

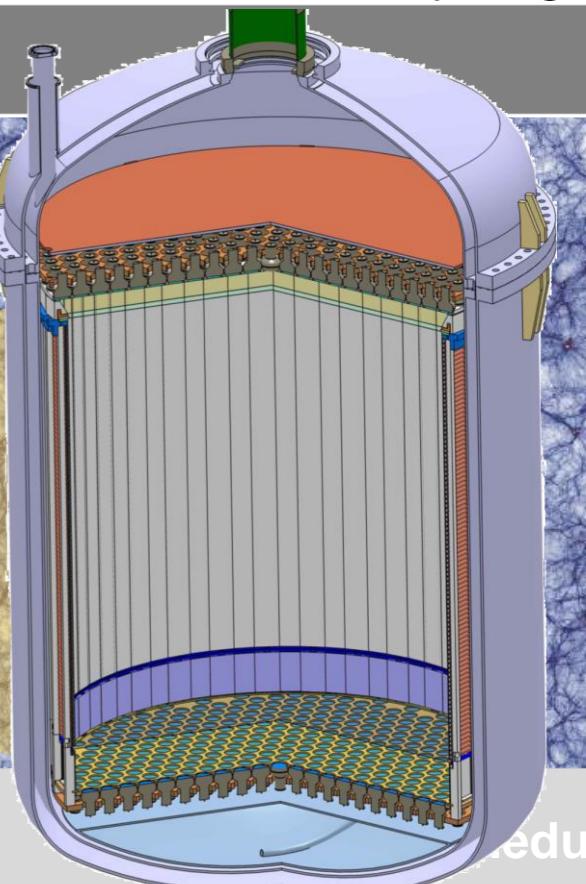
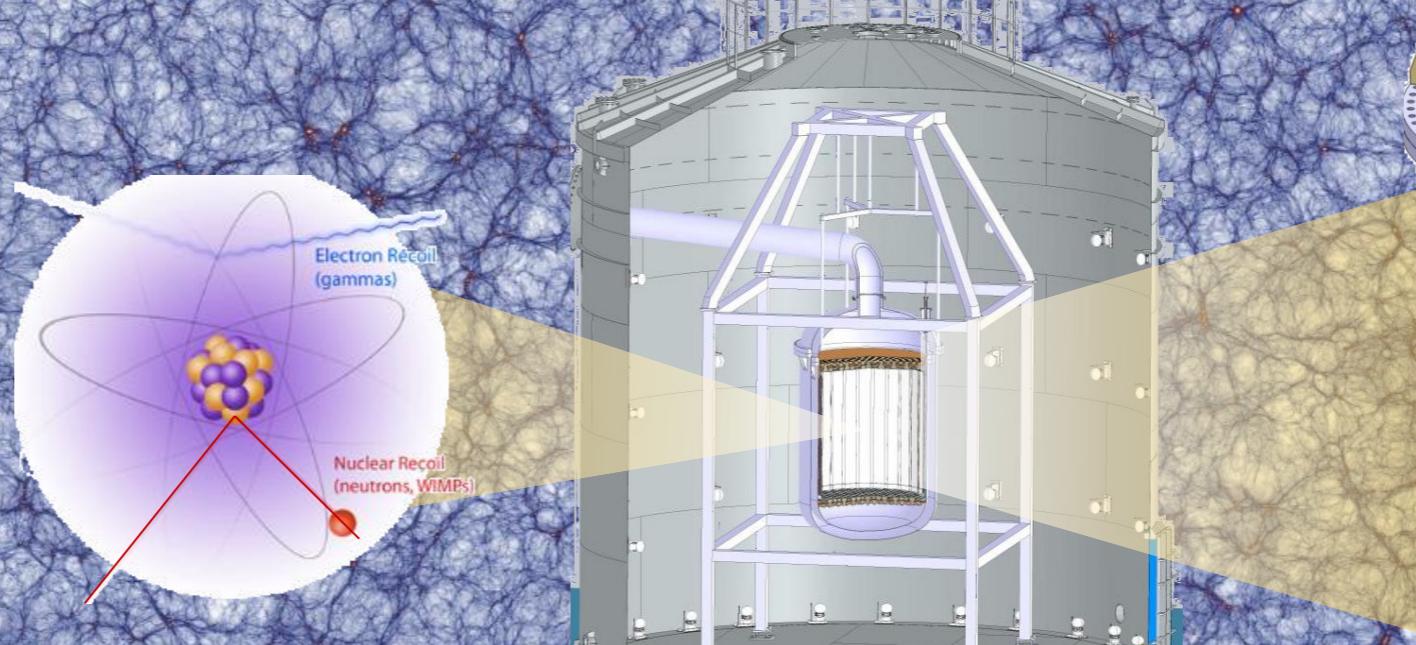
Science and technology of the DARWIN observatory

15th Vienna Conference on Instrumentation, Feb 18-22, 2019

darwin-observatory.org

Guido Drexlin, Institute for Nuclear Physics & Institute of Experimental Particle Physics

Introduction
Science Case
Technological Challenges
Outlook



Dark Matter - WIMPs

■ Dark Matter dominates the matter budget of the universe

- 17% baryons
- 83% Dark Matter

■ WIMPs

- Weakly Interacting Massive Particles
- thermal relics from Big Bang
- GeV/TeV mass scale (& beyond)



■ DARWIN – the ultimate WIMP observatory

DARWIN collaboration

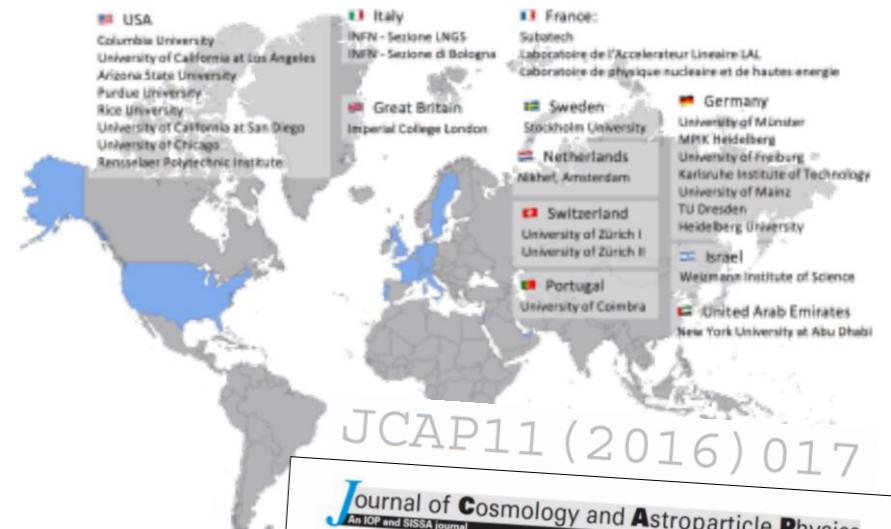


■ DARWIN: DARK matter WIMP search with liquid xenon

- 28 groups from 11 countries (strong European contribution)



DARWIN Collaboration Meeting, December 2018, U Zurich



Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

DARWIN: towards the ultimate dark matter detector



The DARWIN collaboration
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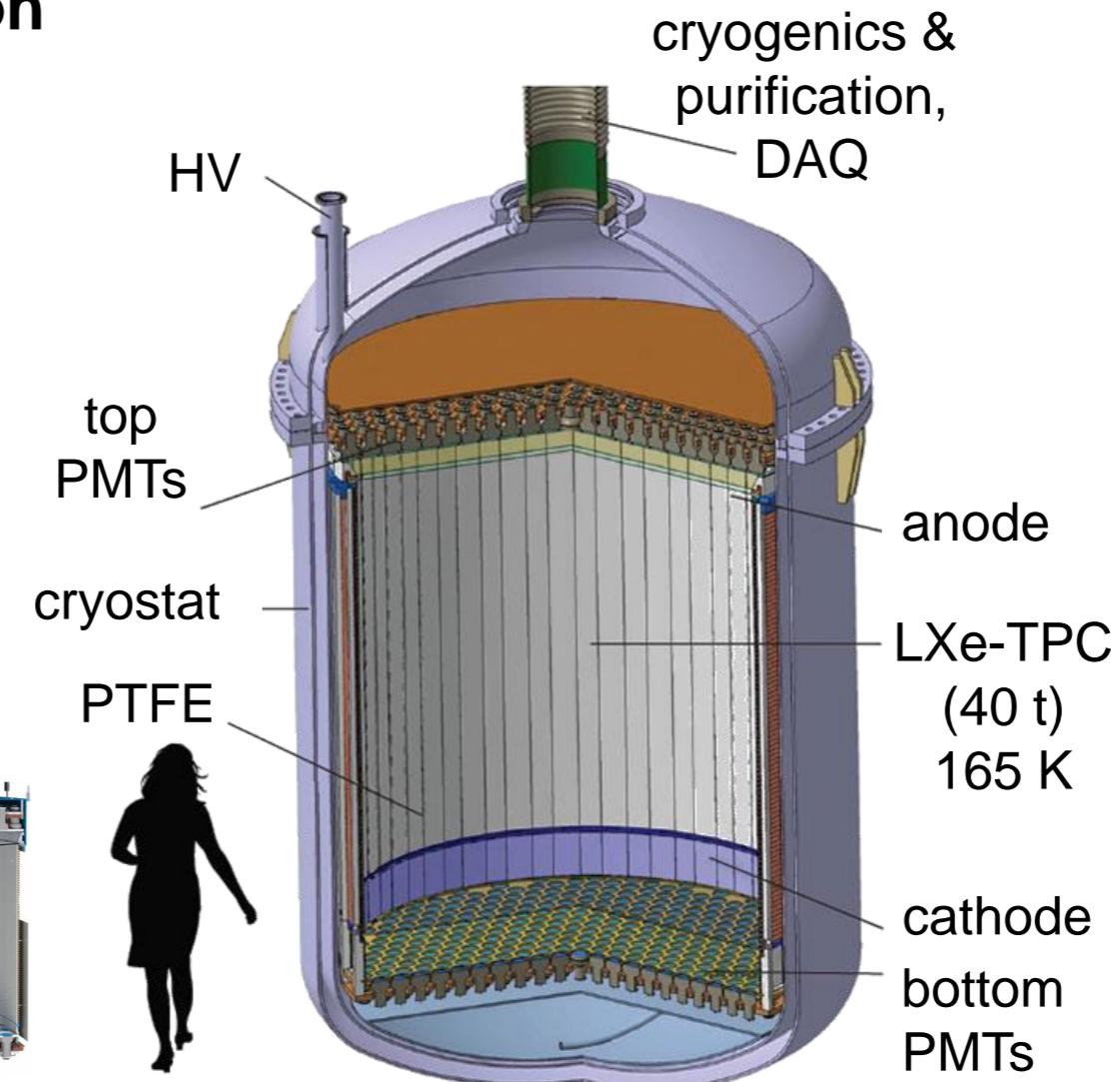
DARWIN observatory – overview

- a large-scale ($\varnothing=2.6$ m, $h=2.6$ m) dual-phase TPC
with **50 tons** of high-purity xenon

- follows successful XENON experiments 10,100, 1T, nT



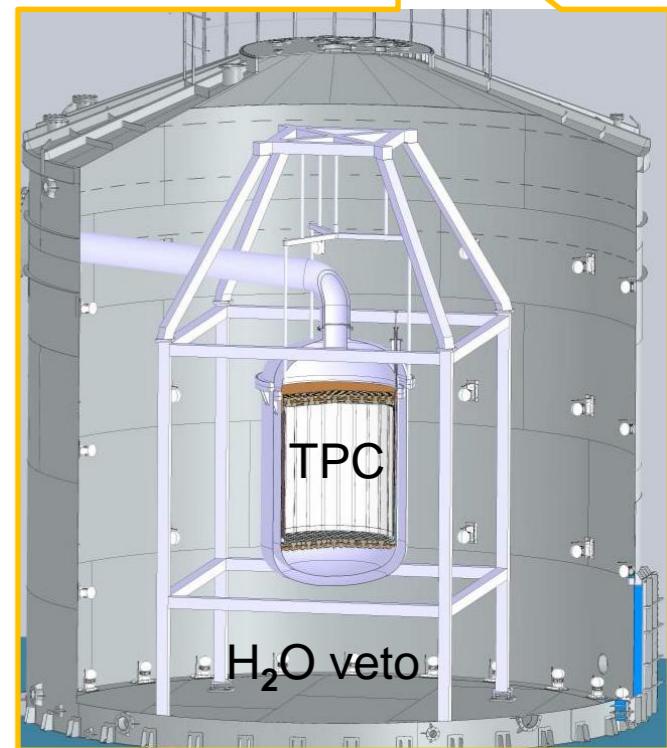
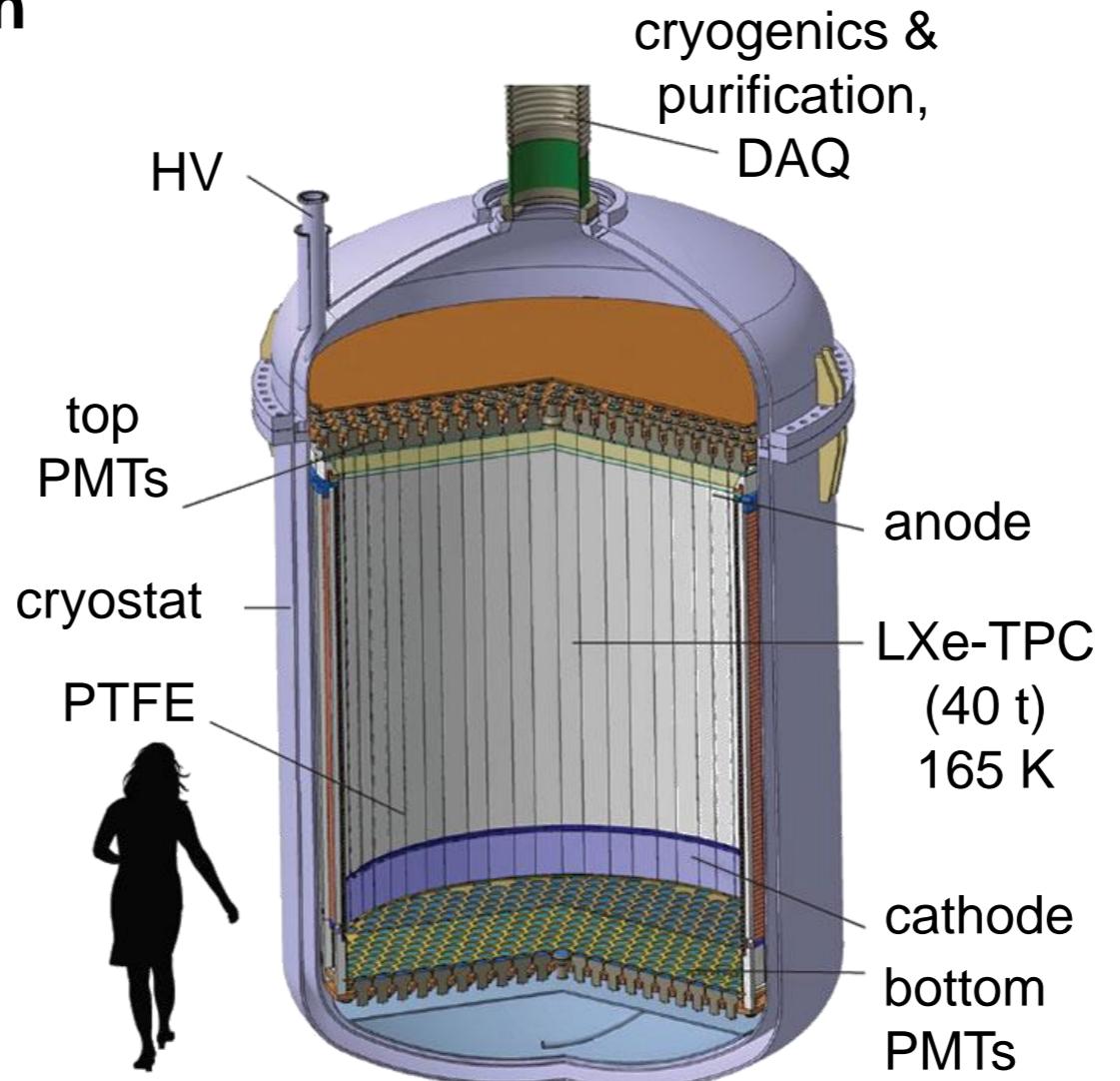
XENON1T
($\varnothing=0.96$ m, $h=0.96$ m)



DARWIN observatory – overview

- a large-scale ($\varnothing=2.6$ m, $h=2.6$ m) dual-phase TPC with **50 tons** of high-purity xenon

- 40 ton target mass in TPC
30 ton fiducial volume
- in large H_2O muon veto (with option Gd-doping)
- possible location: LNGS, Italy
- extremely low level of background & low threshold



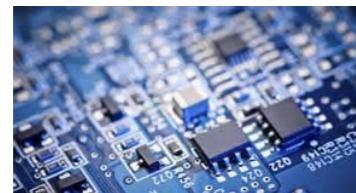
WIMP scattering & xenon recoil energies

- WIMP scattering off Xe – extremely small signal rate at keV-scale

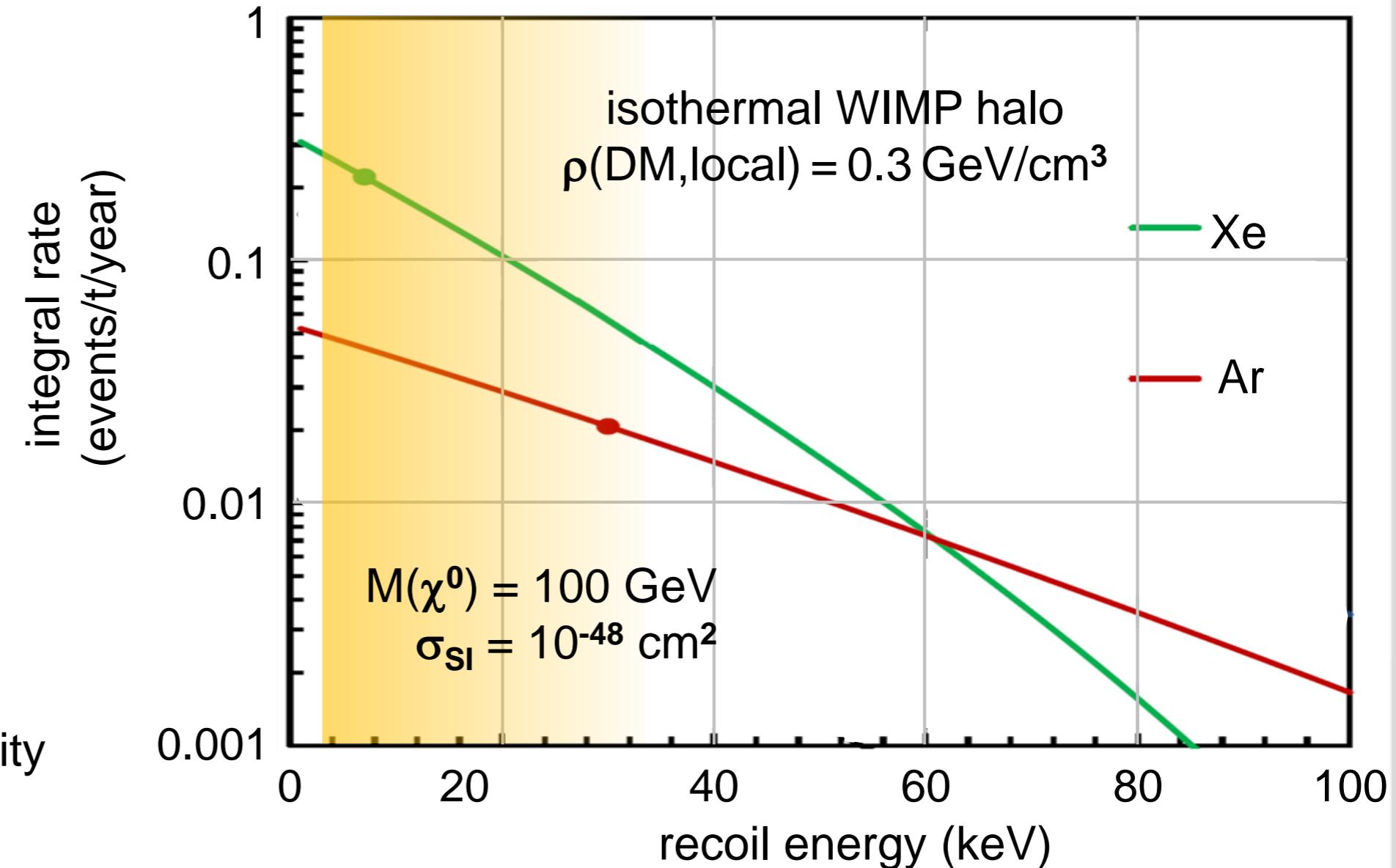
⇒ keV-scale energies
for Nuclear Recoils

