Direct detection of particle dark matter: where do we stand, where are we going?

Physics Colloquium

IFIC, Valencia University

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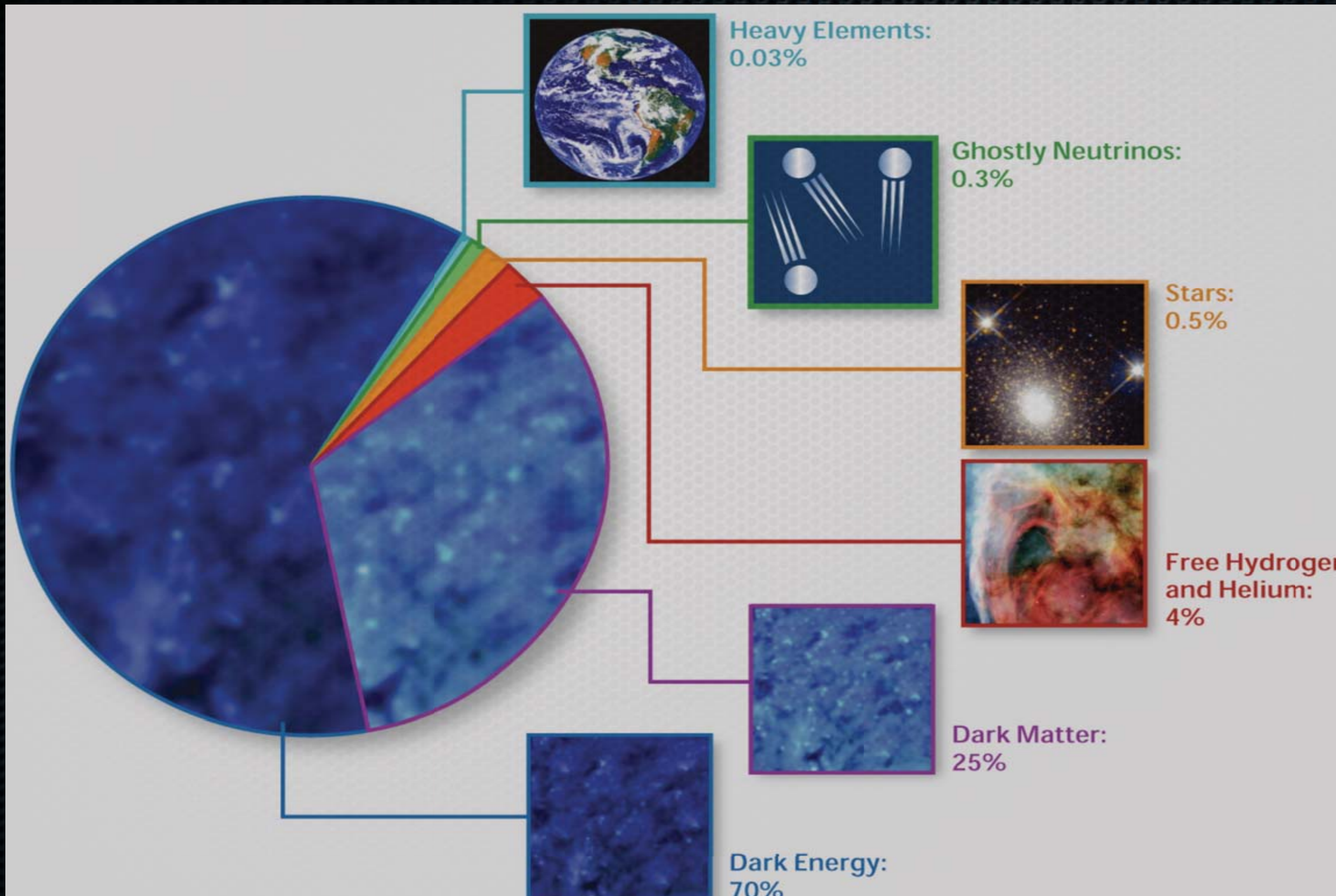
Laura Baudis

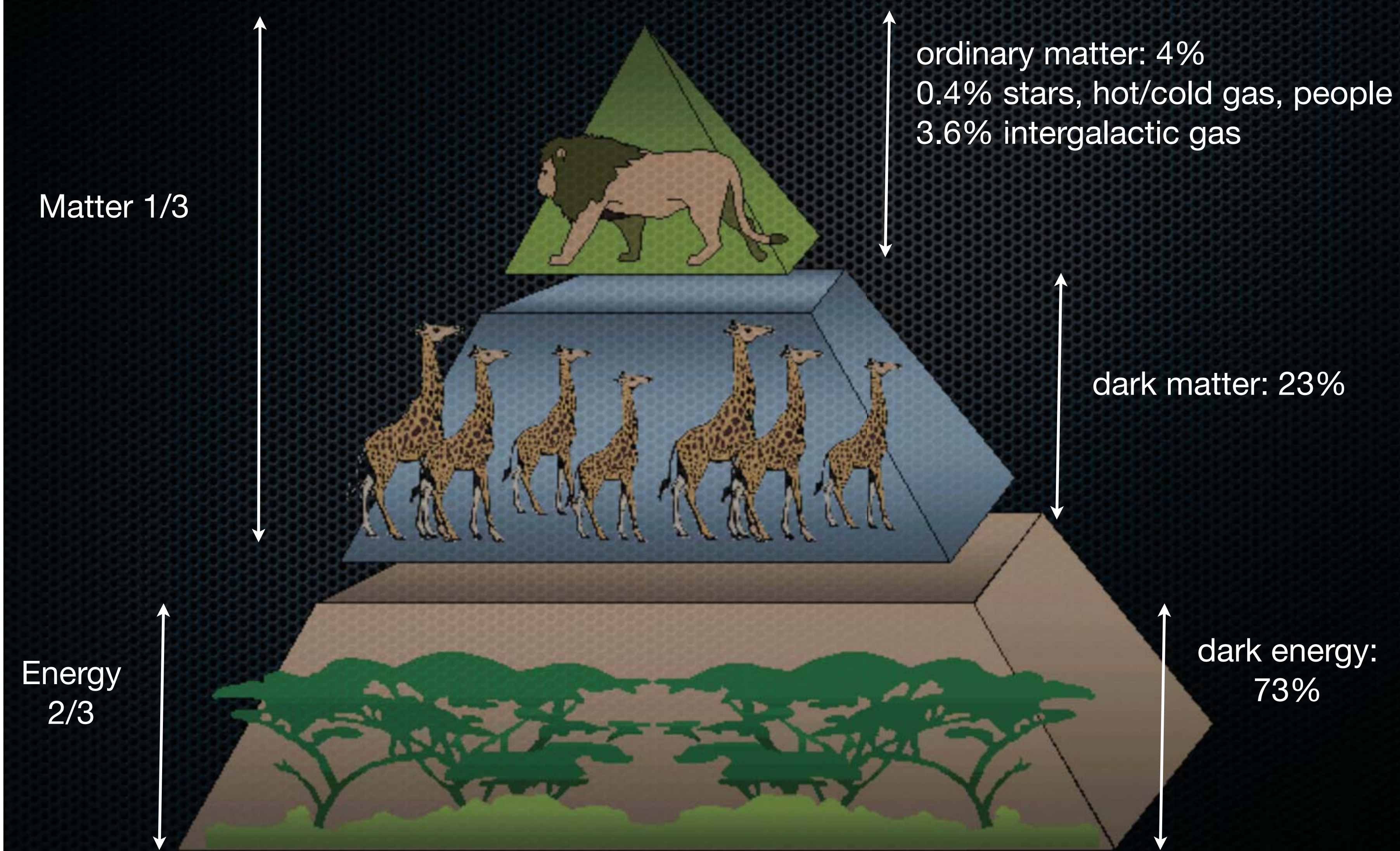
University of Zurich

University of Zurich[UZH]

Matter and Energy Content of our Universe



The Cosmic Food Chain



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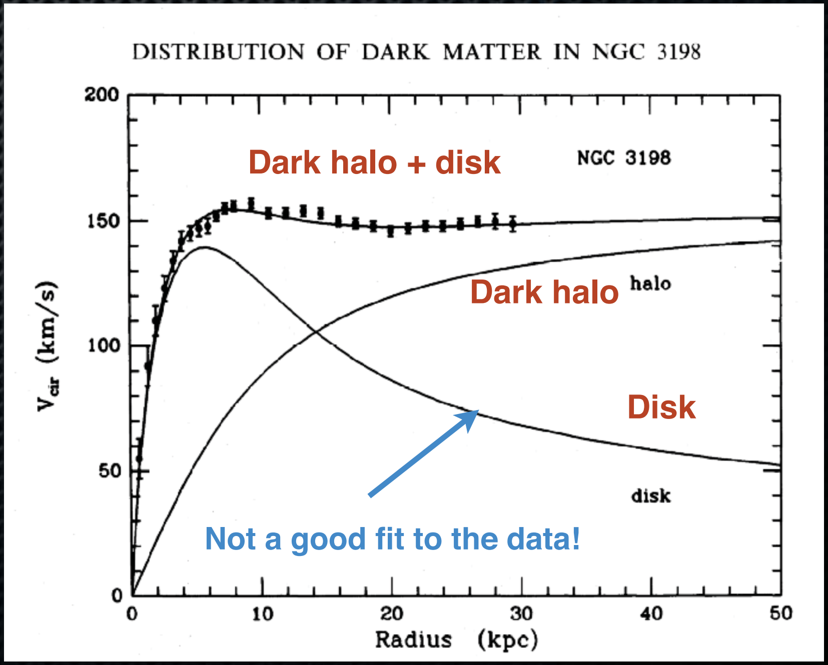
Dark matter in galaxies

- Observations of the movement of stars and interstellar gas at large radii
- The rotation curves are flat, as far out as one can measure
- ~ 10 x more matter as directly visible via radiation



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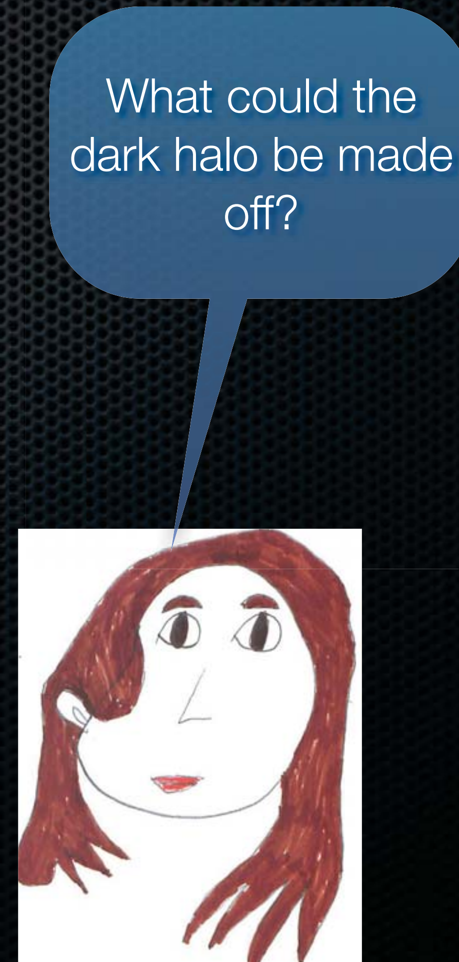
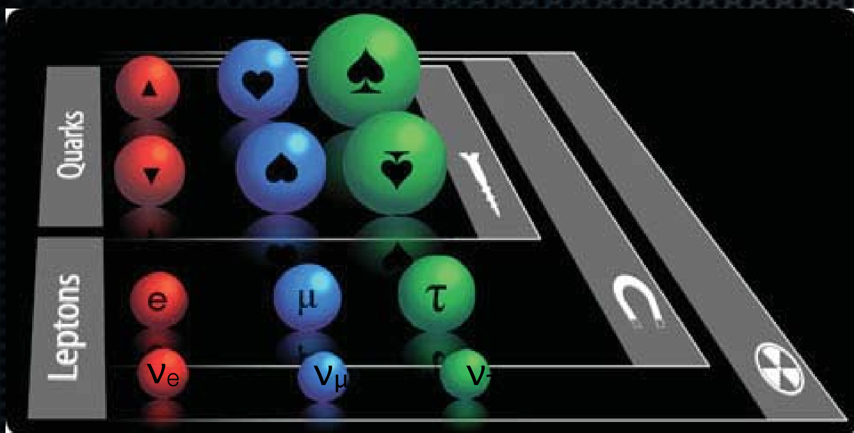
Dark matter in galaxies

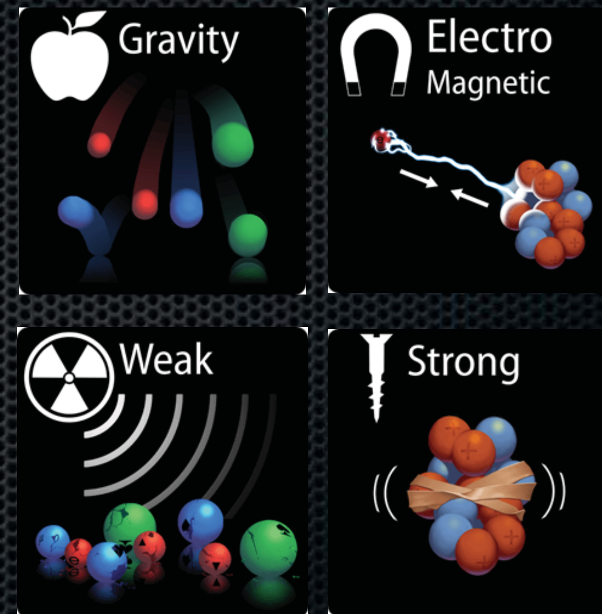


The standard model of particle physics

Fundamental interactions: mediated by bosons

Matter: quarks and leptons





- Very successful theory, describing all observations up to ≈ 1 TeV
- However, only an effective low-energy theory, *we expect new particles and phenomena* as we probe higher and higher energies
- None of the standard model particles is a good dark matter candidate!

