Universität Zürich

Dark Matter: New Results from Direct Detection

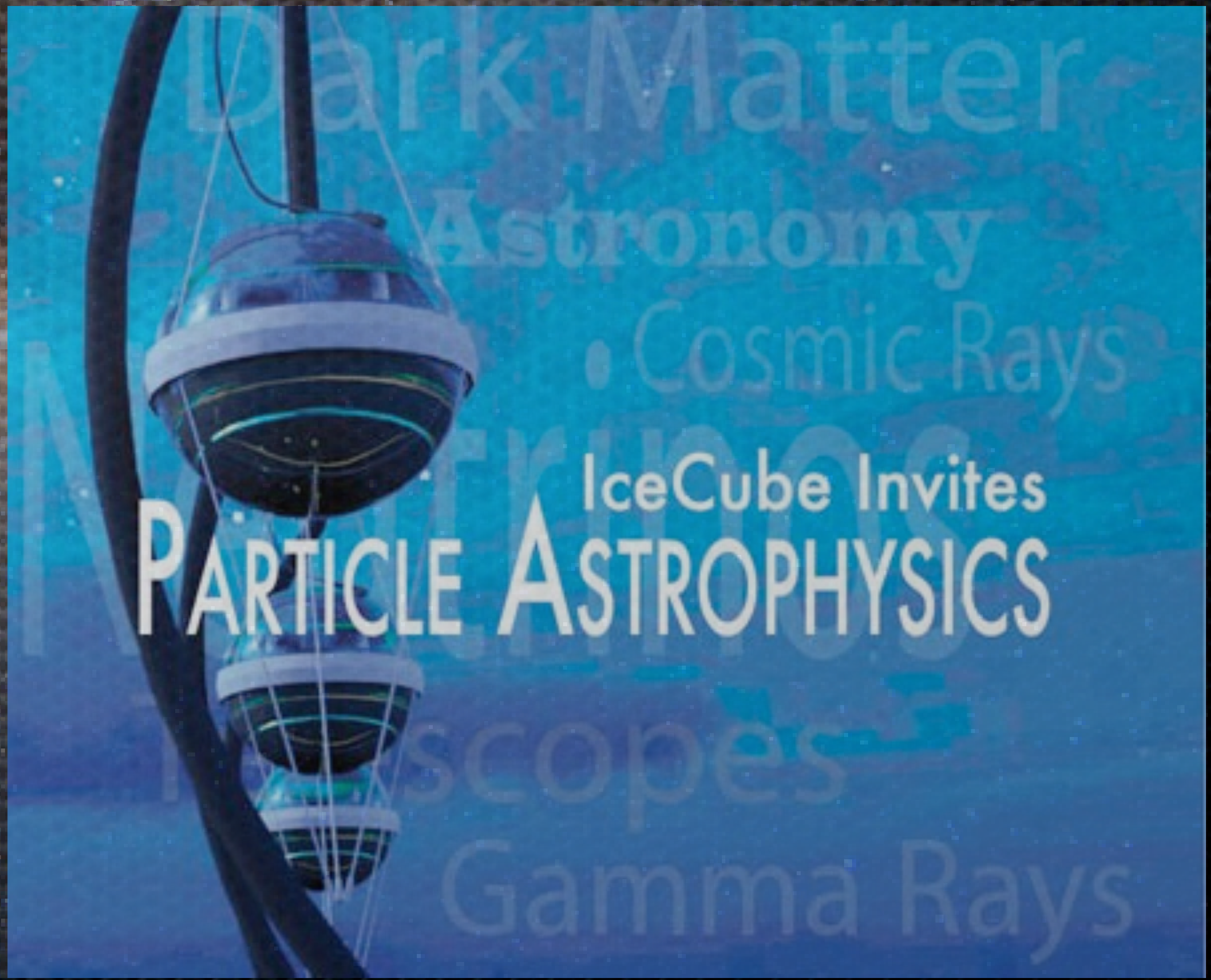
IceCube Inauguration Workshop

University of Wisconsin, Madison

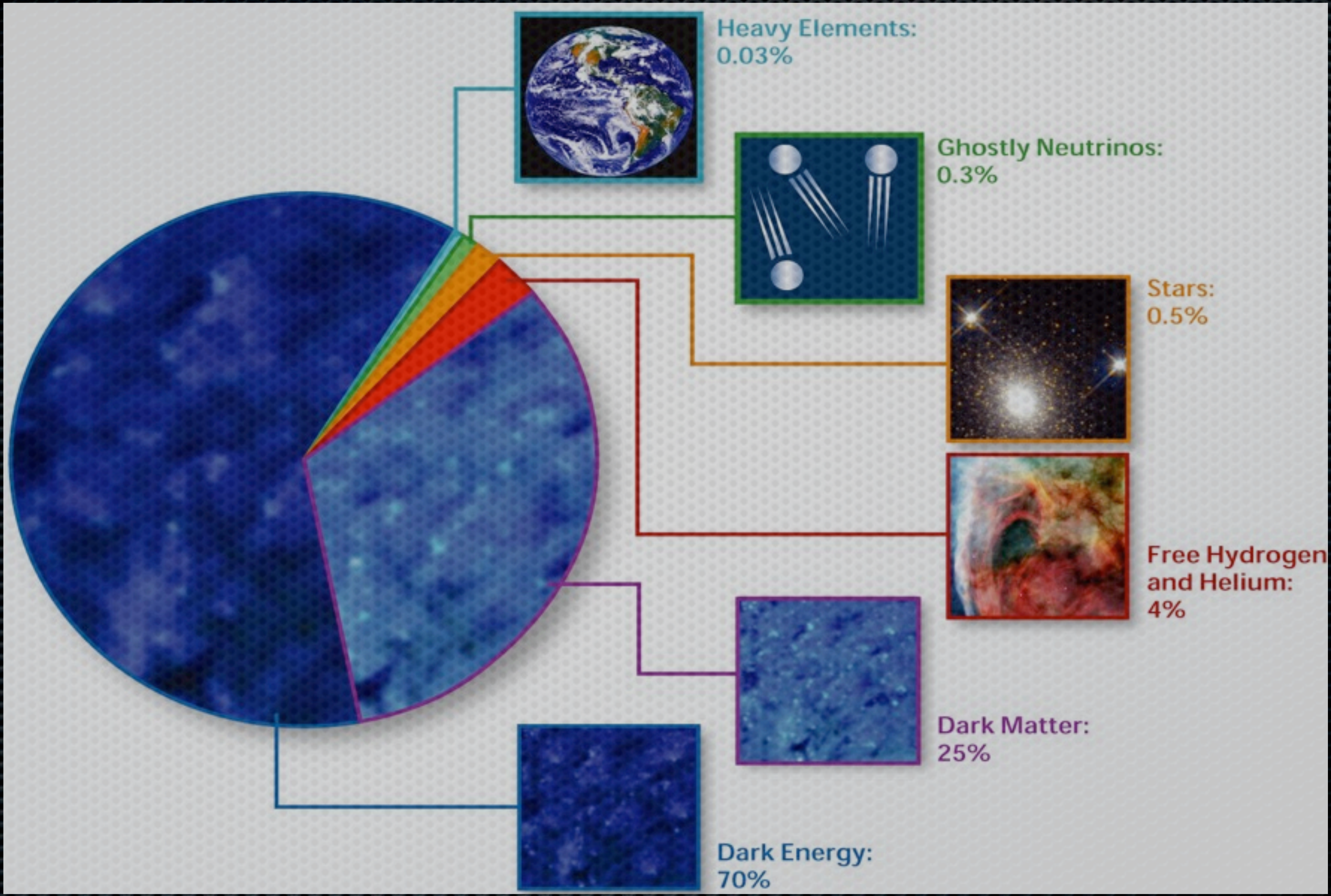
April 29, 2011

Laura Baudis

University of Zurich

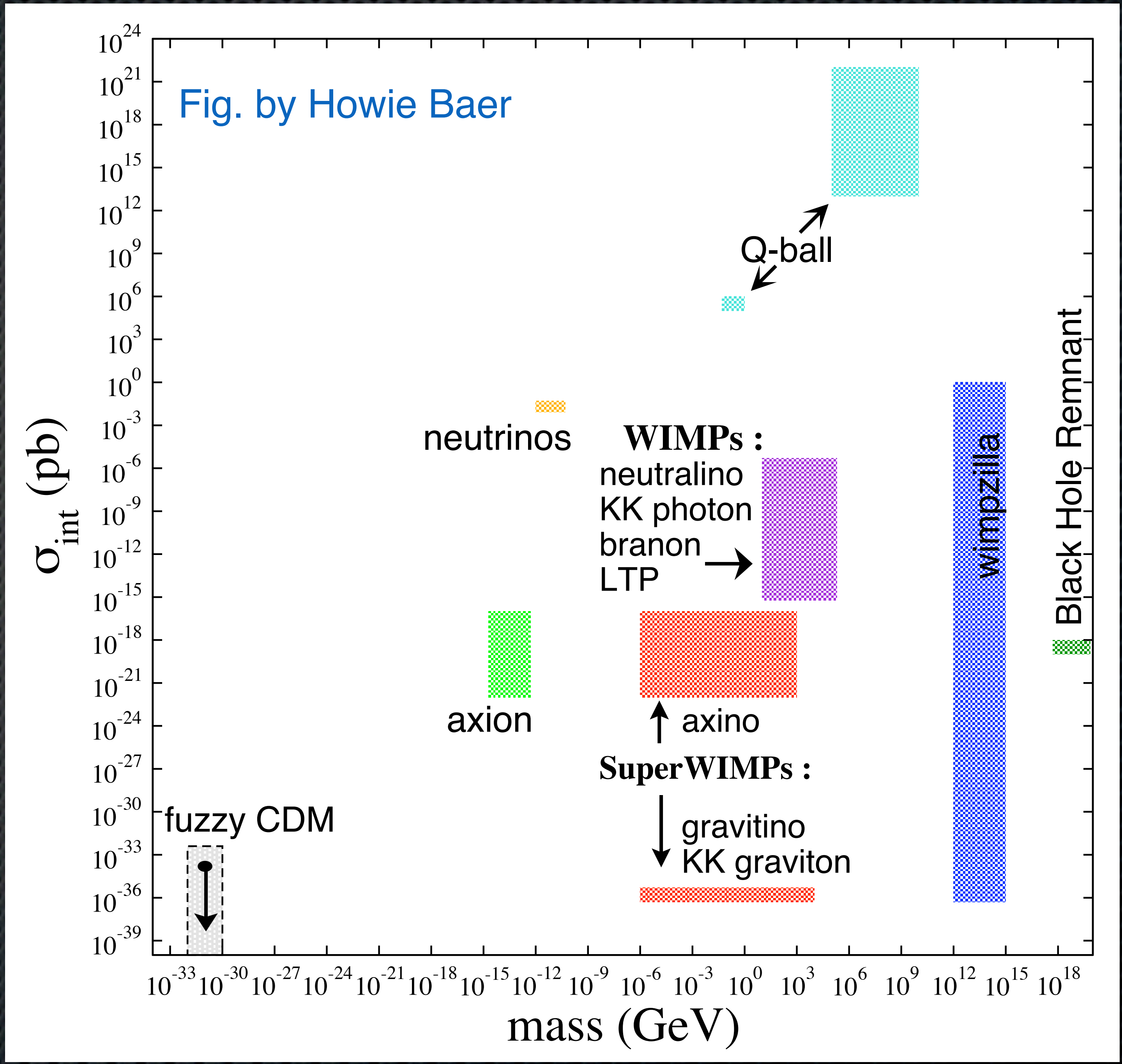


Matter and Energy Content of our Universe



Particle Dark Matter Candidates

- Masses and cross sections span many orders of magnitude
- From 10^{-6} eV to 10^{15} GeV
- From non-interacting to strongly interacting
- We know that the dark matter particle must be some state not contained in the Standard Model



Weakly Interacting Massive Particles

- One good idea: WIMPs; in thermal equilibrium in the early Universe

$$\chi + \bar{\chi} \leftrightarrow X + \bar{X}$$

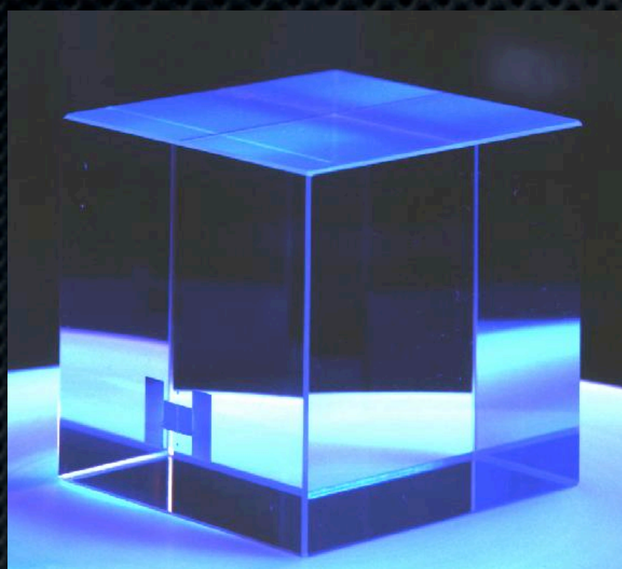
- Decouple from the rest of the particles when M << T ("cold")
- Their relic density can account for the dark matter if the annihilation cross section is weak (~ pb)

$$\Omega_\chi h^2 \simeq 3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1} \frac{1}{\langle \sigma_A v \rangle}$$

- Such particles are predicted to exist in most Beyond-Standard-Model theories (neutralino, lightest Kaluza-Klein particle, etc)

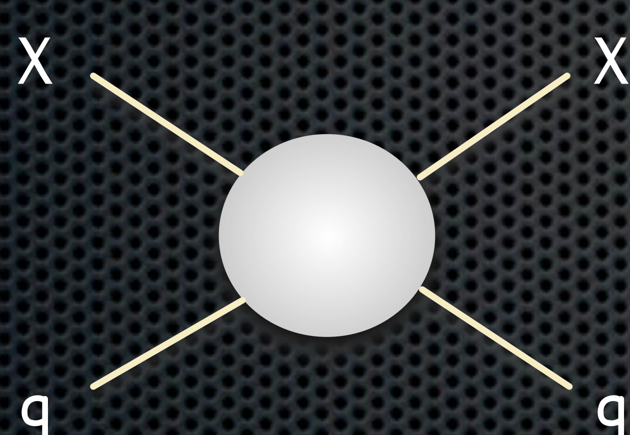
The WIMP Hypothesis is Testable

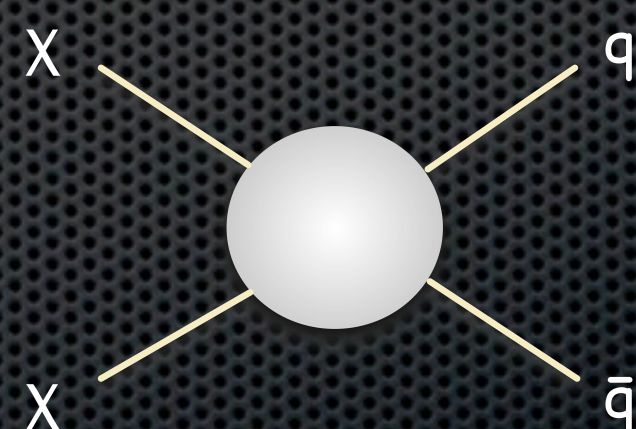
Deep underground

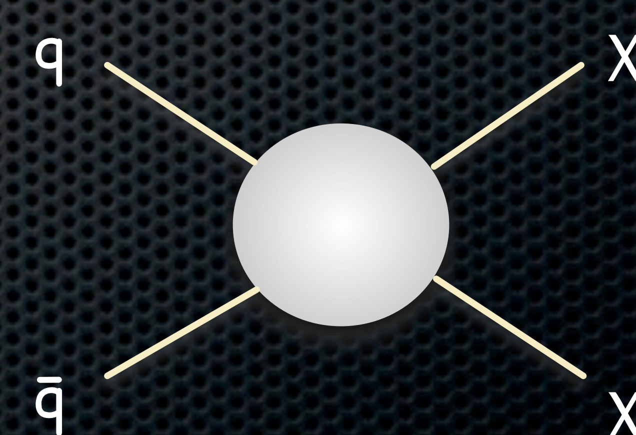


Above ground (in ice)

At the LHC







We hope to learn a lot from direct detectors, from indirect detectors and from accelerators!

Direct Detection of WIMPs: Principle

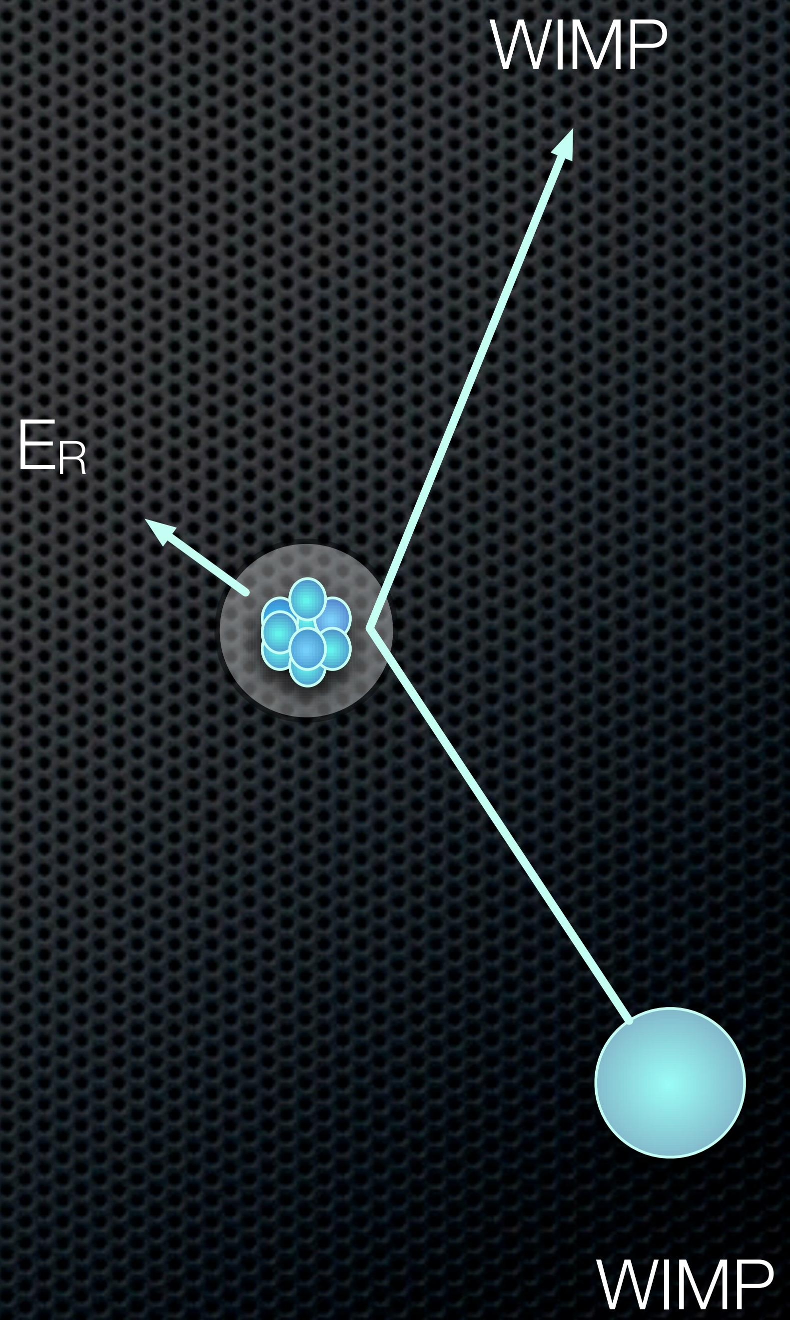
- By their elastic collision with nuclei in ultra-low background detectors
- The energy of the recoiling nucleus is a few tens of keV:

$$E_R = \frac{q^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - cos\theta)$$

