Dark Matter Detection with Noble Liquids

He
Ne
Ar
Kr
Xe

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Rencontres de Moriond EW, La Thuile, Aosta Valley, Italy, 18 March 2011

Overview

- Introduction
- Existing results
- Physics focus: low-mass WIMPs
- Ongoing and future experiments
- Prospects for constraining WIMP properties

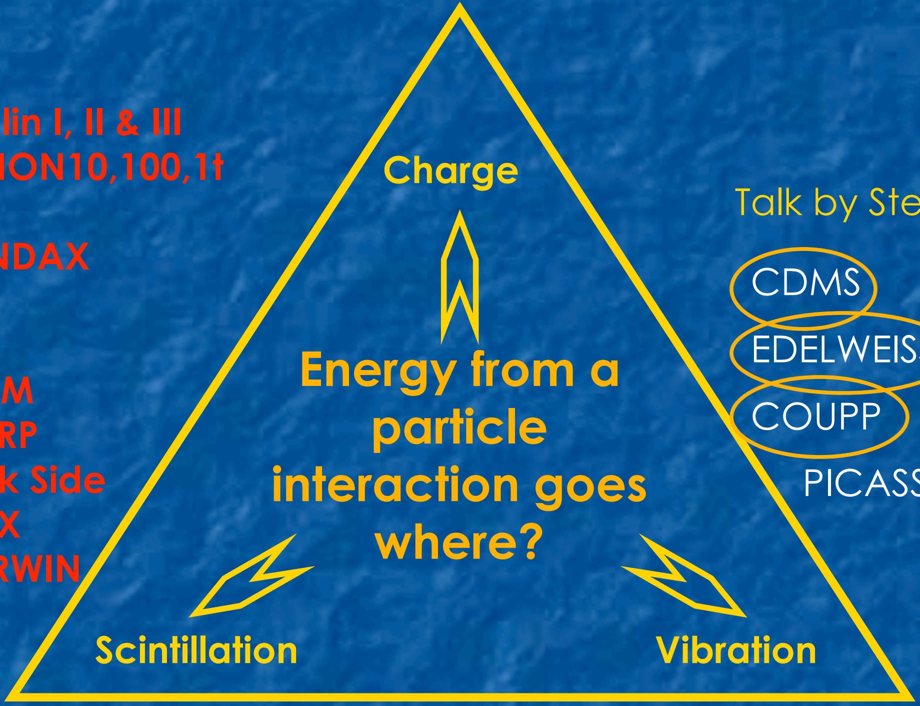
Direct detection

He
Ne
Ar
Kr
Xe
Rn

Talk by Fabiana Cossavella

DRIFT, GERDA, PICASSO, CoGeNT

Zeplin I, II & III
XENON10,100,1t
LUX
PANDAX
LZS
LZD
ArDM
WARP
Dark Side
MAX
DARWIN



Talk by Steven Leman

CDMS
EDELWEISS
COUPP
PICASSO

Talk by Ana Sofia Torrento Coello

Talk by C Eric Dahl

DAMA,
KIMS,
DEAP/CLEAN
XMASS

CRESST
ROSEBUD

CRESST I

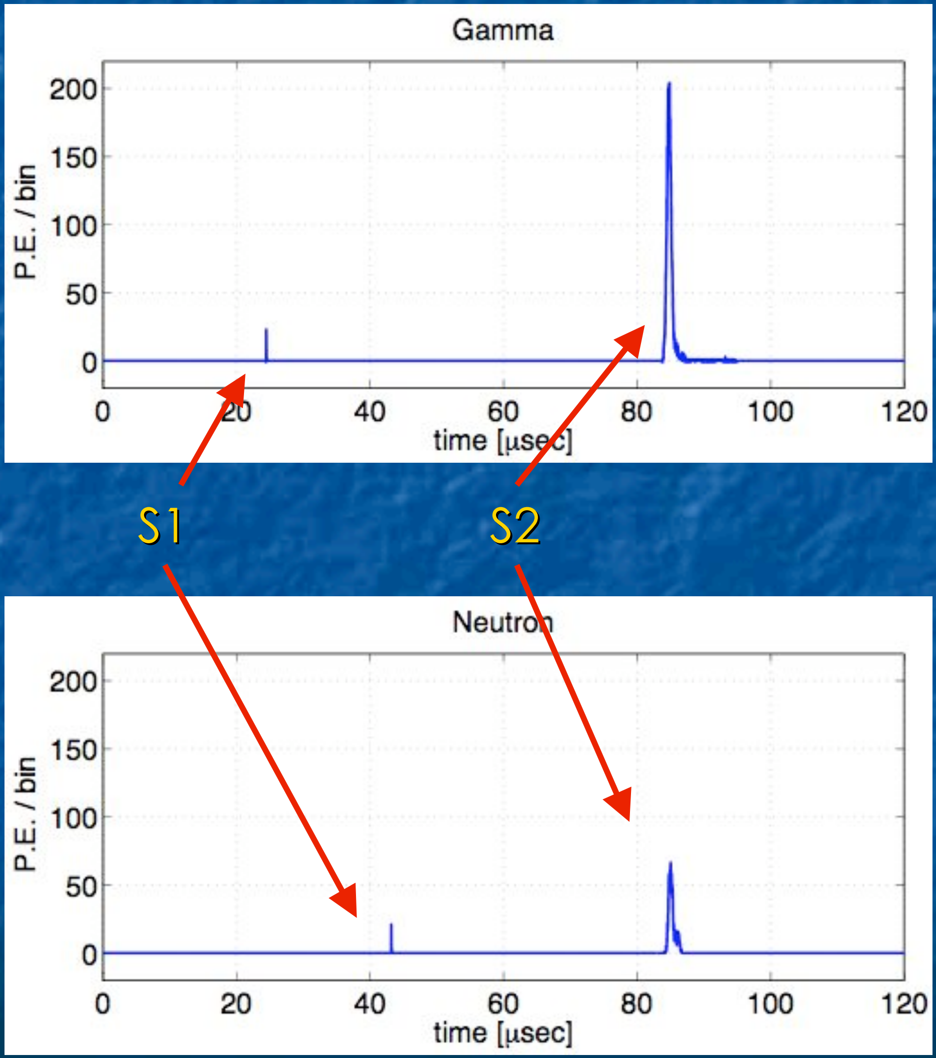
Why use noble liquids?

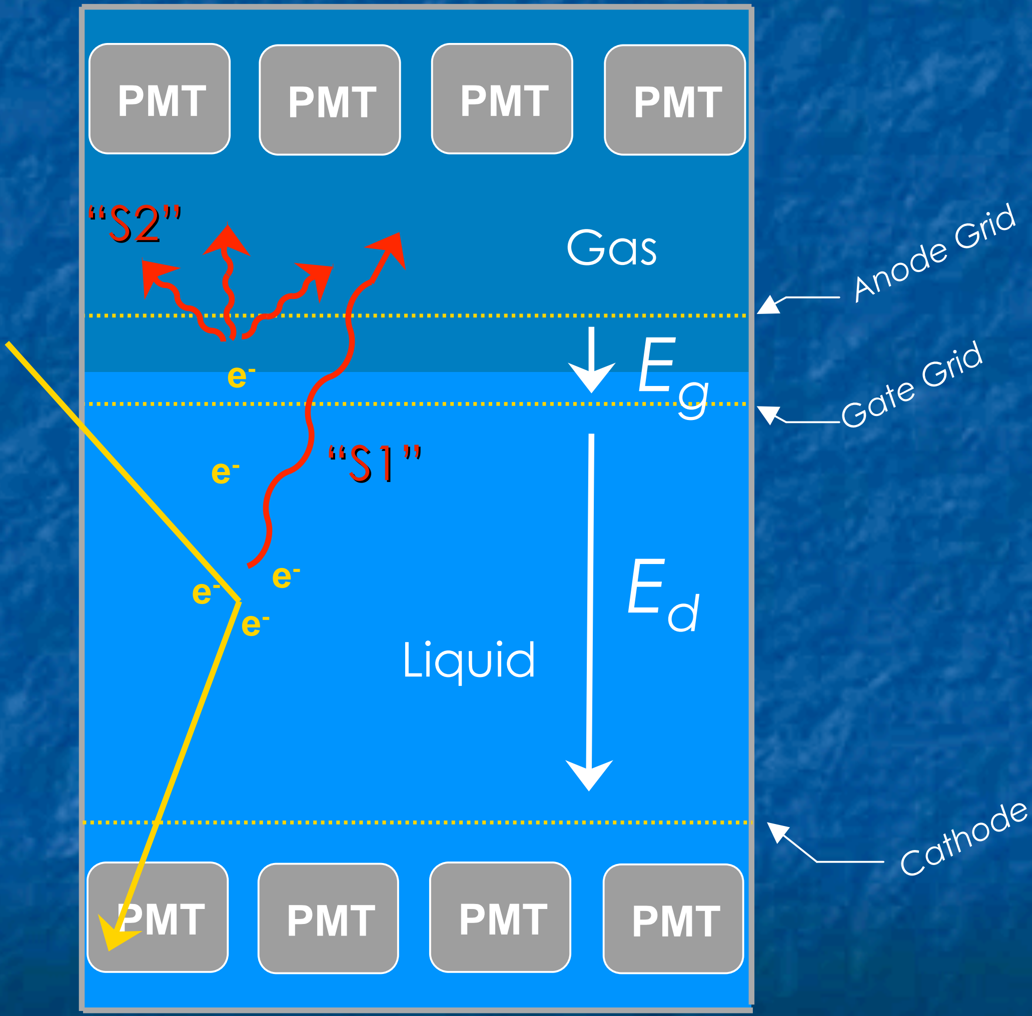
- Easily scalable to almost arbitrary size
- Self shielding *works*
- High yield -> (~75, ~50 quanta/keV in LXe, LAr, respectively) means low thresholds
- 3-D position reconstruction capabilities
- Nuclear recoil discrimination ($\sim 10^{-3}$ in LXe, $\sim 10^{-7}$ in LAr)
- Fast response (scintillation fast component at the ~few ns level)
- “Easy” cryogenics (boiling points: 165 K, 88 K for LXe and LAr, respectively)
- Extremely low attenuation of own scintillation light (compare with organic scintillators)
- LXe: Large nucleus (A~131) means large spin-independent cross section
- LXe: ~50% natural isotopes carry spin, giving spin-dependent sensitivity
- LXe: No long-lived radioisotopes
- LAr: Cheap and easily obtainable
- LAr: Capable of pulse shape discrimination

Detection technique

"Dual-phase Time Projection Chamber (TPC)"

- "S1" = primary scintillation
- "S2" = ionization signal





What should I discuss?

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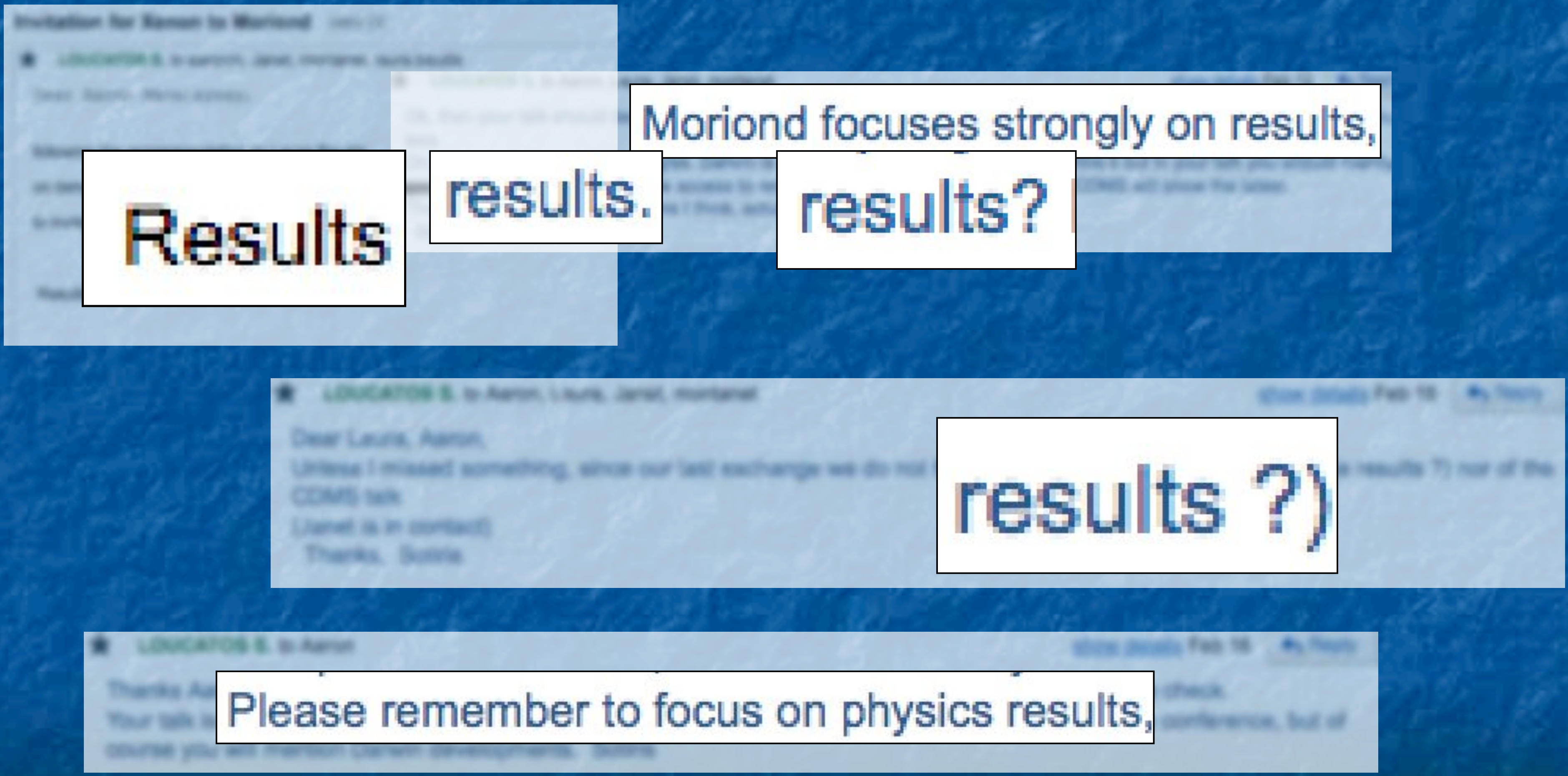


... so RESULTS it is!