Weakly Interacting Massive Particles

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

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

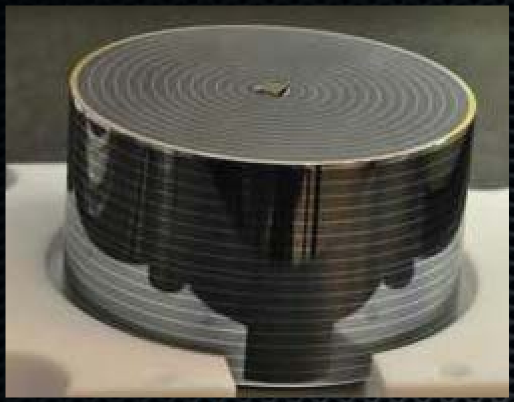
- Decouple from the rest of the particles when **M >> T (“cold”)**
- **Their relic density** can account for the dark matter if the annihilation cross section is weak (~ picobarn range)

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

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

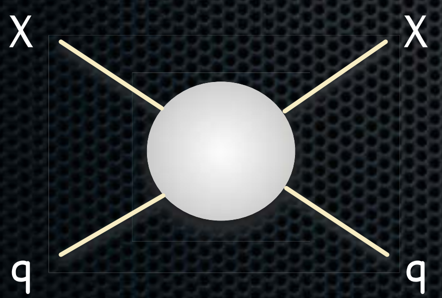
The WIMP Hypothesis is Testable

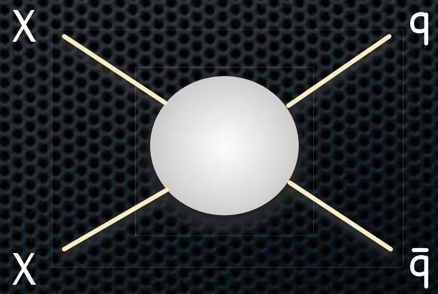
Deep underground

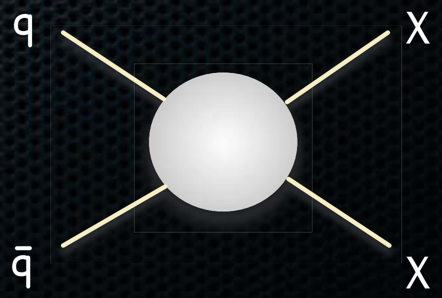


In space

At the LHC



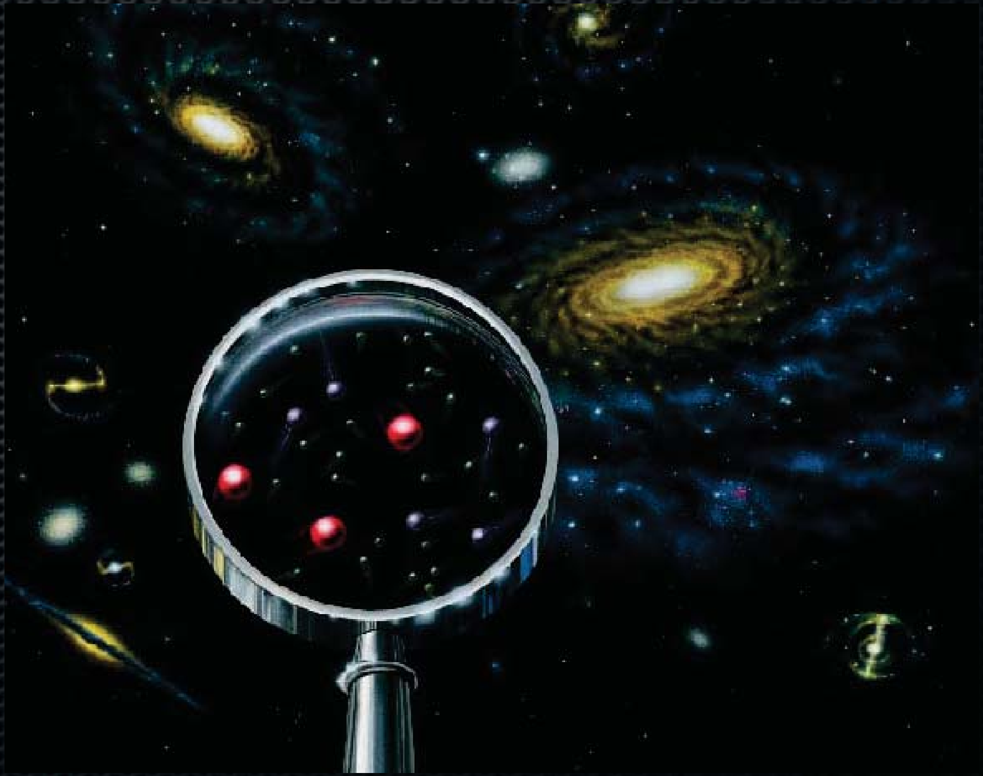




We expect to learn a lot from direct detectors, from indirect detectors and from accelerators!

The WIMP Hypothesis is Testable in the Laboratory

- 10^5 per second through your thumb without being noticed
- 10^{15} through a human body each day: only < 10 will interact, the rest is passing unaffected
- If their interaction is so week, how can we possibly detect them?



Direct Detection of WIMPs: Principle

Goodman and Witten, PRD31, 1985

- **Elastic collisions** with nuclei in ultra-low background detectors
- Energy of recoiling nucleus: ***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 WIMP-nucleus mass
- 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

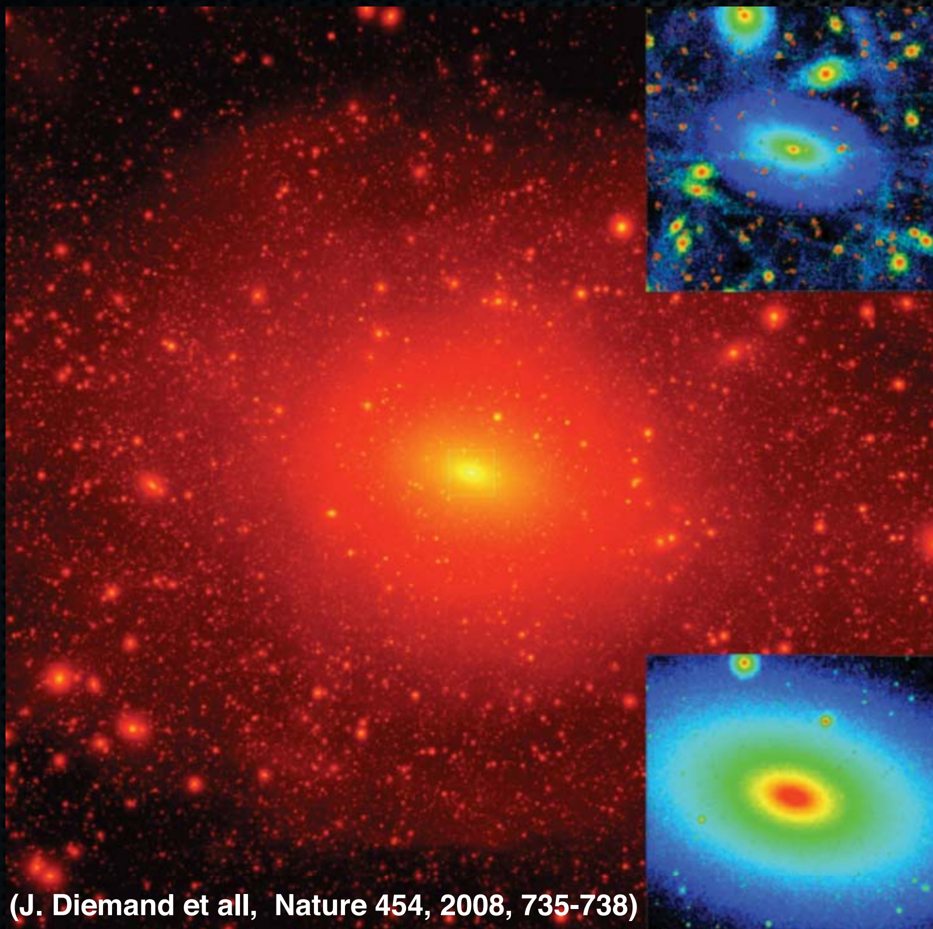
m_χ = WIMP-mass

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

Local Density of WIMPs in the Milky Way

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

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



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

~ 600 kpc

0.3 GeV cm^{-3} ⇒ ~ 3000 WIMPs m^{-3}

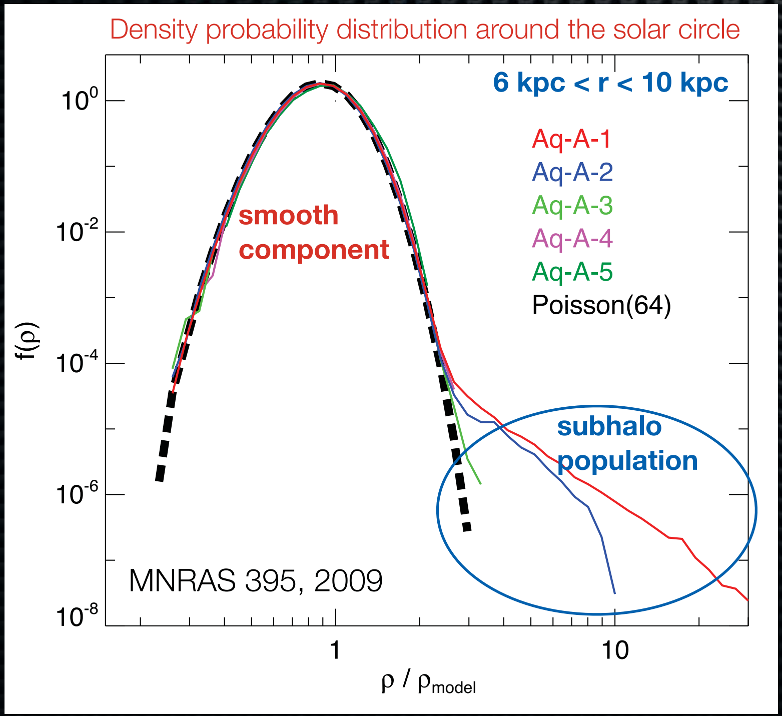
(M_W = 100 GeV)

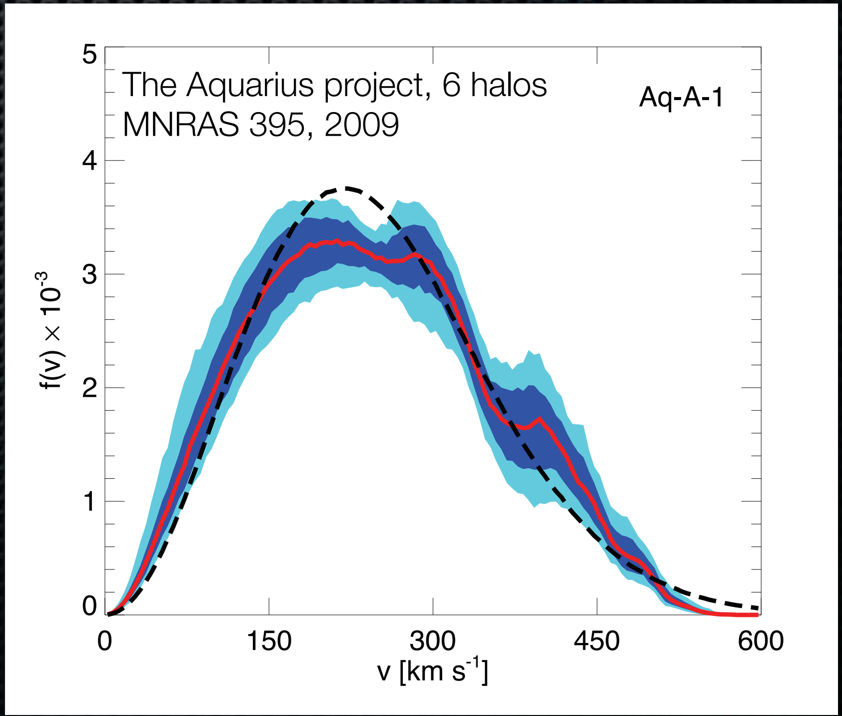
WIMP flux on Earth: ~ 10^5 $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (100 GeV WIMP)

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

The Local Dark Matter Distribution

- The dark matter distribution around the solar position seems very smooth, substructures are far away from the Sun
- The velocity distribution of dark matter at the solar circles is smooth, close to Maxwellian





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
- In the extreme NR limit relevant for galactic WIMPs (10^{-3} c) the interactions leading to **WIMP-nuclei scattering** are classified as (Goodman and Witten, 1985):
  - **scalar interactions** (WIMPs couple to nuclear mass, from the scalar, vector, tensor part of L)

$$\sigma_{SI} \sim \frac{\mu^2}{m_\chi^2}\left[Z f_p + (A-Z) f_n\right]^2$$

f_p, f_n: effective couplings to protons and neutrons

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

$$\sigma_{SD} \sim \mu^2 \frac{J_N+1}{J_N}\left(a_p \langle S_p \rangle + a_n \langle S_n \rangle\right)^2$$

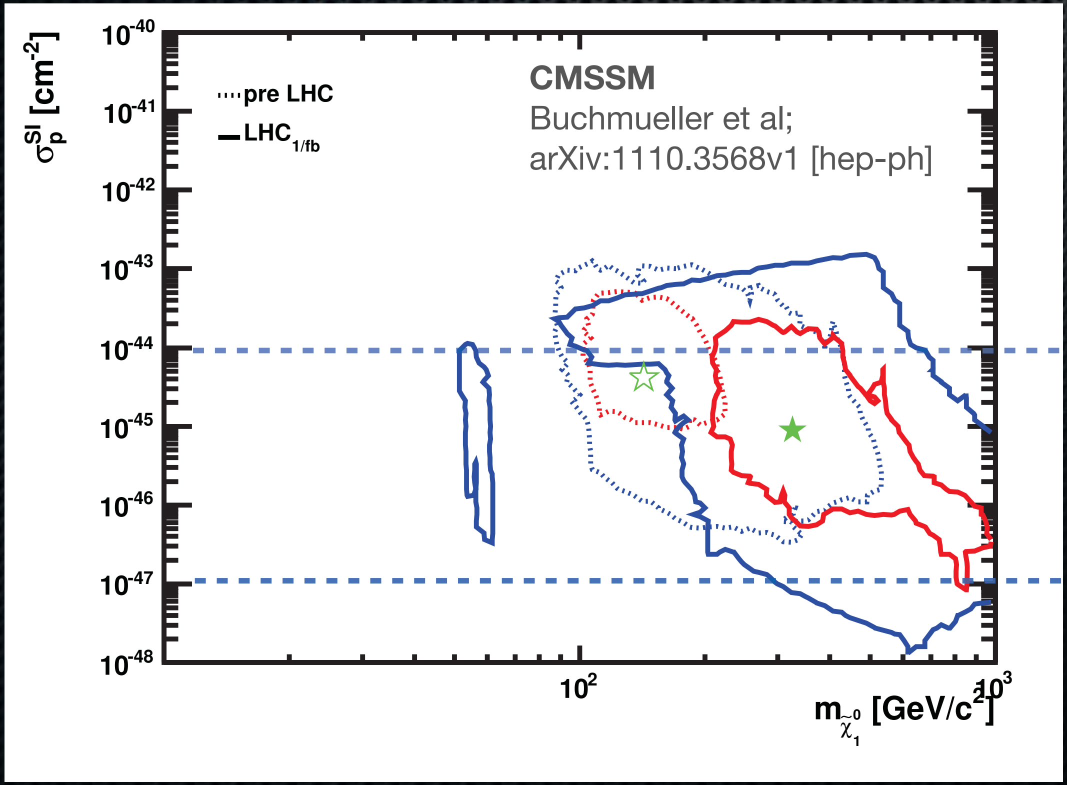
a_p, a_n: effective couplings to protons and neutrons

