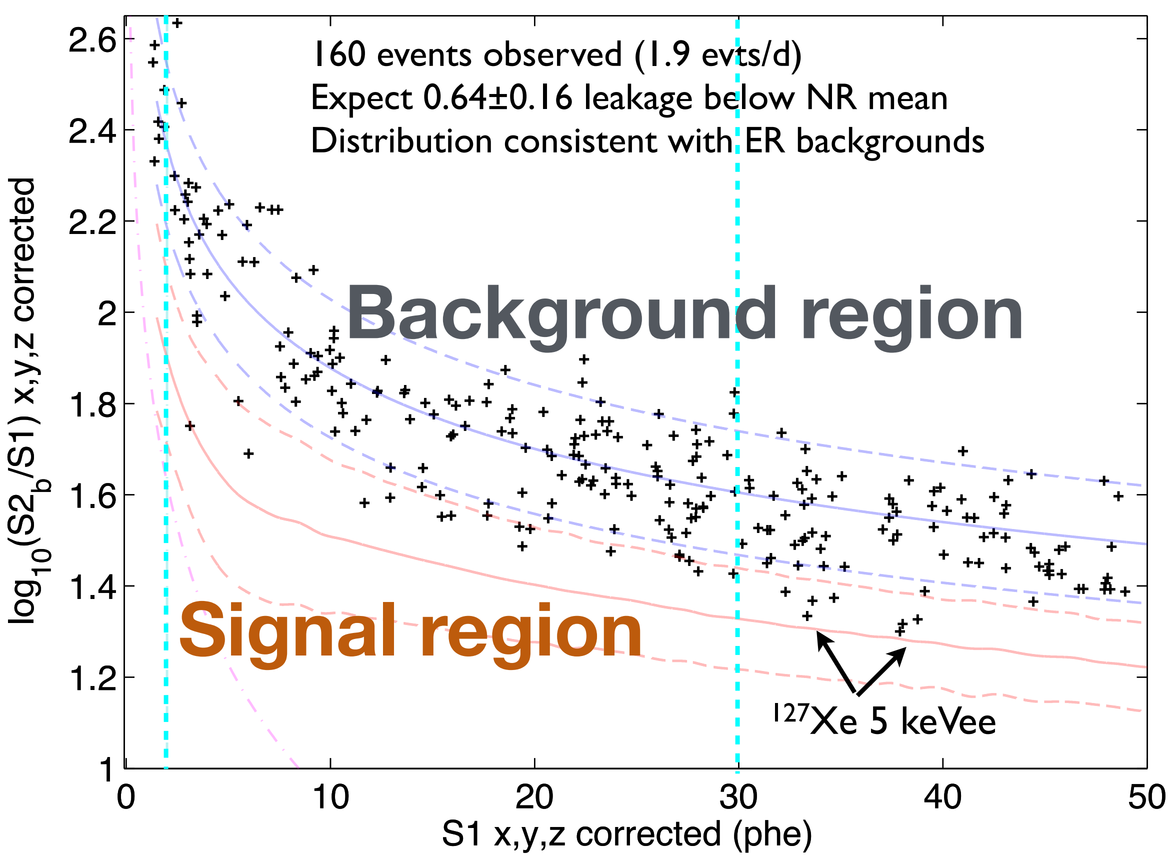
SD, inelastic WIMP-nucleus

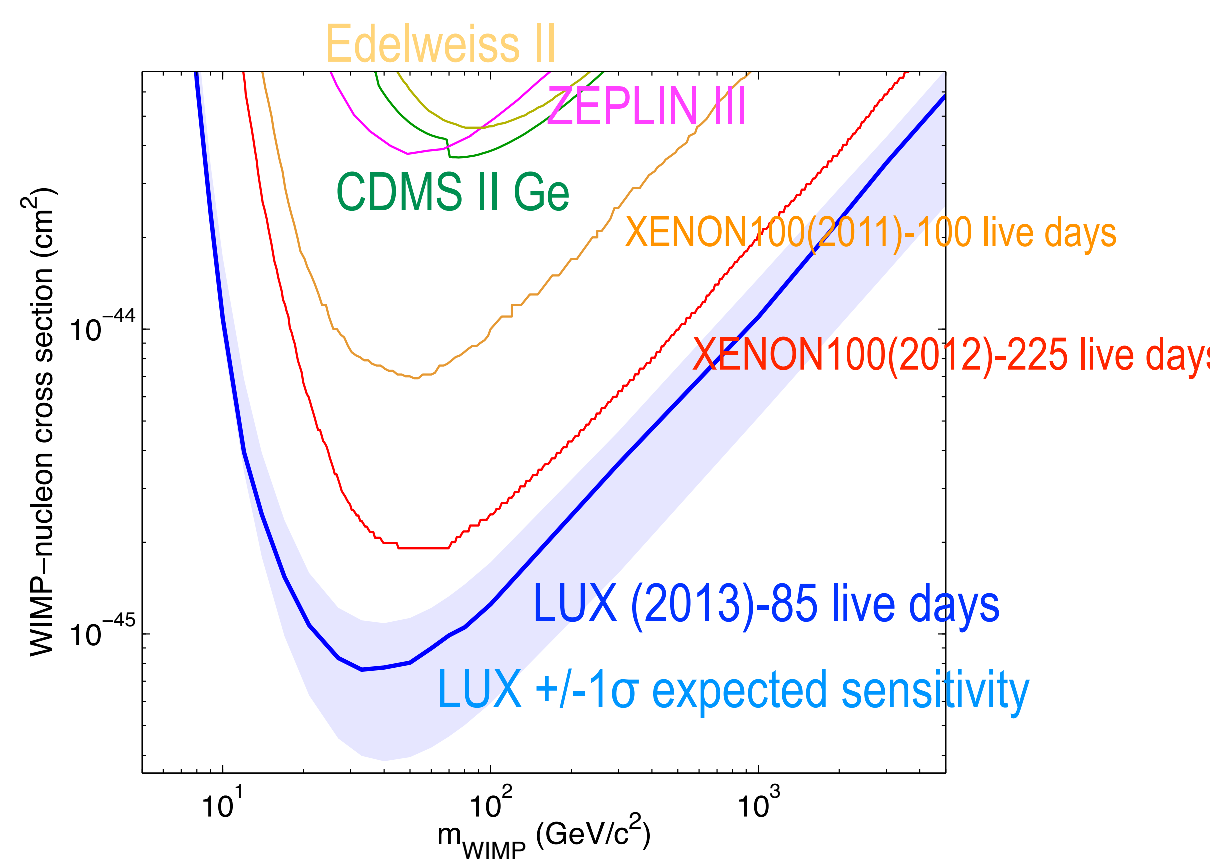


L. Baudis et al, Phys. Rev. D 88, 115014 (2013)

Example: LUX dark matter data

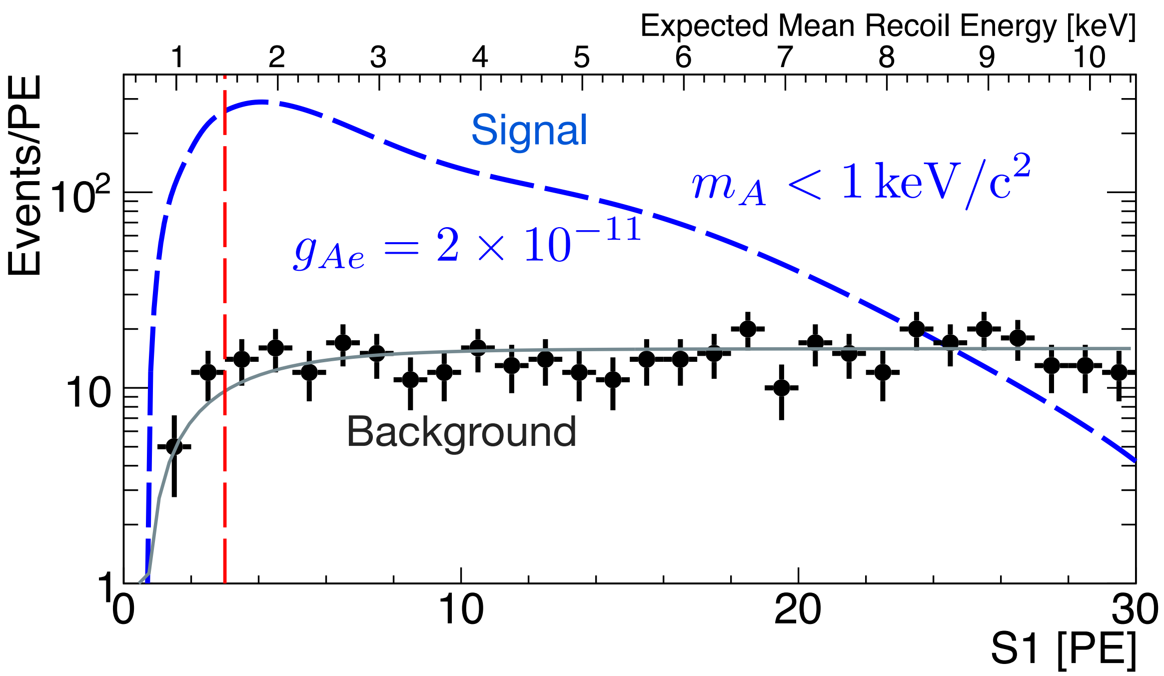
- Exposure: 85.3 days x 118 kg fiducial liquid xenon mass
- No sign of dark matter, observed event distribution consistent with backgrounds
- New run of 300 live-days planned for 2015-2016, sensitivity increase by a factor of 5

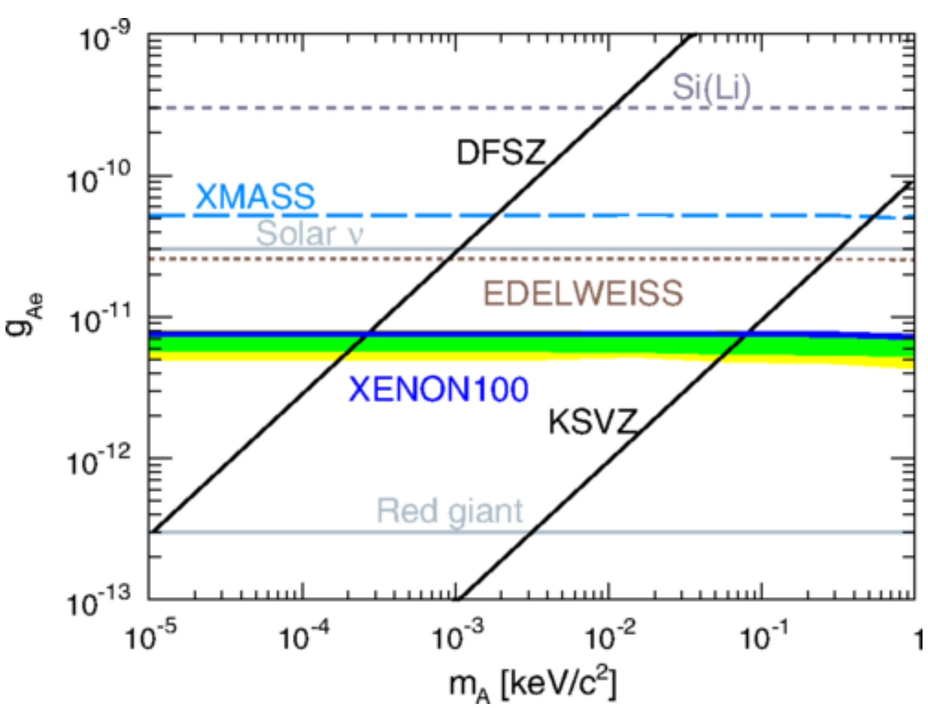




Phys. Rev. Lett. 112 (2014)

Example: Solar axions with XENON100





Look for solar axions via their couplings to electrons, g_{Ae}, through the axio-electric effect

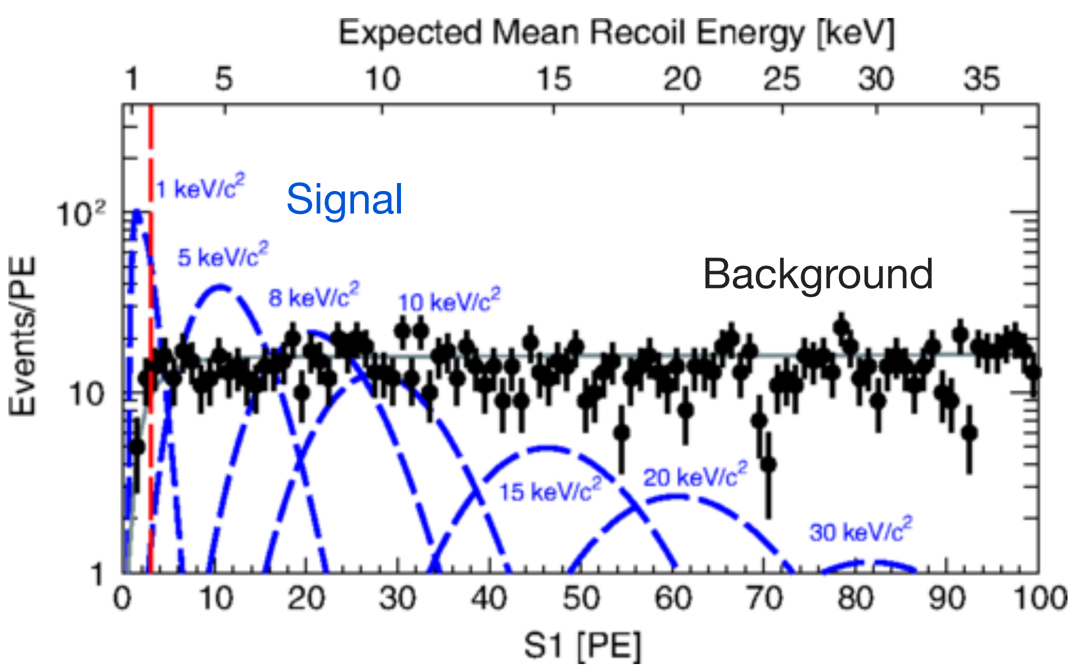
$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{g_{Ae}^2}{\beta_A}\frac{3E_A^2}{16\pi\alpha_{em}m_e^2}\left(1 - \frac{\beta_A^{2/3}}{3}\right)$$

