Dark matter detection in the Milky Way

Laura Baudis
University of Zurich

Physics Colloquium
Princeton University, October 2015

Some (very brief) history

- **1922:** J.C. Kapteyn coined the name *'dark matter'*, in studies of the stellar motion in our galaxy *(he found that no dark matter is needed in the solar neighbourhood)*

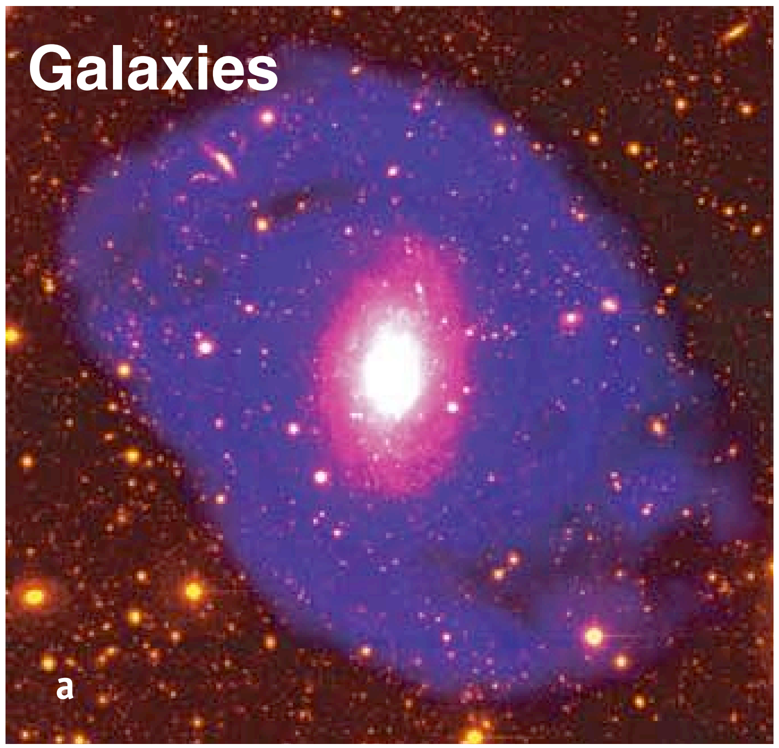
- **1932:** J. Oort suggested that there would be more dark than visible matter in the vicinity of the Sun *(later the result turned out to be wrong)*

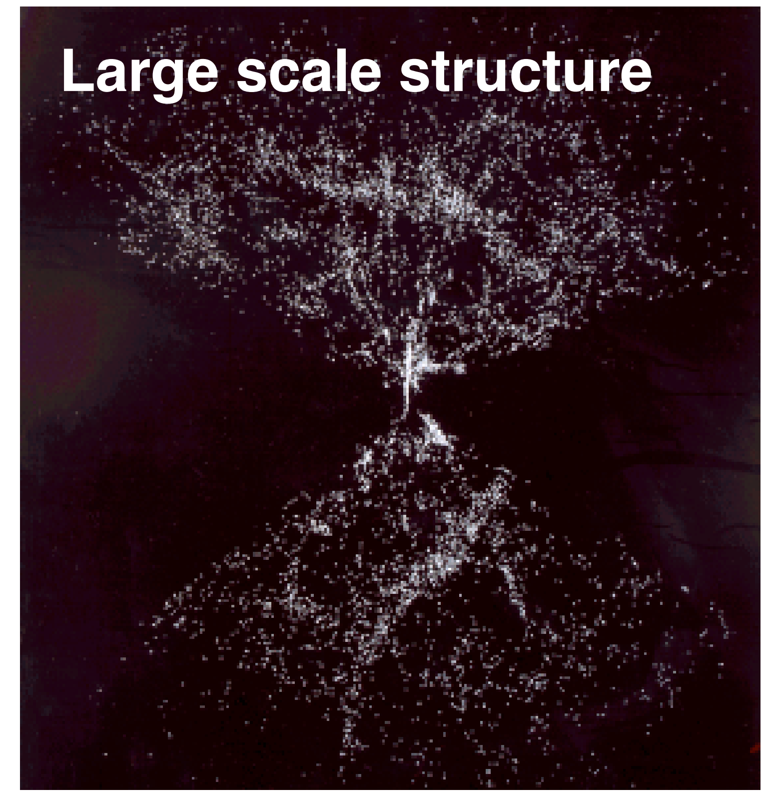
- **1933: F. Zwicky found *'dunkle Materie'* in the Coma cluster *(the redshift of galaxies were much larger than the escape velocity due to luminous matter alone)***

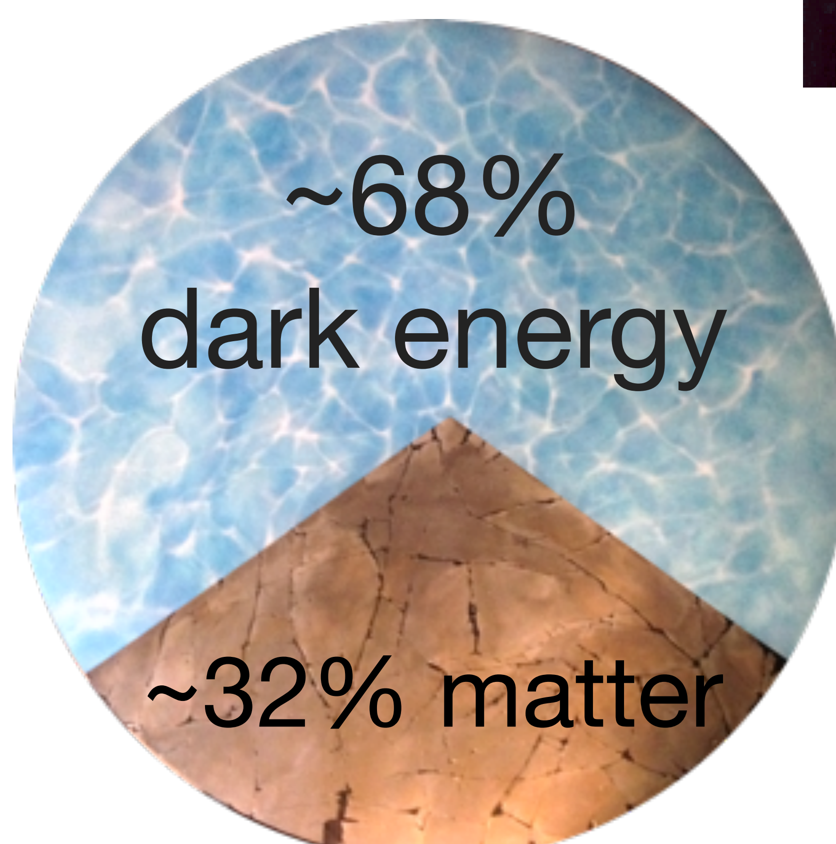
- **1970s:** V.C. Rubin & W. Ford: flat optical rotation curves of spiral galaxies, 1978: Bosma, radio

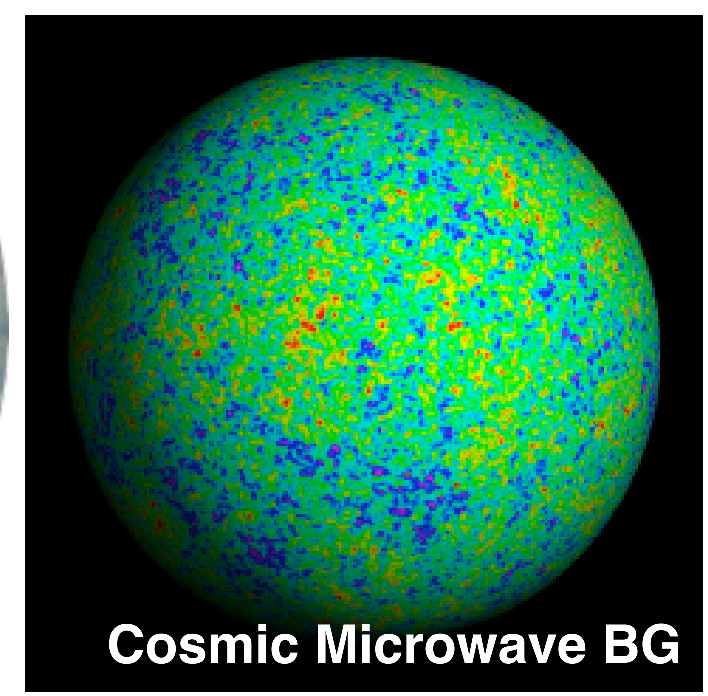
from "Fritz Zwicky, Astrophysiker", Verlag NZZ

Our Universe today: apparently consistent picture from an impressive number of observations









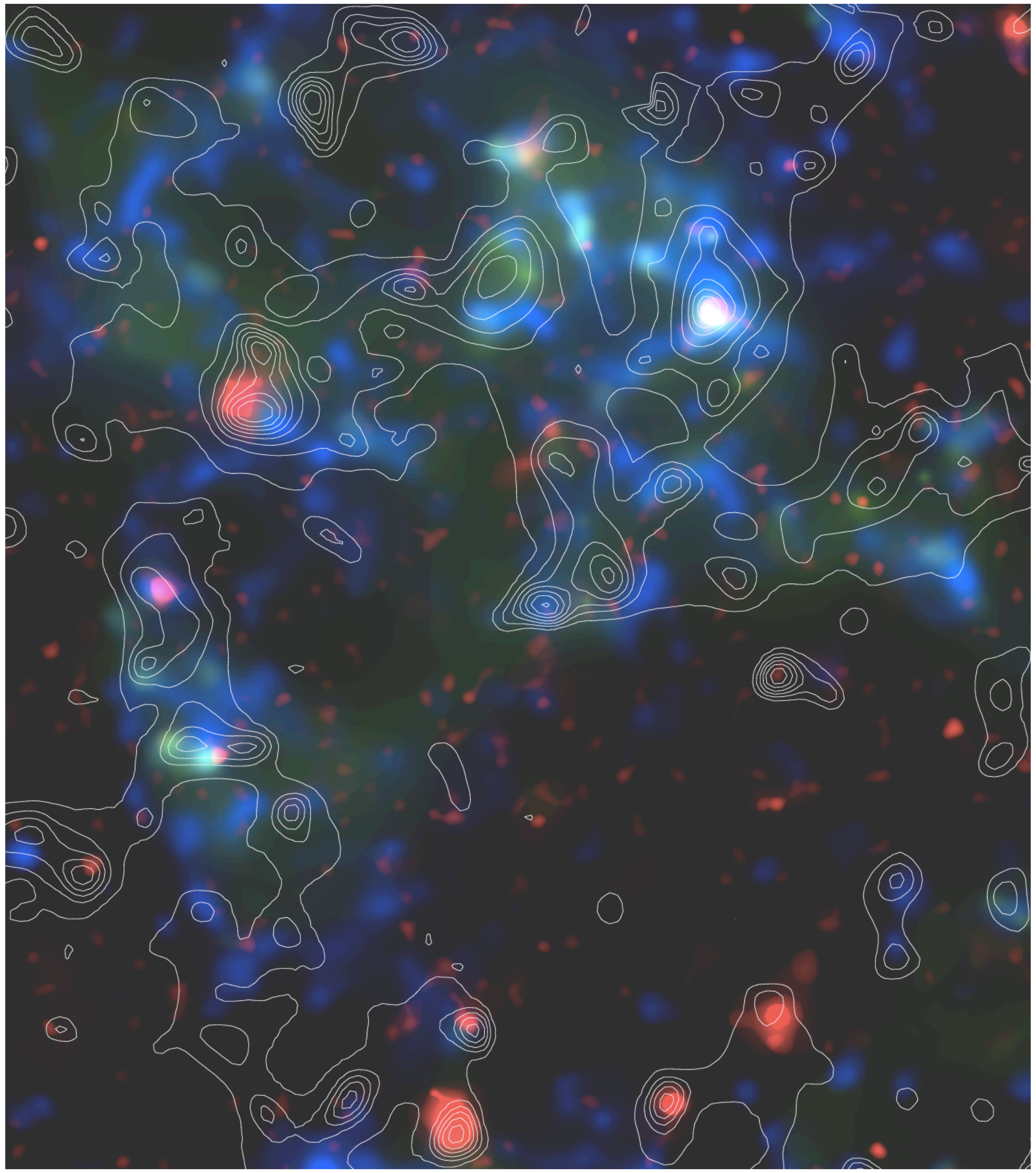
The dark matter puzzle

The dark matter puzzle remains *fundamental*: dark matter leads to the formation of structure and galaxies in our universe

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

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

Large scale distribution of dark matter, probed through gravitational lensing



HST COSMOS survey; Nature 445 (2007), 268

What do we know about the dark matter?

So far, we mostly have “negative” information

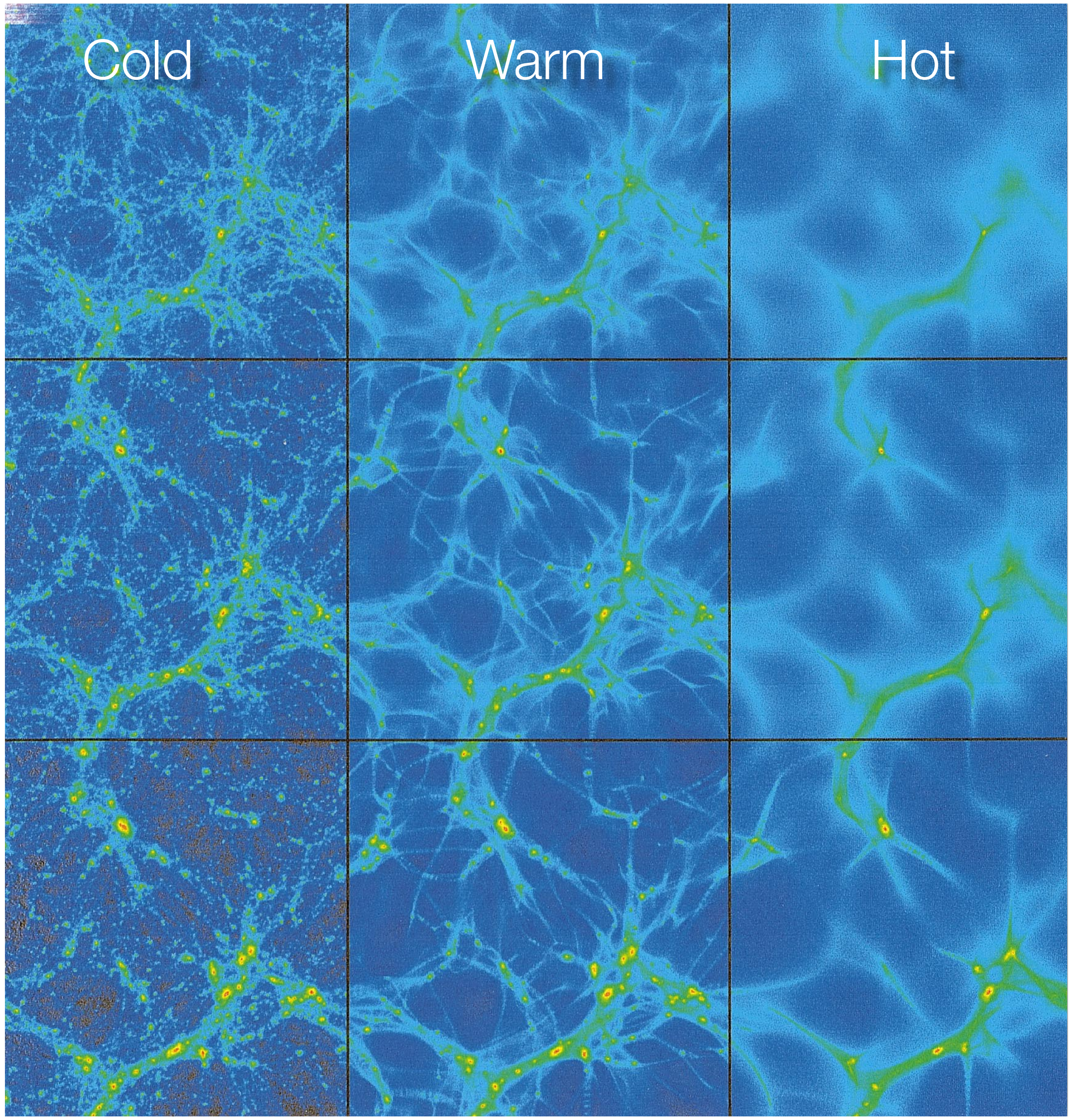
Constraints from astrophysics and searches for new particles:

No colour charge

No electric charge

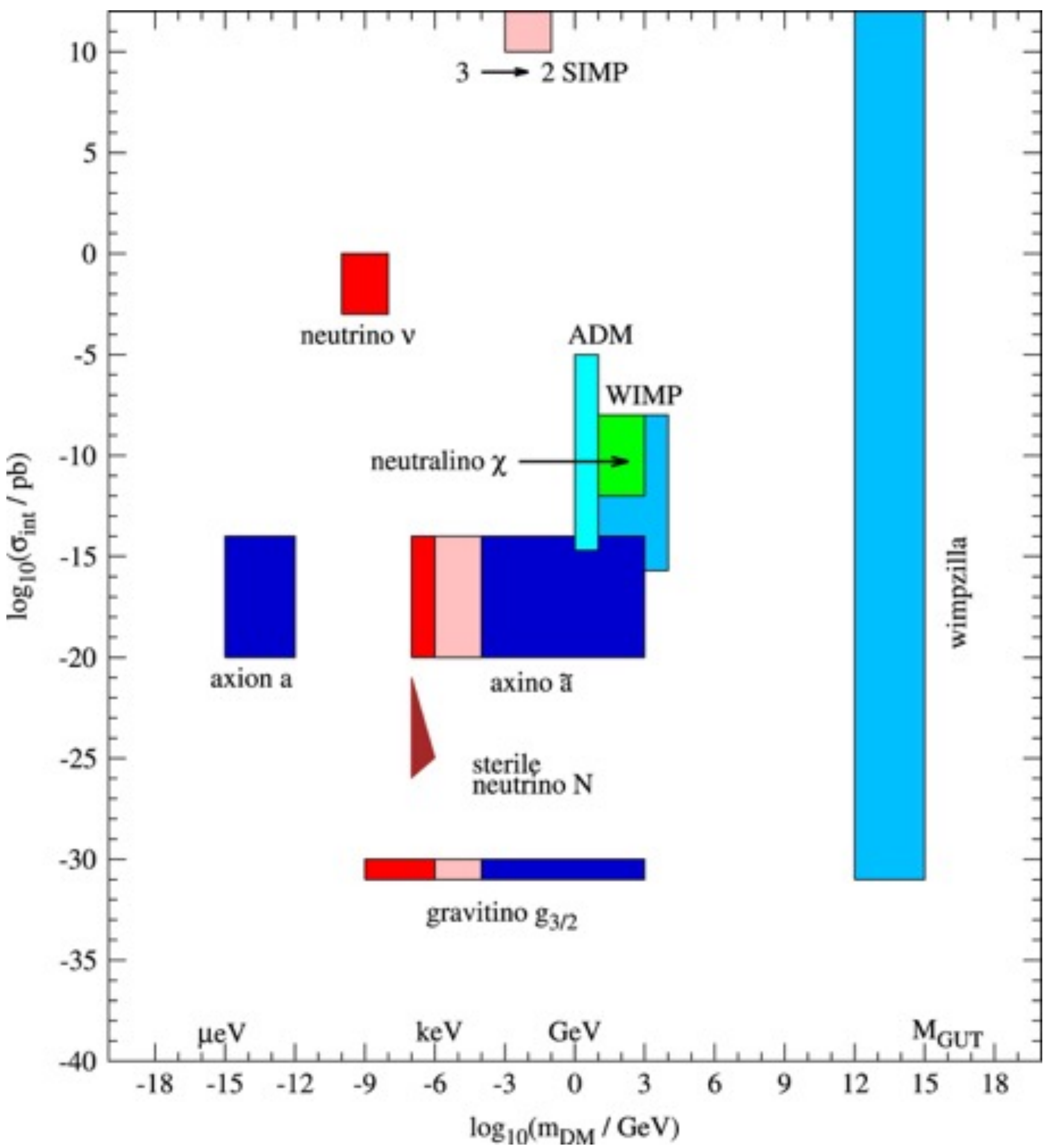
No strong self-interaction

Stable, or very long-lived



Probing dark matter through gravity

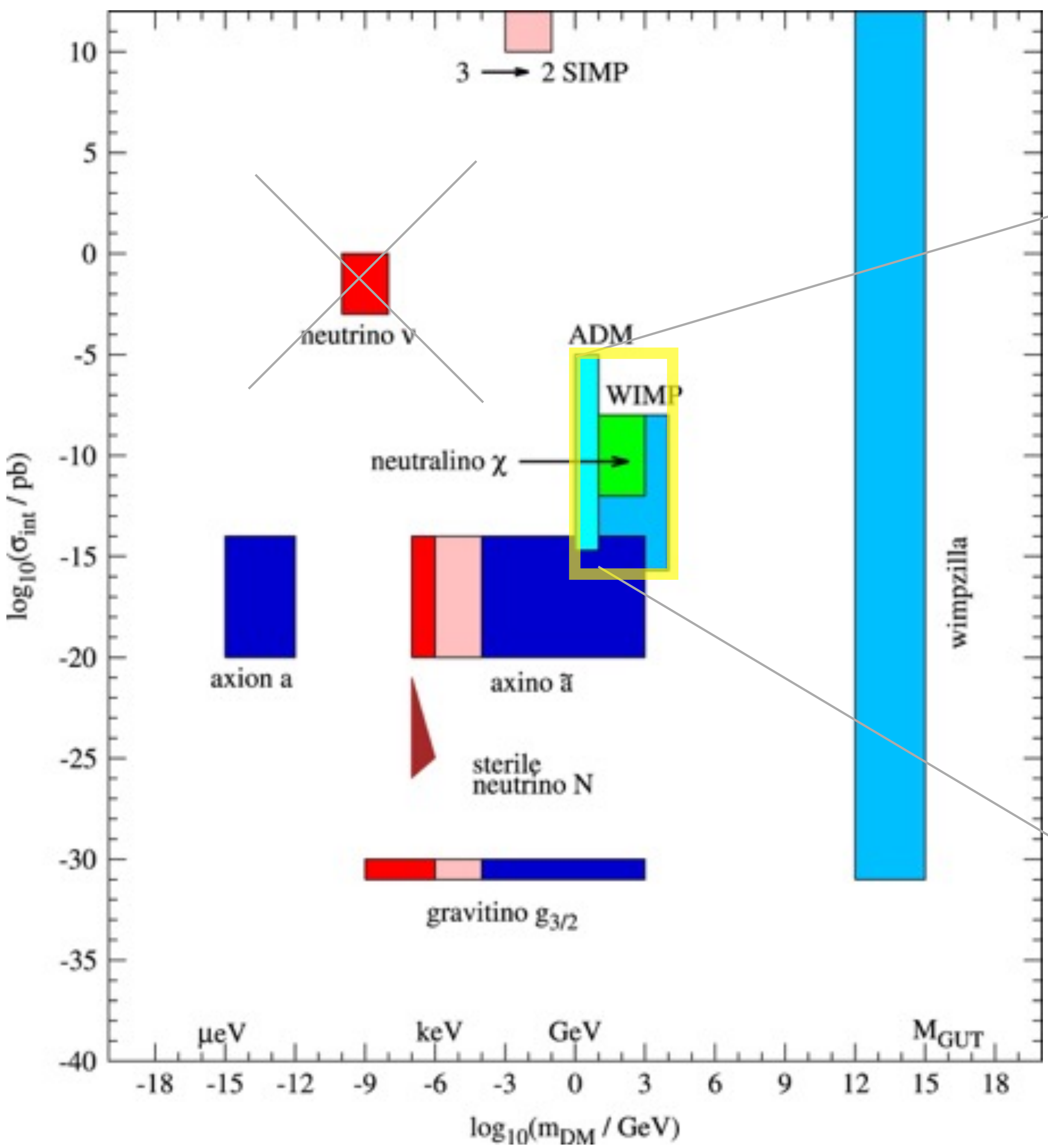
Parameter space for searches



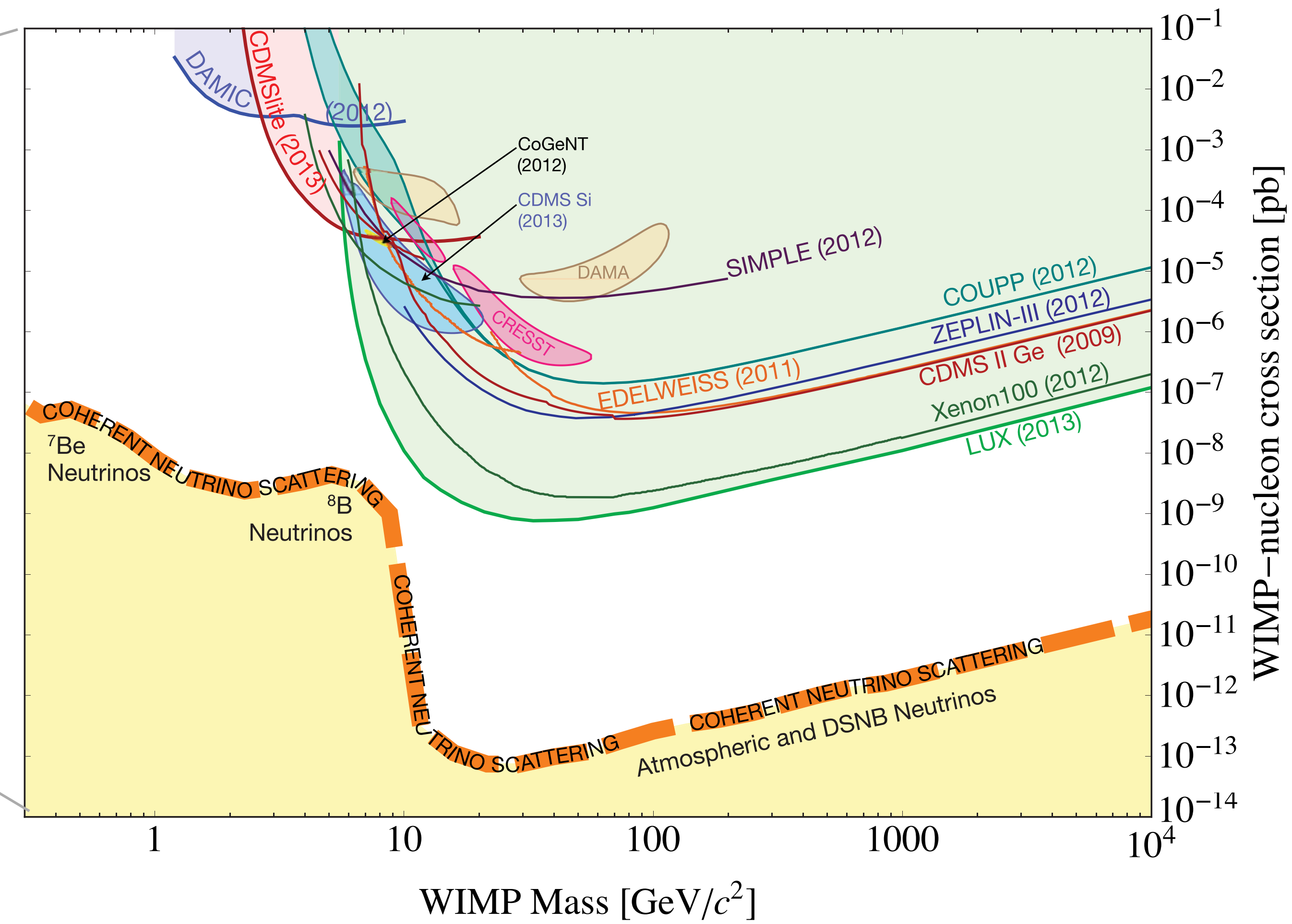
- **Masses & interaction cross sections span an enormous range**
- Most dark matter experiments optimised to search for WIMPs
- However also searches for axions, ALPs, SuperWIMPs, etc

