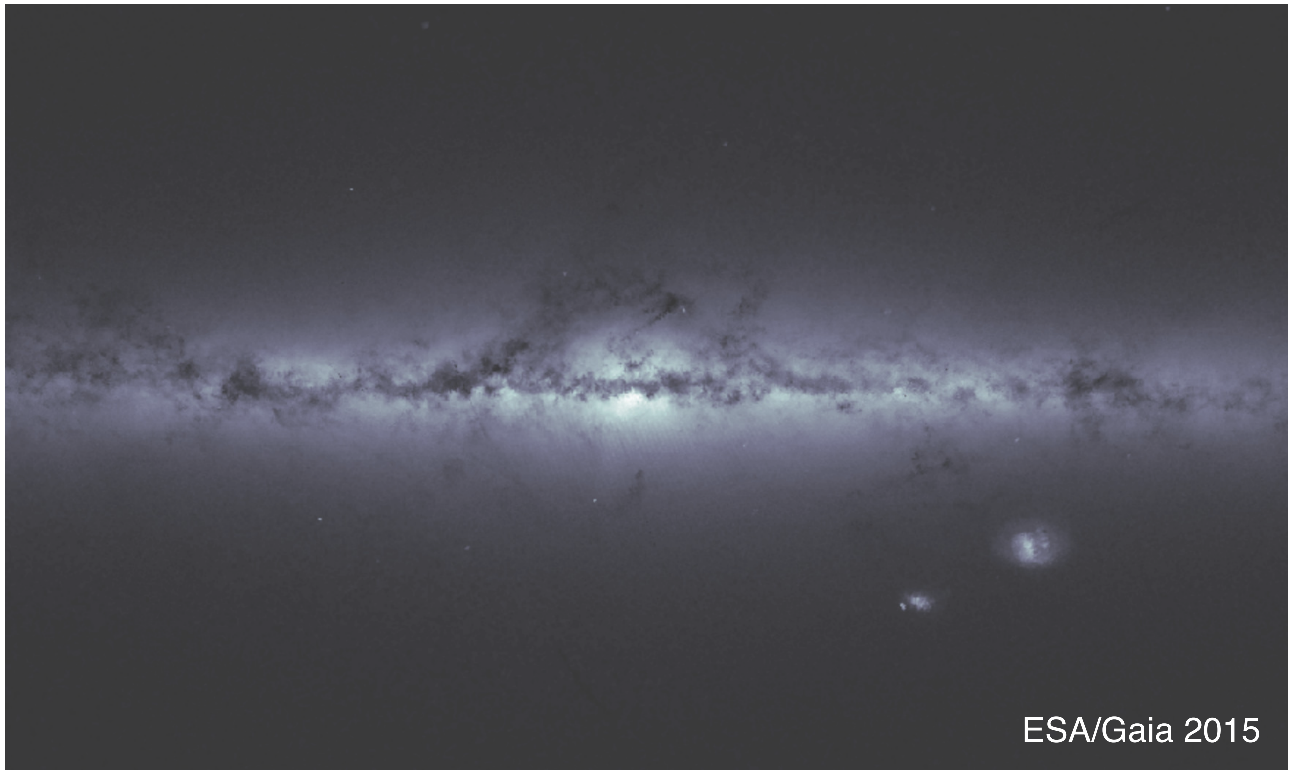
Direct detection of dark matter

Laura Baudis
University of Zurich

LeptonPhoton 2015
Ljubljana, August 20, 2015

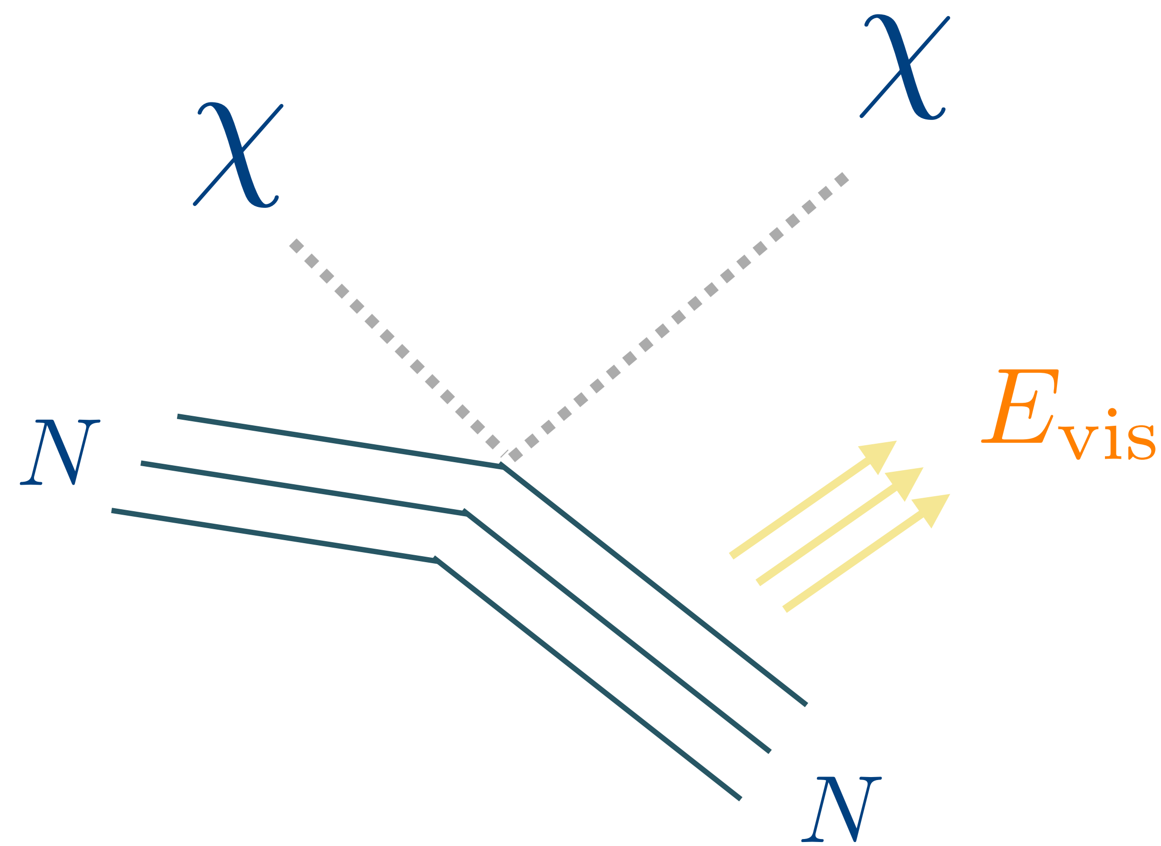


Direct detection principle

Collisions of invisibles particles with atomic nuclei => E_{vis} (q ~ tens of MeV):

- very low energy thresholds
- ultra-low backgrounds, good background understanding (no "beam off" data collection mode), and particle ID
- large detector masses

$$v/c \sim 0.75 \times 10^{-3}$$



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.

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

What to 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

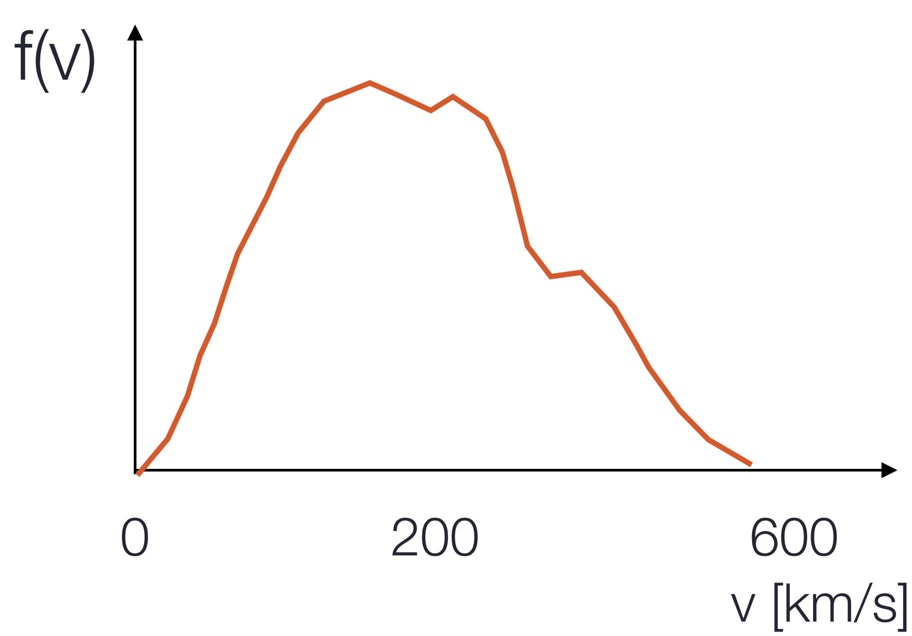
$\rho_0, f(v)$

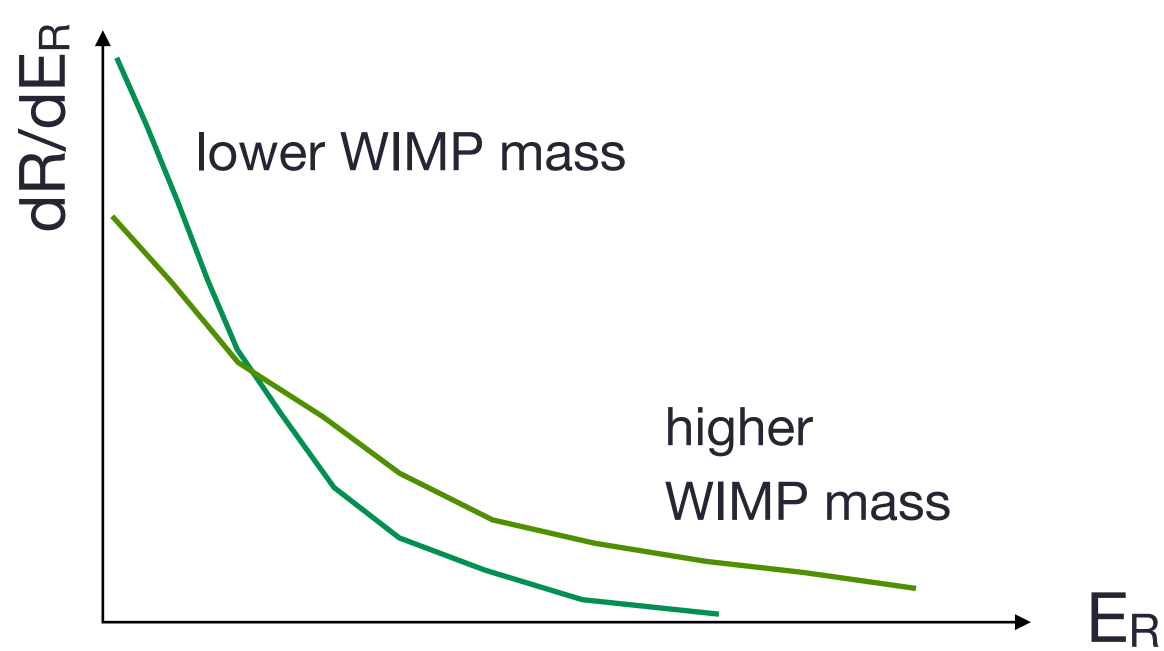
Particle/nuclear physics

$m_W, d\sigma/dE_R$

Detector physics

N_N, E_{th}





Astrophysics

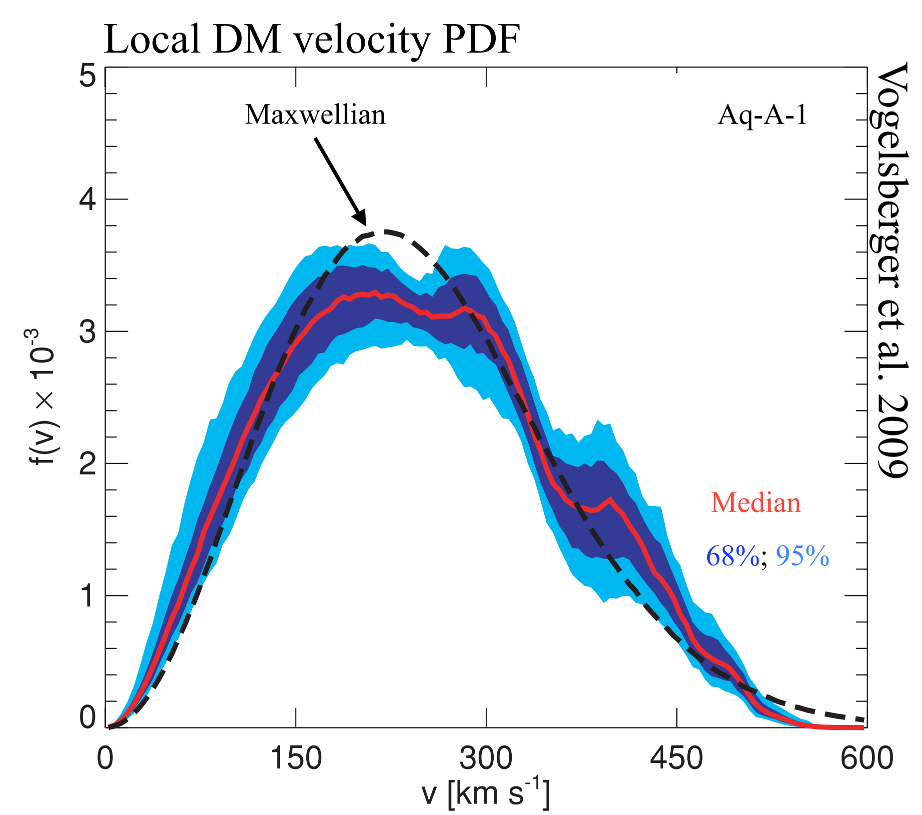
Local density (at R_0 ~ 8 kpc)

local measures use the vertical kinematics of stars near the Sun as 'tracers' (smaller error bars, but stronger assumptions about the halo shape)

global measures extrapolate the density from the rotation curve (larger errors, but fewer assumptions)

also: modelling the phase space distribution over larger volumes around the solar neighbourhood

Velocity distribution of WIMPs in the galaxy



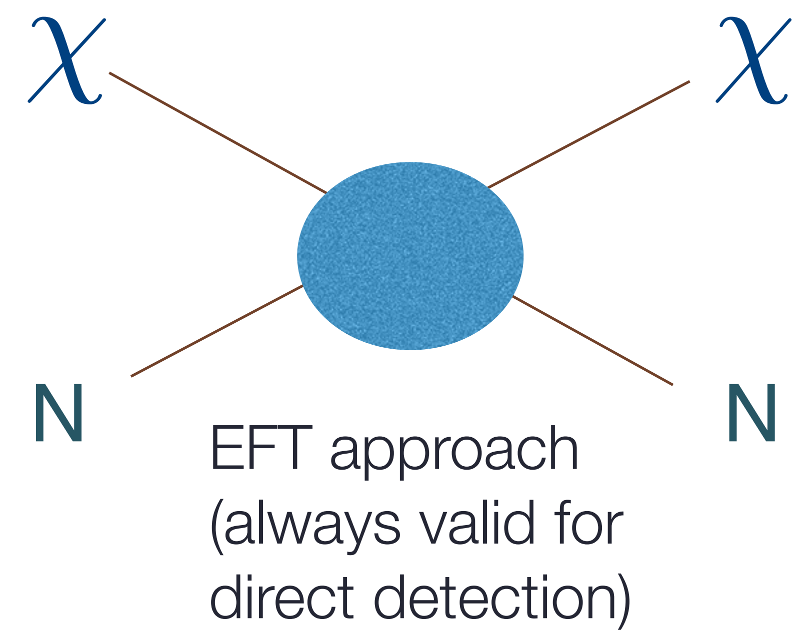
$$\rho(R_0) = 0.2 - 0.56\,\mathrm{GeV\,cm^{-3}} = 0.005 - 0.015\,\mathrm{M_\odot\,pc^{-3}}$$

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

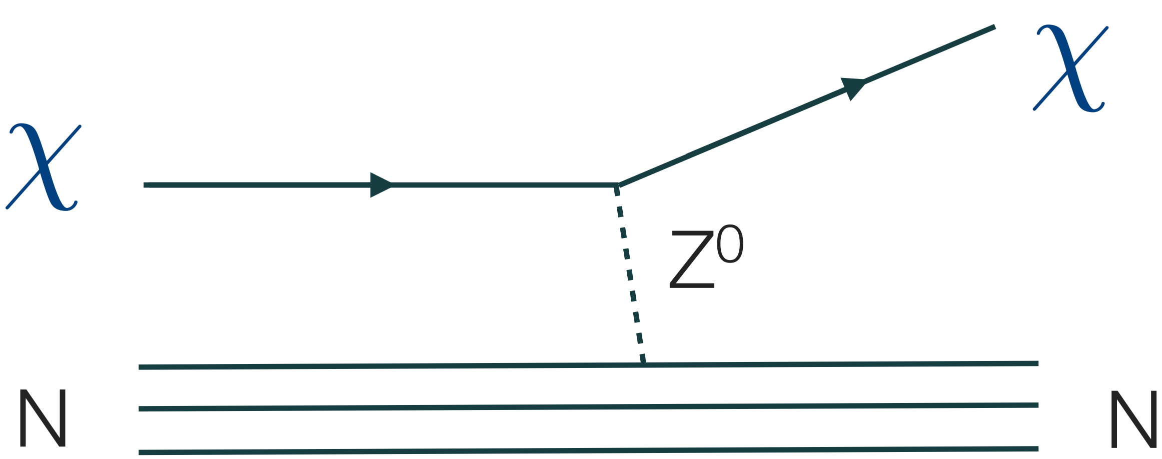
=> **WIMP flux on Earth: ~10^5 $cm^{-2}s^{-1}$** (M_W=100 GeV, for 0.3 GeV cm^{-3})

Particle physics

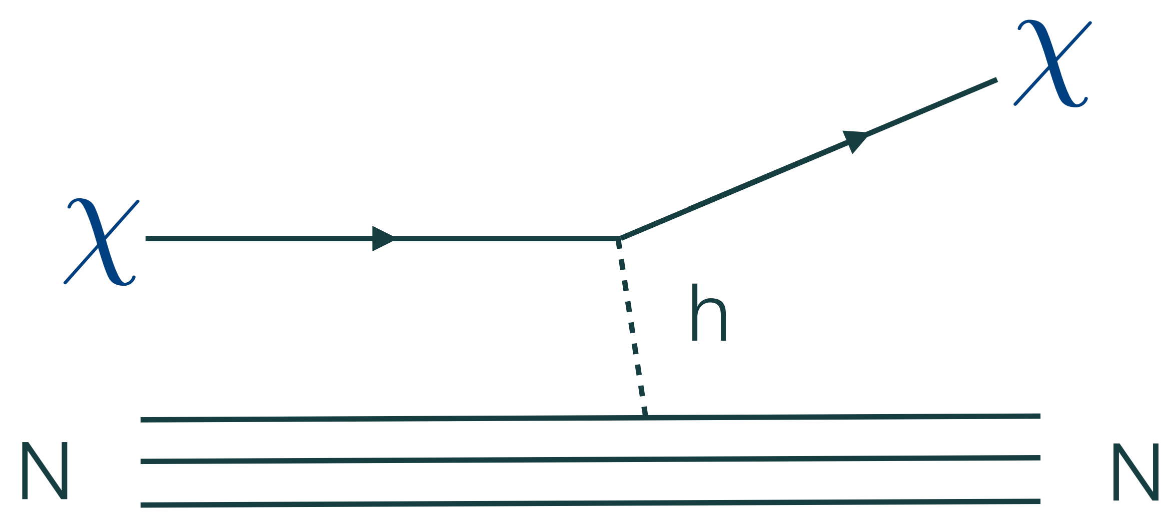
- Use effective operators to describe WIMP-quark interactions
- Example: vector mediator $\mathcal{L}_\chi^{\text{eff}} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$
- The effective operator arises from integrating out the mediator with mass M and couplings g_q and g_χ to the quark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



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



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



$$\sigma_0 \sim 10^{-44} - 10^{-47}\,\text{cm}^2$$

Scattering cross section on nuclei

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

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

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

=> nuclei with large A favourable (but nuclear form factor corrections)

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

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

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

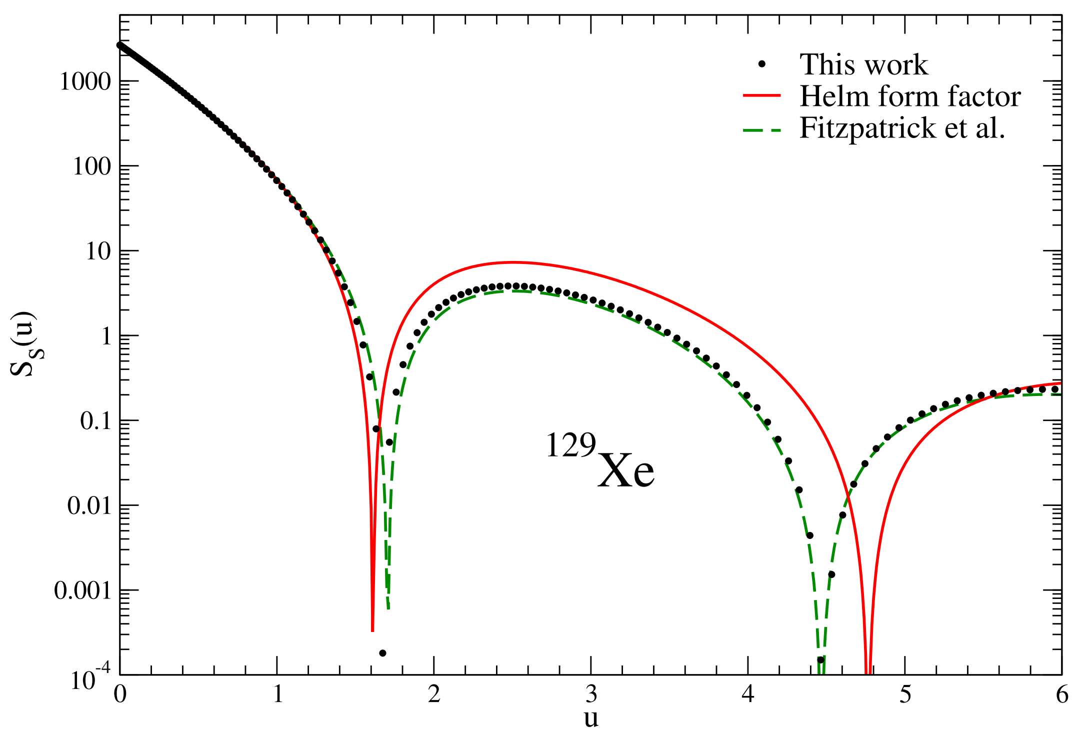
=> nuclei with non-zero angular momentum (corrections due to spin structure functions)

