Dark matter detection review

15th International workshop on Next generation Nucleon Decay and Neutrino Detectors

Paris, November 5, 2014

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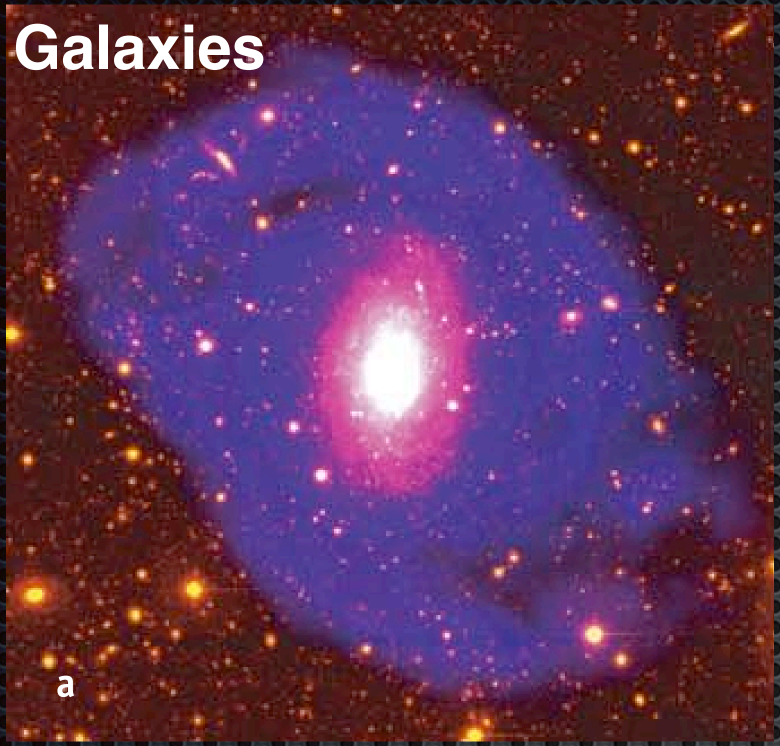
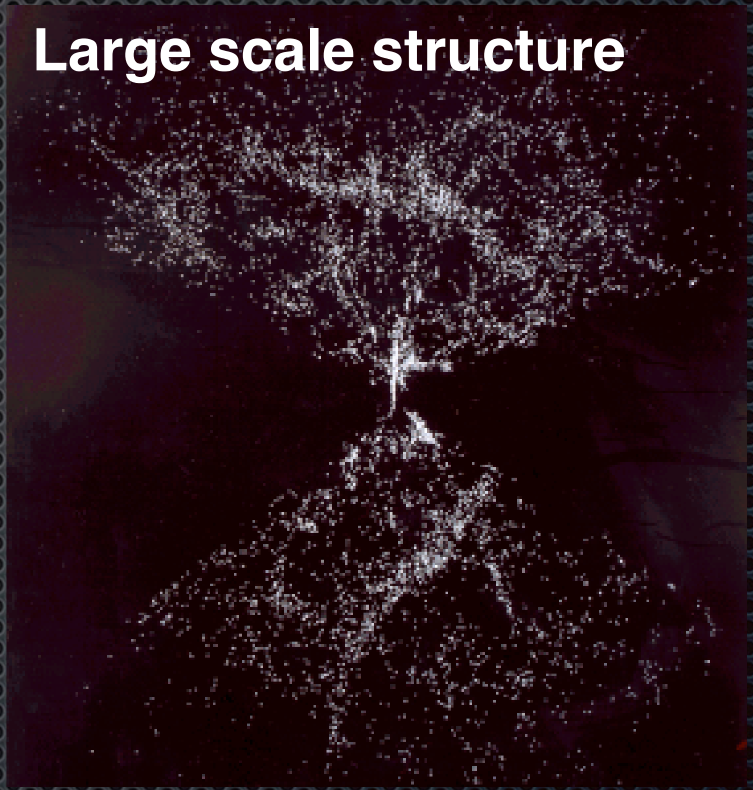
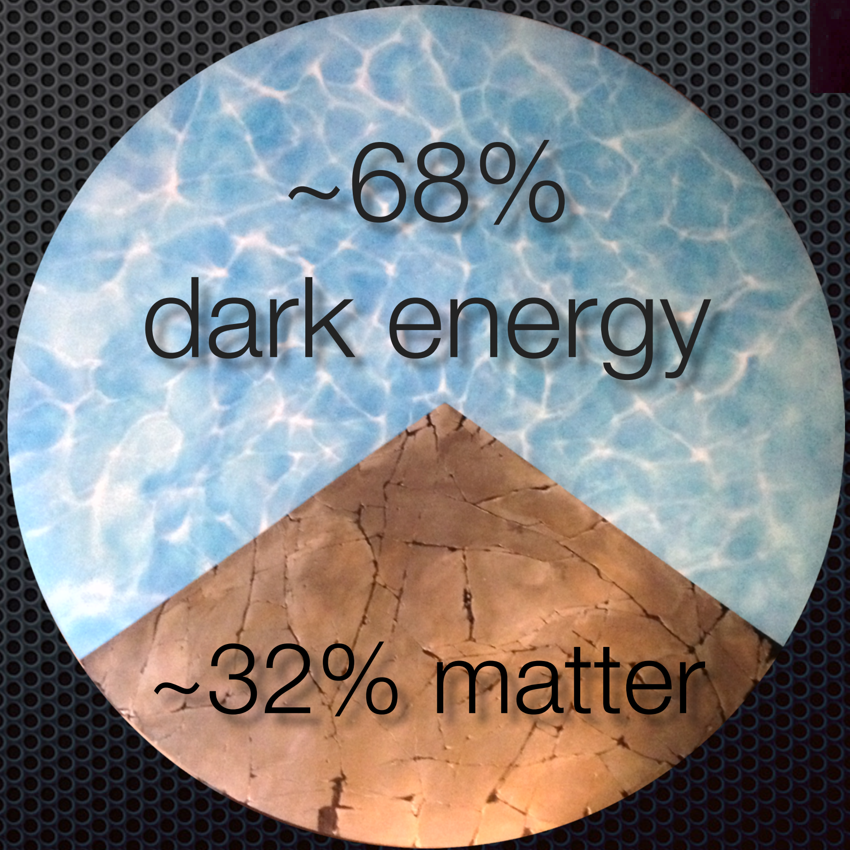
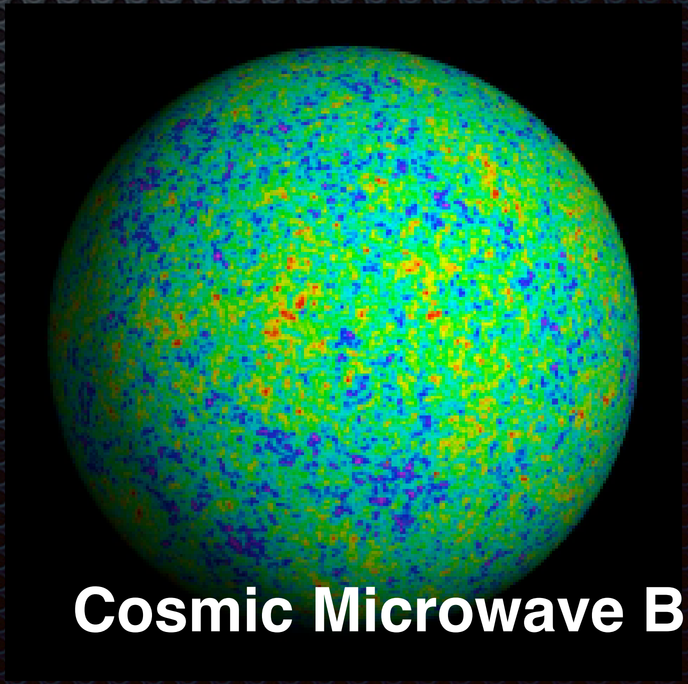
Our Universe today - apparently consistent picture: $\Lambda\mathrm{CDM}$ from an impressive number of observations on all scales







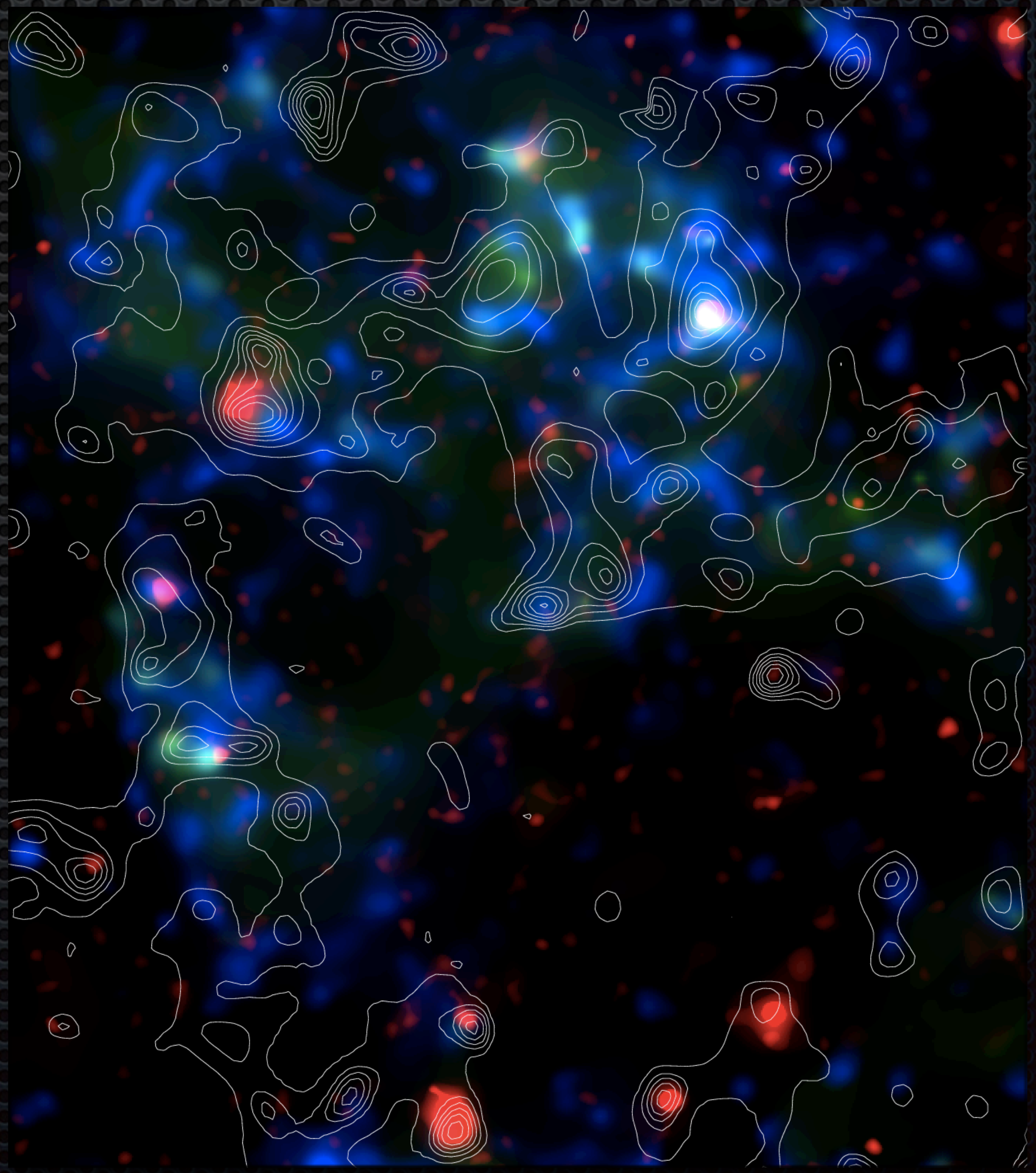


The dark matter puzzle

- Remains fundamental: dark matter leads to the formation of structure and galaxies in our universe

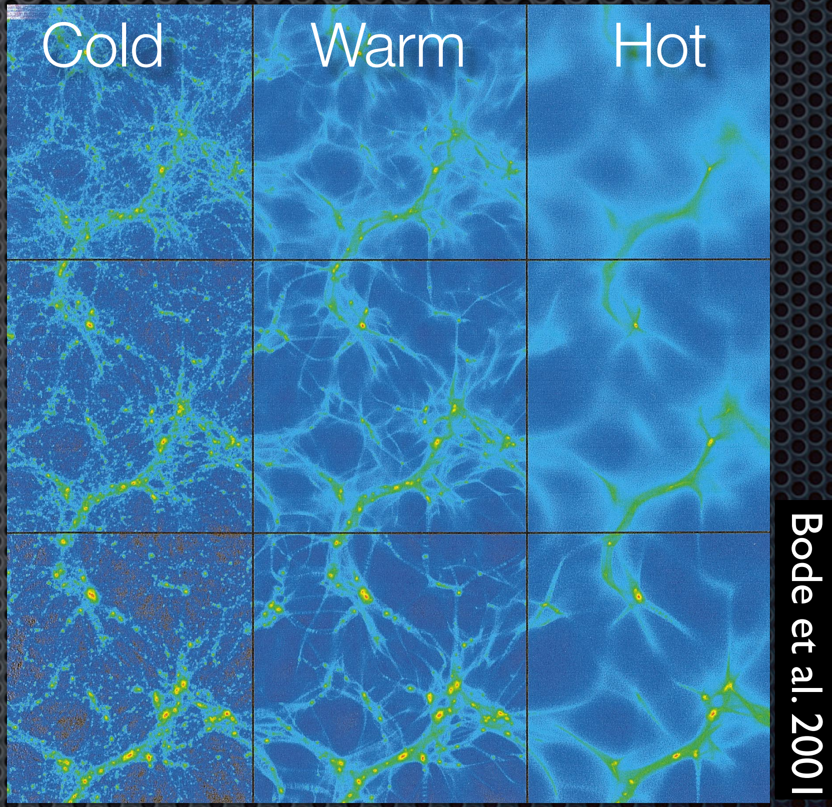
- We have a standard model of CDM, from ‘precision cosmology’ (CMB, LSS): however, *measurement ≠ understanding*

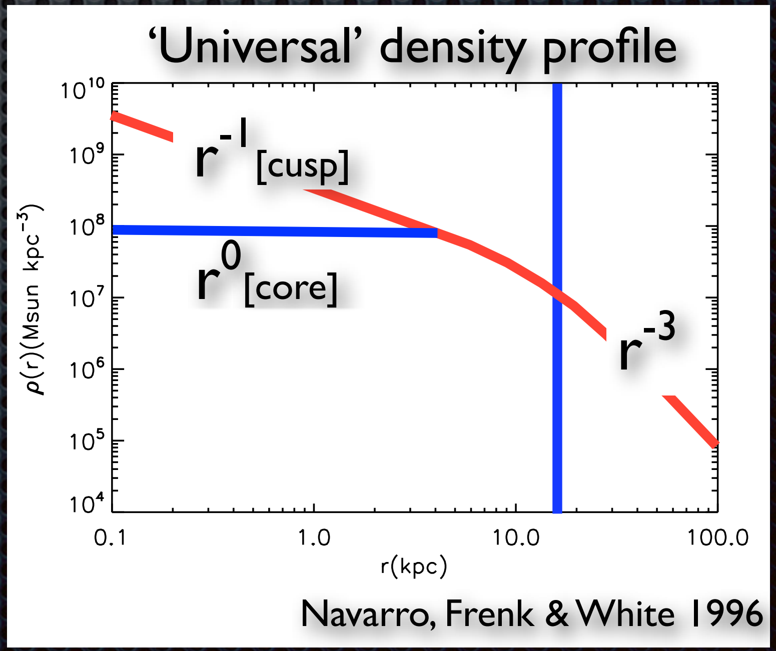
- **For ~85% of matter in the universe is of unknown nature**



What do we know about 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
- *Not a particle in the Standard Model of particle physics*

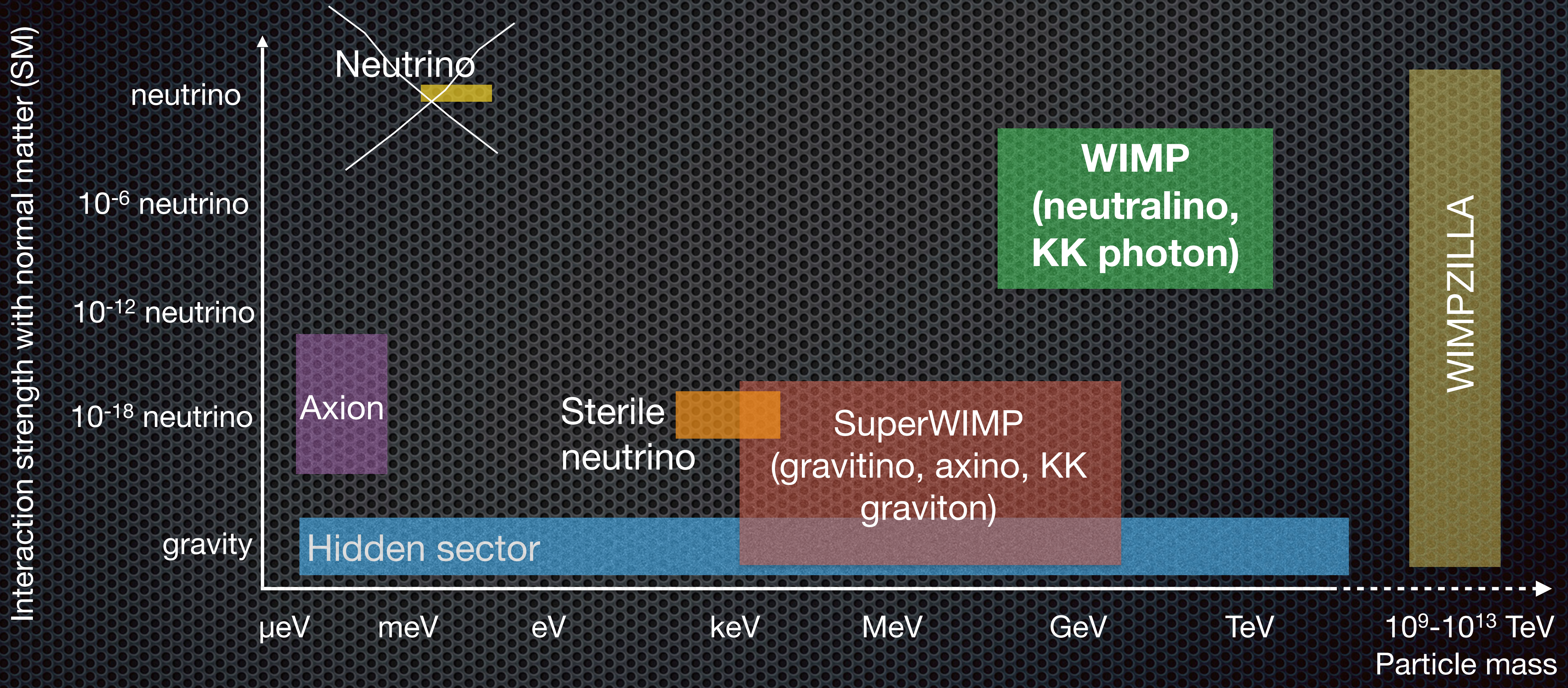




Probing dark matter through gravity

What do we know about dark matter?

- The mass and cross section range span many orders of magnitude
- *Strong guidance from theorists to us experimentalists*



I will mostly focus on axions and WIMPs

Axions

- Introduced by Peccei & Quinn as a solution to the strong CP problem: a global U(1) symmetry is spontaneously broken below an energy scale f_a (originally the weak scale $f_a \approx 200$ GeV~ f_{EW})

- Weinberg & Wilczek: PQ solution implies the existence of a light pseudoscalar, the axion

- No axion detection so far; ‘invisible axion’ models (with arbitrary large f_a) are still viable:

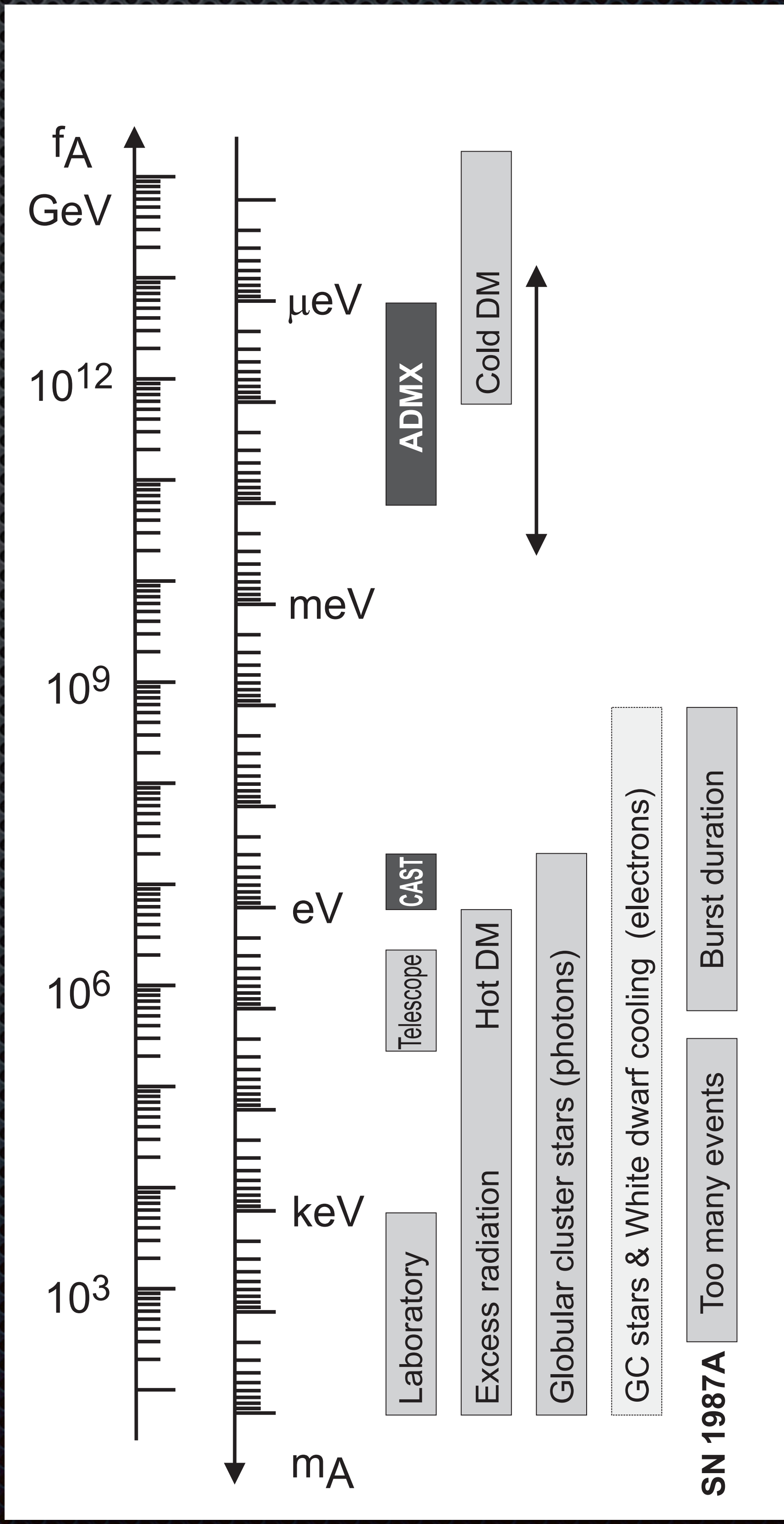
$$m_a \simeq 6 \cdot 10^{-6}\mathrm{eV}\,\frac{10^{12}\,\mathrm{GeV}}{f_a}$$

