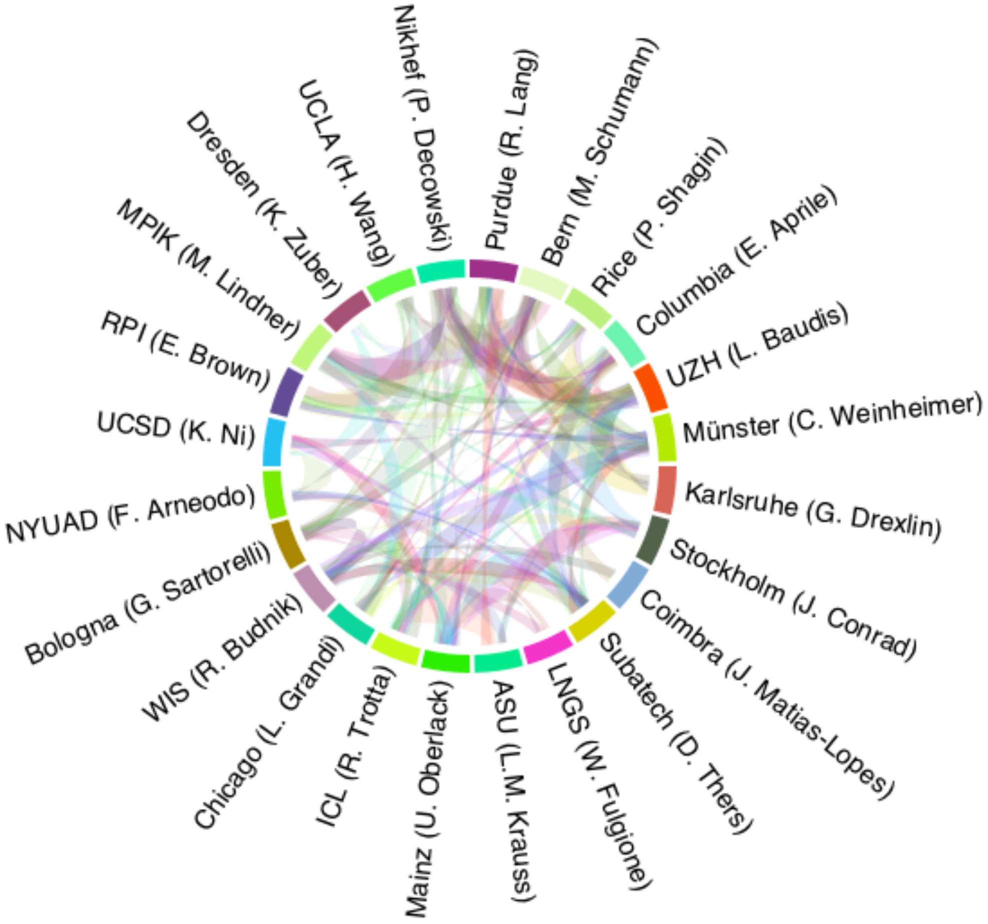
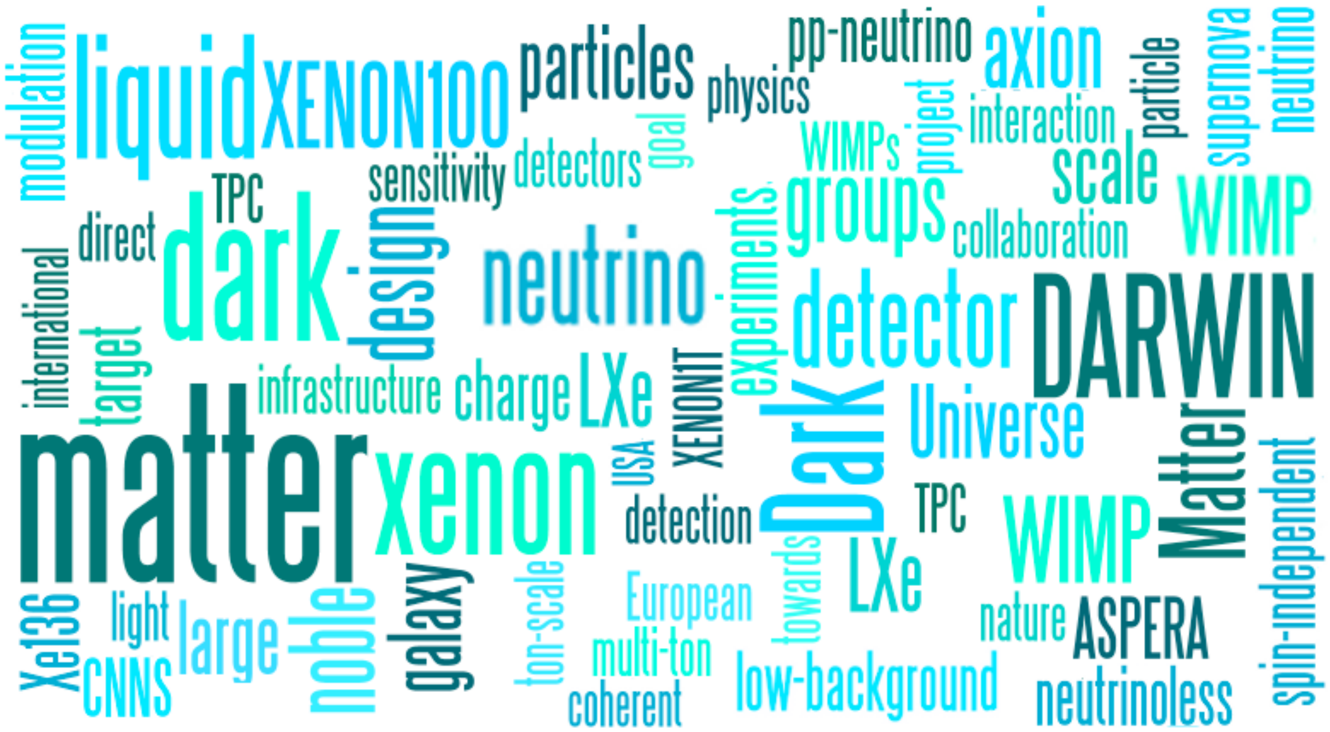
University of Zurich^UZH

TeVPA-2016, CERN
16 September 2016

DARWIN

Towards the Ultimate Dark Matter Detector

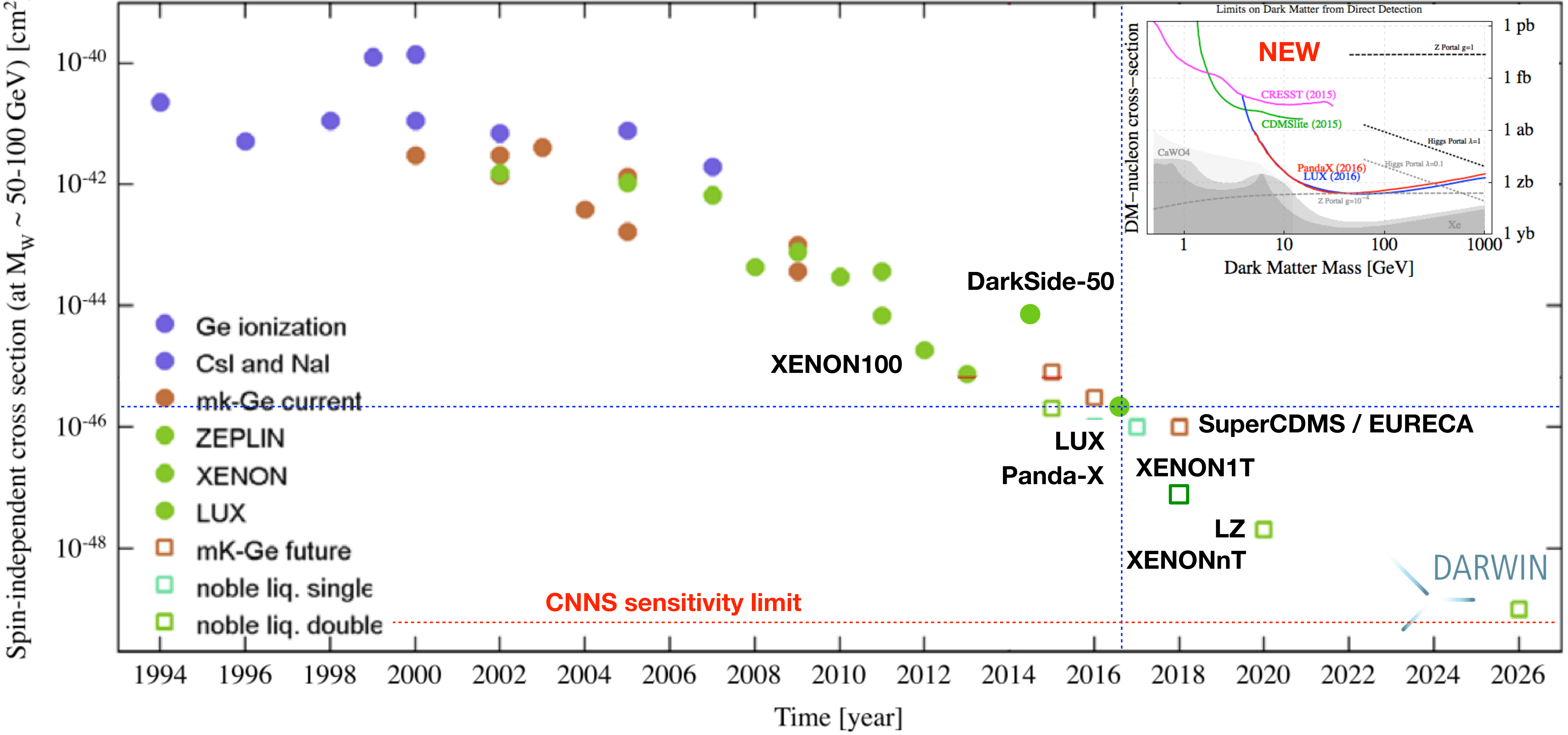




Alexander Kish
for the DARWIN Consortium

www.darwin-observatory.org

Direct Dark Matter Detection: Past, Present and Future

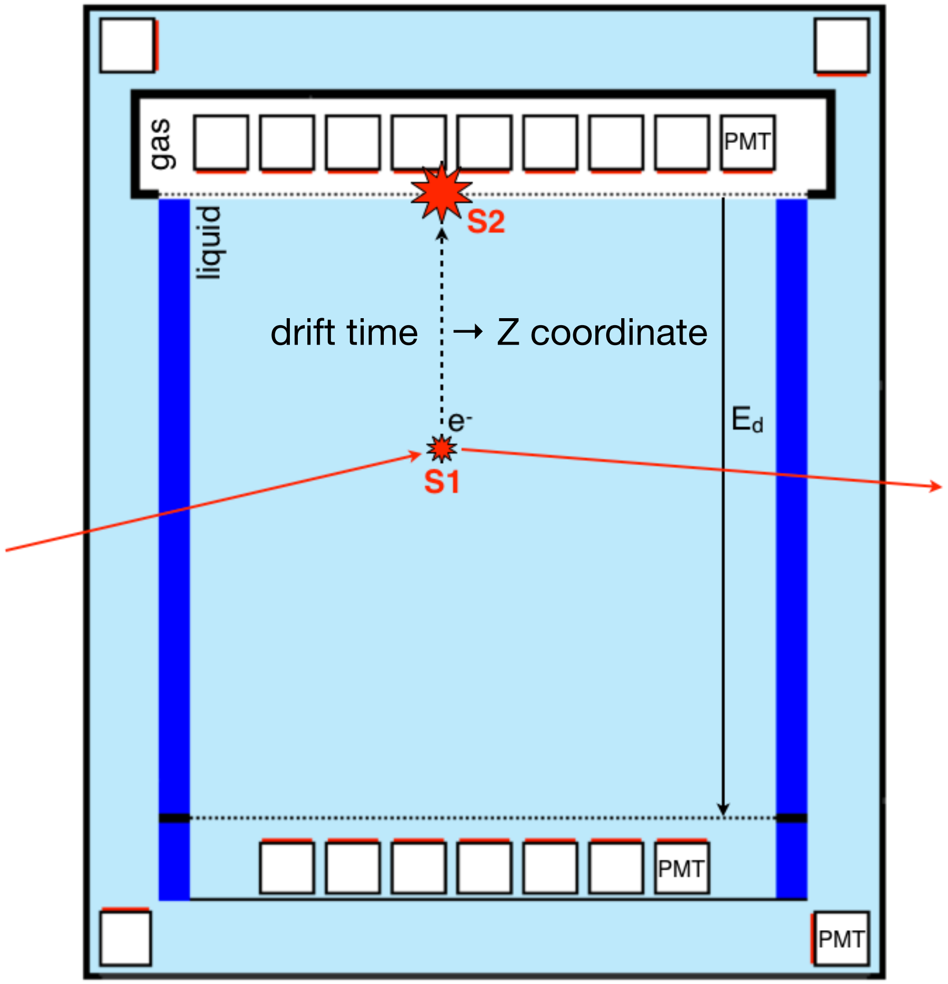


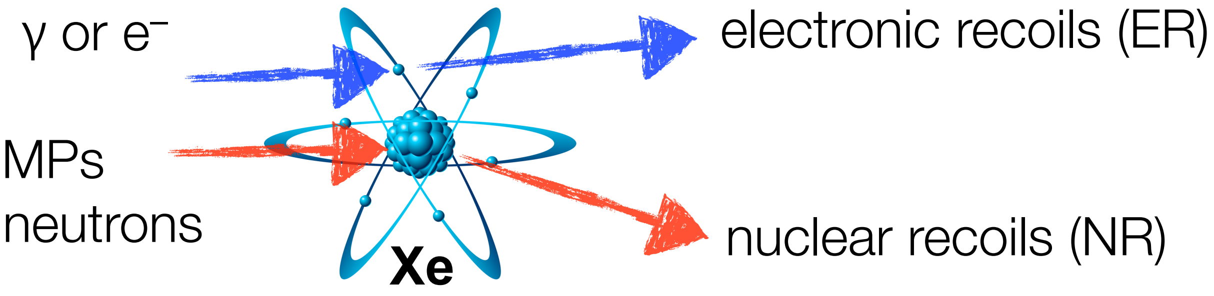
Adapted from L.Baudis, Physics of the Dark Universe (2014) + Resonaances Blog, Sept. 11 (2016)

DM detector requirements:

- heavy target
- detectable signal
- low threshold
- low background
- easy scalability

DARWIN = DARk matter WImp search with liquid xenoN



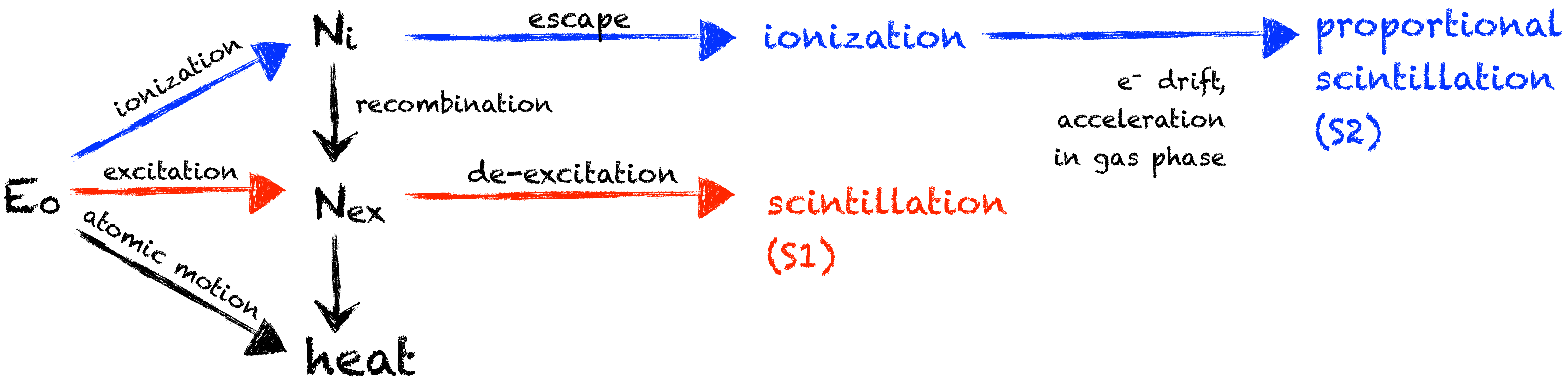


- Two signal channels (S1 and S2)

- Ratio depends on *dE/dx*, different probability for electron-ion pairs recombination

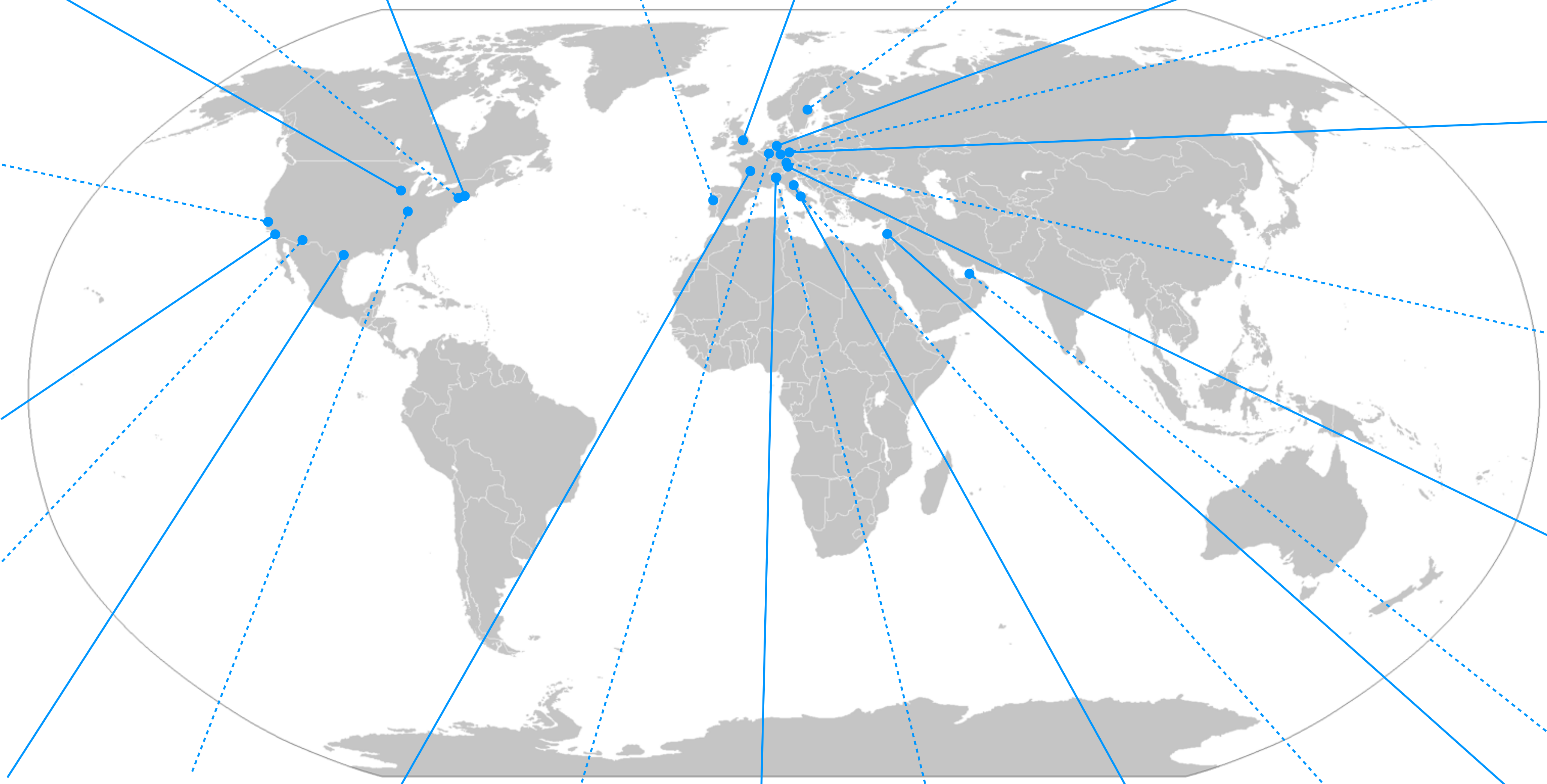
→ event vertex reconstruction in 3D
(sub-mm precision for *Z*, ~cm for XY)

→ particle type discrimination: $(S2/S1)_{\gamma} > (S2/S1)_{WIMP}$
(factor ~ 200 and higher efficiency)



The DARWIN Consortium

- 25 research groups from 11 countries



Chicago

RPI

Columbia

Coimbra

IC London

Stockholm

Mainz

Münster

UCLA

Dresden

Karlsruhe

San Diego

Heidelberg

Arizona

NYAD

Rice

Purdue

Subatech

NIKHEF

Bern

Zurich

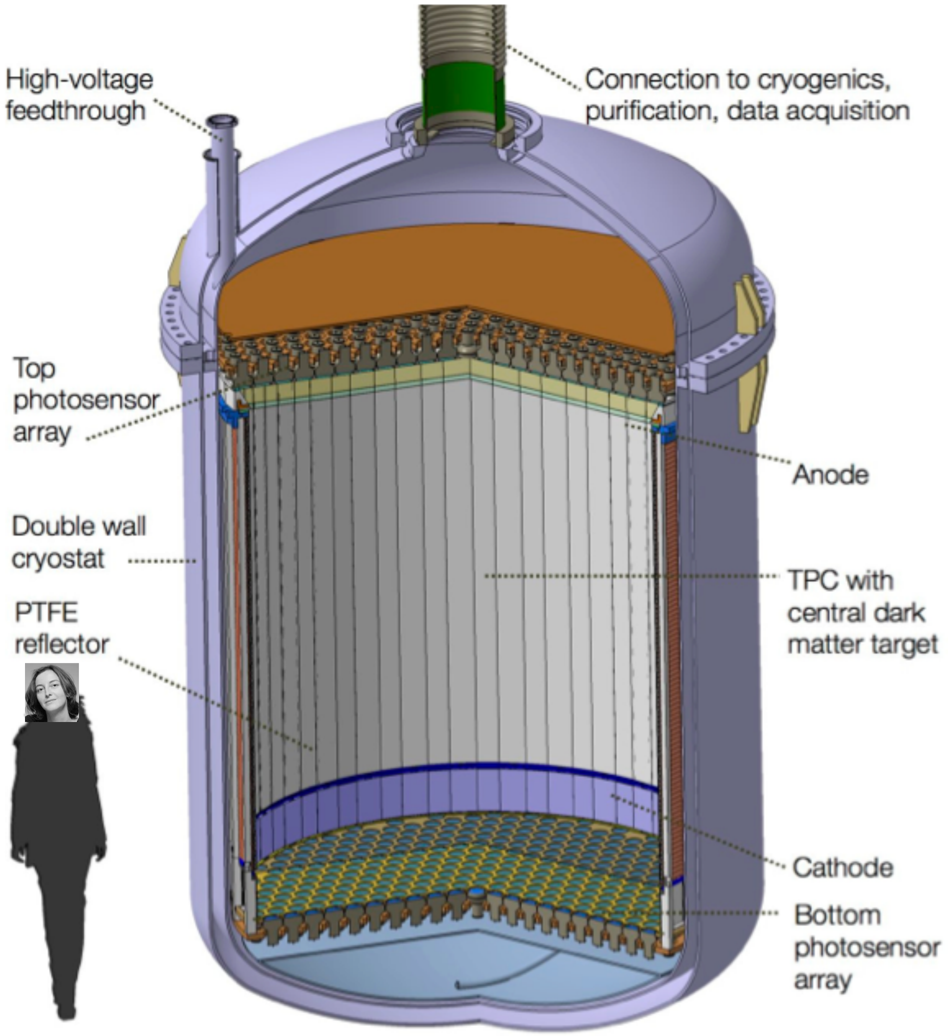
Bologna

LNGS

Weizmann

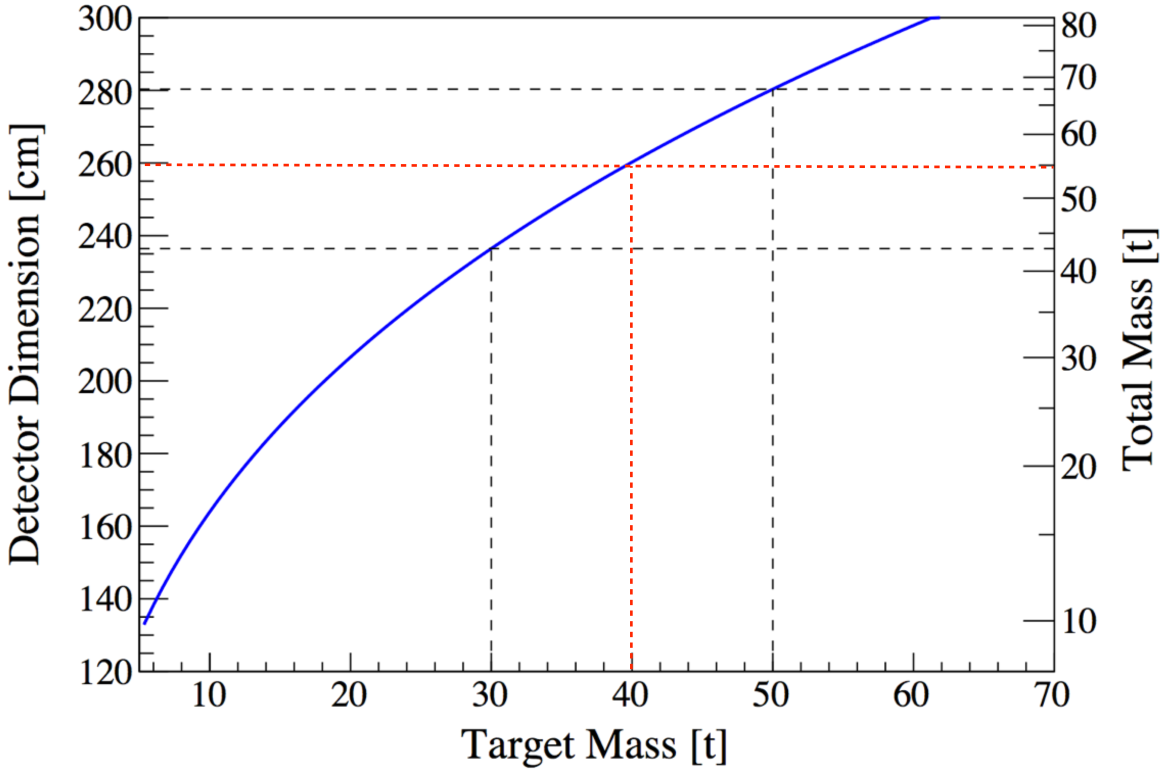
DARWIN Conceptual Design

arXiv:1606.07001
submitted to JCAP



- 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

- Water Cherenkov shield
  (~14m diameter)
- Liquid scintillator neutron veto
  under study
- Possible location LNGS



DARWIN

Backgrounds

JCAP 10, 016 (2015)

- Monte Carlo simulations for main components (PTFE, copper, photosensors)

- Intrinsic backgrounds:

