Dark matter: overview of terrestrial, non-accelerator experiments; DARWIN

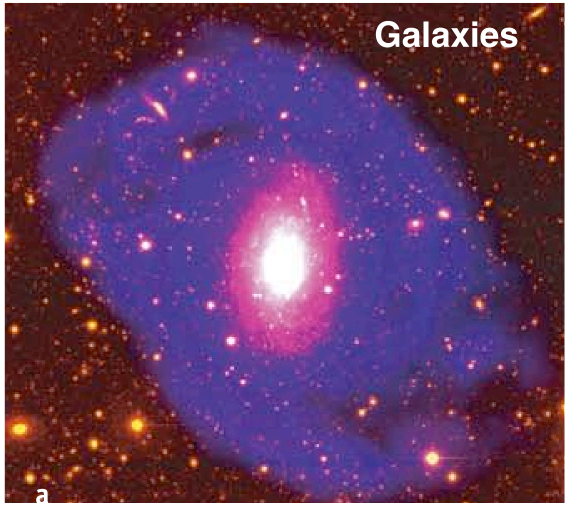
LAUNCH 09

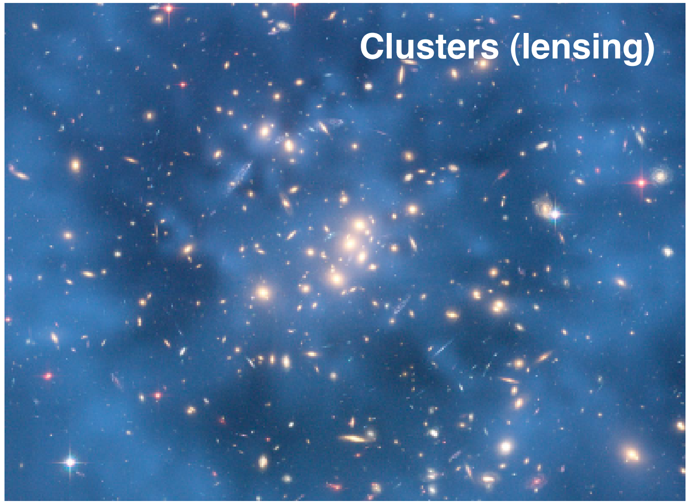
Heidelberg, November 10, 2009

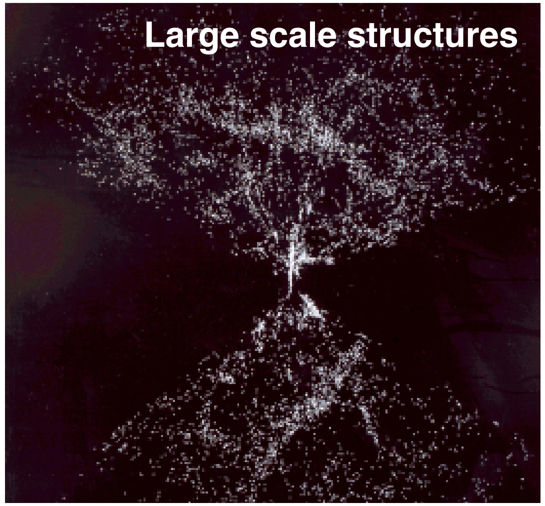
Laura Baudis

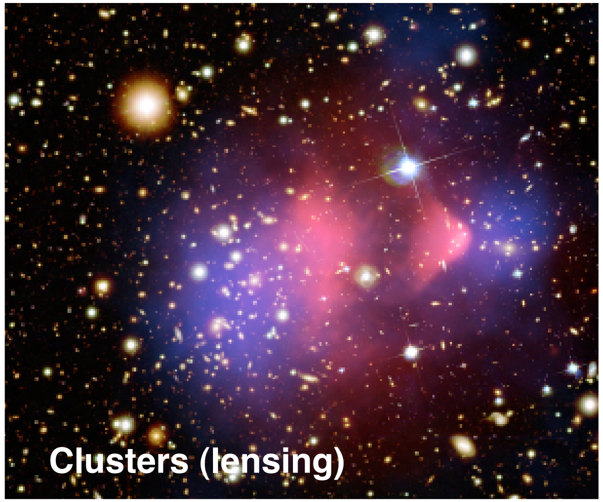
University of Zurich

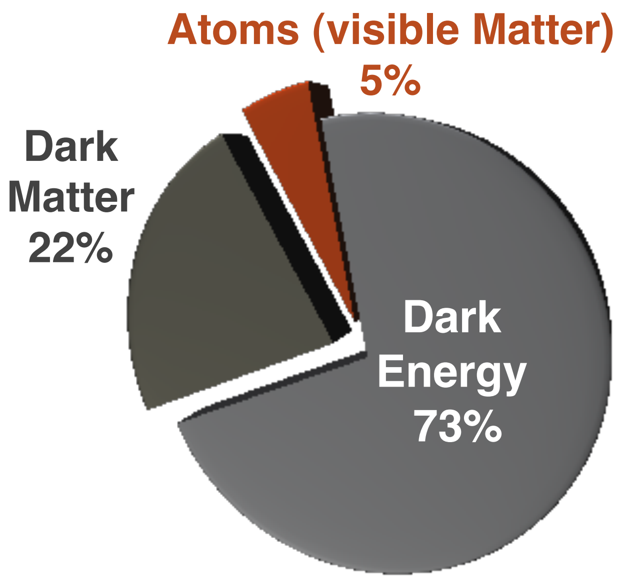
Matter and Energy Content of our Universe

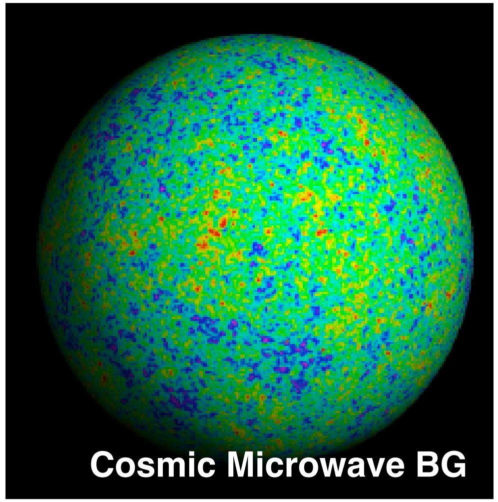












Dark matter candidates

- Theorists provide *strong* guidance to us experimentalists

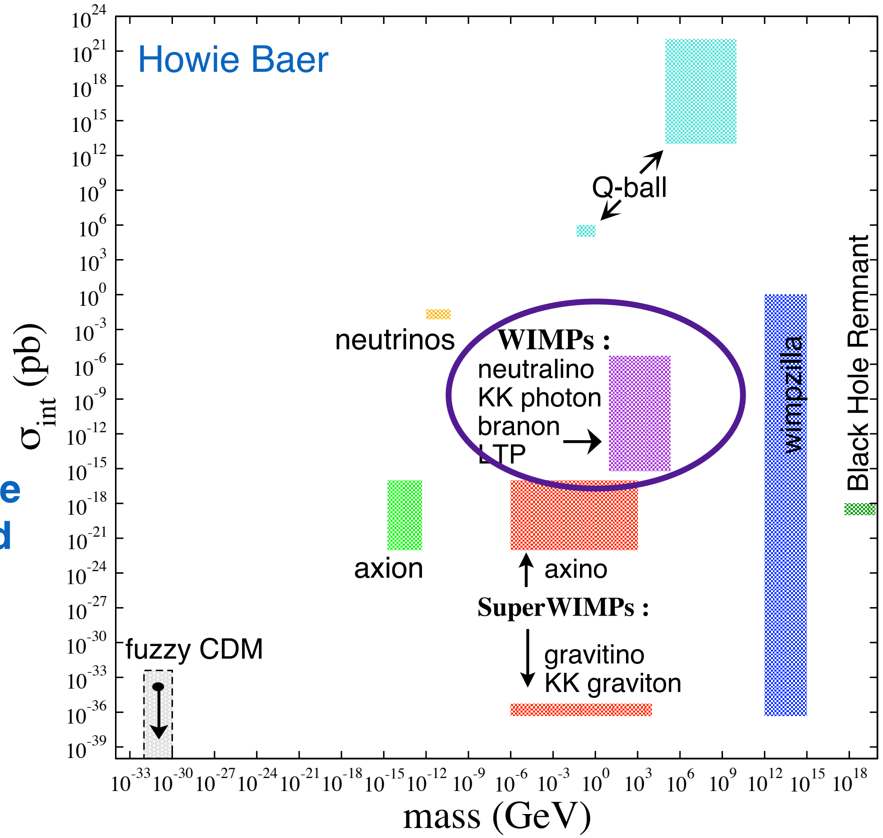
- Prediction for the mass of a dark matter particle span (at least) 29 orders of magnitude:
  - ➡ from **10^{-6} eV** (axion) to **10^{15} GeV** (WIMPzilla)

- Predicted cross sections:
  - ➡ from non-interacting (gravitino)
  - ➡ to strongly interacting (Qballs)

The dark matter must be some particle state not contained in the standard model.

One good idea are WIMPs (weakly interacting massive particles): thermal relics, well motivated (not invented to solve the dark matter problem) and testable

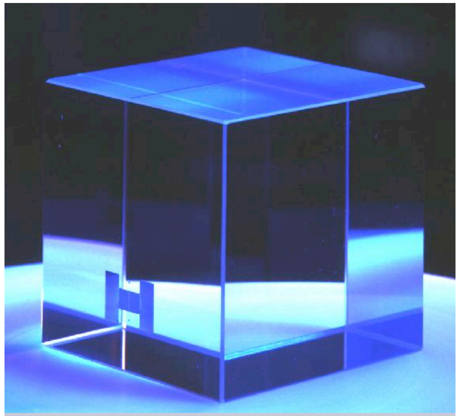
Most popular candidate: the neutralino, as the lightest supersymmetric particle; mass: ~ 10 GeV - few TeV



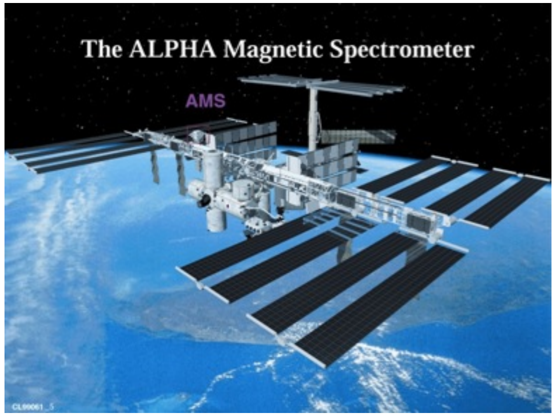
Laura Baudis, University of Zurich, LAUNCH, MPIK Heidelberg, Nov 10, 2009

The WIMP hypothesis is *testable*

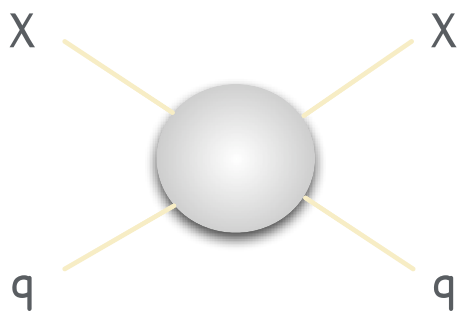
Underground

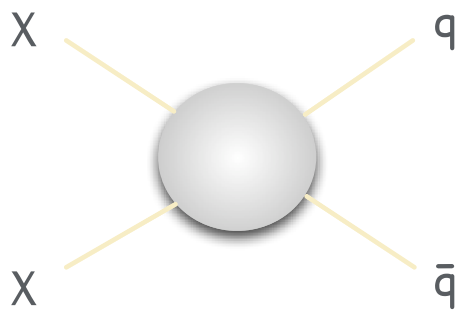


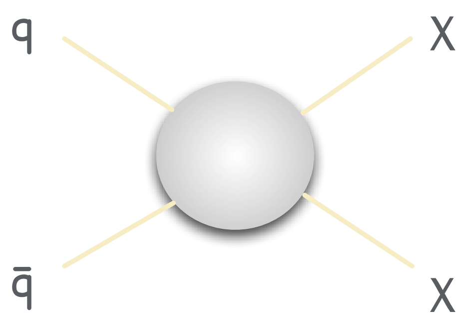
Above ground



At the LHC

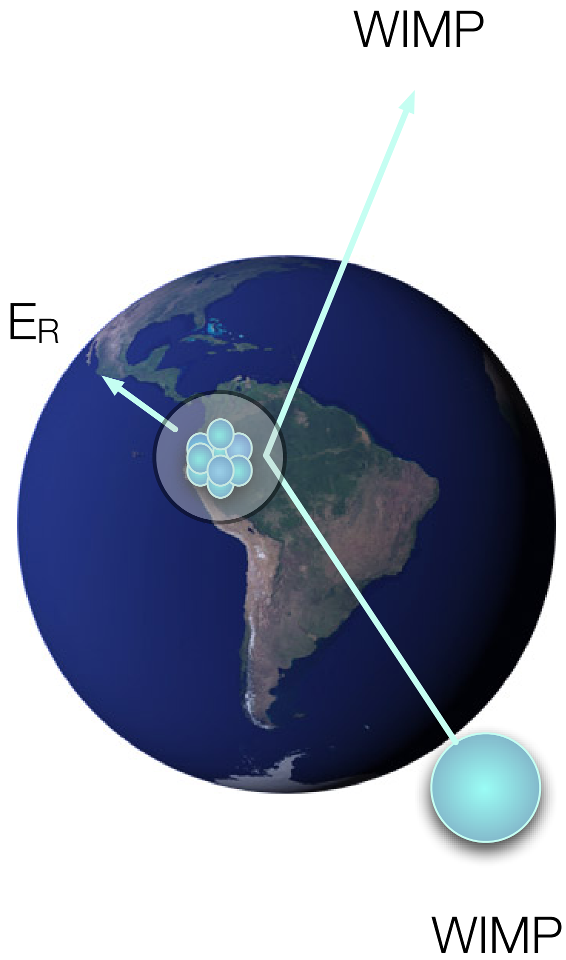






We hope to learn a lot from direct detectors, from indirect detectors and from accelerators!