← corresponds to the observed dark matter density

- Constraints from astrophysics, cosmology and laboratory searches restrict the mass of a QCD dark matter axion to:

$$\sim 1\,\mu\mathrm{eV} \leq m_a \leq 3\,\mathrm{meV}$$

G. Raffelt & L. Rosenberg
PDG 2012



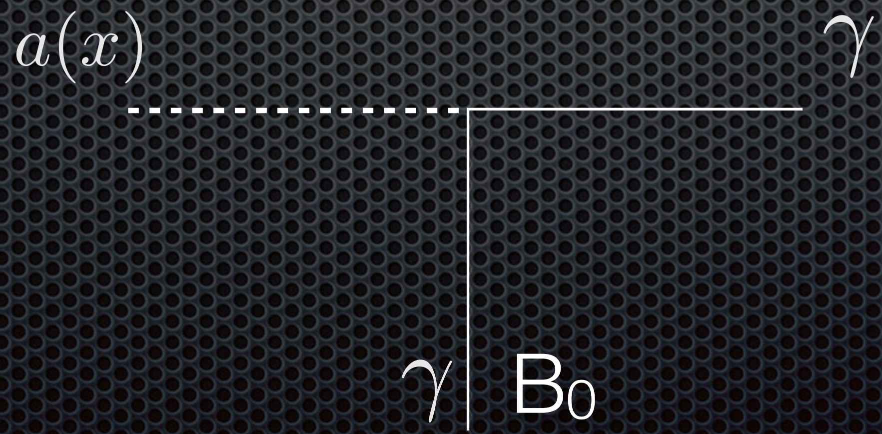
Axion searches

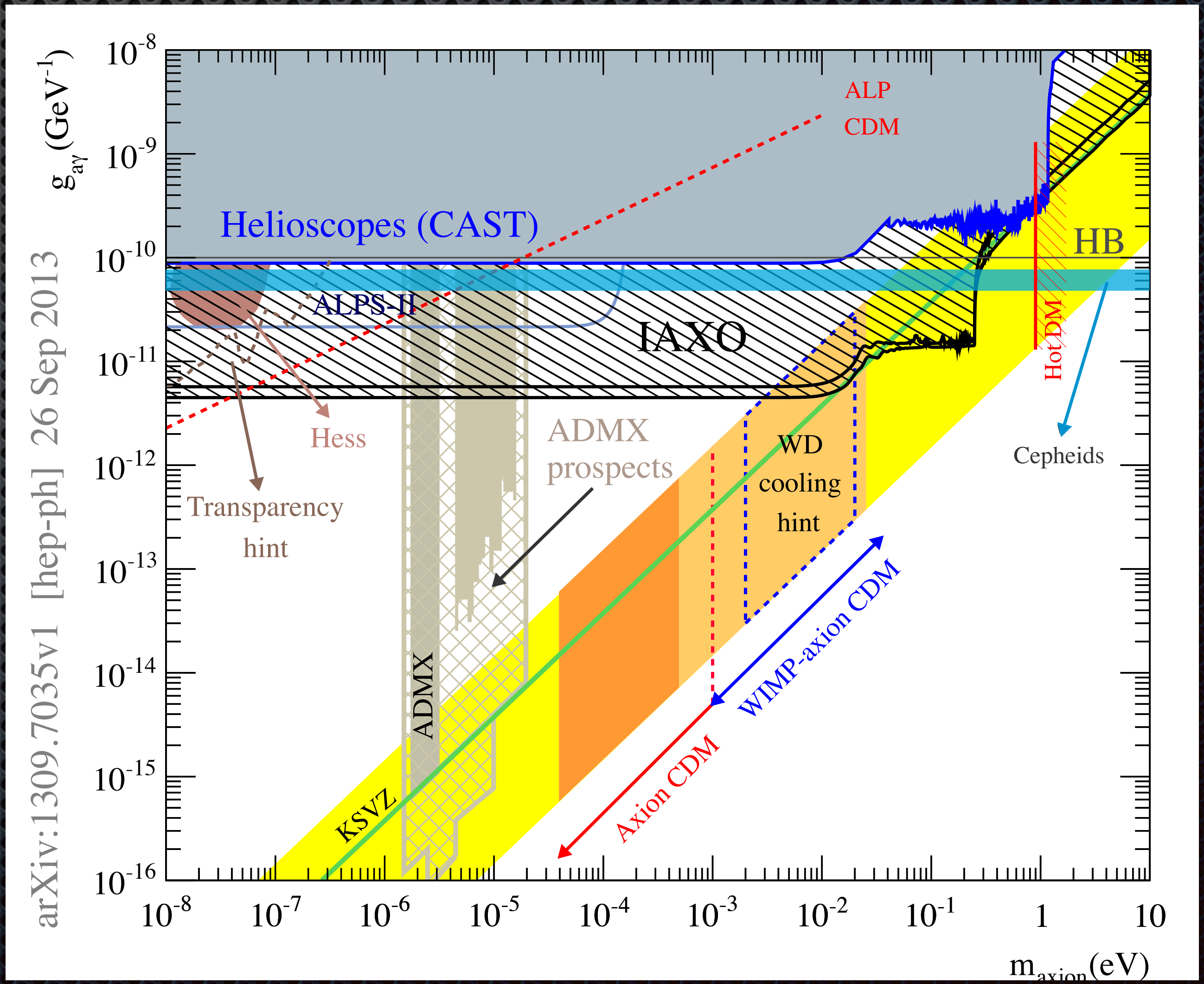
- Mostly exploit the coupling to two photons (also coupling to e^-, hadrons ~ $1/f_a$)
- (ALPs also couple to photons, but do not satisfy the mass-coupling relation)

$$\mathcal{L}_{a\gamma\gamma} = -g_\gamma \frac{\alpha}{\pi}\frac{a(x)}{f_a}\vec{E}\cdot\vec{B} = -g_{a\gamma\gamma}\, a(x)\vec{E}\cdot\vec{B}$$

0.36 (DFSZ)   -0.97 (KSVZ)

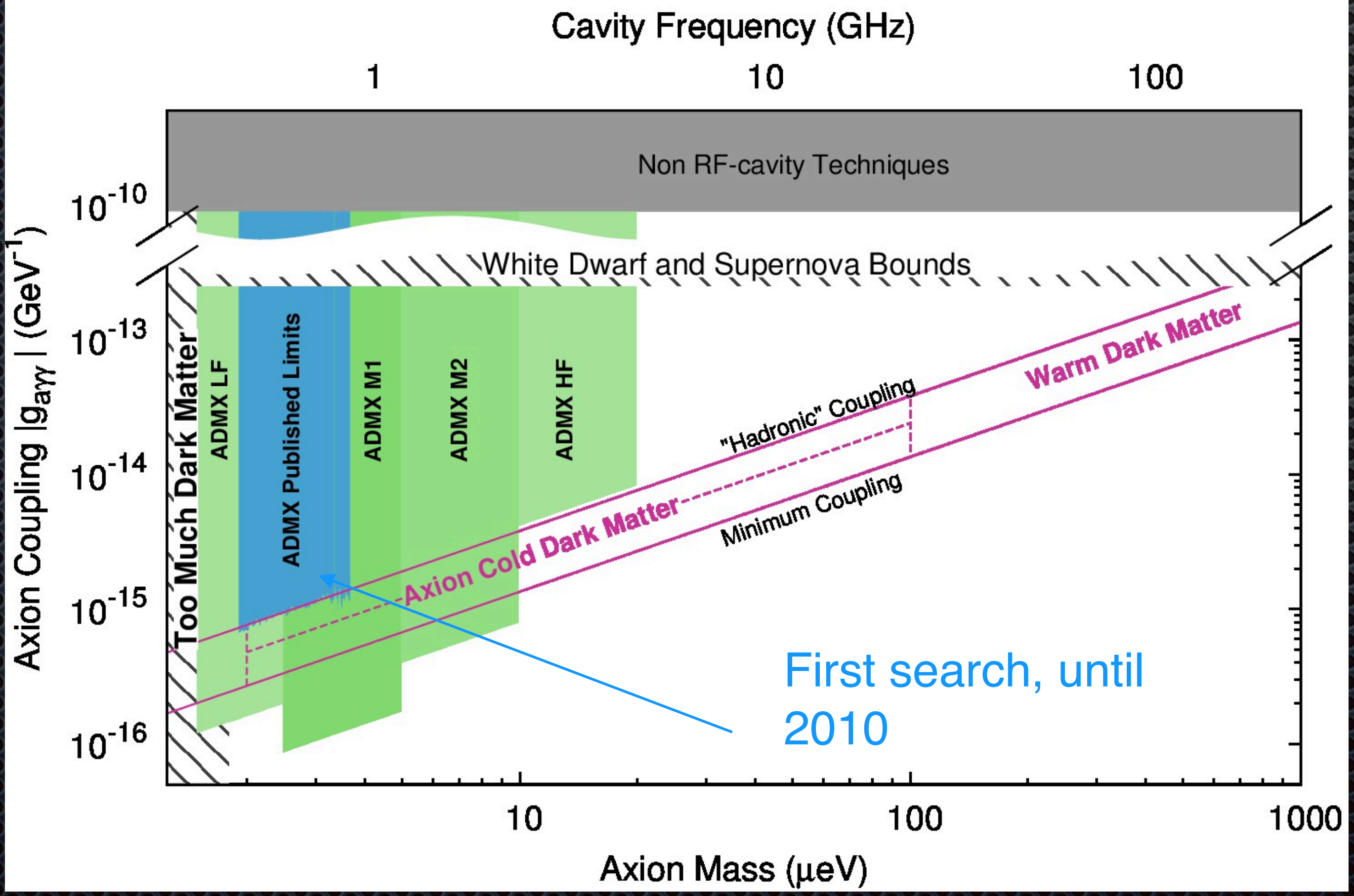
- This coupling is extremely weak, but the axion decay can be accelerated through a static, external magnetic field (inverse Primakoff effect)





The ADMX experiment

- Galactic axions convert into microwave photons inside a resonant cavity permeated by a strong magnetic field
- Noise reduction: dilution refrigerator (<100 mK) and SQUID ampl
- Search frequency range 0.5 - 2 GHz (2-8 μeV); construction & operation: 2015 - 2019
- ADMX-HF sister experiment: look at 4 - 6 GHz (16-24 μev)



Microwave cavity and tuning rods

l = 1 m, d = 0.5 m; in an 8 Tesla SC magnet

Axion haloscope: Sikivie proposal, 1983

Weakly Interacting Massive Particles

G.Steigman & M.S.Turner, 1985

- WIMPs: in thermal equilibrium in the early Universe, freeze-out when annihilation rate drops below expansion rate and $M_{WIMP} > \approx T$ ('cold')

- Their relic density can account for the dark matter if the *annihilation cross section is weak* (~ picobarn range)

$$\Omega_\chi h^2 \simeq 3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1} \frac{1}{\langle \sigma_A v \rangle}$$

$$\Omega_\chi h^2 = \Omega_{\mathrm{cdm}} h^2 \simeq 0.1143 \quad \Rightarrow \langle \sigma v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

- WIMPs arise 'naturally' in BSM-theories (neutralino, lightest Kaluza-Klein particle, etc)

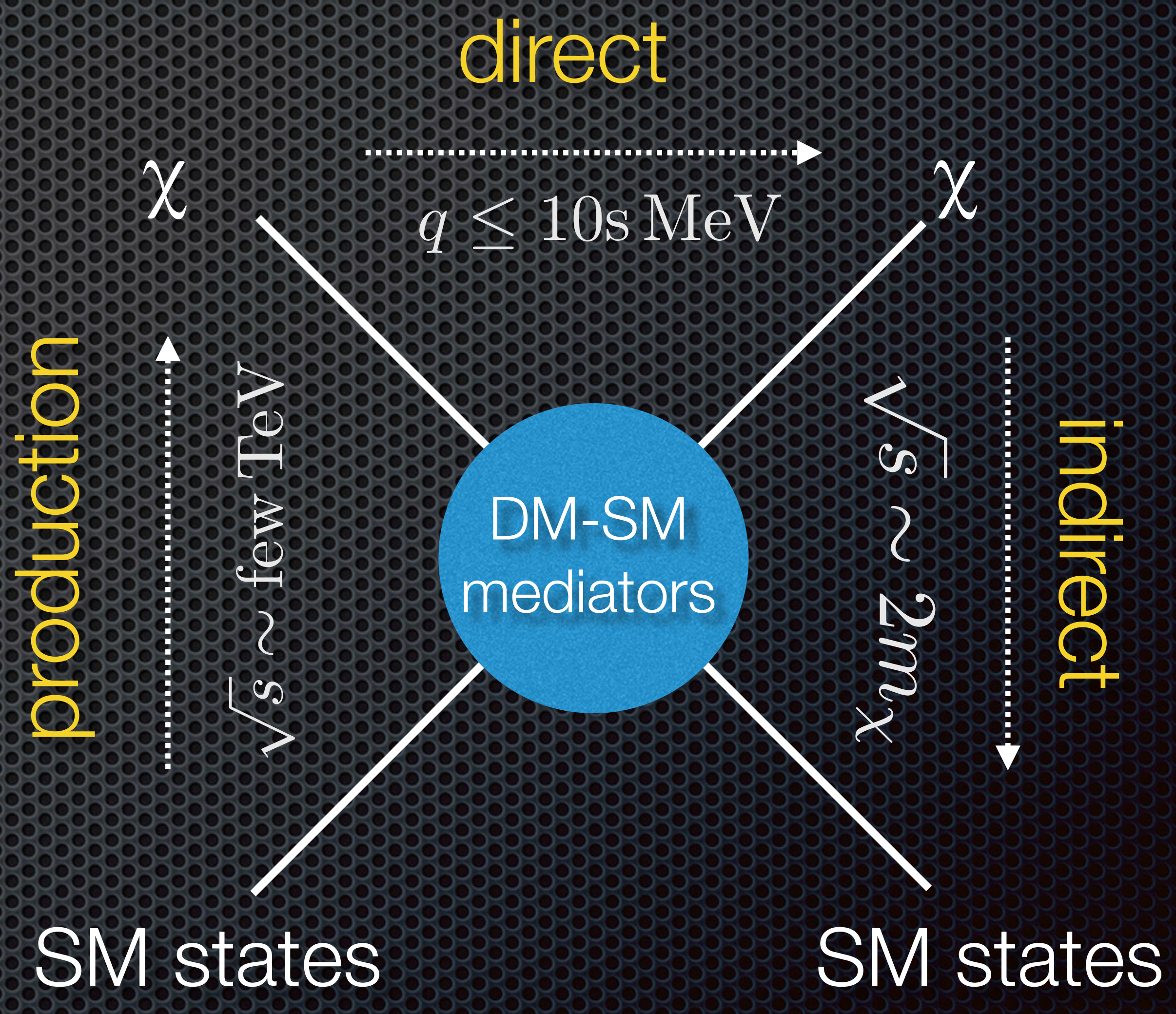
- *However, other models (or rather frameworks): asymmetric dark matter, WIMP-less dark matter, bosonic superWIMPs, sterile neutrinos, etc*

$$n_\chi - n_{\bar{\chi}} \sim n_b - n_{\bar{b}} \qquad \frac{\rho_\chi}{\rho_b} \approx 5 \quad \Longrightarrow \quad m_\chi \sim 5 m_p \simeq 5\,\mathrm{GeV}$$

Example asymmetric DM: dark matter density is set by an asymmetry connected to baryon asymmetry

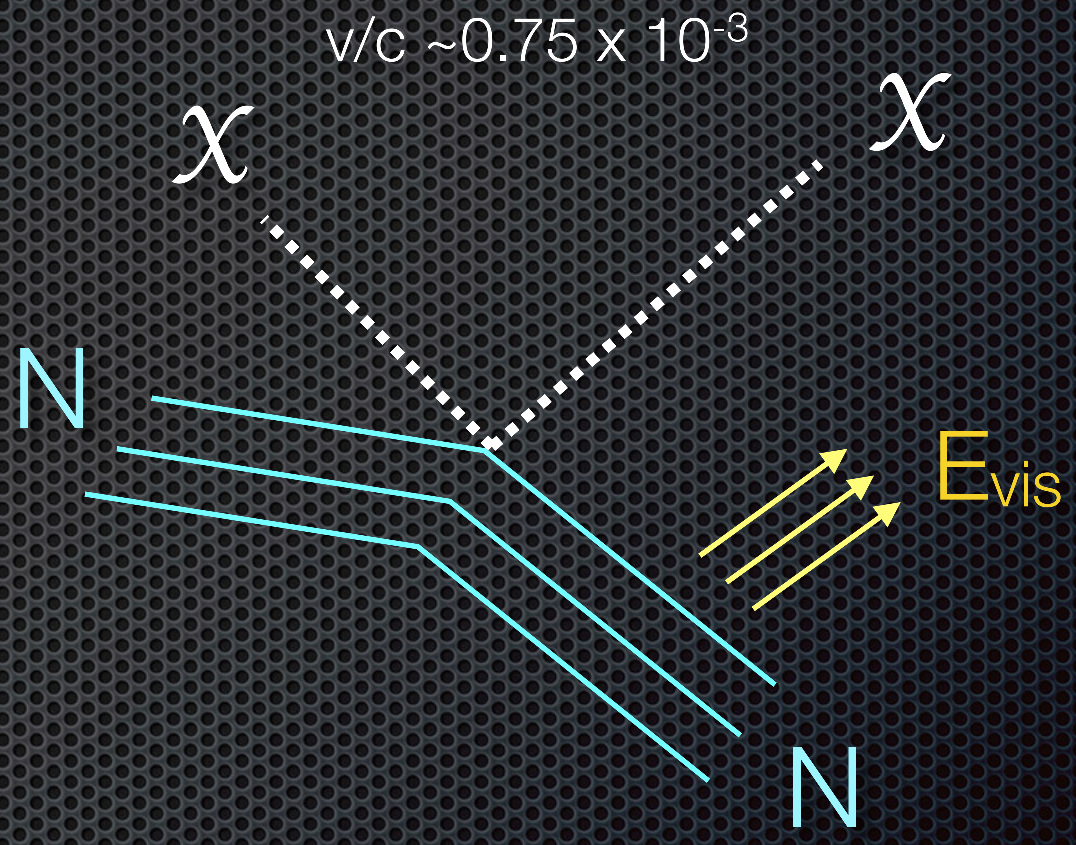
How can we detect a WIMP?

- 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 difficult
- Accelerator searches
  - missing E_T, mono-'objects', simplified models
  - can it establish that the new particle is the DM?

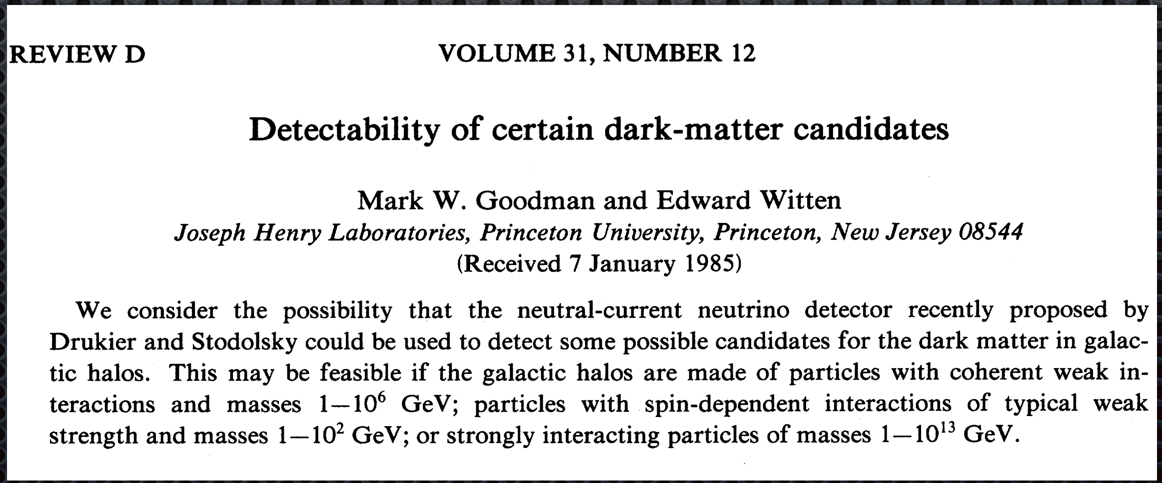


How to directly detect WIMPs in the laboratory?

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



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


REVIEW D VOLUME 31, NUMBER 12

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

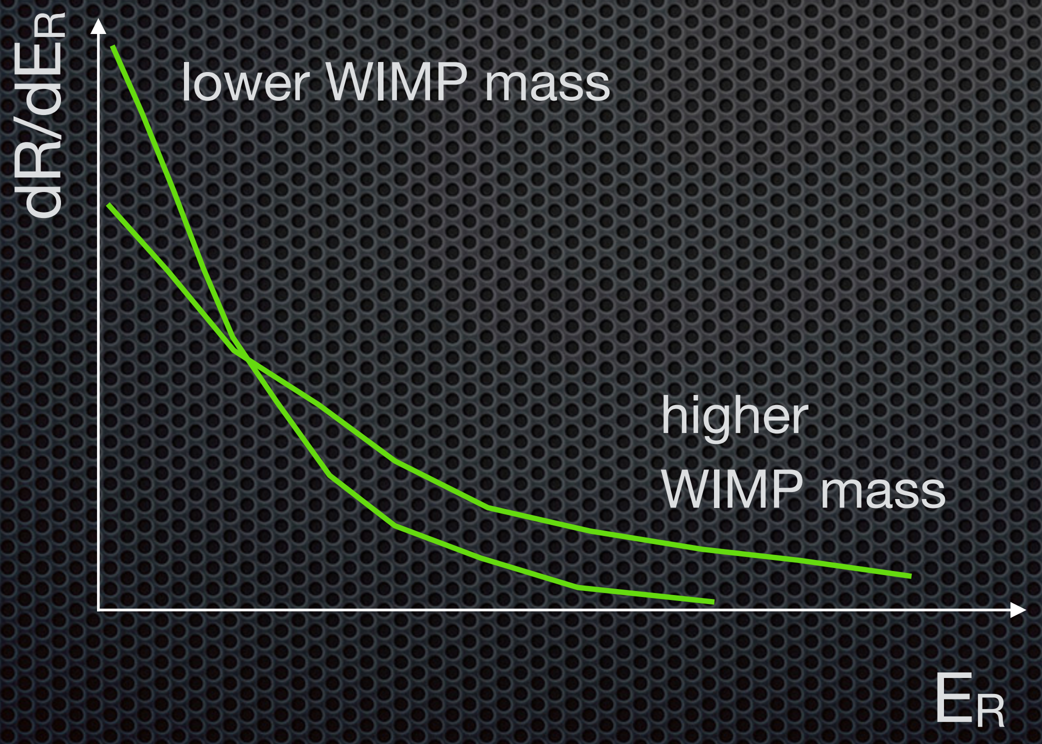
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and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

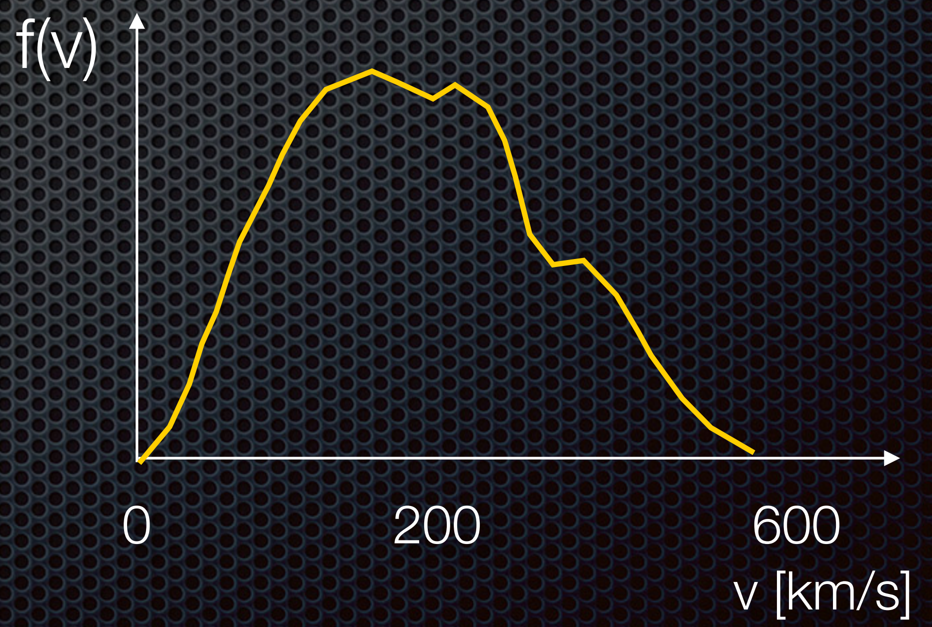
M. Goodman & E. Witten, 1985

What do we expect in a detector?

