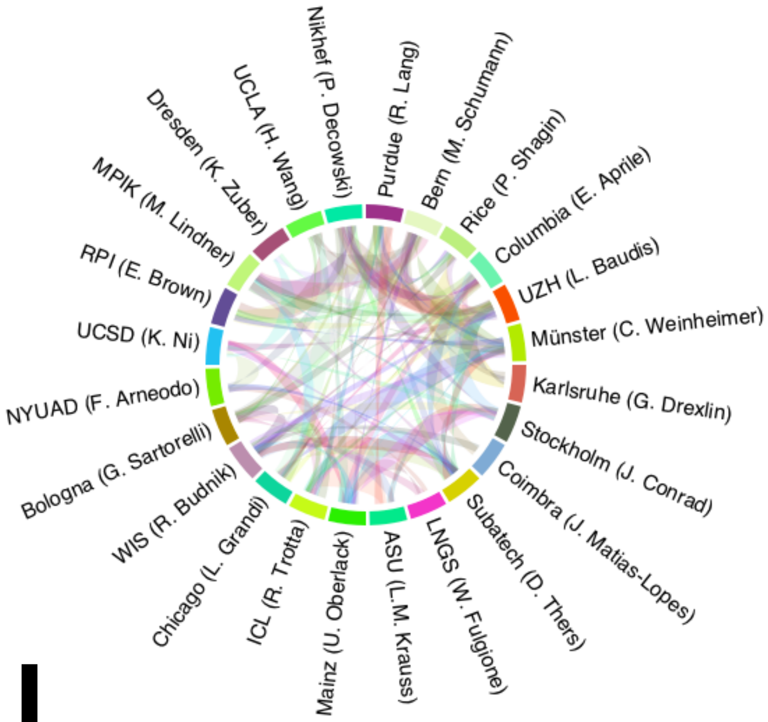
DARWIN



DARWIN

Towards the Ultimate Dark Matter Detector

Patrick Decowski

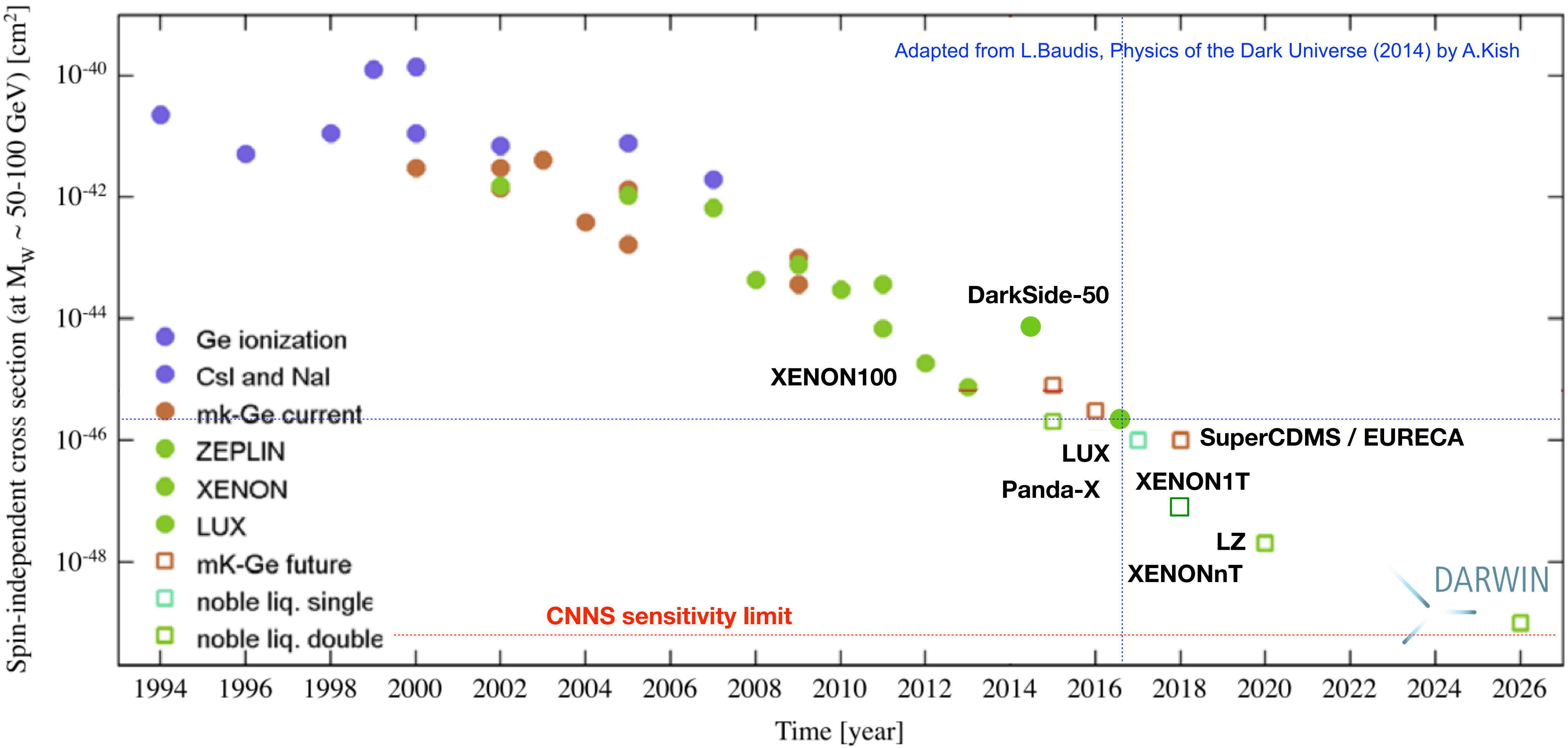
UNIVERSITEIT VAN AMSTERDAM

GRAPPA

GRavitation AstroParticle Physics Amsterdam

Nikhef

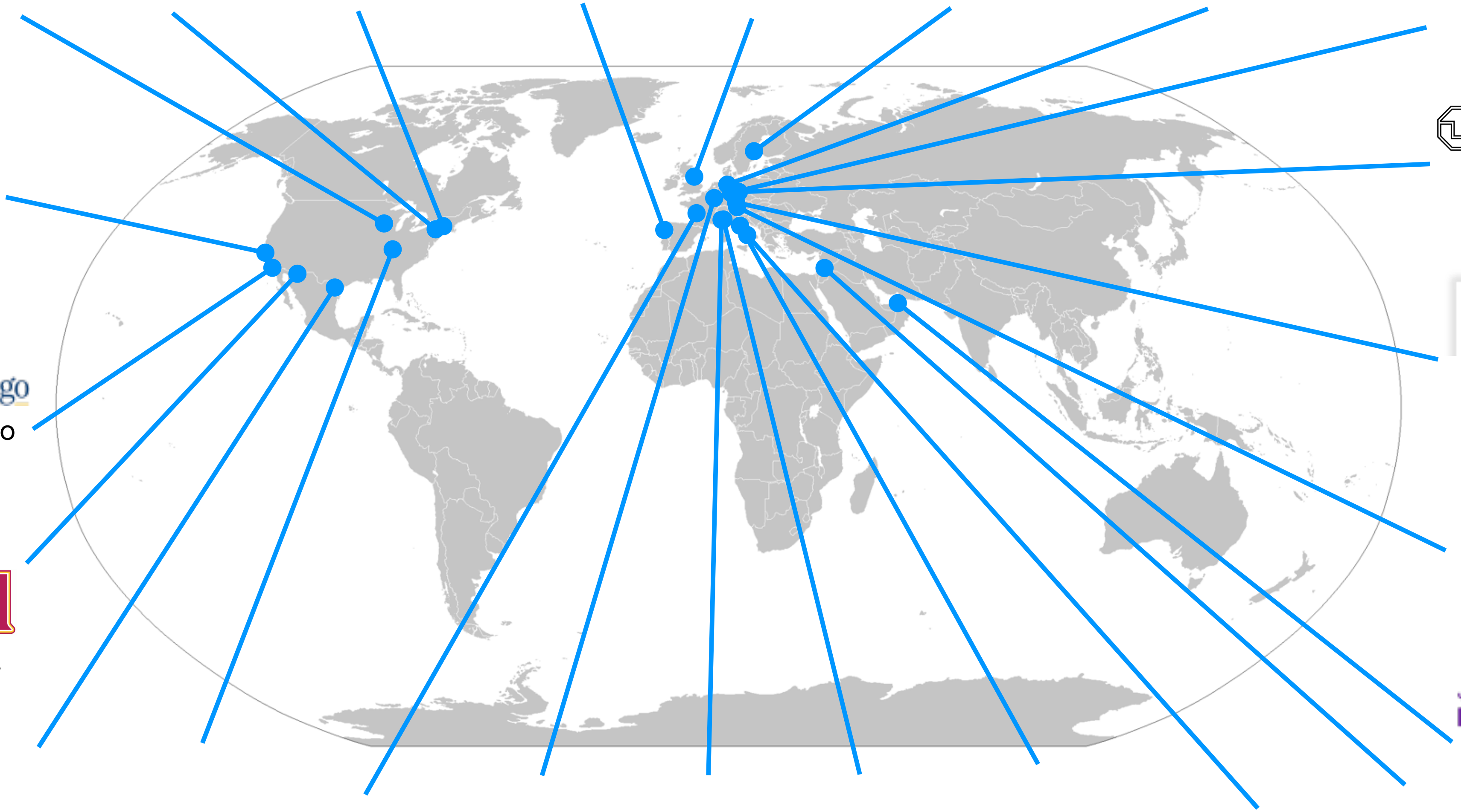
Direct Dark Matter Detection



- Requirements to reach these goals:
  - Large target mass / easily scalable
  - Low threshold
  - Low radioactive background

