Dark matter detection - an experimental overview

Laura Baudis
University of Zurich

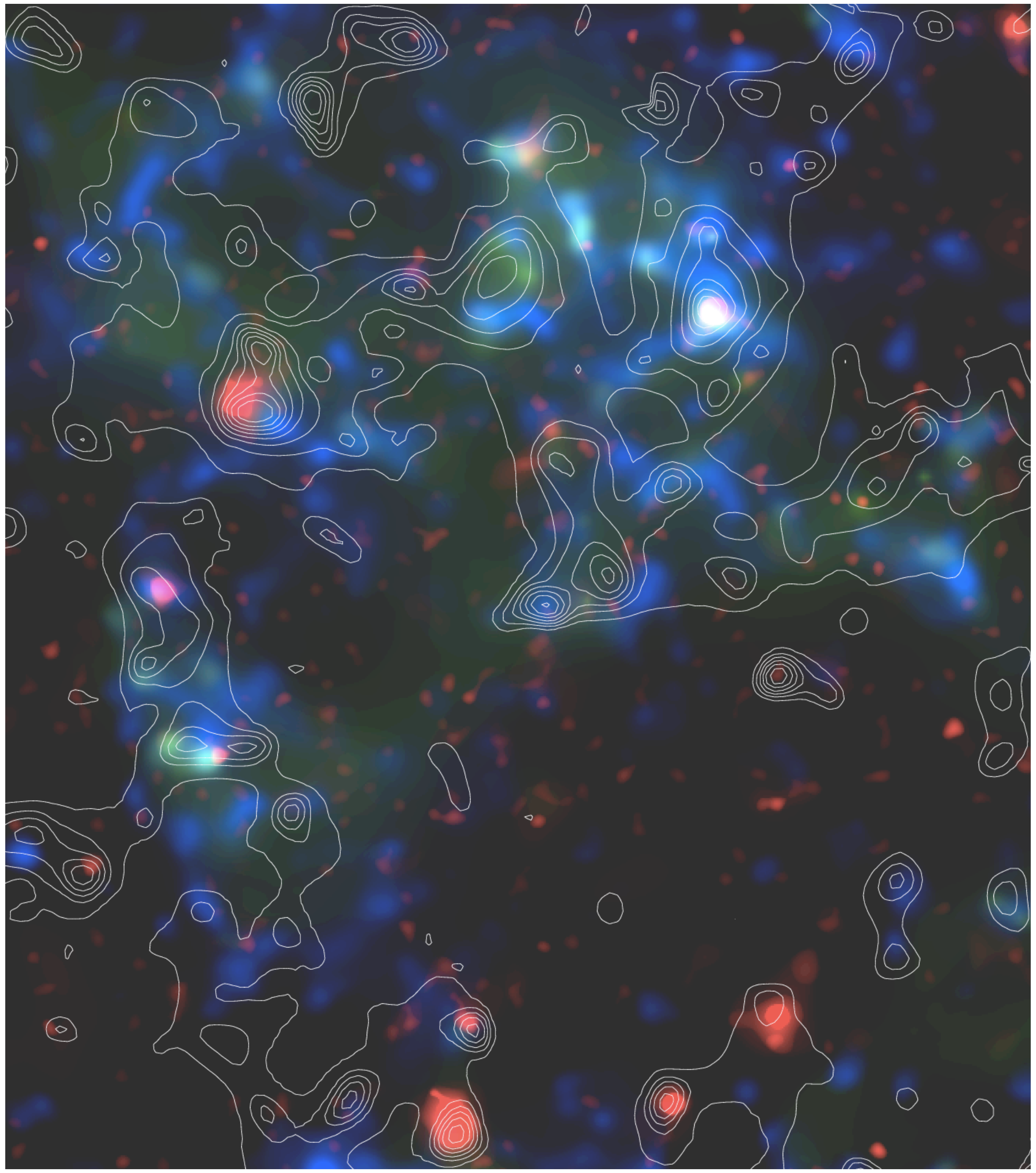
The dark matter puzzle

The dark matter puzzle remains *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

Large scale distribution of dark matter, probed through gravitational lensing



HST COSMOS survey; Nature 445 (2007), 268

What do we know about the dark matter?

So far, we mostly have “negative” information

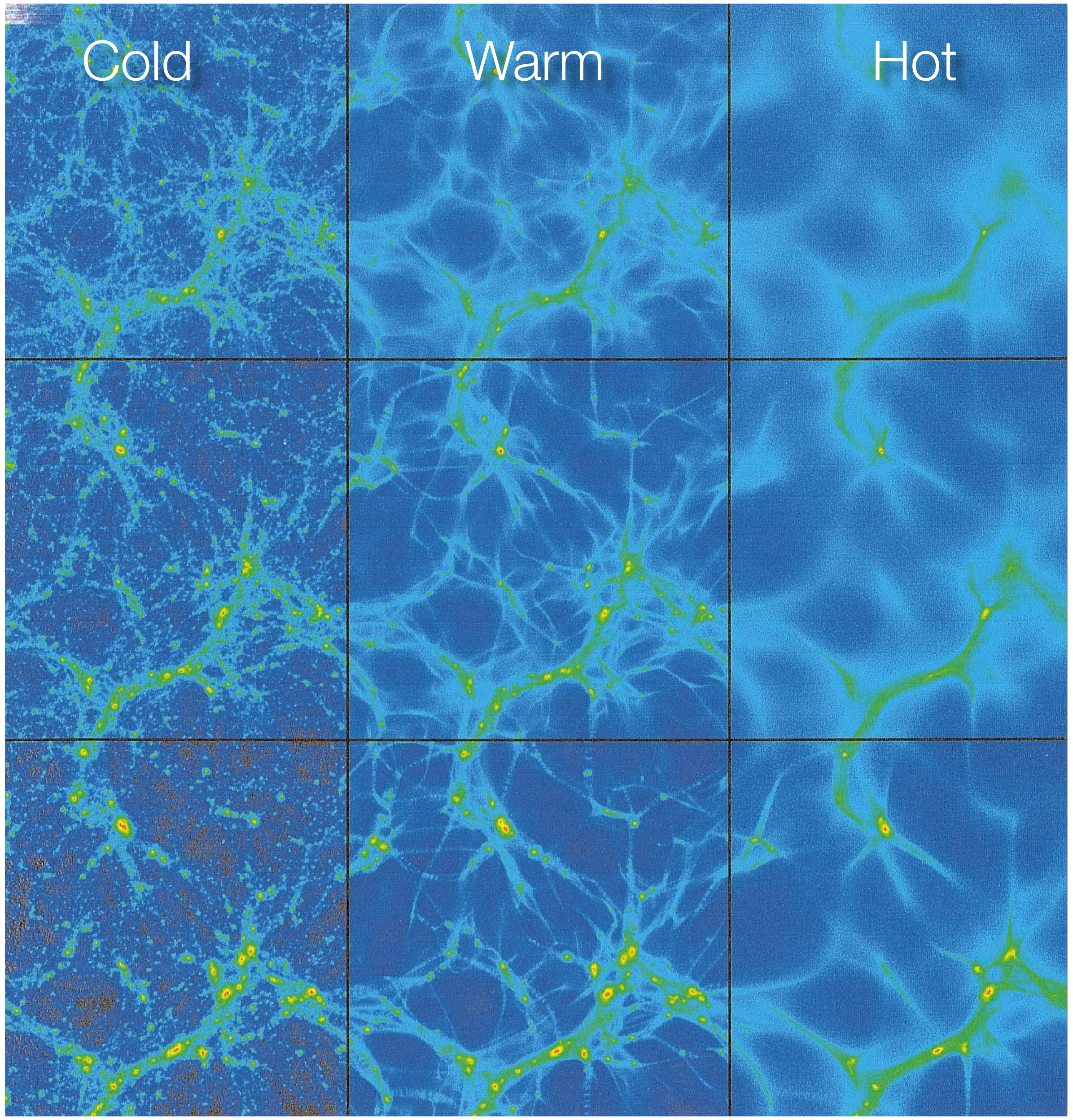
Constraints from astrophysics and searches for new particles:

No colour charge

No electric charge

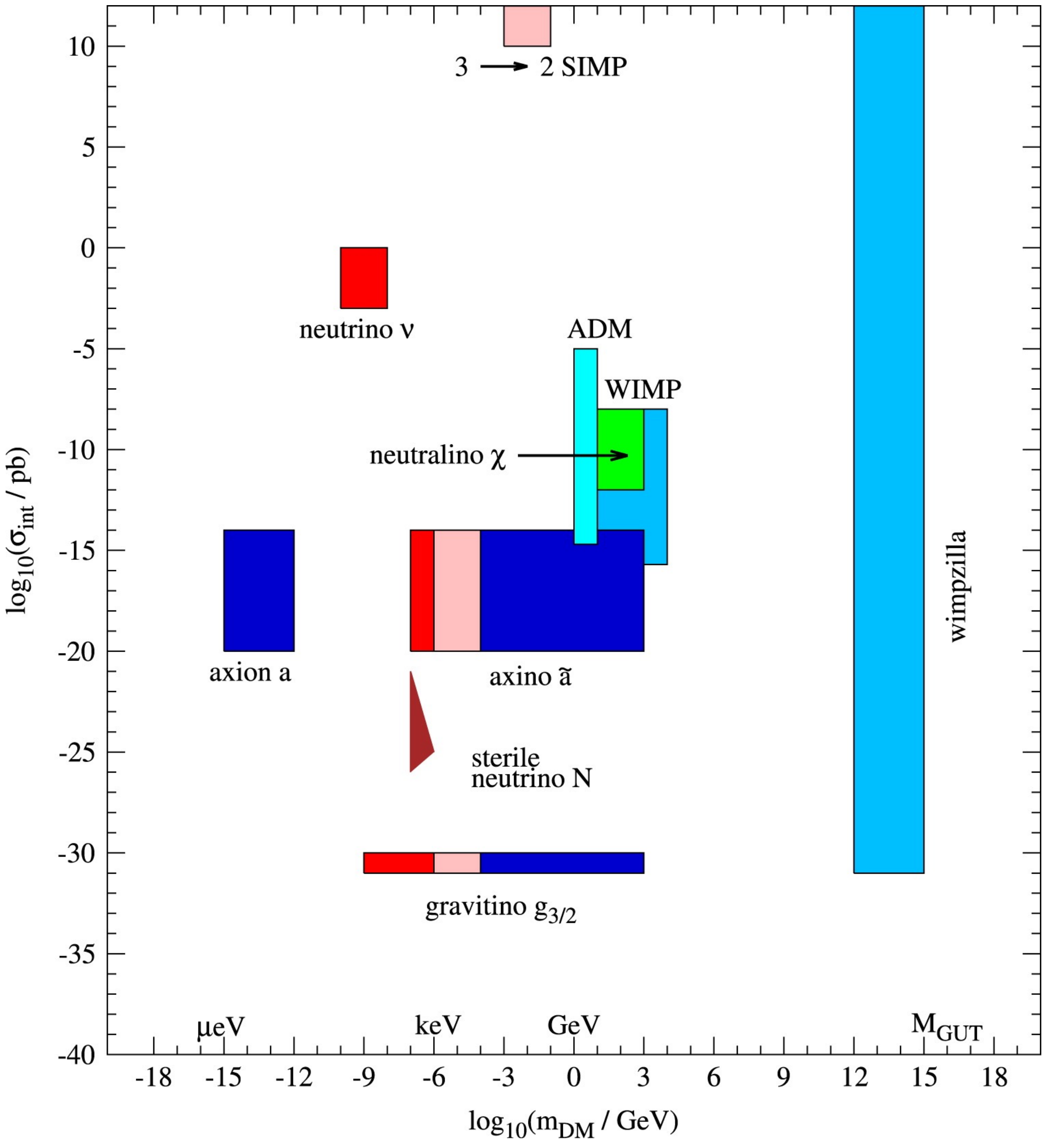
No strong self-interaction

Stable, or very long-lived



Probing dark matter through gravity

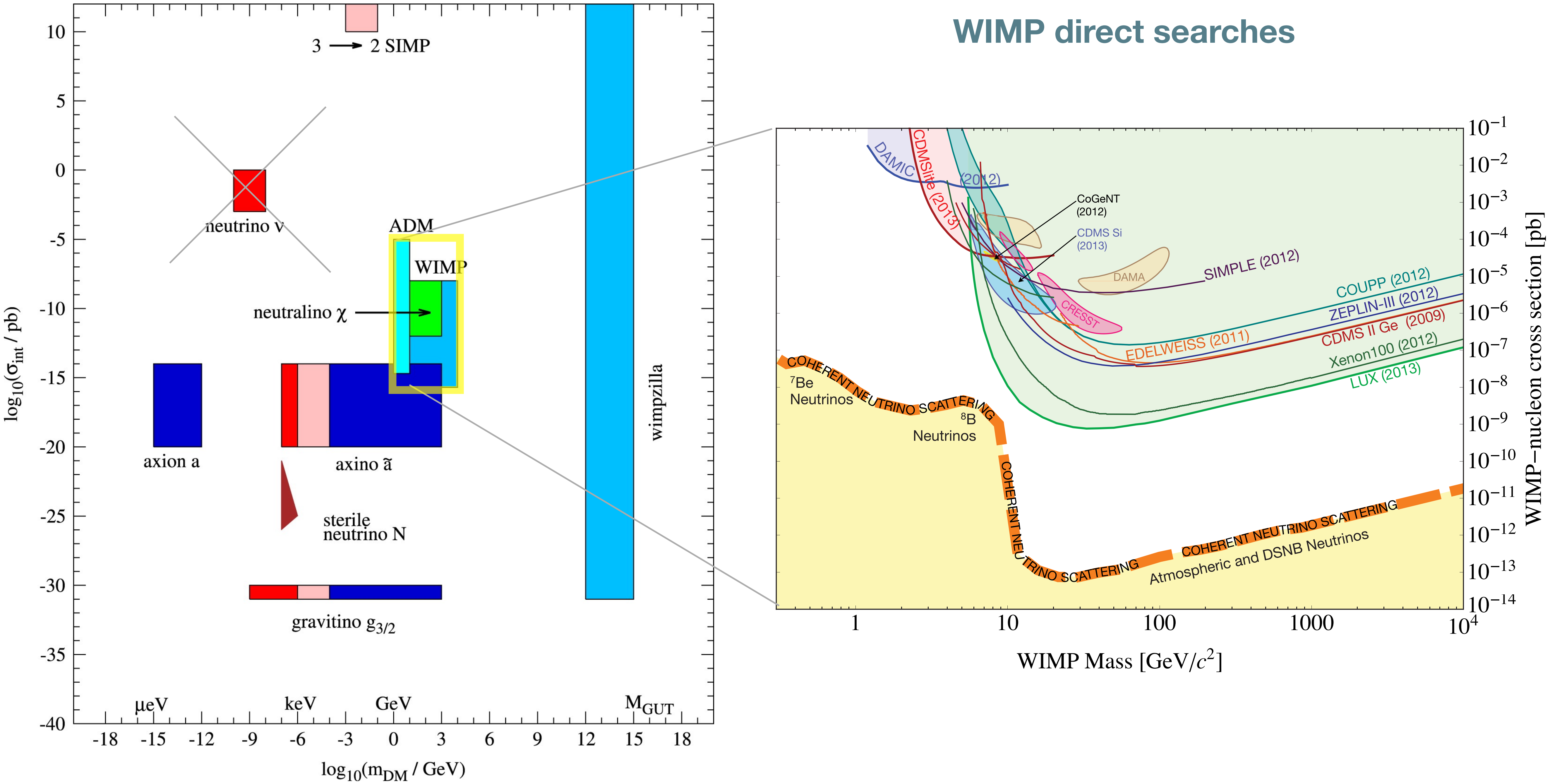
Parameter space for searches



- **Masses & interaction cross sections span an enormous range**
- Most dark matter experiments optimised to search for WIMPs
- However also searches for axions, ALPs, SuperWIMPs, etc