Direct Detection of WIMPs: principle



- **Elastic collision between WIMPs and target nuclei**
- The recoil energy of the nucleus is:

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

- q = momentum transfer $|\vec{q}|^2 = 2\mu^2 v^2 (1 - \cos\theta)$
- μ = reduced mass (m_N = nucleus mass; m_χ = 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

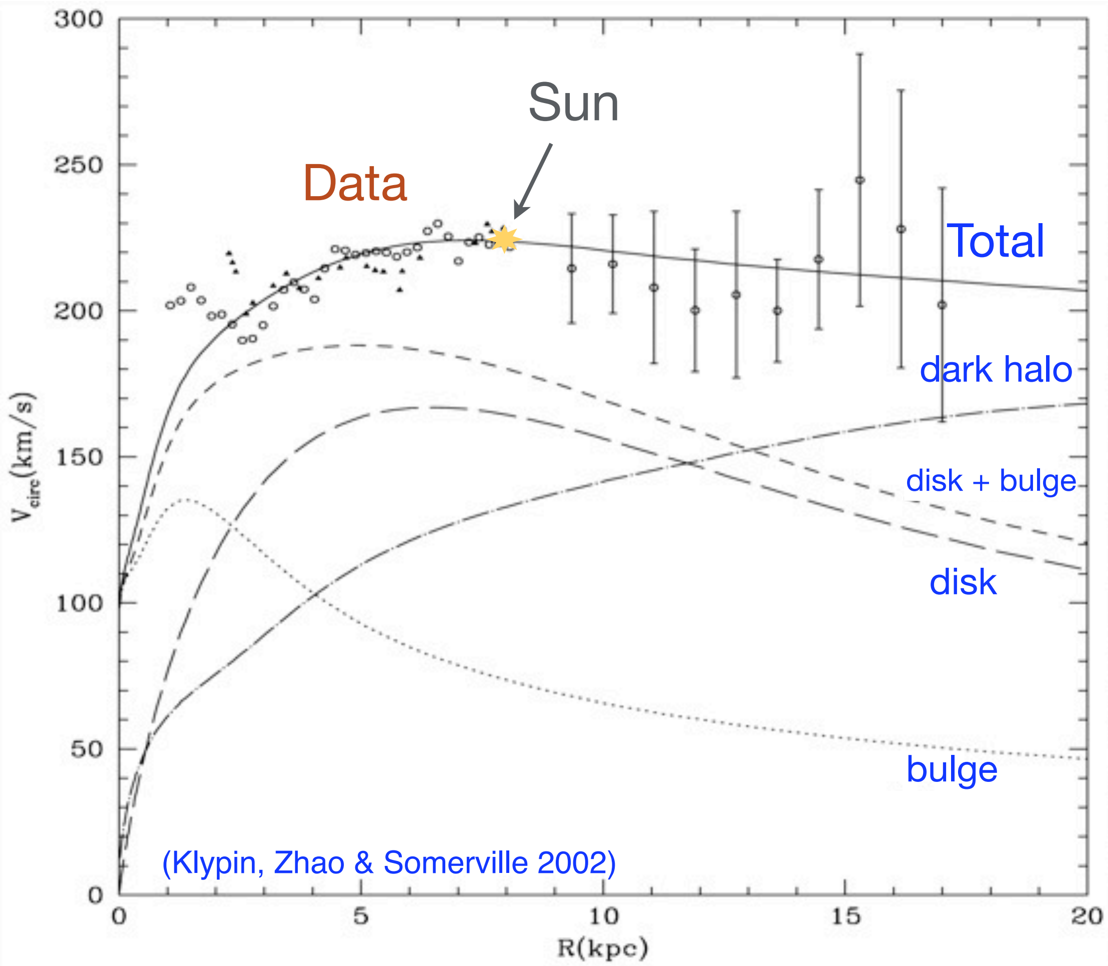
$$R \propto N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \cdot \langle v \rangle$$

Particle physics

- N = number of target nuclei in a detector
- ρ_χ = local density of the dark matter in the Milky Way
- <v> = mean WIMP velocity relative to the target
- m_χ = WIMP-mass
- $\sigma_{\chi N}$ =cross section for WIMP-nucleus elastic scattering

Astrophysics Input

Local Density of WIMPs in the Milky Way



Particle data group:

$$\rho_{halo} = 0.1 - 0.7\ GeVcm^{-3}$$

$$\rho_{disk} = 2 - 7\ GeVcm^{-3}$$

'Standard' value:

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

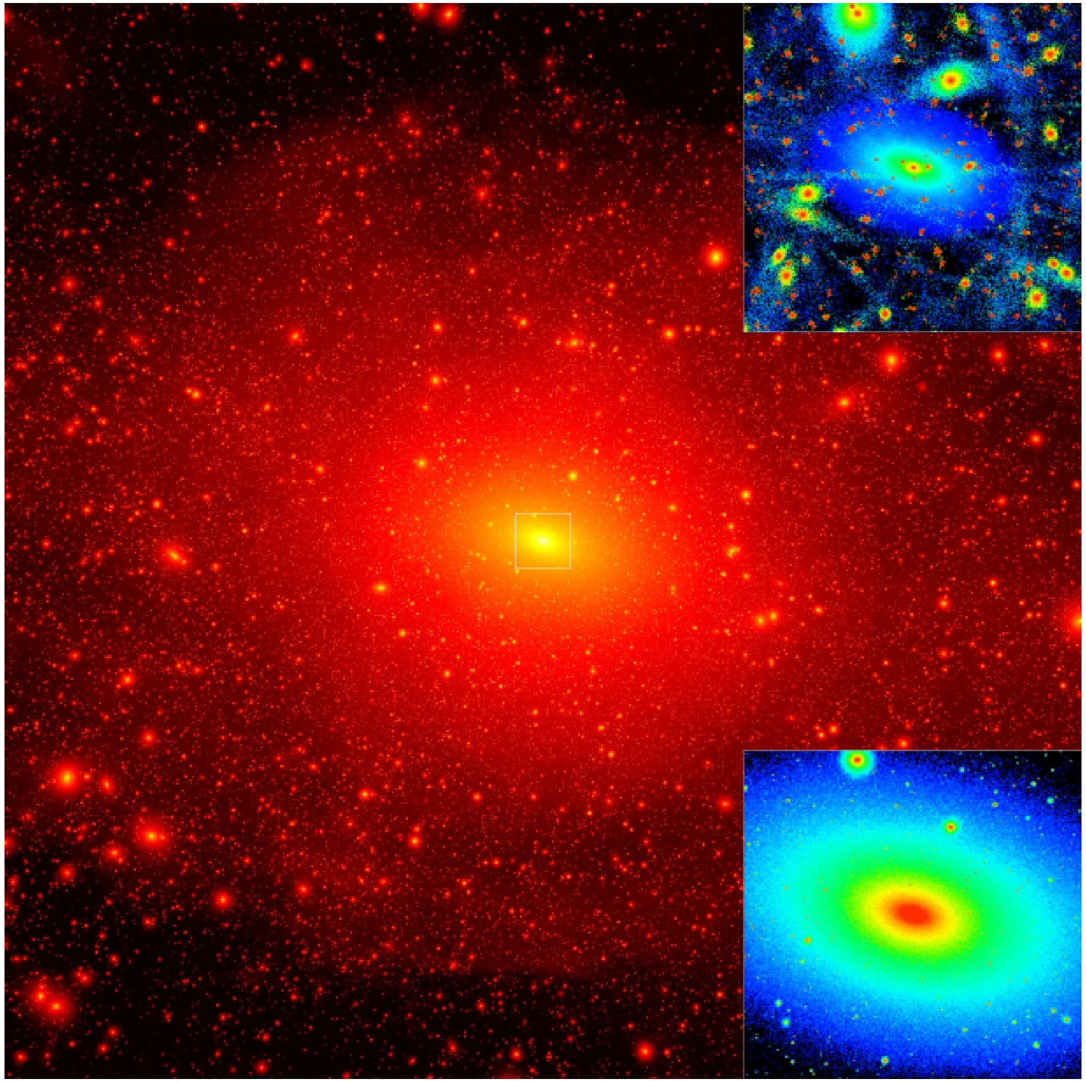
$$\rho_{\chi} \simeq 3000\ \text{WIMPs} \cdot m^{-3}$$

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

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

Simulations of the Milky Way Dark Halo



~ 600 kpc

inner 20 kpc: phase space density

high resolution (10^9 particles) cosmological CDM simulation of a Milky Way type halo

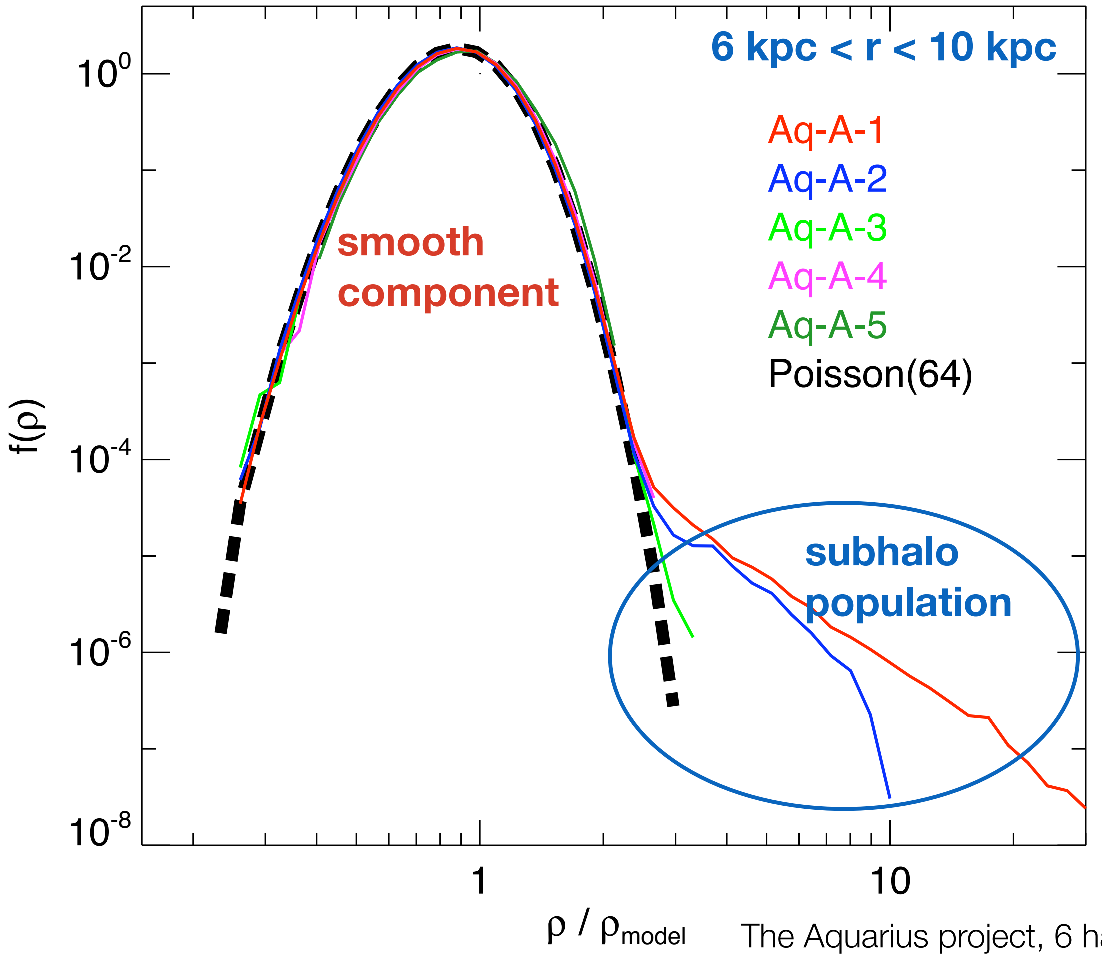
inner 20 kpc: density

Ben Moore et al, UZH, 2008
http://xxx.lanl.gov/pdf/0805.1244v1

Spatial Distribution of the Dark Matter

- **1. Question**: how smooth is the dark matter *mass distribution* at the solar position?

Density probability distribution around the solar circle



The Aquarius project, 6 halos; arXiv: 0812.0362

High resolution simulations of six galaxy halos taken from the Aquarius Project

Parameters for the Aquarius simulations:

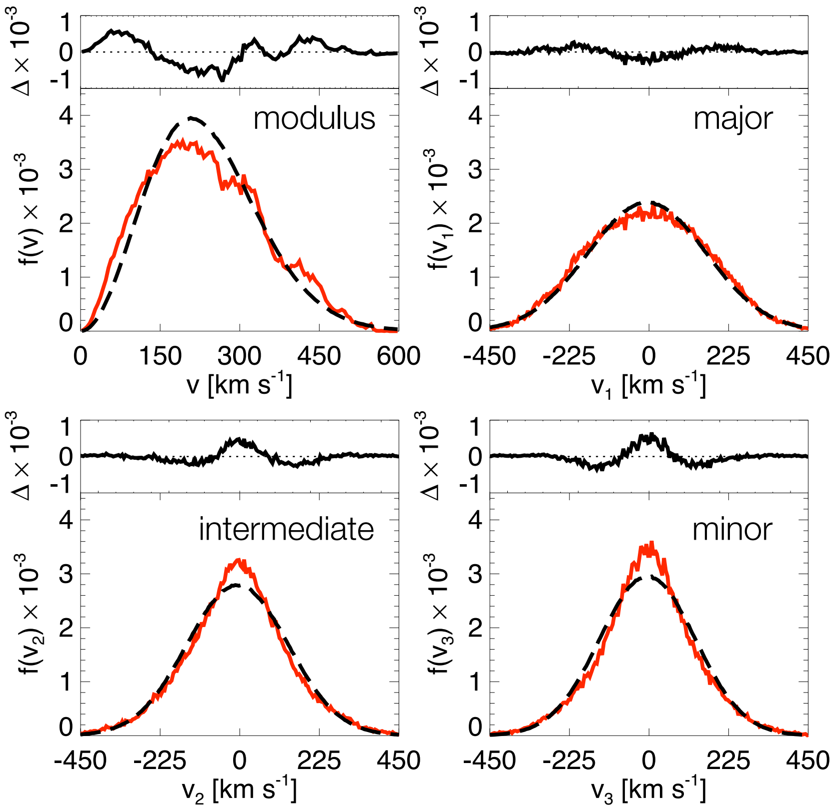
$\Omega_m = 0.25$
$\Omega_\Lambda = 0.75$
$H_0 = 100\ h\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$
$h = 0.73$

Answer:
- very smooth
- substructure is far from Sun

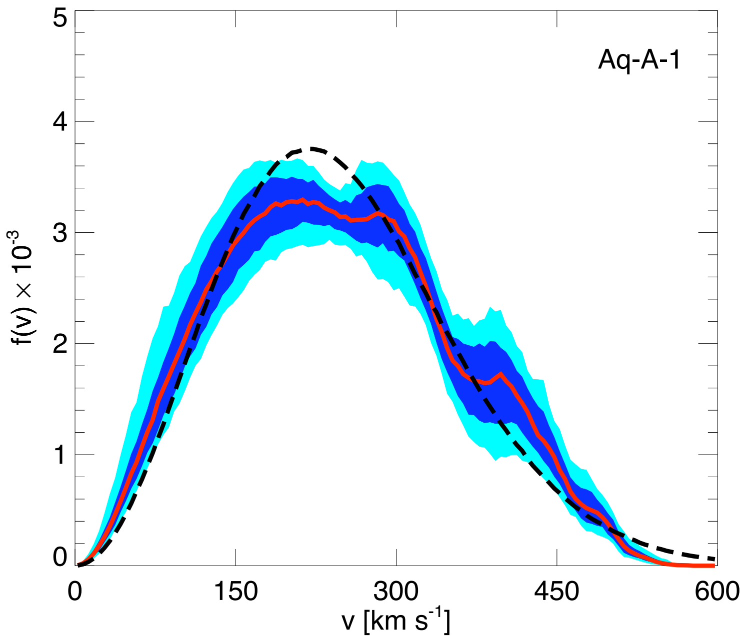
Velocity Distribution of the Dark Matter

- **2. Question:** how smooth is the dark matter *velocity distribution* at the solar position?

Velocity distribution in a 2 kpc box the solar circle



Answer: smooth, no streams almost Maxwellian



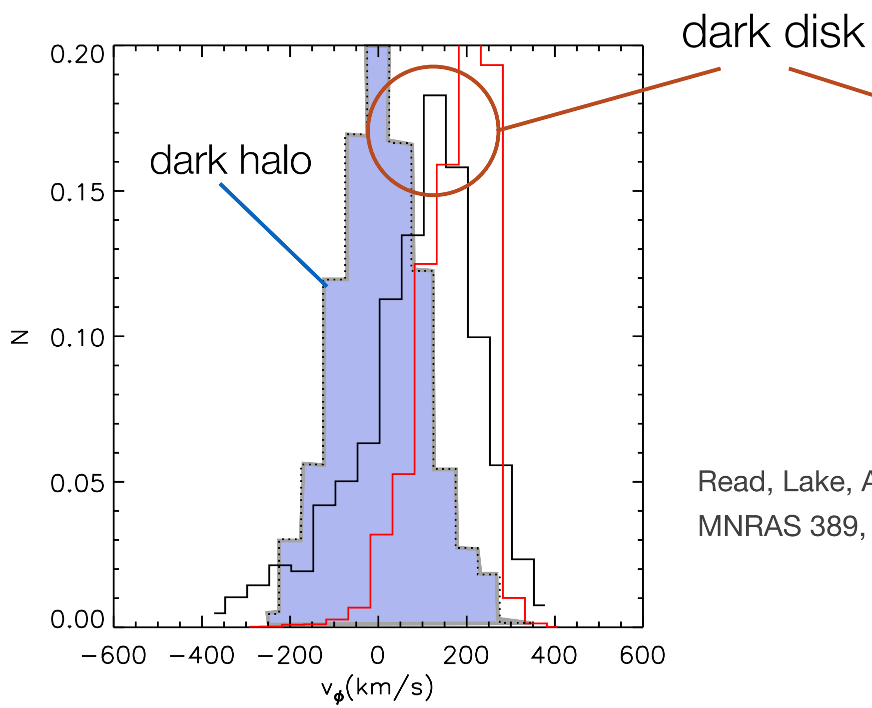
The Aquarius project, 6 halos; arXiv: 0812.0362

- **But: can we ignore the baryons?** The dark matter only simulations have established a baseline for future work.

