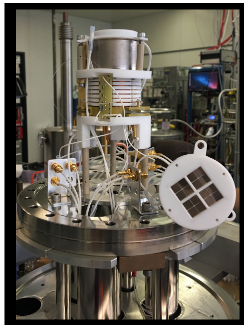
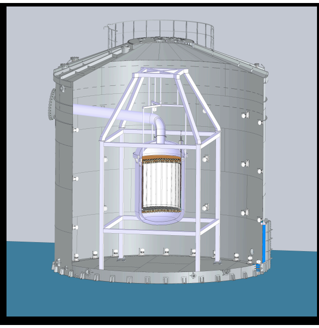
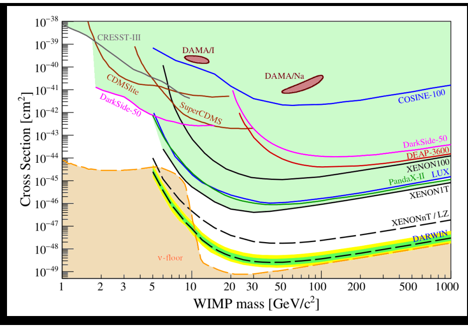
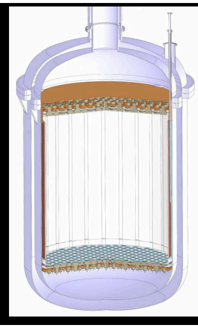






DARWIN: THE ULTIMATE LIQUID XENON DIRECT DETECTION EXPERIMENT

Sara Diglio on behalf of the DARWIN Collaboration

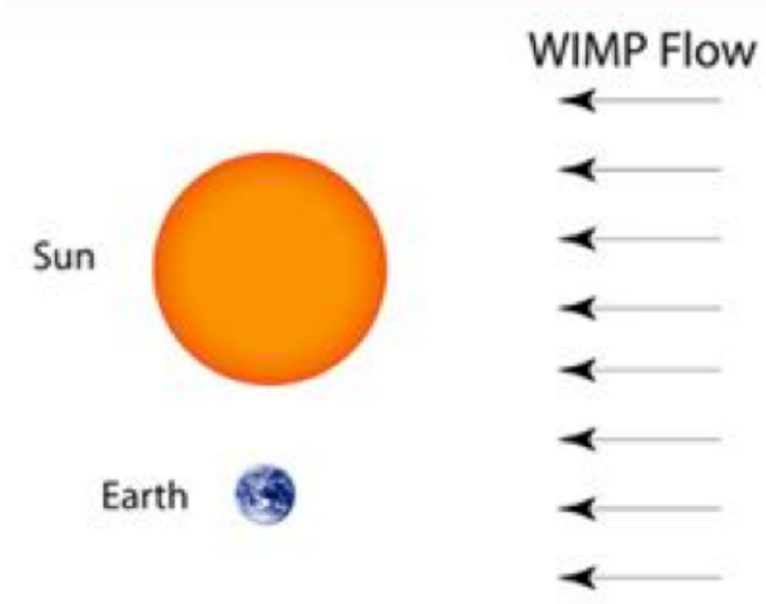
Subatech – Nantes

DARKWIN: 2nd – 13th September 2019, Natal

THE DIRECT DETECTION CHALLENGE

The WIMP DM hypothesis ...

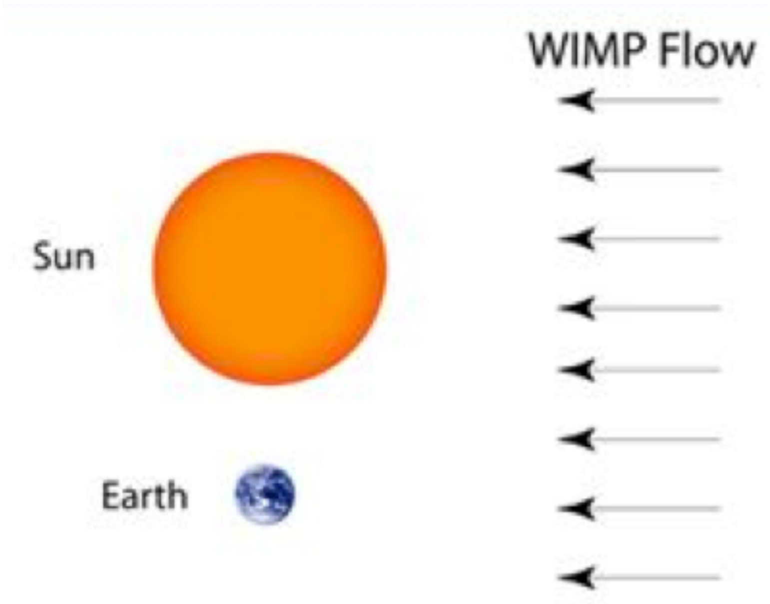
- Galactic rotation curves suggest the Dark Matter forms an extended halo around galaxies
- Earth is passing through a halo of WIMPs
- We feel a WIMP 'wind' as we move through the halo

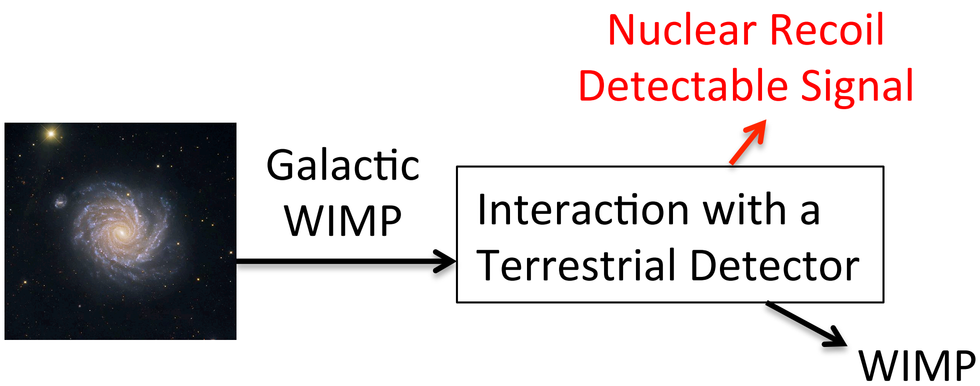


THE DIRECT DETECTION CHALLENGE

The WIMP DM hypothesis ...

- Galactic rotation curves suggest the Dark Matter forms an extended halo around galaxies
- Earth is passing through a halo of WIMPs
- We feel a WIMP 'wind' as we move through the halo
- We search for the rare collisions of WIMPs with target nuclei in detectors on Earth

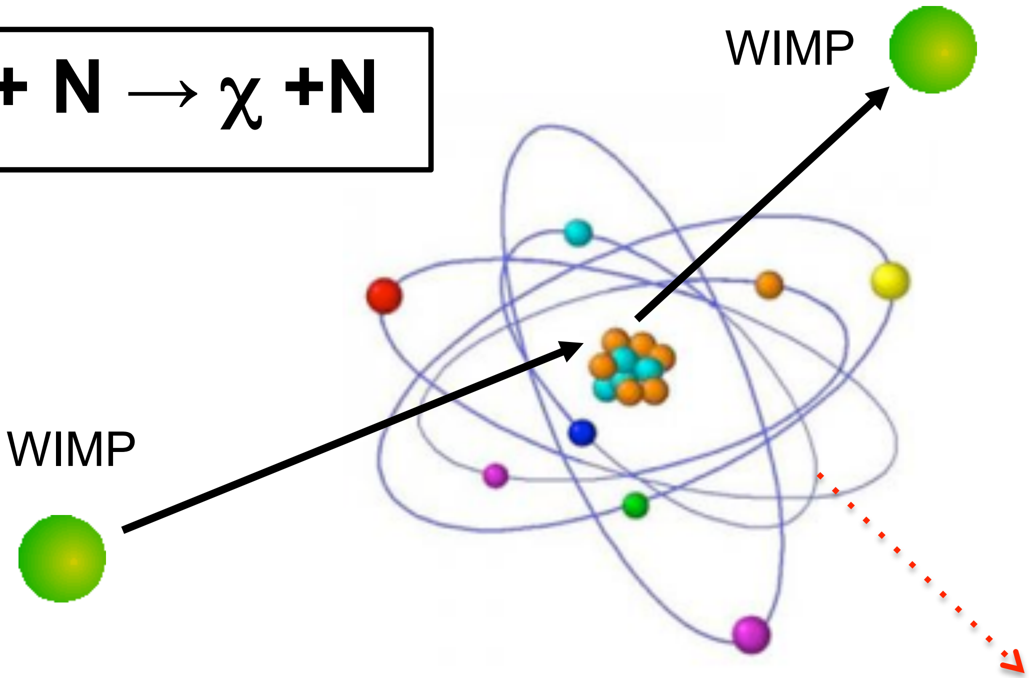




THE DIRECT DETECTION PRINCIPLE

WIMPs elastically scatter off nuclei in targets, producing Nuclear Recoils (NR)

$$\chi + N \rightarrow \chi + N$$



NR: Detectable Signal

$$E_{recoil} \leq 50\, keV$$

For example, by assuming

- WIMP mass: M_χ = 100 GeV/c^2
- WIMP velocity: v_0 = 220 km/s

we have the average recoil energy: $E_0 = \frac{1}{2} M_X v_0^2 \sim 30 \text{ keV}$

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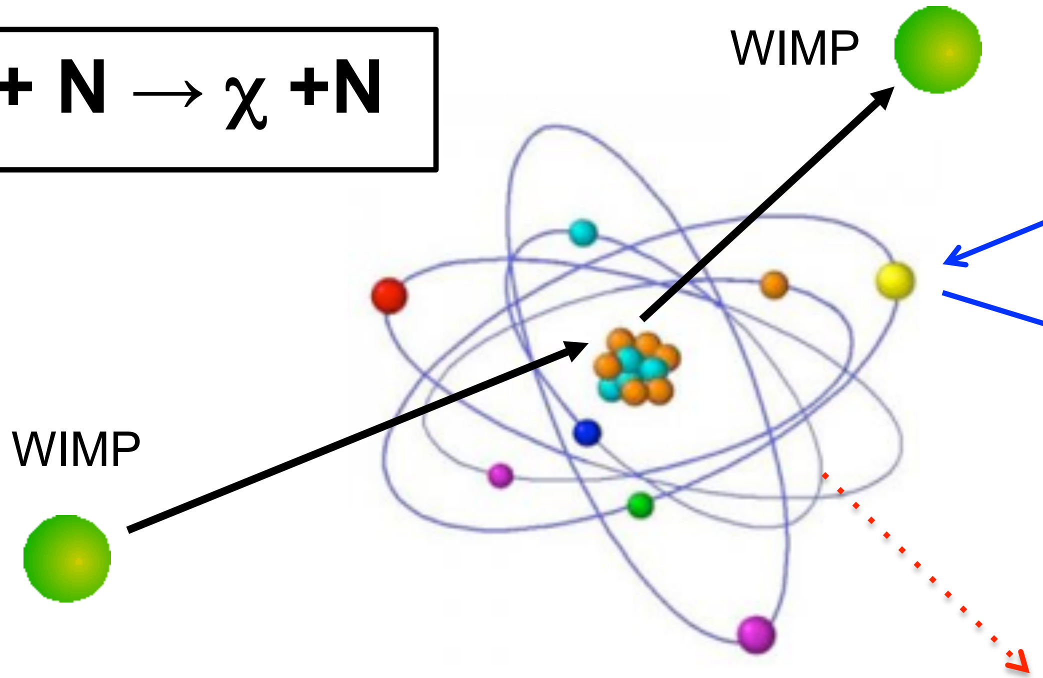

γ- and β-particles (**background**) interact with the atomic electrons → **electronic recoil (ER)**

NR: Detectable Signal

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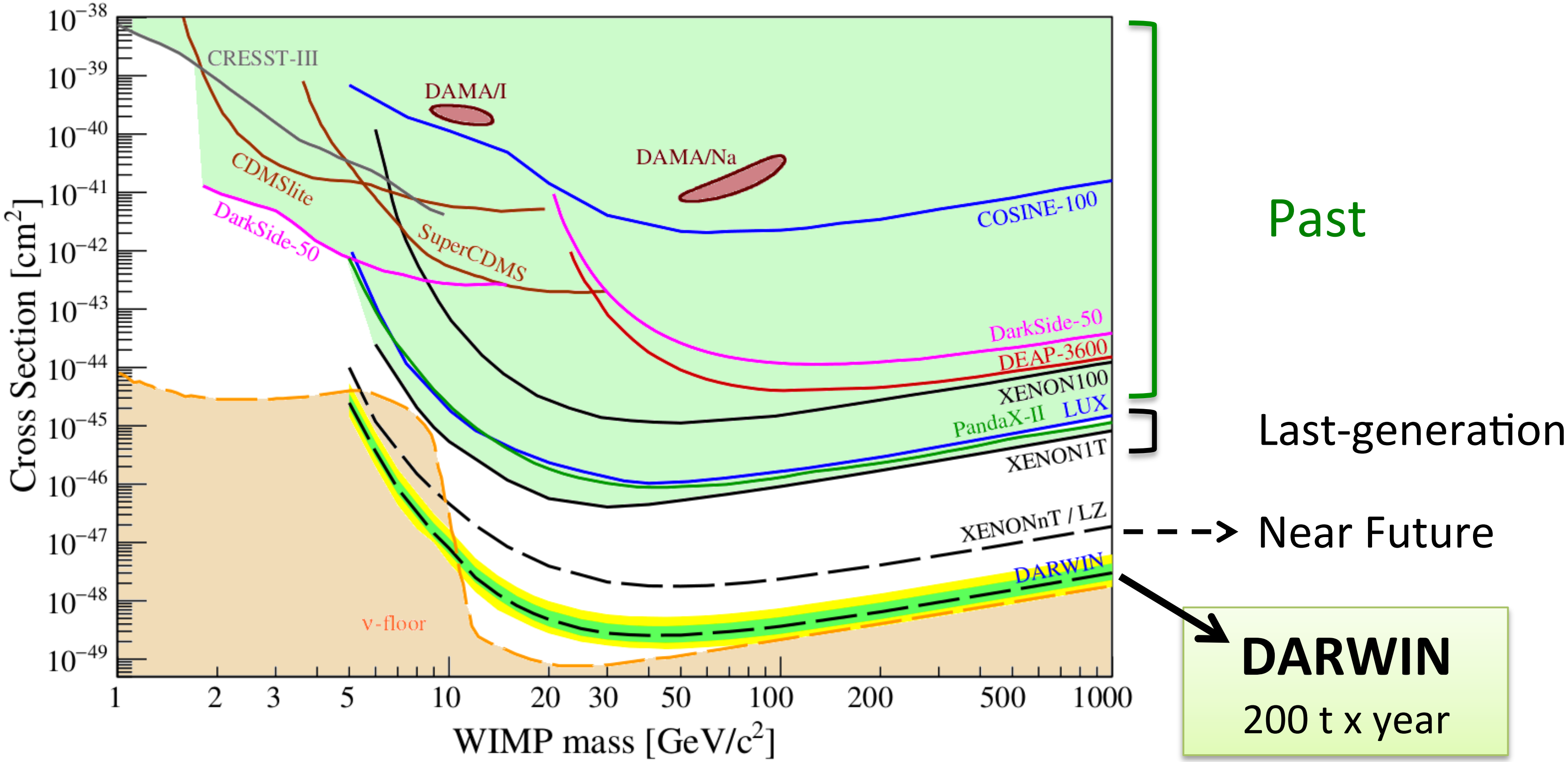
THE STATE-OF-THE-ART OF THE WIMP LANDSCAPE

- LXe Dual Phase Time Projection Chambers detectors are leading the WIMP search above 5 GeV/c^2
- Larger detectors needed to increase the sensitivity reach
- **DARWIN** is targeting the **ultimate WIMP discovery limit**



DARWIN
200 t x year

WHY XENON AS A DETECTOR MEDIUM?

- **High mass number**
  high rate for Spin Independent interactions ($\sigma \sim A^2$)

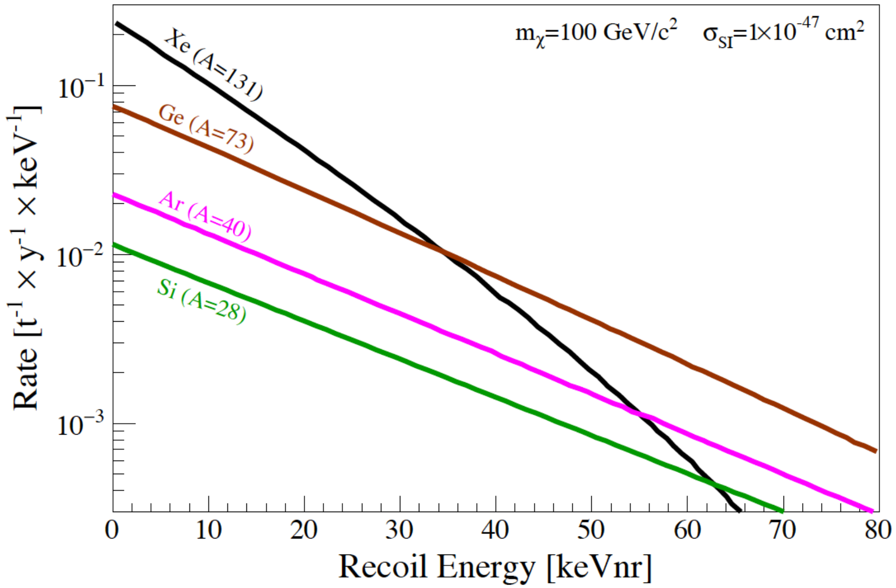
- **Intrinsically pure**
  - no long-lived radioactive isotopes
  - ^{85}Kr that can be reduced to < ppt

- **Self shielding**
  high Z=54, high density ρ~ 3 kg/l

- **Odd-nucleon isotopes**
  ^{129}Xe, ^{131}Xe for Spin Dependent Interactions

- **"Easy" purification**

- **Scalability**
  compact detectors,
  scalable to larger dimension



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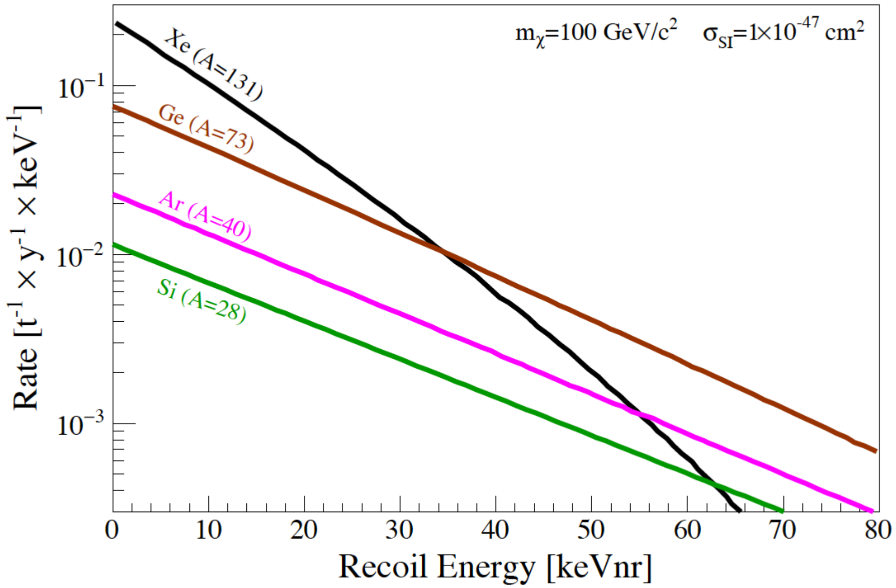

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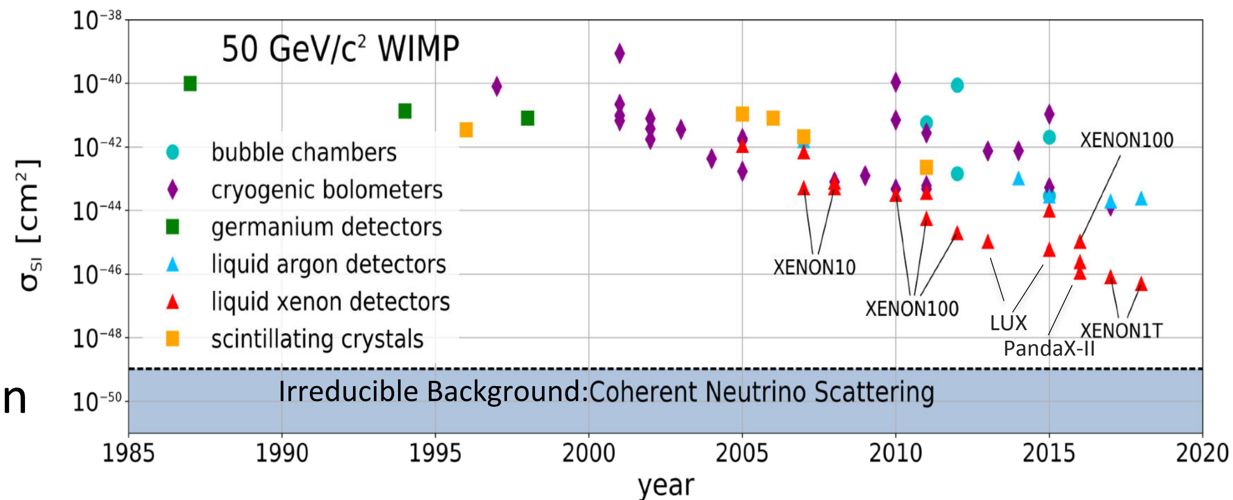
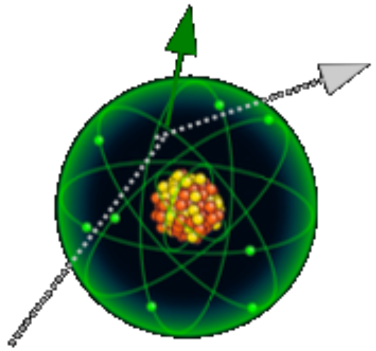
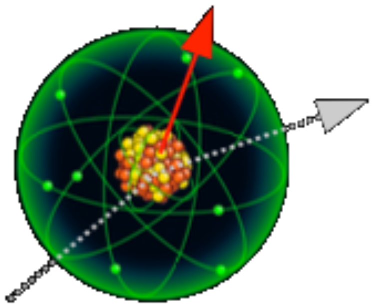