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

Parameter space for searches

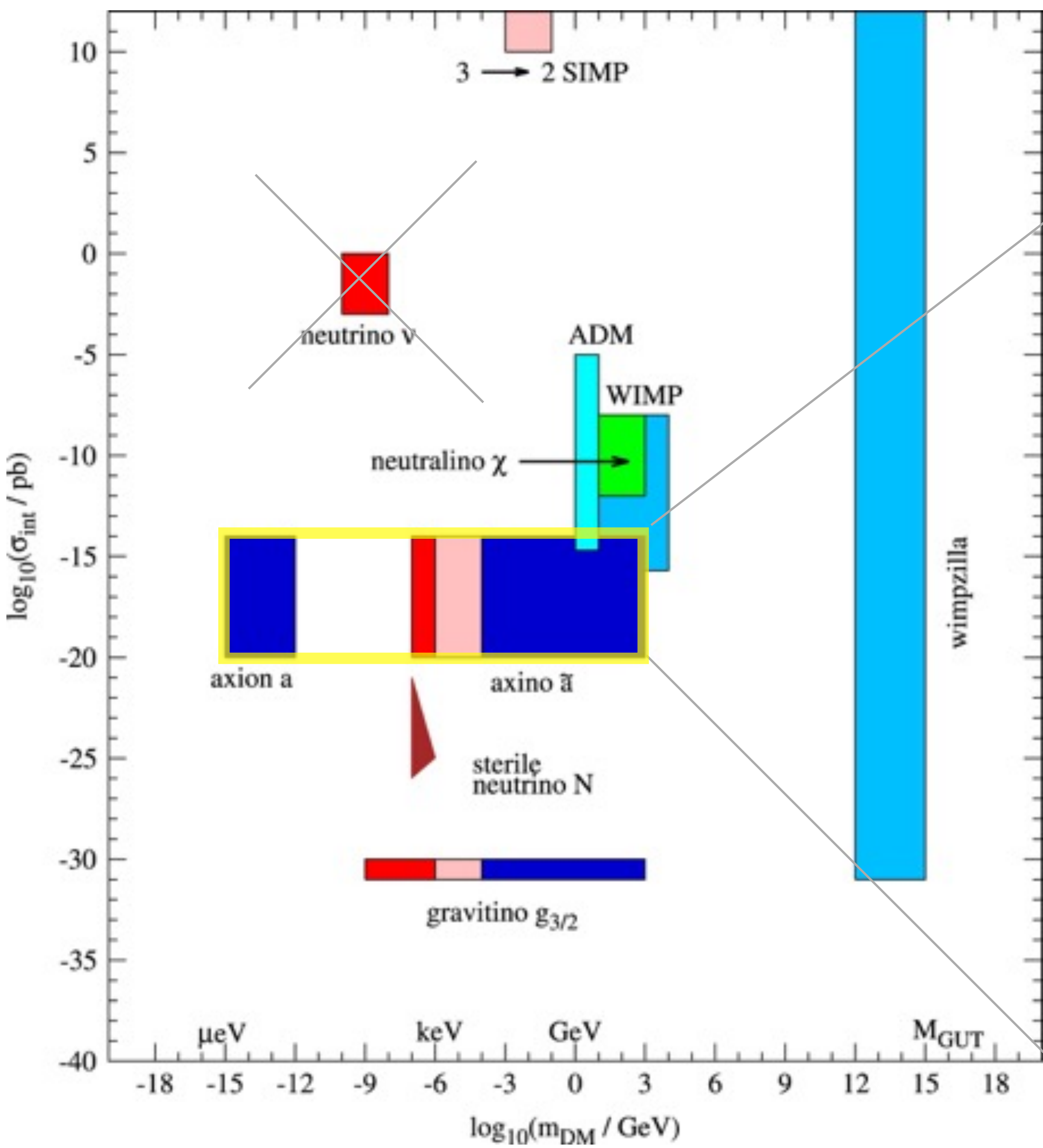


WIMP direct searches



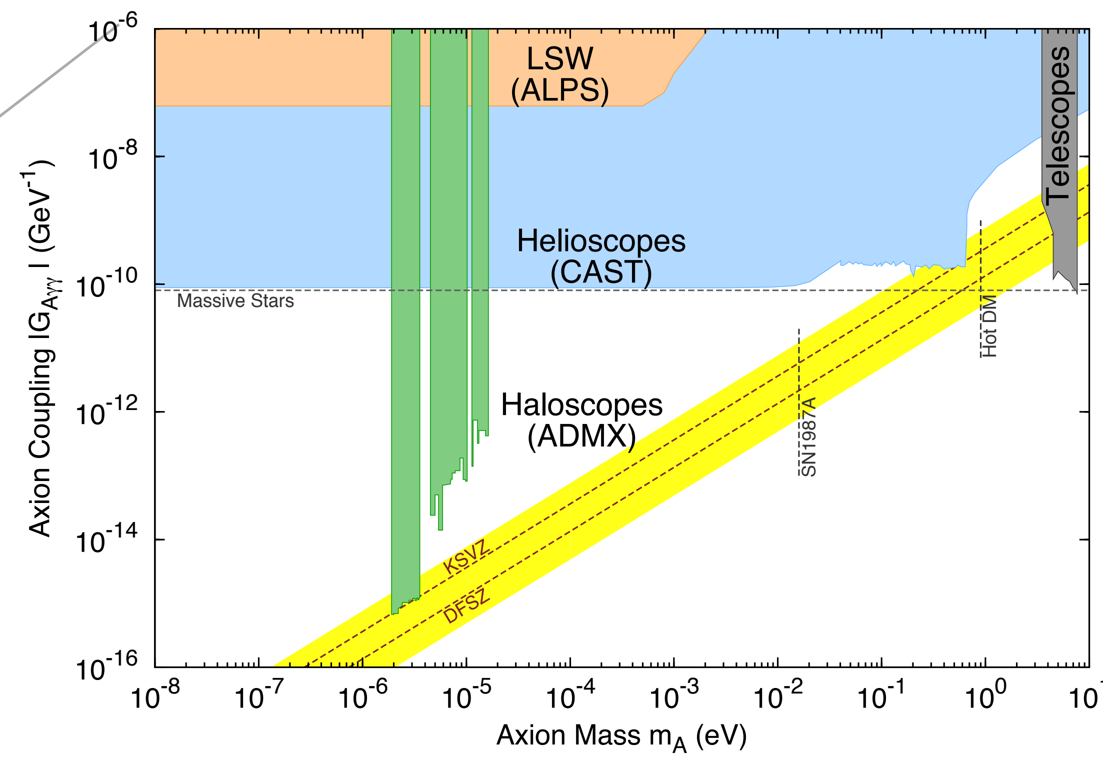
H. Baer et al., Phys. Rept. 555, 2014

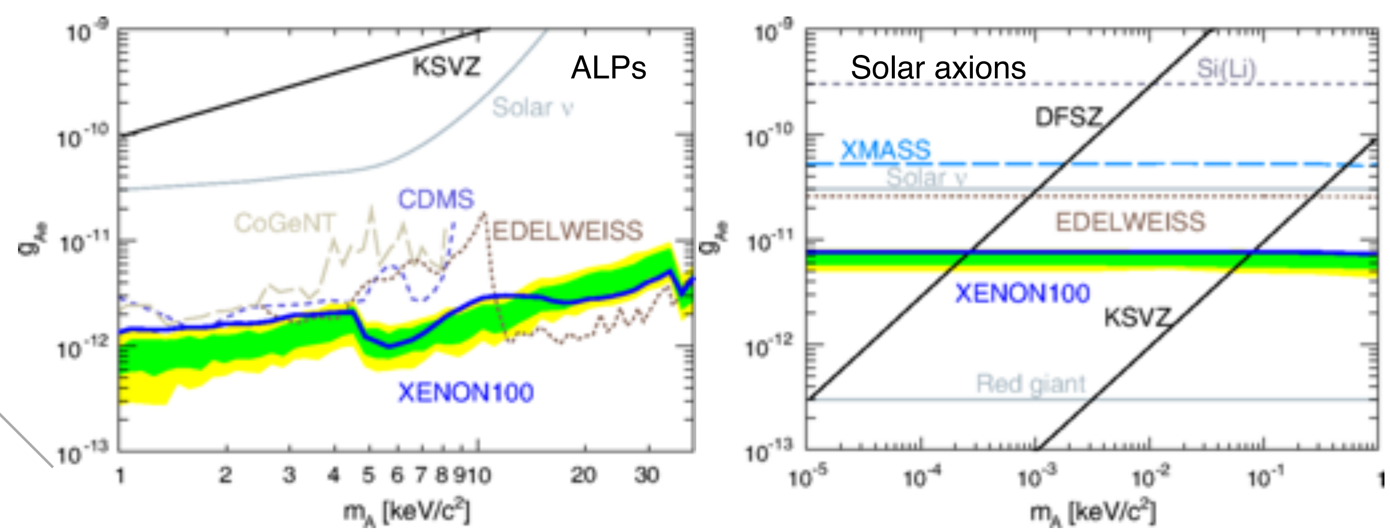
Parameter space for searches



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

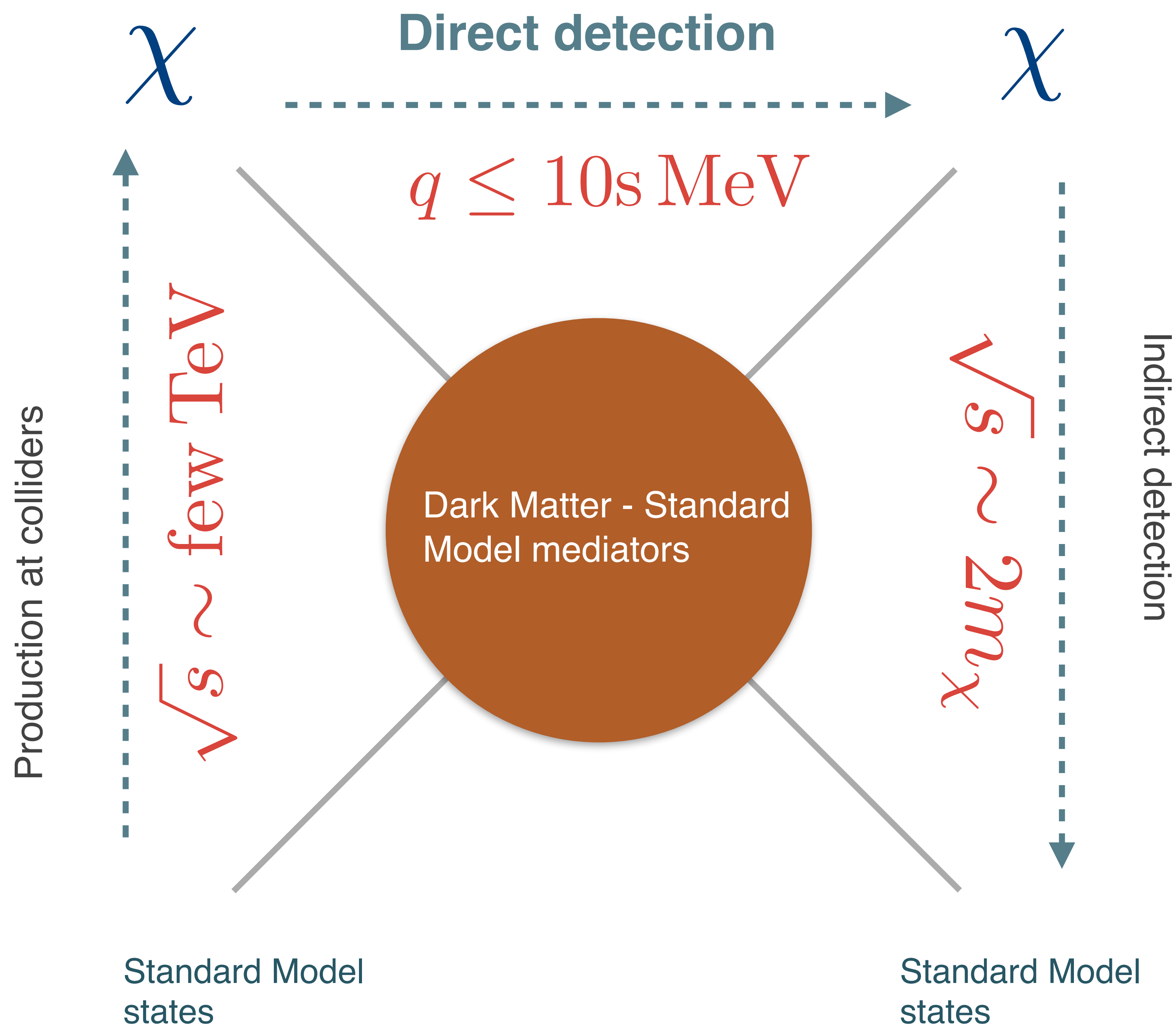
Axion searches





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

Under the WIMP lamppost…

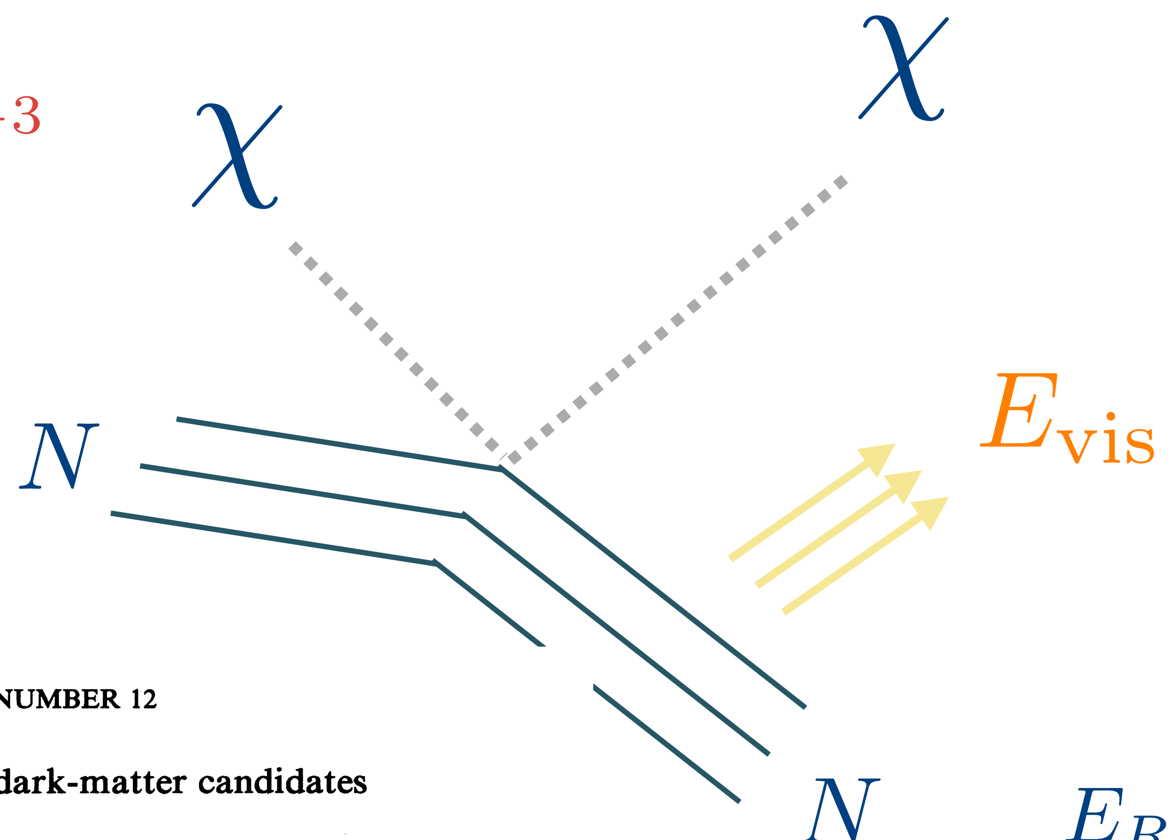


Direct detection

Collisions of invisibles particles with atomic nuclei

=> E_{vis} (q ~ tens of MeV):

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



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

REVIEW D VOLUME 31, NUMBER 12

Detectability of certain dark-matter candidates

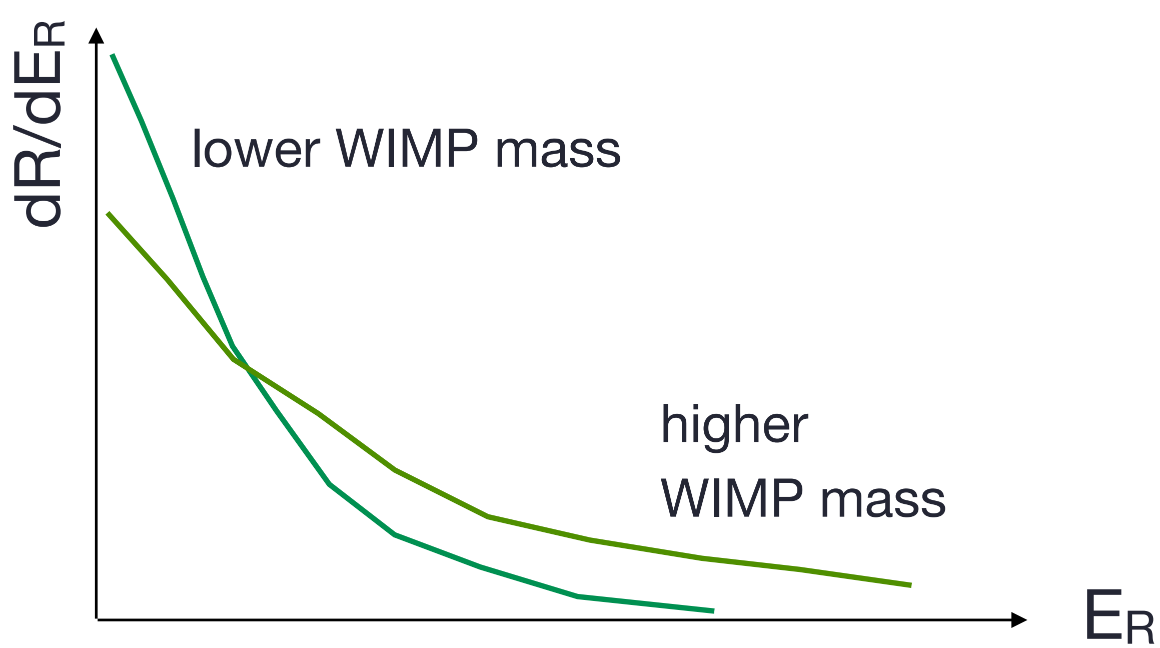
Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

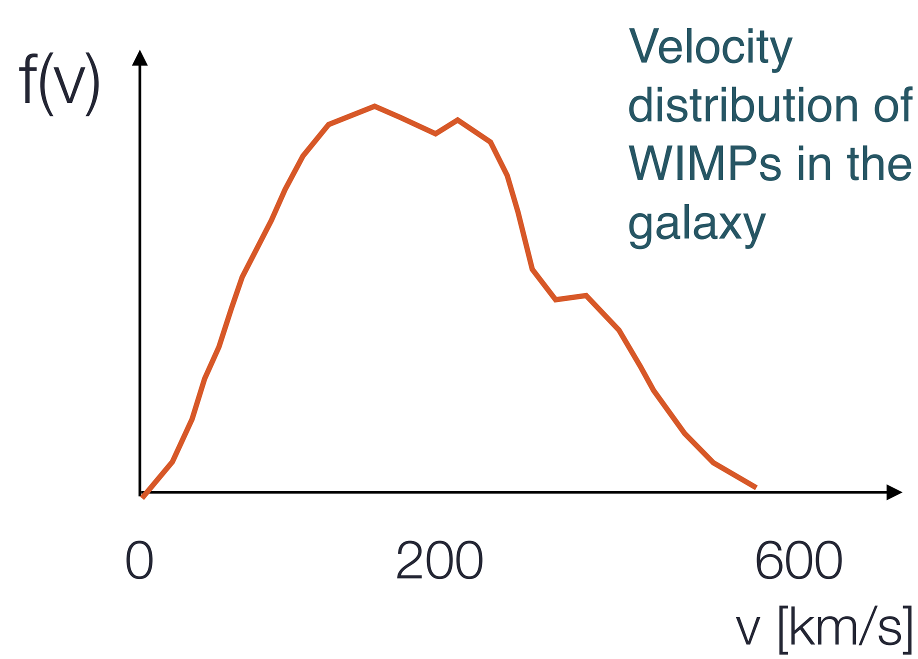
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and 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.

What to expect in a terrestrial detector?

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

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





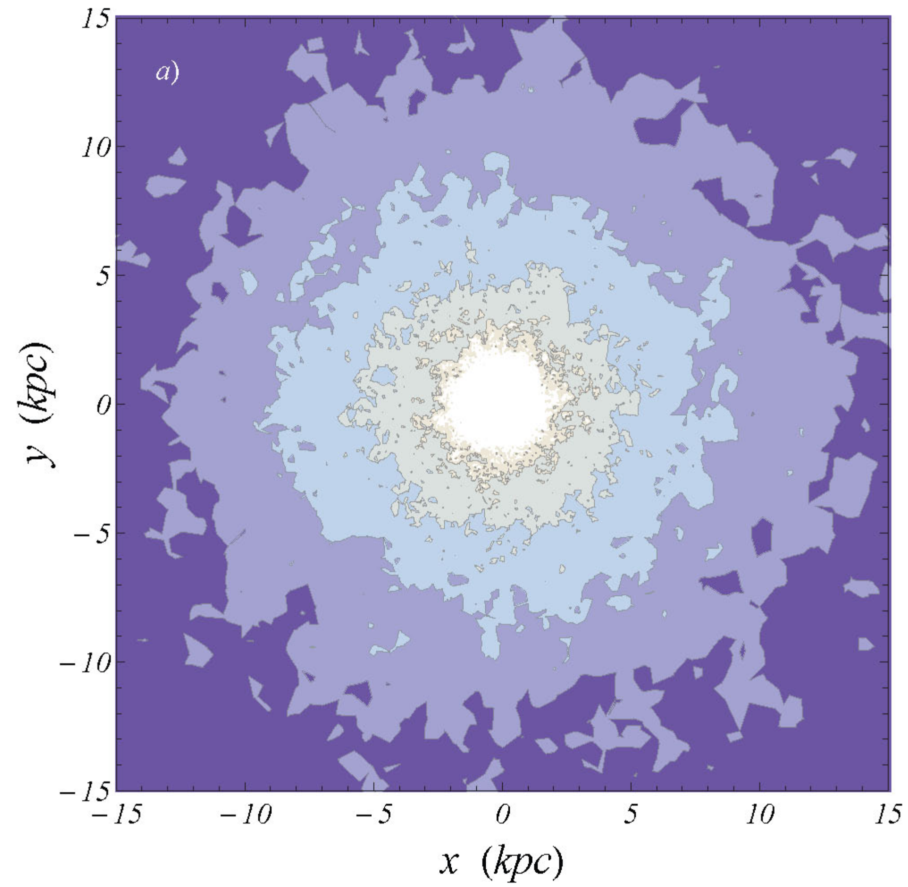
Astrophysics

Local density (at R_0 ~ 8 kpc)

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

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

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



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

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

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

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

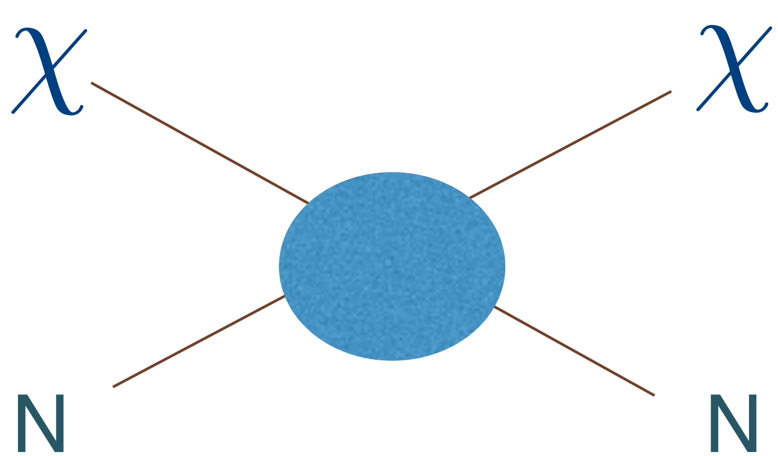
Particle physics

- Use *effective operators* to describe WIMP-quark interactions

- Example: vector mediator

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

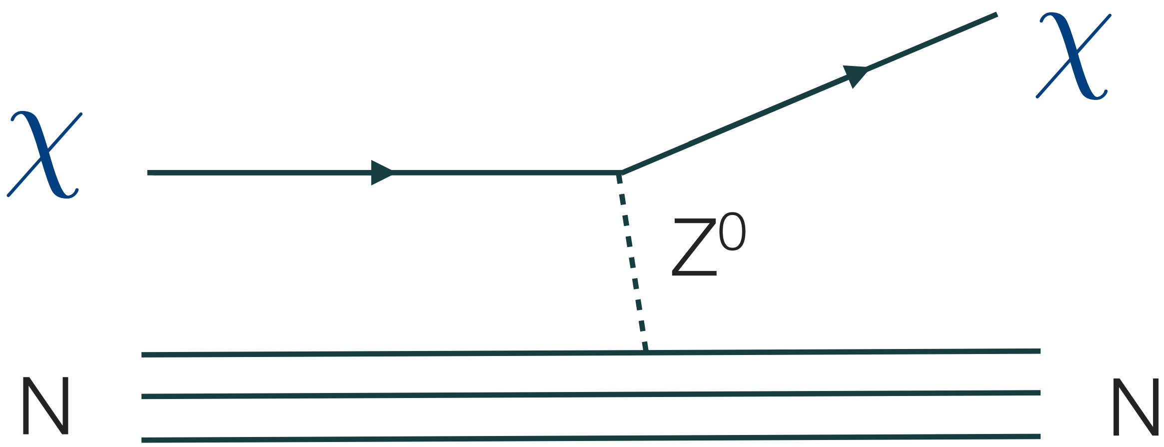
- The effective operator arises from “integrating out” the mediator with mass M and couplings g_q and g_χ to the quark and the WIMP



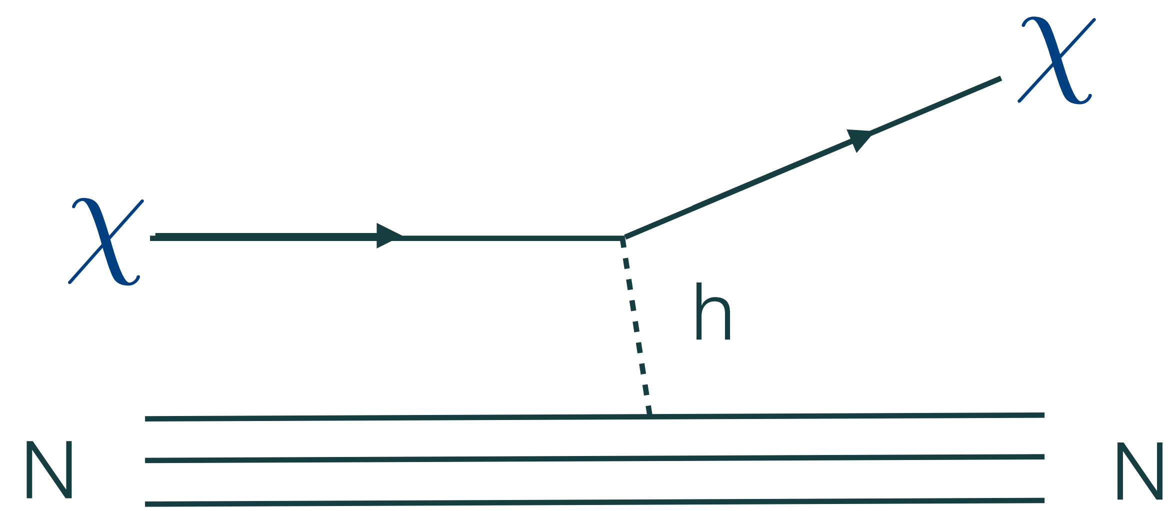
$$\Lambda = \frac{M}{\sqrt{g_q g_\chi}} \quad \Rightarrow \sigma_{\text{tot}} \propto \Lambda^{-4}$$

contact interaction scale

Example cross sections



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

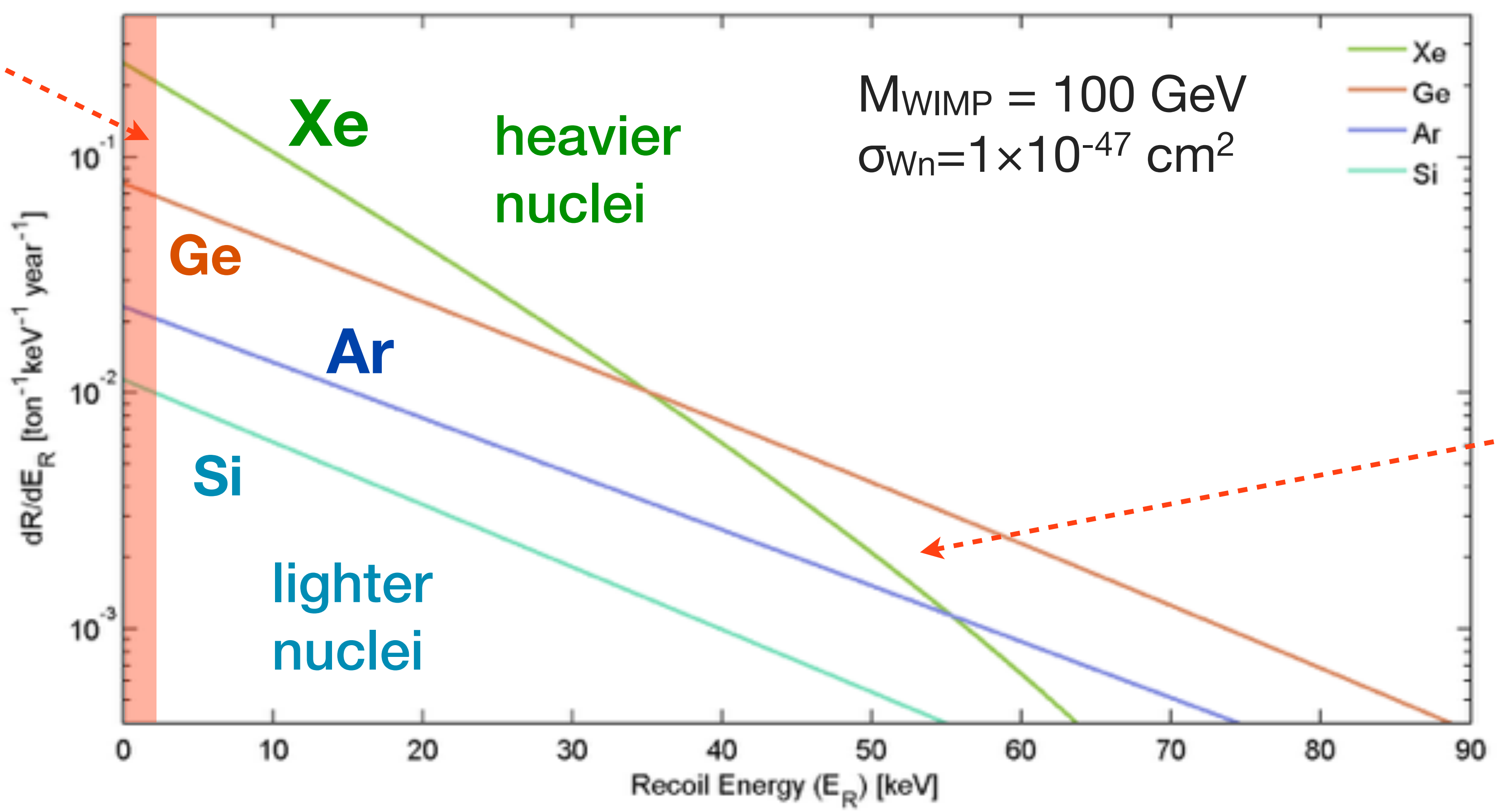


$$\sigma_0 \sim 10^{-44} - 10^{-47}\,\mathrm{cm}^2$$

Expected interaction rates

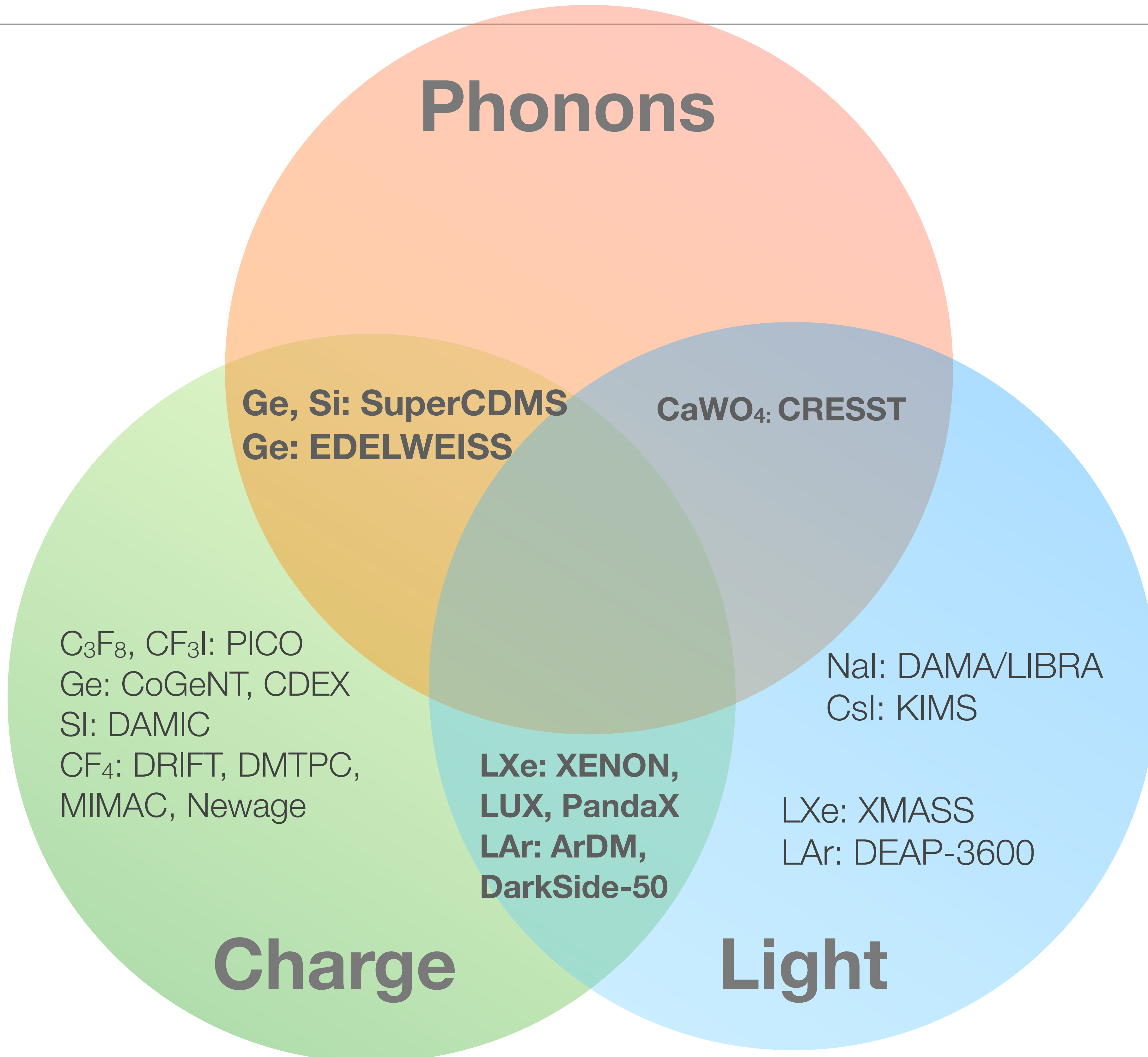
$$R \sim 0.13 \, \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$