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

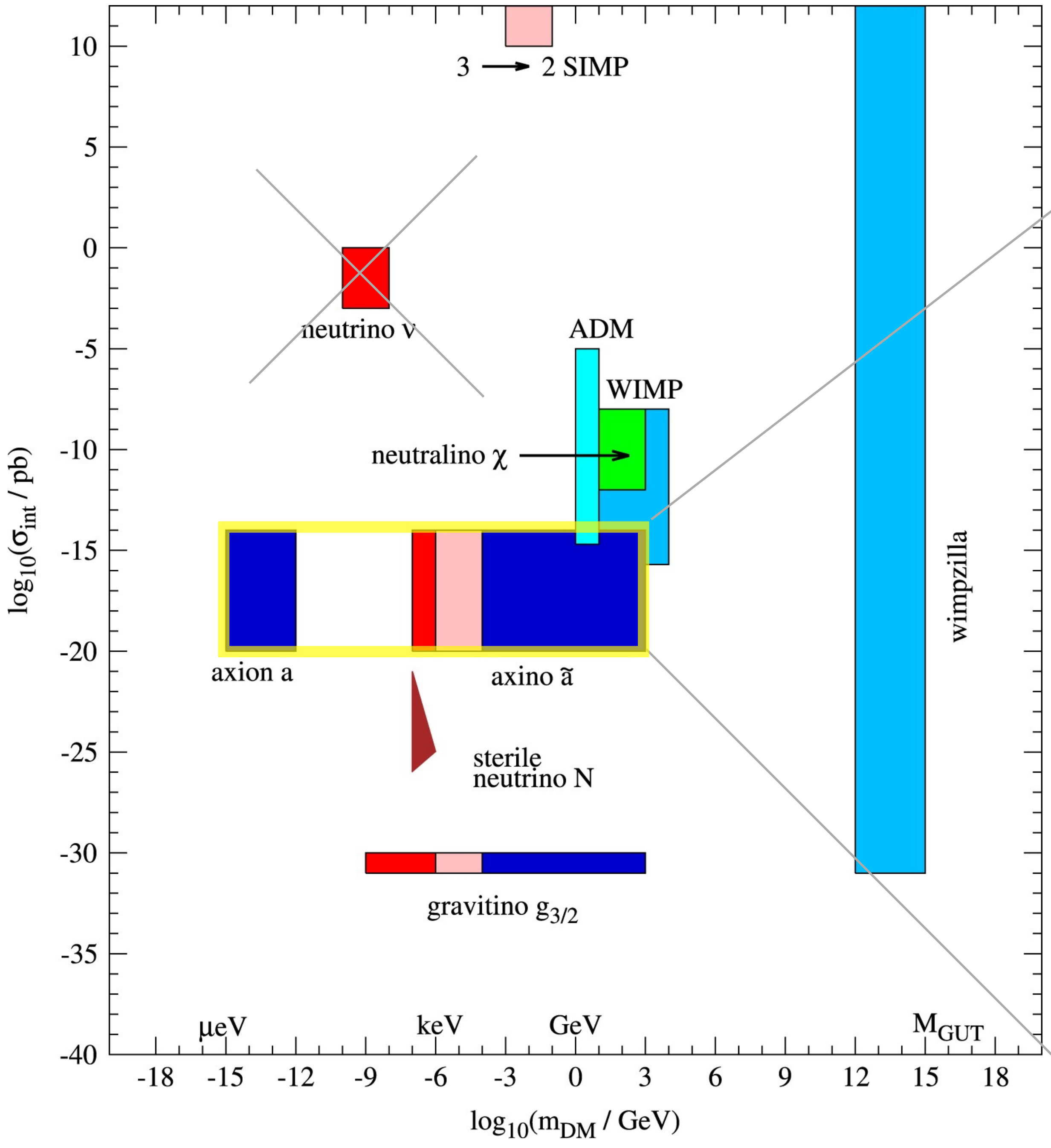
Parameter space for searches



WIMP direct searches

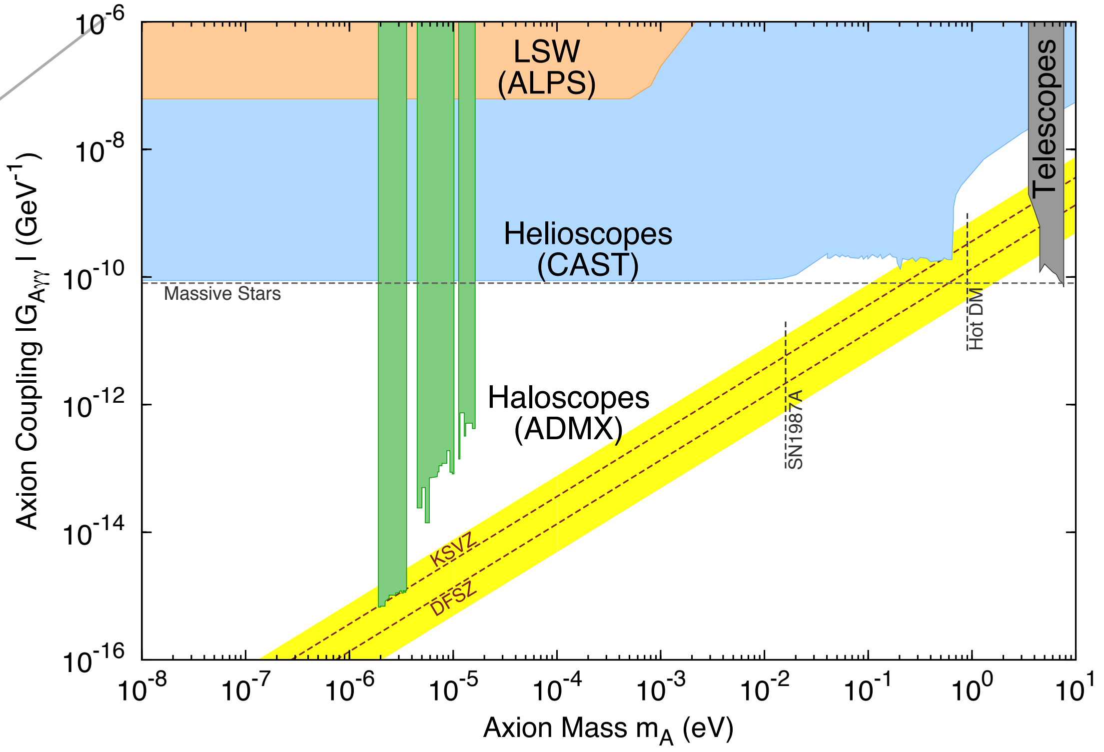
H. Baer et al., Phys. Rept. 555, 2014

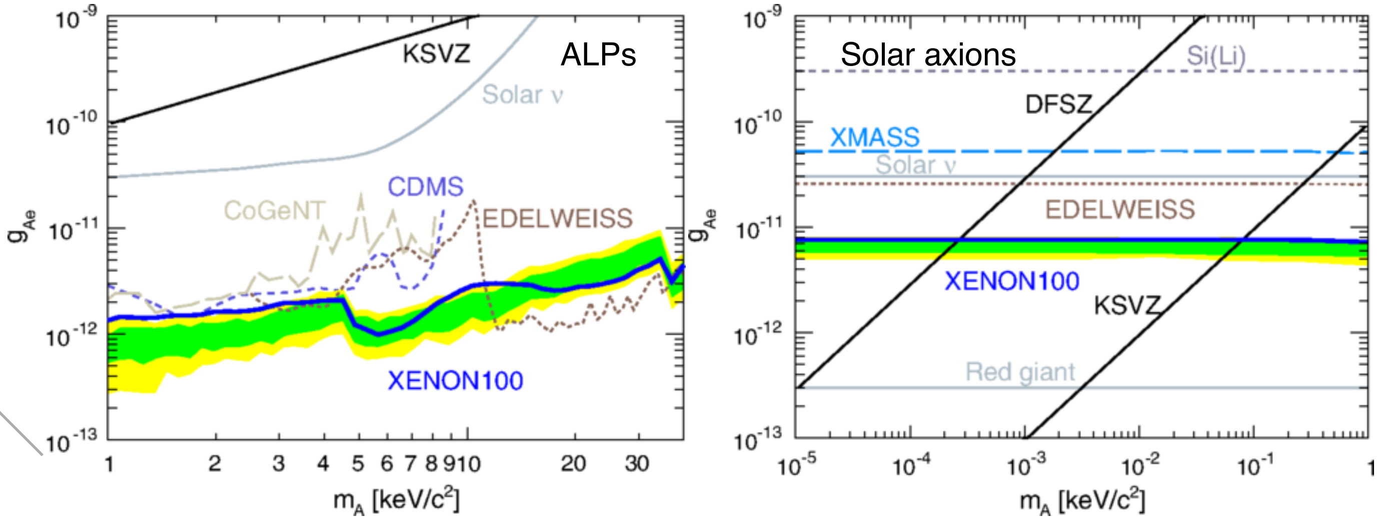
Parameter space for searches



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

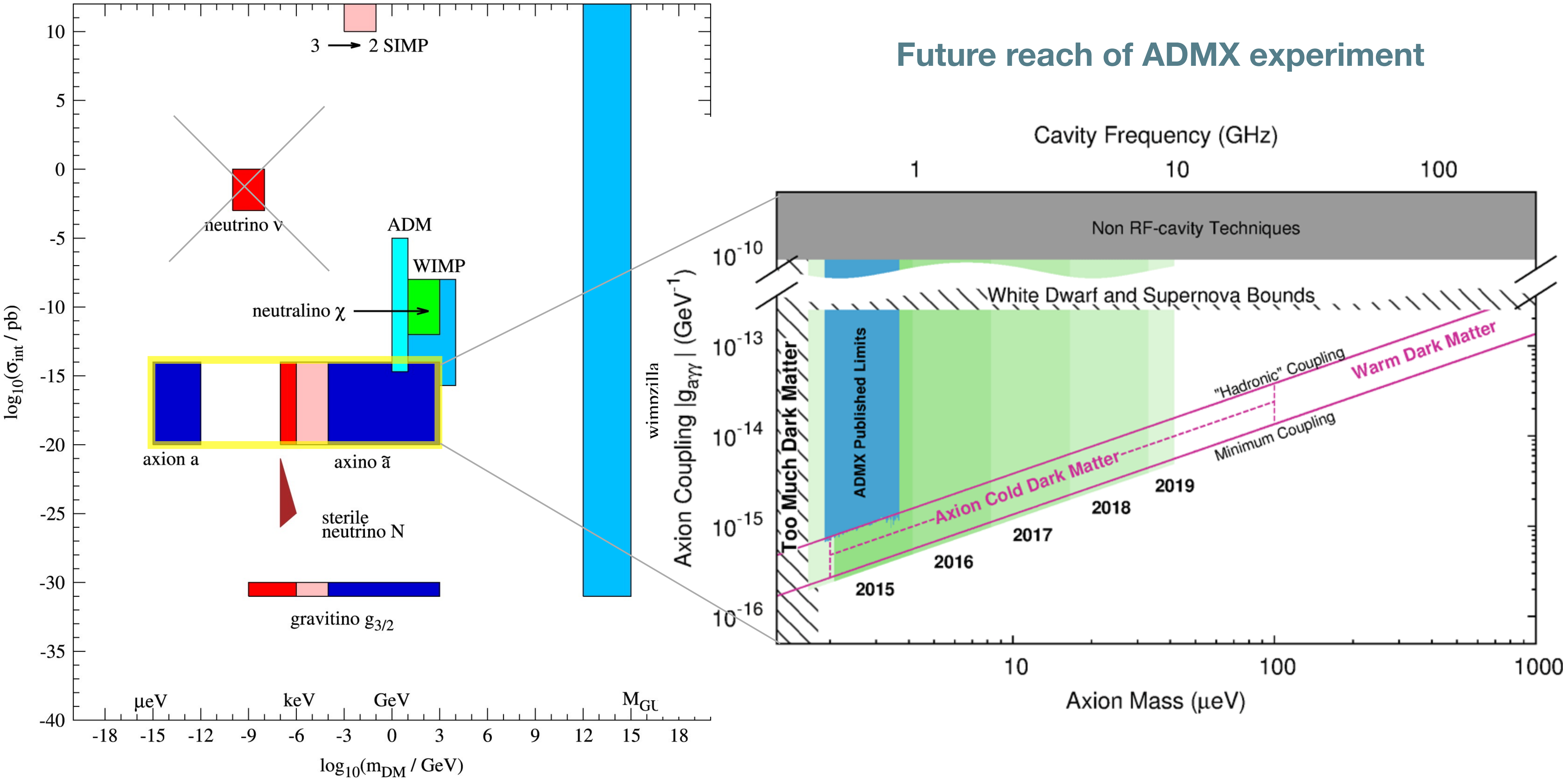
Axion searches





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

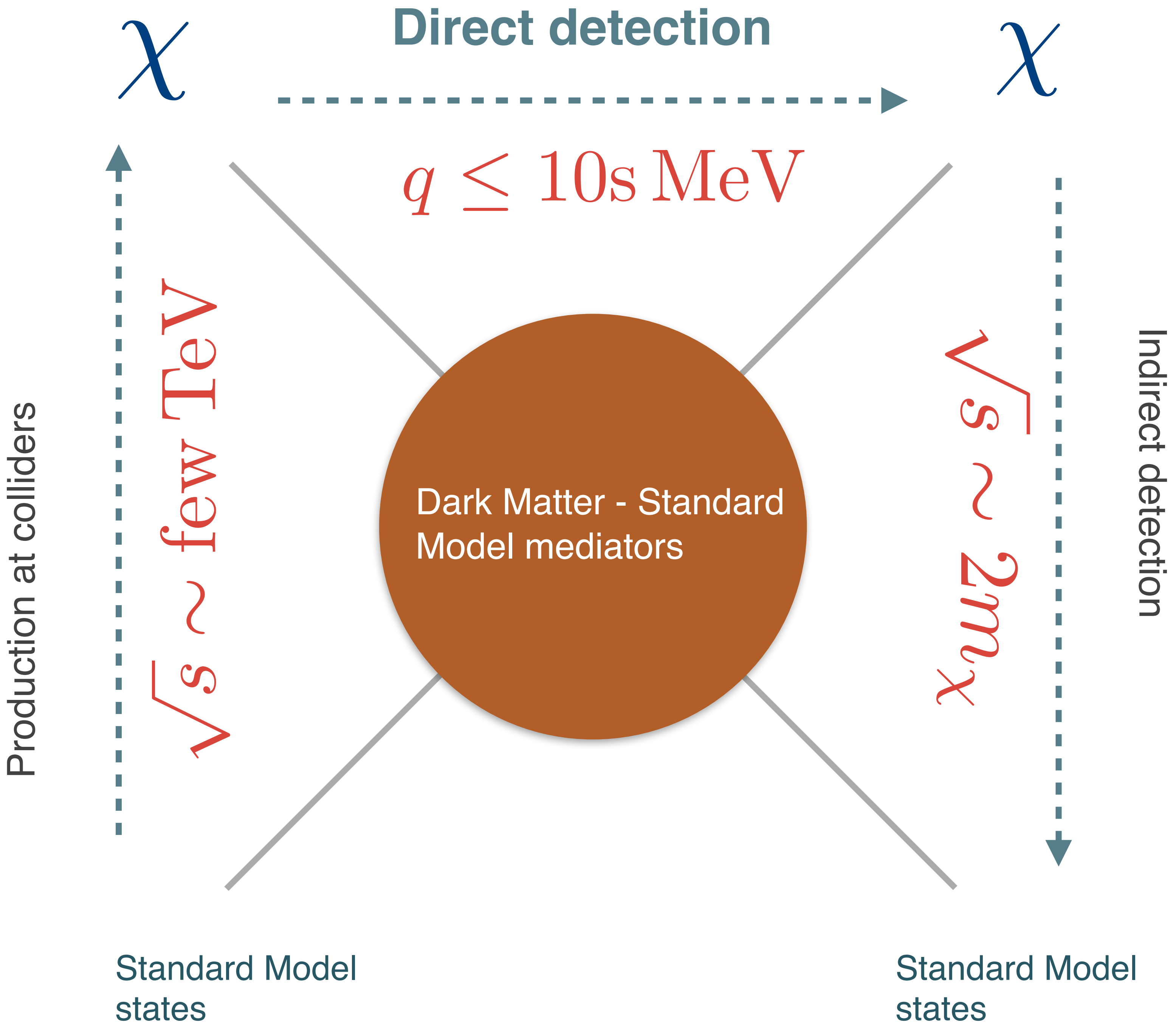
Parameter space for searches



Future reach of ADMX experiment

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

Under the WIMP lamppost…



χ

Direct detection

χ

$q \leq 10\mathrm{s}\,\mathrm{MeV}$

Production at colliders

$\sqrt{s} \sim \text{few TeV}$

Dark Matter - Standard Model mediators

$\sqrt{s} \sim 2m_\chi$

Indirect detection

Standard Model states

Standard Model states

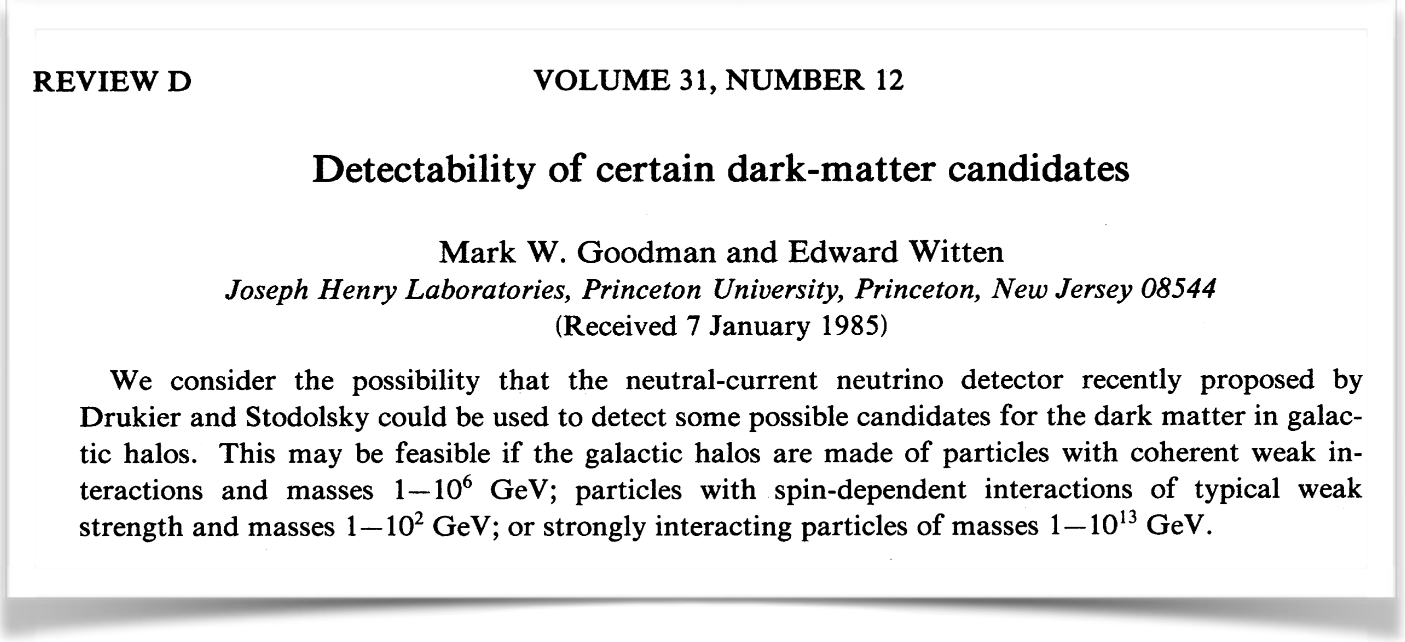
Direct dark matter detection

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



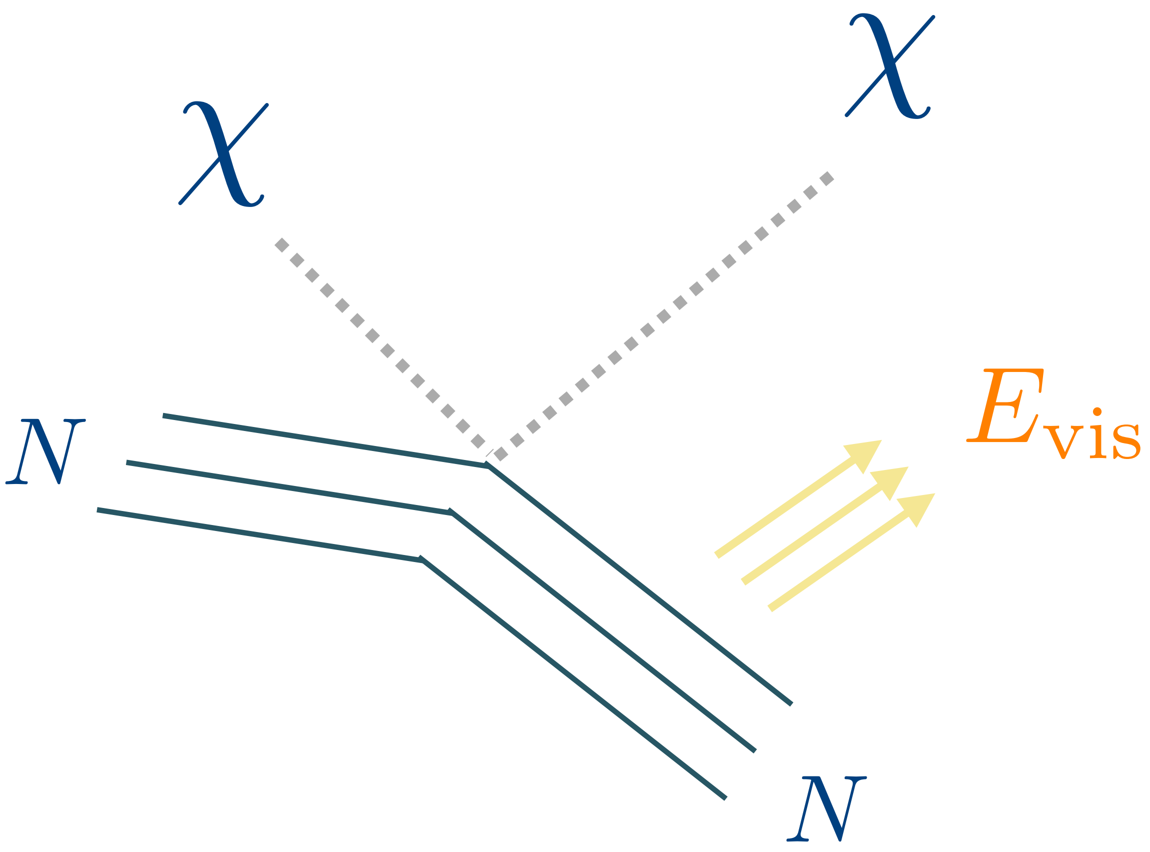
REVIEW D VOLUME 31, NUMBER 12

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.

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



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

What to expect in a terrestrial detector?

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

Detector physics

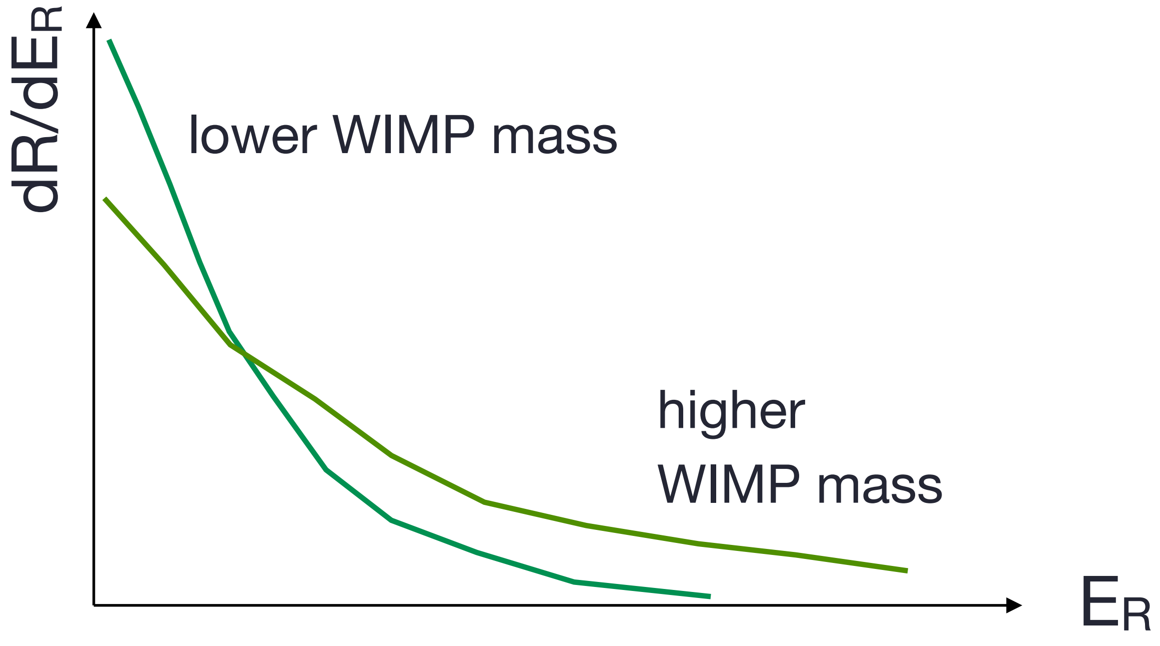
N_N, E_{th}

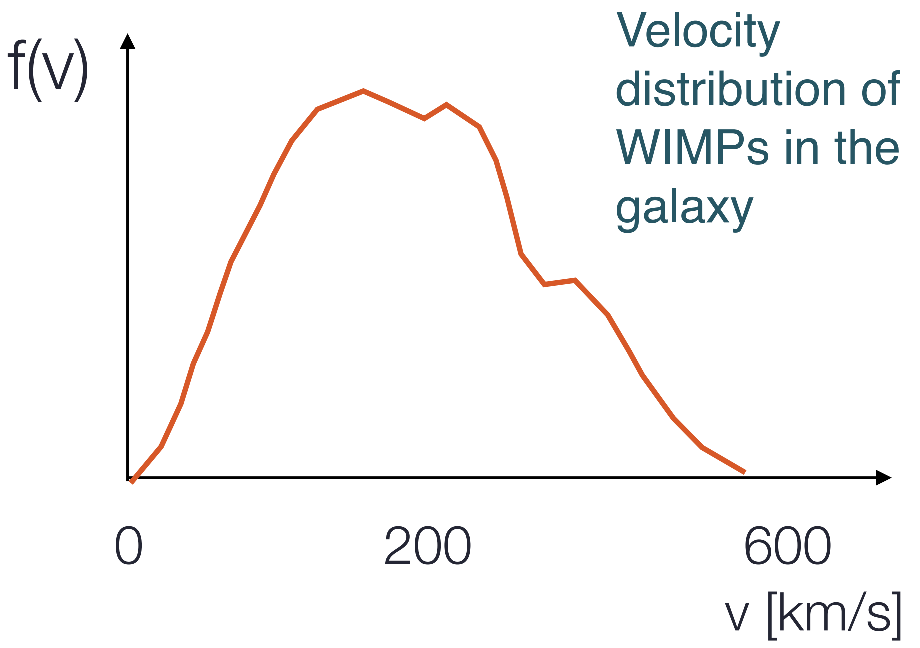
Particle/nuclear physics

$m_W, d\sigma/dE_R$

Astrophysics

$\rho_0, f(v)$





Velocity distribution of WIMPs in the galaxy

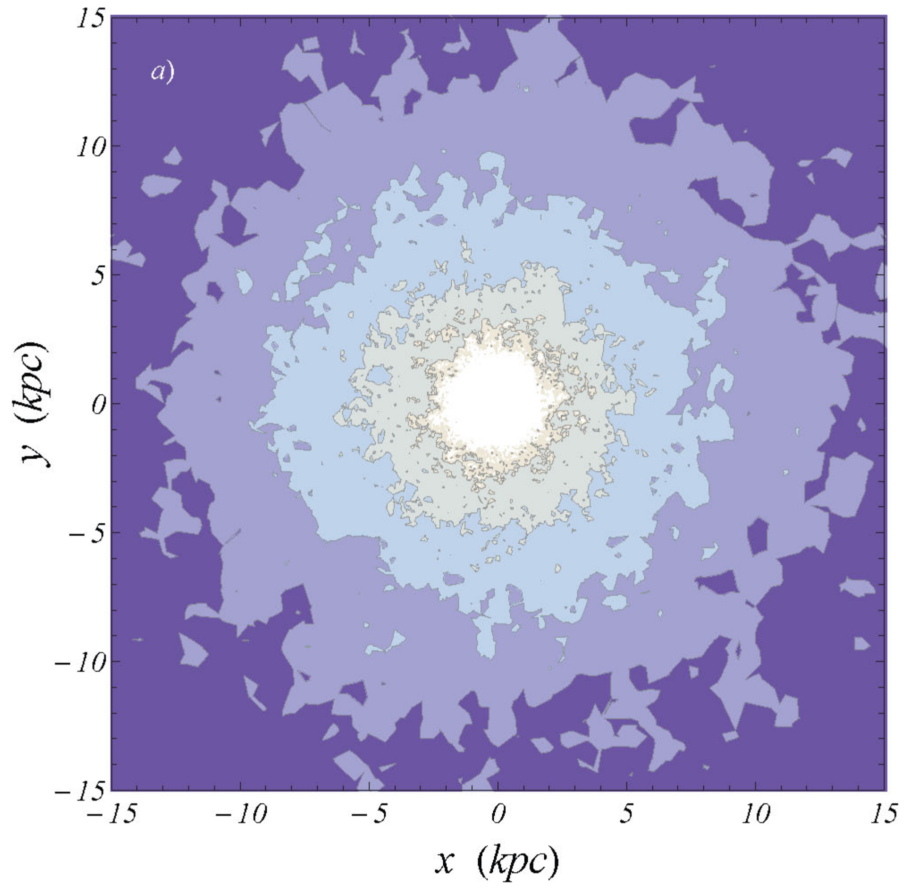
Astrophysics

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)

Density map of the dark matter halo
rho = [0.1, 0.3, 1.0, 3.0] GeV cm^{-3}



High-resolution cosmological simulation with baryons: F.S. Ling et al, JCAP02 (2010) 012

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

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

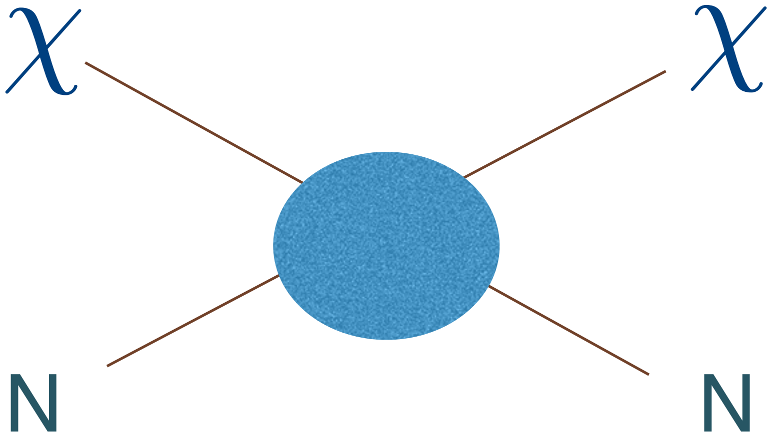
=> **WIMP flux on Earth: ~10^5 cm^{-2}s^{-1}** (M_W=100 GeV, for 0.3 GeV cm^{-3})

Particle physics

- **Use effective operators to describe WIMP-quark interactions**
- **Example: vector mediator**

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

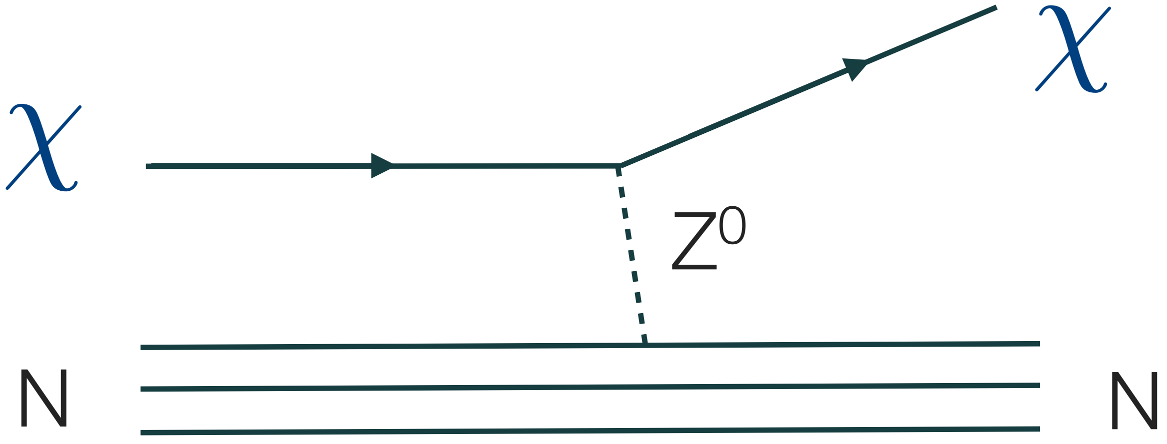
- The effective operator arises from “integrating out” the mediator with mass M and couplings g_q and g_χ to the quark and the WIMP



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

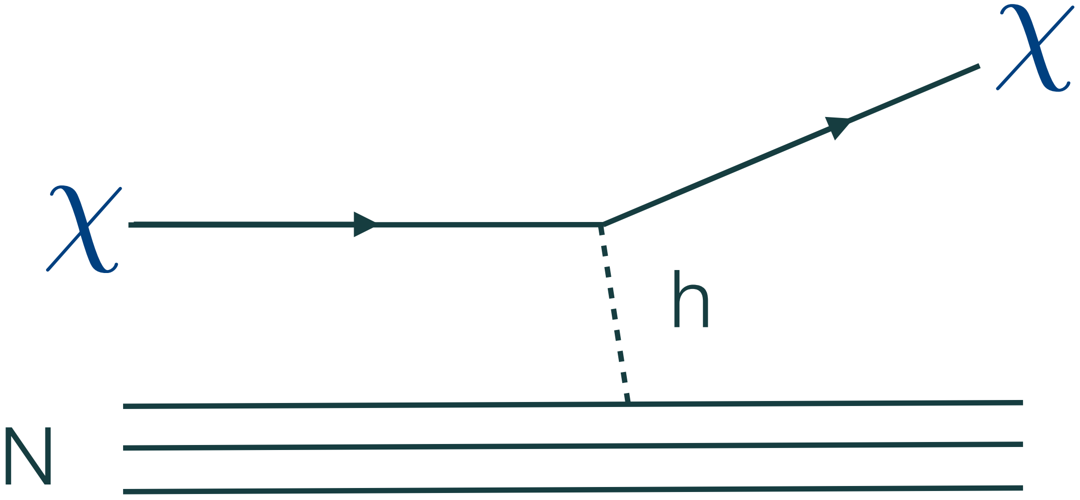
contact interaction scale

What are the expected cross sections?



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

Excluded by direct detection experiments

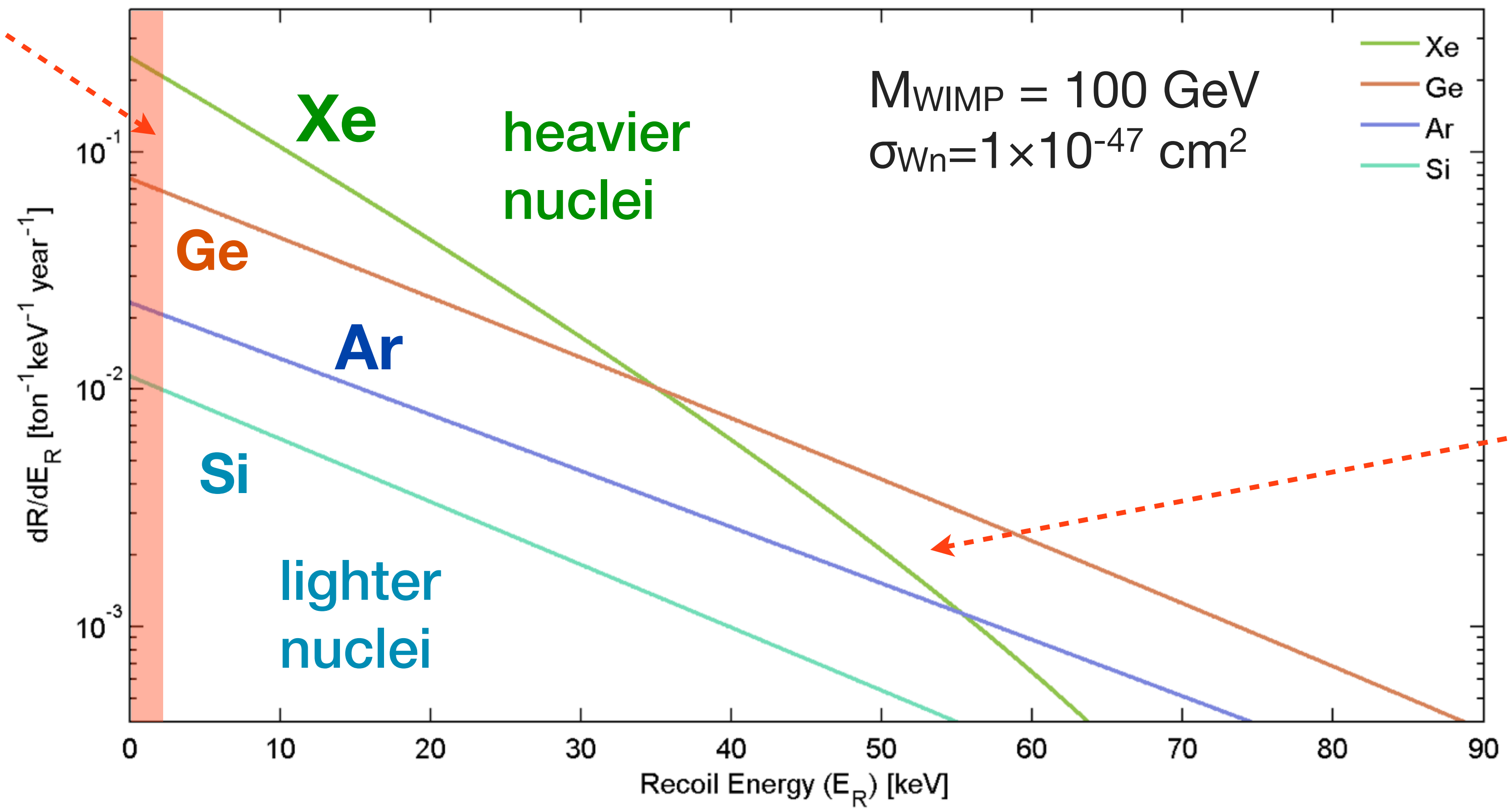


$$\sigma_0 \sim 10^{-44} - 10^{-47}\,\mathrm{cm}^2$$

Expected interaction rates in terrestrial detectors

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

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

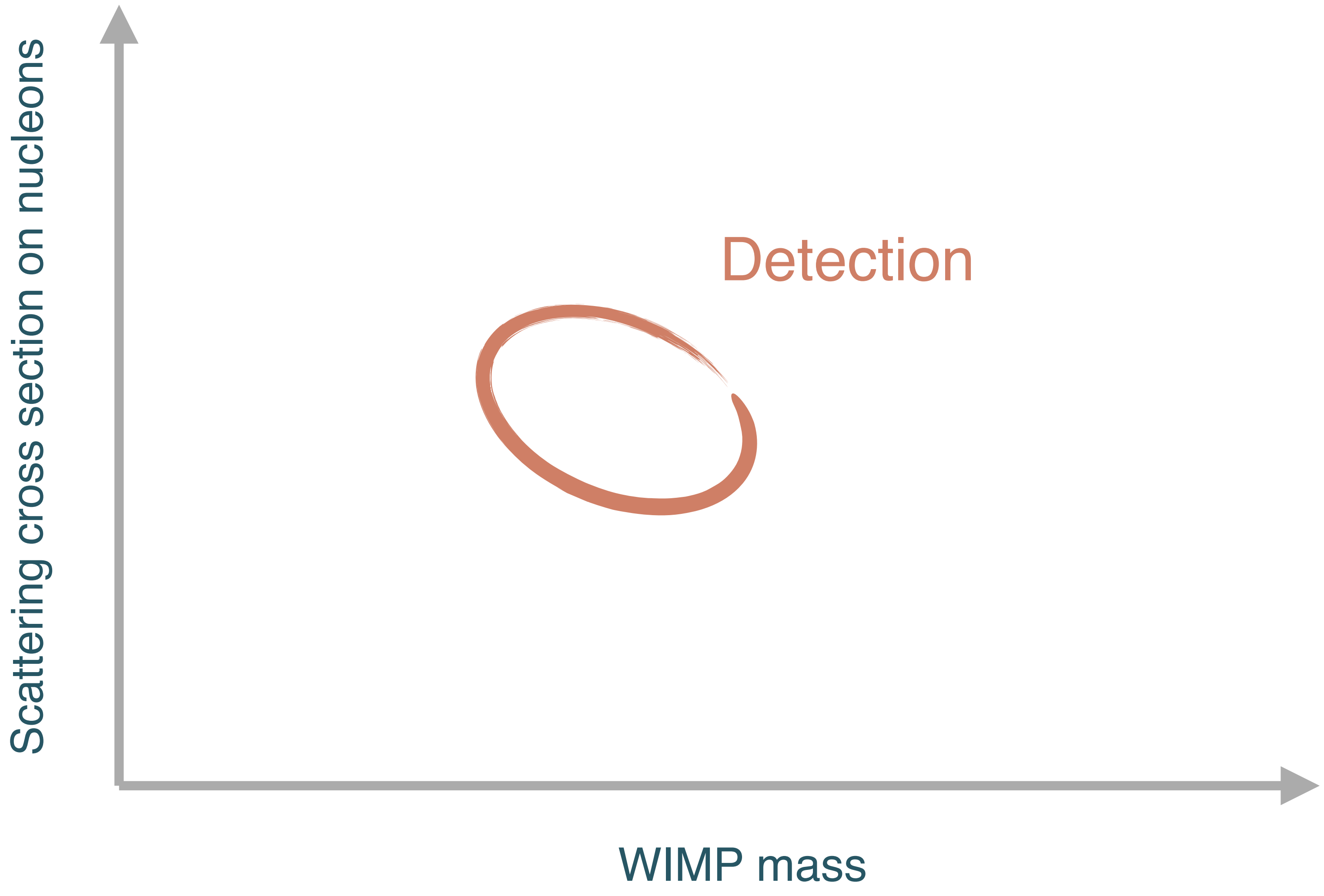


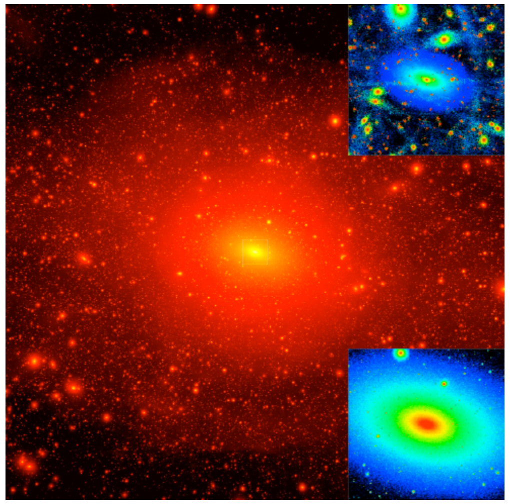
$F^2(E_R)$

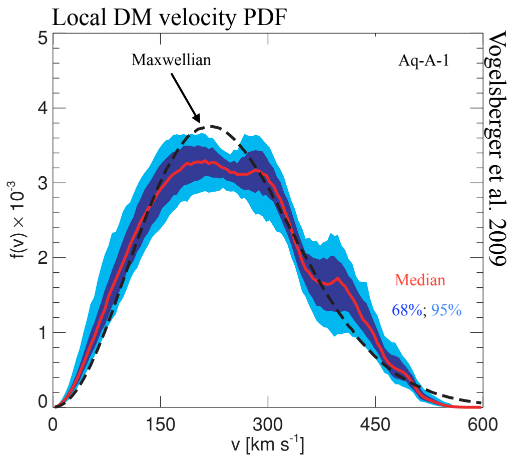
What can we learn about WIMPs?