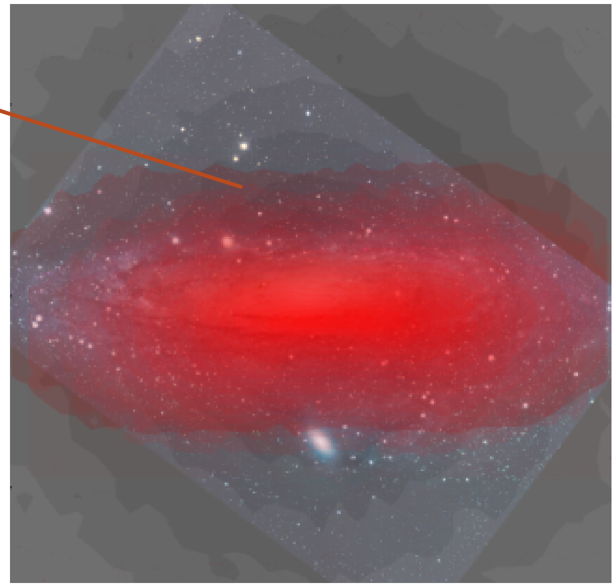
Laura Baudis, University of Zurich, LAUNCH, MPIK Heidelberg, Nov 10, 2009

A Dark Matter Disk in the Milky Way?

- In ΛCDM numerical simulations which include the influence of baryons on the dark matter, it has been found that:
  - ➡ stars and gas settle onto the disk early on, affecting how smaller dark matter halos are accreted
  - ➡ the largest satellites are preferentially dragged towards the disk by dynamical friction, then torn apart, forming a disk of dark matter
  - ➡ in the standard cosmology, the disk dark matter density is constrained to about 0.5 - 2 x halo density
  - ➡ as we shall see, its lower rotation velocity with respect to the Earth has implications for direct detection experiments



Read, Lake, Agertz, Debattista,
MNRAS 389, 1041, 2008



Particle Physics Input

Expected Scattering Cross Sections

- A general WIMP candidate: fermion (Dirac or Majorana), boson or scalar particle
- The most general, Lorentz invariant Lagrangian has 5 types of interactions (S, P, V, A,T)
- 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)

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

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

➡ **spin-spin interactions** (WIMPs couples to nuclear spin $\mathbf{J_N}$, from the axial part of L)

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

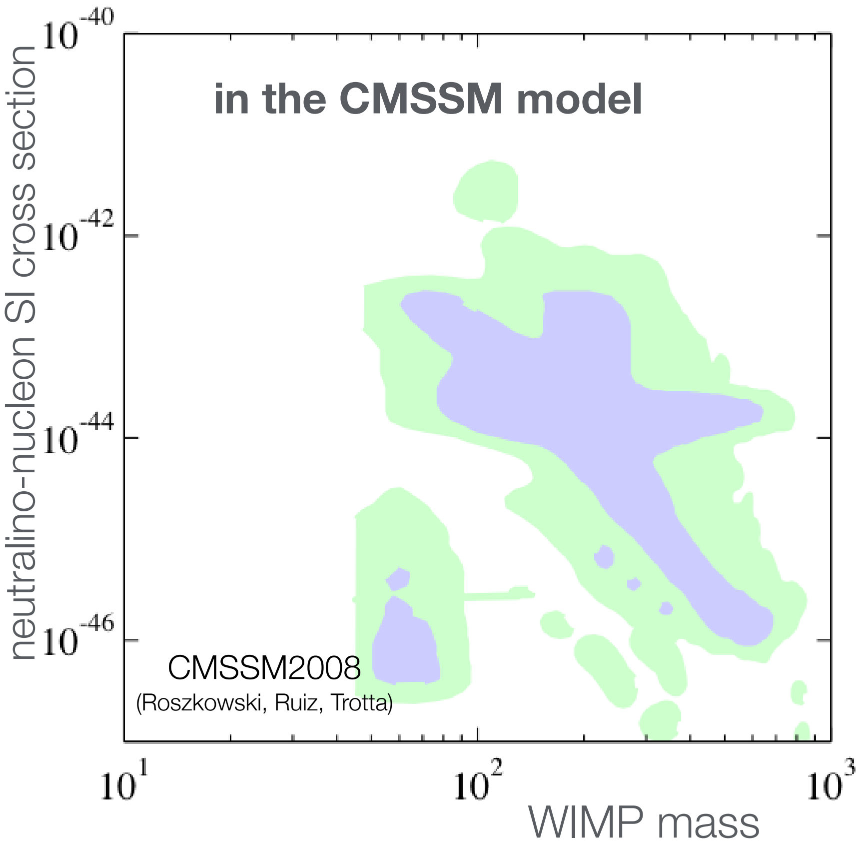
$\langle S_{p,n}\rangle$ = expectation values of the spin content of the p, n in the target nucleus

large hadronic uncertainties in the cross section
J. Ellis, K.A. Olive, C. Savage, PRD 77, 065026 (2008)

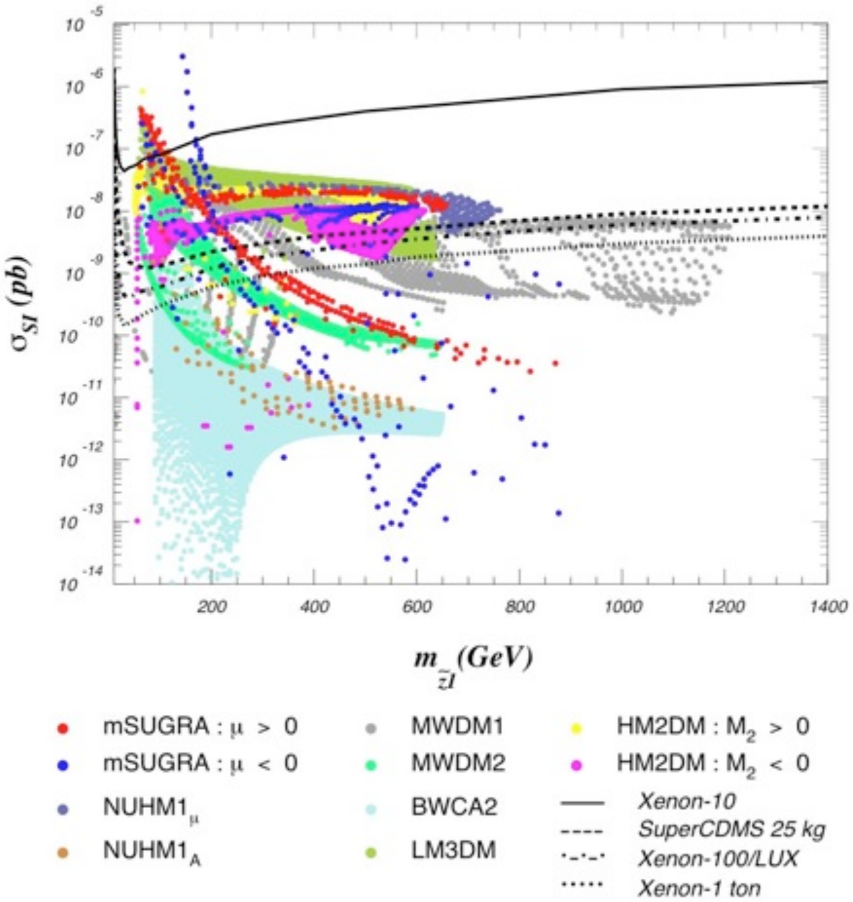
$a_{p,n}$ = effective couplings to p, n

WIMP Mass and SI Cross Section

- Example for predictions from supersymmetry [10^{-8} pb = 10^{-44} cm^2]:



H. Baer, arXiv:0812.2442



Putting it all together

Expected Interaction Rates

- Integrate over WIMP velocity distribution; in general assumed to be a simple 1D Maxwellian (good approximation for isothermal halo with ideal WIMP gas):

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

$$f(\vec{v},t) \propto \exp\left\{ \frac{-(\vec{v}+\vec{v}_E(t))^2}{2\sigma^2} \right\}$$

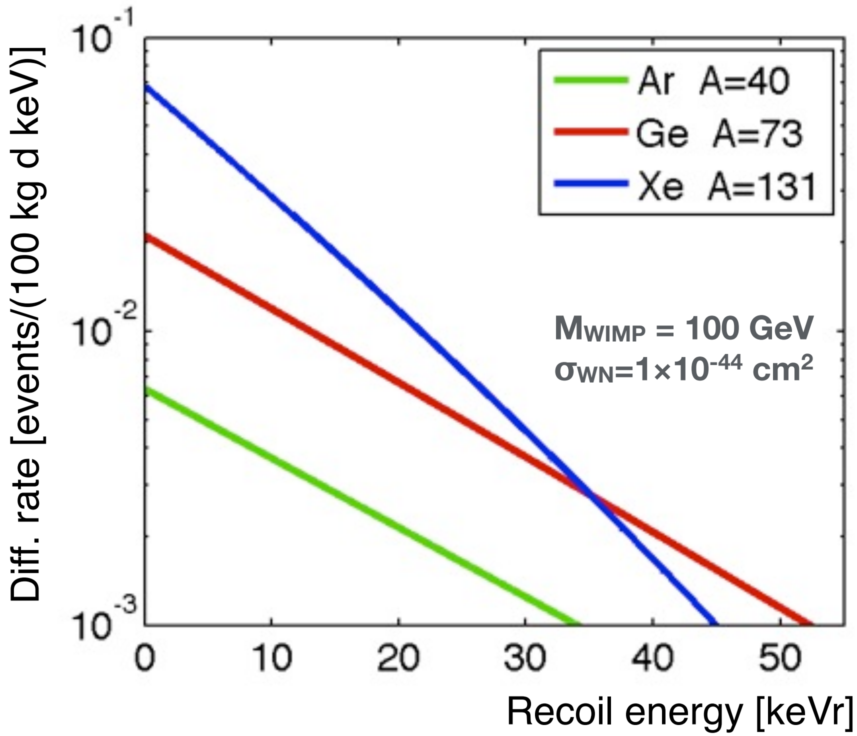
$$F^2(E_R) = \left[\frac{3 j_1(qR_1)}{qR_1} \right]^2 e^{-(qs)^2}$$ **Nuclear form factor**

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

< 1 event/100kg/day

Differential rates (per 100 kg and day) for different targets (Ar, Ge, Xe)

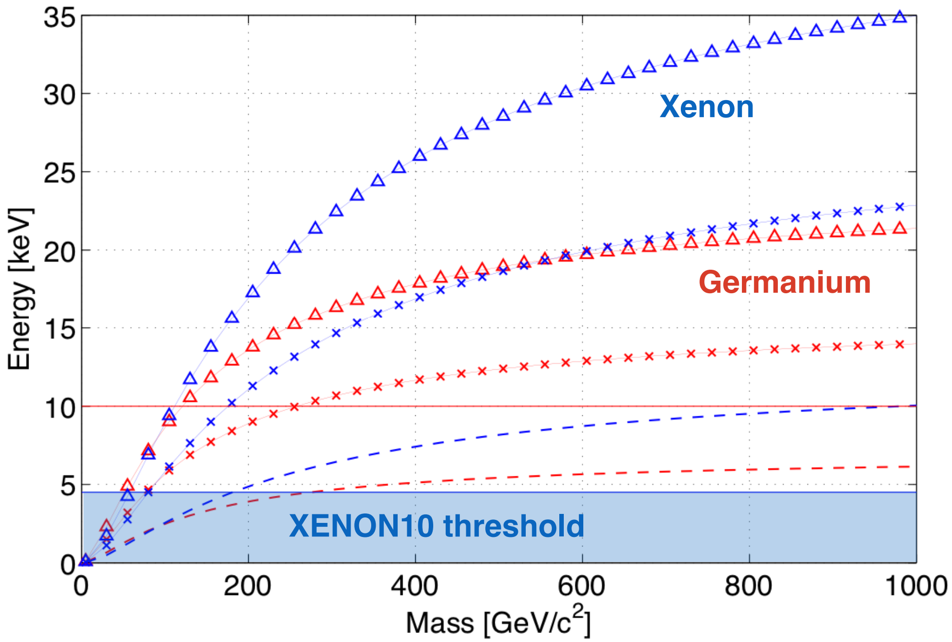
(Standard halo model with ρ= 0.3 GeV/cm³)

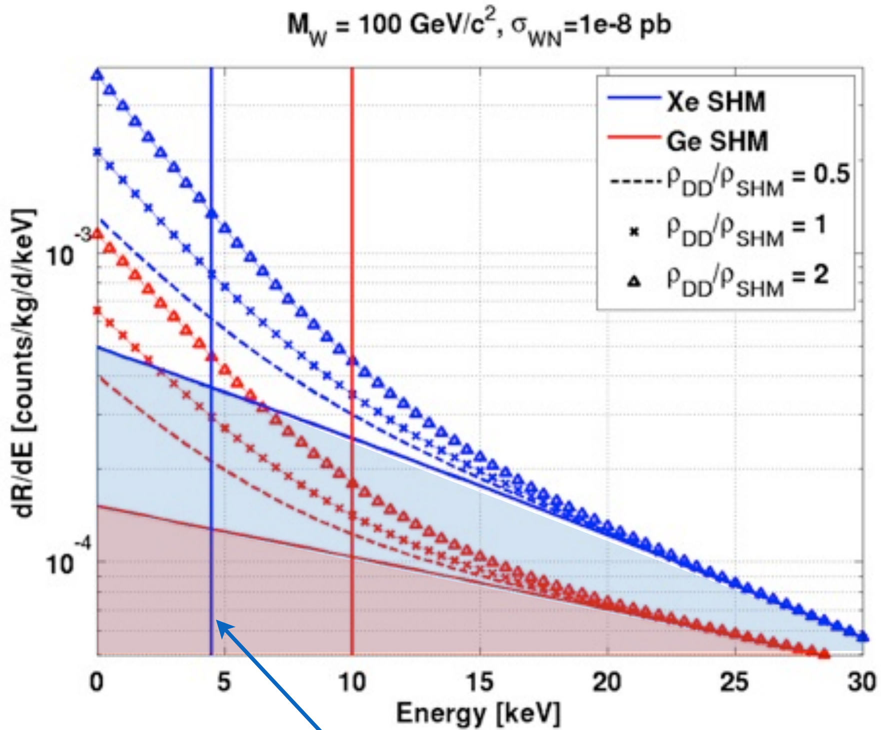


Effects of a Dark Matter Disk in The Milky Way

- **The solar system is embedded into the macroscopic structure of the dark disk**
- the local density is constrained by $\delta = \frac{\rho_{Disk}}{\rho_{SHM}} \leq 2$
- the velocities and dispersions are taken as $\mathrm{v}_{\mathrm{disk}} = [0,50,0]\ km \cdot s^{-1};\ \ \sigma_{\mathrm{disk}} = 50\ km \cdot s^{-1}$
   - ➡ the dark disk increases the rates at low recoil energies and provides and modifies the shape of the recoil spectrum, depending on the WIMP mass

