Dark matter: direct searches for WIMPs

EPS-HEP meeting, Stockholm, July 23, 2013

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Direct Detection of WIMPs: Principle

- Elastic collisions with nuclei in ultra-low background detectors
- Energy of recoiling nucleus: *few keV to tens of keV*

Astrophysics

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

Particle physics

N_N = number of target nuclei in a detector

ρ_0 = local density of the dark matter in the Milky Way

f(v) = WIMP velocity distribution in lab frame

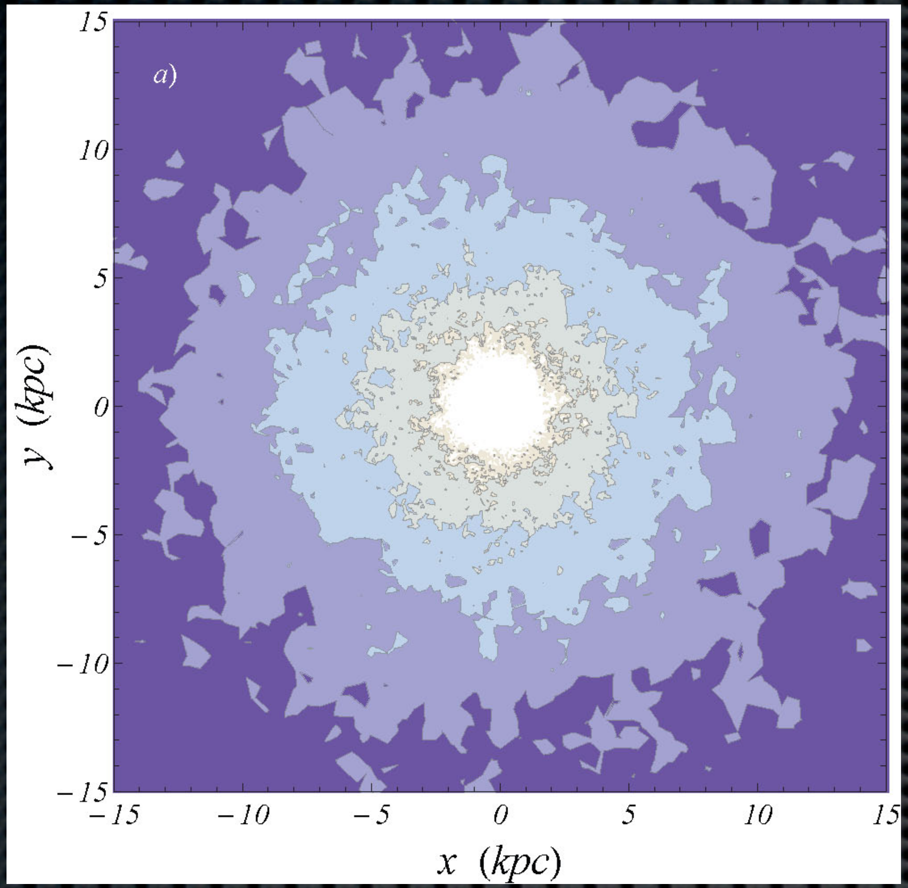
m_W = WIMP-mass

σ =cross section for WIMP-nucleus elastic scattering

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

Astrophysics

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



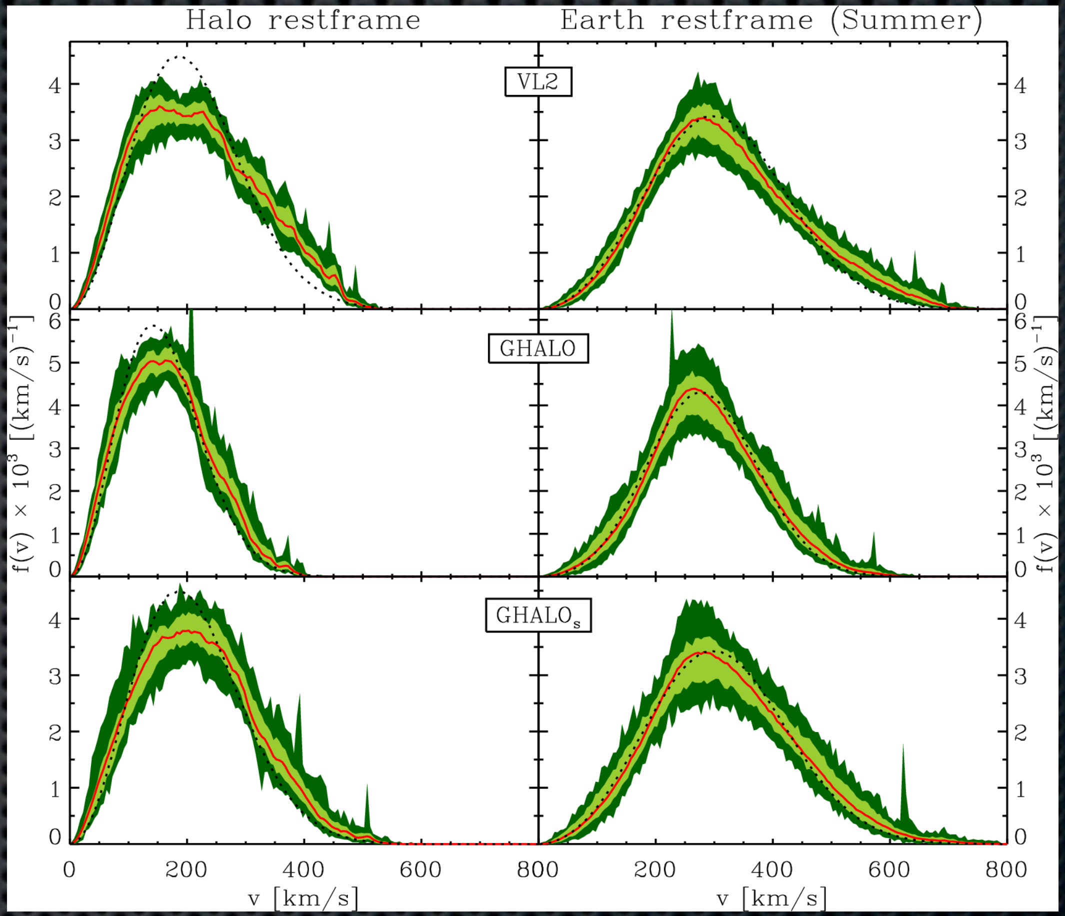
High-resolution cosmological simulation with baryons: F.S. Ling et al, JCAP02 (2010) 012

$$\rho_{halo} \sim 0.3\,\mathrm{GeV}\cdot\mathrm{cm}^{-3}$$

=> WIMP flux on Earth:

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

Velocity distribution of WIMPs in the galaxy



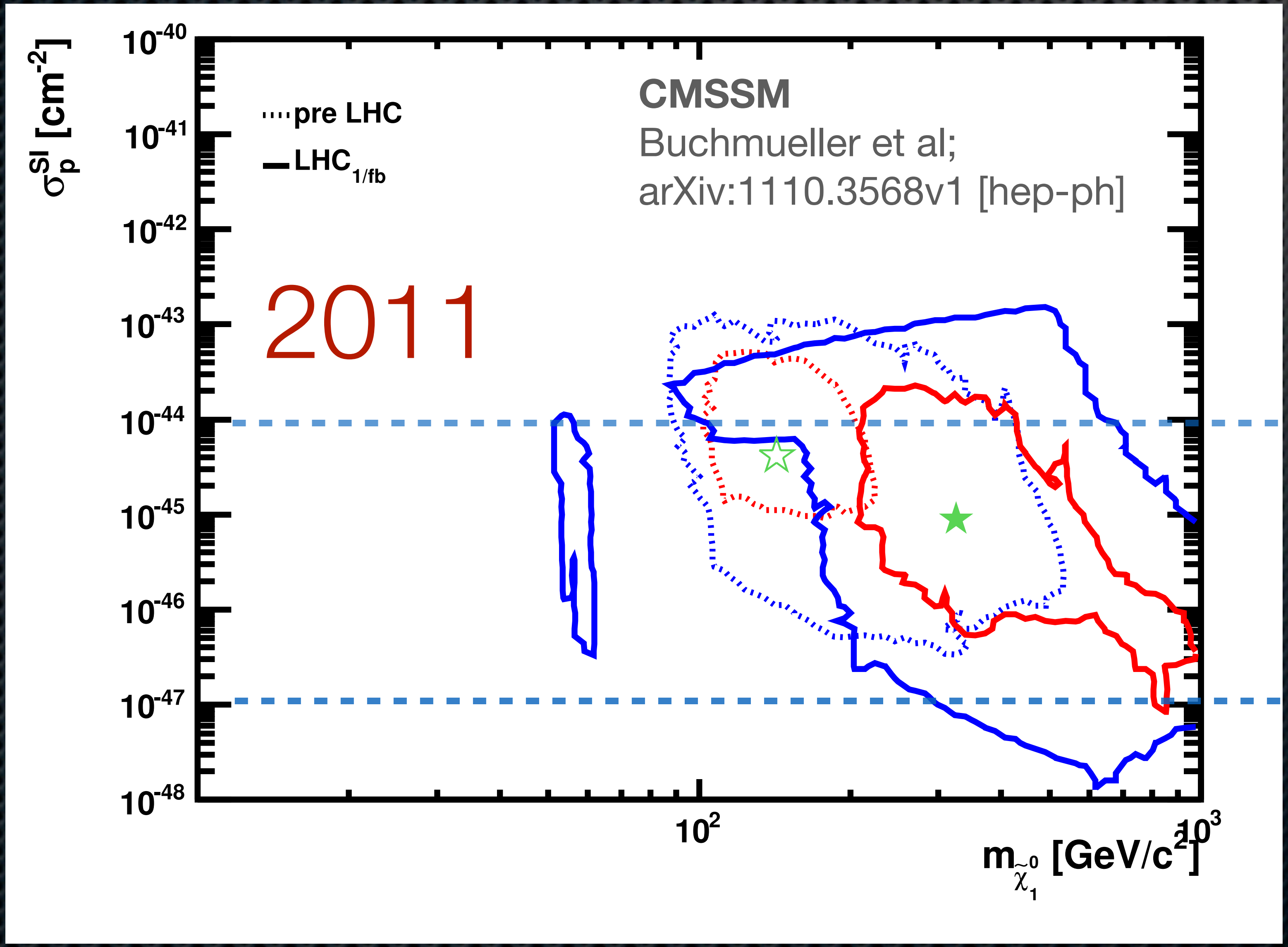
Halo restframe Earth restframe

M. Kuhlen et al, JCAP02 (2010) 030

- 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

Particle physics

- SUSY: scattering cross sections on nucleons down to ~ 10^{-48} cm^2(10^{-12} pb)
- Here example in CMSSM, after LHC 1/fb

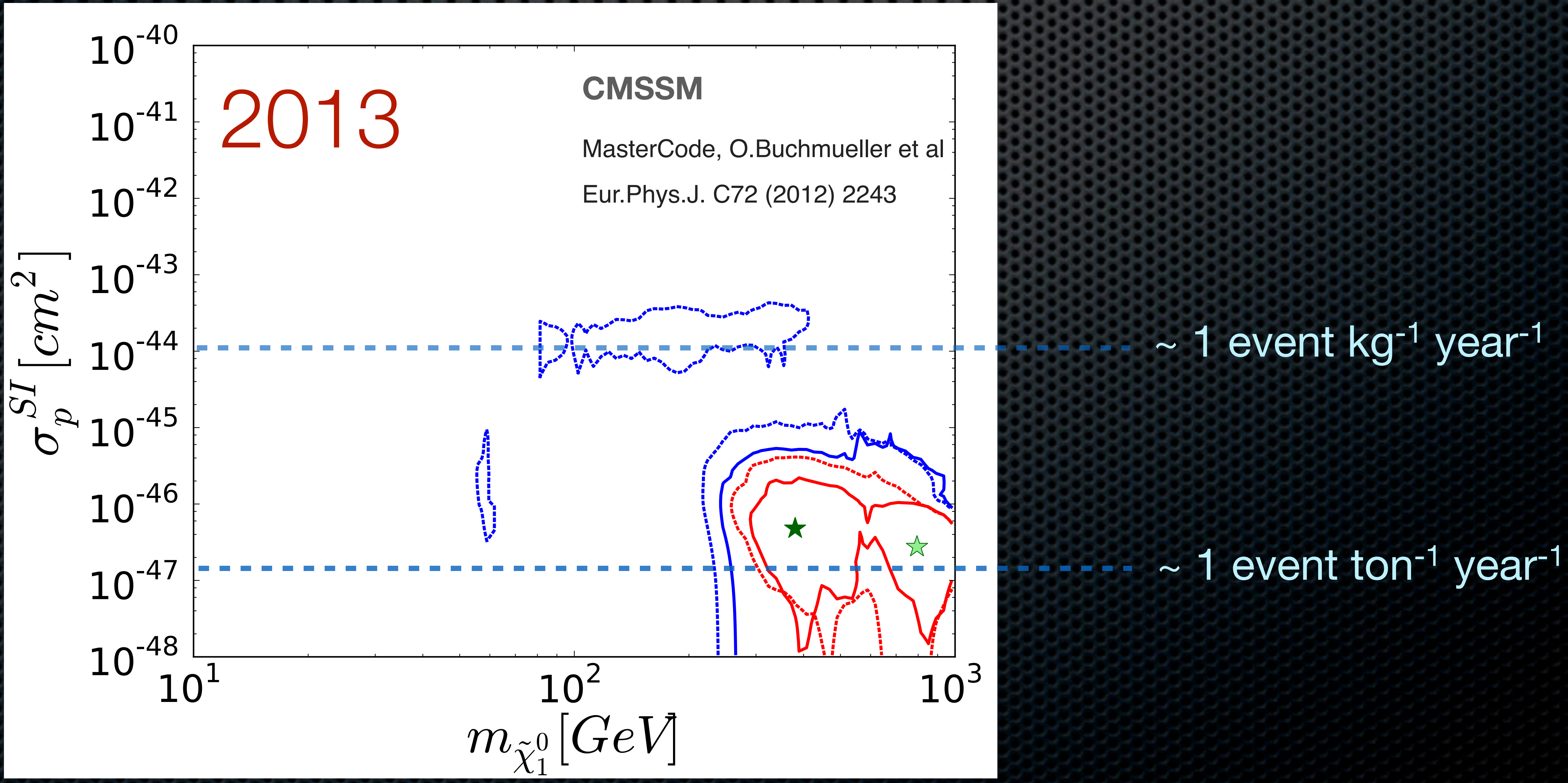


~ 1 event kg^{-1} $year^{-1}$

~ 1 event ton^{-1} $year^{-1}$

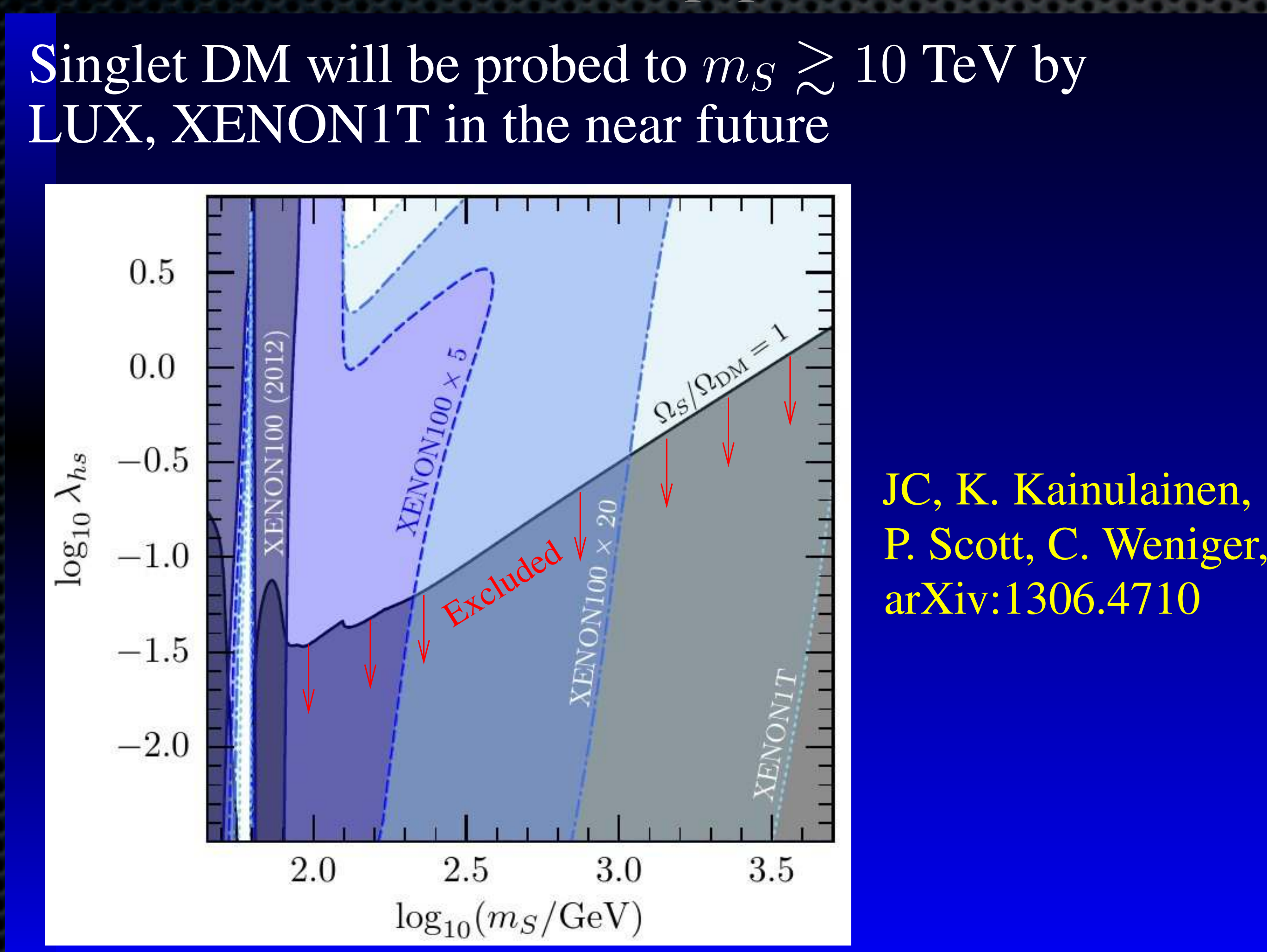
Particle physics

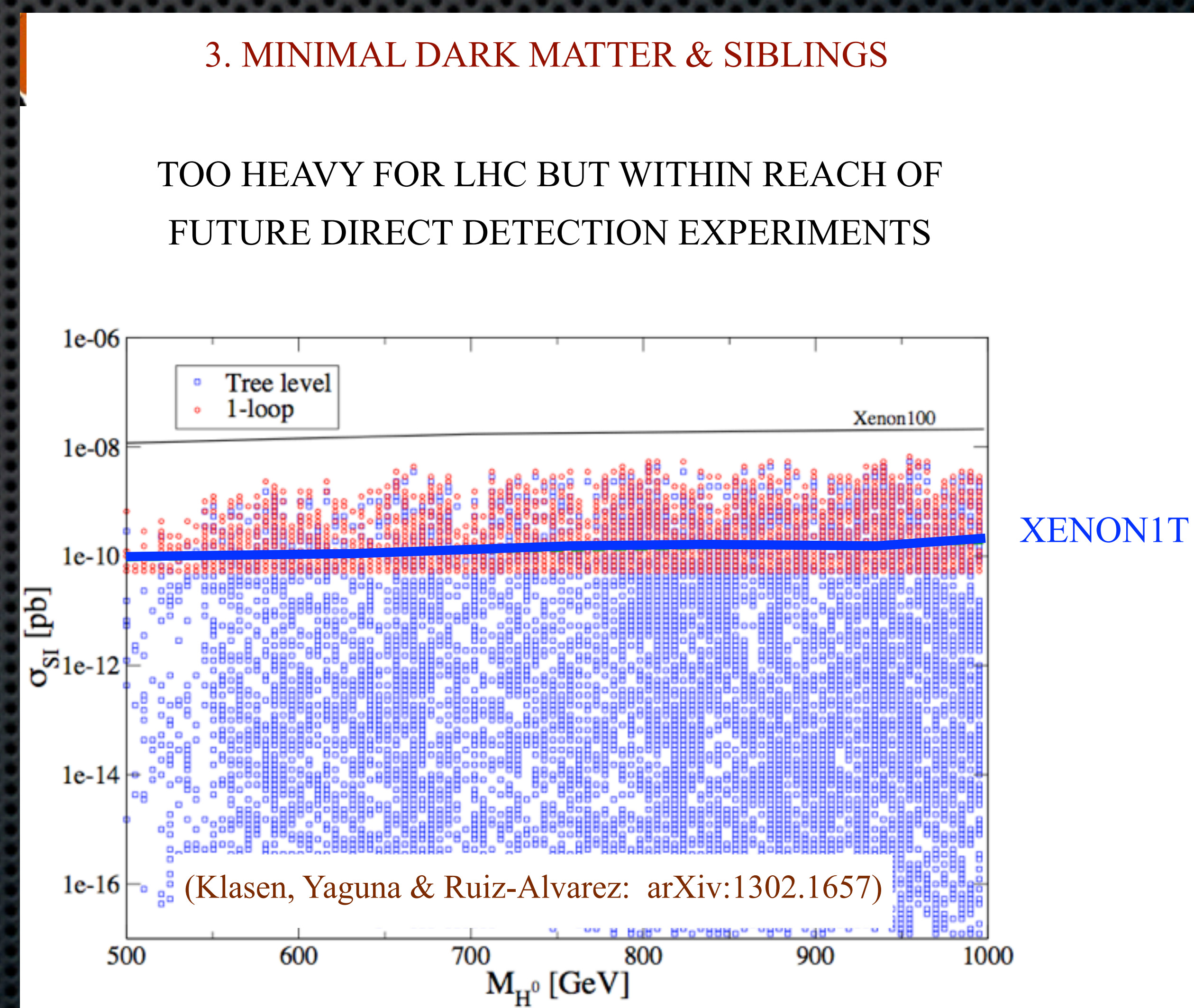
- SUSY: scattering cross sections on nucleons down to ~ 10^{-48} cm^2(10^{-12} pb)
- Here example in CMSSM, after LHC 5/fb, XENON100 and Bs->μμ



