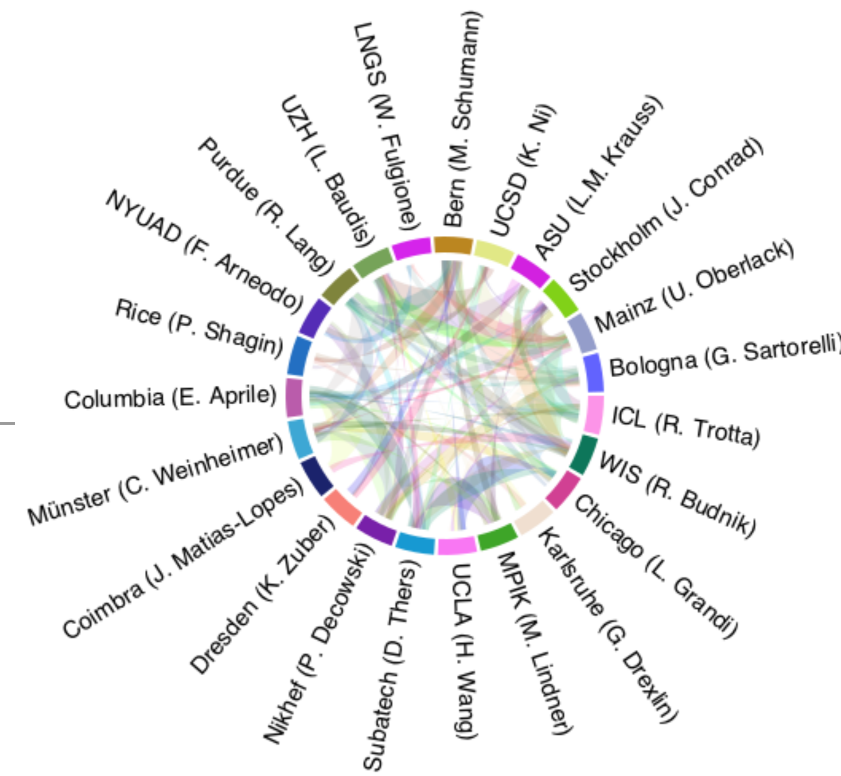
Universität Zürich[UZH]

# Dark matter and other rare event searches with

# DARWIN

darwin-observatory.org





Laura Baudis
University of Zurich
(for the DARWIN Consortium)

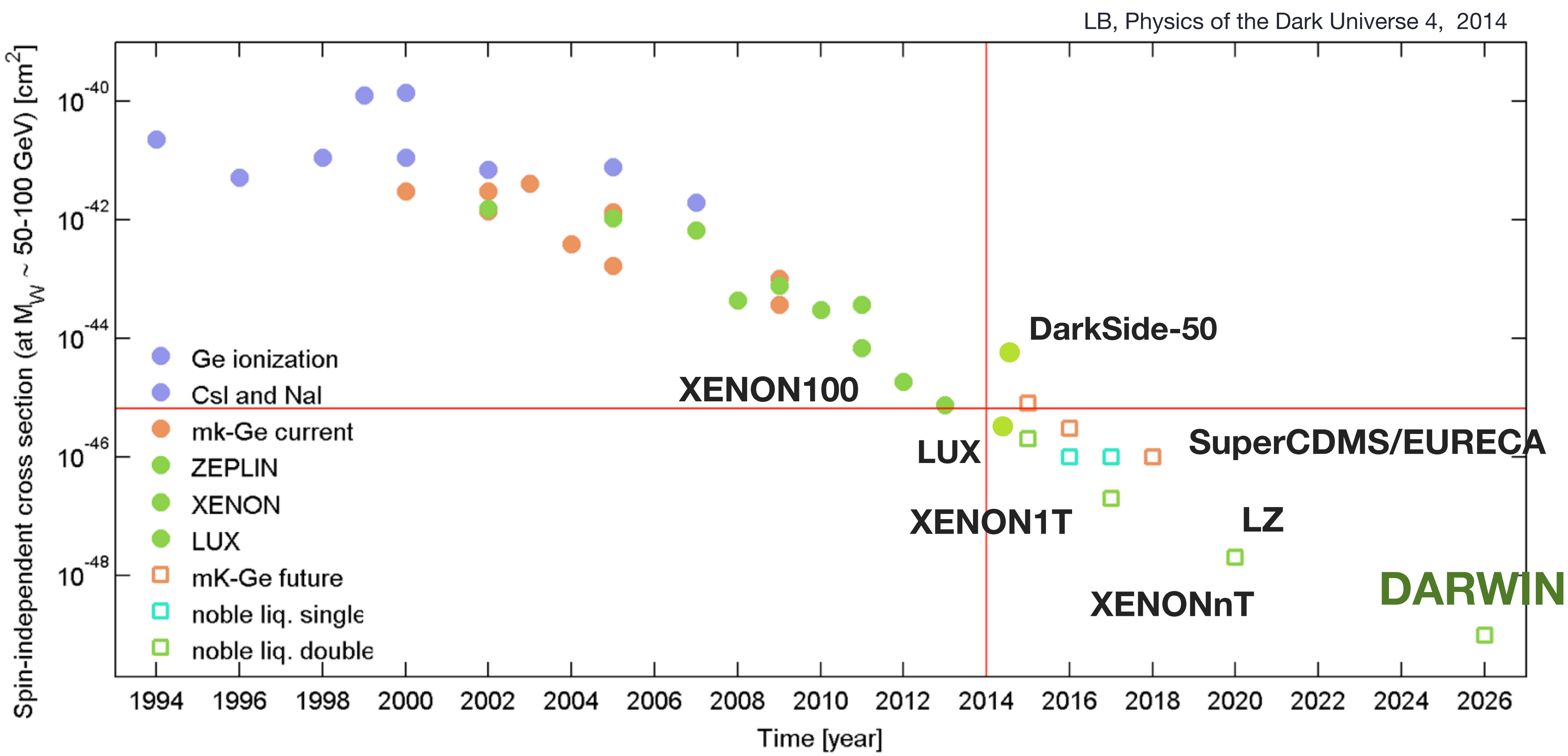

UCLA Dark matter
Los Angeles, February 19, 2016

# DARWIN General Goals

- Build a dark matter detector capable of exploring the experimentally accessible parameter space for WIMP dark matter

- Base this detector on a TPC filled with Xe in its liquid form, a concept successfully proven by the ZEPLIN, XENON, LUX and PandaX programs

- Reach a low energy threshold and an ultra-low background *before* ER/NR discrimination, and probe a variety of other physics channels



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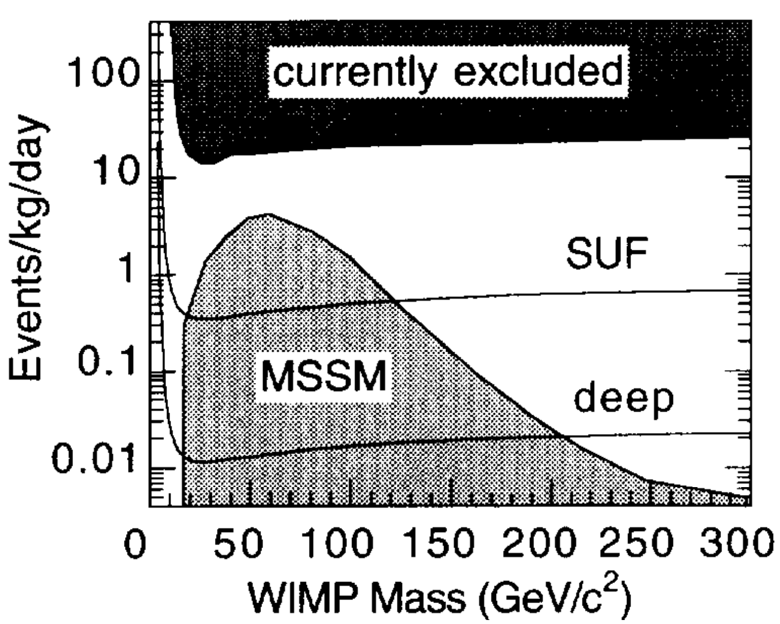
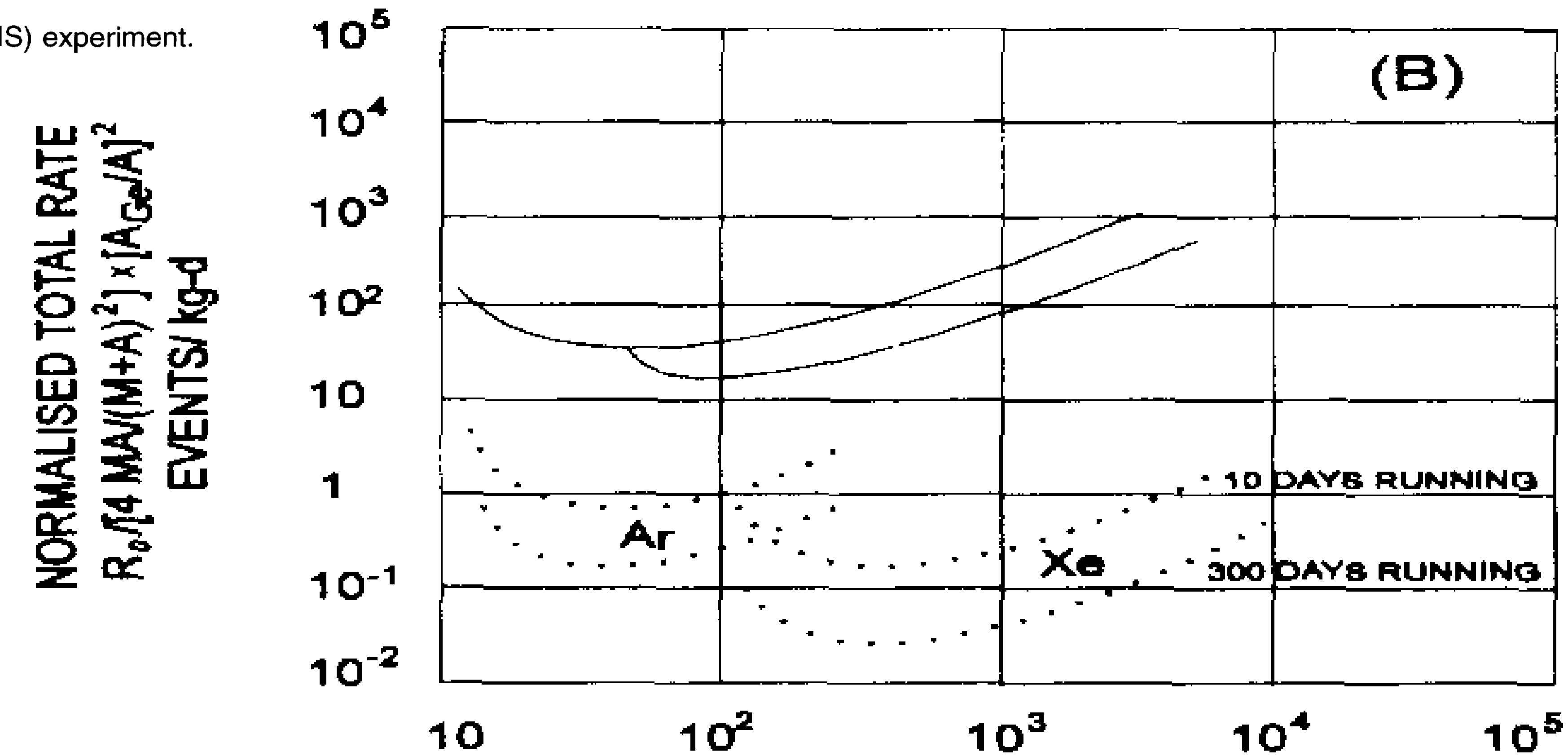
Progress of the Cryogenic Dark Matter Search (CDMS) experiment.




On a discriminating liquid-xenon detector for SUSY dark-matter observation

David B. Cline



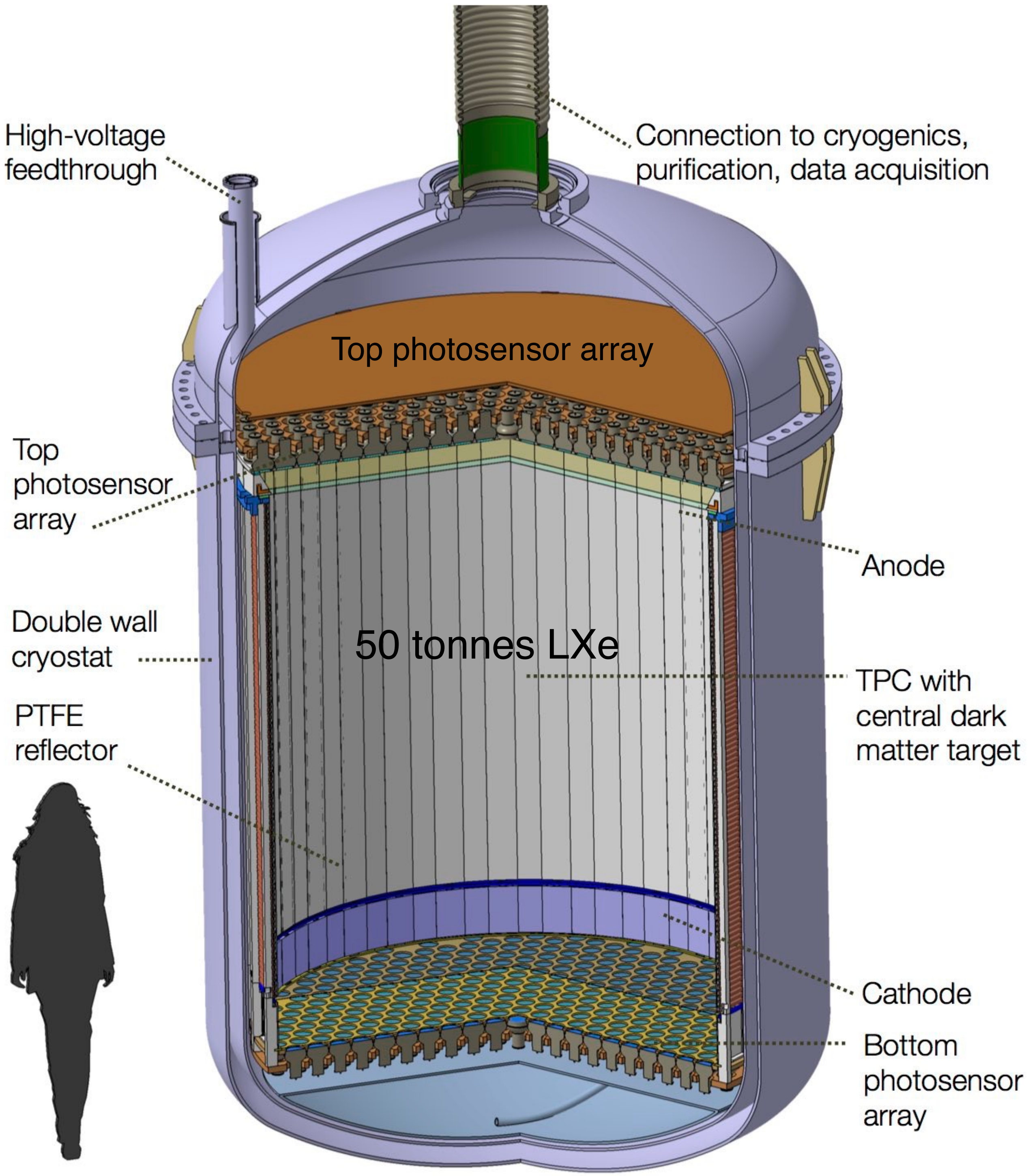

Nuclear Physics B (Proc. Suppl.) 51B (1996) 304–313

# DARWIN Science Goals

- **Probe WIMP-nucleon interactions for WIMP masses above ~5 GeV/$c^2$**
  - via spin-independent, spin-dependent and inelastic interactions
  - probe even lower WIMP masses by using the charge signal alone

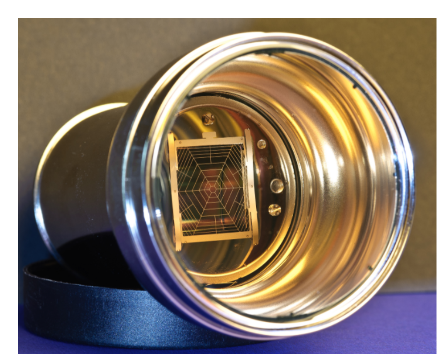
- Look for signatures of DM scattering off electrons
- Detect solar neutrinos: pp-neutrinos via nu-e scattering, $^{8}$B coherent nu scattering
- Search for the neutrinoless double beta decay in $^{136}$Xe
- Probe interaction of axions and axion-like particles, via the axio-electric effect
- Probe sterile neutrinos with masses in the > 10 keV range
- Probe bosonic SuperWIMPs via their absorption by Xe atoms

# DARWIN TPC baseline concept




Bottom photosensor array

- 50 t LXe in total
- 40 t LXe in the TPC
- ~ $10^3$ photosensors
- 2.6 m drift length
- 2.6 m diameter TPC
- PTFE reflectors, Cu field shaping rings
- Background: dominated by neutrinos

