Universität Zürich

Direct Dark Matter Searches - a *Brief* Overview

CHIPP Plenary meeting
Appenberg

Laura Baudis

Physik Institut, University of Zurich

5th Patras Workshop on Axions, WIMPs and WISPs

Durham/UK July 13 - 17, 2009

Organizing committee:

Laura Baudis (University of Zurich)
Joerg Jaeckel (IPPP/Durham University)
Axel Lindner (DESY)
Andreas Ringwald (DESY)
Konstantin Zioutas (University of Patras)

Sponsored by:
IPPP
DESY
CERN
University of Patras
University of Zurich

We should be all very happy

- **Cosmology, particle physics and astrophysics are far from completion!**

Markus Ahlers (Oxford):
"the standard model of particle physics has some *shortcomings*; there are *puzzles* from cosmology, and some *new puzzles* from astrophysics"

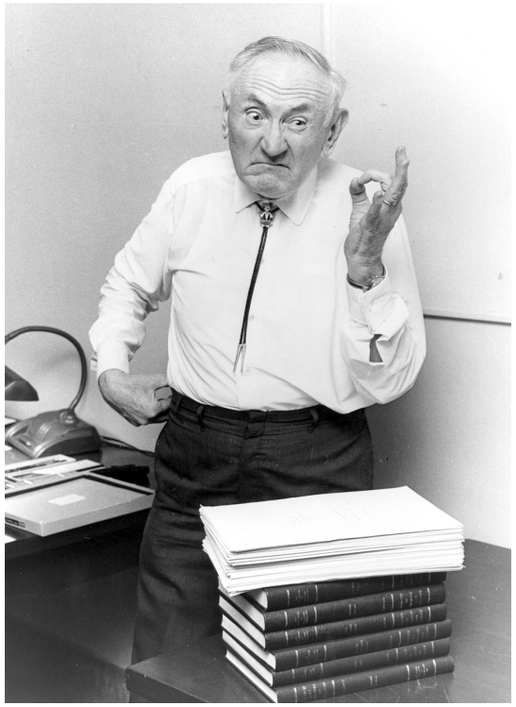
- **In summary:**
  - ➡ there are many open issues; one of them is related to the ***enigmatic dark sector***

- (Some) solutions to these puzzles are motivated by:

  - ➡ **testability** (bottom-up, M. Ahlers, Oxford)
  - ➡ **string theory** (top-down, J. Conlon, Oxford)

The enigmatic dark matter

- The Swiss astronomer, Fritz Zwicky, coined 1933 the term “dunkle Materie”



ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

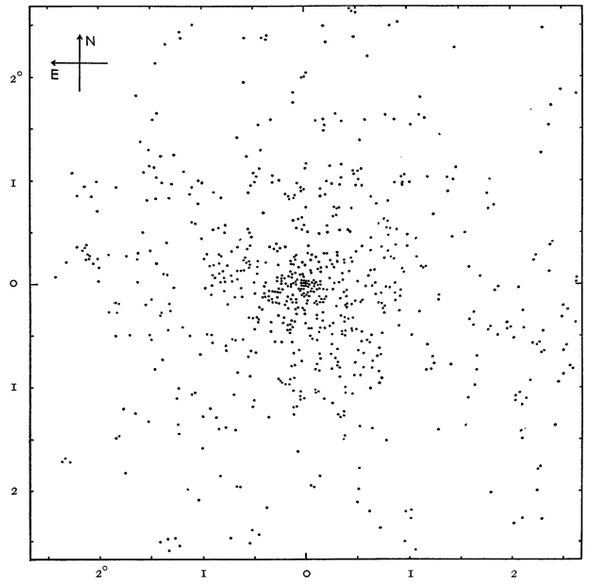


FIG. 3.—The Coma cluster of nebulae

Laura Covi, DESY:

“since the discovery of Zwicky we have learned a lot about dark matter; in particular, *what it is not*”

“the next decade should hopefully bring us some ***more clear answers***”

We are indeed hopeful...

- and certainly we still have *many questions*, in particular:

- **Is the dark matter really as simple as a gas of collisionless particles?**

Leszek Roszkowski, Sheffield:

"is the dark matter made up of particles?"
"suggested by clustering, but otherwise an assumption"

"is the dark matter made up of only/predominantly one species?"
"economical assumption"

"is it all cold?"
"a fraction may be warm"

"what *is* the dark matter? the dark matter is *dark*"

No shortage on dark matter candidates

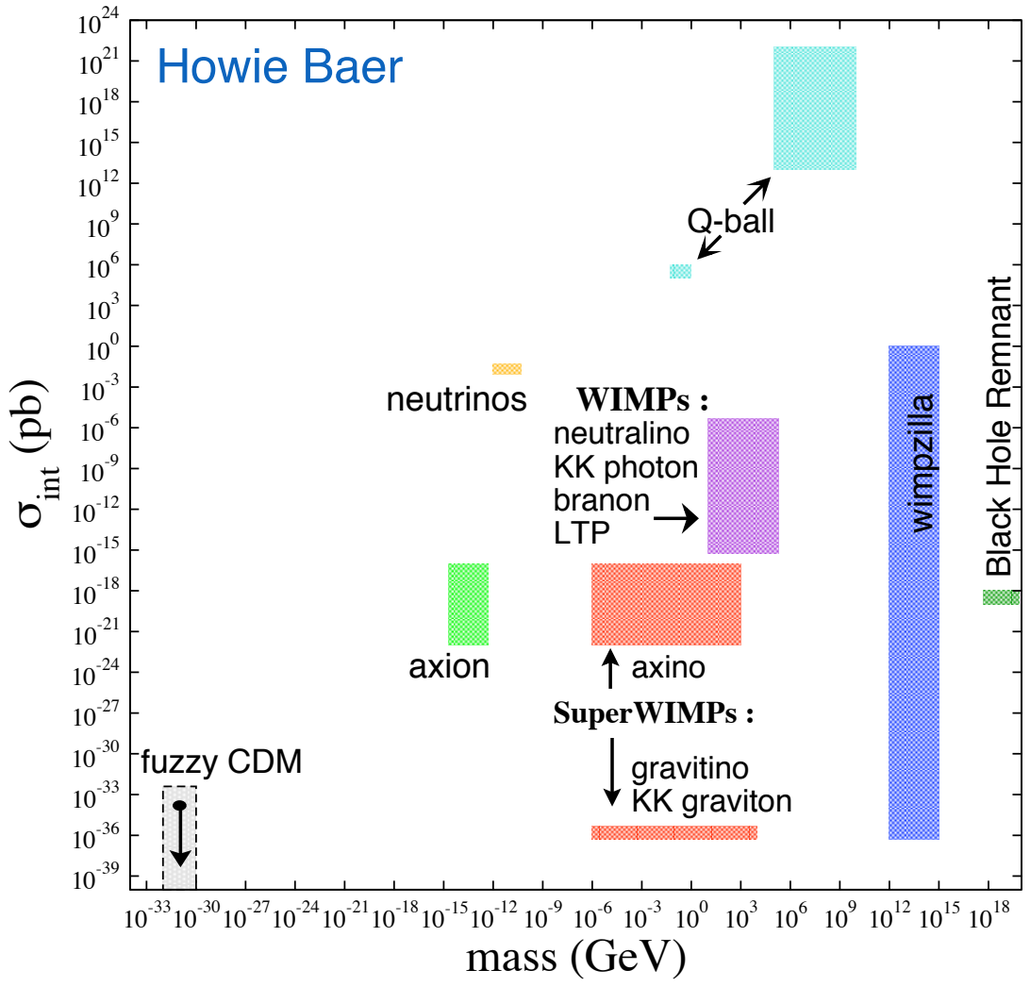
- Theorists provide ***strong*** **guidance** to us experimentalists

- Prediction for the mass 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)

Leszek Roszkowski: “no shortage of ideas... but few good ones... and even fewer long-lasting”

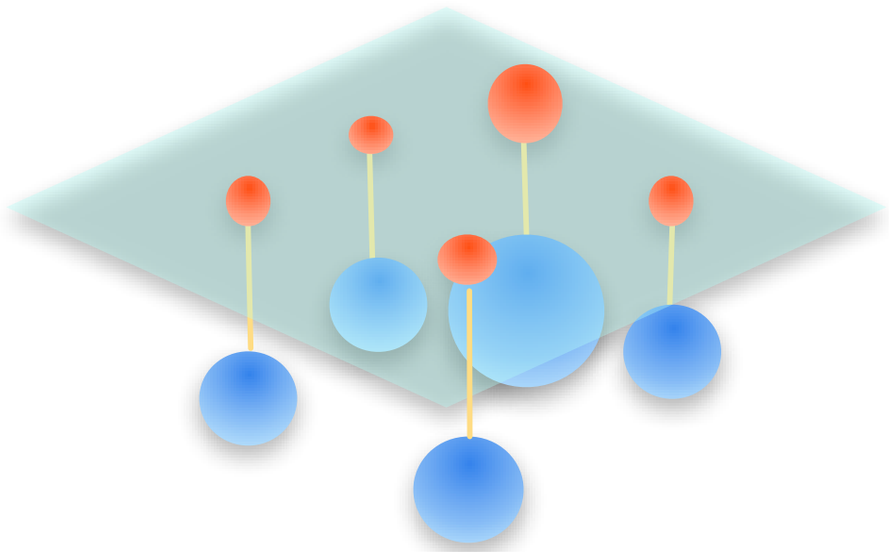
Howie Baer: “dark matter must be some particle state not contained in the standard model”



One good idea: WIMPs

- A miracle (thermal relic*)
- Still here with us (long lasting)
- Well motivated (not invented to solve the dark matter problem)
  - ➡ but (unlike axions) not top-down motivated
  - ➡ (however -> J. Conlon: “weak scale is not a top-down scale”)
- ***Testable***

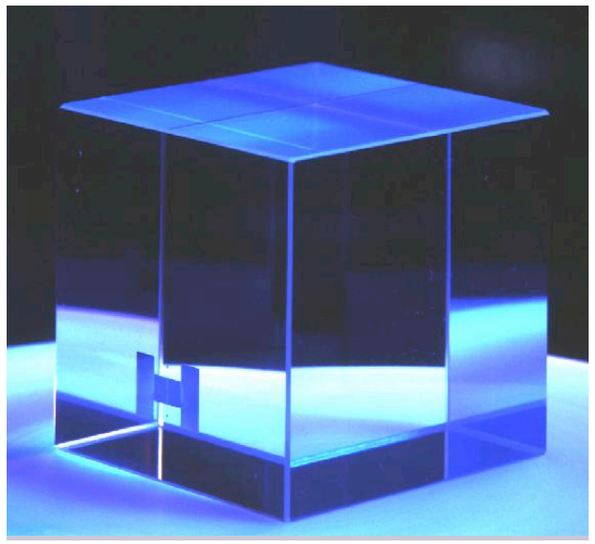
- Most popular examples: neutralinos, lightest Kaluza-Klein particles



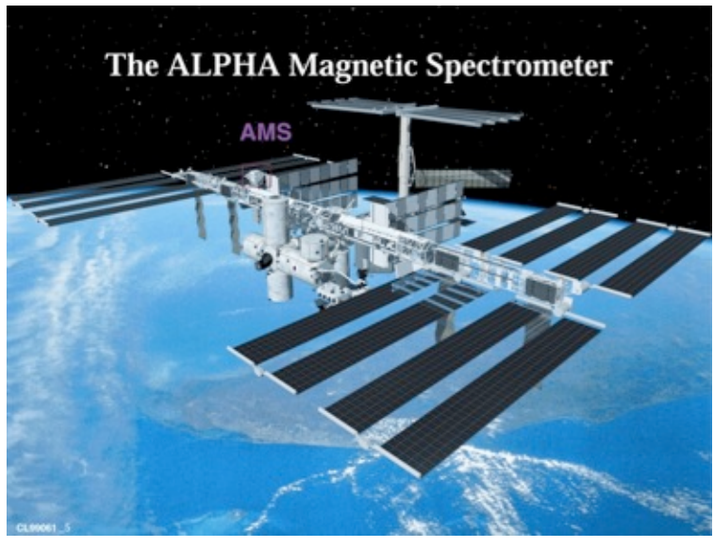
*relic: an object of particular veneration (Roky Kolb, Blois 2009)

The WIMP hypothesis is *testable*

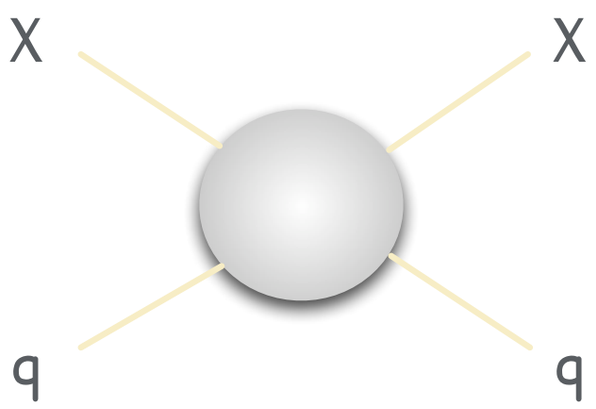
Underground

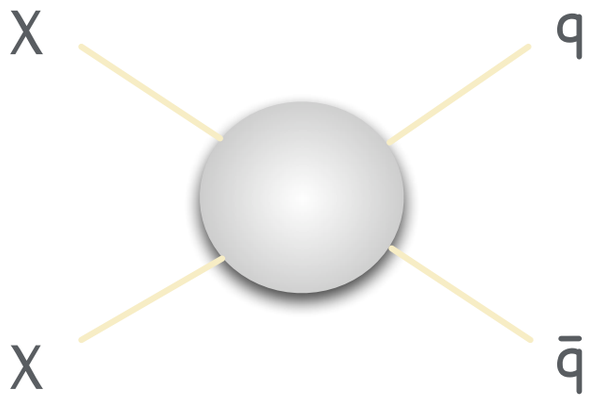


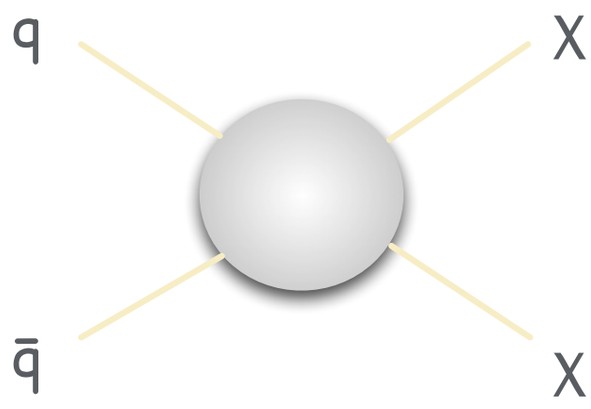
Above ground



At the LHC







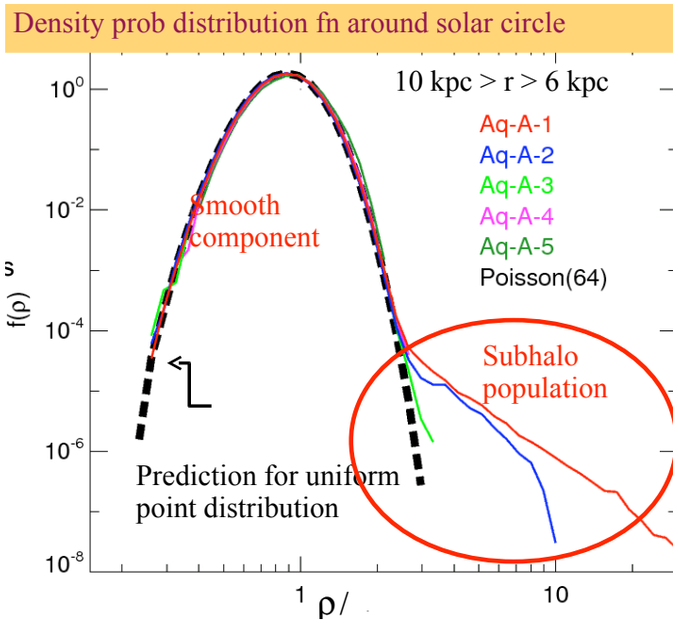
We hope to learn a lot from direct detectors, from indirect detectors and from accelerators!

The distribution of WIMPs in the Milky Way

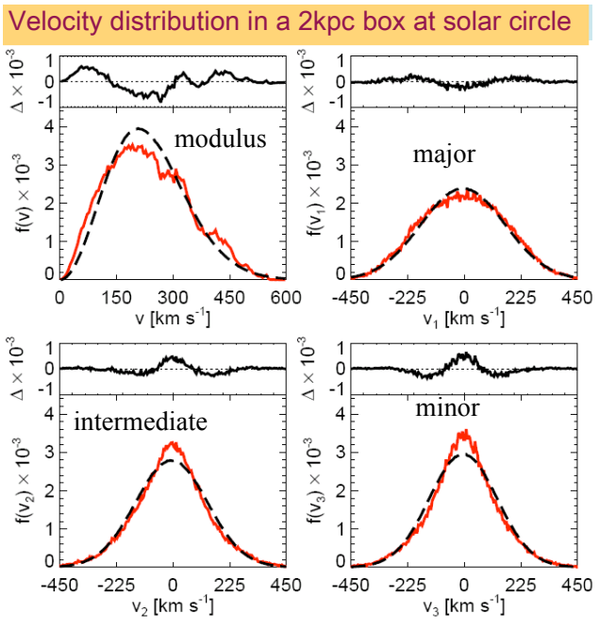
- Important for direct searches:
  - ➡ how smooth is the dark matter mass distribution at the solar position?
  - ➡ how smooth is the dark matter velocity distribution at the solar position?
  - ➡ does the halo formation process leave “observable” imprints?