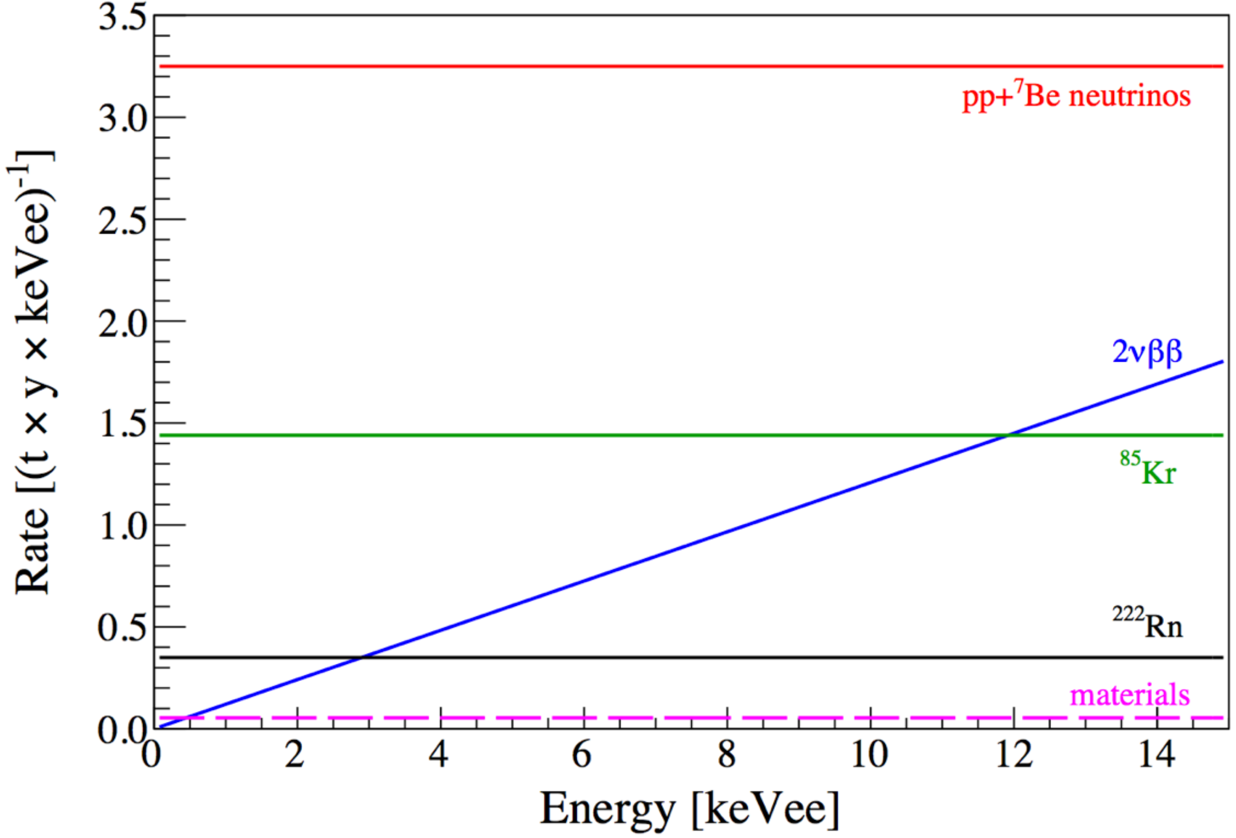
^{85}Kr: ×2 below XENON1T design (^{nat}Kr 0.1 ppt) (achieved 0.03 ppt EPJ C 74, 2746 (2014))

^{222}Rn: ×100 below XENON1T design (0.1 μBq/kg)

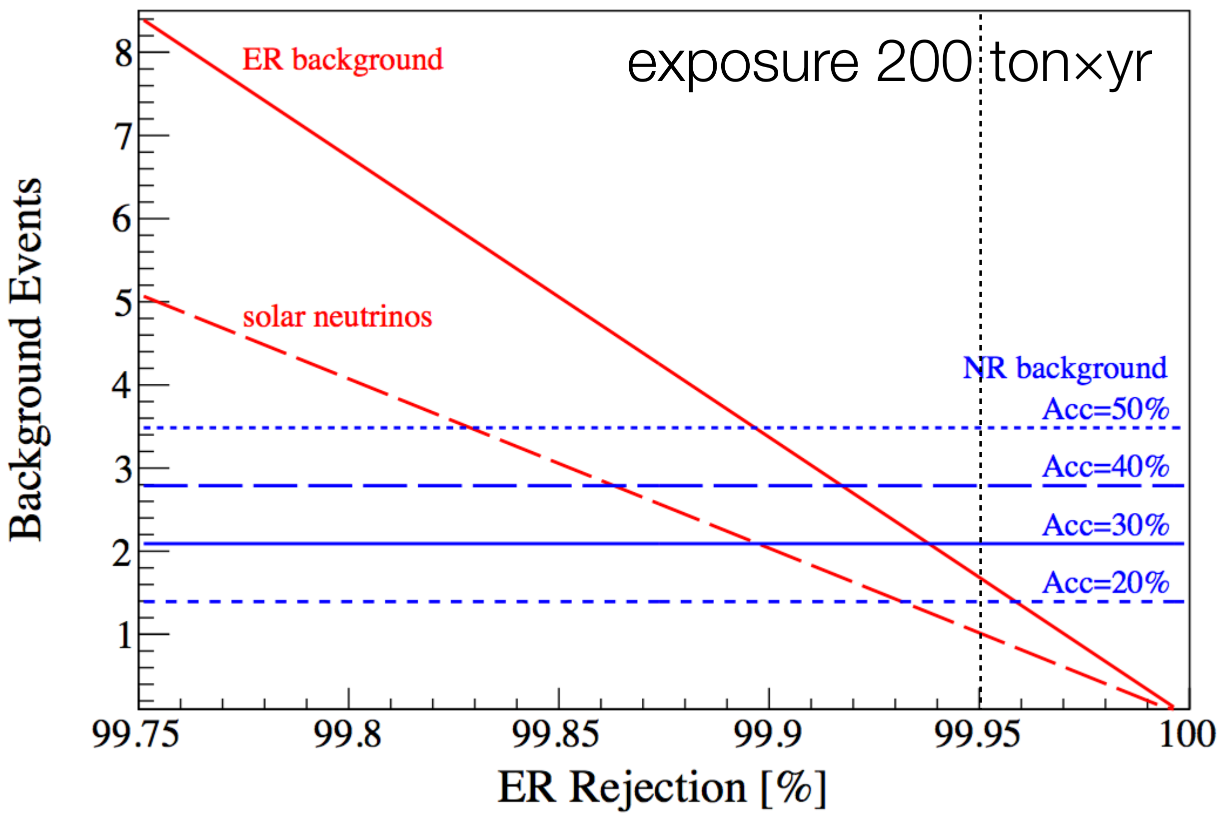
^{136}Xe: assuming natural Xe composition (8.9%)

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

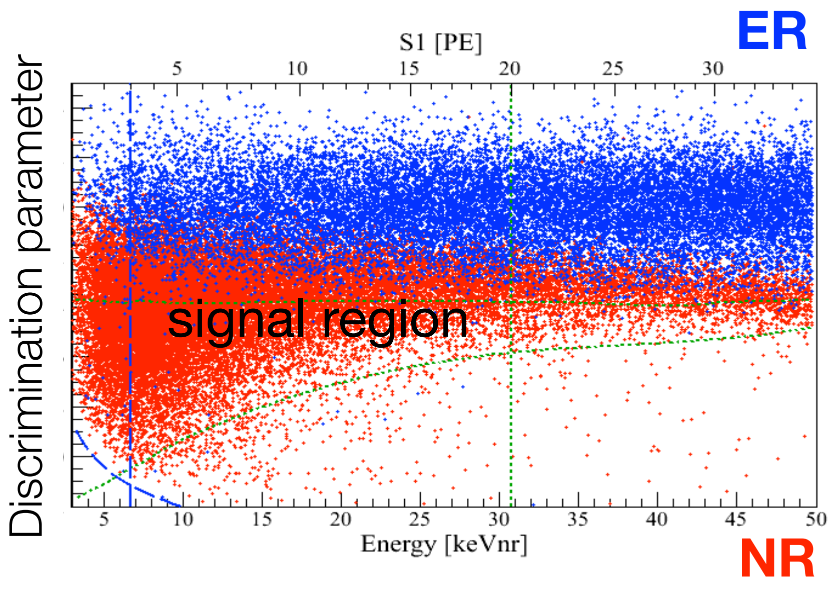


Electromagnetic Background Rejection

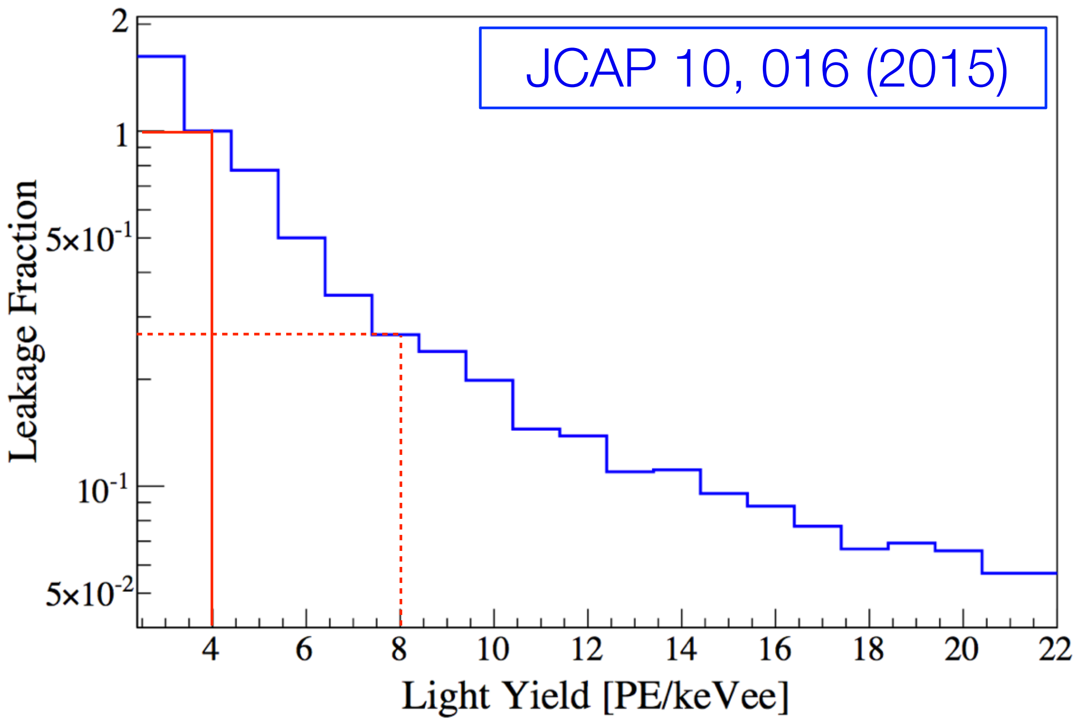
- Required ER rejection >99.9% (discrimination based on ionization/scintillation ratio)

- Experimentally achieved:

	E_{drift} [kV/cm]	LY at 122 keV [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	> 99.999



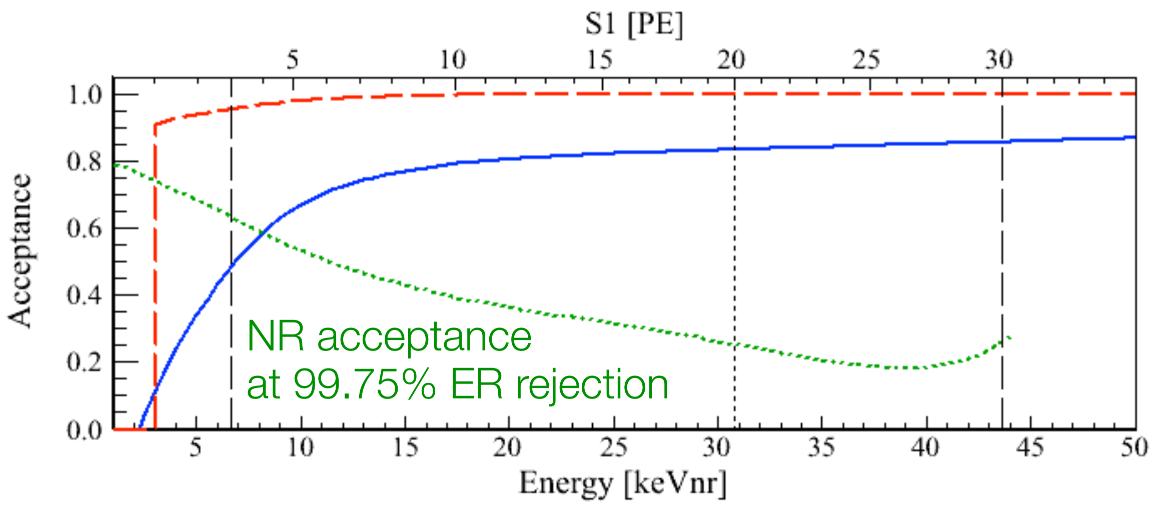
- Higher light yield → better resolution → improved ER/NR band separation



JCAP 10, 016 (2015)

- ×2 higher LY → ×7.5 less leakage

- E-field uniformity plays crucial role



XENON100
PRL 109 (2012)

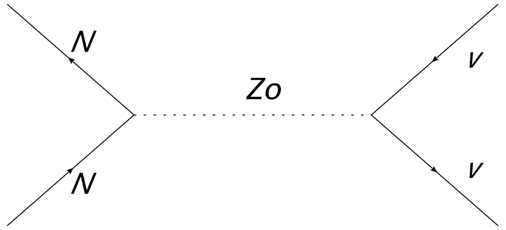
Physics Channels

WIMP searches

- spin-independent, -dependent and inelastic interactions

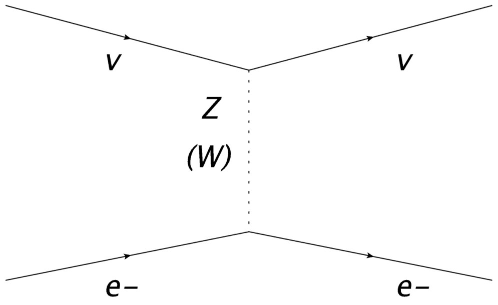
Coherent neutrino-nucleus scattering (CNNS)

- predicted by SM, not yet observed
- 200 ton×yr exposure: ~200 events > 3 $\mathrm{keV_{NR}}$
  ~25 events > 4 $\mathrm{keV_{NR}}$



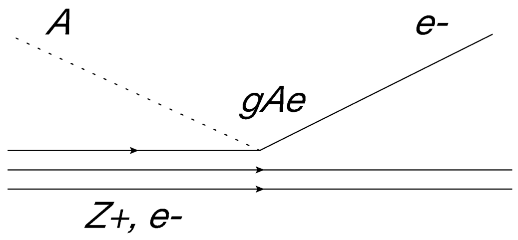
Low-energy solar neutrinos: pp, ^{7}Be

- statistical uncertainty ~1% with 100 ton×yr exposure
- test/improve solar model, test neutrino models



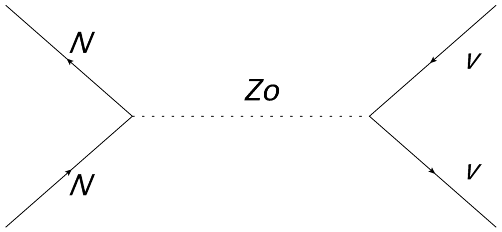
Solar axions and galactic axion-like particles (ALPs)

- alternative dark matter candidates
- coupling to electrons via axio-electric effect