- Constraints on the mass and scattering cross section

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{\boxed{m_W}} \int_{v_{min}}^{v_{max}} dv\, f(v) v \boxed{\frac{d\sigma}{dE_R}}$$





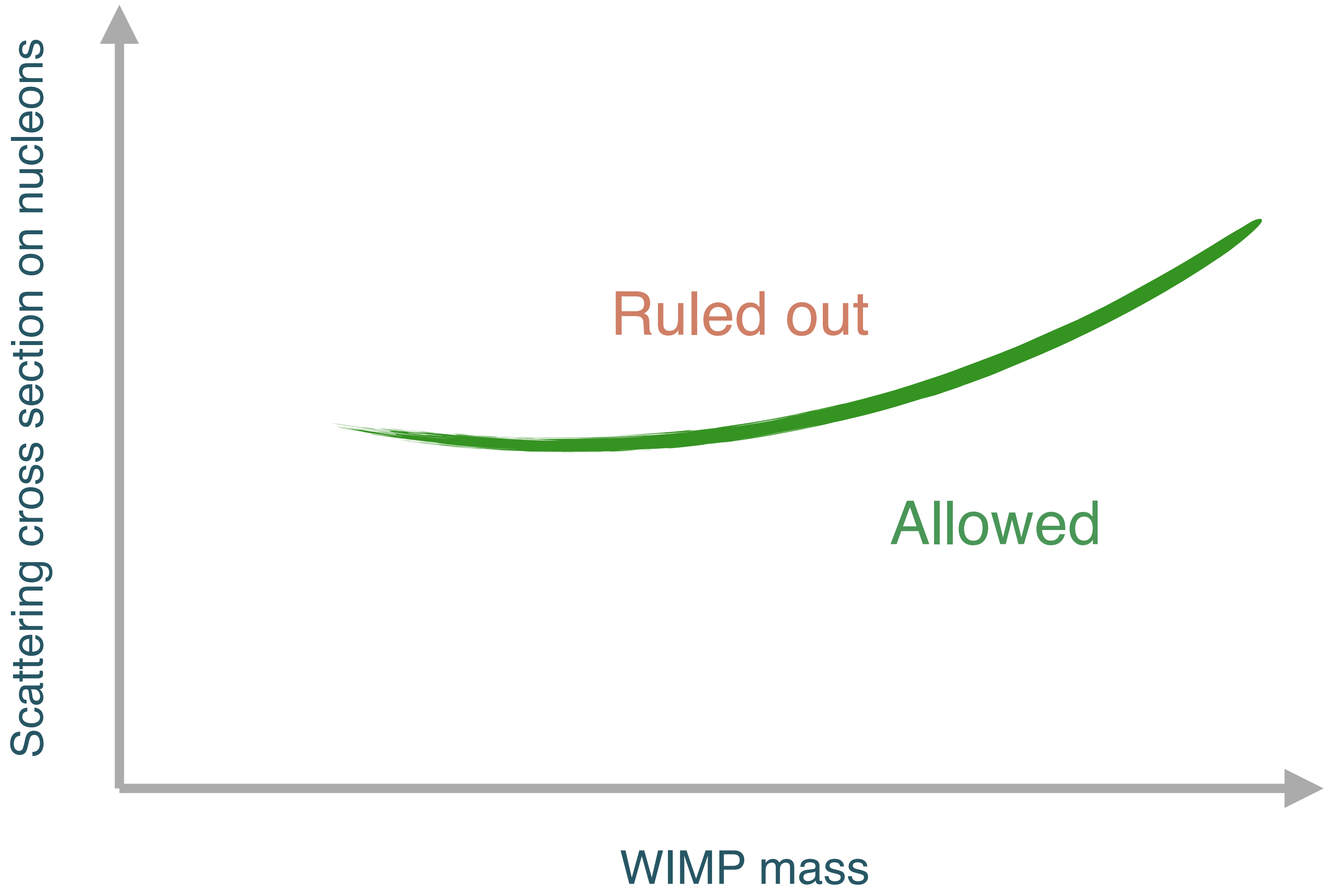


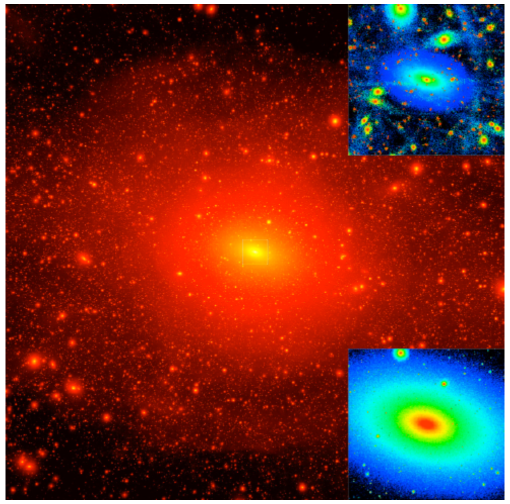
Vogelsberger et al. 2009

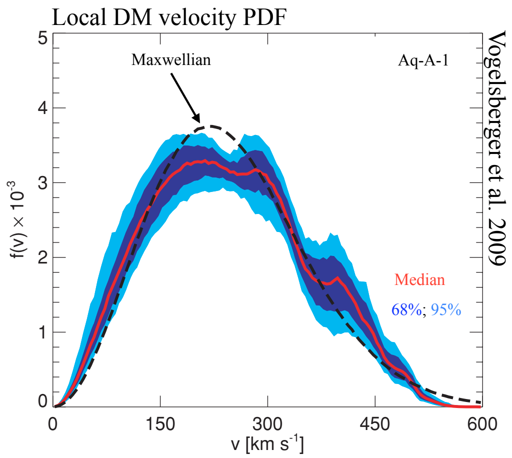
What can we learn about WIMPs?

- Constraints on the mass and scattering cross section

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{min}}^{v_{max}} dv\, f(v)\, v \frac{d\sigma}{dE_R}$$

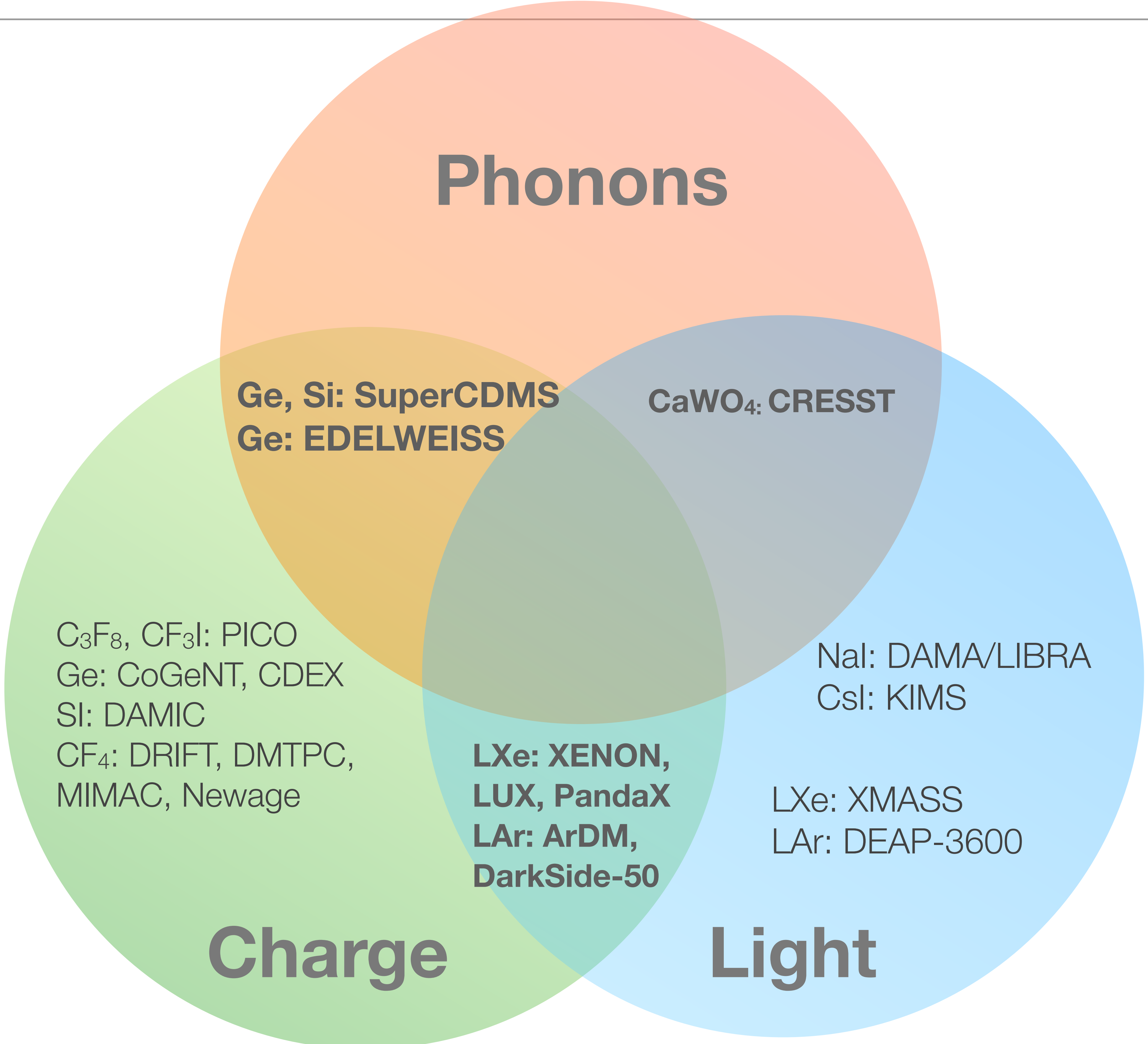






Vogelsberger et al. 2009

Direct dark matter detection zoo



Phonons

Ge, Si: SuperCDMS
Ge: EDELWEISS

$CaWO_4$: CRESST

C_3F_8, CF_3I: PICO
Ge: CoGeNT, CDEX
SI: DAMIC
CF_4: DRIFT, DMTPC,
MIMAC, Newage

NaI: DAMA/LIBRA
CsI: KIMS

LXe: XENON,
LUX, PandaX
LAr: ArDM,
DarkSide-50

LXe: XMASS
LAr: DEAP-3600

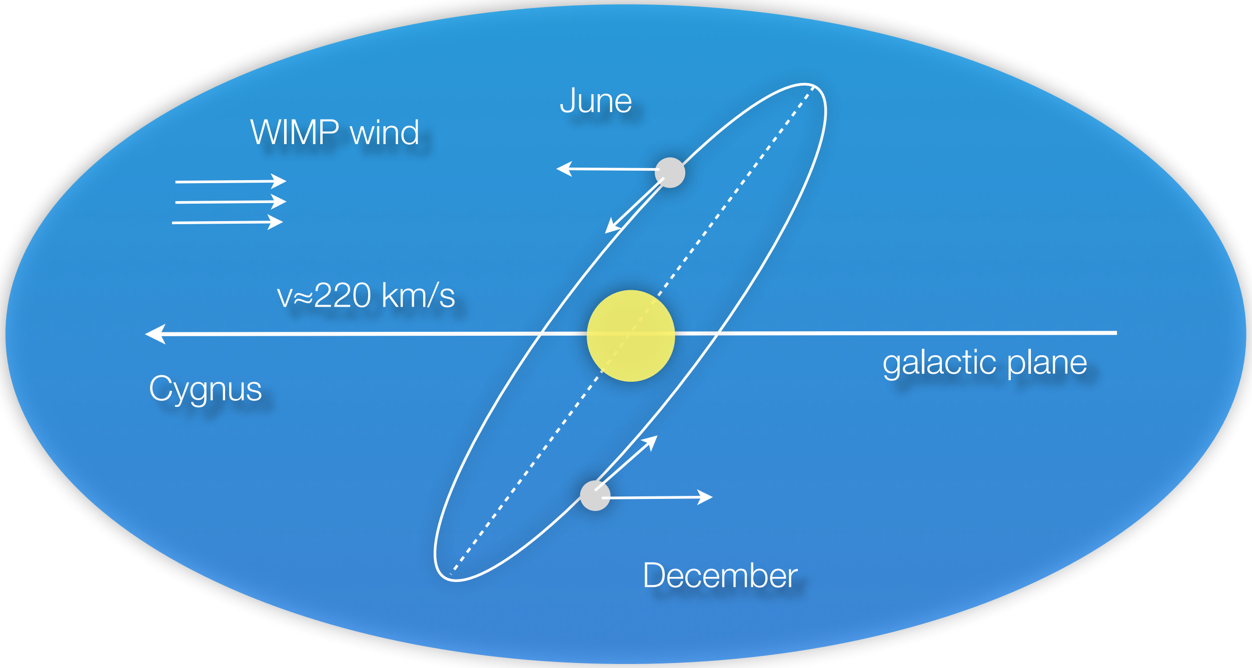
Charge

Light

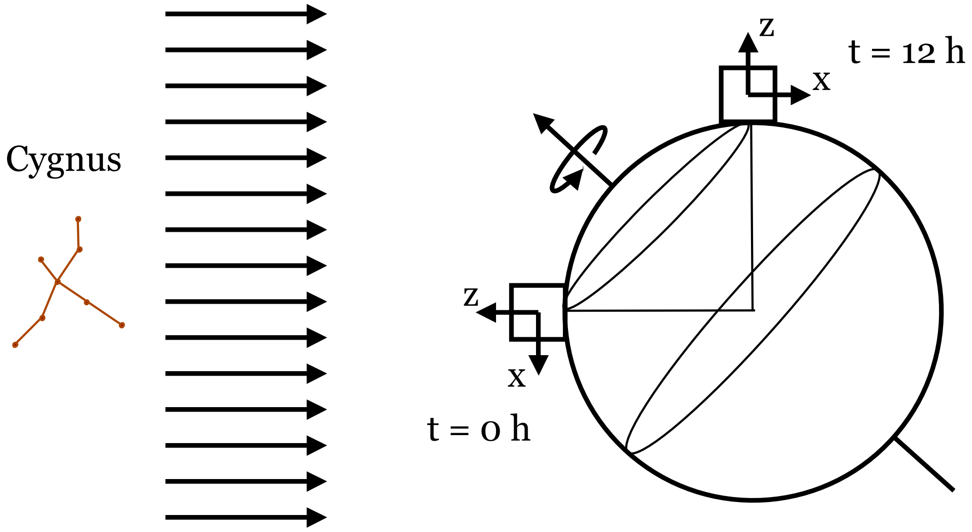
Dark matter signatures

- **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

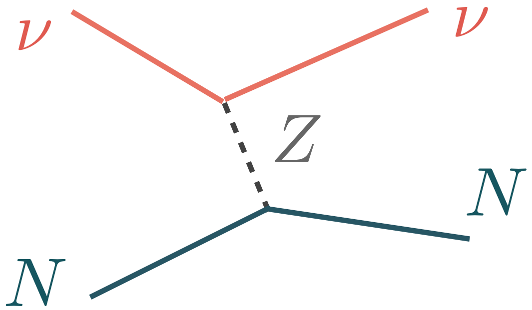


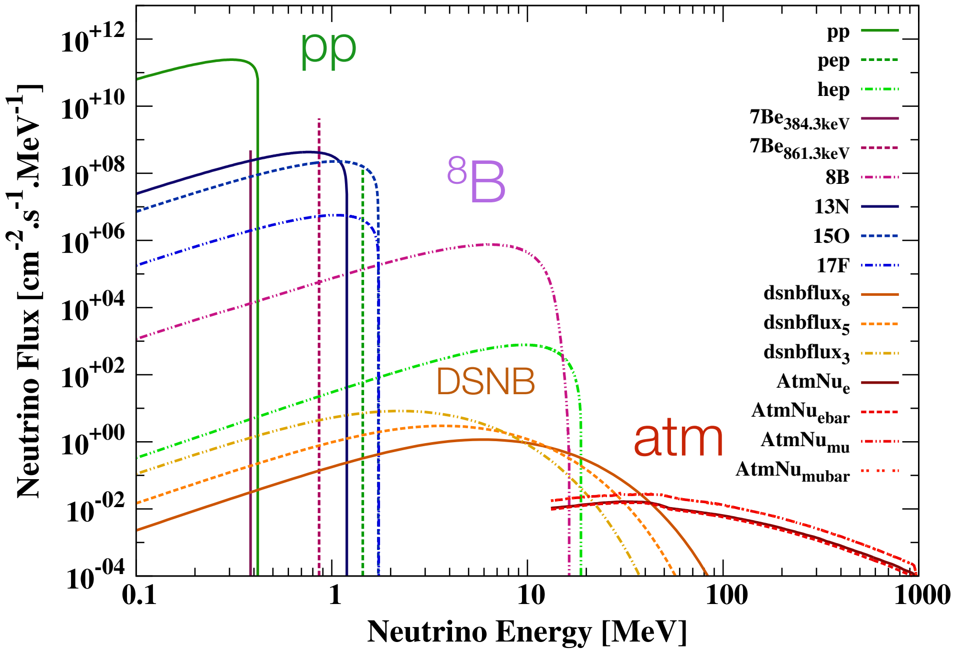
D. Spergel, PRD 36, 1988



Expected backgrounds

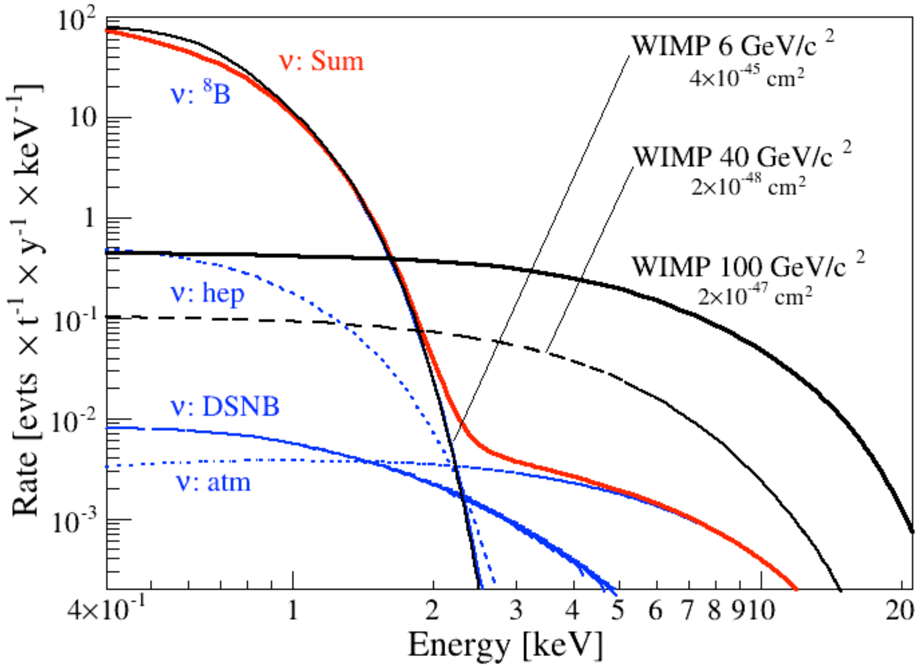
- Cosmic rays & cosmic activation of detector materials
- Natural (^{238}U, ^{232}Th, ^{40}K) & anthropogenic (^{85}Kr, ^{137}Cs) radioactivity: γ, e^-, n, α
- Ultimately: **neutrino-nucleus scattering (solar, atmospheric and supernovae neutrinos)**





F. Ruppin et al., 1408.3581

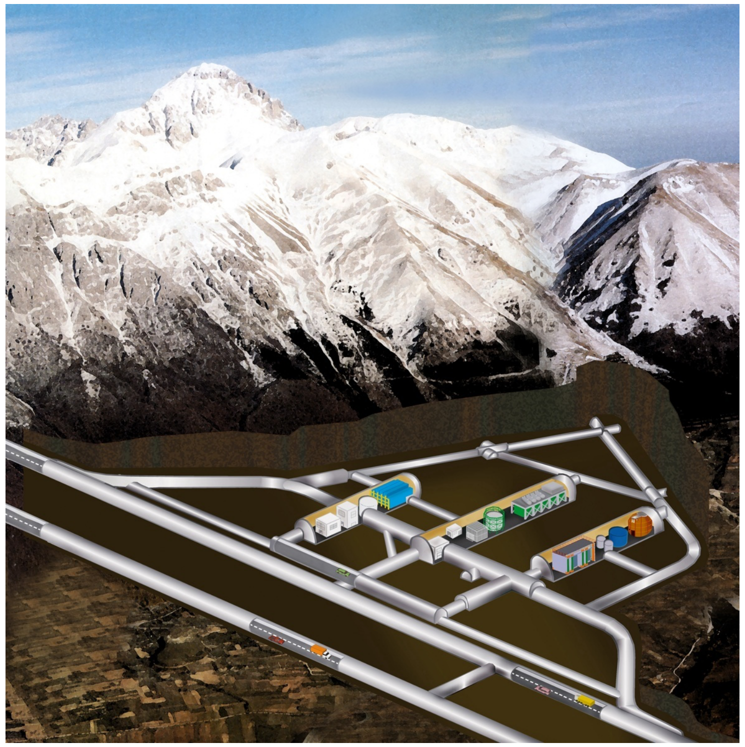
$$\nu + N \longrightarrow \nu + N$$



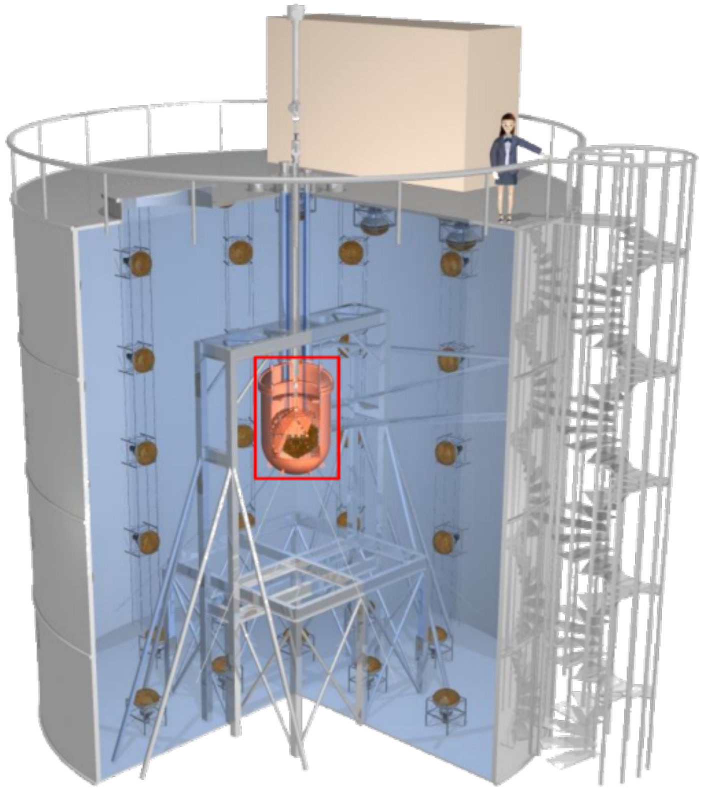
LB et al., JCAP01 (2014) 044

How to deal with backgrounds?

- Go deep underground

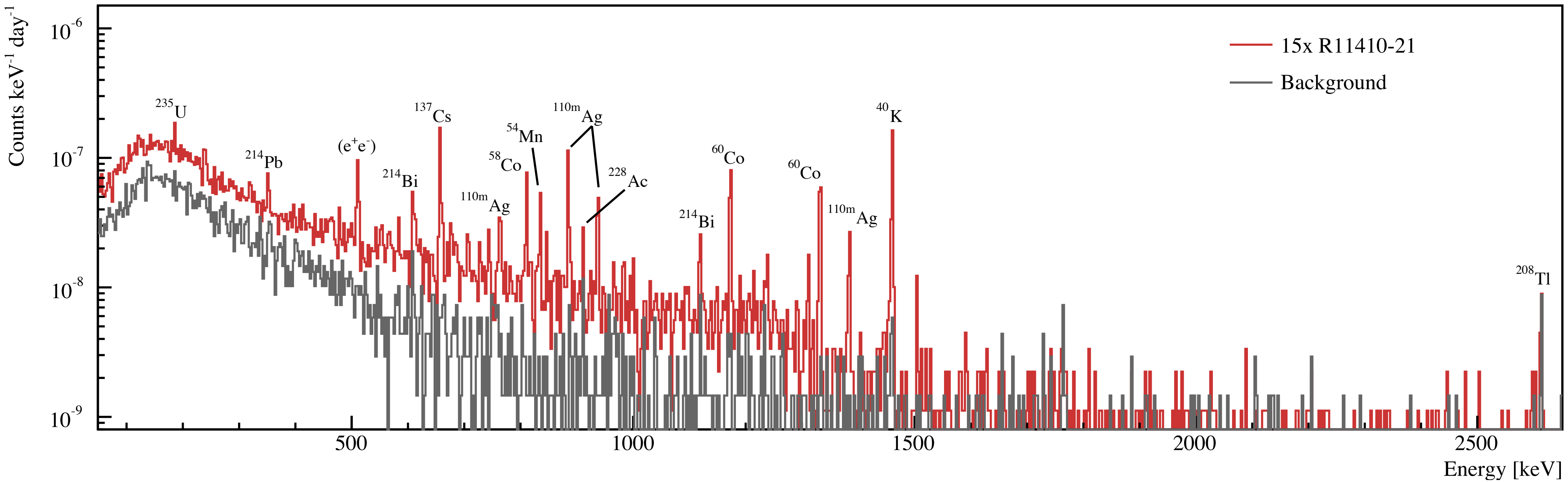


- Use active shields



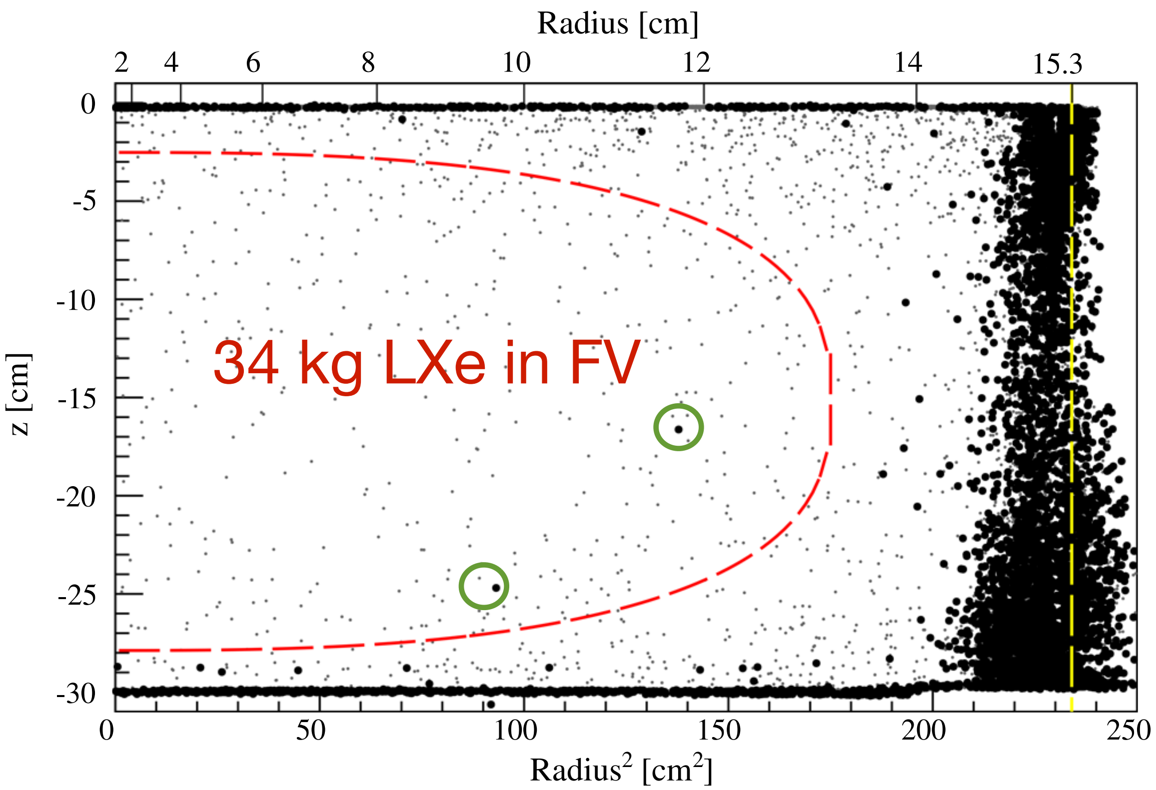
- HPGe material screening

- Select low-background materials

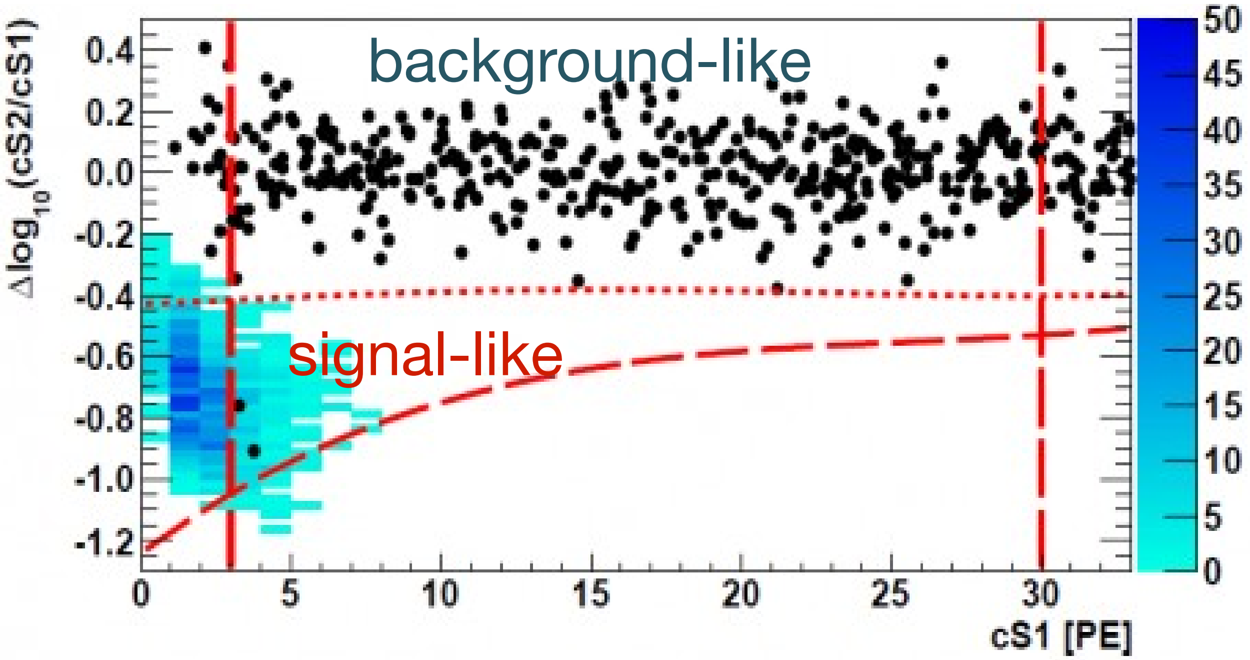


How to deal with backgrounds?