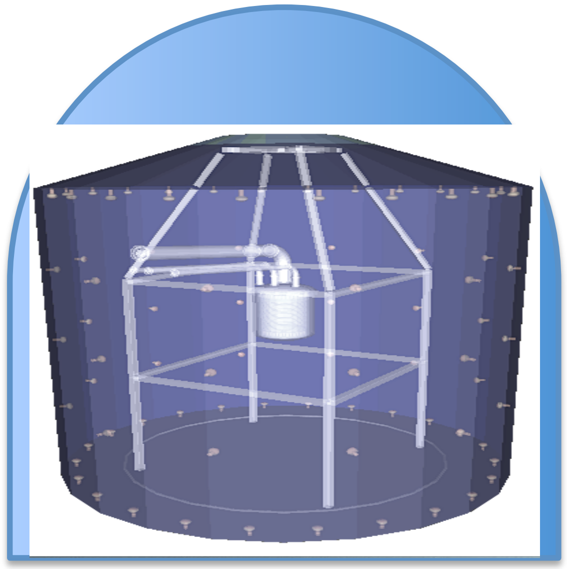


3-inch PMT, R11410-21

4-inch PMT

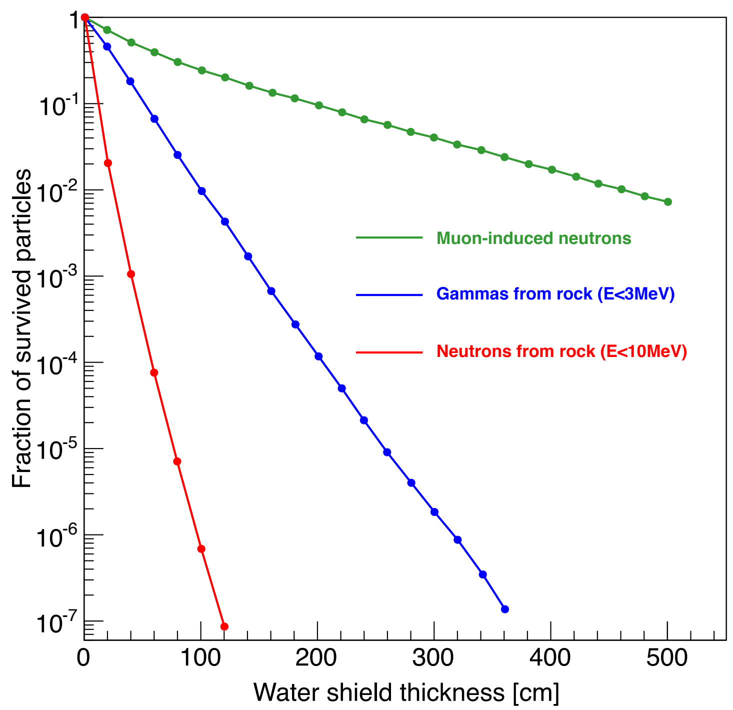
# Backgrounds: nuclear recoils

- **Radiogenic** goal: ~4 x $10^{-5}$ events/(t y) in 30 t fiducial
    - active LS veto around cryostat under study
- **Cosmogenic** (MC: 7.3 x $10^{-10}$ n/(cm$^2$ s) for $E_n$ > 10 MeV)
    - <0.01 events/(t y) in XENON1T/nT shield
    - **<<0.003 events/(t y) in 14 m diameter water shield**
- **XENON1T muon veto performance must be improved by ~ a factor of 10 (conservative)**
- Alternative: line the experimental hall with muon veto - possibility under study via MC



DARWIN in 14 m ø water Cherenkov shield

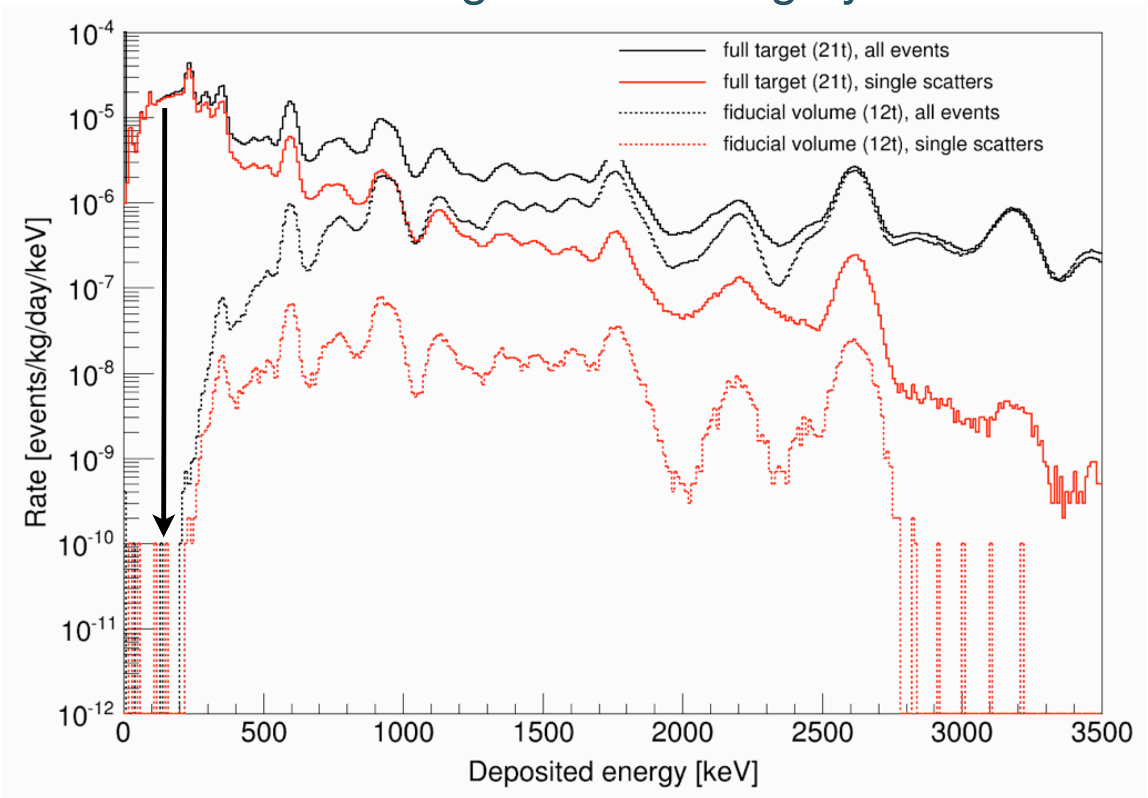
MC simulation for XENON1T



# Backgrounds: electronic recoils

- Materials (cryostat, photosensors, TPC)
- $^{222}$Rn in LXe
- $^{nat}$Kr in LXe ($^{nat}$Kr contains 2 x $10^{-11}$ $^{85}$Kr)
- $^{136}$Xe double beta decay
- Solar neutrinos (mostly pp, $^{7}$Be)

Materials: strong self-shielding by dense LXe




| Channel | Before discr | After discr (99.98%) |
|---|---|---|
| **pp + $^{7}$Be neutrinos** | **95** | **0.488** |
| Materials | 1.4 | 0.007 |
| $^{85}$Kr in LXe (0.1 ppt $^{nat}$Kr) | 40.4 | 0.192 |
| $^{222}$Rn in LXe (0.1 μBq/kg) | 9.9 | 0.047 |
| $^{136}$Xe | 56.1 | 0.036 |

1 t x yr exposure,
2-30 keVee

200 t x yr exposure
4-50 keVnr, 30% acceptance

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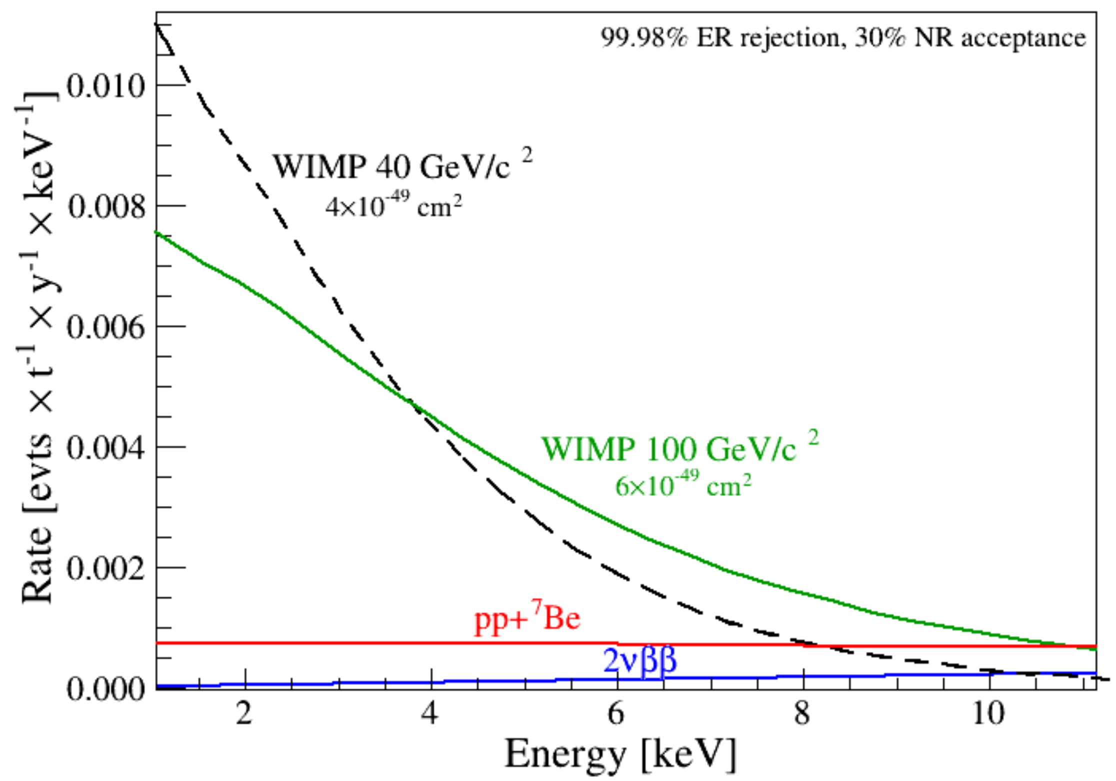
WIMPs and ER backgrounds

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# WIMP physics with xenon nuclei

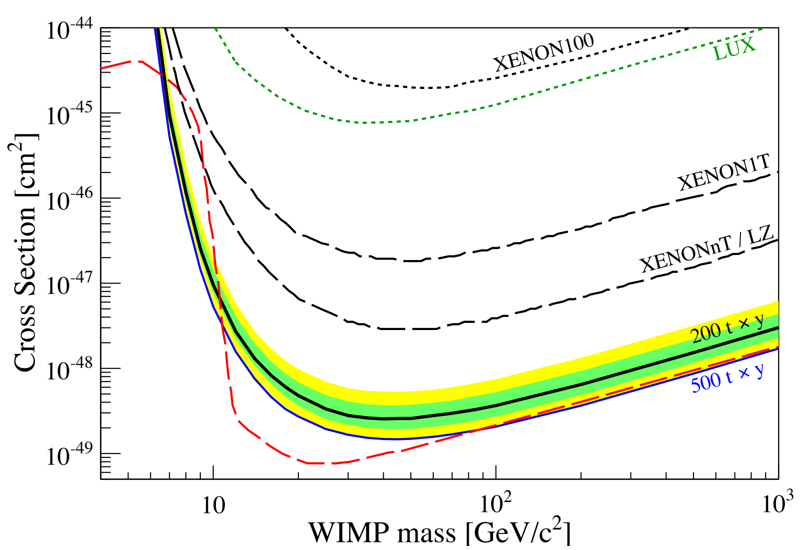
**Probe WIMP-Xe interactions via:**

- spin-independent elastic scattering: $^{124}$Xe, $^{126}$Xe, $^{128}$Xe, $^{129}$Xe, $^{130}$Xe, $^{131}$Xe, $^{132}$Xe (26.9%), $^{134}$Xe (10.4%), $^{136}$Xe (8.9%)
- spin-dependent elastic scattering: $^{129}$Xe (26.4%), $^{131}$Xe (21.2%)
- inelastic WIMP-$^{129}$Xe and WIMP-$^{131}$Xe scatters $\chi + {}^{129,131}Xe \rightarrow \chi + {}^{129,131}Xe^* \rightarrow \chi + {}^{129,131}Xe + \gamma$

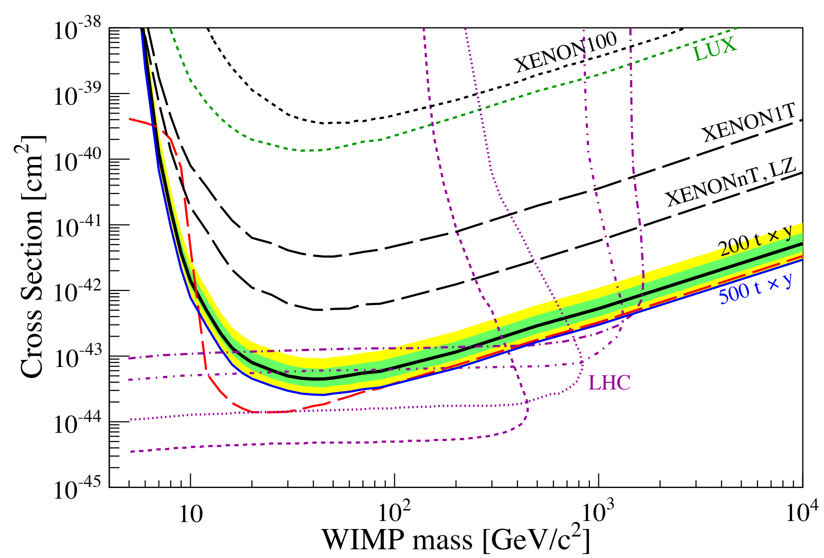
1 ns, 0.5 ns

40 keV, 80 keV

SI, elastic WIMP-nucleus

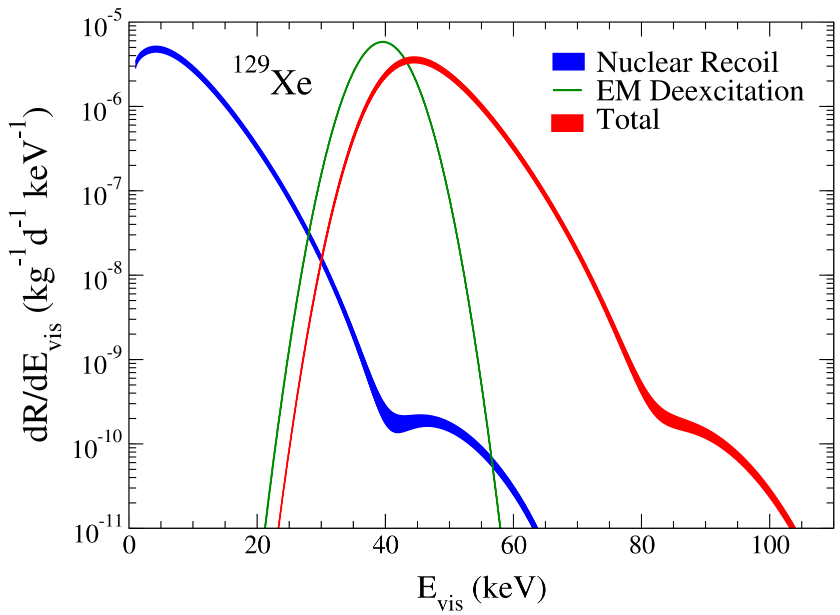



SD, elastic WIMP-nucleus




M. Schumann et al., JCAP10 (2015) 016

SD, inelastic WIMP-nucleus

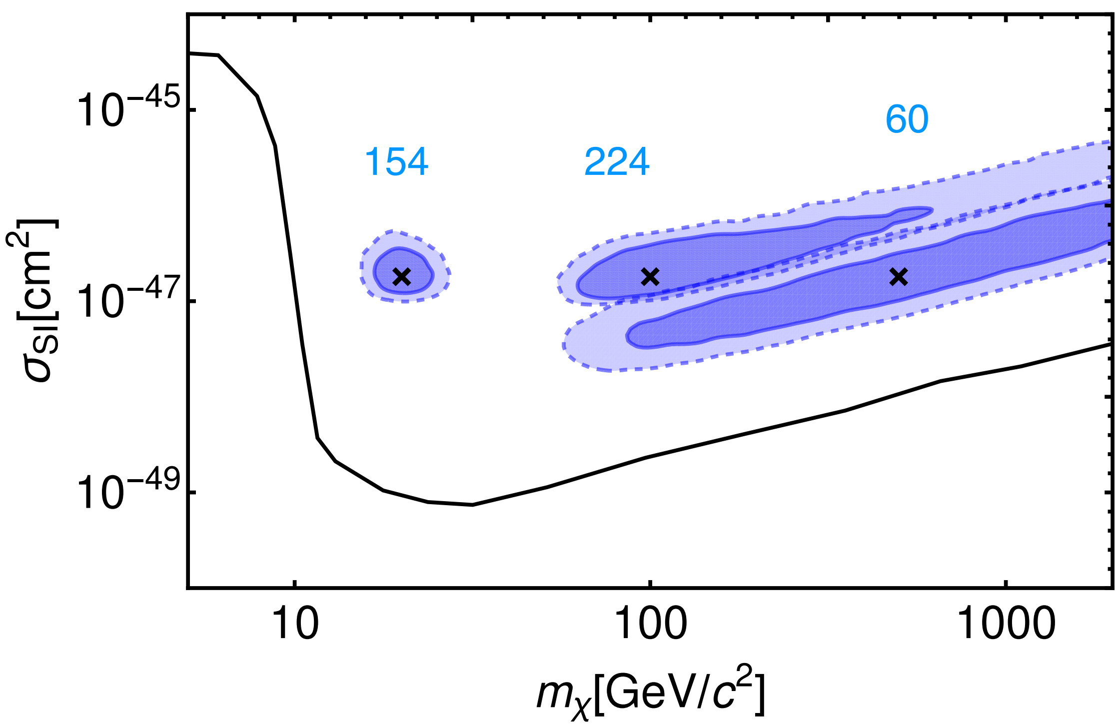



L. Baudis et al, Phys. Rev. D 88, 115014 (2013)

# WIMP physics: spectroscopy

- Capability to reconstruct the WIMP mass and cross section for various masses - here **20, 100, 500 GeV/c$^2$** - and cross sections