The DARWIN Consortium

- 25 groups from 11 countries - formed in 2009



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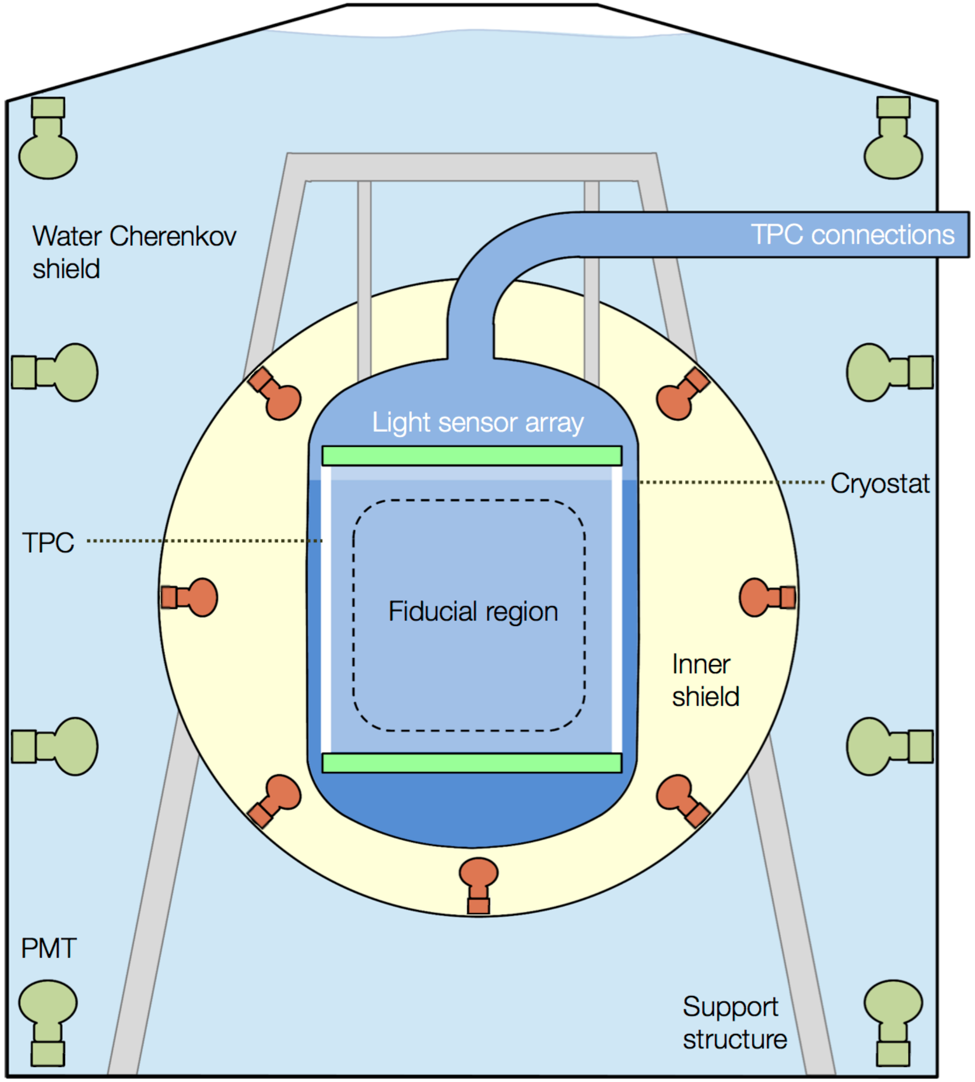
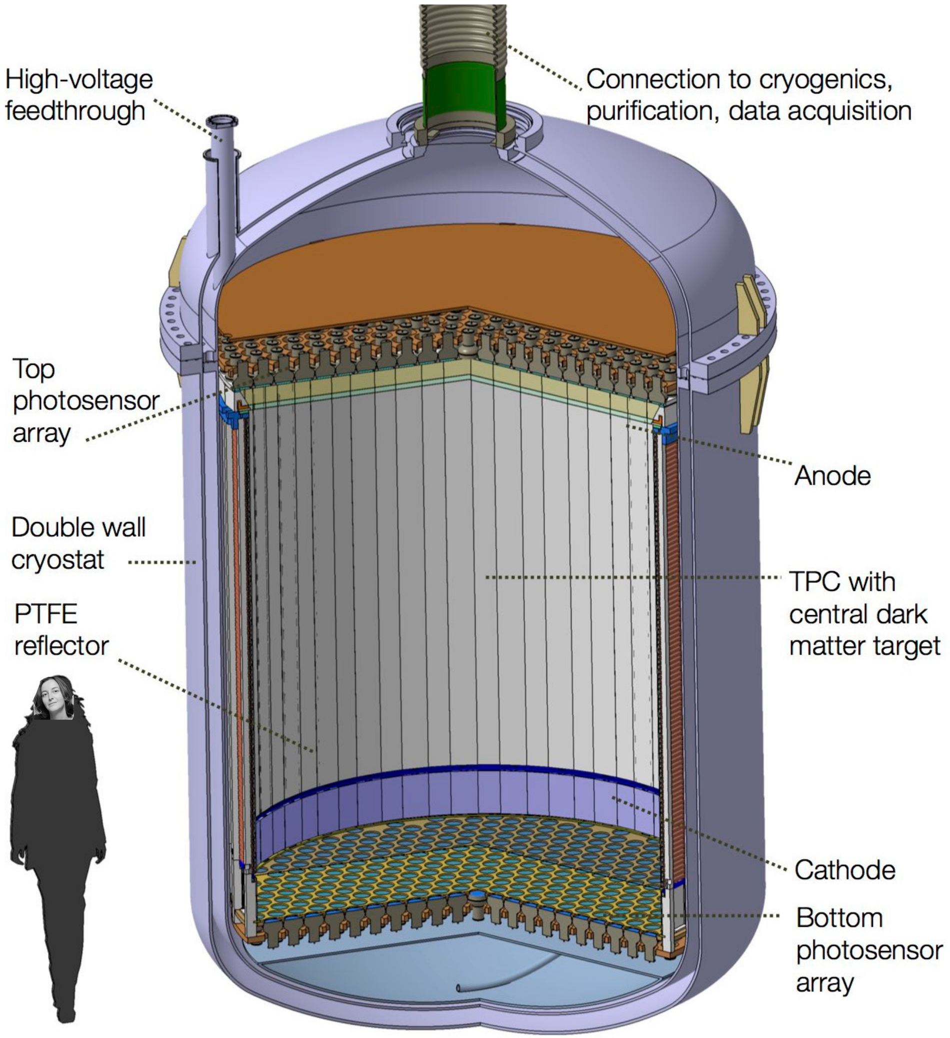
DARWIN Conceptual Design



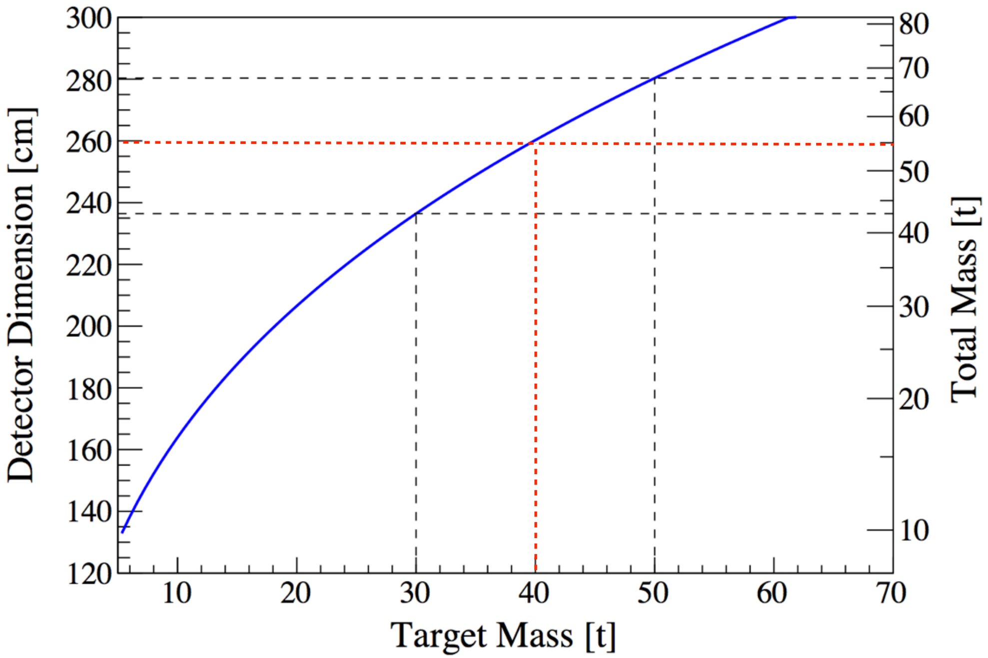
- Conceptual design based on proven technologies
- Water Cherenkov shield: ~14m diameter
- Liquid scintillator neutron veto under study
- Possible location: LNGS

DARWIN Conceptual Design

J. Aalbers et al., JCAP 11 (2016) 017



- 40 ton LXe target
- Exposure >5 years
- TPC height/diameter 2.6m
- 3” PMTs: ~1800 / 4” PMTs: ~1000
- Low-background cryostat
- PTFE reflector panels
- Copper E-field shaping rings



Physics Channels

- **WIMP searches** NR
  - Spin-independent
  - Spin-dependent and inelastic interactions
- **Coherent neutrino-nucleus scattering (CNNS)** NR
  - Predicted by SM, not yet observed
- **Low-energy solar neutrinos: pp, ^{7}Be** ER
  - Test/improve solar model, test neutrino models
- **Solar axions and galactic axion-like particles (ALPs)** ER
  - Alternative dark matter candidates
  - Coupling to electrons via axio-electric effect
- **Supernova neutrinos**
  - Sensitivity to all neutrino flavors (via CNNS) NR
  - Complementarity to large-scale neutrino detectors
- **Neutrinoless double beta decay**
  - Lepton number violating process, effective Majorana mass ER
  - No enrichment in ^{136}Xe required

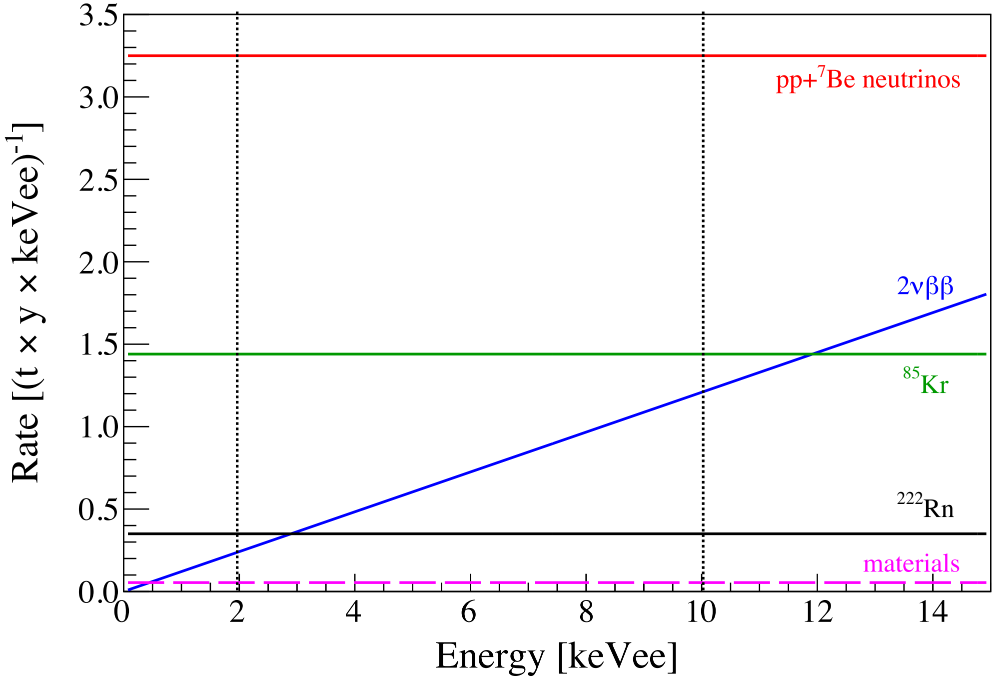
Backgrounds

M. Schumann et al., JCAP 10 (2015) 016

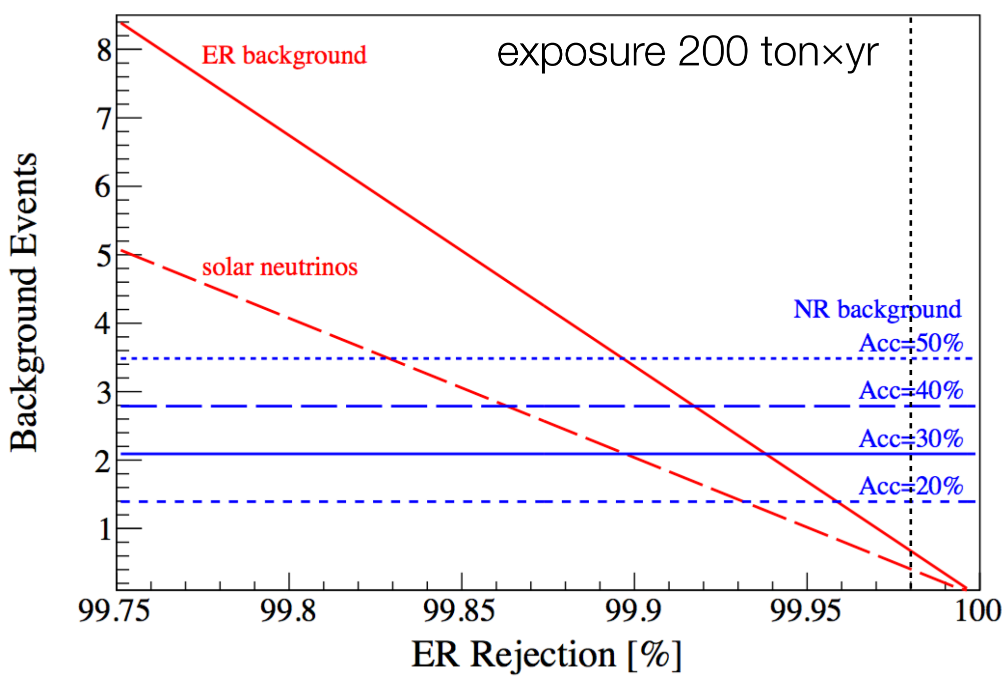
- Monte Carlo simulations for main material components
- Intrinsic backgrounds:
  - ^{85}Kr: 0.1 ppt ^{nat}Kr
    → ×2 below XENON1T design
  - ^{222}Rn: 0.1 µBq/kg
    → ×100 below XENON1T design
  - ^{136}Xe: assuming natural Xe composition (8.9%)