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



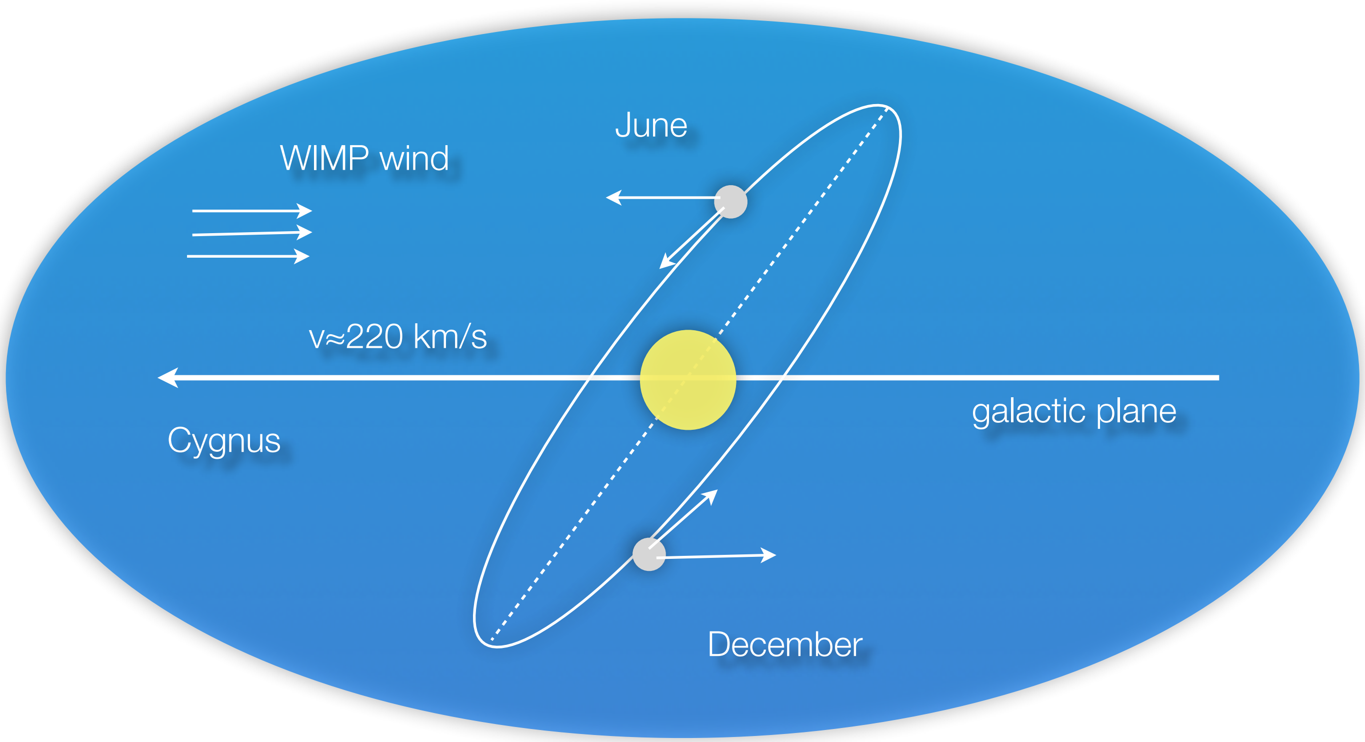
$F^2(E_R)$

Direct dark matter detection zoo

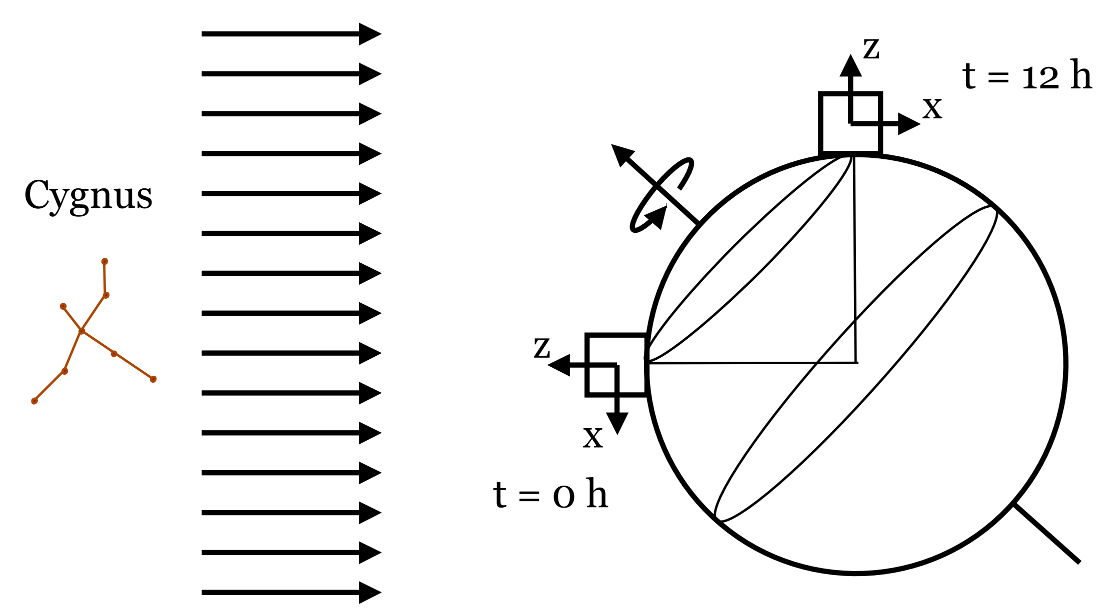


Dark matter signatures

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



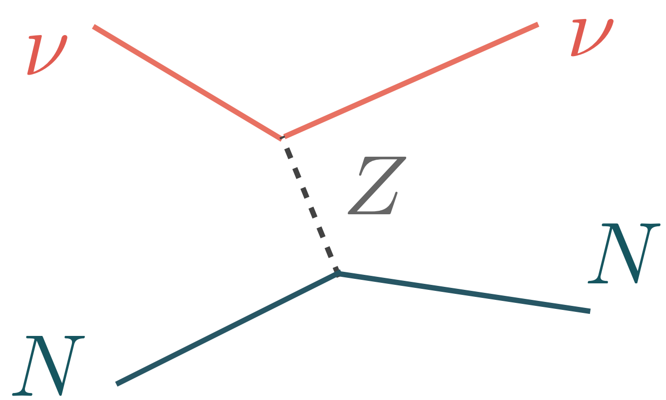
Drukier, Freese, Spergel, PRD 33,1986

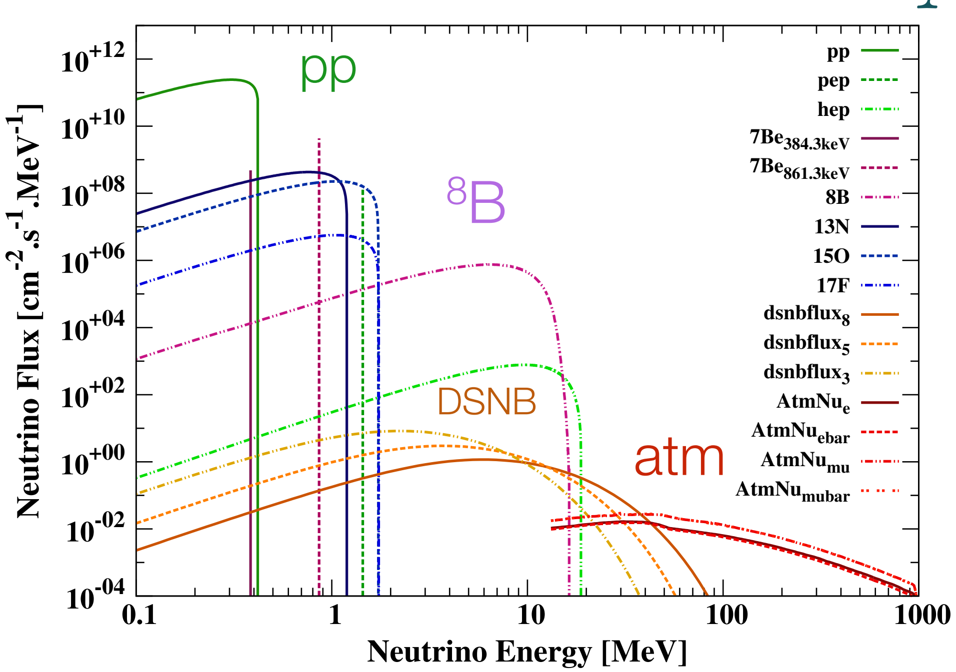


D. Spergel, PRD 36, 1988

Backgrounds

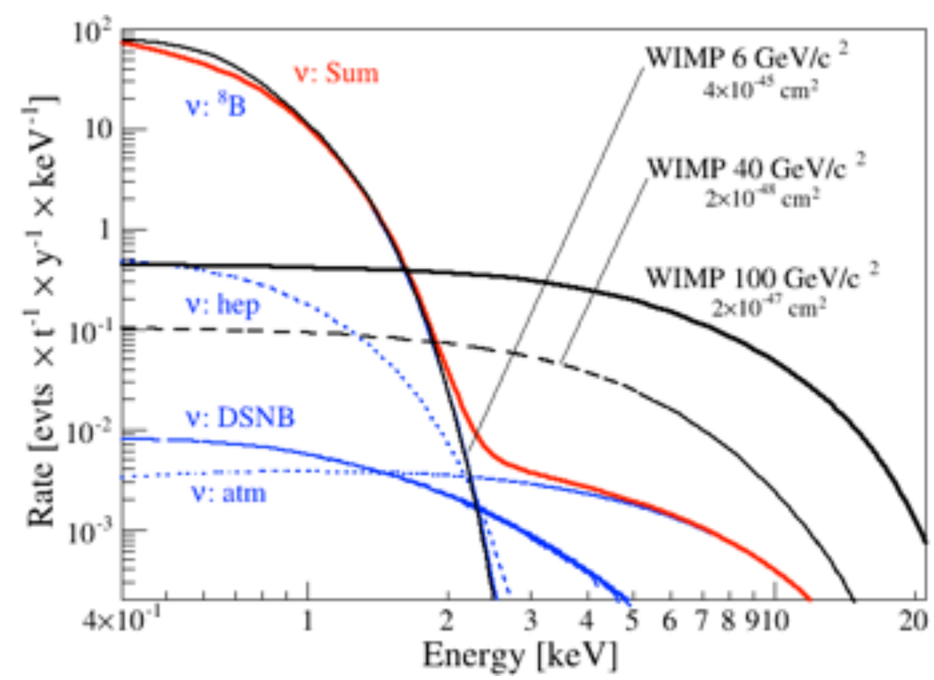
- Cosmic rays & cosmic activation of detector materials
- Natural (^{238}U, ^{232}Th, ^{40}K) & anthropogenic (^{85}Kr, ^{137}Cs) radioactivity: γ, e^-, n, α
- Ultimately: **neutrino-nucleus scattering (solar, atmospheric and supernovae neutrinos)**





F. Ruppin et al., 1408.3581

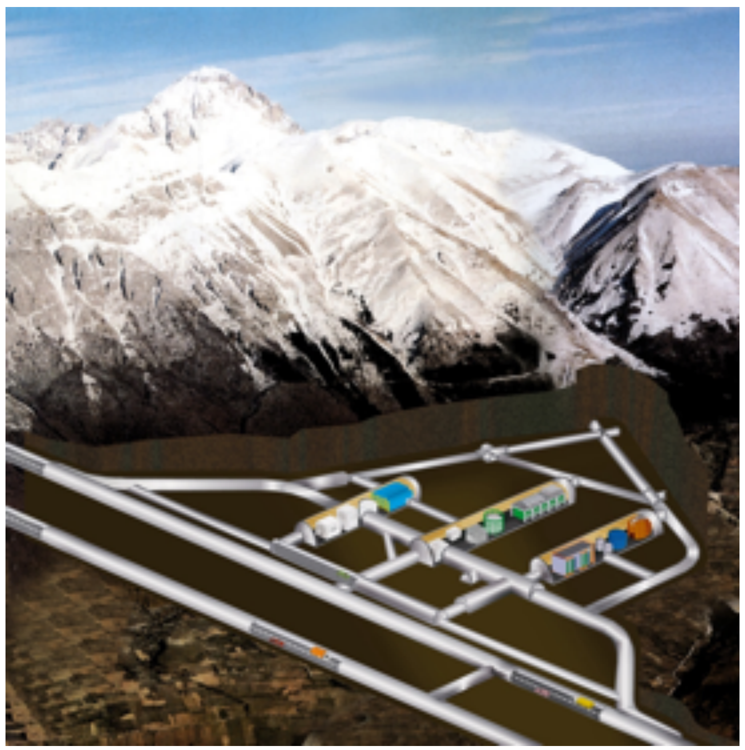
$\nu + N \longrightarrow \nu + N$



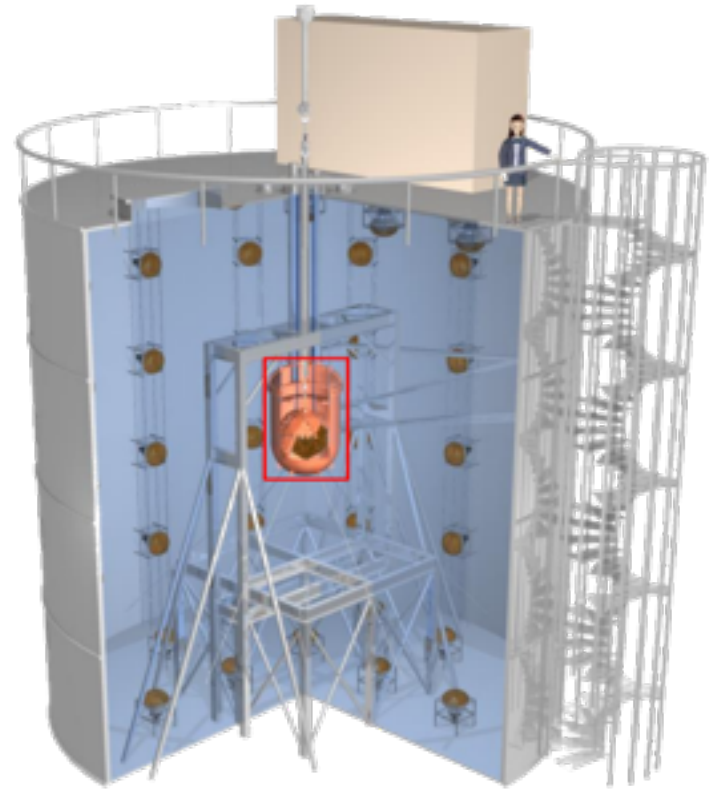
LB et al., JCAP01 (2014) 044

How to deal with backgrounds?

- Go deep underground

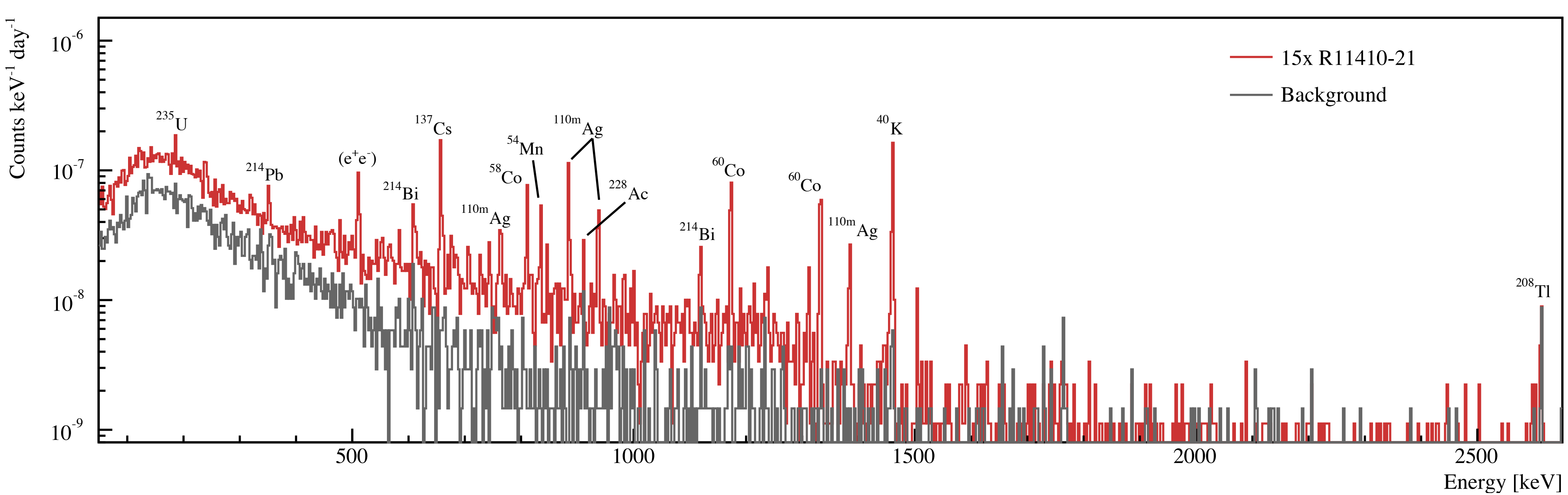


- Use active shields



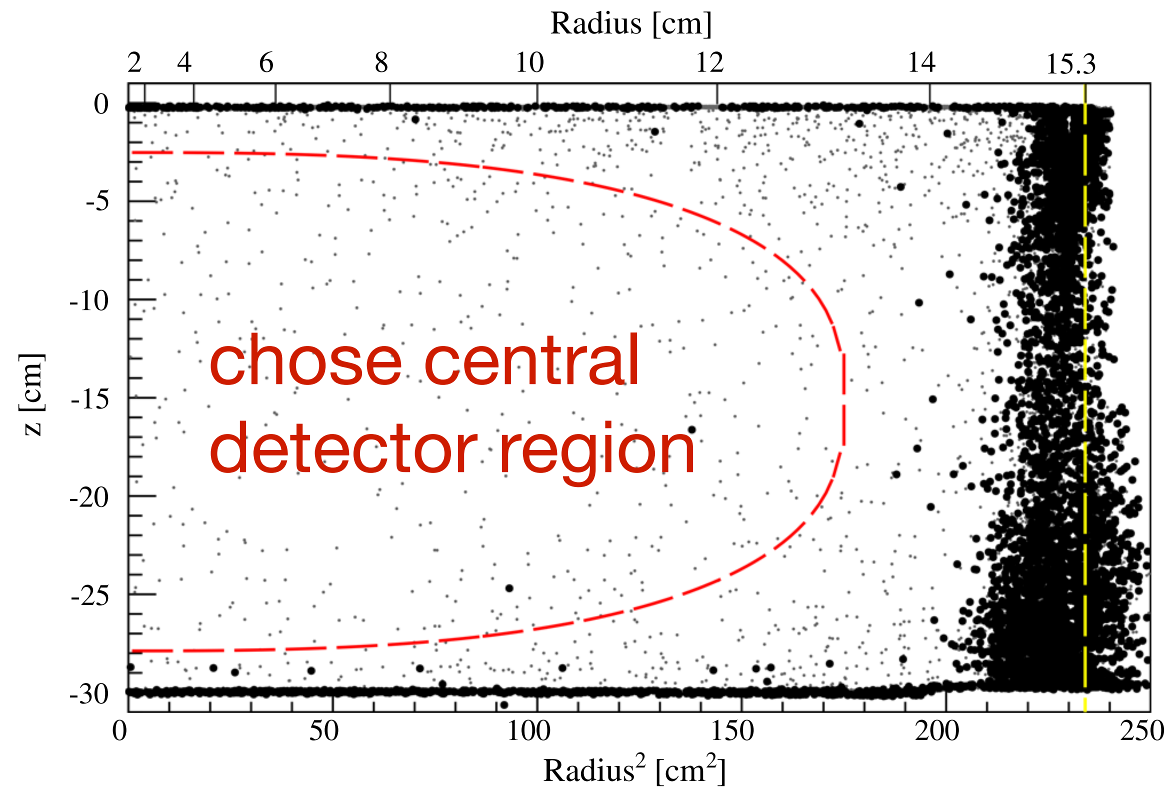
- HPGe material screening

- Select low-background materials

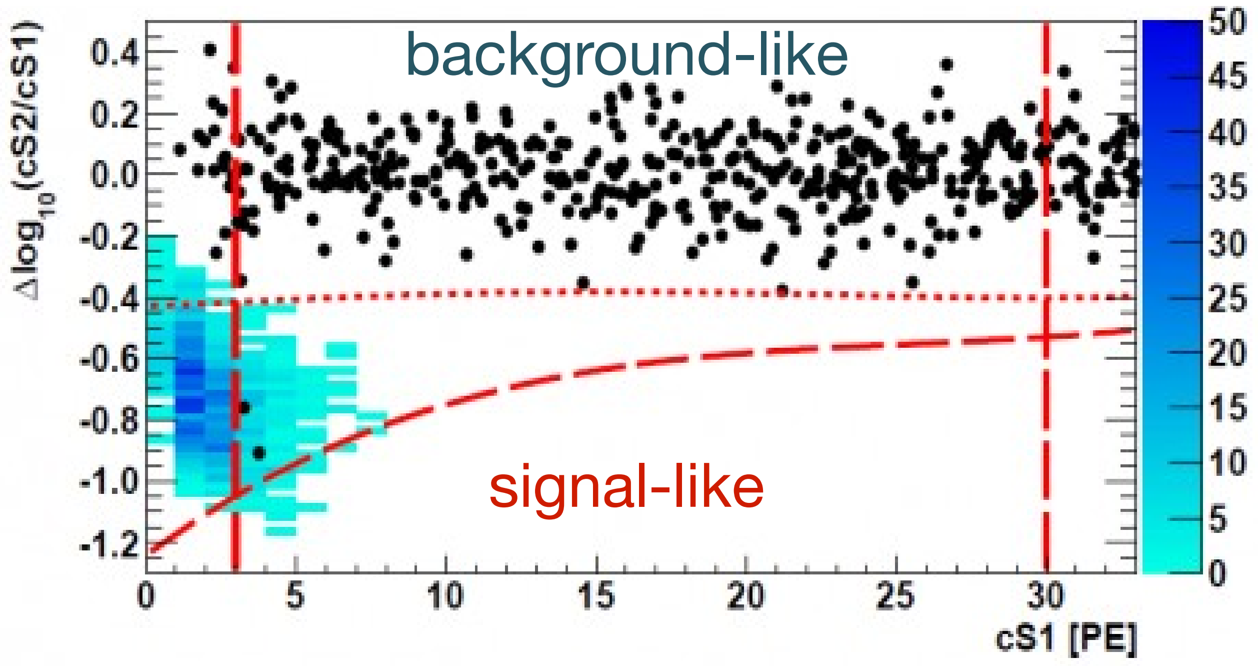


How to deal with backgrounds?

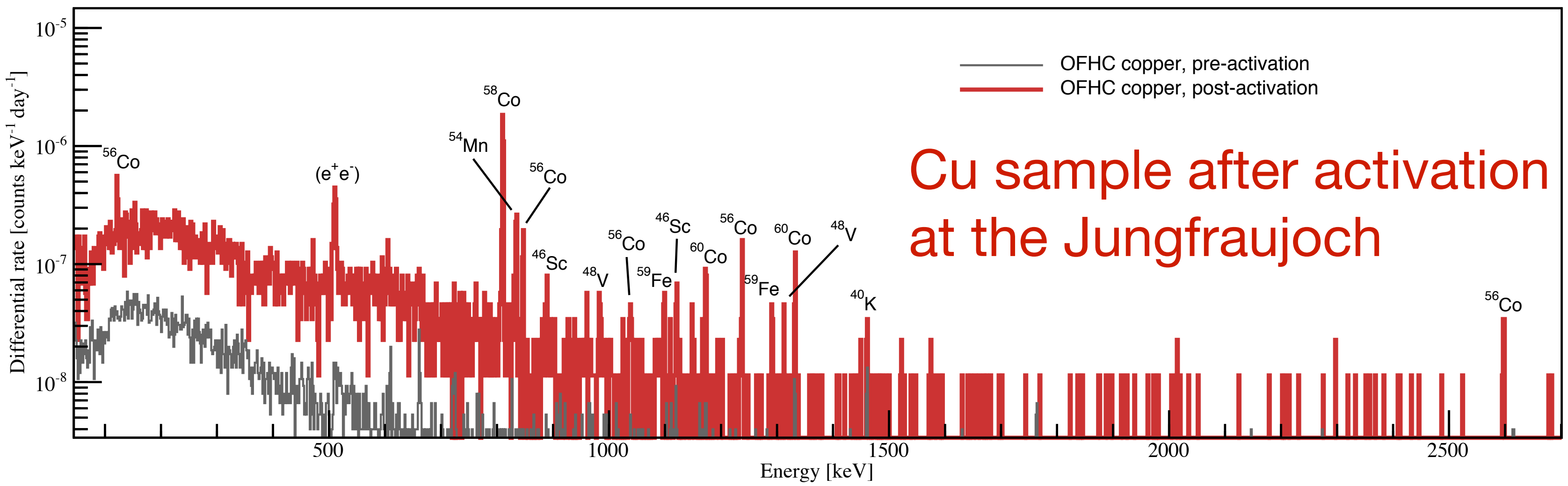
- Fiducialization



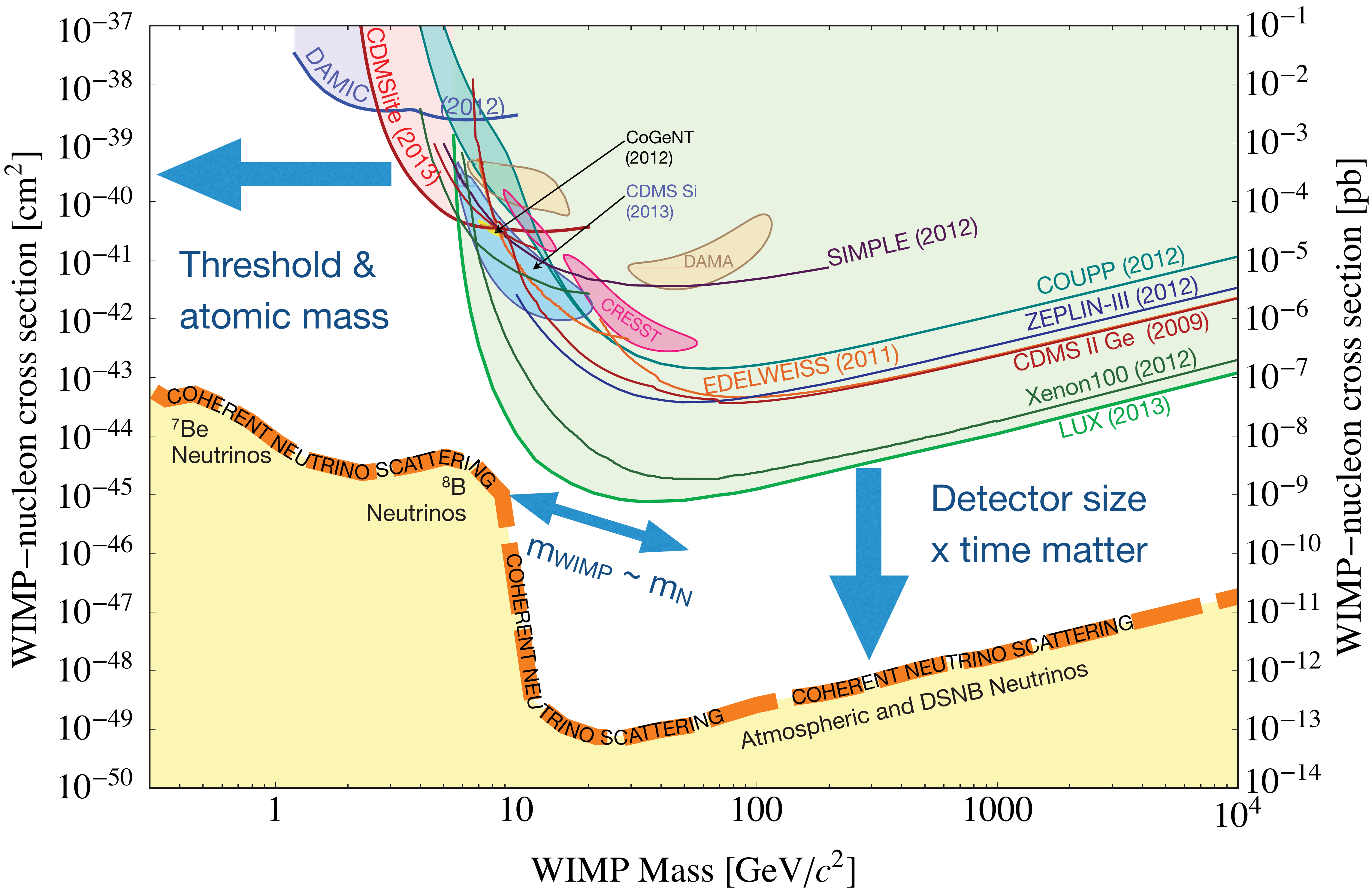
- Discrimination



- Avoid exposure to cosmic rays



The WIMP landscape in 2015

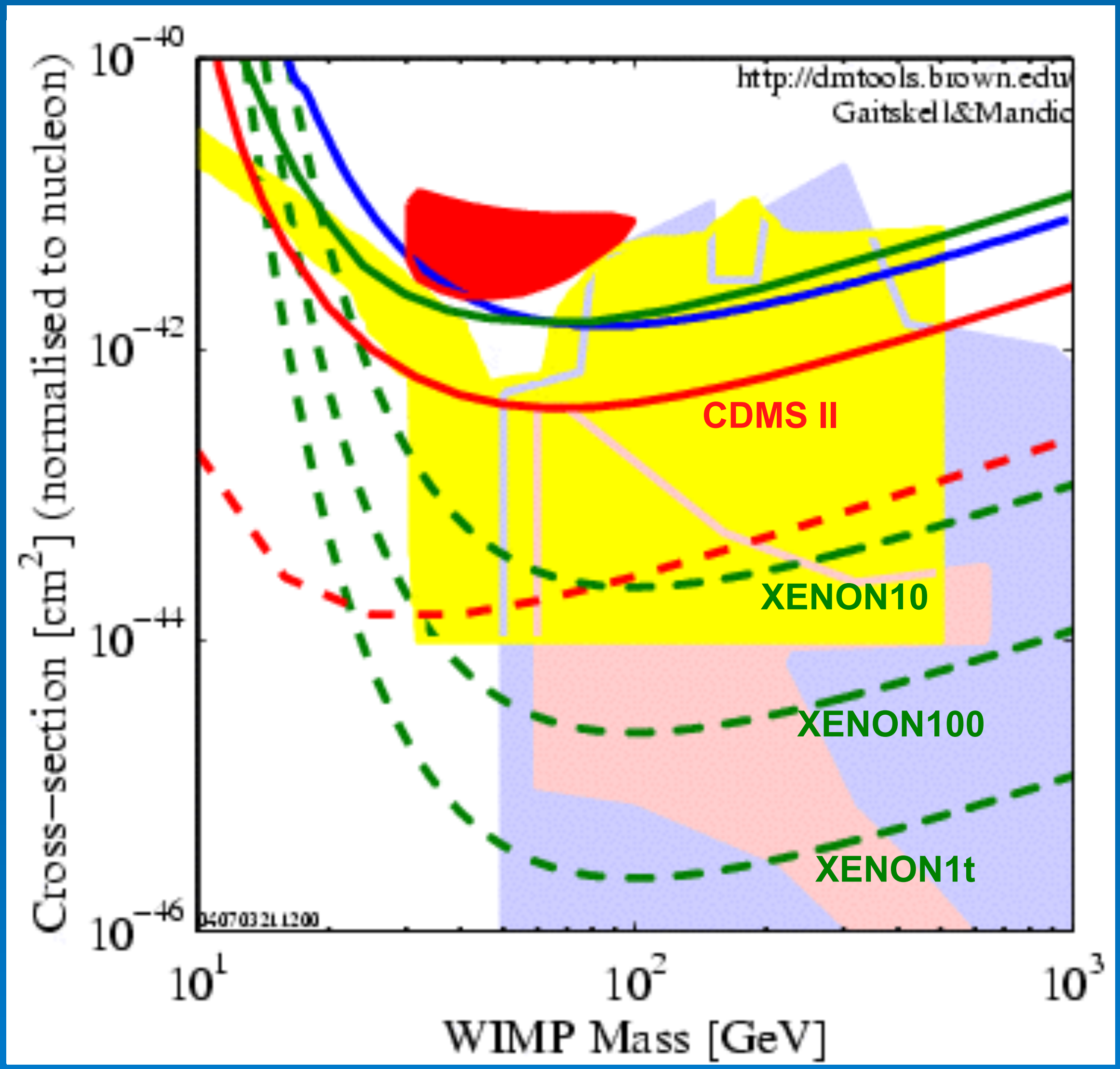


and 10 years ago…

Where do we stand?