**Exposure: 200 t y**

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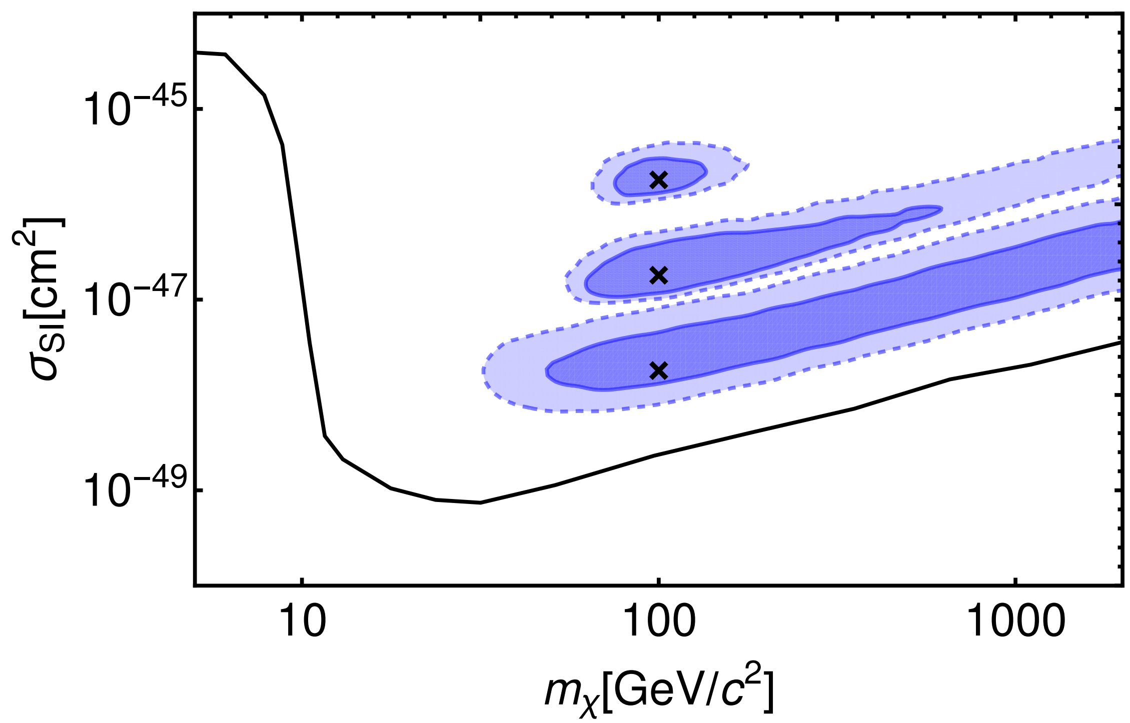



**1 and 2 sigma credible regions after marginalising the posterior probability distribution over:**

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

$$v_0 = 220 \pm 20\,\mathrm{km/s}$$

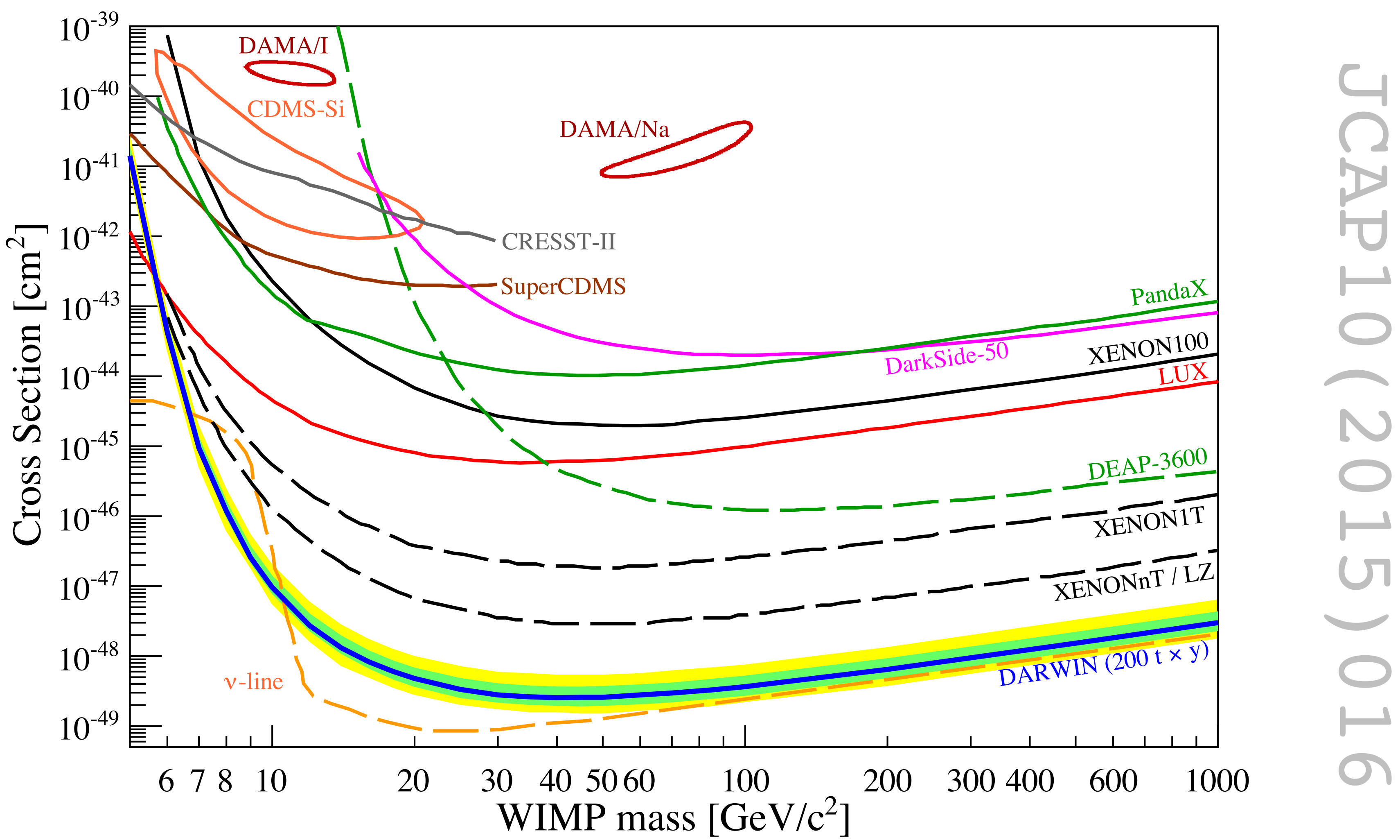
$$\rho_\chi = 0.3 \pm 0.1\,\mathrm{GeV/cm^3}$$

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

# WIMP physics: sensitivity for SI scattering

- E = [3-70] pe ~ [4-50] $keV_{nr}$

200 t y exposure, 99.98% discrimination, 30% NR acceptance, LY = 8 pe/keV at 122 keV



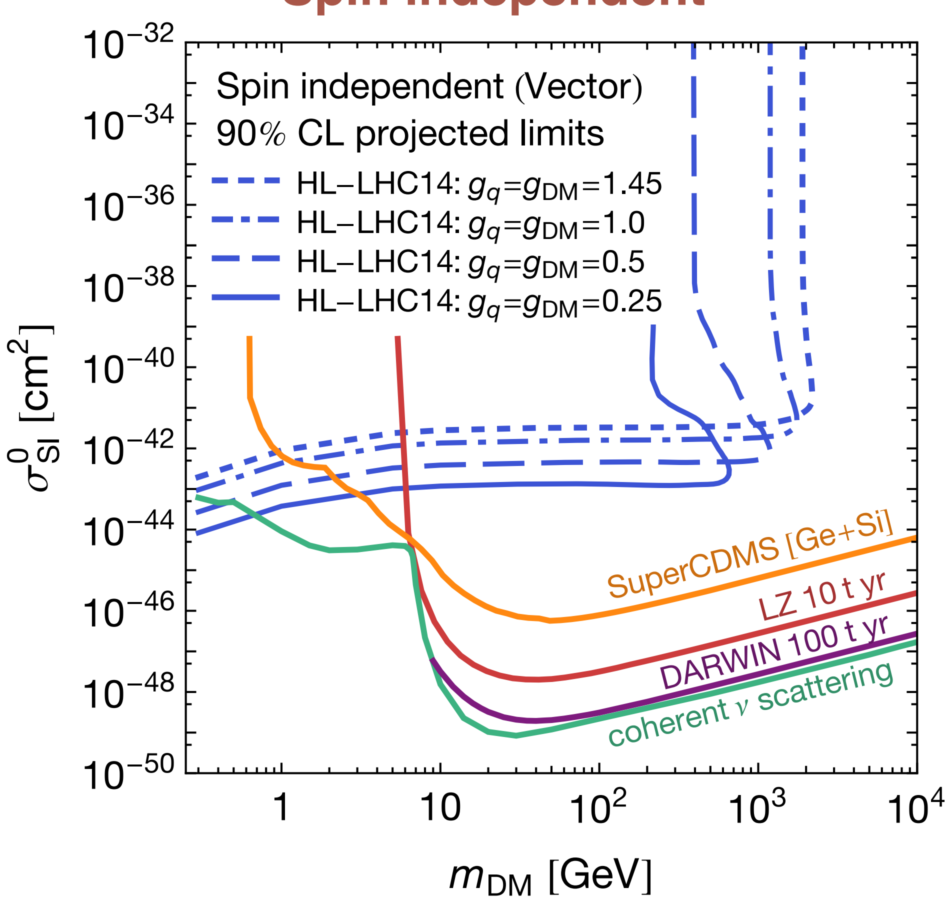

Note: “nu floor” = 3-sigma detection line at 500 CNNS events above 4 keV

# WIMP physics: complementarity with the LHC

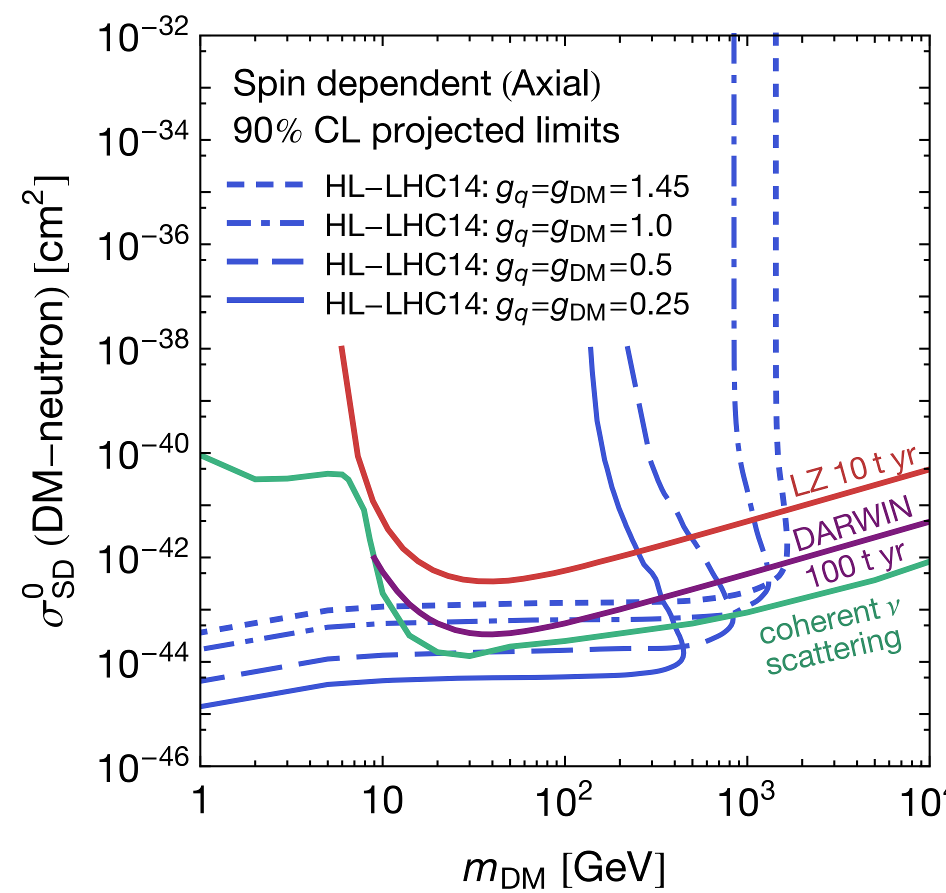
- Minimal simplified DM model with only 4 variables: $m_{DM}$, $M_{med}$, $g_{DM}$, gq
- Here DM = Dirac fermion interacting with a vector or axial-vector mediator; equal-strength coupling to all active quark flavours

$$\sigma_{\rm DD} \propto \frac{g_{\rm DM}^2 g_q^2 \mu^2}{M_{\rm med}^4}$$

**Spin independent**




**Spin dependent**




S. Malik et al., Phys. Dark Univ. 9-10 (2015) 51-58

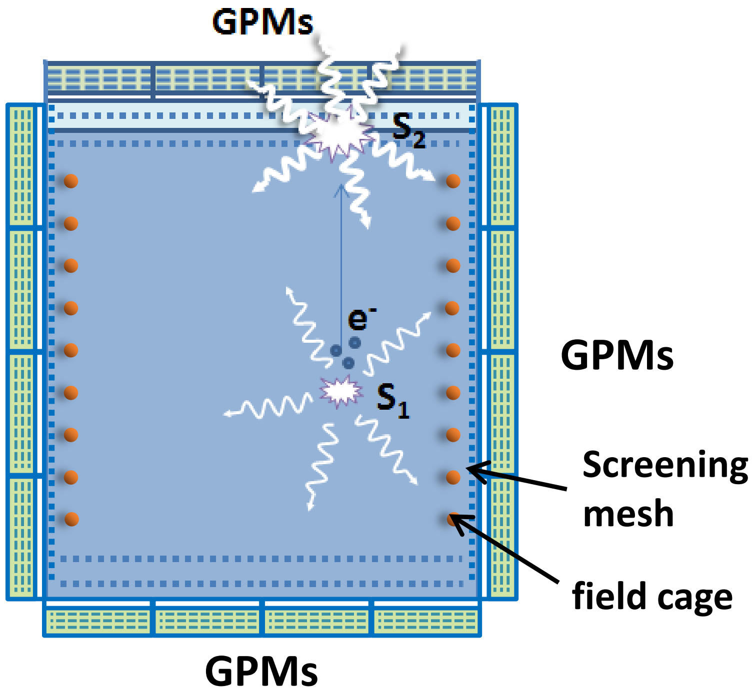
# Technical challenge: discrimination

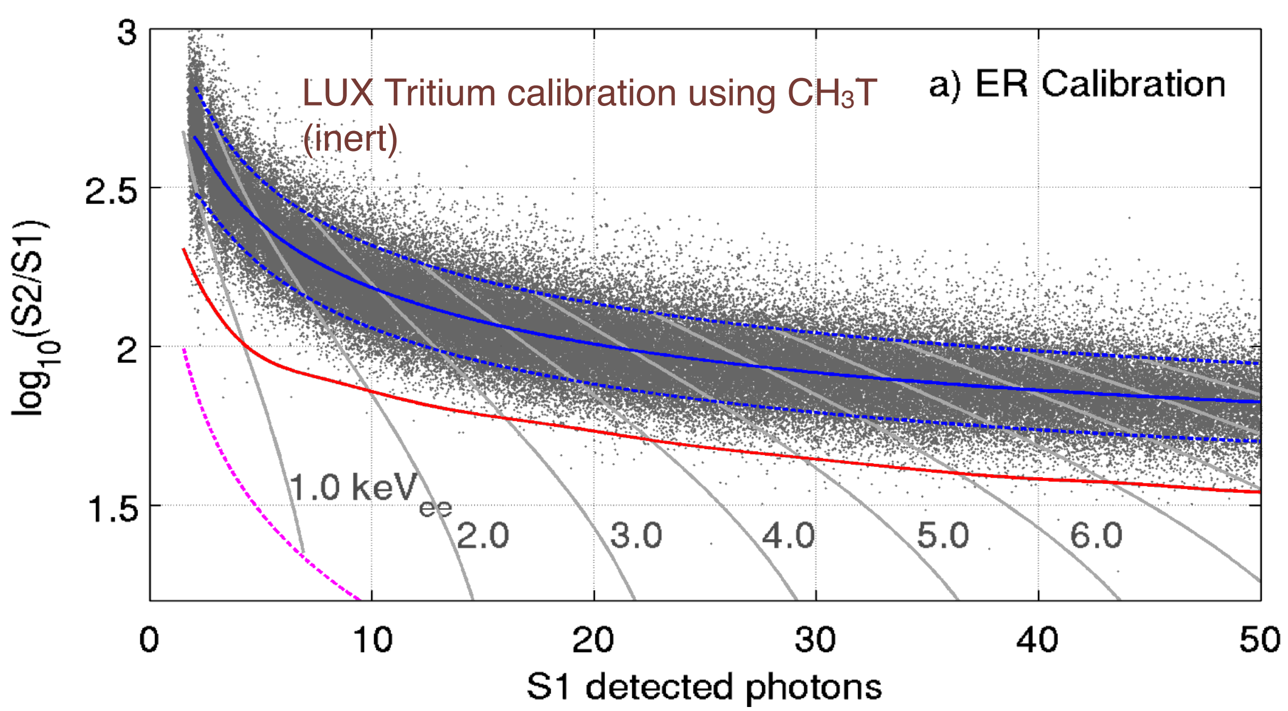
- A level of 99.98% needs factor of 5 improvement w.r.t. XENON100

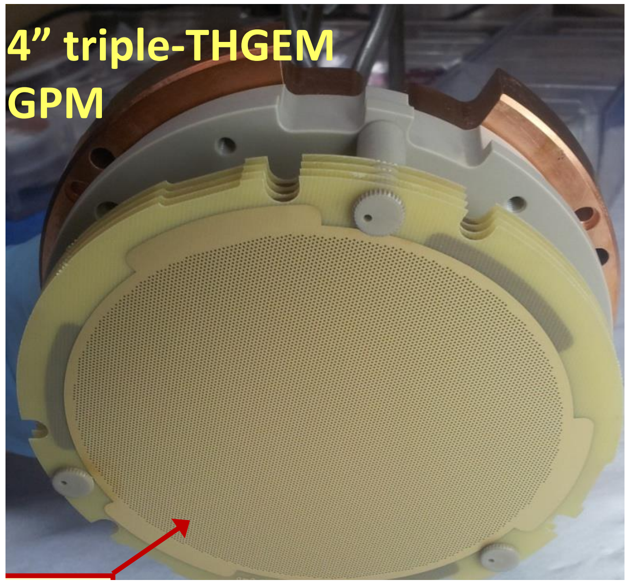
  ➡ high light yield - R&D for high (4-pi) coverage with photosensors is ongoing; options are high QE PMTs, SiPMs and/or GPMs; single-phase TPC also under study