$\langle S_p \rangle$ and $\langle S_n \rangle$

expectation values of the p and n spins within the nucleus

WIMP Mass and Cross Section

- Example for recent predictions from supersymmetry:
  - scattering cross sections on nucleons down to **~ 10^{-48} cm^2(10^{-12} pb)**



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WIMP Mass and Cross Section

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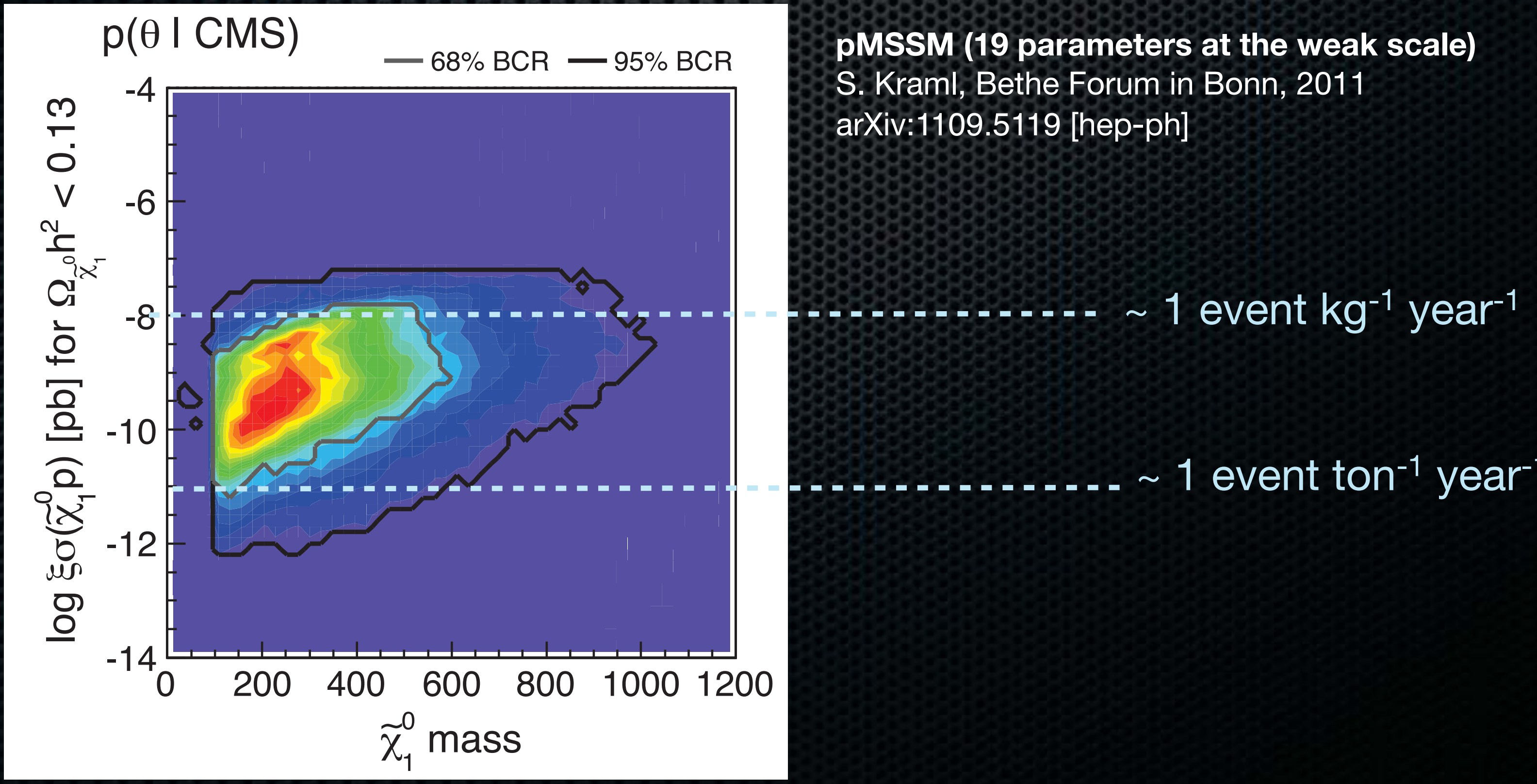

pMSSM (19 parameters at the weak scale)
S. Kraml, Bethe Forum in Bonn, 2011
arXiv:1109.5119 [hep-ph]

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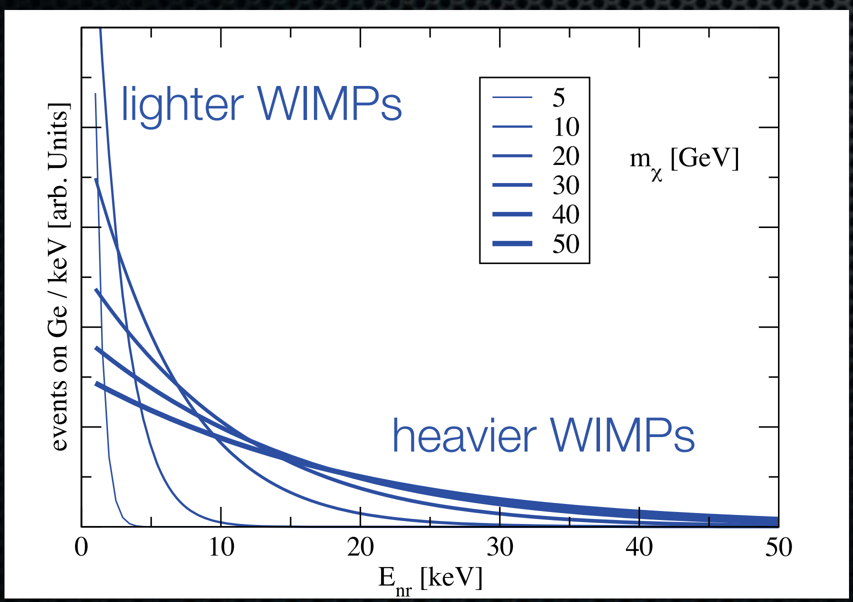
Expected Interaction Rates

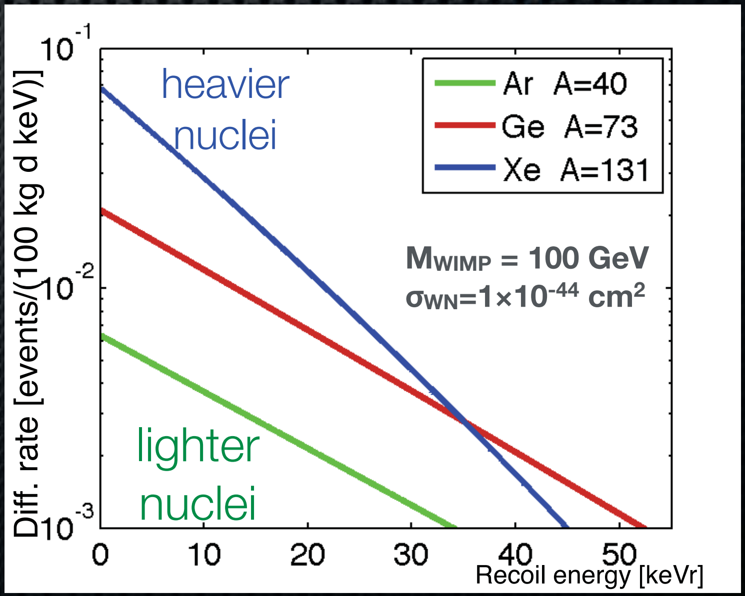
- Differential recoil rate: integrate over WIMP velocity distribution

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

Different WIMP masses



Different target nuclei



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

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Vanilla Exclusion Plot

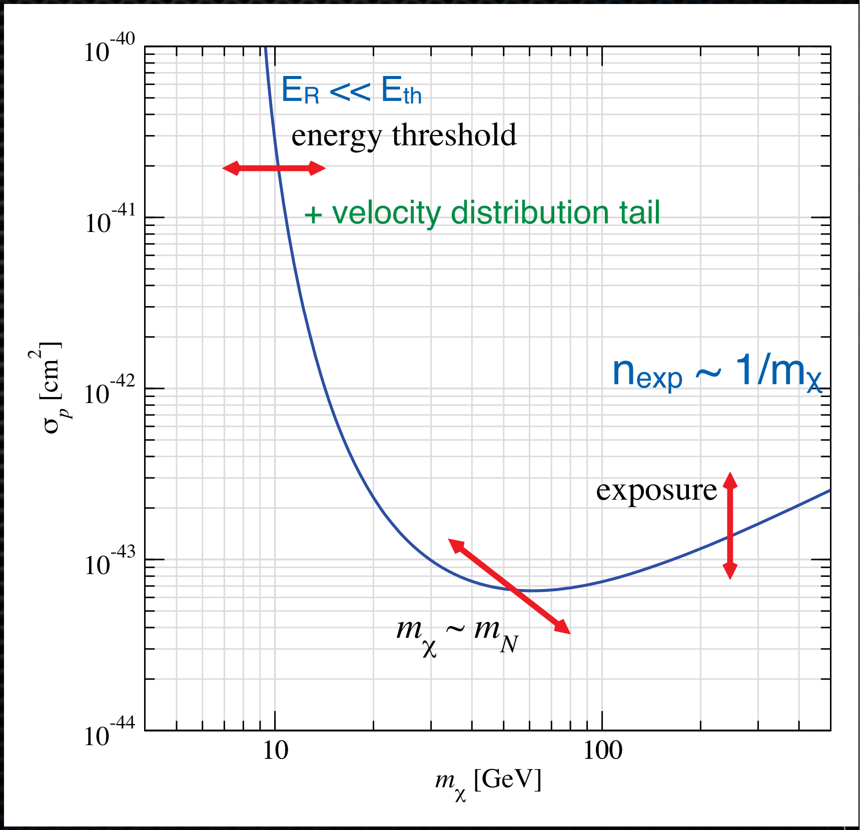
- Assume we have a **detector of mass M taking data for a period of time t:**
- The total exposure will be **ε = M × t [kg days];** nuclear recoils are detected above an energy threshold E_{th}, up to a chosen energy E_{max}. The expected number of events n_{exp} will be:

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

⇒ 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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The Challenge

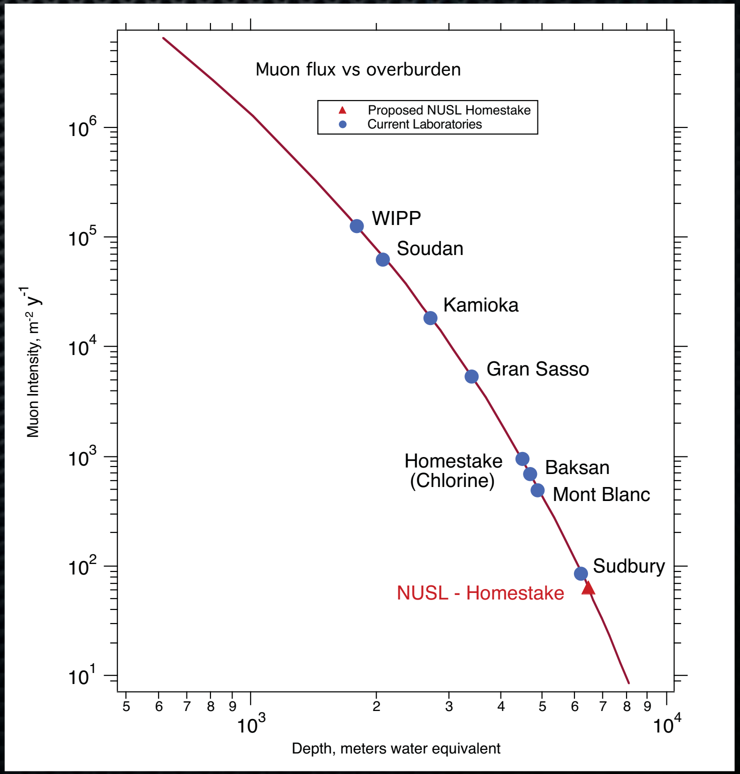
- **To observe a signal which is:**
  - very small (few keV)
  - extremely rare (1 per ton per year?)
  - embedded in a background that is millions of times higher