Particle physics

- Many other possibilities for WIMPs: singlet (scalar, fermionic) dark matter, inert Higgs, minimal DM etc (see previous talk)
  - can be probed by direct detection experiments





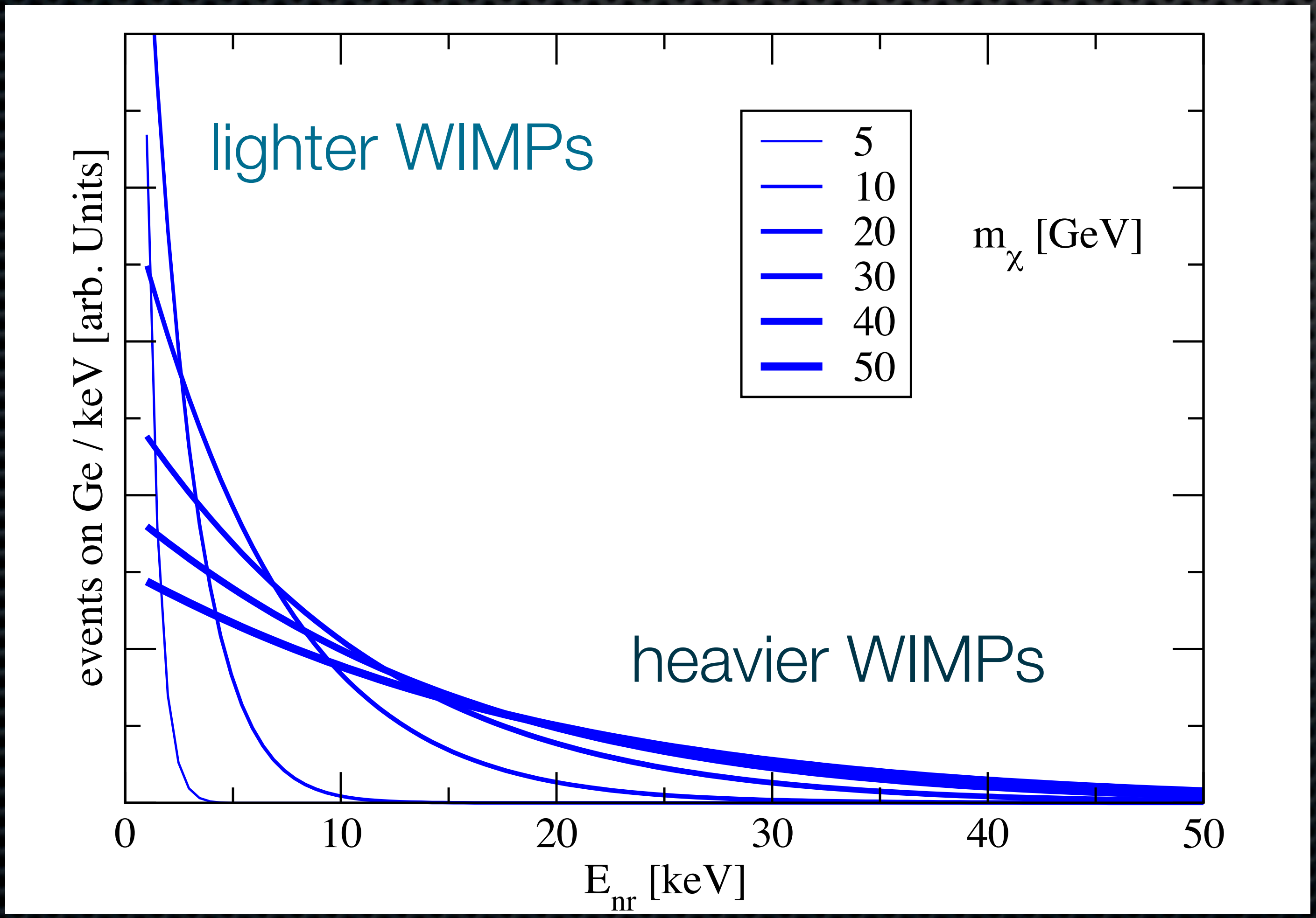
Jim Cline, Invisibles Workshop, Durham, Lumley Castle 2013

Michel Tytgat, Invisibles Workshop, Durham, Lumley Castle 2013

Expected Interaction Rates

- Recoil rate after integration over WIMP velocity distribution

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



Recoil spectrum for different WIMP masses

Expected Interaction Rates

- Recoil rate after integration over WIMP velocity distribution

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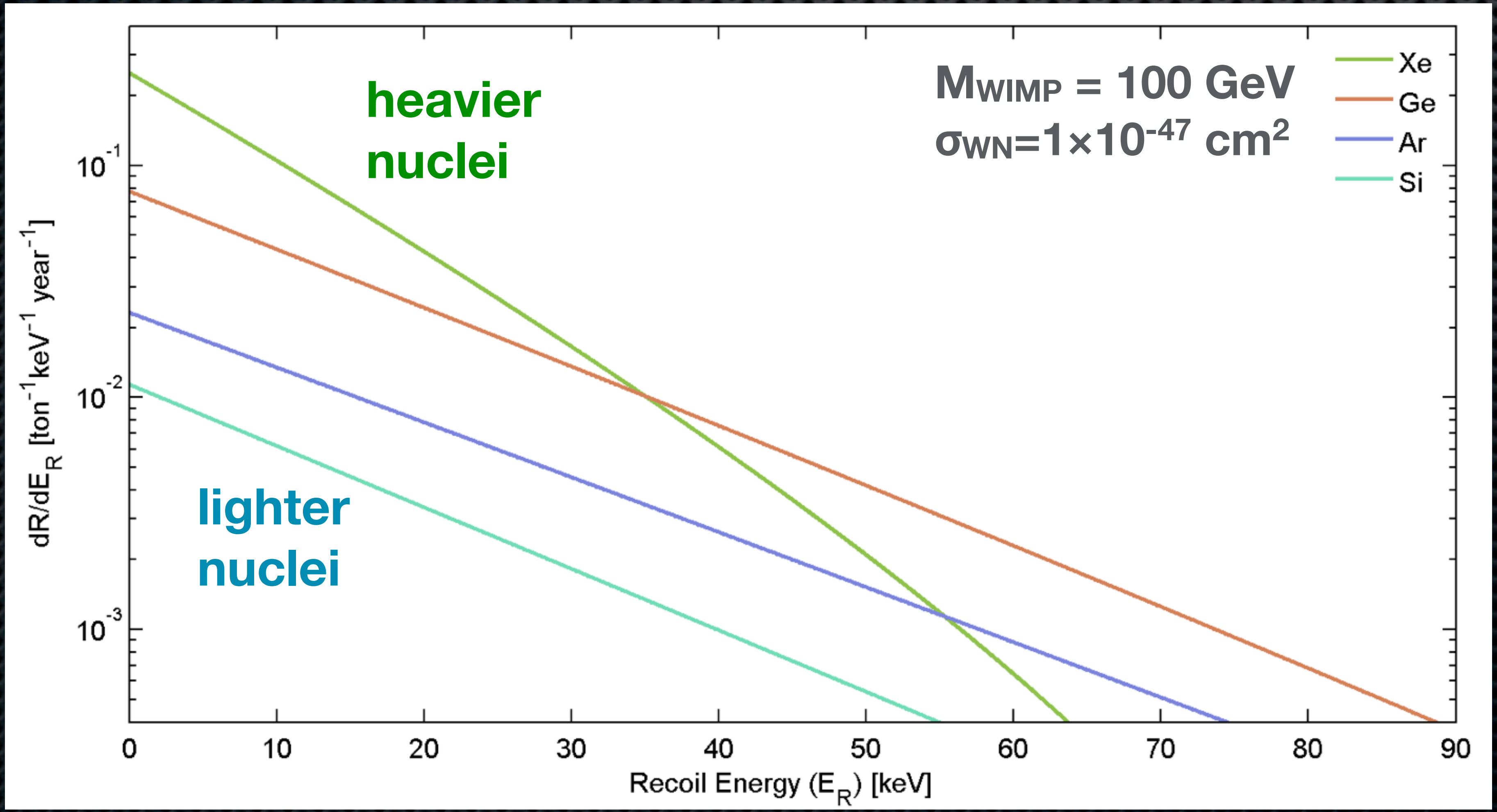
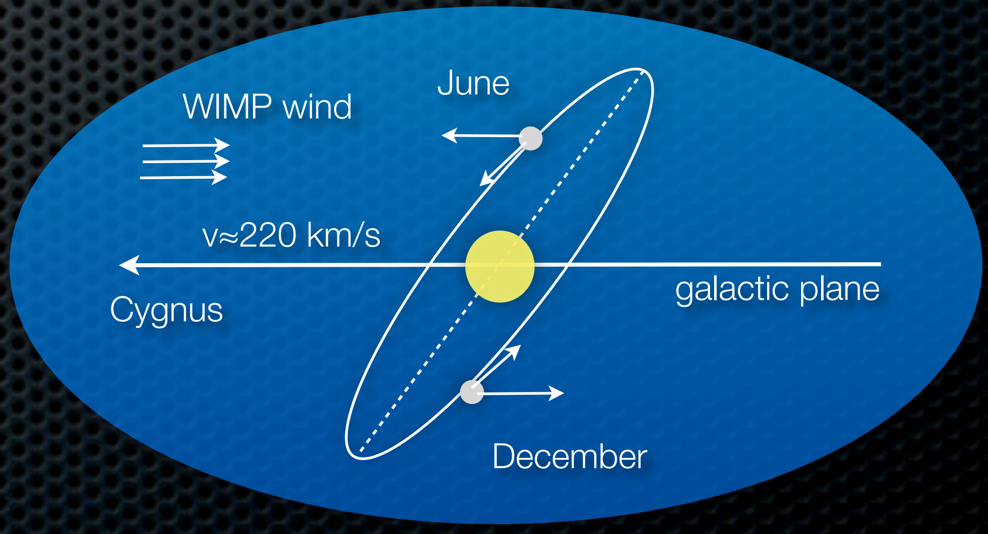


(Standard halo model with ρ= 0.3 GeV/cm³)

Nuclear recoil spectrum for different target nuclei

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
- 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

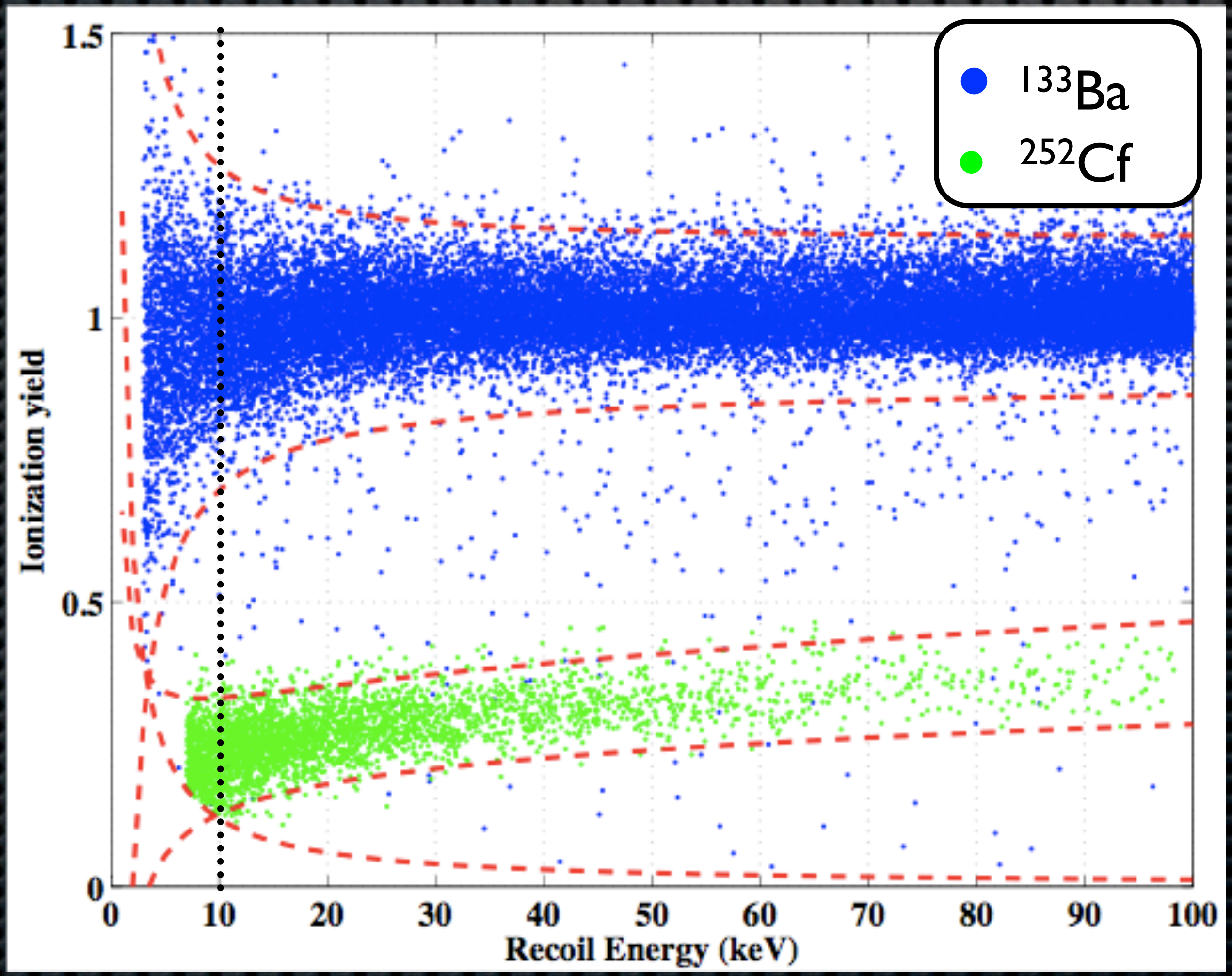


The world wide wimp search

Cryogenic Experiments at T~ mK

- **Advantages**: high sensitivity to nuclear recoils (measure the full energy in the phonon channel); good energy resolution, low energy threshold (keV to sub-keV)
- **Ratio of light/phonon or charge/phonon:**
  - nuclear versus electronic recoils discrimination -> separation of S and B

Ratio of charge (or light) to phonon

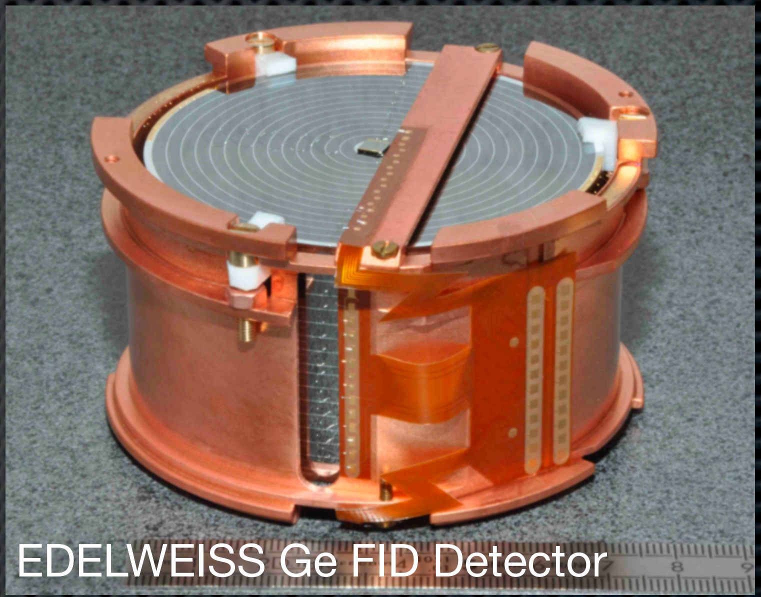


Background region

Expected signal region

Cryogenic Experiments at T~ mK

- Absorber masses from ~ 100 g to 1400 g



SuperCDMS

9 kg Ge running at Soudan (15 x 600 g)

proposed 200 kg Ge at SNOLab (1.4 kg crystals)

CRESST

18 detector modules (5 kg) installed at LNGS

low background run to start in 2013

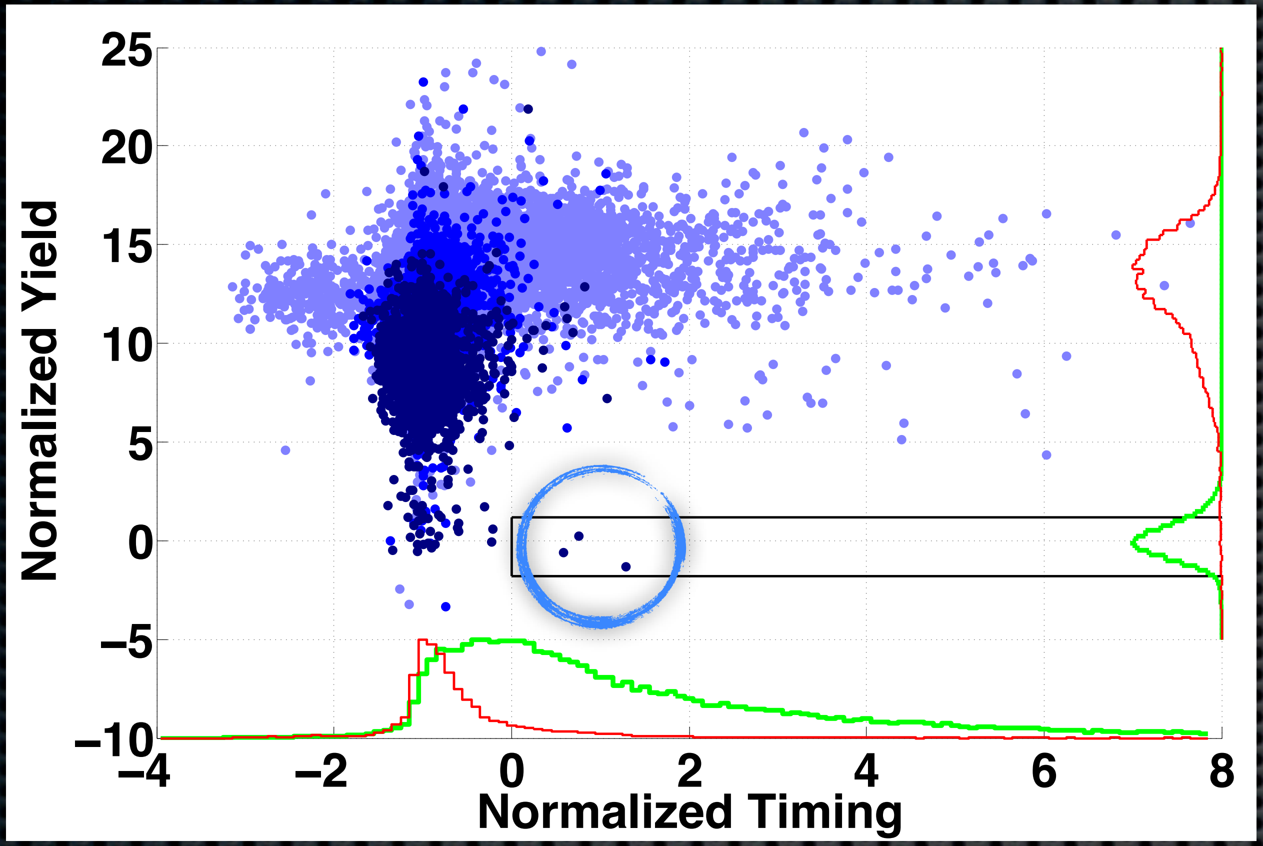
EDELWEISS-III

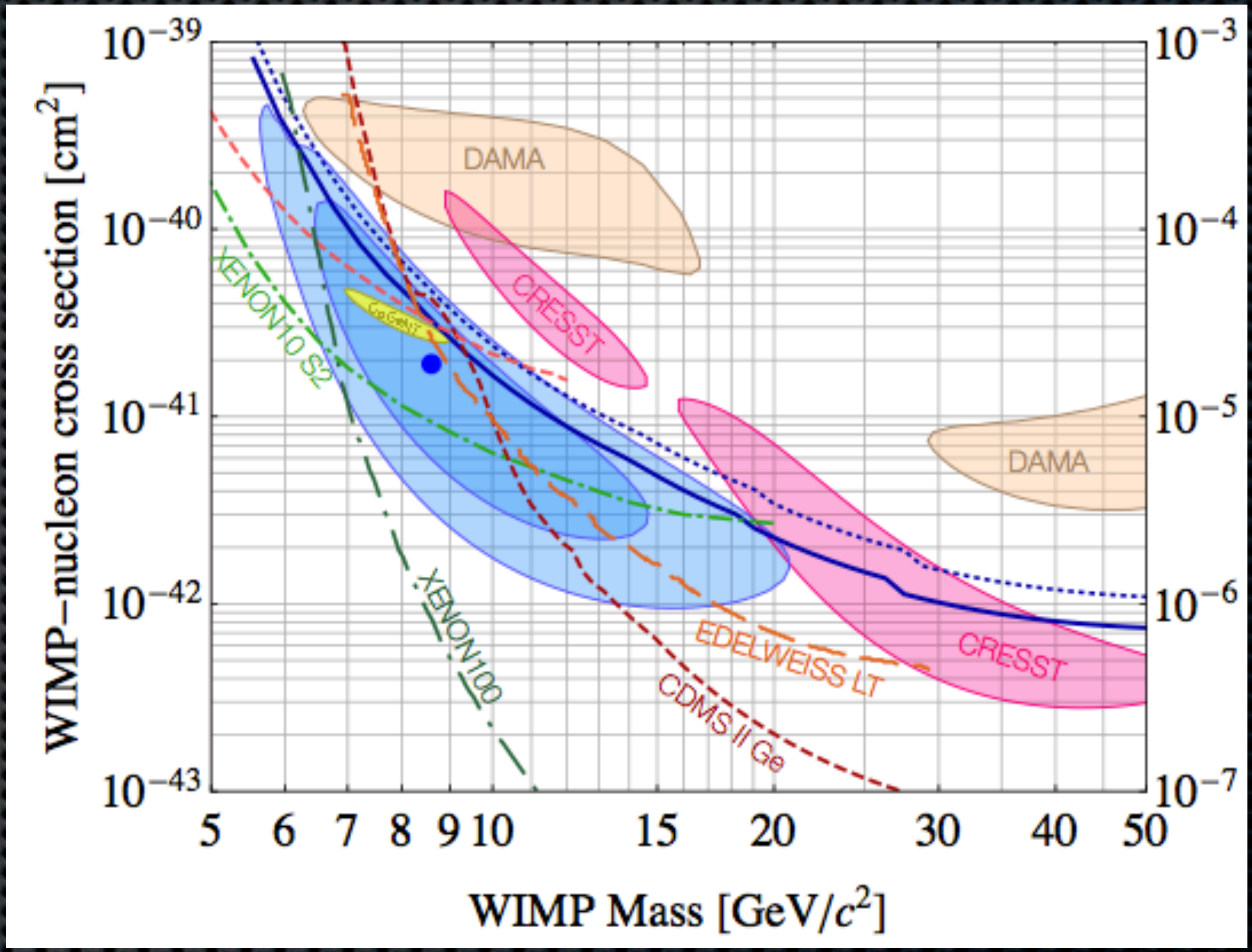
commissioning run with 15 FID detectors in spring 2013 (12 kg Ge)

fall 2013: installation of 40 x 800 g (32 kg Ge)