  ➡ strong R&D program in place

  ➡ high stats ER band calibrations - internal sources, for instance tritiated methane à la LUX; also $^{220}$Rn as in XENON1T



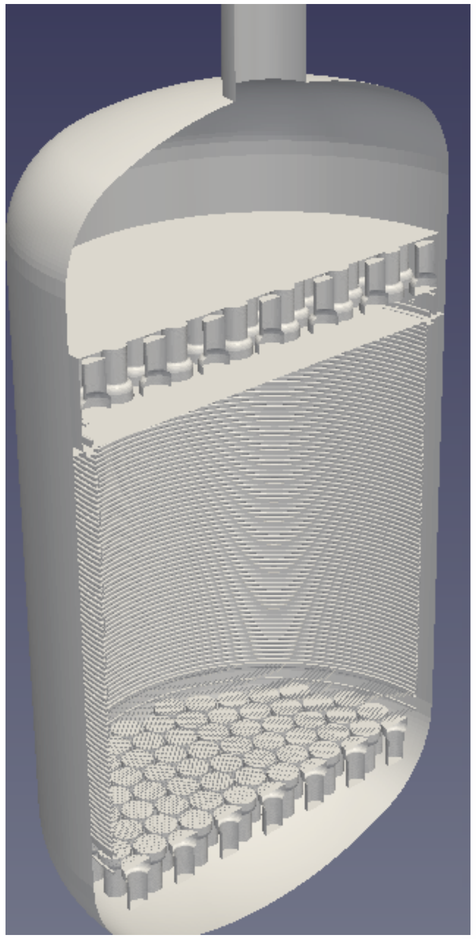



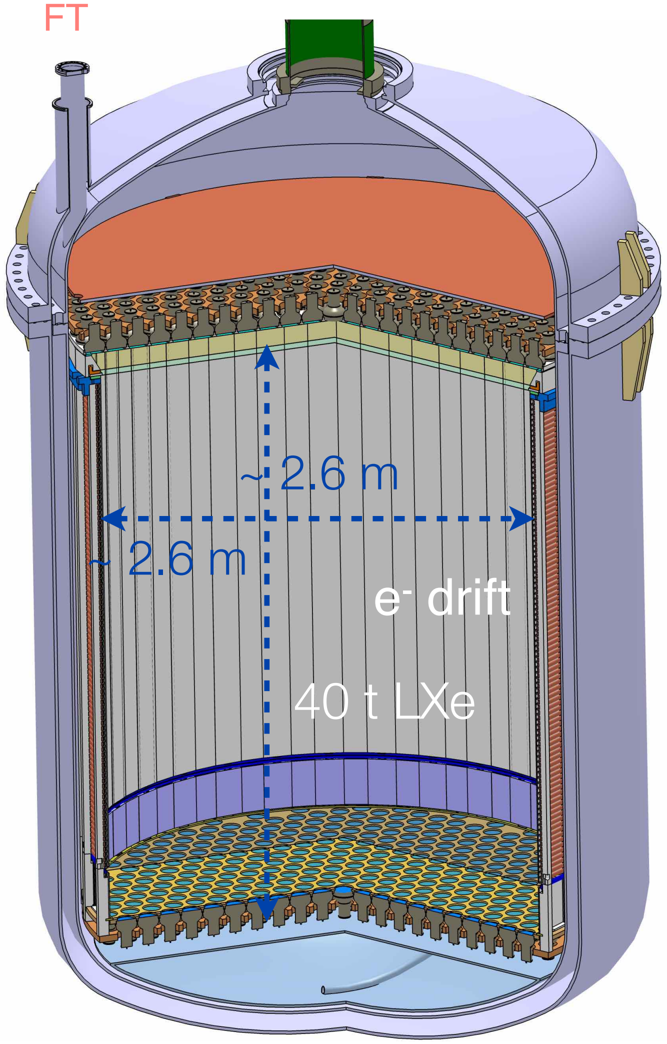

A. Breskin, L. Arazi: bialkali GPM stable operation at gain of 1e5

# Technical challenge: HV & drift field

- Electron drift length of 2.6 m, high purity, and uniform field at the 1% level
- HV to bias the cathode must be -130 to -260 kV to have a drift field of 0.5 - 1 kV/cm
  - build long (2.6 m) TPC demonstrator(s)
- Robust, and transparent grid or wire electrodes with 2.6 m diameter
- Challenge is to combine thin wires O(100 μm) to ensure high LCE
  - build shallow (2.6 m ø) TPC demonstrator(s)
- Very precise, 3D field simulations based on the BEM technique



Geometry in the BEM simulation software



# Technical challenge: liquid target

- Procurement, storage, cooling, high-speed purification of ~50 t of LXe
  - coordinate procurement among institutions, funding agencies and companies
- Storage: à la ReStoX, developed for XENON1T/nT, acts as a demonstrator
  - possible solution: a network of 7 interconnected ReStoX units, with a main storage directly connected to the cryostat
  - study a different mechanism for recovery, based on gravity (recuperation pipe below cryostat)

ReStoX: can store up to 7.6 t of xenon

Max heat leak: ~50 W

# Technical challenge: backgrounds

- ER dominance by solar neutrinos needs:

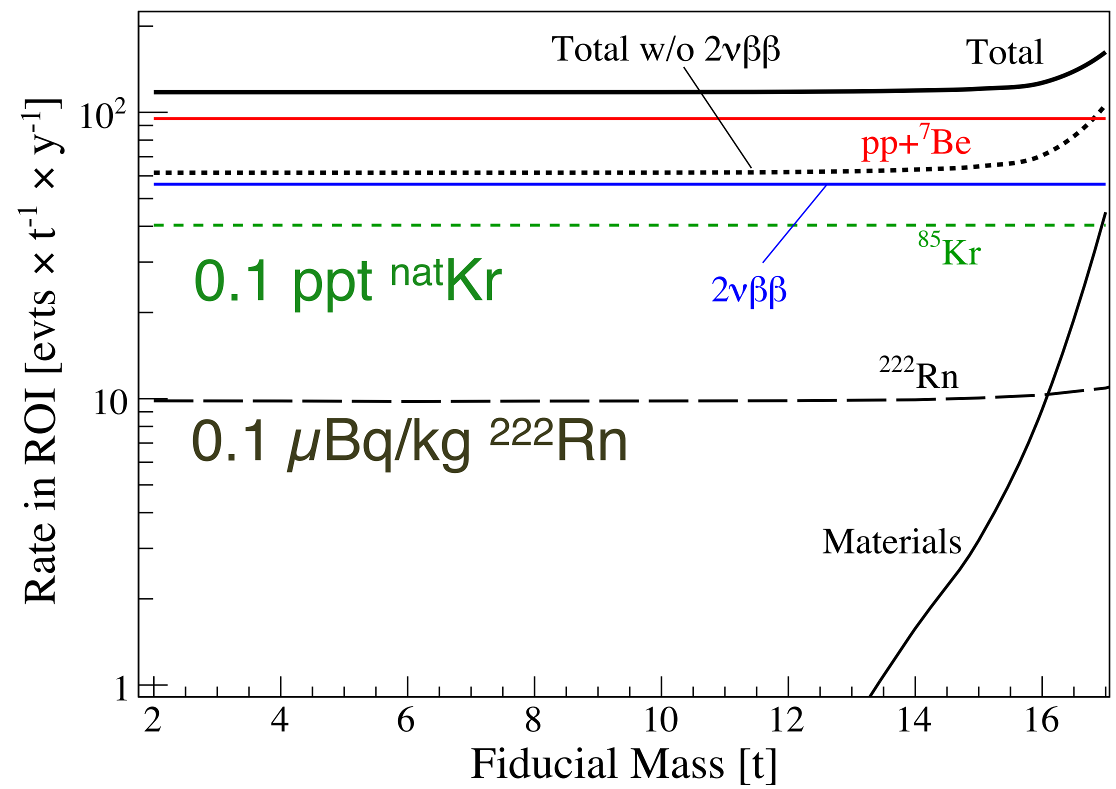
  ➡ low intrinsic levels of $^{85}$Kr and $^{222}$Rn

- $^{85}$Kr: 0.1 ppt $^{nat}$Kr (0.2 ppt $^{nat}$Kr => same background level as solar neutrinos)

  - 0.2 ppt is goal for XENON1T, factor 20 better than this already achieved by Münster group*: separation factor > 120000

- $^{222}$Rn: 0.1 μBq/kg (1 μBq/kg => same background level as solar neutrinos)

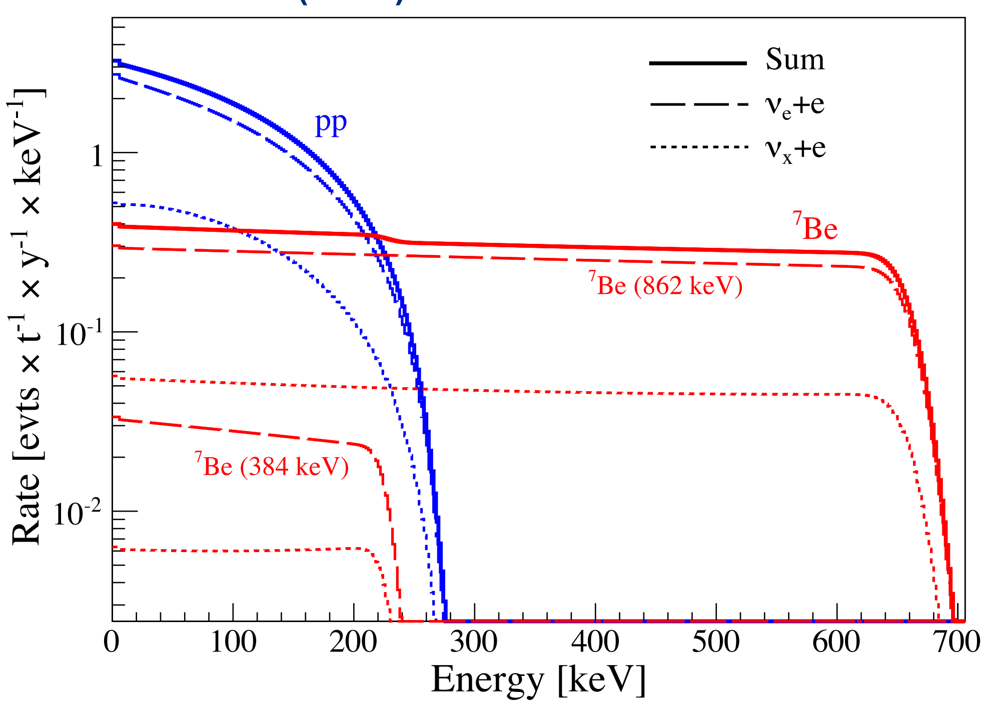
  - 10 μBq/kg is goal for XENON1T): control Rn levels with low-emanation materials & cryogenic distillation (use different vapour pressure), adsorption



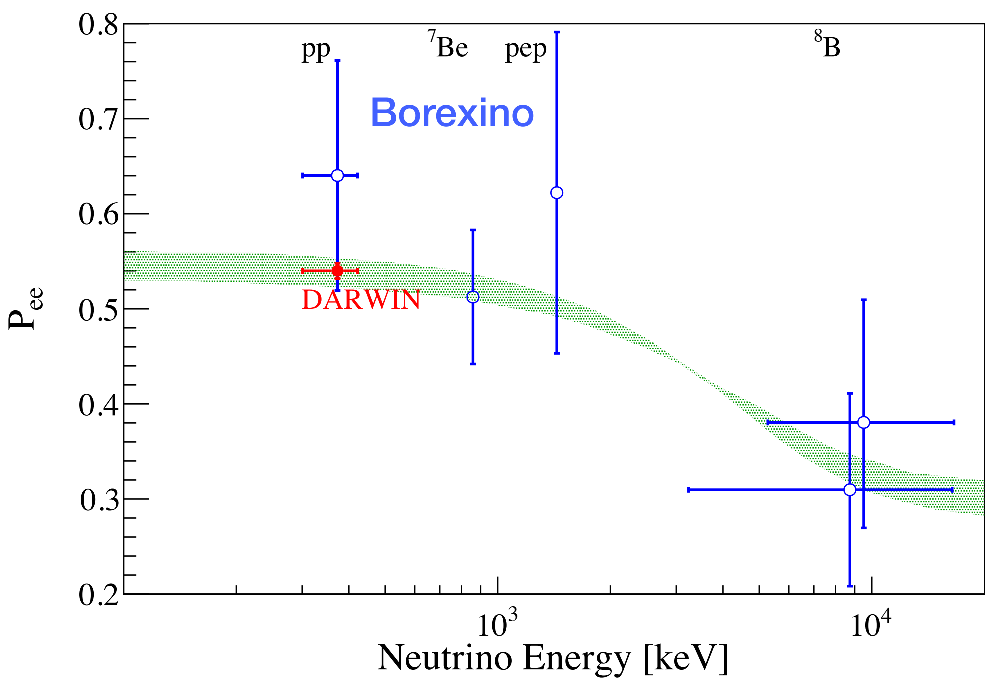

*M. Murra, Münster: $^{nat}$Kr/Xe < 26e-15 = 26 ppq (90% CL); measured with MPIK RGMS system

# Physics reach: solar neutrinos $\nu + e^- \rightarrow \nu + e^-$

JCAP01 (2014) 044




Nature 512 (2014) 383 - Borexino



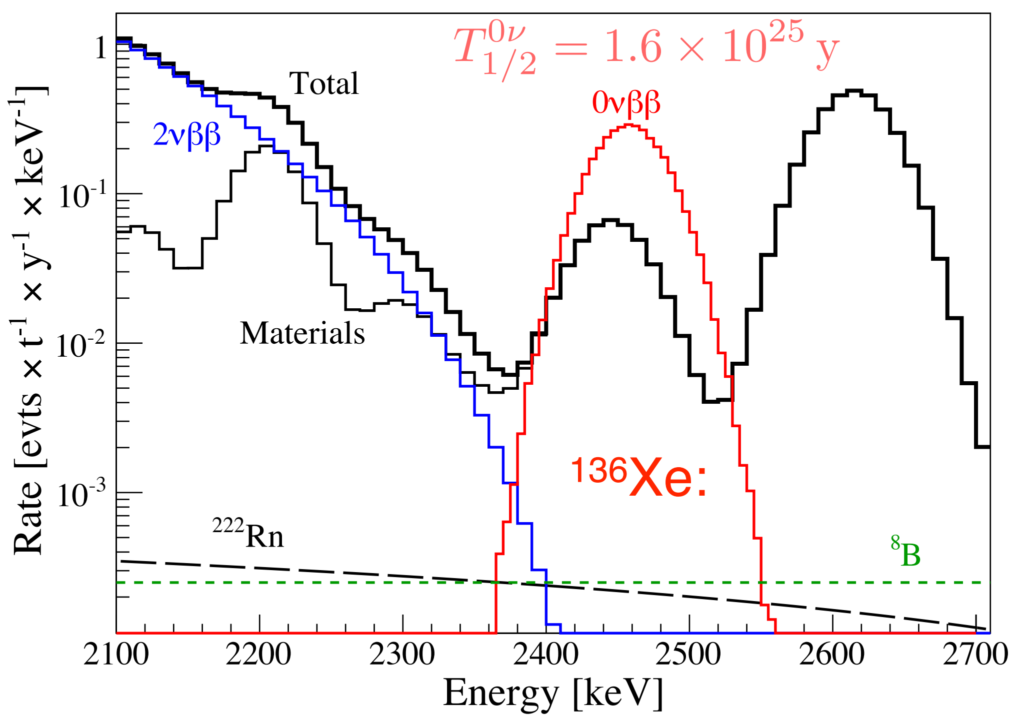

- Rate of solar neutrinos > 2 keV

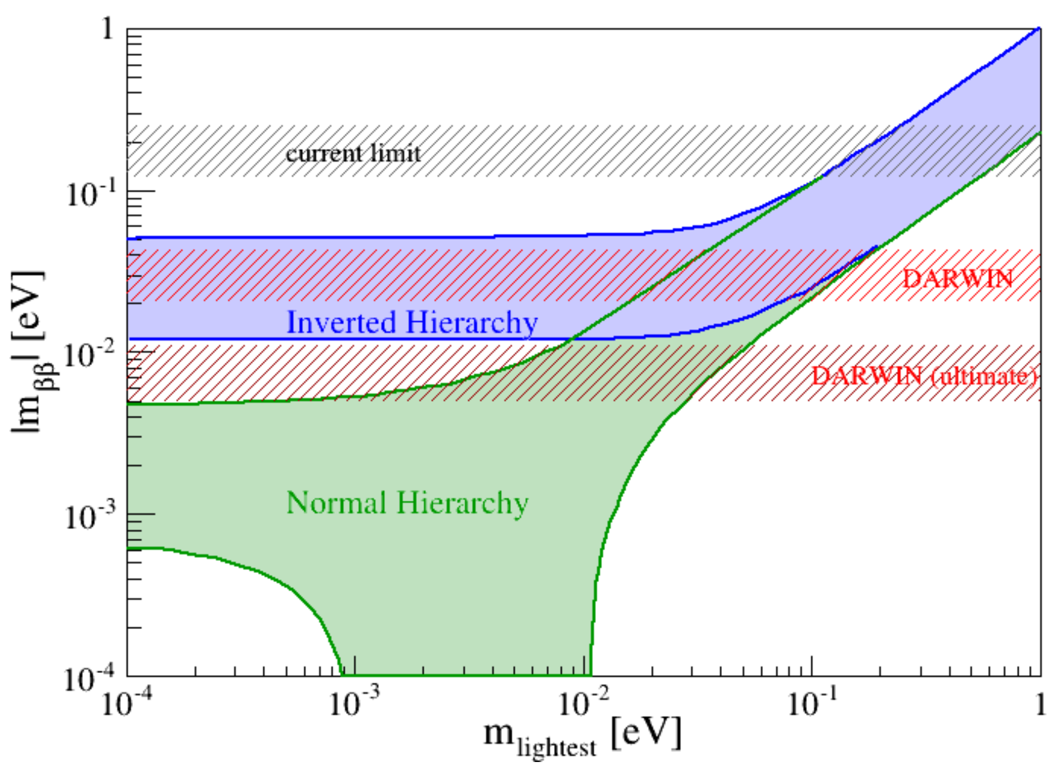
$$R_{pp} \simeq 1.05 \text{ events}/(\mathrm{t\,d})$$

$$R_{^7Be} \simeq 0.51 \text{ events}/(\mathrm{t\,d})$$

- pp neutrinos (2-30 keV):
  - 2571 events/(30 t y)
- $^7$Be neutrinos (2-30 keV):
  - 321 events/(30 t y)
- $^{220}$Rn: 0.1 μBq/kg; $^{nat}$Kr: 0.1 ppt
- **Reach ~ 1% precision after 3 years**