Laura Baudis

Lepton Photon, Uppsala
July 4, 2005



~ 0.2 events/kg/day

Most advanced experiments start to test the predicted SUSY parameter space

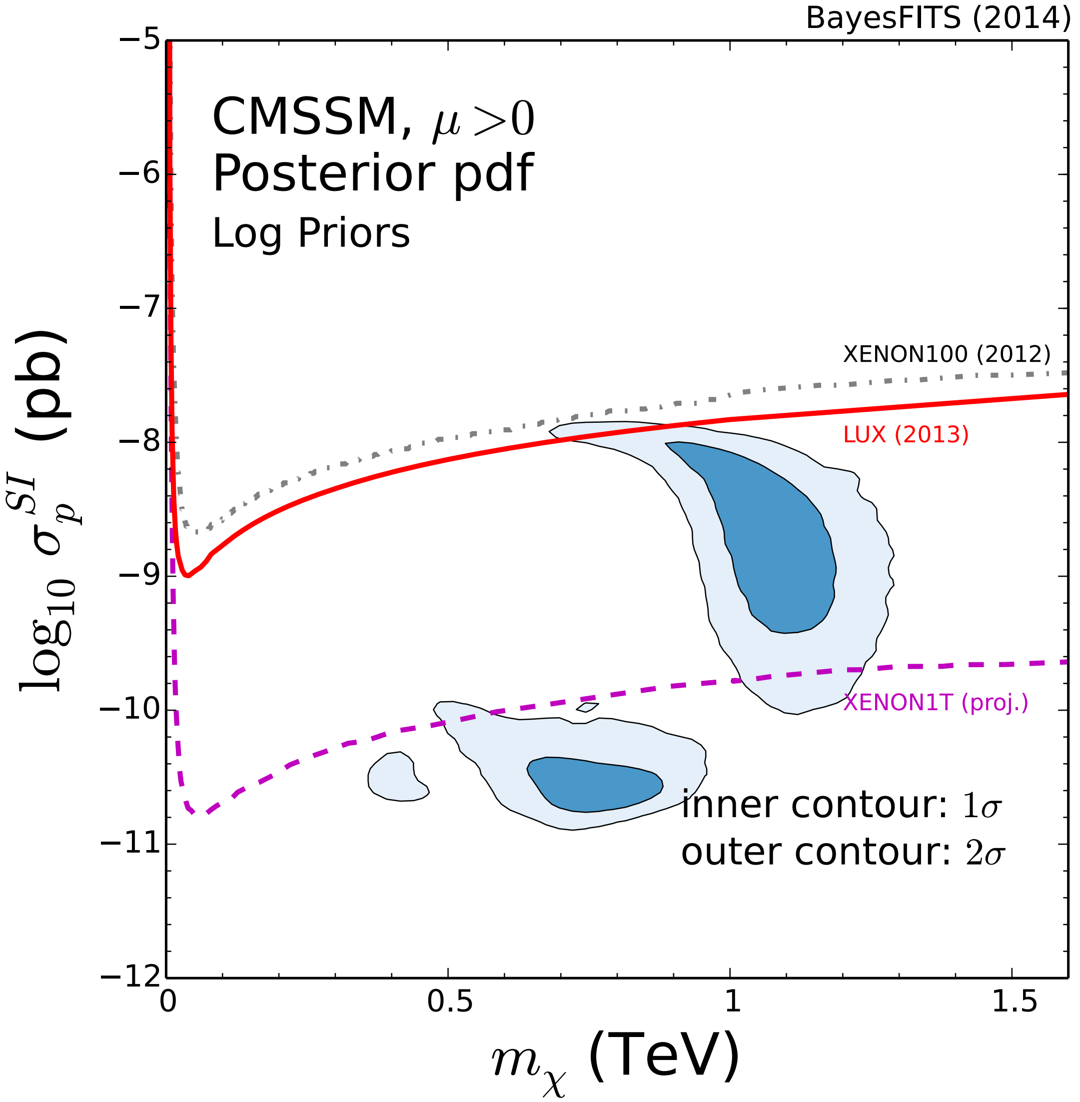
One evidence for a positive WIMP signal (DAMA NaI)

Not confirmed by other experiments

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

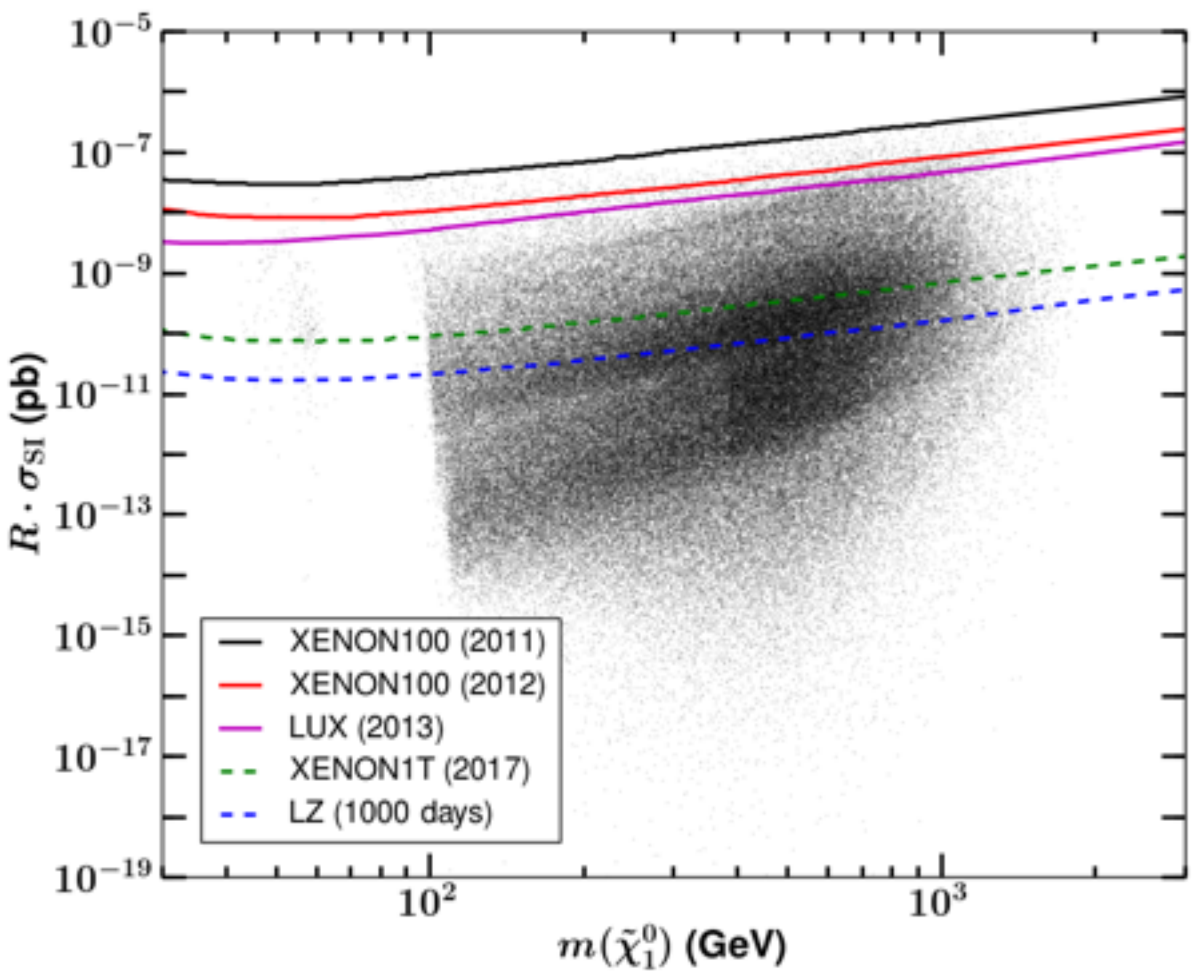
SUSY Predictions: 2 examples

CMSSM



L. Rozkowski, Stockholm 2015

pMSSM

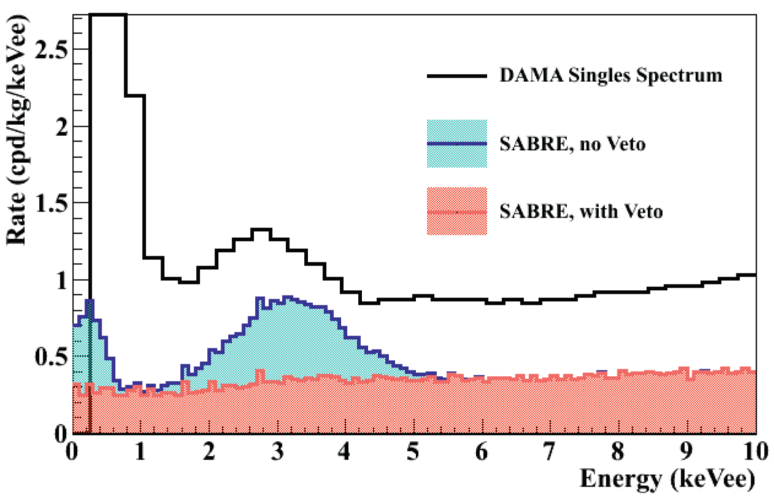


M. Cahill-Rowley, Phys.Rev. D91 (2015) 055011

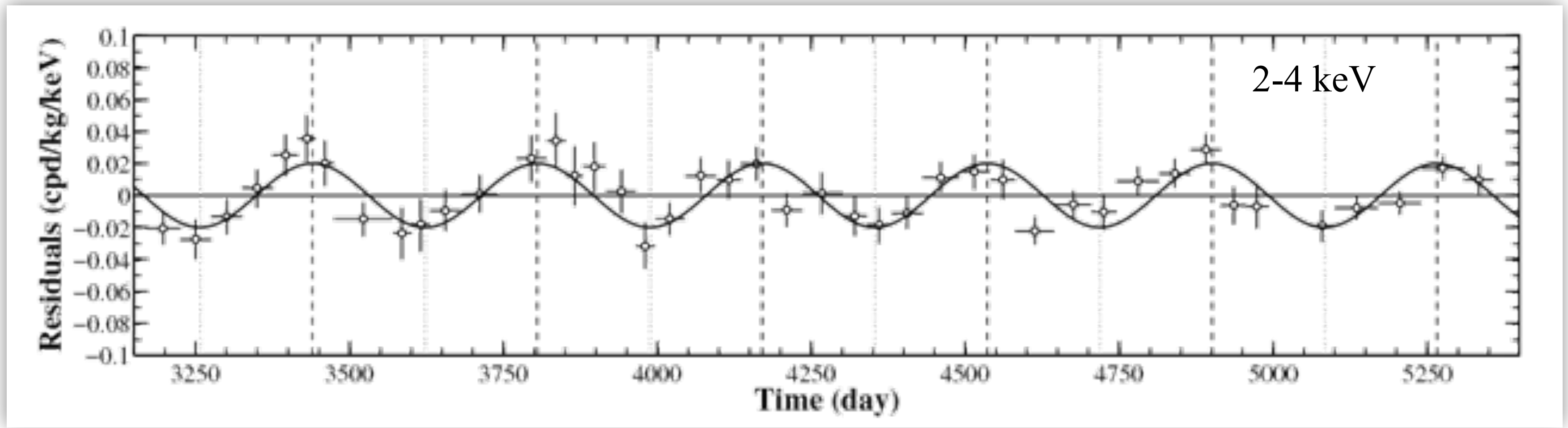
DAMA/LIBRA annual modulation signal

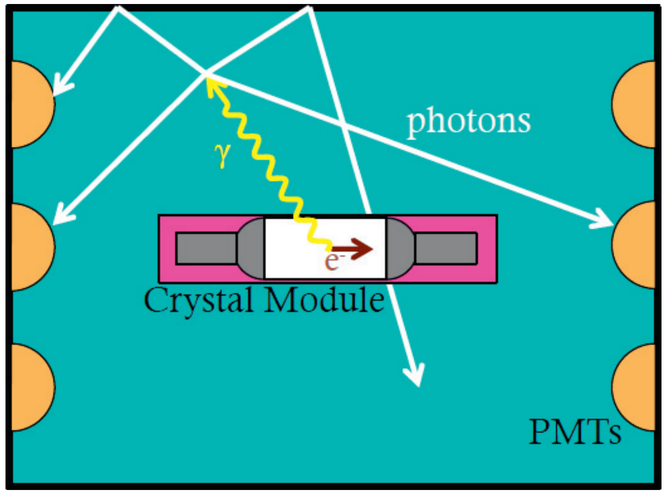
- Period = 1 year, phase = June 2 ± 7 days; 9.3-sigma
- Results in tension with many WIMP searches
- Several experiments to *directly probe the modulation signal* with similar detectors (NaI, CsI): **SABRE, ANAIS, DM-Ice, KIMS**
- **“Leptophilic” models viable (until a few weeks ago…)**

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



DAMA/LIBRA NaI: 2% annual modulation





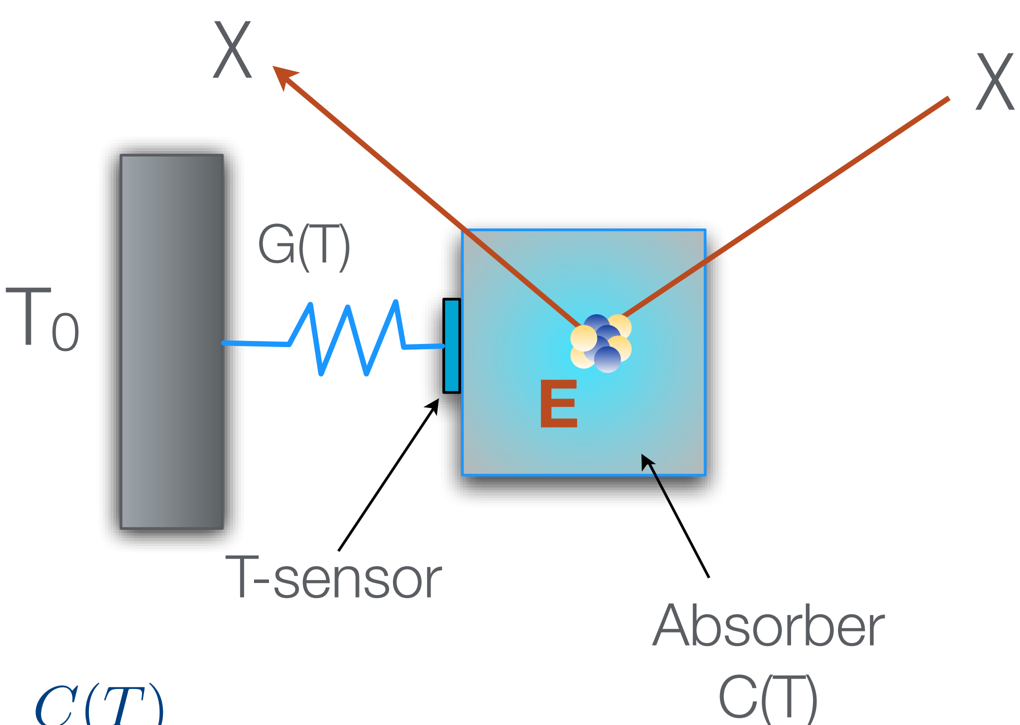
SABRE, 50 kg NaI detectors

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

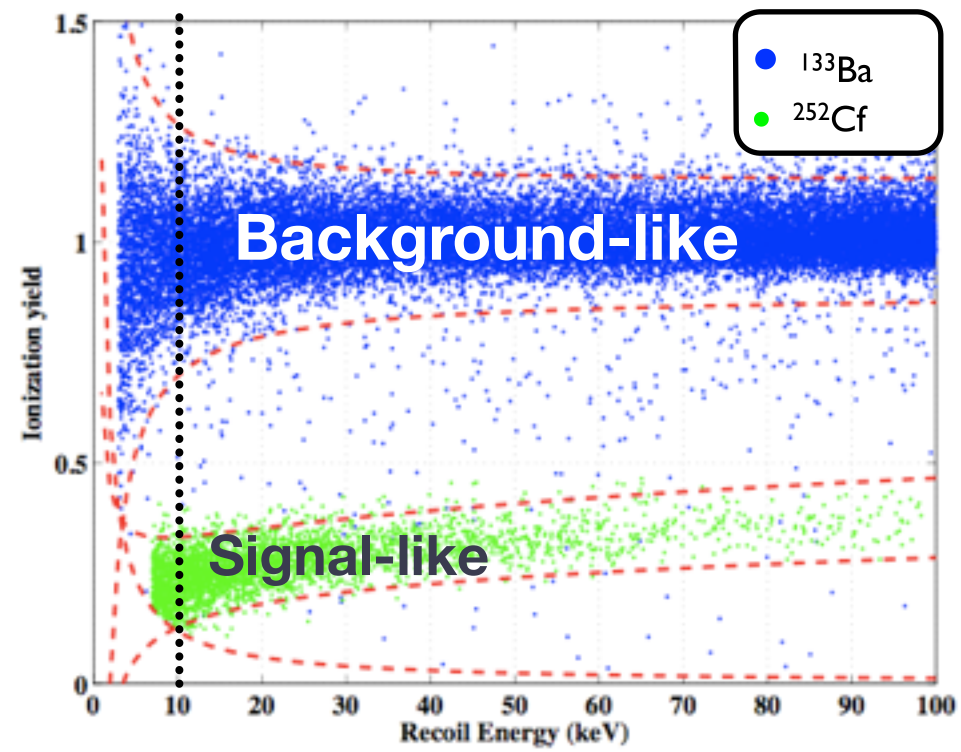
Cryogenic detectors at T ~ mK

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

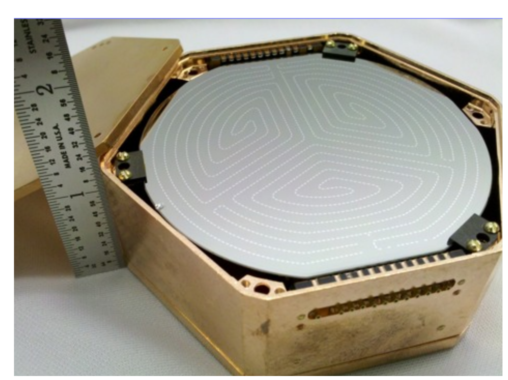
$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}}$$



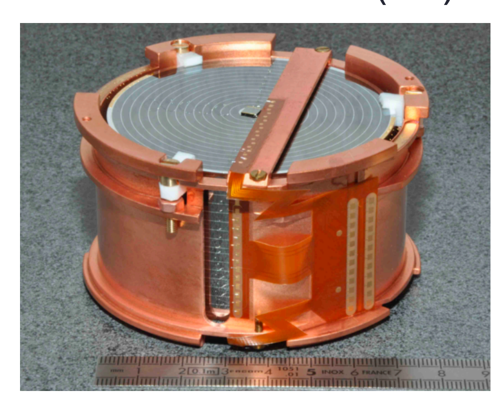
$$\tau = \frac{C(T)}{G(T)}$$



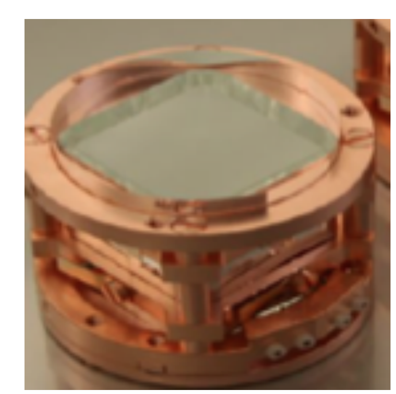
SuperCDMS: Ge, Si



EDELWEISS-III (Ge)

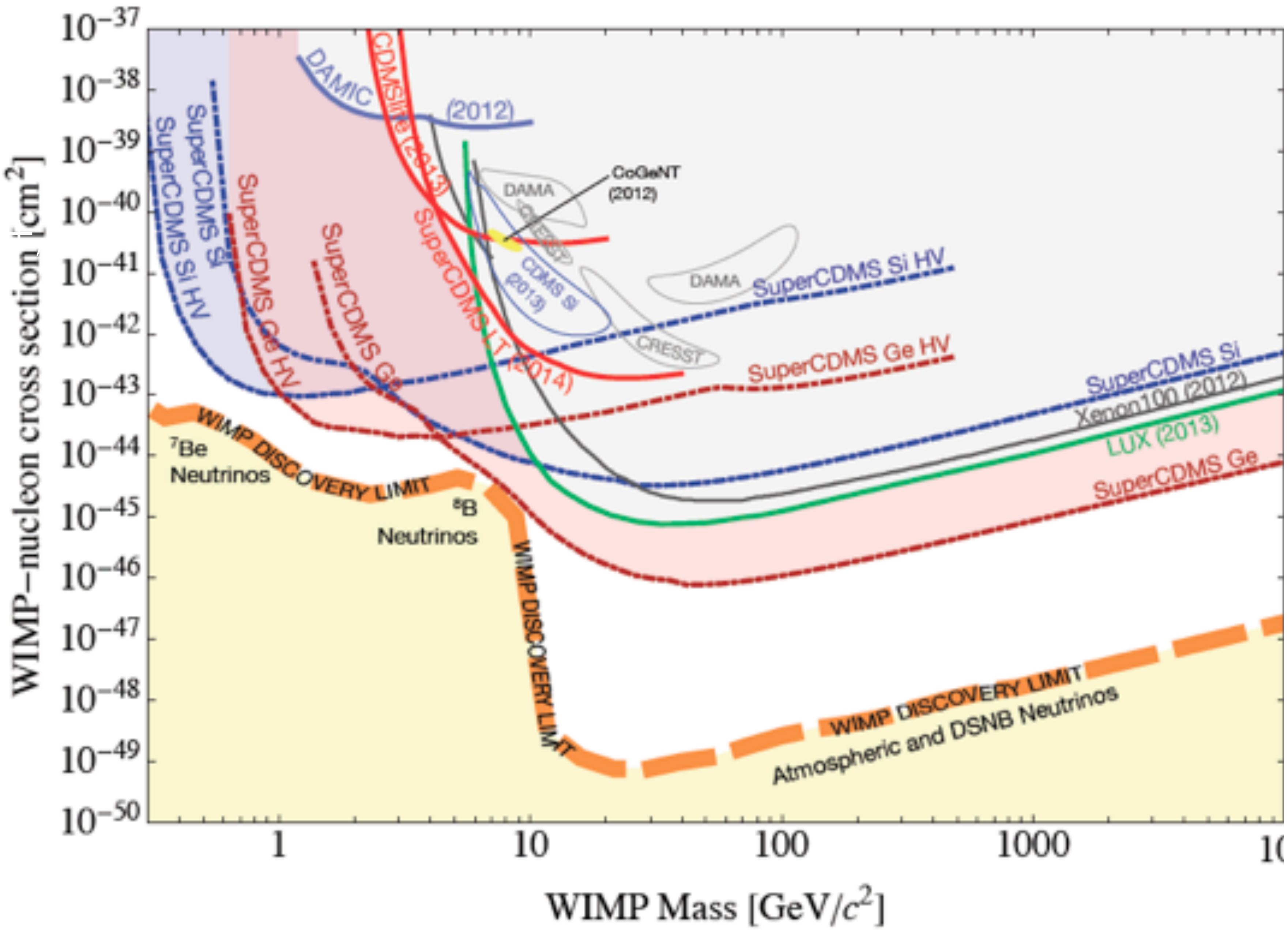


CRESST ($CaWO_4$)



Cryogenic detectors at T ~ mK

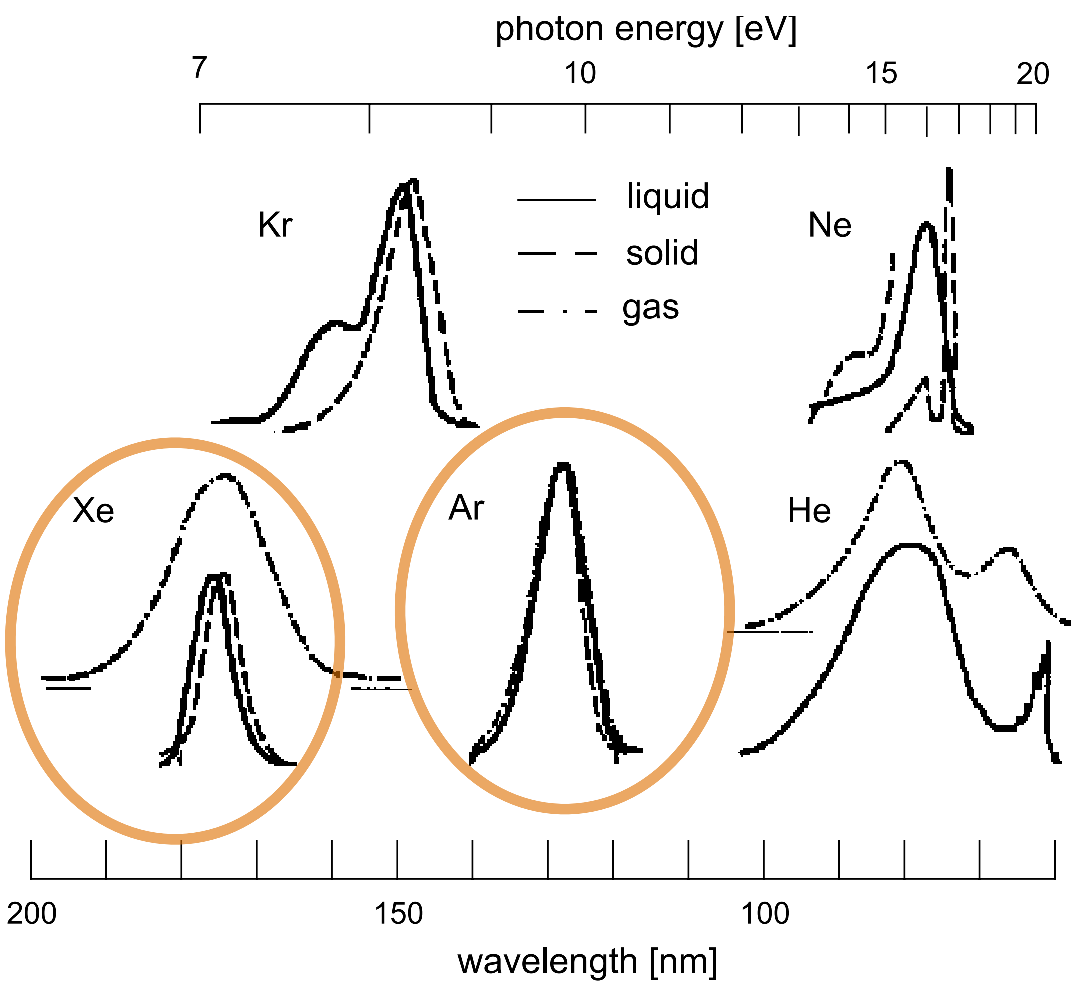
Probe low WIMP mass region



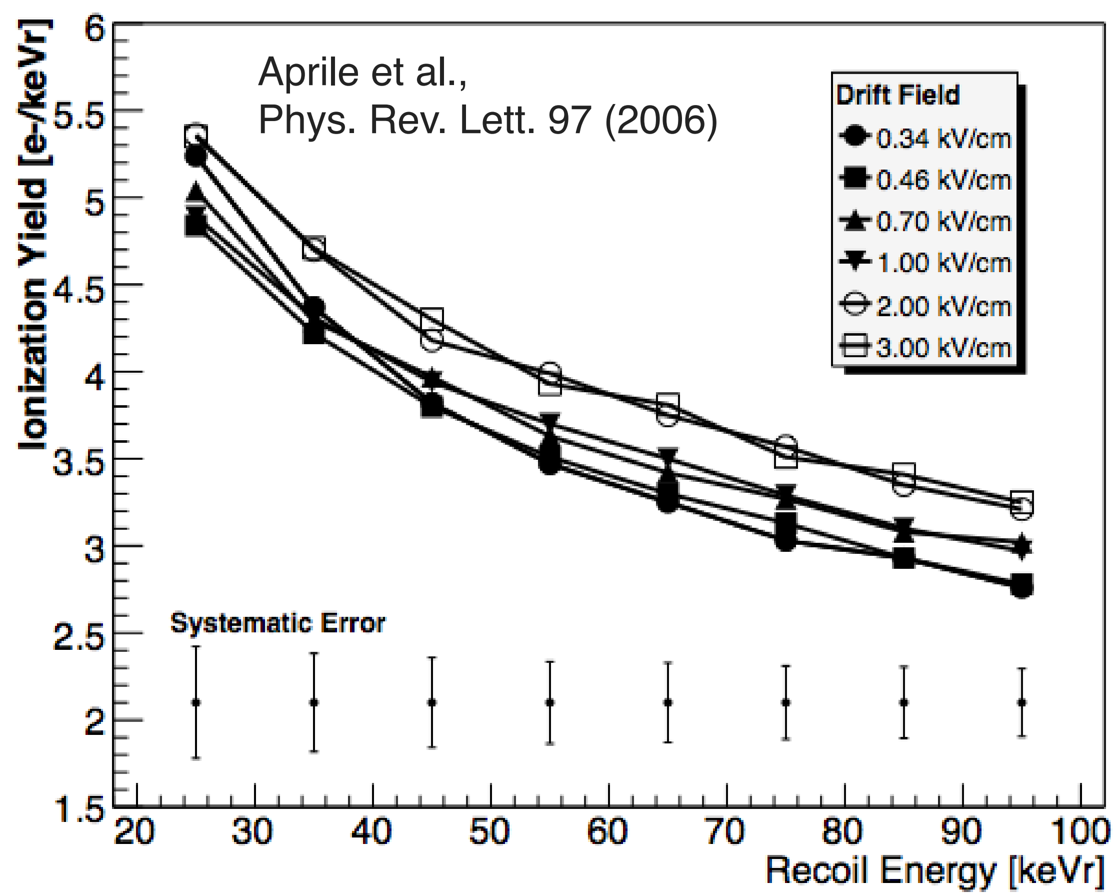
Liquefied noble gases

- High light and charge yield
- **Xenon ("the strange one")** and **argon ("the inactive one")** used in dark matter detectors

Light



Charge

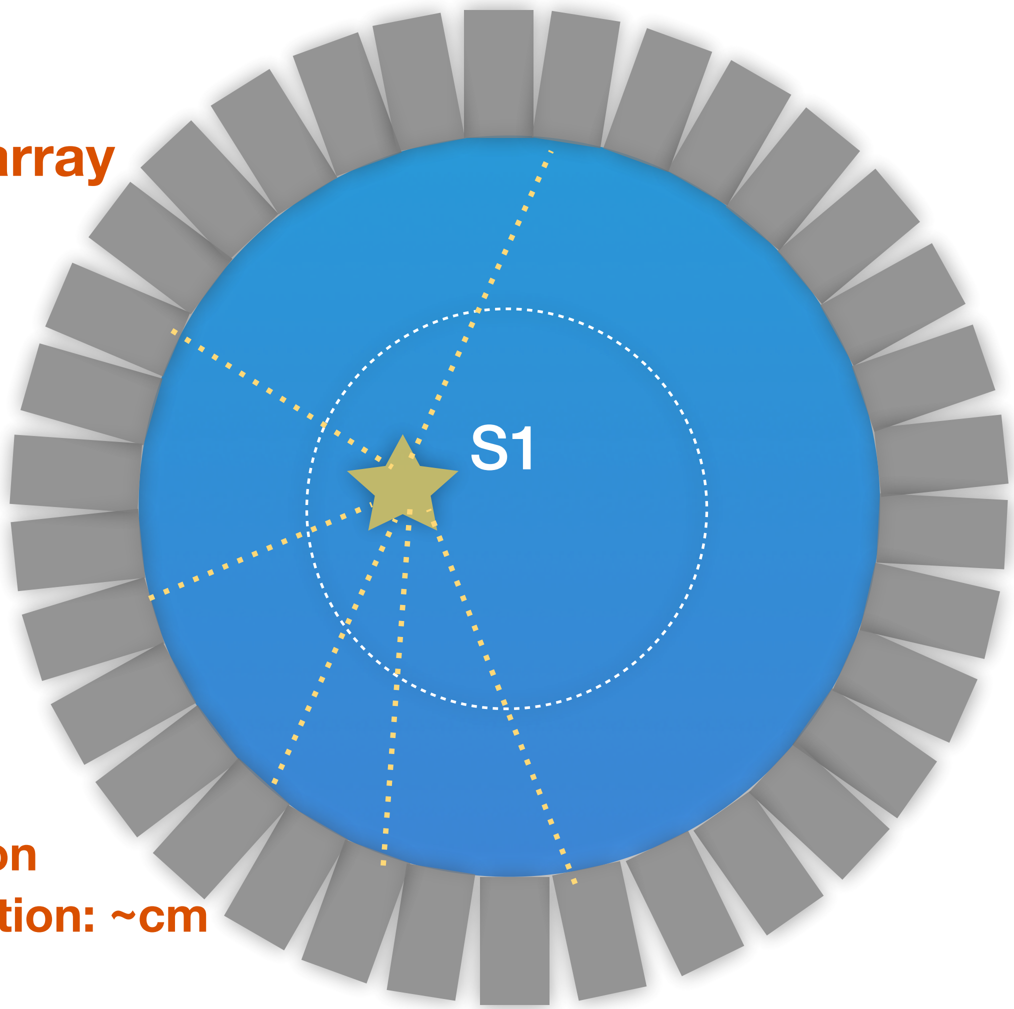


Single-phase noble liquid detectors

Instrumented LAr or LXe volume

Scintillation light in VUV region

PMT array

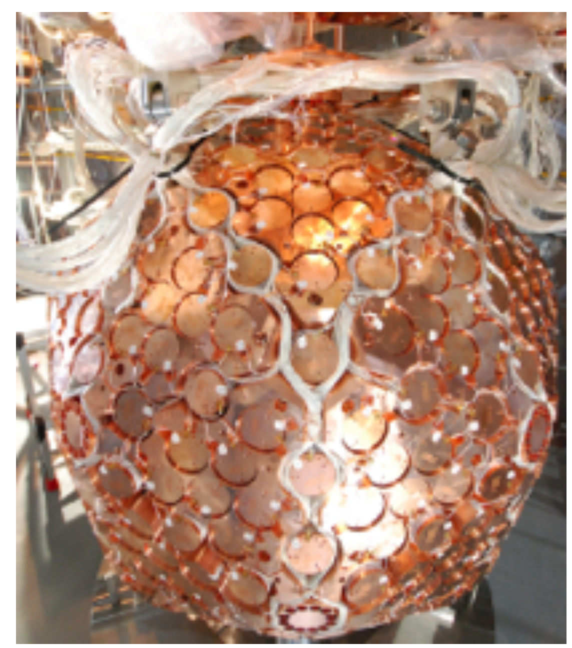


position resolution: ~cm

+ PSD (mostly in LAr)

