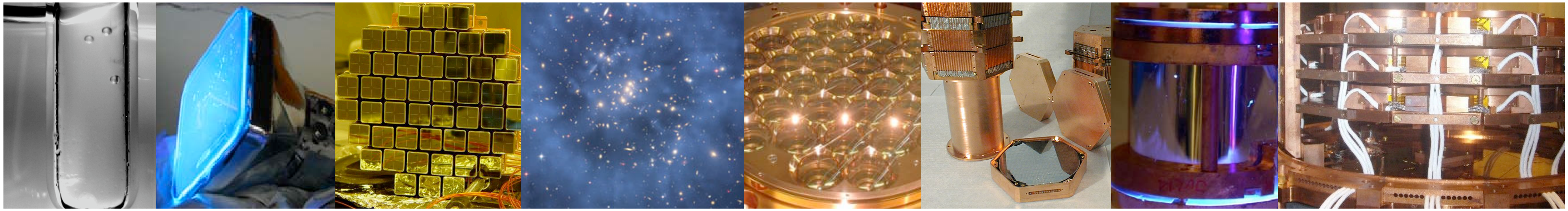
Results and Prospects of Direct Dark Matter Detection

CHIPP Plenary Meeting

Lausanne, September 8-9, 2009

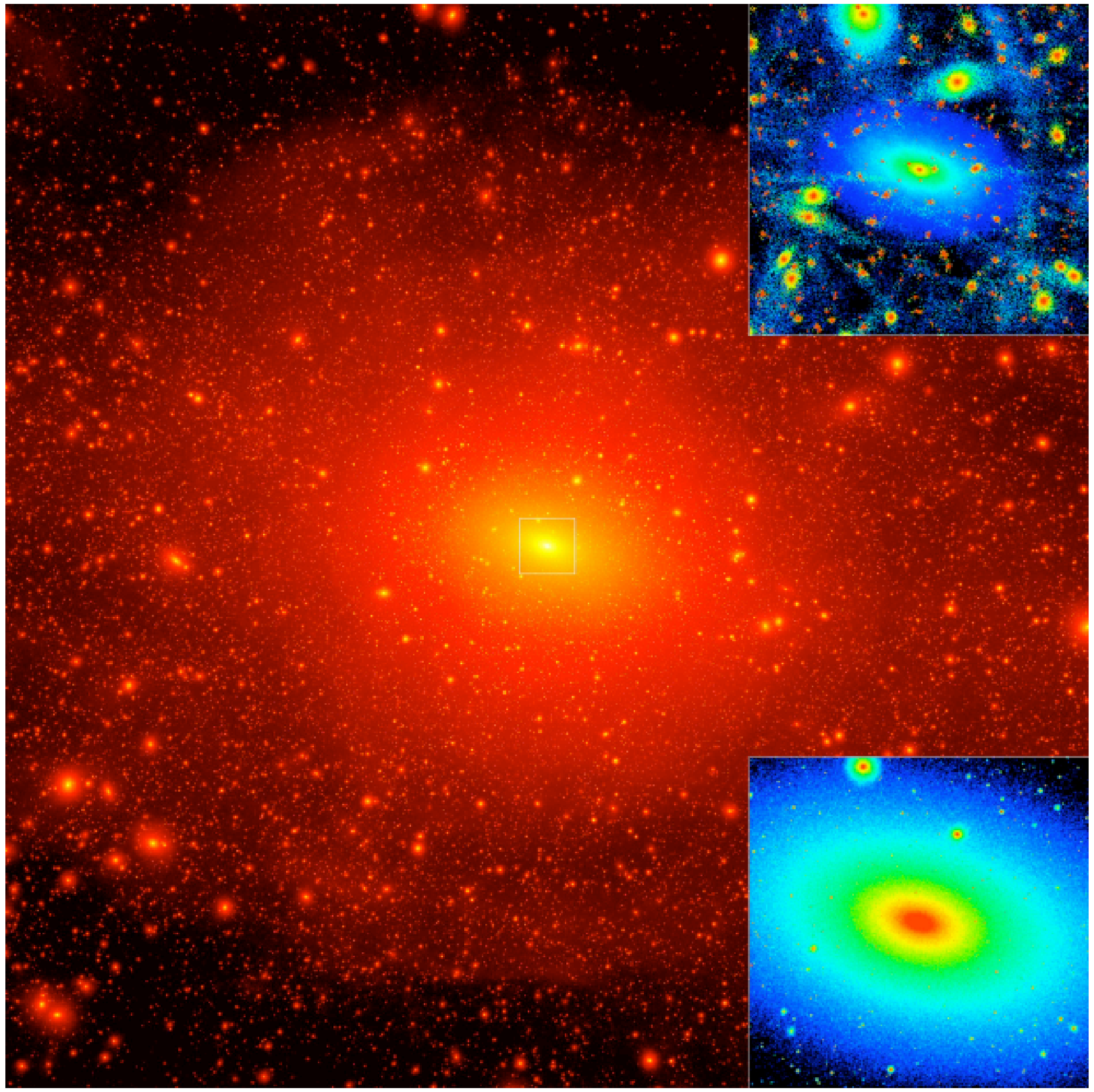
Laura Baudis

University of Zurich

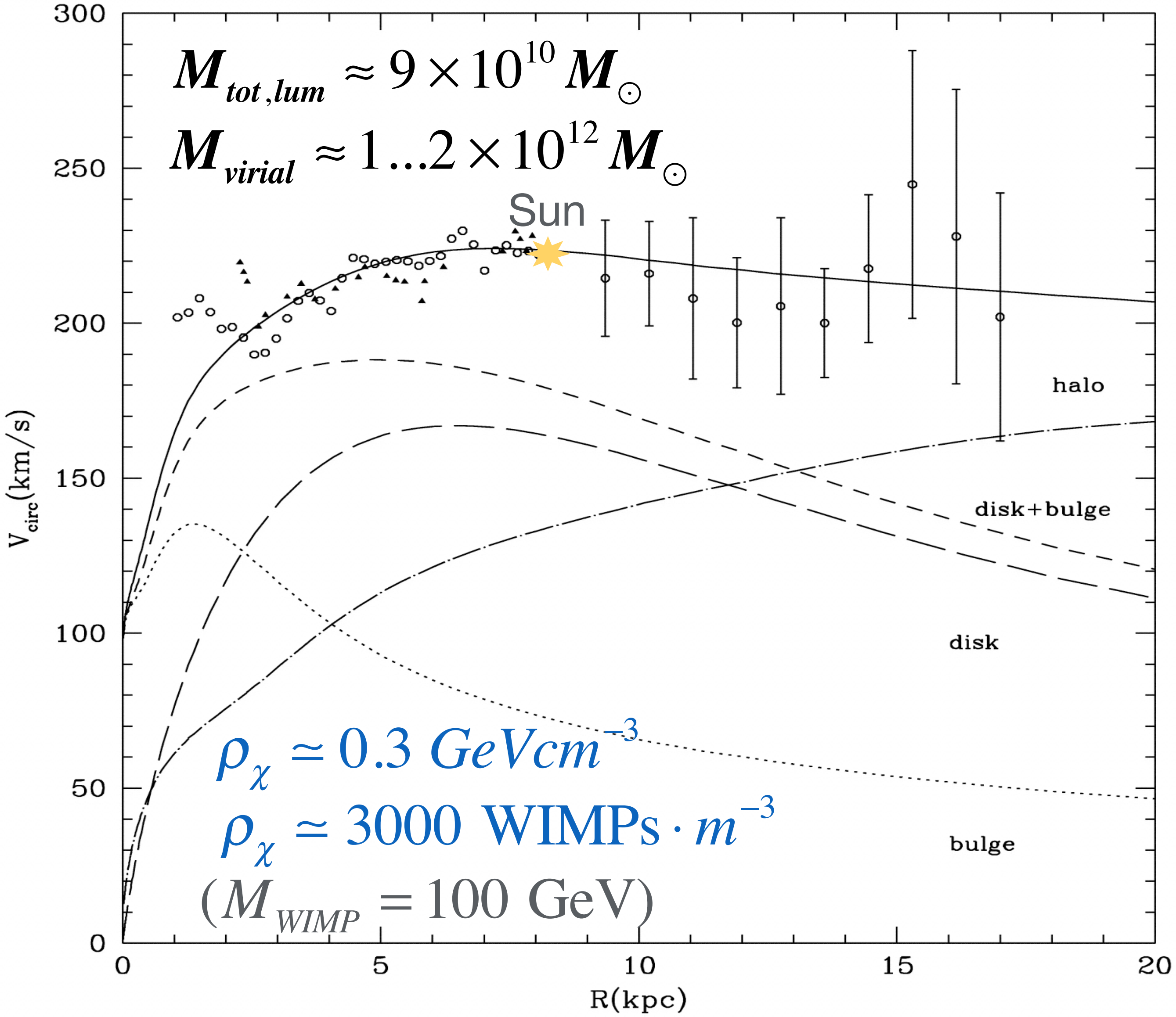


Goal of Direct Detection Experiments

- Detect new, yet undiscovered particles, which may be responsible for the dark matter in our galaxy. Example: WIMPs = heavy (few GeV - few TeV), color and electrically neutral; in thermal equilibrium with the rest of the particles in the early universe, freeze out when $M_W >> T_F$



(B. Moore at all, 2008)



$M_{tot,lum} \approx 9 \times 10^{10} M_{\odot}$

$M_{virial} \approx 1 \ldots 2 \times 10^{12} M_{\odot}$

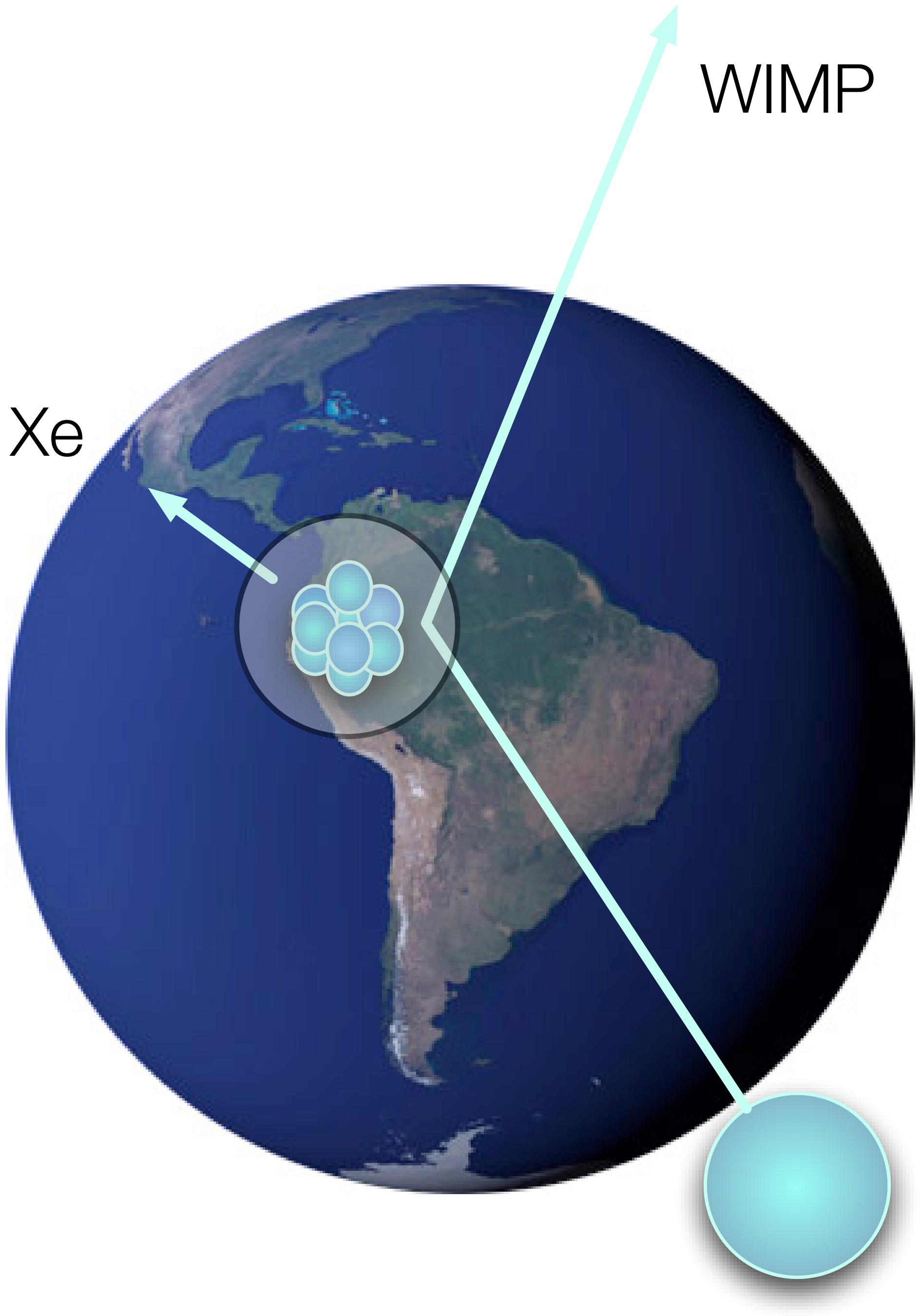
$\rho_{\chi} \simeq 0.3\ GeVcm^{-3}$

$\rho_{\chi} \simeq 3000\ \text{WIMPs} \cdot m^{-3}$

$(M_{WIMP} = 100\ \text{GeV})$

(Klypin, Zhao & Somerville 2002)

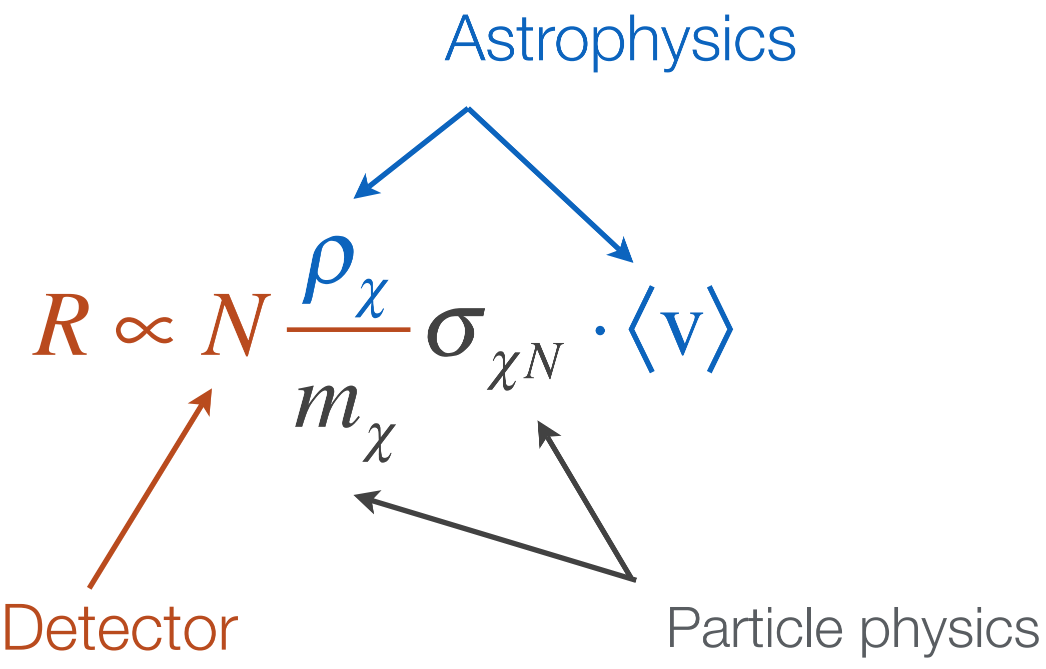
Strategy for WIMP Direct Detection



- Elastic collisions with atomic nuclei
- The recoil energy is:

$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1-\cos\theta) \leq 50\ keV$$

- and the expected rate:



Astrophysics

$$R \propto N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \cdot \langle v \rangle$$

Detector

Particle physics

Expected Scattering Cross Sections

- A general WIMP candidate: fermion (Dirac or Majorana), boson or scalar particle
- The most general, Lorentz invariant Lagrangian has 4 types of interactions (S, P, V, A)
- In the extreme NR limit relevant for galactic WIMPs ($v_{WIMP} \sim 10^{-3}c$), the interactions leading to WIMP-nuclei elastic scattering are classified as:

➡ **scalar interactions** (WIMPs couples to nuclear mass; from the scalar and vector part of L)

$$\sigma_{SI} = \frac{m_N^2}{4\pi(m_W + m_N)^2}\left[Zf_p + (A-Z)f_n\right]^2$$

$f_{p,n}$ = effective couplings to p, n

➡ **spin-spin interactions** (WIMPs couples to nuclear spin J_N, from the axial part of L)

$$\sigma_{SD} = \frac{32}{\pi}G_F^2\frac{m_W^2 m_N^2}{(m_W + m_N)^2}\frac{J_N+1}{J_N}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2$$

$\langle S_{p,n}\rangle$ = expectation values of the spin content of the p, n in the target nucleus

$a_{p,n}$ = effective couplings to p, n

Expected Interaction Rates

- Integrate over WIMP velocity distribution; in general assumed to be of Maxwell-Boltzmann type, which so far is a pretty good approximation (isothermal halo with ideal WIMP gas):

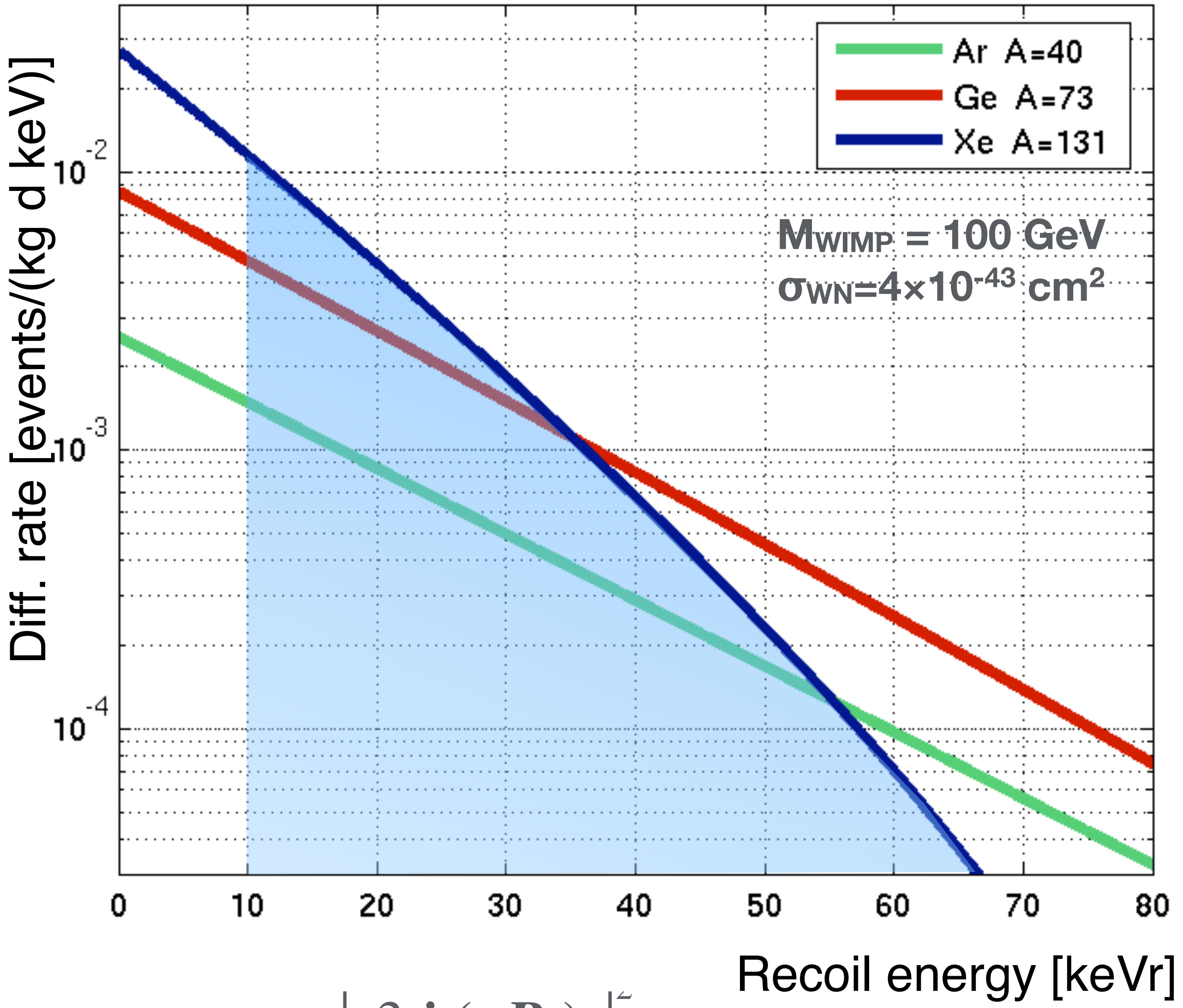
$$\frac{dR}{dE_R} = \frac{\sigma_0 \rho_0}{2 m_\chi \mu^2} F^2(E_R) \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv$$

$$f(v)dv = \frac{4v^2}{v_0^3 \sqrt{\pi}} e^{-v^2/v_0^2} d^3v$$

- with WIMP-nucleon cross sections $< 10^{-7}$ pb, the expected rates are

< 1 event/100kg/day

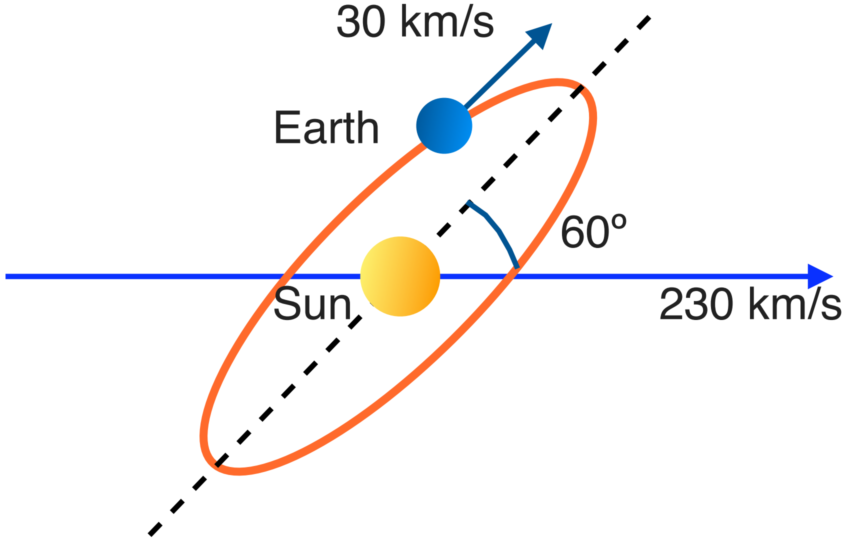
Differential rates for different targets

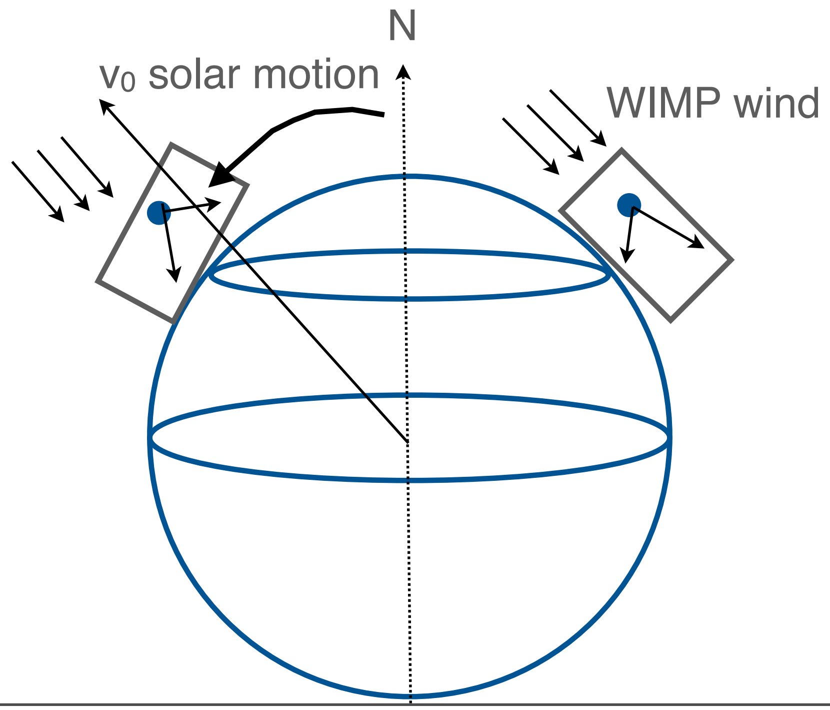


$$F^2(E_R) = \left[\frac{3 j_1(qR_1)}{qR_1} \right]^2 e^{-(qs)^2}$$

Expected WIMP Signatures

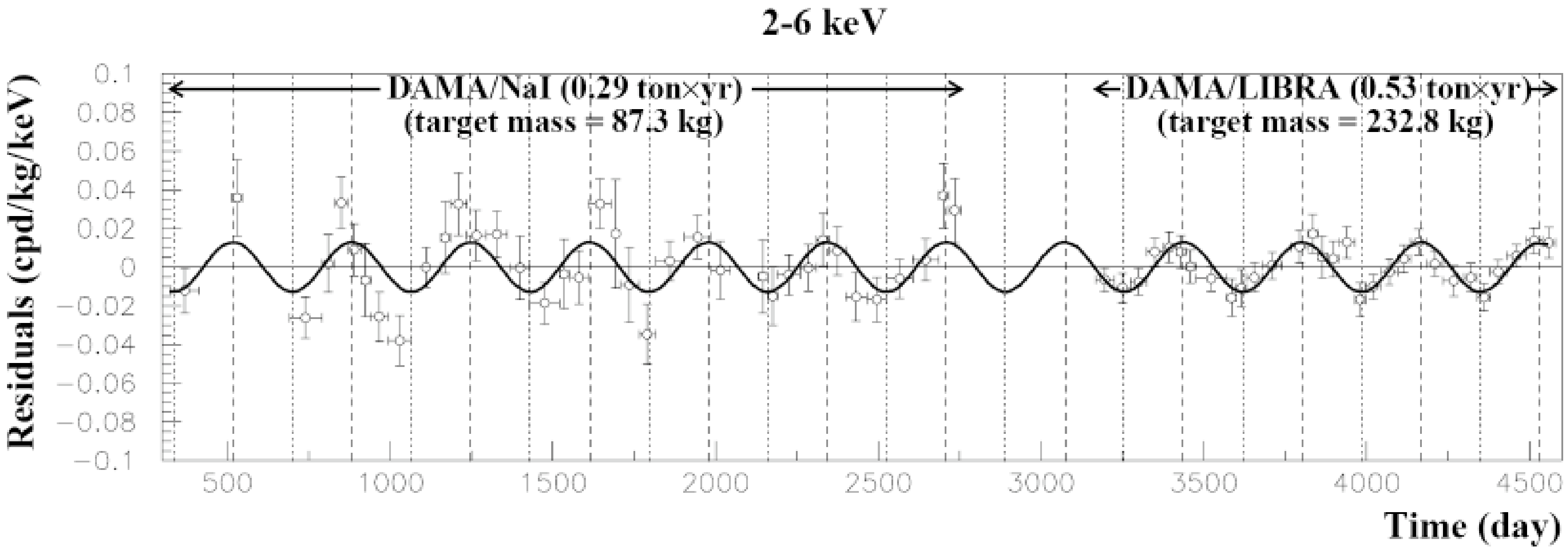
- **WIMP interactions in detector should be:**
  - nuclear recoils
  - single scatters, uniform throughout detector volume
- **Spectral shape** (exponential, however similar to background)
- **Dependance on material** (A^2, $F^2(Q)$, test consistency between different targets)
- **Annual flux modulation** (~ 3% effect, most events close to threshold)
- **Diurnal direction modulation** (larger effect, requires low-pressure gas target)





Evidence for annual modulation?

- DAMA/LIBRA at LNGS (0.82 ton x year in NaI); A = (0.0215 ± 0.0026) cpd/kg/keV (8.3 σ CL)
- Severe tension with other experiments!