- q = momentum transfer
- μ = reduced mass (m_N = nucleus mass; m_X = WIMP mass)

$$\mu = \frac{m_\chi m_N}{m_\chi + m_N}$$

- v = mean WIMP-velocity relative to the target
- θ = scattering angle in the center of mass system



Expected Rates in a Terrestrial Detector

- For now strongly simplified:

Astrophysics

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

Particle physics

N = number of target nuclei in a detector

ρ_χ = local density of the dark matter in the Milky Way

$\langle v \rangle$ = mean WIMP velocity relative to the target

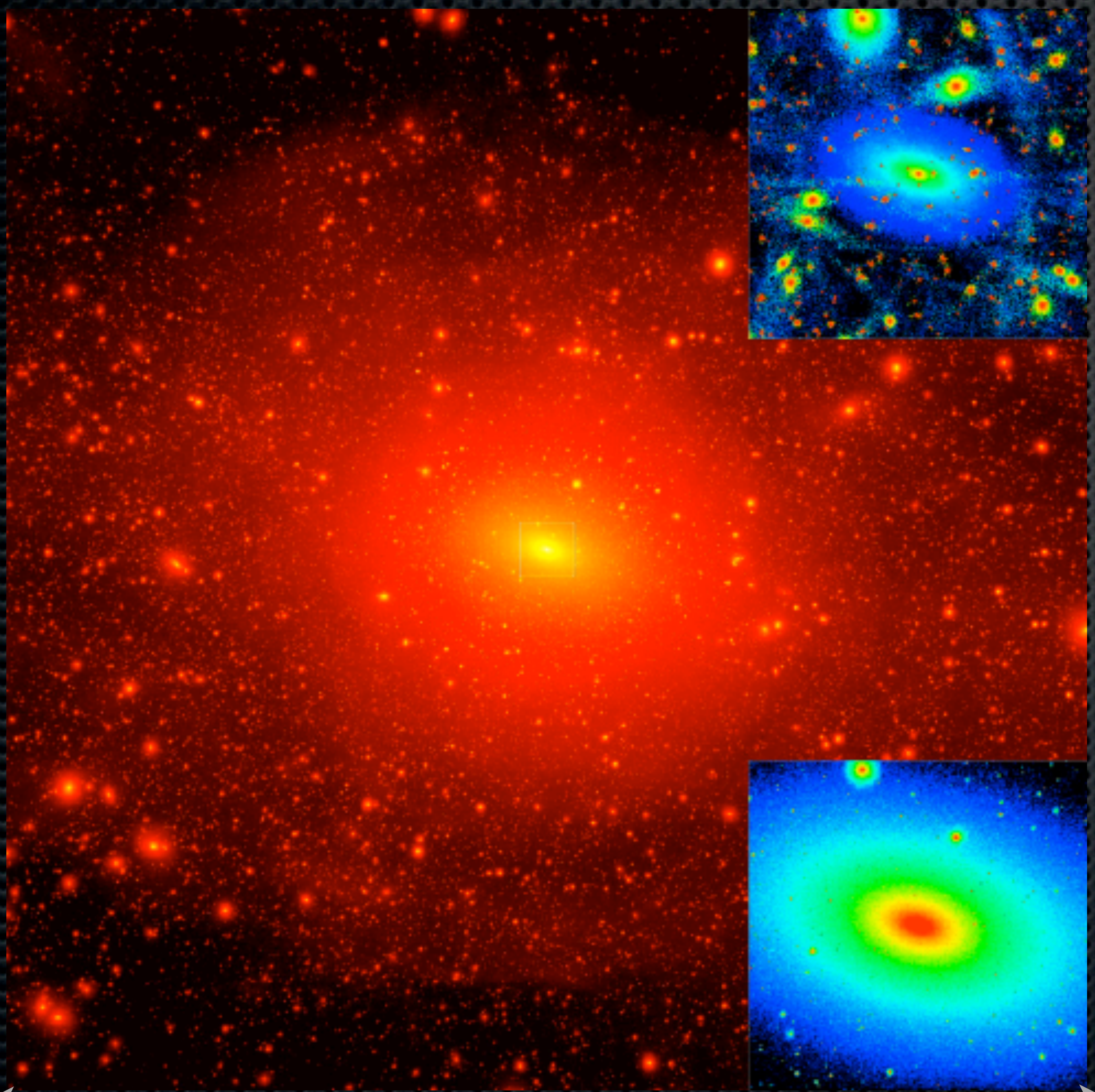
m_χ = WIMP-mass

$\sigma_{\chi N}$ =cross section for WIMP-nucleus elastic scattering

Local Density of WIMPs in the Milky Way

$$\rho_{halo} = 0.1 - 0.7 \mathrm{GeV cm}^{-3}$$

$$\rho_{disk} = 2 - 7 \mathrm{GeV cm}^{-3}$$



~ 600 kpc (J. Diemand et all, Nature 454, 2008, 735-738)

For a density of 0.3 GeV cm^{-3}, we have ~ 3000 WIMPs m^{-3} (M_W = 100 GeV)

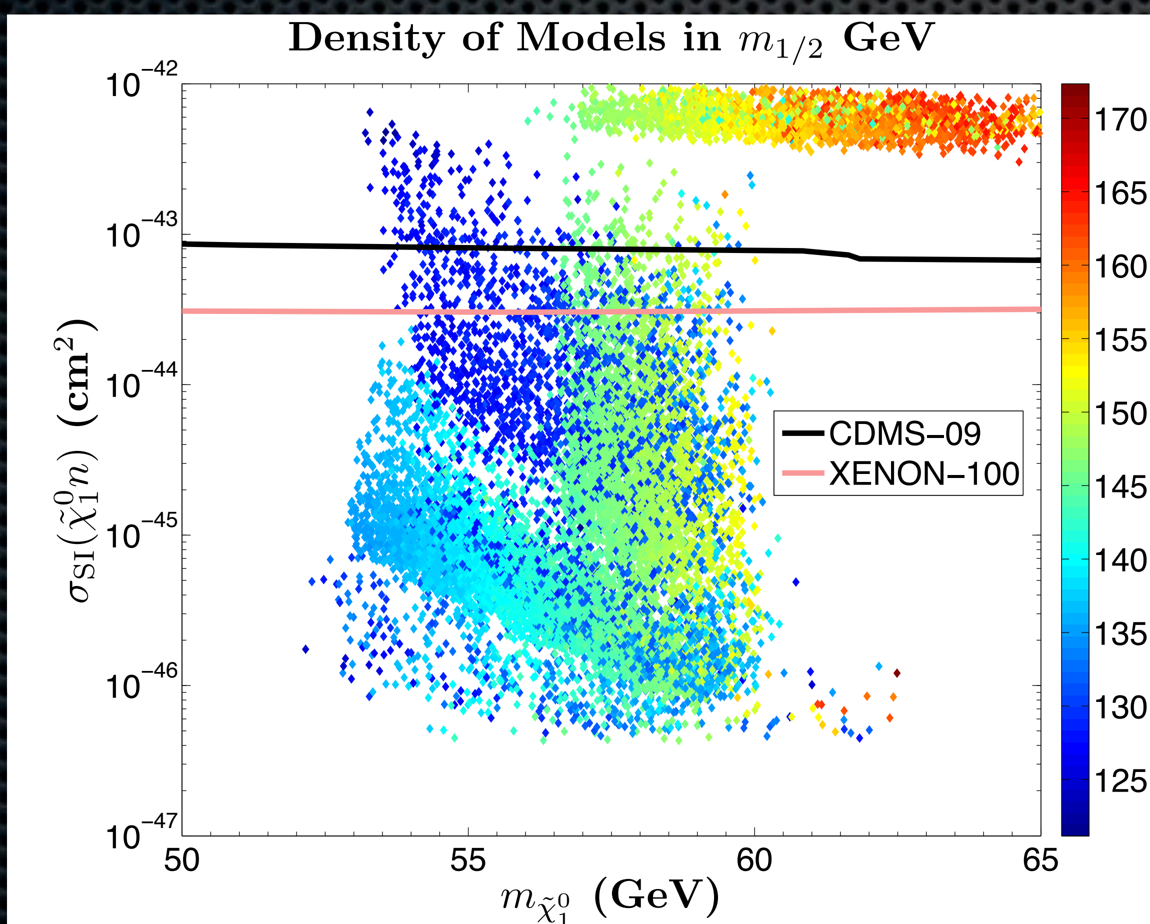
WIMP flux on Earth: ~ 10^5 $cm^{-2}s^{-1}$ (100 GeV WIMP)

Even though WIMPs are weakly interacting, this flux is large enough so that a potentially measurable fraction will elastically scatter off nuclei

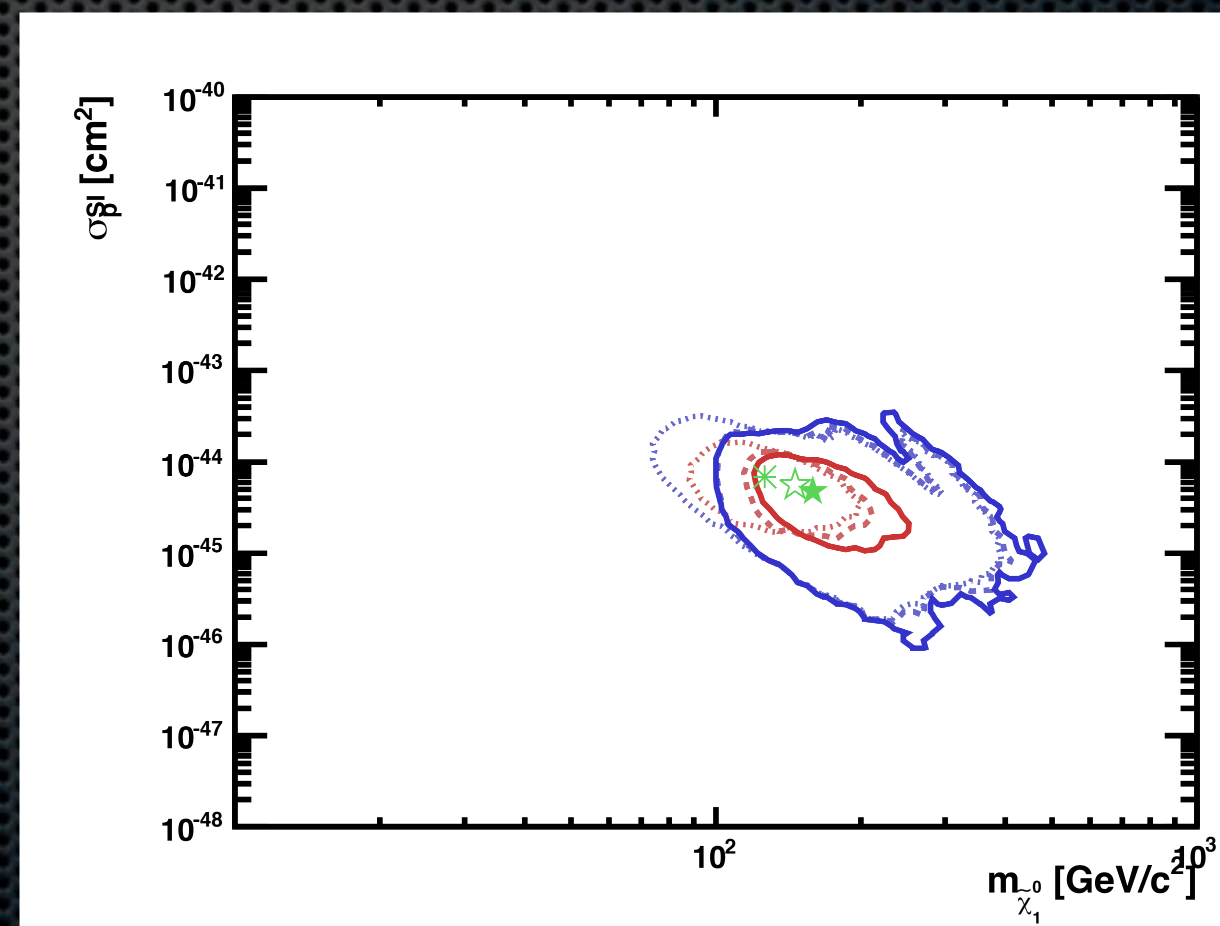
WIMP Mass and Spin-Independent Cross Section

- Examples for recent predictions from supersymmetry: cross sections down to a few $\times 10^{-47}$ cm^2

MSUGRA
Feldmann, Freese, Nath et al;
arXiv:1102.2548v1 [hep-ph]



CMSSM
Buchmueller et al;
arXiv:1102.4585v1 [hep-ph]

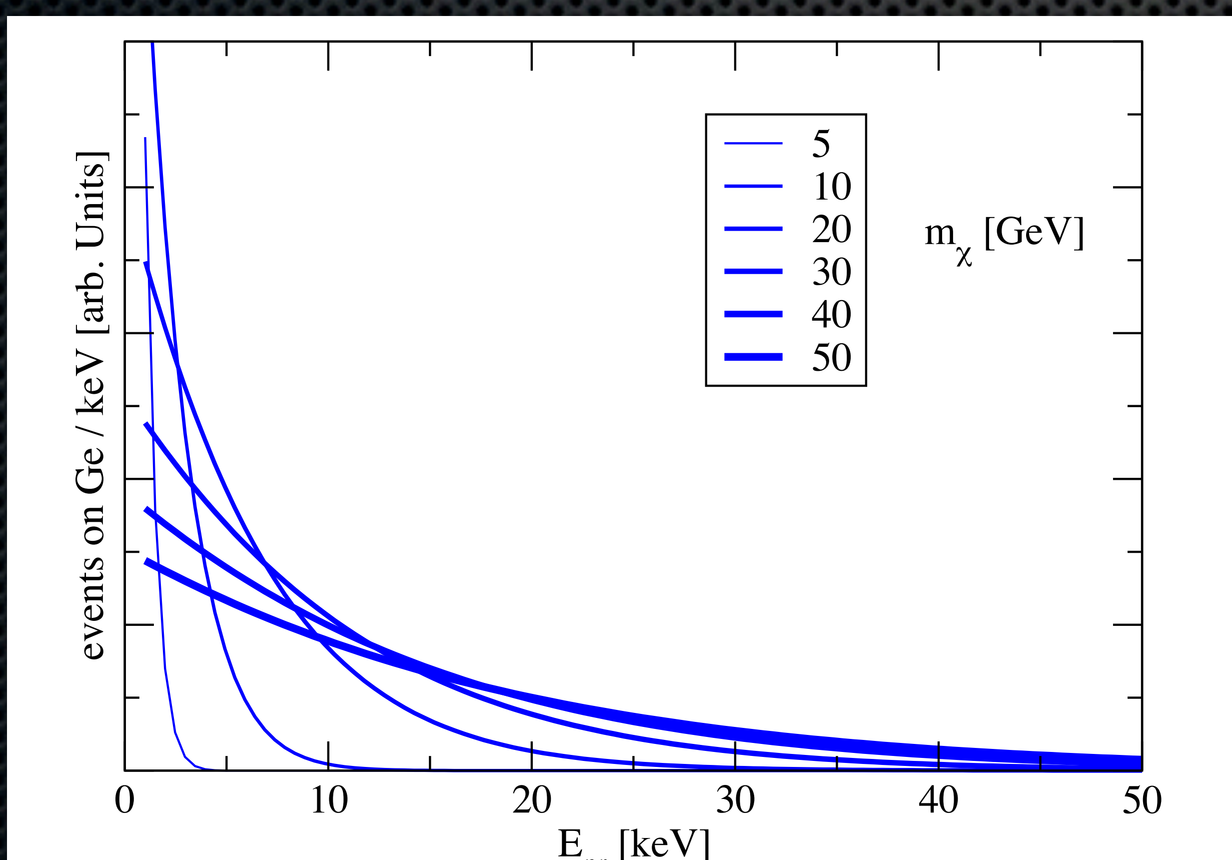


Expected Interaction Rates

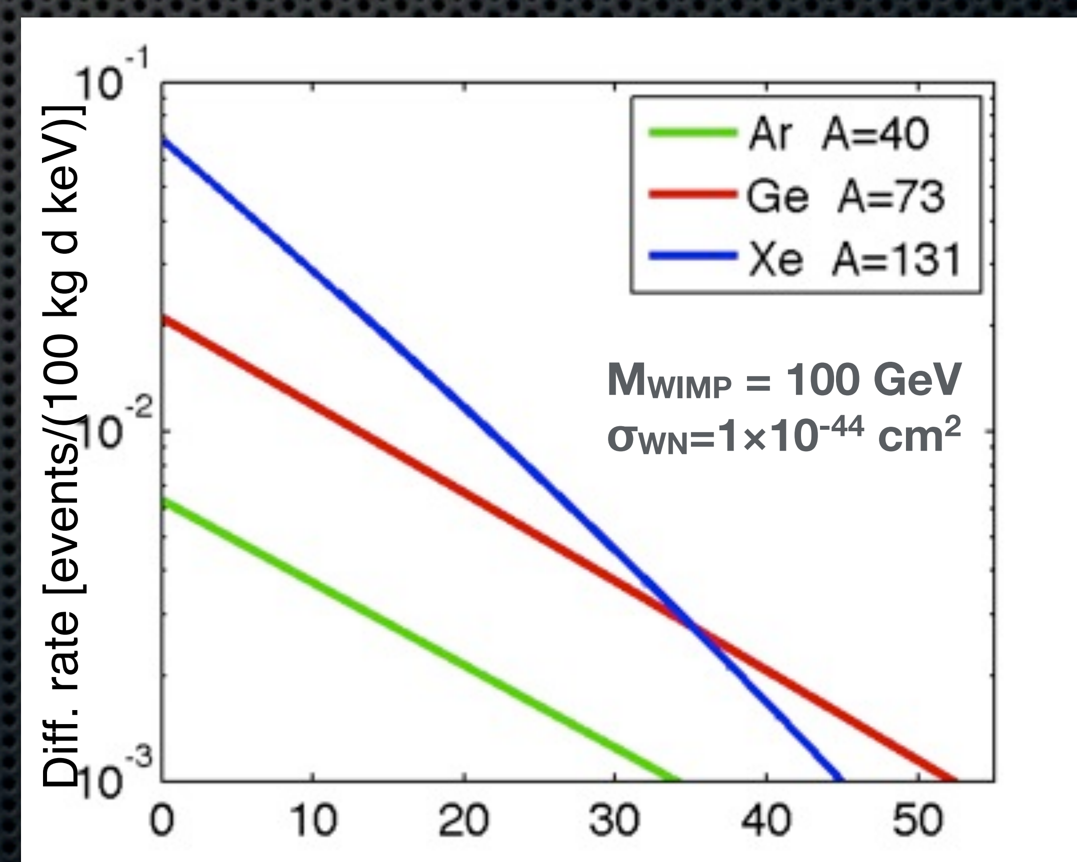
- Calculate the differential recoil rate by integrating over the WIMP velocity distribution

$$\frac{dR}{dE_R} = \frac{\sigma_0 \rho_0}{2 m_\chi \mu^2} F^2(E_R) \int_{v>\sqrt{m_N E_R / 2\mu^2}}^{v_{max}} \frac{f(\vec{v}, t)}{v} d^3 v$$

