Direct Dark Matter Searches

Marc Schumann *Physik Institut, Universität Zürich*

What is ν? Invisibles12, GGI Florence, June 27th 2012

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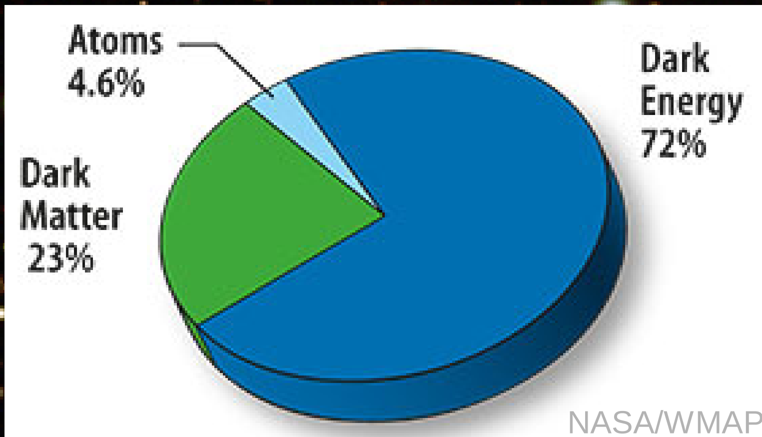
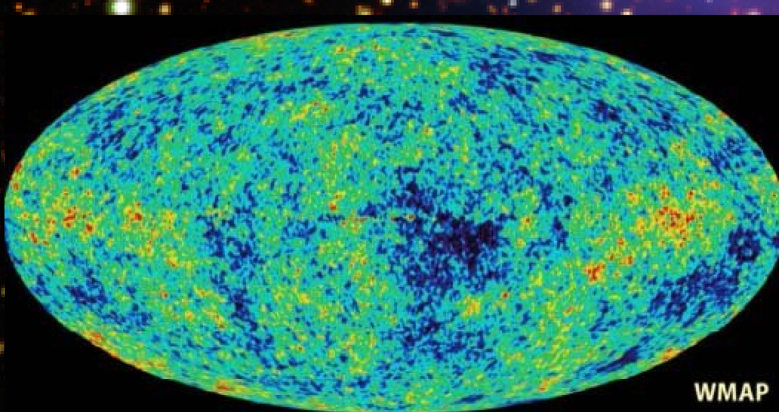
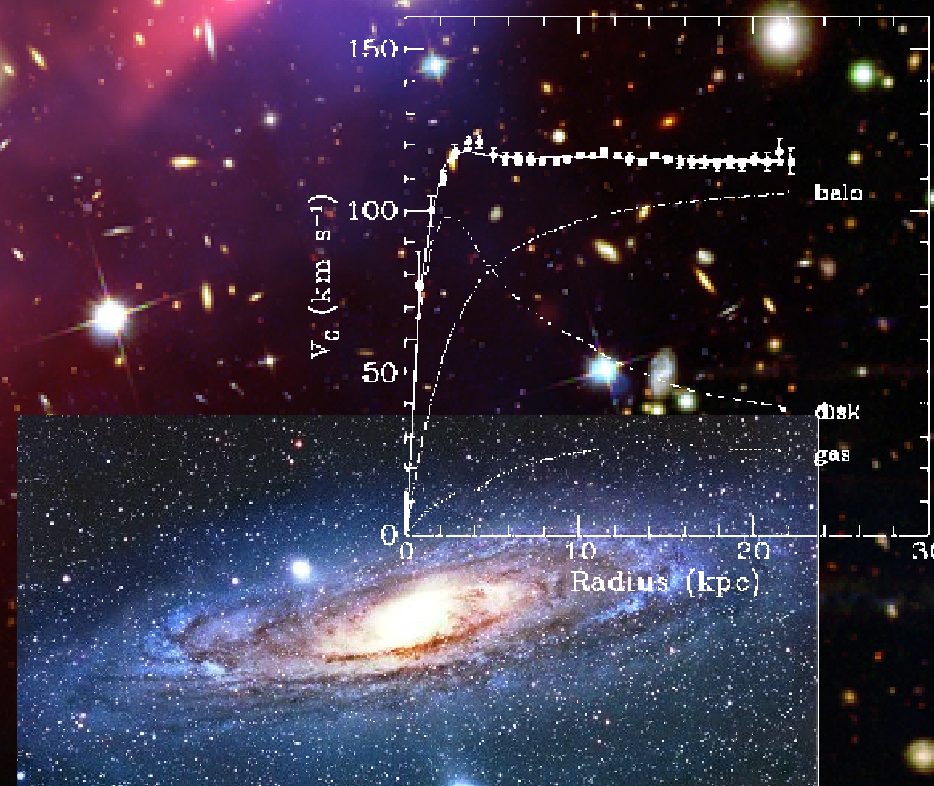
www.physik.uzh.ch/groups/groupbaudis/xenon/

Dark Matter: (indirect) **Evidence**



Particle Dark Matter Candidates:
- WIMP → *„WIMP miracle“*
- Axion
- SuperWIMPs
- sterile neutrinos
- WIMPless dark matter
- Gravitino
- ...





Direct WIMP Search

Elastic Scattering of
WIMPs off target nuclei

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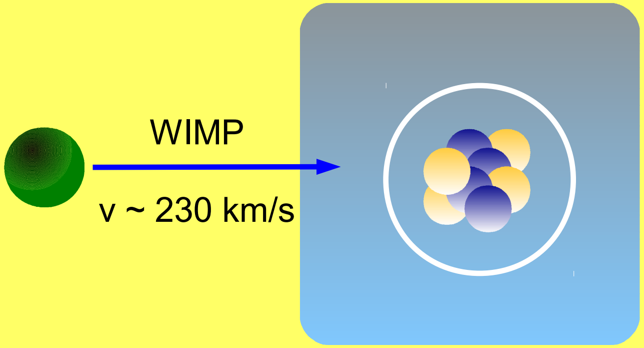

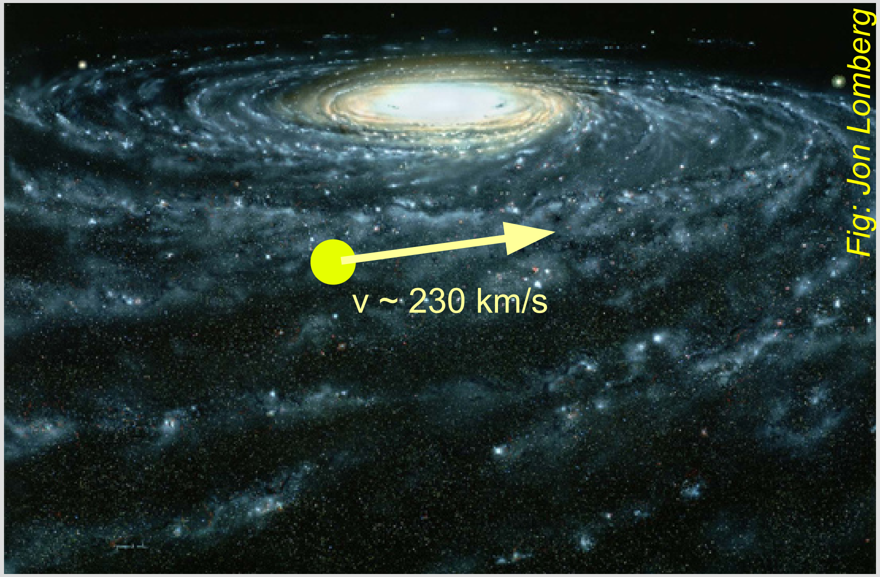

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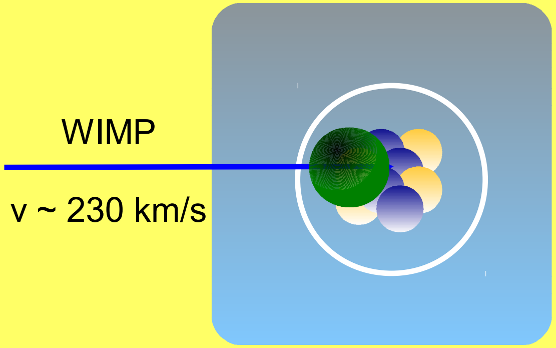
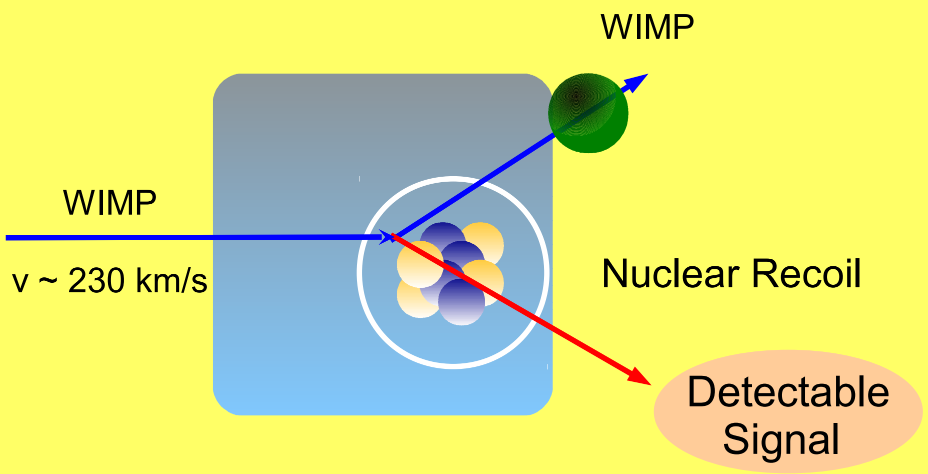


Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil



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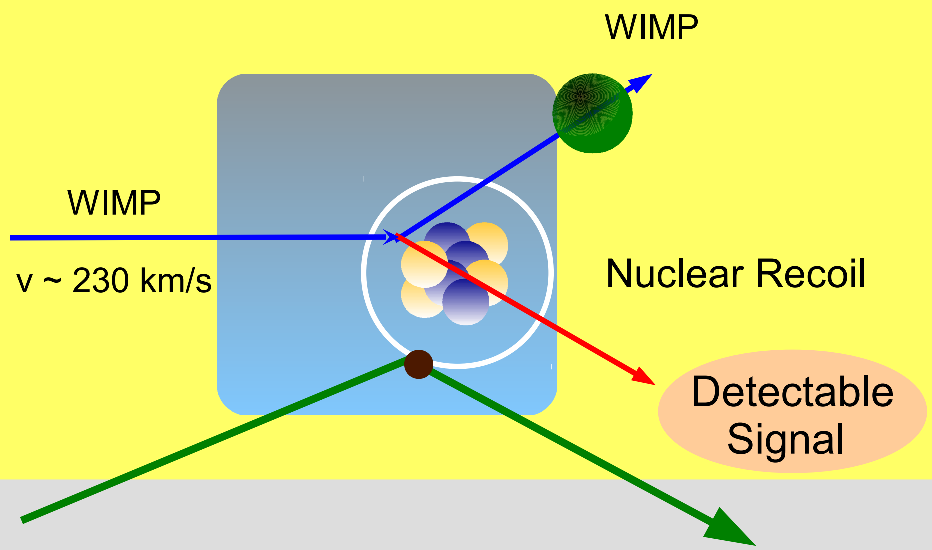

Gamma- and beta-particles (background) interact with the atomic electrons
→ **electronic recoil**

Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
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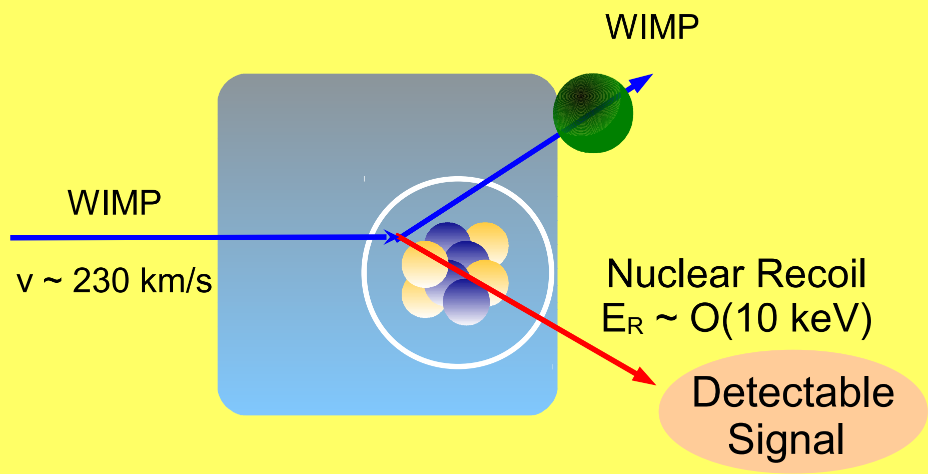


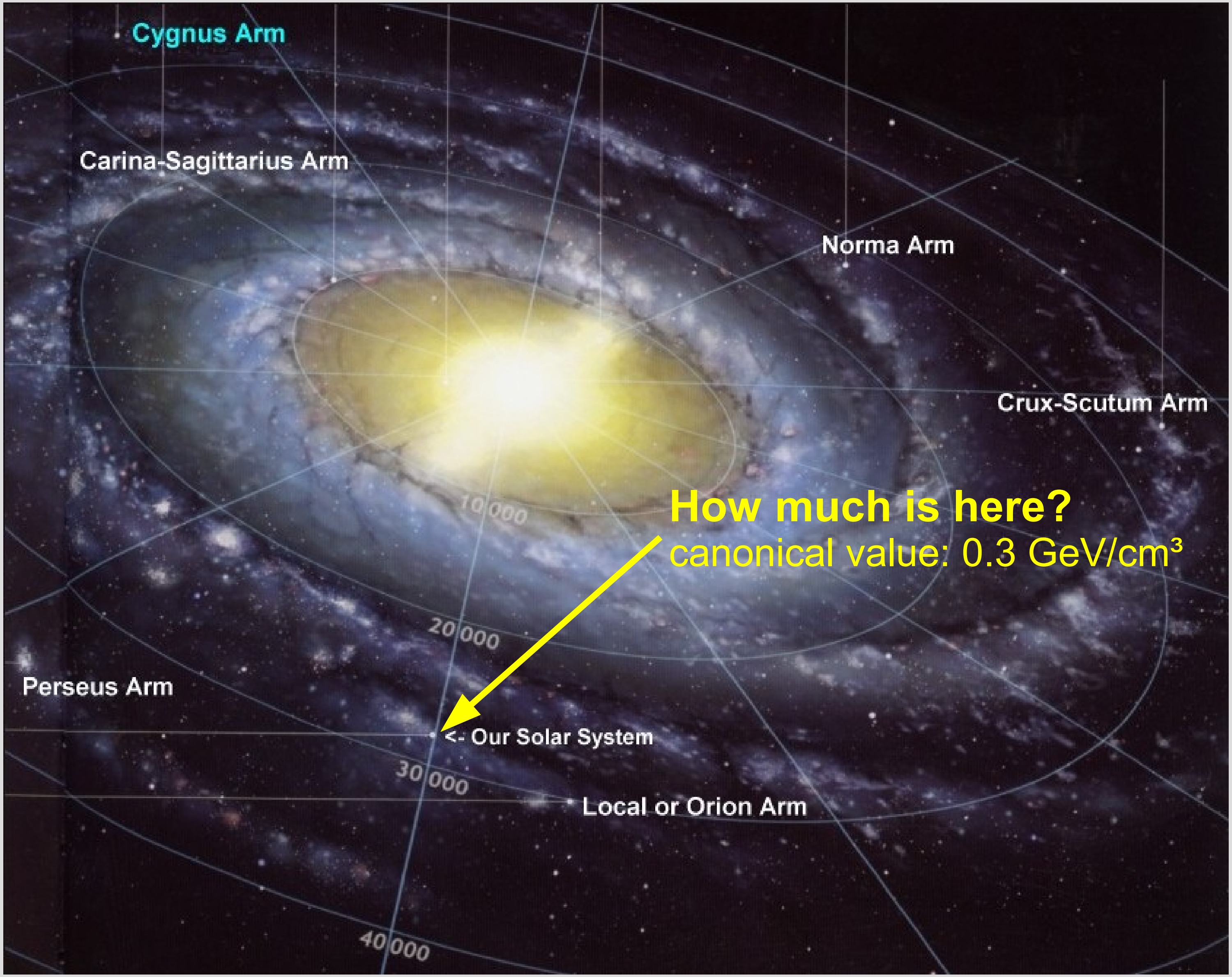
Recoil Energy: $$E_r = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta) \sim \mathcal{O}(10\ \mathrm{keV})$$

Event Rate: $$R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi - N} \rangle$$

Detector — Local DM Density — Physics

- N number of target nuclei
- ρ_χ / m_χ local WIMP density
- $\langle\sigma\rangle$ velocity-averaged scatt. X-section

Dark Matter around us?



arXiv.org > astro-ph > arXiv:1204.3924

Astrophysics > Galaxy Astrophysics

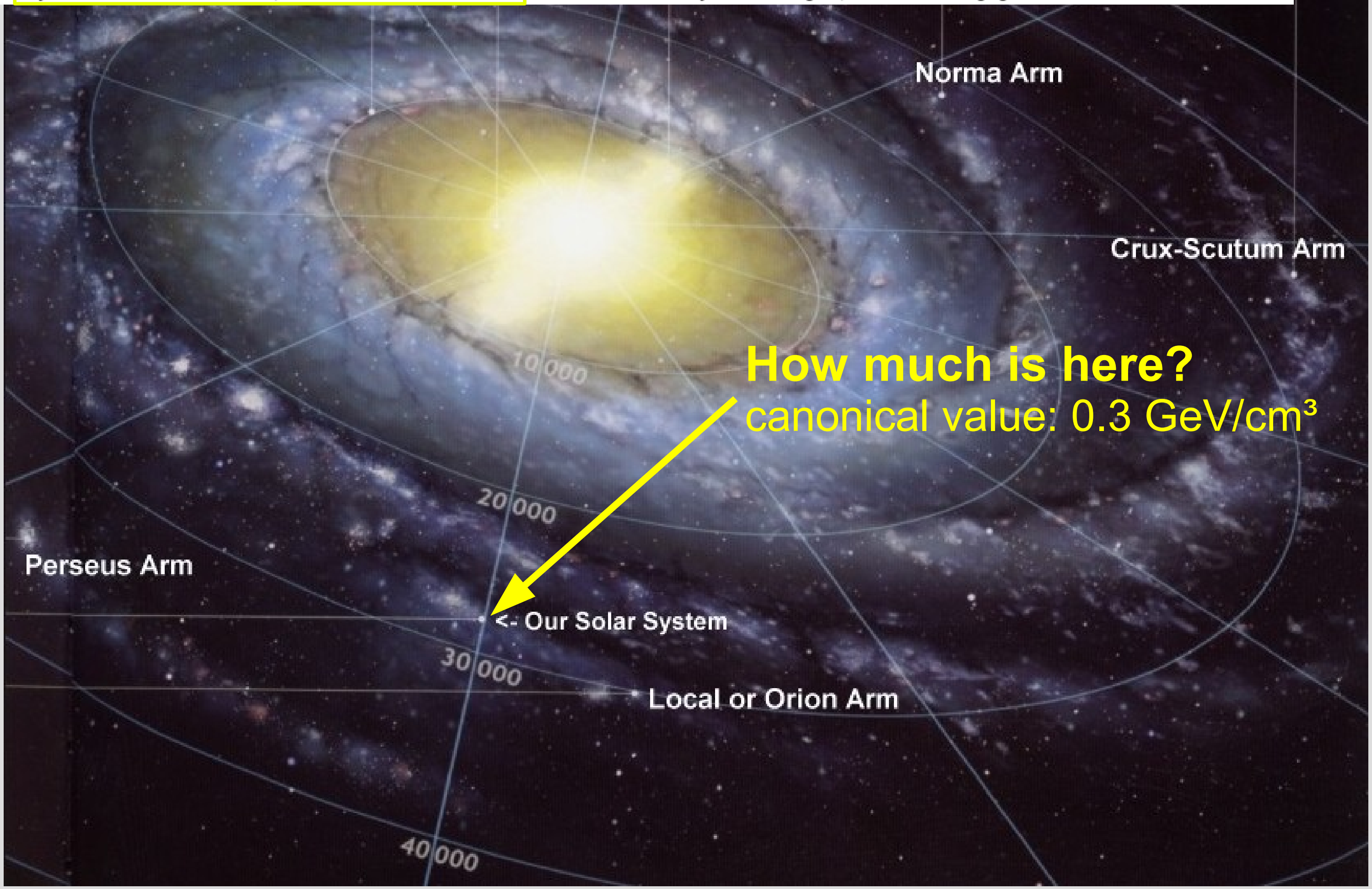
Kinematical and chemical vertical structure of the Galactic thick disk II. A lack of dark matter in the solar neighborhood

C. Moni Bidin, G. Carraro, R. A. Mendez, R. Smith

We estimated the dynamical surface mass density Sigma at the solar position between Z=1.5 and 4 kpc from the Galactic plane, as inferred from the kinematics of thick disk stars.

We extrapolate a dark matter (DM) density in the solar neighborhood of 0+-1 mM_sun pc^-3,

In particular, our results may indicate that any direct DM detection experiment is doomed to fail if the local density of the target particles is negligible.



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arXiv.org > astro-ph > arXiv:1205.4033

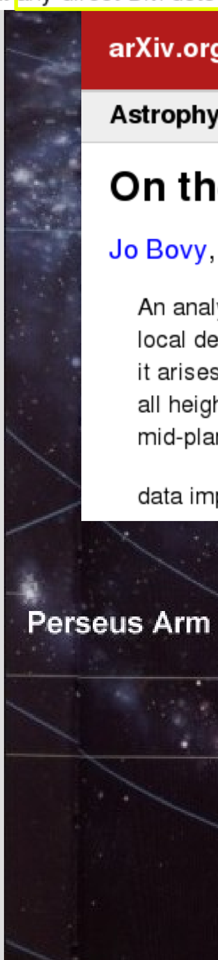
Astrophysics > Galaxy Astrophysics

On the local dark matter density

Jo Bovy, Scott Tremaine (IAS)

An analysis of the kinematics of 412 stars at 1-4 kpc from the Galactic mid-plane by Moni Bidin et al. (2012) has claimed to derive a local density of dark matter that is an order of magnitude below standard expectations. We show that this result is incorrect and that it arises from the invalid assumption that the mean azimuthal velocity of the stellar tracers is independent of Galactocentric radius at all heights; the correct assumption---that is, the one supported by data---is that the circular speed is independent of radius in the mid-plane.

we find that the data imply a local dark-matter density of 0.3 +/- 0.1 Gev/cm^3



arXiv.org > astro-ph > arXiv:1206.0015

Astrophysics > Galaxy Astrophysics

A new determination of the local dark matter density from the kinematics of K dwarfs

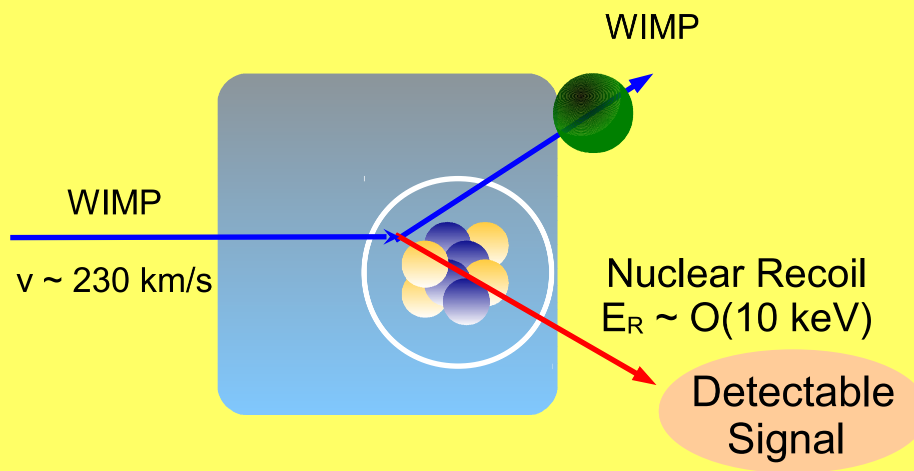
Silvia Garbari, Chao Liu, Justin I. Read, George Lake

We apply a new method to determine the local disc matter and dark halo matter density to kinematic and position data for \sim2000 K dwarf stars taken from the literature.

We perform a series of tests to demonstrate that our results are insensitive to plausible systematic errors in our distance calibration, and we show that our method recovers the correct answer from a dynamically evolved N-body simulation of the Milky Way. We find a local dark matter density of (0.95+0.53-0.49 GeV cm^-3) at 90% confidence assuming no correction for the non-flatness of the local rotation curve, and (0.85+0.57-0.50 GeV cm^-3) if the correction is included.

Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil



Recoil Energy: $E_r \sim \mathcal{O}(10 \text{ keV})$

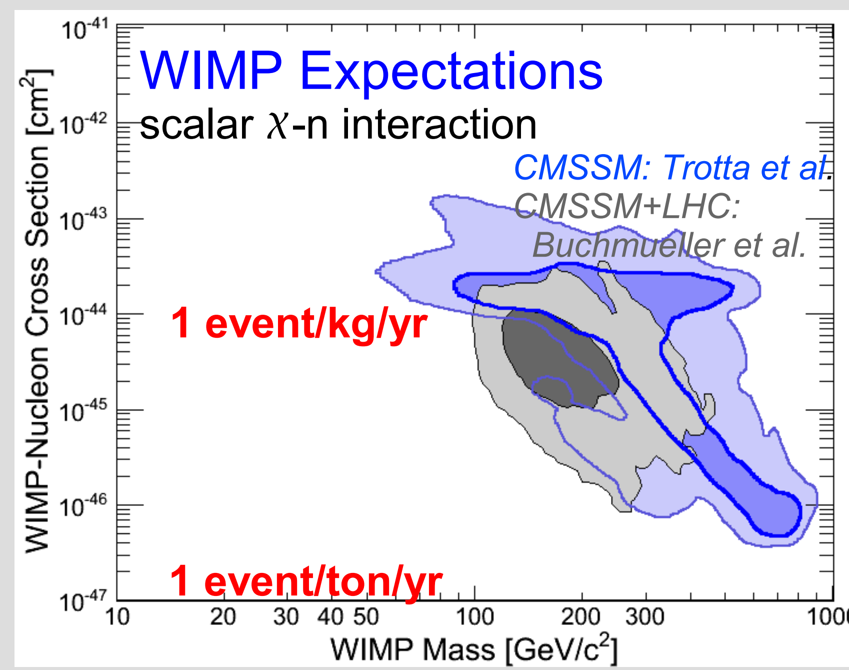
Event Rate: $R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi-N} \rangle$

Detector

Local DM Density

Physics

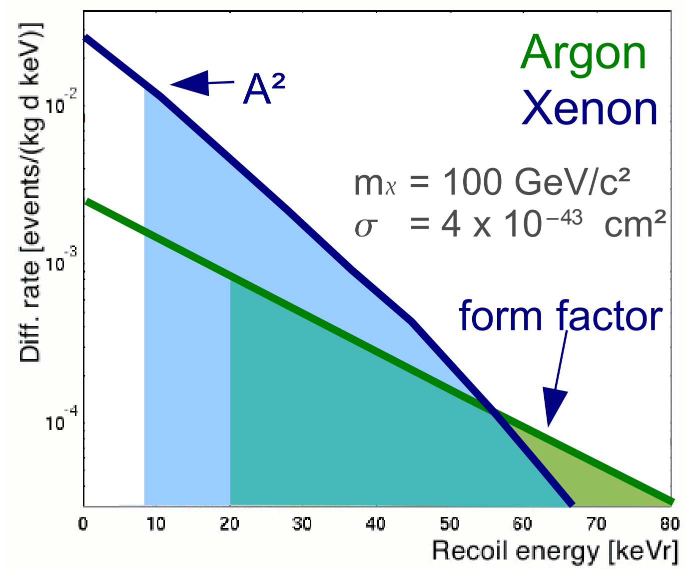
ρ_χ~0.3 GeV/c²



Direct WIMP Search

Summary: Tiny Rates

$R < 0.01$ evt/kg/day
$E_R < 100$ keV



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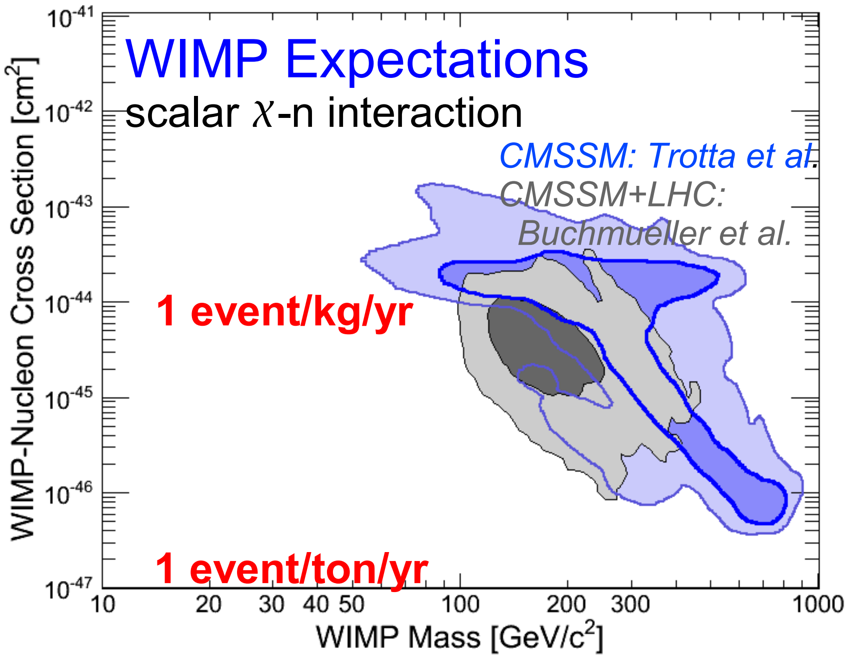
Detector

Local DM Density

Physics

$\rho_\chi \sim 0.3$ GeV/c²



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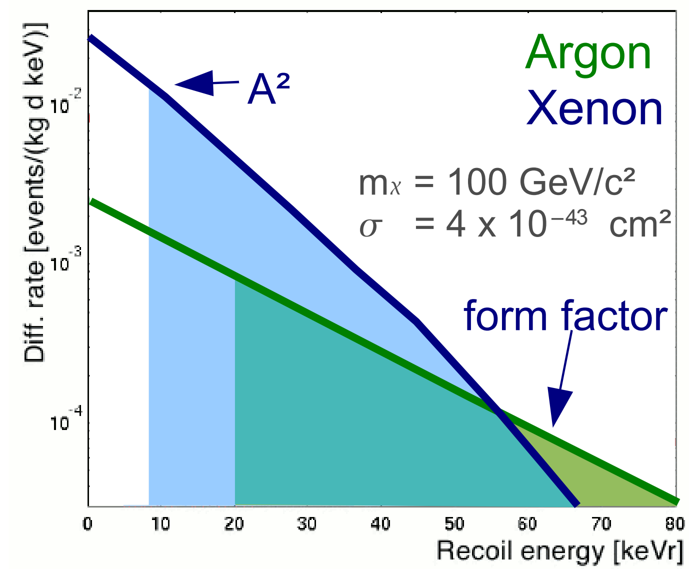
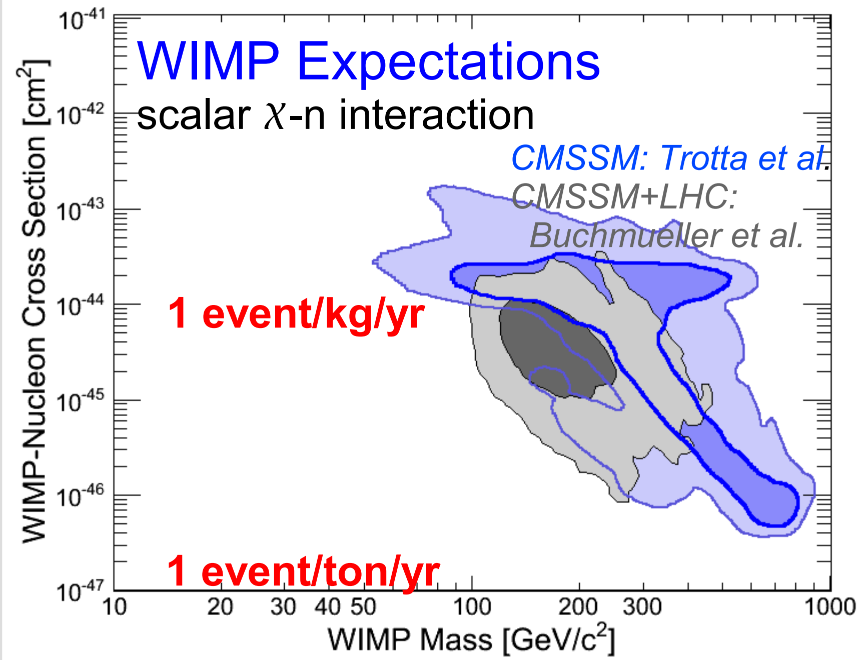


How to build a WIMP detector?

- large total mass, high *A*
- low energy threshold
- ultra low background
- good background discrimination



Backgrounds

Experimental Sensitivity

without background: $\propto (mt)^{-1}$
with background: $\propto (mt)^{-1/2}$

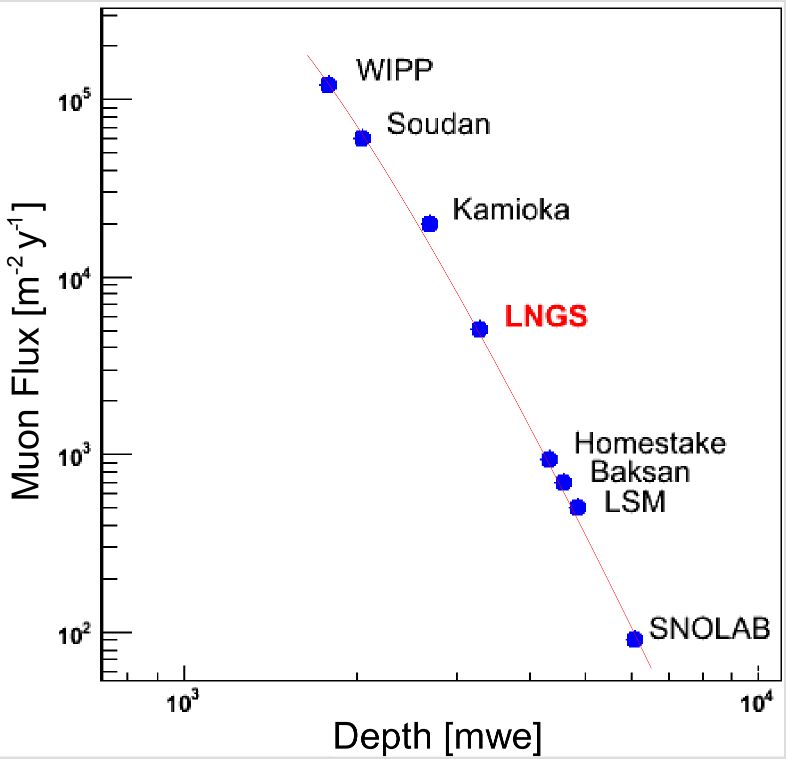
Background Sources

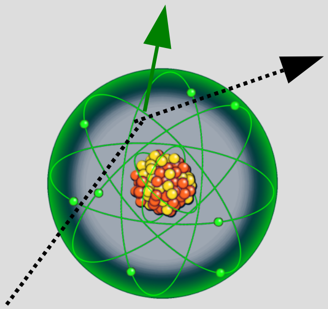
environment: U, Th chains, K

$^{238}U \xrightarrow[\alpha]{} {}^{234}Th \xrightarrow[\beta]{} {}^{234m}Pa \xrightarrow[\beta]{} {}^{234}U \xrightarrow[\alpha]{} {}^{230}Th \xrightarrow[\alpha]{} {}^{226}Ra \xrightarrow[\alpha]{} {}^{222}Rn \xrightarrow[\alpha]{} {}^{218}Po \ldots$

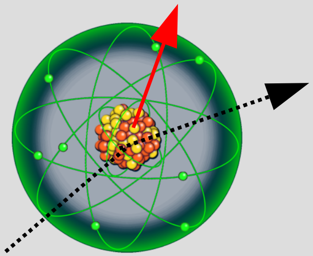
$^{232}Th \xrightarrow[\alpha]{} {}^{228}Ra \xrightarrow[\beta]{} {}^{228m}Ac \xrightarrow[\beta]{} {}^{228}Th \xrightarrow[\alpha]{} {}^{224}Ra \xrightarrow[\alpha]{} {}^{220}Rn \xrightarrow[\alpha]{} {}^{216}Po \ldots$

- γ and β decays (electronic recoil)
- alphas can pose a problem (technology dependent)
- neutrons from (α,n) and sf in rocks and detector parts
- neutrons from cosmic ray muons



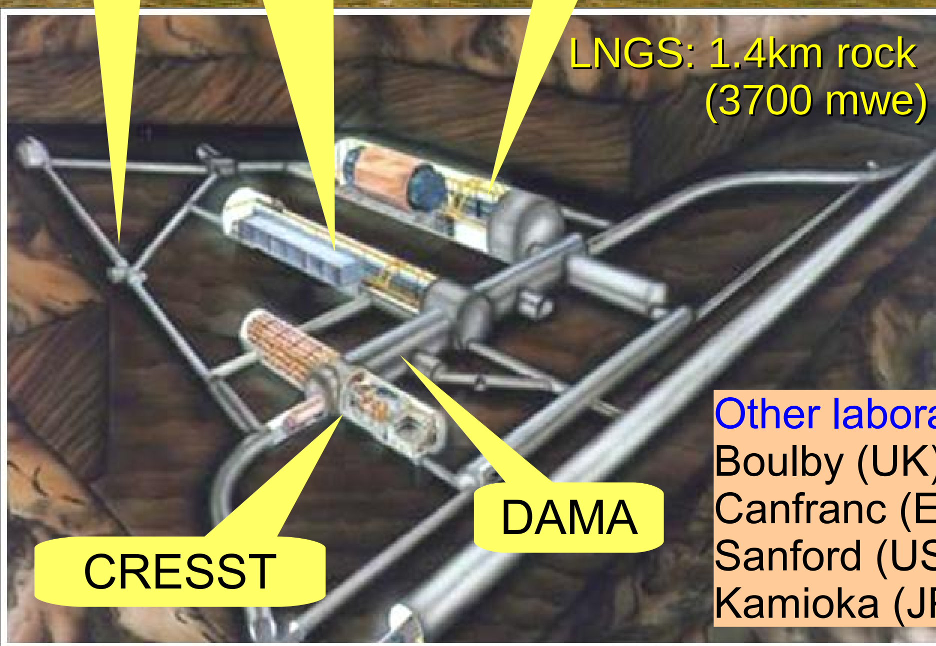


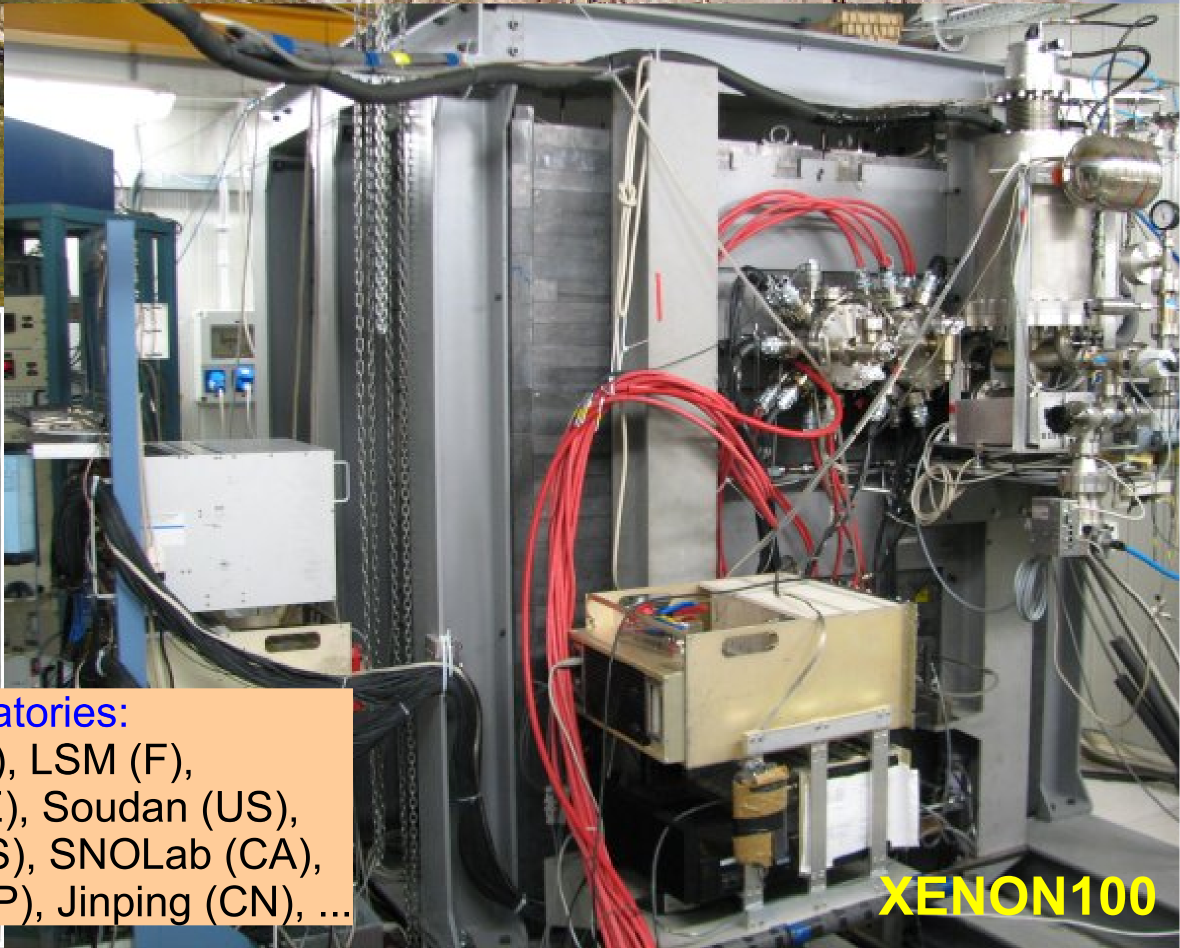
Electronic Recoils (gamma, beta)



Nuclear Recoils (neutron, WIMPs)

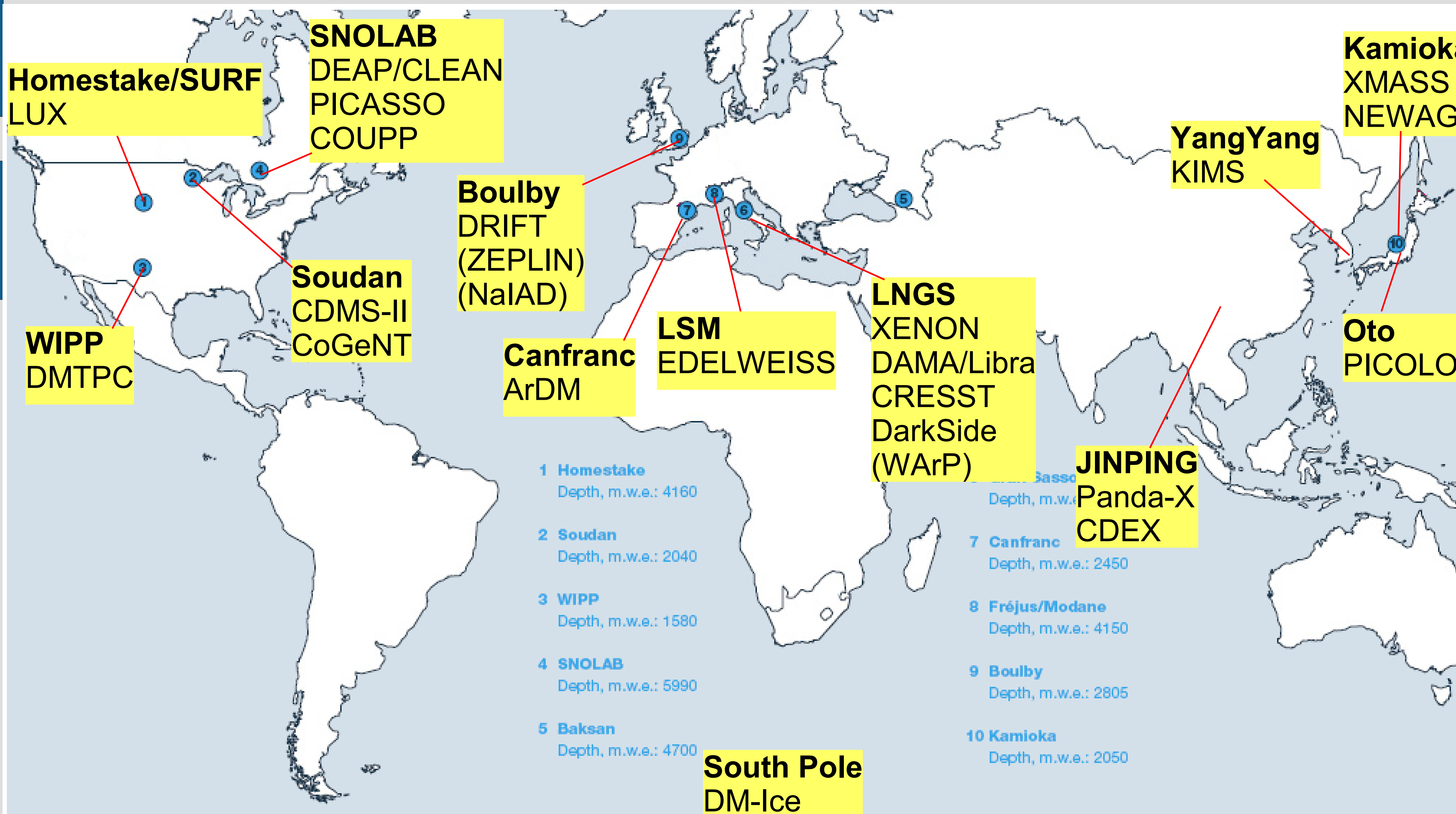
Laboratori Nazionali del Gran Sasso



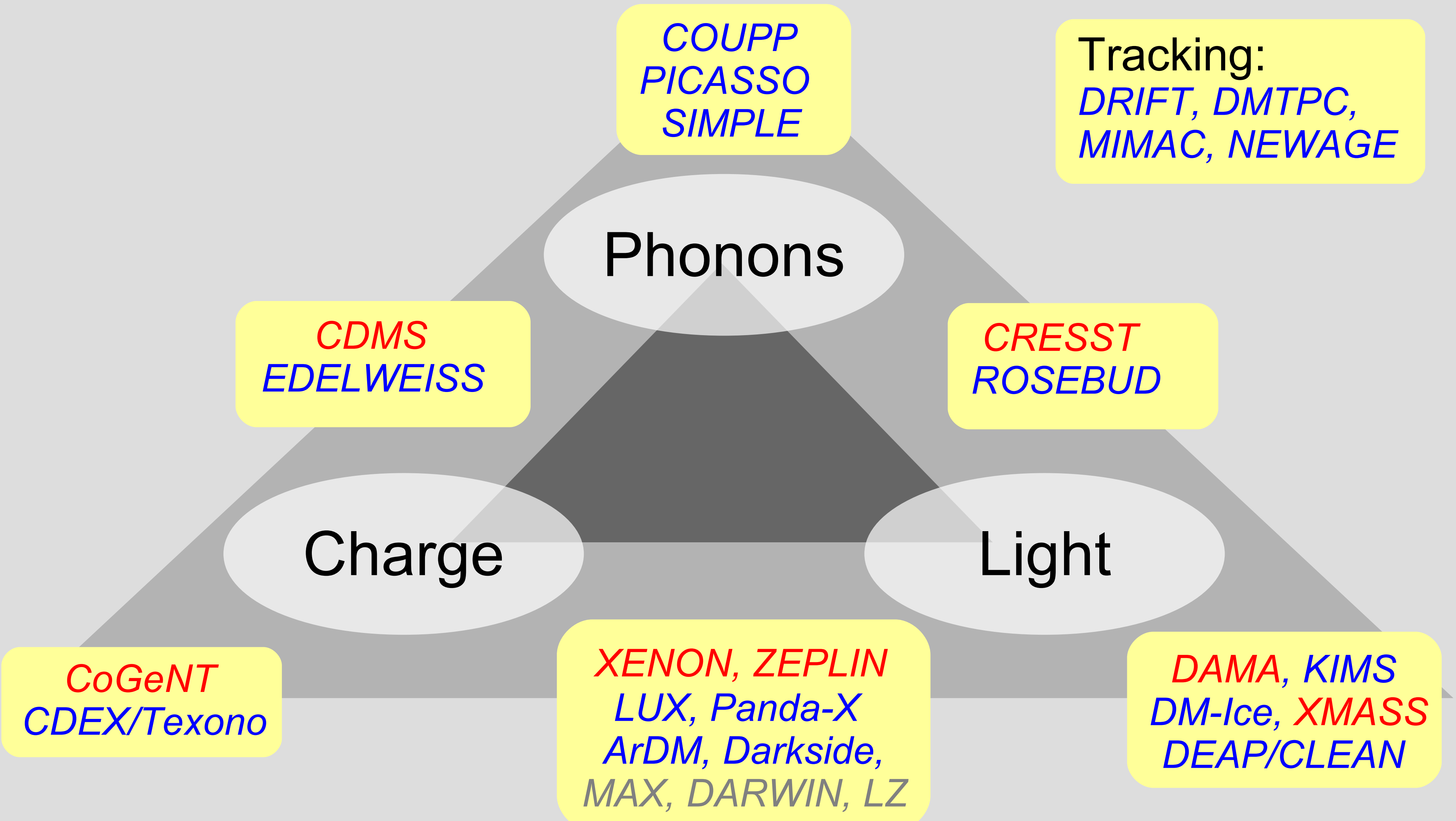


Other laboratories:
Boulby (UK), LSM (F),
Canfranc (E), Soudan (US),
Sanford (US), SNOLab (CA),
Kamioka (JP), Jinping (CN), ...

