The DARWIN Liquid Xenon Detector

12th Terascale Detector Workshop
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Physics Department, TU Dresden

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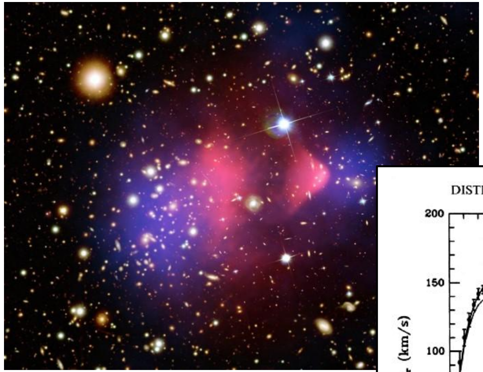
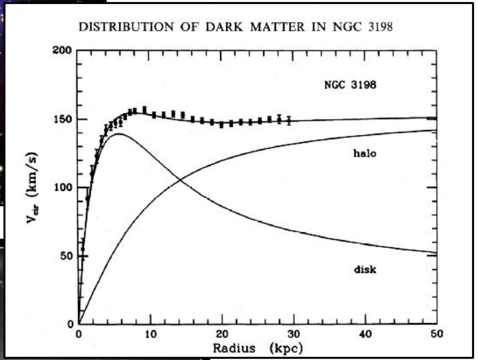
DARWIN

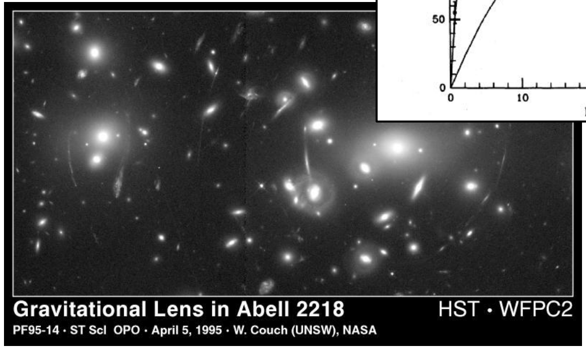
DARk matter WImp search with liquid xenoN

Dark Matter Indications

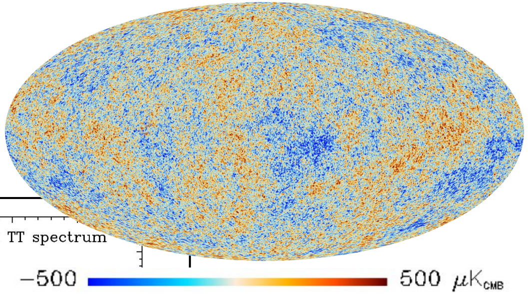
Astronomy

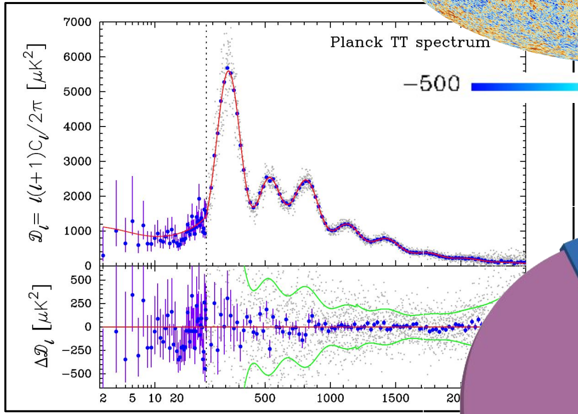


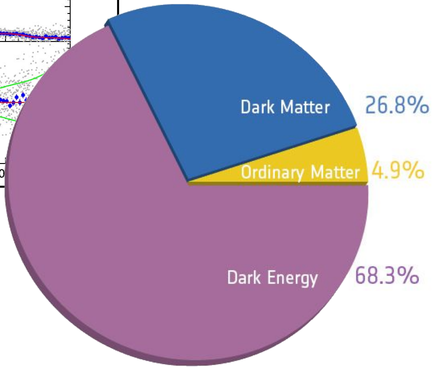




Cosmology



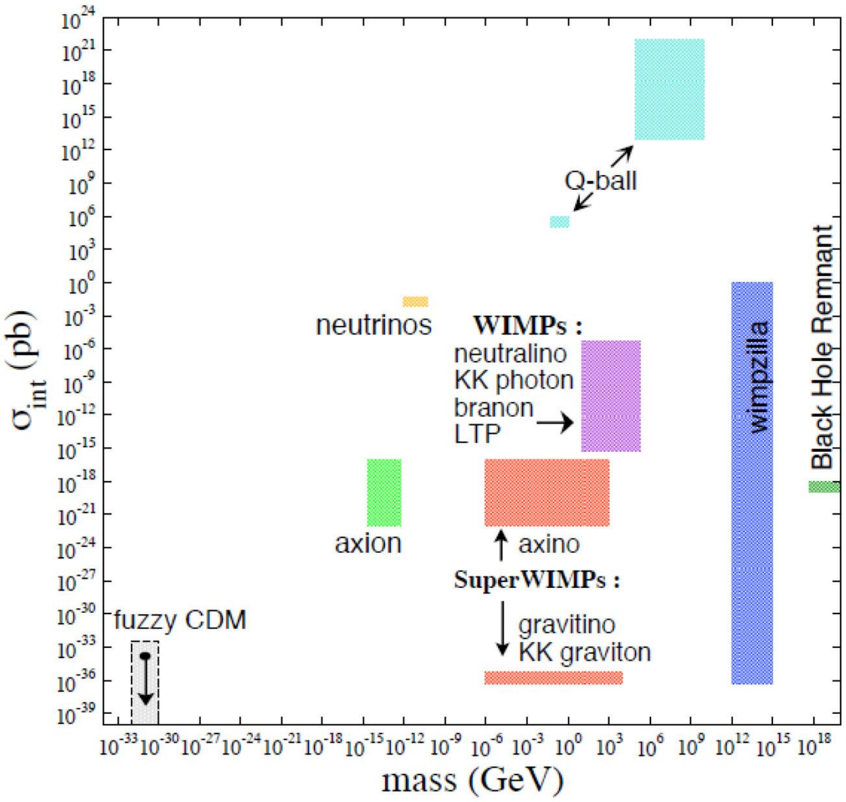




(Some) Dark Matter Candidates

MOND/TeVeS: fails (so far) to simultaneously describe all different scales

MACHOs: likely ~ 20% of DM are massive astrophysical compact halo objects (but not all of it)



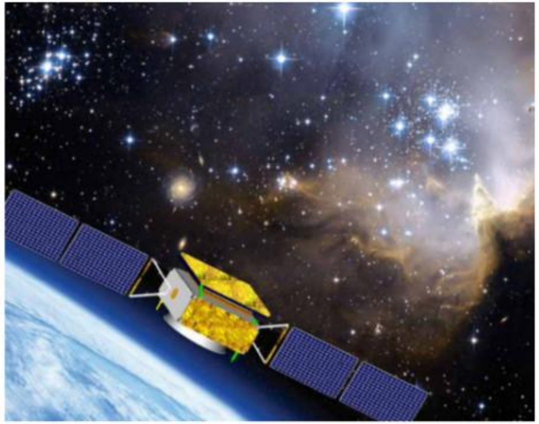
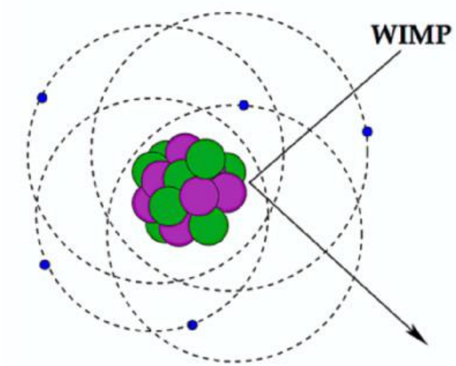
Prerequisites:

- cold (structure formation: no large free-streaming)
- electrically neutral (searches for CHAMPs)
- abundance of 27 % (CMB)
- cosmologically stable (gravitational effects today)
- no strong interaction (cluster collisions)
- **+ additional motivation**

  (smallness of neutrino masses; hierarchy problem; weak and strong unification; ultra high-energy cosmic rays; strong CP-problem)
- **+ signals within reach** → **WIMPs**

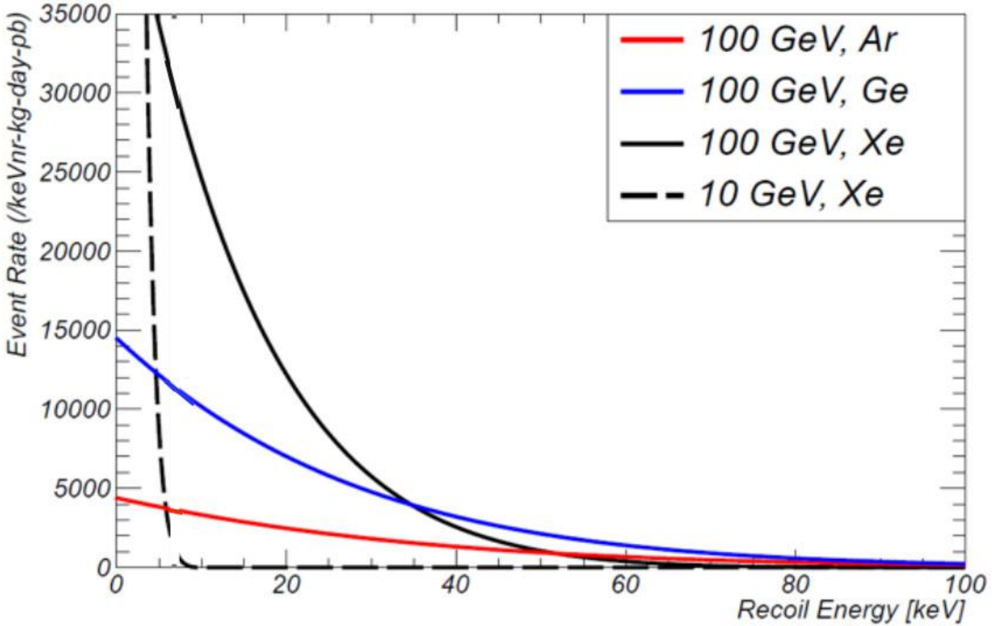
Dark Matter (WIMP) Searches

DARWIN

Indirect detection	Direct detection	Particle colliders
	 	
DM annihilation into SM particle	DM scattering off SM particle	Direct or by decay production DM
$\chi\bar{\chi} \rightarrow q\bar{q}, \gamma\gamma, \ldots$	$\chi N \rightarrow \chi N$	$pp \rightarrow \chi\bar{\chi} + X$

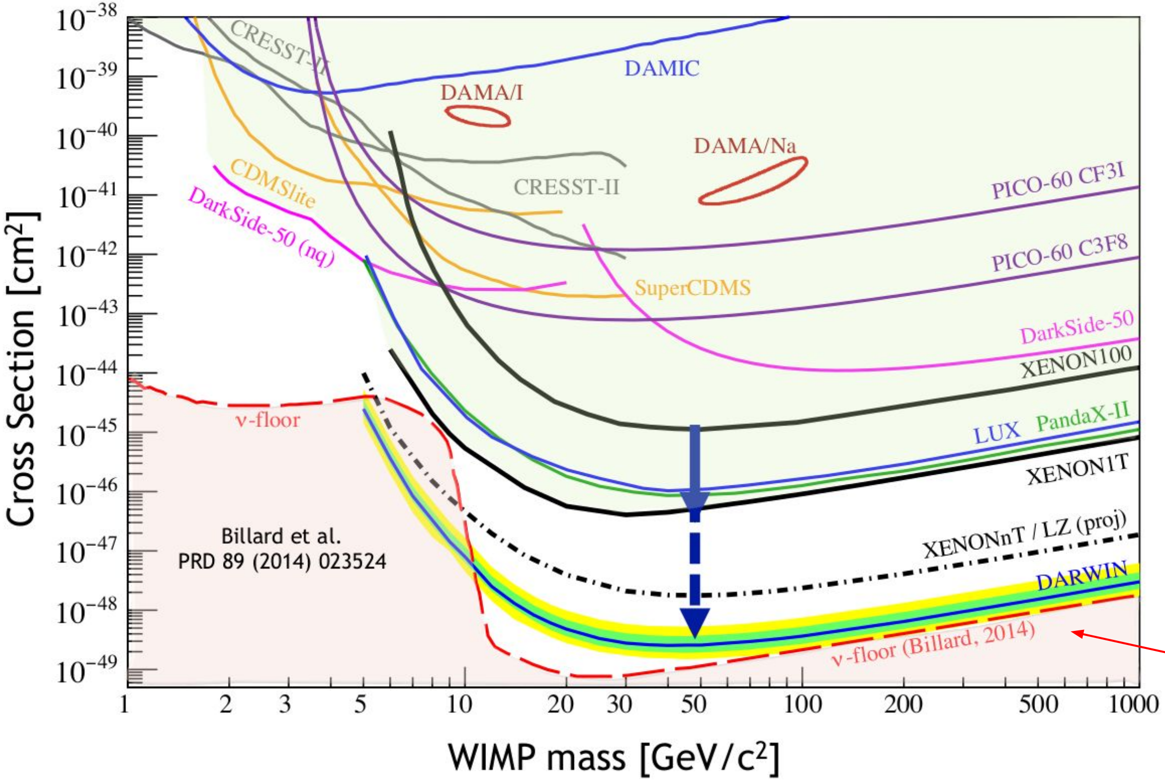
Why liquid xenon (LXe) as detection medium?