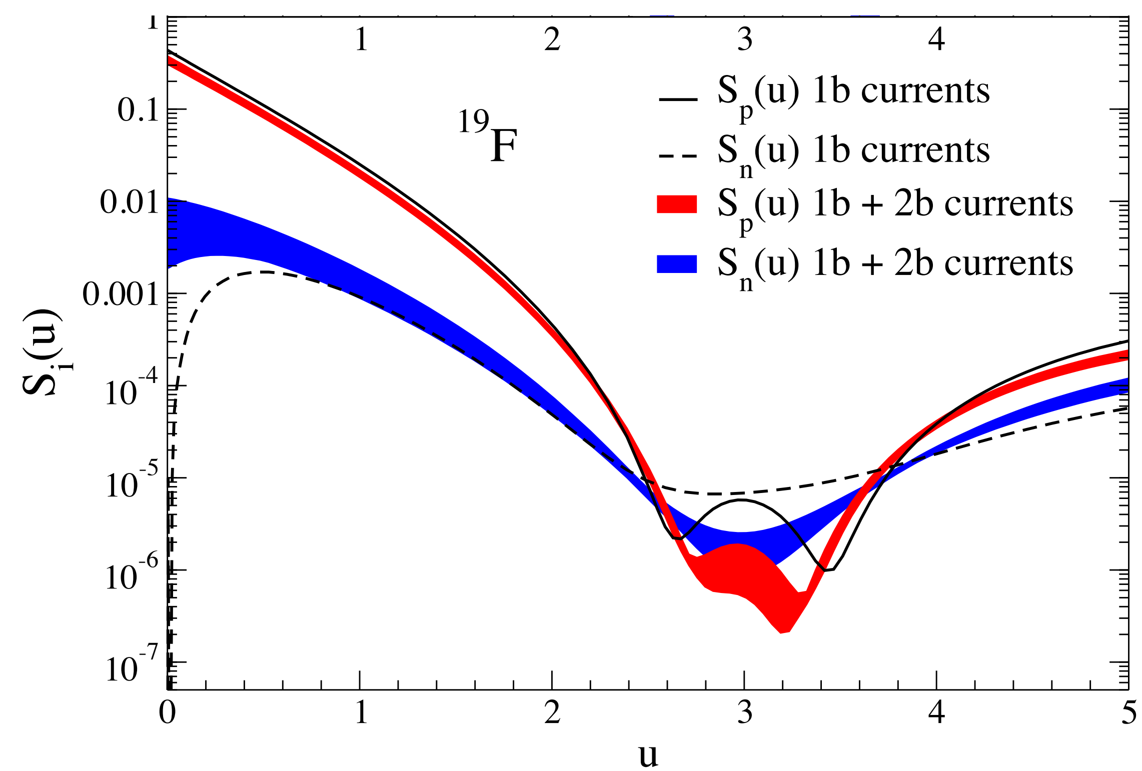
Form factor corrections

- Especially important for heavy WIMPs and/or nuclei and for WIMPs in the tail of the velocity distribution

$$\frac{d\sigma_{SI}}{dq^2} = \sigma_{0,SI} \times S_s(q)$$

$$\frac{d\sigma_{SD}}{dq^2} = \sigma_{0,SD} \times S_A(q)$$





L. Vietze et al., Phys.Rev. D91 (2015)

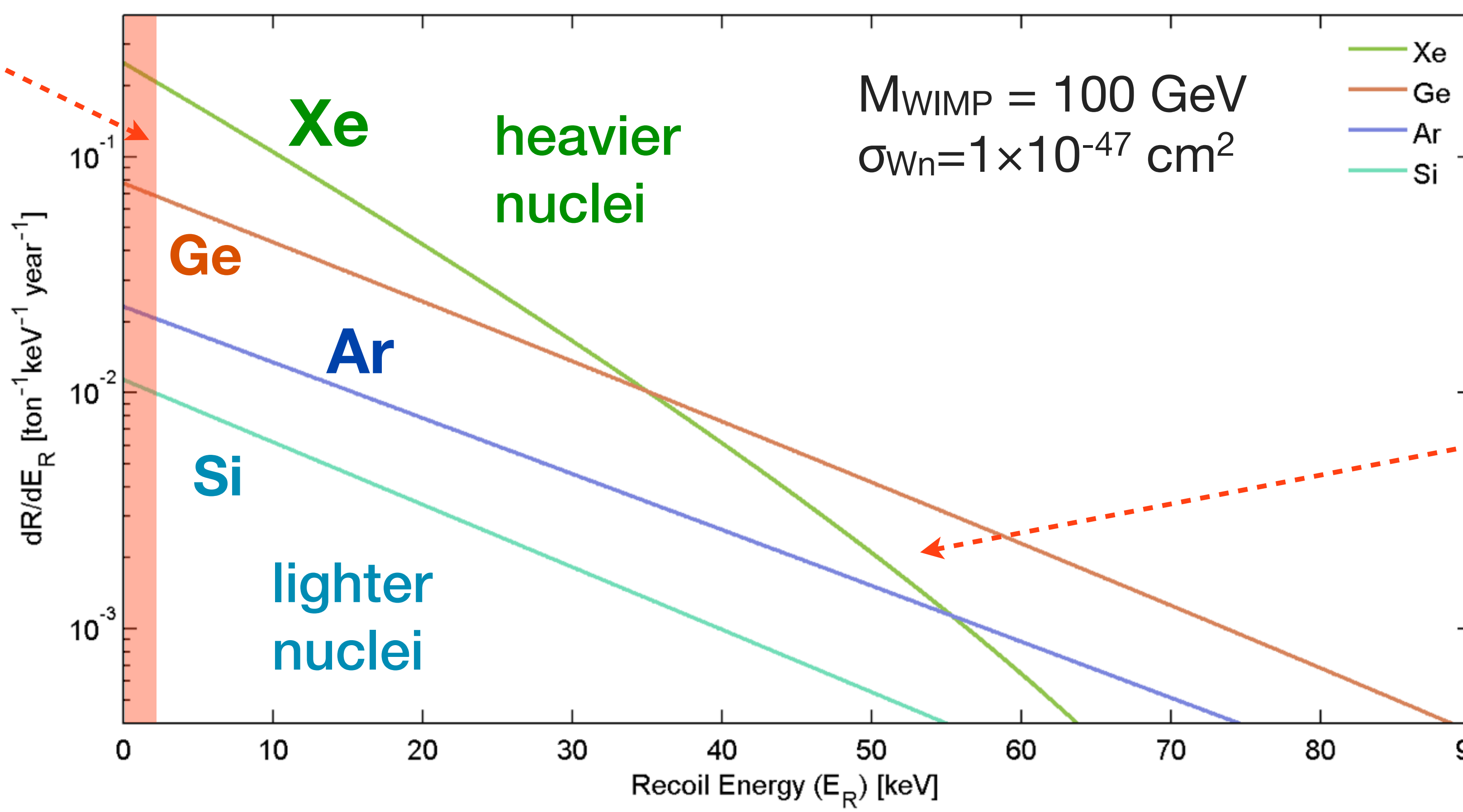
$$u = q^2b^2/2$$

P. Klos et al., PRD 88 (2013)

Expected interaction rates

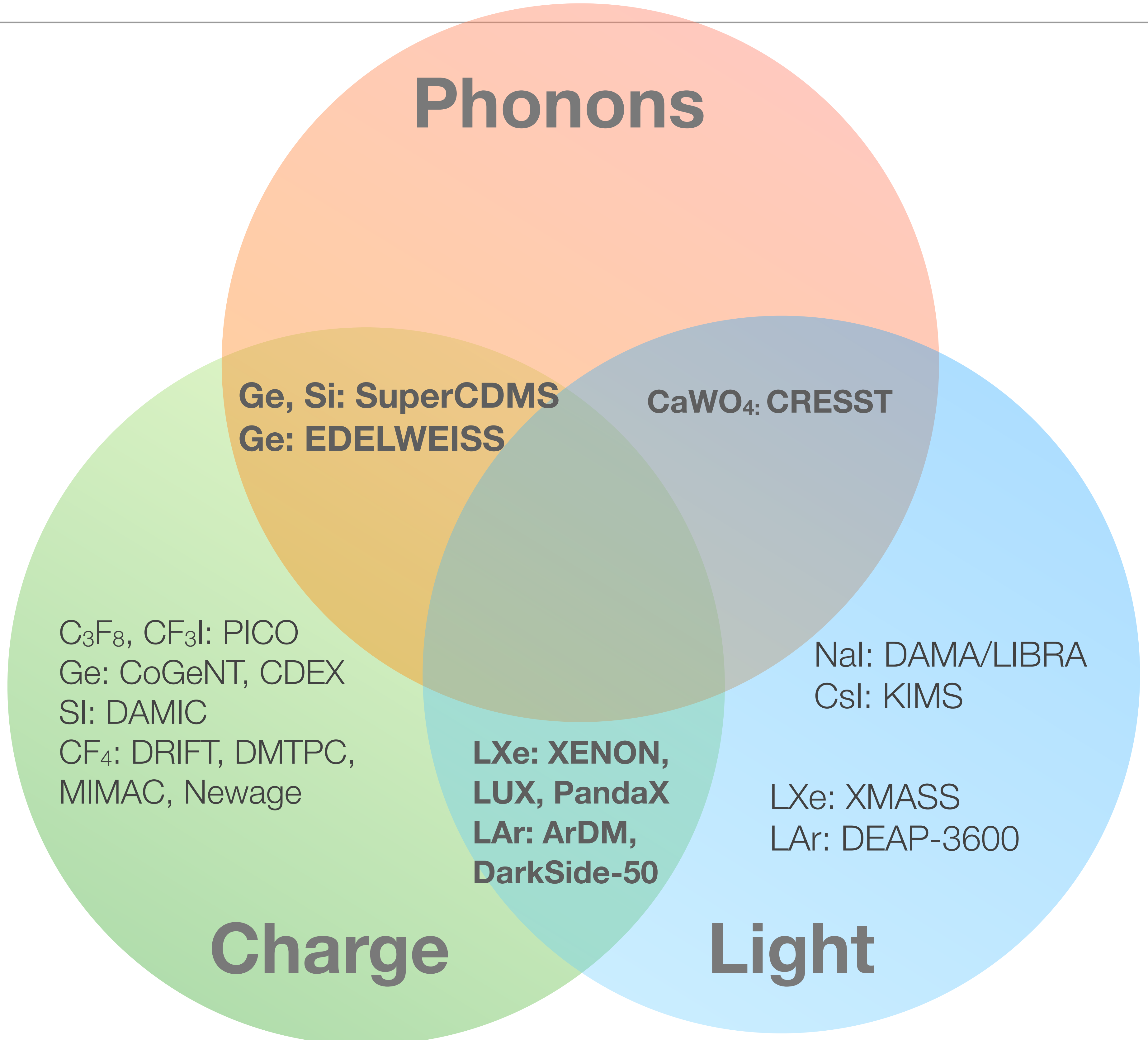
$$R \sim 0.13 \, \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$

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



$F^2(E_R)$

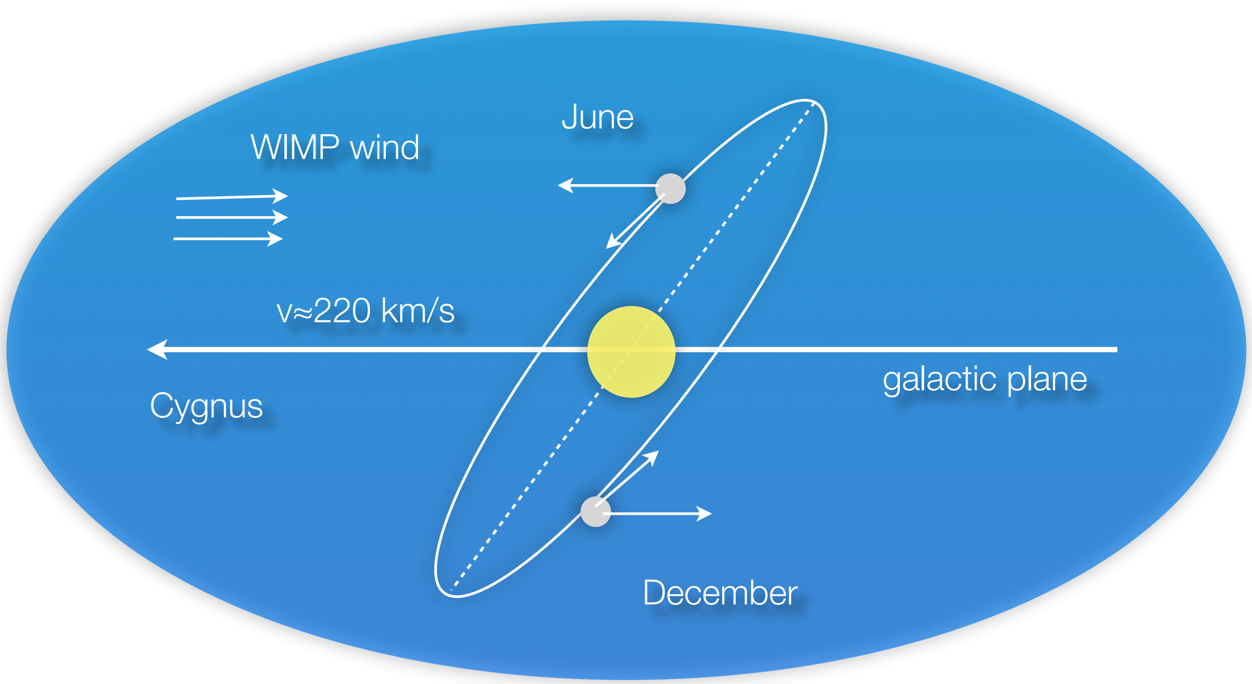
Direct dark matter detection zoo



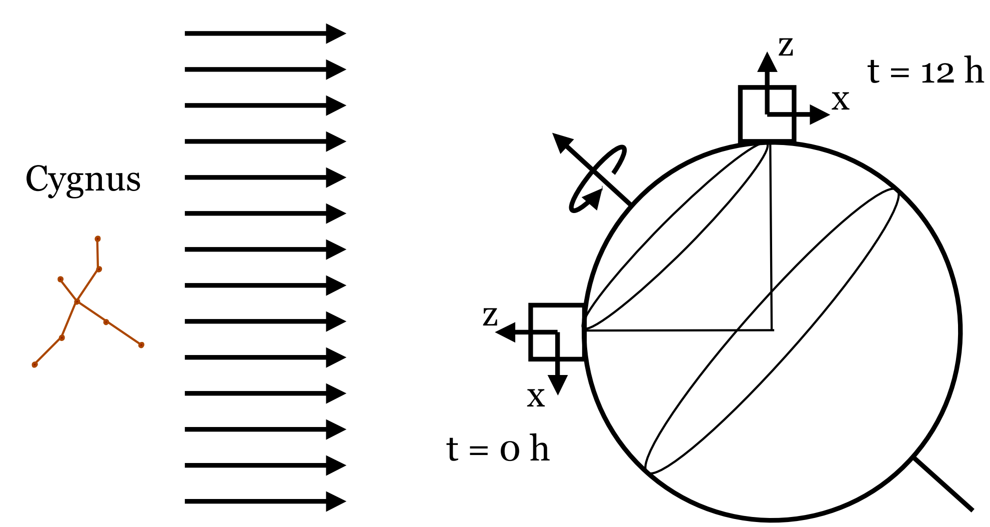
Dark matter signatures

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

Drukier, Freese, Spergel, PRD 33,1986

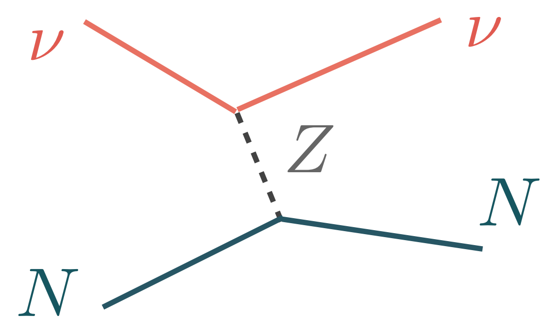


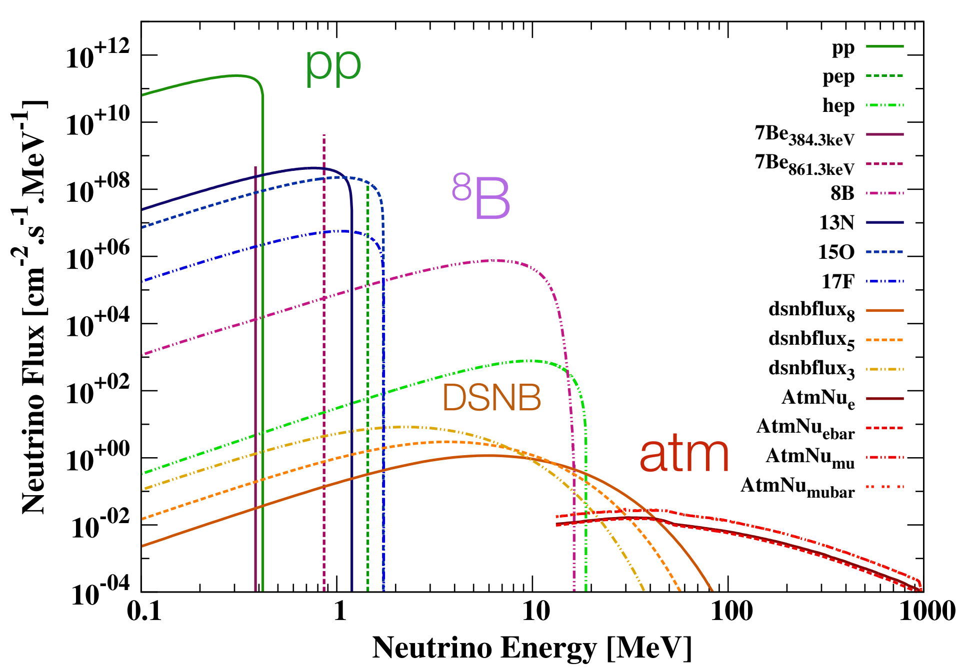
D. Spergel, PRD 36, 1988



Expected backgrounds

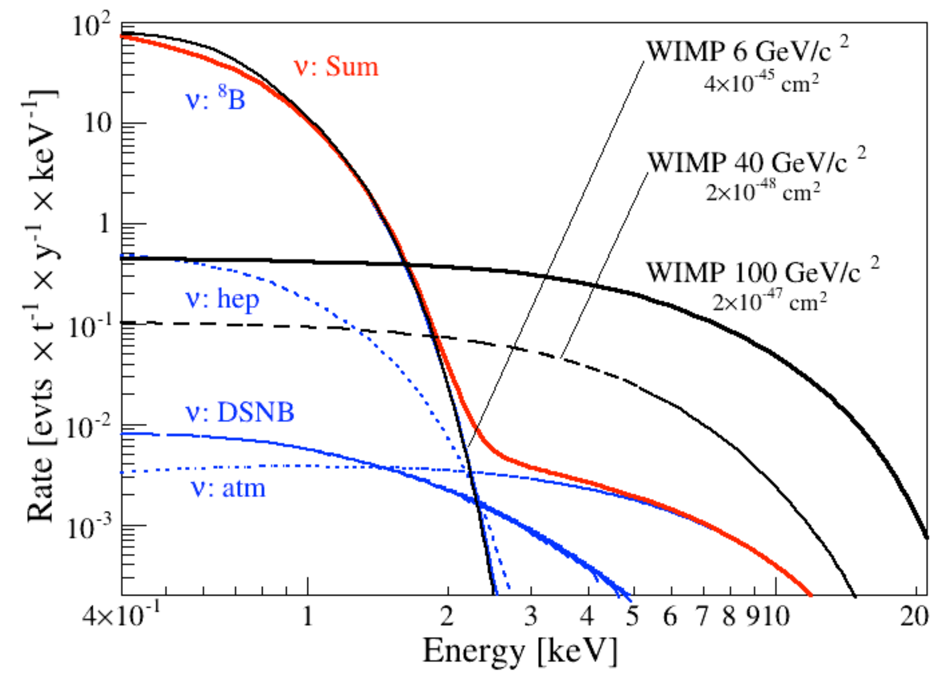
- Cosmic rays & cosmic activation of detector materials
- Natural (^{238}U, ^{232}Th, ^{40}K) & anthropogenic (^{85}Kr, ^{137}Cs) radioactivity: γ, e^-, n, α
- Ultimately: **neutrino-nucleus scattering (solar, atmospheric and supernovae neutrinos)**





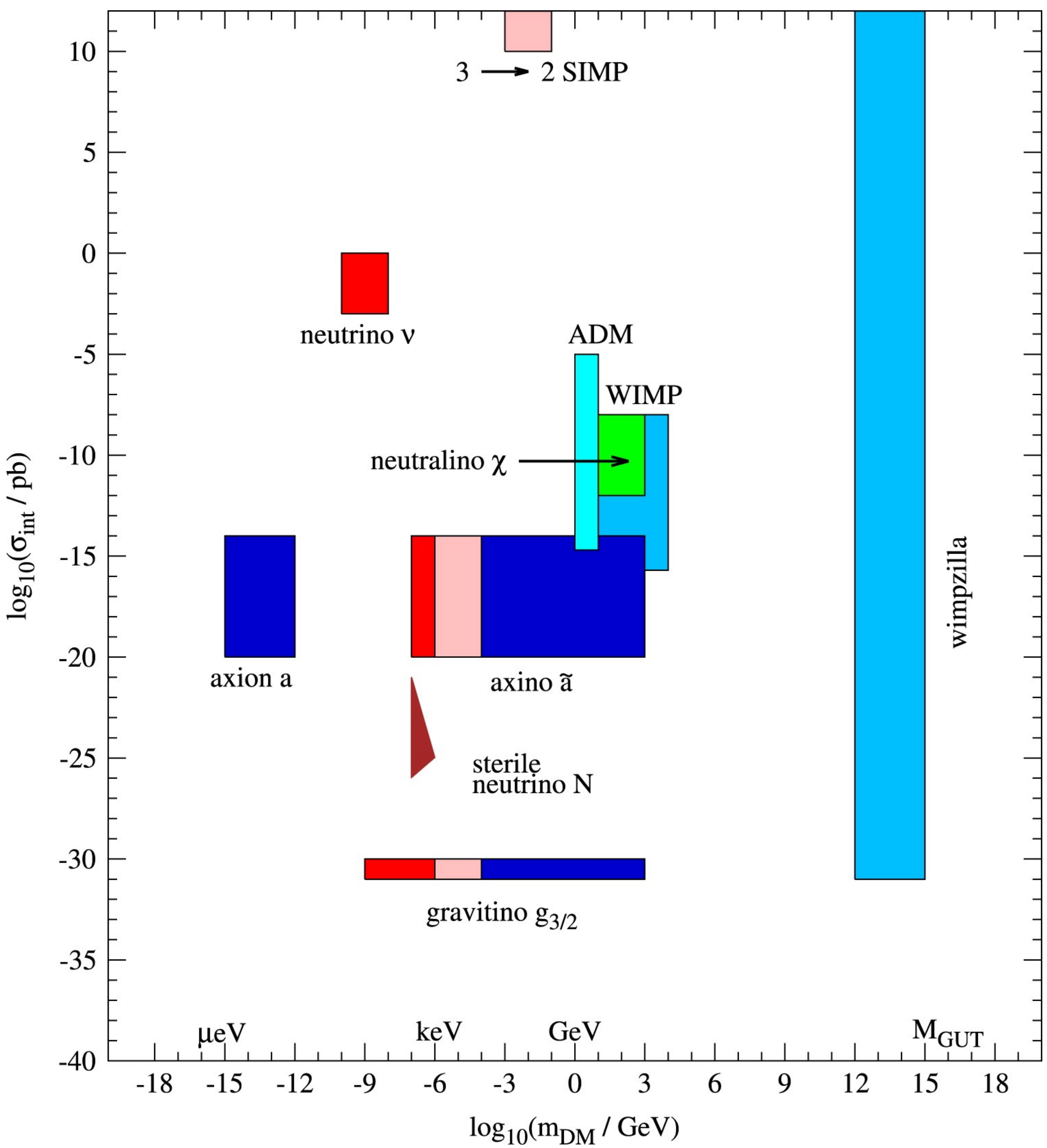
F. Ruppin et al., 1408.3581

$$\nu + N \longrightarrow \nu + N$$



LB et al., JCAP01 (2014) 044

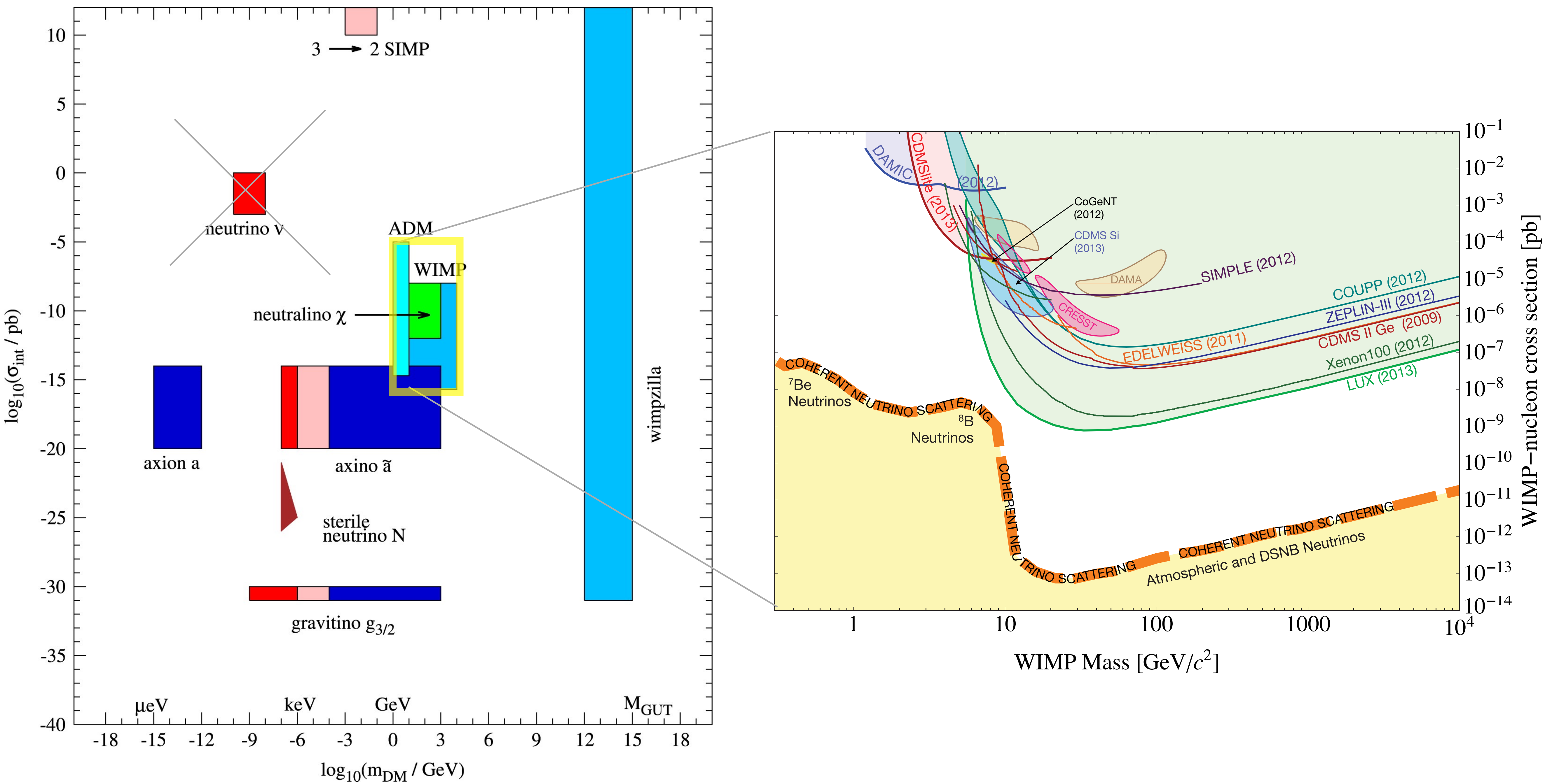
Parameter space for searches



- Masses & cross sections span an enormous range
- Direct detection experiments optimised for WIMPs
- However recently also limits on axions, ALPs, SuperWIMPs