New results from CDMS-Si

arXiv:1304.4279v2 [hep-ex] 4 May 2013





140 kg d exposure

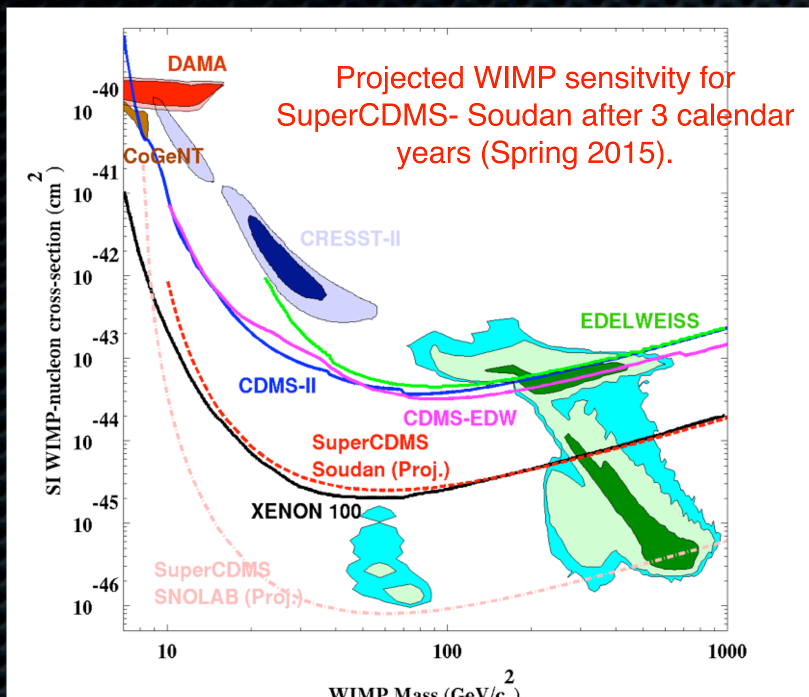
3 events detected, 0.7 expected

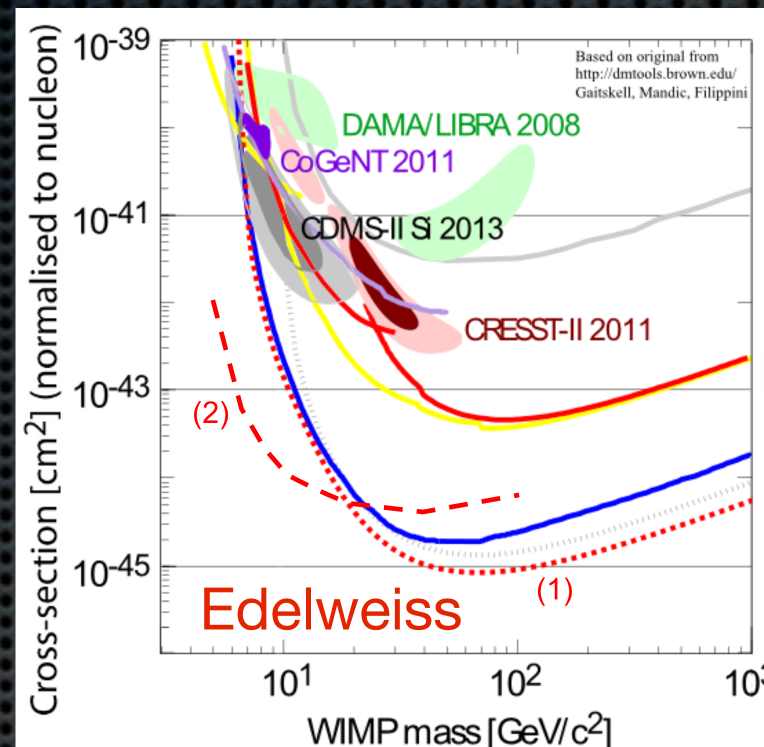
likelihood analysis: 0.19% probability for known background-only hypothesis

best fit: 8.6 GeV, 1.9 x 10^{-42} cm2

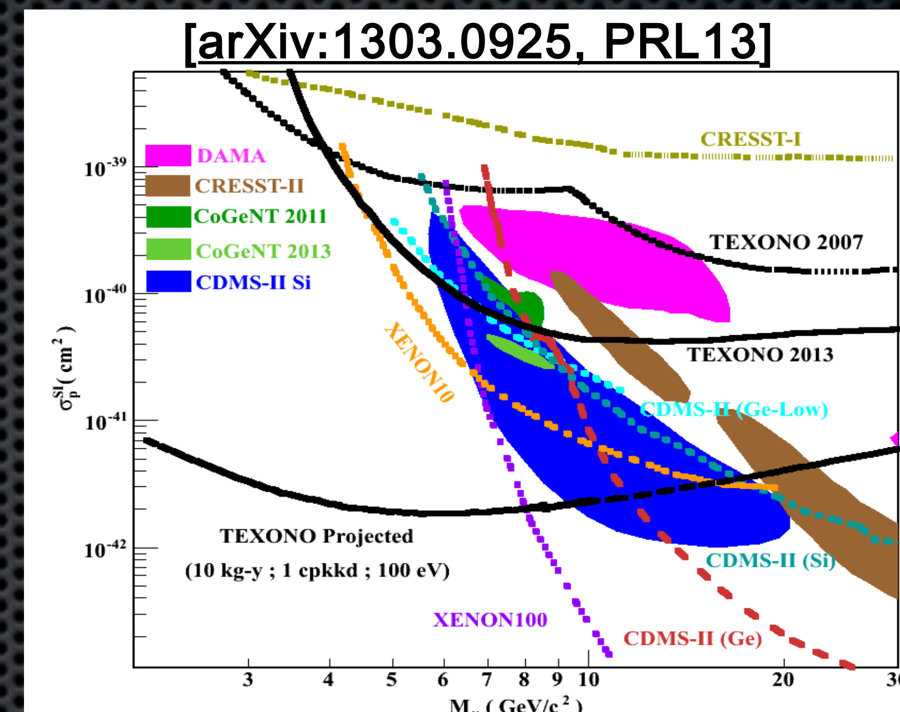
Analysis ongoing of low-threshold run (CDMS-lite) at Soudan with one Ge detector

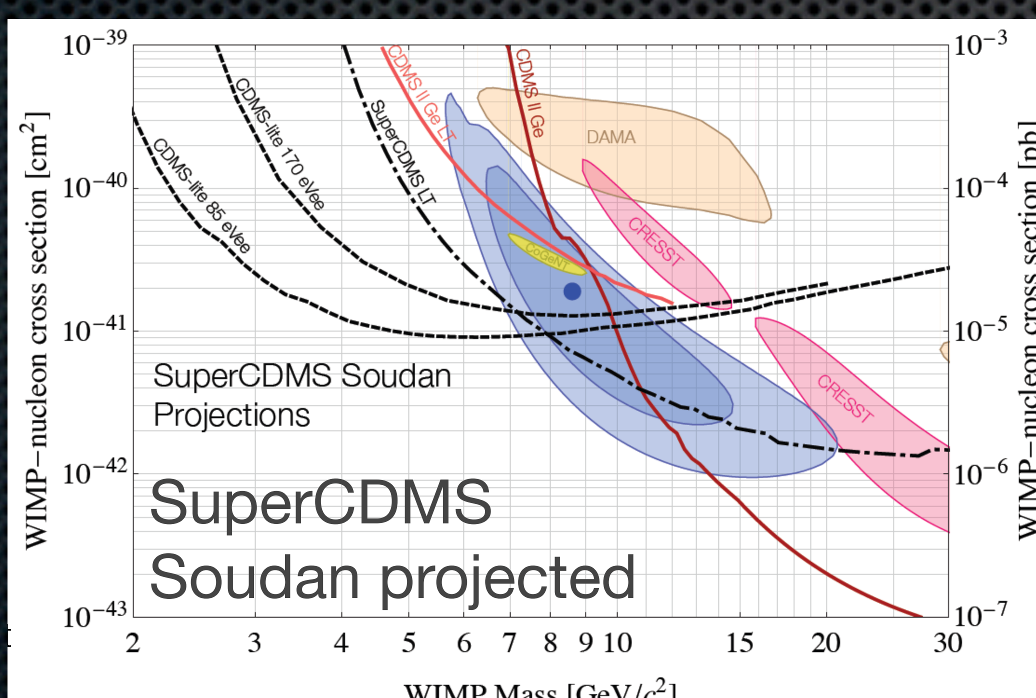
Projections: Cryogenic Experiments

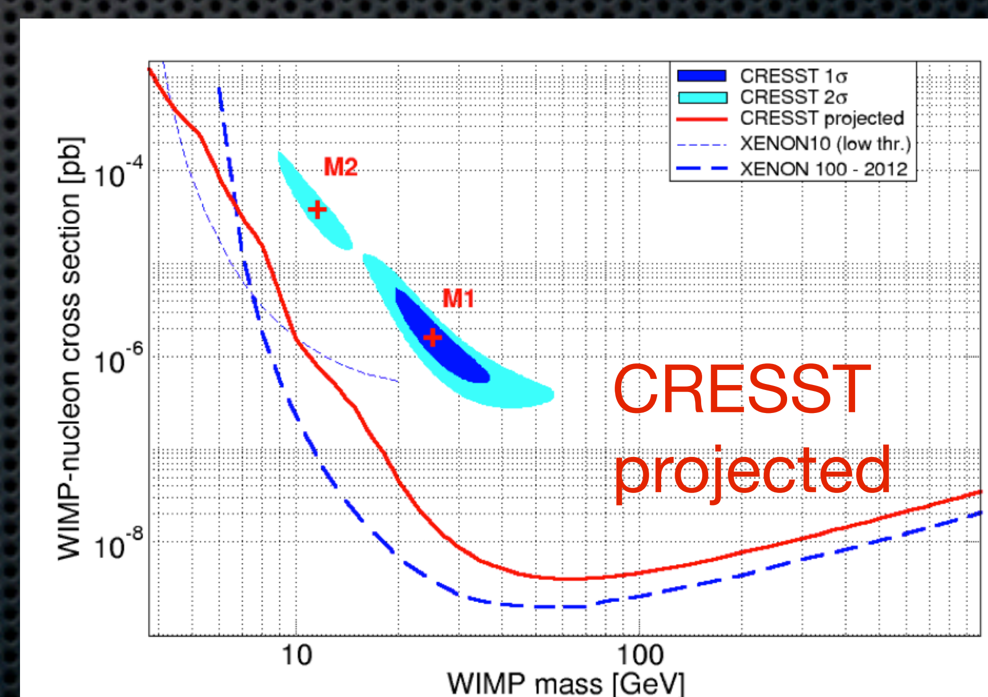




Texono: 1 kg Ge, E_{th}=500 eV

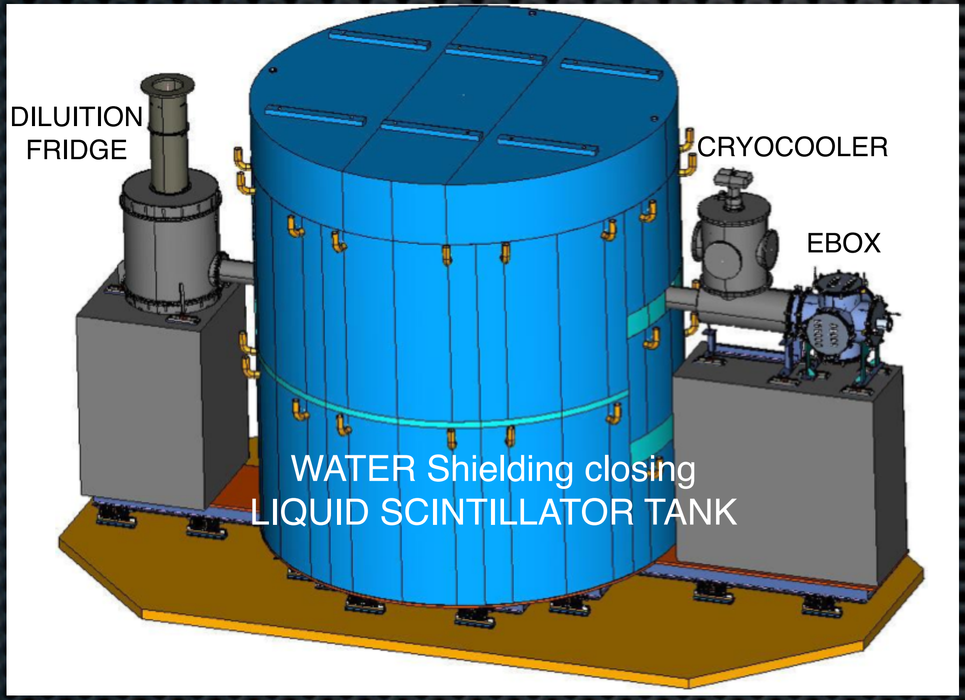




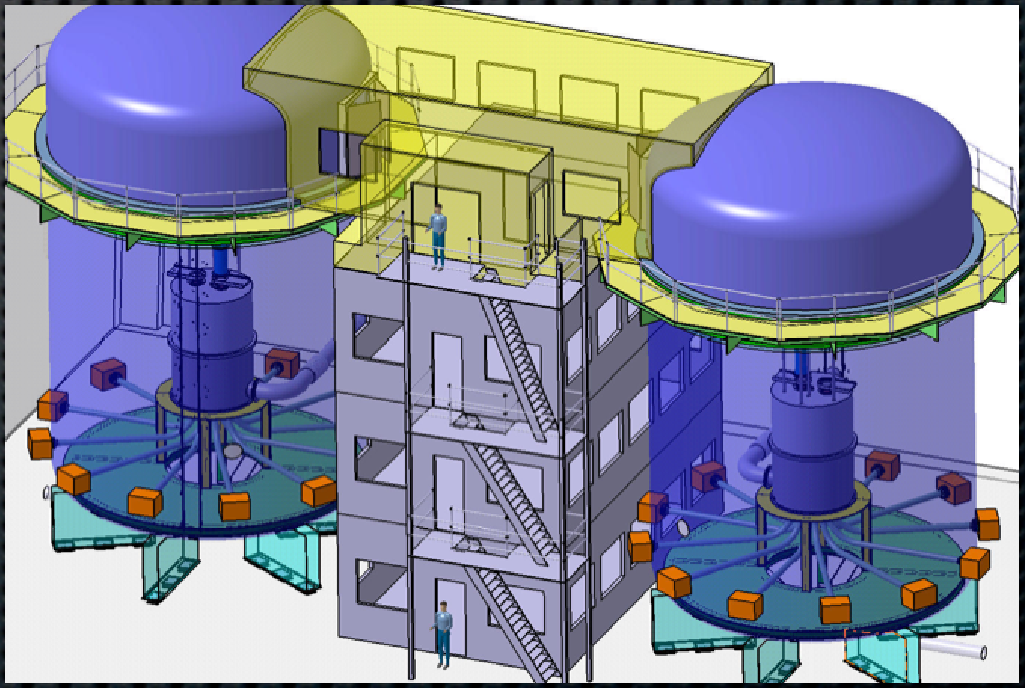


Future Cryogenic Experiments at T~ mK

- SuperCDMS at SNOLab: proposed 200 kg Ge detectors, reach: $8x10^{-47}$ cm^2
- EURECA at LSM extension (approved): phased approach150 kg to 1 ton, multi-target ($CaWO_3$, Ge), reach 10^{-46} - 10^{-47} cm^2
- Potential collaboration between SuperCDMS and EURECA, at the 200 kg level



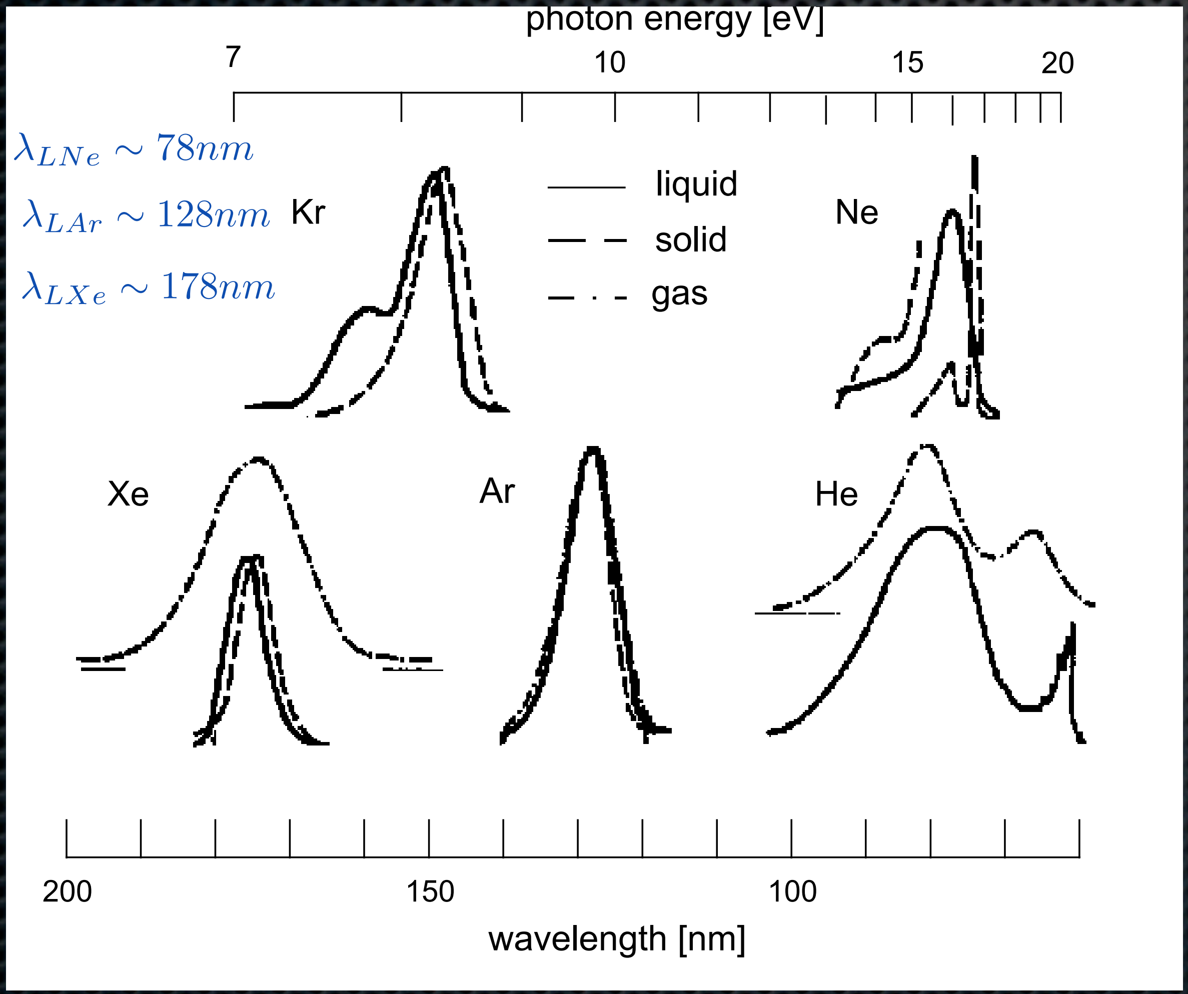
SuperCDMS at SNOLab



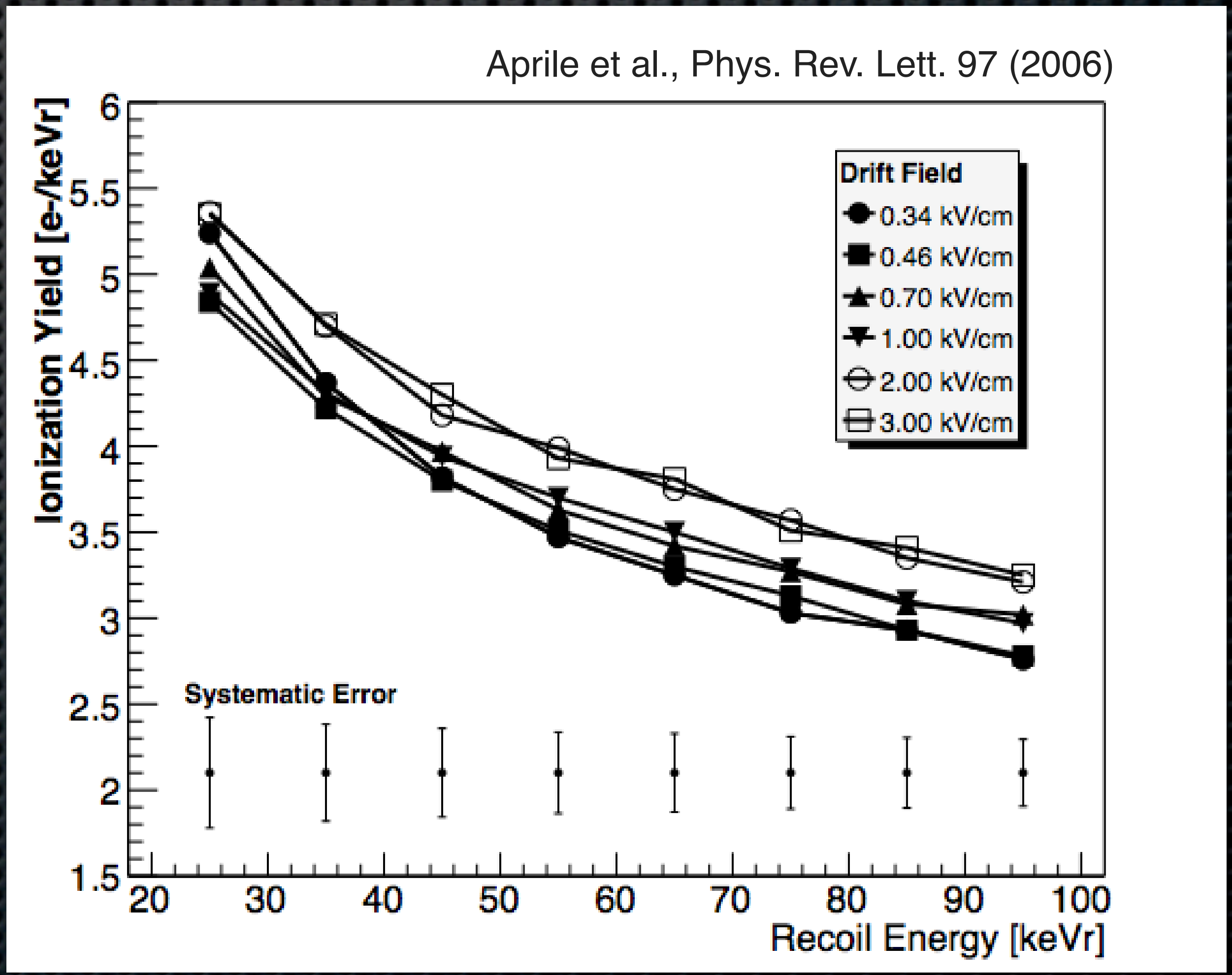
EURECA at DOMUS

Scintillation/Ionization: Noble Liquids

- High light and charge yield; transparent to their own light
- Large, scalable, homogeneous and self-shielding detectors -> fiducialization
- In air, by volume - Ar: 0.93%, Ne: 0.0018%, He: 0.00052%, Kr: 0.00011%, Xe: 0.0000087%