Different WIMP masses



Different target nuclei



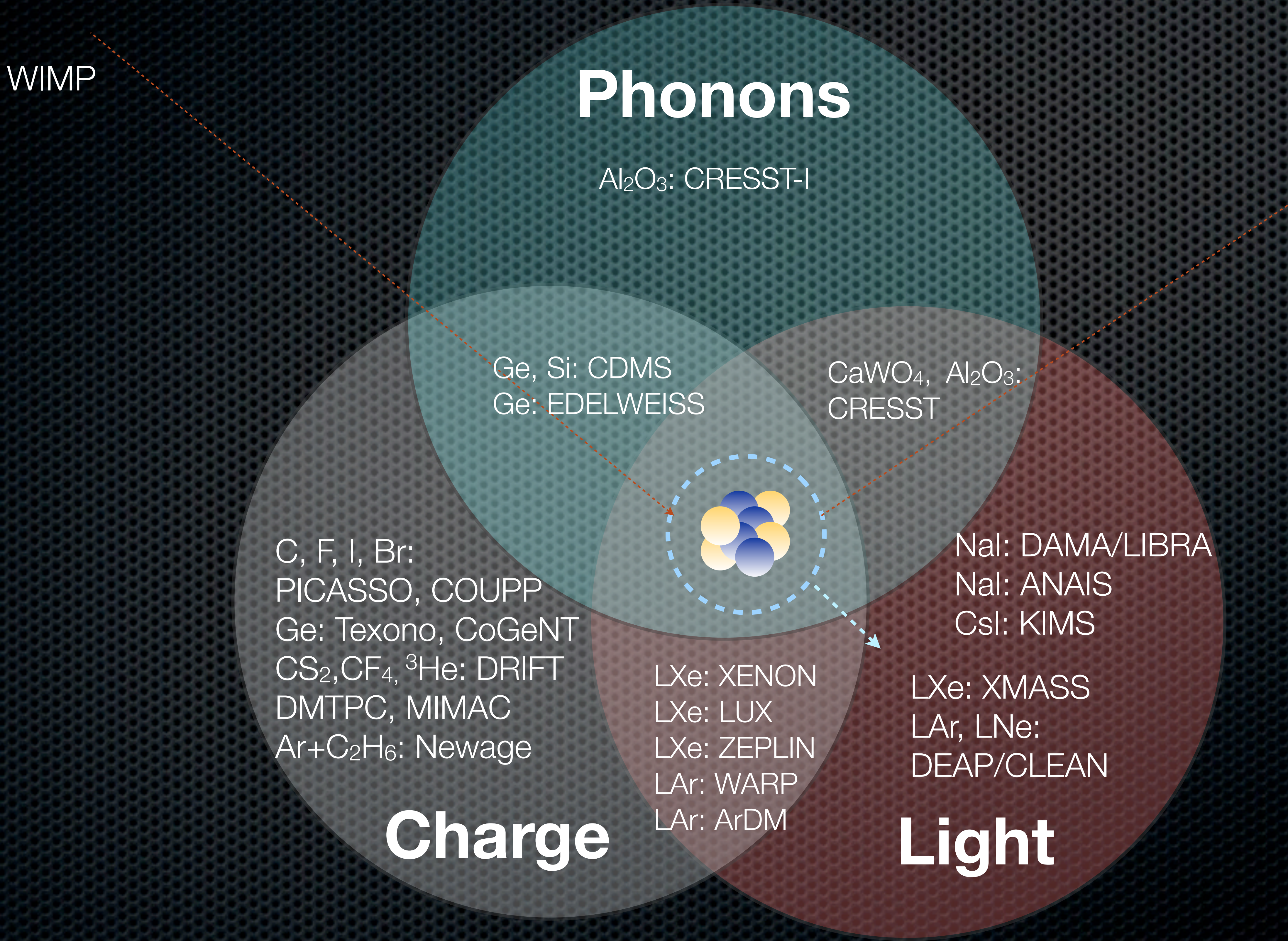
(Standard halo model with ρ= 0.3 GeV/cm^3)

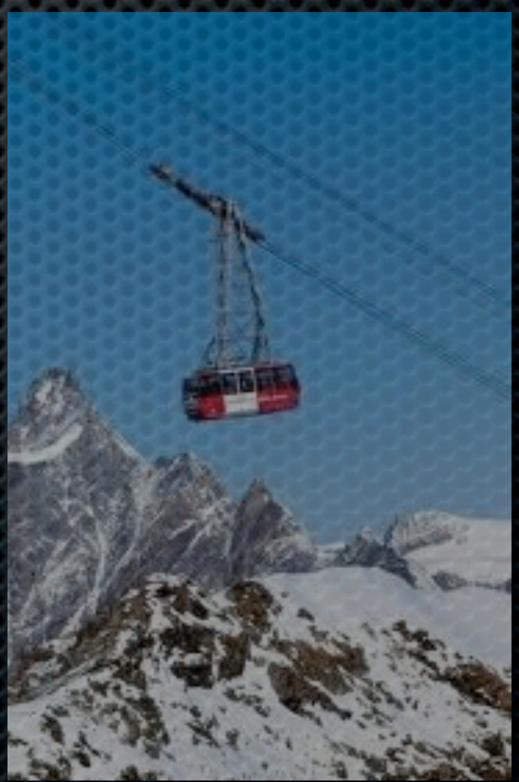
The Challenge

- **To observe a signal which is:**
  - very small (few keV)
  - extremely rare (1 per ton per year?)
  - embedded in a background that is millions of times higher

- **Why is it challenging?**
- Detection of low-energy particles - done!
  ➡e.g. micro-calorimetry with phonon readout
- Rare event searches with ultra-low backgrounds - done!
  ➡e.g SuperK, Borexino, SNO, etc
- **But can we do both?**

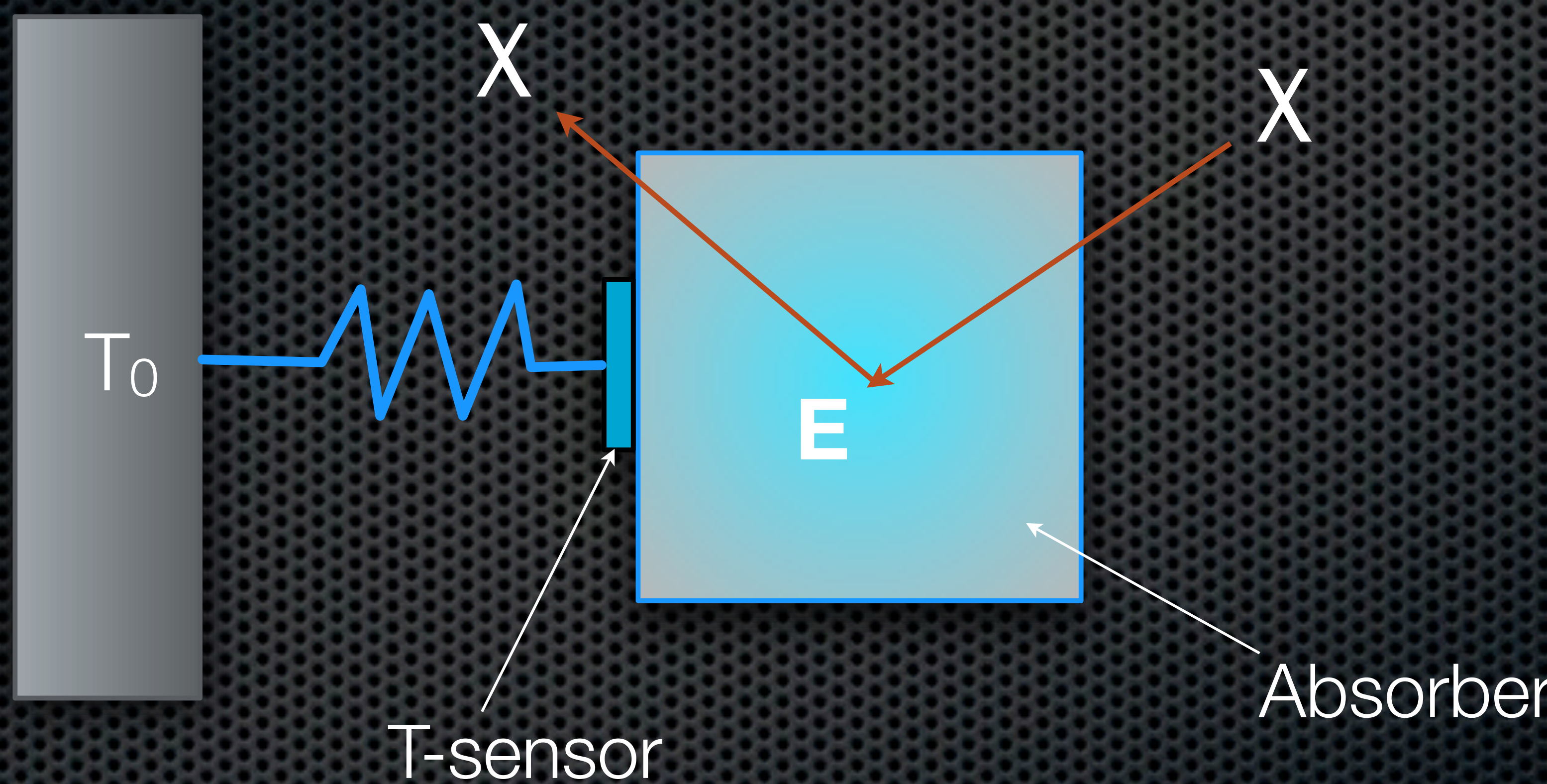
Direct Detection Techniques





Cryogenic Experiments at mK Temperatures

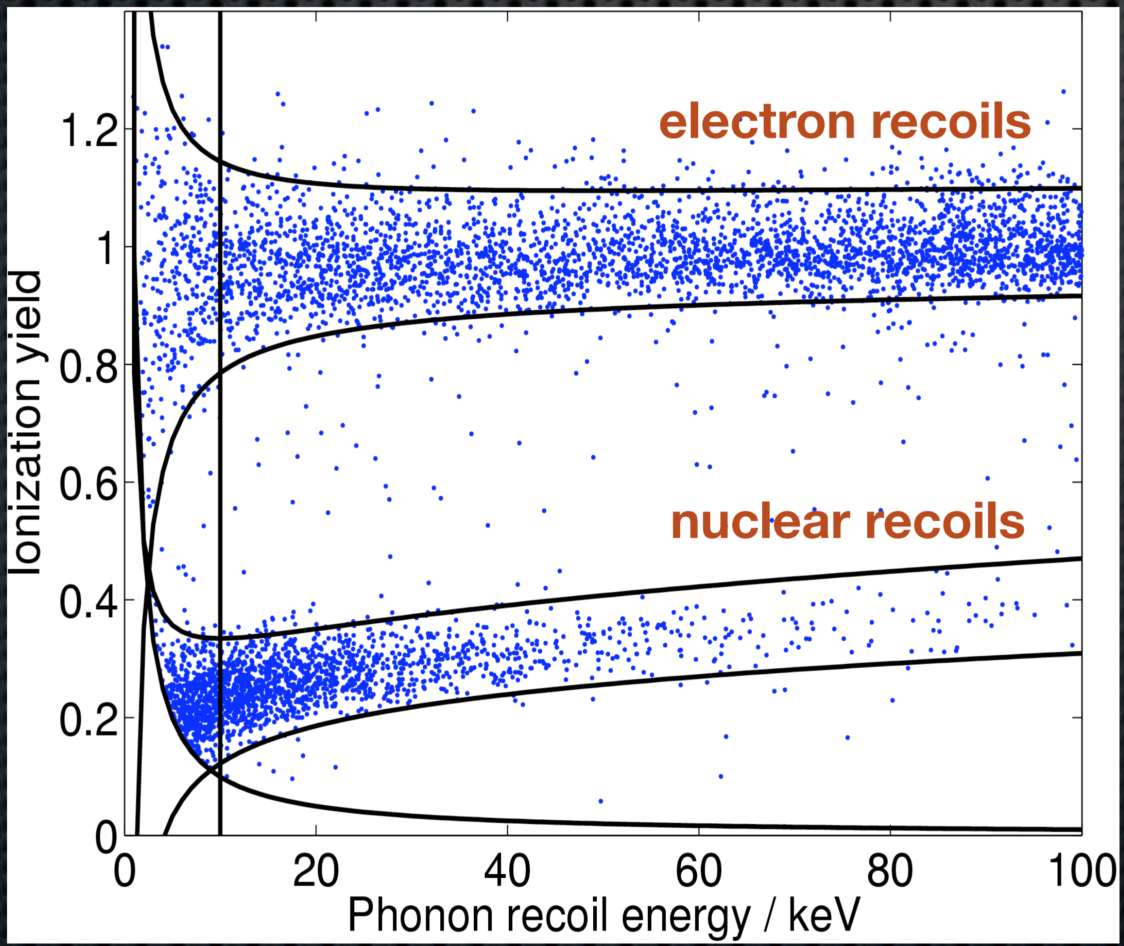
- Detect a temperature increase after a particle interacts in an absorber



- Temperature sensors: superconductor thermistors or superconducting transition sensors

Cryogenic Experiments at mK Temperatures

- Advantages: high sensitivity to nuclear recoils (measure the full energy in the phonon channel); good energy resolution, low energy threshold (keV to sub-keV)
- Ratio of light/phonon or charge/phonon: nuclear versus electronic recoils discrimination

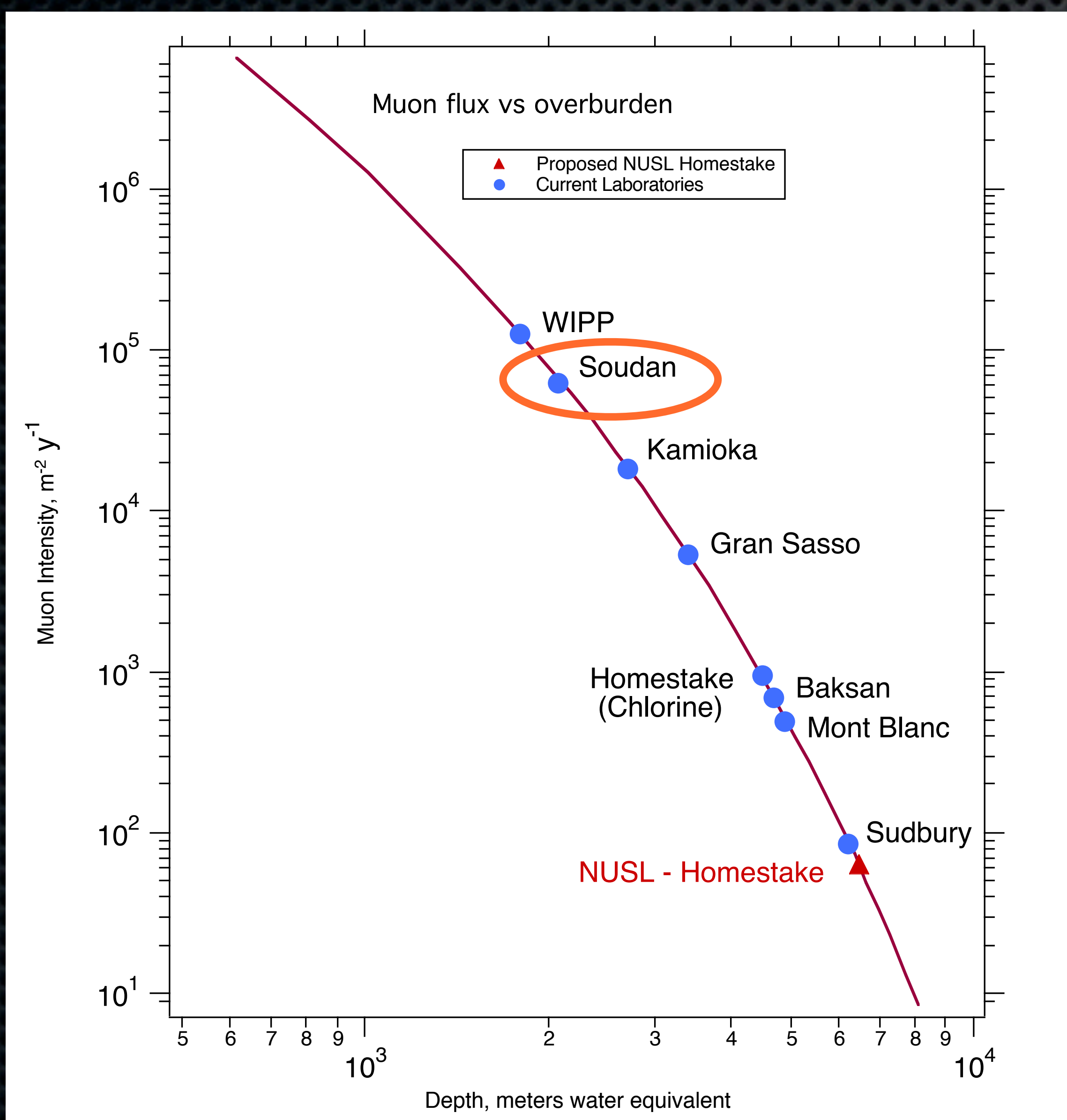


Background region

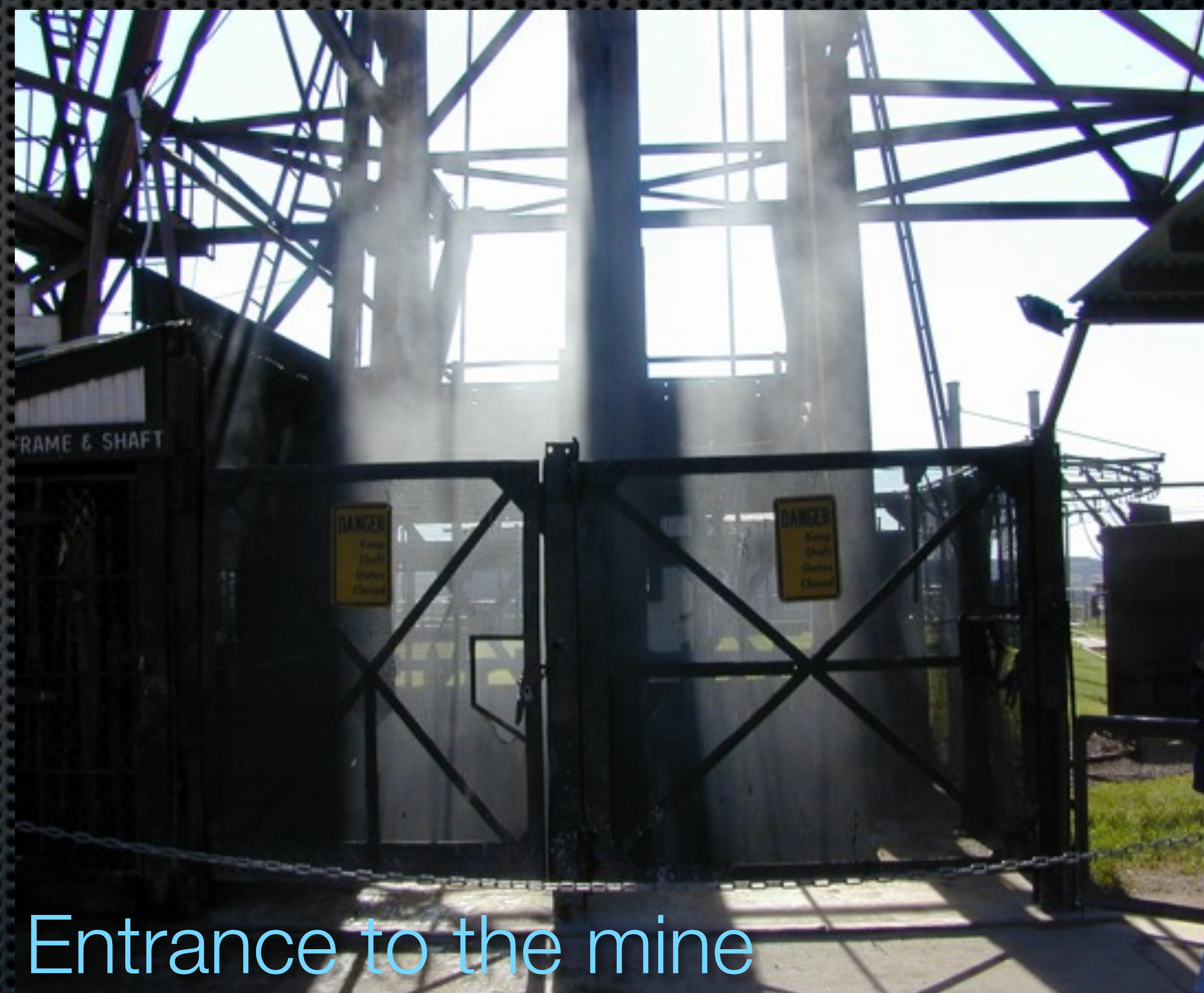
Expected signal region

The Cryogenic Dark Matter Search (CDMS)