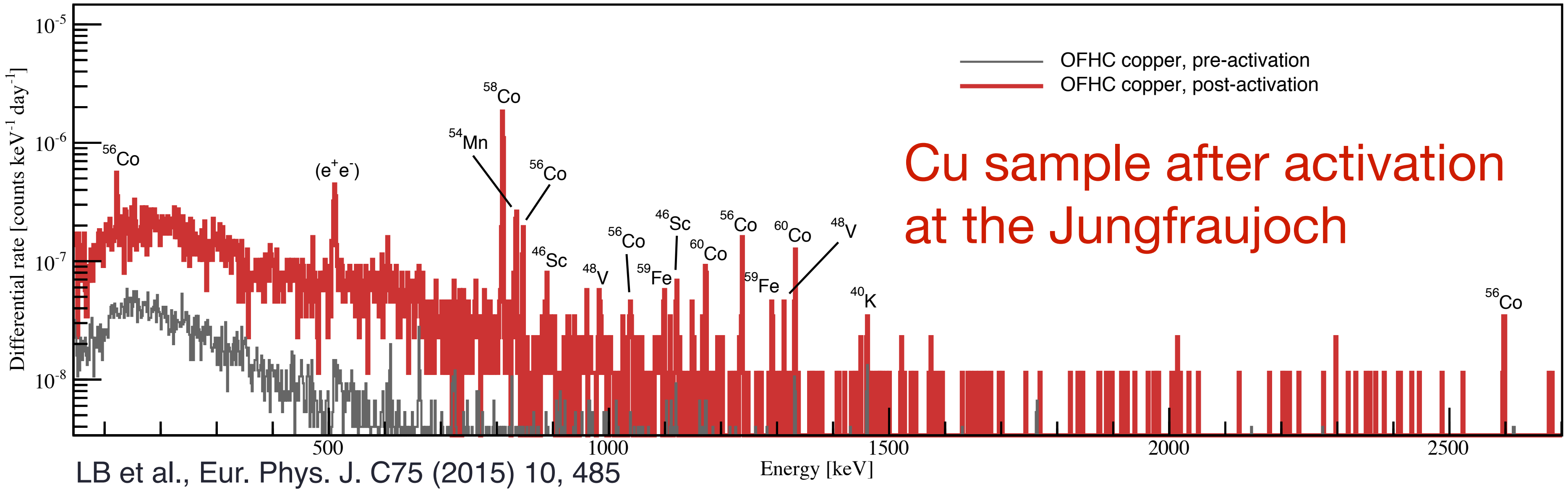
- Fiducialization



- Discrimination

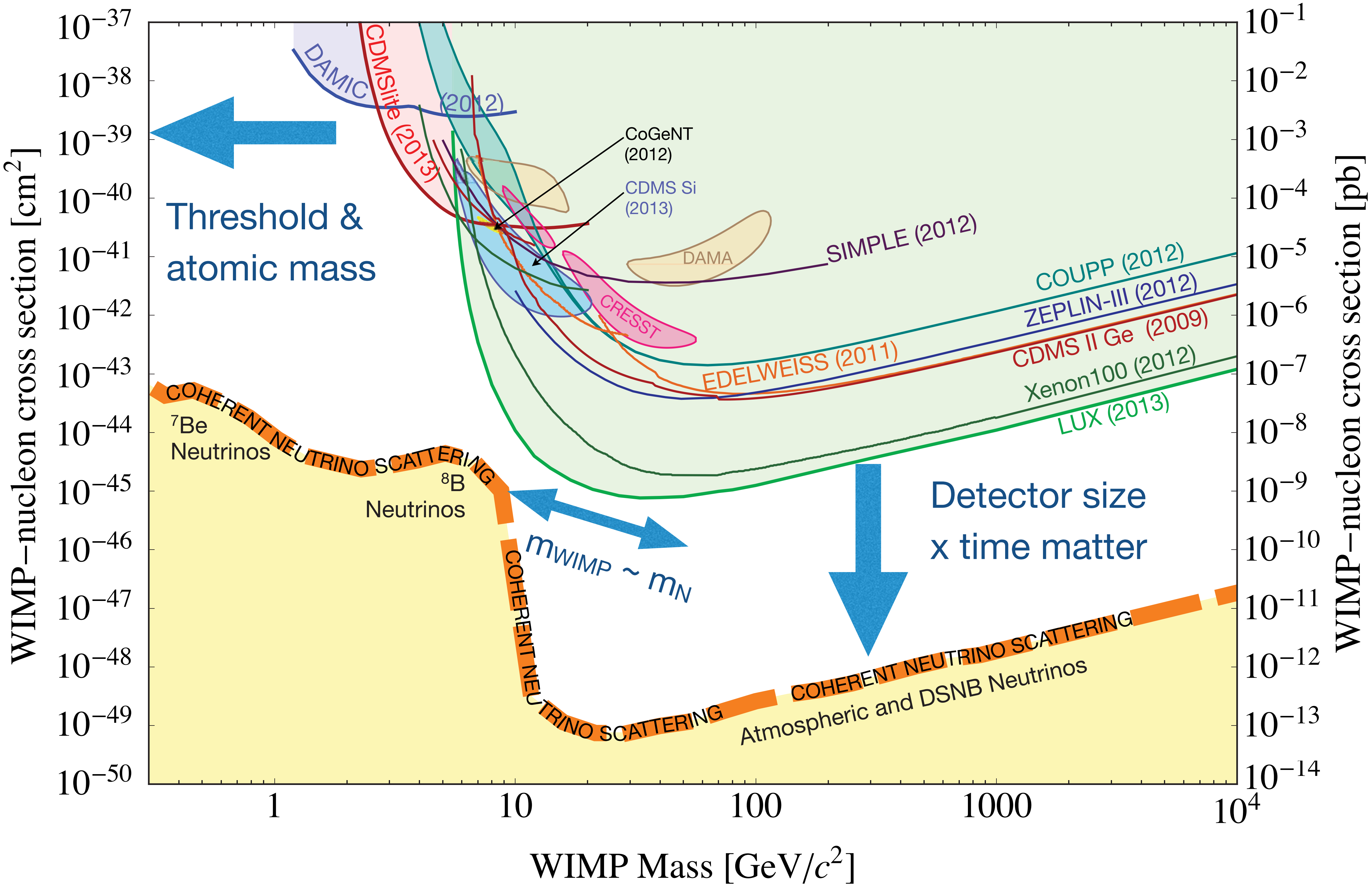


- Avoid exposure to cosmic rays



LB et al., Eur. Phys. J. C75 (2015) 10, 485

The WIMP landscape in (early December) 2015



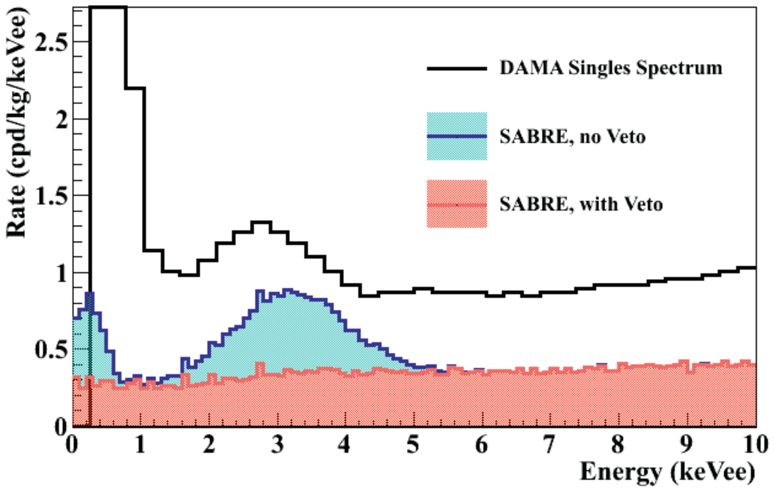
Threshold & atomic mass

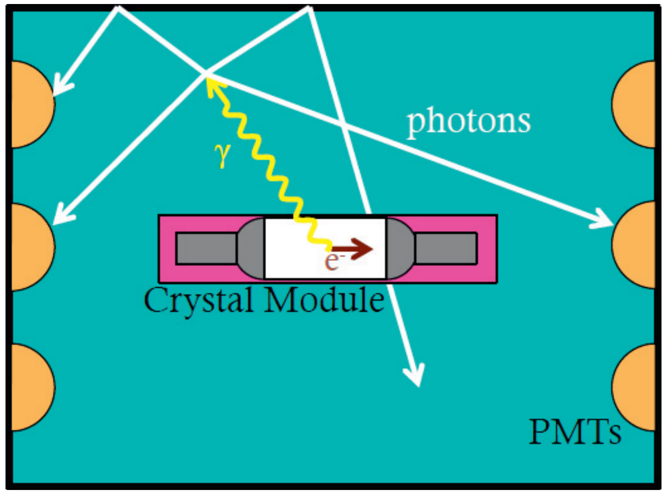
Detector size x time matter

DAMA/LIBRA annual modulation signal

- Period = 1 year, phase = June 2 ± 7 days; 9.3-sigma
- Results in tension with many WIMP searches
- Several experiments to *directly probe the modulation signal* with similar detectors (NaI, CsI): **SABRE, ANAIS, DM-Ice, KIMS**
- **"Leptophilic" models viable (until a few months ago…)**

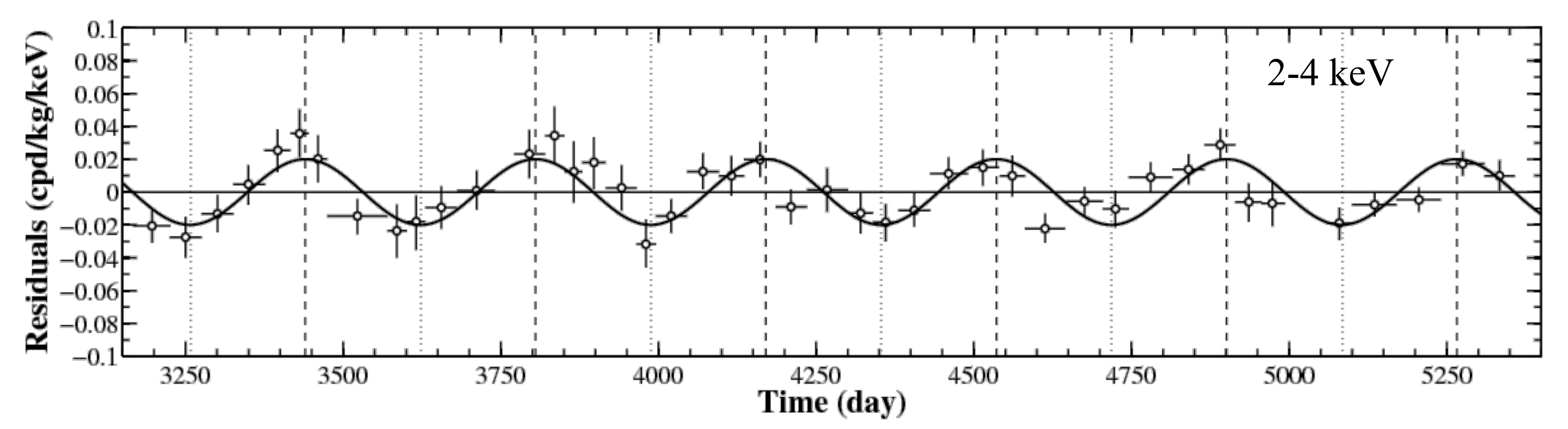
Emily Shields et al. / Physics Procedia 61 (2015) 169 – 178





SABRE, 50 kg NaI detectors

DAMA/LIBRA NaI: 2% annual modulation

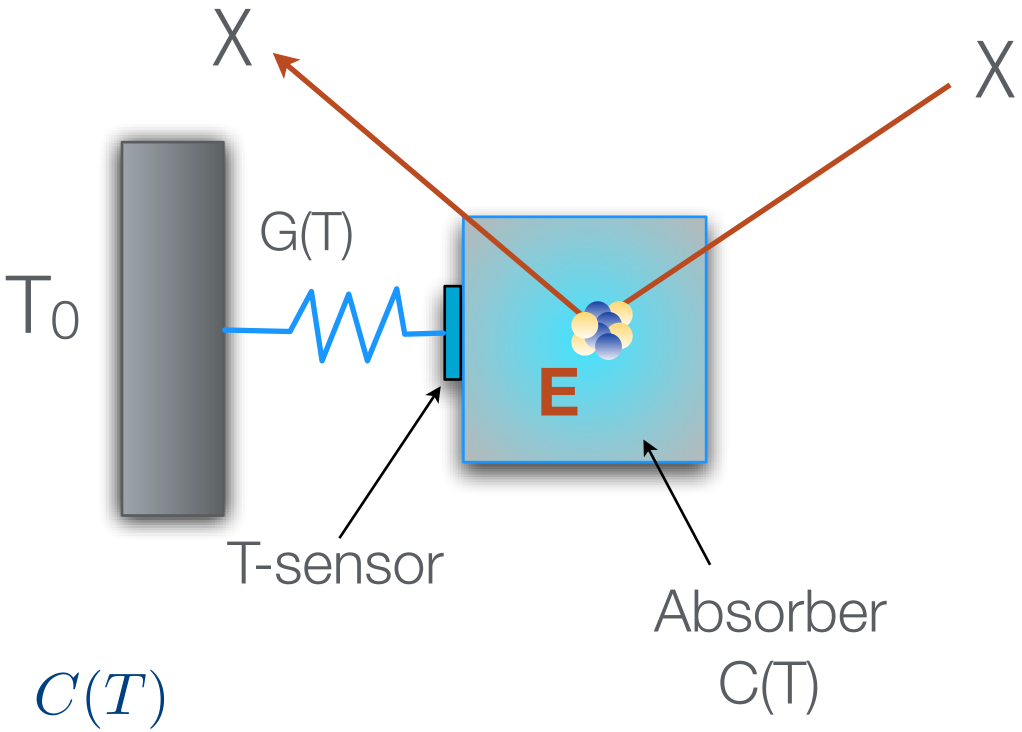


R. Bernabei et al, EPJ-C67 (2010)

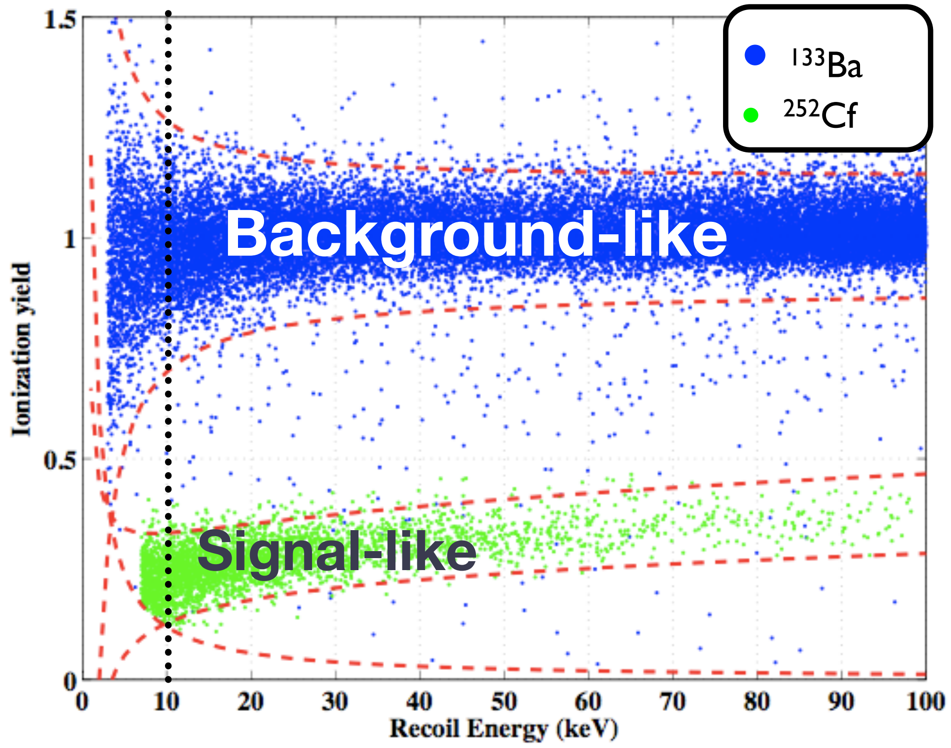
Cryogenic detectors at T ~ mK

- 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

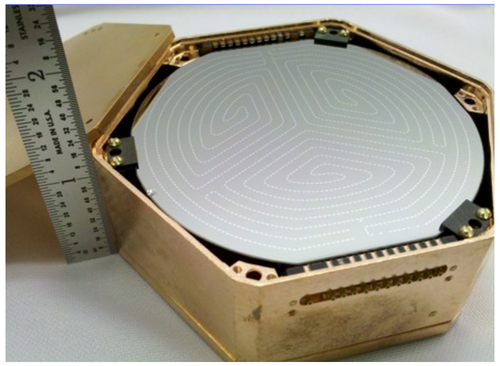
$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}}$$



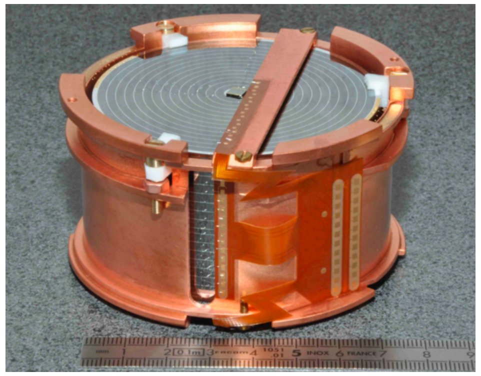
$$\tau = \frac{C(T)}{G(T)}$$



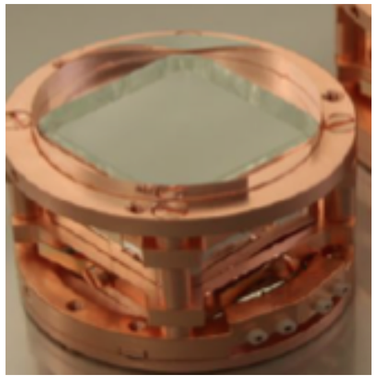
SuperCDMS: Ge, Si



EDELWEISS-III (Ge)



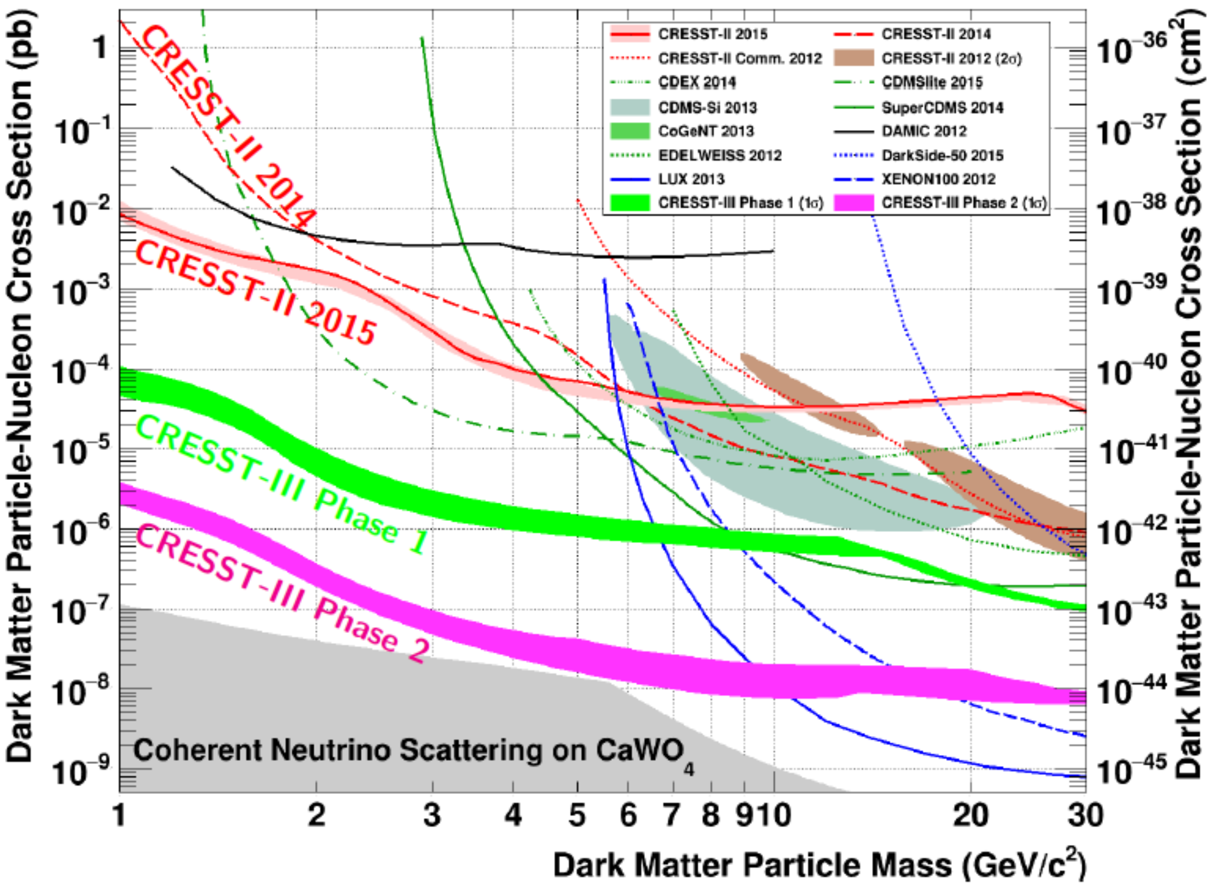
CRESST ($CaWO_4$)



Cryogenic detectors at T ~ mK

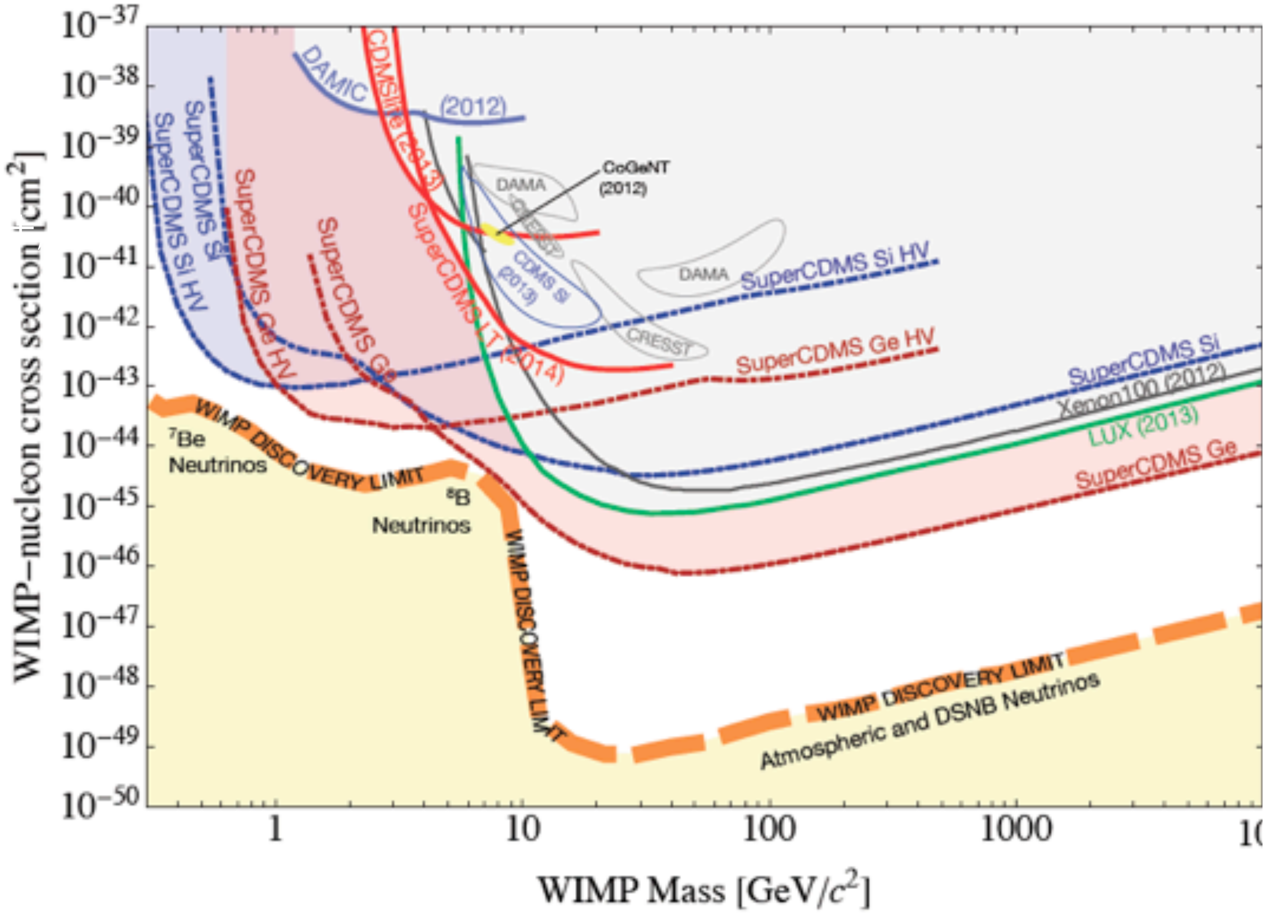
- Goal: reach energy thresholds ≤ 100 eV
- Probe low-mass WIMP region (sub-GeV to few GeV)

CRESST-II and CRESST-III predictions



R. Strauss et al. JCAP 2015 06, 030 (2015)

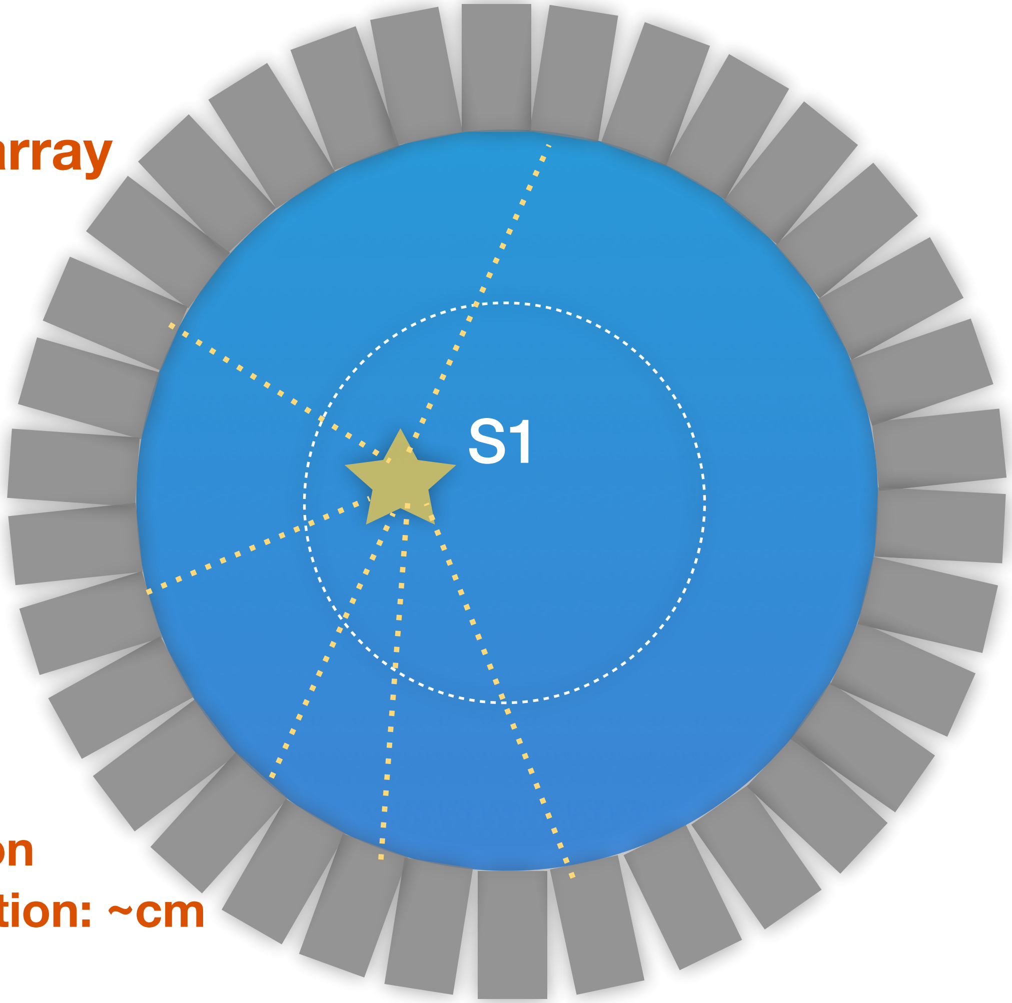
SuperCDMS and predictions



Single-phase noble liquid detectors

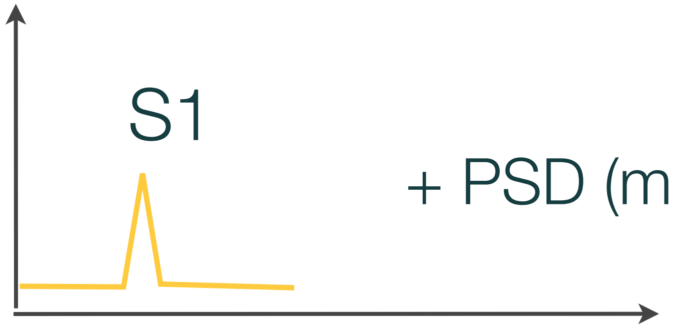
Instrumented LAr or LXe volume

Scintillation light in VUV region



PMT array

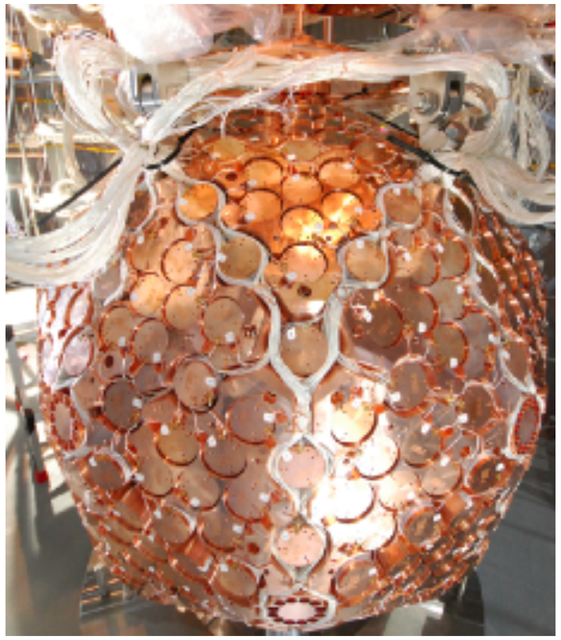
position resolution: ~cm



+ PSD (mostly in LAr)