World-wide Efforts



Direct WIMP Detection



Background Suppression

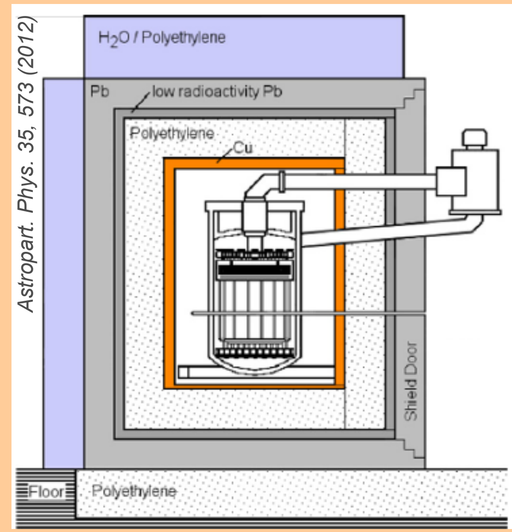
A Avoid Backgrounds

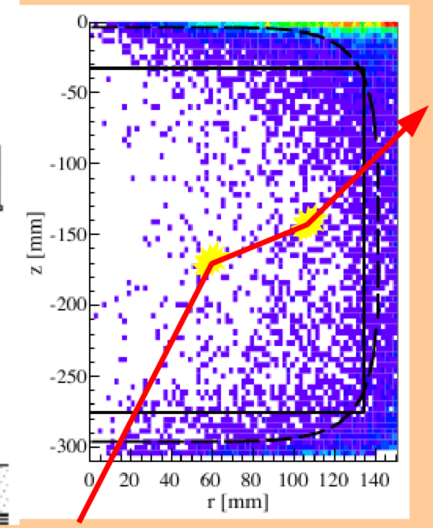
Use of radiopure materials

Shielding

deep underground location
large shield (Pb, water, poly)
active veto (μ, γ coincidence)

self shielding → fiducialization





B Use knowledge about expected WIMP signal

WIMPs interact only once

→ single scatter selection
require some position resolution

WIMPs interact with target nuclei

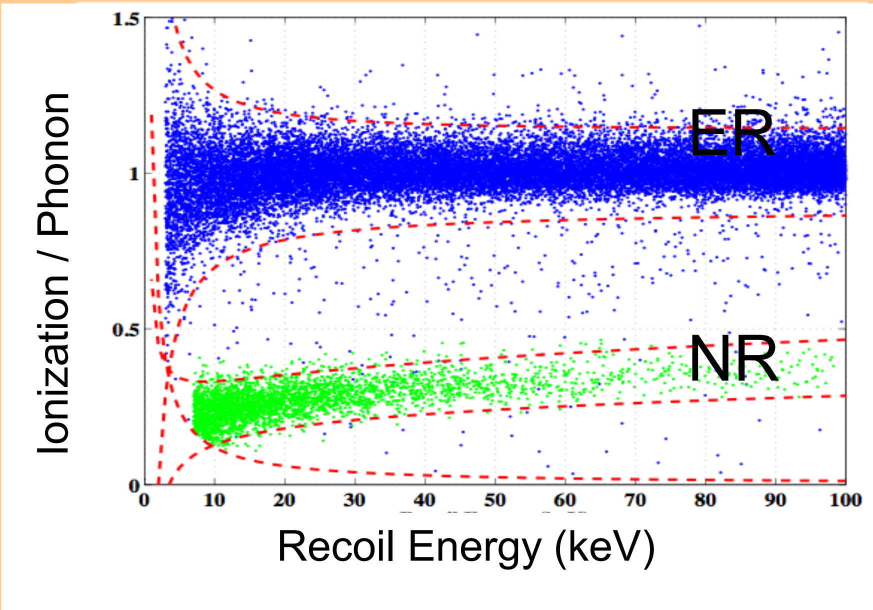
→ nuclear recoils
exploit different d*E*/dx from signal and background

Examples

- Scintillation Pulse Shape
- Charge/Light Ratio
- Charge/Phonon Ratio

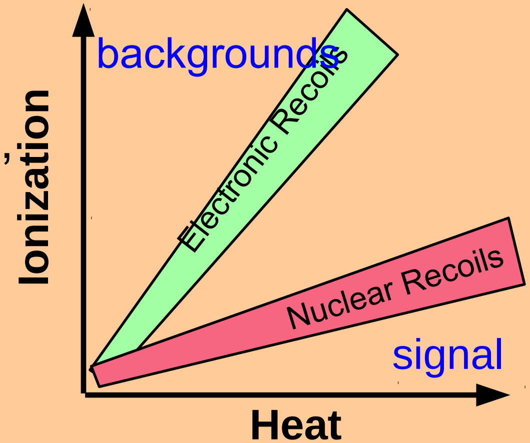
2 Observables for Discrimination

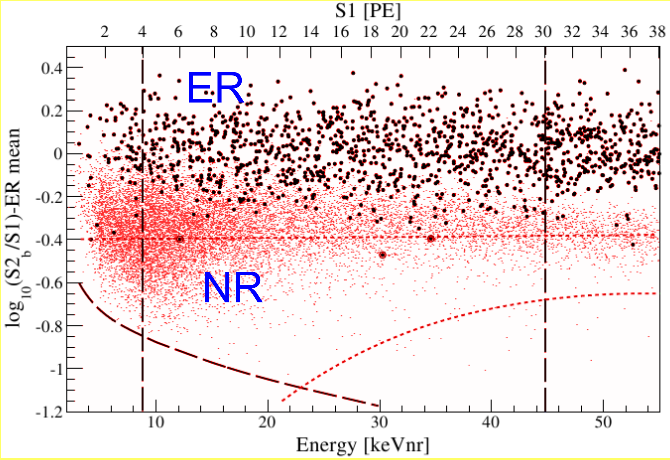
Ionization yield and Charge/Light ratio
depend on dE/dx → discrimination



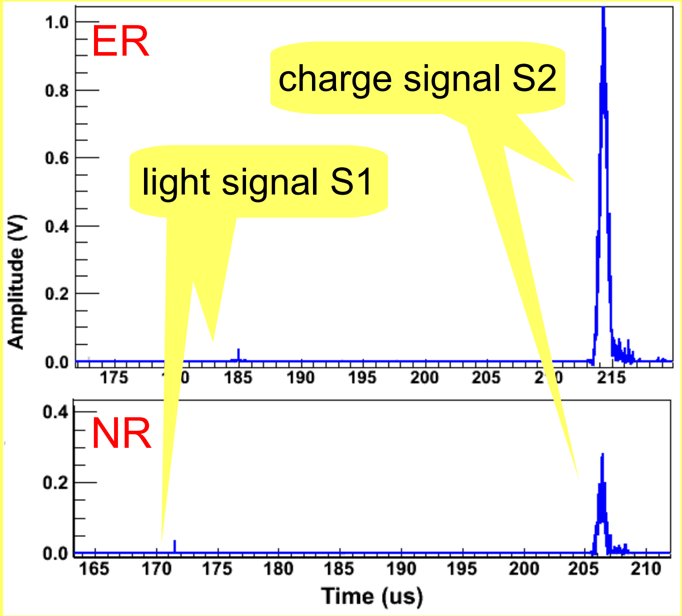
CDMS-II
Discrimination O(10^{-5}),
large acceptance

BUT: „surface events“
→ timing cut



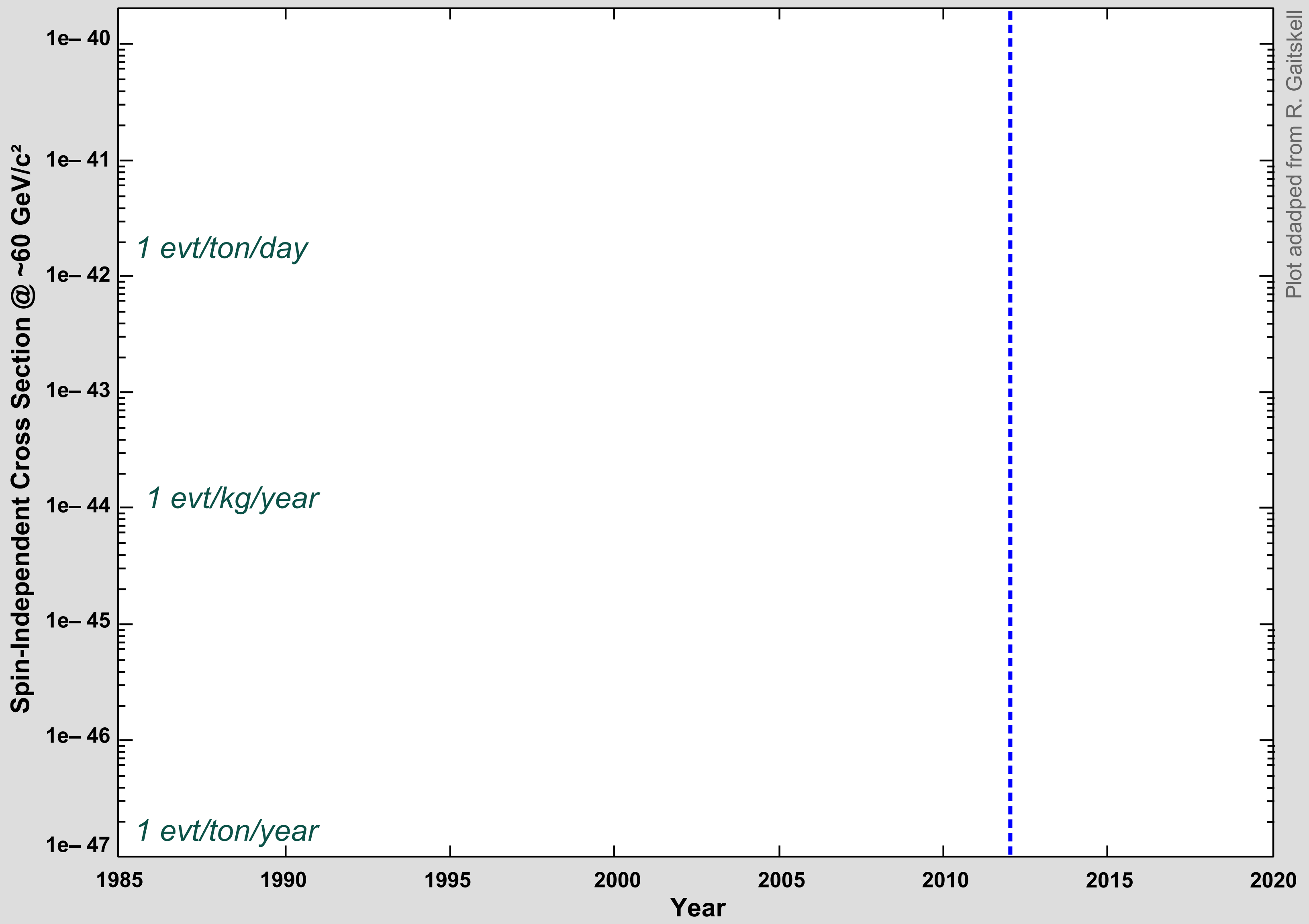


PRL 107, 131302 (2011)



XENON100
~99.5% rejection @ 50% acceptance

WIMP Searches – Evolution



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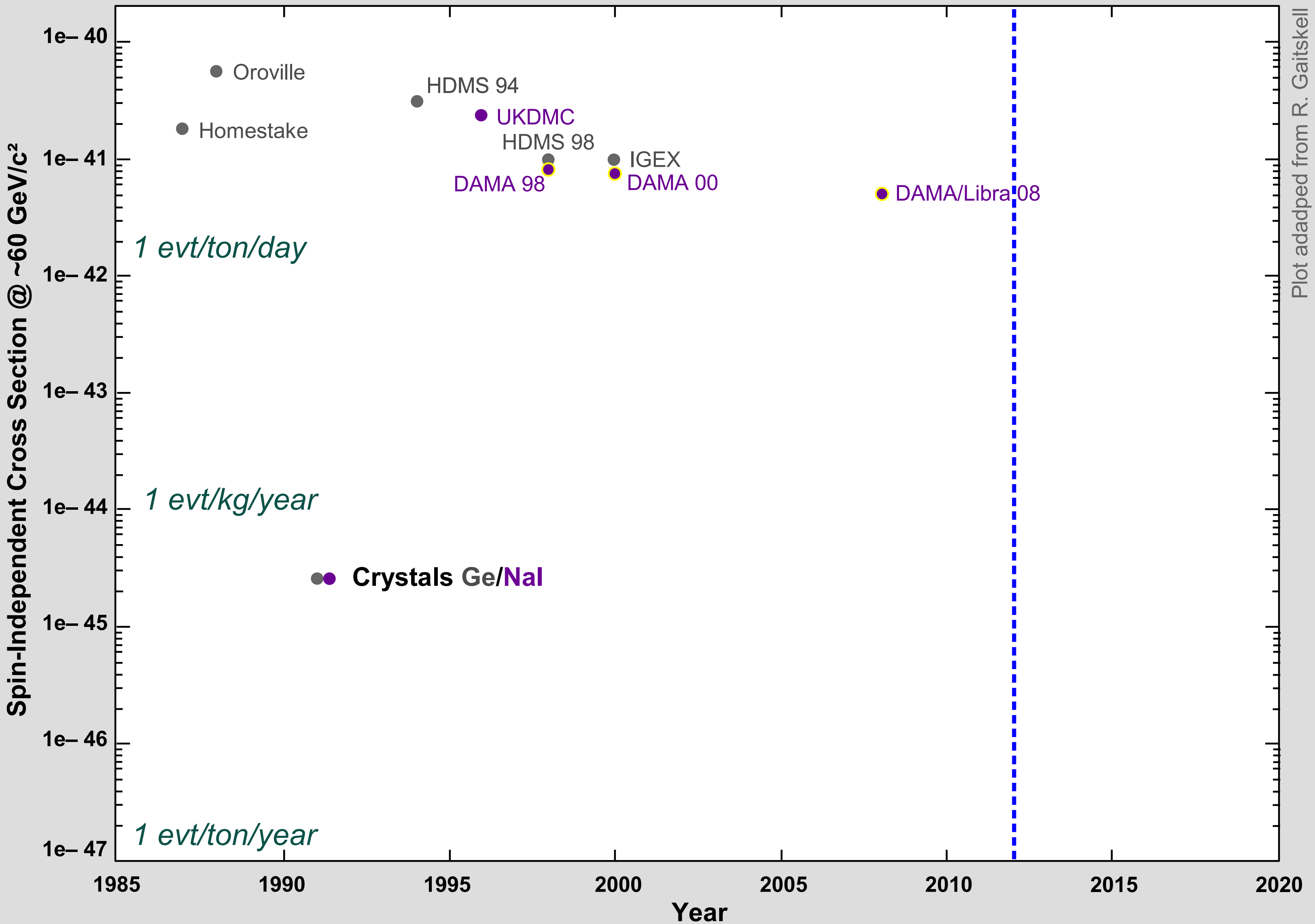

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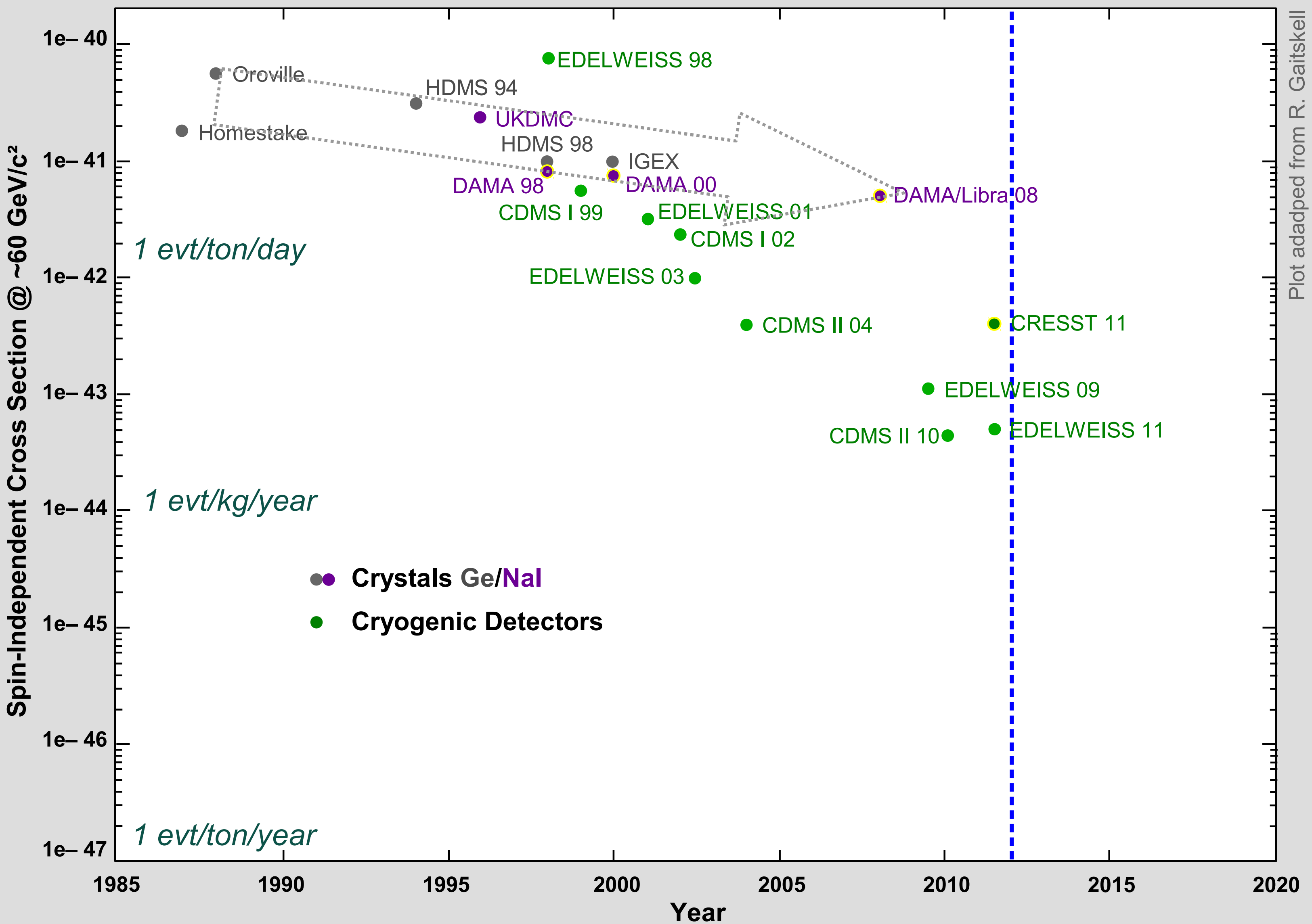

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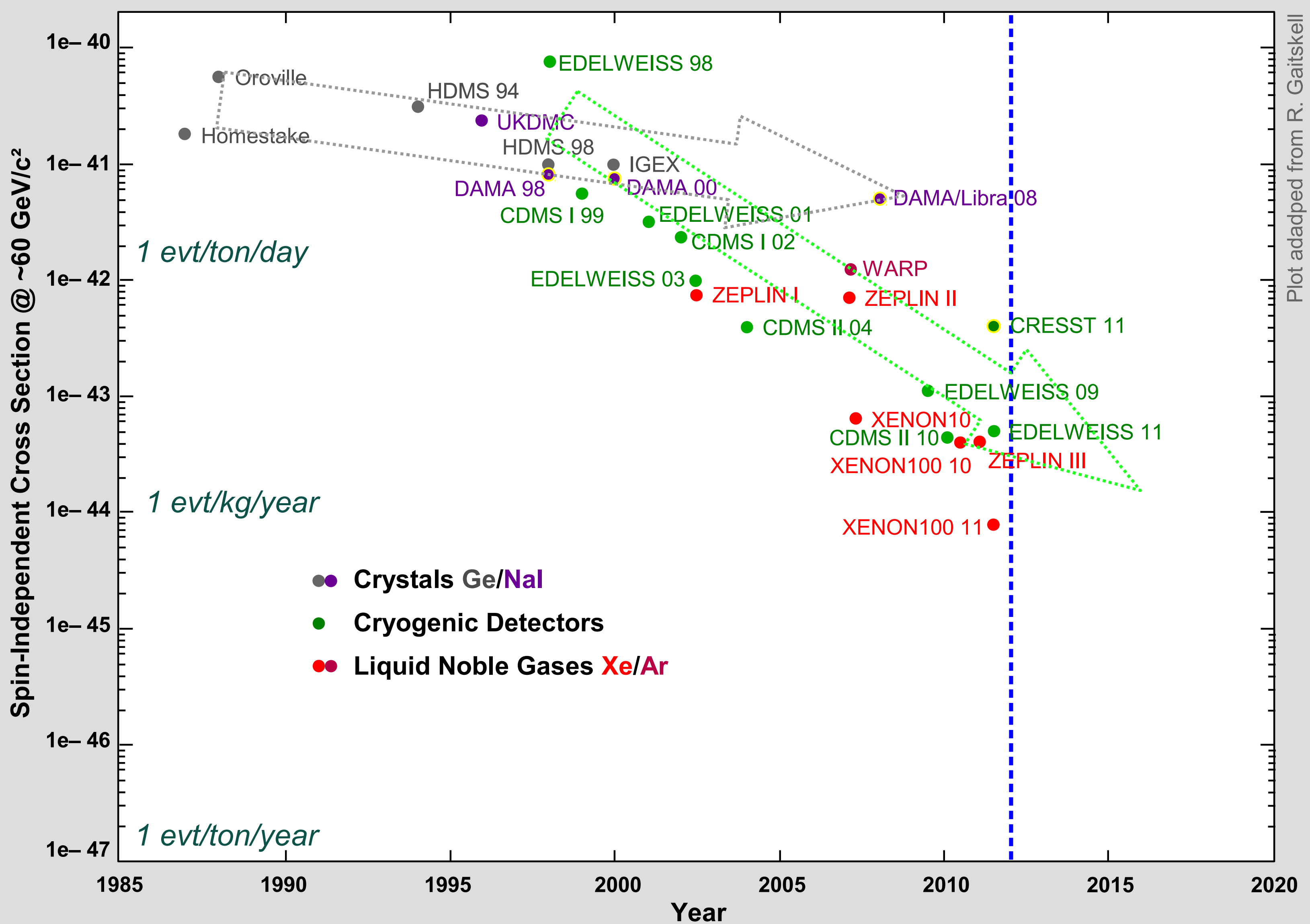