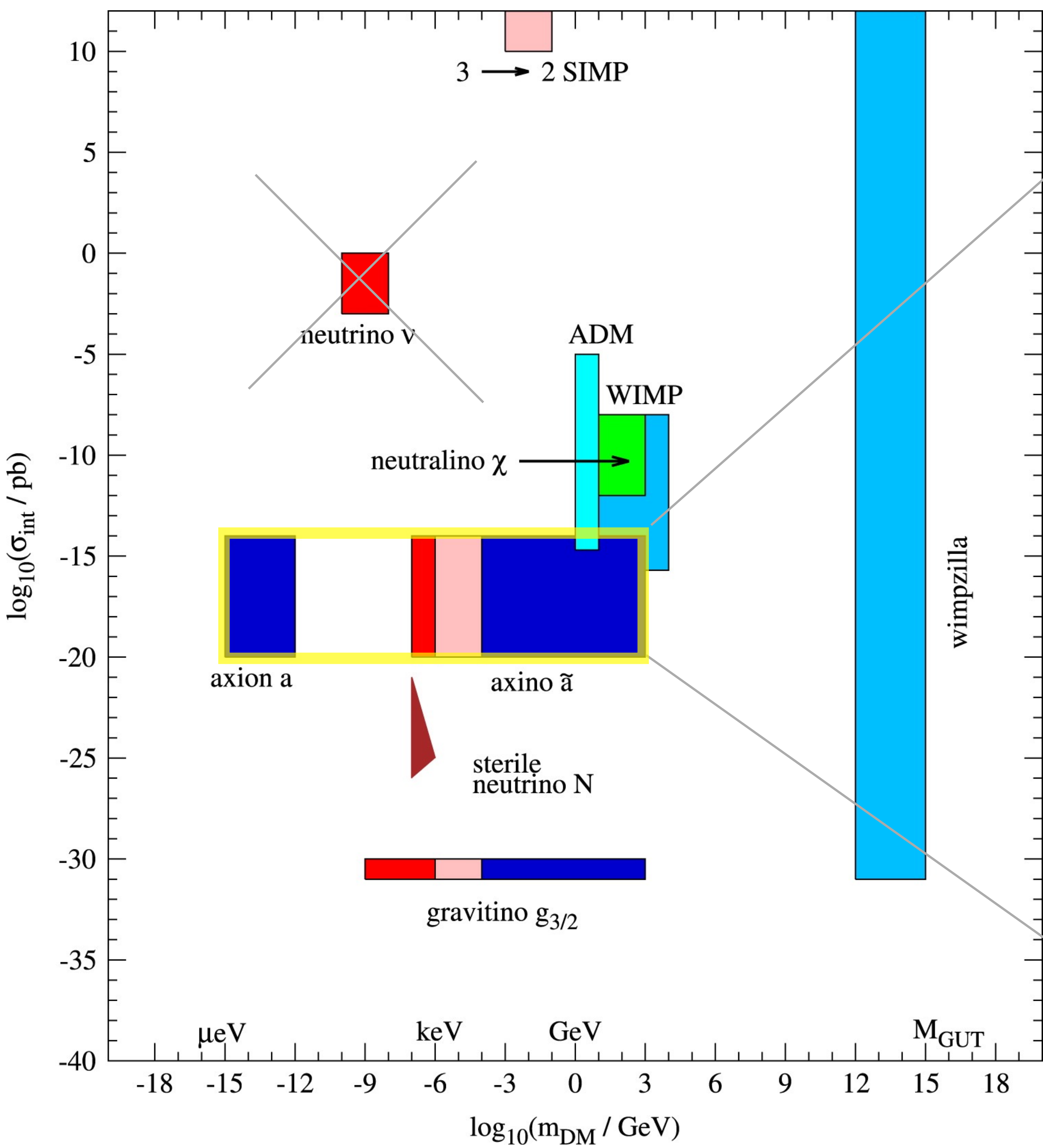
H. Baer et al., Phys. Rept. 555, 2014

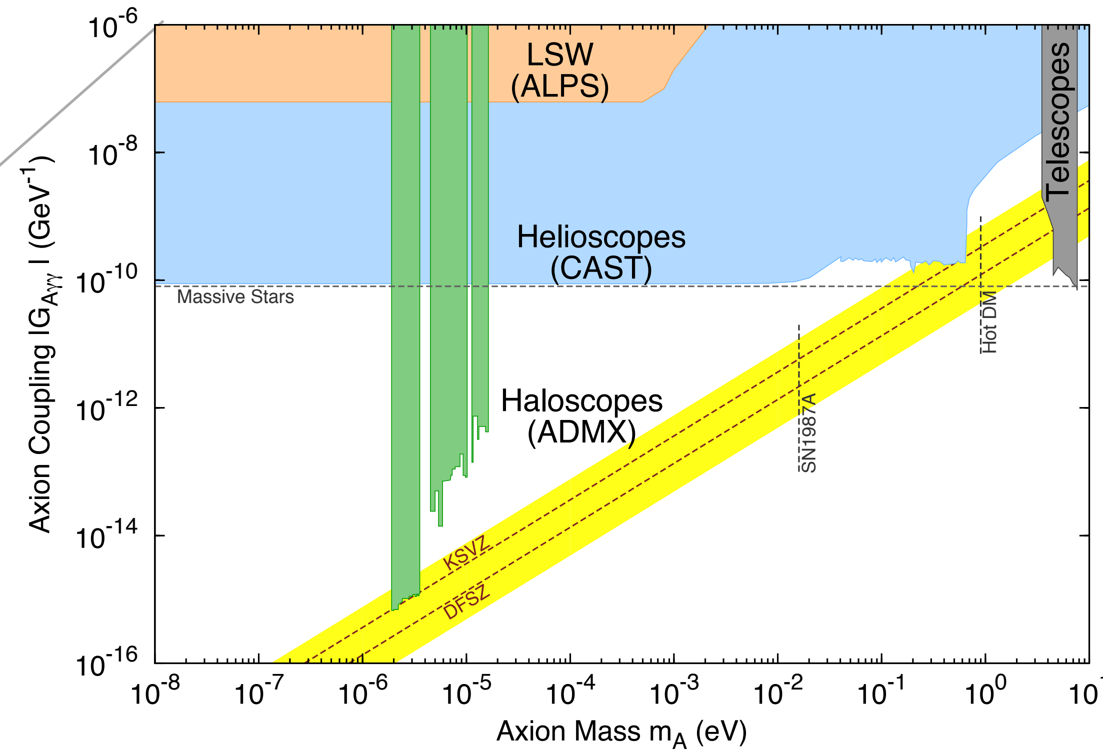
Parameter space for searches

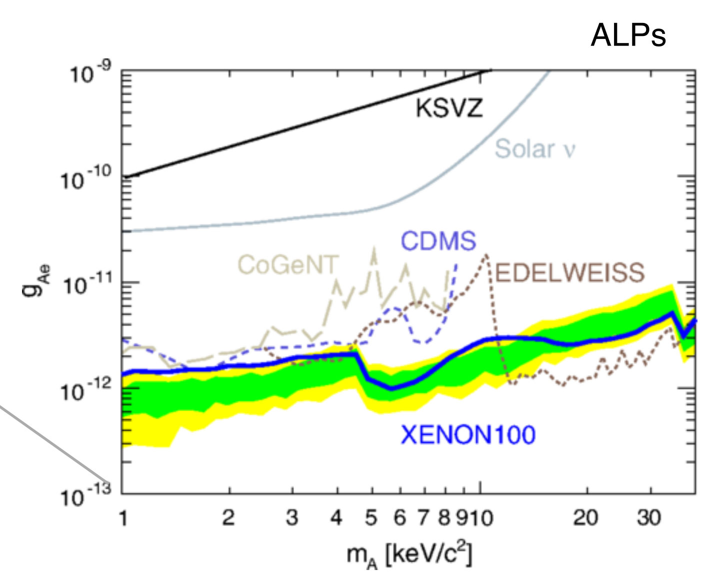


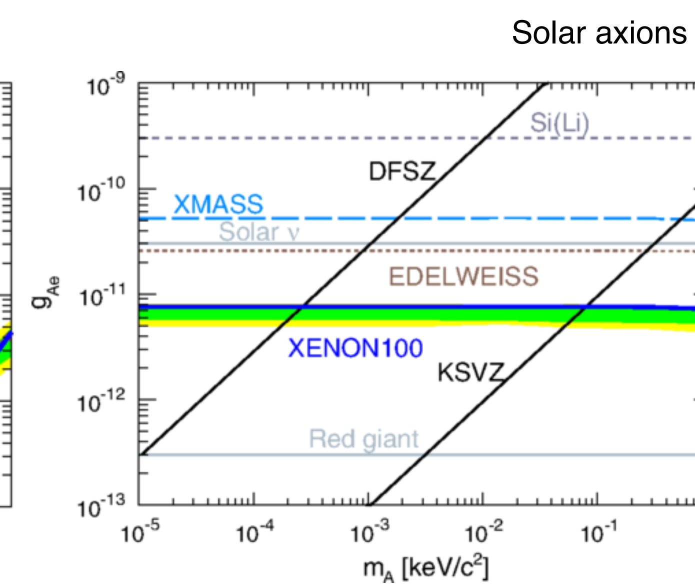
H. Baer et al., Phys. Rept. 555, 2014

Parameter space for searches









H. Baer et al., Phys. Rept. 555, 2014

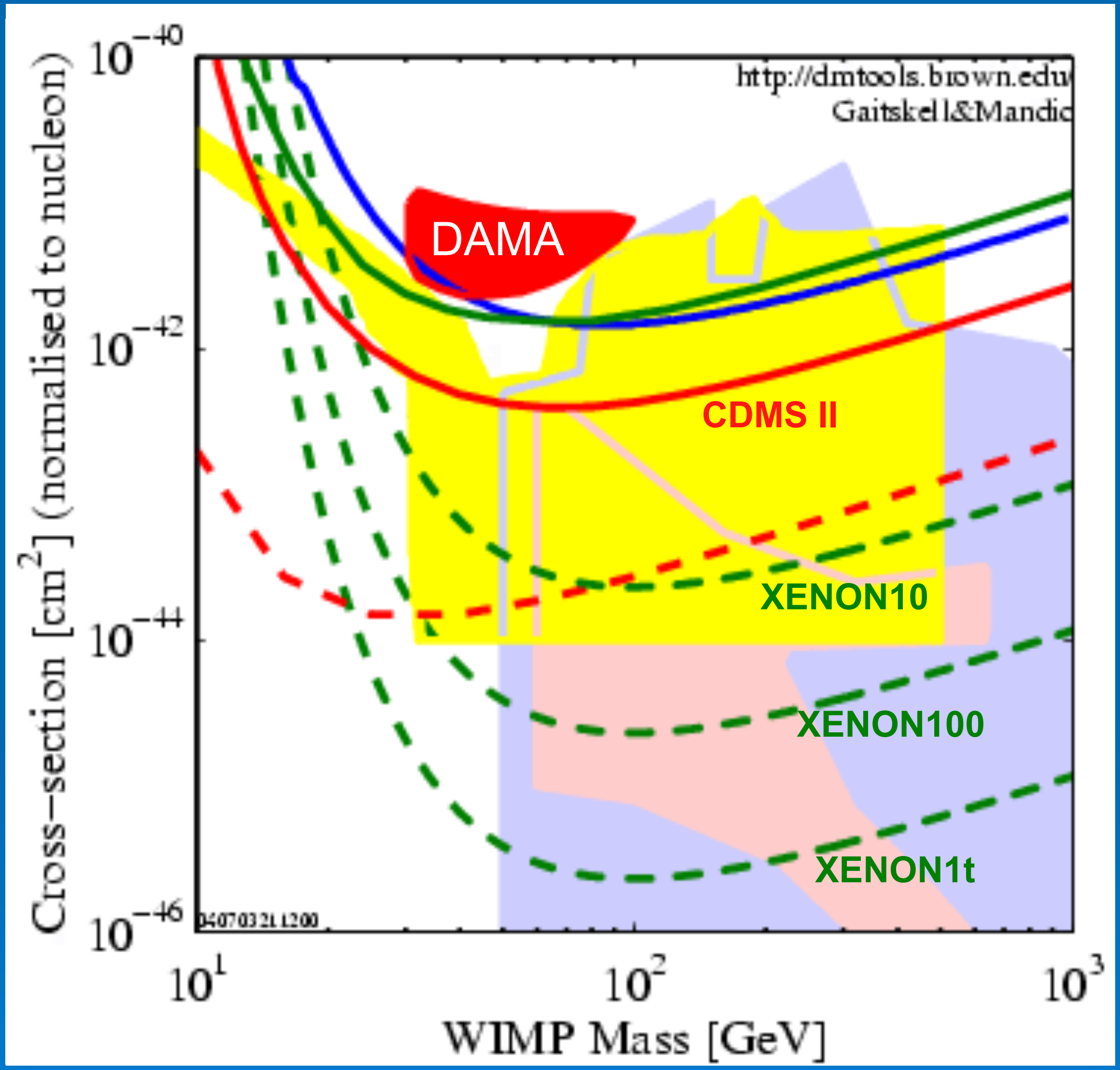
Phys. Rev. D 90, 062009 (2014)

The WIMP landscape 10 years ago…

Where do we stand?

Laura Baudis

Lepton Photon, Uppsala
July 4, 2005



~ 0.2 events/kg/day

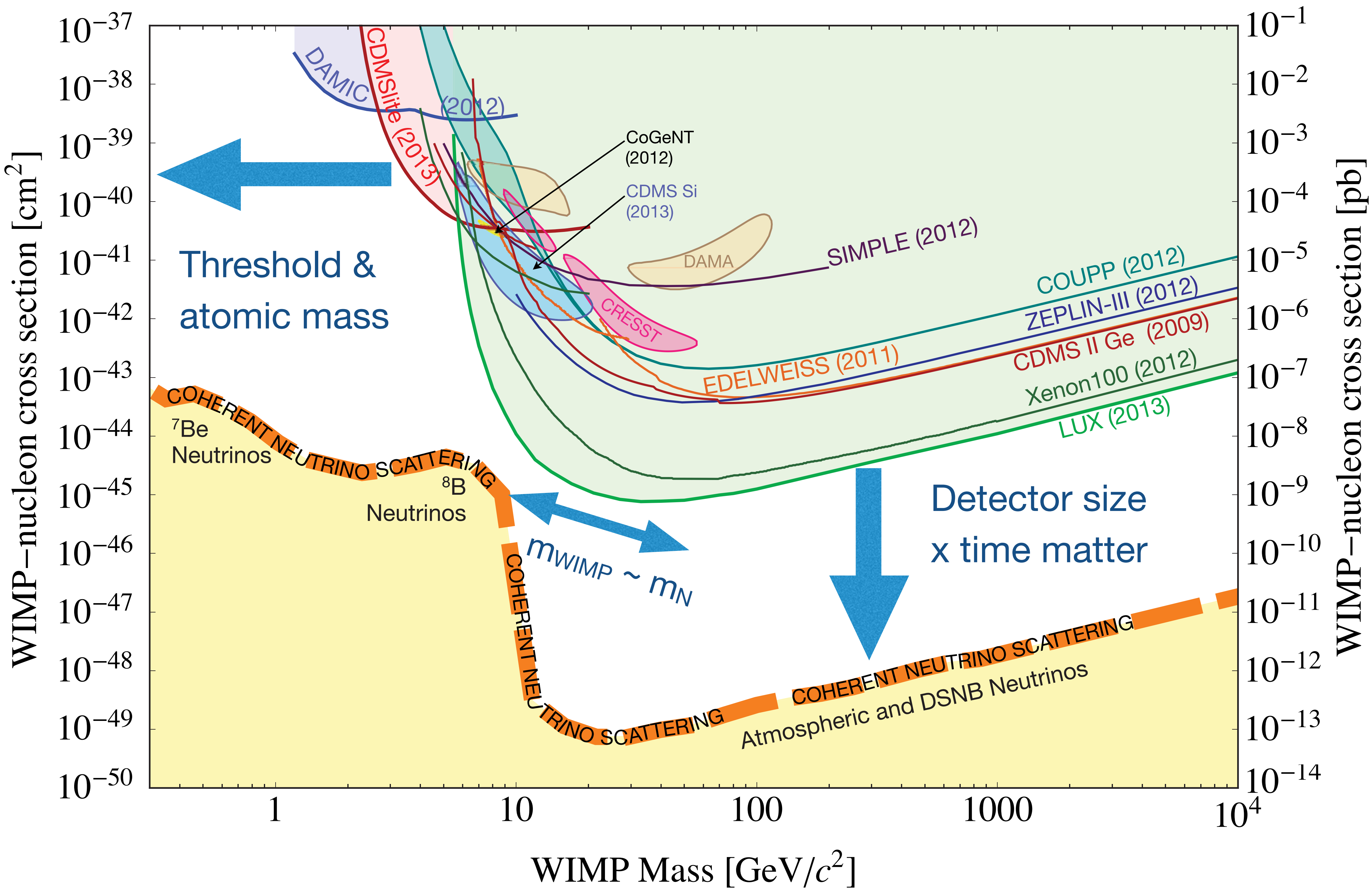
Most advanced experiments start to test the predicted SUSY parameter space

One evidence for a positive WIMP signal (DAMA NaI)

Not confirmed by other experiments

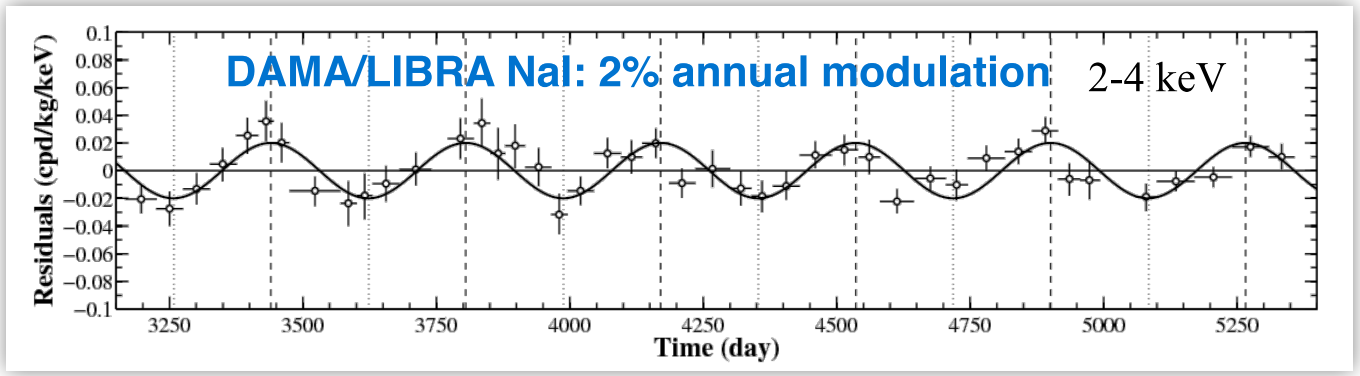
Predictions: Ellis & Olive, Baltz & Gondolo, Mandic & all

The WIMP landscape today

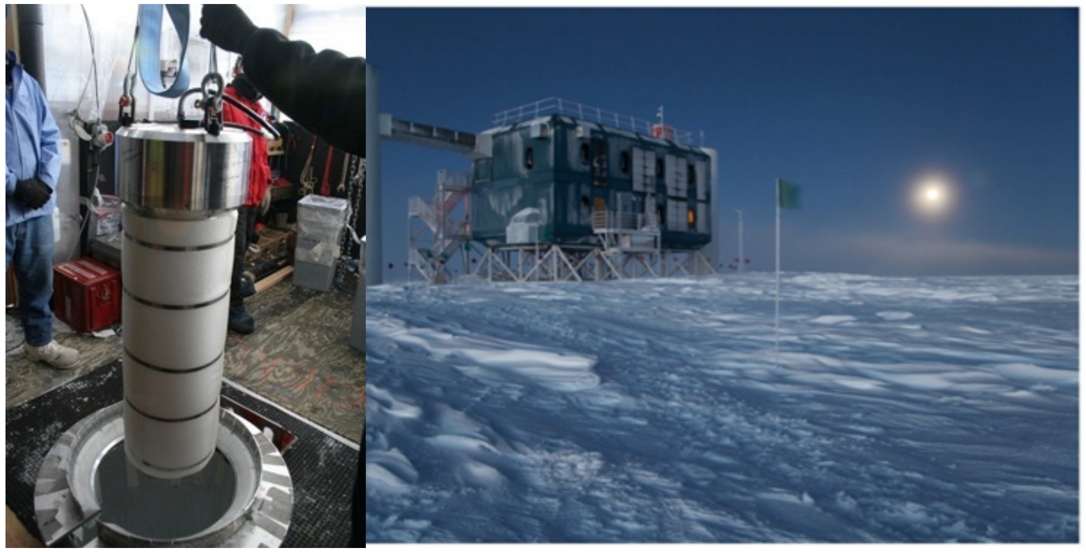


DAMA/LIBRA annual modulation signal

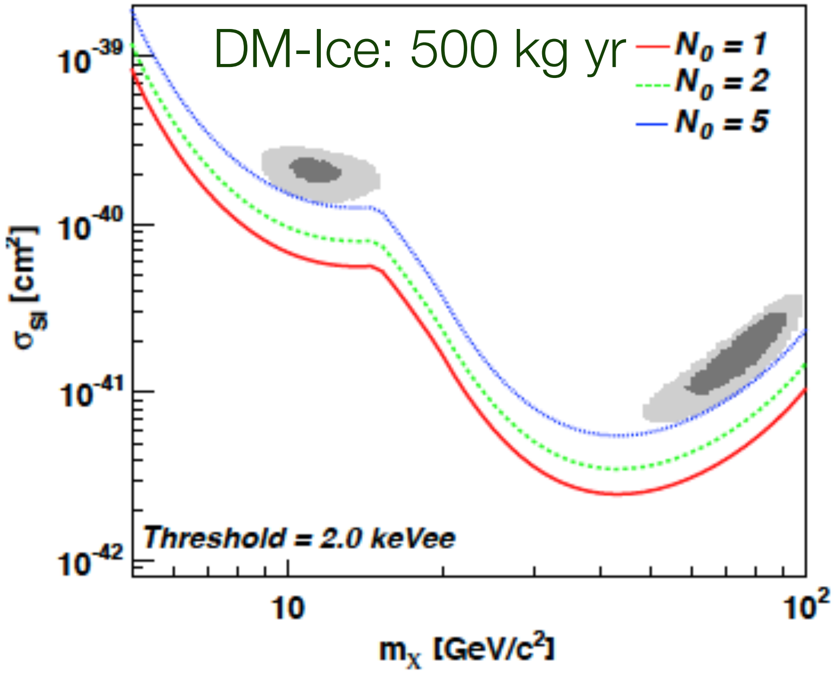
- Period = 1 year, phase = June 2 ± 7 days; 9.3-sigma
- Several experiments to directly probe the modulation signal with similar detectors (NaI, CsI): SABRE, ANAIS, DM-Ice, KIMS
- **Challenge to achieve the same crystal radio-purity as DAMA/LIBRA**



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



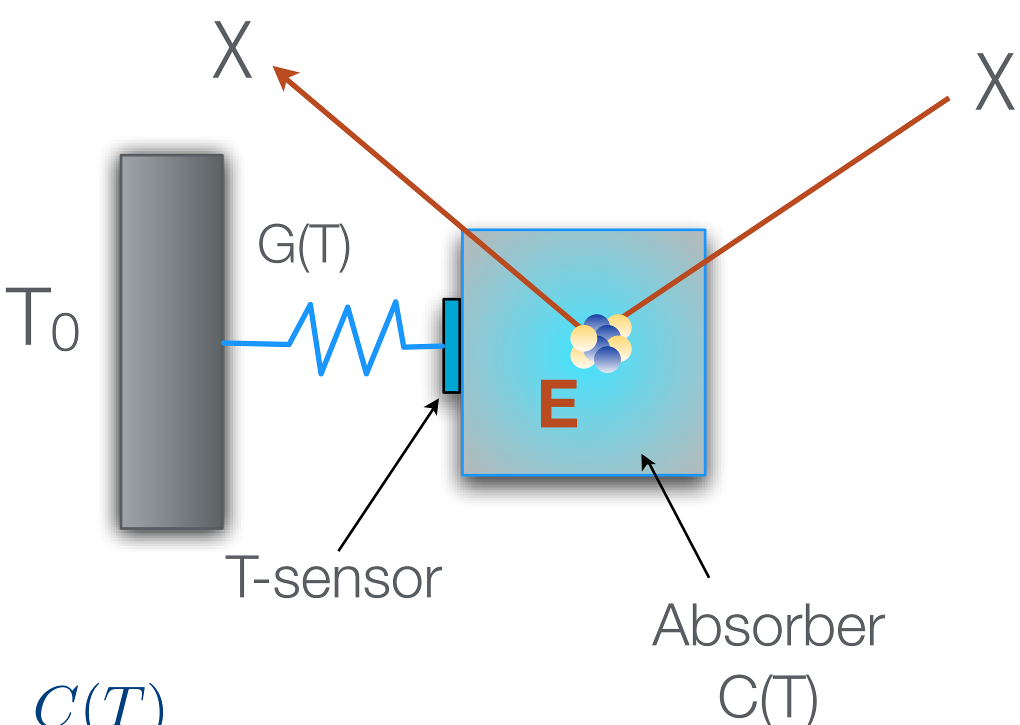
Definitive (5σ) detection or exclusion with 500 kg-yr NaI(Tl) (DAMA x 2 yrs) and same or lower threshold (< 2 keV_{ee})



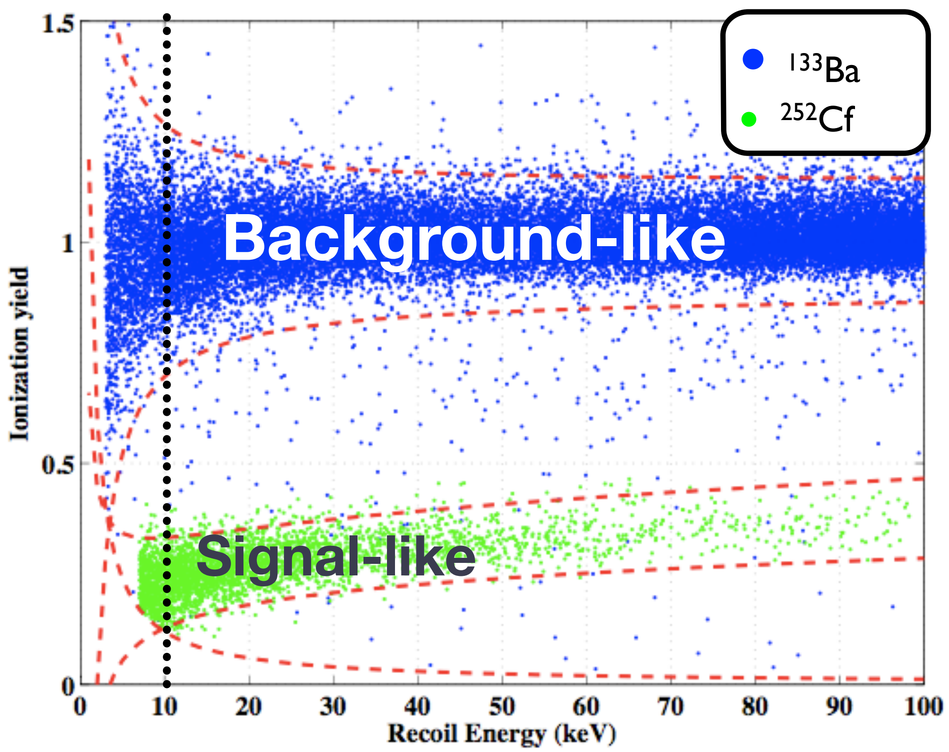
Cryogenic detectors at T ~ mK

- Detect a temperature increase after a particle interacts in an absorber
- Absorber masses from ~100 g to 1.4 kg; TES read out small T changes