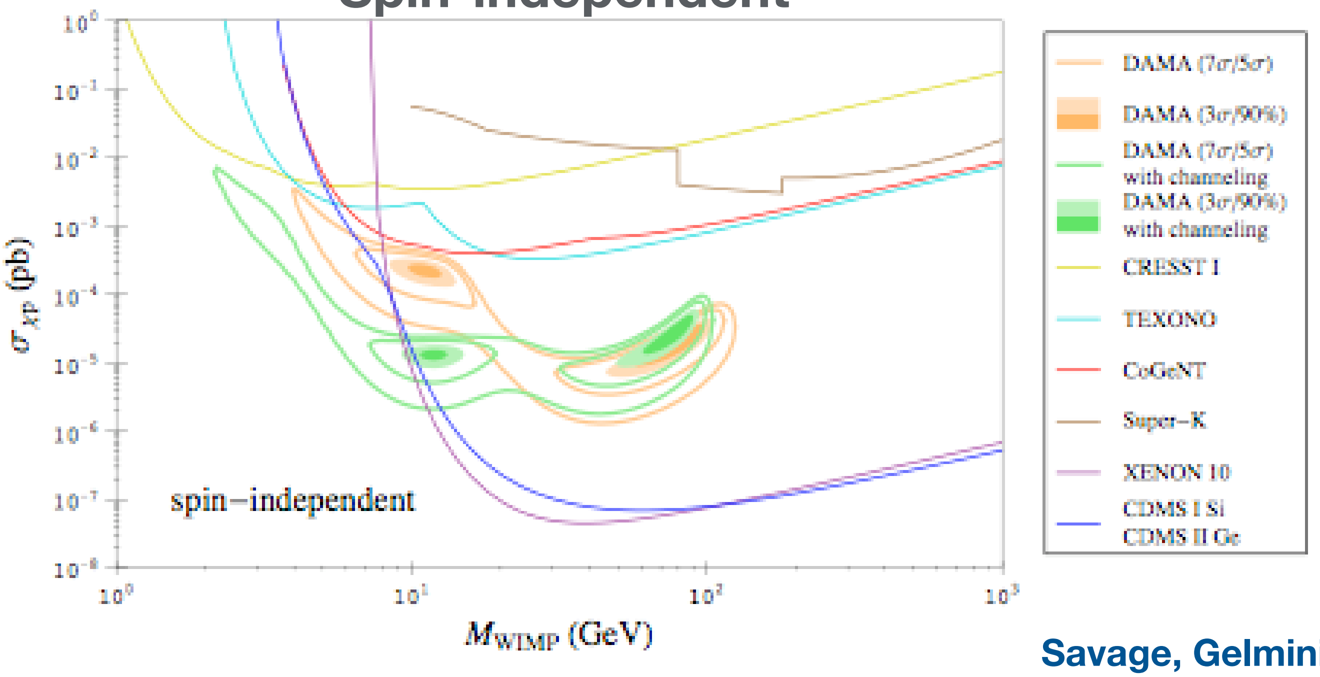
arXiv:0804.2741

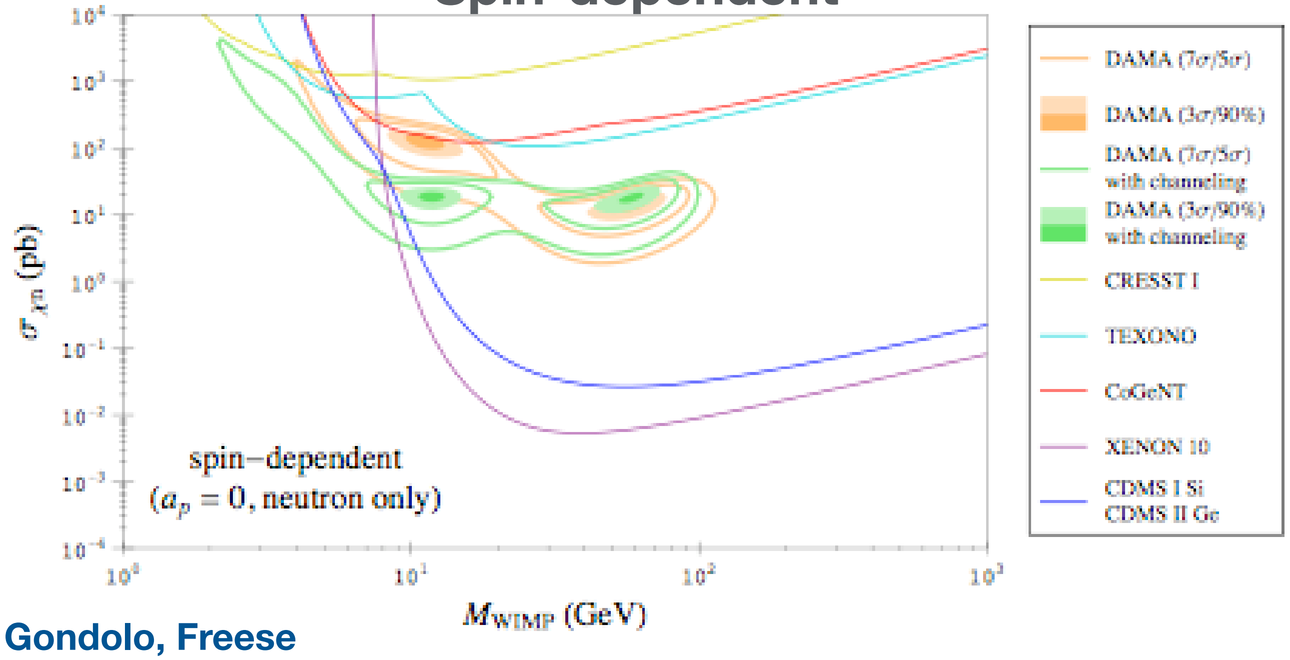
arXiv:0804.2738

Spin-independent

arXiv:0808.3607v1

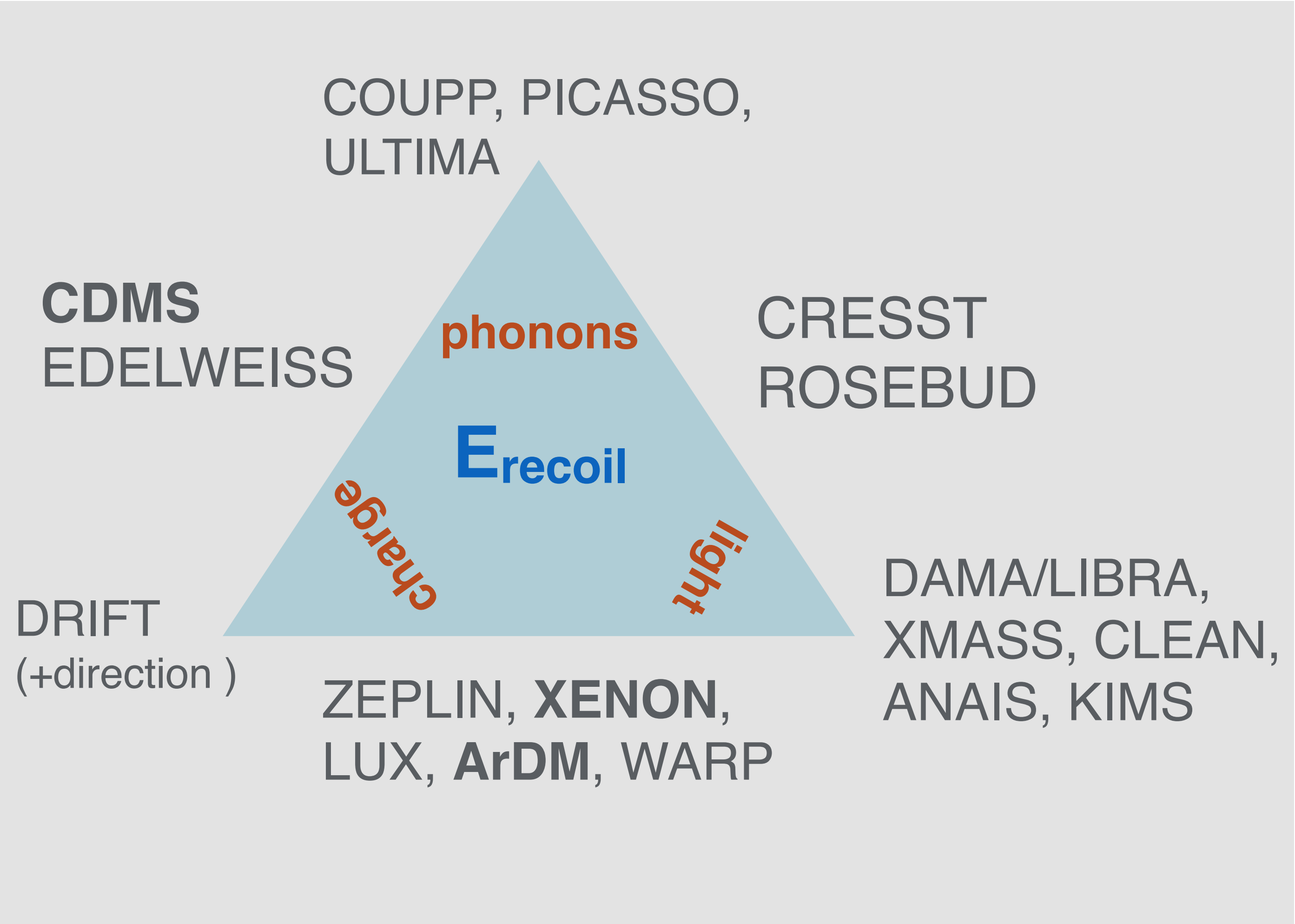
Spin-dependent





Savage, Gelmini, Gondolo, Freese

Direct WIMP Detection Experiments and Results



COUPP, PICASSO,
ULTIMA

CDMS
EDELWEISS

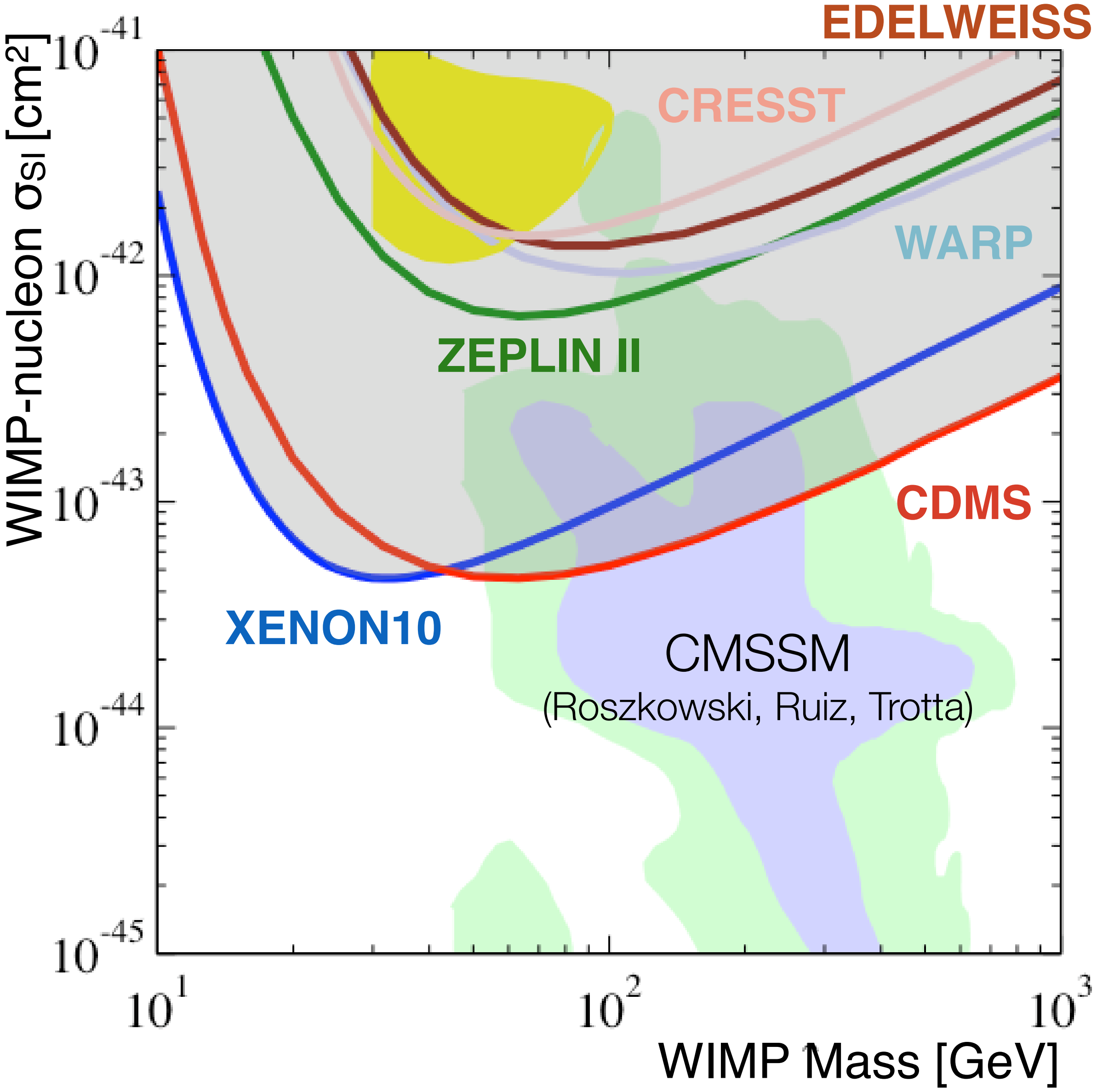
CRESST
ROSEBUD

DRIFT
(+direction)

ZEPLIN, **XENON**,
LUX, **ArDM**, WARP

DAMA/LIBRA,
XMASS, CLEAN,
ANAIS, KIMS

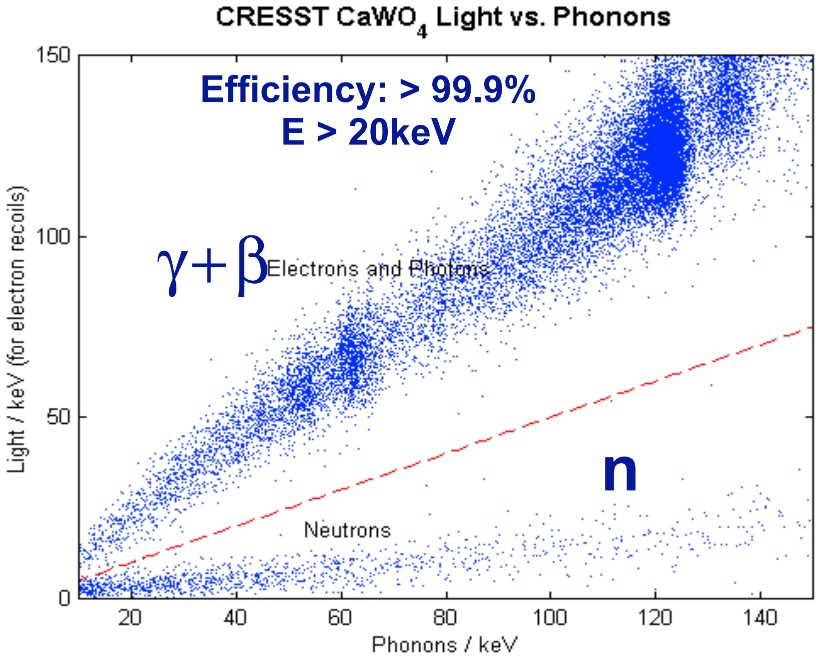
Spin-independent cross section
(normalized to nucleons)

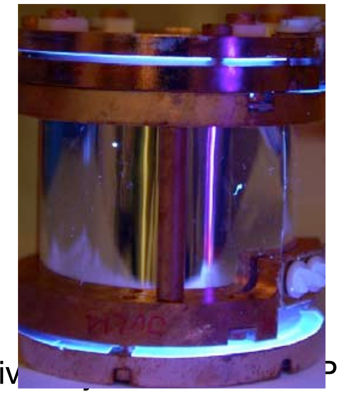


Cryogenic Experiments at mK Temperatures

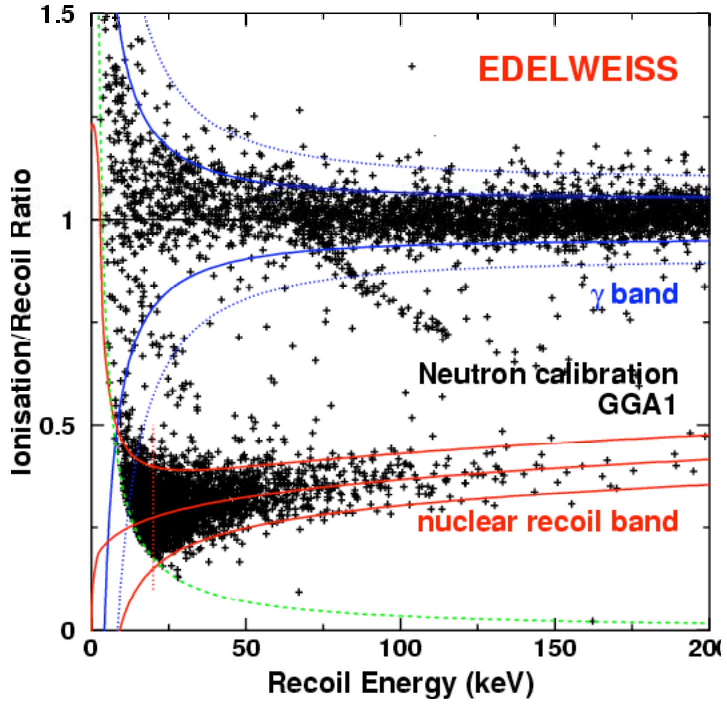
- **Advantages: high sensitivity to nuclear recoils**
  - measuring the full nuclear recoil energy in the phonon channel
  - low energy threshold (keV to sub-keV), good energy resolution
  - light/phonon and charge/phonon: **nuclear vs. electron recoil discrimination**

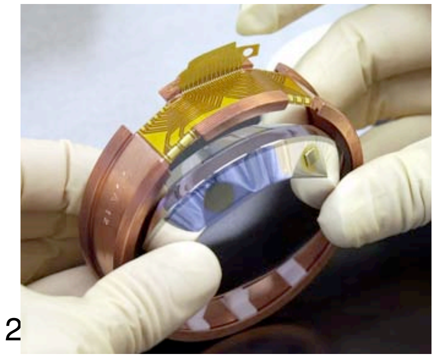
CRESST at LNGS



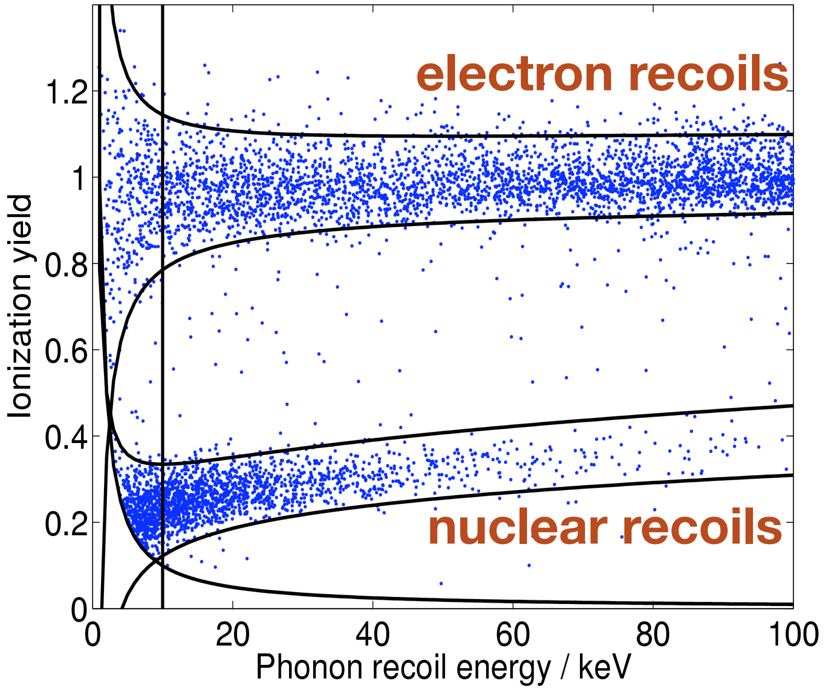


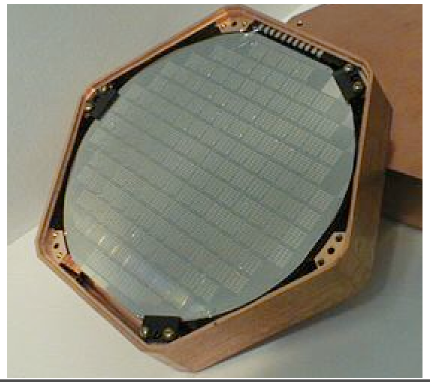
EDELWEISS at LSM





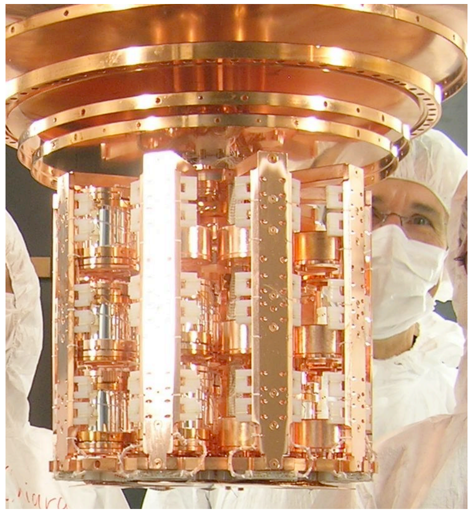
CDMS at Soudan

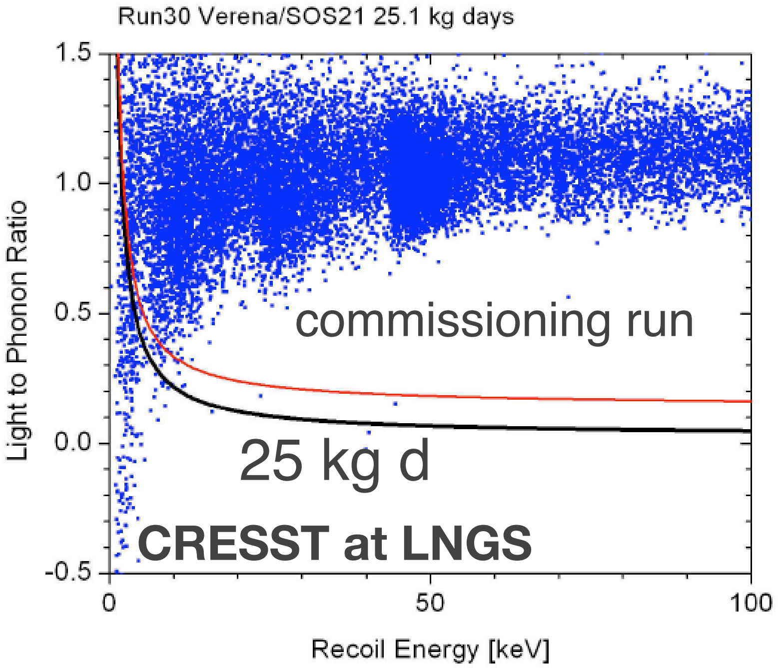




Cryogenic Experiments at mK Temperatures

10 kg array of 33 $CaWO_4$ detectors; 66 SQUID channel array
now cool-down (5 kg)



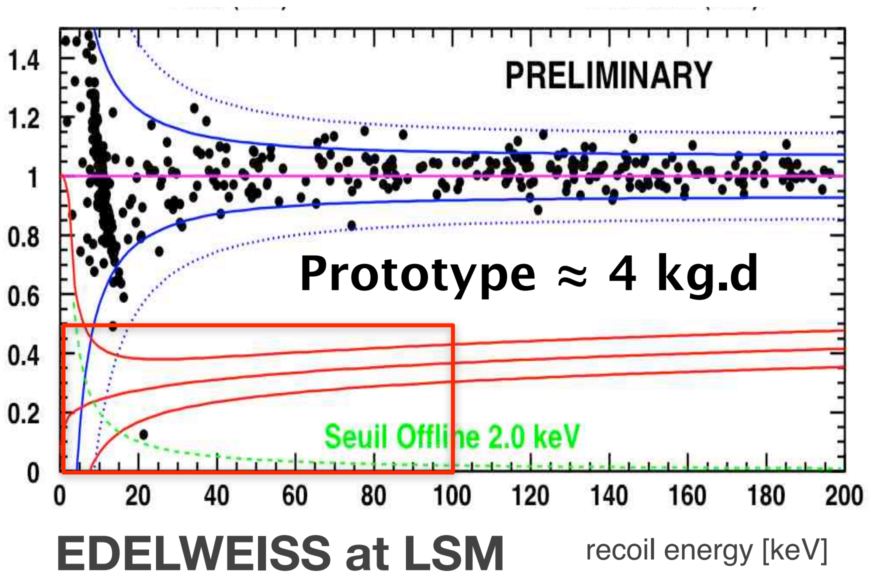


commissioning run

25 kg d

CRESST at LNGS

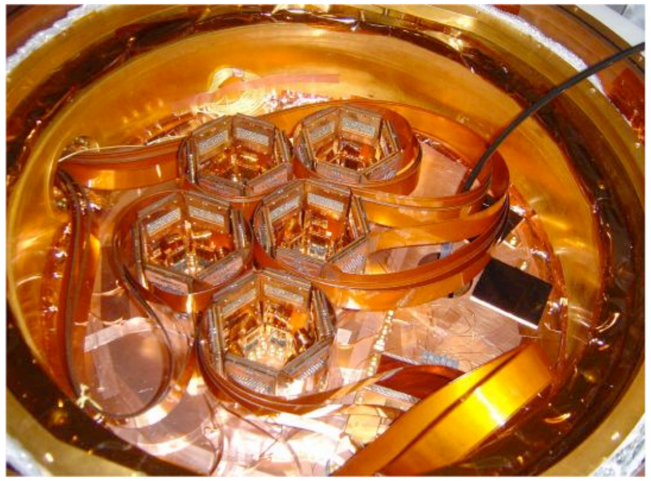
10 kg (30 modules) of NTD and NbSi Ge detectors in new cryostat
- 100 kg d under analysis
- data taking in progress

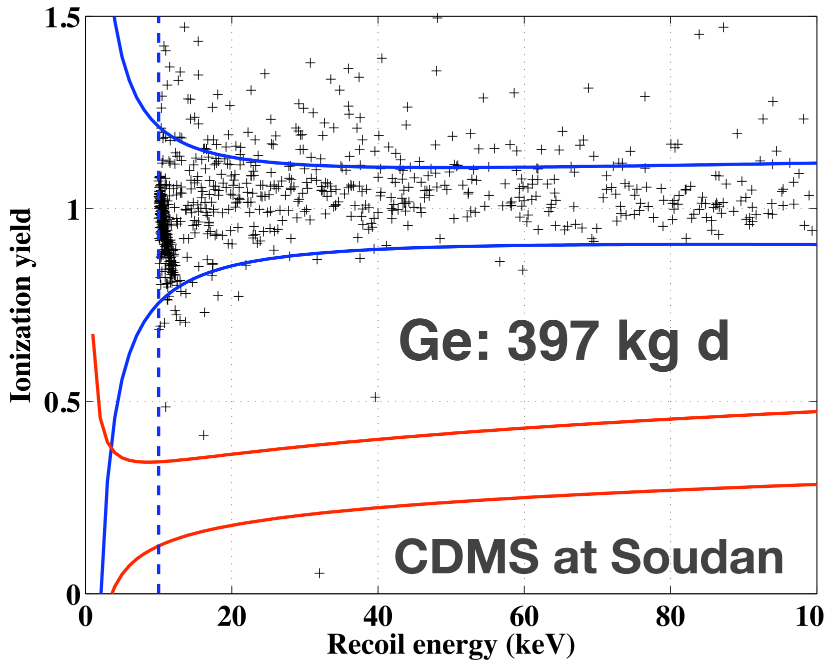


Prototype ≈ 4 kg.d

EDELWEISS at LSM

30 Ge (4.75 kg) and Si (1.1) detectors in 5 towers
Run123+124: 654 kg d Ge
Run 125+126: 740 kg d Ge
Run 127: ongoing





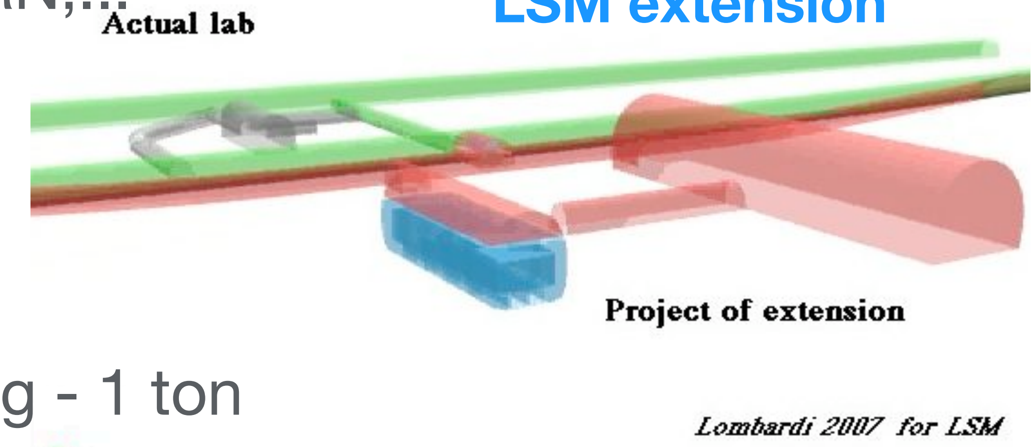
Ge: 397 kg d

CDMS at Soudan

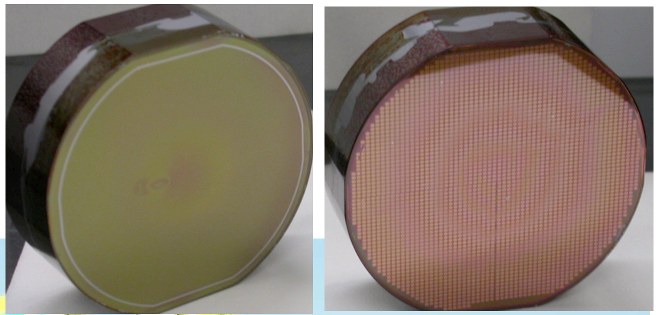
Future mK Cryogenic Dark Matter Experiments