What results are out there?

DAMA LXe	* XENON10
Zeplin I	* XENON100
Zeplin II	XENON1T
* Zeplin III	XMASS
* WARP 2.3l	LUX
WARP 100l	LZS
ArDM	LZD
DEAP/CLEAN	PANDAX
Dark Side	MAX
	DARWIN

Green are those noble liquid experiments that have released DM results

* Four most-recent results

What results are out there?

WARP 2.3l

Zeplin III

XENON10

XENON100

The experimental process follows these steps (in a nutshell, at least):

- Collect background data
- Apply cuts to remove electronic recoils
- Look at the signal region

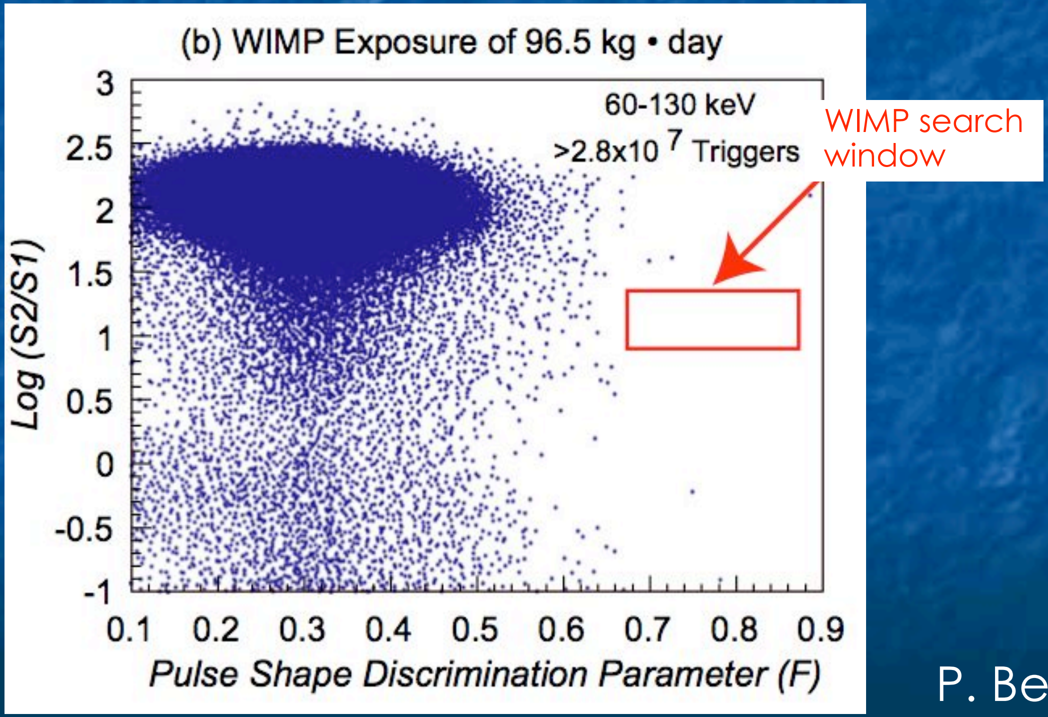
WARP 2.3l

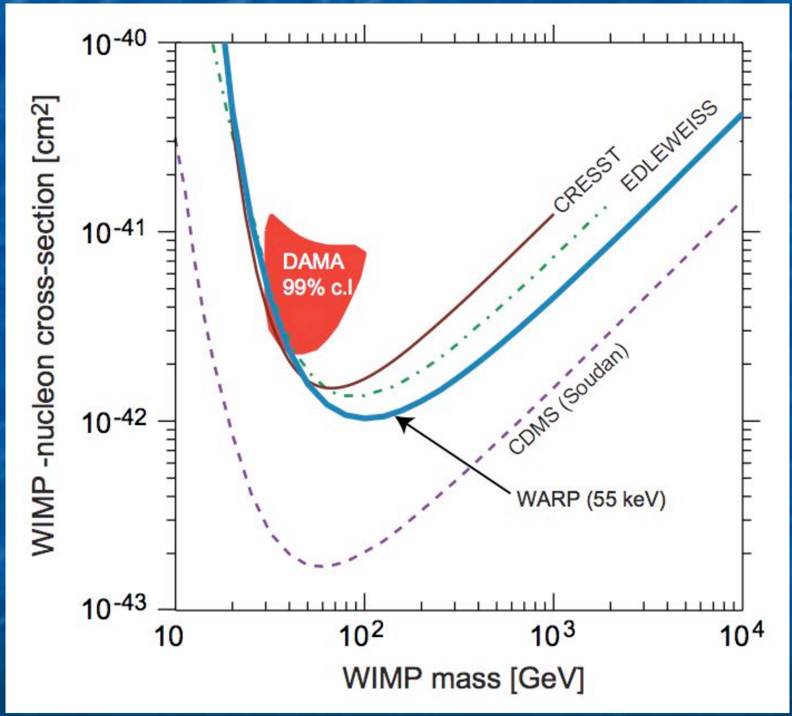
Dual-phase liquid argon TPC, operated at the Gran Sasso National Laboratory (LNGS, Assergi, Italy). First results released 2007. 3.2 kg F.M., 100 kg d exposure.

Exposure of 96.5 kg d, 55-100 keV

~10^{-42} cm^2 sensitivity

Discrimination performed with BOTH ionization/scintillation ratio, AND pulse shape discrimination



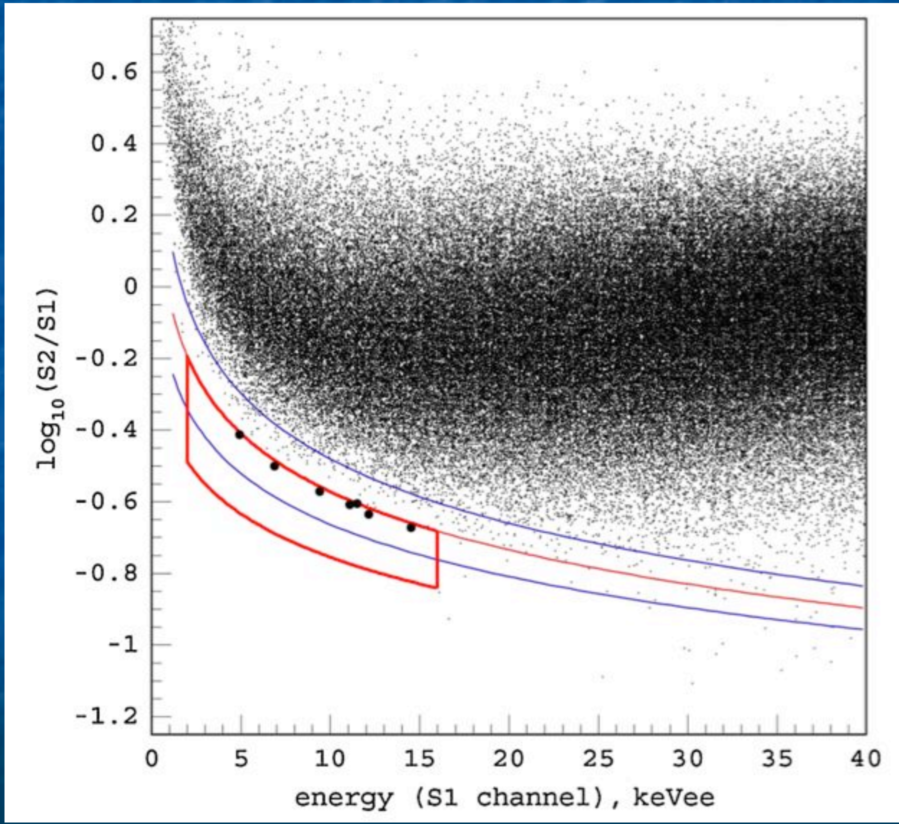


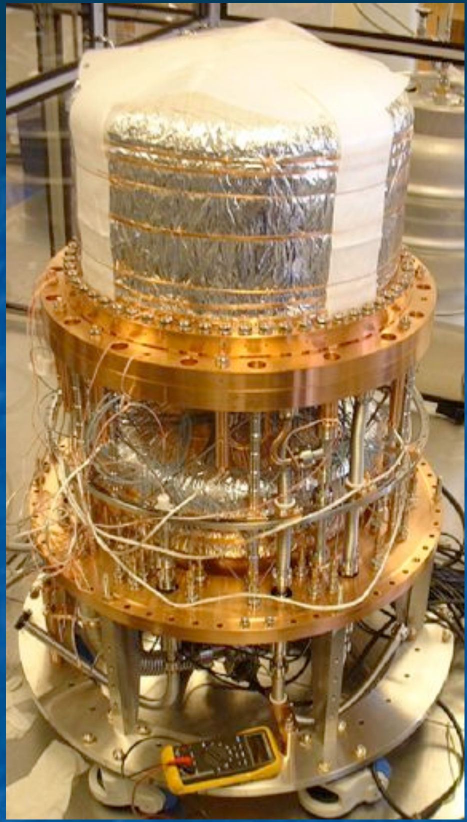
P. Benetti *et al*, Astropart. Phys. **28** (2008) 495

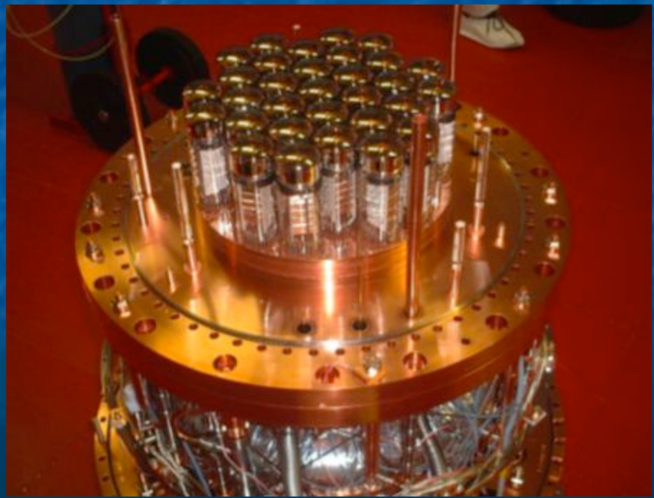
arXiv:astro-ph/0701286

Zeplin-III (1)

Dual-phase liquid xenon TPC, operated at the Boulby mine (UK). 6.52 kg F.M. ~128 kg d exposure, 7 events in the signal region.



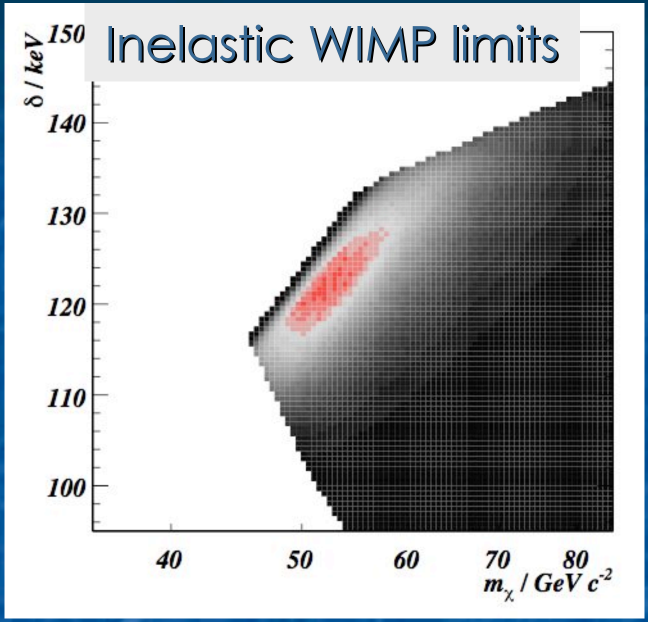




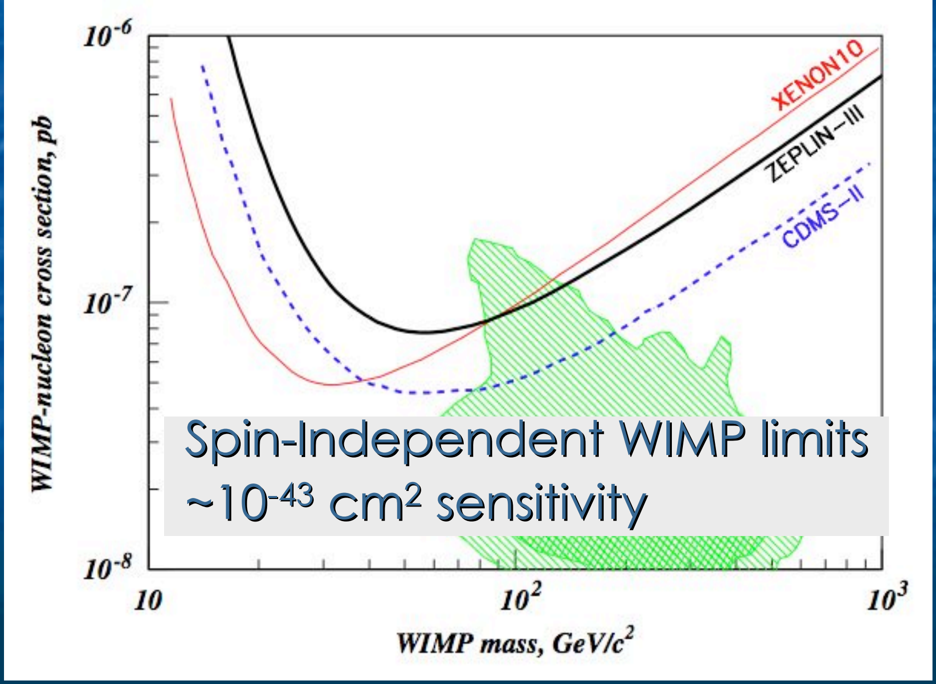
Zeplin-III (2)