⇒ recoil energy spectrum
with exponential slope

⇒ lowest possible threshold



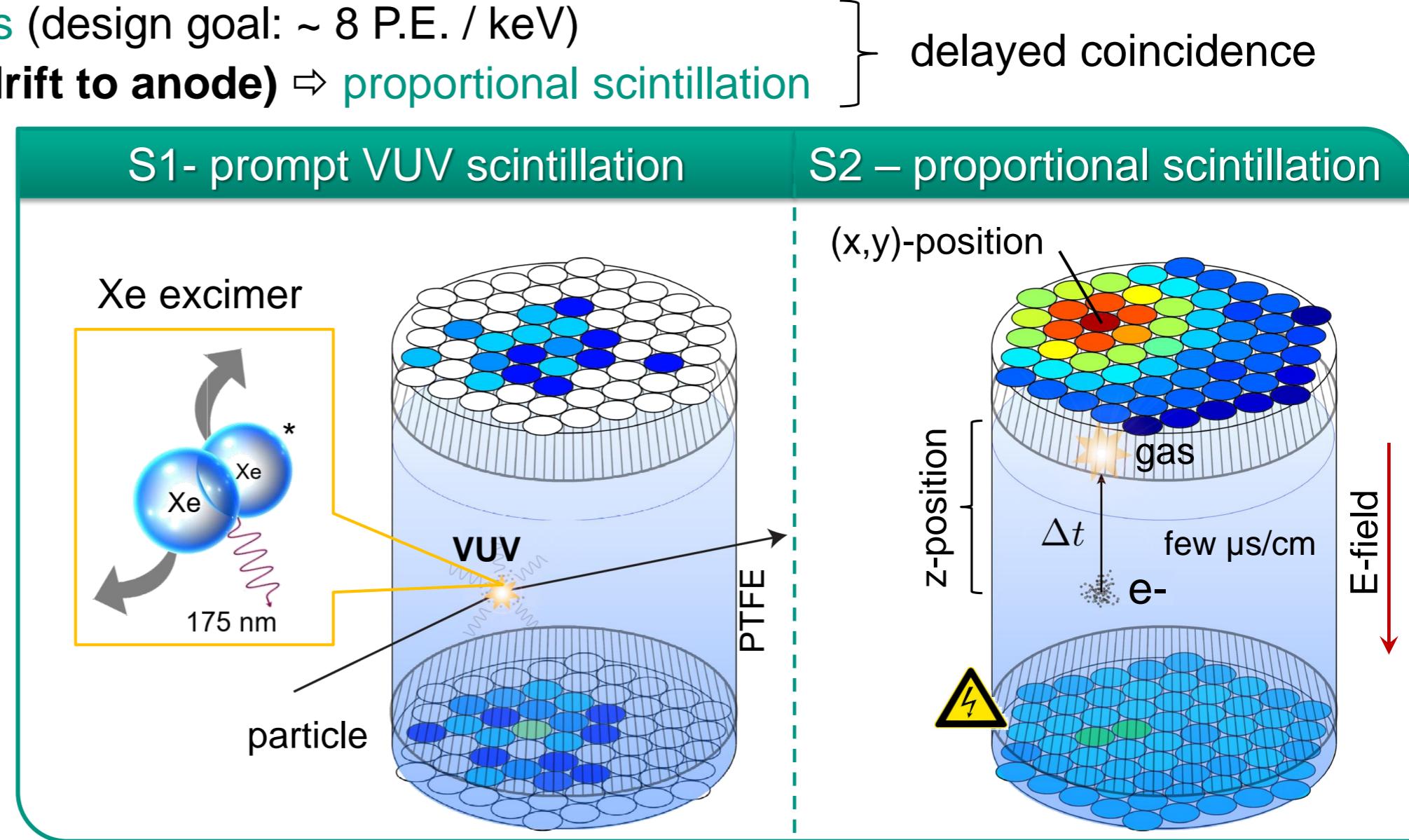
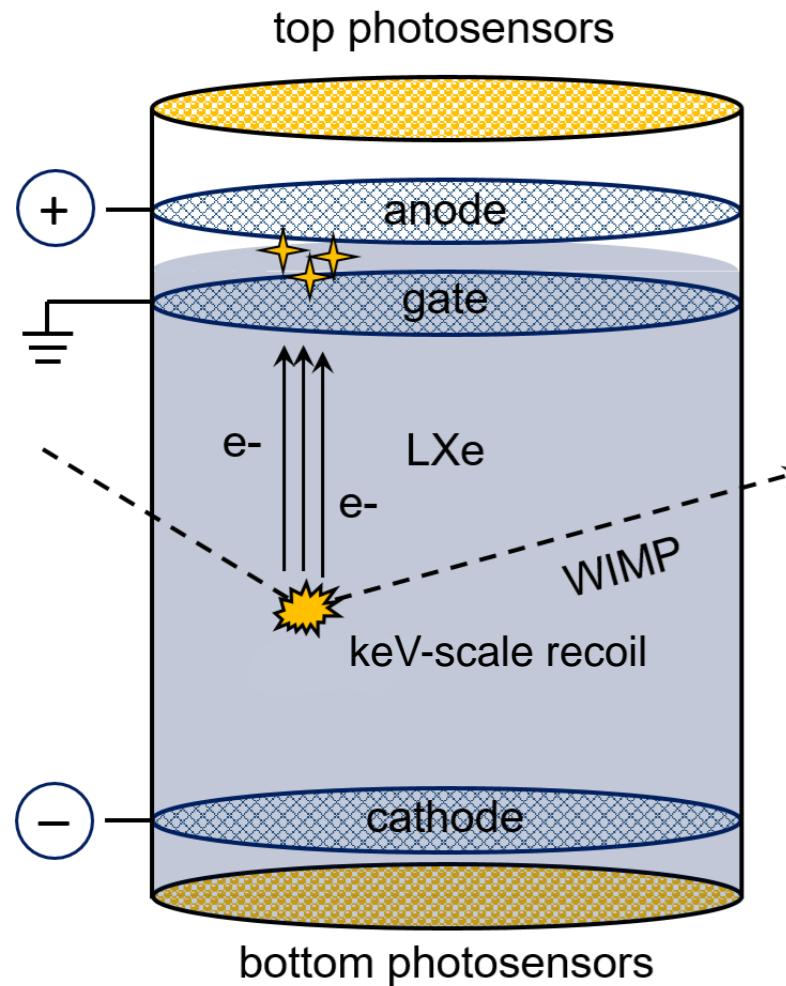
⇒ high light yield & good uniformity



TPC light and charge read-out

■ WIMP scattering off Xe: light and charge read-out via PMT arrays

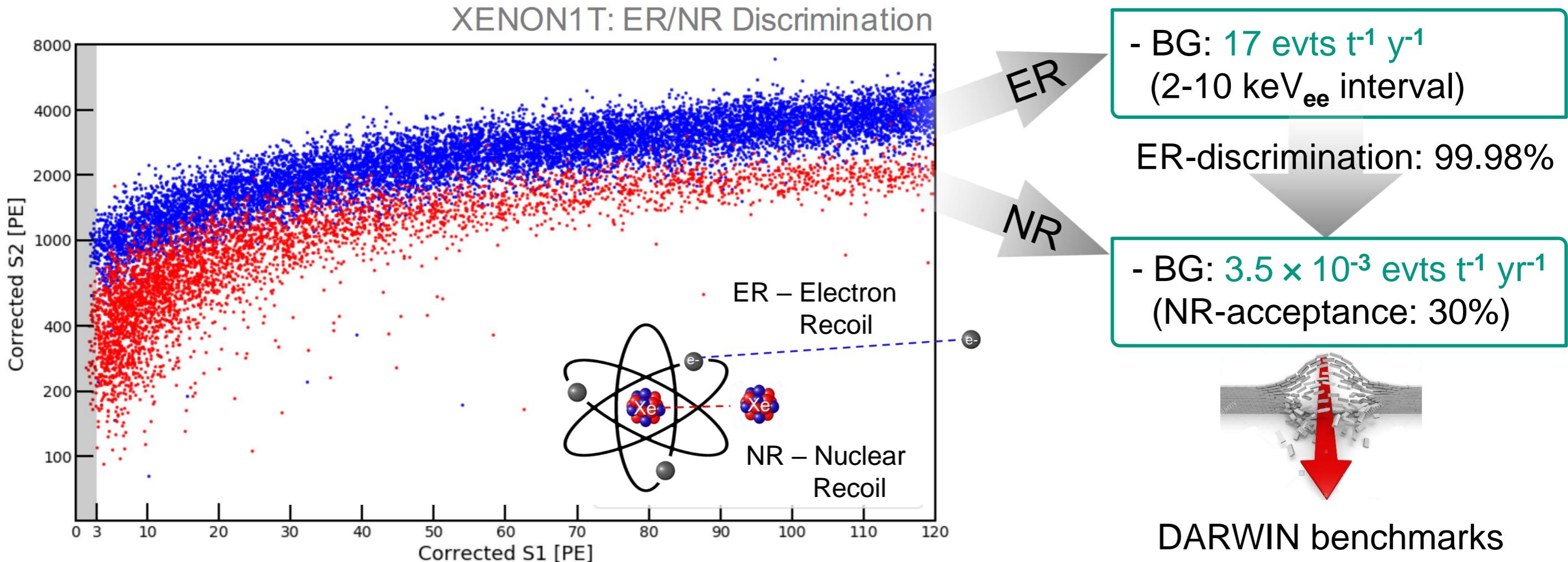
- S1: light \Rightarrow VUV photons (design goal: ~ 8 P.E. / keV)
- S2: charge (electrons drift to anode) \Rightarrow proportional scintillation



DARWIN: S/B-background discrimination for WIMPs

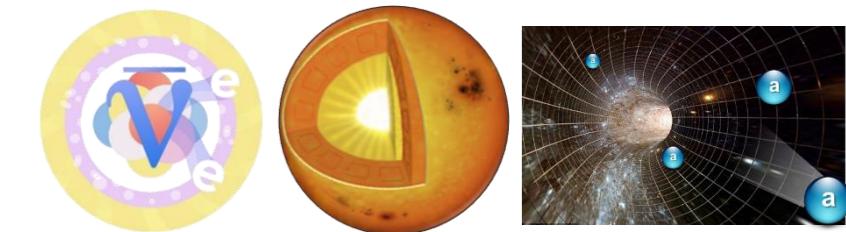
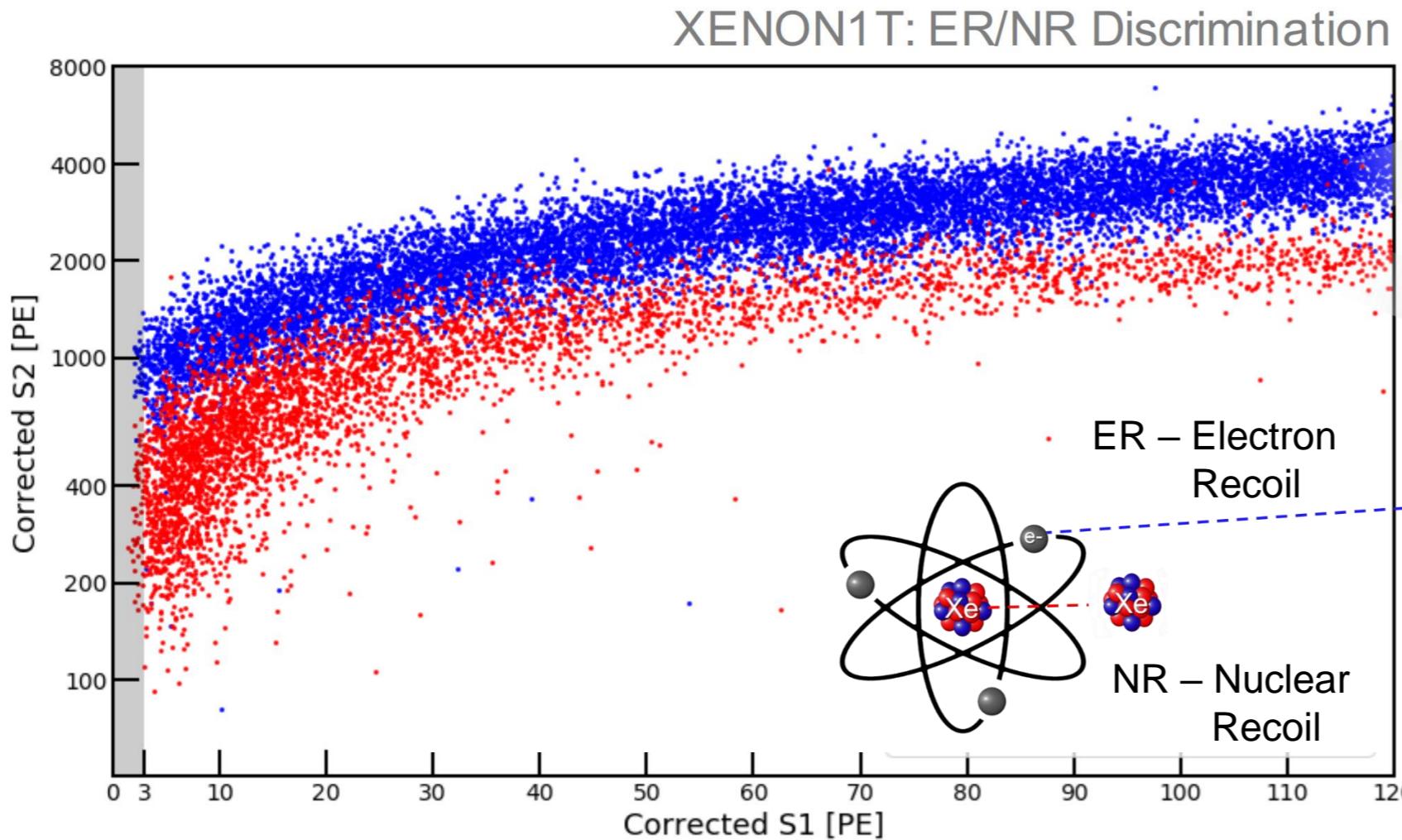
■ background discrimination based on **ratio S1/S2**:

- **WIMP interaction:** small ratio $S2/S1$ - ionisation signal of NR is quenched by ~ factor 3
- **electron interaction:** large ratio $S2/S1$ - ionisation signal of ER is not quenched

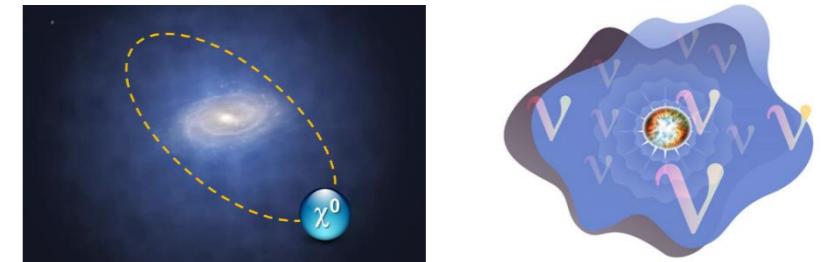


DARWIN: low background for ER and NR channels

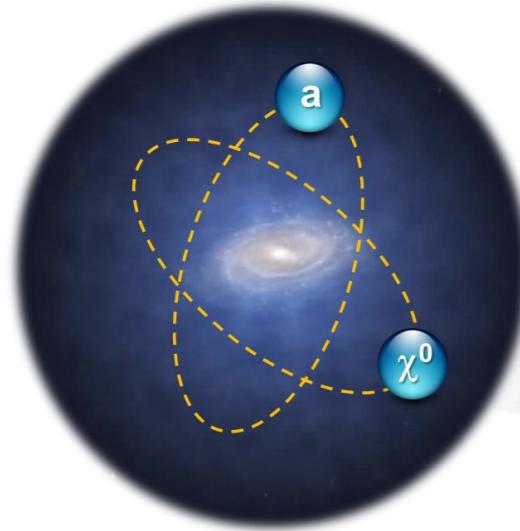
- need **exceedingly low background level** in both ER & NR channel:
 - many non-WIMP science cases accessible in ER channel



- search for $0\nu\beta\beta$
 - solar ν 's
 - search for axions, ALPs, ν_s
-
- **WIMP recoils**
 - SN-burst neutrinos

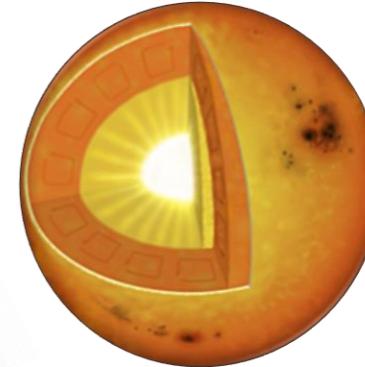
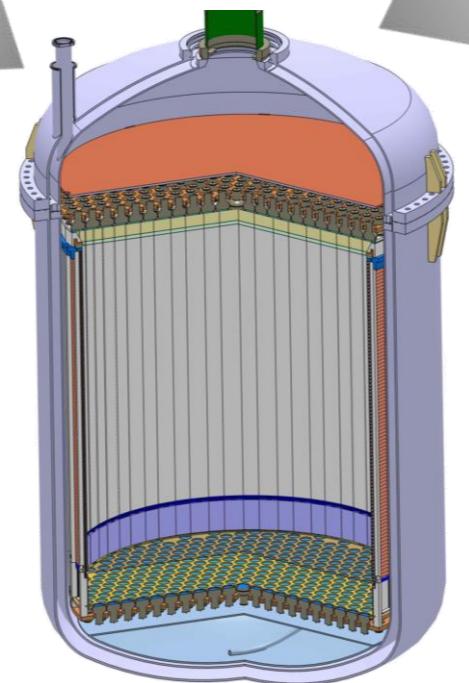