- **EURECA (European Underground Rare Event Calorimeter Array)**
- Joint effort: CRESST, EDELWEISS, ROSEBUD, CERN,...
- Mass: 100 kg - 1 ton, multi-target approach

LSM extension



- **SuperCDMS (US/Canada):** 3 phases 25 kg - 150 kg - 1 ton
- 640 g Ge detectors with improved phonon sensors
- 4 prototype detectors built and tested

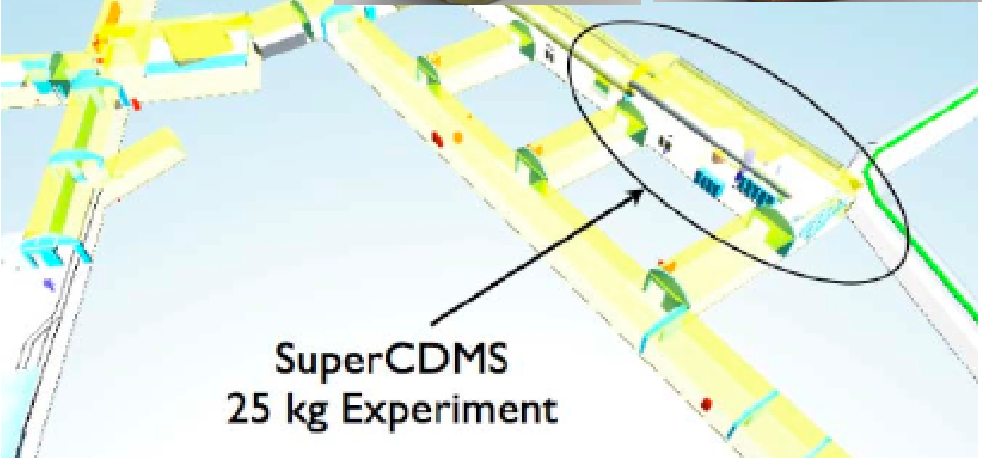


R&D for SuperCDMS:

1” thick **SuperZIPs** (0.64 kg)

2 SuperTowers at Soudan

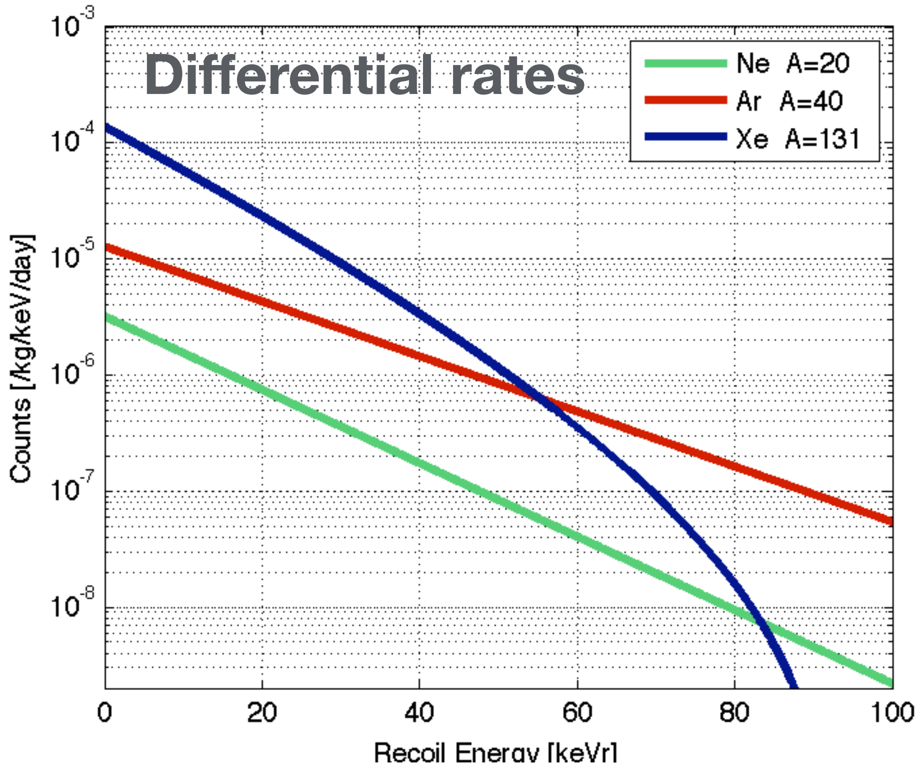
7 SuperTowers at SNOLAB

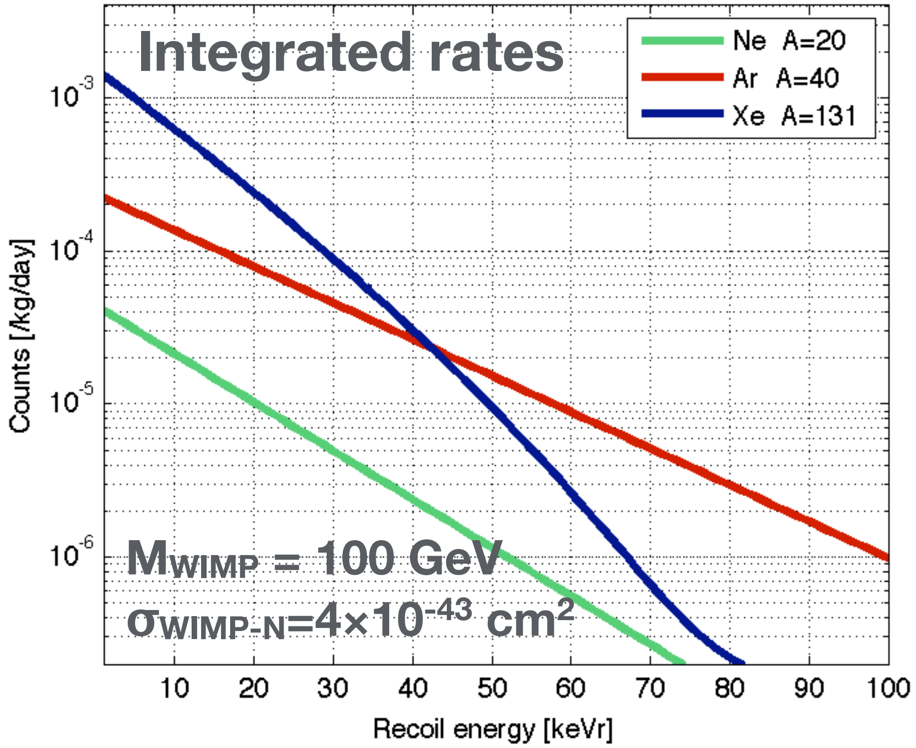


Noble Liquids as Dark Matter Detectors

Dense, homogeneous targets/detectors
High scintillation/ionization yields
Commercially easy to obtain and purify

	Scintillation Light	**Intrinsic Backgrounds**
Ne (A=20) \$60/kg 100% even-even nucleus	**85 nm** requires wavelength shifter	Low BP (20 K), all impurities frozen out No radioactive isotopes
Ar (A=40) \$2/kg 100% even-even nucleus	**128 nm** requires wavelength shifter	Natural Ar contains ^{39}Ar at 1Bq/kg, corresp. to ~150 ev/kg/day/keV at low energies
Xe (A=131) \$800/kg 50% odd nuclei (^{129}Xe, ^{131}Xe)	**175 nm** UV quartz PMT window	No long lived isotopes ^{85}Kr can be removed by active charcoal filter or distillation





Charge and Light in Noble Liquids

Kubota et al., PRB 20, 1979

Ionizing charged particles

holes R^+

electrons

escape

localized ions R^+_2

thermalized electrons

recombination
τ ≈15 ns

excitons

excited molecular states

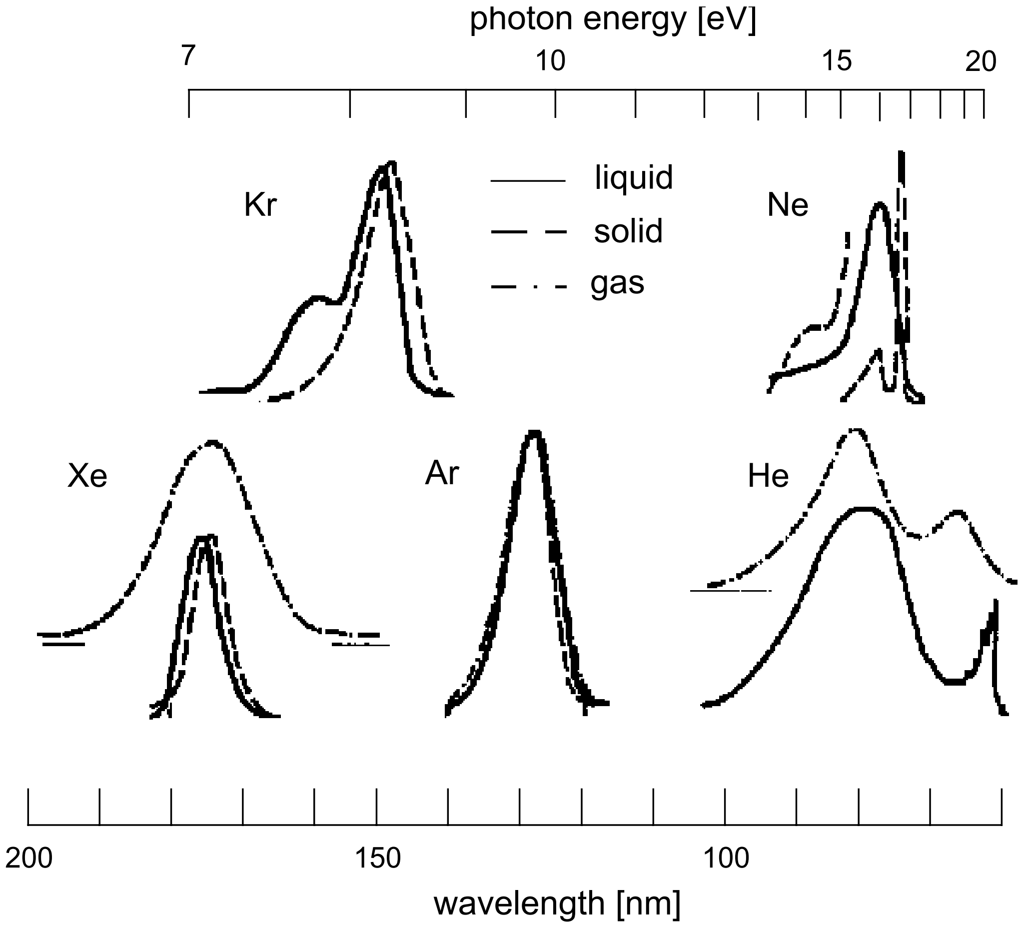
$^1\Sigma^+_u$ $^3\Sigma^+_u$

fast **slow**

luminiscence **VUV light**

time constants:

few ns/15.4μs Ne
10ns/1.5μs Ar
3/27 ns Xe



$$\lambda_{LNe} \sim 77.5\ nm$$
$$\lambda_{LAr} \sim 128\ nm$$
$$\lambda_{LXe} \sim 175\ nm$$

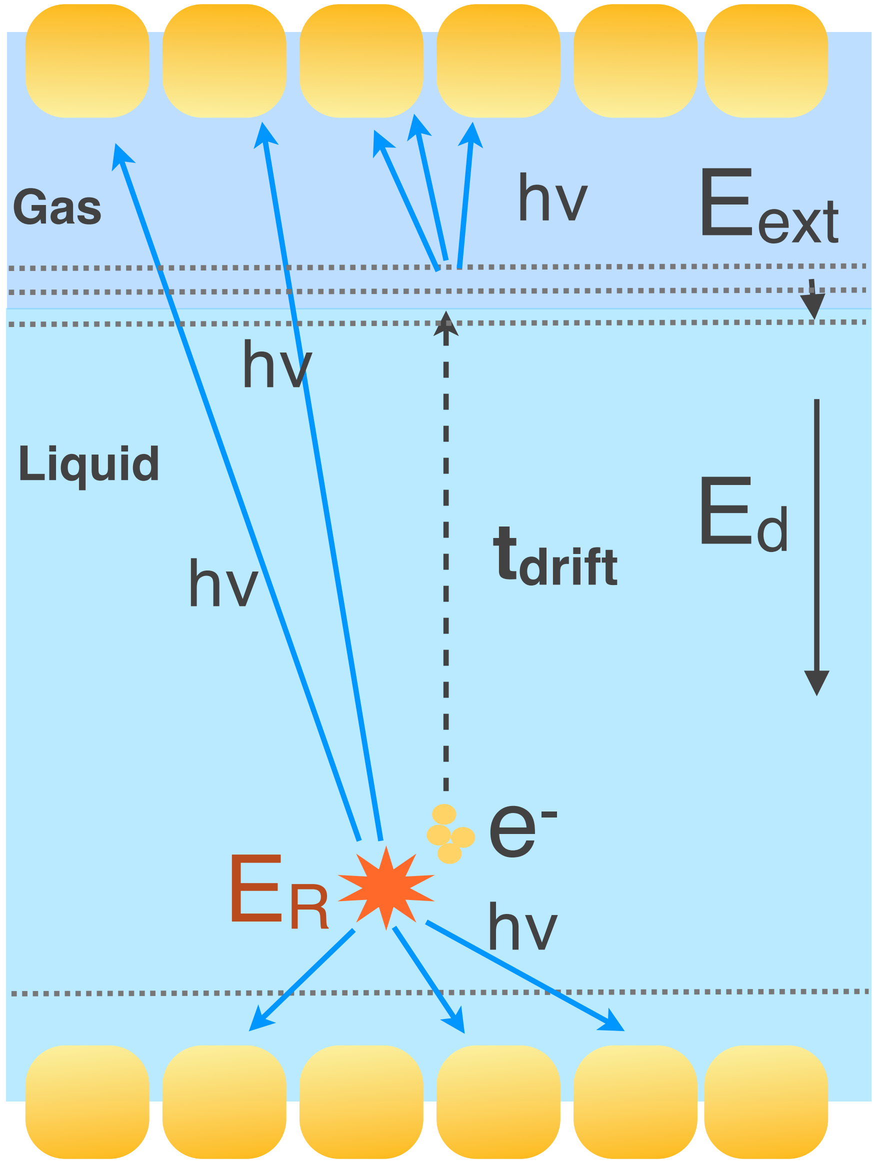
Noble Liquid Detectors: Existing Experiments and Proposed Projects

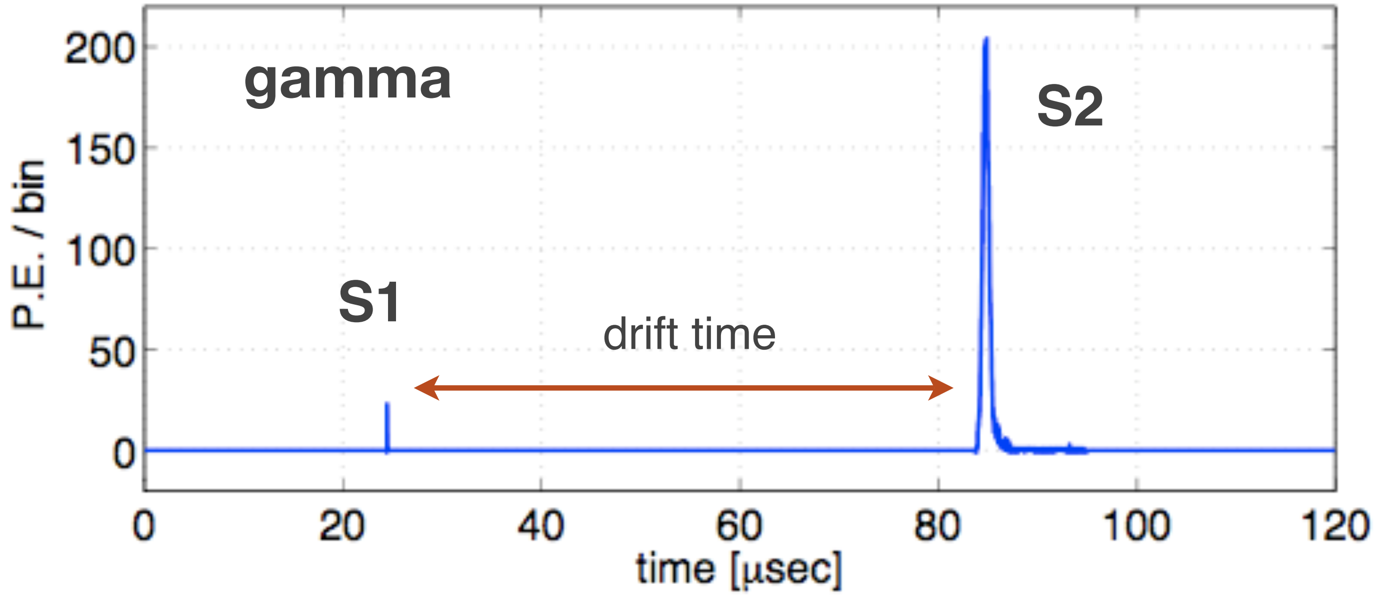
	Single Phase (liquid only) PSD	**Double Phase (liquid and gas) PSD and Charge/Light**
Neon (A=20)	miniCLEAN (100 kg) CLEAN (10-100 t)	SIGN (high P Ne gas)
Argon (A=40)	DEAP-I (7 kg) miniCLEAN (100 kg) CLEAN (10-100 t)	**ArDM (1 ton)** WARP (3.2 kg) WARP (140 kg)
Xenon (A=131)	ZEPLIN I XMASS (100 kg) XMASS (800 kg) XMASS (23 t)	ZEPLIN II + III (31 kg, 8 kg) **XENON10 (15 kg), XENON100 (170 kg)** LUX (300 kg), **XENON1t (3t)**

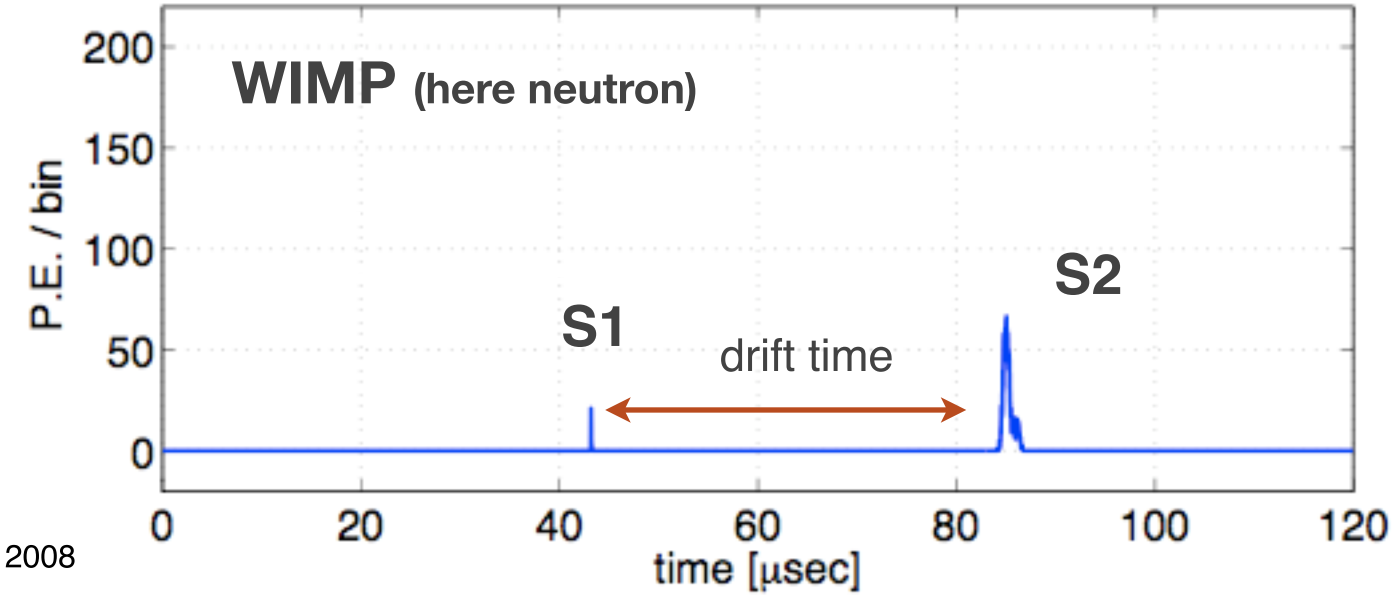
- **Single phase:** e^--ion recombination occurs; singlet/triplet ratio is 10/1 for NR/ER
- **Double phase:** ionization and scintillation; electrons are drifted in ~ 1kV/cm E-field
- **Complementarity between Ar and Xe targets (nuclear mass, spin vs. no spin,...)**

The Double-Phase Detector Concept

- **Prompt (S1) light signal** after interaction in active volume; charge is drifted, extracted into the gas phase and detected either **directly with LEMs**, or as **proportional light (S2)**
- **Challenge:** ultra-pure liquid + high drift field; efficient extraction + detection of e^-



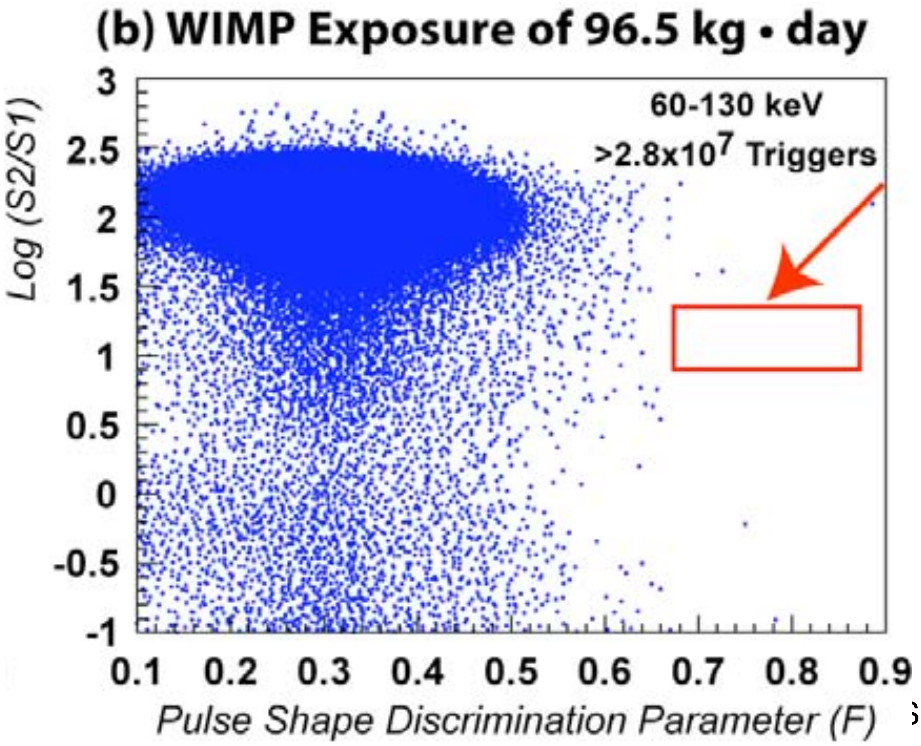


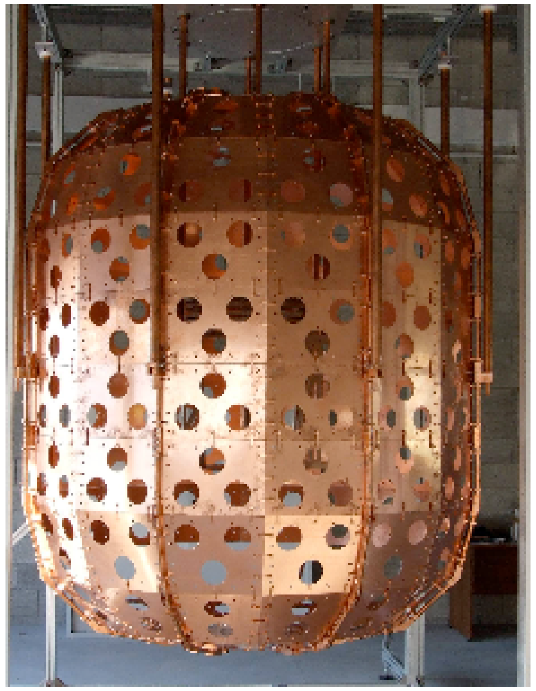


Two-phase Argon Detectors

WARP at LNGS

3.2 kg LAr operated
at LNGS; results from
zero events > 55 keVr

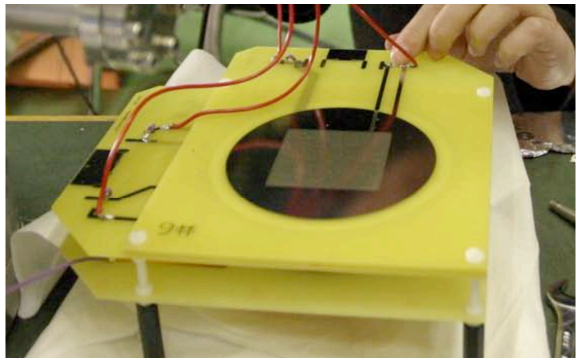

(b) WIMP Exposure of 96.5 kg • day



140 kg LAr, 41 3'' PMTs
under construction
active LAr shield: ~ 8t,
viewed by 300 PMTs

ArDM at CERN

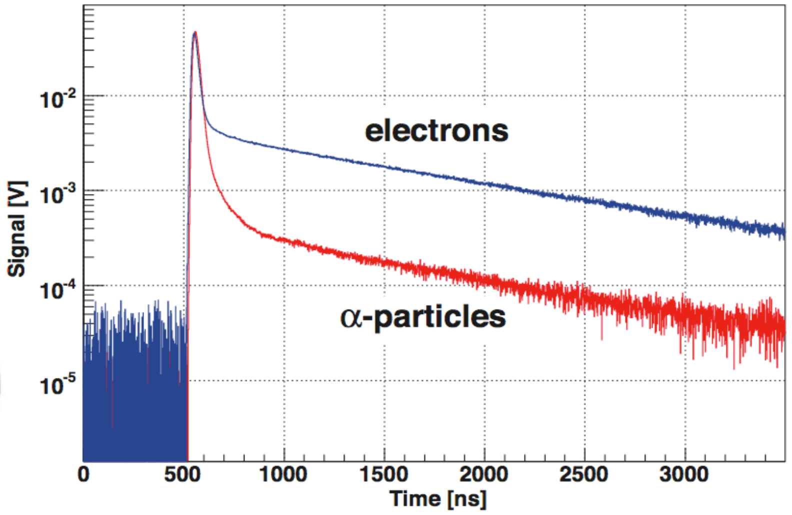
1 t LAr prototype under
construction
direct electron readout via
LEMs (thick macroscopic GEM)
S1 with 14 x 8'' PMTs