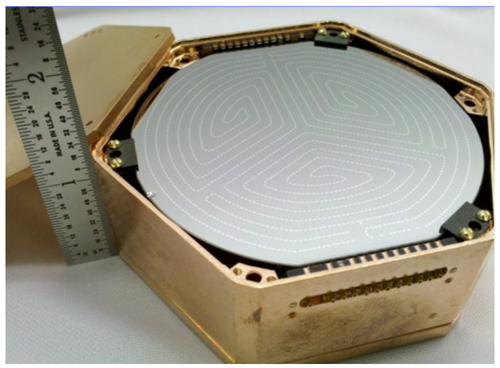
$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}}$$



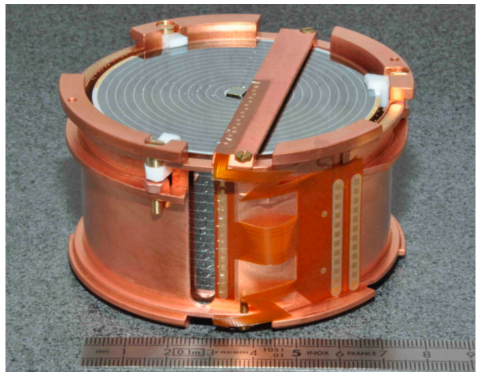
$$\tau = \frac{C(T)}{G(T)}$$



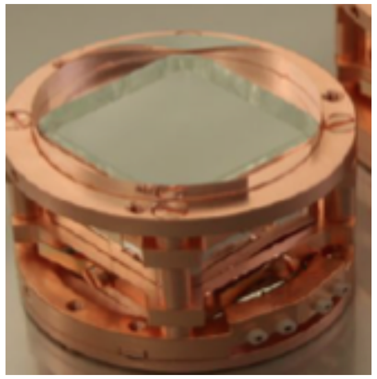
SuperCDMS: Ge, Si



EDELWEISS-III (Ge)

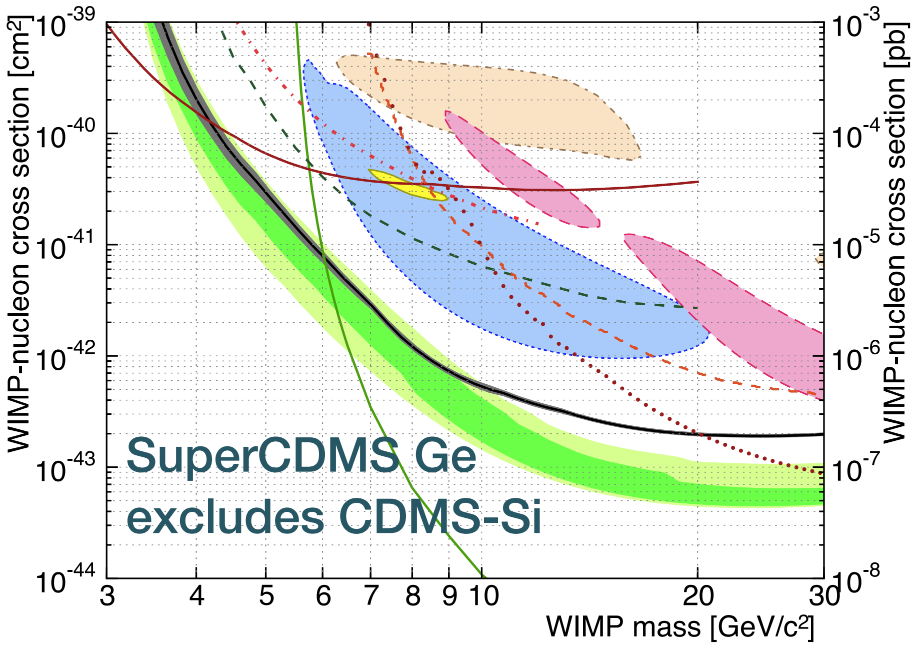


CRESST ($CaWO_4$)

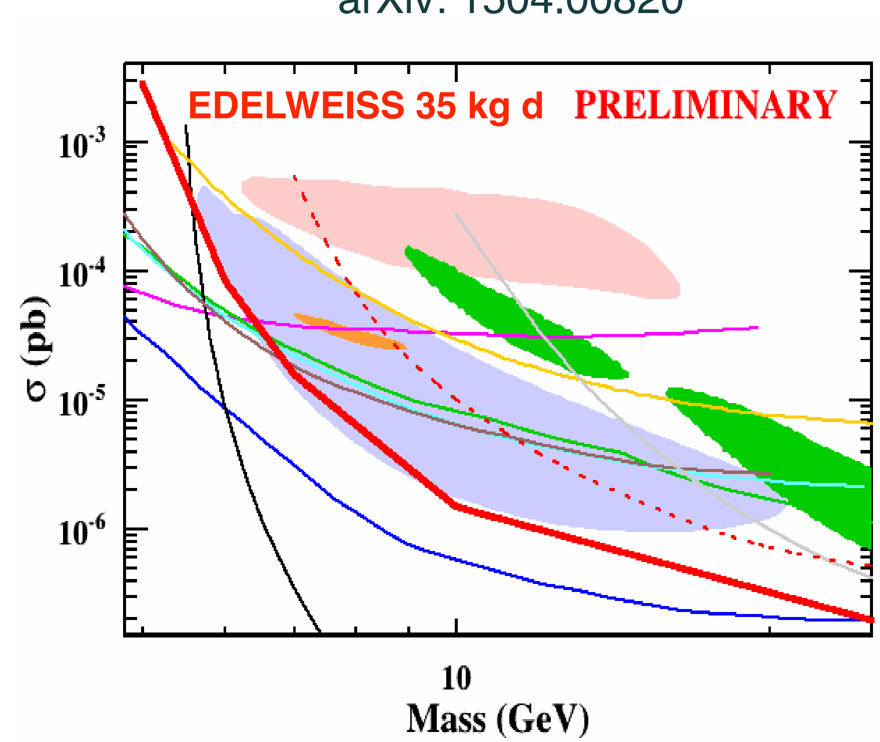


Bolometers: recent results

Phys. Rev. Lett. 112 (2014) 24, 241302

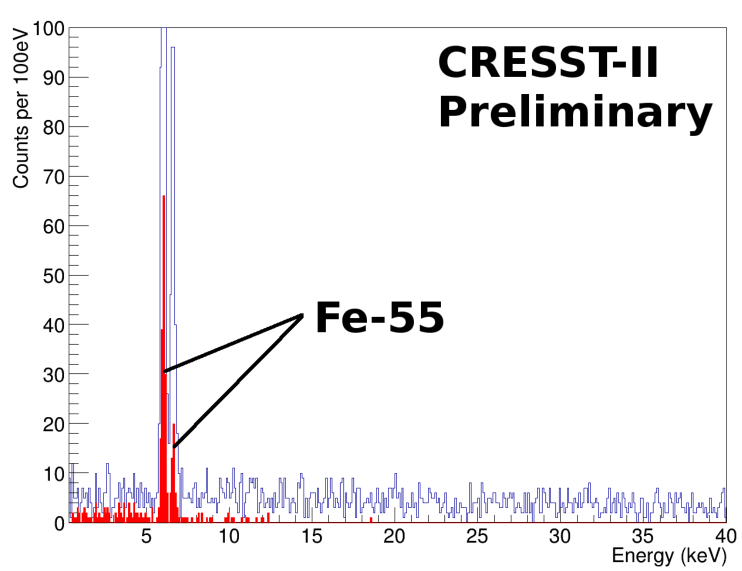


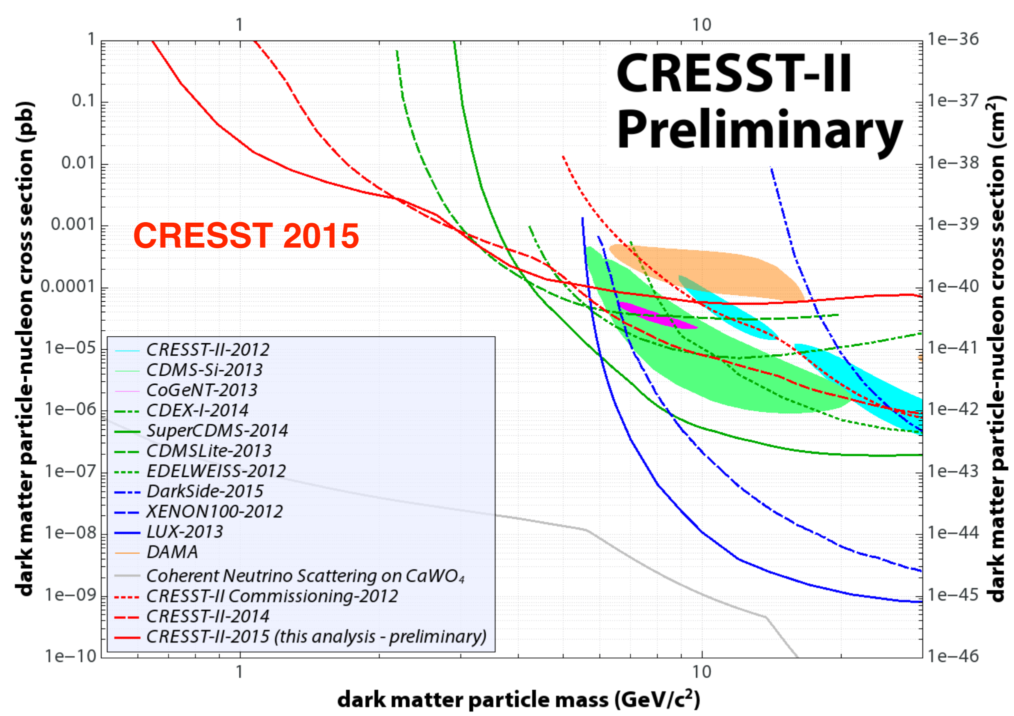
arXiv: 1504.00820



Plan to use several detectors, and decrease the analysis threshold (< 5 GeV WIMP mass)

F. Reindl, EPS-HEP 2015





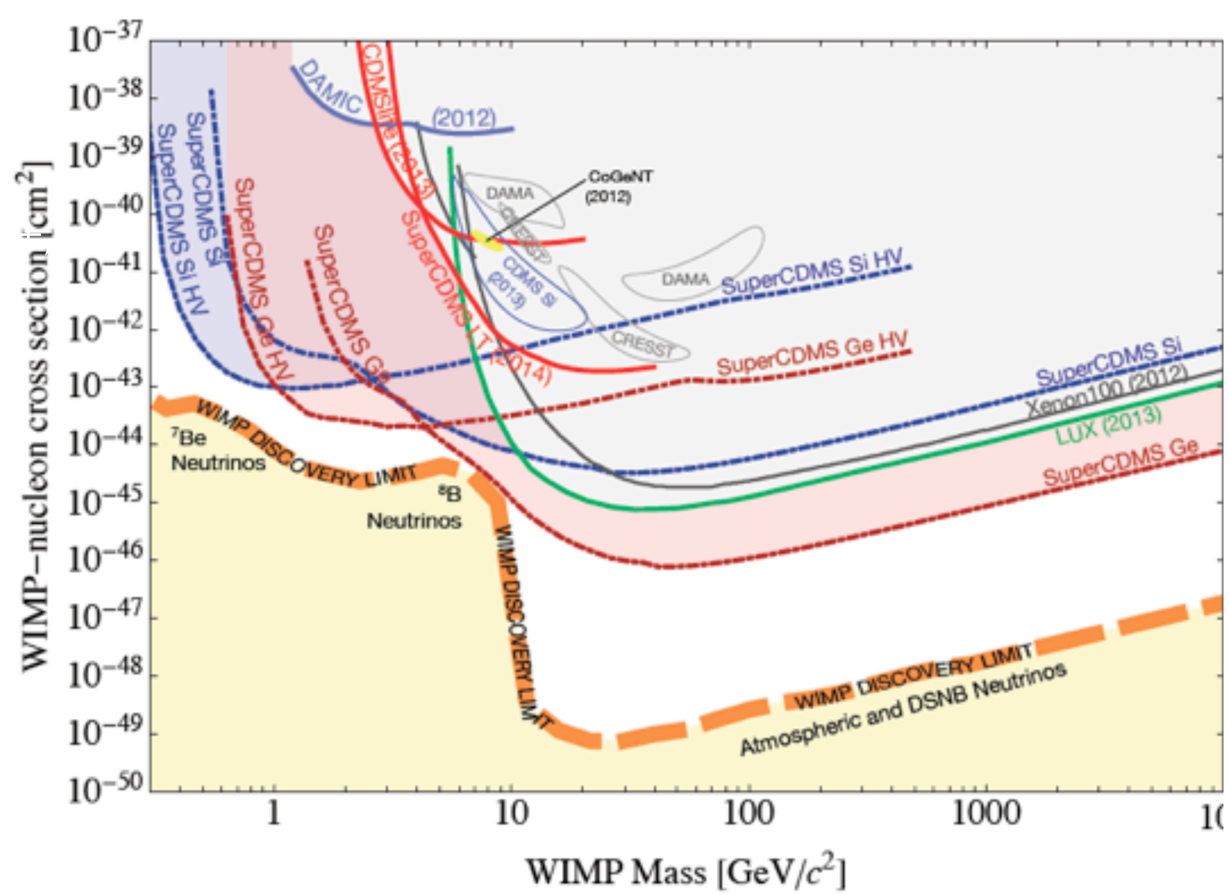
Final, blind analysis in autumn 2015
+ start of CRESST-III at the end of this year (new detector modules, 24 g each, 100 eV E_{th})

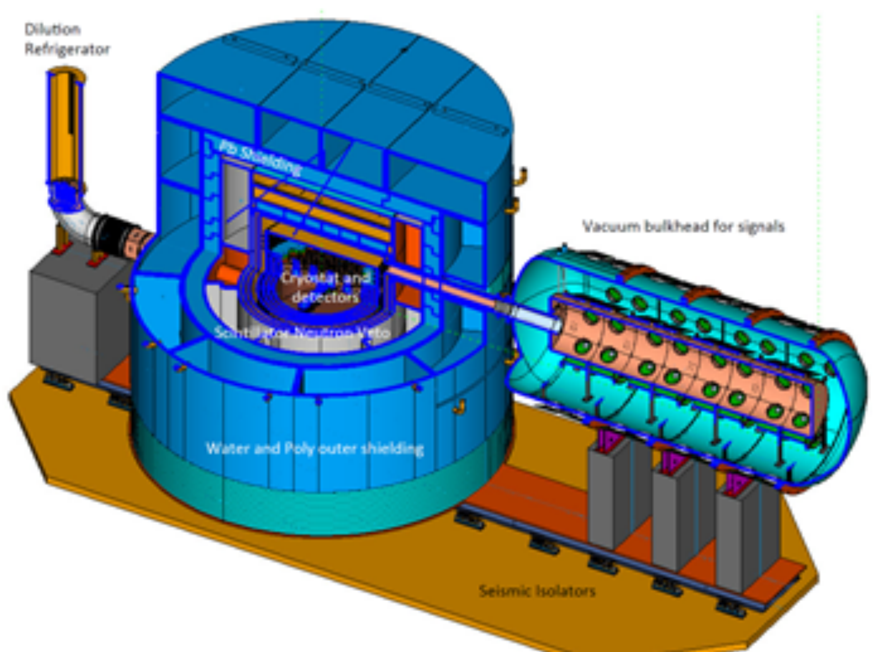
SuperCDMS/EURECA at SNOLAB

- Cooperation between **SuperCDM and EURECA** (CRESST+EDELWEISS) at SNOLAB
- SuperCDMS cryostat payload
  - **initially 50 kg, up to 400 kg**

➡ multi-target approach (Si, Ge, $CaWO_3$) to low-mass WIMP region

Start data taking in 2018

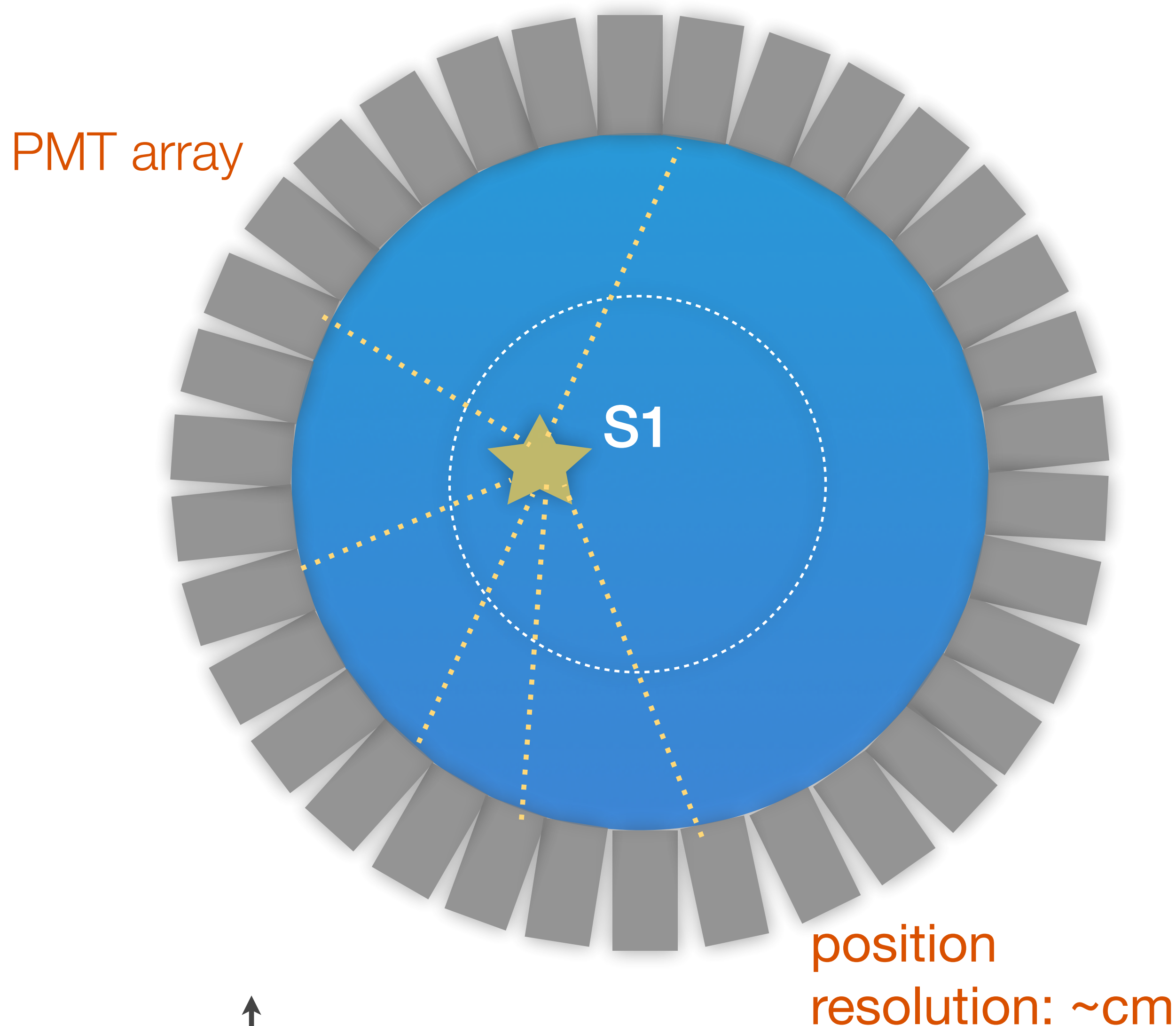




Single-phase noble liquid detectors

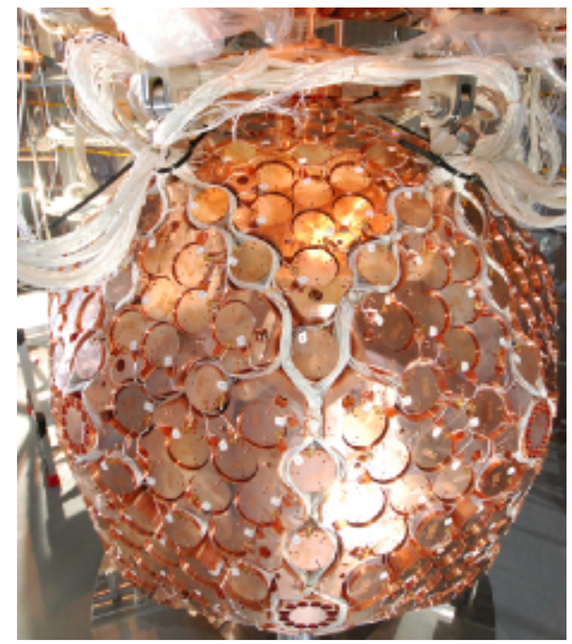
Instrumented LAr or LXe volume

Scintillation light in VUV region



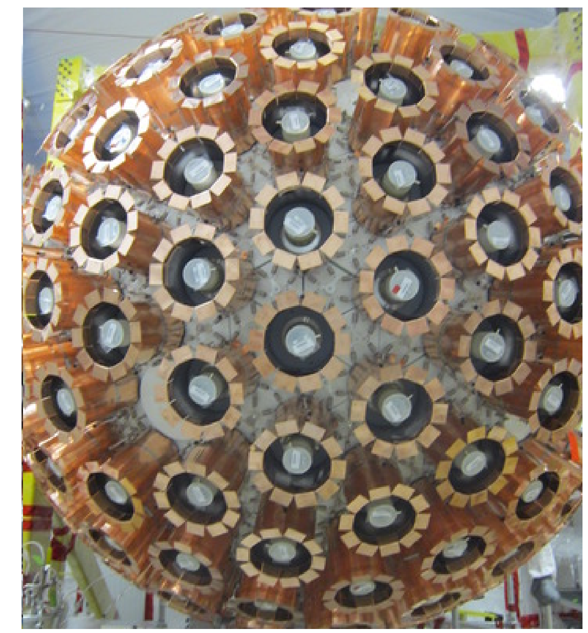
+ PSD

LXe: XMASS at Kamioka, 832 kg

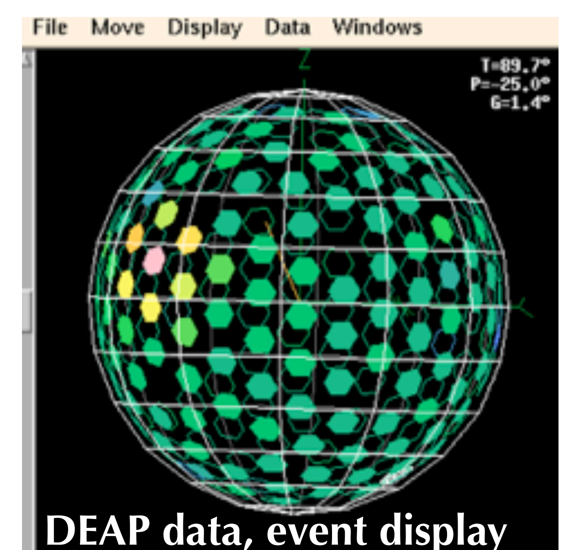


Running since 2013
Plans for 5 t detector

LAr: DEAP-3600 at SNOLAB, 3.6 t

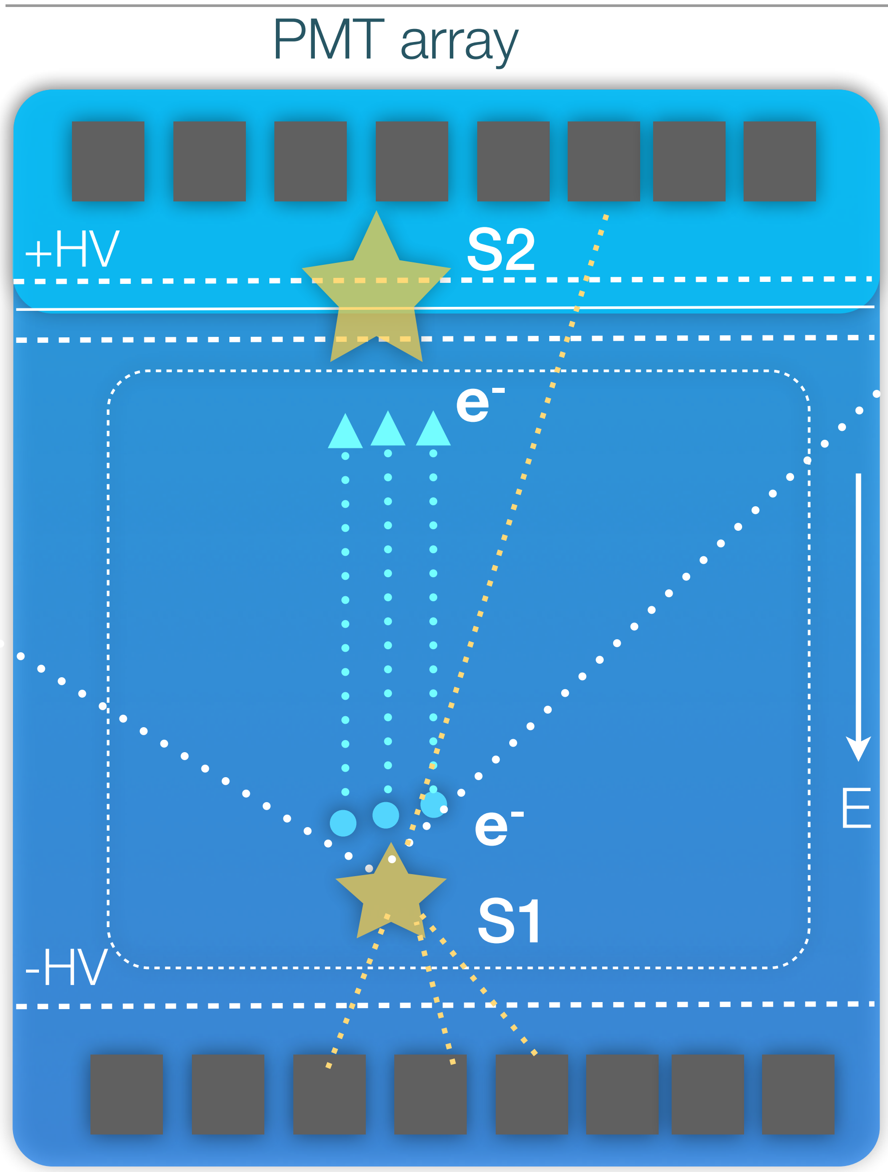


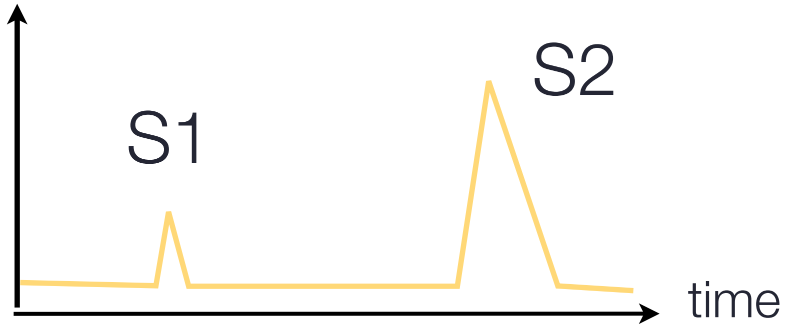
In commissioning
First results in late 2015
1 x 10^{-46} cm^2 sensitivity