Xenon

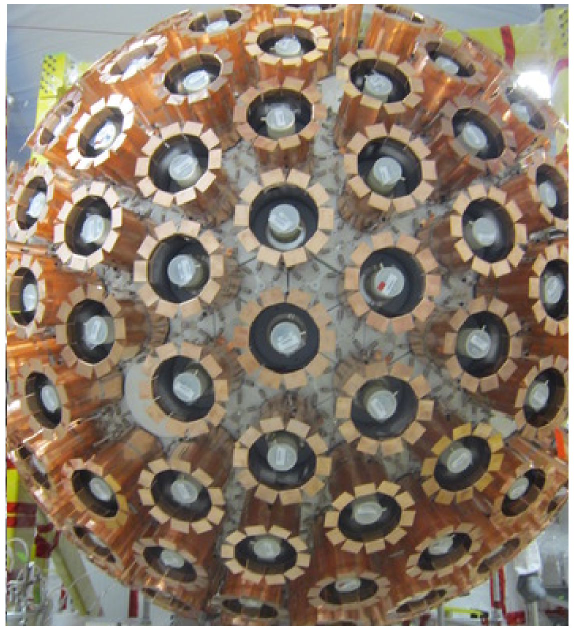
XMASS
at Kamioka, 832 kg



Running since 2013
Results in 2016

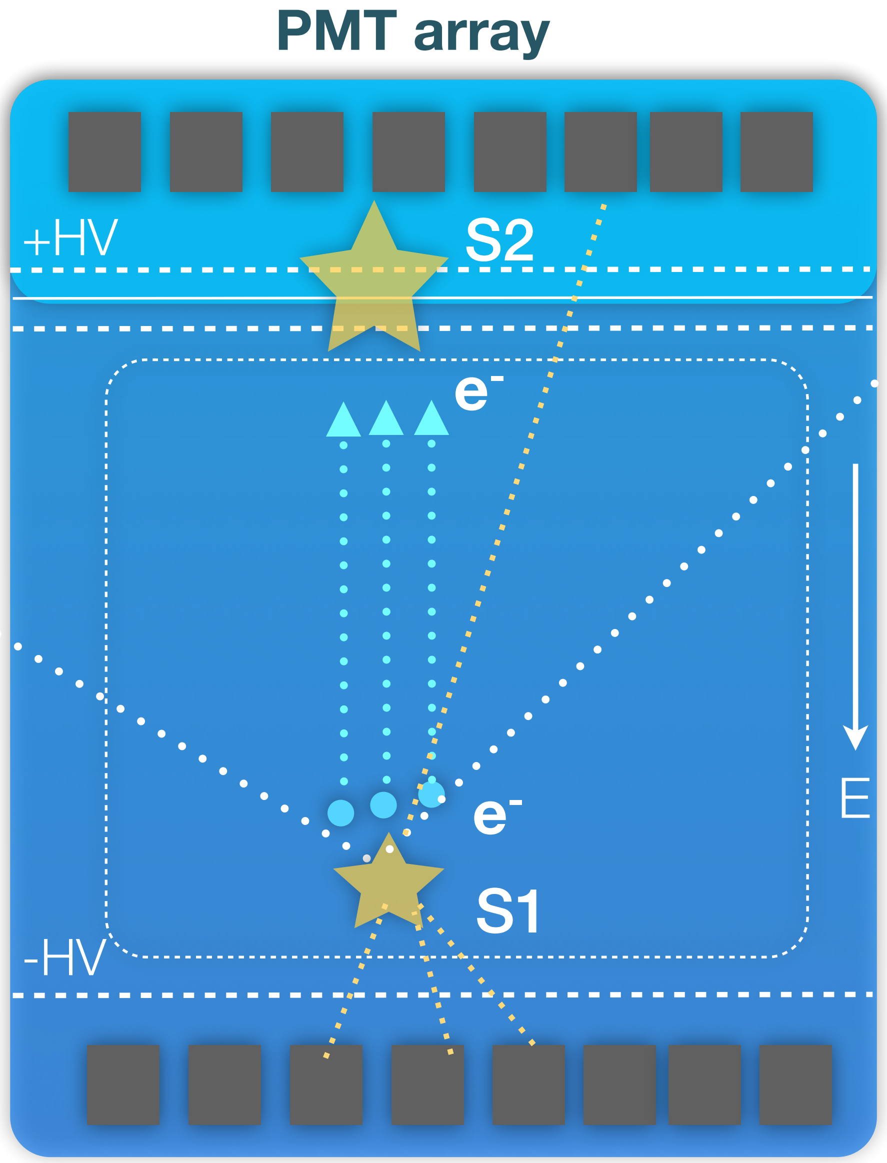
Argon

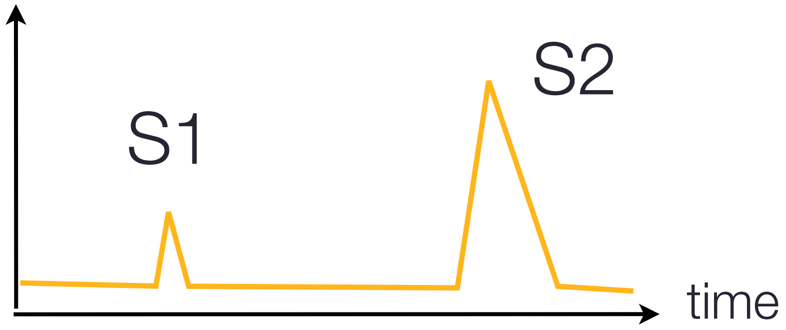
DEAP-3600
at SNOLAB, 3.6 t



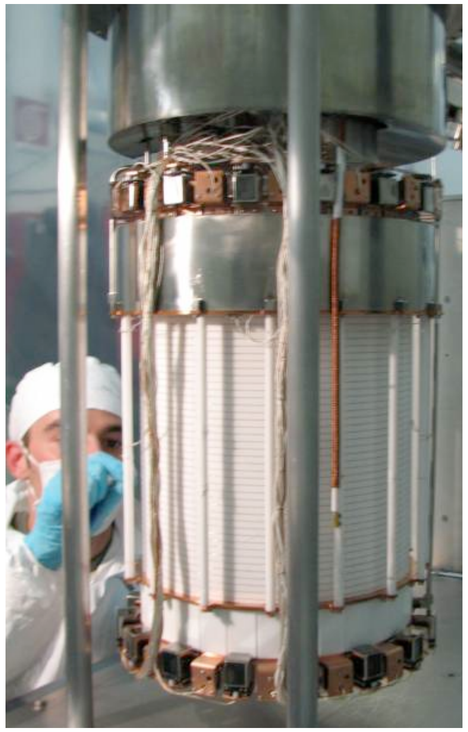
In commissioning
First results in 2016
1 x 10^{-46} cm^2 sensitivity

Dual-phase noble liquid detectors





LXe: XENON100



LXe: LUX

LAr: DarkSide

Xenon

XENON100 at LNGS, LUX at SURF, PandaX at CJPL

Argon

DarkSide-50 at LNGS, ArDM at Canfranc

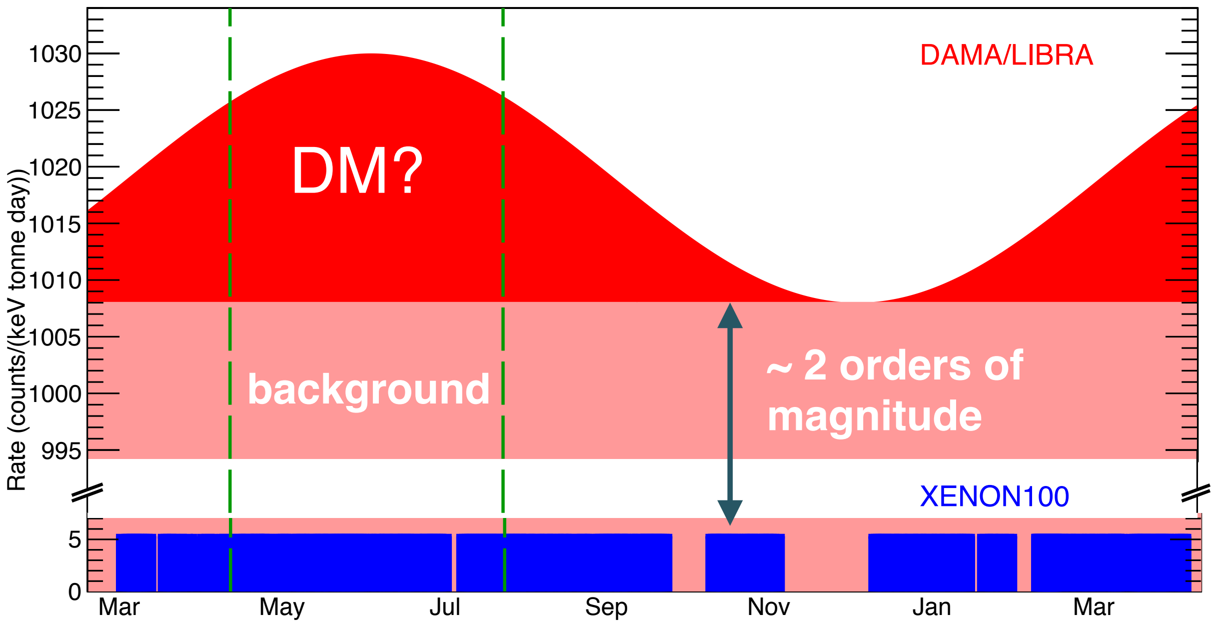
Target masses between ~ 50 kg - 1 ton

New XENON100 results

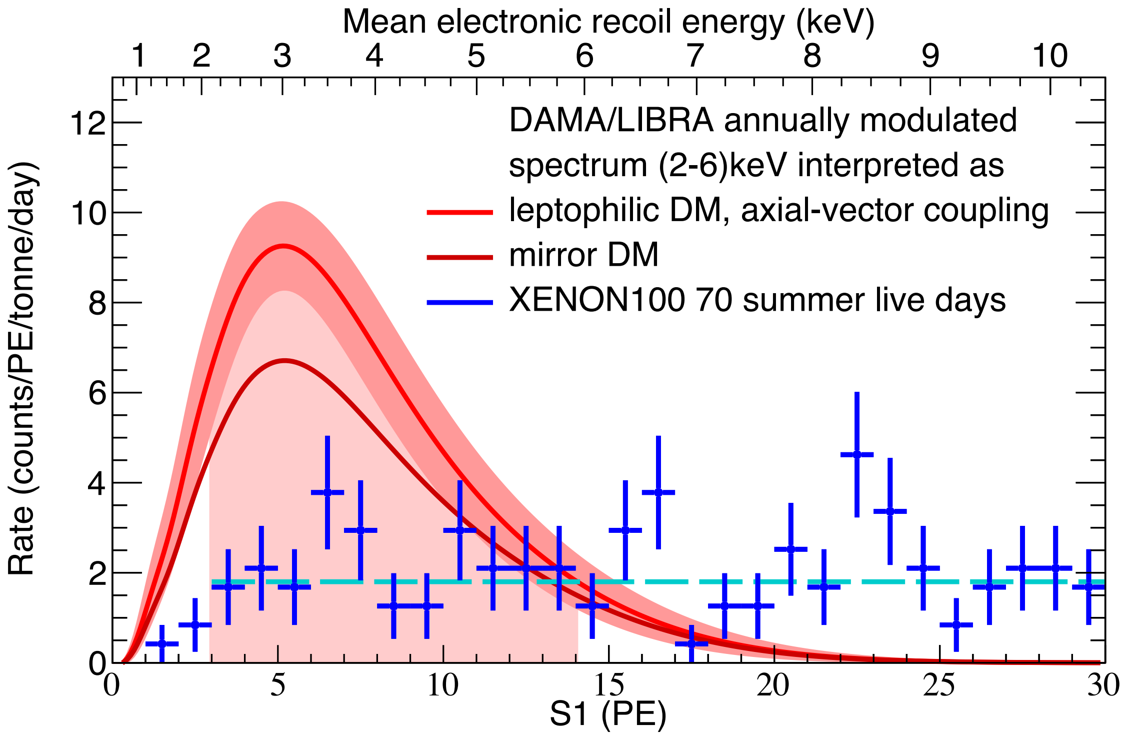
- Dark matter particles interacting with e$^-$
  - XENON100's ER background lower than DAMA modulation amplitude

➡search for a signal above background in the ER spectrum

XENON collaboration, arXiv: 1507.07747, Science 349, 2015



Consider the 70 days with the largest signal

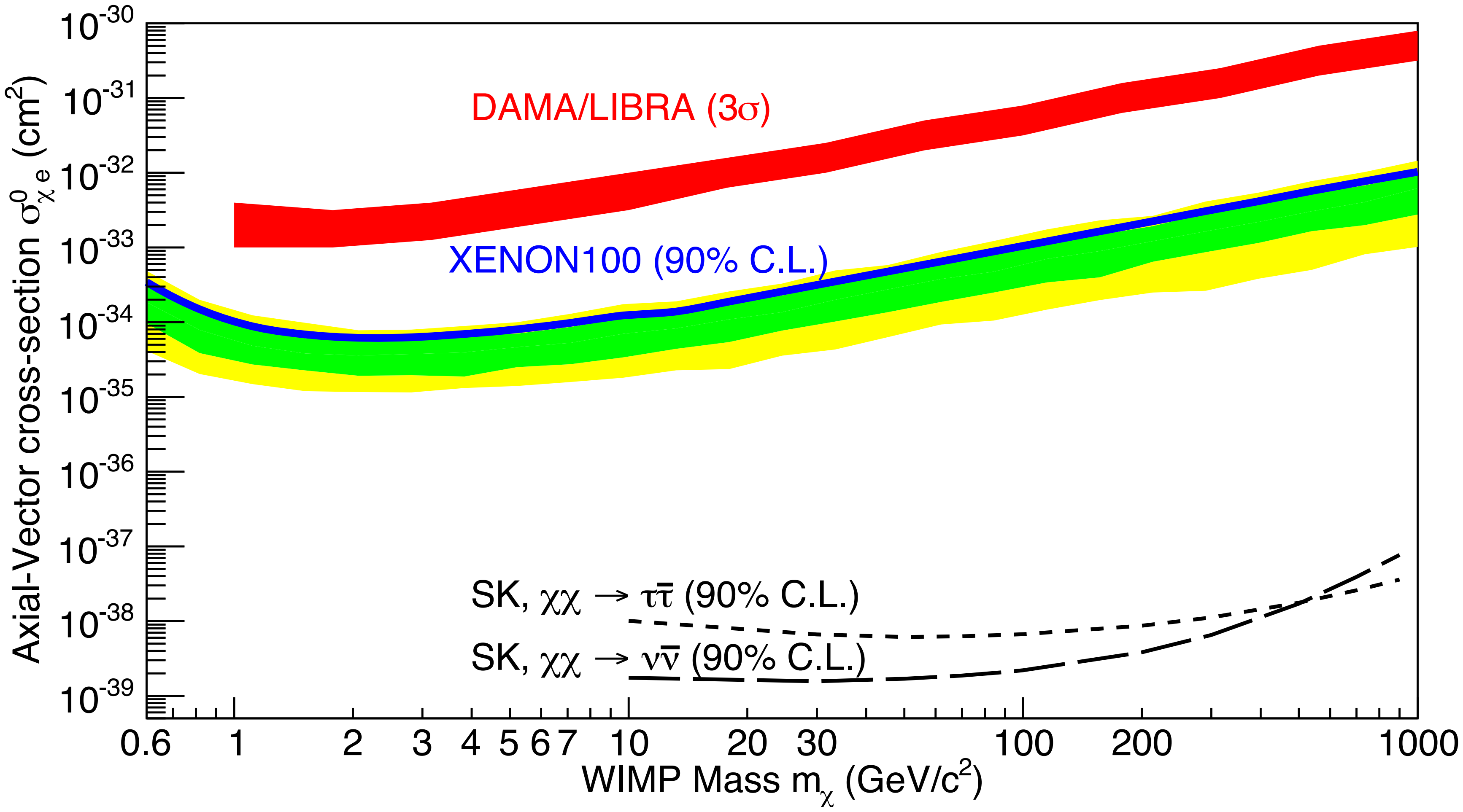


DAMA/LIBRA modulated spectrum as would be seen in XENON100 (for axial-vector WIMP-e$^-$ scattering)

XENON100 excludes leptophilic models

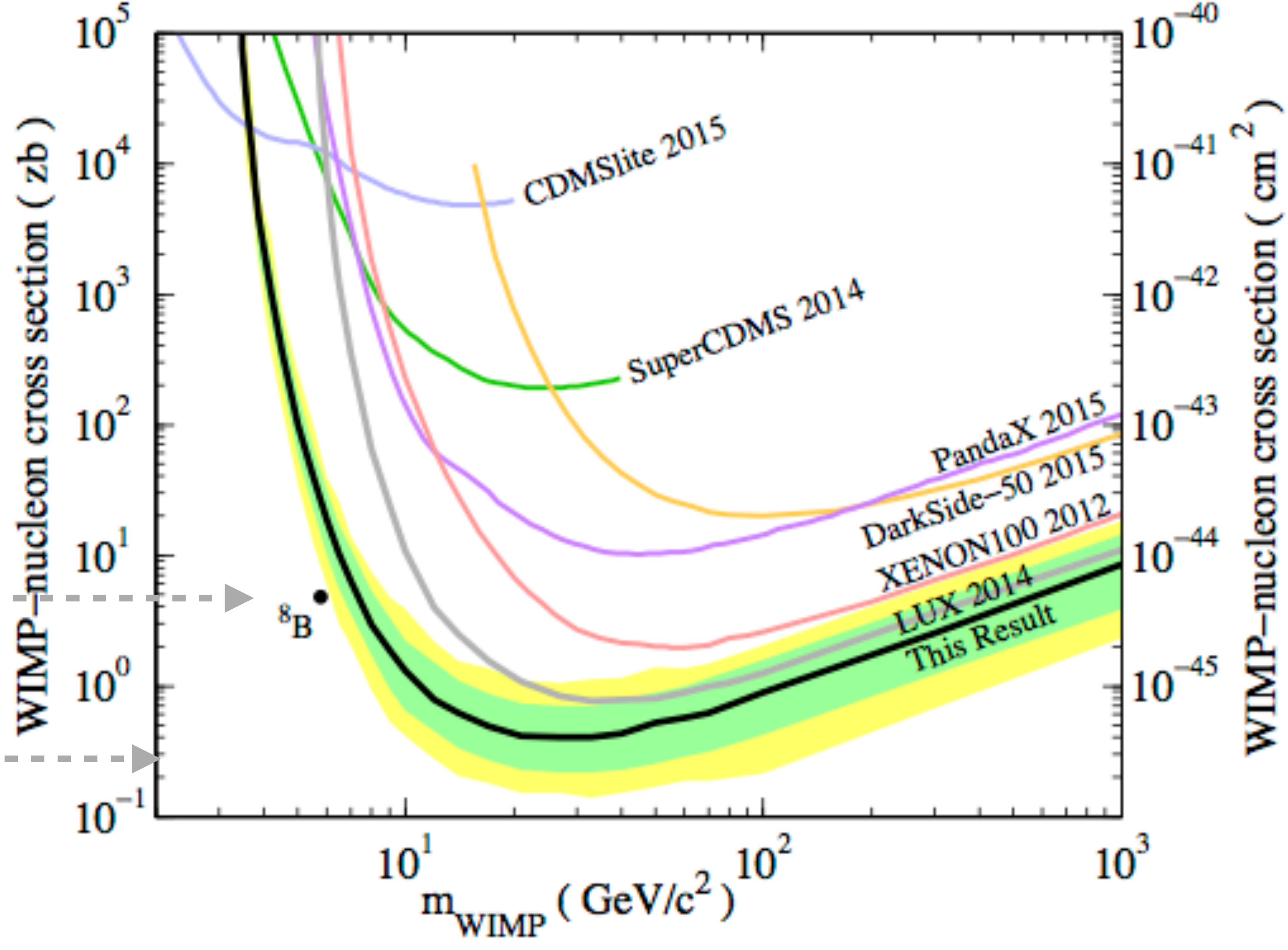
- Dark matter particles interacting with e^-
  1. No evidence for a signal
  2. Exclude various leptophilic models as explanation for DAMA/LIBRA

XENON collaboration, arXiv: 1507.07747, Science 349, 2015



New LUX results

- Re-analysis of 2013 data: 1.4 x 10^4 kg days exposure
- New calibrations (ERs, NRs) at low energies



LUX collaboration, arXiv: 1512.03506

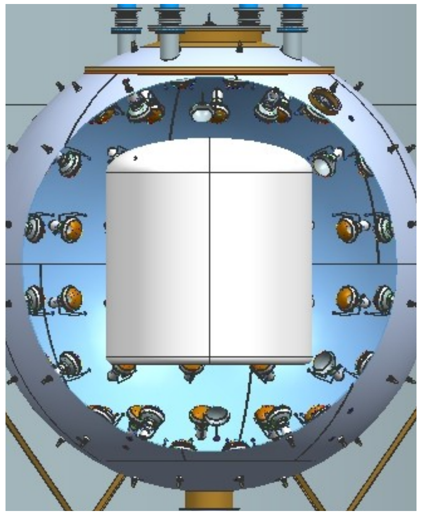
Expected events from ^{8}B neutrinos

Minimum at 0.4 zb

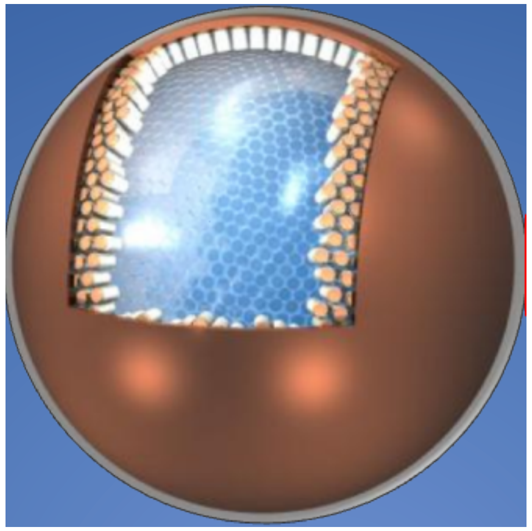
Future noble liquid detectors

- 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

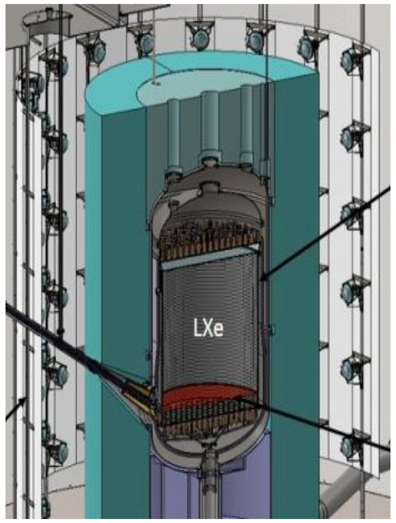
XENON1T: 3.3 t LXe



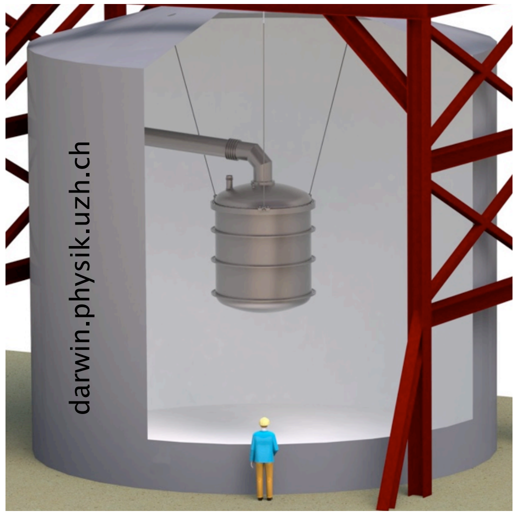
DarkSide: 20 t LAr



XMASS: 5t LXe



LZ: 7t LXe



DARWIN: 50 t LXe

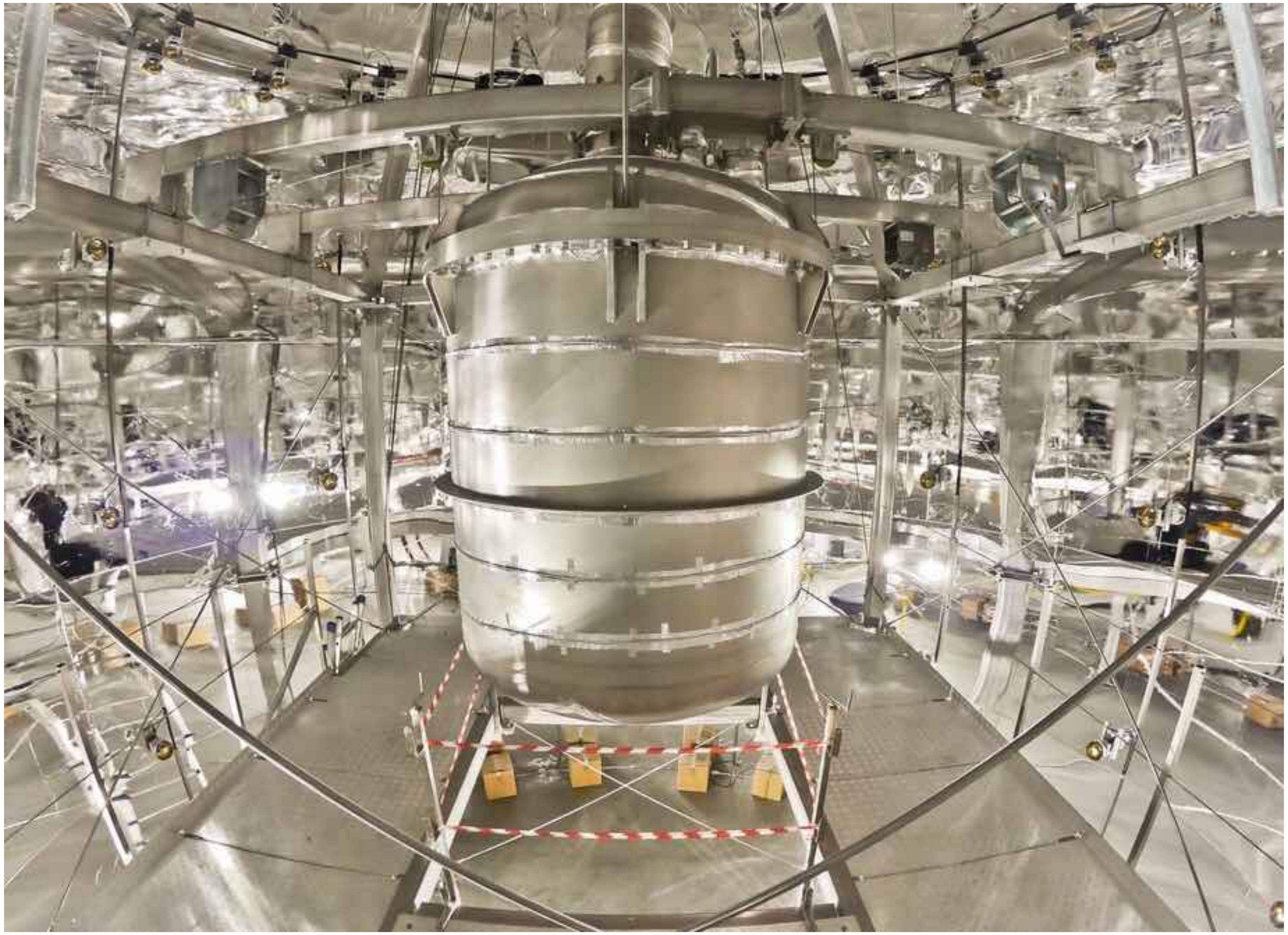
The XENON1T experiment

- Under construction at LNGS since autumn 2013; commissioning planned for late 2015
- Total (active) LXe mass: 3.5 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.org

XENON1T: status of construction work

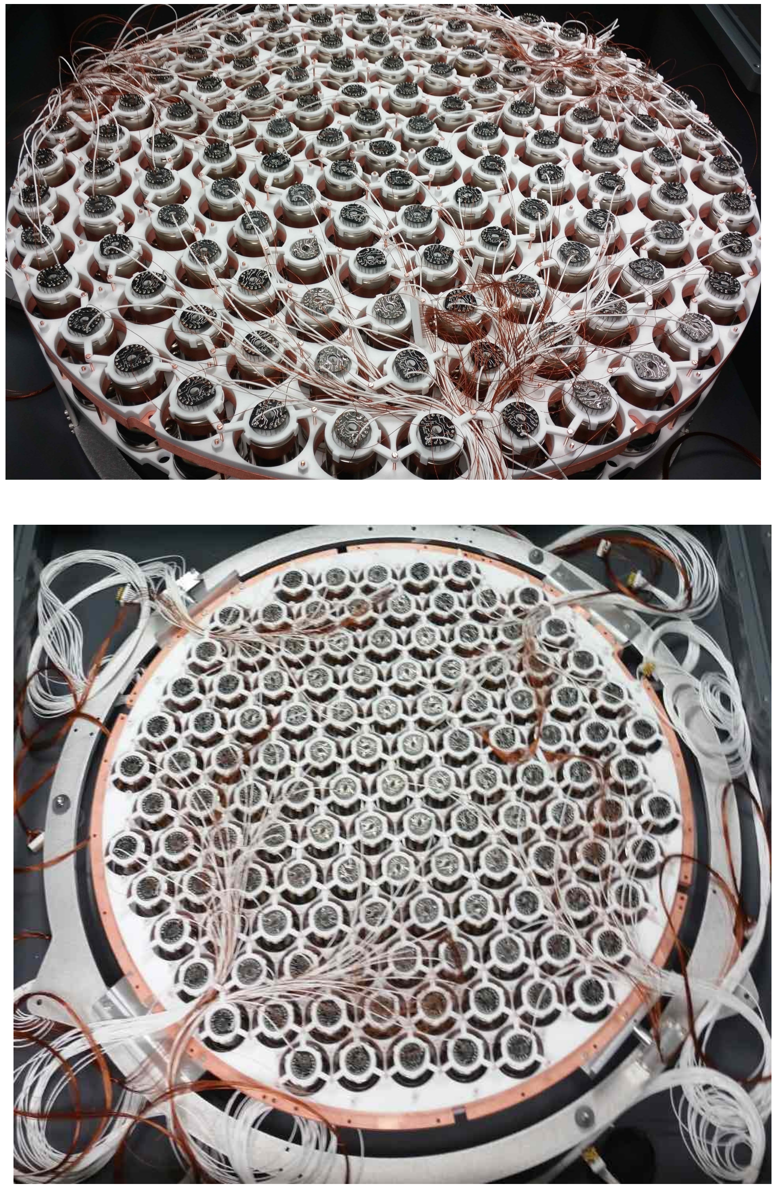
- Water Cherenkov shield, cryostat support, service building, electrical plant completed
- Cryostat, cryogenics, storage, purification, cables, fibres installed and commissioned



The XENON1T inner detector

- PMTs tested at cryogenic temperatures; arrays installed in the TPC
- TPC assembly and cold tests completed; installation at LNGS in October/November 2015