The Aquarius project, 6 halos; arXiv: 0812.0362

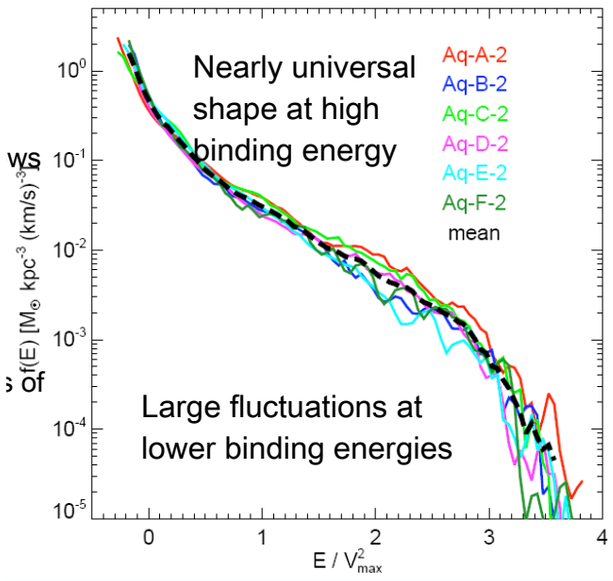
$$f(E) = \frac{dM}{dE}\frac{1}{g(E)}$$



Smooth, substructure far from Sun



Smooth, no streams

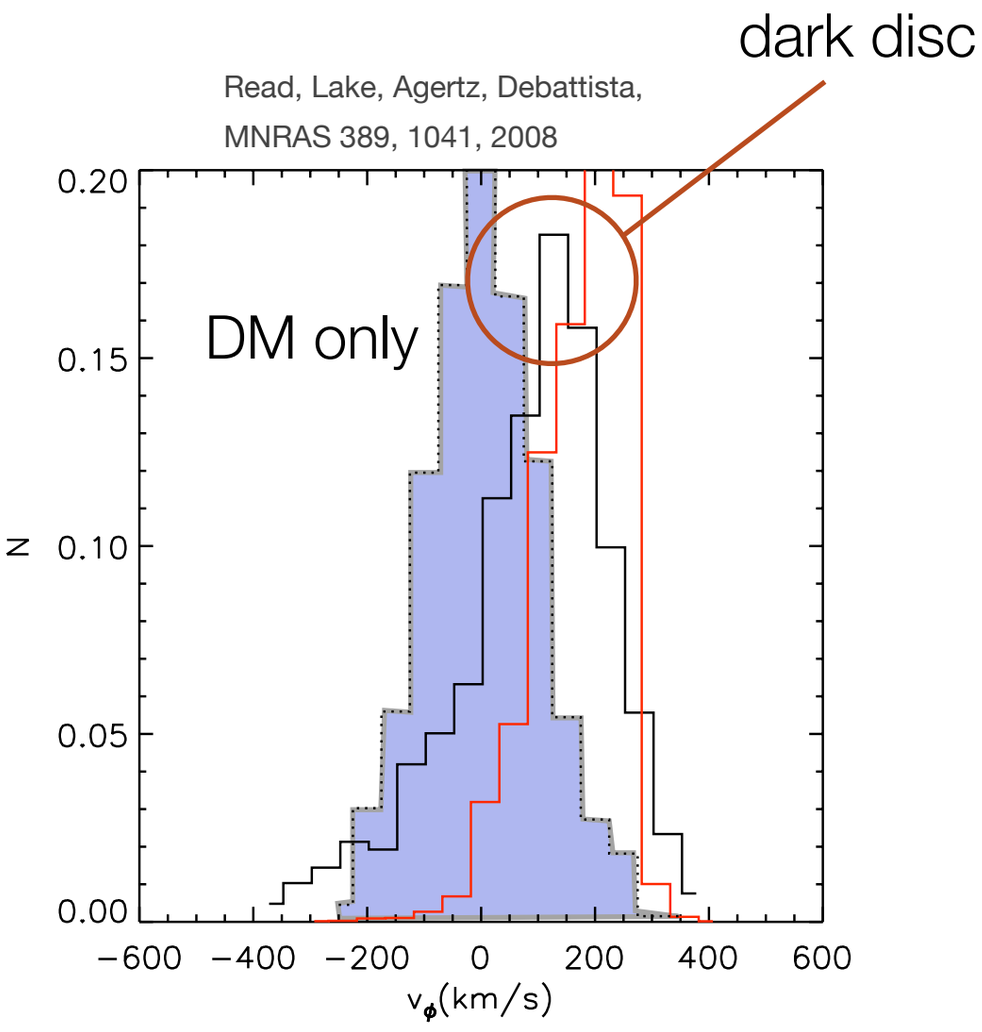


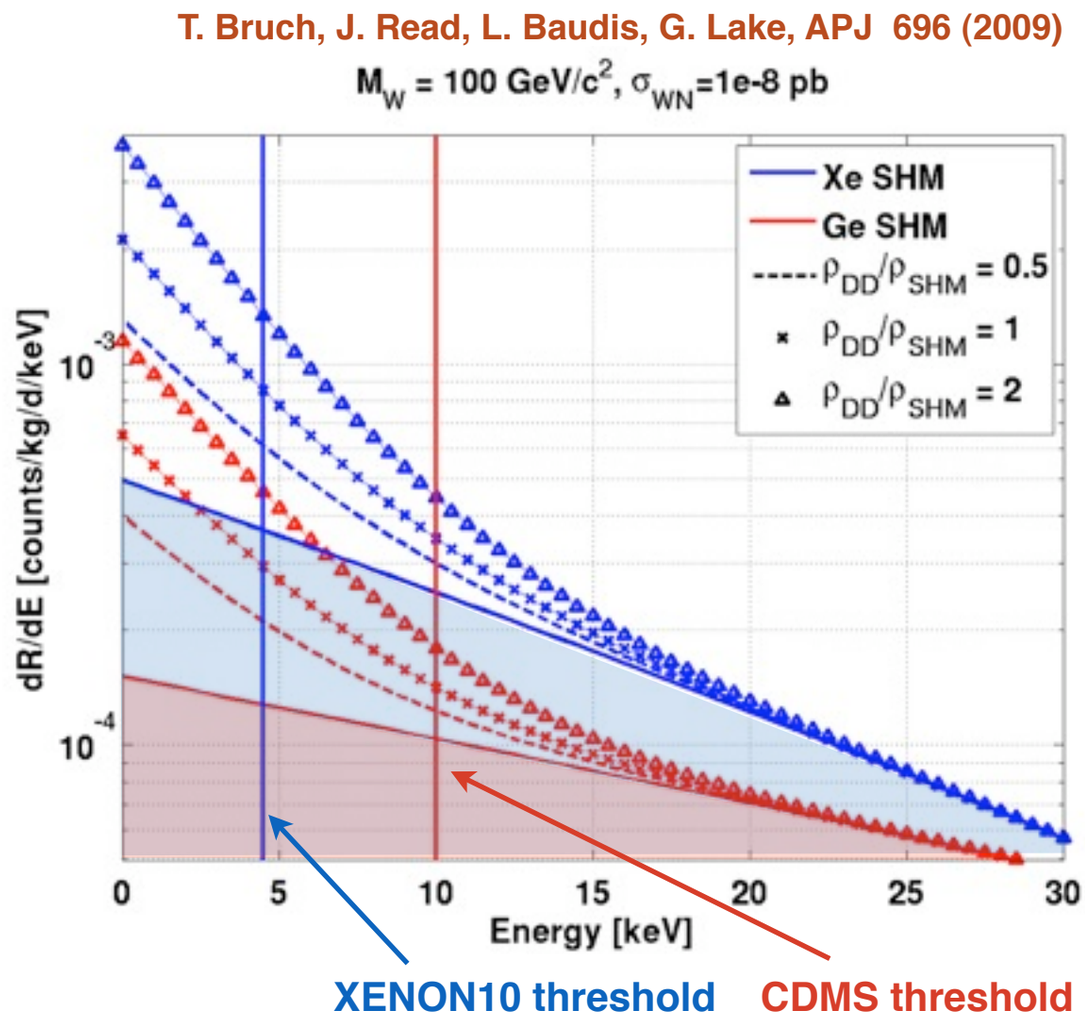
The energy distribution in (2 kpc)³ boxes shows bumps

- **But: can we ignore the baryons?**
- Adrian Jenkins, Durham:
- “almost certain baryons will make a difference to the detailed predictions”
- “the dark matter only simulations establish a baseline for future work”

A dark disc in the Milky Way

Justin Read, UZH: "The Milky Way stellar/gas disc at high redshift biases the accretion of massive satellites. They are dragged towards the disc plane where their accreted material forms a dark matter disc. For our standard cosmology, the Milky Way's dark disc has density in the range: $\rho_{dd} \sim 0.25 - 1 \rho_{shm}$."



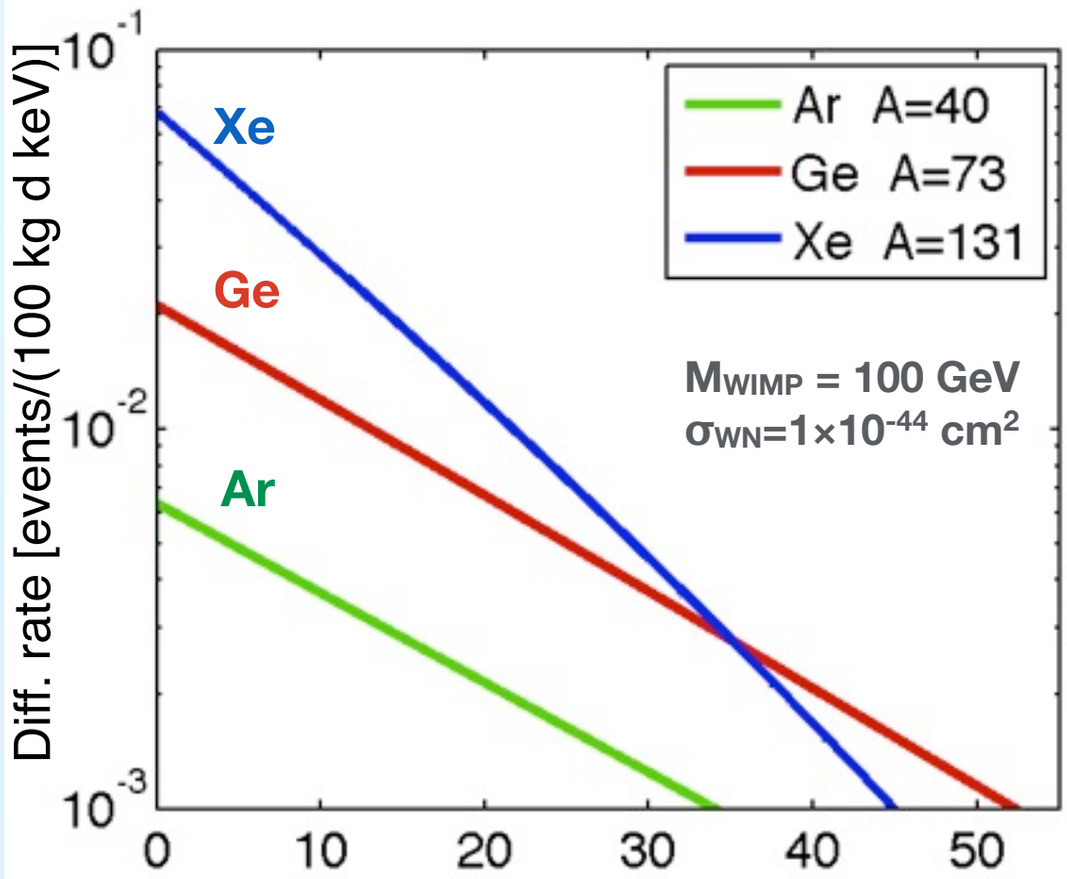


Direct detection of WIMPs: how close?

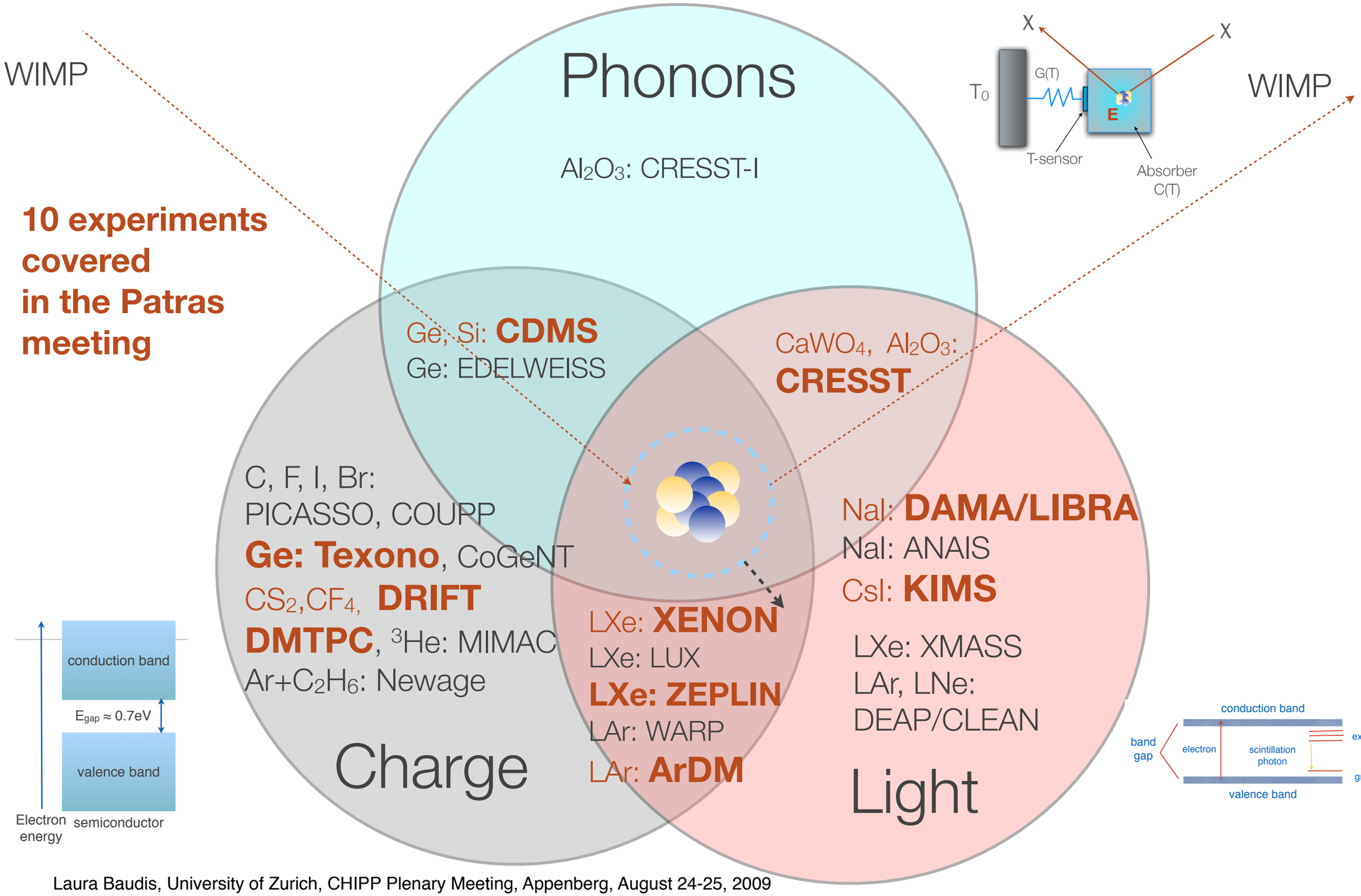
- **Collisions (elastic, inelastic) with atomic nuclei**
- **Rates are highly uncertain:**
  (depend on: **[m_χ, σ], [f(v), ρ_0], [N, $F^2(E_R)$, E_{th}]** ...)
- **But certainly below 1 event/100 kg/day**
  (since SI cross sections < 10^{-7} pb)
- **Energy of recoiling nuclei is tiny (≤ 50 keV)**
- **Recoil spectrum is featureless (no bumps!)**
- **Background is many 10^6 times higher**

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

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



Nonetheless, the race is on...