- **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?**

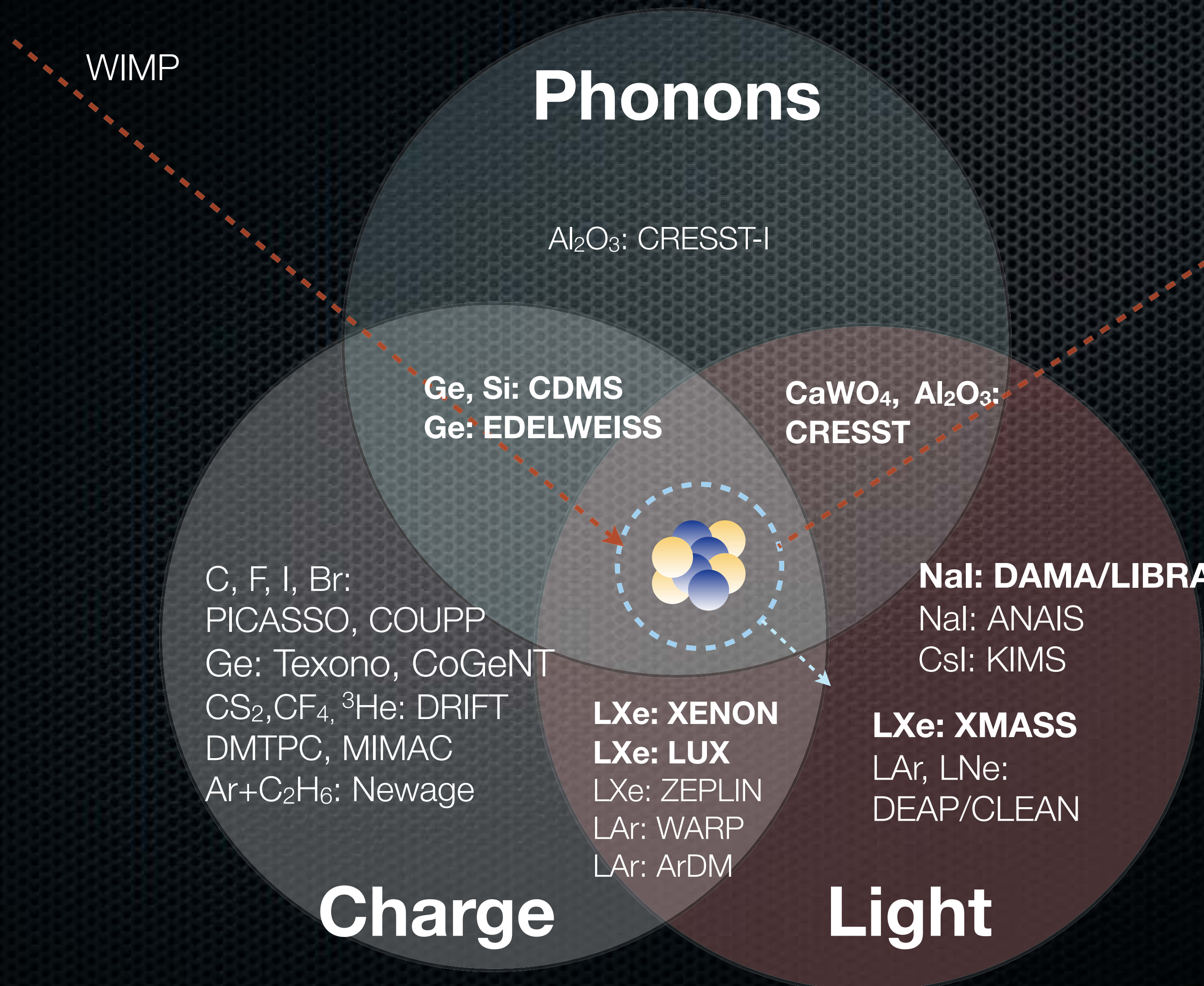
The background noise

- **Electromagnetic radiation**
  - natural radioactivity in detector and shield materials
  - airborne ^{222}Rn
  - cosmic activation of materials during storage/ transportation at the Earth's surface
- **Neutrons**
  - radiogenic from (α,n) and fission reactions
  - cosmogenic from spallation of nuclei in materials by cosmic muons
- **Alpha particles**
  - ^{210}Pb decays at the detector surfaces
  - nuclear recoils from the Rn daughters

Cosmic rays: operate deep underground



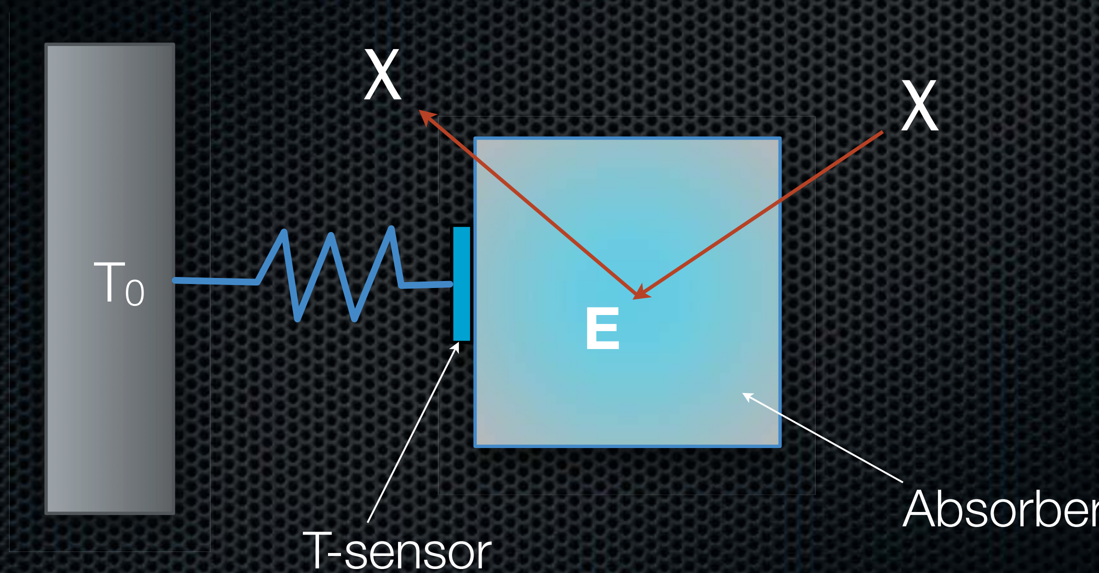
Direct Dark Matter Detection Techniques



here: focus on recent results

Phonons: Cryogenic Experiments at T~ mK

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

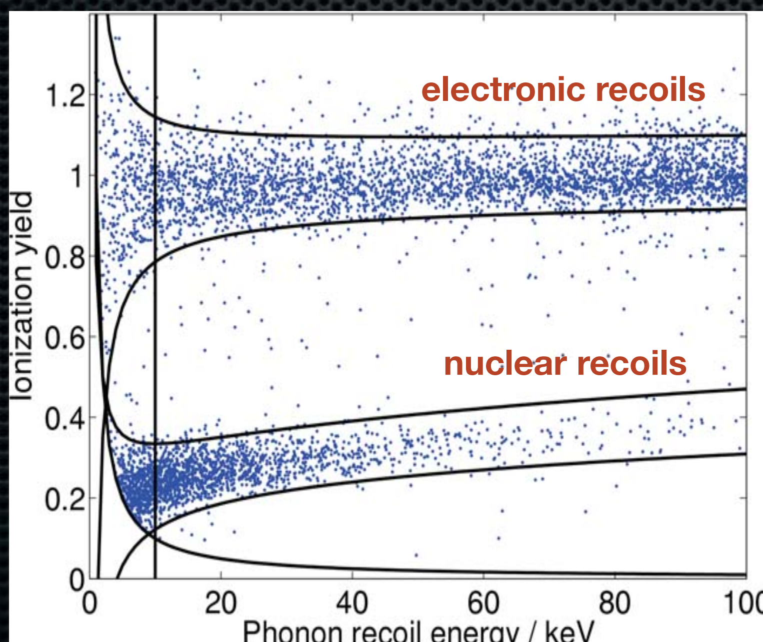


- T-sensors: superconductor thermistors or superconducting transition sensors

Phonons: Cryogenic Experiments at T~ mK

- **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 -> separation of S and B

Ratio of charge (or light) to phonon



Background region

Expected signal region

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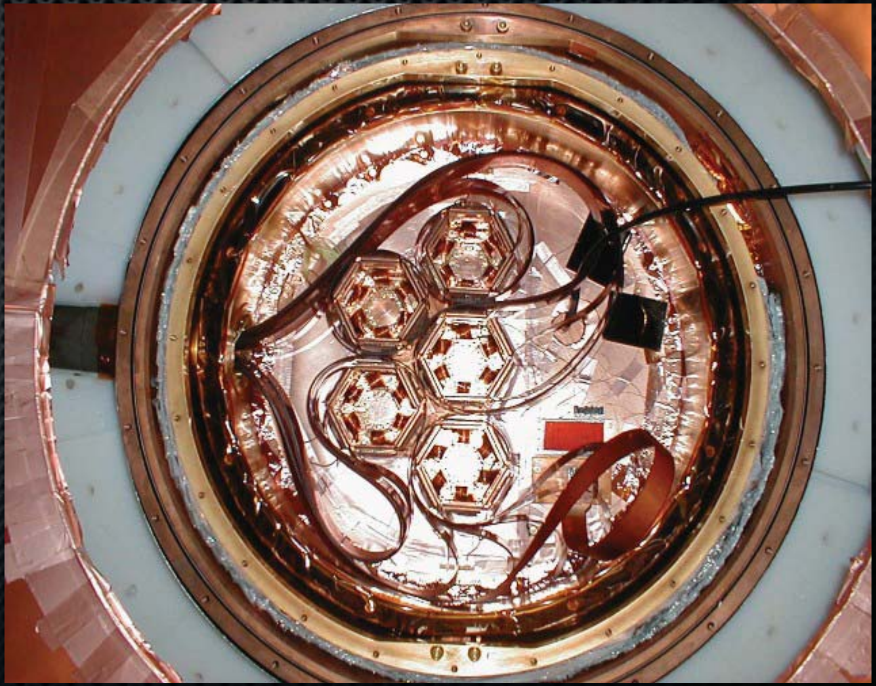
Phonons: The CDMS Experiment

- 30 Ge/Si detectors operated at 40 mK in a low-background shield at the Soudan mine in northern Minnesota
- Neutron background due to muons: ~ 1 kg^{-1} $year^{-1}$

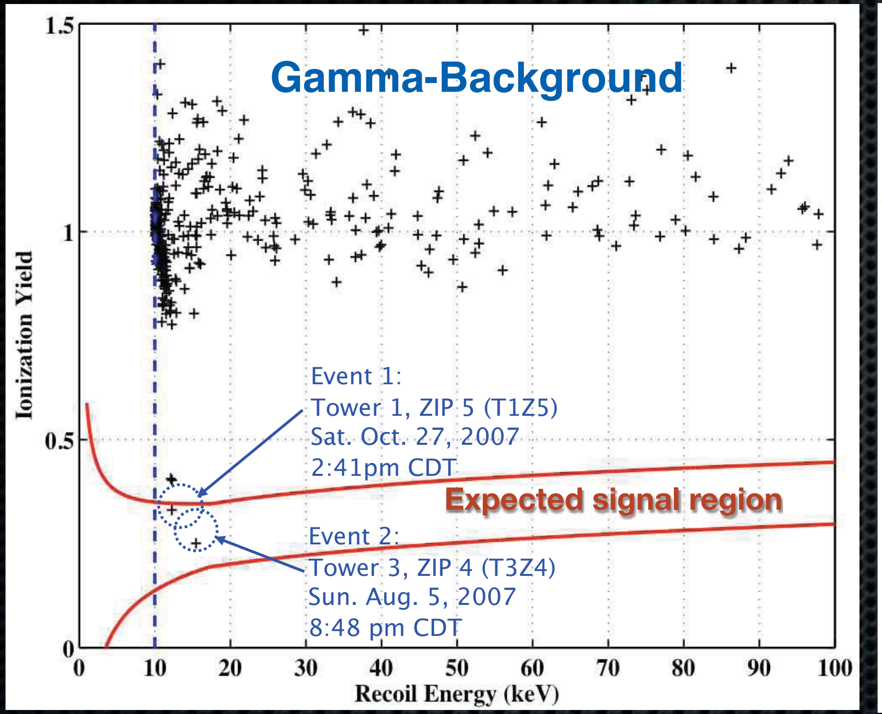
Entrance to the Soudan mine

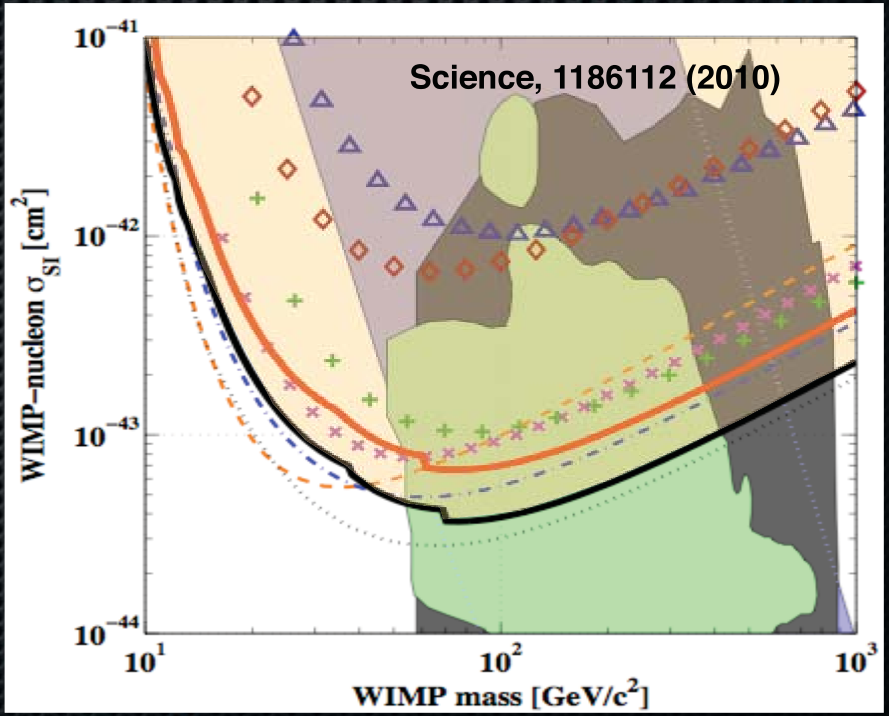


CDMS cryostat

Phonons: The CDMS Experiment

- Final WIMP search runs - 191 kg-d: **2 events passing all cuts**





- Expected background: 0.8 ± 0.1 (stat) ± 0.2 (syst) events
- Probability to observe two or more events is 23%

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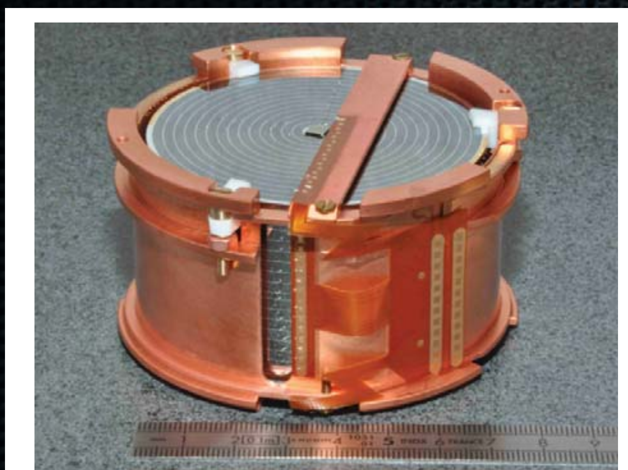
Phonons: CRESST and EDELWEISS