The TPC



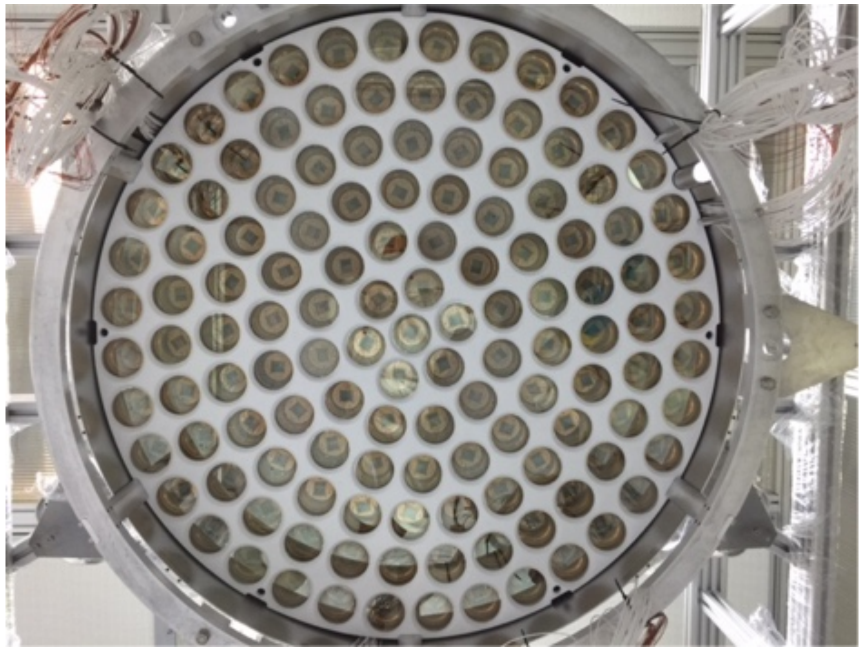
PMT array, bases & cables

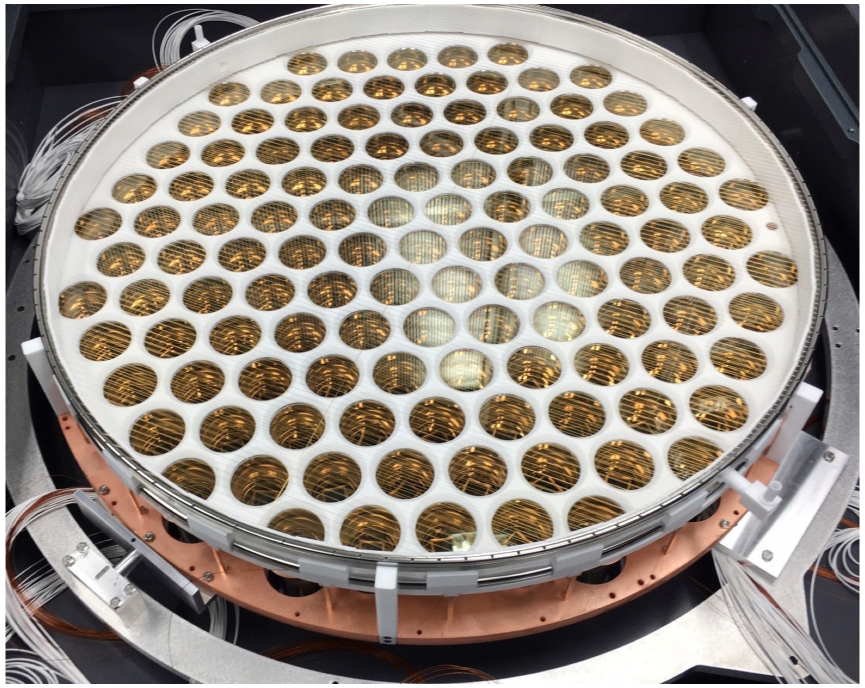
TPC installed at LNGS

The XENON1T inner detector

- Underground in November 2015, cryostat closed
- Next steps: Rn emanation measurement
- **Xenon filling in early January, first science data in early 2016**

Top array: 127 PMTs

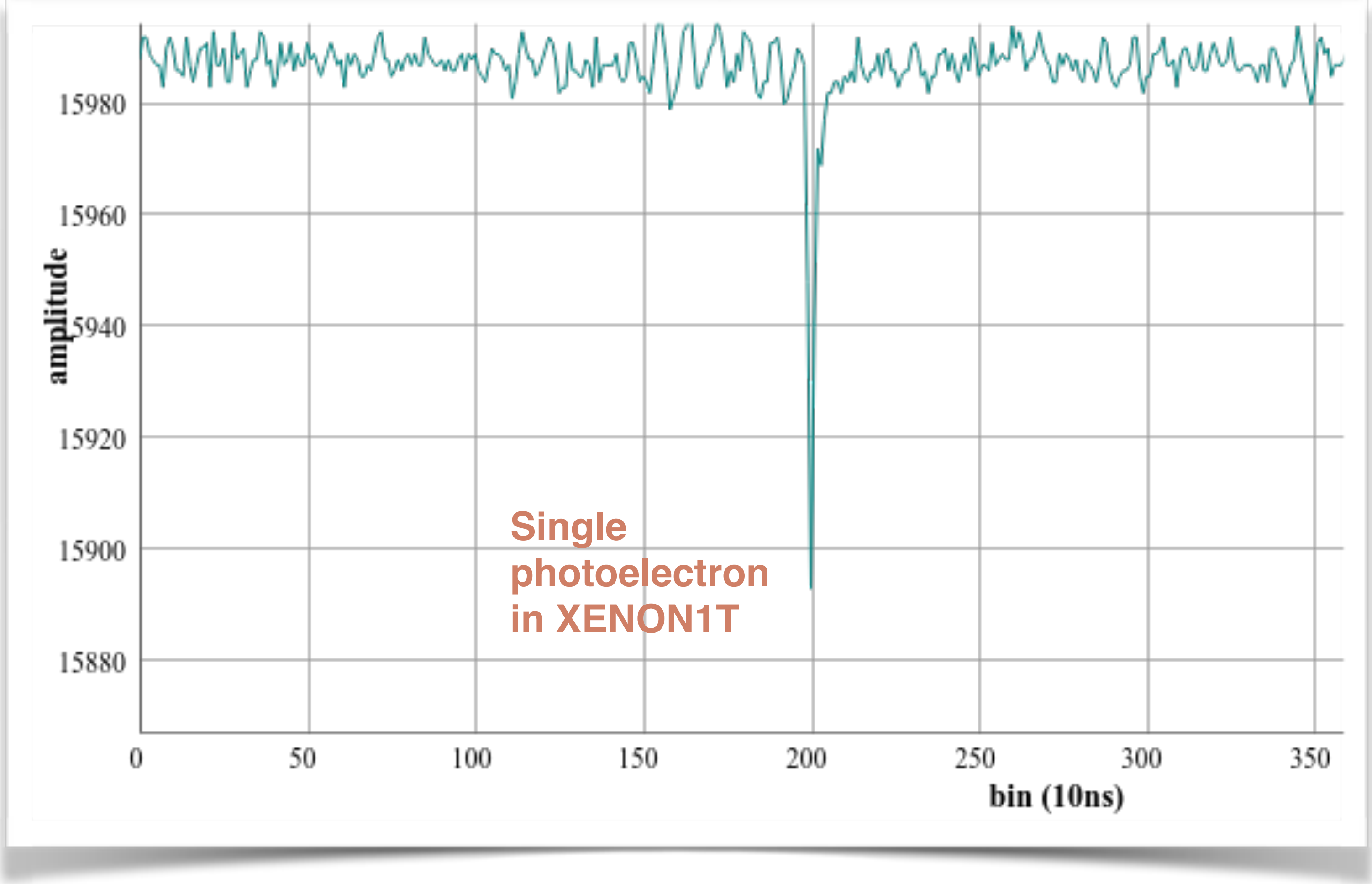




Bottom array: 121 PMTs

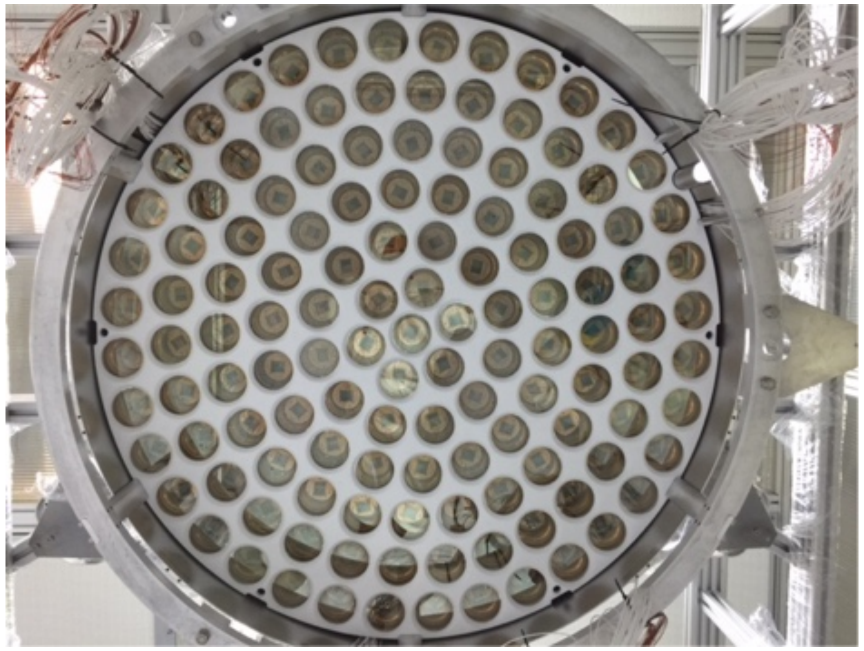
XENON1T: first light

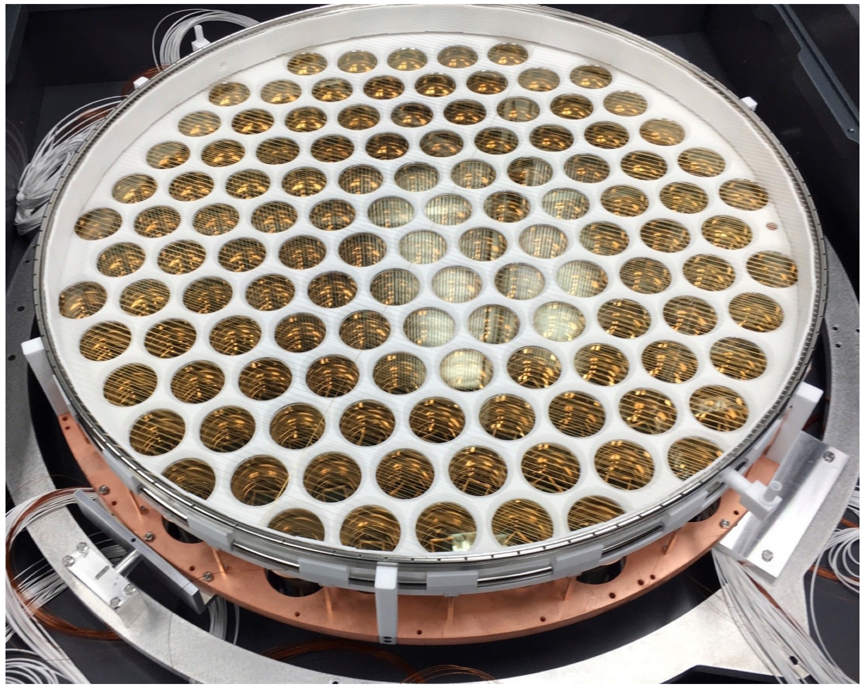
- Underground in November 2015, cryostat closed
- Next steps: Rn emanation measurement
- **Single photoelectron acquired with the new DAQ after cryostat was closed**



Single photoelectron in XENON1T

Top array: 127 PMTs





Bottom array: 121 PMTs

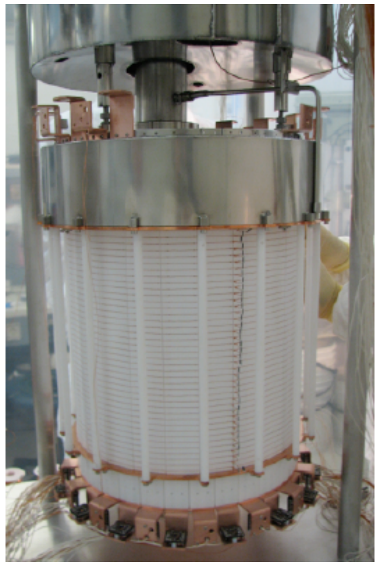
The XENON Programme

XENON10

2005-2007

PRL100
PRL101
PRD 80
NIM A 601

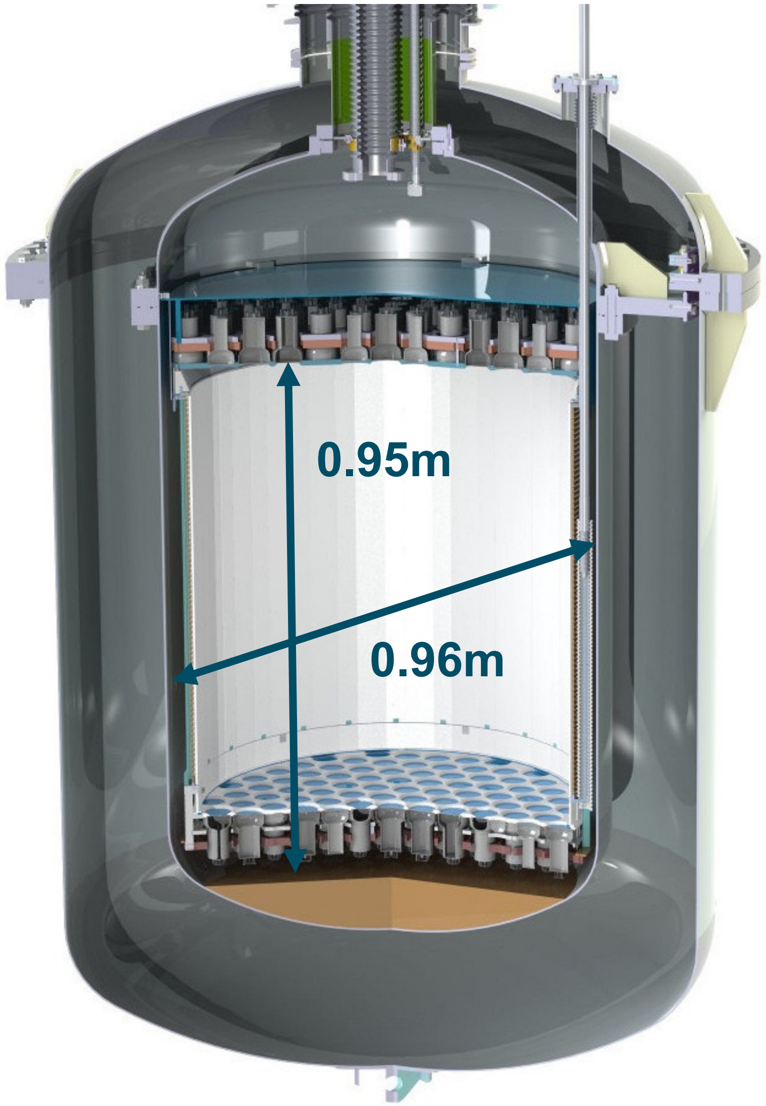
XENON100



2008-2015
calibration data

PRL105
PRL109
PRL111, etc

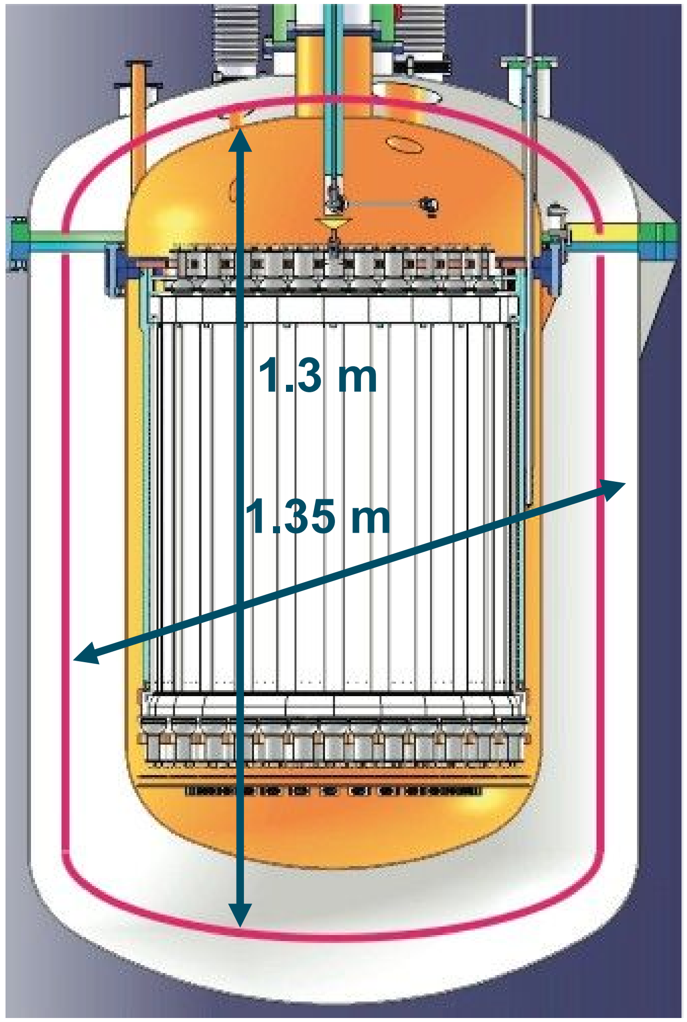
XENON1T



2013-2018

3.5 t LXe
commissioning at LNGS

XENONnT



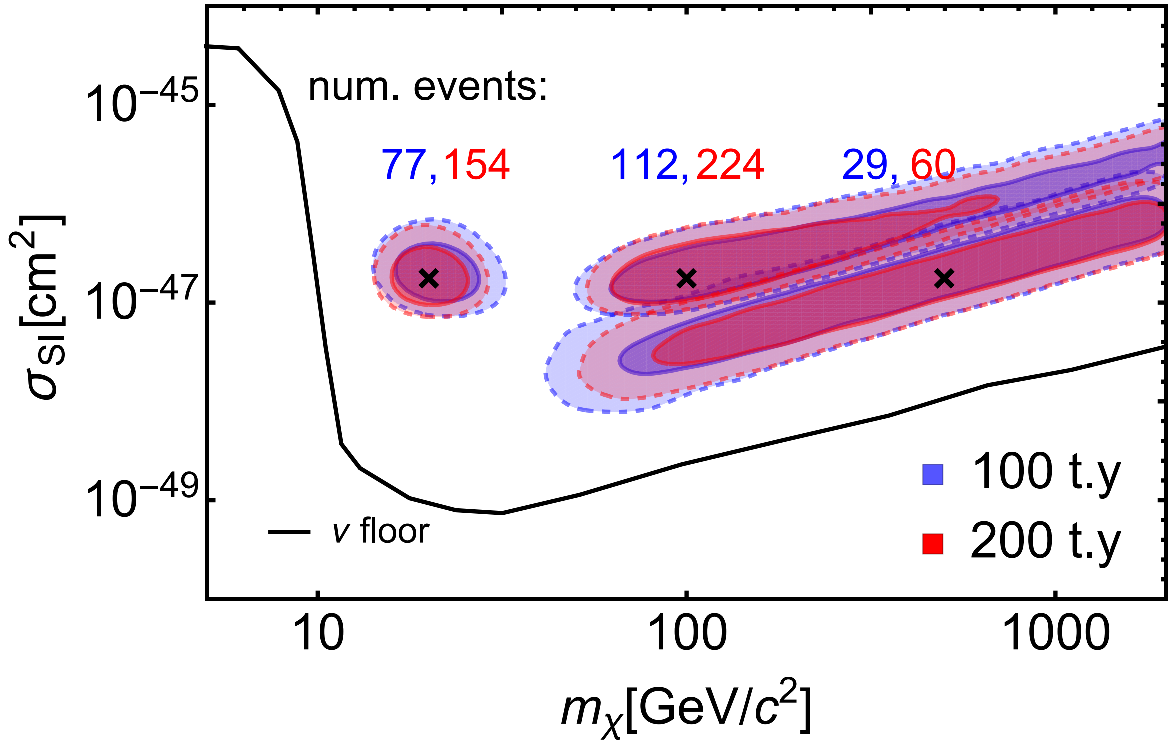
2018-2020

7.5 t LXe
Design stage

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

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

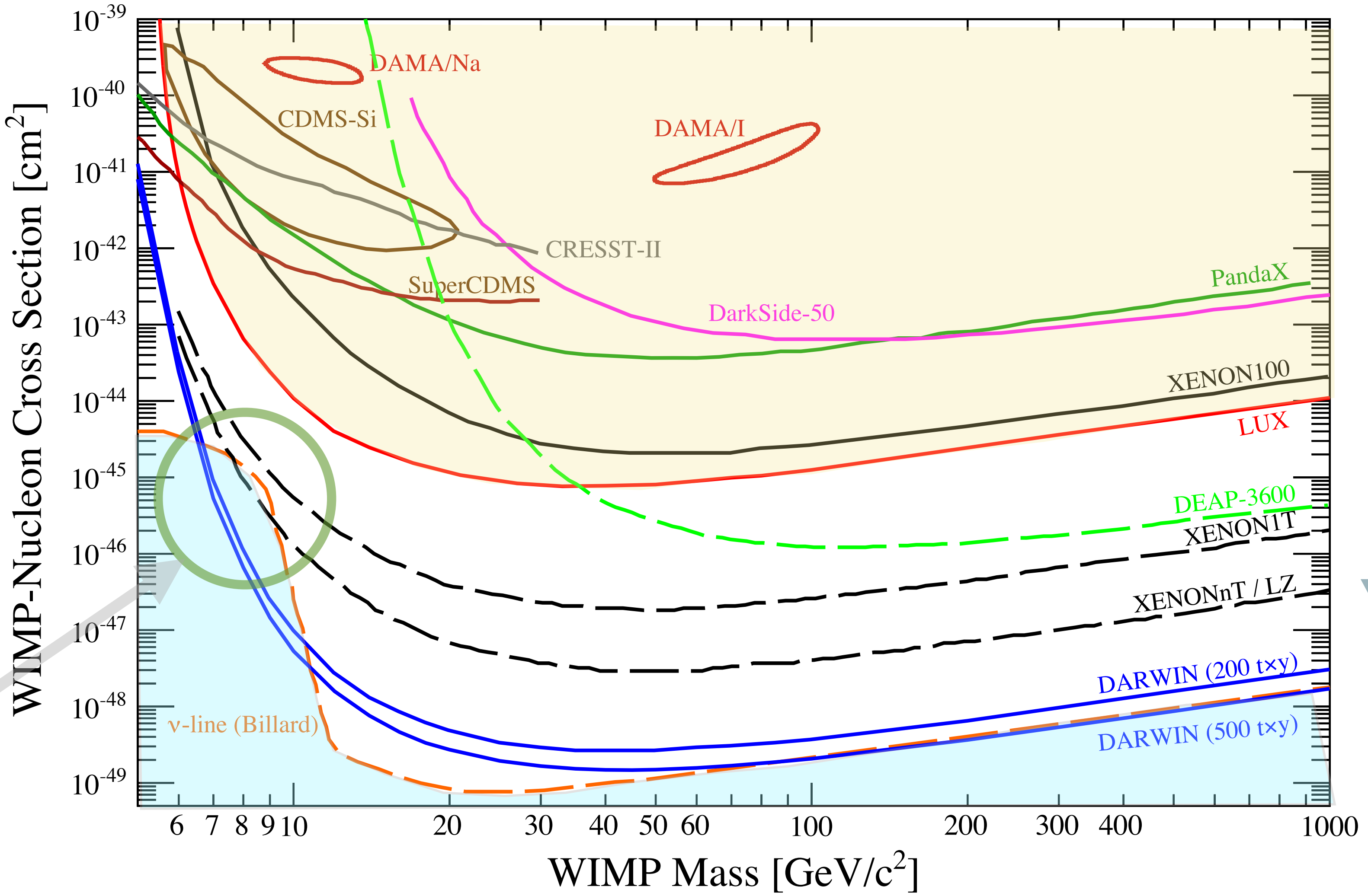
$v_0 = 220 \pm 20\,\mathrm{km/s}$

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

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)

`JCAP10(2015)016`

4 orders of magnitude to go!

^{8}B CNNS neutrinos within reach

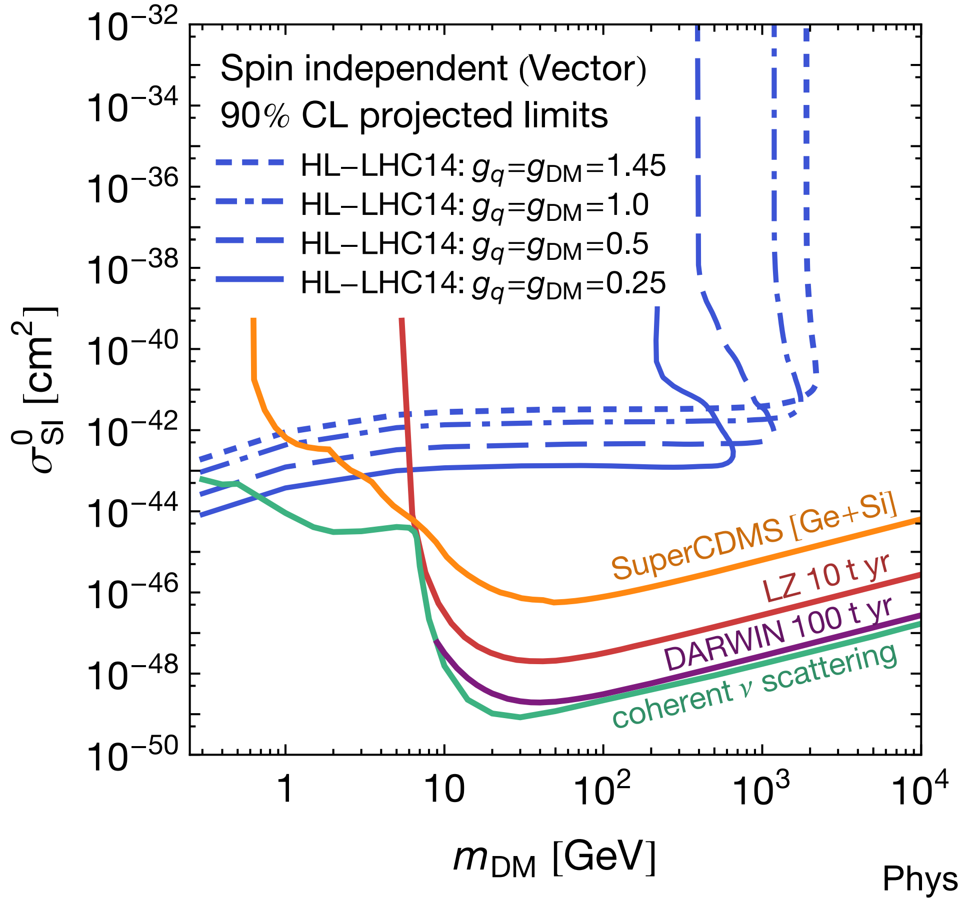
Note: “nu floor” = 3-sigma detection line at 500 CNNS events above 4 keV

Complementarity with the LHC

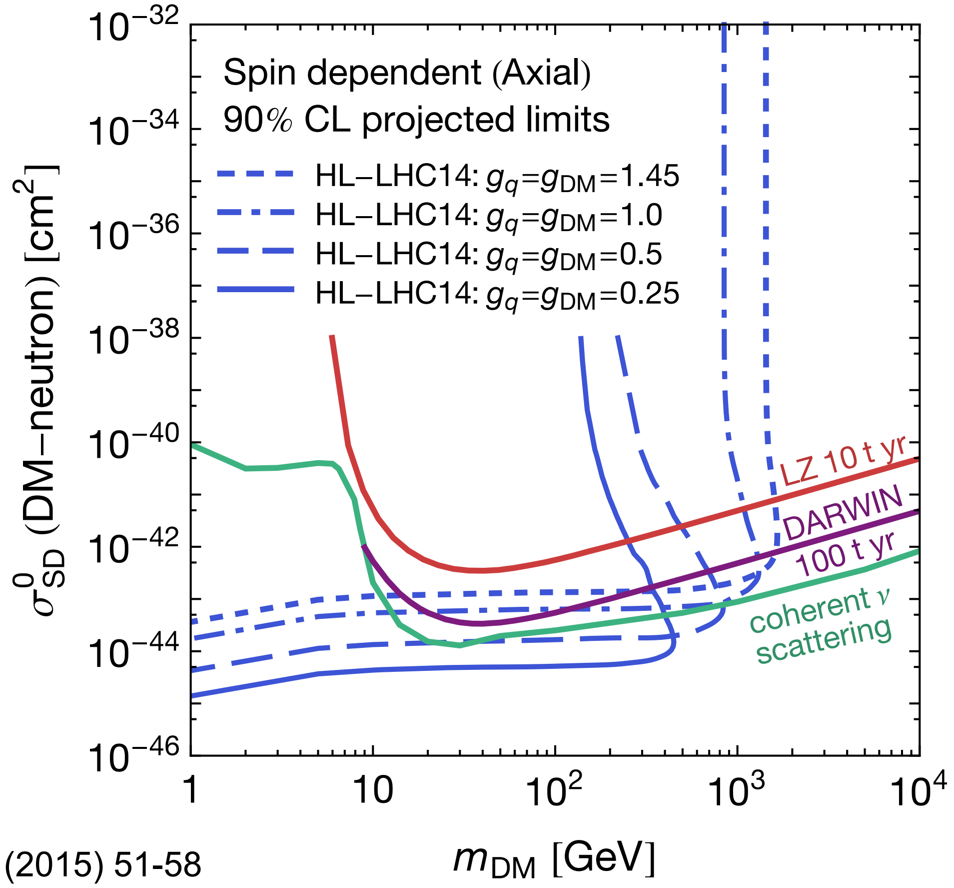
- Minimal simplified DM model with only 4 variables: $m_{\rm DM}$, $M_{\rm med}$, $g_{\rm DM}$, g_q
- Here DM = Dirac fermion interacting with a vector or axial-vector mediator; equal-strength coupling to all active quark flavours

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

Spin independent



Spin dependent

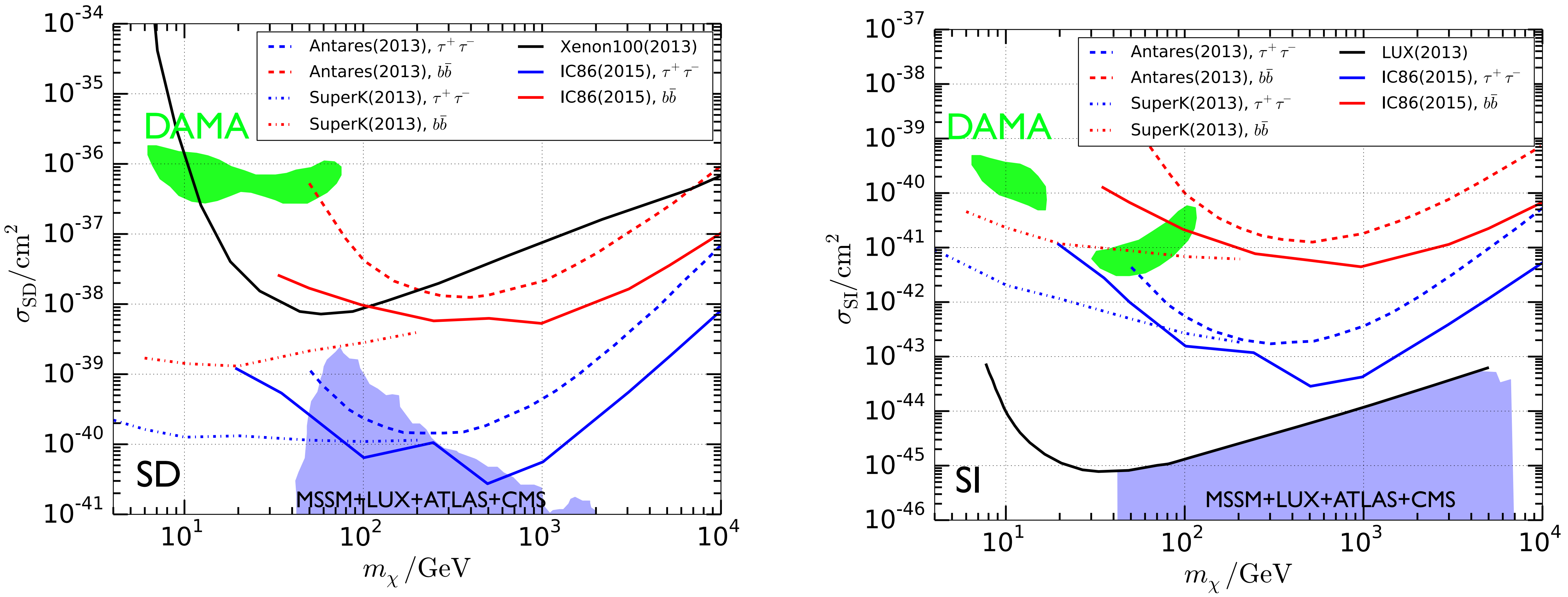


S. Malik et al., arXiv:1409.4075

Phys. Dark Univ. 9-10 (2015) 51-58

Complementarity with (neutrino) 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*