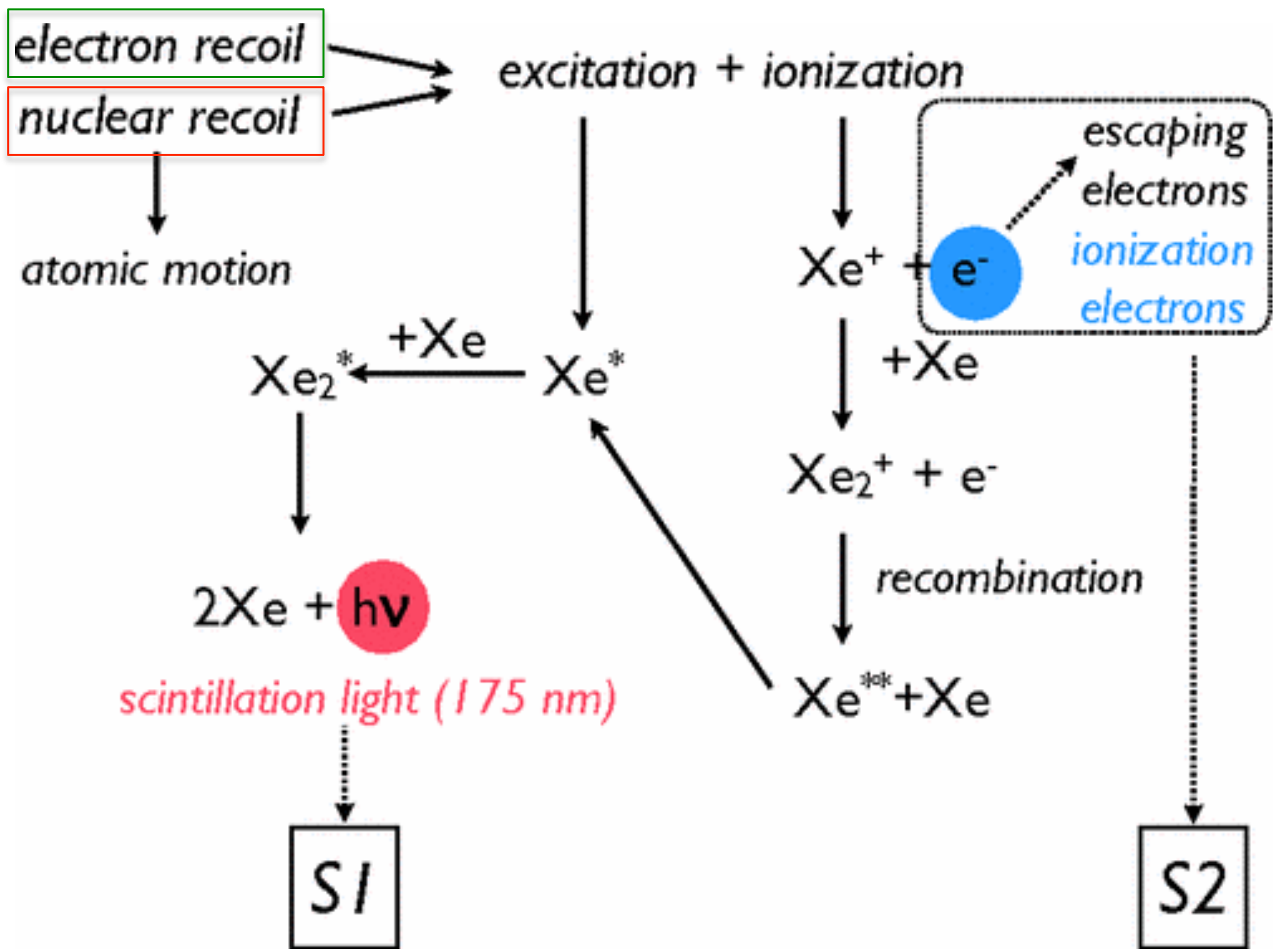
SCINTILLATION AND IONIZATION SIGNALS IN LXE



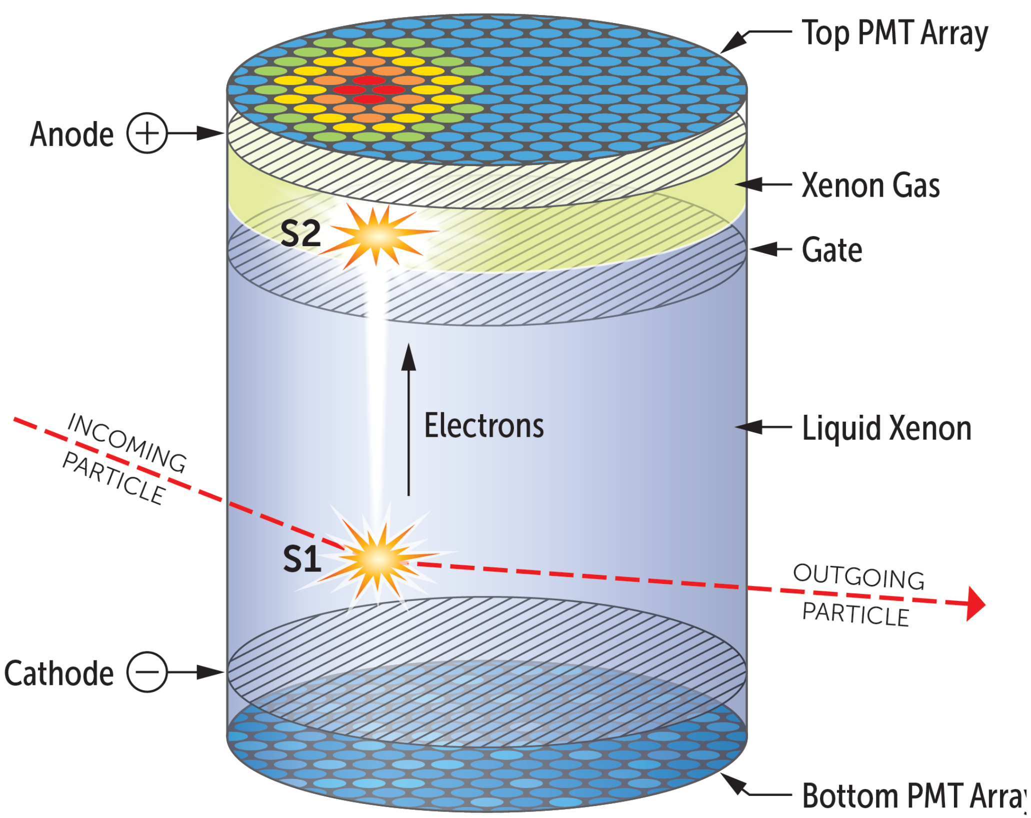
Electron Recoil
(gamma, beta)



Nuclear Recoil
(neutron, WIMP)



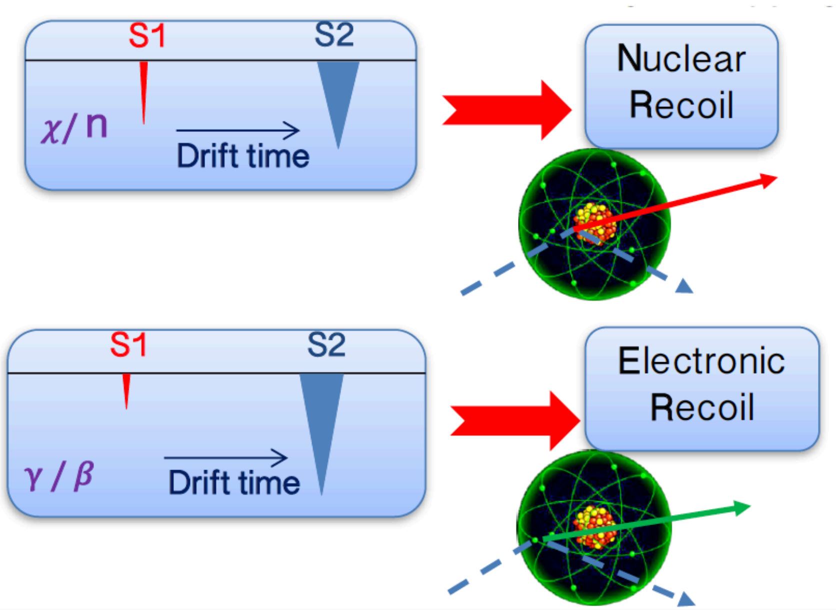
LXe Dual Phase Time Projection Chamber



Credits: Purdue University

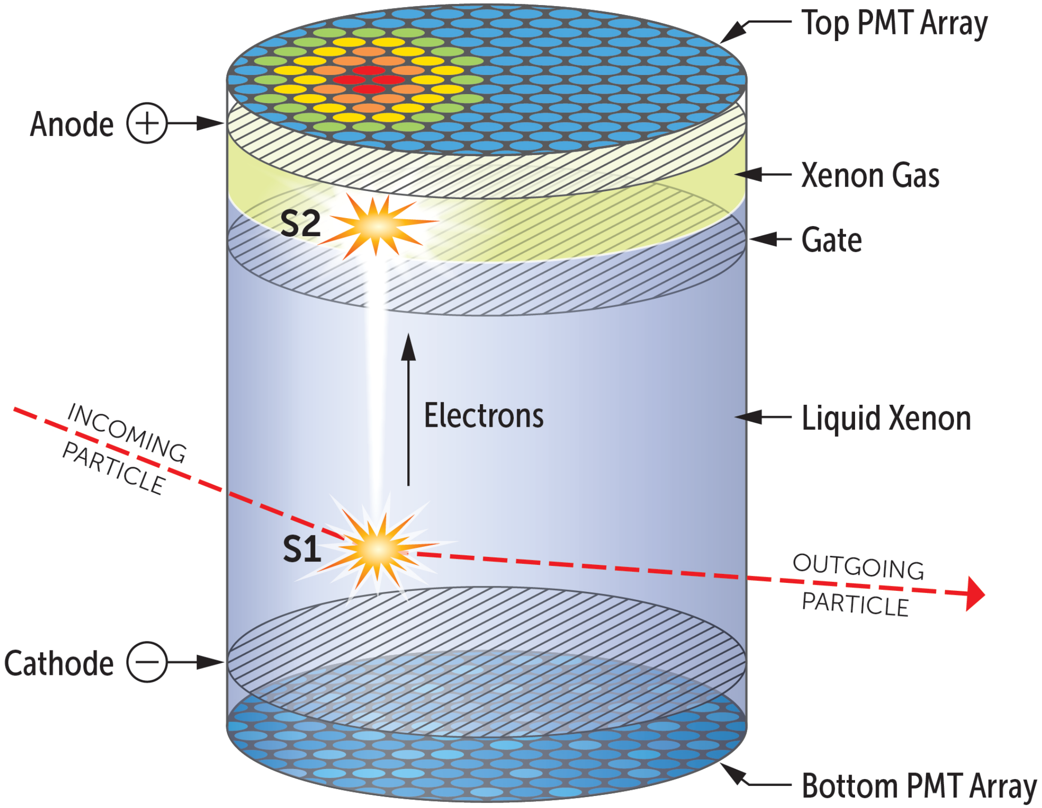
S1: Prompt Scintillation (light)

S2: Proportional scintillation following e$^-$ drift and extraction into gas (charge)



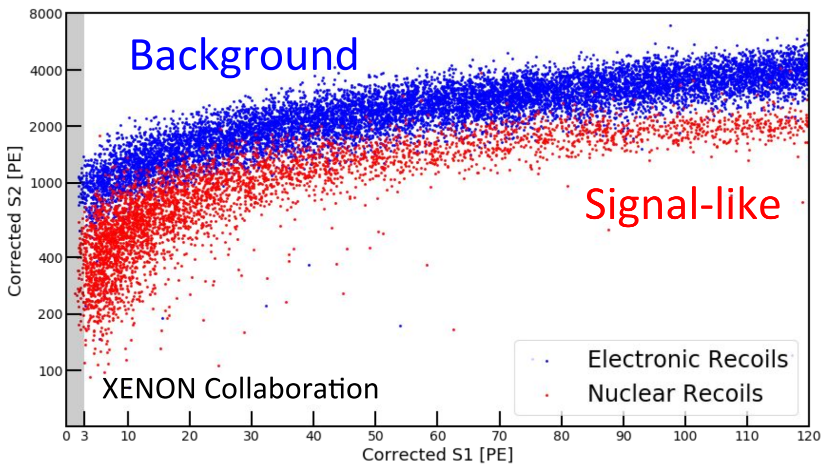
$$(S2/S1)_{WIMP,n} < (S2/S1)_{\gamma,\beta}$$

LXe Dual Phase Time Projection Chamber



Credits: Purdue University

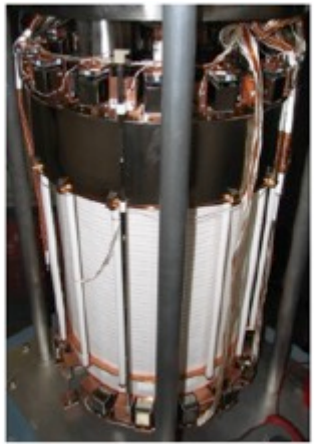
- Energy from S1 and S2 area
- 3D event reconstruction:
  - X , Y from S2 hit pattern on top PMTs
  - Z from electrons drift time
- ER vs NR discrimination



DARWIN IN THE CONTEXT OF THE XENON PROJECT

Time

XENON10	XENON100	XENON1T
2005—2007	2008—2016	2012 – 2019



Total mass : 25 kg	Total mass : 161 kg	Total mass : 3.2 t
Target mass: 14 kg	Target mass: 62 kg	Target mass: 2 t
Drift TPC: 15 cm	Drift TPC: 30 cm	Drift TPC: 96 cm
Limit ~ 10^{-43} cm^2	Limit ~ 10^{-45} cm^2	Limit ~ $10^{-47}cm^2$

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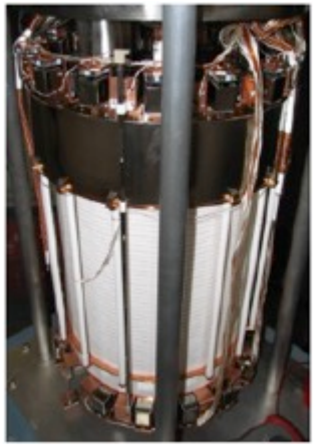


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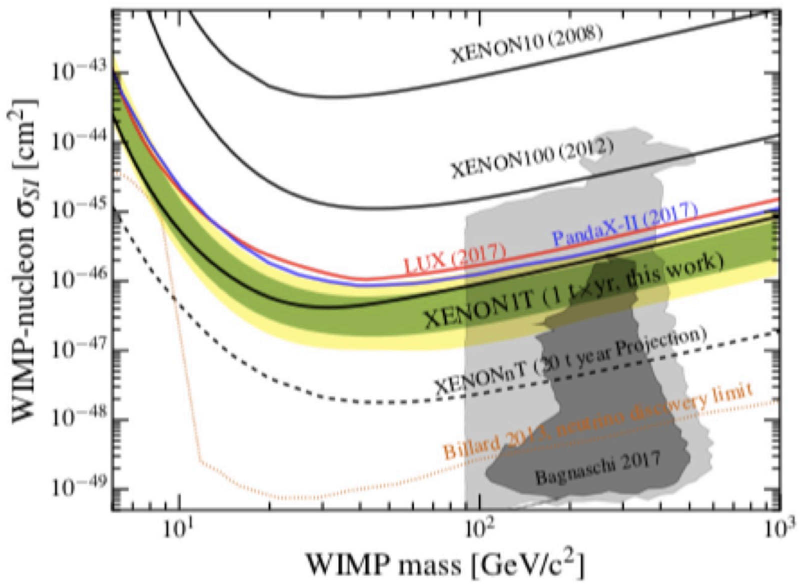
Limit ~ 10^{-43} cm^2	Limit ~ 10^{-45} cm^2	**Limit ~ $10^{-47}$$cm^2$**

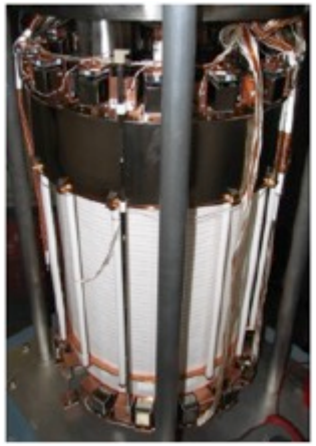
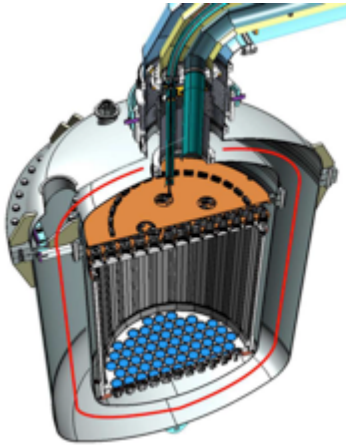


World-wide best limit for masses above 6 GeV/c^2

PRL 121 (2018) no.11

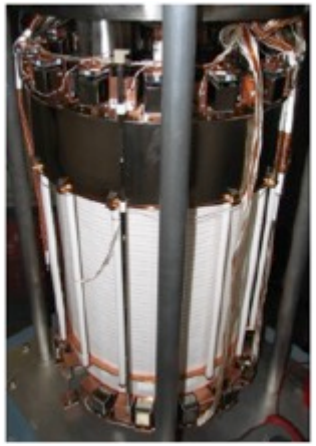
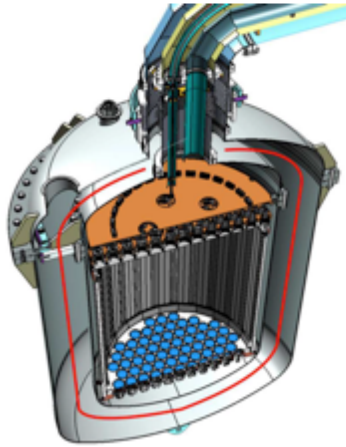
DARWIN IN THE CONTEXT OF THE XENON PROJECT

Time

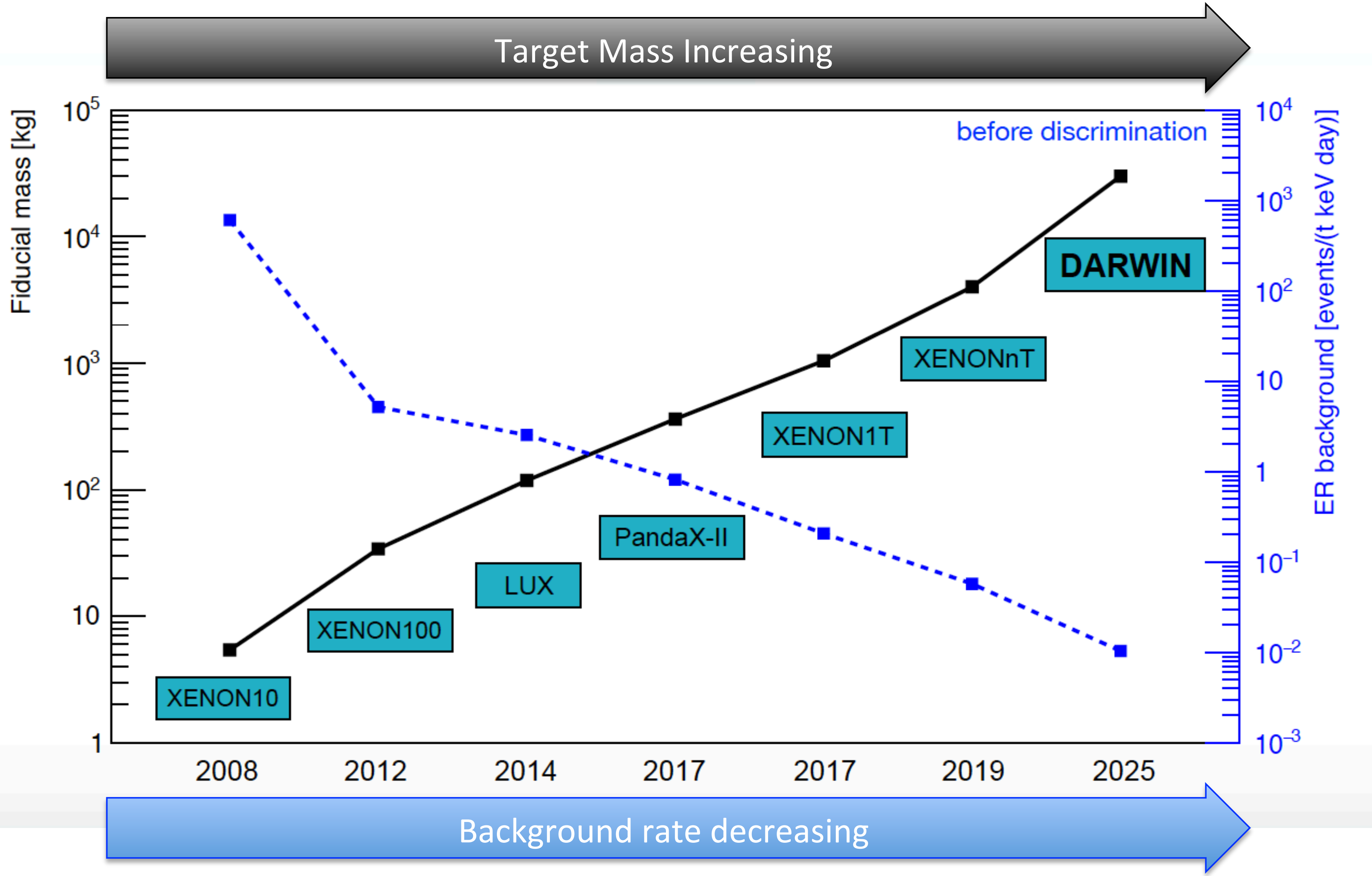
XENON10 2005—2007	XENON100 2008—2016	XENON1T 2012 – 2019	XENONnT 2017 – 2023
			
Total mass : 25 kg	Total mass : 161 kg	Total mass : 3.2 t	Total mass : ~8 t
Target mass: 14 kg	Target mass: 62 kg	Target mass: 2 t	Target mass: ~6 t
Drift TPC: 15 cm	Drift TPC: 30 cm	Drift TPC: 96 cm	Drift TPC: 144 cm
Limit ~ 10^{-43} cm^2	Limit ~ 10^{-45} cm^2	Limit ~ $10^{-47}$$cm^2$	Sensitivity ~ $10^{-48}$$cm^2$

DARWIN in the context of the XENON Project

Time

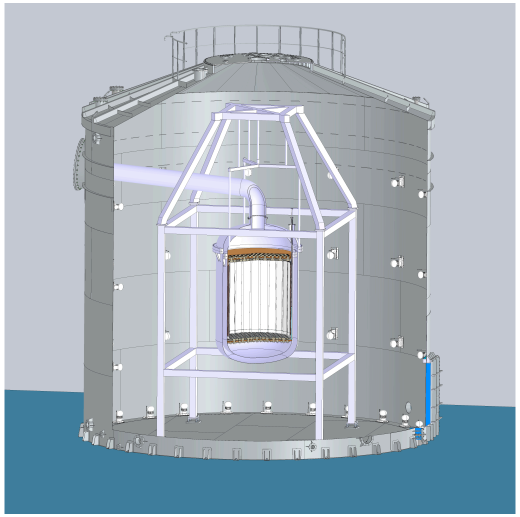
XENON10	XENON100	XENON1T	XENONnT	**DARWIN**
2005—2007	2008—2016	2012 – 2019	2017 – 2023	**~2023 –**
				
Total mass : 25 kg	Total mass : 161 kg	Total mass : 3.2 t	Total mass : ~8 t	**Total mass : ~50 t**
Target mass: 14 kg	Target mass: 62 kg	Target mass: 2 t	Target mass: ~6 t	**Target mass: ~40 t**
Drift TPC: 15 cm	Drift TPC: 30 cm	Drift TPC: 96 cm	Drift TPC: 144 cm	**Drift TPC: 260 cm**
Limit ~ 10^{-43} cm^2	Limit ~ 10^{-45} cm^2	Limit ~ $10^{-47}cm^2$	Sensitivity ~ $10^{-48}cm^2$	**Sensitivity ~ $10^{-49}cm^2$**