- Large mass number **A(131)**, higher rates for **SI** interactions (proportional to $\mathbf{A^2}$)
- **50% odd** isotopes (^{129}Xe, ^{131}Xe) for **SD** interactions
- No long-lived radioisotopes (with exception of ^{136}Xe, $T_{1/2}= 2.2\times10^{21}$ y), **low intrinsic bg**
- High stopping power (Z=54, ρ = 3 g/cm^3), **self shielding**
- **Efficient scintillator** (80% light yield of NaI)
- Light output @ 178 nm (**no WLS needed**)
- Liquid at ~182K @ 2 bar, **easy cryogenics**



Status of the Field

Spin-independent WIMP-nucleon interactions



A decade of direct searches

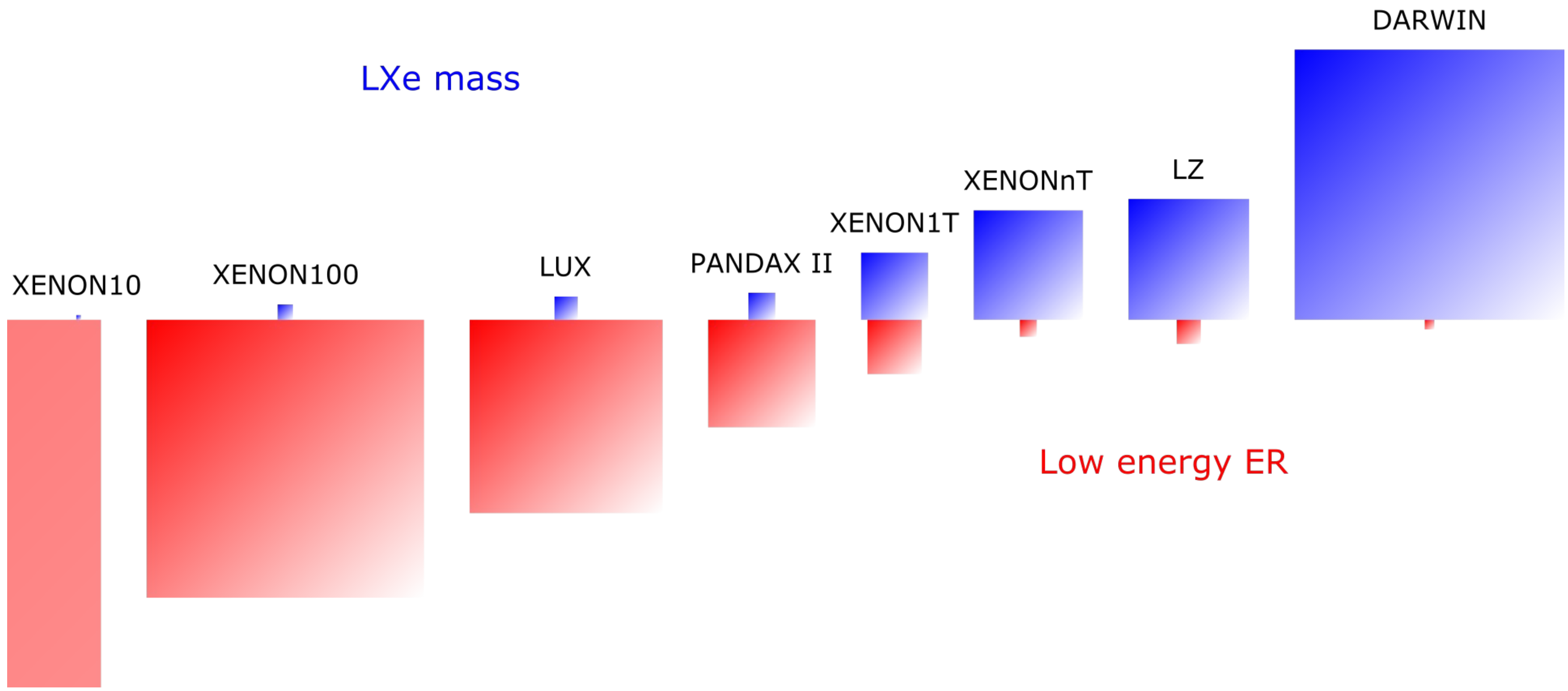
- Larger target mass
- Lower backgrounds
- Heavy targets

⇩

2-phase xenon (LXe/GXe) TPCs from $m_\chi > \sim 5$ GeV/c^2

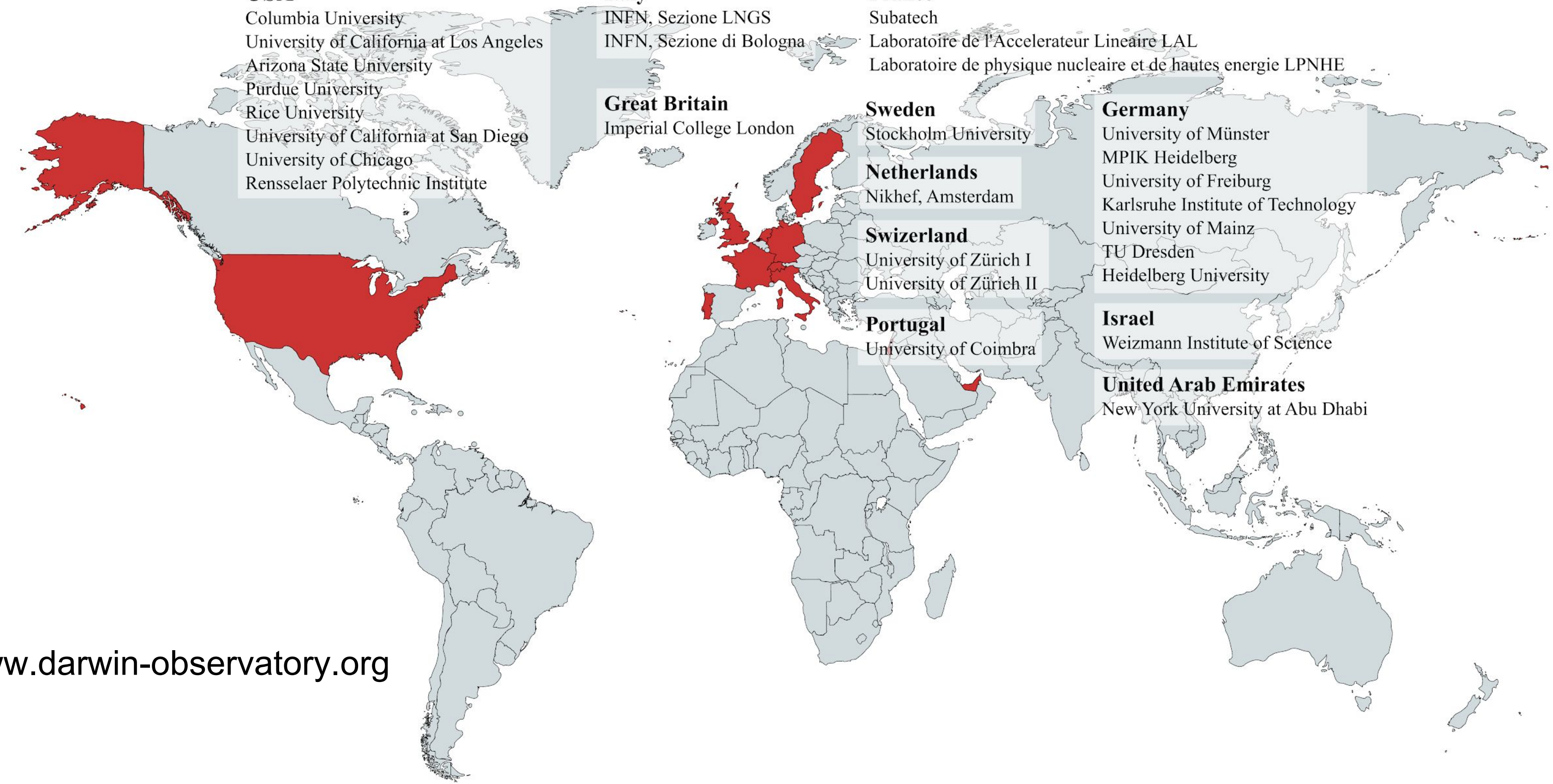
ν-floor: the ultimate limit from CNNS neutrino background
(Billard et al. PRD 89 (2014) 023524)

LXe detectors: How to improve sensitivity



DARWIN Collaboration

DARWIN



USA
Columbia University
University of California at Los Angeles
Arizona State University
Purdue University
Rice University
University of California at San Diego
University of Chicago
Rensselaer Polytechnic Institute

Italy
INFN, Sezione LNGS
INFN, Sezione di Bologna

Great Britain
Imperial College London

France
Subatech
Laboratoire de l'Accelerateur Lineaire LAL
Laboratoire de physique nucleaire et de hautes energie LPNHE

Sweden
Stockholm University

Netherlands
Nikhef, Amsterdam

Swizerland
University of Zürich I
University of Zürich II

Portugal
University of Coimbra

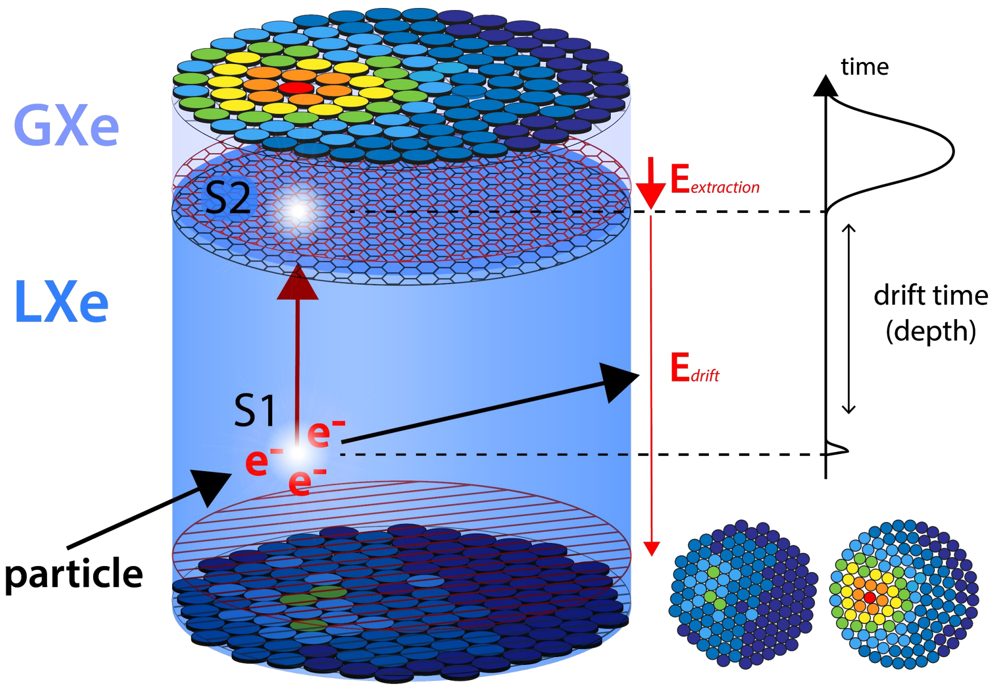
Germany
University of Münster
MPIK Heidelberg
University of Freiburg
Karlsruhe Institute of Technology
University of Mainz
TU Dresden
Heidelberg University