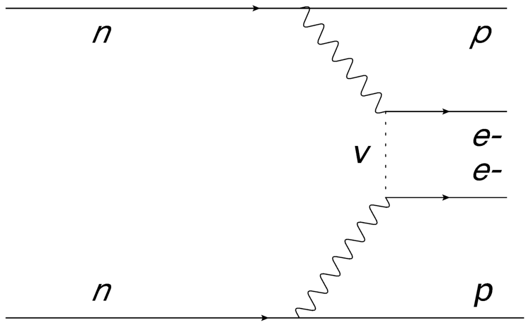
Supernova neutrinos

- sensitivity to all neutrino flavors (via CNNS)
- ~10 events for SN @ 10 kpc
- complementarity to large-scale neutrino detectors



Neutrinoless double beta decay

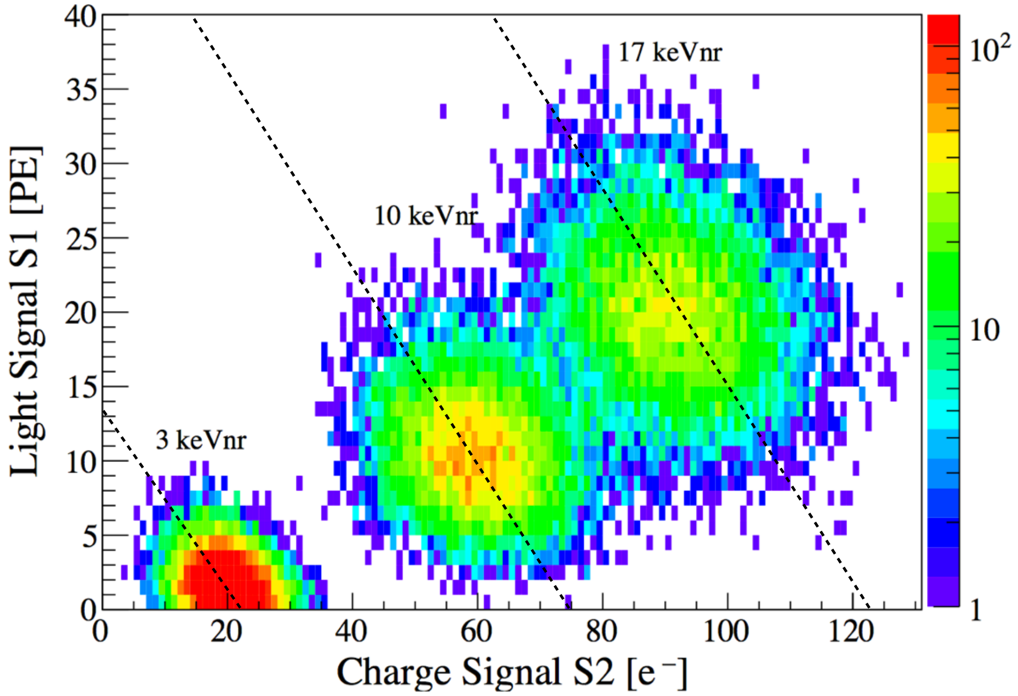
- lepton number violating process
- access to neutrino mass and hierarchy
- no enrichment in ^{136}Xe required

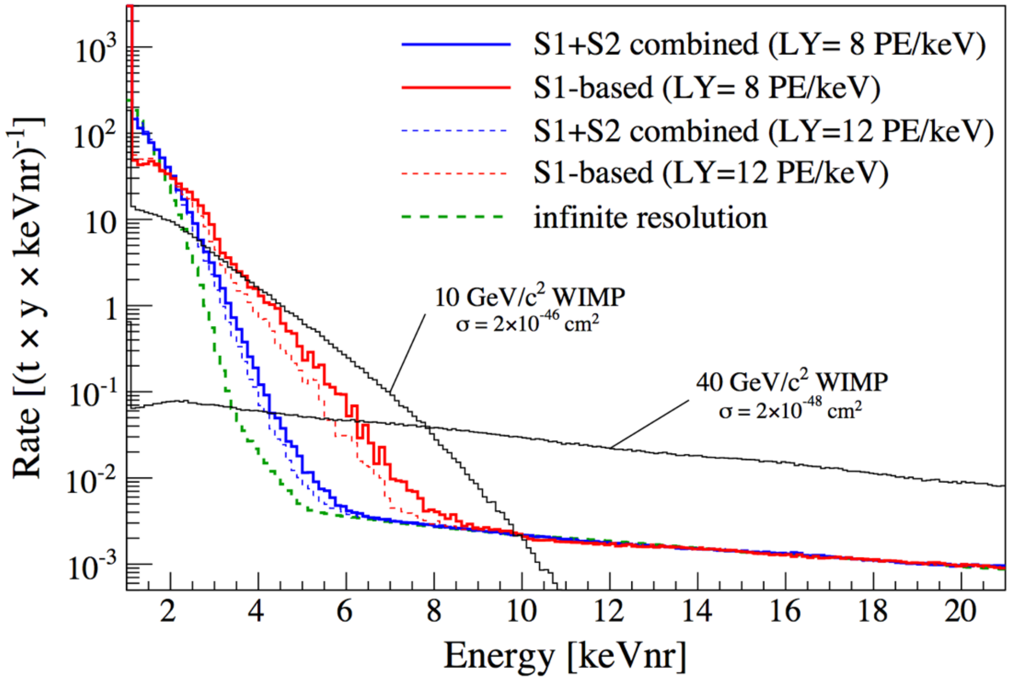


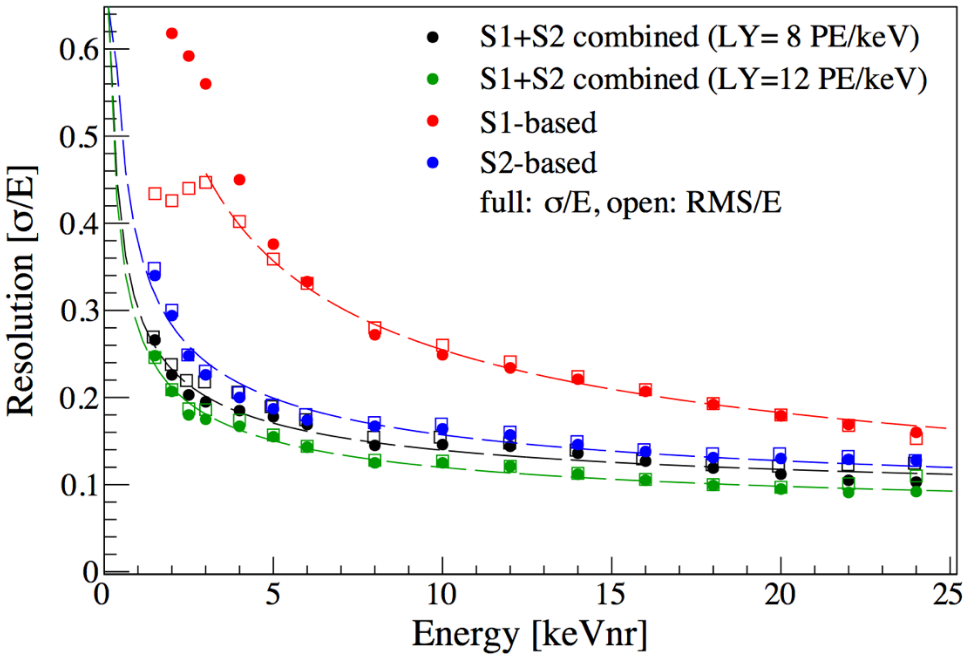
Sensitivity: WIMPs

JCAP 10, 016 (2015)

- Consider all backgrounds:
  - – external (gamma, neutrons)
  - – intrinsic
  - – neutrinos (e⁻ scattering, pp and ^{7}Be)
  - – CNNS (dominated by ^{8}B)
- Study LY, energy scales (S1, S1+S2)
- Study threshold, exposure, ER rejection





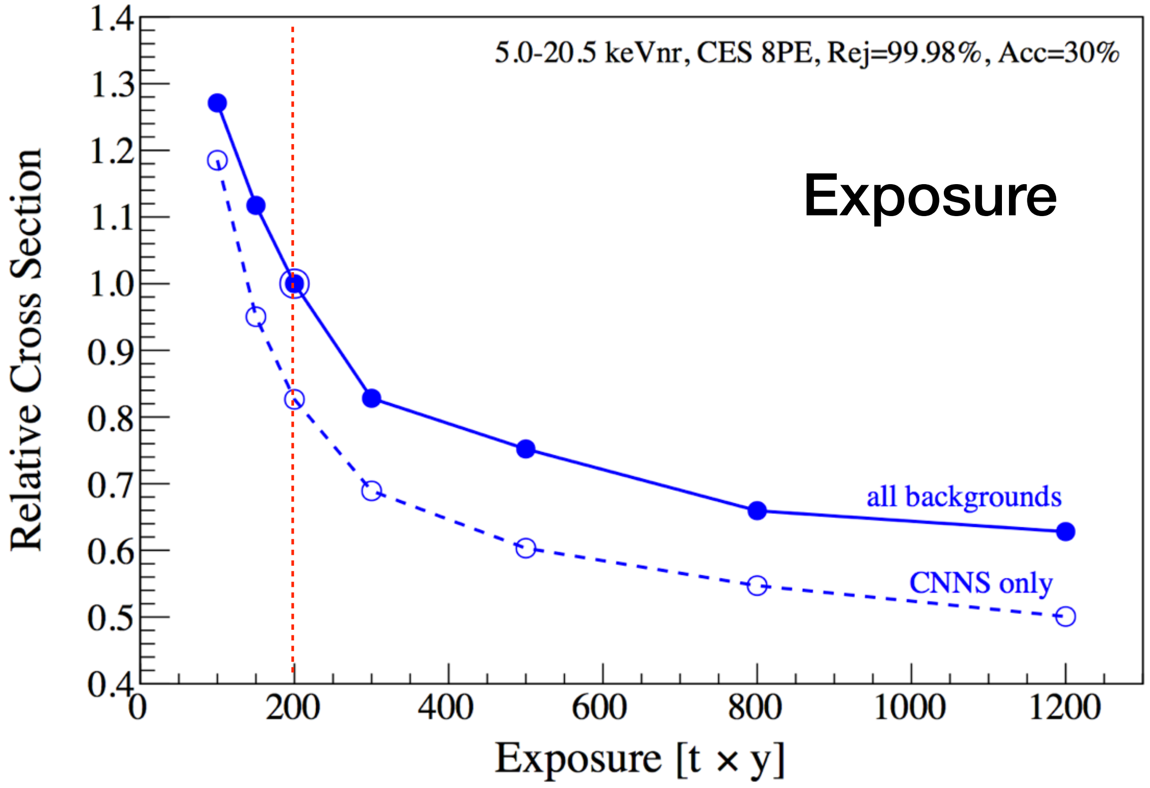


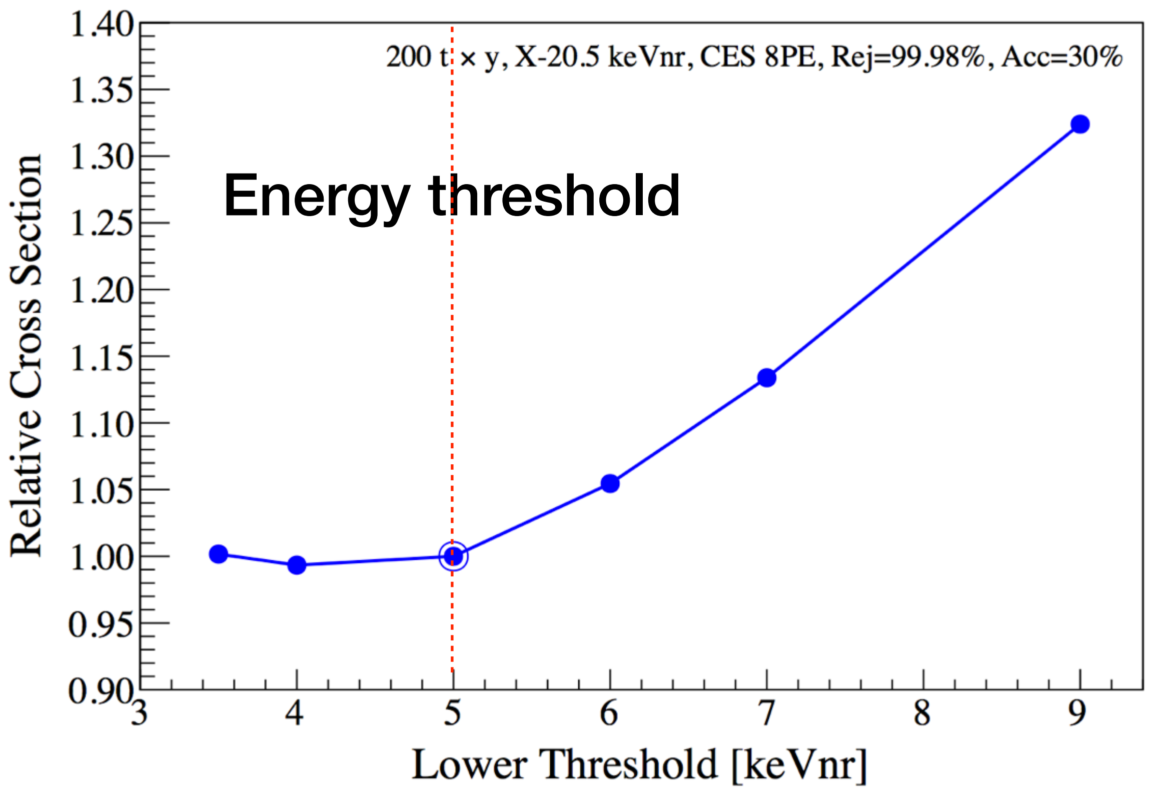
→ Significant improvement in resolution using combined (S1+S2) energy scale

