Westfälische Wilhelms-Universität Münster

Direct Search for Dark Matter

Schule für Astroteilchenphysik, Bärnfels-Obertrubach, Oktober 2014

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- Astrophysical evidence for Dark Matter
- Dark Matter candidates
- WIMP interaction rates and experimental requirements
- Cryobolometer experiments
- Liquid noble gas experiments
- Conclusions

Summary of 3rd lecture

Problems: background and small signal energy
→ go underground and smart screening techniques
→ observe signal in various variables:
charge, light, heat (and annual modulations)

Possible evidences at low WIMP masses
are fading away by better experimental data except DAMA/LIBRA result

DAMA signal: still under discussion, but excluded by many exp.
CoGeNT: explanation by MALBEK
CRESST: new design solves problem with too many alphas

Large progress by cryo-bolometer technology

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Large progress by cryo-bolometer technology

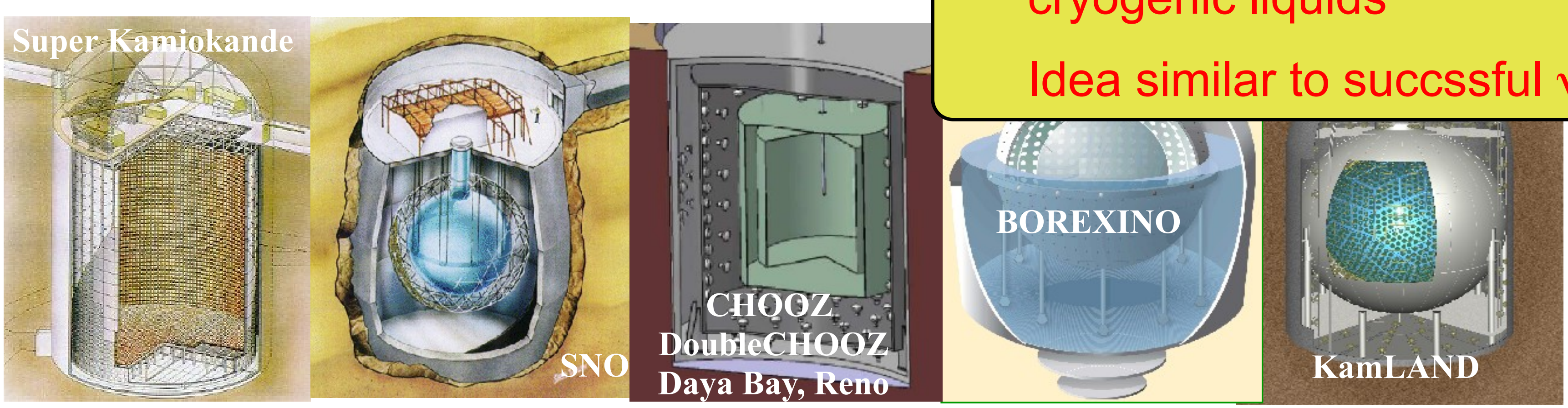
Problems come most of the time from surface contaminations

→ increase volume/surface

Dark matter not yet detected
→ need to have larger detectors to get sensitive to lower σ

→ use the most clean large mass materials available:
cryogenic liquids

Idea similar to succssful ν exp.



Liquid noble gas detectors

	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	40,000	^{39}Ar, ^{42}Ar	1.6
LKr	2.4	120	1200	150	25,000	^{81}Kr, ^{85}Kr	0.09
LXe	3.0	165	2200	175	42,000	^{136}Xe	0.03

269 y (^{39}Ar)

$2\ 10^{21}$ y (^{136}Xe)

Scintillation by forming excited dimers

→ noble gas is transparent for scintillation light

Different live times of singlet and triplet states

→ discrimination between nuclear recoil and electron recoil possible for Argon detectors

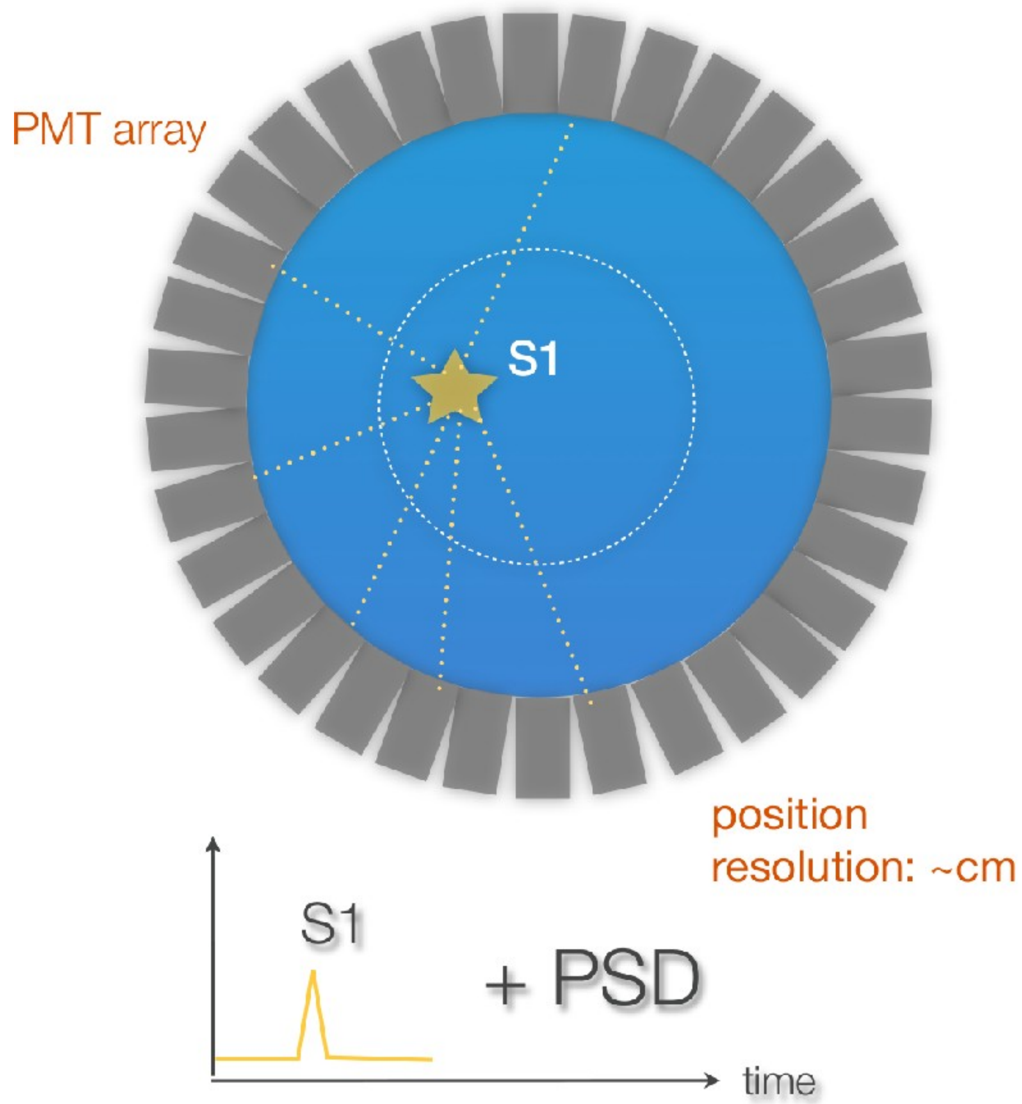
Charge vs light (charge quenching)