LXeTPCs as WIMP detectors Scaling

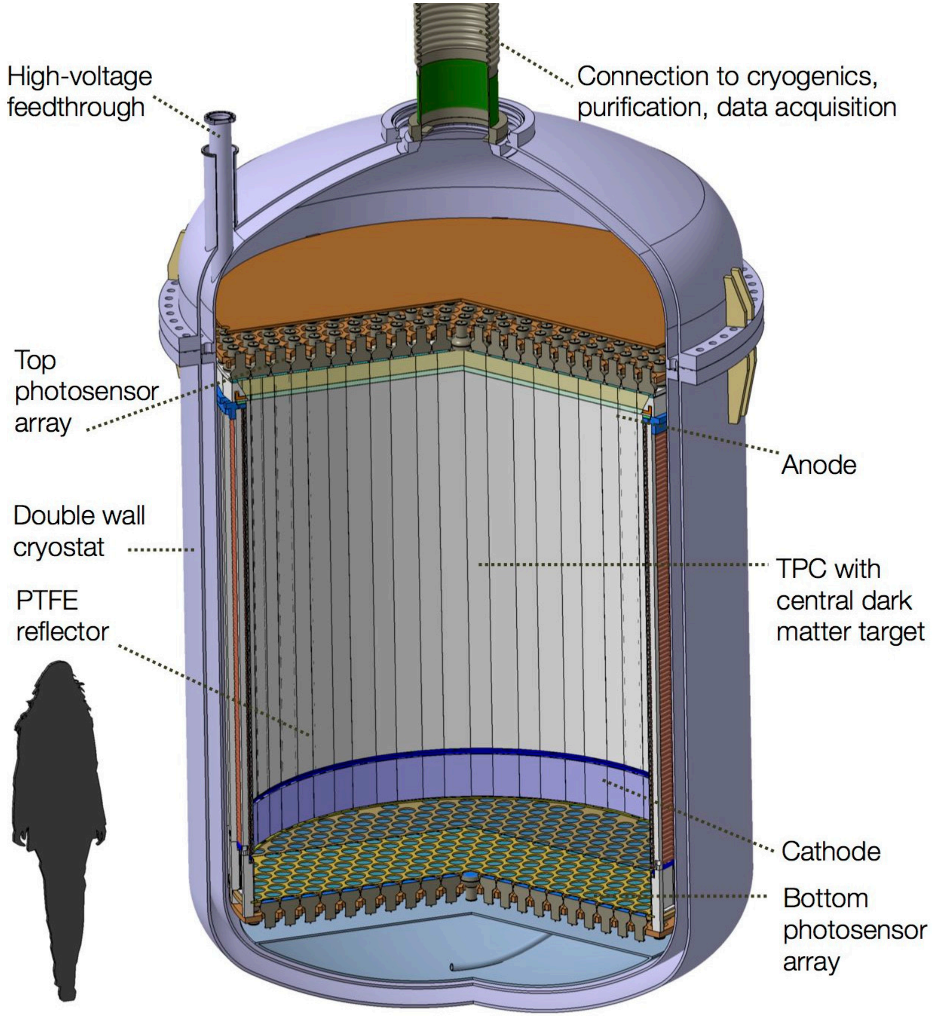


DARWIN BASELINE DESIGN

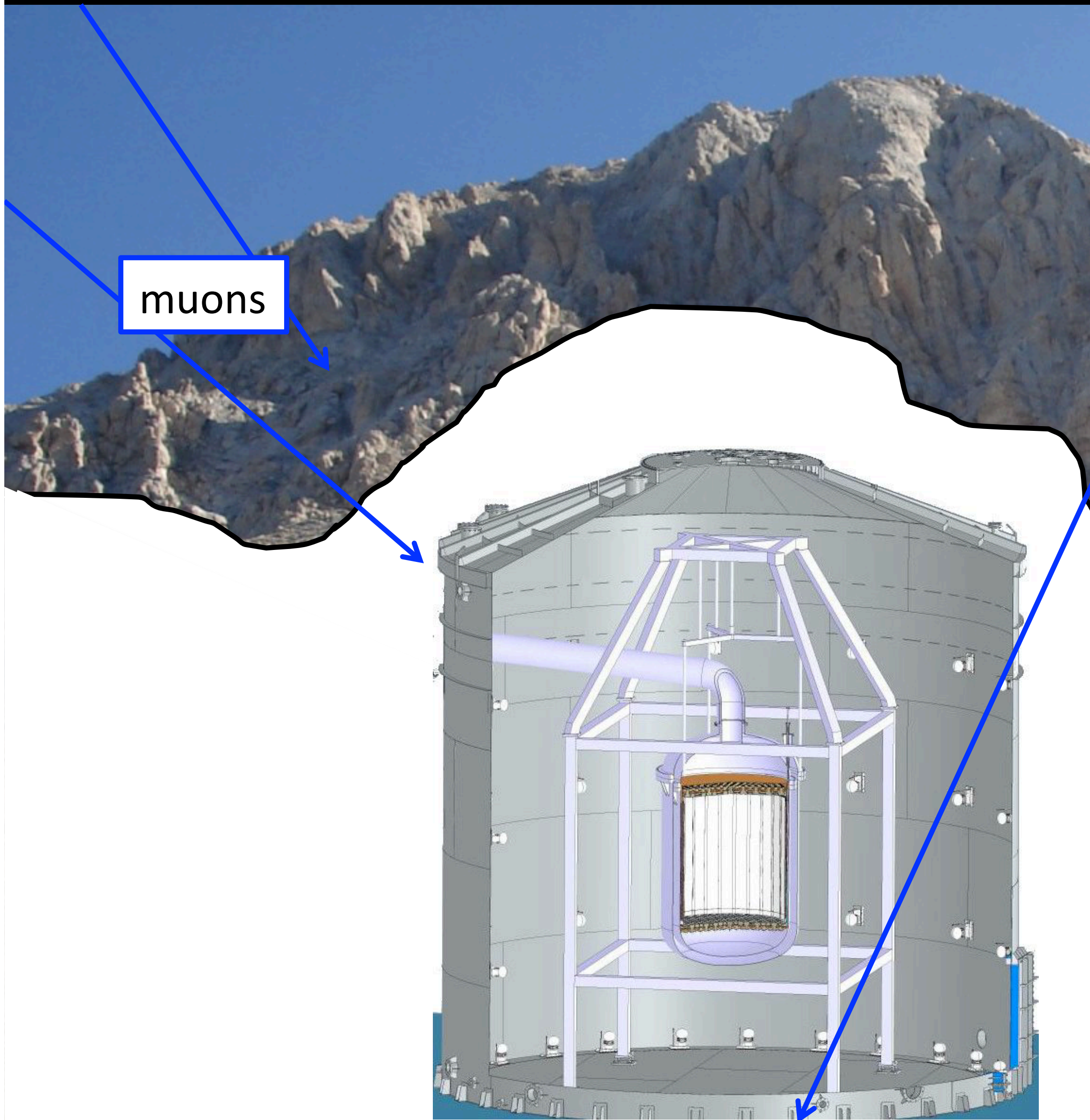
- 2.6 m x 2.6 m Dual Phase TPC
- 50 t (40 t active) LXe target
- Top & bottom arrays of photosensors
- Drift field ~0.5 kV/cm
- 14 m x 14 m water shield and neutron veto

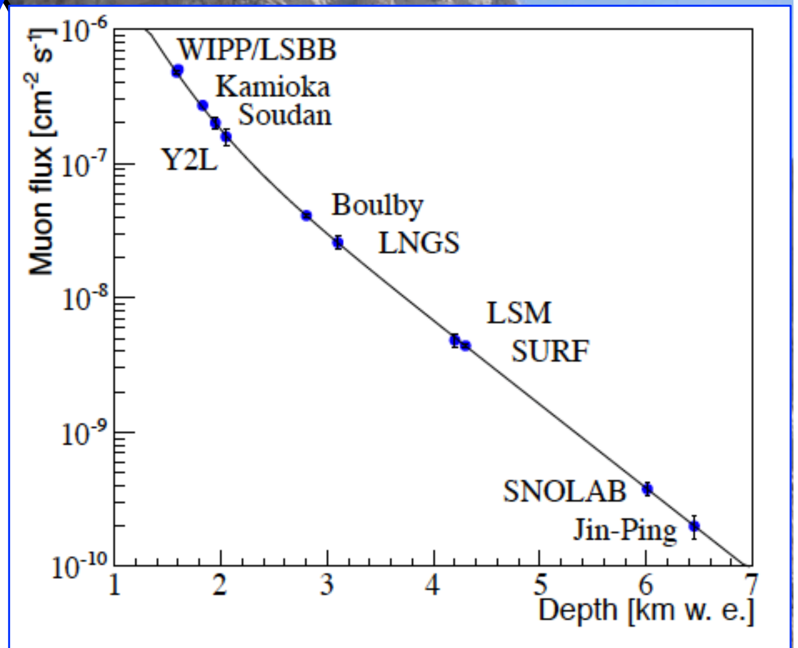


DARWIN Collaboration, JCAP 1611 (2016) 017



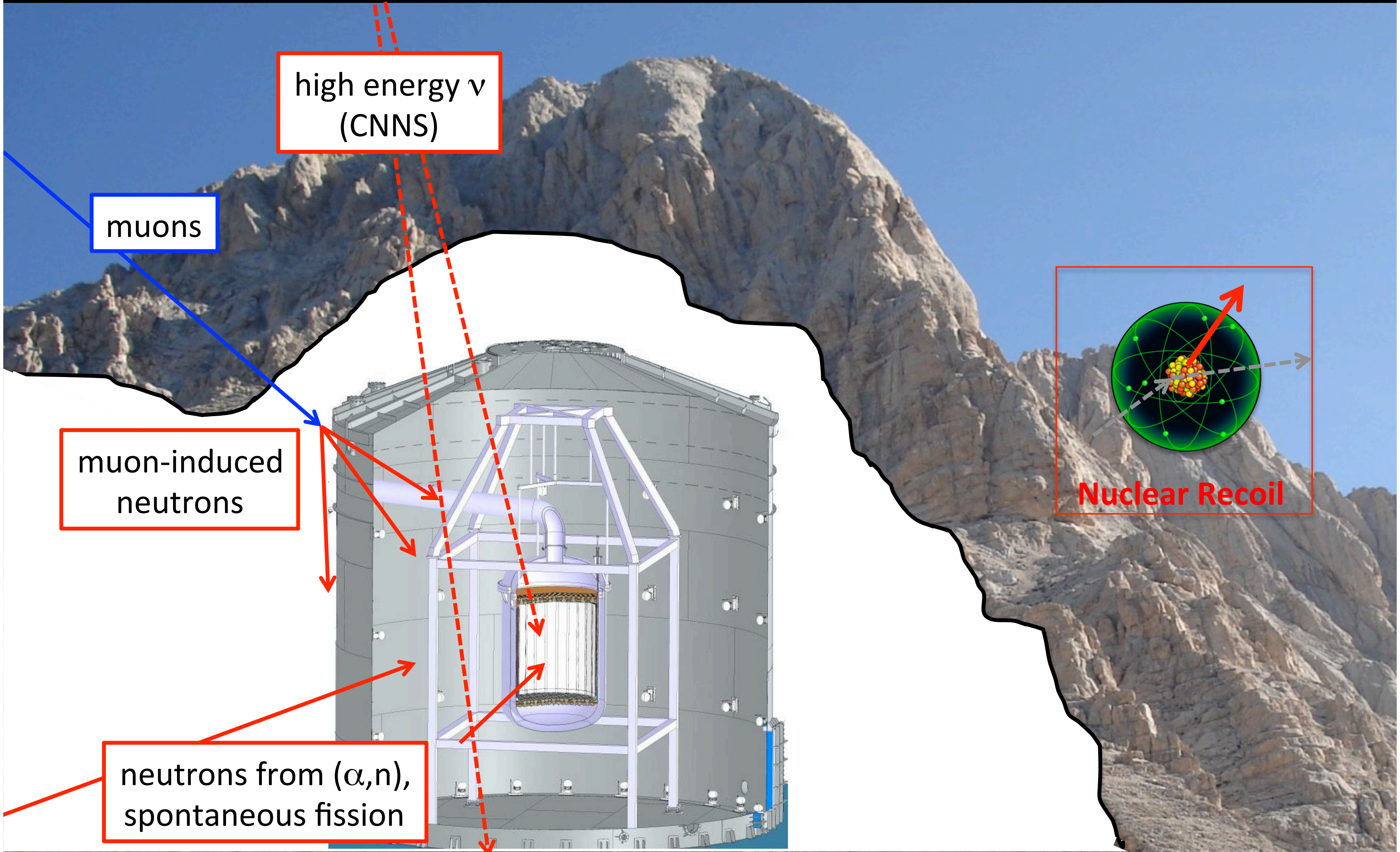
BACKGROUND SOURCES





BACKGROUND SOURCES

DARWIN



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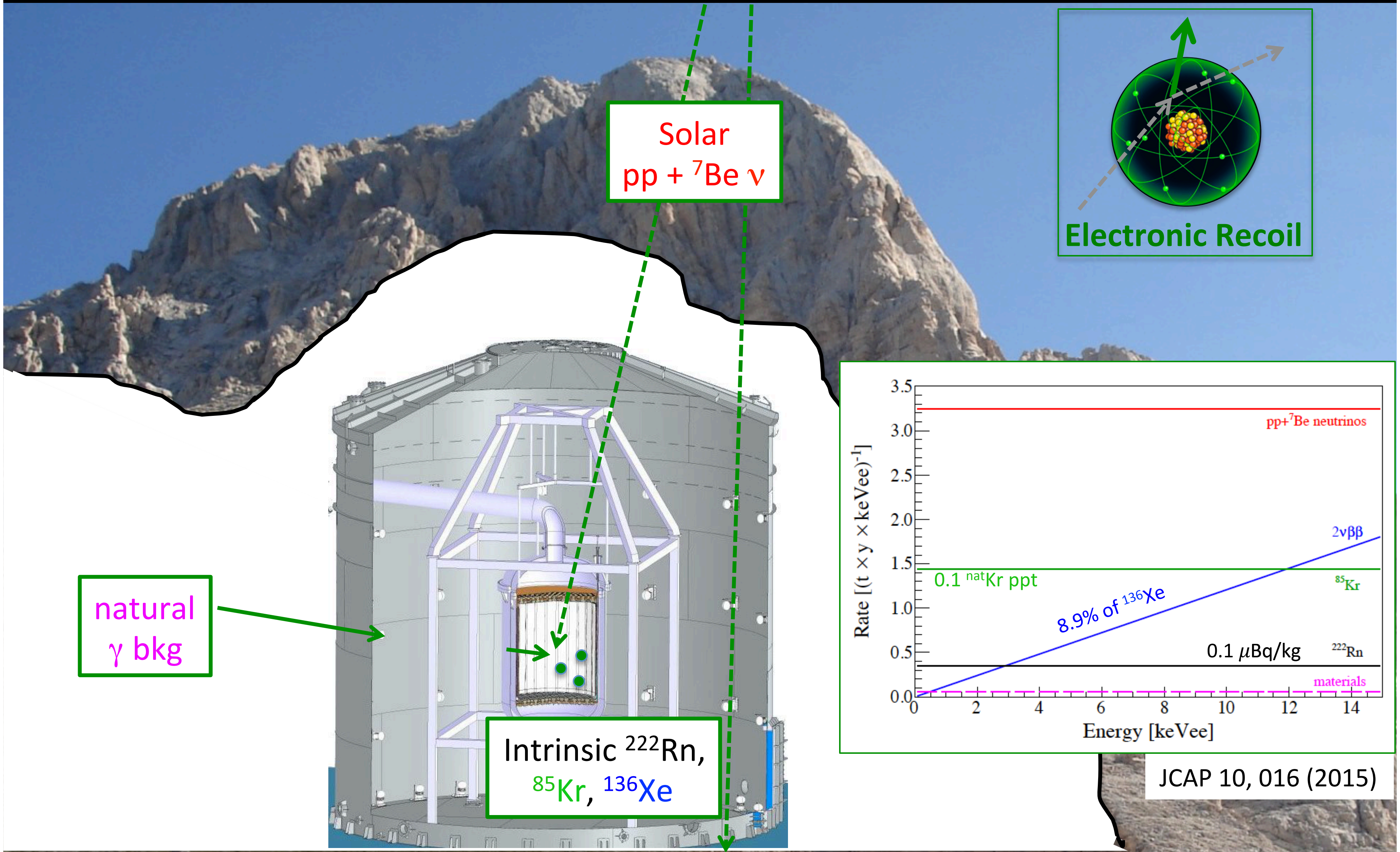
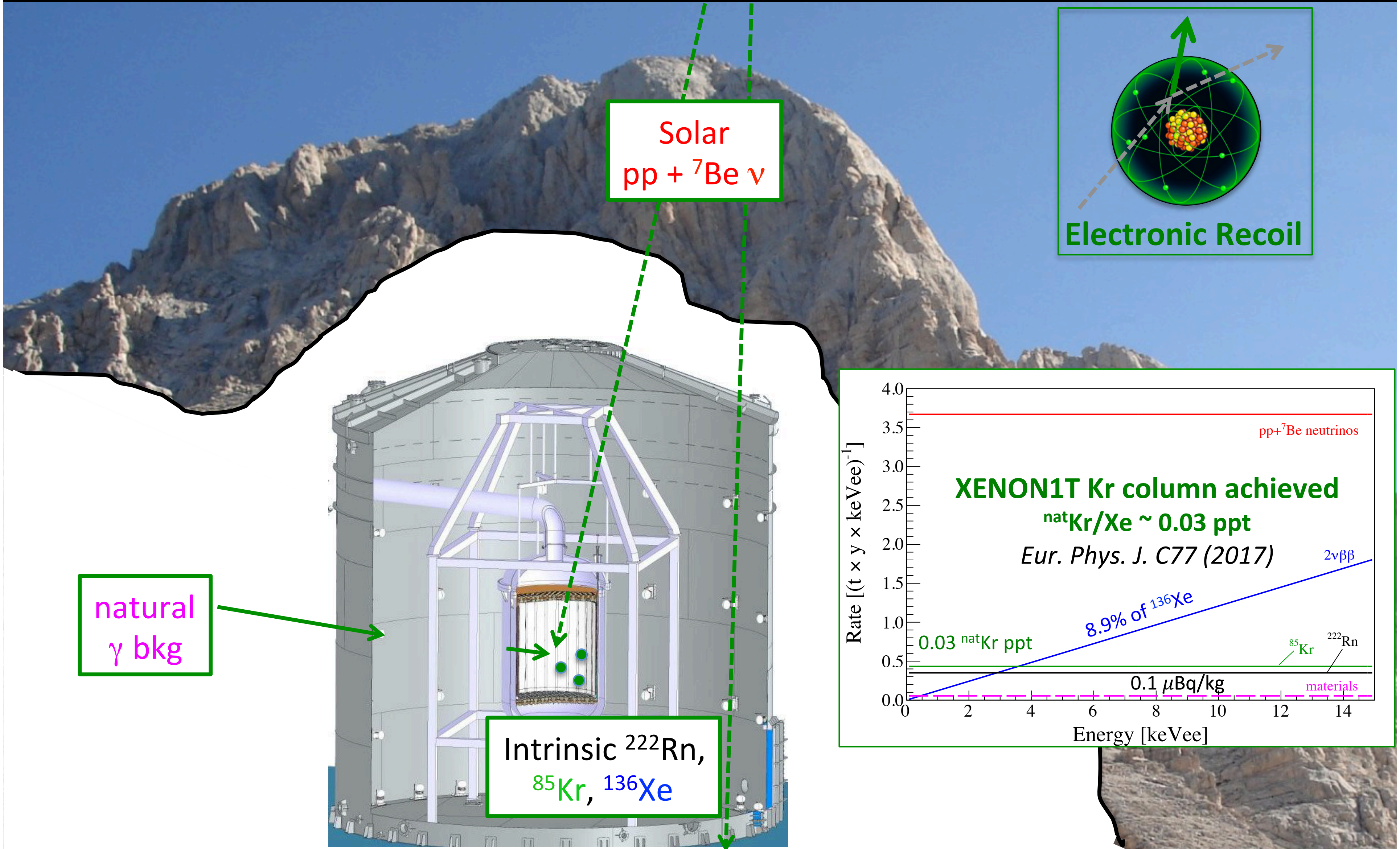


JCAP 10, 016 (2015)