# Physics reach: double beta decay




- $^{136}$Xe: Q-value = 2458.7 ± 0.6 keV
- Fiducial mass 6 t $^{nat}$Xe

➡sensitivity to 0nbb-decay of $^{136}$Xe:

  - $T_{1/2} > 5.6 \times 10^{26}$ yr (95% CL) in 30 t y
  - $T_{1/2} > 8.5 \times 10^{27}$ yr (95%  CL) in 140 t y

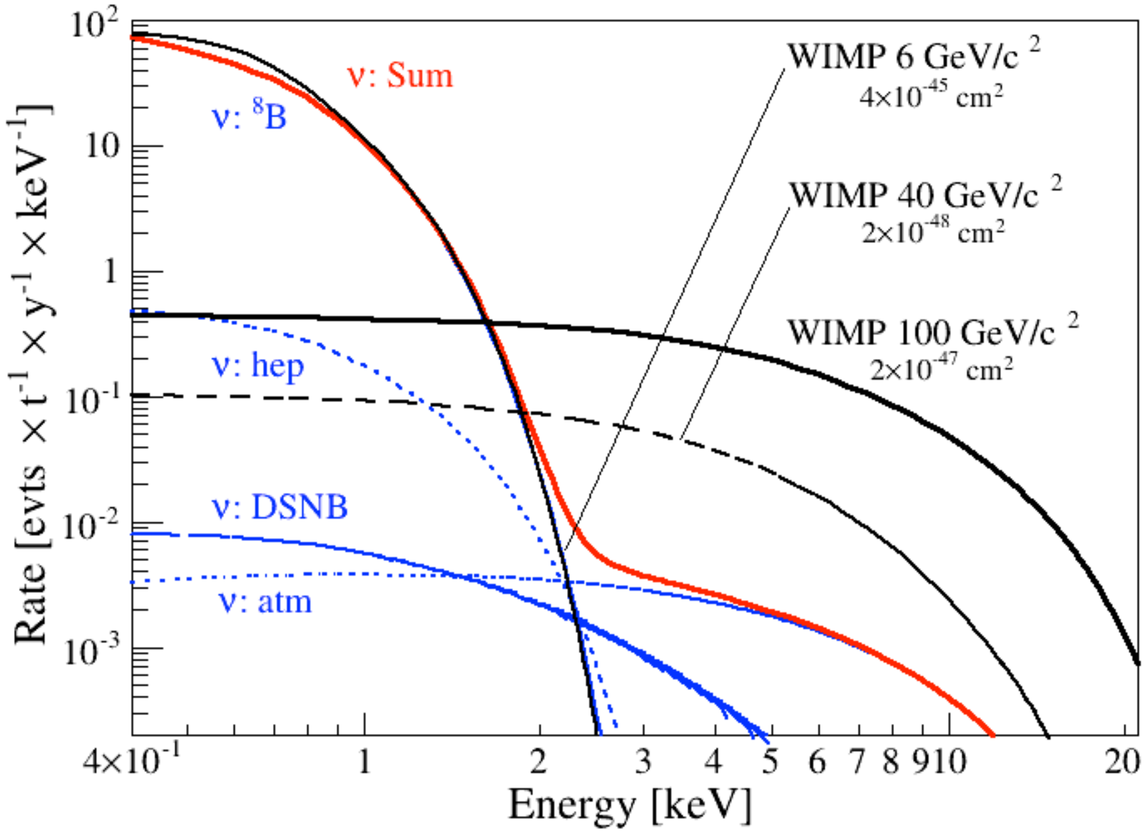
- **Assumptions:**
  - $^{222}$Rn: 0.1 µBq/kg (~ 0.036 events/(t y))
  - ($^{8}$B rate is ~ 0.036 events/(t y))
  - sigma/E = 1% at Q-value

# Physics reach: coherent neutrino scatters

- **Neutrino sources:**
  - $^8$B solar neutrinos
  - DSNB
  - Atmospheric neutrinos

- **Expected rates:**
  - 90 events/(t y) above 1 keVnr
  - 1.8 x $10^{-2}$ events/(t y) above 4 keVnr

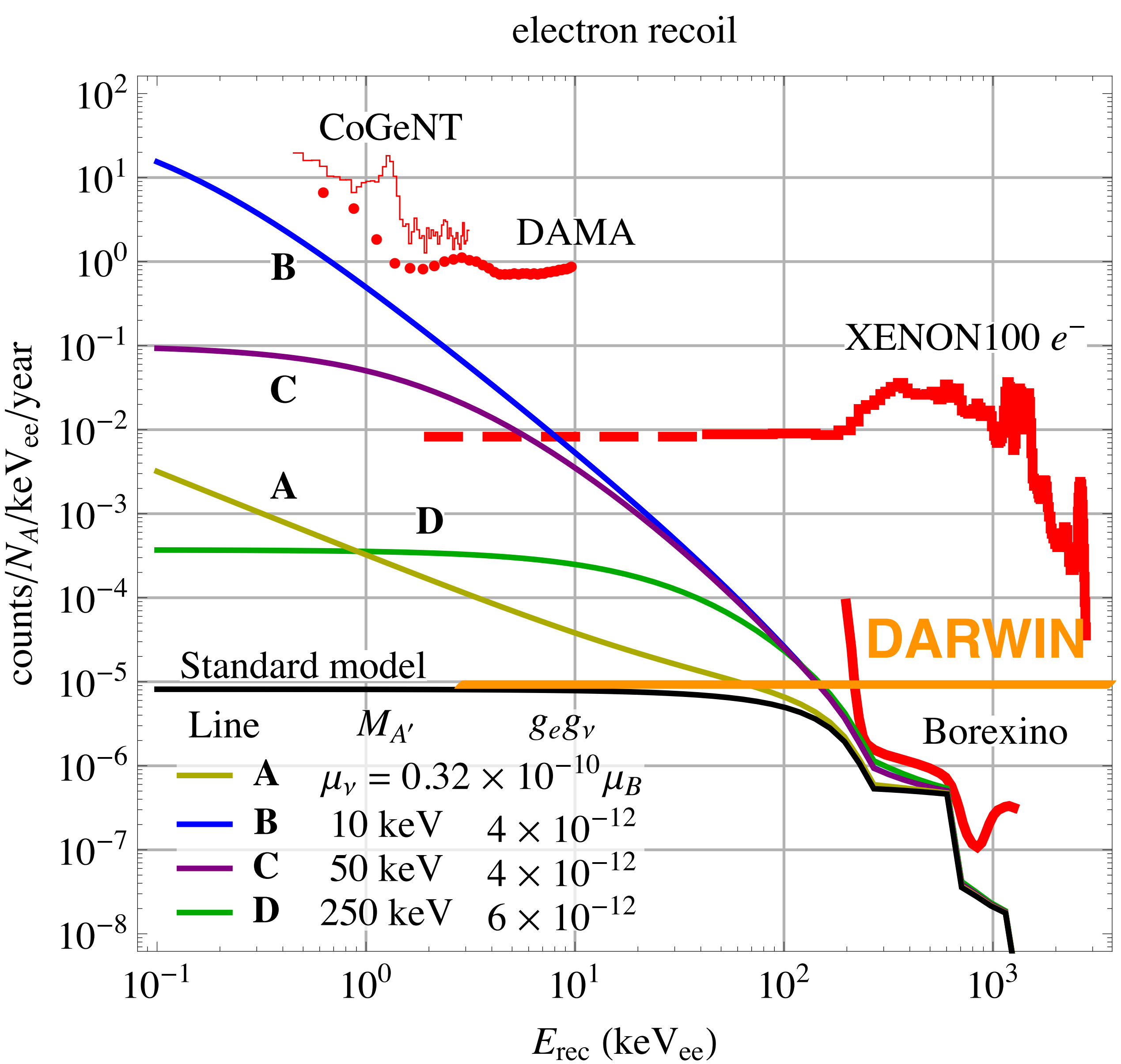
$$\nu + N \rightarrow \nu + N$$




LB et al, JCAP01 (2014) 044

With an energy threshold of ~1 keVnr, DARWIN would detect about 3000 CNNS events per year

# Physics reach: heavy sterile neutrinos

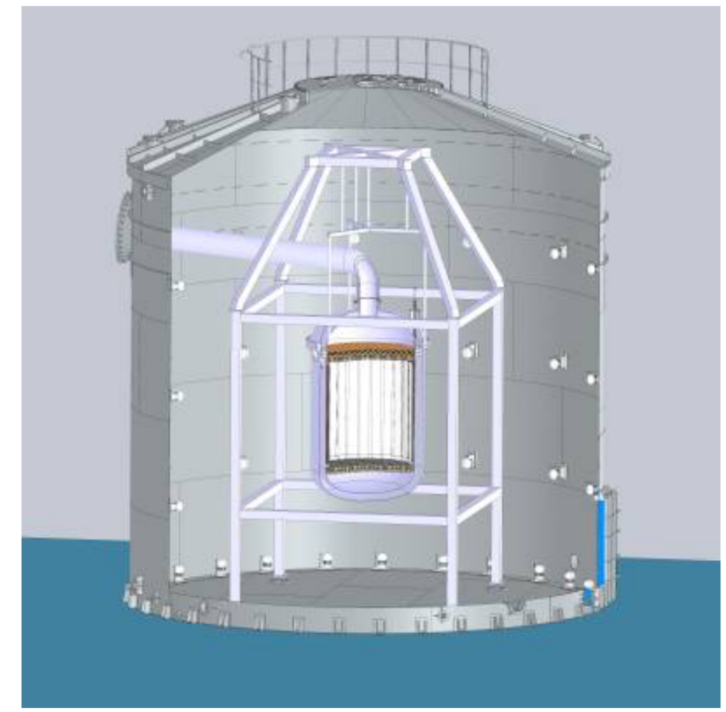



- Explore physics scenarios in which $\nu - e^-$ interactions are enhanced due to BSM processes:
  - new interactions between neutrinos and e⁻ mediated by a very light or massless particle (these would dominate the SM rates at low energies relevant for DD)
- A: nu with magnetic moment of 0.32 x $10^{-10}$ $\mu^B$
- B, C, D: A'-mediated $\nu - e^-$ scattering (sterile neutrinos heavier than ~ 10 keV)
  - A' is a new light gauge boson ("dark photon") that has a small kinetic mixing with the photon

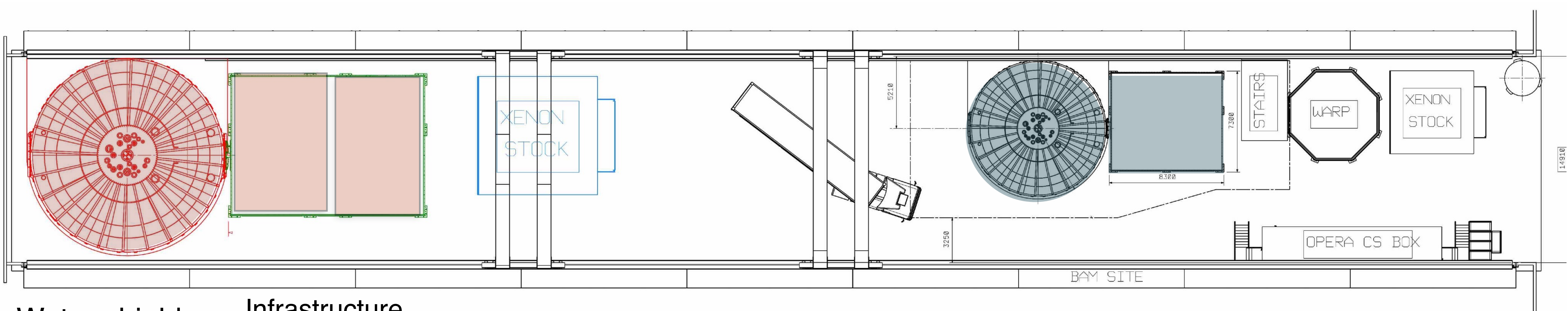
Harnik, Kopp, Machado, JCAP 07 (2012) 026

# Possible location at LNGS

- Minimum water tank dimensions: 14 m diameter
- Space in Hall B (former ICARUS location)
- Or space in Hall C (Borexino shield or other), or Hall A