- _S-I results_: V.N.Lebedenko *et al* Phys.Rev.D **80** (2009) 052010, arXiv:0812.1150 [astro-ph]
- _S-D results_: V.N.Lebedenko *et al* Phys.Rev.Lett. **103** (2009) 151302, arXiv:0901.4348 [hep-ex]
- _iDM results_: D.Yu.Akimov et al arXiv:1003.5626v2 [hep-ex] 2010

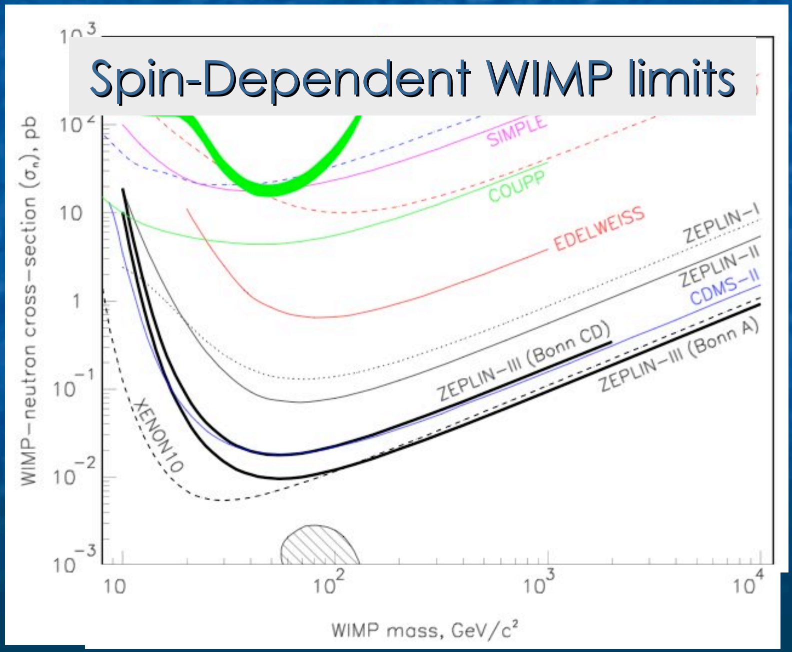
Currently collecting more data with new PMTs and ~10 times lower background!



Inelastic WIMP limits



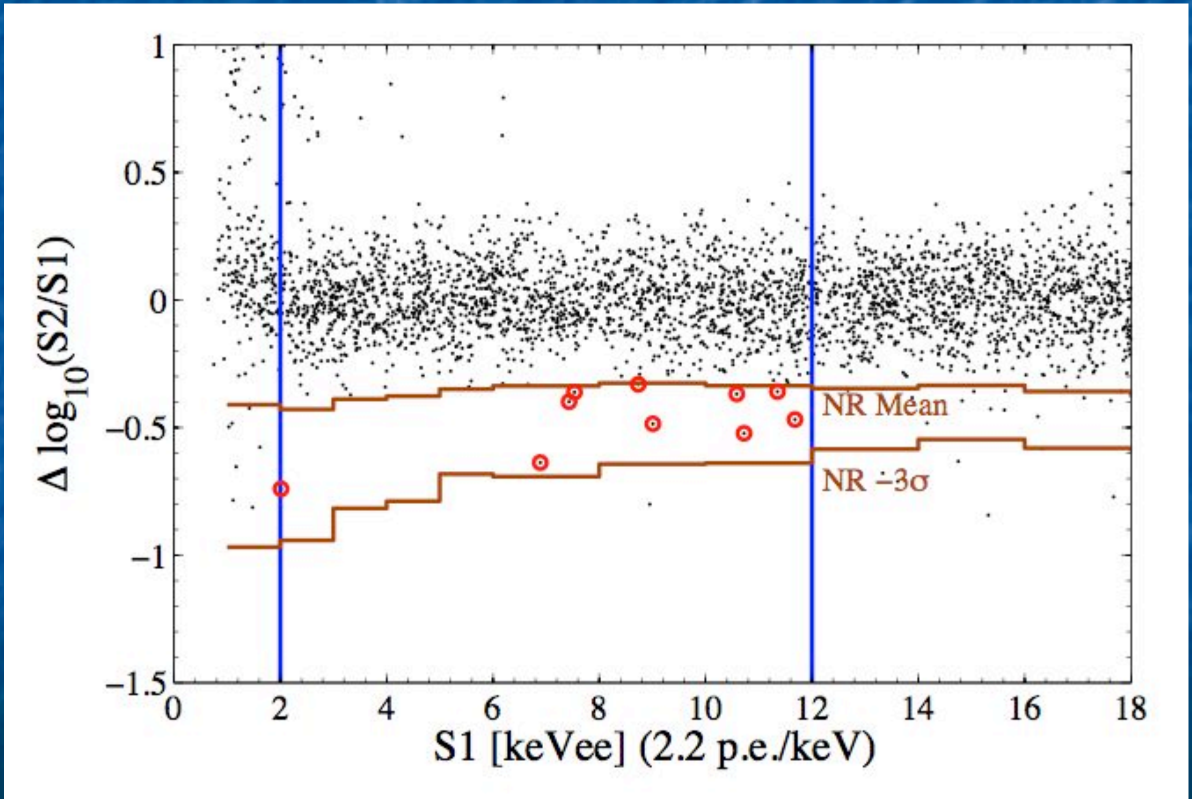
Spin-Independent WIMP limits
~10^{-43} cm^2 sensitivity

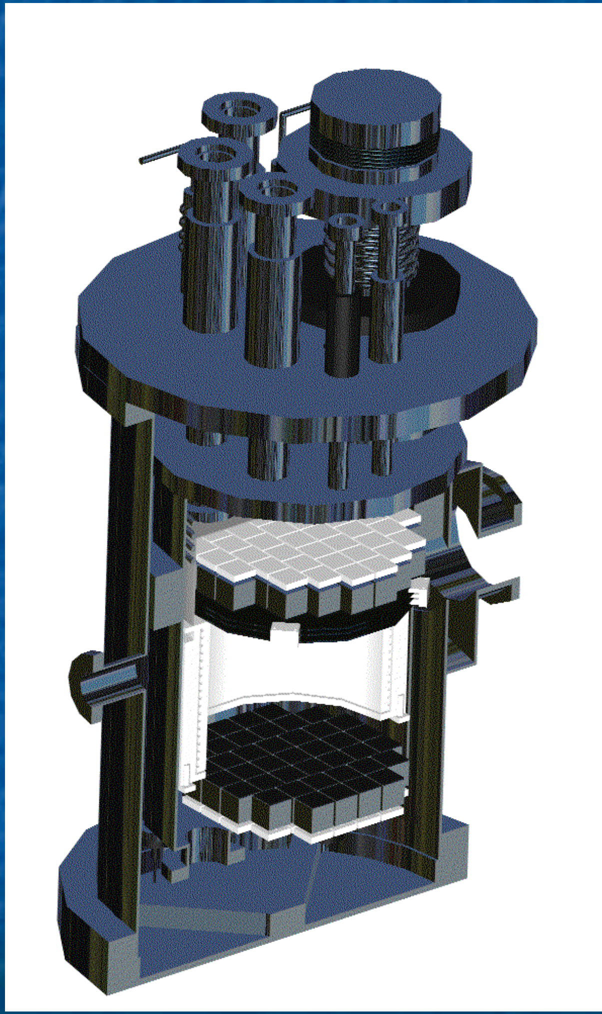


Spin-Dependent WIMP limits

XENON10 (1)

Dual-phase liquid xenon TPC, operated at LNGS (Italy). 5.4 kg F.M. ~136 kg d exposure, 10 events in the signal region.

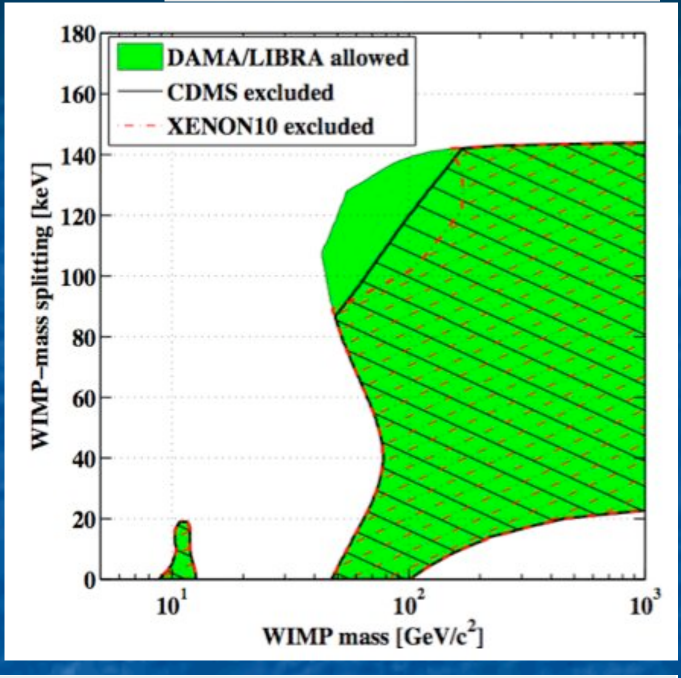




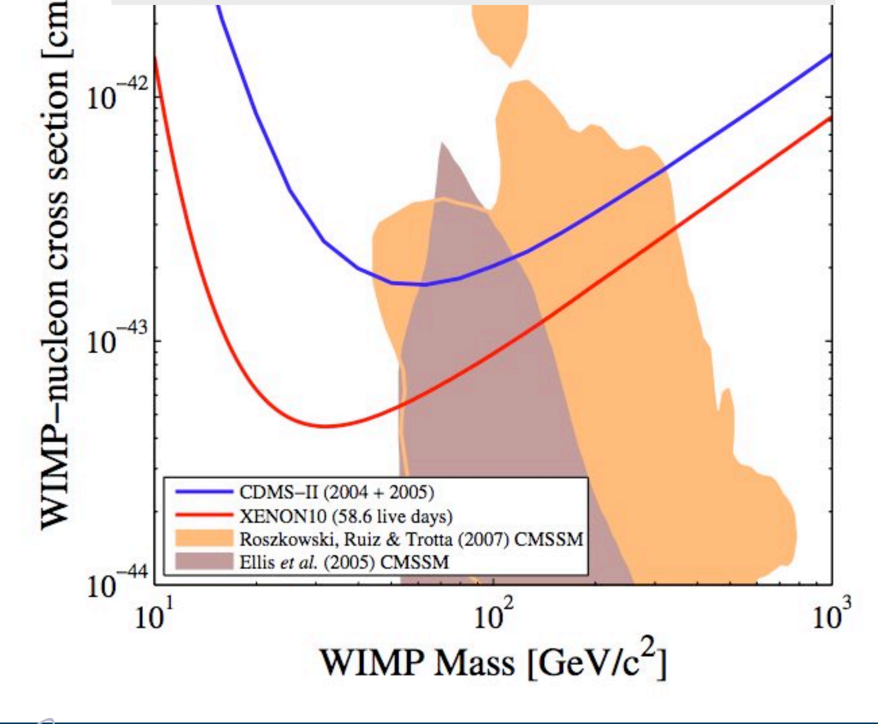
XENON10 (2)

- *S-I results*: J.Angle *et al*, Phys.Rev.Lett. **100** (2008) 021303, arXiv:0706.0039 [astro-ph]
- *S-D results*: J.Angle *et al*, Phys.Rev.Lett. **101** (2008) 091301, arXiv:0805.2939 [astro-ph]
- *iDM results*: J.Angle *et al*, Phys.Rev.D **80** (2009) 115005, arXiv:0910.3698