→ discrimination between nuclear recoil and electron recoil possible

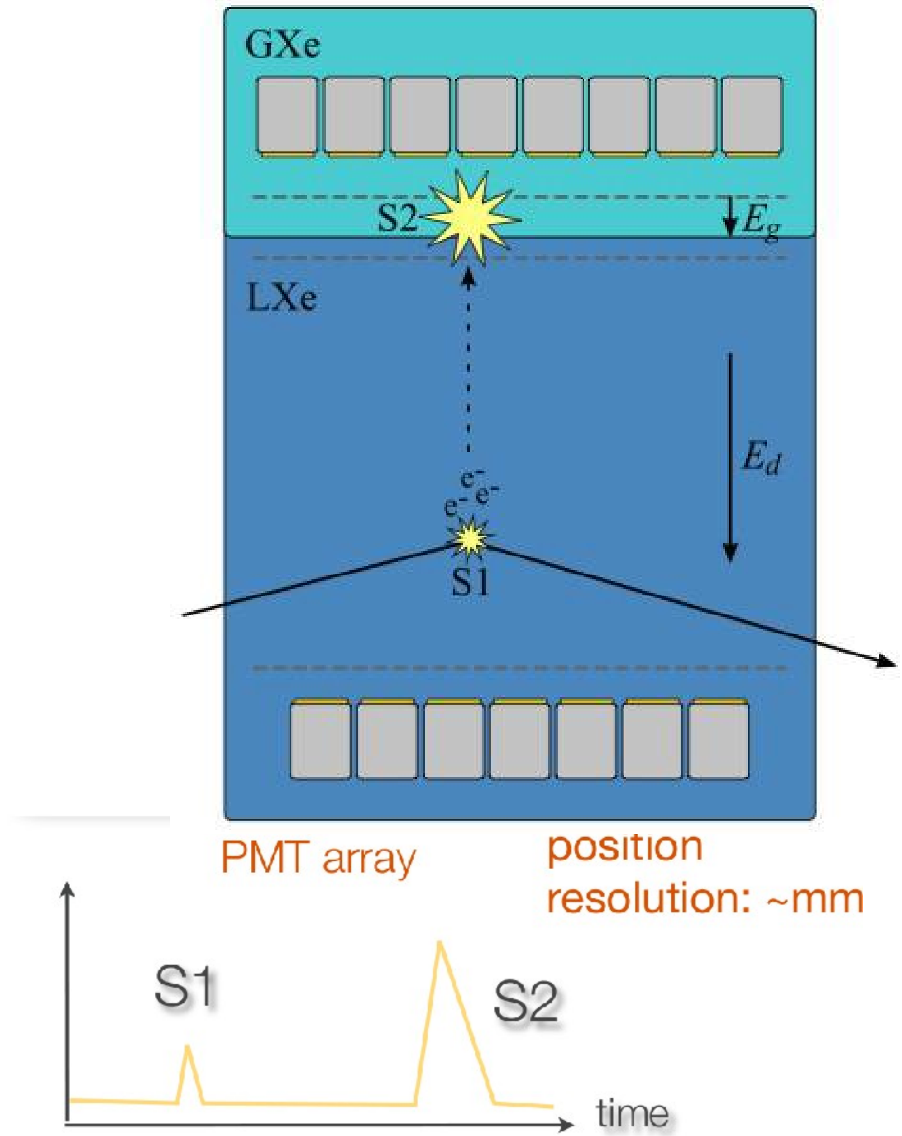
$$\mathrm{Xe}^* + \mathrm{Xe} + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^* + \mathrm{Xe},$$
$$\mathrm{Xe}_2^* \rightarrow 2\mathrm{Xe} + h\nu,$$
$$\mathrm{Xe}^+ + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^+,$$
$$\mathrm{Xe}_2^+ + e^- \rightarrow \mathrm{Xe}^{**} + \mathrm{Xe},$$
$$\mathrm{Xe}^{**} \rightarrow \mathrm{Xe}^* + \mathrm{heat},$$
$$\mathrm{Xe}^* + \mathrm{Xe} + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^* + \mathrm{Xe},$$
$$\mathrm{Xe}_2^* \rightarrow 2\mathrm{Xe} + h\nu.$$

Dual phase liquid noble gas detectors: two basic concepts

Single phase



Dual phase



following a slide from L. Baudis, TAUP 2013

Dual phase liquid noble gas detectors eg. XENON 100: basic principle

Detector: liquid xenon time projection chamber (-91 °C)

in passive shield (γ and neutron shield)

WIMP interaction

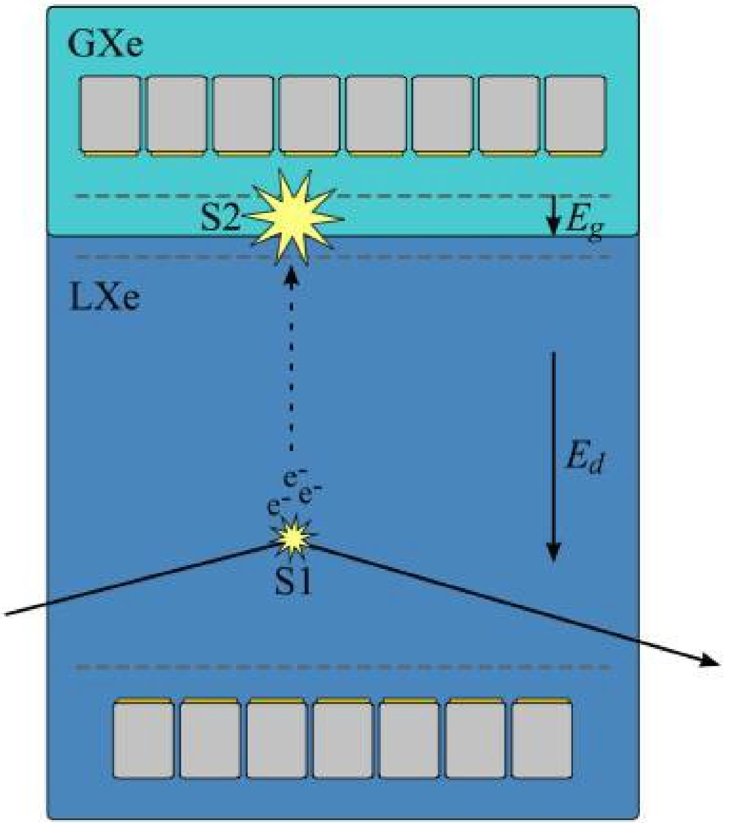
⇒ prompt scintillating light S1

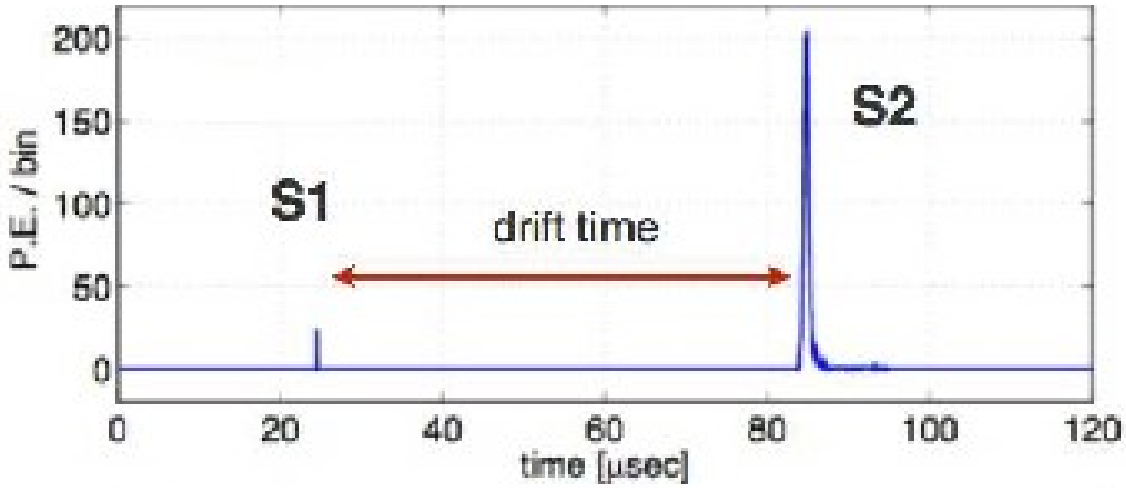
electrons drifted into gas phase

by drift field in LXe (0.5-1 kV/cm)

⇒ proportional light (S2) by electro-luminescense

in GXE (10kV/cm)



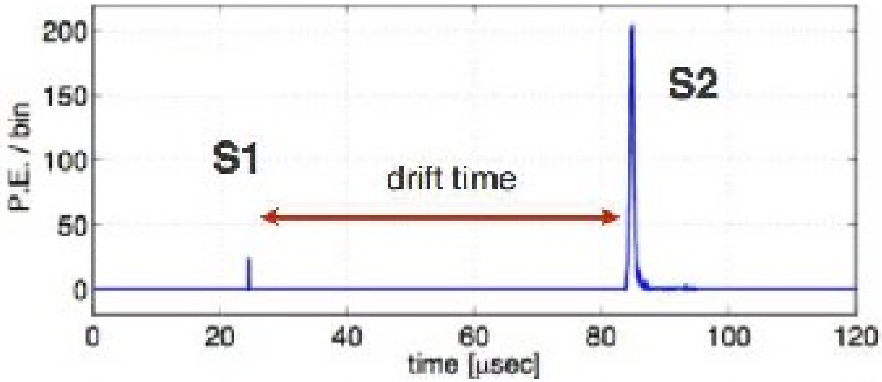


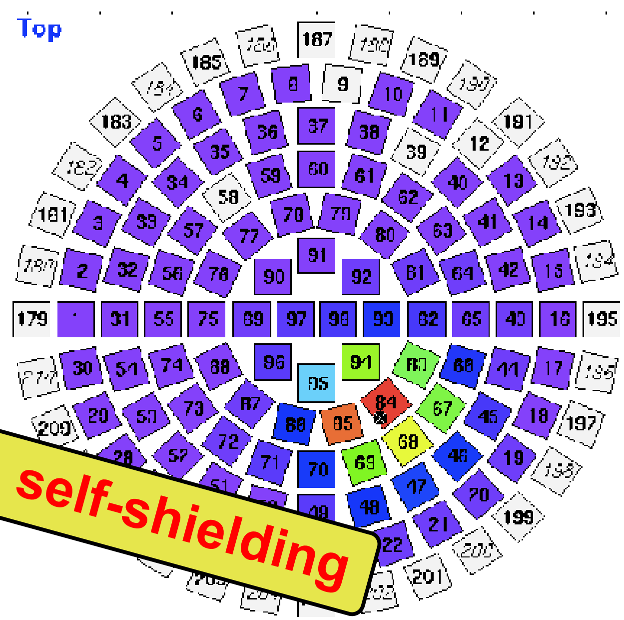
Dual phase liquid noble gas detectors eg. XENON 100: position reconstruction

Drift time of charge to liquid / gas interface = Dt(S1-S2):