Background Sources



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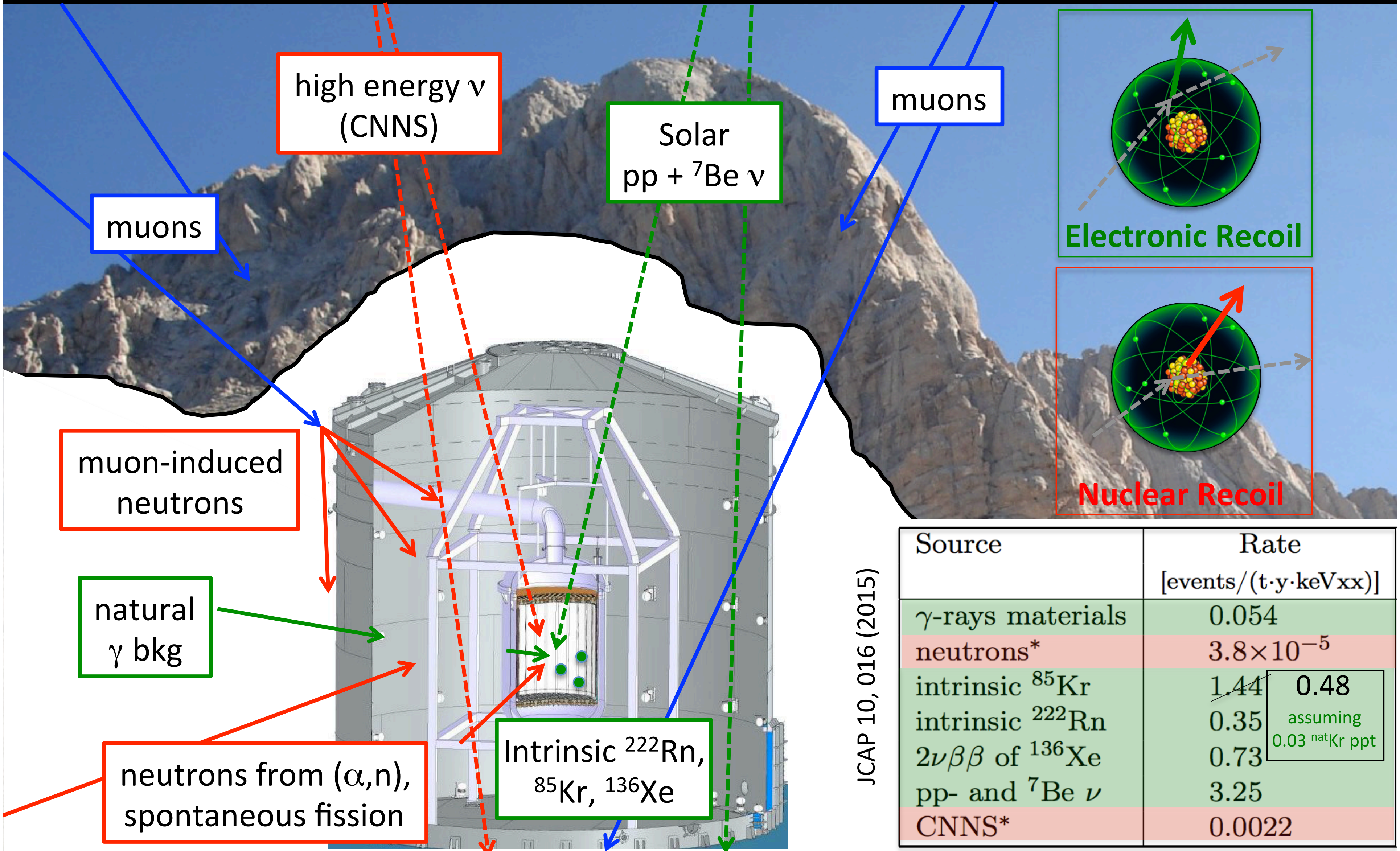
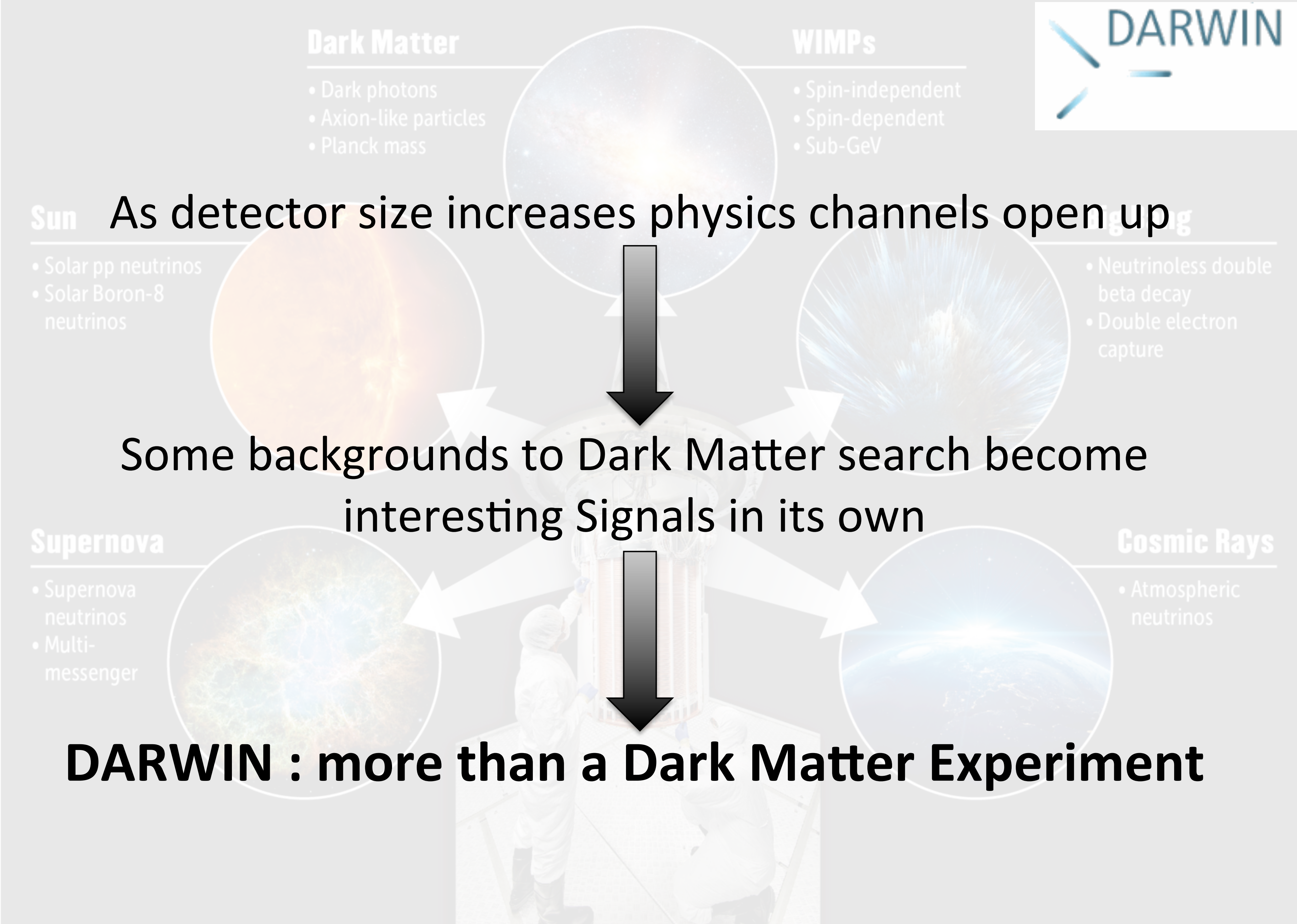


Source	Rate [events/(t·y·keVxx)]
γ-rays materials	0.054
neutrons*	3.8×10^{-5}
intrinsic ^{85}Kr	~~1.44~~ 0.48 assuming 0.03 ^{nat}Kr ppt
intrinsic ^{222}Rn	0.35
$2\nu\beta\beta$ of ^{136}Xe	0.73
pp- and ^{7}Be ν	3.25
CNNS*	0.0022

JCAP 10, 016 (2015)

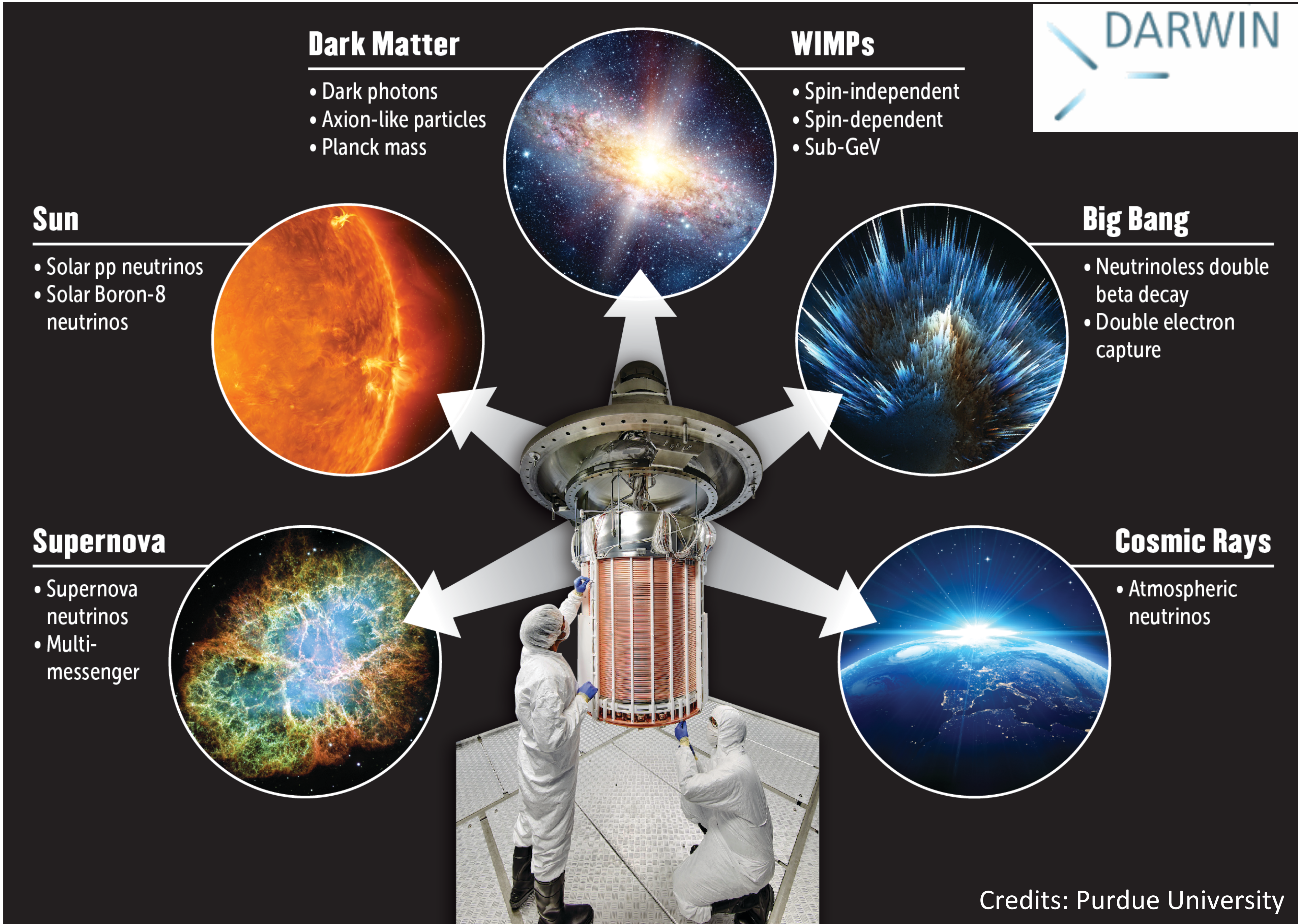
DARWIN

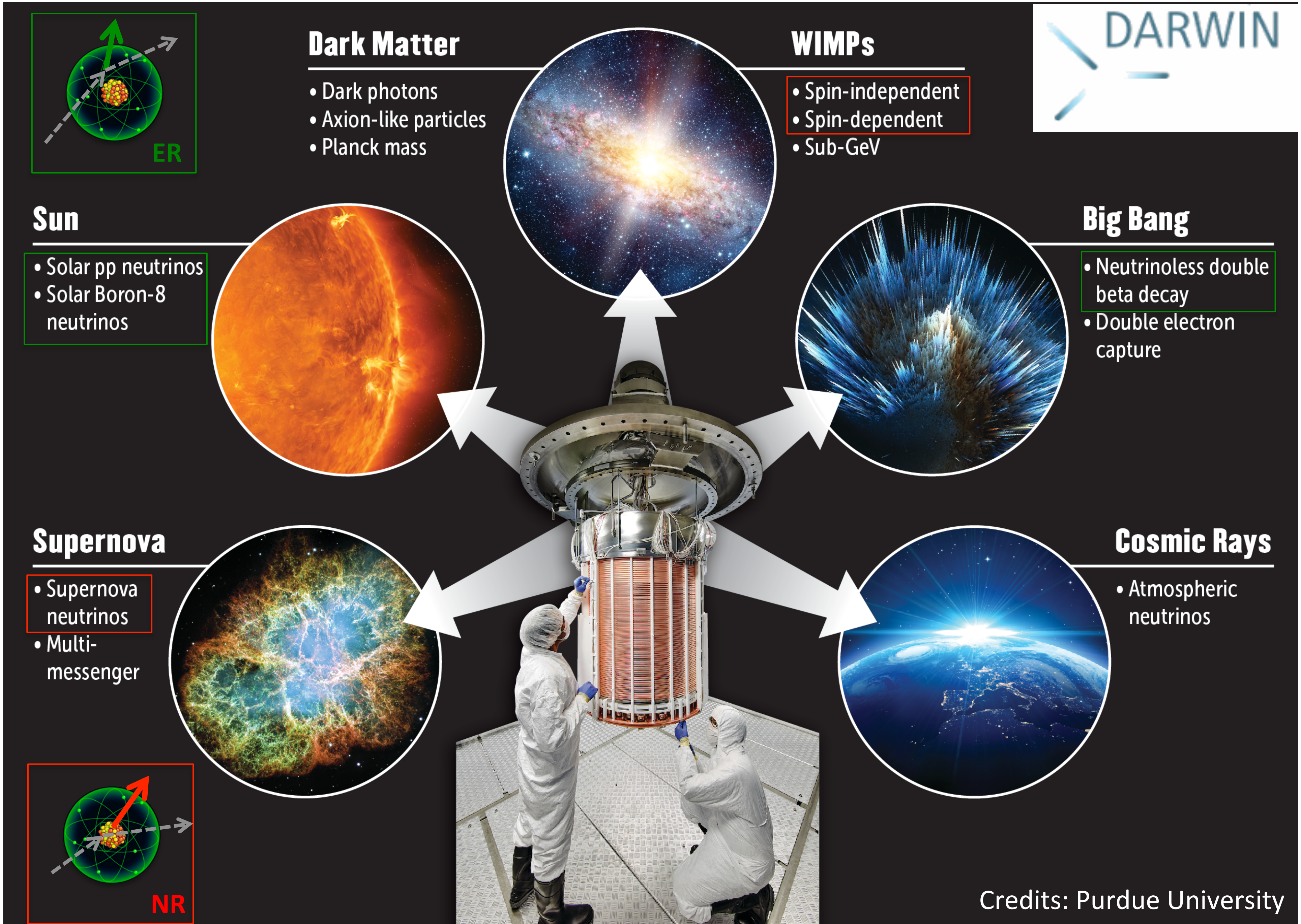


As detector size increases physics channels open up

Some backgrounds to Dark Matter search become interesting Signals in its own

DARWIN : more than a Dark Matter Experiment


DARWIN
Dark Matter
• Dark photons
• Axion-like particles
• Planck mass
WIMPs
• Spin-independent
• Spin-dependent
• Sub-GeV
Sun
• Solar pp neutrinos
• Solar Boron-8 neutrinos
Big Bang
• Neutrinoless double beta decay
• Double electron capture
Supernova
• Supernova neutrinos
• Multi-messenger
Cosmic Rays
• Atmospheric neutrinos
Credits: Purdue University


DARWIN
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• Double electron capture
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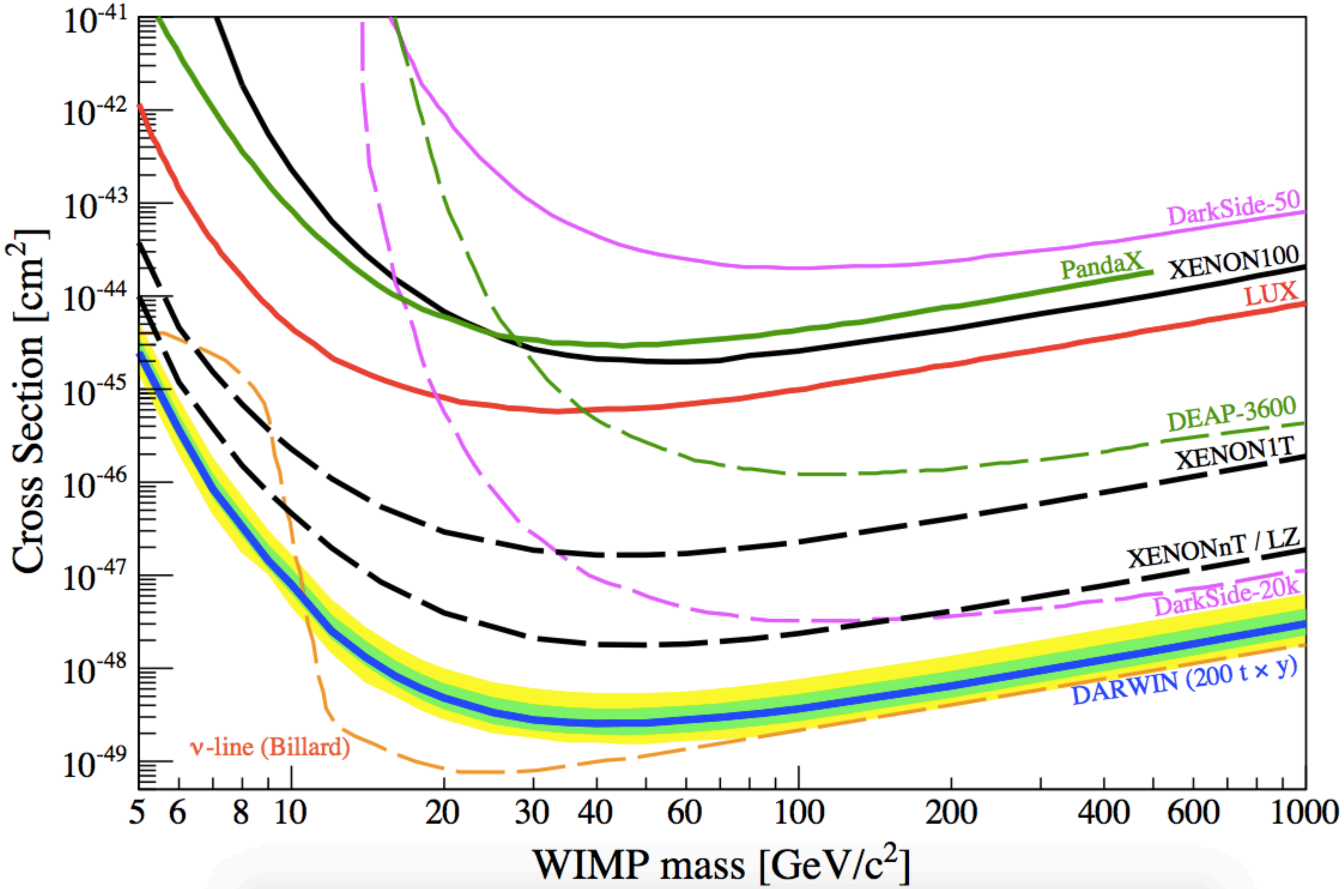
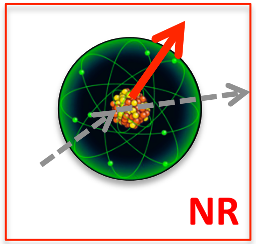
• Supernova neutrinos
• Multi-messenger
Cosmic Rays
• Atmospheric neutrinos
NR
Credits: Purdue University

SPIN INDEPENDENT WIMP SENSITIVITY

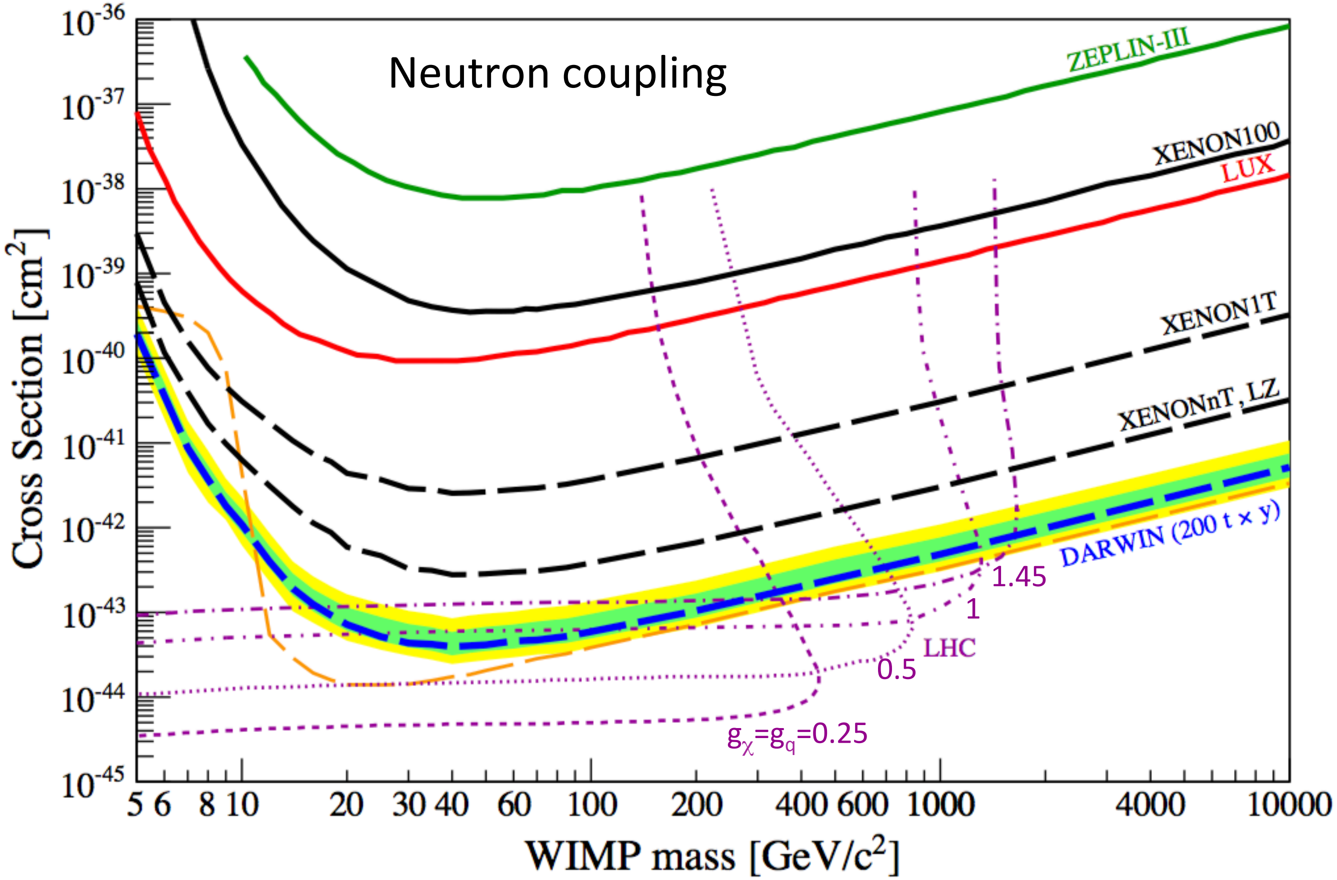
JCAP11 (2016) 017



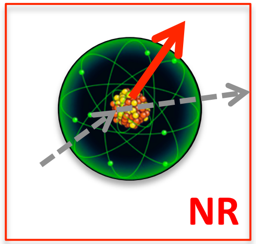


- 30 t fiducial volume
- 99.98% ER rejection @ 30% NR acceptance
- Light yield 8 PE/keV @ 122 keV

SPIN DEPENDENT WIMP SENSITIVITY



JCAP11 (2016) 017



- 30 t fiducial volume
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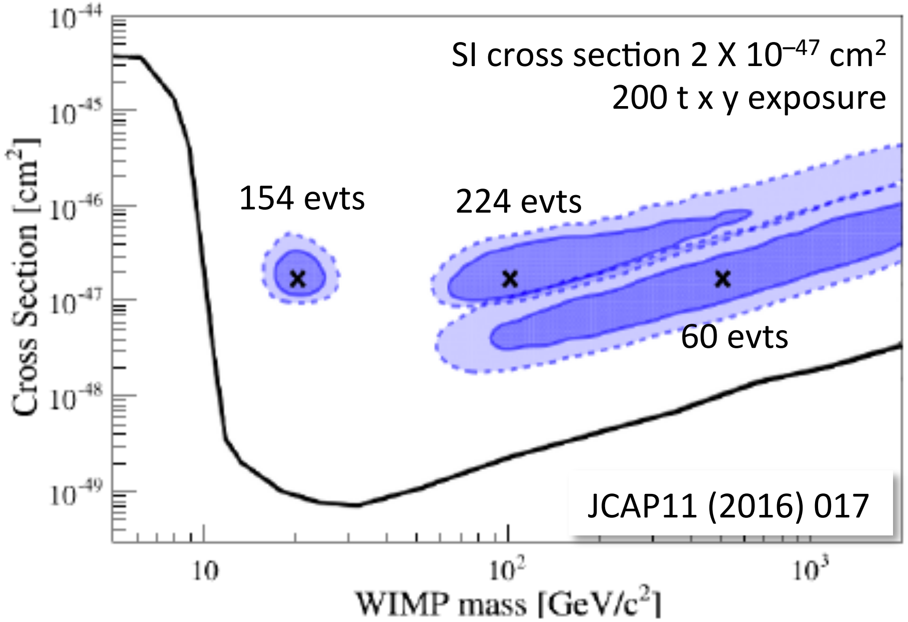
Complementarity with the LHC @14 TeV