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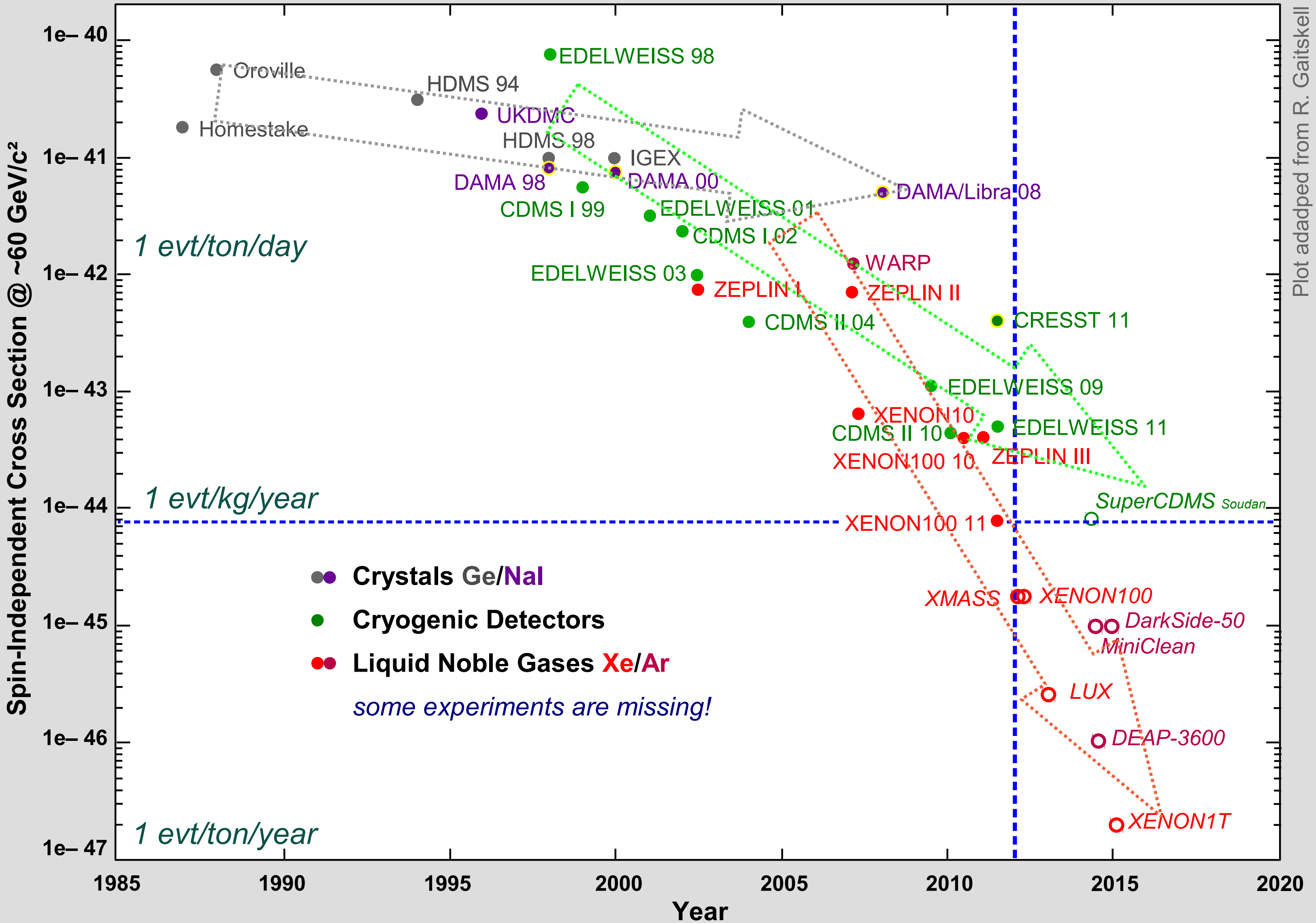
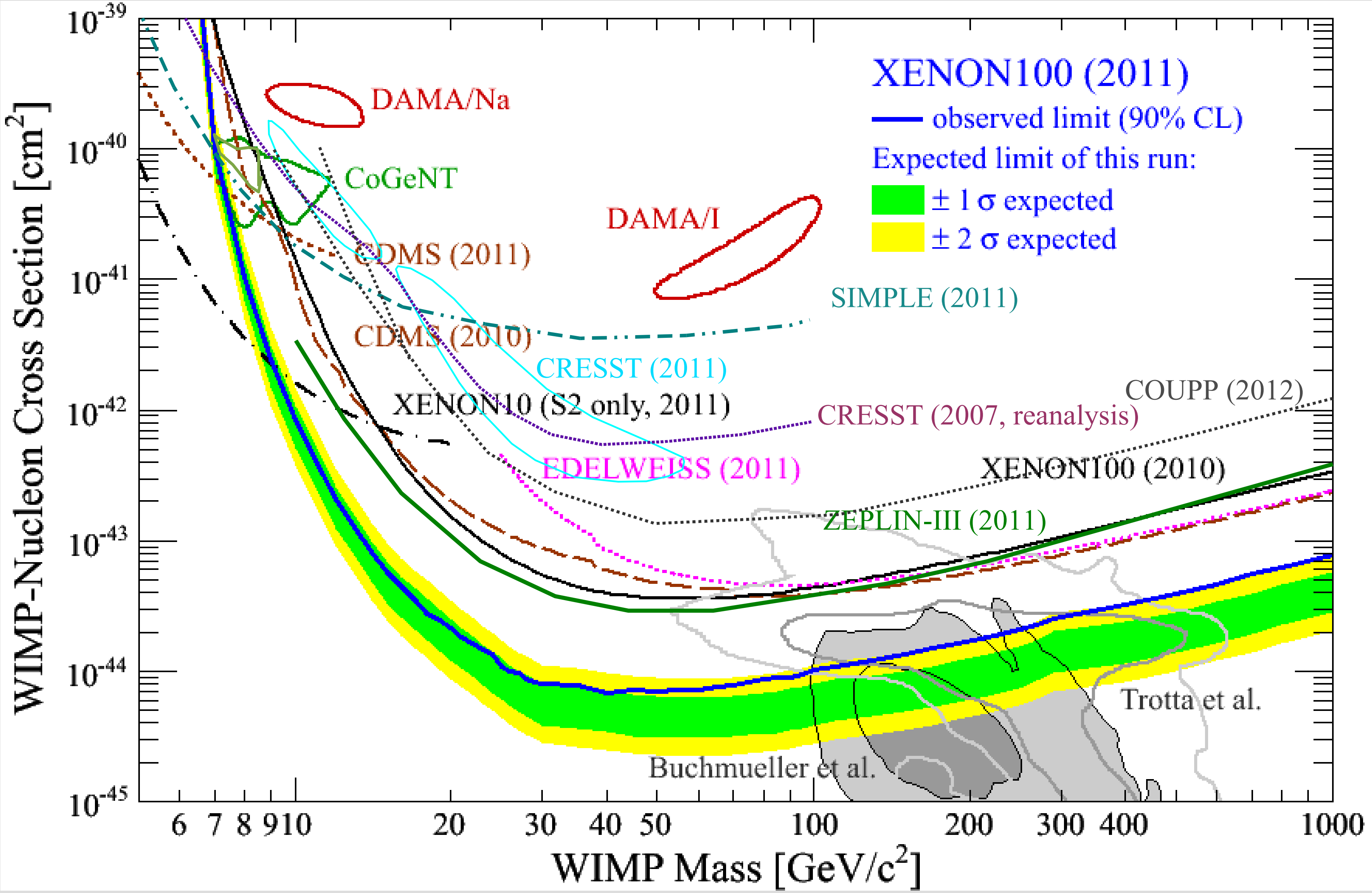


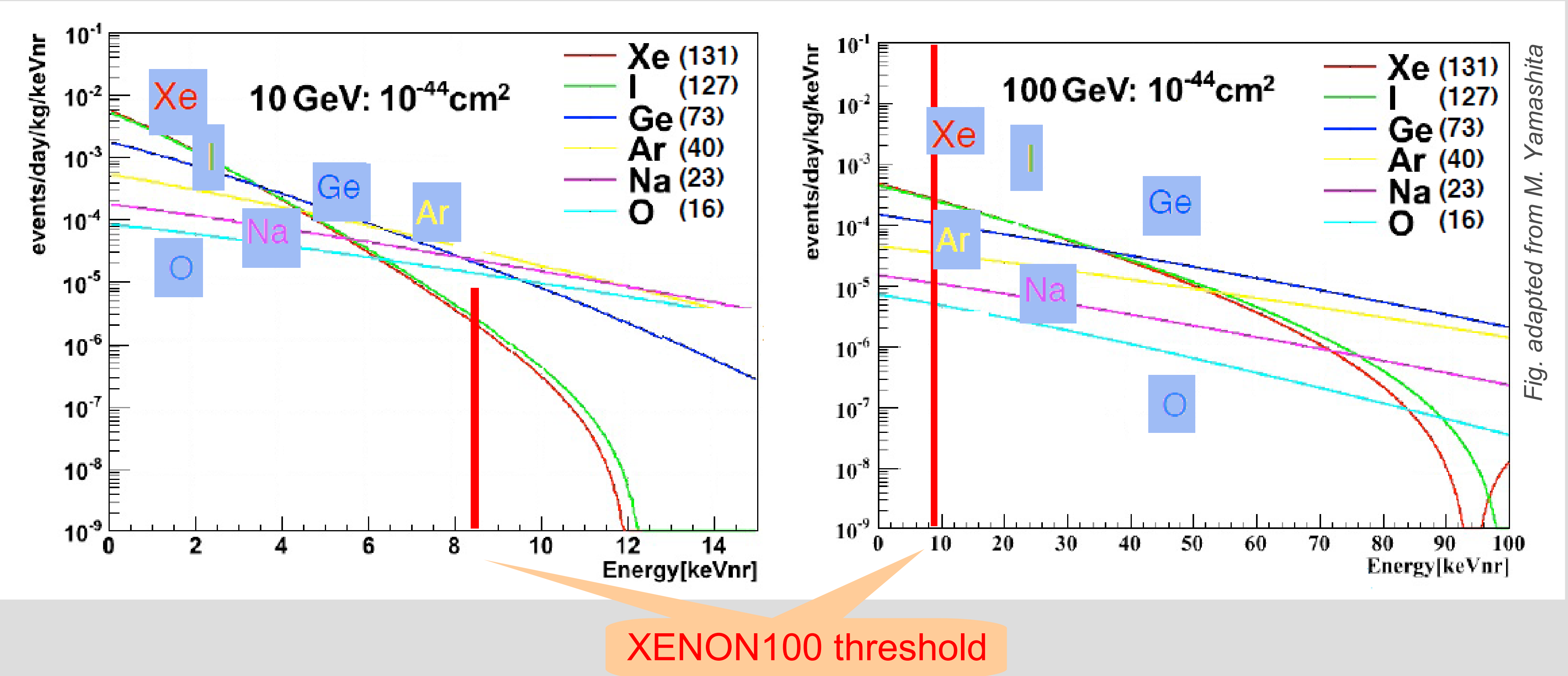
The WIMP Landscape today

→ this talk: focus only on spin-idependent, elastic interactions



some results are missing!

Light and heavy WIMPs



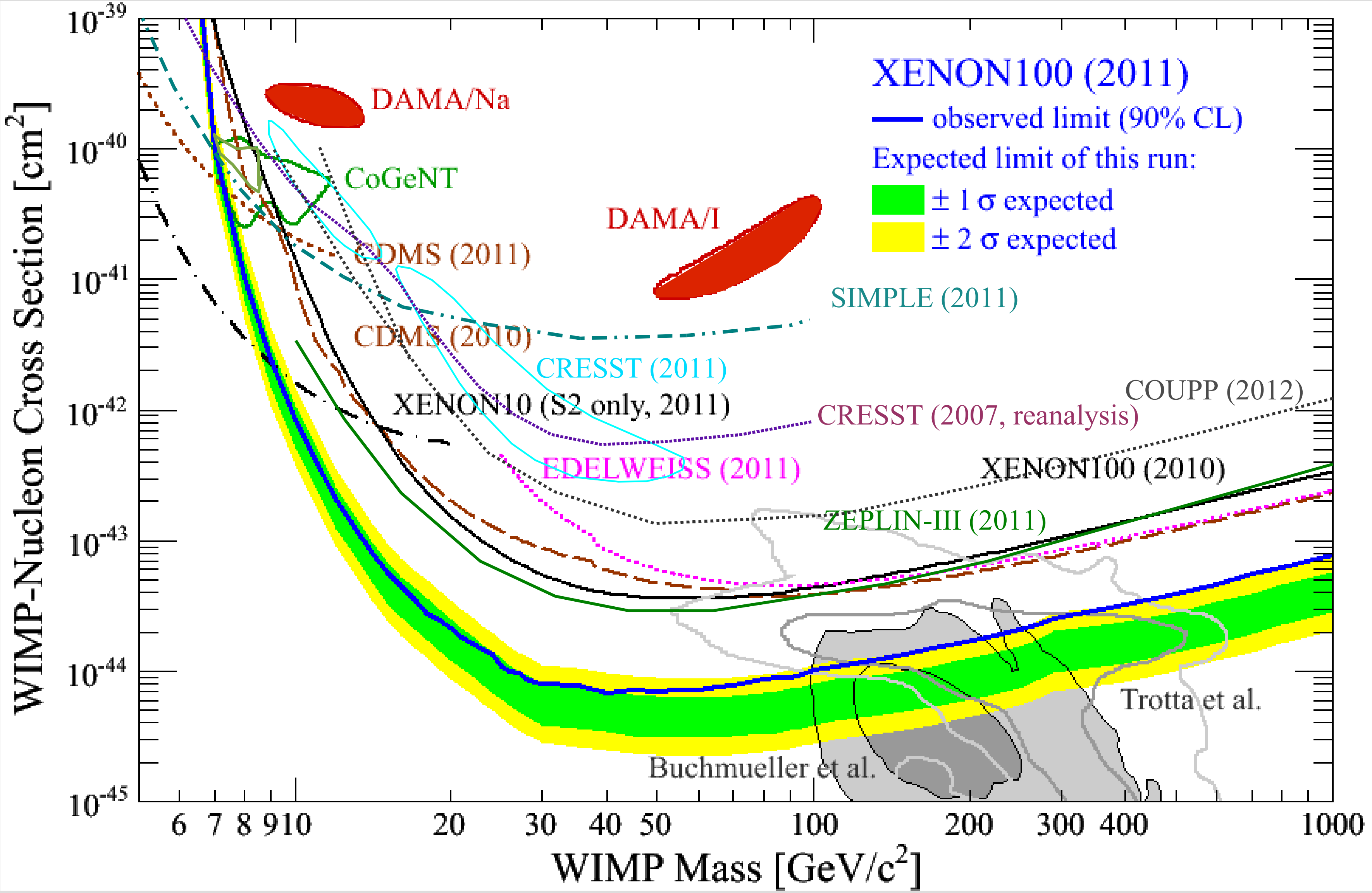
For higher E_{rec}, sensitivity to low mass WIMPs is higher for light targets

→ need low threshold

→ lower sensitivity can be (to some extent) compensated by target mass

(CoGeNT: 0.33 kg, XENON100: 48.0 kg → factor ~150)

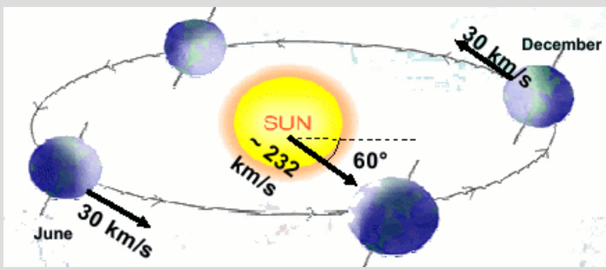
The WIMP Landscape today



some results are missing!

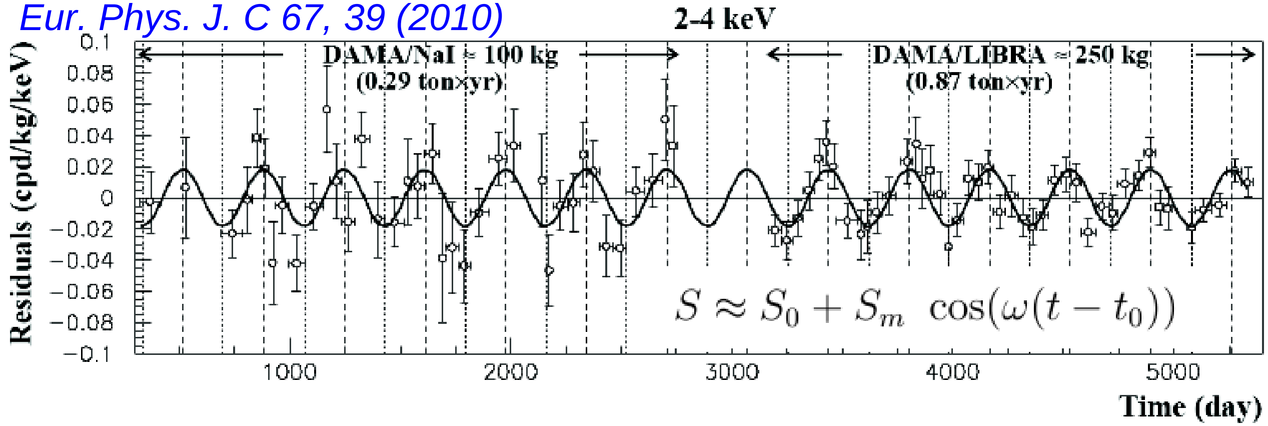
Annual Modulation: DAMA/Libra

- PMTs coupled to **NaI(Tl)** Scintillators @ LNGS
  → extremely clean background necessary
- looks for annual modulation (~3% effect)
- large mass and exposure: 1.17 ton years



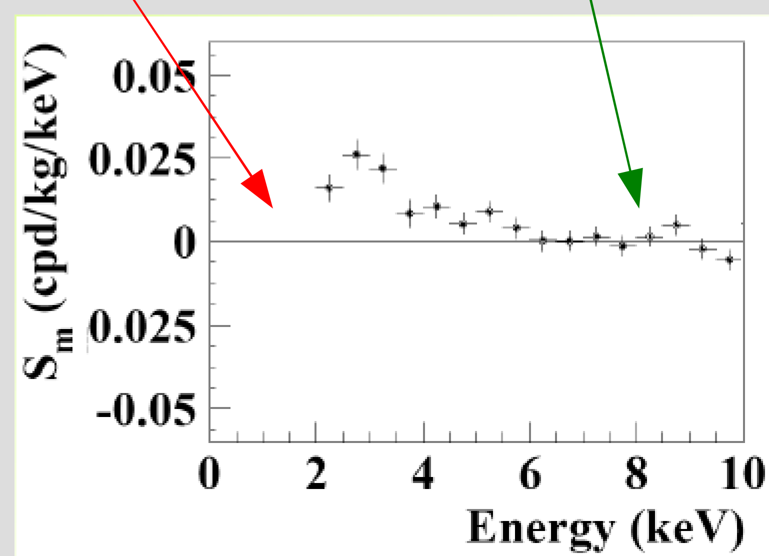
- DAMA finds annual modulation @ 8.8σ C.L.
- BUT: no ER/NR discrimination!

Eur. Phys. J. C 67, 39 (2010)



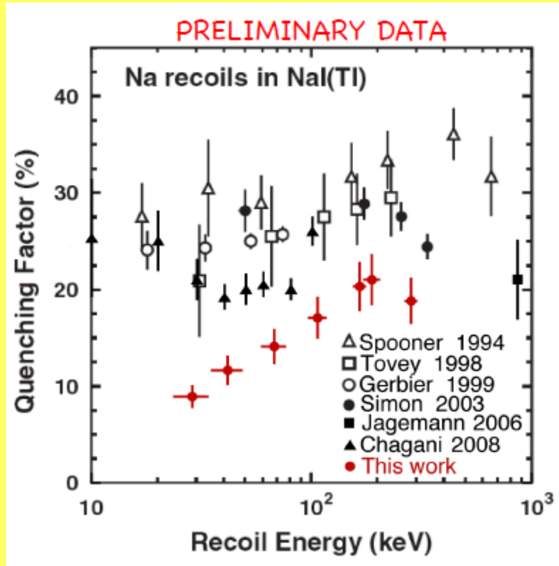
what is here?

no modulation above 6 keV



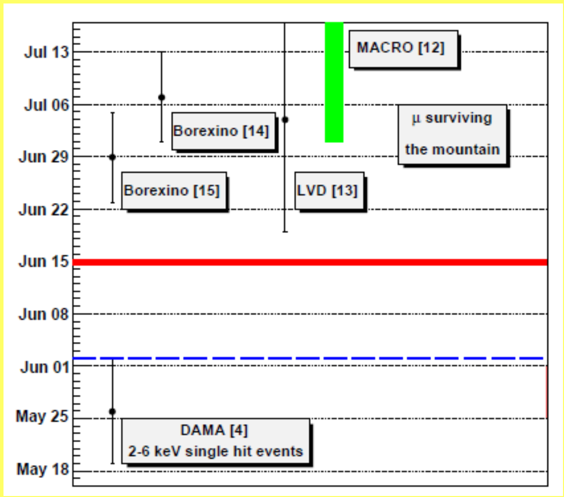
Annual Modulation: DAMA/Libra

NaI quenching factor at low E?
→ relevant for comparison with other experiments



Collar, TAUP2011

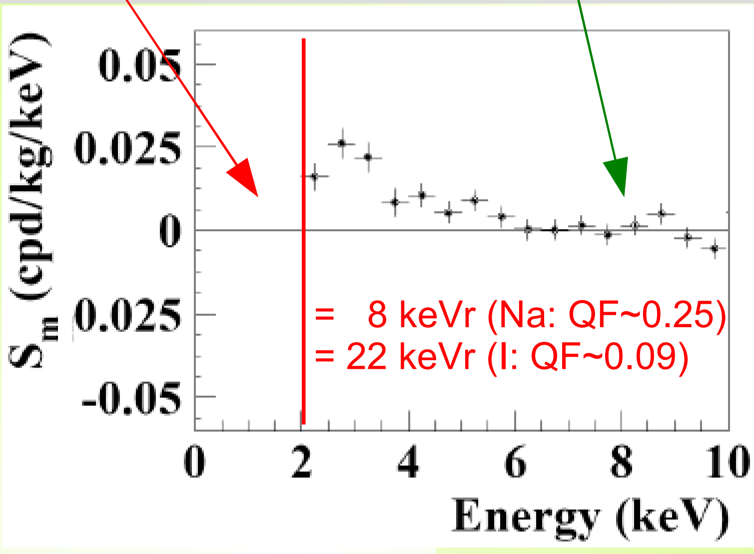
Phase of muon background
→ seems to be different from DAMA modulation



arXiv:1202.4179

what is here?

no modulation above 6 keV

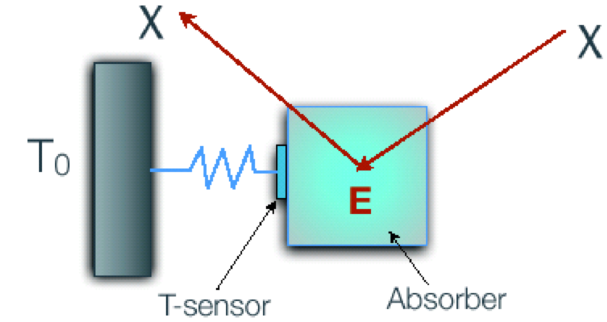


CDMS-II

@ Soudan Lab, Minnesota (USA)

measure charge and heat (phonons):

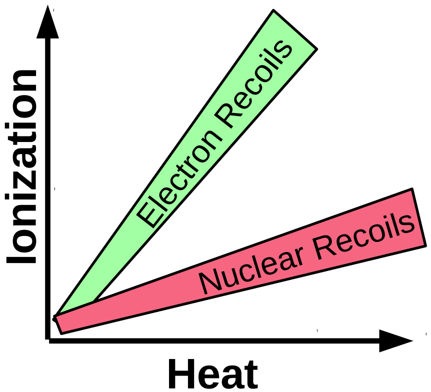
E deposition → temperature rise *ΔT*



Crystals: **Ge**, **Si** cooled to few mK

– low heat capacity

– *ΔT* ~ µK



Very good discrimination

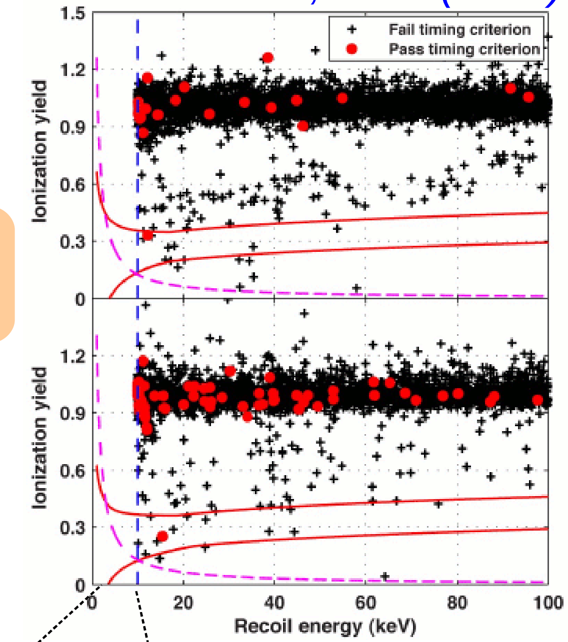
→ BUT: reject surface events via timing

similar: EDELWEISS (F)

Latest Results

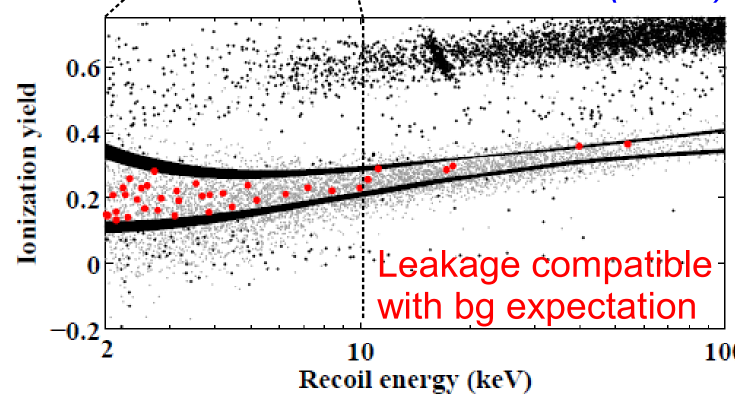
Science 327, 1619 (2010)