Xenon

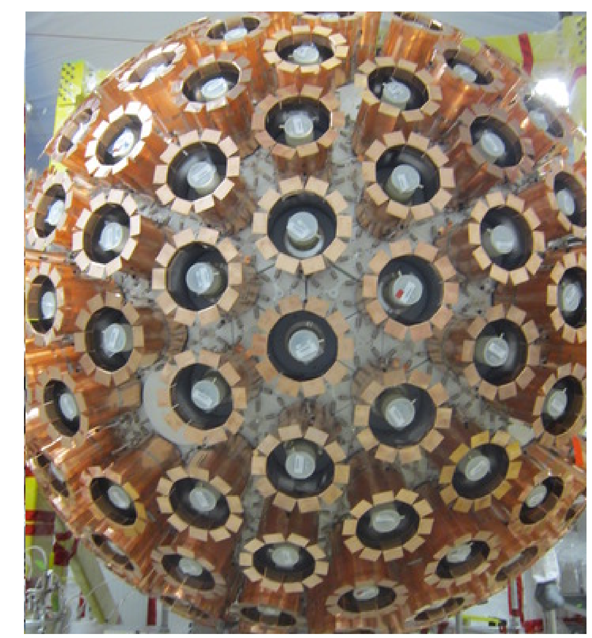
XMASS at Kamioka, 832 kg



Running since 2013
Results in 2016

Argon

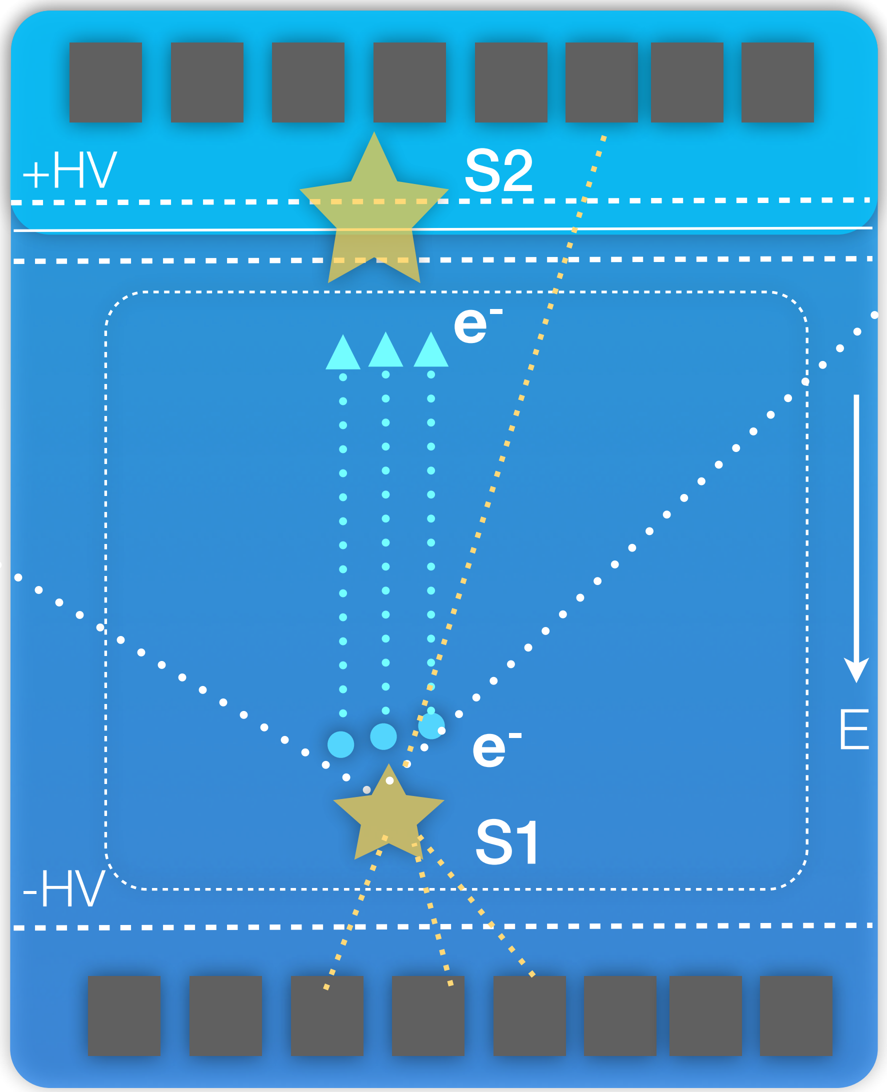
DEAP-3600 at SNOLAB, 3.6 t

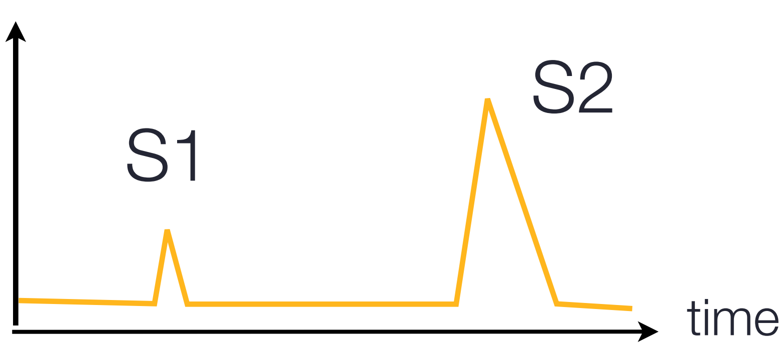


In commissioning
First results in late 2015
1 x 10^{-46} cm^2 sensitivity

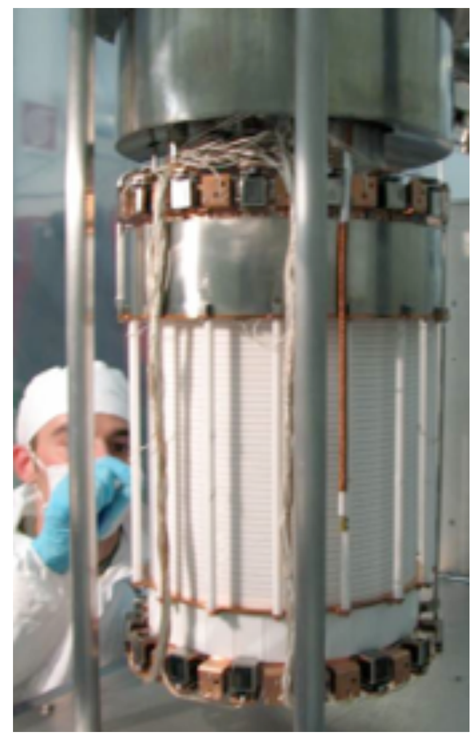
Dual-phase noble liquid detectors

PMT array





LXe: XENON100



LXe: LUX

LAr: DarkSide

Xenon

XENON100 at LNGS, LUX at SURF, PandaX at CJPL

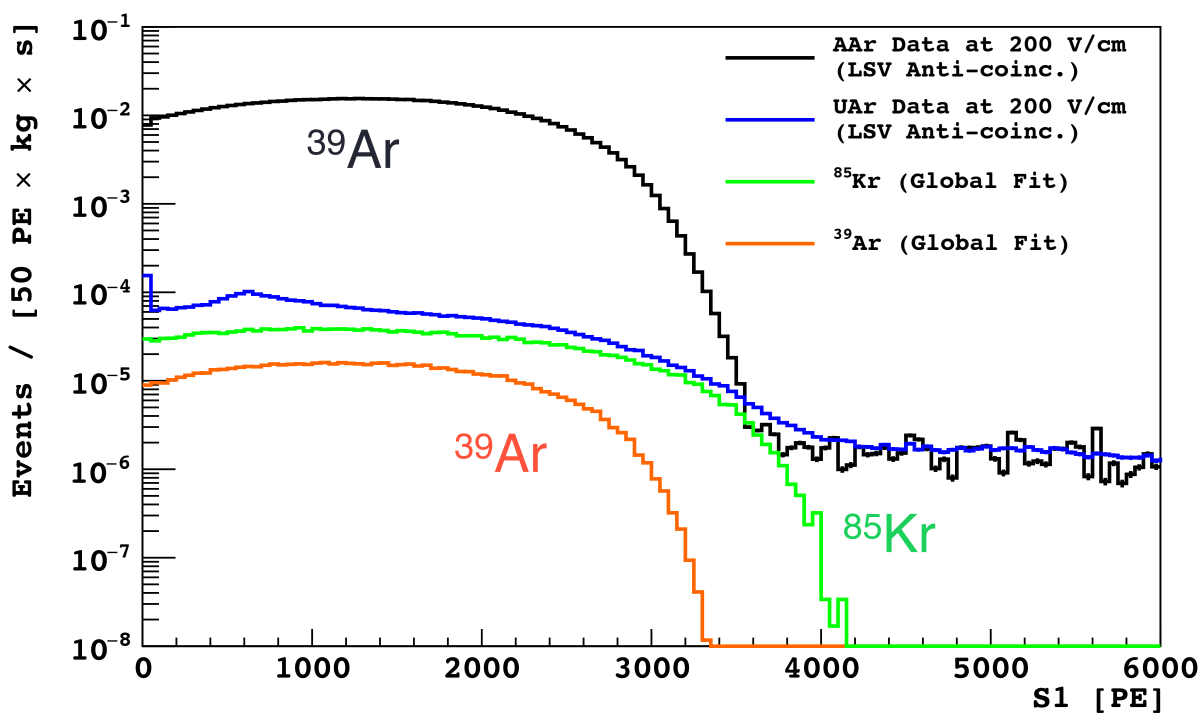
Argon

DarkSide-50 at LNGS, ArDM at Canfranc

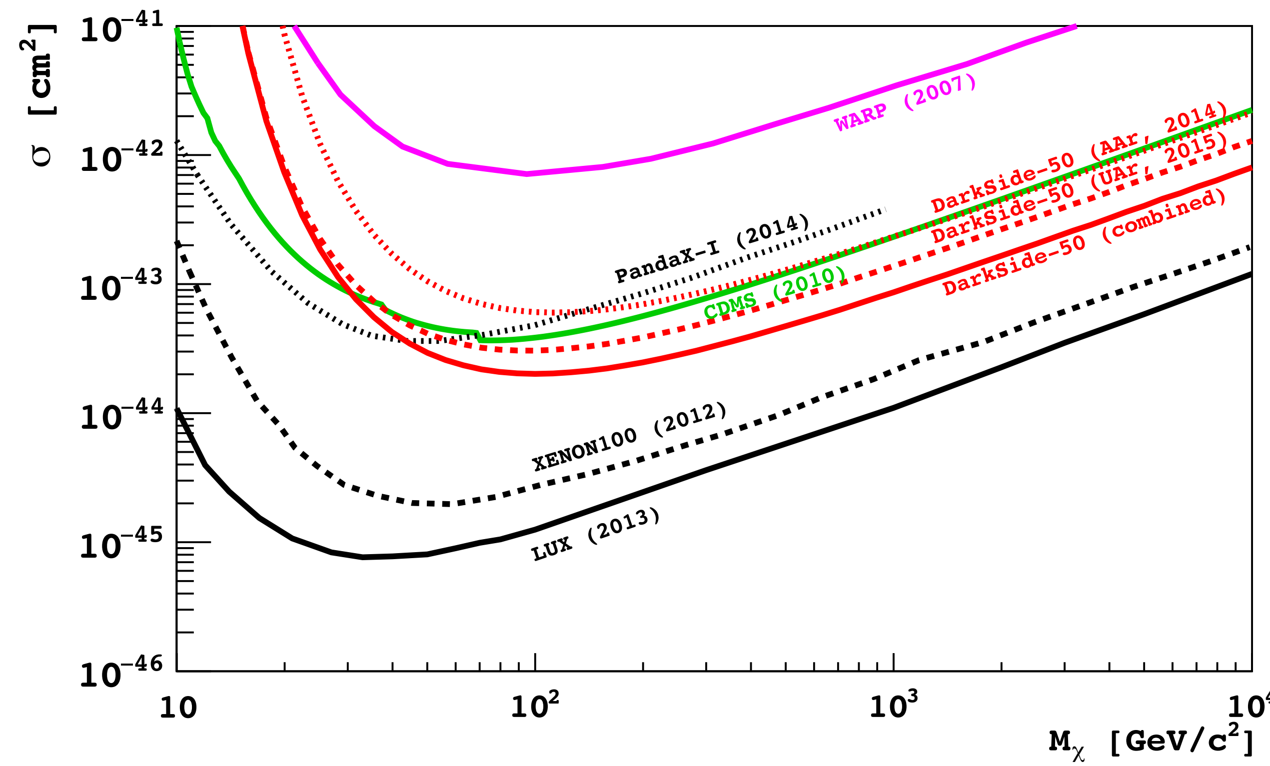
Target masses between ~ 50 kg - 1 ton

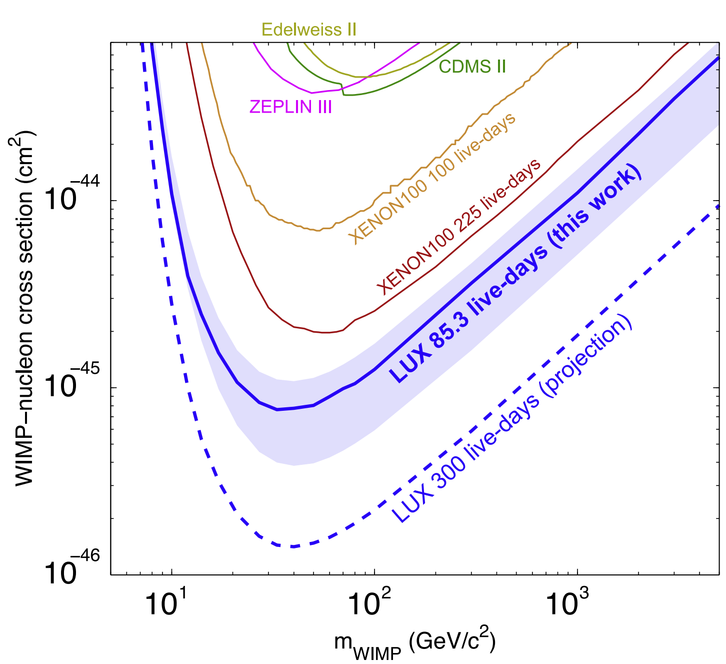
Liquefied noble gases: recent results

DarkSide-50: factor 1.4 x 10^3 depletion of ^{39}Ar

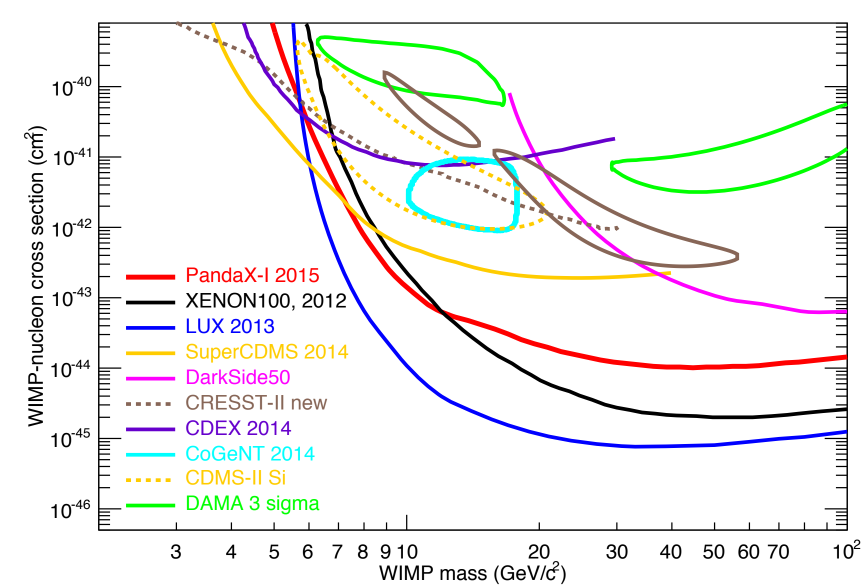


DarkSide-50, 70.9 live days, arXiv:1510.00702





LUX 85.3 live-days, PRL 2014



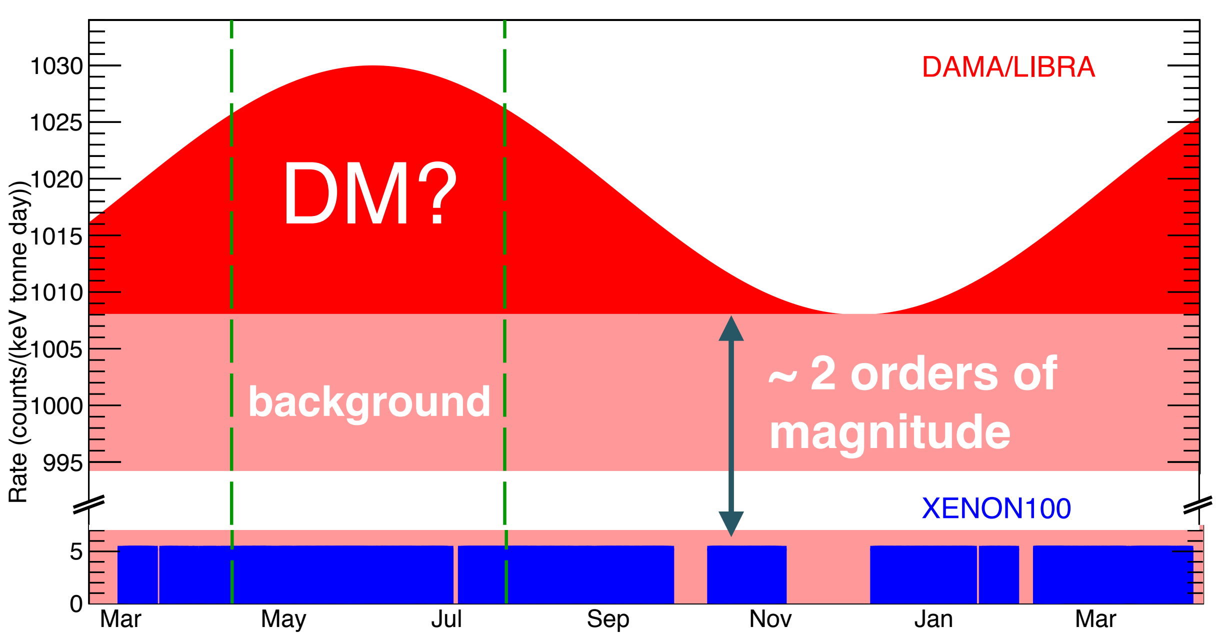
PandaX 80.1 live-days, arXiv 1505.00771

New XENON100 results

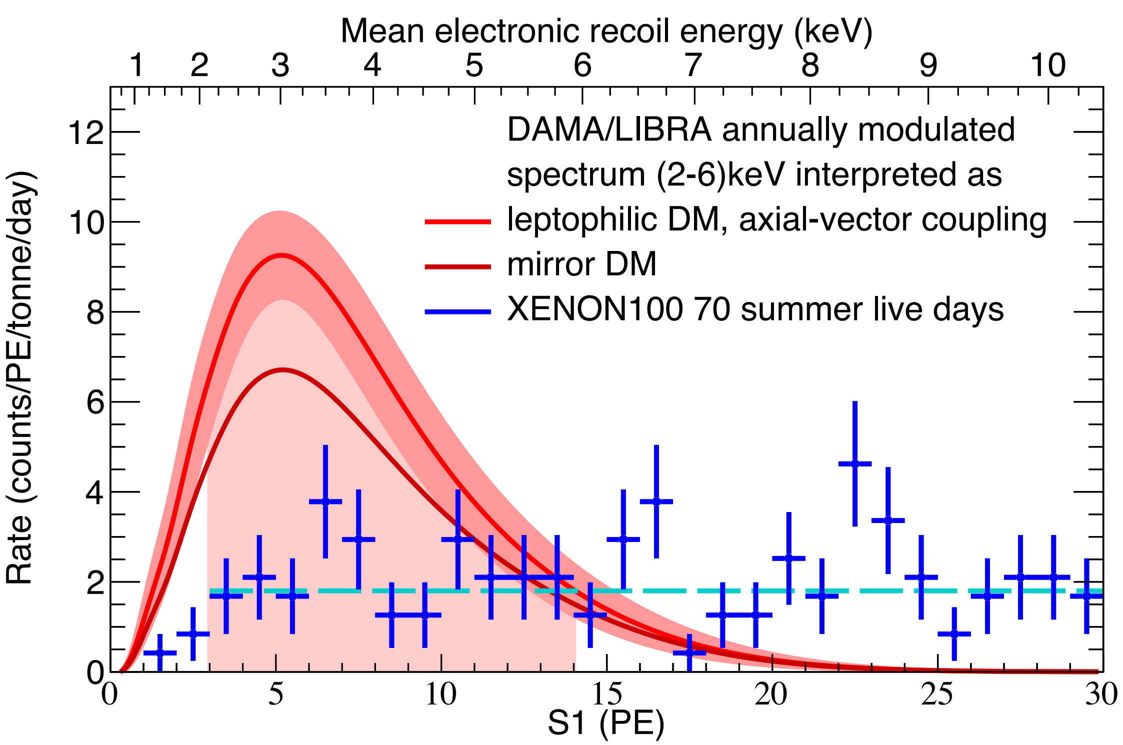
- Dark matter particles interacting with e^-
  - XENON100's ER background lower than DAMA modulation amplitude

➡ search for a signal above background in the ER spectrum

XENON collaboration, arXiv: 1507.07747, Science 349, 2015



Consider the 70 days with the largest signal

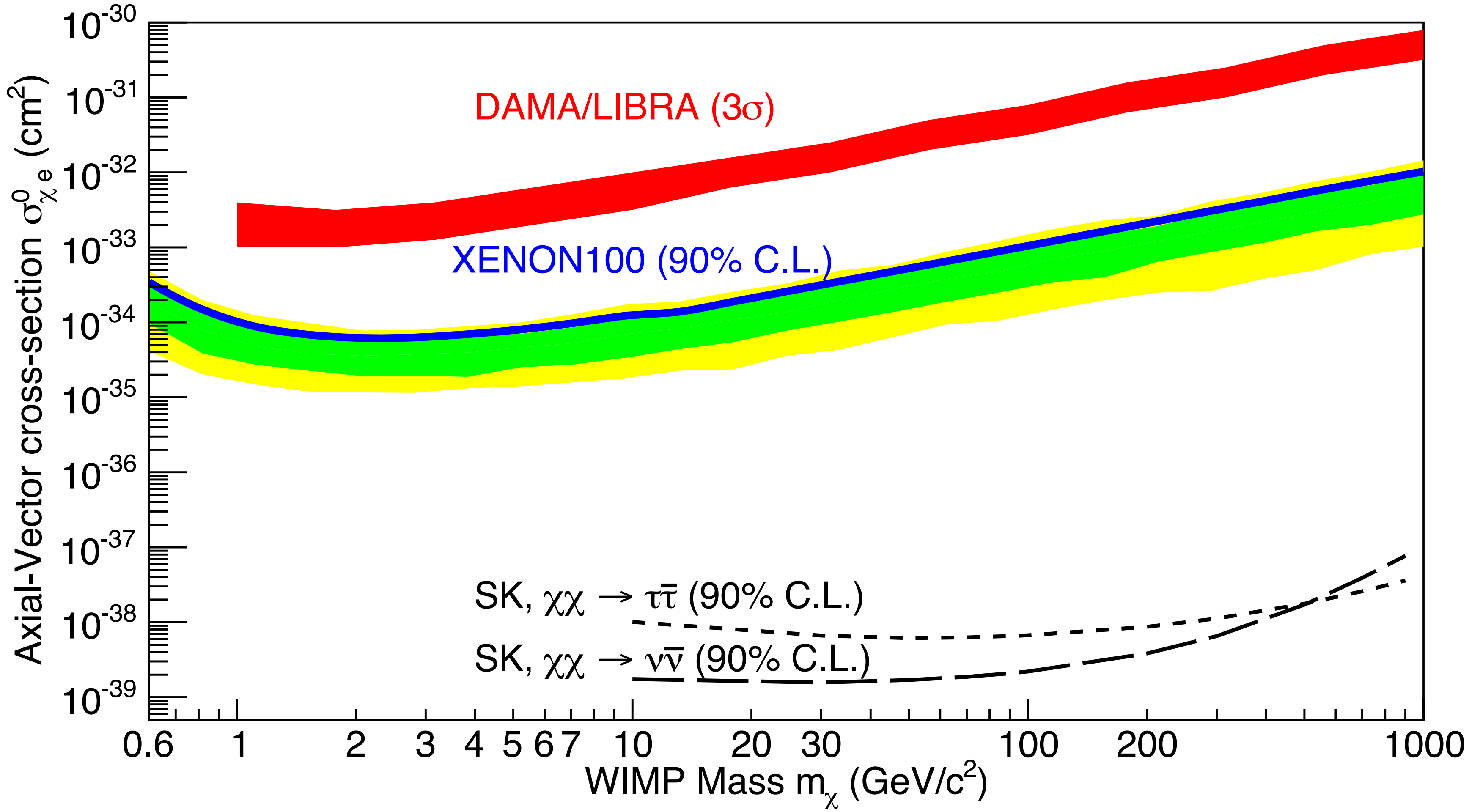


DAMA/LIBRA modulated spectrum as would be seen in XENON100 (for axial-vector WIMP-e^- scattering)

XENON100 excludes leptophilic models

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

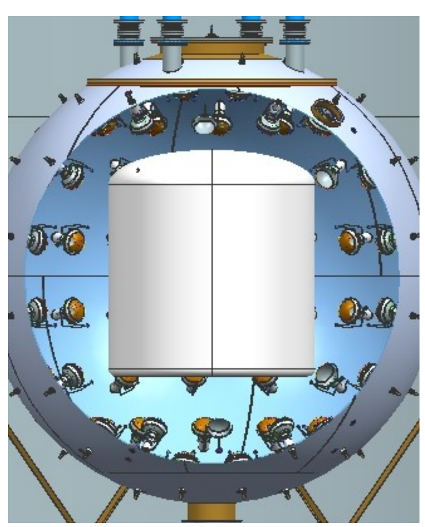
XENON collaboration, arXiv: 1507.07747, Science 349, 2015



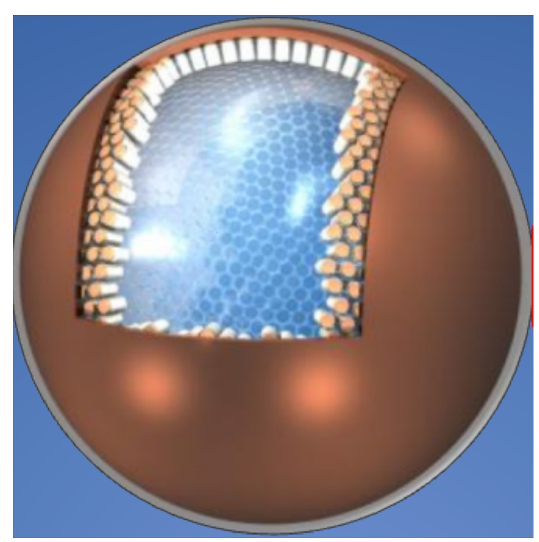
Future noble liquid detectors

- **Under construction: XENON1T/nT (3.3 t/ 7t LXe) at LNGS**
- Proposed LXe: LUX-ZEPLIN 7t *(approved)*, XMASS 5t LXe
- Proposed LAr: DarkSide 20 t LAr, DEAP 50 t LAr
- Design & R&D studies: DARWIN 30-50 t LXe; ARGO 300 t LAr