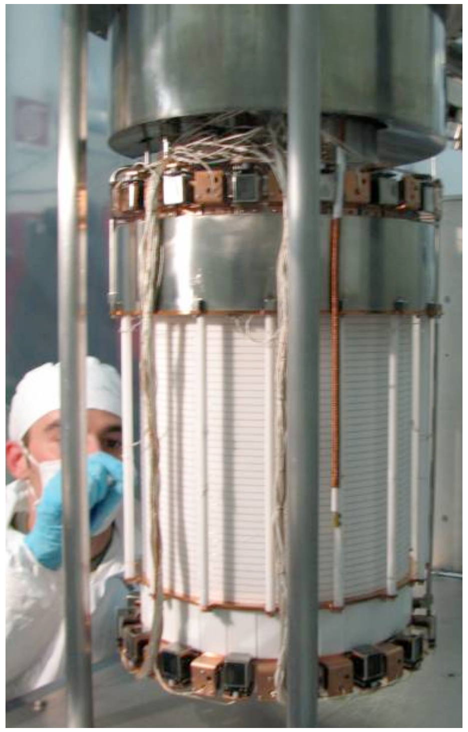
J. Monroe, EPS-HEP2015

Dual-phase noble liquid detectors





LXe: XENON100



LXe: LUX

LAr: DarkSide

LXe

XENON100 at LNGS, LUX at SURF, PandaX at CJPL

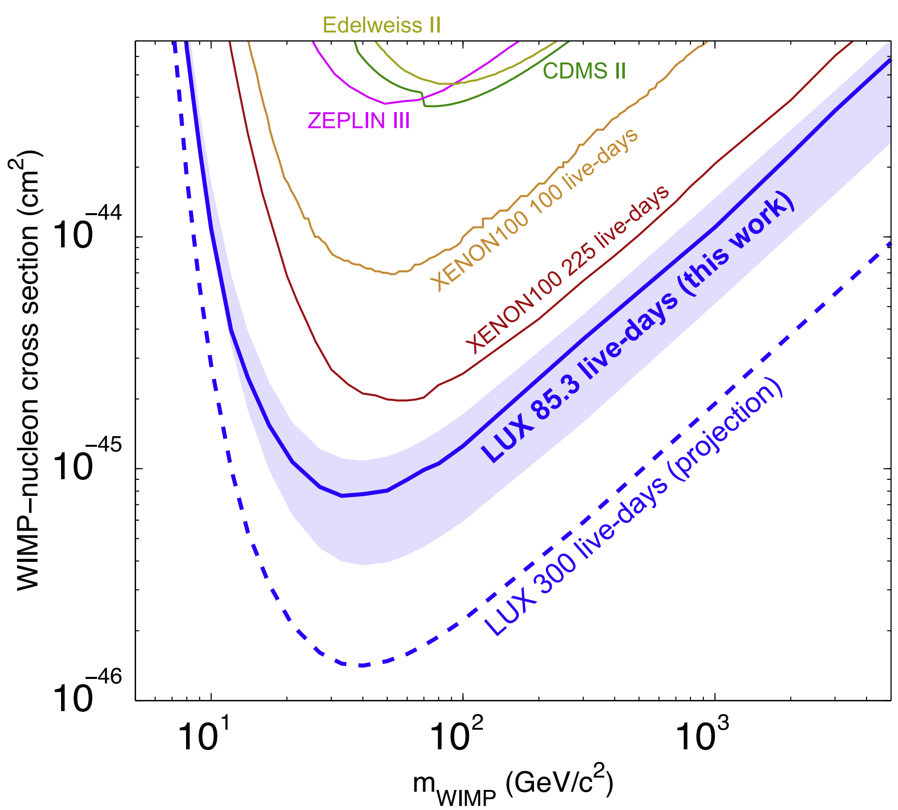
LAr

DarkSide-50 at LNGS, ArDM at Canfranc

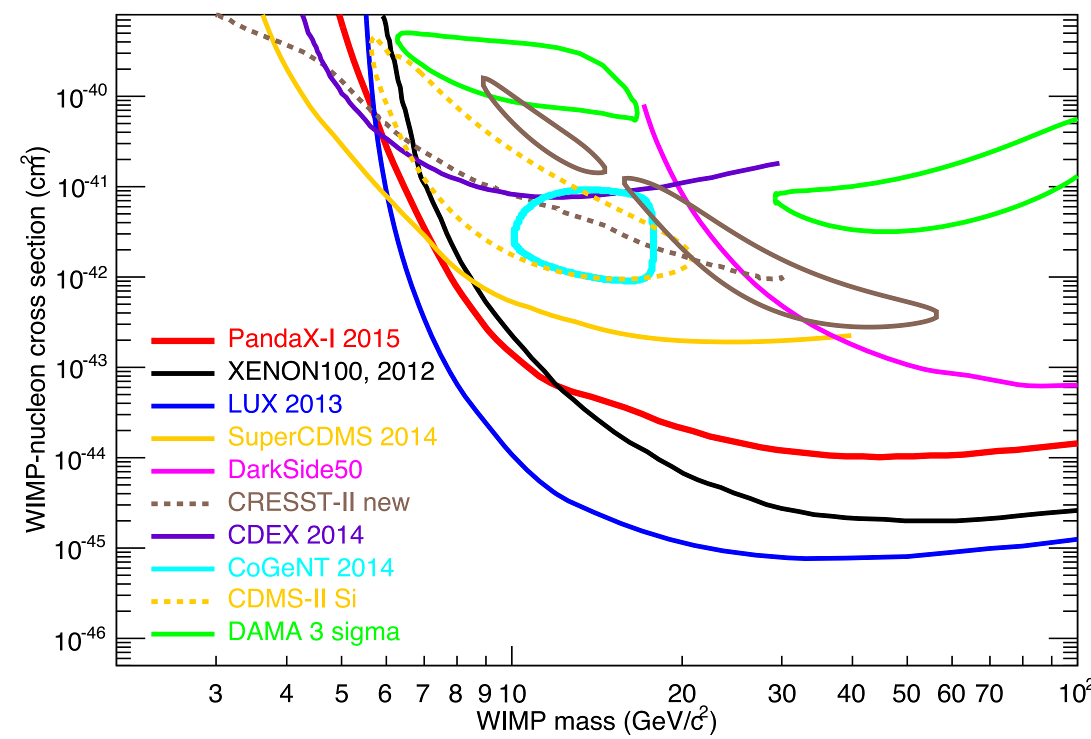
Target masses between ~ 50 kg - 1 ton

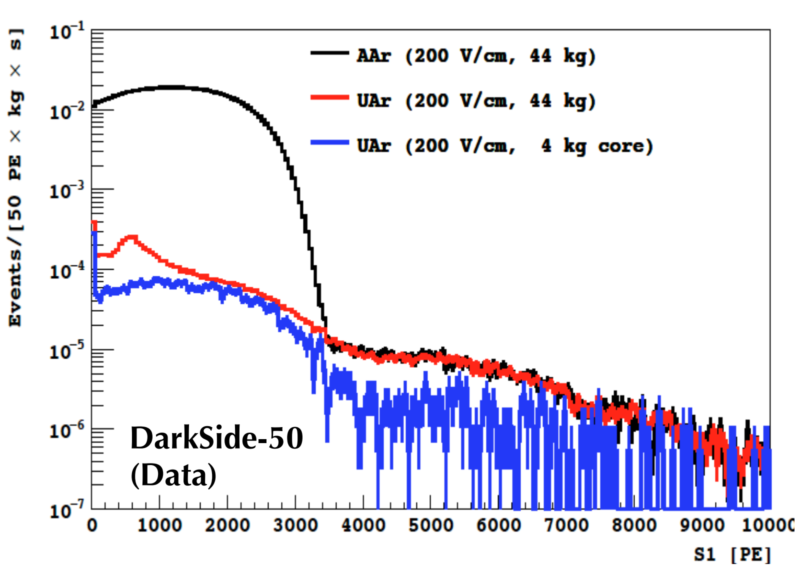
Liquefied noble gases: recent results

LUX 85.3 live-days, PRL 2014



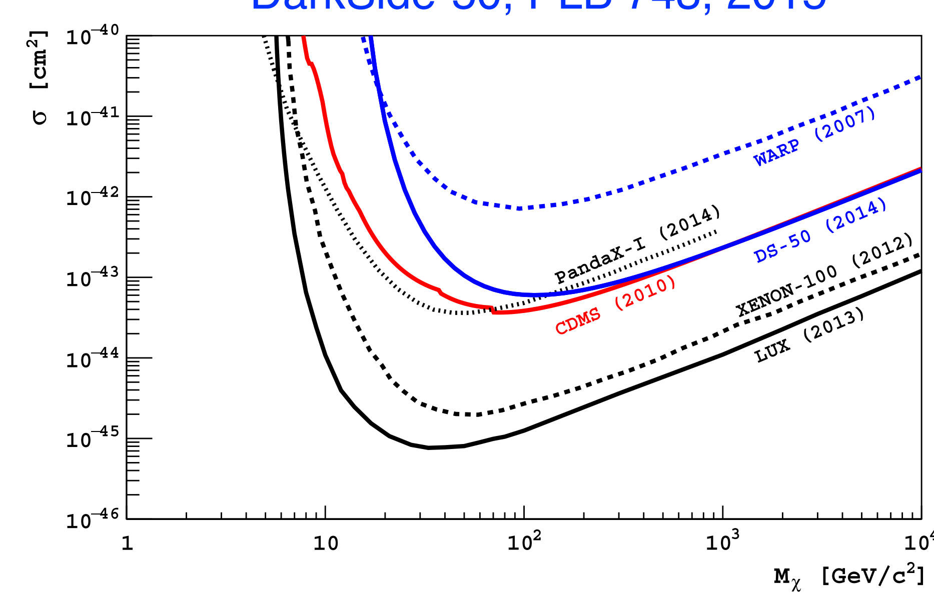
PandaX 80.1 live-days, arXiv 1505.00771





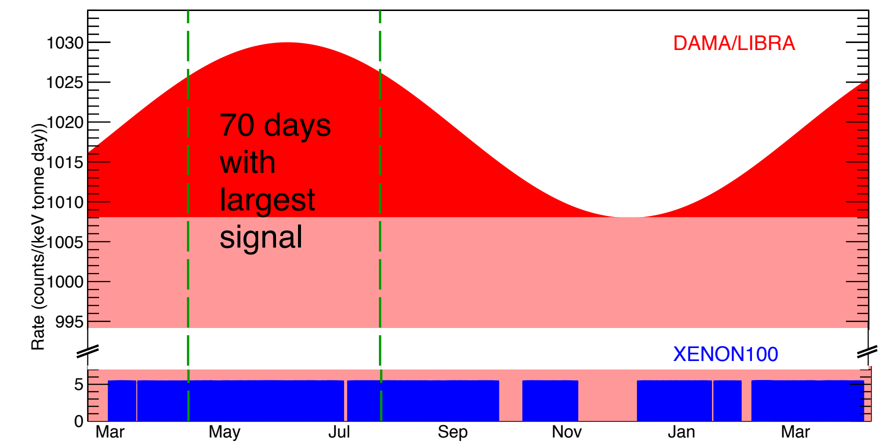
DarkSide-50: factor > 300 depletion of ^{39}Ar

DarkSide-50, PLB 743, 2015

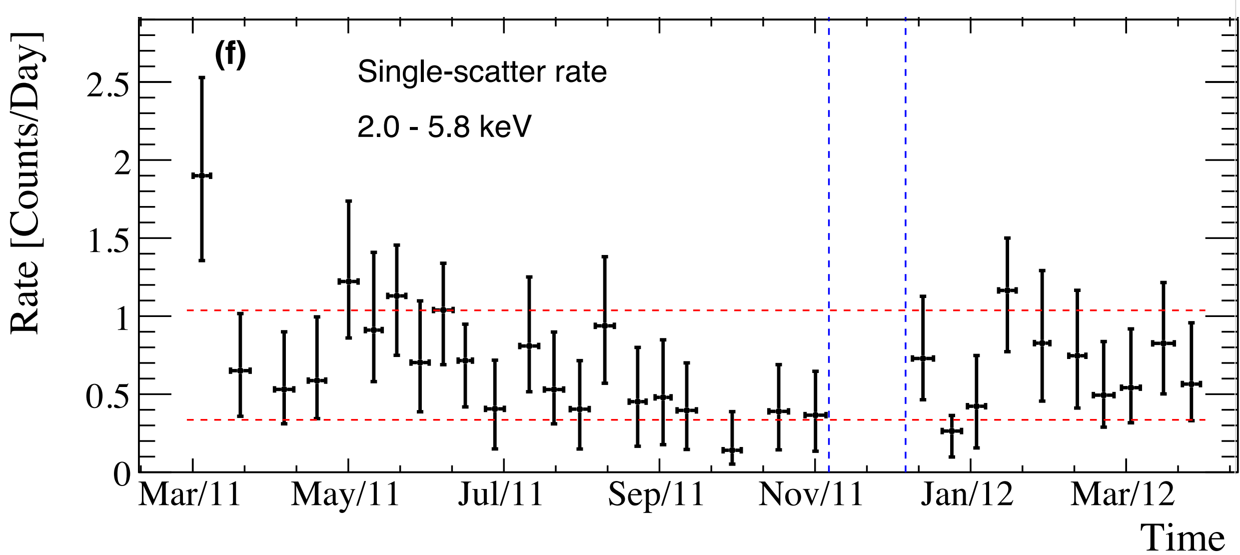


New XENON100 results

- Dark matter particles interacting with e⁻
  1. search for periodic variations of the ER rate in the 2-6 keV region
  2. search for a signal above background in the ER spectrum (use the average ER event rate)

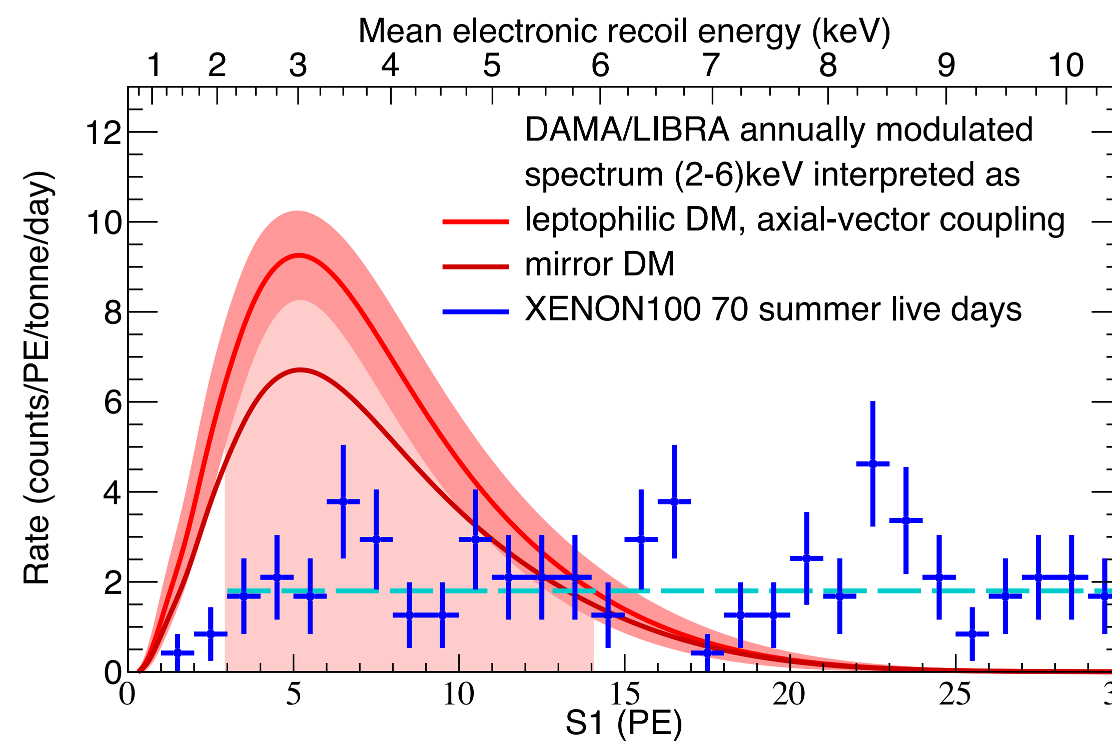


1. XENON collaboration, arXiv: 1507.07748 (accepted in PRL)



Electronic recoil event rate in 34 kg LXe for single-scatters versus time (many other detector parameters monitored as well)

2. XENON collaboration, arXiv: 1507.07747 (accepted in Science)



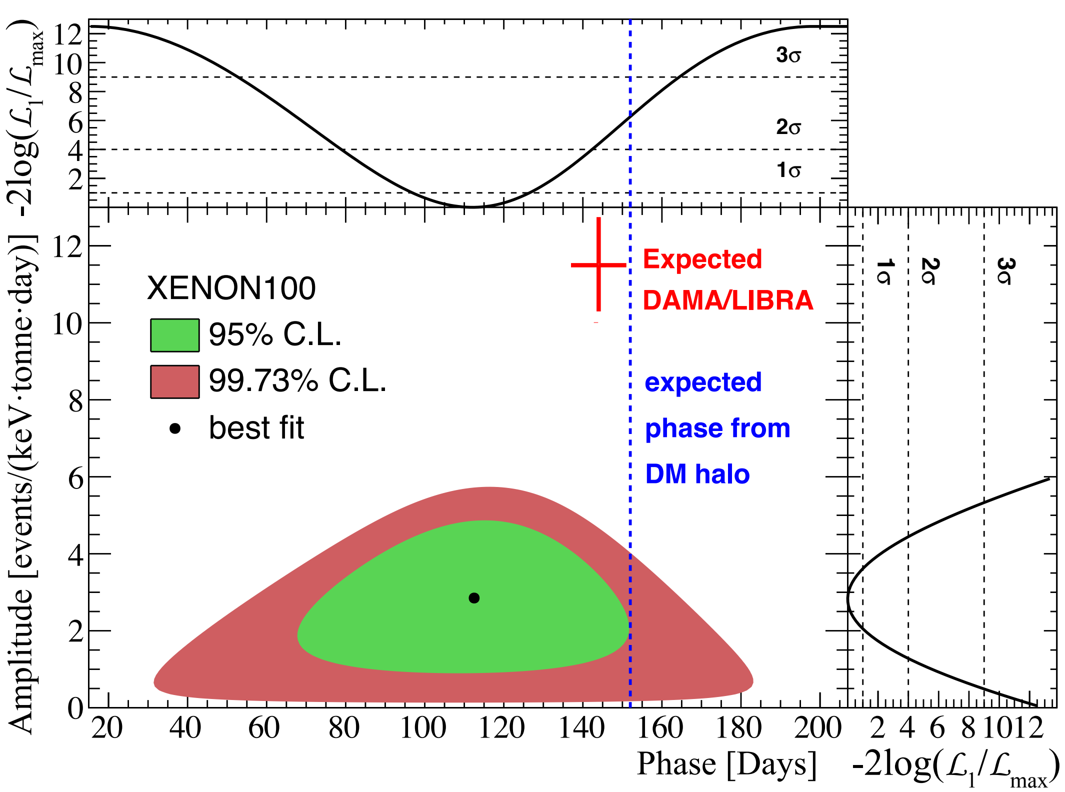
DAMA/LIBRA modulated spectrum as would be seen in XENON100 (for axial-vector WIMP-e⁻ scattering)

New XENON100 results

- Dark matter particles interacting with e⁻

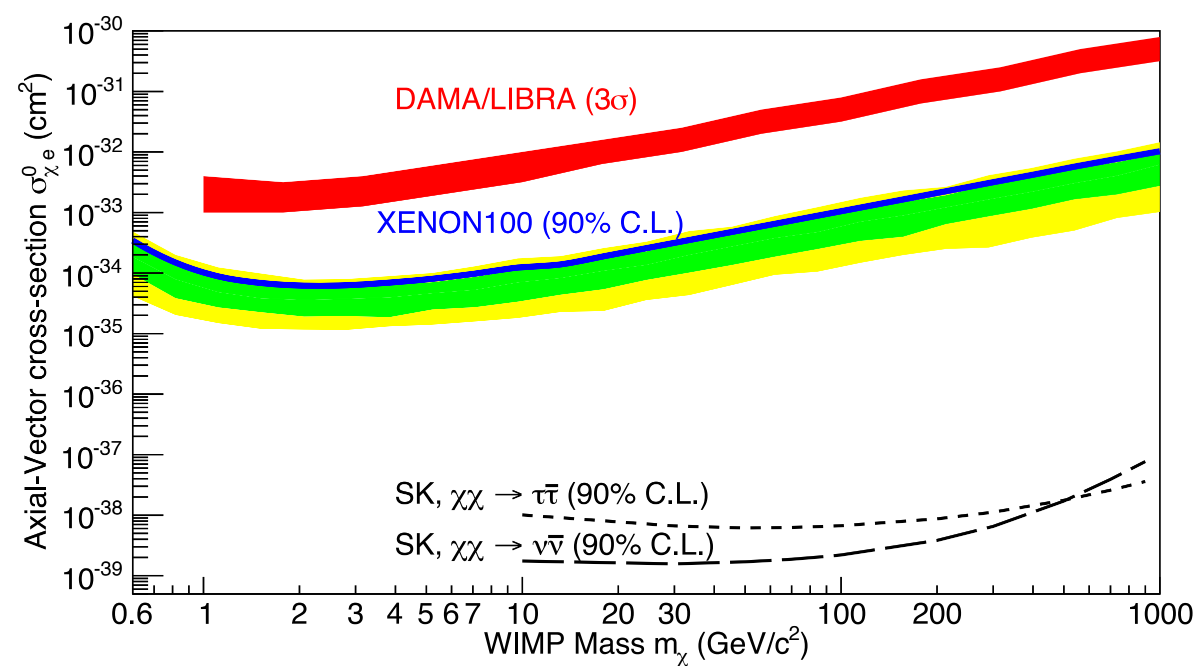
1. search for periodic variations of the ER rate in the 2-6 keV region
2. search for a signal above background in the ER spectrum (use the average ER event rate)

1. XENON collaboration, arXiv: 1507.07748 (accepted in PRL)



Disfavour interpretation of DAMA/LIBRA annual modulation signal as due to WIMP-e- axial-vector scattering ar 4.8 sigma

2. XENON collaboration, arXiv: 1507.07747 (accepted in Science)

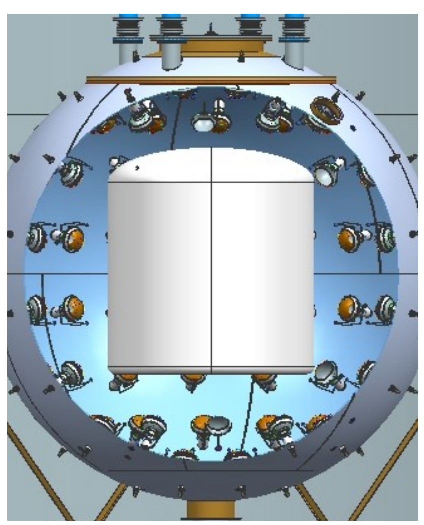


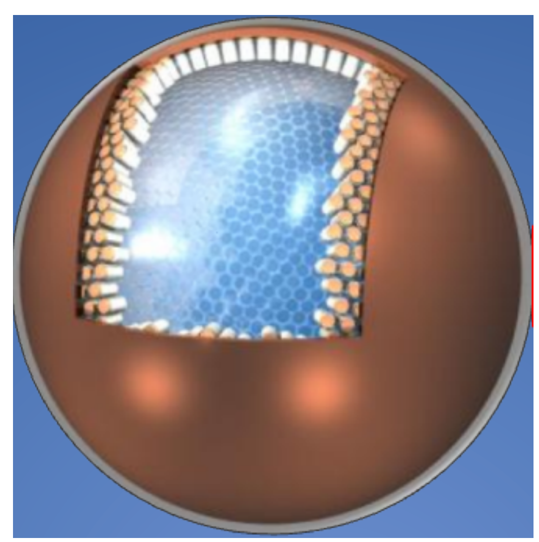
No evidence for a signal; exclude leptophilic models as explanation for DAMA/LIBRA