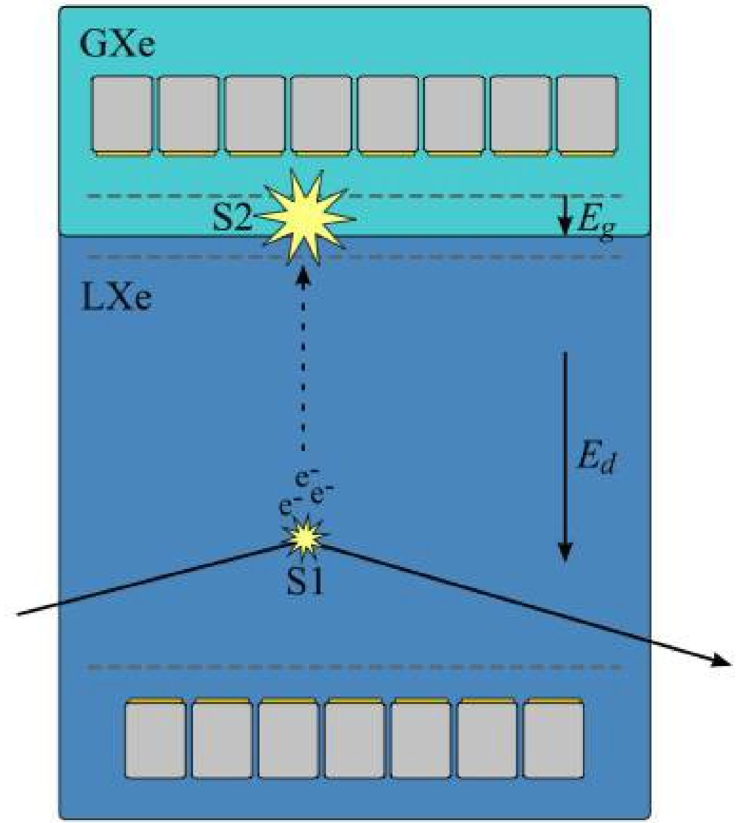
in LXe: 0.53 kV/cm: v_d = 1.7 mm/μs

→ vertical position precision: Δz = 0.3 mm





⇒ fiducialisation & self-shielding

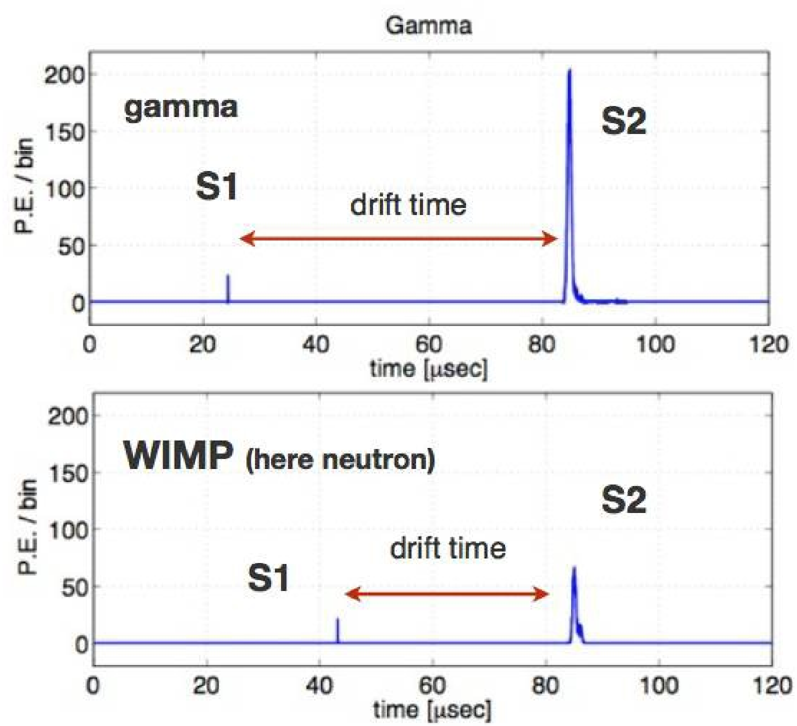


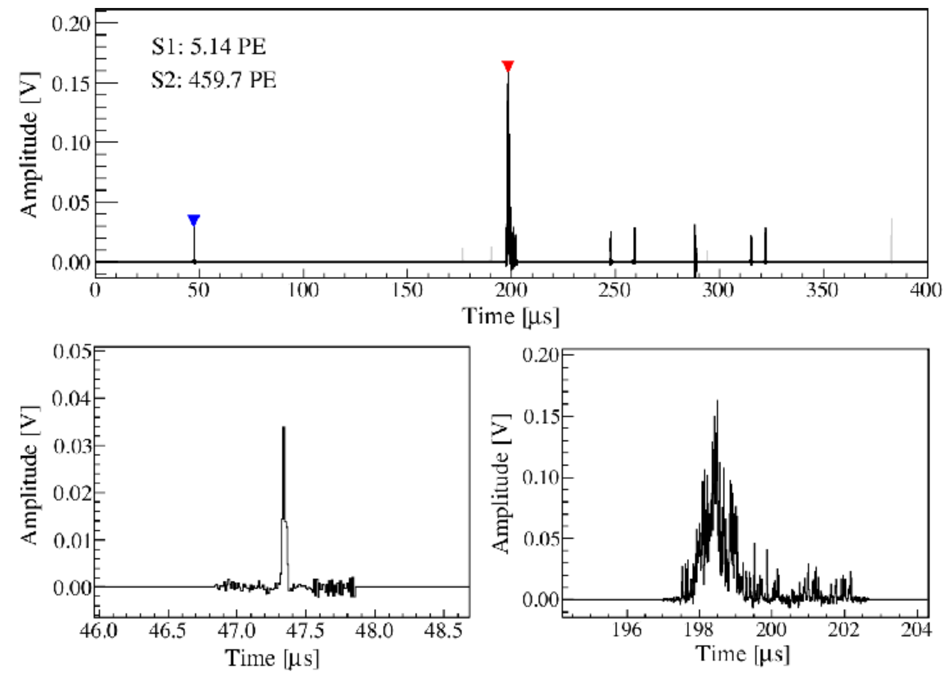
Electroluminescence in GXe

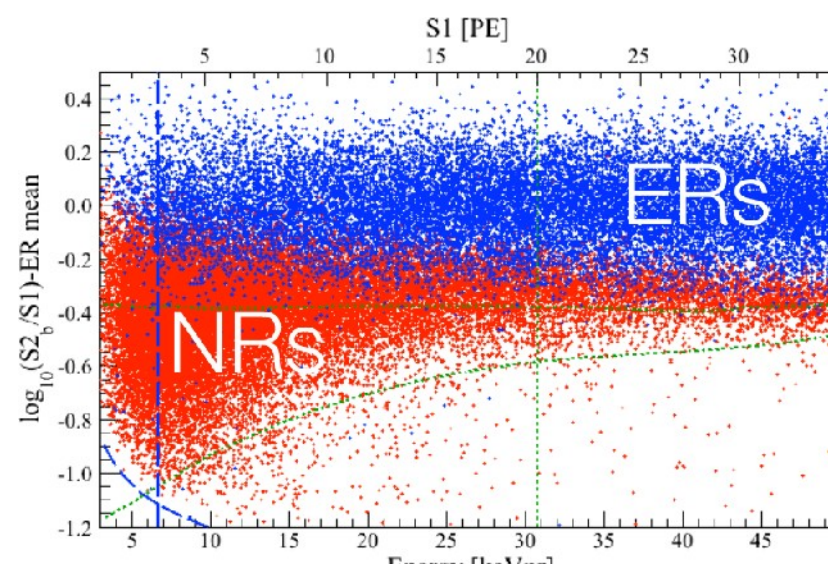
→ light pattern on top PMT array provides horizontal position with Δx = 3 mm = Δy precision

Dual phase liquid noble gas detectors, e.g. XENON 100: nuclear recoil and e-/γ separation

Distinguish nuclear recoil
(WIMP, n → charge quenching)
from electronic recoil (background)
using S2/S1 ratio







⇒ 99.5% background rejection
@ 50% nuclear recoil acceptance

Dual phase liquid noble gas detectors, e.g. DarkSide: nuclear recoil and e-/γ separation

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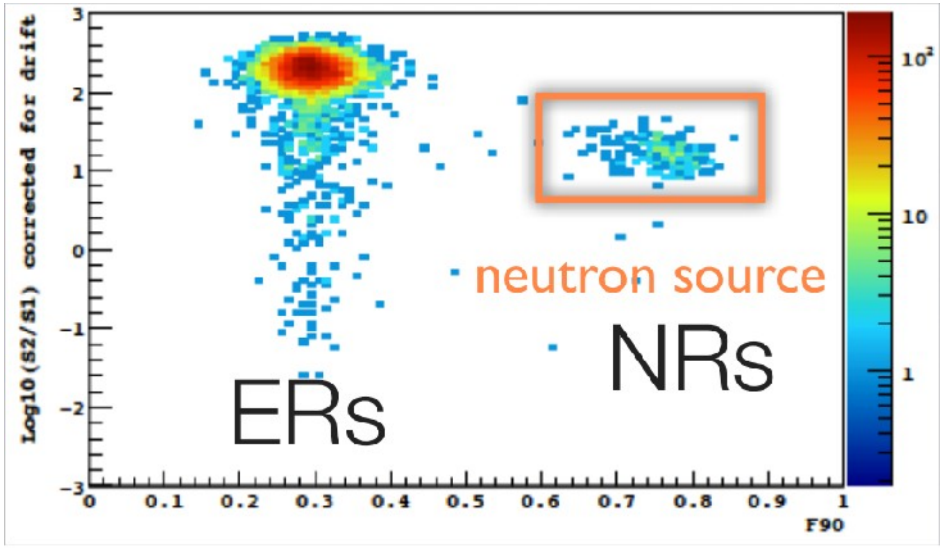
Distinguish nuclear recoil (WIMP, n → charge quenching)
from electronic recoil (background)
using triplet-to-singlet ratio (light decay time)

