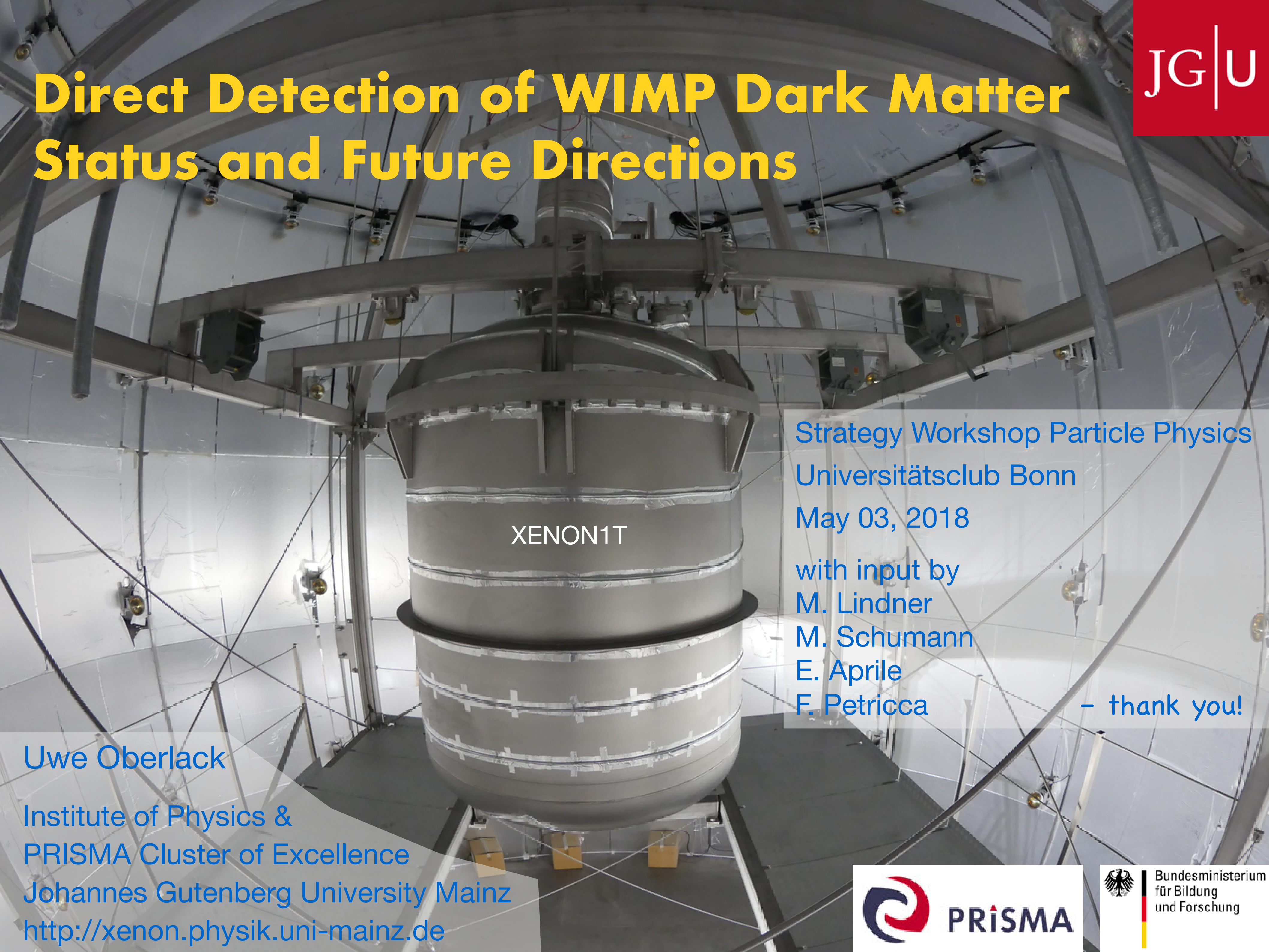
Direct Detection of WIMP Dark Matter
Status and Future Directions



Strategy Workshop Particle Physics
Universitätsclub Bonn
May 03, 2018

with input by
M. Lindner
M. Schumann
E. Aprile
F. Petricca – thank you!

Uwe Oberlack

Institute of Physics &
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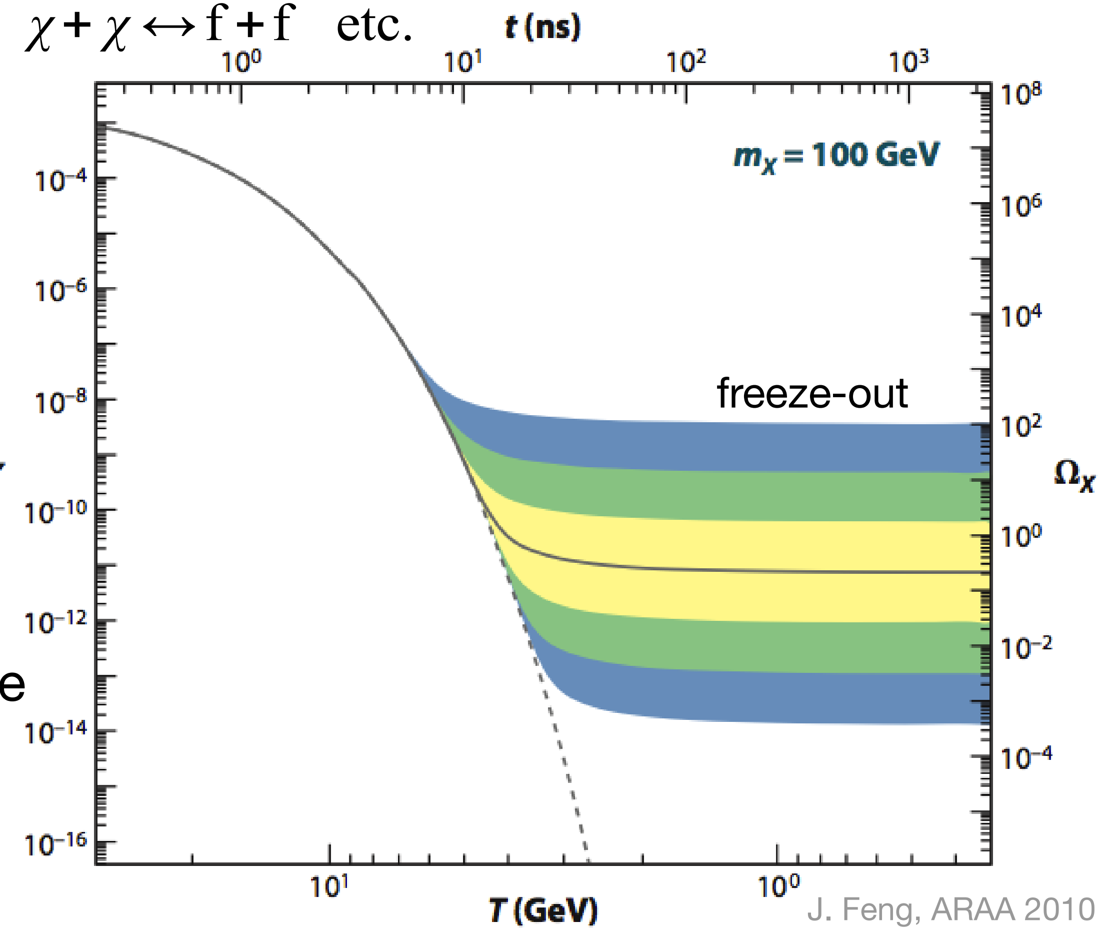
Johannes Gutenberg University Mainz
http://xenon.physik.uni-mainz.de

The Case for WIMP Dark Matter

$\chi + \chi \leftrightarrow f + \bar{f}$ etc.



J. Feng, ARAA 2010

- ✔ WIMP DM as thermal relic at the "right" density via freeze-out
- ✔ Appears as natural candidate in well motivated, UV-complete theories (geared towards solving other particle physics puzzles)
- ✔ Traditional example: SUSY, but also UED, little Higgs, ...

➔ Expect new physics at the TeV scale

☹ Problem: nothing found so far

- at the LHC
- with direct searches
- with indirect searches

→ It's more complicated!

Evolution of Dark Matter Models

Classic WIMP

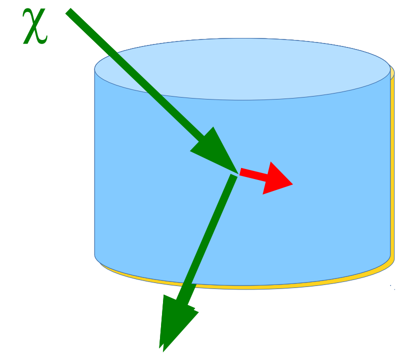
Mies van der Rohe, German Pavillion in Barcelona

Latest Dark Matter Models

Hundertwasser house, Vienna

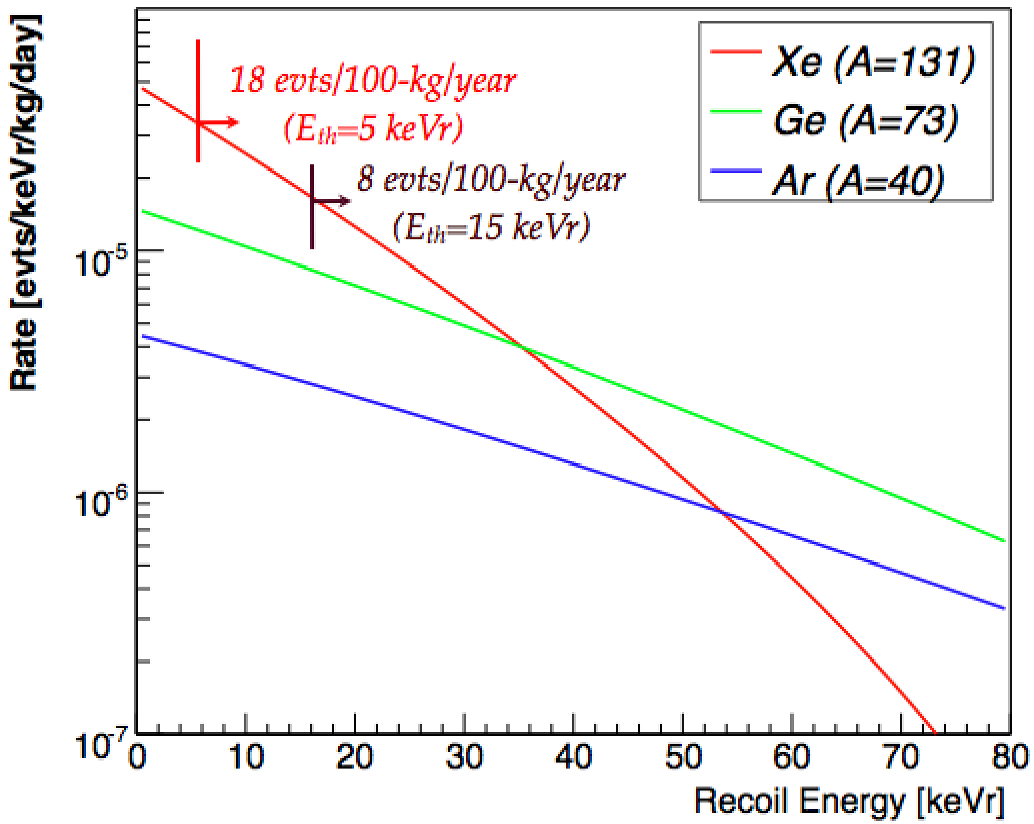
idea borrowed from M. Kamionkowski

WIMP Dark Matter Direct Detection



- Elastic scattering of WIMPs χ off nuclei A.
  → **nuclear recoil**
  - spin-independent (~A^2) or spin-dependent? … EFT op's
- Mass range
  - m_χ ~ 10 – few 10^3 GeV/c^2 ("traditional")
  - < 1 GeV/c^2 to 10^4 GeV/c^2 (extended)
- Energy spectrum:
  - "Standard" spherical halo
  - DM relative velocity: v_χ ~ 230 km/s
    → exponential recoil spectrum
    <E> ~ O(10 keV)
  - large nuclei: coherence ~A^2 for small q
  - nuclear form factor reduction at higher q
  - Local number density of WIMPs: ρ_χ/m_χ
    ρ_χ ~ 0.3 GeV/c^2/cm^3
  - ρ_χ/m_χ ~ 100 / L * (30 GeV/c^2/m_χ)

Rate < 10^{-4} events / kg / day



Backgrounds in Direct DM Search

Cross-sections are *very* small: $<10^{-46}$ cm^2 (spin-independent).
Without background, sensitivity $\propto$ (mass × exposure time)$^{-1}$
With background subtraction $\propto$ $(M\ t)^{-1/2}$ until limited by systematics.