WIMP SPECTROSCOPY

Reconstruction of WIMP properties:
mass and scattering cross-section



- m_χ = 20, 100, 500 GeV/c^2
- $1\sigma/2\sigma$ CI, marginalized over astrophysical parameters
- due to flat WIMP spectra, no target can reconstruct masses > 500 GeV/c^2

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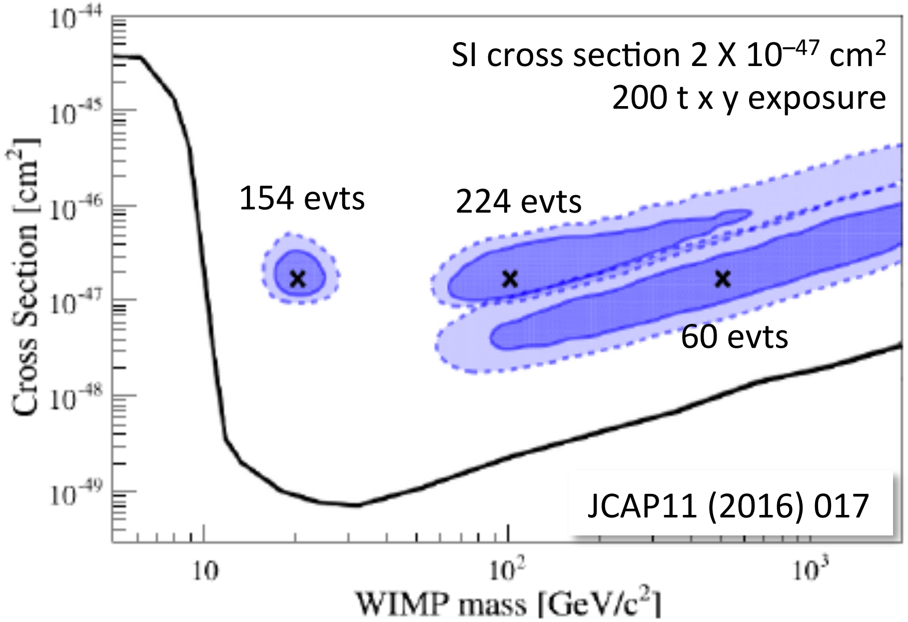
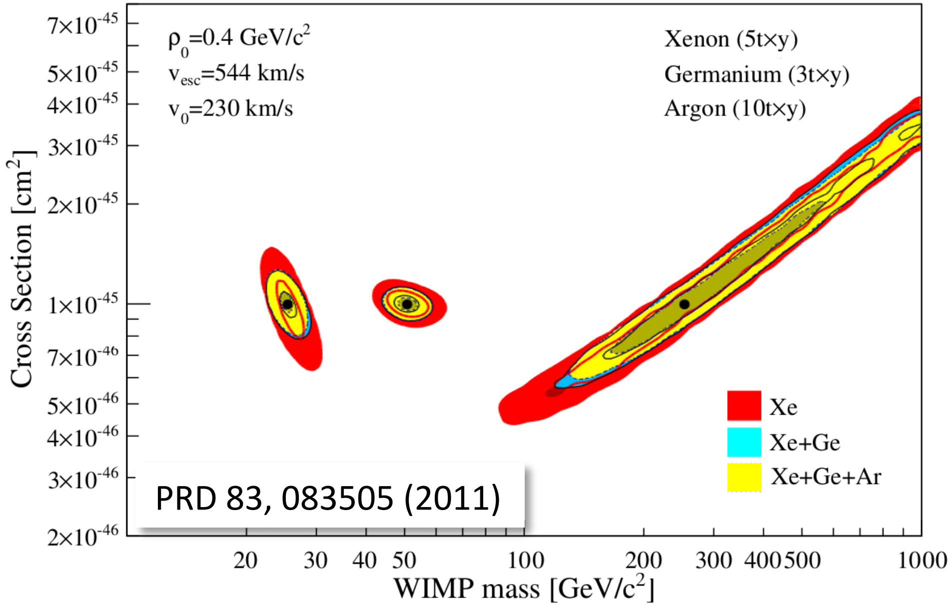


Target Complementarity



- m_χ = 20, 100, 500 GeV/c^2
- $1\sigma/2\sigma$ CI, marginalized over astrophysical parameters
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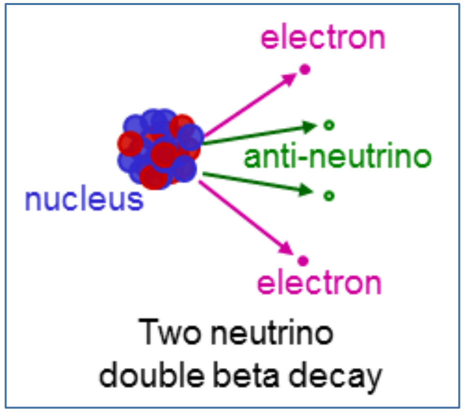
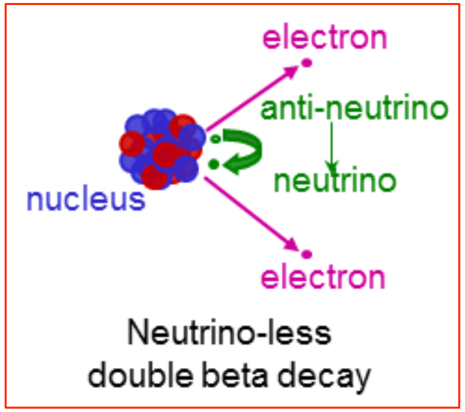
- Reconstruction improves considerably by adding Ge data to Xe
- Only minimal improvement for Ar

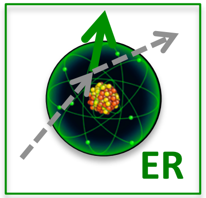
NEUTRINOLESS DOUBLE BETA DECAY

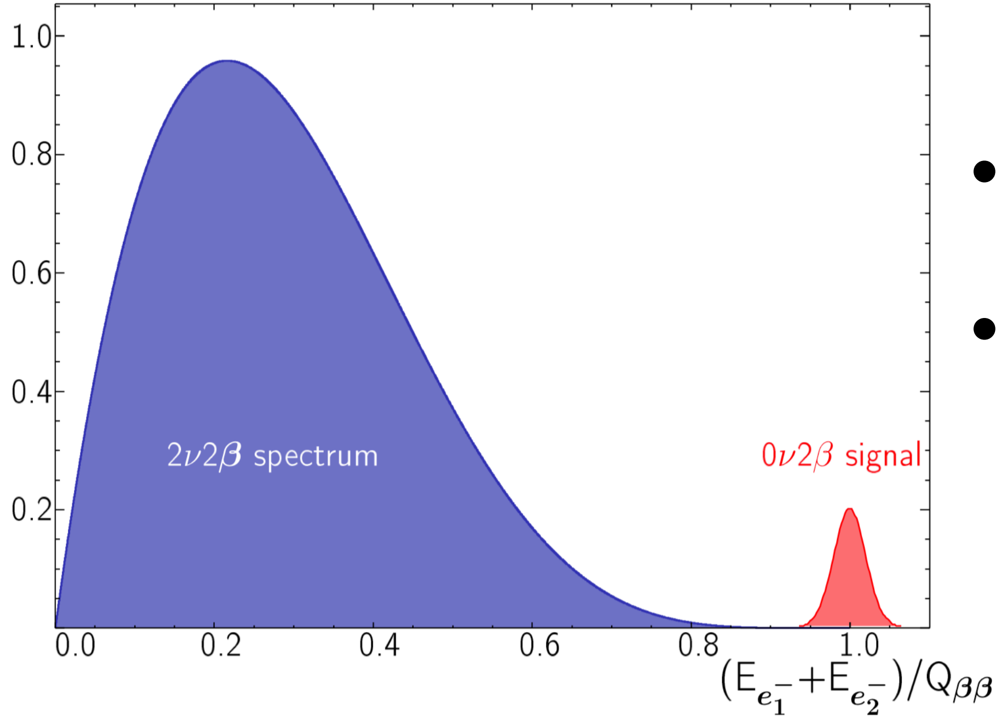




$$(A,Z) \longrightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

$$(A,Z) \longrightarrow (A,Z+2) + 2e^-$$





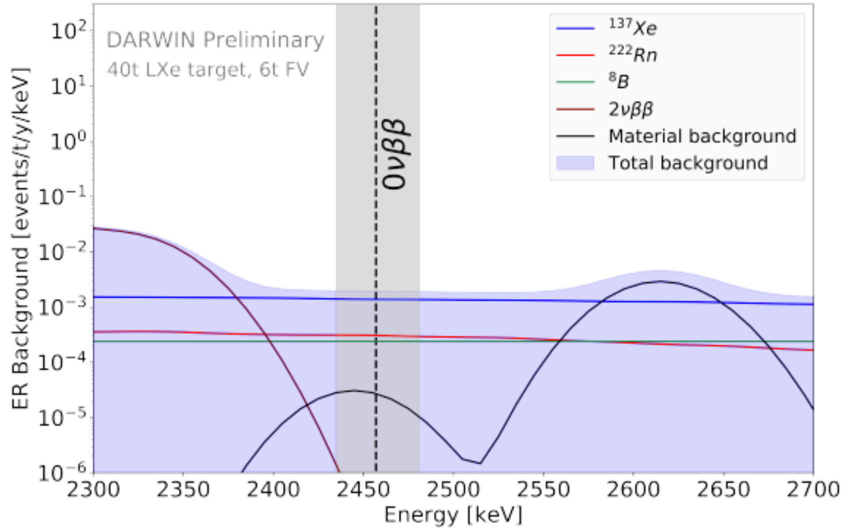
- Test the nature of neutrinos: Majorana or Dirac particles?
- General approach: detect the two final-state electrons
- Signature: two simultaneous electrons with summed energy $Q_{\beta\beta}$, the Q-value of the decay of the isotope under study

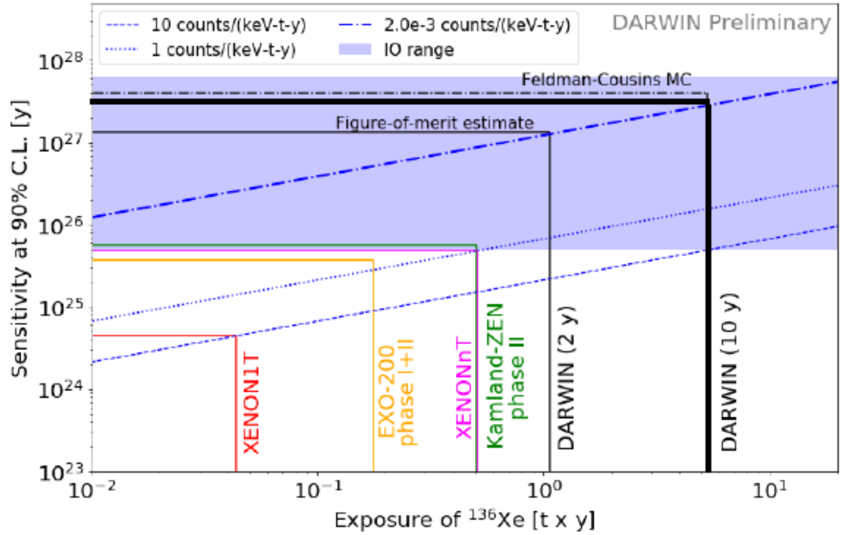
NEUTRINOLESS DOUBLE BETA DECAY

- $^{136}Xe/^{nat}Xe$ ~ 8.9%
- more than 3.5 t of active ^{136}Xe (with no enrichment)
- Q-value = 2.458 MeV
- Assumptions
  - 6 t fiducial mass
  - ^{222}Rn: 0.1 μBq/kg
  - resolution ~1% @ Q-value

- Preliminary sensitivity @ 90% CL
  - $T_{1/2} > 1.3 \times 10^{27}$ yr in 12 t y
  - $T_{1/2} > 3.0 \times 10^{27}$ yr in 60 t y

(nEXO sensitivity prediction $T_{1/2} > 10^{28}$ yr in 20 t y)

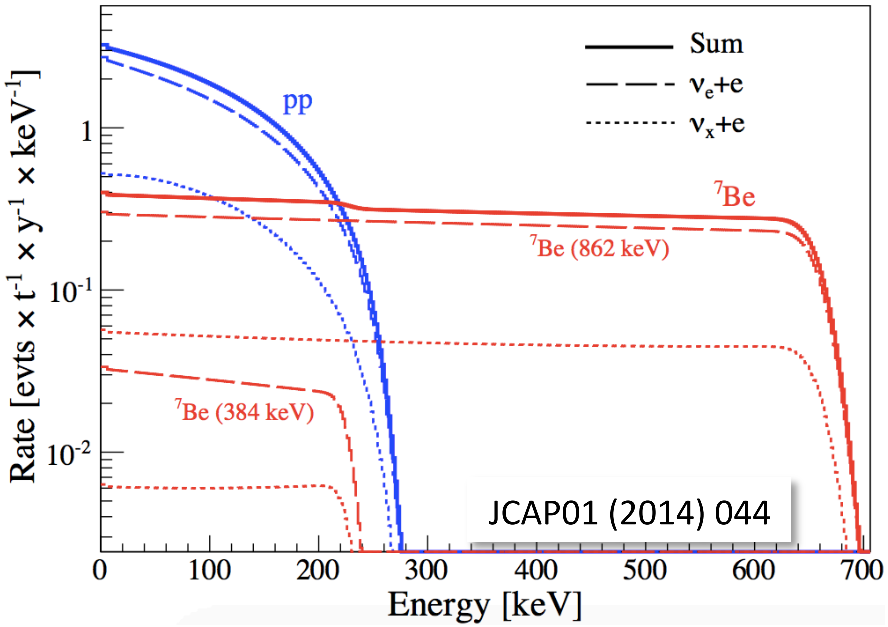


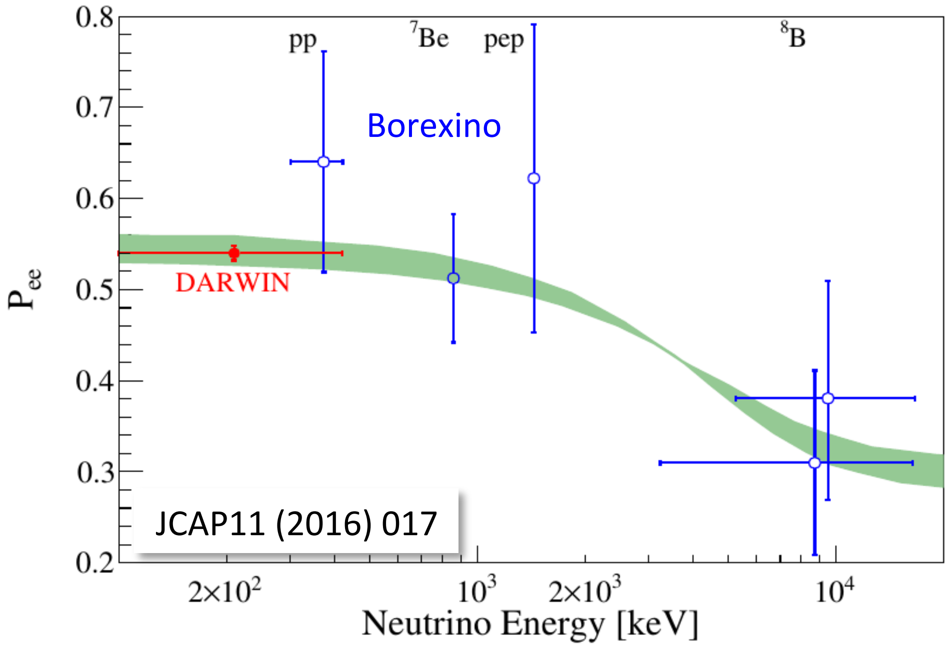


LOW-ENERGY SOLAR NEUTRINOS

Test the energy production mechanism in the Sun via $\nu_x + e \rightarrow \nu_x + e$

- Expected rate at 2-30 keV, fiducial mass 30 t:
  pp neutrinos : 7.2 events/day , ^{7}Be neutrinos : 0.9 events/day
- 2% (1%) statistical precision after 1 year (5 years) → constrain solar models
- Electron-neutrino survival probability → deviation from predictions would indicate new physics

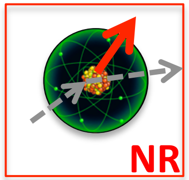




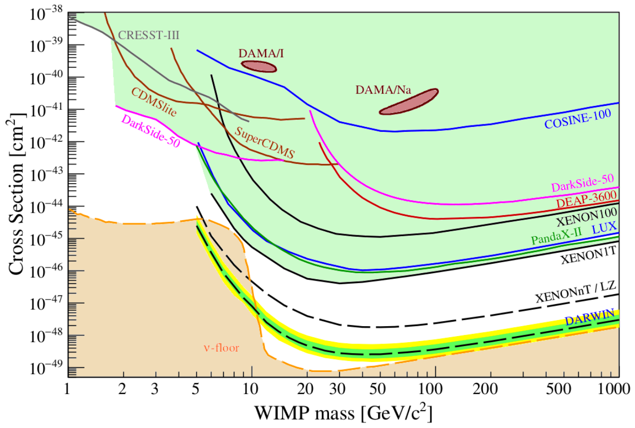
Coherent Neutrino Nucleus Scattering

DARWIN

CNNS is an irreducible bkg for WIMP searches: ν + N → ν + N



- **Impact on WIMP sensitivity**
  - ^{8}B solar neutrinos → low WIMP masses
  - atmospheric neutrinos → higher WIMP masses



Coherent Neutrino Nucleus Scattering

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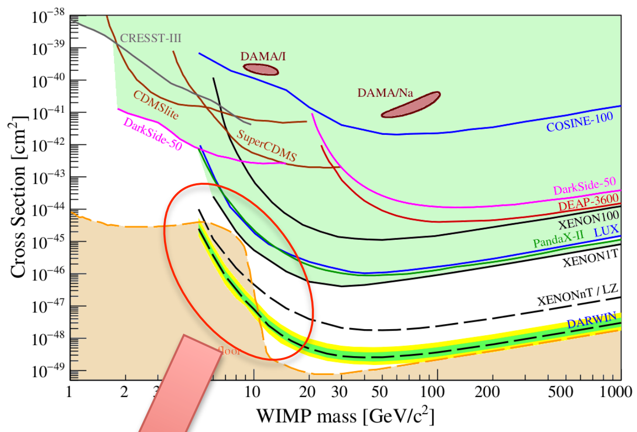
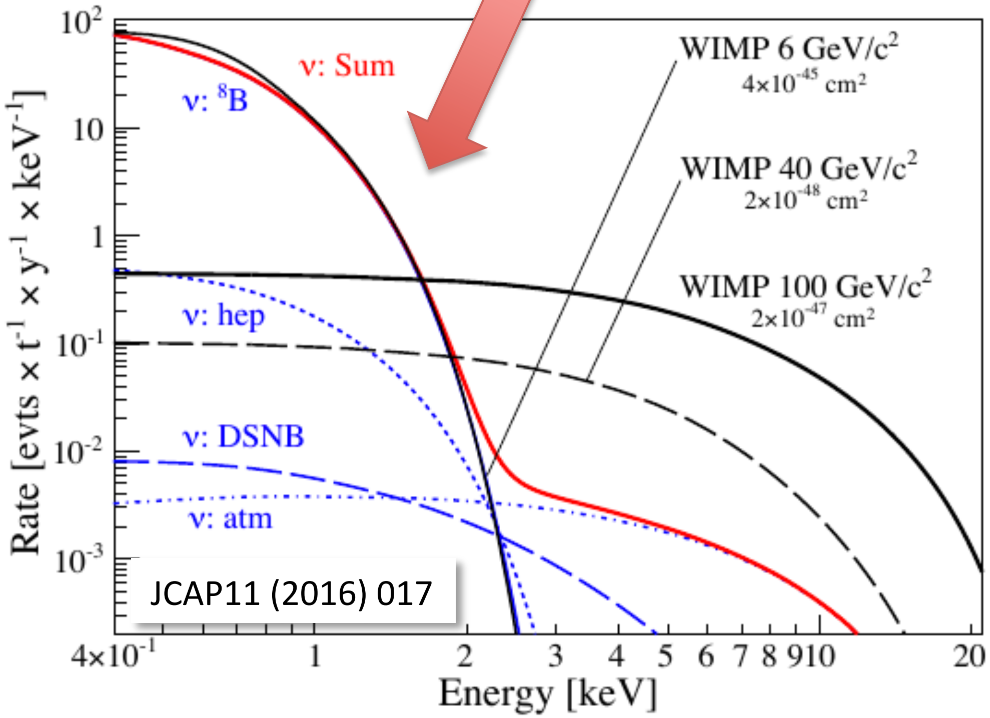
NR

- **Impact on WIMP sensitivity**
  - ^{8}B solar neutrinos → low WIMP masses
  - atmospheric neutrinos → higher WIMP masses



It is a science goal by itself

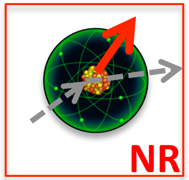
- Predicted by the SM
- ^{8}B solar neutrinos : 90 evt/t/y @ $E_{th} > 1$ keV
- atmospheric neutrinos : 3×10^{-3} evt/t/y @ $E_{th} > 4$ keV
- Deviation from predictions would indicate new physics



SUPERNOVA NEUTRINOS

DARWIN

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



- Low threshold using proportional scintillation signal (S2) only
- Negligible background due to short burst (~sec)
- 5σ significance to a supernova burst far up to ~65 kpc from Earth
- Detection of all 6 neutrino species
- ~700 events for a 27$M_{\odot}$ SN progenitor at 10 kpc