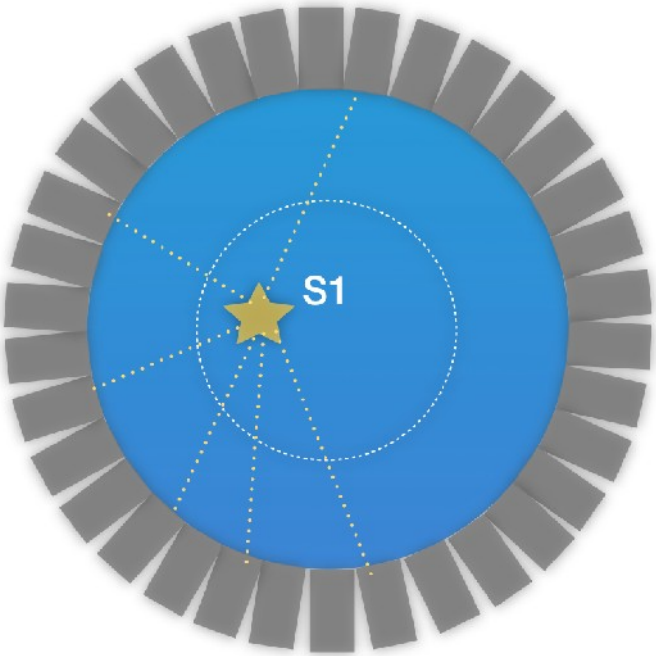


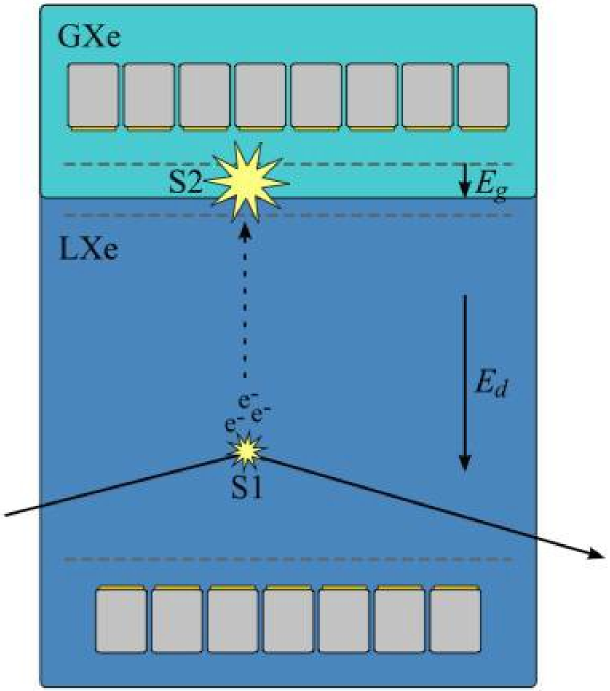
from L. Baudis, TAUP 2013

LAr (DarkSide-10)

⇒ very high background rejection of O(10^{-7}) possible but it is needed because of ^{39}Ar

Dual phase liquid noble gas detectors: challenges





Challenges: ultra-pure liquid noble gas (<1ppb O_2)

reduction of radioactive noble isotopes (^{39}Ar, ^{85}Kr, ^{222}Rn)

efficient charge extraction

high E-field (e.g. 0.5-1kV/cm in LXe, 10kV/cm in GXe)

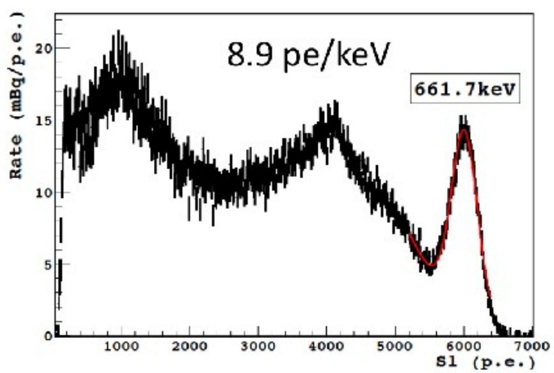
efficient light collection @178 nm (LXe), @128 nm (LAr)

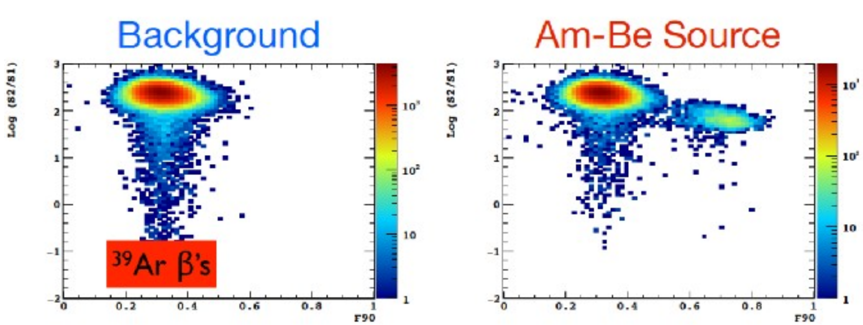
Darkside-50: 2-phase Ar in LNGS depleted in ^{39}Ar, aim: $\sigma = 2\ 10^{-46}\ cm^2$

from D. McKinsey, Aspen 2013

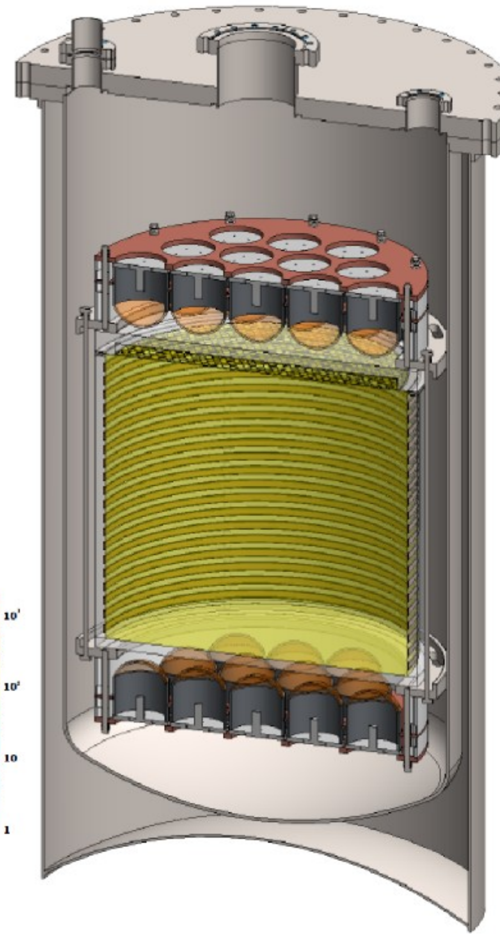
Darkside G2: 5t Ar, aim: $\sigma = 10^{-47}\ cm^2$