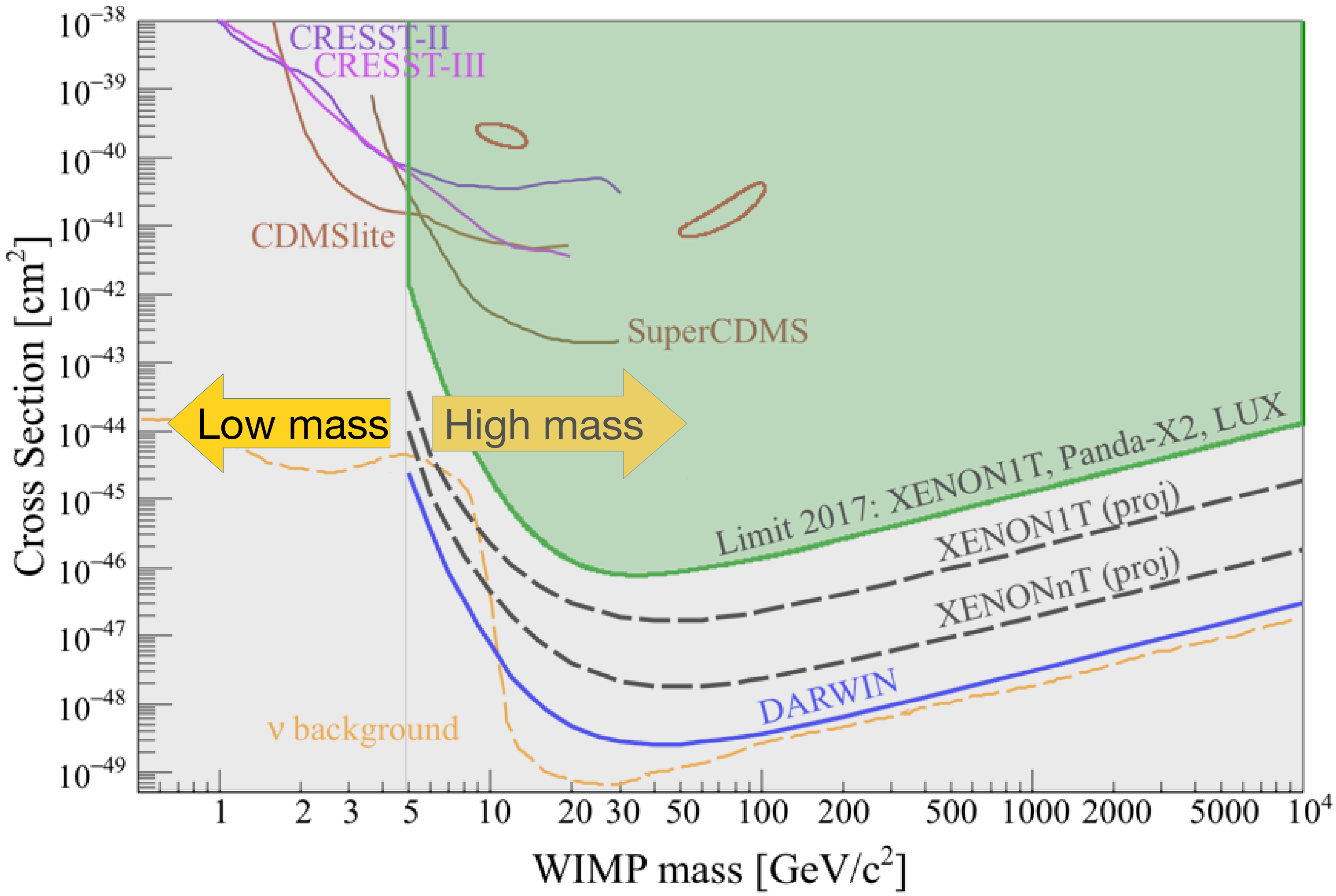
Backgrounds by origin:

- external
  - cosmic → depth, veto
  - radiogenic
    → shielding, self-shielding, veto, material selection
- surface → localization, veto
- internal → minimize!
  - distillation
  - depletion
  - purification, surface treatment
  - store materials underground to reduce cosmogenic activation
  - **discrimination**

Backgrounds by radiation type:

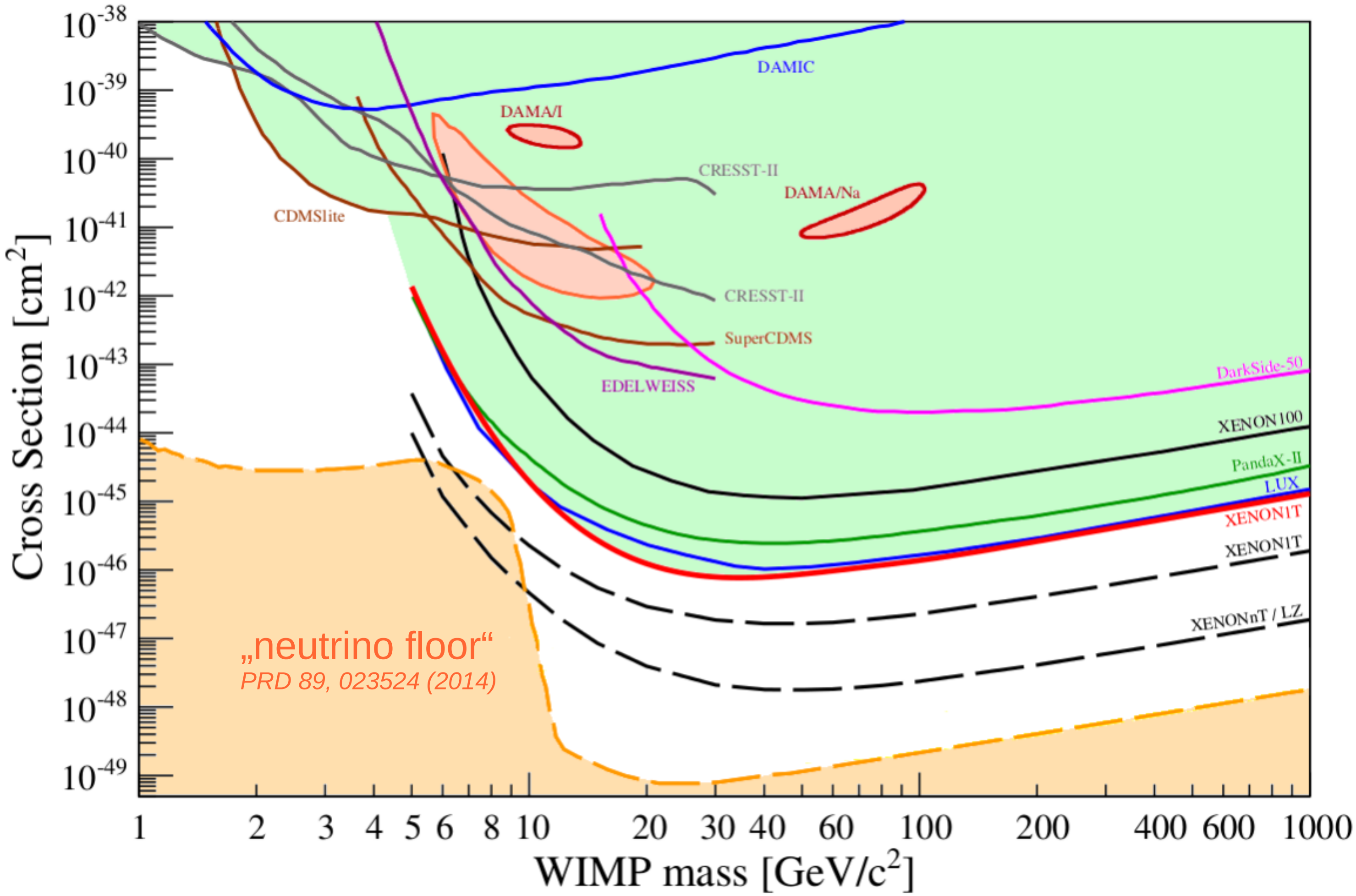
- gamma rays: long range
- beta decays
- α decays from natural decay chains + nuclear recoils
- neutrons from (α, n) reactions and spontaneous fission (up to ~10 MeV)
- neutrons from cosmic ray muons
  >~ 100 MeV
- neutrinos!

Dark Matter Searches: Status



Neutrino Floor:
Nuclear Recoils from Solar, Supernova, and Atmospheric ν's

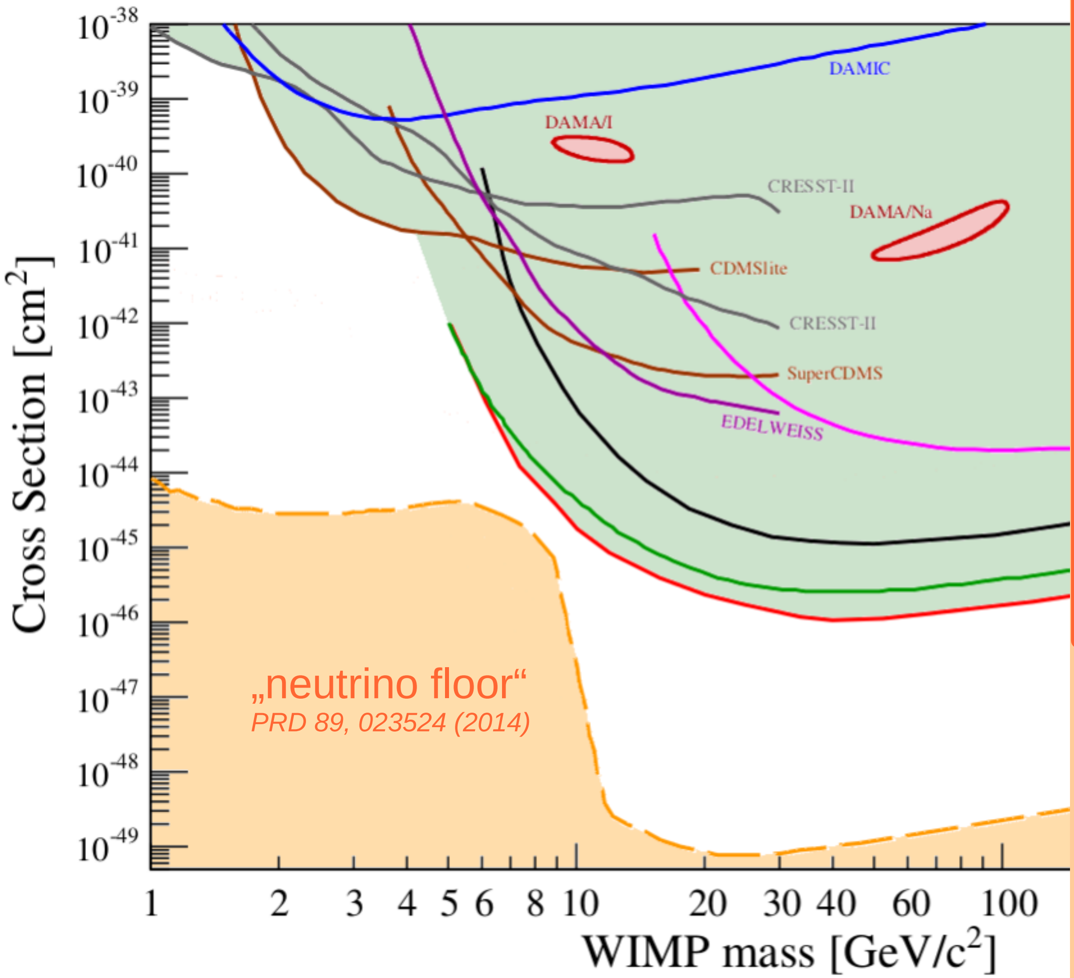
spin-independent WIMP-nucleon interactions

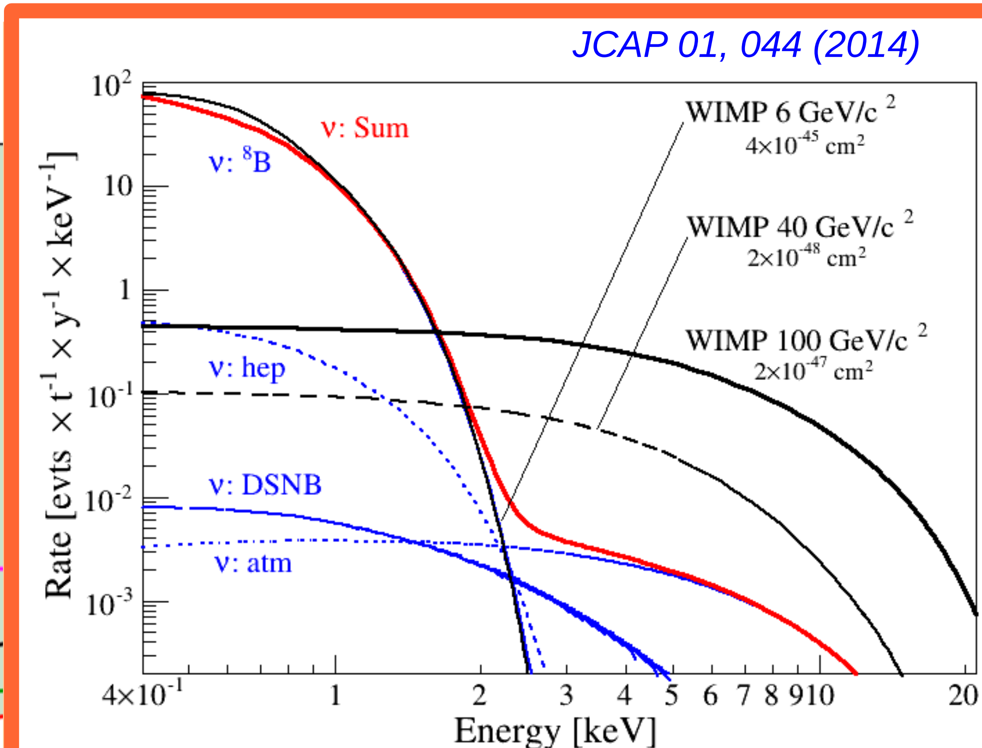


some results are missing...