WIMPs & ALPs
from galactic halo

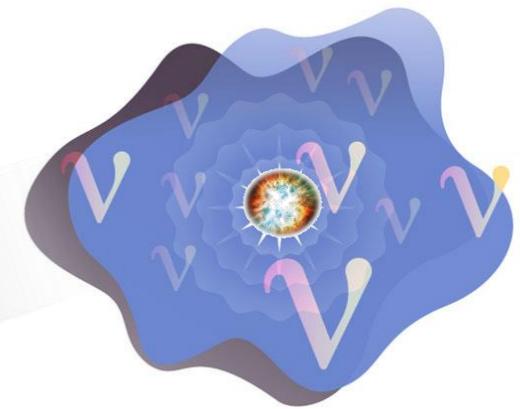


double beta decay

solar pp-neutrinos & axions



SN neutrinos



DARWIN – SCIENCE CASE

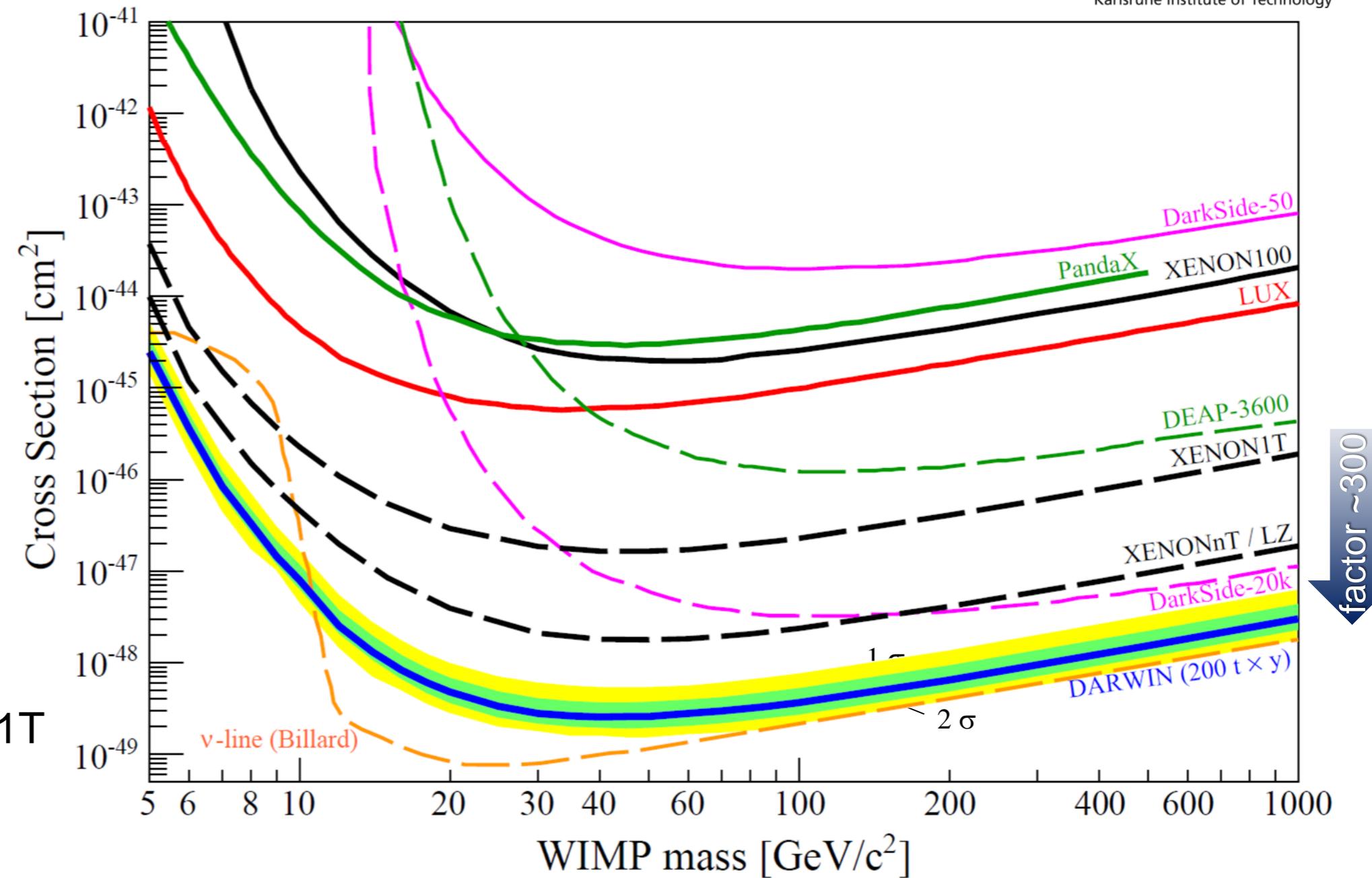
spin-independent scattering σ_{SI}

spin-independent xsec

- ultimate sensitivity for GeV-TeV scale WIMPs from DM halo down to neutrino floor

$$\begin{aligned}\sigma_{\text{SI}} &= 2.5 \times 10^{-49} \text{ cm}^2 \\ &(@ 40 \text{ GeV}) \\ &= 0.25 \text{ yoctobarn}\end{aligned}$$

- factor ~300 improvement relative to actual XENON1T sensitivity

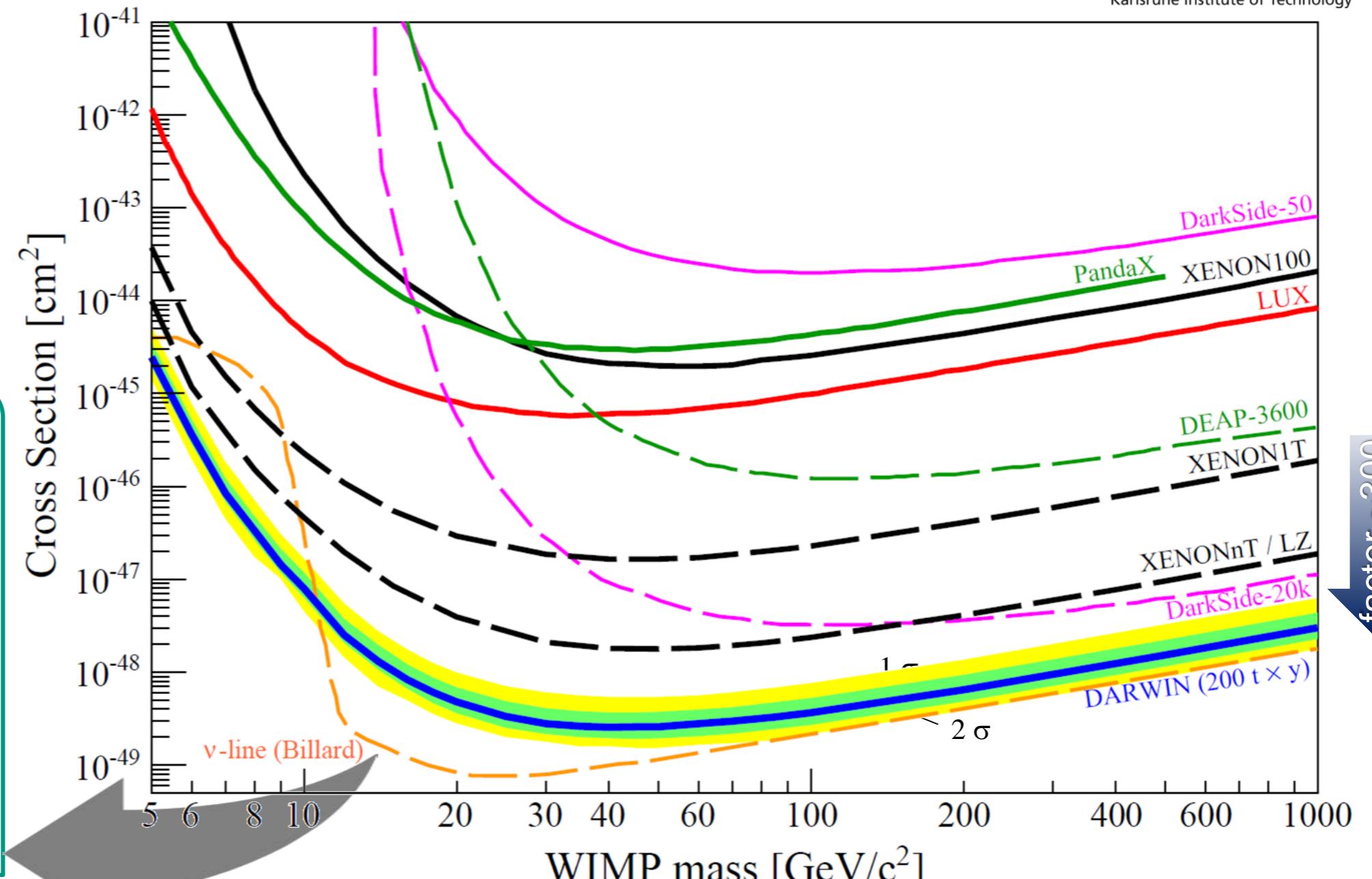
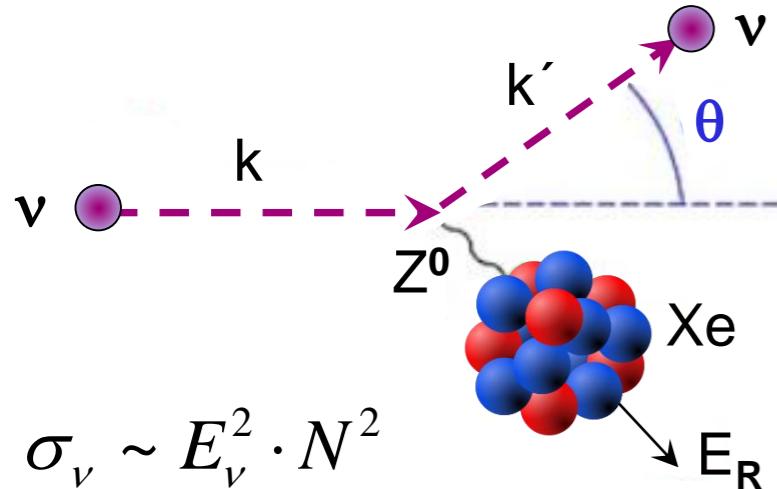


CNNS background from neutrinos and σ_{SI}

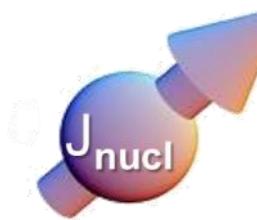


diffuse SN ν 's & atmospheric ν 's

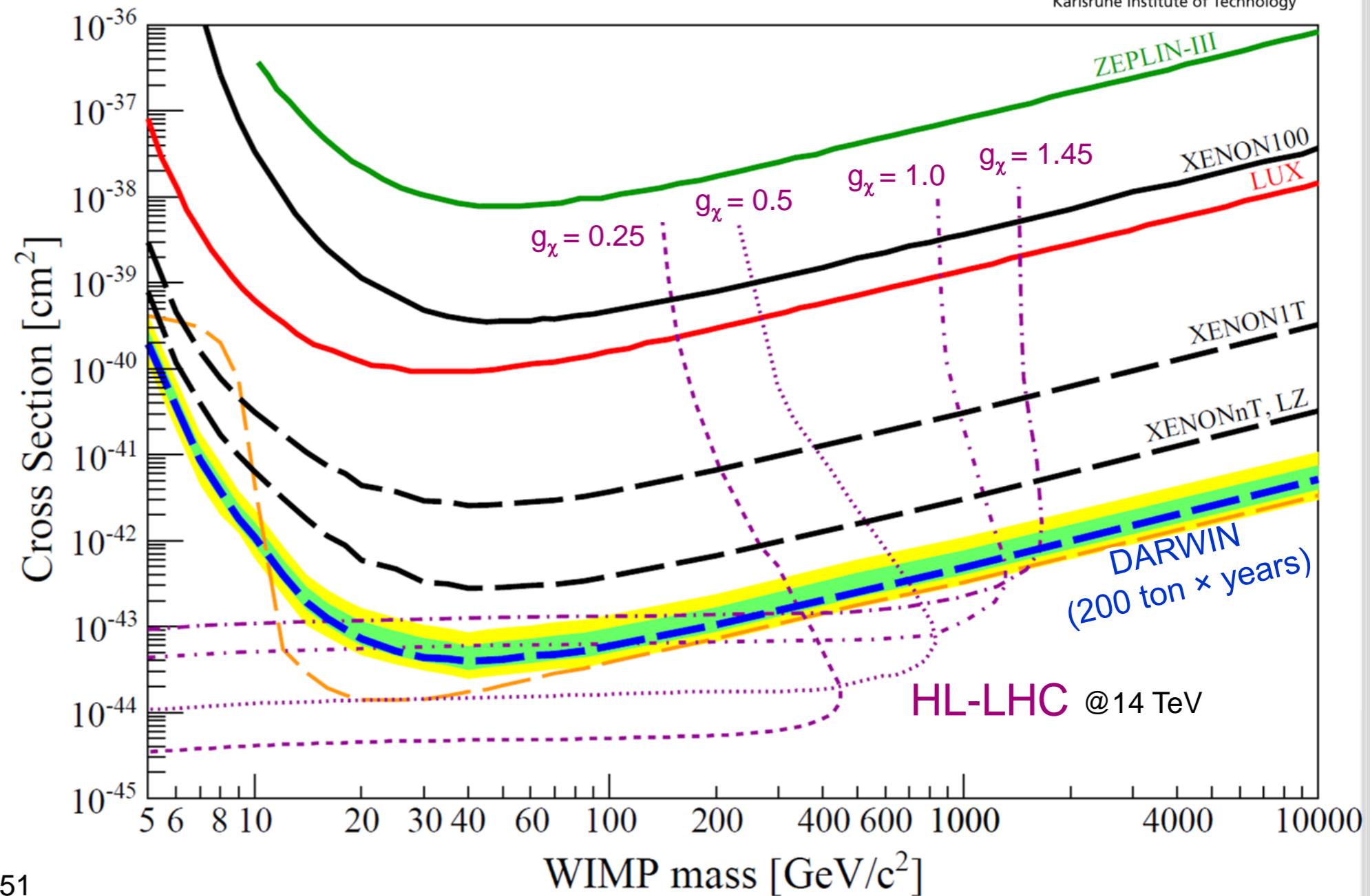
coherent ν -nucleus scattering (CNNS)



spin-dependent WIMP scattering σ_{SD}



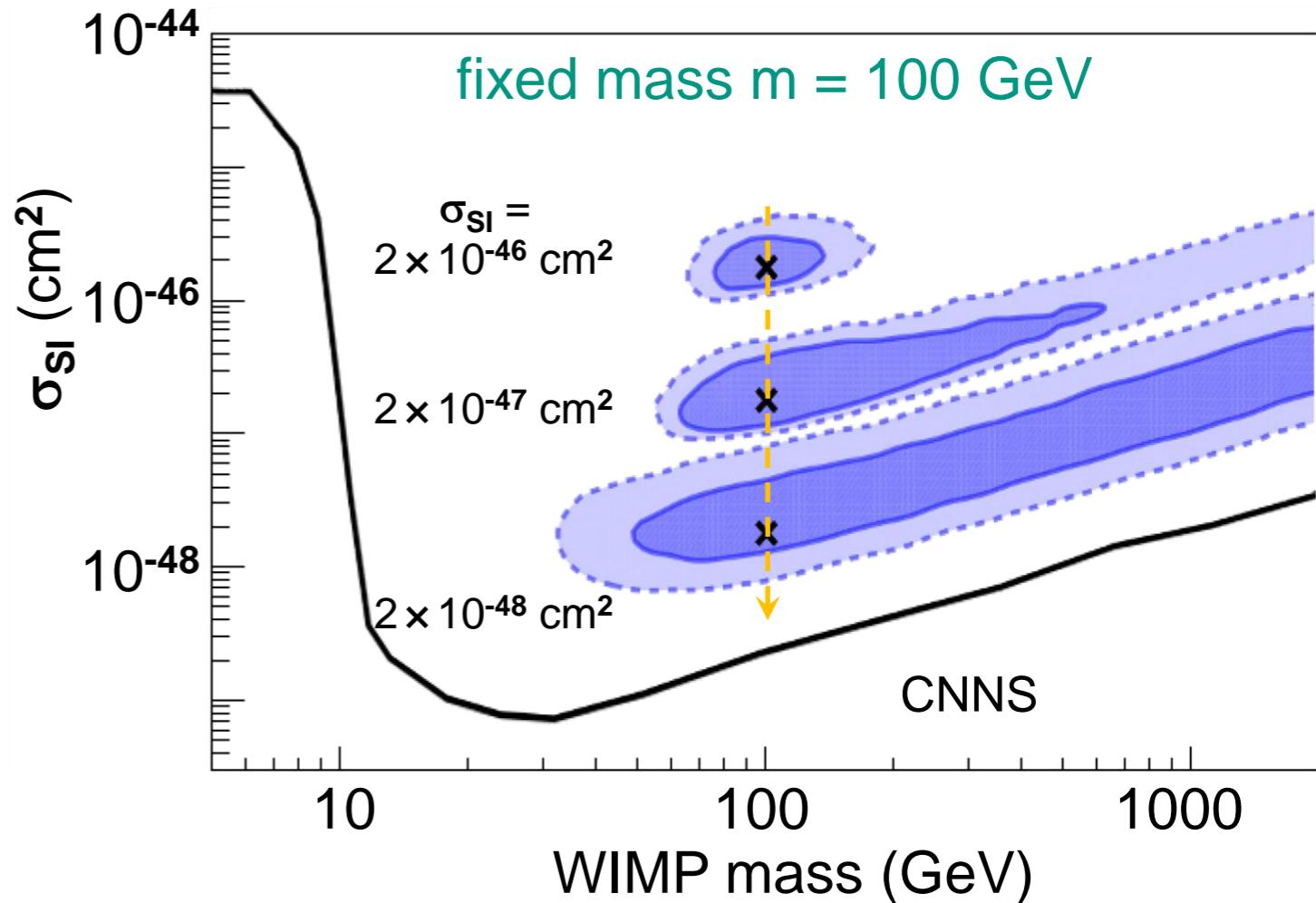
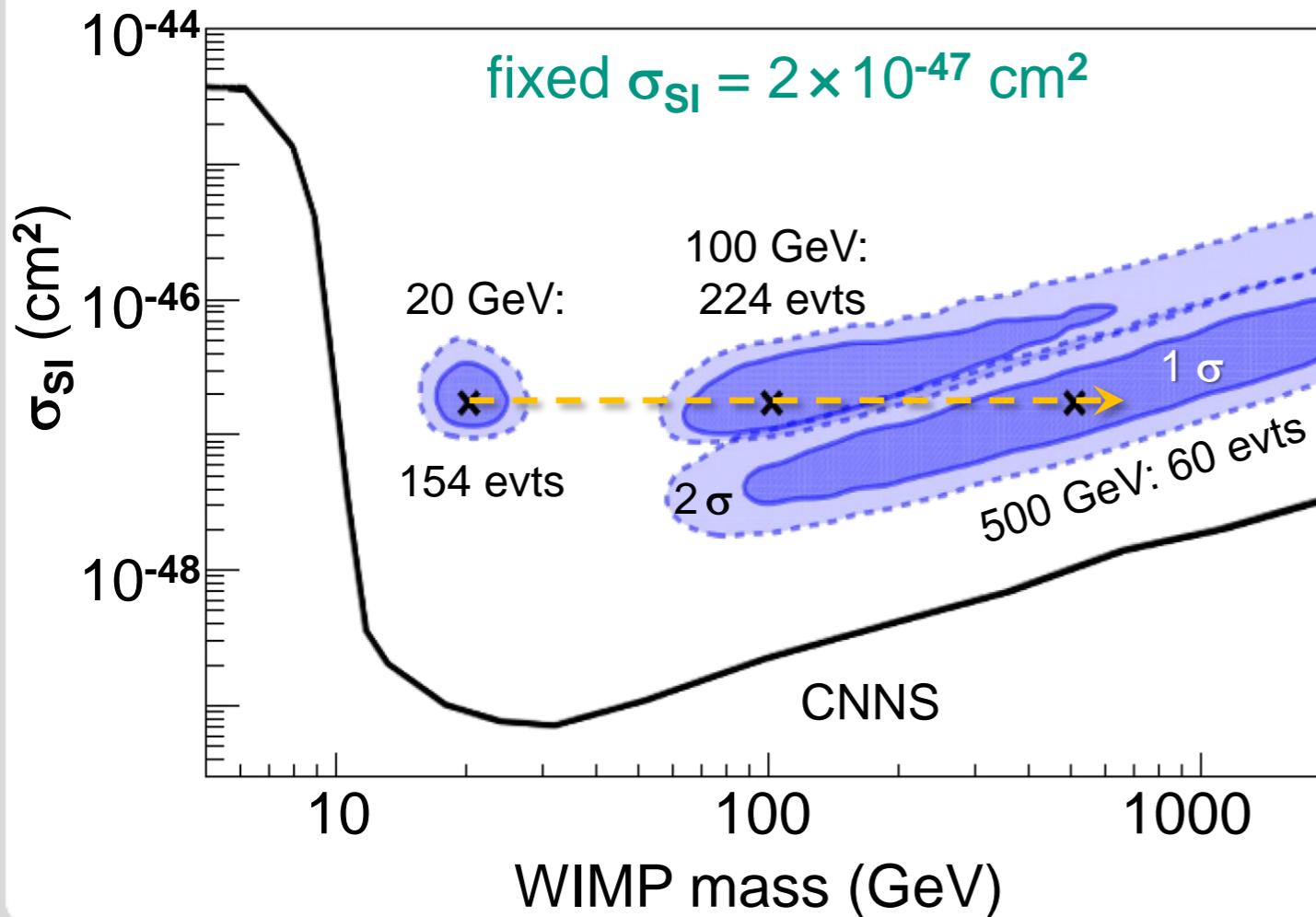
- Xe-target nuclei with $J \neq 0$:
 ^{129}Xe (26.4 %) $J = 1/2$, a_n
 ^{131}Xe (21.2 %) $J = 3/2$, a_n
- Complementarity to LHC:
minimal DM-model with
Dirac fermion interacting
via axial-vector mediator
 $g = g_\chi = g_q$