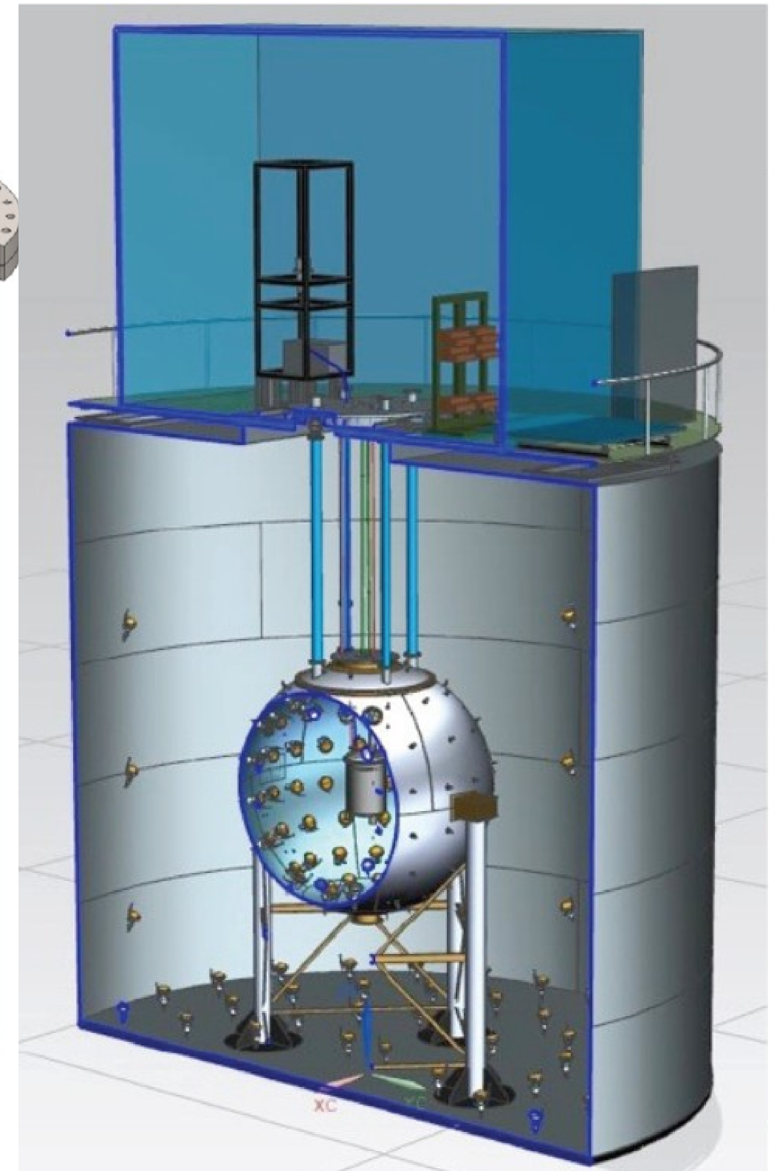
DS-10 data





DS-50 model



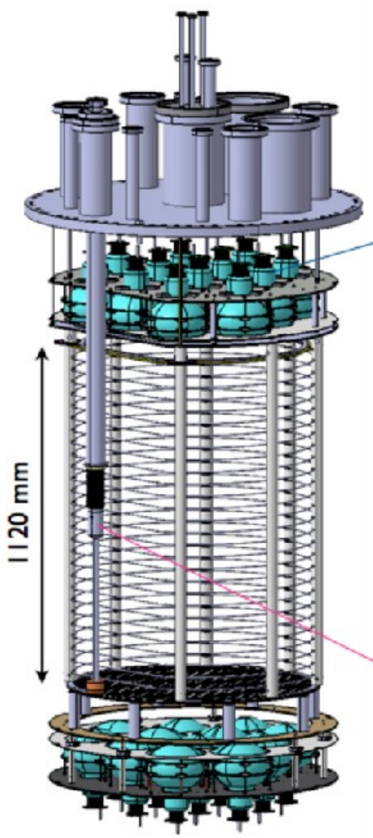


Other Ar detectors: ArDM in Canfranc, Deap/Clean in SNOLab

from D. McKinsey, Aspen 2013

miniClean: 500 kg LAr
commissiong in 2013
^{39}Ar spiking for PSD tests

ArDM



Fully PMT-based readout
(initial configuration)

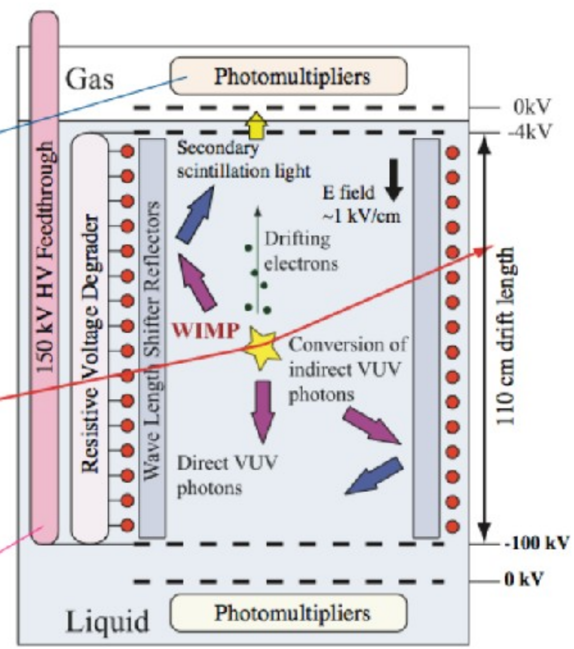
Top PMT array in gas phase
and bottom array in liquid,
both will be newly built :

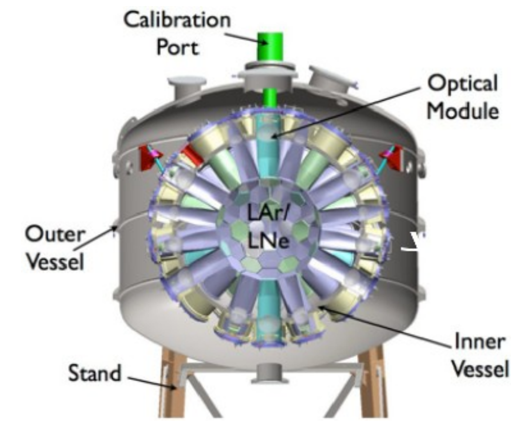
- new PMT supporting structure
- new layout with 12 PMTs
- fresh coating with wave-length shifting TPB

HV feedthrough for drift field

Modified field cage

Slide from A. Rubbia





Deep-3600: 3.6 t LAr
commissiong in 2014

Arguments for a Xenon detector

Heavy nucleus (A~131):
→ good for spin-indenpendent interaction
(coherent scattering off all nucleons)
SD sensitivity too (~50% odd isotopes)

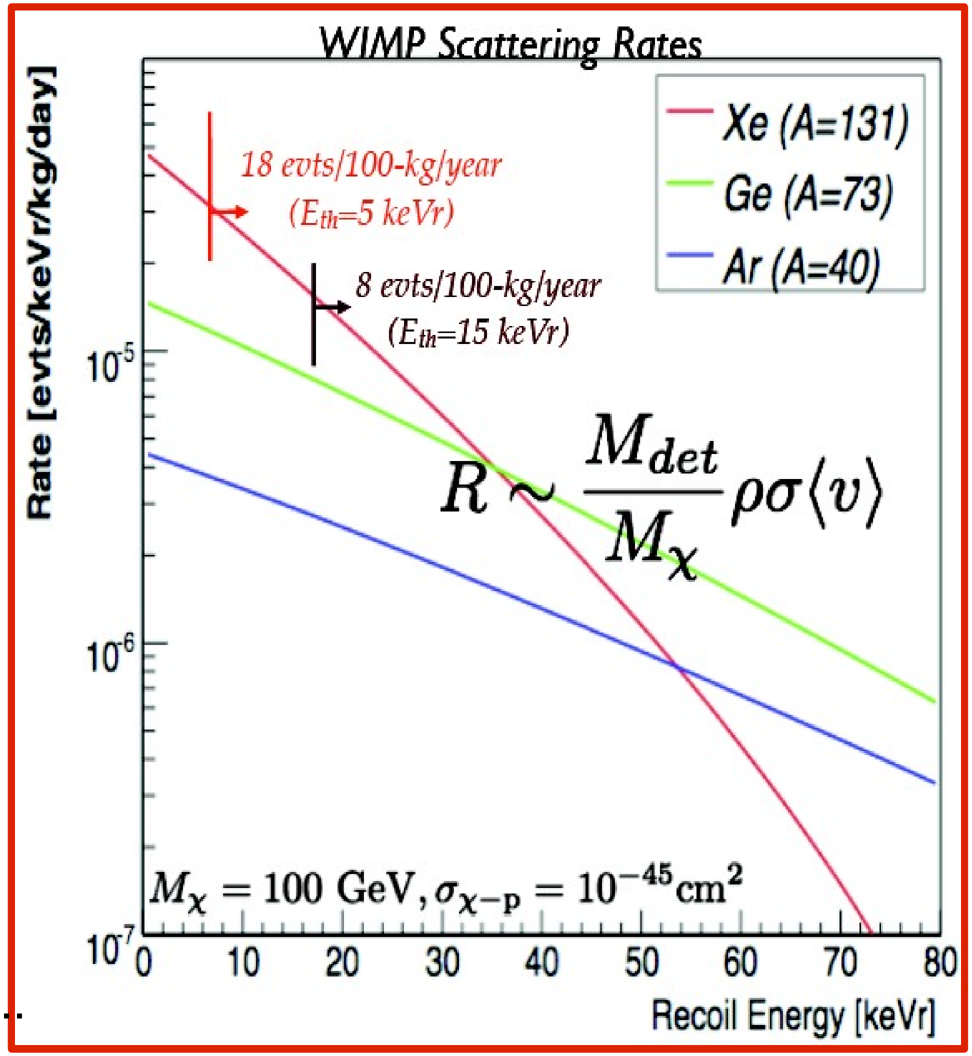
High nuclear charge (Z=54)
→ very good self-shielding

Ultraclean material
liquid noble gases are among the most clean materials
no long-lived isotope except
^{136}Xe: $t_{1/2}$ = 2 10^{21} yr, 8.9% nat. abund.

Very high charge & light yield:
42,000 γ / MeV at 178nm (PMTs exist)

Proven XENON technology with
high efficiency & low energy threshold,
background rejection methods, fiducialisation, ...