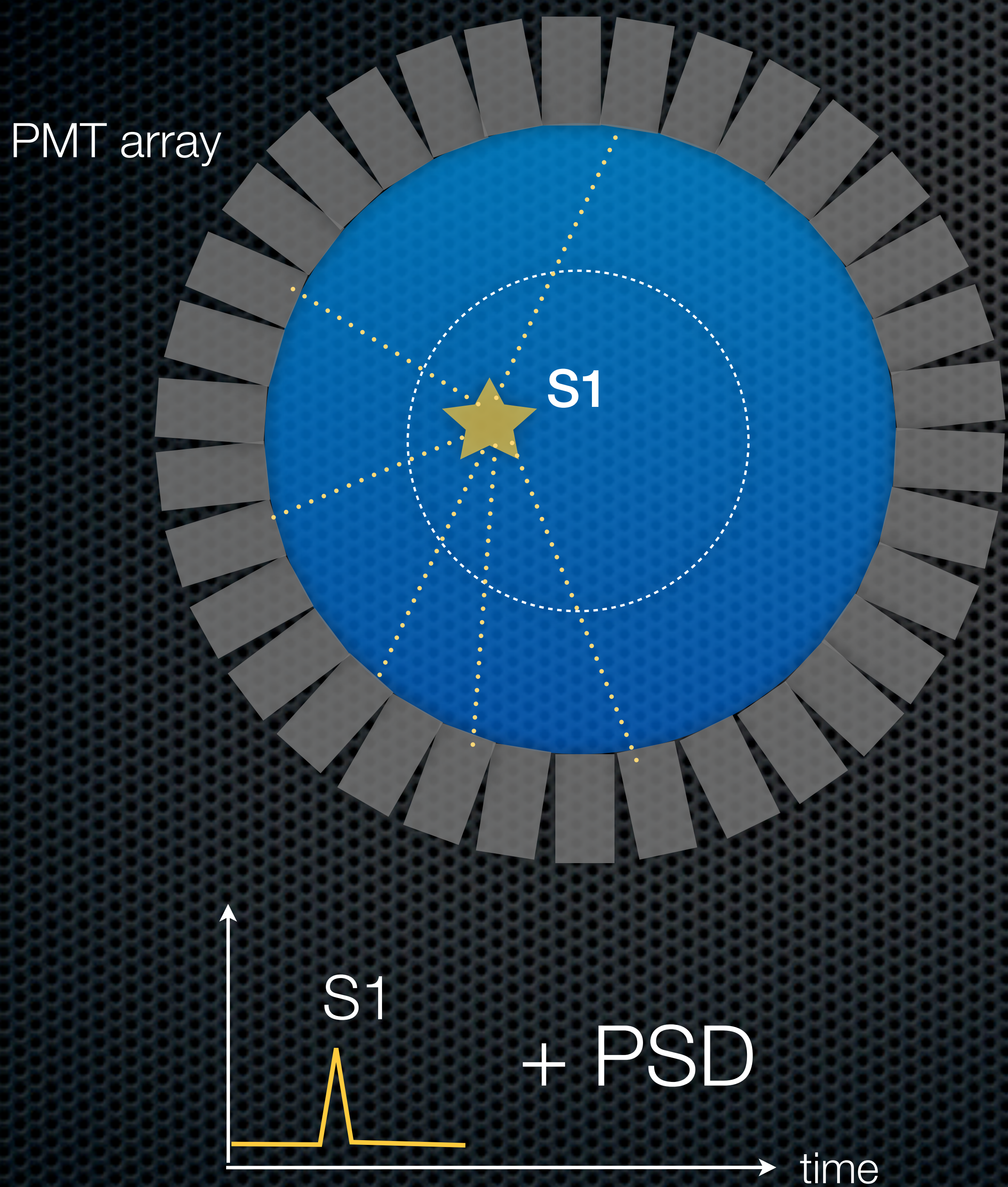
Light



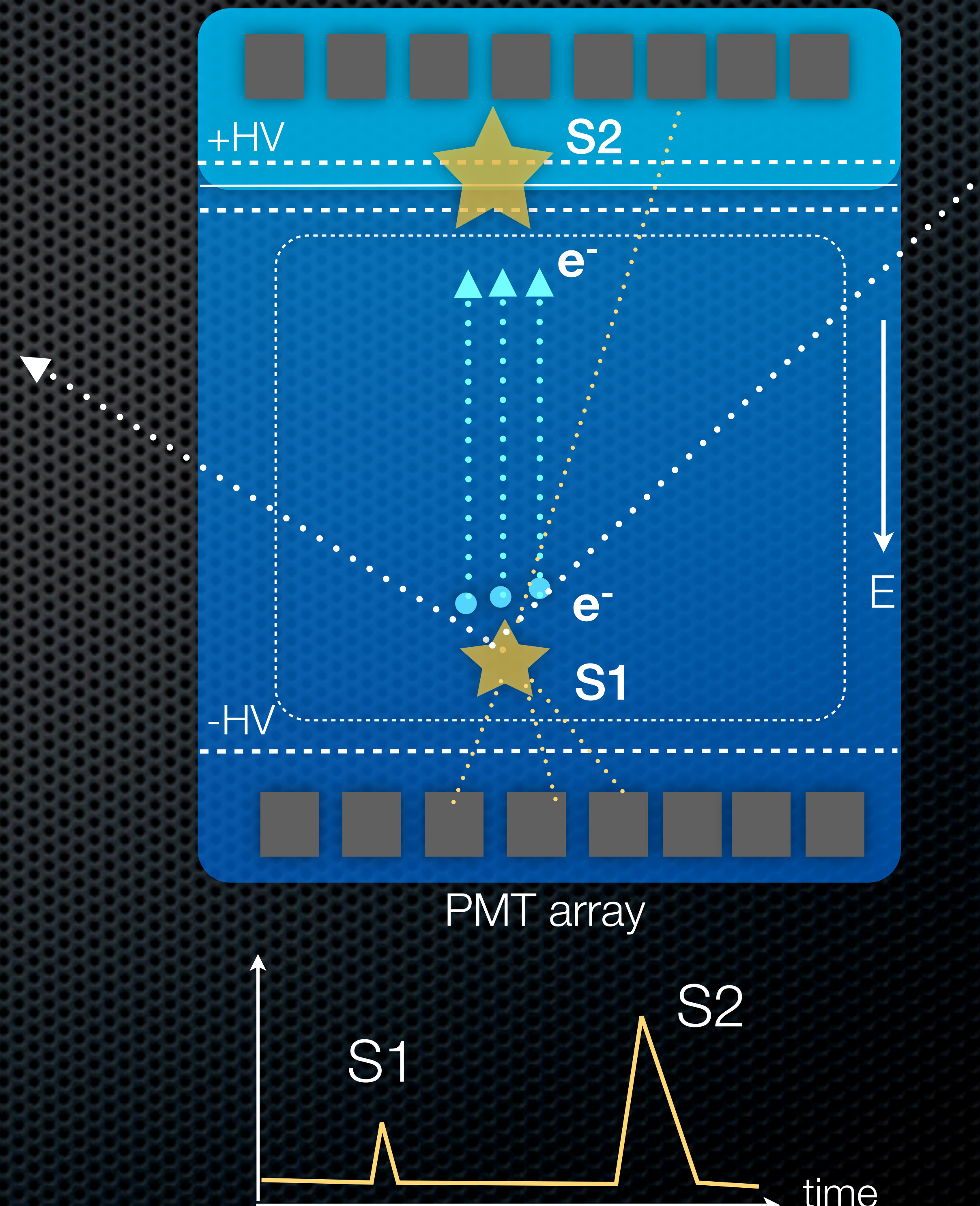
Charge

Two detector concepts

Single phase



Double phase (TPC)



Single-phase detectors

- XMASS at Kamioka (LXe), DEAP and CLEAN at SNOLab (LAr)
- Challenge: ultra-low absolute background (materials, radon, alphas)

XMASS at Kamioka:

835 kg LXe (100 kg fiducial),
single-phase, 642 PMTs
unexpected background found
detector refurbished
new run this fall -> 2013

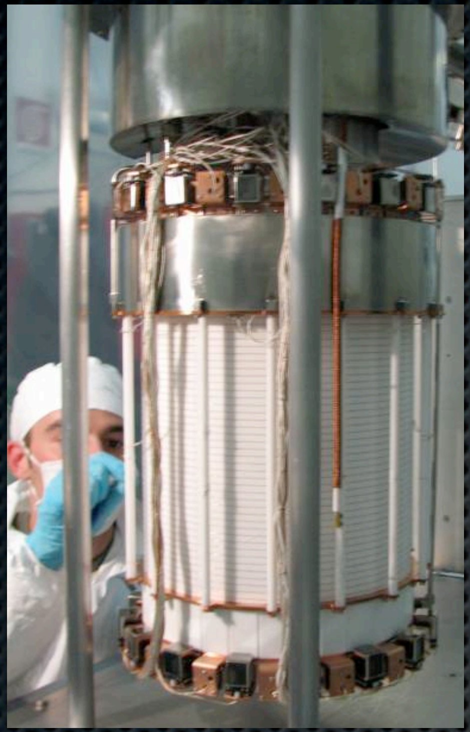
CLEAN at SNOLab:

500 kg LAr (150 kg fiducial)
single-phase open volume
under construction
to run in 2014

DEAP at SNOLab:

3600 kg LAr (1t fiducial)
single-phase detector
under construction
to run in 2014

Liquid xenon and liquid argon TPCs



XENON100 at LNGS:

161 kg LXe
(~50 kg fiducial)

242 1-inch PMTs
taking new science data

LUX at SURF:

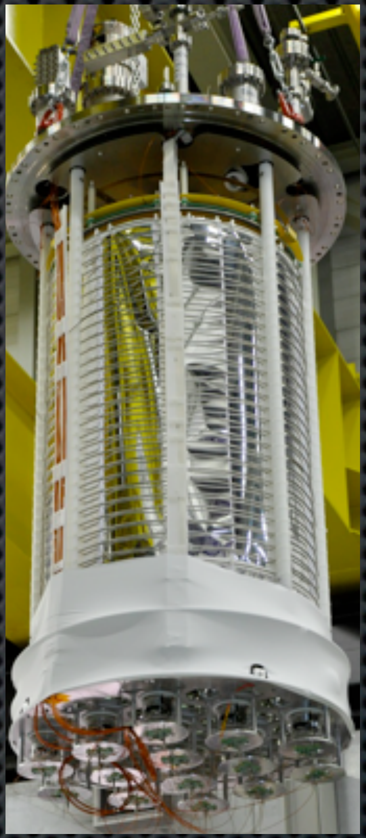
350 kg LXe
(100 kg fiducial)

122 2-inch PMTs
physics run since spring 2013
first result this fall

PandaX at CJPL:

125 kg LXe
(25 kg fiducial)

143 1-inch PMTs
37 3-inch PMTs
started in early 2013



ArDM at Canfranc:

850 kg LAr
(100 kg fiducial)

28 3-inch PMTs
in commissioning
to run 2014

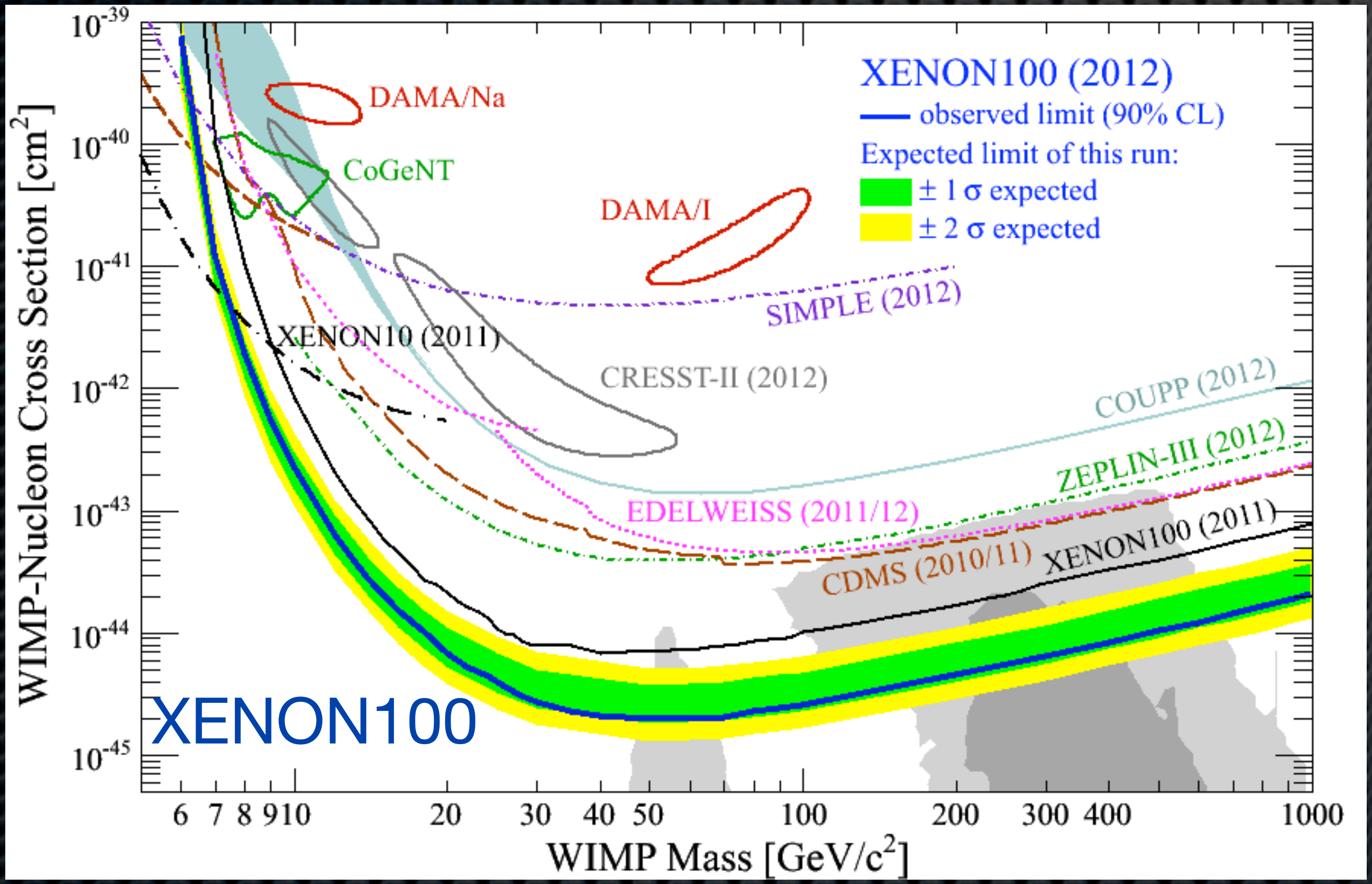
DarkSide at LNGS

50 kg LAr (dep in ^{39}Ar)
(33 kg fiducial)

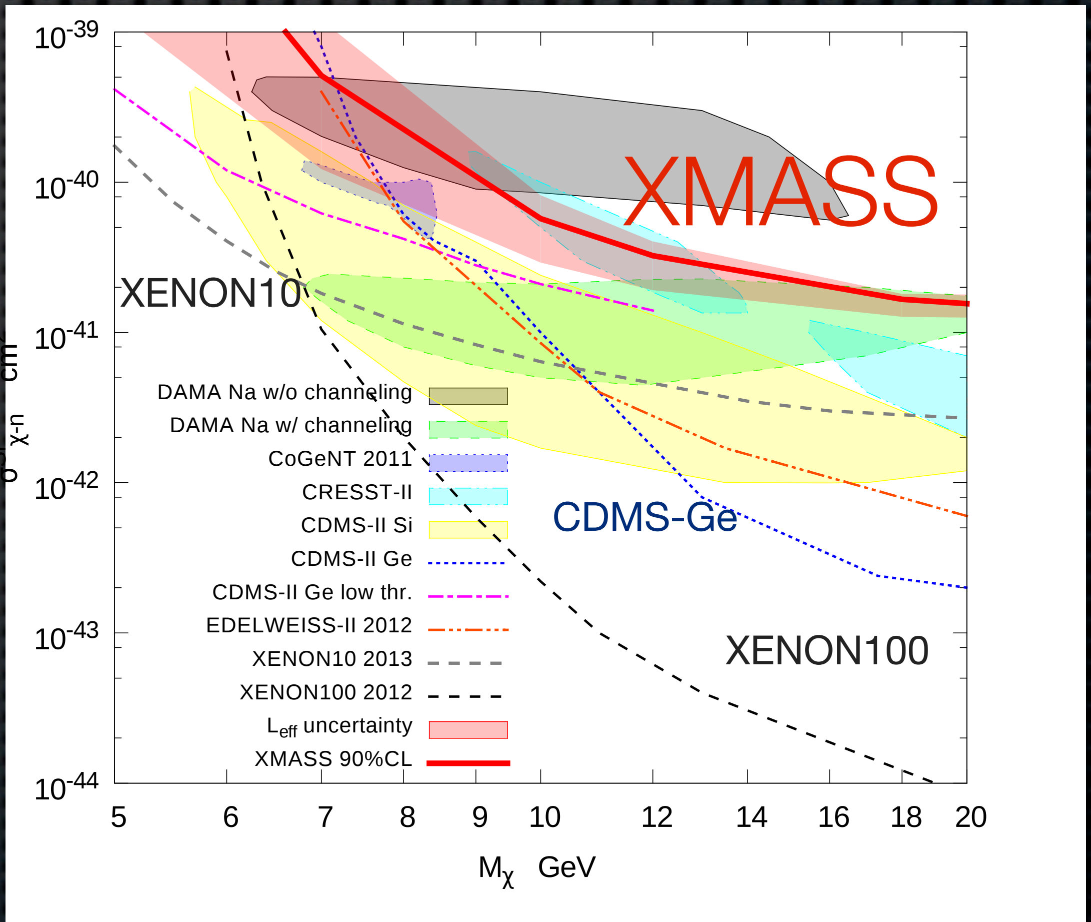
38 3-inch PMTs
in commissioning
since May 2013
to run in fall 2013

Noble liquid recent results: spin-independent cross section

XENON100: Phys. Rev. Lett. 109 (2012)

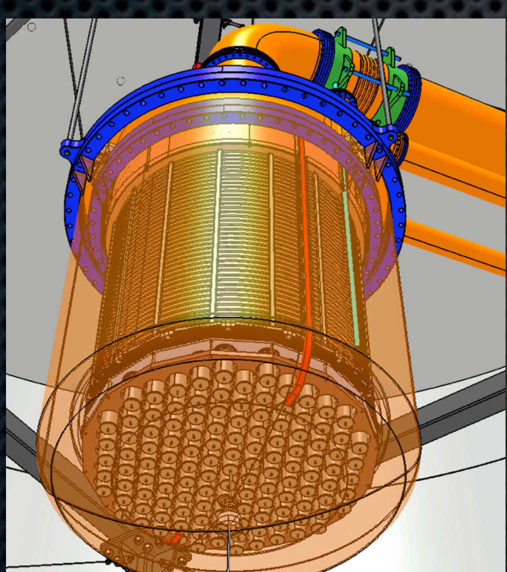


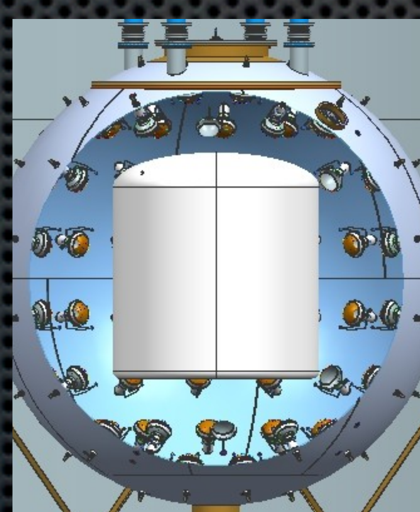
XMASS: Phys. Lett. B 719 (2013)

