Looking forward: DARWIN-LXe another step beyond XENON1T

What's beyond the currently operating/under construction/designed Dark Matter experiments? Can we turn a Dark Matter detector into a multi-purpose experiment?

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What are we looking for?

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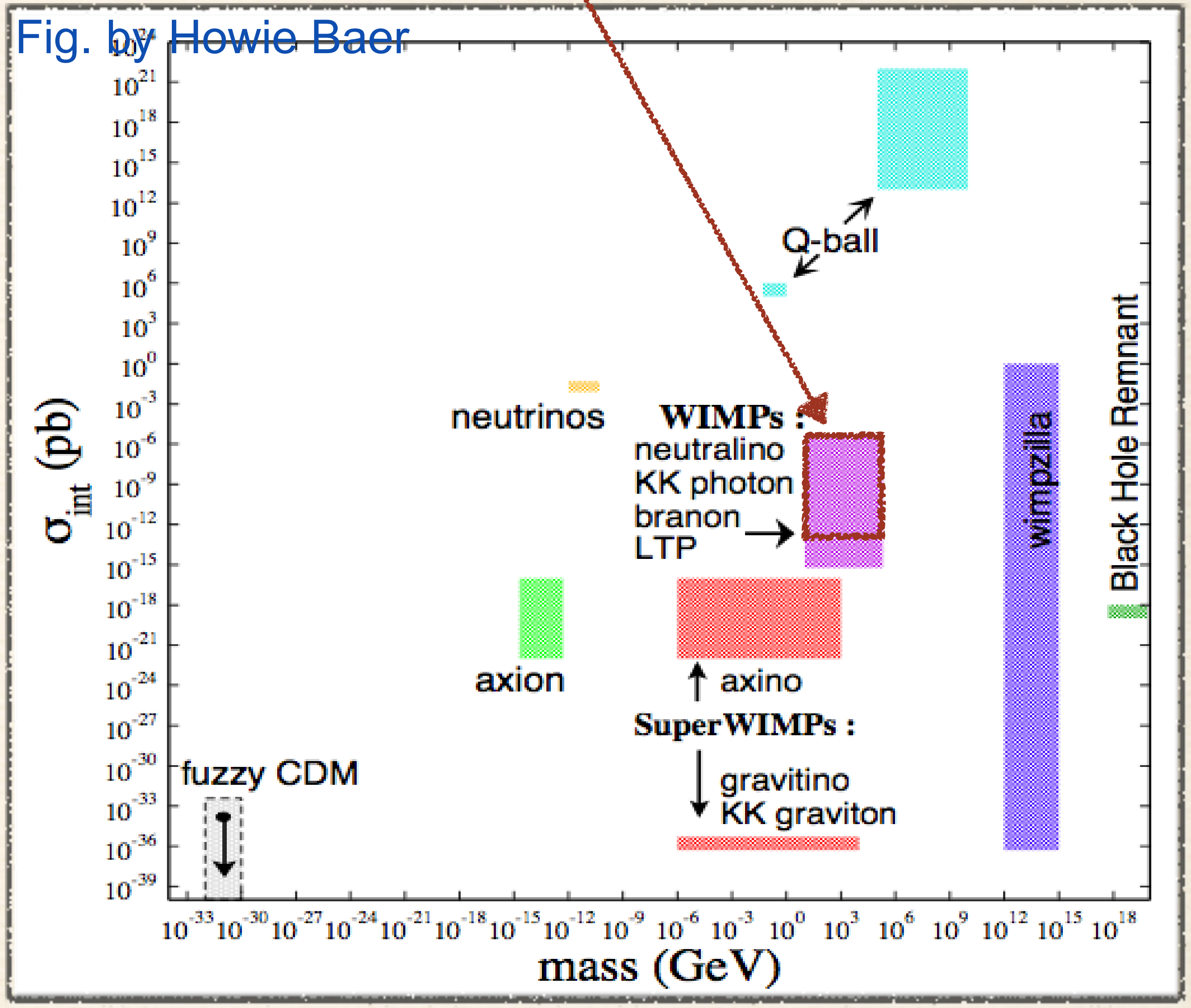
- Massive (gravitation)
- Long-lived (Big Bang relic)
- Electrically neutral (dark)
- Non-baryonic (BBN)
- Collisionless (Bullet cluster)
- Cold, i.e. dissipationless and negligible "free-streaming" effect (Structure formation)

This talk



What have we been doing so far?

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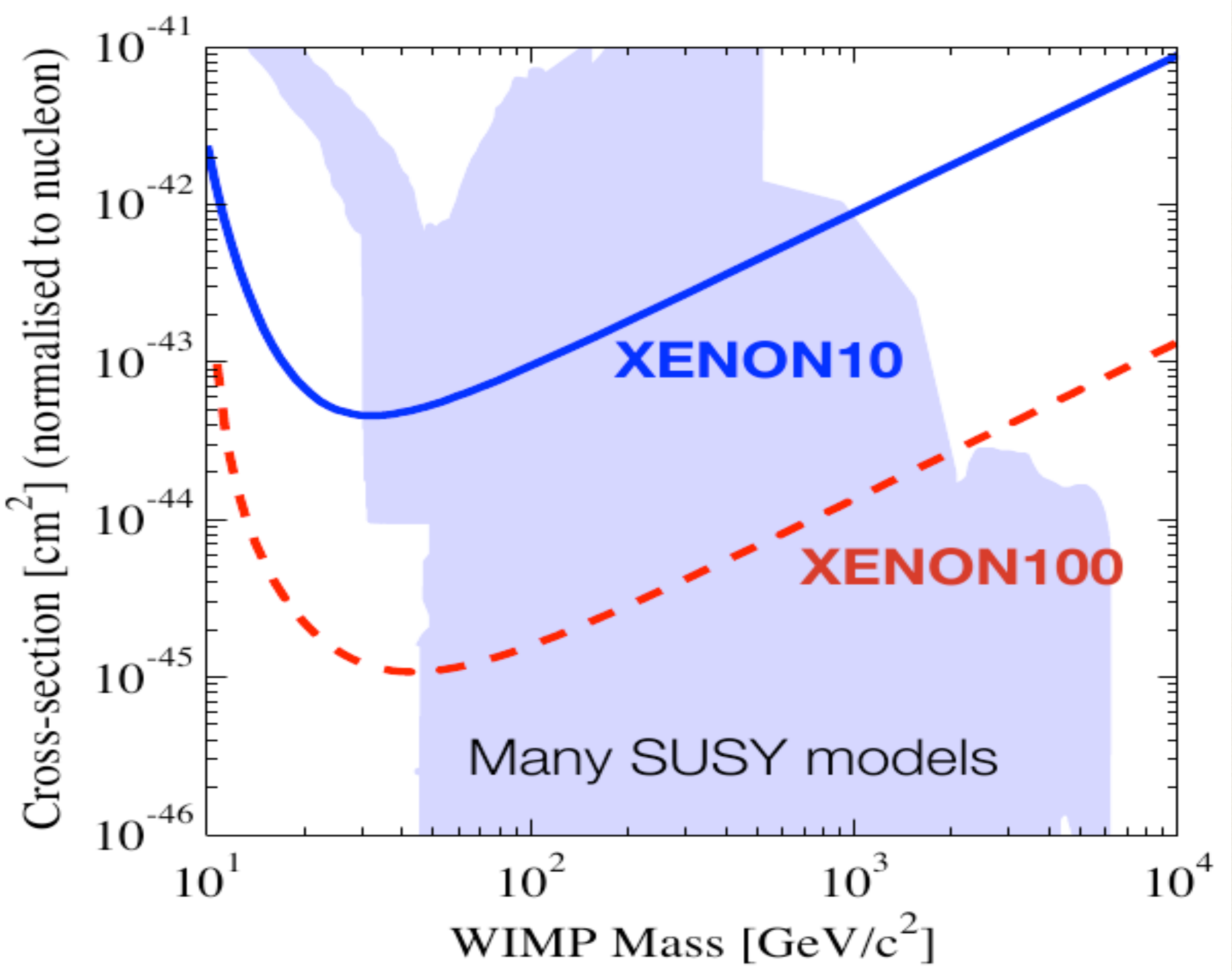
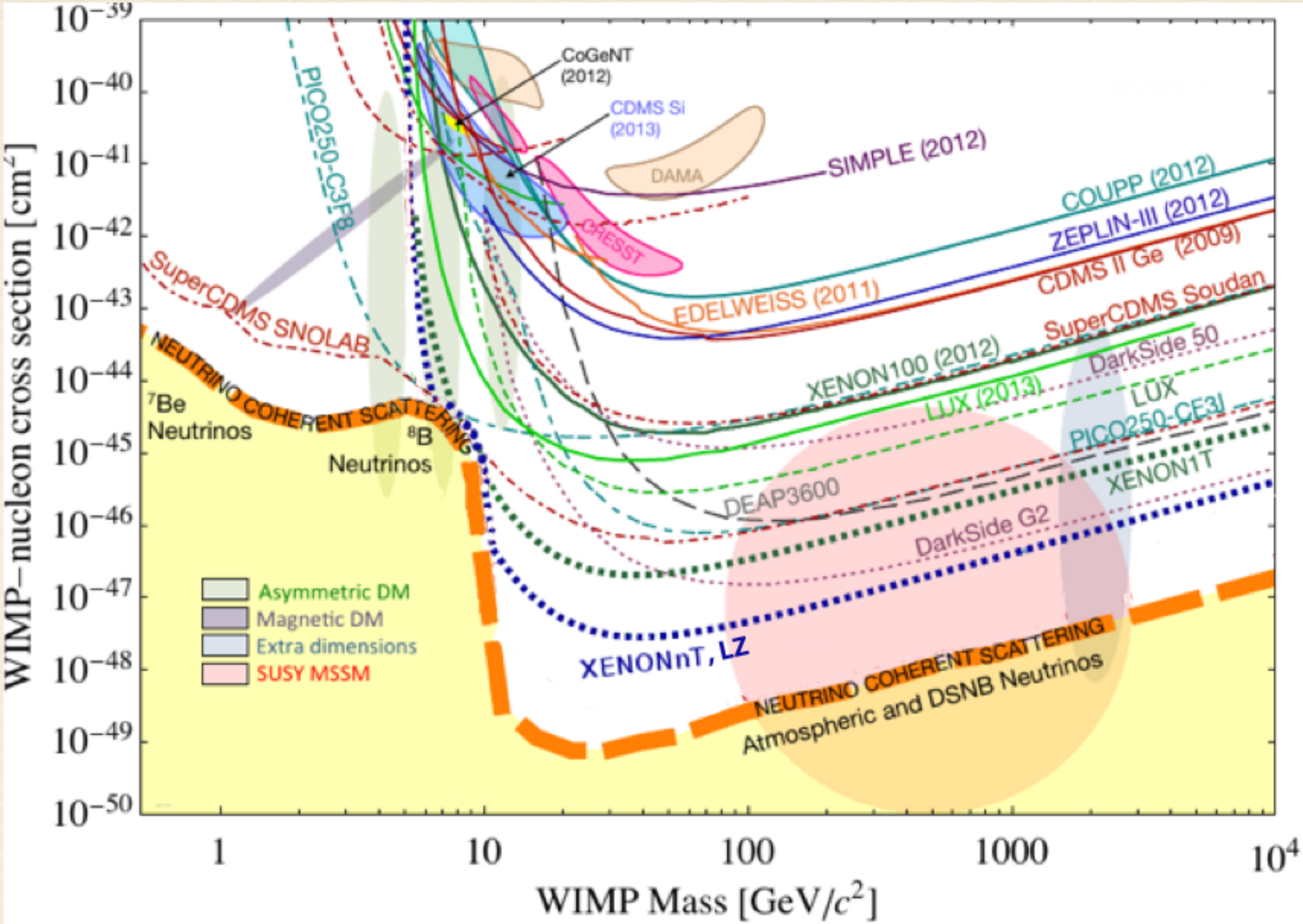
From the XENON history

- Given the XENON10 results the XENON100 goal was to:
    - Improve the sensitivity ~ 50 times over XENON10.
    - Assuming same energy threshold and same discrimination power as XENON10, the required background in the fiducial volume needs to be 100 times lower with a mass increase of a factor 10.



XENON10 SI limit: PRL100, 021303 (2008)

Can we repeat the same game after XENON1T/nT?



Yes and no…

Focus on "G3" experiments

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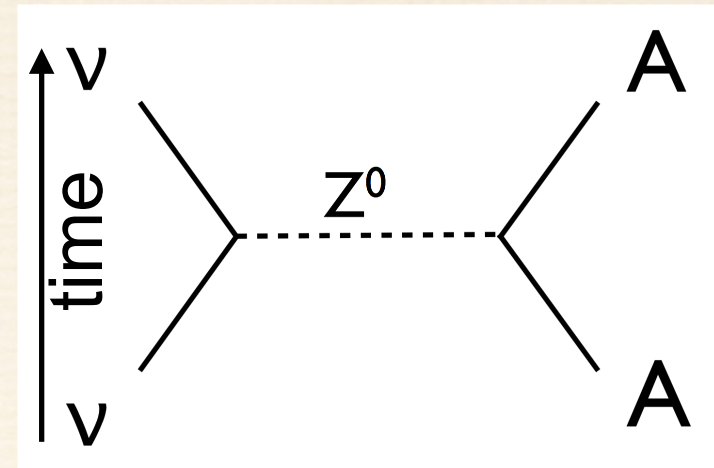
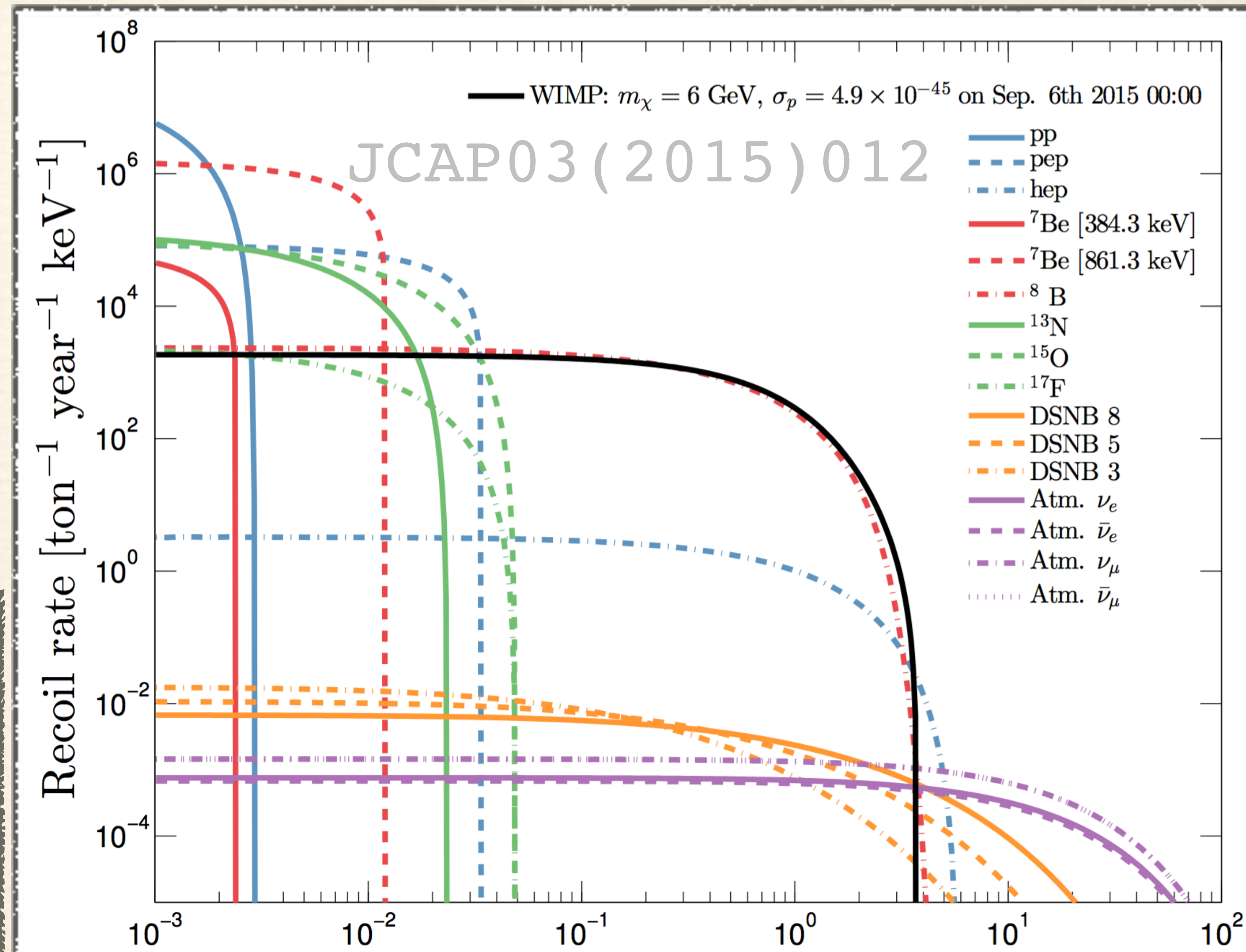
New irreducible background