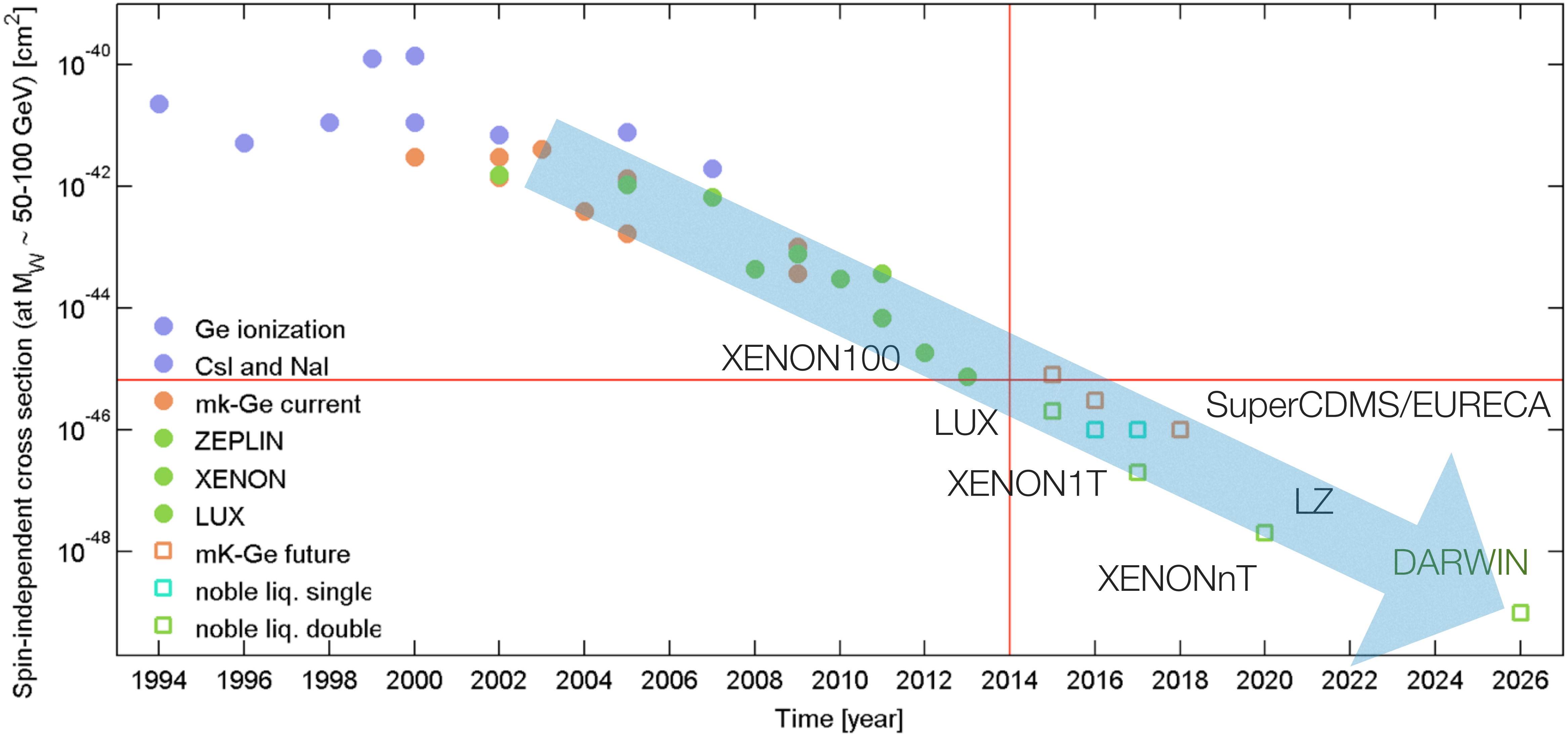

IceCube: WIMP-p; spin-dependent

IceCube: WIMP-p; spin-independent

IceCube ICRC2015, 86 strings

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

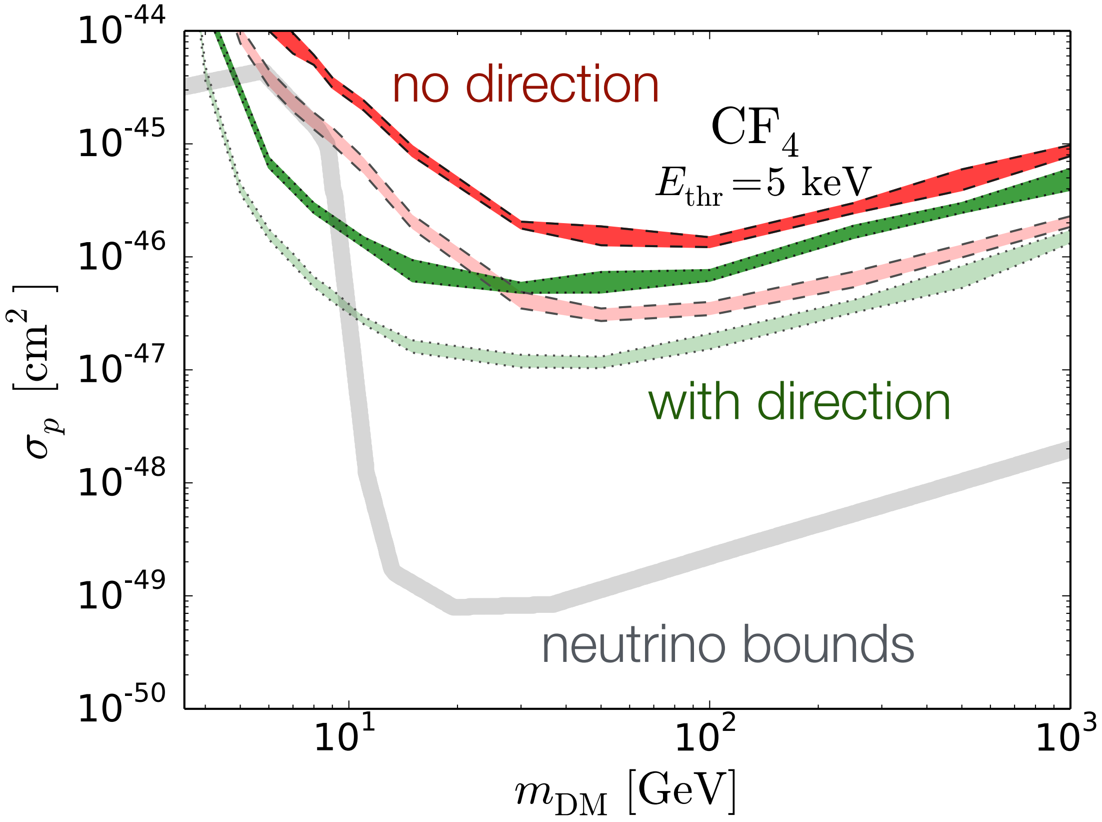
Of course, “the probability of success is difficult to estimate, but if we never search, the chance of success is zero”

G. Cocconi & P. Morrison, Nature, 1959

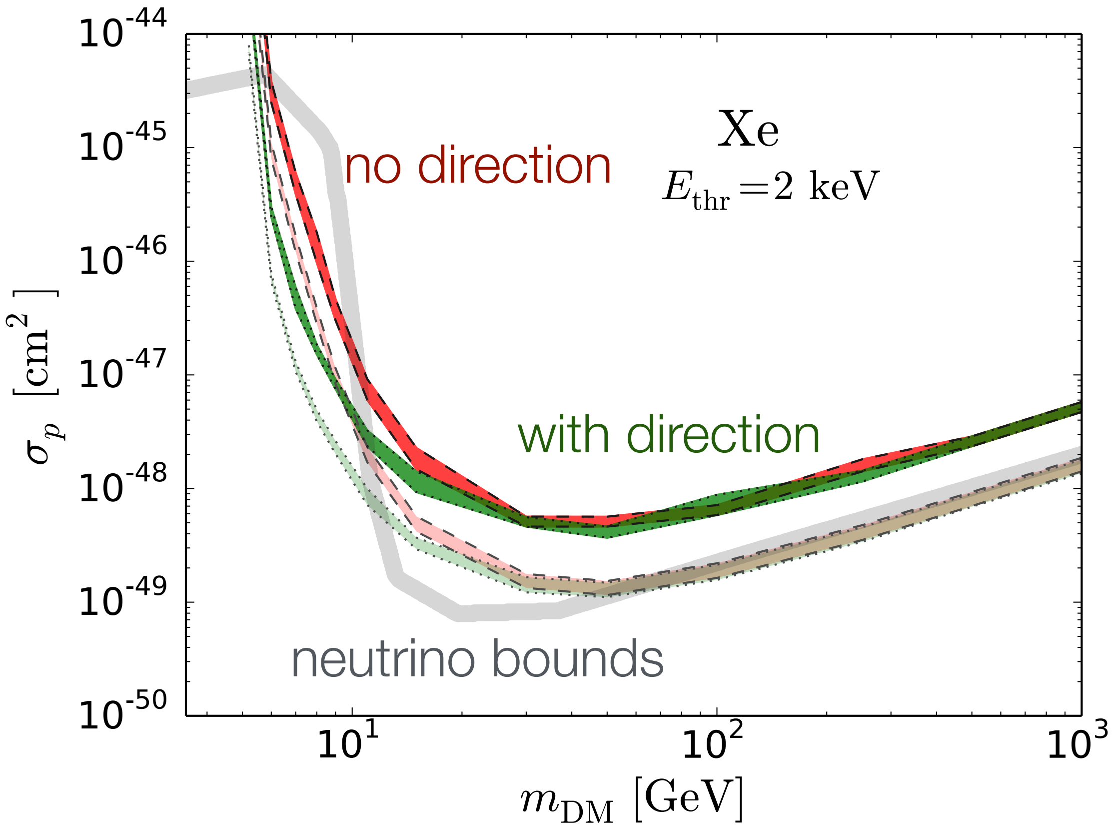
Will directional information help?

- 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



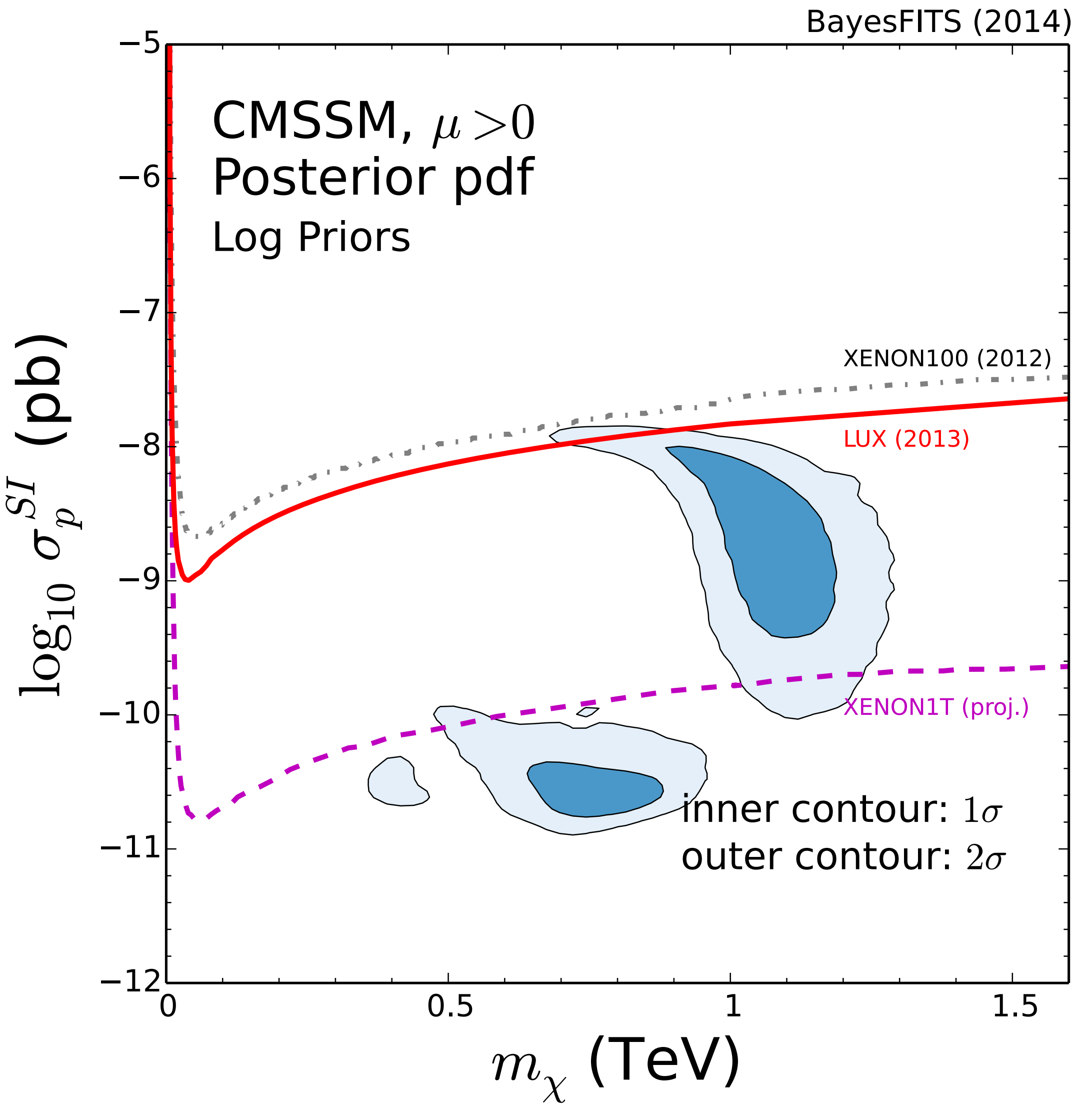
367 t yr exposure, 500 nu events



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

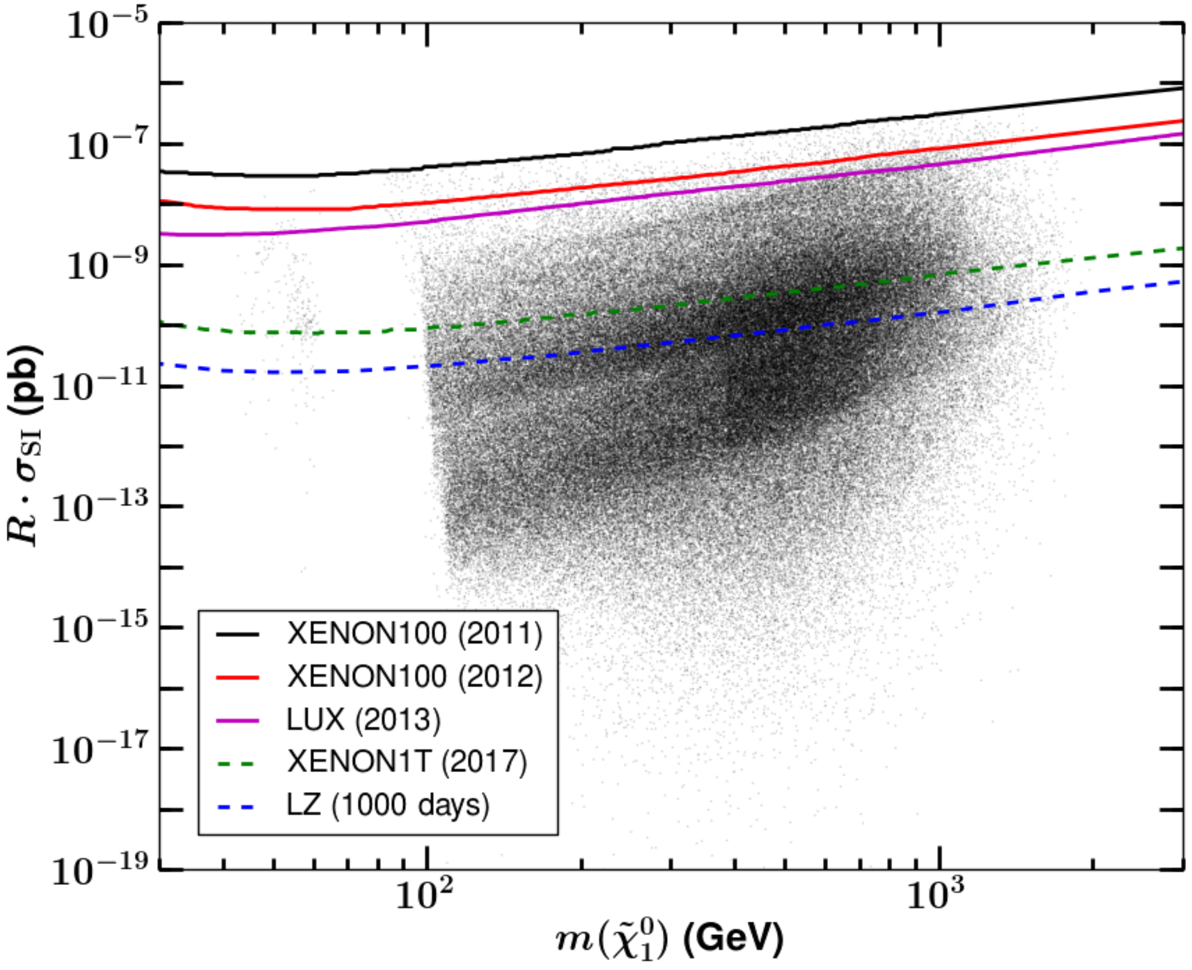
SUSY Predictions: 2 examples

CMSSM



L. Rozkowski, Stockholm 2015

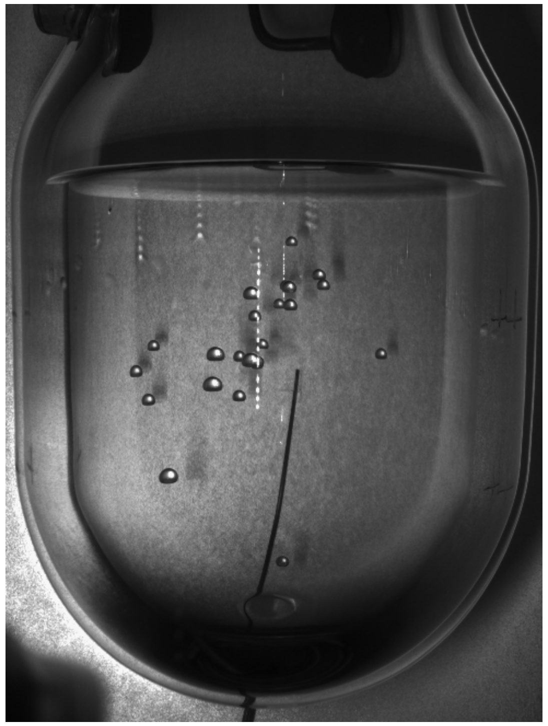
pMSSM



M. Cahill-Rowley, Phys.Rev. D91 (2015) 055011

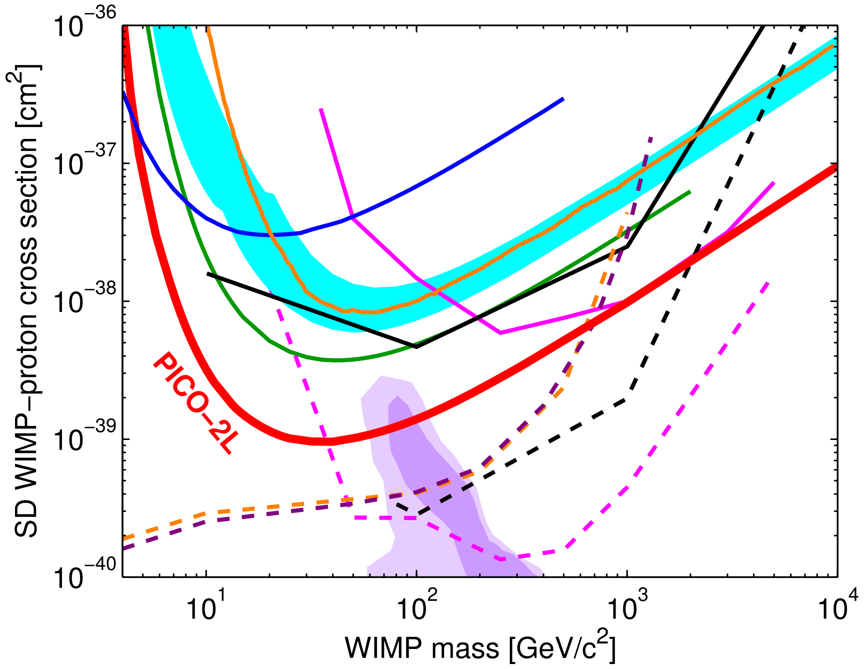
Bubble chambers

- 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

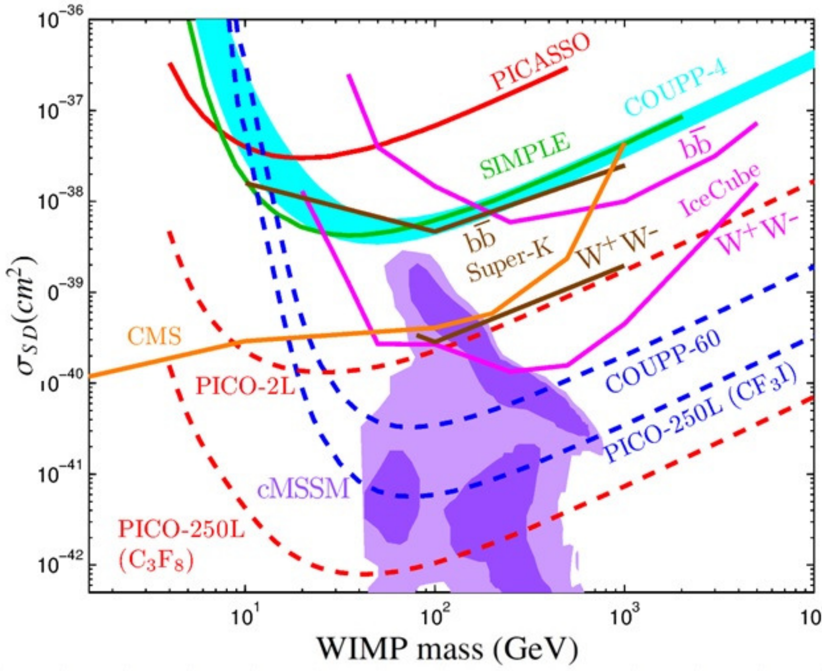


PICO-2L n-calibration

PRL 114, 231302 (2015)

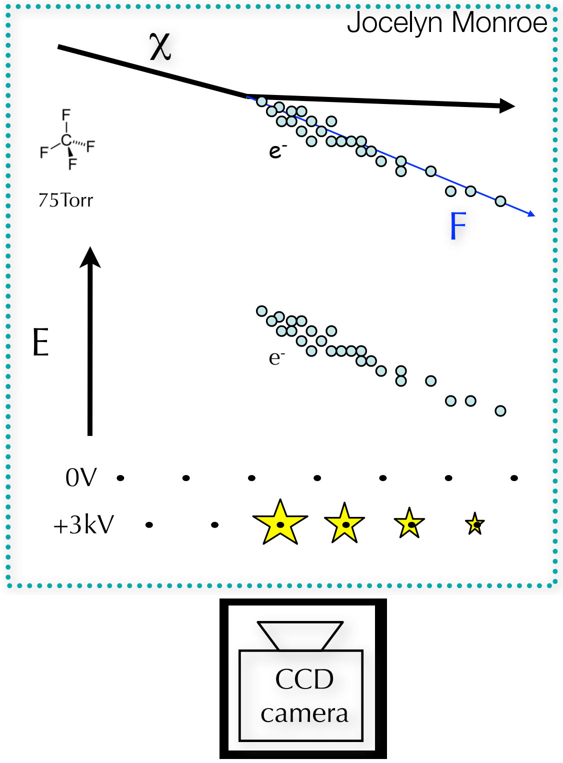


EPJ Web Conf. 95 (2015) 04020

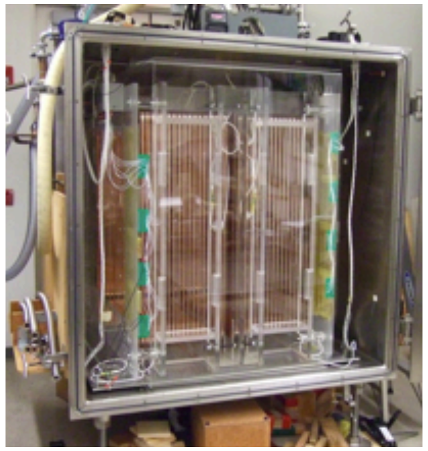


Directional detectors

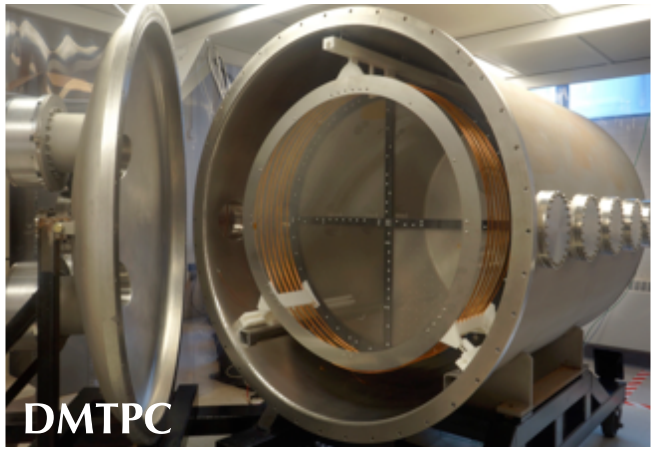
- R&D on low-pressure gas detectors to measure the recoil direction (~30° resolution), correlated to the Galactic motion towards Cygnus
- Challenge: good angular resolution + head/tail at 30-50 keVnr
- **One common technology to be proposed in 2016**



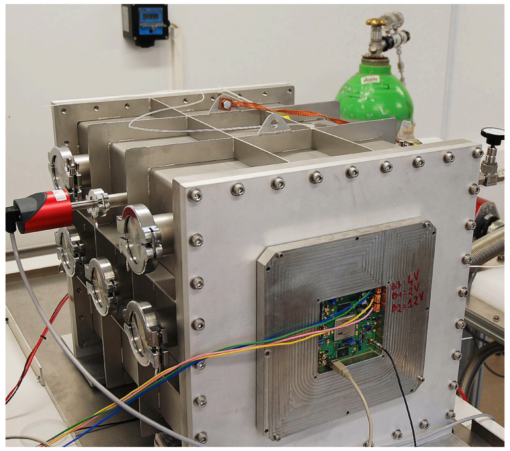
CYGNUS: coordination of directional R&D



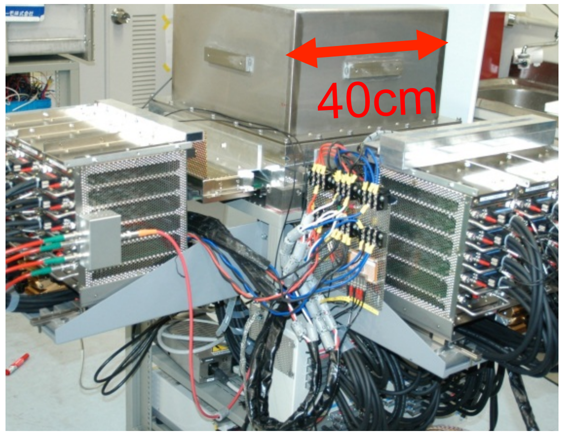
DRIFT, Boulby Mine
1 m^3, negative ion drift
CS_2 +CF_4 gas



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



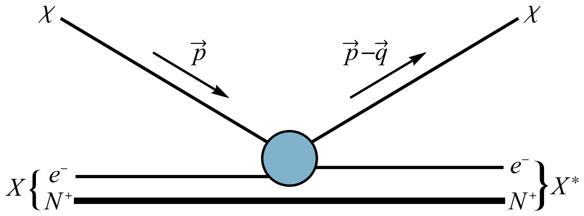
MIMAC 100x100 mm^2
5l chamber at Modane
CF_4 gas

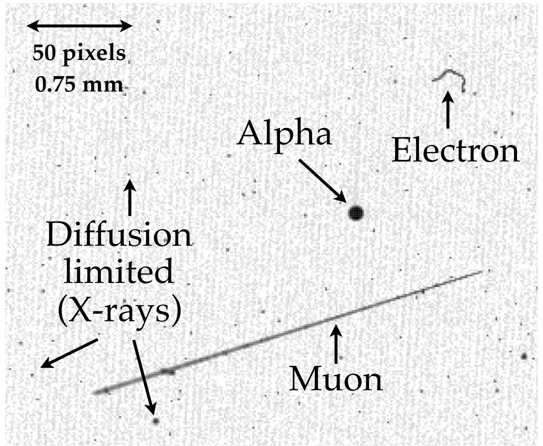


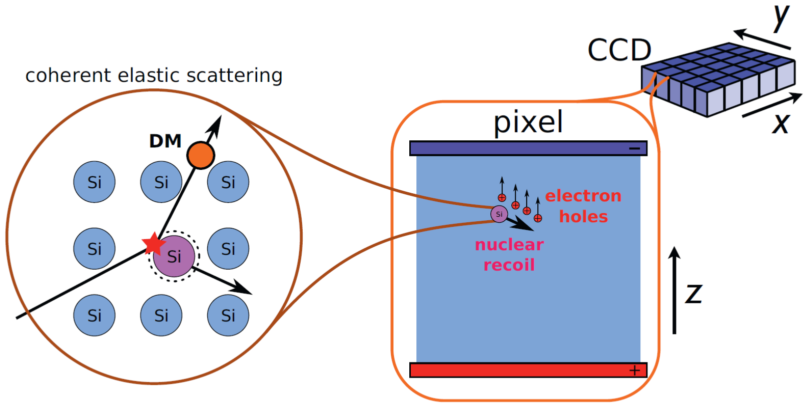
NEWAGE, Kamioka
CF_4 gas at 0.1 atm
50 keV threshold