Recoil energy below which the signal is dominated by the dark disk



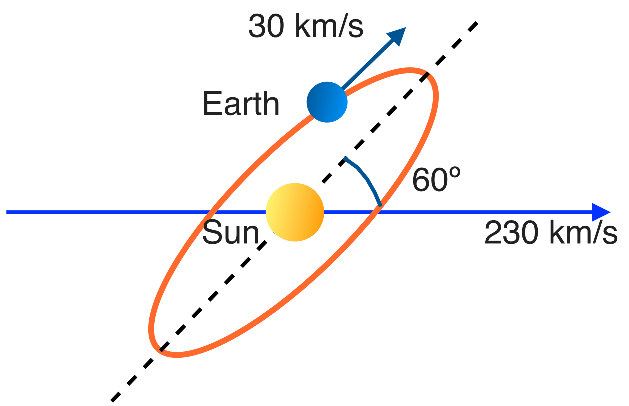


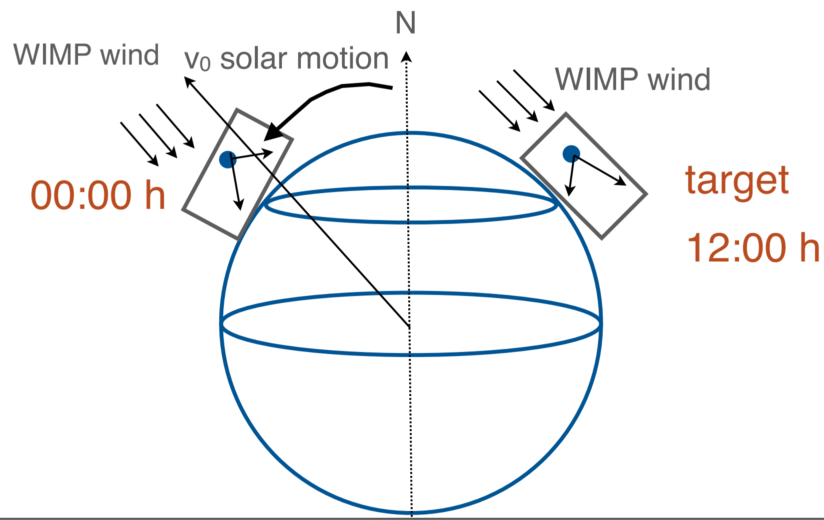
T. Bruch, J. Read, L. Baudis, G. Lake, APJ 696 (2009)

XENON10 threshold

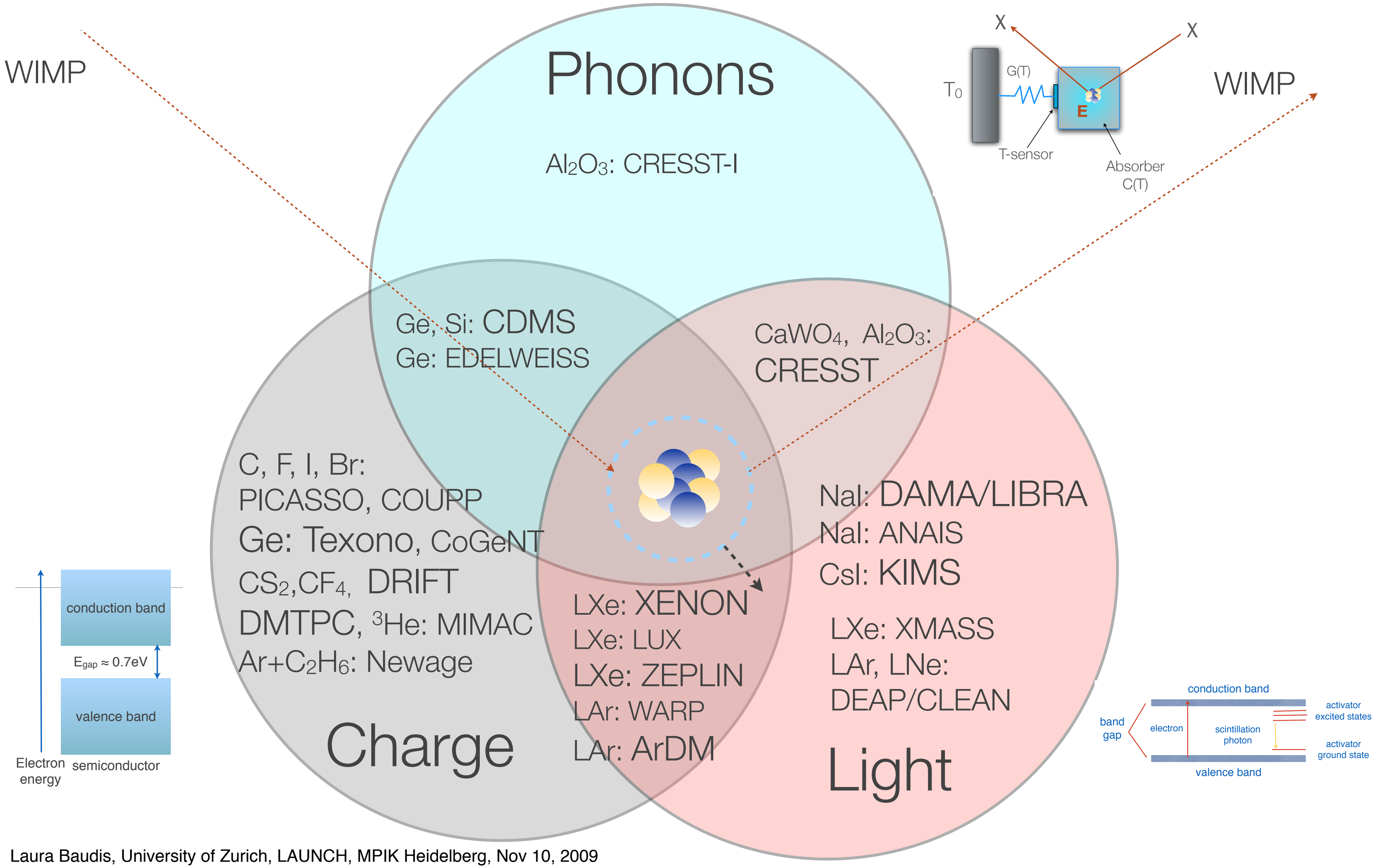
How would a WIMP signal look like?

- **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)
- **Direction dependance** (larger effect, requires low-pressure gas target)



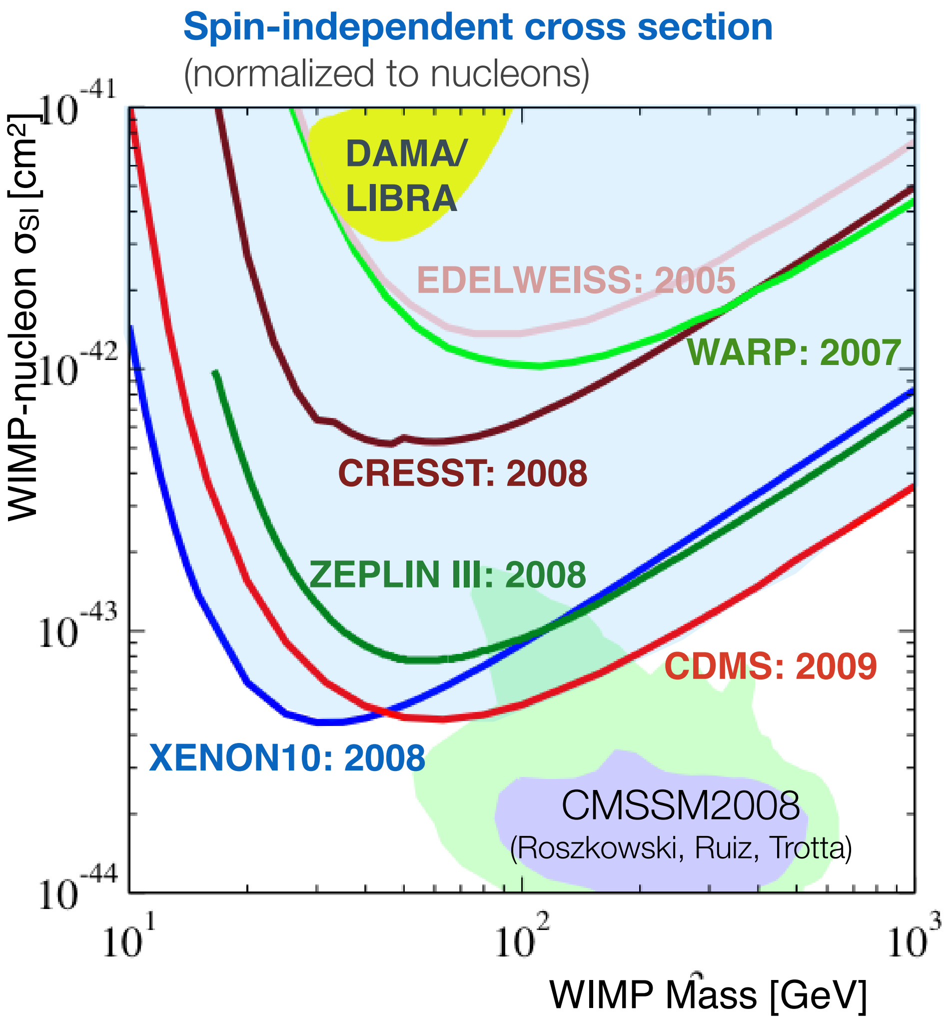


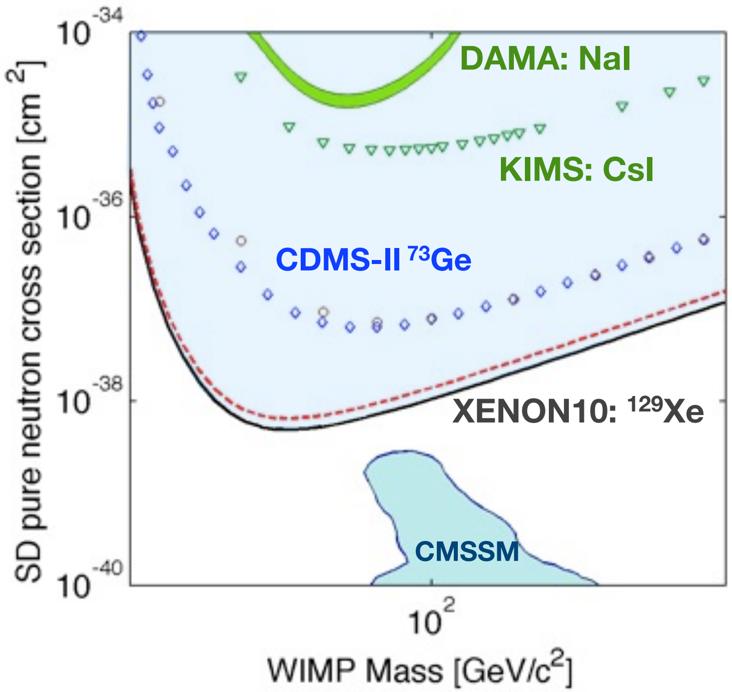
Direct Detection Techniques

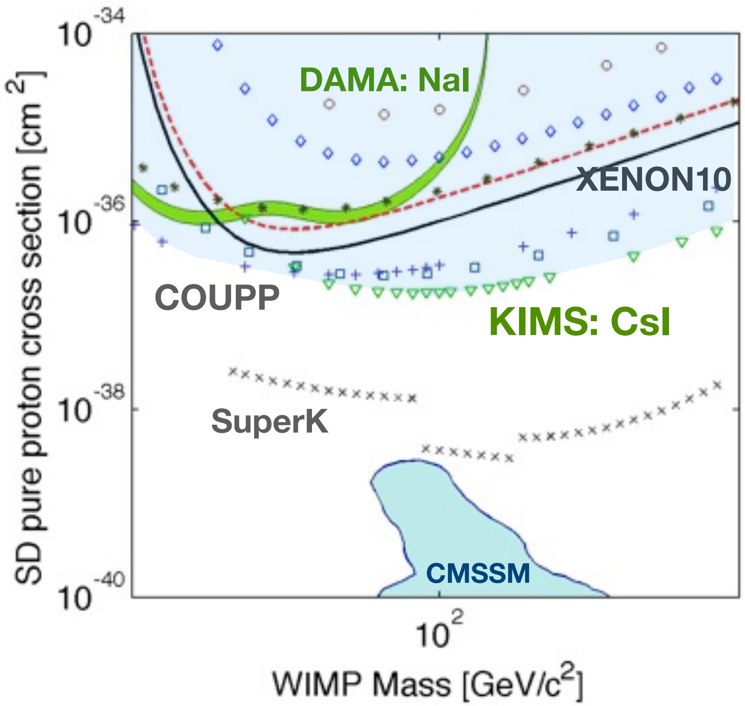


Laura Baudis, University of Zurich, LAUNCH, MPIK Heidelberg, Nov 10, 2009

Experimental Results in November 2009







Spin-dependent

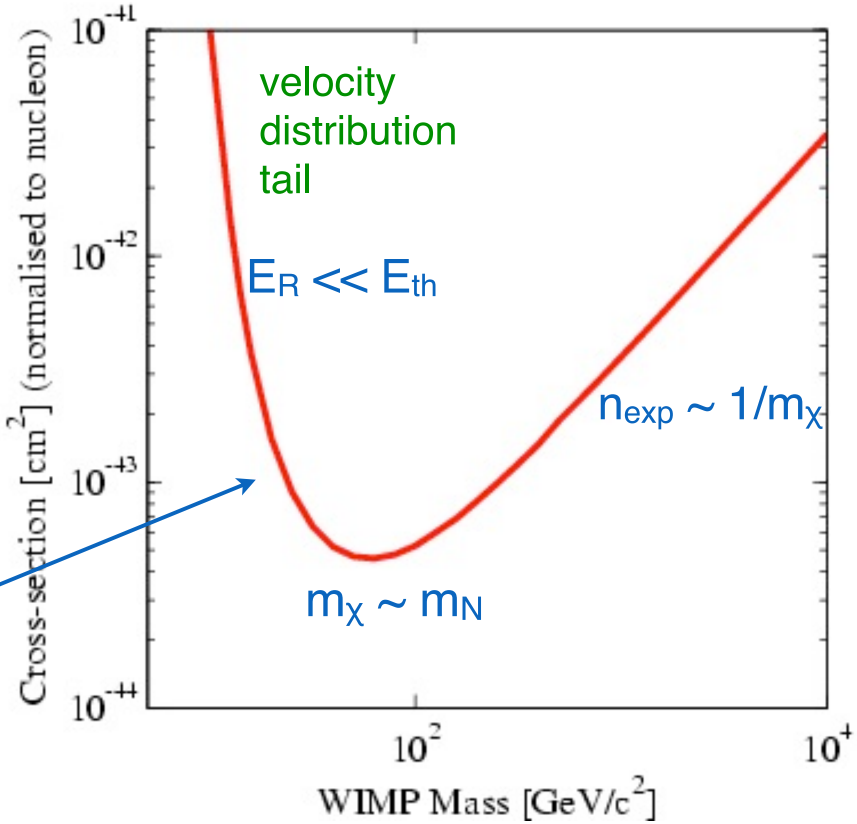
Vanilla Exclusion Plot

- **Assume we have detector of mass M, taking data for a period of time T**
- The total exposure will be **ε = M × T [kg days]**; nuclear recoils are detected above an energy threshold E_{th}, up to a chosen energy E_{max}. The **expected number of events n_{exp}** will be:

$$n_{exp} = \varepsilon \int_{E_{th}}^{E_{max}} \frac{dR}{dE_R} dE_R$$

⇒ cross sections for which $n_{exp} \geq 1$ can be probed by the experiment

- If ZERO events are observed, Poisson statistics implies that $n_{exp} \leq 2.3$ at 90% CL => exclusion plot in the cross section versus mass parameter space (assuming known local density)