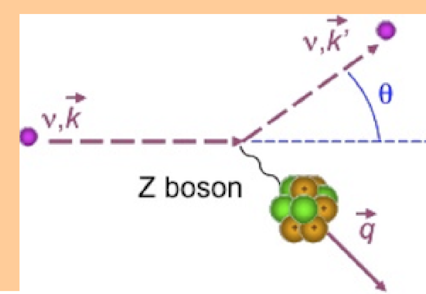
Neutrino Floor:

Nuclear Recoils from Solar, Supernova, and Atmospheric ν's

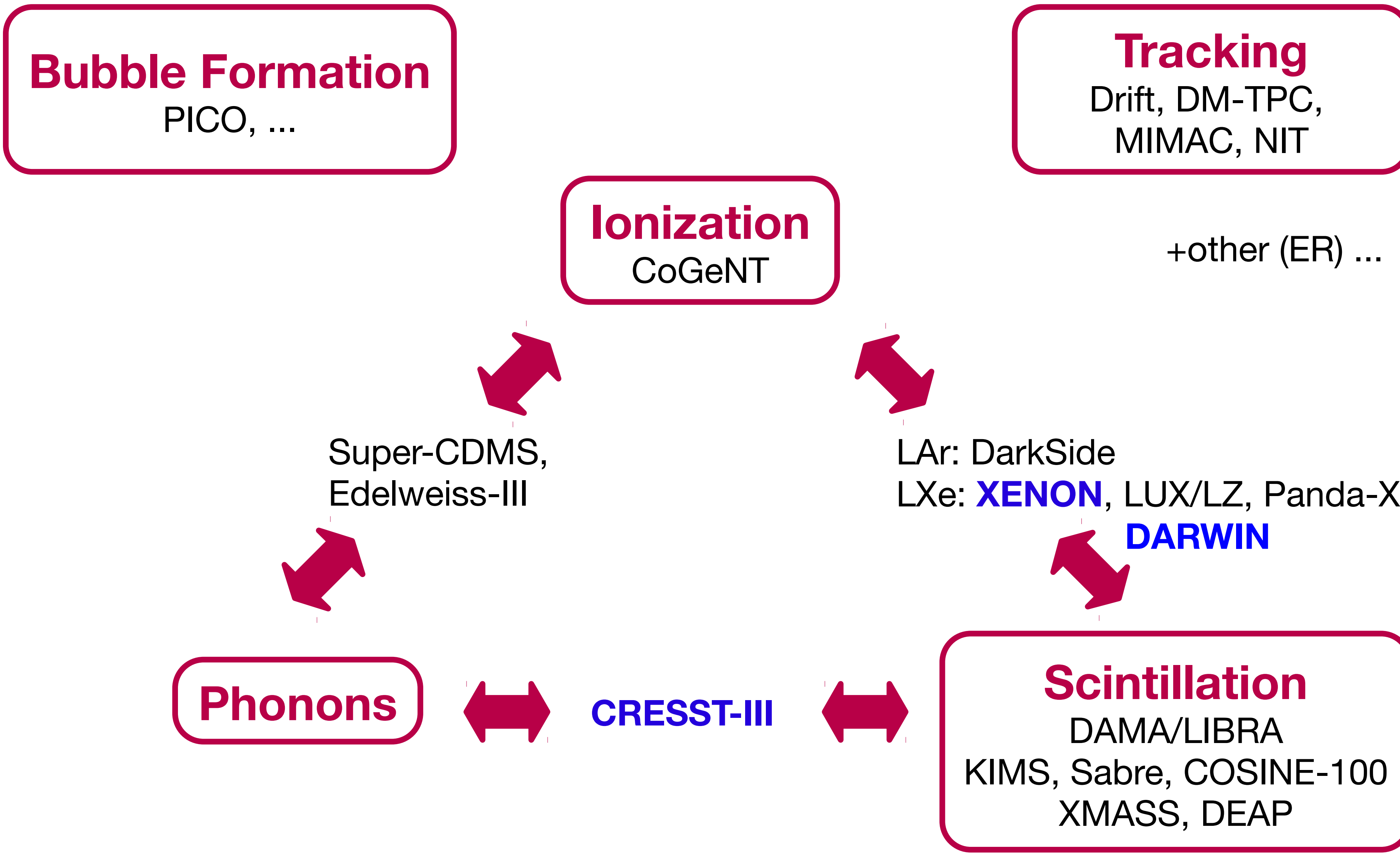




Interactions from coherent neutrino-nucleus scattering (CNNS) will dominate
→ **ultimate background** for direct detection

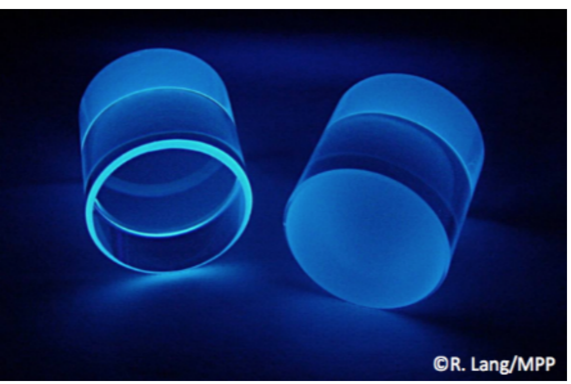


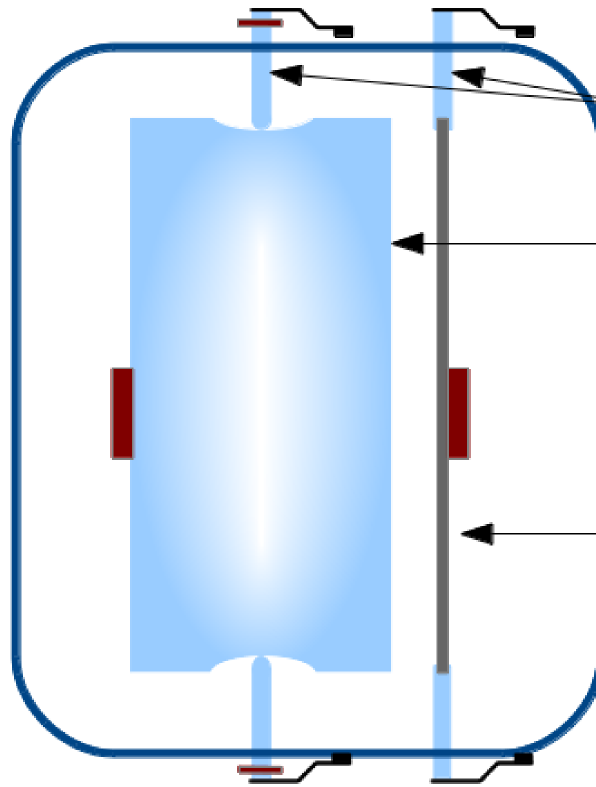
DM Detector Overview
Detection Principles



Cryogenic Detectors – CRESST-III

- Scintillating cryogenic (15 mK) $CaWO_4$ crystals as target
- Separate cryogenic light detector
- Detectors optimized for low mass dark matter
- Absorber volume reduced by a factor ~10 (≈ 24g)
- 100 eV threshold goal
- Veto surface-related background
- particle discrimination





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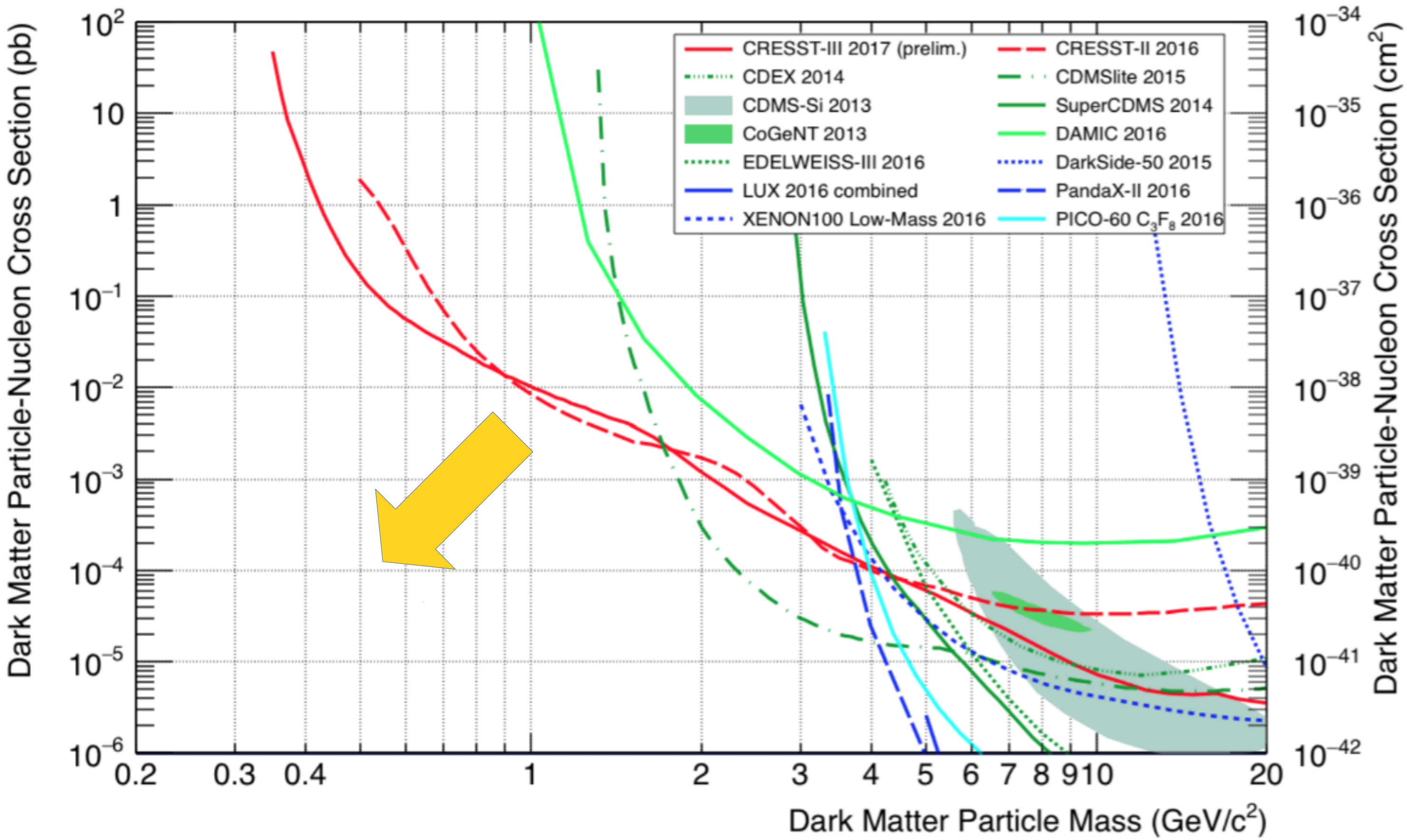
Leading contribution by German groups in **CRESST**:

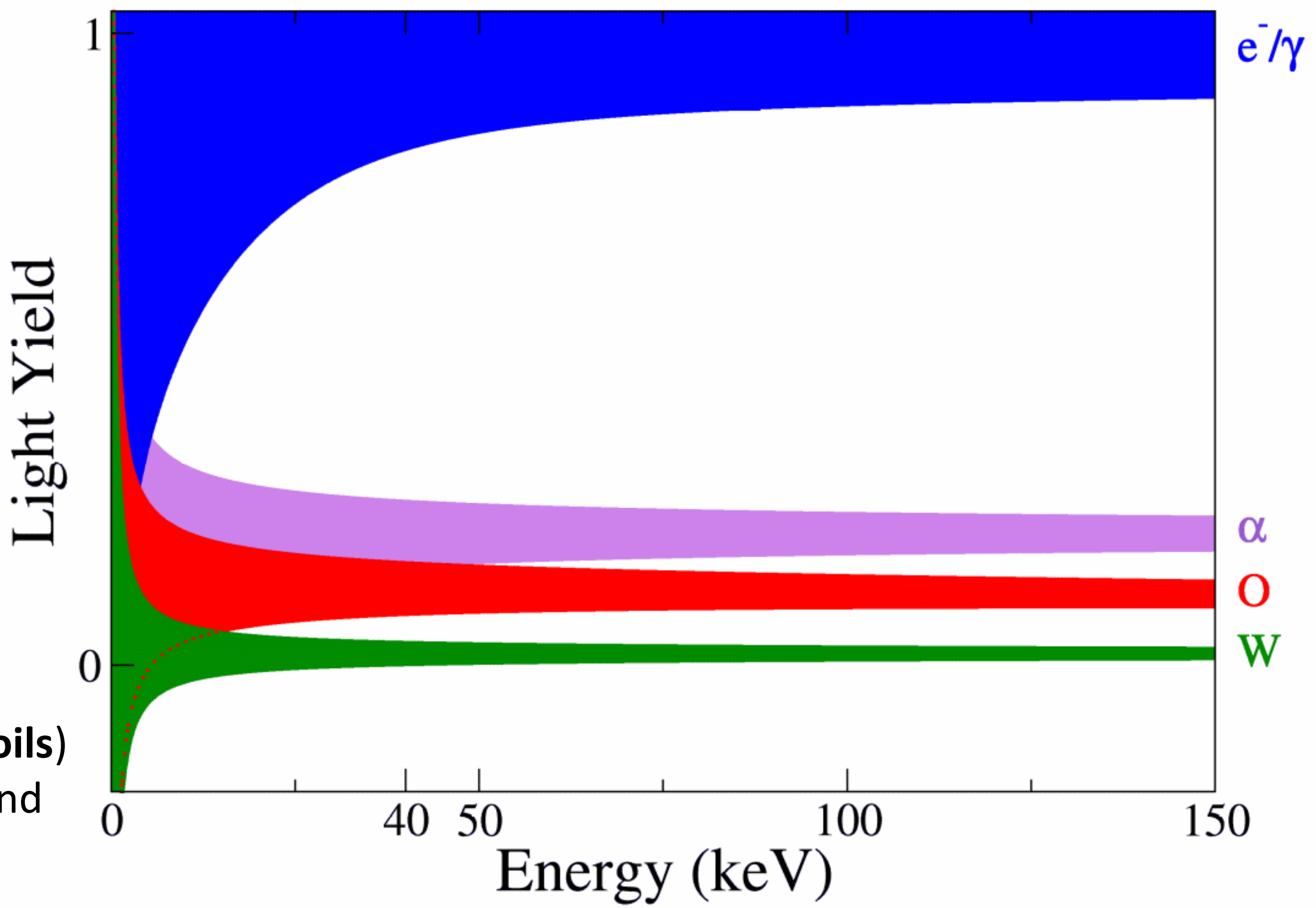
- MPP Munich
- TU Munich
- University of Tübingen