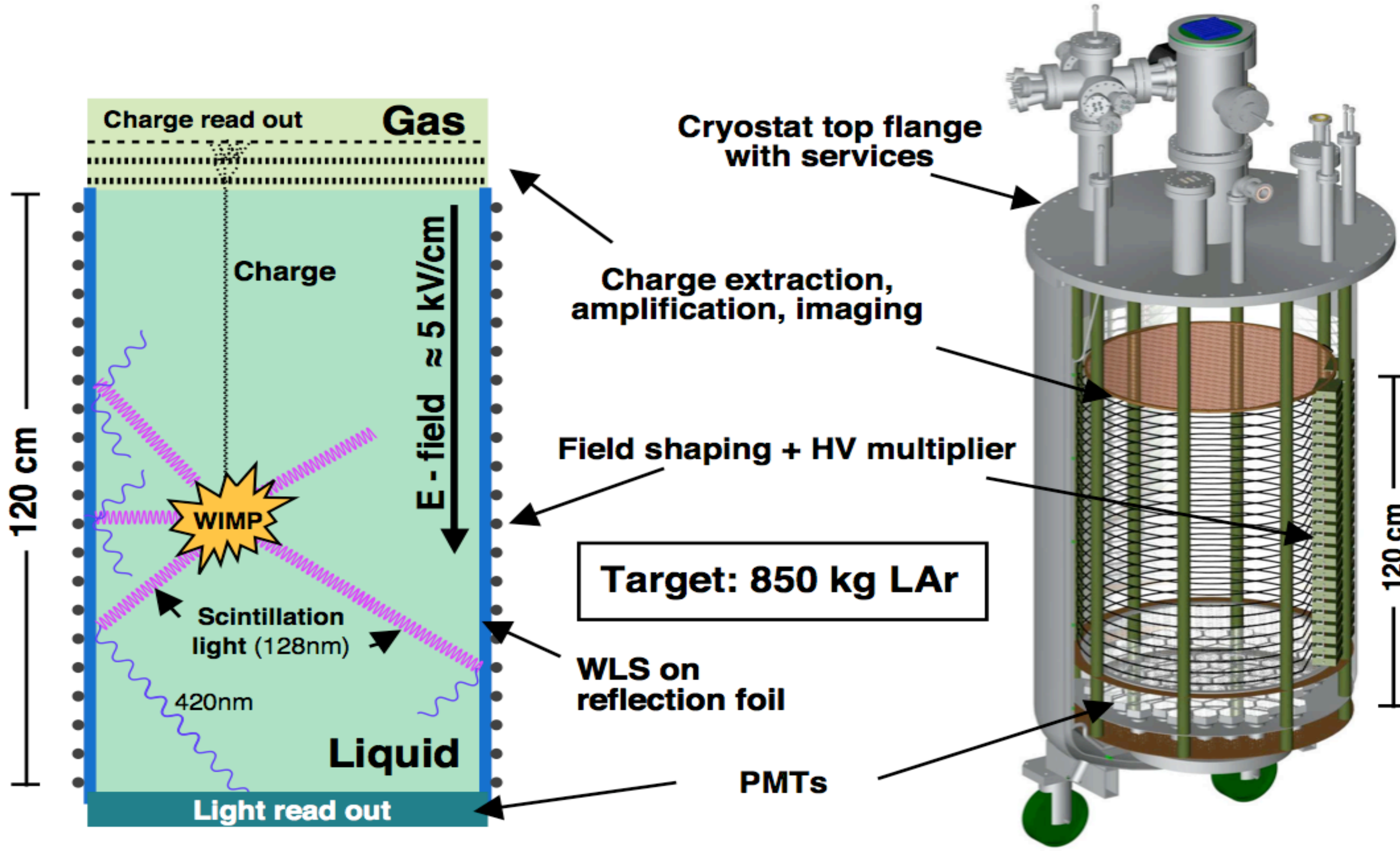


The ArDM Experiment

ETH Zurich, Switzerland: A. Badertscher, L. Kaufmann, L. Knecht, M. Laffranchi, C.Lazzaro, A. Marchionni, G. Natterer, P. Otiougova, F.Resnati, A. Rubbia (spokesperson), J. Ulbricht.
Zurich University, Switzerland: C. Amsler, V. Boccone, A. Dell'Antone S. Horikawa, C. Regenfus, J. Rochet.
University of Granada, Spain: A. Bueno, M.C. Carmona-Benitez, J. Lozano, A. Melgarejo, S. Navas-Concha.
CIEMAT, Spain: M. Daniel,M. de Prado, L. Romero.
Soltan Institute for Nuclear Studies, Poland: P. Mijakowski, P. Przewlocki, E. Rondio.
University of Sheffield, England: P.Lightfoot, K.Mavrokoridis, M. Robinson, N. Spooner.

- **1 ton liquid argon TPC/calorimeter, in construction phase at CERN**
- Goals: $E_{th} \approx 30$ keV, 3D imaging, event-by-event identification of interaction type
- Background rejection by: topology, localization, ionization density (ratio of ionization/scintillation and time distribution of the scintillation light)
- **Expected signal rate: 1 WIMP event/ton/day at 10^{-8} pb**





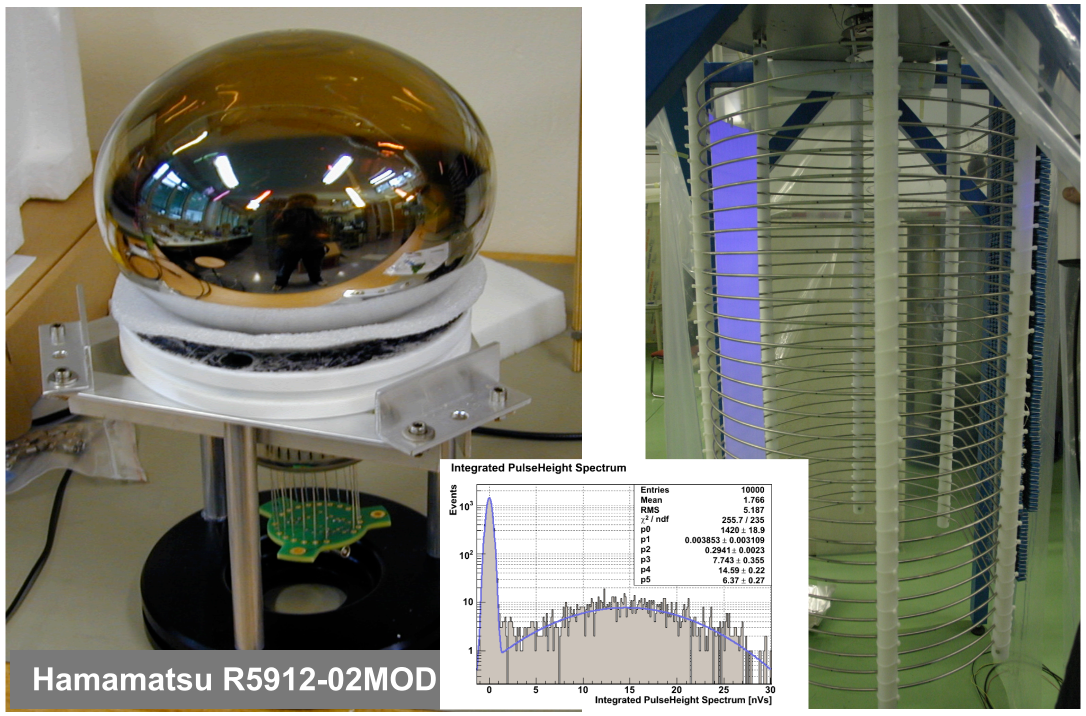
A.Rubbia (Zurich, ETH)
J.Phys.Conf.Ser.39:129-132,2006.

- **Drift length ≈ 120 cm**
- **850 kg target**
- **Drift field: 1..4 kV/cm**
- **LEM on top: res ≈ [mm], gain ≈ 10^4**
- **PMTs at bottom: eff. ≈ 2%**
- **Trigger rate < 1kHz**
- **DAQ: FADCs, buffer length ≈ 1ms**

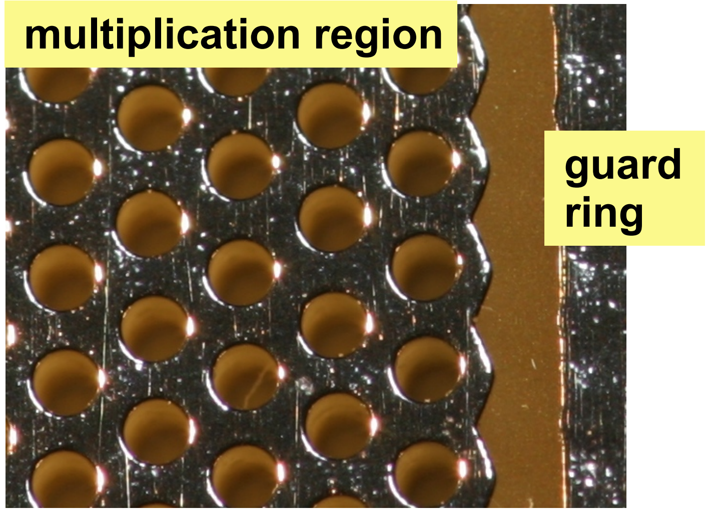
The ArDM Experiment: Status at CERN

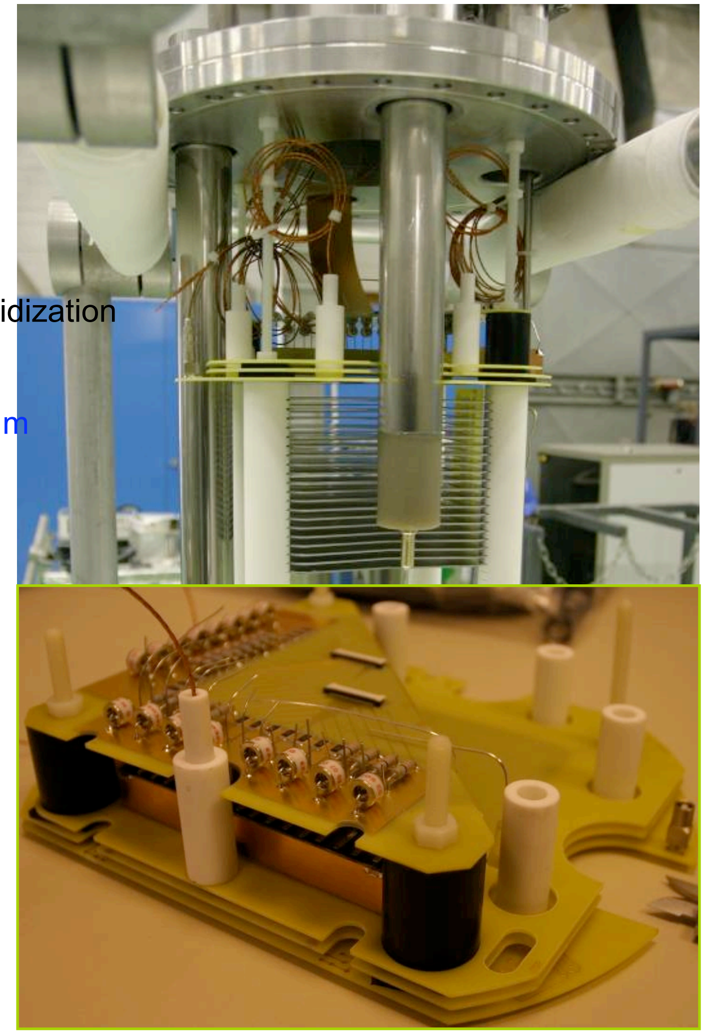
- Cryostat and liquid purification and recirculation built and tested
- HV generator (Greinacher circuit) to reach ≈ 4 kV/cm (V_{tot} = 500 kV) placed in liquid
- Slow Control has been implemented
- Double phase LEMs successfully operated in double phase Ar mode (stable gain of 10^4); with final LEM charge readout segmented; A/D conversion and DAQ system being developed
- 14 bialkali 8” PMTs (TPB coated) installed at the bottom
- 15 light reflector/shifter foils produced and installed

C.Amsler et al., *“Luminescence quenching of the triplet excimer state by air traces in gaseous argon”* arXiv:0708.2621



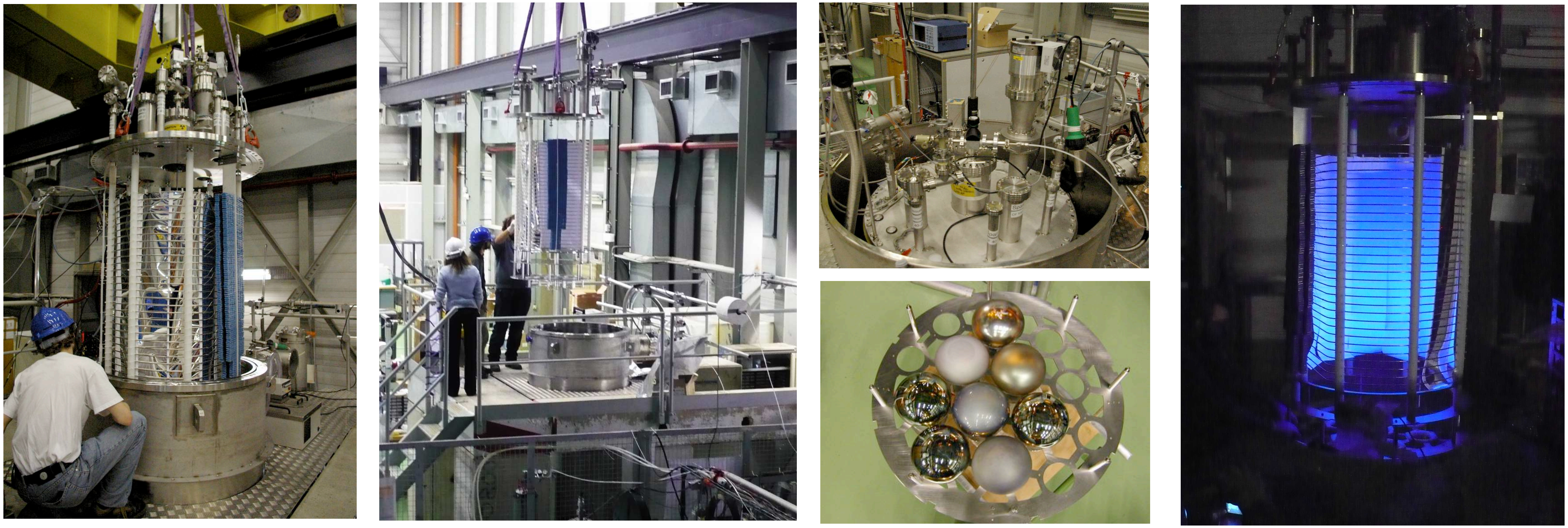
- Double-sided copper-clad (35 μm layer) G-10 plates
- Precision holes by drilling
- Palladium deposition on Cu (<~ 1 μm layer) to avoid oxidization
- Single LEM Thickness: 1.5 mm
- Amplification hole diameter = 500 μm
- Distance between centers of neighboring holes = 800 μm





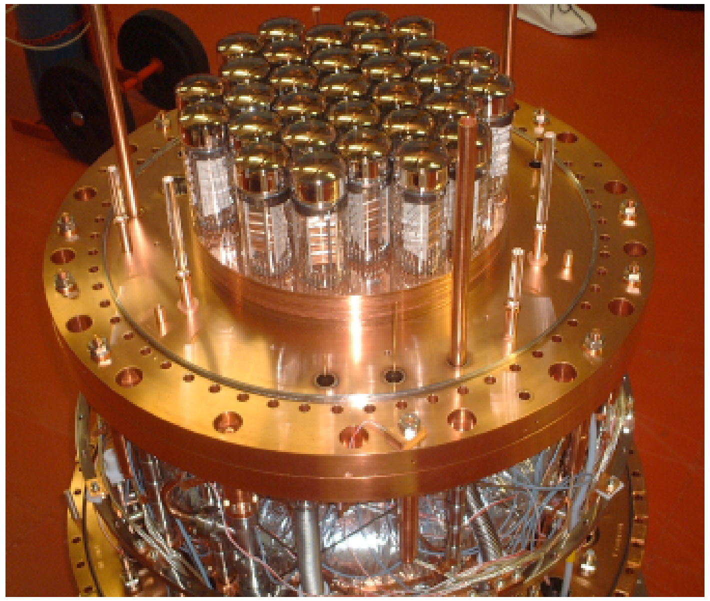
The ArDM Experiment: Assembly and Plans

- Assembled at CERN: Sept. 2007 - May 2008
- First cool down in May 2008 successful, PMTs work well
- To understand light collection: movable source + blue LED installed
- Purity monitoring cell and neutron calibration in progress
- Goals: operate full scale prototype at surface (and evtl. at shallow depth) at CERN
- Consider deep underground operation, for instance at the Canfranc Lab



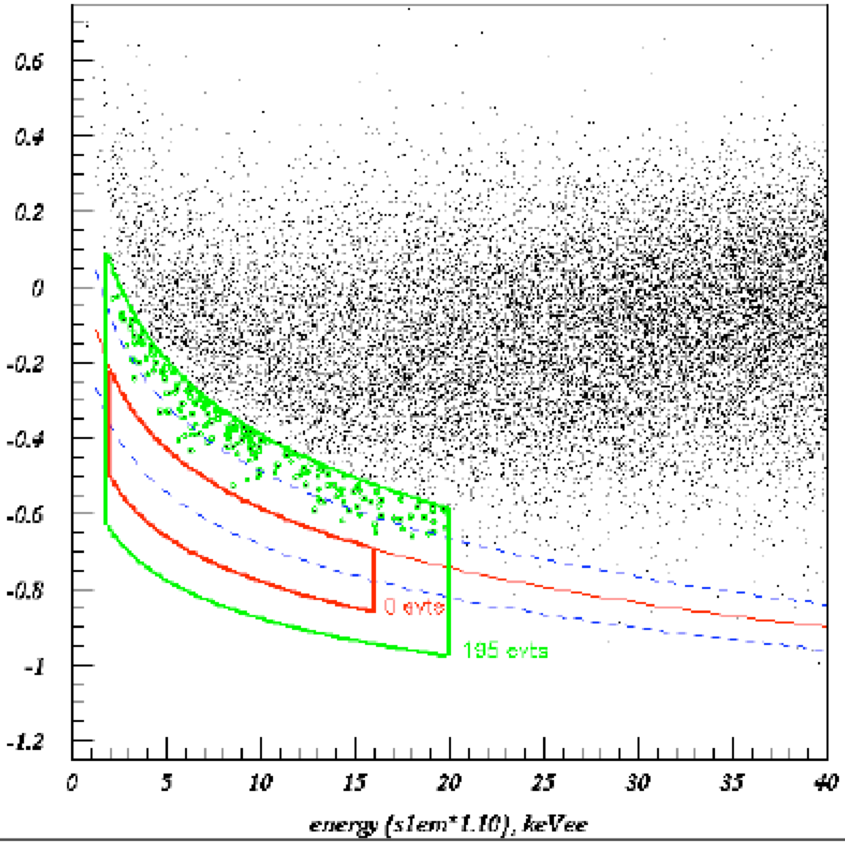
Two-phase Xenon Detectors

ZEPLIN III at Boulby



8 kg LXe (fiducial)
31 x 2” cm PMTs

analysis of
WIMP search run
in progress



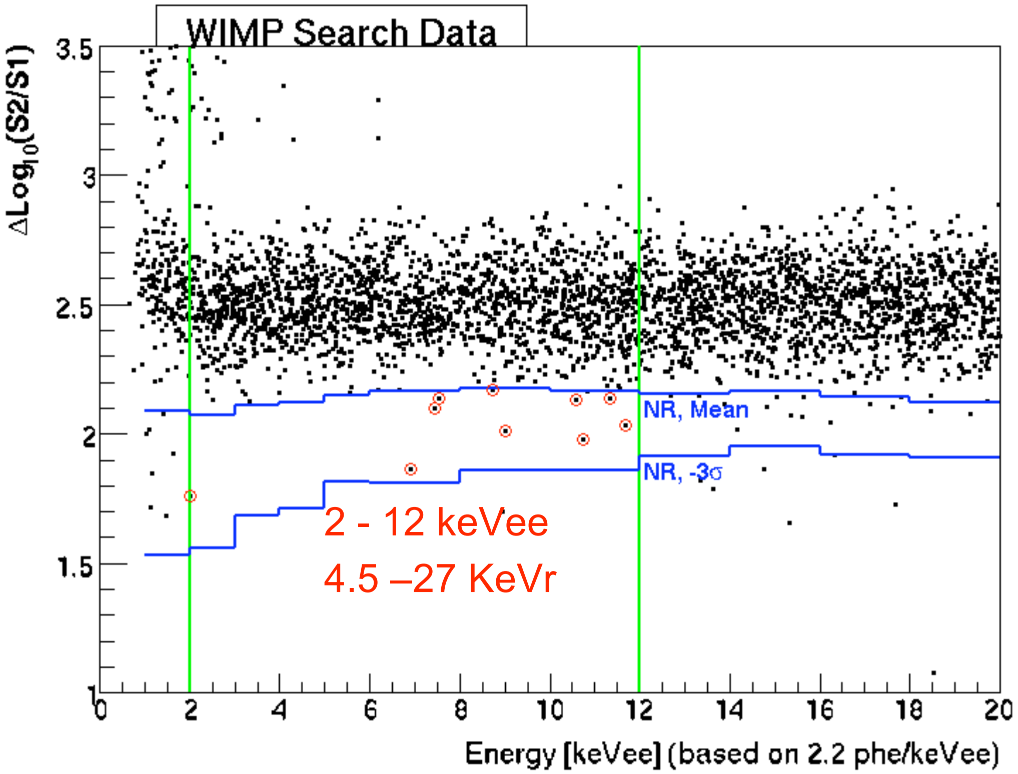
a total of 30%
of WIMP search
data unblinded
=> no events in
the signal region