- At the Soudan Laboratory in Northern Minnesota, 2090 mwe
- Neutron background due to muons: ~ 1 kg^{-1} $year^{-1}$

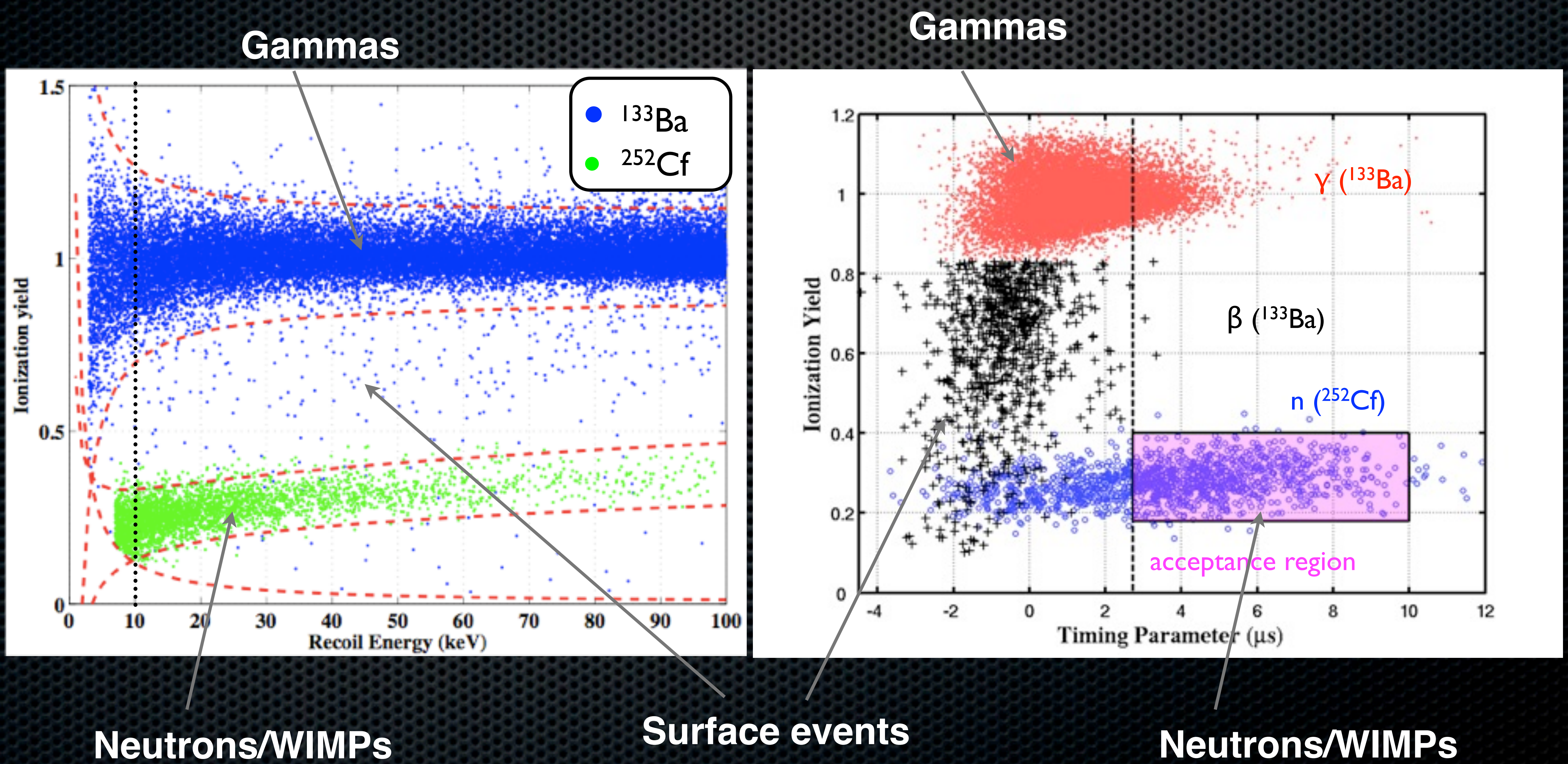


Depth [meters water equivalent]



CDSM: Signal versus Backgrounds

- Ratio of charge-to-phonon signal and time difference between charge and phonon signals to distinguish WIMPs from backgrounds



CDMS-II at the Soudan Mine

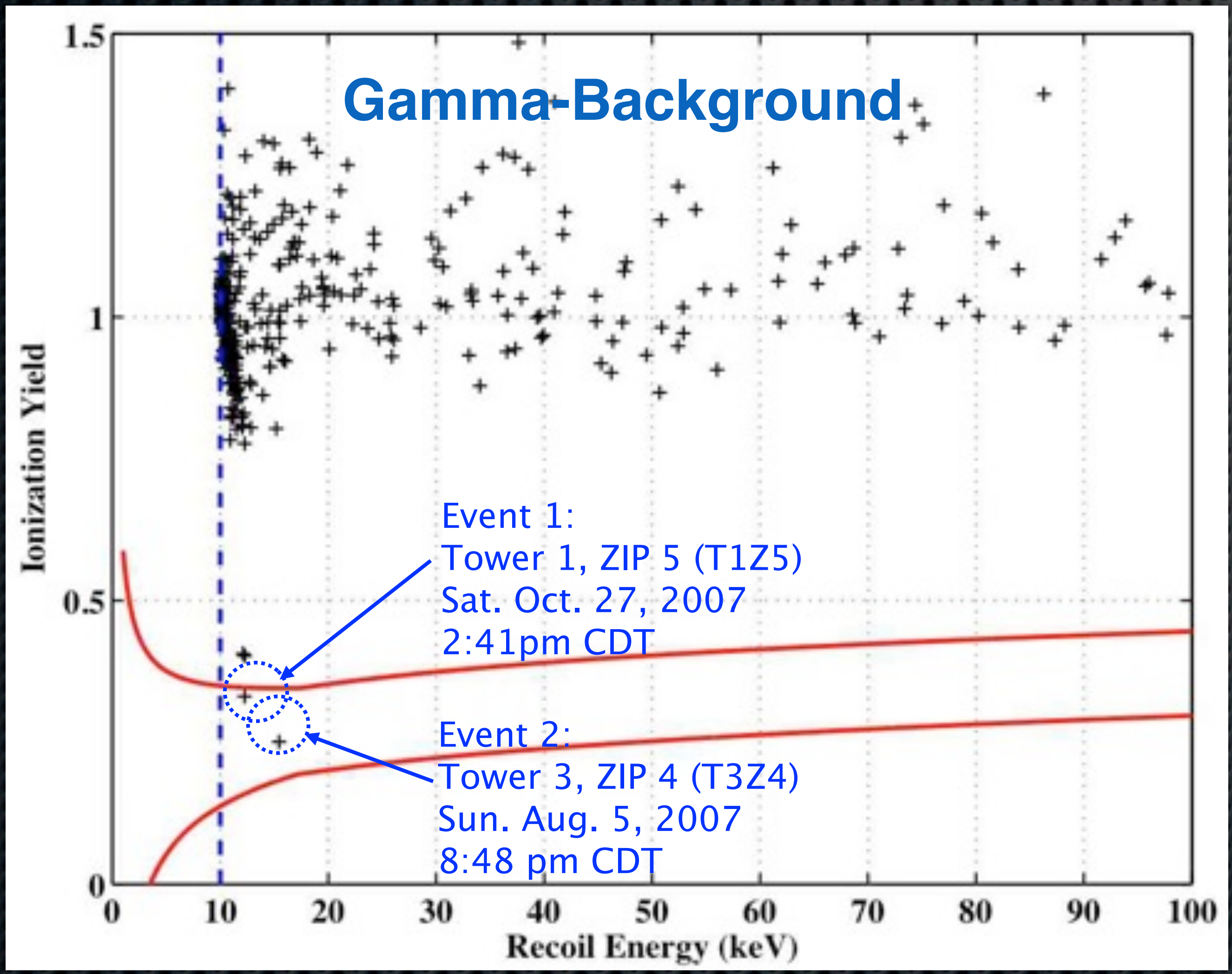
- 5 towers, each with 6 Ge/Si detectors operated at 40 mK at Soudan, in appropriate low-background shield until 2009

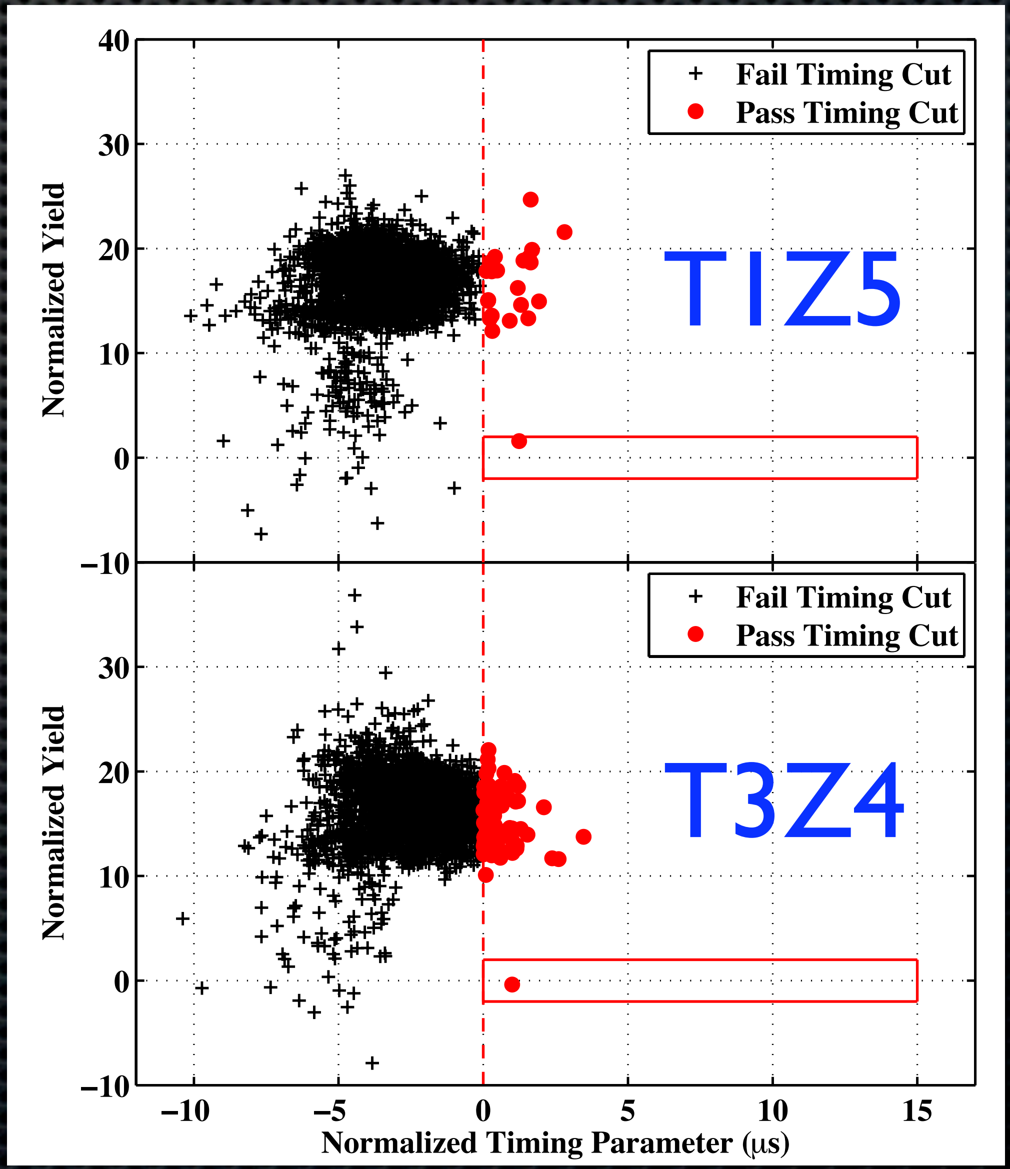
Entrance to the mine

CDMS cryostat

Final CDMS WIMP Search Runs: 191 kg d

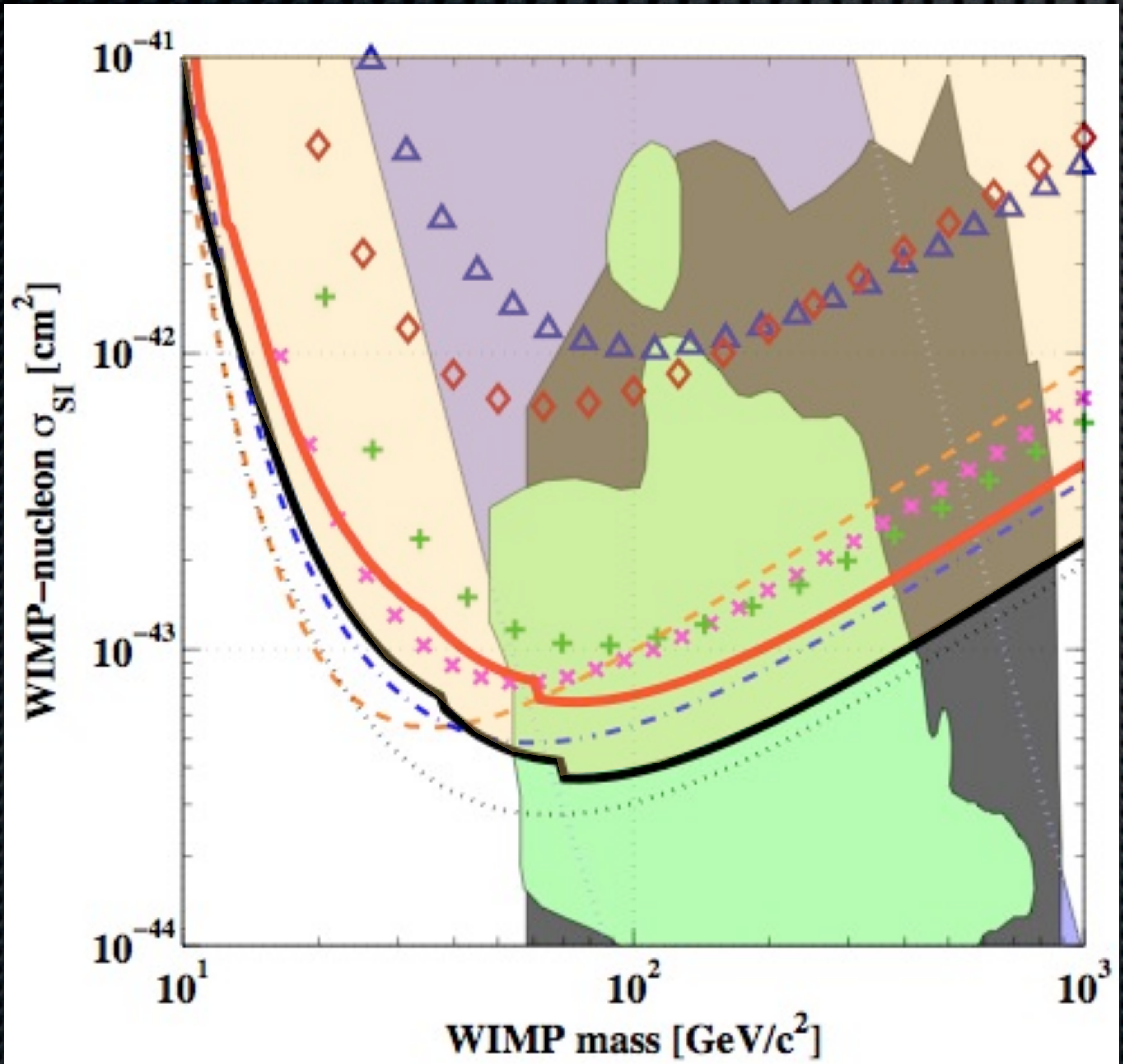
- WIMP search data analysis: Two events passing all cuts (which were set “blind”, based on calibration and background data outside the WIMP search region)





Limits on WIMP-nucleon Cross Sections

Science, 1186112 (2010)

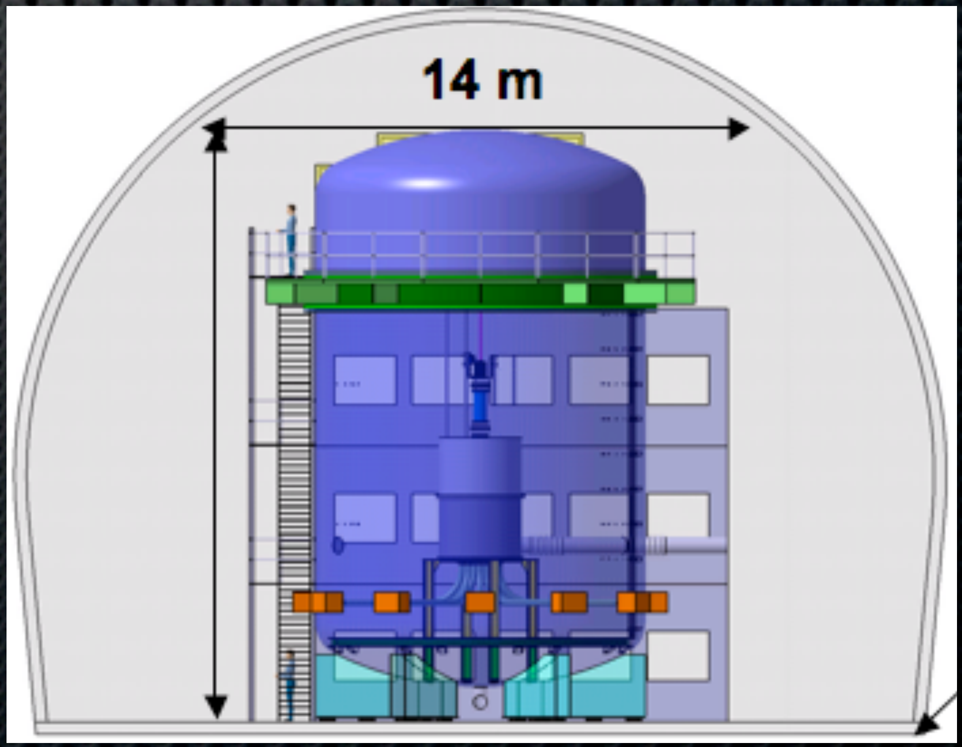


- Background estimate:
- 0.8 ± 0.1 (stat) ± 0.2 (syst) events
- Probability to observe two or more events is 23%
- At a WIMP mass of 70 GeV, the cross section limit is 3.8×10^{-44} cm^2 (90% C.L.)