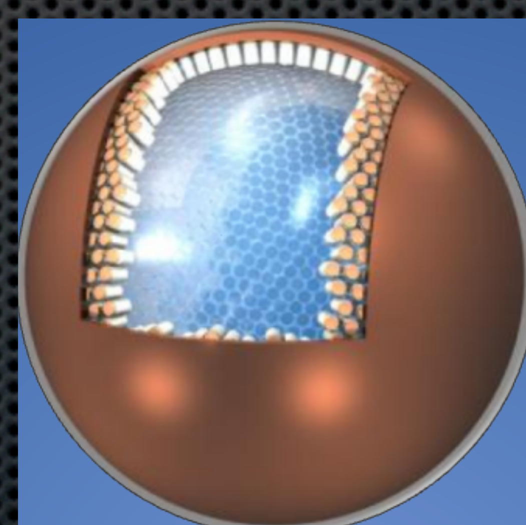


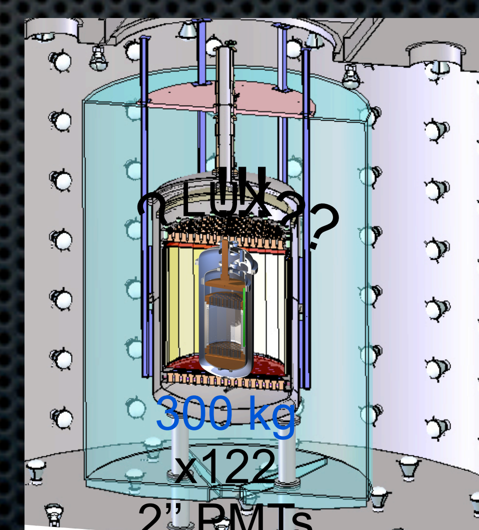
Liquid xenon and liquid argon detectors

- Under construction: XENON1T at LNGS, 3.5 t LXe in total
  - commissioning in 2014, first run in 2015; goal 2 x 10^{-47} cm^2
- Near future: XMASS (5 t LXe), DarkSide-5000 (5 t LAr)
- Design and R&D: LZ (7 t LXe), DARWIN (20 t LXe/LAr)

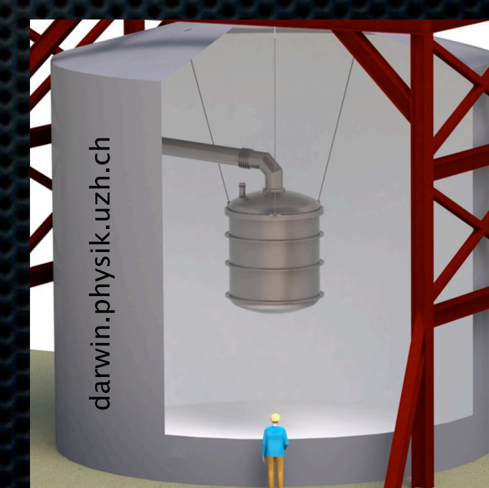

XENON1T: 3.5 t LXe


DarkSide: 5 t LAr


XMASS: 5t LXe



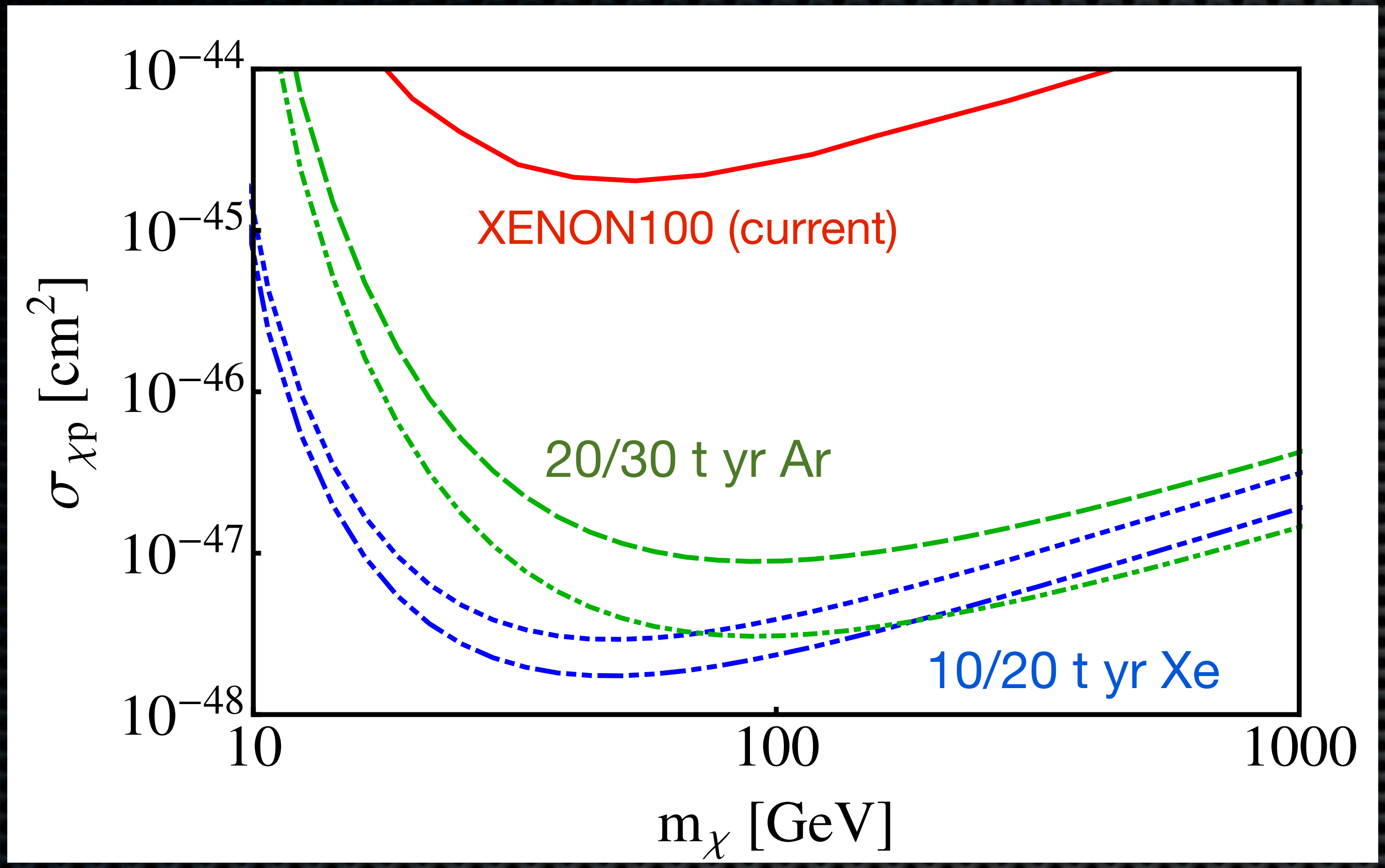
LZ: 7t LXe

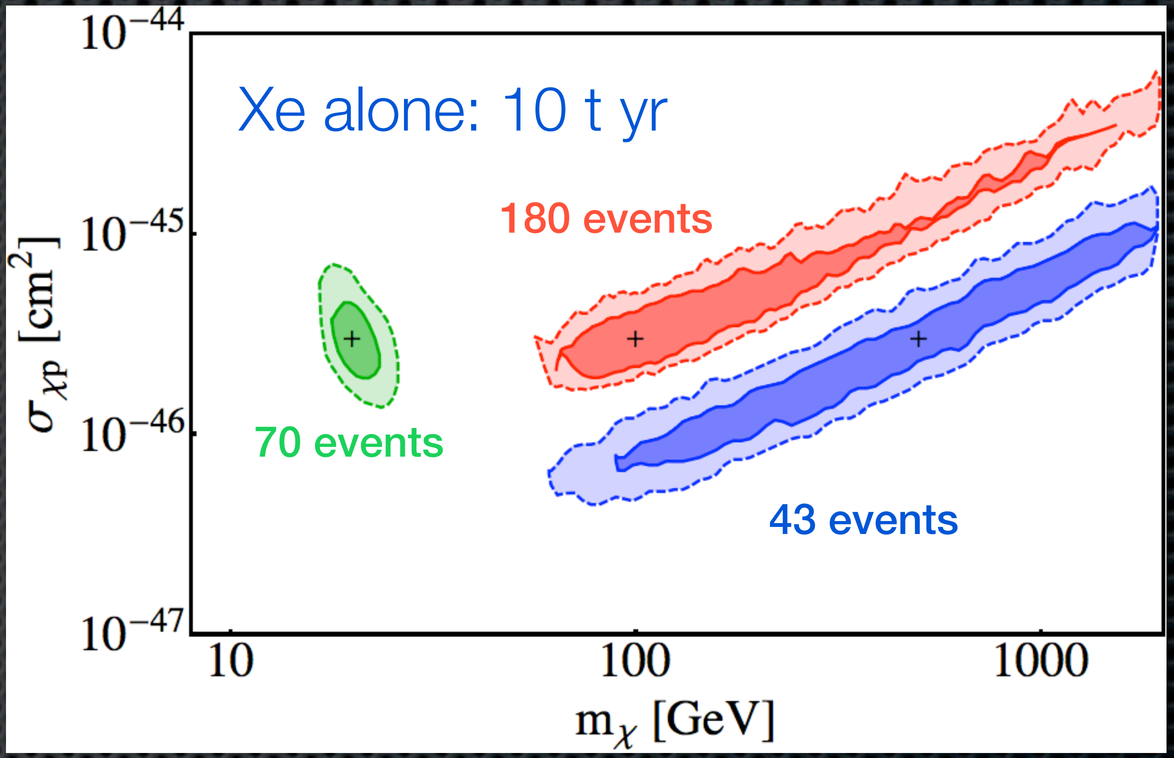


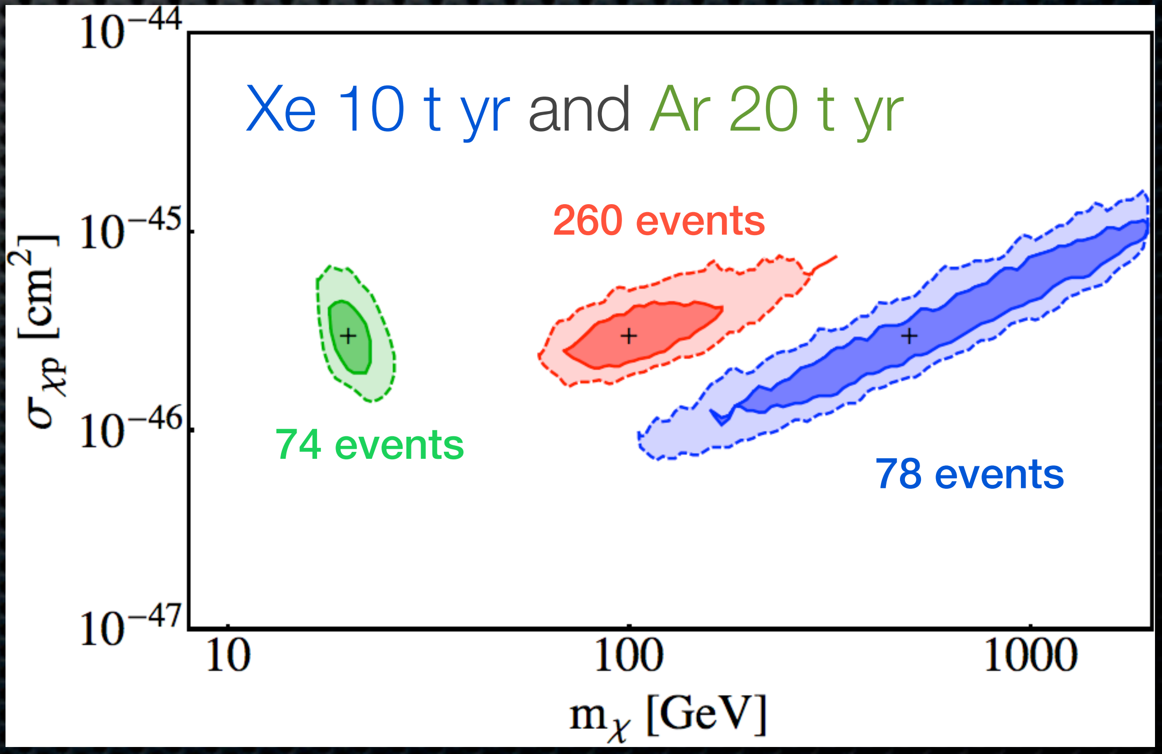
DARWIN: 20 t LXe/LAr

Argon/xenon complementarity

Newstead, Jacques, Krauss, Dent, Ferrer: arXiv:1306.3244 [astro-ph.CO]







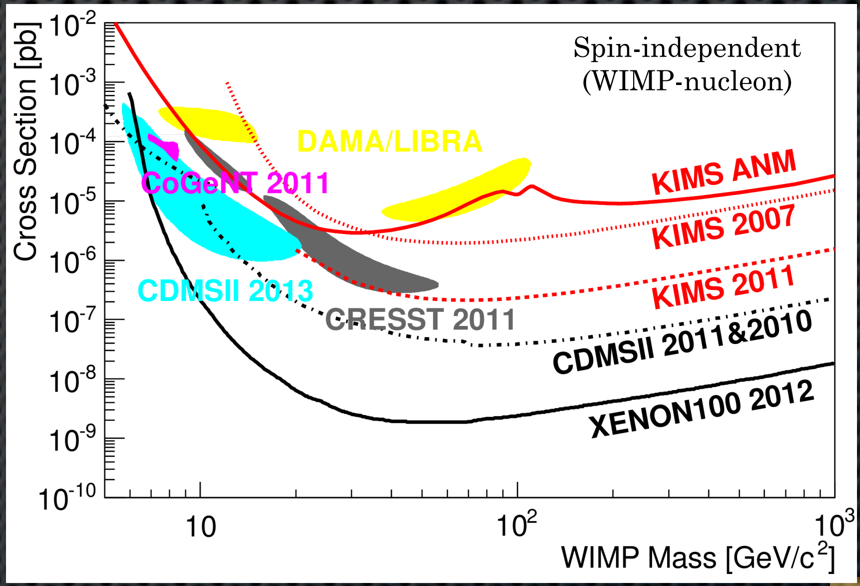
$$\rho_\chi = 0.3 \pm 0.1\,\mathrm{GeV\,cm^{-3}}$$

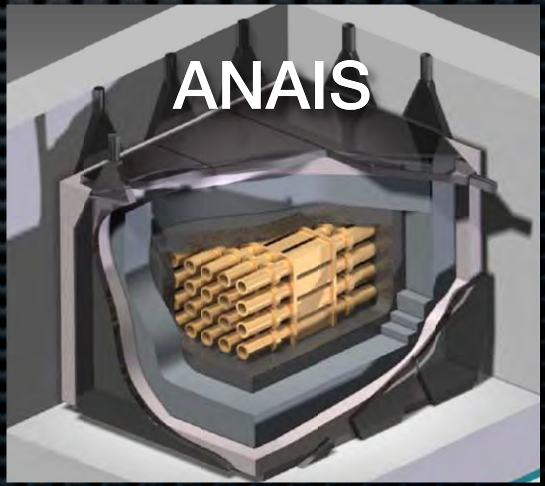
$$v_0 = 220 \pm 20\,\mathrm{km/s}$$

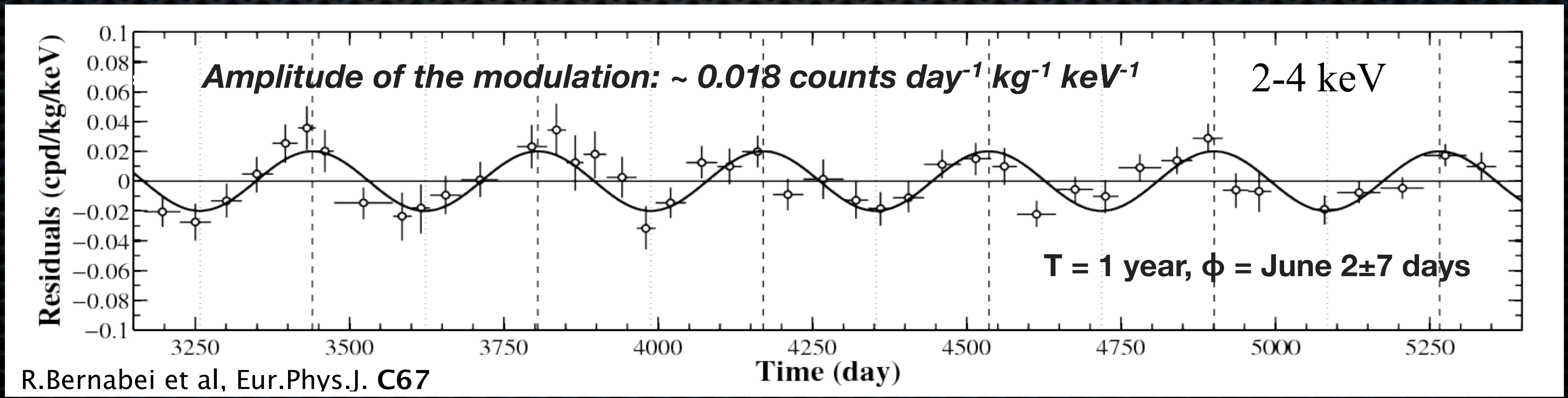
$$v_{esc} = 544 \pm 40\,\mathrm{km/s}$$

Room temperature scintillators

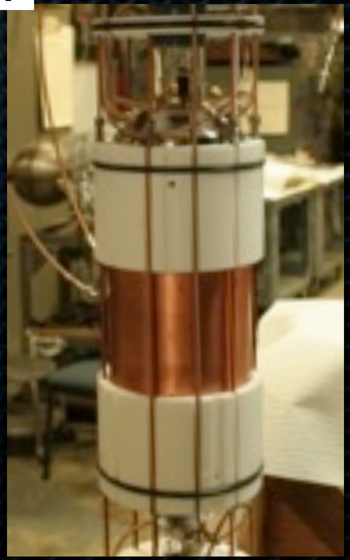
- **NaI**: DAMA/LIBRA 250 kg at LNGS; time variation in the event rate with: T = 1 yr, phase = June 2±7 days, A = 0.018 events/(kg keV day)
- **CsI**: KIMS 103.4 kg at Yangyang laboratory; ER vs. NR discrimination based on time structure of events; does not confirm DAMA/LIBRA in an annual modulation search
- **NaI**: ANAIS, 250 kg, under construction at LSC; DM-Ice, proposed 250 kg at the South Pole







R.Bernabei et al, Eur.Phys.J. **C67**



DM-Ice
17 kg NaI as feasibility study within IceCube 2.4 km deap

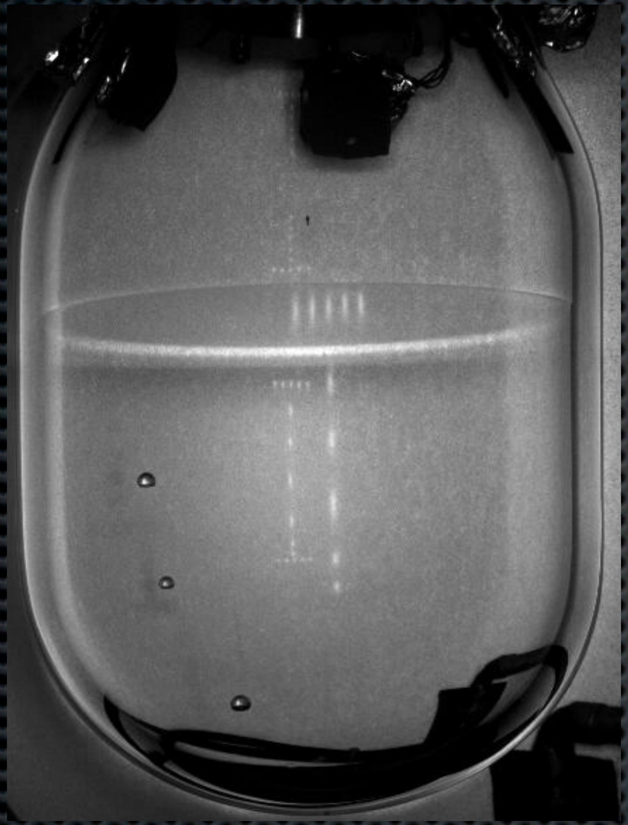
Bubble chambers

- 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)
- Future: COUPP-500 -> ton-scale detector

Example:

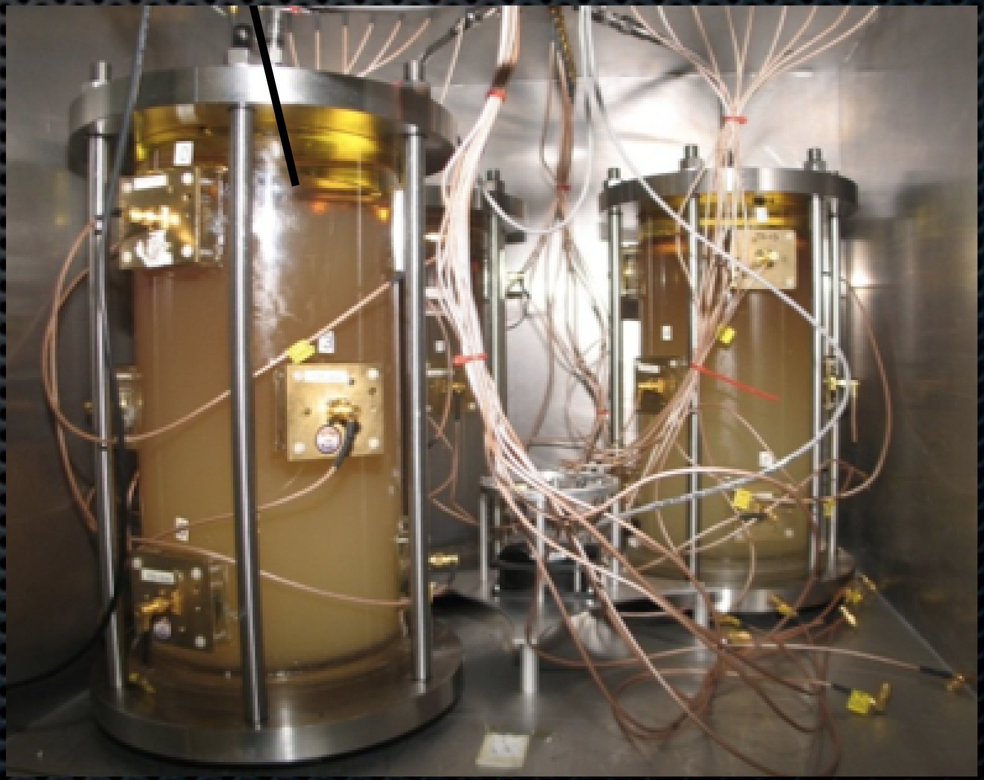
n-induced event (multiple scatter)