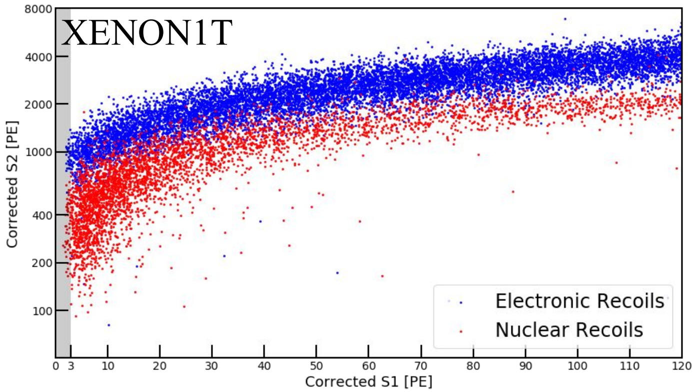
Israel
Weizmann Institute of Science

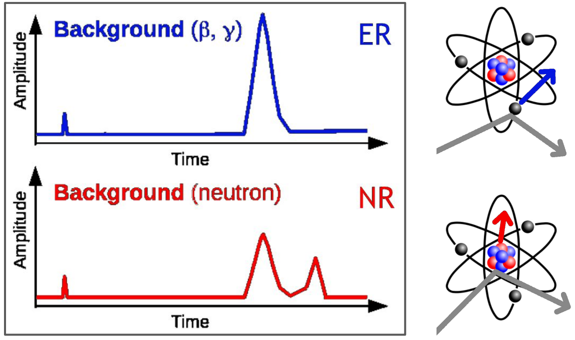
United Arab Emirates
New York University at Abu Dhabi

www.darwin-observatory.org

Detection principle of dual-phase TPC

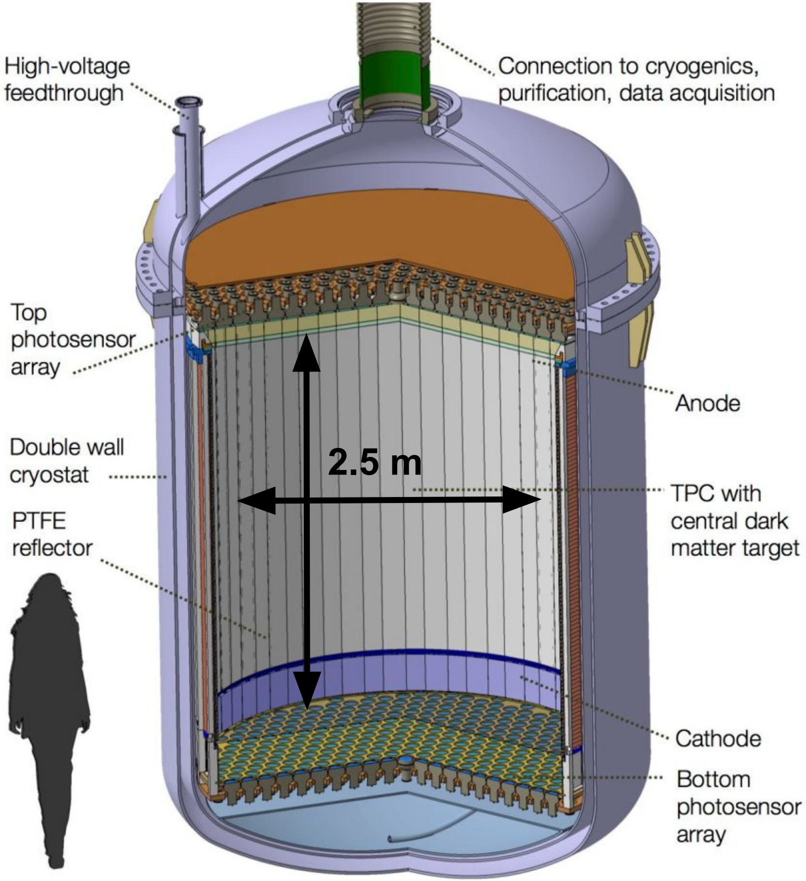




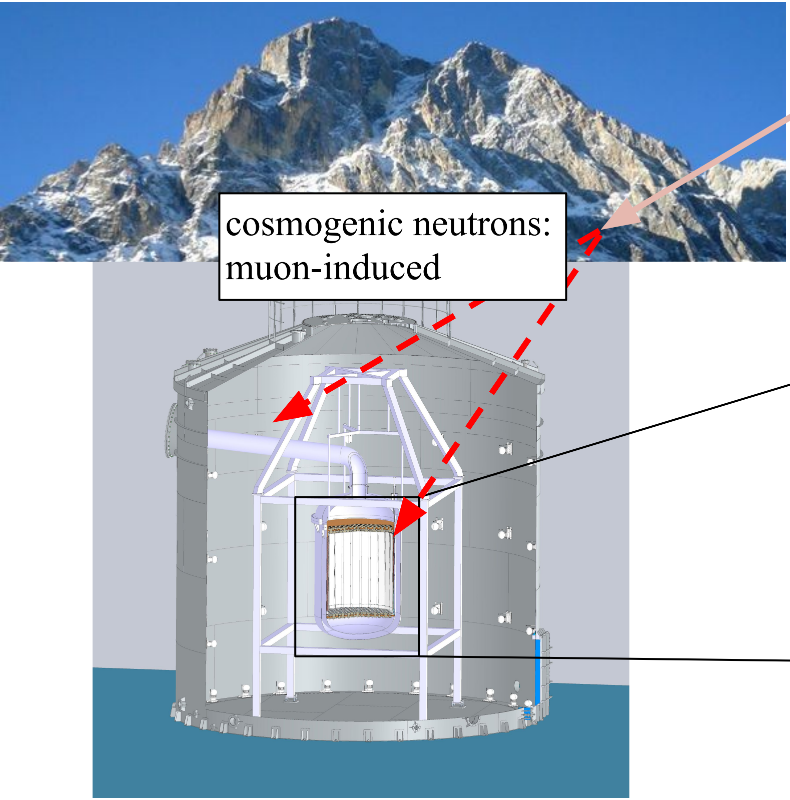


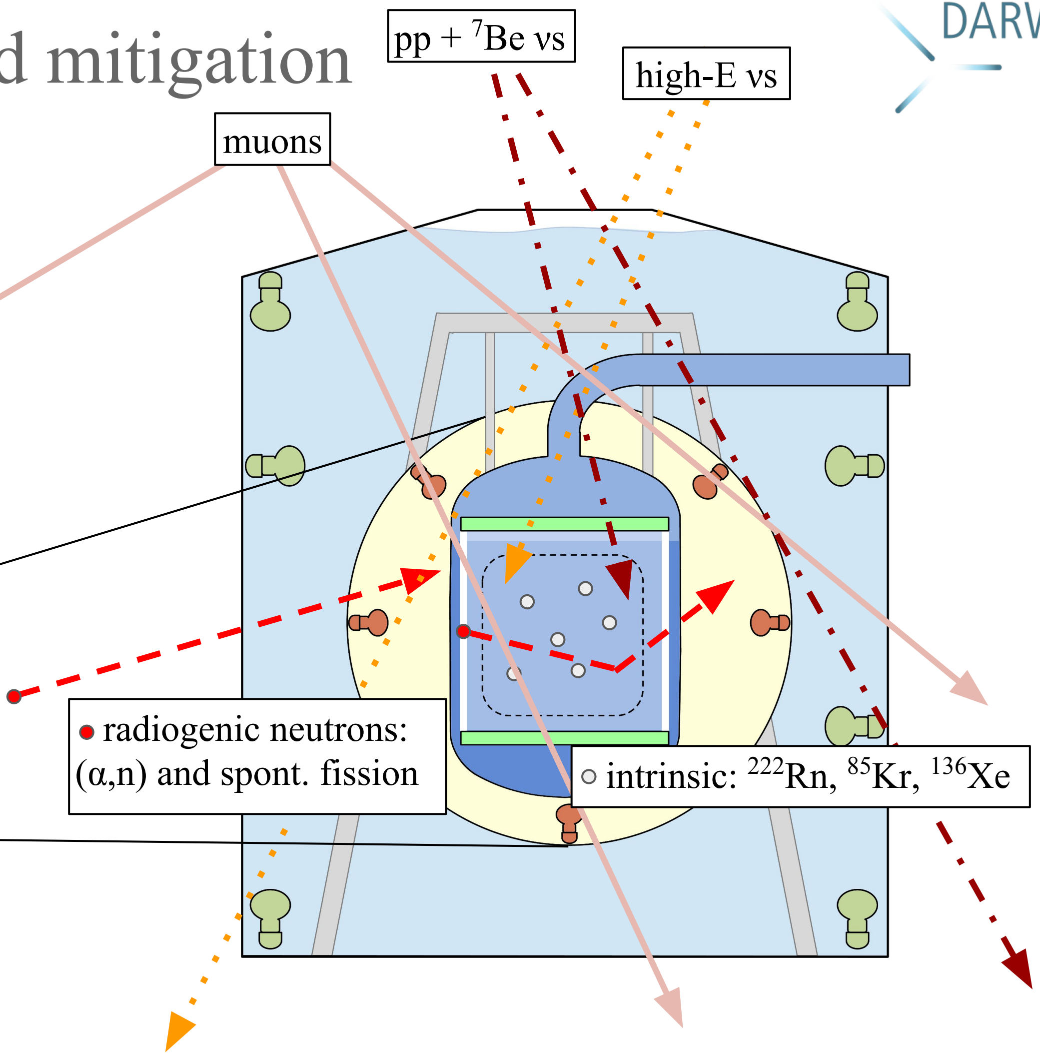
DARWIN: Baseline TPC Design

- ~50 t total LXe (40 t target)
- Double walled cryostat
  - SS, Ti, ...
- 2 photosensor arrays (top/bottom)
  - e.g., 1800 3” R11410-21 PMTs from Hamamatsu
- Reflective PTFE walls
- Charge + light readout
  - 2-phase via prop. scintillation in GXe
  - 1-phase via prop. scintillation in LXe
- Sensitivity goal: $\sigma_{SI} \sim 10^{-49}$ cm^2