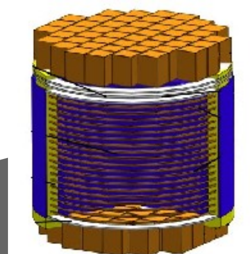
Moderate cost (<1k$/kg),
effort scales with surface not volume



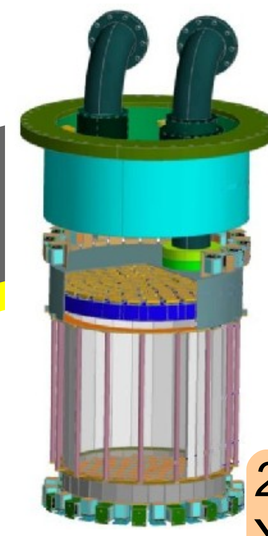
(for details see E. Aprile, T. Doke, Rev. Mod. Phys. 82 (2010) 2053)

The XENON collaboration

XENON: WIMP search in staged phases

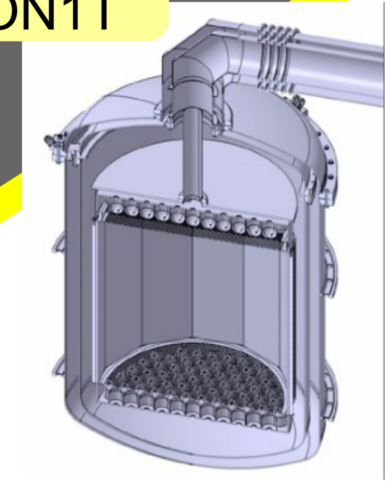


2005-2007:
XENON10



2008-2014:
XENON100

2012- ...:
XENON1T



Columbia Rice UCLA Zürich Coimbra LNGS INFN Purdue RPI

Bologna Subatech Münster Heidelberg Nikhef Weizmann Mainz Bern

XENON100

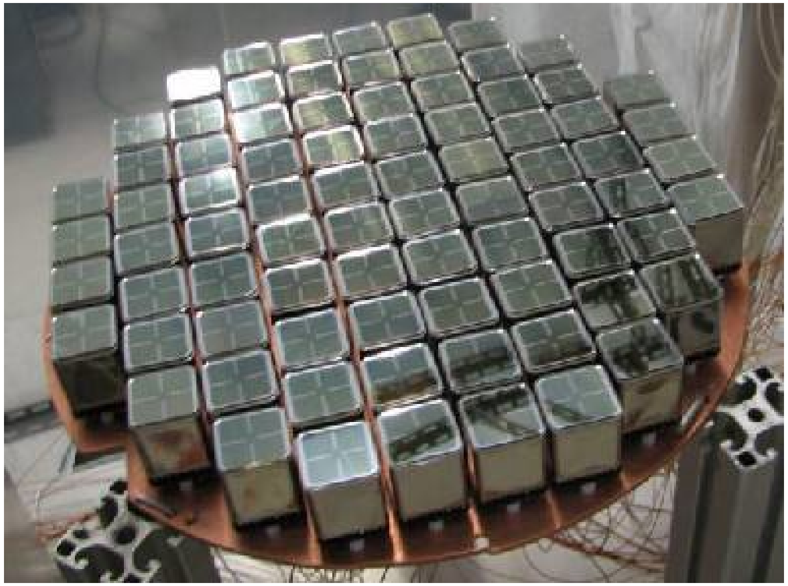
TPC:

161 kg two phase GXe & LXe TPC

TPC: 30.5 cm diameter
30.6 cm height
→ 62 kg active target
99 kg LXe veto (> 4 cm)

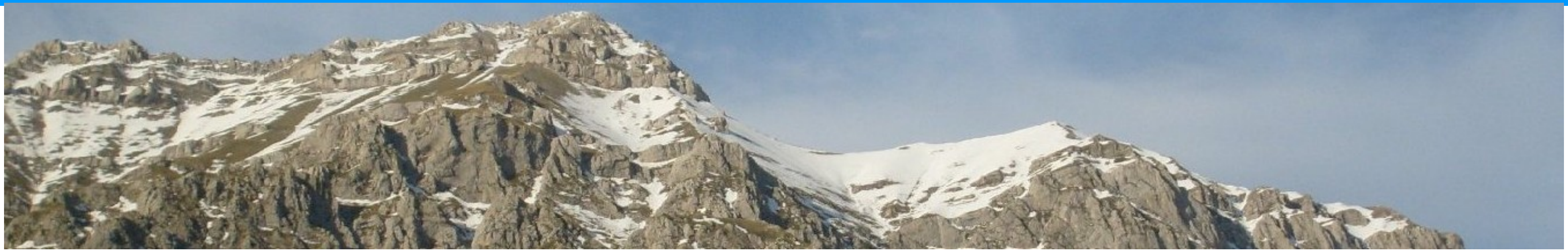
98 + 80 (+64) 1“ x 1“ R8520-AL PMTs

Xe purified by distillation to ≈ 20 ppt Kr

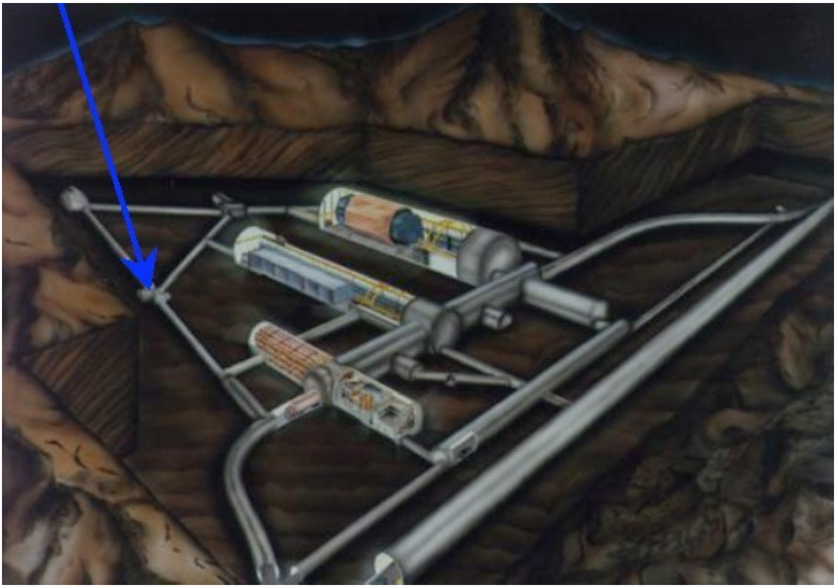


E. Aprile et al., Astropart. Phys. 35 (2012) 573

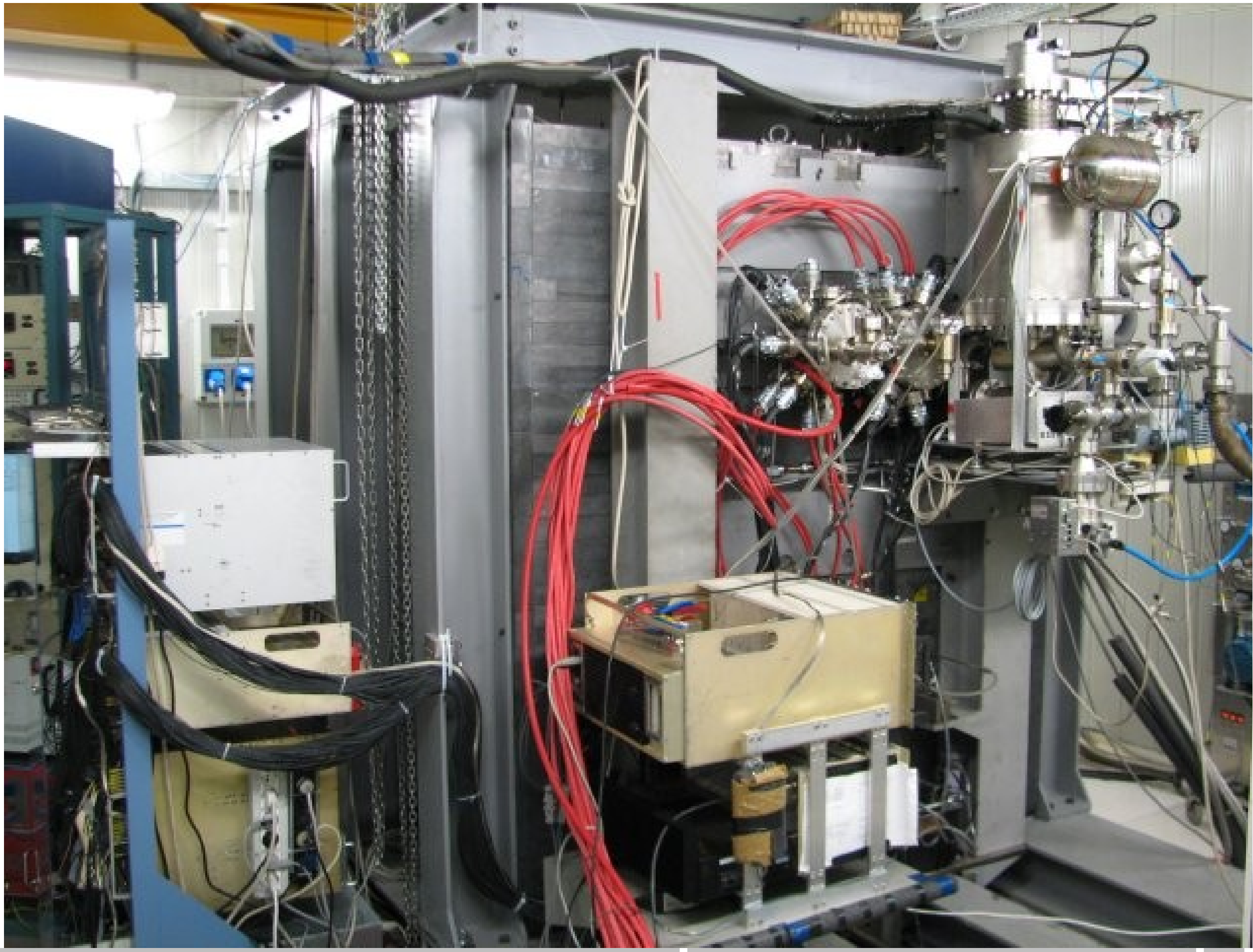
XENON100 @ LNGS



LNGS: 1.4km rock
(3700 mwe)