Particle discrimination

Light Yield= $\frac{\text{Light signal}}{\text{Phonon signal}}$

Characteristic of the event type

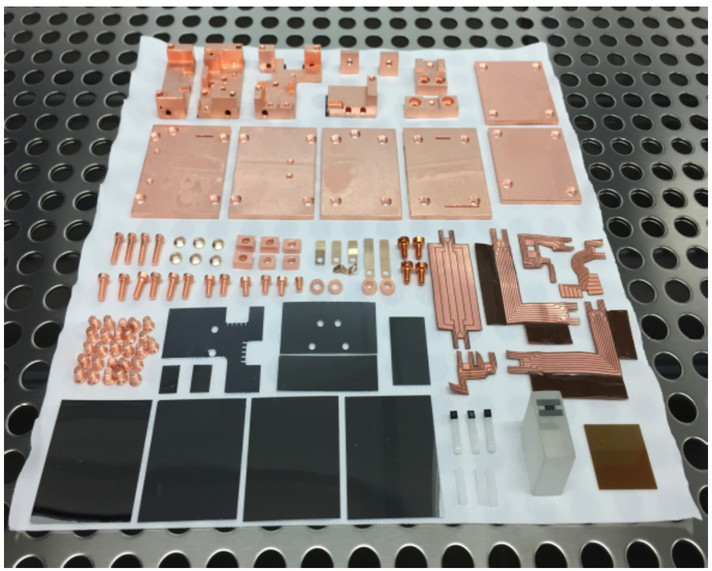


Excellent discrimination between potential signal events (**nuclear recoils**) and dominant radioactive background (**electron recoils**)

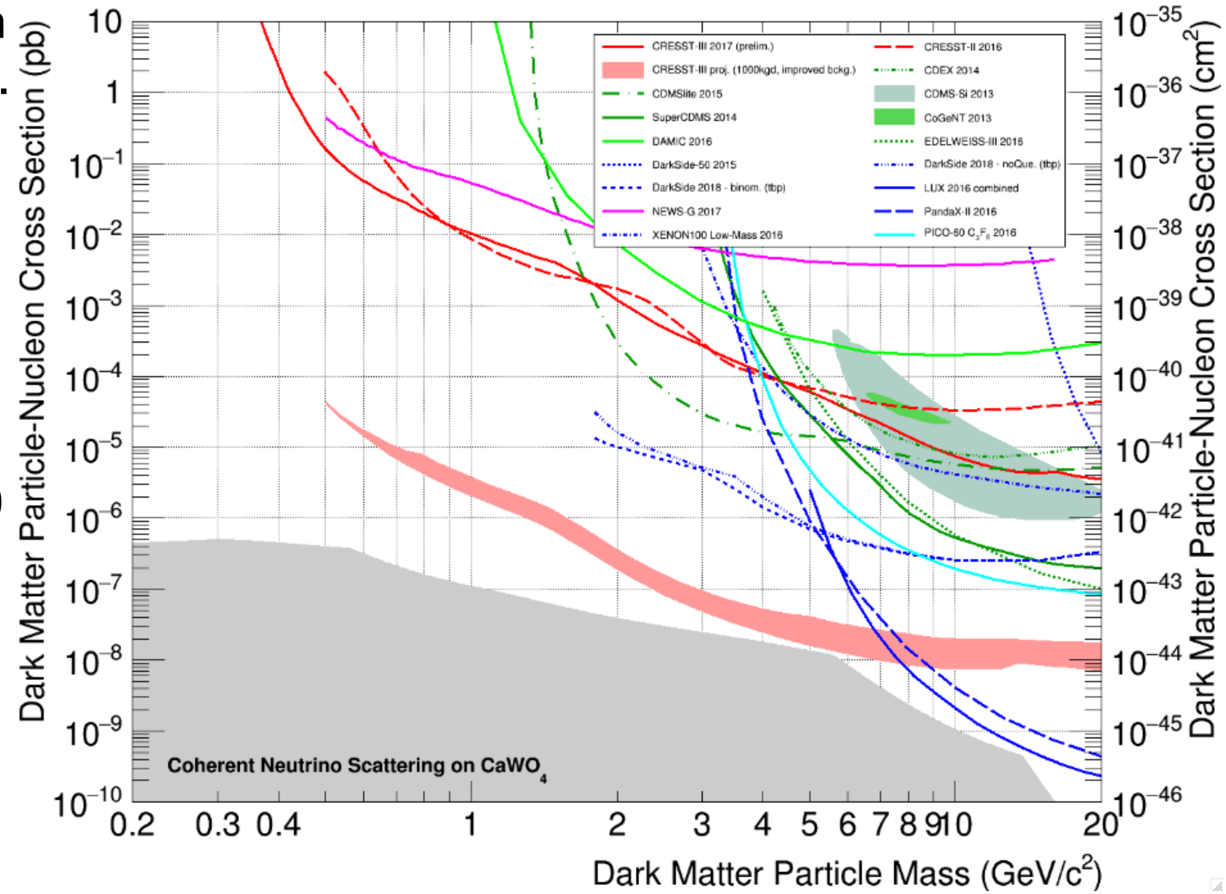
Future: Upgrade to CRESST-III Phase 2

Goals:

- 100 × background reduction.
  material screening and purification of raw material for crystal production
- Exposure 1000 kg days in 2 years.
  facility upgrade to operate 100 detectors



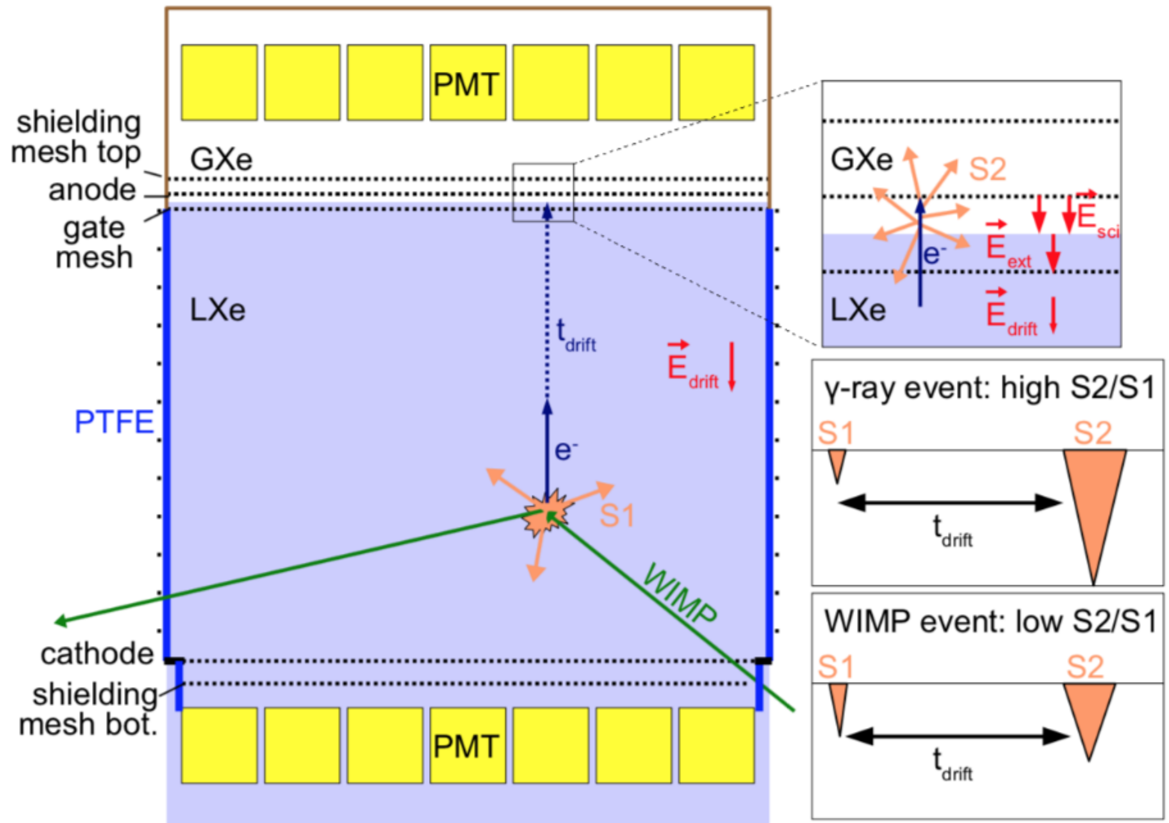
x 100



- Planning, prototyping and testing ongoing
- Start data taking after a major upgrade of the setup in 2020
- Leading sensitivity in the low mass region
- SFB1258, BMBF, Großgeräteantrag @ MPG

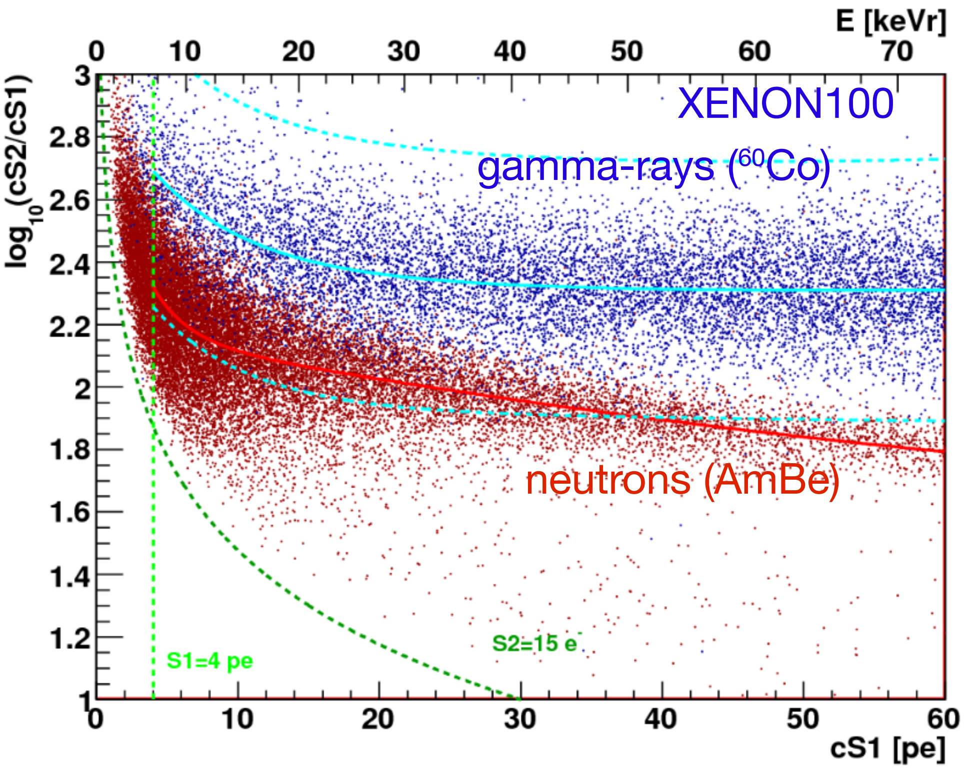
The Dual Phase Noble Liquid TPC (Ar, Xe)

- WIMP recoil on nucleus in dense liquid
  → Ionization + UV Scintillation
- Detection of **primary scintillation** signal (S1) with PMTs.
  Ar: wavelength shifting necessary
- **Charge drift** towards liquid/gas interface at
  low field: ~0.1- < 1 kV/cm.
- **Charge extraction** liquid/gas at high field between ground mesh (liquid) and anode (gas)
- **Proportional scintillation** signal (S2) in the gas phase
  high field: ~10 kV/cm
- **3D position measurement**
  - X/Y from S2 signal. Resolution few mm.
  - Z from electron drift time (~ 1 mm).