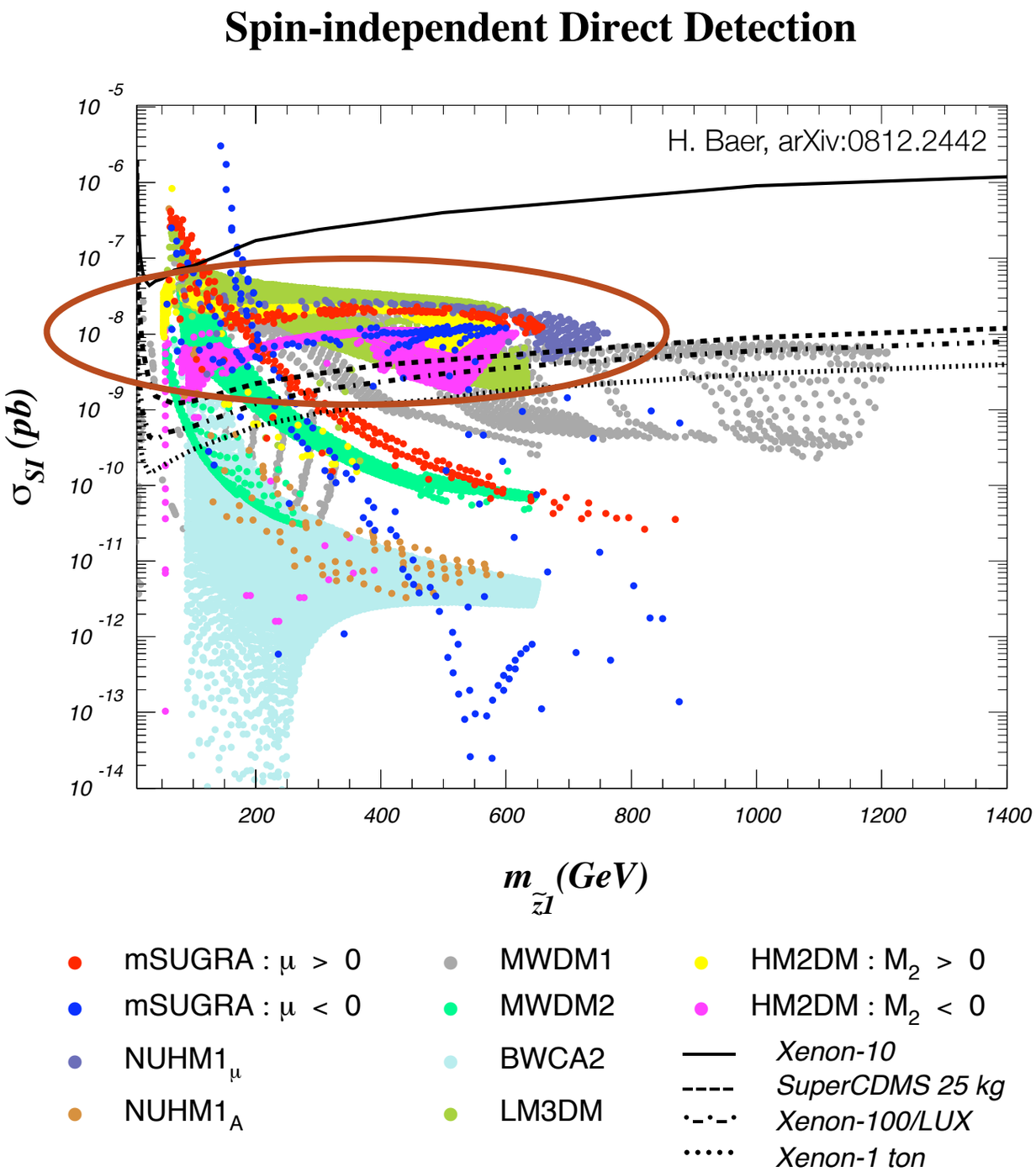
The WIMP-nucleon cross section: how low can it go?

- Example: well-tempered neutralino
  (for instance, in SO(10) SUSY GUTs
  with $m_{10(higgs)} > m_{16(scalars)}$ and the neutralino
  composition adjusted such that
  it gives the measured relic density)

- Howie Baer:
- "scan over 10 models with and without universality; keep only models with correct relic abundance"

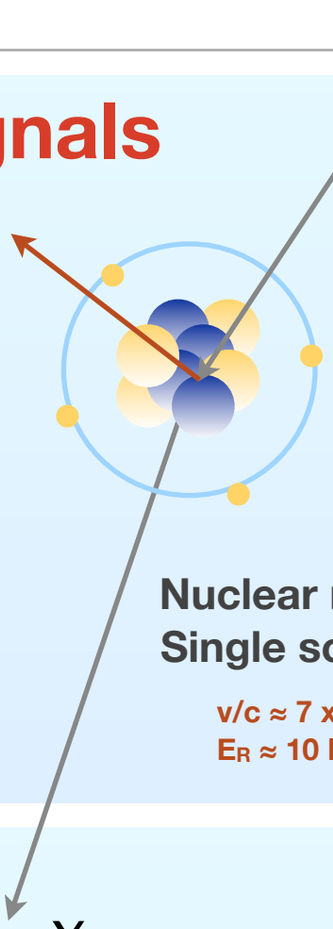
- **"bulk of models asymptote at 10^{-8} pb"**

This region is accessible by the current round of experiments!



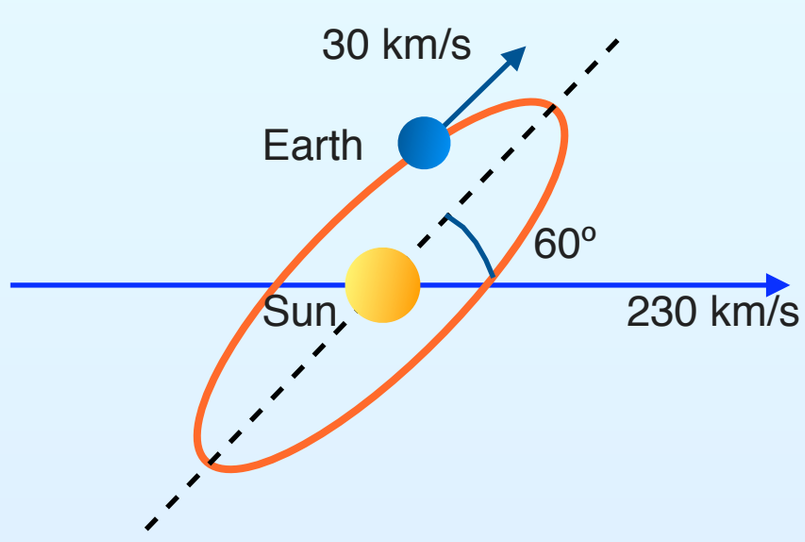
Signals and Backgrounds

Signals

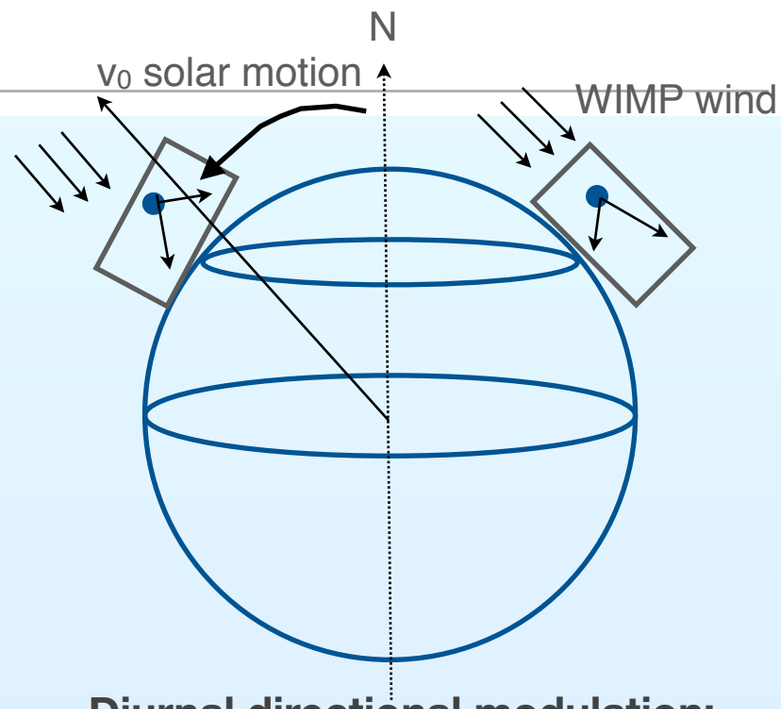


Nuclear recoils
Single scatters

$v/c \approx 7 \times 10^{-4}$
$E_R \approx 10$ keV

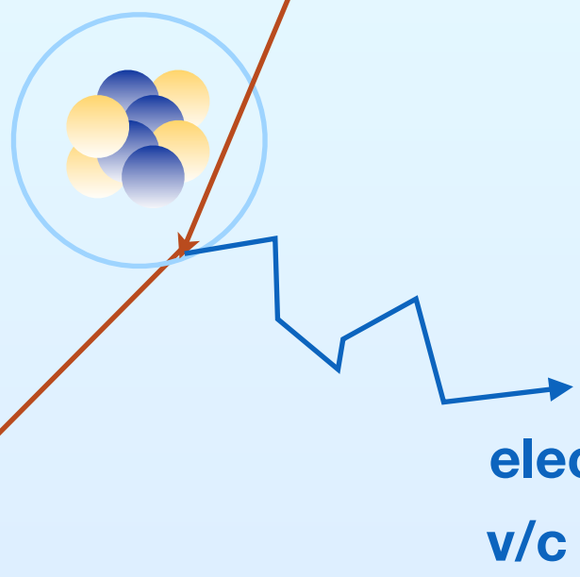


Annual rate variation
~ few % effect



Diurnal directional modulation:
~ 50% effect

Backgrounds



electron
v/c ≈ 0.3

gamma, betas: ER vs NR discrimination and self-shielding

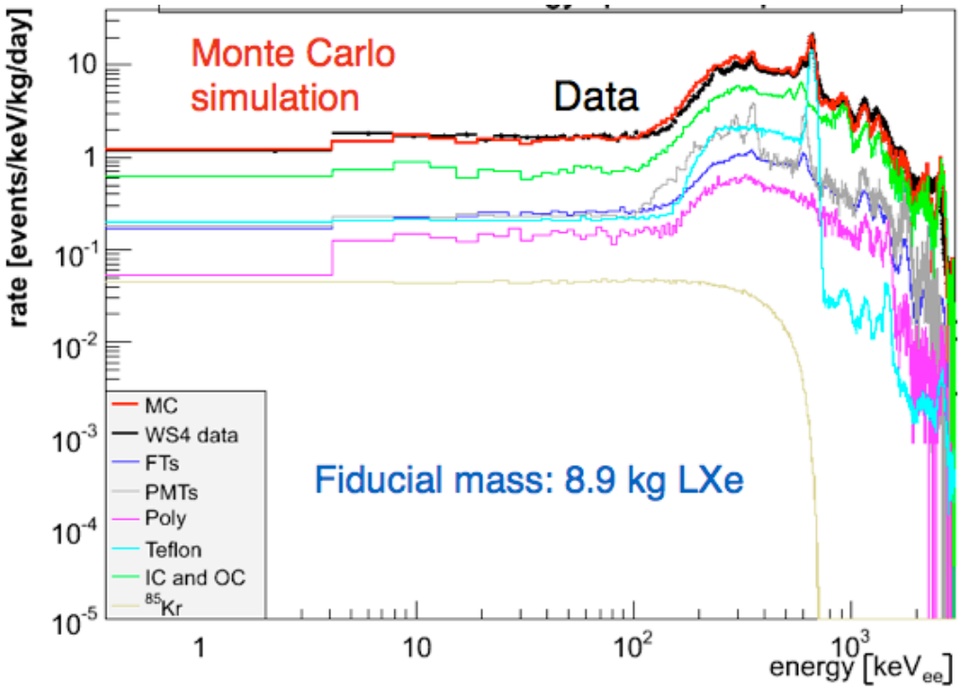
muons: go deep underground, add muon veto

neutrons: NRs, but also capture and multiple scatters

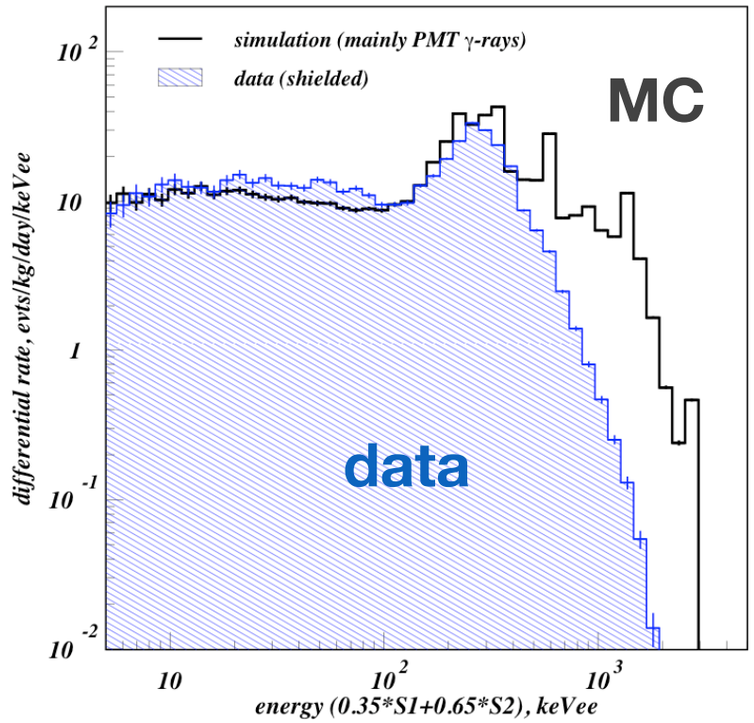
alphas: much higher energy depositions, but recoiling nuclei a problem if **α** energy not seen in active detector volume

Backgrounds are here, and well under control (but *be prepared for the unexpected!*)