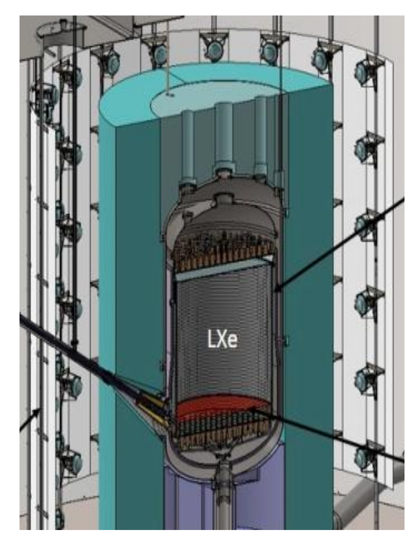
Future noble liquid detectors

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

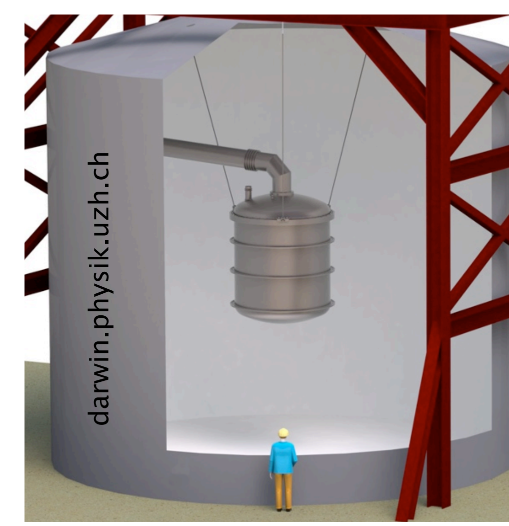

XENON1T: 3.3 t LXe


DarkSide: 20 t LAr


XMASS: 5t LXe



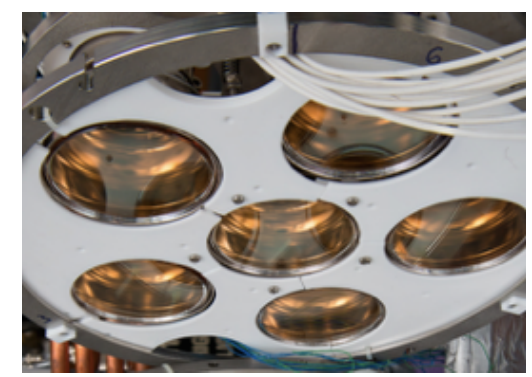
LZ: 7t LXe



DARWIN: 50 t LXe

XENON1T/nT goal and status

- Background goal: 100 x lower than XENON100 ~ 5×10^{-2} events/(t d keV)
- Most subsystems (water shield, service building, electrical plant, cryostat, cryogenics, Xe storage, purification, cables & fibres, pipes) installed and tested underground
- TPC under construction; installation in fall 2015; commissioning in late 2015

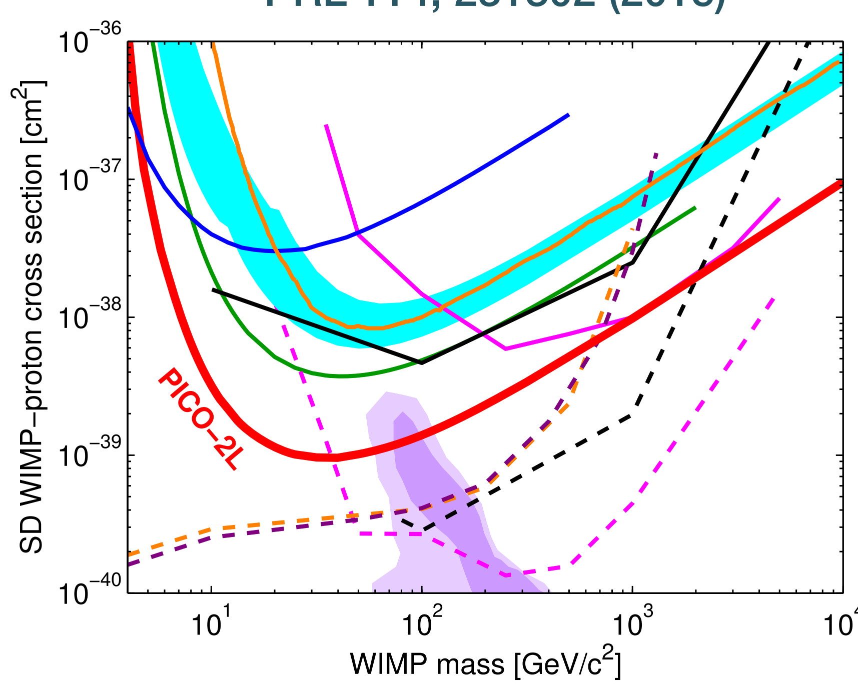


Bubble chambers

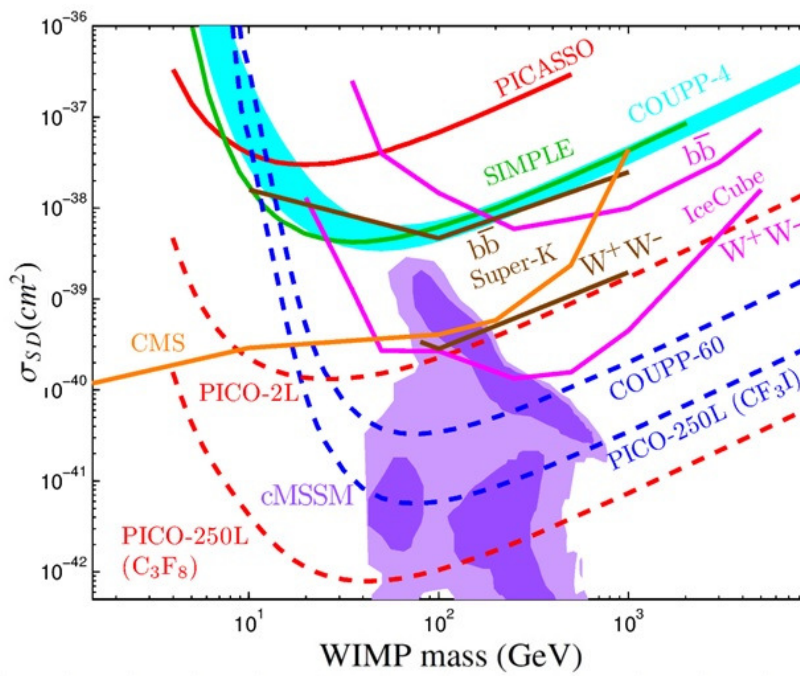
- Detect single bubbles induced by high dE/dx NRs in superheated liquid target:
  - acoustic and visual readout; measure integral rate above threshold
  - large rejection factor (~10^{10}) for MIPs; scalable to large masses; high spatial granularity
- New results: PICO-2L (PICASSO + COUP), 2.9 kg C_3F_8 target, best SD WIMP-proton limit
- PICO-60L to run in 2015; proposed: PICO-250L C_3F_8 target at SNOLAB

PICO-2L n-calibration

PRL 114, 231302 (2015)

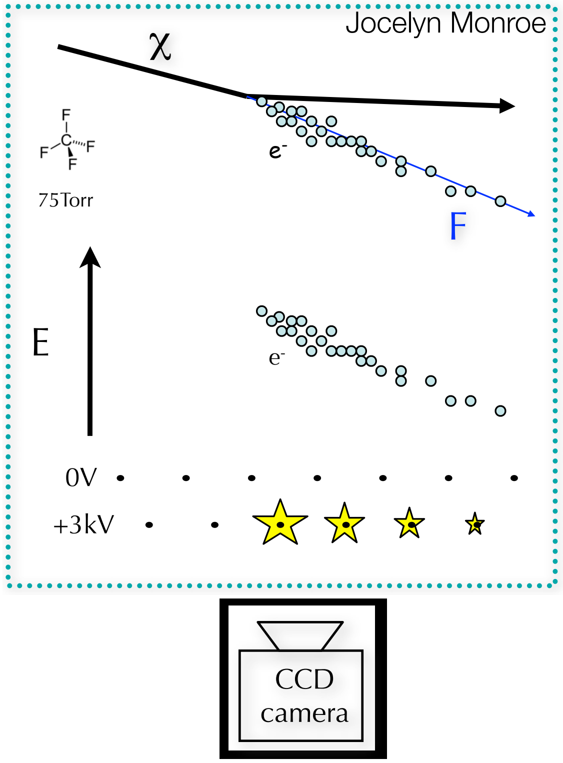


EPJ Web Conf. 95 (2015) 04020

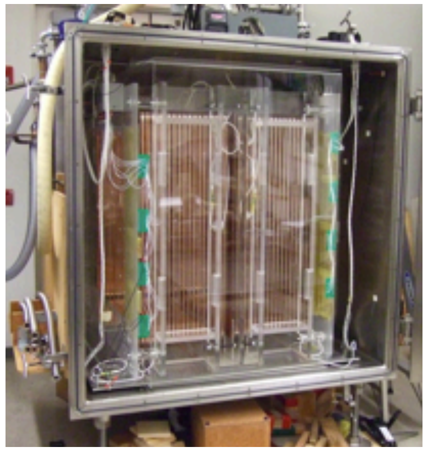


Directional detectors

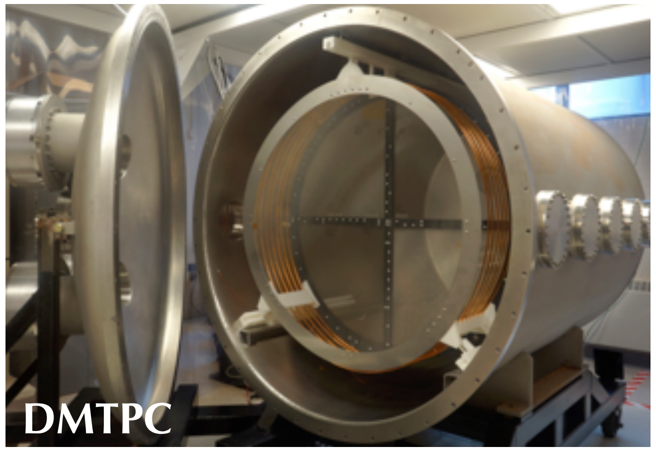
- R&D on low-pressure gas detectors to measure the recoil direction (~30° resolution), correlated to the Galactic motion towards Cygnus
- Challenge: good angular resolution + head/tail at 30-50 keVnr
- One common technology to be proposed in 2016



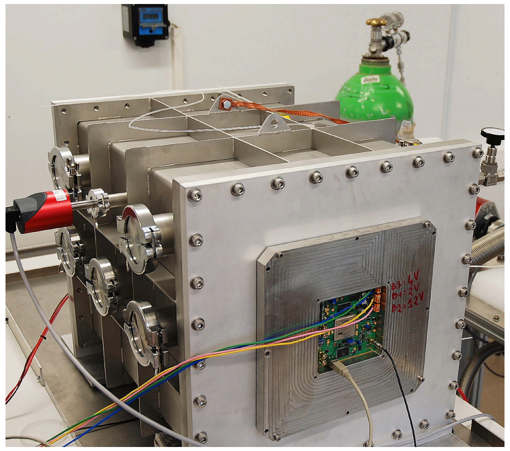
CYGNUS: coordination of directional R&D



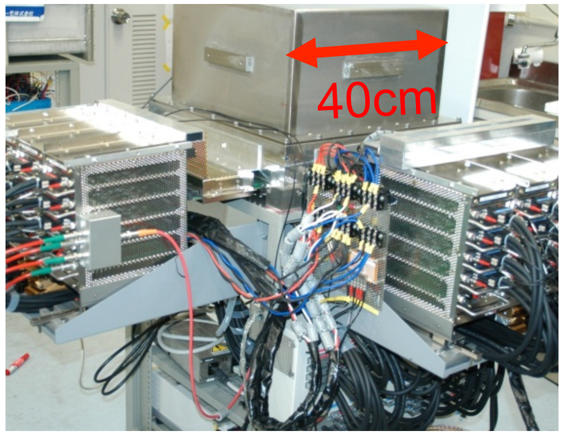
DRIFT, Boulby Mine
1 m^3, negative ion drift
CS_2 +CF_4 gas



DMTPC, MIT
Optical and charge readout
CF_4 gas
commissioning 1 m^3 module



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

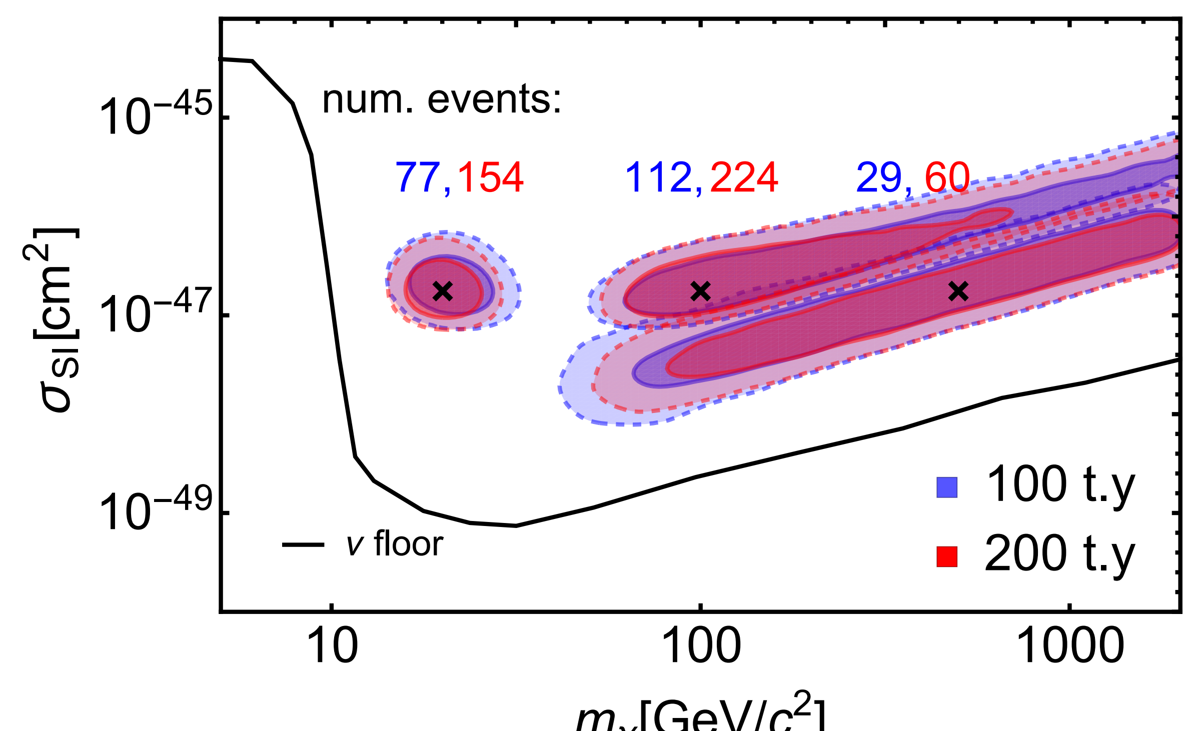


NEWAGE, Kamioka
CF_4 gas at 0.1 atm
50 keV threshold

DARWIN - towards WIMP spectroscopy

darwin-observatory.org arXiv:1506.08309

- Design study for 30-50 tons LXe detector
- Background goal: dominated by neutrinos
- Physics goal:
  - WIMP spectroscopy
  - many other channels (pp neutrinos, bb-decay, axions/ALPs, bosonic SuperWIMPs…)



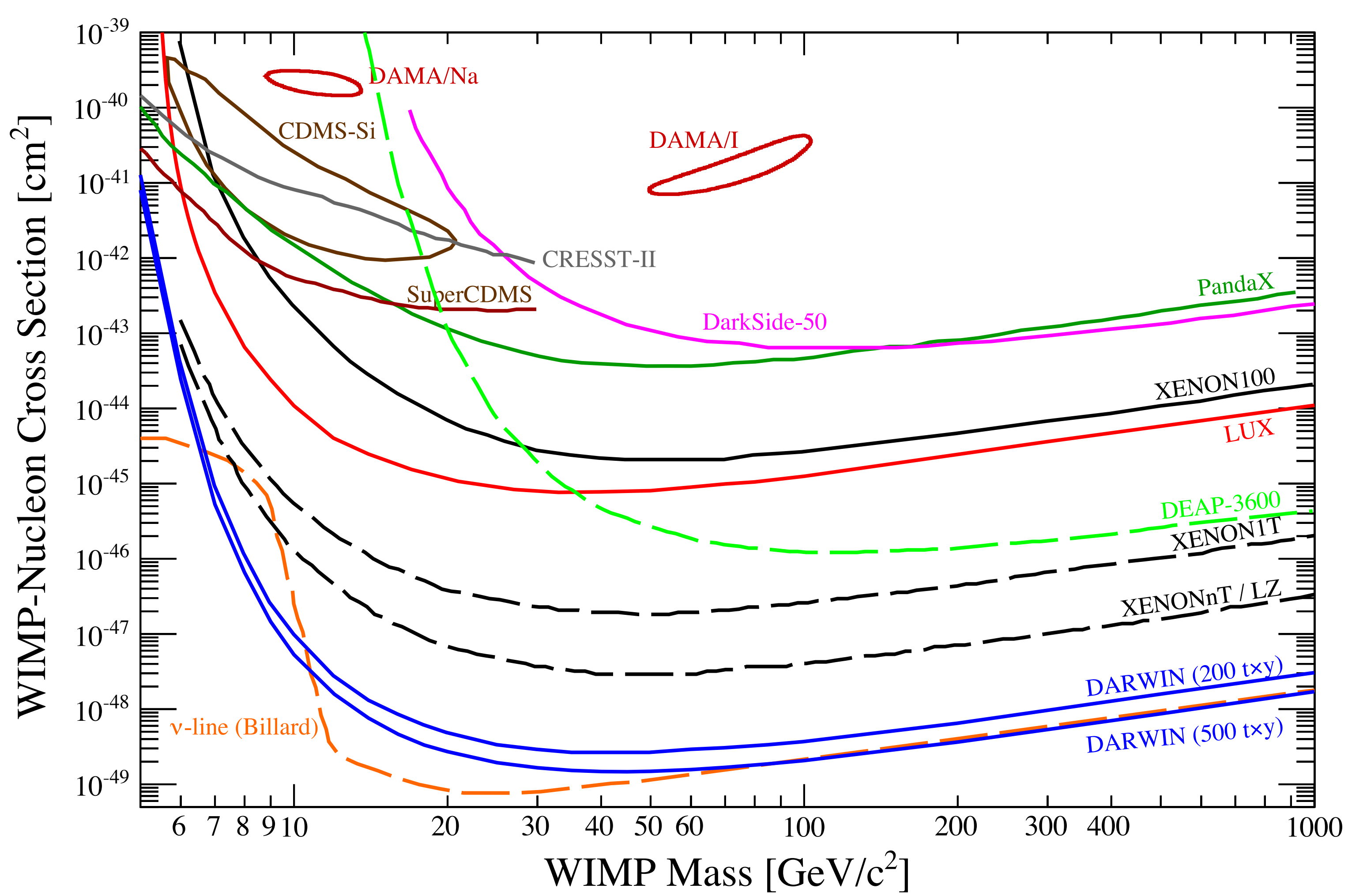
Update: Newstead et al., PRD 88, 2013

$v_{esc} = 544 \pm 40\,\mathrm{km/s}$
$v_0 = 220 \pm 20\,\mathrm{km/s}$
$\rho_\chi = 0.3 \pm 0.1\,\mathrm{GeV/cm^3}$

Sensitivity for spin-independent cross sections

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

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



arXiv:1506.08309
(detailed WIMP study)

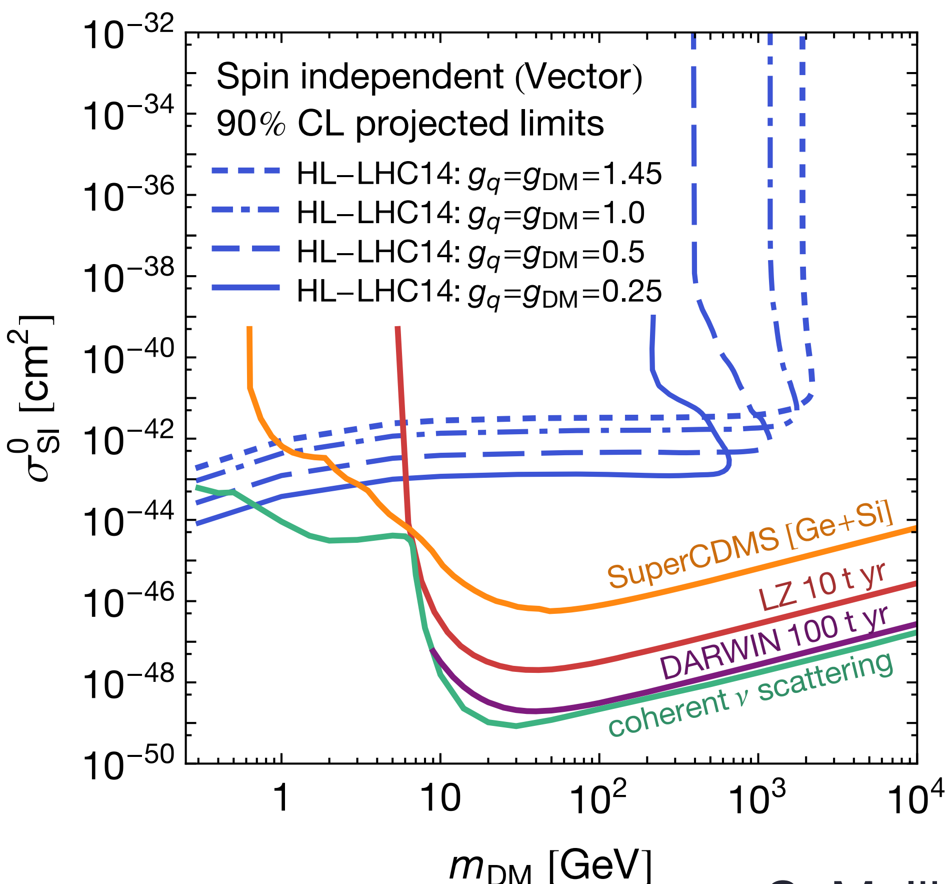
Note: “nu floor” = 3-sigma detection line at 500 CNNS events above 4 keV

Complementarity with the LHC

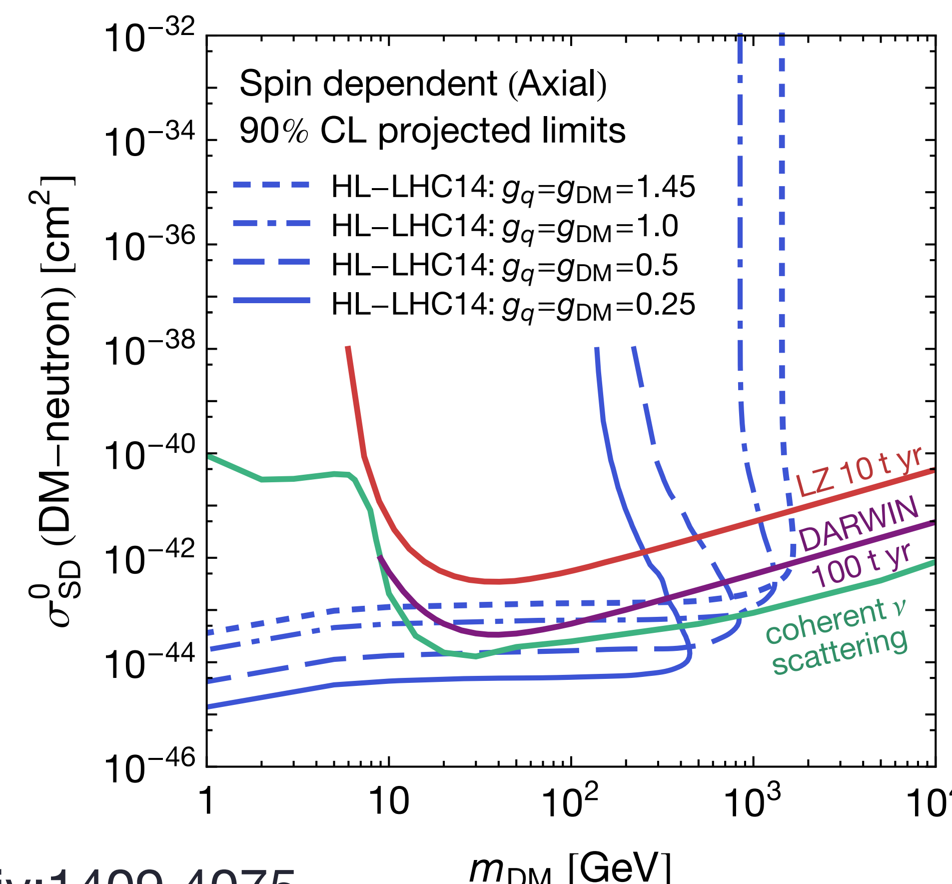
- Minimal simplified DM model with only 4 variables: m_{DM}, M_{med}, g_{DM}, g_q
- Here DM = Dirac fermion interacting with a vector or axial-vector mediator; equal-strength coupling to all active quark flavours

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

Spin independent



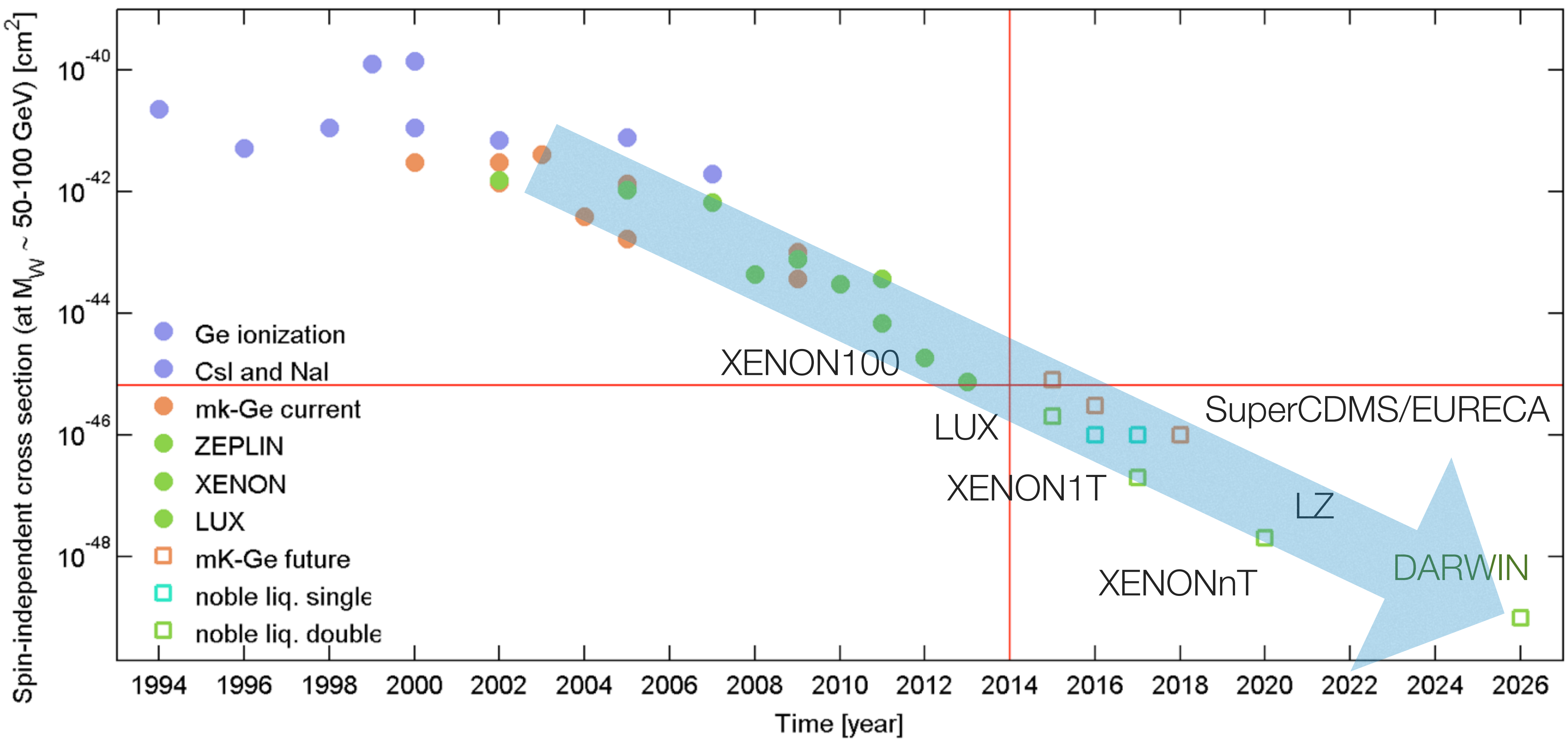
Spin dependent



S. Malik et al., arXiv:1409.4075

WIMP-nucleon cross sections versus time

- About a factor of 10 increase every ~ 2 years
- Can we keep this rate of progress?