Source	Rate [events/(t·y·keVxx)]	Spectrum
γ-rays materials	0.054	flat
neutrons*	3.8×10^{-5}	exp. decrease
intrinsic ^{85}Kr	1.44	flat
intrinsic ^{222}Rn	0.35	flat
$2\nu\beta\beta$ of ^{136}Xe	0.73	linear rise
pp- and ^{7}Be ν	3.25	flat
CNNS*	0.0022	real

ER



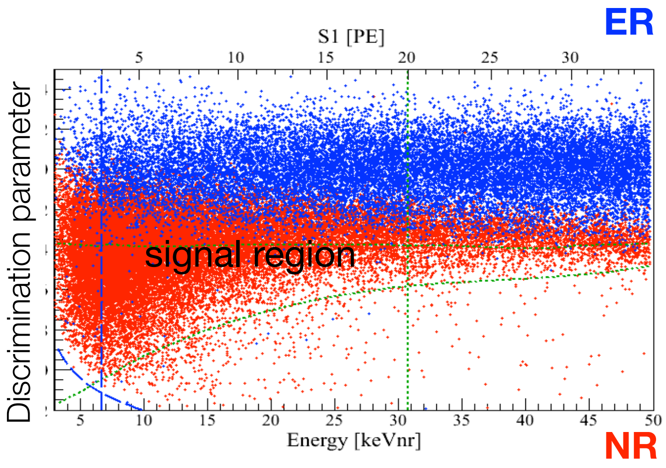
NR



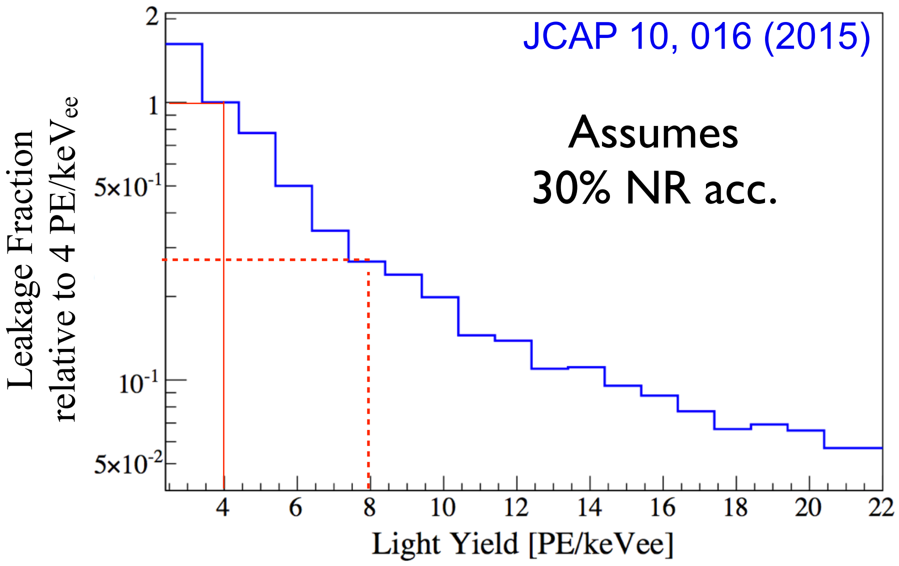
Background Rejection

- Required ER rejection >99.9%
  - discrimination based on ionization/scintillation ratio
- Experimentally achieved:

	E_{drift} [kV/cm]	LY @ 122keV [PE/keV]	NR acc. [%]	ER rejection [%]
XENON100	0.53	3.8	40	99.75
XENON100	0.53	3.8	30	99.9
LUX	0.18	8.8	50	99.0 – 99.9
ZEPLIN-III	3.4	4.2	50	99.987
K.Ni et al.	0.2 – 0.7	10	50	99.99-99.999



Higher light yield → better resolution → reduced (less wide) ER band width



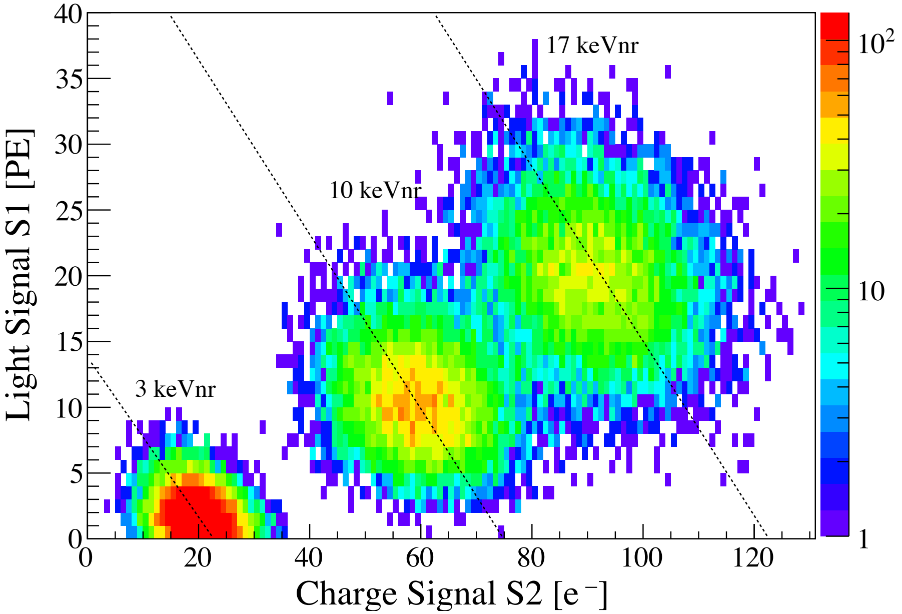
JCAP 10, 016 (2015)

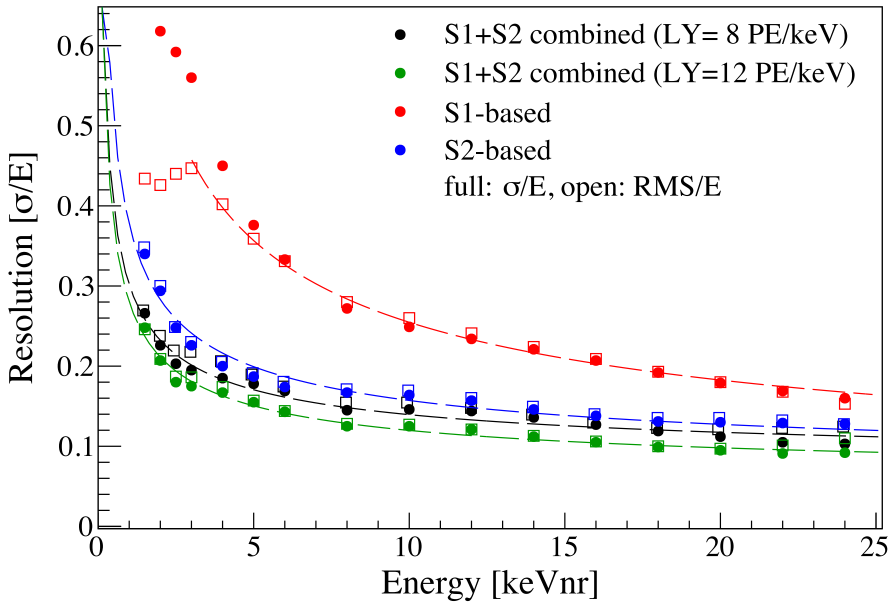
Assumes
30% NR acc.

- ×2 higher LY → ×7.5 less leakage
- E-field uniformity plays crucial role

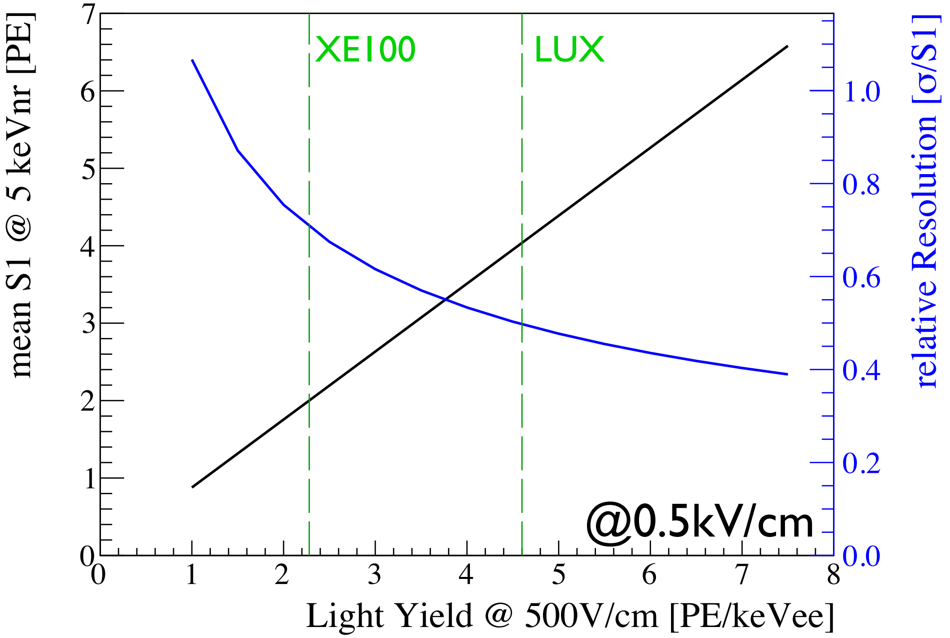
WIMP Sensitivity

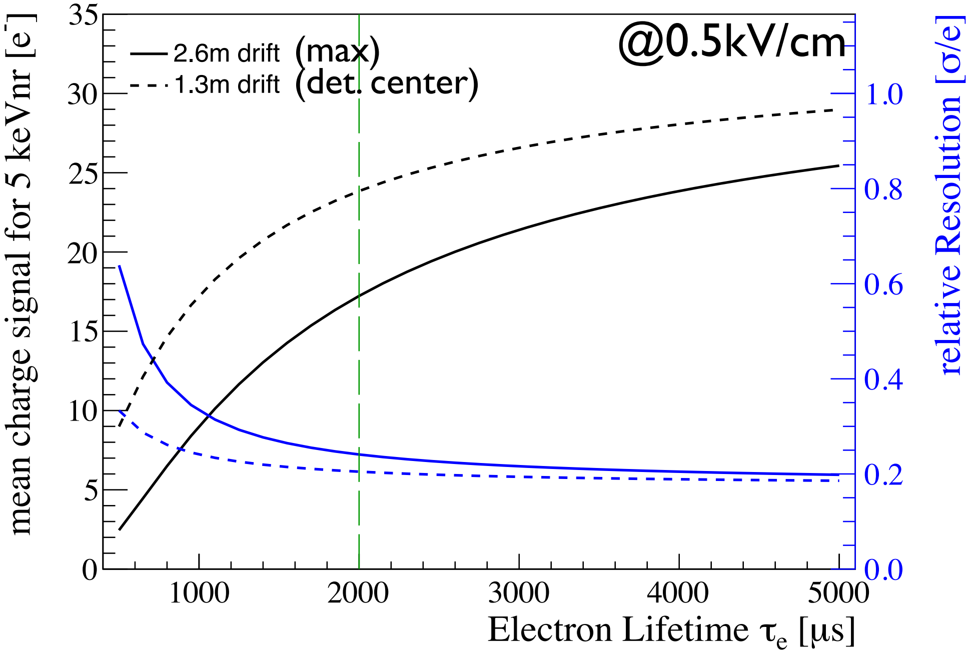
JCAP 10, 016 (2015)