constraining WIMP parameters

■ DM-properties: cross section σ_{SI} & mass m_{WIMP}

- numerical model with realistic DARWIN detector & bg-parameters for 200 ton \times y exposure
- with DM-halo uncertainties: $\rho_{\text{DM,loc}} = (0.3 \pm 0.1) \text{ GeV cm}^{-3}$, $v_0 = (220 \pm 20) \text{ km s}^{-1}$

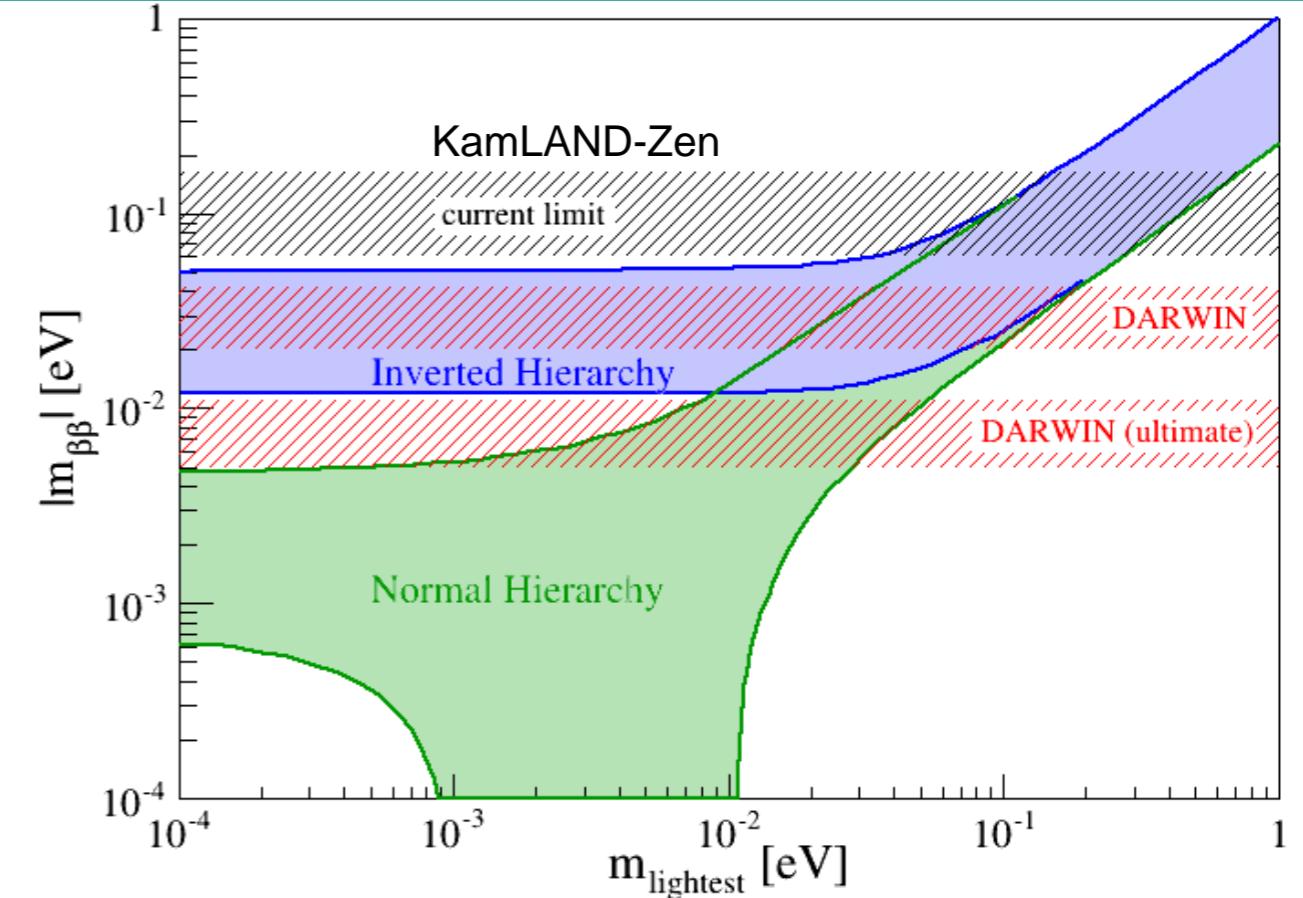
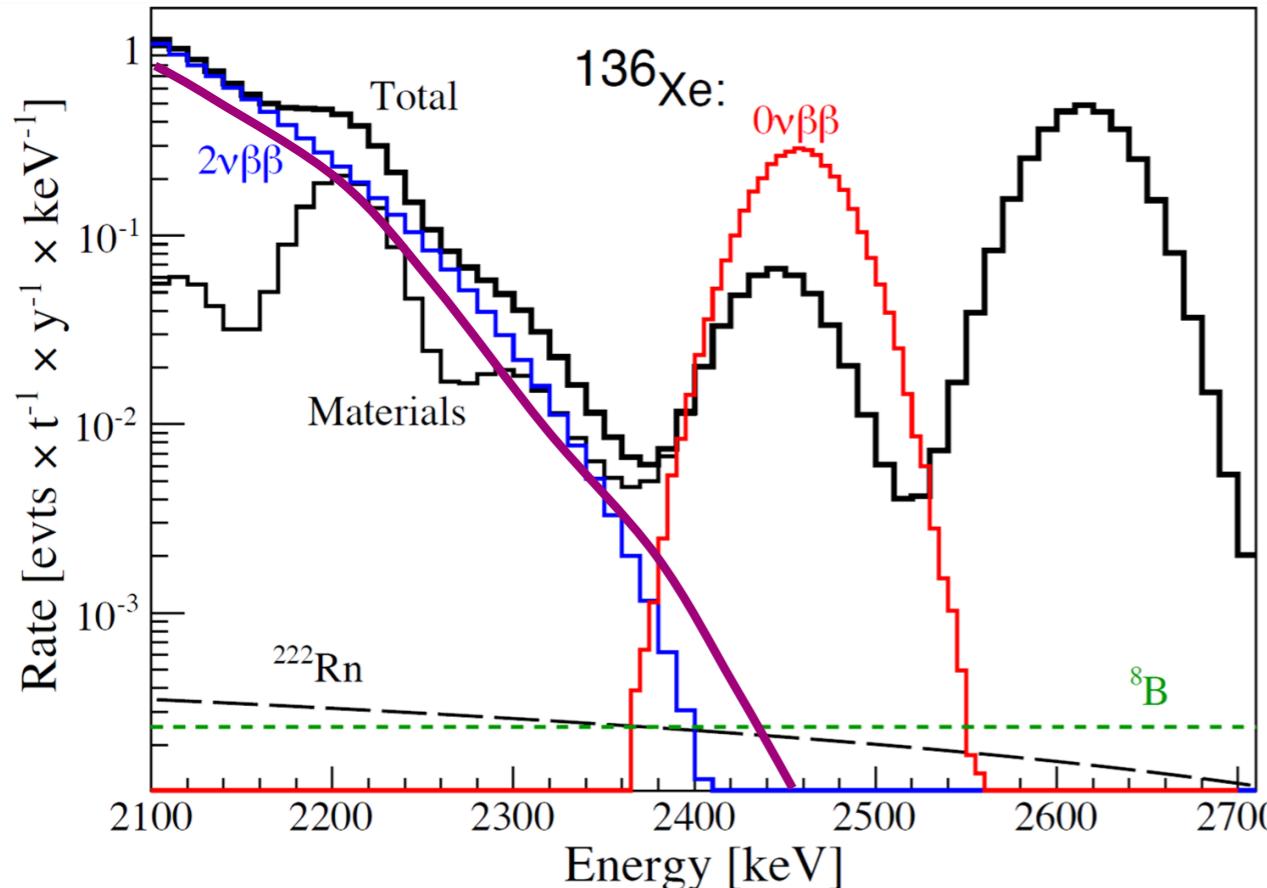


search for $0\nu\beta\beta$ of ^{136}Xe

■ **$0\nu\beta\beta$ -decay of isotope ^{136}Xe ($Q = 2.458 \text{ MeV}$, $\varepsilon = 8.9\%$, $M > 3.5 \text{ t}$)**

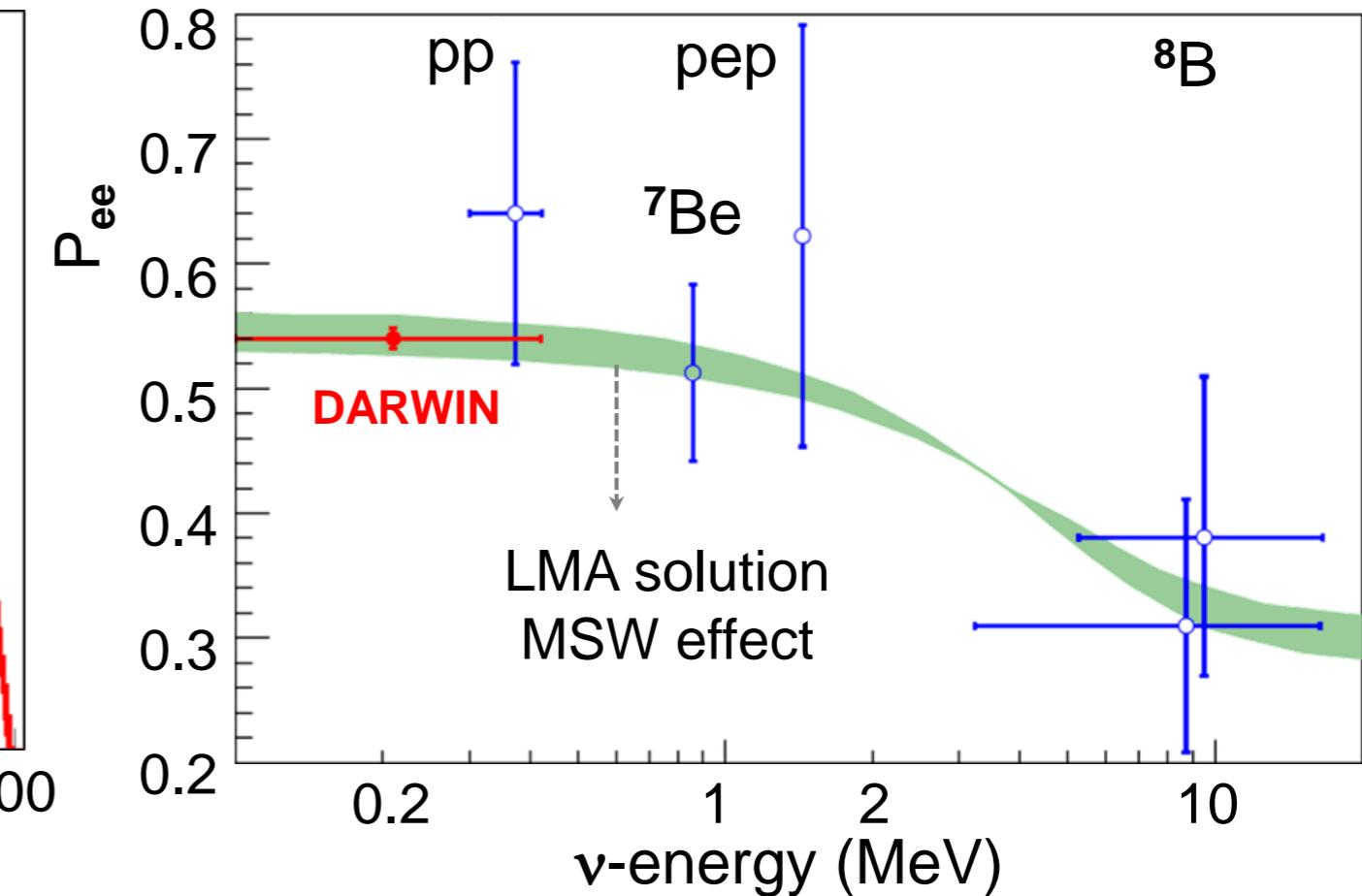
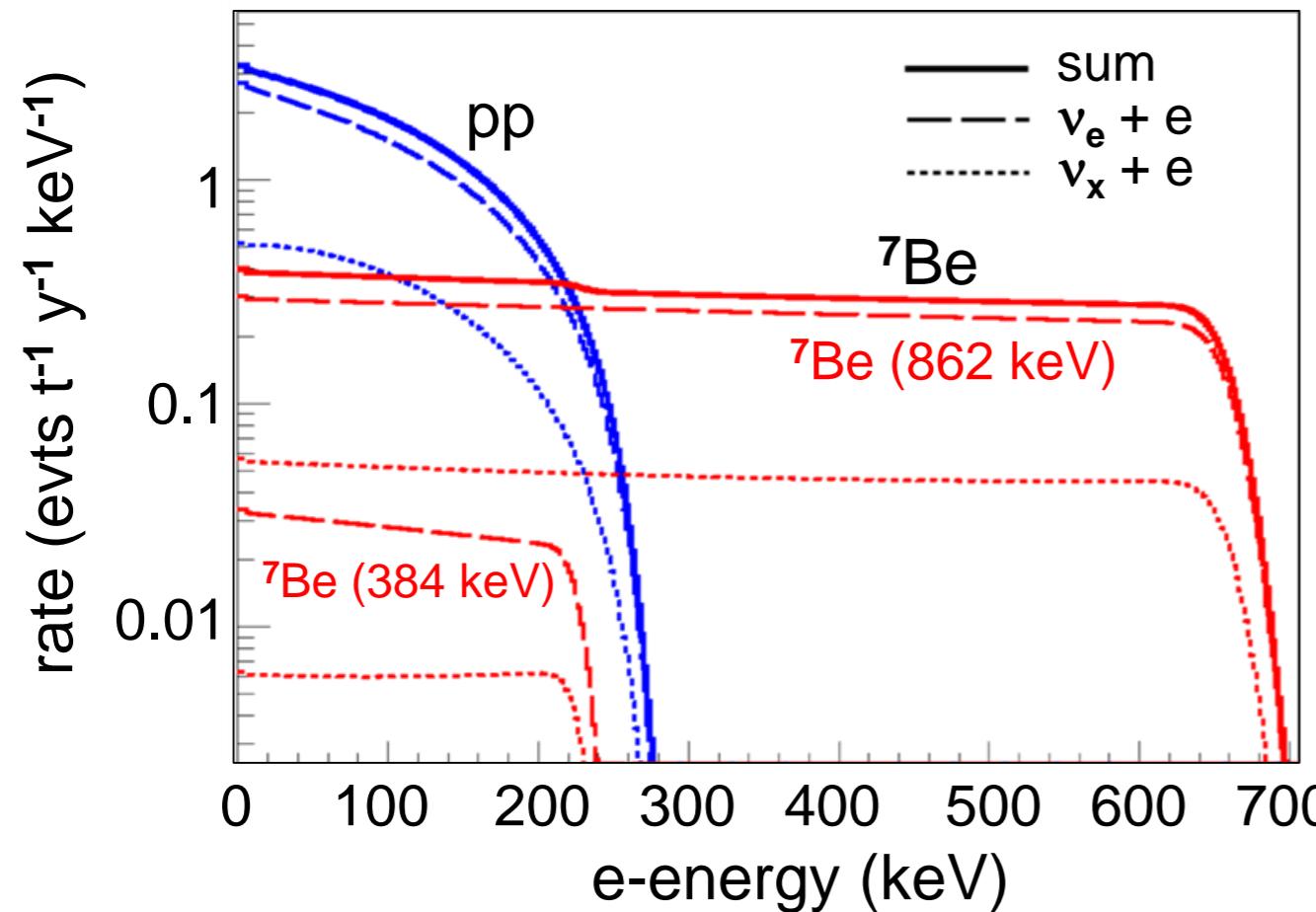
strategy: restricted fiducial volume & very good energy resolution: 1-2% @ $Q_{\beta\beta}$

- phase-I: exposure of $30 \text{ ton} \times \text{y}$ & external γ -bg $\Rightarrow t_{1/2}(0\nu) > 5.6 \times 10^{26} \text{ y}$ [DARWIN]
- phase-II: exposure of $140 \text{ ton} \times \text{y}$ & no external γ 's $\Rightarrow t_{1/2}(0\nu) > 8.5 \times 10^{27} \text{ y}$ [DARWIN (ultimate)]



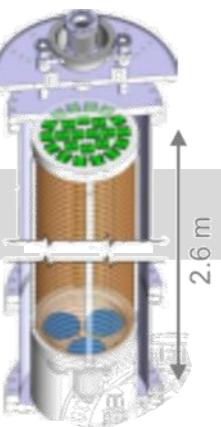
precision measurement of solar neutrinos

- solar neutrinos (pp, ${}^7\text{Be}$) measured via elastic $\nu + e^- \rightarrow \nu + e^-$ scattering (ER channel)
 - accuracy: $\pm 0.3\%$ for $\Phi(\text{pp})$ and $\pm 2.3\%$ for $\Phi({}^7\text{Be})$
 \Rightarrow test main energy production in sun & search for NSI of ν 's
 - energy window 2-30 keV_{ee}: $n_{\text{pp}} = 7.2 \text{ evts/day}$, $n_{{}^7\text{Be}} = 0.9 \text{ evts/day}$