rest (70%) will be
unblinded soon

XENON10 at LNGS

15 kg (5.4 fiducial),
89 2” PMTs

136 kg d (after cuts)
of WIMP search
data



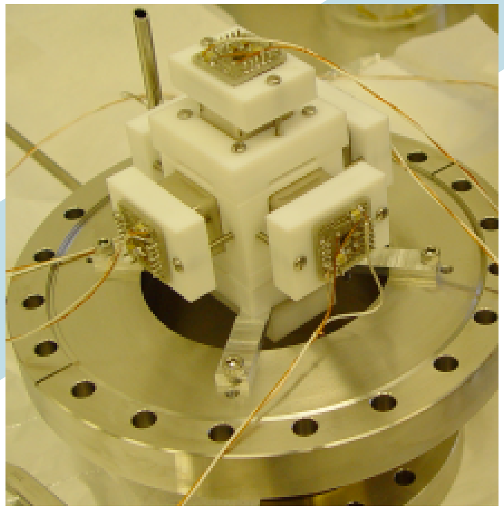
2 - 12 keVee
4.5 –27 KeVr

10 events
observed,
all BG

Results:
PRL100,
PRL101

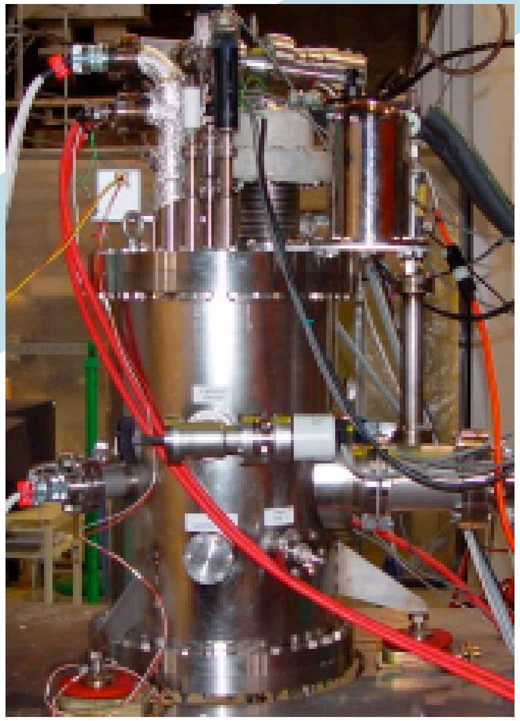
The XENON Program

XENON R&D



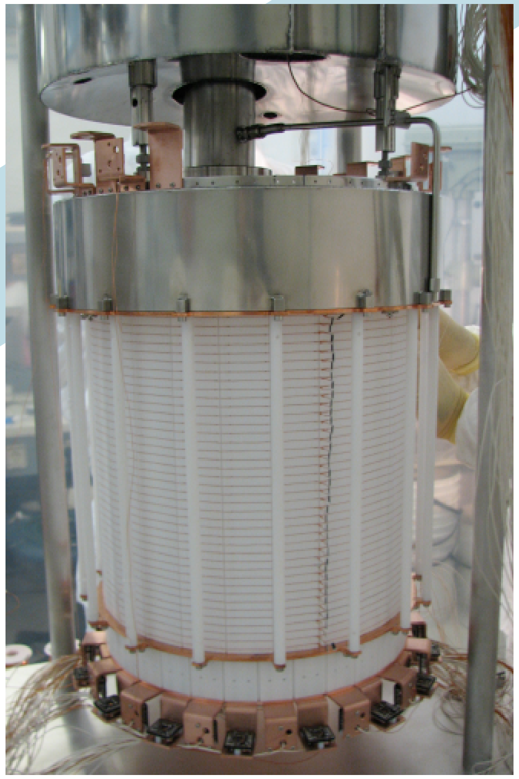
ongoing

XENON10



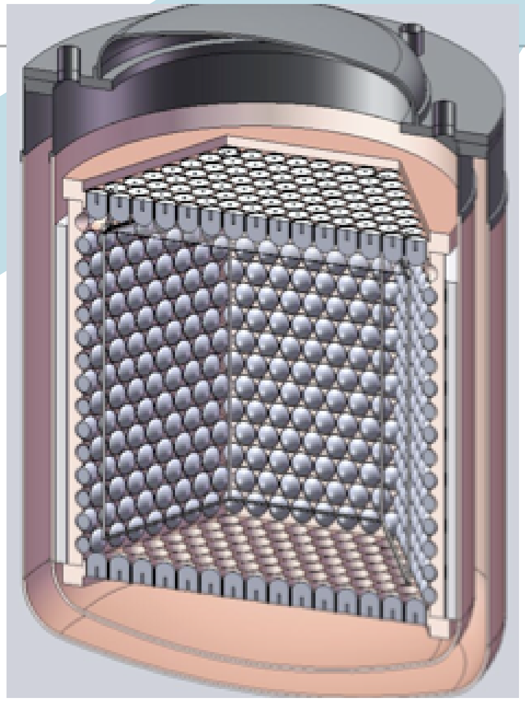
2006-2007

XENON100



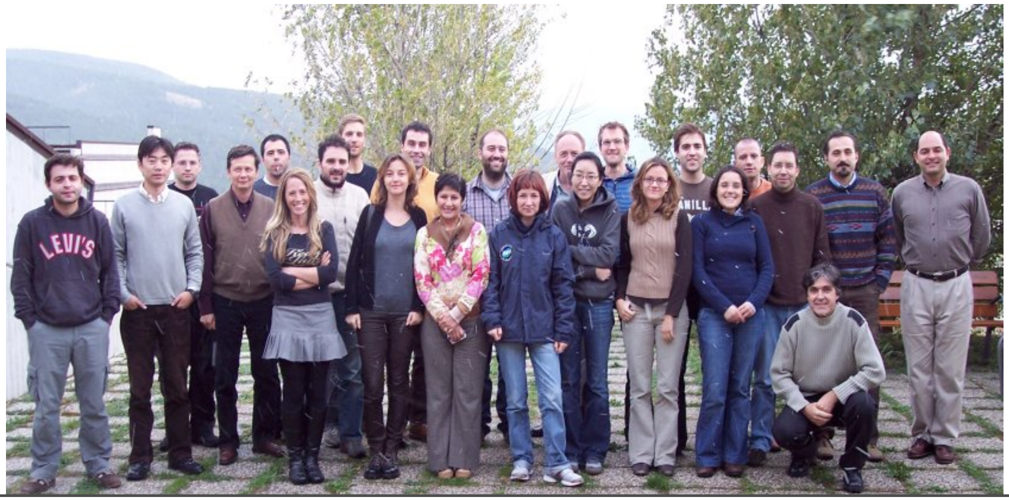
in commissioning

XENON1t



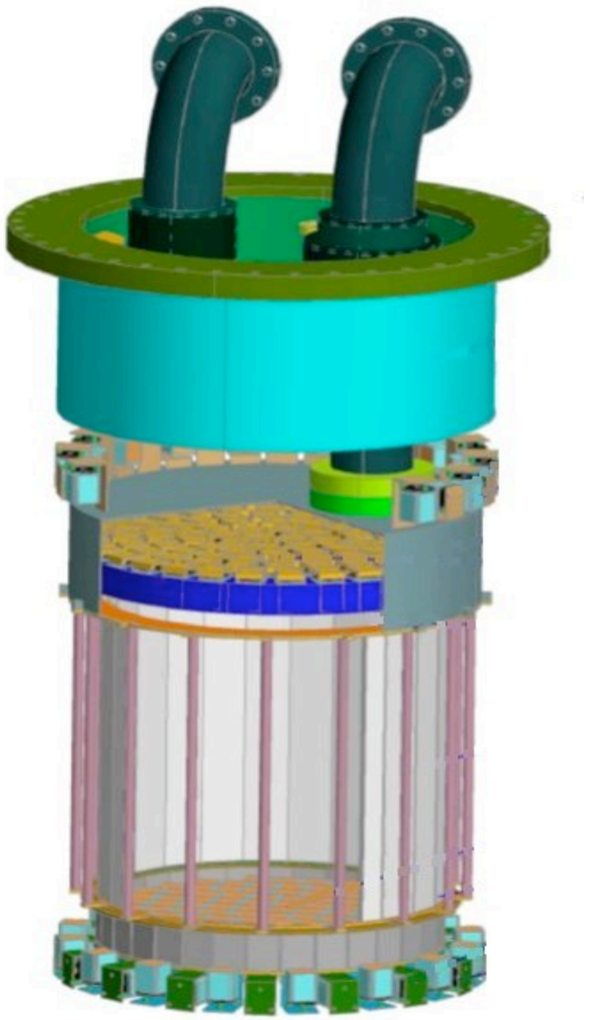
2009-2013
studies in progress

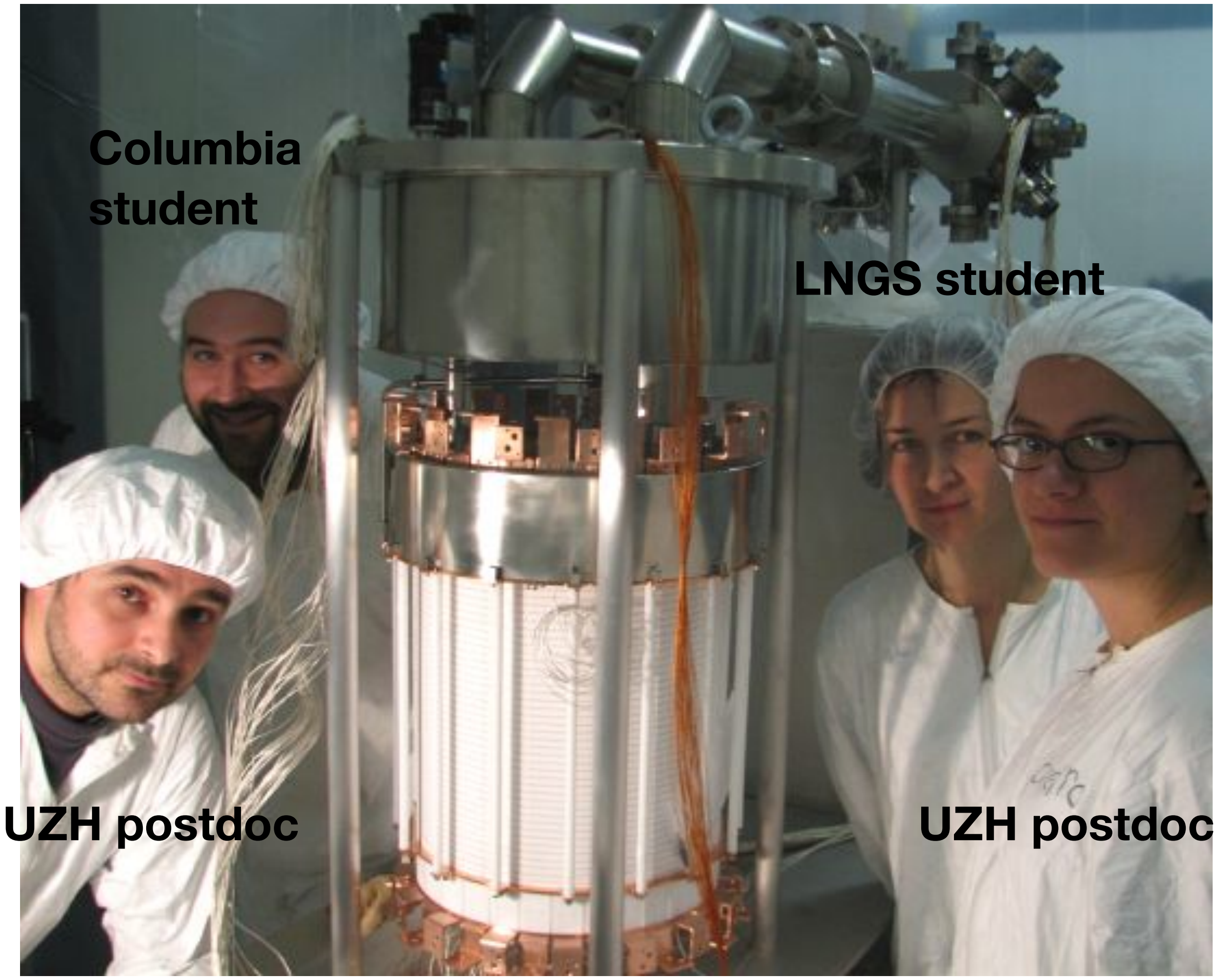
???



The XENON100 Detector

- TPC (total of 170 kg LXe) with active veto (100 kg LXe) installed underground since February 2008
- New cryostat design: PTR and feed-throughs outside the low-background shield
- All (detector/shield) materials were screened for their radio-purity: MC predictions of backgrounds
- Test runs showed that background is at the expected level
- Xe is now being purified to ppt ^{85}Kr-levels ($T_{1/2}$ = 10.7 y, β^- 678 keV) with dedicated column at LNGS
- **Expect to start WIMP search run in November 2008**

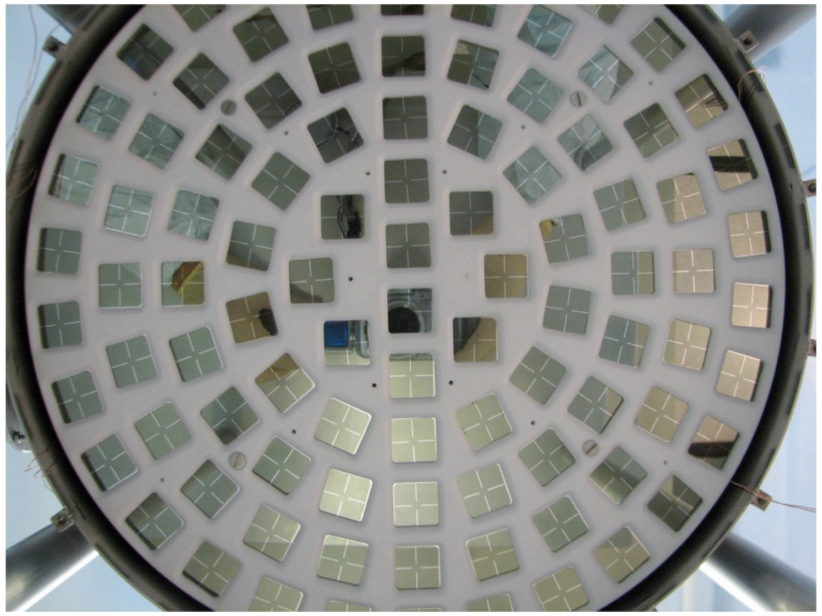


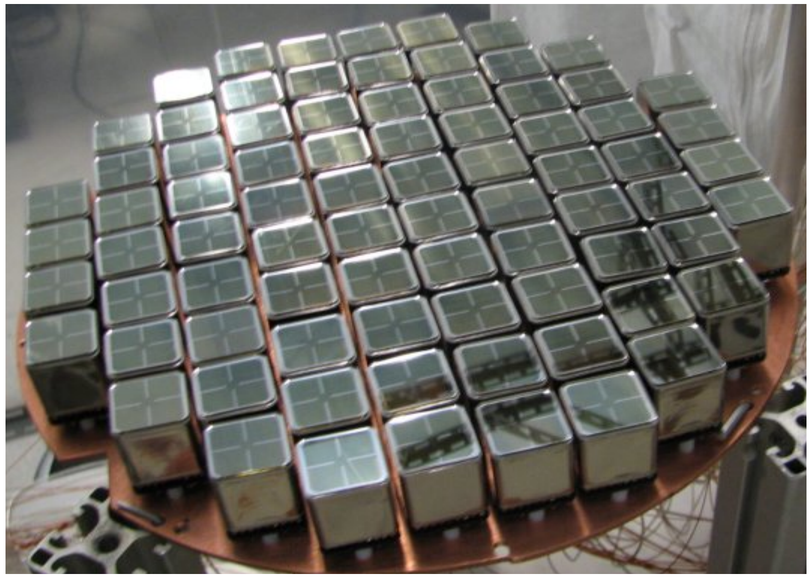


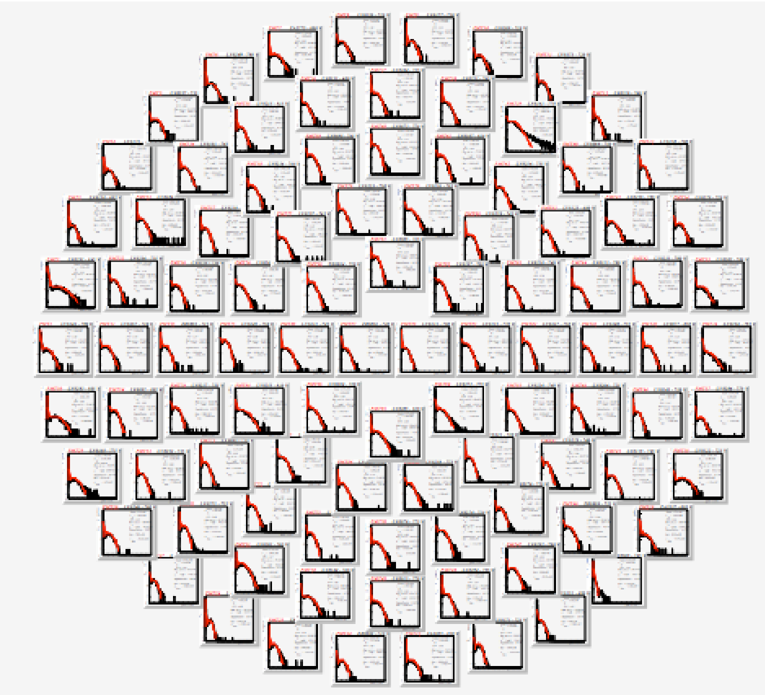
Laura Baudis, University of Zurich,CHIPP Plenary Meeting, September 9, 2008

XENON100 PMTs

- 242 (Hamamatsu R8520) 1”x1”, low radioactivity PMTs; 80 with high QE of 33%
- 98 top: for good fiducial volume cut efficiency
- 80 bottom: for optimal S1 collection efficiency (thus low threshold); 64 in active LXe shield
- PMT gain calibration with blue LEDs; the SPE response is measured







top PMT array

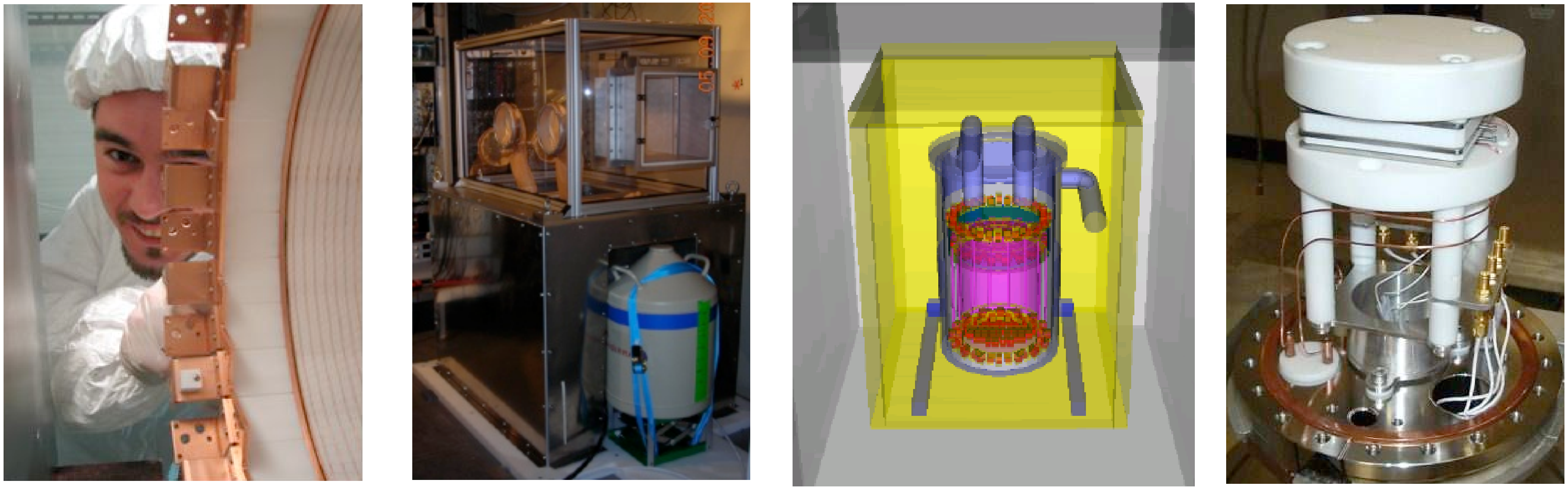
(gain equalized to $2x10^6$)

bottom PMT array

(gain equalized to $2x10^6$)

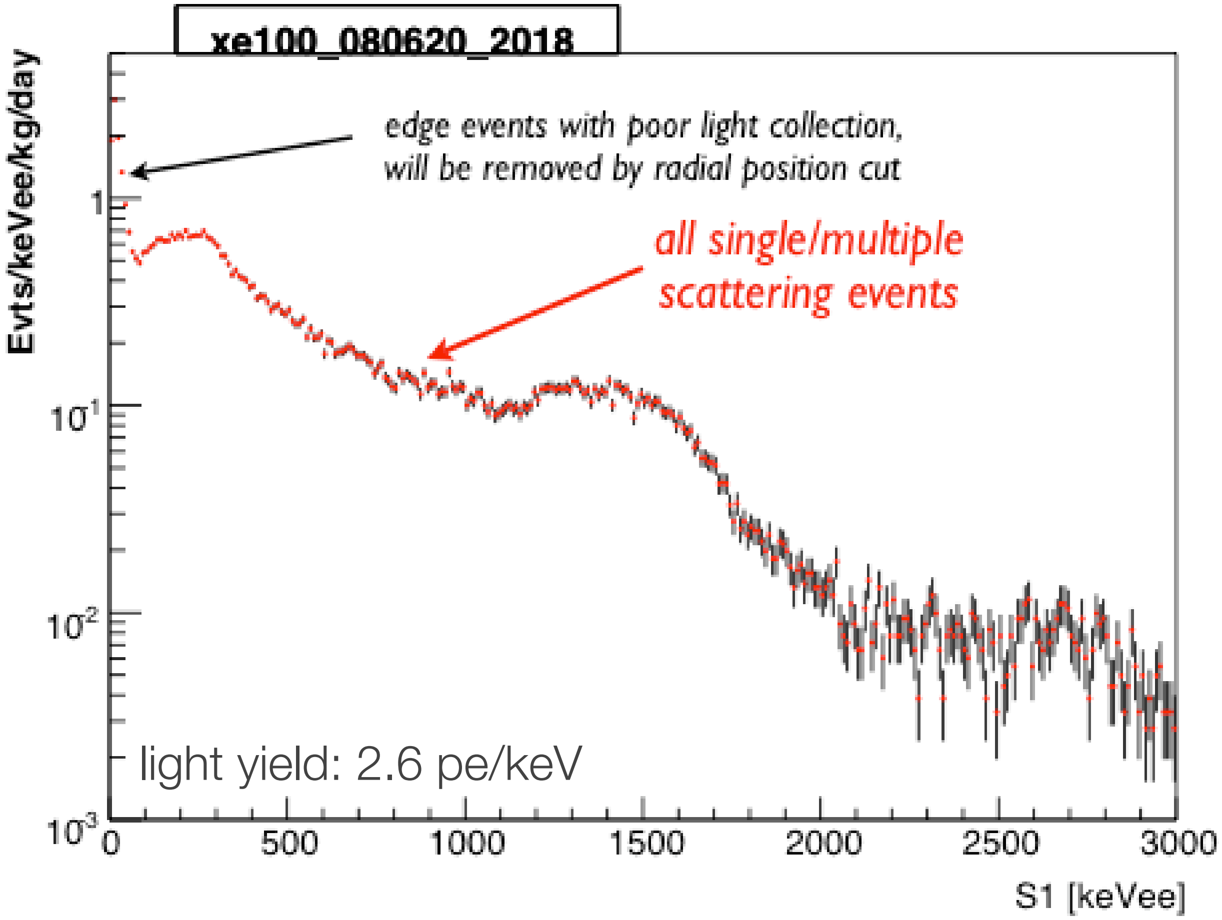
Responsibilities of UZH Group in XENON

- PMT testing, calibrations and gain monitoring (+ PMT database)
- Material screening with ultra-low BG HPGe detector at LNGS and identification of low-background materials
- MC geometry (Geant4) and simulations of gamma/alpha/beta and neutron backgrounds
- Calibration (sources/data/MC) with gamma and neutron sources
- Charge and light yield measurements (+ R&D) with small prototype detector at UZH lab
- Various hardware components (inner PTFE TPC structure + PMT holder built at UZH)
- 3 postdocs (A. Ferella, R. Santorelli, E. Tziaeri), 4 graduate students (A. Askin, A. Kish, A. Manalaysay, M. Haffke)



Preliminary Background from XENON100 Data

data (S1 only)

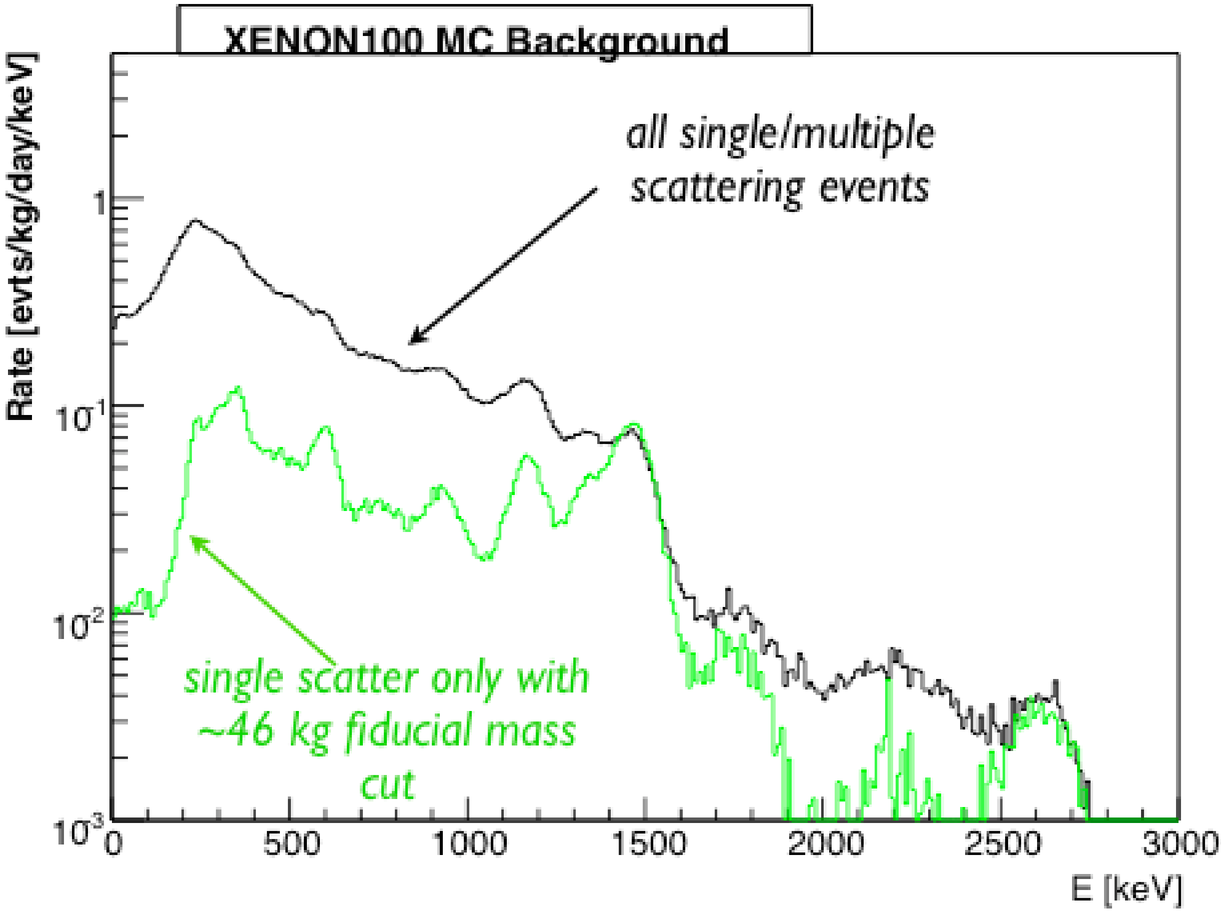


edge events with poor light collection, will be removed by radial position cut

all single/multiple scattering events

light yield: 2.6 pe/keV

Monte Carlo simulations



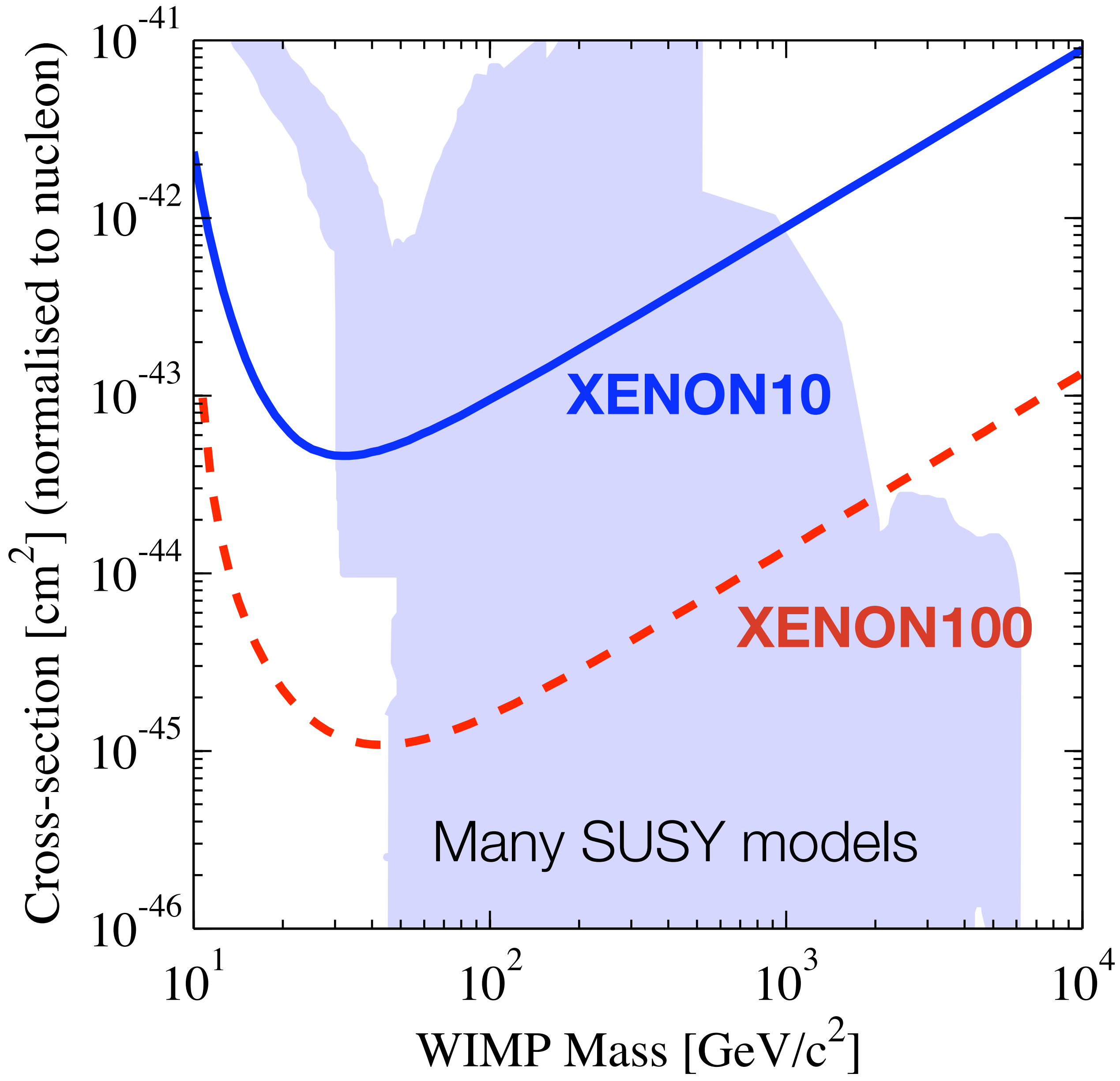
all single/multiple scattering events

single scatter only with ~46 kg fiducial mass cut

Data and Monte Carlo predictions are in good agreement for overall rate

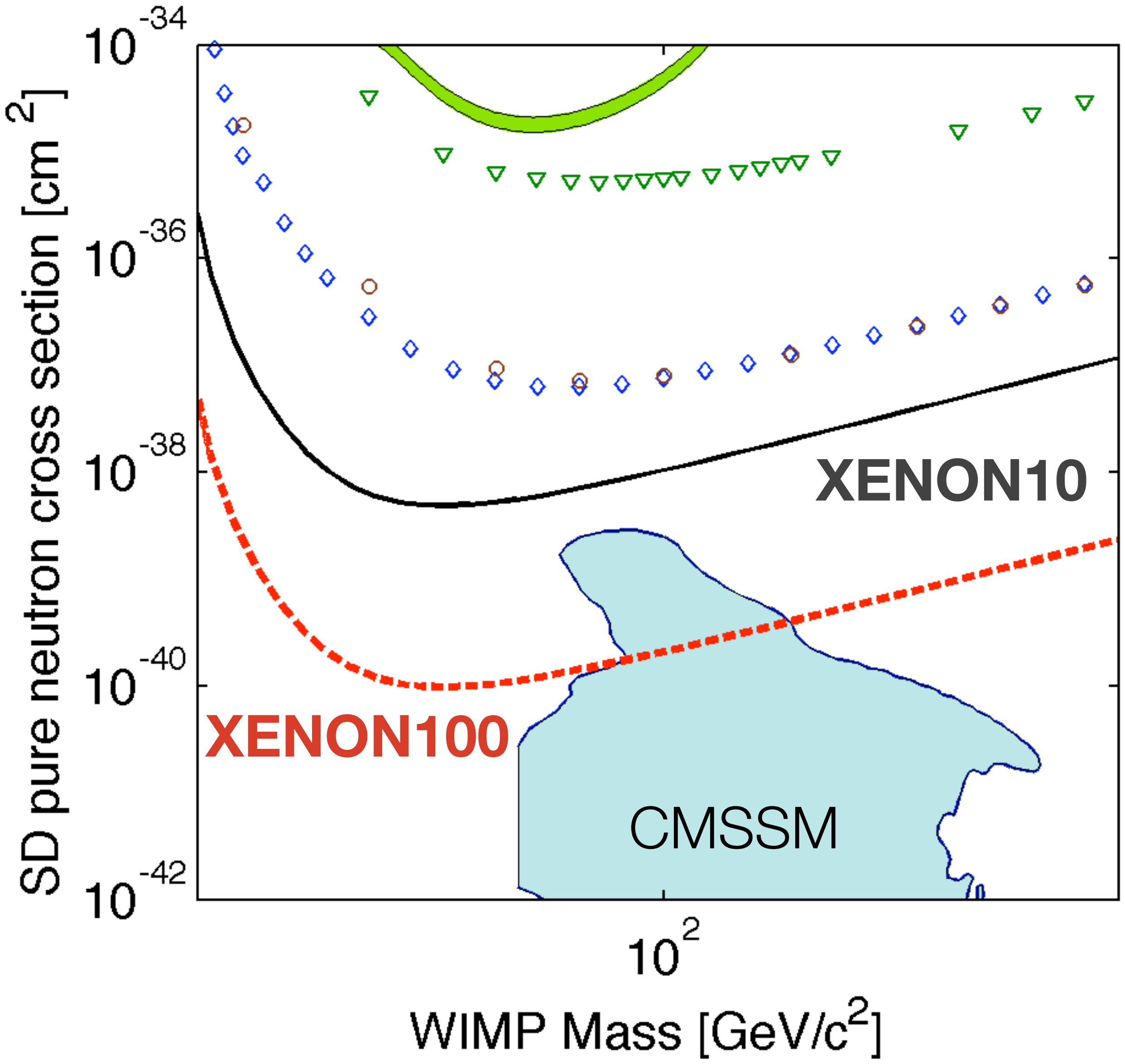
Expected Sensitivity for WIMPs and SUSY Predictions