LB, Physics of the Dark Universe 4, 2014

Conclusions

Direct detection experiments have reached tremendous sensitivities

- probe cross sections down to 10^{-45} cm^2 at WIMP masses ~ 50 GeV
- probe particle masses below 10 GeV (new models)
- complementary with the LHC and with indirect searches
- test various other particle candidates

Excellent prospects for discovery

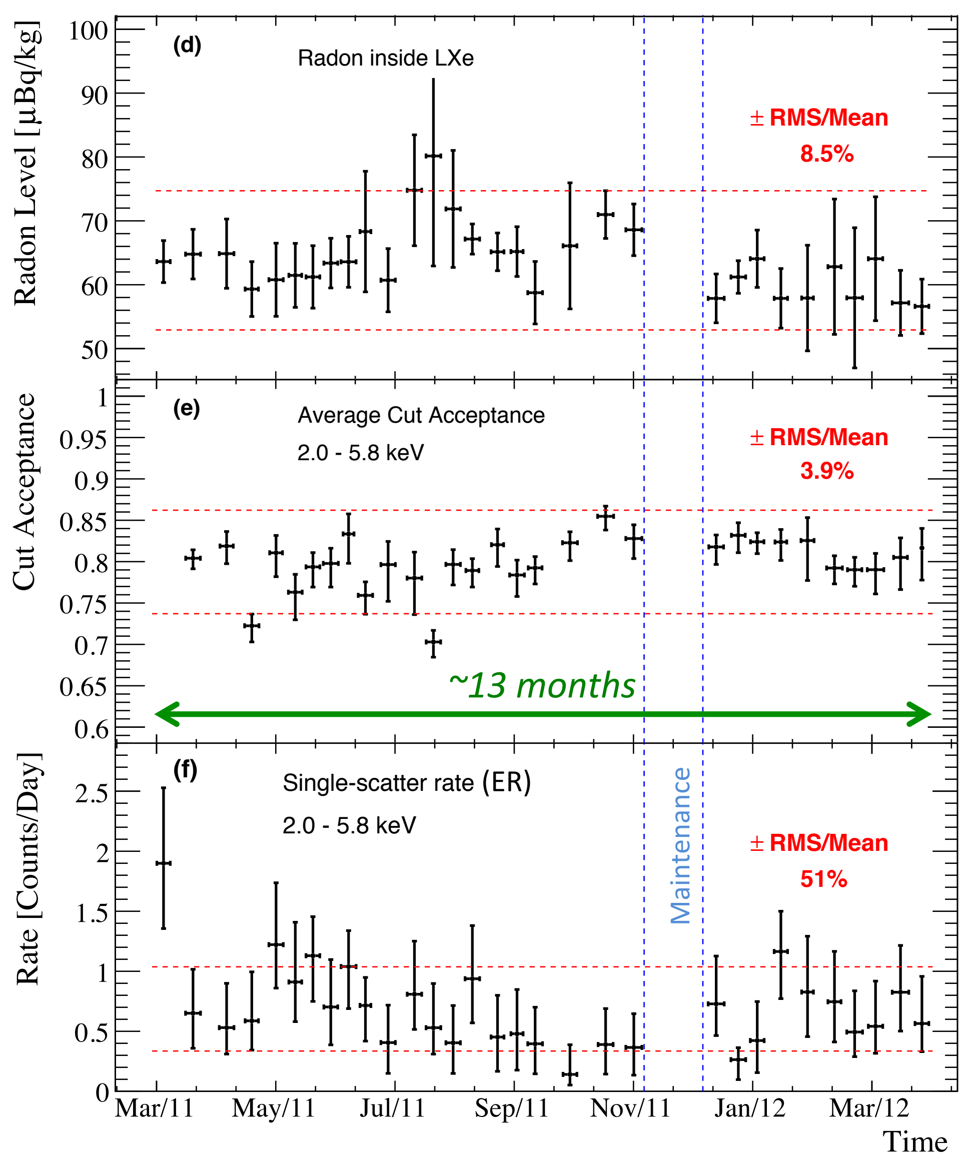
- increase in WIMP sensitivity by 2 orders of magnitude in the next few years
- reach neutrino background (measure neutrino-nucleus coherent scattering!) this/next decade

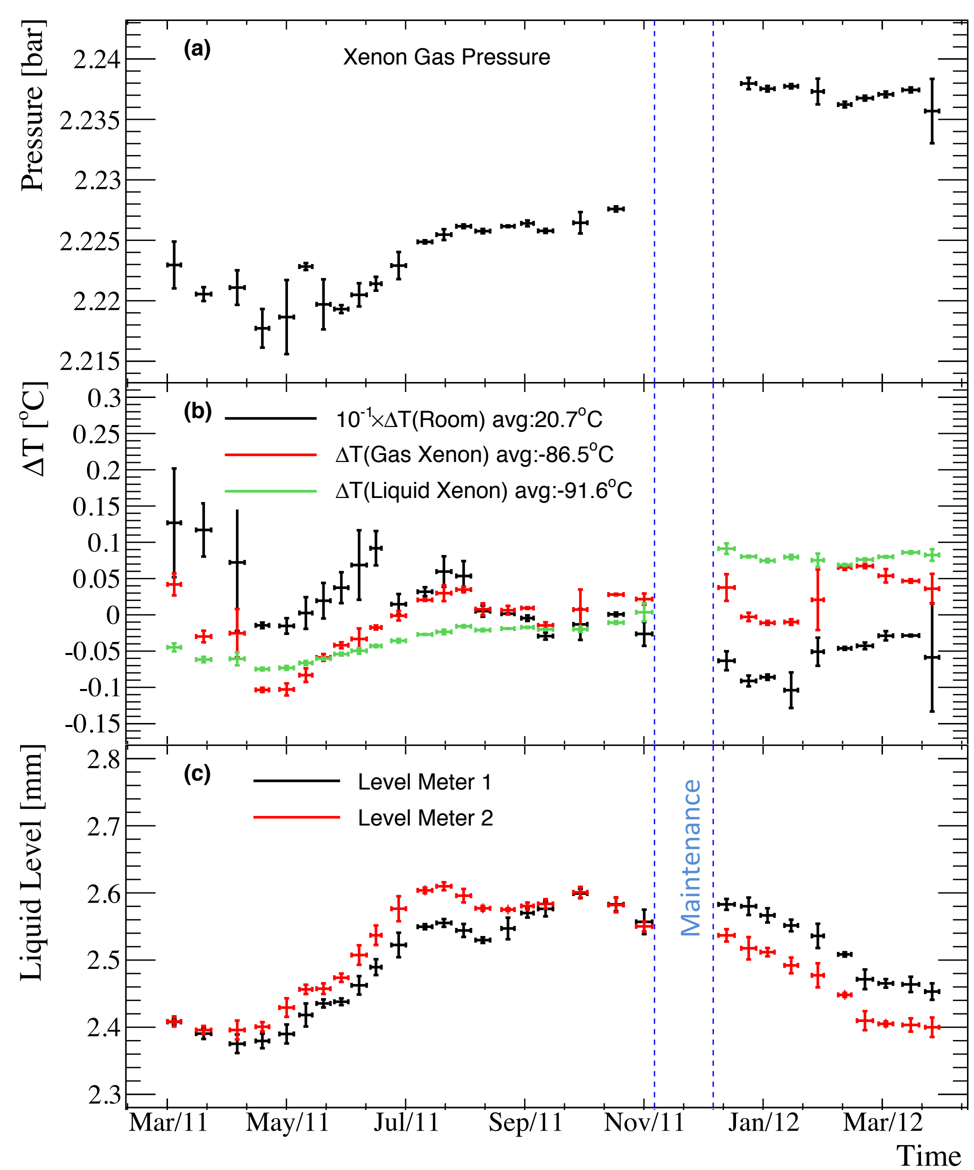
The end

XENON100 detector stability

- Detailed stability and correlation analysis of all detector and background parameters
- No significant correlation with event rate observed

arXiv:1507.07748 (Accepted into PRL)





Probing a modulation signal in XENON100

- Unbinned PL analysis of ER data assuming periodic signal hypothesis (L_1)

Acceptance; Background from known air leak; Modulation

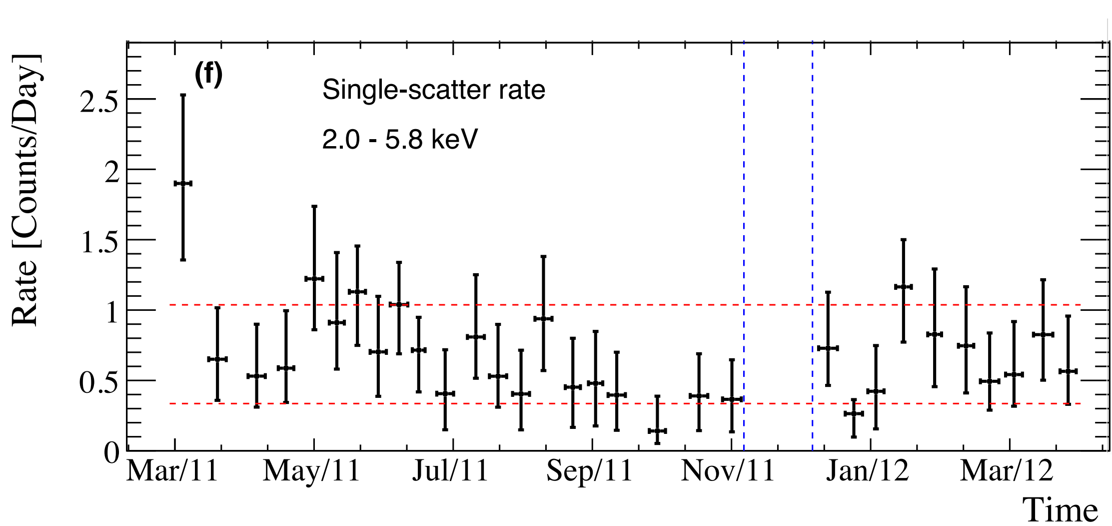
$$f(t) = \epsilon(t)\left(C + Kt + A\cos\left(2\pi\frac{(t-\phi)}{P}\right)\right)$$

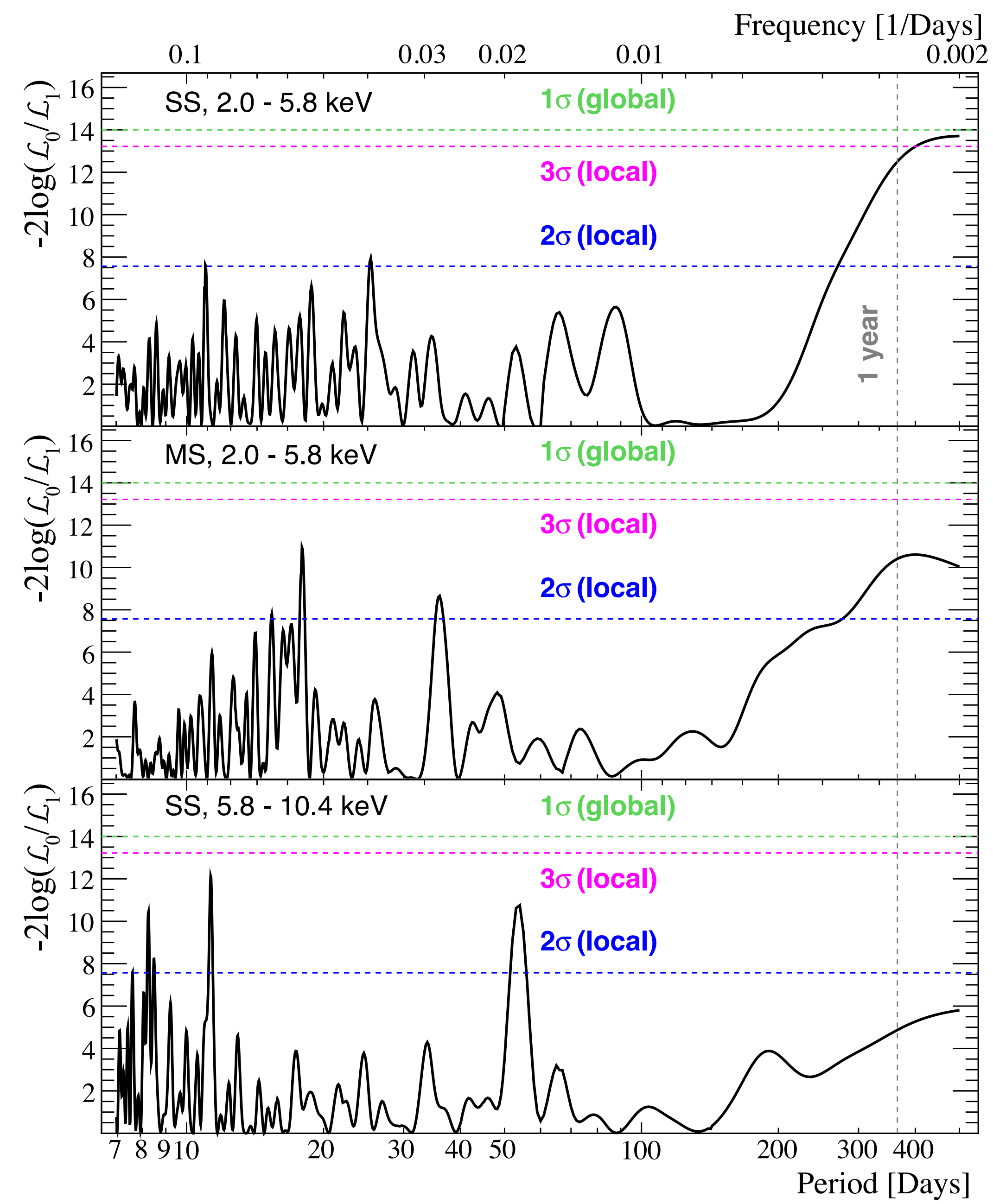
Normalized

$$\mathcal{L} = \left(\prod_{i=1}^{n} \tilde{f}(t_i)\right) \mathrm{Poiss}\left(n|N_{\mathrm{exp}}(E)\right) \mathcal{L}_\epsilon \mathcal{L}_K \mathcal{L}_E$$

Total observed events; Constraint terms

- Compare to null hypothesis (L_0), A=0, for several samples





Probing a modulation signal in XENON100

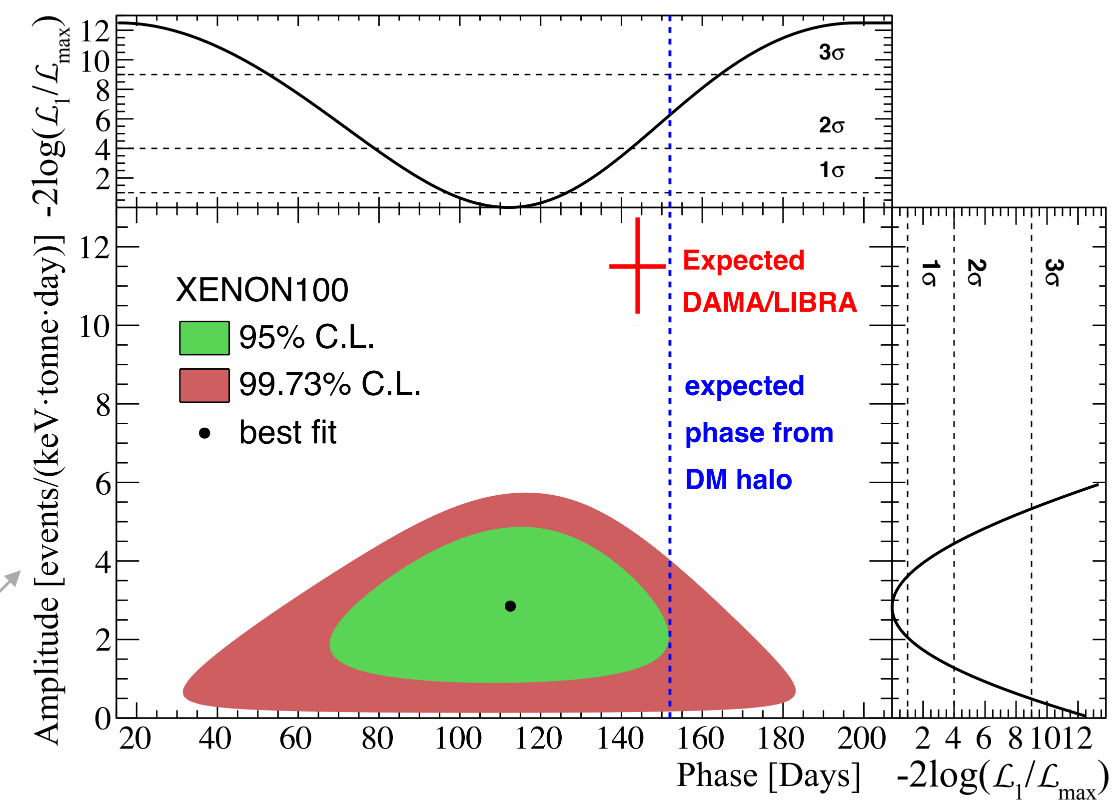
- Unbinned PL analysis of ER data assuming periodic signal hypothesis (L_1)

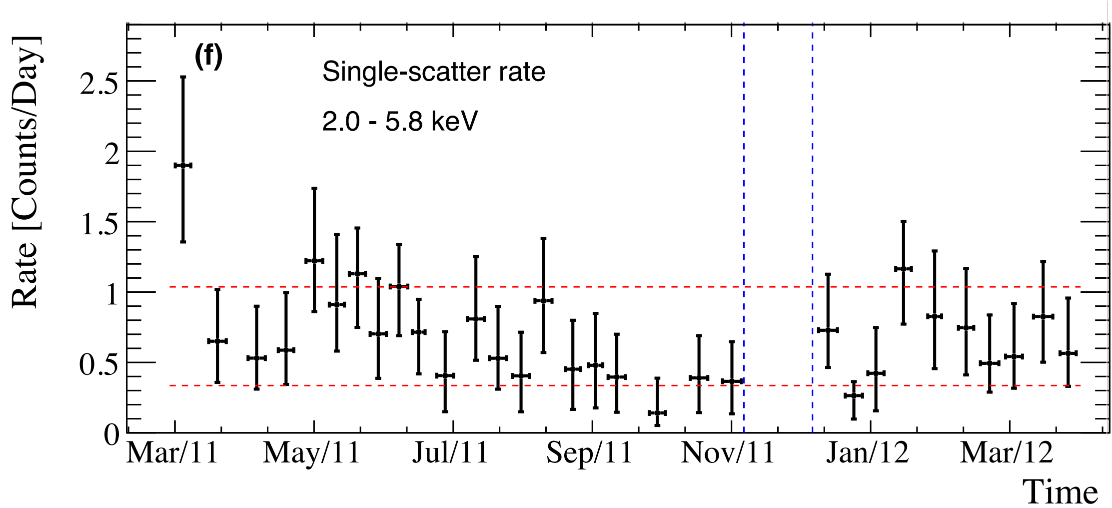
$$f(t) = \epsilon(t)\left(C + Kt + A\cos\left(2\pi\frac{(t-\phi)}{P}\right)\right)$$

$$\mathcal{L} = \left(\prod_{i=1}^{n}\tilde{f}(t_i)\right)\mathrm{Poiss}\left(n|N_{\mathrm{exp}}(E)\right)\mathcal{L}_\epsilon\mathcal{L}_K\mathcal{L}_E$$

Acceptance · *Background from known air leak* · *Modulation* · *Normalized* · *Total observed events* · *Constraint terms*

- Compare to maximum likelihood (L_{max}), fixing period to 1 year



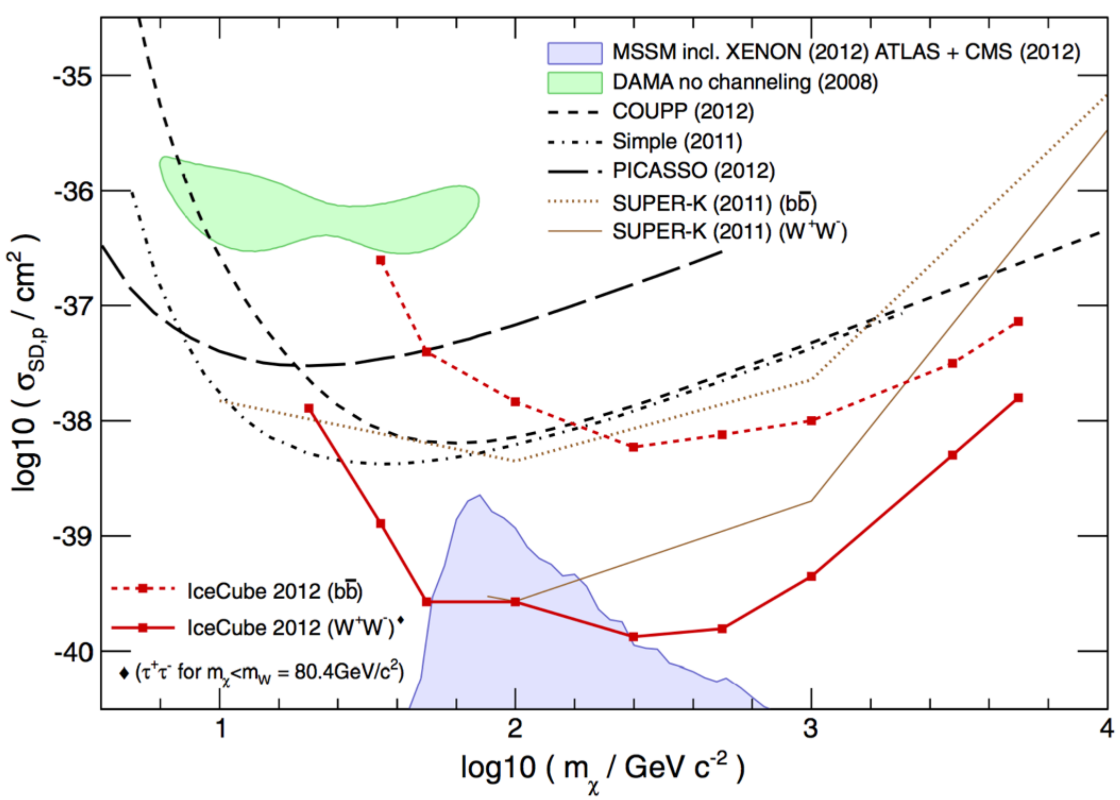


- Standard dark matter halo phase is disfavoured by 2.5-sigma
- Assuming V-A coupling of WIMPs to e^-, DAMA/LIBRA annual modulation is excluded at 4.8-sigma