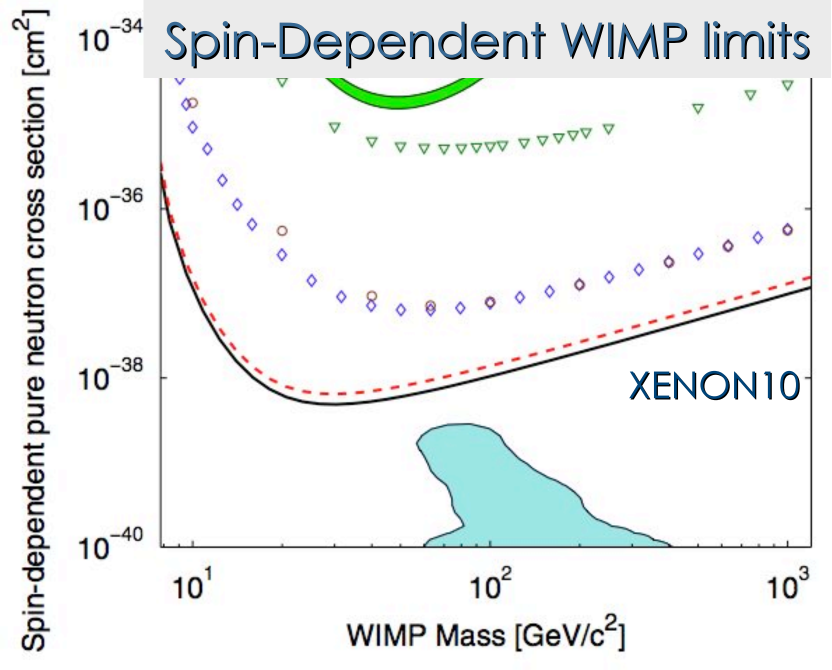
Inelastic WIMP limits



Spin-Independent WIMP limits
~5x10^{-44} cm^2 sensitivity

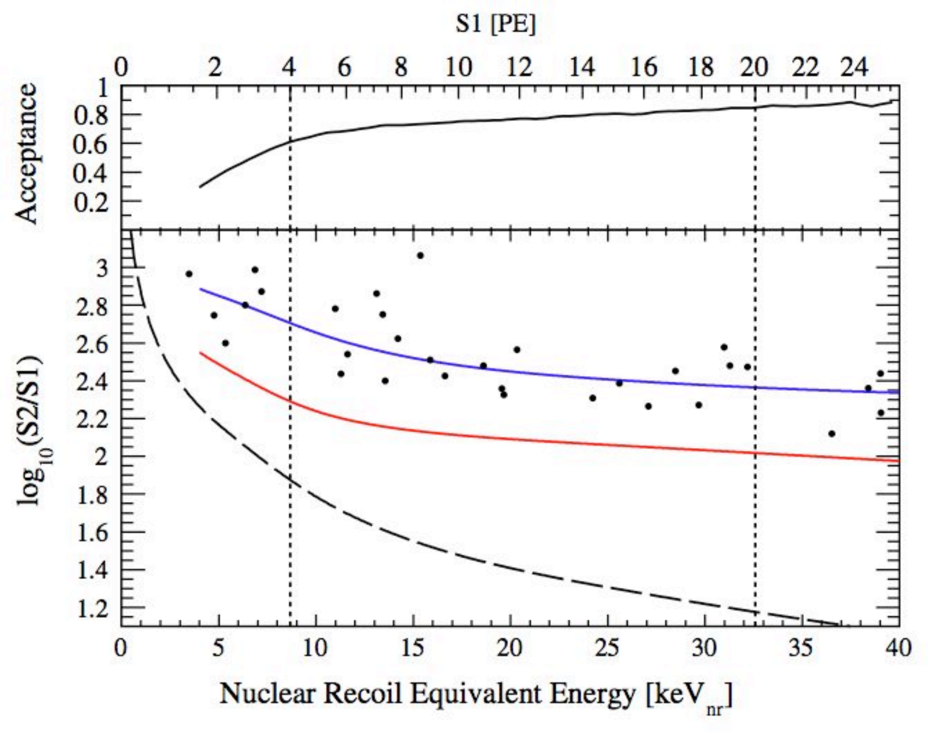


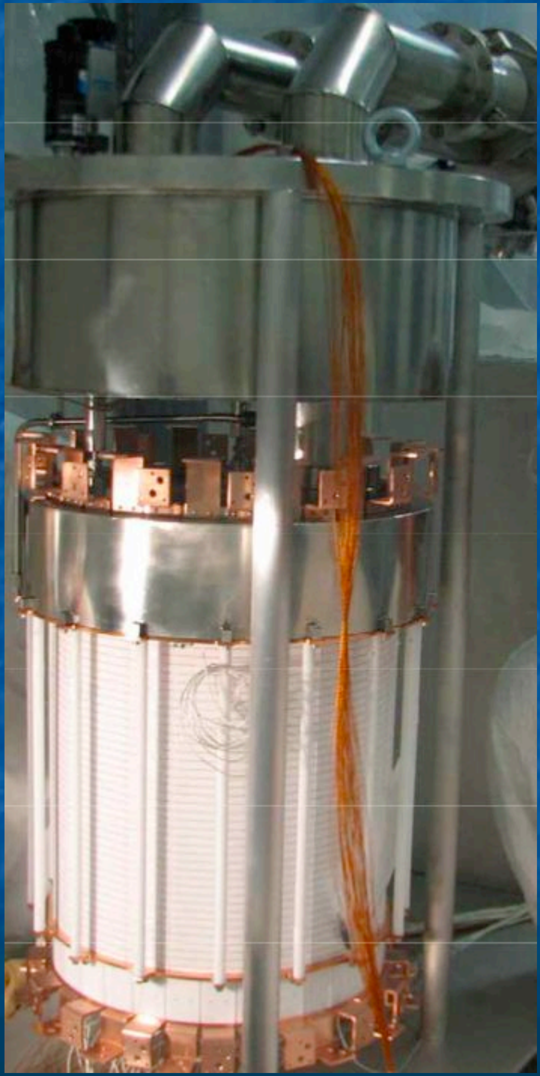
Spin-Dependent WIMP limits



XENON100 (1)

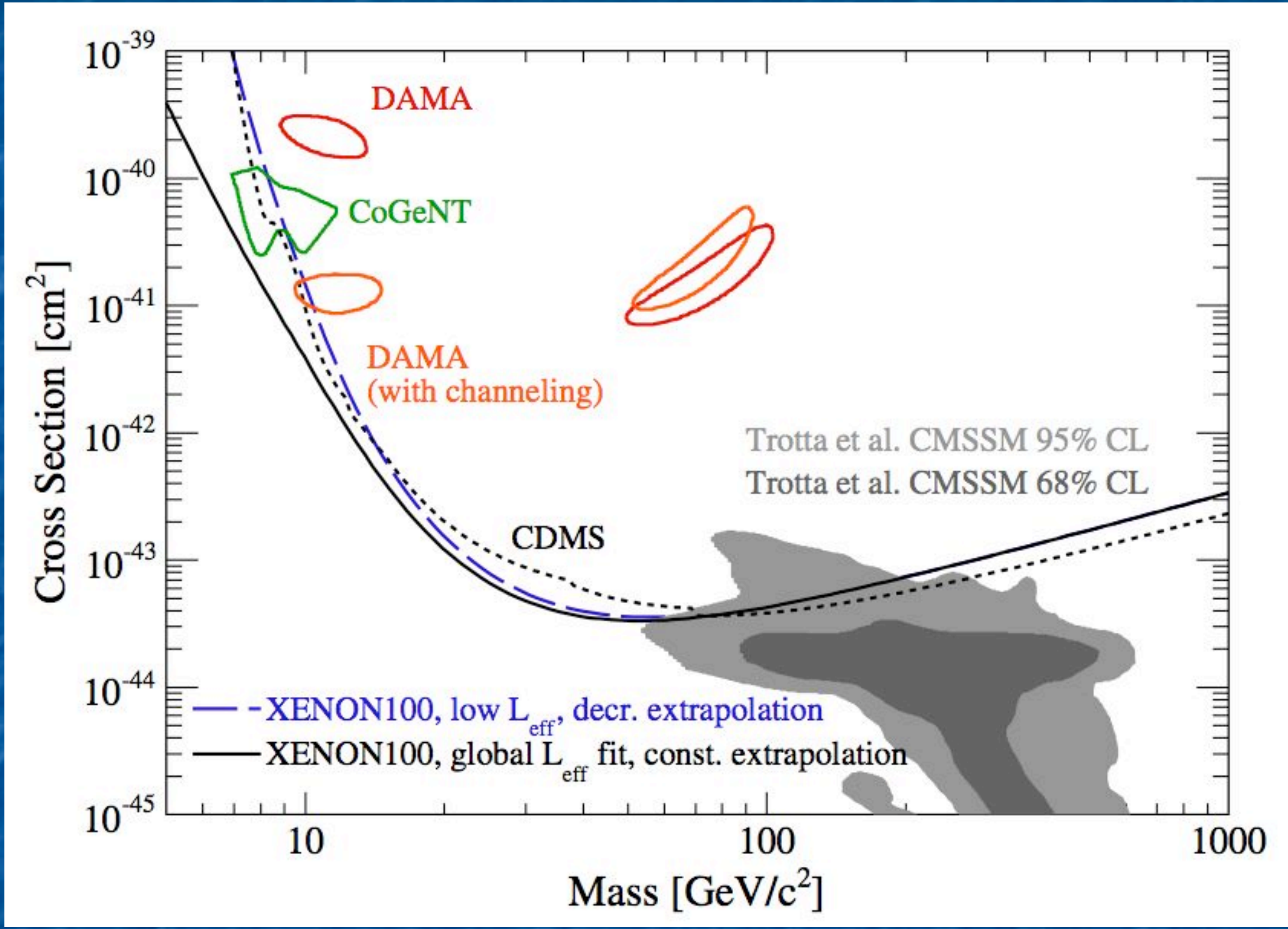
Dual-phase liquid xenon TPC, operated at the LNGS (Italy). 40 kg F.M. ~156 kg d exposure, 0 events in the signal region. Still collecting data! (~2 tonne d blind!)





XENON100 (2)

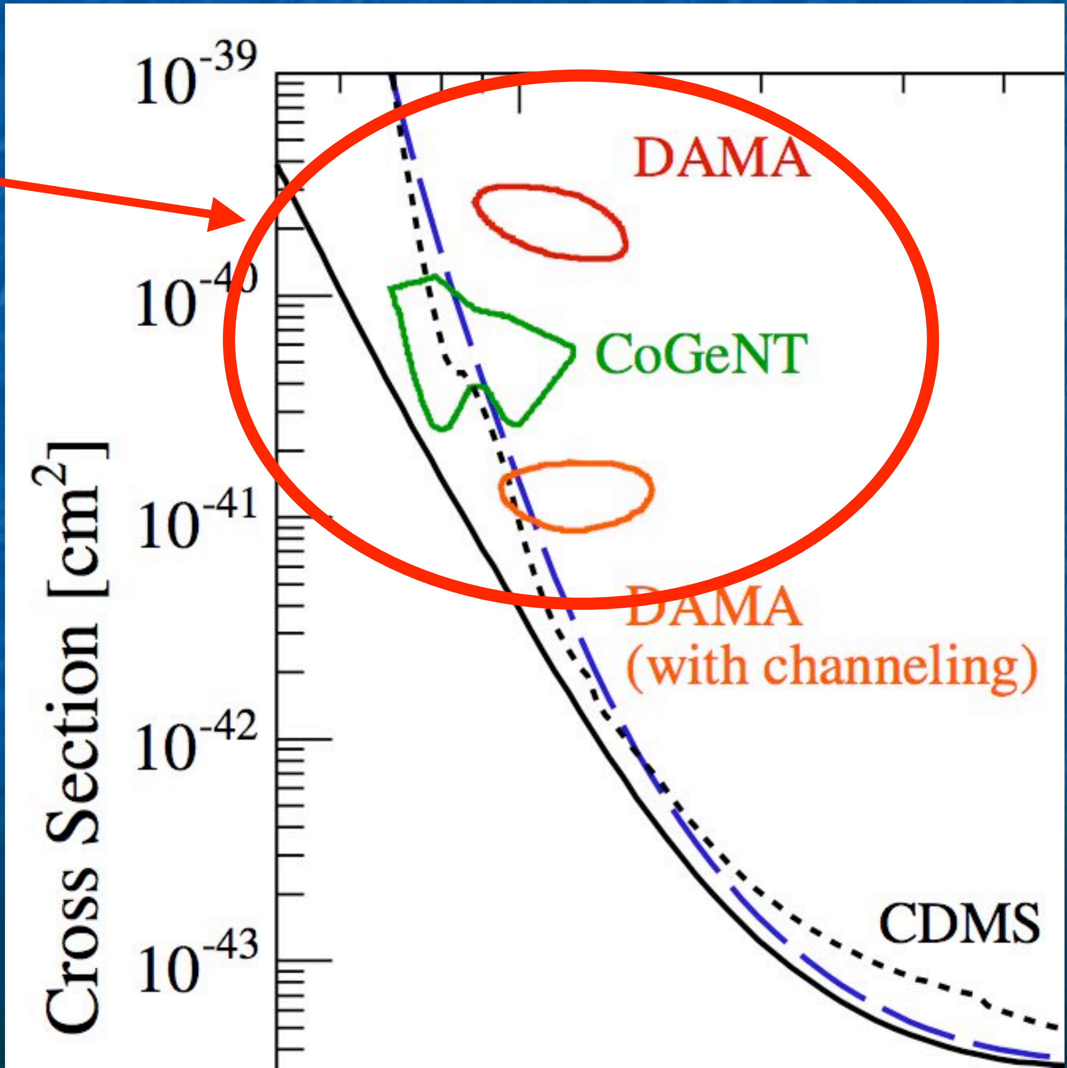
Spin-Independent limits only for now, at the ~3.5x10^{-44} cm^2 level



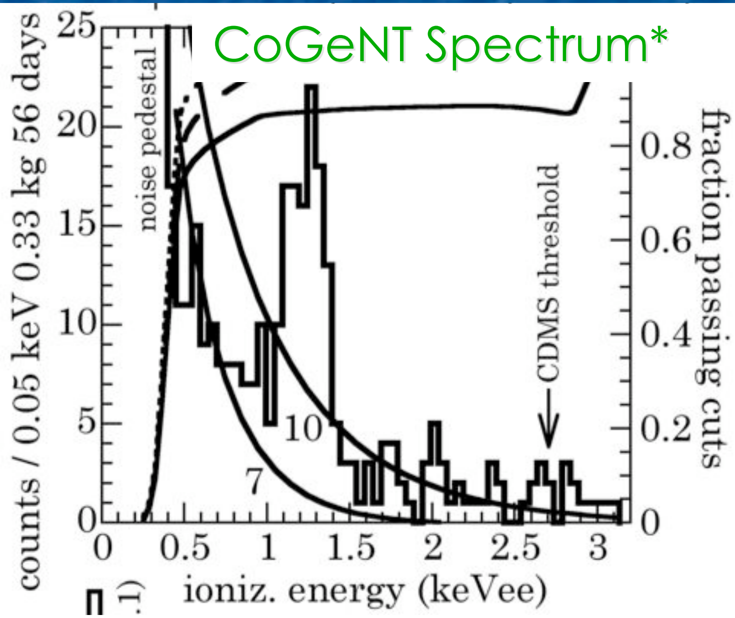
- *S-I results*: E.Aprile *et al*, Phys.Rev.Lett. **105** (2010) 131302, arXiv:1005.0380 [astro-ph.CO]
- *Alt. Analysis:* E.Aprile *et al*, arXiv:1103.0303 [hep-ex]