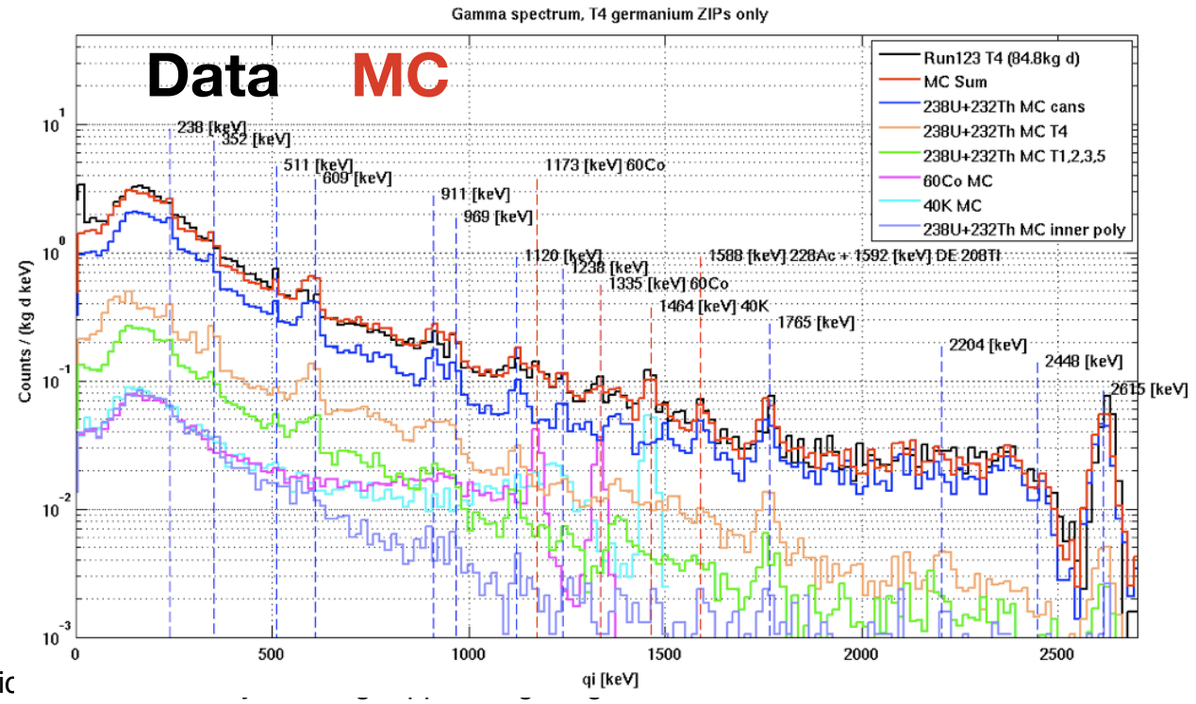
XENON10



ZEPLIN-III

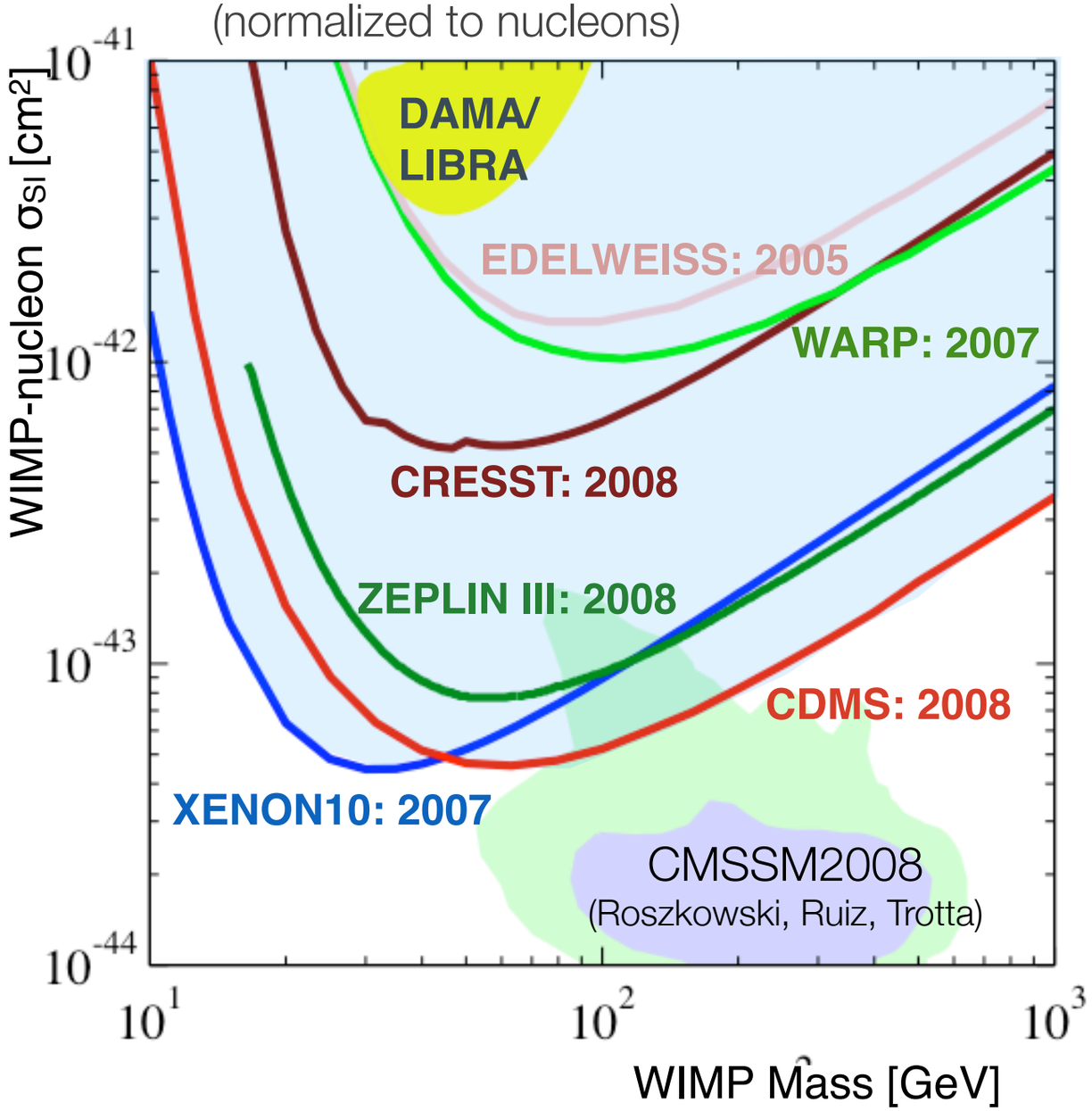


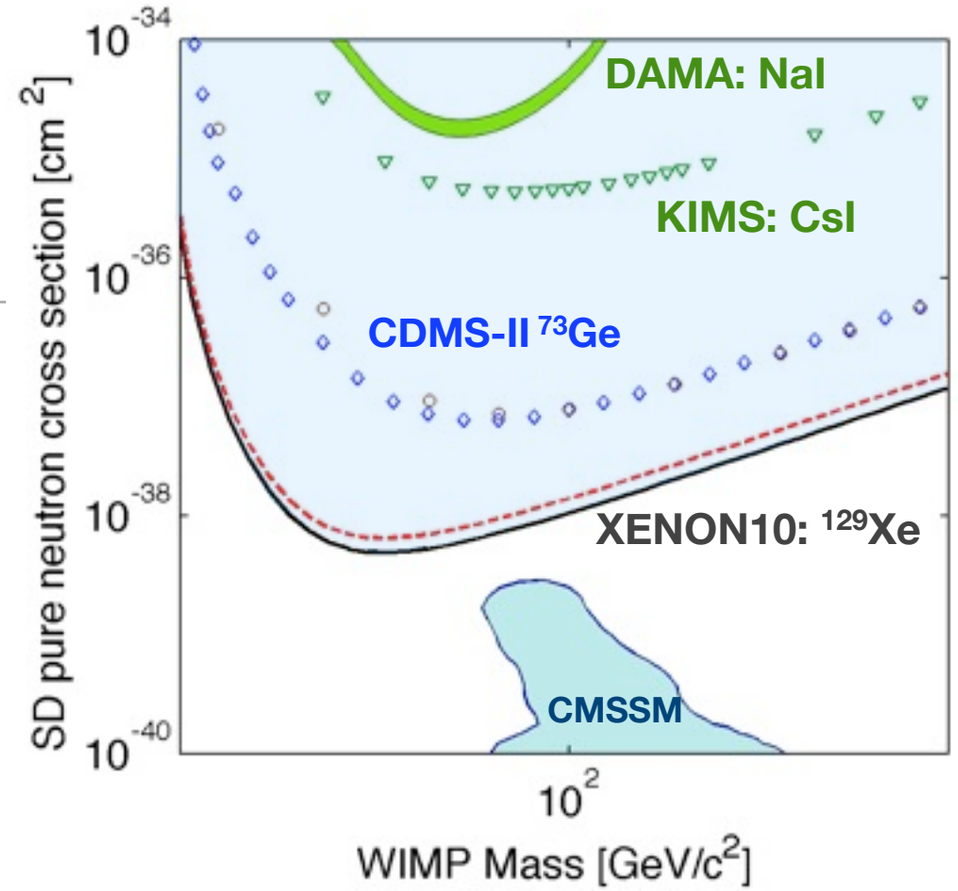
CDMS

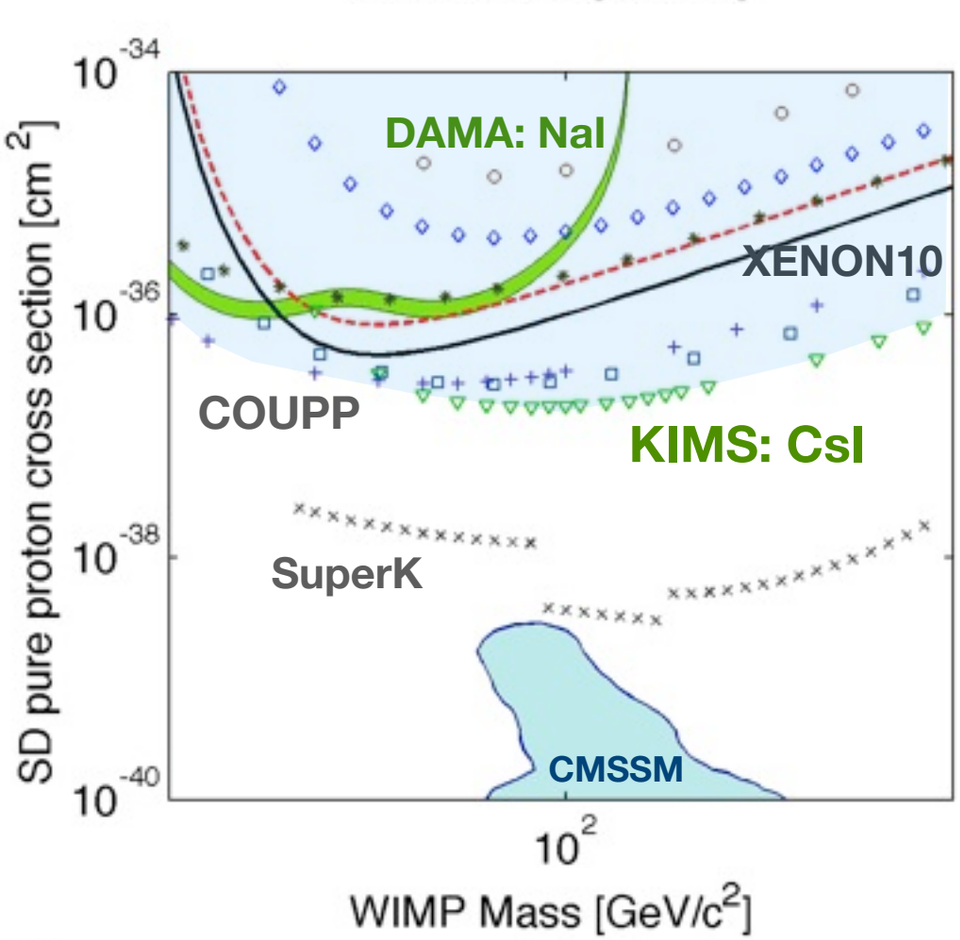


Experimental Results August 2009

Spin-independent cross section
(normalized to nucleons)





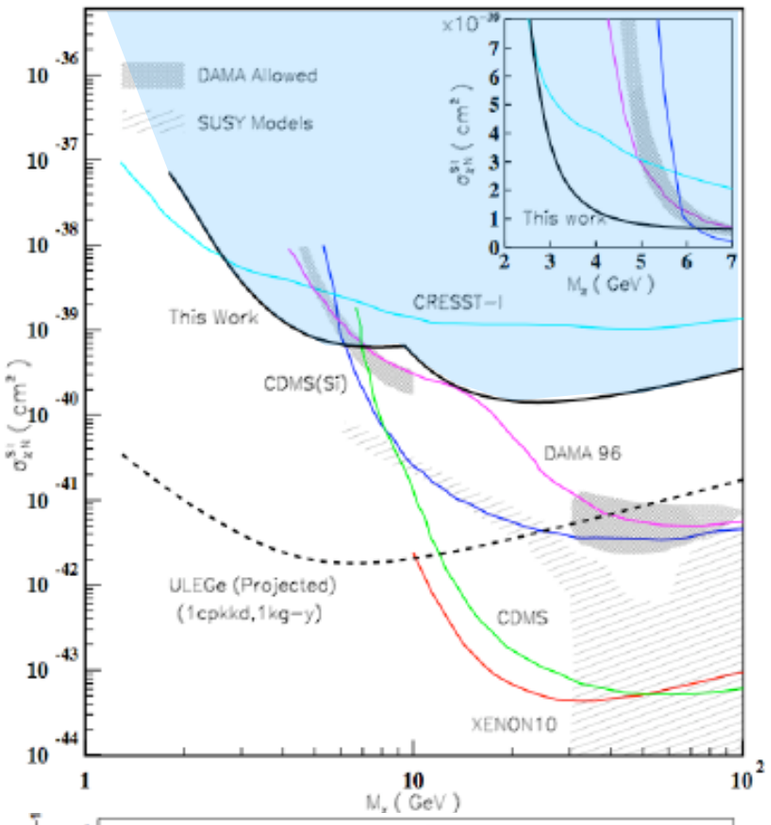


Spin-dependent

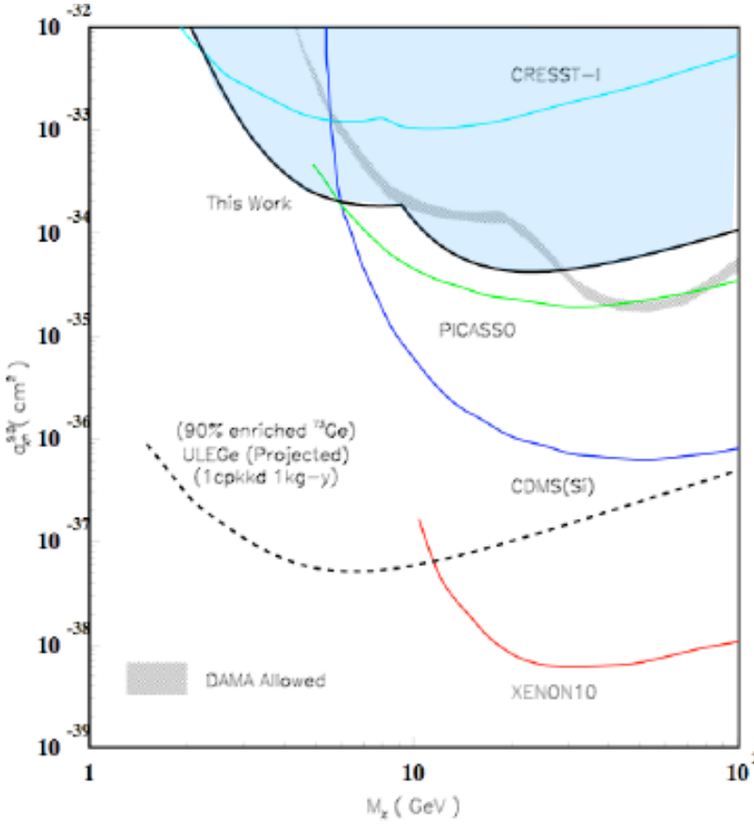
New Experimental Results at Low WIMP Masses

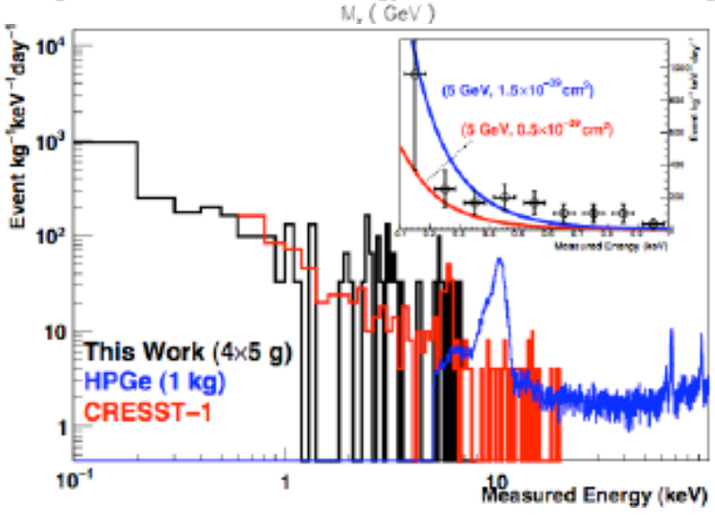
TEXONO: 4 x 5 g Ge in 30 mwe lab in Taiwan