- Coherent ν-nucleus scattering (CNNS)
  - For low mass WIMPs (< 10 GeV/c^2) the solar (^{8}B and hep) ν give a (modulating) nuclear recoil (NR) spectrum (σ ~ 5 x 10^{-45} cm^2)
  - For medium mass WIMPs (10 - 30 GeV/c^2) DSN (isotropic) give a (non-modulating) NR spectrum
  - For high mass WIMPs (> 30 GeV/c^2) atmospheric ν (isotropic) give a (non-modulating) NR spectrum

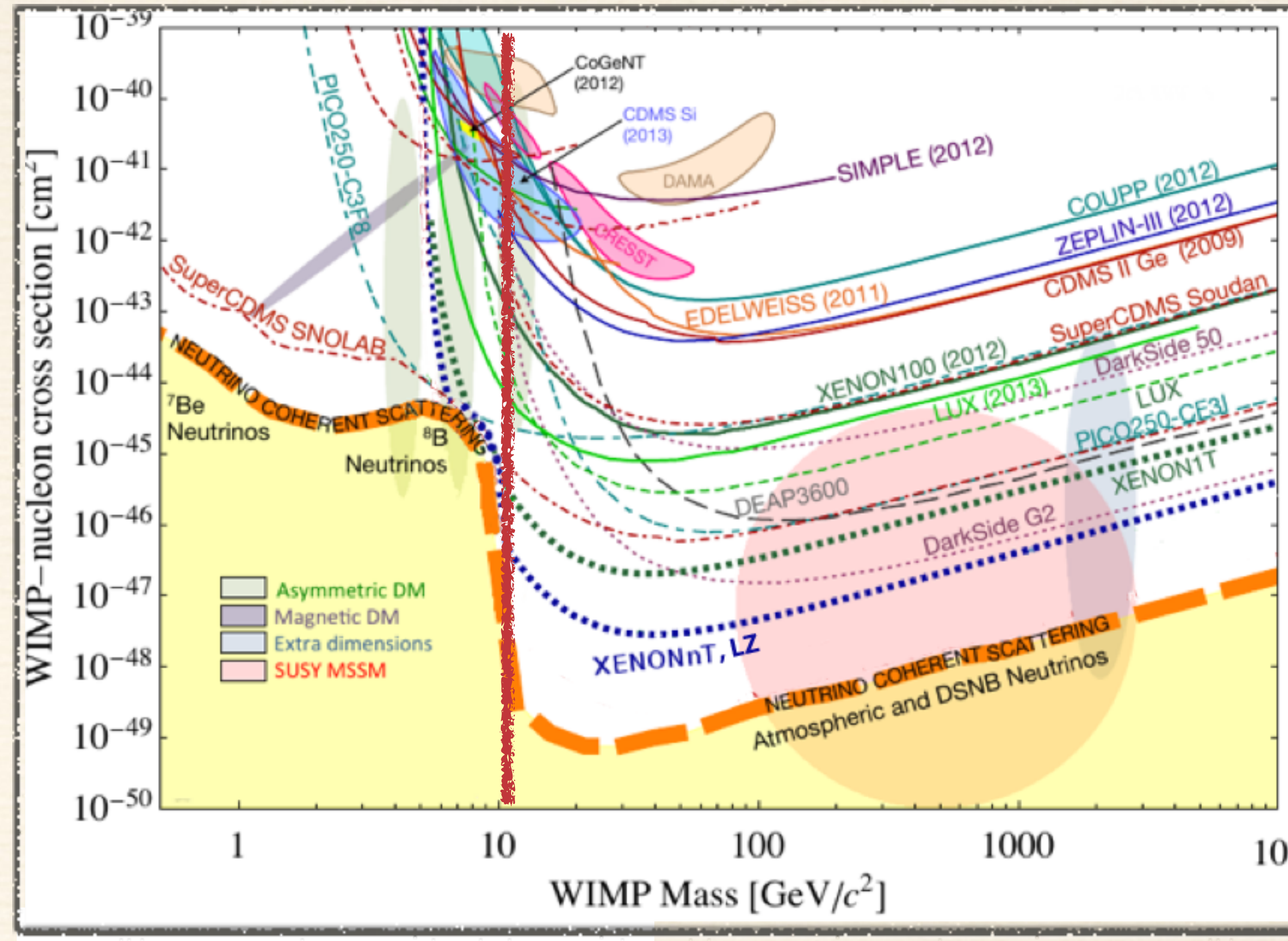


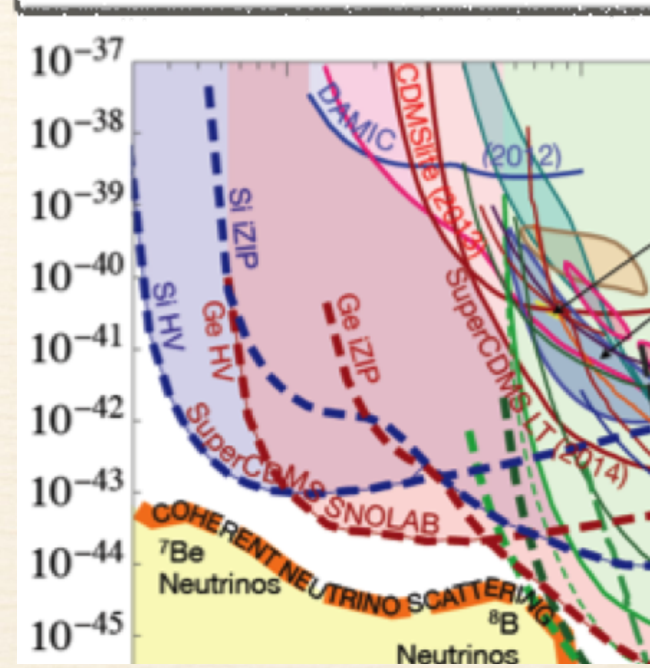
ν-electron elastic scattering also give a sizable signal and depending on the rejection power it might also become a source of irreducible background



Same thing from another perspective

- Two regions:
  - Low mass (< 10 GeV/c^2) background dominated by solar neutrino
    - Low threshold (< 1 keV), $\mathcal{O}$(100 kg) experiments
  - High mass (> 10 GeV/c^2) background dominated by atmospheric and DSN
    - Mostly noble liquid based, multi-ton experiments





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Background requirements for > 10 GeV/c²

Xenon and Argon

Assumption:

Rejection power with 50% sig. acceptance
10^2-10^3
$>10^7$
?

G3	Xe-nat (2-30keV)	UAr (30-200keV)
Kr-nat	(0.03)->0.01ppt	
^{222}Rn ER	4->0.1μBq/kg	<1ppt
^{136}Xe ER	<600 10ty (depletion?)	
^{39}Ar ER		3 -> <1 mBq/kg (depletion)
ν ER	<1000 10ty	<2000 10ty
ν NR	<1 10ty ?	<1 10ty ?

Background requirements for < 10 GeV/c^2

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Mostly solid state detectors

	Xe-nat 2phase	Ge/Si	CaWO4	Si (CCD)
Kr-nat ER	0.2->0.1ppt			
isotope ER	^{136}Xe<600 10ty			^{32}S~1ev/keVr kgd
^{222}Rn/^{210}Pb	4->0.1μBq/kg (ER)	5.6mBq/m2(Cu) (alpha act)	1-3mBq/kg (alpha act)	<46ev/kgd
"surface" ^{206}Pb NR	?	907-> <20ev/kgy	<12ev/kgy	?
Compton ER (other beta)	<<	10^3->5ev/keV$_r$ kgy	10^3 ev/keV kgy	500->0.5 DRU$_{ee}$ ^{238}U/^{232}Th<5-15ev/kgd
Activation ER	^{127}Xe,^{46}Sc(Ti)	^{3}H(Ge), many lines	many lines	?
1/2/3 e-	<24/4/1 ->?ev/kgd			
ν ER	<10ev/keVr ty	<10ev/keVr ty	<	?
ν NR	<	<	<	<

Fighting the CNNS: target complementarity

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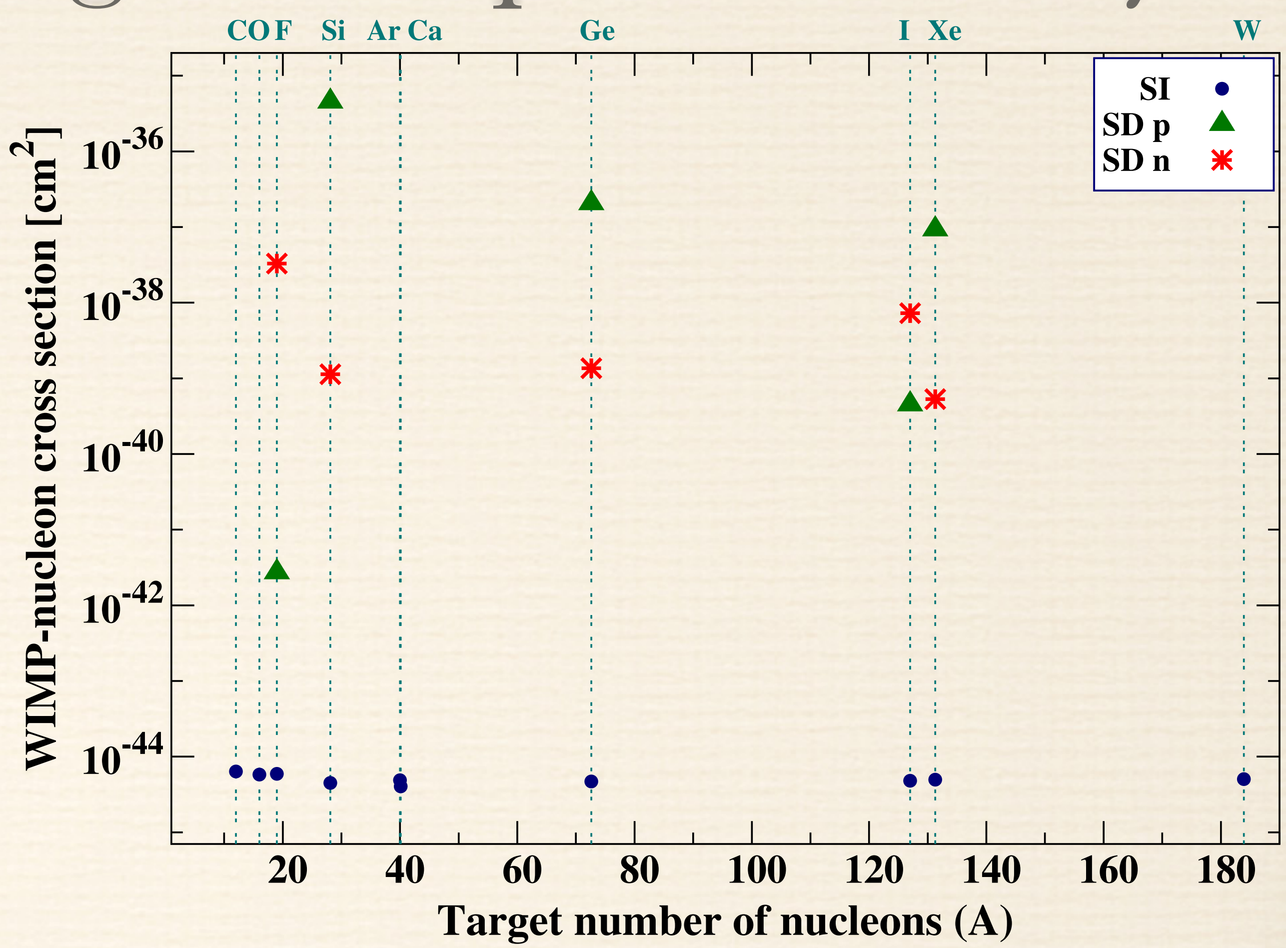
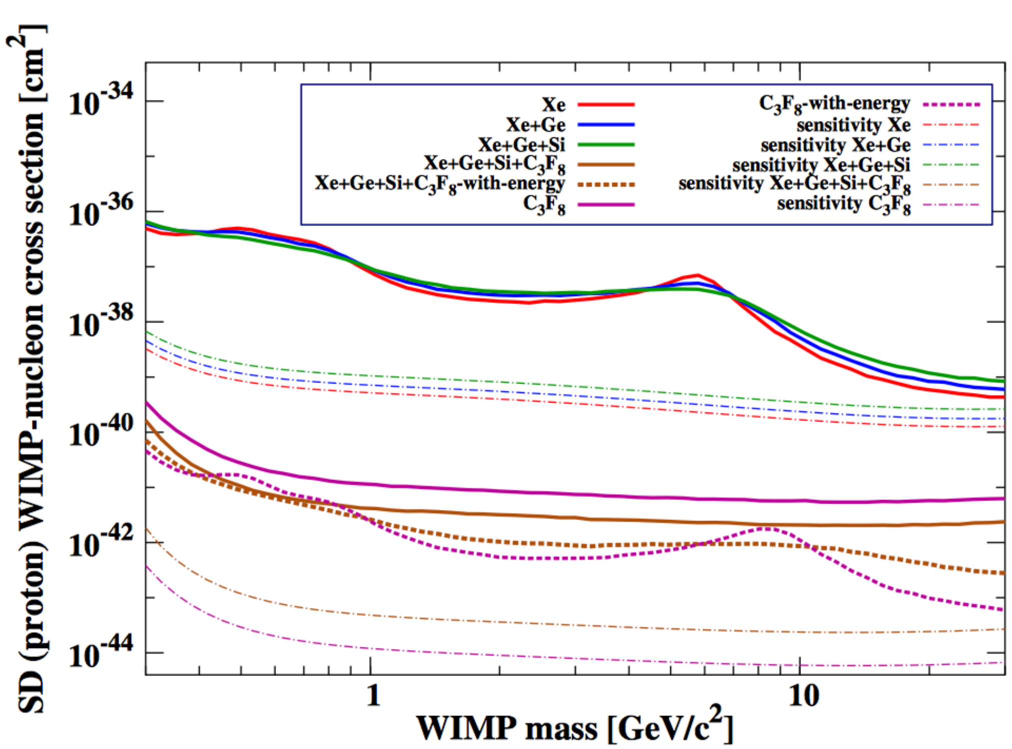
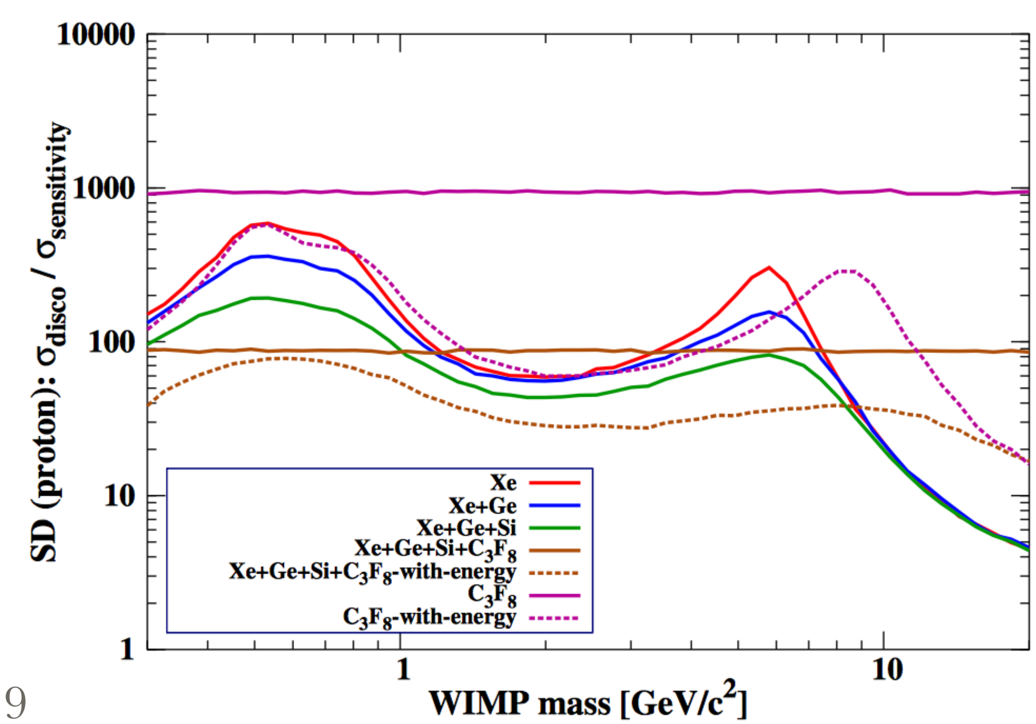
Limitation of DM discovery limit due to CNS:

1. is more relevant for low-mass DM up to G3.
2. can only be moderately improved for SI interactions due to similarity in DM and neutrino signals in the different target nuclei.
3. can be notably improved for SD targets.

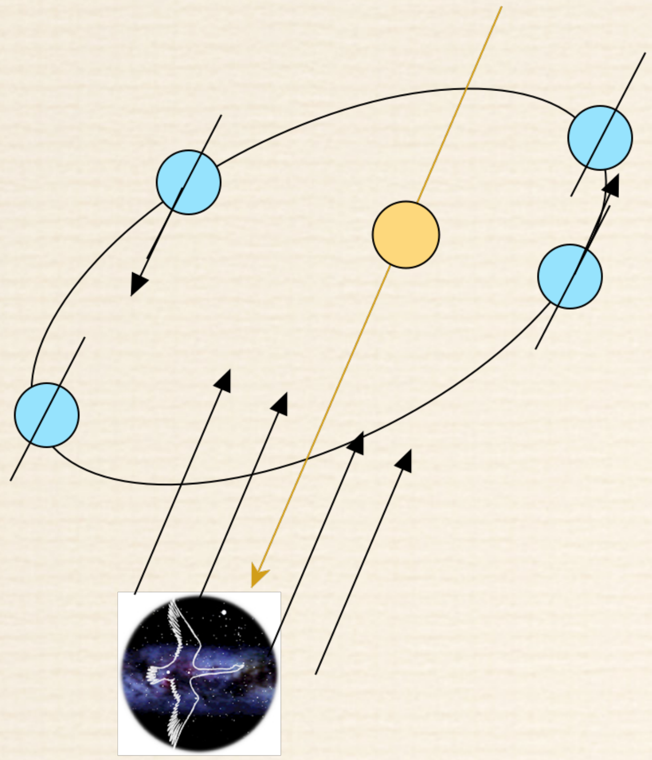


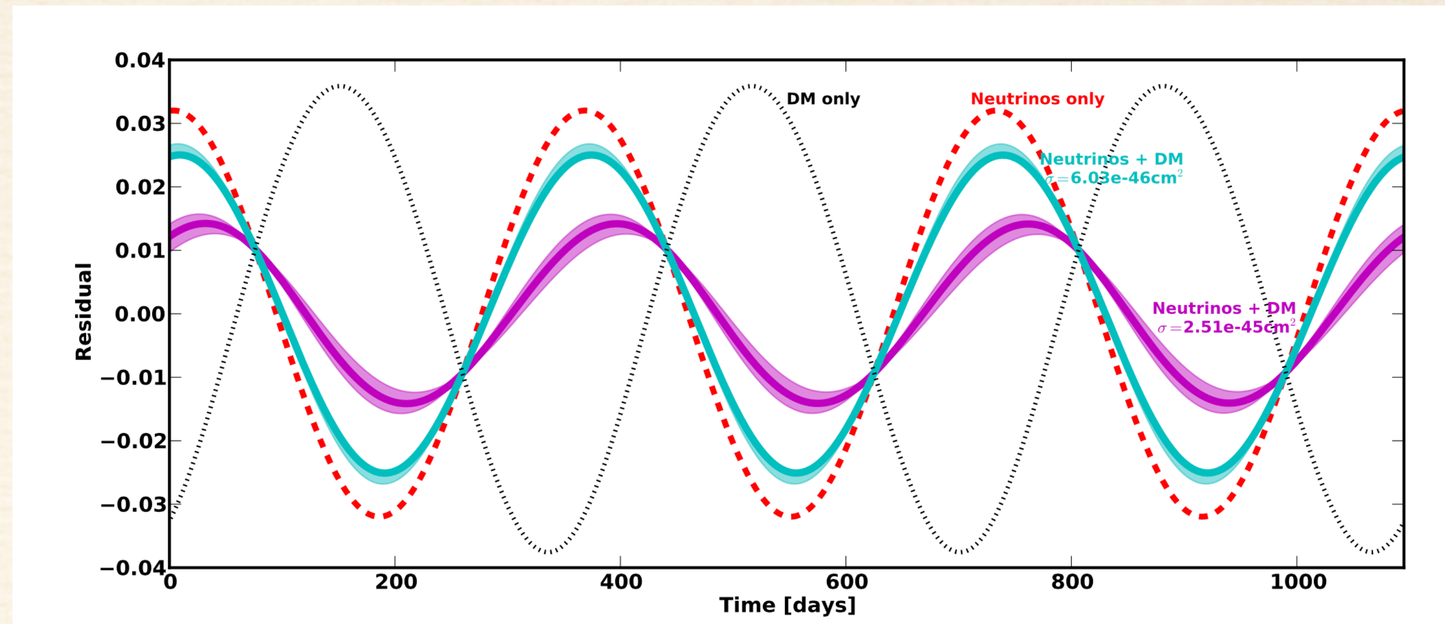
F. Ruppin, et al., PRD 90 (2014)!





Fighting the CNNS: annual modulation

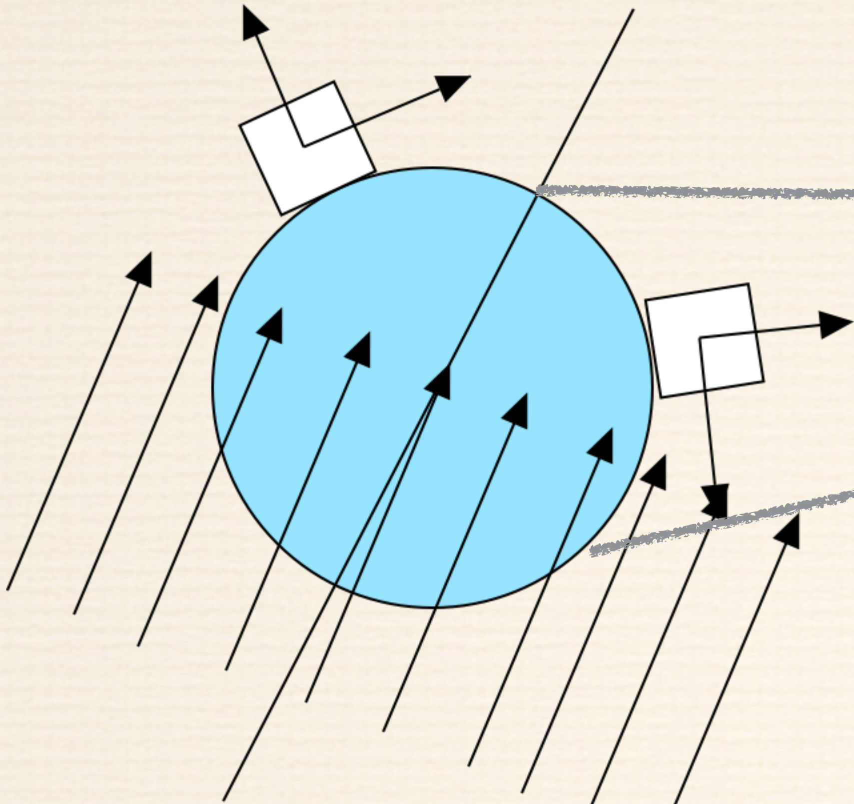


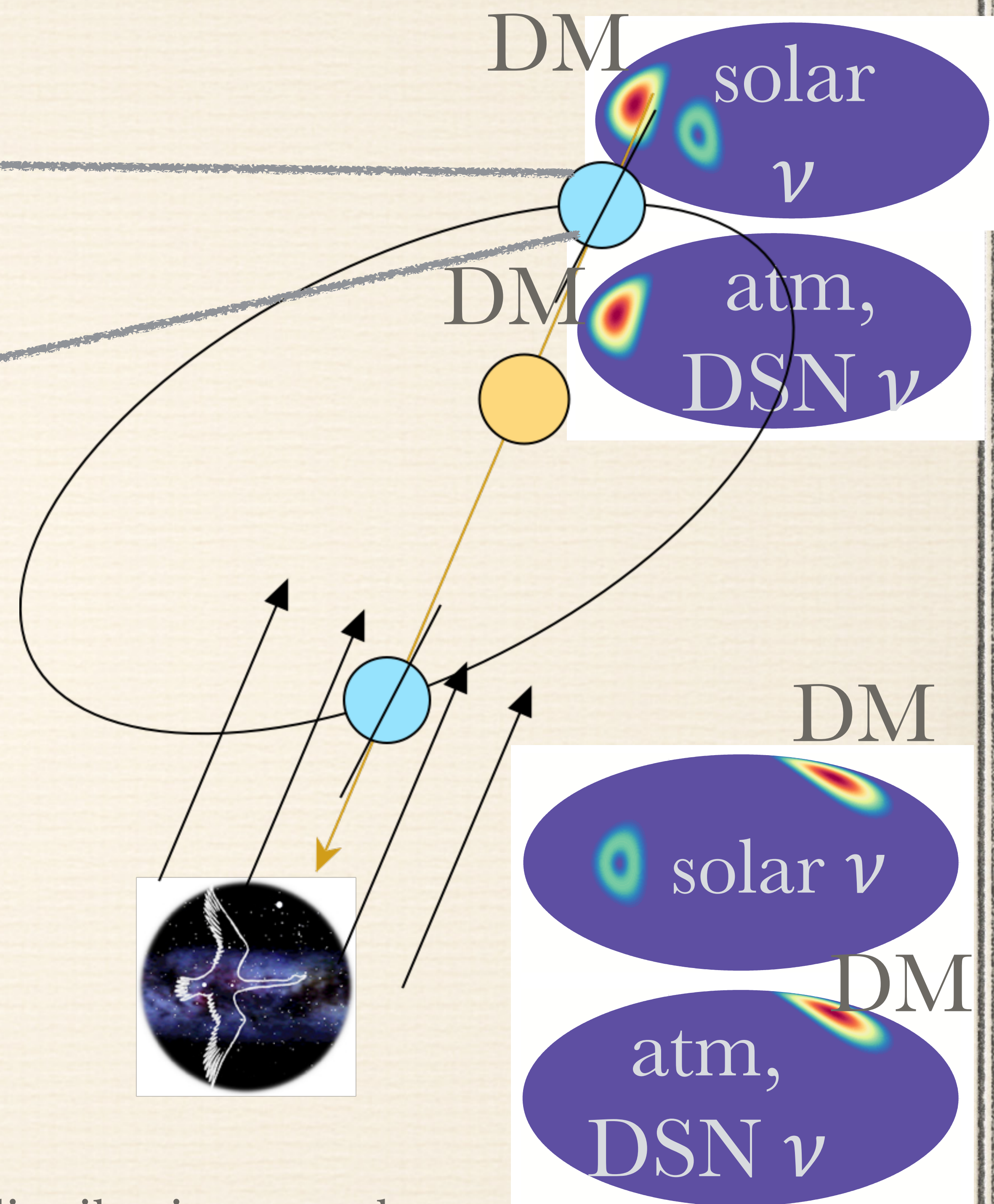


- The sun "follows" the Cygnus constellation around the galactic orbit. We revolve around the Sun and modulate this rate (~3-5%) with max in June.
- The Sun-Earth distance changes during revolution and modulates the neutrino flux (~3-5%) with max in January.
- Below the neutrino floor the DM signal is observable through a phase shift and a smaller amplitude for the time-dependent event rate

JCAP03(2015)012

Fighting the CNNS: sidereal modulation





Recoil direction is strongly correlated with the lab's motion in the galactic frame.

"Source" point of DM wind rises and sets each sidereal day!

arXiv:1505.08061

DM and solar ν recoil distributions can be distinguished as long as the angular resolution is better than 30^o.