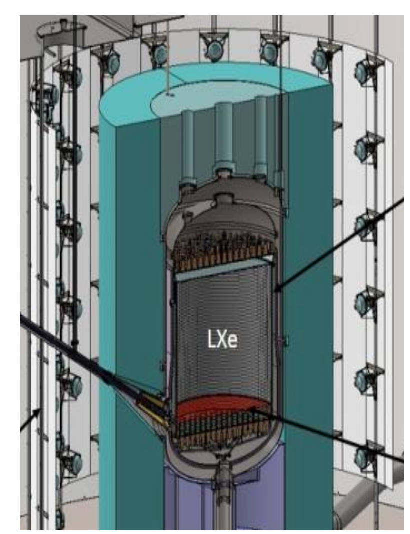
XENON1T: 3.3 t LXe



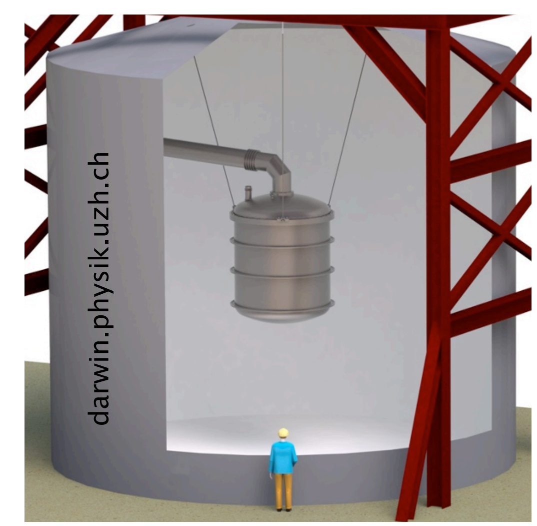
DarkSide: 20 t LAr



XMASS: 5t LXe



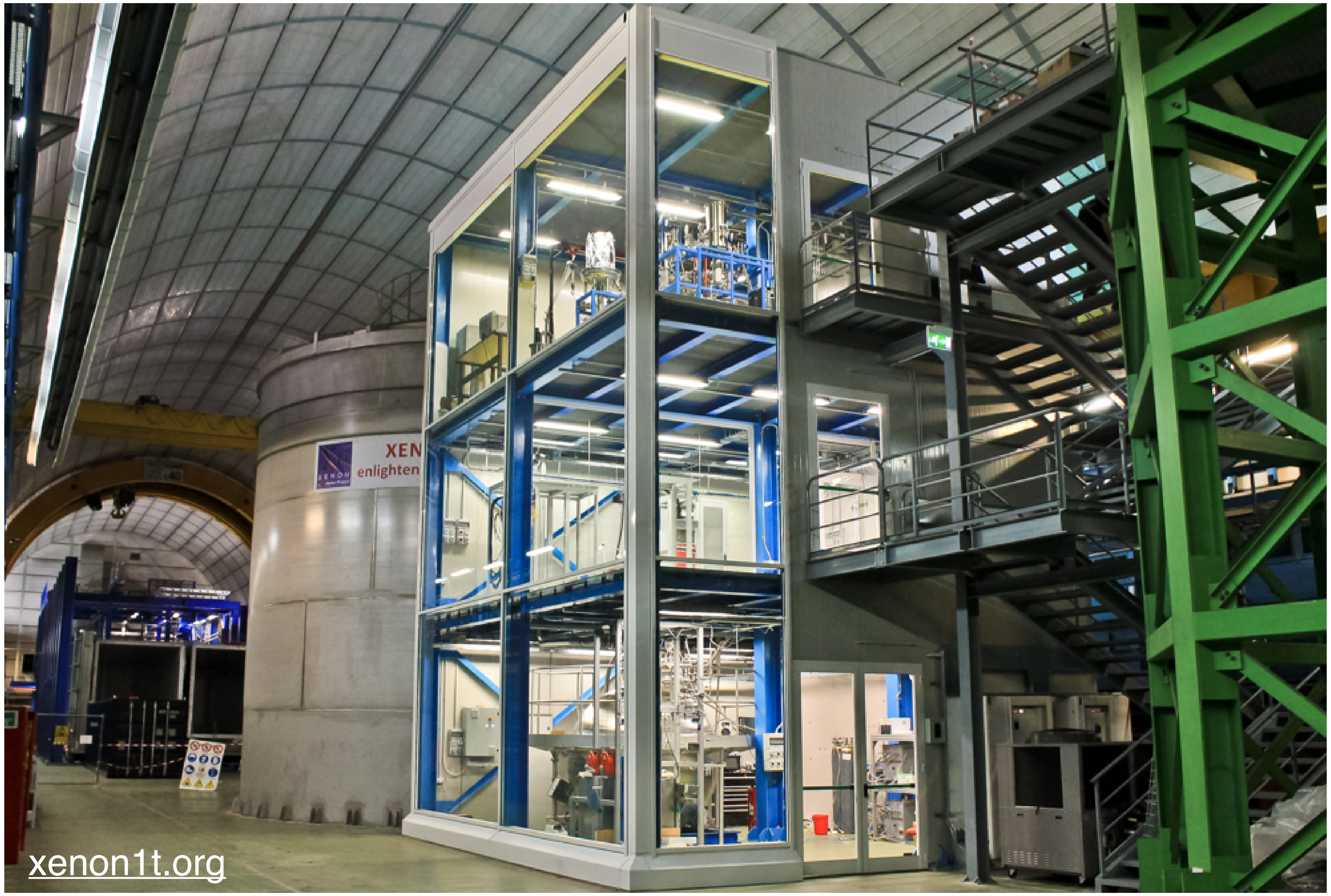
LZ: 7t LXe



DARWIN: 50 t LXe

The XENON1T experiment

- Under construction at LNGS since autumn 2013; commissioning planned for late 2015
- Total (active) LXe mass: 3.3 t (2 t), 1 m electron drift, 248 3-inch PMTs in two arrays
- Background goal: 100 x lower than XENON100 ~ 5×10^{-2} events/(t d keV)

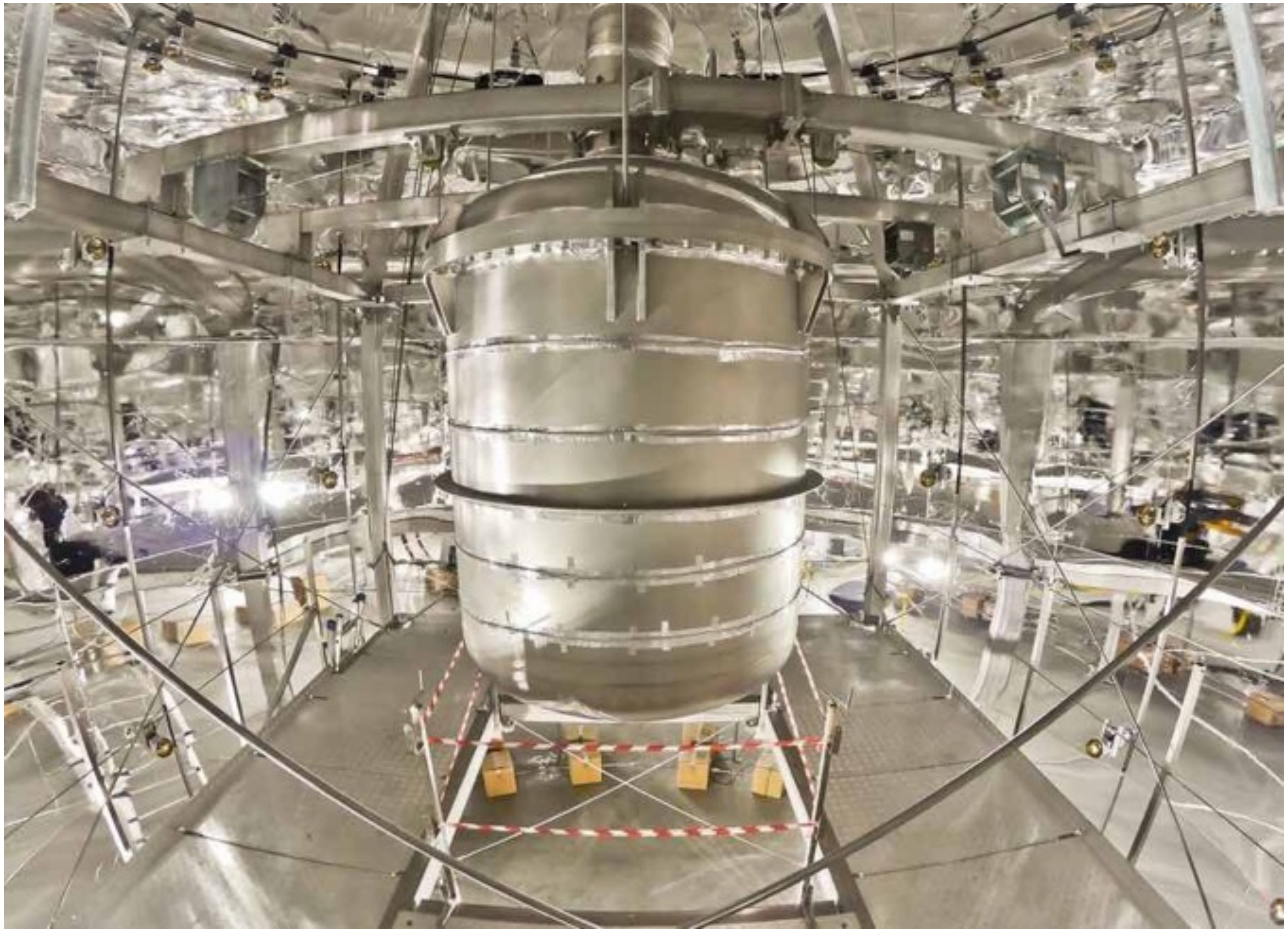


XENON1T: status of construction work

- Water Cherenkov shield built and instrumented
- Cryostat support, service building, electrical plant completed
- Several subsystems (cryostat, cryogenics, storage, purification, cables & fibres, pipes) installed and under commissioning underground

XENON1T: status of construction work

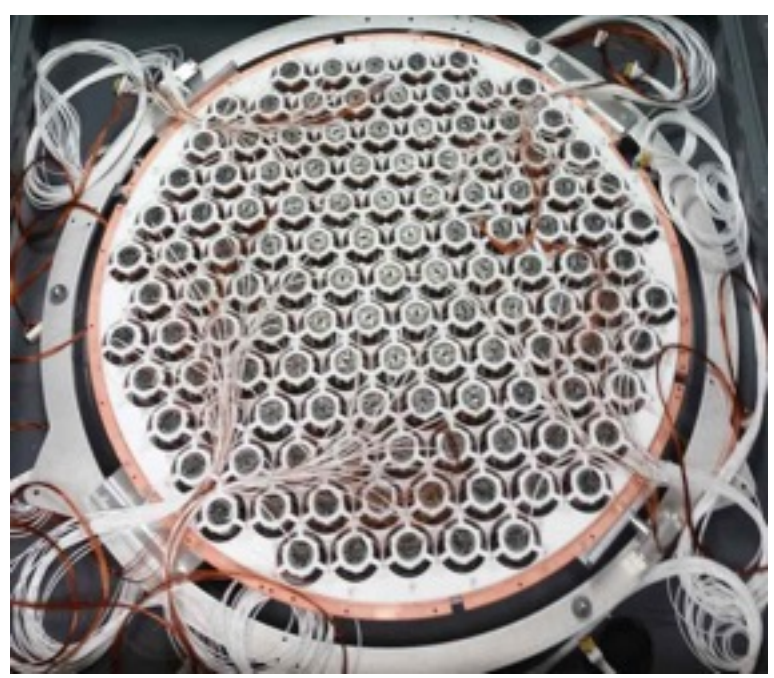
- Water Cherenkov shield built and instrumented



The XENON1T inner detector

- PMTs tested at cryogenic temperatures; arrays with electronics & cables assembled
- TPC assembly and cold tests completed; **installation at LNGS in October/November 2015**

The TPC



PMT array, bases & cables

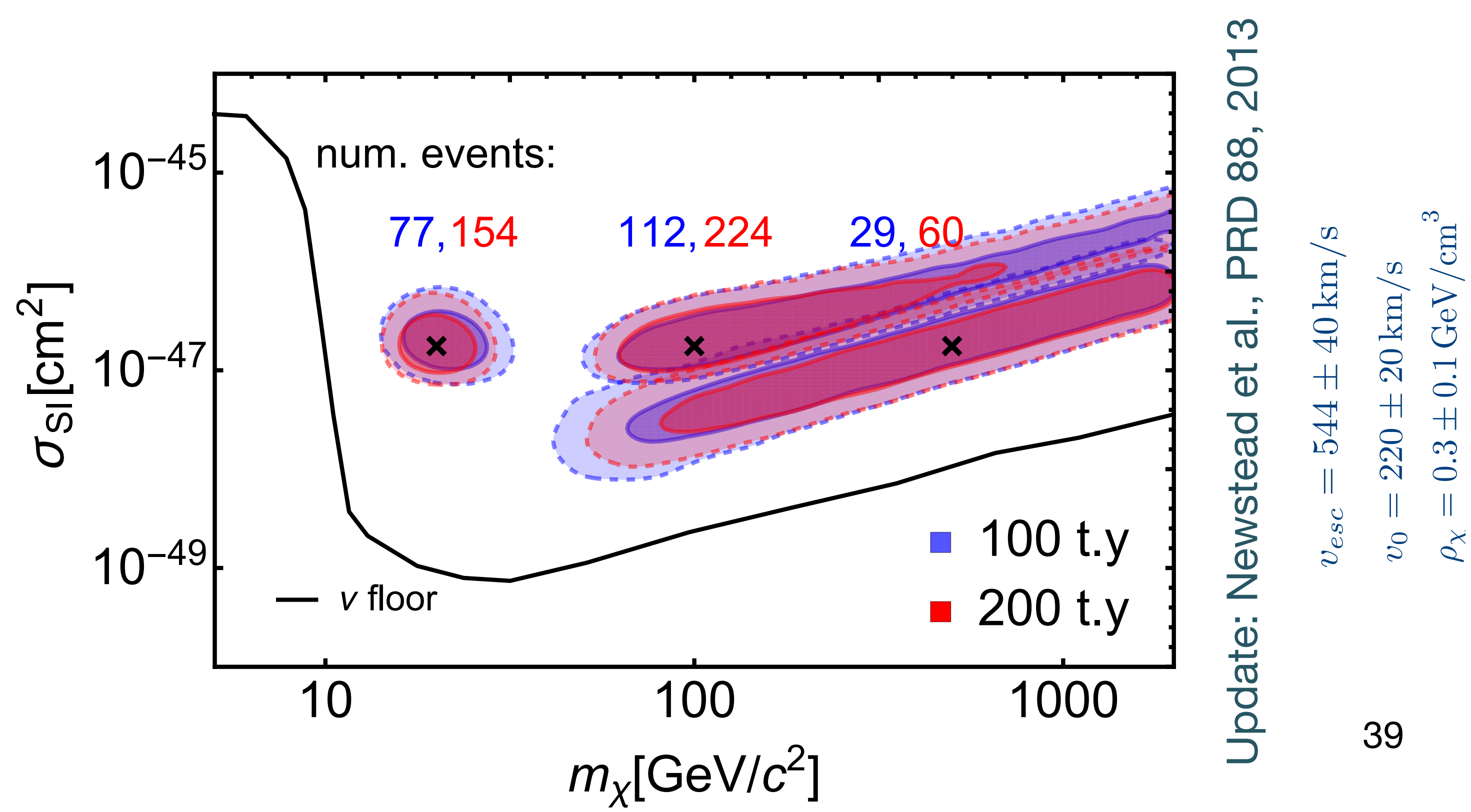
TPC assembly, cool down tests

The XENON1T inner detector

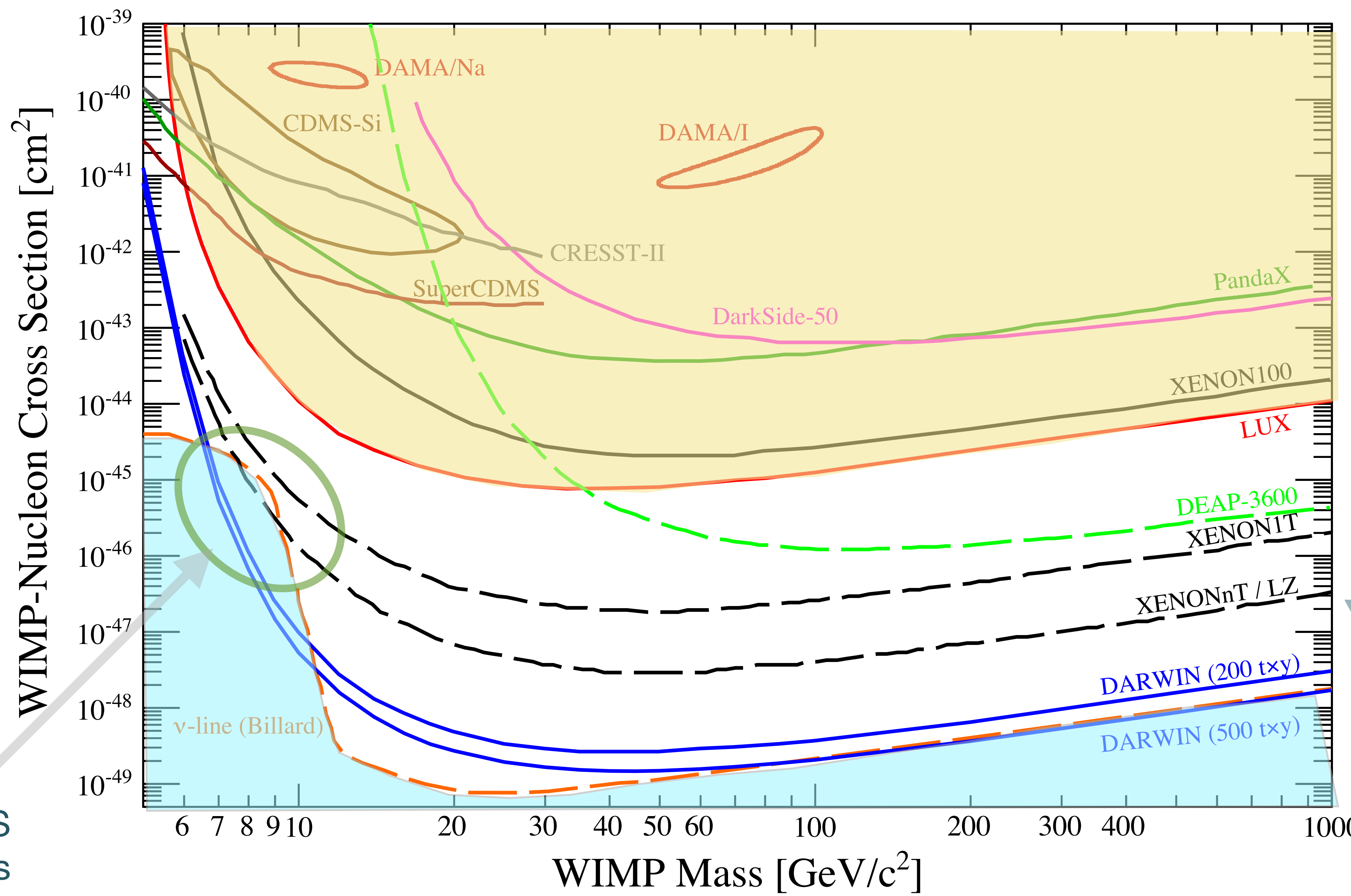
- PMTs tested at cryogenic temperatures; now arrays under final assembly
- TPC assembly and cold tests completed; installation at LNGS in October/November 2015

DARWIN - towards WIMP spectroscopy

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



Sensitivity for spin-independent cross sections



arXiv:1506.08309 (detailed WIMP study)

JCAP10(2015)016

4 orders of magnitude to go!

^{8}B CNNS neutrinos within reach

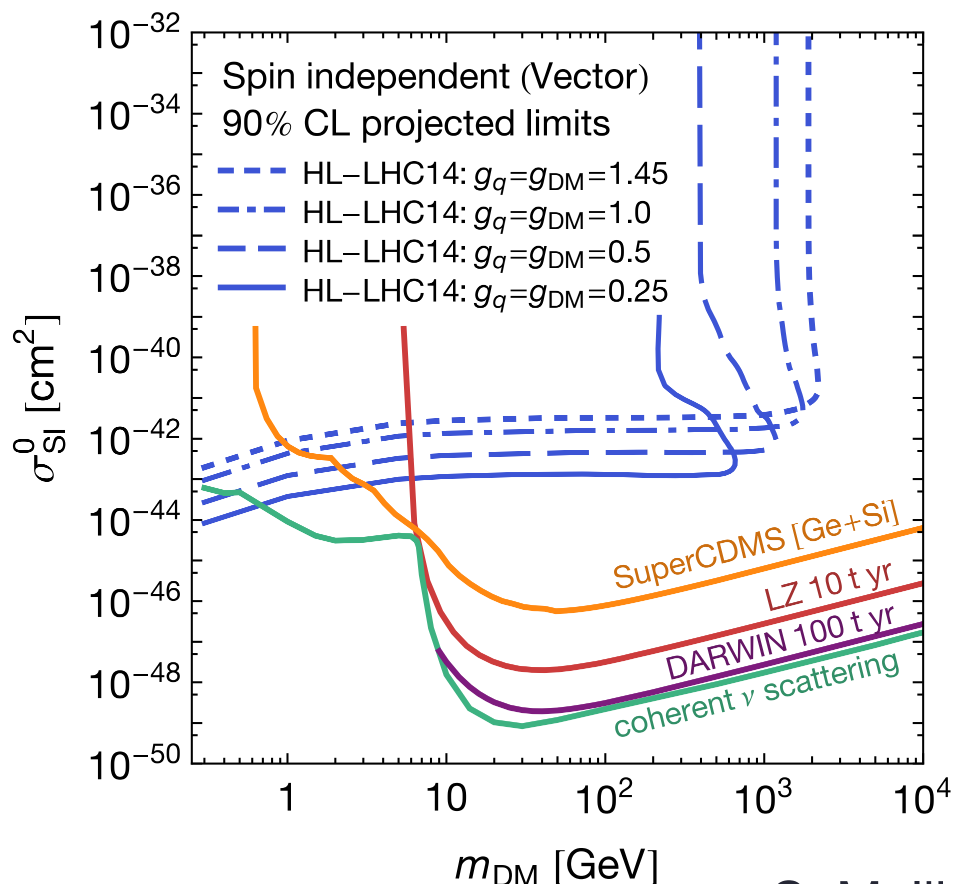
Note: “nu floor” = 3-sigma detection line at 500 CNNS events above 4 keV

Accelerator searches

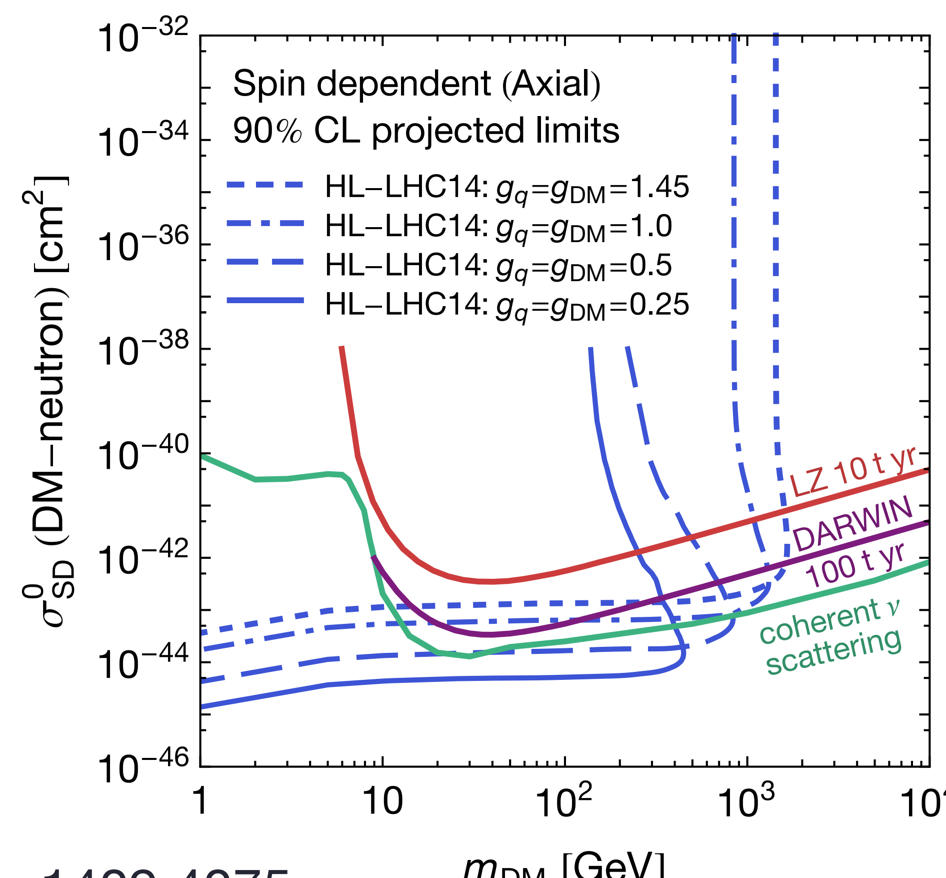
- **Minimal simplified DM model with only 4 variables: m_{DM}, M_{med}, g_{DM}, g_q**
- Here DM = Dirac fermion interacting with a vector or axial-vector mediator; equal-strength coupling to all active quark flavours

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

Spin independent



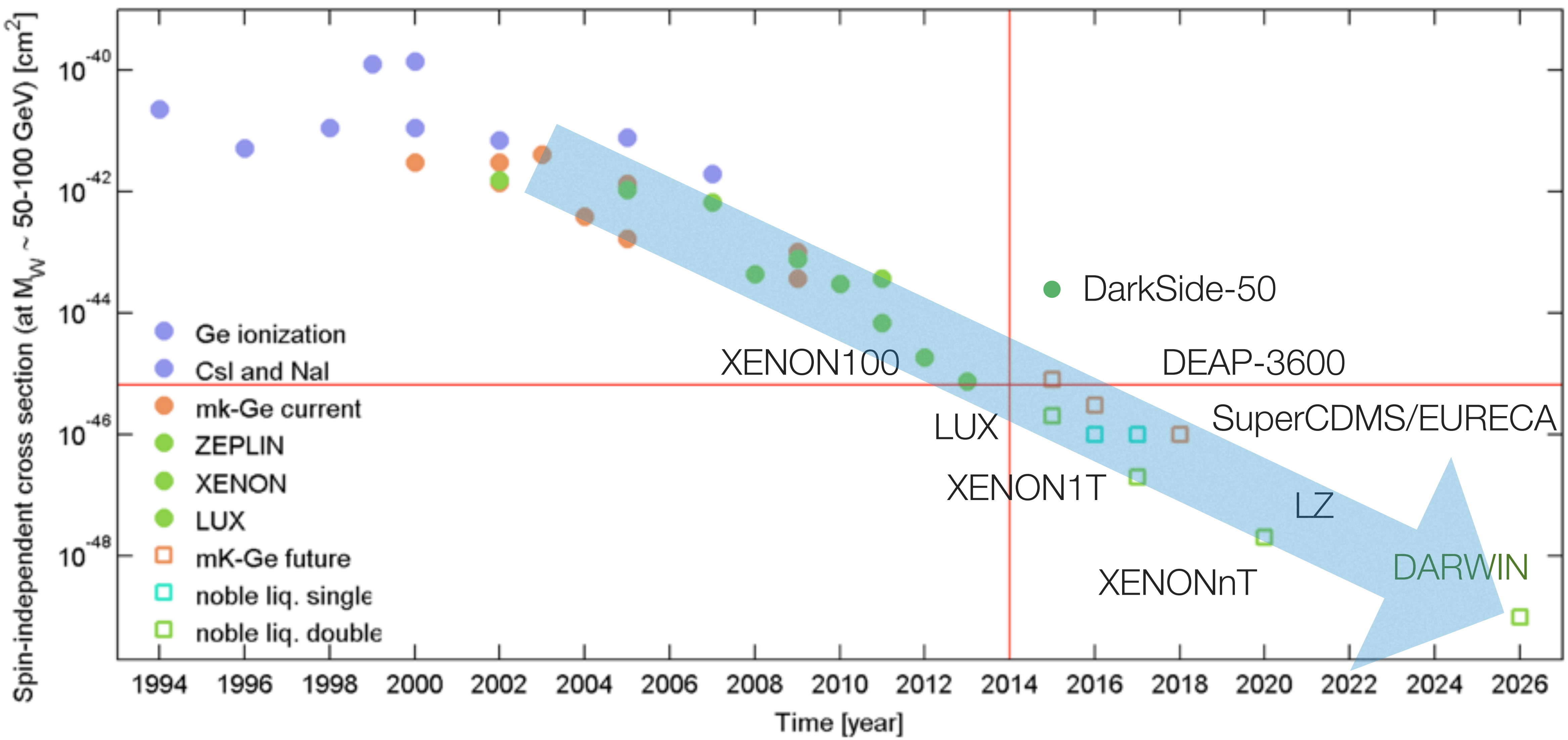
Spin dependent



S. Malik et al., arXiv:1409.4075

WIMP-nucleon cross sections versus time

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



LB, Physics of the Dark Universe 4, 2014

Conclusions

Direct detection experiments have reached tremendous sensitivities

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

Excellent prospects for discovery

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

The end

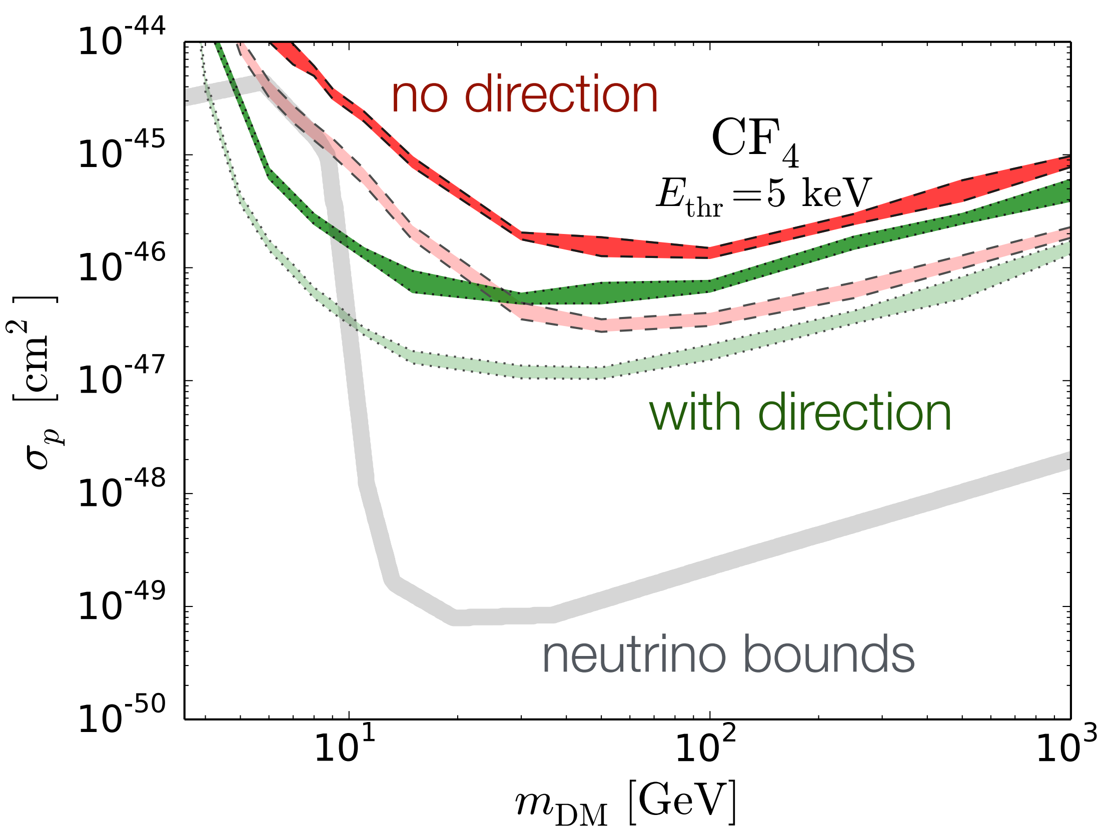
Of course, **“the probability of success is difficult to estimate, but if we never search, the chance of success is zero”**

G. Cocconi & P. Morrison, Nature, 1959

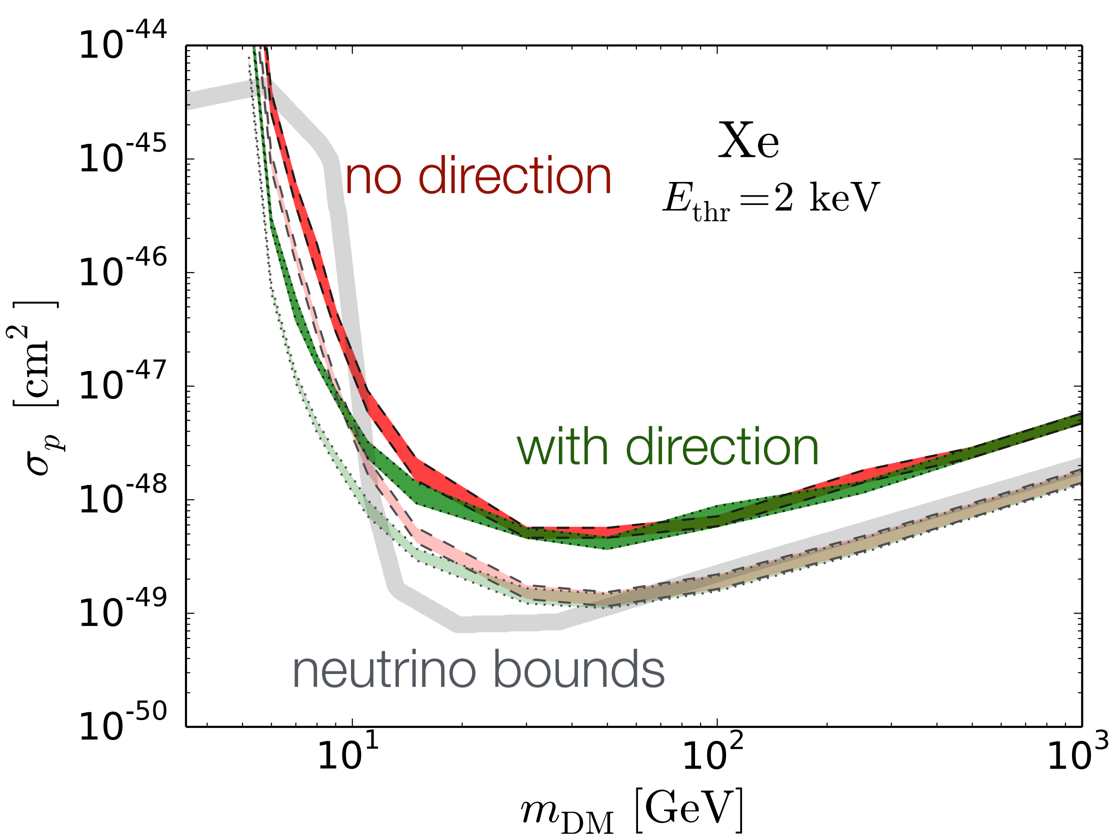
Will directional information help?