$$\phi_A \propto g_{Ae}^2 \Longrightarrow R \propto g_{Ae}^4$$

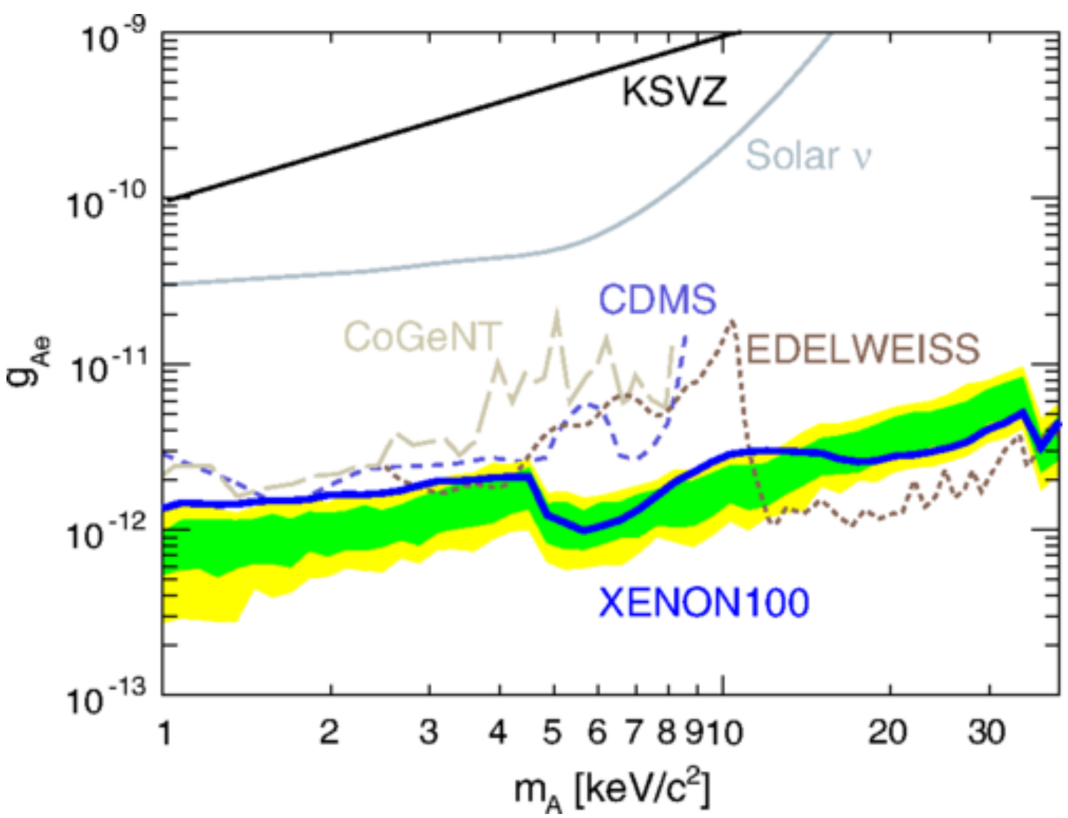
- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs (LB et al., PRD 87, 2013; arXiv:1303.6891)

XENON, Phys. Rev. D 90, 062009 (2014)

Example: Galactic axion-like particles with XENON100



XENON, Phys. Rev. D 90, 062009 (2014)



Look for ALPs via their couplings to electrons, g_{Ae}, through the axio-electric effect

Expect line feature at ALP mass

Assume $\rho_0 = 0.3\,\mathrm{GeV/cm}^3$

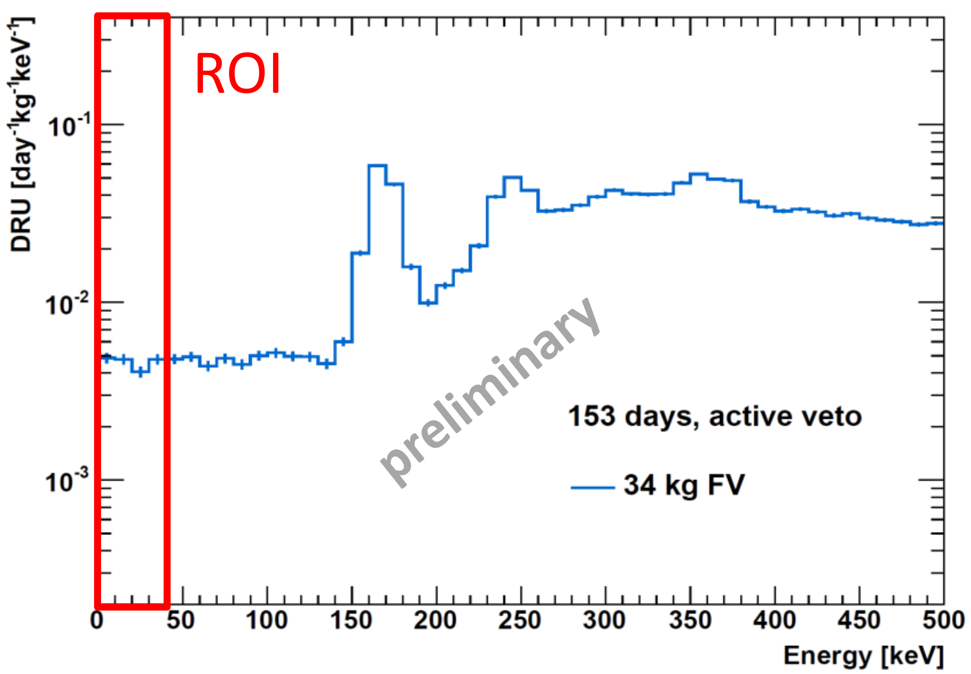
$$\phi_A = c\beta_A \times \frac{\rho_0}{m_A}$$

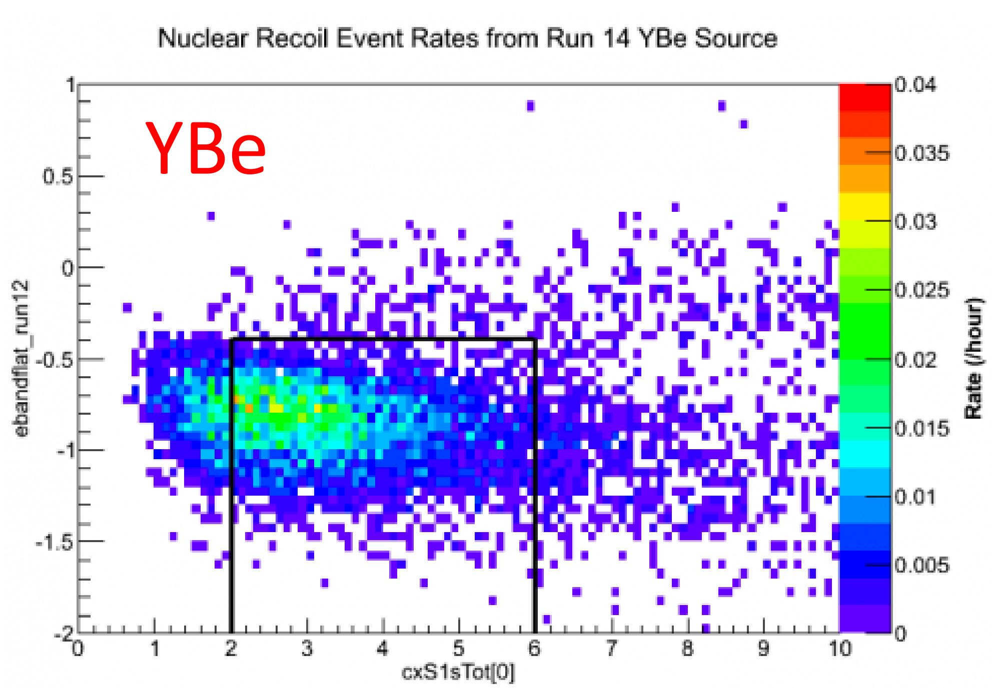
$$R \propto g_{Ae}^2$$

- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs (LB et al., PRD 87, 2013; arXiv:1303.6891)

XENON, Phys. Rev. D 90, 062009 (2014)

Upcoming results from XENON100

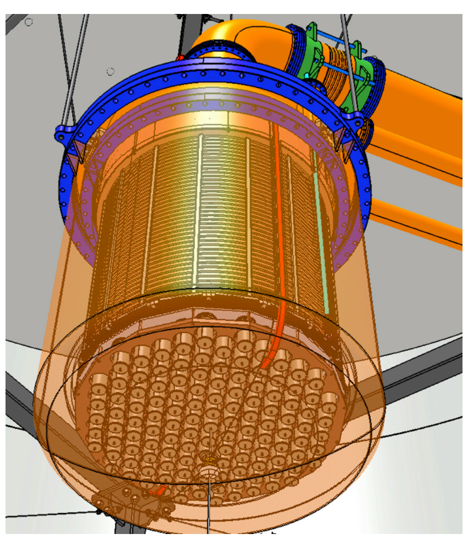


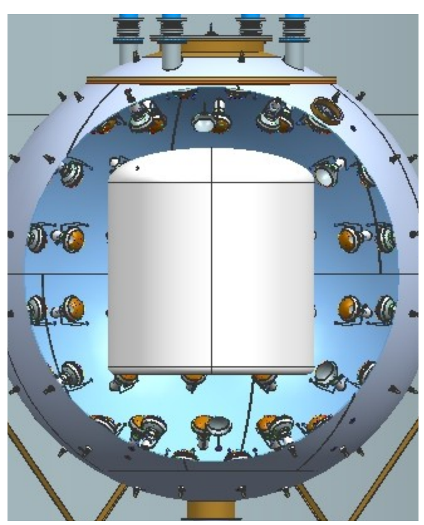


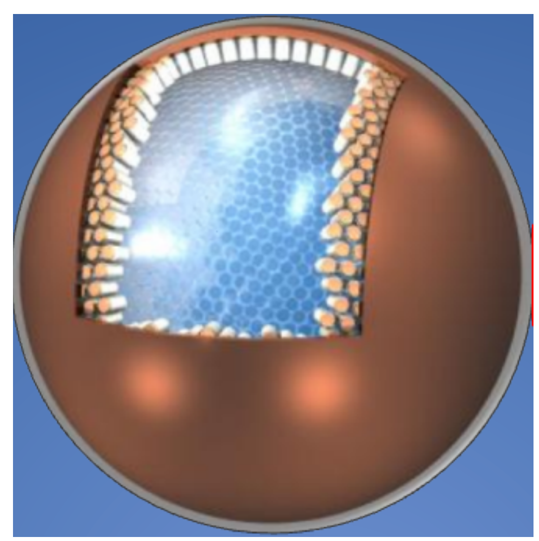
- Search for annual modulation (2 papers submitted)
- Analysis of 153 live days of blinded dark matter search data close to unblinding; search for inelastic scattering on ^{129}Xe, search for low-mass WIMPs
- Calibration measurements:
  - probe lowest nuclear recoil energies (max at 4.5 keVnr) with YBe source placed inside the shield; more than 80 live days collected and clear signal due to neutron scatters observed
  - currently ^{83m}Kr calibration run & analysis
- XENON100 is also used as a test facility for XENON1T/nT: novel online radon purification technique, by cryogenic distillation (Rn has 10 x lower vapour pressure than xenon) verified

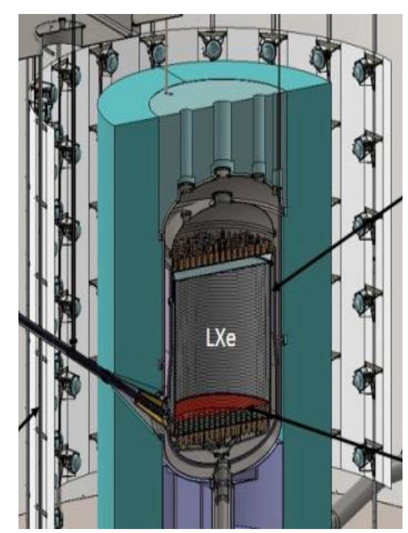
Future noble liquid detectors

- Under construction: XENON1T/nT (3.3 t/ 7t LXe) at LNGS
- Proposed: LUX-ZEPLIN 7t LXe (approved), XMASS 5t LXe, DarkSide 20 t LAr, DEAP 50 t LAr
- Design & R&D: DARWIN, 30-50 t LXe; ARGO 150 t LAr