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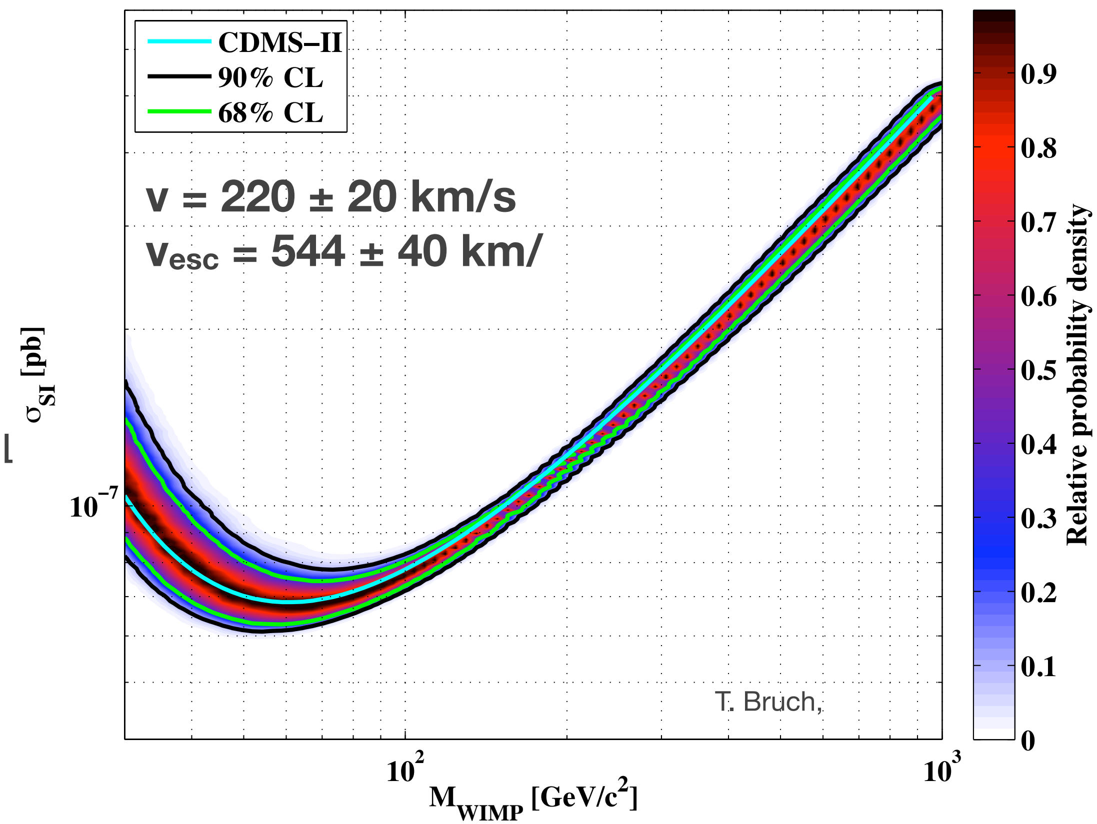
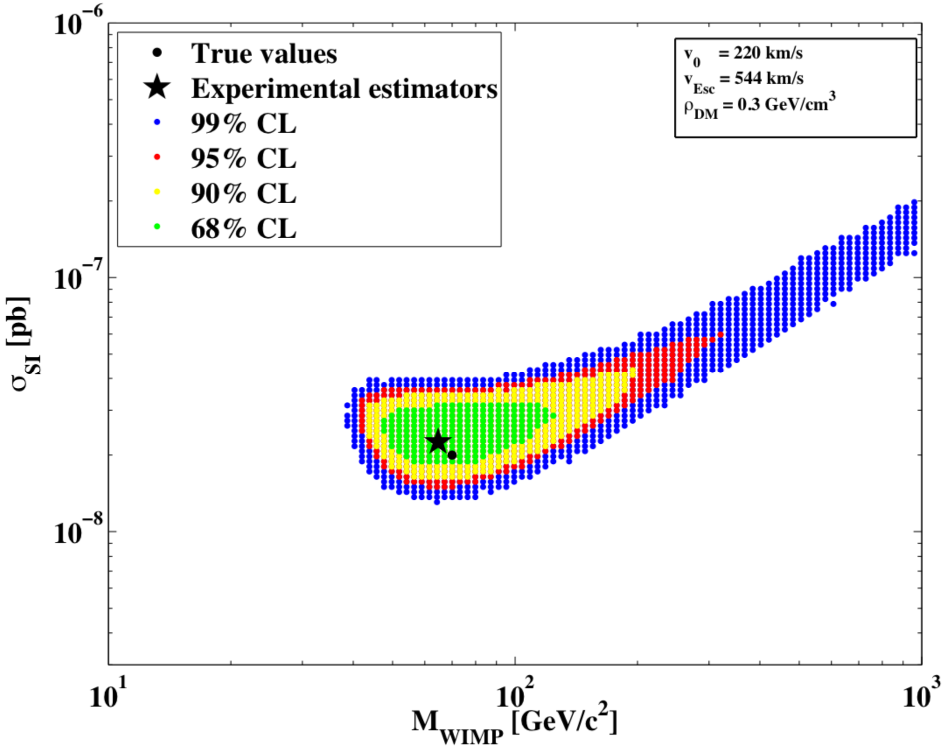
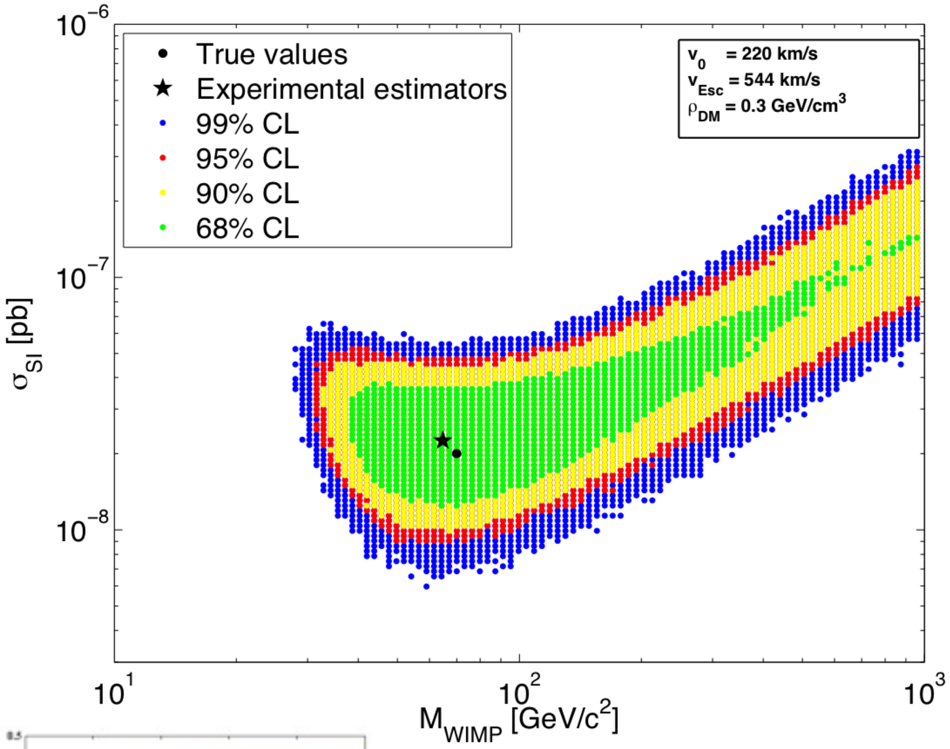


How well could we determine the WIMP mass?

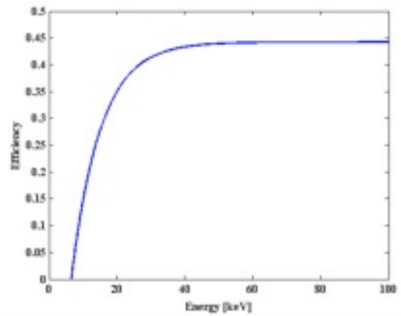
30 events in 12'250 (raw) kg days



8 events in 3'500 (raw) kg days



Preliminary study:
T. Bruch, UZH



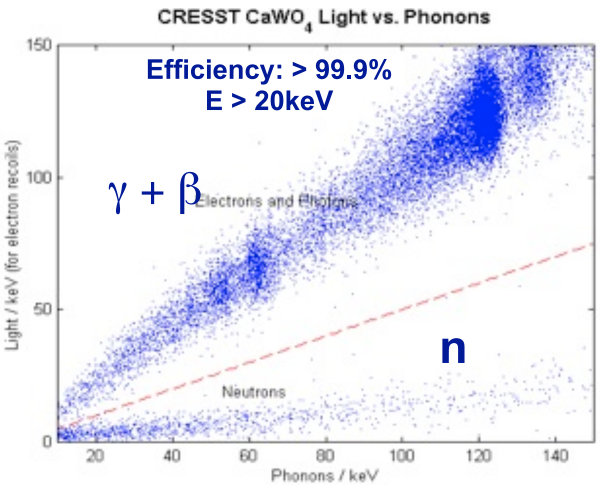
detection efficiency

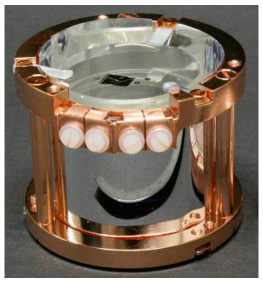
Laura Baudis, University of Zurich, LAUNCH, MPIK Heidelberg, Nov 10, 2009

Cryogenic Experiments at mK Temperatures

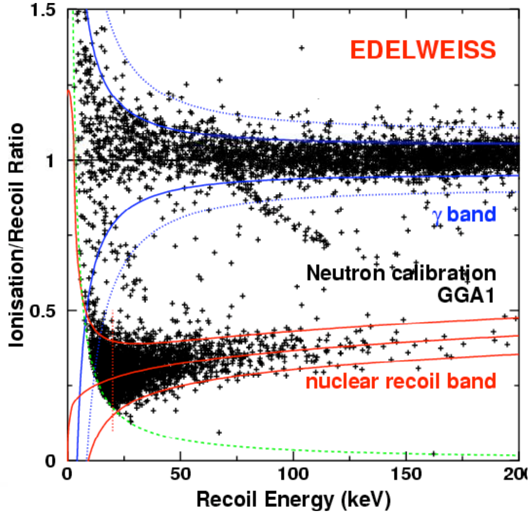
- **Advantages: high sensitivity to nuclear recoils**
  - measuring the full nuclear recoil energy in the phonon channel
  - low energy threshold (keV to sub-keV), good energy resolution
  - light/phonon and charge/phonon: **nuclear vs. electron recoil discrimination**

CRESST at LNGS

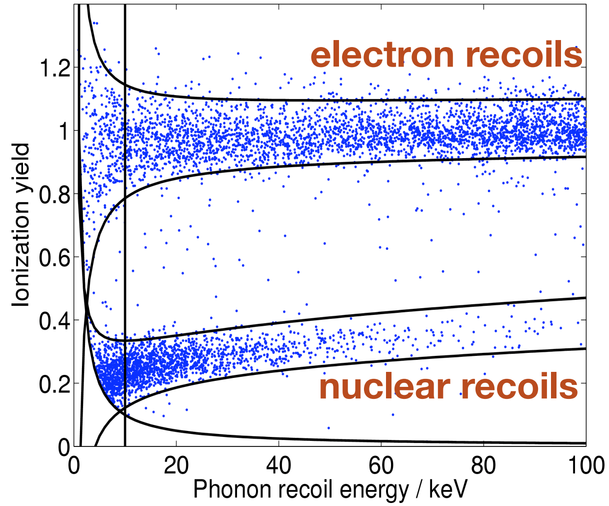


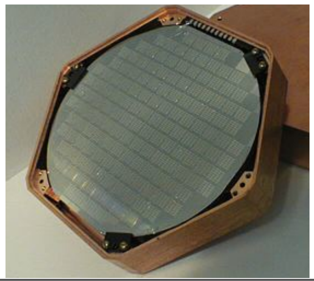


EDELWEISS at LSM



CDMS at Soudan





Cryogenic Experiments at mK Temperatures

CRESST at LNGS

Goal: 10 kg array of 33 $CaWO_4$ detectors

- new limit from operating 2 detectors (48 kg d) published in 2008, arXiv:0809.1829v1

- new run with 10 detector modules ($CaWO_4$) is in progress

EDELWEISS at LSM

Goal: 10 kg (30 modules) of Ge detectors in new cryostat

- new ID electrodes with much improved surface event rejection (1 in $6x10^4$)
- accepted in PLB

- 470 kg day raw exposure accumulated

- under analysis; paper by end of 2009

CDMS at Soudan

Run 123-124: results in PRL102

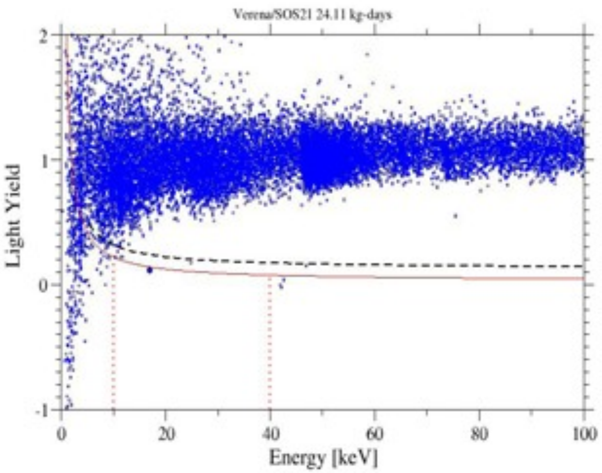
Run 125-128: analyzed

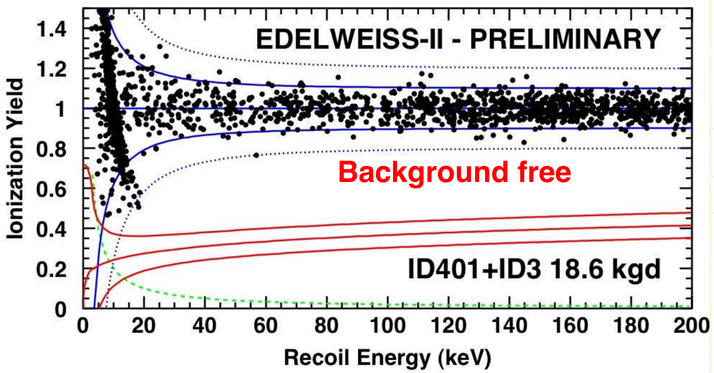
(~185 kg days after all cuts)

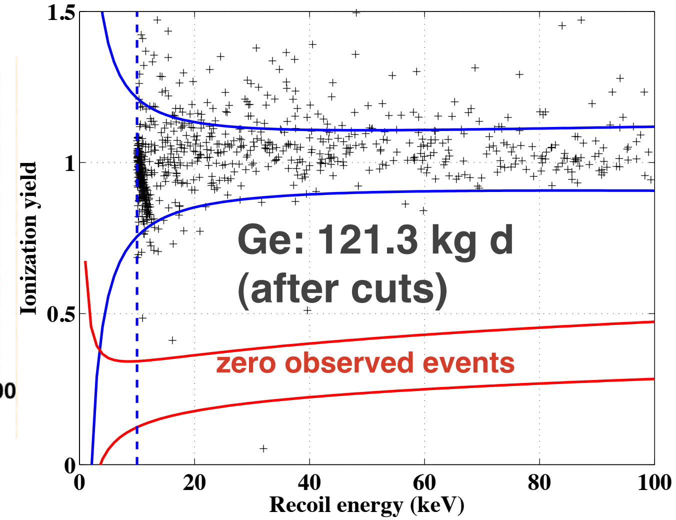
- results to be released soon

First SuperTower (1" thick ZIPs, each 650 g of Ge) **installed at Soudan (3 kg of WIMP target) and working**

Goal: 5×10^{-45} cm^2 with 16 kg Ge







EURECA European Rare Event Calorimeter Array

- A European coordinated effort to build a ton-scale cryogenic dark matter experiment
- Joint effort of ~110 physicists from EDELWEISS, CRESST, ROSEBUD, CERN + others
- Part of ILIAS / ASPERA / ApPEC strategy (roadmap)
- Cryogenic detectors are modular and inherently scalable
- Multi-element target for WIMP identification (Ge and solid state scintillators)