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DM direct detection: today and tomorrow

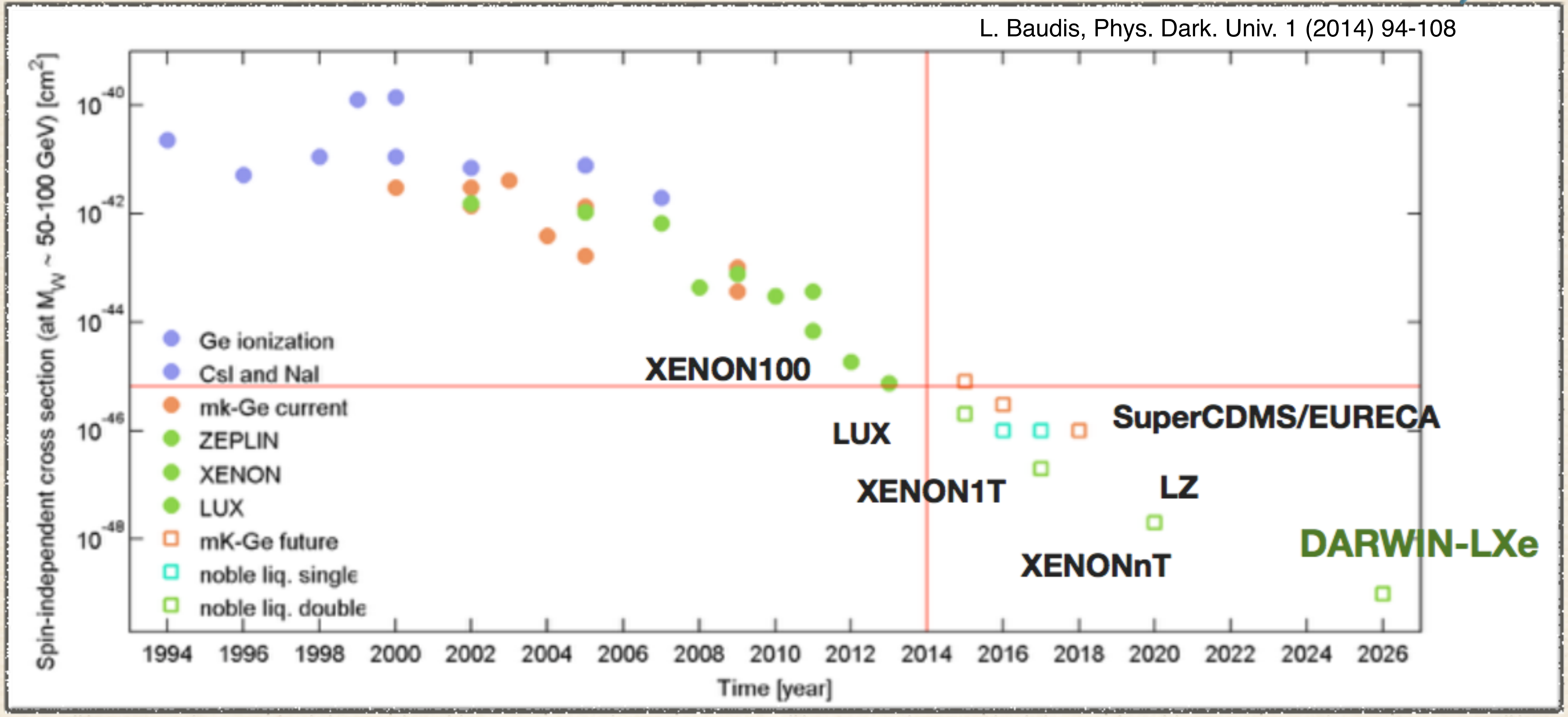
Data taking
DAMA/LIBRA
Xenon100
XMASS
LUX
DarkSide50
CRESST-II upgrade
COUPP-60
PICO-2L
CDEX-1kg
DM-Ice17

Commissioning
XENON1T
ArDM
DEAP-3600

Installation/Construction/R&D
DAMIC100
CDEX-10kg
SuperCDMS-Snolab
LZ
XENONnT
PICO-500
SABRE
DM-Ice37
XMASS1.5
EDELWEISS-III
PandaX
CDEX-10kg
All directional TPC
...

Future
EURECA
DARWIN
DarkSide20T
PandaX-1T
CDEX-1T
DM-Ice250

Surely other.
Sorry for not mentioning!



DARWIN-LXe goals

- *Explore the experimentally accessible parameter space*
- *Use the well-known (XENON, ZEPLIN, LUX, PandaX) 2-phase TPC technique*
- *Probe a variety of other physics channels*

DARWIN-LXe: science goals

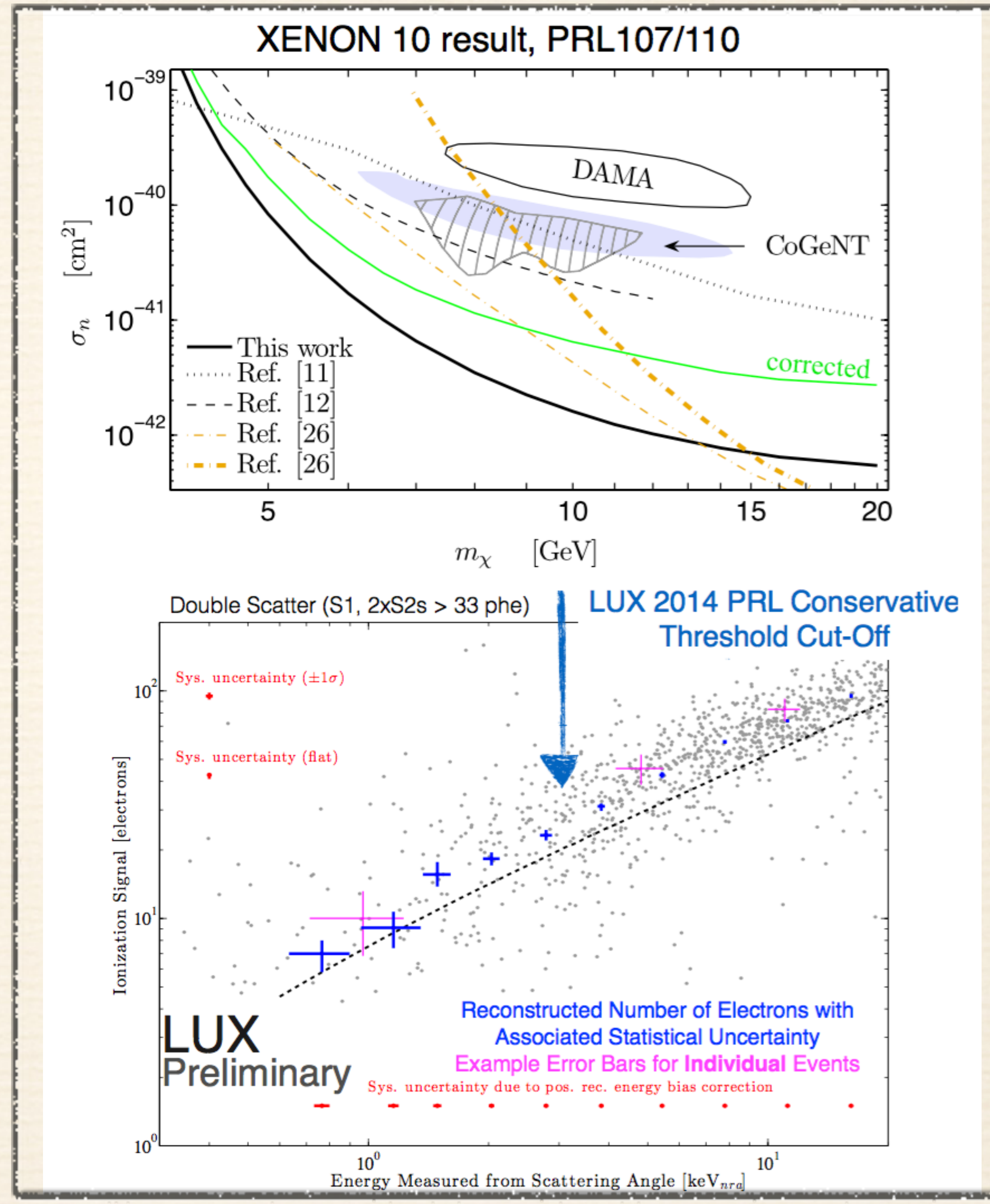
- Probe WIMP-nucleon interactions for WIMP masses above 6 GeV/c^2
  - spin-independent, spin-dependent and inelastic
  - low WIMP masses by using the charge signal alone
- Look for signatures of DM scattering off electrons
- Detect solar neutrinos: pp-neutrinos via ν-e scattering, ^{8}B coherent ν scattering
- Search for the neutrinoless double beta decay in ^{136}Xe
- Probe interaction of solar axions and axion-like particles, via the axio-electric effect
- Probe sterile neutrinos with masses in the > 10 keV range
- Probe bosonic SuperWIMPs via their absorption by Xe atoms
- …

DARWIN-LXe: the baseline concept

- 30-50 tons LXe in total
- ~ few x 10^3 photosensors
- >2 m drift length
- >2 m diameter TPC
- PTFE walls with Cu field shaping rings
- Background goal: dominated by neutrinos

DARWIN-LXe: WIMP search

- Elastic Spin Independent
- Elastic Spin Dependent
- Inelastic Spin Dependent on ^{129}Xe
- Using S2 based energy scale lower the threshold and increase the sensitivity to low mass WIMPs
- In this case no use of S1 —> no discrimination —> sensitivity 100 times worse
- From LUX measurements charge is created down to 1 keV



DARWIN-LXe: backgrounds

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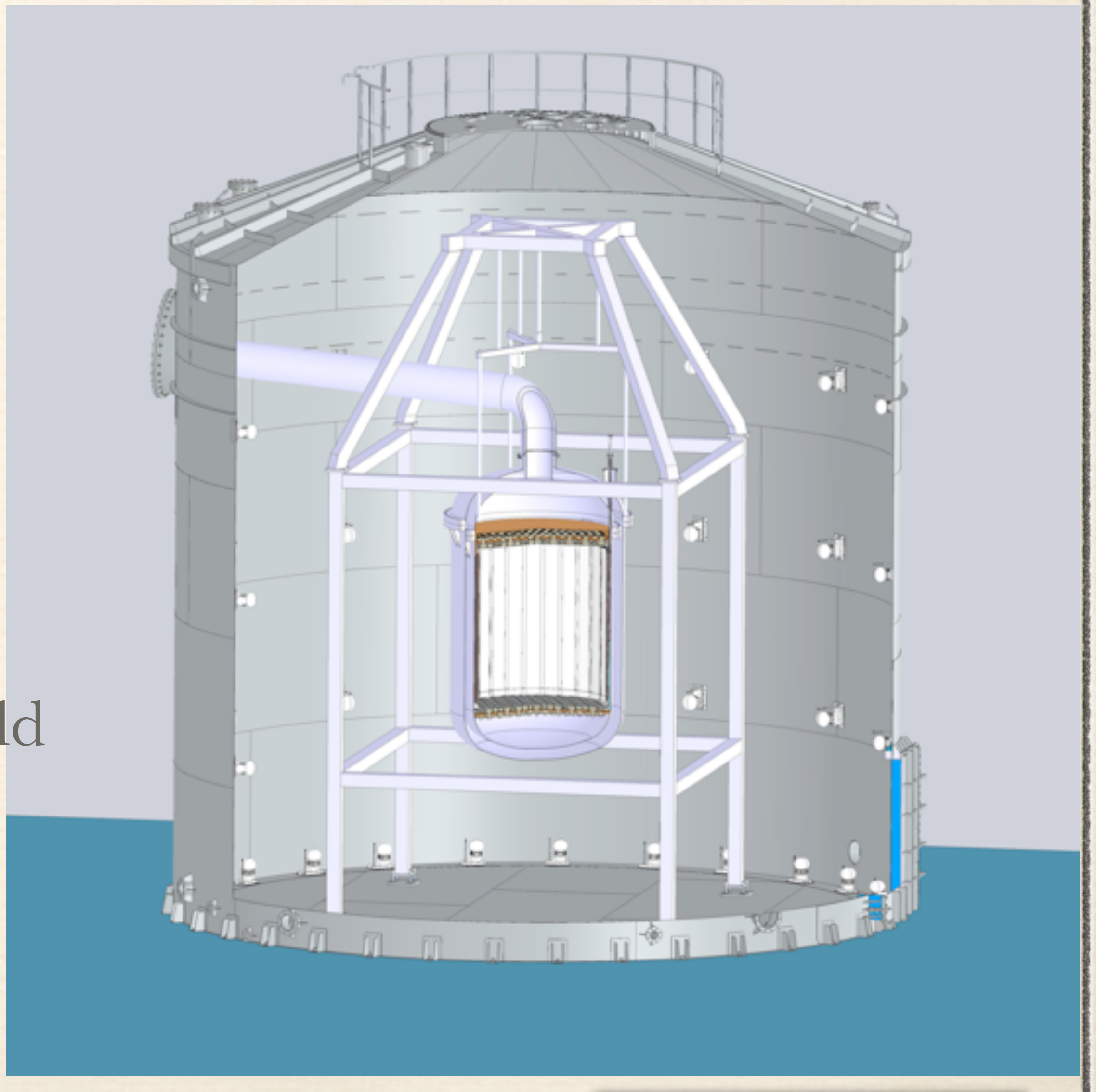
The assumptions:

- The best results from XENON100 and XENON1T screening campaigns have been selected
- The modeled photosensors are 3”
- Intrinsic contamination:
- 0.1 ppt of ^{nat}Kr, 0.1μBq/kg of ^{222}Rn
- XENON100: (1.0±0.2) ppt of krypton
  - EXO-200: (3.7±0.4) ppt of radon