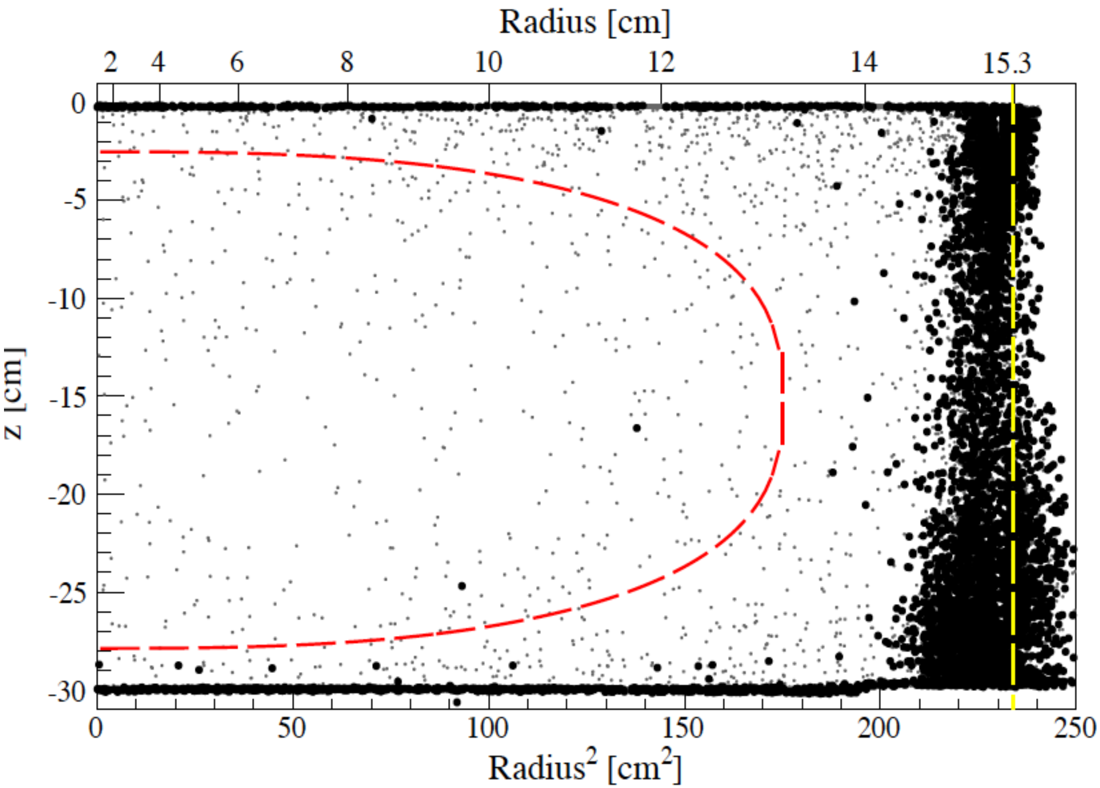


Background Discrimination in Dual Phase Liquid Xenon TPCs

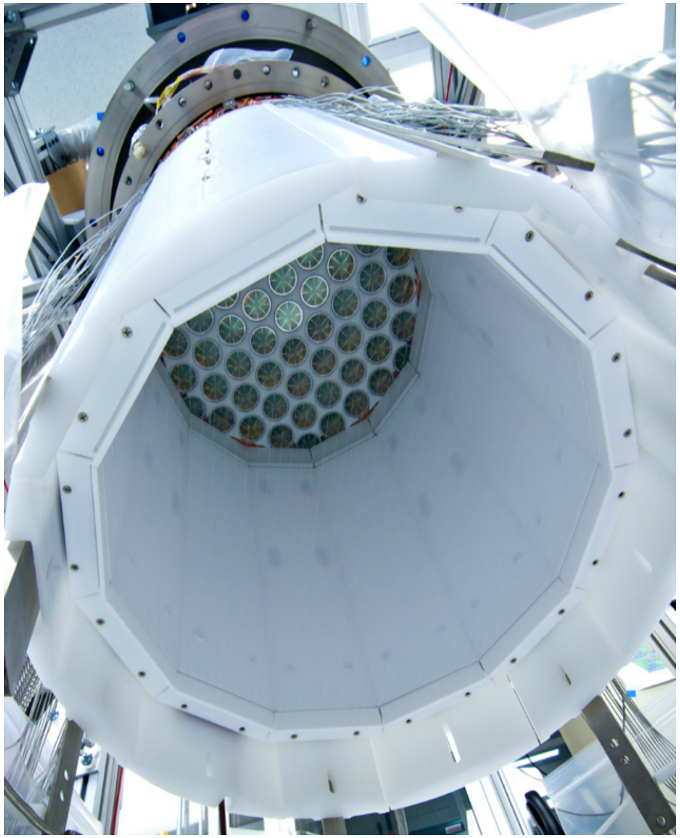
Ionization/Scintillation Ratio S2/S1



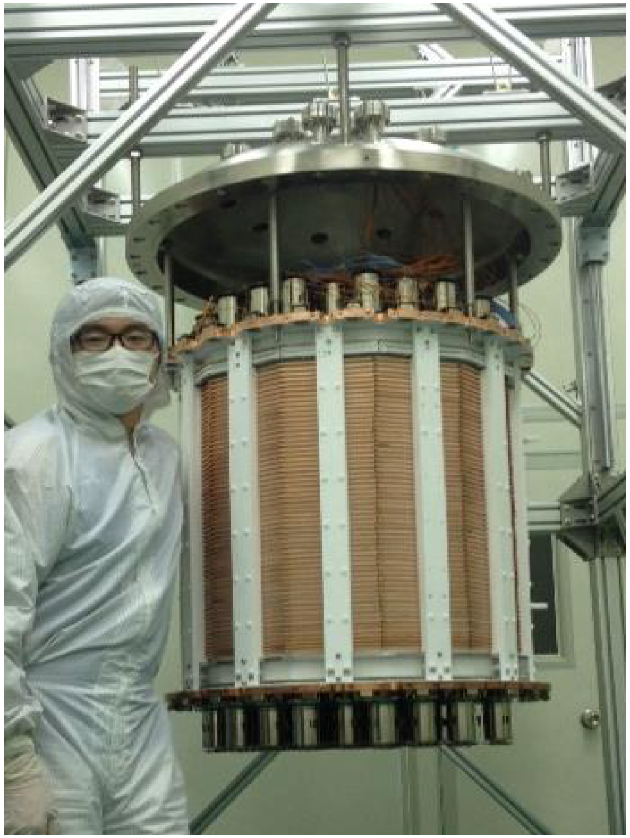
3D Position Resolution: fiducial cut, singles/multiples



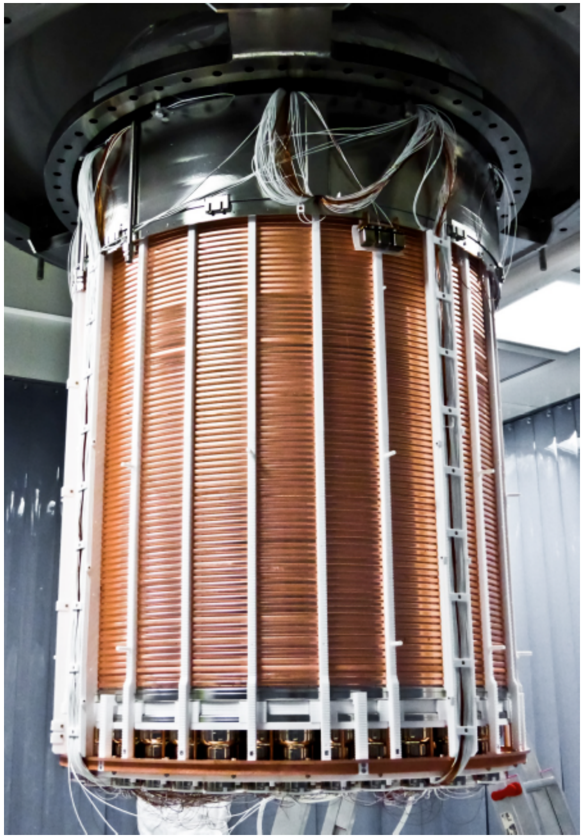
Liquid Xenon Dual Phase TPCs Present Experiments



LUX
0.5 m x 0.5 m
(finished)



PandaX-II
0.6 m x 0.6 m
(running)

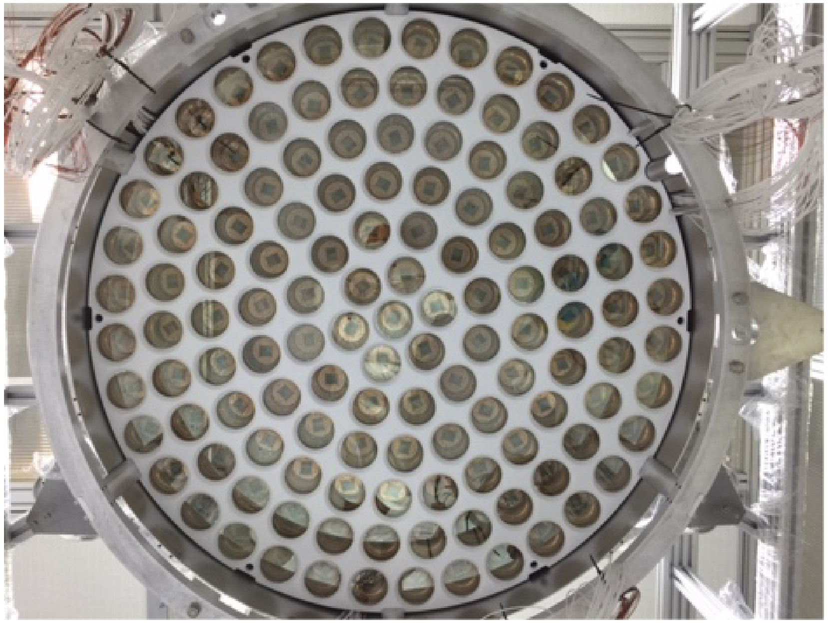


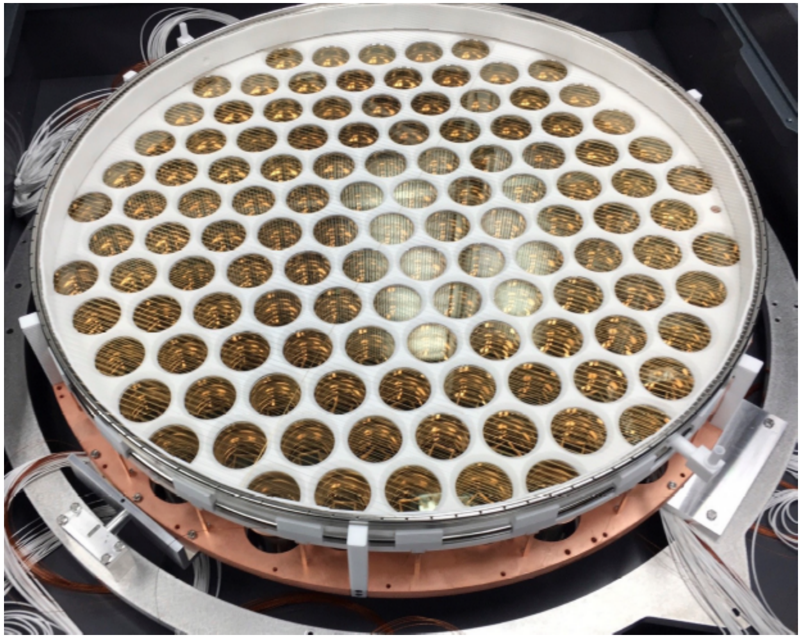
XENON1T
1 m x 1 m
(running)

Liquid Xenon Dual Phase TPC
XENON1T >2 ton sensitive

- 2016 – present
- Mass: >3 ton / 2.2 ton sensitive
- Background in FV: ~0.2 mdru*
  dominated by ^{222}Rn
- exposure: 35 ton-day published,
  result with ~1 ton-yr upcoming
- predicted sensitivity @2 ton-yr:
  ~2 10^{-47} cm^2
- min. of limit curve:
  7.7×10^{-47} cm^2 at 35 GeV/c^2

→ **Lowest background,**
most sensitive DM detector operating.

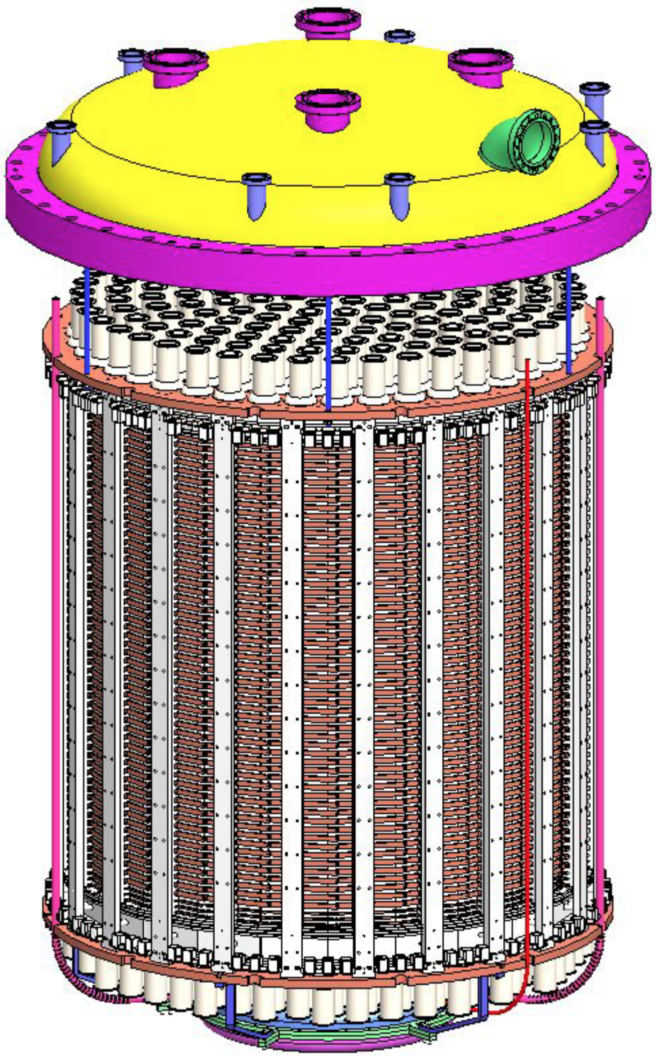




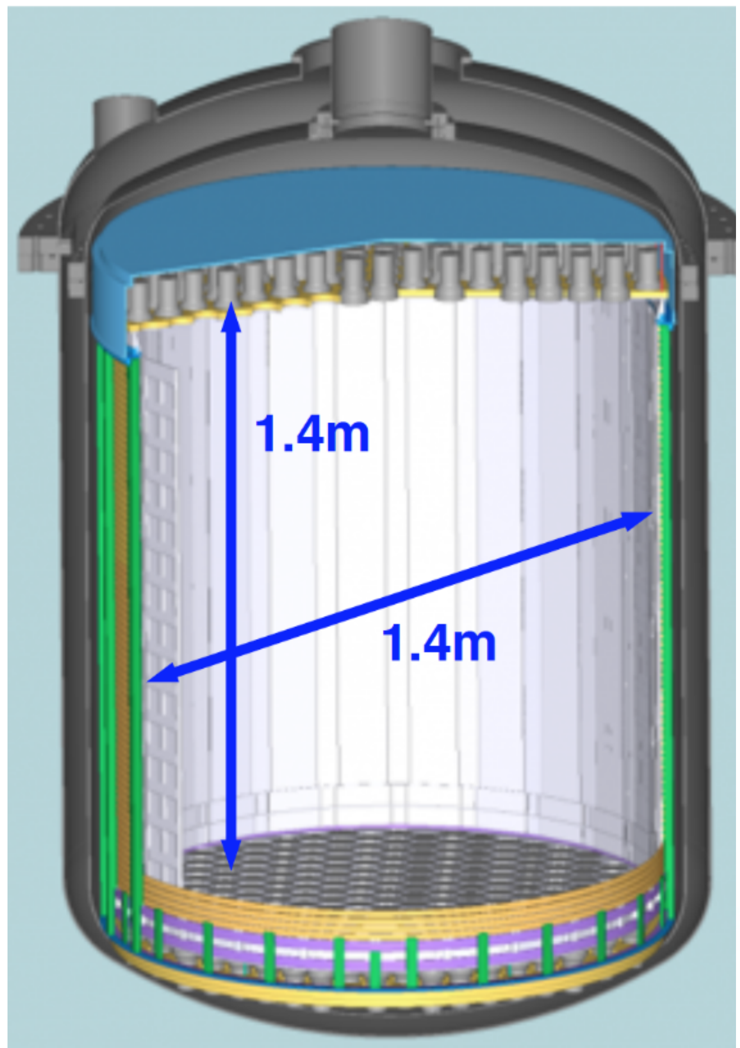
German XENON groups provide leading contributions
MPIK Heidelberg
Universities Freiburg, Mainz, Münster

