Dark matter searches: where do we stand, where are we going?

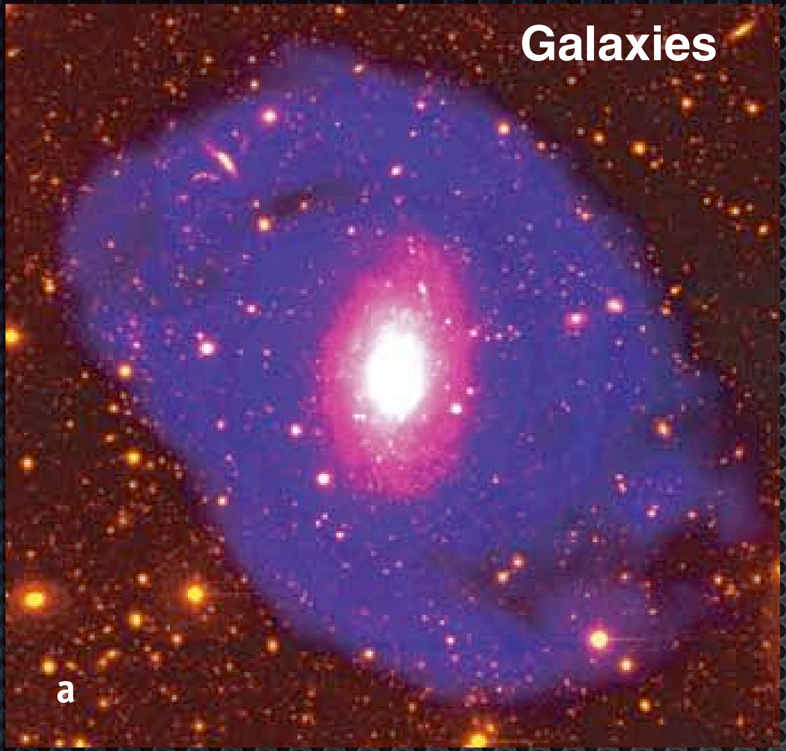
SIF Congresso Nazionale

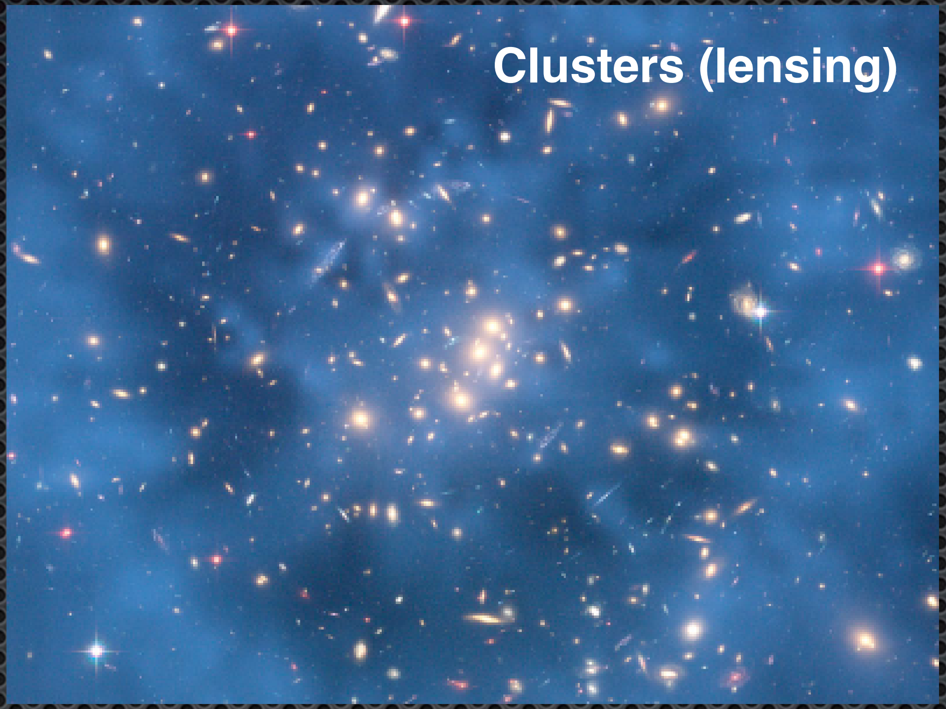
Pisa, September 25, 2014

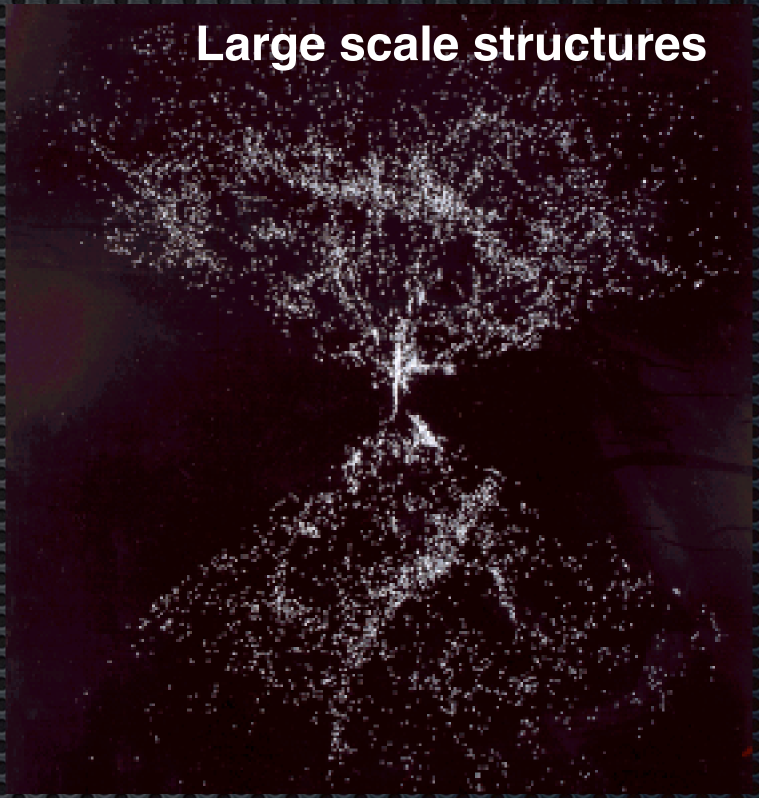
Laura Baudis

University of Zurich

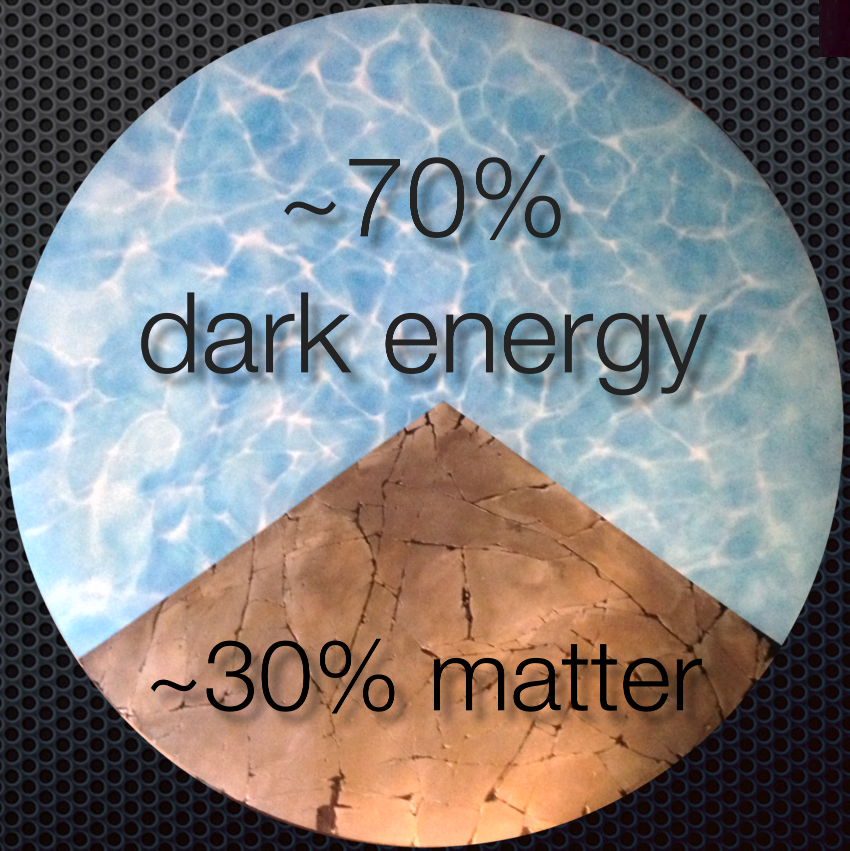
Matter and Energy Content of our Universe

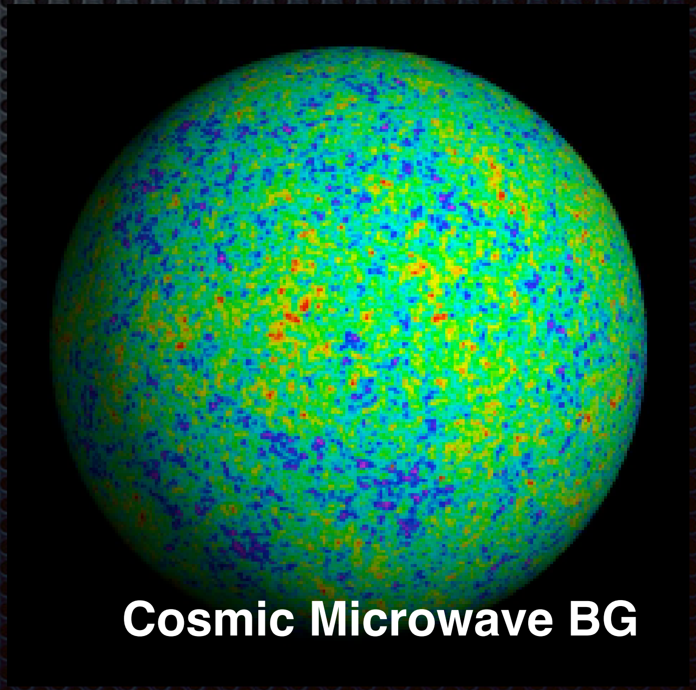

Galaxies


Clusters (lensing)


Large scale structures

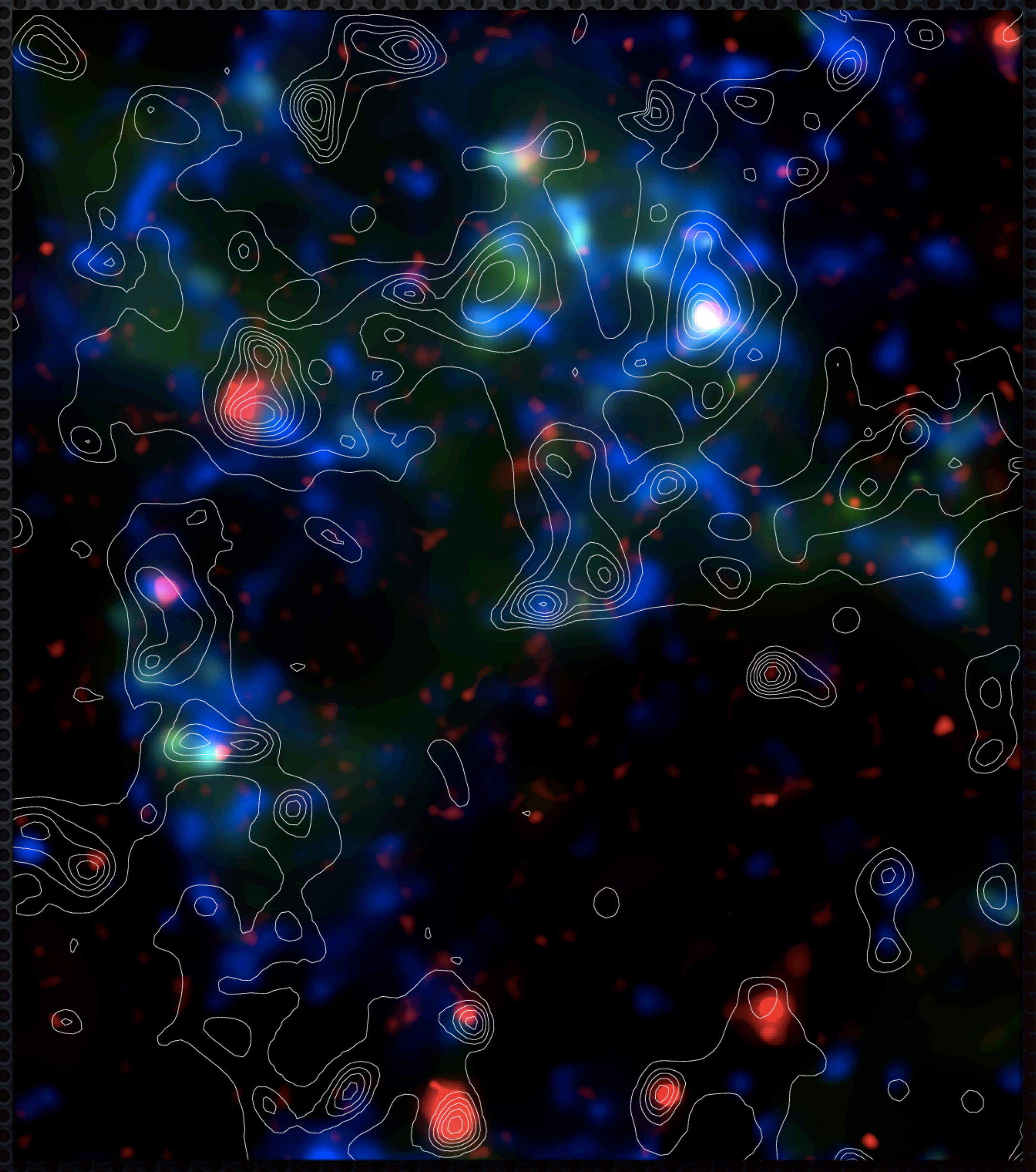

Clusters (lensing+X-ray)




Cosmic Microwave BG

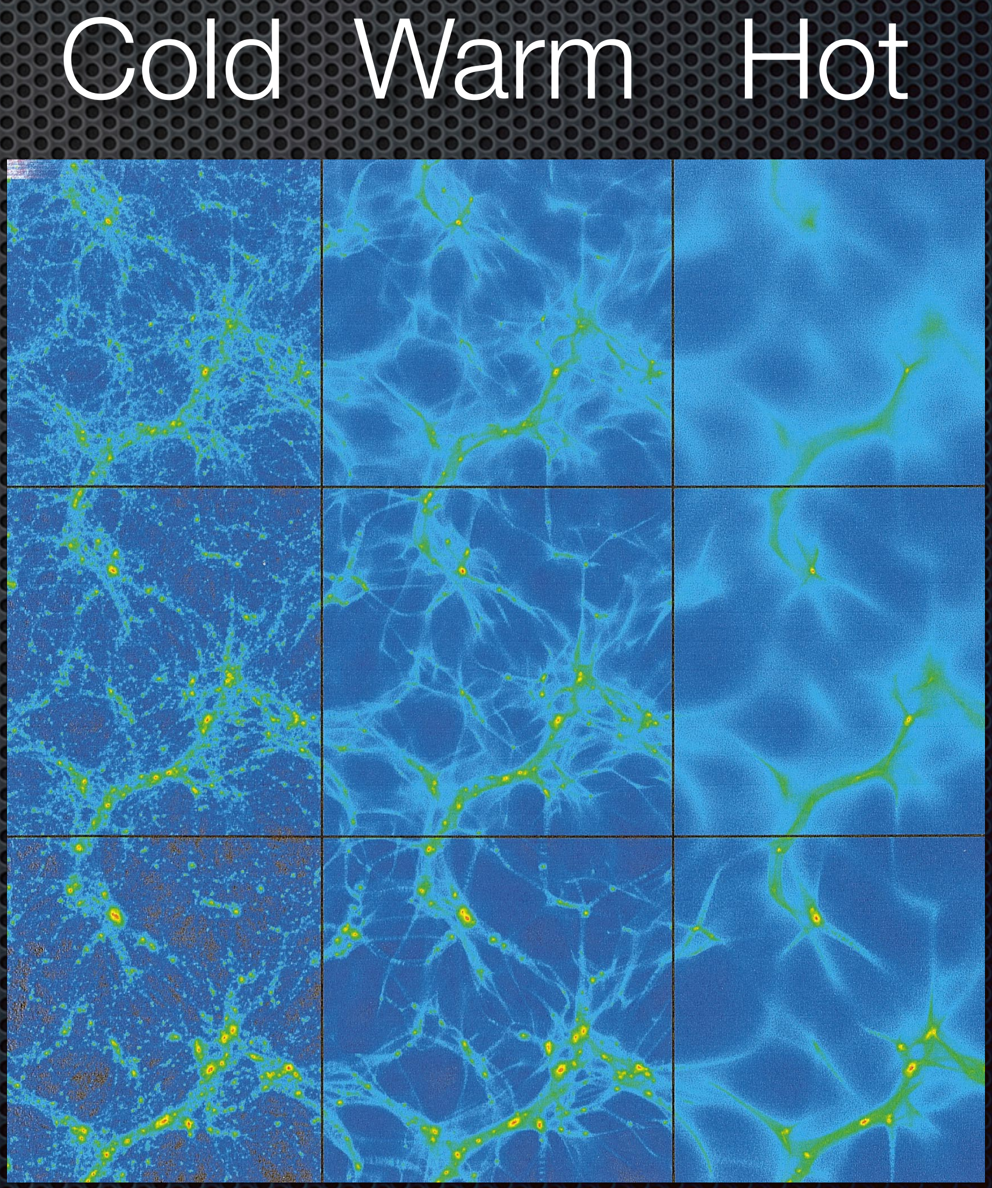
The dark matter puzzle

- The dark matter puzzle is *fundamental*: dark matter leads to the formation of structure and galaxies in the universe
- We have a so-called “standard model” of CDM, from “precision cosmology”: however, *measurement ≠ understanding*
- **For 85% of matter in the universe is of unknown nature**



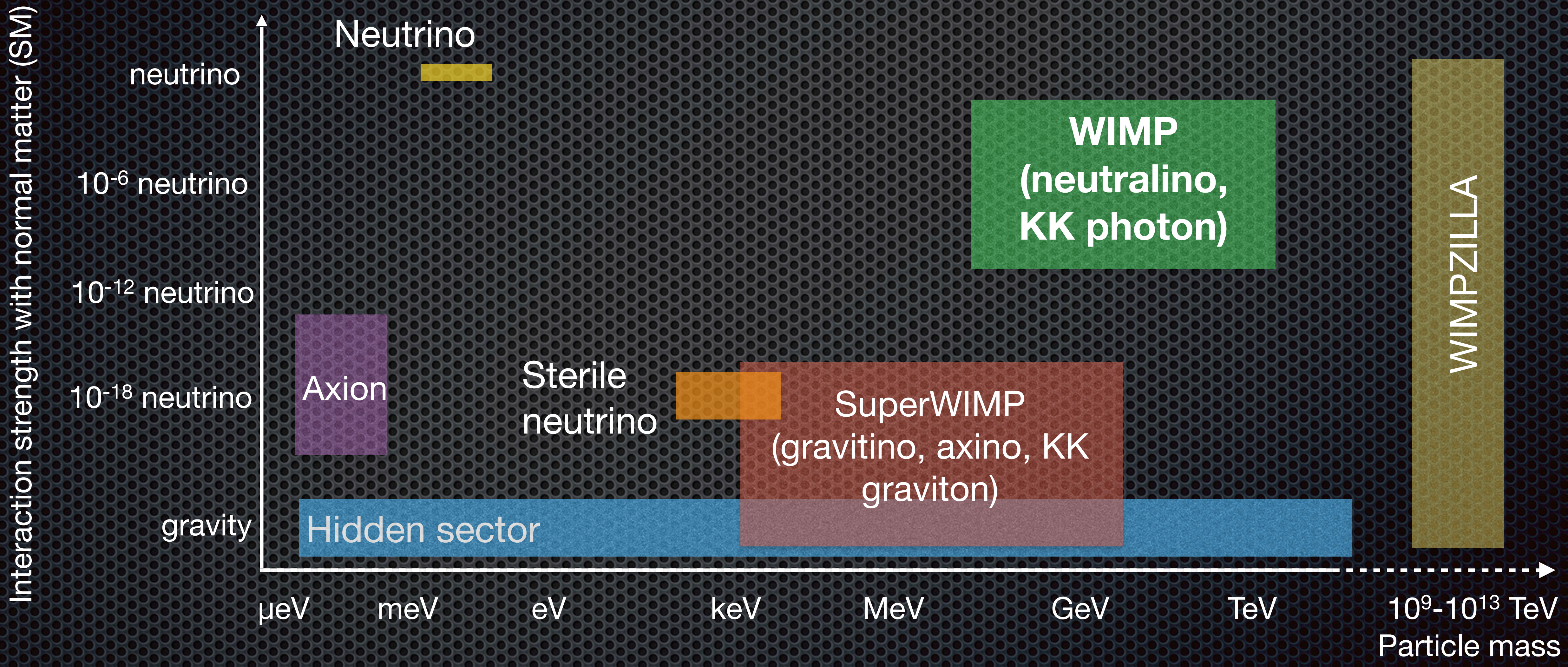
What do we know about dark matter?

- So far, we mostly have “negative” information:
  - No color charge
  - No electric charge
  - No strong self-interaction
- *Not a particle in the Standard Model of particle physics*



What do we know about dark matter?

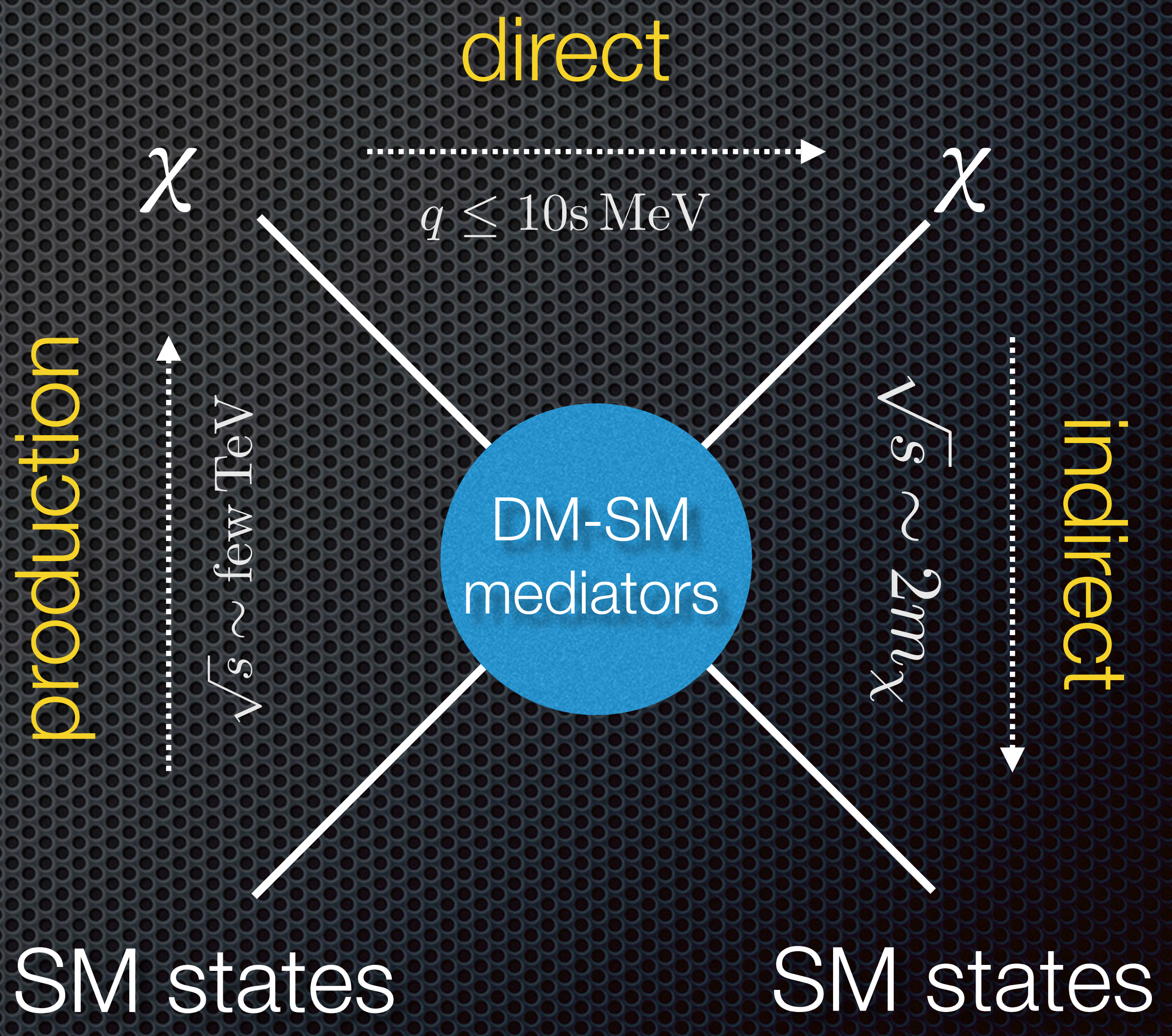
- The mass and cross section range span many orders of magnitude



In this talk I will focus on the **weak scale,** and on **direct detection**

How to detect a WIMP

- **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
- **Accelerator searches**
  - missing ET, mono-jets, etc
  - can it establish that the new particle is the DM?

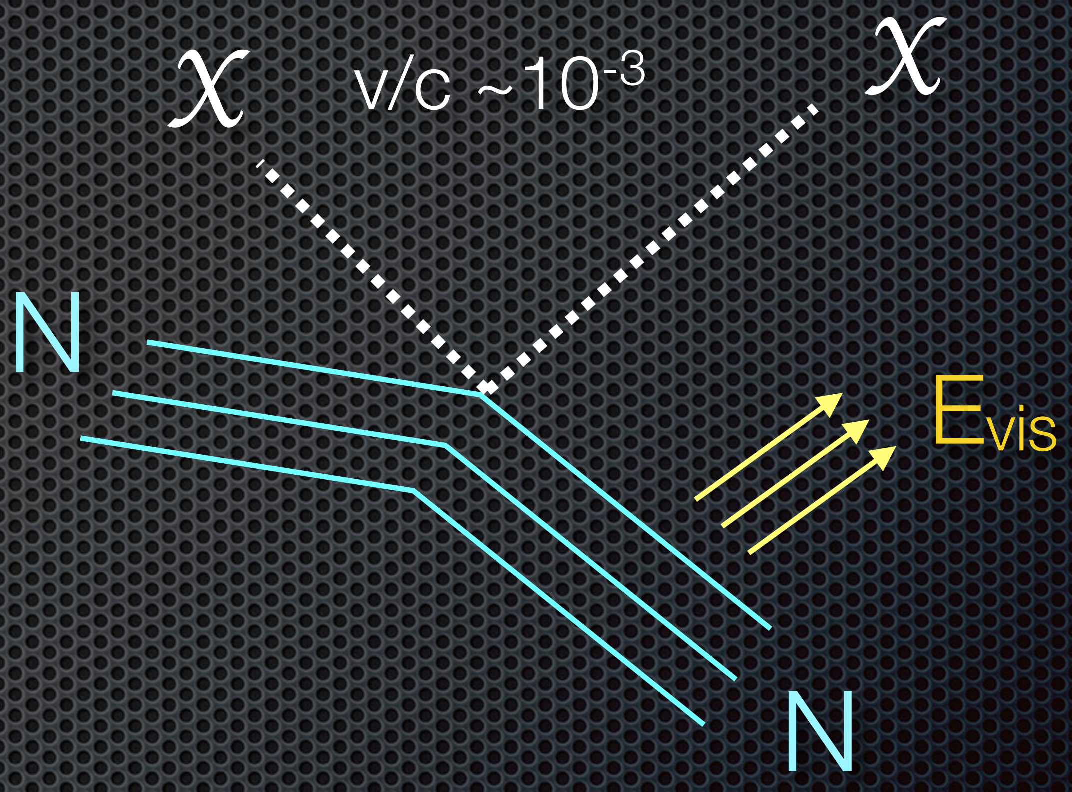


see talks by
M.M. Perego, M.G. Ratti,…

see talk by M. Cirelli

How to directly detect it in the lab?

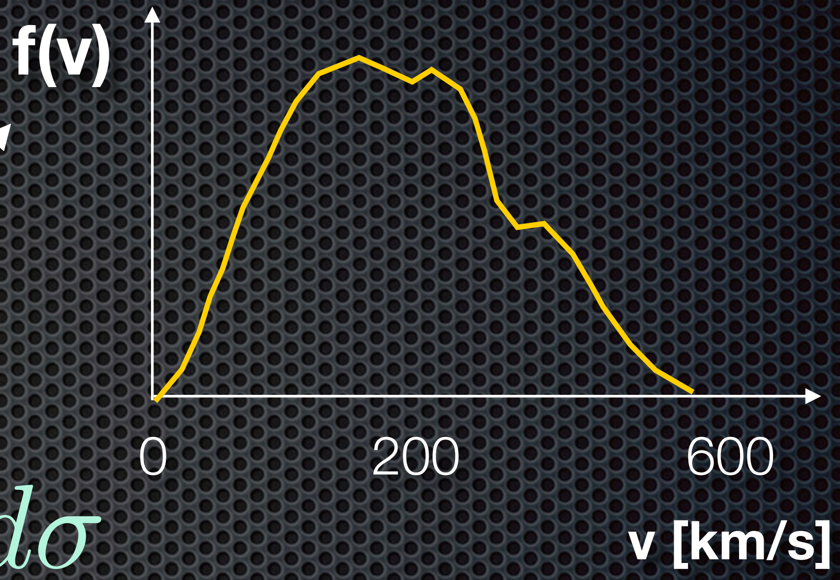
- By searching for collisions of invisibles particles with atomic nuclei => E_{vis} (q ~ tens of MeV)
- Need *very low energy thresholds*
- Need *ultra-low backgrounds*, good background understanding (no “beam off” data collection mode) and discrimination
- Need *large detector masses* (remember neutrino detectors)



$$E_R = \frac{q^2}{2m_N} < 100\,\mathrm{keV}$$

What do we expect in a detector?