- R&D on detector design,
sensor technologies, detector operation,
background suppression, analysis strategies
horizontal & vertical demonstrators
⇒ CDR document in 2020/21



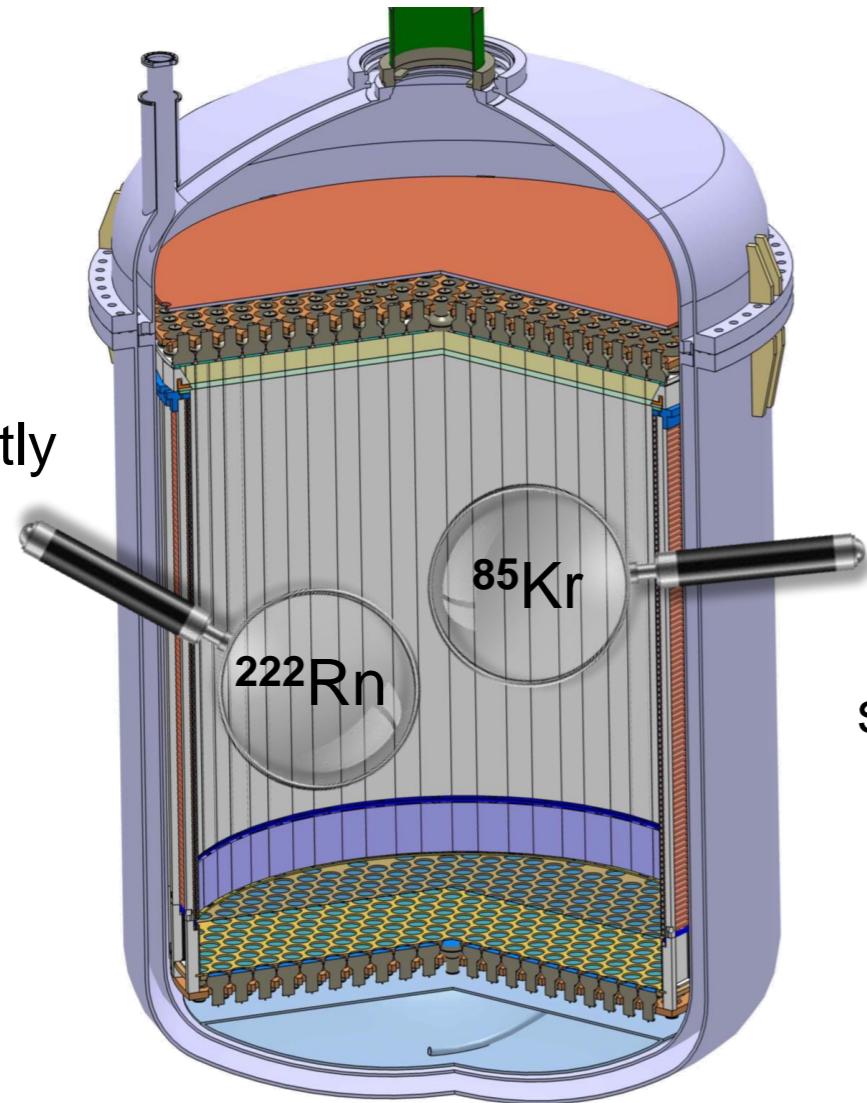
TECHNOLOGICAL CHALLENGES

Challenge: radiopurity level

■ challenges in background reduction:

- radiopurity of 50 t LXe target

emanates
permanently
from all
detector
materials



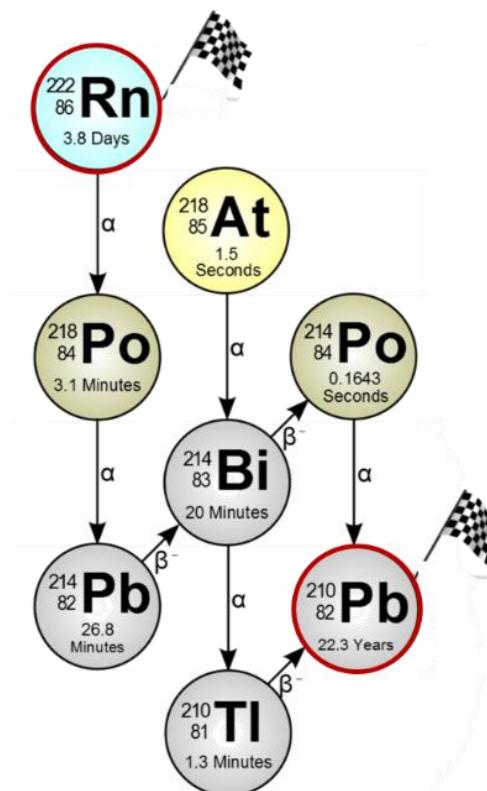
^{78}Kr 77.92039 0.35% Stable	^{80}Kr 79.916379 2.25% Stable	^{81}Kr $t_{1/2}=23,000\text{ yrs}$ radioactive	^{82}Kr 81.913485 11.60% Stable
^{83}Kr 82.914137 11.50% Stable	^{84}Kr 83.911508 57.0% Stable	^{85}Kr $t_{1/2}=10.8\text{ yrs}$ radioactive/ anthropogenic	^{86}Kr 85.910615 17.30% Stable

- ^{85}Kr level in LXe

- XENON1T: < 0.03 ppt [upper limit]
DARWIN: 0.1 ppt

- ^{222}Rn level in LXe

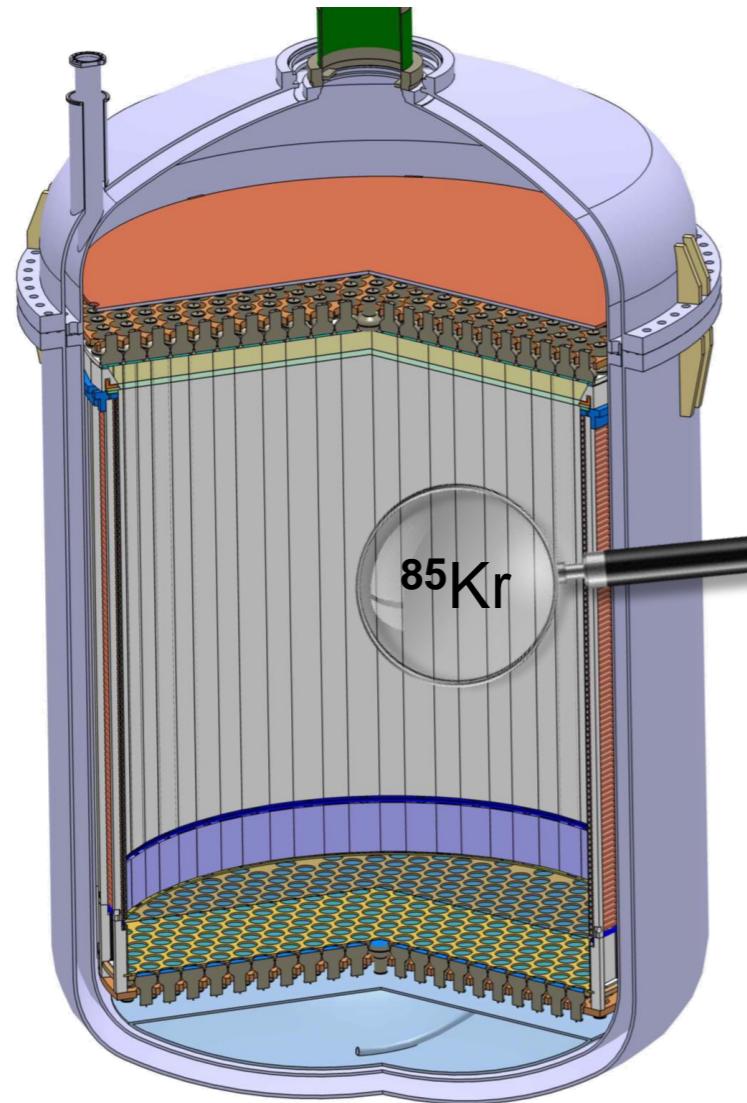
- XENON1T: 10 $\mu\text{Bq/kg}$
DARWIN: 0.1 $\mu\text{Bq/kg}$



Challenge: Kr-85 radiopurity level

■ challenges in background reduction:

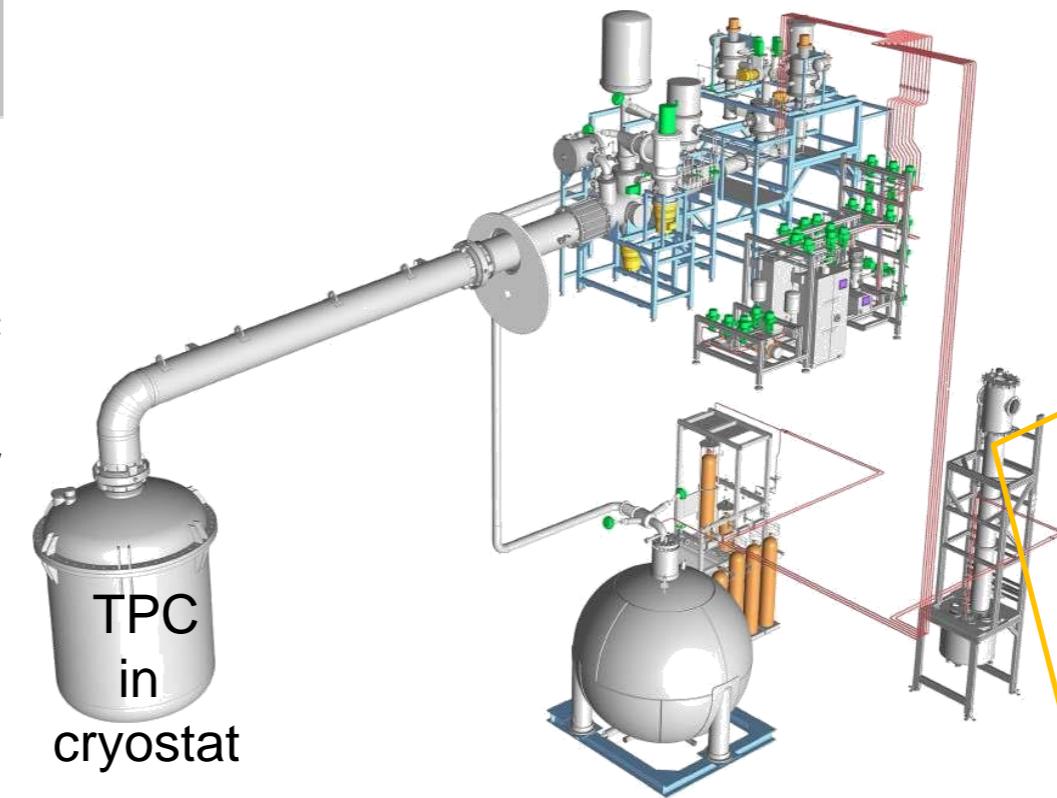
- radiopurity of 50 t LXe target



intrinsic
to xenon
due to air
separation

■ countermeasures:

- ^{85}Kr level in LXe
single stage cryodestillation

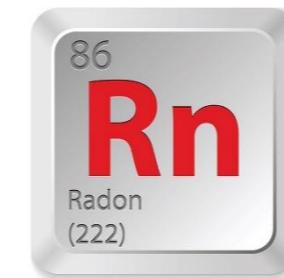
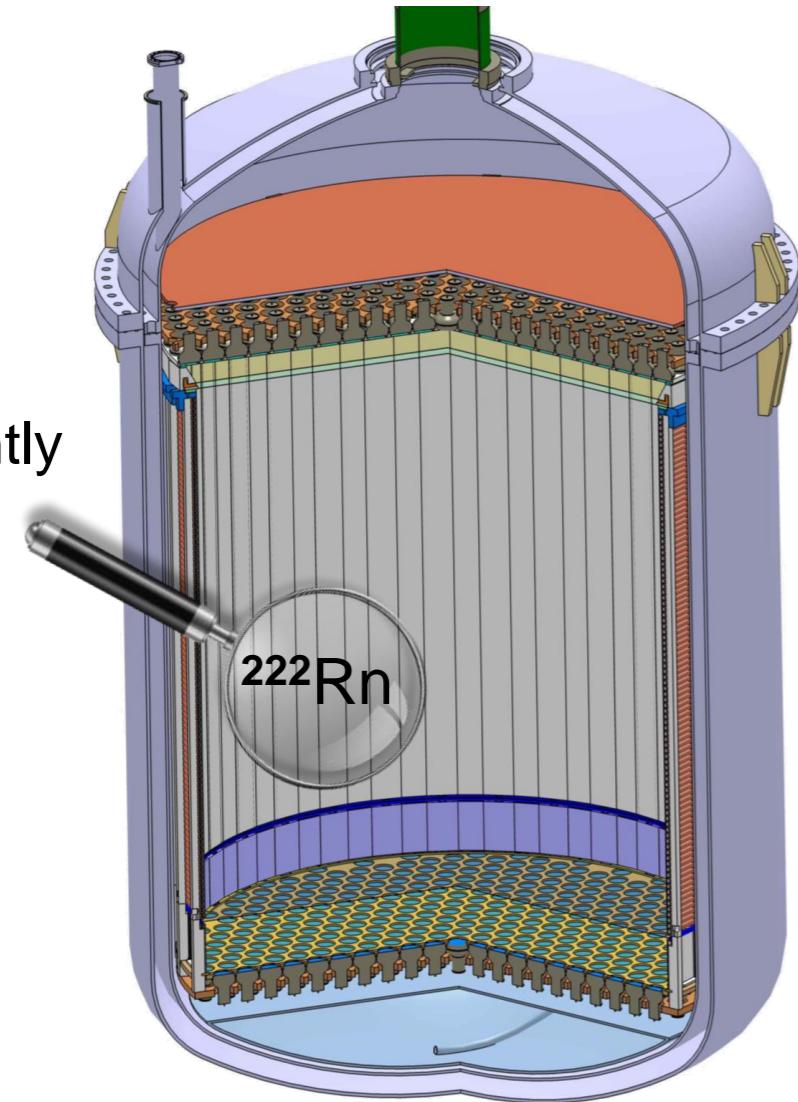


Challenge: Rn-222 radiopurity level

■ challenges in background reduction:

- radiopurity of 50 t LXe target

emanates
permanently
from all
detector
materials



■ countermeasures:

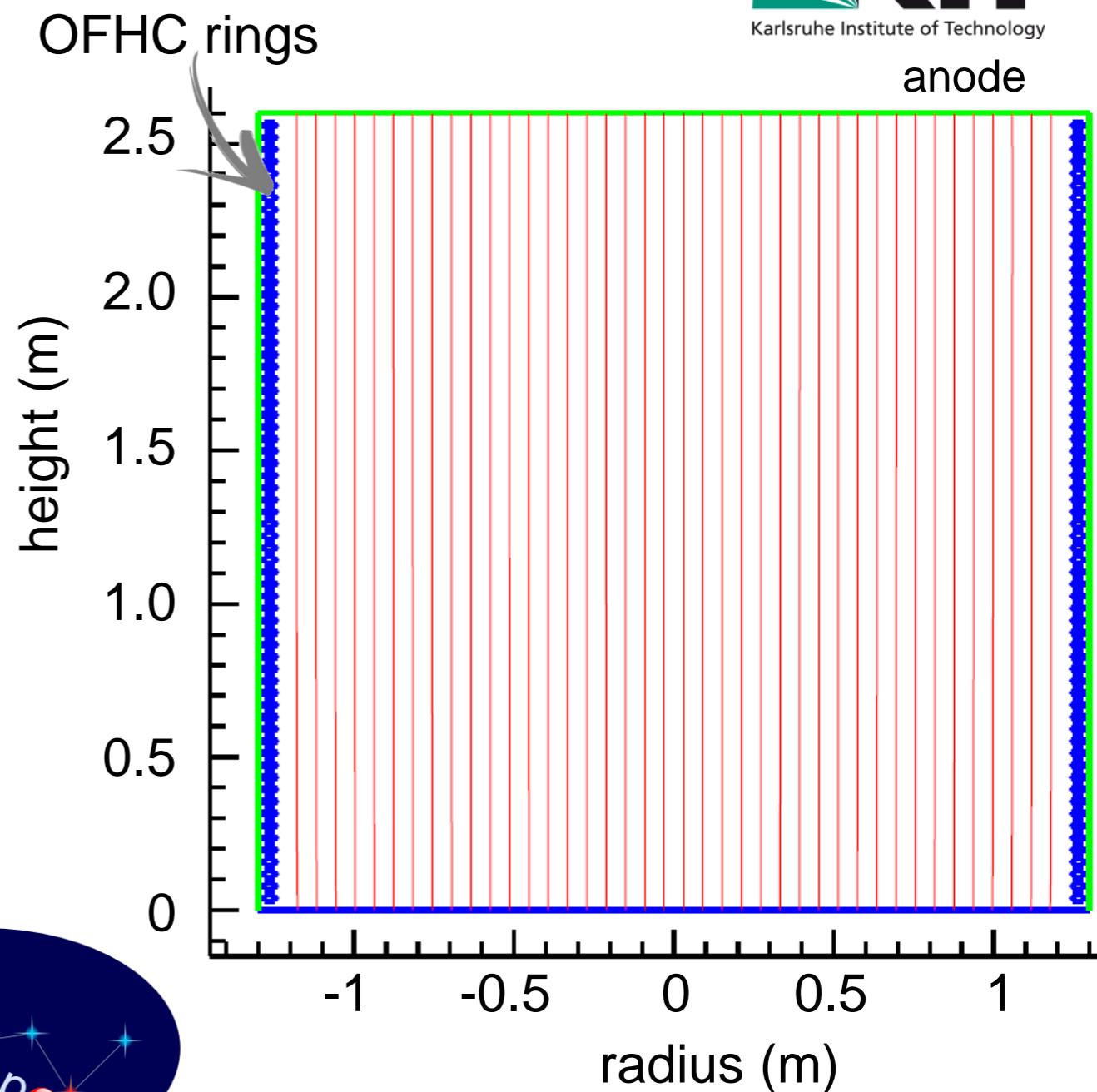
- **222Rn** level in LXe
- permanent cryodestillation
- all detector materials:
selection & screening
coating