WIMP: single scatter



COUPP 4 kg CF_3I detector at SNOLAB

COUPP 60 kg CF_3I detector installed at SNOLAB; physics run since March 2013



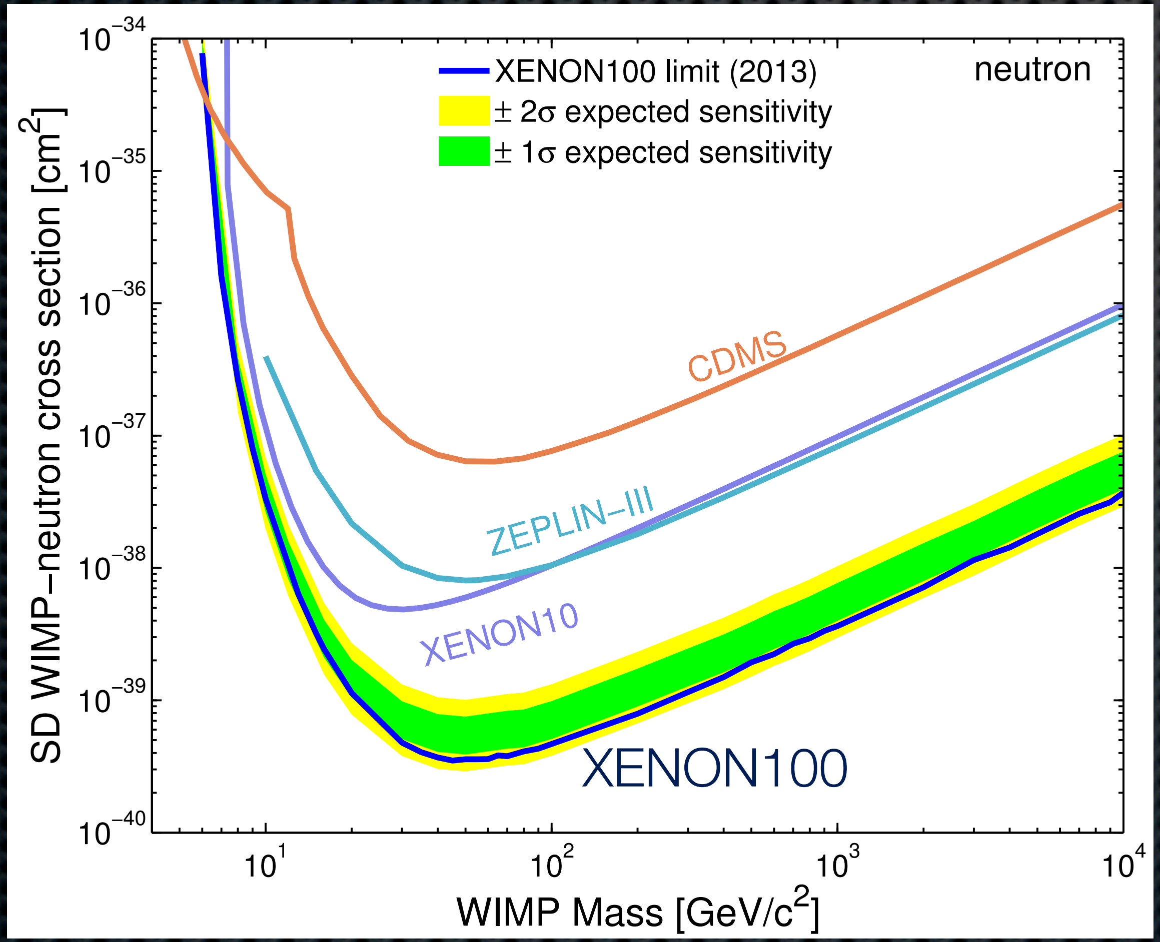
PICASSO at SNOLAB

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

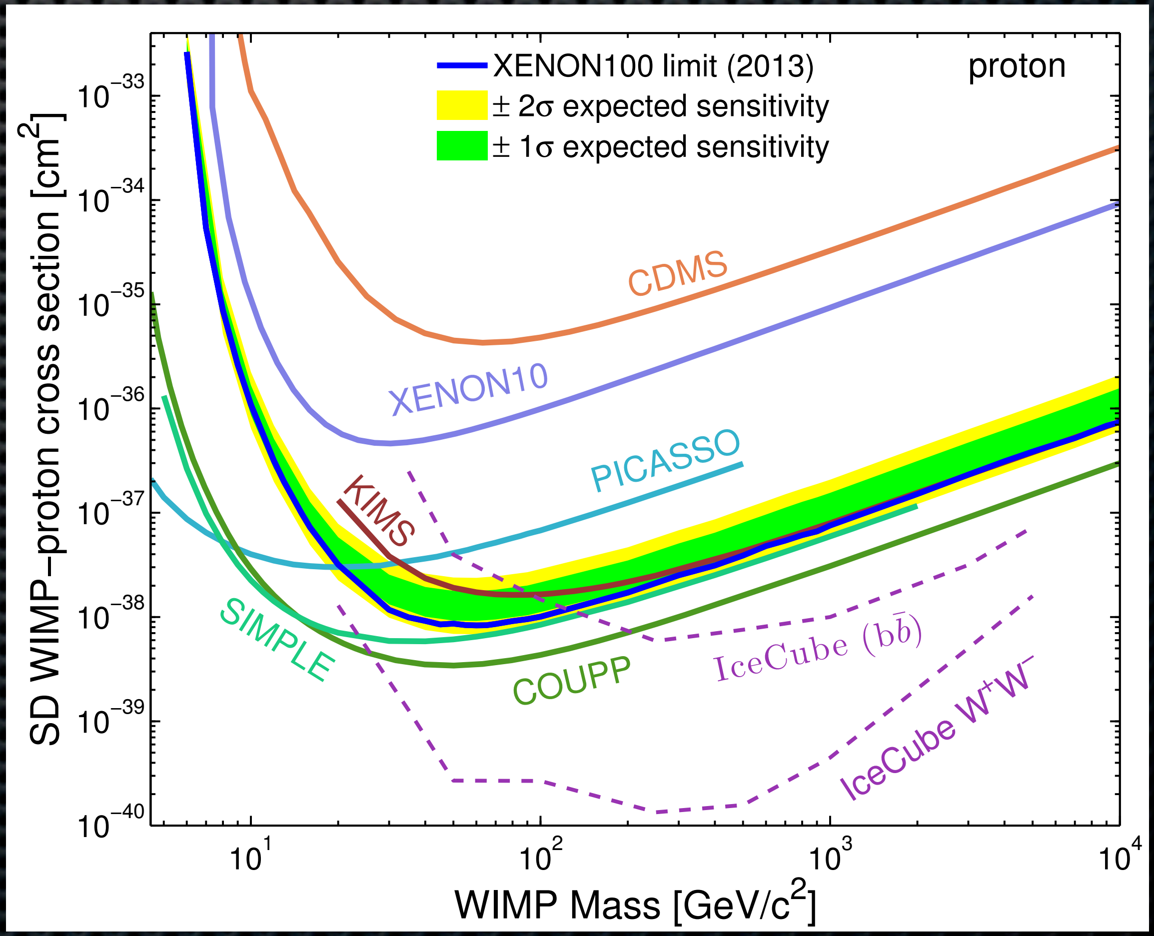
Spin-dependent results

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

WIMP-neutron coupling



WIMP-proton coupling

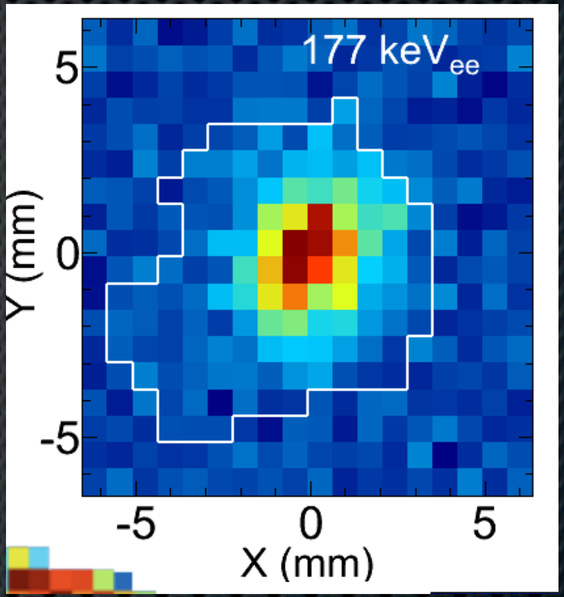


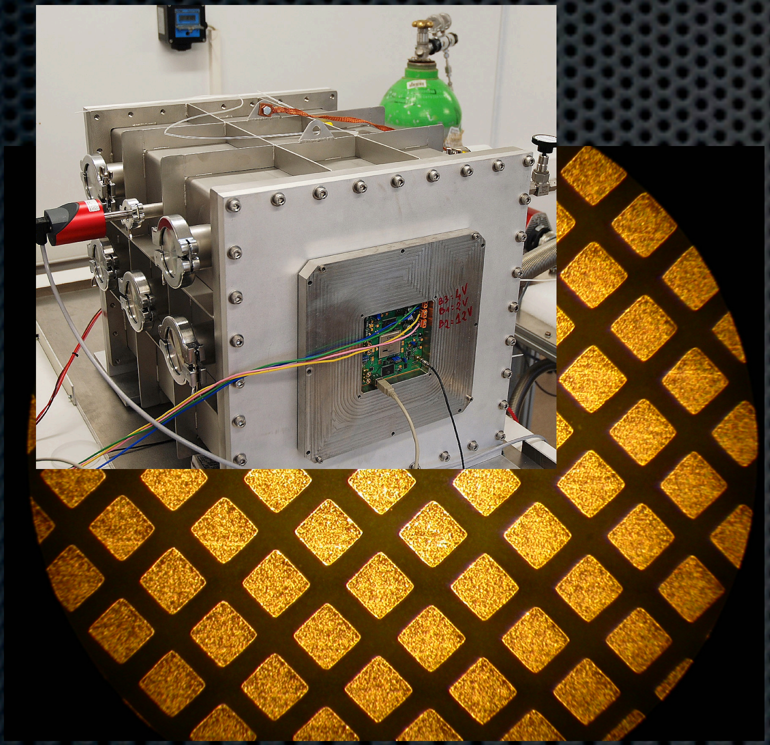
Phys. Rev. Lett. 111 (2013)

Directional detectors

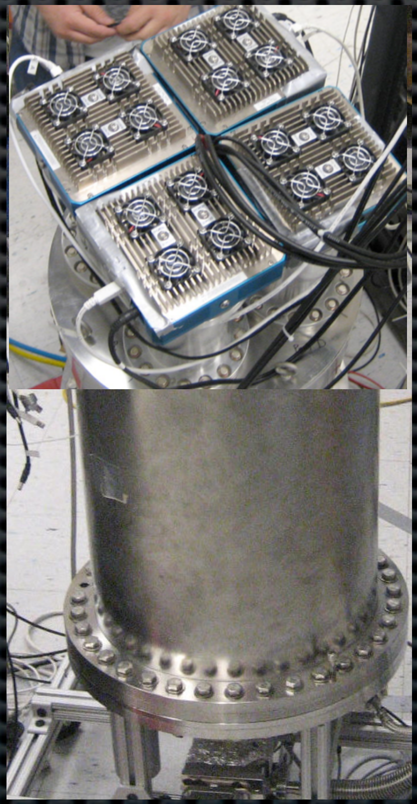
- R&D on low-pressure gas detectors to measure the recoil direction, correlated to the galactic motion towards Cygnus
- MicroTPCs: MIMAC (CF_4, CHF_3, H gas), NEWAGE (CF_4 gas)
- TPC: DRIFT (negative ion, CS_2), DM-TPC (CF_4 gas)

DM-TPC
n-calibration



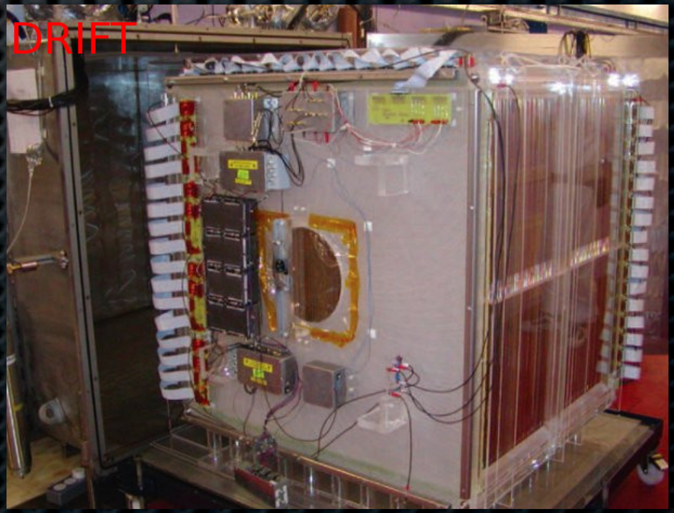


MIMAC 100x100 mm^2
5l chamber at Modane



18l DM-TPC at MIT
CCD readout

NEWAGE, Kamioka



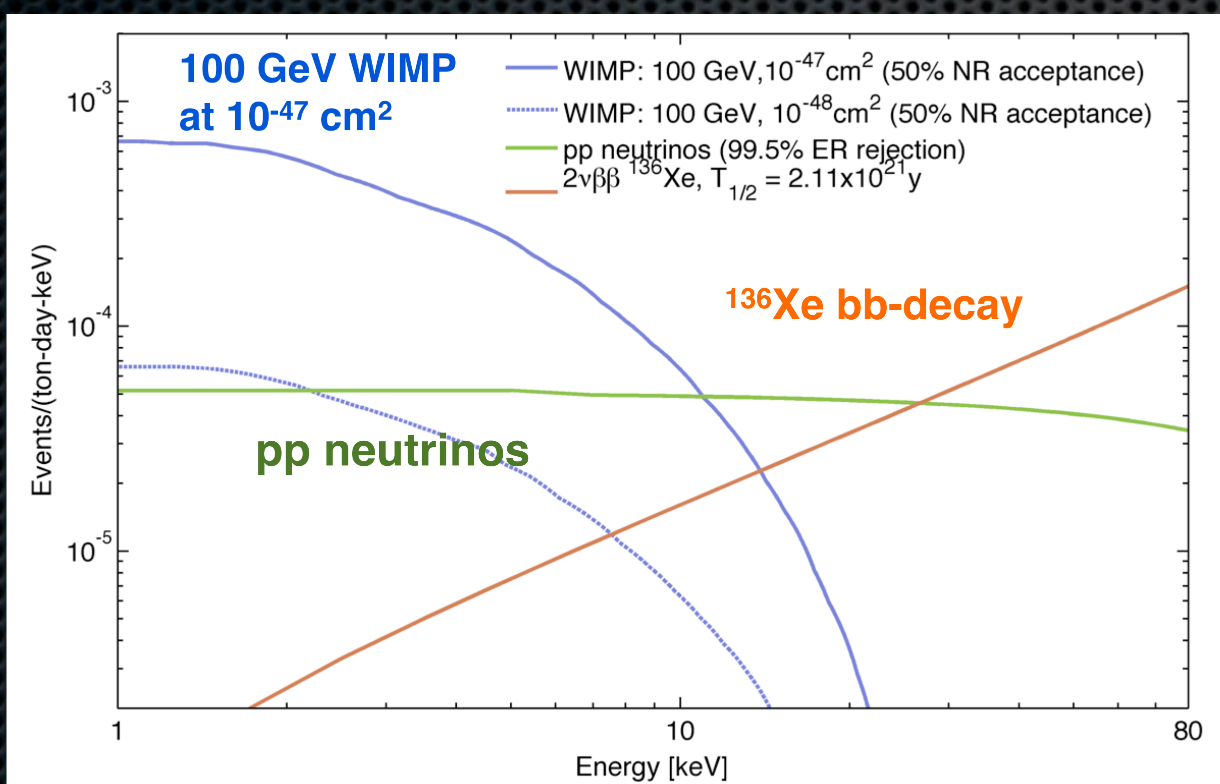
DRIFT, Boulby Mine

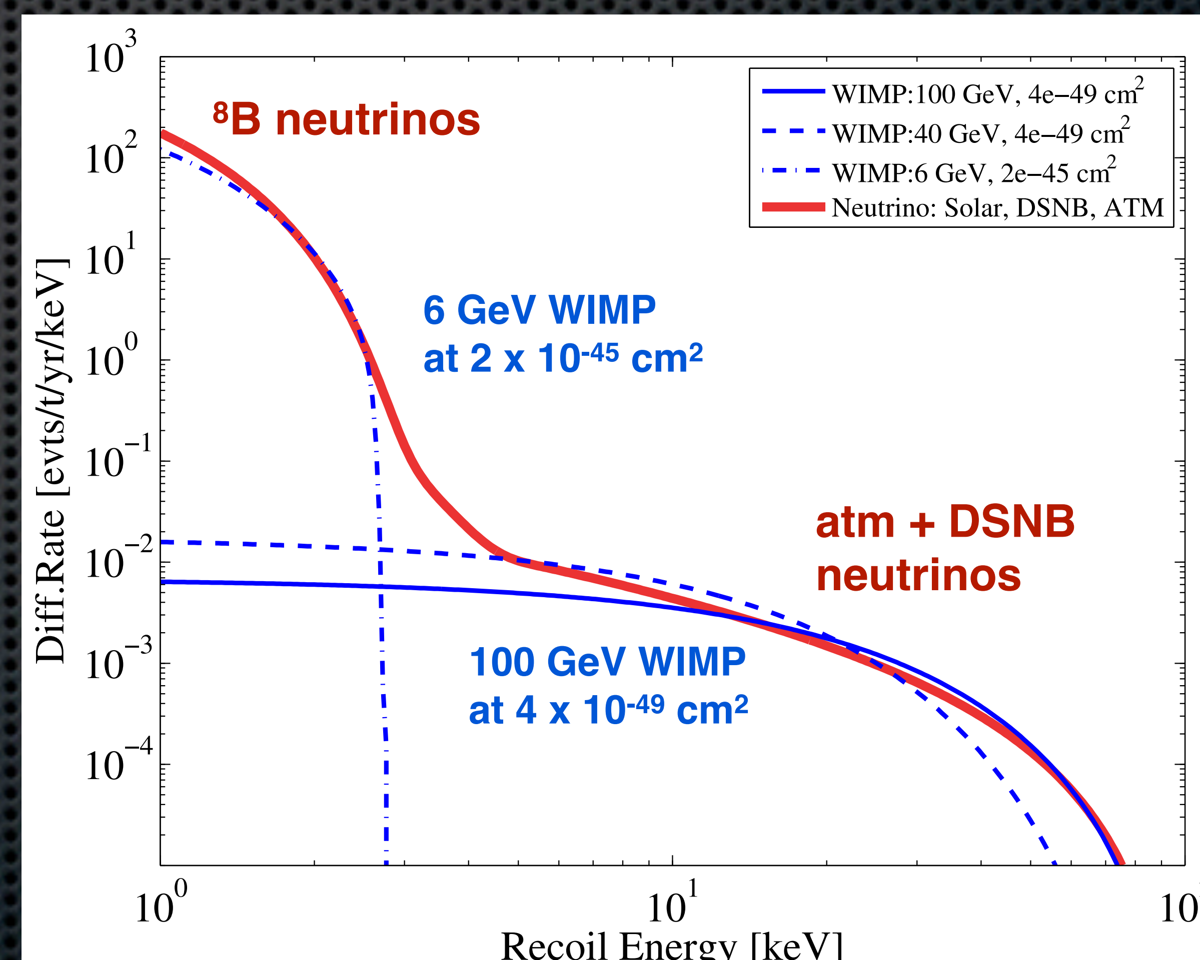
Neutrinos as backgrounds

- Electronic recoils from pp solar neutrinos: ~ 10^{-48} cm^2
- Nuclear recoils from ^{8}B solar neutrinos: below 10^{-44} cm^2 for low-mass WIMPs
- Nuclear recoils from atmospheric + DSNB: below 10^{-48} cm^2

after Strigari, New J. Phys. 11 (2009) 105011

LB, Physics of the Dark Universe 1, 94 (2012)

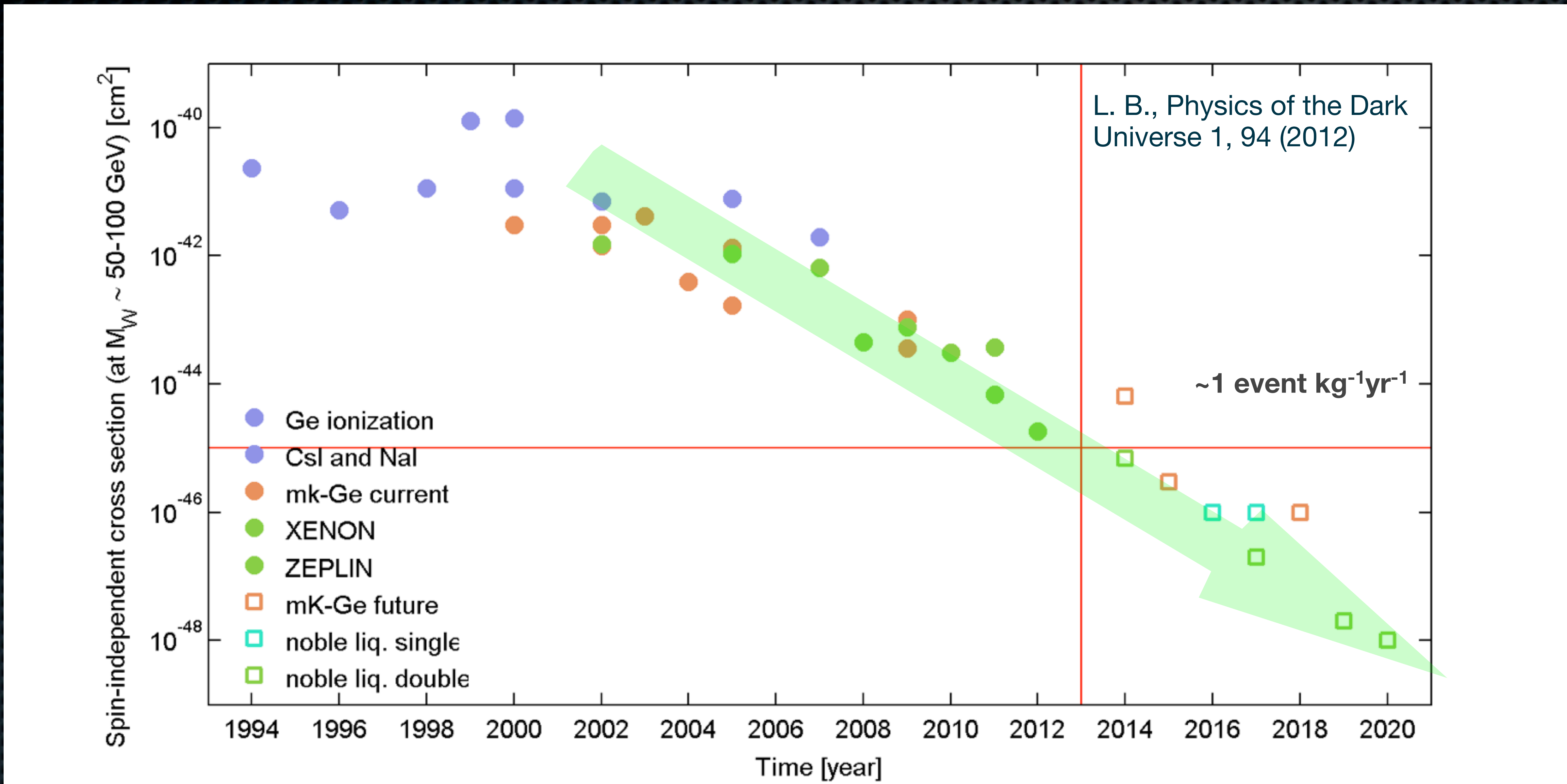




$$\nu + e^- \rightarrow \nu + e^-$$

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

WIMP search evolution in time



About a factor of 10 every 2 years!
Can we keep this rate of progress?