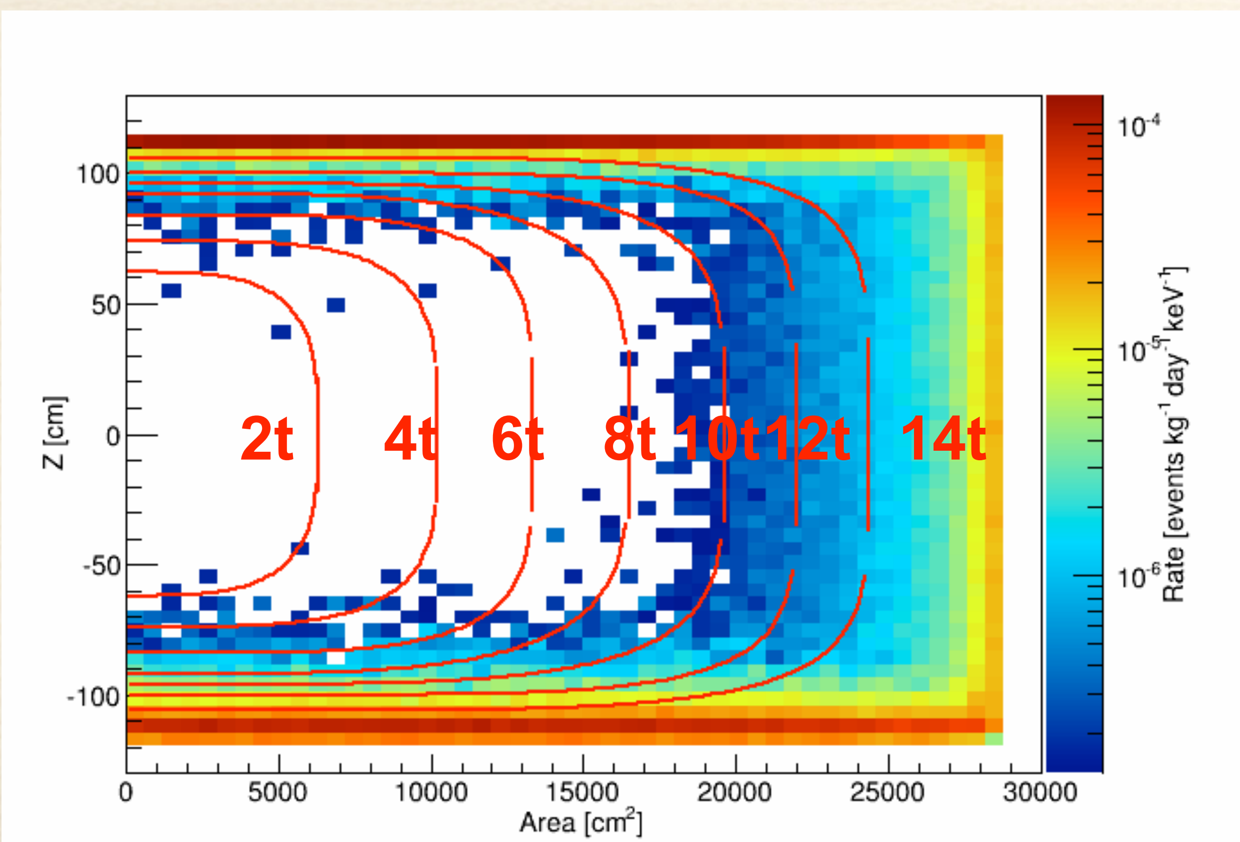
The goal:

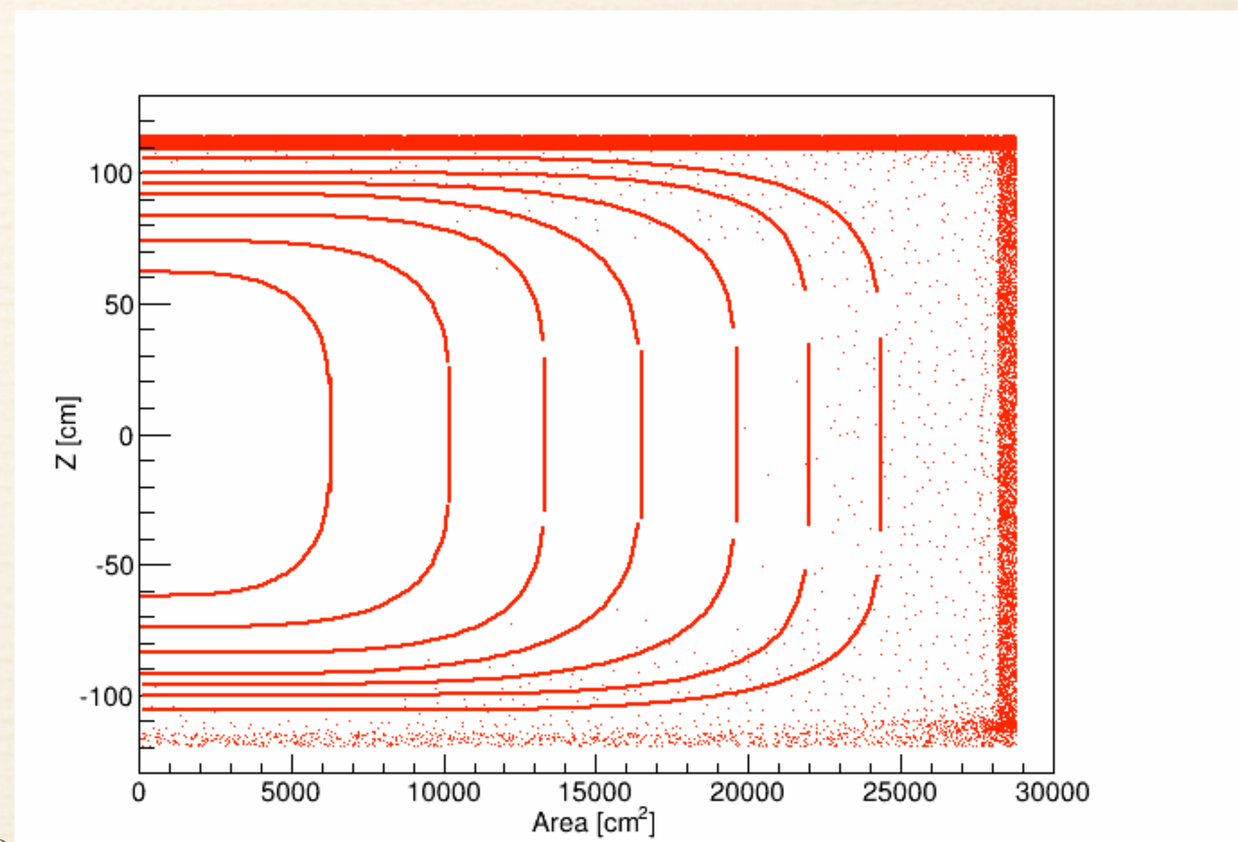
- from materials (radiogenic): < 7 x 10^{-4} ev/ty
- from cosmogenic:
  - < 0.01 if in the same XENON1T/nT water tank
  - <<0.003 events/(t y) in 14 m diameter water shield
- XENON1T/nT water shield is too small
  - the muon veto performance have to be improved



DARWIN-LXe: background reduction

- 3D position reconstruction – fiducialization of the LXe target
- Z coordinate from delay time between S1 and S2
  → resolution ~3mm (typical S2 width 2μs, electron drift velocity 1.5 mm/μs)
- XY resolution of about 8 mm can be achieved with 3 inch phototubes
  → not considered for multiple scatter rejection
  (probability to have such an event is already low)

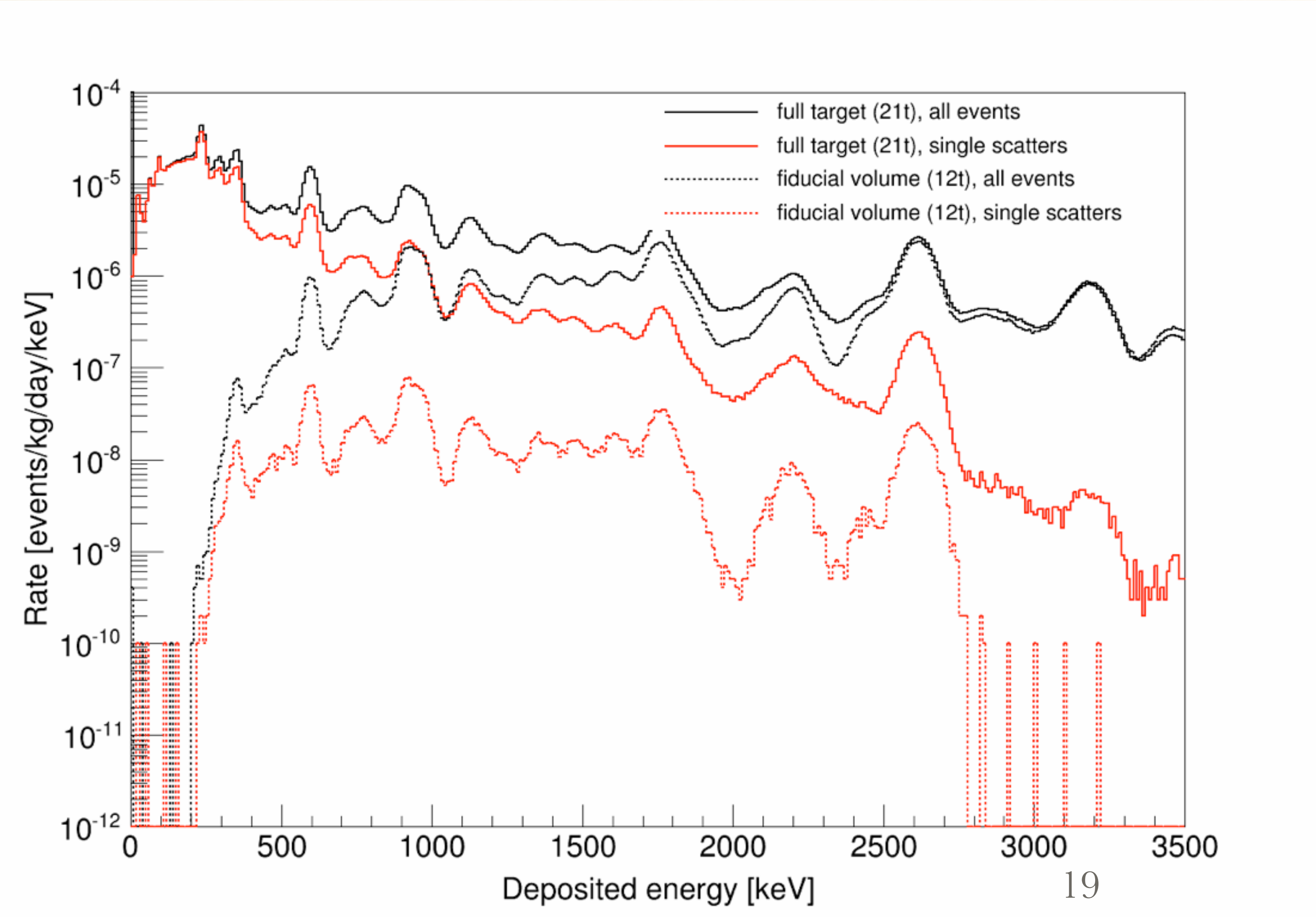


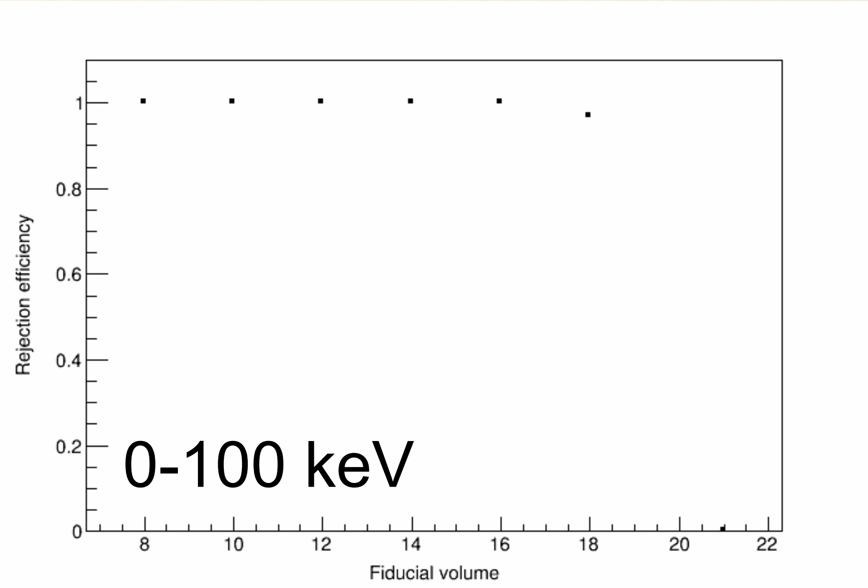


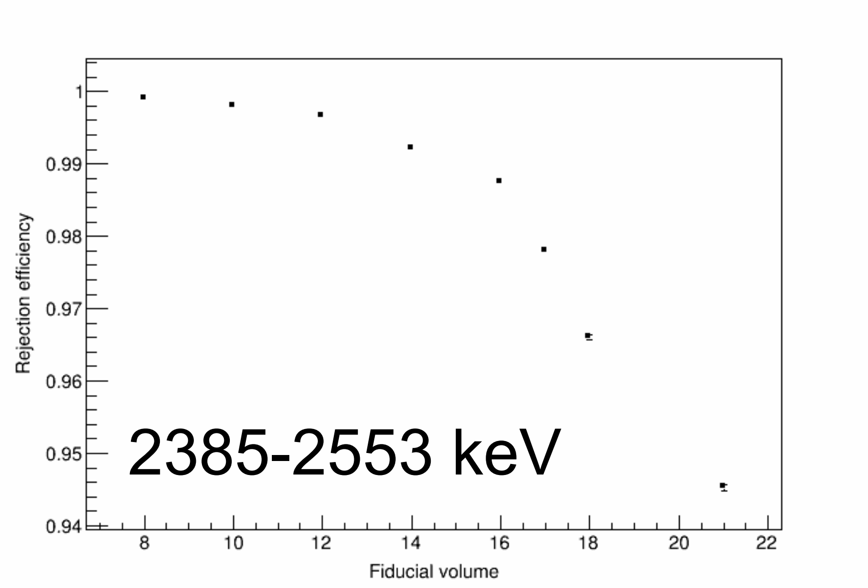
DARWIN-LXe: background reduction

- Due to the geometry of the detector (large outer edge surface area), it is likely for a particle to scatter only once and leave the active volume. Instead, when an interaction happens in the center of the target, the remaining xenon acts as an active veto for multiple scattering events

- Rejection of the multiple scattering events has to be calculated with the combination of the multisite and fiducial volume cuts (>99.5%)