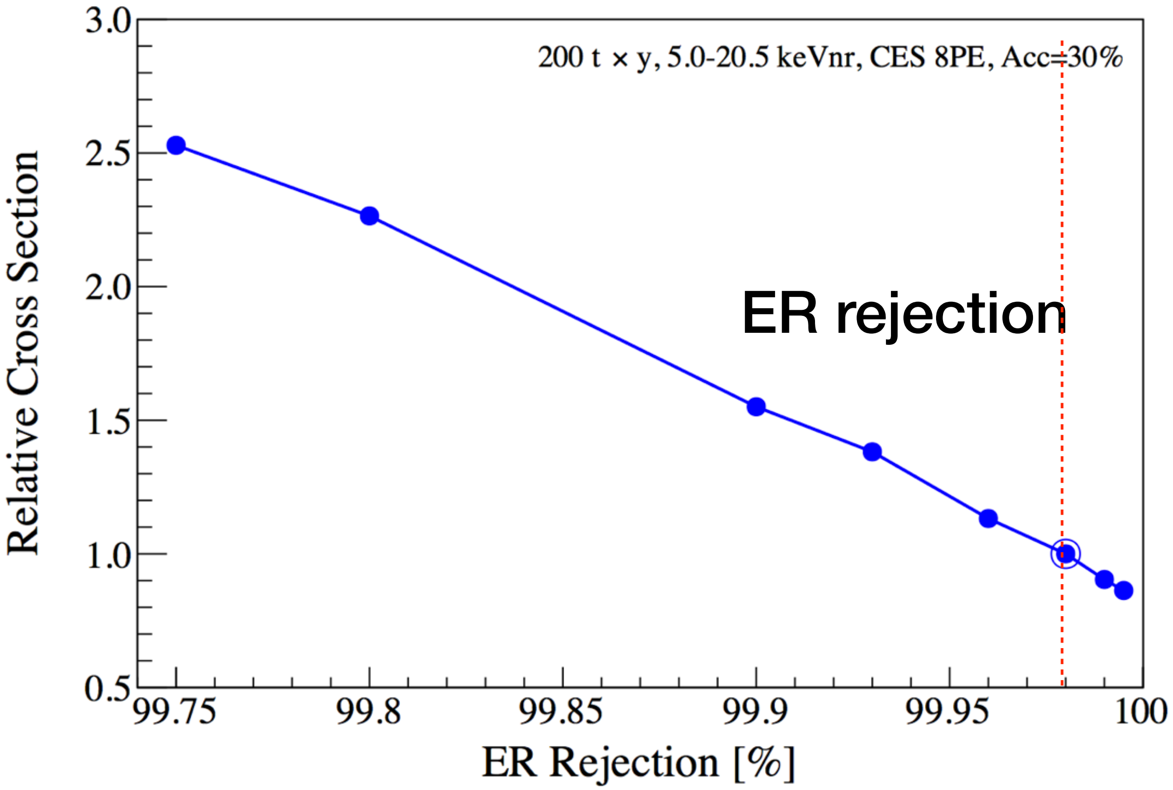
Sensitivity: WIMPs

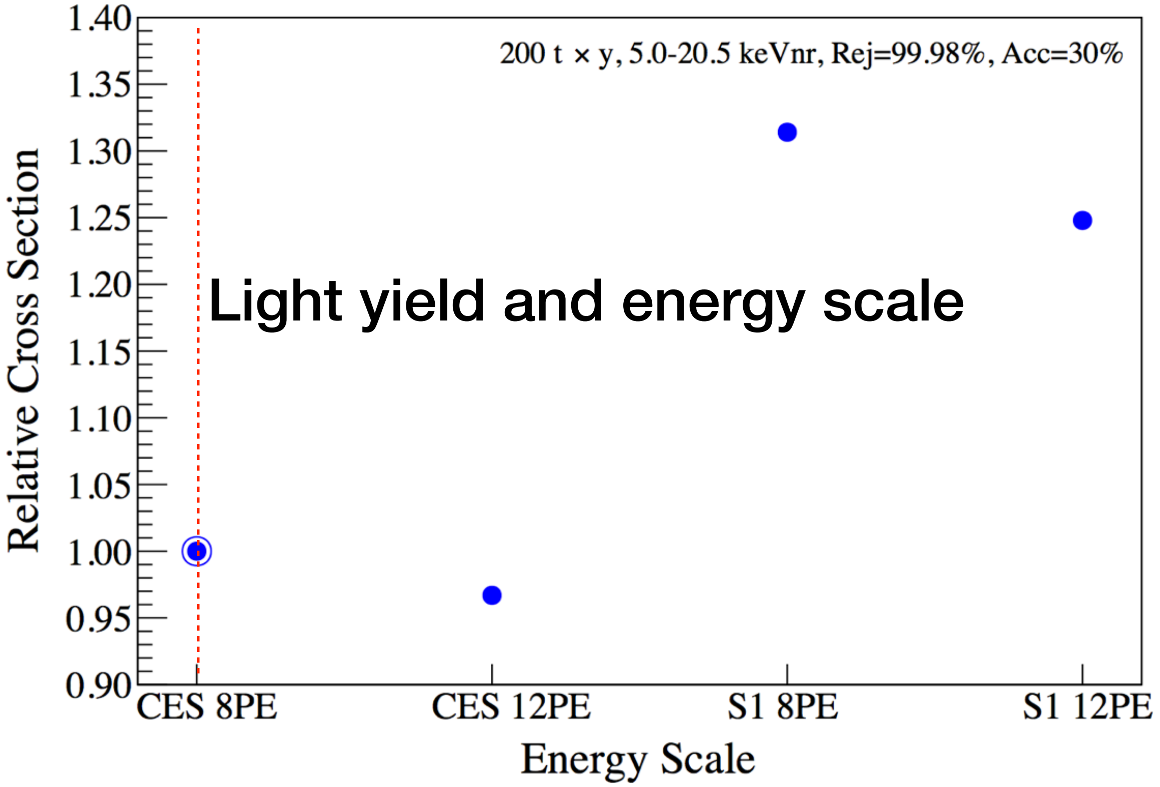
JCAP 10, 016 (2015)

- For WIMP mass 40 GeV/c^2:







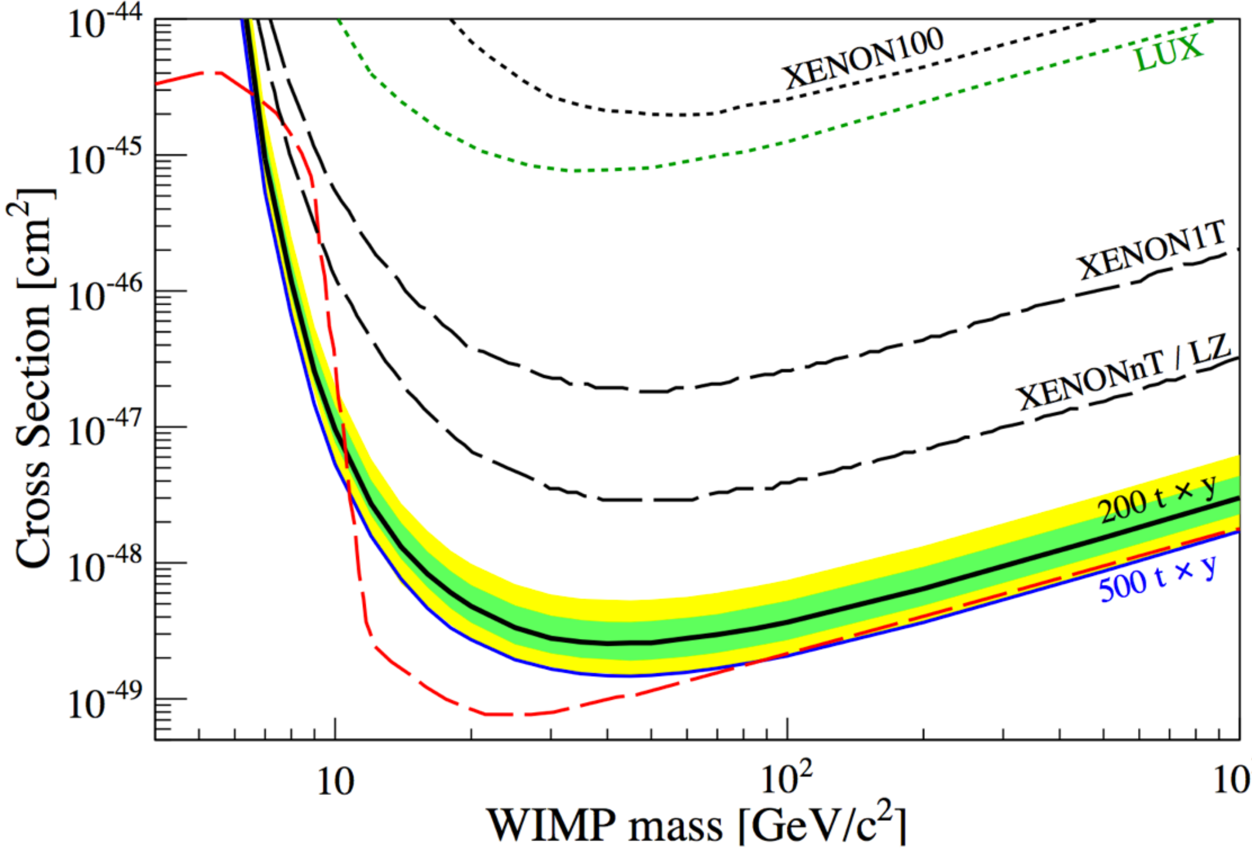


Sensitivity: WIMPs

JCAP 10, 016 (2015)

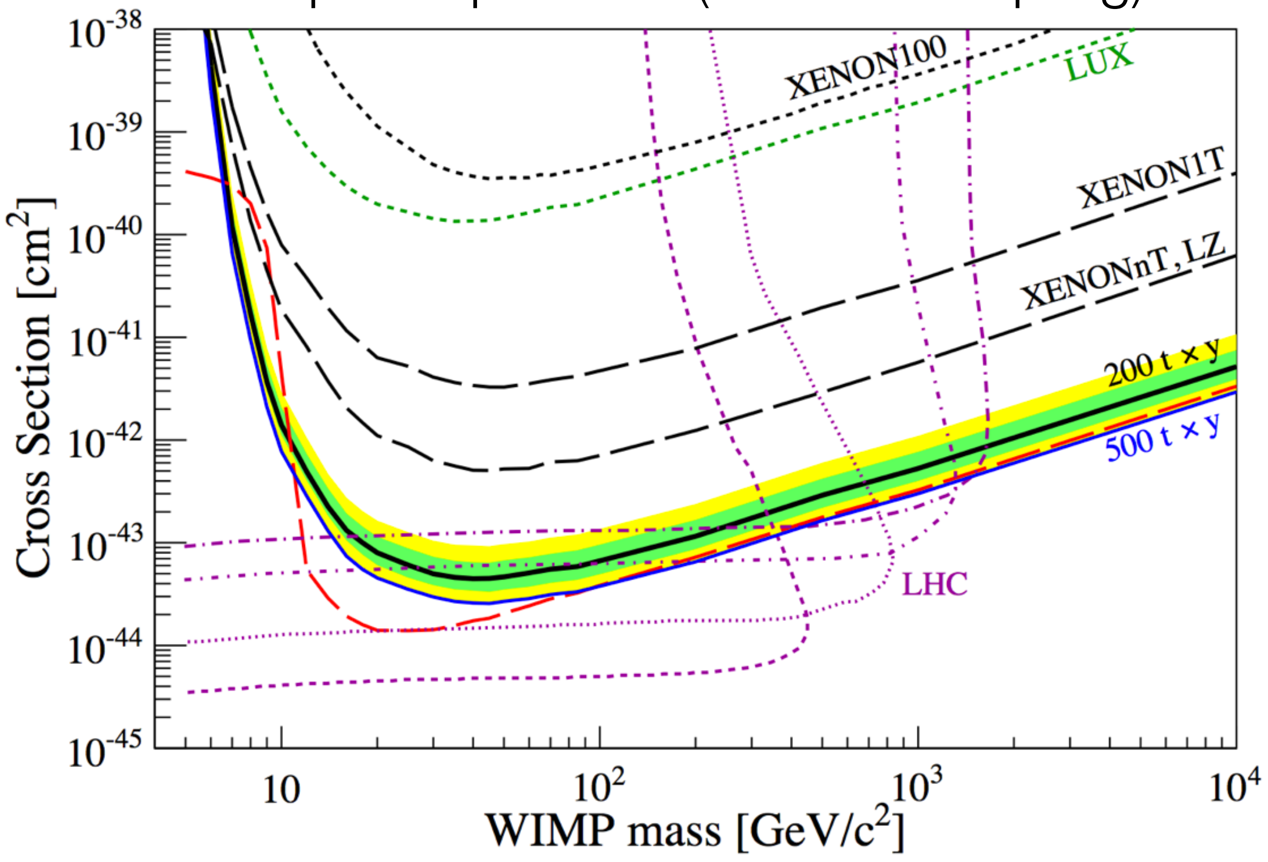
- assumed exposure 200 ton×yr, all backgrounds included
- likelihood analysis: 99.98% ER rejection, 30% NR acceptance
- combined (S1+S2) energy scale
- energy window 5-35 $\mathrm{keV_{NR}}$
- light yield 8 PE/keV

spin-independent interaction



→ minimum sensitivity: 2.5×10^{-49} cm² @ 40 GeV/c²

spin-dependent (neutron coupling)



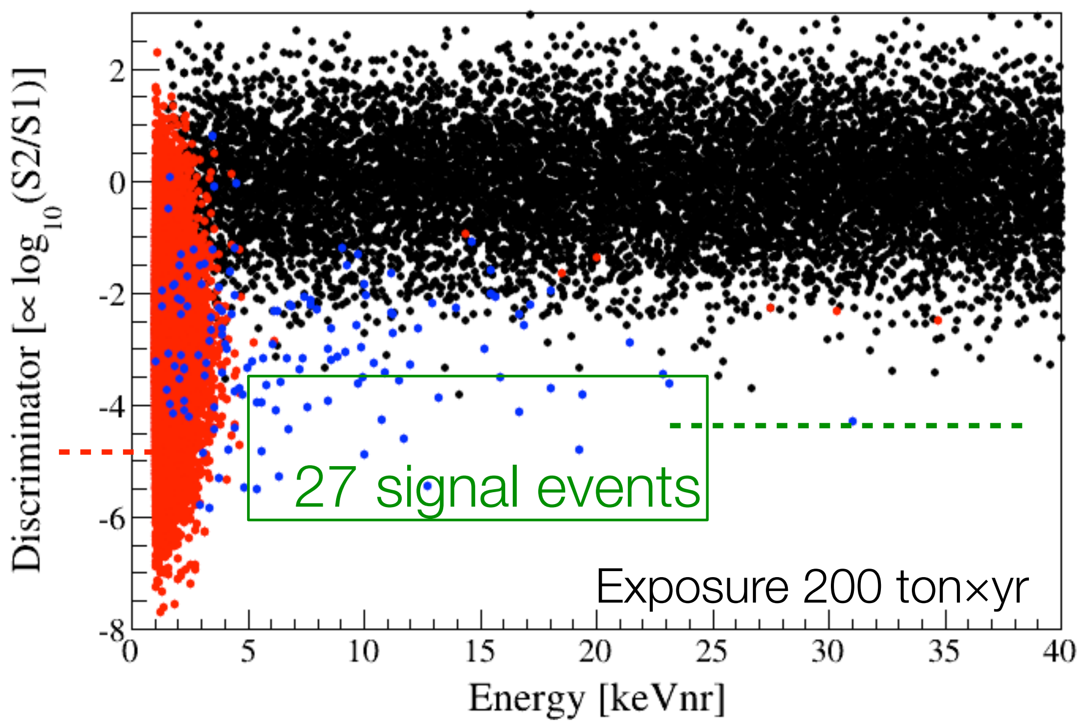
→ complementarity to LHC searches

DARWIN

WIMP Spectroscopy

DM halo parameters:

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

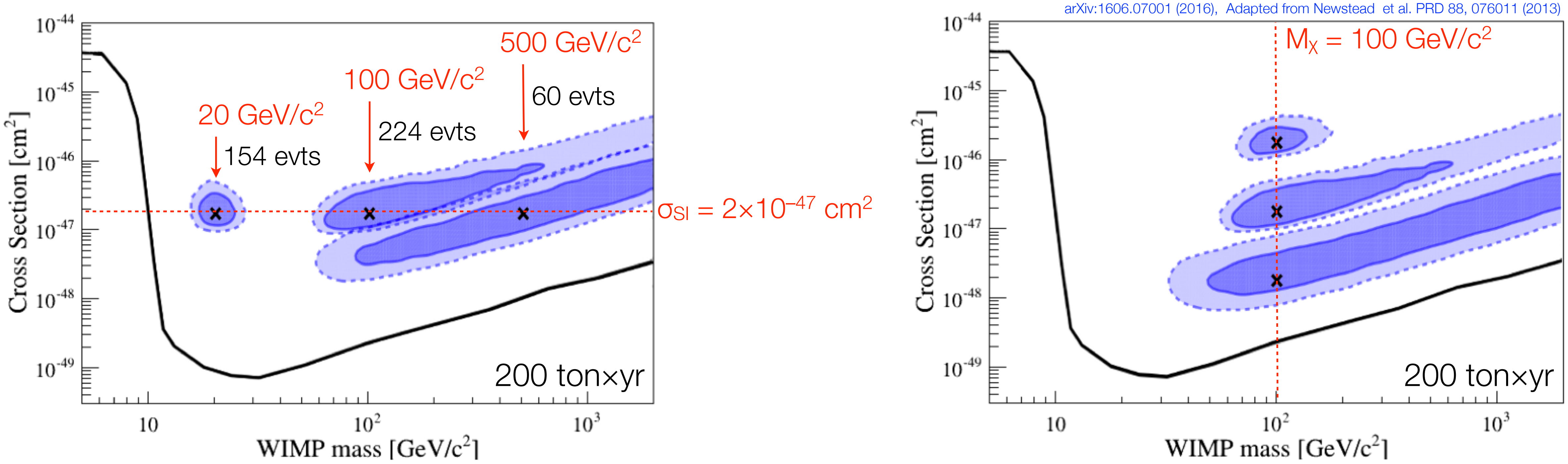


ER background
- materials
- intrinsic (Rn, Kr)
- solar ν-e$^-$ scattering
- ^{136}Xe 2νββ

neutrons and CNNS

30 GeV/c^2 WIMP
σ_{SI} = 2×10^{-48} cm^2

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



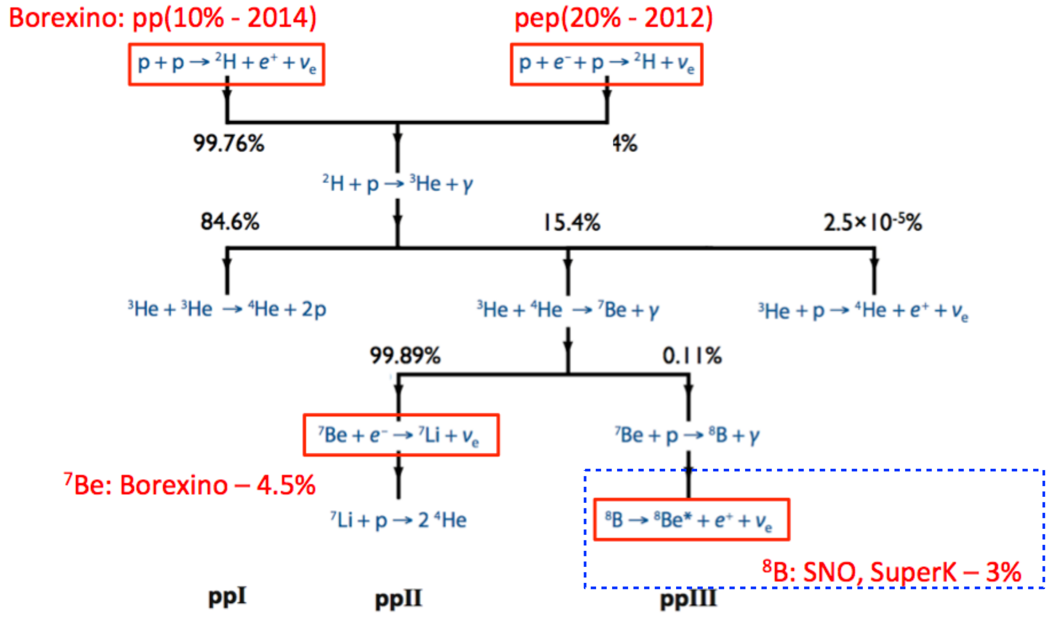
σ_{SI} = 2×10^{-47} cm^2

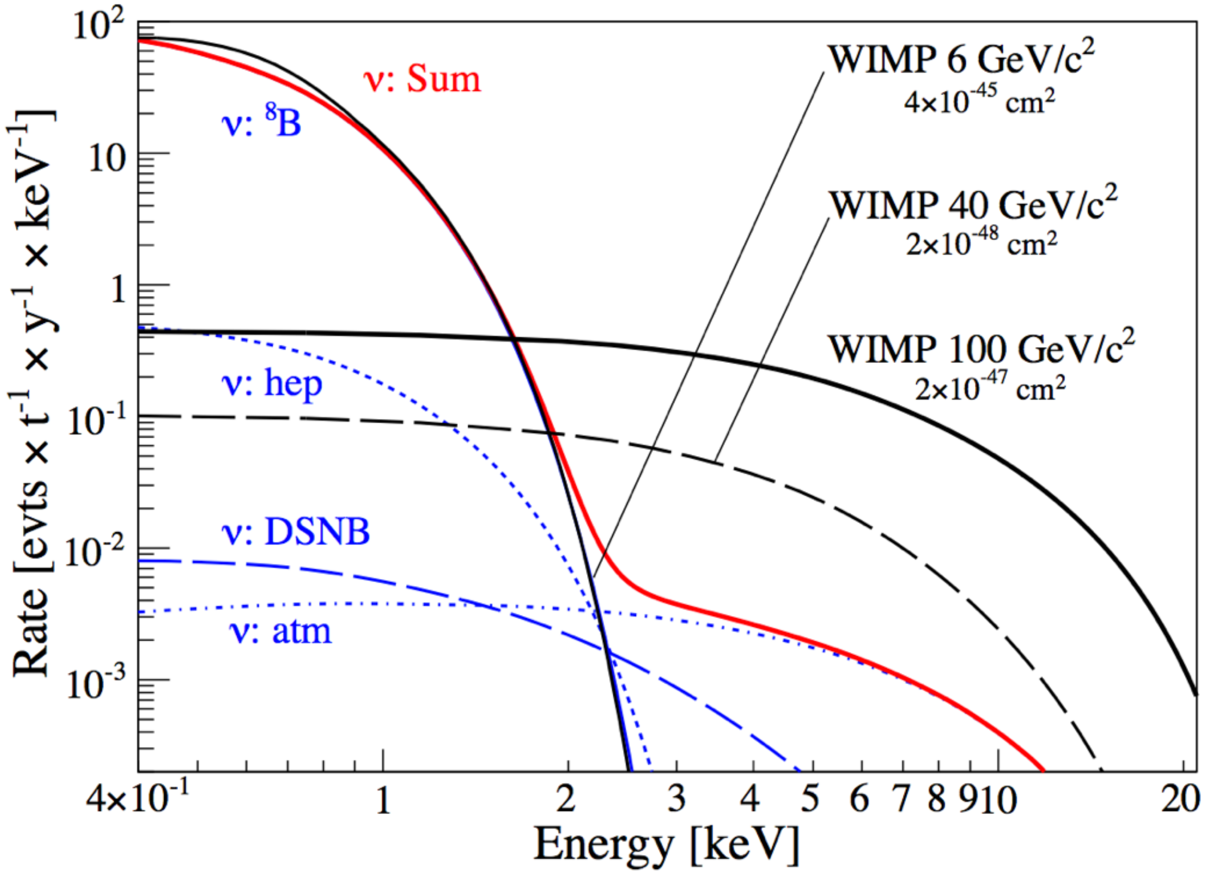
- Extended regions due to uncertainties on DM halo parameters
- For higher WIMP masses (> 500 GeV/c^2) only lower limits can be derived (shape of the NR spectrum depends on the WIMP-nucleus reduced mass)

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, but one of the scientific goals of DARWIN
- Steeply falling spectrum with $E_R < 4\ keV_{NR}$



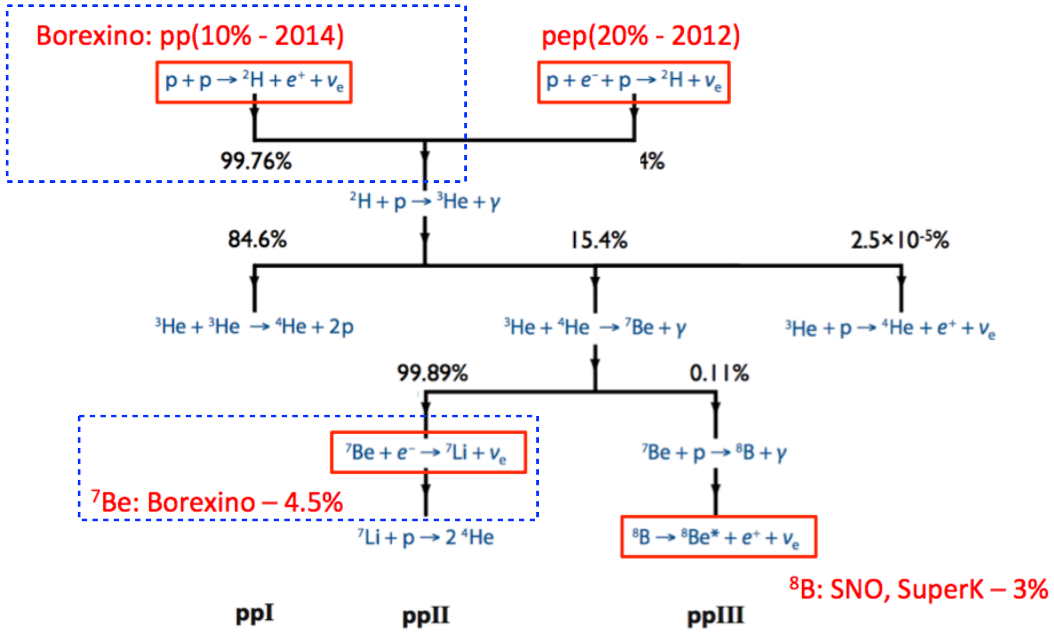


- ${}^8B$ neutrinos from the Sun:
  → 90 events/ton/yr, $E_R > 1$ keV
- Atmospheric neutrinos:
  → 3×10^{-3} events/ton/yr, $E_R > 3$ keV

DARWIN as Solar Observatory

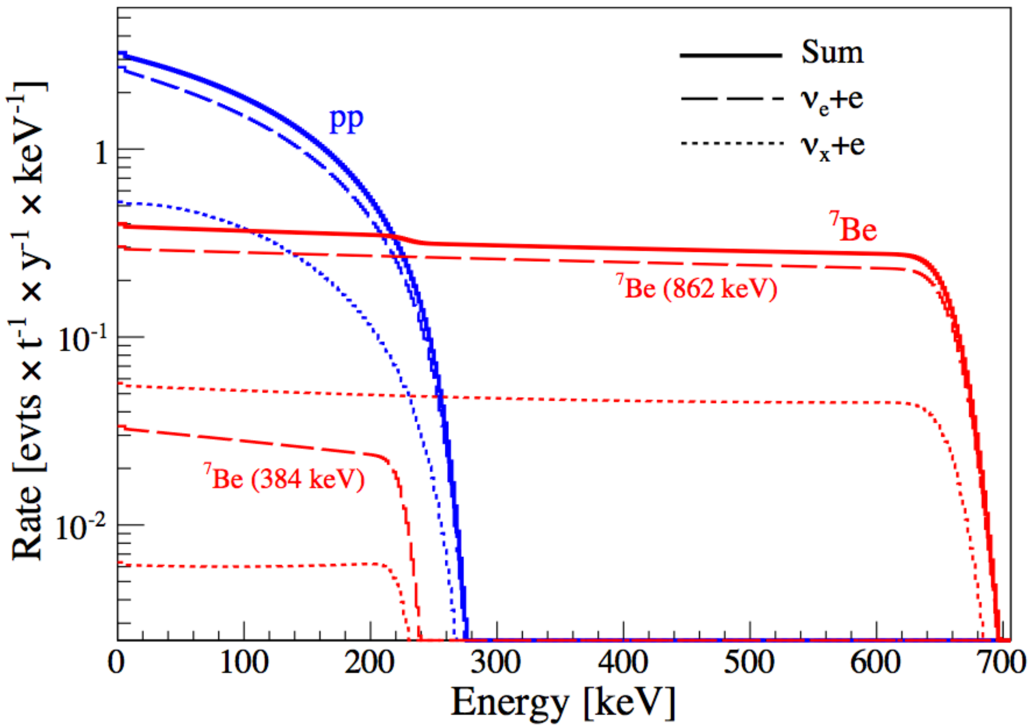
JCAP 01, 044 (2014)