**DARWIN-LXe** Example: space in hall B **XENON1T/nT**




Water shield
15 m ø

Infrastructure
building
+ clean room

Xe storage

# Estimated DARWIN timescale

**2010 - 2013**

First R&D phase, Aspera funded

June 2013: Aspera final report

**2014 - 2019**

R&D and design study

2018: CDR/TDR

**2019 - 2021**

Engineering studies

2019-20: demonstrators at home institutions

2021: construction/integration at LNGS

**2022 - 2032**

Construction, commissioning, science run

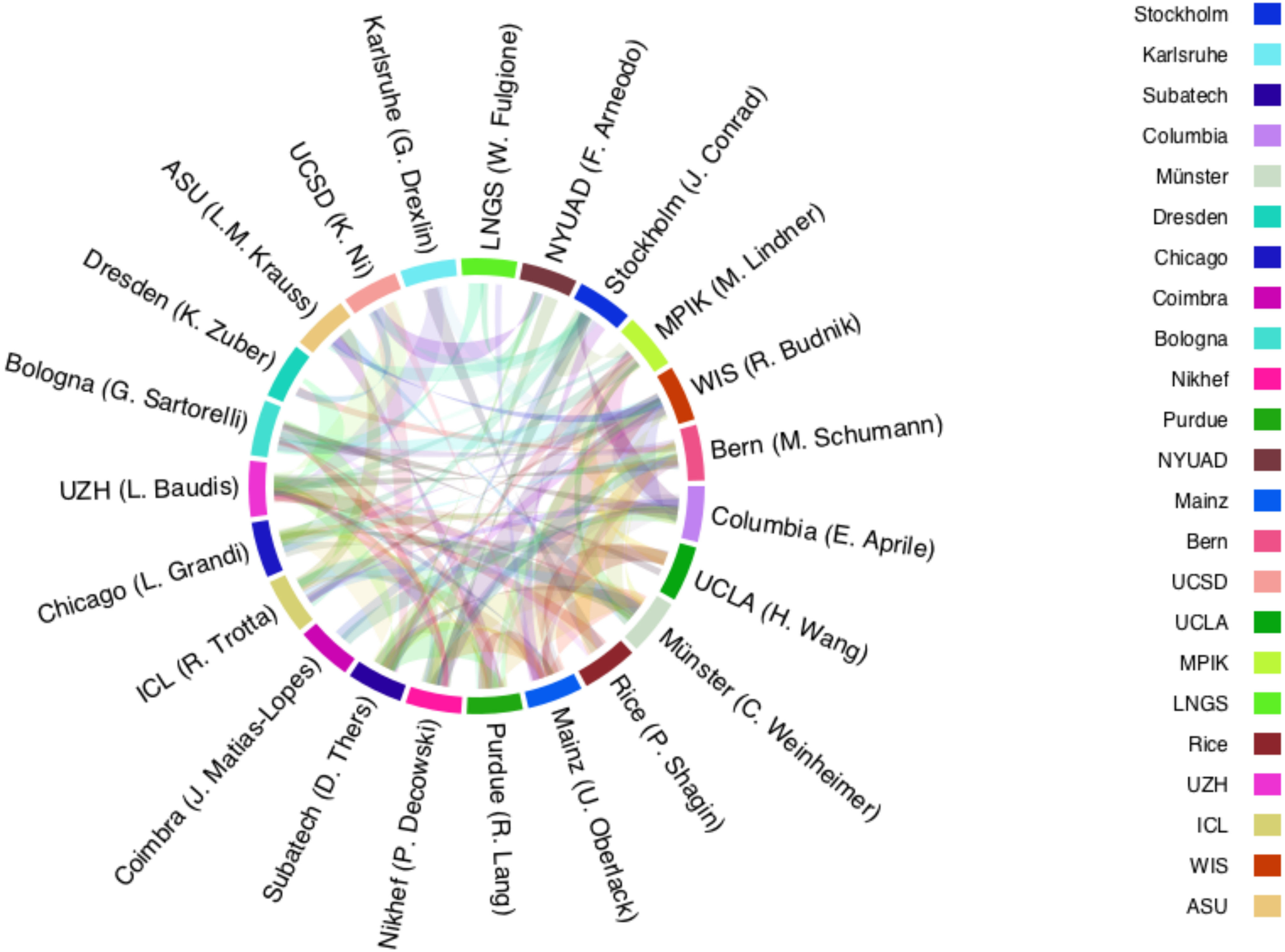
2022: construction/integration at LNGS

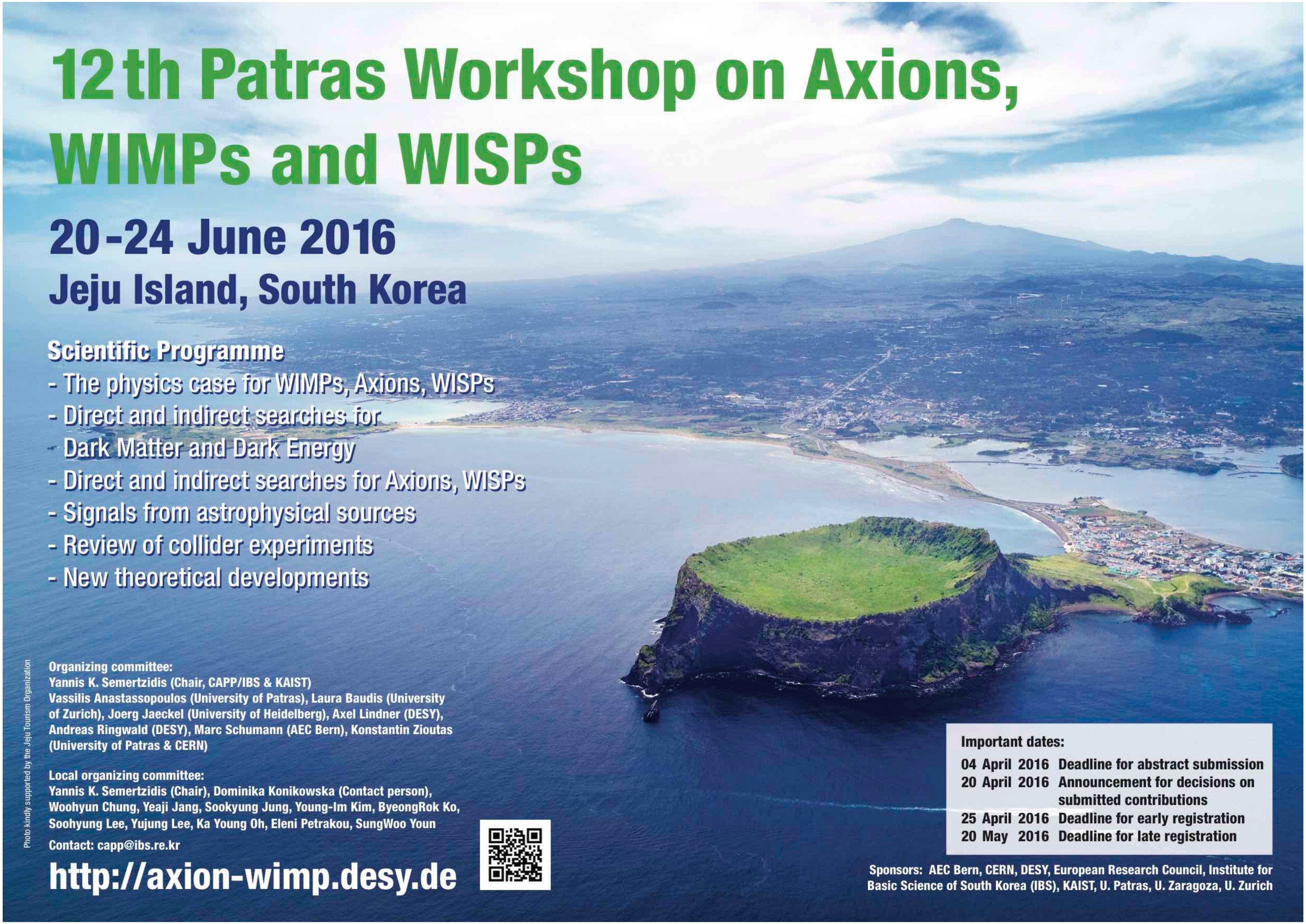
2023: commissioning

2024: physics runs start

# The DARWIN Consortium

23 groups from 9 countries




12th Patras Workshop on Axions, WIMPs and WISPs
20-24 June 2016
Jeju Island, South Korea
Scientific Programme
- The physics case for WIMPs, Axions, WISPs
- Direct and indirect searches for Dark Matter and Dark Energy
- Direct and indirect searches for Axions, WISPs
- Signals from astrophysical sources
- Review of collider experiments
- New theoretical developments
Organizing committee:
Yannis K. Semertzidis (Chair, CAPP/IBS & KAIST)
Vassilis Anastassopoulos (University of Patras), Laura Baudis (University of Zurich), Joerg Jaeckel (University of Heidelberg), Axel Lindner (DESY), Andreas Ringwald (DESY), Marc Schumann (AEC Bern), Konstantin Zioutas (University of Patras & CERN)
Local organizing committee:
Yannis K. Semertzidis (Chair), Dominika Konikowska (Contact person), Woohyun Chung, Yeaji Jang, Sookyung Jung, Young-Im Kim, ByeongRok Ko, Soohyung Lee, Yujung Lee, Ka Young Oh, Eleni Petrakou, SungWoo Youn
Contact: capp@ibs.re.kr
http://axion-wimp.desy.de
Important dates:
04 April 2016 Deadline for abstract submission
20 April 2016 Announcement for decisions on submitted contributions
25 April 2016 Deadline for early registration
20 May 2016 Deadline for late registration
Sponsors: AEC Bern, CERN, DESY, European Research Council, Institute for Basic Science of South Korea (IBS), KAIST, U. Patras, U. Zaragoza, U. Zurich
Photo kindly supported by the Jeju Tourism Organization

# End

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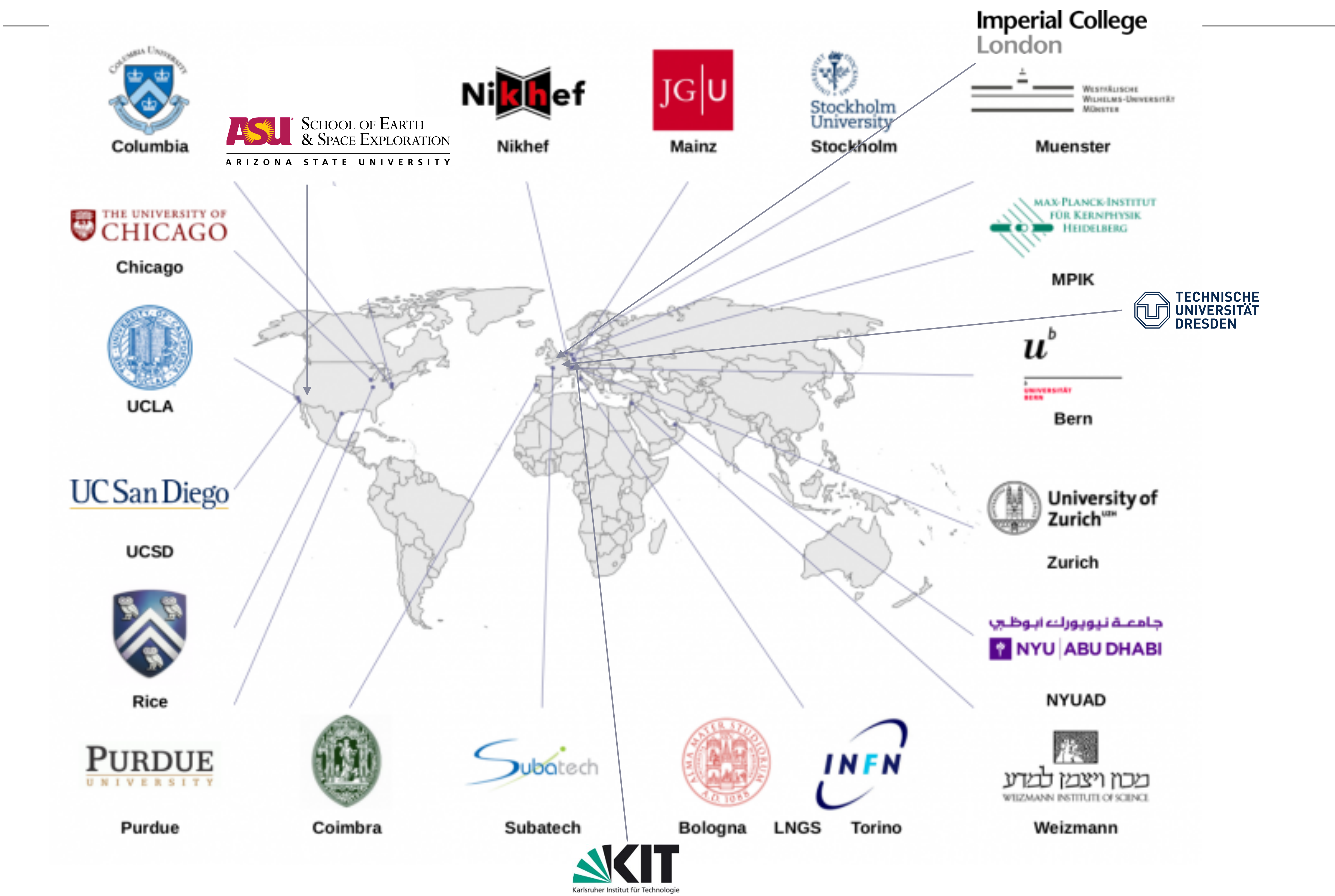
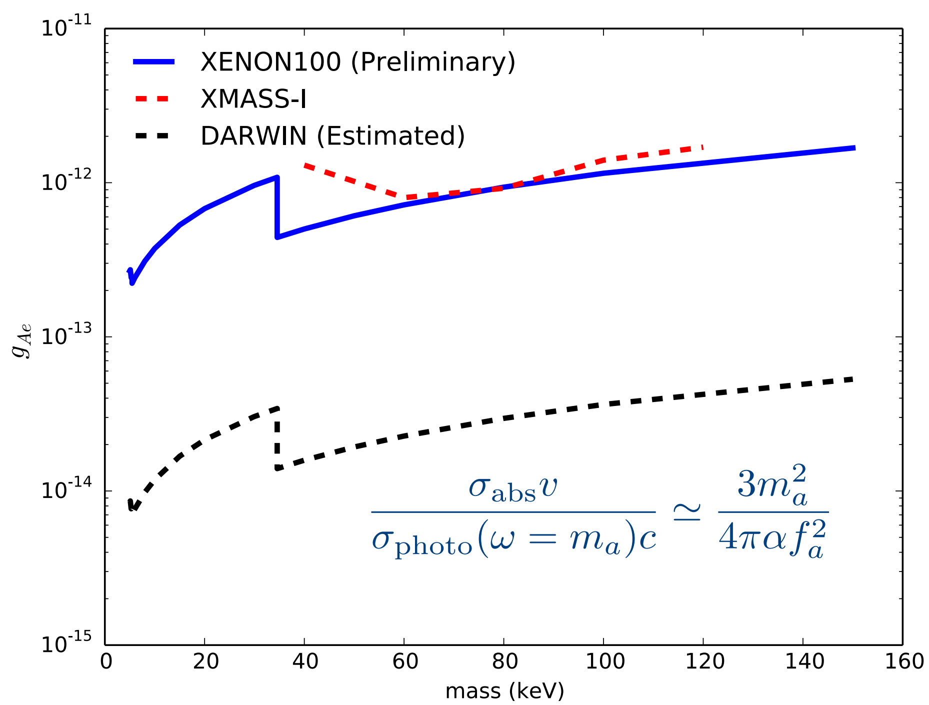
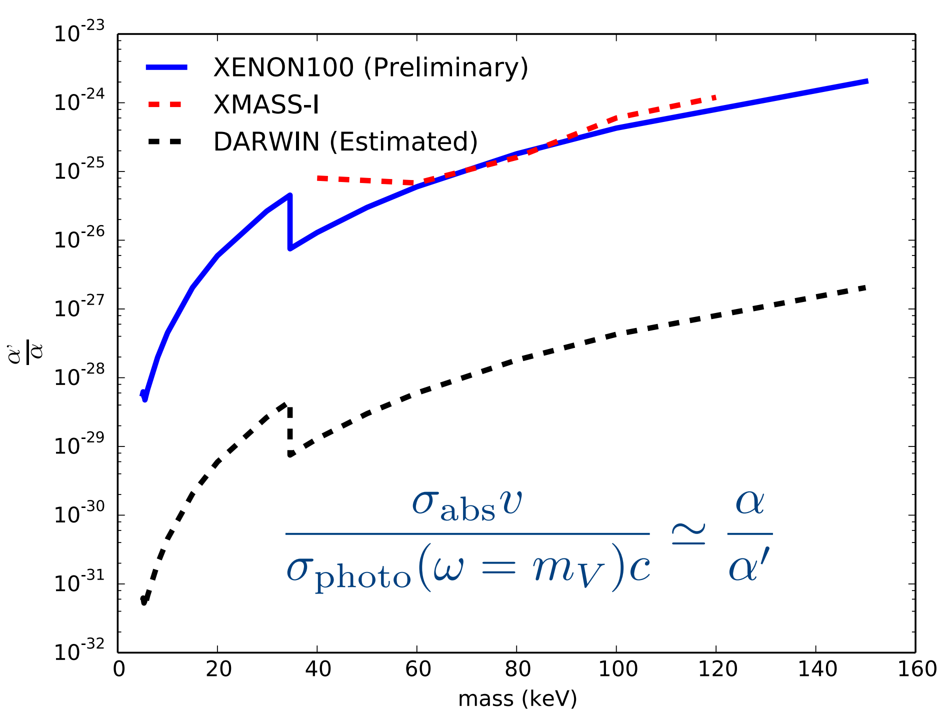


# Physics reach: bosonic SuperWIMPs




- Bosonic, light, super weakly interacting cold dark matter (mass in the 10-100 keV range)
- Scattering cross section is many orders of magnitude below the weak-scale cross section, but such particles could be absorbed in LXe and produce a detectable signal
- **Signature: a line at the rest mass of the boson**

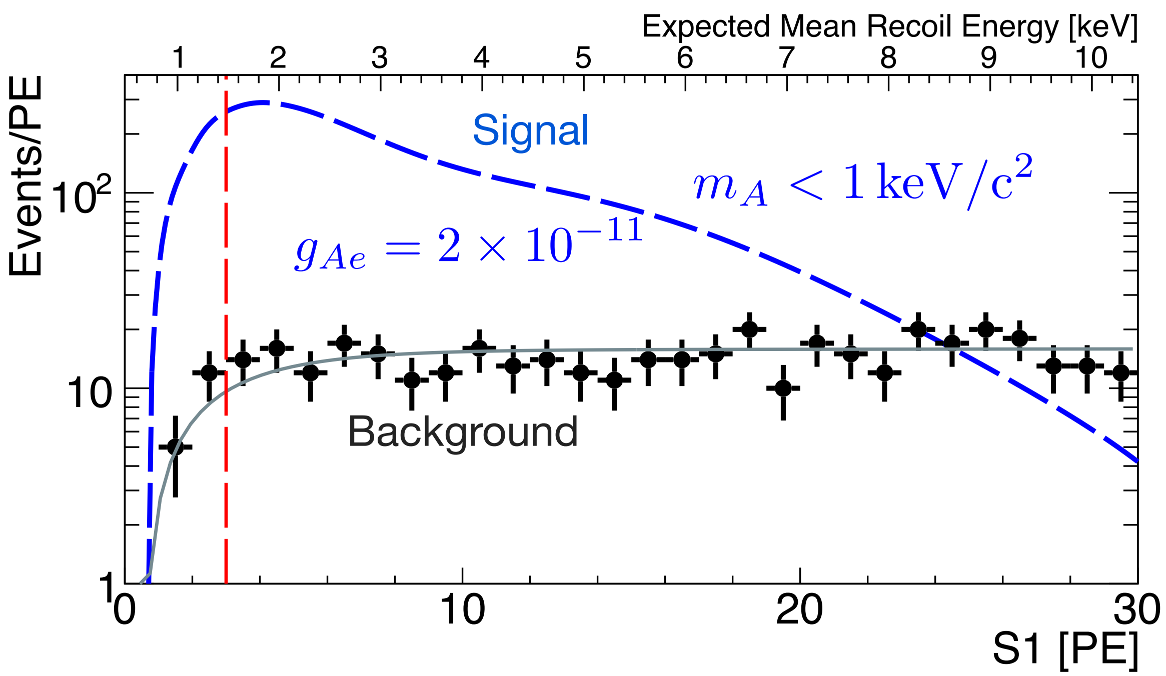
axial-vector $$R \simeq \frac{1.2 \times 10^{19}}{A} g_{aee}^2 \frac{m_a}{\rm keV} \frac{\sigma_{\rm photo}}{\rm b} \, {\rm kg}^{-1}\,{\rm d}^{-1}$$

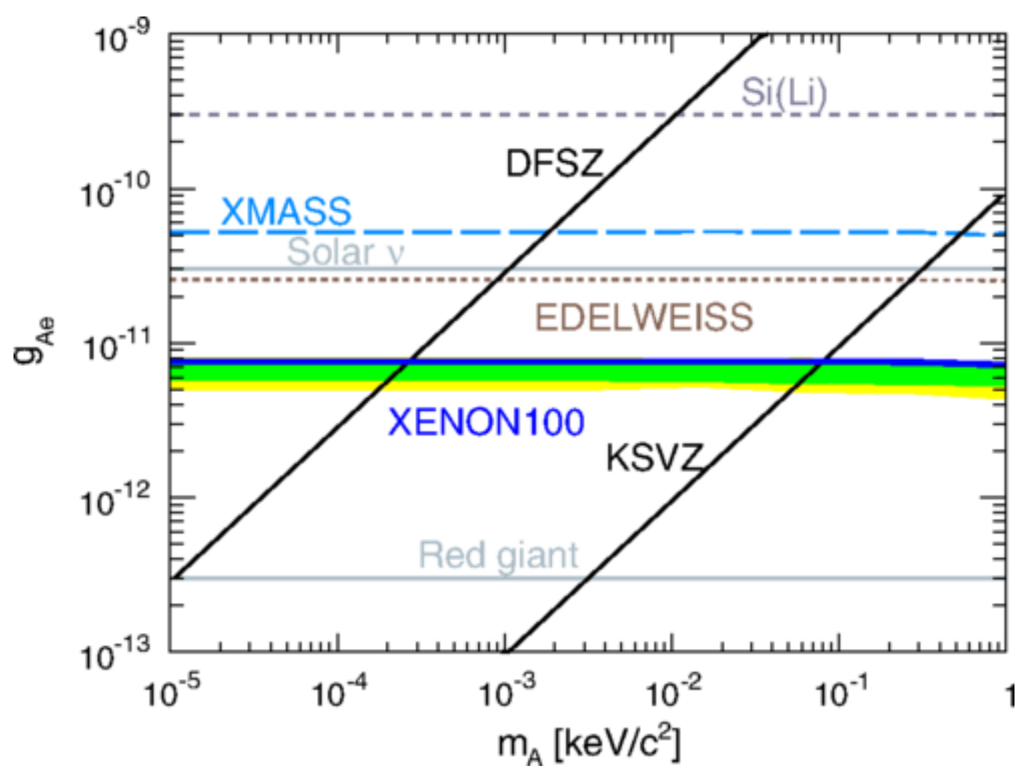
$$g_{aee} = \frac{2m_e}{f_a}$$

vector $$R \simeq \frac{4 \times 10^{23}}{A} \frac{\alpha}{\alpha'} \frac{\rm keV}{m_V} \frac{\sigma_{\rm photo}}{\rm b} \, {\rm kg}^{-1}\,{\rm d}^{-1}$$