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

Astrophysics	Particle/nuclear physics	Detector physics
$\rho_0, f(v)$	$m_W, d\sigma/dE_R$	N_N, E_{th}

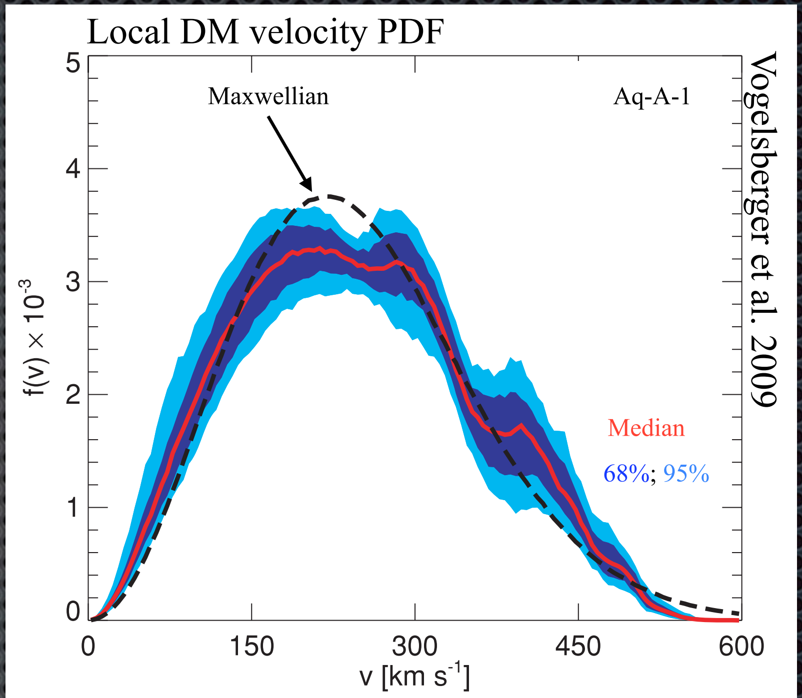




Astrophysics

- Local density (at R_0 ~ 8 kpc)
  - local measures use the vertical kinematics of stars near the Sun as 'tracers' (smaller error bars, but stronger assumptions about the halo shape)
  - global measures extrapolate the density from the rotation curve (larger errors, but fewer assumptions)
  - also, modelling the phase space distribution over larger volumes around the solar neighbourhood

Velocity distribution of WIMPs in the galaxy



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

$$\rho(R_0) = 0.3 \pm 0.1 \mathrm{GeV\,cm}^{-3} = 0.008 \pm 0.003 \mathrm{M}_{\odot} \mathrm{pc}^{-3}$$

J. Bovy, S. Tremaine, APJ 756, 2012

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

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

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

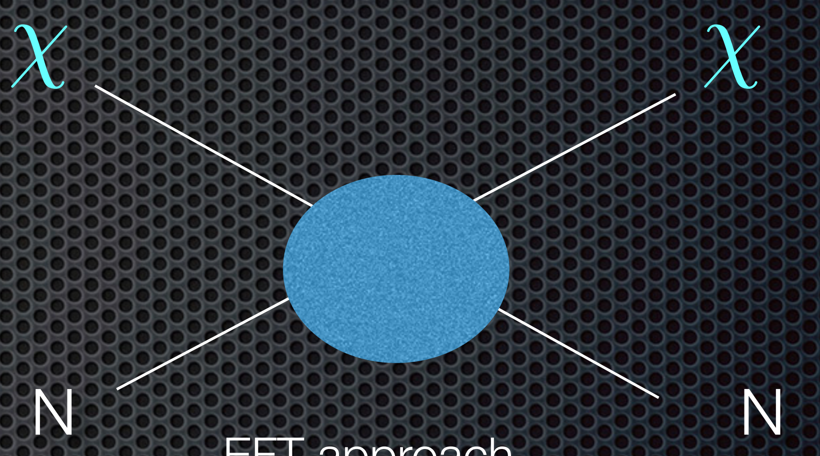
Particle physics: scattering cross section

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

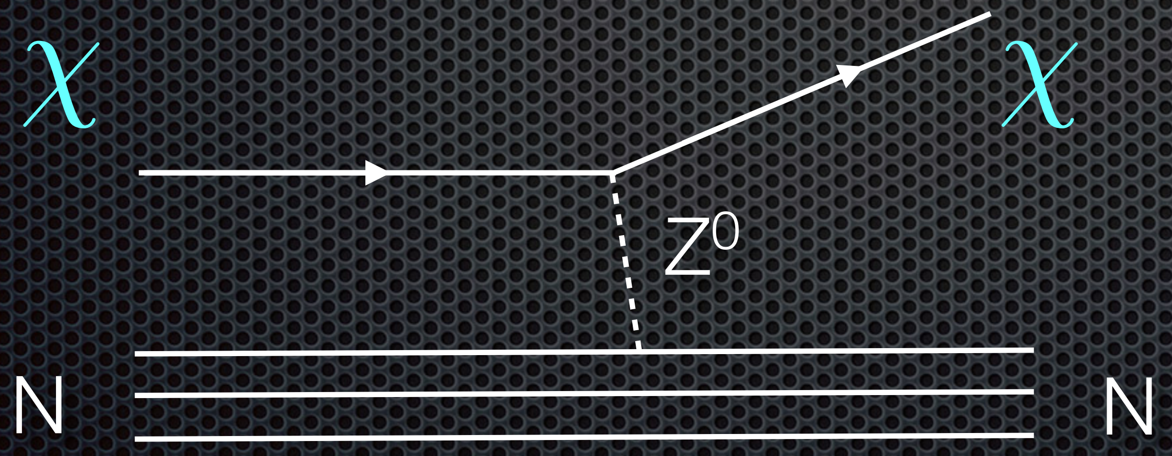
$$\mathcal{L}_\chi^{\text{eff}} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$

- The effective operator arises from integrating out the mediator with mass M and couplings g_q and q_χ to the quark and WIMP:

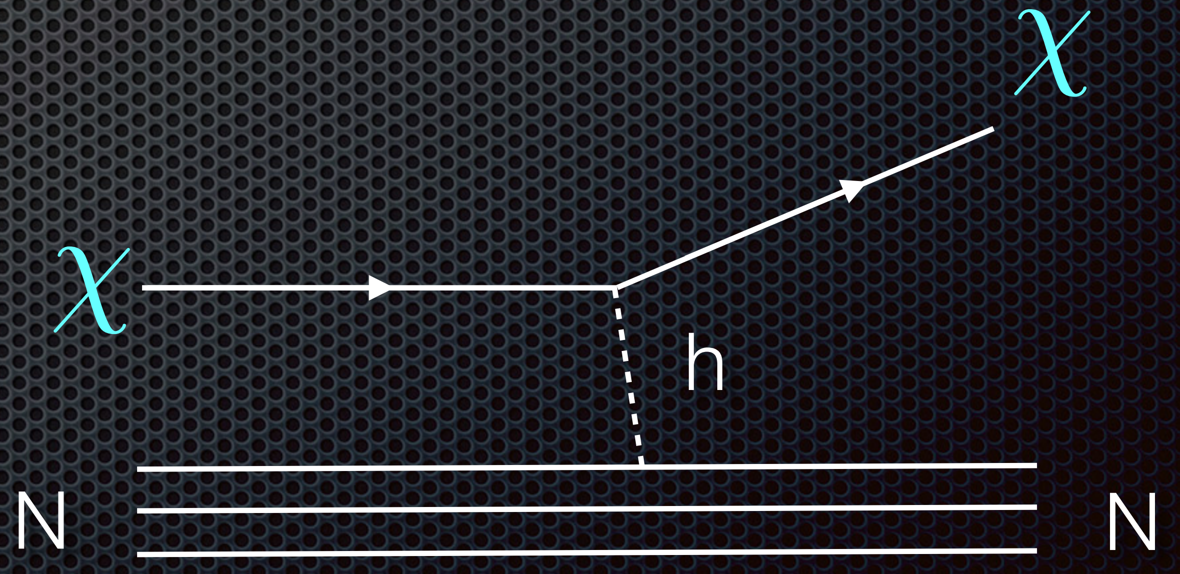
$$\Lambda = \frac{M}{\sqrt{g_q g_\chi}} \qquad \Rightarrow \sigma_{tot} \propto \Lambda^{-4}$$



EFT approach (always valid for direct detection)



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



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

Scattering cross section

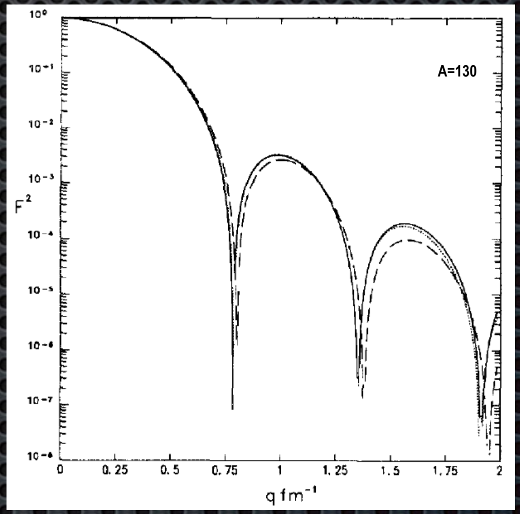
- Interactions leading to WIMP-nuclei scattering are parameterized as:

G. Jungman, M. Kamionkowski, K. Griest, 1995

  - *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 p and n



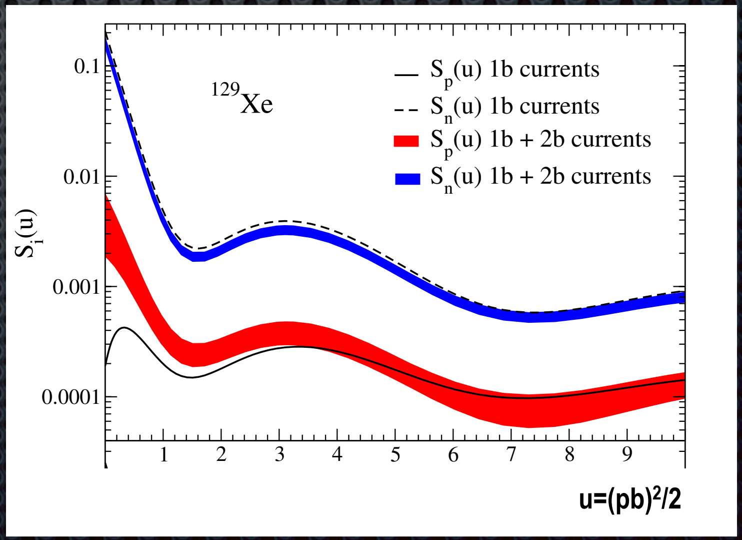
=> nuclei with large A - but nuclear form factor corrections

Lewin & Smith, 1996

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

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

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



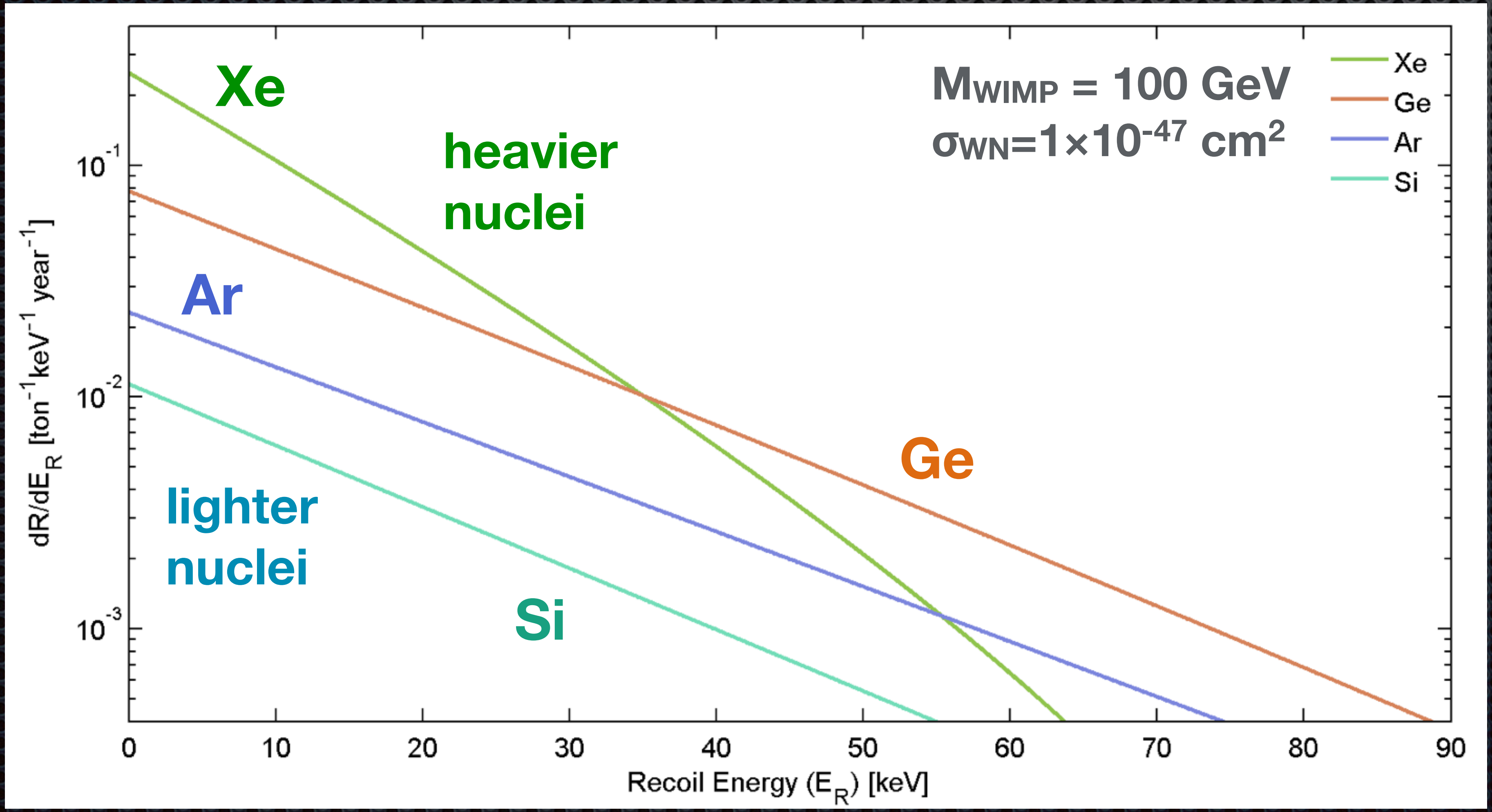
=> nuclei with non-zero angular momentum - corrections due to spin structure functions

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

Expected Interaction Rates

- Recoil rate after integration over WIMP velocity distribution (and considering a SI nuclear form factor):

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



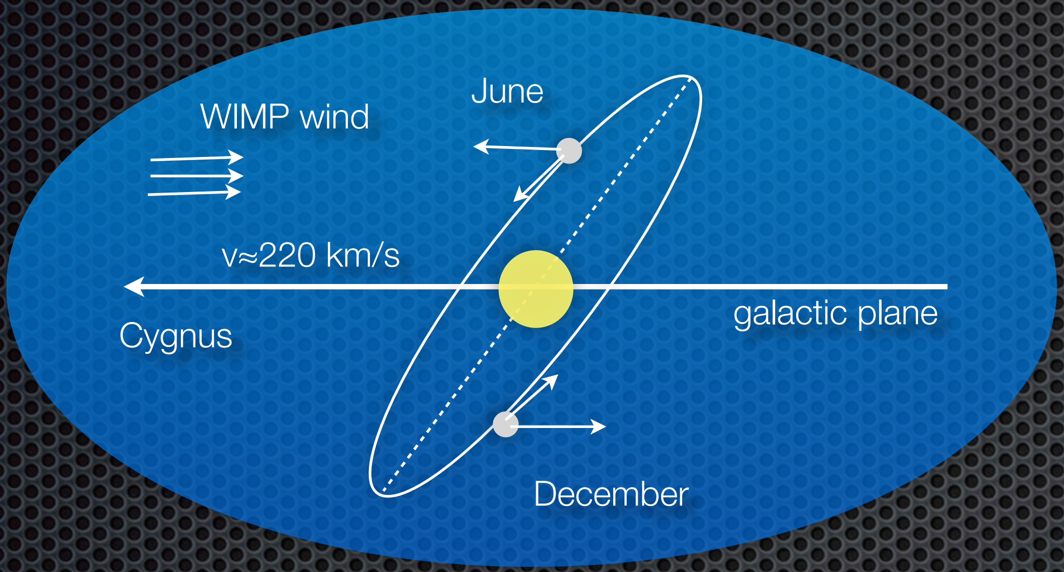
Nuclear recoil spectrum for various dark matter target nuclei

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

Dark matter signatures

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

Drukier, Freese, Spergel 1986;



D. Spergel 1988

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

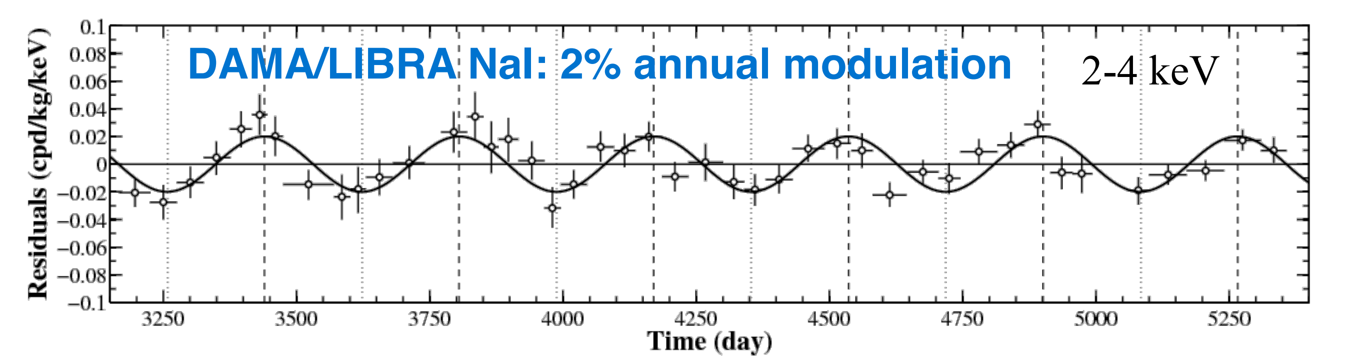
David N. Spergel*
Institute for Advanced Study, Princeton, New Jersey 08540

(Received 21 September 1987)

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

$$\frac{dR}{dE\,d\cos\gamma} = \frac{\rho_0\sigma_0}{\sqrt{\pi}}\,\frac{(m_x+m_n)^2}{2m_x^3 m_n v_{\text{halo}}} \times \exp\left[\frac{-[(v_E+v_\odot)\cos\gamma - v_{\min}]^2}{v_{\text{halo}}^2}\right] . \qquad (7)$$

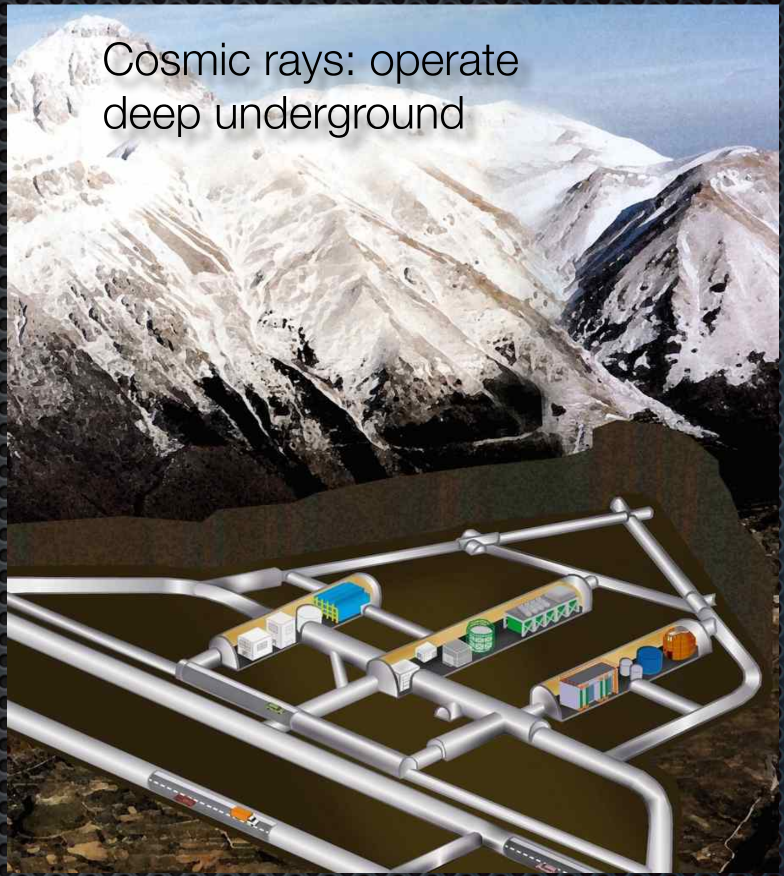
Equation (7) shows that the nuclear recoil direction has a very strong angular dependence. The number of events in the forward direction will significantly exceed the number of events in the backward direction for any energy threshold E_{th}. This strong effect suggests that even

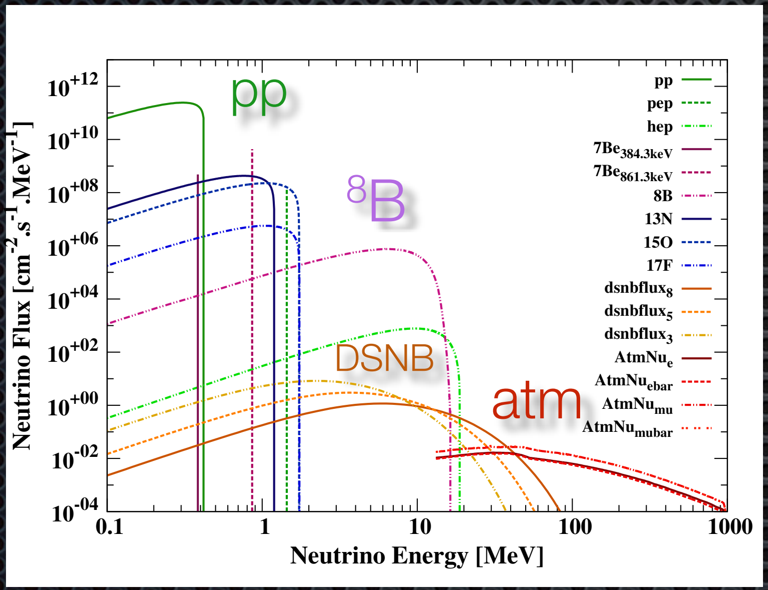


R. Bernabei et al, EPJ-C67 (2010)

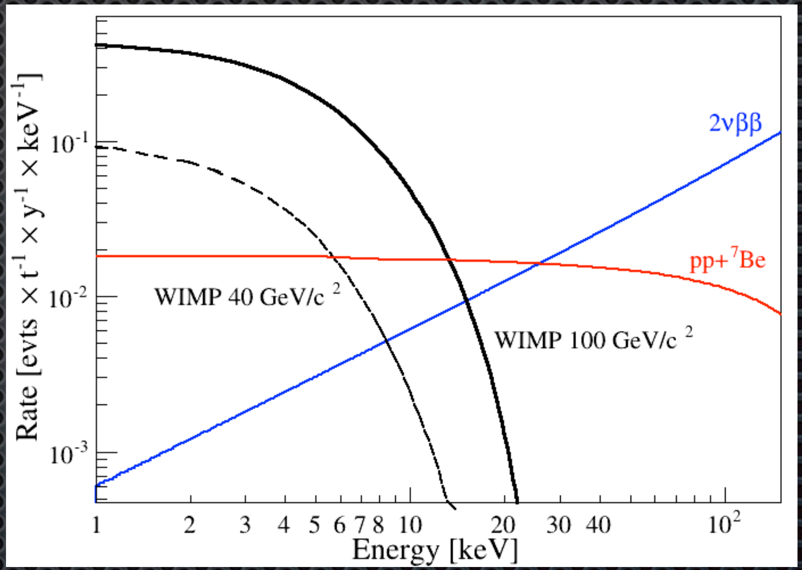
Backgrounds

- Cosmic rays; cosmic activation of detector materials at the Earth's surface
- Natural (^{238}U, ^{232}Th, ^{222}Rn, ^{40}K) radioactivity
- Anthropogenic (^{85}Kr, ^{137}Cs, etc) radioactivity
- *Ultimately: solar, atmospheric and supernovae neutrinos*