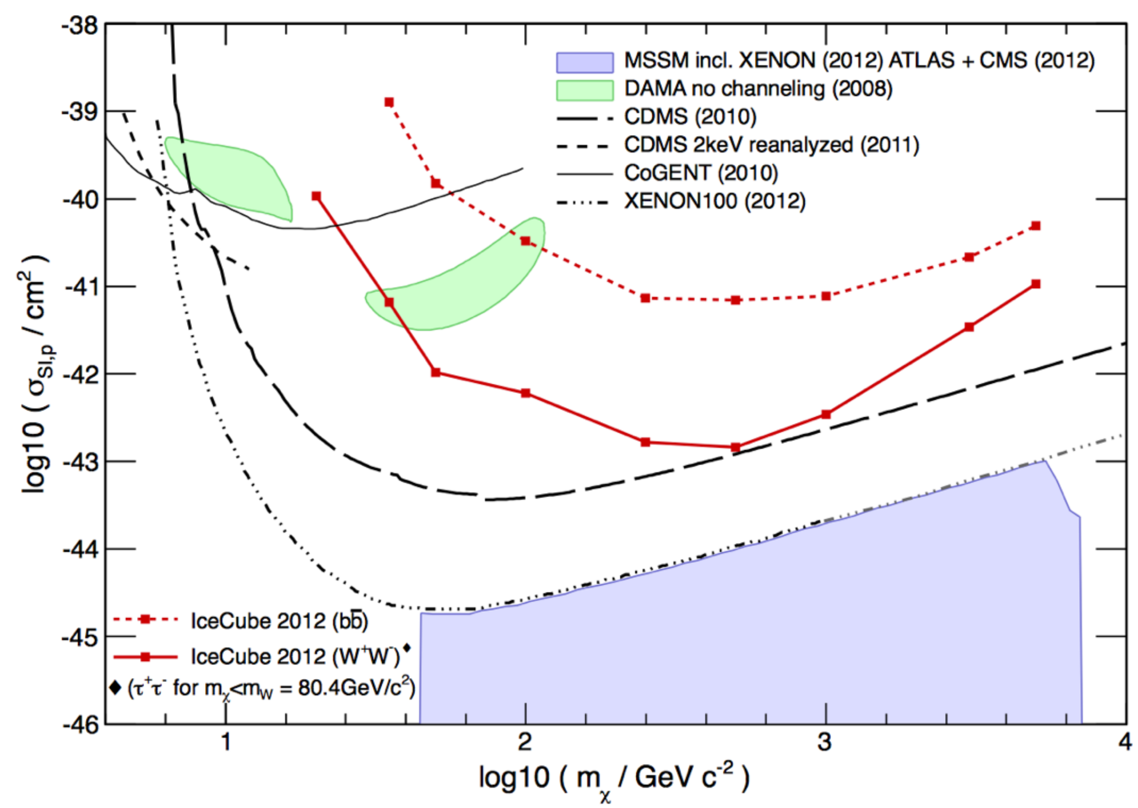
Complementarity with indirect searches

- 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

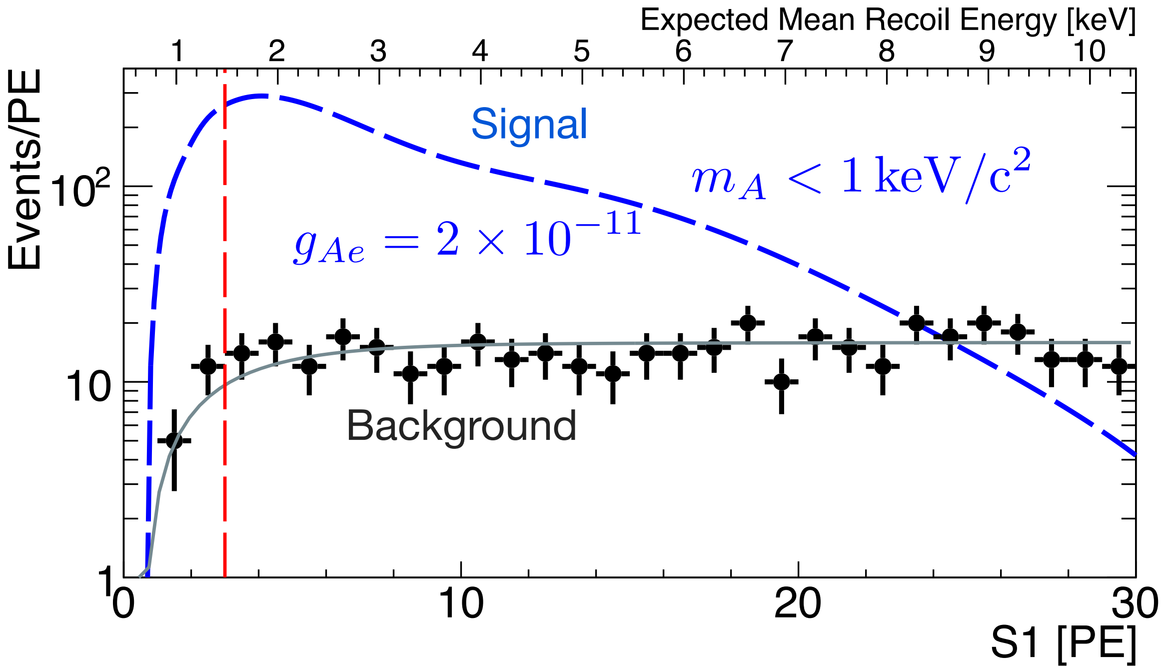


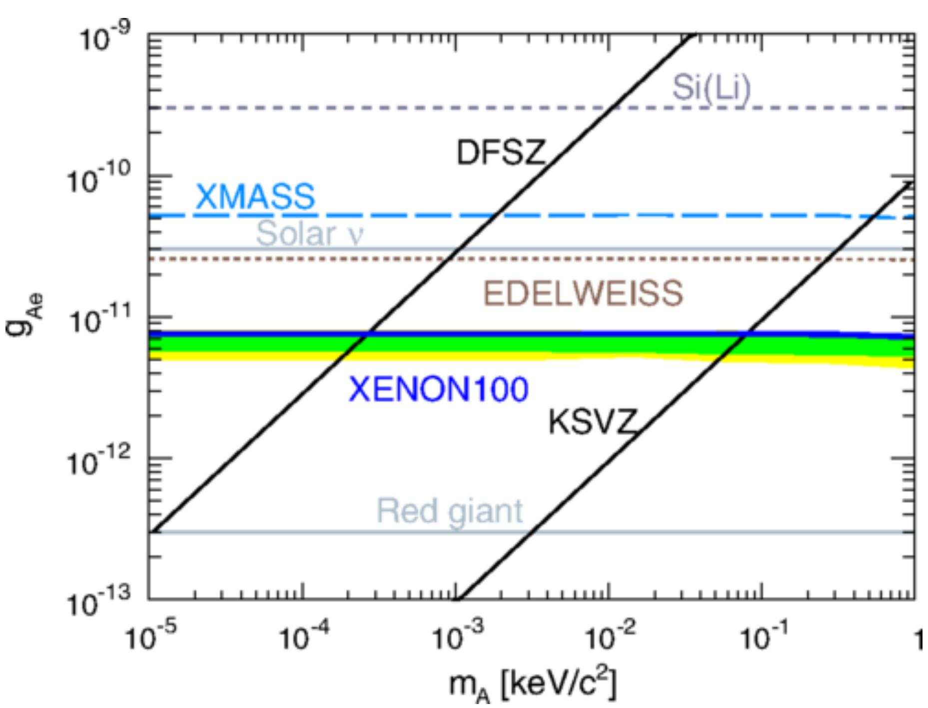
IceCube: WIMP-p; spin-independent



IceCube collab. PRL 110, 2013 (79 string)

Example: Solar axions with XENON100





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

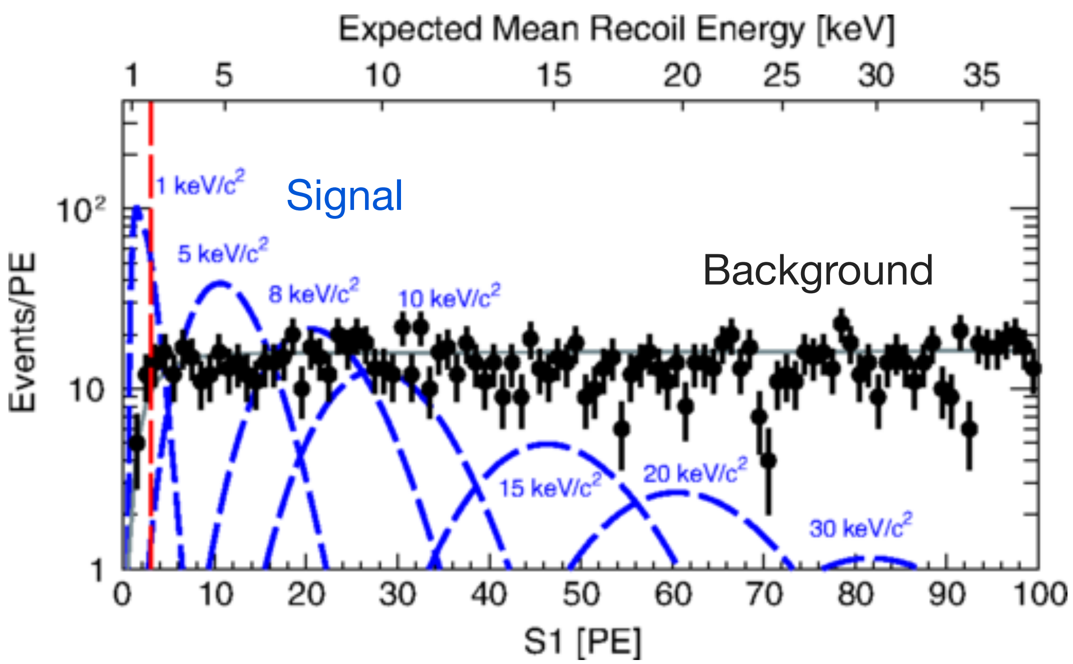
$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{g_{Ae}^2}{\beta_A}\frac{3E_A^2}{16\pi\alpha_{em}m_e^2}\left(1 - \frac{\beta_A^{2/3}}{3}\right)$$

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

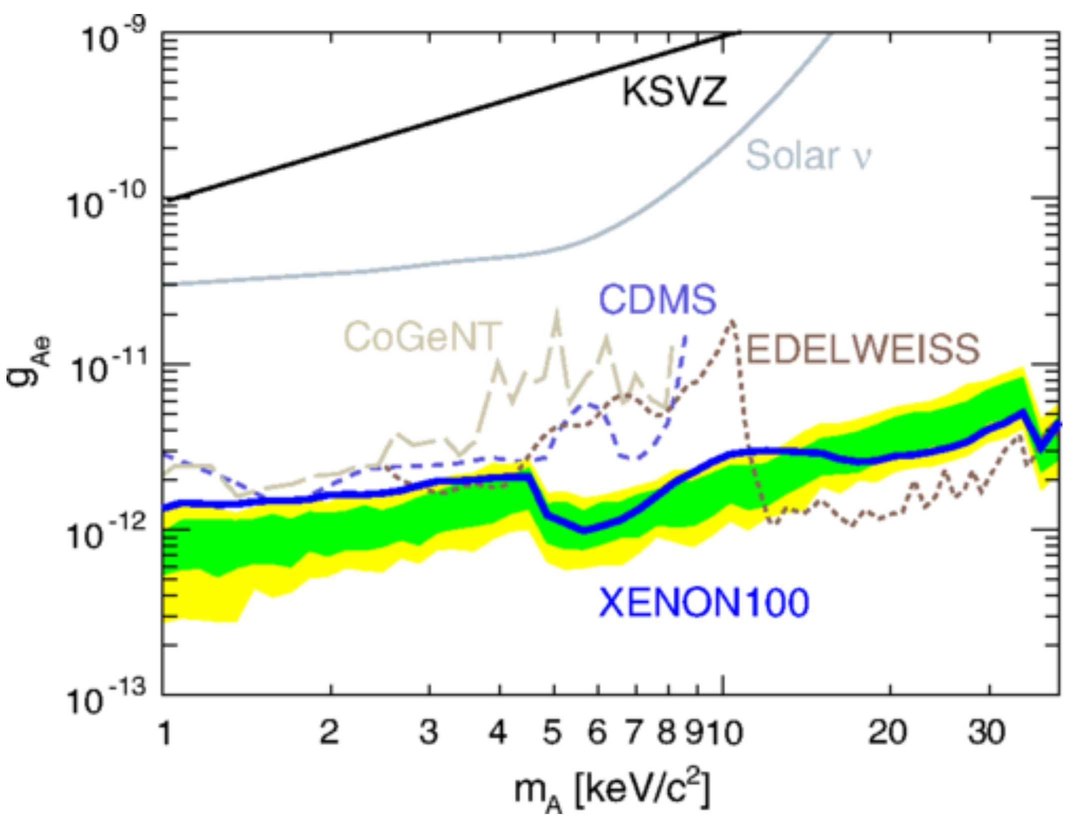
- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs (LB et al., PRD 87, 2013; arXiv:1303.6891)

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

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

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

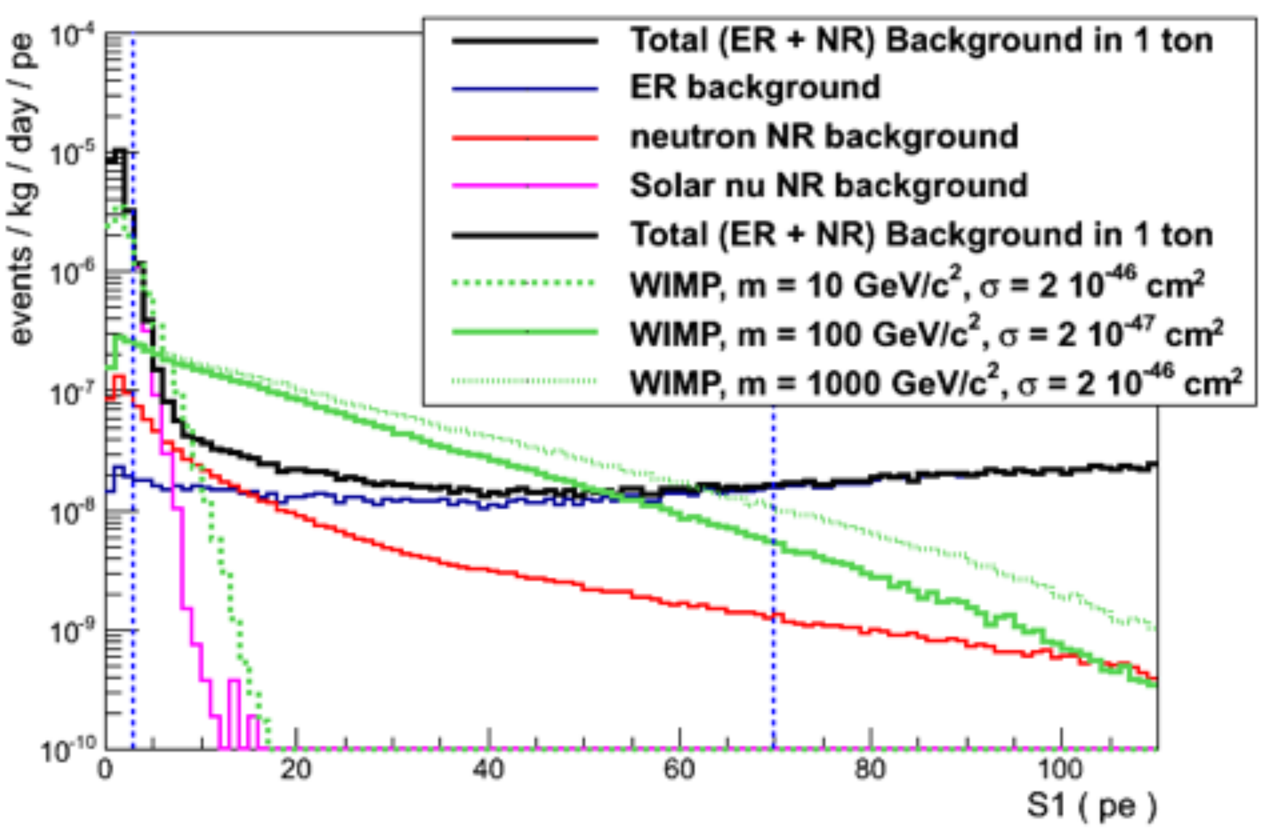
- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs (LB et al., PRD 87, 2013; arXiv:1303.6891)

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

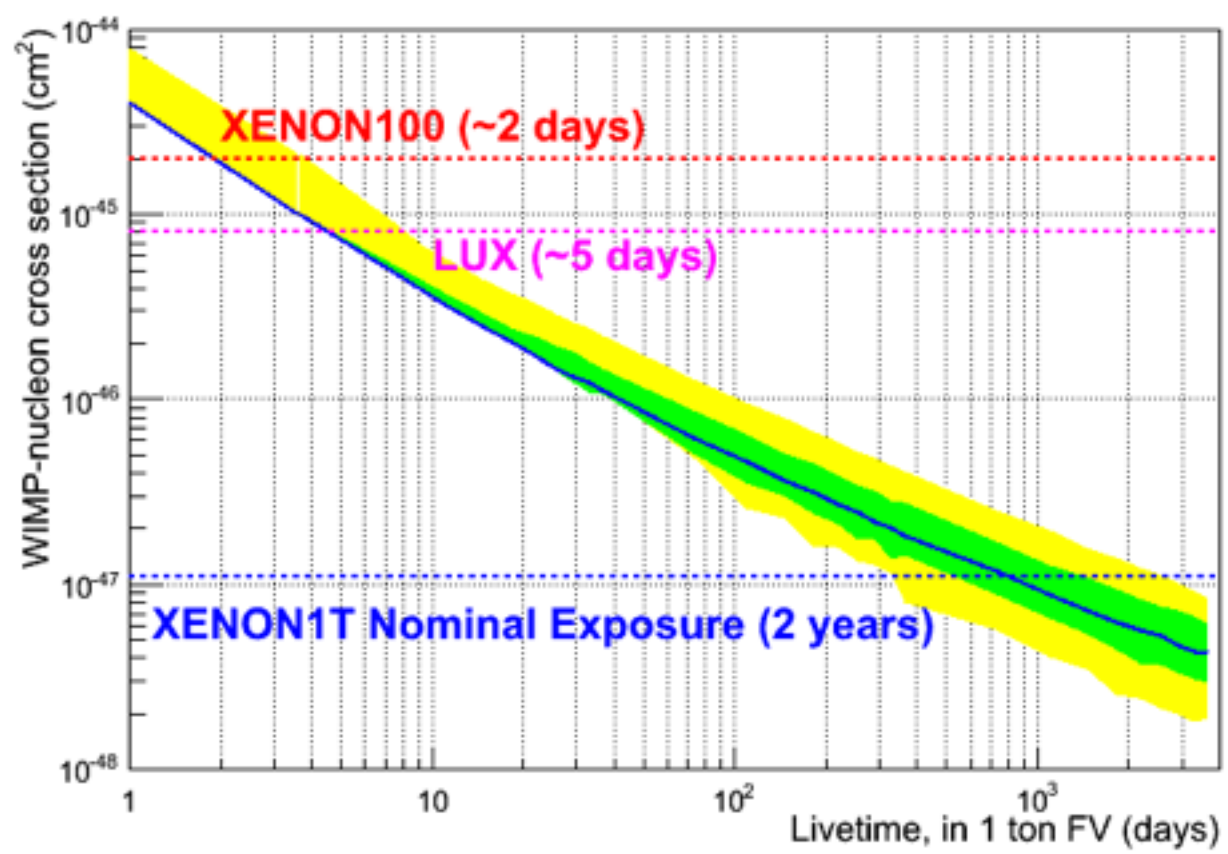
XENON1T backgrounds and WIMP sensitivity

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

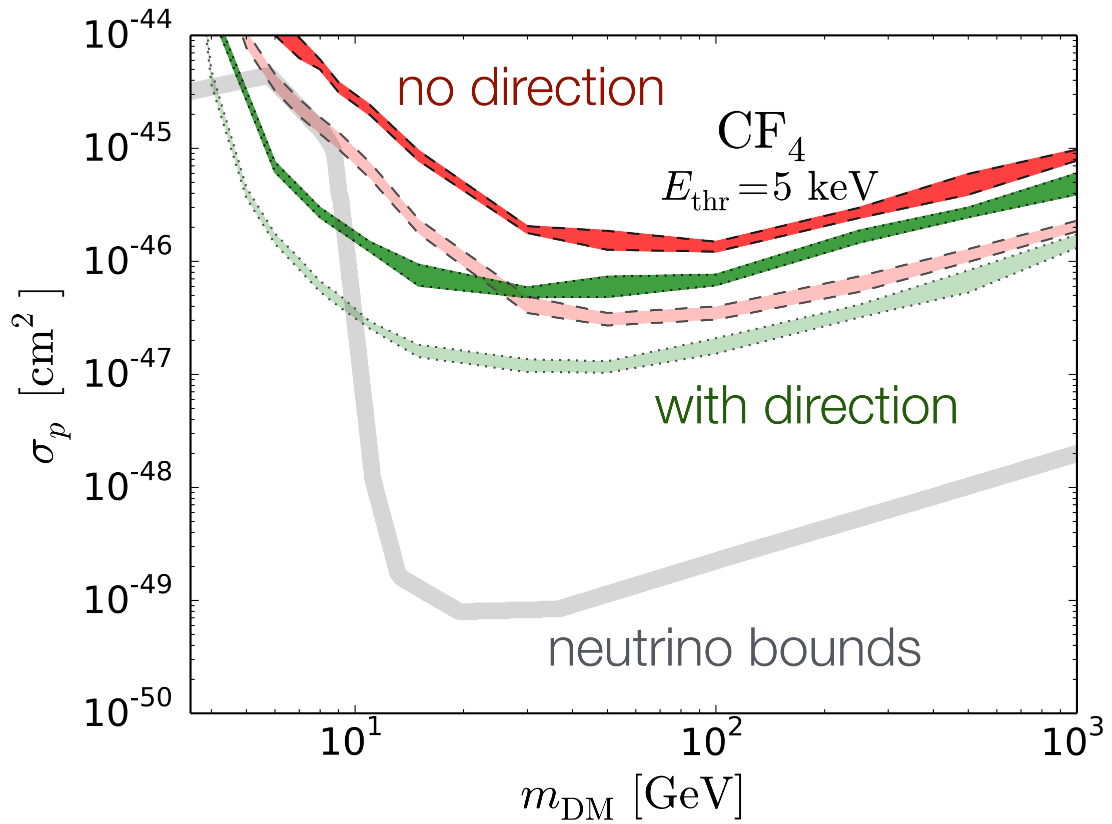


Sensitivity versus exposure (in 1 ton fiducial mass)

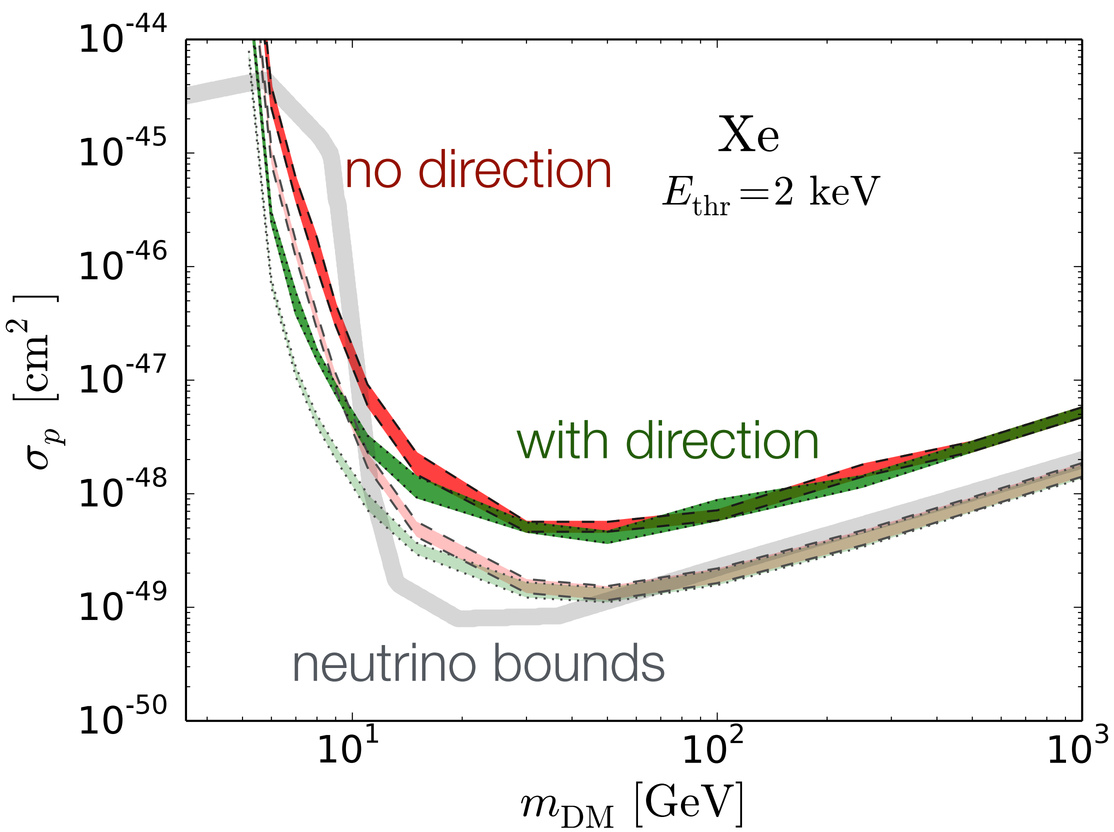
Will directional information help?

- 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