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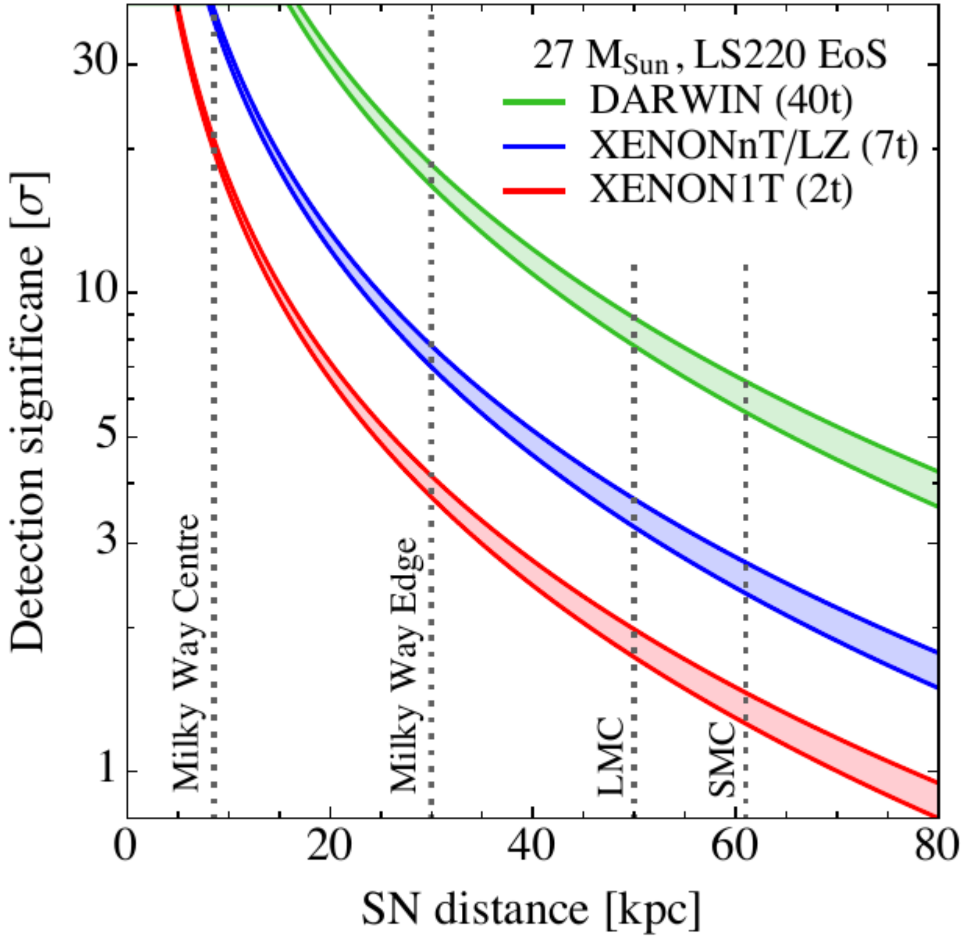
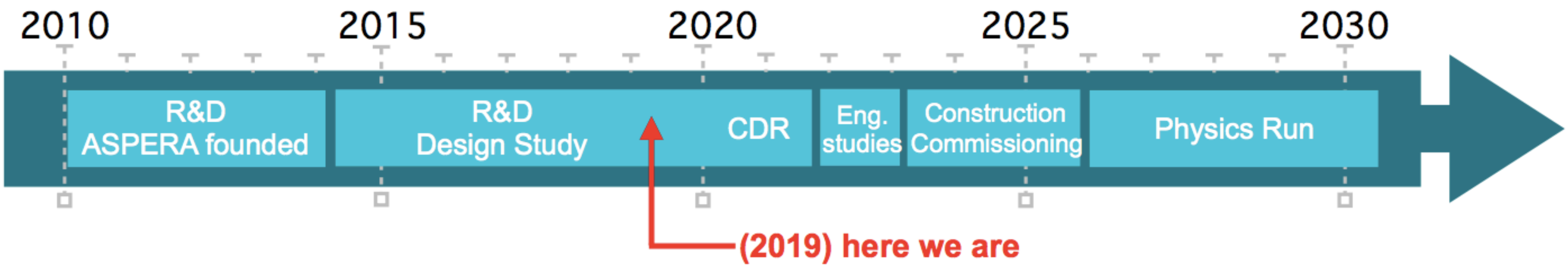
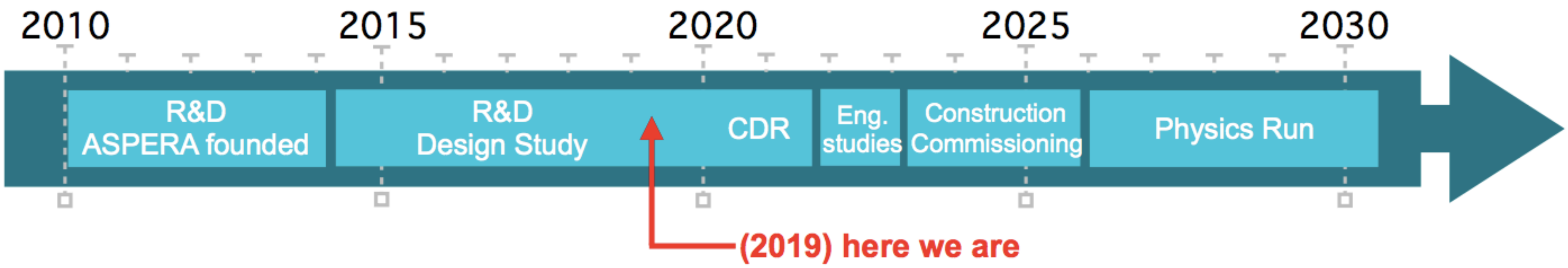


The DARWIN Collaboration & Current Status



- **29 groups from 12 countries**
- DARWIN is in the APPEC roadmap
- 2 ERCs grants for R&D:
  - Xenoscope (UZH)
  - ULTIMATE (UniFr)
- 6 Working Packages for perspective studies and R&D activities

The DARWIN Collaboration & Current Status



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- 2 ERCs grants for R&D: →
  - Xenoscope (UZH)
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- 6 Working Packages for perspective studies and R&D activities

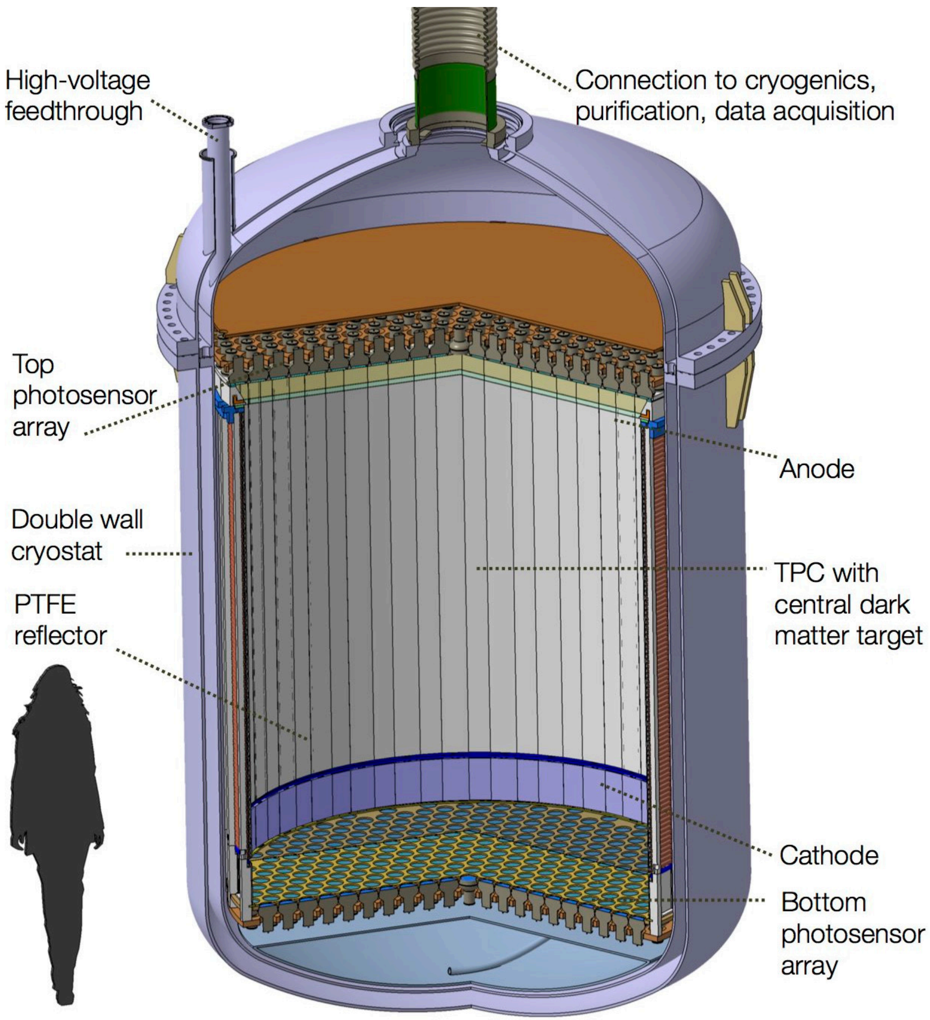
- detector design
- photosensors technologies
- large scale demonstrators
- cryogenics
- ...

DARWIN

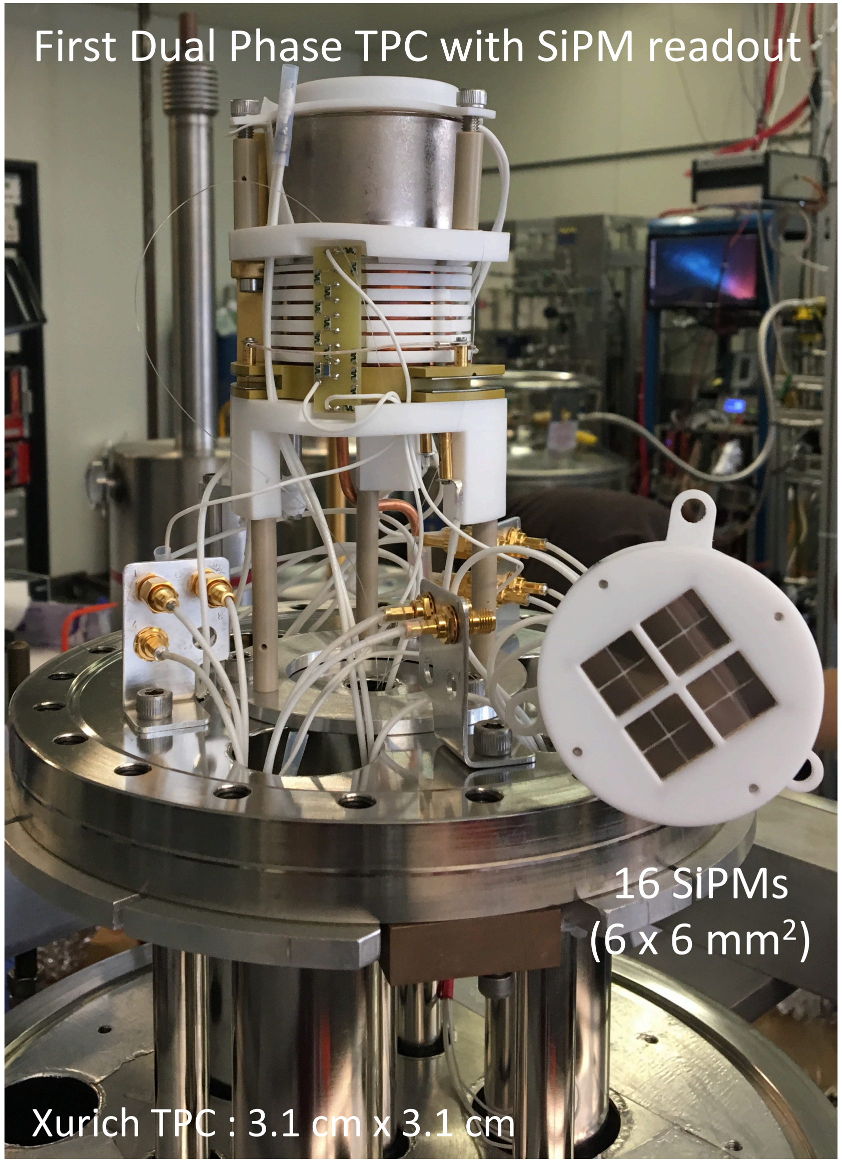
DARWIN CHALLENGES

DARWIN Collaboration, JCAP 1611 (2016) 017

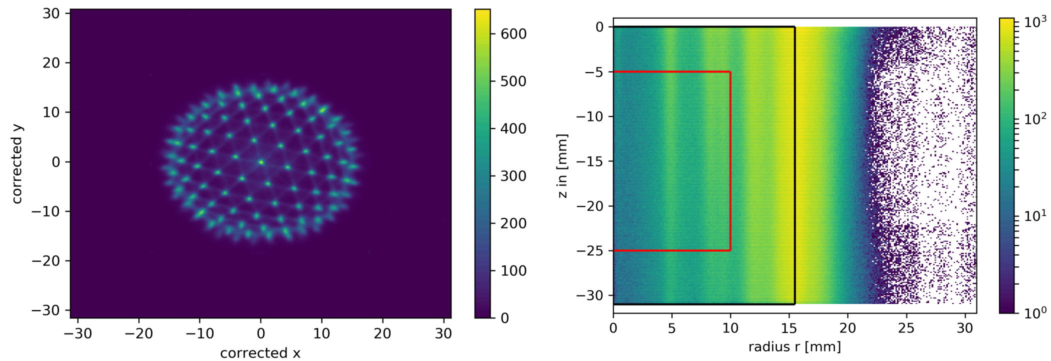
- Top & bottom arrays of photosensors
  → alternatives to traditional PMTs (improving discrimination, radiopurity, cost, compactness,...)
- 2.6 m x 2.6 m Dual Phase TPC
  →high voltage, proportional scintillation
- 50 t (40 t active) LXe target
  → improving storage, purification, cooling



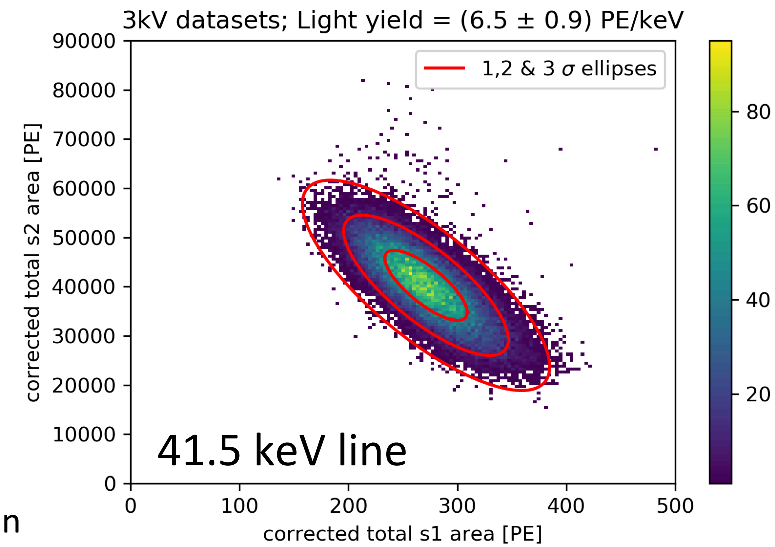
R&D ON PHOTOSENSORS



- 3D position reconstruction



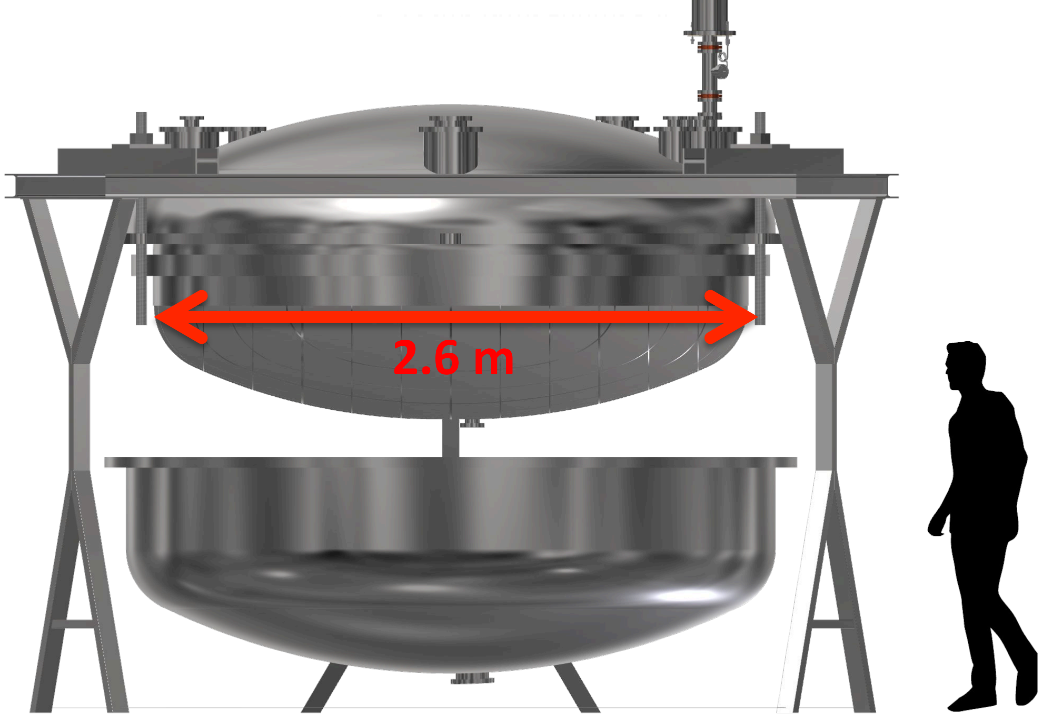
- ^{83m}Kr (done) and ^{37}Ar (ongoing) calibrations



Credits:
S. Hochrein

FULL – (X,Y) DEMONSTRATOR

DARWIN



Courtesy of F. Tönnies

The main goal is to test components at the real DARWIN diameter under realistic conditions

- (X,Y) scale TPC
  - **diameter 2.6 m**
  - height ~0.5 m
  - filled with ~400 kg of LXe
- Tests of
  - electrodes flatness
  - strength of the extraction field
  - (x,y) homogeneity of the extraction field

FULL - LENGTH DEMONSTRATOR

The main goal is the demonstration of the electron drift over the full height of DARWIN

→ z position reconstruction

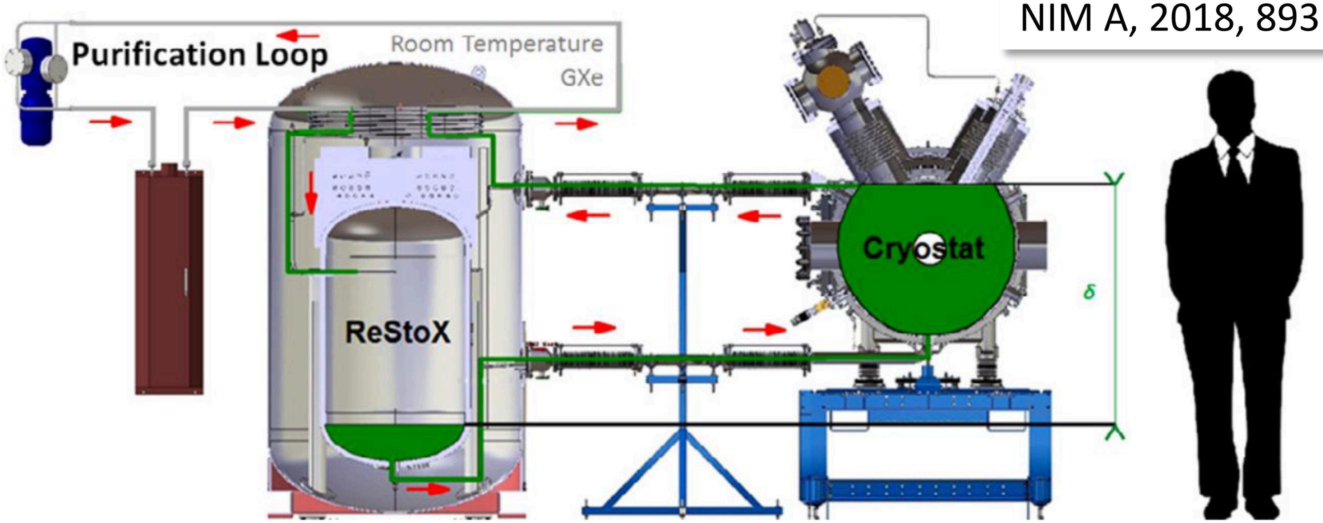
- Full vertical scale TPC
  - **height 2.6 m**
  - diameter ~20 cm
  - filled with ~300 kg of LXe
- Goal for electric field: 200 V/cm
- Required e-lifetime > 2 ms

XE RECOVERY AND STORAGE SYSTEM (RESTOX)

DARWIN

New Challenge for a 50 tons detector

- Just increasing the storage size is not reasonable → towards a modular approach
- Evaluating and testing the new concept of the LXe fast recovery by gravity



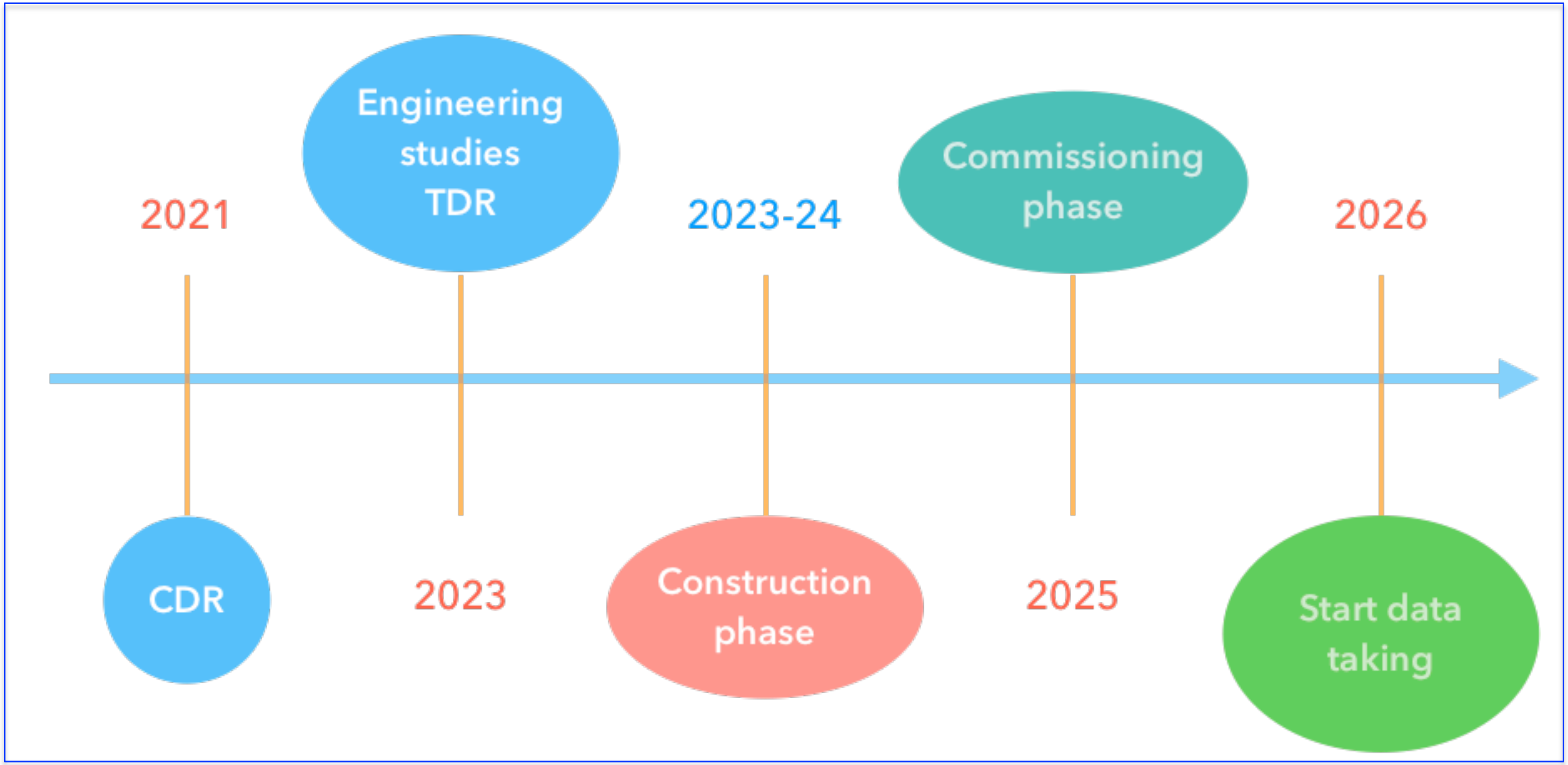
NIM A, 2018, 893

SUMMARY

- DARWIN will be the **ultimate low-background astroparticle physics observatory**
- DARWIN will probe a variety of physics channels
  - Dark Matter
  - Neutrinoless double beta decay
  - Low energy solar neutrinos
  - Coherent neutrino nucleus scattering
  - ...
- DARWIN is a challenging detector→ R&D on different aspects are ongoing
- DARWIN is growing: currently 29 groups from 12 countries