**M. Pospelov, A. Ritz, M. Voloshin, PRD 78, 2008**

# Physics reach: solar axions




XENON, Phys. Rev. D 90, 062009 (2014)

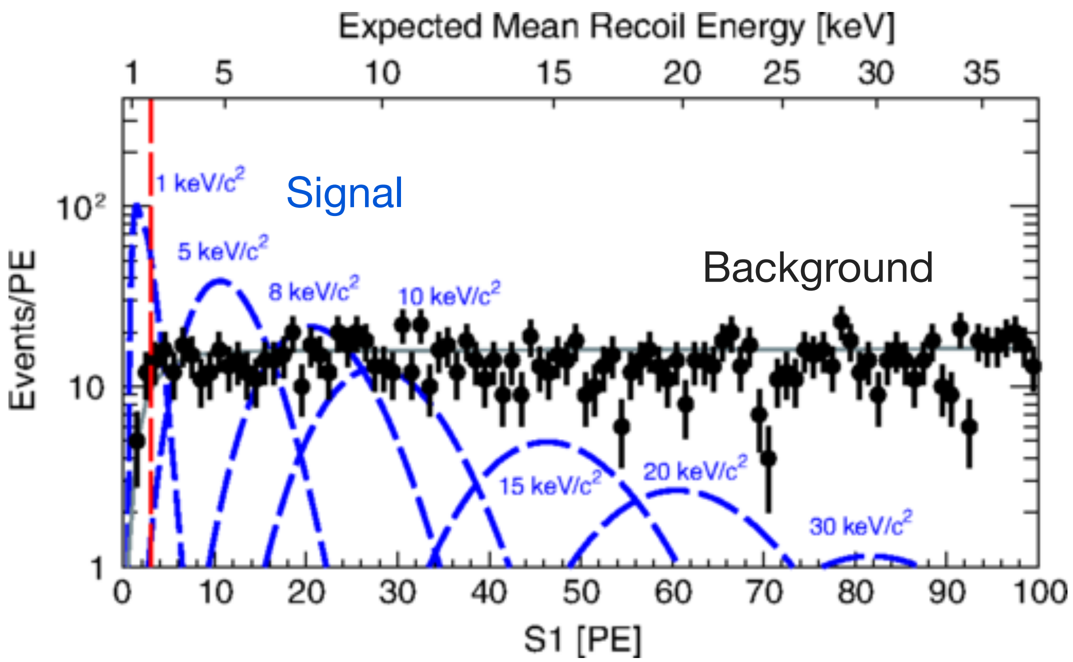
Look for solar axions via their couplings to electrons, $g_{Ae}$, through the axio-electric effect

$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{g_{Ae}^2}{\beta_A}\frac{3E_A^2}{16\pi\alpha_{em}m_e^2}\left(1 - \frac{\beta_A^{2/3}}{3}\right)$$

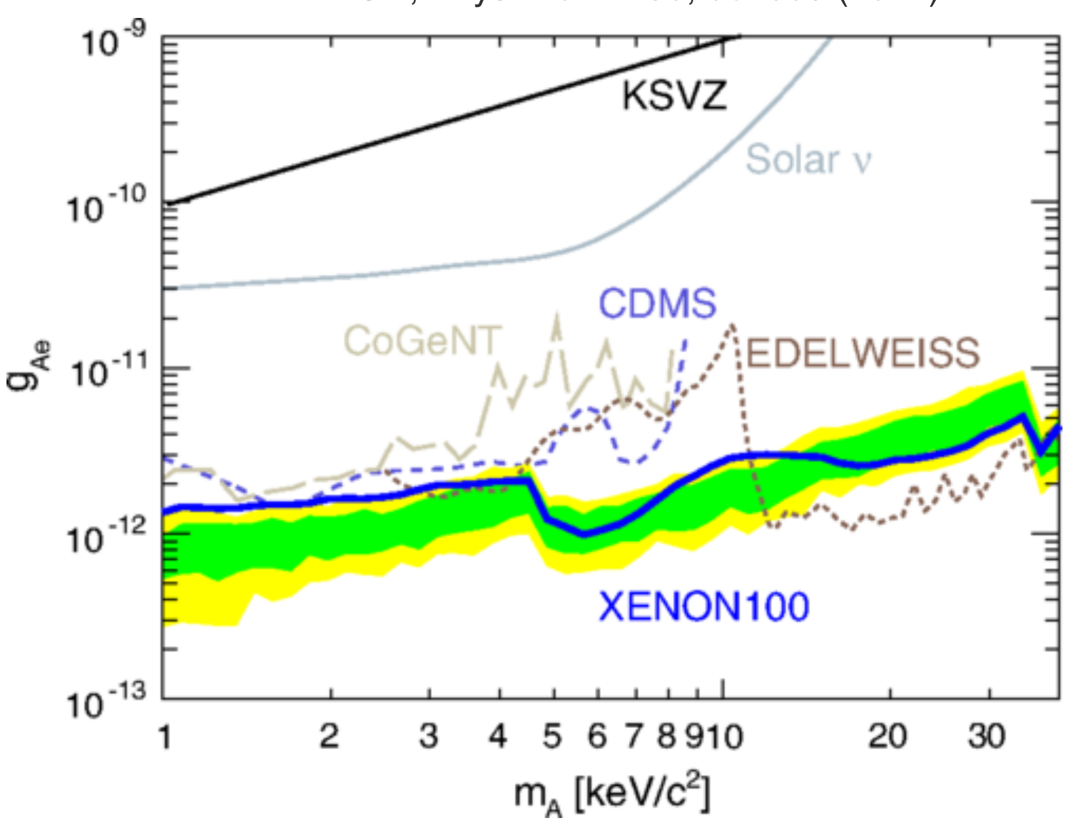
$$\phi_A \propto g_{Ae}^2 \Longrightarrow R \propto g_{Ae}^4$$

- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs
- **Factor of ~10 improvement with DARWIN**

# Physics reach: galactic axion-like particles (ALPs)




XENON, Phys. Rev. D 90, 062009 (2014)




Look for ALPs via their couplings to electrons, $g_{Ae}$, through the axio-electric effect

Expect line feature at ALP mass

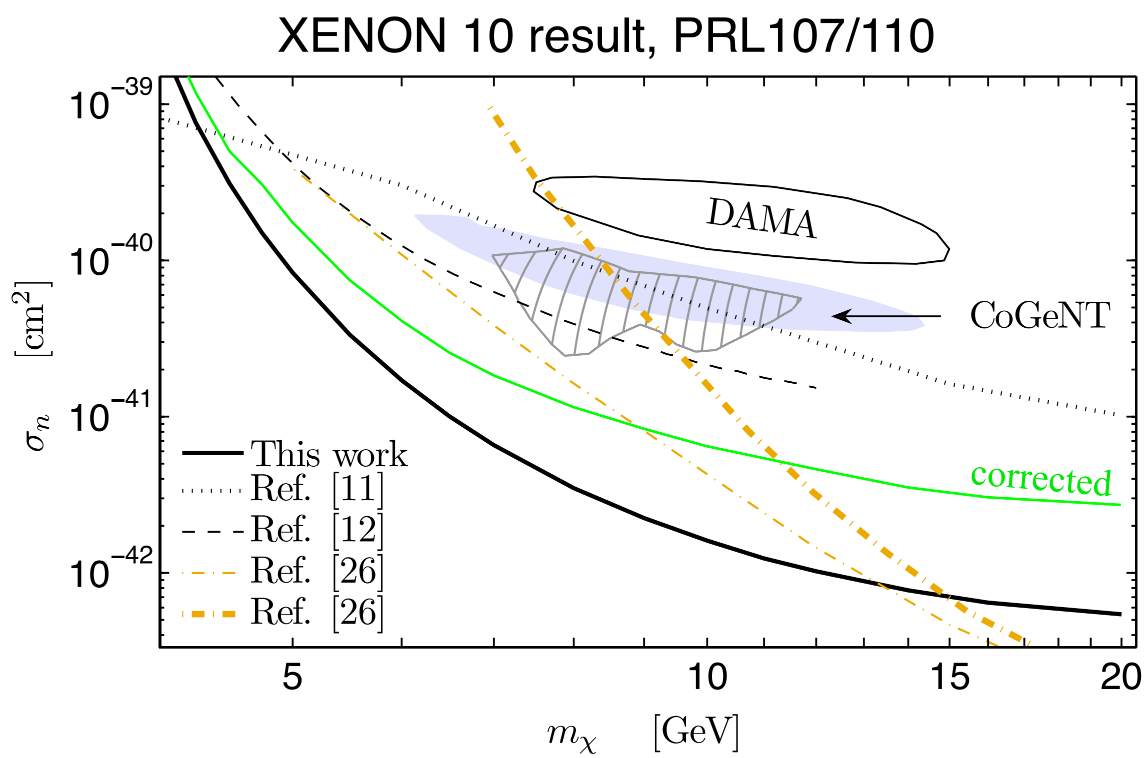
assume $\rho_{dm} = 0.3$ GeV/cm$^3$

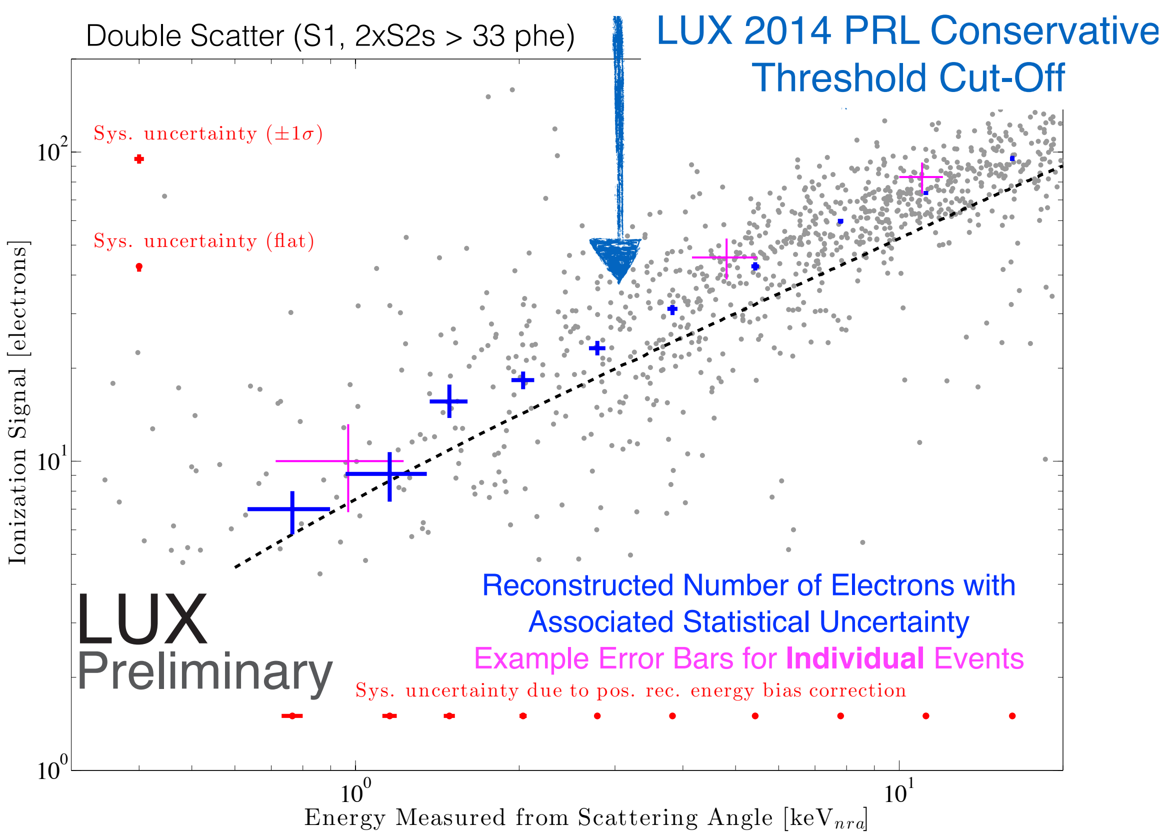
$$\phi_A = c\beta_A \times \frac{\rho_{\mathrm{dm}}}{m_A}$$

$$R \propto g_{Ae}^2$$

- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs
- **Factor of ~100 improvement with DARWIN**

# Physics reach: low WIMP masses



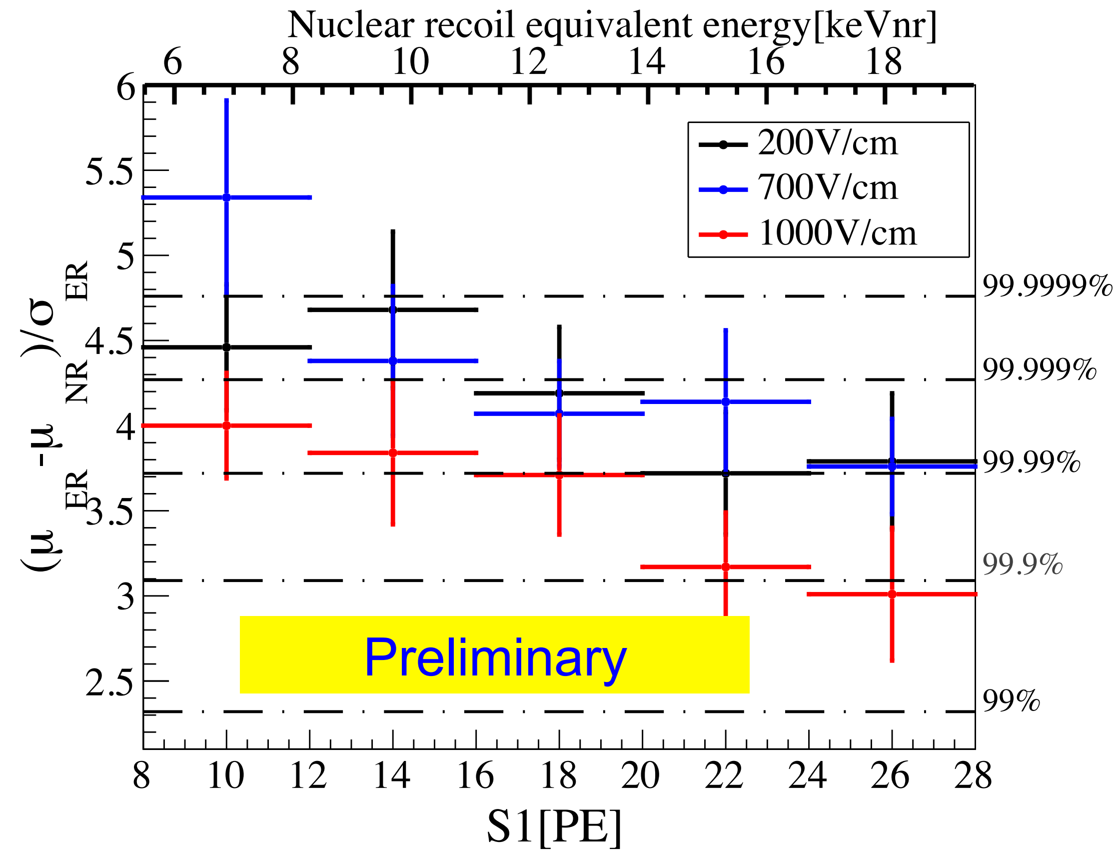




- Achieve a lower energy threshold for NRs if the energy is measured by the S2 signal (e$^-$), with ~ 20-25 PE per extracted e$^-$ in the gas phase
- **XENON10: threshold of E$_{nr}$ ~ 1 keV reached**
- **XENON100: analysis ongoing**
- Loss of S2/S1 discrimination: sensitivity reduction by ~ factor 100, compared to higher WIMP masses; acceptable because at low WIMP masses the solar neutrinos will dominate the NR rate
- **LUX (APS2015): ionization signal absolutely measured below 1 keVnr**

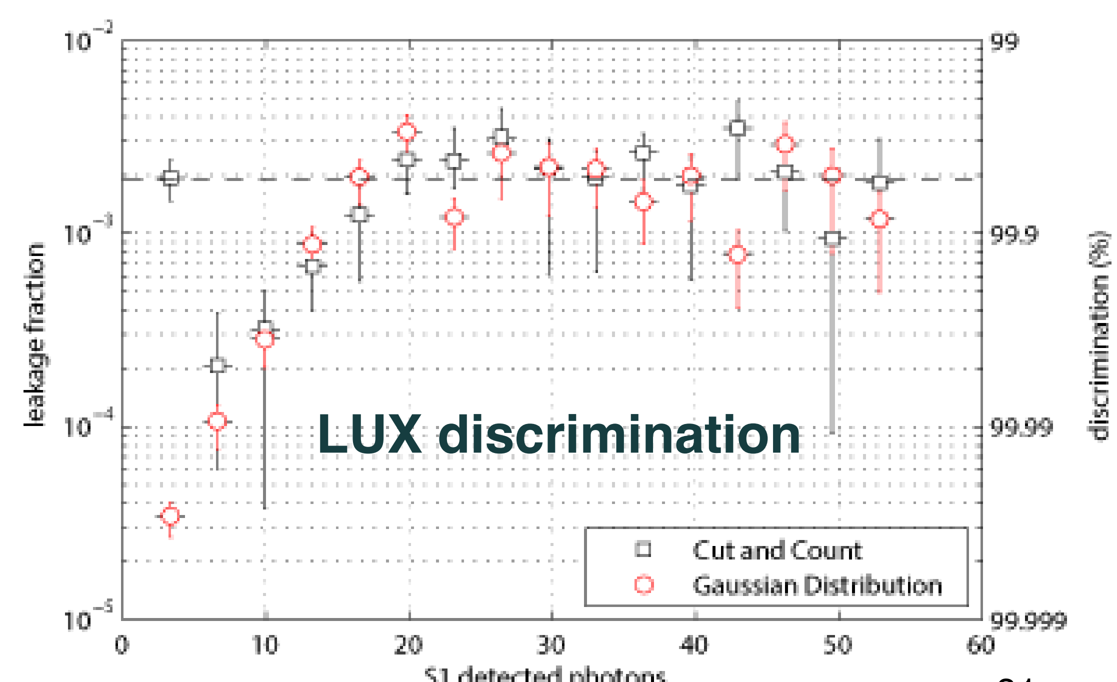
# Technical challenge: discrimination

K. Ni, AP2014

- **Best value in LXe by ZEPLIN-III, 99.987%**
- LUX: 99.9% - 99% (at 50% NR acceptance)
- K. Ni: ER power > $10^5$ at 50% acceptance
  - **weak dependance on field strength, but field uniformity crucial**