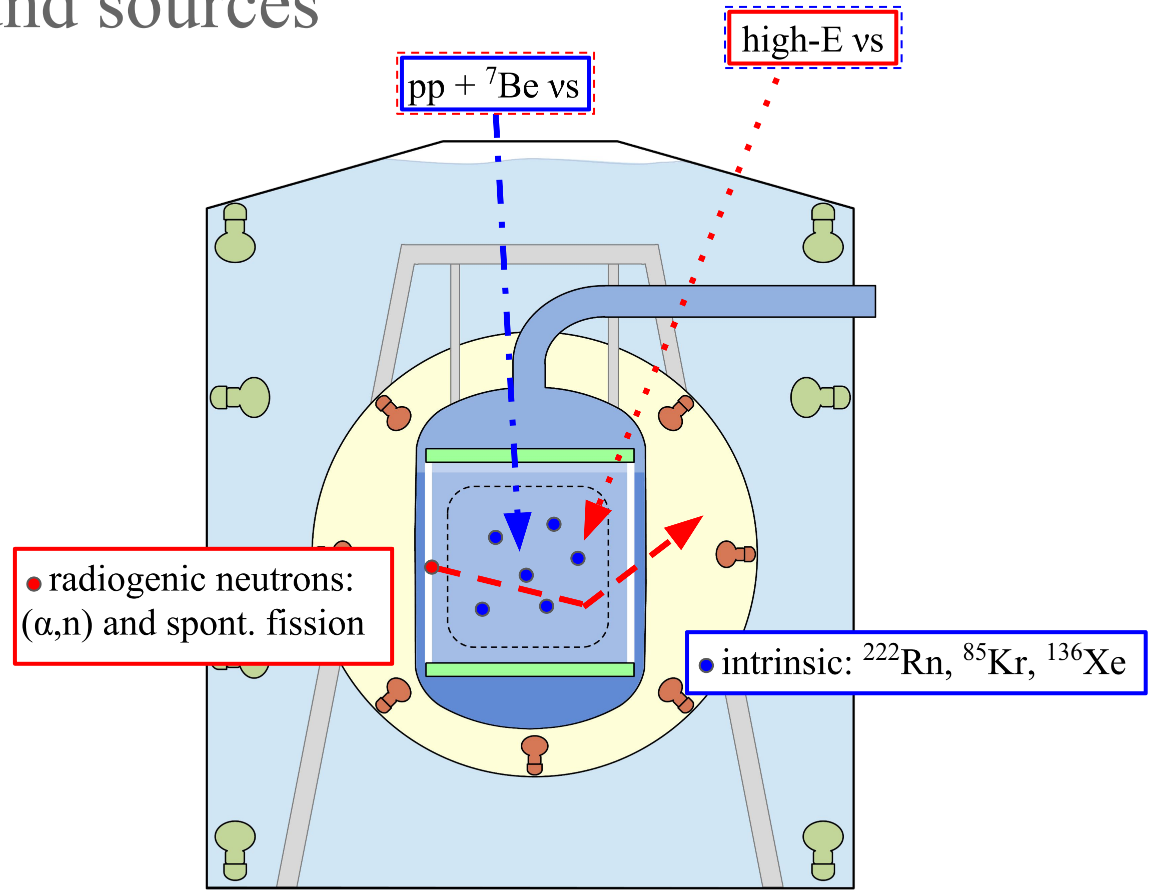


Background sources and mitigation

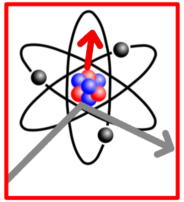




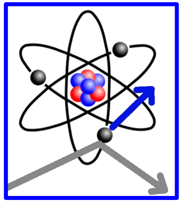
Background sources



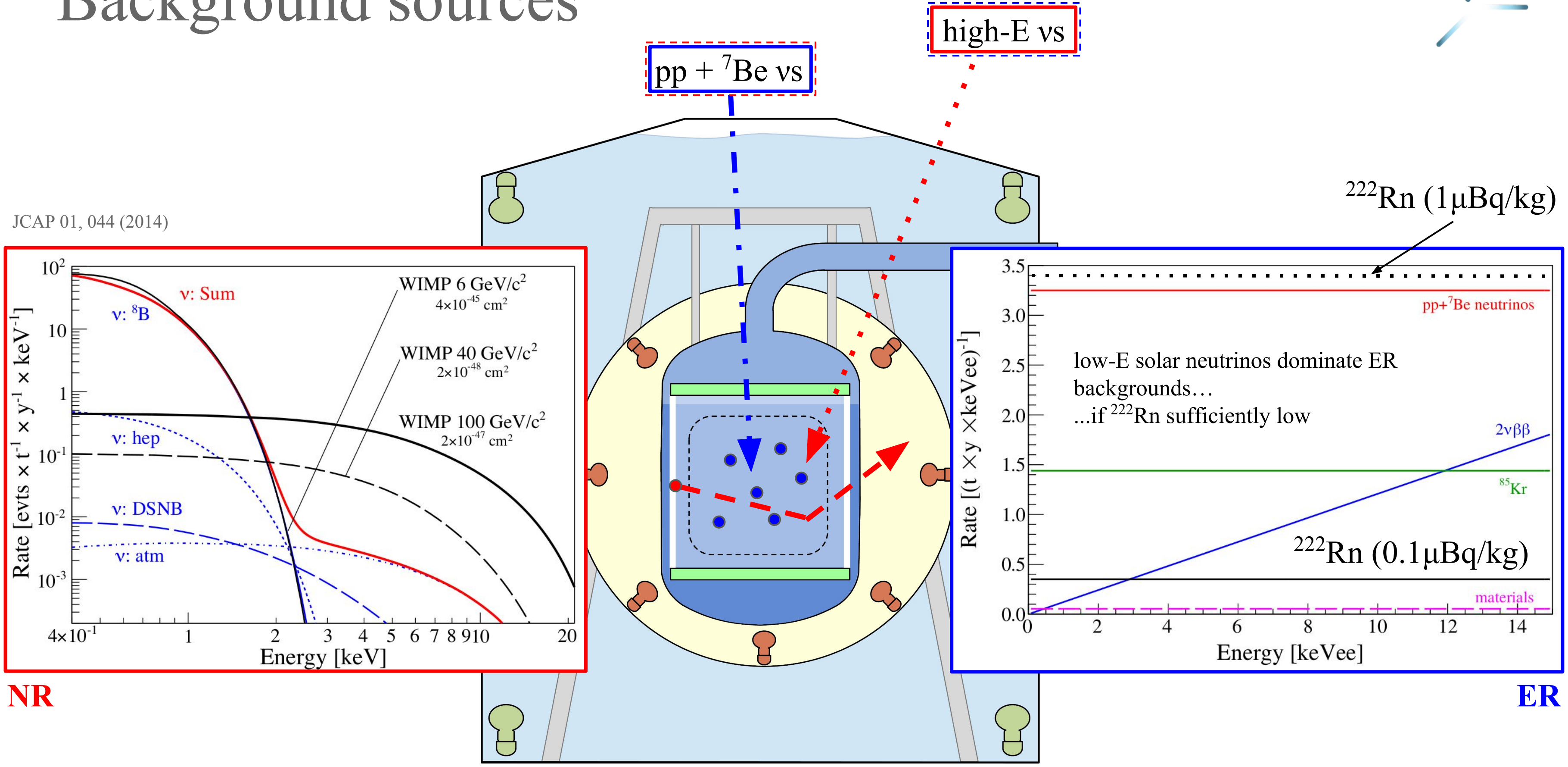
NR



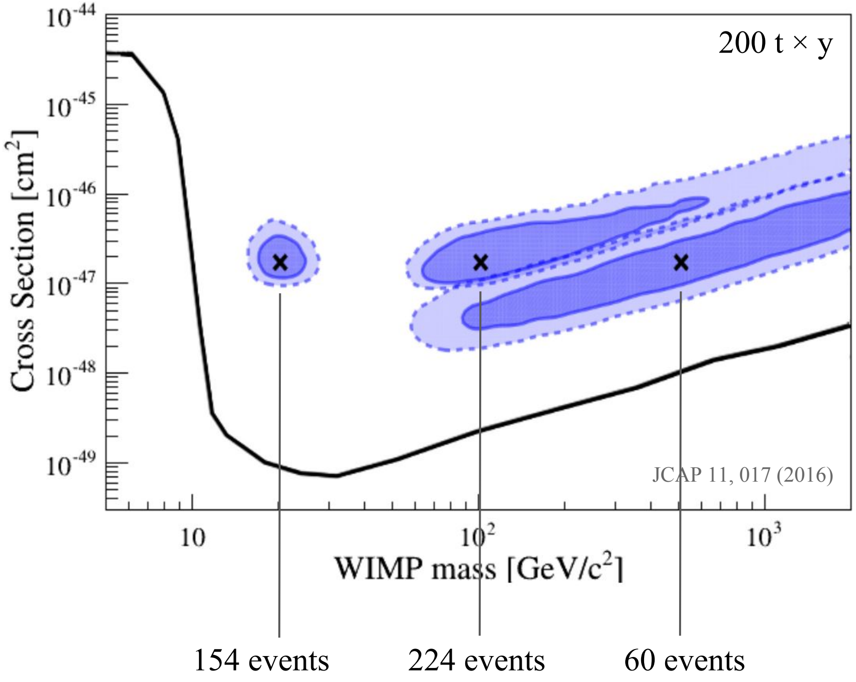
ER



Background sources



WIMP Spectroscopy

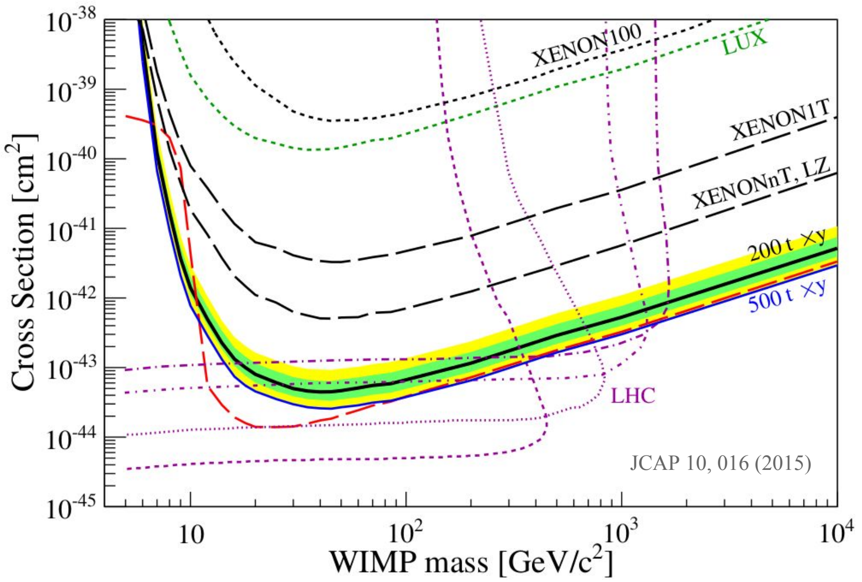


Reconstruction of WIMP properties:

Mass and scattering cross-section

- m_{WIMP} = 20, 100, 500 GeV/c^2
- Spin-independent cross section: 2×10^{-47} cm^2
- 1σ/2σ credible regions shown; marginalized over astrophysical parameter uncertainties (local DM density and distribution,)

WIMP Complementarity

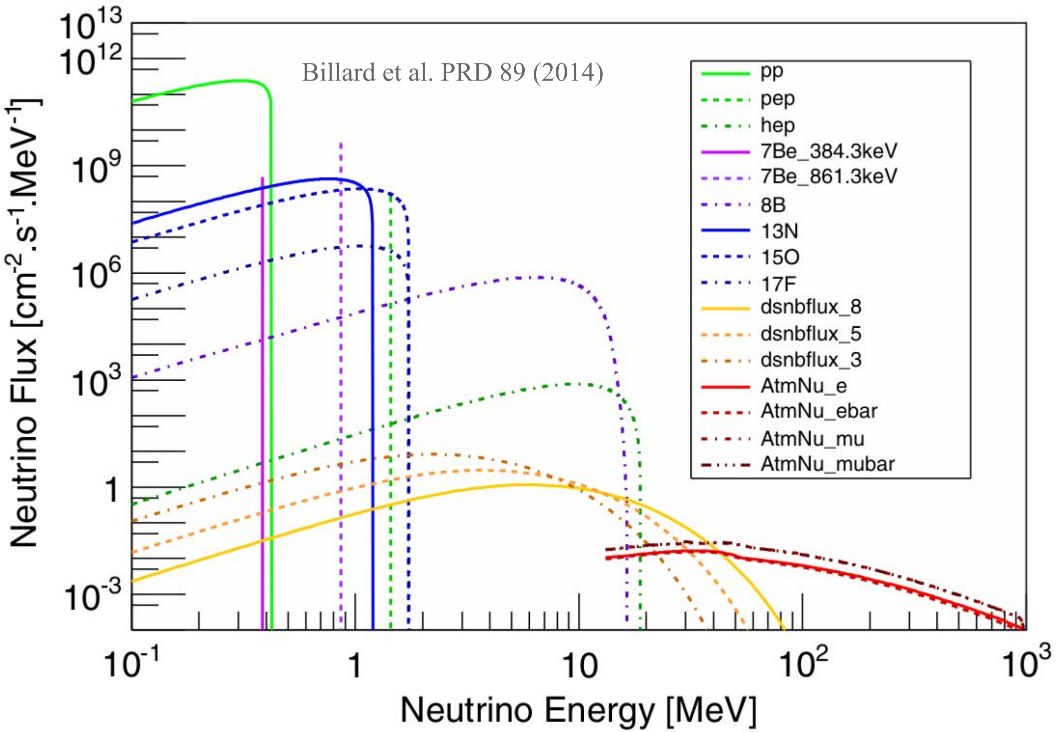


Sensitivity of DARWIN to spin-dependent WIMP-nucleon cross sections

- Likelihood analysis for 200 t × y and 500 t × y
- DARWIN and the high-luminosity LHC will cover common parameter space.
- 14 TeV LHC limits for the coupling constants $g_\chi = g_q = 0.25, 0.5, 1.0, 1.45$ (bottom to top)