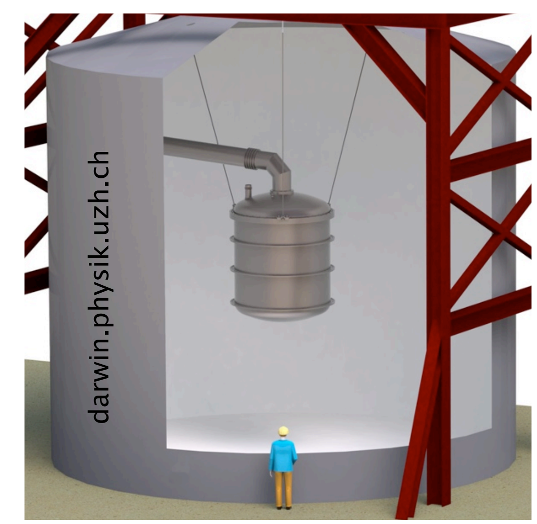

XENON1T: 3.3 t LXe


DarkSide: 5 t LAr


XMASS: 5t LXe



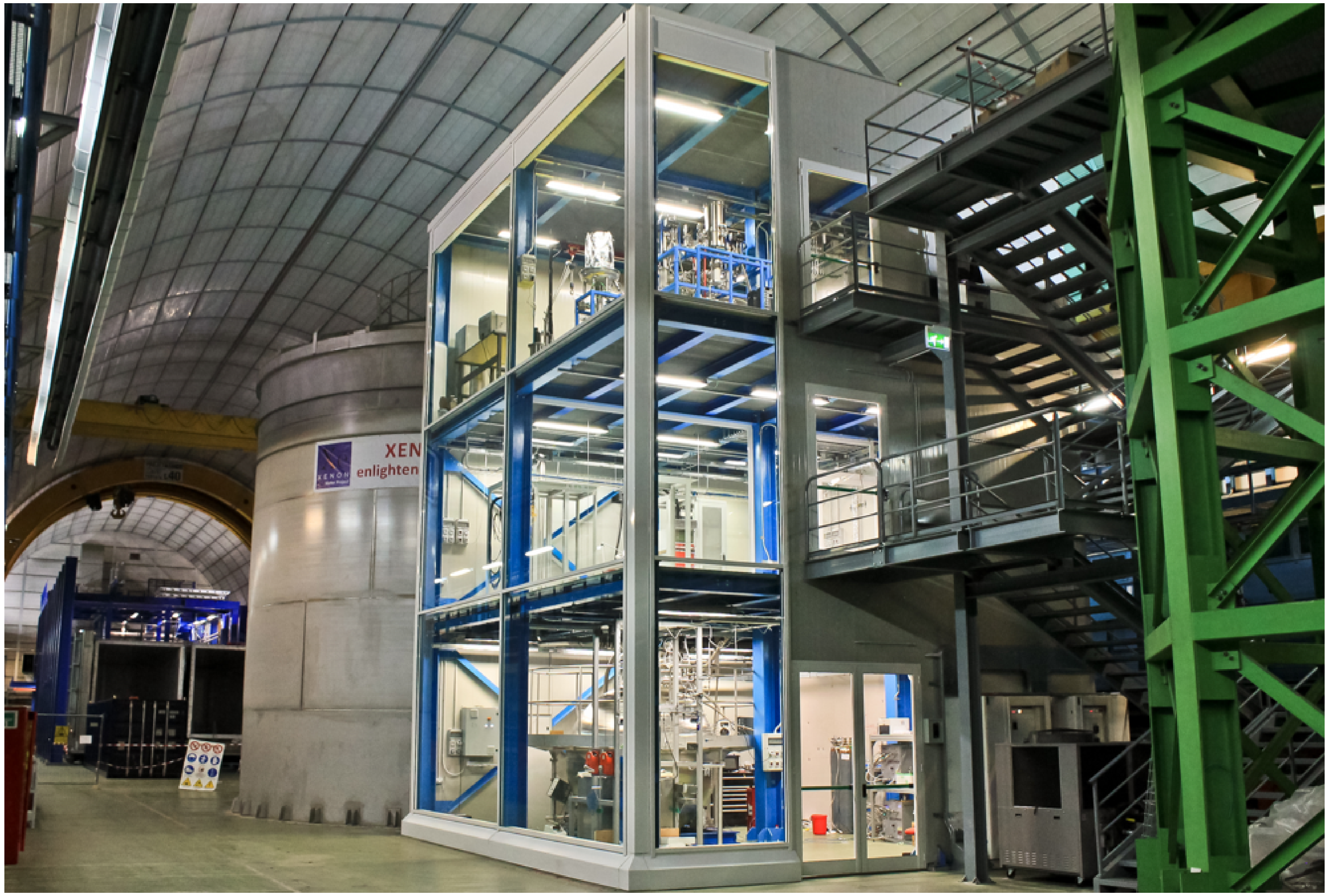
LZ: 7t LXe



DARWIN: 50 t LXe

The XENON1T experiment

- Under construction at LNGS since autumn 2013; commissioning planned for late 2015
- Total (active) LXe mass: 3.3 t (2 t), 1 m electron drift, 248 3-inch PMTs in two arrays
- Background goal: 100 x lower than XENON100 ~ 5×10^{-2} events/(t d keV)



XENON1T/nT: status of construction work

- Water Cherenkov shield built and instrumented
- Cryostat support, service building, electrical plant completed
- Several subsystems (cryostat, cryogenics, storage, purification, cables & fibres, pipes) installed/ being tested underground





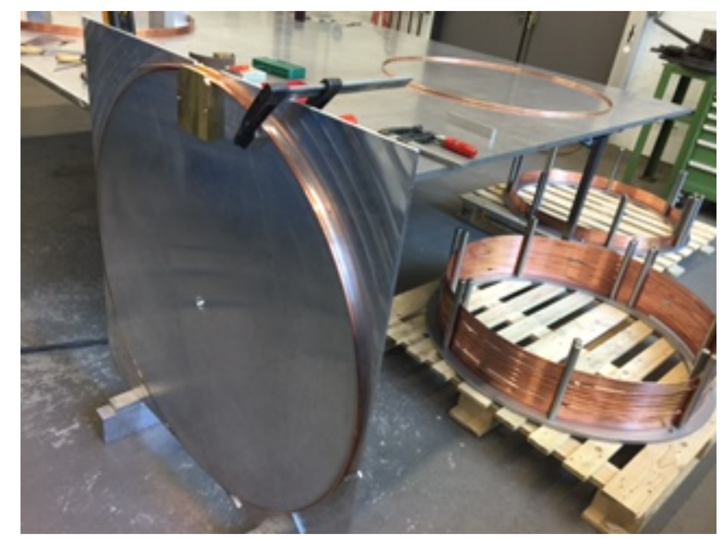
The XENON1T detector

- PMTs are screened with HPGe, then tested in cold gas and - a subsample - in LXe
- TPC design is finalised, currently under prototyping, materials being screened

The TPC

PMT test facility

Field shaping rings production



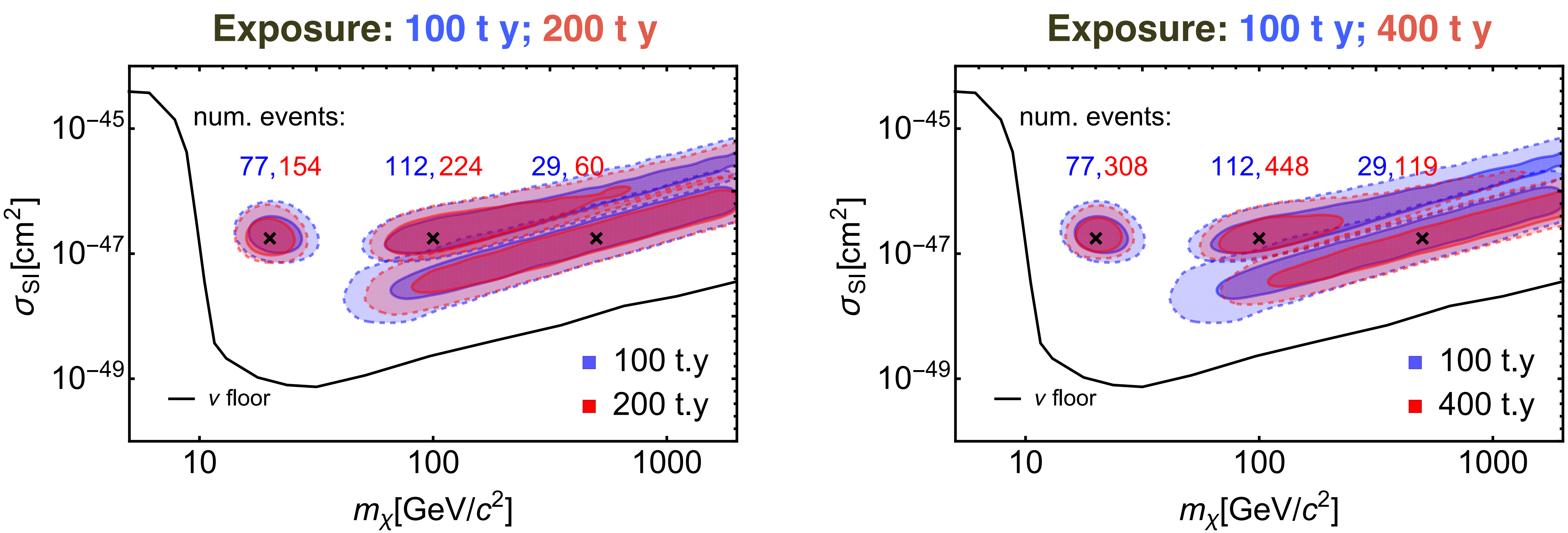
DARWIN Dark matter WIMP search with noble liquids

darwin-observatory.org

- R&D and design study for 30-50 tons LXe detector
- ~ few x 10^3 photosensors
- >2 m drift length
- >2 m diameter TPC
- PTFE walls with Cu field shaping rings (baseline scenario, 4-π readout under study)
- Background goal: dominated by neutrinos
- Physics goal:
  - WIMP spectroscopy
  - many other channels (pp neutrinos, double beta decay, axions and ALPs, bosonic SuperWIMPs…)

WIMP physics: spectroscopy

- Capability to reconstruct the WIMP mass and cross section for various masses (**20, 100, 500 GeV/c²**) and a spin-independent cross section of 2×10^{-47} cm^2 (assuming different exposures)



1 and 2 sigma credible regions after marginalizing the posterior probability distribution over:

$$v_{esc} = 544 \pm 40\,\mathrm{km/s}$$

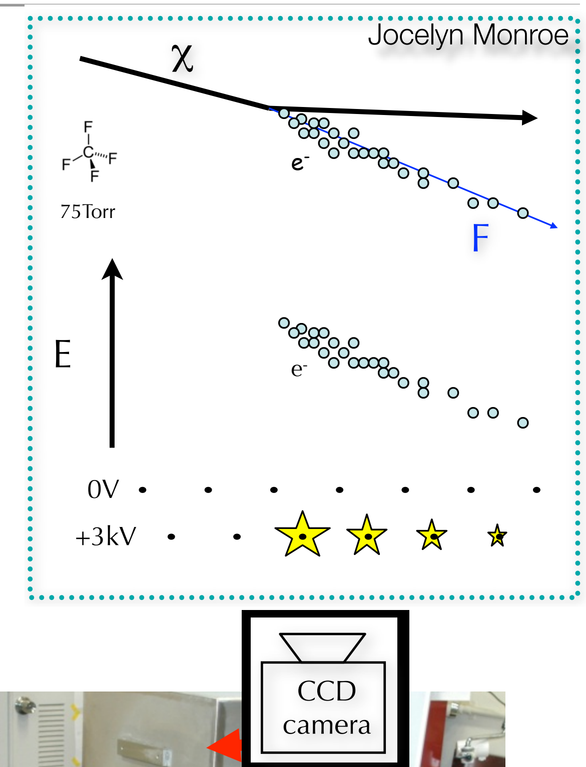
$$v_0 = 220 \pm 20\,\mathrm{km/s}$$

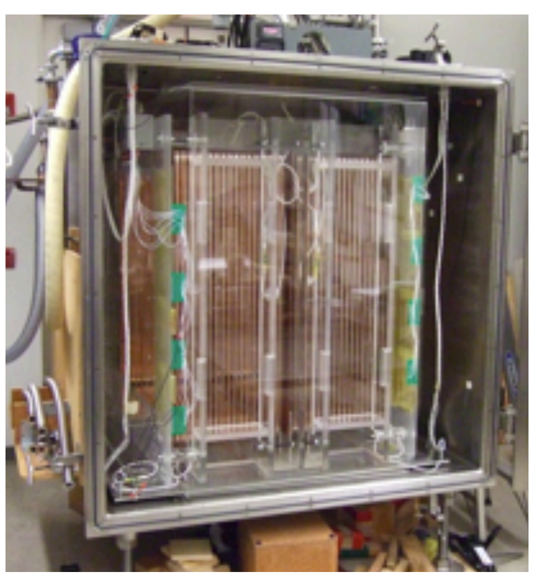
$$\rho_\chi = 0.3 \pm 0.1\,\mathrm{GeV/cm^3}$$

Update: Newstead et al., PHYSICAL REVIEW D 88, 076011 (2013)

Directional detectors

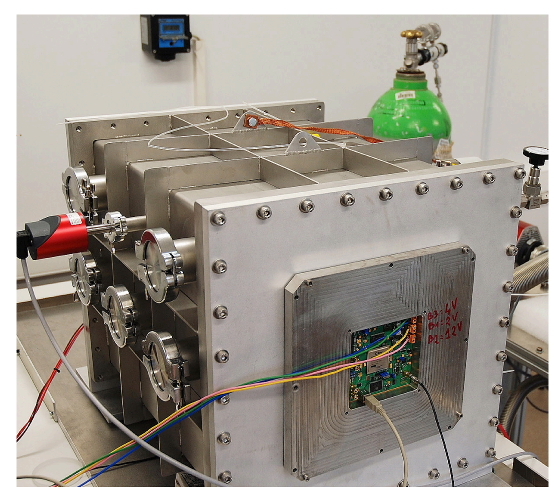
- R&D on low-pressure gas detectors to measure the recoil direction, correlated to the Galactic motion towards Cygnus
- Challenge: good angular resolution + head/tail at 30-50 keVnr
- One technology to be proposed in 2016



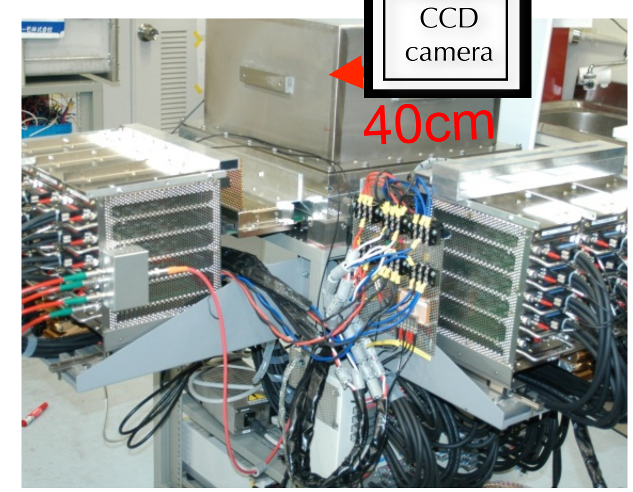


DRIFT, Boulby Mine
1 m^3, negative ion drift
CS_2, CF_4, O_2 gas

DMTPCino TPC at MIT
CCD readout
1 m^3 prototype, CF_4 gas
commissioning fall 2014