Standard Analysis

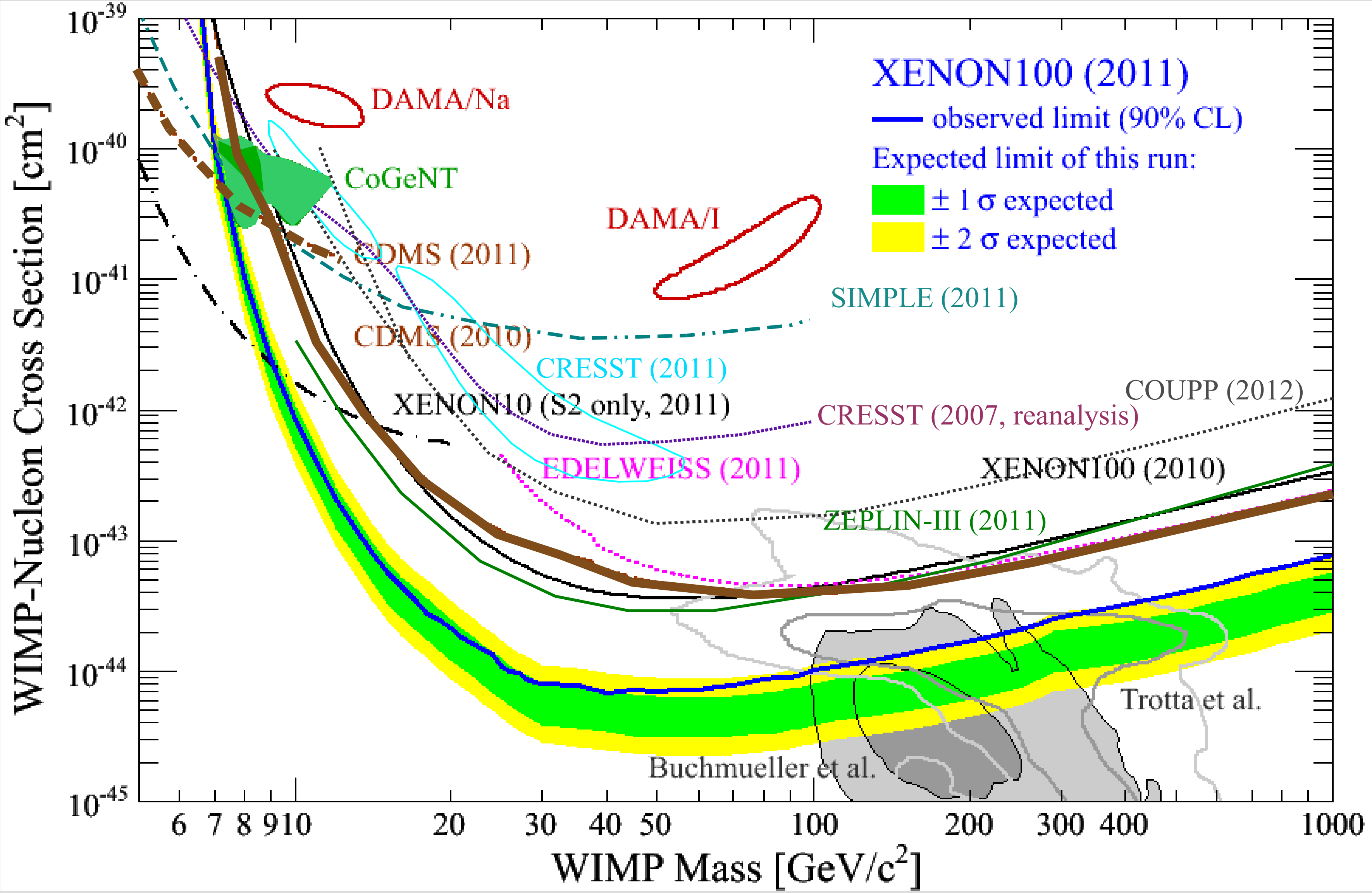


Low Threshold

PRL 106, 131302 (2011)



The WIMP Landscape today

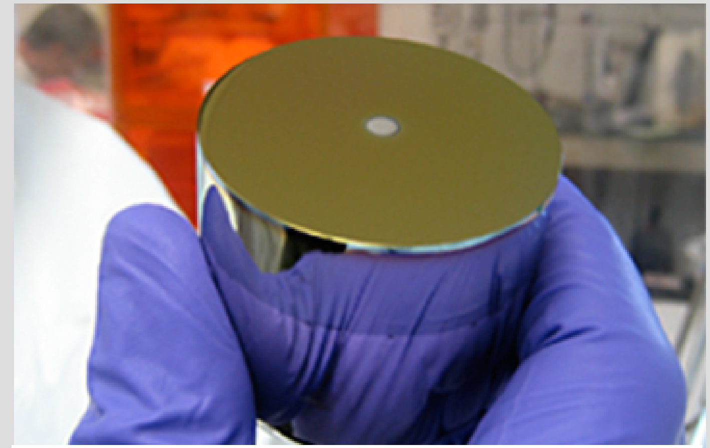


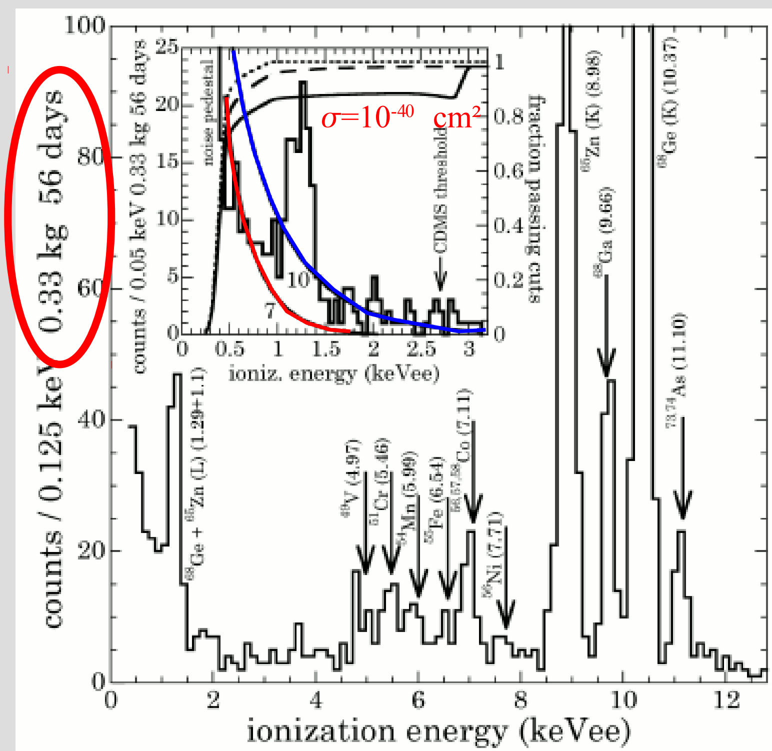
some results are missing!

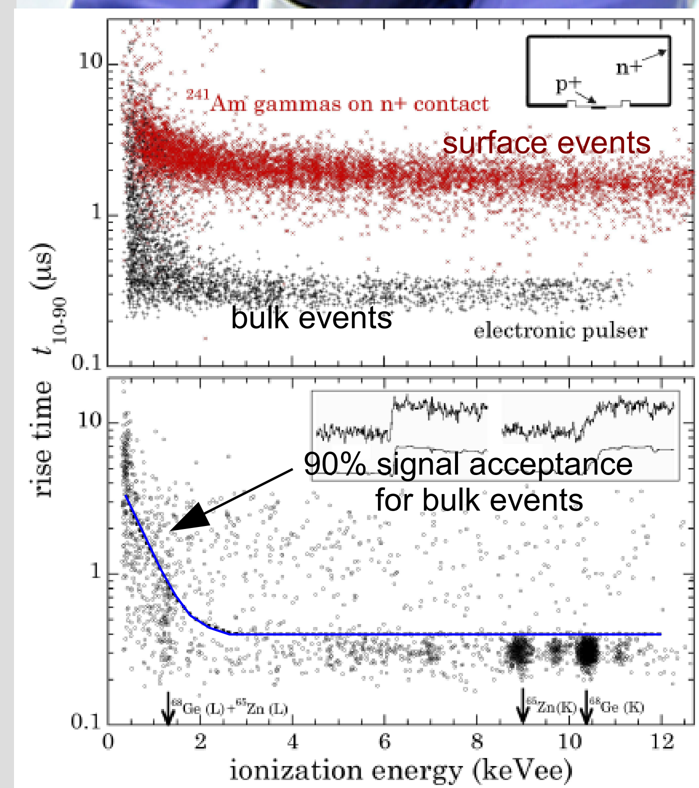
CoGeNT

PRL 106, 131301 (2011)

- p-type point contact **Ge-detector**, ultra low noise, very low threshold: 0.4 keVee
- underground @ Soudan
- no ER/NR discrimination, reduce surface events by risetime cut
- excess at lowest energies



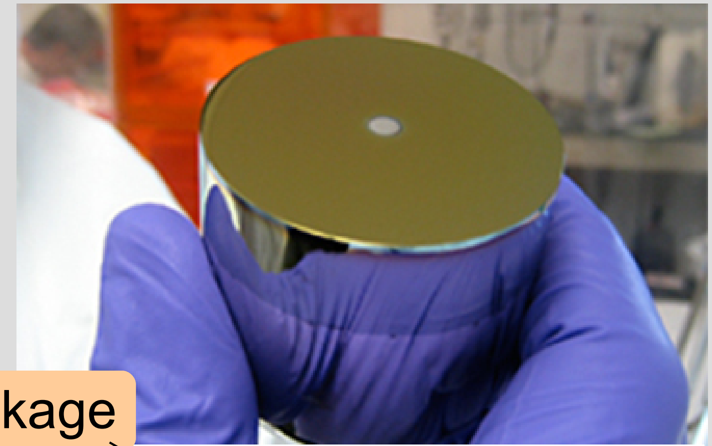


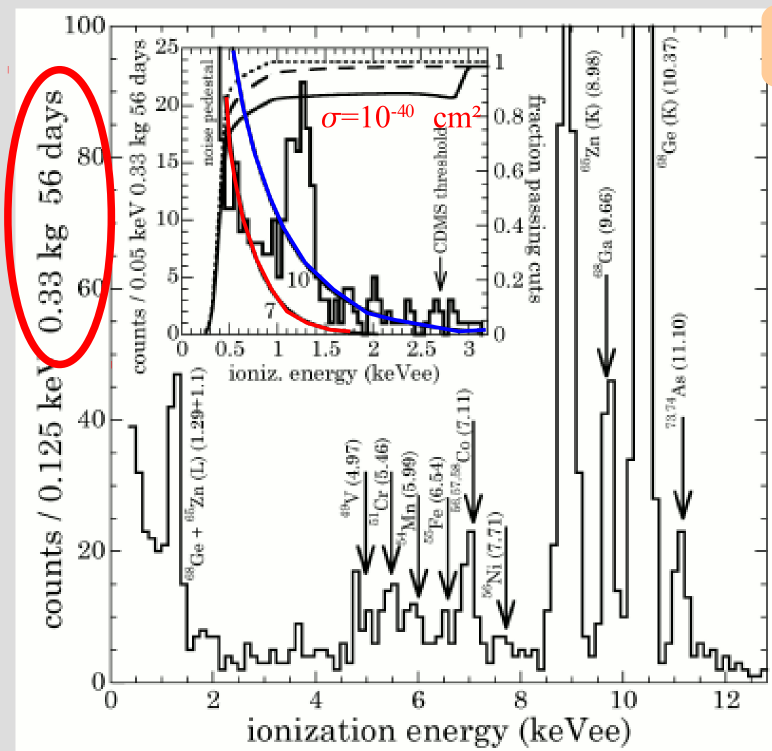


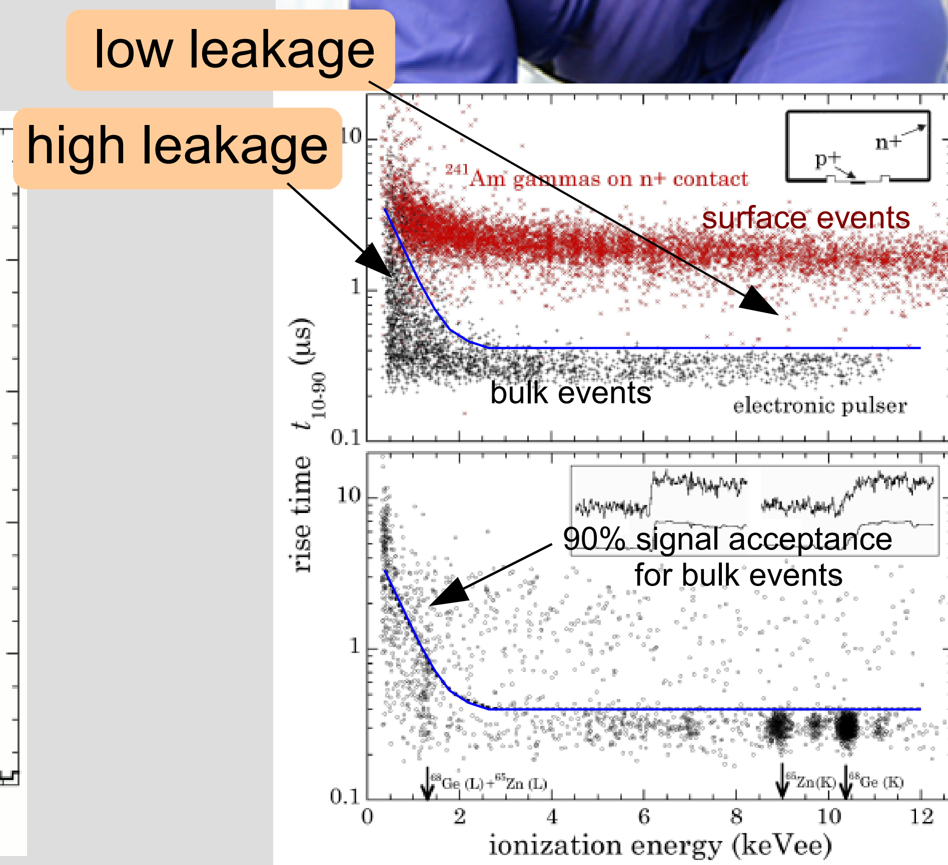
CoGeNT

PRL 106, 131301 (2011)

- p-type point contact **Ge-detector**,
  ultra low noise, very low threshold: 0.4 keVee
- underground @ Soudan
- no ER/NR discrimination,
  reduce surface events by risetime cut
- excess at lowest energies







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PRL 106, 131301 (2011)

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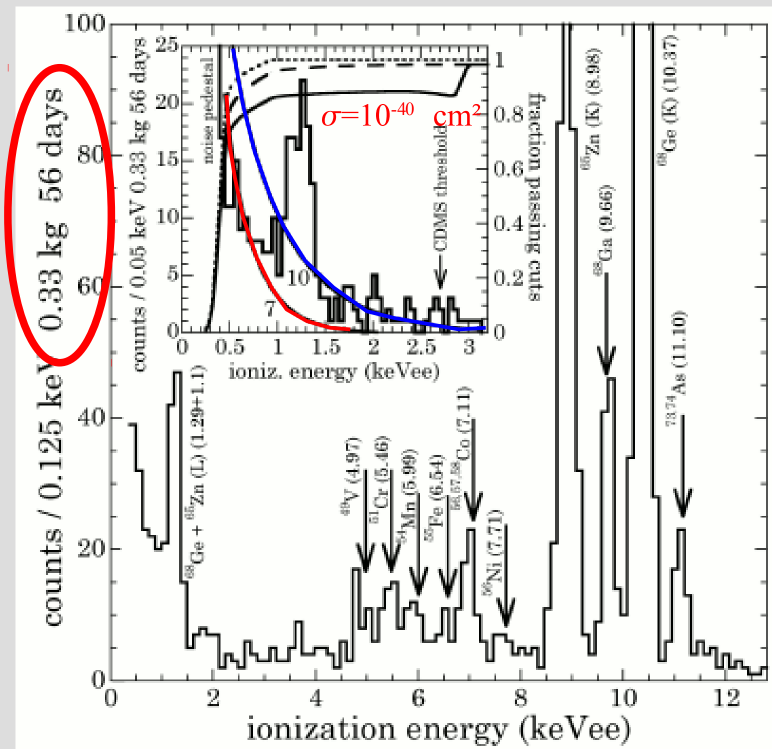
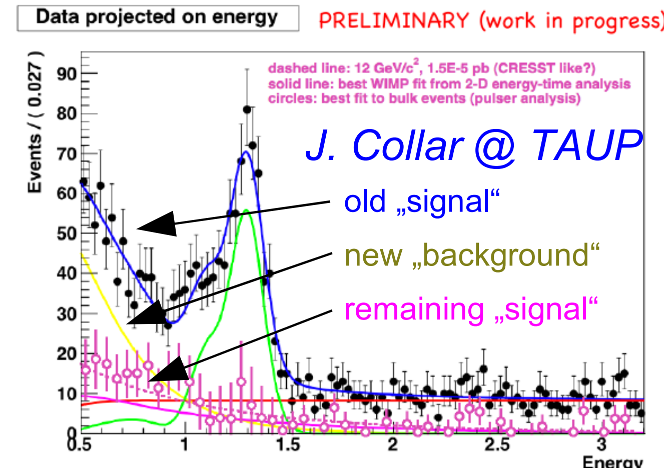
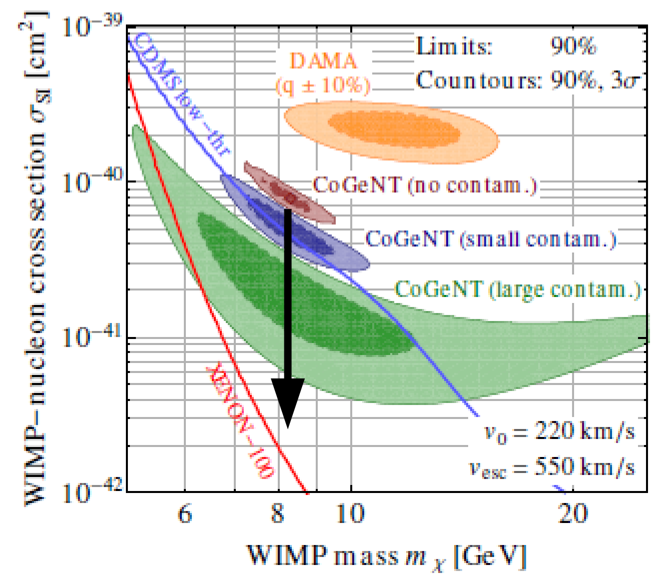


Recent CoGeNT news:



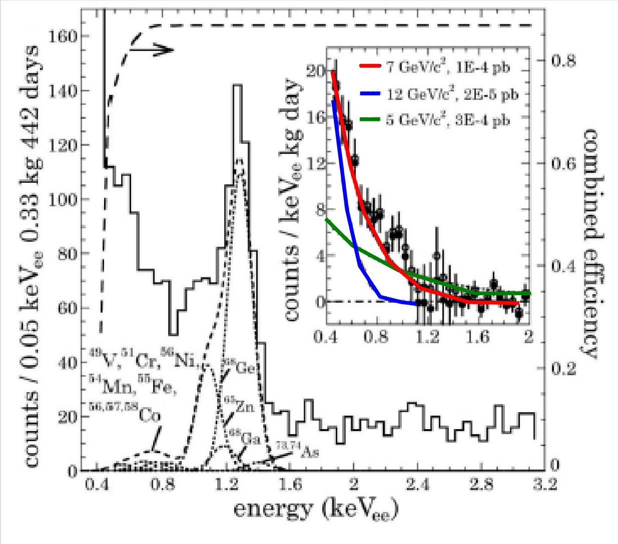


Kopp, Schwetz, Zupan, arXiv:1110.2721
Kelso, Hooper, Buckley, arXiv:1110.5338

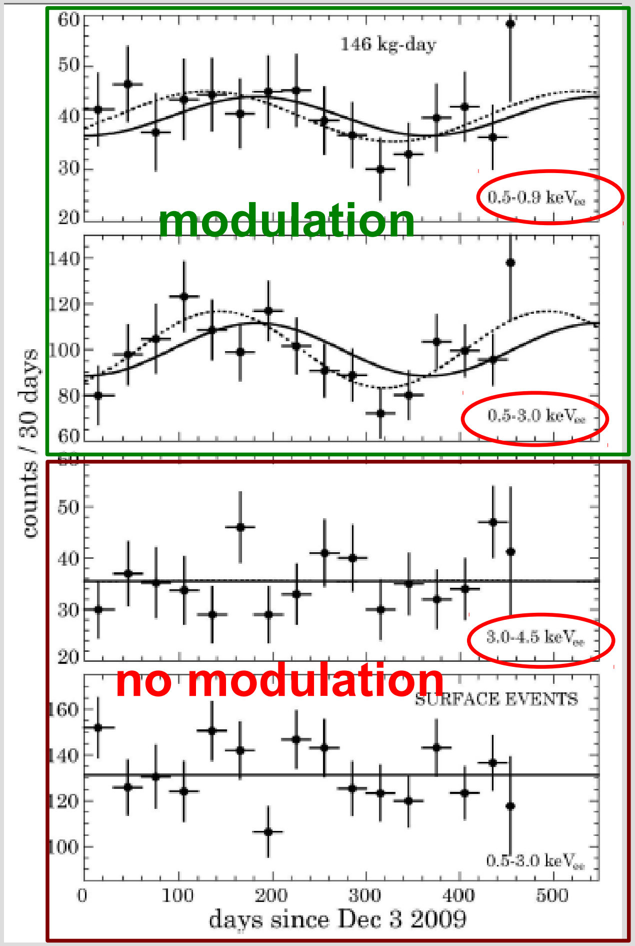
CoGeNT annual modulation

PRL 107, 141301 (2011)

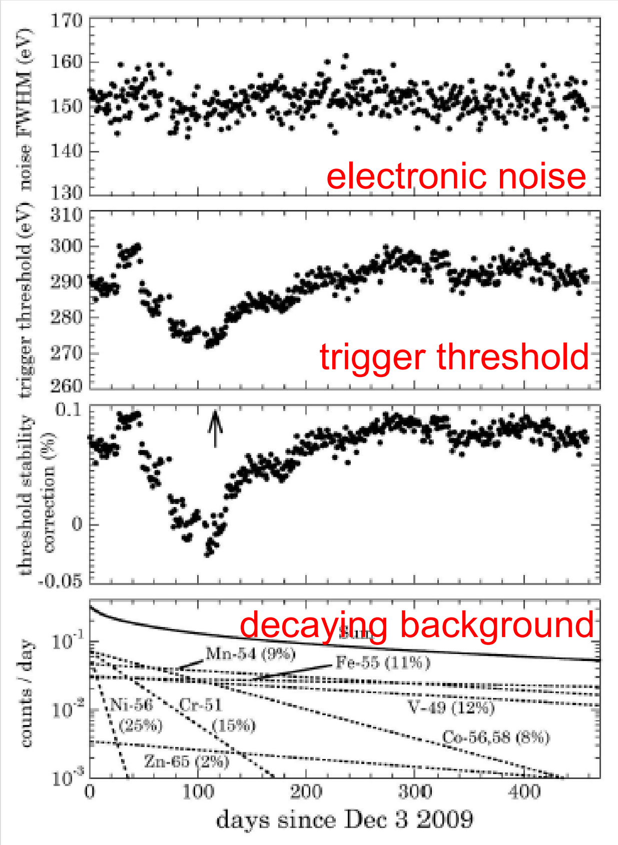
Spectrum:



Rate vs Time::



Stability:



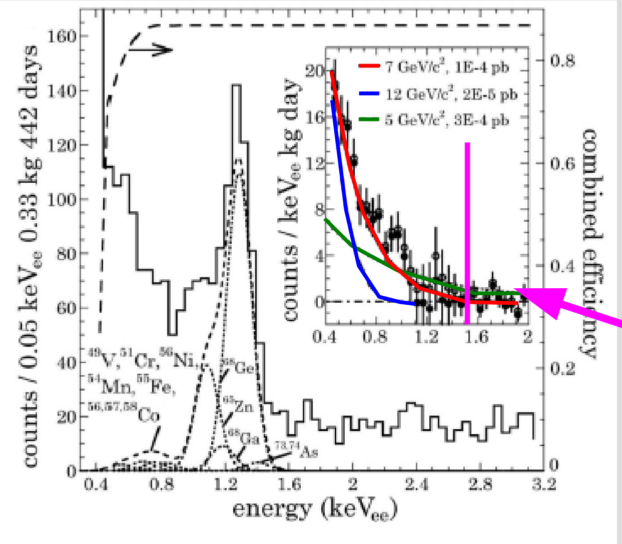
clear modulation in 15 months data
modulation up to 3 keVee (~10 keVr)

CoGeNT stability not yet demonstated with DAMA standards

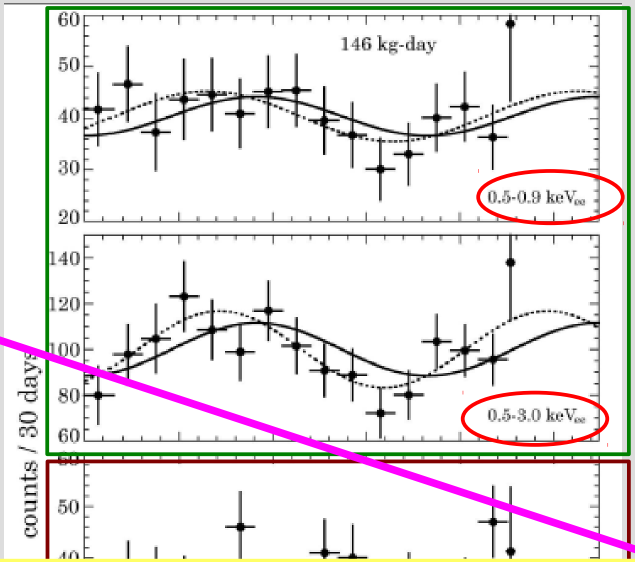
CoGeNT annual modulation

PRL 107, 141301 (2011)

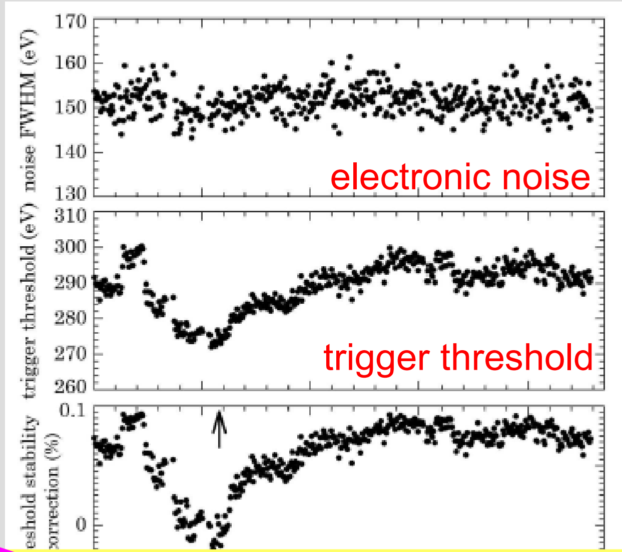
Spectrum:



Rate vs Time::



Stability:



Observations regarding the modulation

e.g. Fox et al, arXiv:1107.0717, also others...