Phys. Dark Univ. 9-10 (2015)

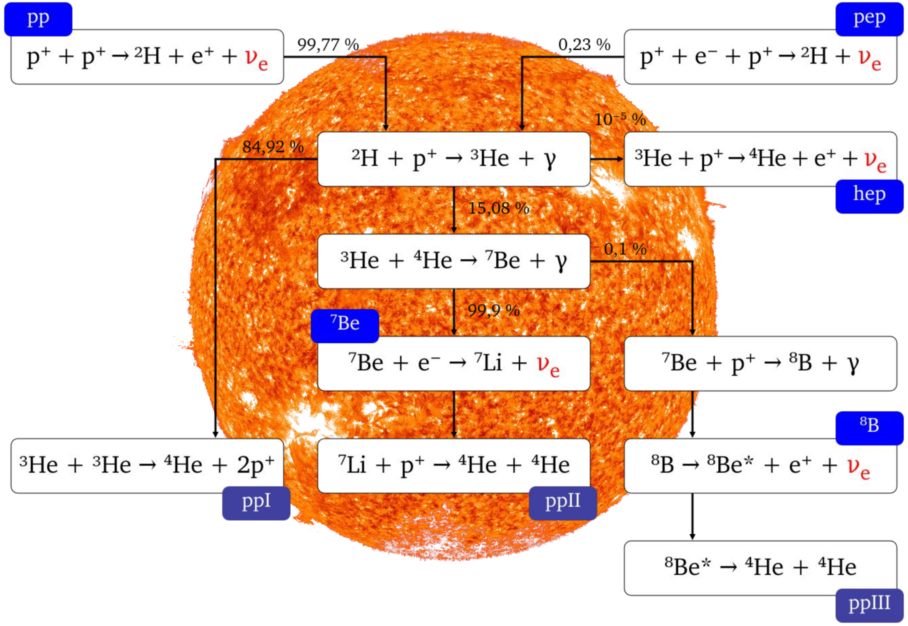
Detour: Neutrino sources

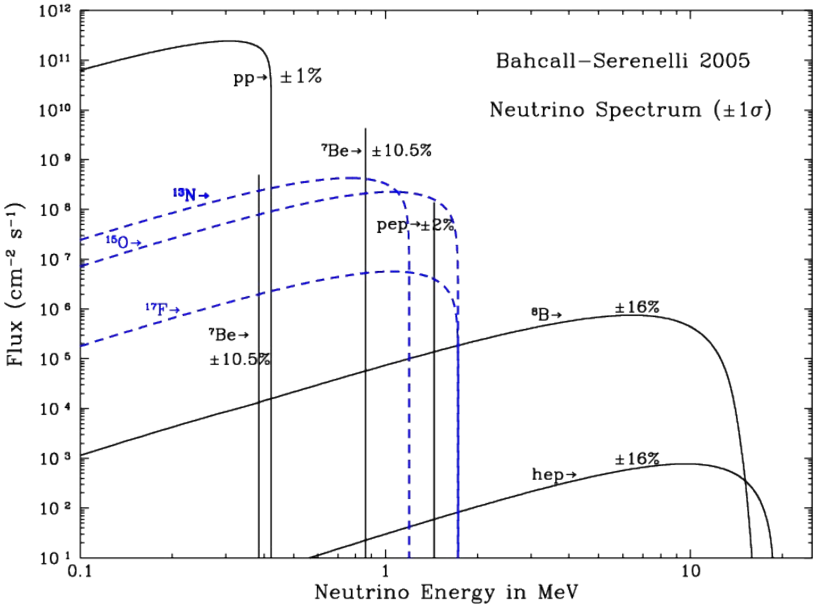


- Solar neutrinos
  (see next slide)
- Diffuse supernova neutrinos
  (history of all supernova explosions)
- Atmospheric neutrinos
  (through cosmic ray collisions in Earth’s atmosphere)

Detour: Solar Neutrinos

DARWIN

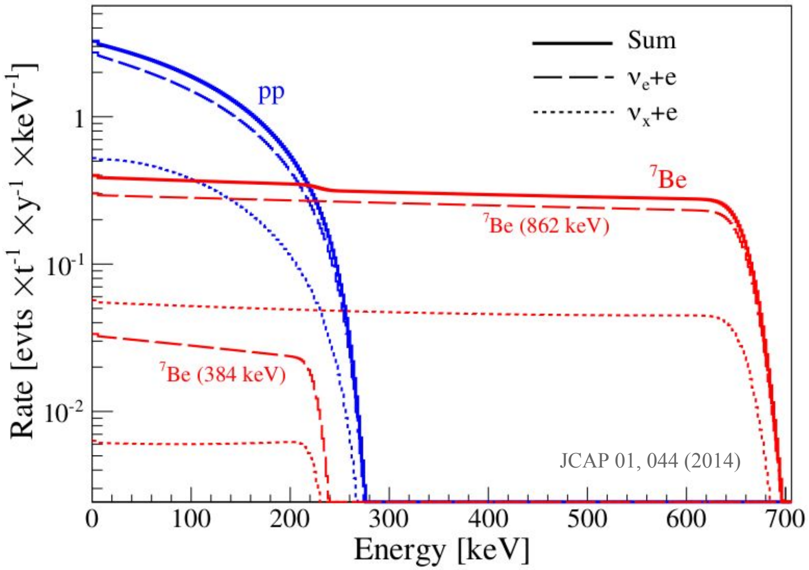




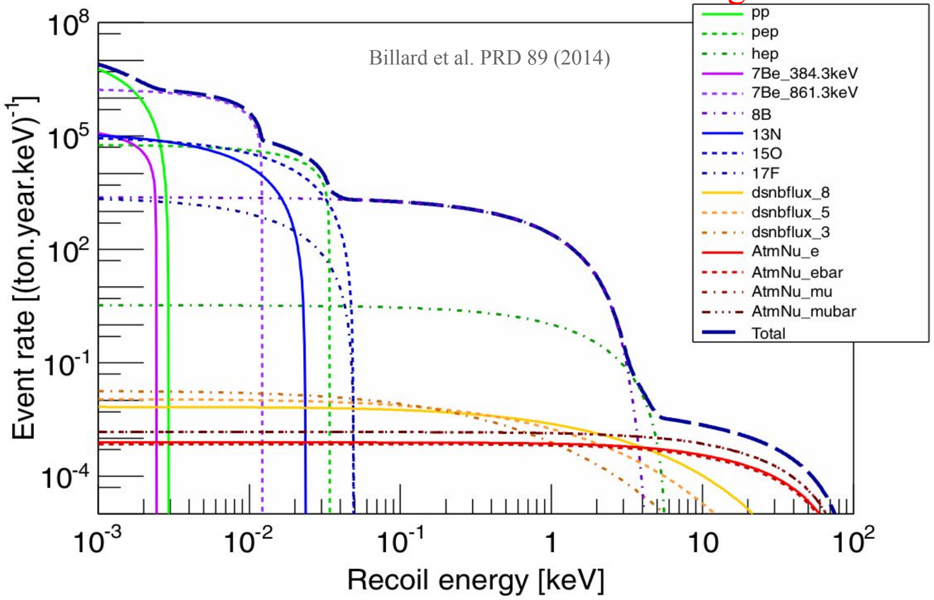
Neutrino observatory

DARWIN

ER: Elastic Neutrino Electron Scattering



NR: Coherent Neutrino Nucleus Scattering



Neutrino observatory

DARWIN

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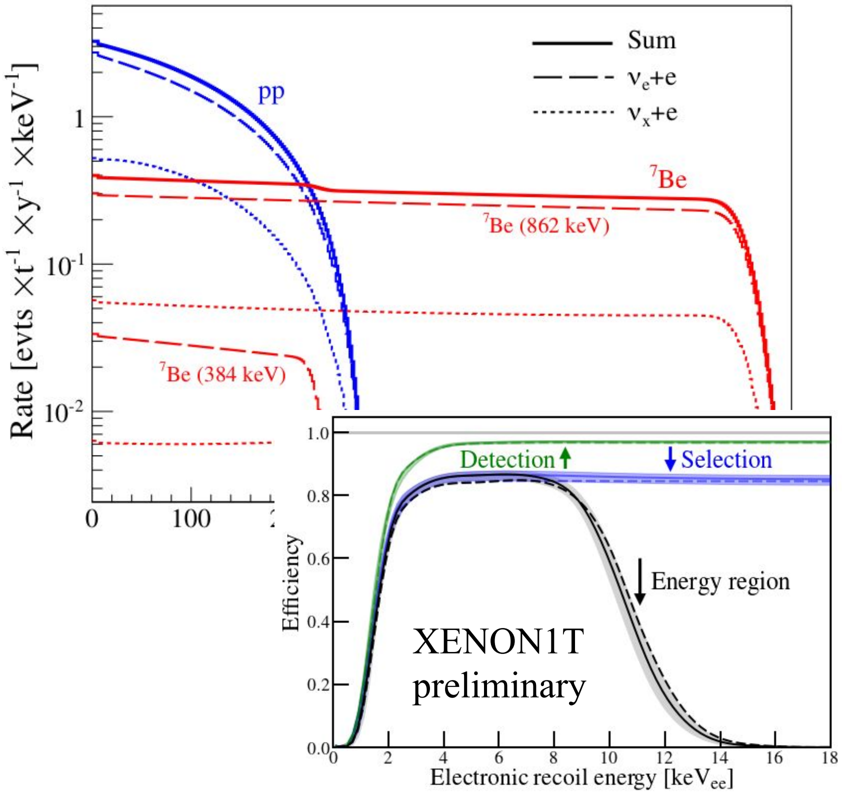