Astrophysics

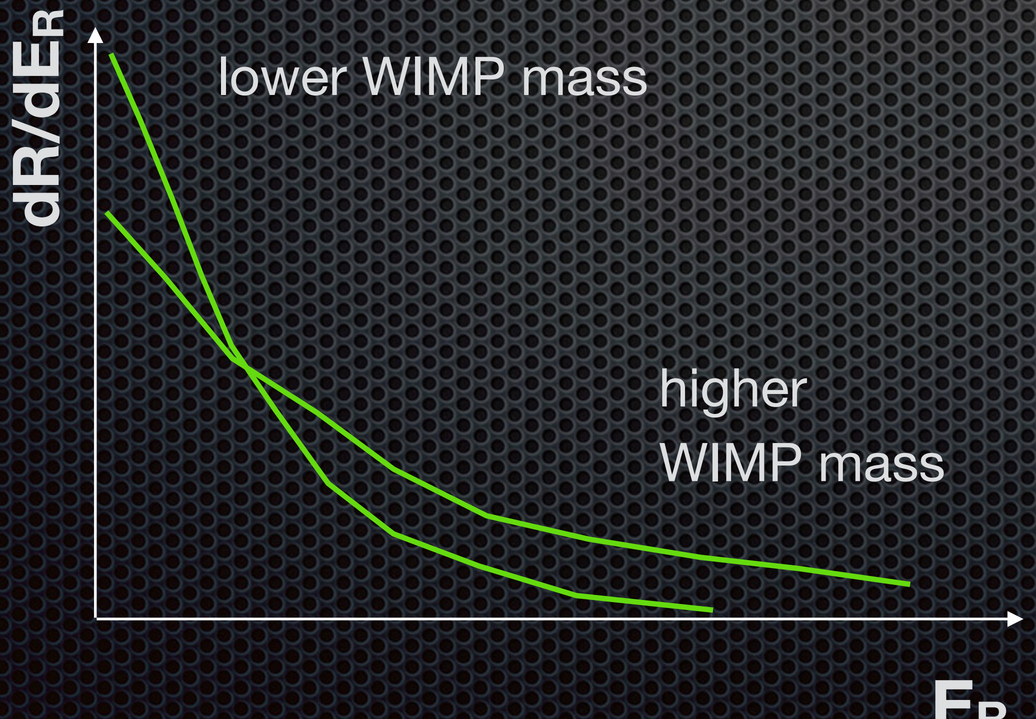


$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_\mathrm{min}}^{v_\mathrm{max}} d\mathbf{v}\, f(\mathbf{v})\, v\, \frac{d\sigma}{dE_R}$$

Detector physics

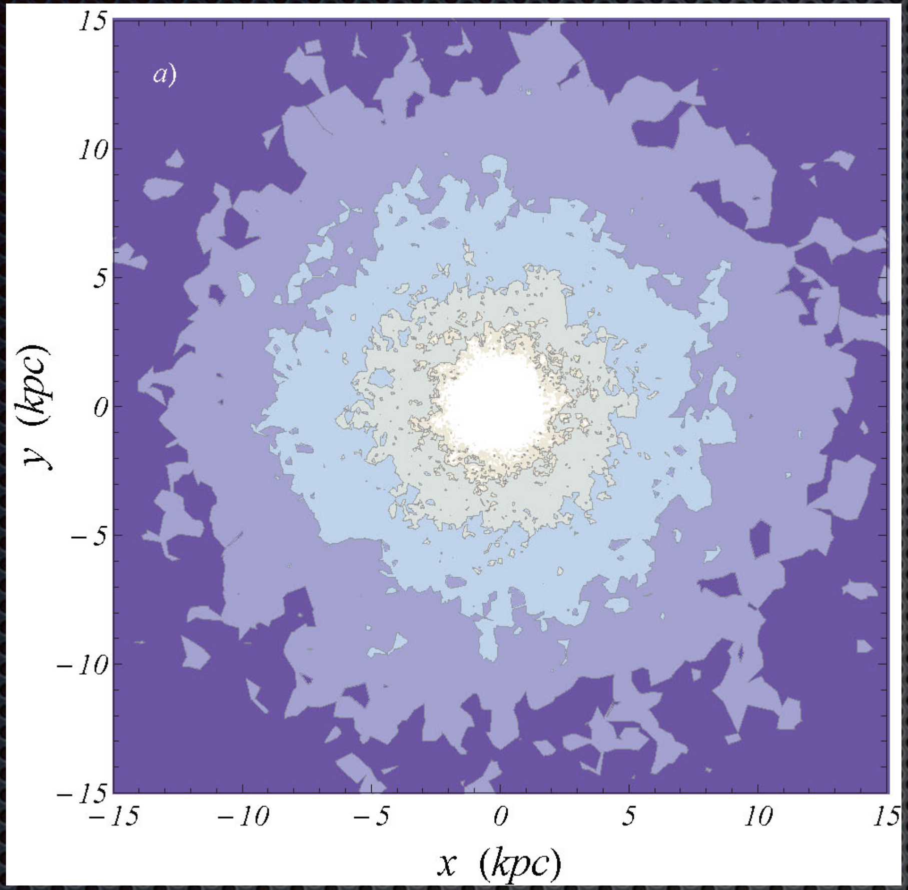
Particle/nuclear physics

$$v_\mathrm{min} = \sqrt{\frac{m_N E_{th}}{2 m_\mathrm{r}^2}}$$



Astrophysics

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

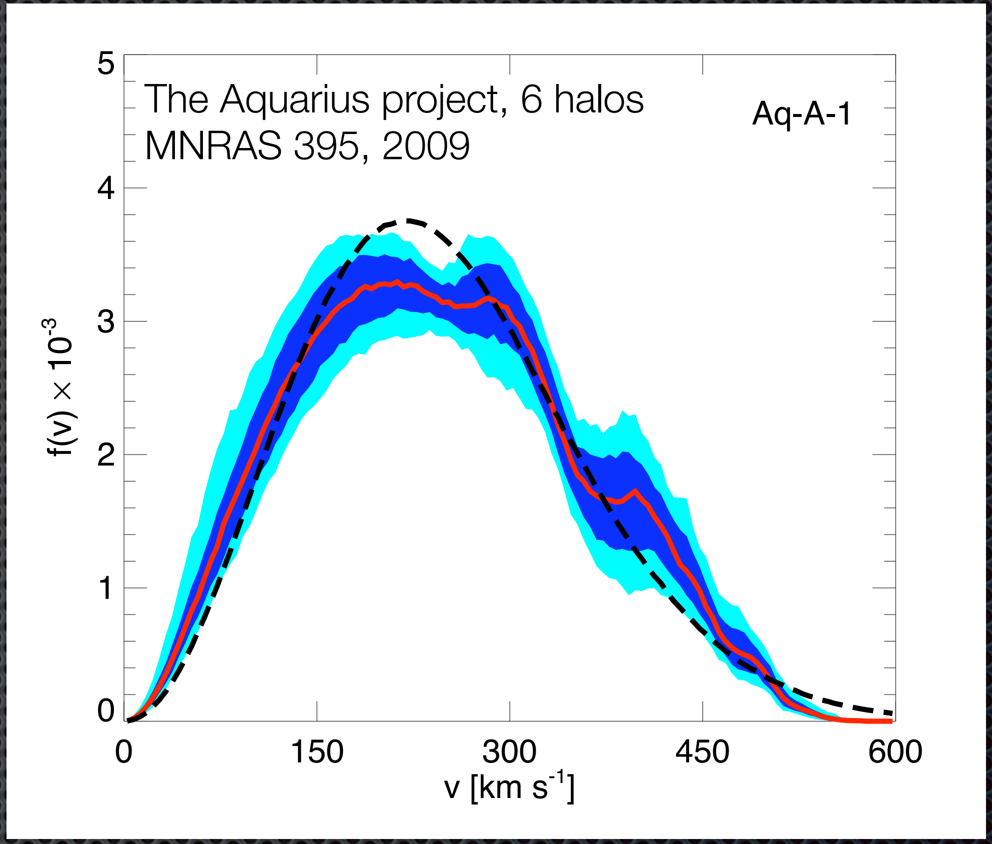
$$\rho(R_0) = 0.2 - 0.56\,\mathrm{GeV}\cdot\mathrm{cm}^{-3}$$

Justin Read, arXiv:1404.1938

=> WIMP flux on Earth:

~10^5 cm^{-2}s^{-1} (M_W=100 GeV)

Velocity distribution of WIMPs in the galaxy



Halo restframe

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

However, a simple MB distribution is a good approximation, and yields conservative results

WIMP scattering cross section

$$\text{Scalar (S)} \quad \mathcal{L} = \frac{\mathrm{G_S}}{\sqrt{2}}\bar{\chi}\chi\bar{\mathrm{f}}\mathrm{f}$$

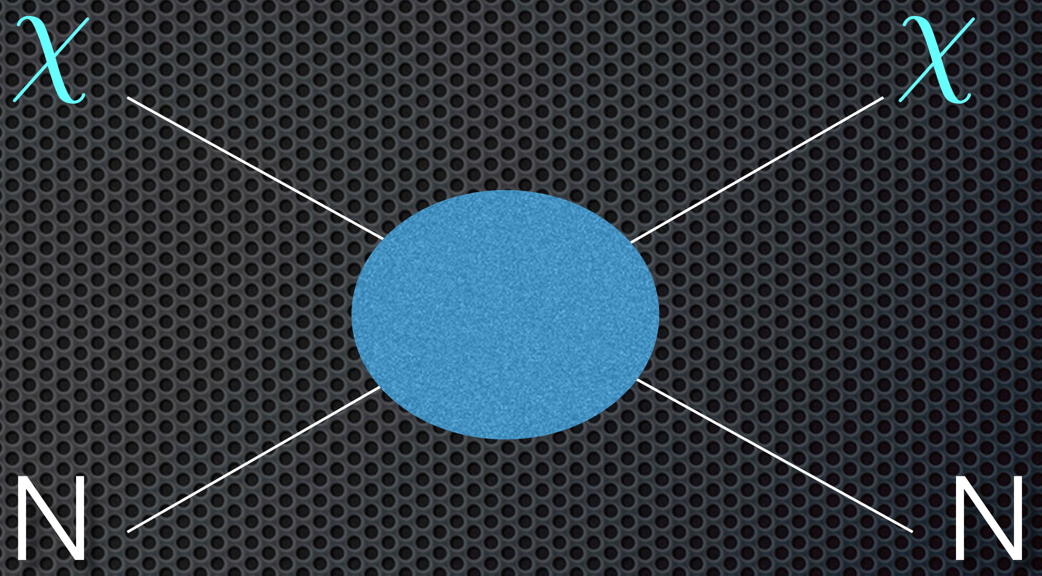
$$\text{Pseudoscalar (P)} \quad \mathcal{L} = \frac{\mathrm{G_P}}{\sqrt{2}}\bar{\chi}\gamma^5\chi\bar{\mathrm{f}}\gamma_5\mathrm{f}$$

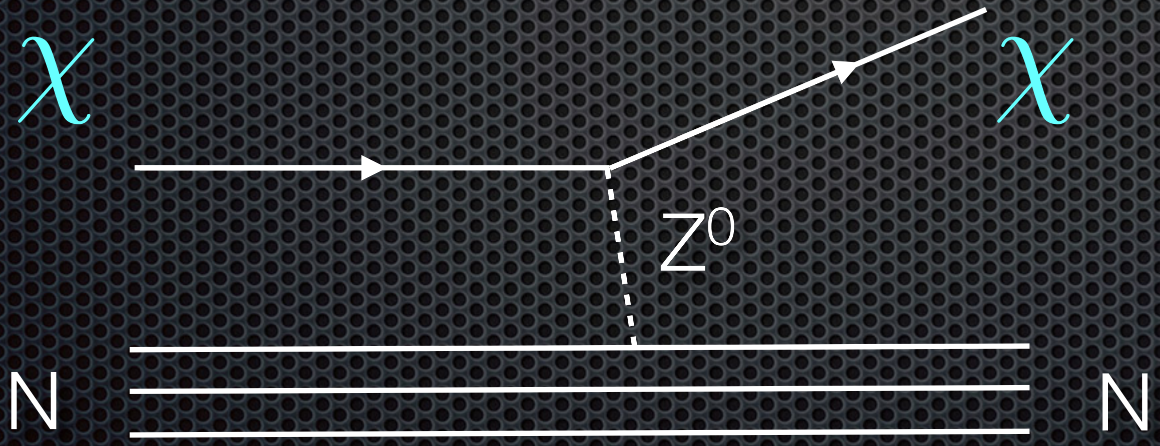
$$\text{Vector (V)} \quad \mathcal{L} = \frac{\mathrm{G_V}}{\sqrt{2}}\bar{\chi}\gamma^\mu\chi\bar{\mathrm{f}}\gamma_\mu\mathrm{f}$$

$$\text{Axialvector (A)} \quad \mathcal{L} = \frac{\mathrm{G_A}}{\sqrt{2}}\bar{\chi}\gamma^\mu\gamma_5\chi\bar{\mathrm{f}}\gamma_\mu\gamma^5\mathrm{f}$$

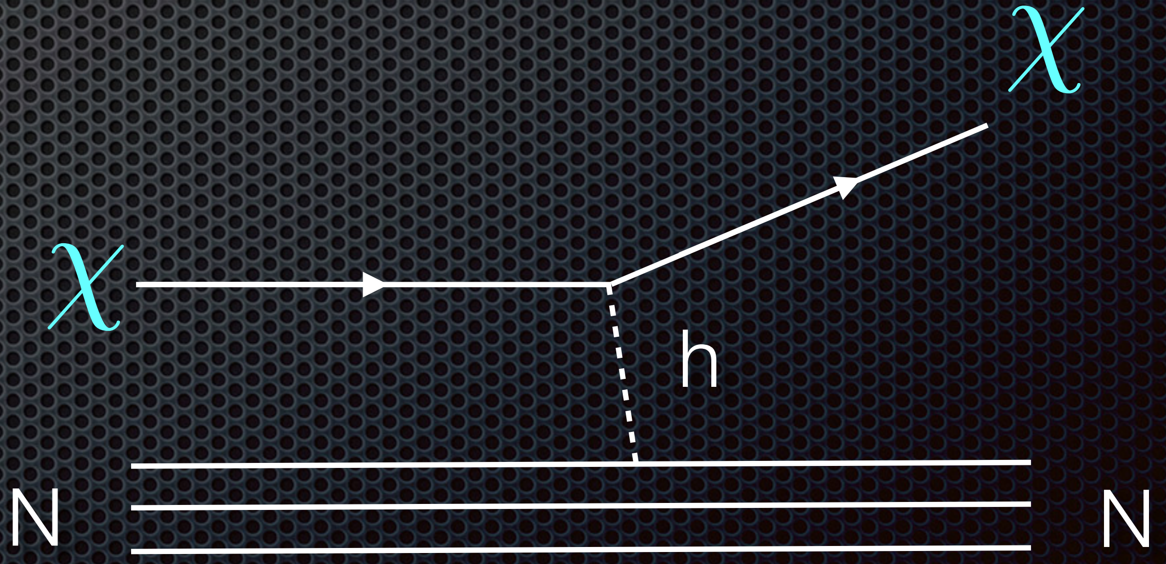
$$\text{Tensor (T)} \quad \mathcal{L} = \frac{\mathrm{G_T}}{\sqrt{2}}\bar{\chi}\sigma^{\mu\nu}\gamma_5\chi\bar{\mathrm{f}}\sigma_{\mu\nu}\gamma^5\mathrm{f}$$

Effective field theory approach, always valid for direct detection





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

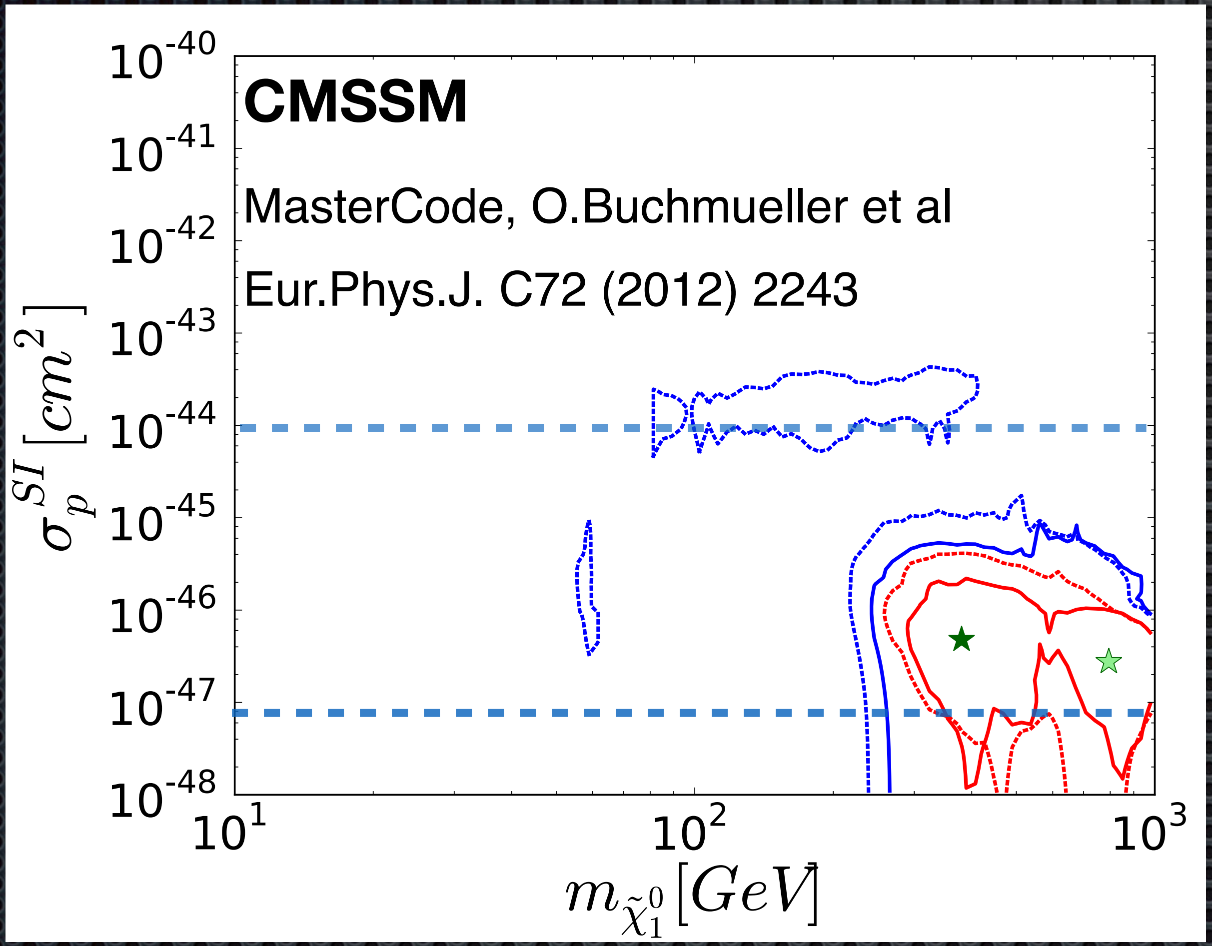


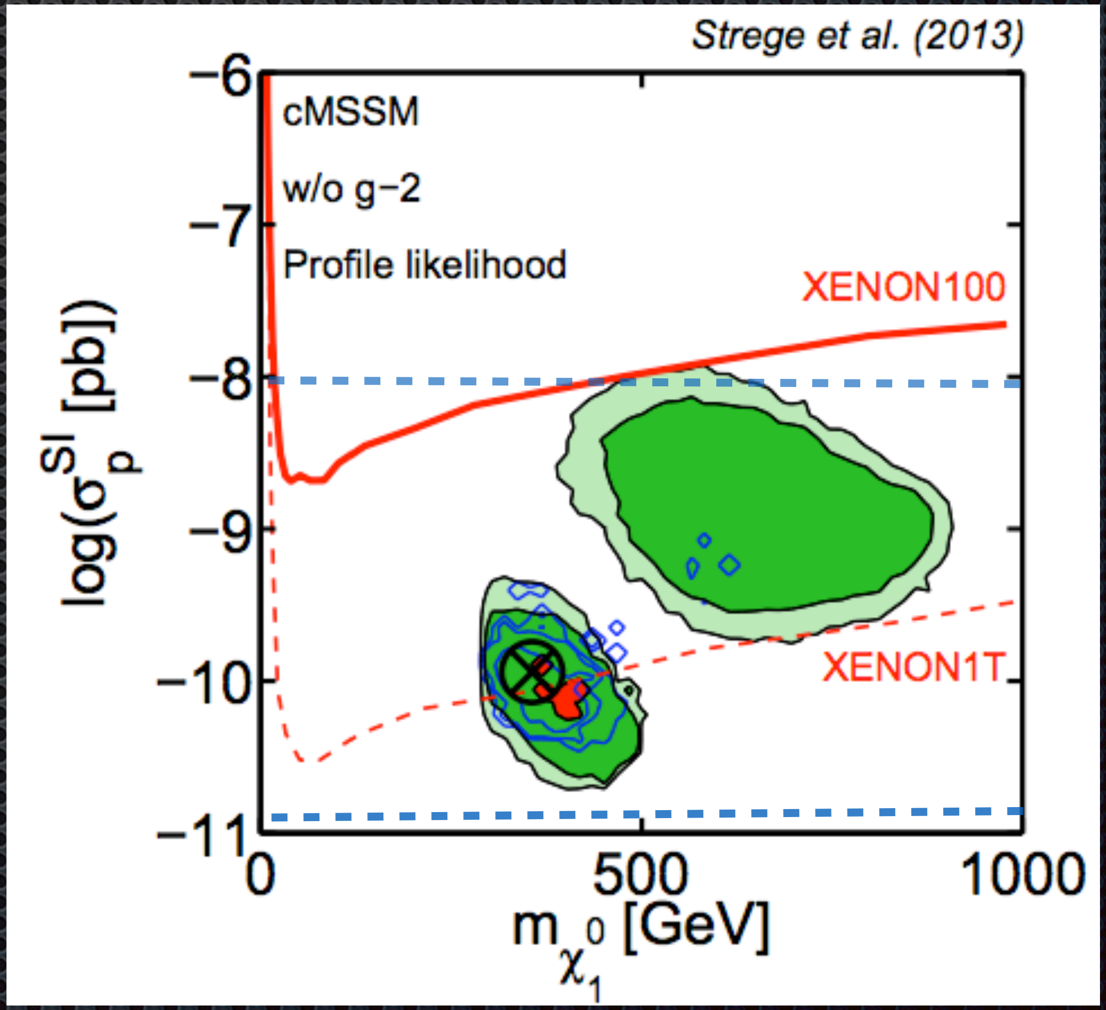
$$\sigma_0 \sim 10^{-45}\,\mathrm{cm}^2$$

Particle physics

- SUSY: scattering cross sections on nucleons down to < 10^{-48} cm^2(10^{-12} pb)

10^{-44} cm^2: ~ 1 event kg^{-1} year^{-1}



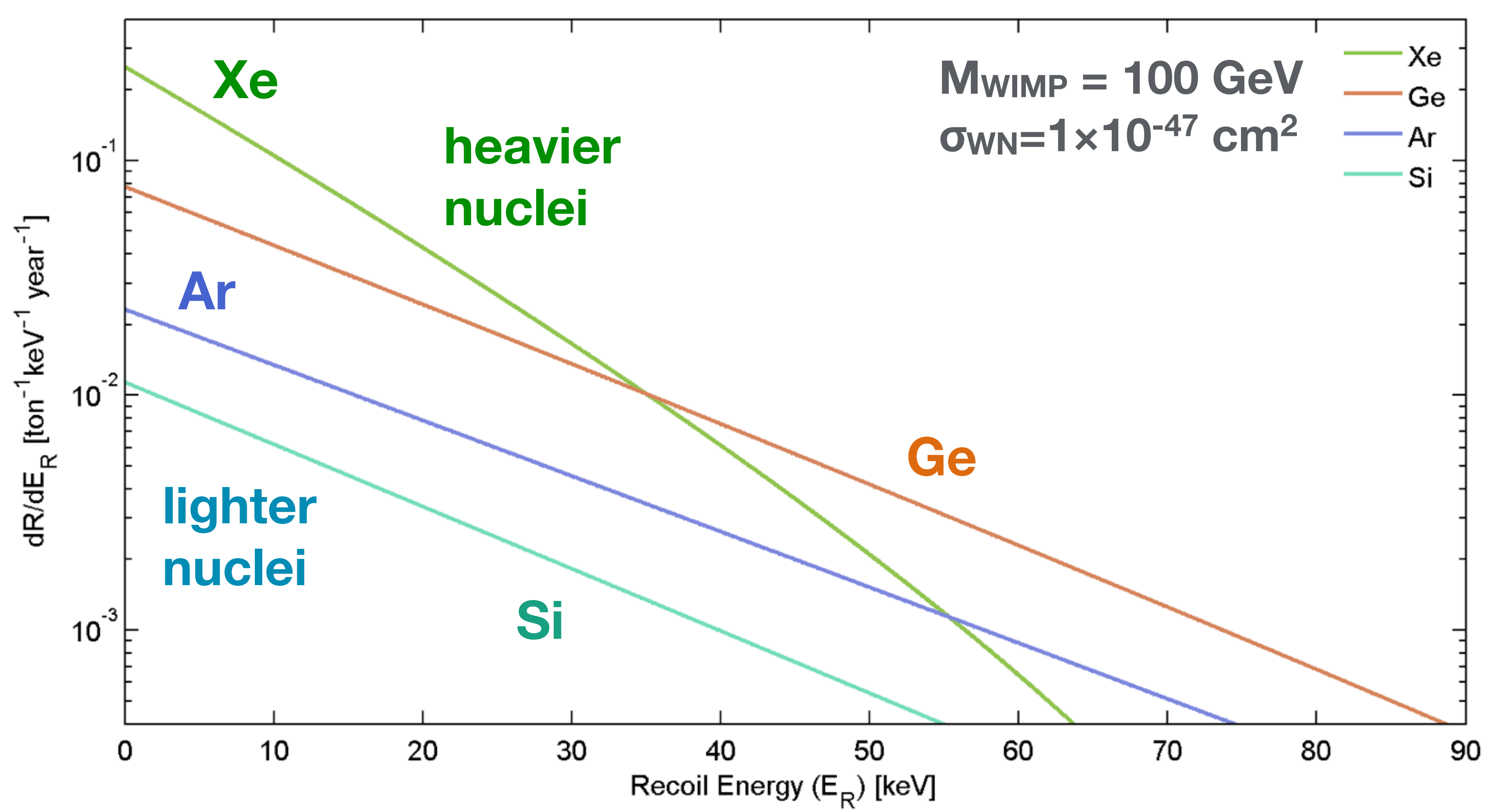


10^{-47} cm^2: ~ 1 event t^{-1} year^{-1}

Expected Interaction Rates

- Recoil rate after integration over WIMP velocity distribution

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



Nuclear recoil spectrum for different target nuclei

(Standard halo model with ρ= 0.3 GeV/cm^3)

The experimental challenge

- **To observe a signal which is:**
  - very small (few keV - tens of keV)
  - extremely rare (1 per ton per year?)
  - embedded in a background that is millions of times higher

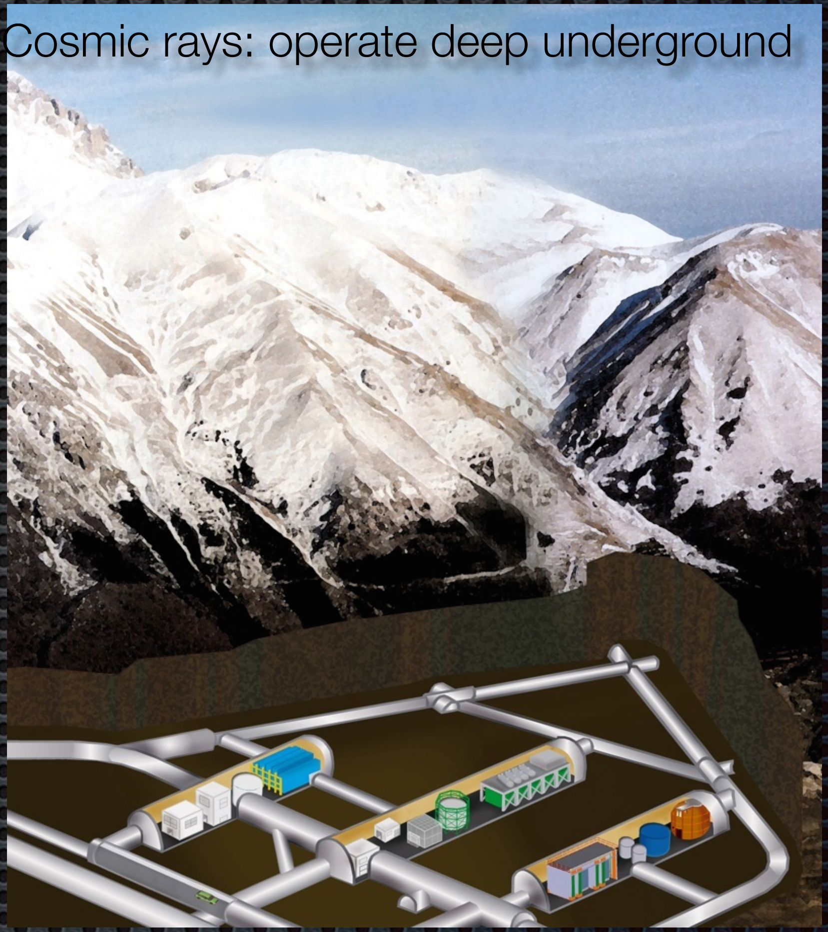
- **Why is it challenging?**
- Detection of low-energy particles - done!
  - ➡e.g. micro-calorimetry with phonon readout

- Rare event searches with ultra-low backgrounds - done!
  - ➡e.g Borexino, SNO, SuperK etc

- **But: can we do both?**

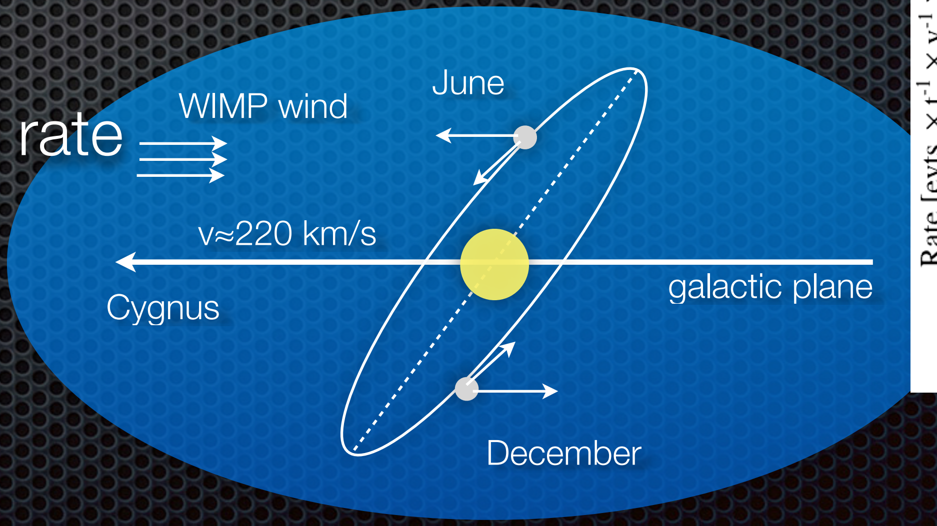
Backgrounds and signatures

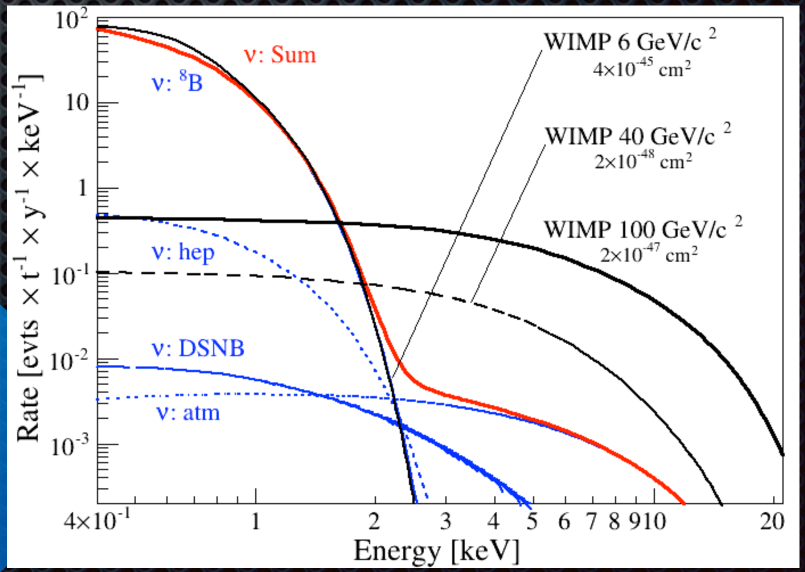
- **Backgrounds**
  - cosmic rays; cosmic activation of detector materials at the Earth's surface
  - natural (^{238}U, ^{232}Th, ^{40}K) and anthropogenic (^{85}Kr, ^{137}Cs, etc) radioactivity
  - **ultimately: solar, atmospheric and supernovae neutrinos** (coherent neutrino-nucleus scattering)