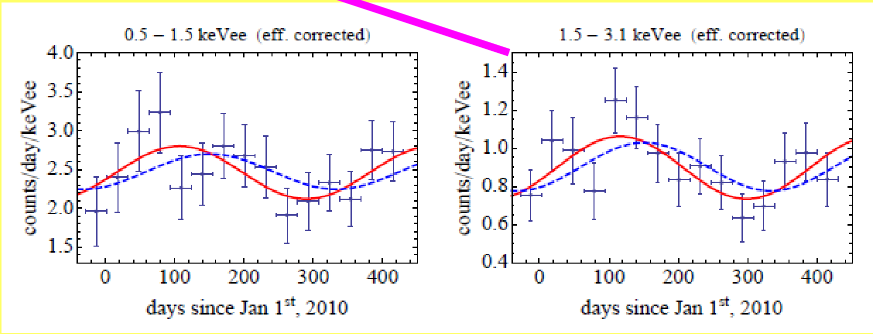
there is a modulation

there is a significant component >1.5 keV

modulation not well explained by standard Maxwellian DM halo

XENON100 should have seen 10-30 events

CDMS-II should see O(1) modulation

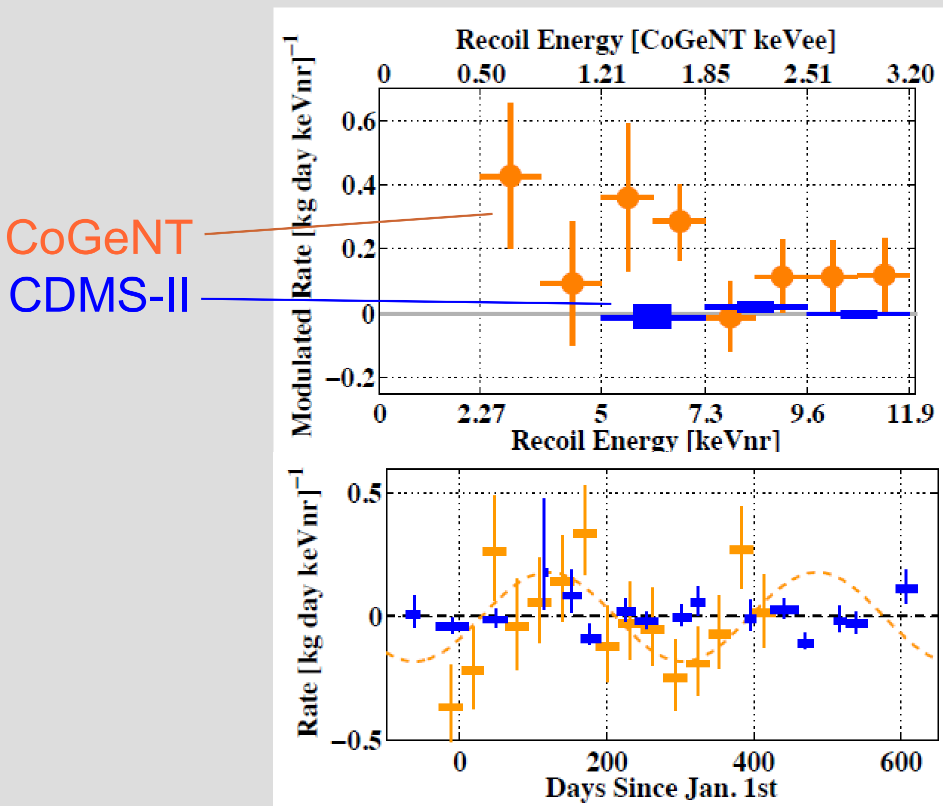


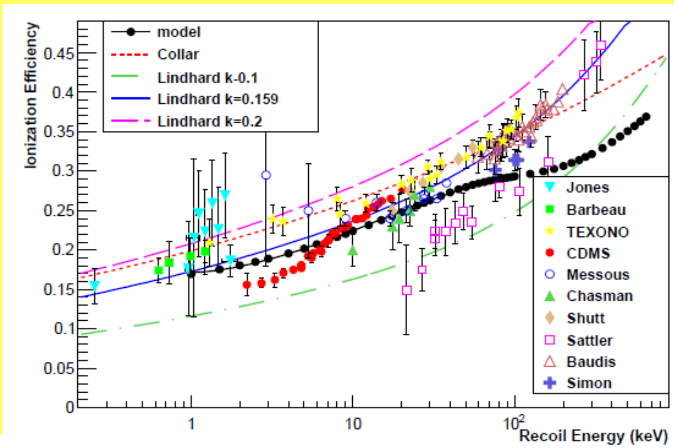
arXiv:1107.0717

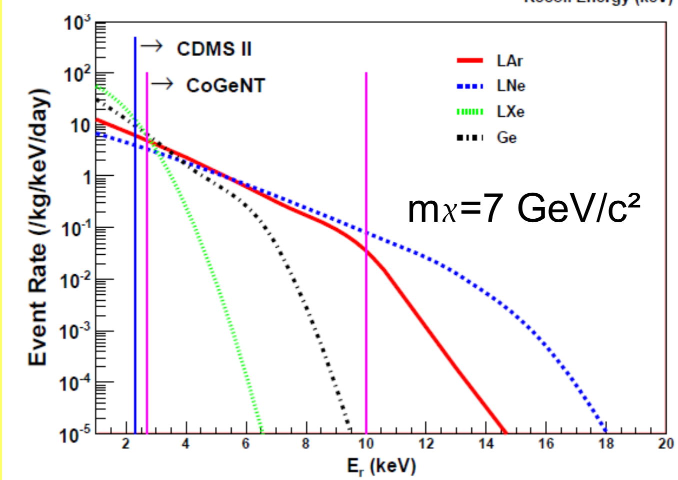
CDMS Annual Modulation

arXiv:1203.1309

- annual modulation analysis on NR data (with discrimination!)
- No modulation is found: <0.06 evt/keVnr kg day in 5-11.9 keVnr at 99% CL
- Inconsistent with CoGeNT in 1.2-3.2 keVee range at 98% CL



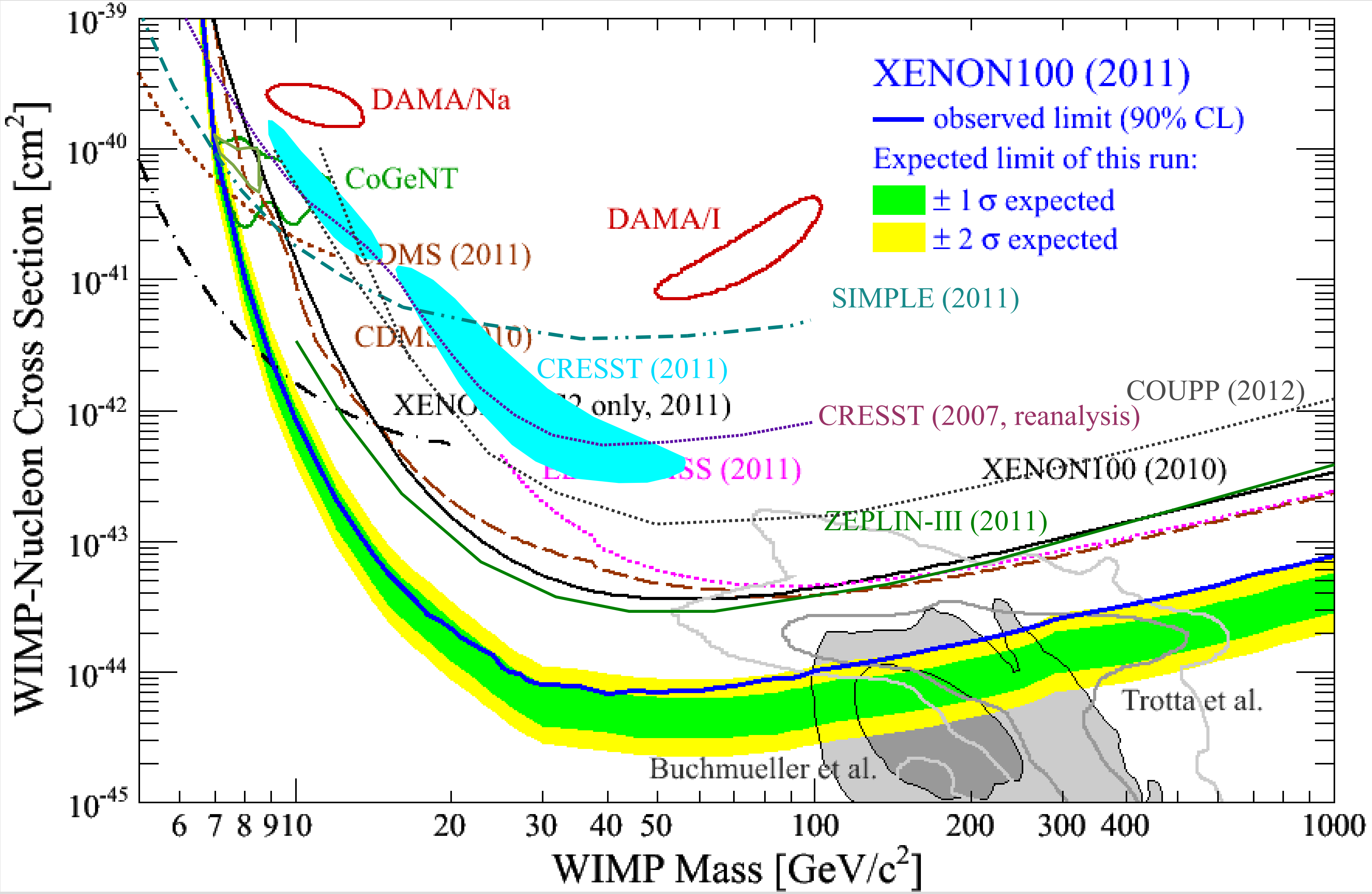




A recent re-assesment of the low *E* quenching factor of Ge suggests that the whole CoGeNT region is covered by CDMS-II.

Barker, Mei: arXiv: 1203.4620

The WIMP Landscape today



some results are missing!

CRESST-II

Eur.Phys.J. C72 (2012) 1971

scintillating **$CaWO_4$ crystals**

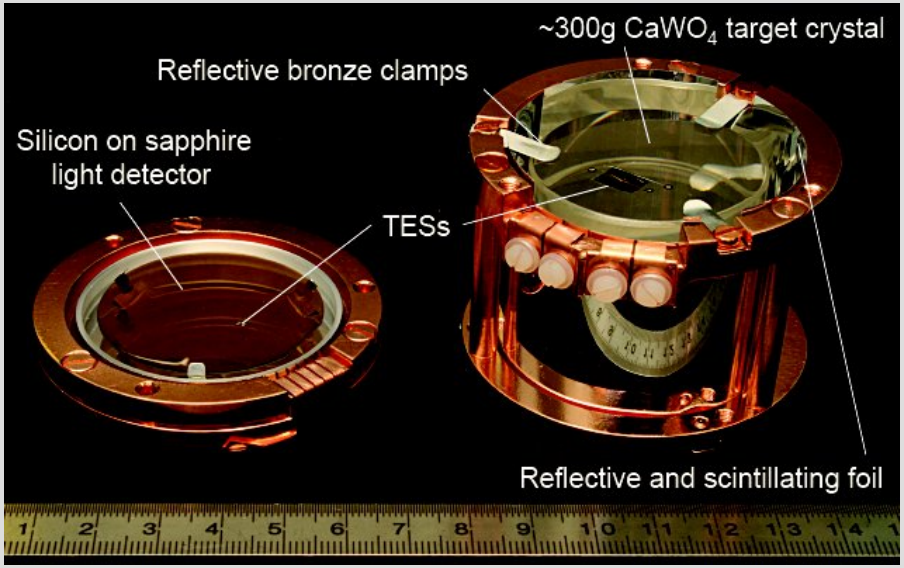
detect light (silicon on sapphire+TES) and phonons (TES)

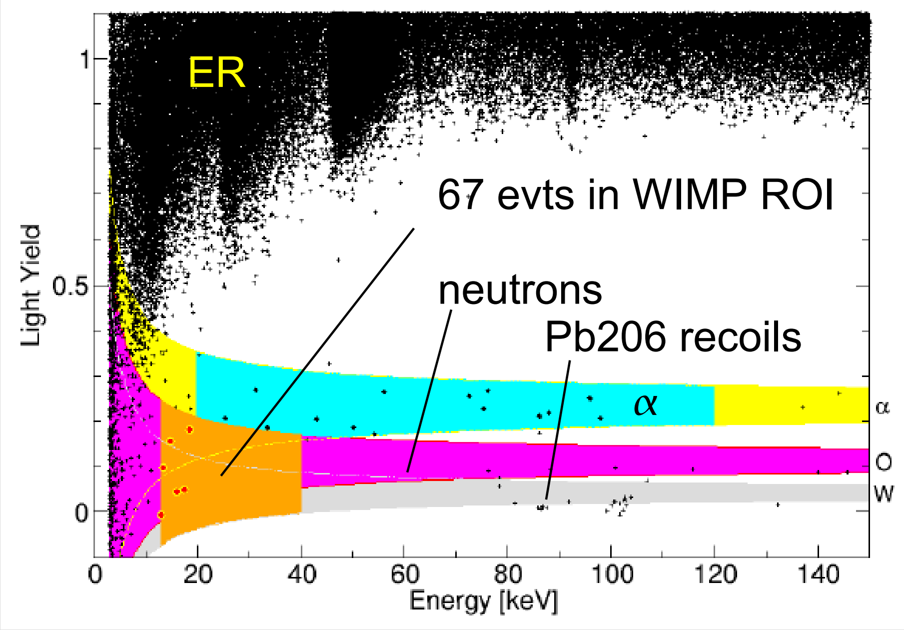
multi-target approach

excellent n-γ discrimination

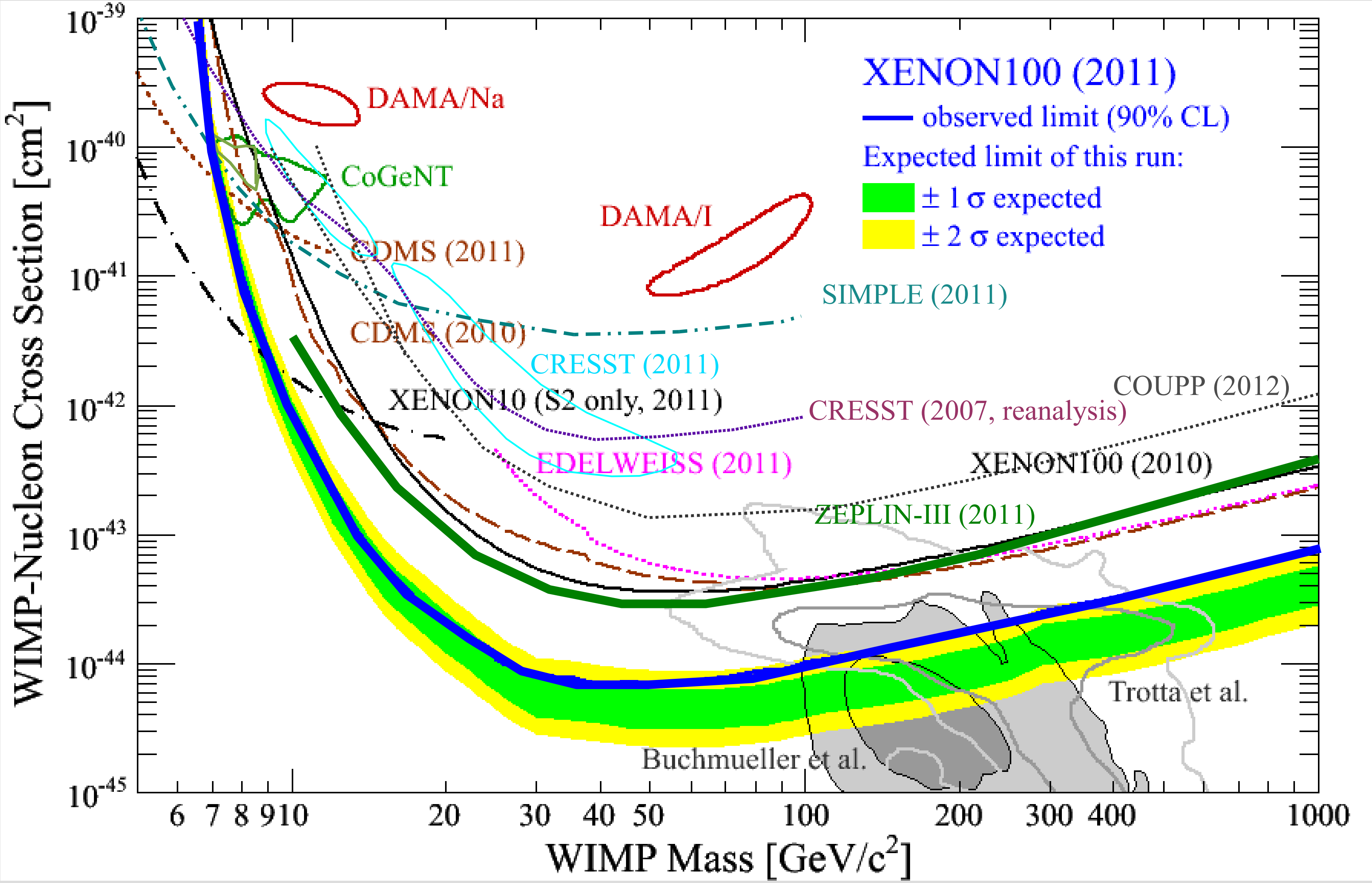
730 kg $\times$ d exposure published in 2011
→ rather large background
→ new run in 2012 to reduce bg

	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]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$



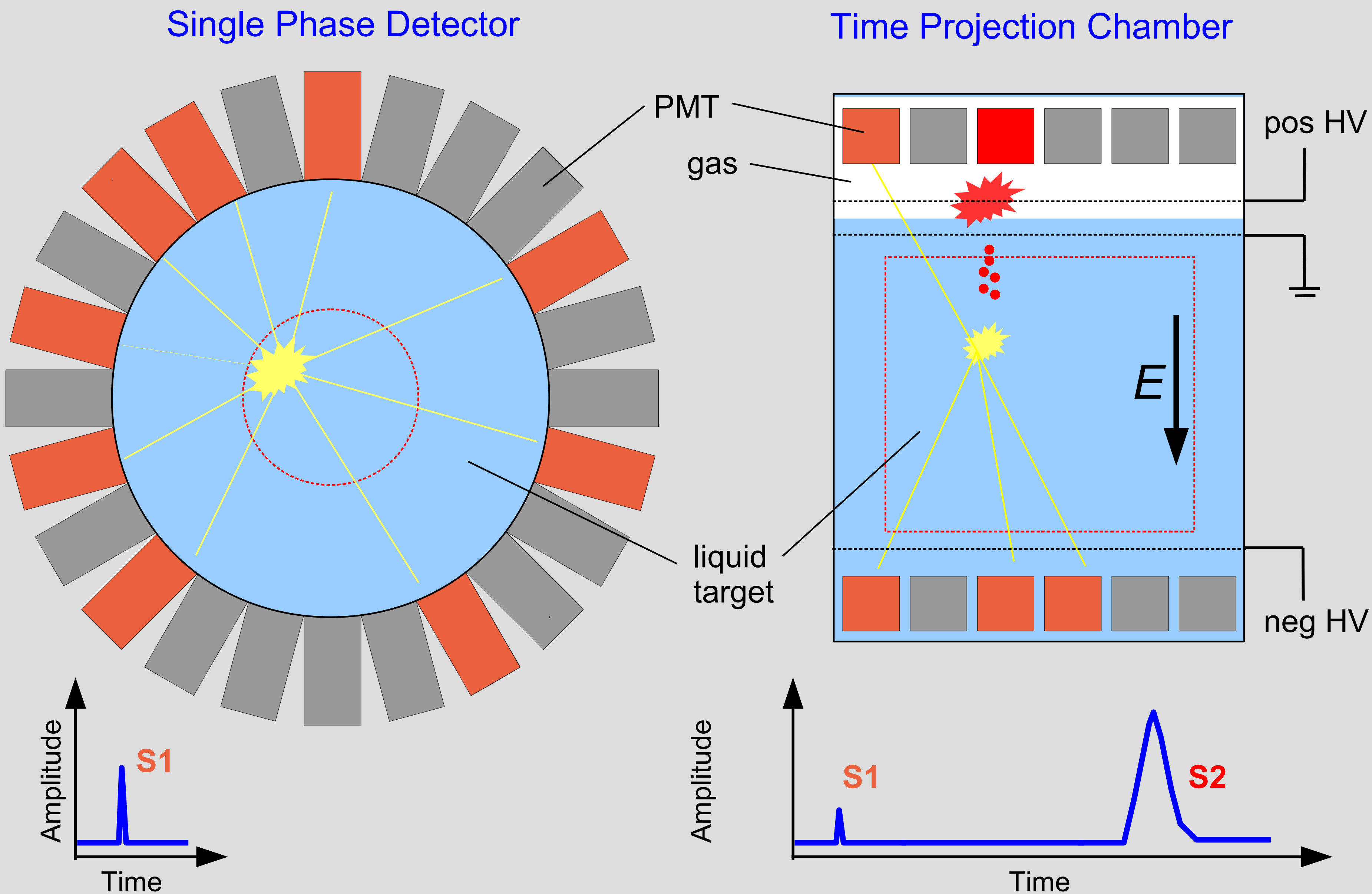


The WIMP Landscape today



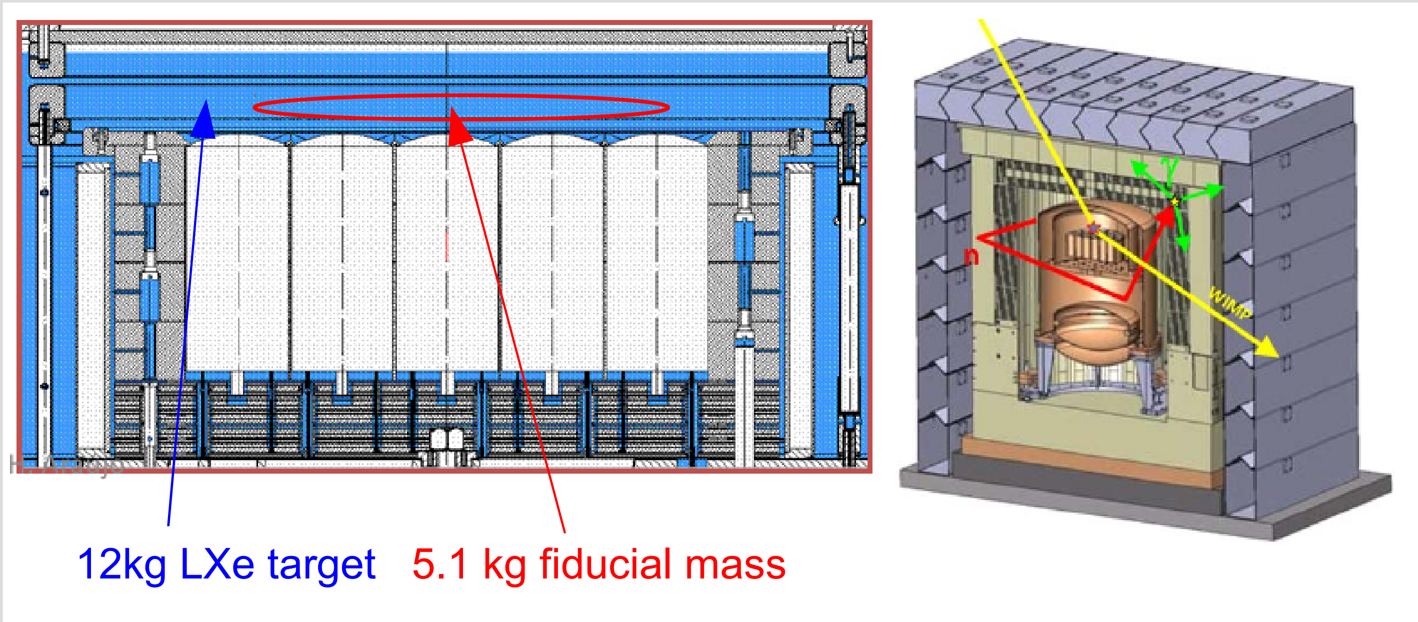
some results are missing!