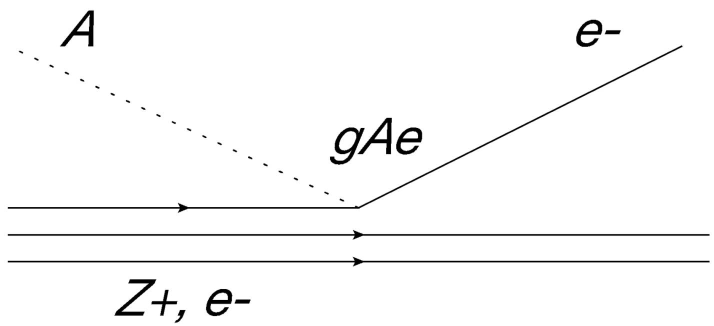
Summary

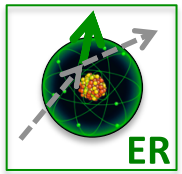
- DARWIN will be the **ultimate low-background astroparticle physics observatory**

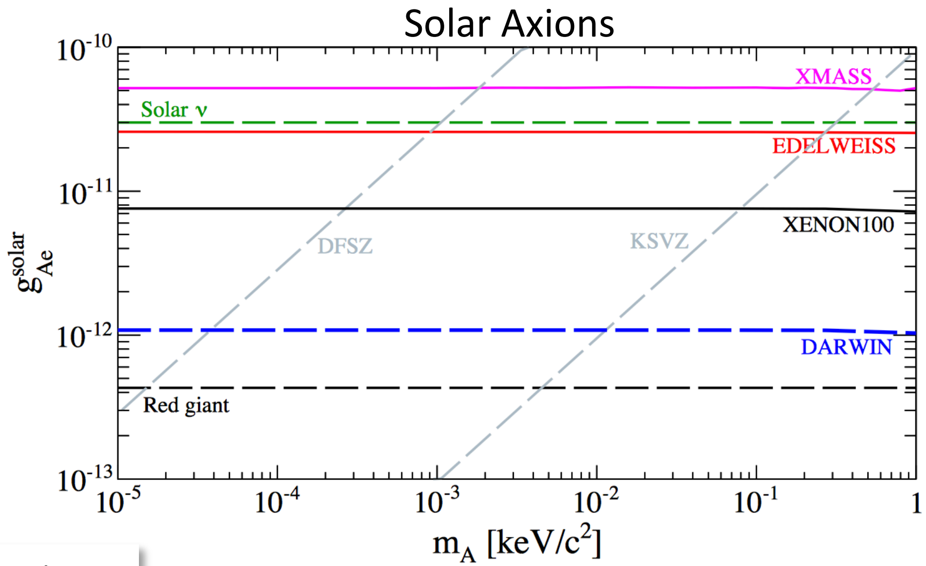


Backup

Solar Axions and Axion-Like Particles

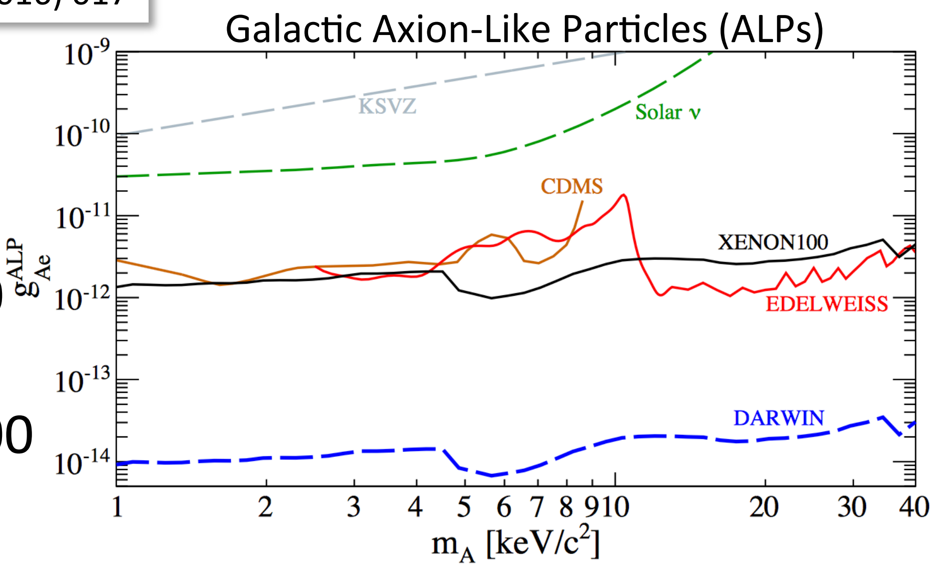






- Measurement via axio-electric effect
- Expect mono-energetic peak at the particle mass

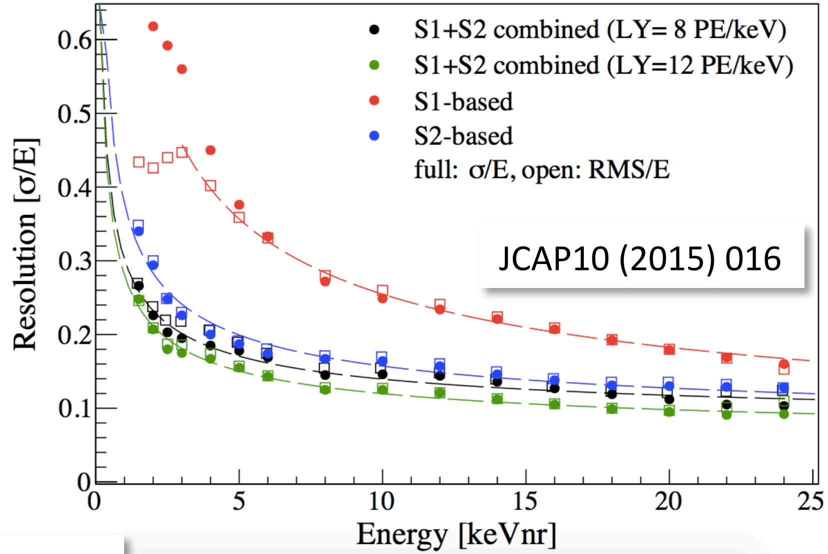
JCAP11 (2016) 017



- Dominant backgrounds:
  - solar neutrinos
  - 2νββ of ^{136}Xe
- Sensitivity to Solar Axions
  - → x10 improvement wrt XENON100
- Sensitivity to ALPs
  - → x100 improvement wrt XENON100
- Sensitivity scales poorly with exposure

DIRECT WIMP SENSITIVITY

- 200 t × y exposure
- 30 t fiducial volume
- all backgrounds included
- 99.98% ER rejection @ 30% NR acceptance
- Combined (S1+S2) energy scale
- Light yield 8PE/keV @ 122 keV



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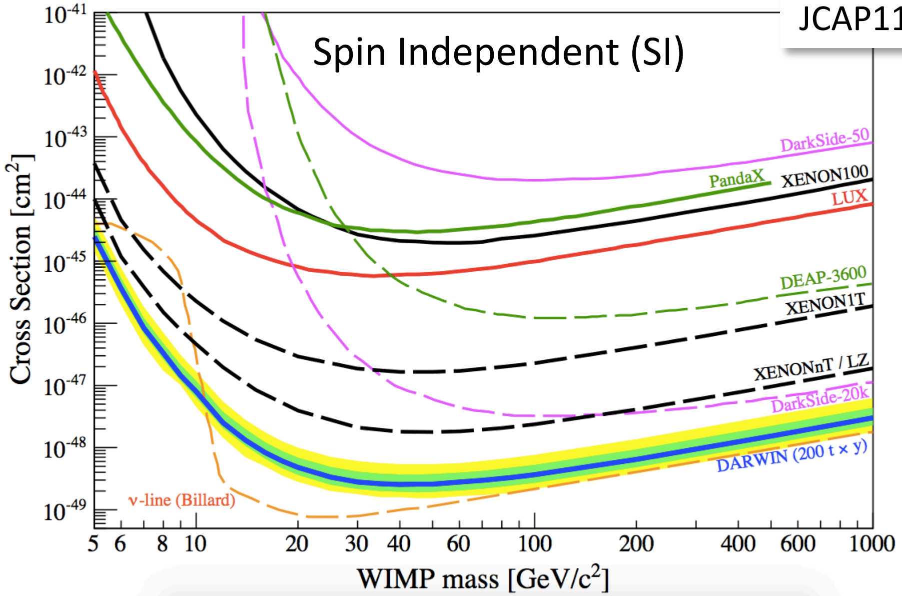
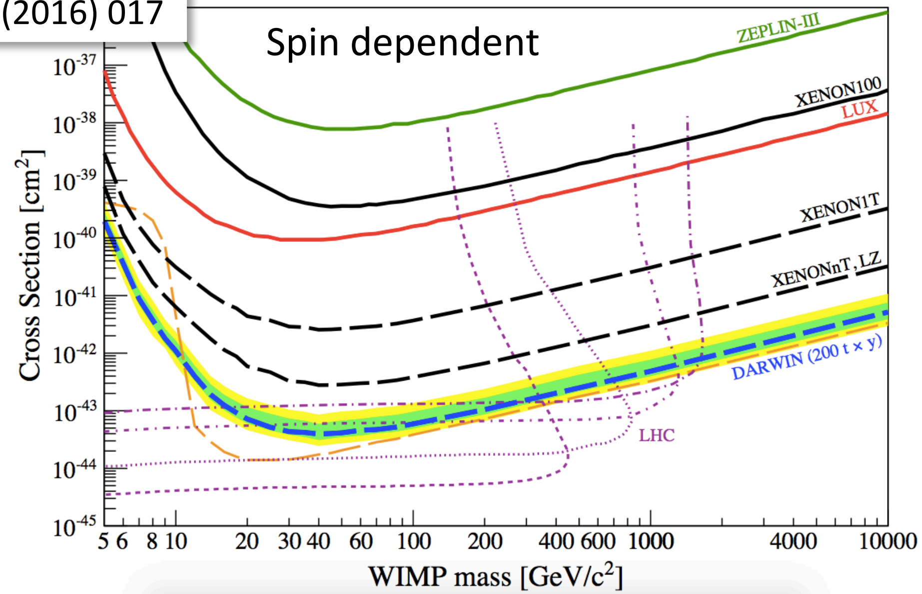
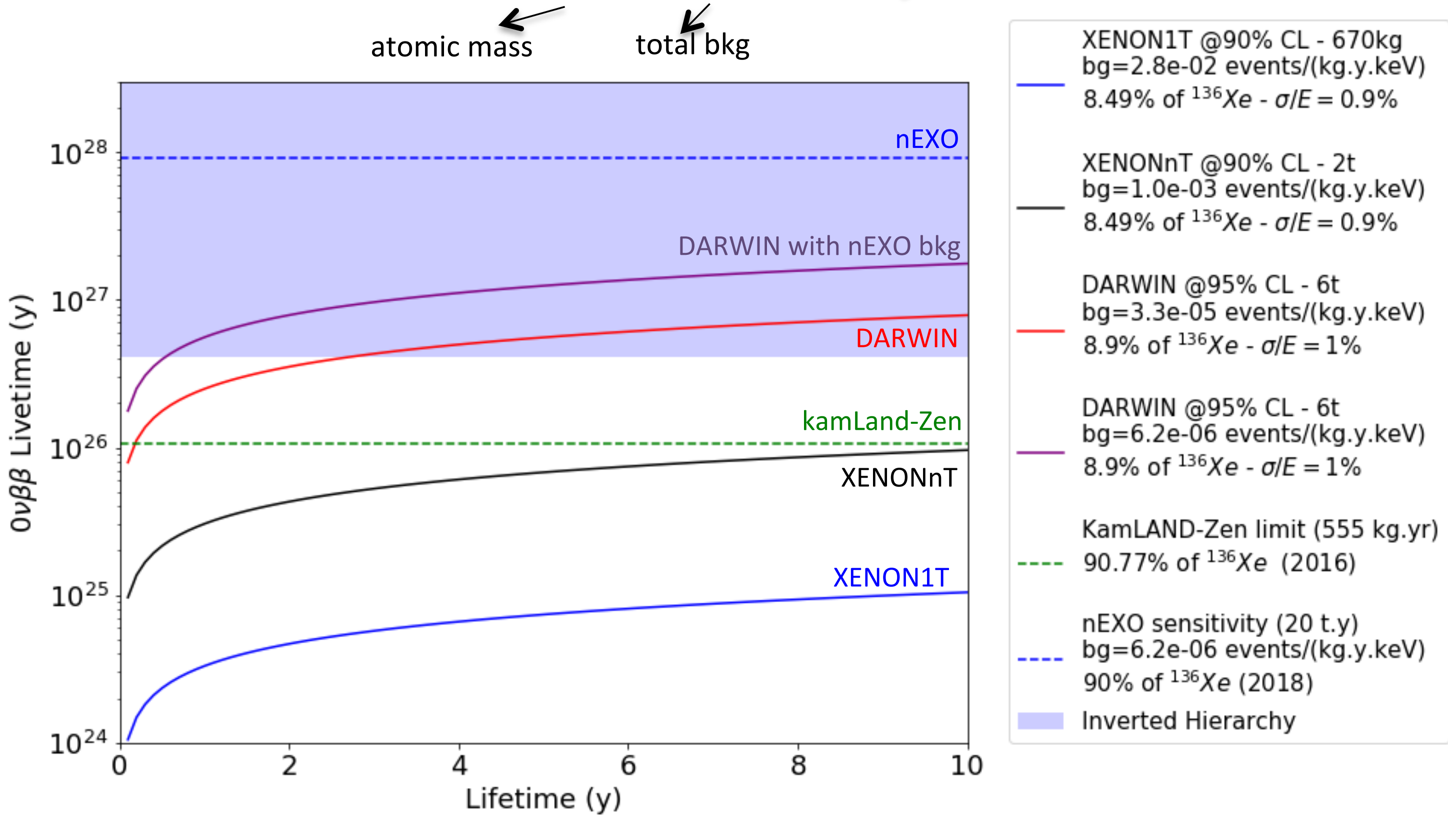




Sensitivity to 0ν2β

$$S(T^{0\nu}_{\frac{1}{2}}) \propto \frac{\epsilon\ a}{A}\sqrt{\frac{m\ t}{b\ \Delta E}}$$

- ϵ: efficiency 90%
- a: isotopic abundance
- A: atomic mass
- m: fiducial mass
- t: lifetime
- b: total bkg
- ΔE: Energy resolution at Q value: 1%



Is it possible **to increase the sensitivity of the Neutrinoless double decay search** without affecting (too much) the WIMPs search?

Sensitivity study

$$S^{0\nu} = \frac{ln(2) \times N_a \times \epsilon \times enr}{\sigma_{CL} \times M_{molar}} \sqrt{\frac{exposure}{bkg_{index} \times \Delta E}}$$

Physical constant:

- N_a the Avogadro number (/mol)
- σ_{CL} factor to take into account the Confidence Level. 1.64 at 90% C.L

Isotope properties:

- M_{molar} the molar mass of ^{136}Xe
- enr is the 136Xe abundance (Natural: 8.9%)

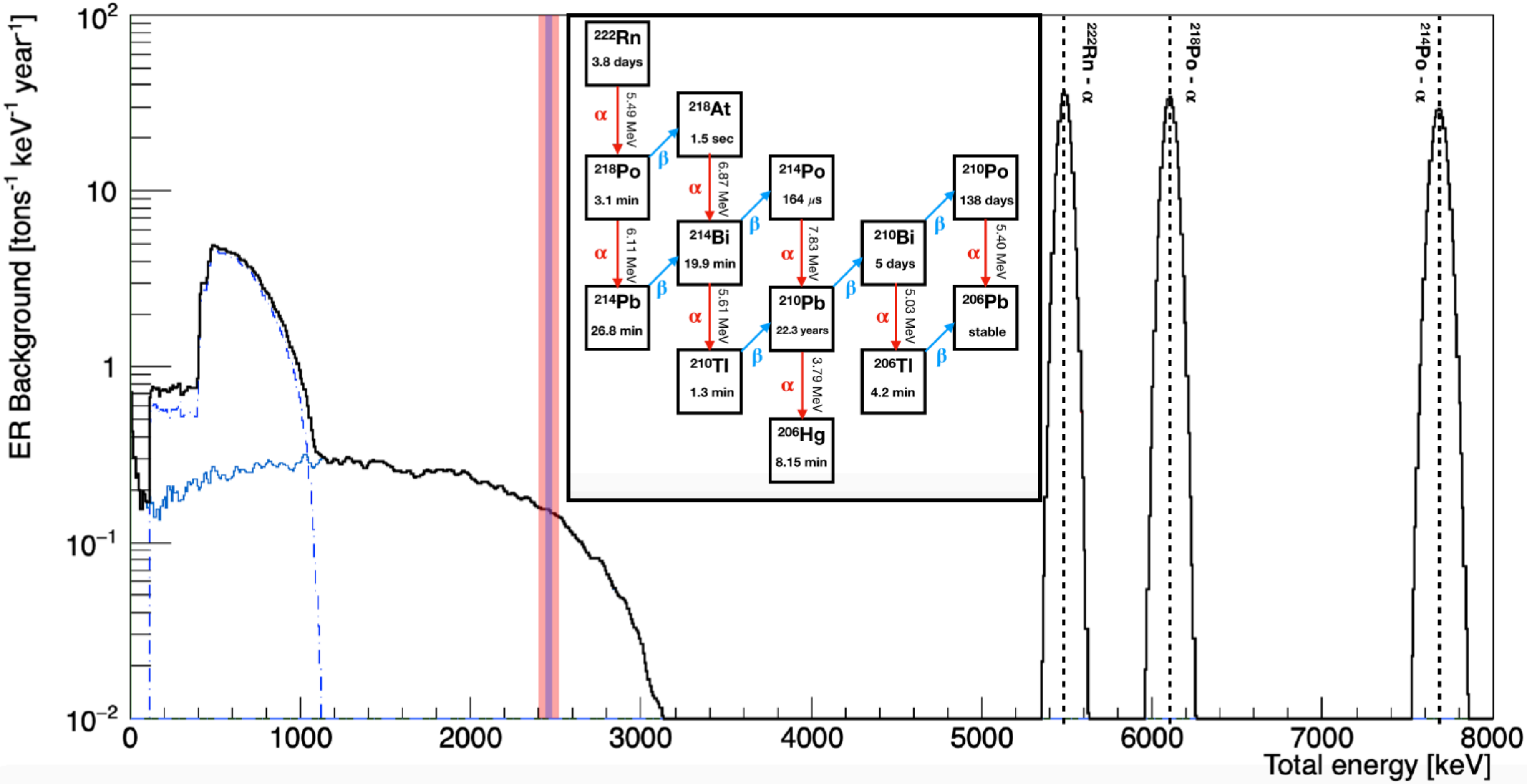
Detector characteristics:

- ε = 0.8 is the detection efficiency
- exposure = 30 t.y is the running time of the experiment times the target mass
- ΔE is the FWHM energy resolution at the Q-value (2457 keV)

Backgrounds estimations:

- bkg_{index} is the number of background events per unit of time, mass and energy in the ROI

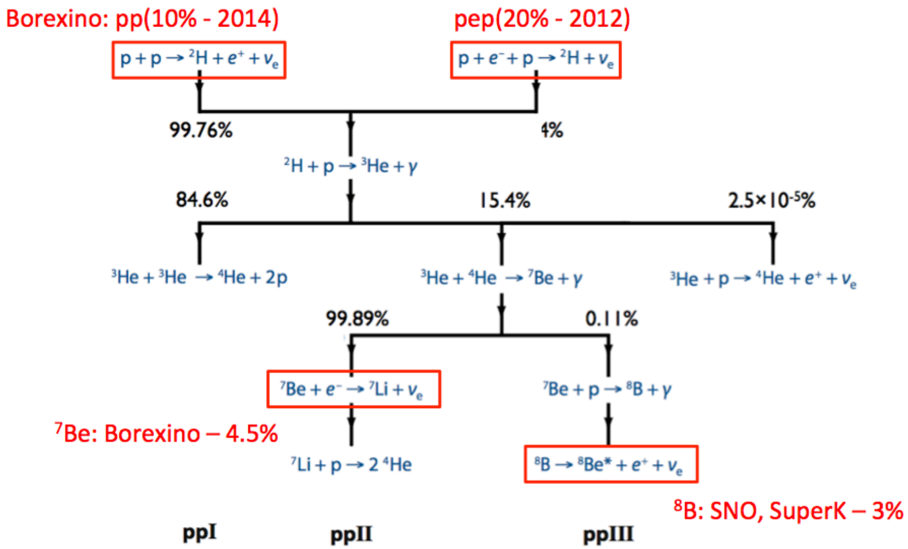
^{222}Rn

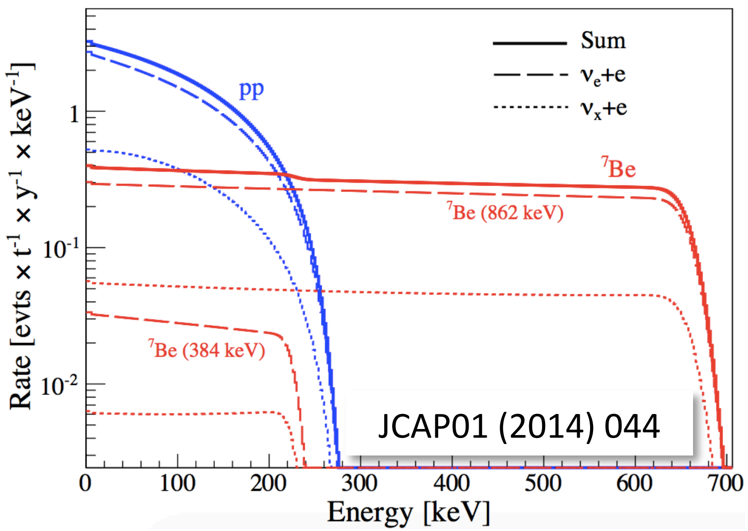


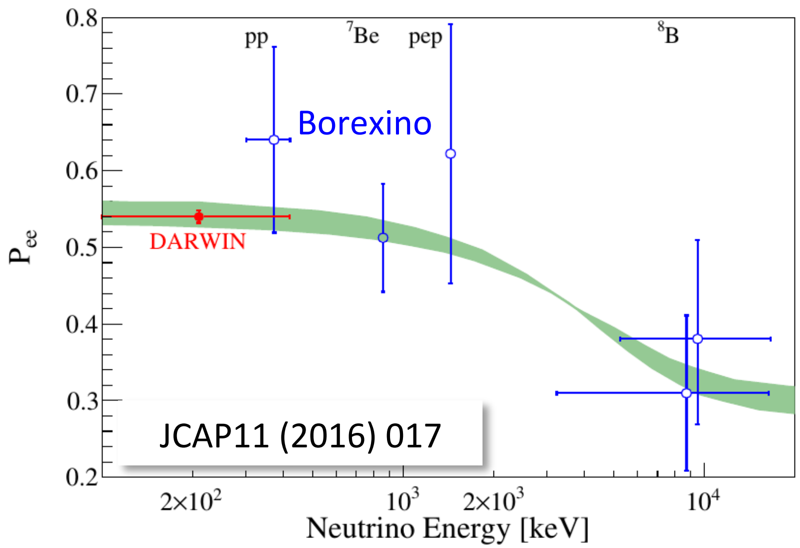
- **Main contributor in the $0\nu\beta\beta$ ROI -> ^{214}Bi**
- **Applying a BiPo tagging will reduce the ^{214}Bi & ^{214}Po contamination -> 99.8%**