→ Significant improvement in resolution using combined (S1+S2) energy scale

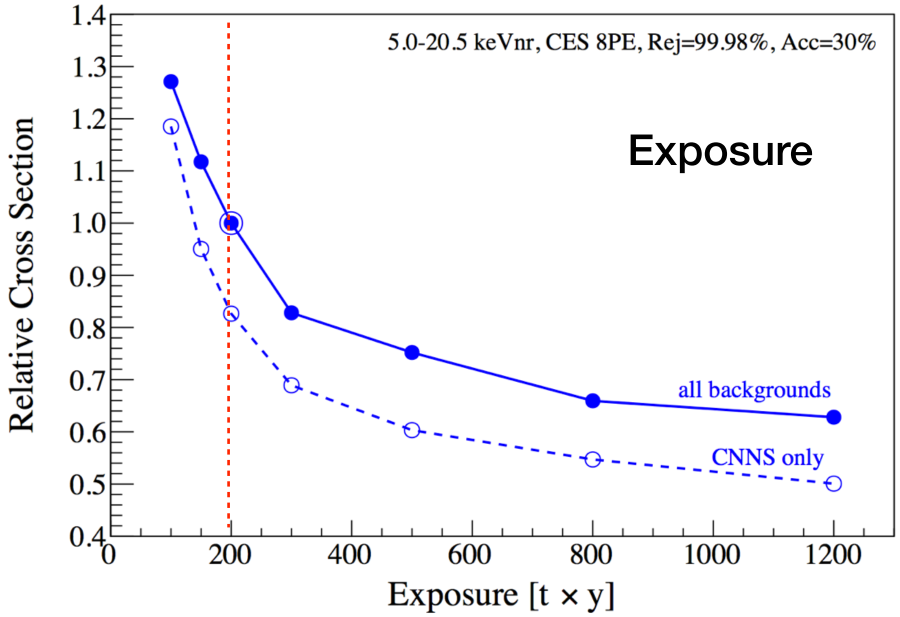


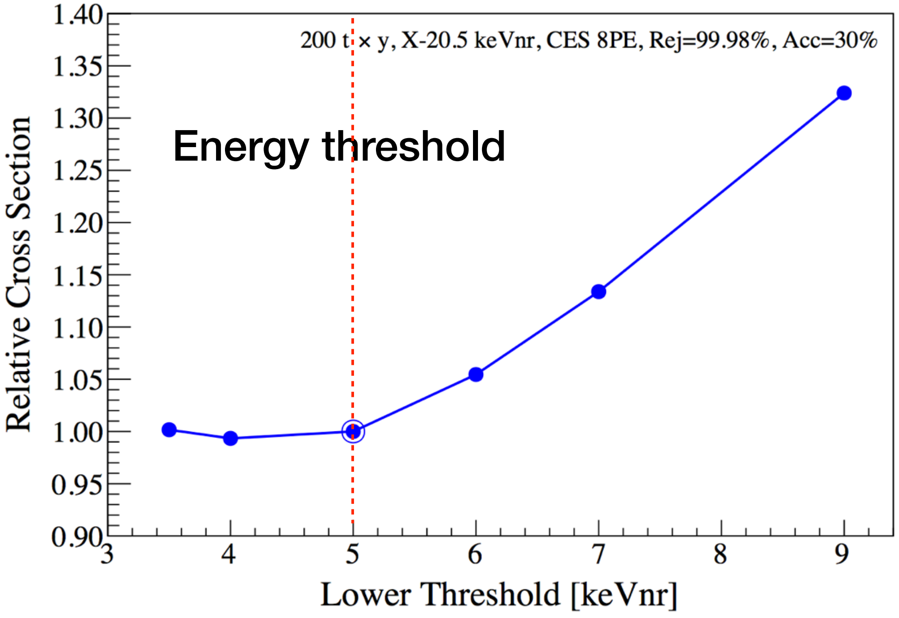


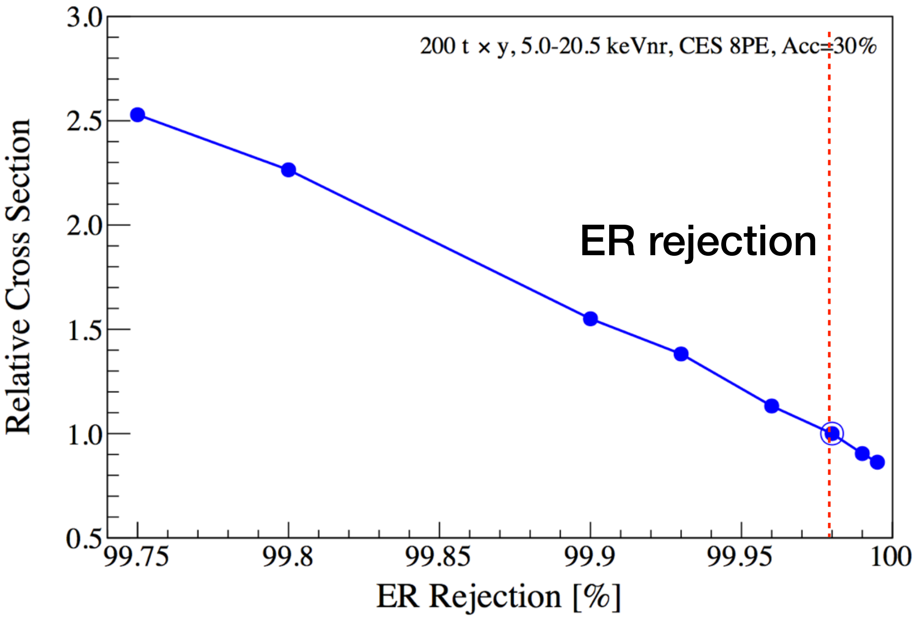
WIMP Sensitivity Studies

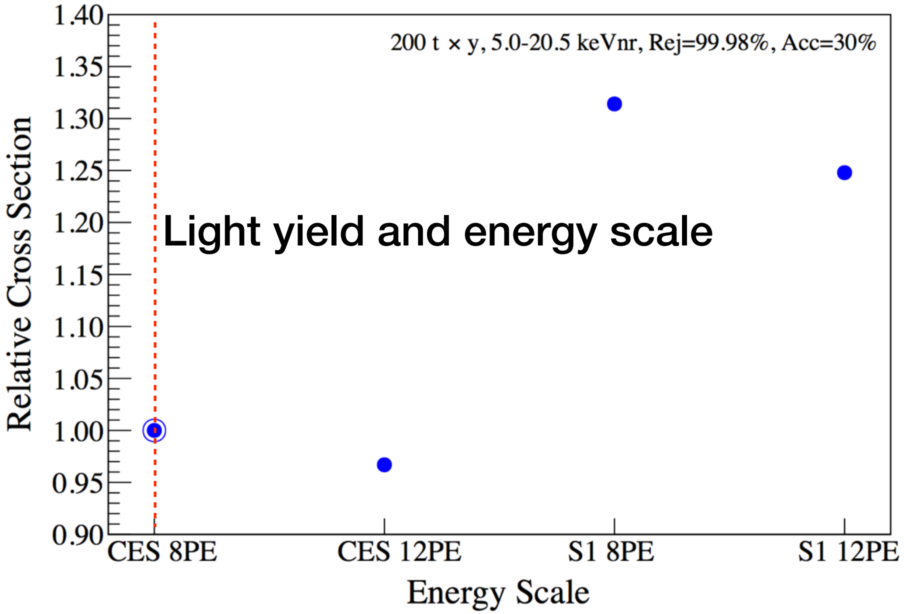
JCAP 10, 016 (2015)

- For WIMP mass 40 GeV/c^2:







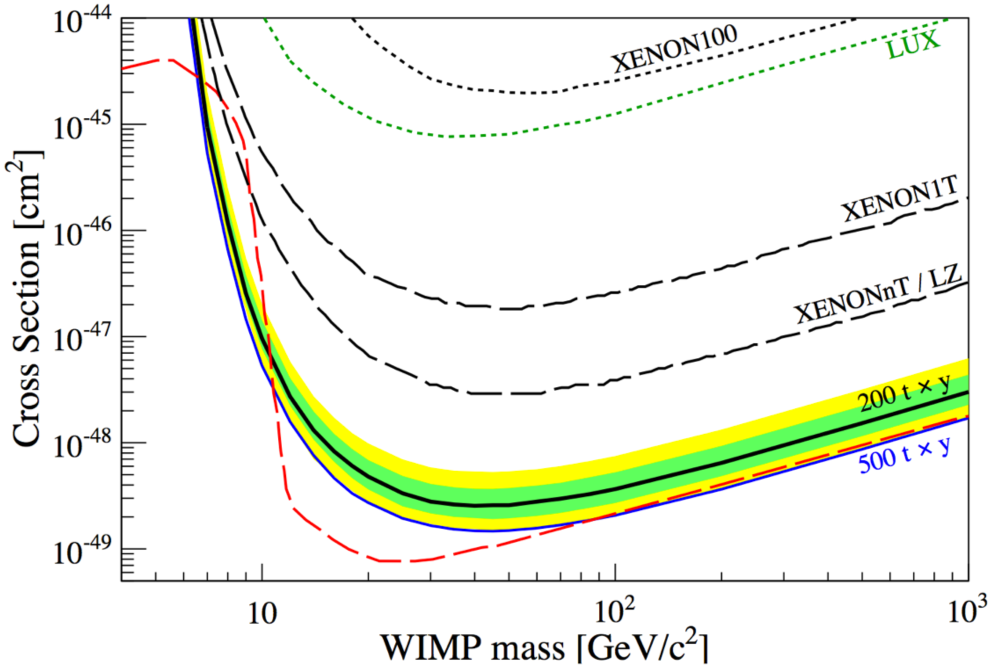


DARWIN WIMP Sensitivity

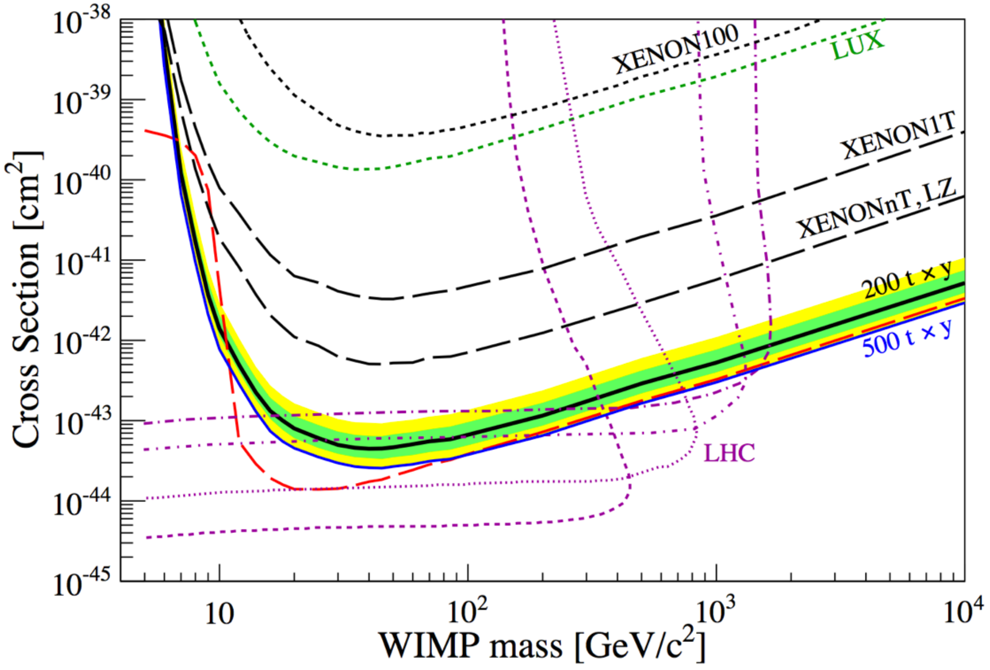
JCAP 10, 016 (2015)