Liquid Noble Gases: Detector Concepts

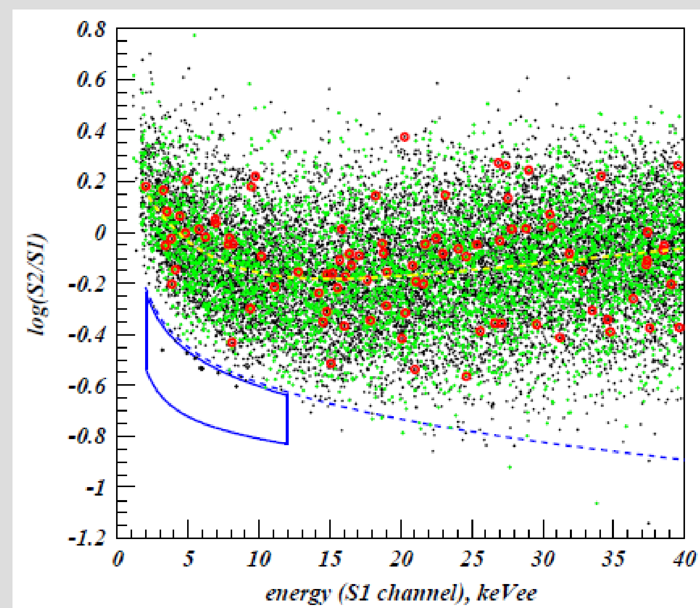


ZEPLIN III

PLB 709, 14 (2012)



- **LXe** dual phase detector
- was operated at Boulby mine (UK)
- science run 2011:
  1344 kg x days raw exposure
  8 events observed in the ROI (7-29 keVr)
  → compatible with background expectation
- ZEPLIN program has come to an end

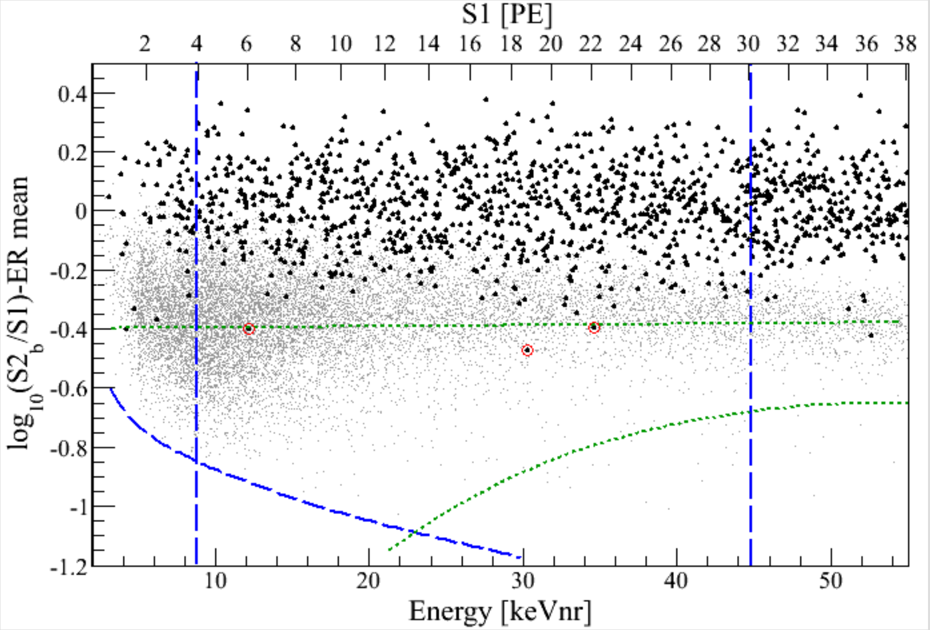


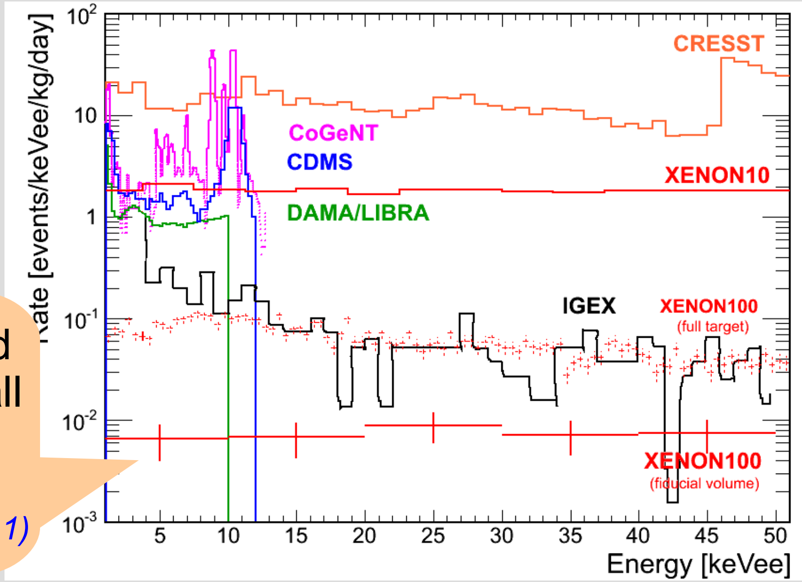
XENON100

PRL 107, 131302 (2011)

Quick Facts

- 62 kg **LXe** target
- Dual phase TPC
- active LXe veto
- 242 PMTs
- running @ LNGS (IT)





lowest published background of all running DM experiments
PRD 83, 082001 (2011)

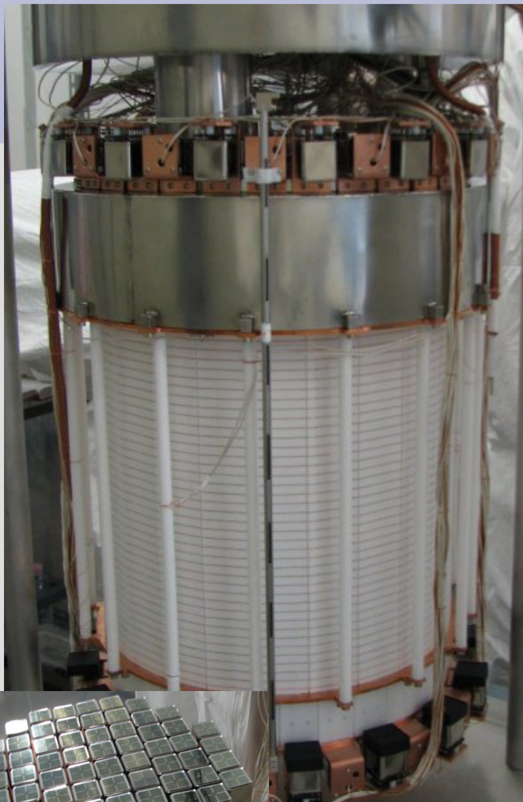
Last science run:

4800 kg x d raw exposure
1471 kg x d acpt. corrected (100 GeV/c²)

3 events observed
→ fully compatible with background
→ best WIMP limit over large mass range

XENON100

PRL 107, 131302 (2011)



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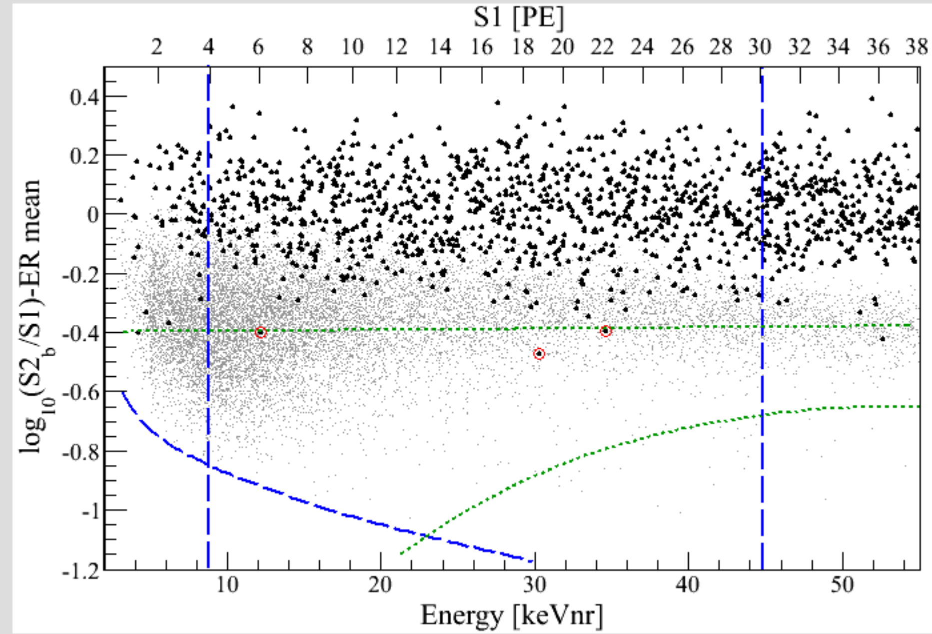

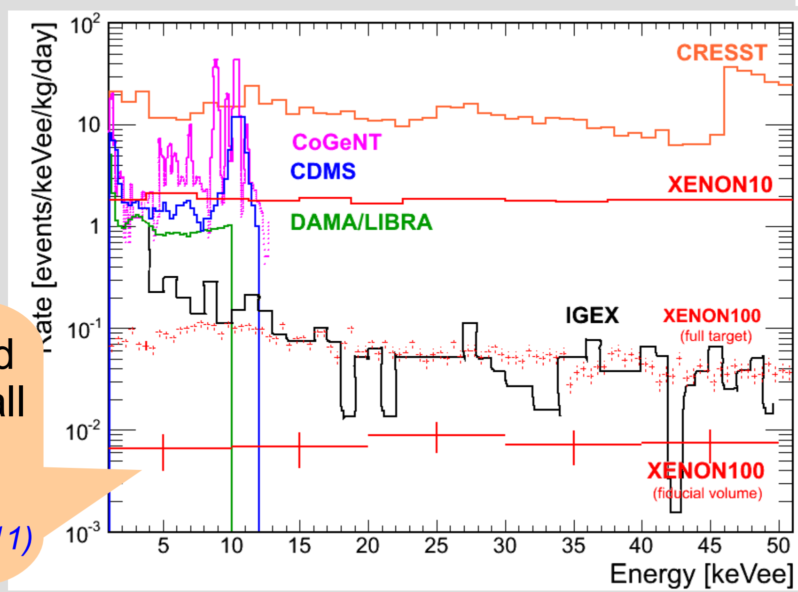

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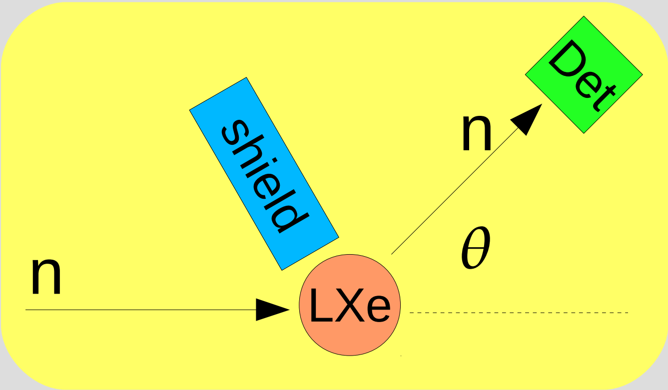
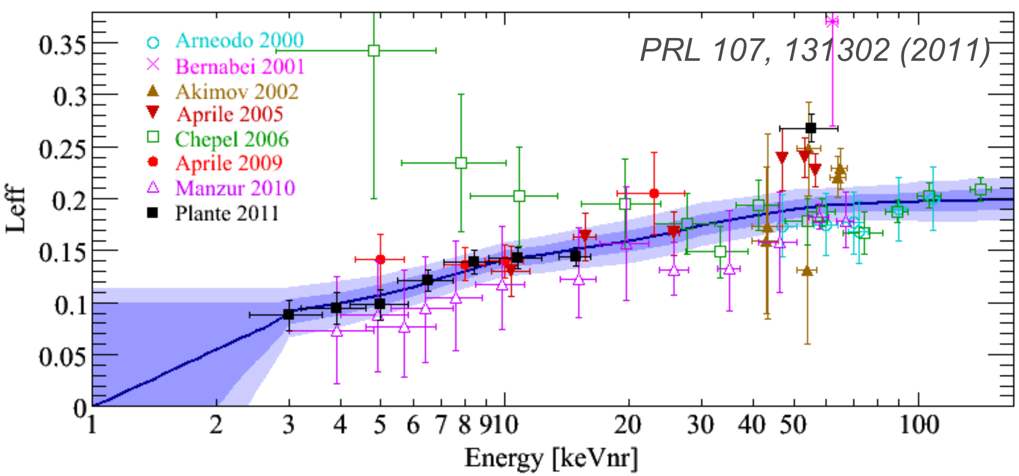
Nuclear Recoil Energy Scale

- WIMPs interact with target nucleus
  ➡ nuclear recoil (*nr*) scintillation
  (β and γ's produce electronic recoils)
- absolute measurement is difficult
  ➡ measure relative to ^{57}Co (122keV)
- relative scintillation efficiency L_{eff}:

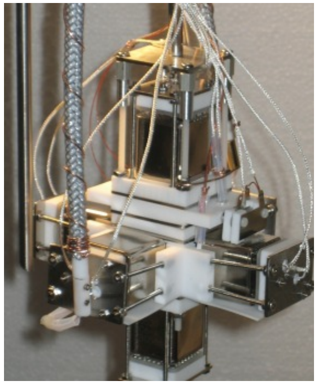
$$\mathcal{L}_{\mathrm{eff}}(E_{\mathrm{nr}}) = \frac{\mathrm{LY}(E_{\mathrm{nr}})}{\mathrm{LY}(E_{\mathrm{ee}} = 122\ \mathrm{keV})}$$

measurement principle:



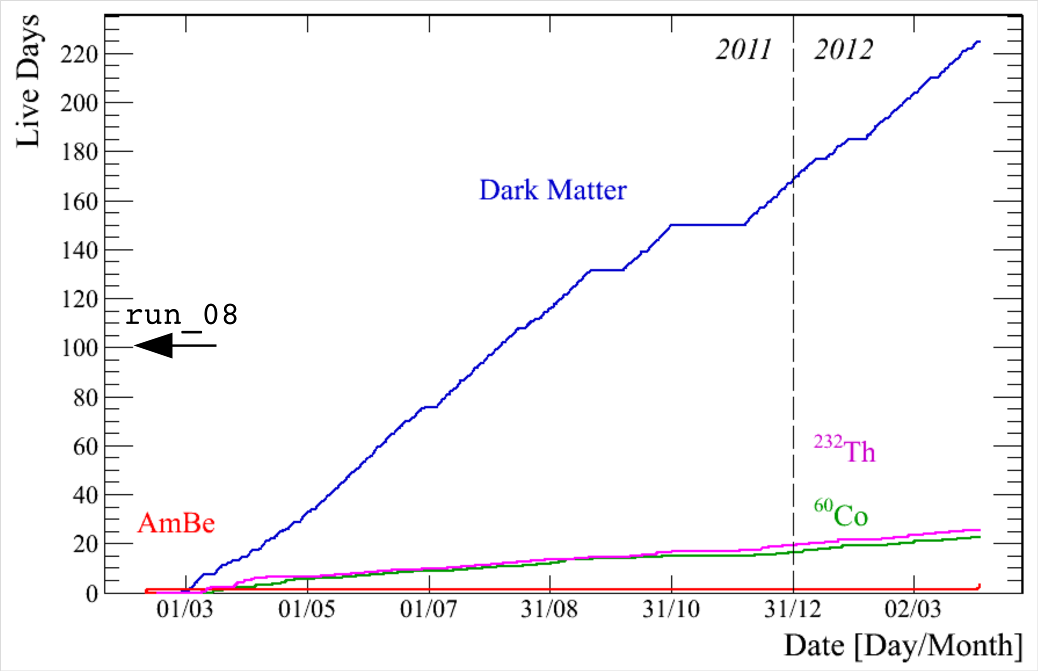


Most precise measurement with Values down to 3 keVr by CU:
PRC 84, 045805 (2011)



XENON100:
– take average of all existing measurements
– take into account uncertainty in PL analysis
→ get real 90% CL contour (stat AND syst)

XENON100



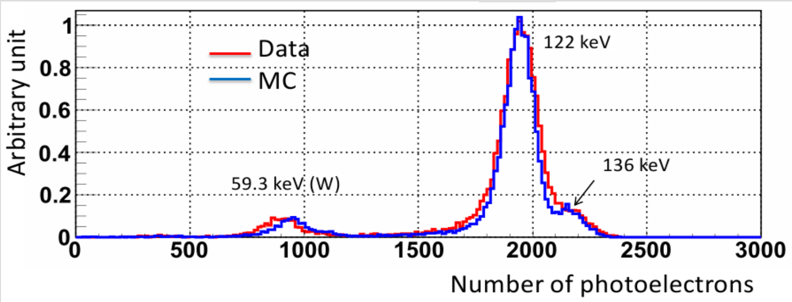
Current Science Run

- decreased background
- lower threshold
- more than 2x of 2010 dark matter data
- much more calibration data

→ data analysis is almost done
→ expect new results very soon

XMASS

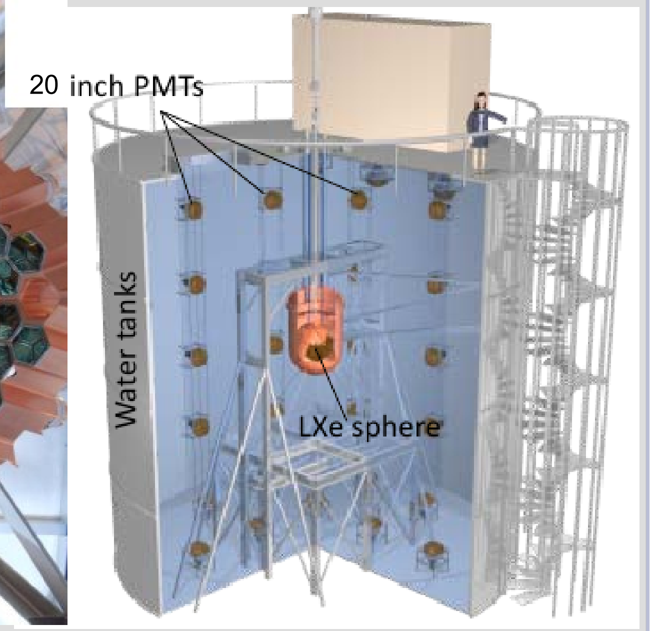
- single phase **LXe** detector
- 800kg total, 100kg fiducial mass
- 60% of surface covered with 642 hexagonal PMTs
- very high LY (~7x higher than Xe100)



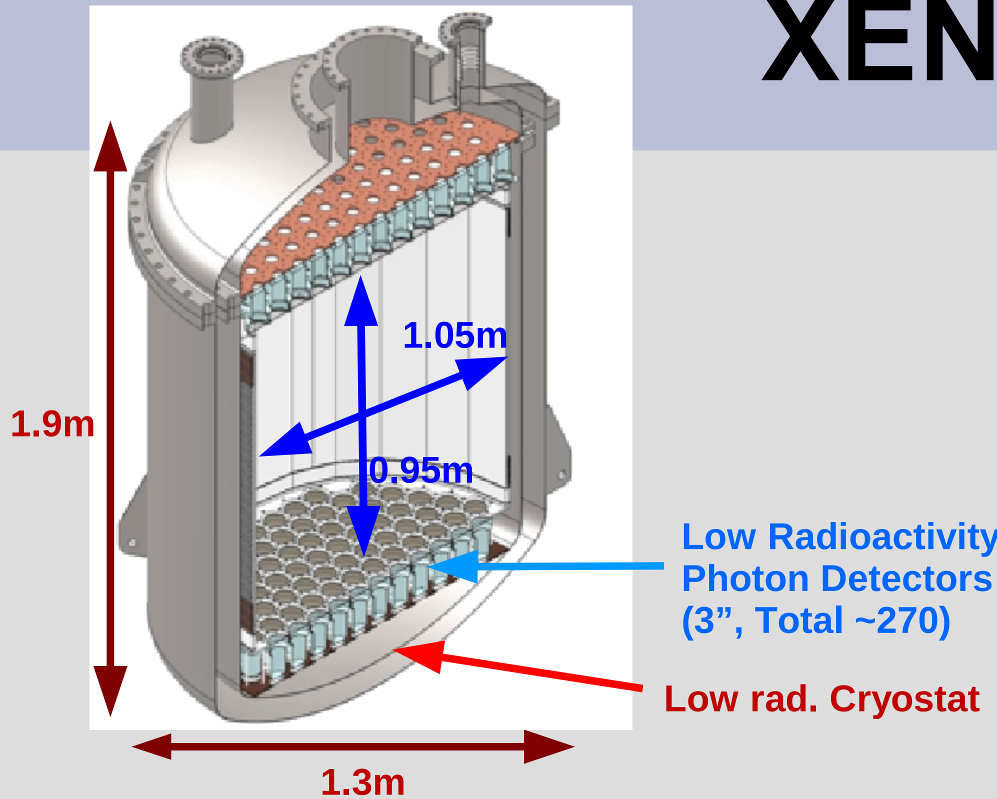
- located in Kamioka (JP)
- running since end of 2010; ultra low Kr85 background

XMASS announced background problems (surface events on Cu and from Al ring on PMTs) in March 2012