Future Cryogenic Dark Matter Projects

- US/Canada: SuperCDMS (15 kg to 1.5 tons Ge experiment)
- Larger Ge detectors (650g) with improved readout
- To be located at SnoLAB

- Europe: EURECA (100 kg to 1.0 ton cryogenic experiment)
- Multi-target approach
- To be located at the ULISSE Lab (Modane extension) in France

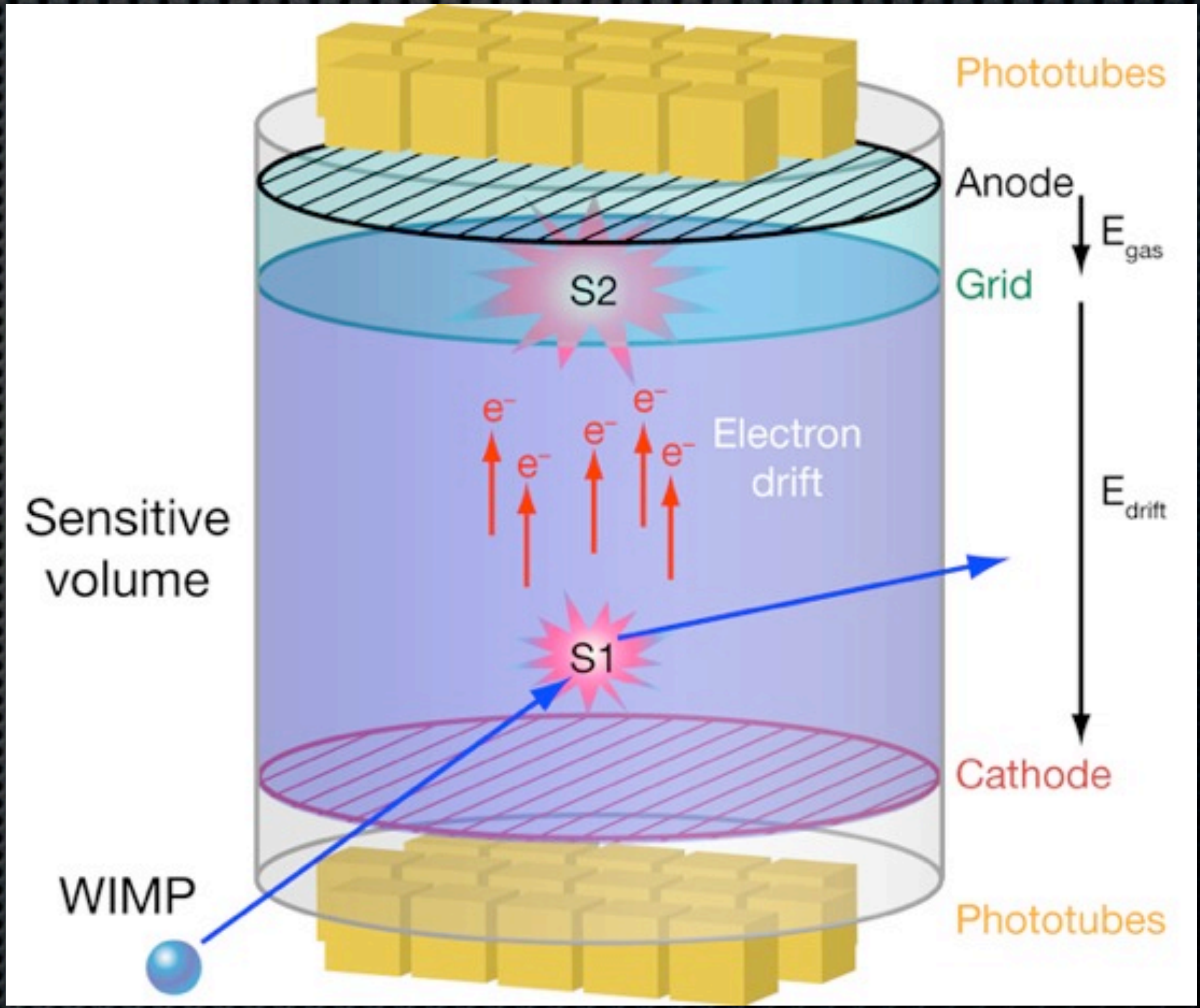


Noble Liquids Time Projection Chambers

- Large, scalable, homogeneous and self-shielding detectors
- Prompt (S1) light signal after interaction in the active volume
- Charge is drifted, extracted into the gas phase and detected as proportional light (S2)

- S2/S1 depends on dE/dx
- good 3D position resolution

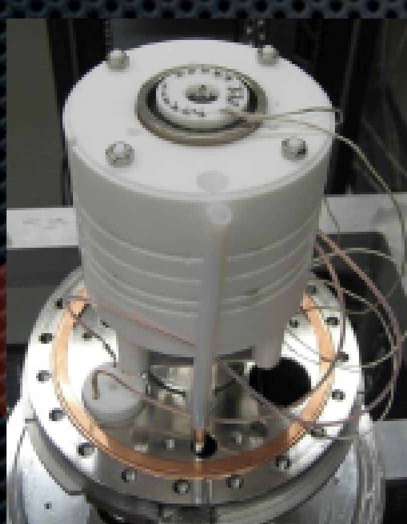
=> particle identification



Ar (A = 40); λ = 128 nm
Xe (A=131); λ = 178 nm

The XENON Program

XENON R&D



ongoing

XENON10

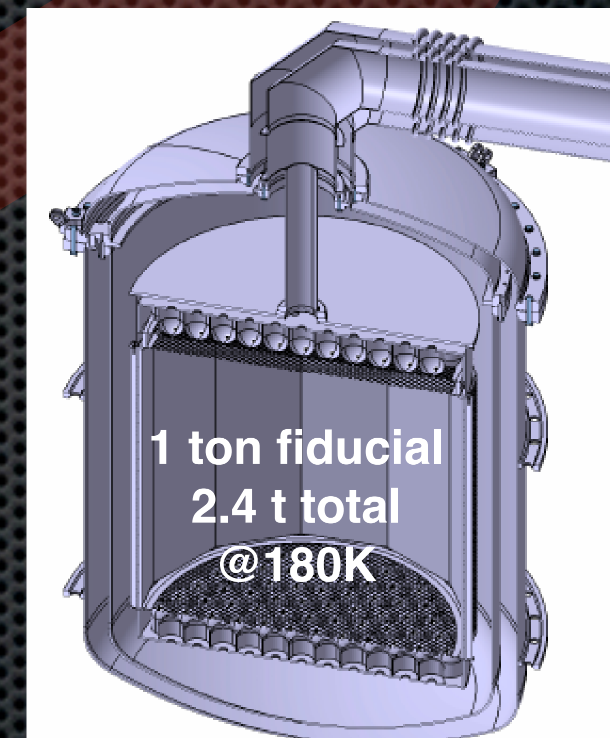
2005-2007

PRL100
PRL101
PRD 80
NIM A 601

XENON100

2008-2011
taking science data
first results: PRL105

XENON1T



2011-2015

Proposal submitted to LNGS in April 2010

TDR submitted to LNGS mid October, 2010

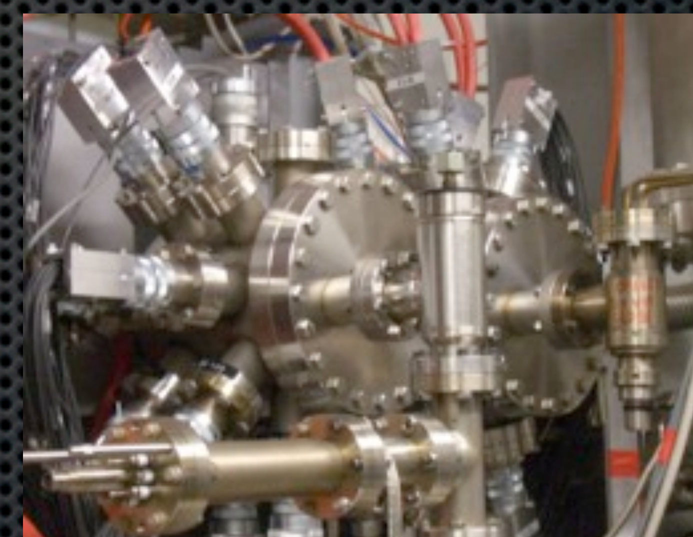
XENON: Columbia, Zürich, Coimbra, Mainz, LNGS, WIS, Münster, MPIK, Subatech, UCLA, Bologna, Torino, Nikhef

The XENON100 Experiment

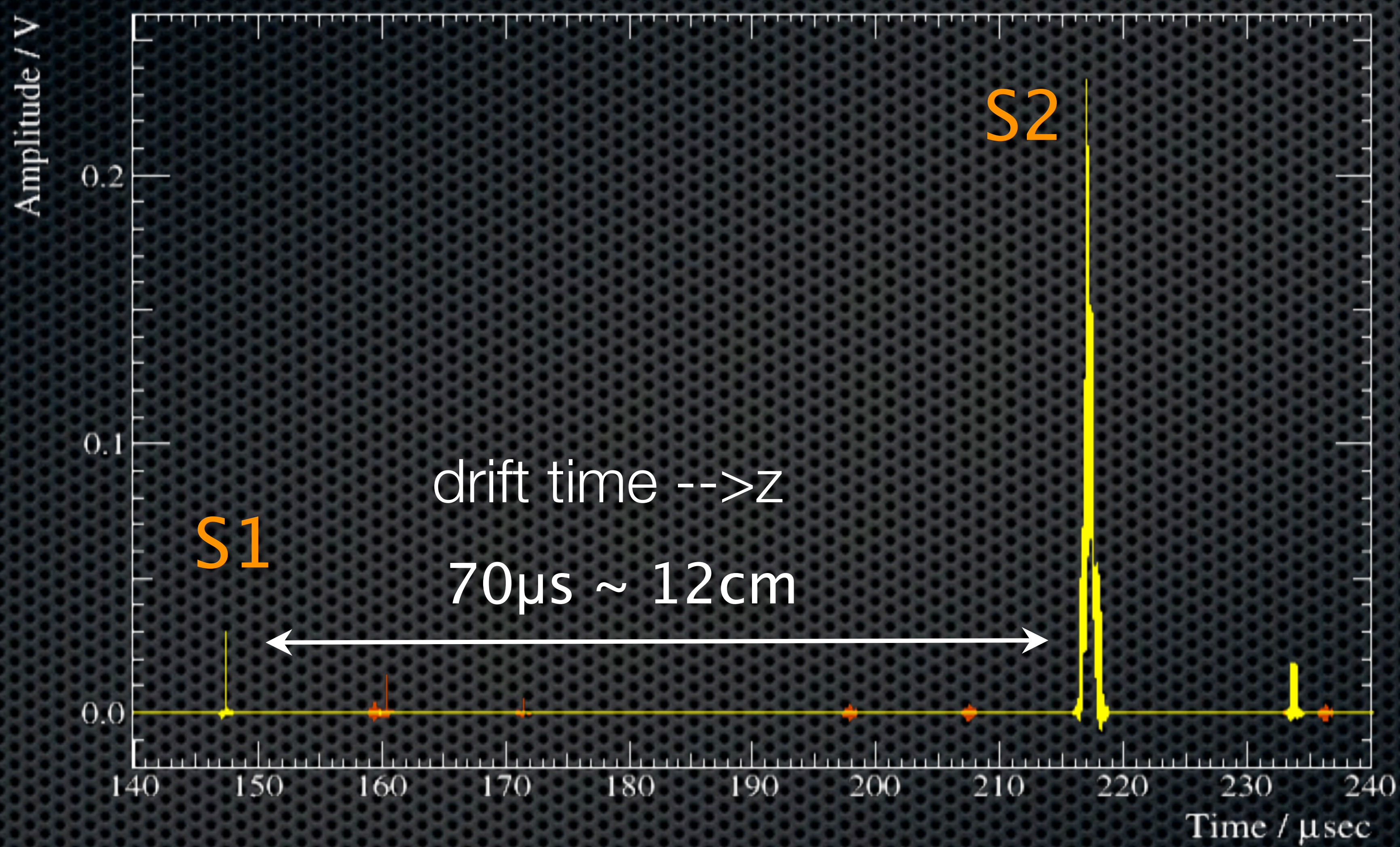
- At the Gran Sasso Laboratory in Italy, ~ 3600 mwe
- Operated in conventional passive shields (Cu, Poly, Pb, $H_2$0)

The XENON100 Detector

- 161 kg of ultra-pure liquid xenon (LXe), 62 kg in the active target volume
- 30 cm drift gap TPC with two PMT arrays (242 PMTs) to detect the prompt and proportional scintillation signals

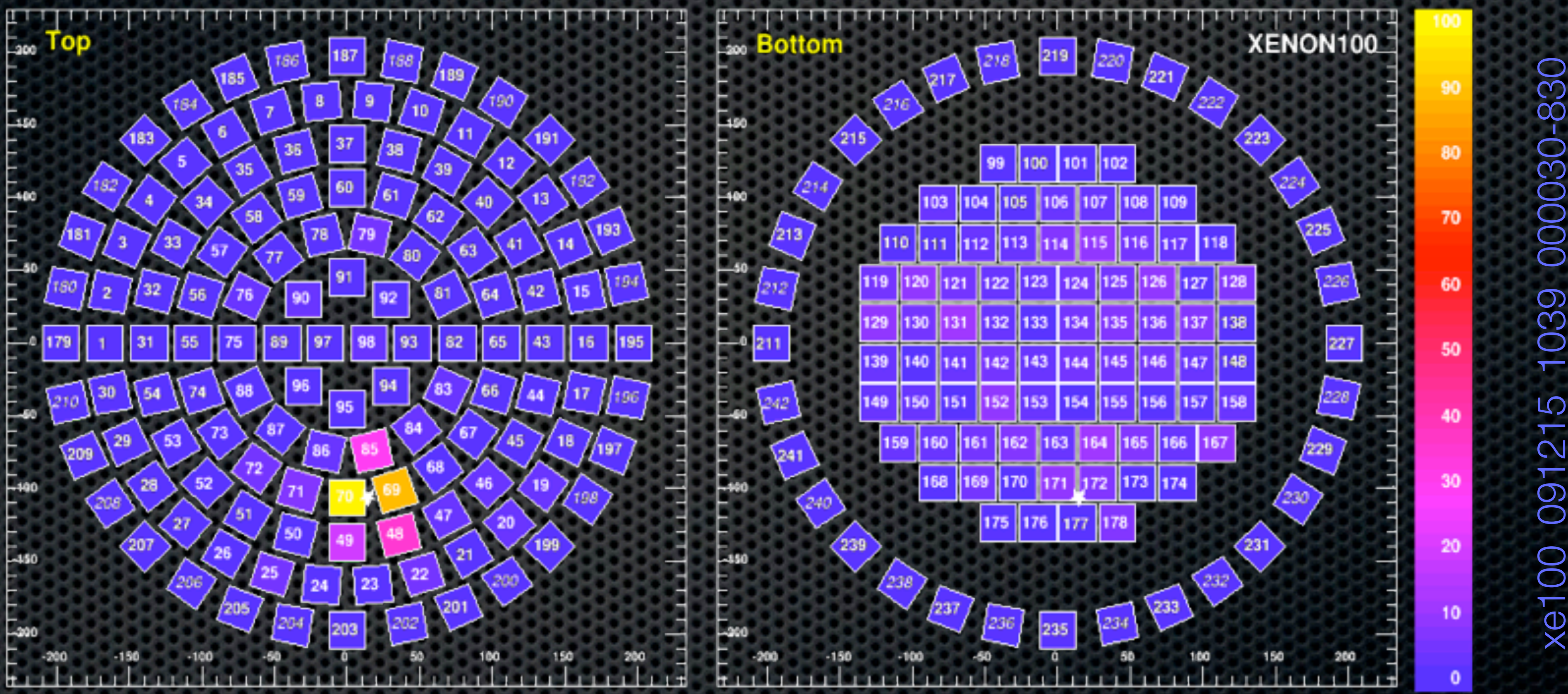


Example of a 9 keV Nuclear Recoil Event



- 4 photoelectrons detected from about 100 S1 photons
- 645 photoelectrons detected from 32 ionization electrons which generated about 3000 S2 photons