Spin-independent



XENON10 SI limit: PRL100, 021303 (2008)

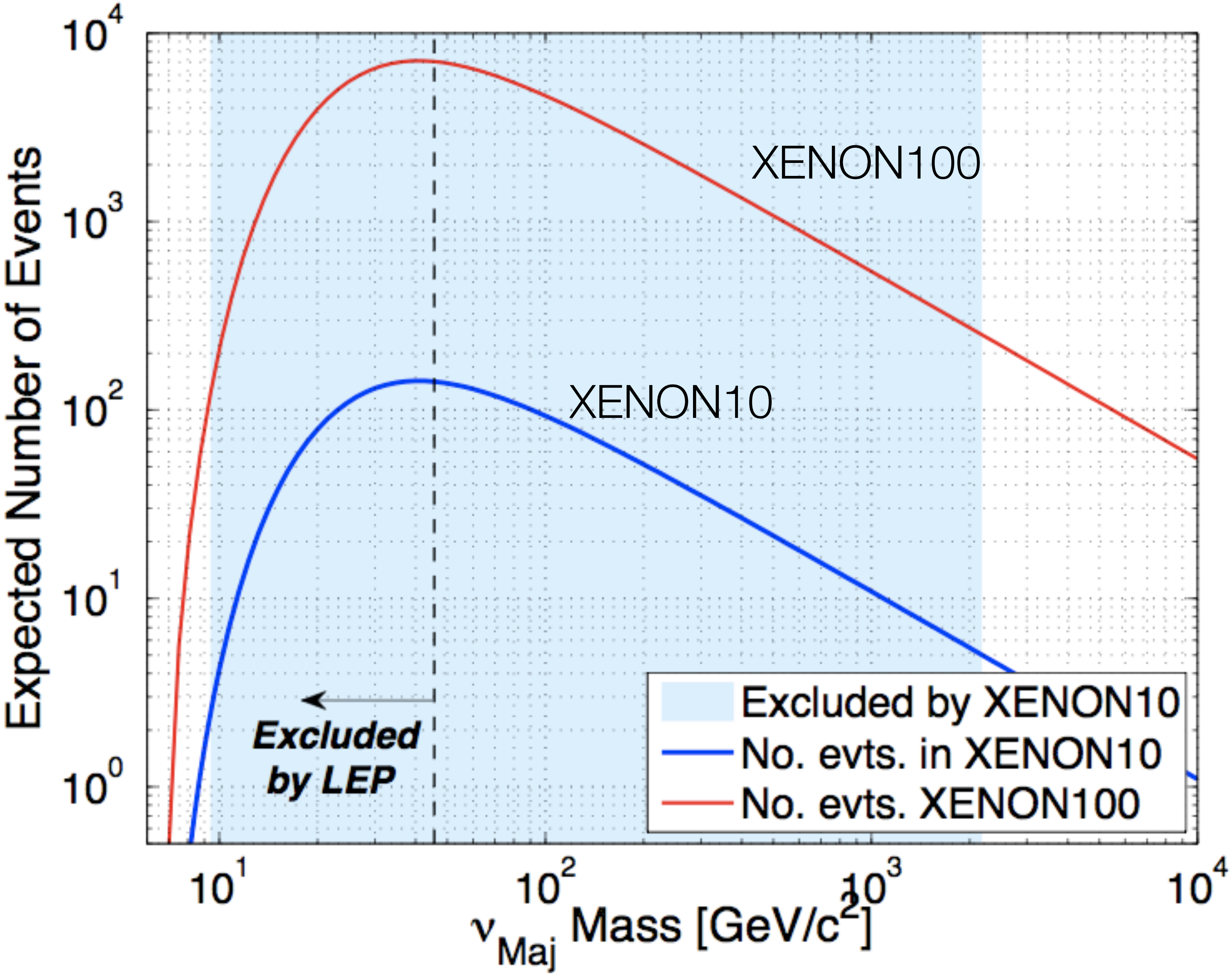
Spin-dependent (pure n-couplings)



XENON10 SD limit: PRL101 091301 (2008)

Laura Baudis, University of Zurich,CHIPP Plenary Meeting, September 9, 2008

Expected sensitivity for heavy Majorana Neutrinos



XENON100:
expected number of events
in **50 kg x 300 days**

XENON10:
expected number of events
in **5.4 kg x 58.6 days**
⇒$M_{\nu M}$ < 9.4 GeV and > 2.2 TeV

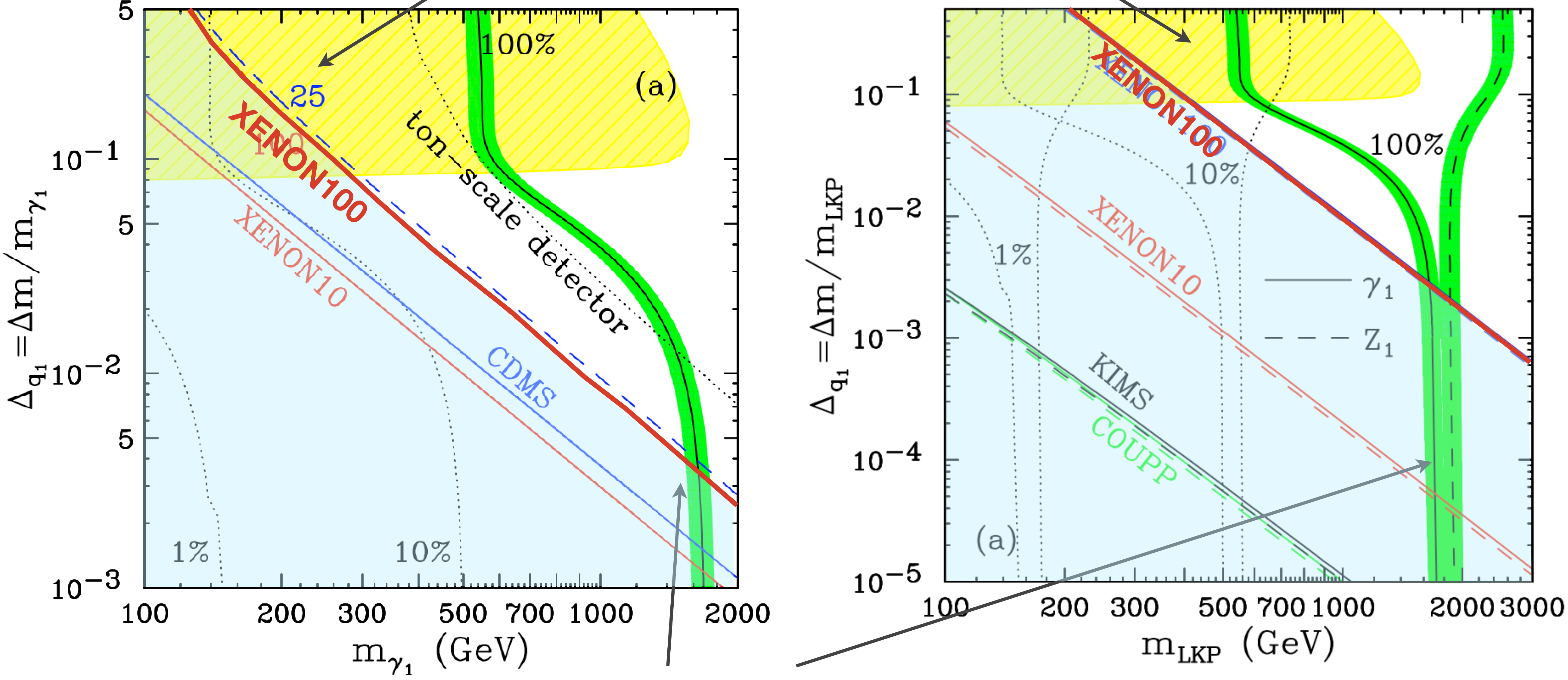
arXiv: 0805.2939
PRL101 091301 (2008)

Expected Sensitivity for WIMPs and UED Predictions

Spin-independent

Spin-dependent

LHC reach in 4l+E$_T$ channel



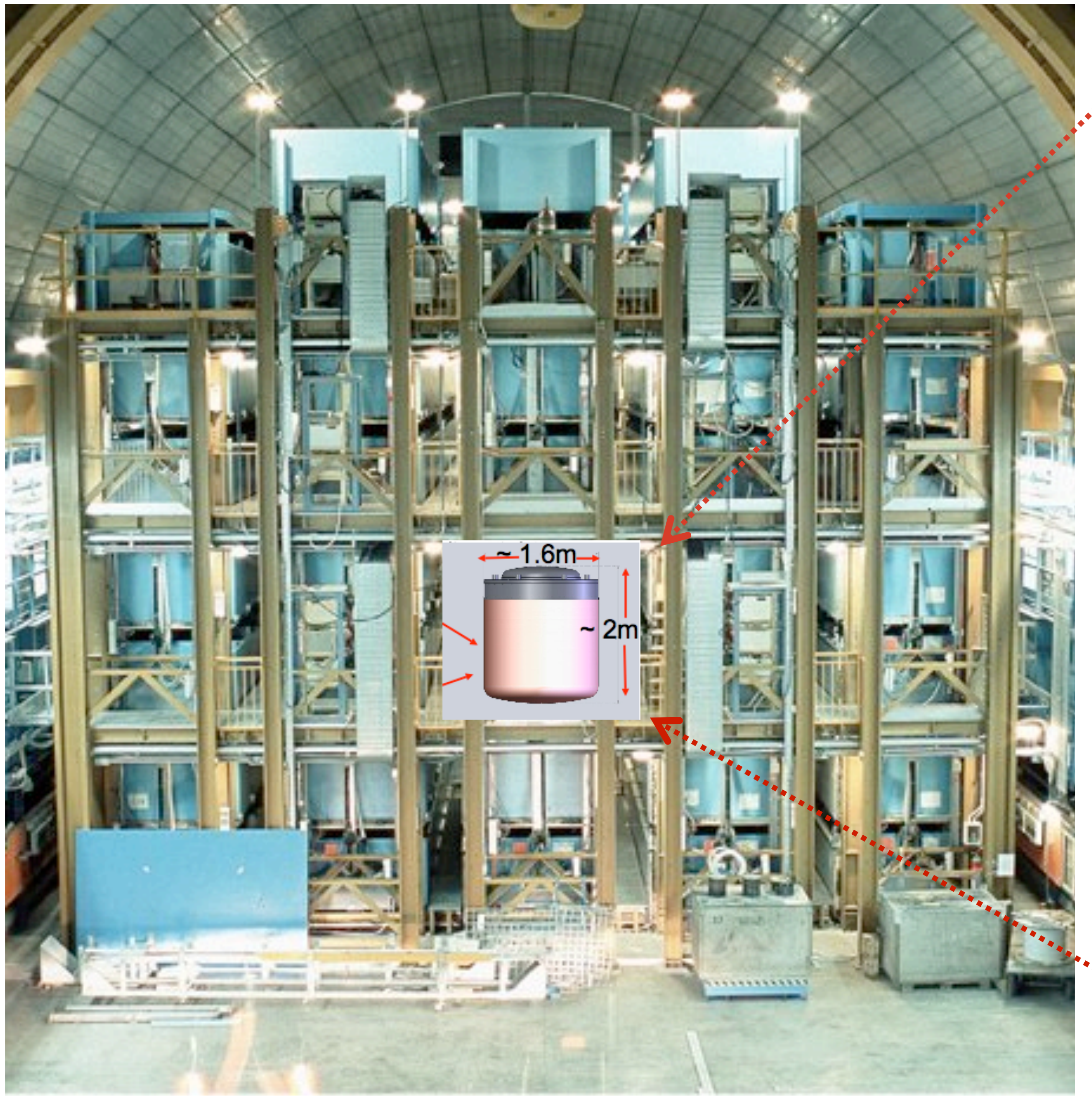
WMAP5 region

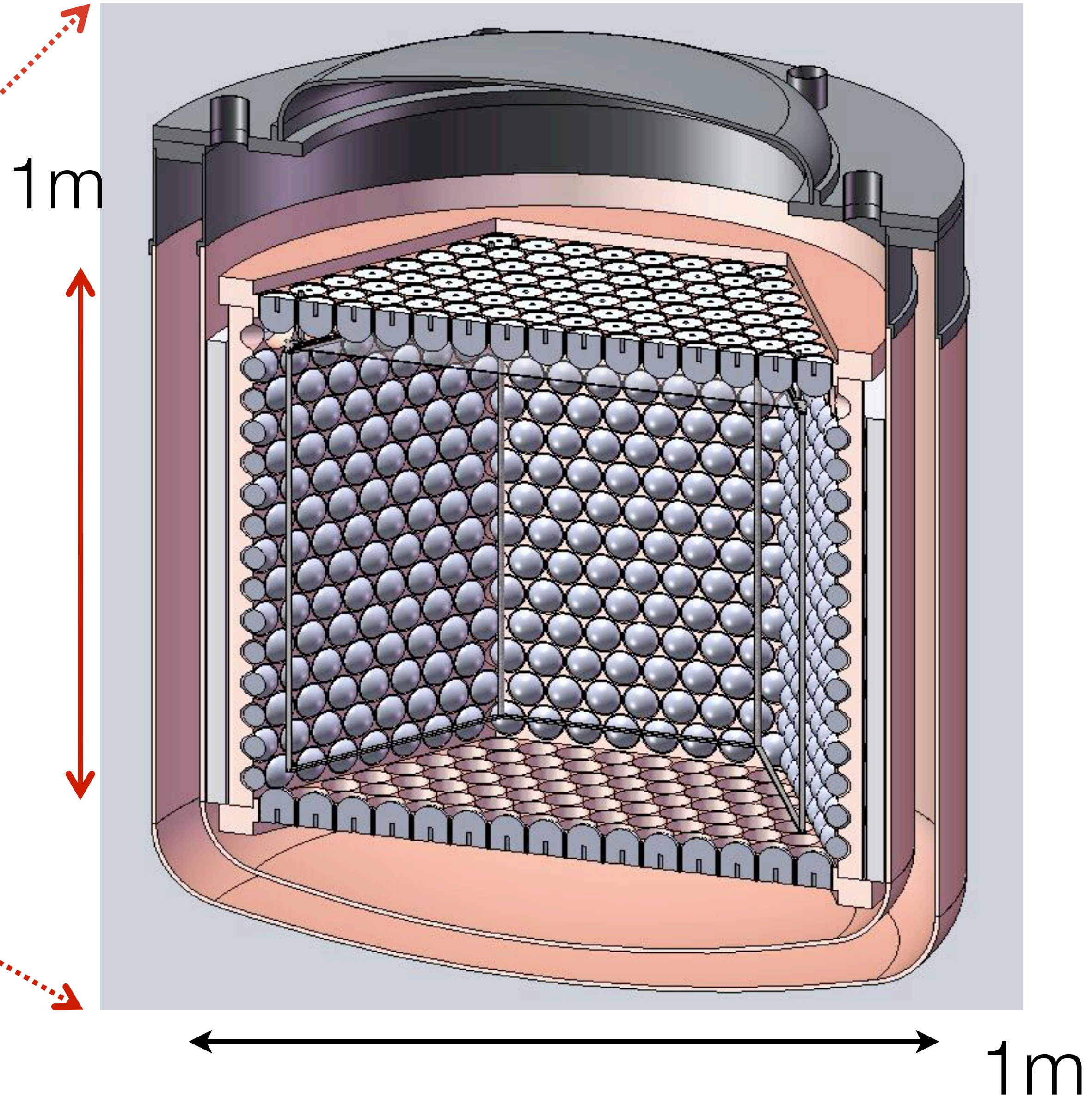
(WIMPs make 100% of the dark matter)

S. Arrenberg, L. Baudis, K.C. Kong,
K. Matchev, J. Yoo,
PRD2008 (arXiv:0805.4210)

Next Step: XENON1t

- Studies in progress for 3 ton (1 ton fiducial) LXe detector
- Possible location: inside LVD SN neutrino detector at LNGS -> active veto for μ-induced neutrons
- Gamma flux inside LVD structure: 10-20 times lower than in main halls (detailed mapping of gamma and neutron background in progress)





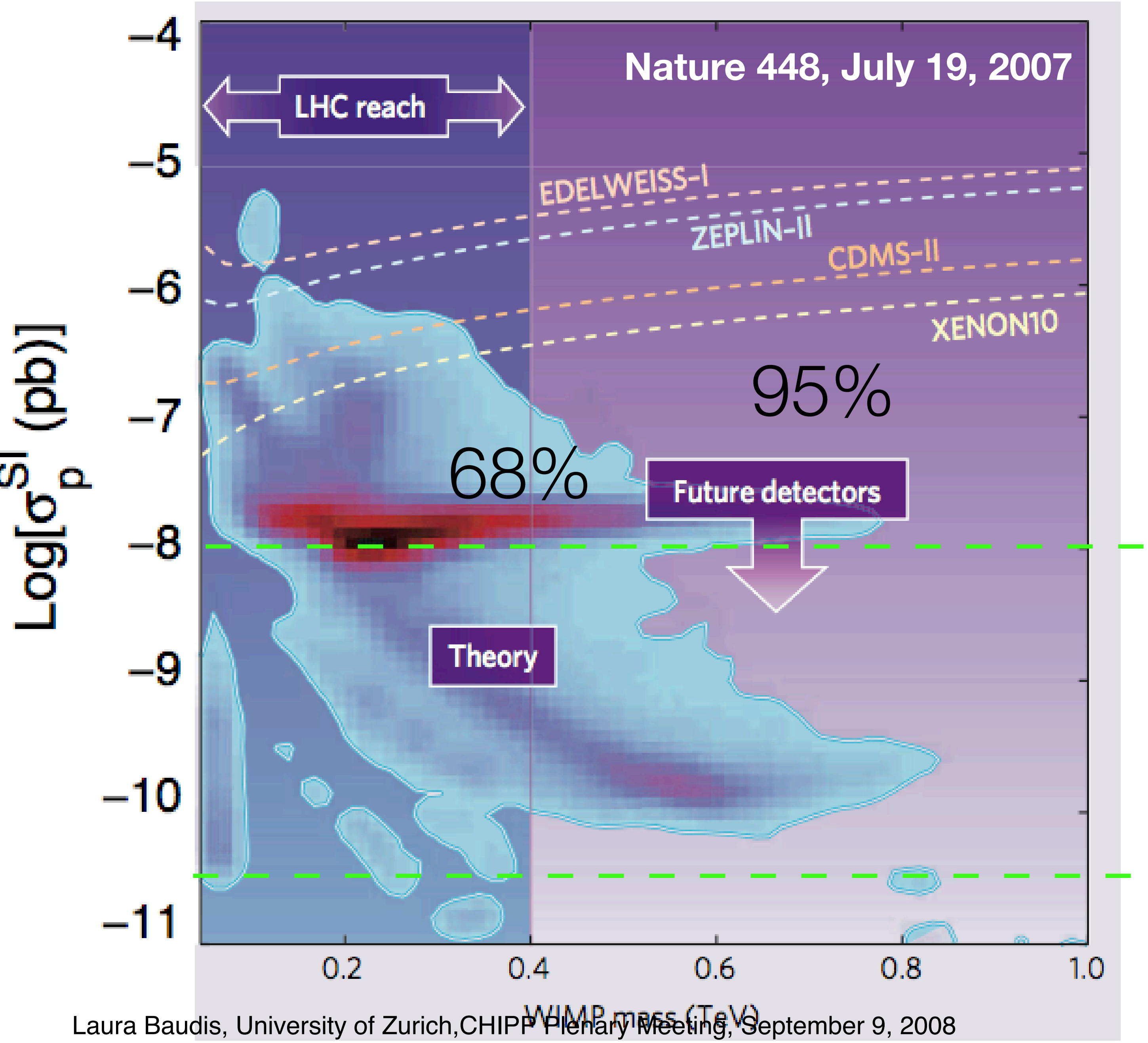
Summary

Many different techniques/targets are being employed to search for dark matter particles

Experiments are probing the theoretically interesting regions

In CH: complementarity between the LAr and LXe WIMP targets!

Next generation projects: should reach the ≲ 10^{-10} pb level => WIMP (astro)-physics



Theory example: CMSSM (Roszkowski, Ruiz, Trotta)
see also: Balz, Baer, Bednyakov, Bottino, Cirelli, Chattopadhyay, Ellis, Fornengo, Giudice, Gondolo, Massiero, Olive, Profumo, Santoso, Spanos, Strumia, Tata,...+ many others

1 event/kg/yr

CDMS-II, XENON100, ArDM, COUPP, CRESST-II, EDELWEISS-II, ZEPLIN-III,...

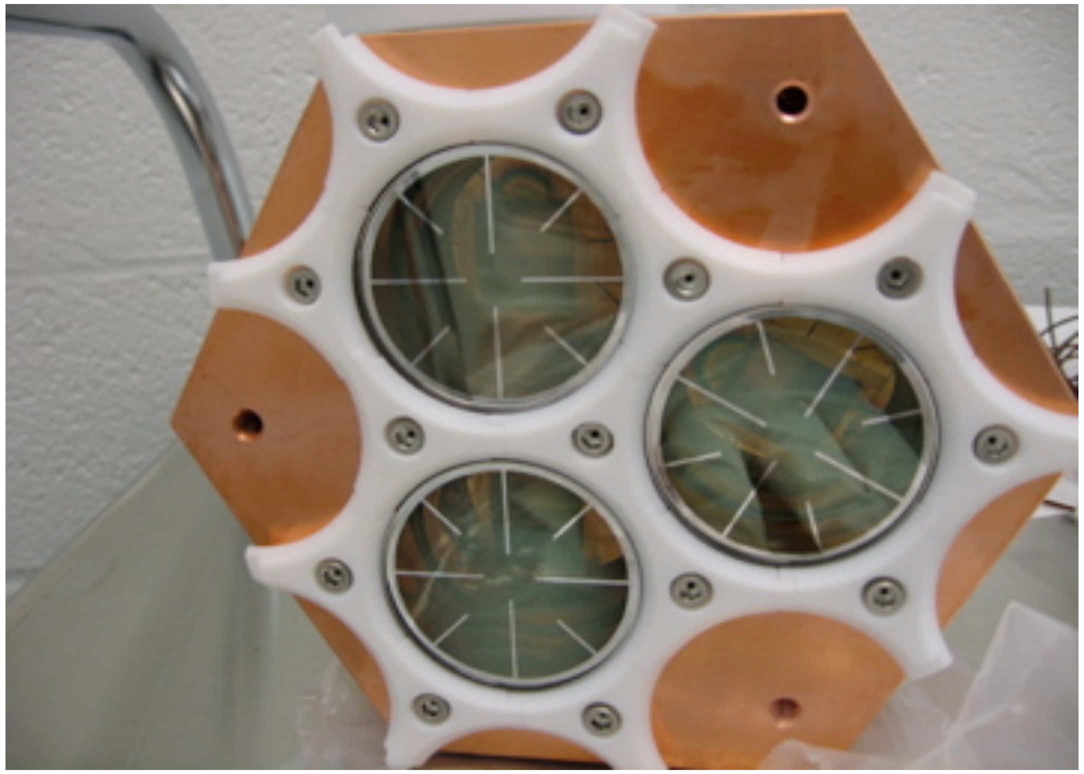
1 event/t/yr

SuperCDMS1t, WARP1t, ArDM XENON1t, EURECA, XMASS, ...