Physics focus: low-mass WIMPs

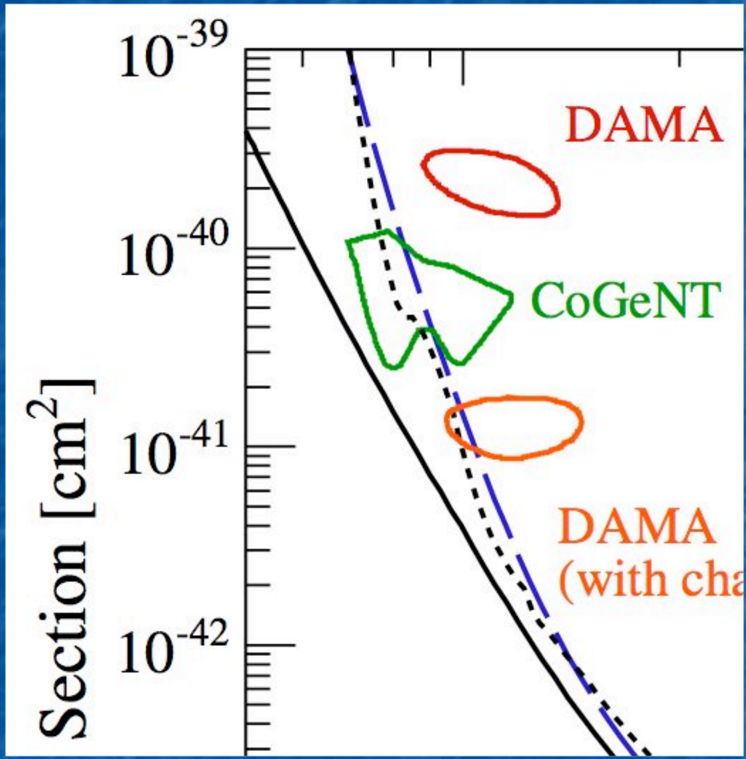
What's going on here!?

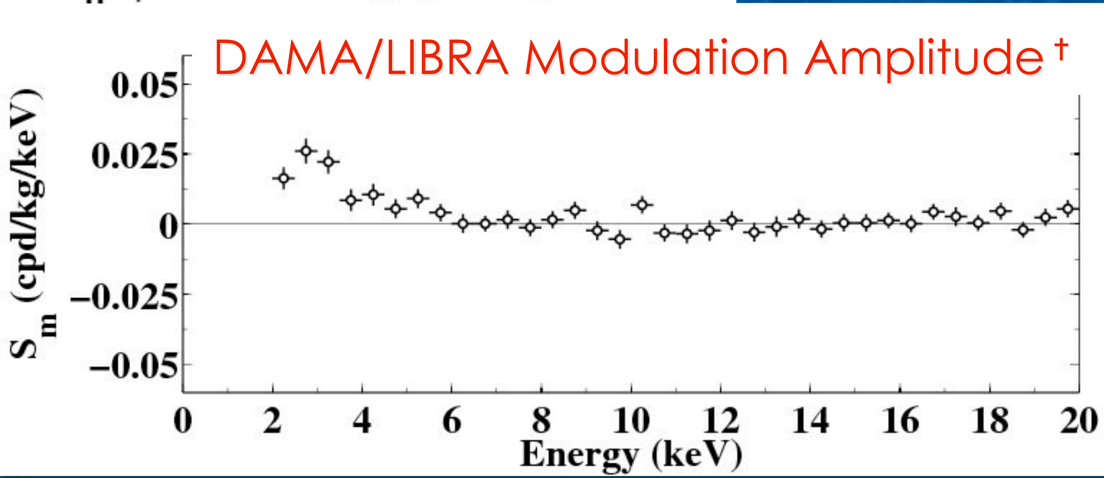


Physics focus: low-mass WIMPs



Possible signal detection in the two searches that use no rejection of electromagnetic backgrounds





*C.E.Aalseth *et al*, arXiv:1002.4703v2 [astro-ph.CO]

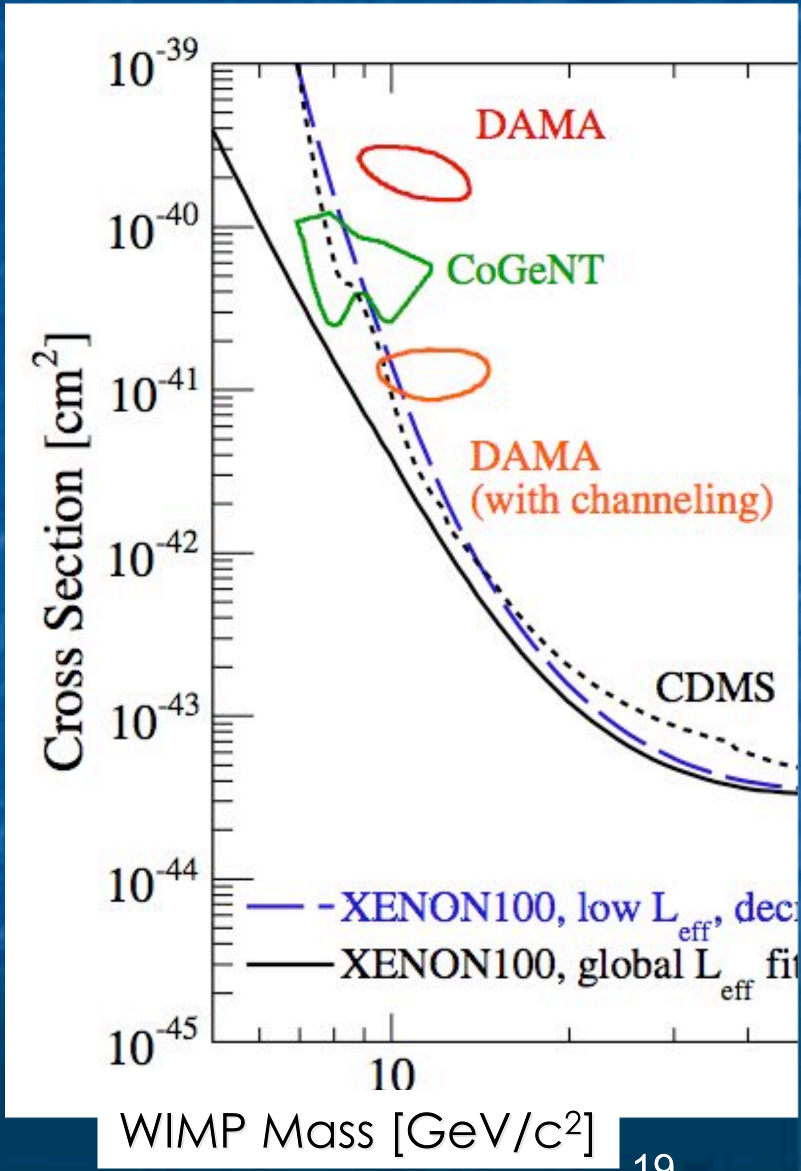
† R.Bernabei *et al*, Eur.Phys.J. **C67** (2010) 39-49

Physics focus: low-mass WIMPs

Two limits based on different reconstructed energy scales

XENON100's reported limit for low-mass WIMPs depends strongly on how one reconstructs the energy scale. This reconstruction is quantified by the parameter "L_{eff}" (the "effective Lindhard factor").

L_{eff} quantifies the nonlinear relationship between the energy of a nuclear recoil and the average number of scintillation photons it produces.



Physics focus: low-mass WIMPs

This discrepancy causes some tension in the field…

energy of nuclear recoil (NR)

measured signal in p.e.

quenching of scintillation yield for 122 keV γ due to drift field

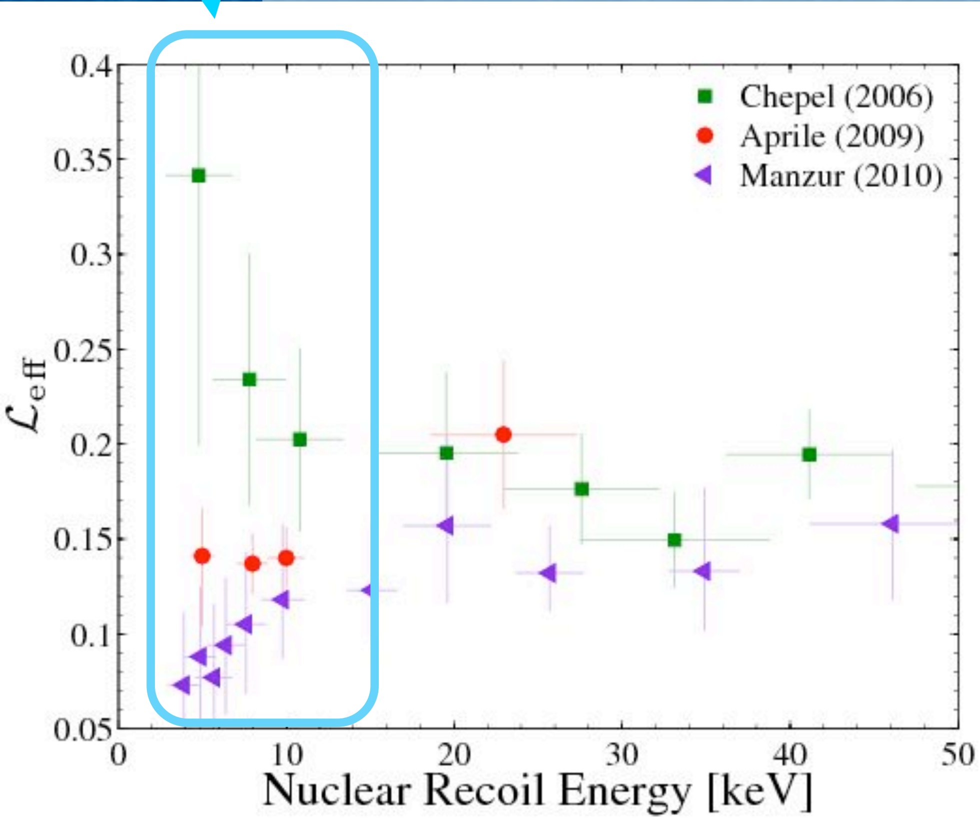
$$E_{\mathrm{nr}} = \frac{S1}{L_y \mathcal{L}_{\mathrm{eff}}} \times \frac{S_{\mathrm{e}}}{S_{\mathrm{nr}}}$$

light yield for 122 keV γ in p.e./keV

relative scintillation efficiency of NR to 122 keV γ at zero field

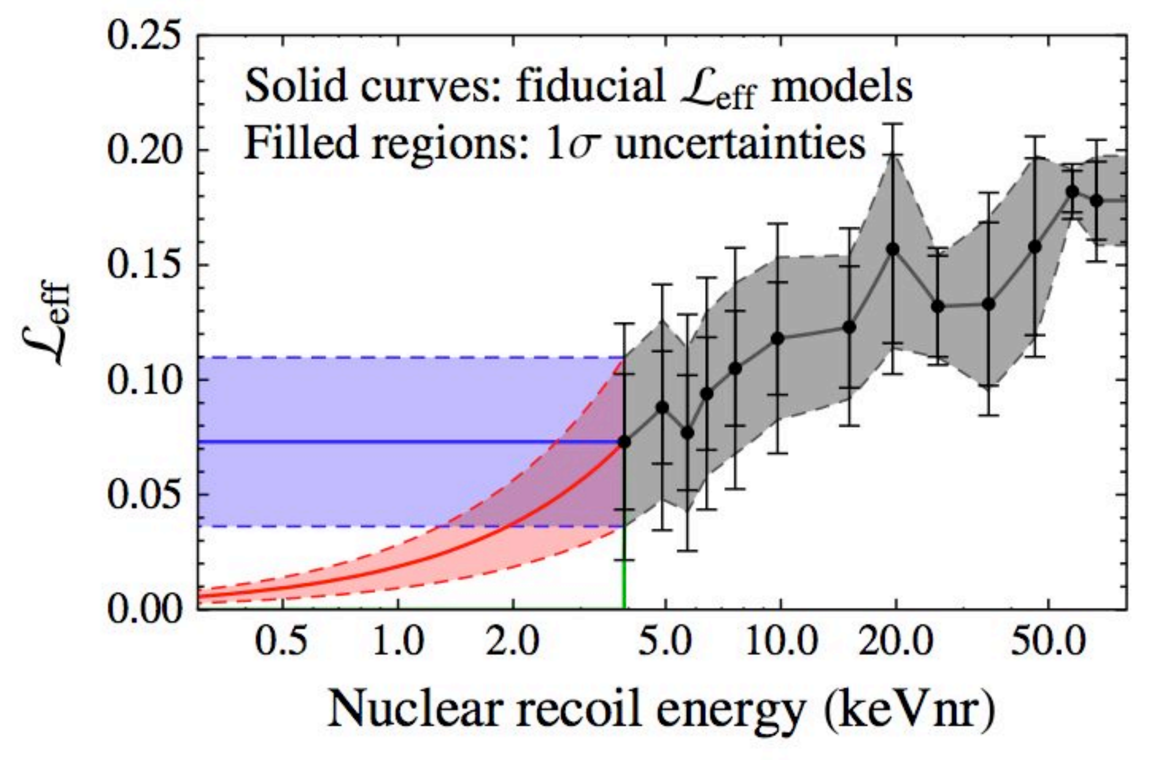
quenching of scintillation yield for NR due to drift field