- Assumed exposure 200 ton×yr, all backgrounds included
- Likelihood analysis: 99.98% ER rejection, 30% NR acceptance
- Combined (S1+S2) energy scale
- Energy window 5-35 keV$_{\text{nr}}$
- Light yield 8 PE/keV

spin-independent interaction



spin-dependent (neutron coupling)



→ minimum sensitivity: 2.5×10^{-49} cm^2 @ 40 GeV/c^2

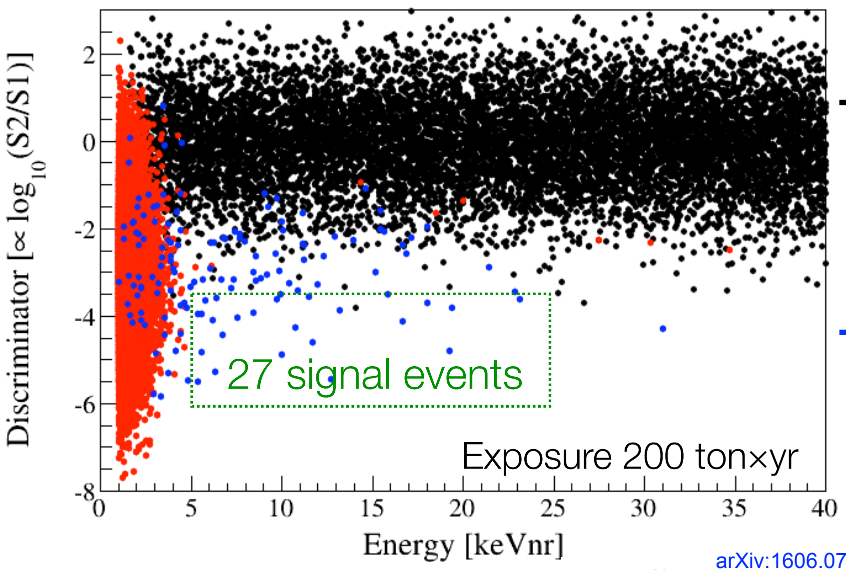
→ complementarity to LHC searches

What would we see?

DM halo parameters:

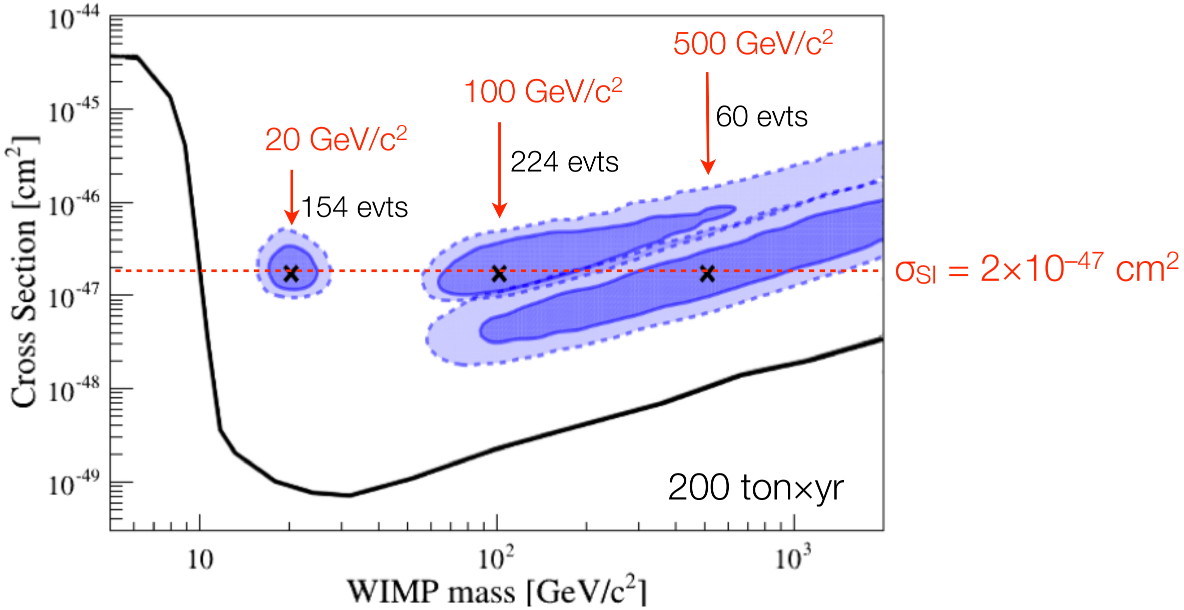
ρ_χ = (0.3±0.1) GeV/cm^3
v_0 = (220±20) km/s
v_{esc} = (544±40) km/s

neutrons and CNNS

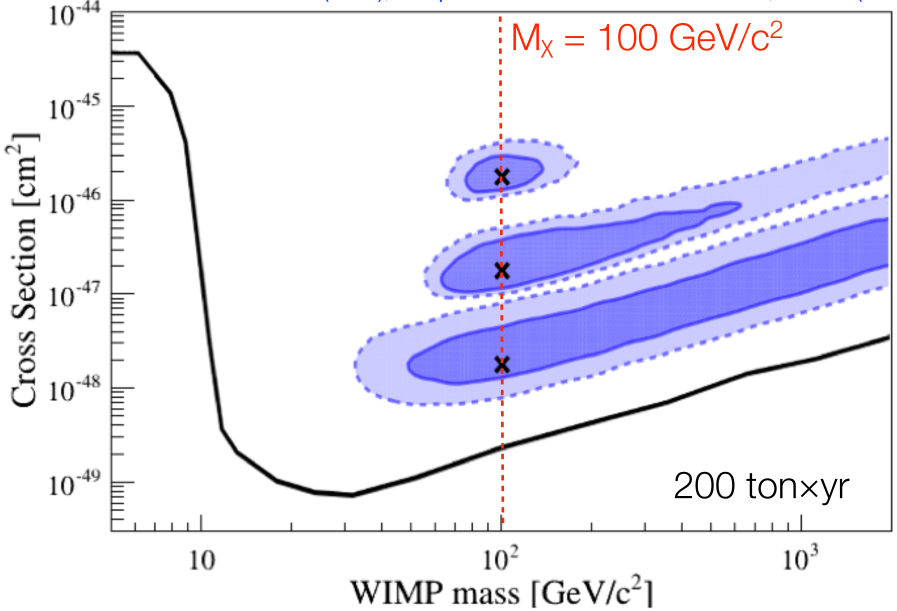


ER background
- materials
- intrinsic (Rn, Kr)
- solar ν-e$^-$ scattering
- ^{136}Xe 2νββ

30 GeV/c^2 WIMP
$\sigma_{SI} = 2\times10^{-48}$ cm^2



arXiv:1606.07001 (2016), Adapted from Newstead et al. PRD 88, 076011 (2013)