Cosmic rays: operate deep underground

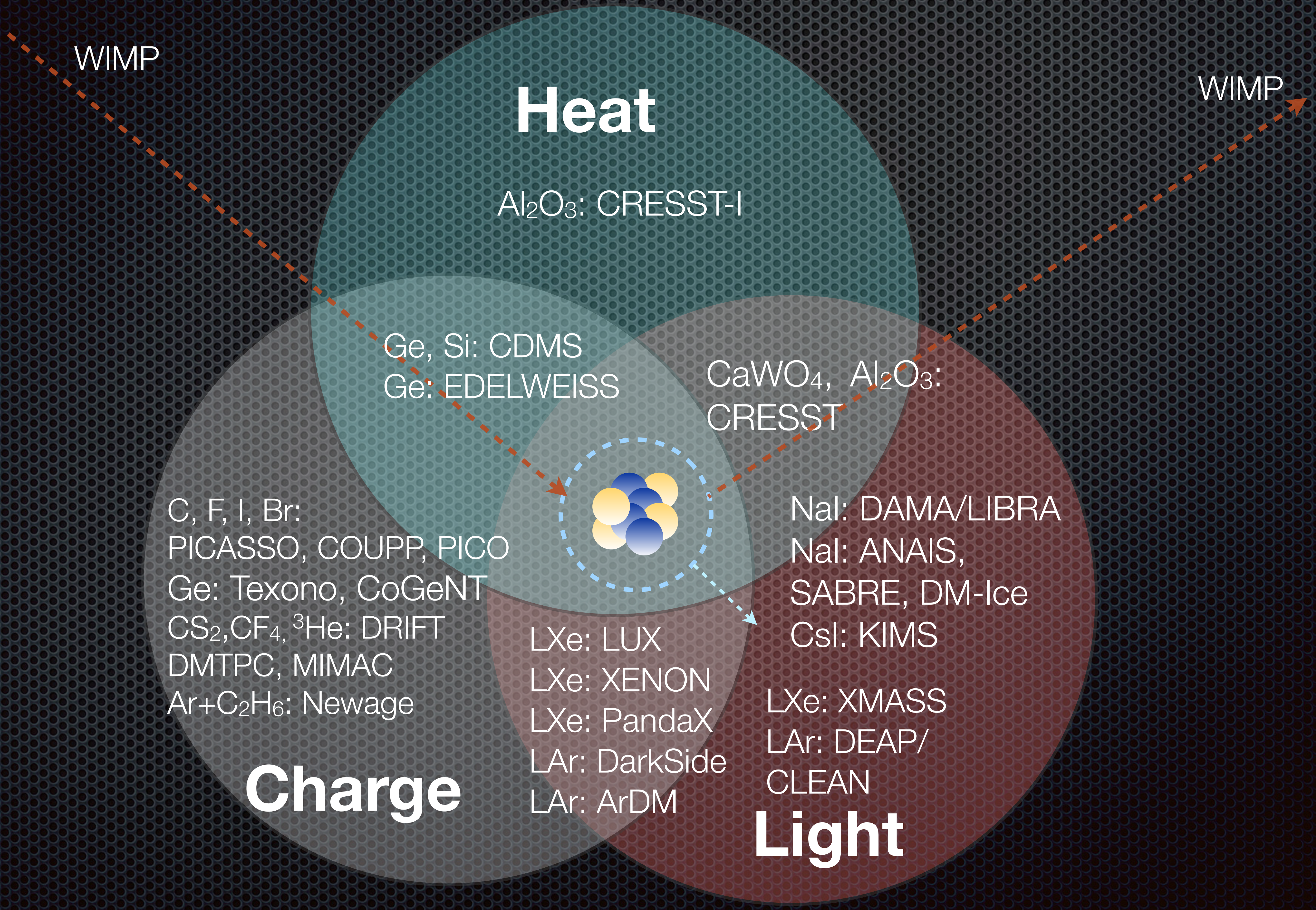
- **Specific dark matter signatures**
  - rate and shape of recoil spectrum depend on target material
  - motion of the Earth cause a
    - temporal variation in the rate
    - directional dependance





LB et al., JCAP01 (2014) 044

Direct Dark Matter Detection Techniques



WIMP

WIMP

Heat

Al_2O_3: CRESST-I

Ge, Si: CDMS
Ge: EDELWEISS

$CaWO_4$, Al_2O_3:
CRESST

C, F, I, Br:
PICASSO, COUPP, PICO
Ge: Texono, CoGeNT
CS_2, CF_4, ^3He: DRIFT
DMTPC, MIMAC
$Ar+C_2H_6$: Newage

NaI: DAMA/LIBRA
NaI: ANAIS,
SABRE, DM-Ice
CsI: KIMS

LXe: LUX
LXe: XENON
LXe: PandaX
LAr: DarkSide
LAr: ArDM

LXe: XMASS
LAr: DEAP/
CLEAN

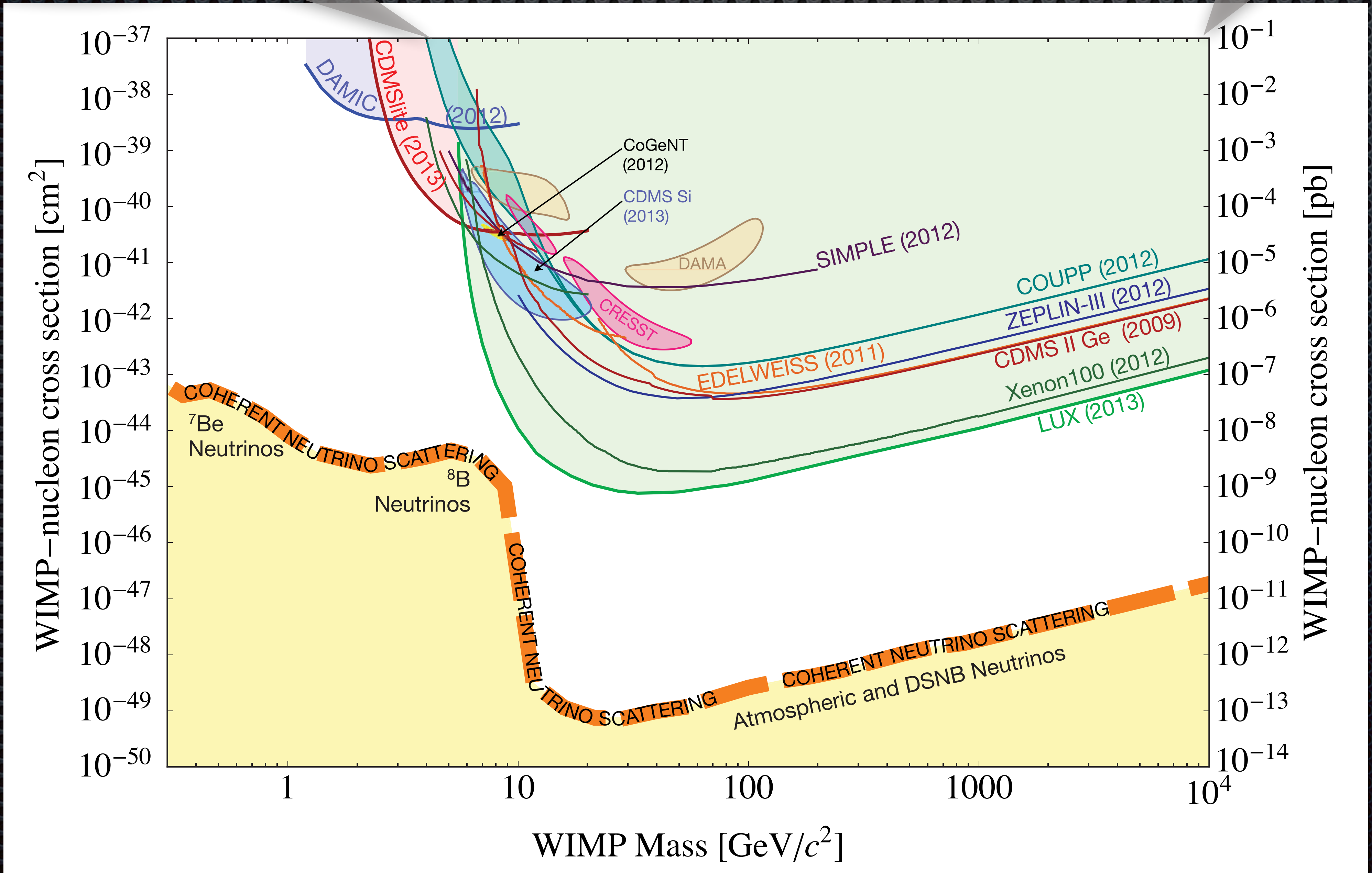
Charge

Light

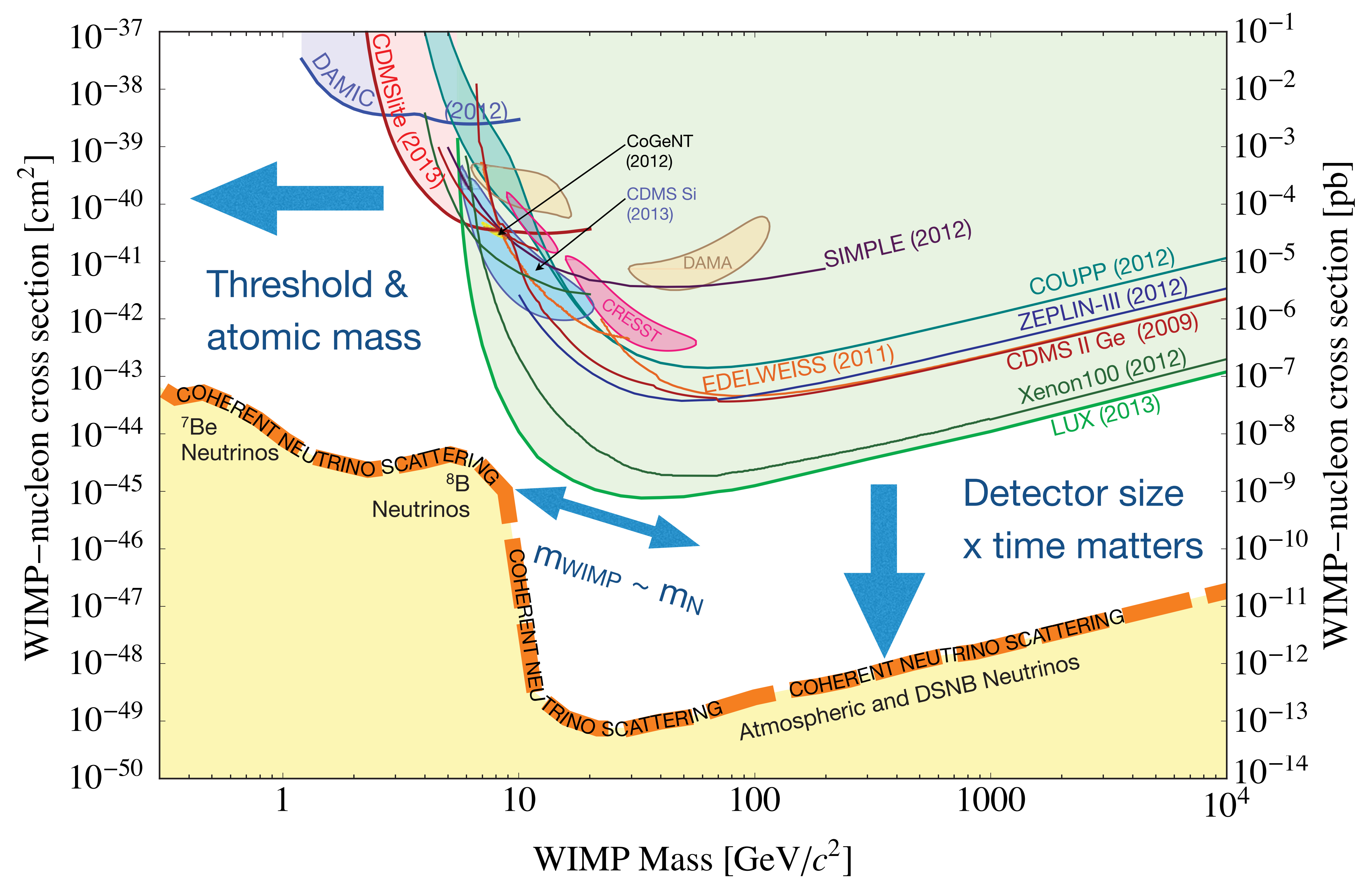
The WIMP landscape in 2014

"Anomalies" at low WIMP masses

Sensitivity to masses up to 10 TeV and above!



The WIMP landscape in 2014

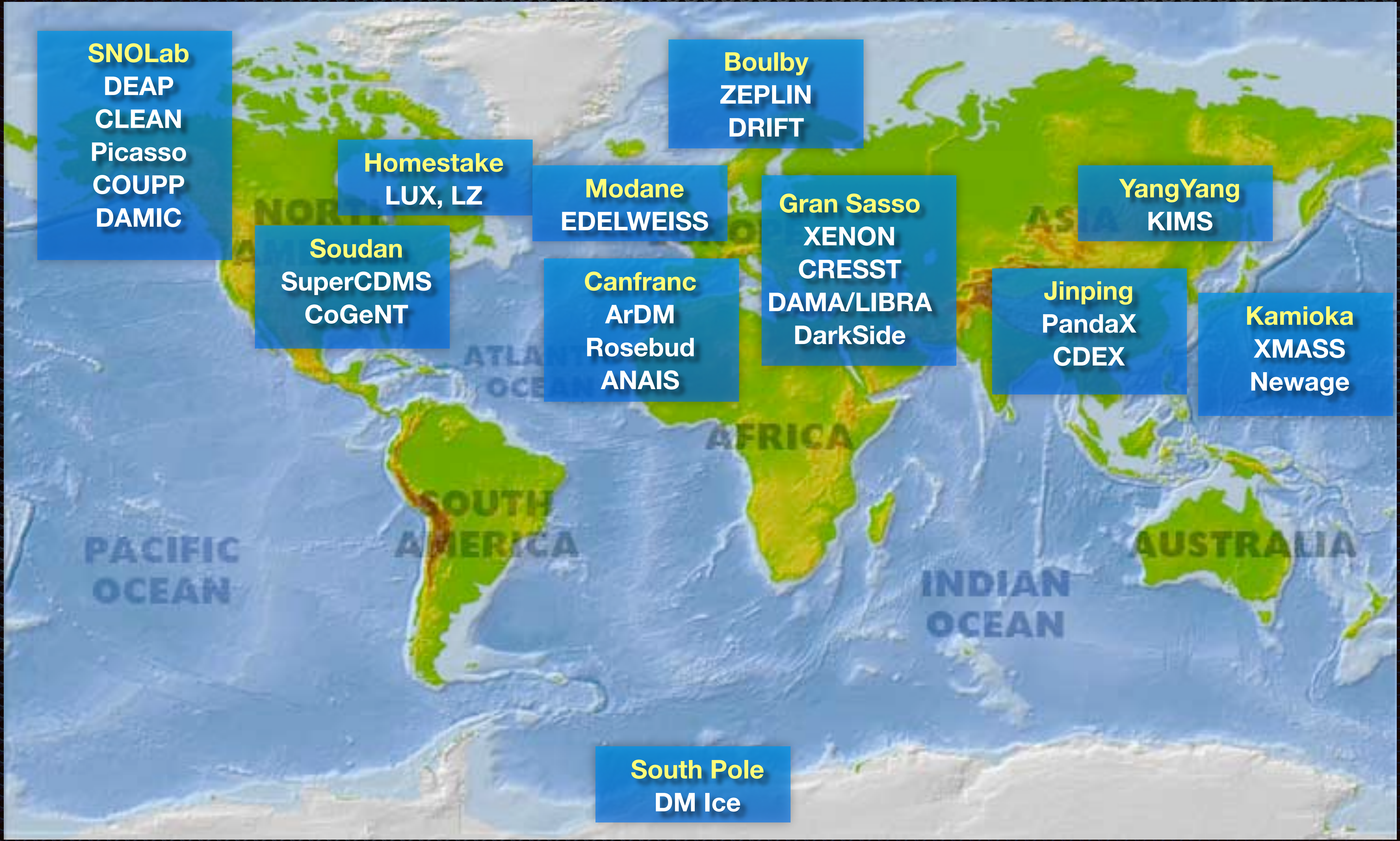


Threshold & atomic mass

$m_{WIMP} \sim m_N$

Detector size x time matters

What next? We need *a variety of techniques* to convincingly discover and constrain WIMPs!



SNOLab
DEAP
CLEAN
Picasso
COUPP
DAMIC

Homestake
LUX, LZ

Soudan
SuperCDMS
CoGeNT

Boulby
ZEPLIN
DRIFT

Modane
EDELWEISS

Canfranc
ArDM
Rosebud
ANAIS

Gran Sasso
XENON
CRESST
DAMA/LIBRA
DarkSide

YangYang
KIMS

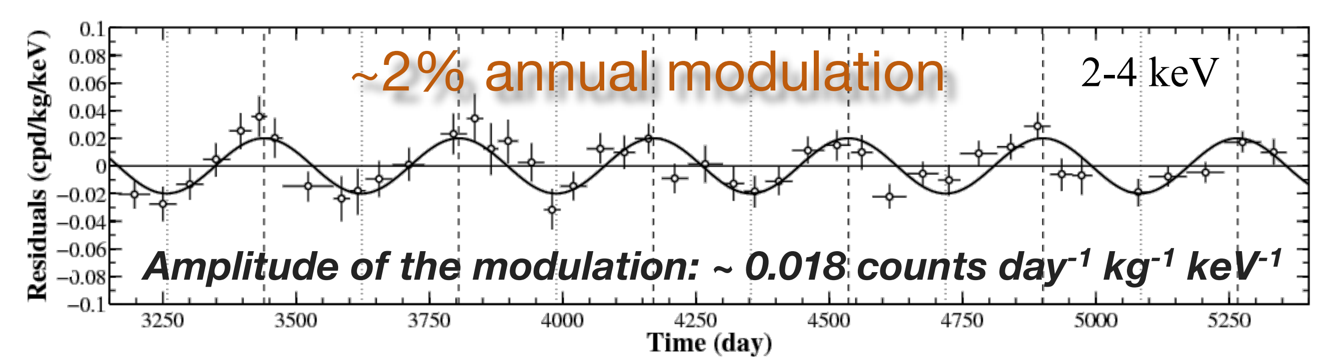
Jinping
PandaX
CDEX

Kamioka
XMASS
Newage

South Pole
DM Ice

DAMA/LIBRA annual modulation signal

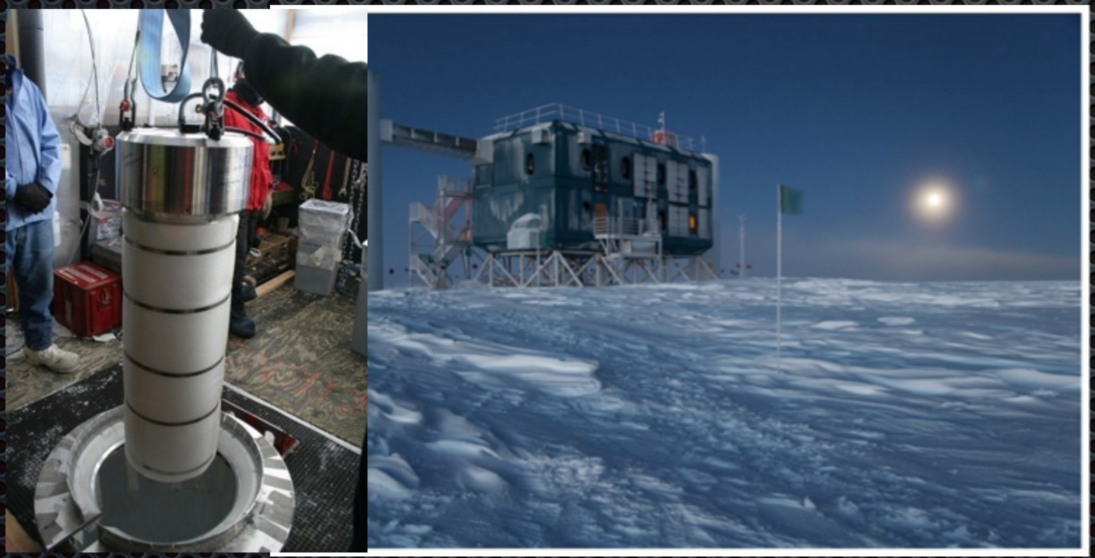
- The DAMA/LIBRA signal remains robust and generally consistent with a dark matter interpretation (period = 1 year, phase = June 2 ± 7 days)



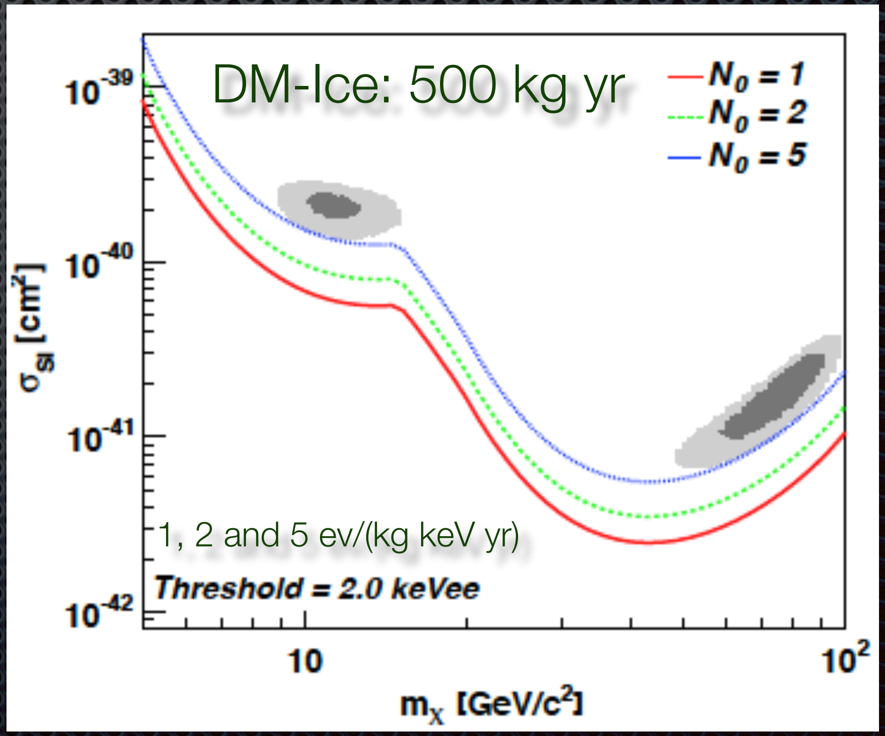
R. Bernabei et al, EPJ-C67 (2010)

see talks by P. Belli, F. Cappella

- Several experiments aim to directly probe the results: KIMS, ANAIS, Sabre, DM-Ice
- DM-Ice at the South Pole: only experiment in the southern hemisphere, where seasonal variation different from DM modulation (IceCube provides muon monitoring)

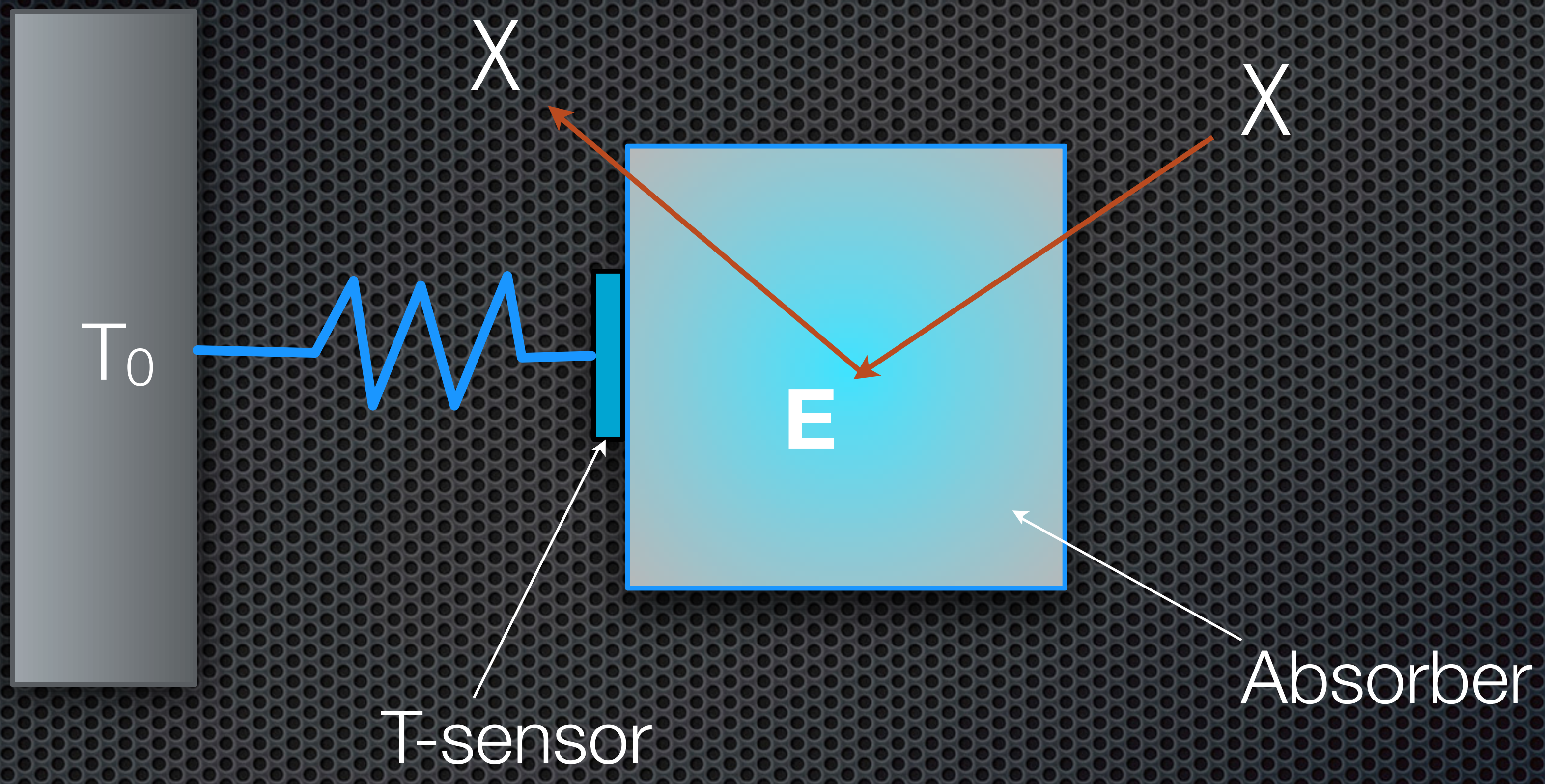


Definitive (5σ) detection or exclusion with 500 kg-yr NaI(Tl) (DAMA x 2 yrs) and same or lower threshold (< 2 keV$_{ee}$)



Cryogenic Experiments at T~ mK

- Detect a *temperature increase* after a particle interacts in an absorber

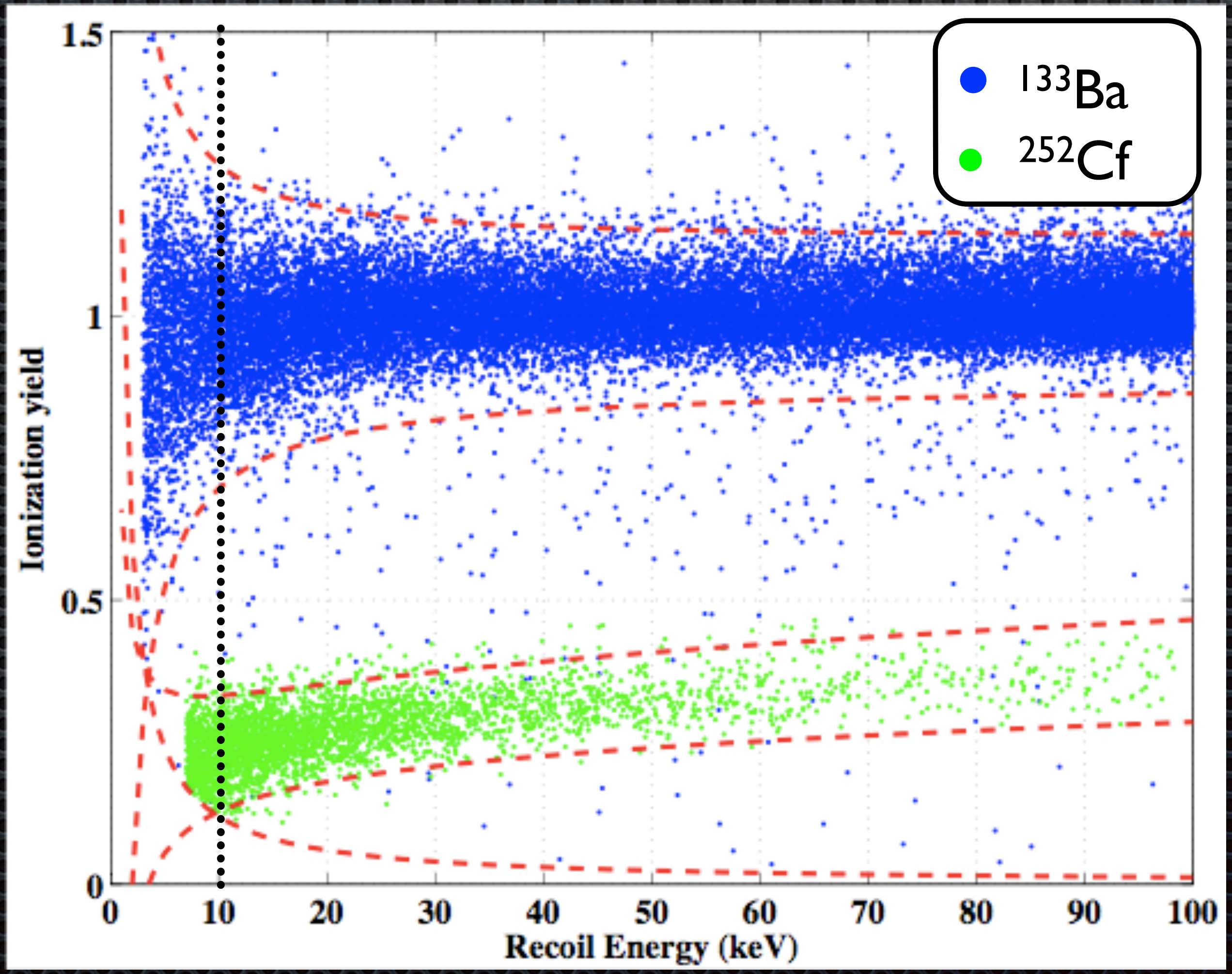


- T-sensors: superconductor thermistors or superconducting transition sensors

Cryogenic Experiments at T~ mK

- **High** sensitivity to nuclear recoils, good energy resolution, **low energy threshold (keV to sub-keV) => low-mass WIMPs**
- **Ratio of light/phonon or charge/phonon:**
  - nuclear versus electronic recoils discrimination **-> separation of S and B**