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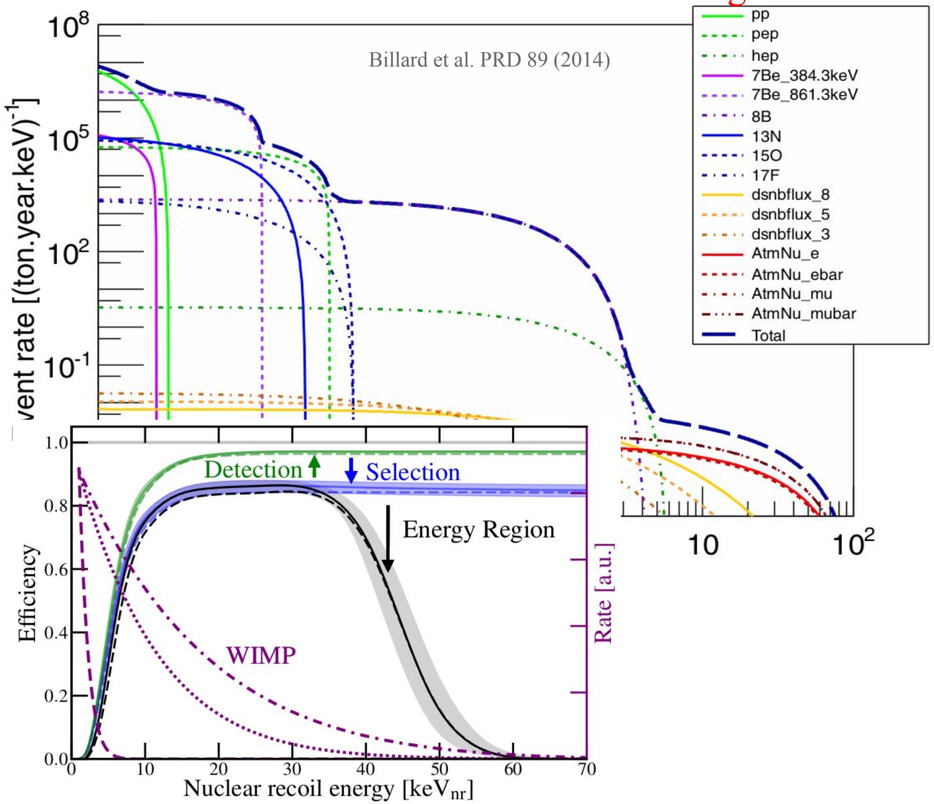
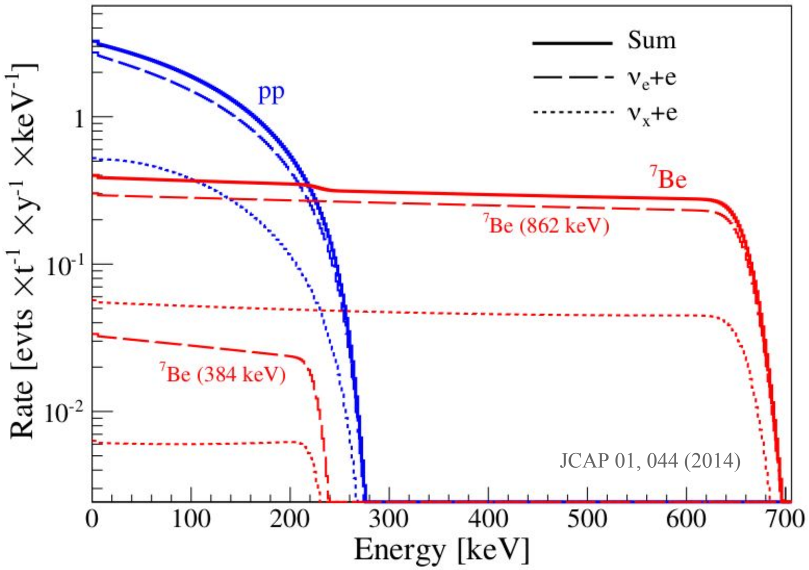
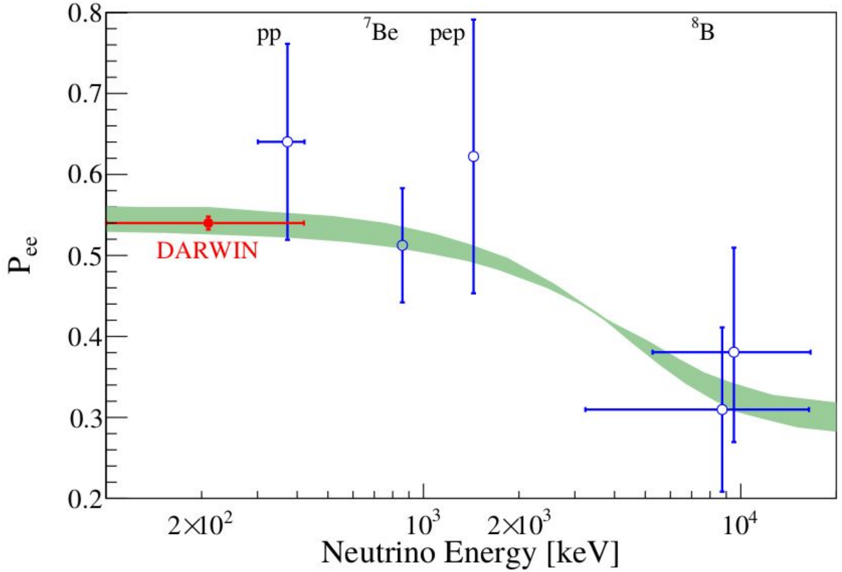


PRL 121 (2018), 111302

Elastic Neutrino Electron Scattering

ER: Elastic Neutrino Electron Scattering





- High statistics measurement of pp-flux: 1% precision after 5 years (9500 ν in 100 t × y)
- E.g., look for non-standard neutrino interactions (modified survival probability P_{ee} also at pp-energies)

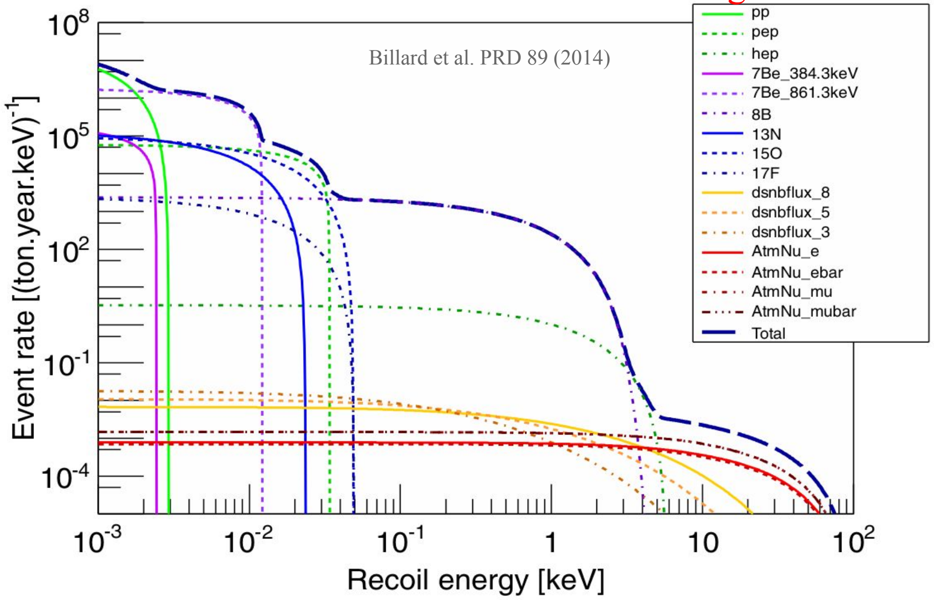
Coherent Neutrino Nucleus Scattering (CNNS)

Process interesting by itself

- Cleanly predicted in the SM
  (predicted cross-section is the largest of all low-E ν couplings)
- Measurement provides a SM test
- First observed by Coherent Coll.
  (Science 357 (2017), 6356)

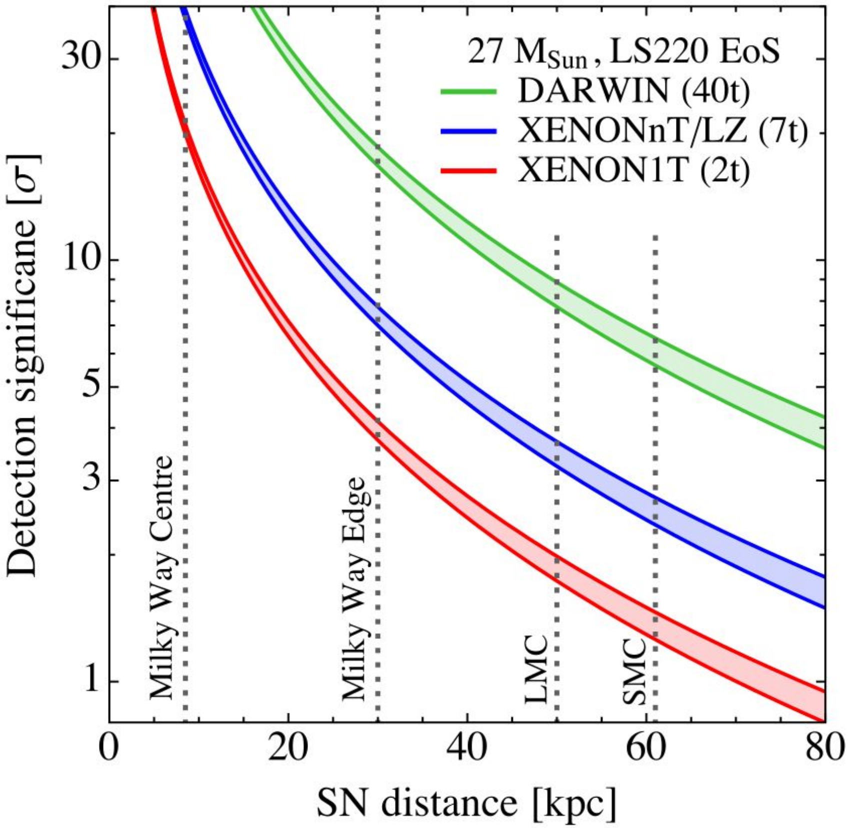
… and can be exploited to detect a supernova in (or close to) our galaxy ...

NR: Coherent Neutrino Nucleus Scattering



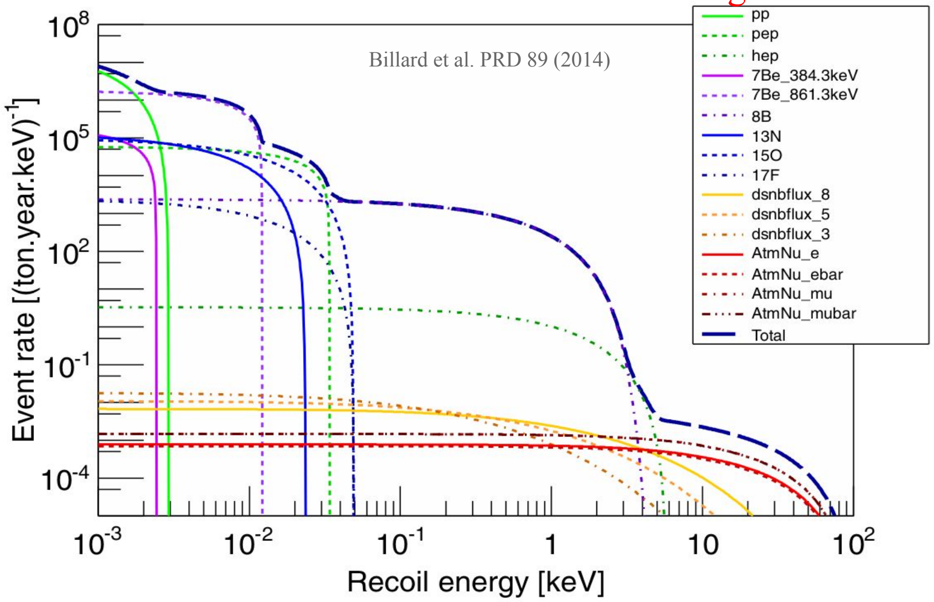
Coherent Neutrino Nucleus Scattering (CNNS)

DARWIN



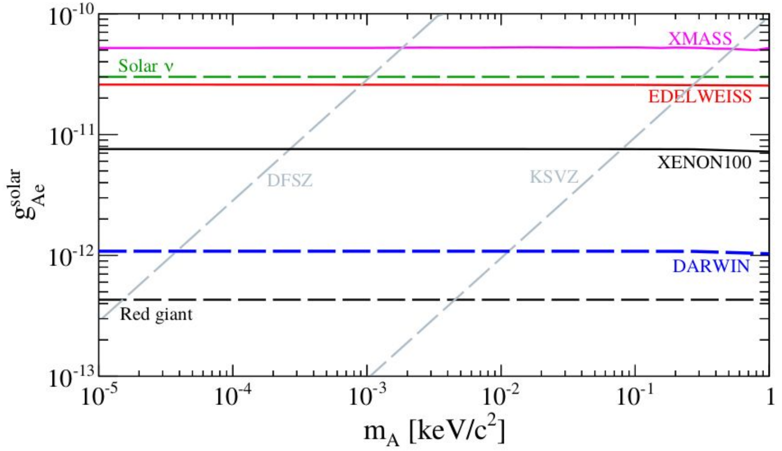
Lang et al., PRD 94, 103009 (2016)