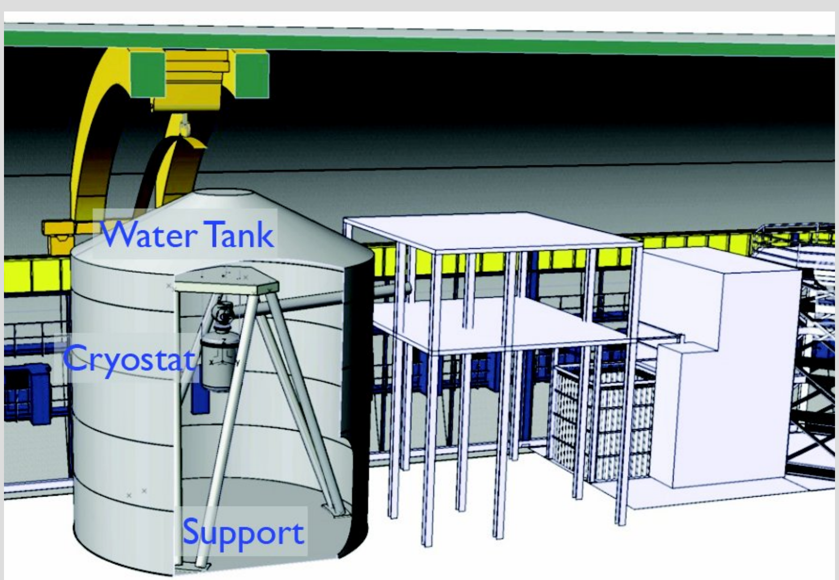
→ needs more investigation

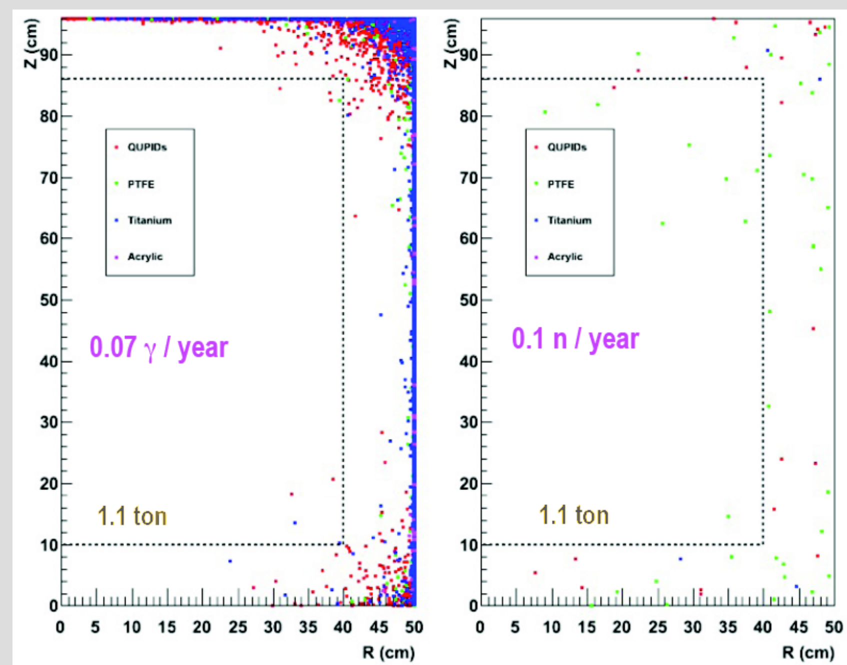


XENON1T

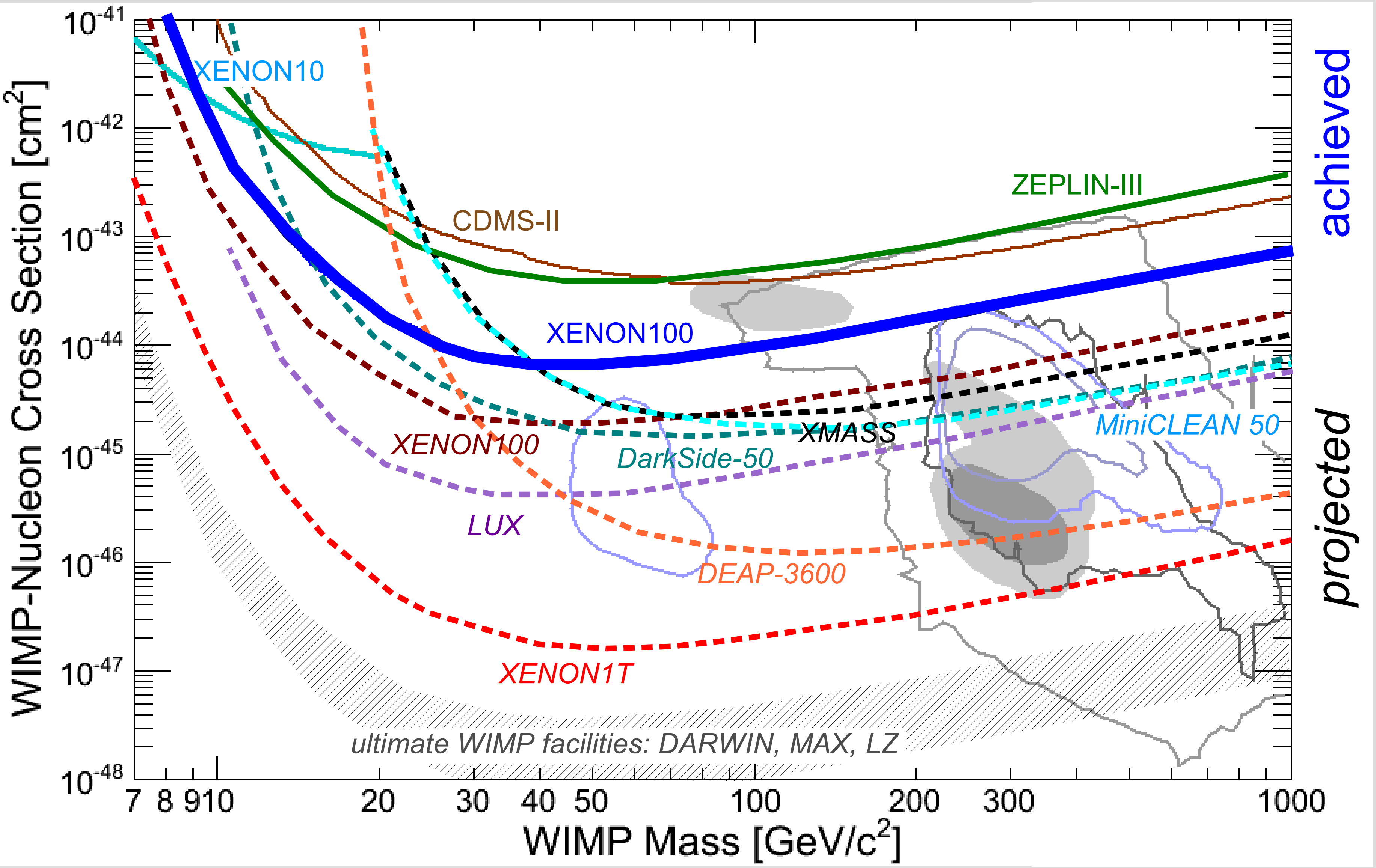


- dual phase **LXe** TPC
- 2.4t LXe ("1m³ detector")
  1t fiducial mass
- 100x lower background than Xe100
  (self shielding, low radioactivity components)
- Timeline: 2010 – 2015
- start construction at LNGS this year



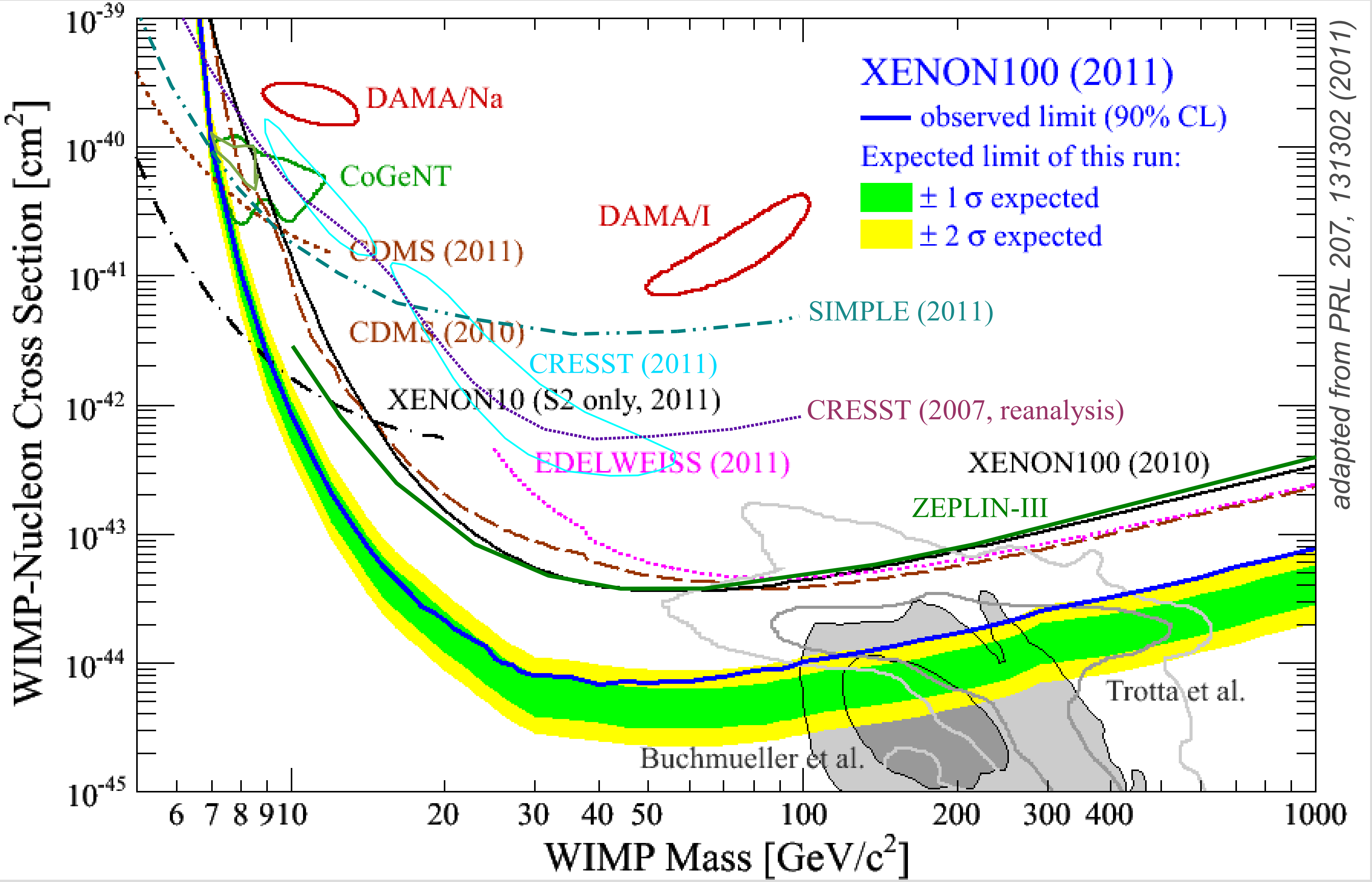


The Future...



Note: plot contains only experiments using noble liquids

Summary



XENON100 (2011)
observed limit (90% CL)
Expected limit of this run:
± 1 σ expected
± 2 σ expected
DAMA/Na
CoGeNT
DAMA/I
CDMS (2011)
SIMPLE (2011)
CDMS (2010)
CRESST (2011)
XENON10 (S2 only, 2011)
CRESST (2007, reanalysis)
EDELWEISS (2011)
XENON100 (2010)
ZEPLIN-III
Trotta et al.
Buchmueller et al.
WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
6 7 8 9 10 20 30 40 50 100 200 300 400 1000
adapted from PRL 207, 131302 (2011)

Backup

XENON10 „S2 only“ Analysis

PRL 107, 051301 (2011)

trade z-position+discrimination for lower threshold

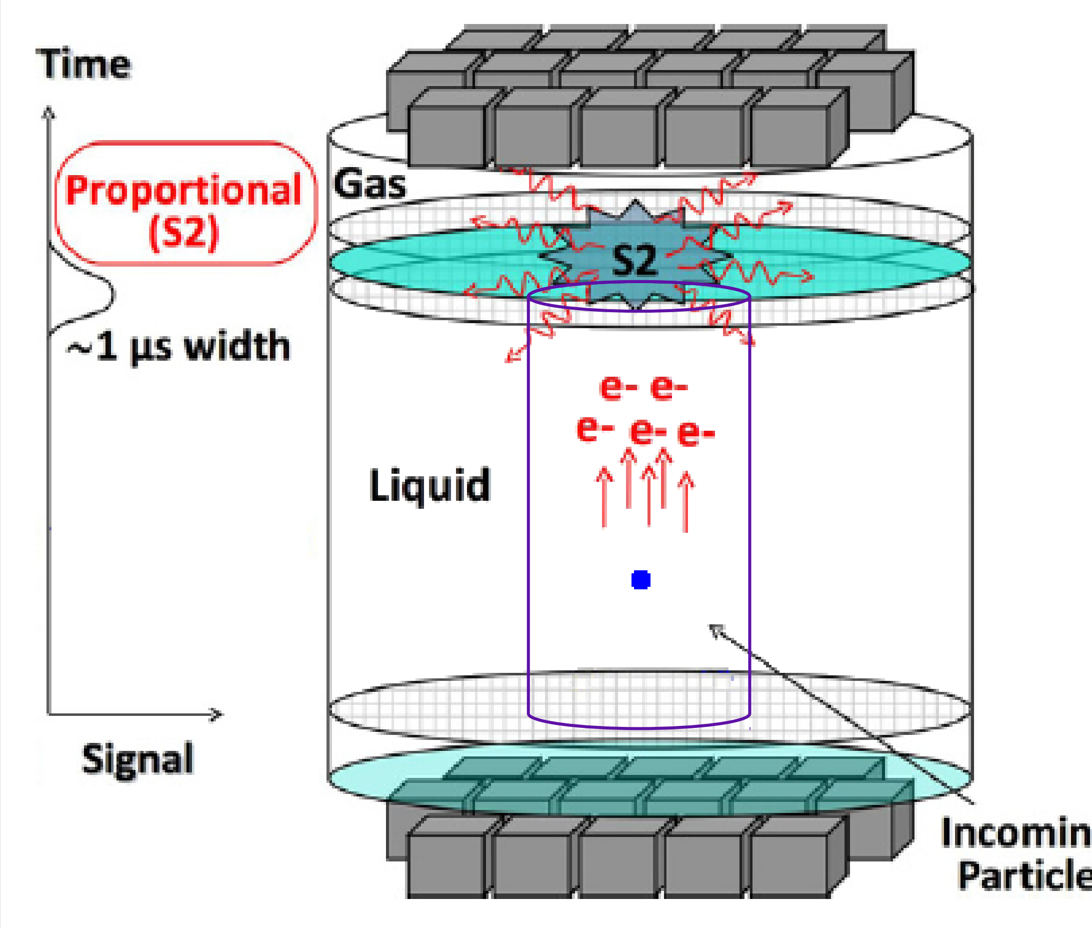


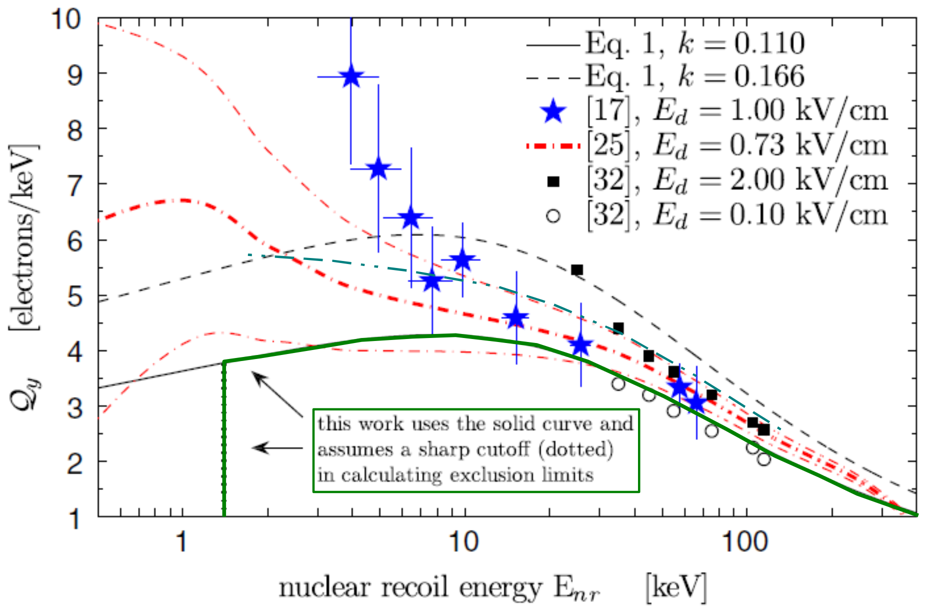
Fig. adapted from Astro.Part.Phys. 34, 679 (2011)

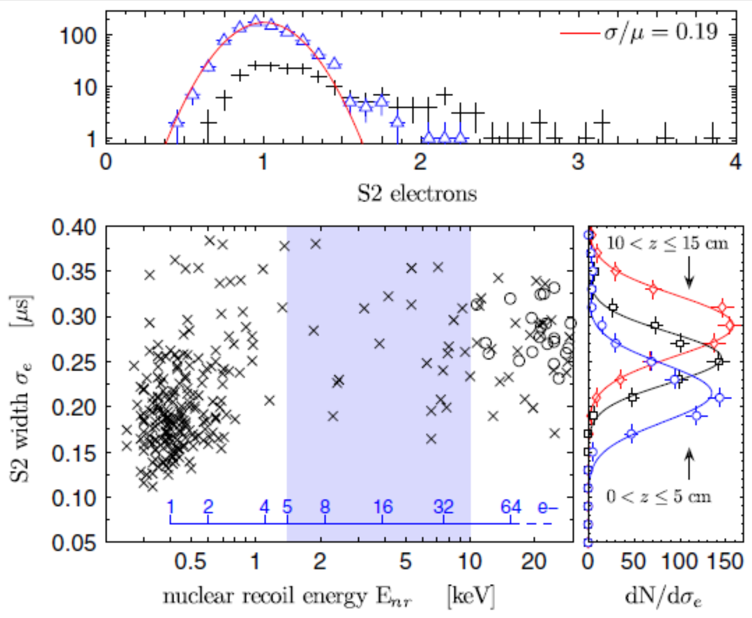
XENON10 „S2 only“ Analysis

PRL 107, 051301 (2011)

- 12.5d data from 2006
- trigger threshold at single electron level; data not used before
- require S2>5 e⁻ (~1.4 keV)
- radial cut r<3 cm, basically no z-cut → 1.2 kg
- choosing Qy 40% higher (lower) would yield a 2x stronger (weaker) limit @ 7 GeV/c²

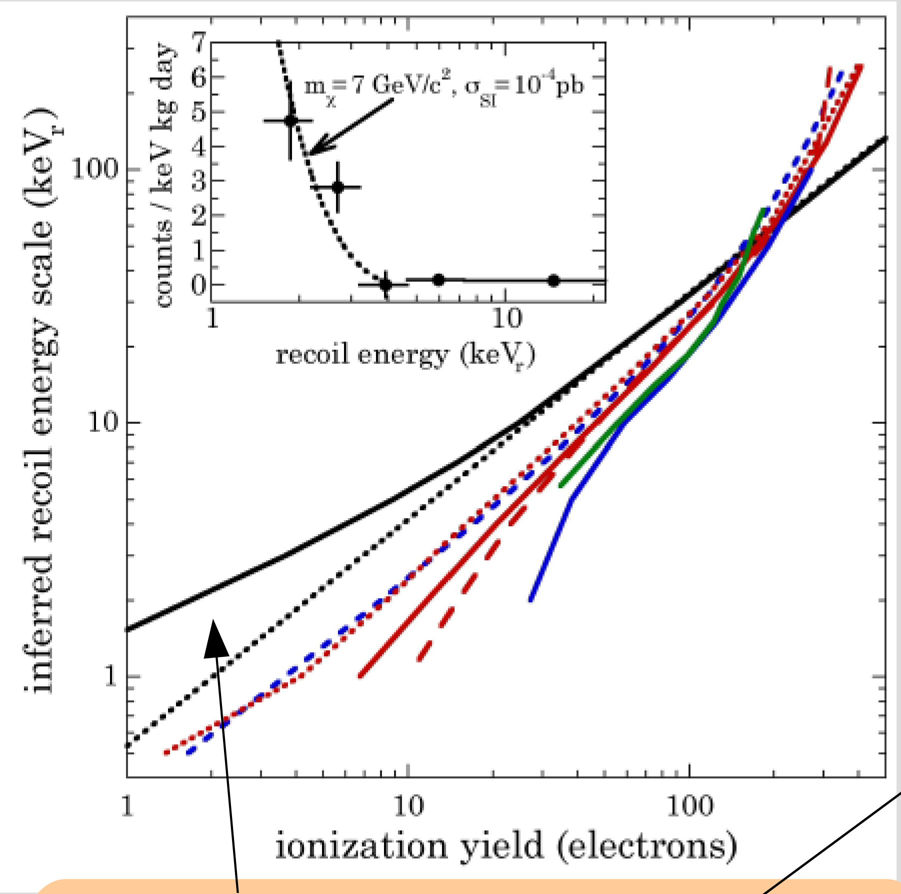
Models:
Sorensen/Dahl, PRD83, 063501 (2011)
Bezrukov et al., – – Astropart.Phys. 35, 119 (2011)



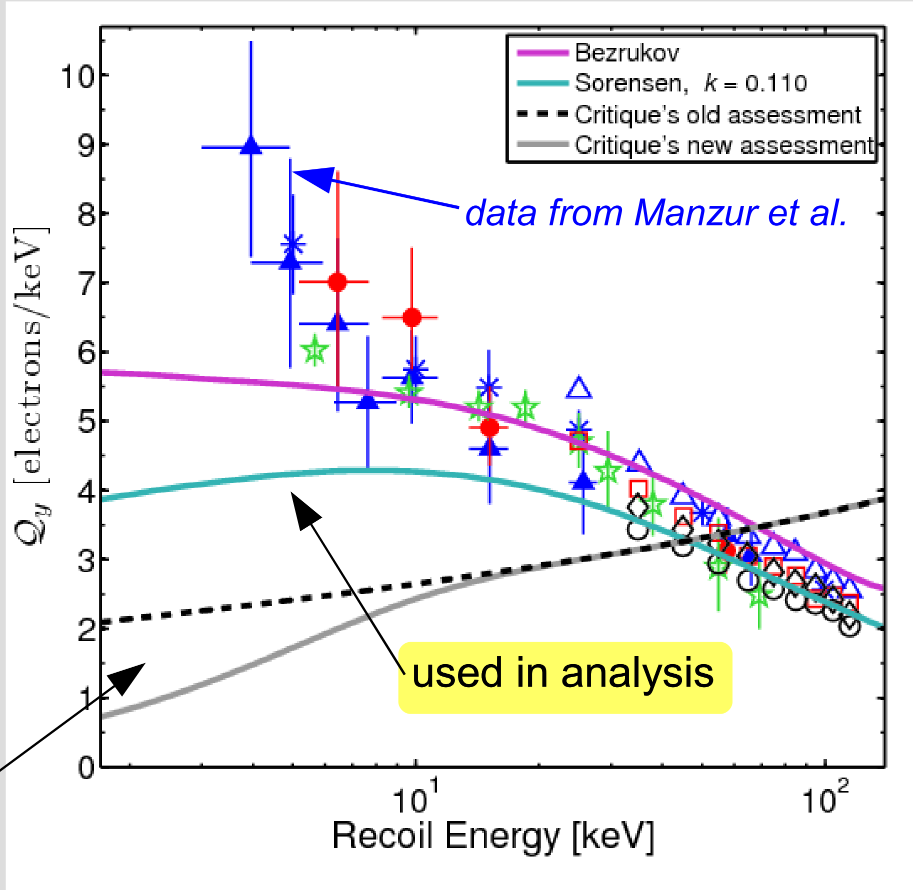


Criticism or Confusion?

J. Collar, arXiv:1106.0653



Put it in the usual style...

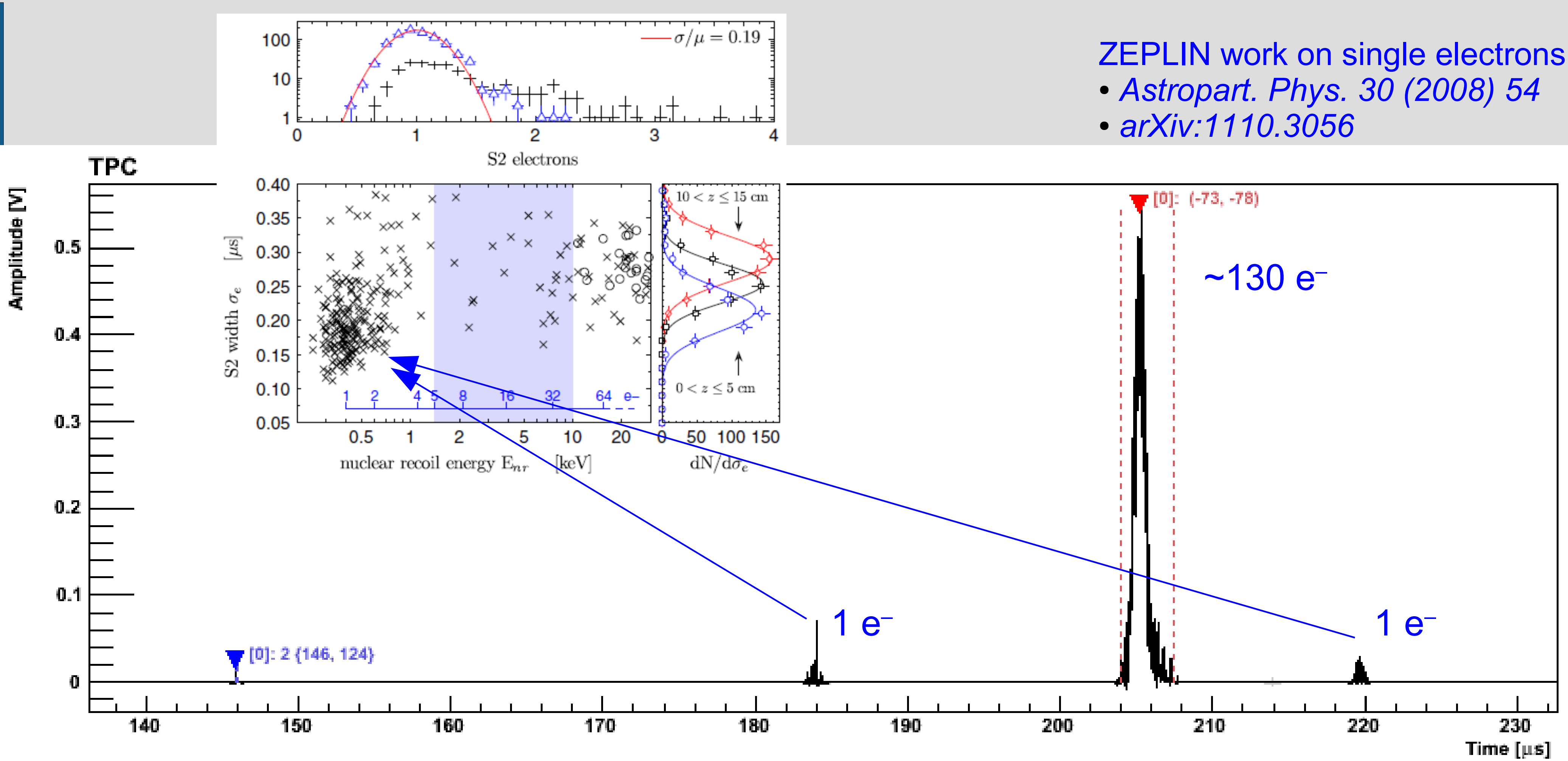


„Predictions" are due to a mistake. Xenon is not Germanium! One has to consider the electron-ion recombination and the exciton to ion ratio, which vary with E.

Conclusion: only if Q_y is incompatible with data and theoretical understanding one can avoid the XENON10 contraints.

Criticism or Confusion?

ZEPLIN work on single electrons:
- *Astropart. Phys. 30 (2008) 54*
- *arXiv:1110.3056*



Conclusion: only if Q_y is incompatible with data and theoretical understanding one can avoid the XENON10 contraints.