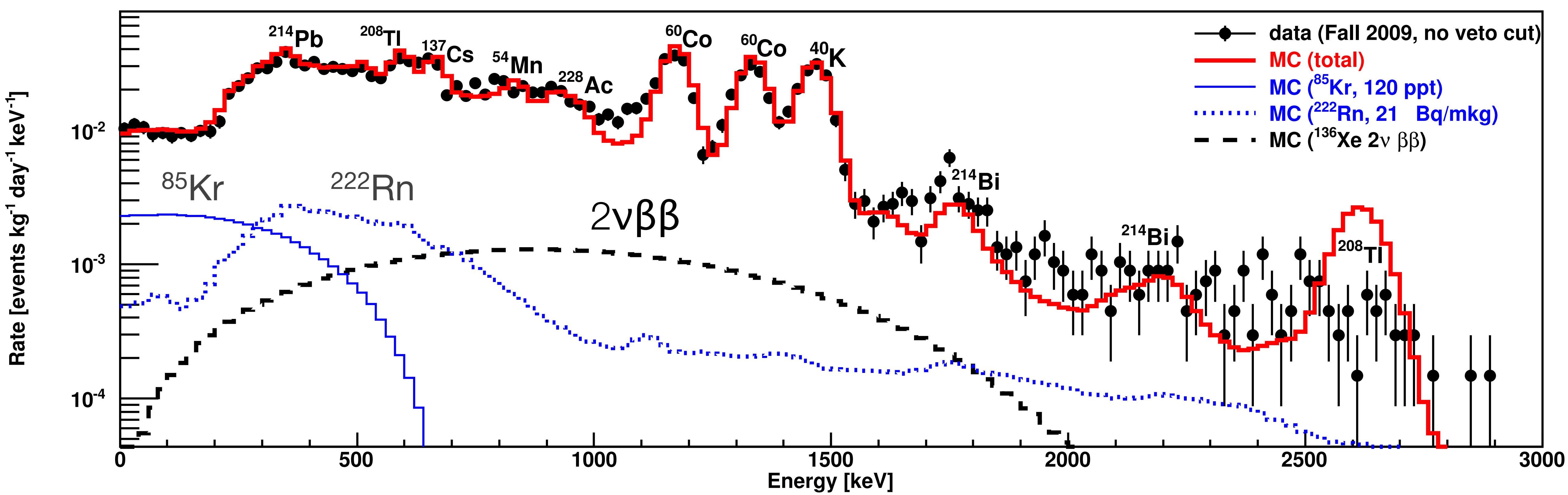
Example of a 9 keV Nuclear Recoil Event



XENON100 Backgrounds: Data and Predictions

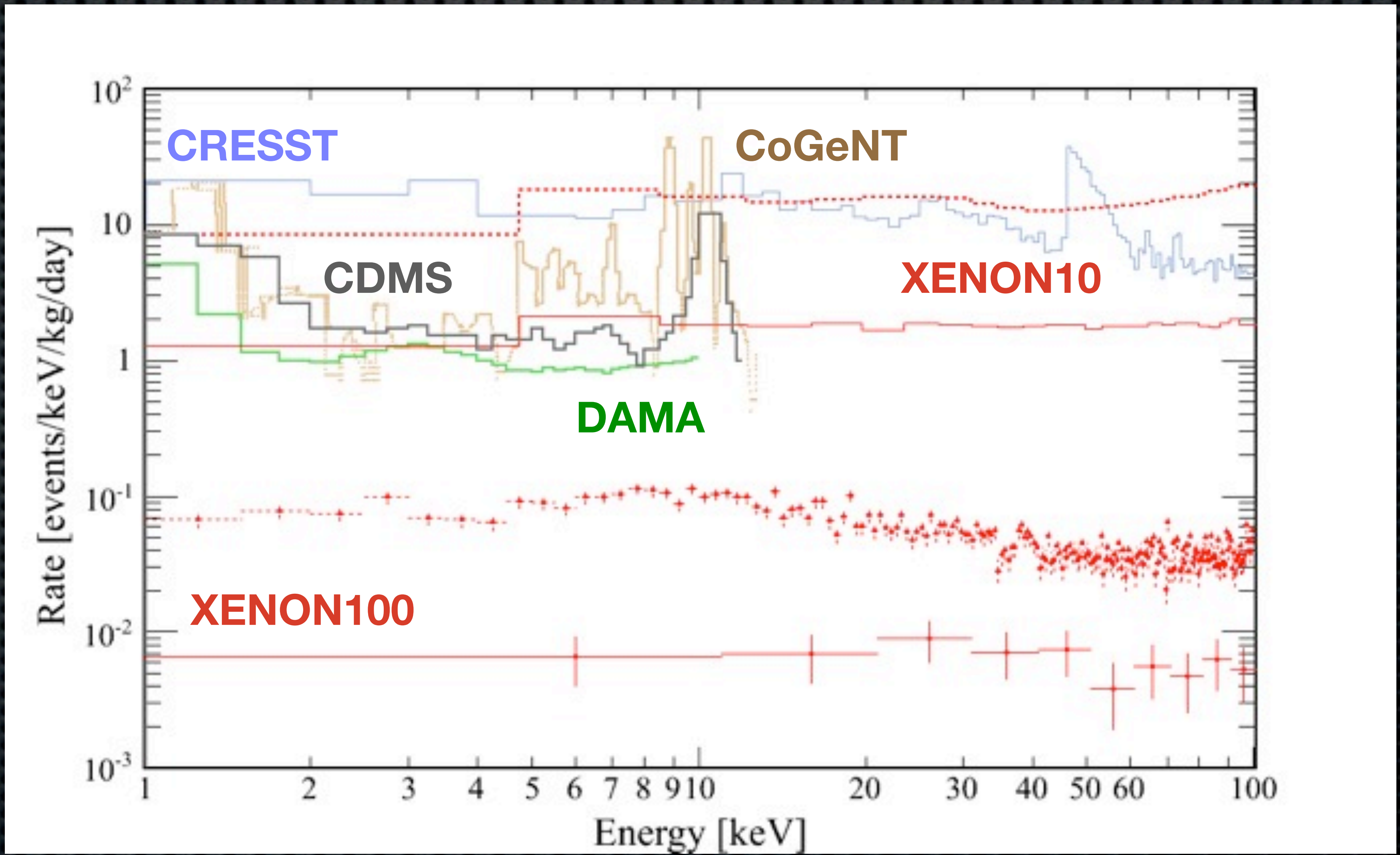
- Data versus Monte Carlo simulations (no MC tuning, input from screening values for U/Th/K/Co/Cs etc of all detector components); no active liquid xenon veto cut
- Background is 100 times lower than in XENON10 and meets design specifications

XENON100 collaboration, arXiv:1101.3866, PRD 83, 082001 (2011)



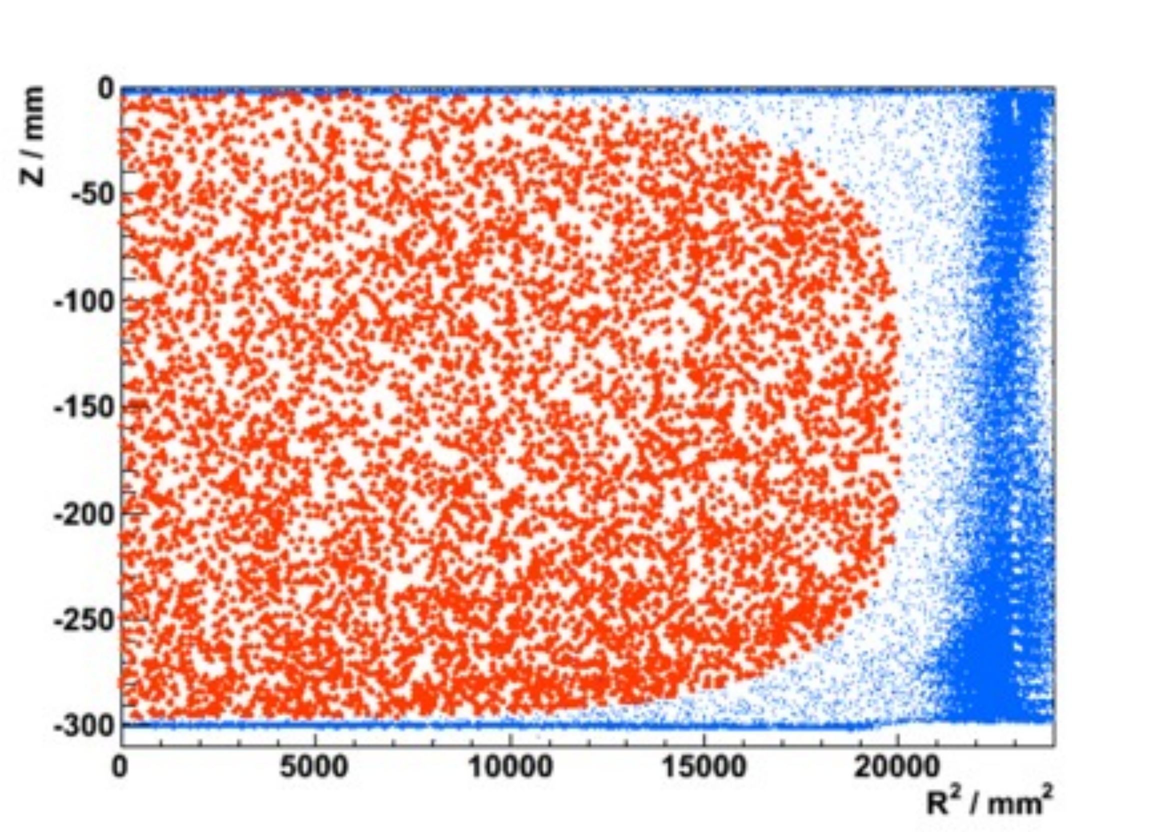
XENON100 Backgrounds: Data and Predictions

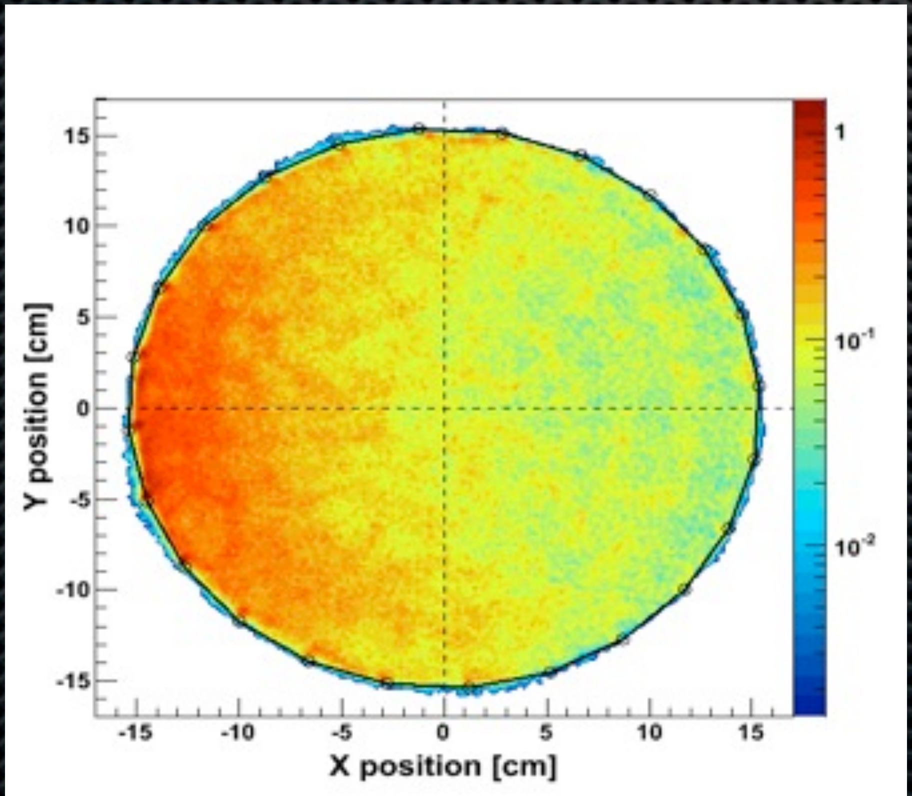
- Data versus Monte Carlo simulations (no MC tuning, input from screening values for U/Th/K/Co/Cs etc of all detector components); no active liquid xenon veto cut
- Background is 100 times lower than in XENON10 (and any other dark matter experiment) and meets design specifications

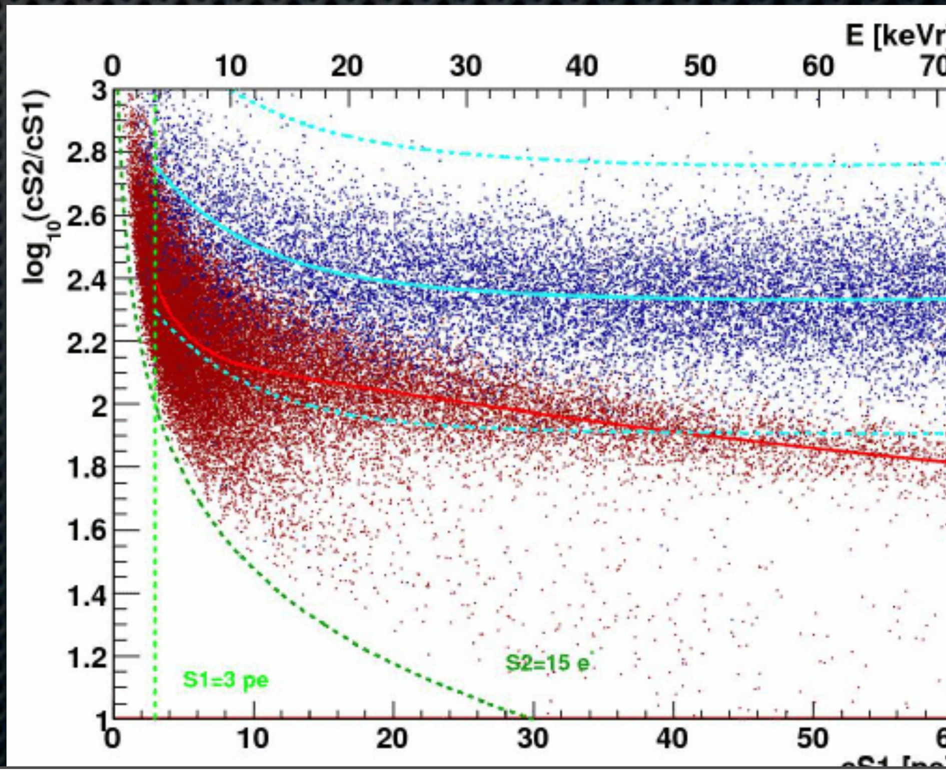


Background Rejection in XENON100

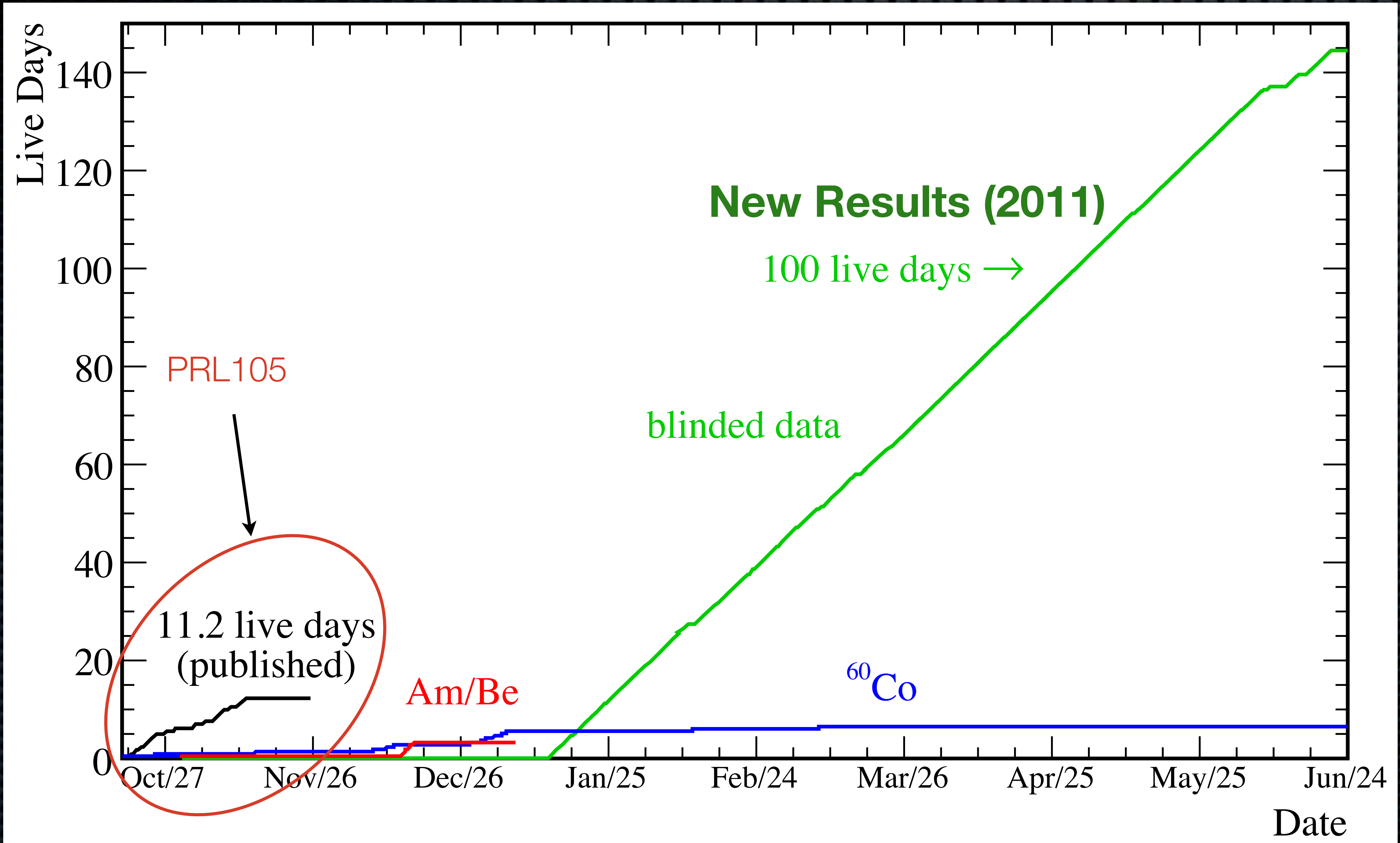
- LXe self-shielding from penetrating radiation
- Additional identification/rejection of gammas and neutrons by:
  - charge/light (S2/S1): > 99.5% rejection
  - 3D event localization with mm precision: a) fiducial volume b) single scatters