Liquid Xenon Dual Phase TPCs
Near Future

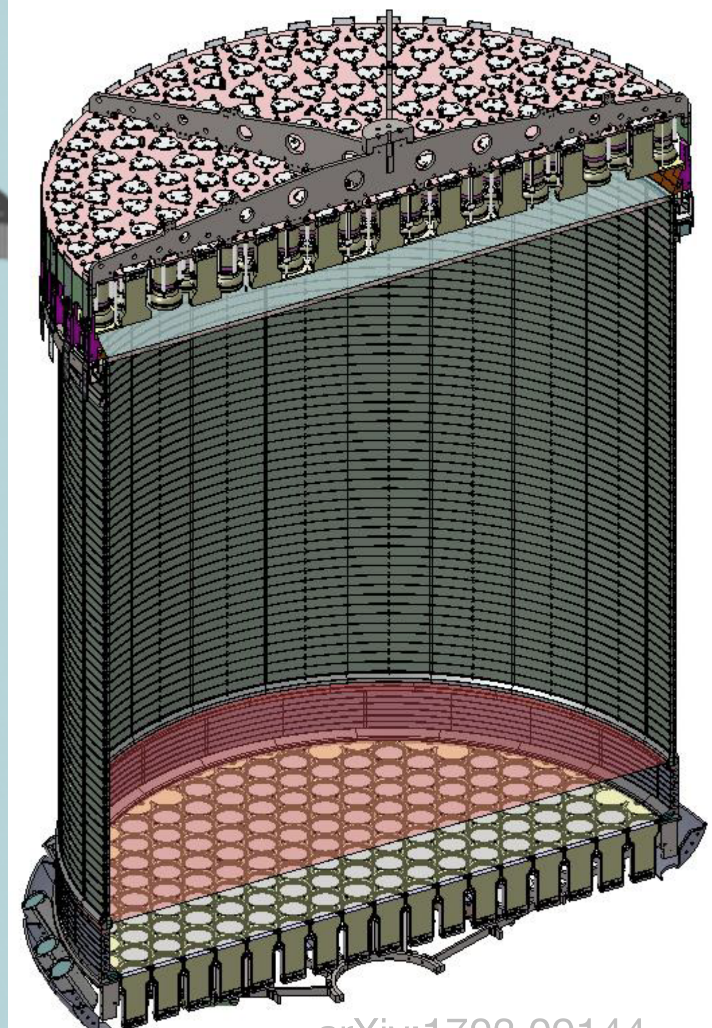
Panda X-4T
~ 4 t sens



XENONnT
~ 6 t sens



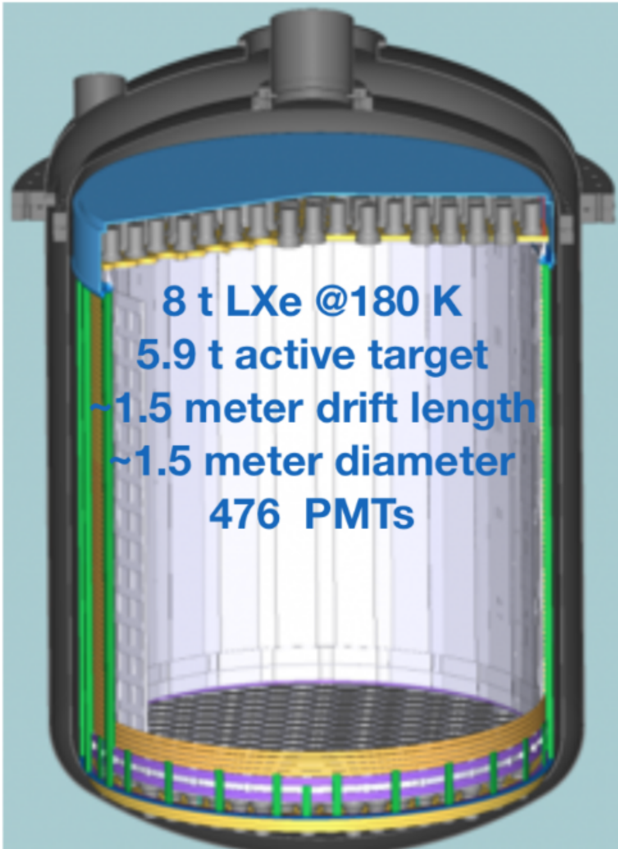
LZ
~7 t sens

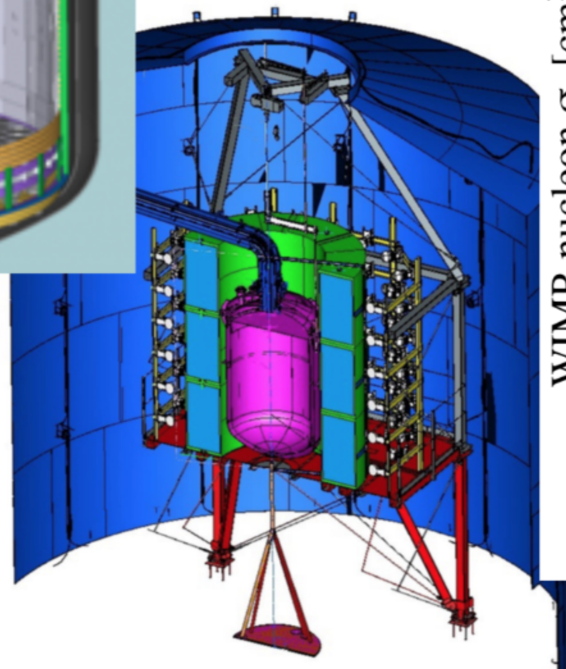


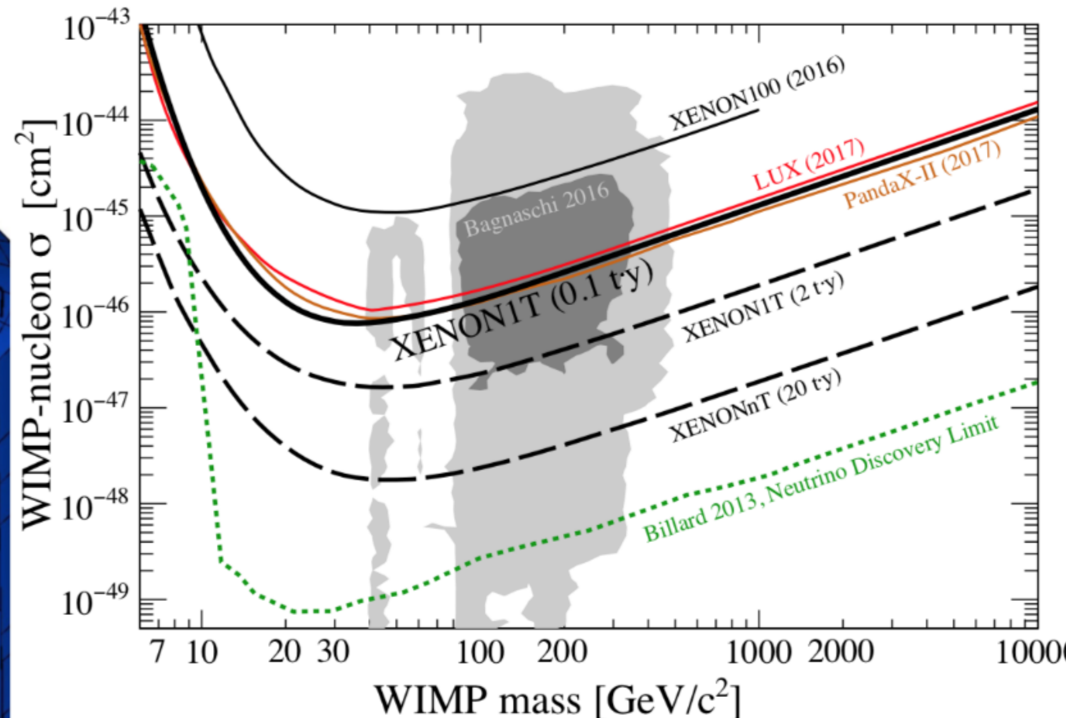
arXiv:1703.09144

The next step: XENONnT

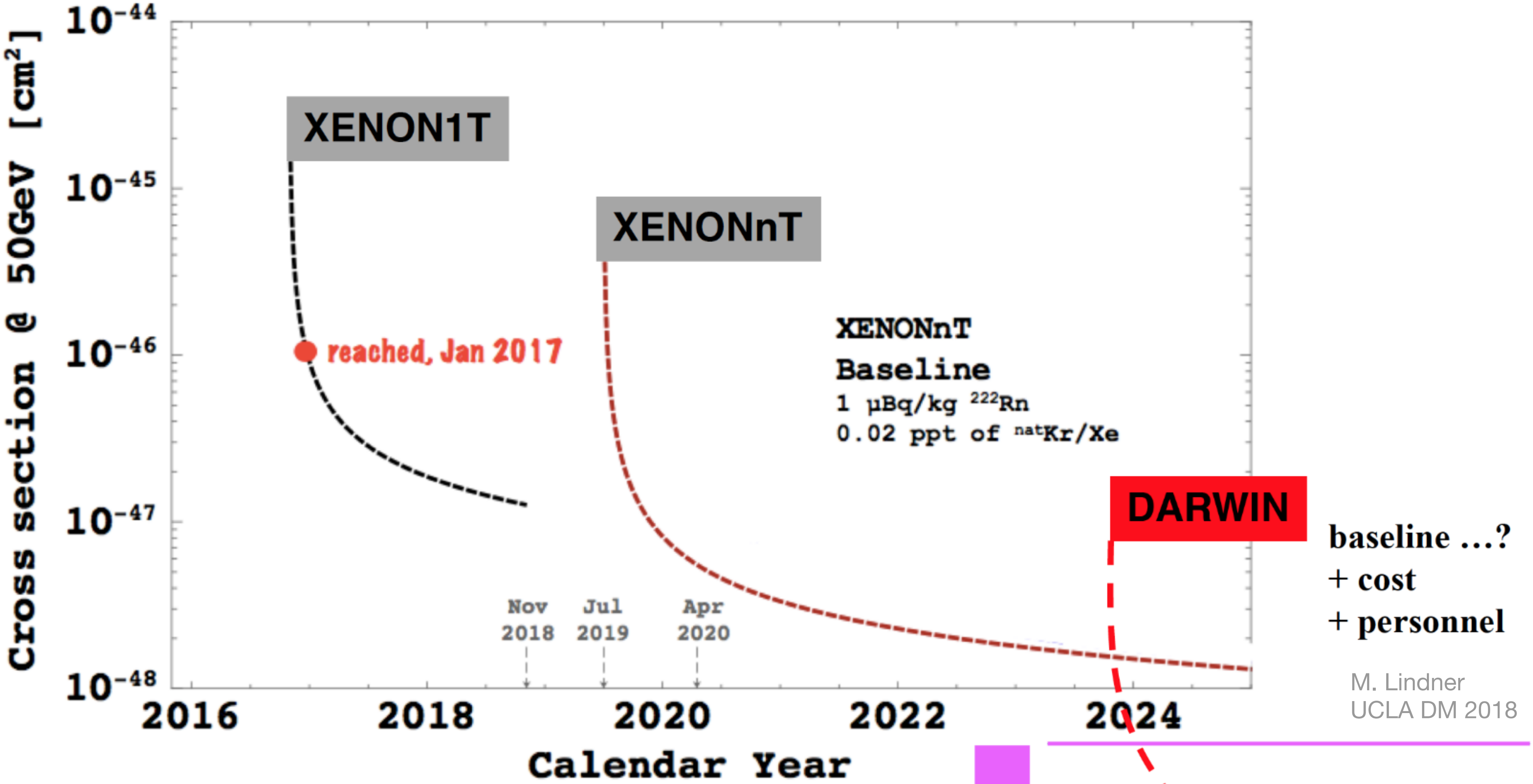
- A rapid upgrade to XENON1T, with a new TPC with 4 x target mass than XENON1T
- Most sub-systems, already operative, designed with this upgrade in mind
- Main challenge: reduce Radon by x 10