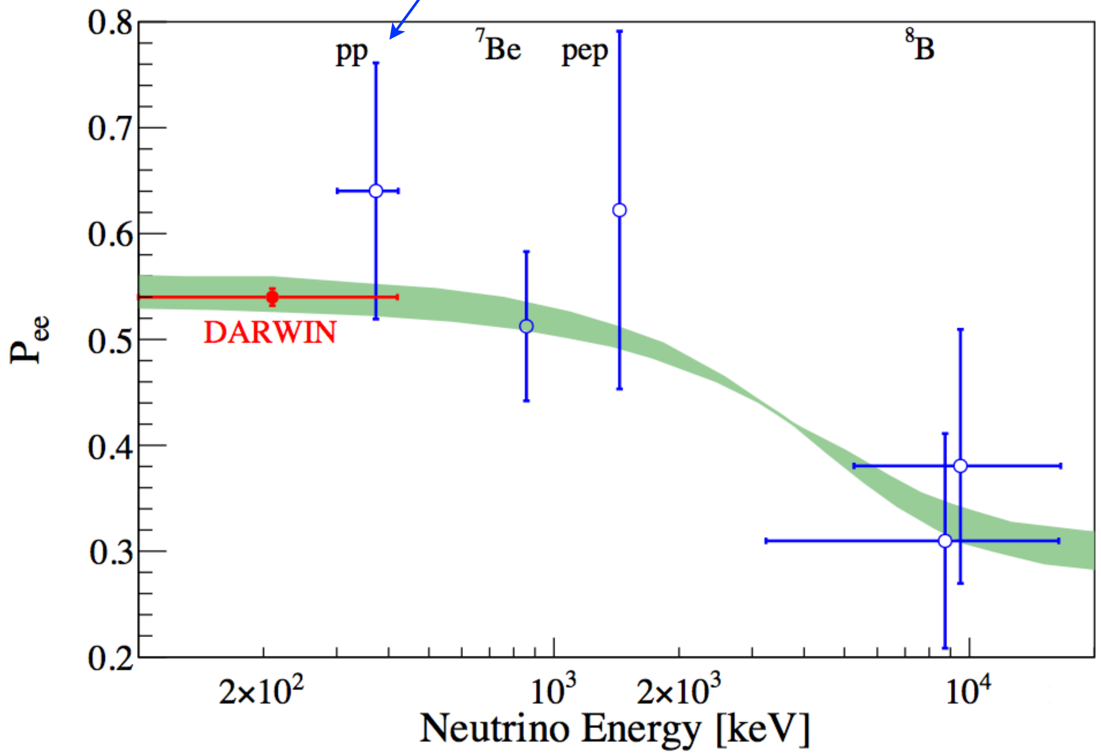
- neutrino-electron elastic scattering
- real-time measurement of neutrino flux
  → 7.2 events/day from pp
  → 0.9 events/day from ^{7}Be
- 2% (1%) precision after 1 year (5 years)
  → constrain solar models
- Neutrino survival probability measurement
  → deviation from prediction indicates new physics



Aldo Serenelli (TeVPA-2016)

Borexino (Nature 512, 383-386, 2014)



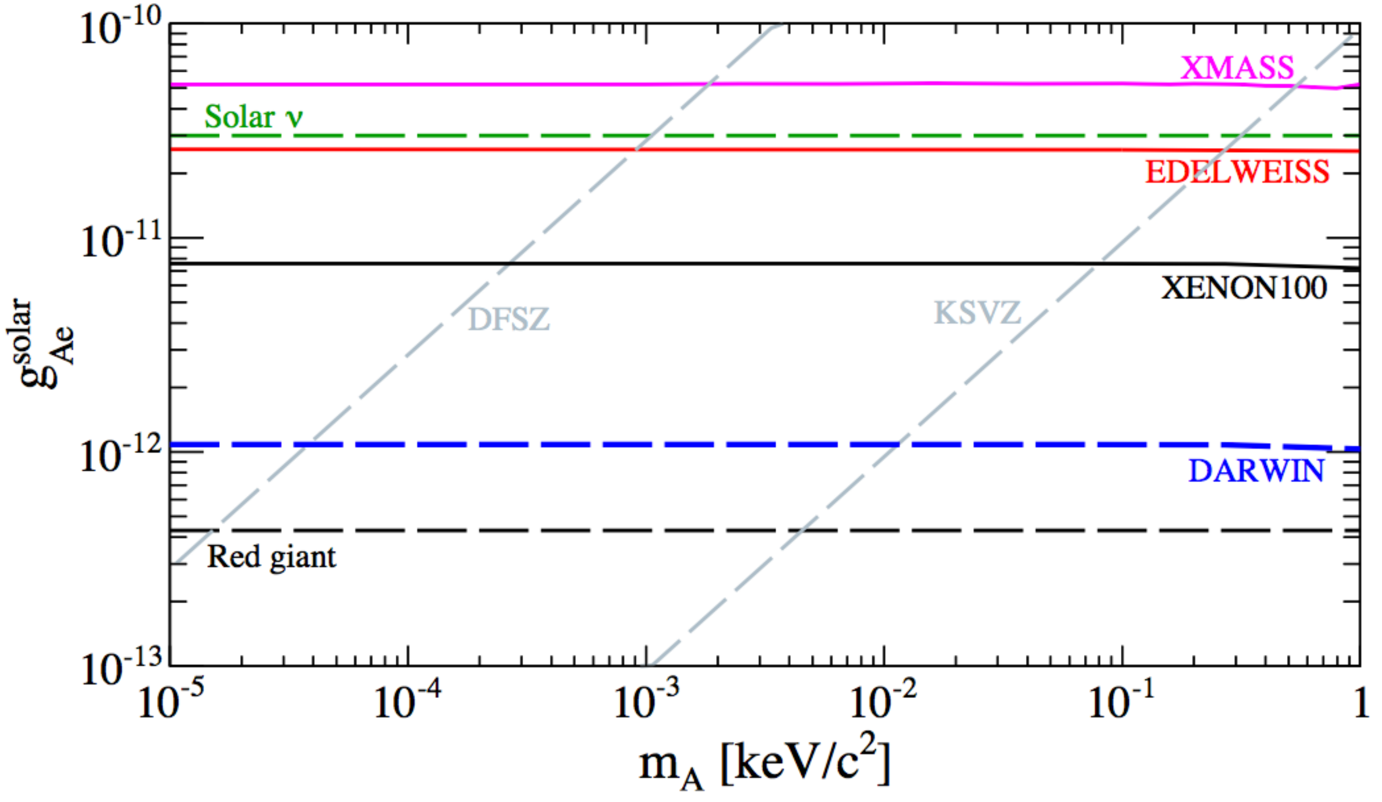


Sensitivity: Axions and ALPs

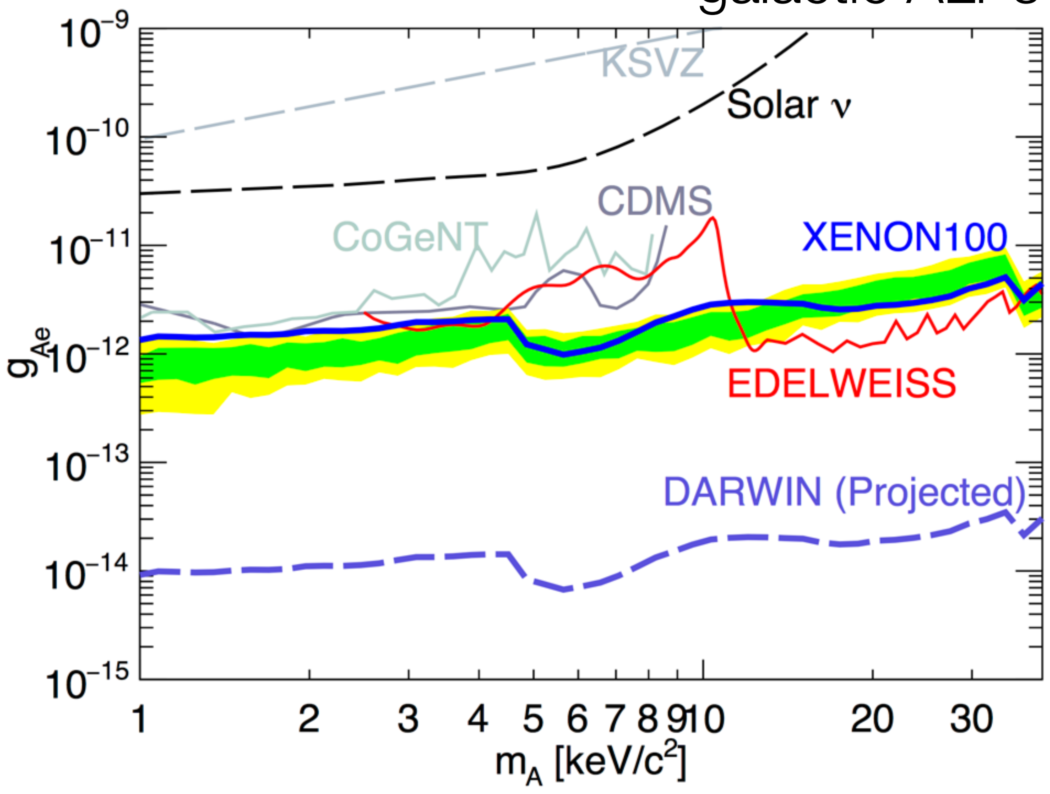
arXiv:1606.07001

- measurement via axio-electric effect (ER channel)
- expect mono-energetic peak at the particle mass
- moderate sensitivity to axions (weak dependence of the coupling on the exposure: $g_{Ae}^{\text{solar}} \propto (MT)^{-1/8}$)
- sensitivity to ALPs two orders of magnitude better than current limits ($g_{Ae}^{\text{ALP}} \propto (MT)^{-1/4}$)
- dominant backgrounds: solar neutrinos and 2νββ of ^{136}Xe

solar axions



galactic ALPs

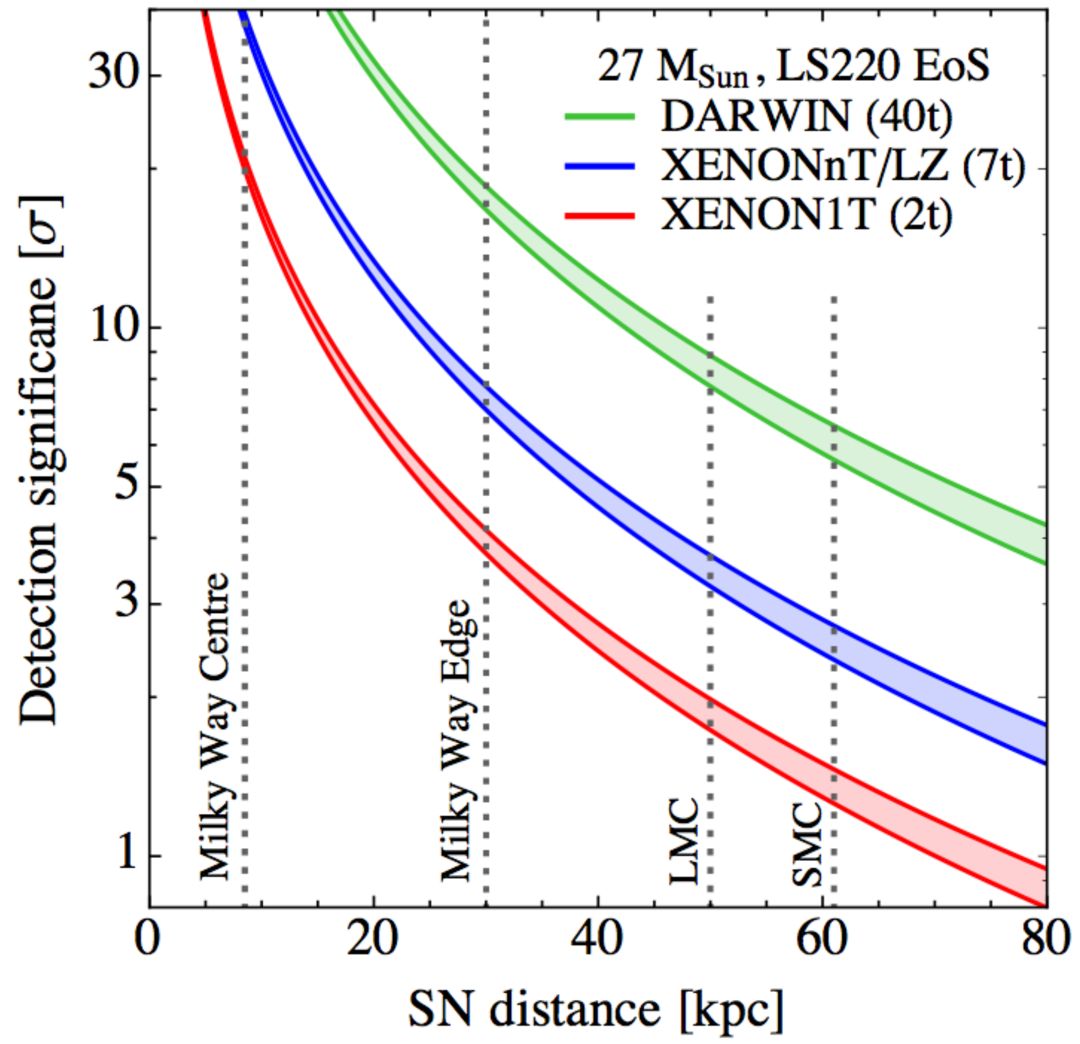


DARWIN

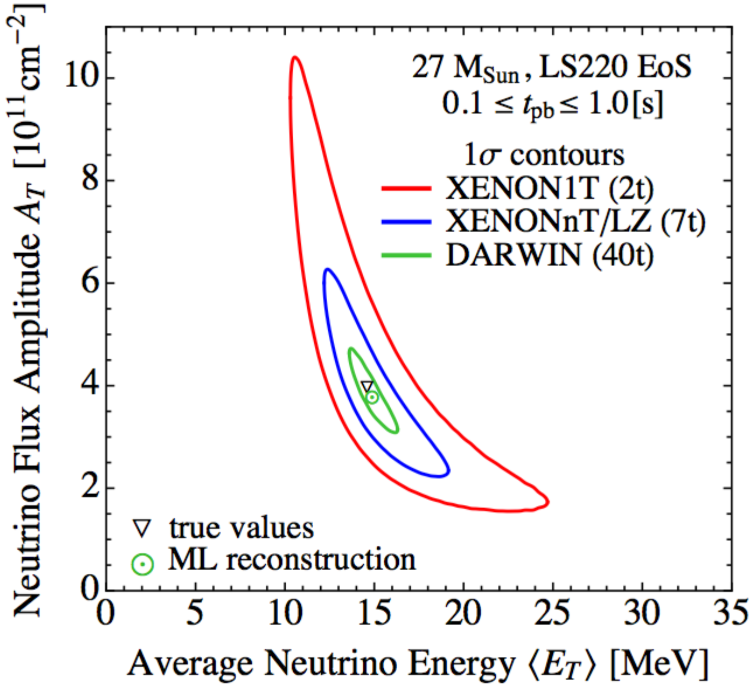
Supernova Neutrinos in DARWIN

arXiv:1606.09243

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



- 5σ sensitivity for a 27$M_\odot$ SN progenitor at 10 kpc (~700 events)
- flavor-insensitive neutrino energy measurement → constrain total explosion energy and reconstruct the SN light curve