- Yes, but mostly at low WIMP masses
- Directional detection techniques currently in R&D phase
- Would be very challenging to reach 10^{-48} - 10^{-49} cm^2 with these techniques

36.6 t yr exposure, 500 (solar) nu events



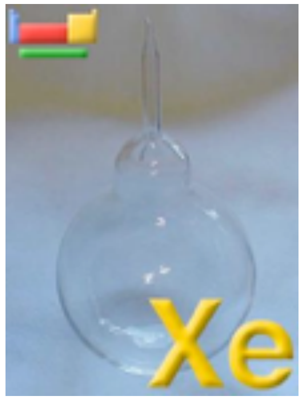
367 t yr exposure, 500 nu events



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

Why xenon for direct dark matter detection?

- Dense, homogeneous target with self-shielding; fiducialization
- Large detector masses feasible at moderate costs
- High light (40 photons/keV) and charge (W_{LAr} = 24 eV, W_{LXe} = 15 eV) yields

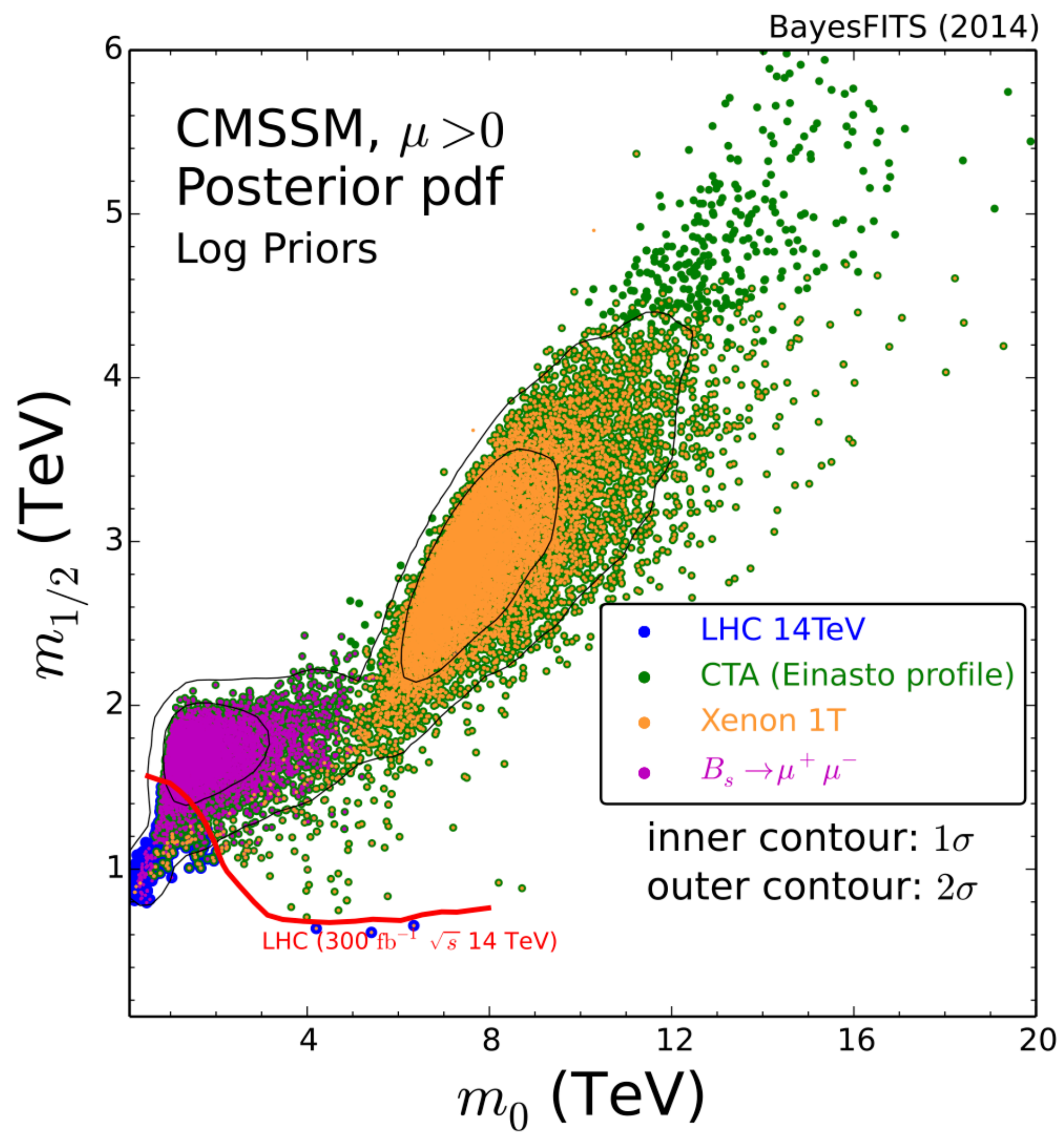


Properties [unit]	**Xe**	**Ar**	**Ne**
Atomic number:	54	18	10
Mean relative atomic mass:	131.3	40.0	20.2
Boiling point T_b at 1 atm [K]	165.0	87.3	27.1
Melting point T_m at 1 atm [K]	161.4	83.8	24.6
Gas density at 1 atm & 298 K [g l^{-1}]	5.40	1.63	0.82
Gas density at 1 atm & T_b [g l^{-1}]	9.99	5.77	9.56
Liquid density at T_b [g cm^{-3}]	2.94	1.40	1.21
Dielectric constant of liquid	1.95	1.51	1.53
Volume fraction in Earth's atmosphere [ppm]	0.09	9340	18.2

W. Ramsay: "These gases occur in the air but sparingly as a rule, for while argon forms nearly 1 hundredth of the volume of the air, neon occurs only as 1 to 2 hundred-thousandth, helium as 1 to 2 millionth, krypton as 1 millionth and xenon only as about 1 twenty-millionth part per volume. *This more than anything else will enable us to form an idea of the vast difficulties which attend these investigations*. "

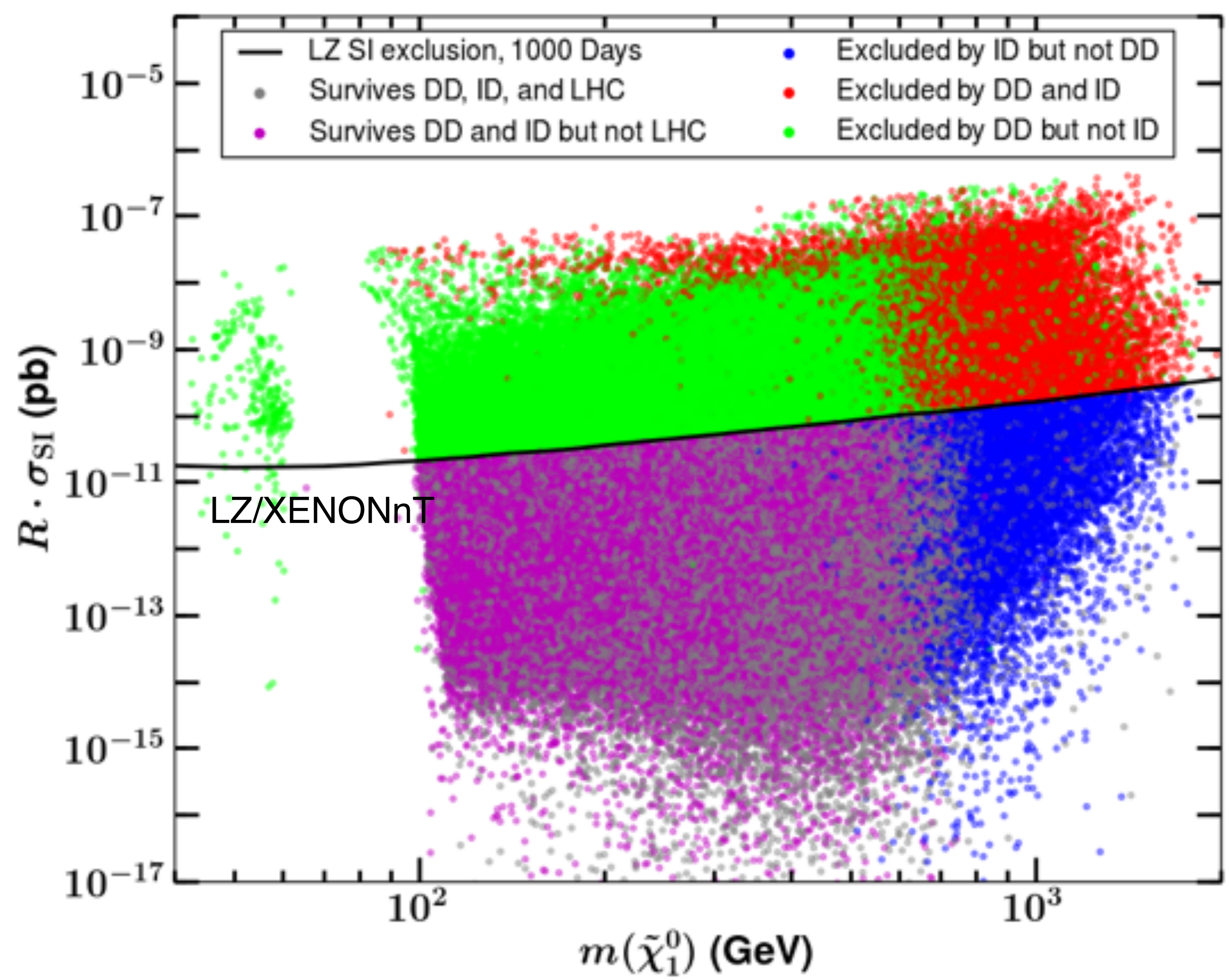
Complementarity DD, ID, LHC

CMSSM



L. Rozkowski, Stockholm 2015

pMSSM



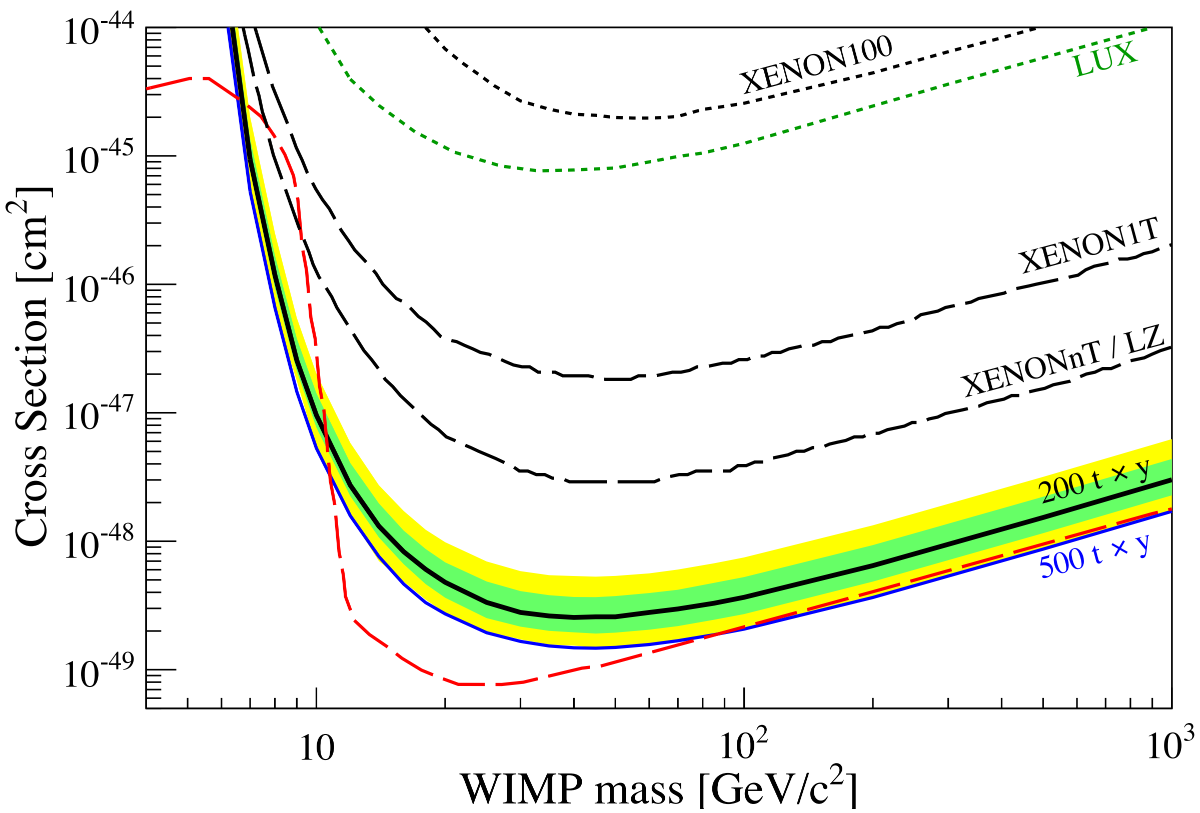
M. Cahill-Rowley, Phys.Rev. D91 (2015) 055011

DARWIN WIMP sensitivity

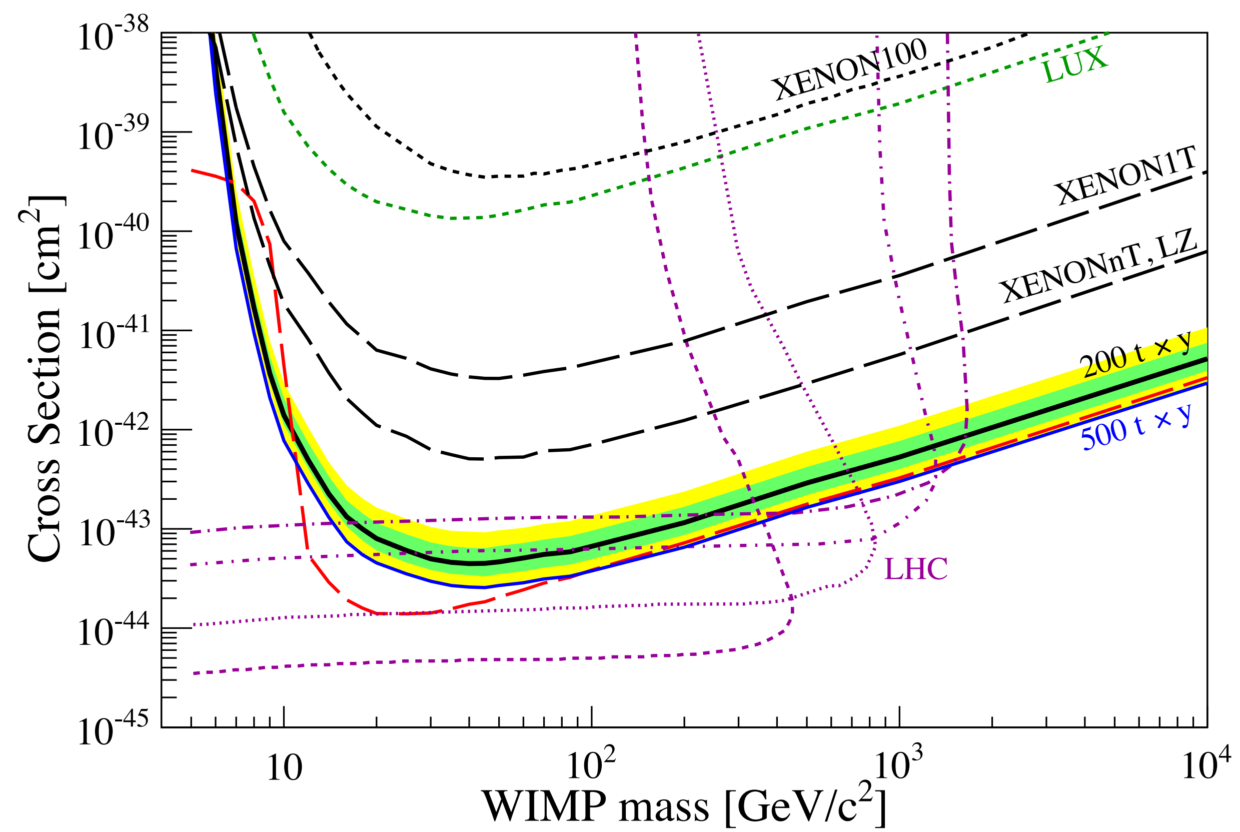
- E = [5-35] keV_{nr}

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

Spin-independent



Spin-dependent



arXiv:1506.08309, JCAP 2015

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

Probing a modulation signal in XENON100

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

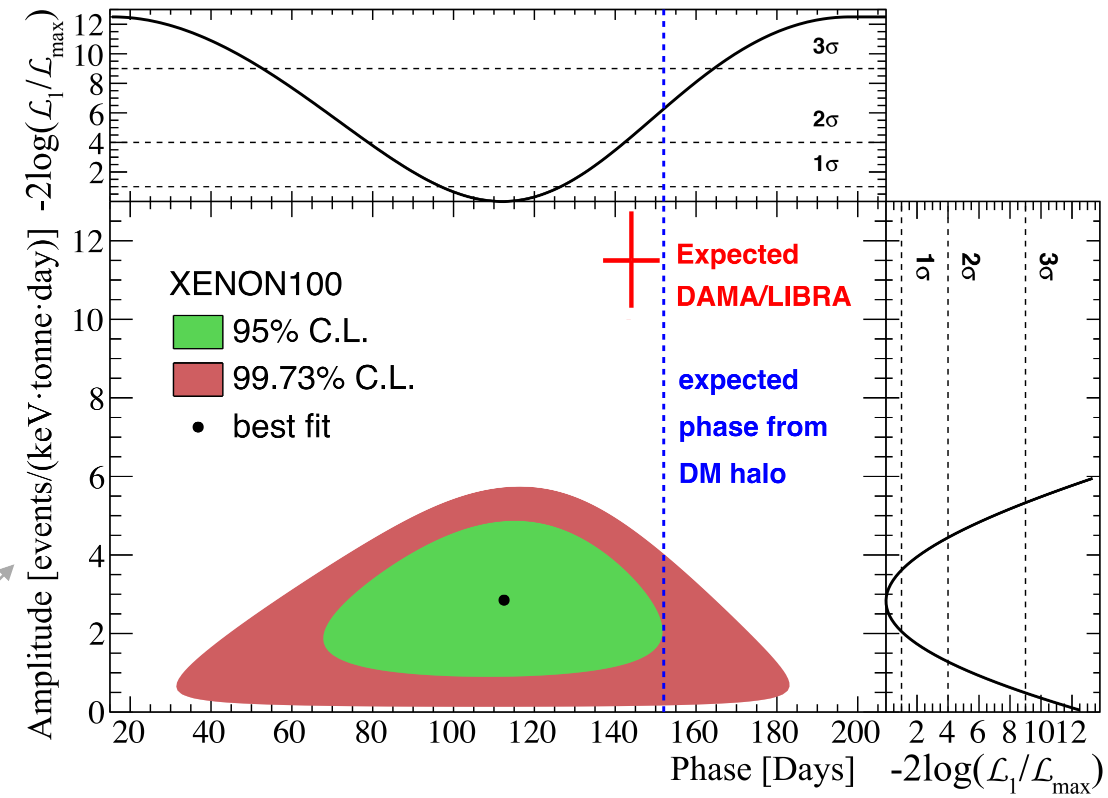
Acceptance *Background from known air leak* *Modulation*

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

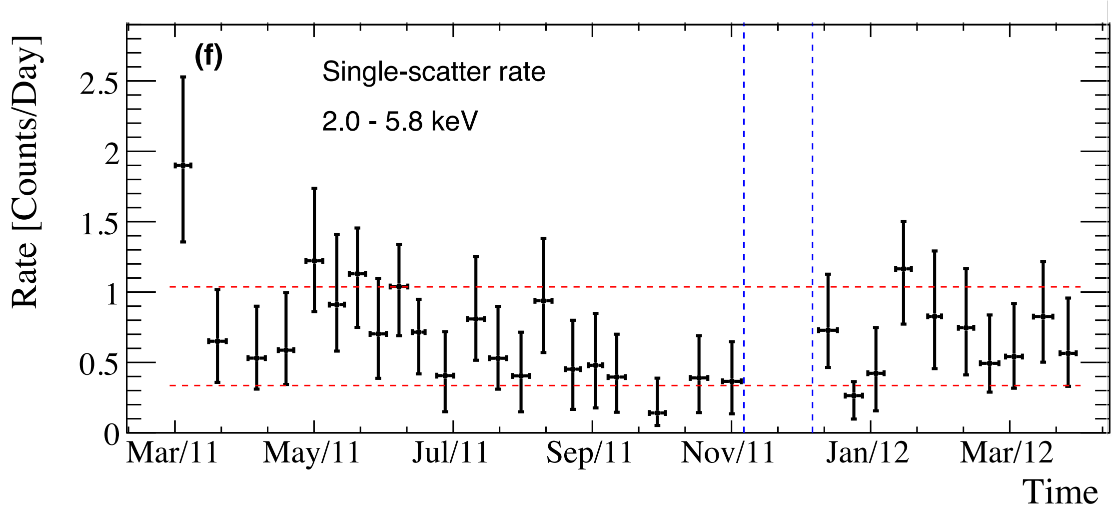
Normalized

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

Total observed events



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

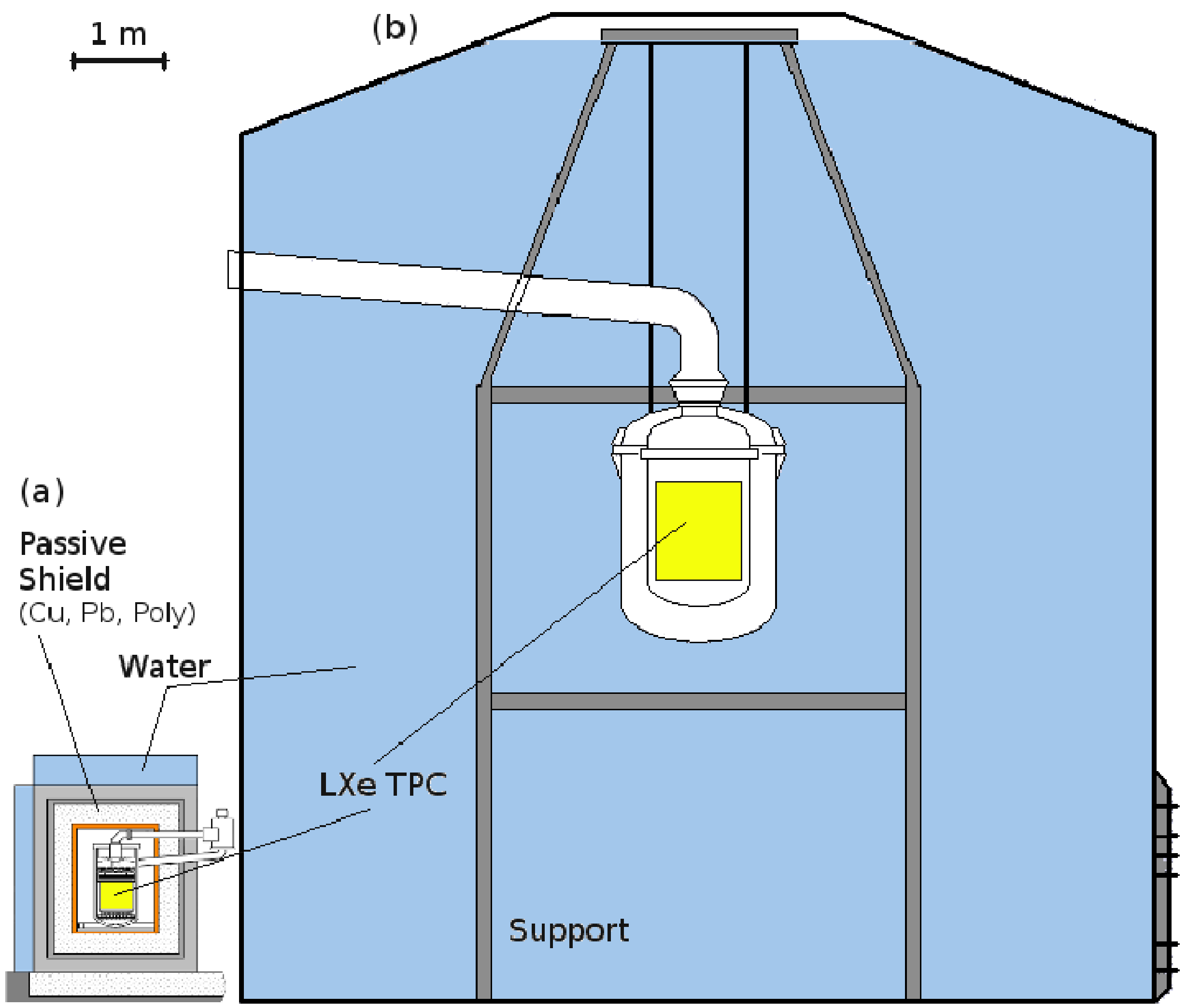


- Standard dark matter halo phase is disfavoured by 2.5-sigma

- Assuming V-A coupling of WIMPs to e^-, DAMA/LIBRA annual modulation is excluded at 4.8-sigma

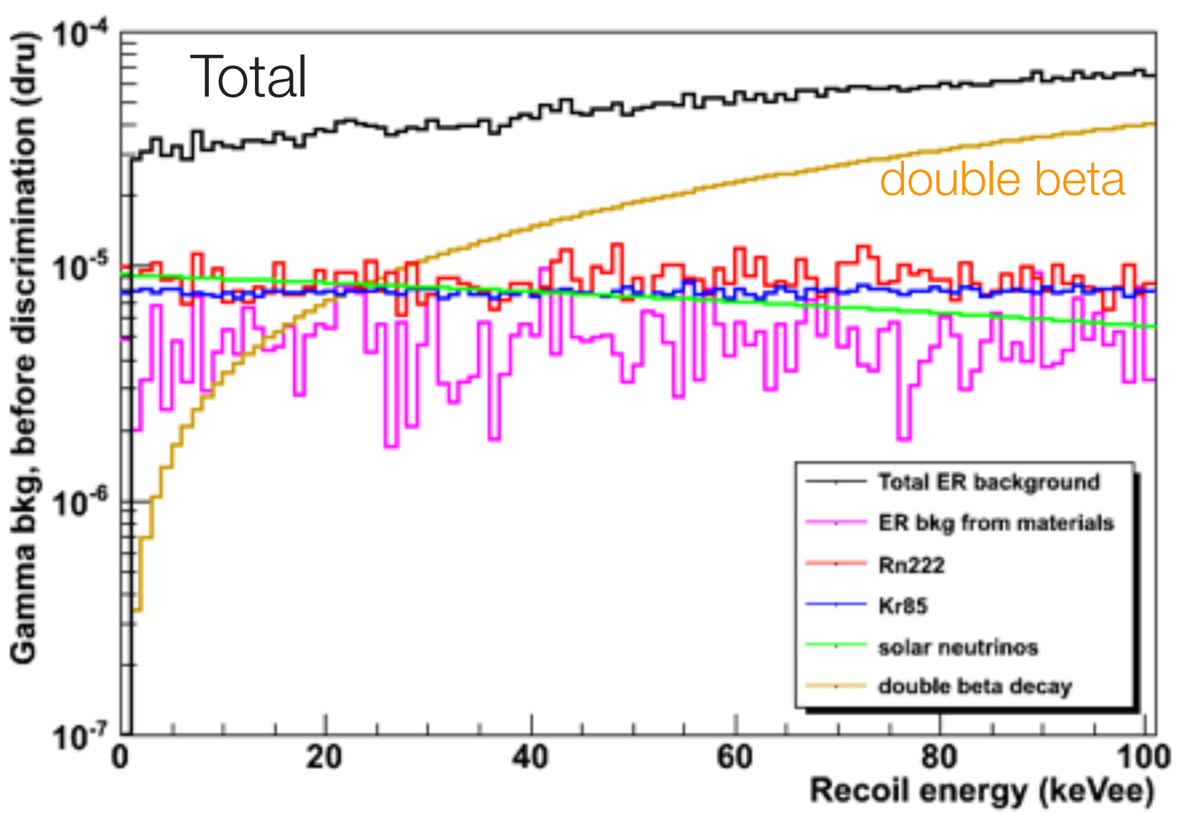
From XENON100 to XENON1T in numbers

	XENON100	XENON1T
Total LXe mass [kg]	161	3300
Background [dru]	5×10^{-3}	5×10^{-5}
^{222}Rn [μBq/kg]	~ 65	~ 1
^{nat}Kr [ppt]	~120	~0.2
e- drift [cm]	30	100
Cathode HV [kV]	-16	-100

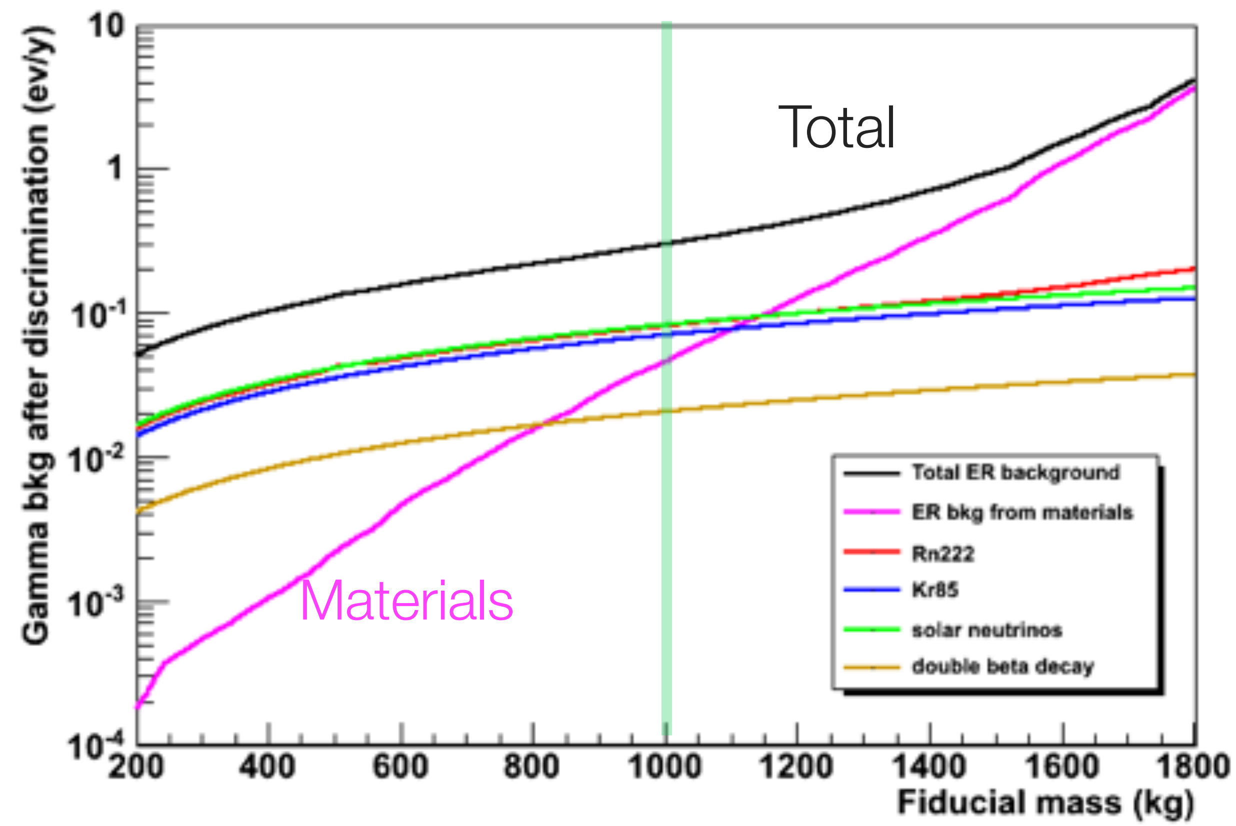


XENON1T background predictions

- Materials background: based on screening results for all detector components
- ^{85}Kr: 0.2 ppt of ^{nat}Kr with 2x10^{-11} ^{85}Kr; ^{222}Rn: 1 μBq/kg; ^{136}Xe double beta: 2.11x10^{21} y
- ER vs NR discrimination level: 99.75%; 40% acceptance for NRs
  - ➡ Total ERs: 0.3 events/year in 1 ton fiducial volume, [2-12] keV$_{ee}$
  - ➡ Total NRs: 0.2 events/year in 1 ton, [5-50] keV$_{nr}$ (muon-induced n-BG < 0.01 ev/year)