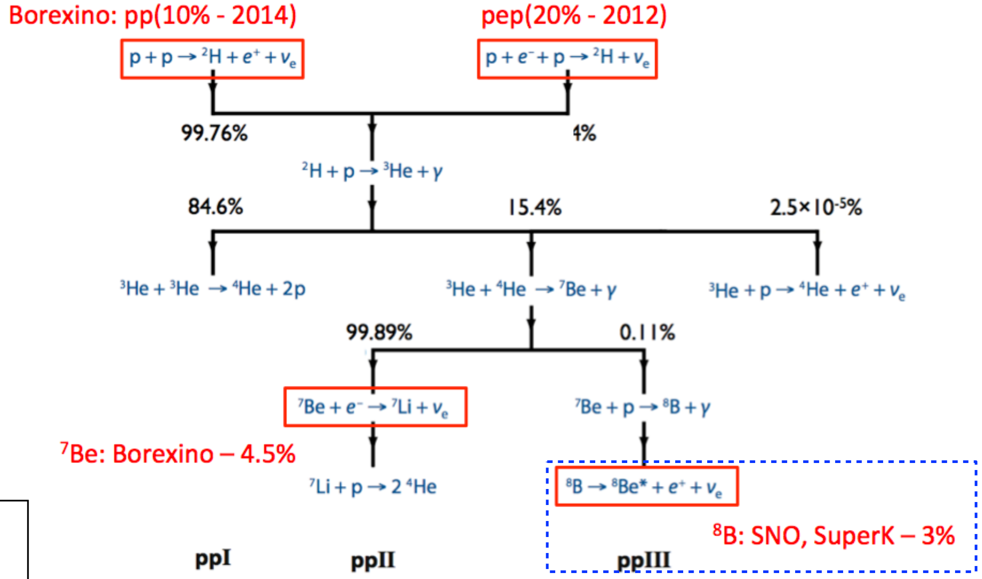


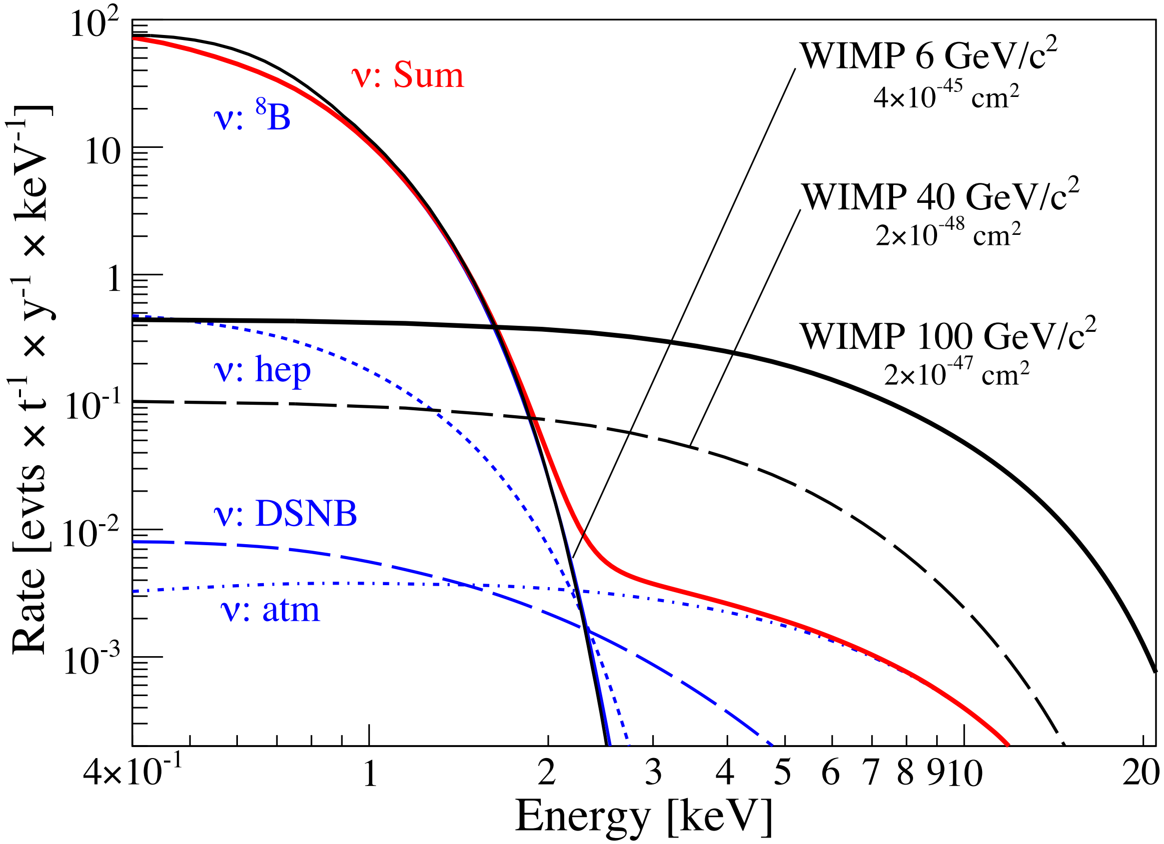
- Extended regions due to uncertainties on DM halo parameters
- For higher WIMP masses (> 500 GeV/c^2) only lower limits can be derived

Coherent Neutrino-Nucleus Scattering

JCAP 01, 044 (2014)

- $\nu + N_{Xe} \rightarrow \nu + N_{Xe}$
- Predicted by SM but not yet observed
- CNNS is background for WIMPs,
- Steeply falling spectrum





- ${}^8B$ neutrinos from the Sun:
  → 90 events/ton/yr, $E_R > 1$ keV
- Atmospheric neutrinos:
  → 3×10^{-3} events/ton/yr, $E_R > 3$ keV

Solar Neutrinos

- Neutrino-electron elastic scattering

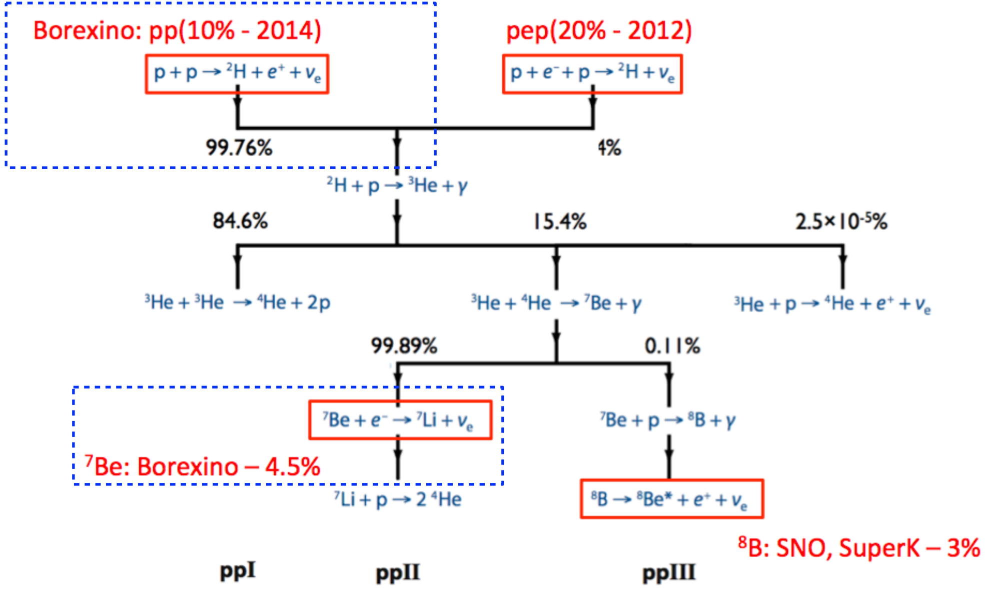
- Real-time measurement of neutrino flux
  → 7.2 events/day from pp
  → 0.9 events/day from ^{7}Be

- 2% (1%) *statistical* precision after 1 year (5 years)
  → constrain solar models

- Neutrino survival probability measurement
  → deviation from prediction indicates new physics
- Atomic binding effects have to be taken into account!

Chen et al, arXiv:1610.04177

JCAP 01, 044 (2014)



Borexino: pp(10% - 2014)

$p + p \rightarrow {}^2H + e^+ + \nu_e$

pep(20% - 2012)

$p + e^- + p \rightarrow {}^2H + \nu_e$

99.76%

4%

${}^2H + p \rightarrow {}^3He + \gamma$

84.6%

15.4%

2.5×10-5%

${}^3He + {}^3He \rightarrow {}^4He + 2p$

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$

99.89%

0.11%

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

^{7}Be: Borexino – 4.5%

${}^7Li + p \rightarrow 2\,{}^4He$

${}^7Be + p \rightarrow {}^8B + \gamma$

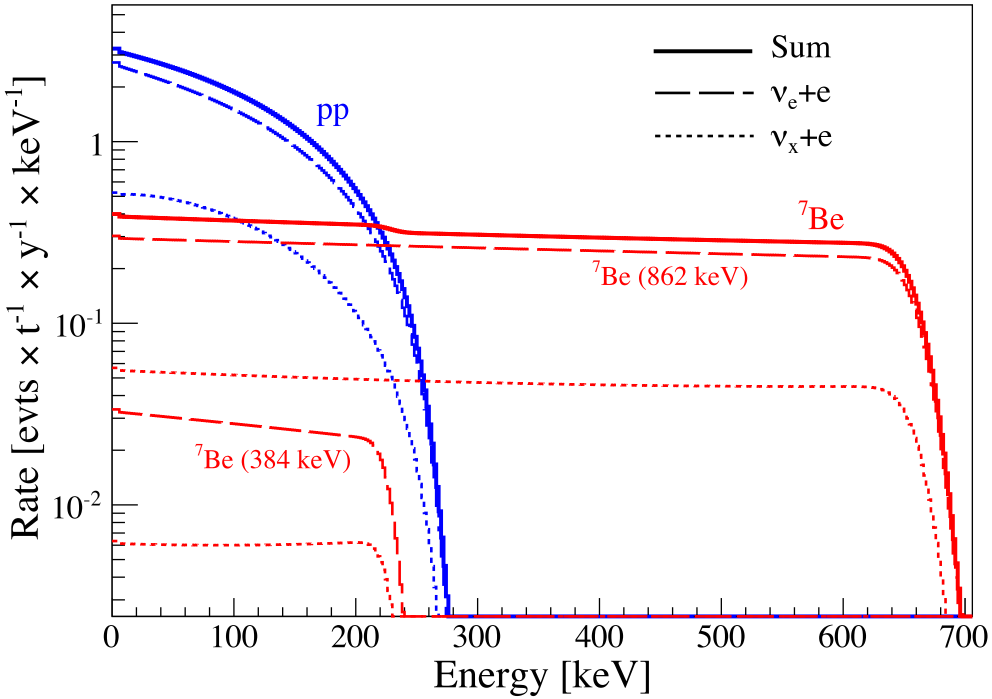
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