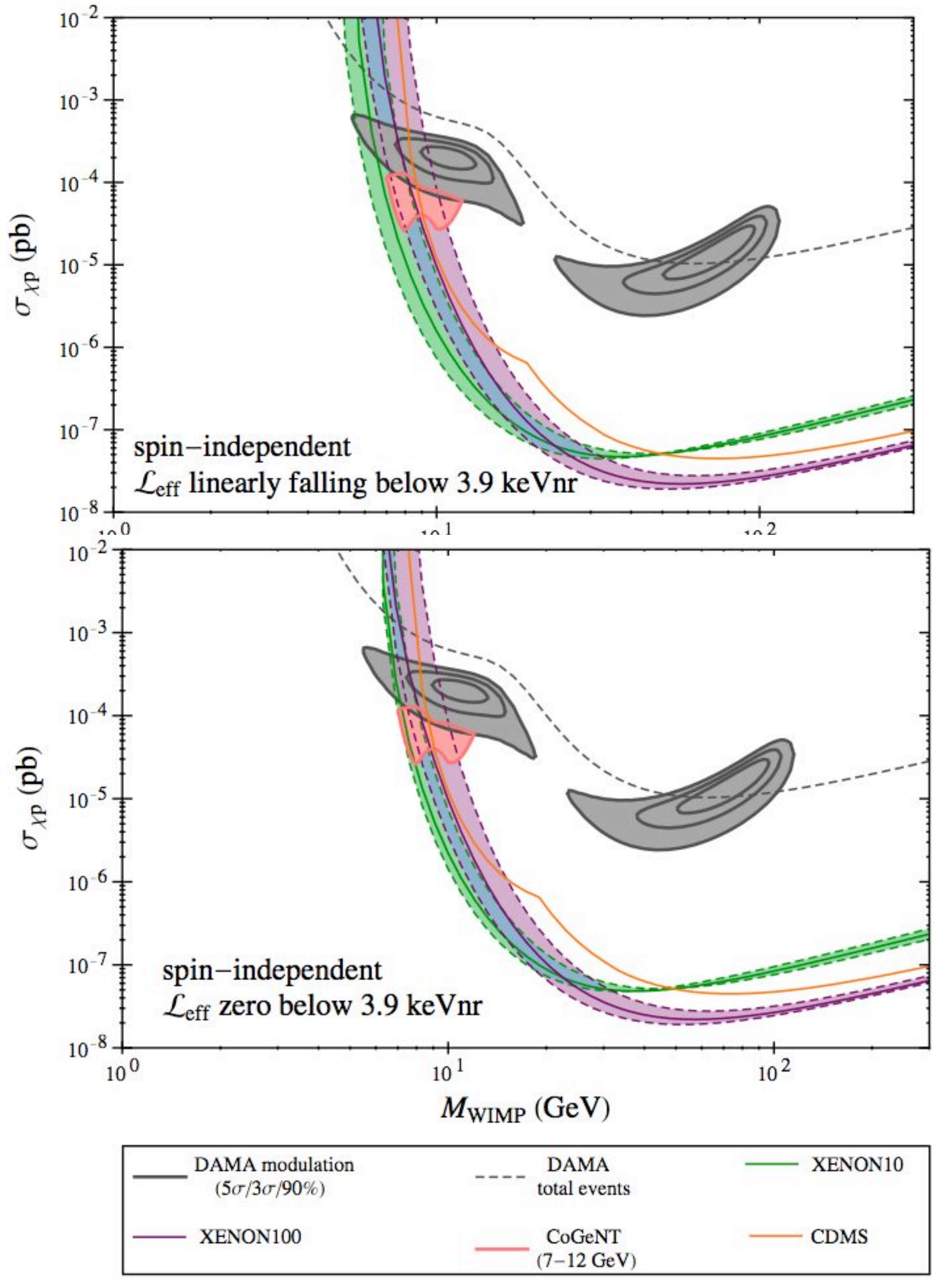
V.Chepel *et al*, Astropart.Phys. **26** (2006) 58
E.Aprile *et al*, Phys.Rev.C **79** (2009) 045807
A.Manzur *et al*, Phys.Rev.C **81** (2010) 025808



see A.Manalaysay, arXiv:1007.3746 [astro-ph.IM]

Physics focus: low-mass WIMPs



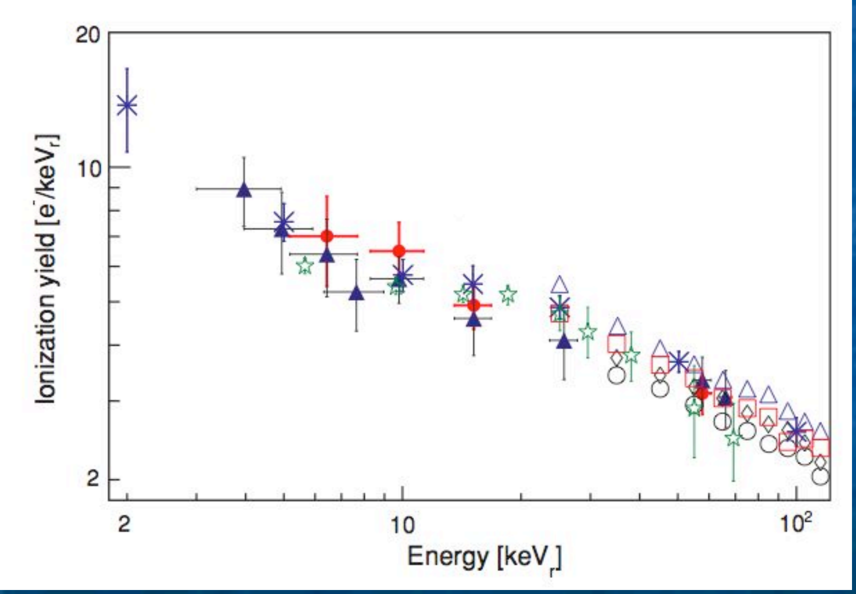


C.Savage has done a thorough investigation of the impact of Leff on the low-mass limits for both XENON10 and XENON100.

C.Savage, G.Gelmini, P.Gondolo, K.Freese, Phys.Rev.D **83** (2011) 055002, arXiv:1006.0972 [astro-ph.CO]

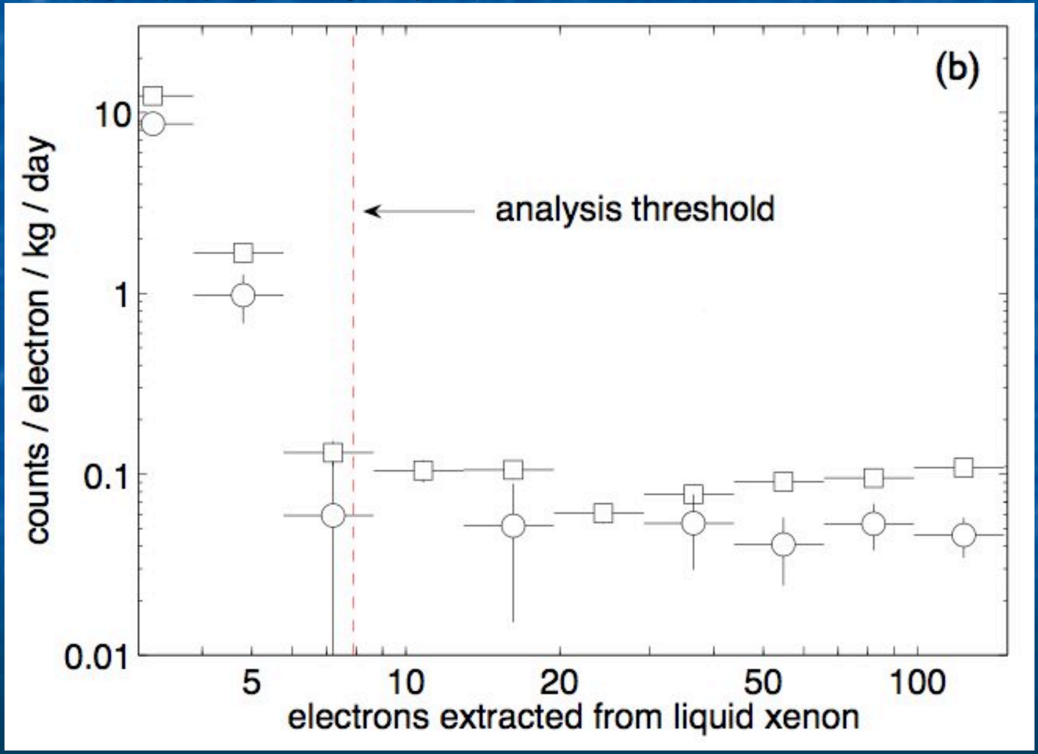
Physics focus: low-mass WIMPs

What if we want to avoid L_{eff}? Dual-phase TPCs also measure ionization. It turns out that measurements of the nuclear recoil ionization yield in LXe are not only consistent with one another, they show a rise at low energies!



plot from: A.Manzur *et al*, Phys.Rev.C **81** (2010) 025808

XENON10's hardware trigger was based on the ionization signal. In one background run, the trigger threshold was at the single electron level! After fiducial cuts, there remained 4 events in 5.8 kg d above a threshold of 1.6 keV.



See P.Sorensen et al, arXiv:1011.6439 [astro-ph.IM]

Physics focus: low-mass WIMPs

What if we wa
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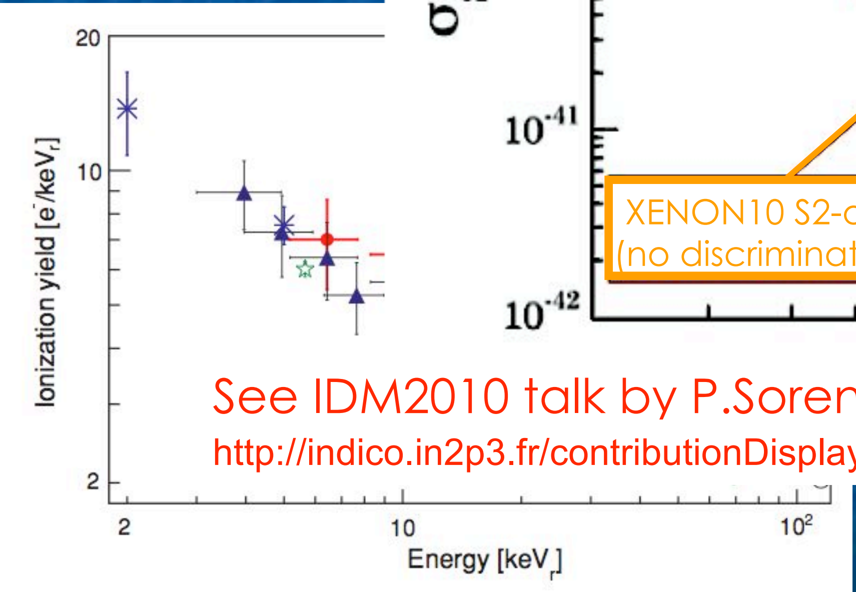
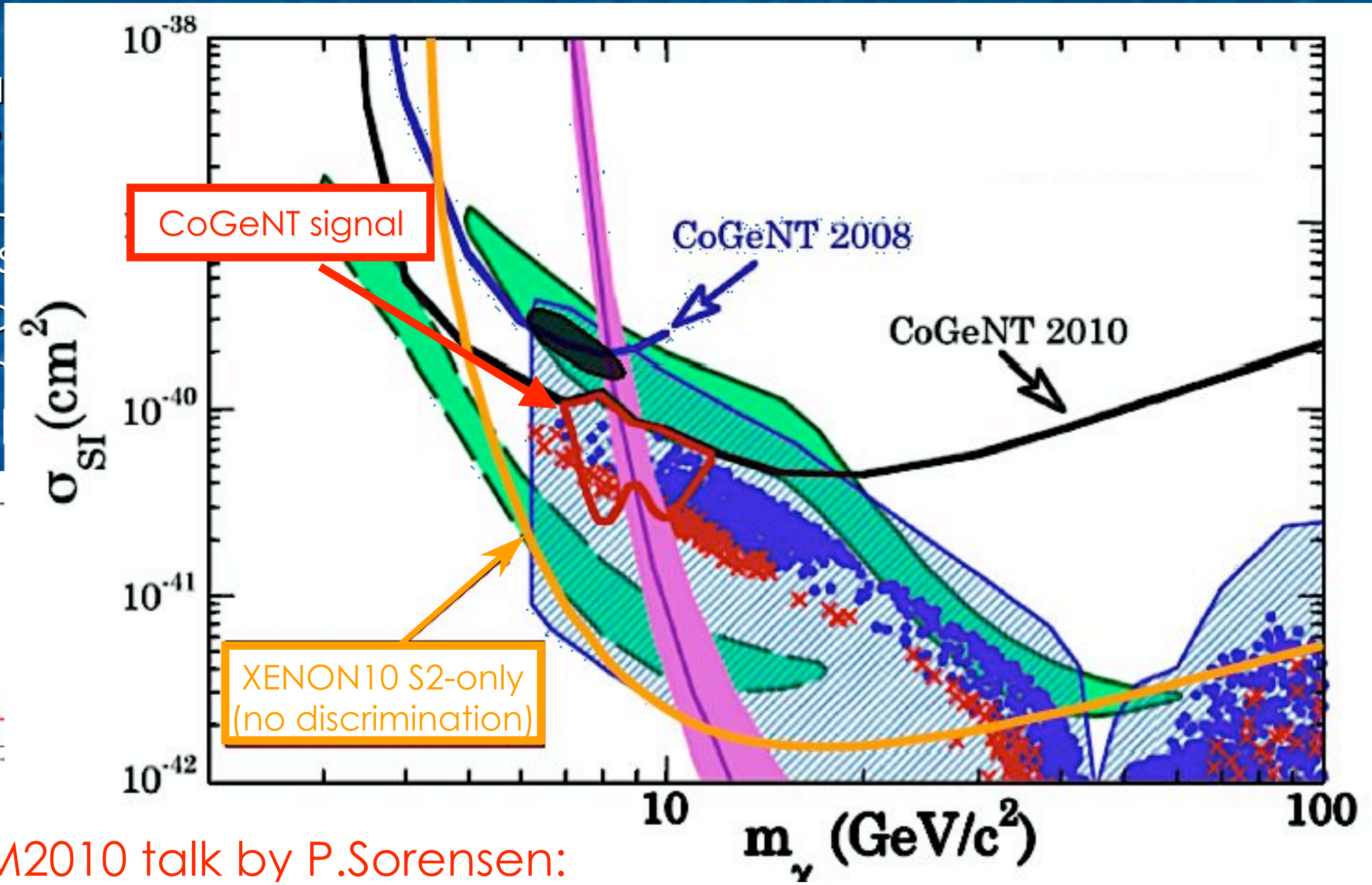
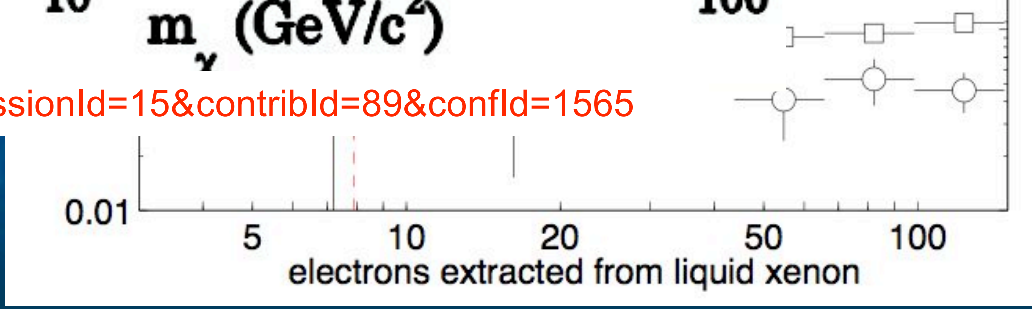