- **Current topics:**

  design study, technology down selection

  major effort in background control and detector fabrication

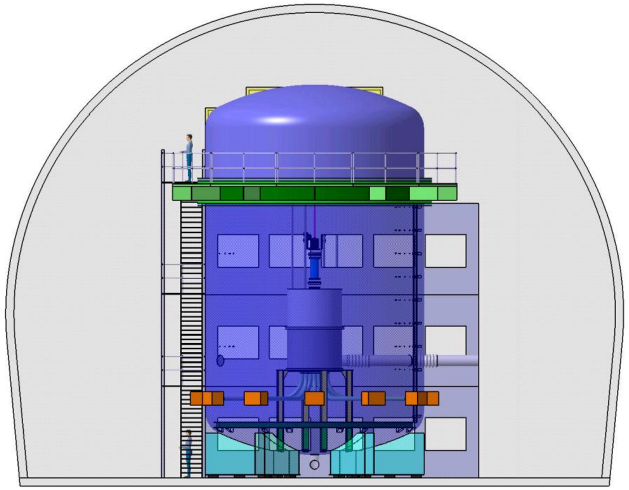
Preferred site: 60 000 m^3 extension of present Laboratoire Souterrain de Modane

- R&D and design study: 2009-2011; Construction: 2011-2015; Science > 2015

- funded by the first ASPERA common call:

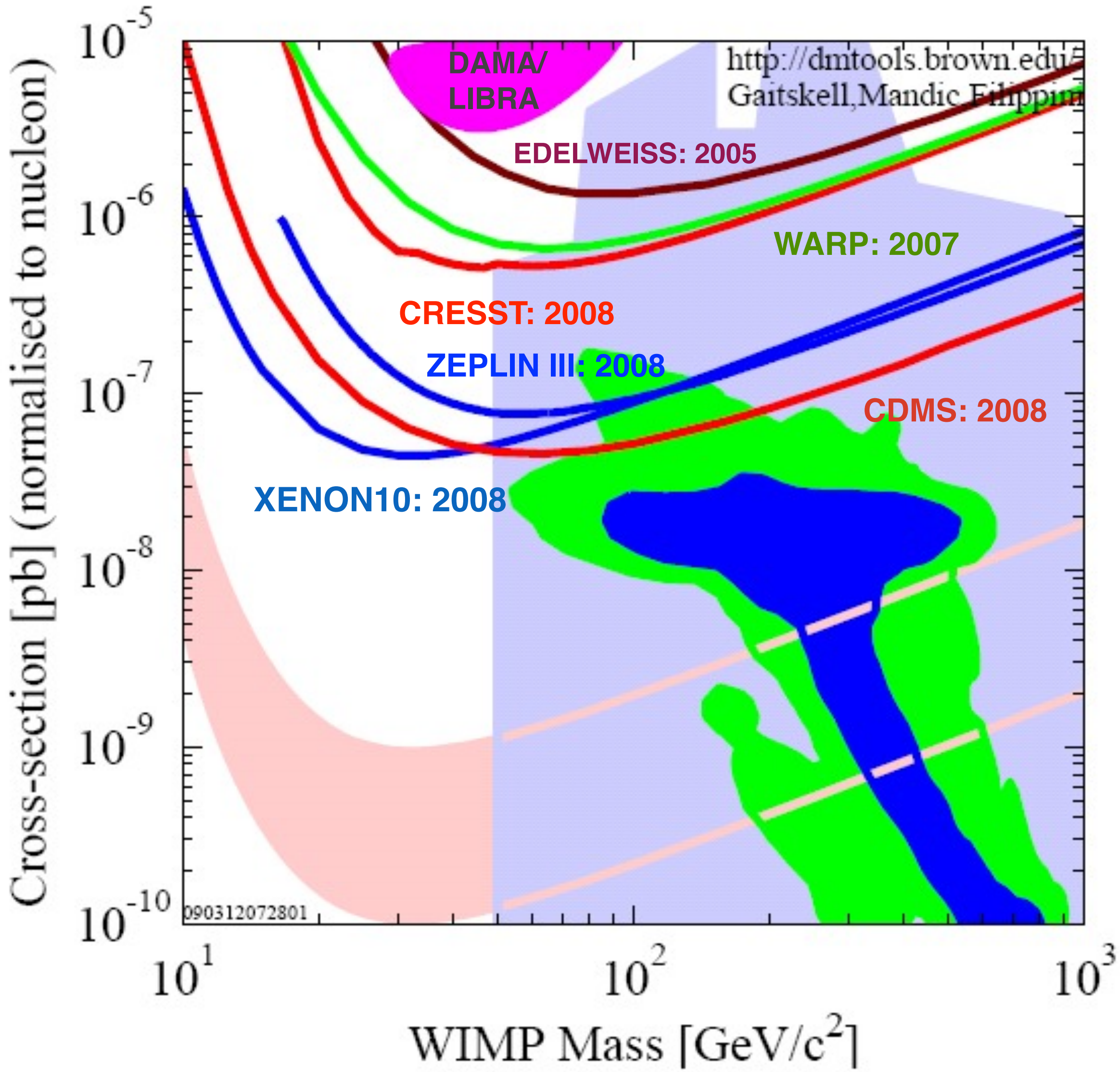
ASPERA News: "Groups in France, Spain and the UK will work on this project. A maximum funding of €606k will be provided."

EURECA European Rare Event Calorimeter Array



EURECA aim

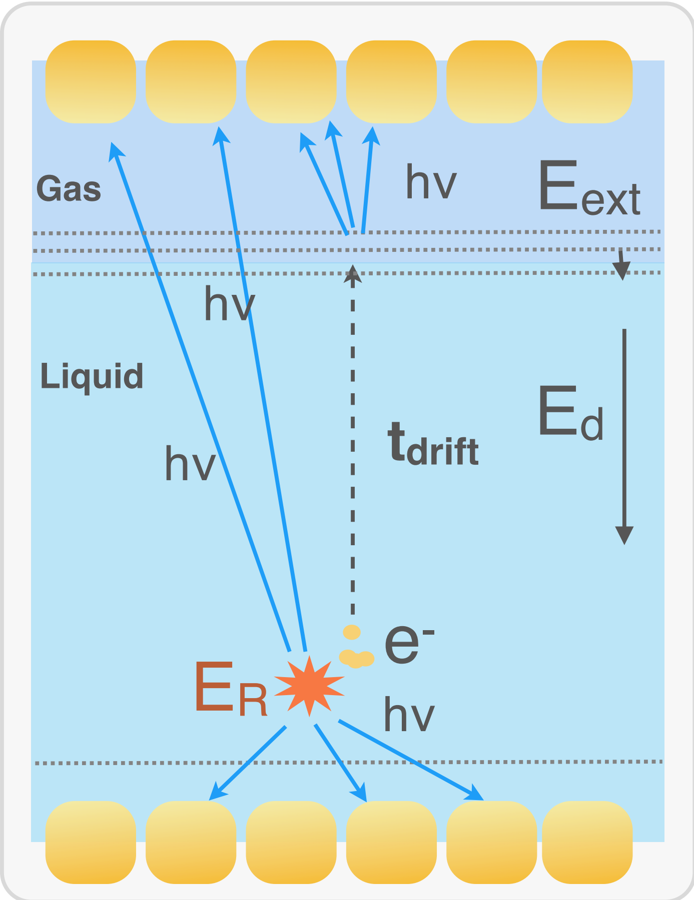
~30 evt/ton/year



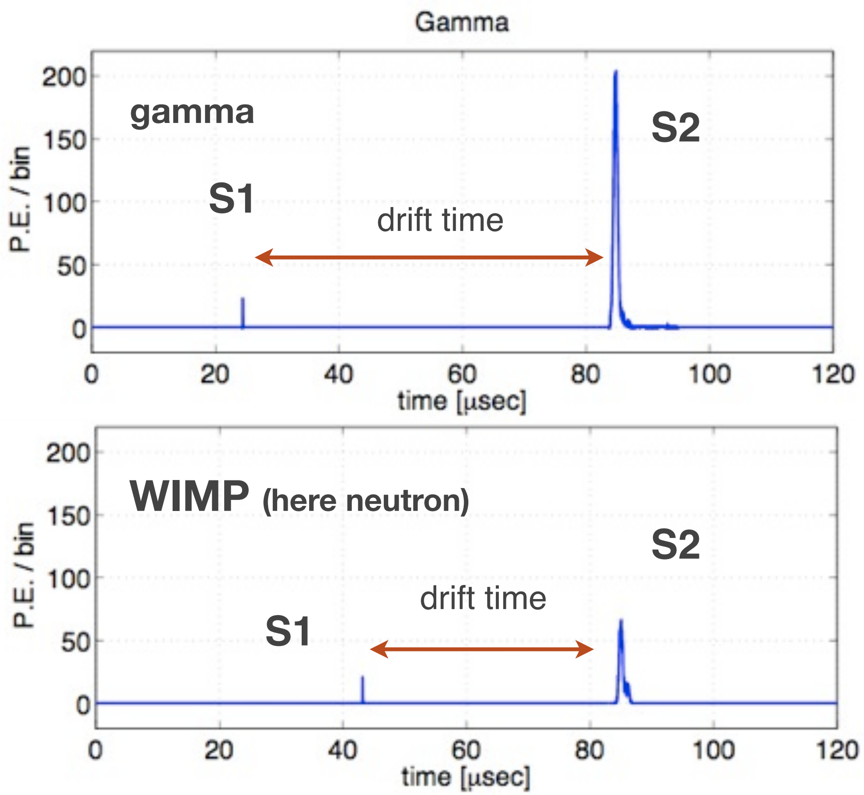
Noble Liquids Time Projection Chambers

Ar (A = 40); λ = 128 nm
Xe (A=131); λ = 175 nm

- **Dense, homogeneous targets/detectors; high light and charge yields**
- **Prompt (S1) light signal** after interaction in active volume; charge is drifted, extracted into the gas phase and detected as **proportional light (S2)**
- **Challenge:** ultra-pure liquid + high drift field; efficient extraction + detection of e^-

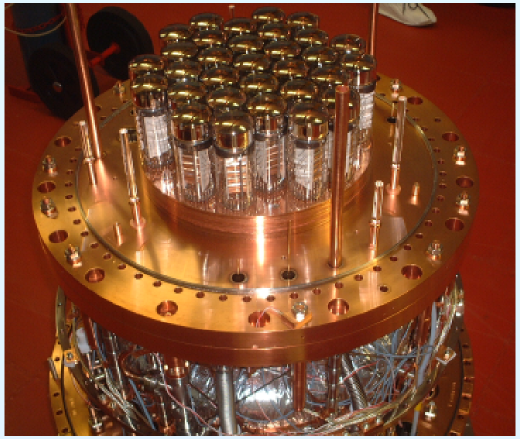


- S2/S1 depends on dE/dx
- good 3D position resolution
} => particle identification



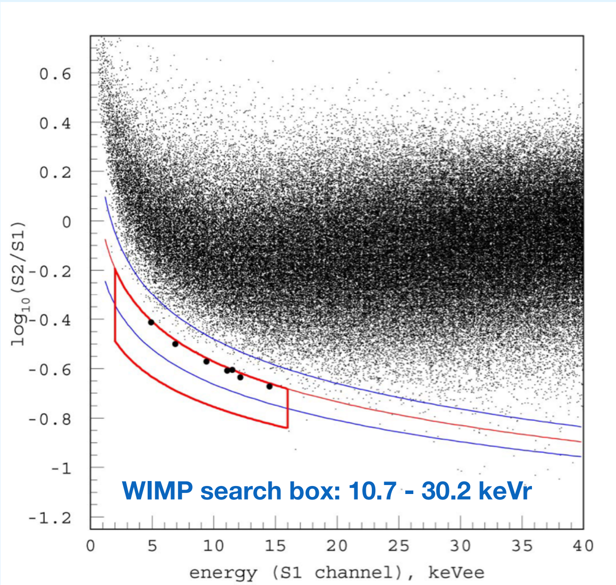
Two-phase Xenon Detectors

ZEPLIN III at Boulby



6.7 kg LXe (fiducial)
31 x 2" cm PMTs

WIMP search run analyzed: 127 kg d



7 events obs.
in WIMP box
11.6±3.0 expected from backgrounds

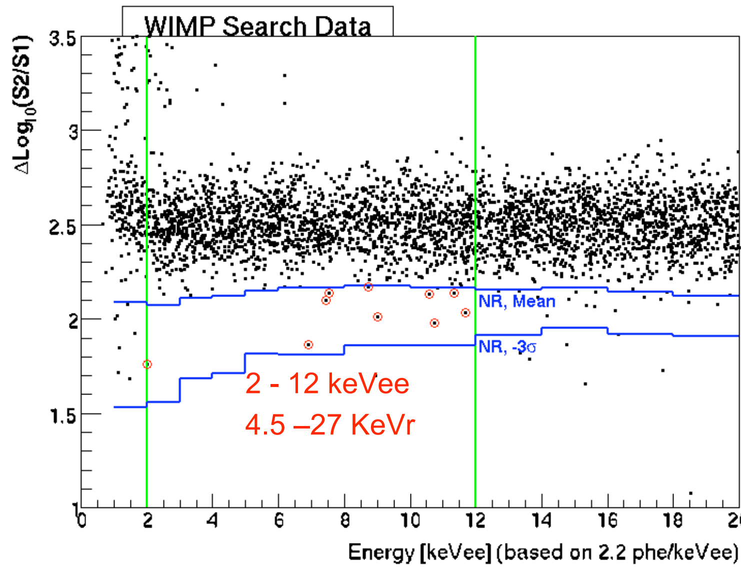
limit with BG subtraction

arXiv:0812.1150v1

XENON10 at LNGS

15 kg (5.4 fiducial),
89 2" PMTs

136 kg d (after cuts) of WIMP search data

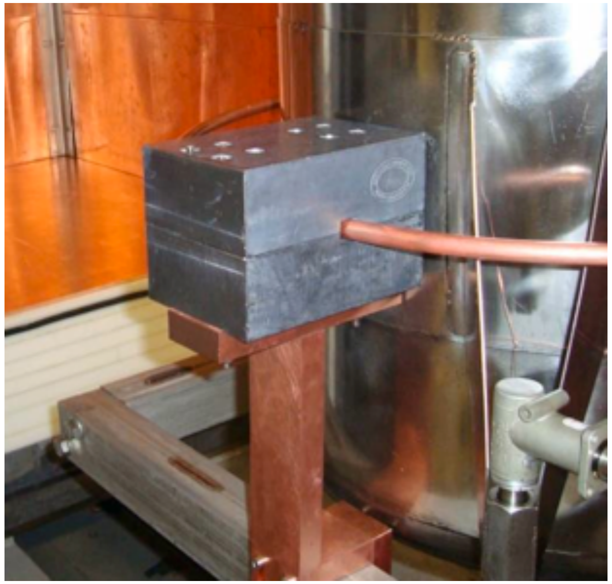


10 events observed, all BG, no subtraction

Results: PRL100, PRL101

The XENON100 Experiment at Gran Sasso

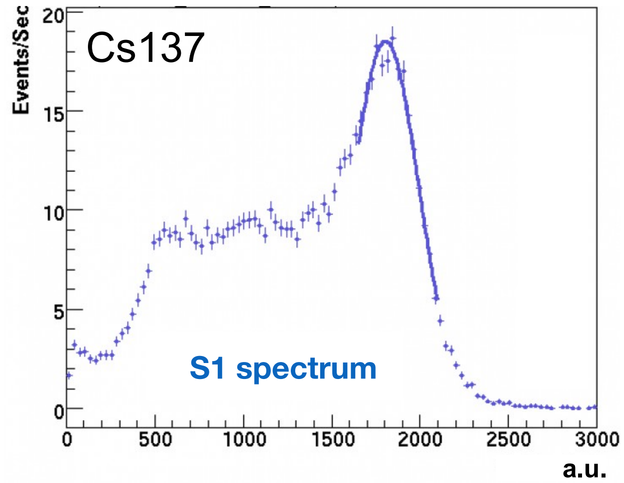
- Dual-phase, Xe-TPC to search for WIMPs by their collision with Xe-nuclei
- 165 kg (100 kg in active veto) LXe, viewed by 242 PMTs, 30 cm ∅, 30 cm drift
- 3D position reconstruction based on detection of S1 and S2
- Factor of 100 lower background, factor 10 higher mass than XENON10
- Under operation at LNGS since spring 2008