Challenge: optimised TPC charge read-out

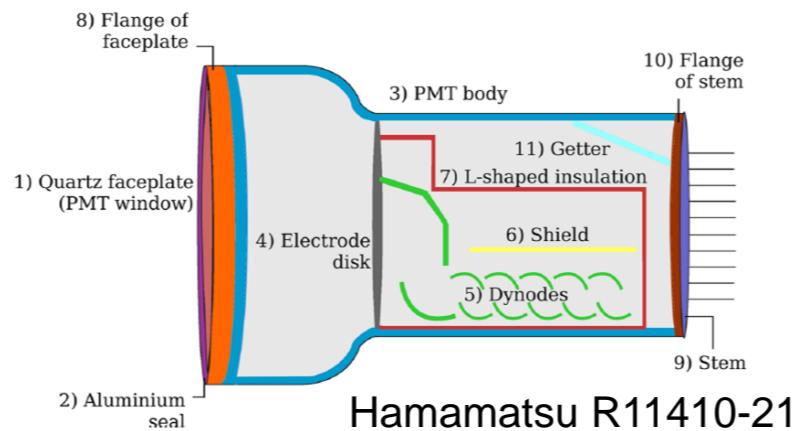
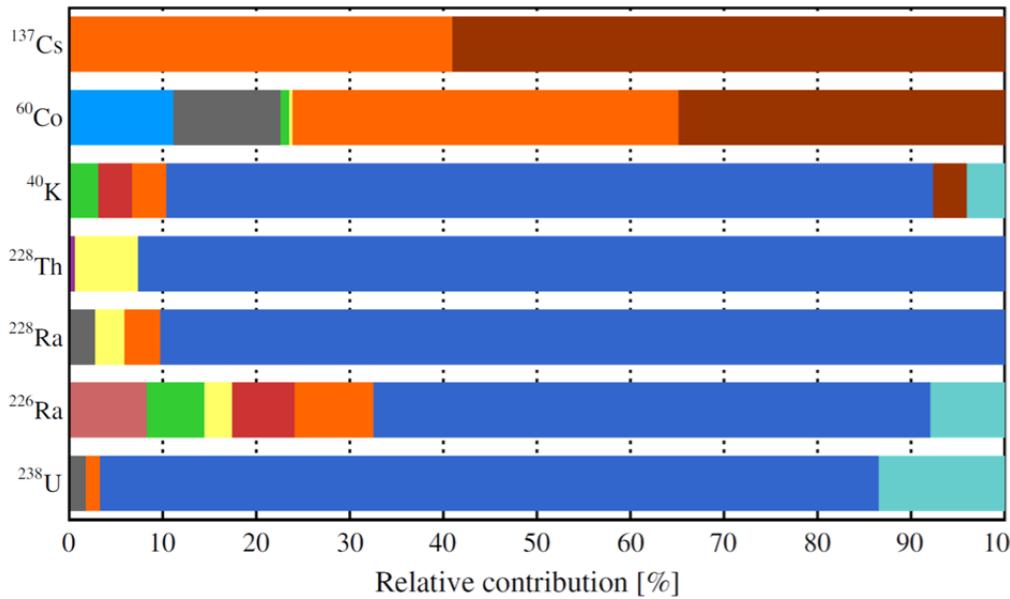
■ Very homogenous large-scale drift field

- design goal: uniform drift field $E_D = 0.5 \text{ kV/cm}$
- optimize potentials for field shaping elements (KEMfield, COMSOL) & countermeasures against PTFE surface charging
- stable HV operation of cathode at -130 kV
- optimized electrode geometries (here anode)
 - flat shape for uniform fields
 - optimal light transmission for S1
 - optimal electron transmission for S2



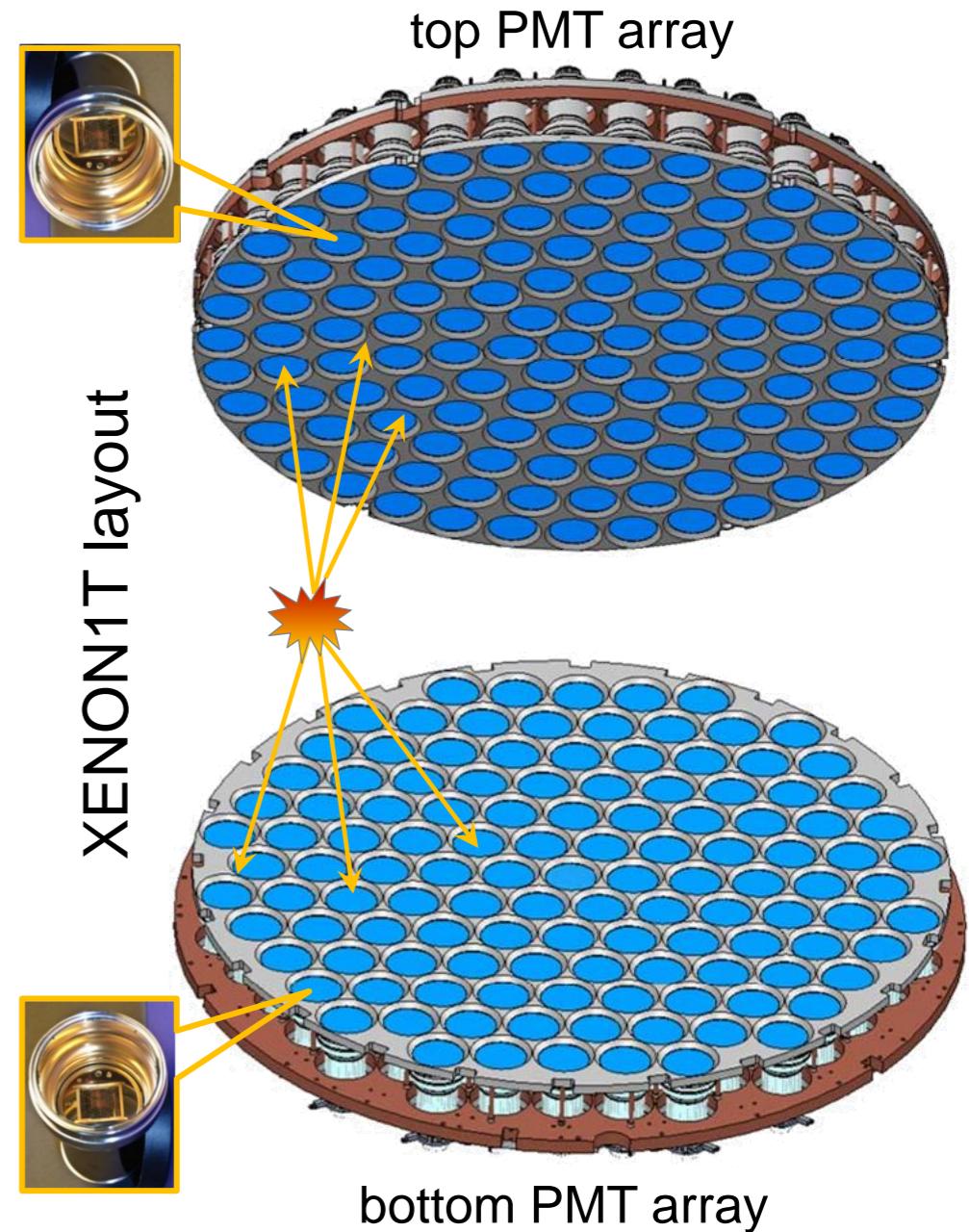
Challenge: optimised TPC light read-out

- Maximize photon yield from scintillation (S1) & proportional scintillation (S2), with low background
 - base option: 3-inch PMT
 - further lowering PMT radioactivity, screeing
 - R&D on Si-PMT types & other light sensors



Hamamatsu R11410-21

- 1) Quartz: faceplate (PMT window)
- 2) Aluminum: sealing
- 3) Kovar: Co-free body
- 4) Stainless steel: electrode disk
- 5) Stainless steel: dynodes
- 6) Stainless steel: shield
- 7) Quartz: L-shaped insulation
- 8) Kovar: flange of faceplate
- 9) Ceramic: stem
- 10) Kovar: flange of ceramic stem
- 11) Getter



Outlook

- DARWIN – **the ultimate WIMP observatory** with broad science reach:
double beta decay, solar & SN ν 's, axions, sterile ν 's,...
- DARWIN – many technological challenges
background suppression (Xe purification), TPC light and charge read-out

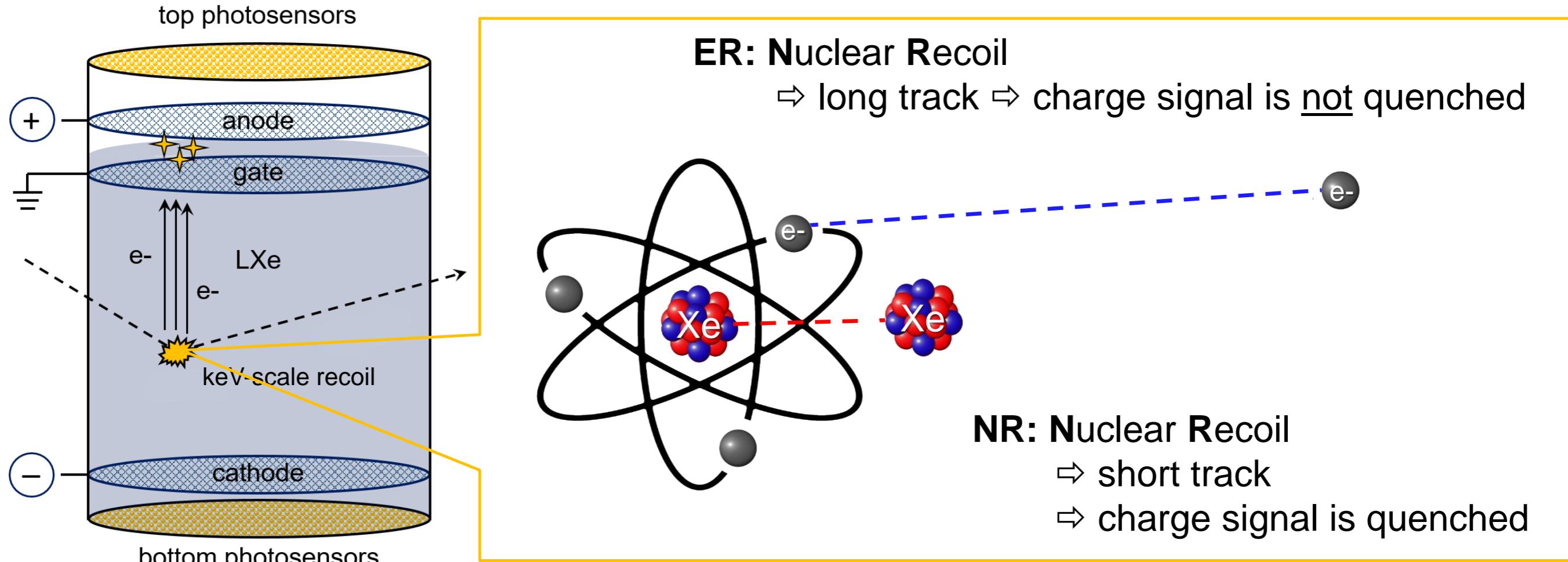


ADDITIONAL TRANSPARENCIES

DARWIN: signal-background discrimination

■ S/B discrimination: ratio of light and charge is different for NR and ER

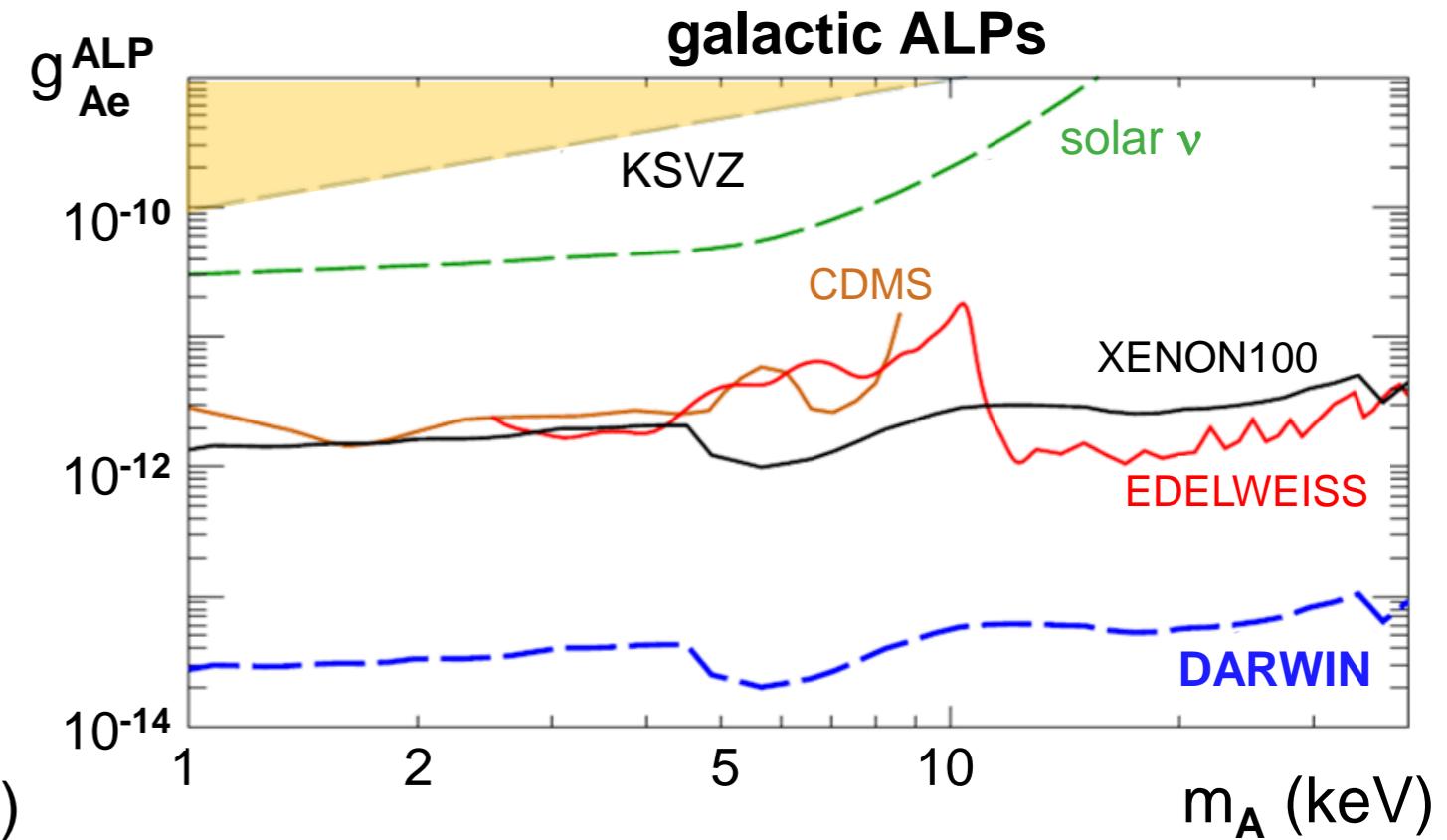
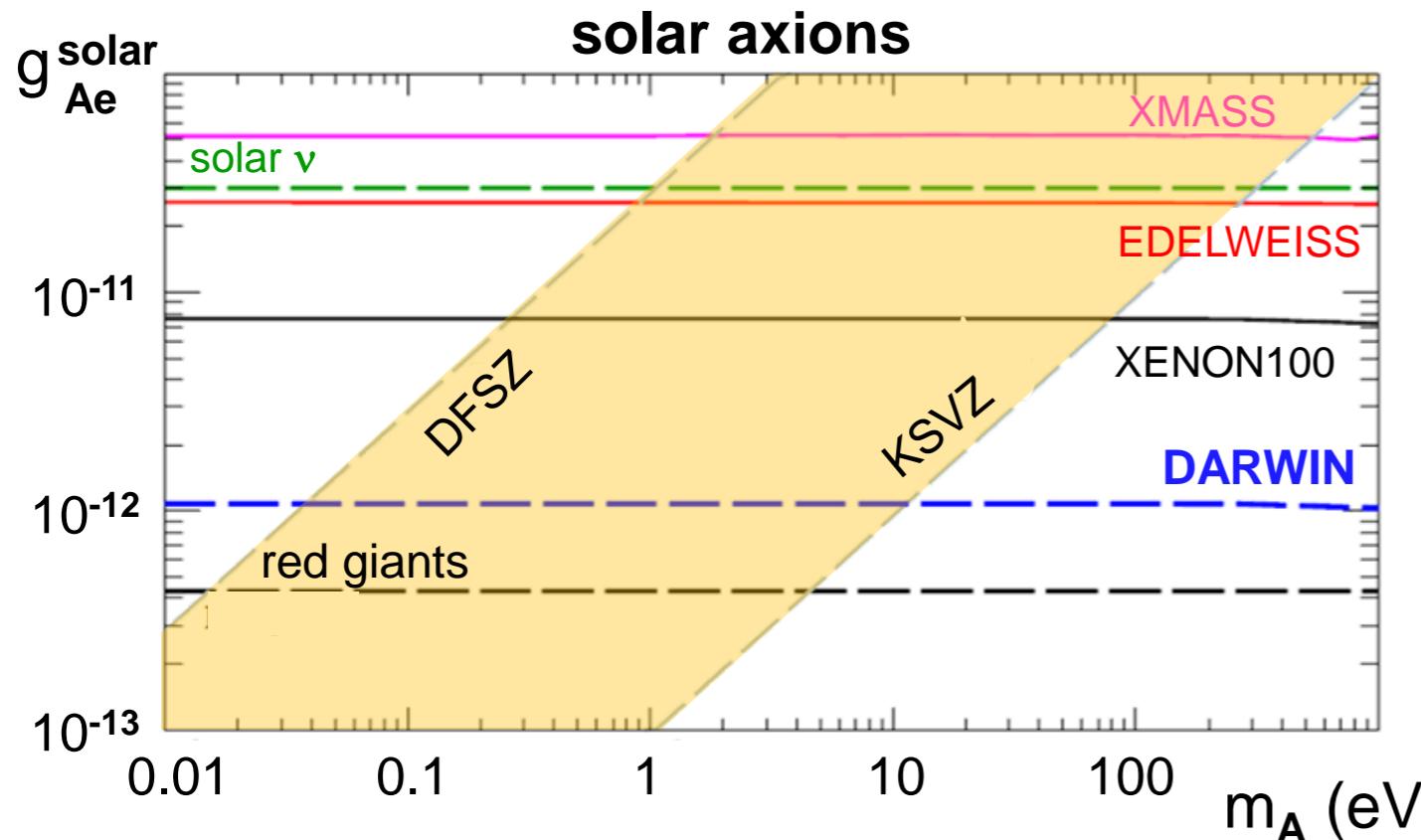
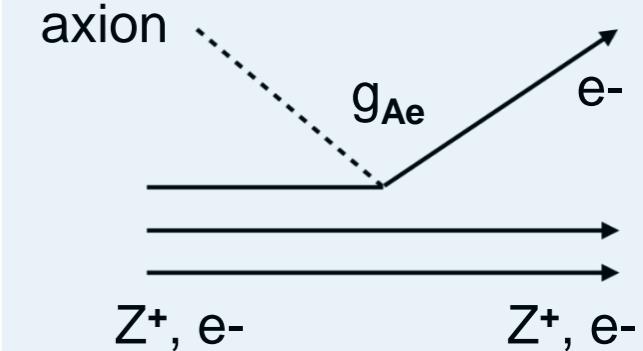
- ⇒ WIMP signal: Nuclear Recoil (NR)
- ⇒ WIMP background: Electron Recoil (ER) (from gammas)



sensitivity to axions & ALPs

■ solar axions and galactic ALPs (Axion Like Particles)