Ratio of charge (or light) to phonon

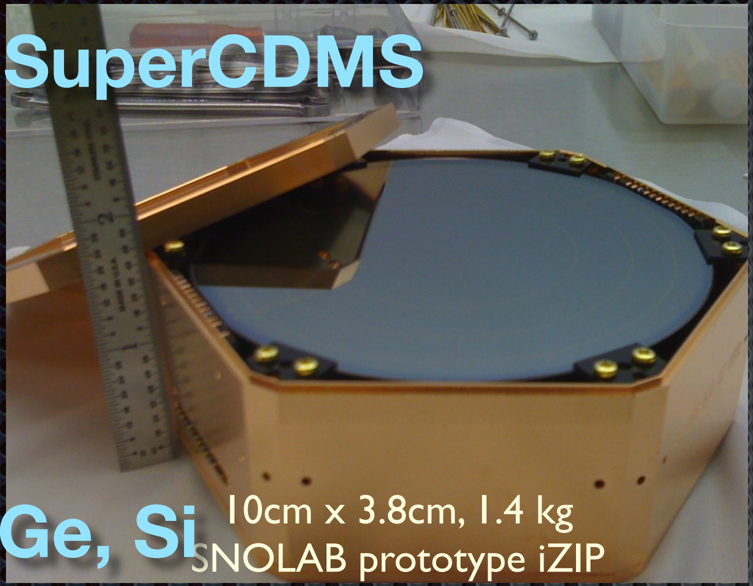


Background region

Expected signal region

Cryogenic Experiments at T~ mK

- Absorber masses from ~ 100 g to 1400 g

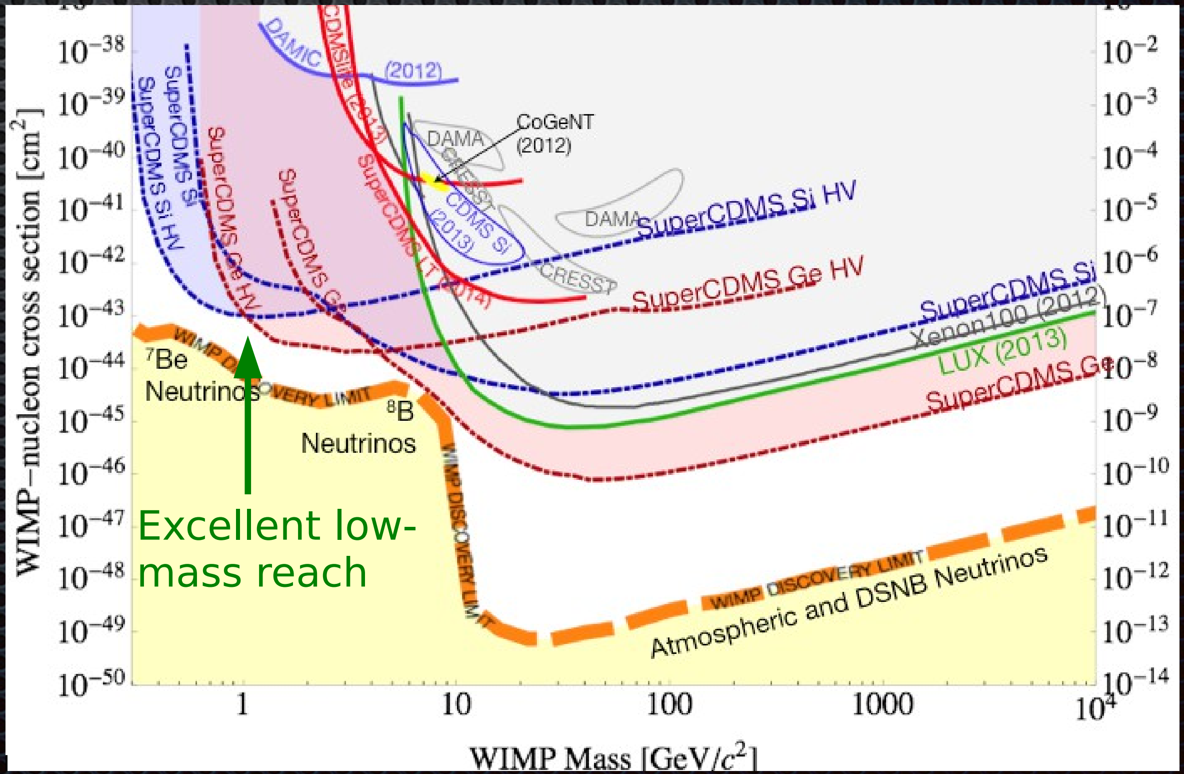


10cm x 3.8cm, 1.4 kg
SNOLAB prototype iZIP

New CRESST detector modules for Run33

EDELWEISS Ge FID Detector

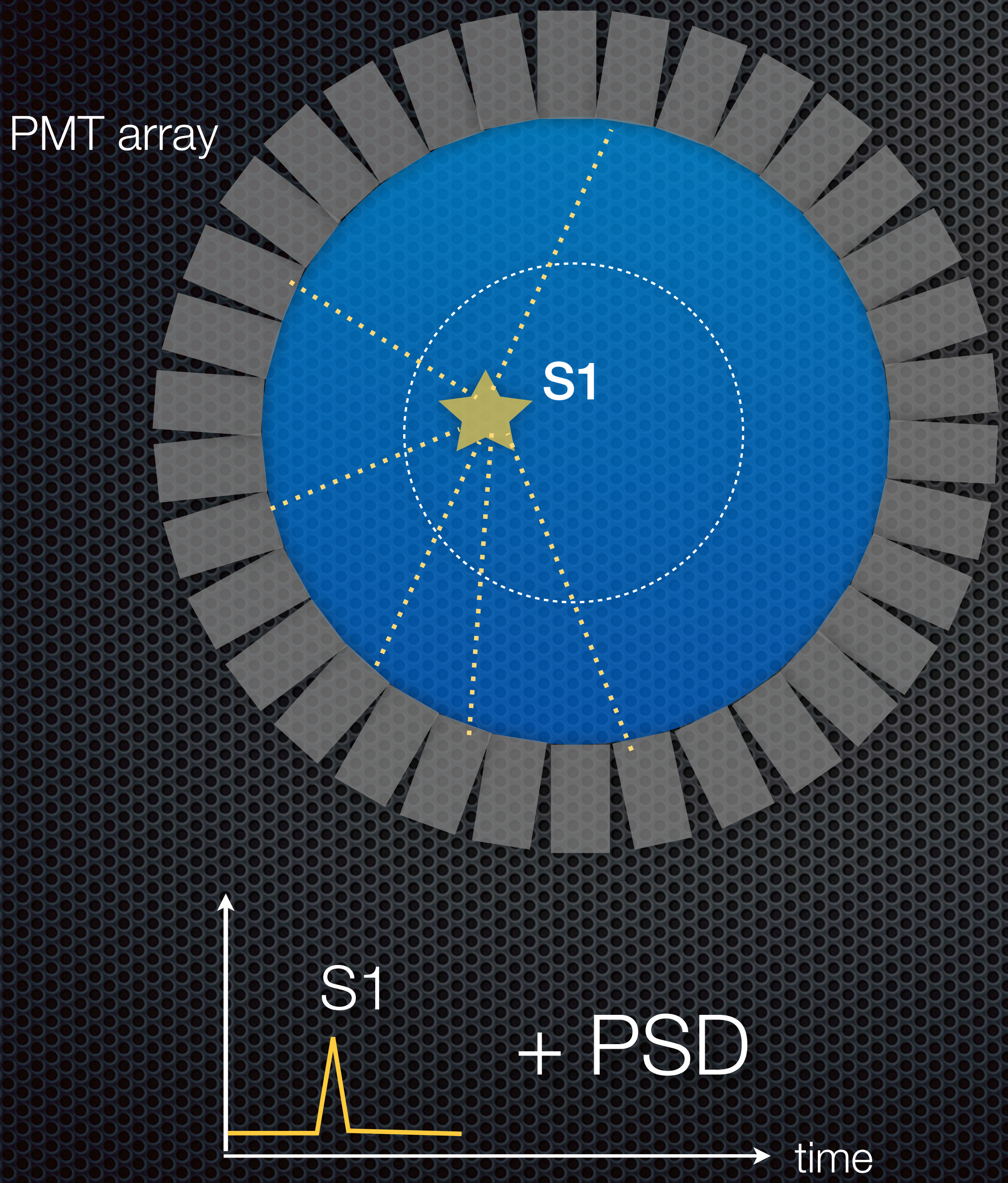
- Collaboration between SuperCDMS and EURECA (CRESST + EDELWEISS) at SNOLAB, at the ~100 kg level (cryostat can house up to 400 kg target material)
- Start data taking in 2018
- SI cross sections: 8×10^{-47} cm^2



Excellent low-mass reach

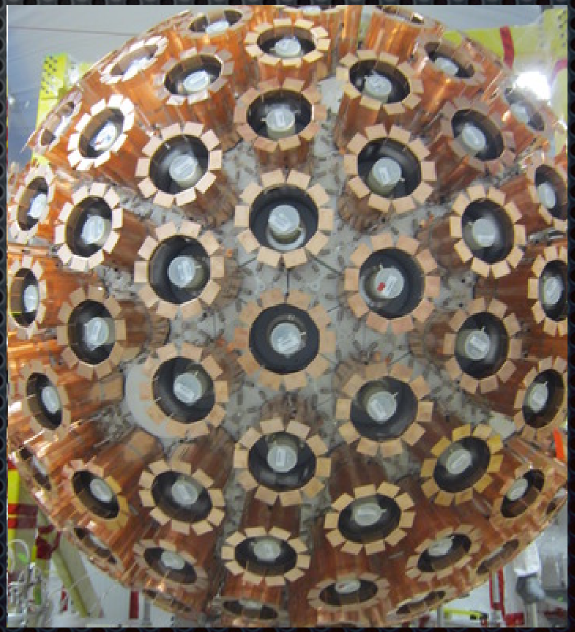
Single-phase noble liquid detectors

Single phase



+ PSD

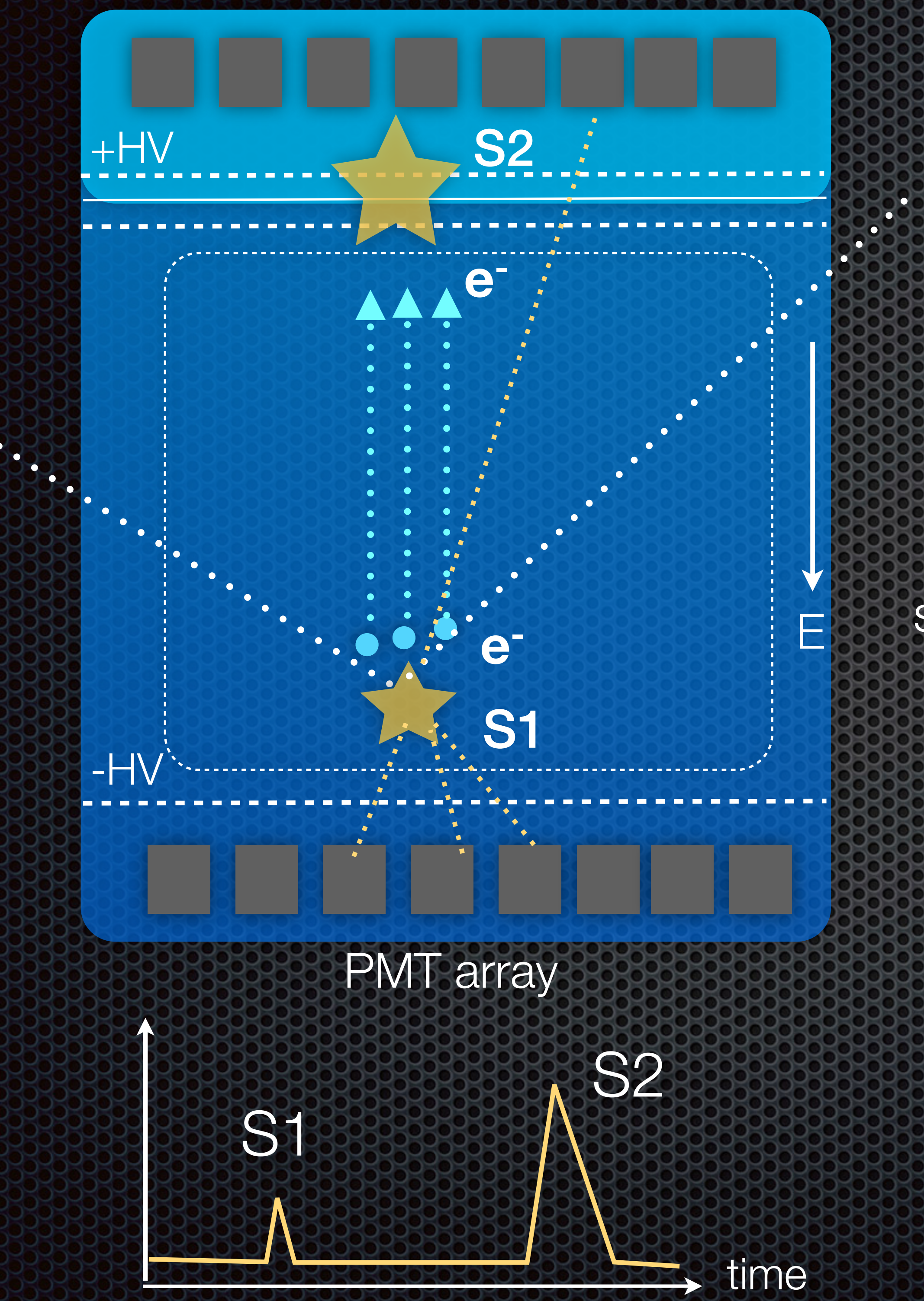
XMASS at Kamioka



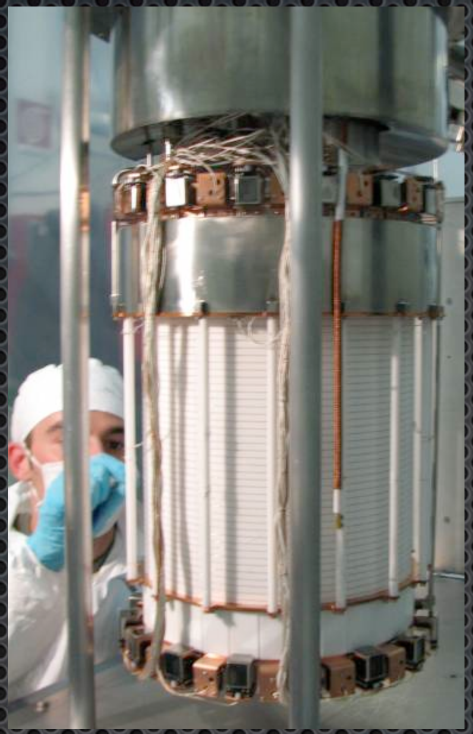
DEAP and CLEAN at SNOLAB

Double-phase noble liquid detectors

Double phase (TPC)



XENON100



see talk by M. Selvi

LUX

DarkSide

see talk by S.M. Mari

XENON100 (LXe) and DarkSide (LAr) at LNGS

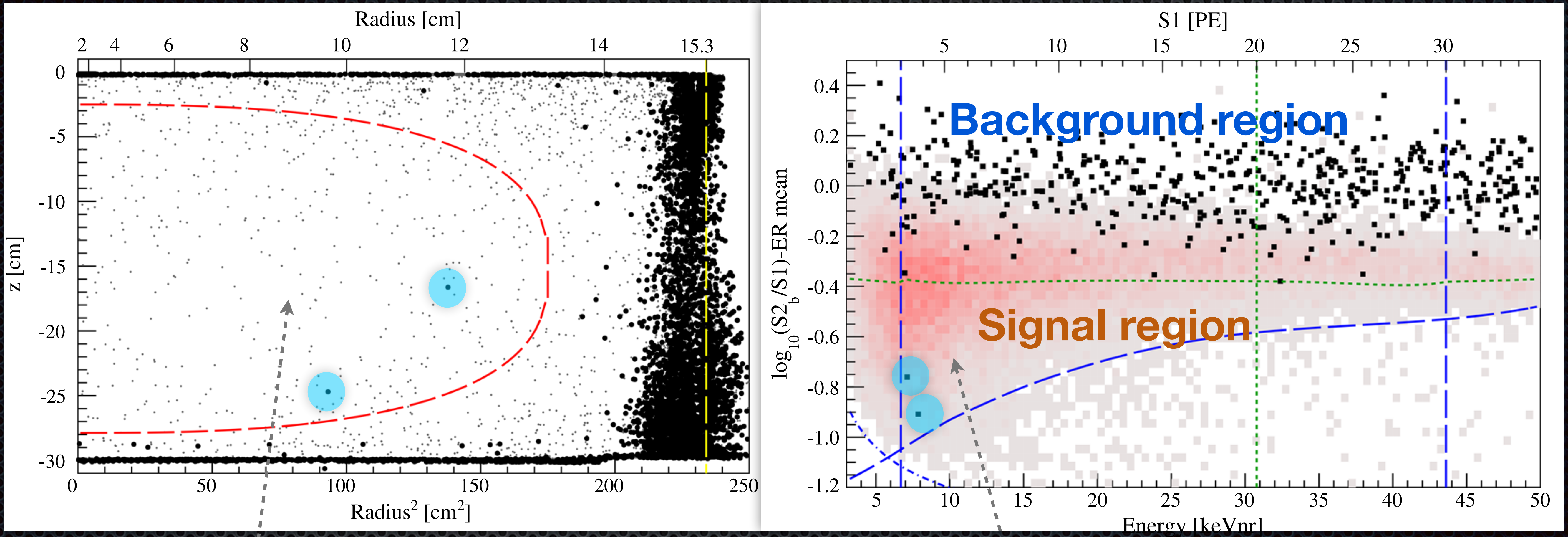
LUX (LXe) at SURF, PandaX (LXe) at CJPL

ArDM (LAr) at Canfranc

Target masses between ~ 50 kg - 1 ton

Example: XENON100 dark matter data

- Exposure: ~ 225 days x 34 kg fiducial liquid xenon mass
- No dark matter signal: 2 events observed, 1 expected from backgrounds



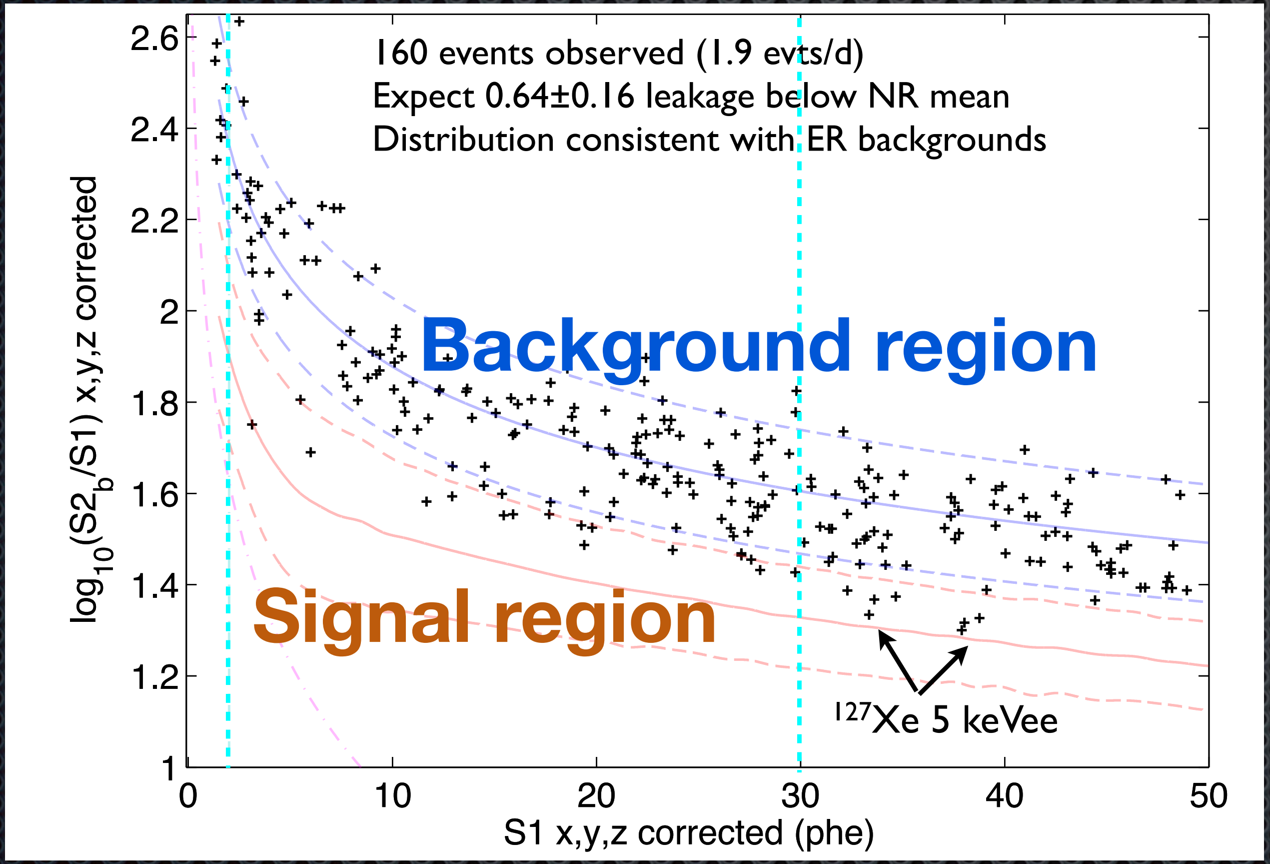
Phys. Rev. Lett. 109 (2012)

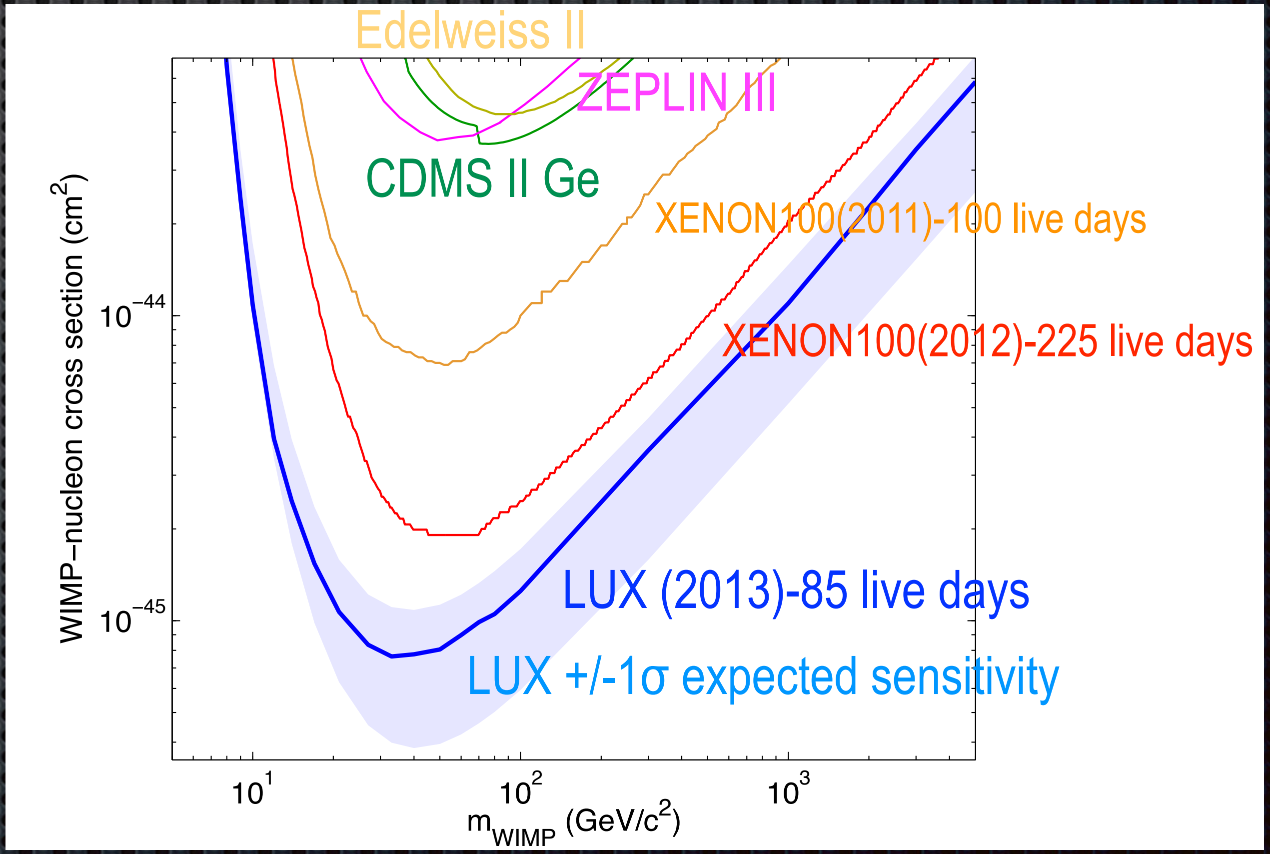
Fiducial mass region:
34 kg of liquid xenon
406 events in total

Signal region:
2 events are observed
0.79 ± 0.16 gamma leakage events expected
0.17 +0.12-0.7 neutron events expected

Example: LUX dark matter data

- Exposure: 85.3 days x 118 kg fiducial liquid xenon mass
- No sign of dark matter, observed distribution consistent with backgrounds
- New run of 300 live-days planned for 2014/15, sensitivity increase by a factor of 5

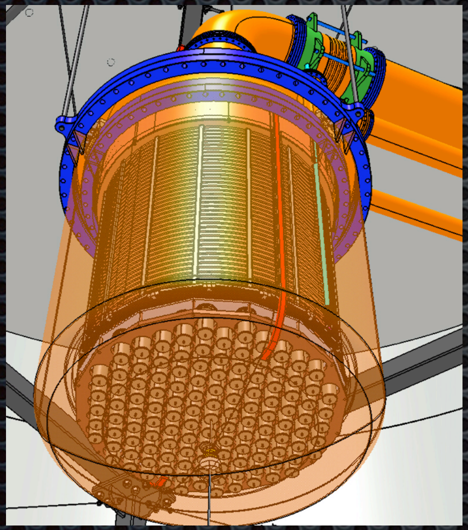




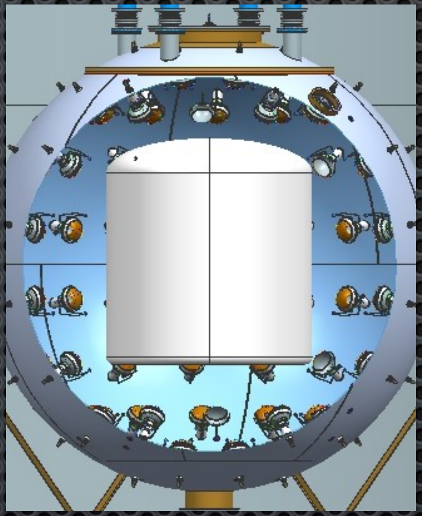
Accepted in PRL, arXix: 1310.8214

Future noble liquid detectors

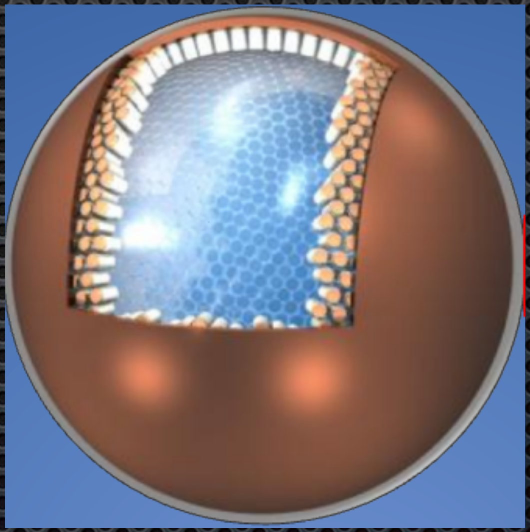
- **Under construction**: XENON1T at LNGS, 3.1 t LXe in total
- **Future:** LUX-ZEPLIN (7 t LXe), XENONnT (7 t LXe), XMASS (5 t LXe), DarkSide (5 t LAr)
- **Design and R&D:** “ultimate detector” DARWIN (~20 t LXe and/or 50 t LAr)