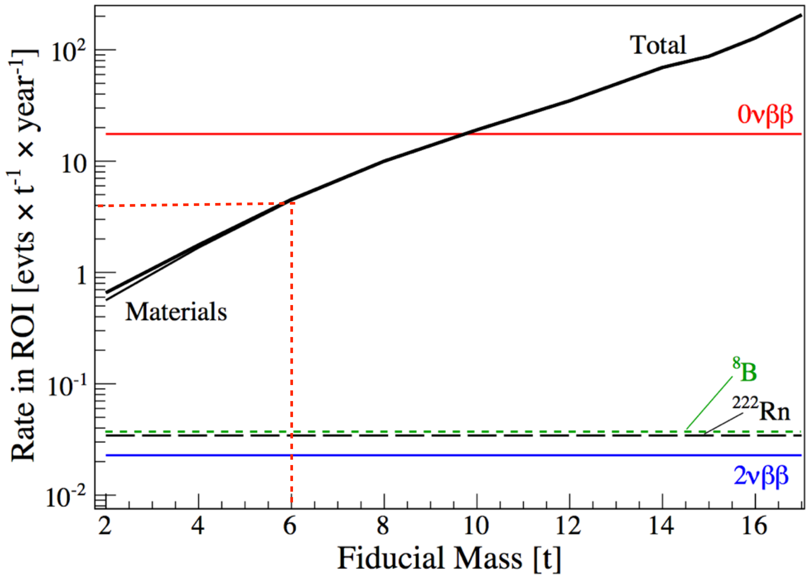


DARWIN

Sensitivity: 0νββ of ^{136}Xe

JCAP 01, 044 (2014)

- ^{136}Xe abundance in natural xenon 8.9%
- Q-value (2458.7±0.6) keV
- MC assuming $T_{1/2} = 1.6 \times 10^{25}$ yr (EXO-200 limit)
- Consider 6t fiducial volume
- Energy resolution (σ/μ) at $Q_{\beta\beta}$ 1%



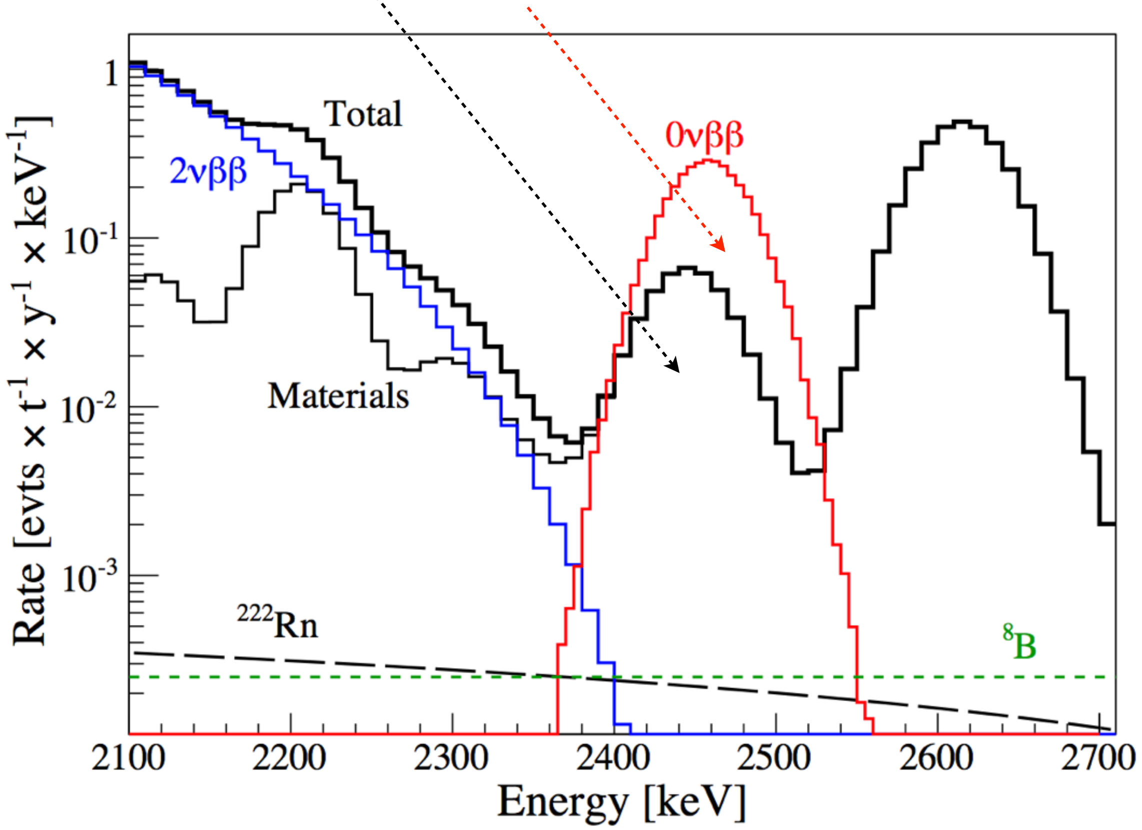
$T_{1/2} = 1.6 \times 10^{25}$ yr

0.1 μBq/kg

$T_{1/2} = 2.11 \times 10^{21}$ yr

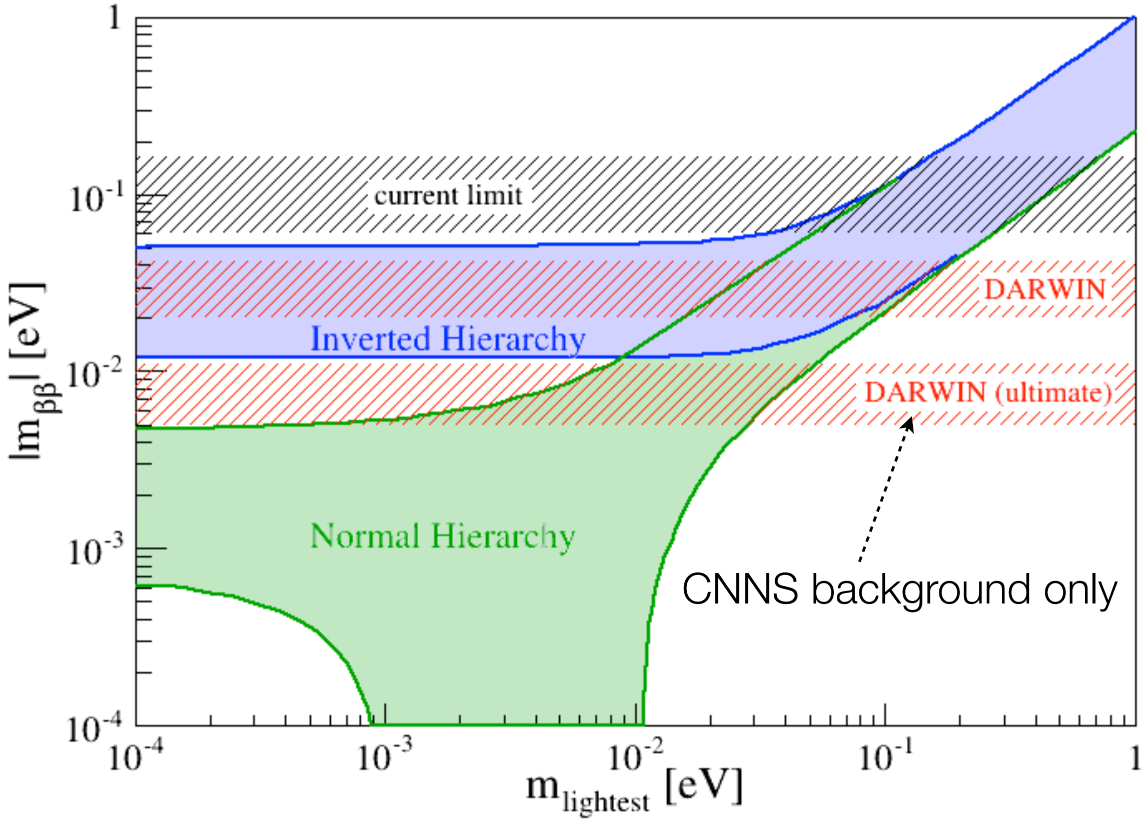
^{214}Bi → ^{214}Po + e⁻ + γ (2448 keV)

4.6 events/year within ±3σ



Projected sensitivity at 95% CL:

- 30 ton×yr exposure → $T_{1/2} > 5.6 \times 10^{26}$ yr
- 140 ton×yr → $T_{1/2} > 8.5 \times 10^{27}$ yr



CNNS background only

Technical Challenges and R&D

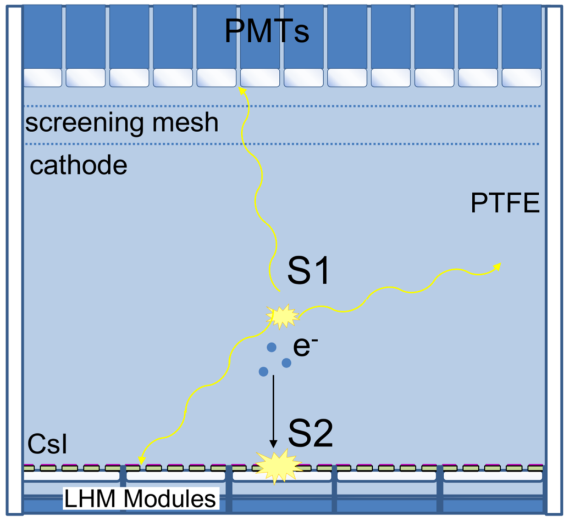
High voltage:

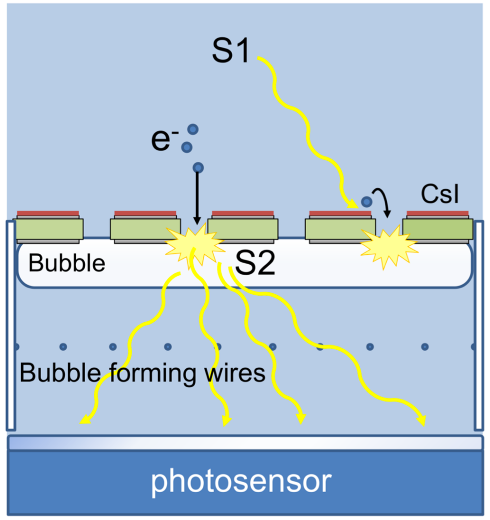
- drift field: 0.5 kV/cm requires cathode HV of 130 kV, uniformity is important
- anode: constant gap, parallel to liquid surface over 2.6m

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

High light yield:

- baseline design PMTs
- alternatives: SiPM, SiGHT, GPM
- single-phase TPC with liquid hole multipliers (LHM)





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

High purity:

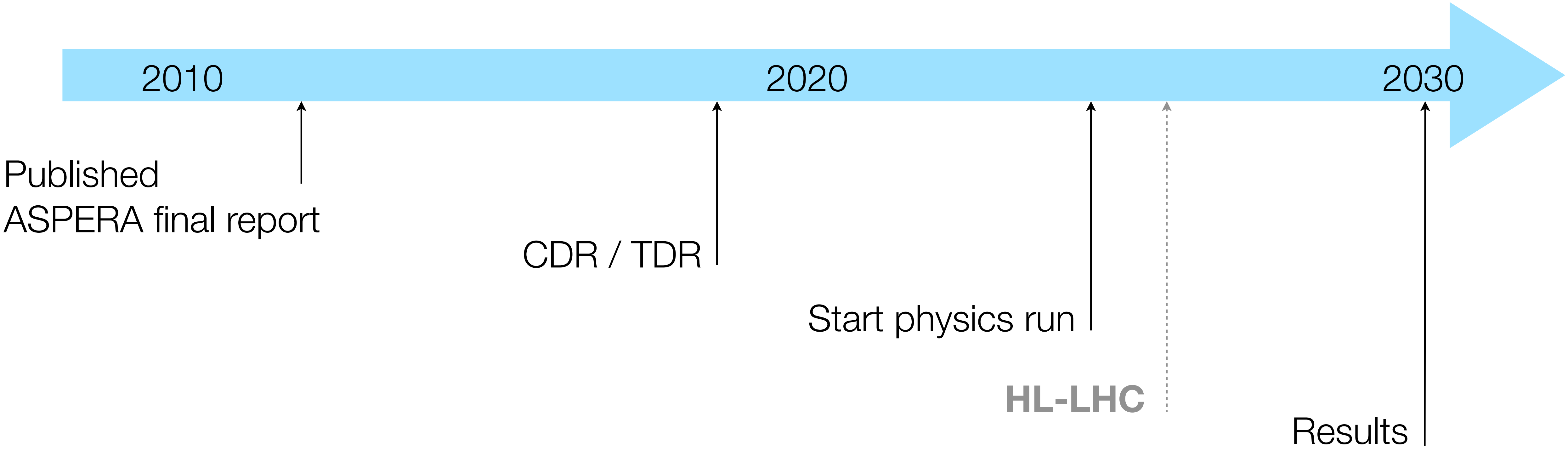
- novel magnetically driven piston pumps with hermetically sealed pumping volumes
- cryogenic distillation to remove Kr (sub-ppt level)
- careful selection of materials for low Rn emanation
- surface treatment (electropolishing, etching etc.)

Conclusions

DARWIN

- Push low-background technology to the next level
- ‘Ultimate’ discovery machine for WIMPs
- Neutrino physics program
- Solar observatory

- Just 10 years away...



2010

2020

2030

Published
ASPERA final report

CDR / TDR

Start physics run

HL-LHC

Results

www.darwin-observatory.org