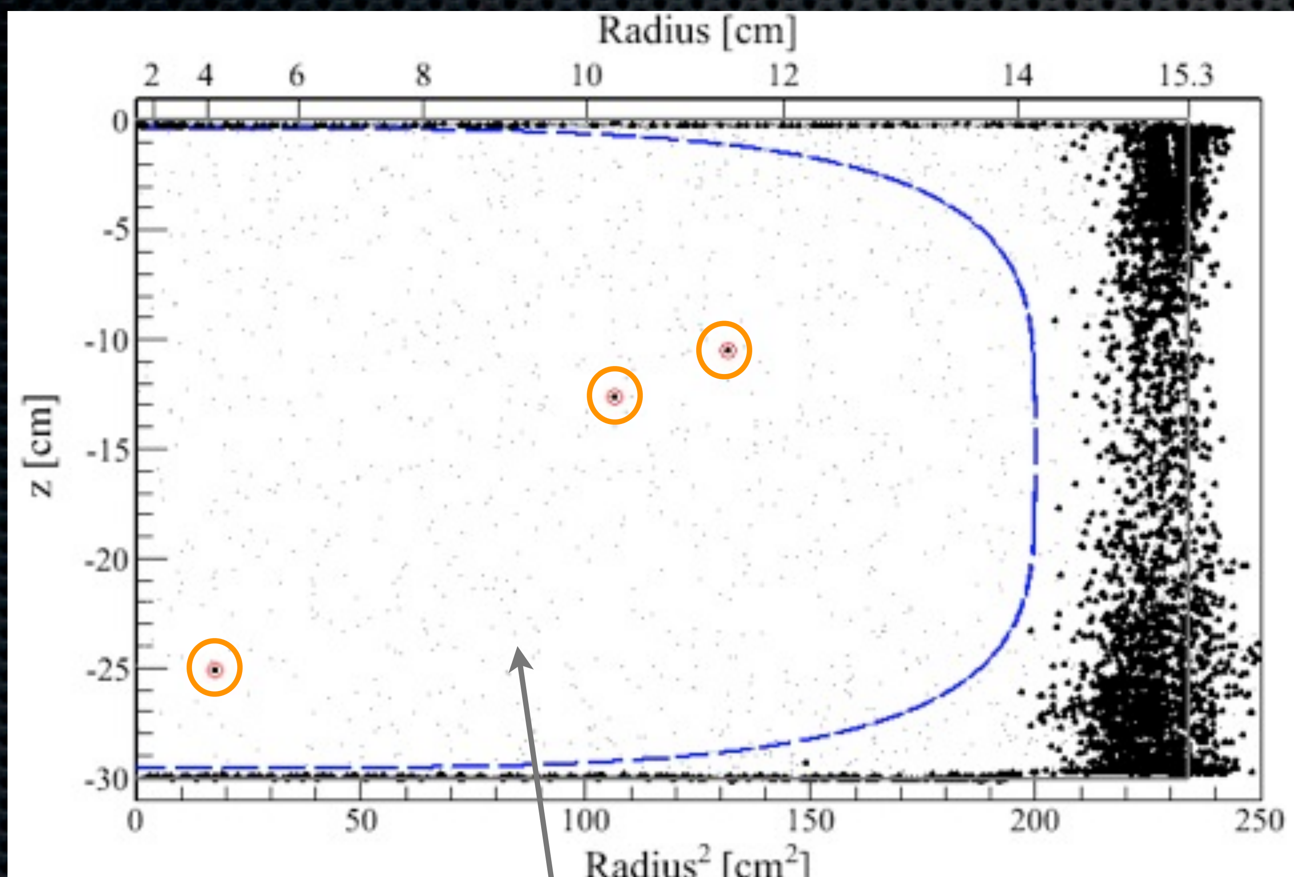


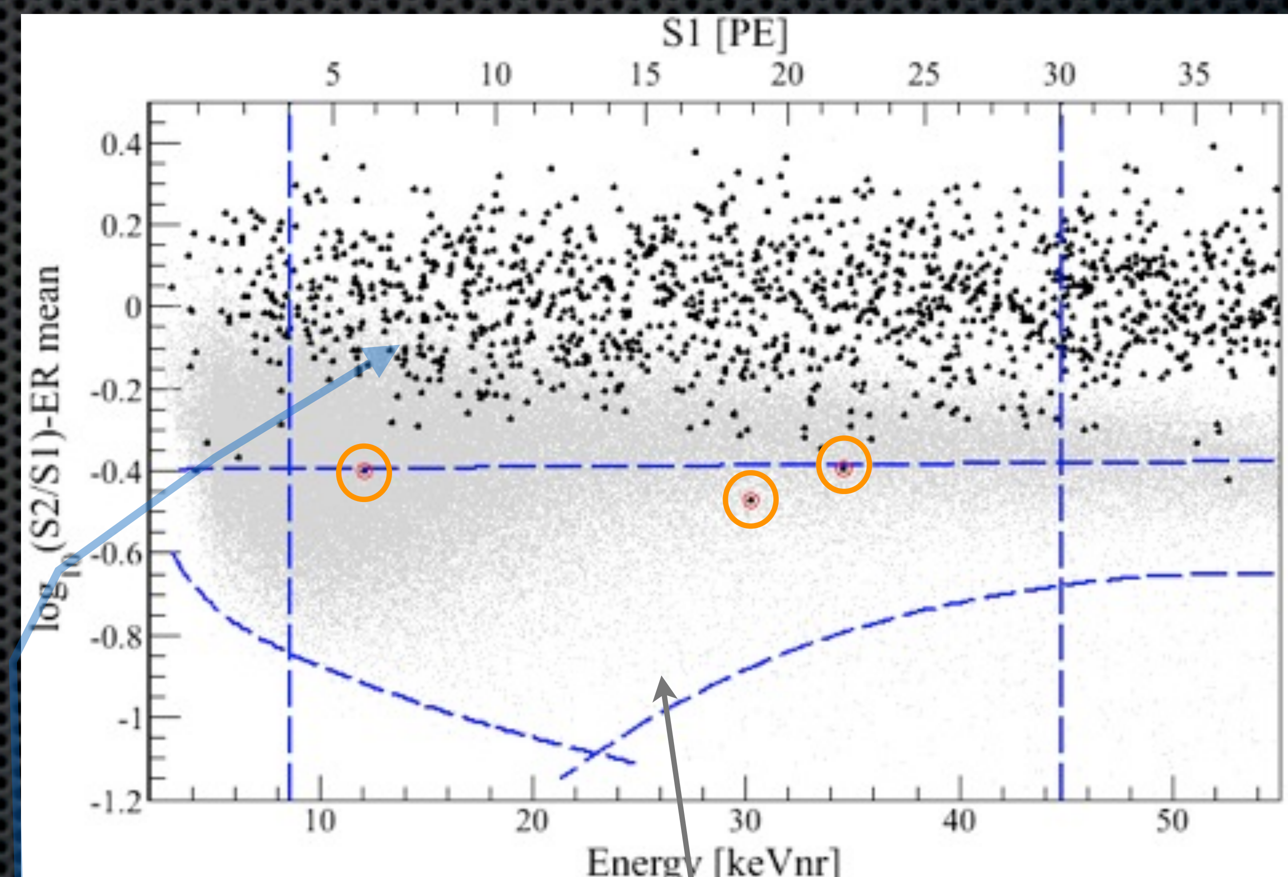
XENON100 2010 Dark Matter Run



XENON100: New Results

- Exposure: ~ 1471 kg days; data taken during January - June 2010



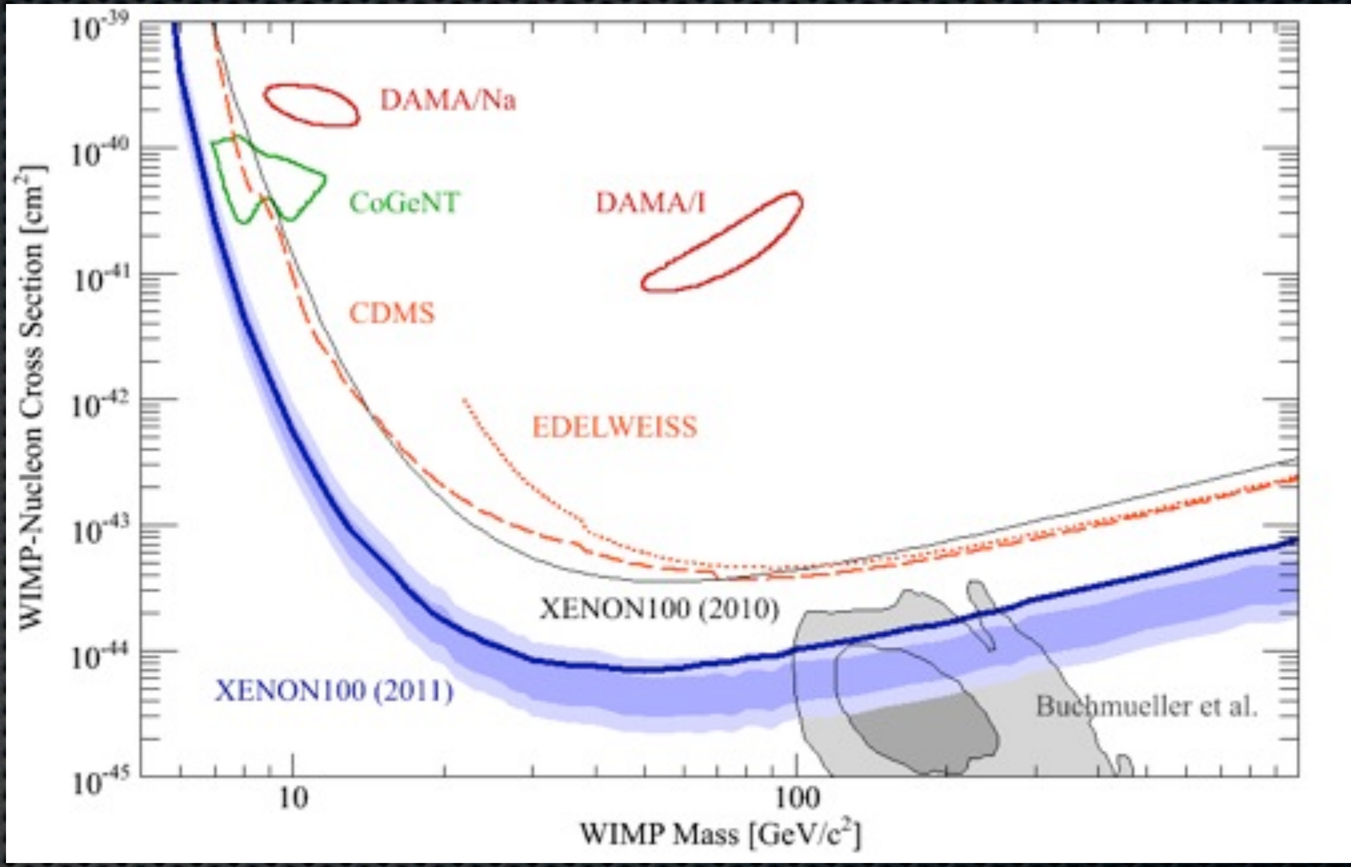


Fiducial mass region:
48 kg of liquid xenon
900 events in total

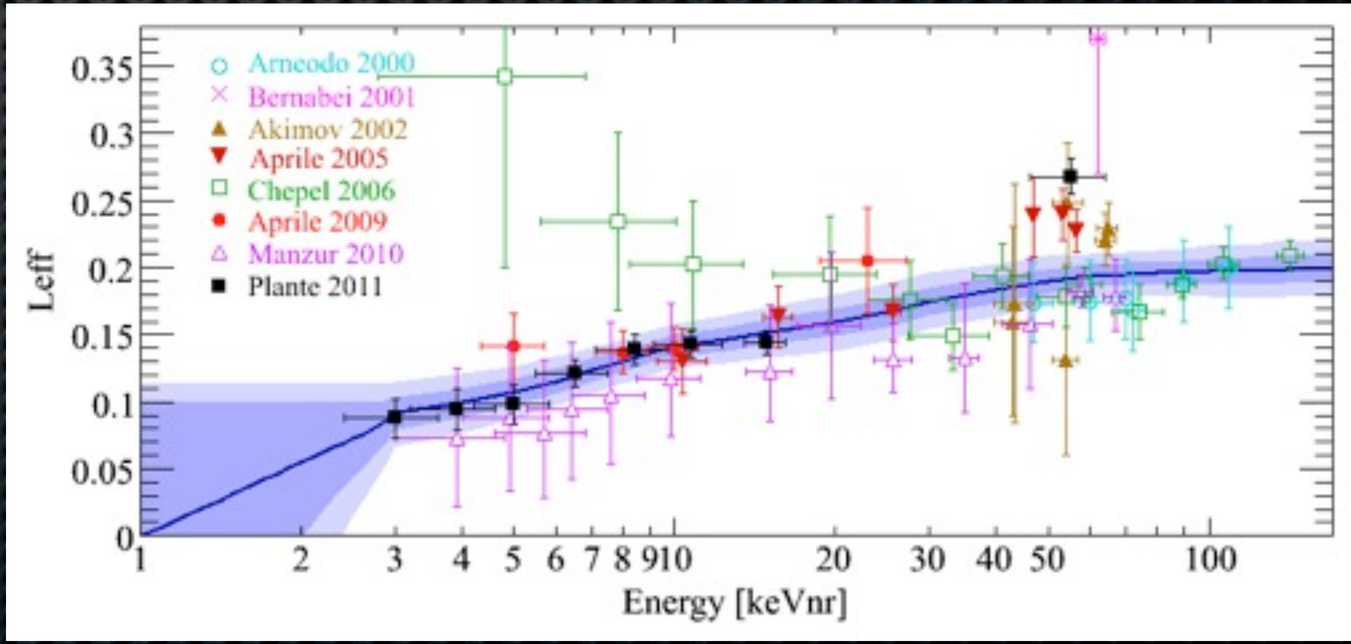
Signal region:
3 events are observed
1.8 ± 0.6 gamma leakage events expected
0.1 ± 0.08 ± 0.04 neutron events expected

XENON100: New Results

XENON collaboration, arXiv:1104.2549v1 [astro-ph.CO]

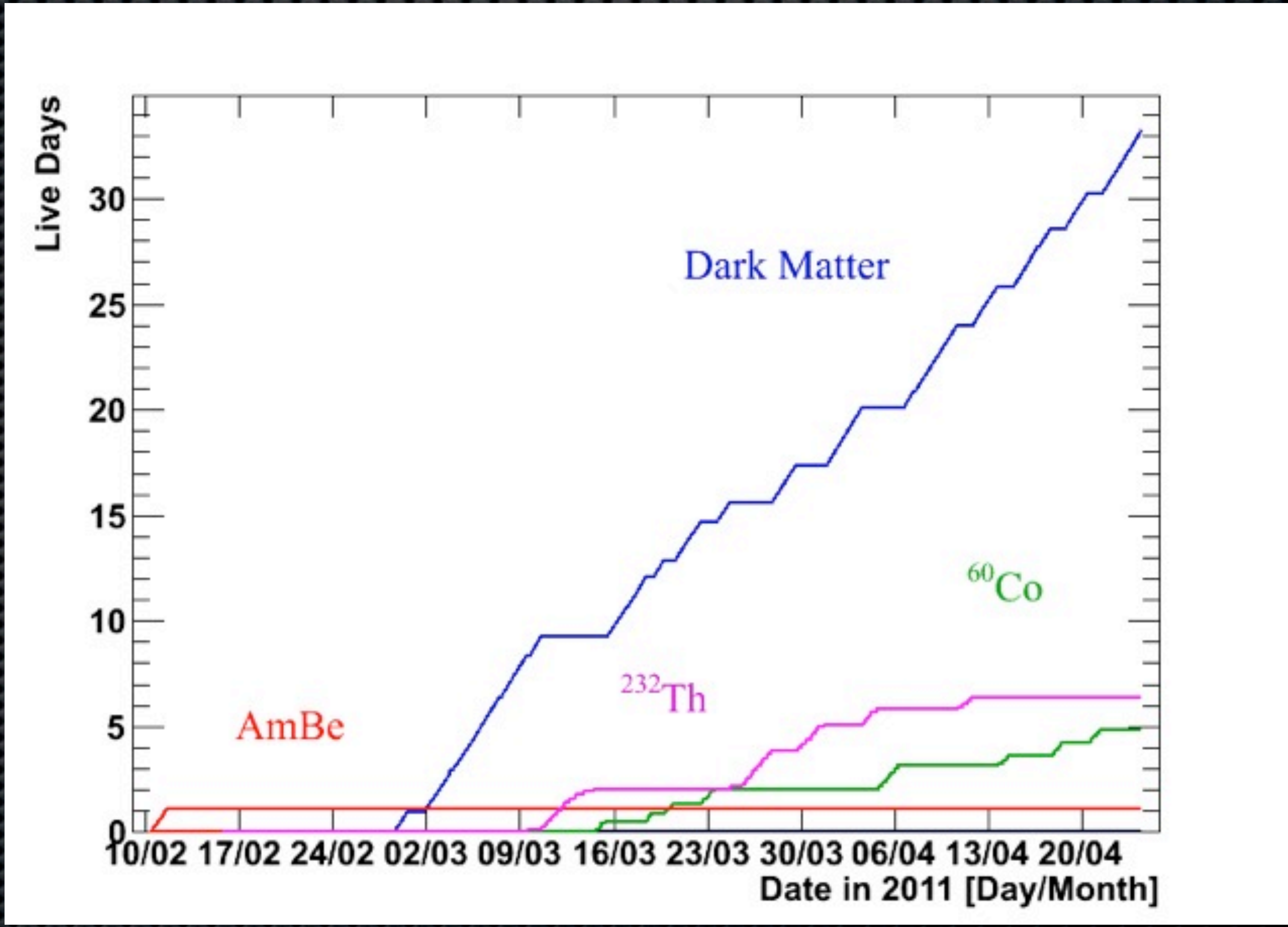


- Blue bands: 1- and 2-sigma expectations, based on zero signal
- Limit (dark blue) is 1.5-2 sigma worse than expectations, given 2 events observed at high S1
- At a WIMP mass of 50 GeV, the limit on the SI WIMP-nucleon cross section is 7×10^{-45} cm^2 (90% C.L.)
- Limit is robust against extrapolation of L_{eff} below 3 keVr

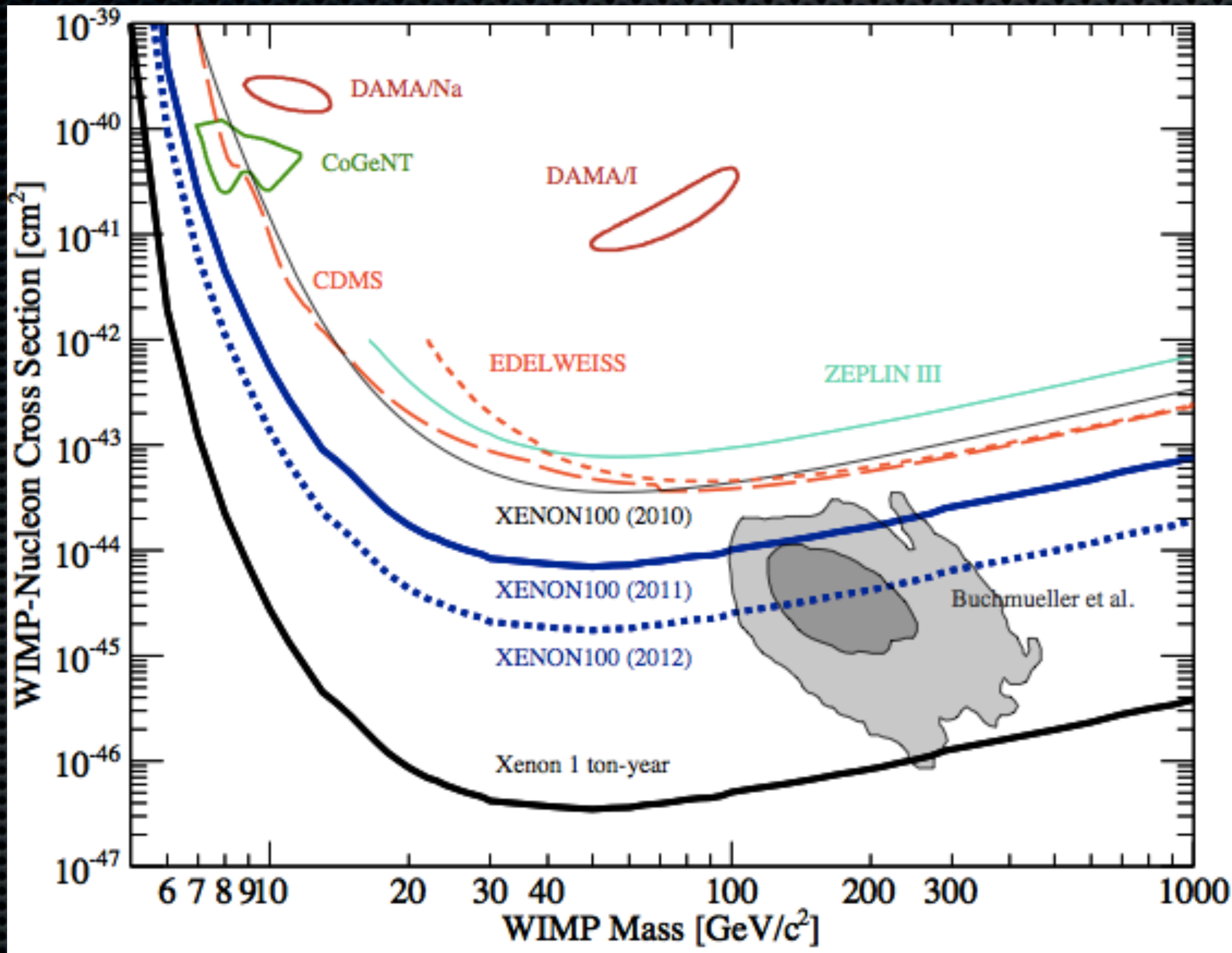


XENON100: Status

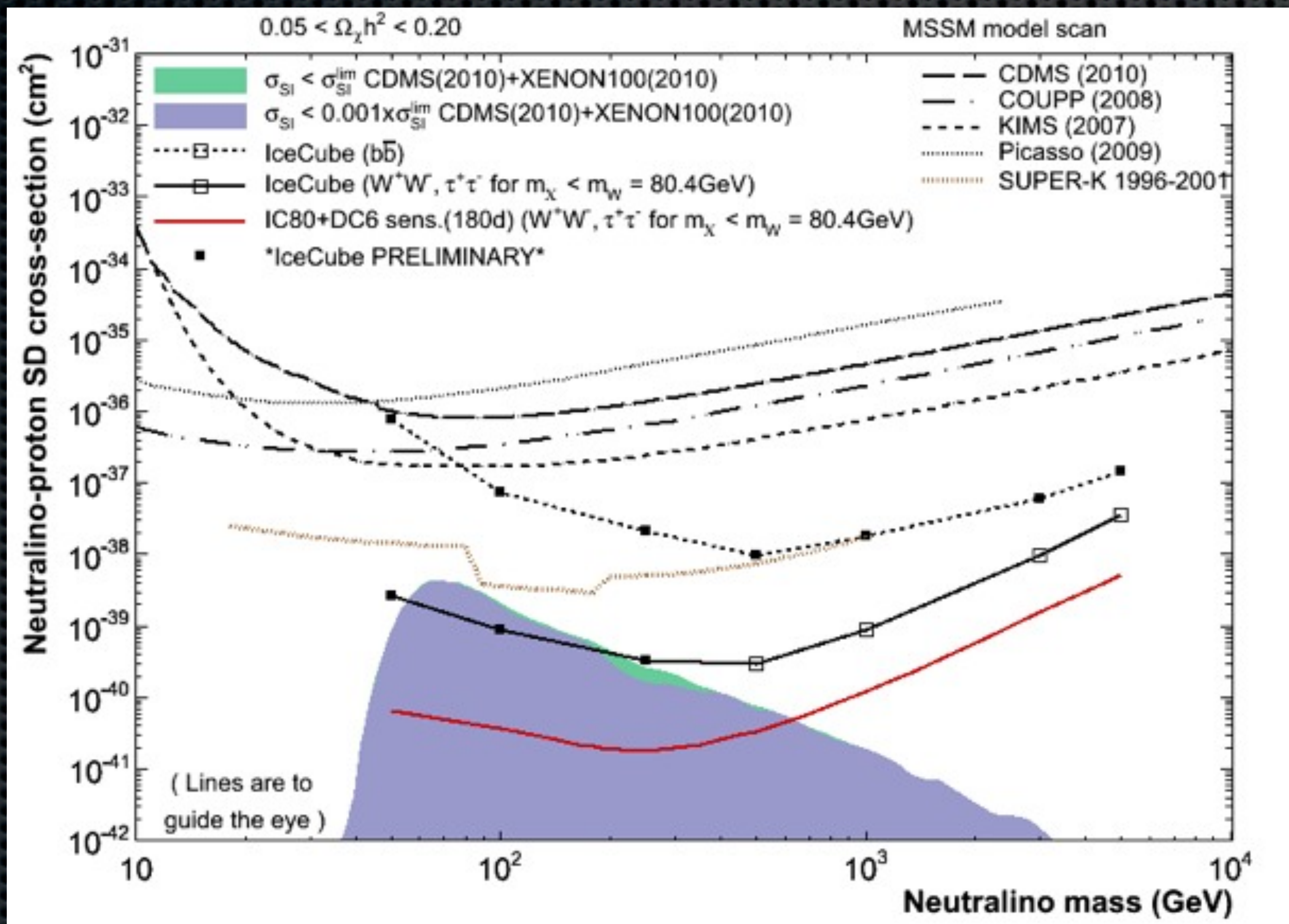
- New AmBe calibration
- Taking ^{60}Co and ^{232}Th calibration data
- Dark matter run since March
- Background back to level in 2009