spin-independent



spin-dependent

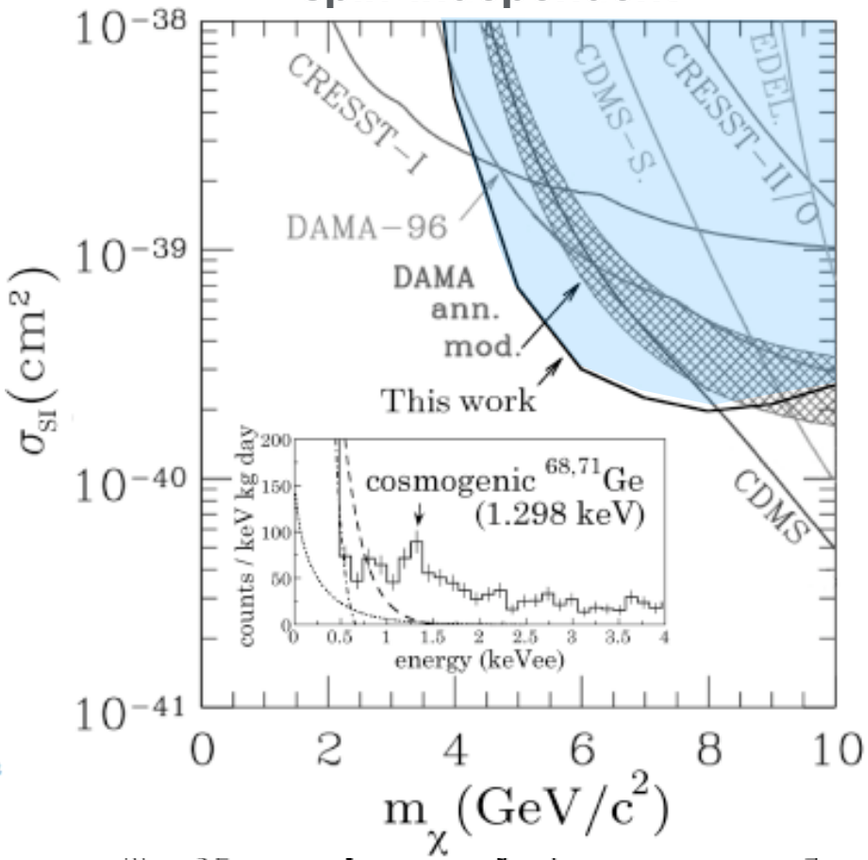


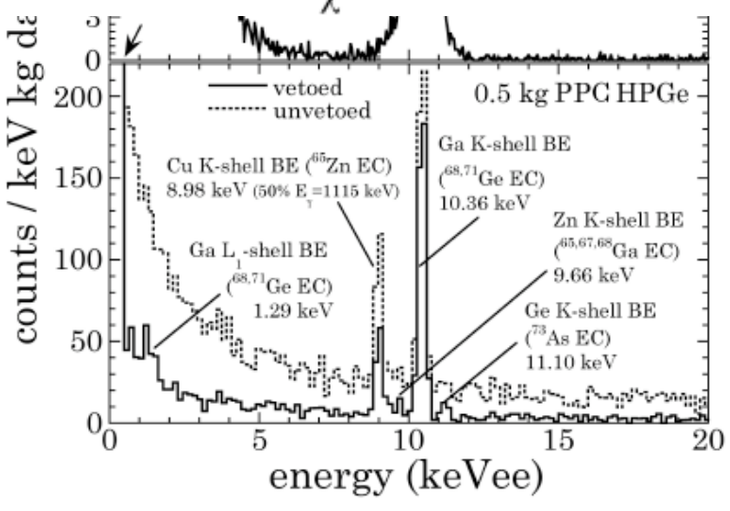


S.T. Lin et al.
0712.1645v4

CoGeNT: 500 g PPC Ge

spin-independent



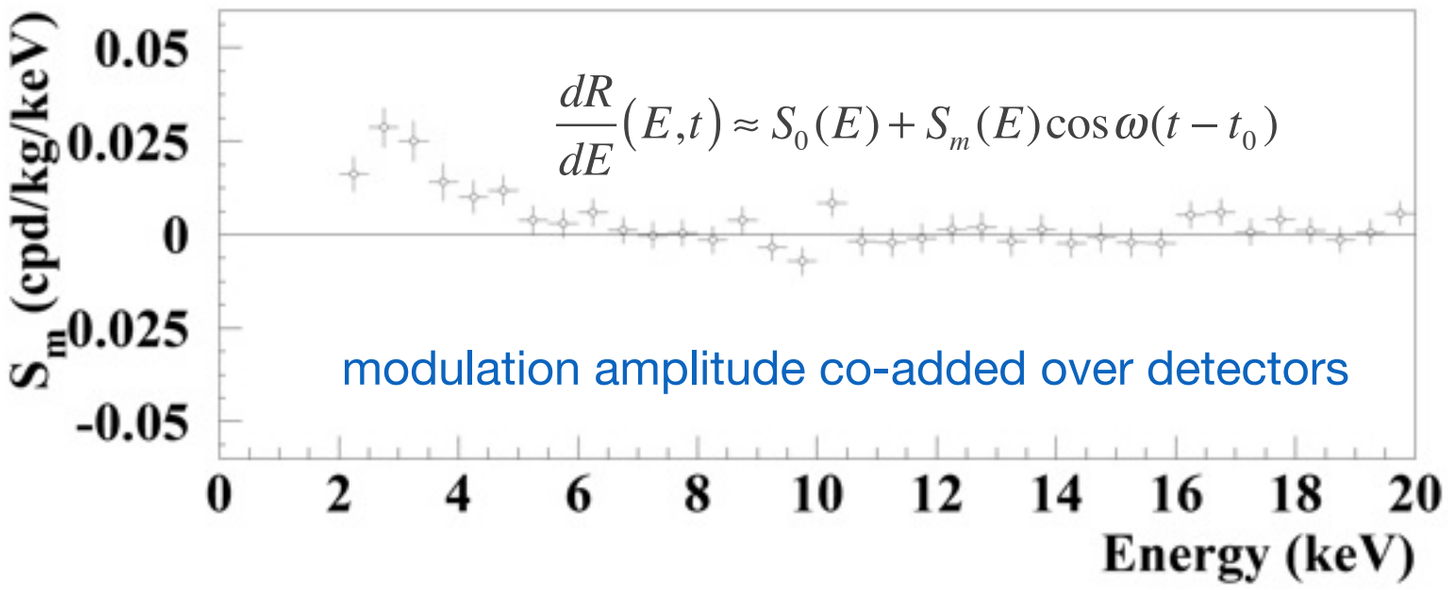


Aalseth et al.
PRL 101 (2008)

DAMA/LIBRA: highest exposure, 0.82 ton x year

Pierluigi Belli, Rome:
"the data favor the presence of a modulated behavior with proper features at 8.2 sigma C.L."

The question remains: what is causing this modulation in the event rate at energies 2-6 keV?



- New run since October 2008
- Next upgrade: replace PMTs with high QE one => lower the energy threshold
- Proposed: a 1 ton, highly radio-pure NaI experiment

Inelastic dark matter *(testable)*

- Two states with a mass splitting around 100 keV: by “coincidence” equal to the kinetic energy of WIMPs in the halo

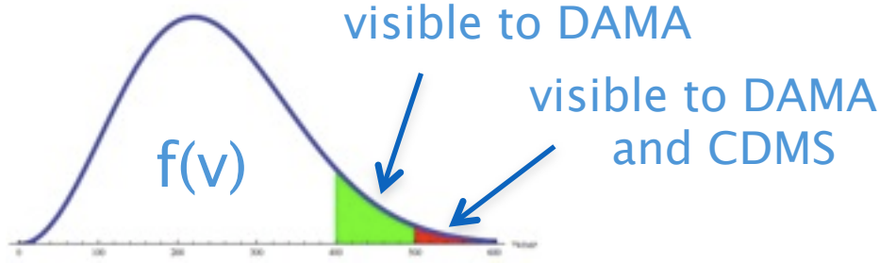
$$\delta = m_{\chi^*} - m_\chi \sim \beta^2 m_\chi \sim 100 \text{ keV}$$

➡ WIMP-nucleus scattering occurs through a transition to a WIMP excited state

➡ (elastic scattering $\chi + N \rightarrow \chi + N$ is forbidden, inelastic scattering $\chi + N \rightarrow \chi^* + N$ is allowed)

➡ only WIMPs with sufficient kinetic energy to up-scatter into the heavier state will scatter off nuclei

$$\beta_{\min} = \sqrt{\frac{1}{2 m_N E_R}} \left(\frac{m_N E_R}{\mu} + \delta \right)$$



Neil Weiner, IDM08

- Consequences for experiments:

S. Chang et al., Phys.Rev.D79:043513,2009

➡ suppression of signals on lighter vs heavier target

➡ enhancement of the modulated vs unmodulated signal (20-30%)

➡ elimination of low energy events; signal peaks at ≈ 70 keV for Ge, 35 keV for I/Xe, 25 keV for W

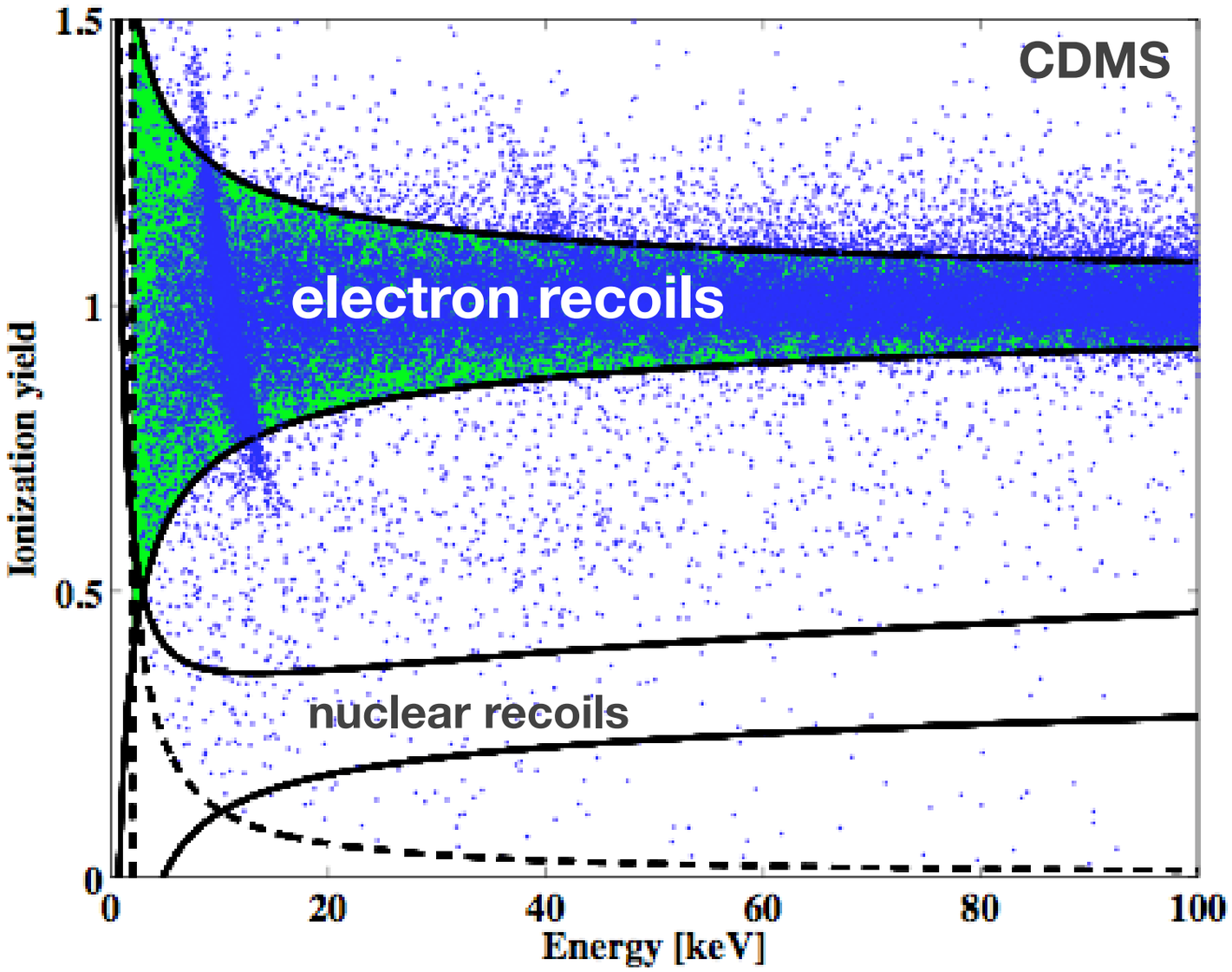
In agreement with all current results

Upcoming data from Ge, Xe, I and W should test the inelastic dark matter model very soon

Laura Baudis, University of Zurich, CHIPP Plenary Meeting, Appenberg, August 24-25, 2009

Dark matter interacting with electrons?

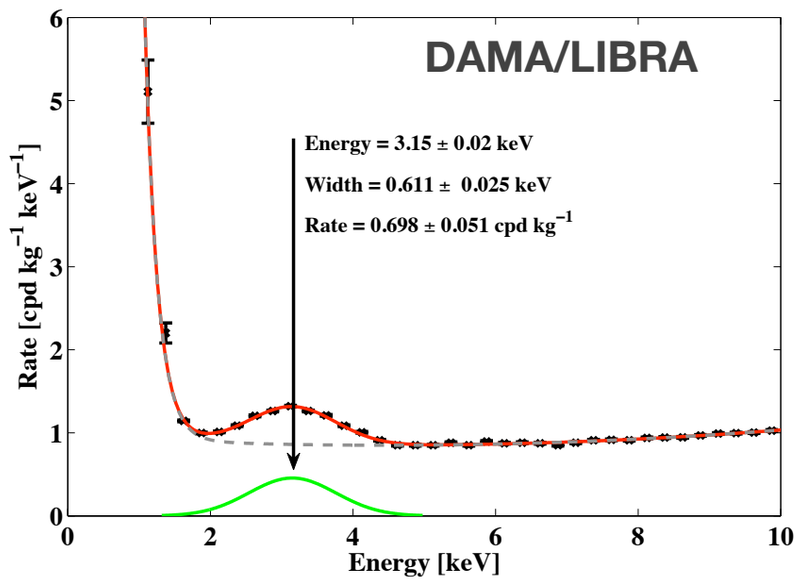
- Tobias Bruch, UZH: “what if we miss a signal due to an electron recoil interaction?”



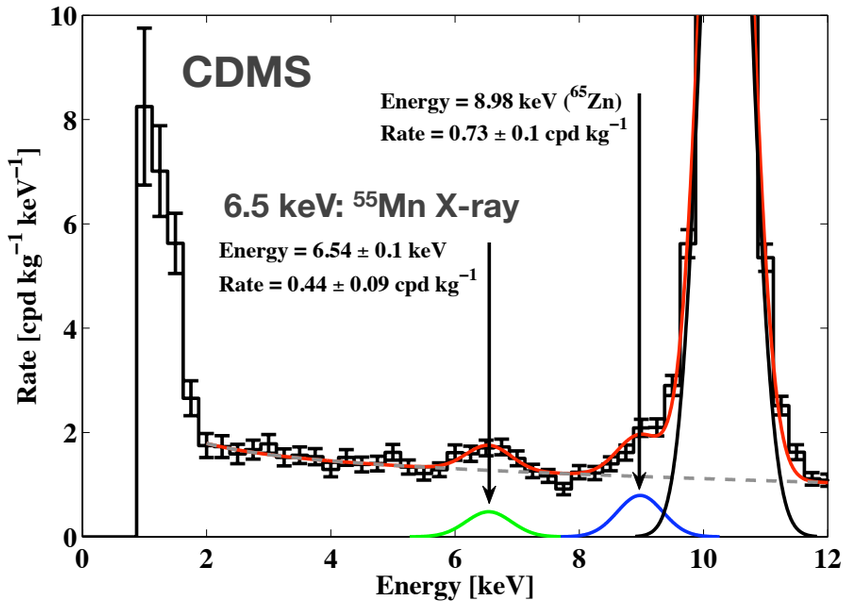
Dark matter interacting with electrons?

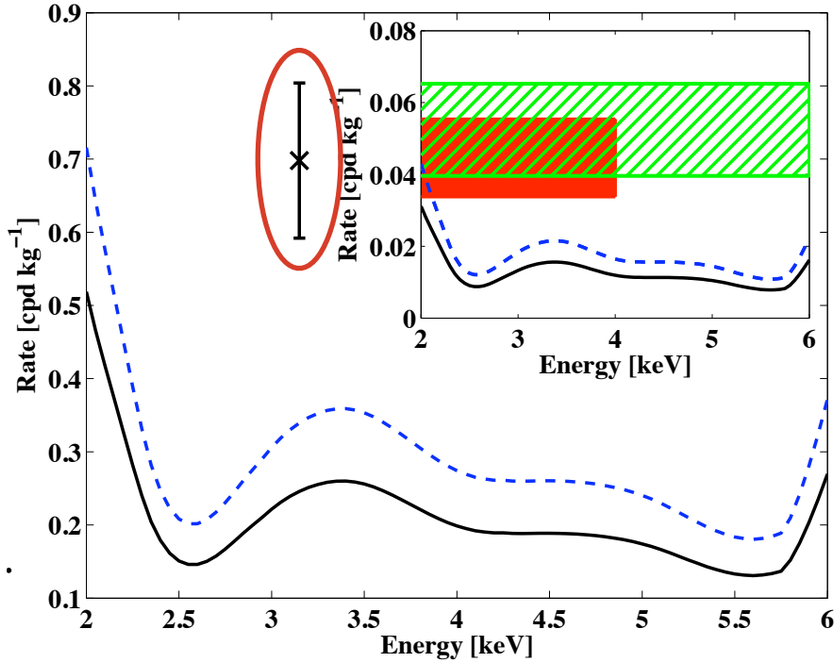
- Sterile neutrino decaying to light ν + X-ray, or something else?
- Message to theorists: *we are in need of a model!*

DAMA: modulation at 2-4 keV and excess of events at 3.15 keV



CDMS ER spectrum at low-energies



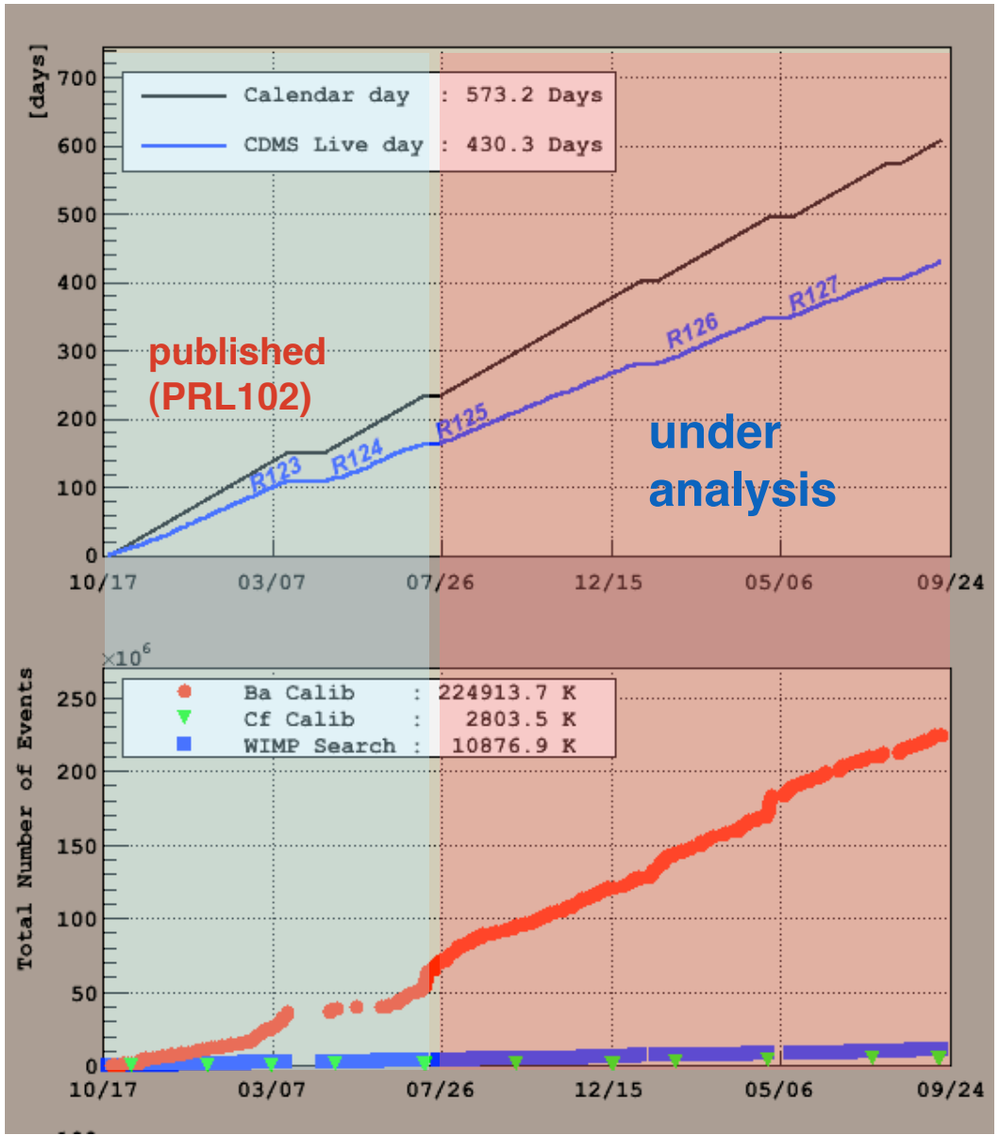


Upper limit on the total counting rate in Ge
- direct (solid)
- Z2-scaling (dashed)

arXiv:0907.1438.v1
(CDMS collaboration)