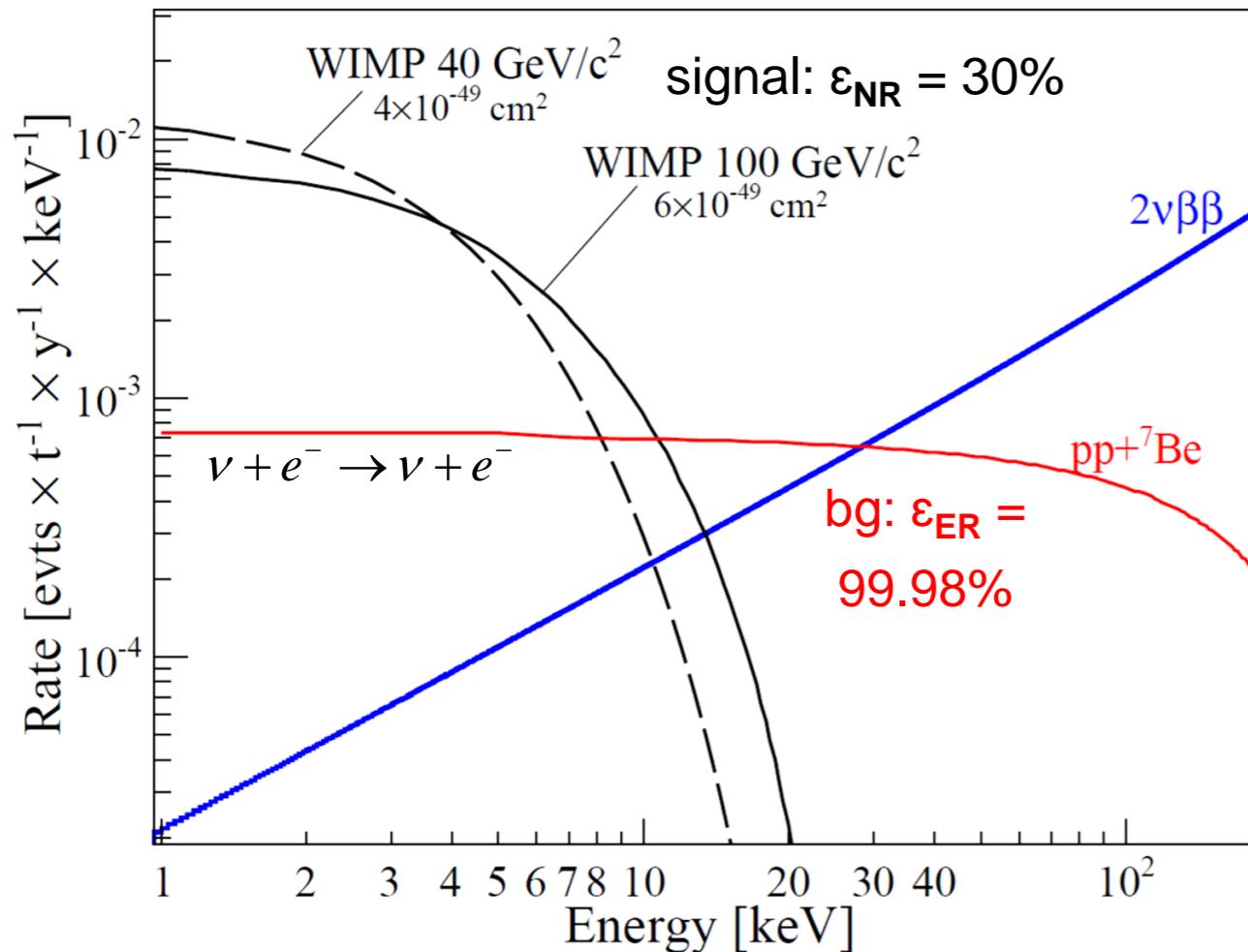
- **detection**: via axio-electric effect (coupling to e- results in ionisation)
- **signature**: mono-energetic peak at axion mass in **ER channel**
- exposure ($M \cdot T$) [ton·y] scales as $g_{Ae}^{solar} \propto (M \cdot T)^{-1/8}$ $g_{Ae}^{ALP} \propto (M \cdot T)^{-1/4}$



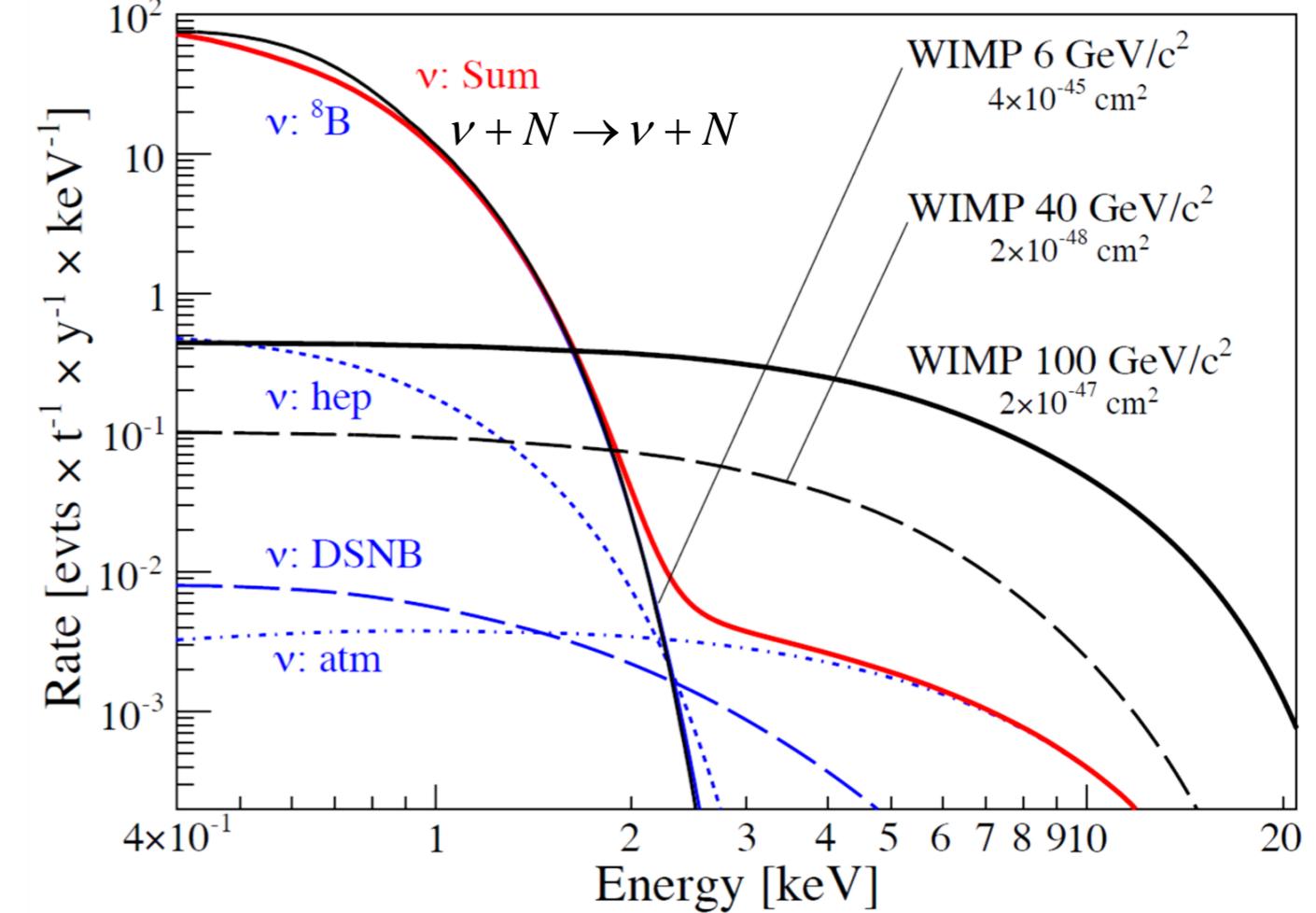
neutrino backgrounds in ER and NR channels

- ν -interactions: an irreducible background for WIMPs, in NR channel: **CNNS** via $\nu + N \rightarrow \nu + N$
CNNS: ${}^8\text{B}$ - ν 's $\sim 10^3$ evts $t^{-1} y^{-1}$ (below 3 keV), atmospheric ν 's dominant bg for $m_{\text{WIMP}} > 10$ GeV

ER channel: ν -background via $\nu + e^- \rightarrow \nu + e^-$



NR channel: ν -background via $\nu + N \rightarrow \nu + N$



science case: sensitivity to keV-mass sterile ν's

■ Sterile neutrinos in keV-mass range N_s could contribute to DM content of universe

- detection of galactic halo sterile ν's via inelastic CC & NC scattering off bound electrons

$$N_s + e^- \rightarrow \nu_e + e^- \quad N_s + e^- \rightarrow \bar{\nu}_e + e^-$$

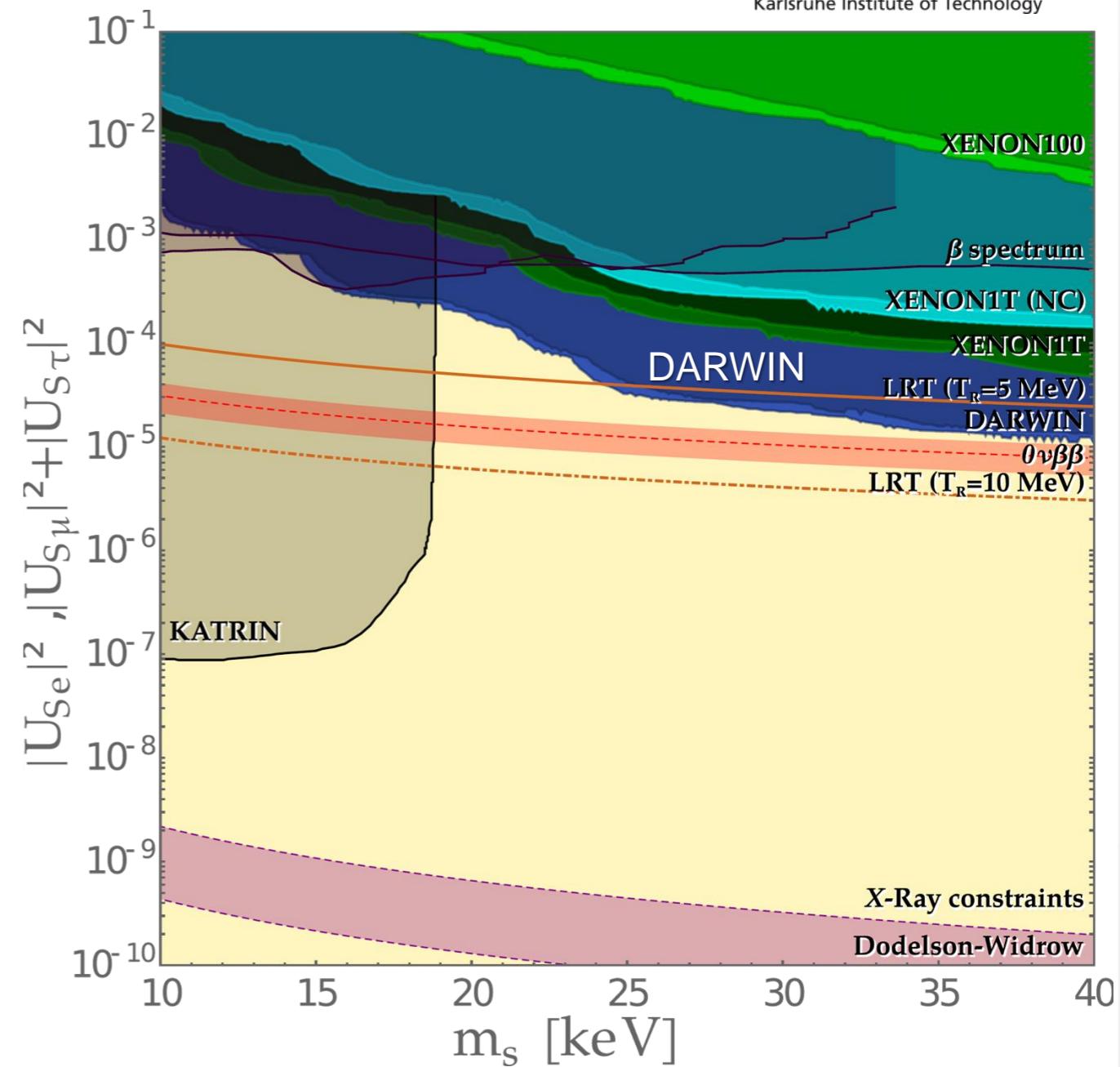
- rate is suppressed by mixing of N_s with active ν-flavours ν_α : $\sim |U_{s\alpha}|^2$

■ Signature & sensitivity:

- electrons in keV-energy range in ER channel
- sensitivity depends on exposure (ton·y) and actual bg-level in ER channel (fiducial vol.)

M.D. Campos, W. Rodejohann, arXiv:1605.02918v1

Testing keV sterile neutrino dark matter in future direct detection experiments

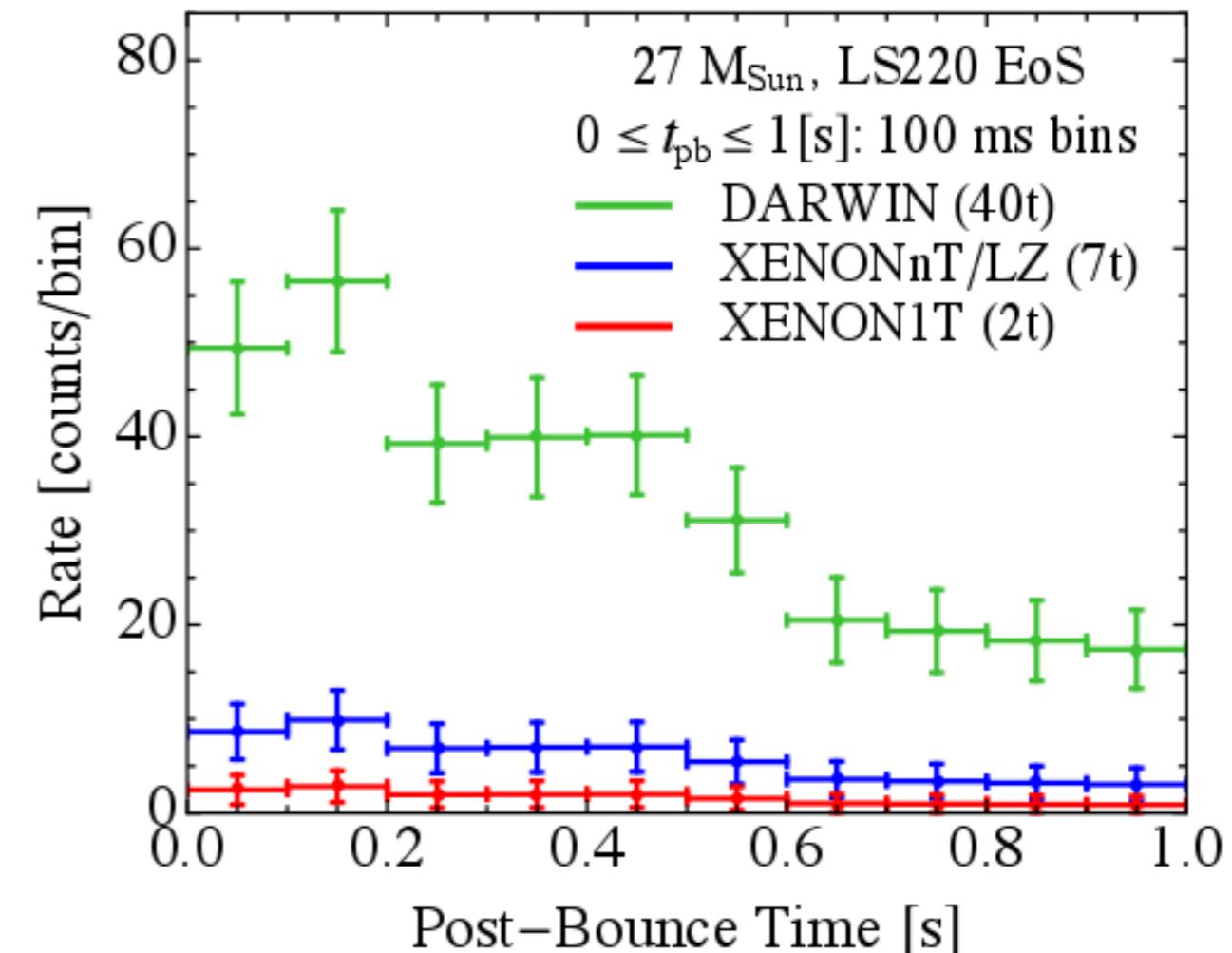
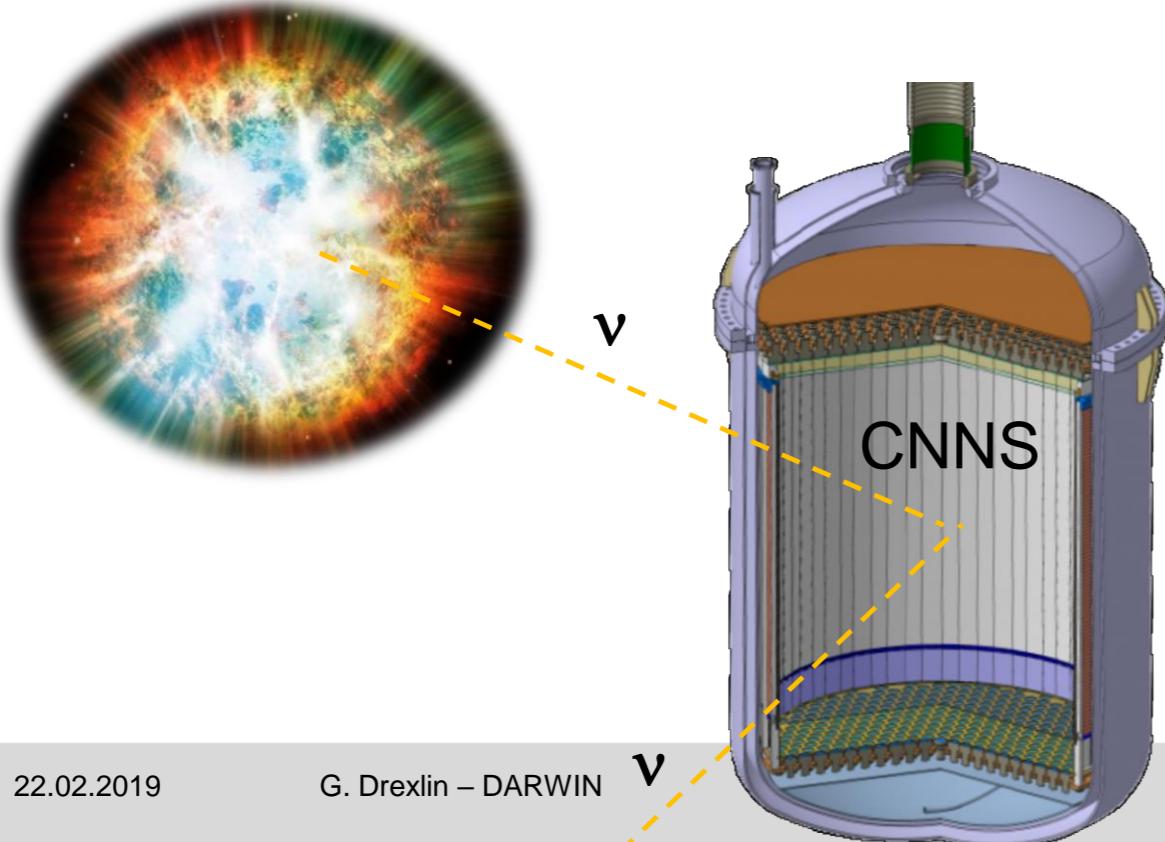


Supernova neutrinos

■ unique discovery potential beyond the ultimate WIMP search

a premier **astrophysical observatory** for bolometric flux of supernova neutrinos (CNNS)

5 σ significance of **SN- ν 's**
for core-collapse at $d = 70$ kpc
via coherent ν -scattering (CNNS)