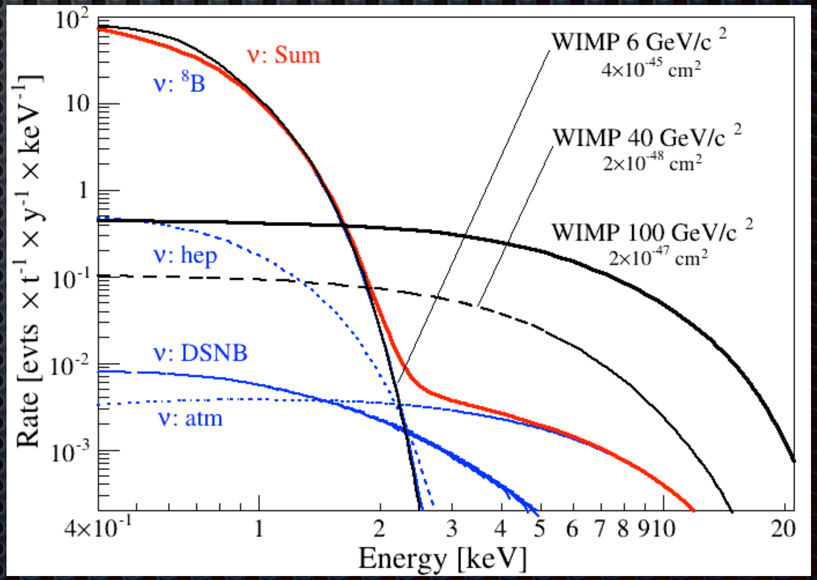




F. Ruppin et al., 1408.3581



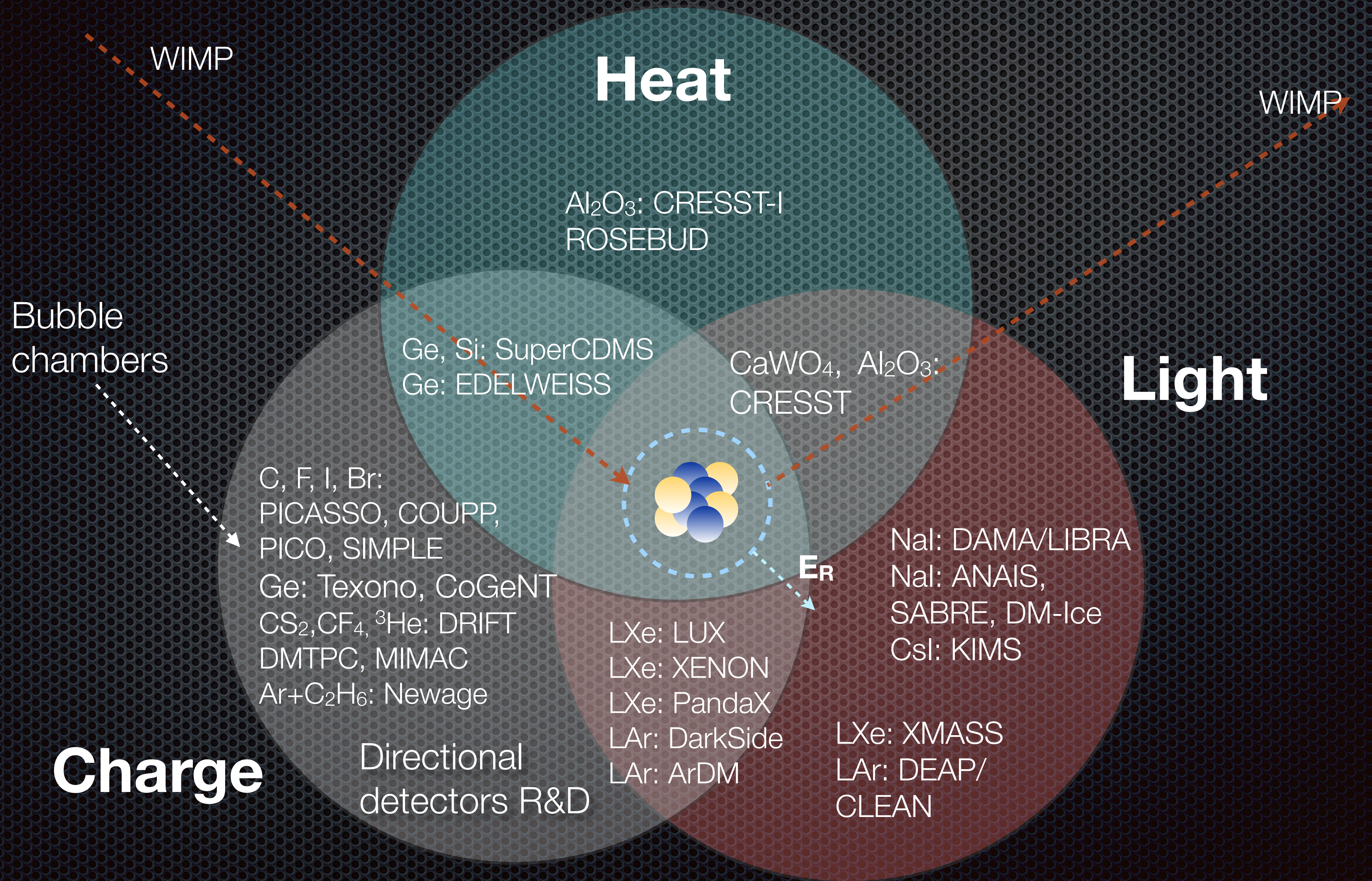
$$\nu + e^- \rightarrow \nu + e^-$$



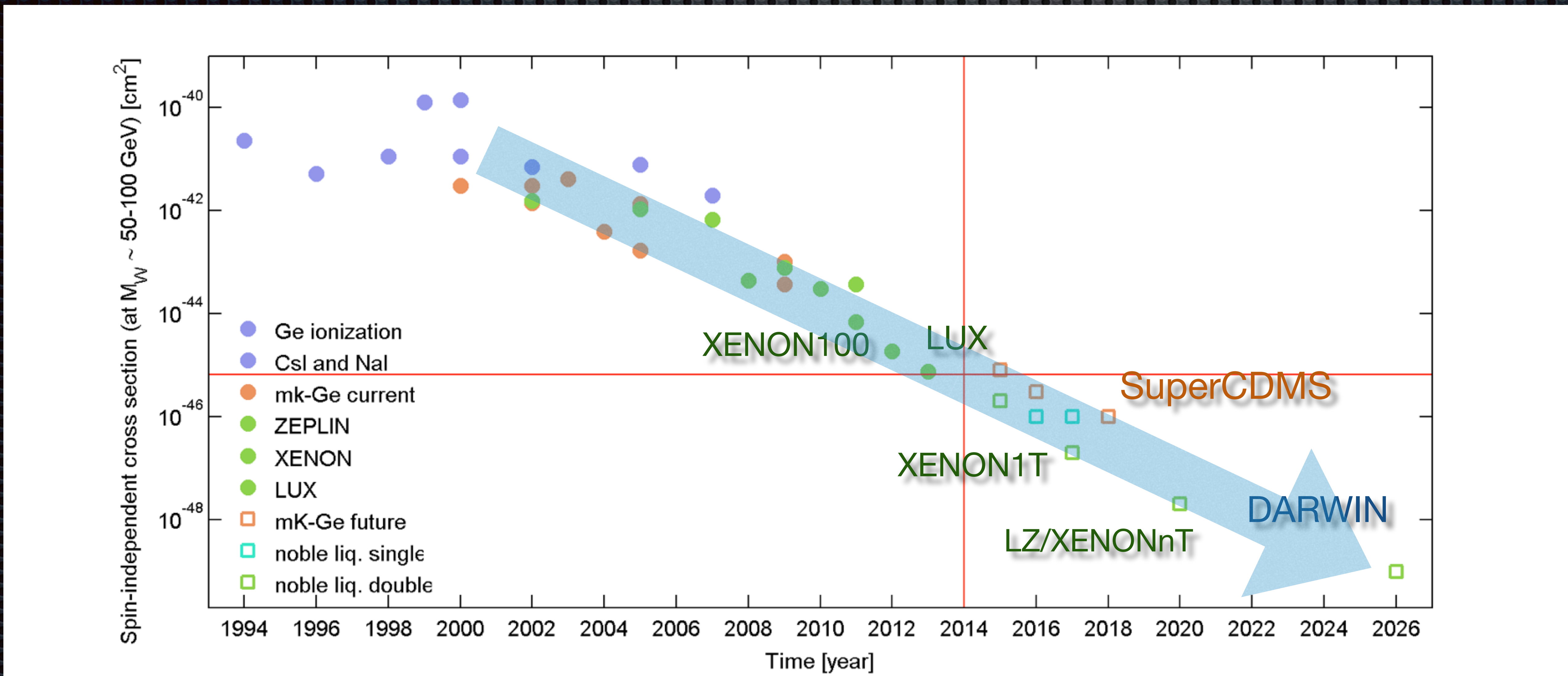
$$\nu + N \rightarrow \nu + N$$

LB et al., JCAP01 (2014) 044

Direct Dark Matter Detection Zoo



A brief history of direct detection limits



LB, Physics of the Dark Universe 4, 2014

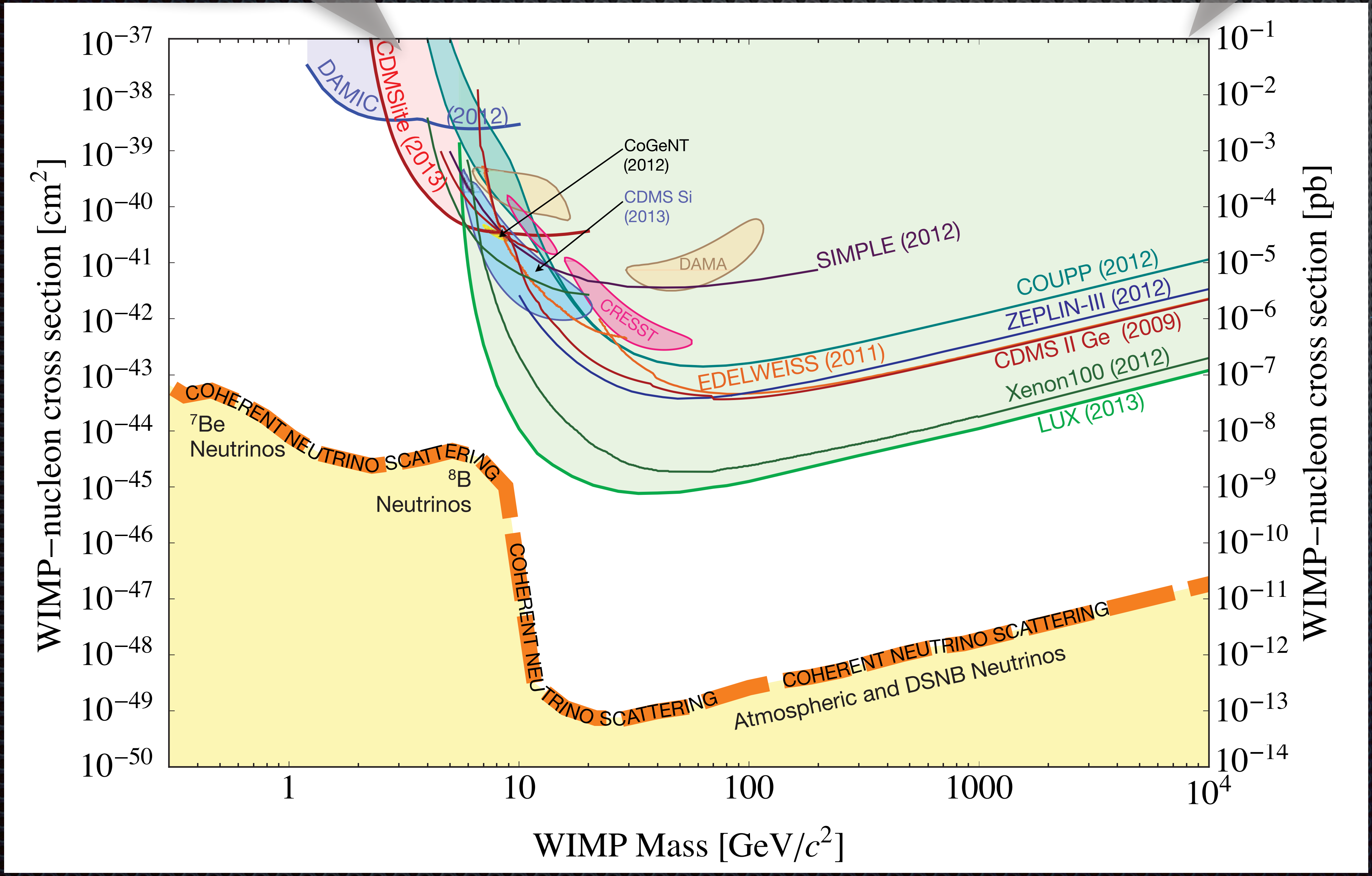
About a factor of *10 increase in sensitivity every ~2 years*

Can we keep this rate of progress?

The WIMP landscape in 2014

“Anomalies” at low WIMP masses (*‘thresholdinos’?*)

Sensitivity to masses up to 10 TeV and beyond



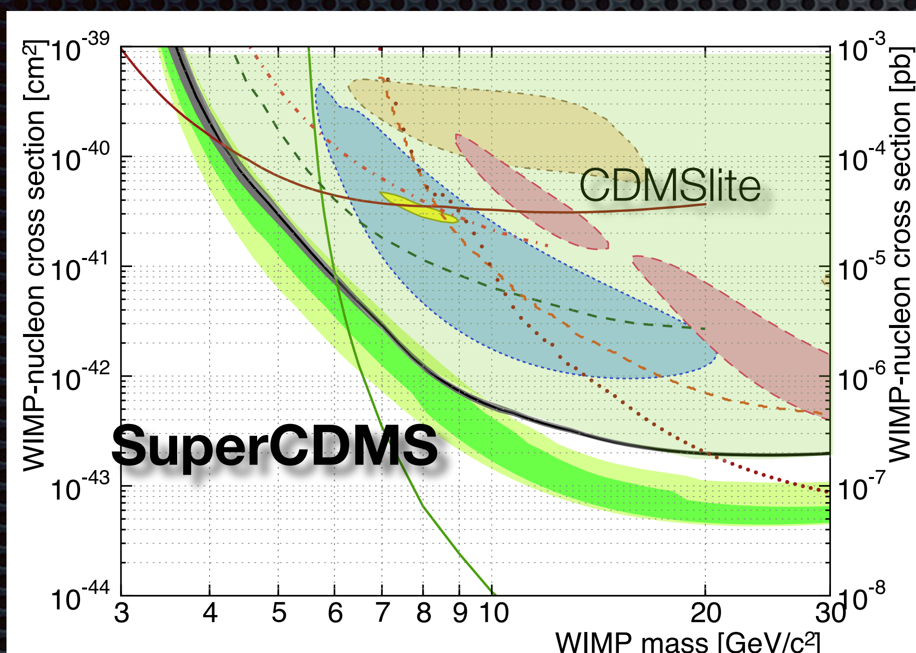
1 event/(kg d)

1 event/(ton d)

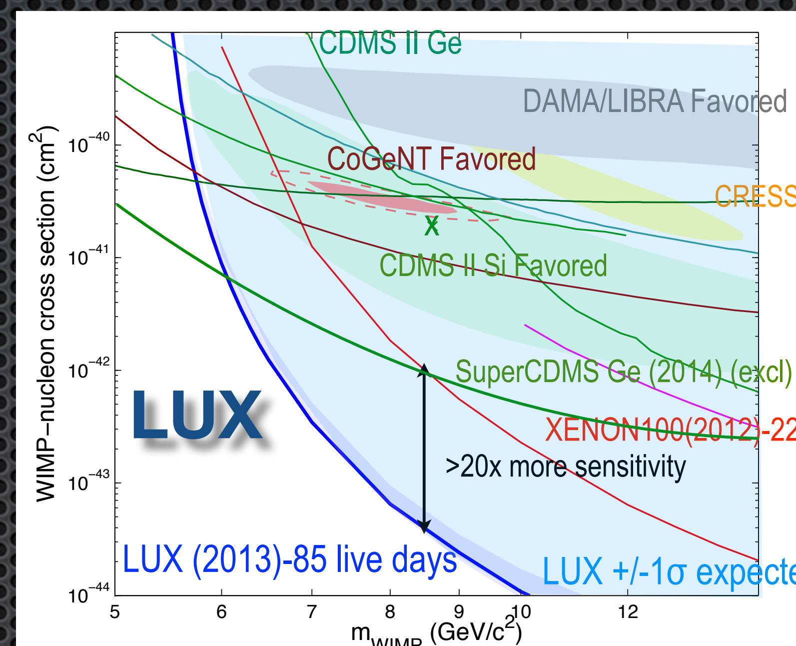
1 event/(ton y)

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

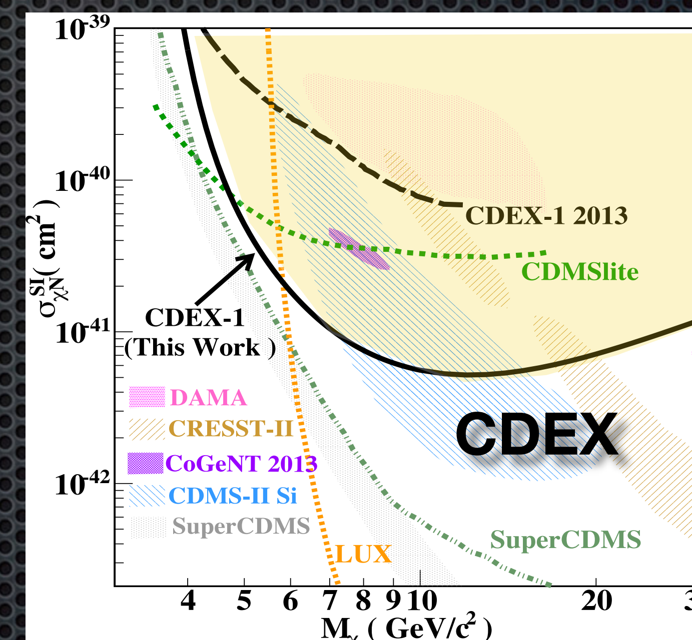
CDMS, PRL 112, 2014

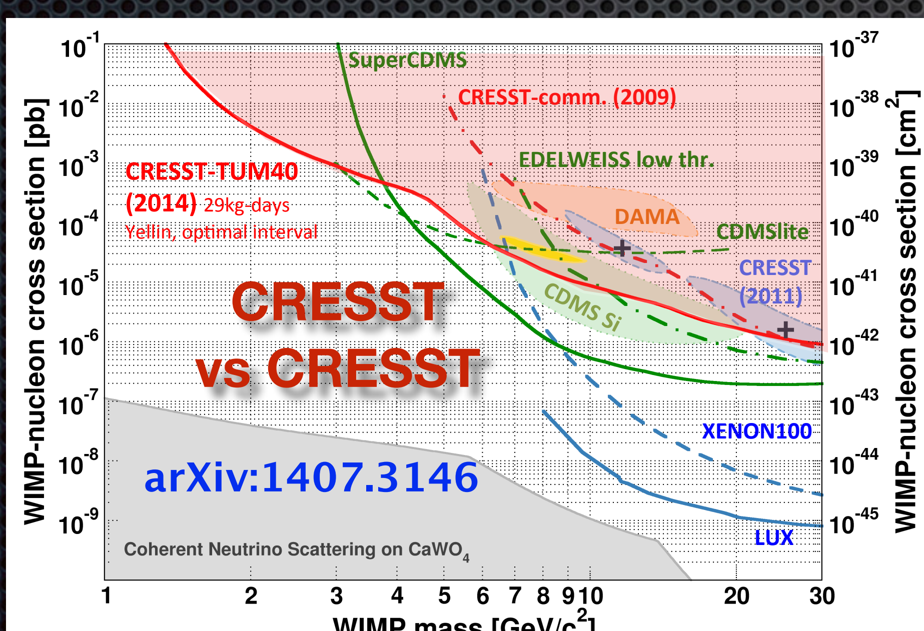


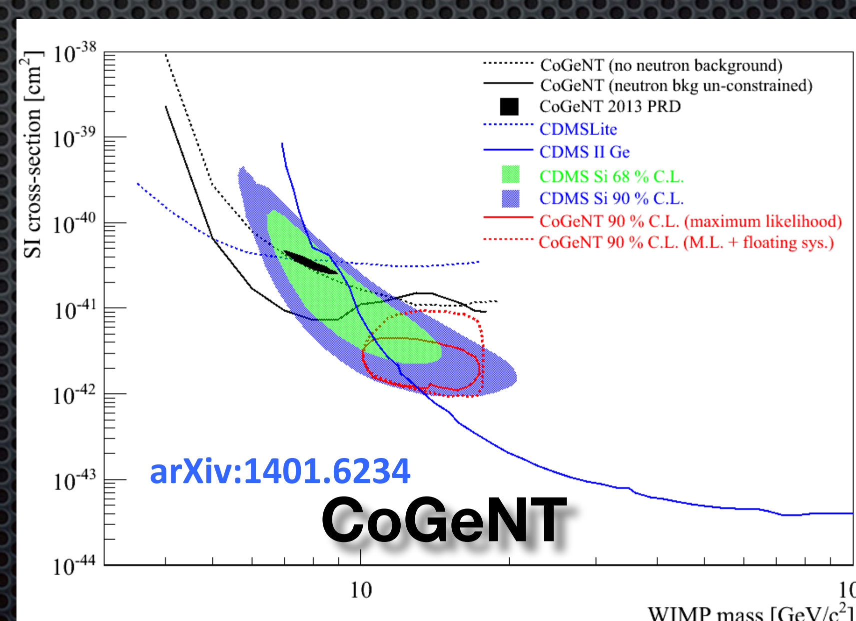
LUX, PRL, arXix: 1310.8214

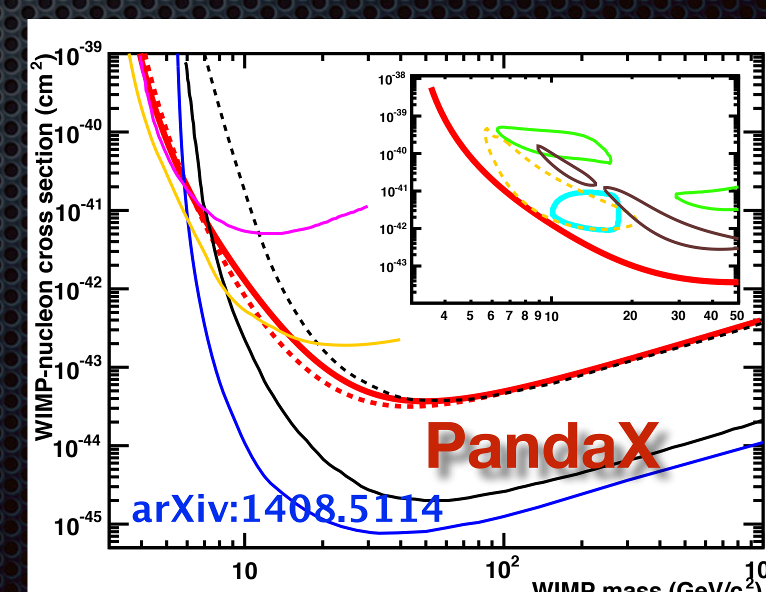


CDEX, arXiv:1404.4946









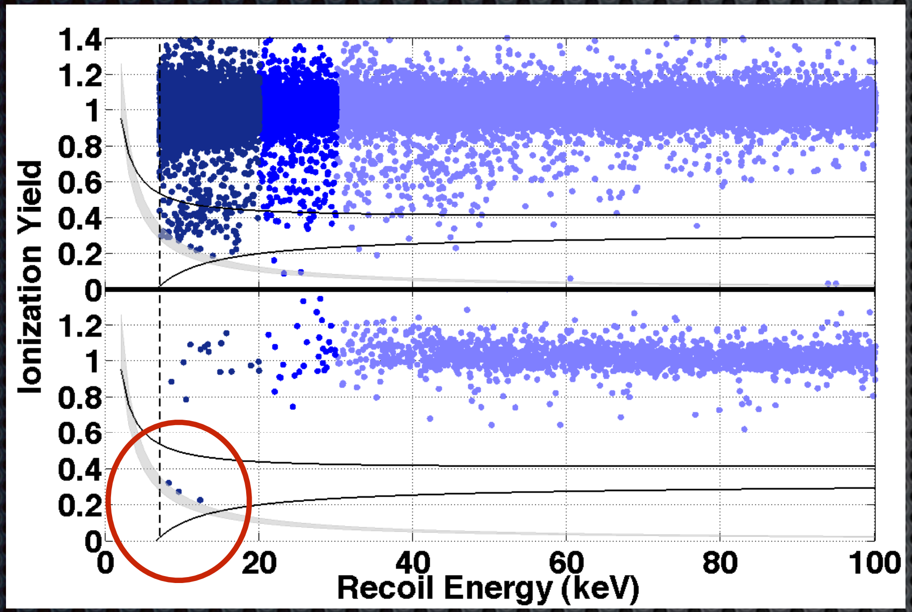
Example: a CDMS-Si like signal in Xe detectors

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

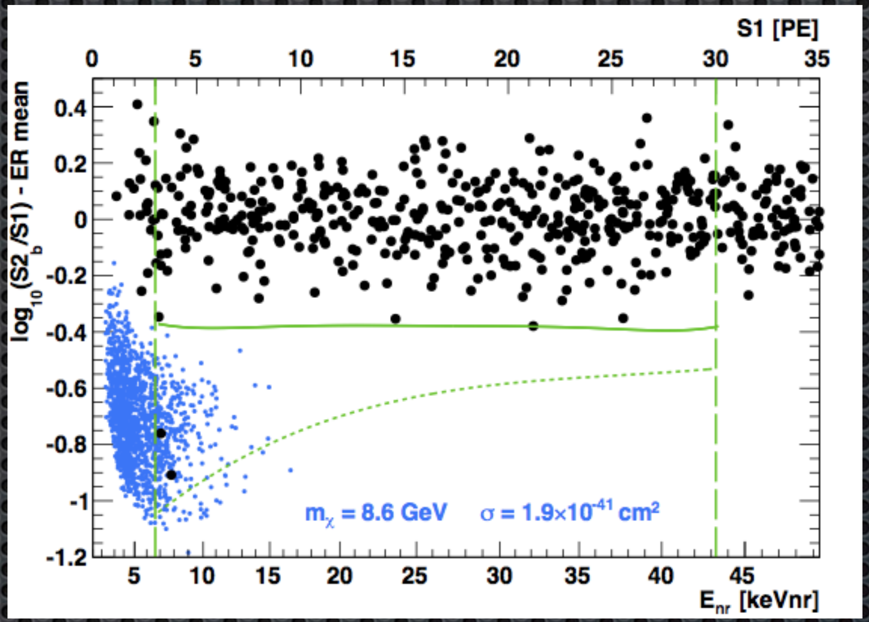
CDMS-Si
3 events observed
<1 expected (known BGs)

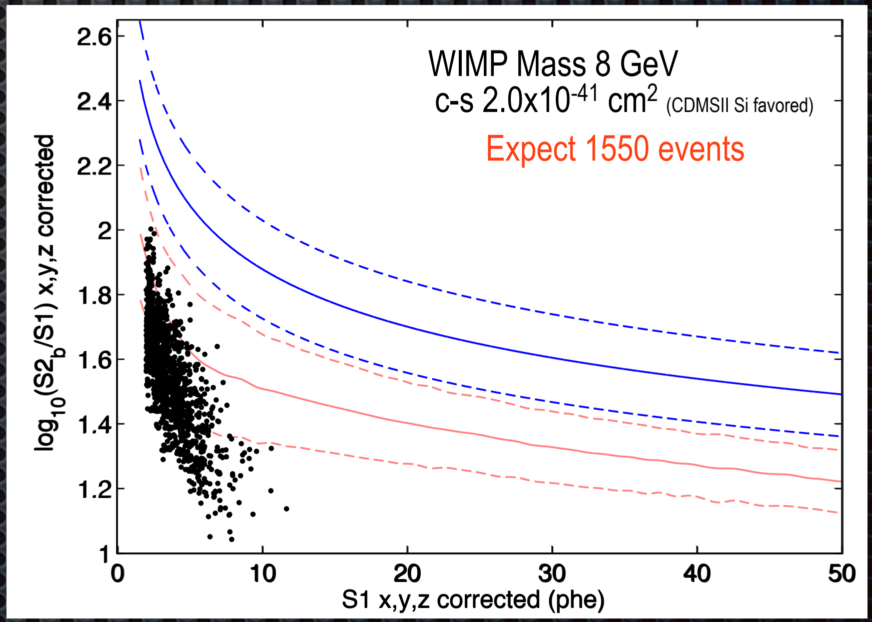
XENON100 Run10, PRL 111
expect: ~ 220 events