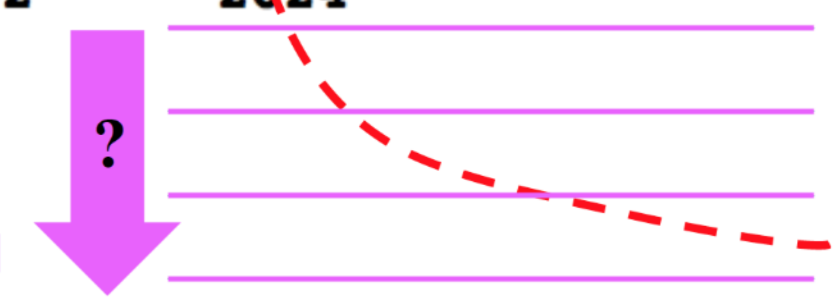






Sensitivity with XENON and beyond

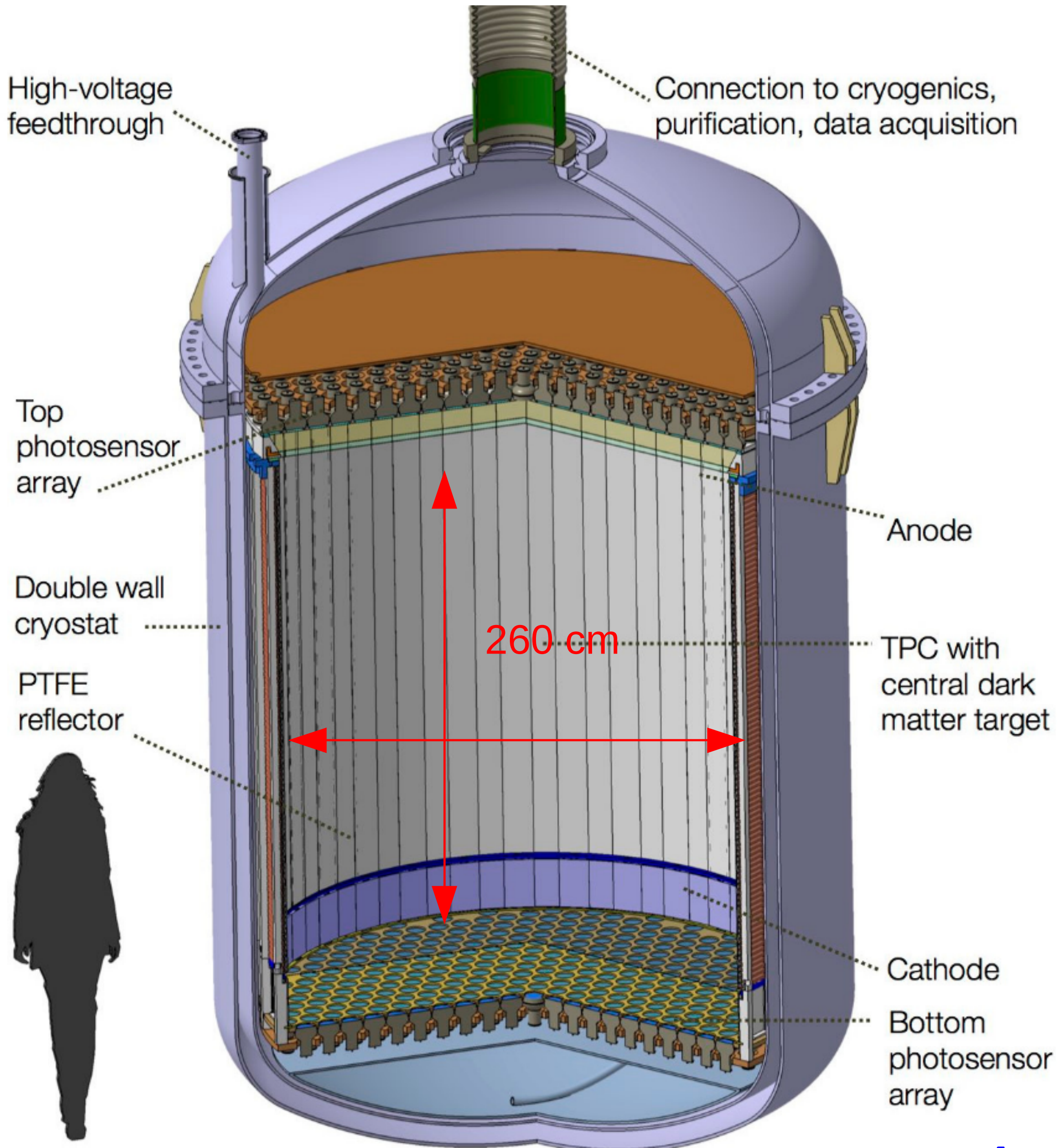




assumptions are easy

➔ must demonstrate low background

DARWIN The ultimate WIMP Detector



JCAP 11, 017 (2016)

- aim at sensitivity of a few 10^{-49} cm^2, limited by **irreducible ν-backgrounds**
- international consortium, 24 groups XENON + new groups

> Baseline scenario
> ~50t total LXe mass
> **~40 t LXe TPC**
> ~30 t fiducial mass

- Timescale: start after XENONnT
- R&D within XENON collaboration plus **two ERC projects**
  - *ULTIMATE* (Freiburg)
  - *Xenoscope* (Zürich)
- Part of two excellence cluster proposals

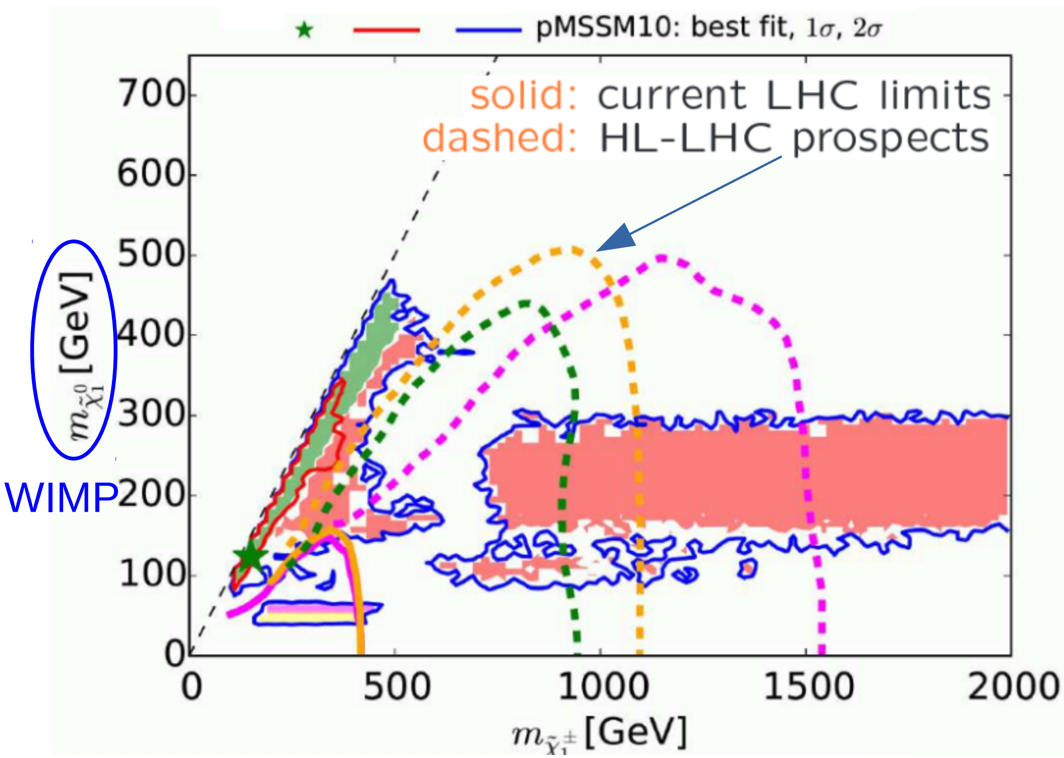
www.darwin-observatory.org

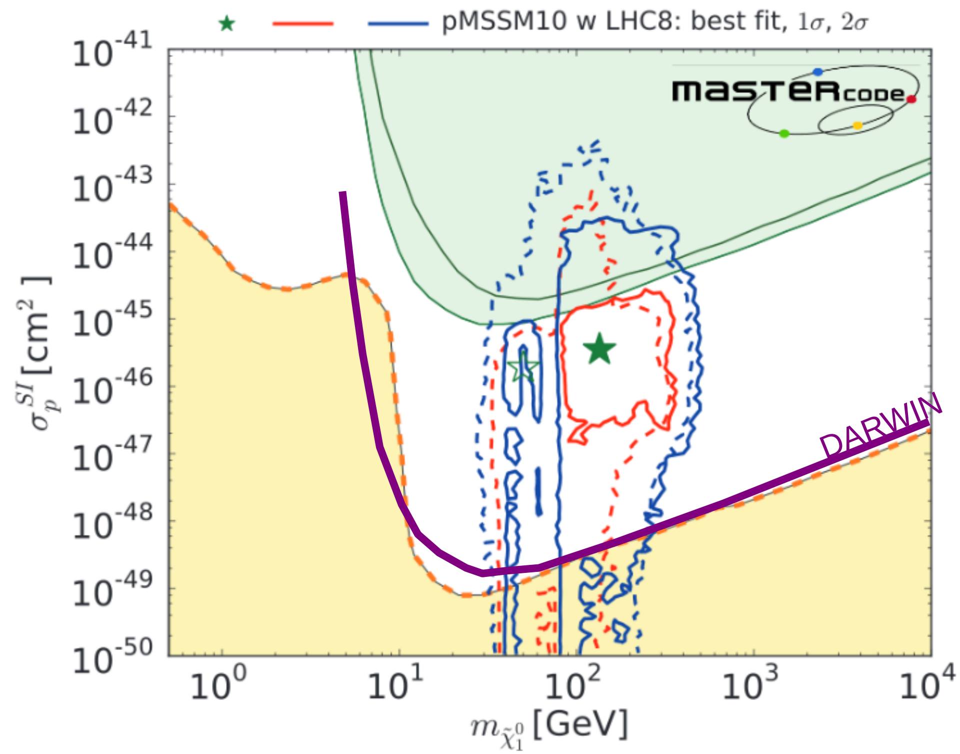
SUSY Dark Matter

plots: Sven Heinemeyer (MasterCode 2015)

SUSY under pressure because not found at LHC?
→ true for some very constraint models (CMSSM etc.) but looks different
when more parameters are left unconstrained

Example: pMSSM10 ← 10 SUSY parameters, *e.g. EPJ C75, 422 (2015)*

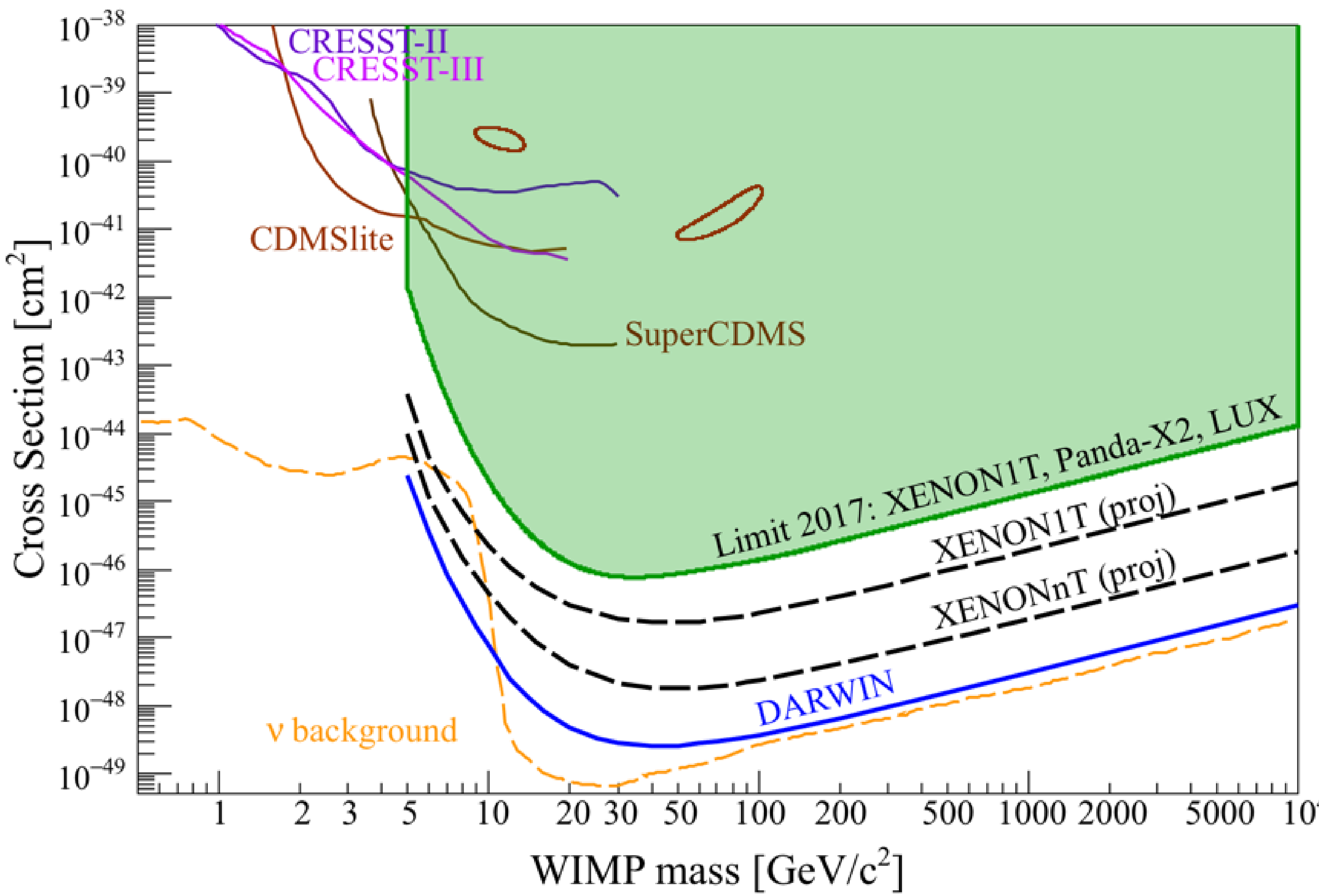




$m_{neutralino} \approx m_{chargino}$

WIMP out of reach of HL-LHC (best-fit regions not covered), but accessible by DARWIN