Background rate from various components

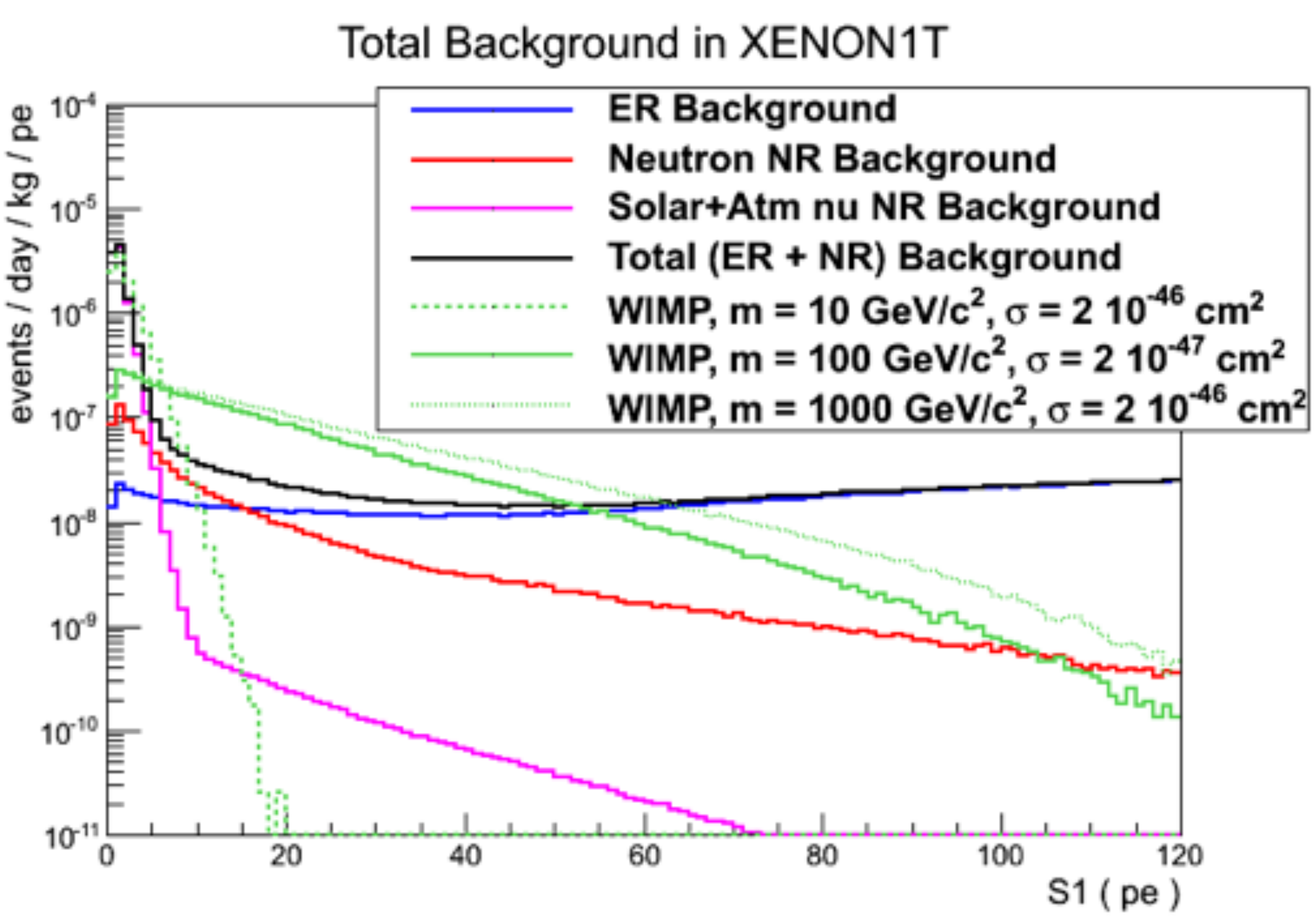


Background versus fiducial LXe mass

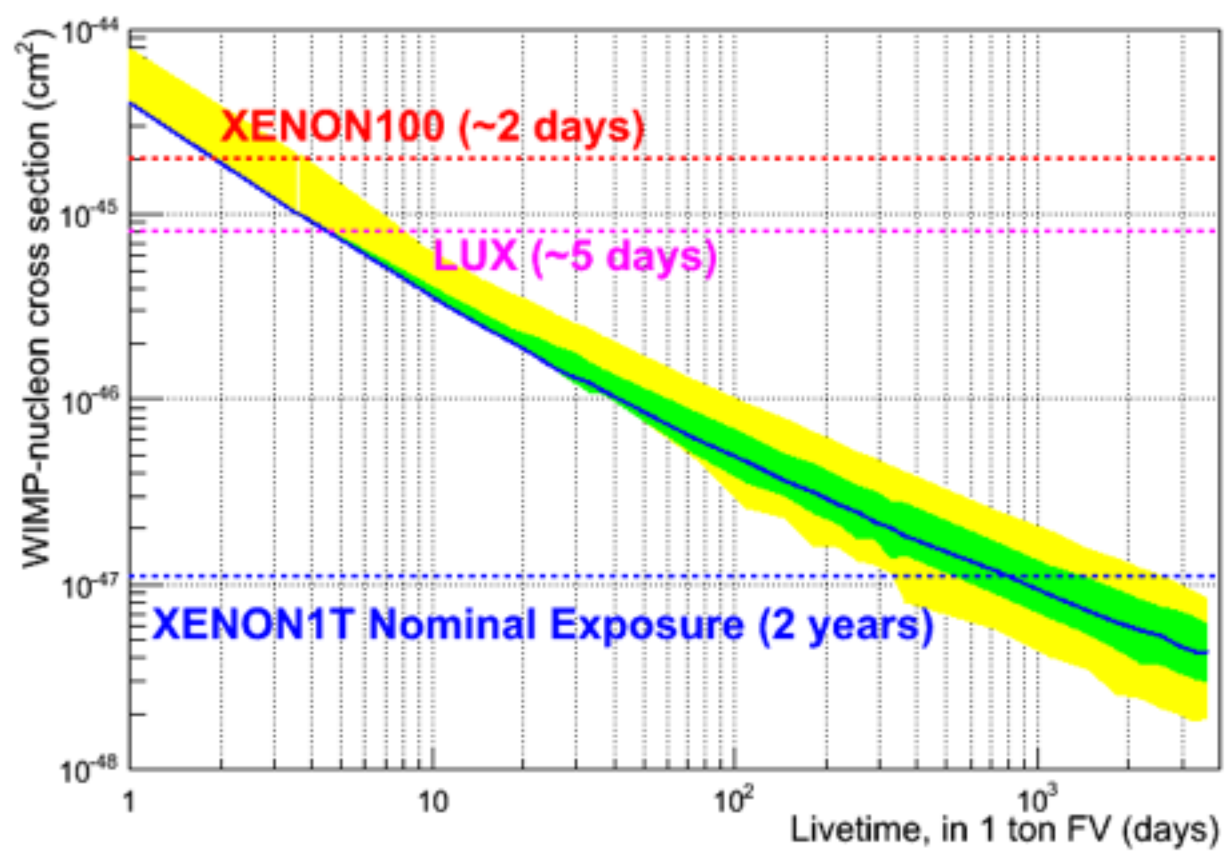
XENON1T backgrounds and WIMP sensitivity

Single scatters in 1 ton fiducial
99.75% S2/S1 discrimination
NR acceptance 40%
Light yield = 7.7 PE/keV at 0 field
L_{eff} = 0 below 1 keVnr

WIMP mass: 50 GeV
Fiducial LXe mass: 1 t
Sensitivity at 90% CL



ER + NR backgrounds and WIMP spectra

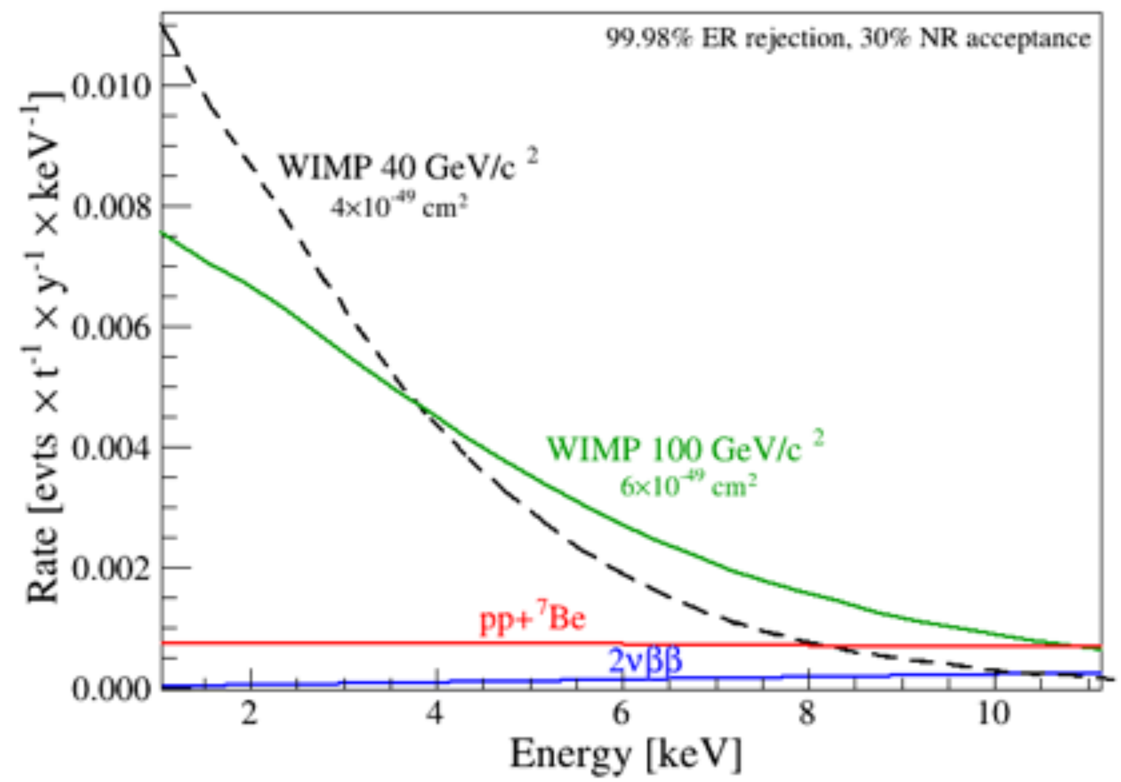


Sensitivity versus exposure (in 1 ton fiducial mass)

DARWIN backgrounds: electronic recoils

- Materials (cryostat, photosensors, TPC)
- ^{222}Rn in LXe: **0.1 μBq/kg (1 μBq/kg** => same background level as solar neutrinos)
- ^{nat}Kr in LXe: **0.1 ppt ^{nat}Kr (0.2 ppt ^{nat}Kr** => same background level as solar neutrinos)
- ^{136}Xe double beta decay
- Solar neutrinos (mostly pp, ^{7}Be)

WIMPs and backgrounds

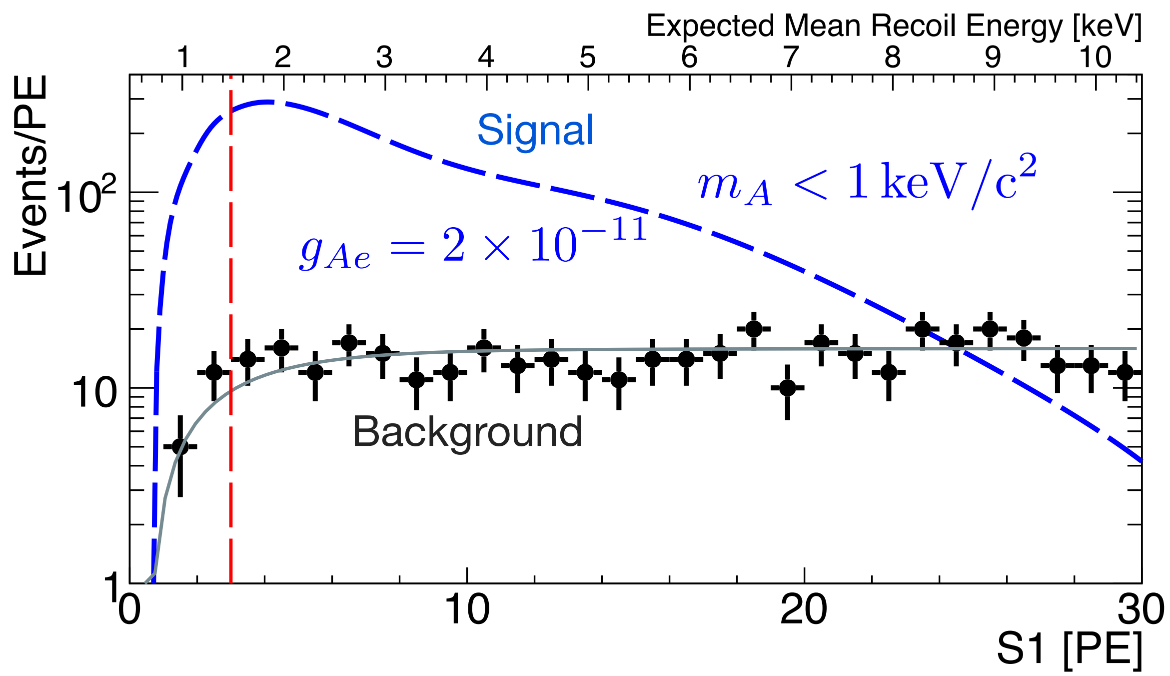


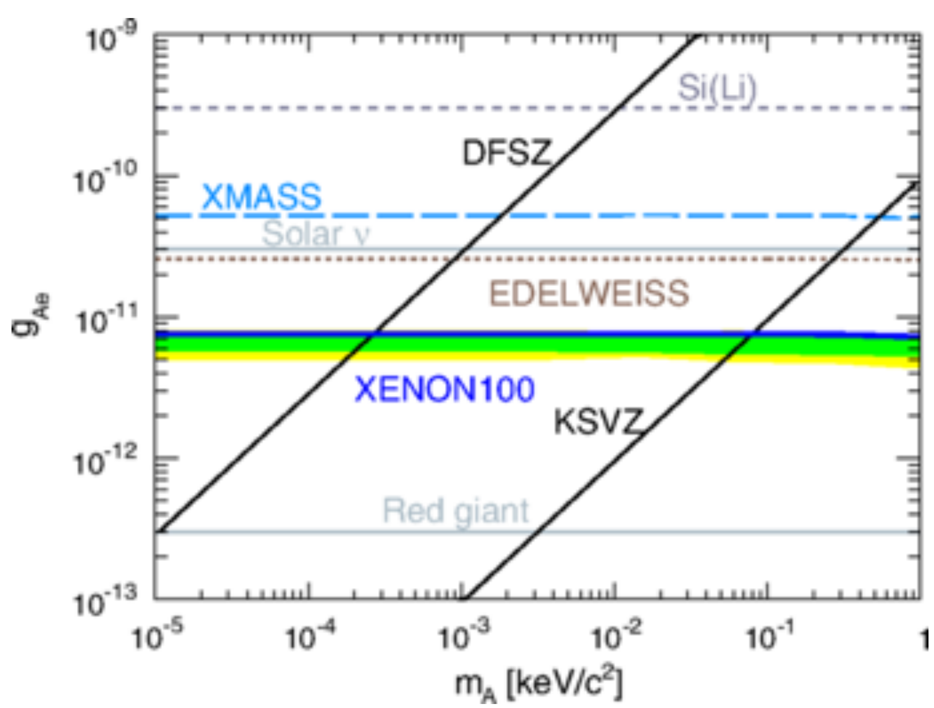
Channel	Before discr	After discr (99.98%)
pp + ^{7}Be neutrinos	95	0.488
Materials	1.4	0.007
^{85}Kr in LXe (0.1 ppt ^{nat}Kr)	40.4	0.192
^{222}Rn in LXe (0.1 μBq/kg)	9.9	0.047
^{136}Xe	56.1	0.036

1 t x yr exposure,
2-30 keVee

200 t x yr exposure
4-50 keVnr, 30% acceptance

Example: Solar axions with XENON100





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

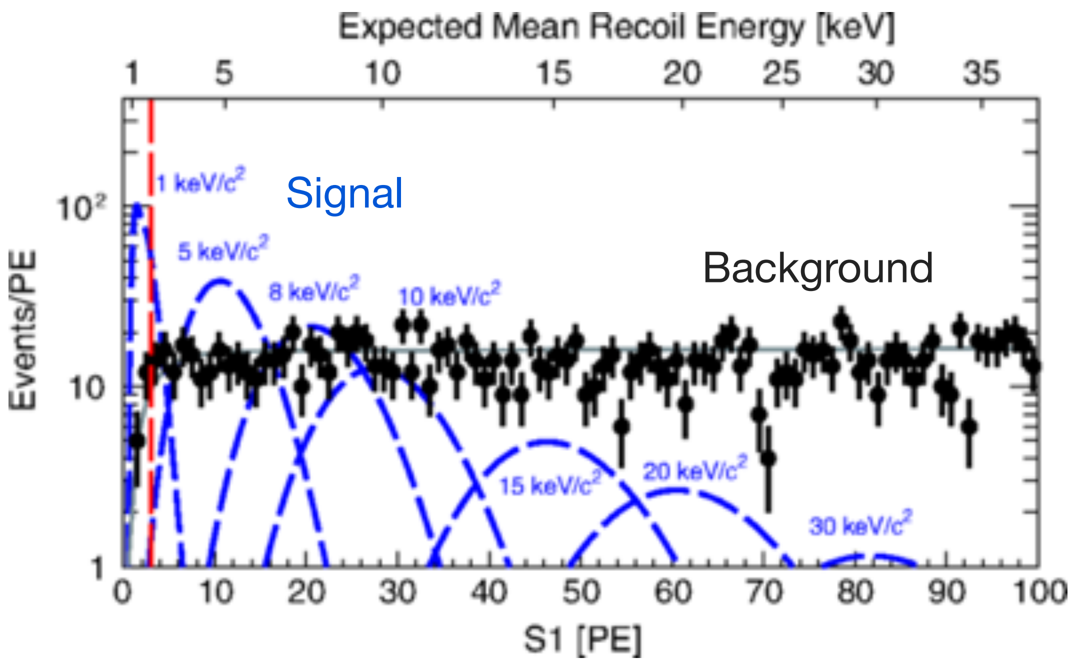
$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{g_{Ae}^2}{\beta_A}\frac{3E_A^2}{16\pi\alpha_{em}m_e^2}\left(1 - \frac{\beta_A^{2/3}}{3}\right)$$

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

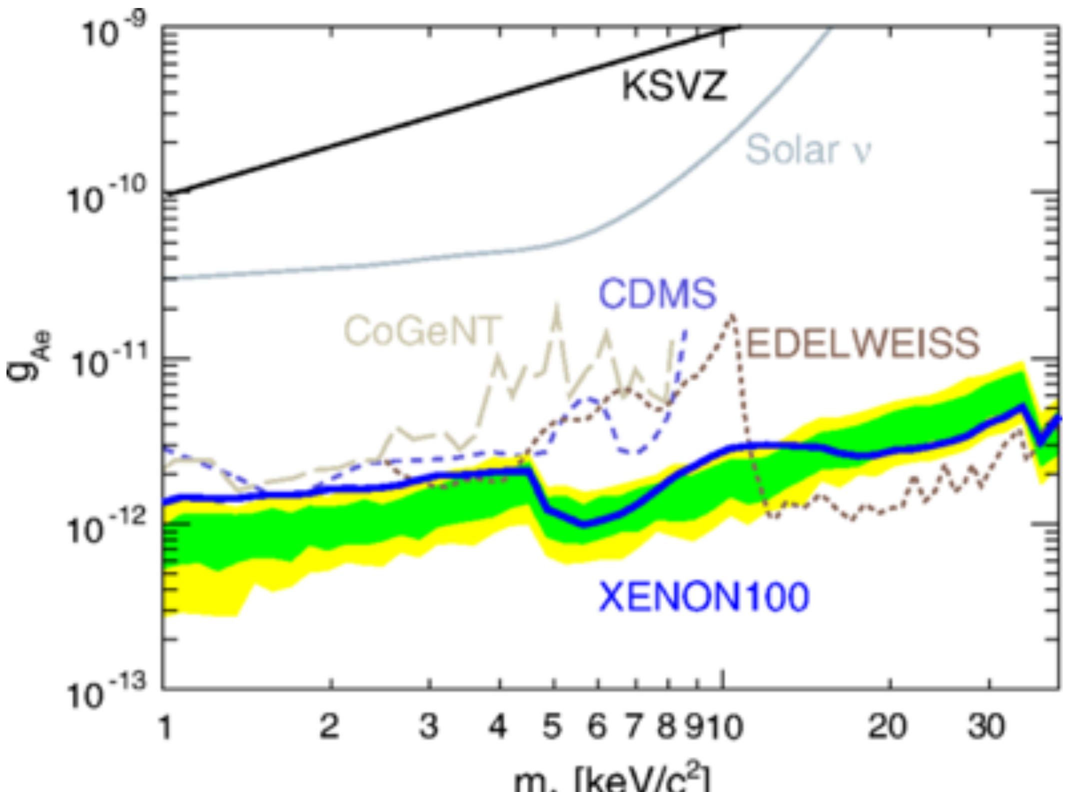
- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs (LB et al., PRD 87, 2013; arXiv:1303.6891)

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

Example: Galactic axion-like particles with XENON100



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



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

Expect line feature at ALP mass

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

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

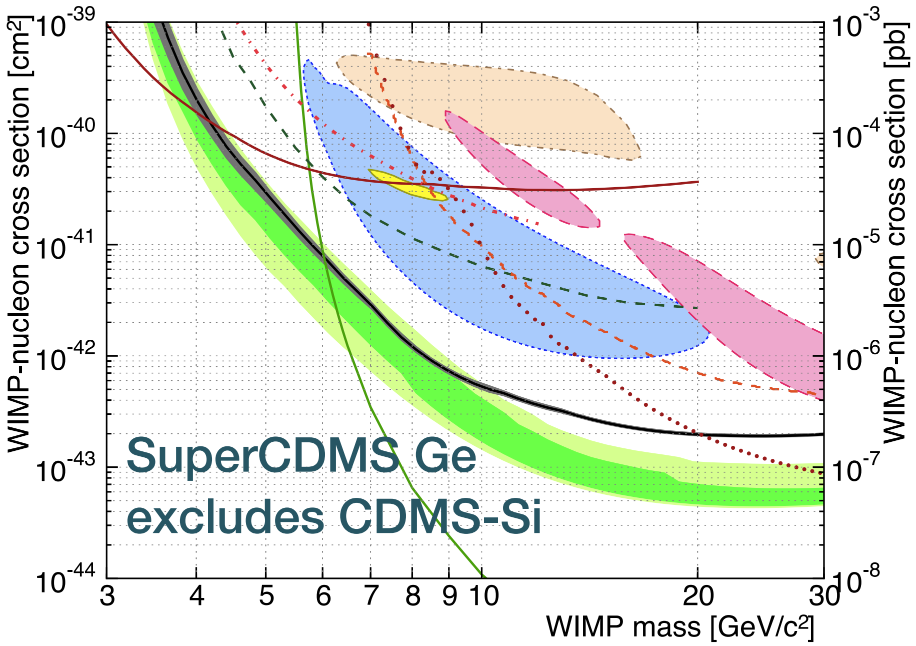
$$R \propto g_{Ae}^2$$

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

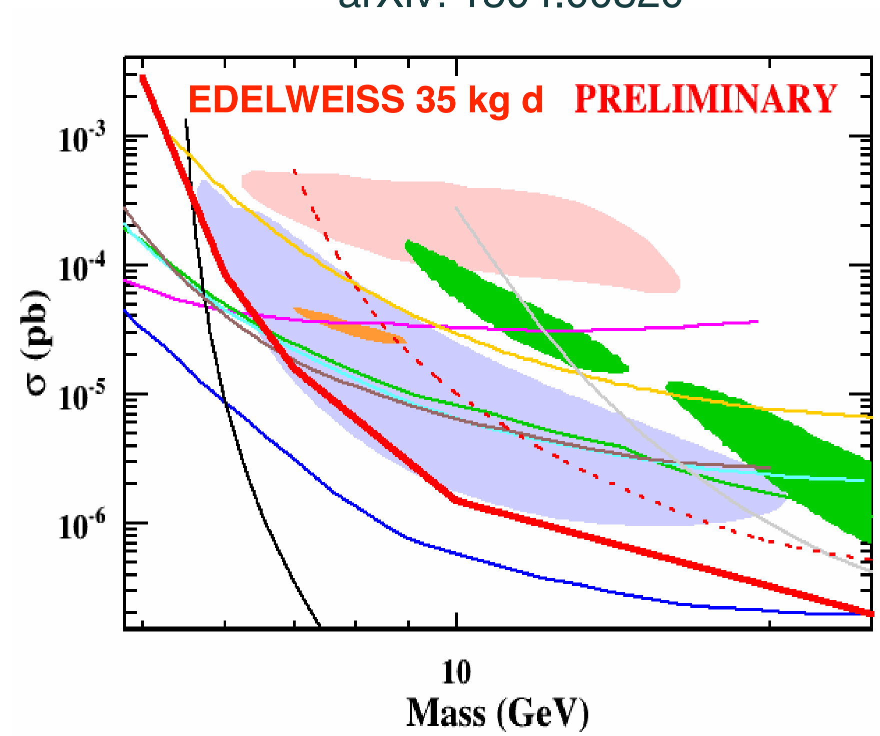
XENON, Phys. Rev. D 90, 062009 (2014)

Bolometers: recent results

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

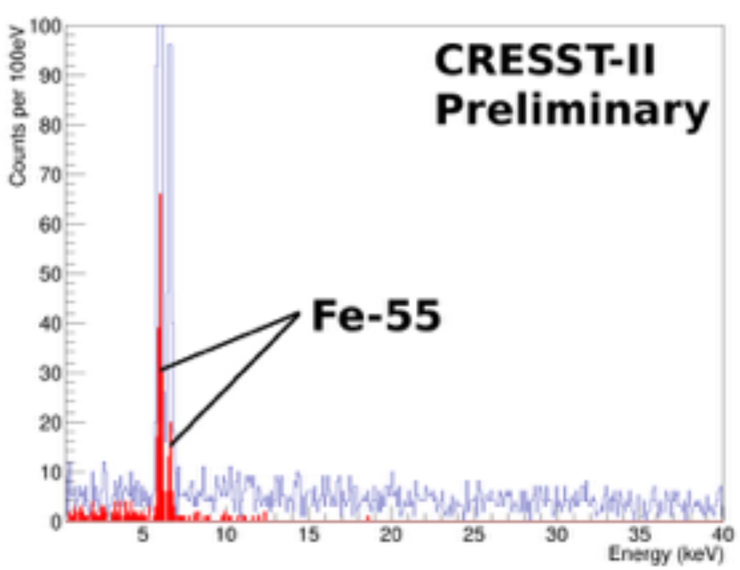


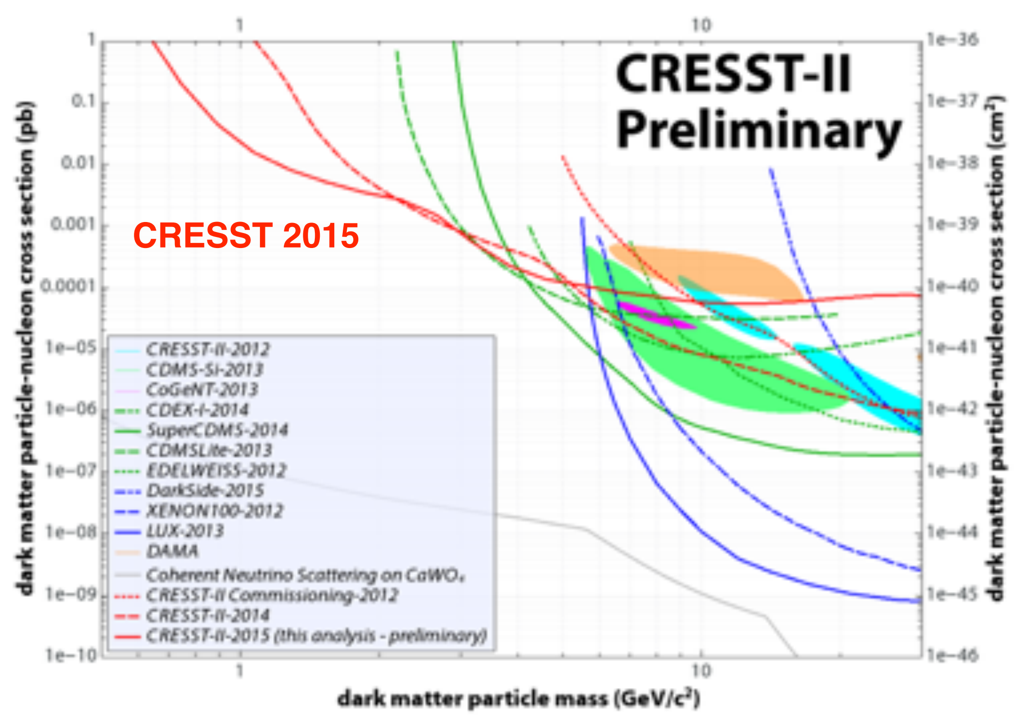
arXiv: 1504.00820



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

F. Reindl, EPS-HEP 2015





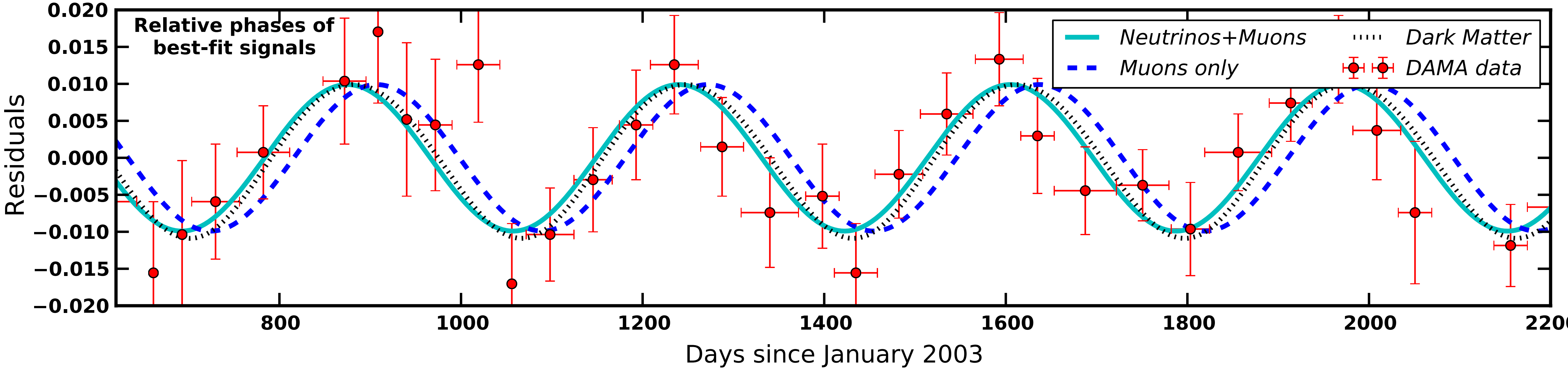
Final, blind analysis in autumn 2015
+ start of CRESST-III at the end of this year (new detector modules, 24 g each, 100 eV E_{th})

What is the origin of the DAMA signal?

Possible explanation: **a combination of neutrinos and muons**

Solar ^{8}B neutrino- and atmospheric muon-induced neutrons

Combined phase of muon and neutrino components: good fit to the data*



Jonathan 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