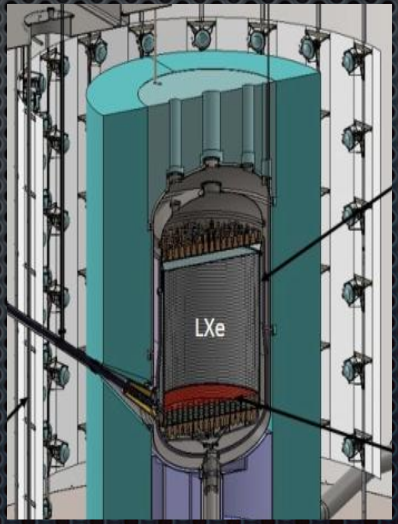
XENON1T: 3.3 t LXe



DarkSide: 5 t LAr



XMASS: 5t LXe

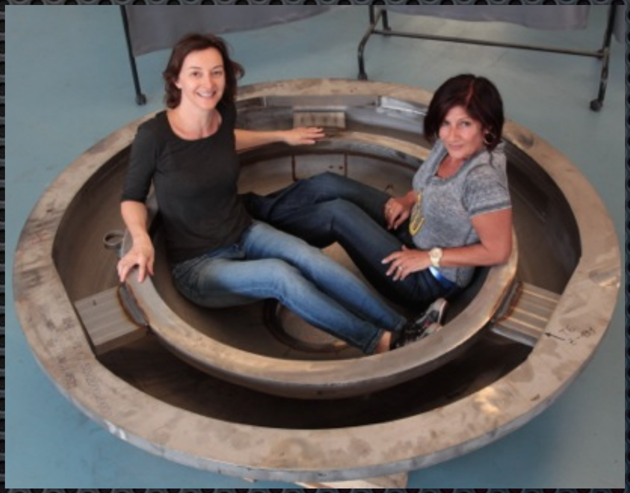


LZ: 7t LXe

DARWIN: 20 t LXe/LAr

The XENON1T Experiment

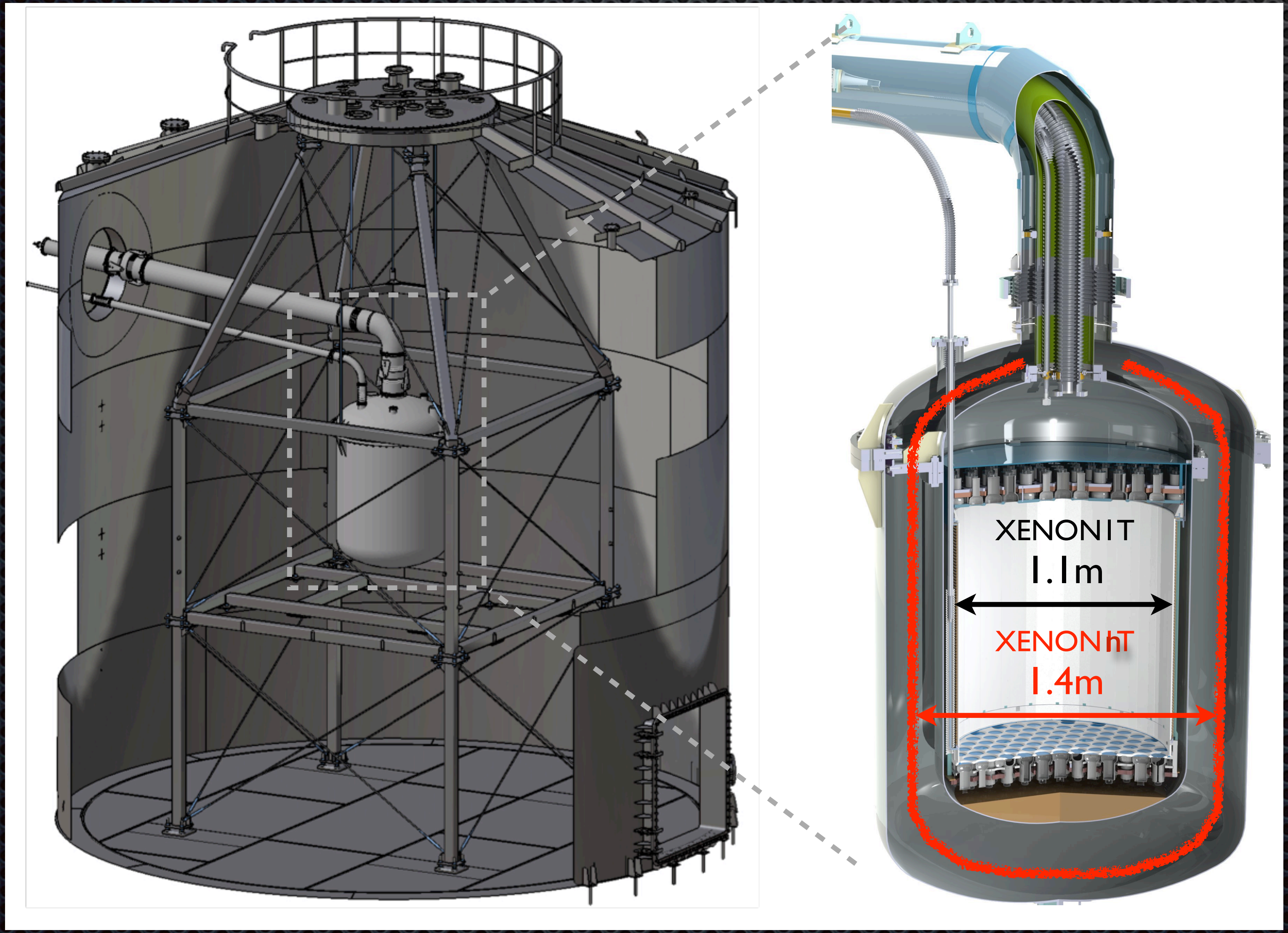
- Under construction at LNGS since fall 2013
- Total LXe mass: 3.1 t, 1 m charge drift; 248 3-inch PMTs; background goal:*100 x lower than XENON100, ~5 x* 10^{-2} *events/(t-d-keV)*
- Commissioning and science run: mid and late 2015
- Goal: 2 x 10^{-47} cm^2 at a WIMP mass of ~ 50 GeV



see talk by M. Selvi

XENONnT: 2018 - 2020

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



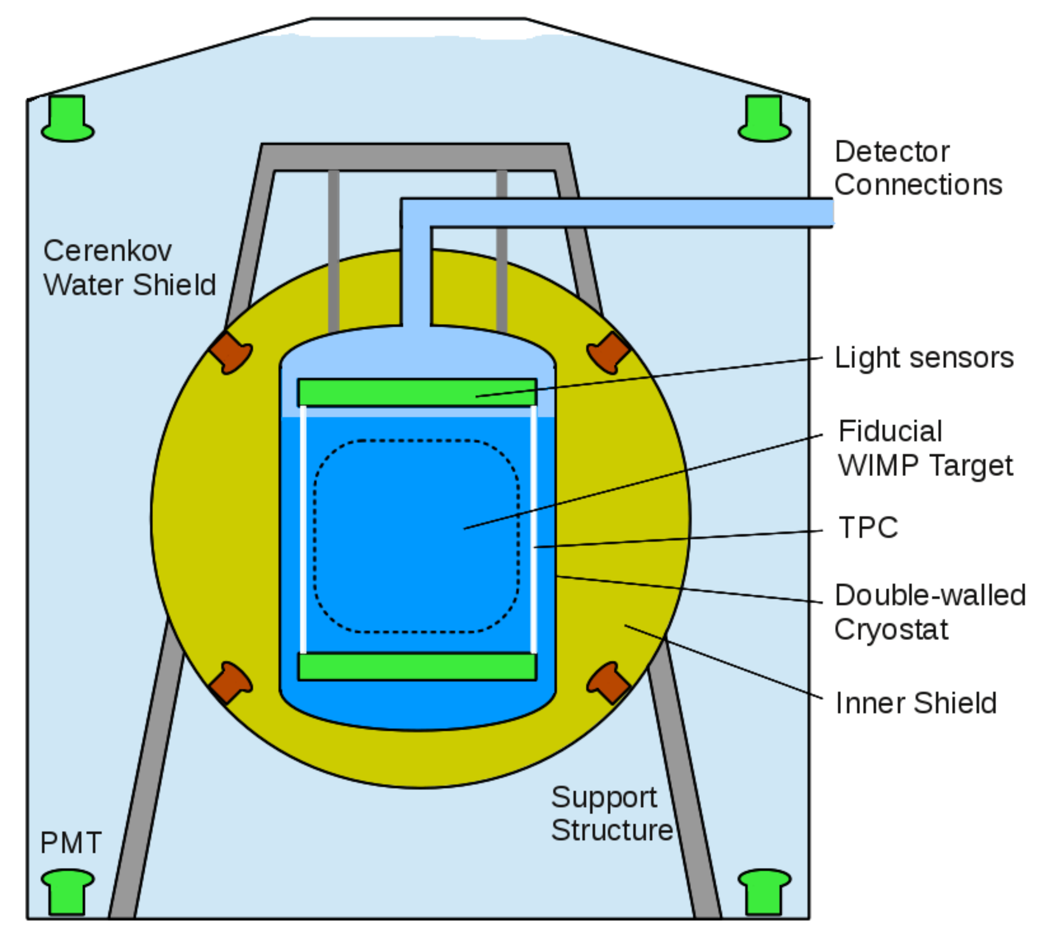
- Water tank + muon veto
- Outer cryostat and support structure
- Cryogenics and purification system
- LXe storage system
- Cables installed for XENONnT as well
- More LXe, PMTs, electronics will be needed

DARWIN

DARk matter WImp search with Noble liquids

- R&D and design study for next-generation noble liquid detector for $m_W > 6$ GeV
- Physics goal: build the “ultimate WIMP detector”, before the possibly irreducible neutrino background takes over; probe WIMP cross sections down to ~10^{-49} cm^2

darwin.physik.uzh.ch



~20 t LXe and/or 50 t LAr cryostat
in large water Cherenkov shield at LNGS

DARWIN Consortium: 28 groups from 10 countries (Europe, USA, Israel)

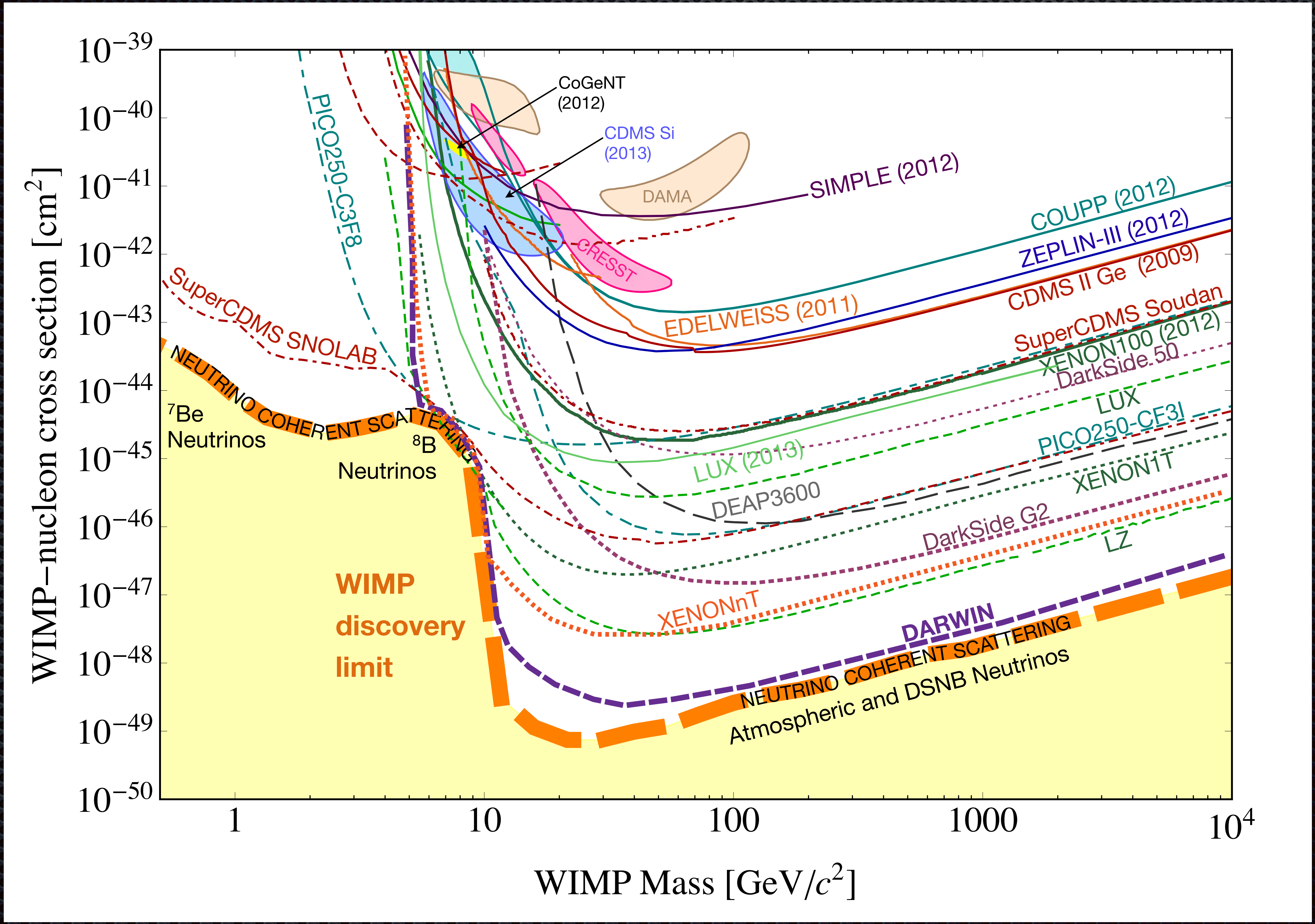
On the European and Swiss astroparticle physics roadmaps

Initial funding by ASPERA

LZ

Construction 2020; physics runs 2022-2026

The WIMP landscape: prospects

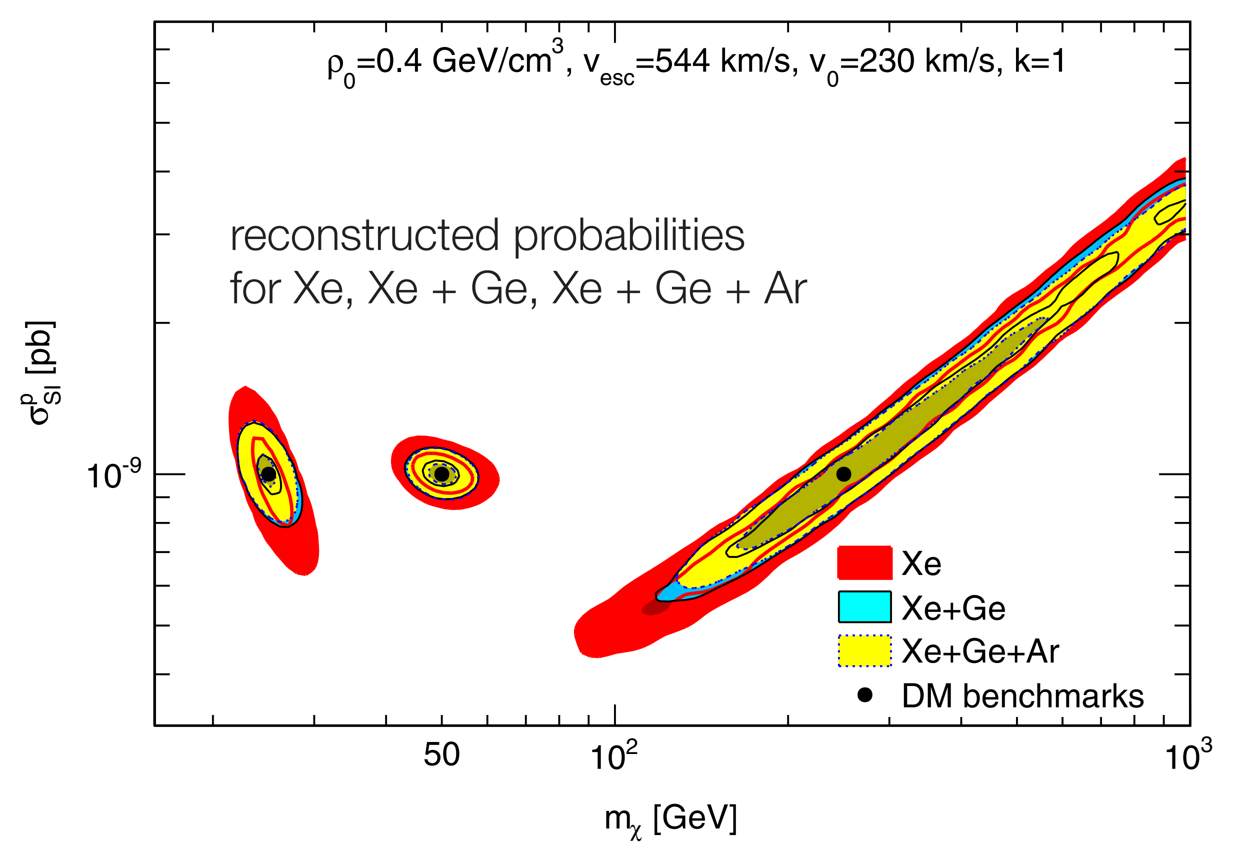


What can we say about the dark matter should we find it?

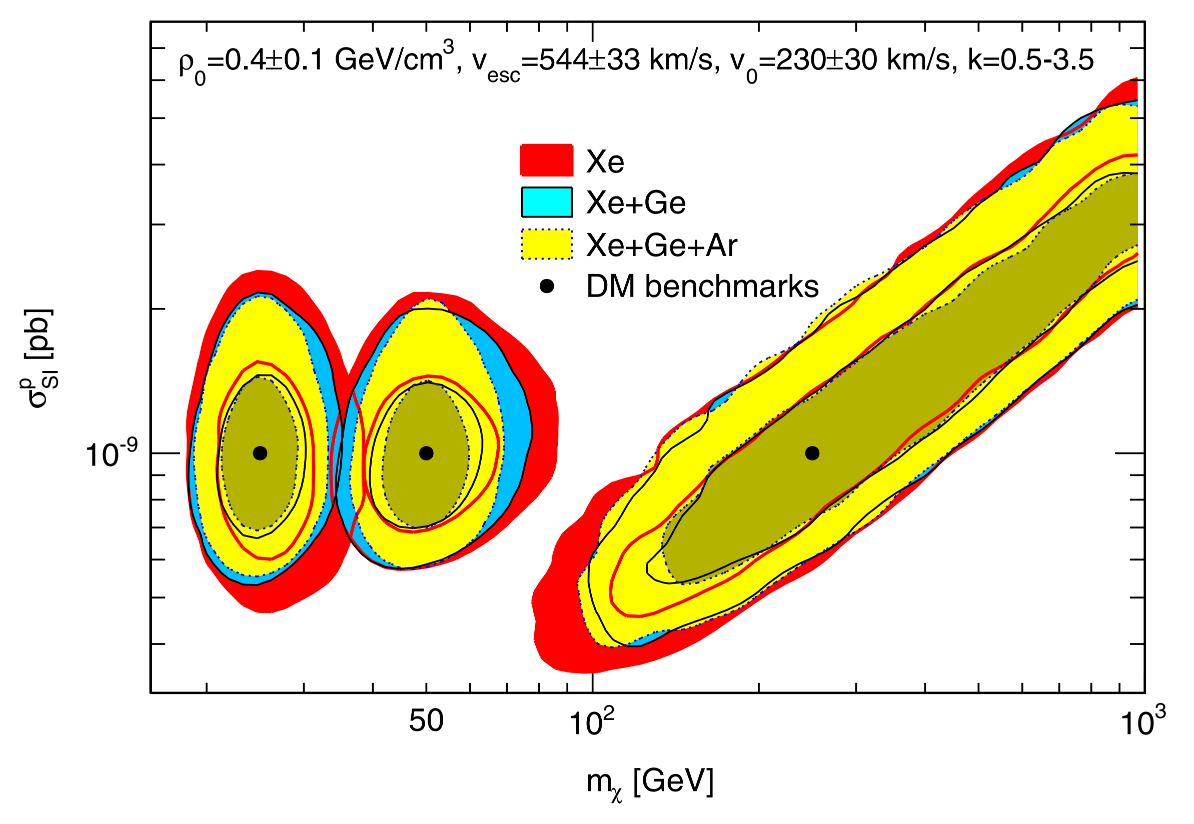
- Different targets are sensitive to different directions in the m_χ- σ_{SI} plane

Xe: 2.0 t x yr, 10 keV threshold
Ge: 2.2 t x yr, 10 keV threshold
Ar: 6.4 t x yr, 30 keV threshold

fixed galactic model



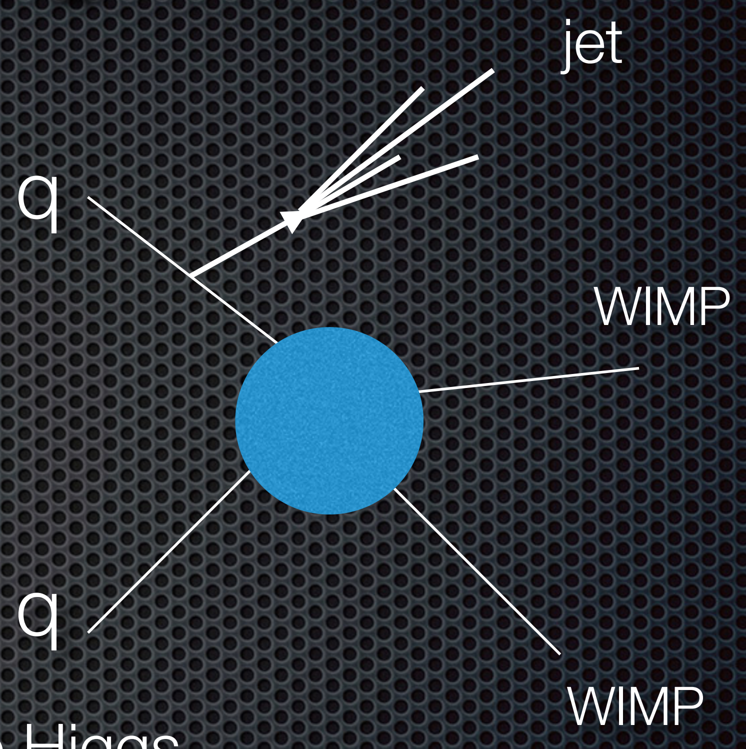
including galactic uncertainties



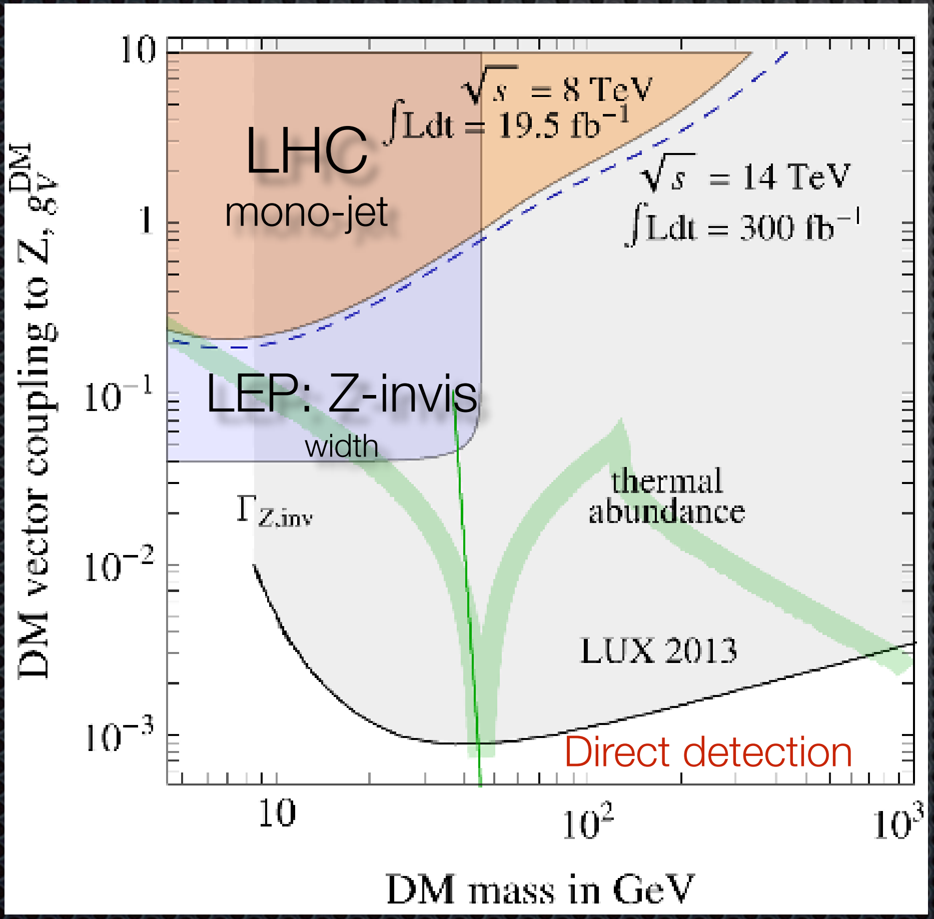
Miguel Pato, Laura Baudis, Gianfranco Bertone, Roberto Ruiz de Austri, Louis E. Strigari and Roberto Trotta
Phys. Rev. D 83, 083505 (2011)

Comparison with accelerators

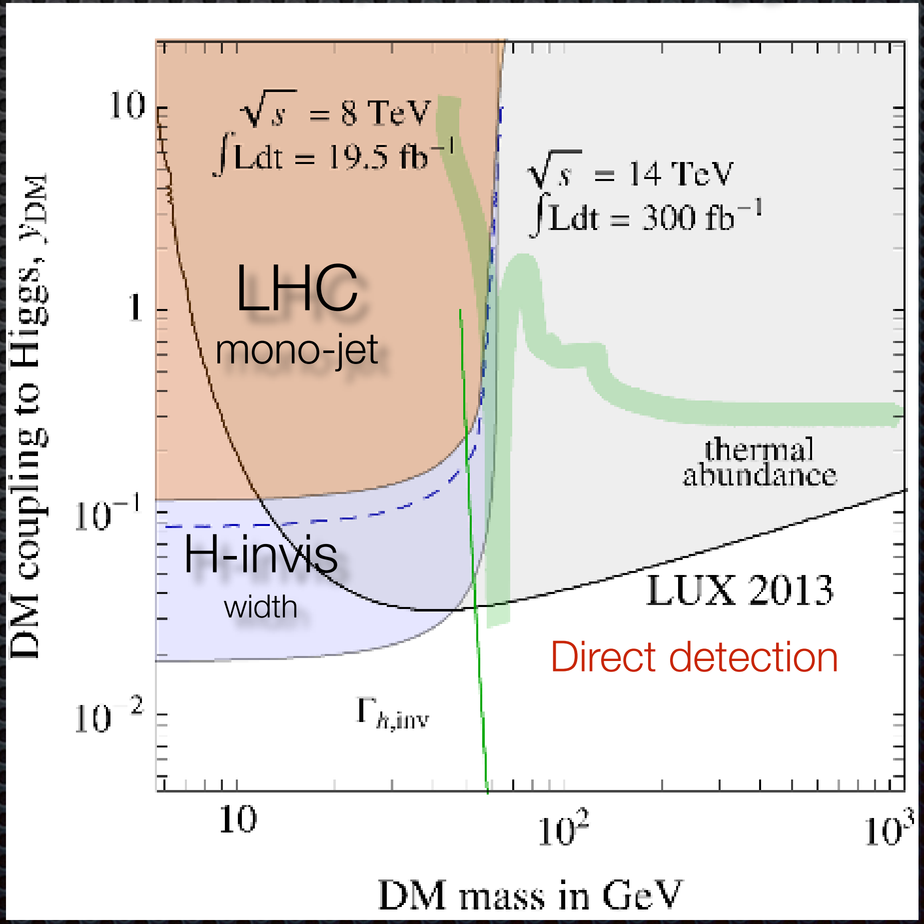
- WIMPs produced at colliders will leave the detector unnoticed
- If other particles (jets) are produced along with a pair of WIMPs, large amounts of missing transverse energy can be observed
- Examples: dark matter that couples to SM particles (Z and Higgs)

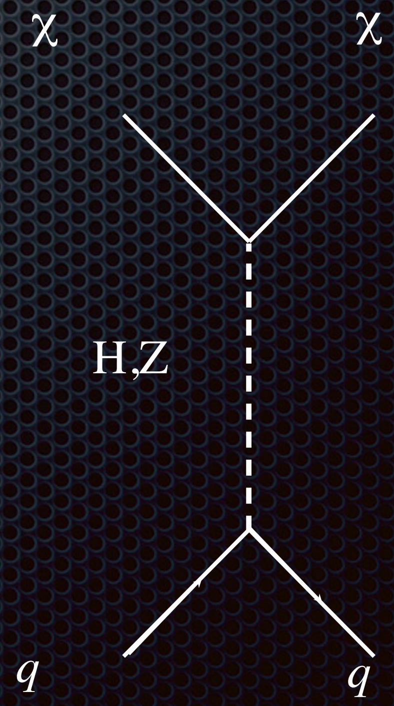


DM couples to the Z



DM couples to the Higgs

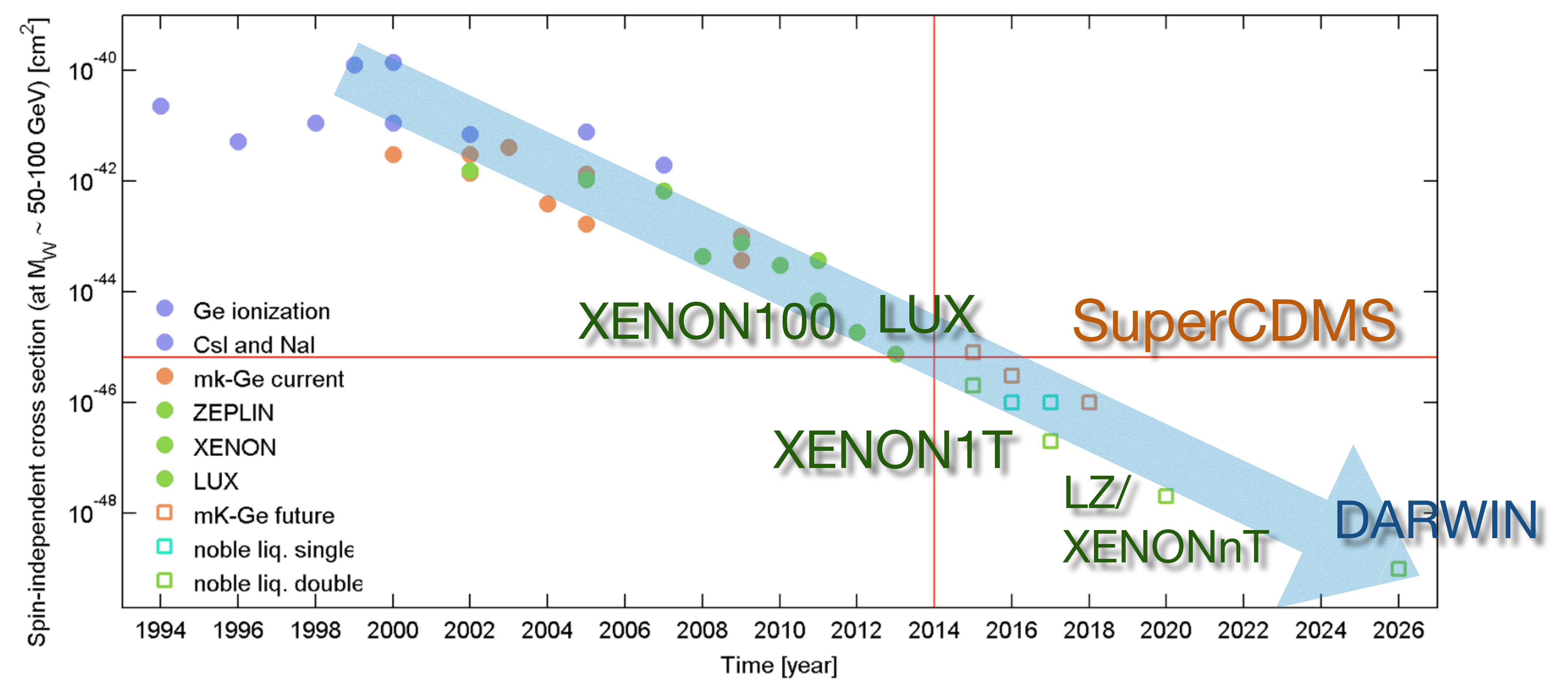




De Simone, Giudice, Strumia, JHEP 06, 2014

Will we detect WIMP dark matter soon?