XENON100: expected sensitivity



IceCube: competitive limits for SD WIMP-nucleon interactions



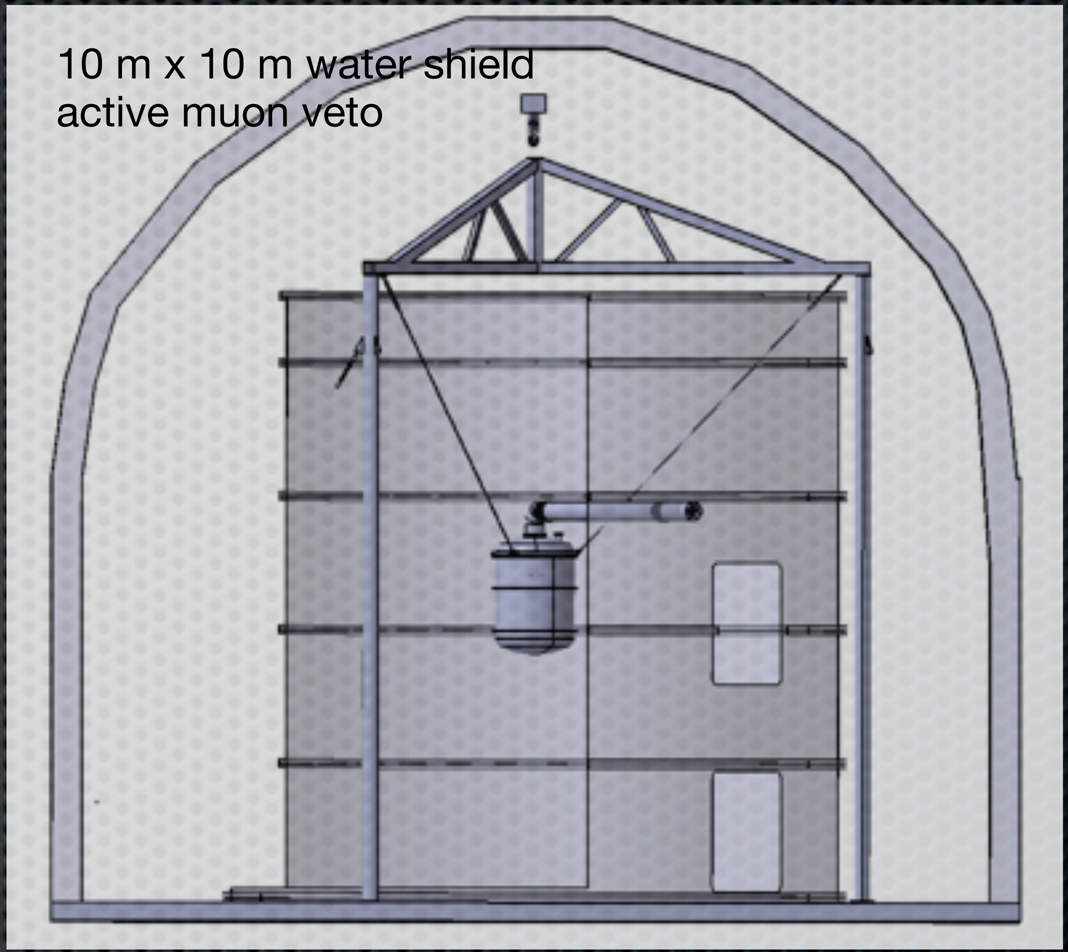
C. de los Heros
Madrid, April 2011

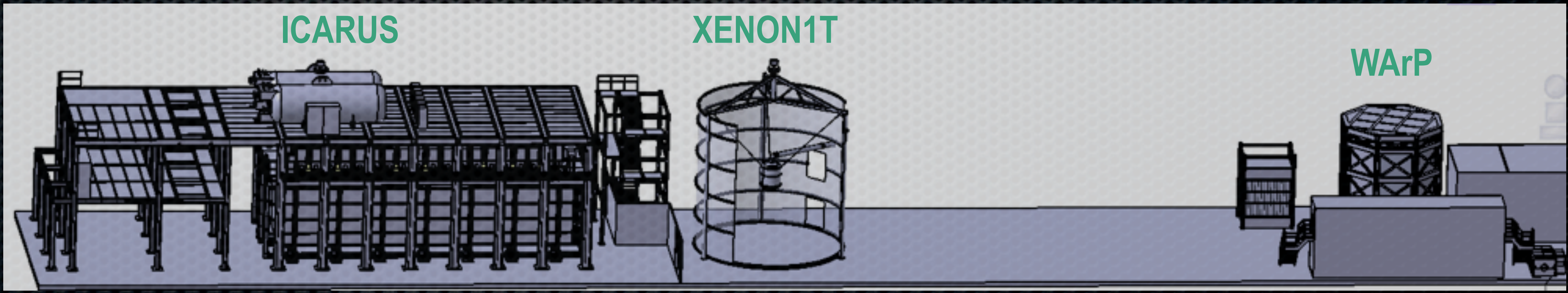
Next Phase: XENON1T

Designed to probe the σ-region down to 5×10^{-47} cm^2

TDR submitted to LNGS in October, 2010

Construction to start in late 2011
Full physics reach by 2015

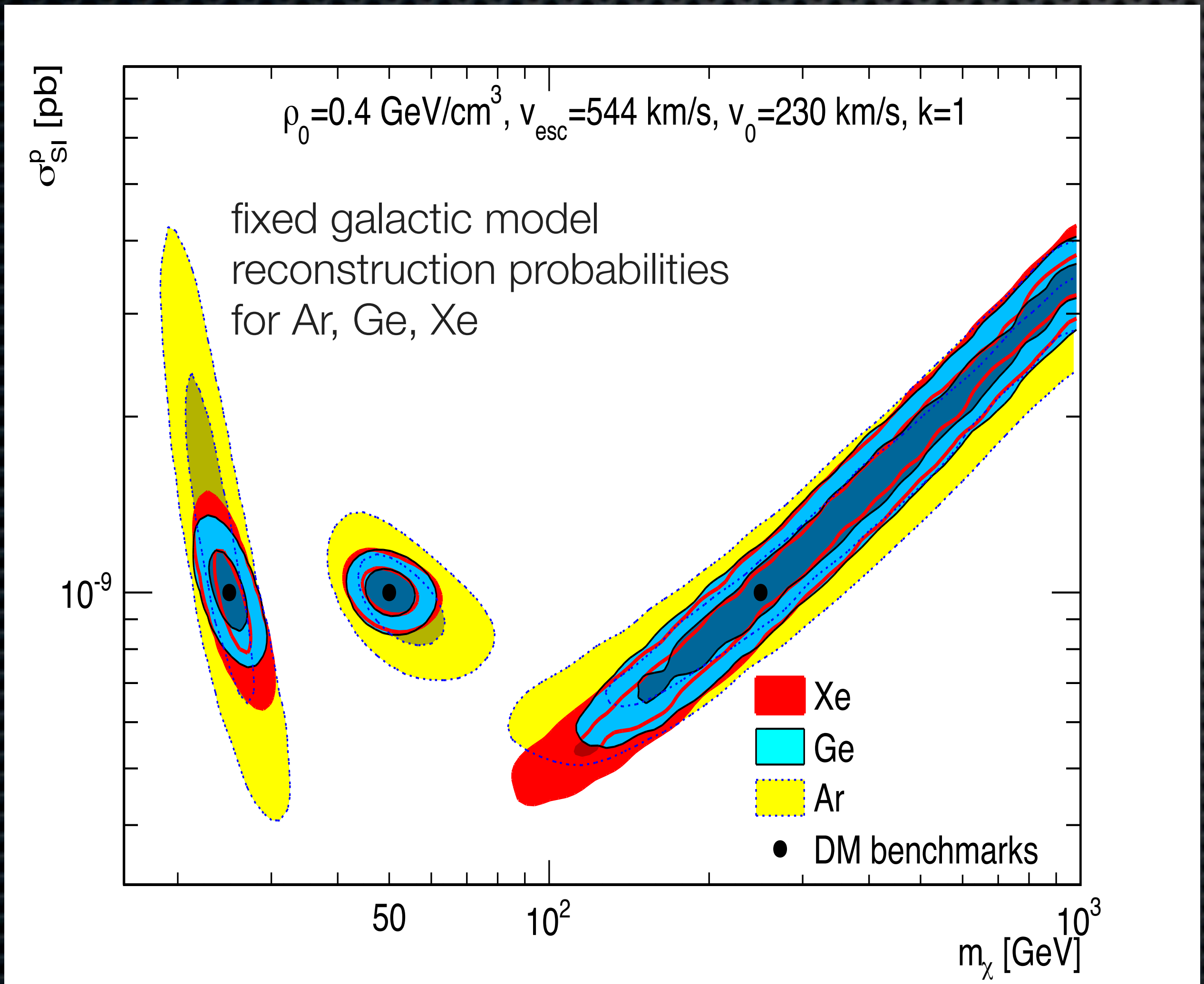


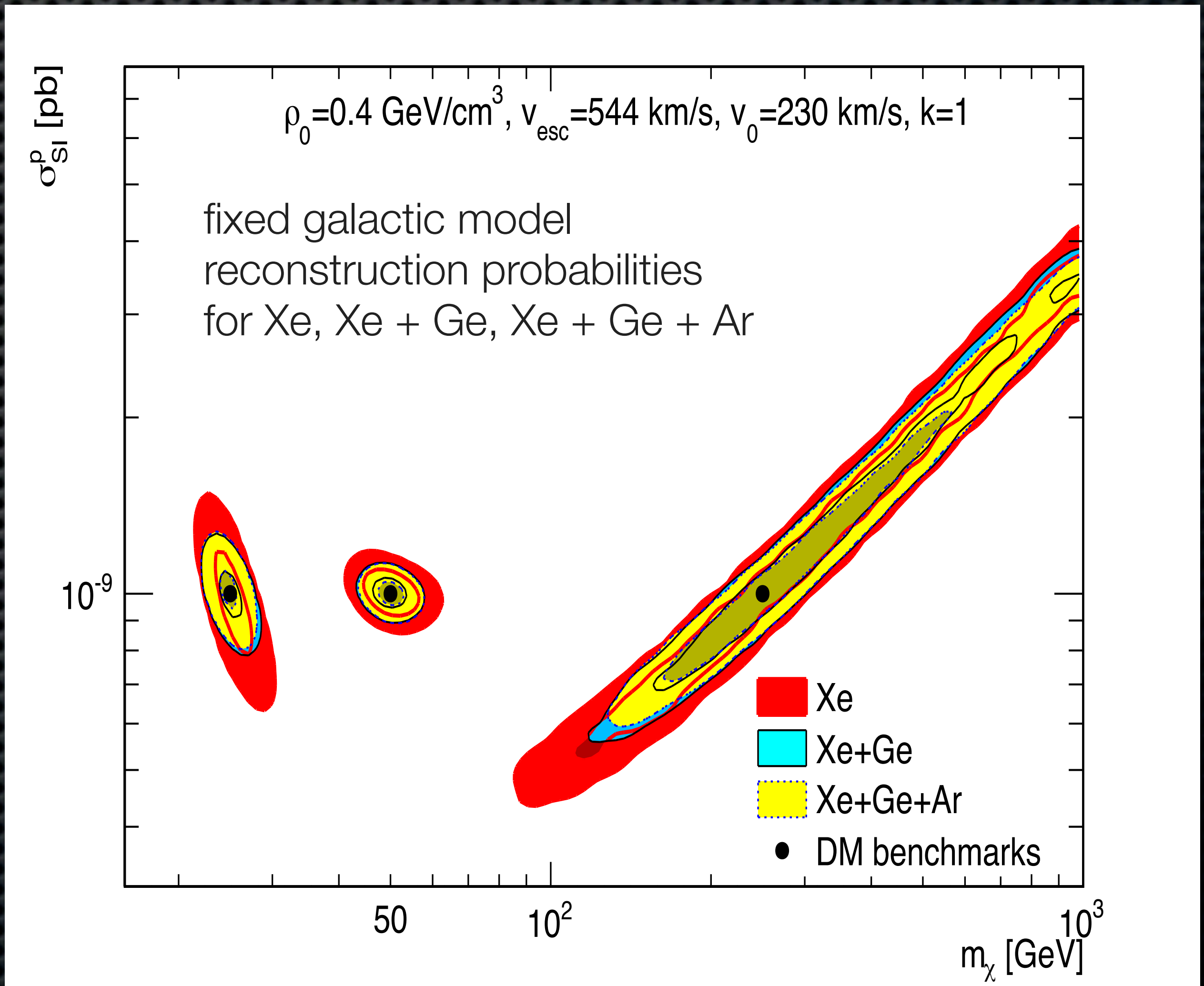


Beyond Current Detectors: DARWIN

- To reconstruct WIMP properties such a mass and scattering cross section we will (likely) need larger detectors for high-stats recoil spectra

astro-ph.CO: 1012.3458, accepted in PRD (2011)

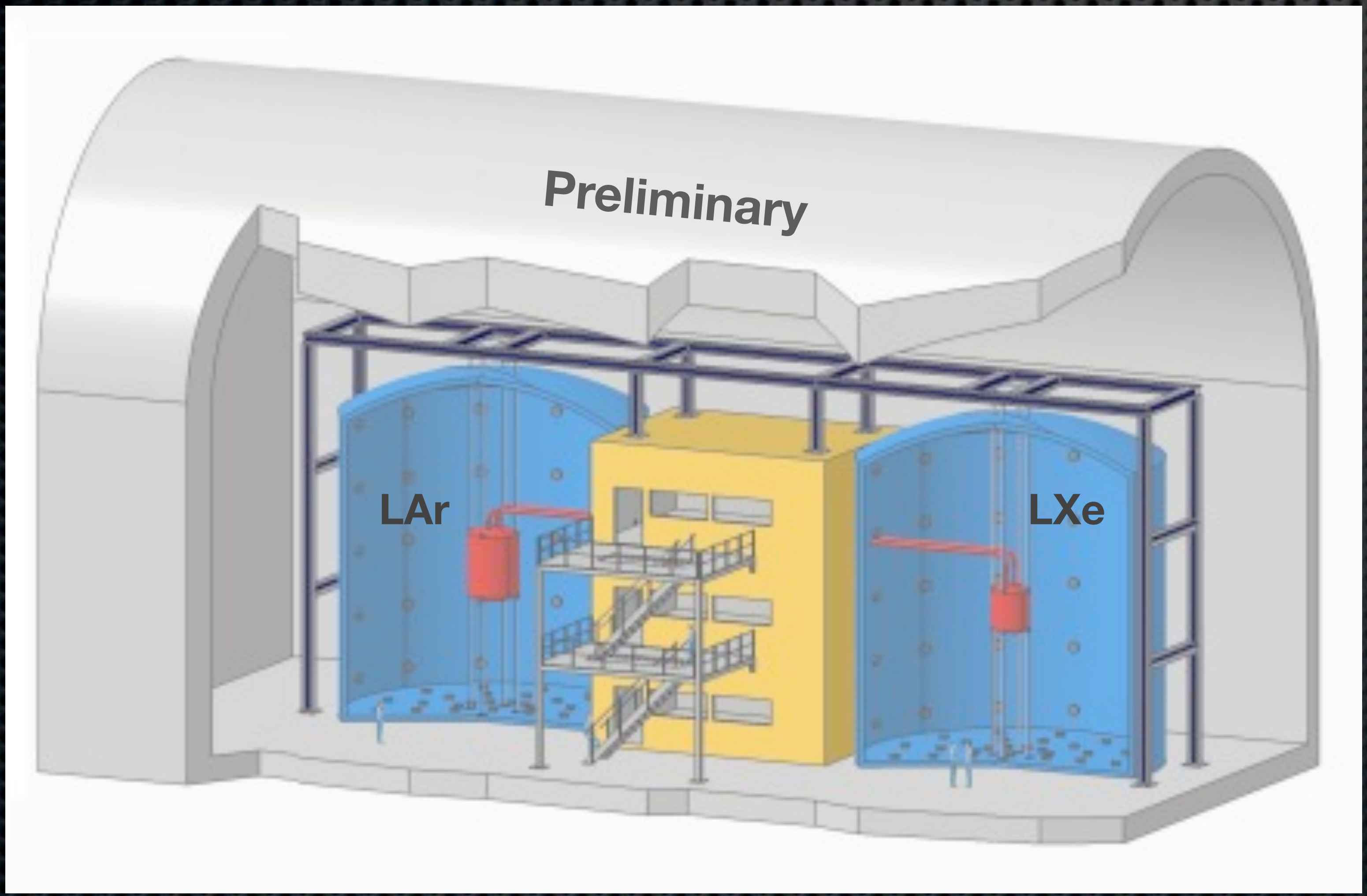




Miguel Pato, Laura Baudis, Gianfranco Bertone, Roberto Ruiz de Austri, Louis E. Strigari and Roberto Trotta

DARWIN: DARk matter WImp search with Noble liquids

- R&D and design study for next-generation noble liquid detector in Europe
- Location: Gran Sasso (Italy) or ULISSE (Modane Lab extension, France)
- Physics goal: prove WIMP-nucleon cross sections beyond 10^{-47} cm^2



DARWIN

2009 - 2012: R&D and Design Study
2013: Submission of LoI, engineering studies
2014 - 2015: Construction and commissioning
2016 - 2020: Operation, physics data

(darwin.physik.uzh.ch)

arXiv:1012.4764v1

Summary and Prospects

Direct detection

discover relic particle

constrain $(m, \rho\times\sigma)$

with input from LHC/ILC

determine ρ_{local}

LHC/ILC

discover new particles

determine physics model and m_{WIMP}

predict direct/indirect cross sections

Indirect detection

discover relic particle

constrain $(m, \sigma\times\int\rho^2)$

with input from LHC/ILC

determine $\rho_{GC/halo}$

End