End

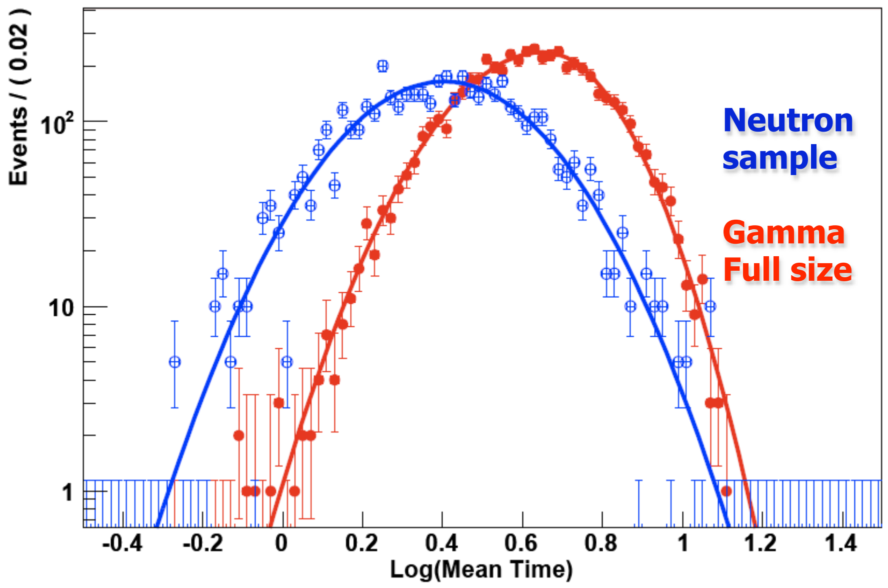
The LUX Experiment

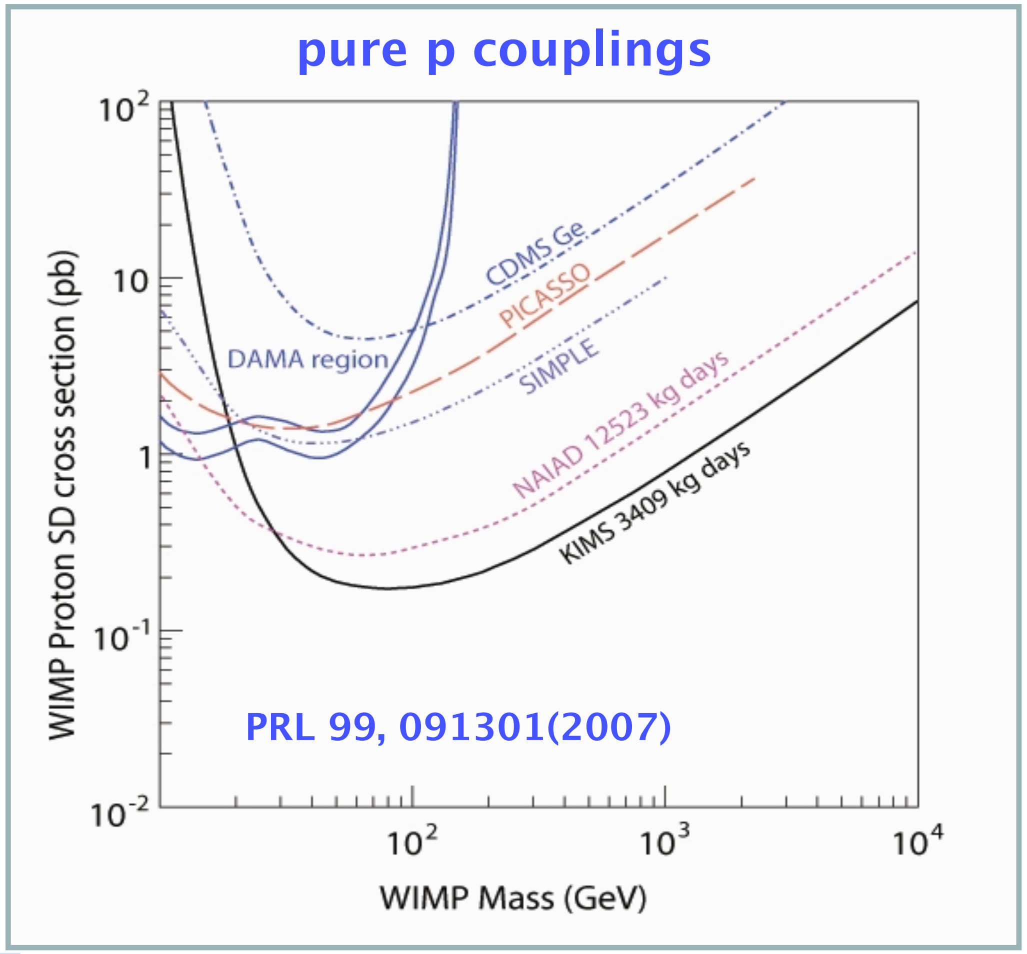
- 300 kg dual phase LXe TPC (100 kg fiducial), with 122 PMTs in large water shield with muon veto
- 50 kg LXe prototype with 4 R8778 PMTs being assembled and tested at CWRU
- full detector to be installed at Homestake Davis Cavern, 4850 ft in 2008-2009 (in 8 m ∅ water tank)
- WIMP sensitivity goal: 7 × 10^{-10} pb after 10 months



The KIMS Experiment

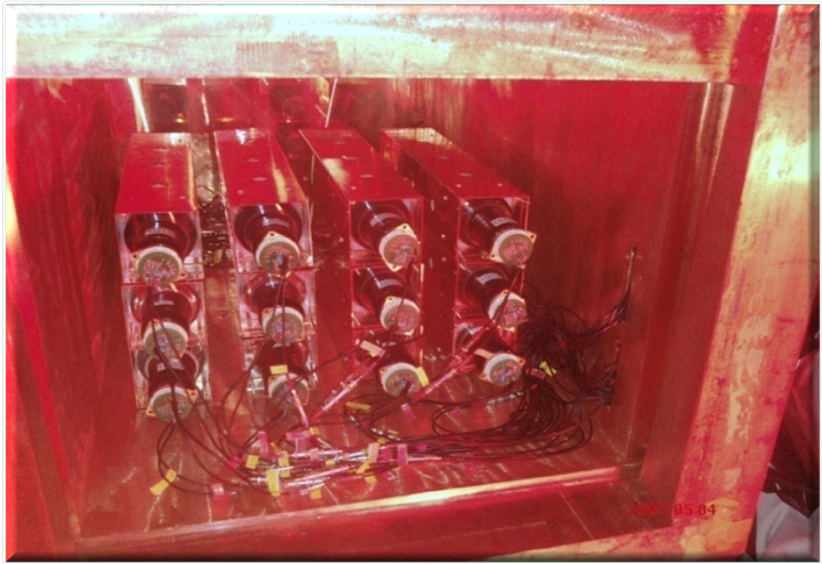
- At the Yangyang Lab in Korea (2000 mwe)
- 4 x 8.7 kg CsI(Tl) crystals for 3407 kg yr
- background reduction by PSD
- best SD limit for pure-p





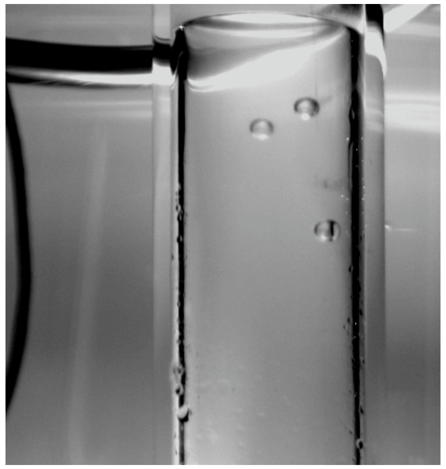
Current status:
12 detectors (104.4 kg) installed
- muon veto (liquid scintillator+56 PMTs)
- optimization runs finished (BG ~ 1 dru)

stable operation in progress
-> probe the DAMA modulation signal
-> study annual modulation of ‘muon tail ‘ events



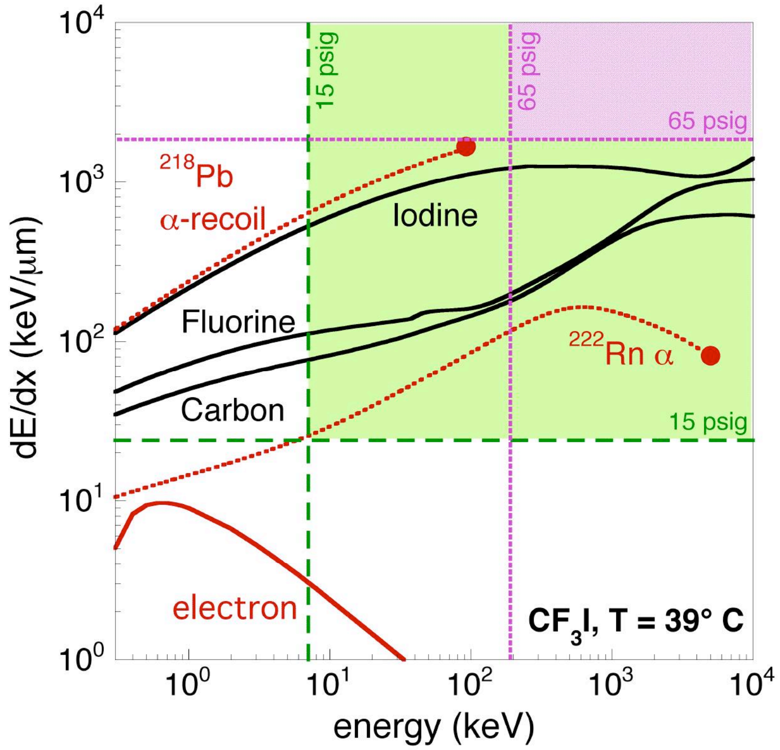
Bubble Chambers as WIMP Detectors

- **COUPP**: superheated liquid -> detects single bubbles induced by high dE/dx nuclear recoils; **advantage:** large masses, low costs, SD, SI (I, Br, F, C), high spatial granularity, ‘rejection’ of ERs 10^{10} at $10keV_r$; **challenge:** reduce alpha background



n-induced event (multiple scatter)

WIMP: single scatter

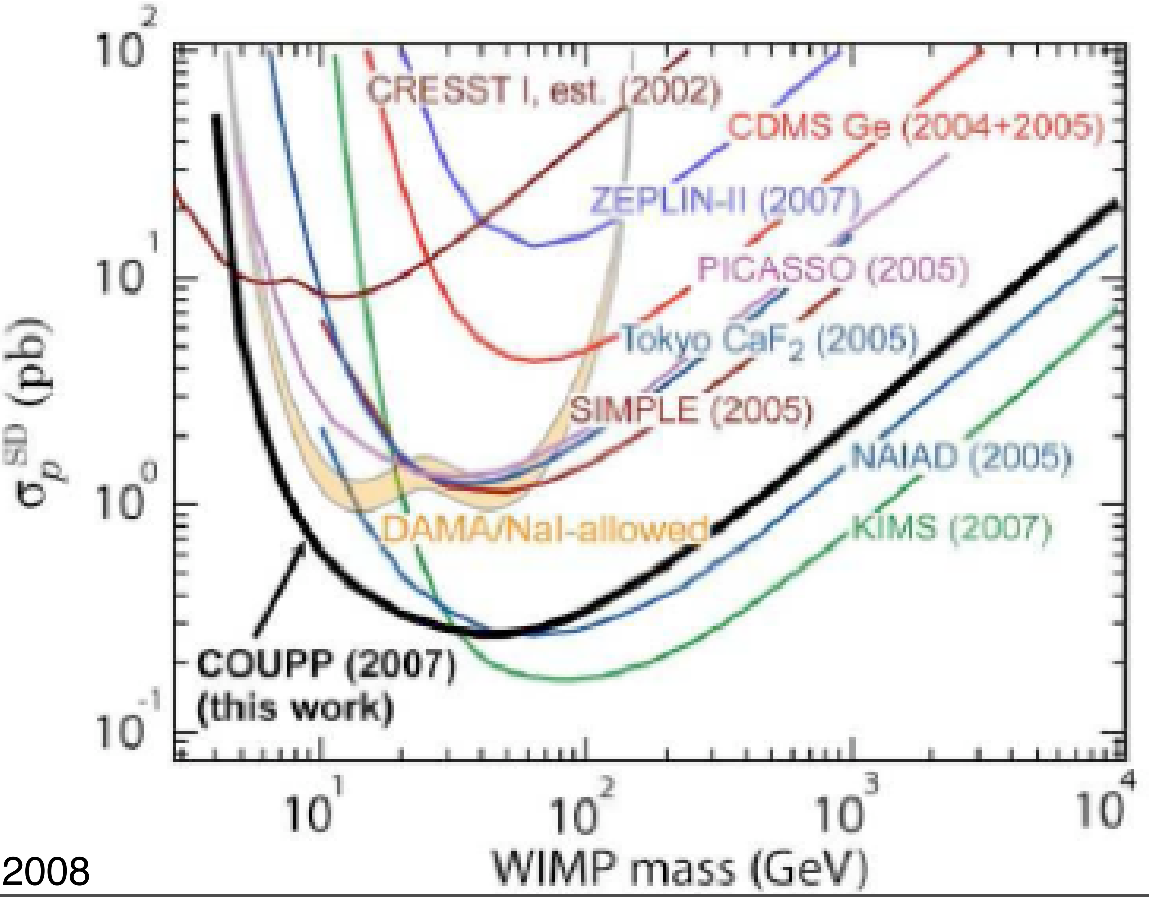


2 kg detector at 300 mwe in 2006: α BG from walls ^{222}Rn decays -> ^{210}Pb plate-out + ^{222}Rn emanation

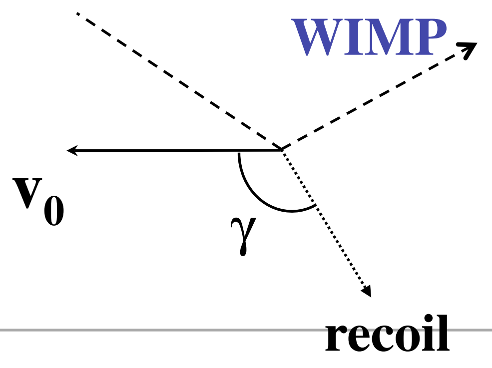
run with 2 kg in 2007 (reduced backgrounds)

80 kg module approved by FNAL -> 3 x 10^{-8}pb

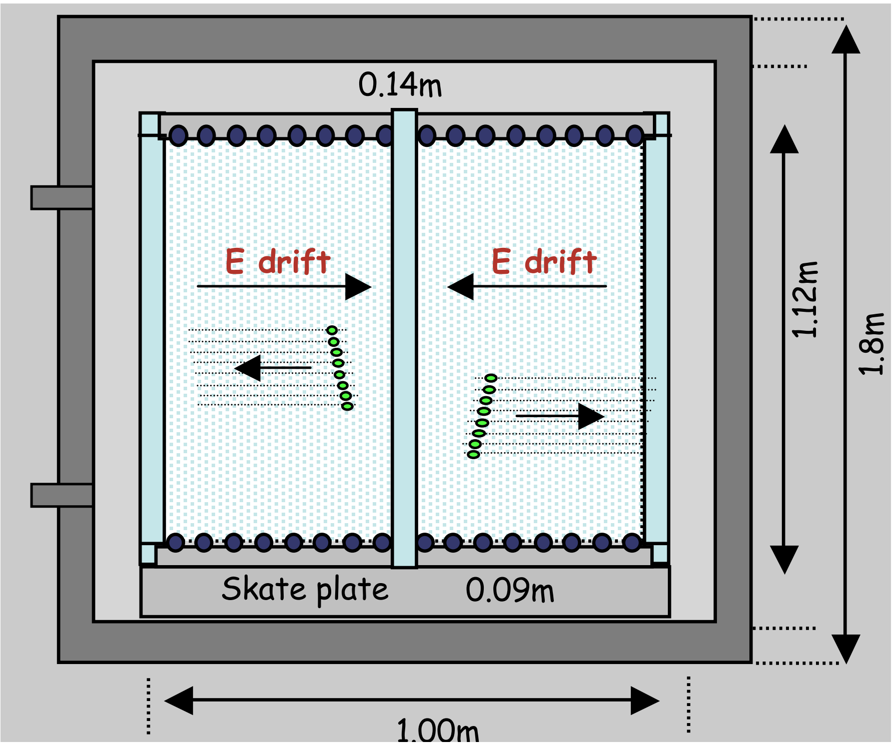
Behnke, Collar et al. Science 319, 15 February 2008, p. 933-936

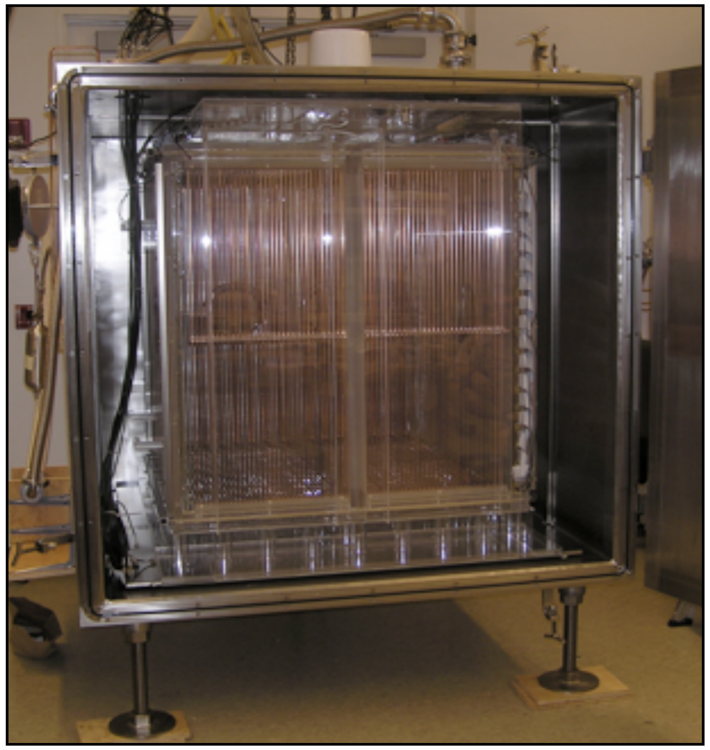


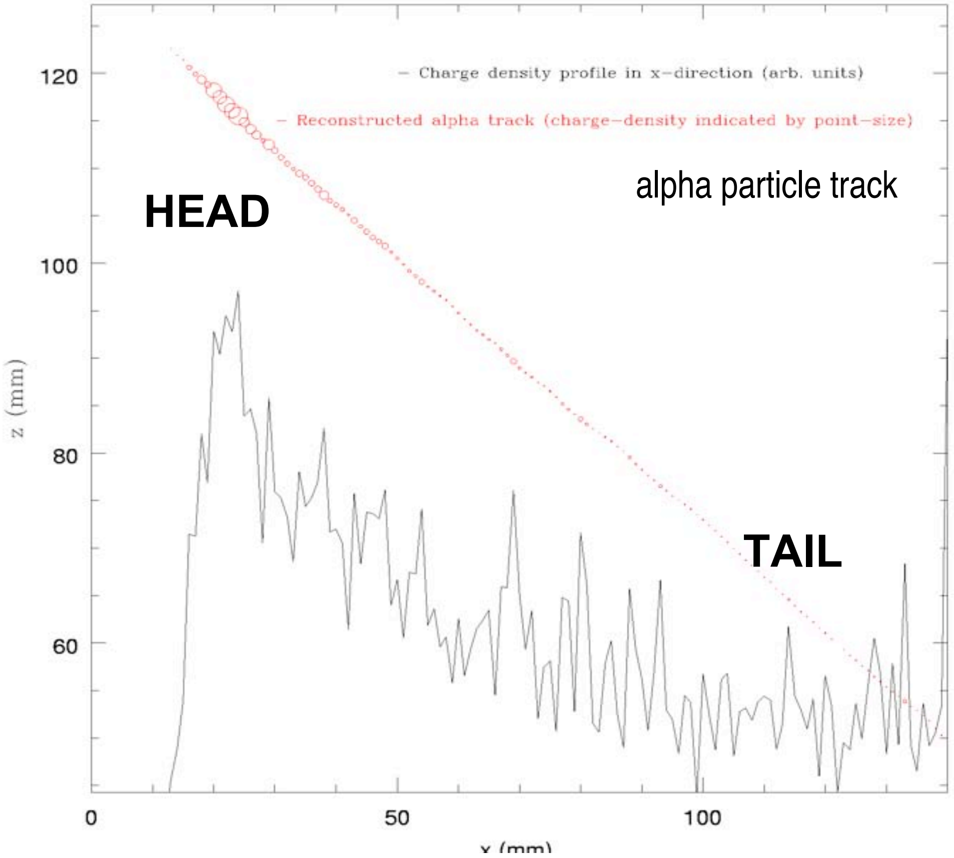
Directional Detector: DRIFT



- **Negative ion (CS_2) TPC**: 1 m^3 40 Torr CS_2 gas (0.17 kg); 2 mm pitch anode + crossed MWPC grid->2D
- NR discrimination via track morphology in gas (gamma misidentification probability < 5 x 10^{-6})
- **3D track reconstruction** for recoil direction: find head-tail of recoil based on dE/dx
- DRIFT IIa operated at Boulby in 2005: background from Rn emanation of detector components (recoiling nuclei from alpha-decays on cathode wires); 6 kd-d of data being analyzed
- **DRIFT IIb: installed in 2006/07, new run with strongly reduced Rn backgrounds**
- **WIMP Telescope!**

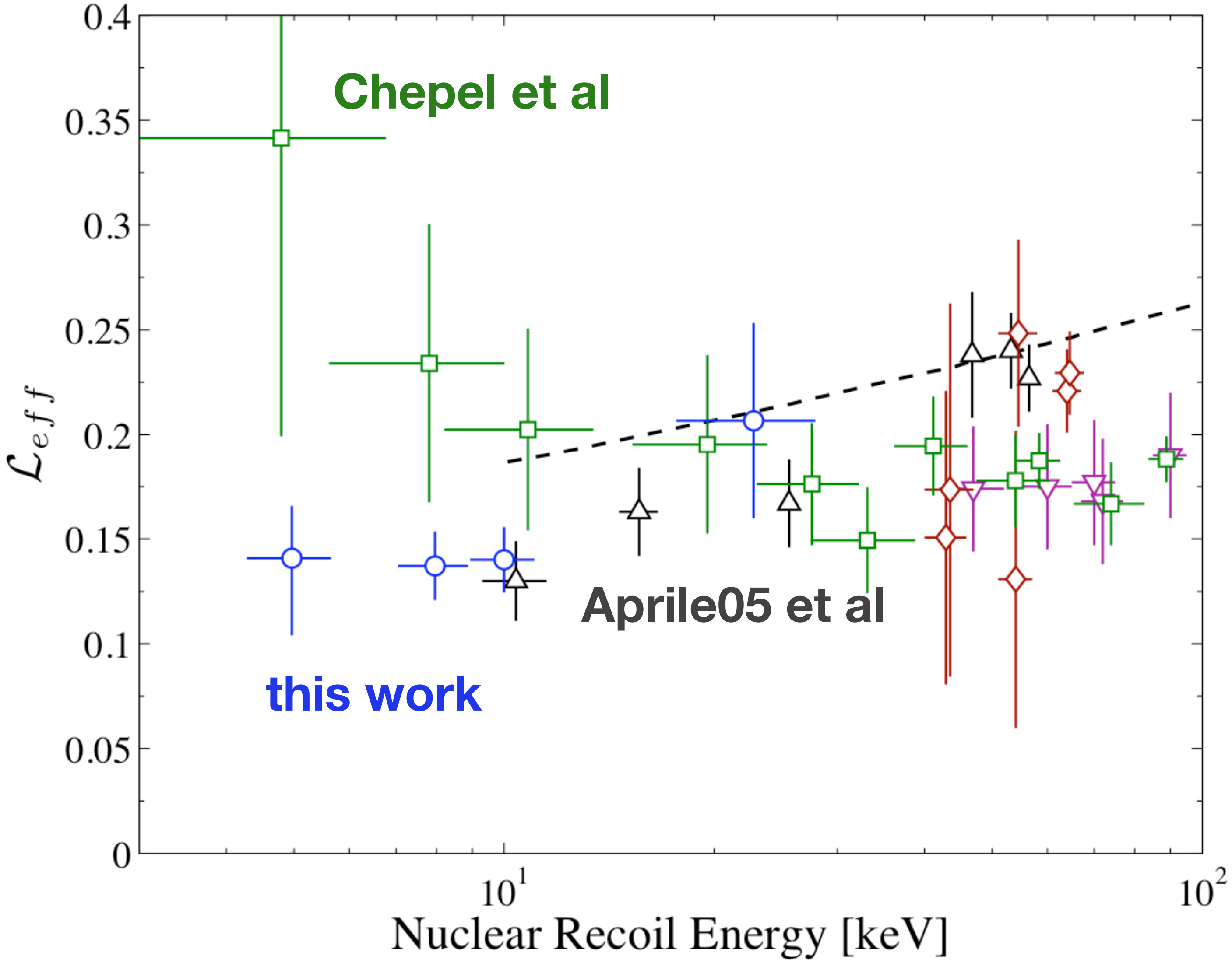


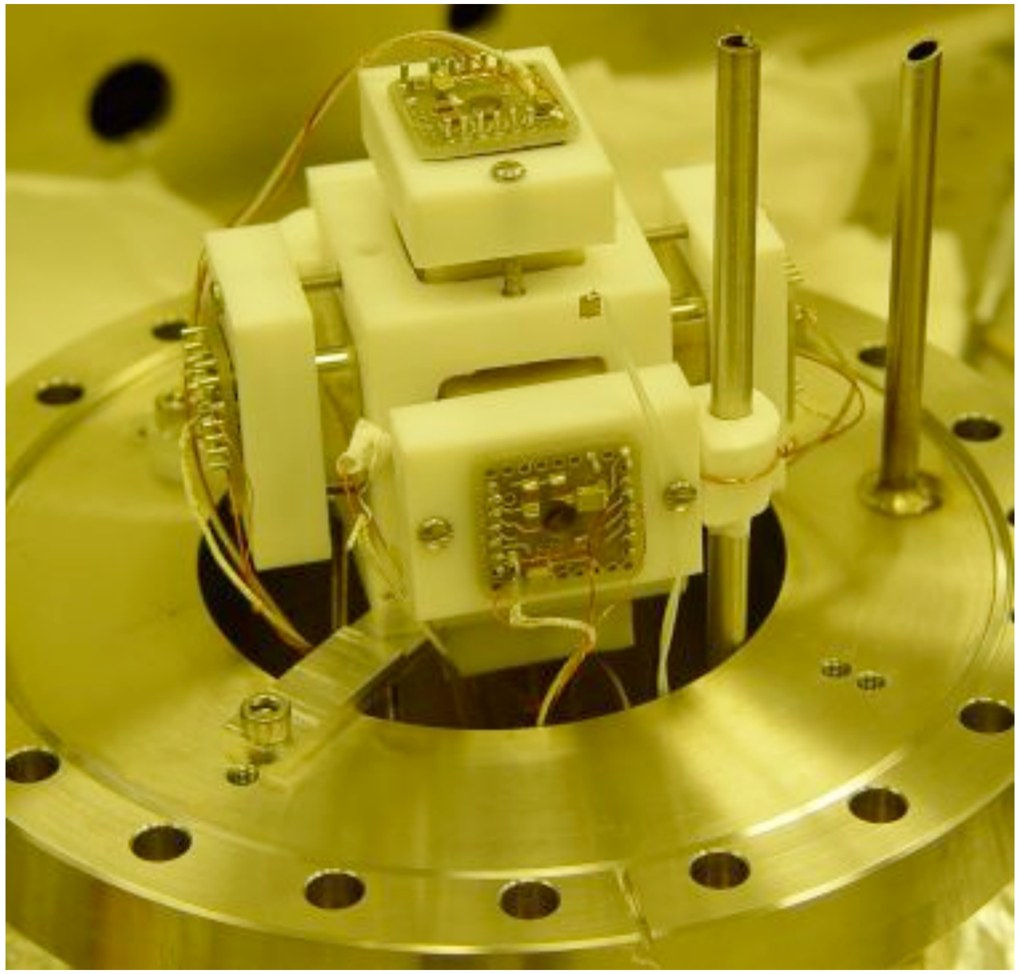




New measurements of the Light Yield in LXe

- Columbia + Zurich: at RaRAF (Nevis Labs), 1 MeV n-beam
- Detector: XeCube, 6 R8520 PMTs, 2.5 cm³ LXe, zero field
- New experiment for charge/light under preparation at UZH (using D-D neutron generator)

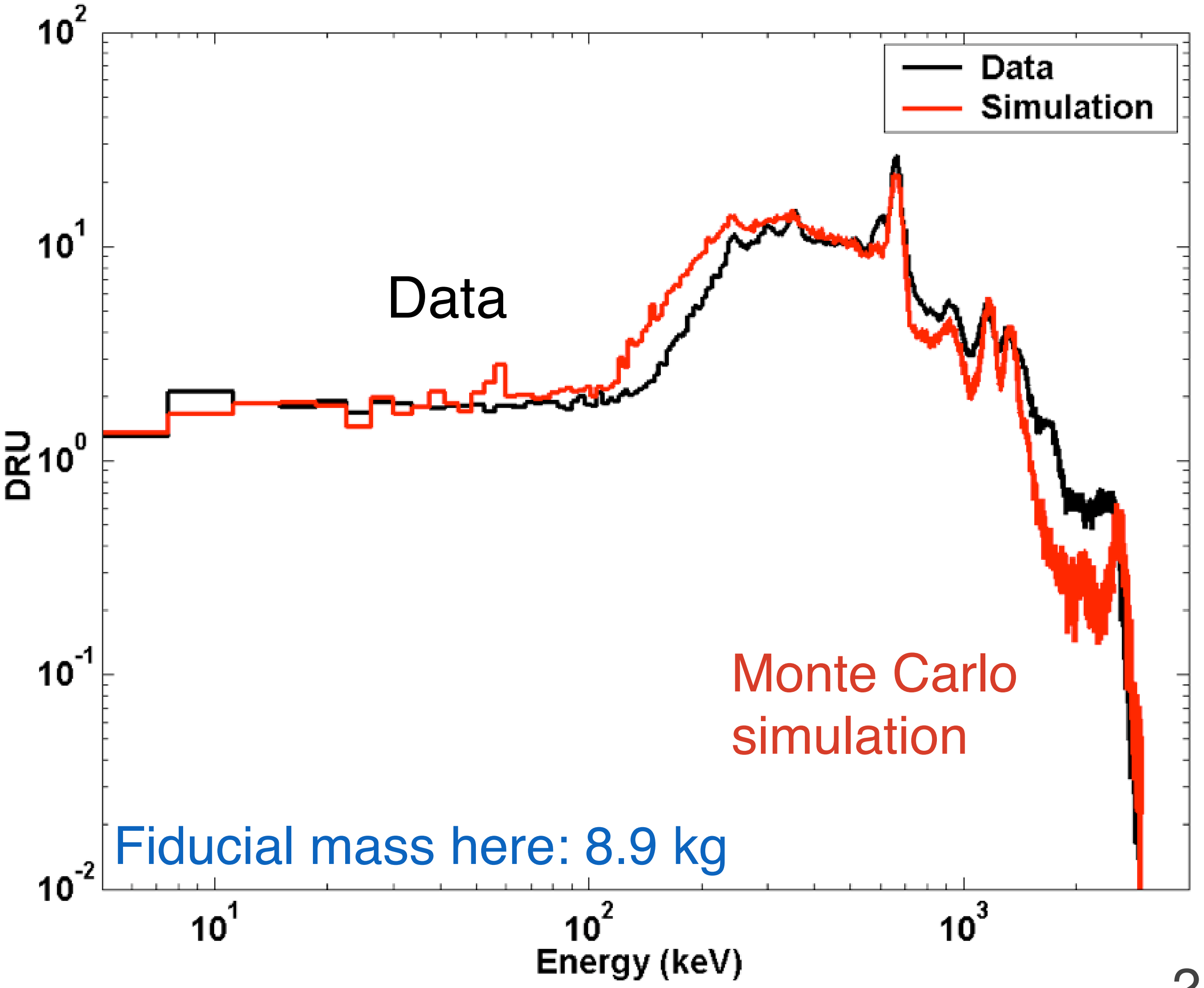




Publication to be submitted to PRD

Reminder: Backgrounds in XENON10

- Dominated by contribution from detector materials:
- steel (~ 180 kg, ^{60}Co), PMTs (89 R8520, U/Th/K/Co) and ceramic HV feed-throughs (U/Th/K)