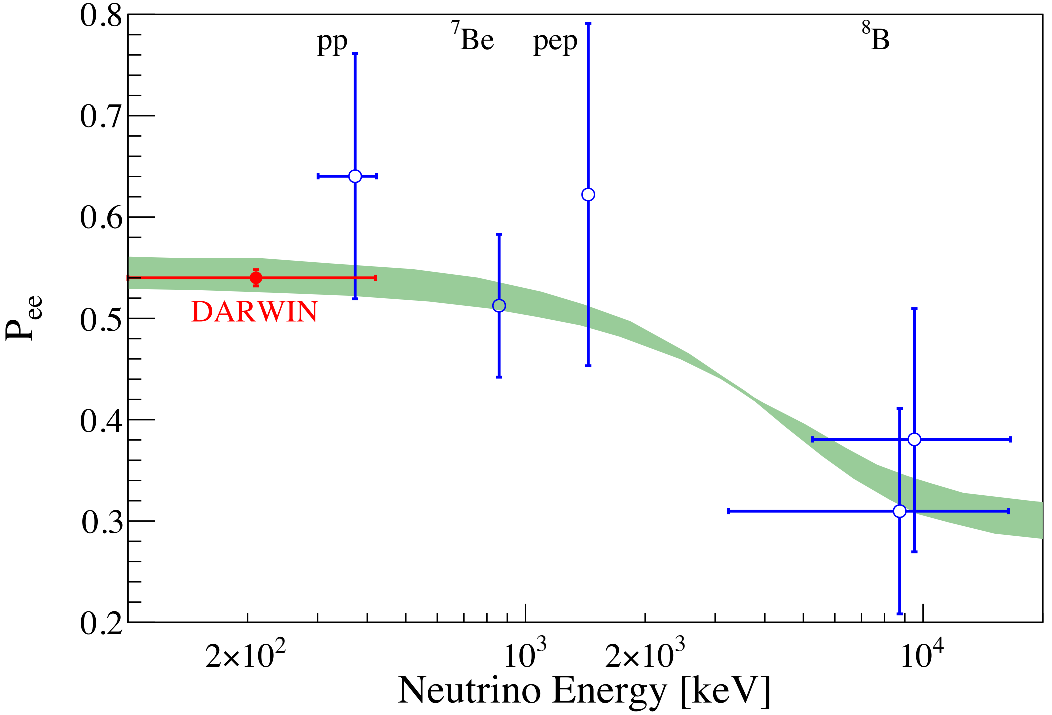
^{8}B: SNO, SuperK – 3%

ppI

ppII

ppIII

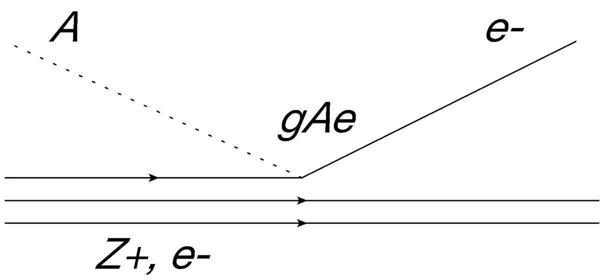


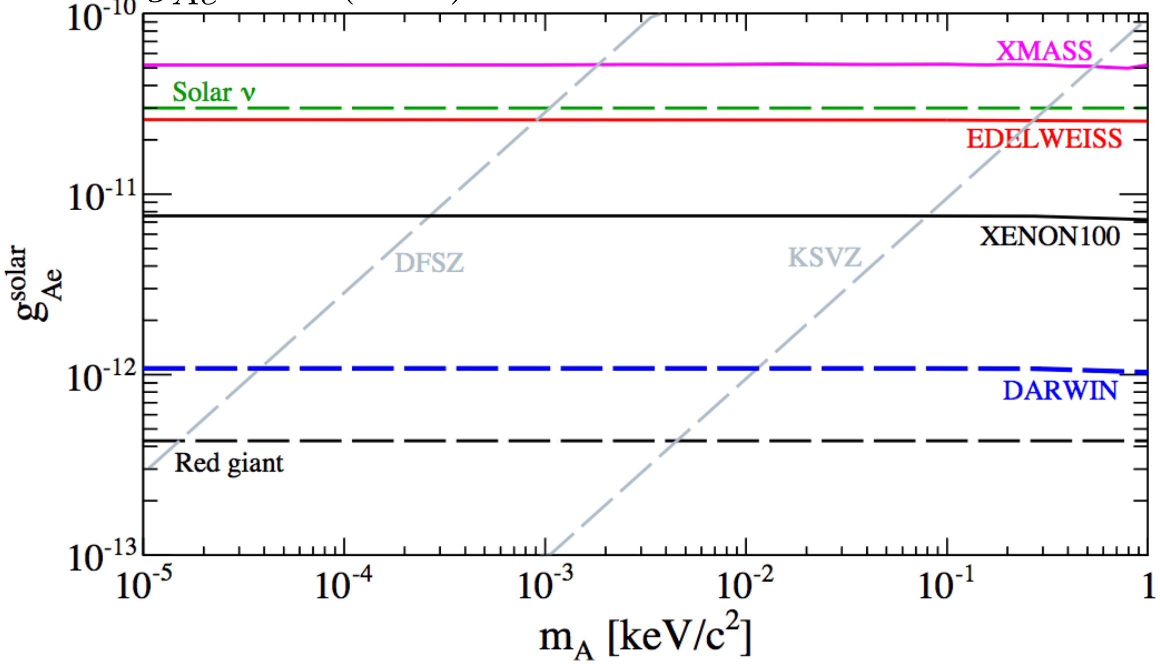


Axions and ALPs

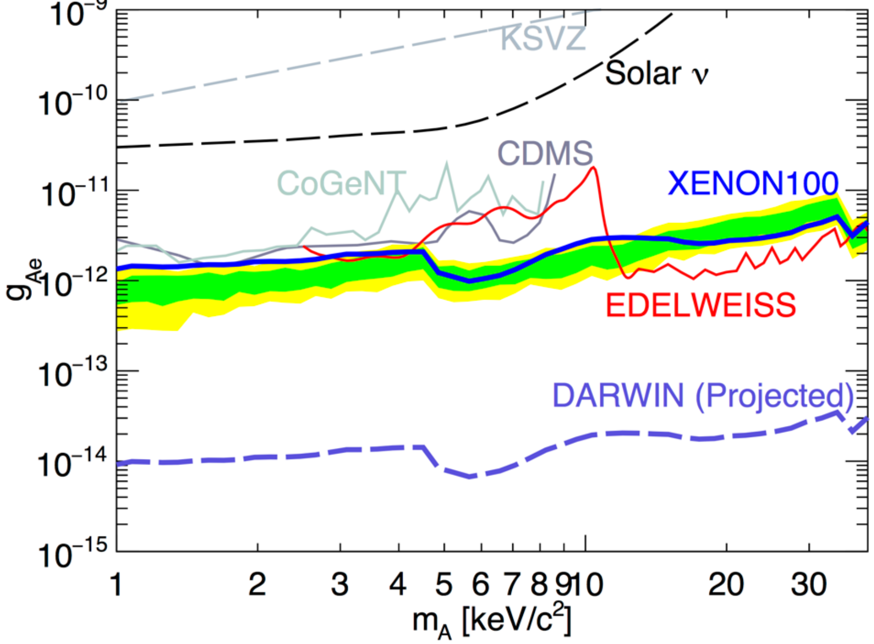
JCAP 11 (2016) 017

- Measurement via axio-electric effect (ER channel)
- Expect mono-energetic peak at the particle mass
- Sensitivity to solar axions
  - x10 improvement relative to XENON100
- Sensitivity to galactic Axion Like Particles (ALPs)
  - x100 improvement relative to XENON100
- Dominant backgrounds: solar neutrinos and 2νββ of ^{136}Xe





$g_{Ae}^{\text{solar}} \propto (M\,T)^{-1/8}$ solar axions

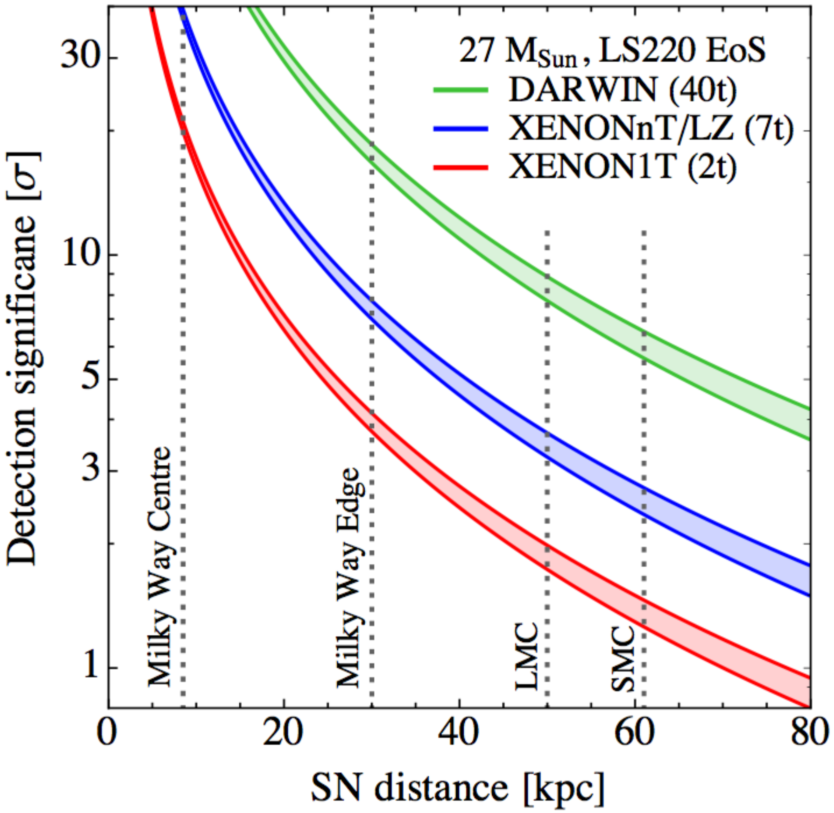


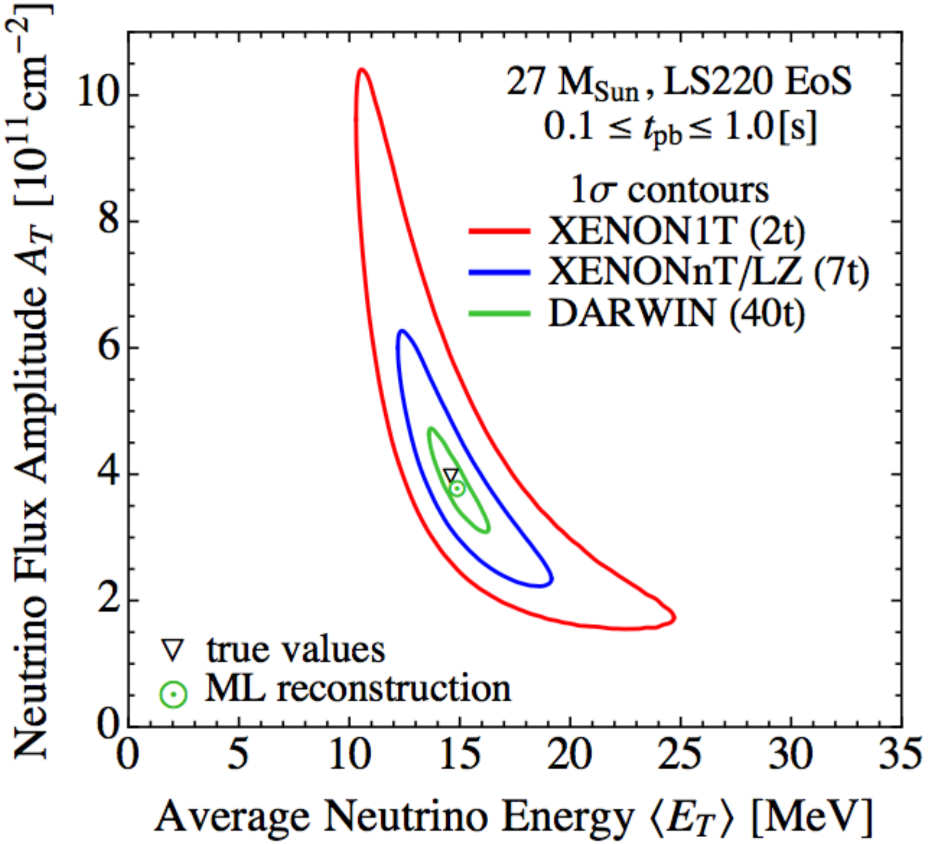
$g_{Ae}^{\text{ALP}} \propto (M\,T)^{-1/4}$ galactic ALPs

Supernova Neutrinos

R. Lang et al., arXiv:1606.09243

- Low threshold using proportional scintillation signal (S2) only
- Negligible background due to short burst (~sec)
- 5σ sensitivity to a supernova burst up to 65 kpc from Earth
- Detection of all 6 neutrino species via neutral current reactions



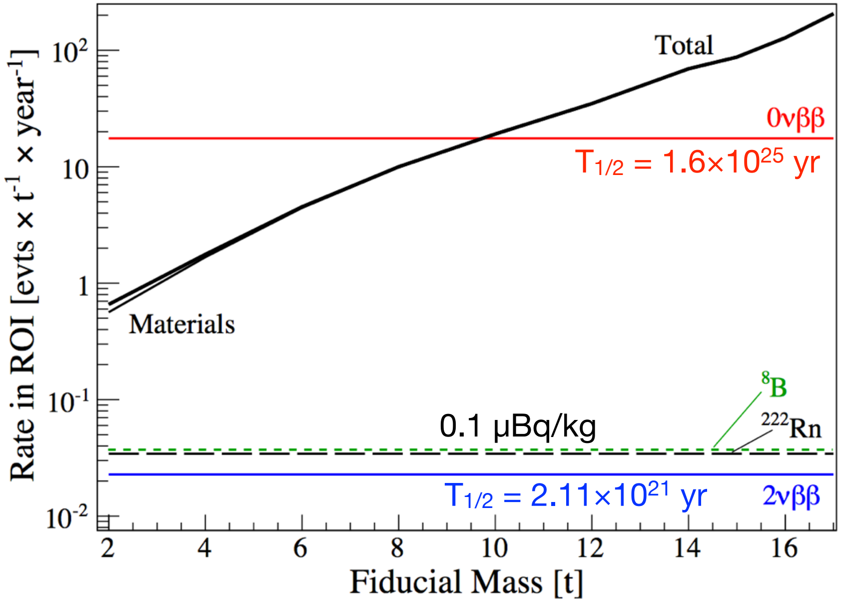


- ~700 events for a 27M⊙ SN progenitor at 10 kpc
- Flavor-insensitive neutrino energy measurement
  - → constrain total explosion energy and reconstruct the SN light curve