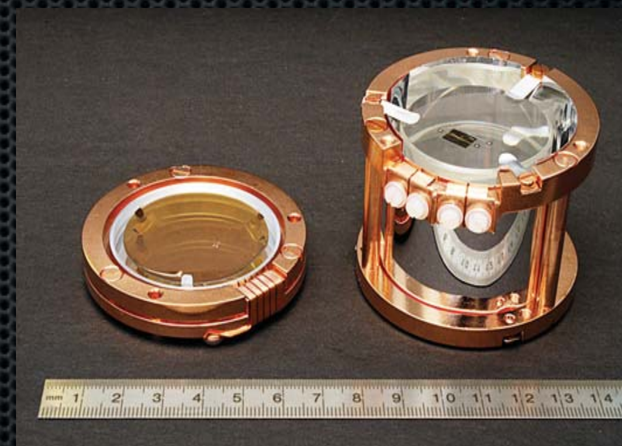
EDELWEISS at Modane

- Ge detectors at 18 mK
- Detect phonons and charge



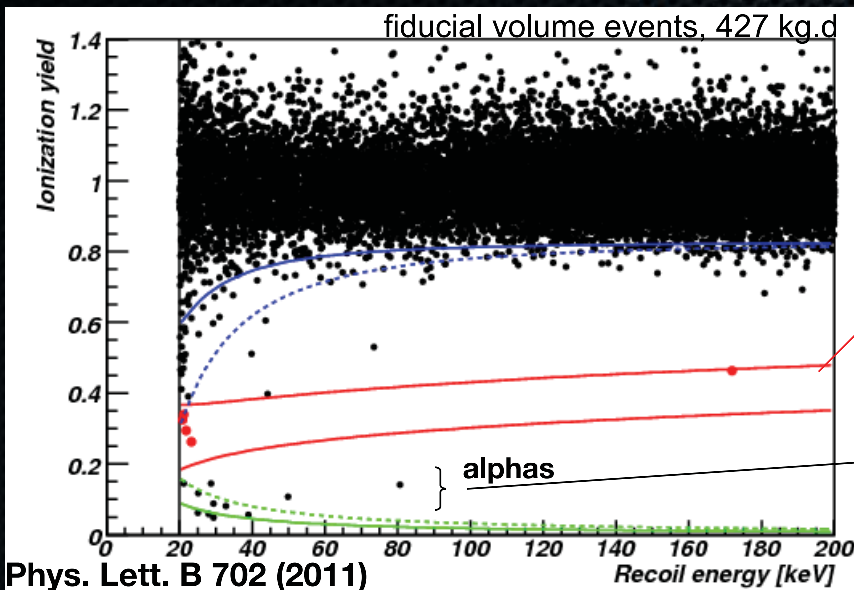
CRESST at LNGS

- $CaWO_3$ detectors at 10 mK
- Detect phonons and light



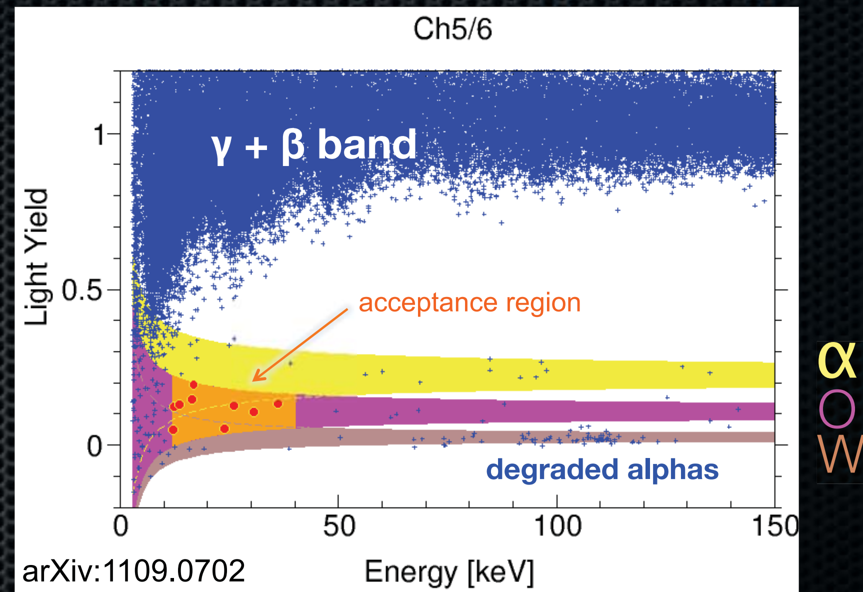
Phonons: CRESST and EDELWEISS

EDELWEISS at Modane



- Ge detectors at 18 mK
- 5 events (427 kg-day)
- 3 expected from backgrounds
- operates new, 8 x 800 g crystals with improved background rejection

CRESST at LNGS



- $CaWO_3$ detectors at 10 mK
- 67 events observed (730 kg-day)
- ~ 37 expected from backgrounds
- room for a signal?
- focus on reducing backgrounds

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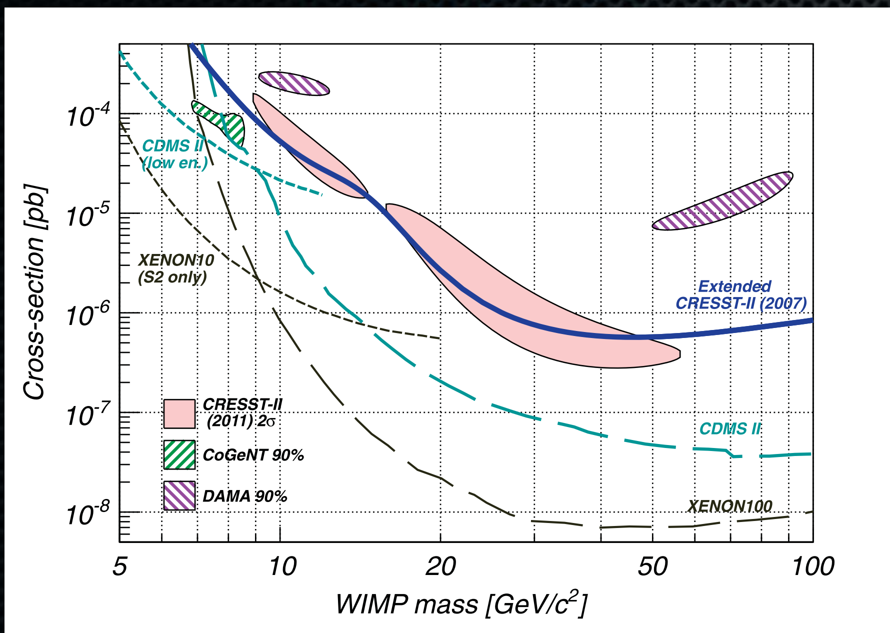
Recent CRESST results

Talk at TAUP 2011, and arXiv:1109.0702

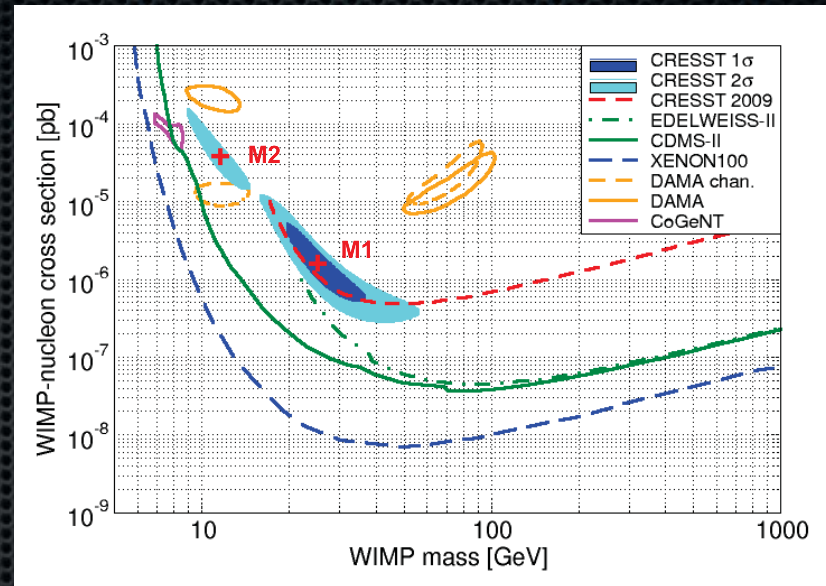
PHYSICAL REVIEW D **85**, 021301(R) (2012)

Extending the CRESST-II commissioning run limits to lower masses

Andrew Brown,[1,*] Sam Henry,[1] Hans Kraus,[1] and Christopher McCabe[2]
[1]*Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, United Kingdom*
[2]*Rudolf Peierls Centre for Theoretical Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, United Kingdom*
(Received 19 September 2011; published 18 January 2012)



47.9 kg-days exposure in $CaWO_4$

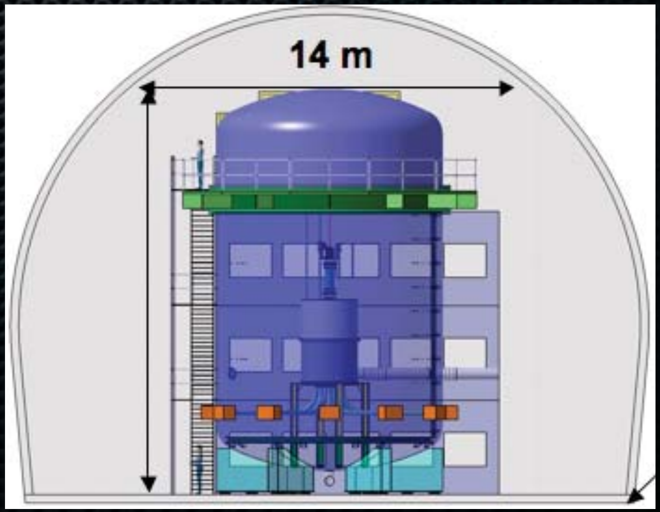


	M1	M2
e/γ events	8.00 ± 0.05	8.00 ± 0.05
α events	$11.5^{+2.6}_{-2.3}$	$11.2^{+2.5}_{-2.3}$
neutron events	$7.5^{+6.3}_{-5.5}$	$9.7^{+6.1}_{-5.1}$
Pb recoils	$15.0^{+5.2}_{-5.1}$	$18.7^{+4.9}_{-4.7}$
signal events	$29.4^{+8.6}_{-7.7}$	$24.2^{+8.1}_{-7.2}$
m_χ [GeV]	25.3	11.6
σ_{WN} [pb]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$

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; EDELWEISS + CRESST
- To be located at the ULISSE Lab (Modane extension) in France



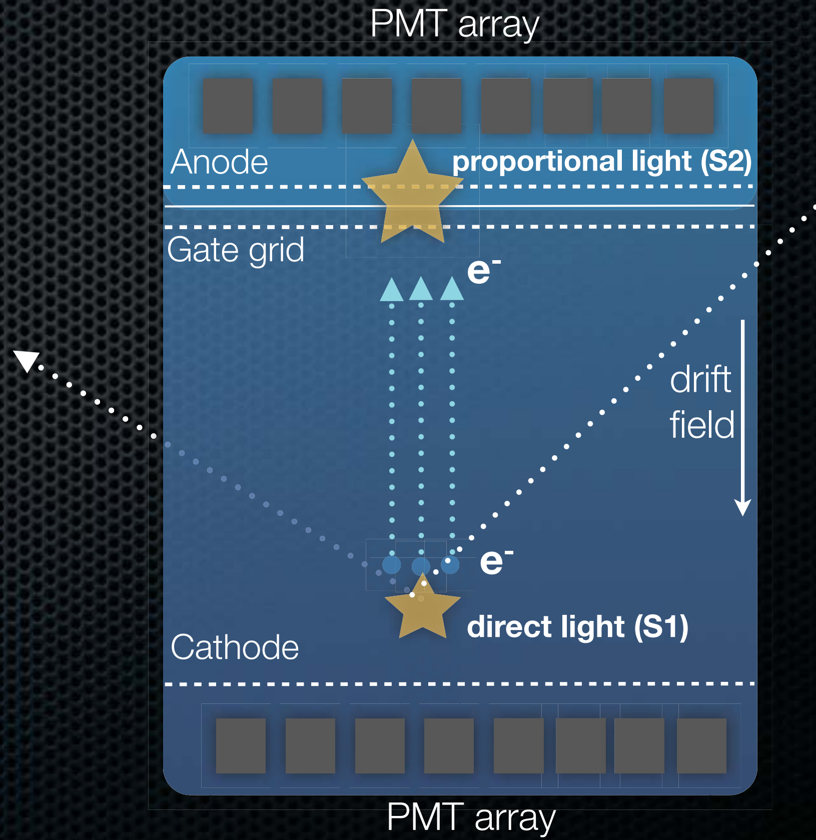
Light: Noble Liquids TPCs

- 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)*

- charge/light depends on dE/dx
- good 3D position resolution

=> particle identification
=> fiducial volume cuts
+ self-shielding

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



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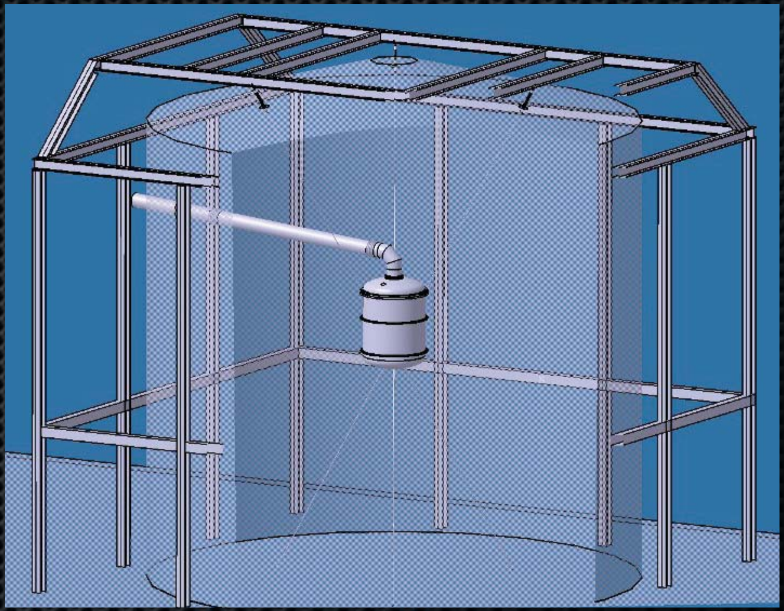
The XENON Experiment