MIMAC 100x100 mm^2
5l chamber at Modane
CF_4, CHF_3, H gas

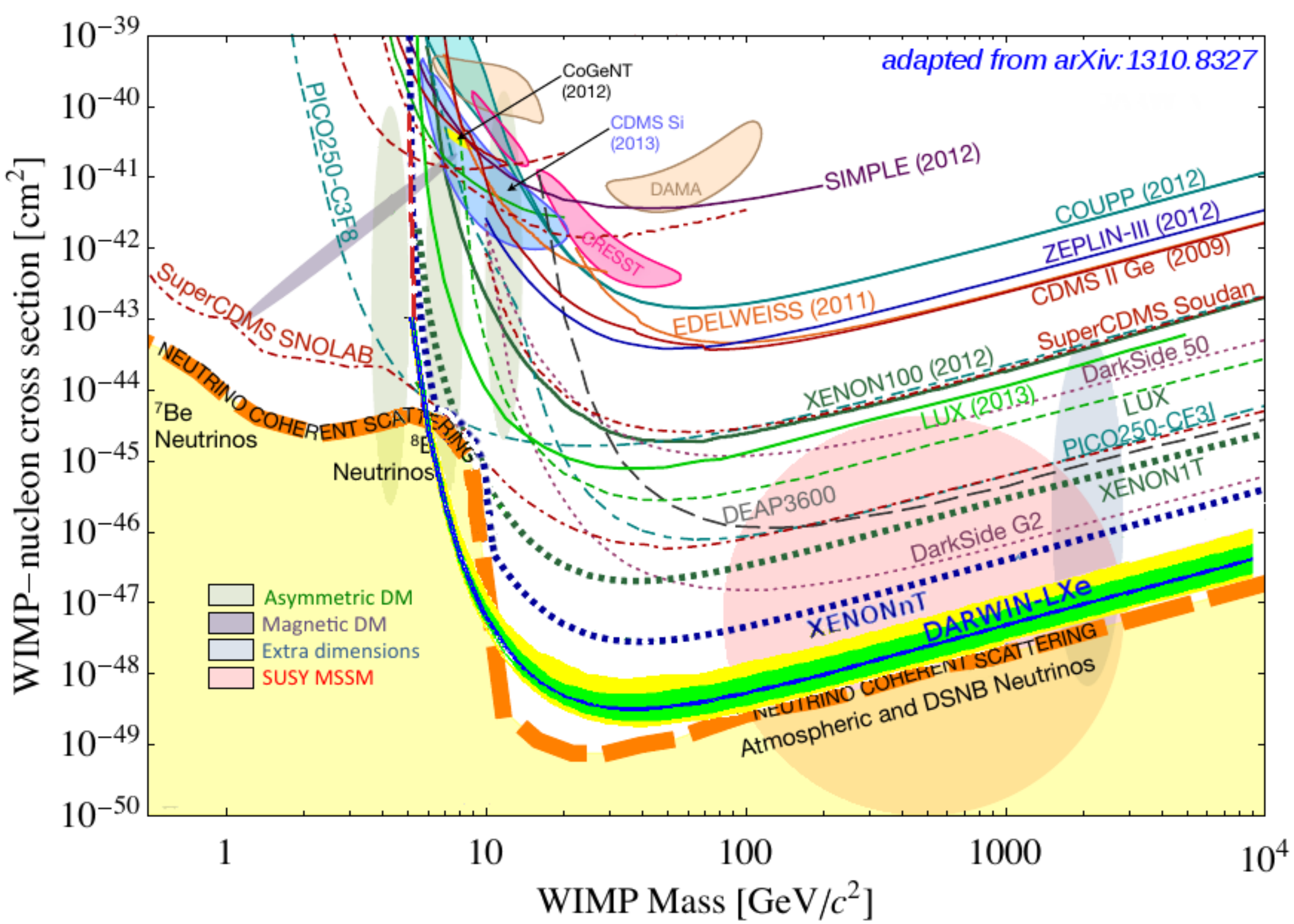


NEWAGE, Kamioka
CF_4 gas at 0.1 atm
50 keV threshold

Sensitivity for spin-independent cross sections

- E = [3-70] pe ~ [4-50] keV_{nr}

DARWIN: 200 t y exposure, 99.98% discrimination, 30% NR acceptance, LY = 8 pe/keV at 122 keV

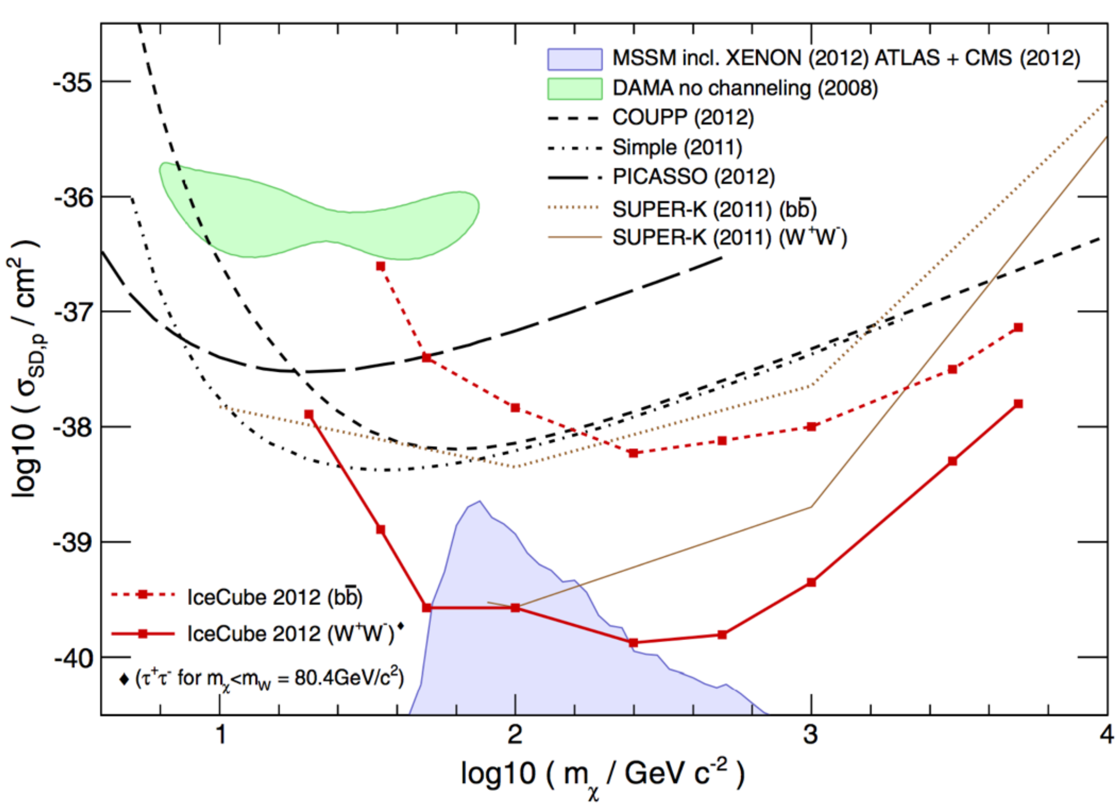


Note: "nu floor" = 3-sigma detection line at 500 CNNS events above 4 keV

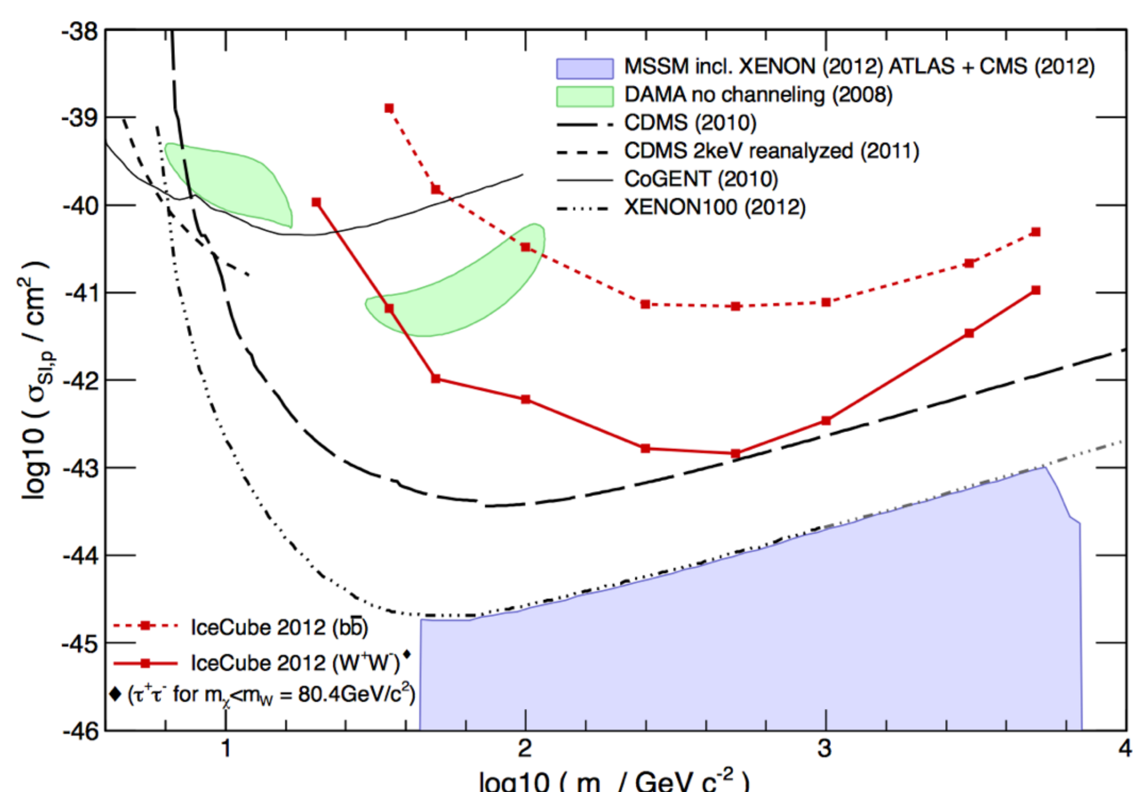
Complementarity with indirect searches

- High-energy neutrinos from WIMP capture and annihilation in the Sun (point-source)
- Sun is made of protons => strong constraints on SD WIMP-p interactions

IceCube: WIMP-p; spin-dependent



IceCube: WIMP-p; spin-independent



IceCube collab. PRL 110, 2013 (79 string)

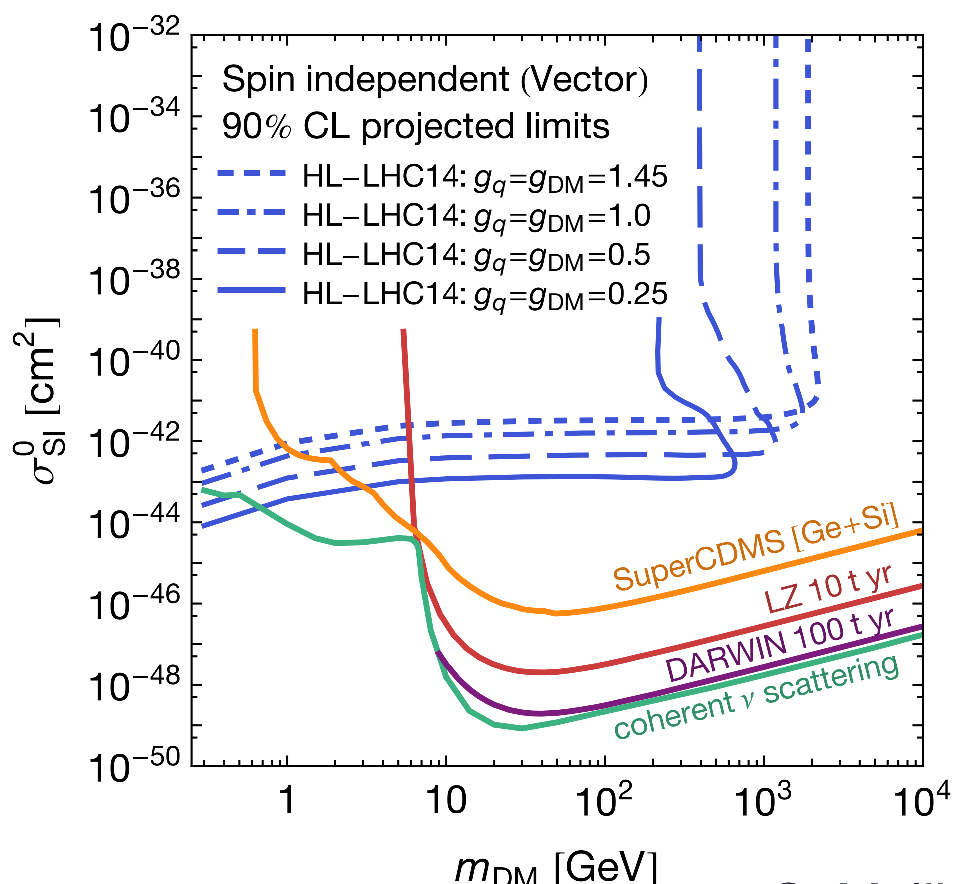
Complementarity with the LHC

Complementarity with the LHC

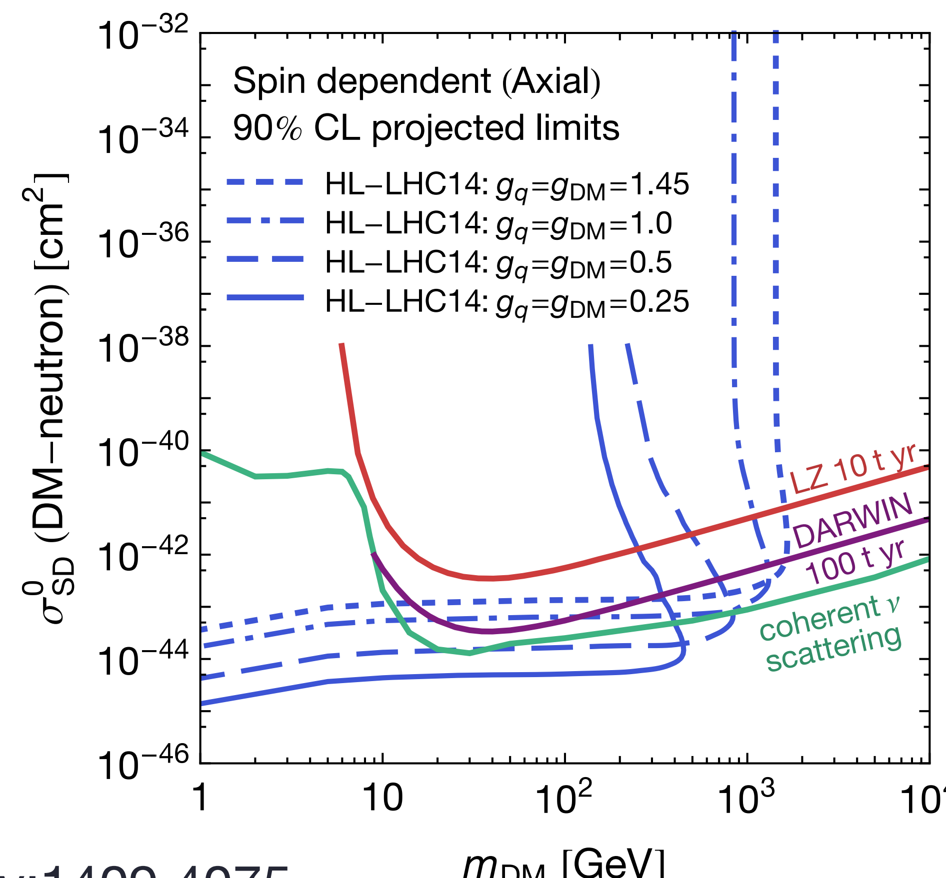
- Minimal simplified DM model with only 4 variables: m_{DM}, M_{med}, g_{DM}, gq
- Here DM = Dirac fermion interacting with a vector or axial-vector mediator; equal-strength coupling to all active quark flavours