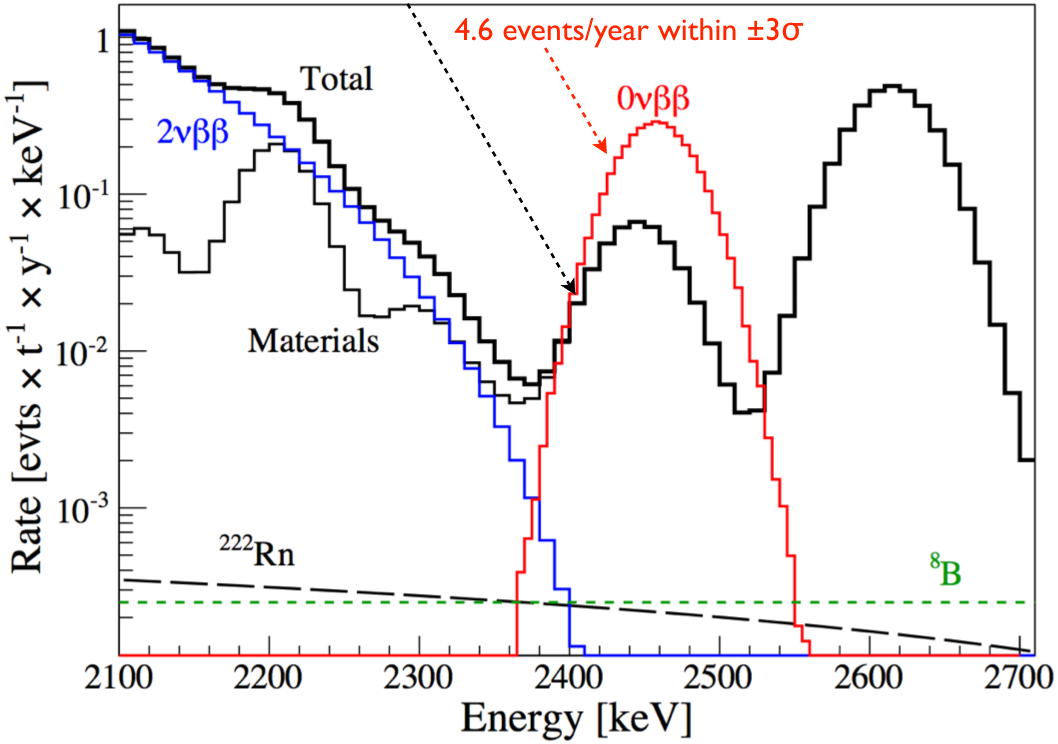
Neutrinoless Double Beta Decay

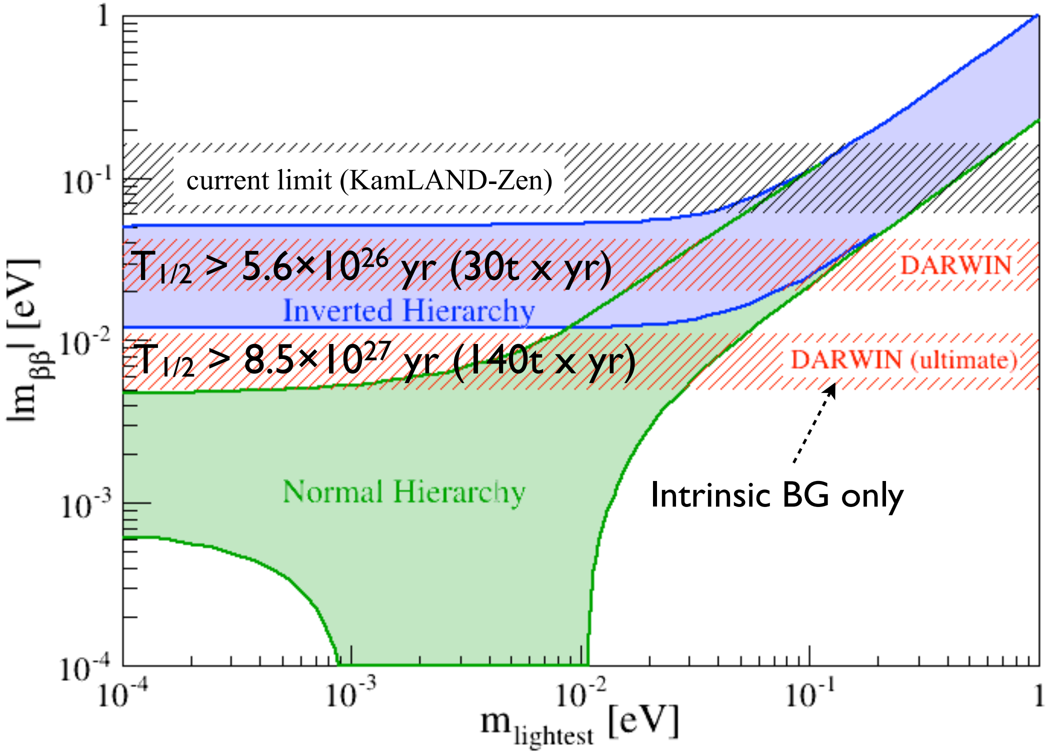
JCAP 01, 044 (2014)

- ^{136}Xe abundance in natural xenon 8.9%
  - 40t of Xe has 3.6t of ^{136}Xe
- Q-value (2458.7±0.6) keV
- MC assuming
  - $T_{1/2} = 1.6\times10^{25}$ yr (superseded)
  - Energy resolution (σ/μ) at $Q_{\beta\beta}$ 1%



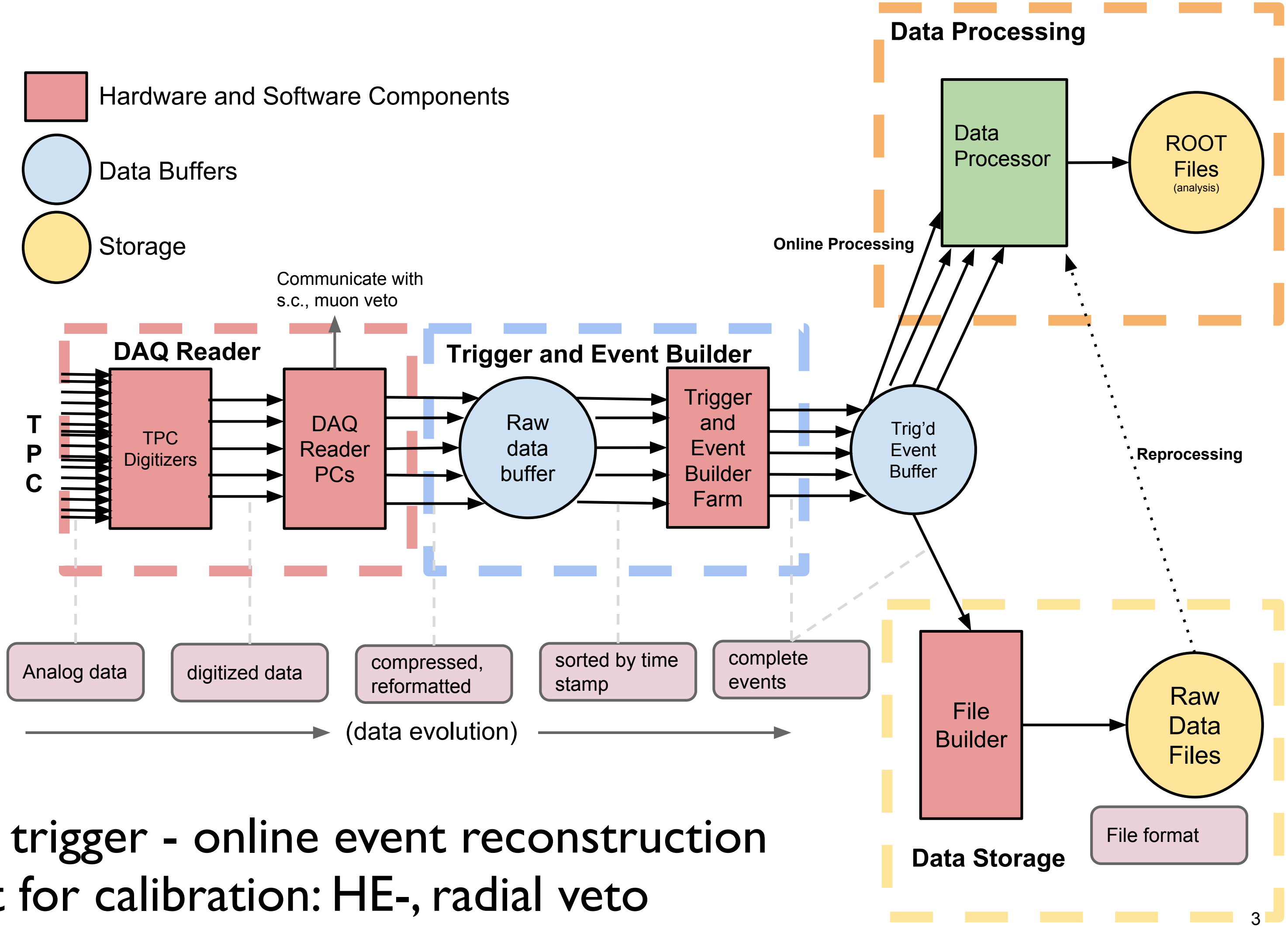
^{214}Bi → ^{214}Po + e^- + γ (2448 keV)





Data Acquisition System

Software-based trigger using commodity computing:



- Flexible trigger - online event reconstruction
  - Adapt for calibration: HE-, radial veto
  - Prescale backgrounds
  - SN trigger
  - …

Technical Challenges and R&D

High voltage:

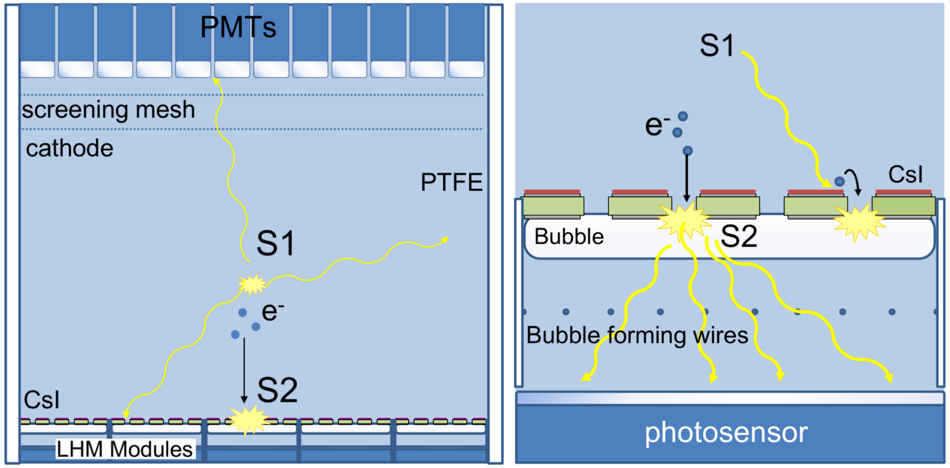
- drift field: 0.5 kV/cm requires cathode HV of 130 kV, uniformity is important
- anode: constant gap, parallel to liquid surface over 2.6m

→ 3D field simulations with KEMField (boundary element method)

JINST 10, P08015 (2015)
JINST 10, P11002 (2015)

High light yield:

- baseline design PMTs
- alternatives: SiPM, SiGHT, GPM
- single-phase TPC with Liquid Hole Multipliers



High purity:

- magnetically driven piston pumps with sealed pumping volumes
- cryogenic distillation to remove Kr (sub-ppt level) and Rn
- careful selection of materials for low Rn emanation
- surface treatment (electropolishing, etching etc.)

Conclusions

DARWIN

- Push low-background technology to the next level
- "Ultimate" WIMP discovery experiment
- Large mass and low threshold allow for a rich neutrino physics program
    - Solar observatory of pp and ^{7}Be neutrinos
    - (Most?) sensitive $0\nu2\beta$ experiment
    - Supernova neutrinos
- All starting in 2025 or so…

www.darwin-observatory.org