LUX first run, RPL 113
expect: ~ 1550 events



arXiv:1304.4279v3



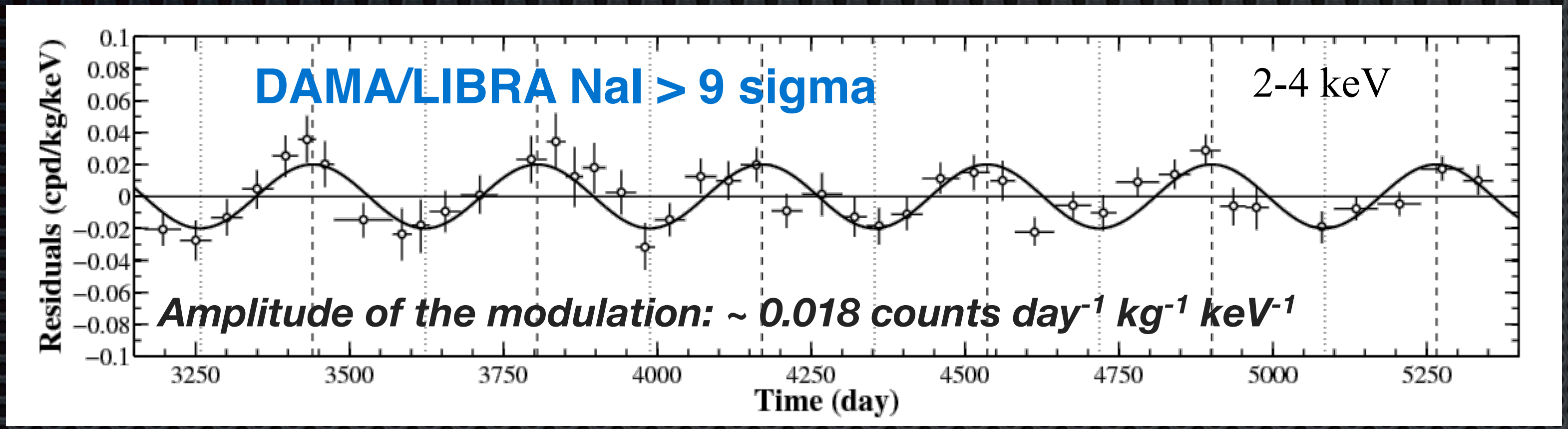


Keep common sense about 'anomalies'
Some good things:

- push to understand detectors in regimes we did not anticipate
- push to make data public
- new techniques to relate classes of experiments ('halo-independent' limits)

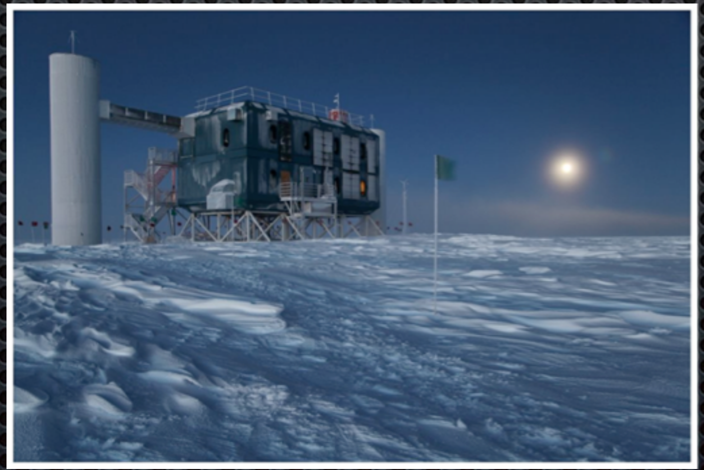
DAMA/LIBRA annual modulation signal

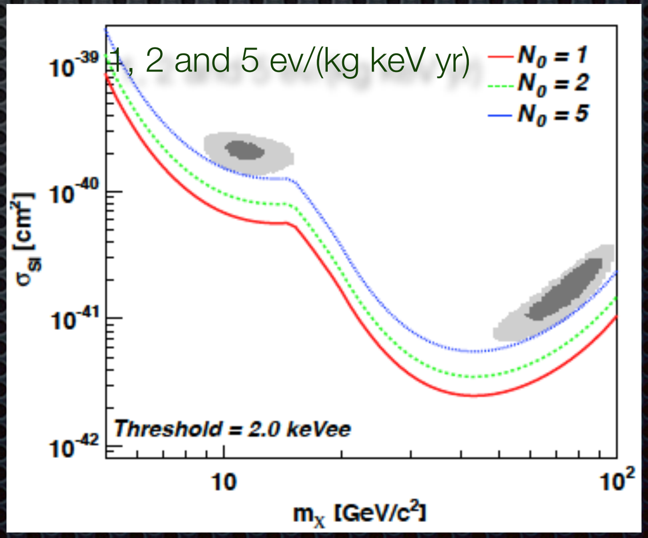
- The DAMA/LIBRA signal remains *robust and generally consistent with a dark matter interpretation* (period = 1 year, phase = June 2 ± 7 days)



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

- DM-Ice at the South Pole: only experiment in the southern hemisphere, where seasonal variation different from DM modulation (IceCube provides muon monitoring); other: KIMS, ANAIS, SABRE

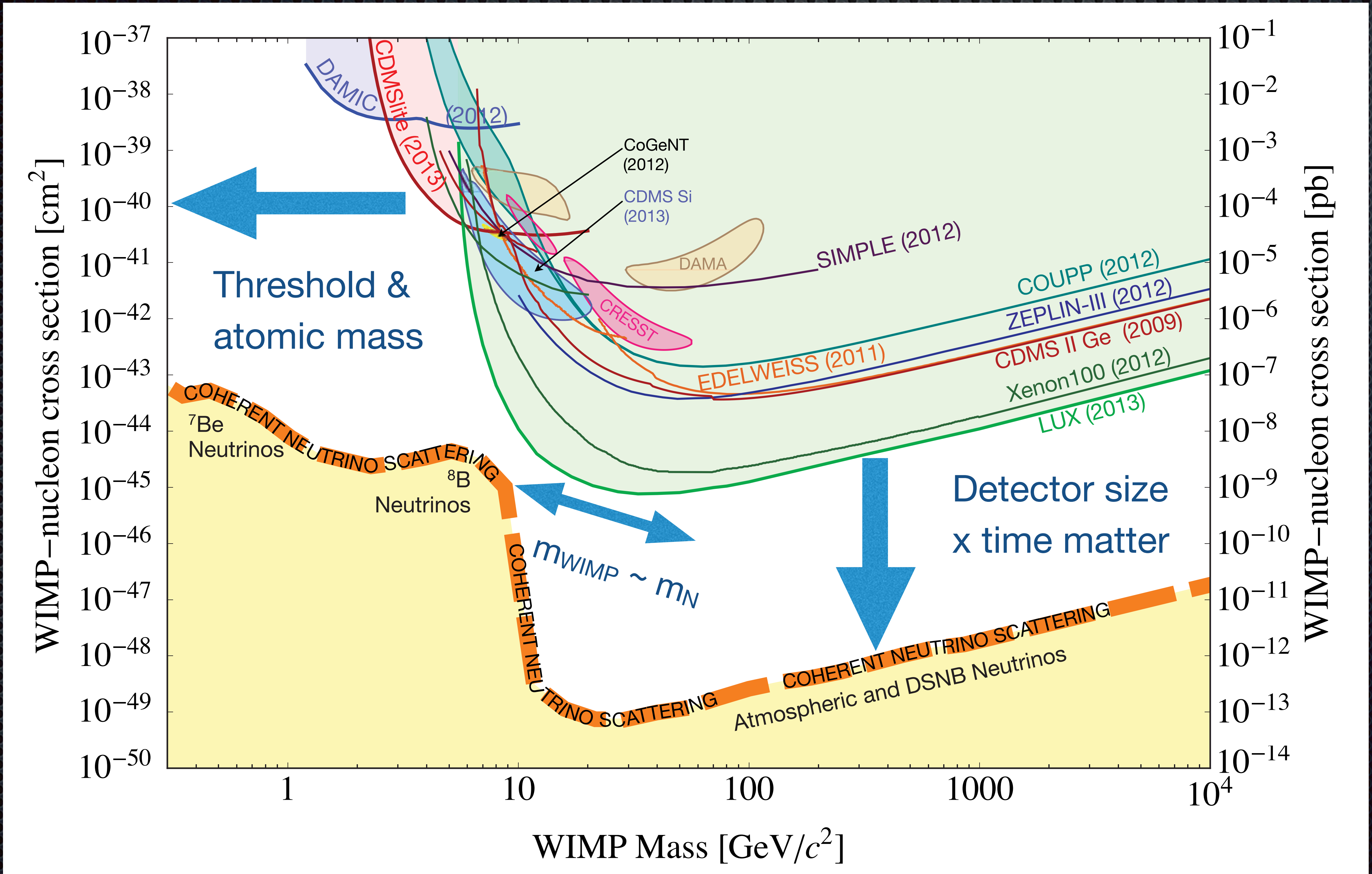




DM-Ice: 500 kg yr

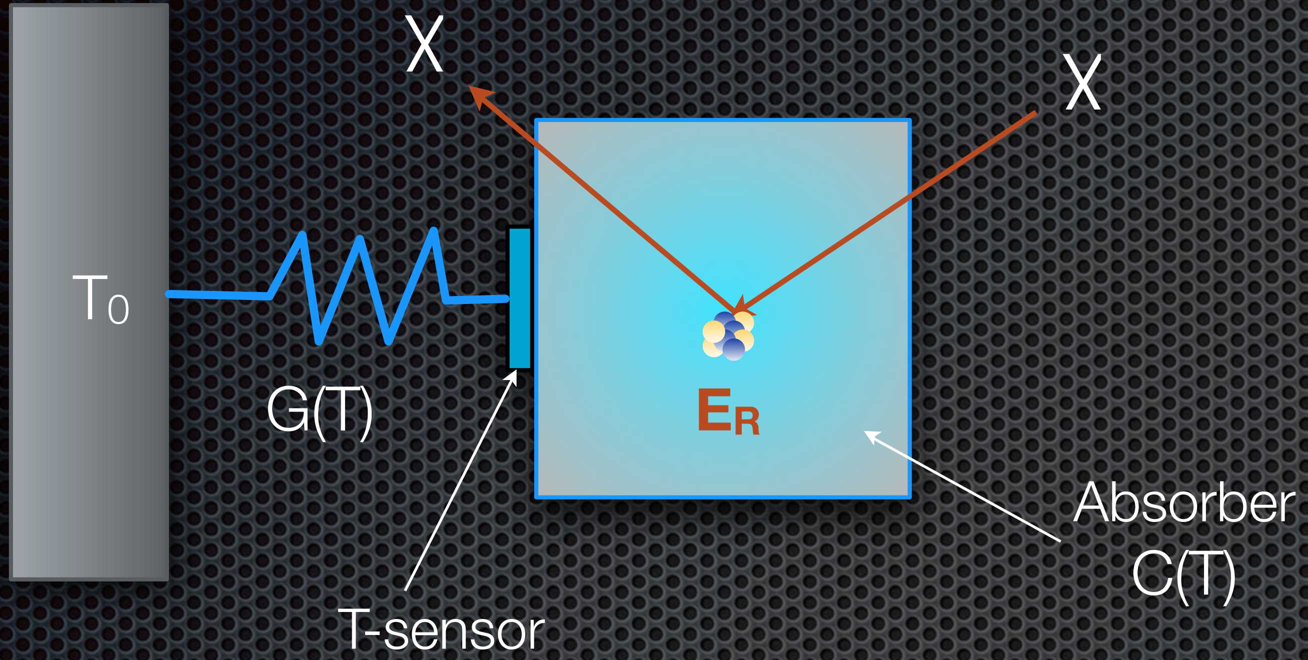
Definitive (5σ) detection or exclusion with 500 kg-yr NaI(Tl) (DAMA x 2 yrs) and same or lower threshold (< 2 keV_{ee})

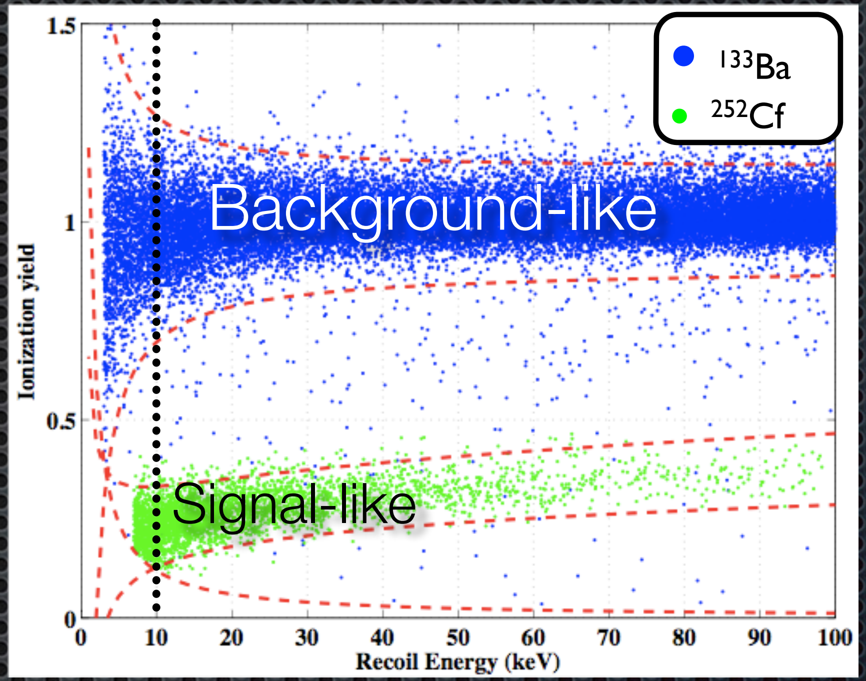
How to probe the WIMP landscape?



Cryogenic Experiments at T~ mK

- Absorber masses from ~ 100 g to 1400 g; TES to read out small T-changes

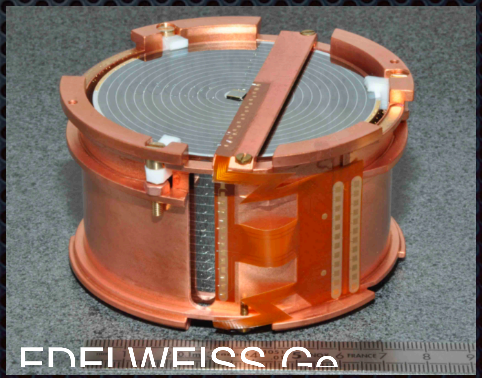




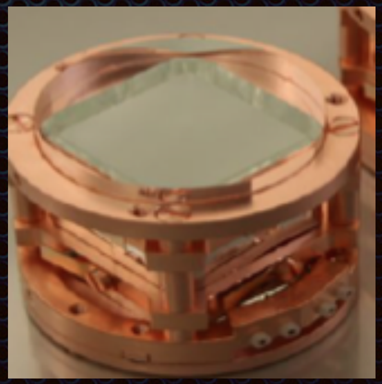
- Collaboration between SuperCDMS and EURECA (CRESST + EDELWEISS) at SNOLAB, at the ~100 kg target level
- Data taking: start in 2018

SuperCDMS: Ge, Si

EDELWEISS-III (Ge)

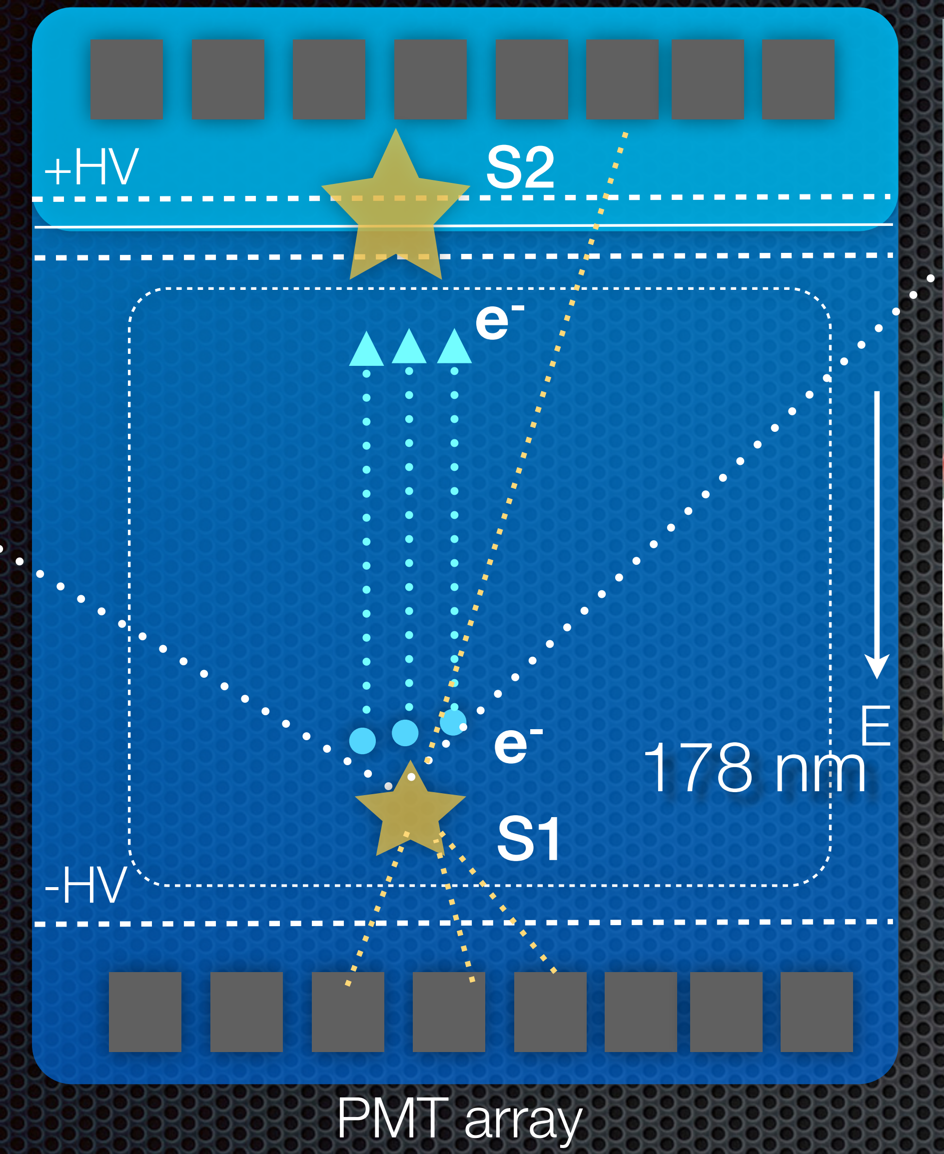


CRESST (CaWO3)

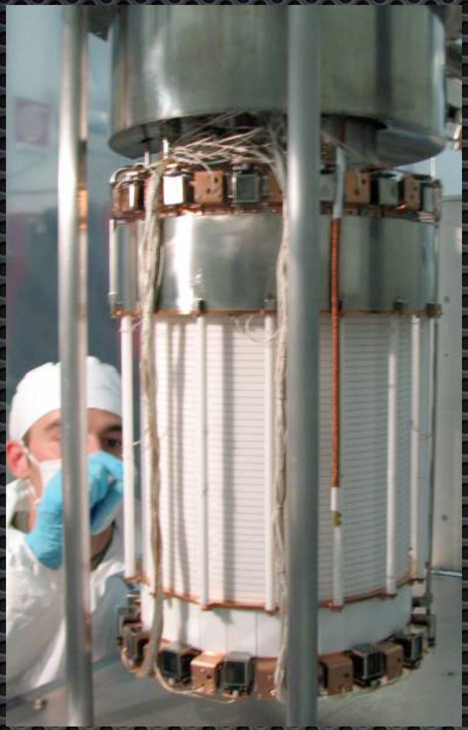


Noble liquid time projection chambers

Double phase (TPC)



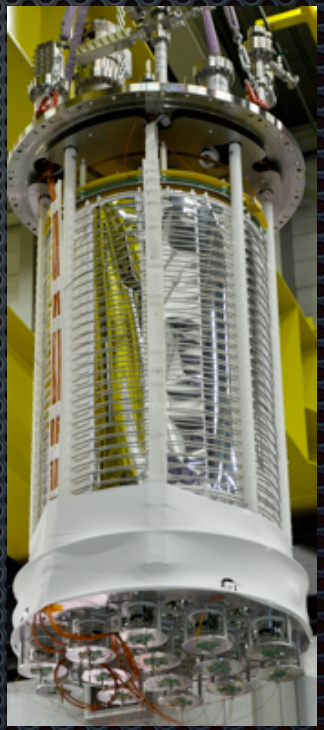
LXe: XENON100



LXe: LUX

LAr: DarkSide

LAr: ArDM



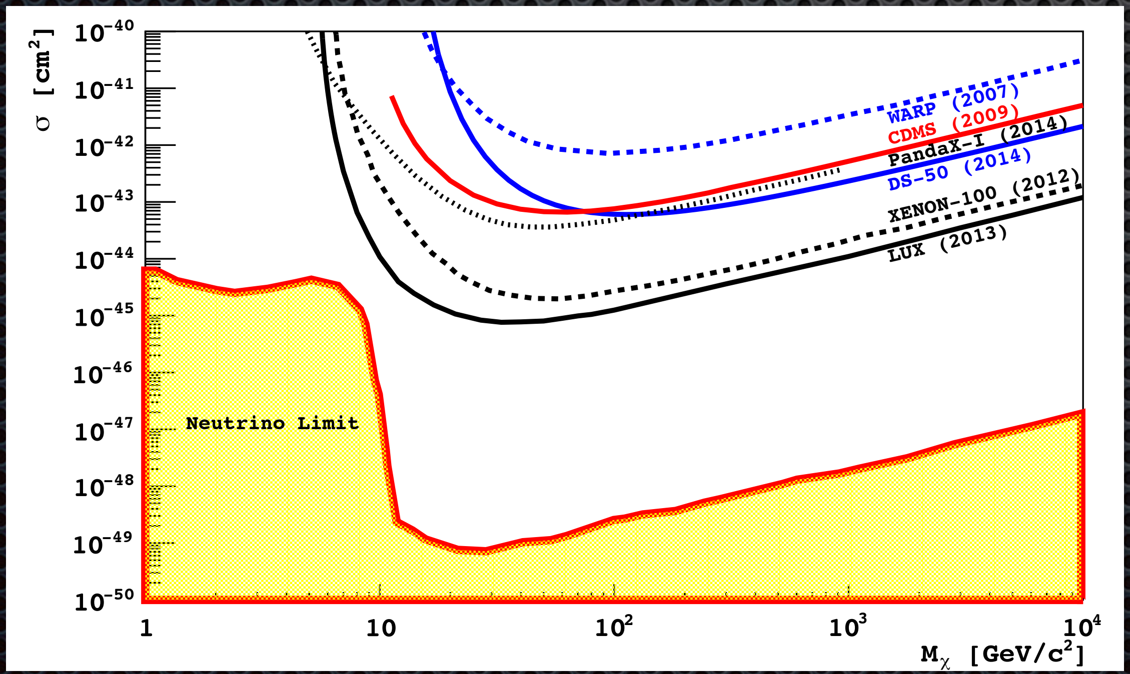
Also, single-phase detectors (XMASS, DEAP, CLEAN)
WIMP target masses between ~ 50 kg - 1 ton

Under construction: XENON1T (3t LXe), data in 2015; proposed: LZ (7t LXe), XENONnT (7t LXe), XMASS (5t LXe), DarkSide (5t LAr)

R&D and design: DARWIN (20 t LXe and/or 50 t LAr)
(darwin.physik.uzh.ch)

Noble liquid time projection chambers

- DarkSide-50 at LNGS
- Total LAr mass: ~ 47 kg
- First results from ^{atm}Ar, 1422 kg d
- 6.1 x 10^{-44} cm^2 at a WIMP mass of ~ 100 GeV
- corresp. to a zero background run in 0.6 ton yr with ^{undergr}Ar