The CDMS/SuperCDMS Experiment (Soudan)

- Exposure for new runs (125-128): **750 kg days** (total exposure CDMS-II: 1300 kg days)
- **Tobias Bruch, UZH: "analysis is ongoing while we speak"**
- We expect the first release of results this fall



SuperCDMS detectors (1'' thick ZIPs, each 650 g of Ge) have been validated

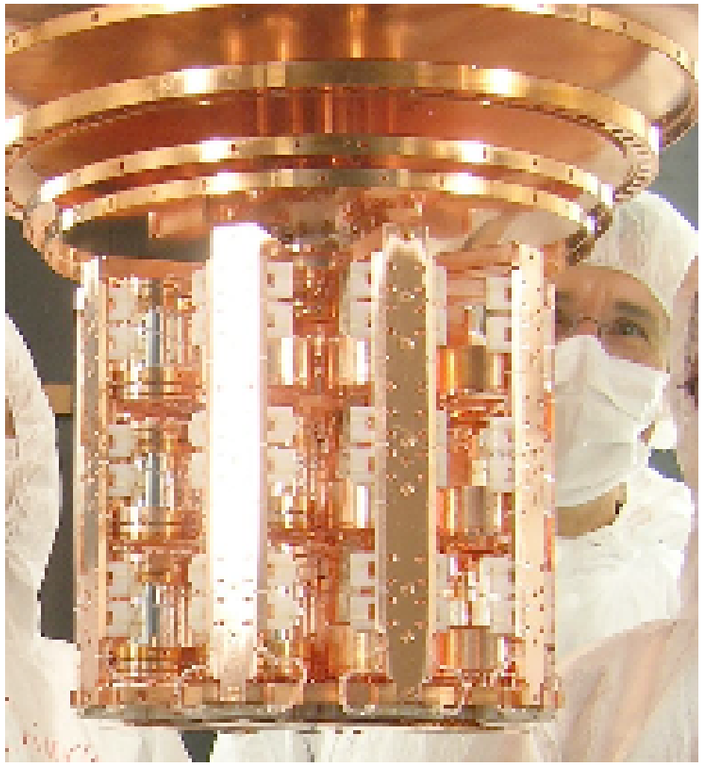
First SuperTower installed at Soudan (3 kg of WIMP target) and working

Goal: 5 x 10^{-45} cm^2 with 16 kg Ge

Goal: 7 SuperTowers at SNOLAB

The CRESST experiment (Gran Sasso)

- Goal: operate 10 kg array of 33 $CaWO_4$ detectors at 20 mK
  - **new limit from operating 2 detectors (48 kg d) published in 2008,** arXiv:0809.1829v1
  - Hans Kraus, Oxford : "new run successfully started in June 2009"
    "9 detector module operational; cryostat still cooling, more modules may come into transition. All crystals have new clamps."



EURECA (CRESST, EDELWEISS, ROSEBUD, CERN + others)

Joint effort for a 100 kg - 1 ton cryogenic (mK) experiment in Europe

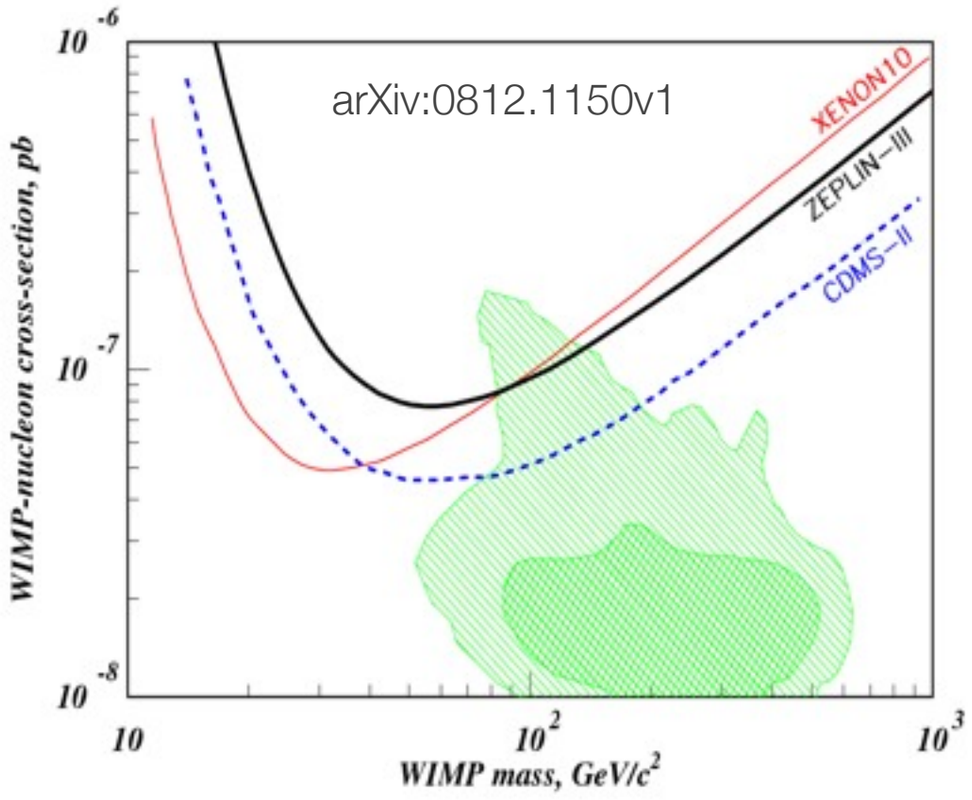
Proposal for design study submitted to ASPERA

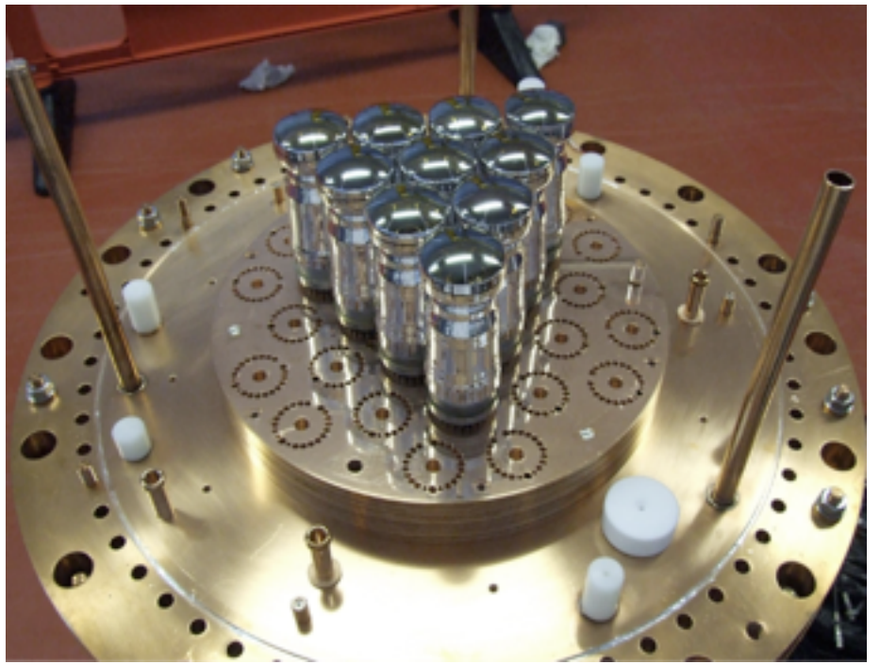
Data taking with 100 kg: 2015; 1 ton installed: 2018

ZEPLIN-III (Boulby Mine)

- Dual-phase Xe-TPC; WIMP target: 6.7 kg LXe, viewed by 31 x 2” PMTs
- 127 kg day of data analyzed; 7 events in WIMP box, 11.6±3.0 expected
- Upper limits on cross section based on background subtraction

- Henrique Araujo: “world-level SI and SD results”
- “second science run to begin soon with upgraded instrument”
- “tenfold sensitivity improvement within reach”

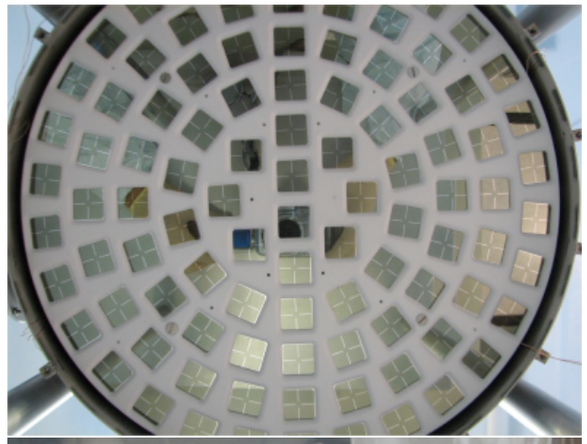


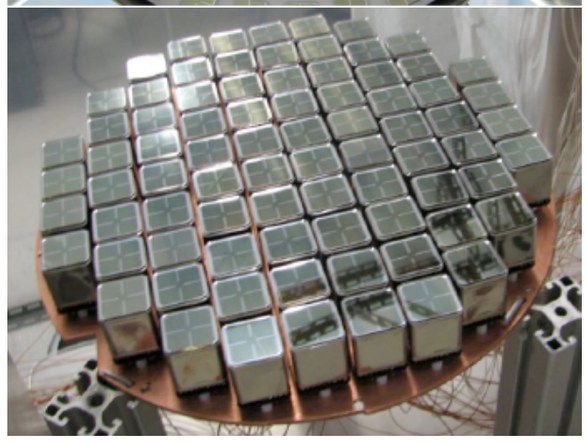


The XENON100 Experiment at Gran Sasso

- Dual-phase, Xe-TPC to search for WIMPs by their collision with Xe-nuclei
- Target: 170 kg (100 kg in active veto) LXe, viewed by 242 PMTs, 30 cm ⌀, 30 cm drift
- Goal: factor 100 lower background, factor 10 higher mass than XENON10
- CH participation -> UZH **L. Baudis**, A. Ferella, T. Marrodan, R. Santorelli, E. Tziaferi, A. Askin, A. Kish, A. Behrens, M. Haffke

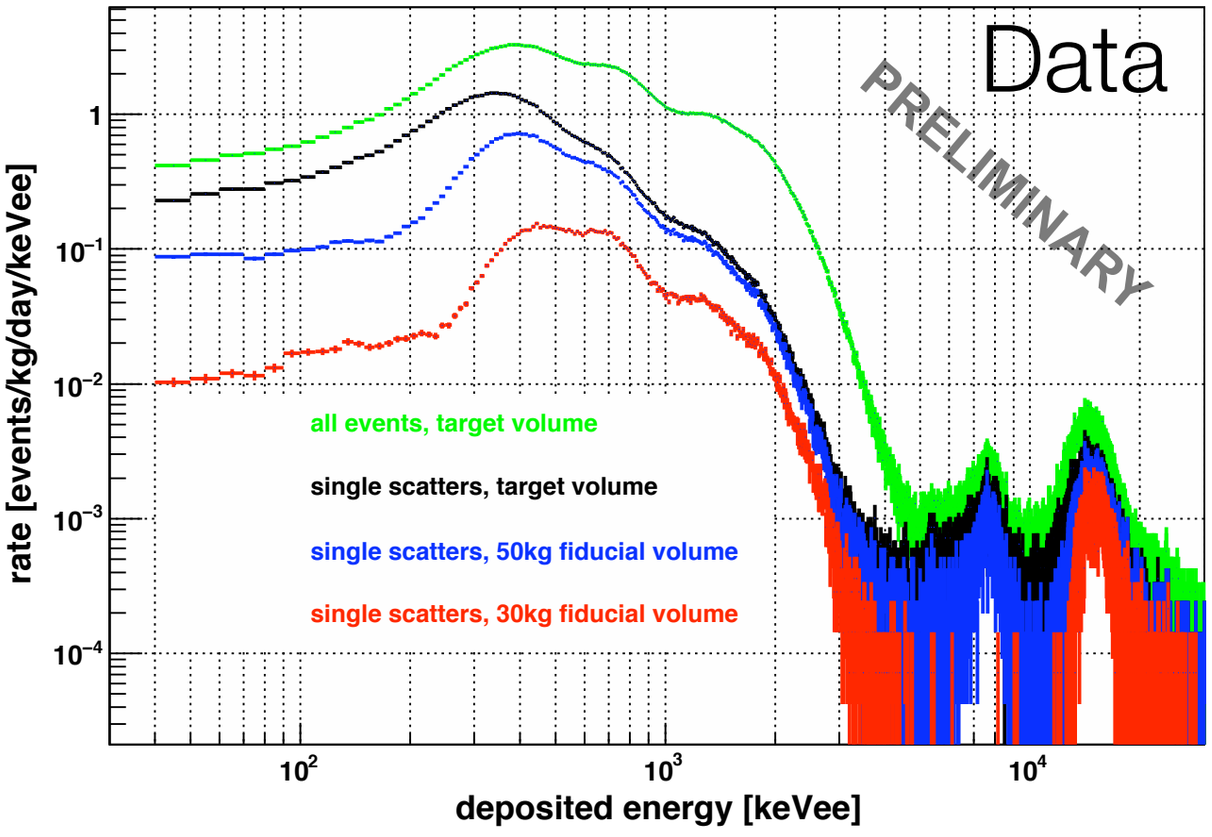
XENON100 in its shield





The XENON100 Experiment at Gran Sasso

- Alexander Kish, UZH: “the detector is fully operational underground”
- “A first dark matter search is planned before the end of 2009”
- Dark matter run: until end of 2010
- Measured background: factor 100 lower than in XENON10 (preliminary)



Purification for 85-Kr finished this weekend

Now: check light and charge yield

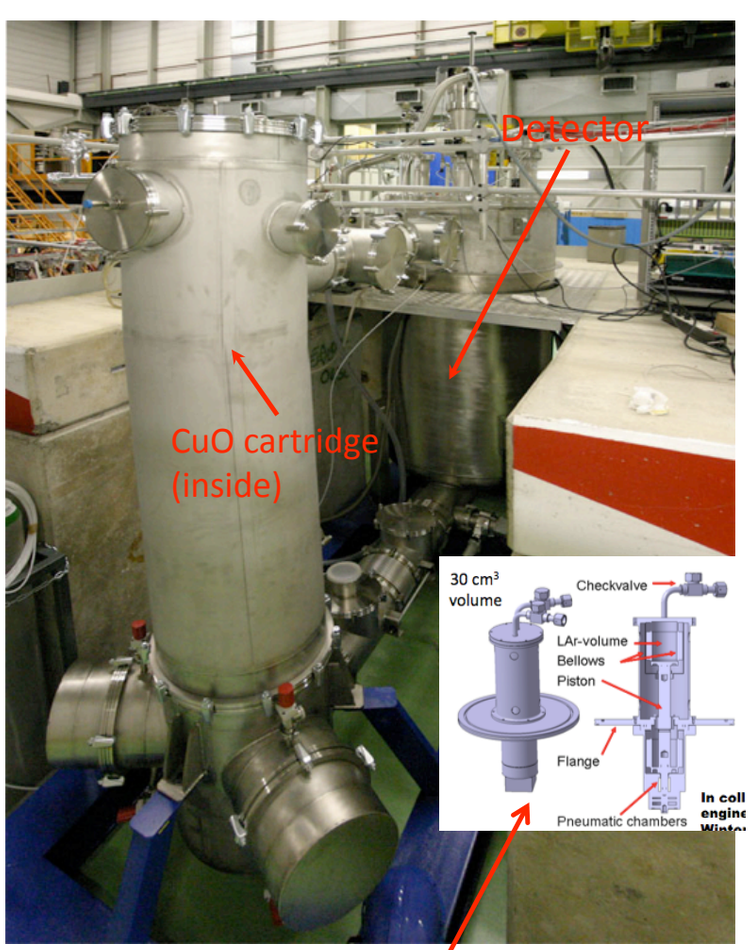
Take ^{83m}Kr and AmBe calibration data

Start science run

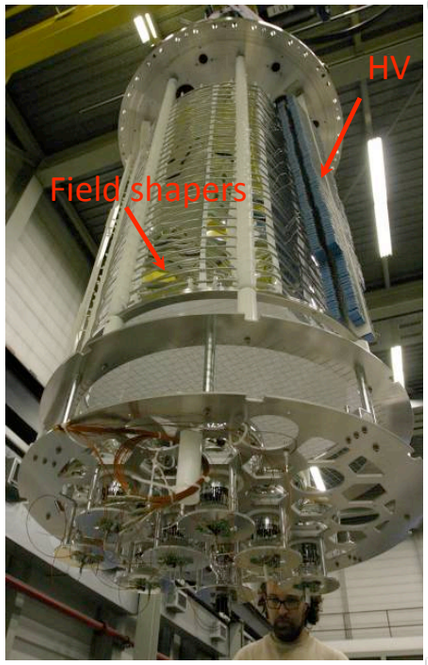
XENON100 Upgrade:
260 kg (total) mass of LXe
QUPID light detectors
Construction 2010