Summary and Prospects

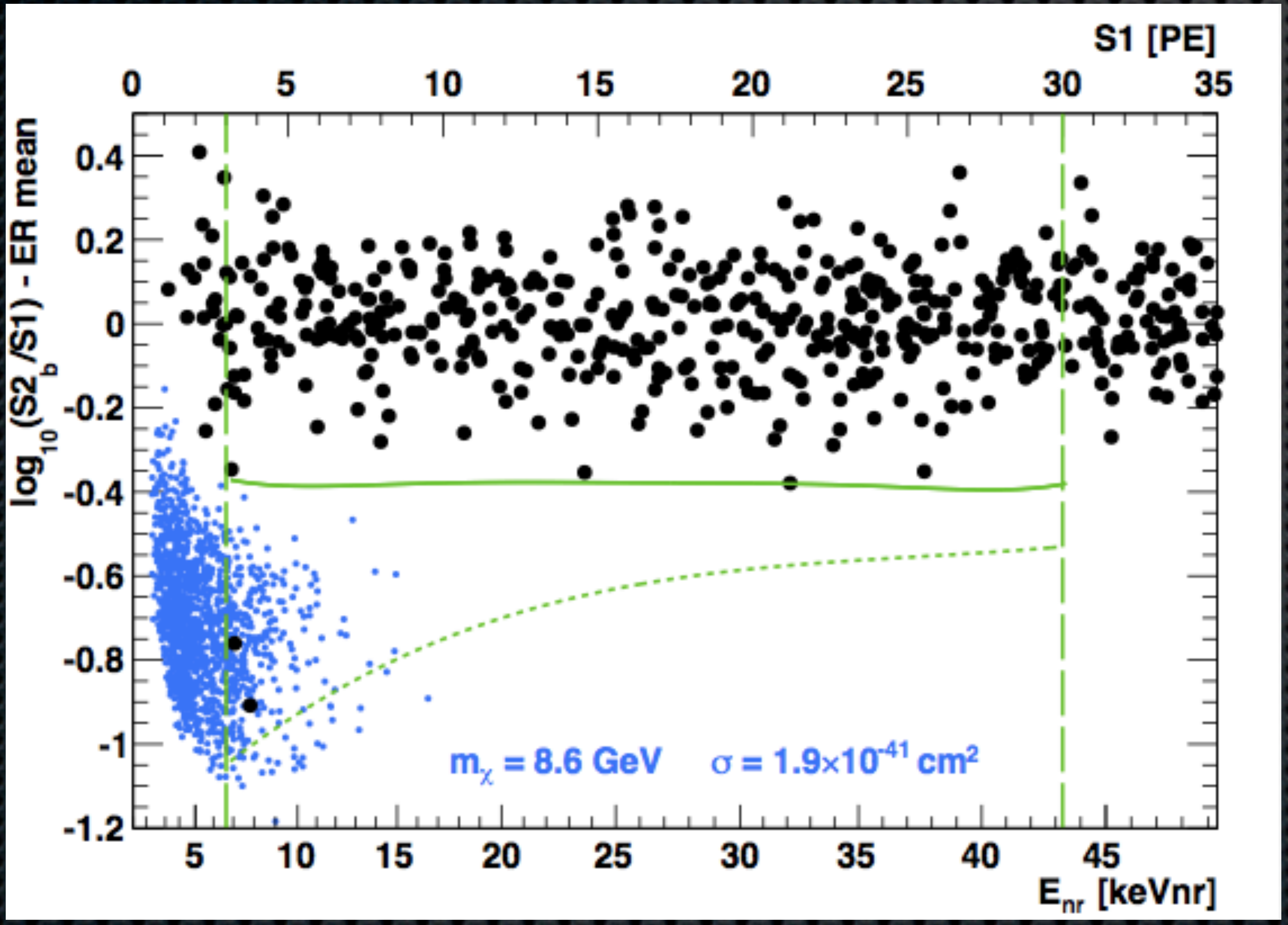
- Cold dark matter is still here with us
- It could be made of a new, heavy, neutral, stable and weakly interacting particle
- *We have entered the era of data: direct detection, the LHC, indirect detection*
- Direct detection experiments have reached unprecedented sensitivity (cross sections down to 10^{-8} pb) and can probe WIMP with masses from a few GeV to a few 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!

End

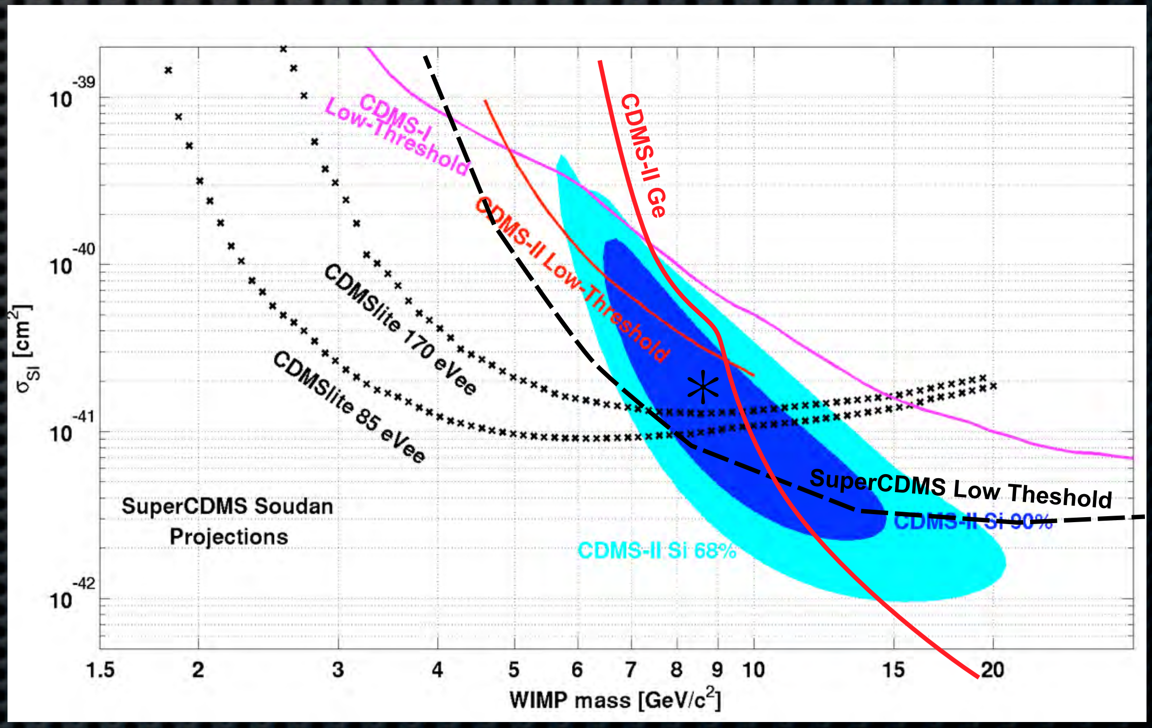
XENON100 predictions for light WIMPs

- How would the CDMS-Si signal look like in XENON100's Run10 data?

WIMP with m_W = 8.6 GeV



CDMS Si results, 140 kg d



WIMP-nucleon cross section : 1.9×10^{-41} cm^2
~ 220 (+300, -85) events in the ROI (high, and low contours of L_{eff} and Q_y error bands)

WIMP Scattering Cross Sections

- In the extreme NR limit relevant for galactic WIMPs (10^{-3} c) the interactions leading to WIMP-nuclei scattering are classified as (Goodman and Witten, 1985):
  - scalar interactions (WIMPs couple to nuclear mass, from the 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: effective couplings to protons and neutrons

  - spin-spin interactions (WIMPs couple to the nuclear spin, from the axial part of L)

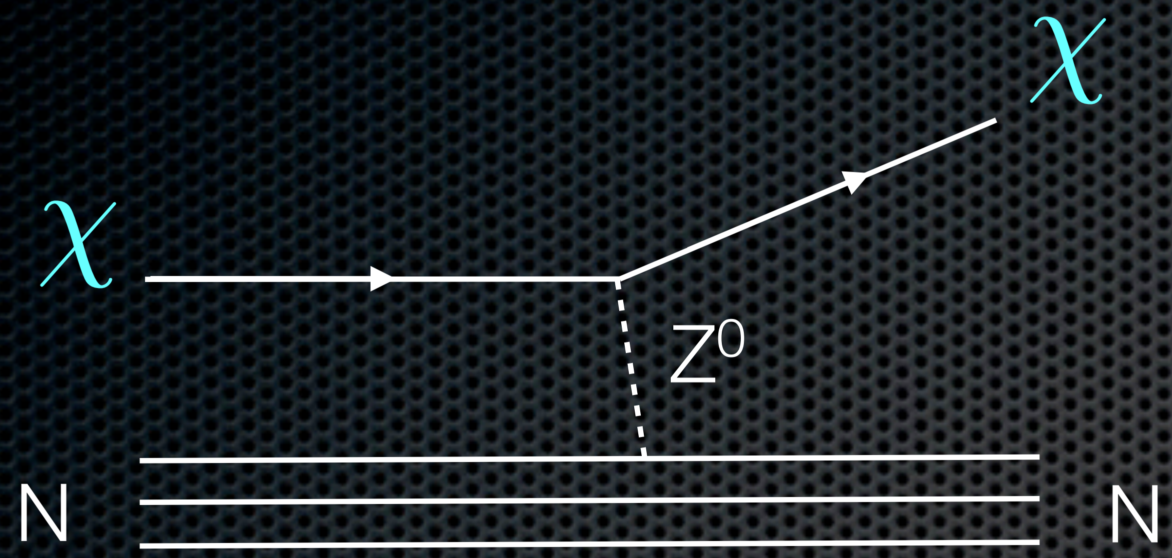
$$\sigma_{SD} \sim \mu^2 \frac{J_N+1}{J_N}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2$$

a_p, a_n: effective couplings to protons and neutrons

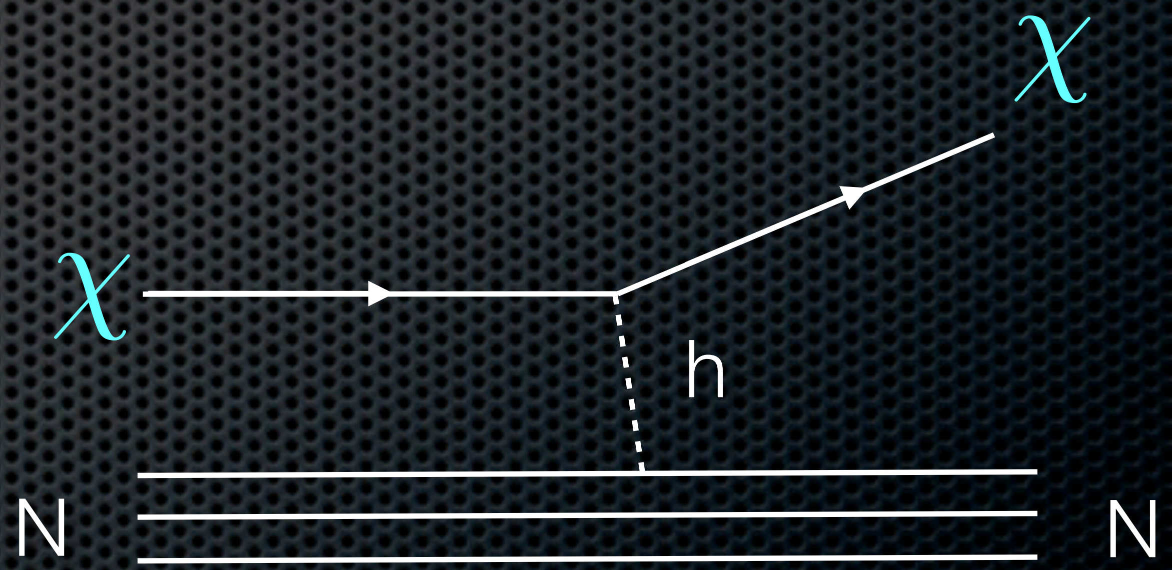
$\langle S_p\rangle$ and $\langle S_n\rangle$

expectation values of the p and n spins within the nucleus

WIMP scattering cross section



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



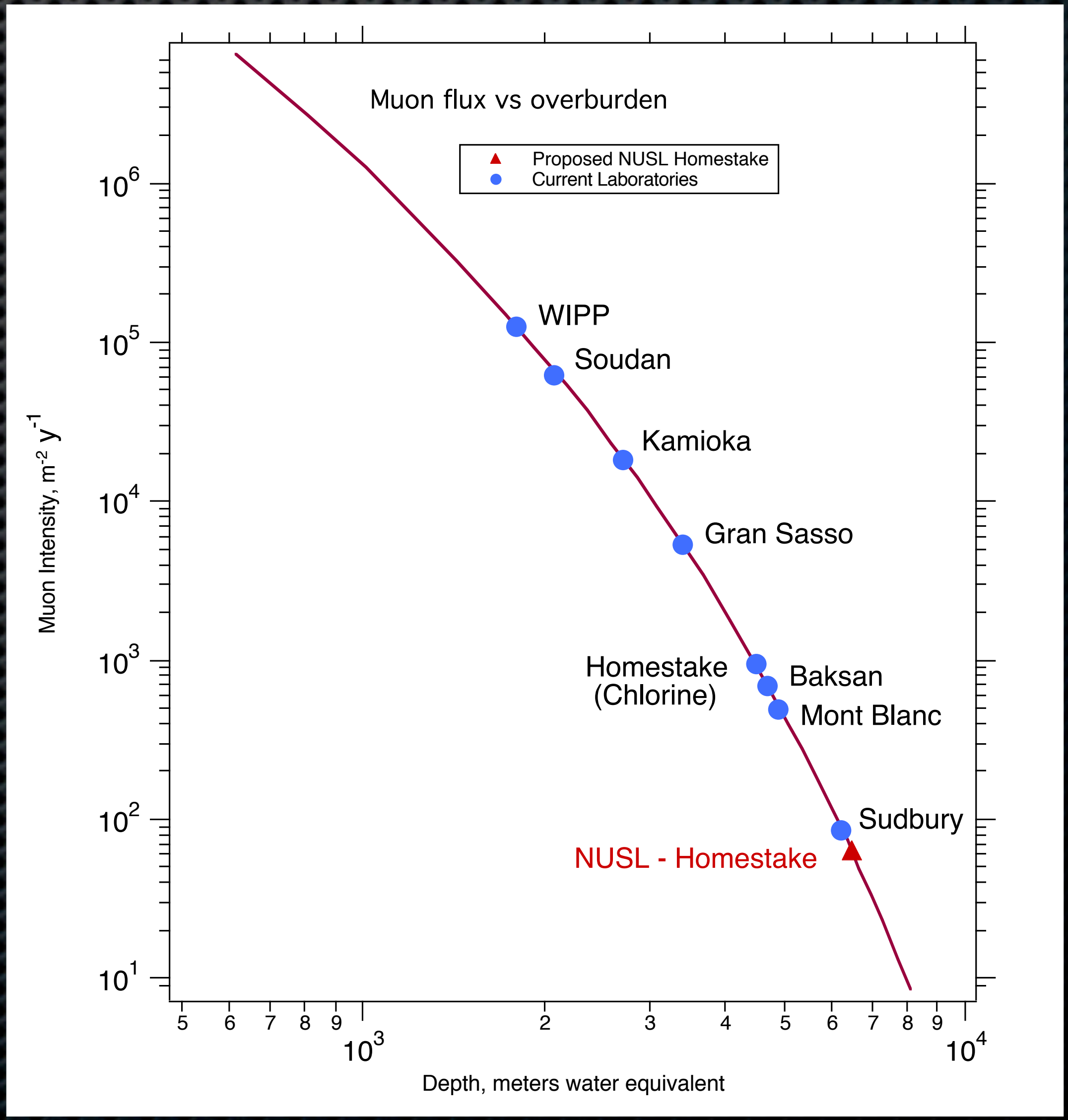
$\sigma_0 \sim 10^{-45}\,\mathrm{cm}^2$

See DarkSusy for detailed predictions
http://www.physto.se/~edsjo/darksusy/

The background noise

- **Electromagnetic radiation**
  - natural radioactivity in detector and shield materials
  - airborne radon (^{222}Rn)
  - cosmic activation of materials during storage/ transportation at the Earth's surface
- **Neutrons**
  - radiogenic from (α,n) and fission reactions
  - cosmogenic from spallation of nuclei in materials by cosmic muons
- **Alpha particles**
  - ^{210}Pb decays at the detector surfaces
  - nuclear recoils from the Rn daughters

Cosmic rays: operate deep underground

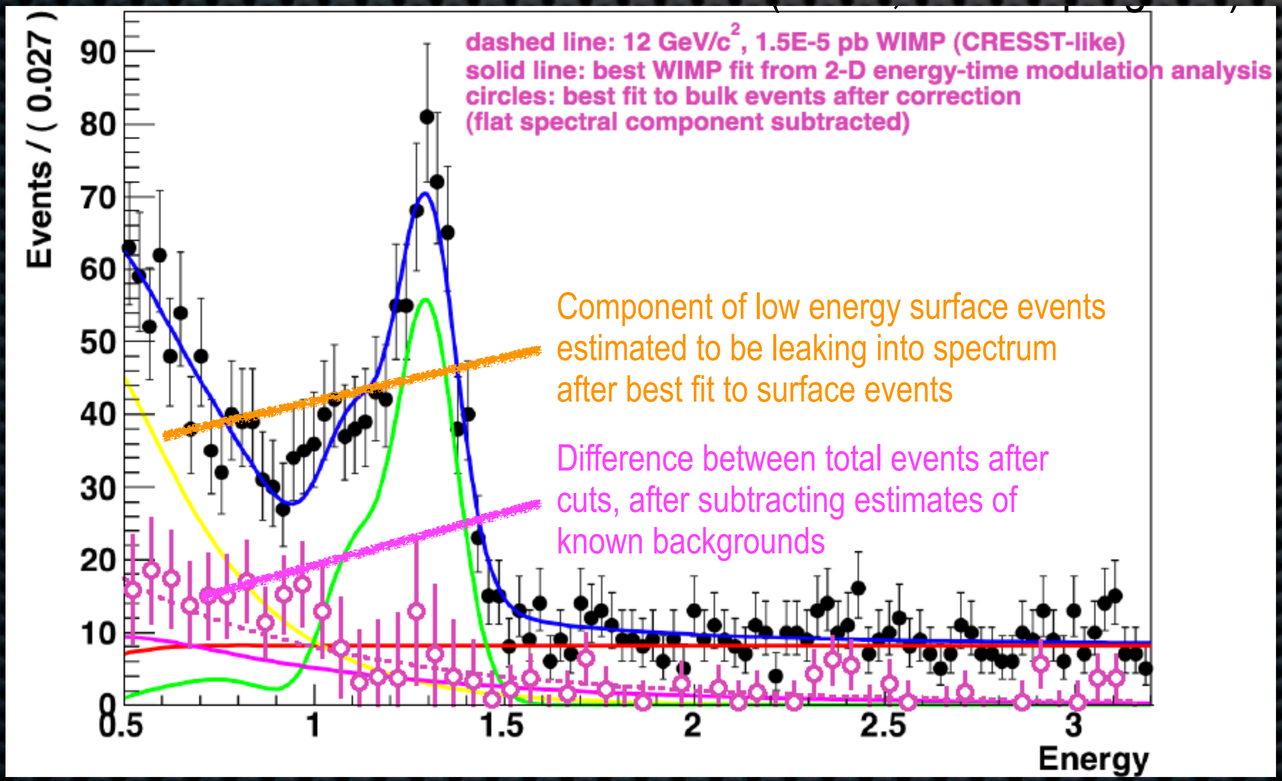


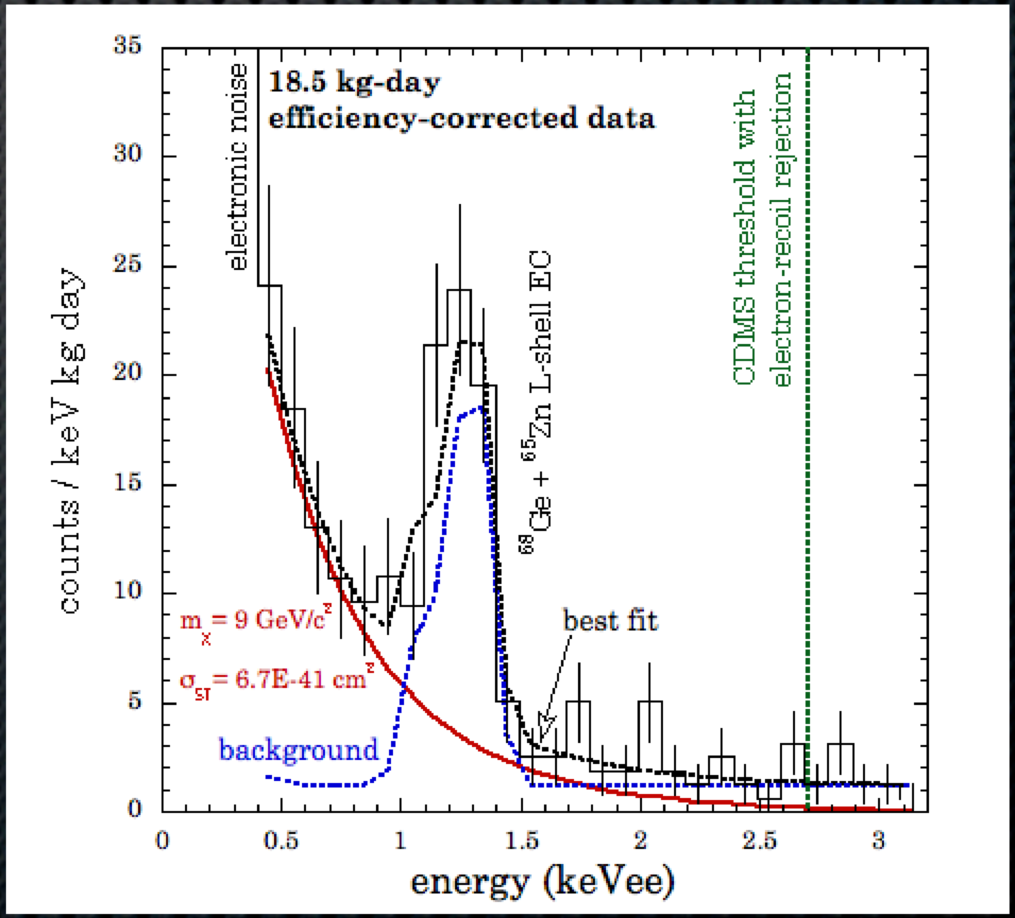
CoGeNT: low-mass WIMPs?