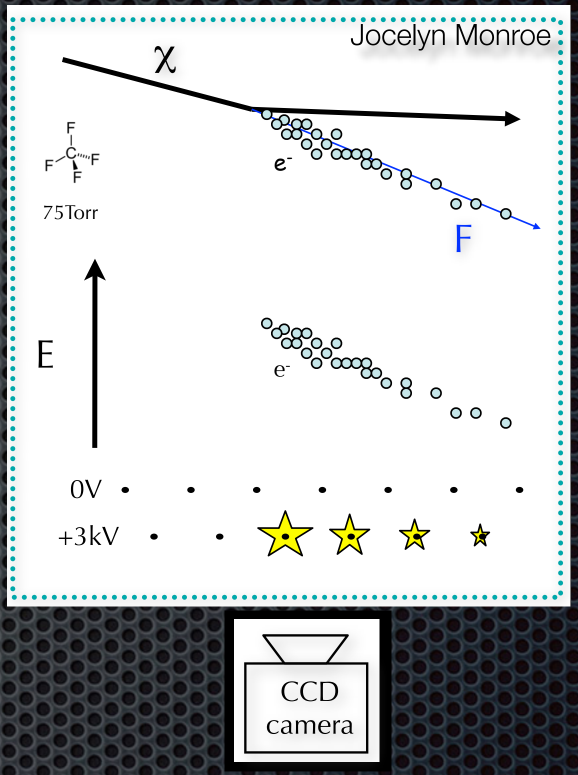


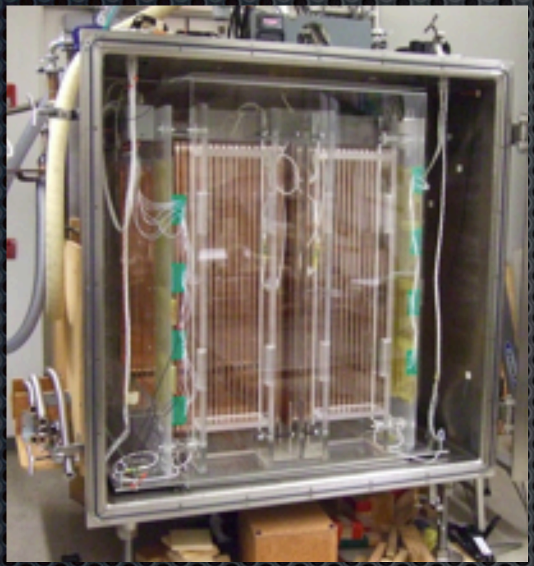
arXiv:1410.0653, DarkSide collaboration

- XENON1T at LNGS, under construction
- Total LXe mass: 3.3 tons, 1 m charge drift
- Commissioning and science run: mid and late 2015
- Goal: 2 x 10^{-47} cm^2 at a WIMP mass of ~ 50 GeV

Directional detectors

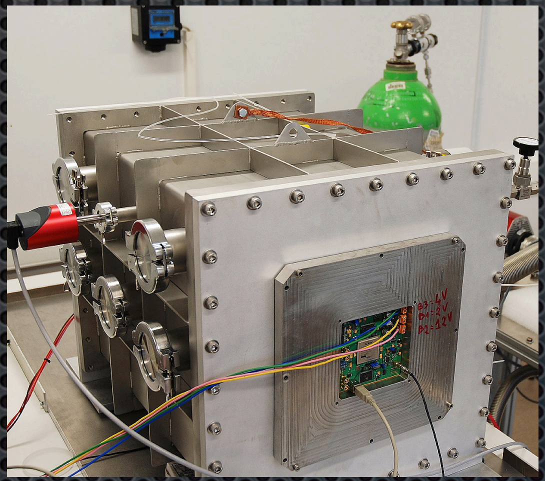
- R&D on low-pressure gas detectors to measure the recoil direction, correlated to the galactic motion towards Cygnus
- Challenge: good angular resolution + head-tail at E_{thr} (~30-50 keV)
- One technology to be proposed in ~ 2016



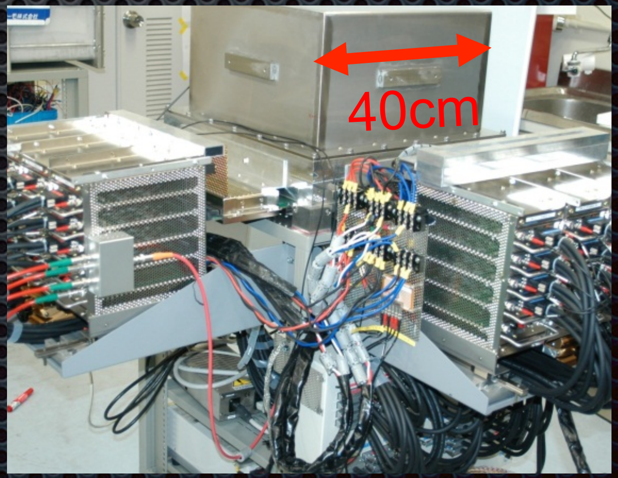


DRIFT, Boulby Mine
1 m^3, negative ion drift
CS_2, CF_4, O_2 gas

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

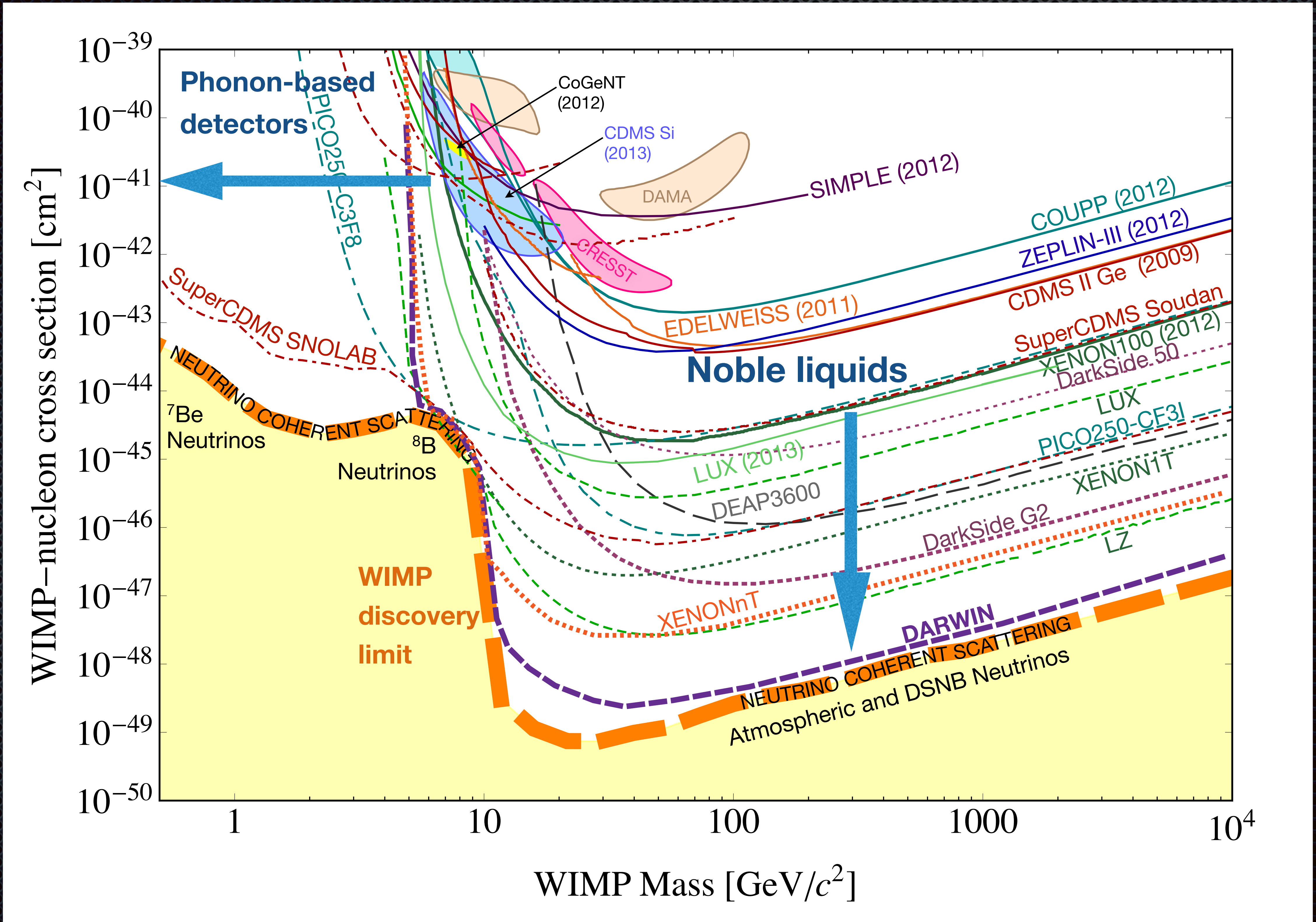


MIMAC 100x100 mm^2
5l chamber at Modane
CF_4, CHF_3, H gas



NEWAGE, Kamioka
CF_4 gas at 0.1 atm
50 keV threshold

The WIMP landscape: prospects

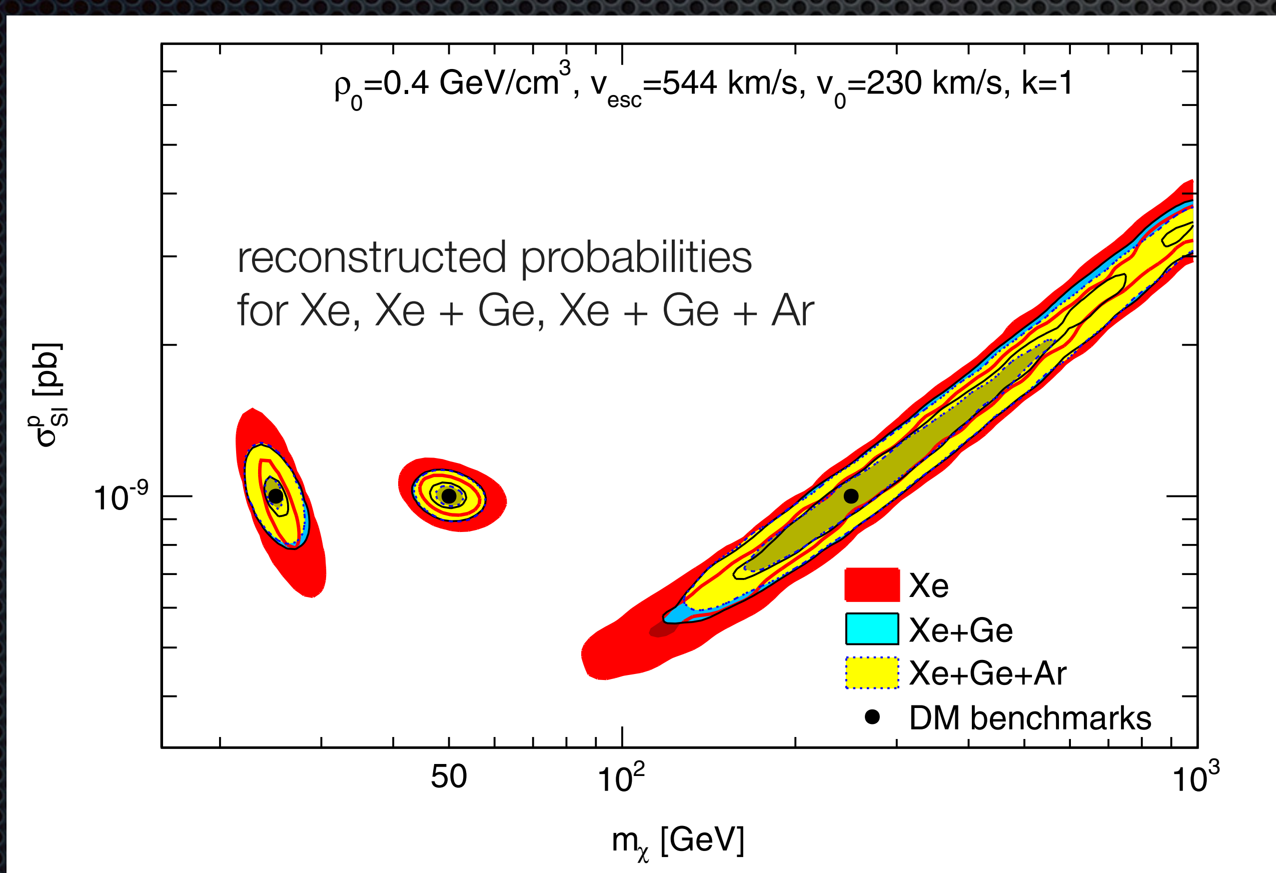


What can we learn about the dark matter should we find it?

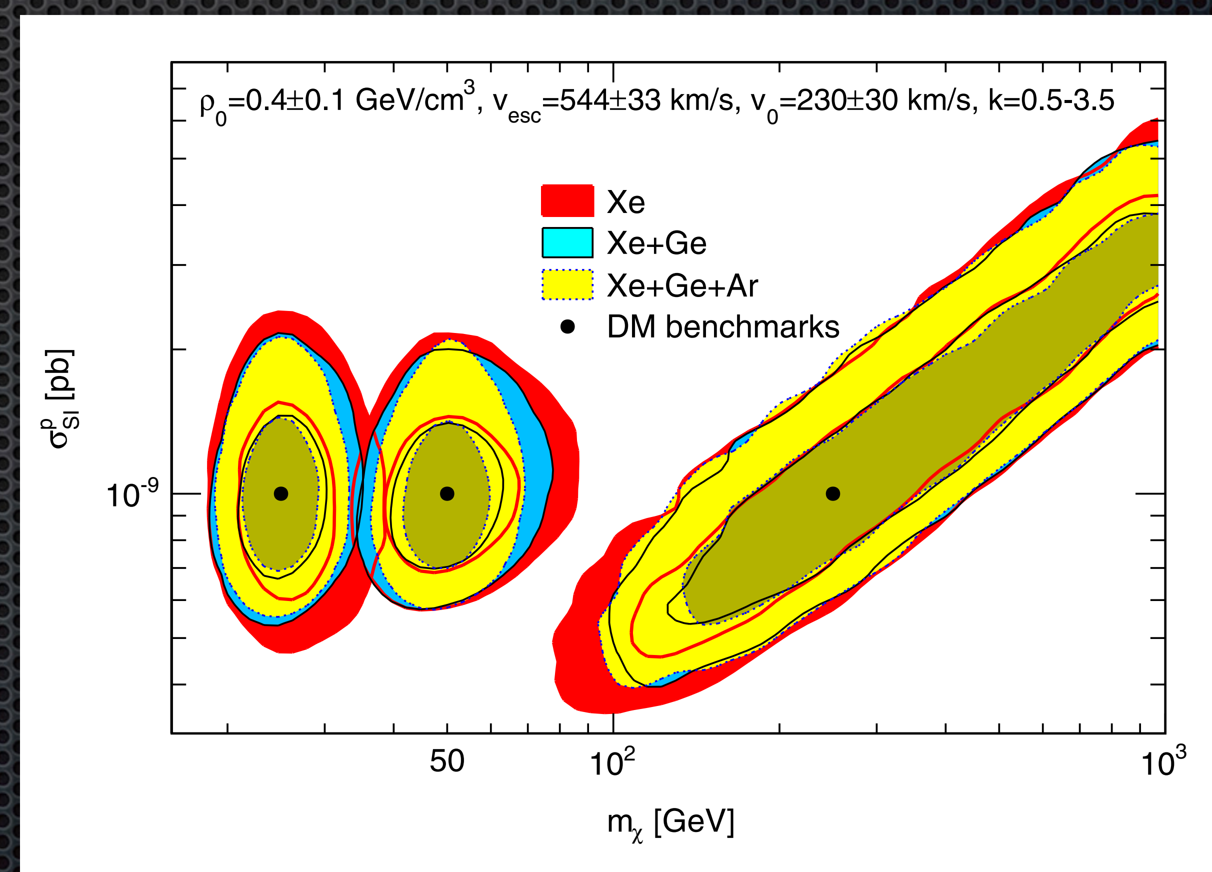
- Different targets are sensitive to different directions in the m_χ- σ_{SI} plane

Xe: 2.0 t x yr, E_{th} =10 keV
Ge: 2.2 t x yr, E_{th} =10 keV
Ar: 6.4 t x yr, E_{th} =30 keV

fixed galactic model



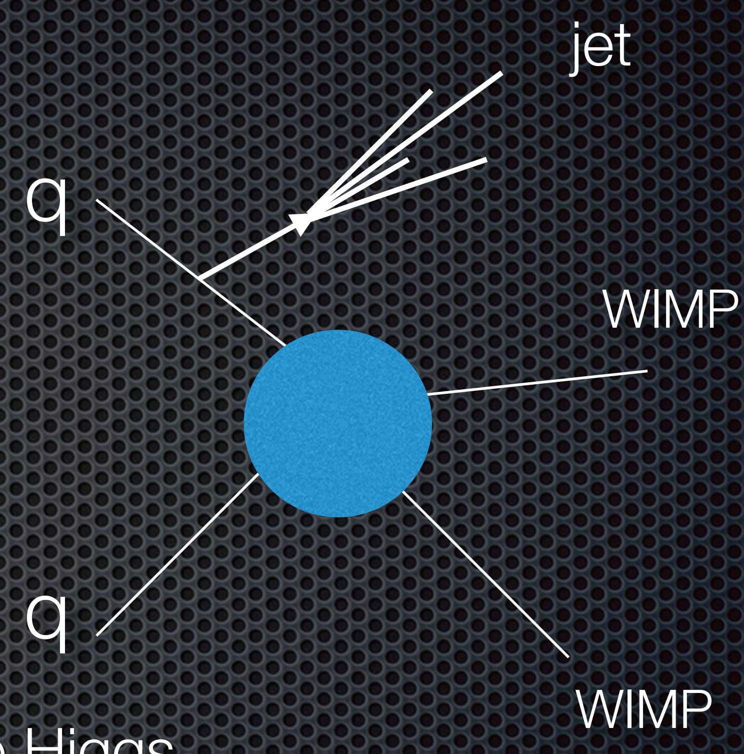
including galactic uncertainties



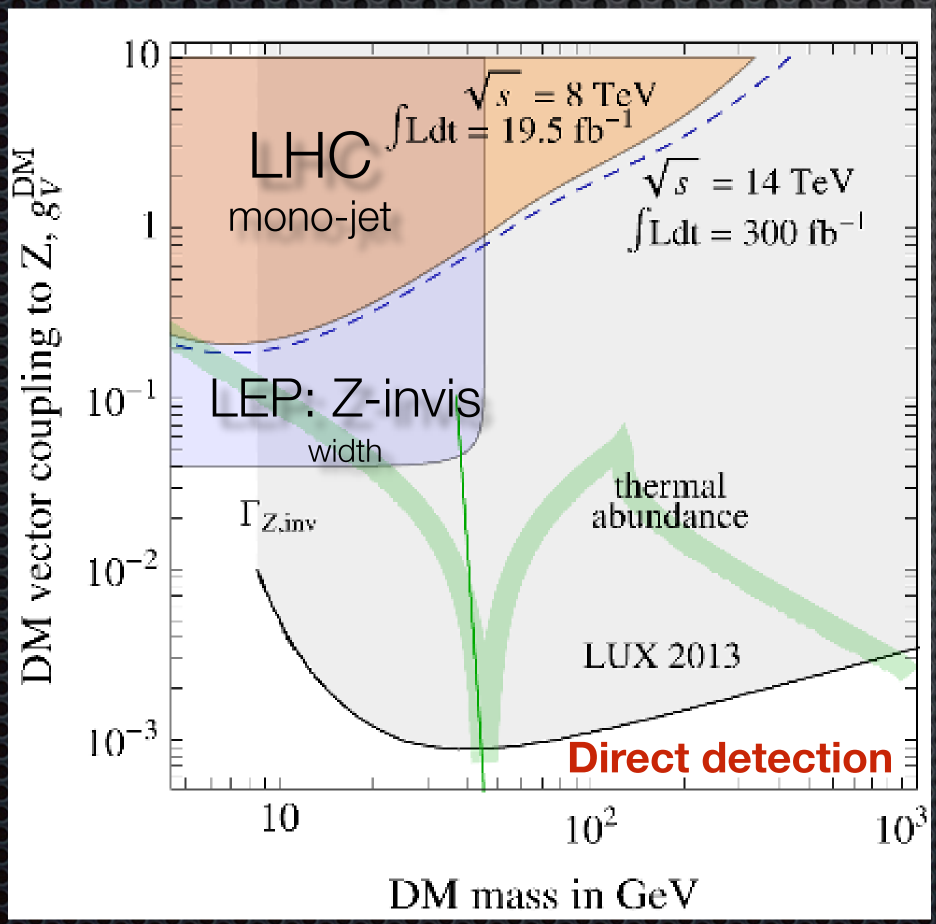
M. Pato, LB, G. Bertone, R. Ruiz de Austri, L. E. Strigari and R. Trotta Phys. Rev. D 83, 2011

Input from accelerators

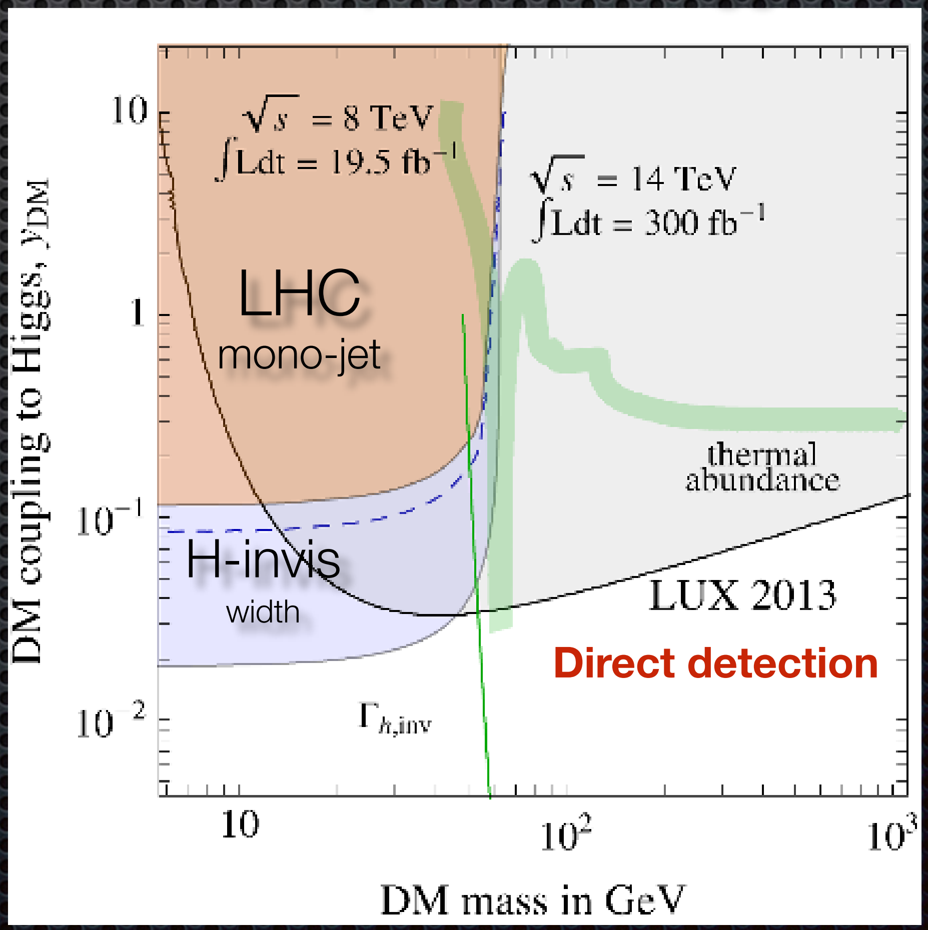
- WIMPs produced at colliders will leave the detector unnoticed
- If other particles (jets) are produced along with a pair of WIMPs, large amounts of missing transverse energy can be observed
- Example: dark matter that couples to SM particles (Z and Higgs)