DARWIN-LXe: background summary

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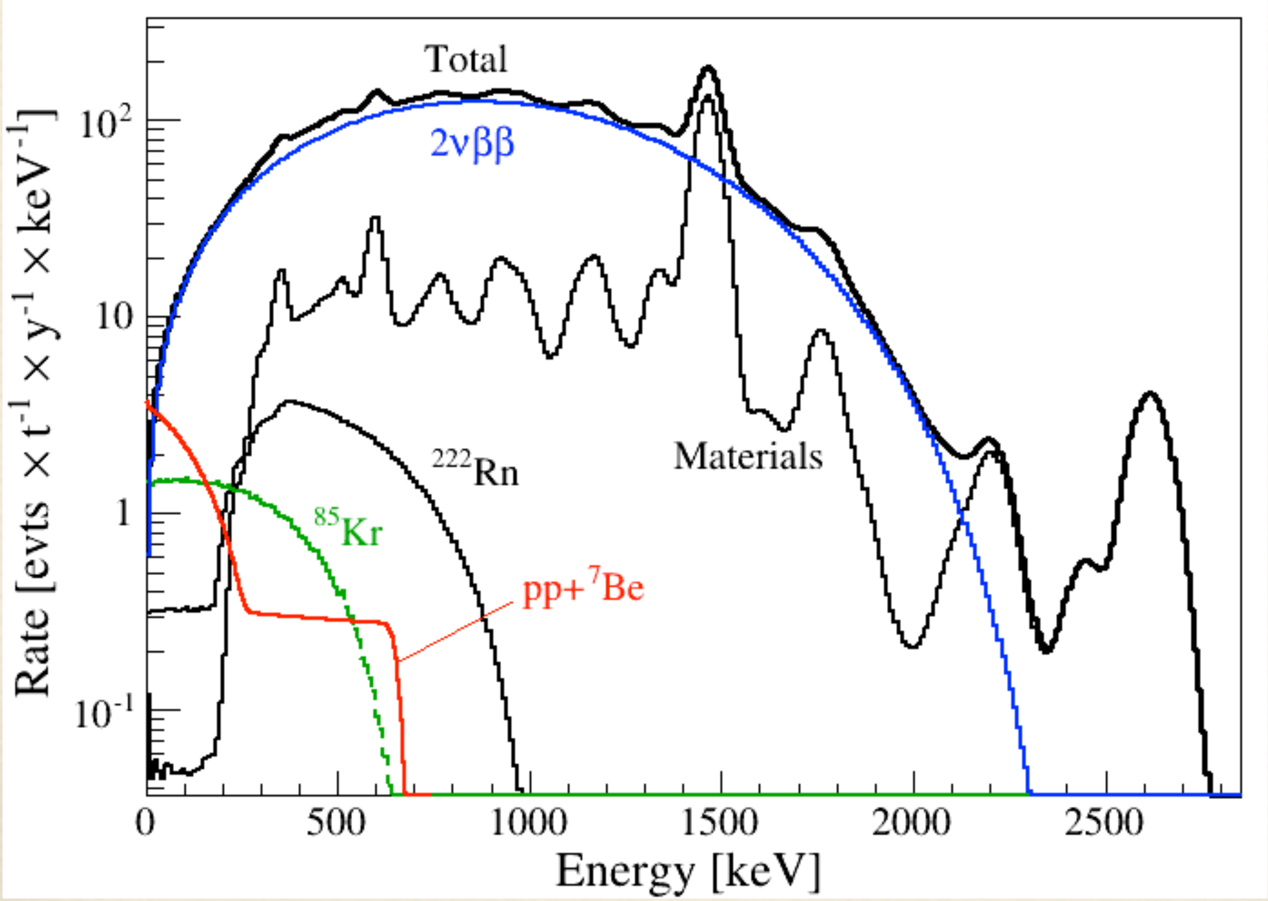
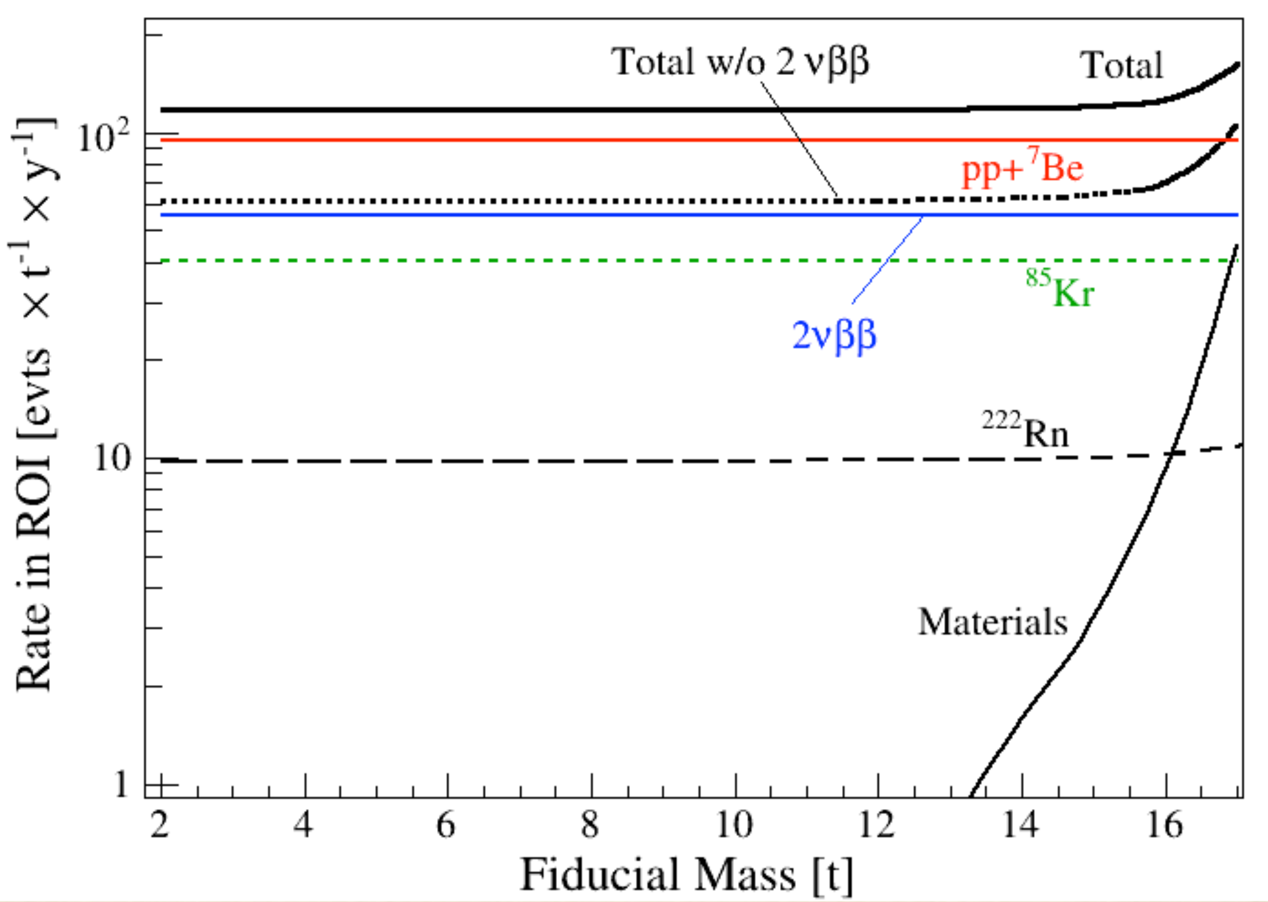
- The total background at low energies is dominated by 2νββ-decays of ^{136}Xe ($T_{1/2}$ = 2.11×10^{21} years, as measured by EXO-200), followed by krypton
- Chose 14t of LXe in the central detector region
- Energy range for neutrino measurement up to 30 keV_{ee} (intersect with ^{136}Xe 2νββ curve)
- WIMP ROI 2–10 keV_{ee} + electronic recoil rejection 99.5%

JCAP01(2014)044





DARWIN-LXe: WIMP spectroscopy

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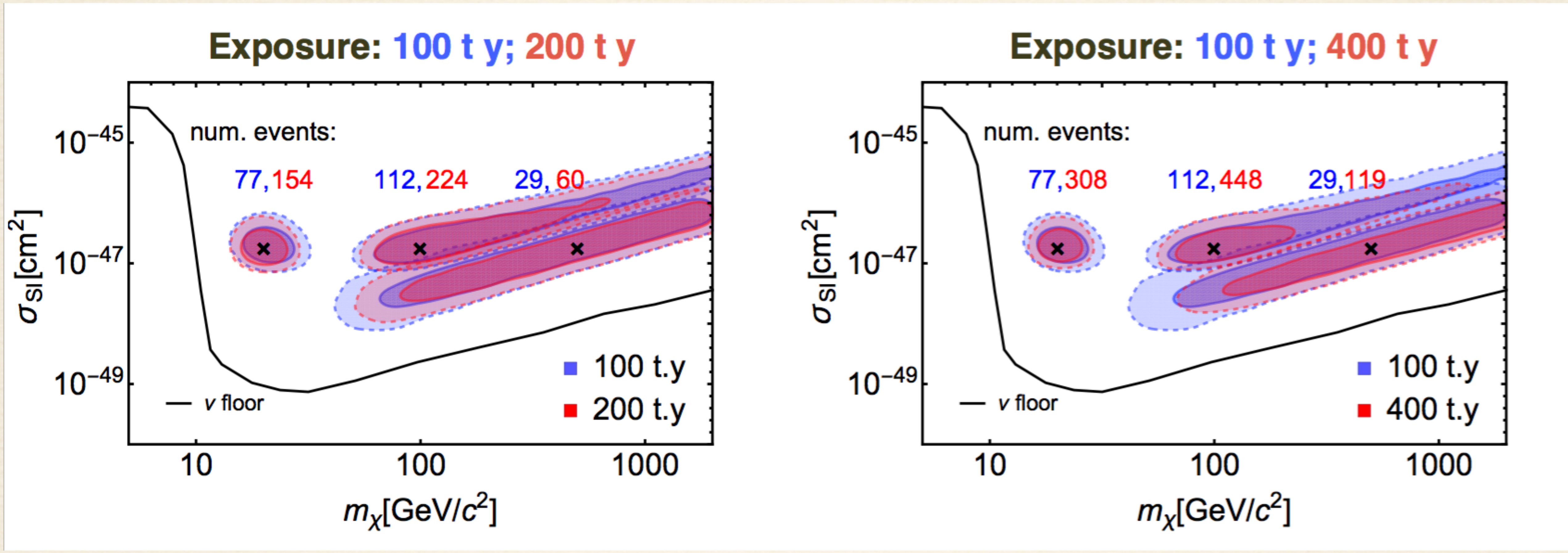
- Capability to reconstruct the WIMP mass and cross section for various masses (20, 100, 500 GeV/c^2) and hypothetical cross section for spin-independent interaction of 2 x 10^{-47} cm^2 (assuming different exposures)



Update: Newstead et al., Phys. Rev D 88, 076011 (2013)

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

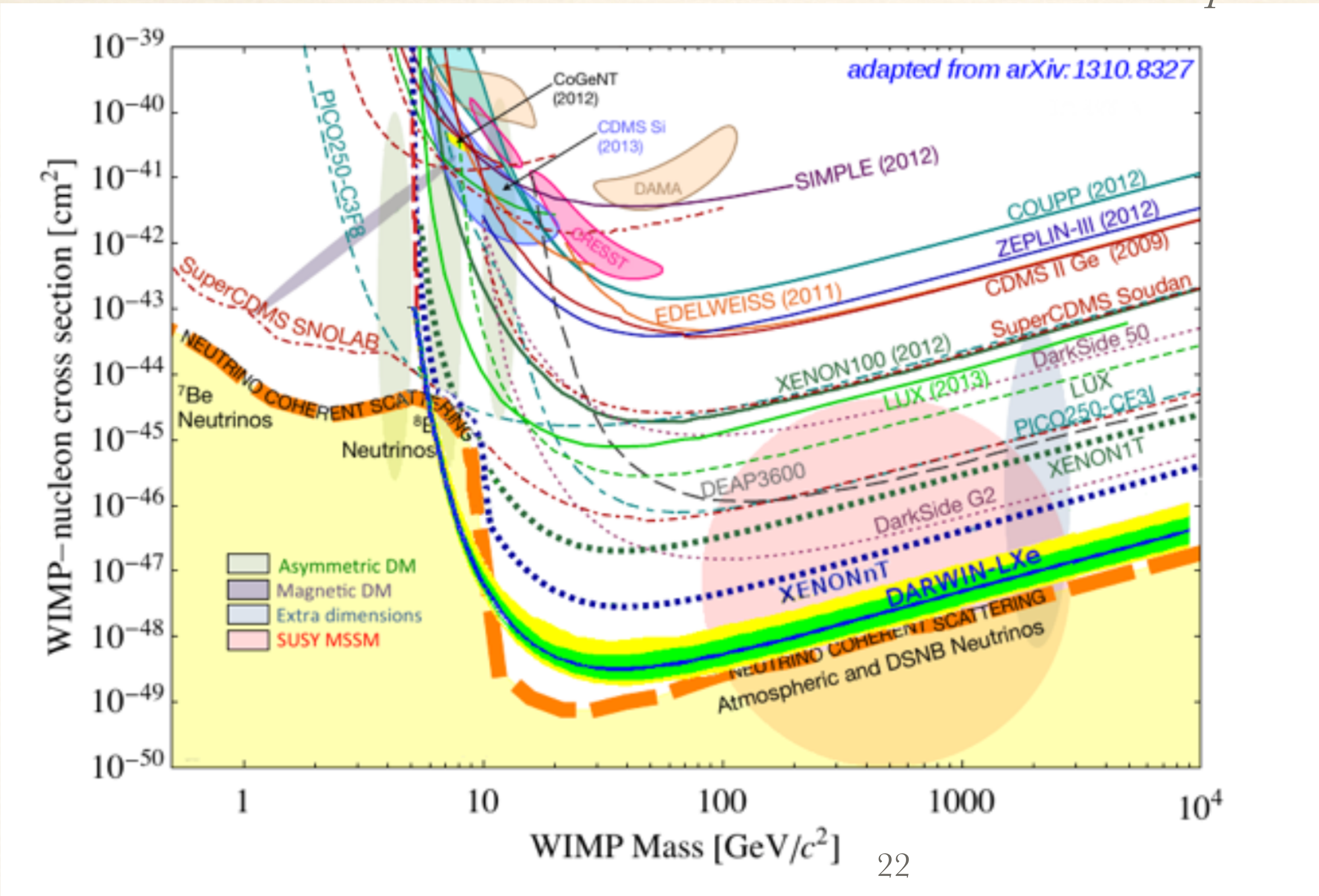
$v_o = 220 \pm 20\ km/s$

$\rho_\chi = 0.3 \pm 0.1\ GeV/cm^3$

DARWIN-LXe: WIMP sensitivity

ROI = 3 - 70 PE —> 4 - 50 keV$_{nr}$
200 t y
99.98 % rejection
30 % NR acceptance
LY: 8 pe/keV @ 122 keV