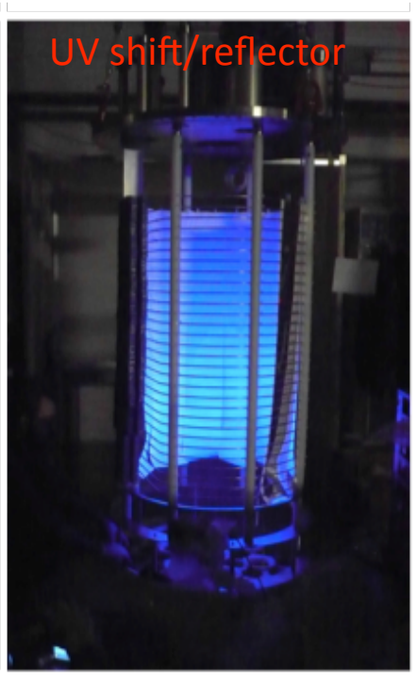
The ArDM Experiment at CERN

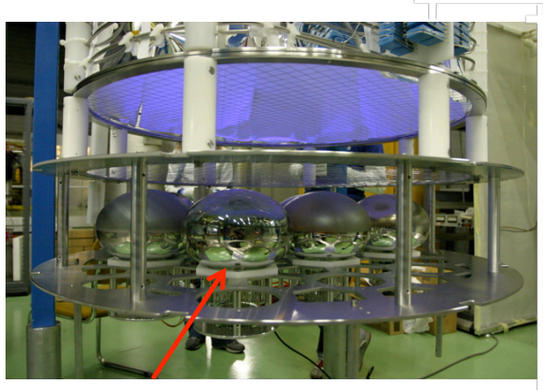
- Dual-phase Ar-TPC; WIMP target: 1 ton of LAr; light read out: PMTs; charge read out: LEMs
- Detector assembled and tested above ground at CERN
- CH participation -> ETH: **A. Rubbia,** A. Badertscher, A. Marchionni, A. Curioni, S. Horikawa, L. Epprecht, F. Resnati, D. Lussi, U. Degunda, C. Lazzaro, **C. Amsler**, C. Regenfus, P. Otyugova, L. Scotto, W. Creuss



LAr bellow pump
flux ≈ 20 lt LAr/hr



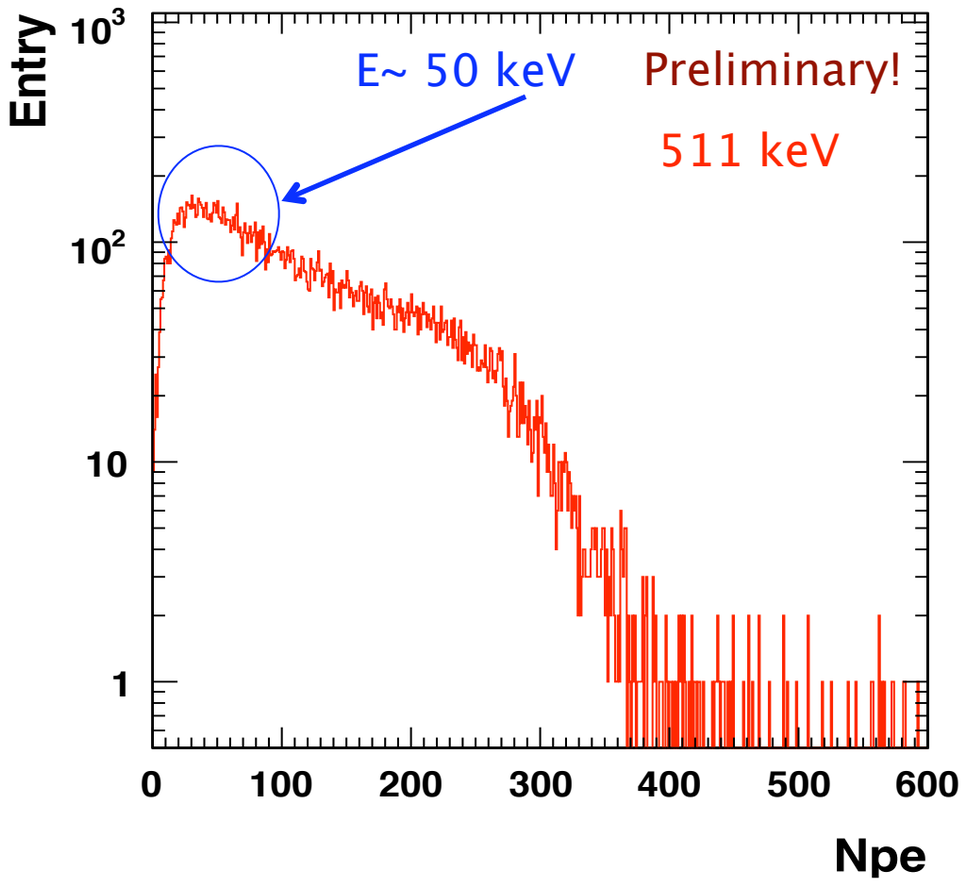


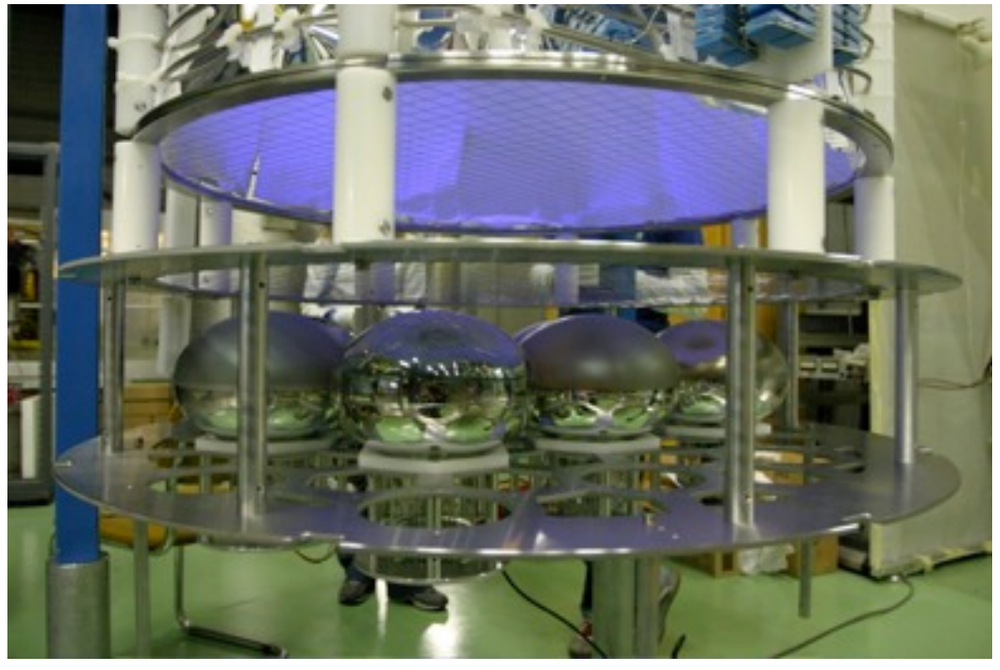


PMTs

The ArDM Experiment at CERN

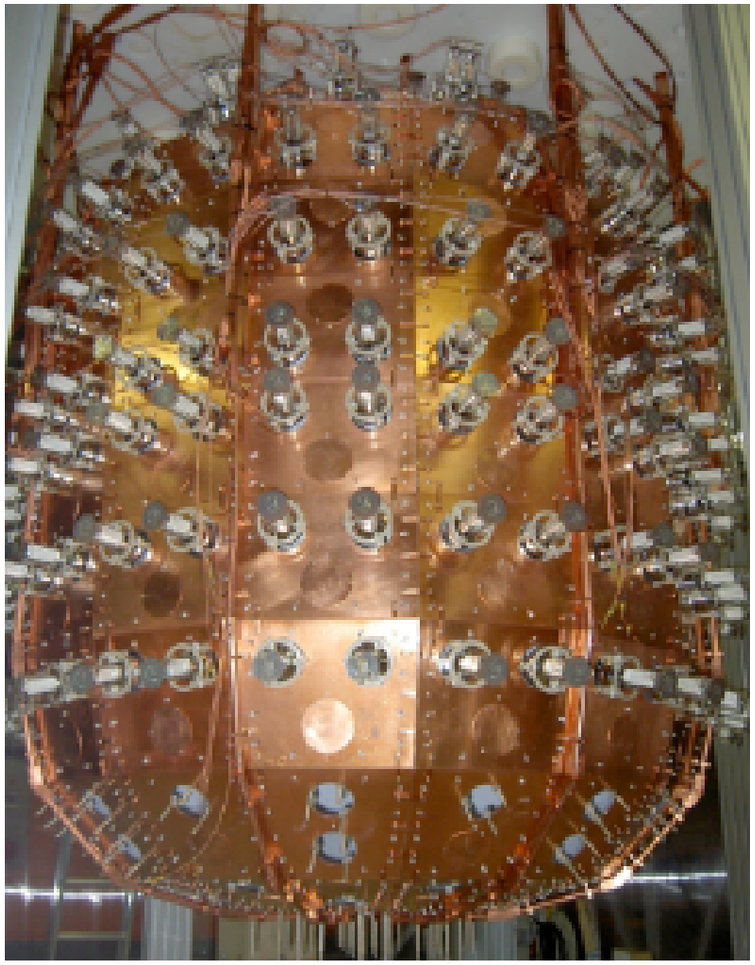
- Polina Otyugova, UZH: “for the first time the ArDM was operated above ground at CERN”
  - ➡ light yield (0.5 phe/keVee with 7 PMTs) consistent with expectations
  - ➡ first successful detection of 50 keV energy in 1 ton-scale detector
  - ➡ preliminary evidence for nuclear recoils (analysis in progress)
  - ➡ next tests in fall 2009: 14 PMTs and drift field to measure ionization
  - ➡ the detector will be moved to an underground location by the end of 2010 (Canfranc, or Sunlab in Poland, or Slanic in Romania)

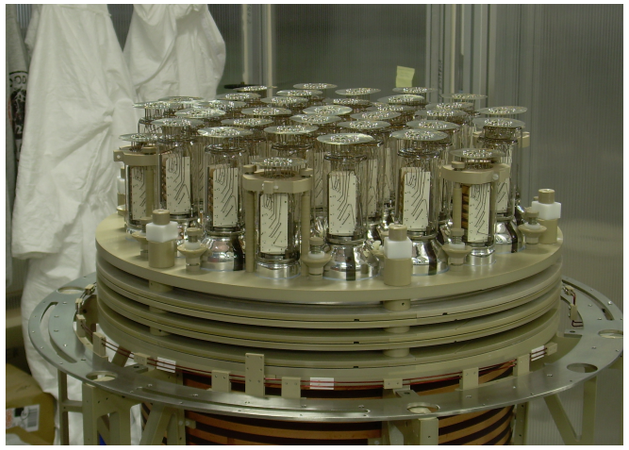


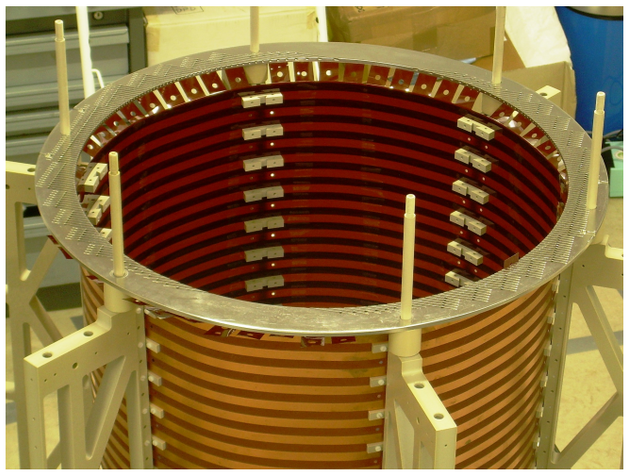


The WARP Experiment at Gran Sasso

- Dual-phase Ar-TPC; WIMP target: 140 kg of LAr seen by 38 PMTs; 8t LAr active shield
- Construction: finished in November 2008; Commissioning: finished in May 2009
- Calibration runs in progress
- “Will start science data taking soon” (C. Montanari, TAUP 2009)







DARWIN
(DARk matter WImp search with Noble liquids)

- Design study for **Next-generation noble liquid facility in Europe** submitted (in response to the first ASPERA common call) on June 4th, 2009, 3:57 pm
- **Goals:**
  - ➡ **unify and coordinate extensive existing expertise in Europe** (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 2-3 years from now
  - ➡ submit full proposal in response to second ASPERA call

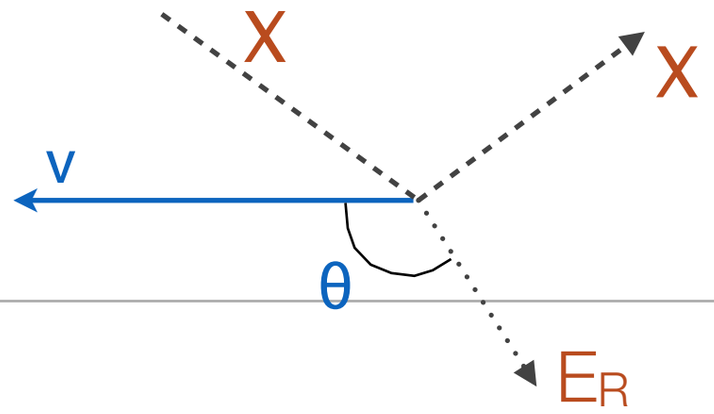
- **Possible locations**: LNGS (Italy), ULISSE (Modane extension, France), or SUNLAB (Poland)

- **Participants: Switzerland** (ETHZ, UZH), **Germany** (MPIK, KIT, Münster), **France** (Subatech), **Italy** (INFN: L'Aquila, Milano, Napoli, Padova, Pavia, Torino), **Netherlands** (Nikhef), **Poland** (IFJ PAN, US, PWr), **USA** (Columbia, Princeton, Rice, UCLA)

- **CH:** UZH **L. Baudis (PC)**, A. Ferella, T. Marrodan, M. Schumann, R. Santorelli, T. Bruch, A. Manalaysay, A. Behrens;
- UZH: **C. Amsler**, C. Regenfus, P. Otyugova, L. Scotto, W. Creuss; ETH: **A. Rubbia,** A. Badertscher, A. Marchionni, A. Curioni, S. Horikawa, L. Epprecht, F. Resnati, D. Lussi, U. Degunda, C. Lazzaro

- **Funding:** provided by the national instruments of each participant ('virtual pot')
- **Decision:** expected in fall 2009, start in October 2009

Directional Detectors

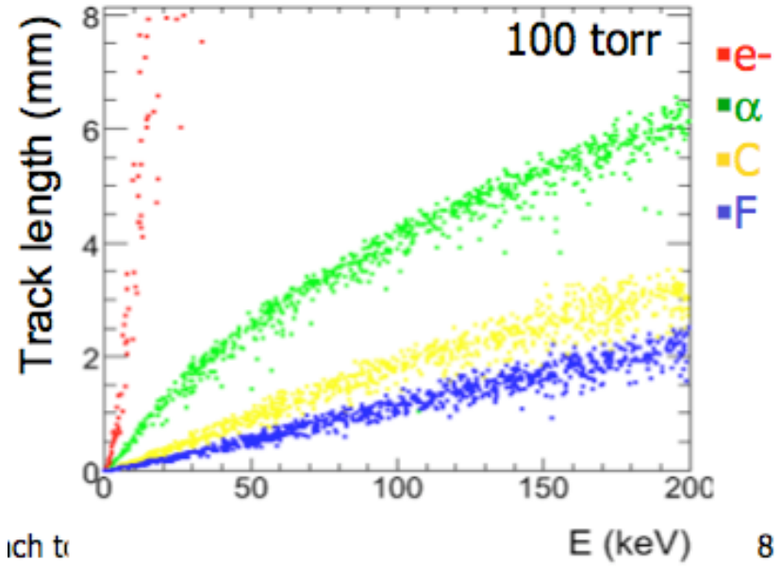


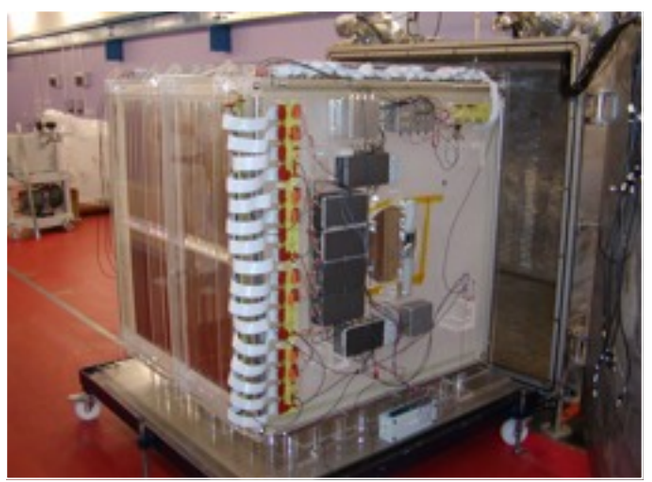
- Would provide robust signature
- 10-100 events needed, depending on direct. capability
- These detectors are still in R&D phase