Dark Matter Searches to the Neutrino Floor

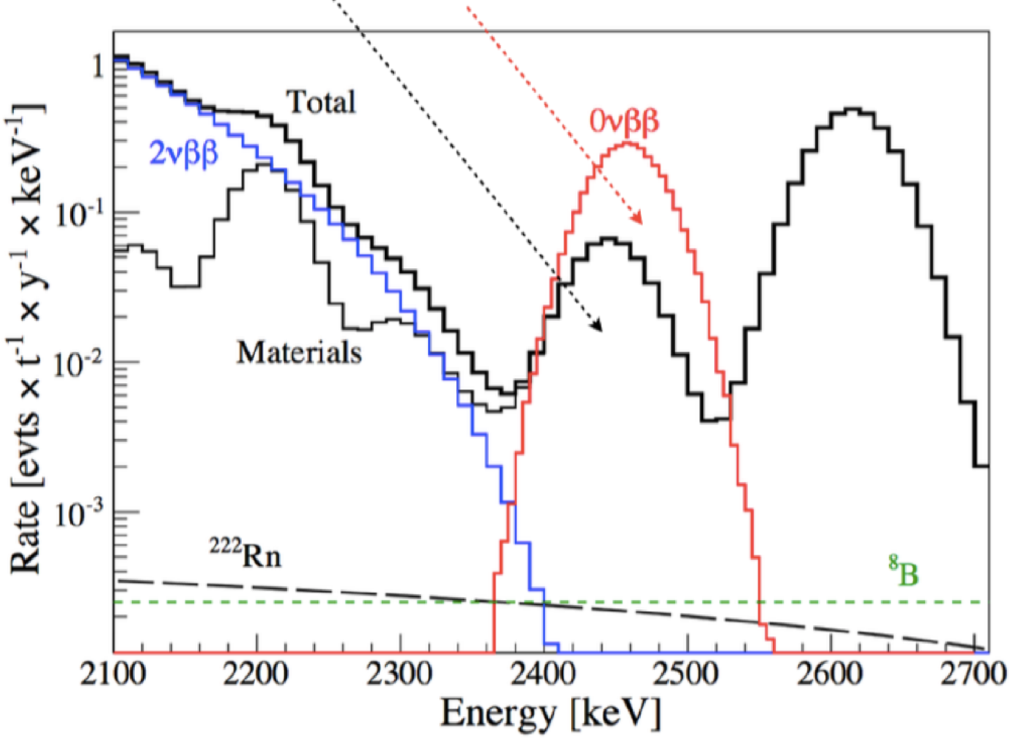


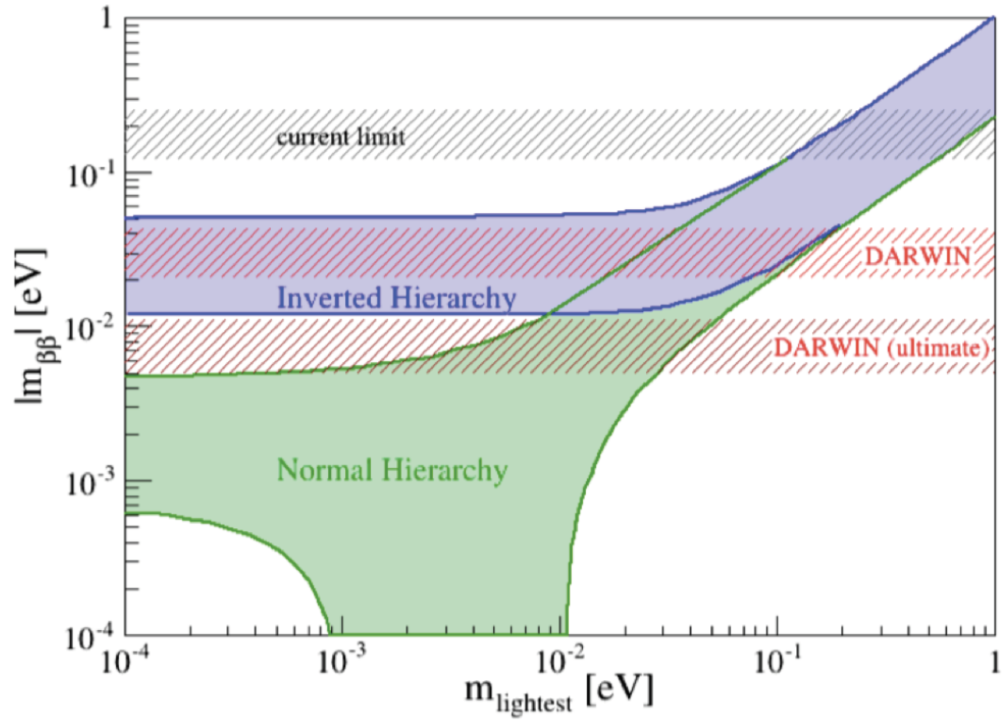
Neutrino Physics with DARWIN:
$0\nu\beta\beta$ Decay with ^{136}Xe

- 8.9% natural abundance
  → 3.5 t ^{136}Xe in 40t without enrichment
- $Q_{\beta\beta}$ = (2458.7 + 0.6) keV
- Assume:
  - 6t fiducial
  - energy resolution at $Q_{\beta\beta}$ ~ 1%

$^{214}Bi \rightarrow ^{214}Po + e^{-} + \gamma$ (2448 keV)

4.6 events/year within ±3σ





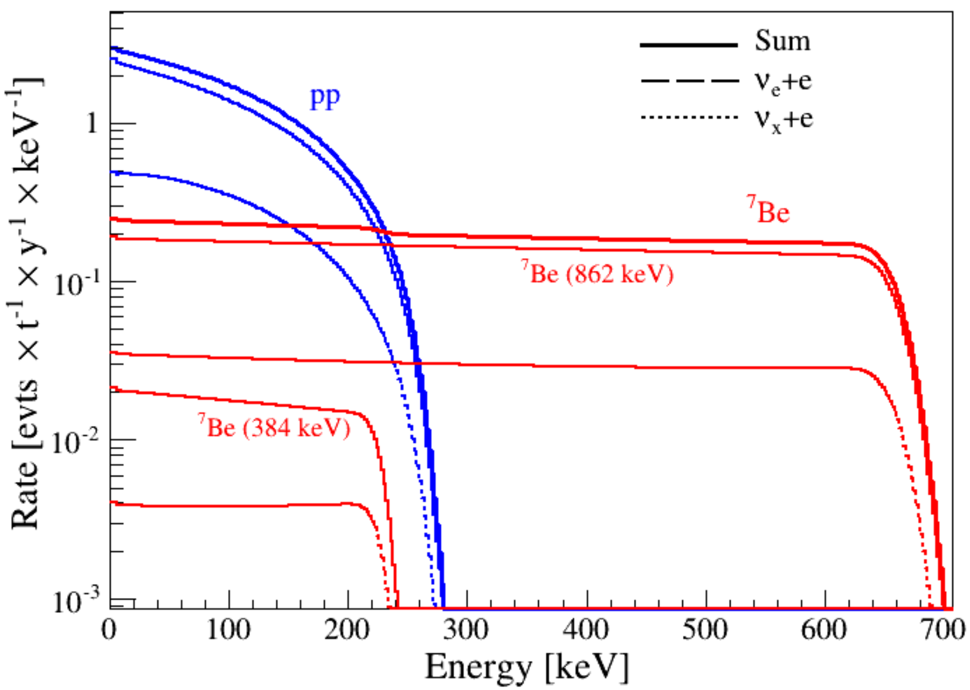
- Sensitivity @ 95% CL:
  - 30 t*yr : $T_{1/2} > 5.6 \cdot 10^{26}$ yr
  - 140 t*yr: $T_{1/2} > 8.5 \cdot 10^{27}$ yr

DARWIN might become a powerful, cost effective and time-wise competitive $0\nu\beta\beta$ experiment (no enrichment!)

Solar pp-Neutrinos with DARWIN

JCAP 11, 017 (2016)

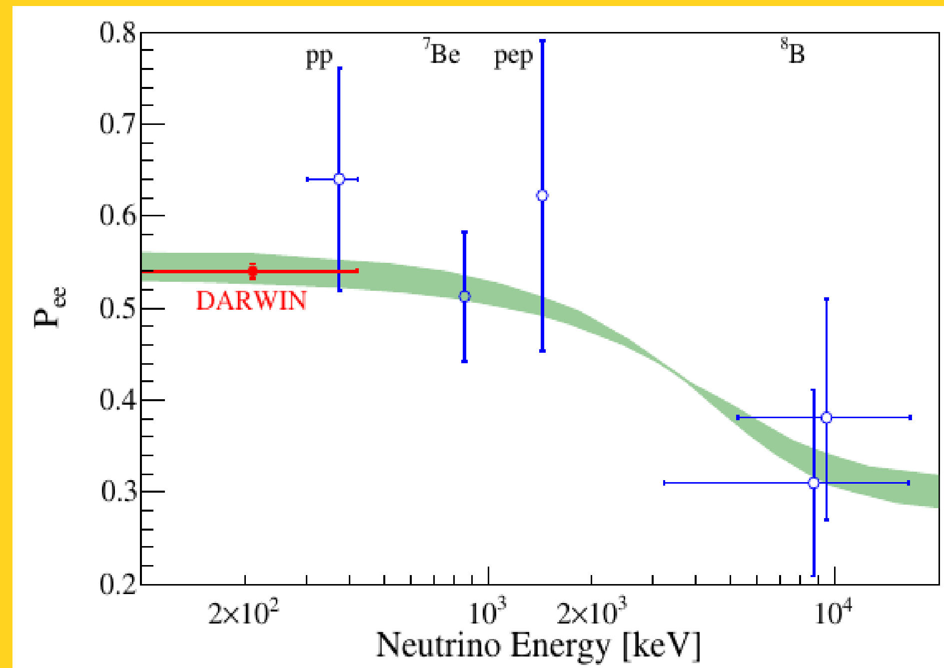
Differential Recoil Spectrum in Xe



- neutrinos interact with Xe electrons
  → electronic recoil signature
- continuous recoil spectrum
  → largest rate at low E

  ~0.26 ν evts/t/d in low-E region (2-30 keV)

Neutrino interactions



30t target mass, 2-30 keV window
→ 2850 neutrinos per year (89% pp)
→ achieve 1% statistical precision on pp-flux (→P_{ee}) with 100 t x yr

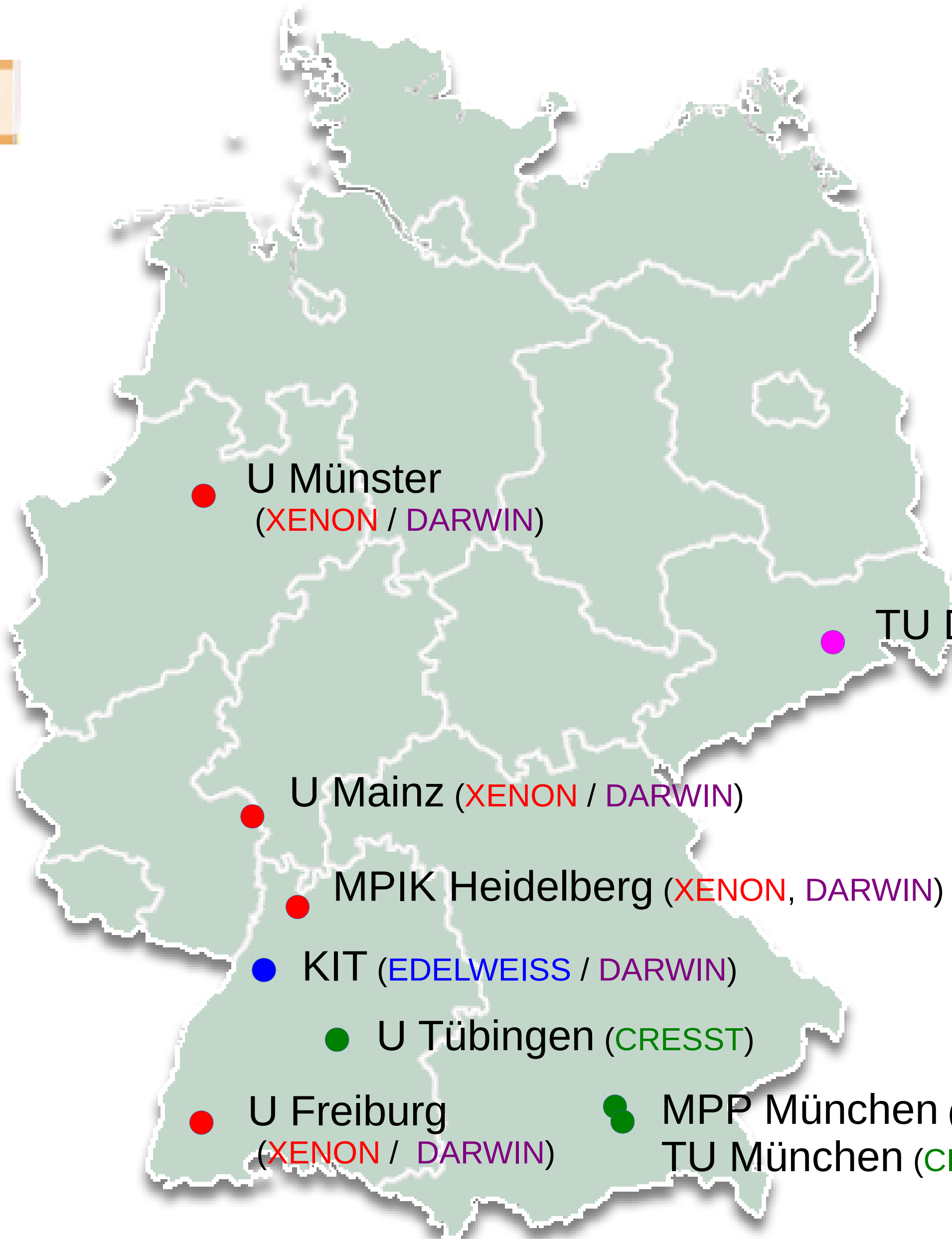
Direct Detection in Germany

CRESST

Edelweiss

XENON Dark Matter Project

DARWIN



Conclusions

- WIMP direct searches are a highly active field with tremendous progress in sensitivities, covering large fractions of relevant parameter space
- Updates since Mainz workshop 2017:
  - first results from XENON1T (world-leading) and Panda-X2
  - first results from CRESST-III (world-leading)
- Low masses: cryogenic detectors (CRESST, Super-CDMS).
- High masses (>5 GeV/c^2): liquid xenon TPCs.
  - Completion of search and analysis with XENON1T.
  - Construction of XENONnT
- Key technologies and strong groups in Germany
- Longer term future: DARWIN, …

Concluding statement from Strategy Workshop Non-Collider Physics 5/'17:

> **WIMPs** wären auf natürliche Weise beim Urknall mit der richtigen Dichte erzeugt worden. Zur Zeit führen die Experimente CRESST-III (niedrige Massen) und XENON1T (mittlere und große Massen) die direkte WIMP-Suche an. Mit dem weiteren Ausbau von CRESST-III auf 100 Detektoren und XENON1T auf XENONnT wird diese Suche deutlich empfindlicher werden. Abhängig von den Ergebnissen sollte der große Flüssig-Xenon-Detektor DARWIN, der auch ein breites Neutrinophysikprogramm hat, realisiert werden.