Low-Energy Solar Neutrinos

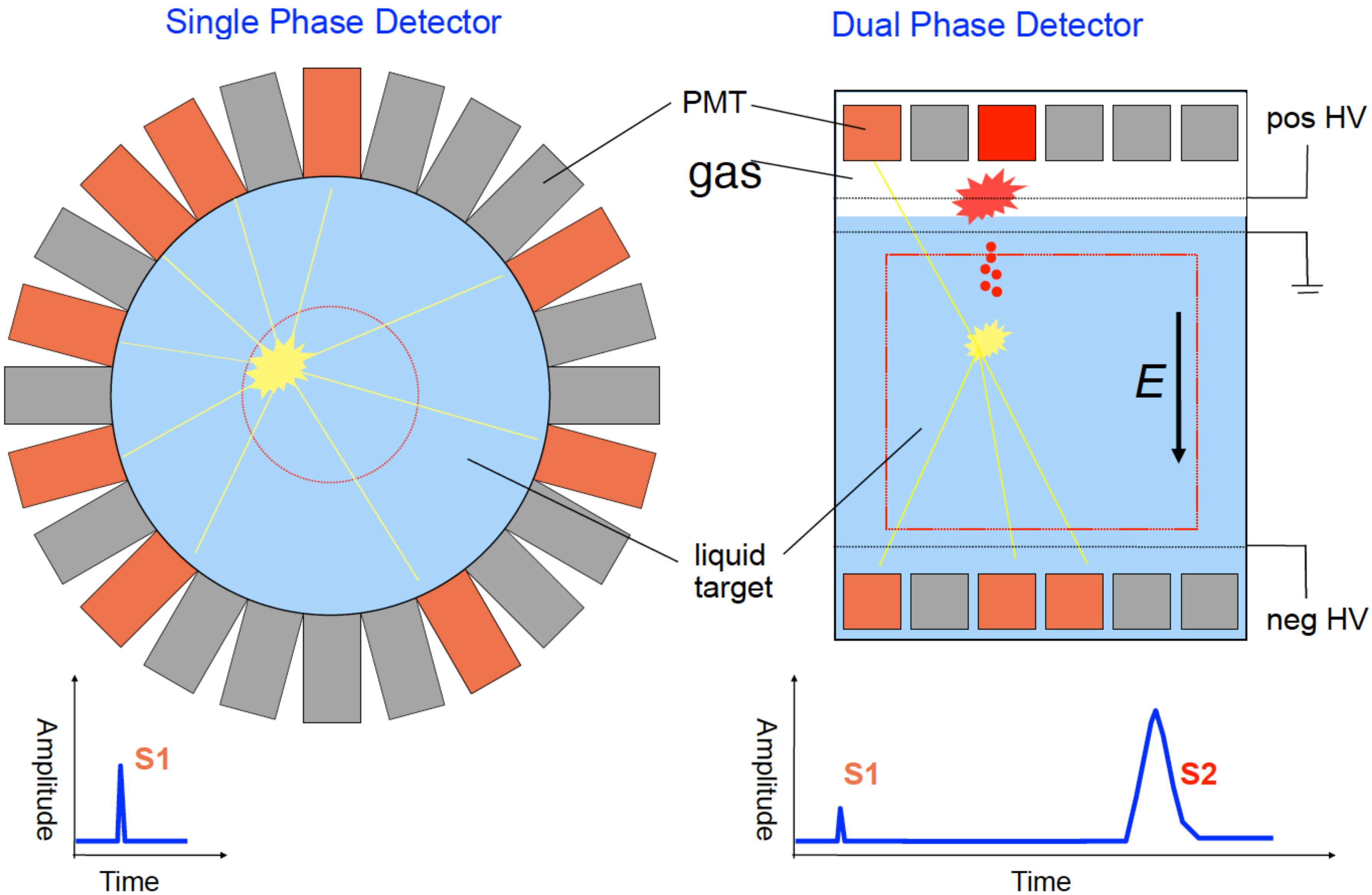
- Expected rate at 2-30 keV, fiducial mass 30 t:
  pp neutrinos : 7.2 events/day , ^{7}Be neutrinos : 0.9 events/day
- 2% (1%) statistical precision after 1 year (5 years) → constrain solar models
- Electron-neutrino survival probability → deviation from predictions would indicate new physics



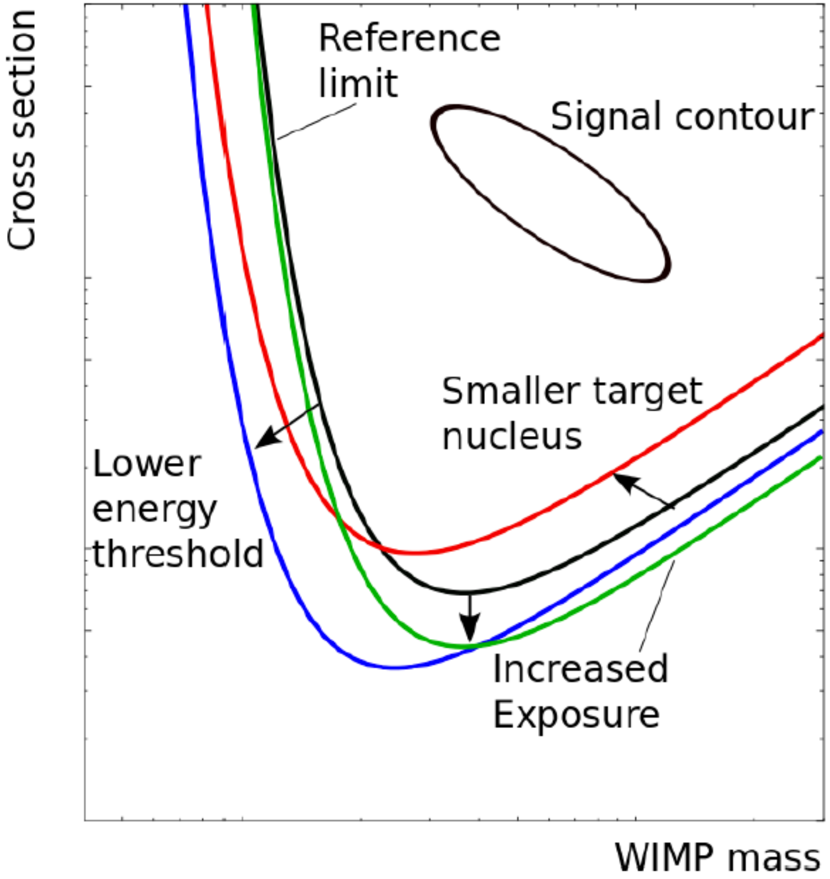


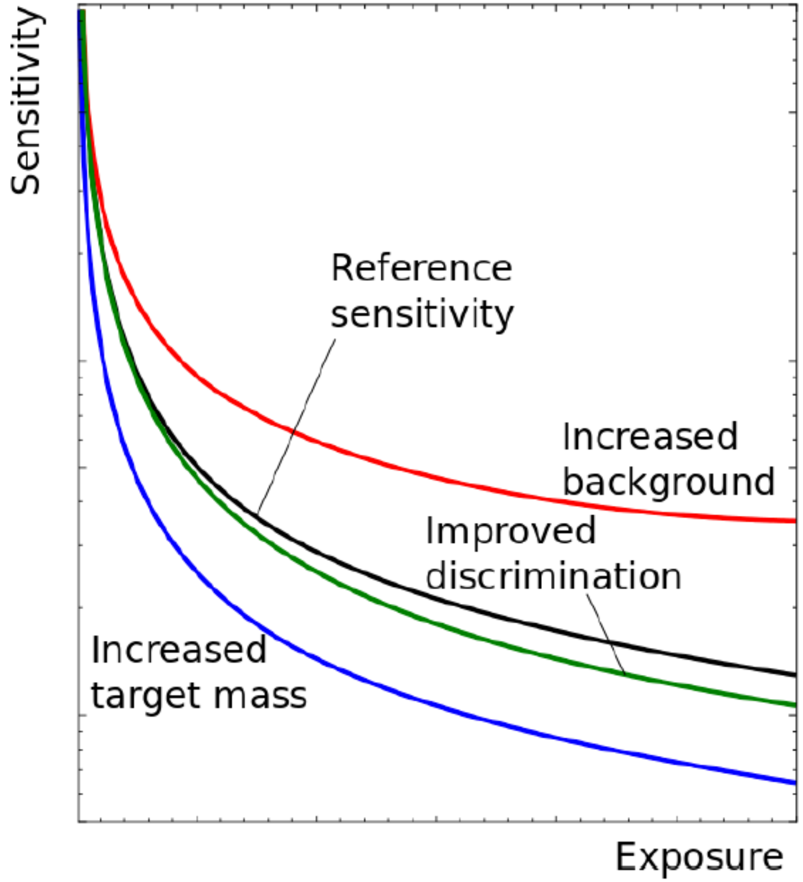


Noble Liquids detectors concepts

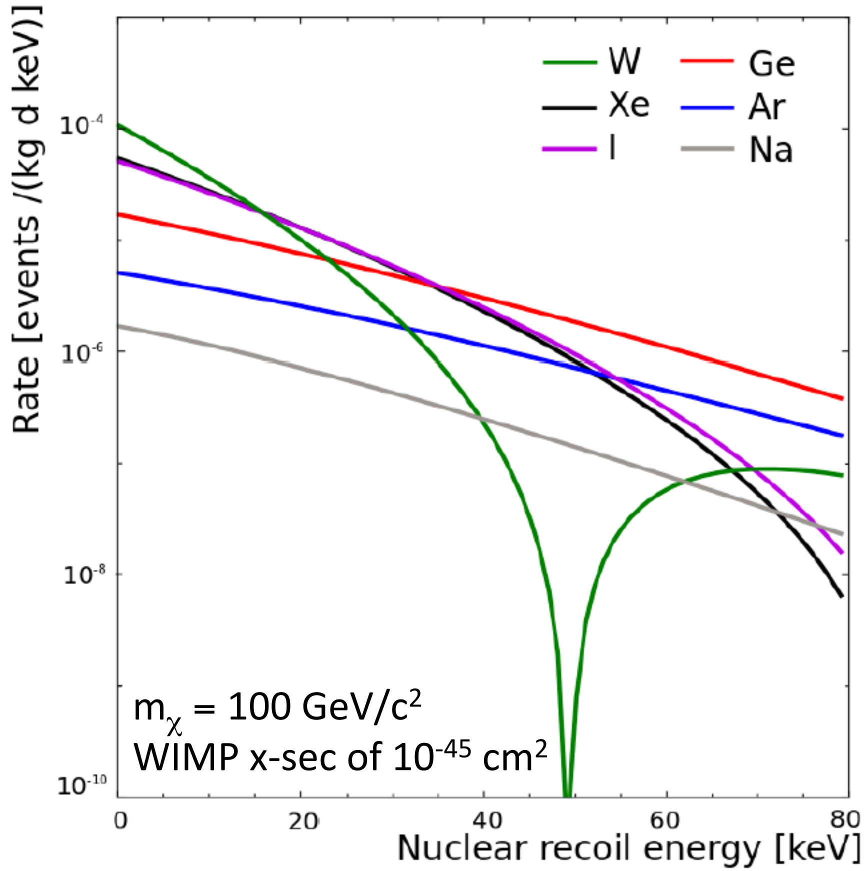


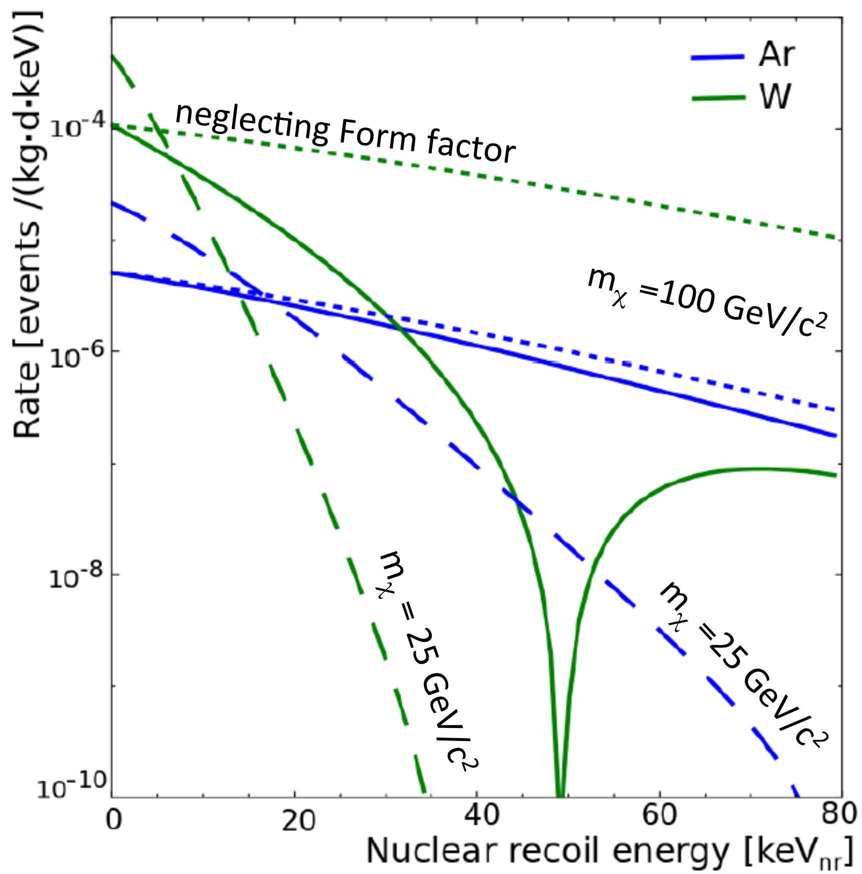
WIMP SENSITIVITY





RATE & FORM FACTORS

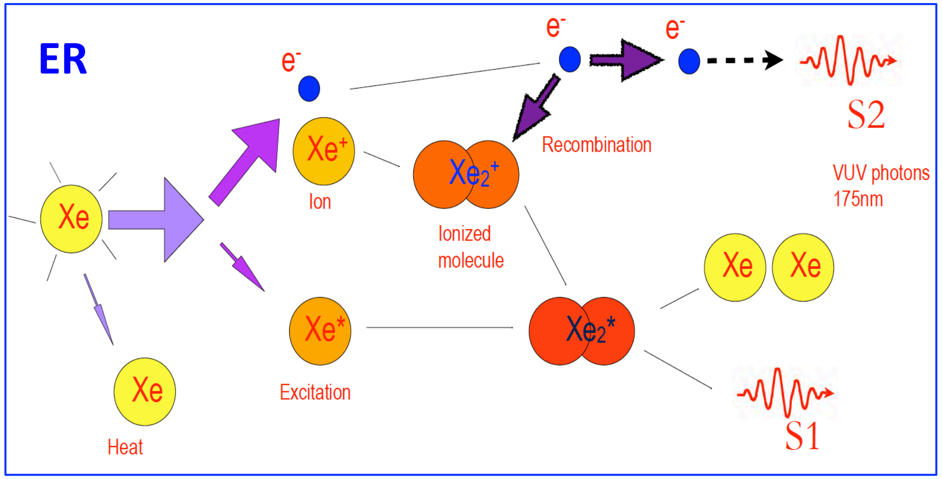


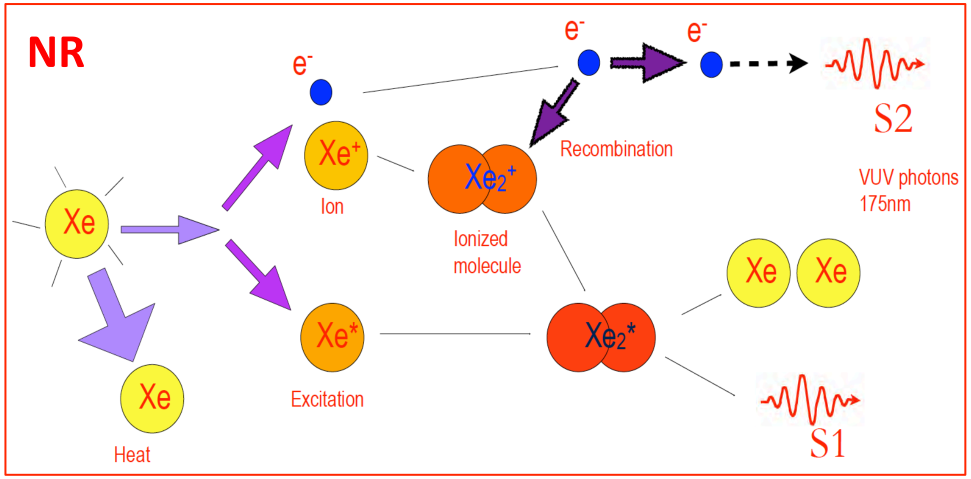


For lighter targets a low energy threshold is of less relevance than for the heavier ones

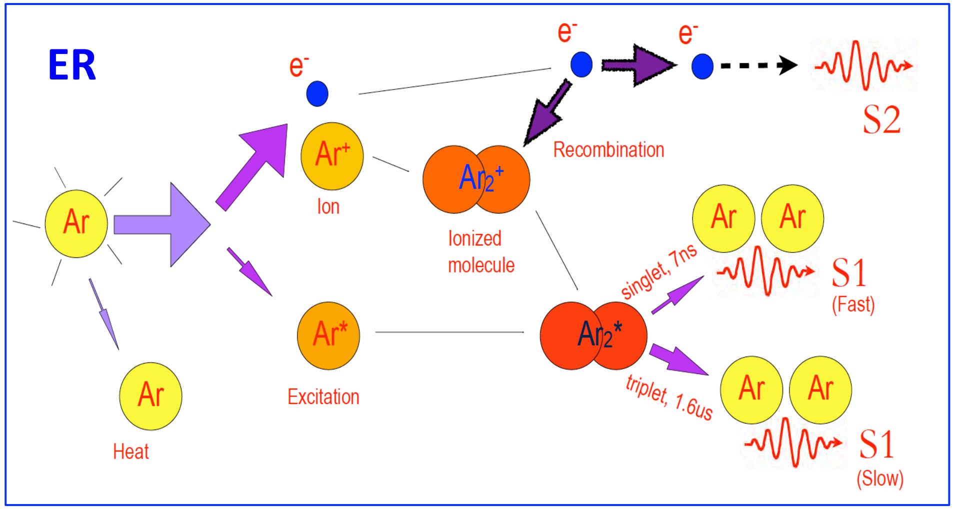
The form factor correction for a heavy target is more important than for light targets.

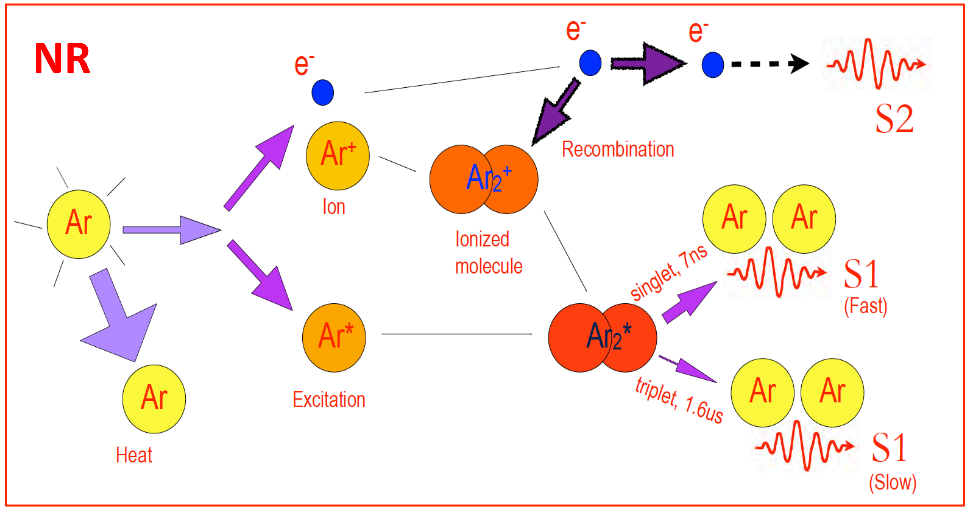
Signals Production in Noble Liquids





PSD is used in LAr experiment to improve the ER/NR discrimination





Noble Liquids Comparison

Noble Gas	LXe	LAr
Atomic mass [g/mol]	131.3	39.95
Density [g/cm^3]	3.06	1.40
Wavelenght [nm]	178	128
Average ionization energy W [eV]	15.6	23.3
Ionization Yield [e$^-$/keV]	64	42
Scintillation Yield [photon/keV]	46	40

- Higher mass number in Xe wrt Ar → higher WIMP rate in Xe
- Ar has a smaller wavelength emission light wrt Xe that requests a light shifter to allow its detection
- The average ionization energy (W) in LXe is smaller than the one in LAr
- The ionization and scintillation yields are highest in LXe

The drift field struggle

	XENON10	XENON100	LUX	XENON1T	DARWIN	
Drift length	15 cm	30.5 cm	48 cm	97 cm	260 cm	
Design field	1000 V/cm	1000 V/cm	2000 V/cm	1000 V/cm	500 V/cm	
Actual field	730 V/cm	530 V/cm	181 V/cm	117 V/cm	500 V/cm	60 V/cm
Actual V	11 kV	16.1 kV	8.7 kV	11.3 kV	130 kV	15 kV

Changing quantities

- Light and charge yields
- Diffusion constant
- S1 pulse shape
- Drift velocity
- Electron lifetime