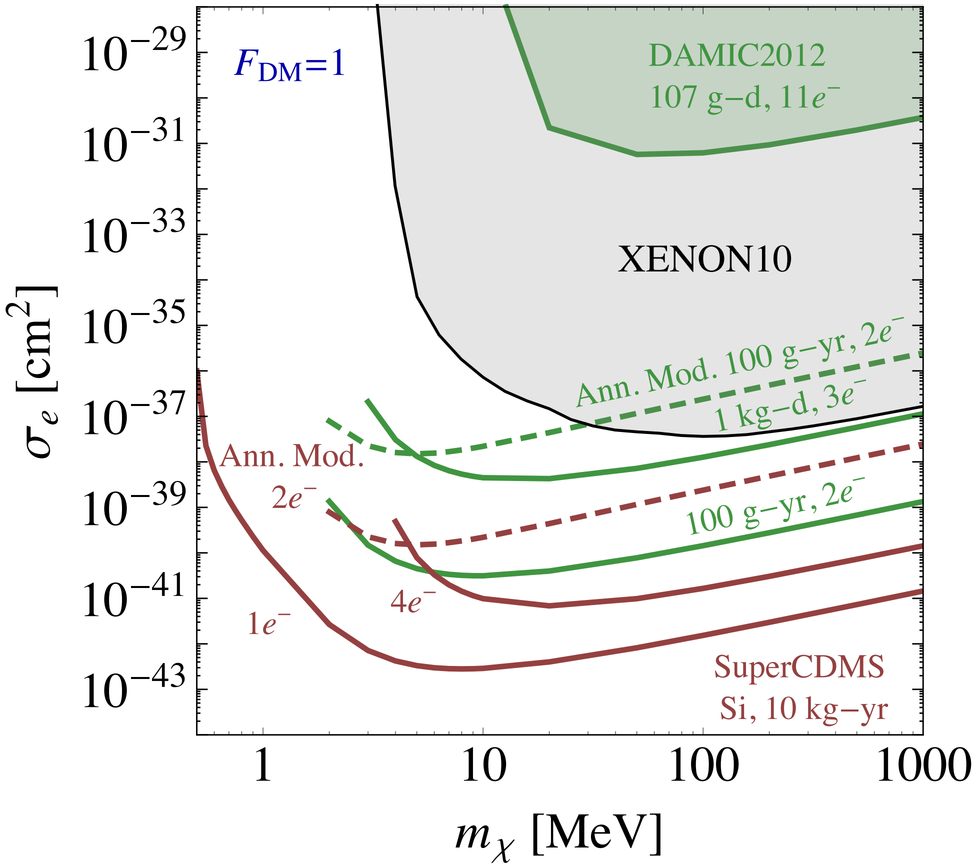
DAMIC at SNOLAB

- CCD-based experiment, 50 eV$_{ee}$ energy threshold (or 0.5 keV$_{nr}$)
- DAMIC100 g is currently under installation at SNOLAB
- Also look for DM-electron scatters (test LDM models)

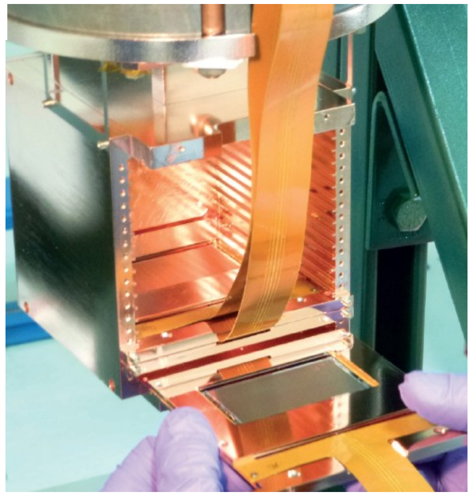


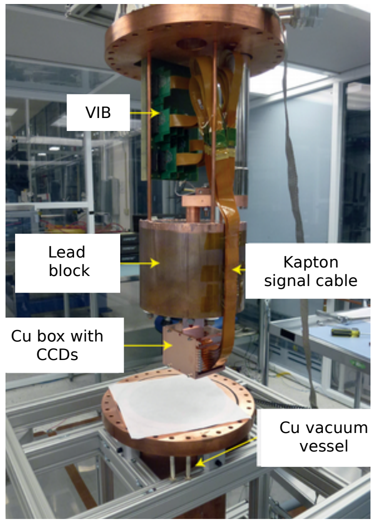






R. Essig et al., arXiv: 1509.01598





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

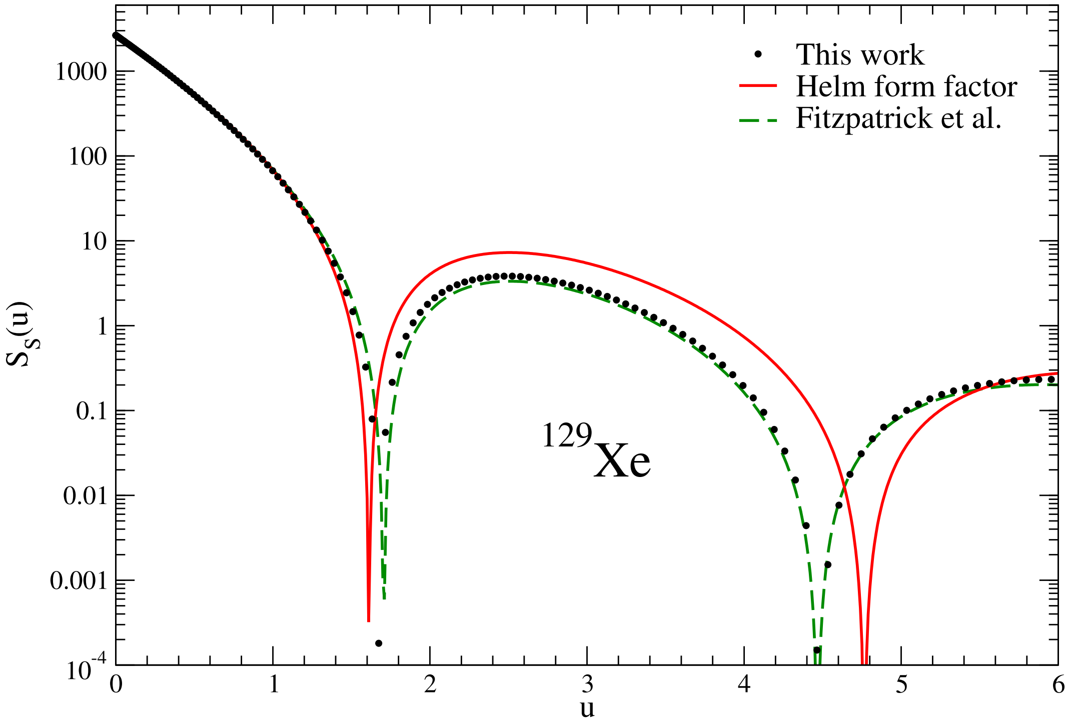
=> nuclei with non-zero angular momentum (corrections due to spin structure functions)

Form factor corrections

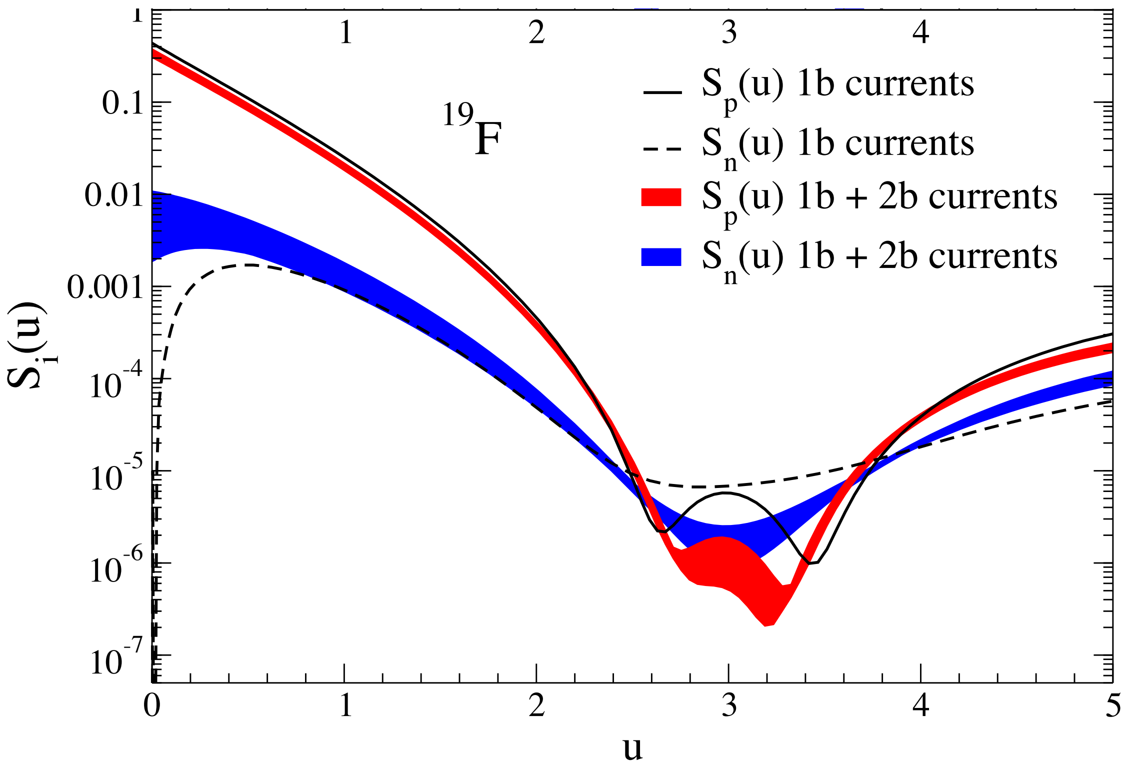
- WIMPs scatter off nuclei, not nucleon or quarks

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

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



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



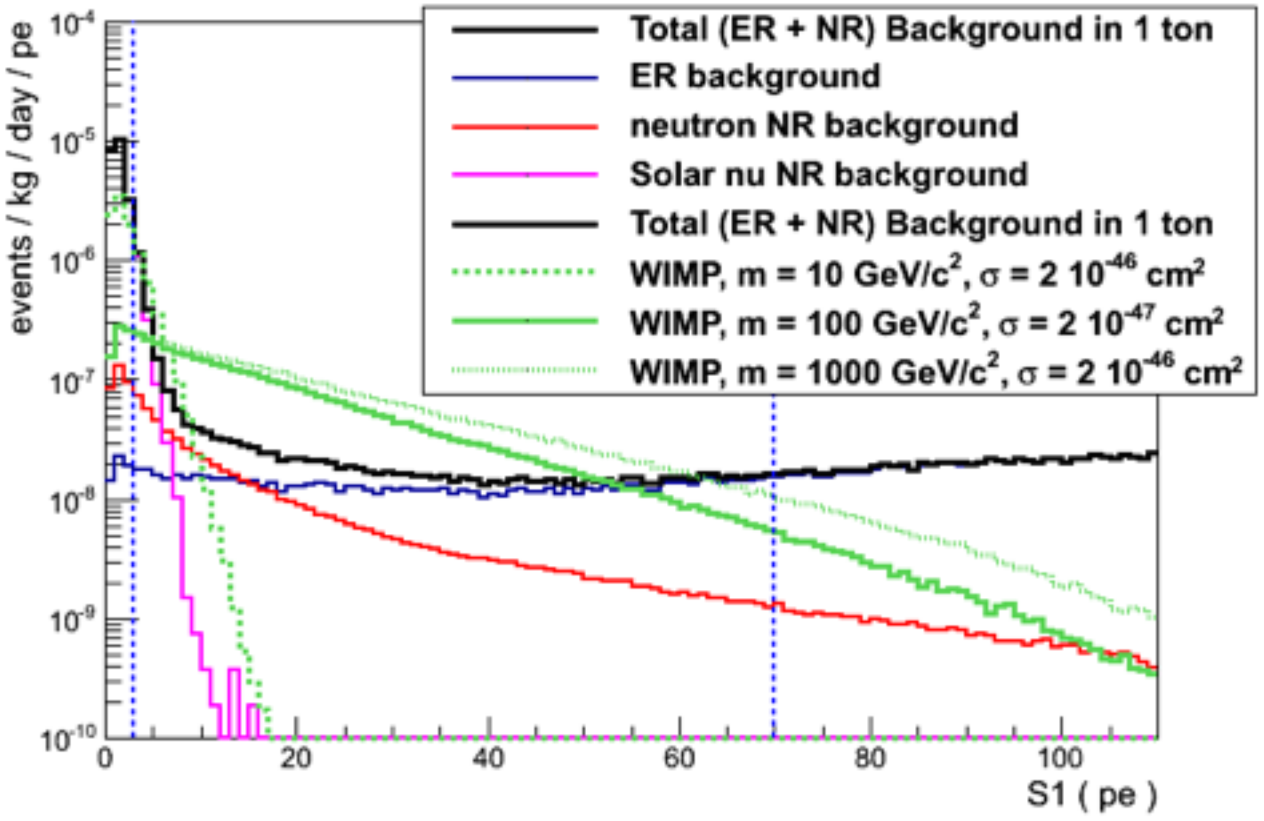
P. Klos et al., PRD 88 (2013)

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

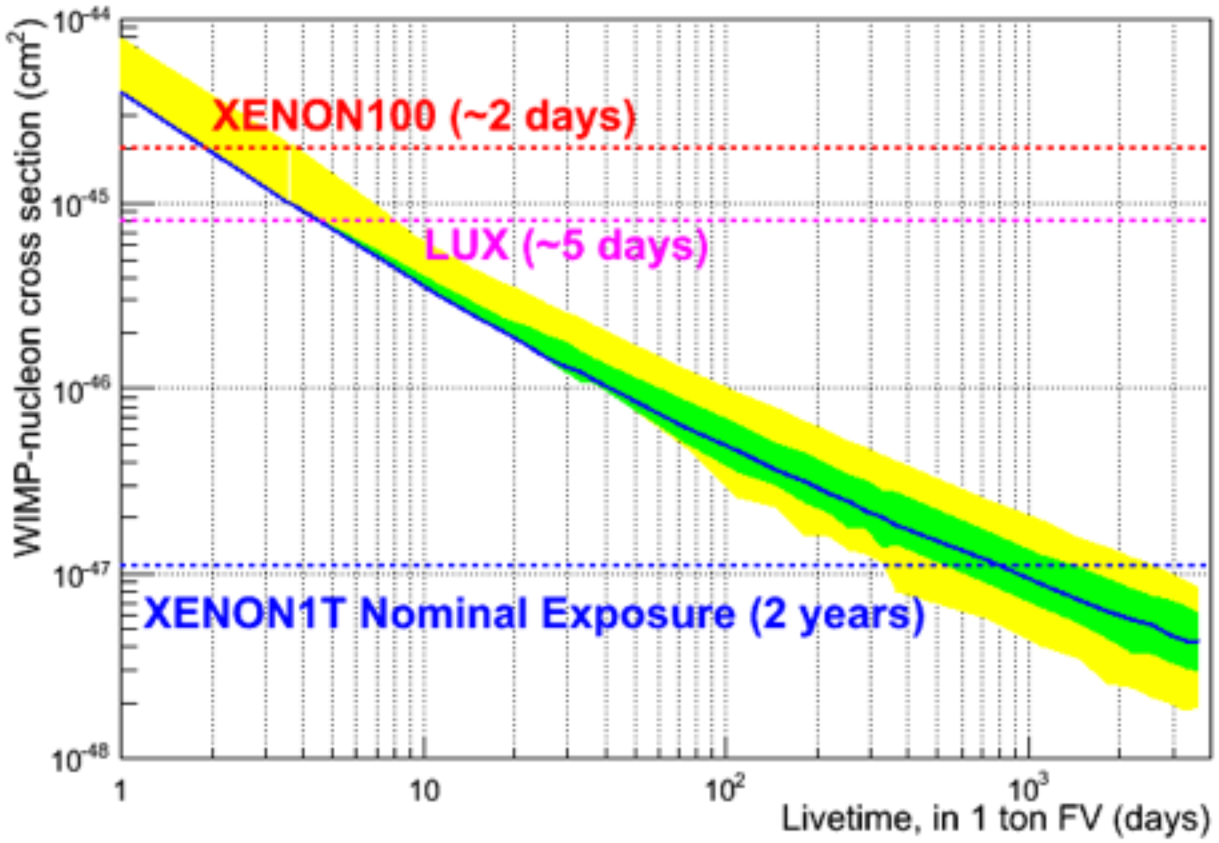
XENON1T backgrounds and WIMP sensitivity

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



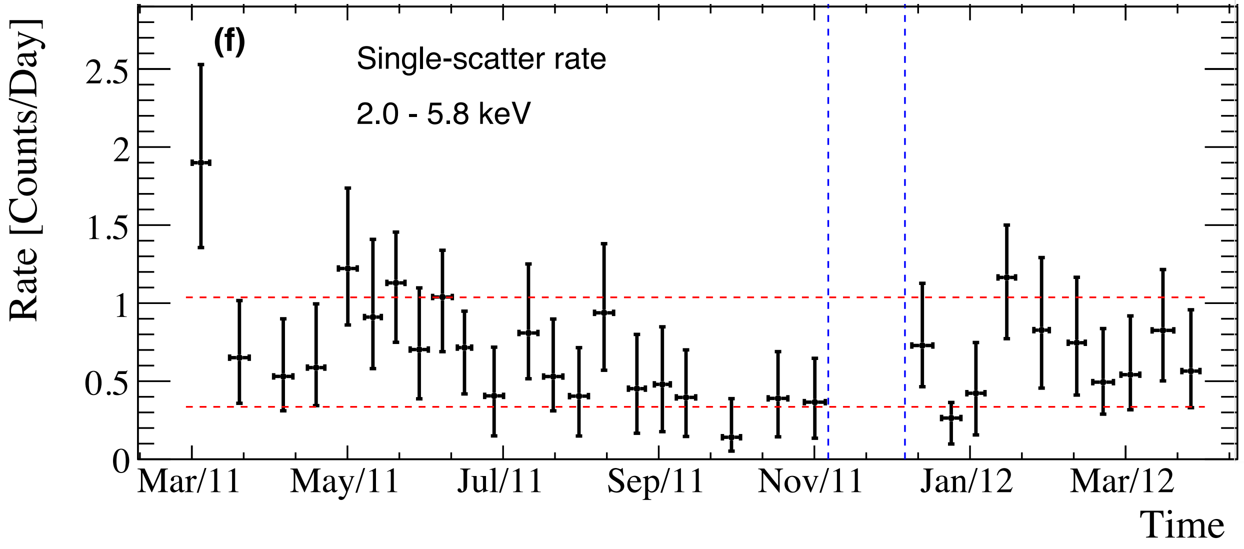
Sensitivity versus exposure (in 1 ton fiducial mass)

New XENON100 results

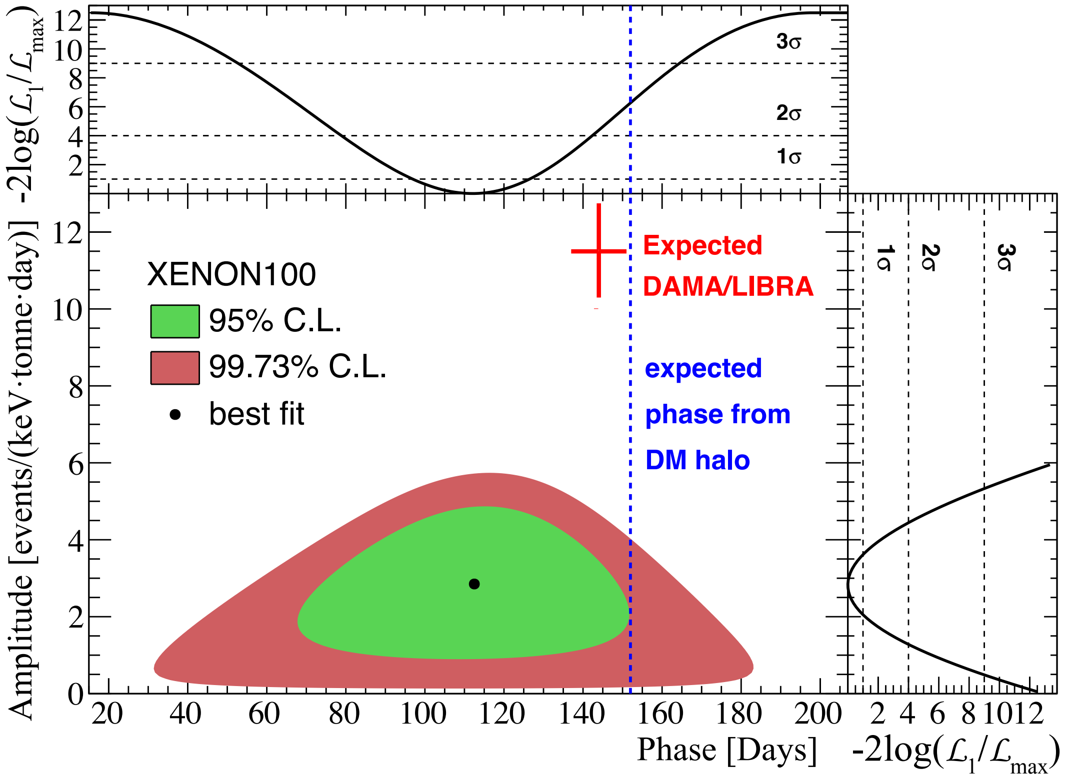
- Dark matter particles interacting with e$^-$

1. search for periodic variations of the ER rate in the 2-6 keV region
2. no periodic signal with DAMA/LIBRA phase & amplitude found

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

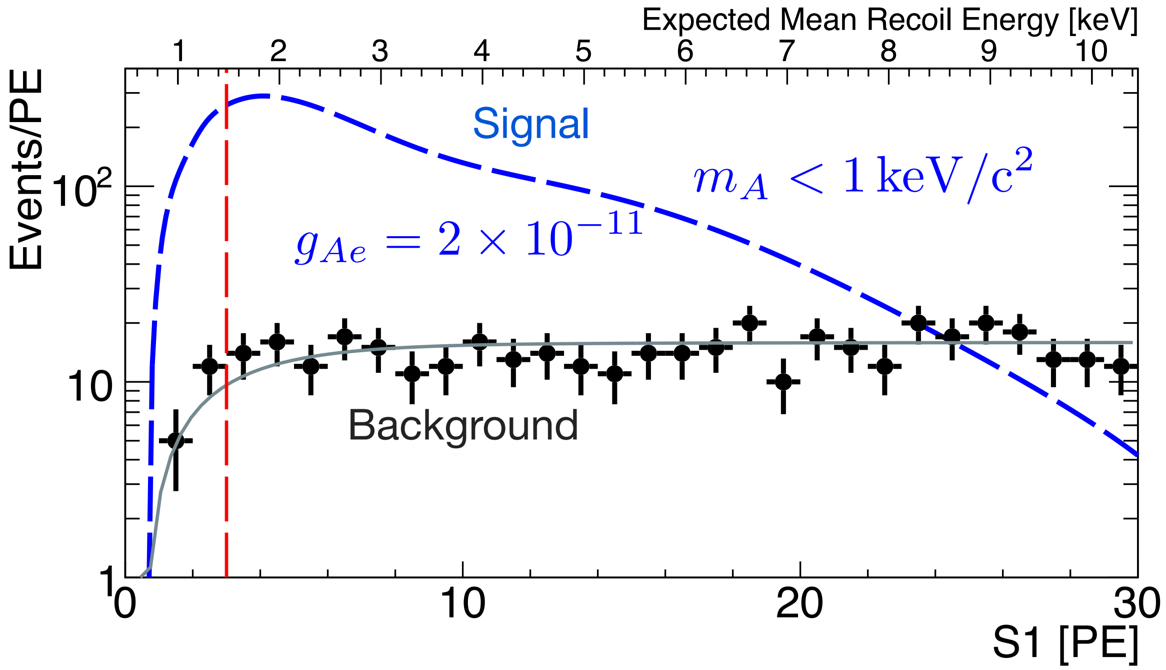


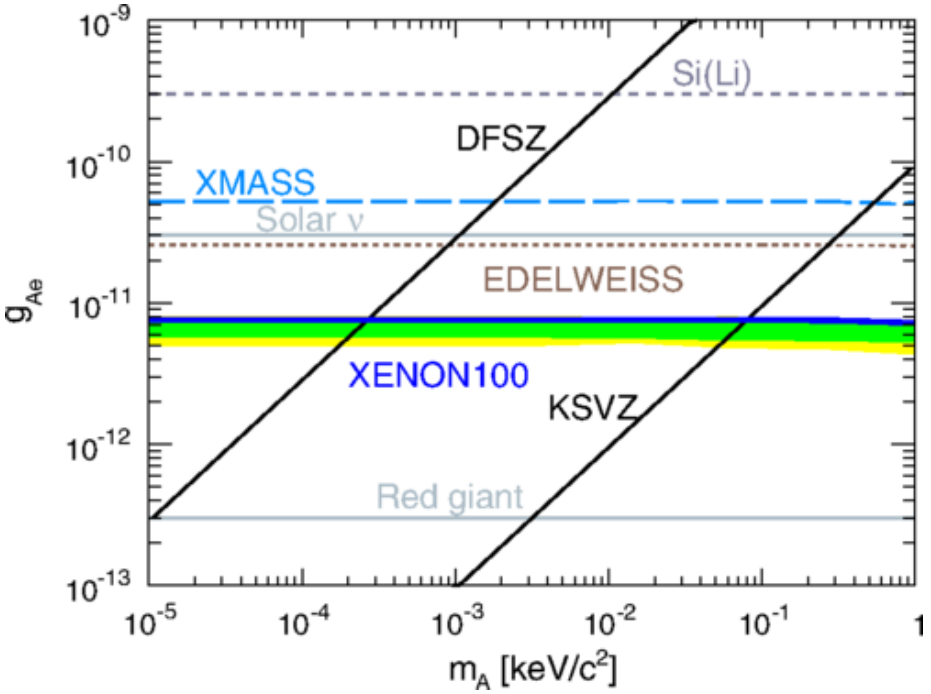
Electronic recoil event rate in 34 kg LXe for single-scatters versus time (many other detector parameters monitored as well)



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

Example: Solar axions with XENON100





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

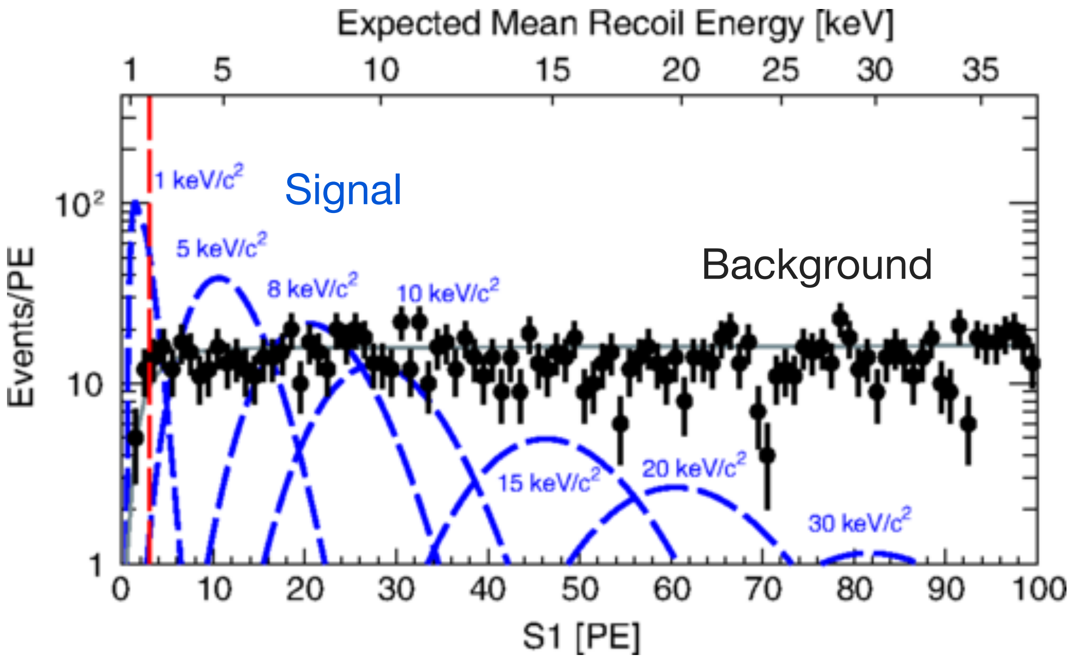
$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{g_{Ae}^2}{\beta_A}\frac{3E_A^2}{16\pi\alpha_{em}m_e^2}\left(1-\frac{\beta_A^{2/3}}{3}\right)$$

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

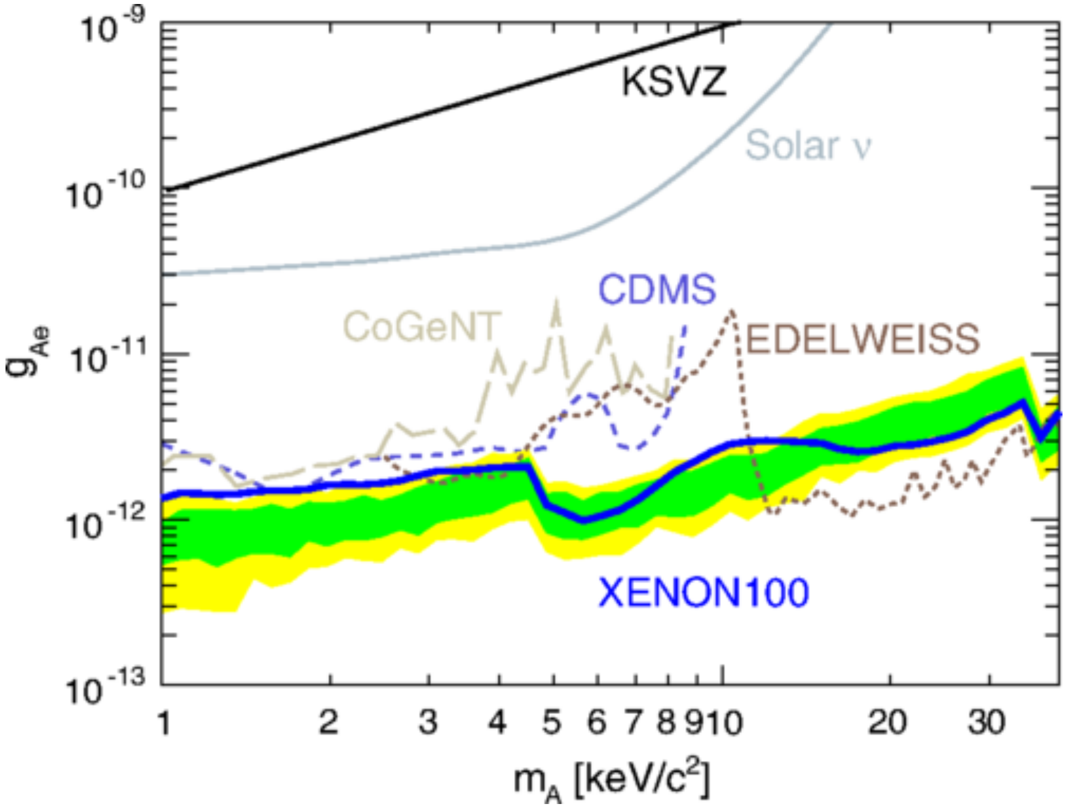
- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs (LB et al., PRD 87, 2013; arXiv:1303.6891)

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)