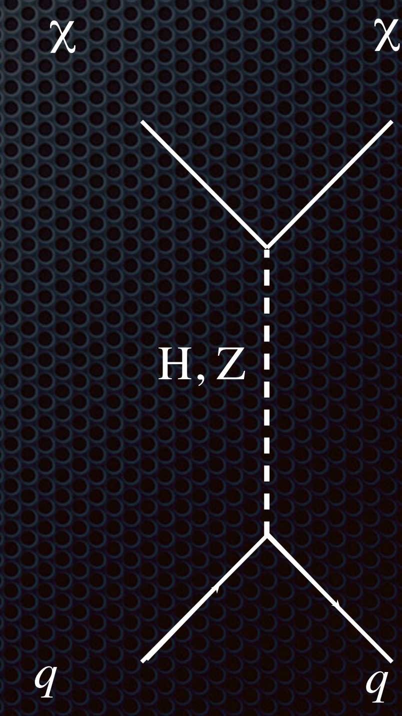


DM couples to the Z



DM couples to the Higgs

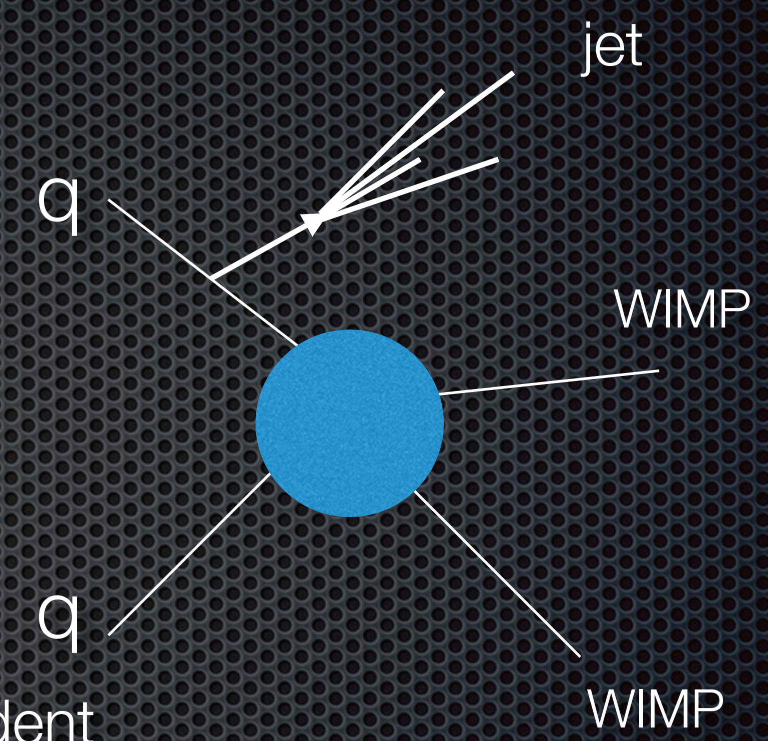


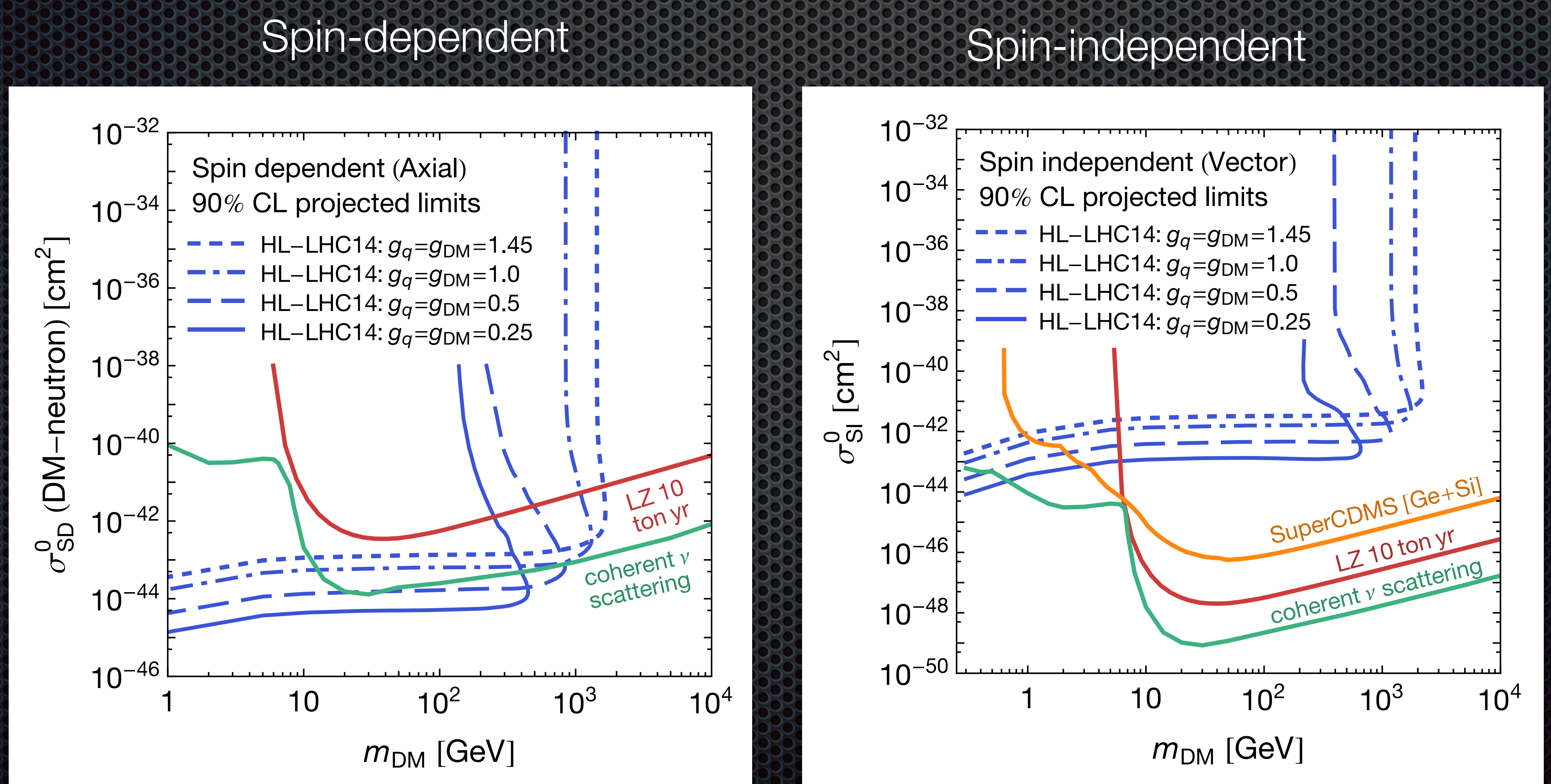


De Simone, Giudice, Strumia, JHEP 06, 2014

Input from 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
- Example: minimal simplified dark matter model (m_{DM}, M_{med}, g_q, g_{DM})



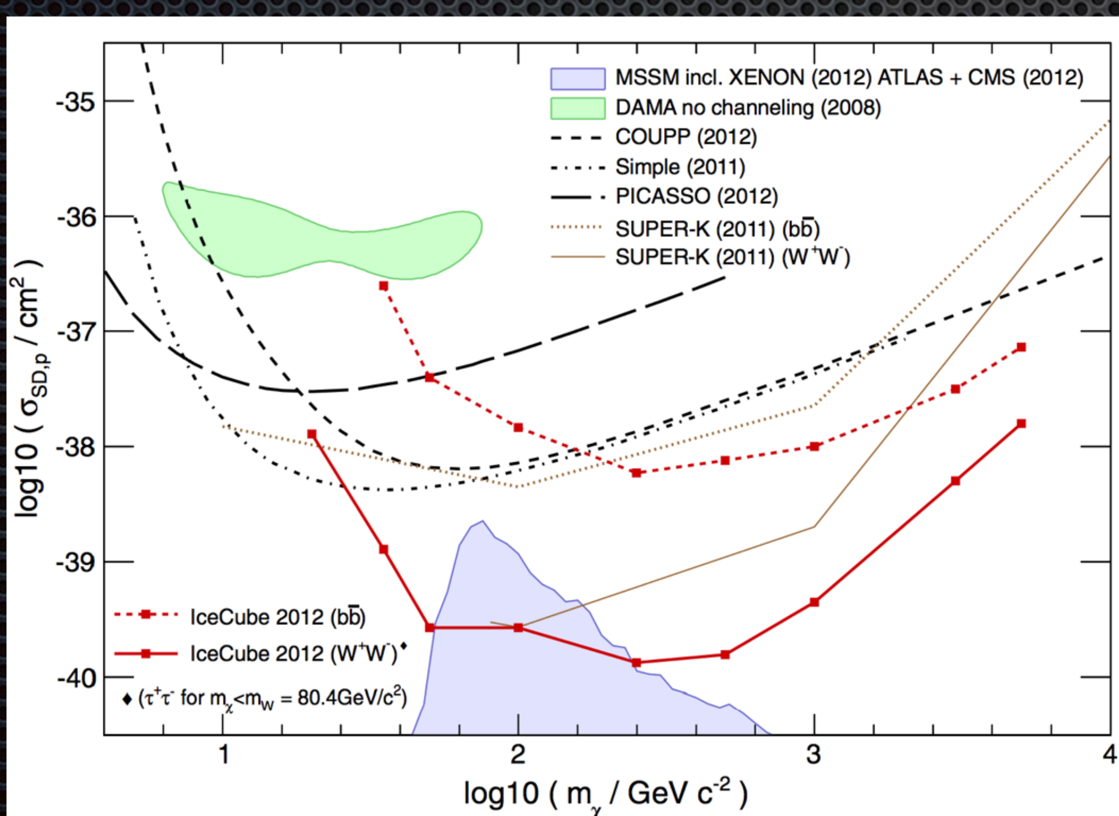


S. A. Malik et al., arXiv:1409.4075

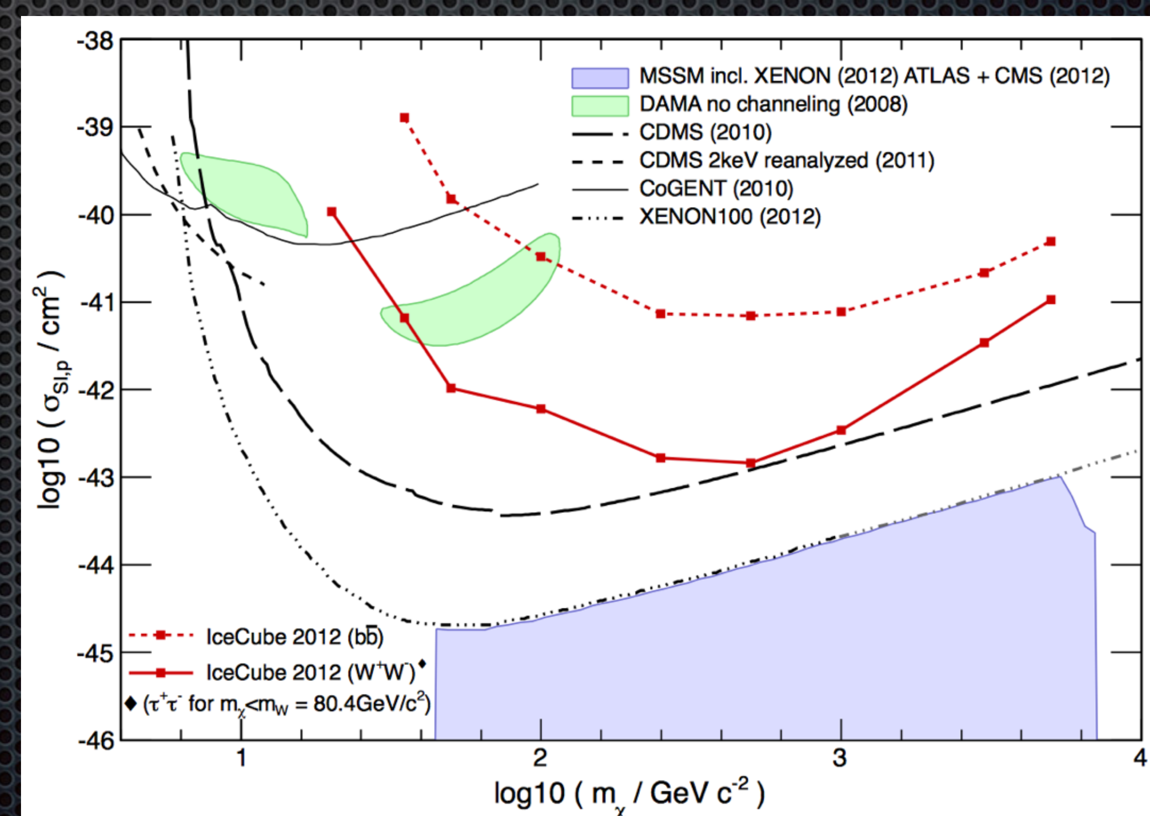
Indirect searches: comparison with direct detection

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

IceCube: WIMP-p; spin-dependent



IceCube: WIMP-p; spin-independent



IceCube collab. PRL 110, 2013 (79 string)

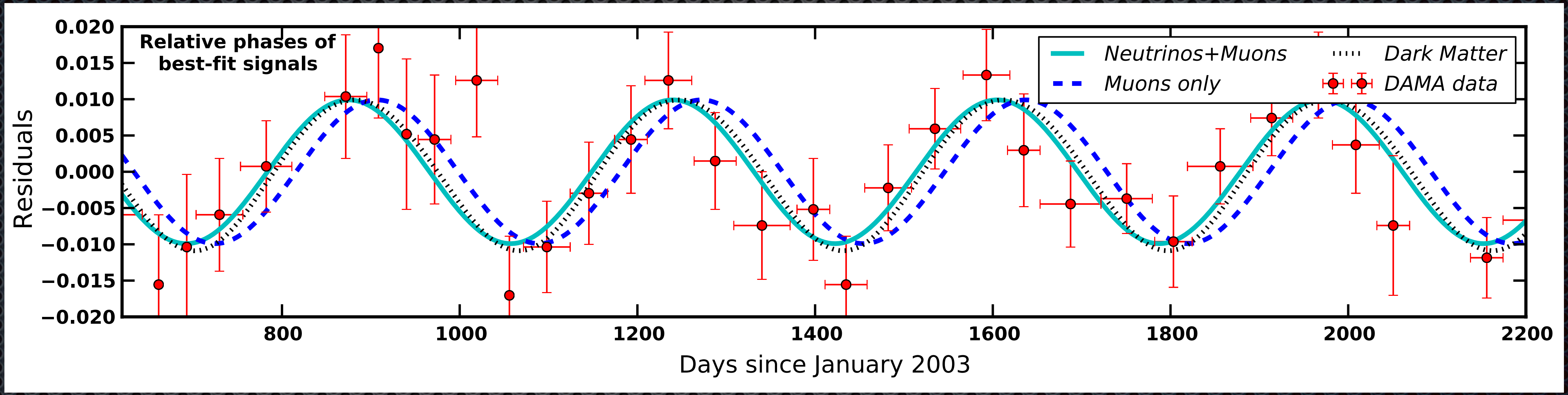
Summary

- Cold dark matter is still a viable paradigm explaining cosmological & astrophysical observations
- It could be made of axions, and/or WIMPs (+ many other options, some less predictive and/or more difficult to test in the laboratory)
- So far, no convincing detection of a dark matter particle
- In the best of all worlds: multiple discoveries (direct detection, the LHC, indirect detection) & constraints of the dark matter properties
- If no discovery: “ultimate” detectors might at least be able to disprove the axion & WIMP hypotheses (still valuable information)
- However, we should be open for new theoretical ideas & new experiments!

The End

What might be the origin of the DAMA signal?

- A combination of solar ^{8}B neutrino- and atmospheric muon-induced neutrons?
- *Combined phase of muon and neutrino components*: good fit to the data*
- *However, the amplitudes seem many orders of magnitude too low*



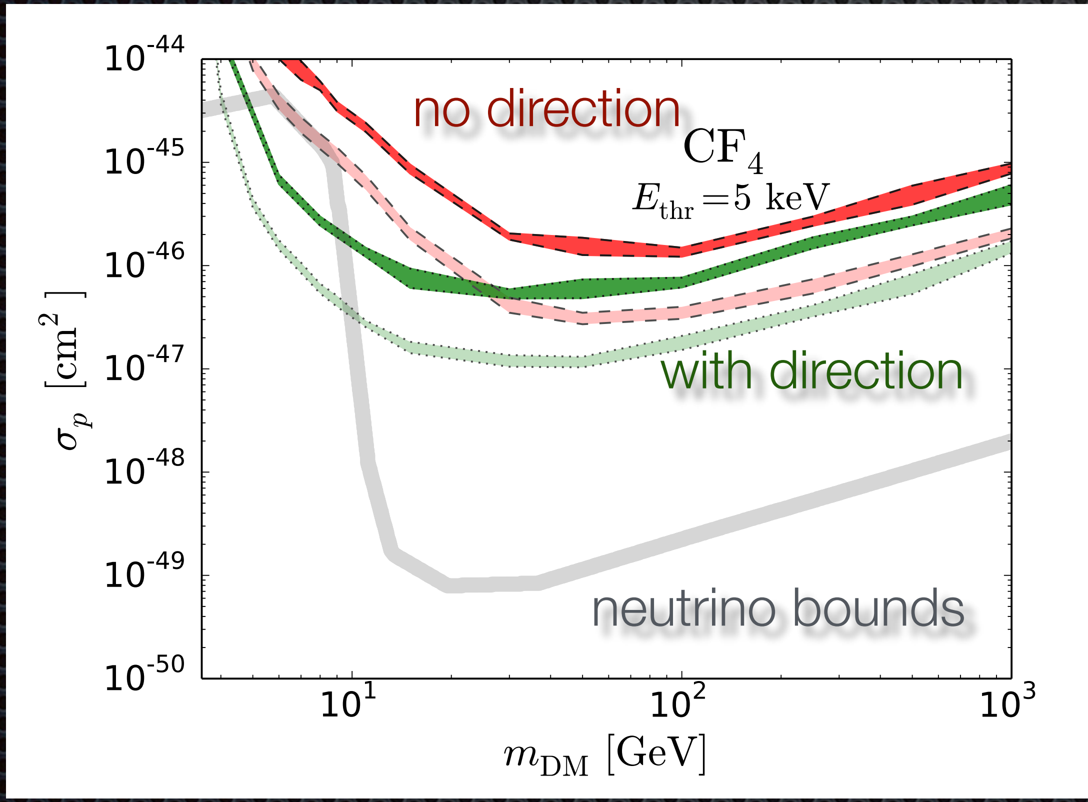
J. Davis, PRL 113, 081302 (2014)

*Muons: flux correlated with T of atmosphere; period is ok but phase is 30 d too late
*Neutrinos: flux varies with the Sun-Earth distance; period is ok but phase peaks in early Jan

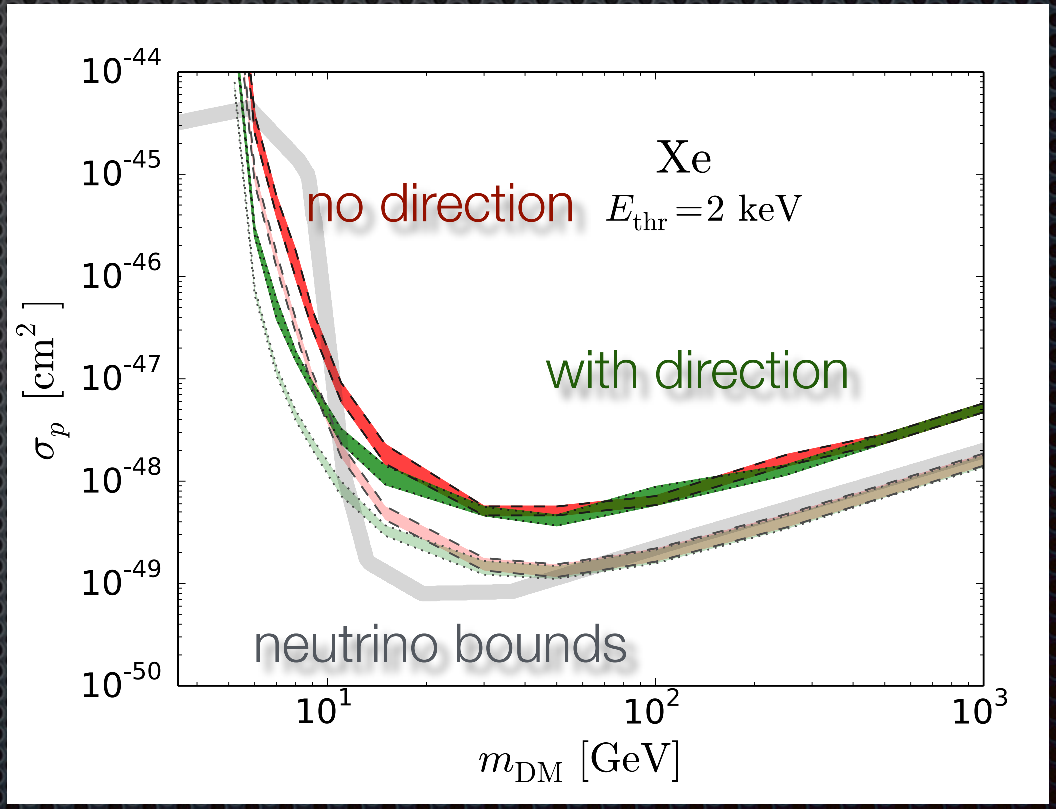
Will directional information help?

- 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

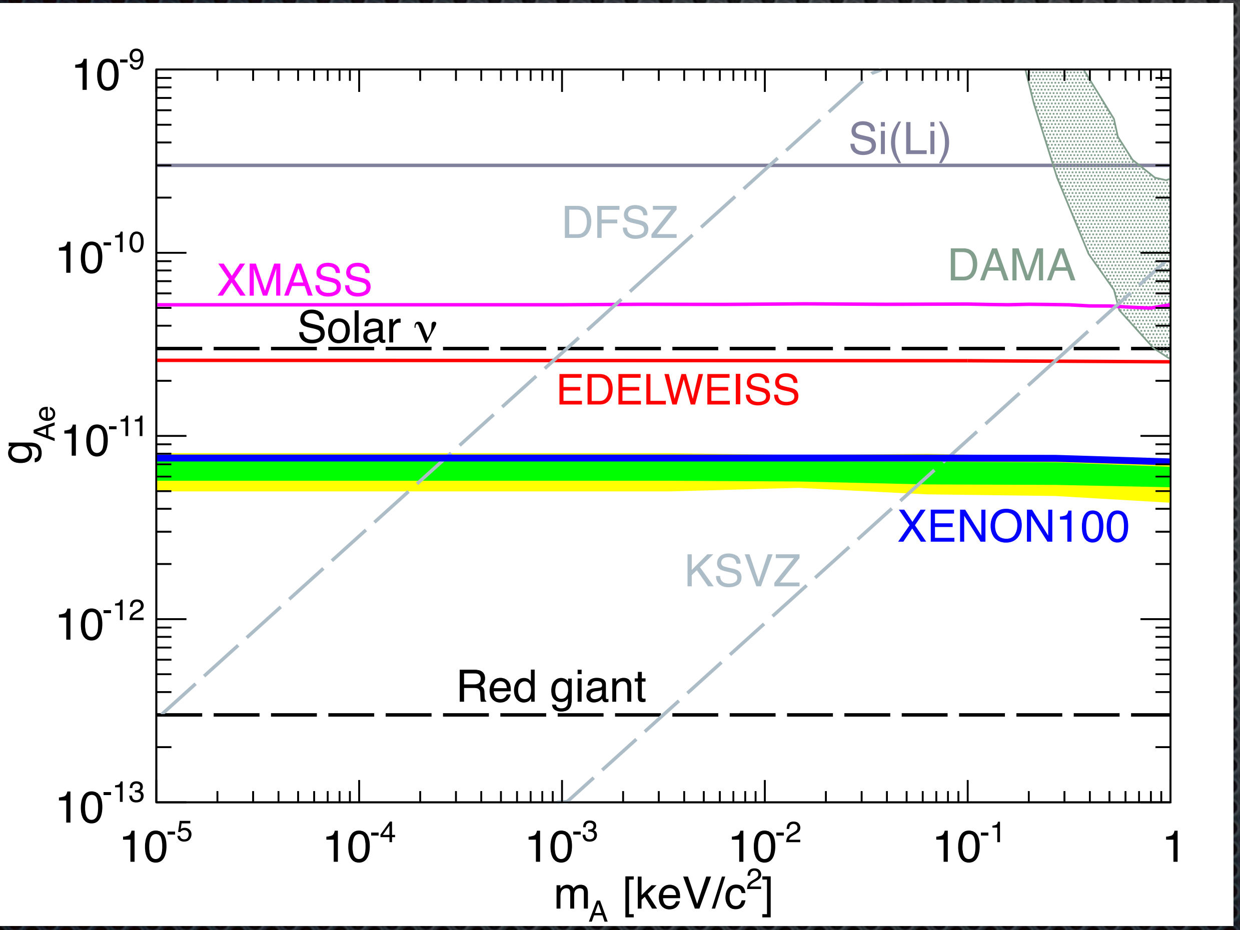


P. Grothaus, M. Fairbairn, J. Monroe, arXiv: 1406.5047

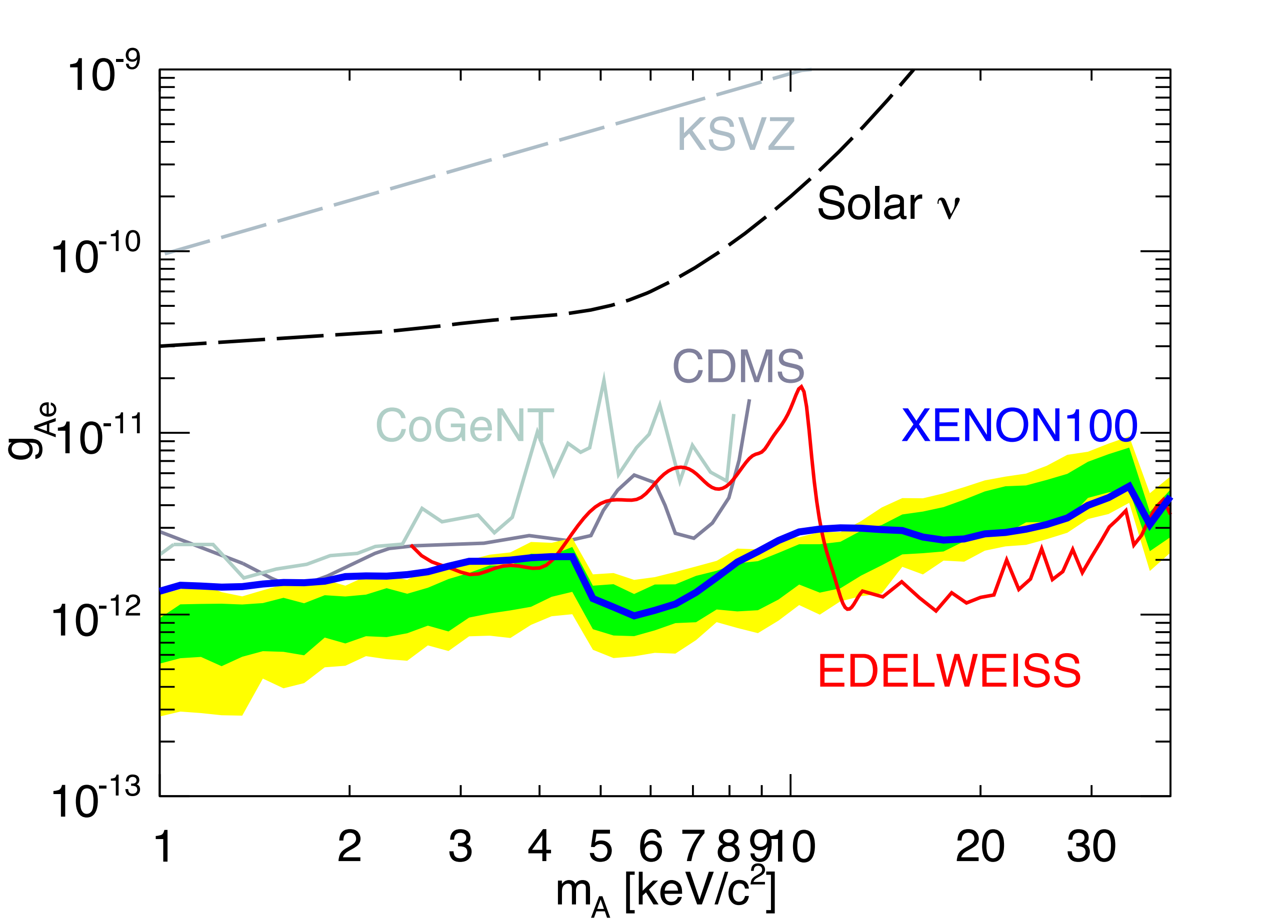
Direct-detection experiments search for solar axions & ALPs