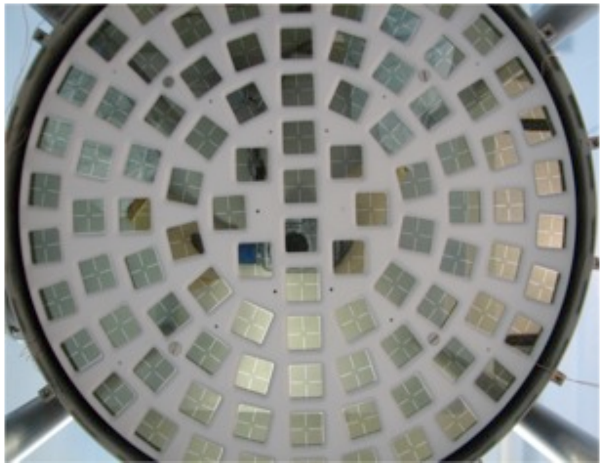


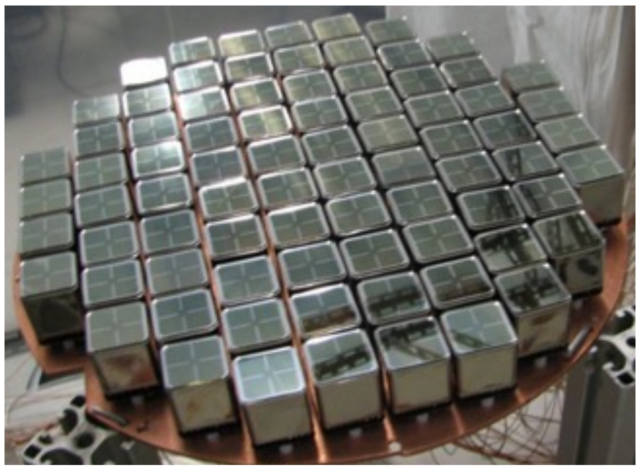
XENON100 Photodetectors and Calibration

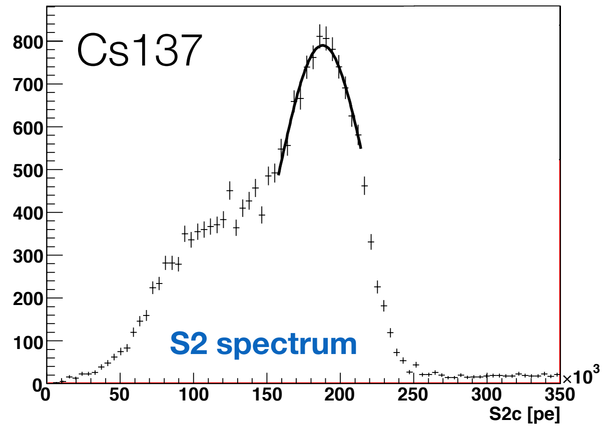
- 242 Hamamatsu R8520 1"x1" PMTs
- low-radioactivity (U/Th < 0.2 mBq/PMT), 80 with high QE of 33%
  - ➡ 98 in top array: optimized for fiducial cut efficiency
  - ➡ 80 in bottom array: optimized for S1 collection -> low E_{thr}
  - ➡ 64 in active veto: BG reduction by factor 3-4
  - ➡ PMT gain calibration: with LEDs, the SPE response measured

- XENON100 Calibration:
  - ➡ gamma-sources: ^{83m}Kr, ^{57}Co, ^{137}Cs, ^{60}Co, ^{228}Th, ^{129m}Xe, ^{131m}Xe
  - ➡ neutron source: AmBe





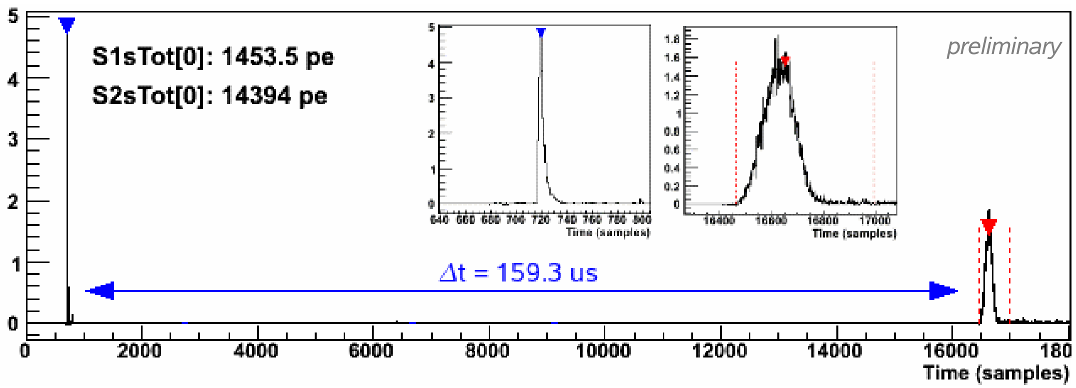


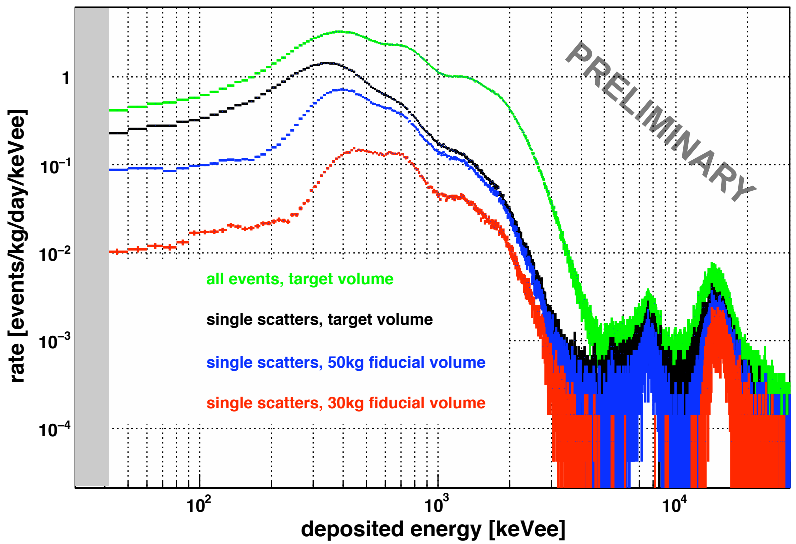


XENON100 Status and Plans

- Detector fully functional, tested on calibration data
- Several short background runs (BG at the level predicted by Monte Carlo simulations!)
- ^{85}Kr ($T_{1/2}$ = 10.7 y, β^- 678 keV) purification in August 2010: 15 - 150 ppt (limited by current stats)
- Detailed LXe veto mapping in 80 different positions; mean veto threshold: 50 keV
- Maximum light yield recently reached (4.5 p.e. at 122 keV); currently improving electron lifetime (>160μs)

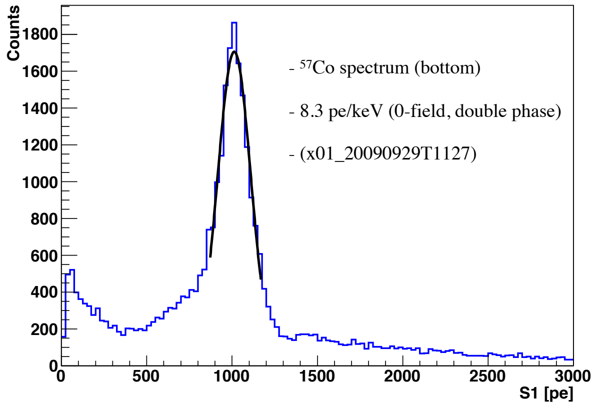
- **Next:**
  - ➡ establish gamma band with high stats ^{60}Co calibration data (ongoing)
  - ➡ neutron calibration run (establish nuclear recoil band)
  - ➡ ^{83m}Kr calibration (9 keV and 30 keV, establish signal position dependance)
  - ➡ WIMP search run in 2010
  - ➡ 200 days: $\sigma = 2 \times 10^{-45}$ cm^2 (at M_W =100 GeV)

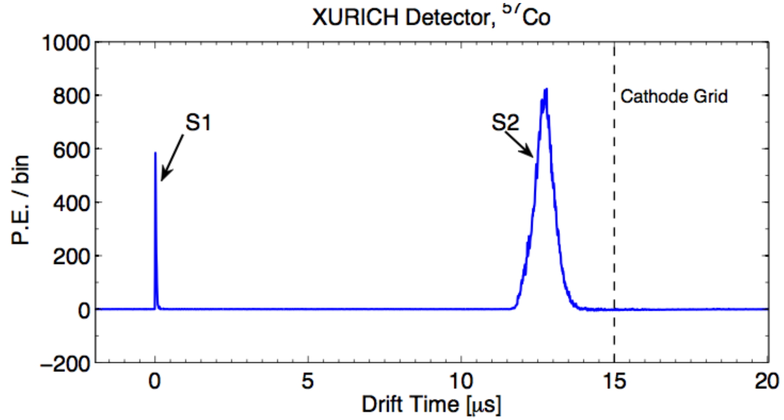


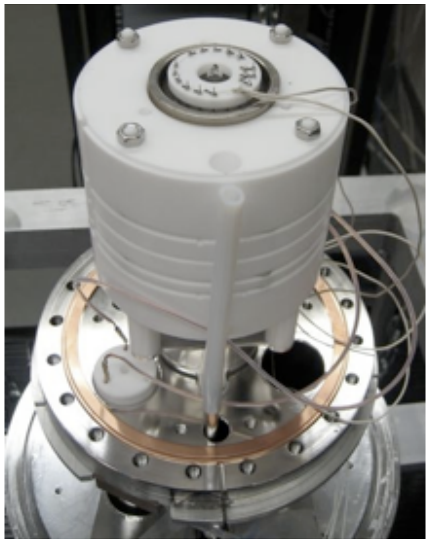


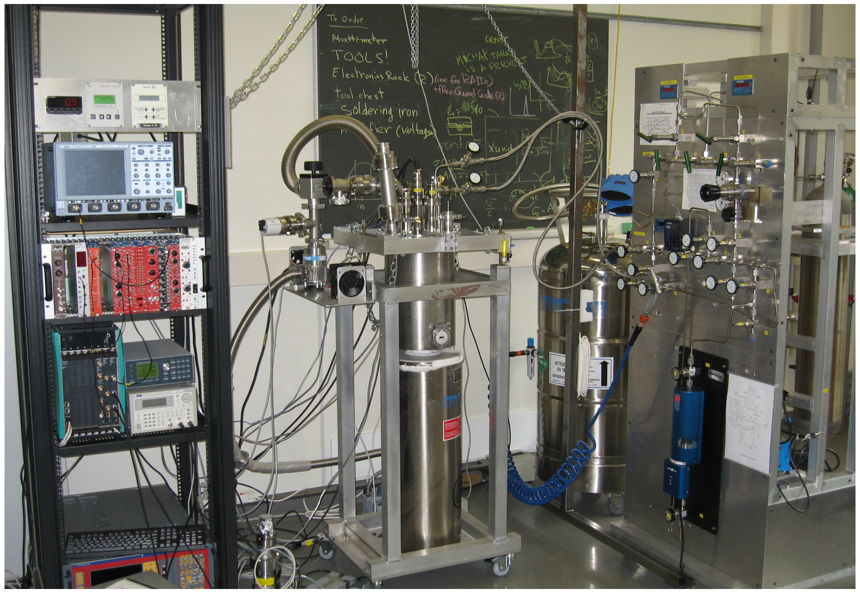
The Xürich Detector

- 1.65 kg dual-phase LXe-TPC, 3 cm drift, viewed by 2 Hamamatsu R9869 PMTs



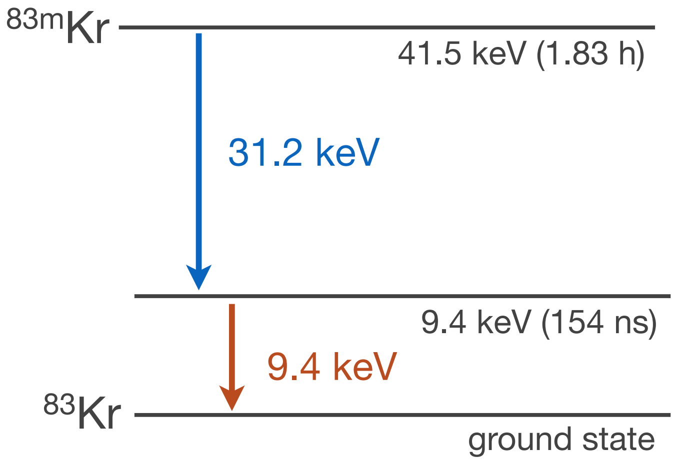


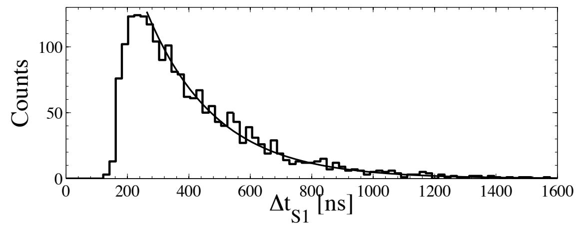


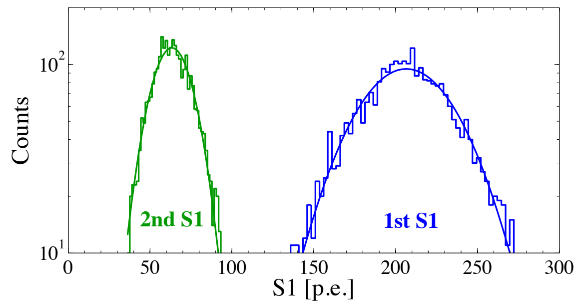


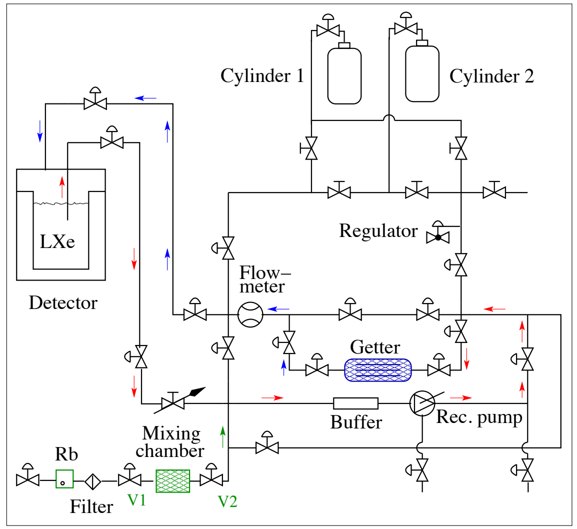
The Xürich Detector: Tests of ^{83m}Kr source

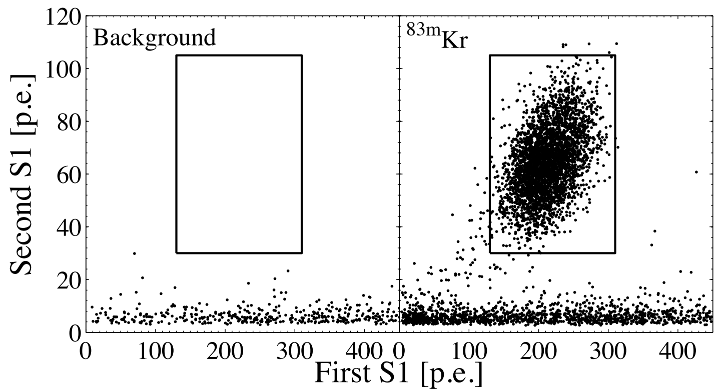
- ^{83m}Kr: EC decay product of ^{83}Rb; lines at 9.4 keV and at 32.1 keV (also used in KATRIN)