$$\sigma_{\rm DD} \propto \frac{g_{\rm DM}^2 g_q^2 \mu^2}{M_{\rm med}^4}$$

Spin independent



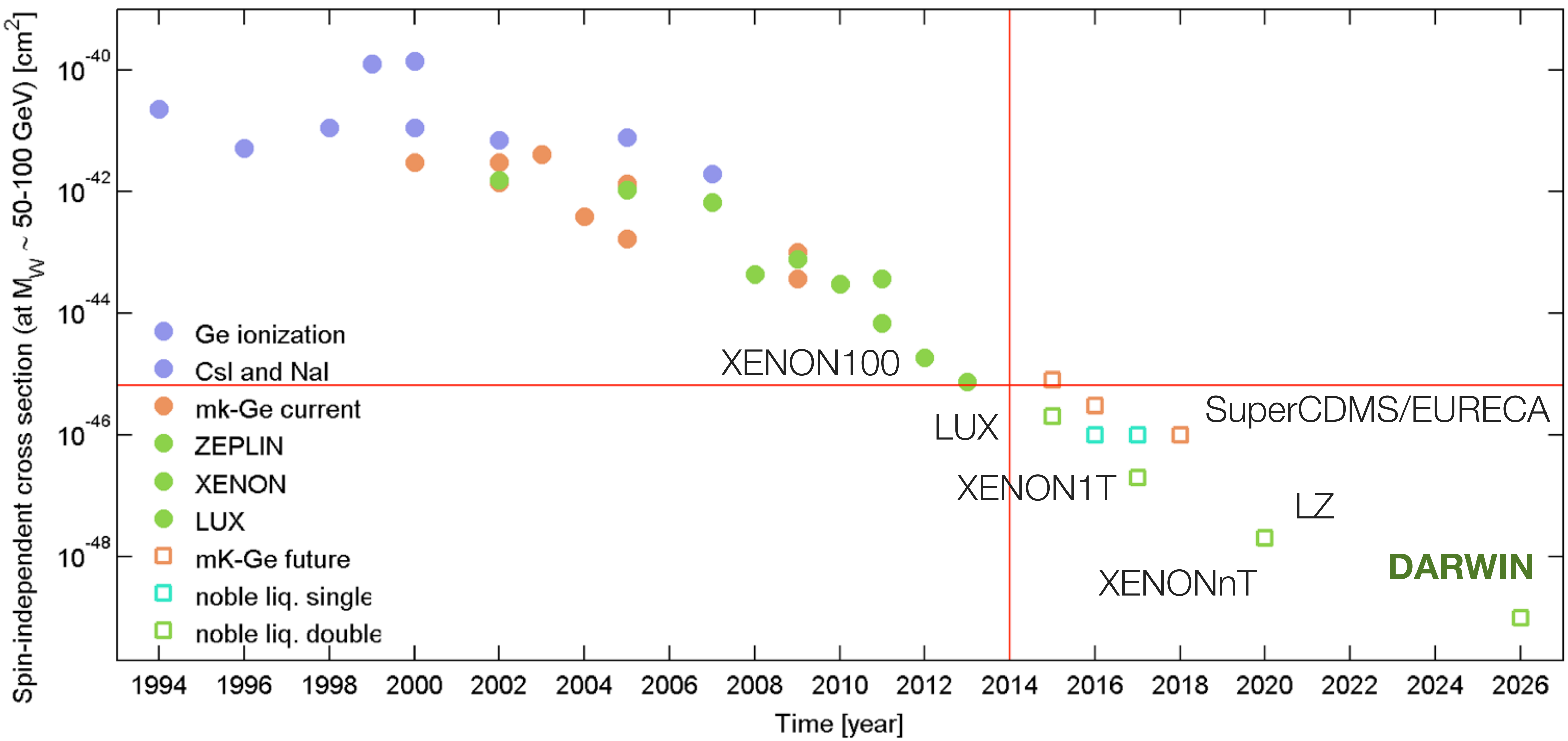
Spin dependent



S. Malik et al., arXiv:1409.4075

Evolution of the experimentally probed WIMP-nucleon cross section

- Sensitivity at WIMP masses above ~ 6 GeV/c^2 is clearly dominated by *noble liquid (Xe) time projection chambers*



Update from Physics of the Dark Universe 1, 94 (2012)

Summary

Cold dark matter is still a viable paradigm explaining cosmological & astrophysical observations

It could be made of WIMPs (and axions, + many other options, some less predictive and/or more difficult to test in the laboratory)

So far, no convincing detection of a dark matter particle

In the best of all worlds: multiple discoveries (direct detection, the LHC, indirect detection) & constraints of the dark matter properties & dark matter astronomy

If no discovery: “ultimate” dark matter detectors might at least be able to disprove the WIMP hypotheses (still valuable information)

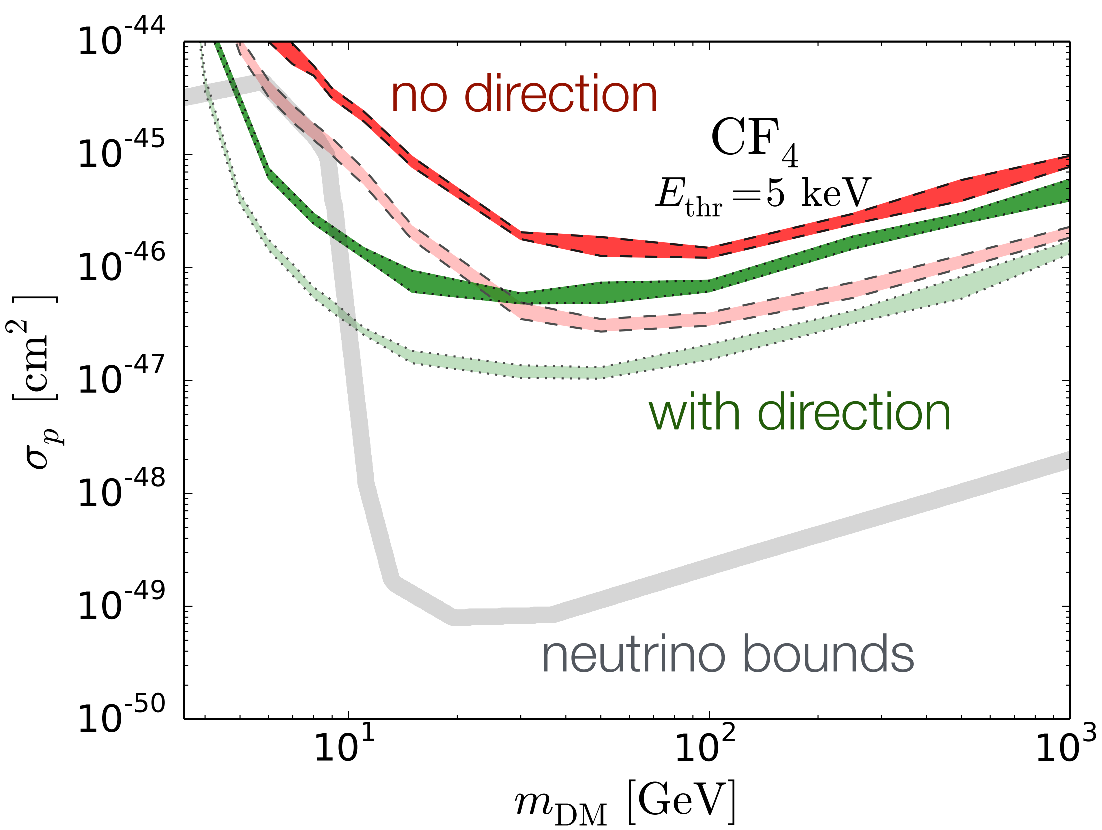
However, we should be open for new theoretical ideas & new experiments!

The end

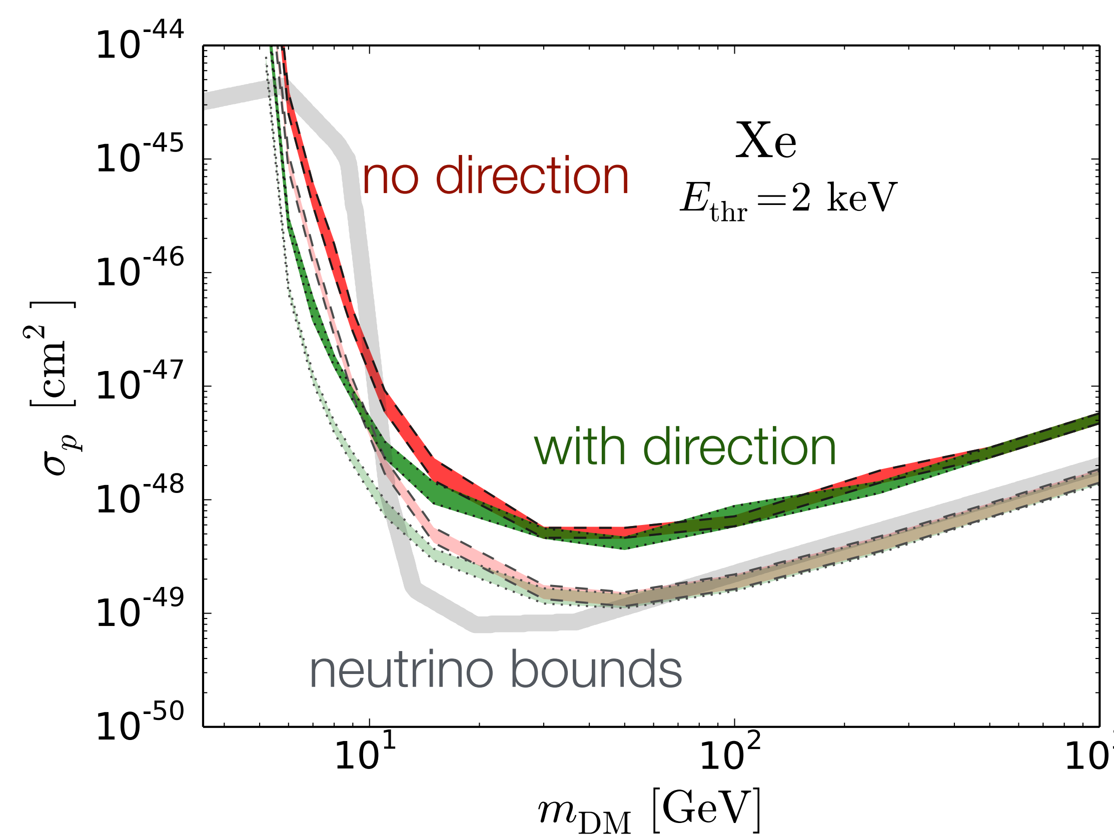
Will directional information help?

- Yes, but mostly at low WIMP masses
- Directional detection techniques currently in R&D phase
- Would be very challenging to reach 10^{-48} - 10^{-49} cm^2 with these techniques

36.6 t yr exposure, 500 (solar) nu events



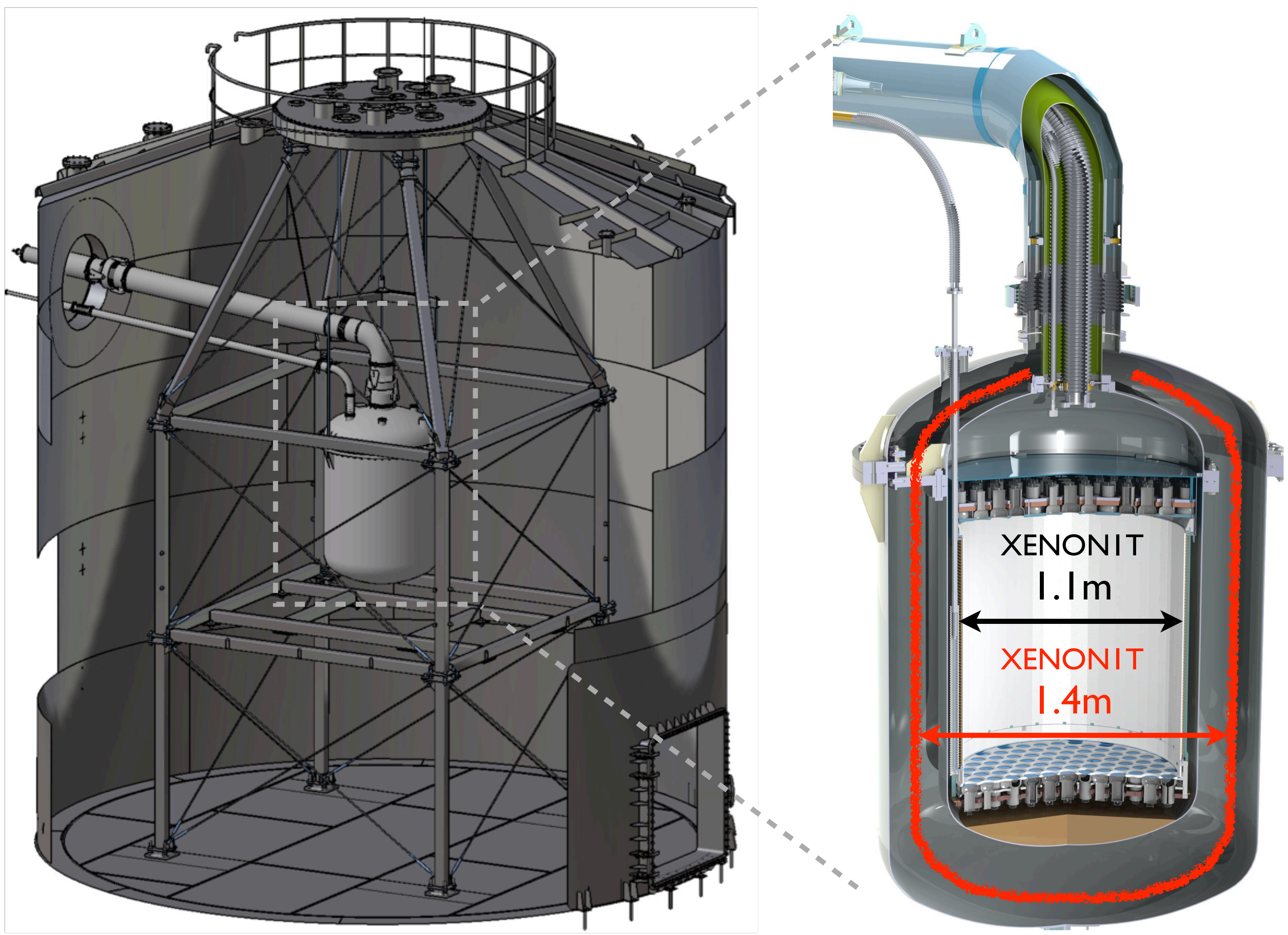
367 t yr exposure, 500 nu events



P. Grothaus, M. Fairbairn, J. Monroe, arXiv: 1406.5047

XENONnT: 2018-2020

- Plan: double the amount of LXe (~7 tons), double the number of PMTs
- XENON1T is constructed such that many sub-systems will be reused for the upgrade:

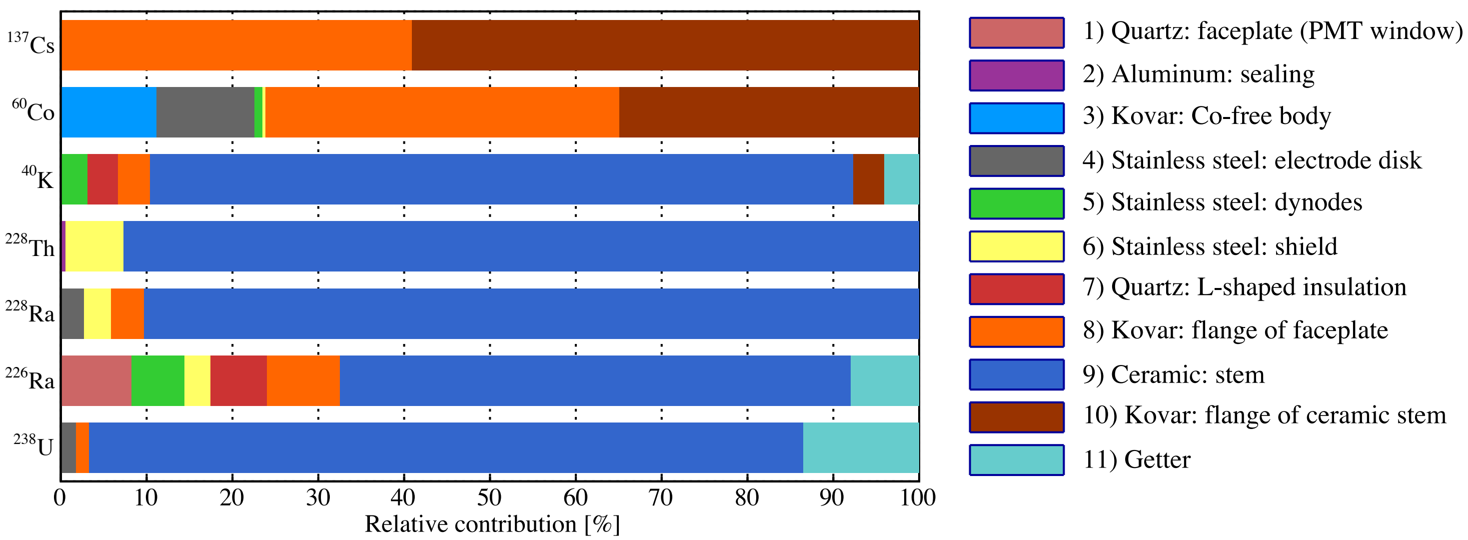


- Water tank + muon veto
- Outer cryostat and support structure
- Cryogenics and purification system
- LXe storage system
- Cables installed for XENONnT as well
- More LXe, PMTs, electronics will be needed

The XENON1T photosensors

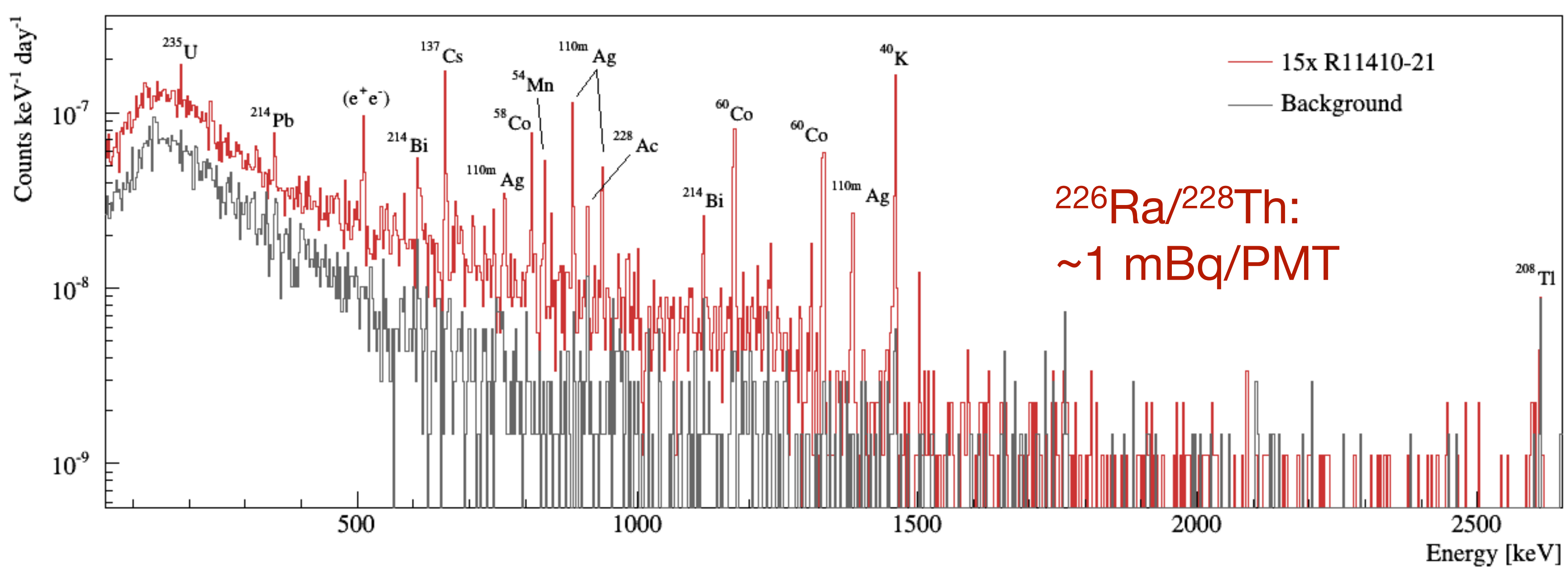
R11410-21 3-inch PMTs; average QE at 175 nm: 36%, average gain: 2 x 10^6 at 1500 V

Material screening/selection for PMT production



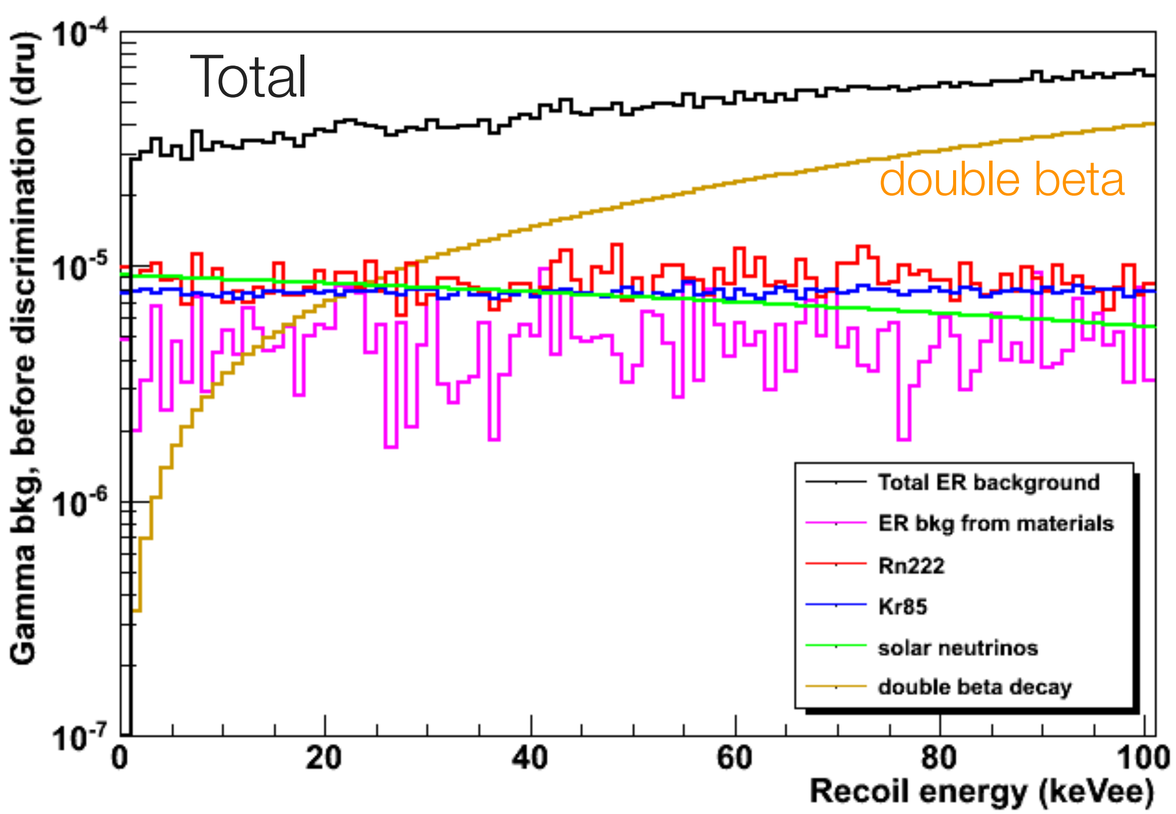
Screening of final product

XENON collaboration, arXiv:1503.07698v1

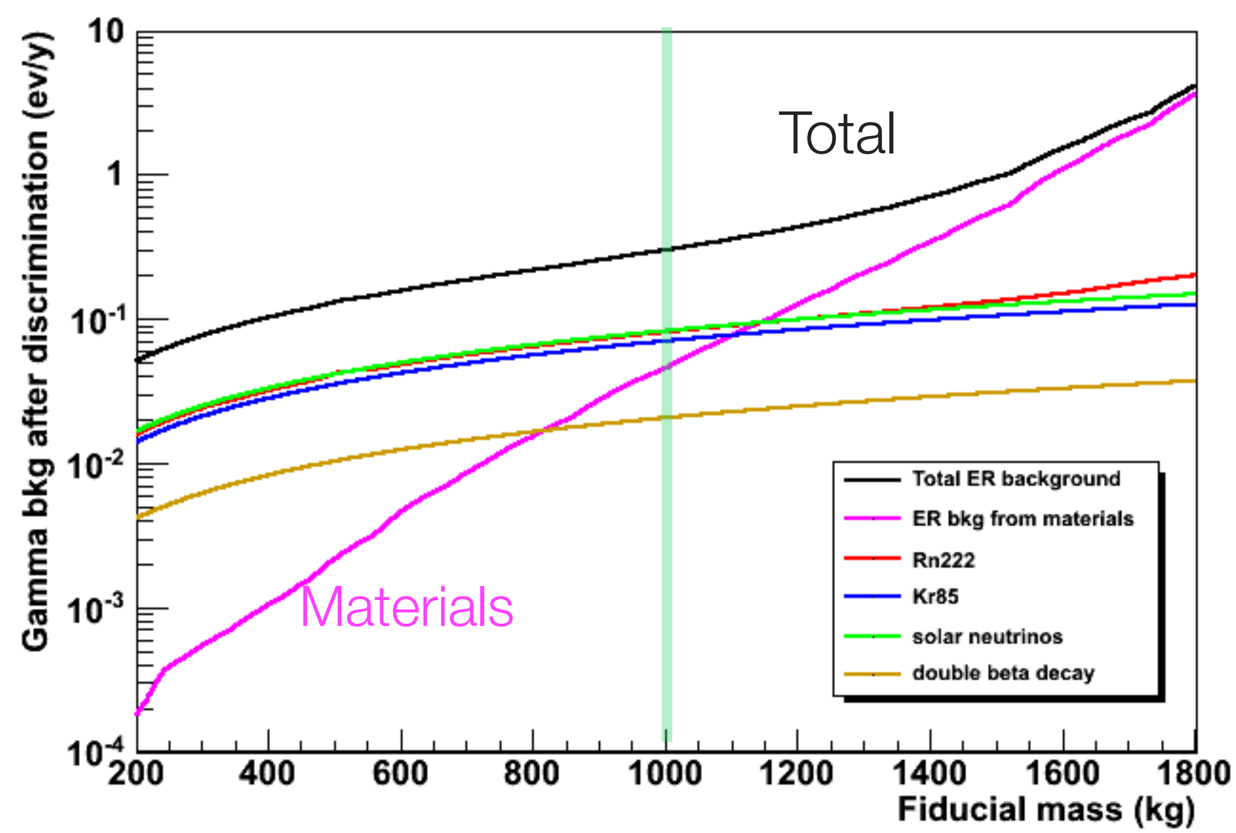


XENON1T background predictions

- Materials background: based on screening results for all detector components
- ^{85}Kr: 0.2 ppt of ^{nat}Kr with 2×10^{-11} ^{85}Kr; ^{222}Rn: 1 μBq/kg; ^{136}Xe double beta: 2.11×10^{21} y
- ER vs NR discrimination level: 99.75%; 40% acceptance for NRs
  - ➡ Total ERs: 0.3 events/year in 1 ton fiducial volume, [2-12] keV_{ee}
  - ➡ Total NRs: 0.2 events/year in 1 ton, [5-50] keV_{nr} (muon-induced n-BG < 0.01 ev/year)