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

Solar axions



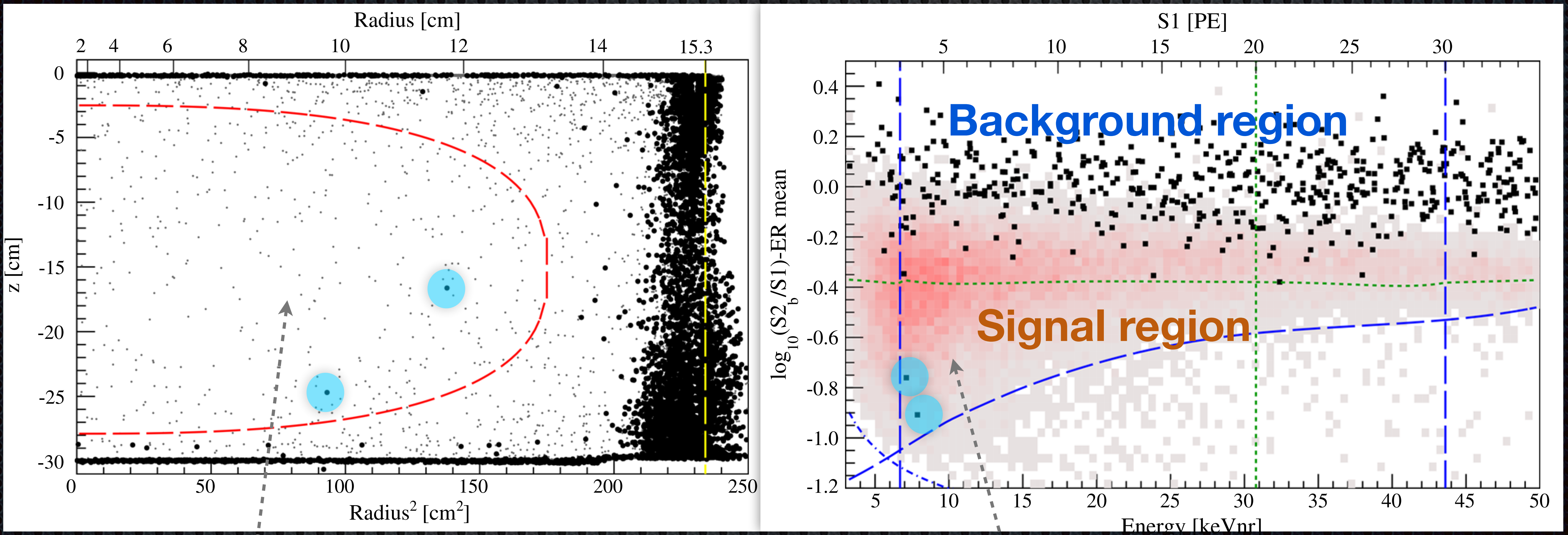
Galactic ALPs



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

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



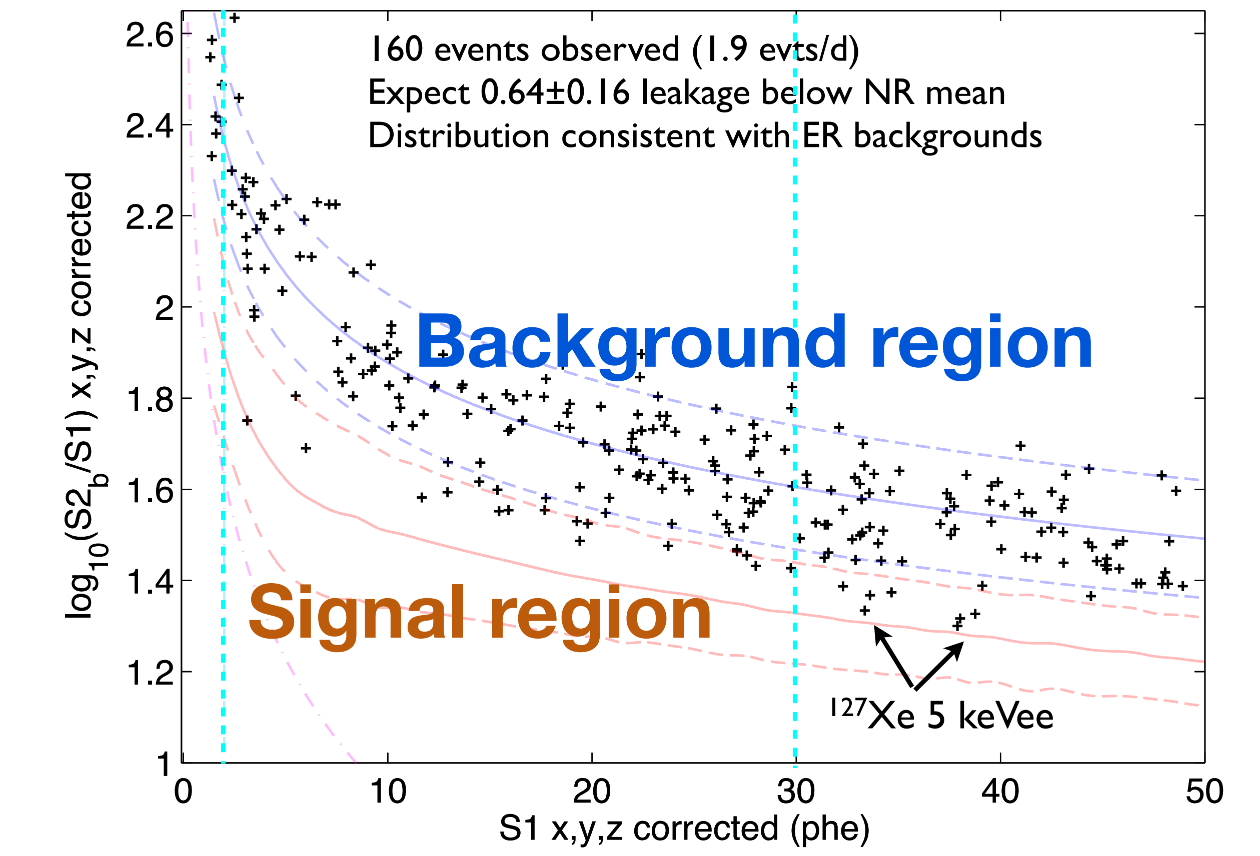
Phys. Rev. Lett. 109 (2012)

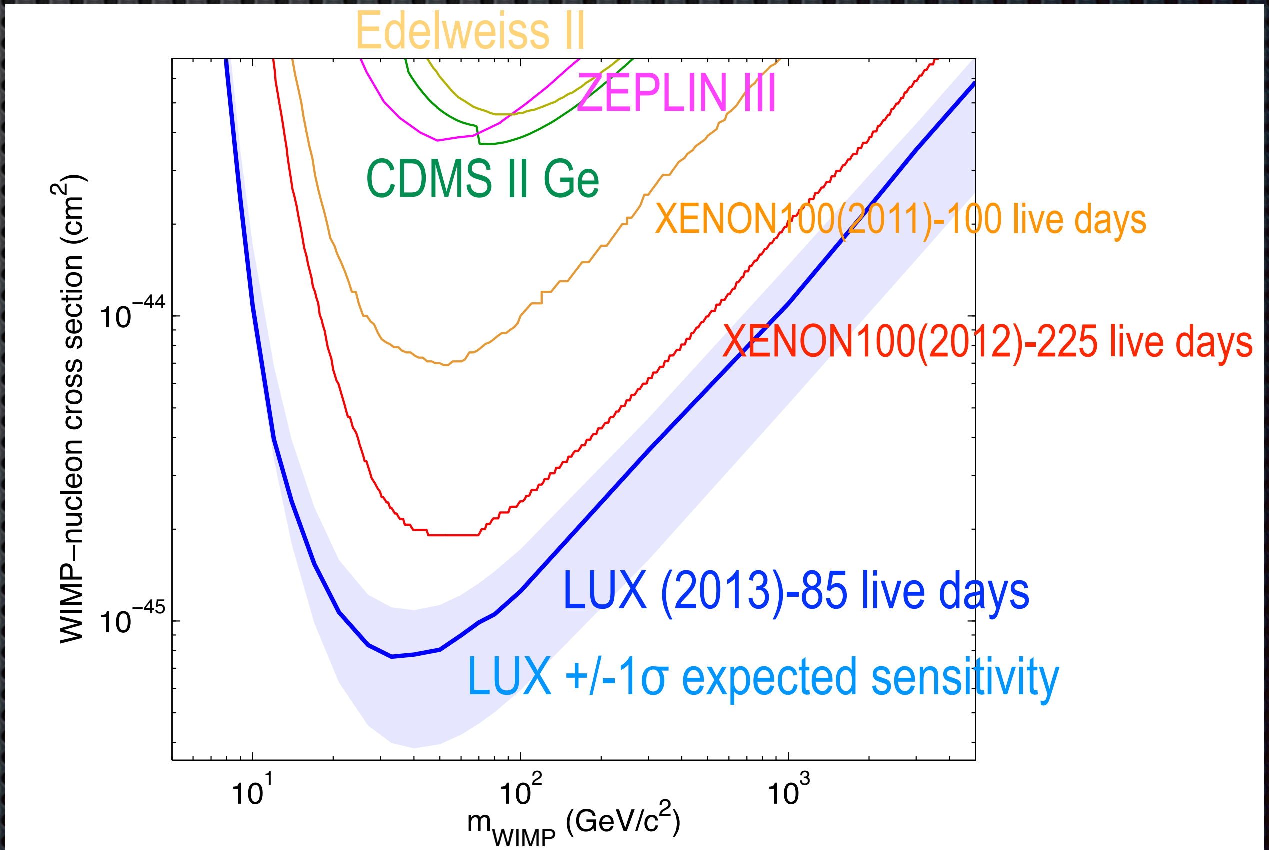
Fiducial mass region:
34 kg of liquid xenon
406 events in total

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



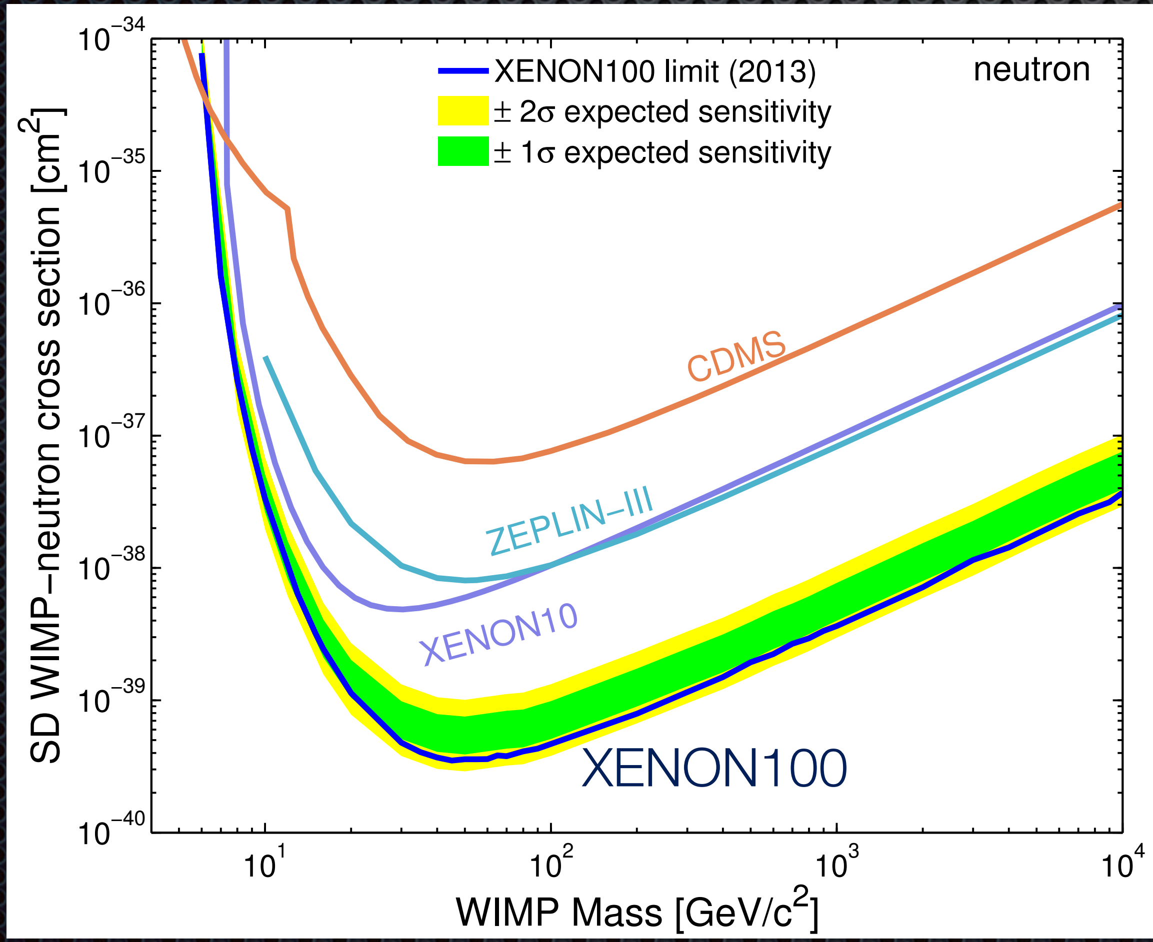


Accepted in PRL, arXix: 1310.8214

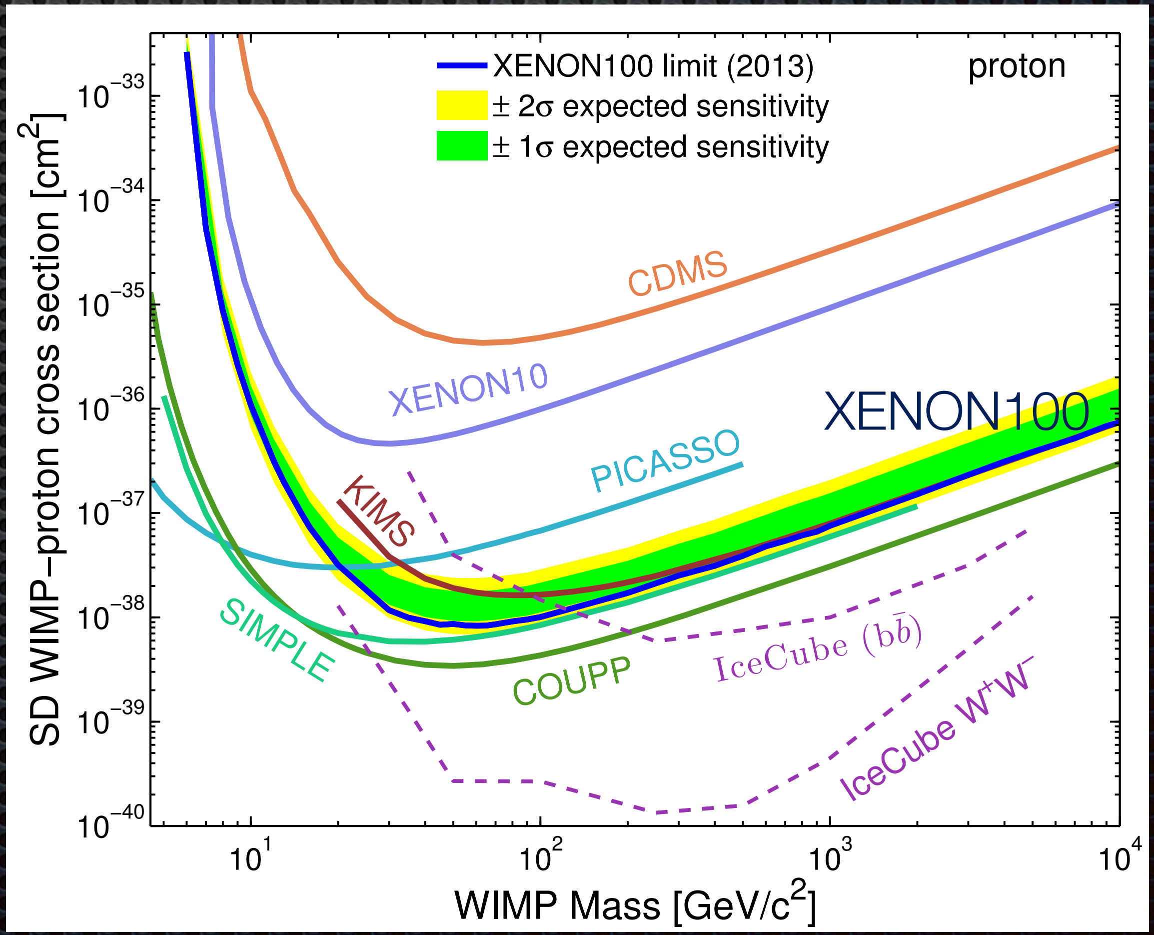
Spin-dependent results

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

WIMP-neutron coupling



WIMP-proton coupling

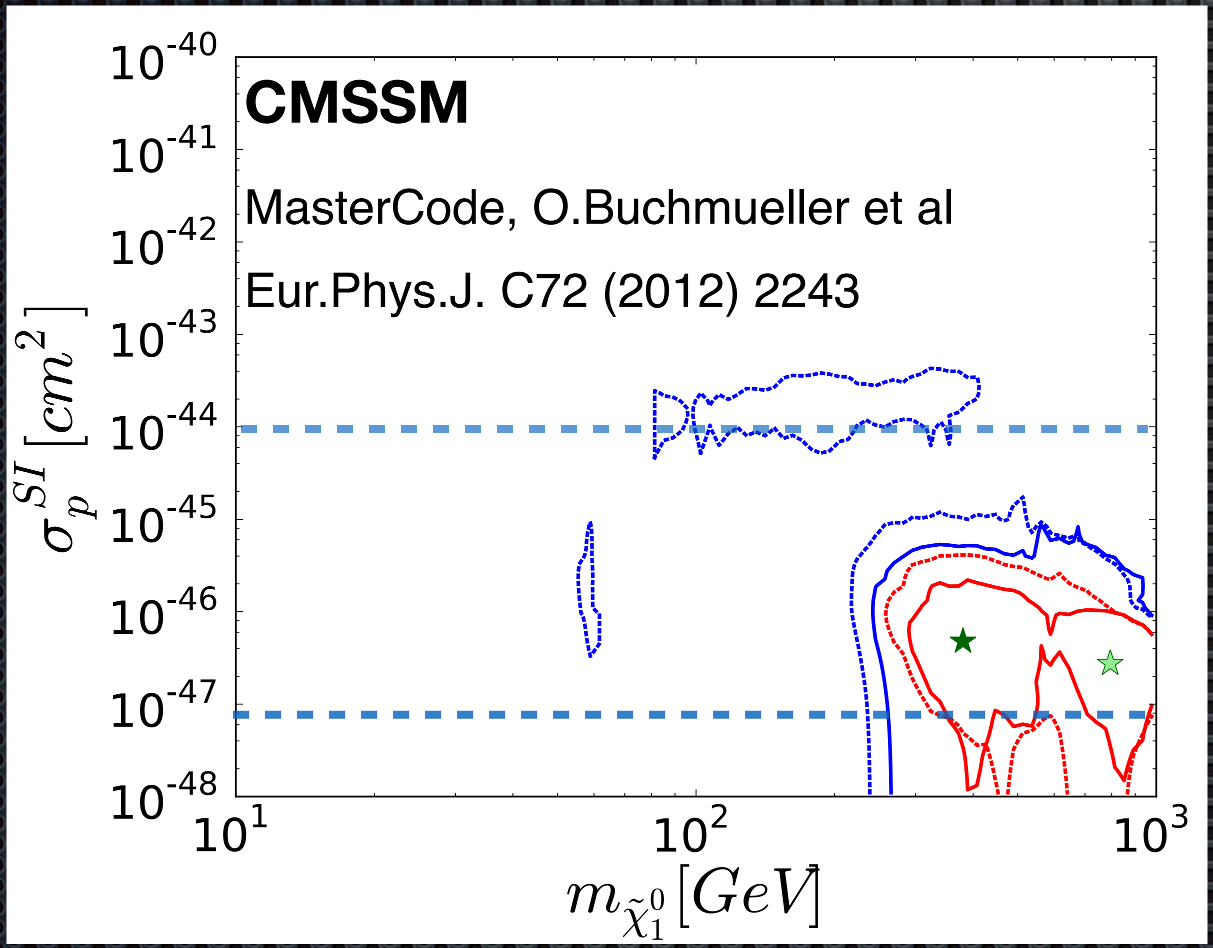


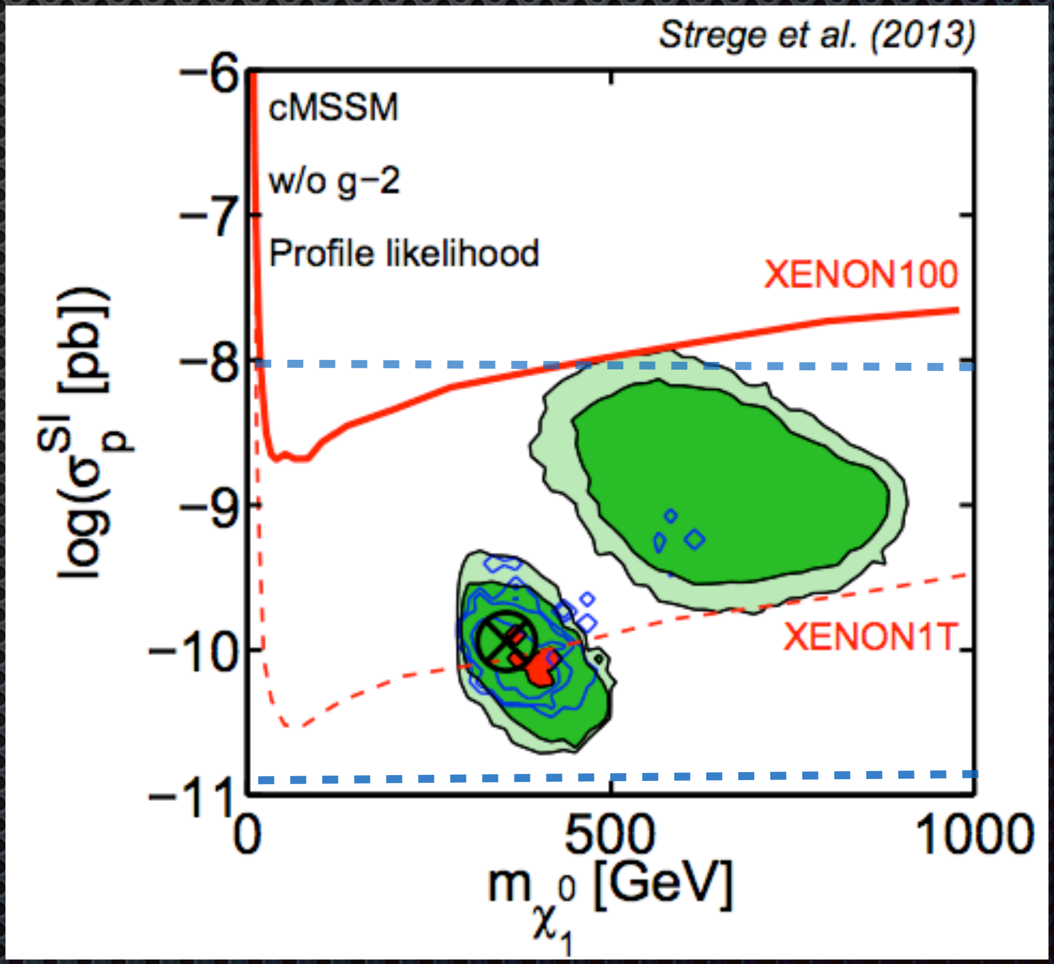
Phys. Rev. Lett. 111 (2013)

Particle physics: SUSY predictions

- Scattering cross sections on nucleons down to < 10^{-49} cm^2(10^{-13} pb)

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





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