passive shield: H_20, lead, polyethylene, copper



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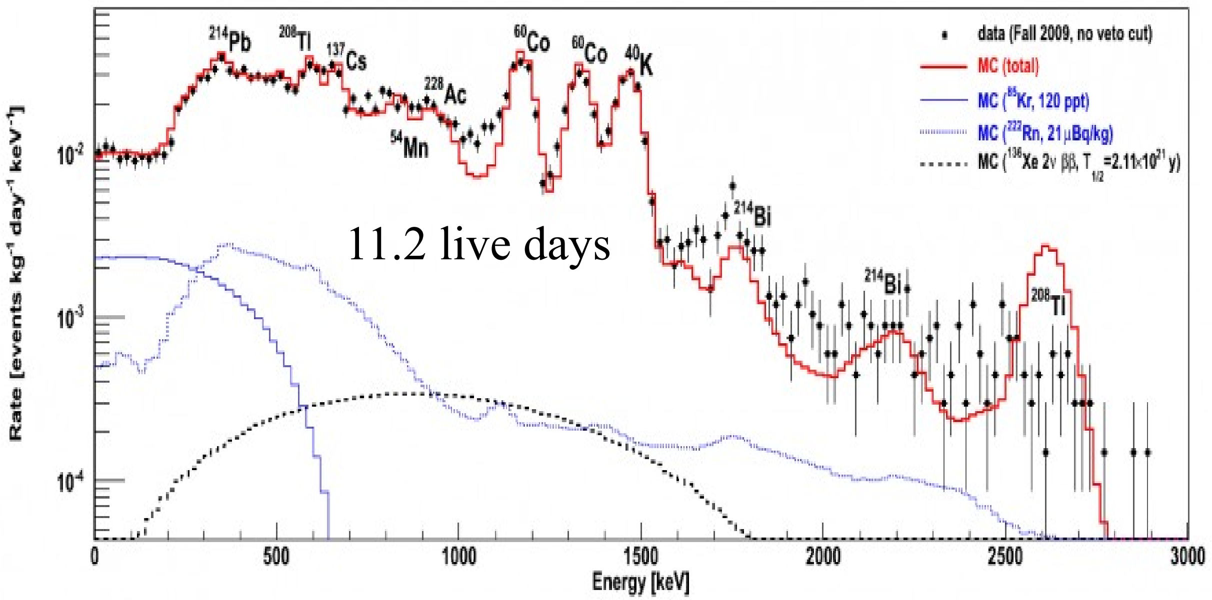
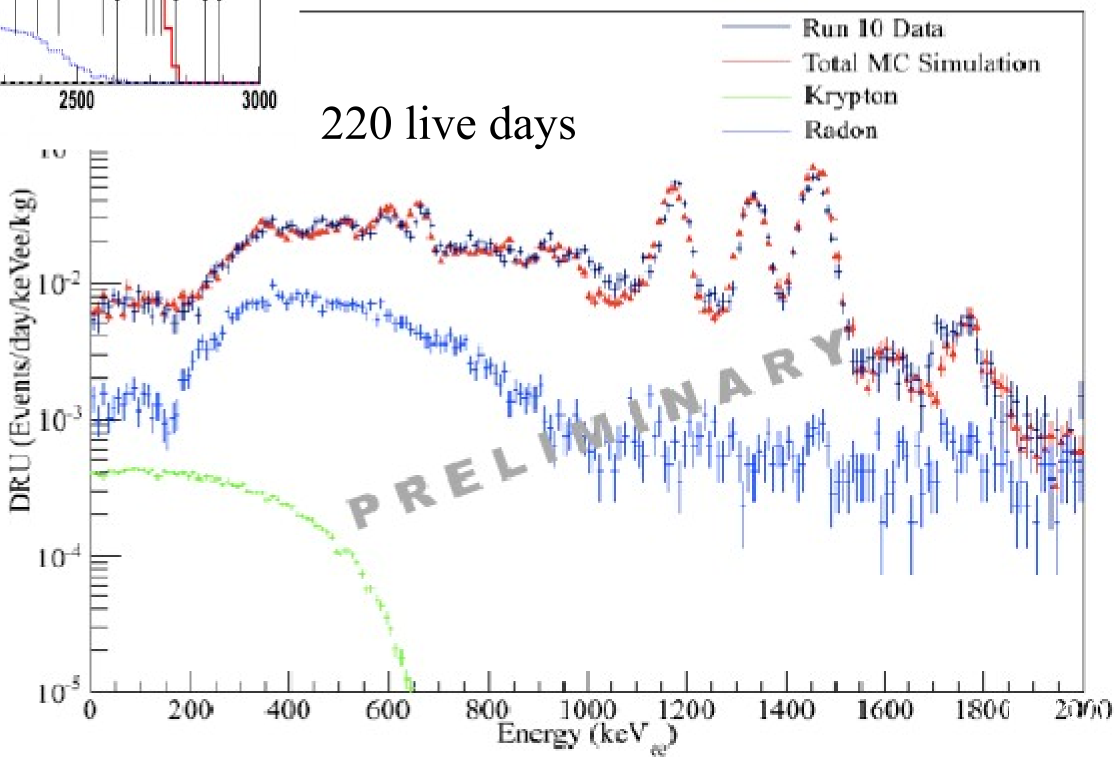
XENON100 Dark Matter run 10: improved background at low energies



E. Aprile et al. Phys.Rev.D83 (2011) 082001

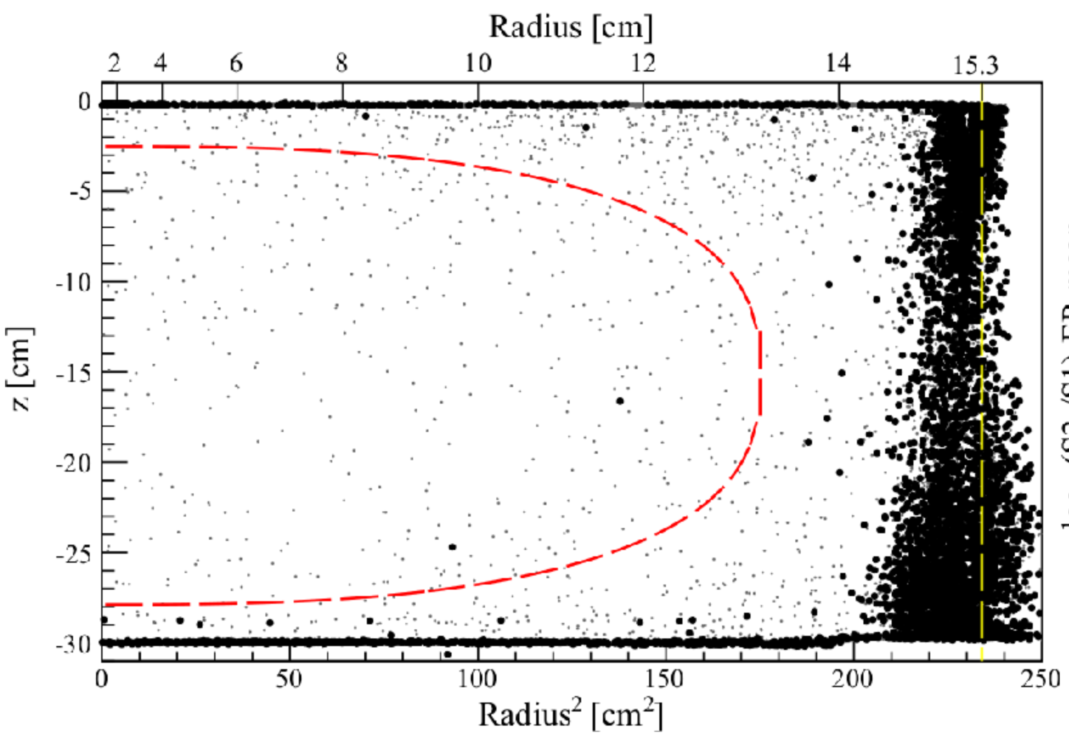
Excellent agreement
No fine tuning required
Radioactivities taken from measurements