Xenon physical properties

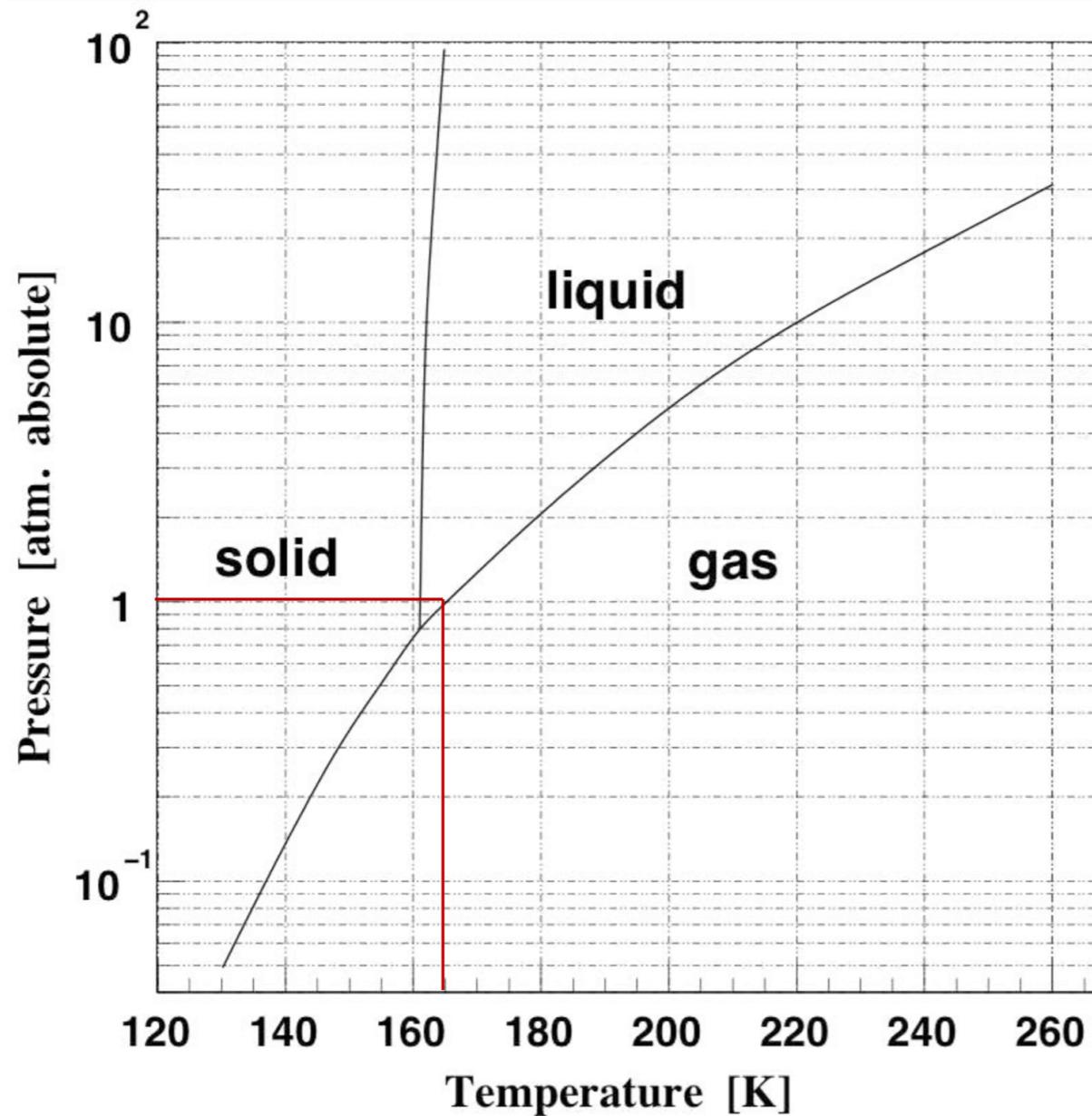
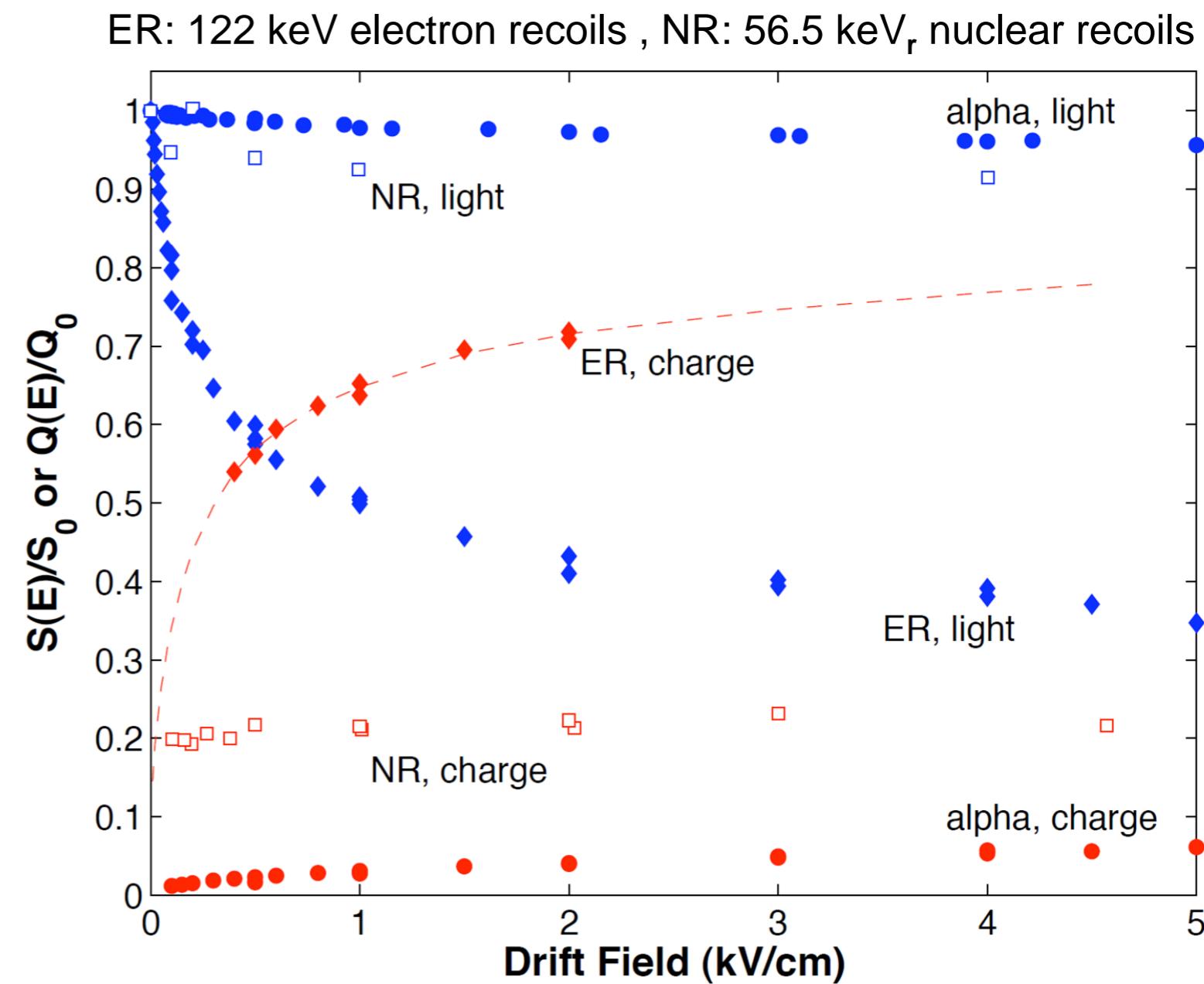
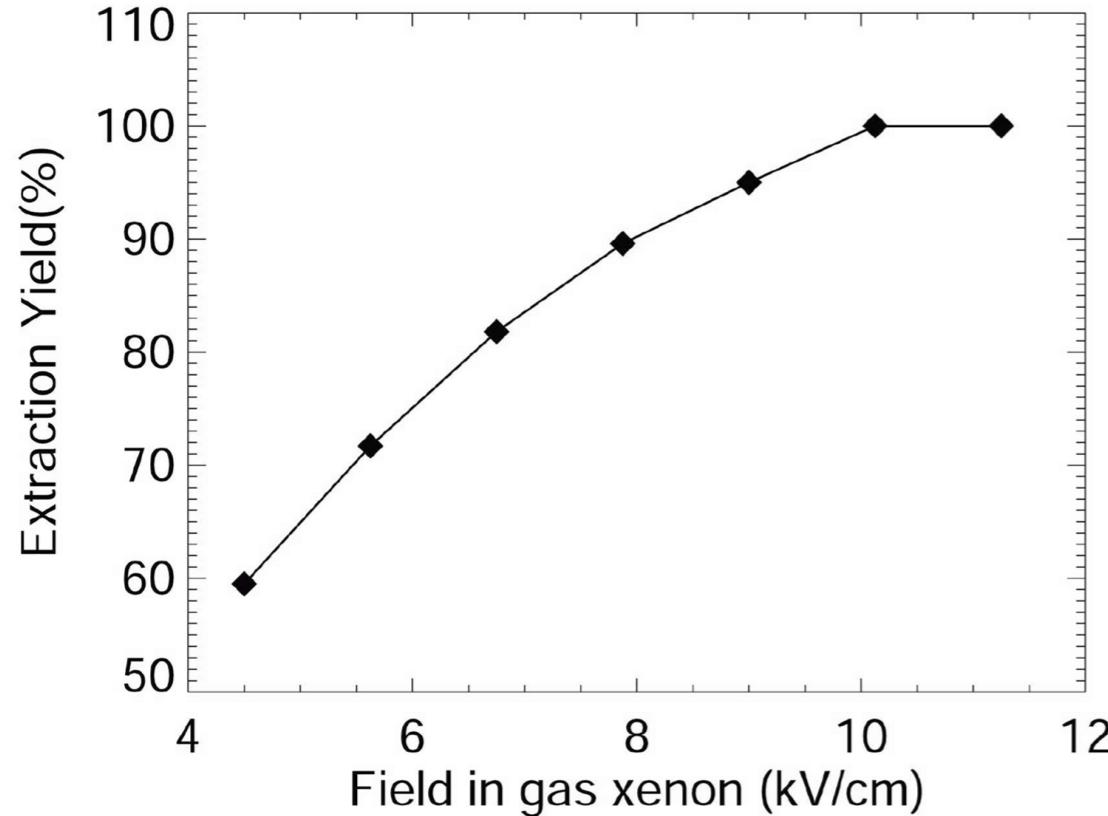


TABLE I Physical Properties of Liquid Xenon

Property	Value
Atomic number Z	54
Isotopes	$^{124}\text{Xe}(0.09\%)$, $^{126}\text{Xe}(0.09\%)$, $^{128}\text{Xe}(1.92\%)$, $^{129}\text{Xe}(26.44\%)$ $^{130}\text{Xe}(4.08\%)$, $^{131}\text{Xe}(21.18\%)$ $^{132}\text{Xe}(26.89\%)$, $^{134}\text{Xe}(10.44\%)$ $^{136}\text{Xe}(8.87\%)$
Mean atomic weight A	131.30
Density	$3 \text{ g}\cdot\text{cm}^{-3}$
Boiling point	$T_b = 165.05 \text{ K}$, $P_b = 1 \text{ atm}$ $\rho_b = 3.057 \text{ g}\cdot\text{cm}^{-3}$
Critical point	$T_c = 289.72 \text{ K}$, $P_c = 58.4 \text{ bar}$ $\rho_c = 1.11 \text{ g}\cdot\text{cm}^{-3}$
Triple point	$T_t = 161.3 \text{ K}$, $P_t = 0.805 \text{ bar}$ $\rho_t = 2.96 \text{ g}\cdot\text{cm}^{-3}$
Volume ratio (ρ_{liquid}/ρ_{gas})	519
Thermal properties	
Heat capacity	$10.65 \text{ cal}\cdot\text{g}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$ for $163 - 166 \text{ K}$
Thermal conductivity	$16.8 \times 10^{-3} \text{ cal}\cdot\text{s}^{-1}\cdot\text{cm}^{-1}\cdot\text{K}^{-1}$
Latent heat of a) evaporation at triple point	$3048 \text{ cal}\cdot\text{g}\cdot\text{mol}^{-1}$
b) fusion at triple point	$548.5 \text{ cal}\cdot\text{g}\cdot\text{mol}^{-1}$
Electronic properties	
Dielectric constant	$\epsilon_r = 1.95$

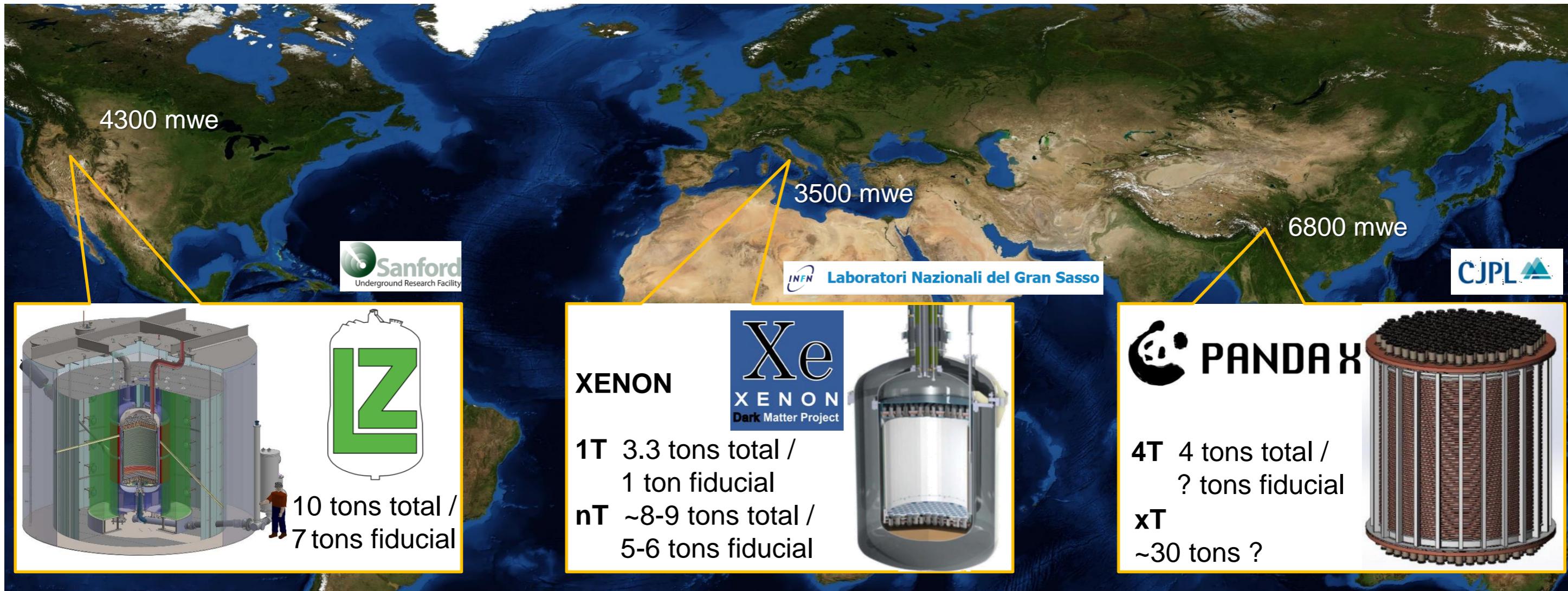
drift- & extraction field values of electrons in xenon

- **drift field** (0.5-1 kV/cm) influences
ER-signal from scintillation & charge
- **extraction field** (5-10 kV/cm) influences
extraction yield of charge signal



Liquid noble gas (xenon) experiments for WIMPs

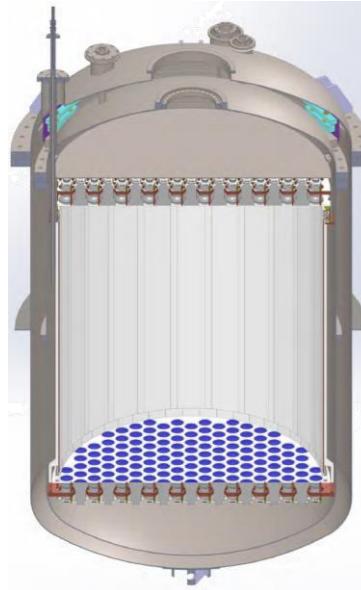
- Future two-phase liquid noble gas (xenon) detectors with **multi-ton target mass**:
LZ experiment @ SURF / XENON1T-nT @ LNGS / PandaX-xT @ CJPL



xenon applications – dark matter & $0\nu\beta\beta$

■ xenon-based DM experiments & search for $0\nu\beta\beta$ in Xe-136

Xe
XENON
Dark Matter Project



-nT

~8 tons of ^{nat}Xe

- procurement of xenon completed, >8 t gas in hand
- long-term runs 2019-23 planned
- assume: use xenon for DARWIN...



-experiment



~10 tons of ^{nat}Xe

- procurement of xenon completed (soon?)
- long-term runs planned until 2023, 2024+ running?
- assume: stays in US



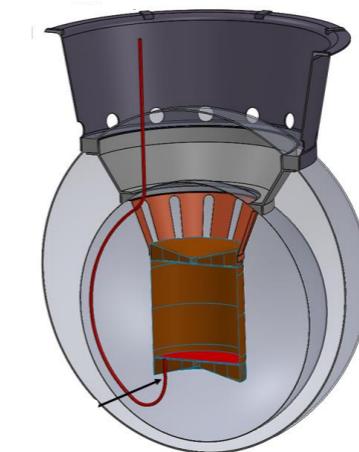
PANDAX -4T



6 tons of ^{nat}Xe

- 0.5 t from PANAX-II
- ~ up to 6 t of ^{nat}Xe**
- long term runs from 2020ff
- plans for ultimate larger dual-phase detector (**30 tons?**)

nEXO

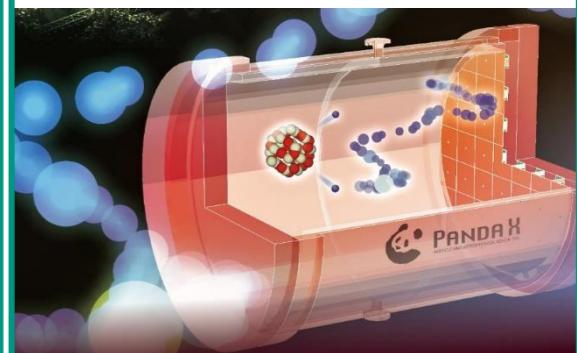


5 tons of ^{enr}Xe

- needs to process ~ **50 t of ^{nat}Xe**
- enrichment in Russia with ~1 t ^{enr}Xe / year
- depleted Xe returned to manufacturers (restocking fee?)



PANDAX -III



0.2-1 ton of ^{enr}Xe

- needs to process ~ **up to 10 t of ^{nat}Xe**
- enrichment tbd
- depleted Xe to be used by PandaX-xT?
- a guide for nEXO?

purification of xenon by cryogenic distillation

- **crude gas** from ASU is shipped to **purification plants**
only ~ 20 world-wide [status 2018] (US, China, D, F, RUS, Ukraine)
 - purification capacity is 2-3 x capacity of crude gas (some plants seemingly not fully used)
 - plant separates & purifies xenon to 99.999% via **distillation columns**