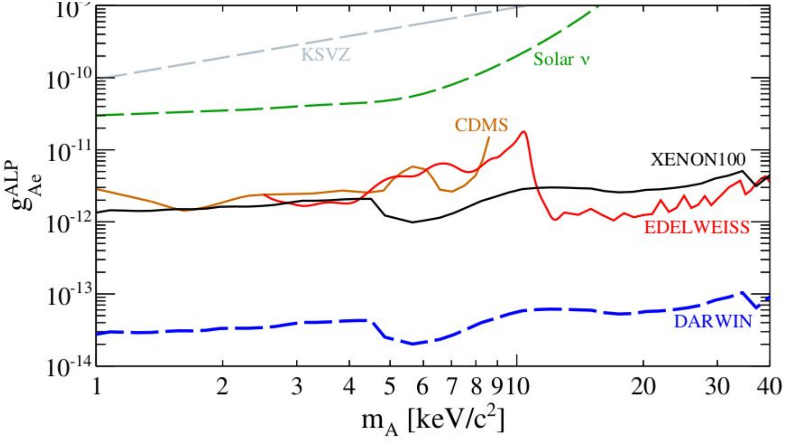
NR: Coherent Neutrino Nucleus Scattering



- Generate SNEWS trigger
- Provide complementary information to other experiments (sensitive to all six neutrino species)

Axion and ALP searches





Axion:

- Peccei-Quinn (1977) solution to strong CP problem in QCD (pseudo-Nambu-Goldstone boson of broken global U(1) symmetry)
- Interacts with matter via axio-electric effect

Galactic axions and axion like particles (ALPs):

- well-motivated DM candidates

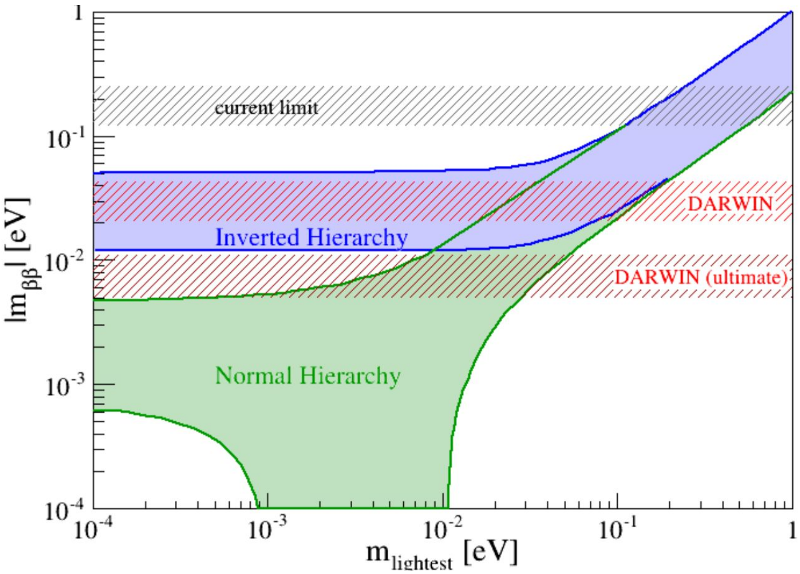
Solar axions:

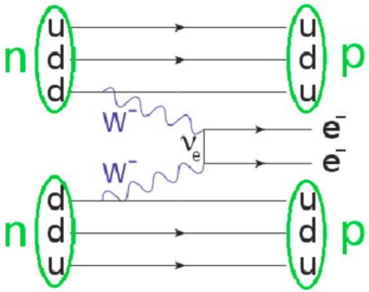
- could be abundantly produced in sun

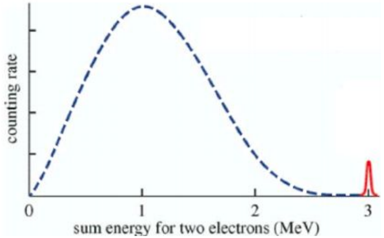
Neutrinoless double beta decay ($0\nu\beta\beta$) of ^{136}Xe

DARWIN

- Neutrino: Majorana or Dirac particle?
- Probe effective Majorana mass
- Determine mass hierarchy
- Test lepton number conservation







$Q_{\beta\beta}(^{136}Xe) = 2.46$ MeV

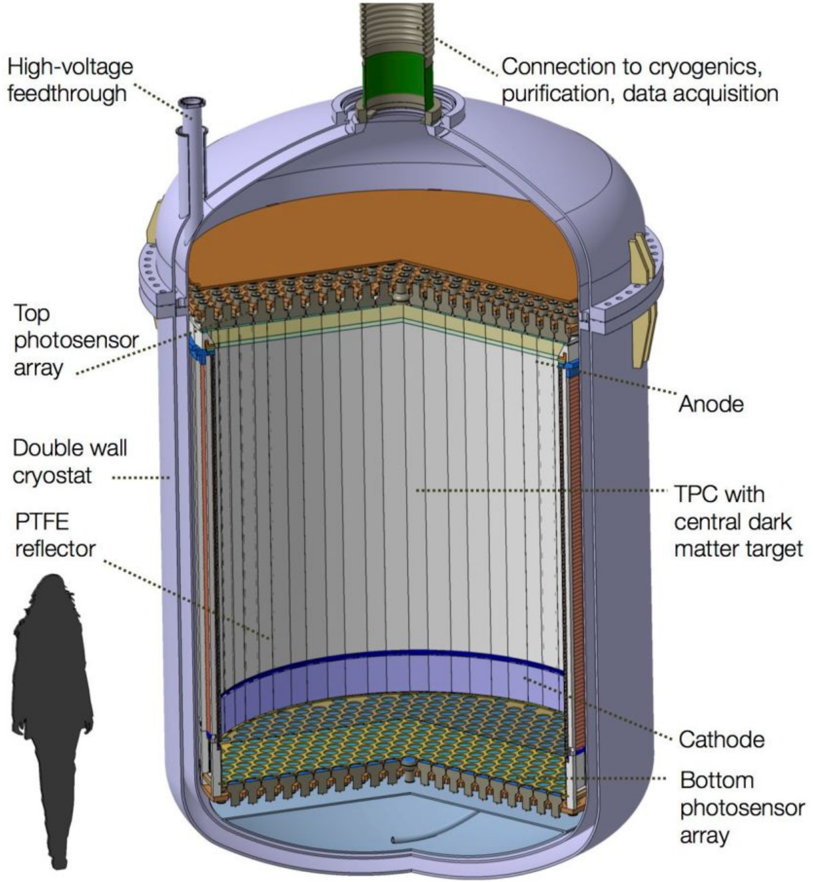
^{136}Xe abundance: 8.9% in ^{nat}Xe

R&D for DARWIN

DARWIN

(Some) important requirements:

- Good light collection
  - SiPM, SiGHT, Abalone, 4π coverage, ...
- Stable, strong and homogeneous E-fields
  - Electrodes development, Single Phase
- Xenon purity
  - e^- drift and ER backgrounds
- Material purity
  - Screening (NR and ER), hermetic TPC
- Triggerless DAQ readout

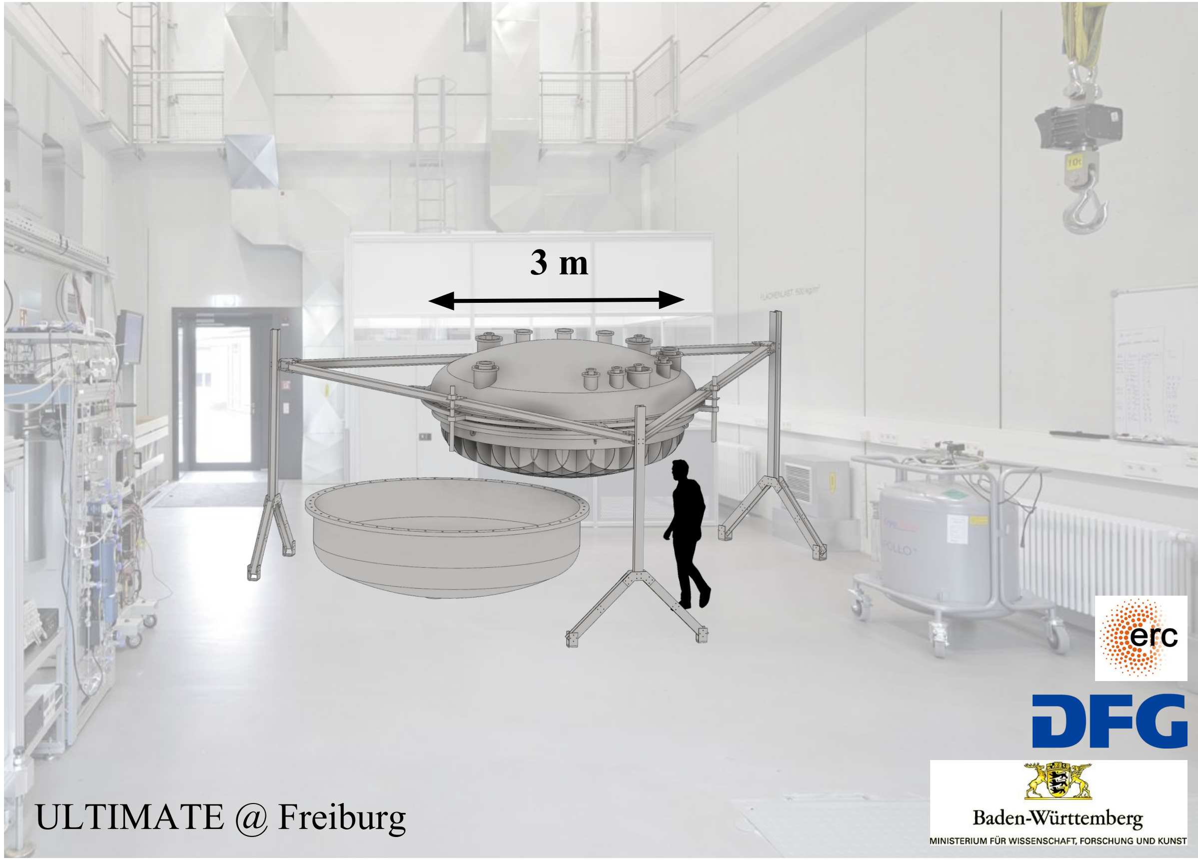


R&D for DARWIN

Test Platforms: (x,y) and z

3.7 m

XENOSCOPE @ Zuerich



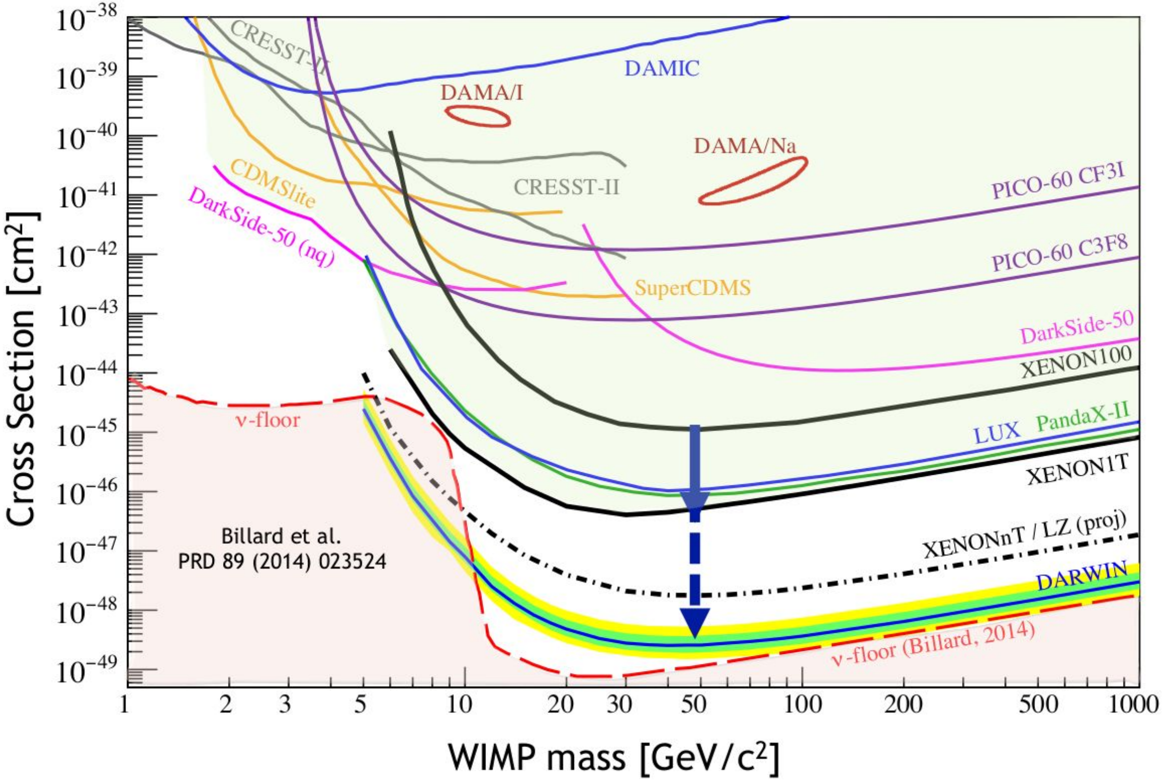
ULTIMATE @ Freiburg

erc

DFG

Baden-Württemberg
MINISTERIUM FÜR WISSENSCHAFT, FORSCHUNG UND KUNST

DARWIN Summary



Timeline construction ~2025

Primary scientific goal:

- Direct detection of WIMP Dark Matter; ultimately limited by ν-floor

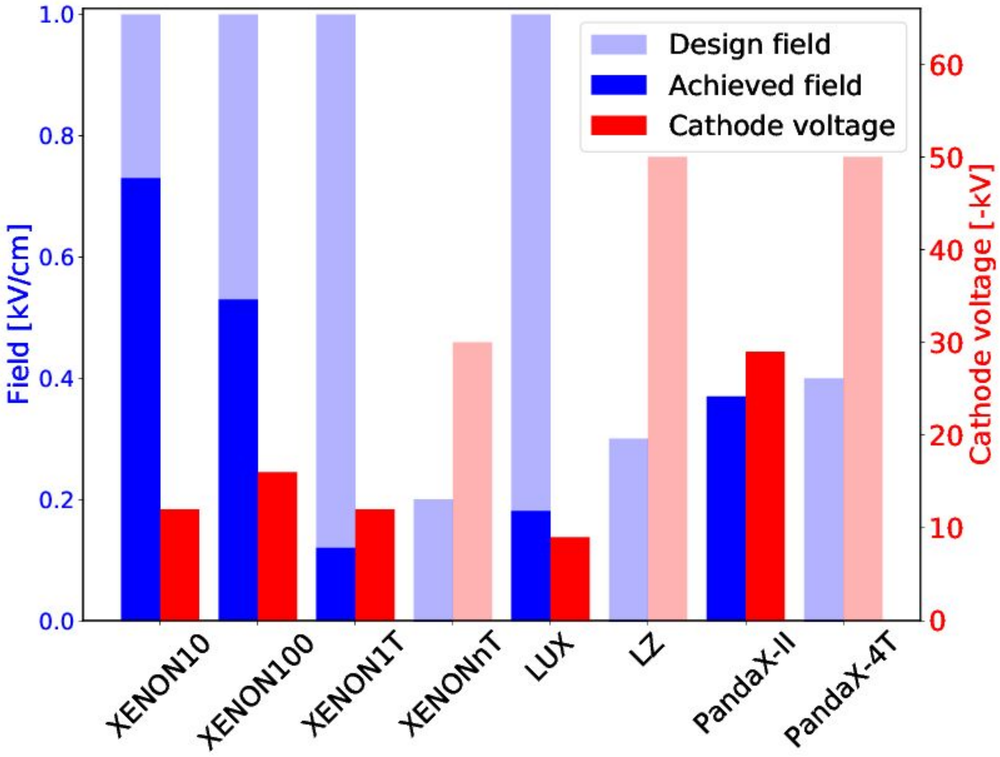
Further science channels:

- Search for alternative DM candidates
  - e.g., ALPs
- Neutrino observatory
  - pp-flux, SN neutrinos
- Rare event searches
  - Axion, $0\nu\beta\beta$ (^{136}Xe)

Backup

R&D for DARWIN

Electric field - Lessons learned



Drift field

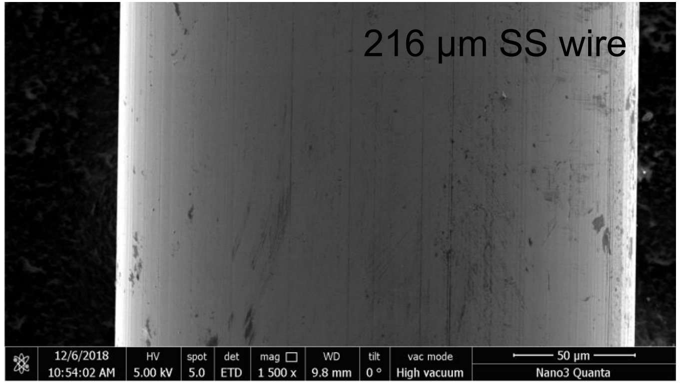
- bare minimum: ~80 V/cm (e.g., XENON1T [PRL 121, 111302])
- requires: -20 kV @ cathode

Electrodes

- Solid metal frame with parallel/woven wires or etched meshes
- Minimal (wire) sagging under electrostatic forces
- Small electrode frames to maximize sensitive volume

R&D for DARWIN

Electric field



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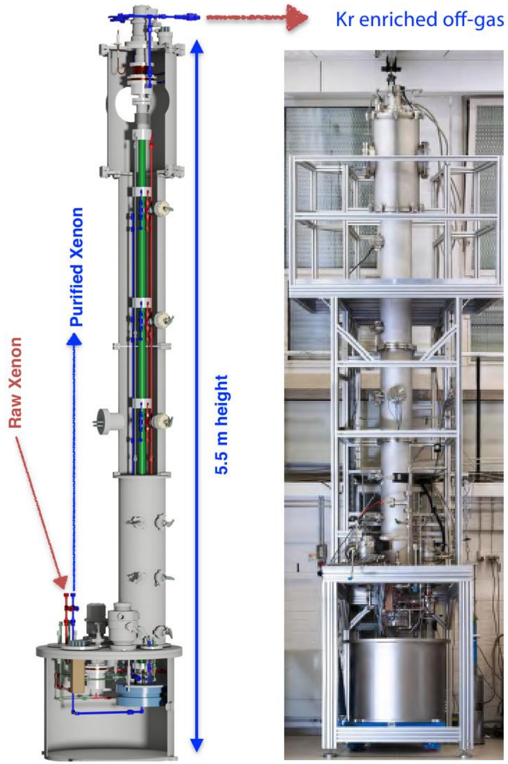
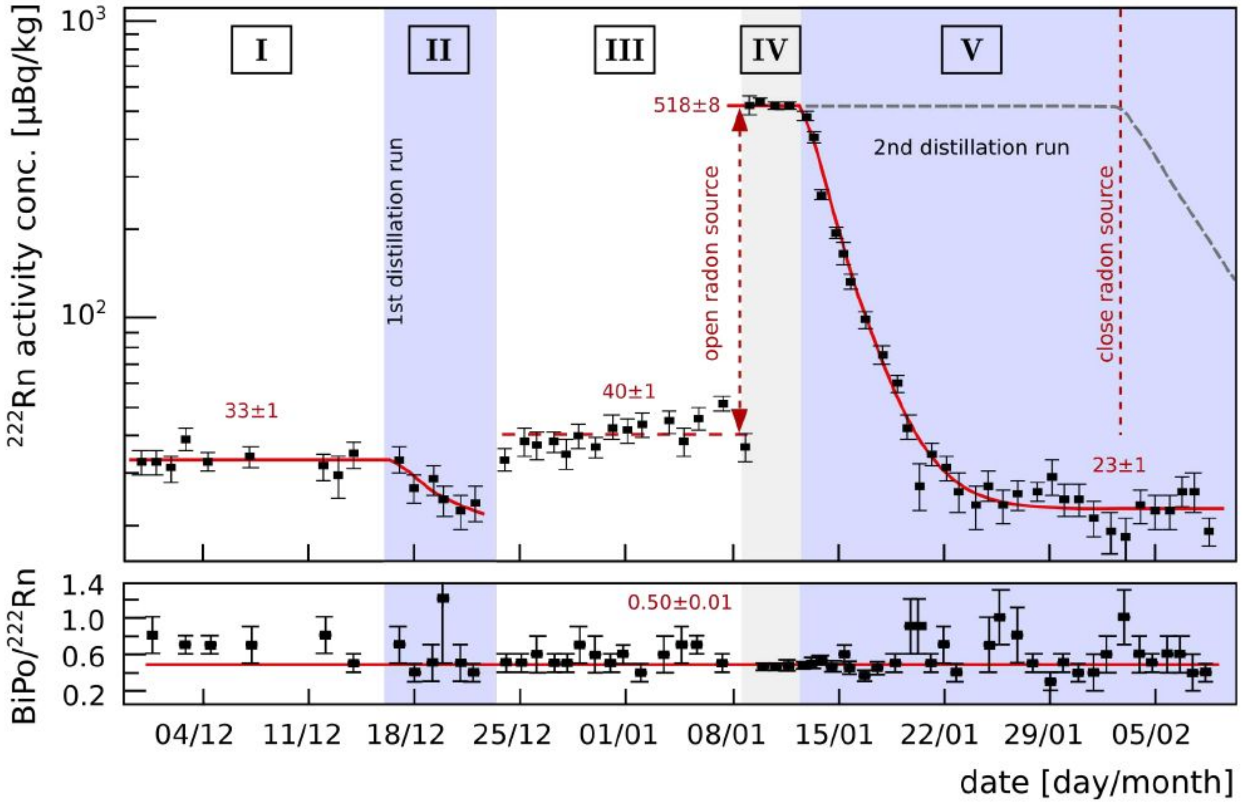
R&D for DARWIN

Rn/Kr mitigation

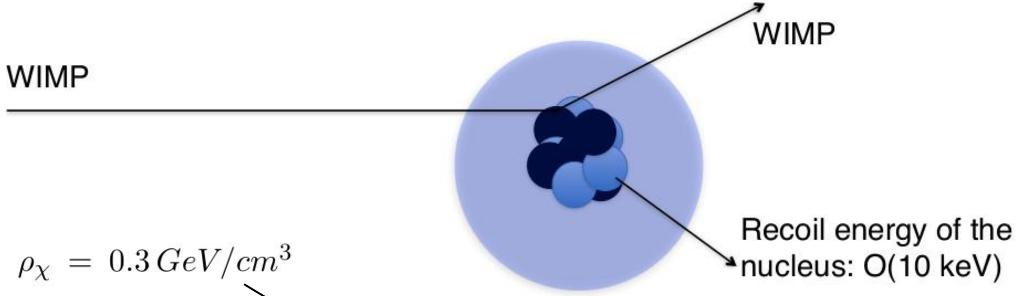
Eur. Phys. J. C 77, 358 (2017)





Direct DM Detection – What to expect?

DARWIN



$$\rho_\chi = 0.3\, GeV/cm^3$$

$$\overbrace{\frac{dR}{dE}(E,t)}^{Scatt.\,Rate} = \underbrace{N_T}_{Target\ Dependence} \overbrace{\frac{\rho_\chi}{m_\chi}}^{Number\ density} \int_{v_{min}} \underbrace{\frac{d\sigma}{dE}(v,E)}_{Diff.\ Cross\ Section}\, v\, \overbrace{f_E(\vec{v},t)}^{veloc.\ distribution}\, d^3\vec{v}$$

(arXiv:1605.08788)

$$\frac{d\sigma}{dE} = \frac{m_N}{2\mu^2 v^2}\left(\sigma_{SI} F^2(q) + \sigma_{SD} S(q)\right)$$

proportional to A^2

requires nucleus with non-zero spin (e.g. ^{129}Xe, ^{131}Xe)