L. B., Physics of the Dark Universe 4, Sept 2014

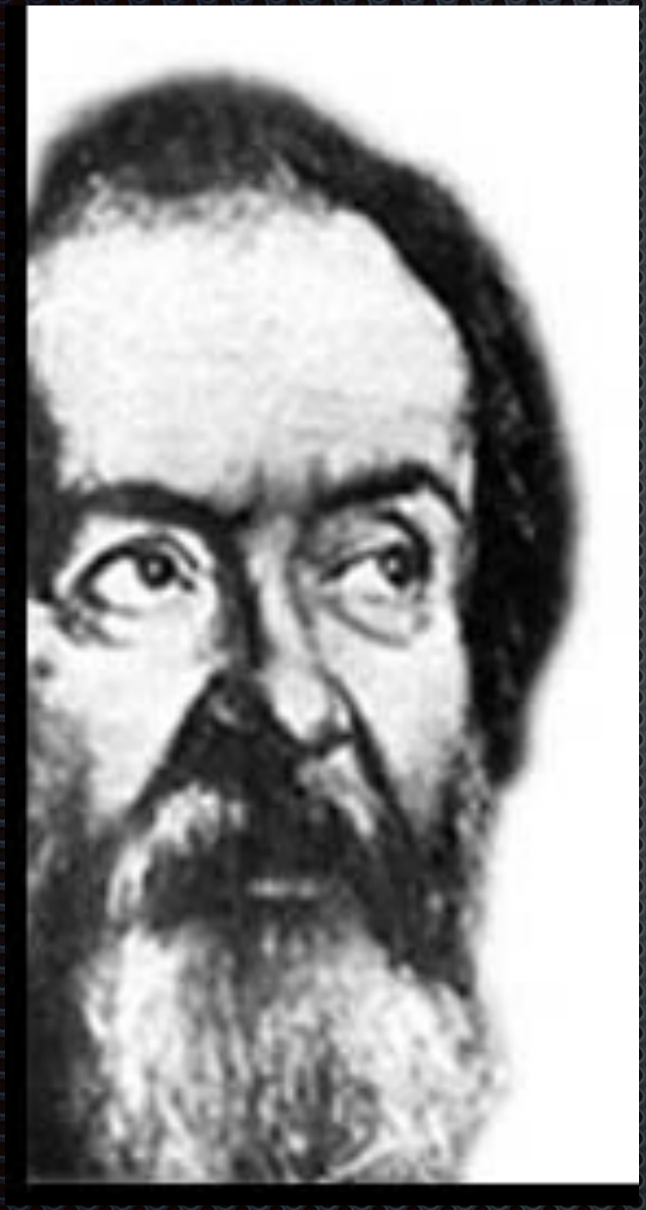


About a factor of *10 increase in sensitivity every 2 years*

Who knows! Perhaps (hopefully?!) by 2026…

Summary and Prospects

- Cold dark matter is still here with us
- It could be made of a new, heavy, neutral, stable and weakly interacting particle
- *We have entered the era of data: direct detection, the LHC, indirect detection*
- Direct detection experiments have reached unprecedented sensitivity (cross sections down to few x 10^{-9} pb) and can probe WIMP with masses from a few GeV to tens of TeV
- "Ultimate" WIMP detectors might be able to prove or disprove the WIMP hypothesis and provide complementary information to *indirect searches and the LHC*
- However, we should be prepared for surprises!



‘The constitution of the universe may be set in first place among all natural things that can be known.

For coming before all others in grandeur by reason of its universal content, it must also stand above them all in nobility as their rule and standard.’

Galileo Galilei, *Dialogue*

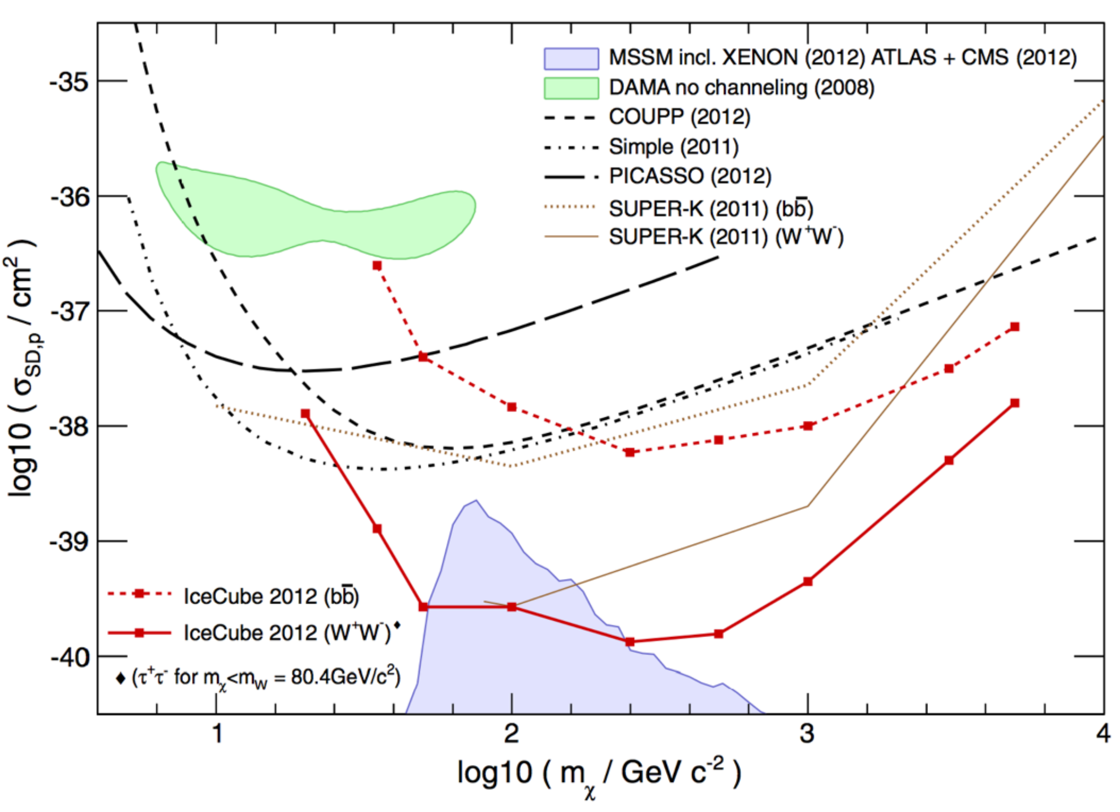
The End

Comparison with indirect detection

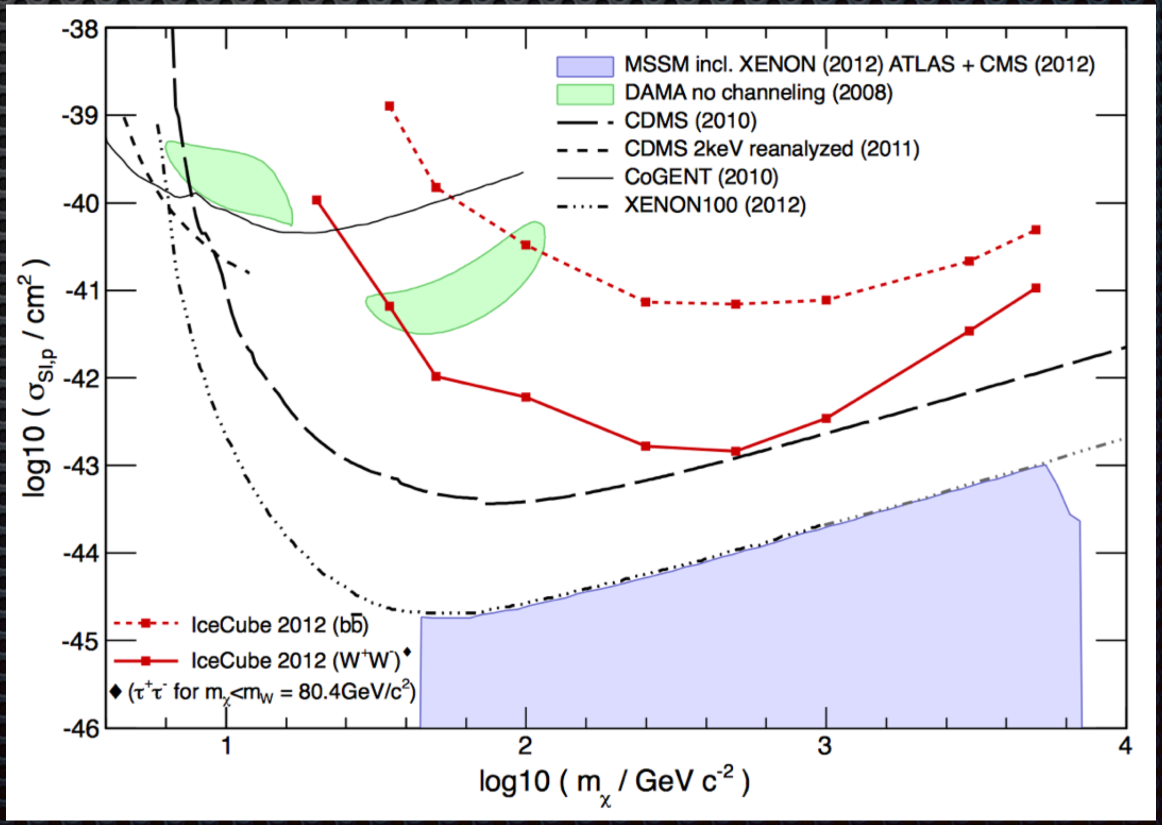
- Early universe: WIMPs are kept in equilibrium with SM particles via self-annihilation
- Today: WIMPs expected to annihilate with the same cross section in regions where density is enhanced

$$\Omega_{\mathrm{WIMP}} = 0.23 \times \frac{10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

IceCube SD

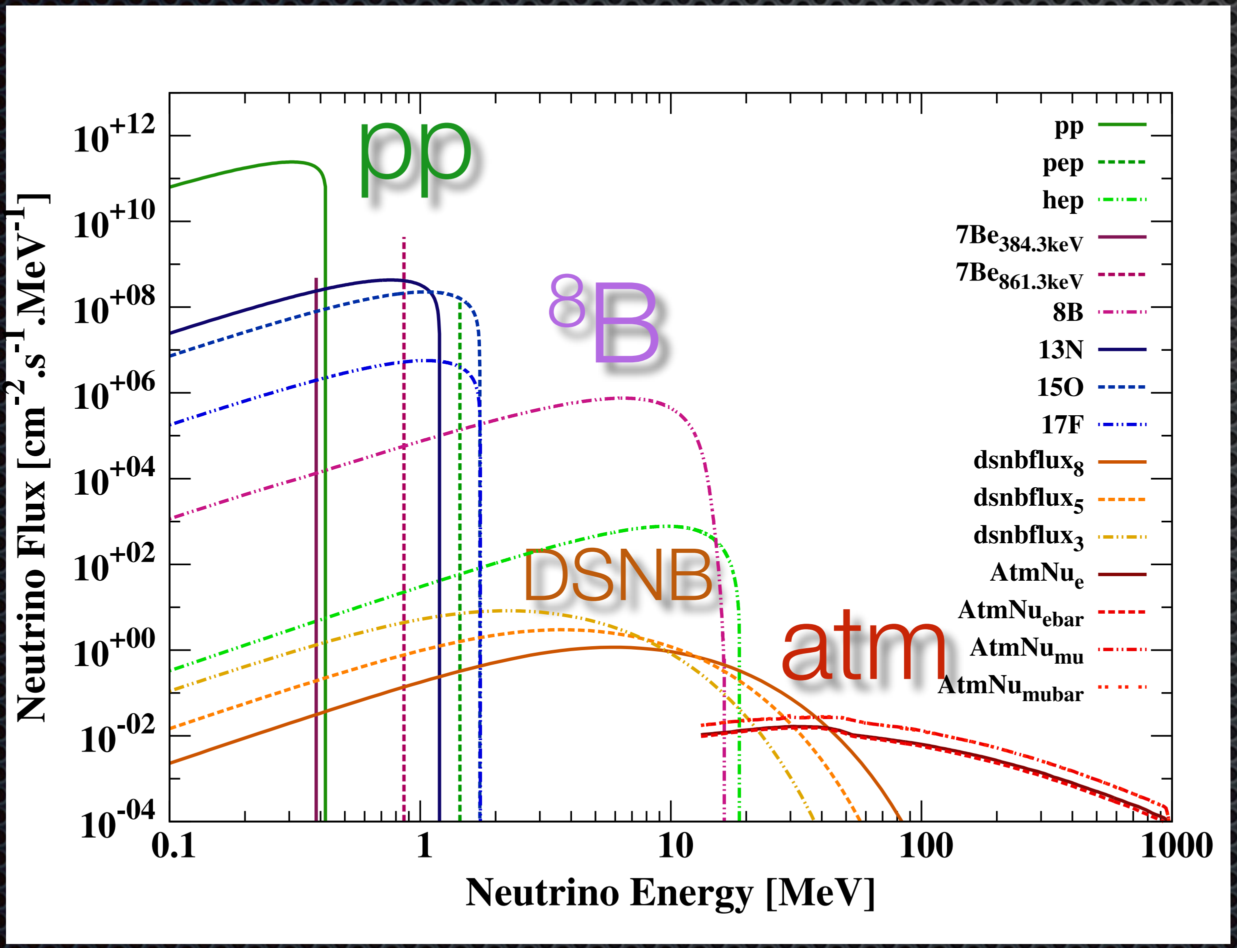


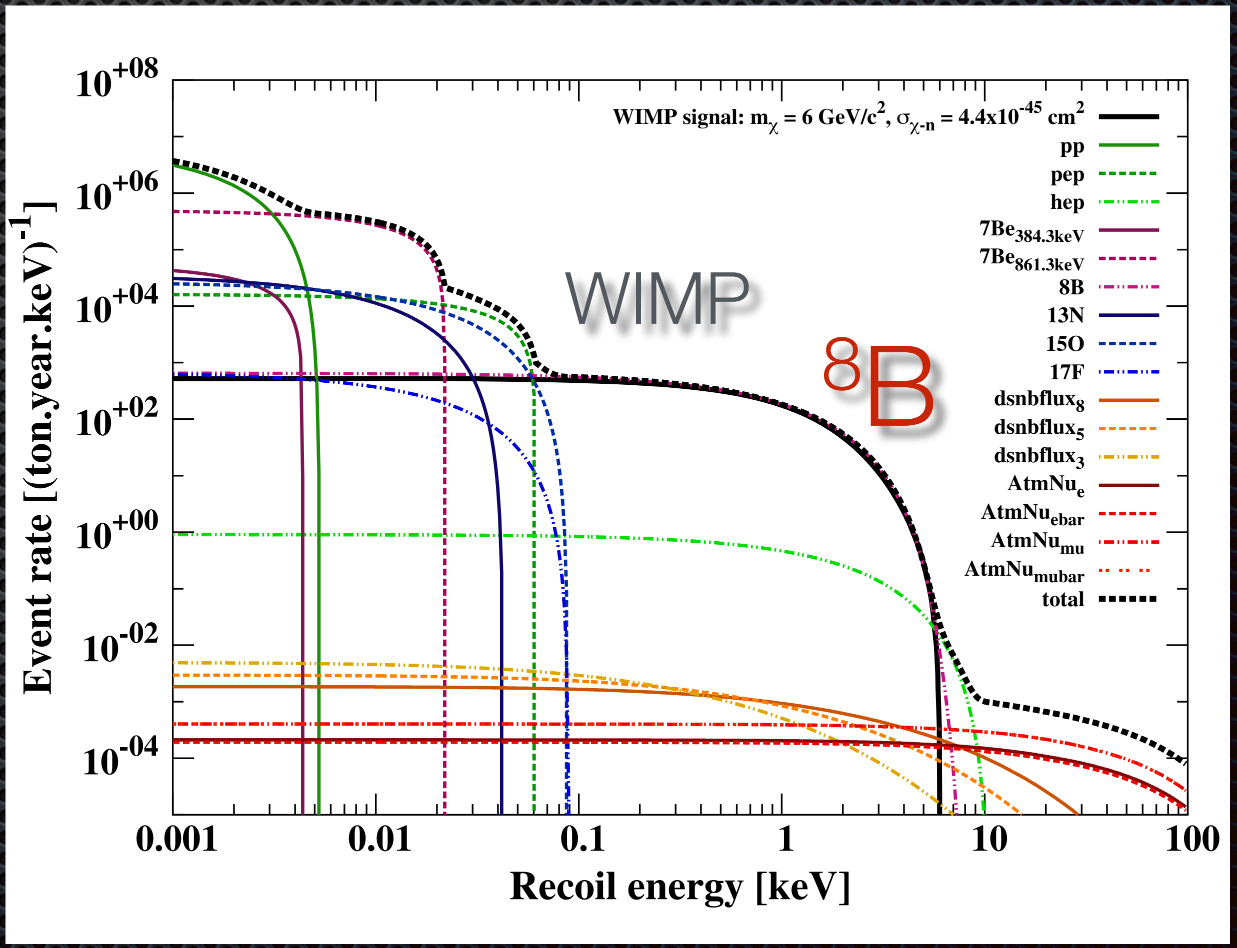
IceCube SI



Neutrino backgrounds

- Electronic recoils from solar neutrinos: neutrino - electron scattering
- Nuclear recoils from ^{8}B solar neutrinos: neutrino - nucleus coherent scattering
- Nuclear recoils from atmospheric + DSNB: neutrino - nucleus coherent scattering

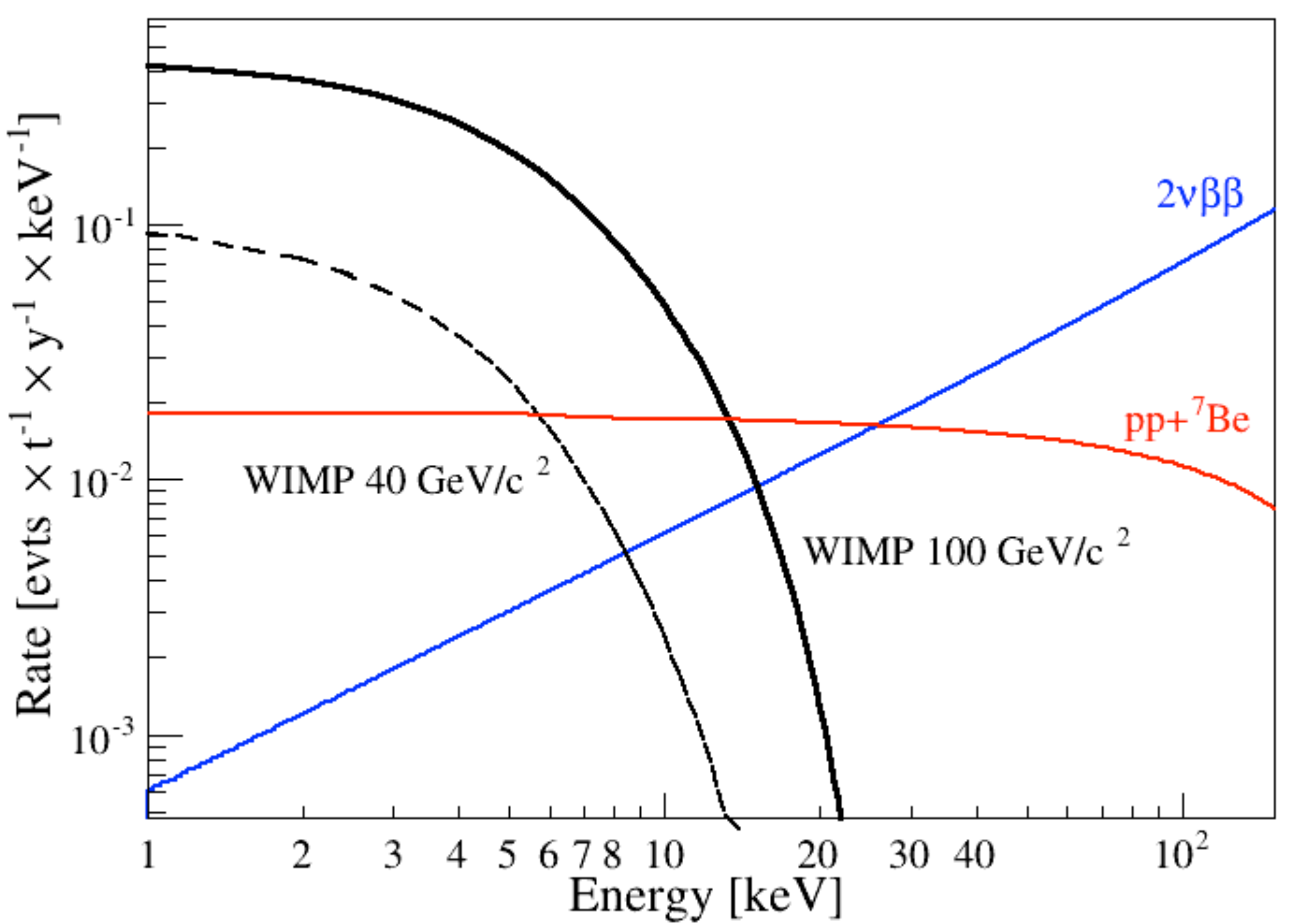


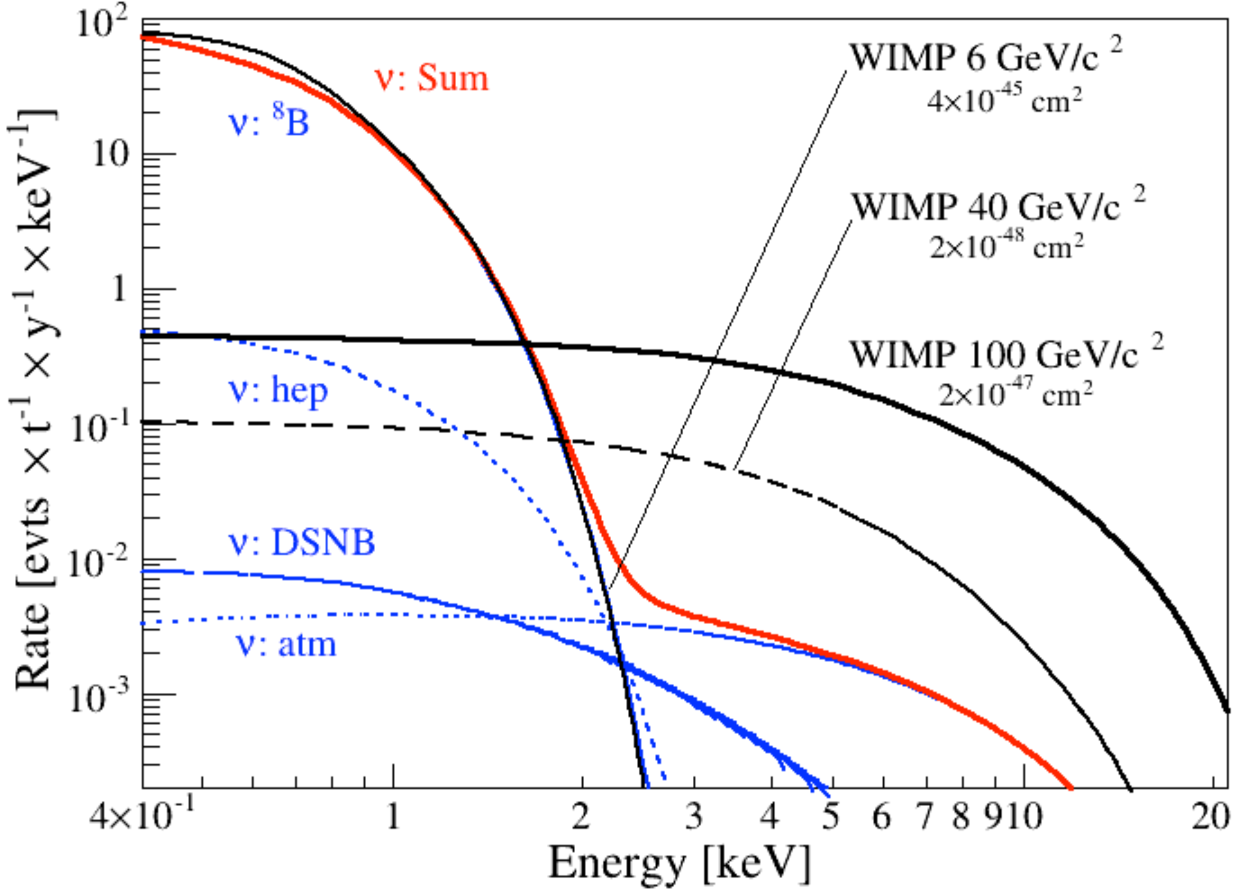


F. Ruppin J. Billard E. Figueroa-Feliciano L. Strigari arXiv:1408.3581

Neutrino backgrounds

- Electronic recoils from pp solar neutrinos: ~ 10^{-48} cm^2 (depending on ER vs NR discr.)
- Nuclear recoils from ^{8}B solar neutrinos: below ~ 4 x10^{-45} cm^2 for low-mass WIMPs
- Nuclear recoils from atmospheric + DSNB: below 10^{-49} cm^2





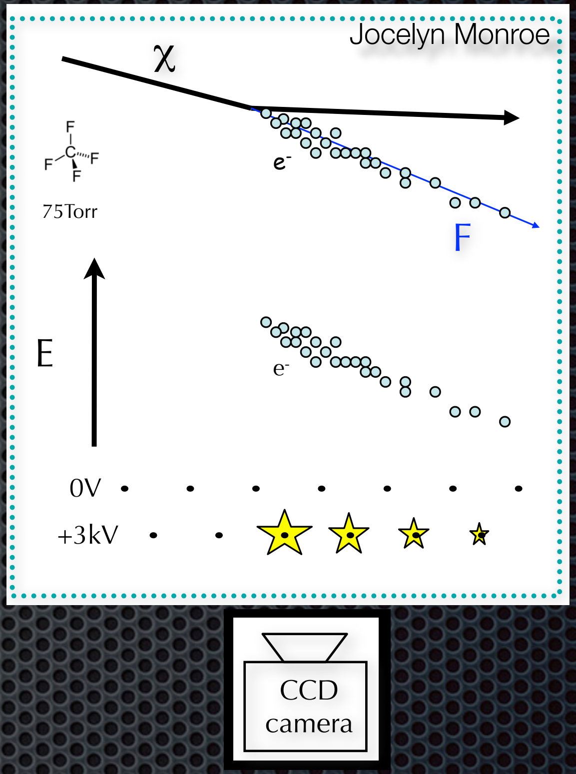
$$\nu + e^- \rightarrow \nu + e^-$$

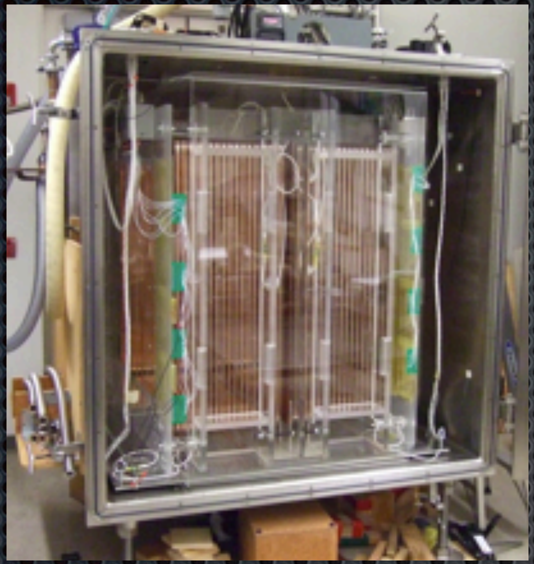
$$\nu + N \rightarrow \nu + N$$

LB et al., JCAP01 (2014) 044

Directional detectors

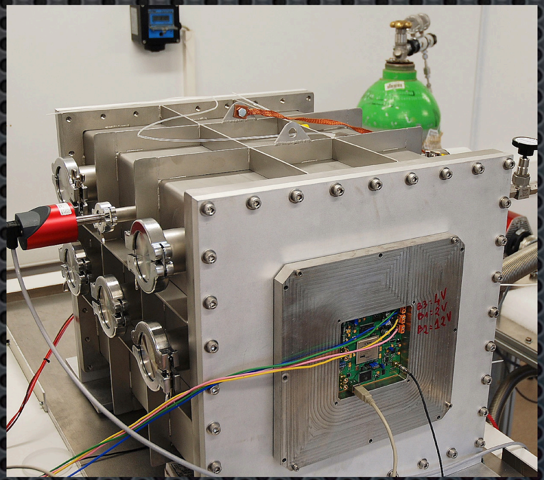
- R&D on low-pressure gas detectors to measure the recoil direction, correlated to the galactic motion towards Cygnus
- Challenge: good angular resolution + head-tail at E_{thr} (~30-50 keV)



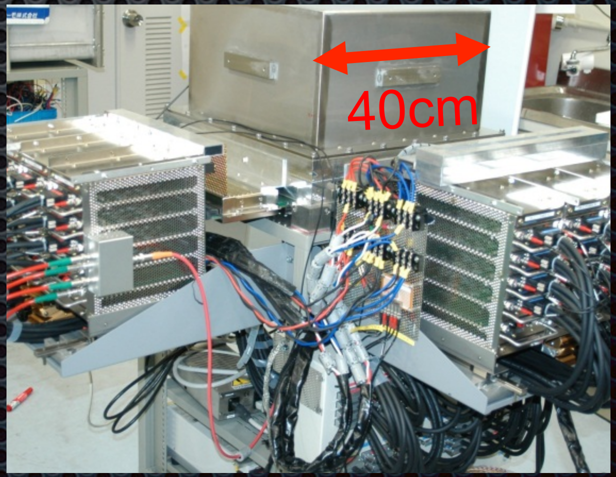


DRIFT, Boulby Mine
1 m3, negative ion drift
CS_2, CF4, O2 gas
DRIFTIII plans:
24 m^3 (3 x 8 m3 cells) at Boulby
4 kg target mass

DMTPCino TPC at MIT
CCD readout
1 m3 prototype, CF4 gas
commissioning fall 2014



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

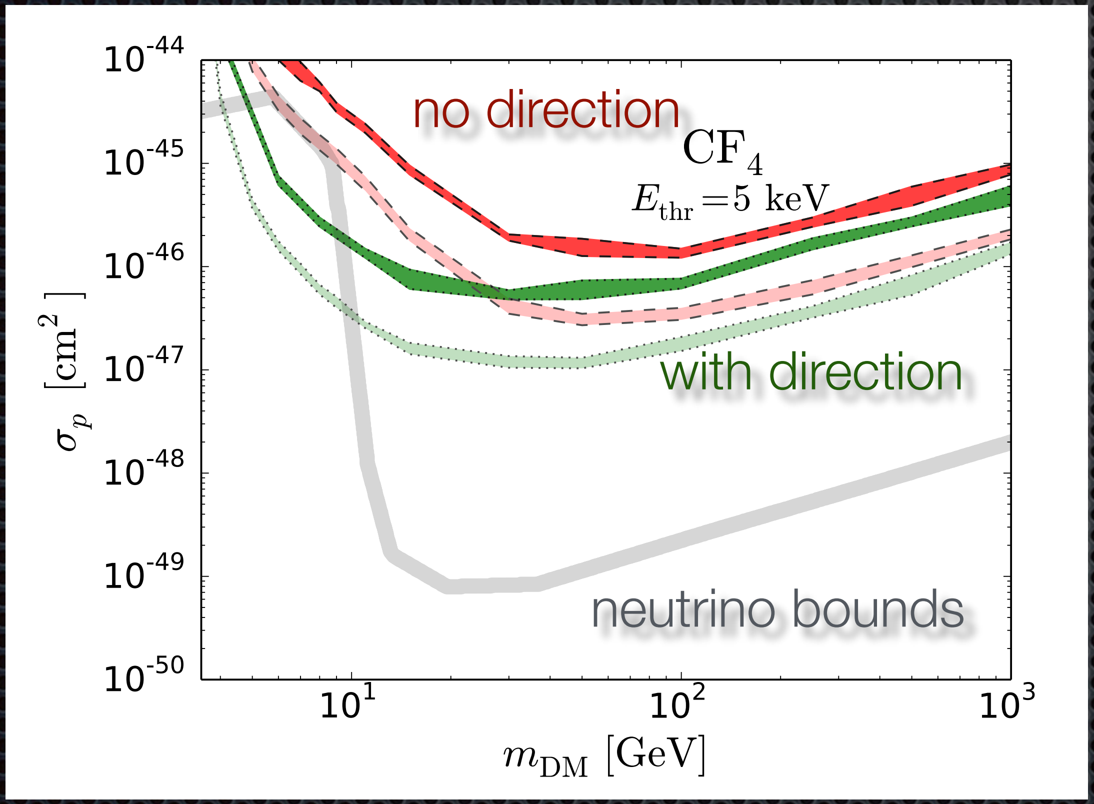


NEWAGE, Kamioka
CF_4 gas at 0.1 atm
50 keV threshold

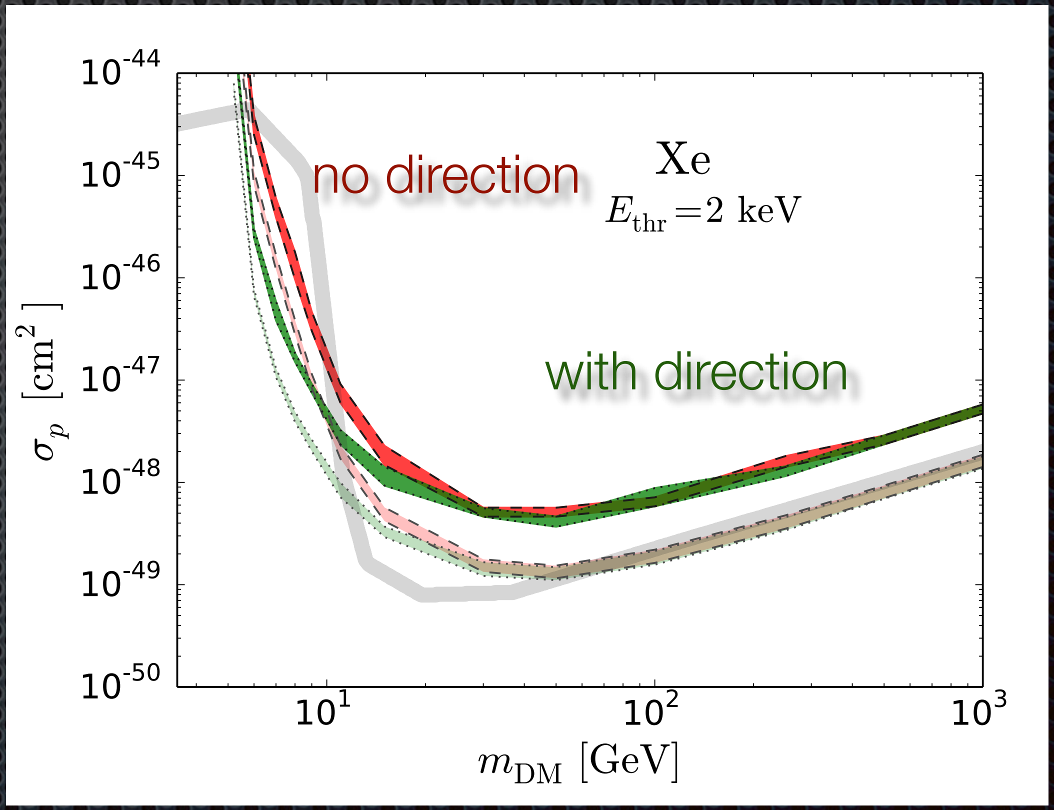
Will directional information help?