Background rate from various components

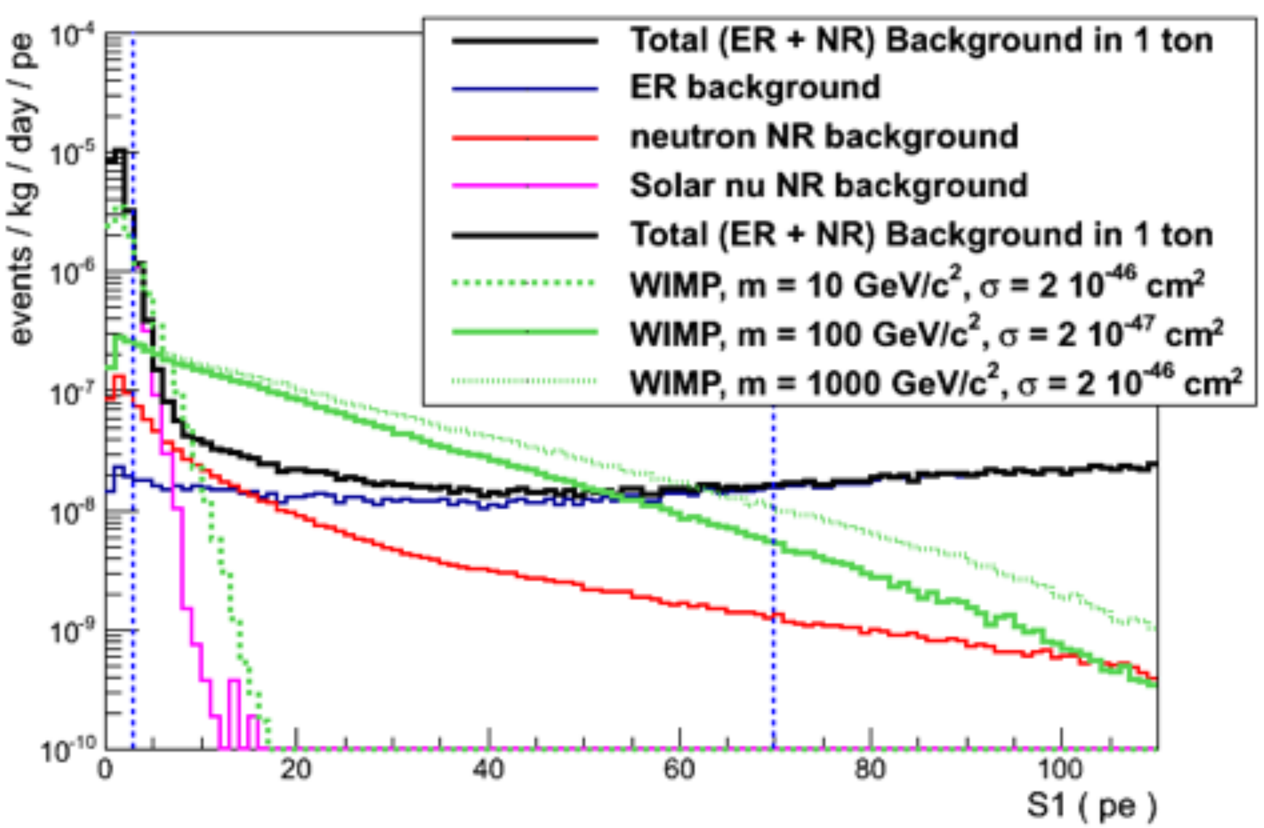


Background versus fiducial LXe mass

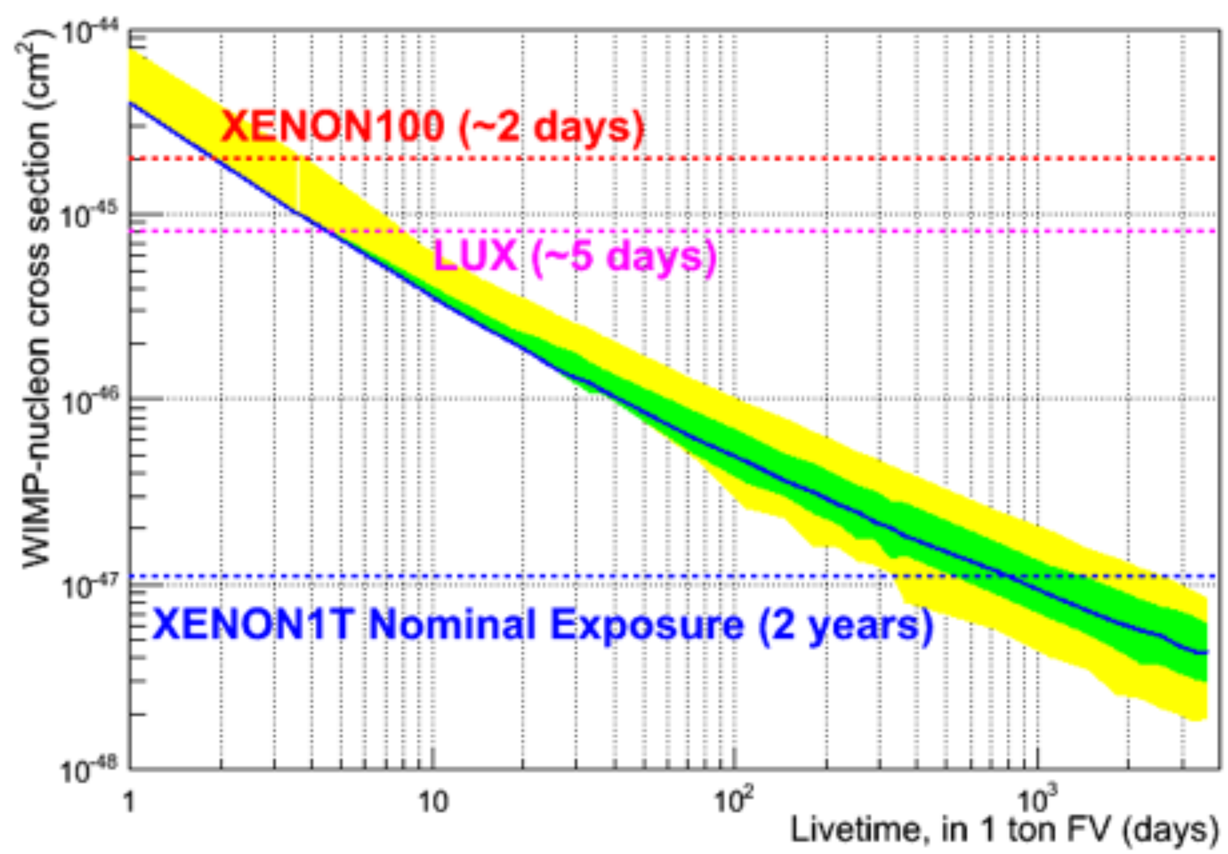
XENON1T backgrounds and WIMP sensitivity

Single scatters in 1 ton fiducial
99.75% S2/S1 discrimination
NR acceptance 40%
Light yield = 7.7 PE/keV at 0 field
L_{eff} = 0 below 1 keVnr

WIMP mass: 50 GeV
Fiducial LXe mass: 1 t
Sensitivity at 90% CL

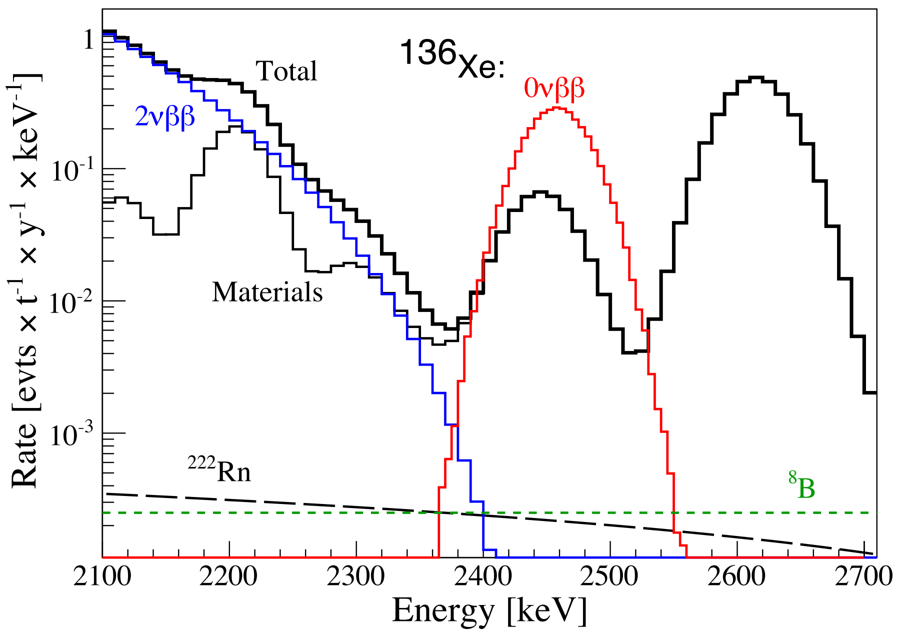


ER + NR backgrounds and WIMP spectra

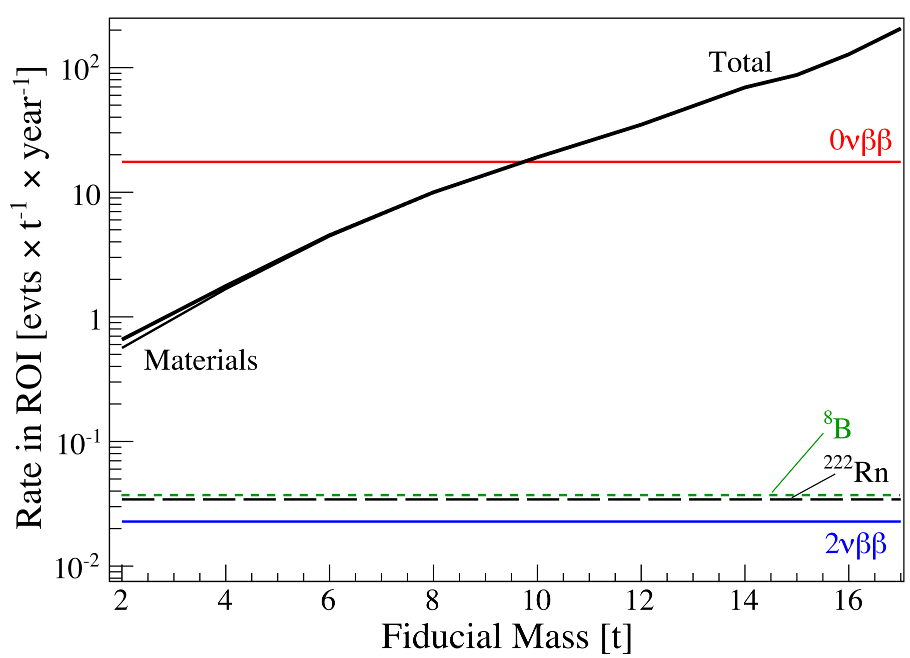


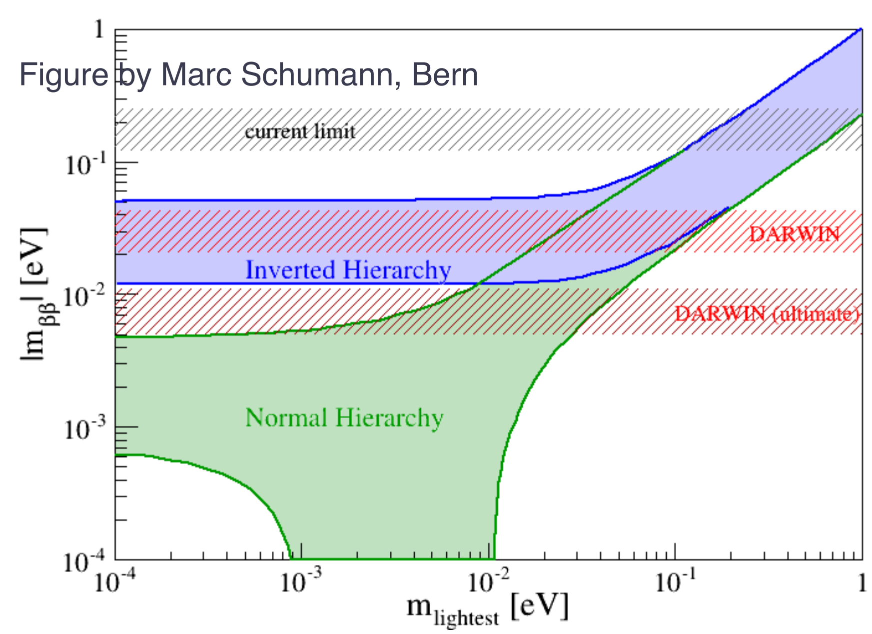
Sensitivity versus exposure (in 1 ton fiducial mass)