XENON100

1 m

In conventional shield at LNGS
2008 - 2012; taking science data

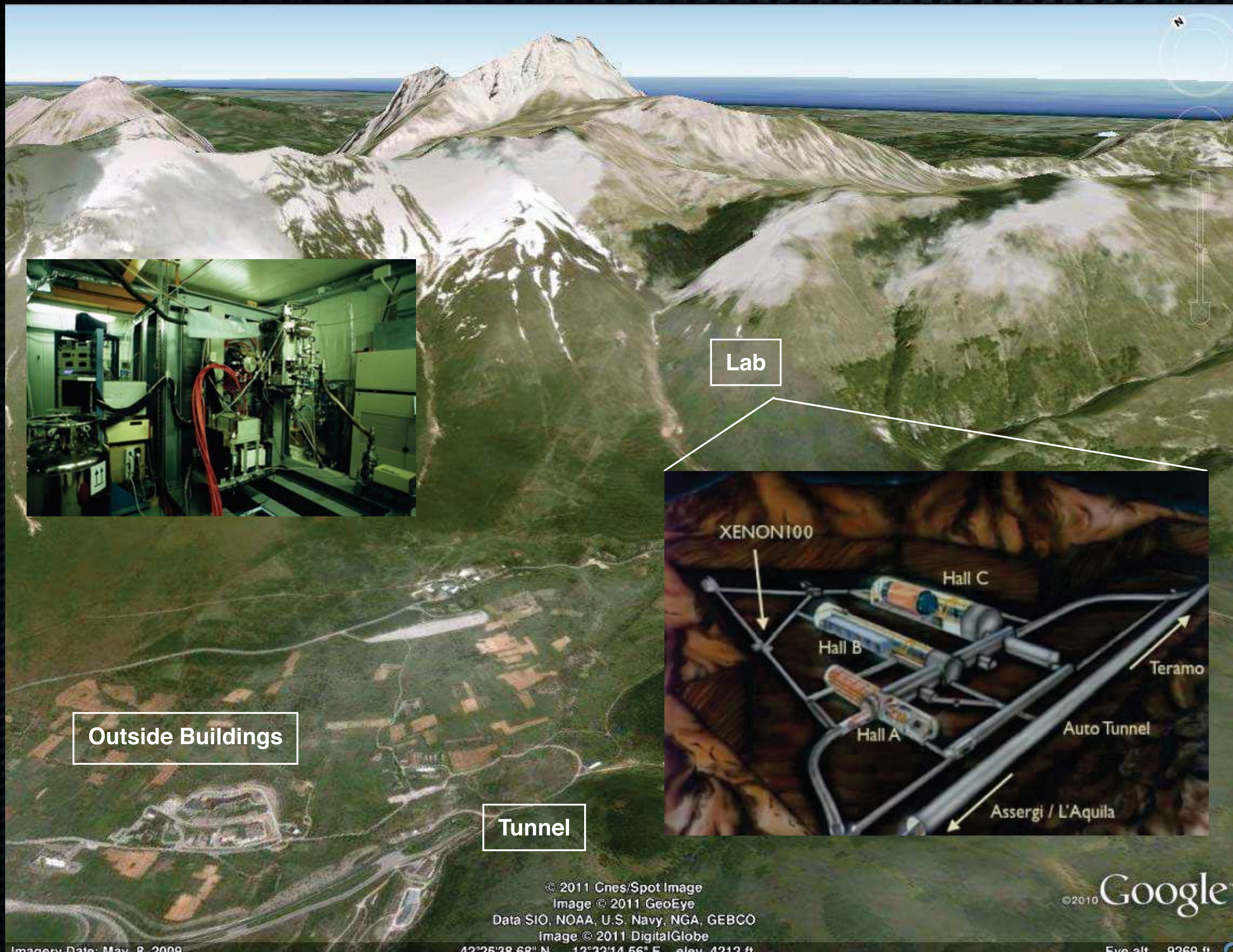
XENON1T



10 m

In water Cerenkov shield at LNGS
2011- 2015; construction to start in
second half of 2012

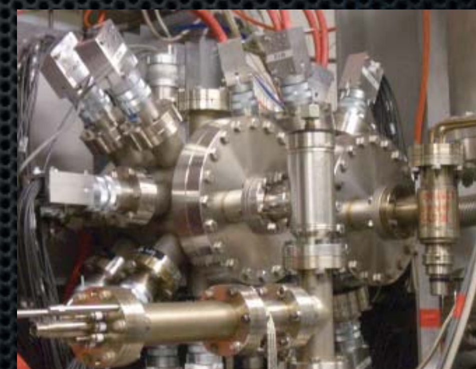
The Gran Sasso National Laboratory



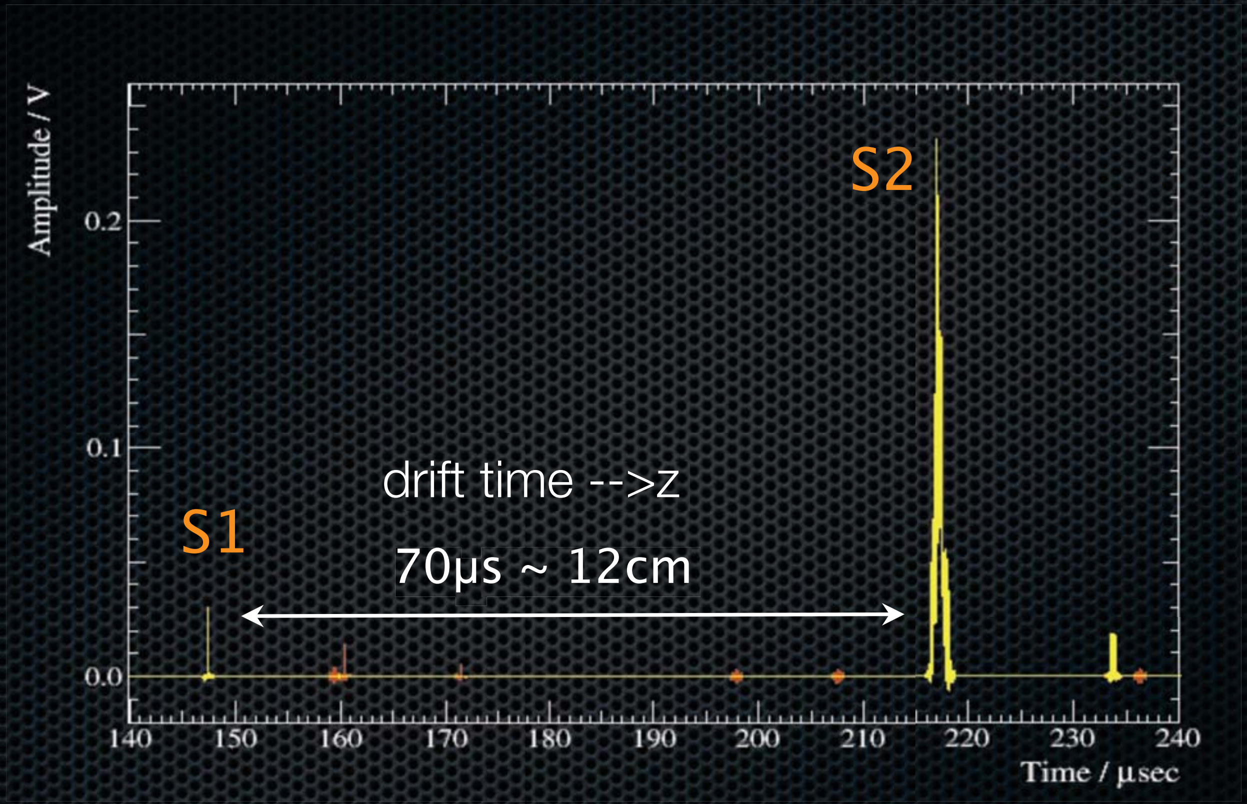
The XENON100 Detector

- 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

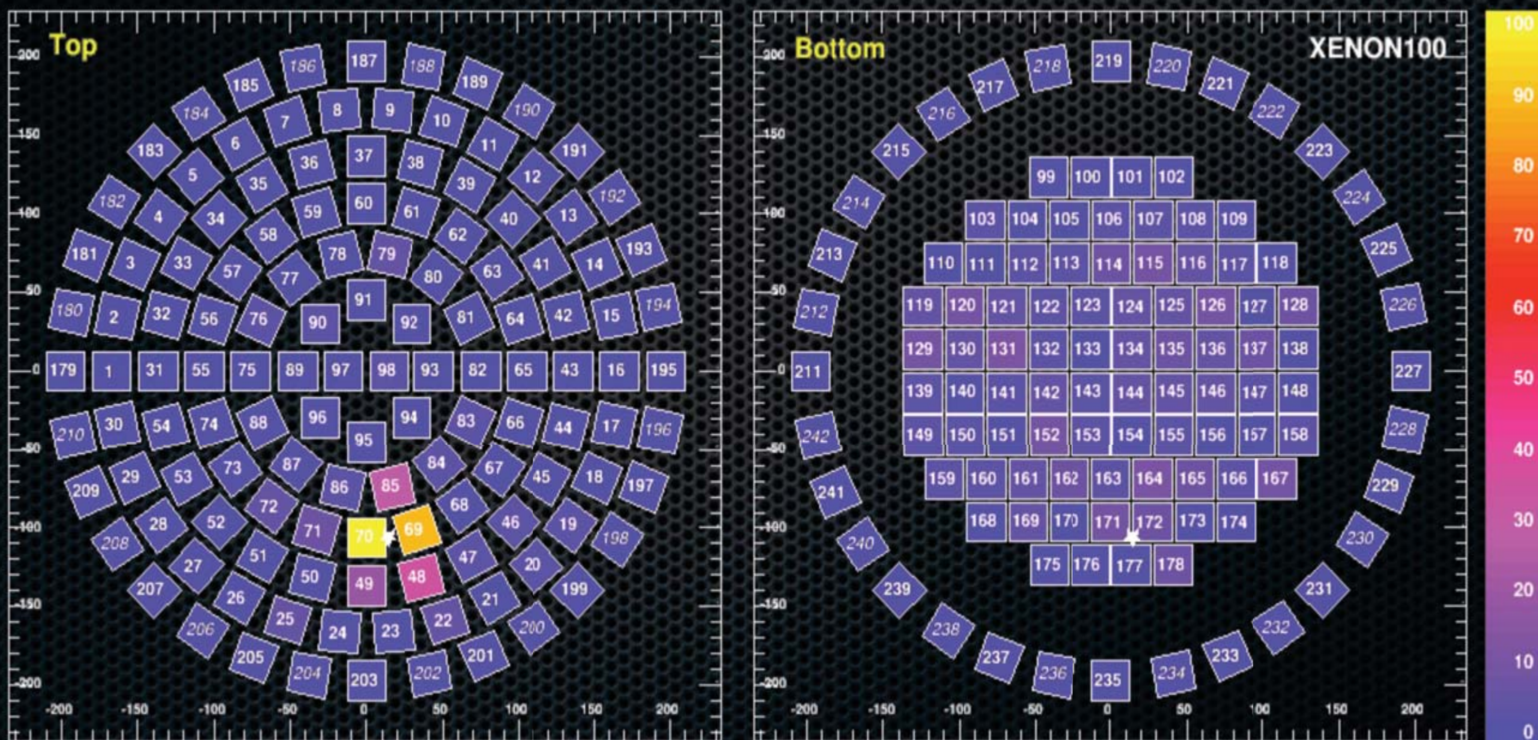


- 4 photoelectrons detected from about 100 S1 photons
- 645 photoelectrons detected from 32 ionization electrons which generated about 3000 S2 photons

Example of a 9 keV Nuclear Recoil Event

Top PMT array

Bottom PMT array

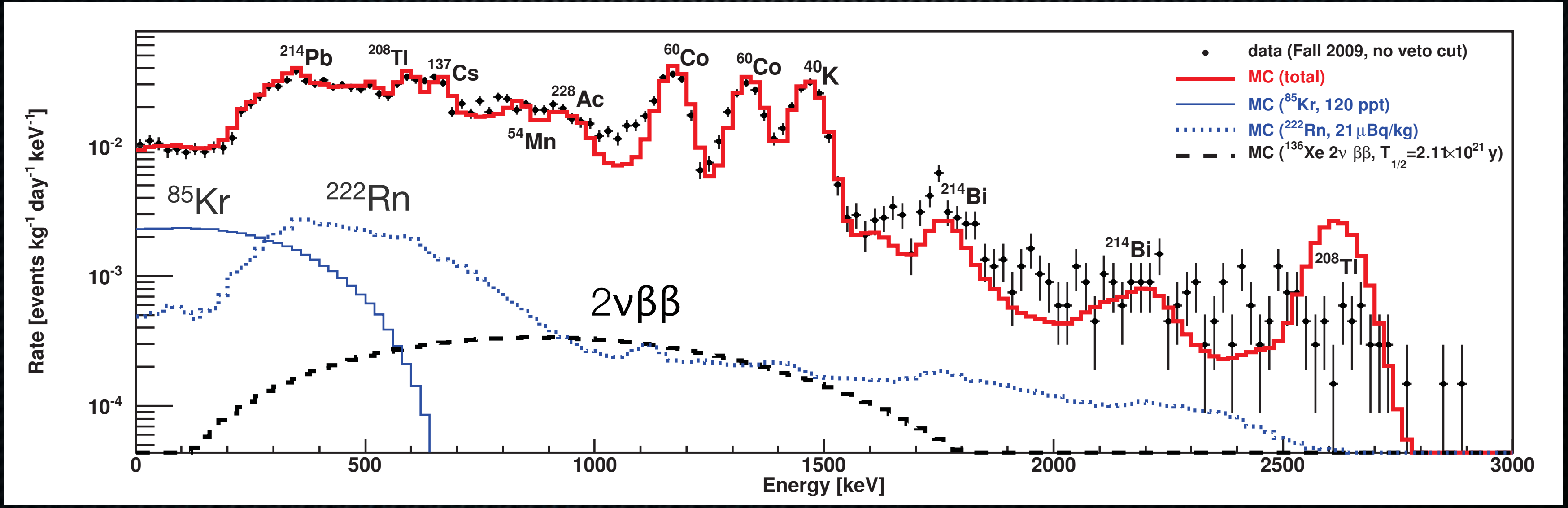


xe100_091215_1039_000030-830

- light pattern in top array => x-y position of an 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 (the previous XENON phase)