See IDM2010 talk by P.Sorensen:
http://indico.in2p3.fr/contributionDisplay.py?sessionId=15&contribId=89&confId=1565

plot from: A.Manzur *et al*, Phys.Rev.C **81** (2010) 025808

See P.Sorensen et al, arXiv:1011.6439 [astro-ph.IM]

Ongoing and future experiments

Zeplin III
WARP 100l
ArDM
DEAP/CLEAN
Dark Side
LZS

XENON100
XENON1T
XMASS
LUX
PANDAX

Current and next-ish generation noble liquid DM searches

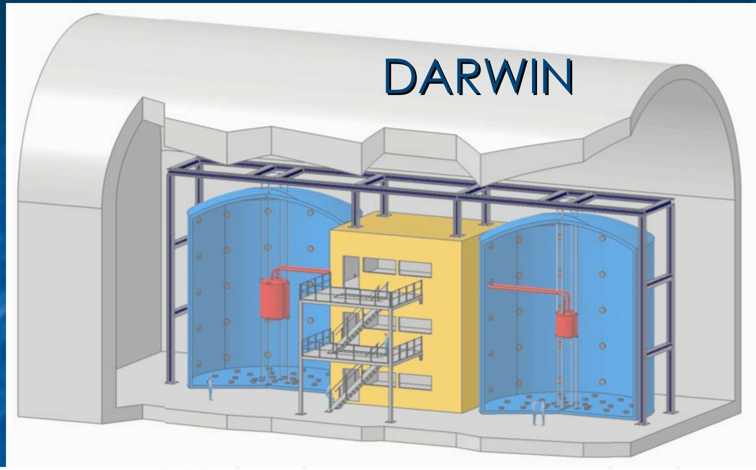
DARWIN

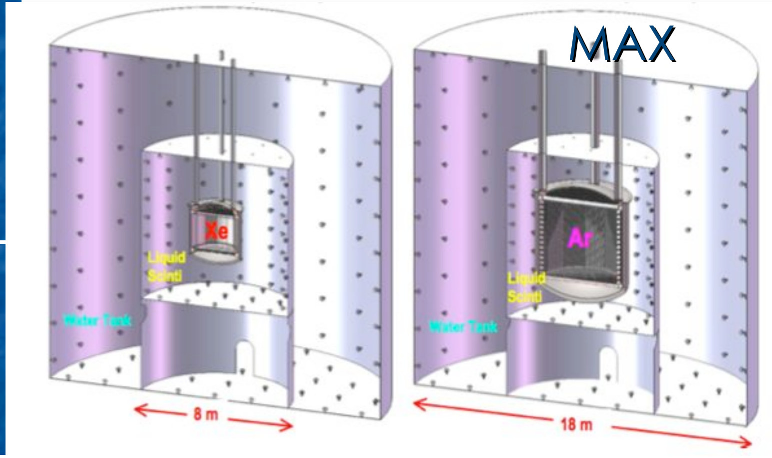
MAX

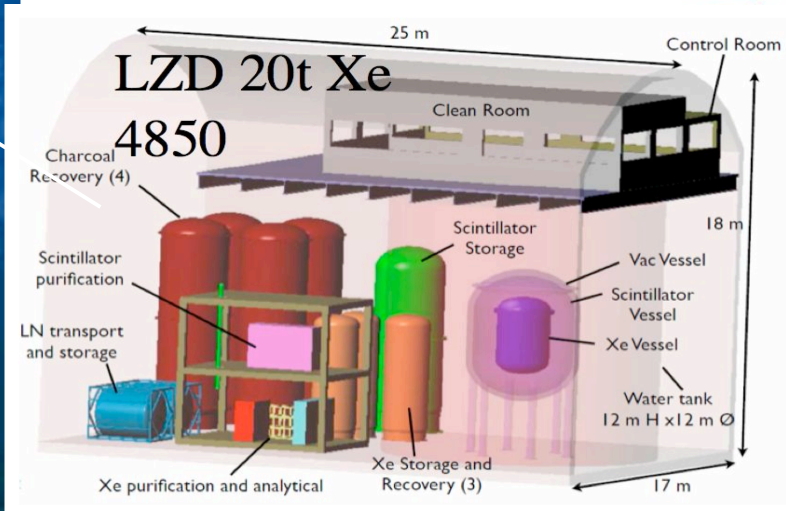
LZD

Ultimate generation

(multi-tonne)



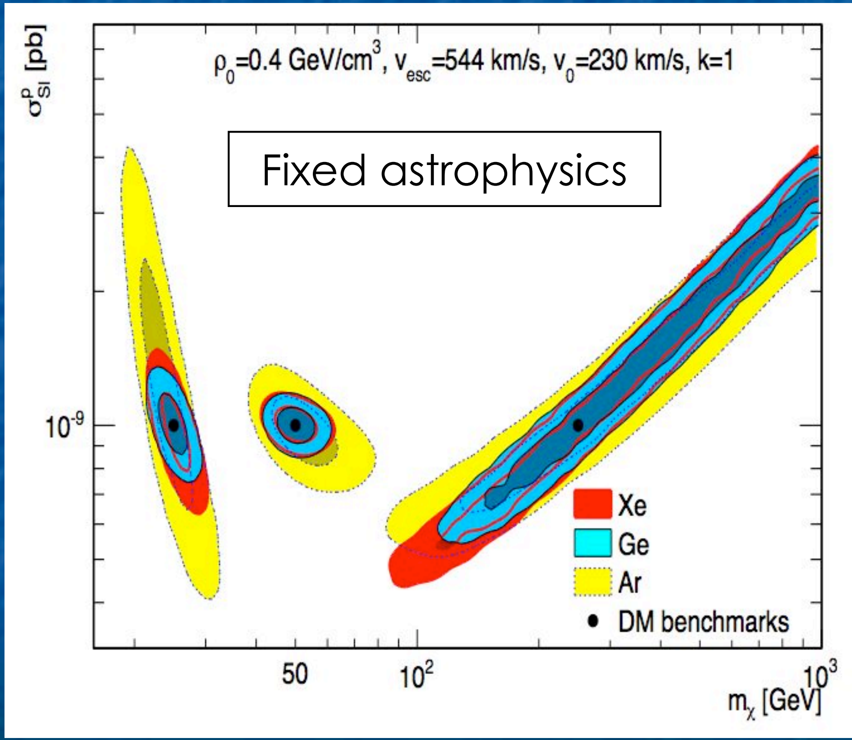




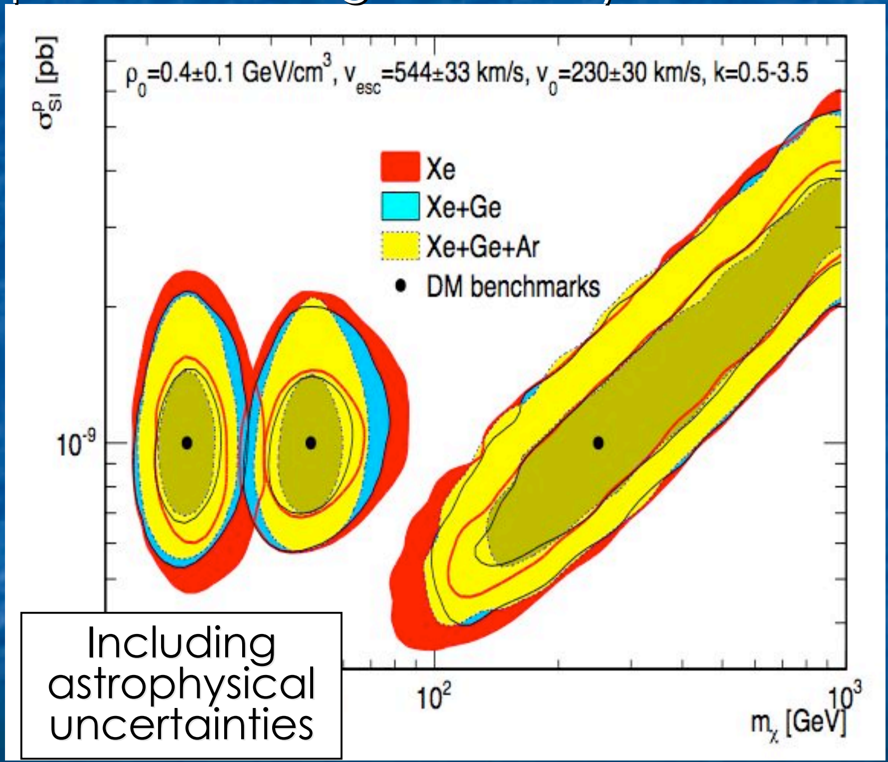
If we get a detection, then what?

Assumptions here:
- *1 tonne Ge, 3 yr op*
- *5 tonne Xe, 1yr op*
- *10 tonne Ar, 1 yr op*

- The constraining power of three targets at the multi-tonne scale is shown for three benchmark cases.

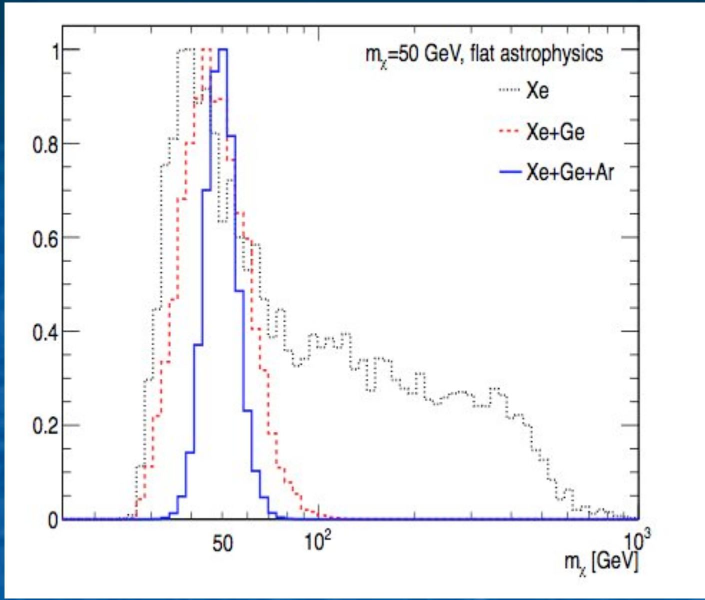


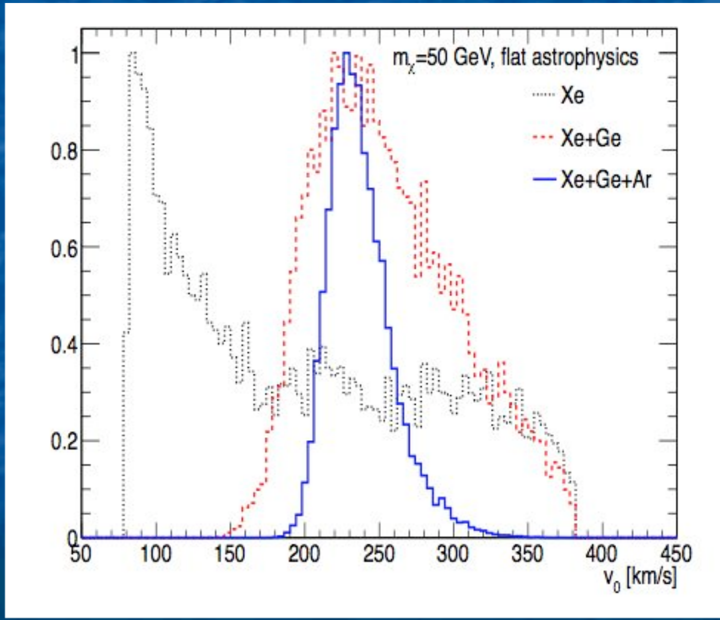
- These are the corresponding constraints if uncertainties in the astrophysical models are also considered. (difficult due to parameter degeneracies)



M.Pato, L.Baudis, G.Bertone, R.Ruiz, L.Strigari, R.Trotta, arXiv:1012.3458 [astro-ph.CO] (accepted in PRD)

If we get a detection, then what?