- Point-contact, 330 g Ge detector at Soudan
- Energy threshold: ~ 0.5 keV ionization (~ 2 keV NR energy)
- 2011: claim of an annual modulation at 2.8-σ level (0.5 - 3 keVee), ~ 450 days

arXiv: 1002.4703; C. E. Aalseth et al., PRL106

J. Collar, Feb 2012

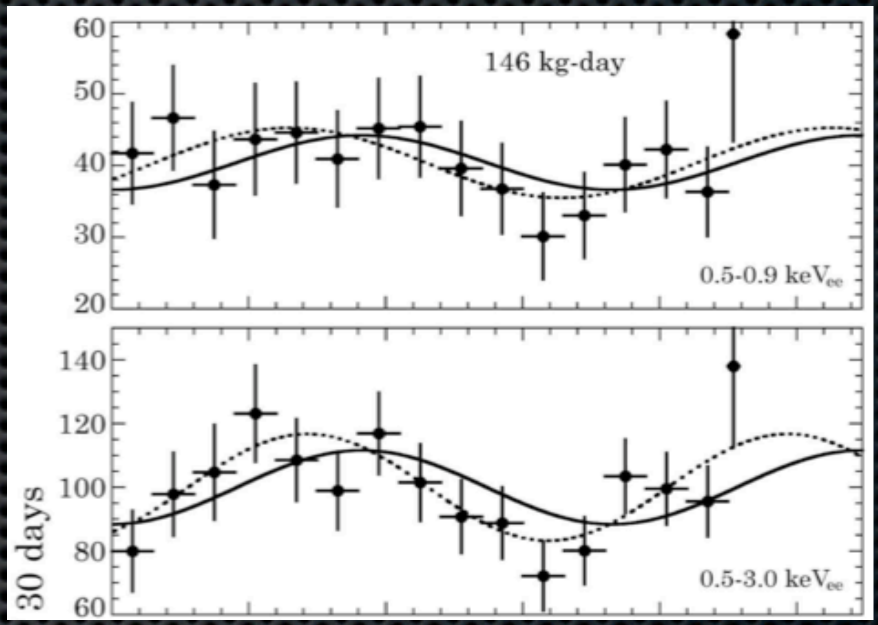


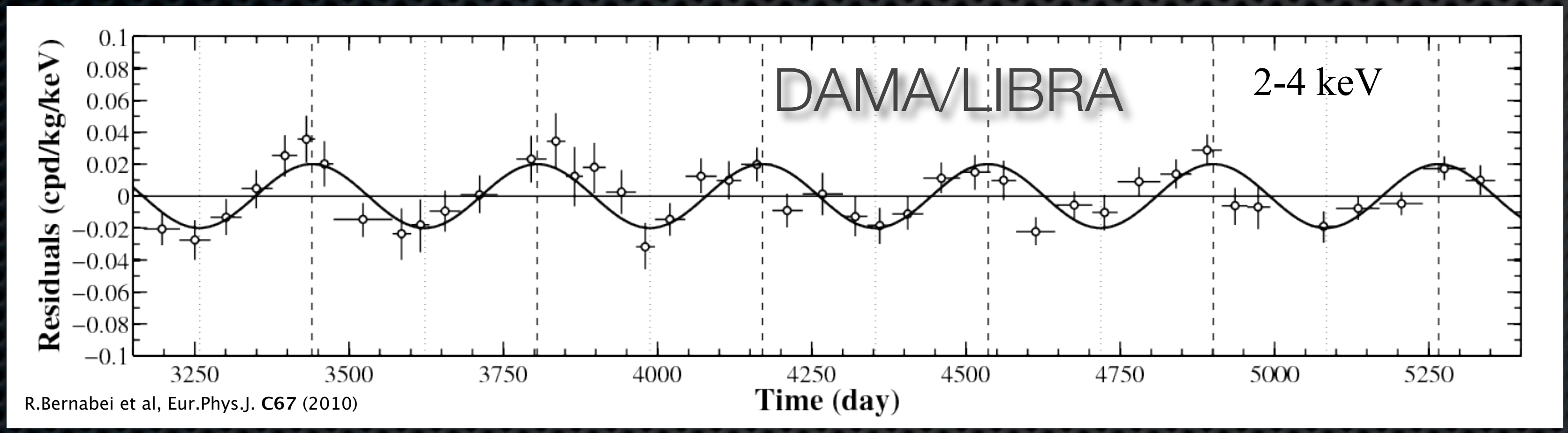


Modulation: DAMA/LIBRA, CoGeNT

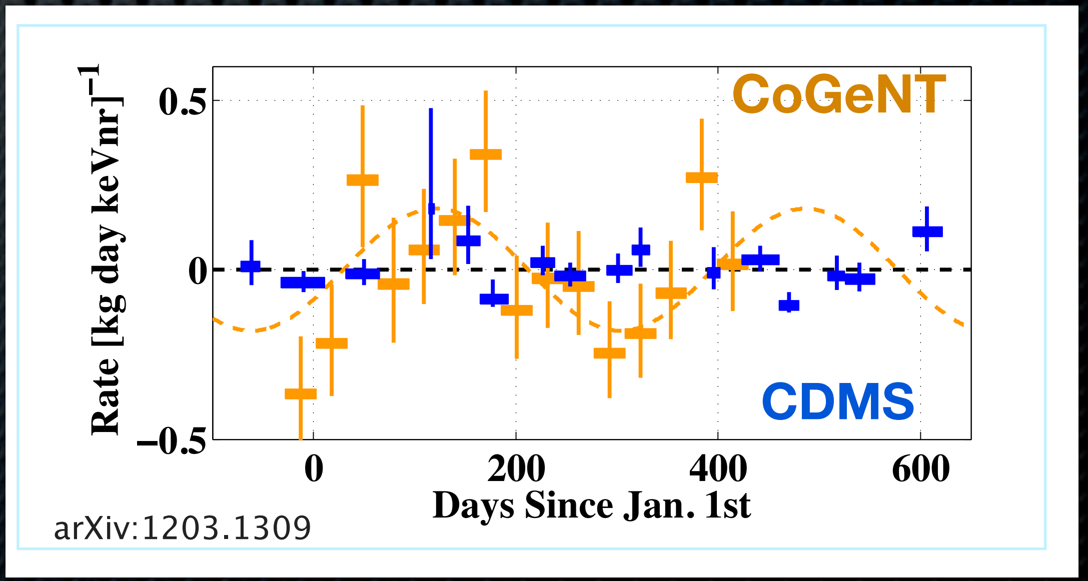
- DAMA/LIBRA (250 kg NaI, 0.82 tons-year): 8.9-σ effect
- CoGeNT (330 g HPGe, 450 d): 2.8-σ effect

CoGeNT





CDMS

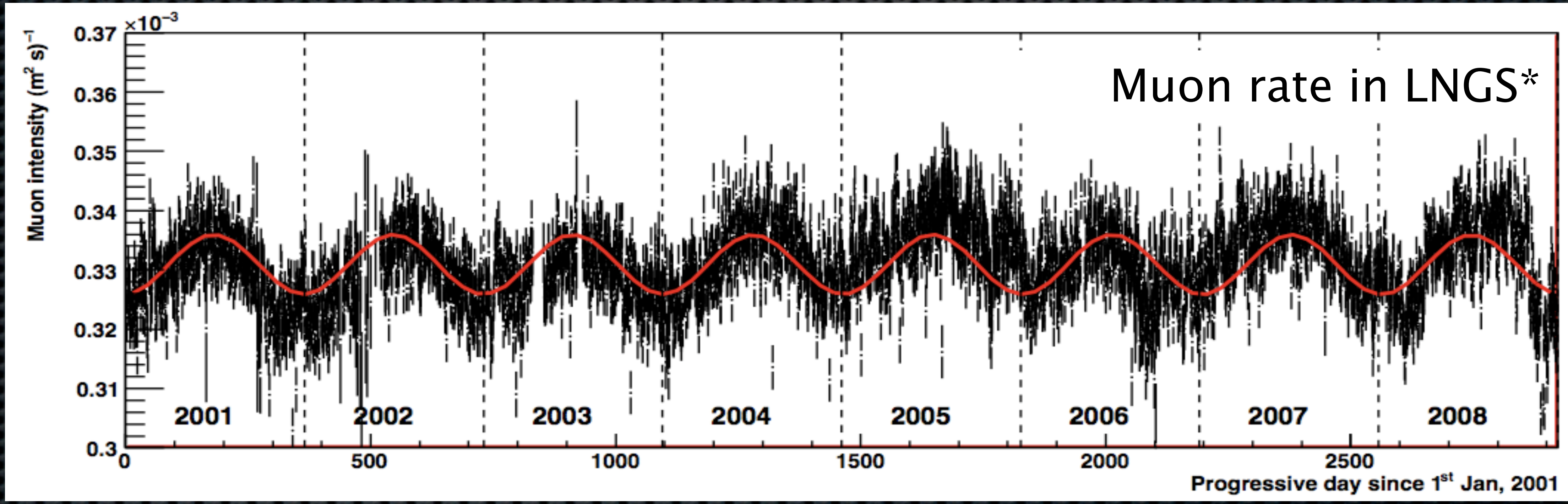


- Origin of the time variation in the observed rate - unclear!
- Movement of the Earth-Sun system through the dark matter halo?
- Environmental?

Light: DAMA/LIBRA

- Origin of the time variation in the observed rate:
  - motion of the Earth-Sun system through the WIMP halo?
  - environmental effects?
  - unclear!

see also David Nygren, arXiv:1102.0815

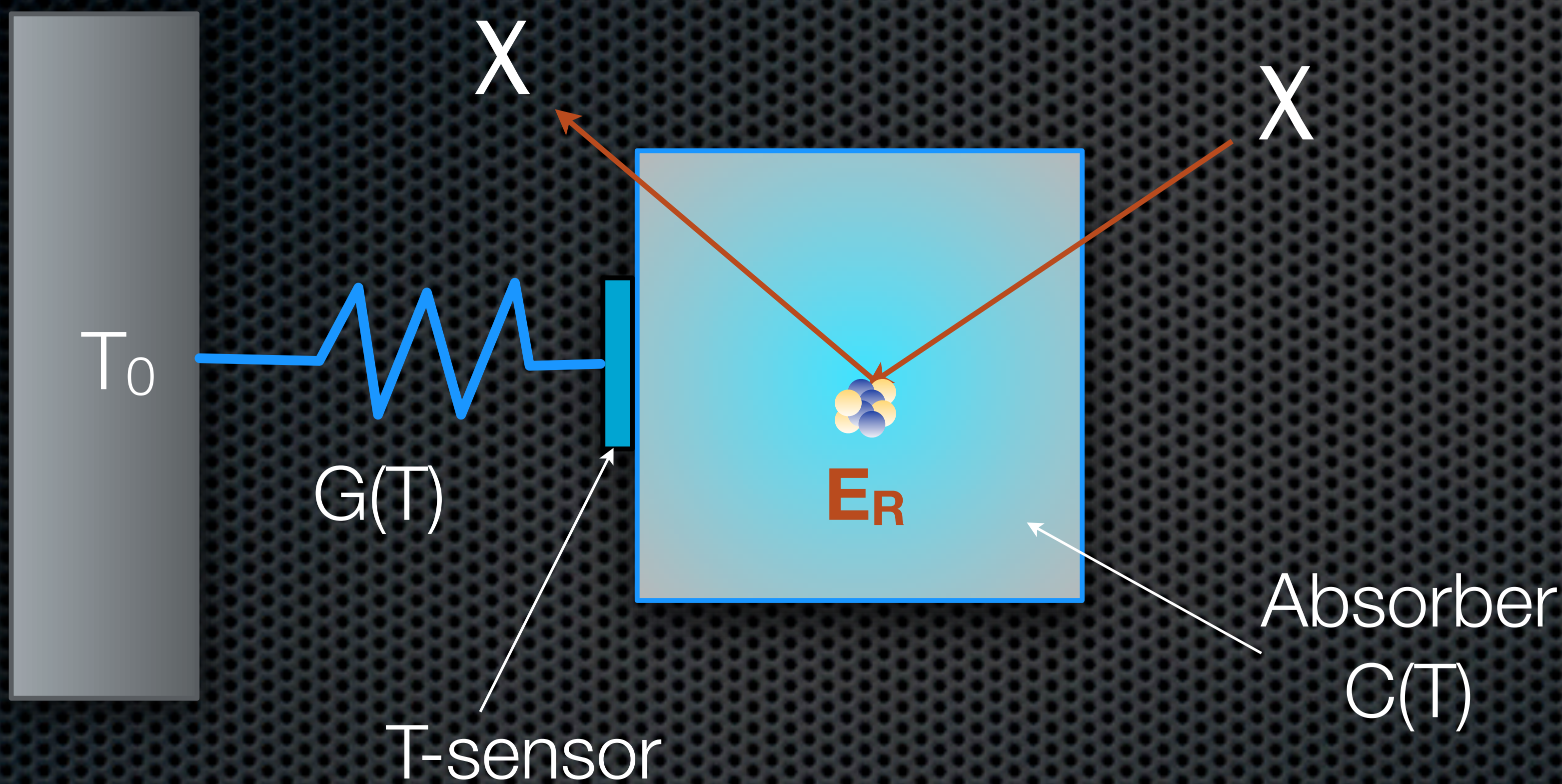


Muon rate variation at LNGS: Amplitude: ~ 0.015; T = 1 year, ϕ = July 15±15 days

* M.Selvi et al., Proc. 31st ICRC, ŁÓDŹ 2009

Phonons: Cryogenic Experiments at T~ mK

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



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

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

$$C(T) \propto \frac{m}{M} \left(\frac{T}{\Theta_D} \right)^3 J K^{-1}$$

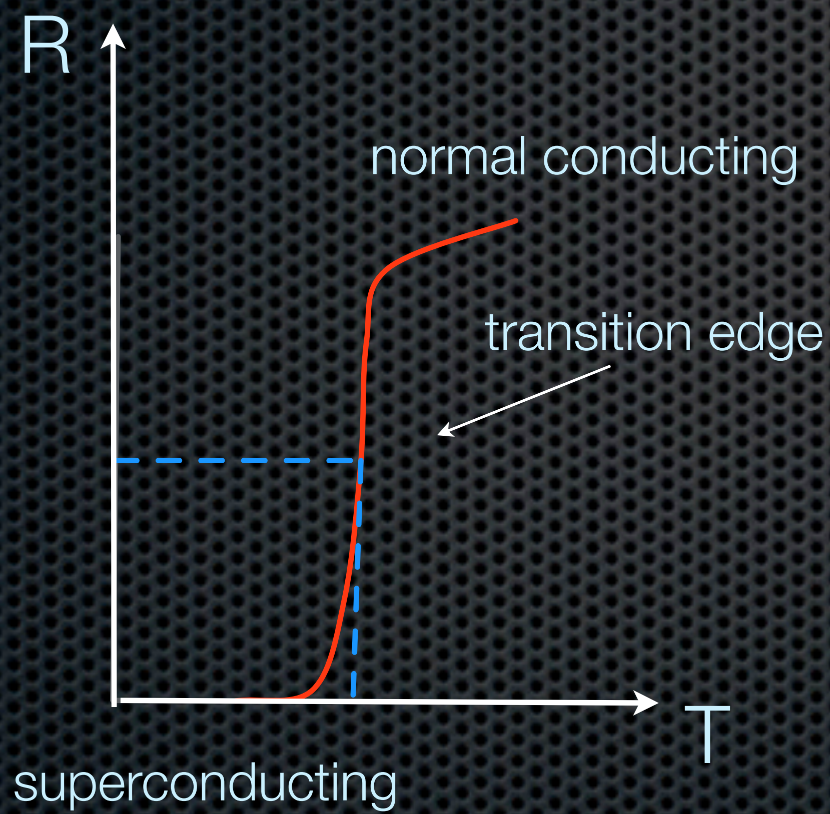
m = absorber mass

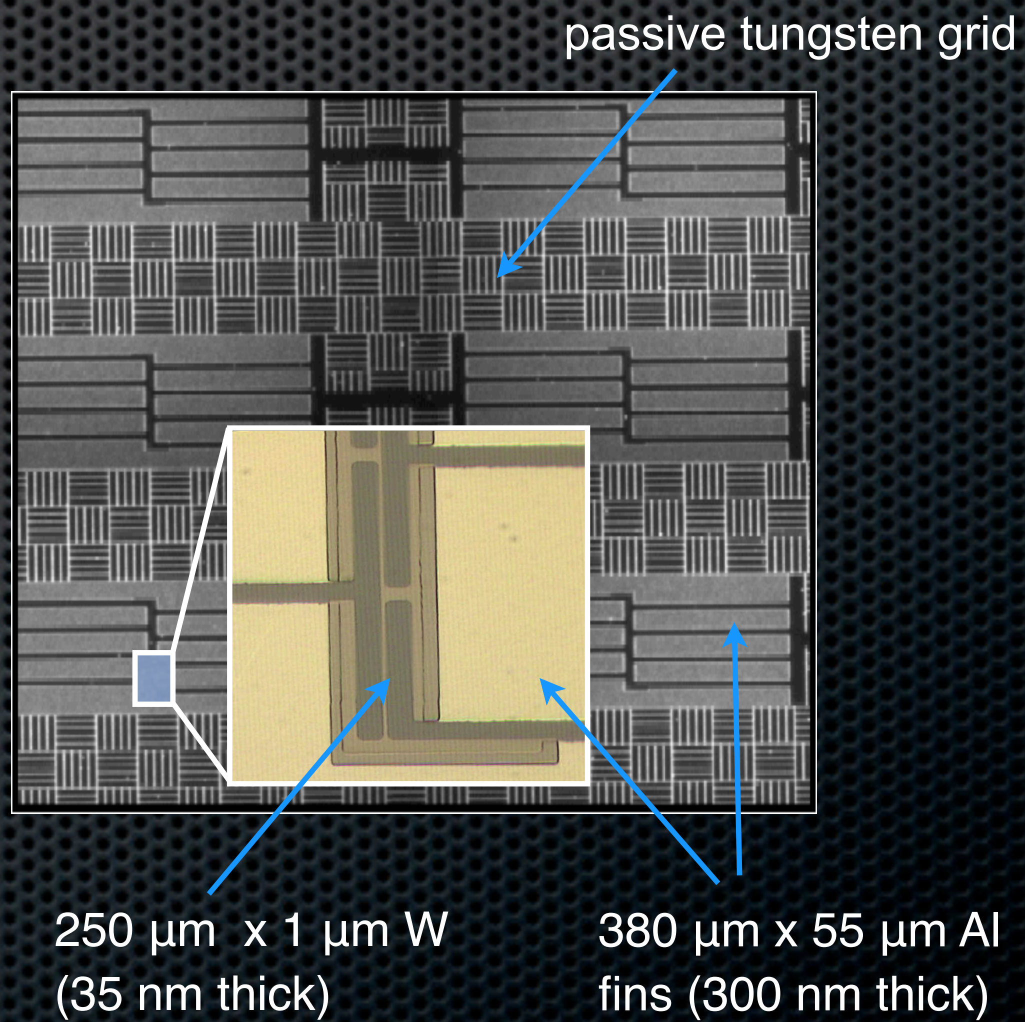
M = molecular weight of absorber

Θ_D = Debye temperature (at which the highest frequency gets excited)

Transition Edge Sensors

- The substrate is cooled well below the SC transition temperature T_C
- The temperature rise (~ μK) is measured with TES





Example: TES for CDMS detectors