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

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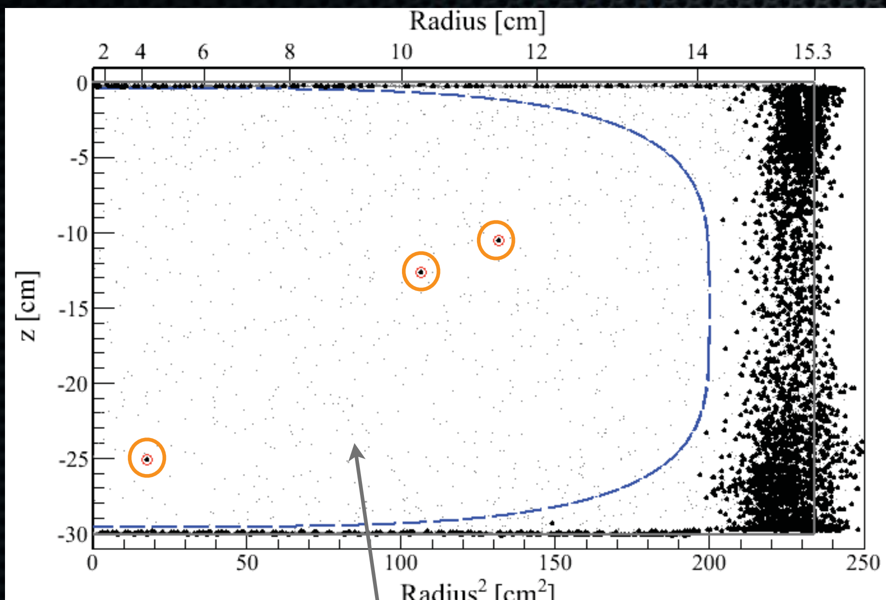
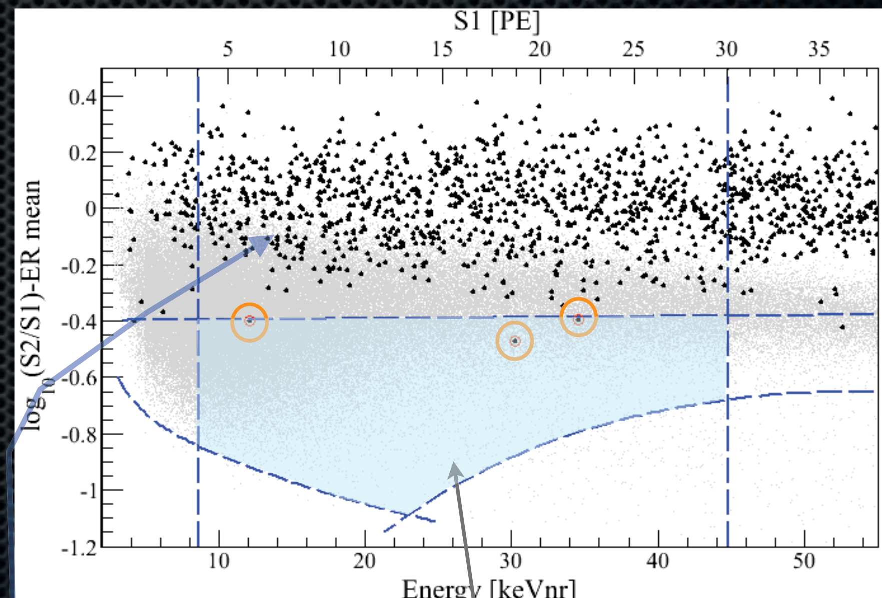
XENON100: Recent Results

- Exposure: ~ **1471 kg-days** (48 kg fiducial mass); January - June 2010



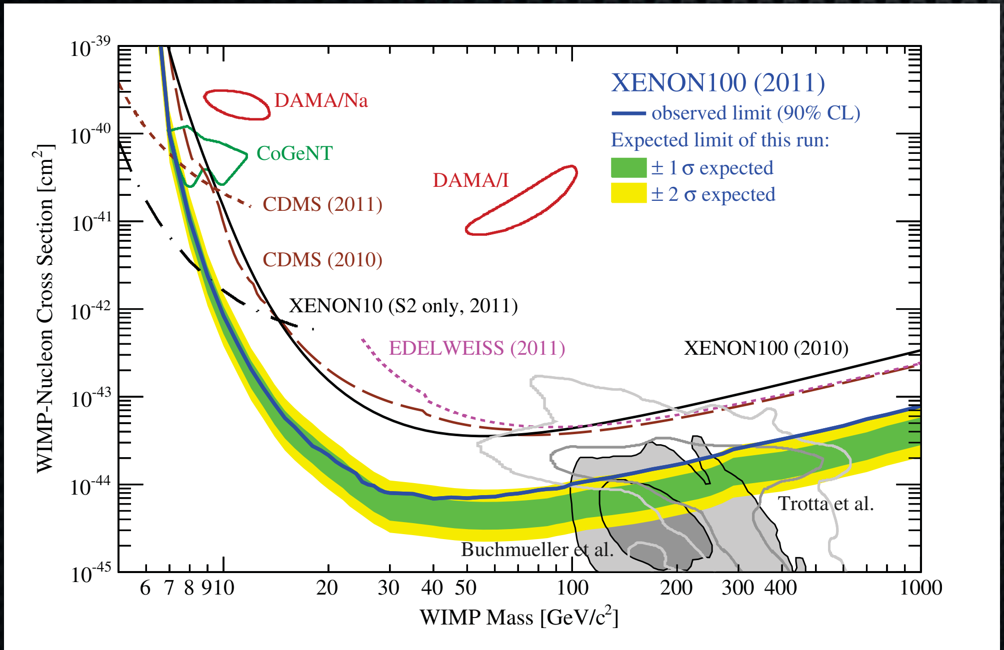


Fiducial mass region:
48 kg of liquid xenon
900 events in total

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

XENON100: Recent Results

Phys. Rev. Lett. 107, 131302 (2011)



Green/yellow bands:

1- and 2-σ expectation, based on zero signal

Limit (dark blue):

1.5 - 2 σ worse, given 2 events at high S1

Limit at M_W = 50 GeV:

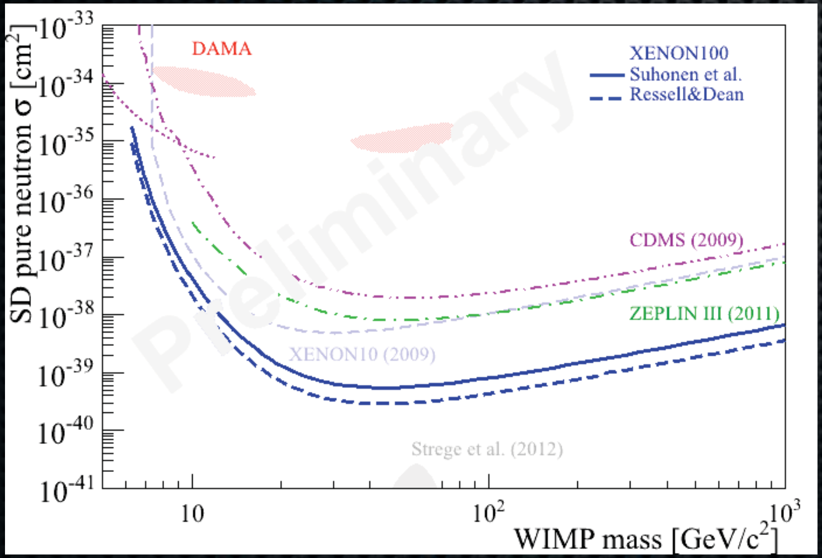
7 x 10^{-45} cm^2 (90% C.L.)

Laura Baudis, University of Zurich Physics Colloquium, IFIC Valencia

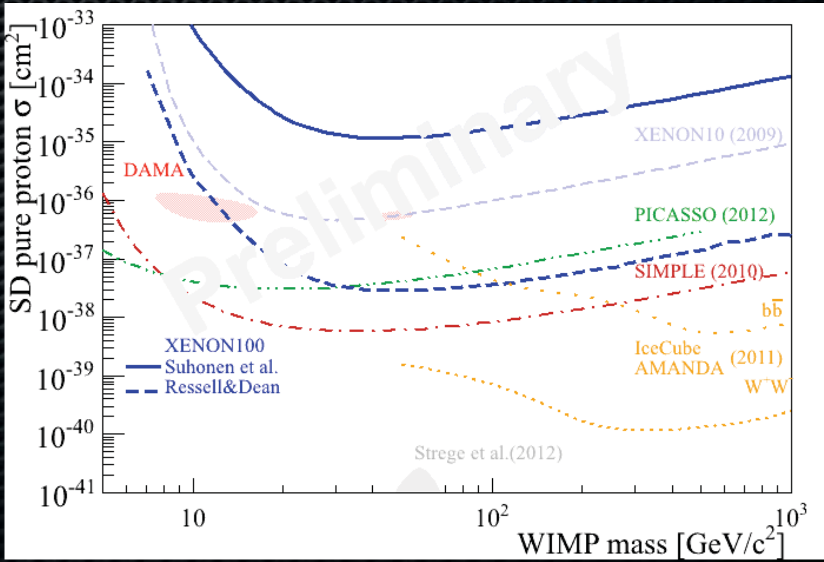
New XENON SD limits

- Analysis of 100.9 days for SD coupling to WIMPs for ^{129}Xe and ^{131}Xe
- Same data and event selection as for the SI analysis
- Two nuclear models

coupling to n



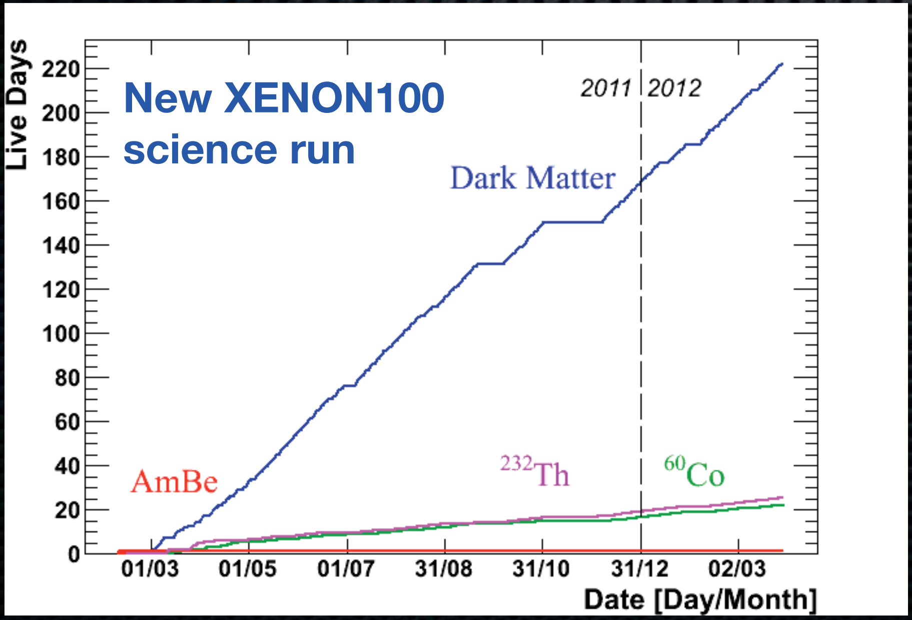
coupling to p

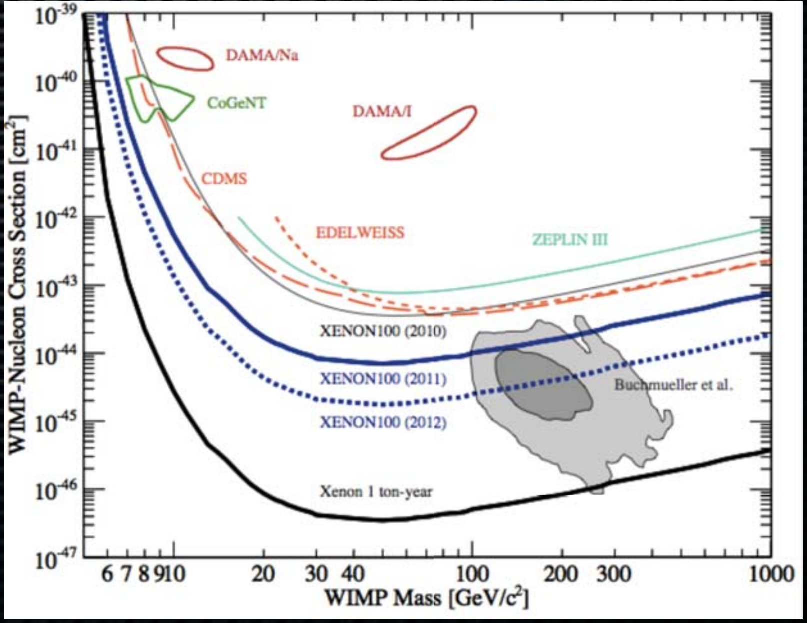


Laura Baudis, University of Zurich   Physics Colloquium, IFIC Valencia

XENON: status and sensitivity

- New dark matter run started in March 2011 (~ 220 live days of data)
- Concentration of ^{85}Kr: lower by a factor of 20
- Improved LXe purity and lower trigger threshold
- Analysis in progress; release of results soon
- In parallel: construction of XENON1T @ LNGS





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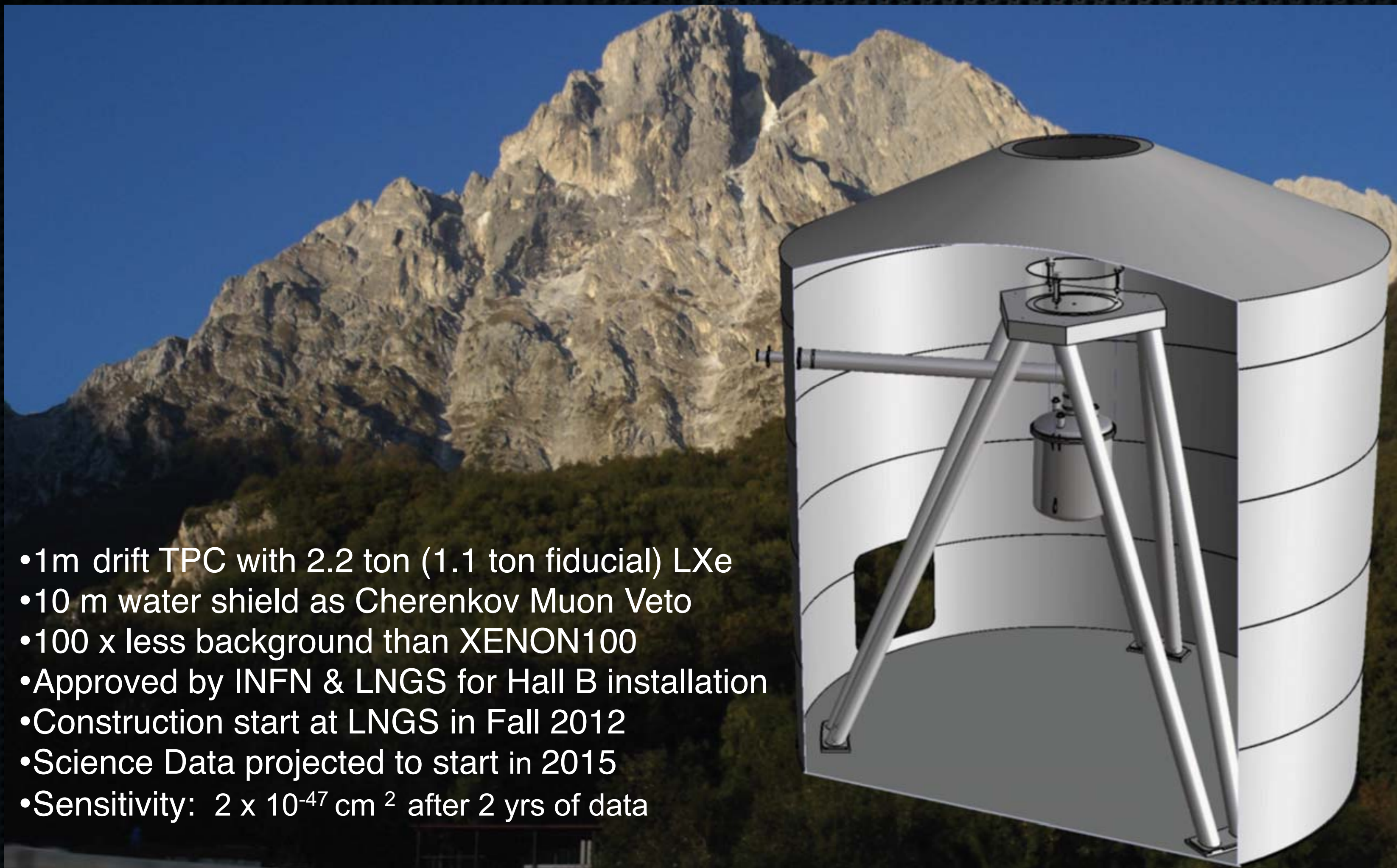
XENON1T at LNGS