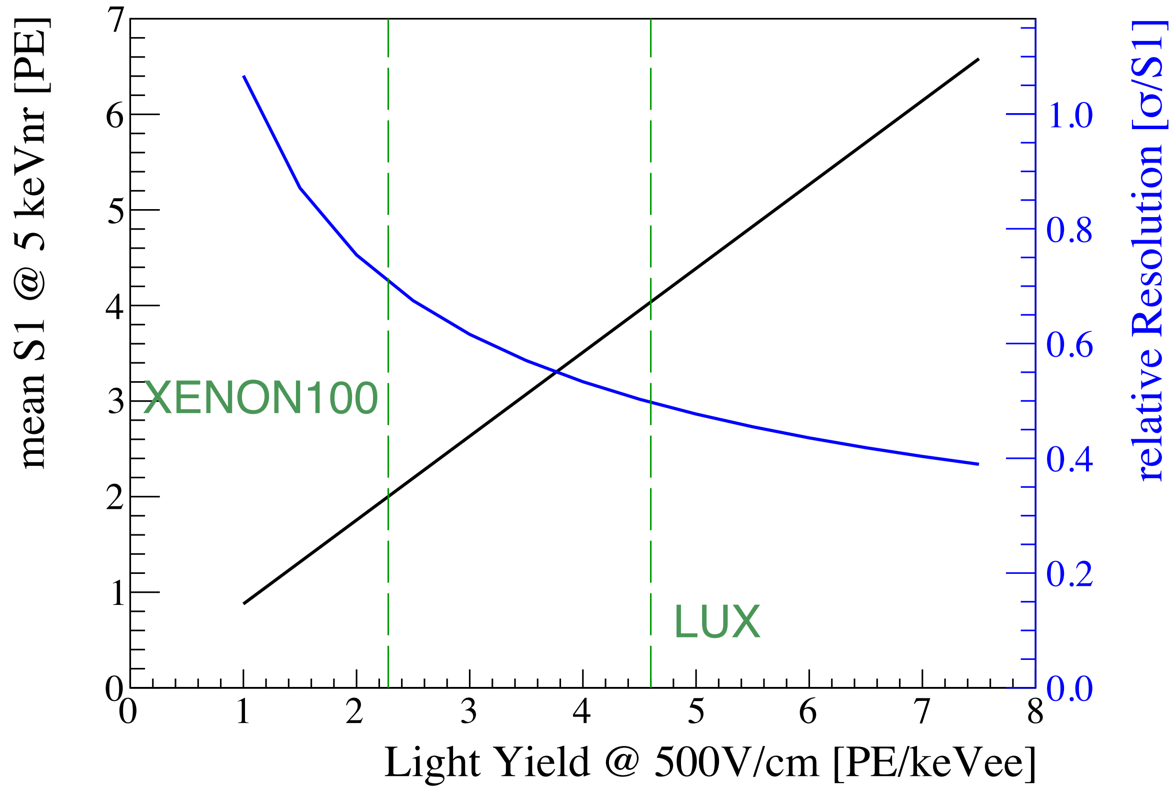



| | Field (kV/cm) | Light yield (pe/keVee, for 122 keV at zero field) | Energy ROI (keVnr) | NR acceptance | ER rejection power |
|---|---|---|---|---|---|
| ZEPLIN-II | 1.0 | 1.1 | 14-58 | 50% | 98.5% |
| XENON10 | 0.73 | 5.4 | 4.5~26.9 | 45%~49% | 99.9~99.3% |
| ZEPLIN-III | 3.4 | 3.1-4.2 | 7-35 | ~50% | 99.987% |
| XENON100 | 0.53 | 3.8 | 6.6-43.3 | 60%~20% | 99.75% |
| LUX | 0.18 | 8.8 | 3-27 | 50% | 99.9~99% |

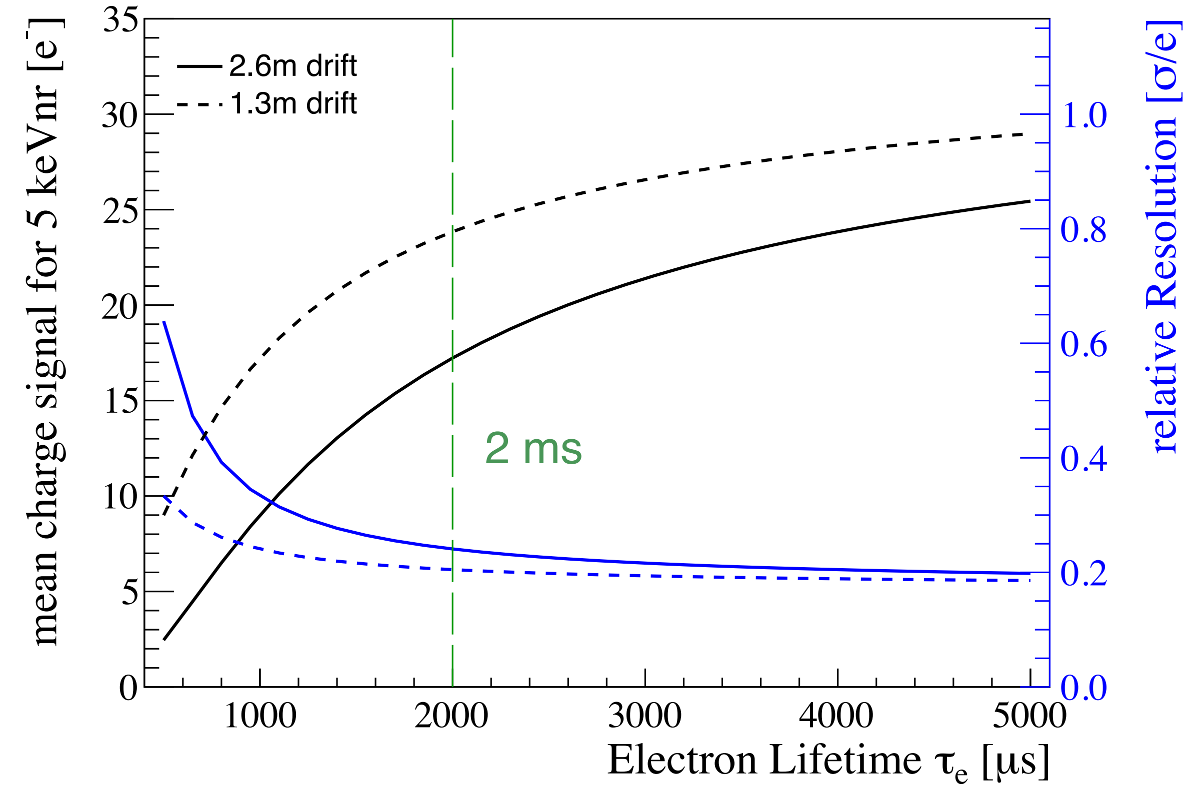


# Energy resolution

S1 resolution of 5 keVnr versus light yield

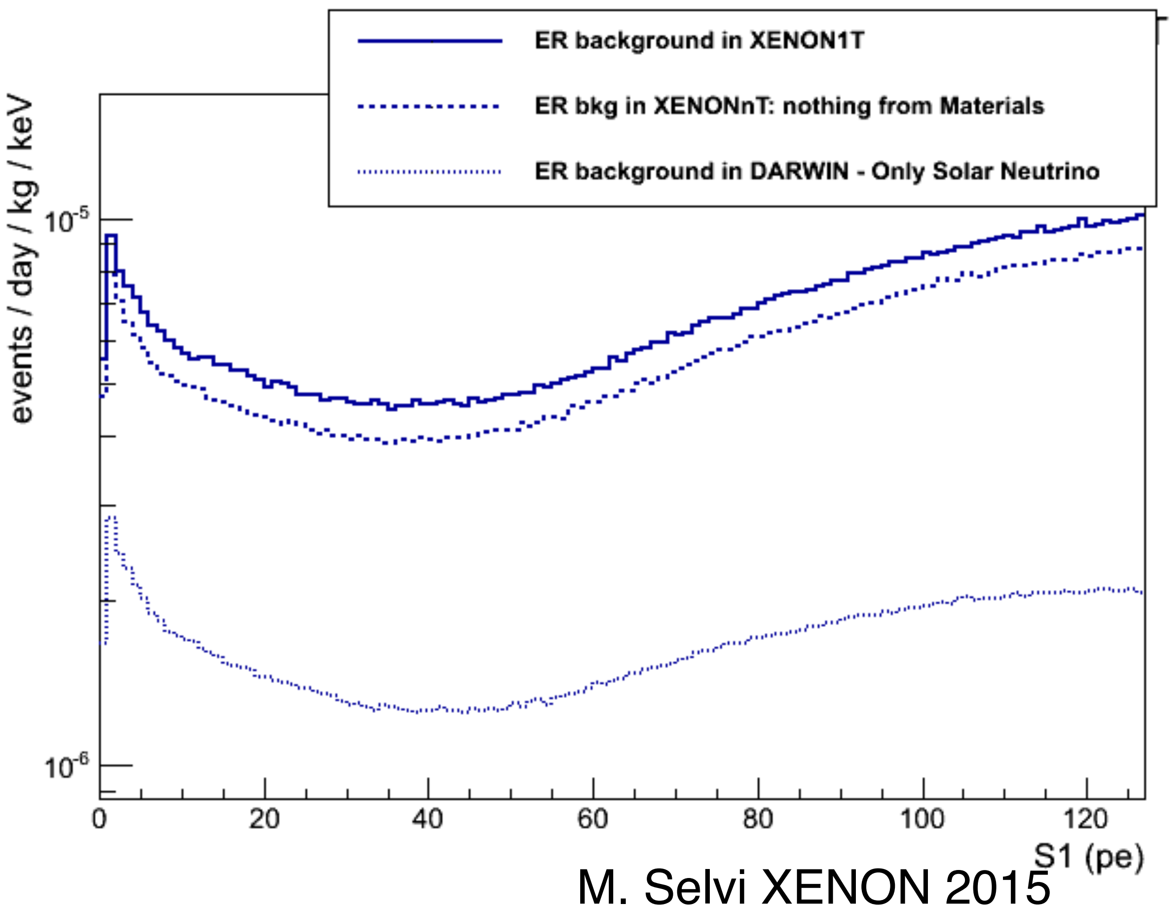



S2 resolution of 5 keVnr versus e-lifetime



# ER backgrounds: XENON1T/nT & DARWIN-LXe

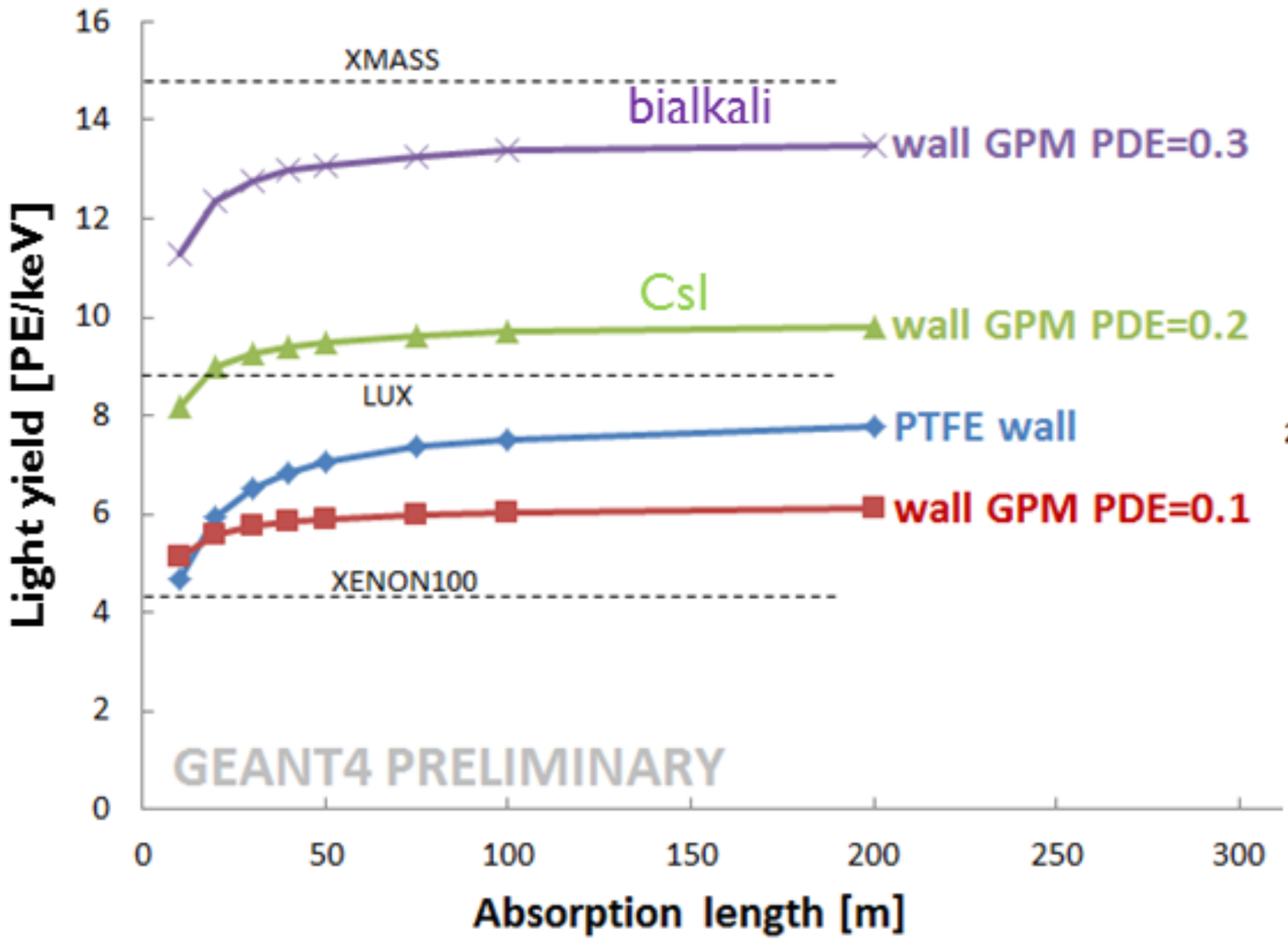
- ER background before discrimination, in [2-12] keVee
- XENON1T: ~ 128 events/(t y)
  - materials + 0.2 ppt Kr + 1μBq/kg Rn + solar nu + 2nbb
- XENONnT: ~ 109 events/(t y)
  - 0.2 ppt Kr + 1μBq/kg Rn + solar nu + 2nbb
- DARWIN: ~ 35 events/( t y)
  - 0.1 ppt Kr + 0.1μBq/kg Rn
  - solar neutrino dominated

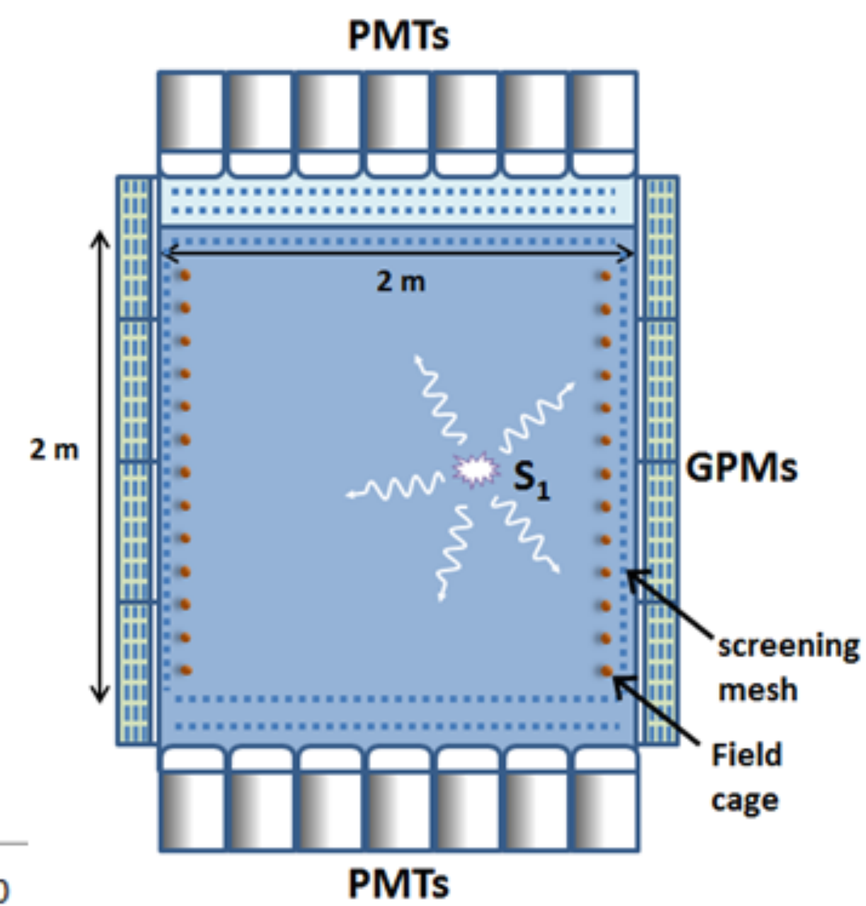



M. Selvi XENON 2015

# Technical challenges: light yield

MC simulation for a 2 m tall and 2 m diameter LXe TPC with XENON1T grids




**Light yield for 122 keV, E = 0**

PDE = photon detection efficiency

(for photons hitting the GPM window)

- PTFE reflectivity = 95%
- Rayleigh scattering length = 30 cm
- XENON1T PMTs and meshes
- 90% transparent field cage

Slide from Lior Arazi