DARWIN physics reach: double beta decay



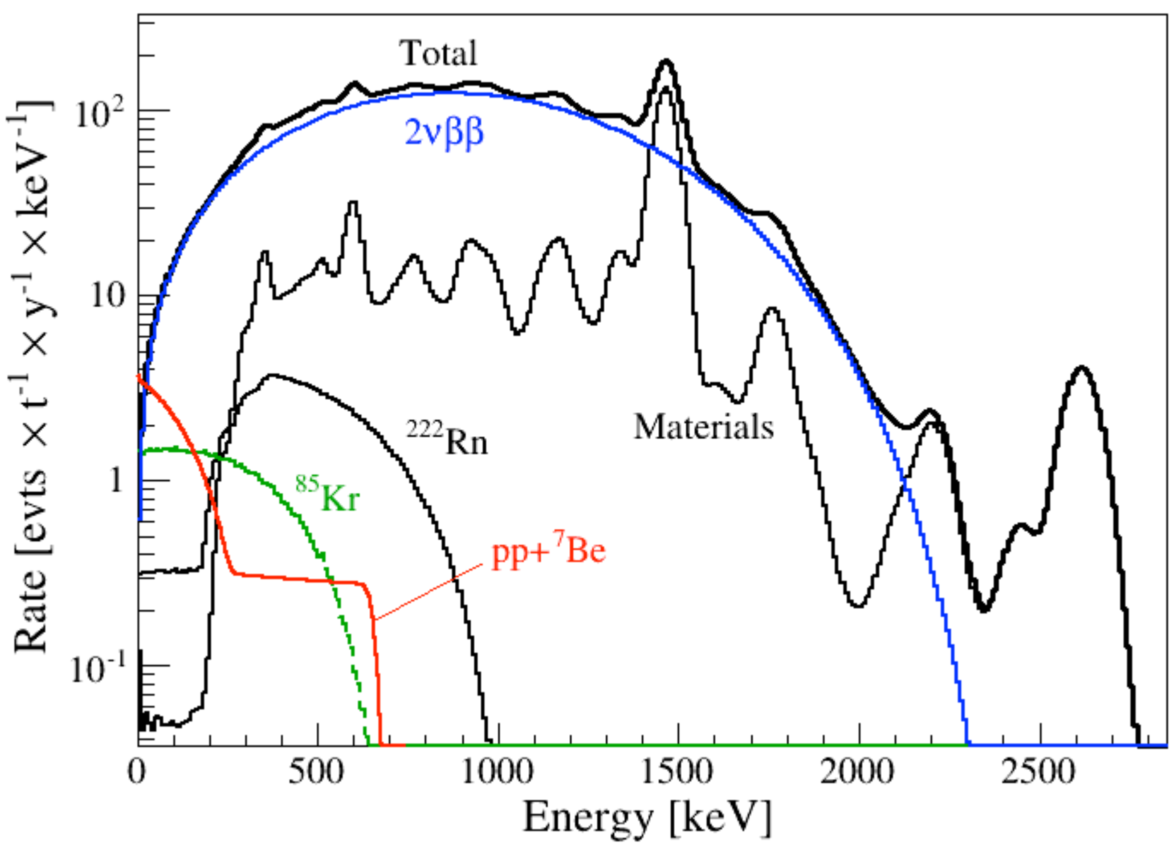
- ^{136}Xe: Q-value = 2458.7 ± 0.6 keV
- Fiducial mass of 6 t of xenon
- sensitivity to the neutrinoless double beta decay of ^{136}Xe:
- **$T_{1/2}$ > 5.6 x 10^{26} yr (95% CL) in 30 t yr**
- **$T_{1/2}$ > 8.5 x 10^{27} yr (95% CL) in 140 t yr,** assuming negligible backgrounds from detector materials

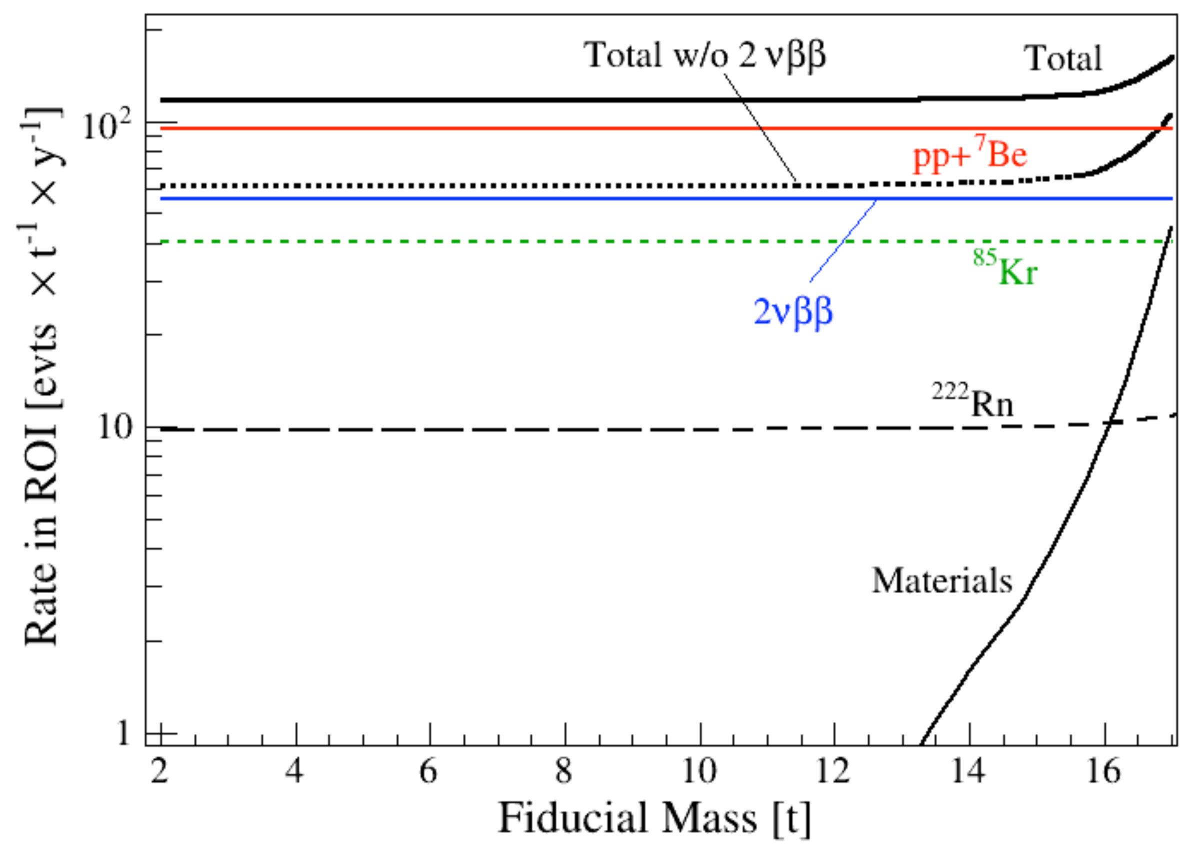




Expected backgrounds in DARWIN

- From detailed MC simulations, employing 20 t LXe geometry and Geant4
- Electronic recoils: dominated by solar neutrinos and 2-neutrino double beta decays of ^{136}Xe (assumptions: 0.1 ppt of ^{nat}Kr, 0.1 μBq/kg ^{222}Rn)
- Nuclear recoils (as expected from WIMPs and fast neutrons): < 0.03 events/t/y

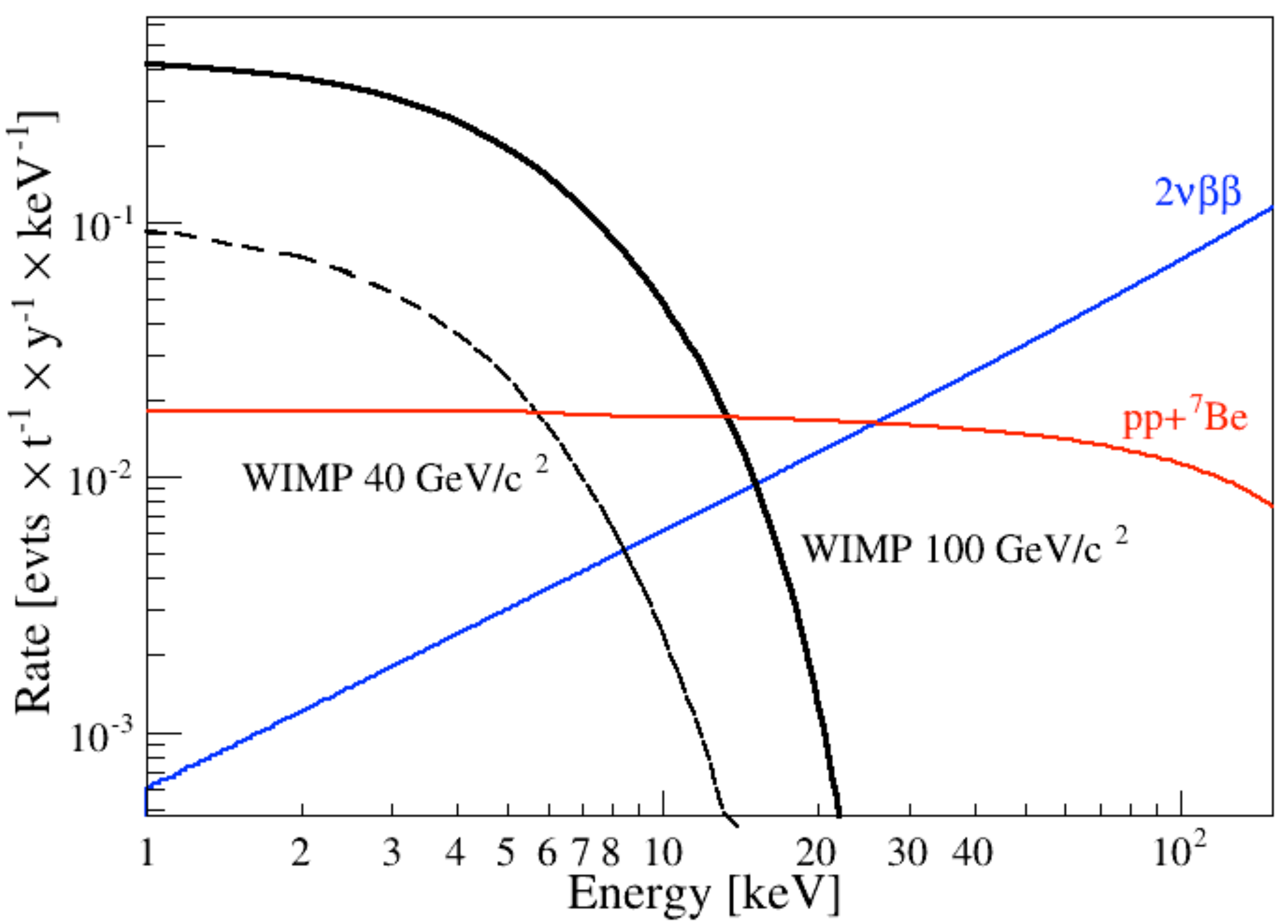




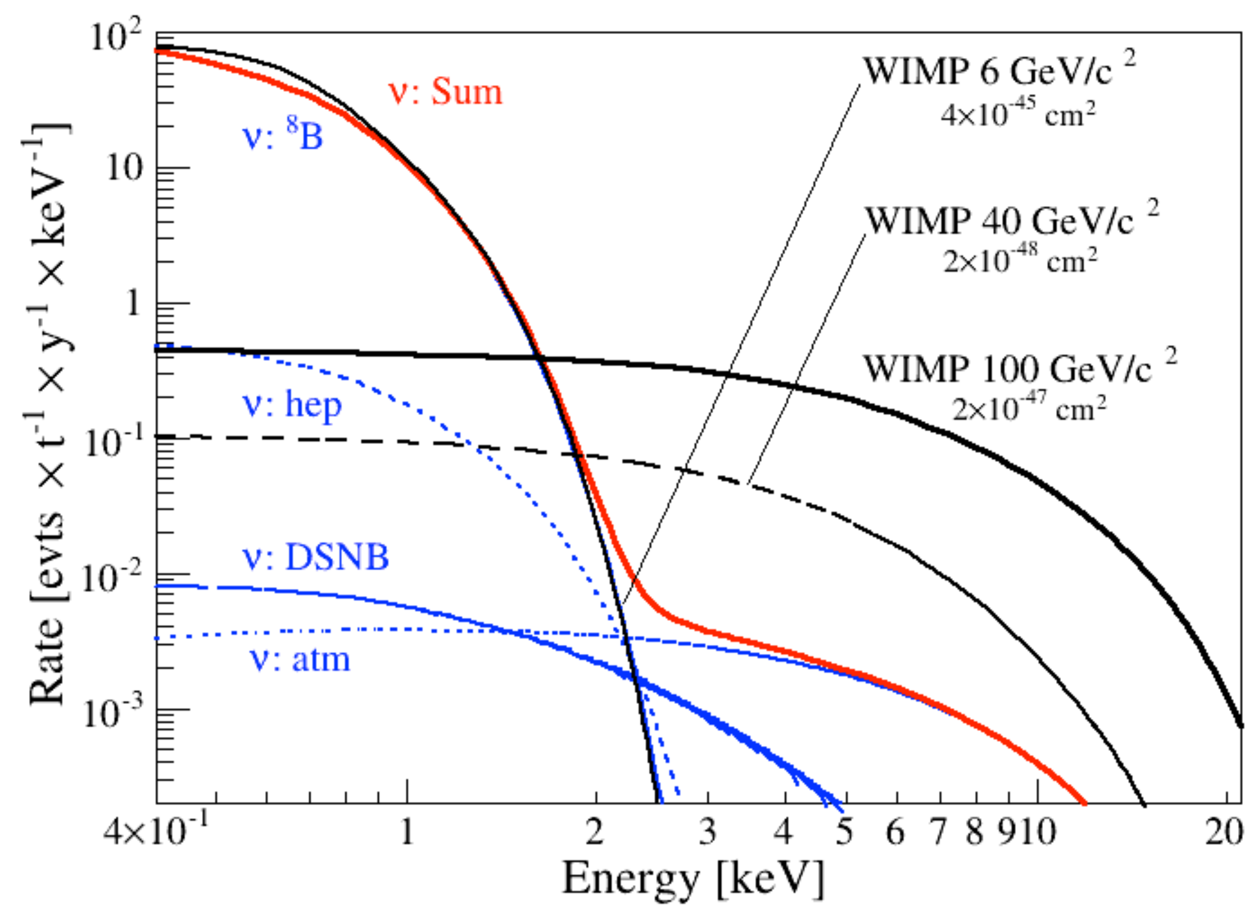
LB et al., JCAP01 (2014) 044

Backgrounds and WIMPs

- A WIMP with a mass of 40 GeV (100 GeV) and sigma=2×10^{-48} cm^2 (2×10^{-47} cm^2) is well above the solar neutrino background
- A WIMP with a mass of 6 GeV and sigma=4×10^{-45} cm^2 has a similar rate as solar ^{8}B neutrinos interacting via coherent neutrino-nucleus scatters



$$\nu + e^- \rightarrow \nu + e^-$$



$$\nu + N \rightarrow \nu + N$$

LB et al., JCAP01 (2014) 044