Or one can do a self-calibration by considering the astrophysicals as free parameters as well. In this way, it may be possible to constrain also the astrophysical parameters even better than they are currently measured. But to do this requires signals in complementary target nuclei.

Assumptions here:

- *1 tonne Ge, 3 yr op*
- *5 tonne Xe, 1yr op*
- *10 tonne Ar, 1 yr op*

M.Pato, L.Baudis, G.Bertone, R.Ruiz, L.Strigari, R.Trotta, arXiv:1012.3458 [astro-ph.CO] (accepted in PRD)

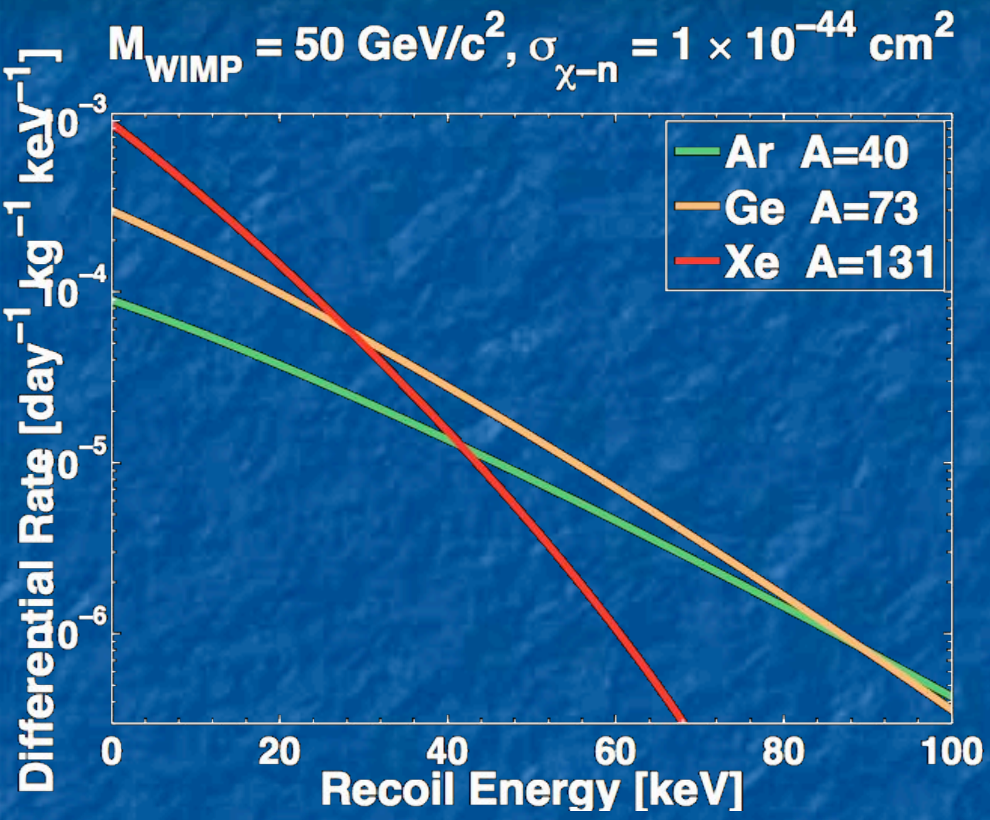
Summary

- Noble liquids are natural for DM detection due to ease of scalability and background reduction.
- Noble liquid DM searches are at the forefront of sensitivity in the field, with current sensitivities at the level of a ~few 10^{-44}.
- The exact sensitivity of XENON100 to low-mass WIMPs (~10 GeV/c^2) depends strongly on the choice of energy scale, but can nonetheless exclude a large portion of parameter space favored by DAMA/LIBRA and CoGeNT.
- The high charge yield of LXe allows XENON10 S2-only data to set very stringent limits on low-mass WIMPs, excluding CoGeNT.
- Multi-tonne liquid noble DM searches will explore WIMPs with deep sensitivity and potentially be able to constrain both particle and astrophysical dark matter parameters.

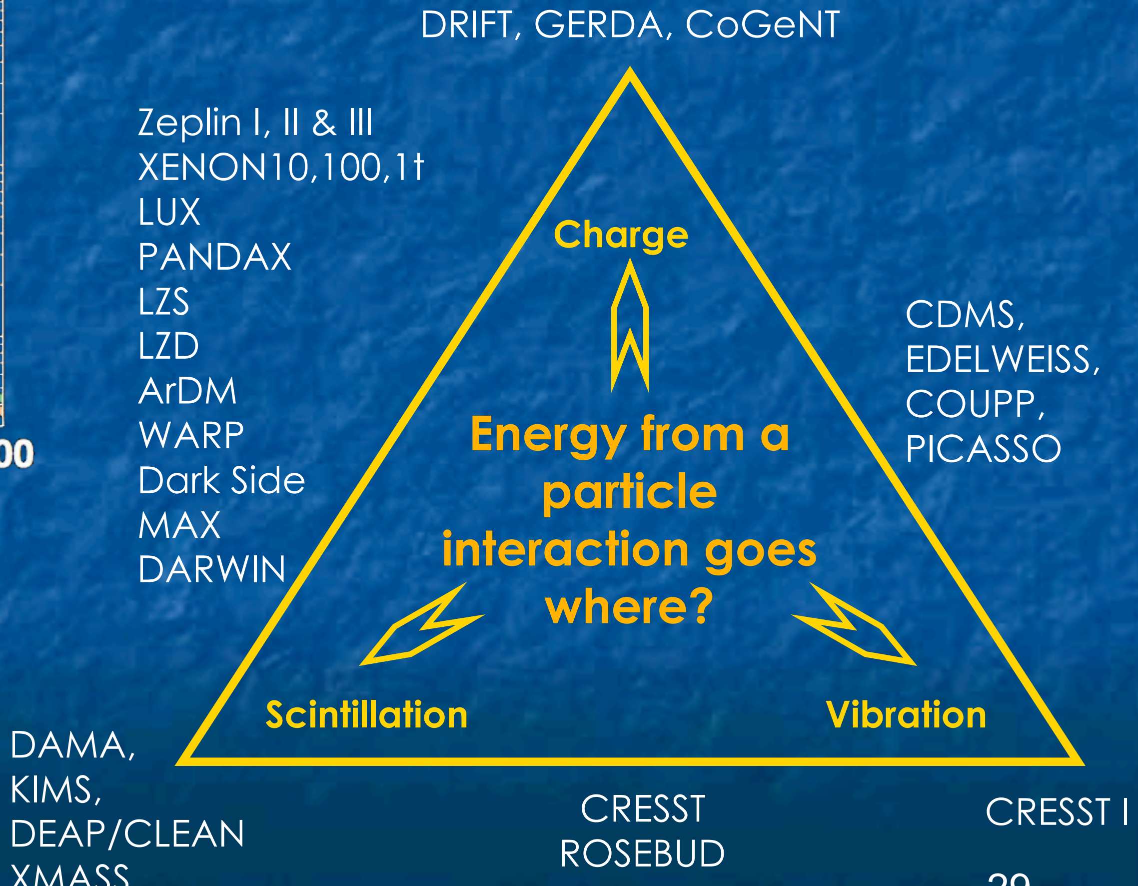
Thanks for your attention!

Fin.

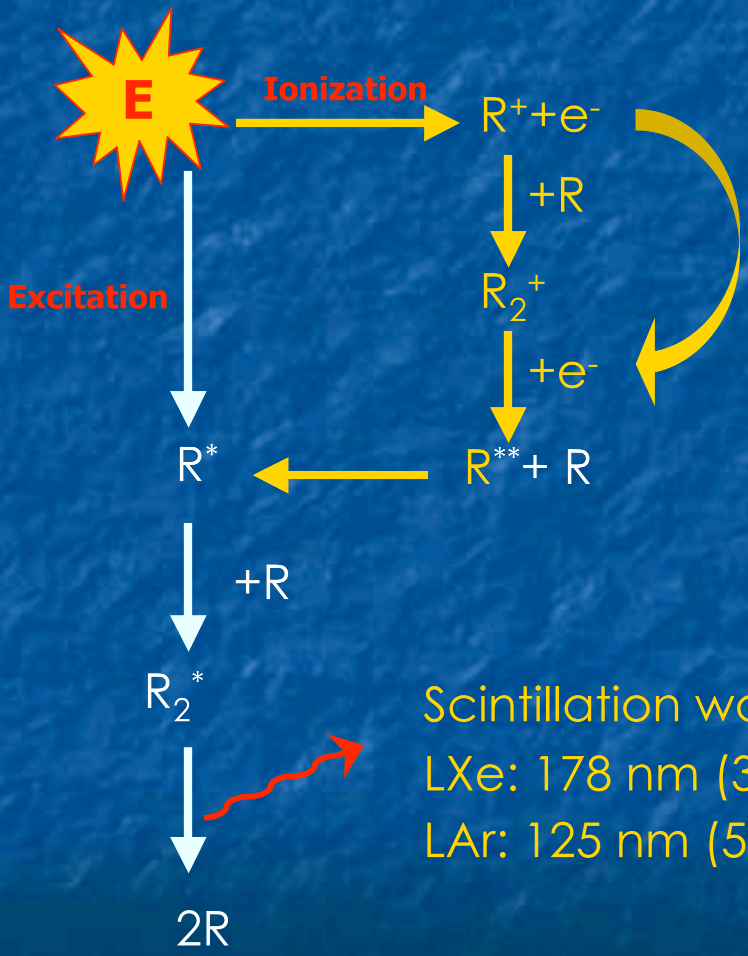
Direct detection



Backgrounds in these experiments are predominantly electronic recoils (gamma, beta), so we need need a technique for identifying/rejecting these interactions from a DM search.



Particle interactions



An applied E field can partially interrupt this step to collect these electrons

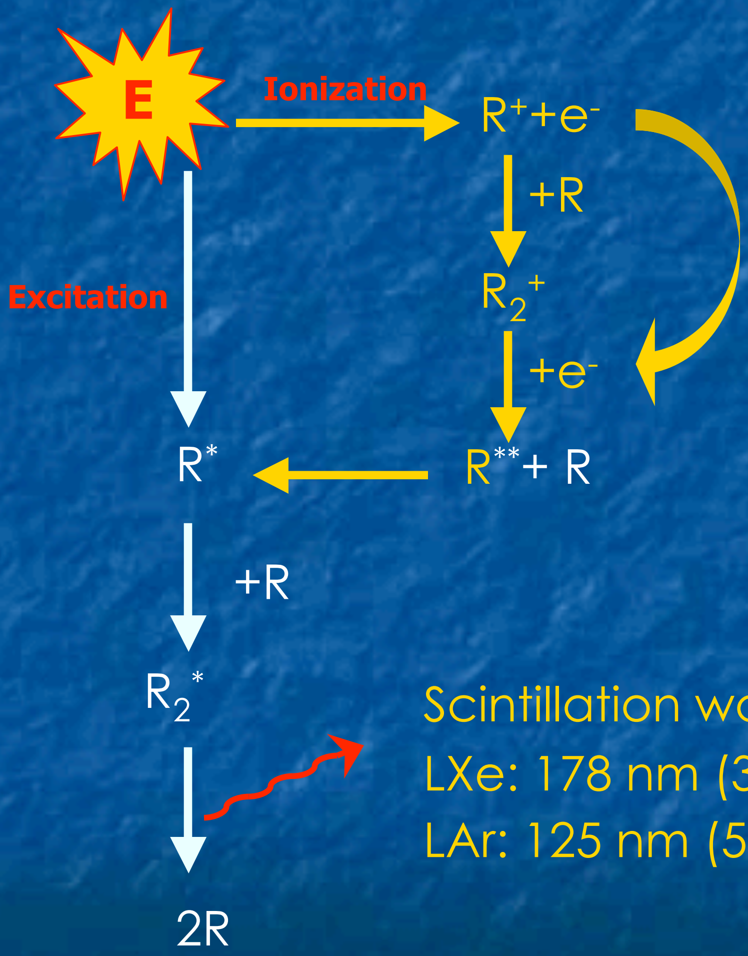
Scintillation wavelength (singlet/triplet times)

LXe: 178 nm (3 ns / 27 ns)

LAr: 125 nm (5 ns / 1.6 μs)

"R" = noble liquid atom

Particle interactions



Nuclear recoil discrimination uses the ratio of electrons/photons, and/or ratio of single/triplet components. The e/ph ratio gives electronic recoil rejection at the level of ~99.5-99.9%. In liquid argon, combining that with the sing/trip ratio gives 99.99999-99.999999% rejection!

Scintillation wavelength (singlet/triplet times)

LXe: 178 nm (3 ns / 27 ns)

LAr: 125 nm (5 ns / 1.6 μs)

"R" = noble liquid atom

WARP 2.3l (1)

Dual-phase liquid argon TPC, operated at the Gran Sasso National Laboratory (LNGS, Assergi, Italy). First results released 2007. 3.2 kg F.M., 100 kg d exposure.