arXiv:1506.08309



DARWIN-LXe: complementarity with LHC

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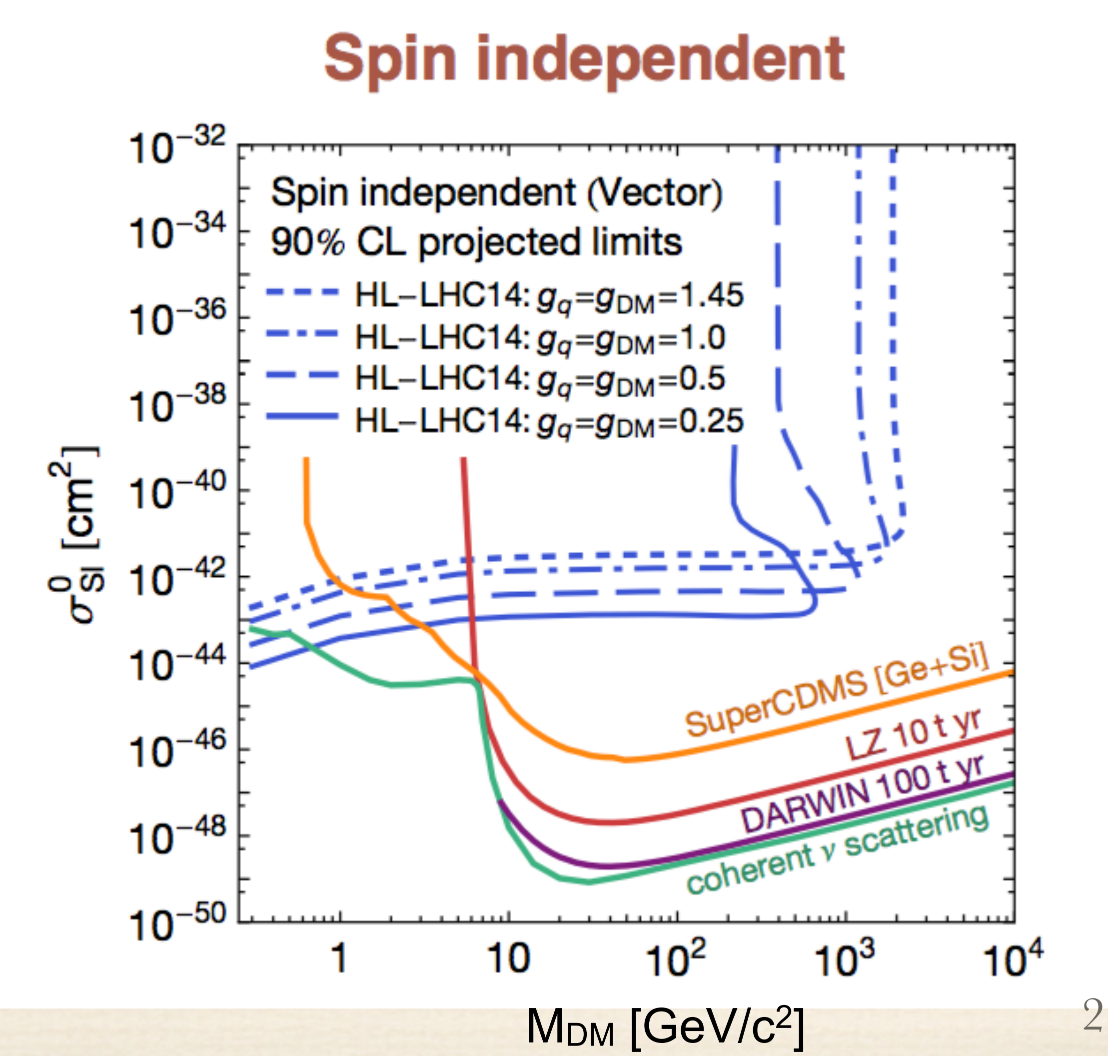
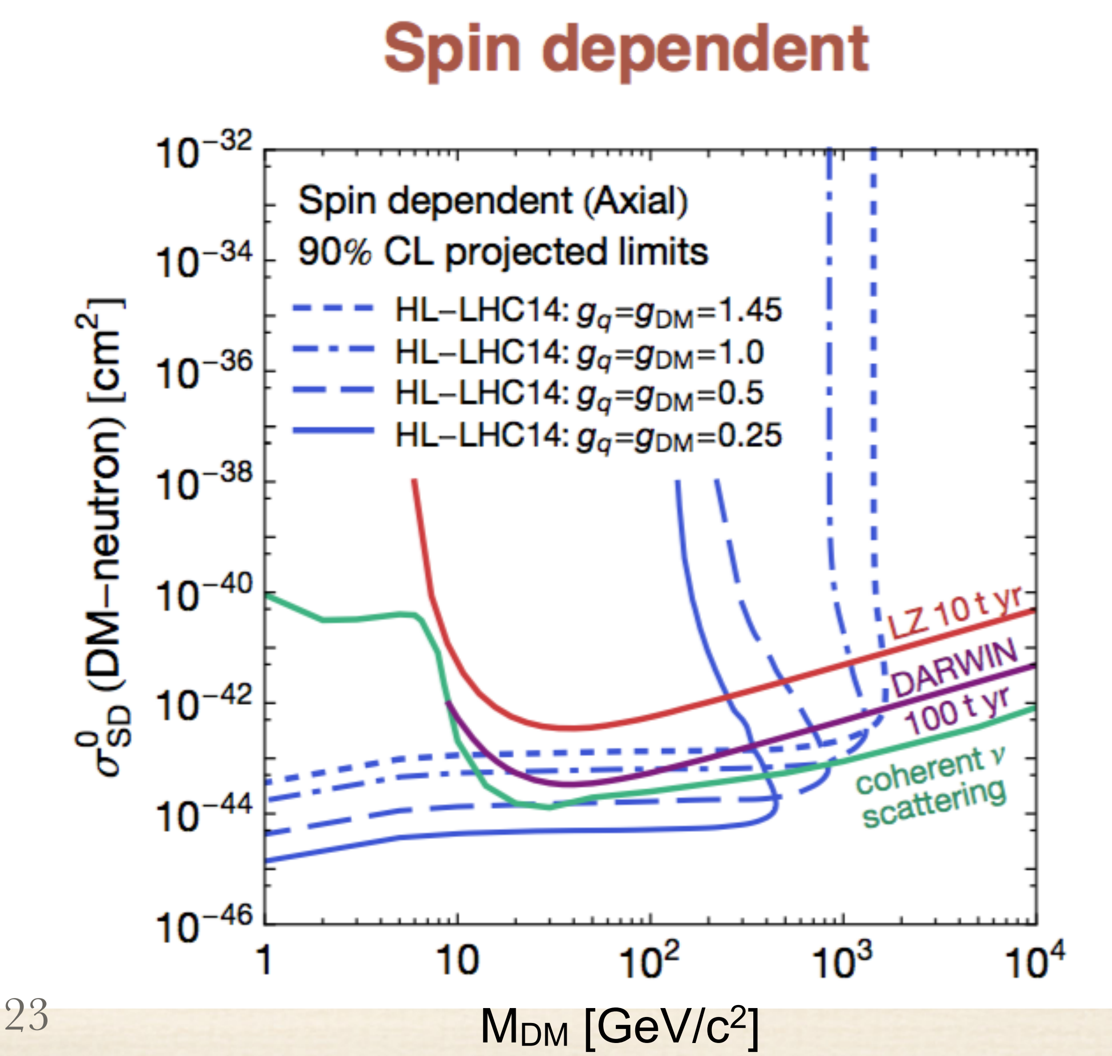
Assumptions:

- 4 variables: M_{DM}, M_{med}, g_{DM}, g_q
- DM:
  - is fermion
  - interacts with vector or axial-vector mediators
  - g_q is the same for all quark flavor

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





DARWIN-LXe: axions and ALPs

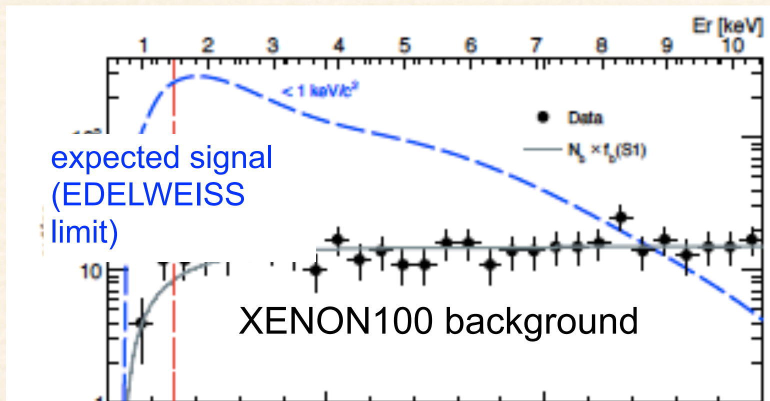
- solar axions and galactic axion-like particles (ALPs) couple to electrons
    - via axio-electric effect

Solar axions:

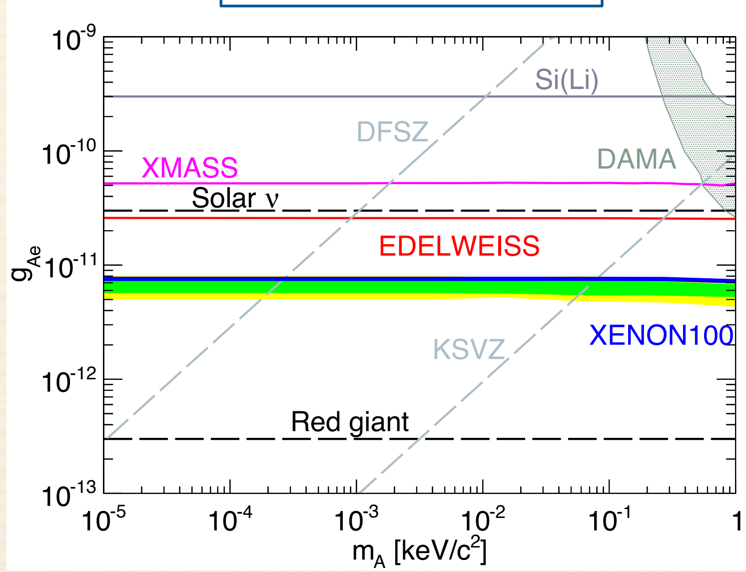
- Factor of ~10 improvement with DARWIN (R ~ g_{Ae}^4)

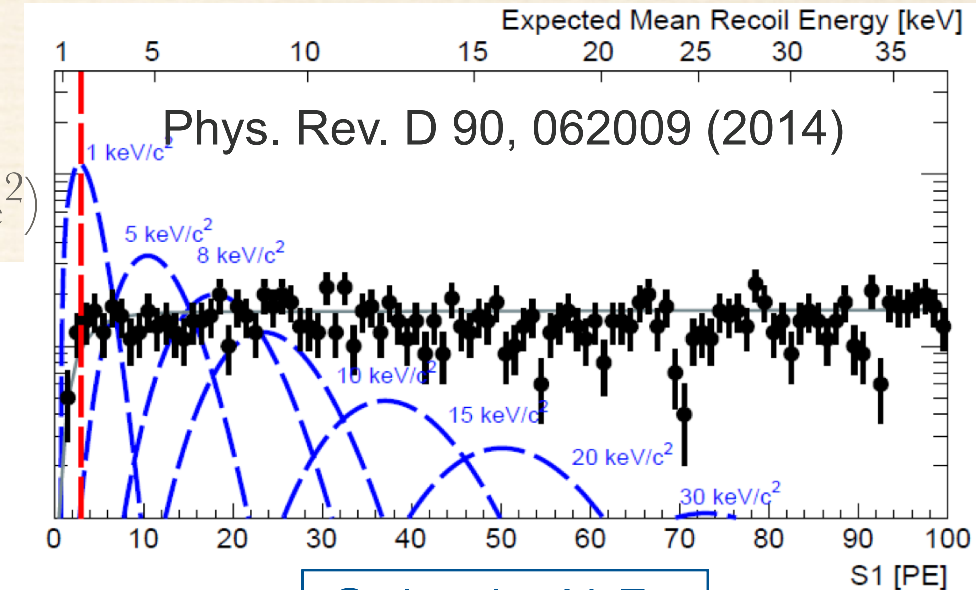
ALPs:

- Expect line feature at ALP mass
- Factor of ~ 100 improvement with DARWIN (R ~ g_{Ae}^2)

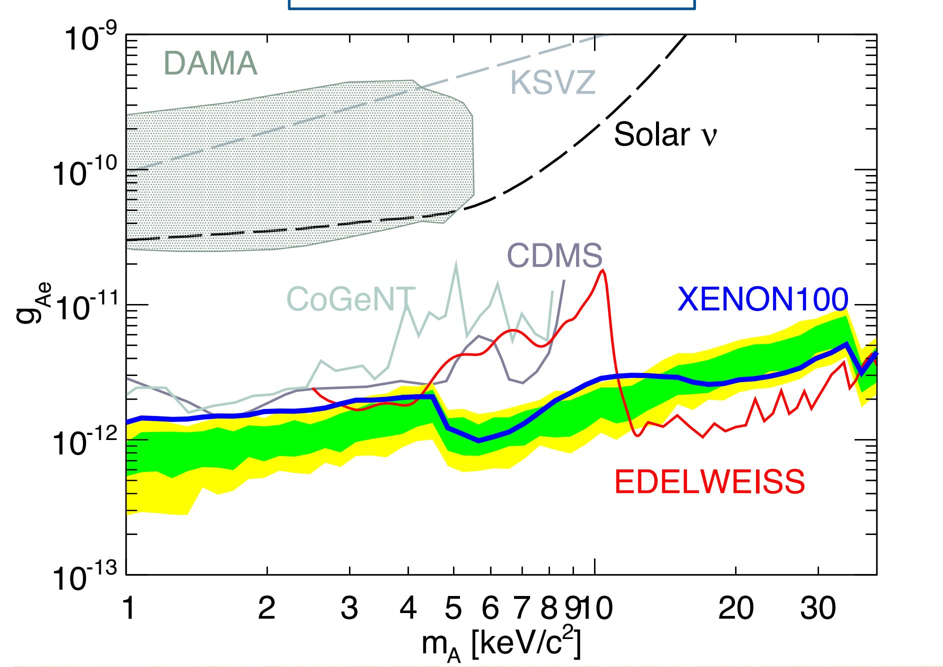


Solar axions





Galactic ALPs



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DARWIN-LXe:solar neutrinos

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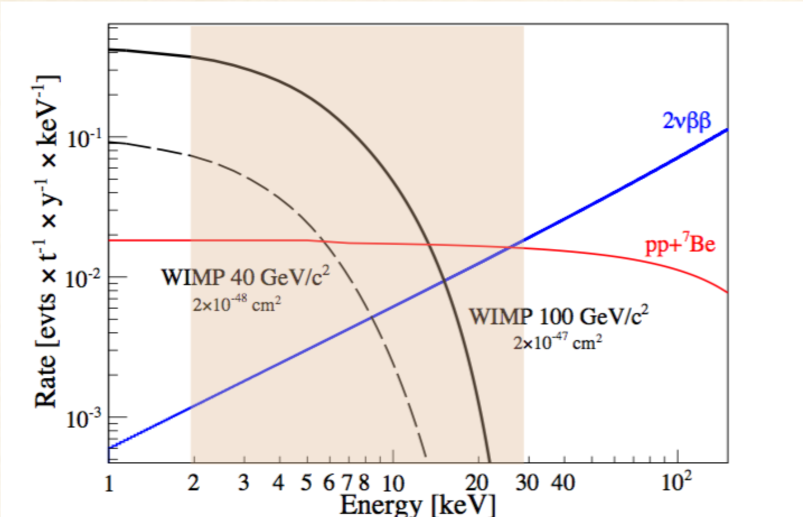
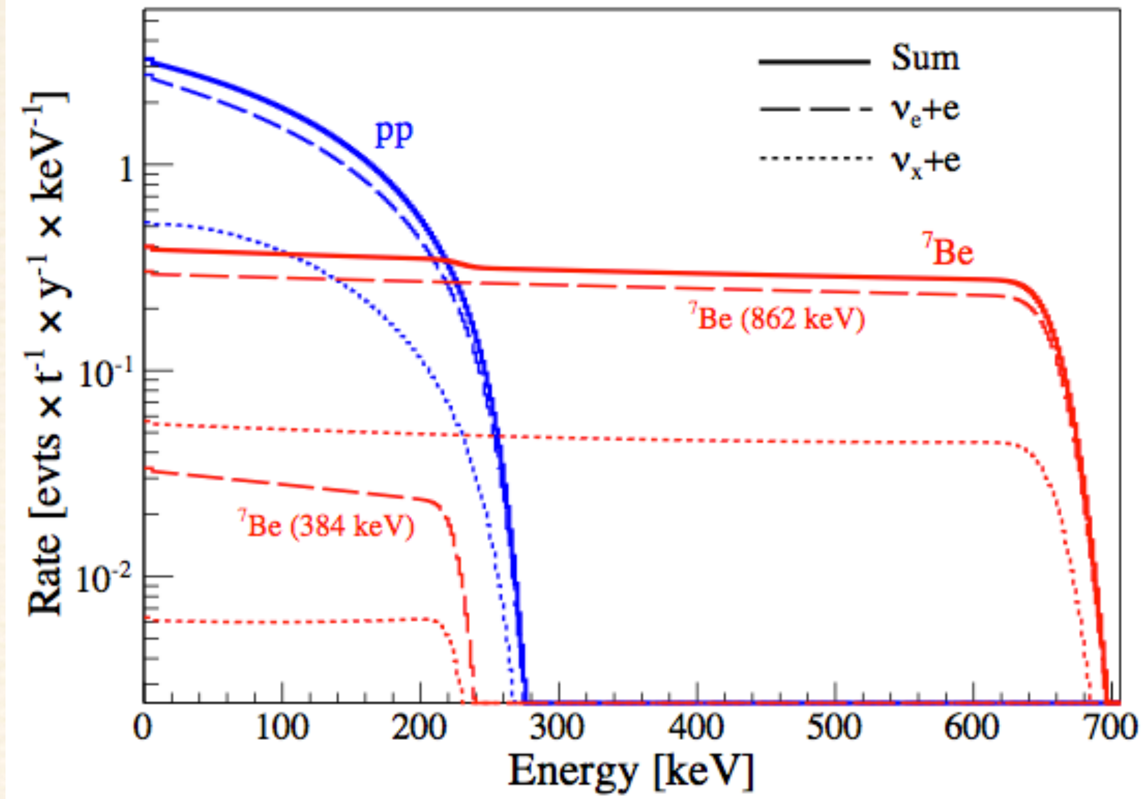
$$P_{ee} = \cos^4\theta_{13}\left(1-\frac{1}{2}\sin^2 2\theta_{12}\right)+\sin^4\theta_{13}$$