- Yes, but mostly for low WIMP masses
- Many directional techniques currently in R&D phase
- Might be difficult to reach the 10^{-48} - 10^{-49} cm^2 cross section with this technique

36.6 t yr exposure, 500 (solar) nu events



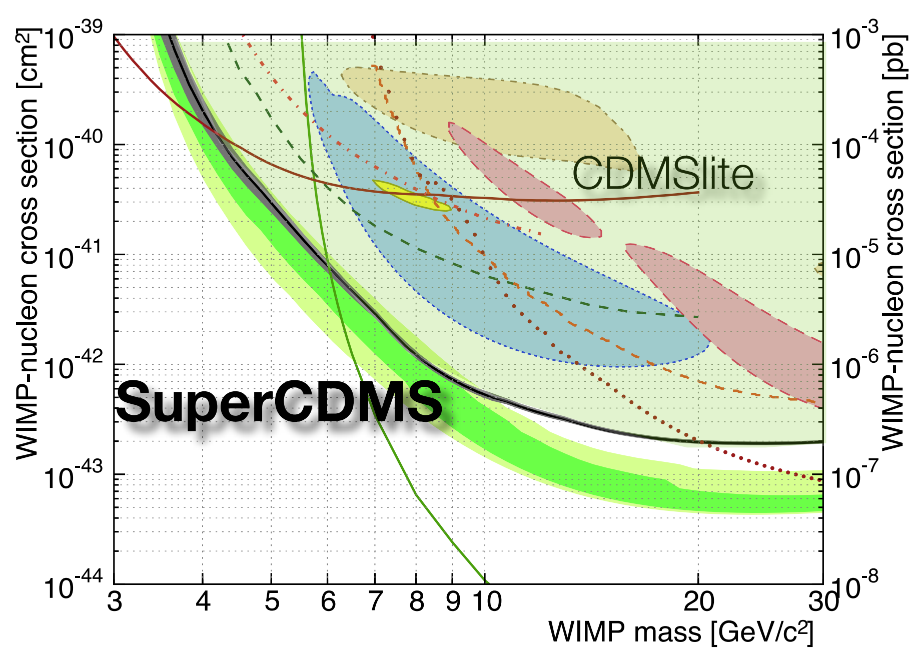
367 t yr exposure, 500 nu events



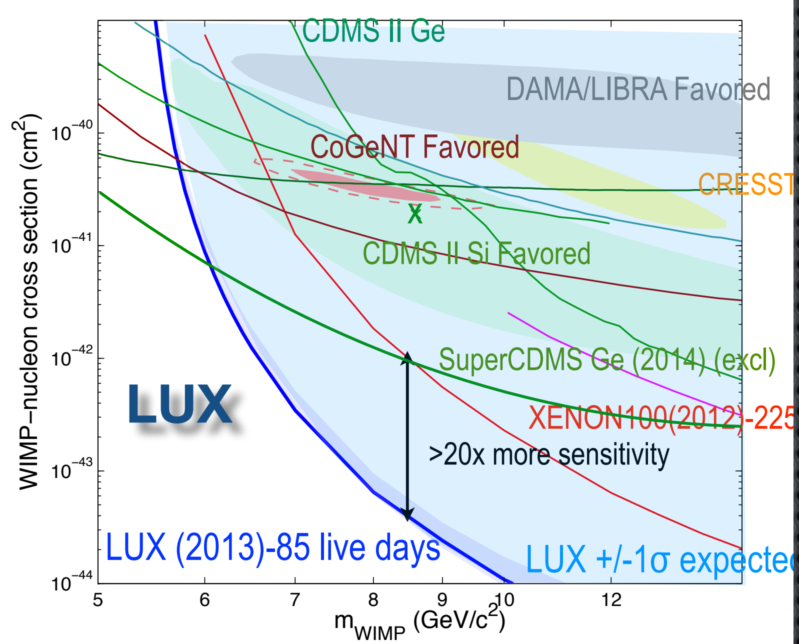
P. Grothaus, M. Fairbairn, J. Monroe, arXiv: 1406.5047

Low-mass region: *heavily constrained* by CDMS-Ge, XENON10, XENON100, LUX, EDELWEISS, CRESST, CoGeNT, PandaX,…

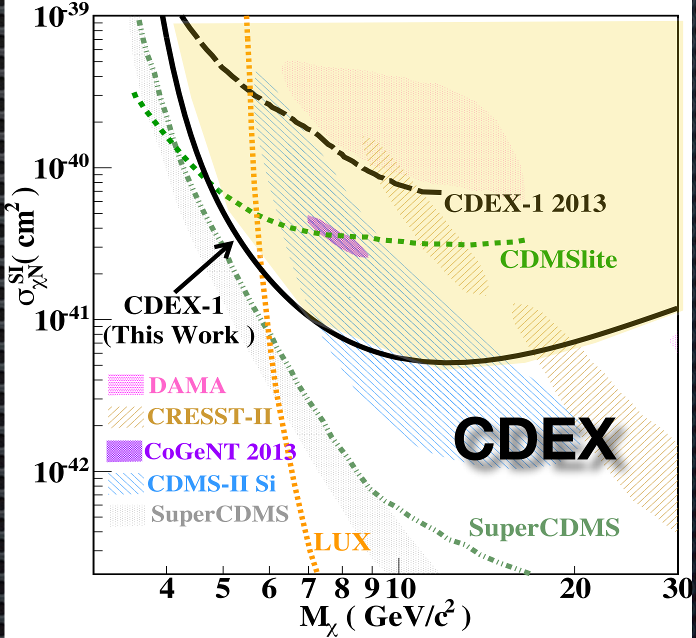
CDMS, PRL 112, 2014

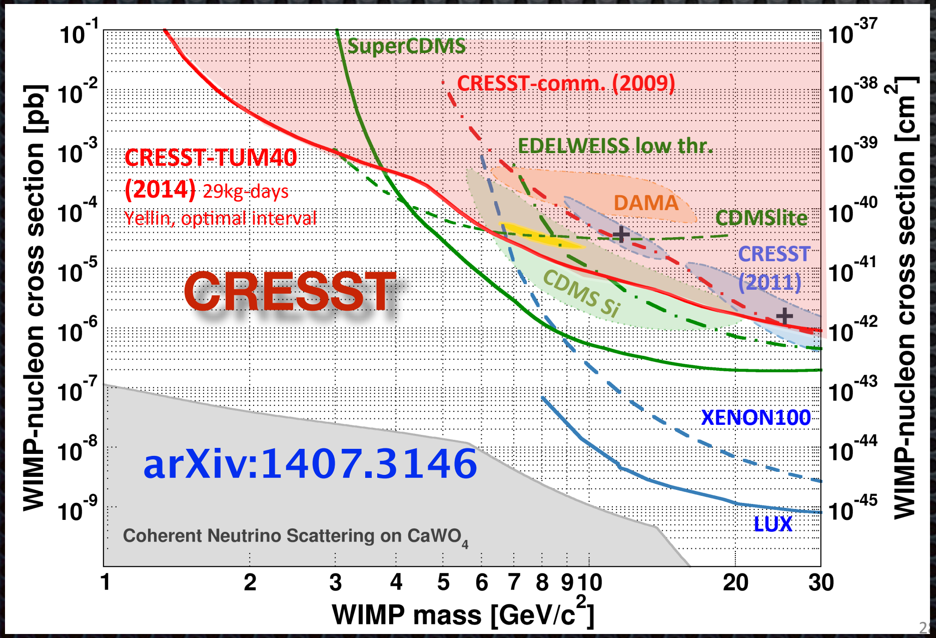


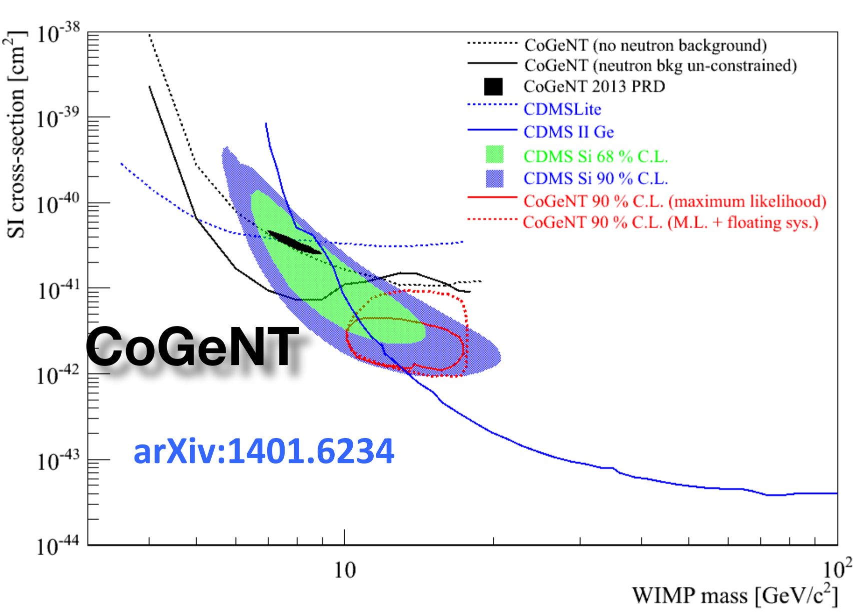
LUX, PRL, arXix: 1310.8214

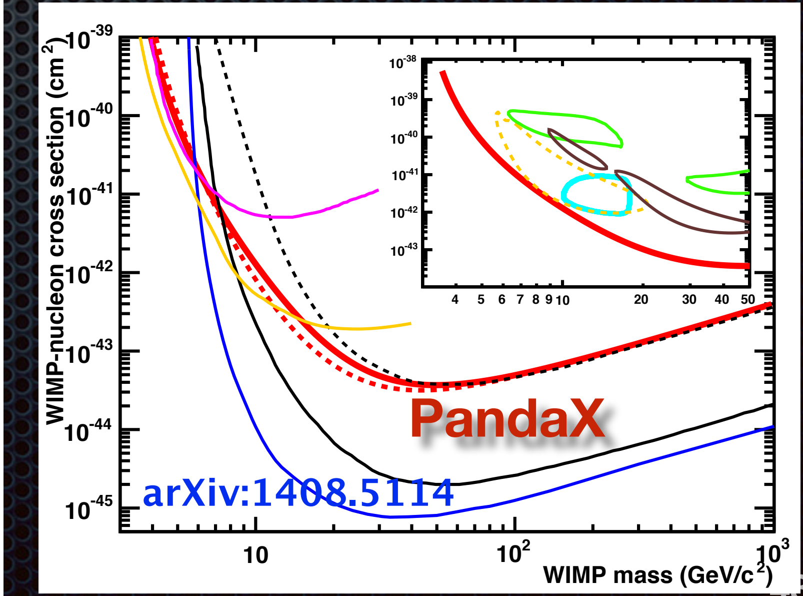


CDEX, arXiv:1404.4946





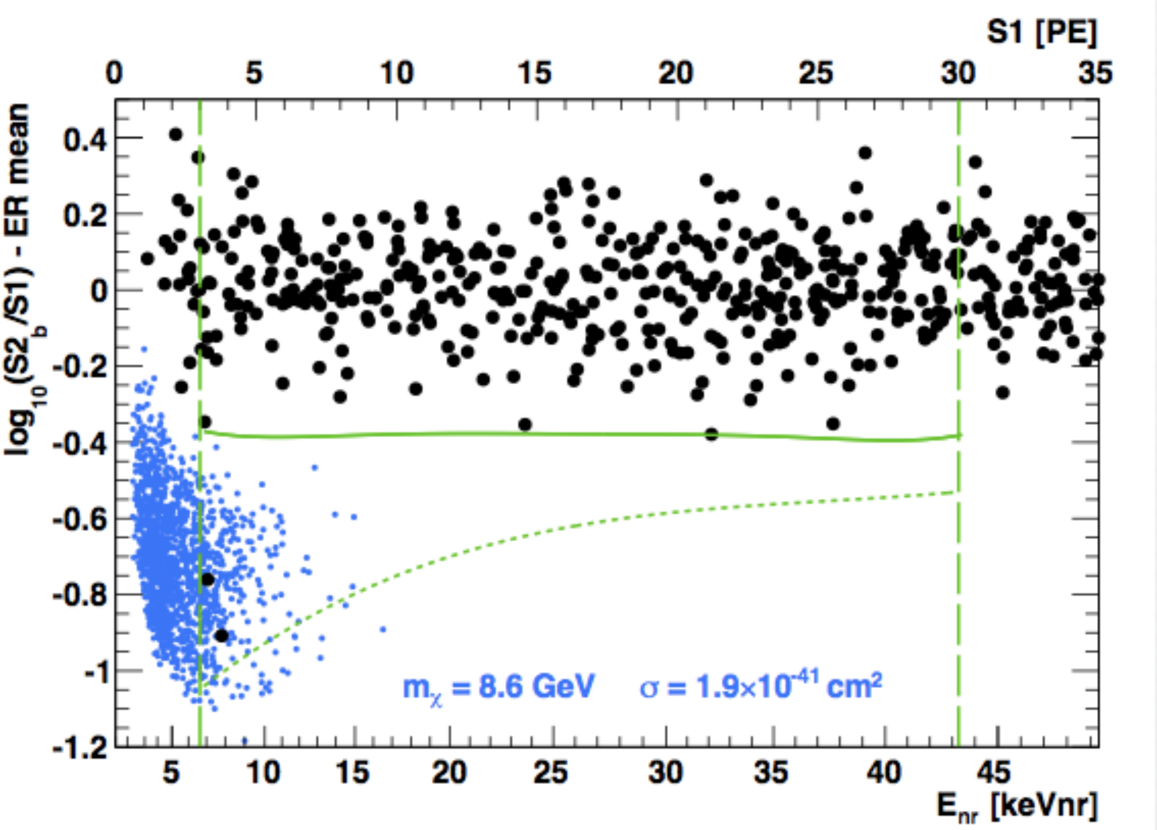




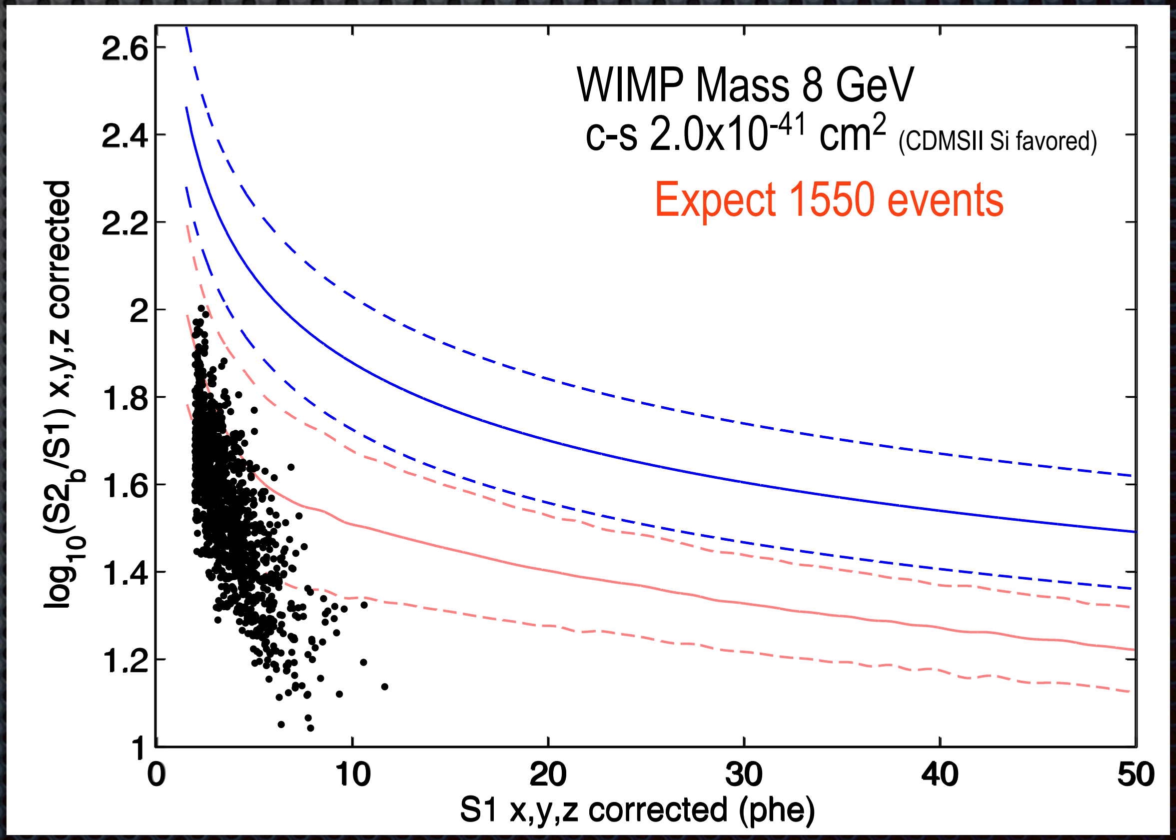
How would a CDMS-Si like signal look like in XENON100 and LUX?

Assumption:
m_W = 8.6 GeV and WIMP-nucleon cross section of 1.9×10^{-41} cm^2

XENON100 Run10
expect: ~ 220 events



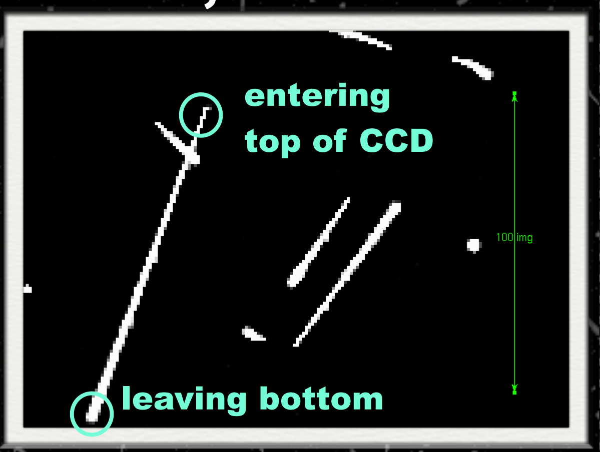
LUX first run
expect: ~ 1550 events

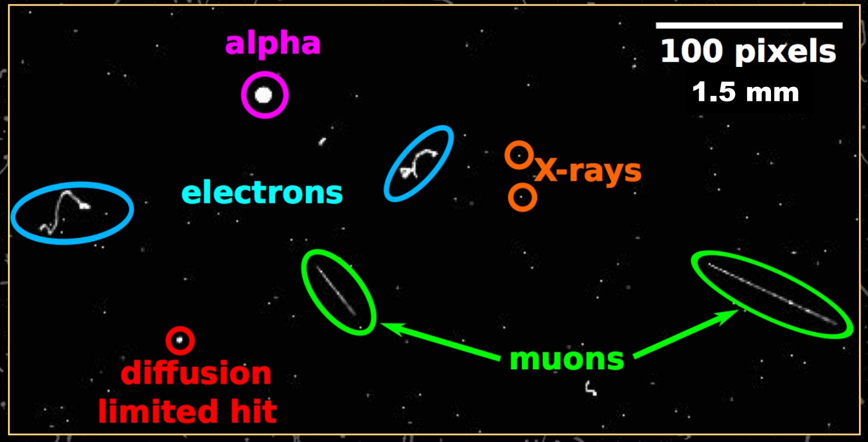


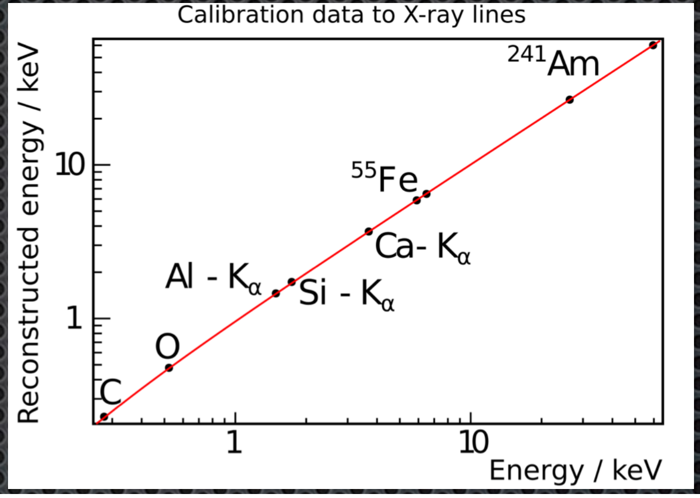
CCDs for low-mass WIMPs: DAMIC

- Particle identification
- Fiducialisation to reject surface events (X-rays)
- DAMIC100 (100 g Si active mass) under construction at SNOLAB; results in 2015

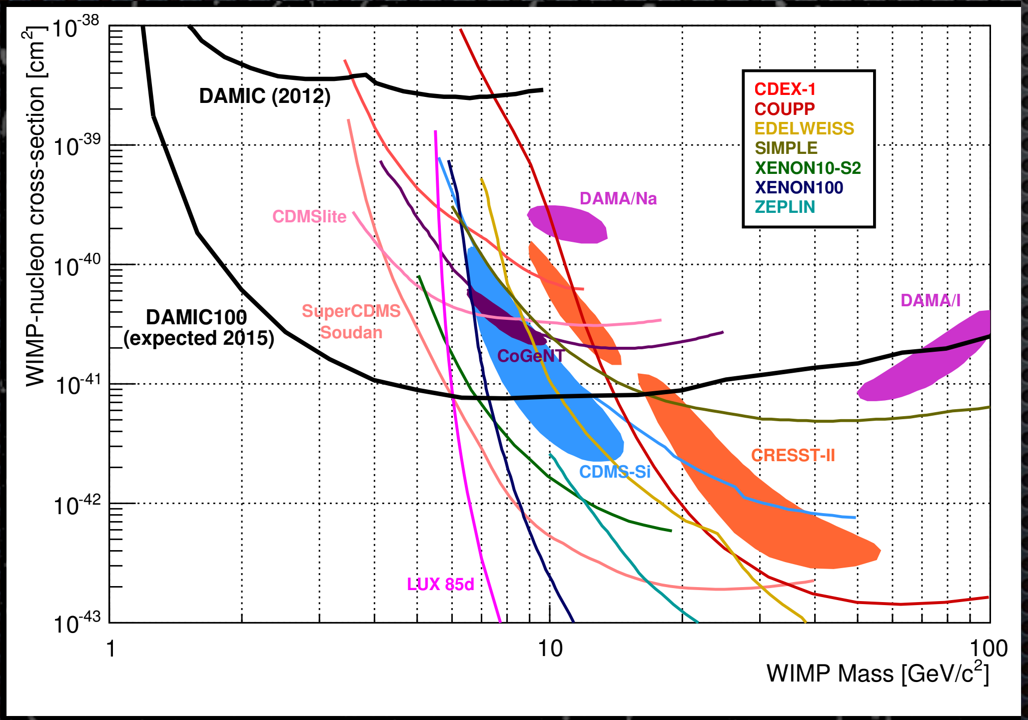
2012 DAMIC limit 107 g-days with 0.04 keV energy threshold Phys.Lett. B711 (2012) 264-269

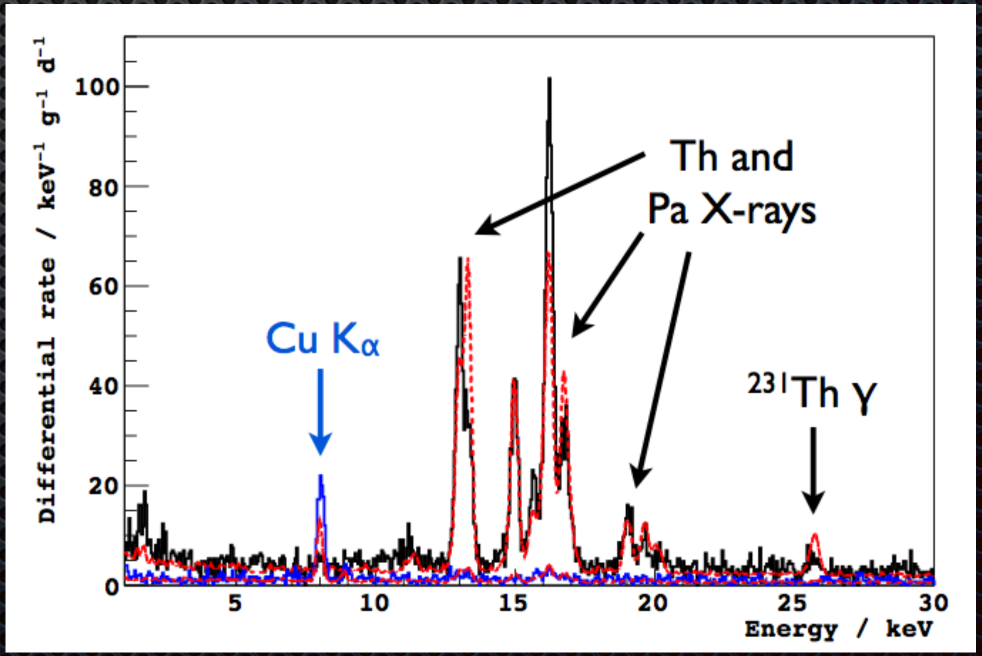


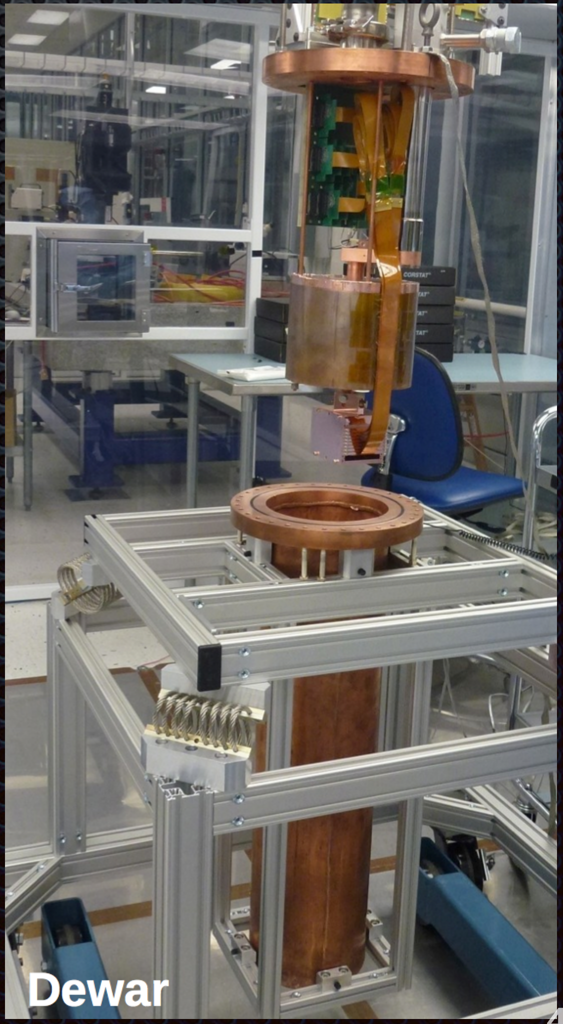




Ben Kilminster, PATRAS 2014

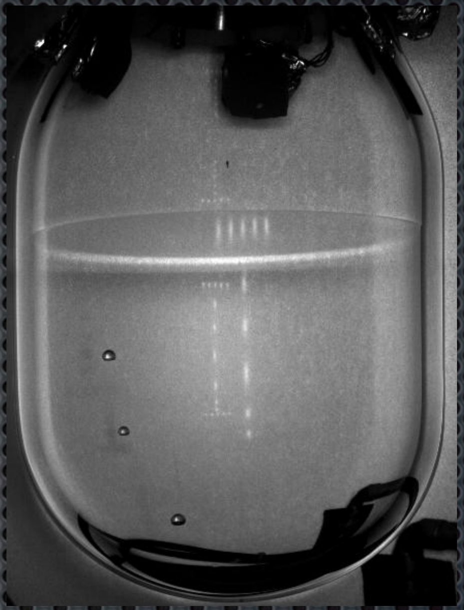






Bubble chambers

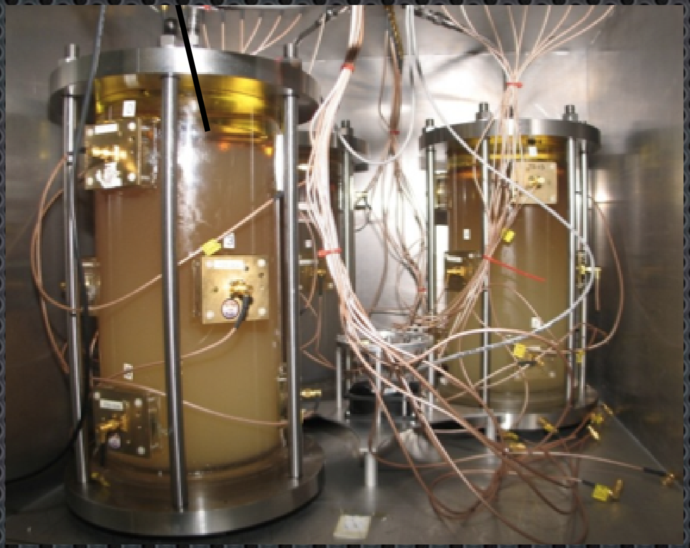
- Detect single bubbles induced by high dE/dx nuclear recoils in heavy liquid bubble chambers (with acoustic, visual or motion detectors)
- Large rejection factor for MIPs (10^{10}), scalable to large masses, high spatial granularity
- Existing detectors: SIMPLE, COUPP, PICASSO, PICO 2 L
- Future: PICO (PICASSO + COUPP) -> 250 l detector detector at SNOLAB, C3F8 with 3 keV threshold



n-induced event (multiple scatter)