- **DMTPC** (CF_4 gas TPC, at MIT)
- Asher Kaboth: "demonstrated operation of a CCD-based gas detector with directional sensitivity"
- "collected and analyzed surface run background data"
- "plans for underground operation at WIPP"

- **DRIFT-II** (negative ion, CS_2, TPC at Boulby)
- Neil Spooner: "big progress in the last two years (published)"
- "directional signal possible at $1m^3$ scale"
- "head-tail (sense) exists and is understood at $1m^3$ scale"

- **ASPERA proposal: CYGNUS (UK, France, Germany, Spain)**

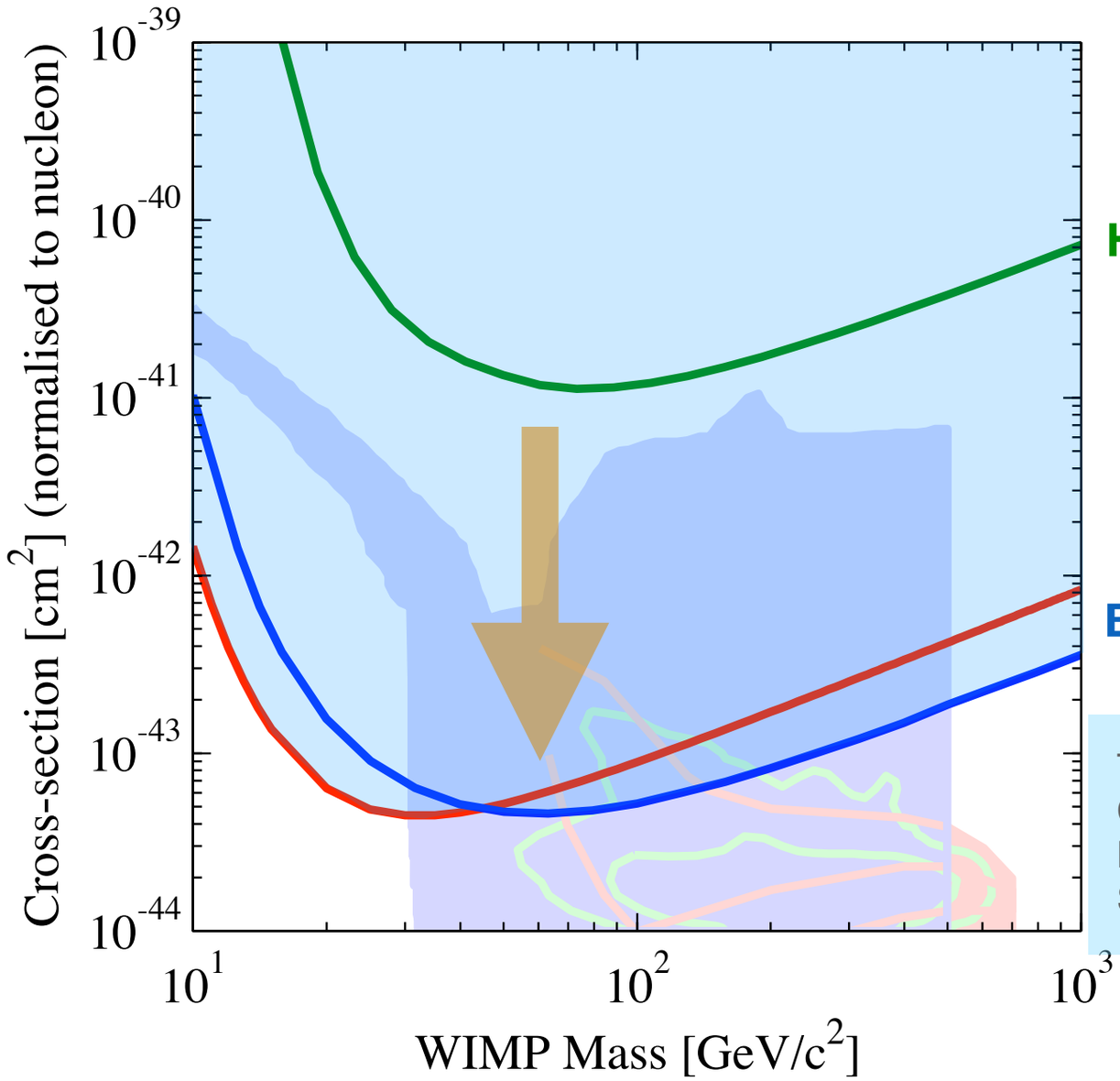




DRIFT-IIa @ Boulby

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!**



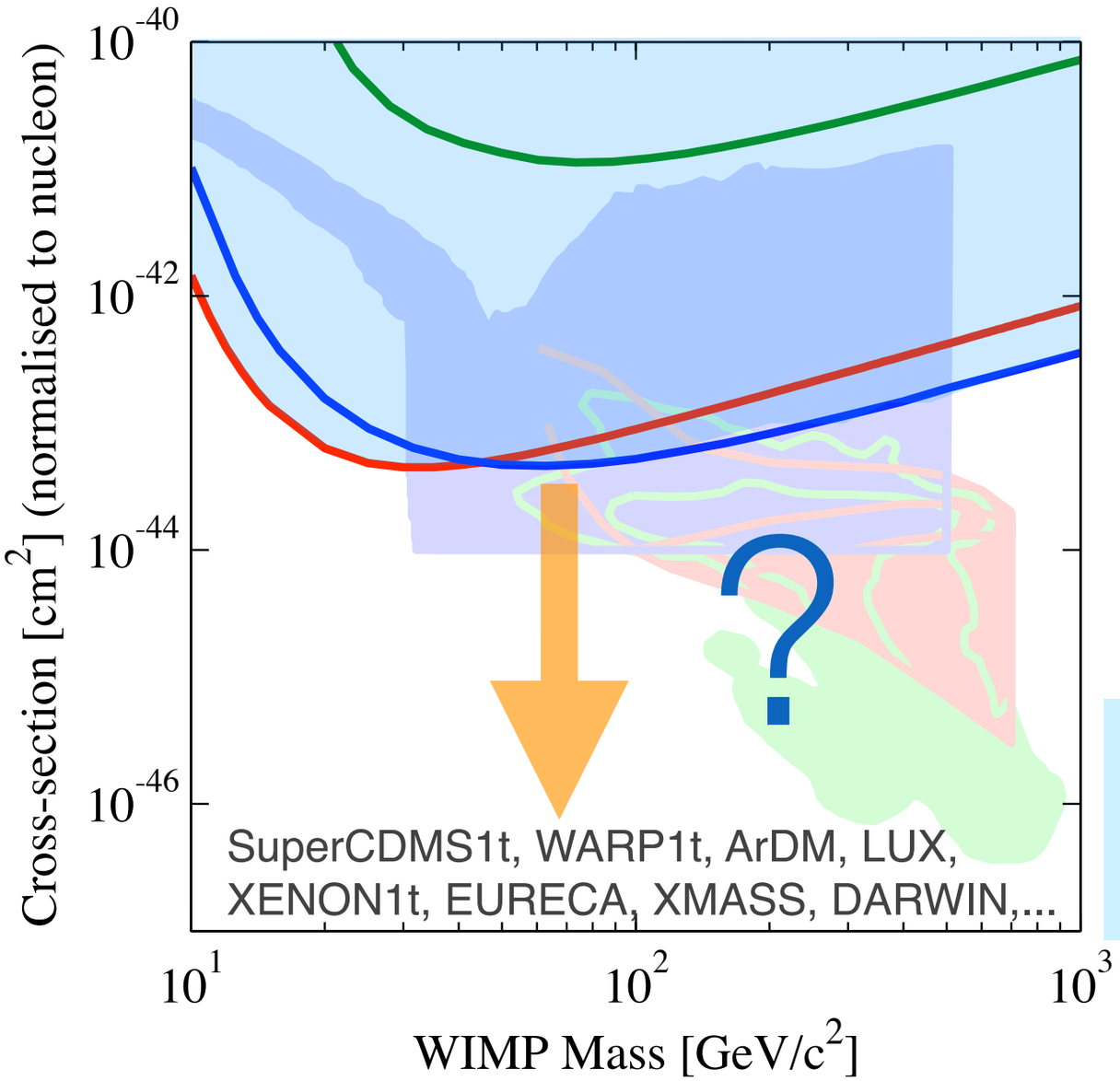
Heidelberg -Moscow 1998

Best limits in 2009

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
- Visions: next generation projects should reach the ≲ 10^{-10} pb level
- What will they see? *(nobody has been there before!)*



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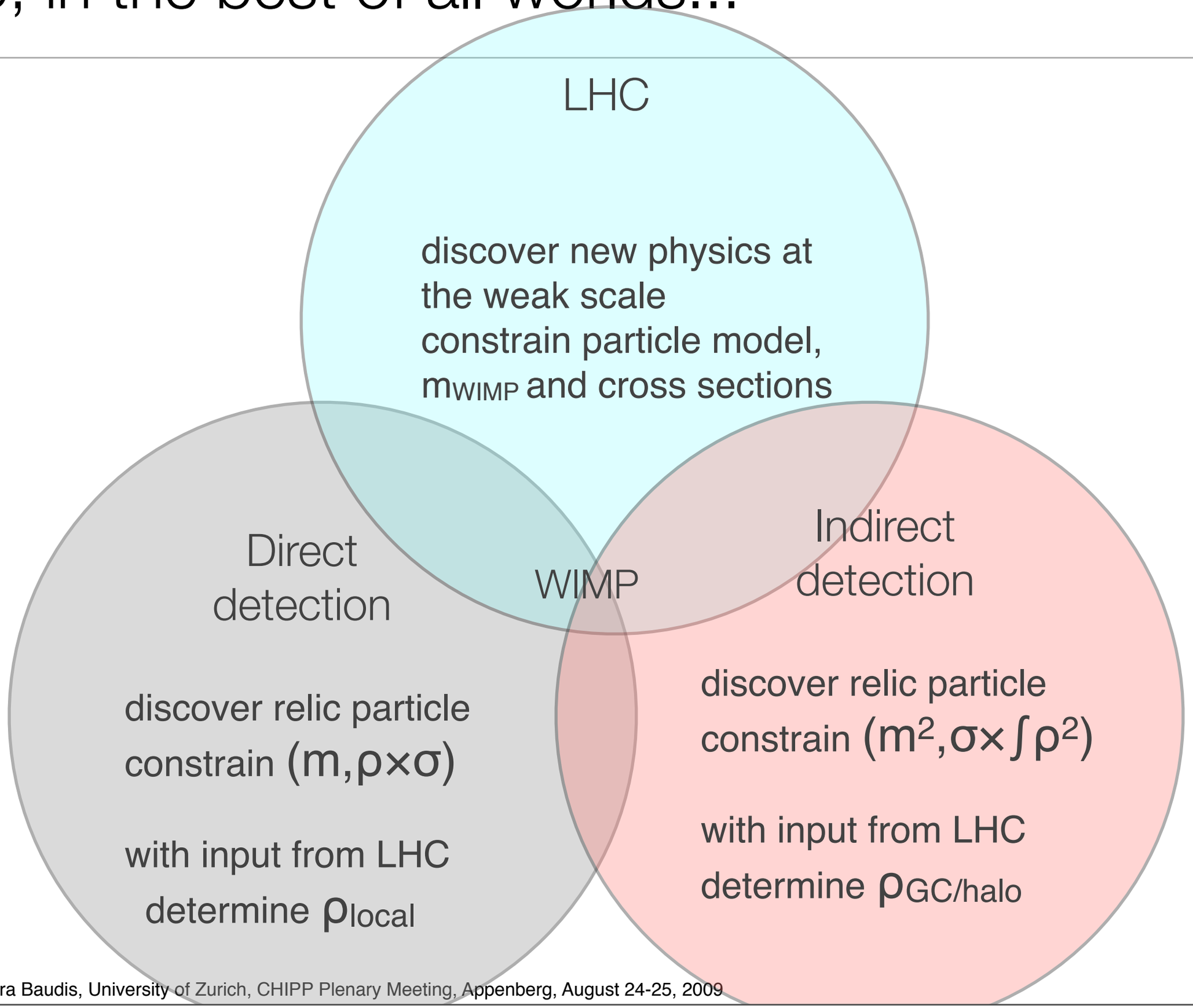
So, in the best of all worlds...



Let's assume that...

- We will have credible evidence from all three by 2010
- Question: how will we know we are seeing the same phenomenon?
- Many different opinions/papers (we will learn enough from the LHC; we need the ILC; depending where in SUSY space; etc)
- ***Let's wish for this problem!***
- [dark matter may have only gravitational interaction: no accelerator production, no direct detection, no indirect detection - an inconvenient truth]

Next (6th) Patras Workshop: Zurich

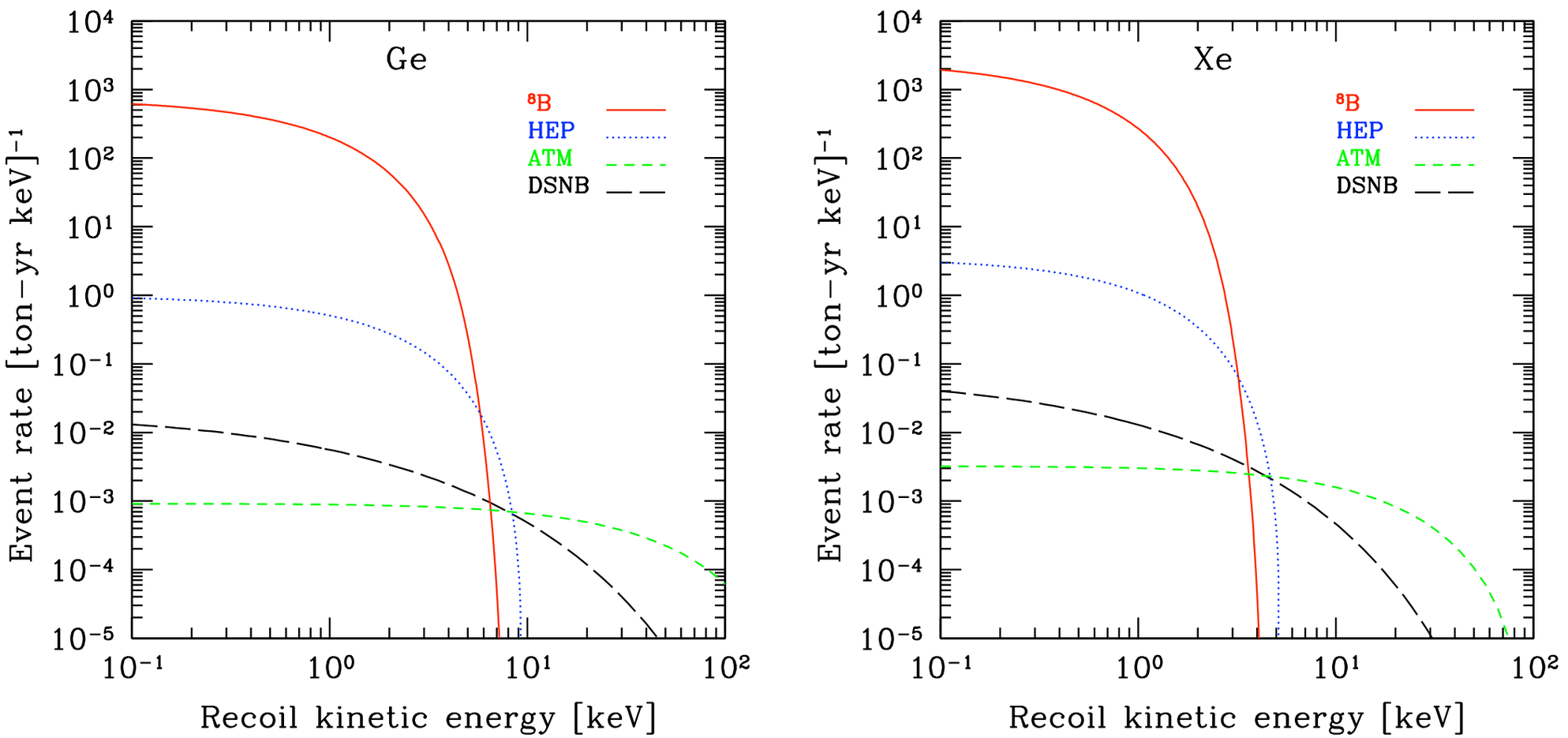
- July 5 - July 9, 2010
- Hope to see some of you there

End

Neutrino induced backgrounds

- Neutrino-nucleus elastic scattering
- ^{8}B neutrinos dominate: background if the WIMP-nucleon cross section < 10^{-10} pb
- Energy of nuclear recoils: <4 keV (heavy targets, Xe, I etc) to <30 keV in light targets (F, C)
- Non-^{8}B neutrino backgrounds: impact on WIMP detectors at much lower WIMP-nucleon cross sections

L. E. Strigari, arXiv: 0903.3630v1



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 cm^3 LXe, zero field
- New experiment for charge/light yield under preparation at UZH (using D-D neutron generator)