- 1m drift TPC with 2.2 ton (1.1 ton fiducial) LXe
- 10 m water shield as Cherenkov Muon Veto
- 100 x less background than XENON100
- Approved by INFN & LNGS for Hall B installation
- Construction start at LNGS in Fall 2012
- Science Data projected to start in 2015
- Sensitivity: 2×10^{-47} cm ^{2} after 2 yrs of data

Light: LUX and XMASS

- **LUX in the US (+ UK groups)**
  - ➡ 350 kg LXe TPC, 100 kg fiducial
  - ➡ in commissioning above ground at Homestake in South Dakota
  - ➡ to be placed underground in 2012
- **XMASS in Japan**
  - ➡ 800 kg single phase detector (642 PMTs), 100 kg fiducial, 10x10 m water shield
  - ➡ commissioning run in 2011
  - ➡ new results in 2012

LUX at Homestake

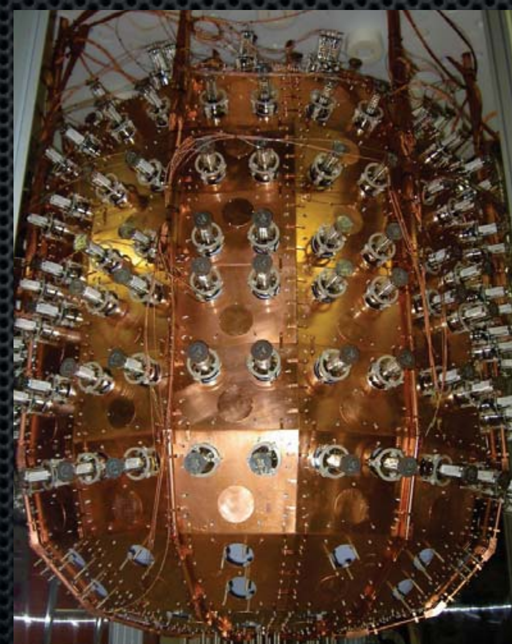
XMASS at Kamioka

Light: Liquid Argon Detectors

- WARP at LNGS
  - ➡ 140 kg LAr TPC
  - ➡ 8.4 t LAr veto shield
  - ➡ technical runs in 2008 and 2010
  - ➡ new technical run since June 2011

- ArDM at Canfranc
  - ➡ 850 kg LAr TPC
  - ➡ commissioned at CERN
  - ➡ approved by LSC in Oct 2010
  - ➡ to be installed underground by the end of 2012

WARP at LNGS

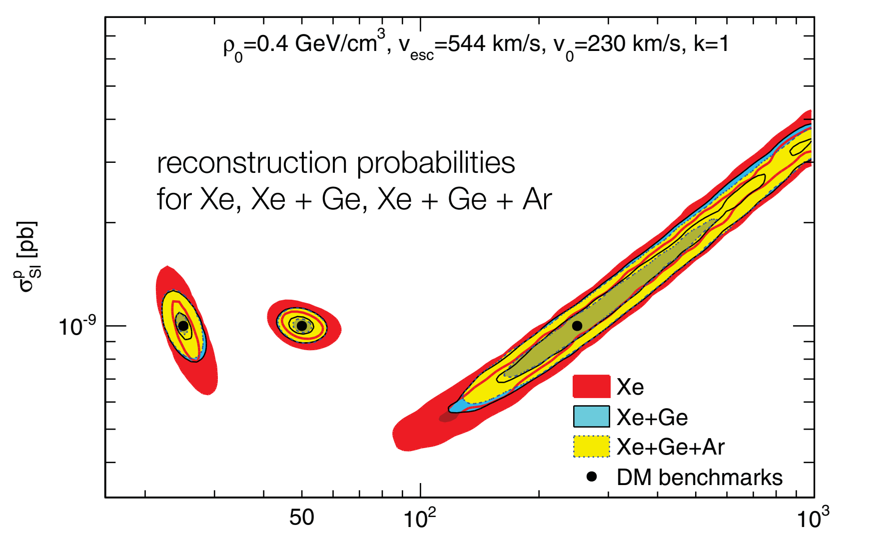


ArDM at Canfranc

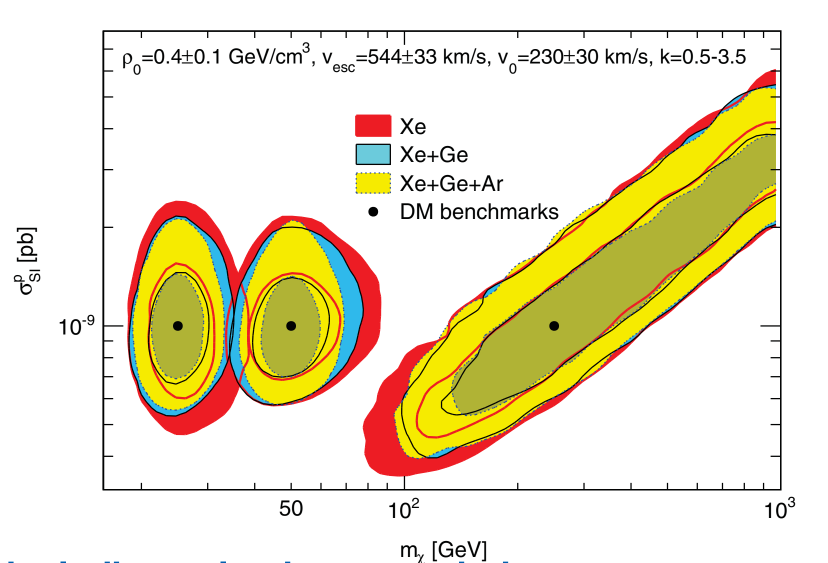
Beyond Current Detectors

- To reconstruct WIMP properties, *larger detectors are needed*
- Different targets are sensitive to different directions in the m_χ- σ_{SI} plane

target	ϵ [ton×yr]	η_{cut}	A_{NR}	ϵ_{eff} [ton×yr]	E_{thr} [keV]	$\sigma(E)$ [keV]	background events/ϵ_{eff}
Xe	5.0	0.8	0.5	2.00	10	Eq. (7)	< 1
Ge	3.0	0.8	0.9	2.16	10	Eq. (6)	< 1
Ar	10.0	0.8	0.8	6.40	30	Eq. (8)	< 1



fixed galactic model



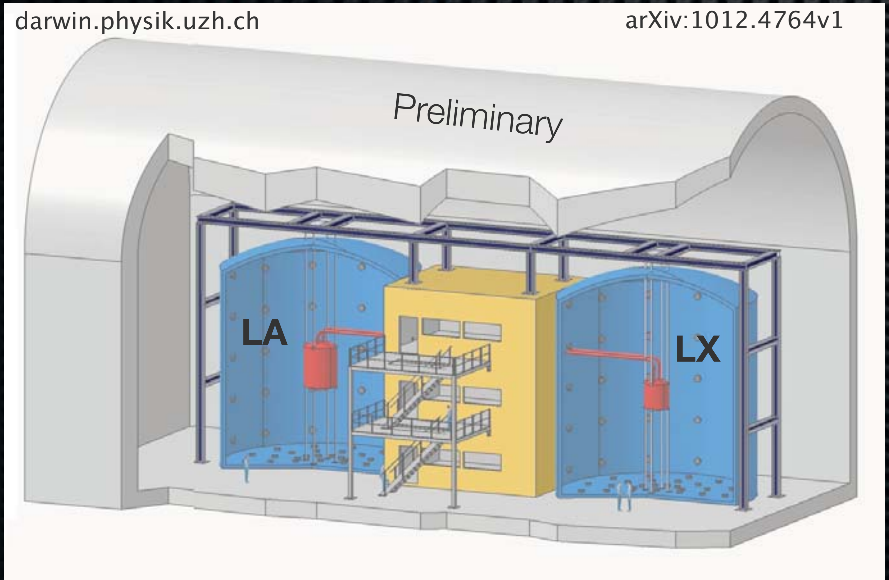
including galactic uncertainties

Miguel Pato, Laura Baudis, Gianfranco Bertone, Roberto Ruiz de Austri, Louis E. Strigari and Roberto Trotta   Phys. Rev. D 83, 083505 (2011)

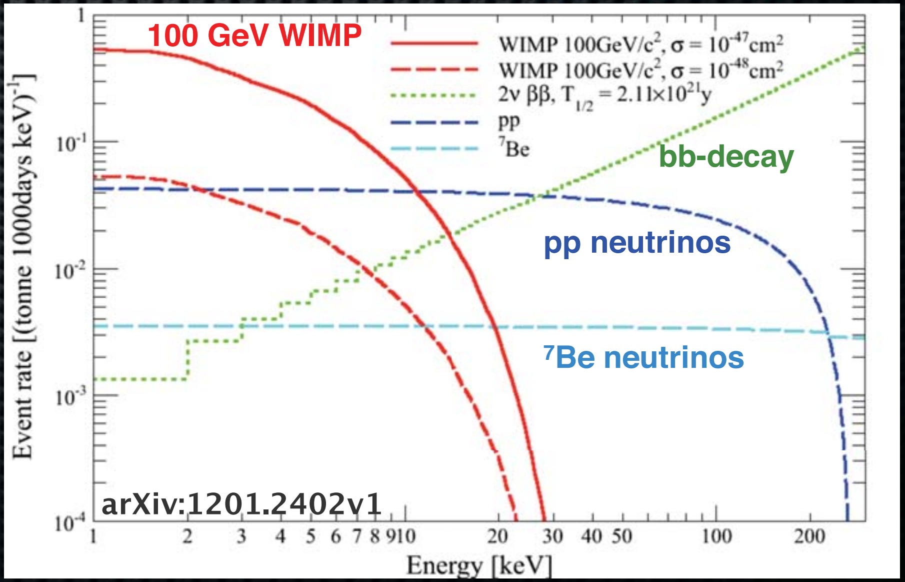
DARWIN

DARk matter WImp search with Noble liquids

- R&D and design study for next-generation noble liquid detector
- Physics goal: build the "ultimate WIMP detector", before the possibly irreducible neutrino background takes over



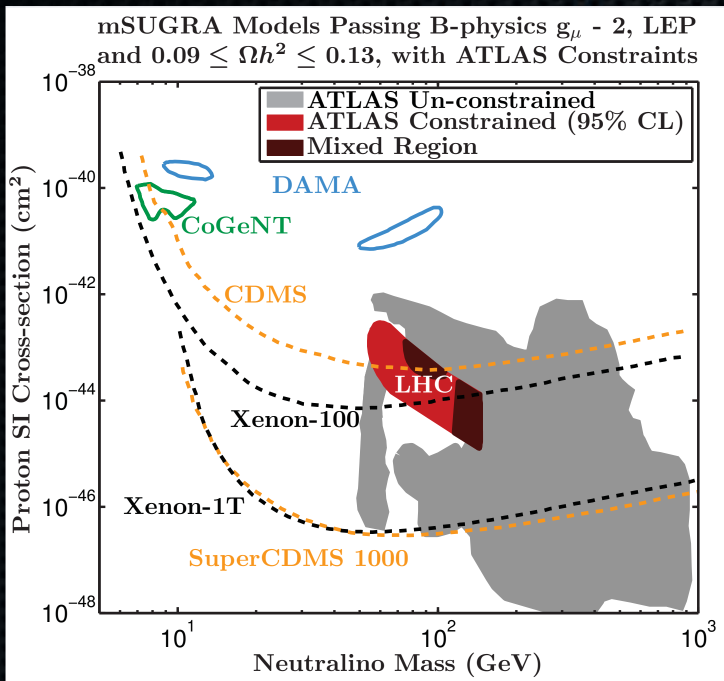
Sketch of possible layout for LAr and LXe cryostats in large water Cherenkov shields



2vbb: EXO measurement of ^{136}Xe $T_{1/2}$
Assumptions: 50% NR acceptance, 99.5% ER discrimination
Contribution of 2vbb background can be reduced by depletion

The LHC starts to probe the DM region

http://xxx.lanl.gov/abs/1103.5061



http://arxiv.org/pdf/1104.3572v3

excluded bei XENON

excluded
bei LHC

68%, 95%, 99.7% CL
preferred regions

New Constraints on Dark Matter from CMS and ATLAS data

Sujeet Akula,[1] Daniel Feldman,[2] Zuowei Liu,[3] Pran Nath,[1] and Gregory Peim[1]

[1]*Department of Physics, Northeastern University, Boston, MA 02115, USA*
[2]*Michigan Center for Theoretical Physics,*
University of Michigan, Ann Arbor, MI 48109, USA
[3]*C.N. Yang Institute for Theoretical Physics,*
Stony Brook University, Stony Brook, NY 11794, USA

Implications of XENON100 and LHC results for Dark Matter models

Marco Farina[a], Mario Kadastik[b], Duccio Pappadopulo[c], Joosep Pata[d], Martti Raidal[b], Alessandro Strumia[b,e]

Summary and Prospects (I)

- Cold dark matter is still here with us
- It could be made of a new, heavy, neutral, stable and weakly interacting particle
- *We have entered the era of data: direct detection, the LHC, indirect detection*
- Direct detection experiments have reached unprecedented sensitivity (cross sections down to 10^{-8} pb) and can probe WIMP with masses from a few GeV to a few TeV
- "Ultimate" WIMP detectors based on the mK technology and on noble liquids should be able to prove or disprove the WIMP hypothesis and provide complementary information
- However, we should be prepared for surprises!

Summary and Prospects (II)

Direct detection

discover relic particle

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

with input from LHC

determine ρ_{local}

LHC

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

determine $\rho_{GC/halo}$