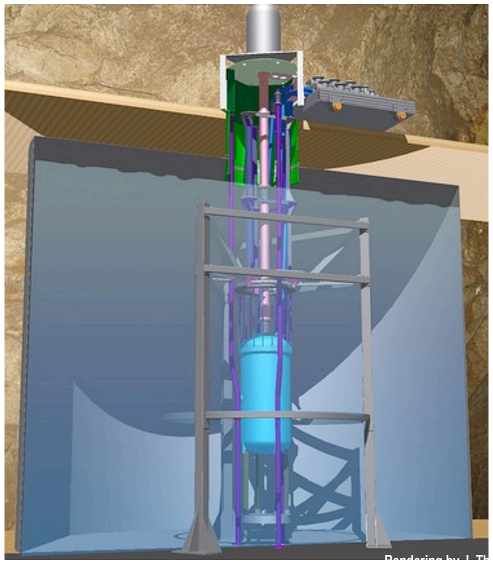
arXiv:0908.0616v1

The LUX Experiment

- **350 kg dual phase LXe TPC (100 kg fiducial), with 122 PMTs in large water shield with muon veto**
- LUX 0.1: 50 kg LXe prototype with 4 R8778 PMTs was assembled and tested at CWRU
- PMTs: 2” diameter, 175 nm > 30% QE; radioactivity: U/Th ~ 9/3 mBq/PMT
- LUX 1.0: full detector to be operated above ground at Homestake in fall 2009
- LUX 1.0: to be installed at Homestake Davis Cavern, 4850 ft in spring 2010 (in 8 m ∅ water tank)
- **Predicted WIMP sensitivity: 7×10^{-10} pb after 10 months**

R8778 PMT

LUX 0.1



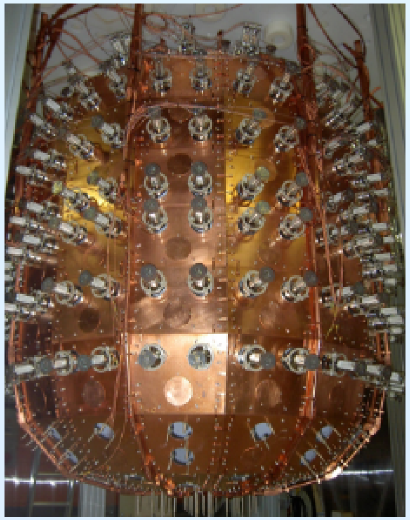
In water shield @ Homestake 4850 ft level

Two-phase Argon Detectors

WARP at LNGS

WIMP target: 140 kg LAr
- S1 and S2 read-out with 41 x 3" PMTs
- active LAr shield: ~ 8t, viewed by 300 PMTs

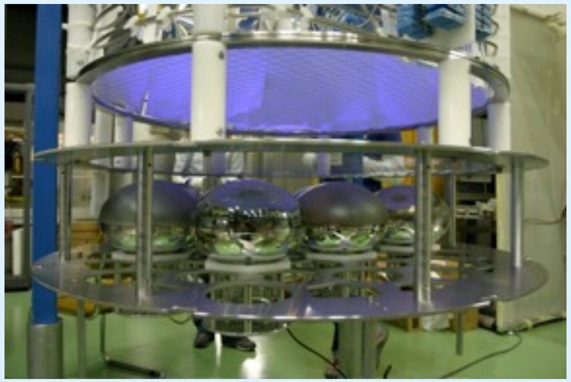
Detector has been installed in December 08
Now under commissioning in Gran Sasso

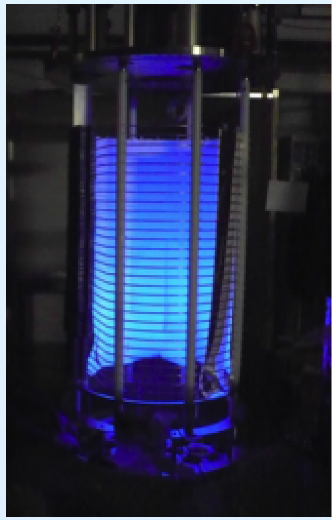


ArDM at CERN

WIMP target: 1 ton LAr
- S1 read-out with 14 x 8" PMTs
- direct electron readout via LEMs
  (thick macroscopic GEM)

Detector filled May 2009 at CERN
Calibrations with various sources ongoing
Underground operation: LSC or SunLab





DARWIN

DARWIN
Dark matter Wimp search in Noble liquids

- R&D and design study for **Next-generation noble liquid facility in Europe**

- **Primary goals:**
  - ➡ unify and coordinate extensive existing expertise in Europe (groups from XENON, WARP, ArDM plus new groups, including US groups from XENON and WARP)
  - ➡ study both argon and xenon as WIMP target media and provide recommendation for facility (full technical design report) in 3 years from now
  - ➡ submit full proposal in response to second ASPERA call

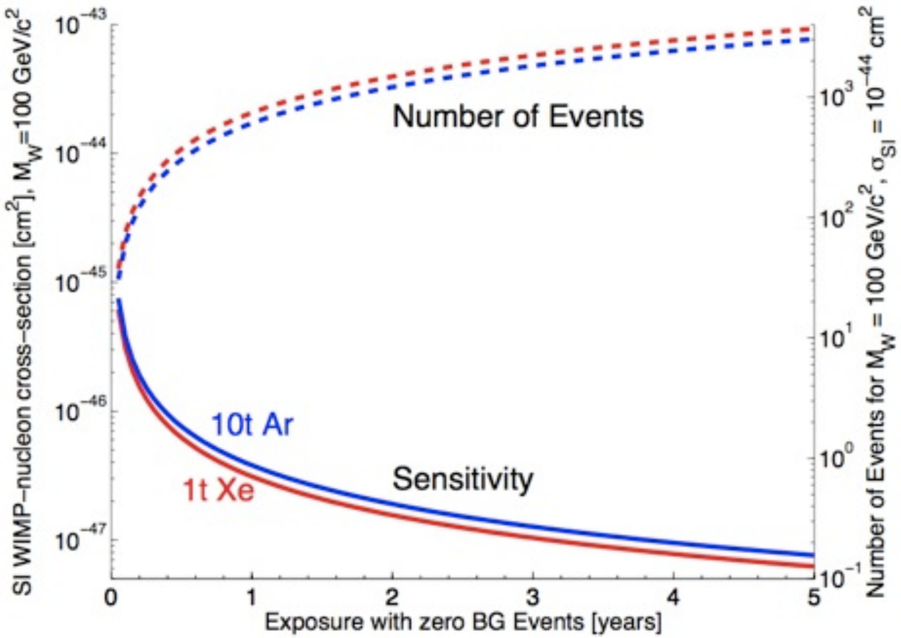
- **Components:**
  - ➡ optimize detector design (use real data from current 'prototypes': XENON100, WARP140, ArDM)
  - ➡ optimize noble gas purification procedures (for traces of H_2O, O_2, etc and radioactivity)
  - ➡ identify material selection and process control needed for ultra-low BG operation
  - ➡ define ancillary equipment requirements
  - ➡ explore the optimal underground location and cost effective shielding configuration
  - ➡ study science impact

- **Possible locations**: LNGS (Italy), ULISSE (Modane extension, France), or SUNLAB (Poland)

DARWIN

DARWIN
Dark matter Wimp search in Noble liquids

- Aimed physics reach: $\sigma_{SI}=10^{-47}$ cm^2 with 1t (10t) LXe (LAr) fiducial mass in 3 years

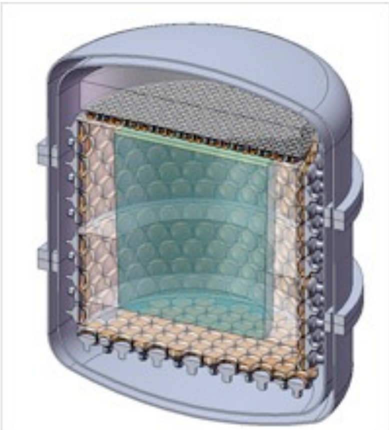


Participants:
Switzerland (ETHZ, UZH), PIs: C. Amsler, L. Baudis (PC), A. Rubbia
Germany (MPIK, KIT, Münster), PIs: M. Lindner, G. Drexlin, C. Weinheimer
France (Subatech), PI: D. Thiers
Italy (INFN: L'Aquila, Milano, Napoli, Padova, Pavia, Torino), PI: G. Fiorillo
Netherlands (Nikhef), PIs: P. Decowski, F. Linde
Poland (IFJ PAN, US, PWr), PIs: A. Zalewska, J. Kisiel, M. Chorowski
USA (Columbia, Princeton, Rice, UCLA), PIs: E. Aprile, C. Galbiati, U. Oberlack, K. Arisaka

- **Funding:** provided by the national instruments of each participant ('virtual pot')
- ASPERA News: "Groups in Italy, France, the Netherlands and Switzerland will be funded to work on this project at a total cost of €633k."

MAX: Multi-ton Argon & Xenon

- S4 Proposal for an engineering study to design in parallel a large Ar and Xe detector for the ISE (DUSEL Initial Suite of Experiments)
- Aimed physics reach: $\sigma_{SI}=10^{-47}$ cm^2 for 5t Ar-TPC (5 yr run) and 2.4 t Xe-TPC (2 yr run)

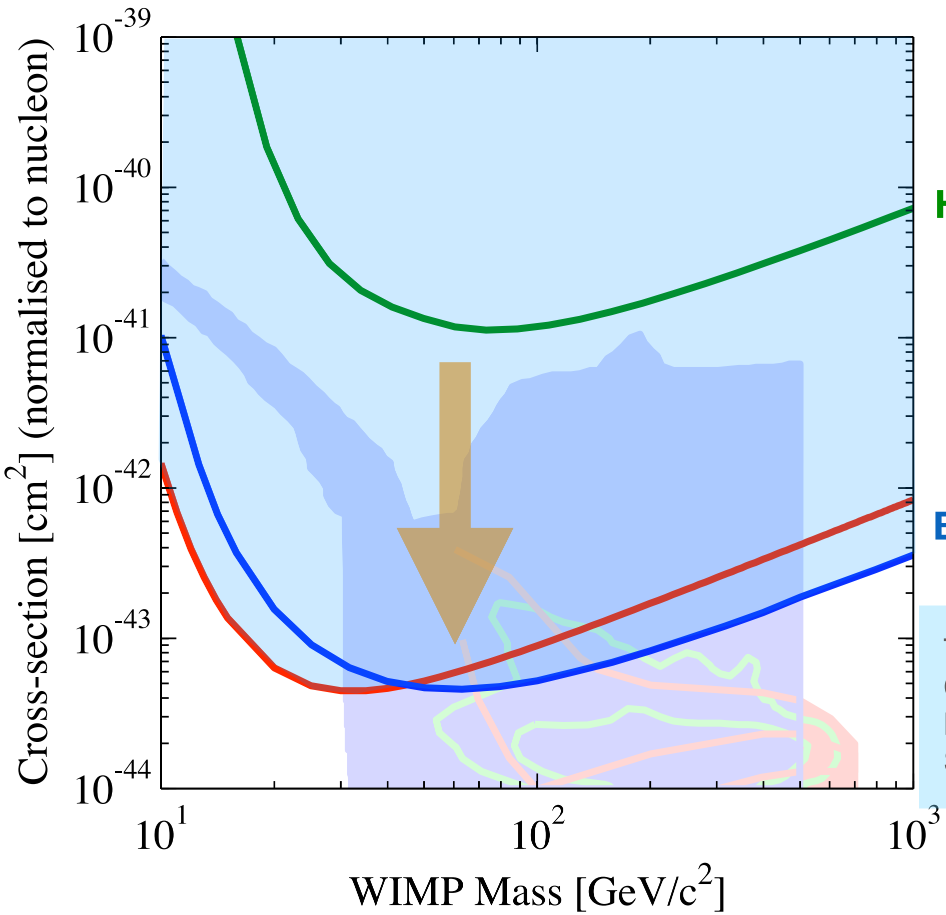


MAX Collaboration: groups from DarkSide, XENON + others; USA, Italy, Portugal, Germany, Japan, China, Switzerland

MAX has funded with 3.5 M US$ (the competing study, LUX/LZ3, has been funded at the same level) for 3 years

Summary (I)

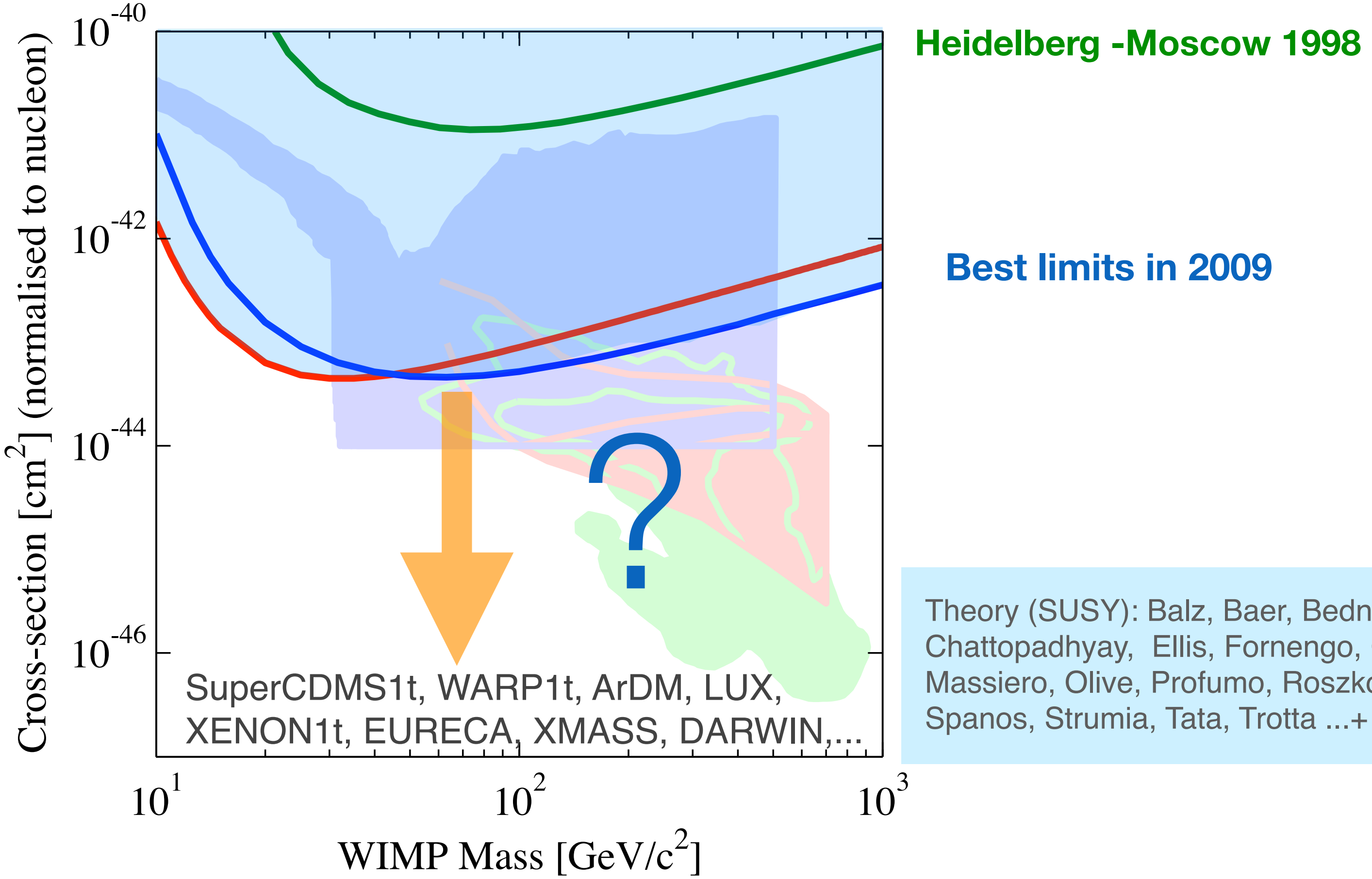
- Various targets and techniques are being employed to search for WIMPs
- **Steady progress** in the last ~ 10 years: **> factor 100 increase in sensitivity!**



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

Summary (II)

- Good news: experiments are probing some of the theory regions
- Next generation projects should reach the ≲ 10^{-10} pb level
- What will they see? *(nobody has been there before!)*



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