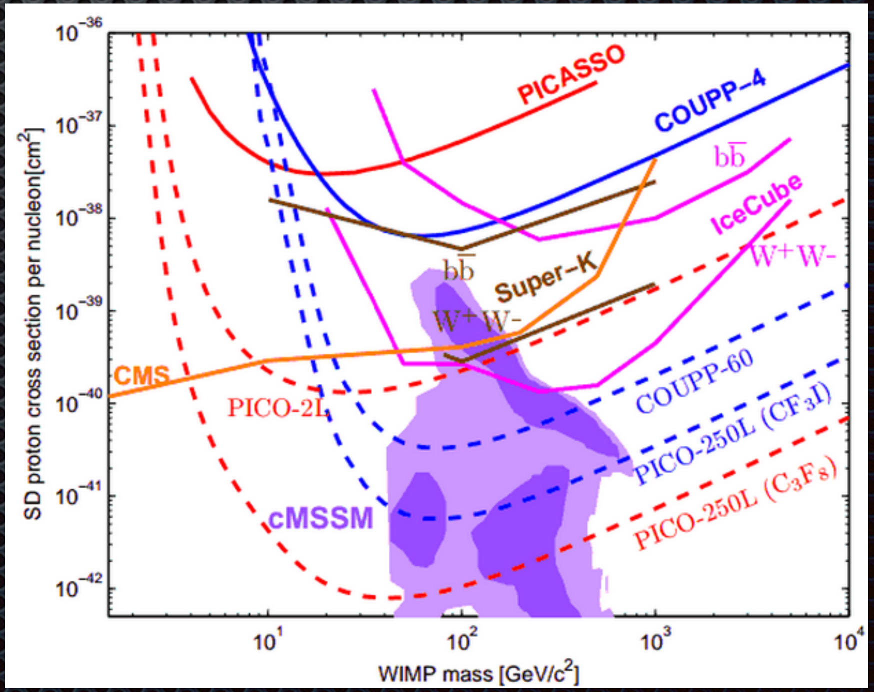
WIMP: single scatter

COUPP 60 kg CF_3I detector installed at SNOLAB; physics run until May 2014



PICASSO at SNOLAB

PICO 2L



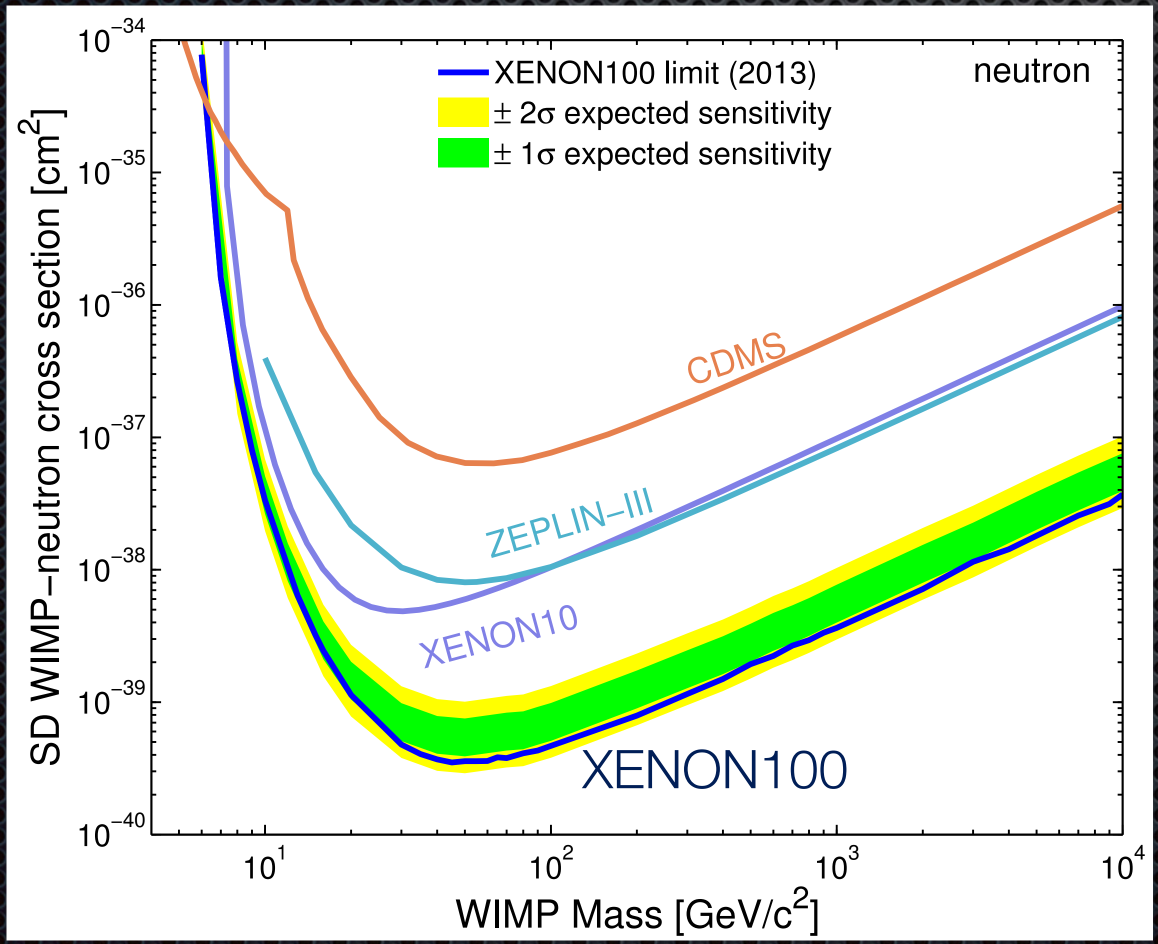
Spin-dependent limits

Recoil range << 1 μm in a liquid - very high dE/dx

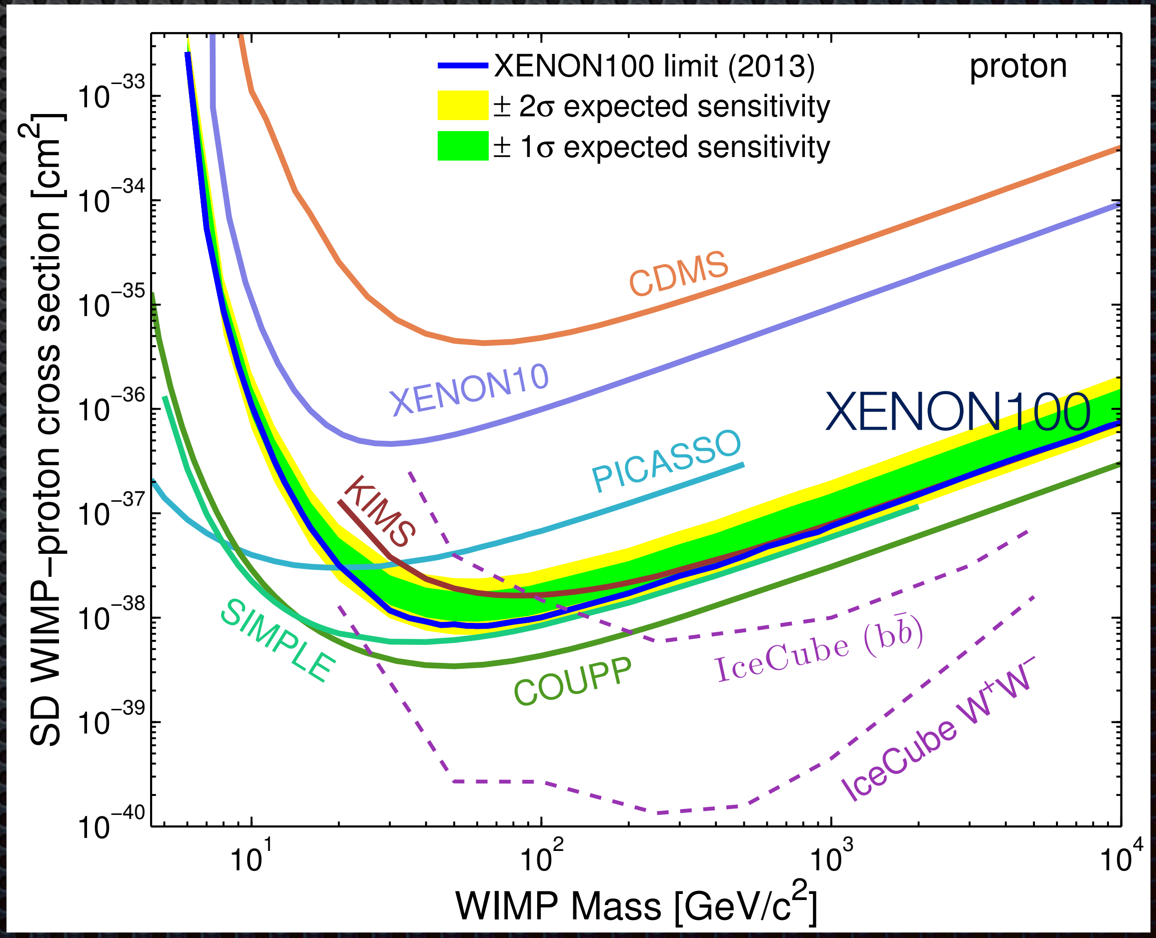
Spin-dependent results

$$\frac{d\sigma_{\rm SD}(q)}{dq^2} = \frac{8G_F^2}{(2J+1)v^2} S_A(q) \qquad S_A(0) = \frac{(2J+1)(J+1)}{\pi J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2$$

WIMP-neutron coupling



WIMP-proton coupling

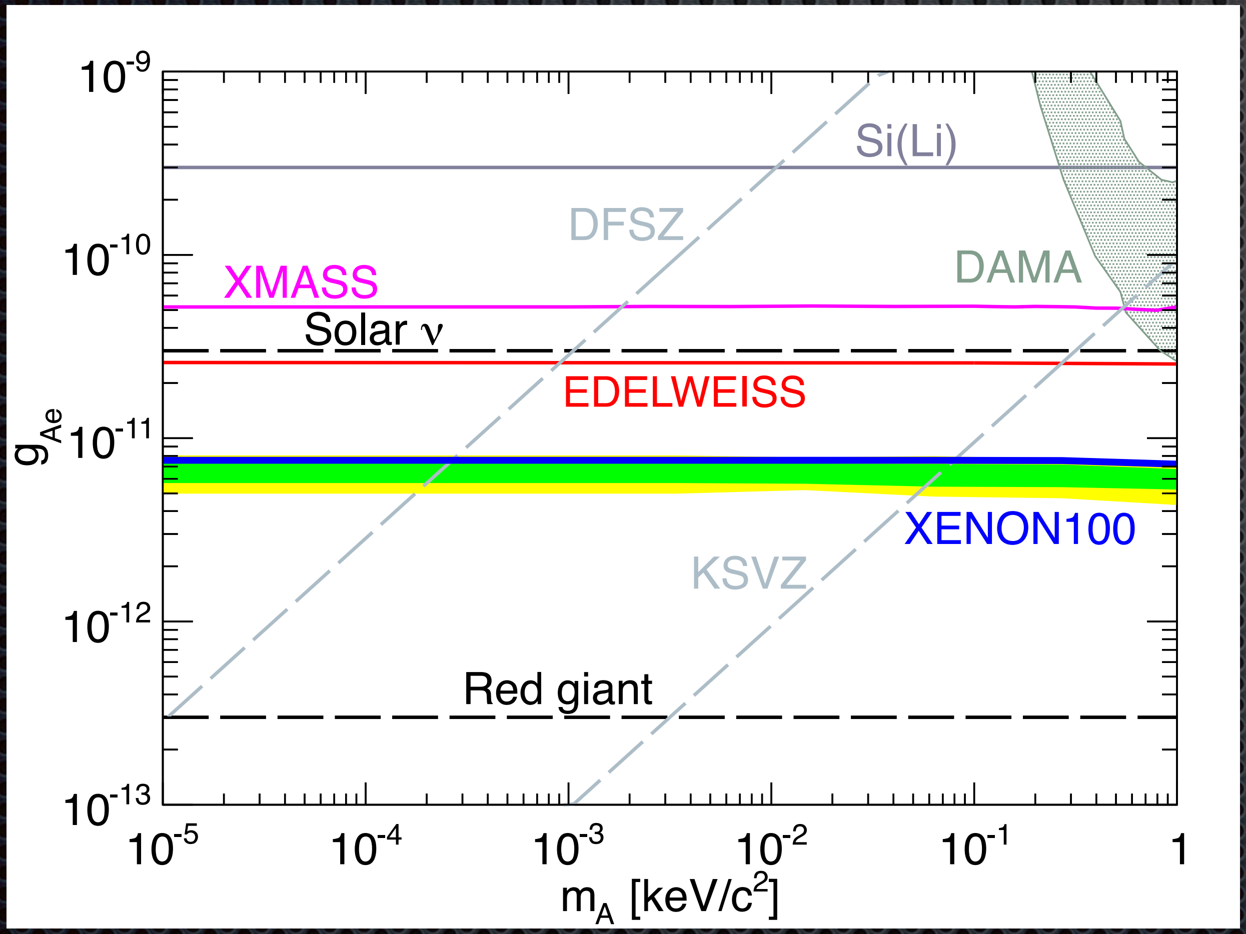


Phys. Rev. Lett. 111 (2013)

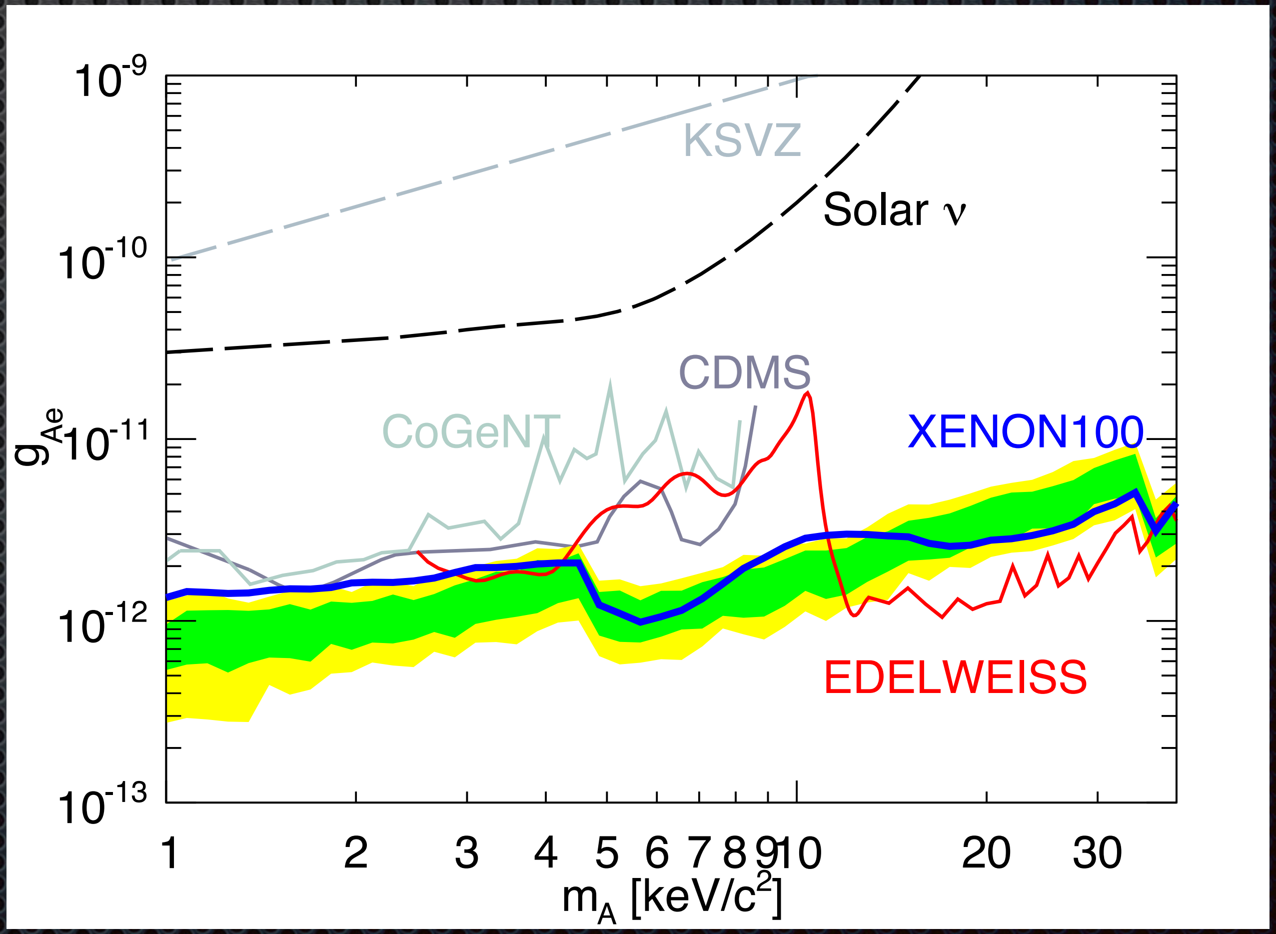
Direct-detection experiments can also search for solar axions, ALPs, vector…

- Limits on axions and ALPs from CDMS, DAMA, CoGeNT, XMASS, EDELWEISS, XENON100

Solar axions

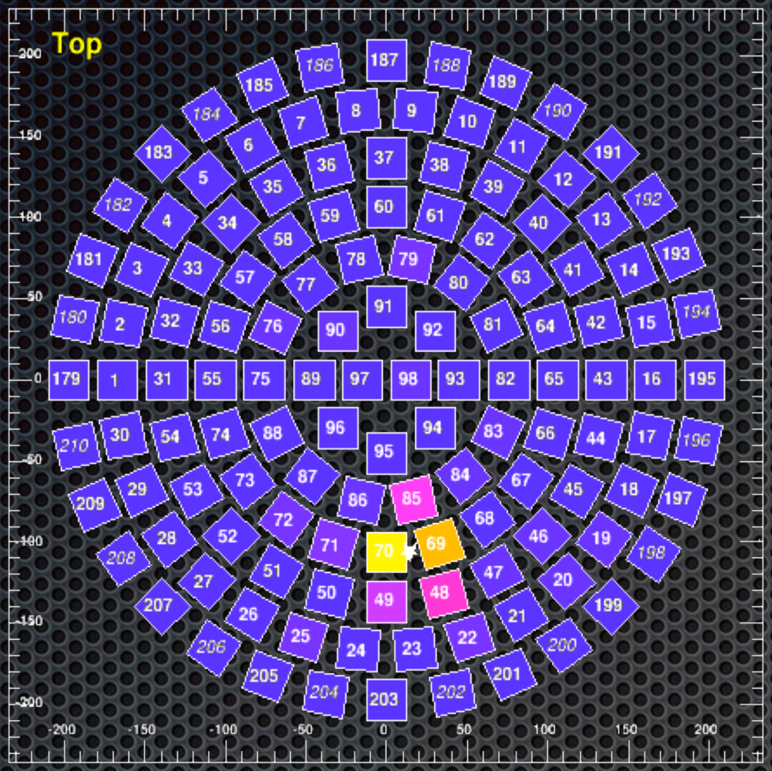


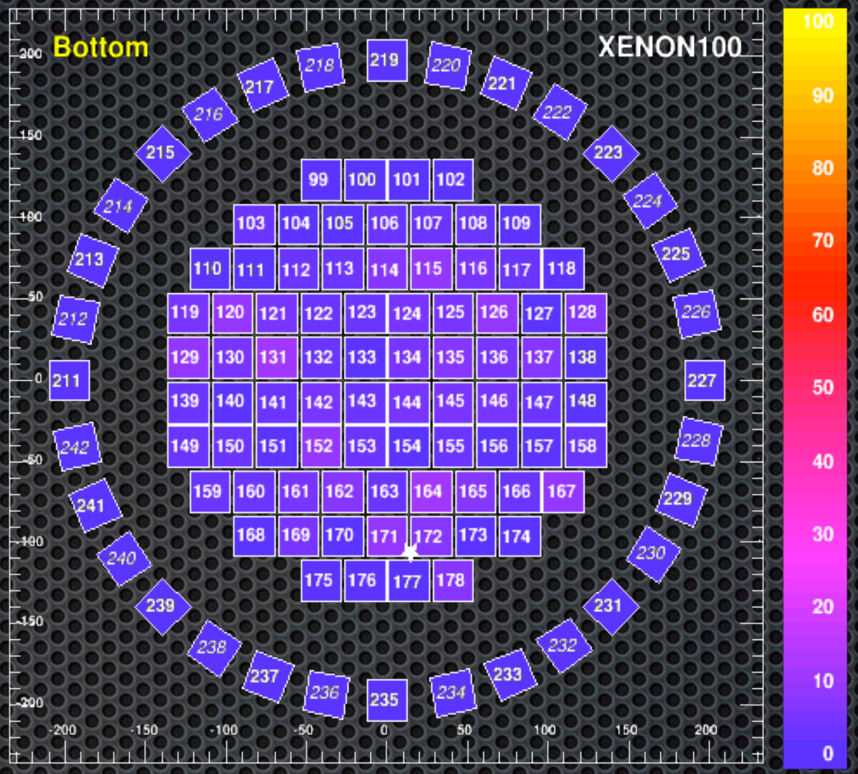
Galactic ALPs



Example of a 9 keV nuclear recoil event

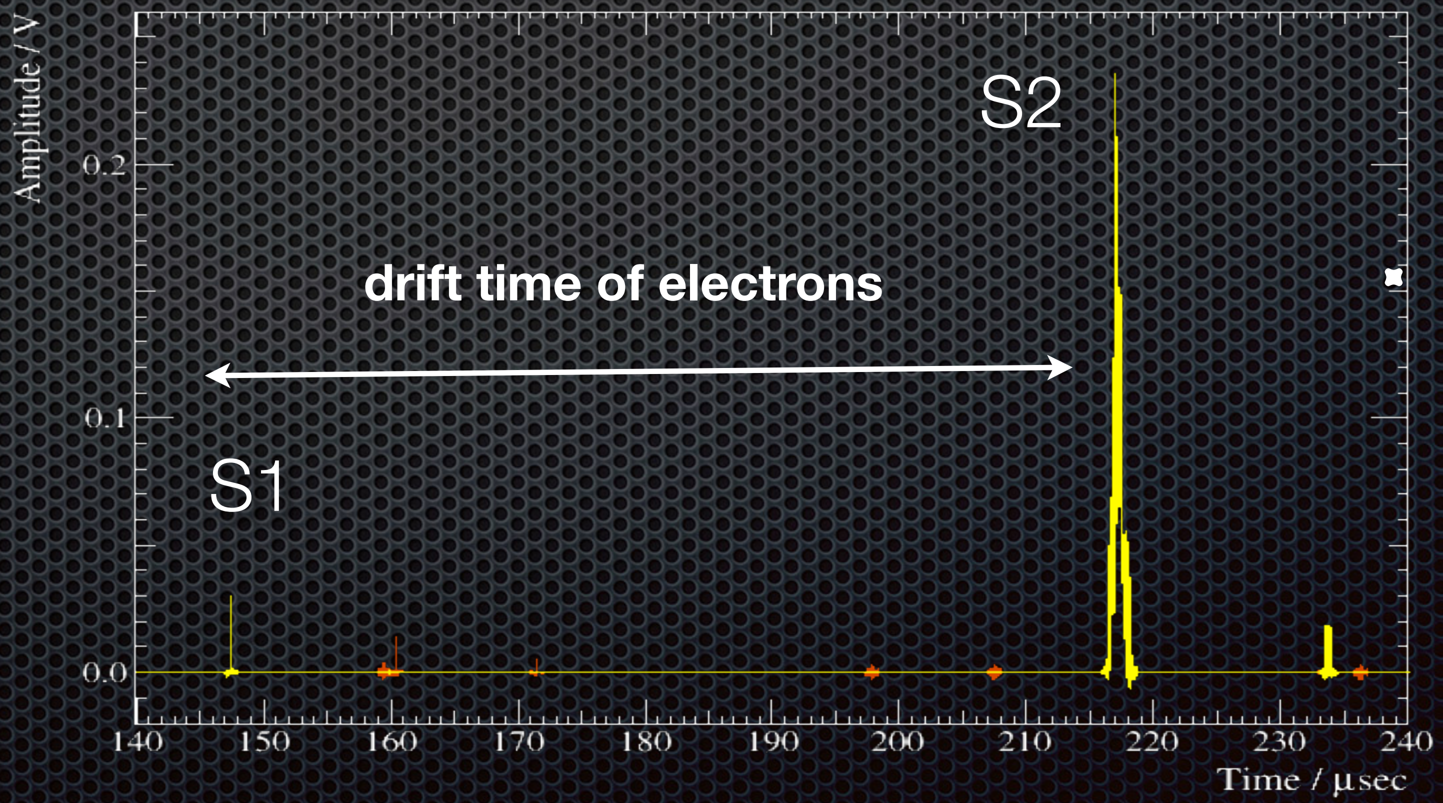
XENON100
top
PMT array





XENON100
bottom
PMT array

S1: 4 photoelectrons detected from about 100 S1 photons



S2: 645 photoelectrons detected from 32 ionization electrons which generated about 3000 S2 photons

Expected Scattering Cross Sections

- The WMP-nucleus scattering is NR for galactic WIMPs (**v/c ~10^{-3}**) -> simple NR effective theory, q ~ O(10-100 MeV)

- Interactions leading to **WIMP-nuclei scattering** are parameterized as:
  - **scalar interactions** (coupling to nuclear 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 protons and neutrons

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

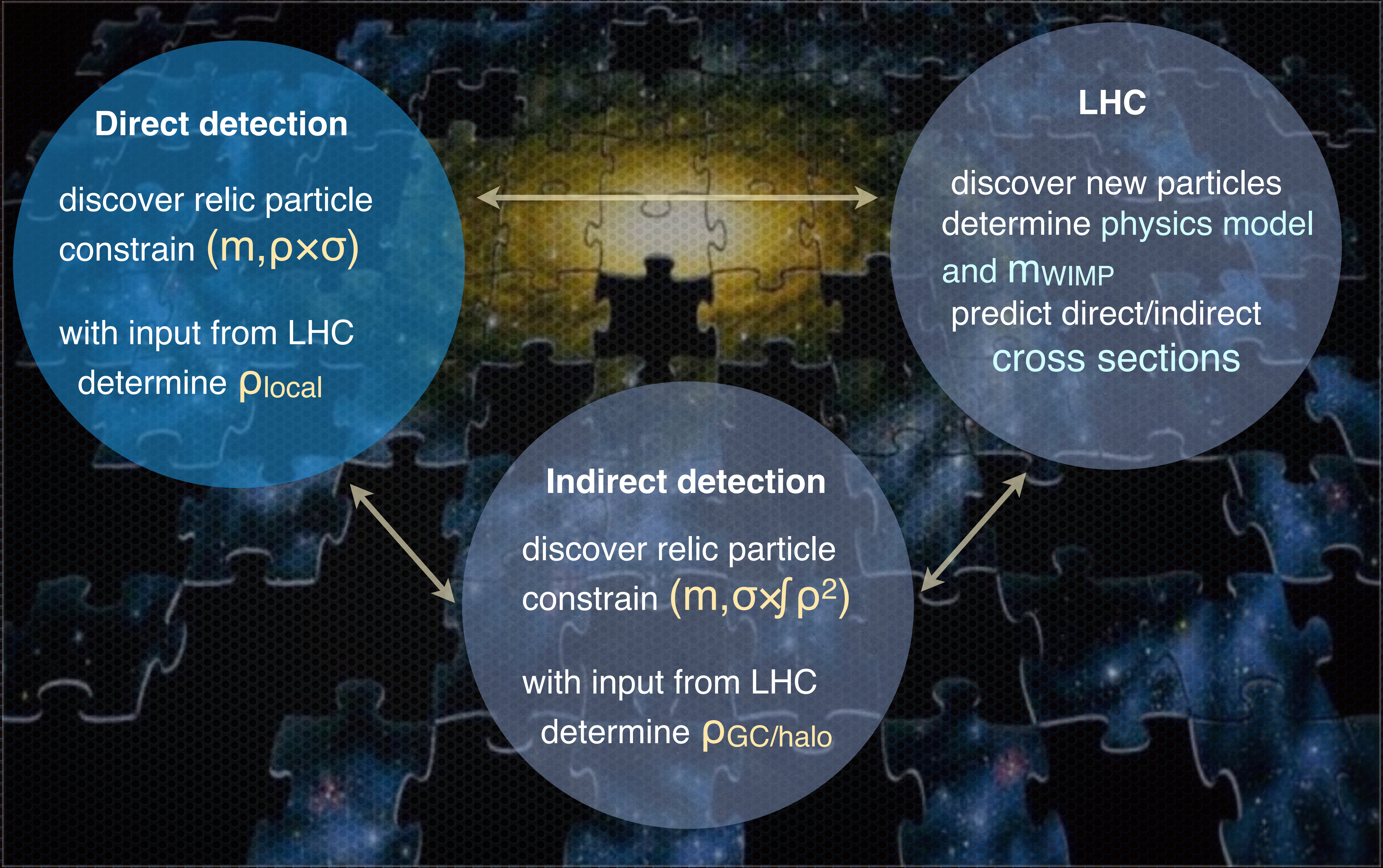
a_p, a_n: effective couplings to protons and neutrons

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

$\langle S_p \rangle$ and $\langle S_n \rangle$

expectation values of the p and n spins within the nucleus

Summary and Prospects (II)



Direct detection

discover relic particle
constrain $(m,\rho\times\sigma)$

with input from LHC
determine ρ_{local}

LHC

discover new particles
determine physics model and m_{WIMP}
predict direct/indirect cross sections

Indirect detection

discover relic particle
constrain $(m,\sigma\times\int\rho^2)$

with input from LHC
determine $\rho_{GC/halo}$