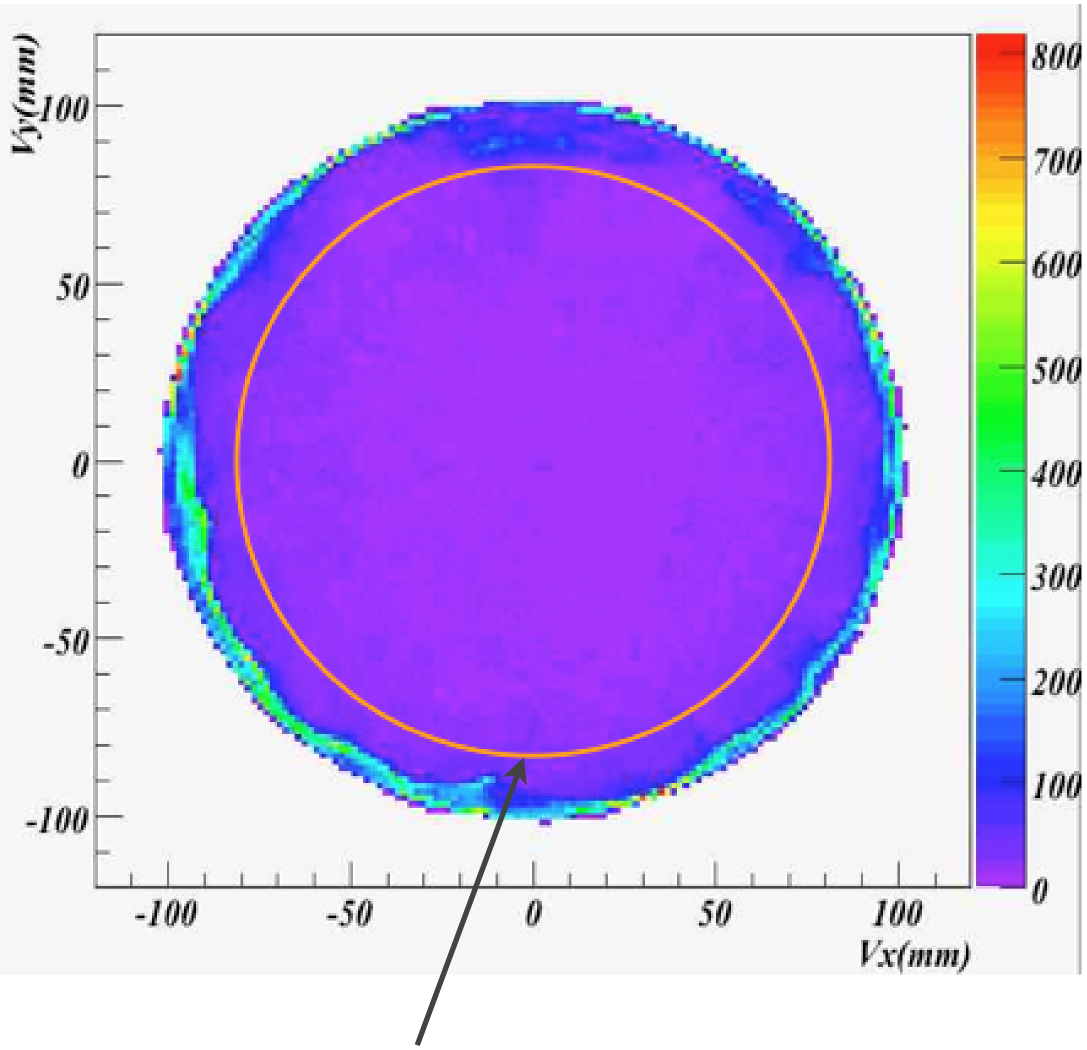


Data

Monte Carlo simulation

Fiducial mass here: 8.9 kg

dru = events/(kg day keV)

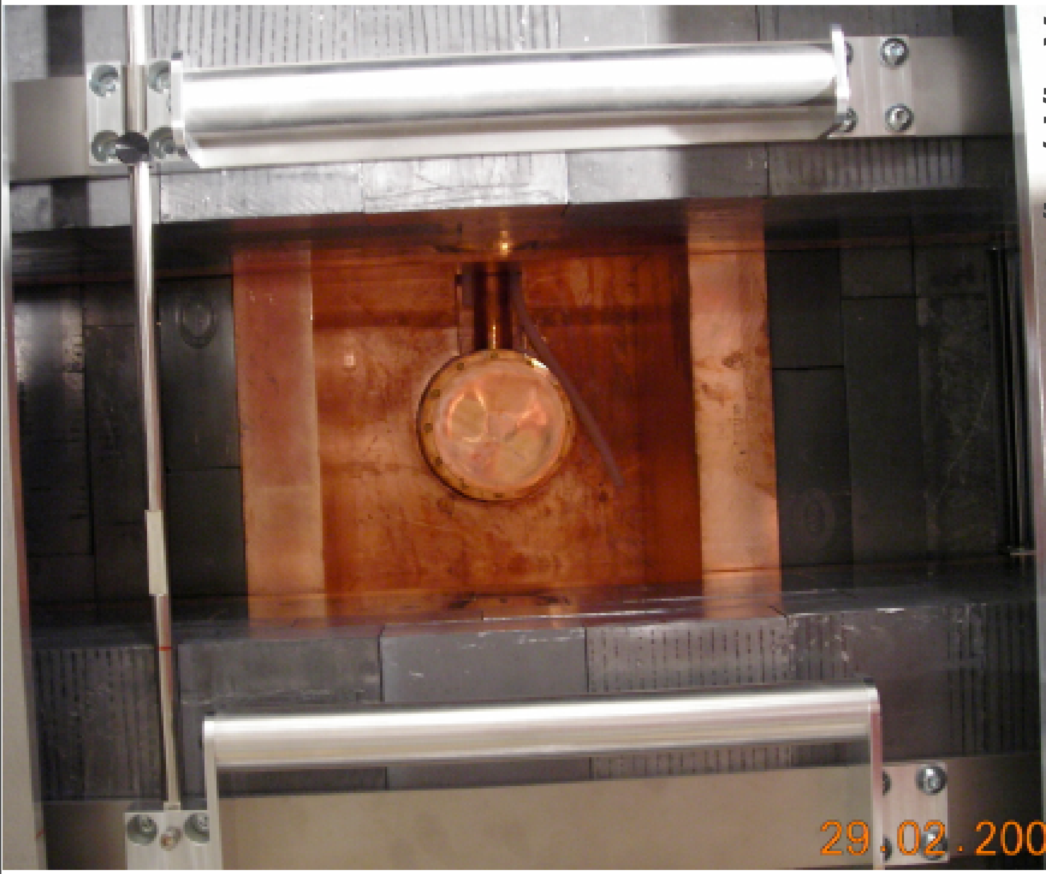


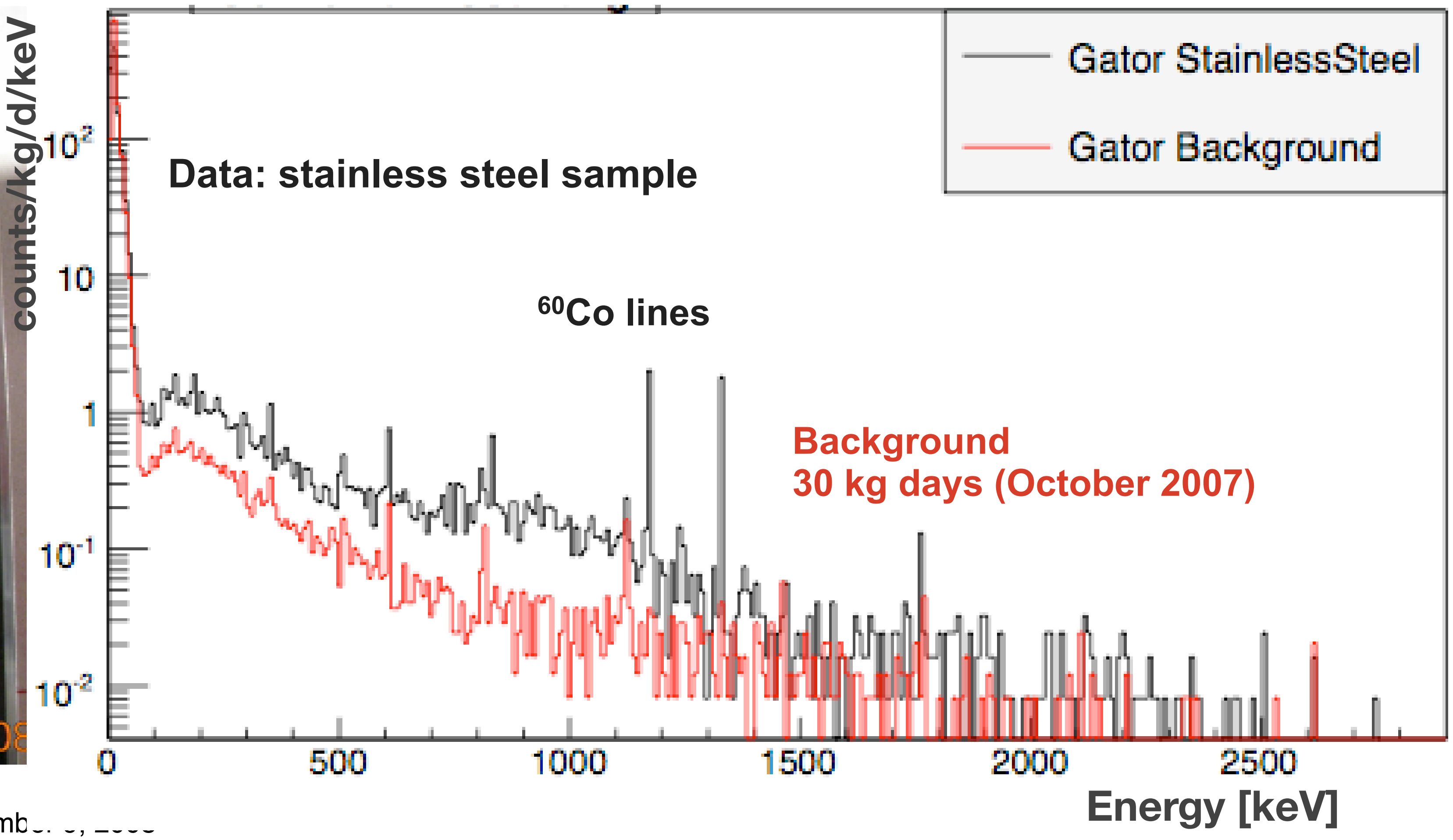
2 cm radial cut (+ z-cut) → 5.4 kg LXe mass

=> background rate of 0.6 events/(kg d keV)

XENON100 Material Screening

- Ultra-low background, 100 % efficient (2 kg) HPGe-spectrometer, operated at LNGS (plus detectors from LNGS screening facility)
- **Shield**: 5 cm of OFRP Cu (Norddeutsche Affinerie); 20 cm Pb (Plombum, inner 5 cm: 3 Bq/kg ^{210}Pb), air-lock system and nitrogen purge against Rn, slow control for online monitoring of HV, N_2 flow rate, leakage current and LN level
- **Background spectrum: < 1 event/(kg d keV) above 40 keV**
- **Screened all XENON100 detector/shield components for a complete BG model**





Data: stainless steel sample

^{60}Co lines

Background
30 kg days (October 2007)

XENON100 Material Screening

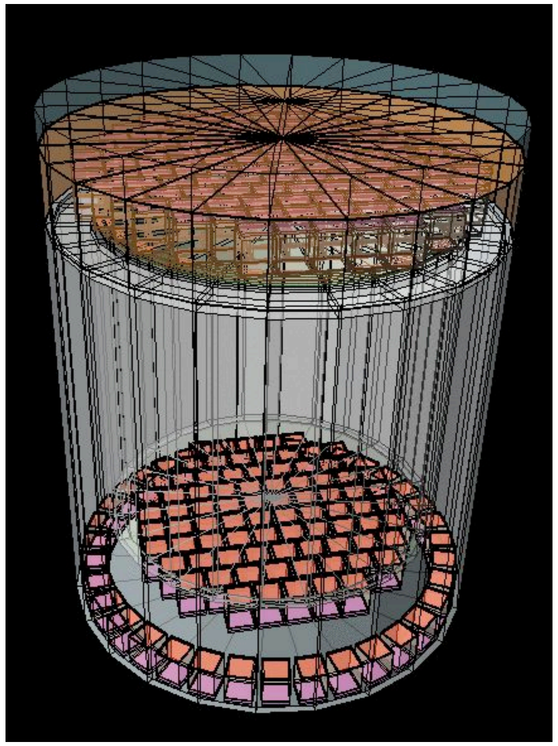
Material*	**^{238}U**	**^{232}Th**	**^{40}K**	**^{60}Co**
Stainless Steel 1.5 mm (316Ti, Nironit; cryostat)	<2 mBq/kg	<2 mBq/kg	10.5 mBq/kg	8.5 mBq/kg
Stainless Steel 25 mm (316Ti, Nironit, cryostat)	<1.3 mBq/kg	<0.9 mBq/kg	<7.1 mBq/kg	1.4 mBq/kg
PMTs (R8520-AL)	< 0.24 mBq/PMT	0.18 mBq/PMT	7.0 mBq/PMT	0.67 mBq/PMT
PMT Bases	0.16 mBq/pc	0.10 mBq/pc	<0.16 mBq/pc	<0.01 mBq/pc
Teflon (TPC)	< 0.3 mBq/kg	<0.16 mBq/kg	< 2.3 mBq/kg	--
Poly I (shield)	< 3.8 mBq/kg	< 2.7 mBq/kg	< 5.88 mBq/kg	--
Poly II (shield)	2.43 mBq/kg	< 0.67 mBq/kg	<4.66 mBq/kg	--
Polish Pb (outer shield)	< 5.7 mBq/kg	< 1.6 mBq/kg	14 mBq/kg	< 1.1 mBq/kg
French Pb (inner shield)	< 6.8 mBq/kg	< 3.9 mBq/kg	< 28 mBq/kg	< 0.19 mBq/kg

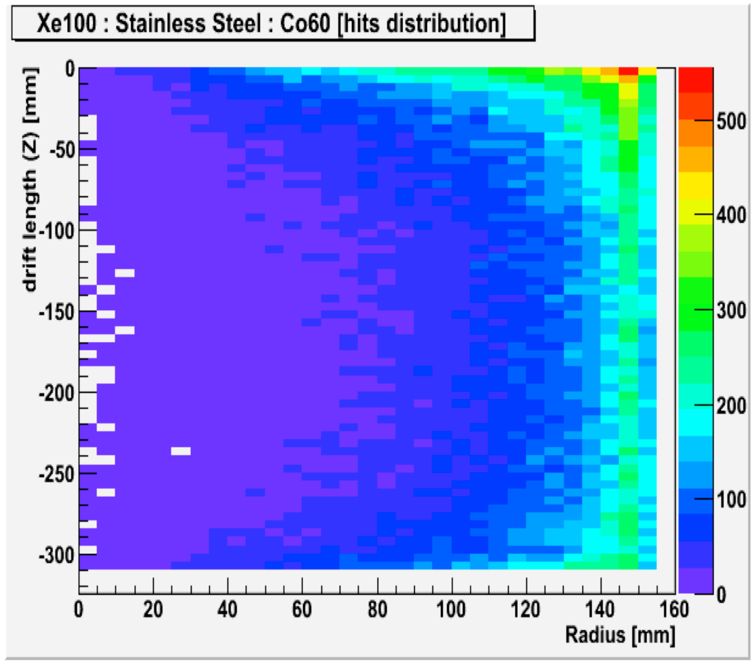
*** only a selection is shown here, all PMTs are screened and show consistent values; also screened: copper, cables, screws, ...**

**** thanks also to Matthias Laubenstein (LNGS screening facility)**

Gamma Background Predictions from MC Simulations

Material	Rate [mdru]
Stainless steel (cryostat, 65 kg)	2.01 ± 0.22
Teflon (TPC, 10.7 kg)	0.18 ± 0.02
PMTs (including bases, 242)	4.91 ± 0.60
Polyethylene (shield, 2t)	2.50 ± 0.29
Copper (shield, 2t)	0.026 ± 0.002
Total*	9.63 ± 0.70



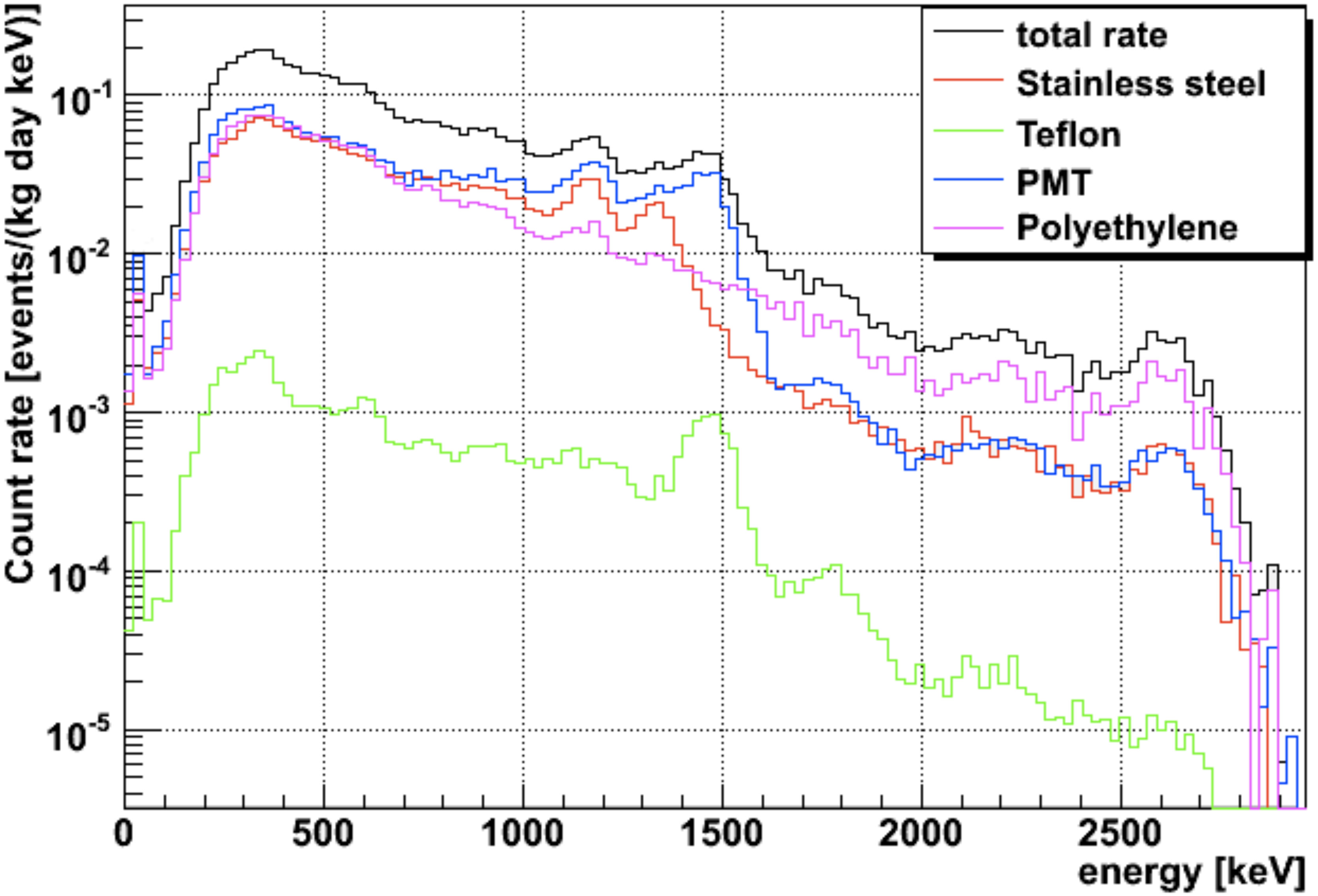


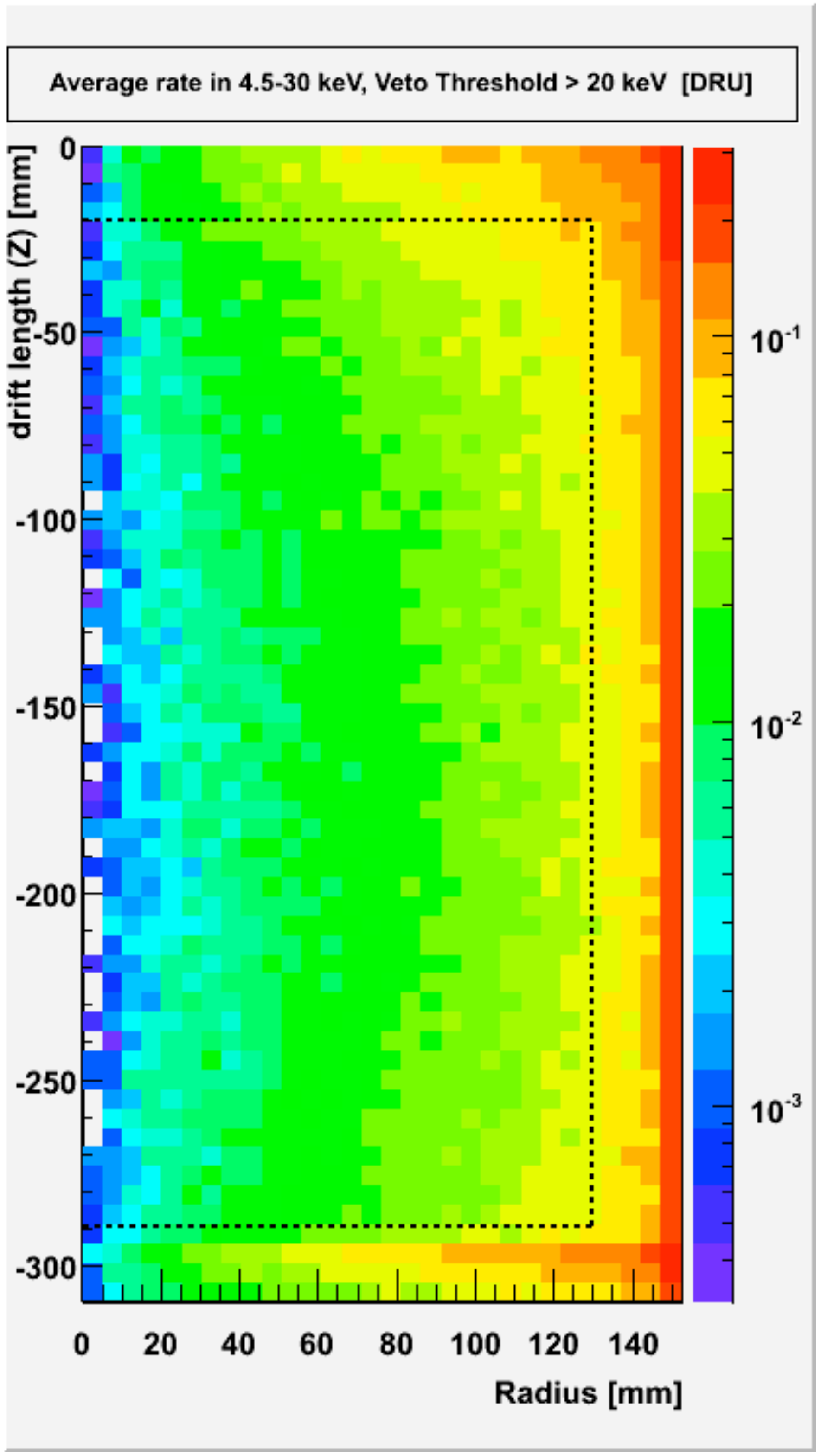
*** dominant background rate before S2/S1 discrimination in fiducial mass**

dru = events/(kg day keV)

Gamma Background Predictions from MC Simulations

Total single scatters in fiducial volume



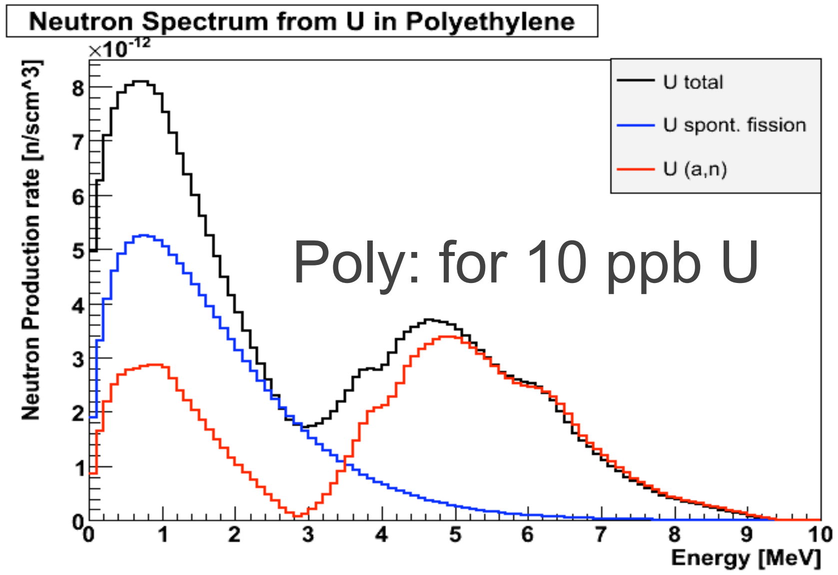


Neutron Backgrounds: MC Simulations

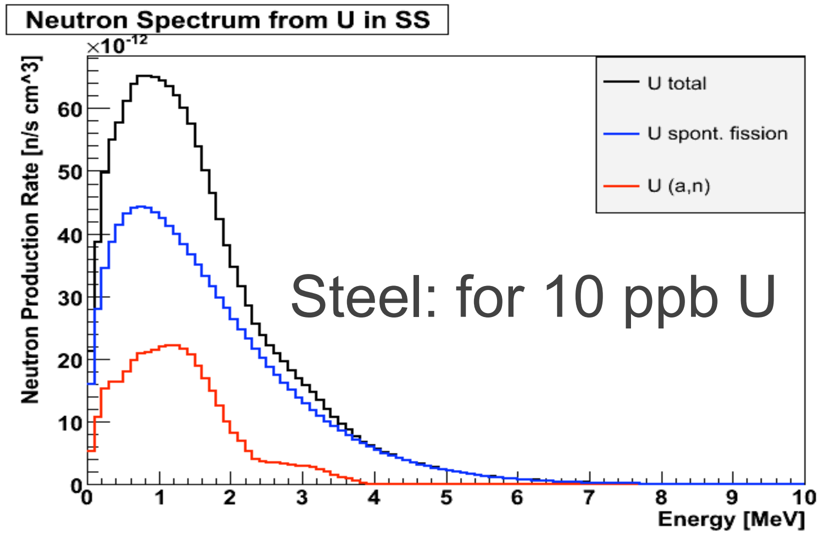
- Internal neutron BG from detector materials + shield, from (α,n) and fission reactions
- Numbers based on detailed MC, with measured U/Th activities of all materials

Material	Total n-rate [yr^{-1}]	Single NR rate [μdru]
Stainless steel	15.0	0.18
Teflon	10.1	0.58
PMTs	7.0	0.32
LXe	0.81	0.007
Copper	1.6	0.01
Poly shield	416.3	0.49
Polish Pb	5805	0.38
French Pb	1579	
Total		~ 1.6

=> ~ 0.6 single NRs/year in FV
(~ 44% of events are singles)



Poly: for 10 ppb U



Steel: for 10 ppb U

WIMP rate versus neutron background

- assumptions:
  - ➡ spin-independent WIMP-nucleon cross section: **2×10^{-45} cm^2**
  - ➡ local WIMP density: **0.3 GeV/cm^3**