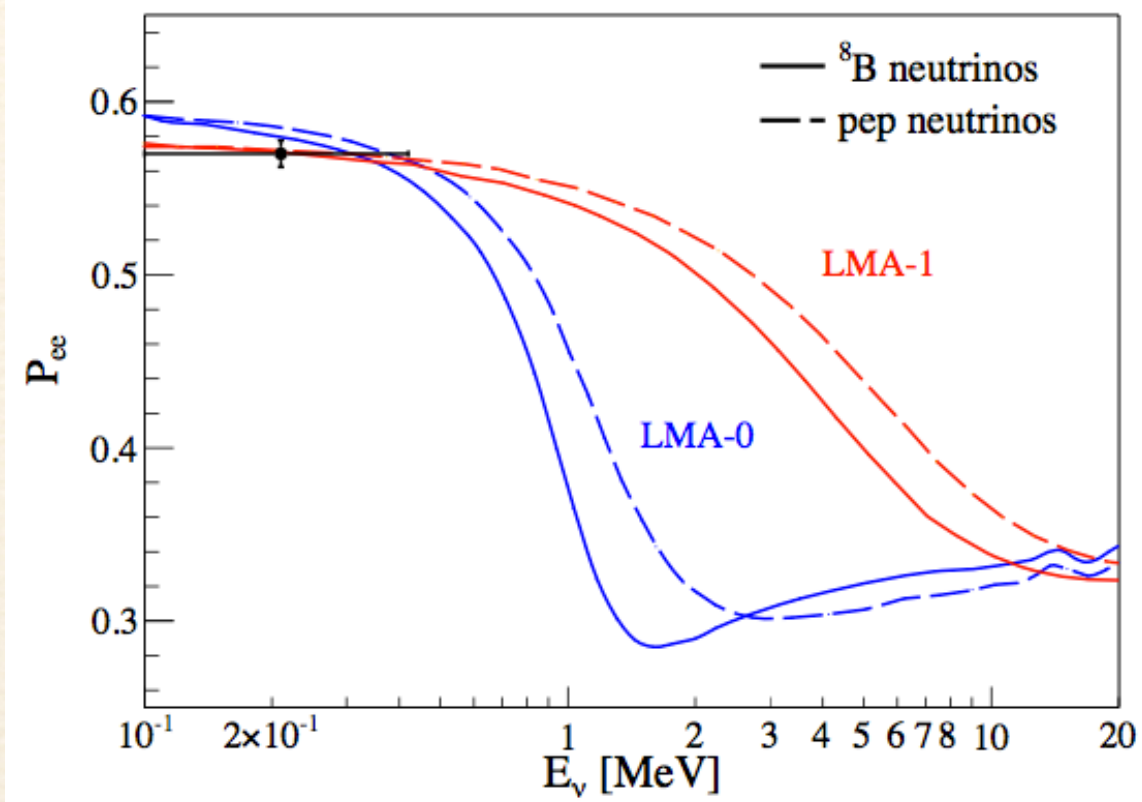
$$\frac{dN_e(E_e)}{dE_e} = N_0 \times t \times \sum_i^{flavours} \int dE_\nu \frac{d\phi_i(E_\nu)}{dE_\nu}\frac{d\sigma_i(E_e,E_\nu)}{dE_e}$$

- Reach ~ 1% precision after 5 years
- Test different oscillation scenarios (non-standard neutrino interactions that can modify P_{ee} as a function of energy?)
- Higher stats reachable:
  - increase energy range (^{136}Xe depletion)



  - use larger fiducial mass





DARWIN-LXe: 0νββ sensitivity

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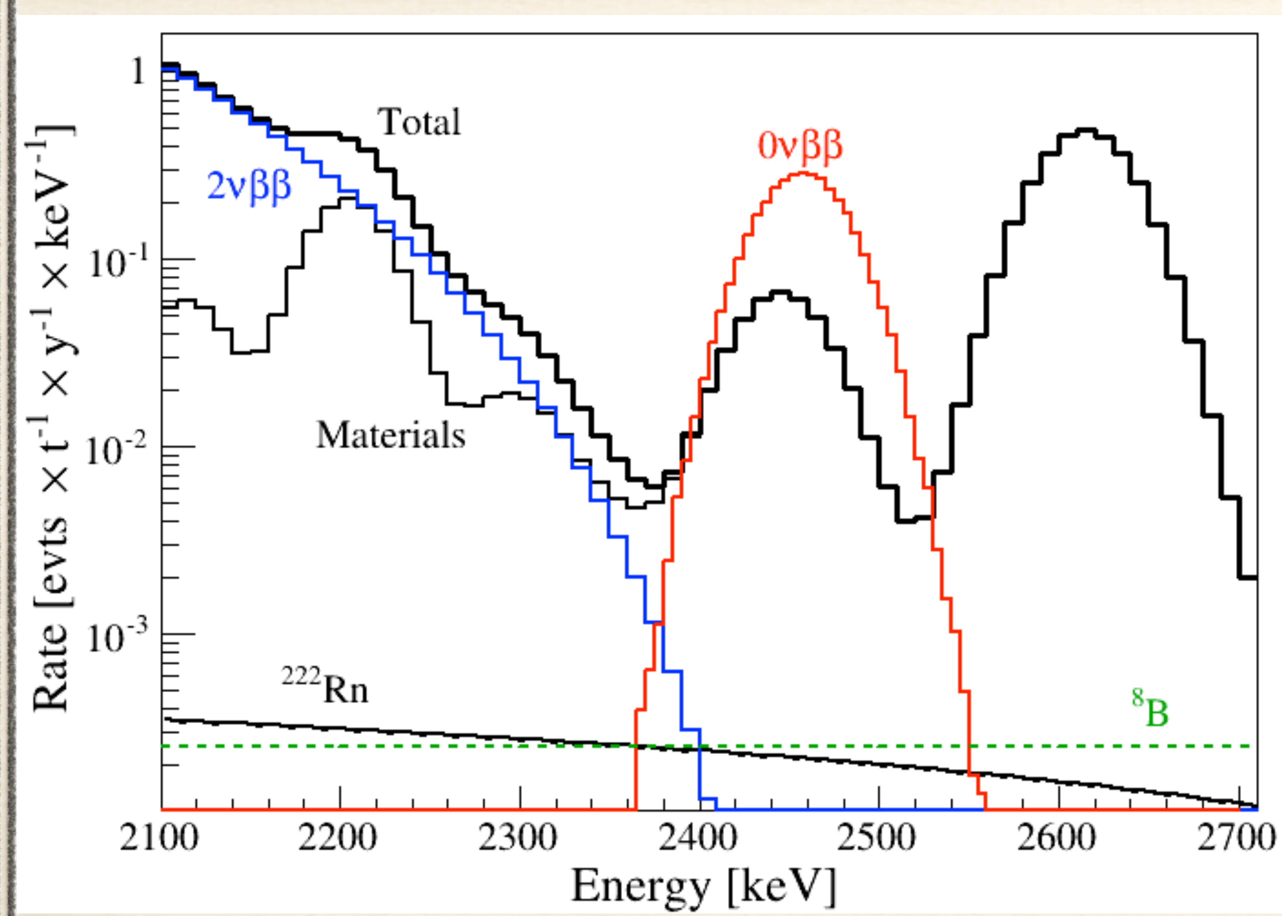
- Fiducial mass 6t
- BG dominated by ^{226}Ra sub-chain decays (^{214}Bi) in the cryostat and photosensors
- Assuming:
  - $T_{1/2}(0\nu\beta\beta) = 1.6\times10^{25}$ years
  - $T_{1/2}(2\nu\beta\beta) = 2.11\times10^{21}$ years

	Events/(6 t y)
Energy range	2385–2533 keV
Signal events	106
Detector components	27
^{222}Rn in LXe (0.1μBq/kg)	0.21
^{8}B (ν-e scattering)	0.22
^{136}Xe ($2\nu\beta\beta$)	0.14



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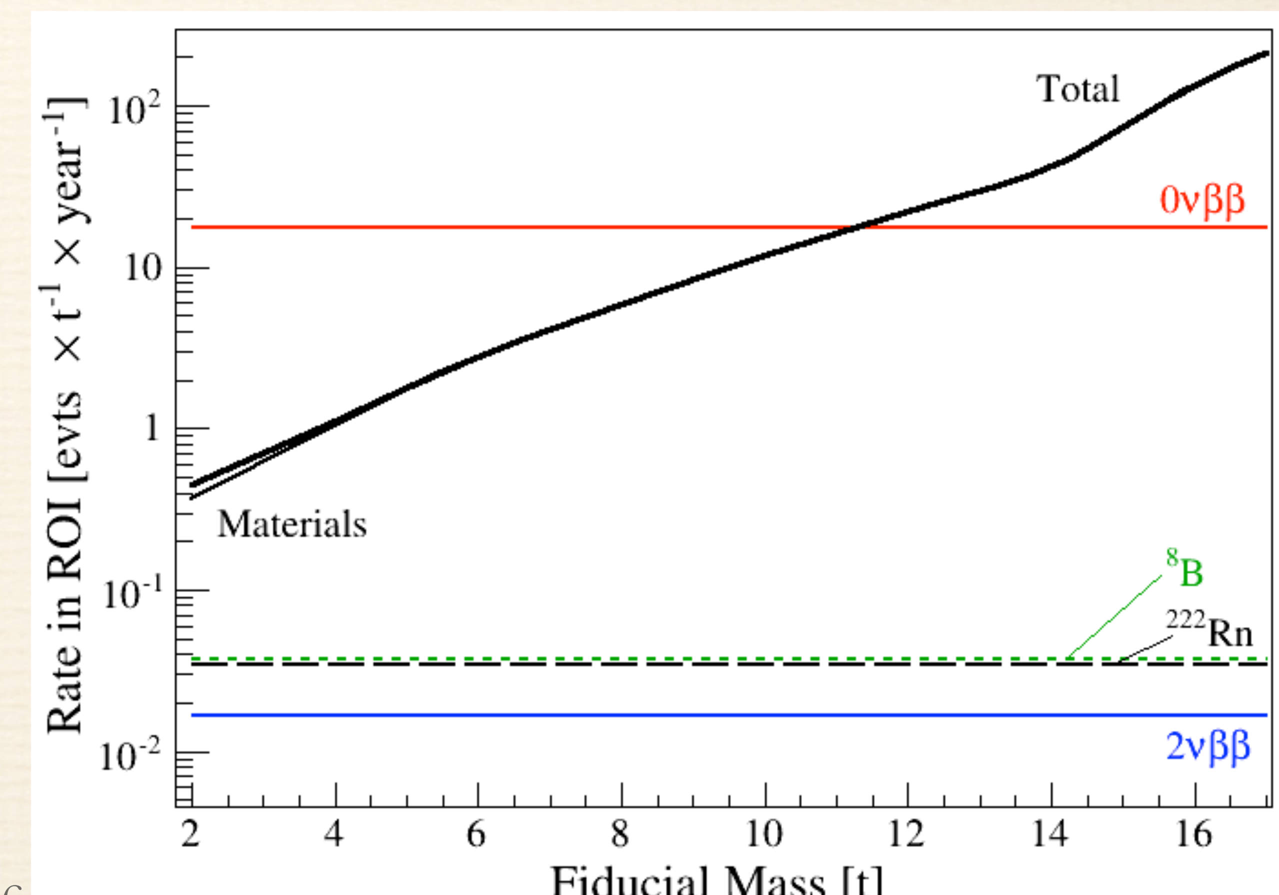

DARWIN-LXe: technical challenges

- Discrimination:
  - A level of 99.98% needs factor of 5 improvement wrt XENON100
- HV, drift field
  - Electron drift length of > 2 m, high purity, and uniform field at the 1% level
  - HV to bias the cathode must be -100 to -200 kV to have a drift field of 0.5 - 1 kV/cm
  - Robust, and transparent grid or wire electrodes with >2 m diameter
- Liquid target:
  - Procurement, storage, cooling, high-speed purification of 30-50 t of LXe
- Backgrounds:
  - ^{85}Kr: 0.1 ppt ^{nat}Kr (0.2 ppt ^{nat}Kr at same level as solar neutrinos)
  - ^{222}Rn: 0.1 μBq/kg (~ 10 times lower than solar neutrinos level)
- R&D and ideas under study:
  - development of alternative signal readout
  - development of single-phase TPC
  - use of stable and high drift field (good discrimination)
  - 4-π light sensors coverage

DARWIN-LXe: estimated time scale

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2010 - 2013

First R&D phase, Aspera funded

June 2013: Aspera final report

2013 - 2018

R&D and design study

2018: CDR/TDR

2018 - 2020

Engineering studies

2018-19: demonstrators at home institutions

2020: construction/integration at UL

2020 - 2030

Construction, commissioning and science run

2020: construction/integration at UL

2021: commissioning

2022: physics run

The DARWIN Consortium

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ASU School of Earth & Space Exploration
Arizona State University

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29 groups from 9 countries