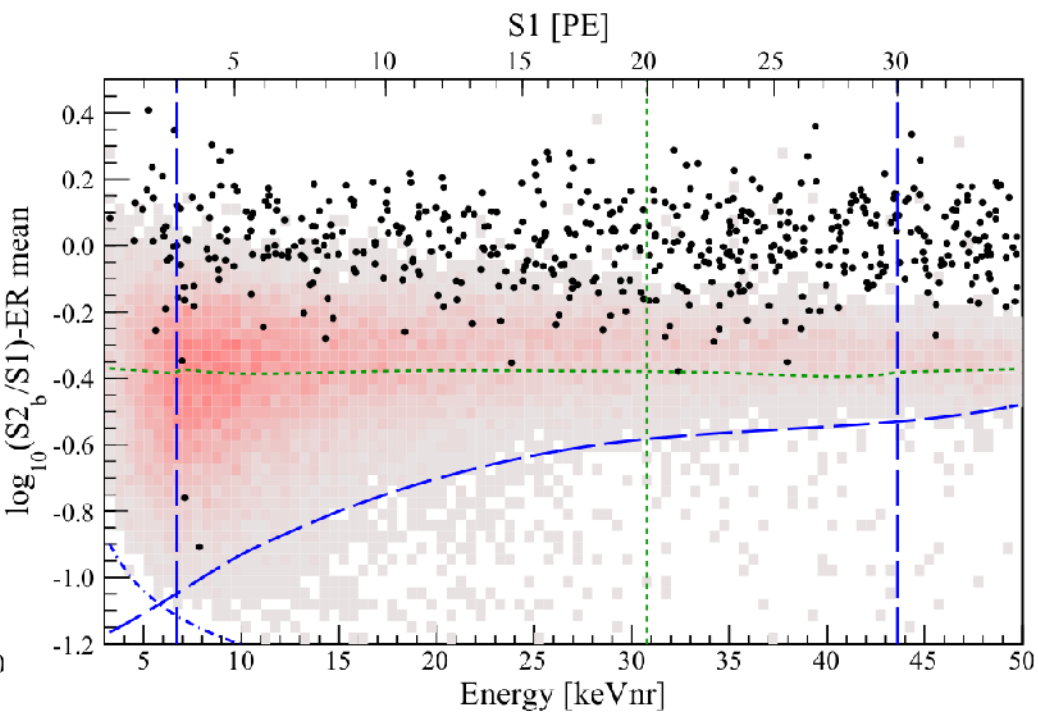
Rate below 100 keV significantly reduced
Kr reduced to 19 ± 1 ppt in run10 as measured by rare gas mass spectrometry



Run 10: 225 live days in 2011/2012

E. Aprile et al., Phys. Rev. Lett. 109 (2012) 181301





blind analysis, use 34 kg fiducial mass

cut-based analysis:

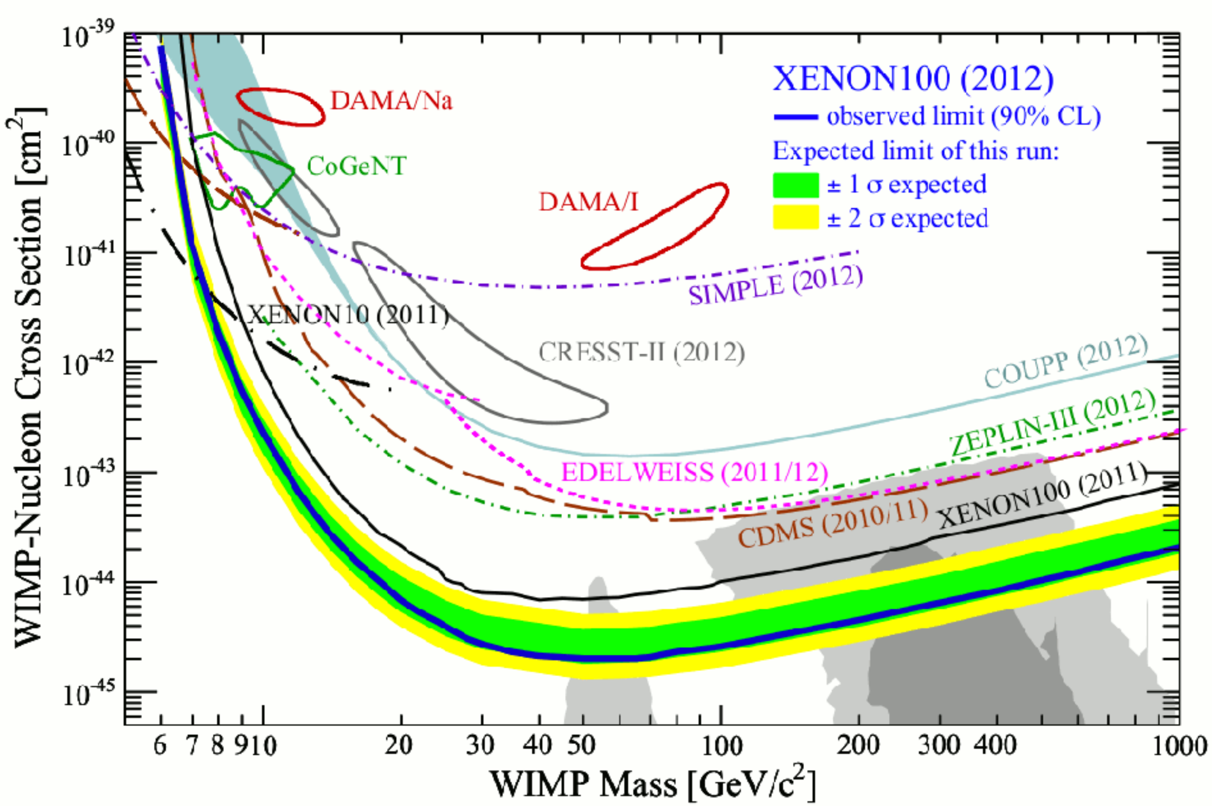
expected background: 1 event, measured: 2 events

→ statistical consistent with no signal

→ no dark matter found, only upper limit

XENON100 run 10: 225d data of 2011/2012

E. Aprile et al., Phys. Rev. Lett. 109 (2012) 181301



Profile Likelihood Analysis:

- all observed events
- full energy information,
  no discrimination
- incorporate calibration informations
- include systematic uncertainties
  (v_{esc}, L_{eff}, …)
- method makes smooth transition
  between rejection/discovery

→ calculate only one true 90%CL limit

Details of the profile likelihood analysis:

E. Aprile et al.,
Phys. Rev. D 84 (2011) 052003

World´s best sensitivity on WIMPs
but nothing found yet !

disfavours DAMA & CoGeNT (& CRESST) possible signal regions
(also IDM@DAMA ruled out, E. Aprile et al, Phys. Rev. D 84 (2011) 061101)

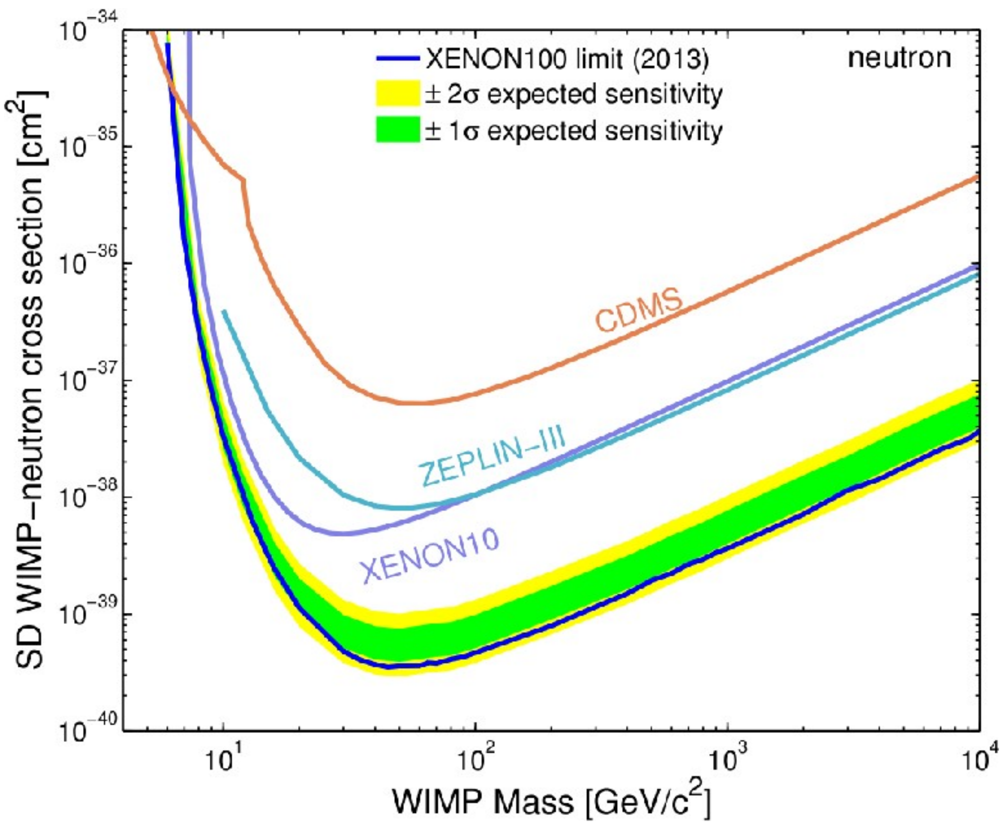
XENON100 Dark Matter run 10: Limits on spin-dependent interaction

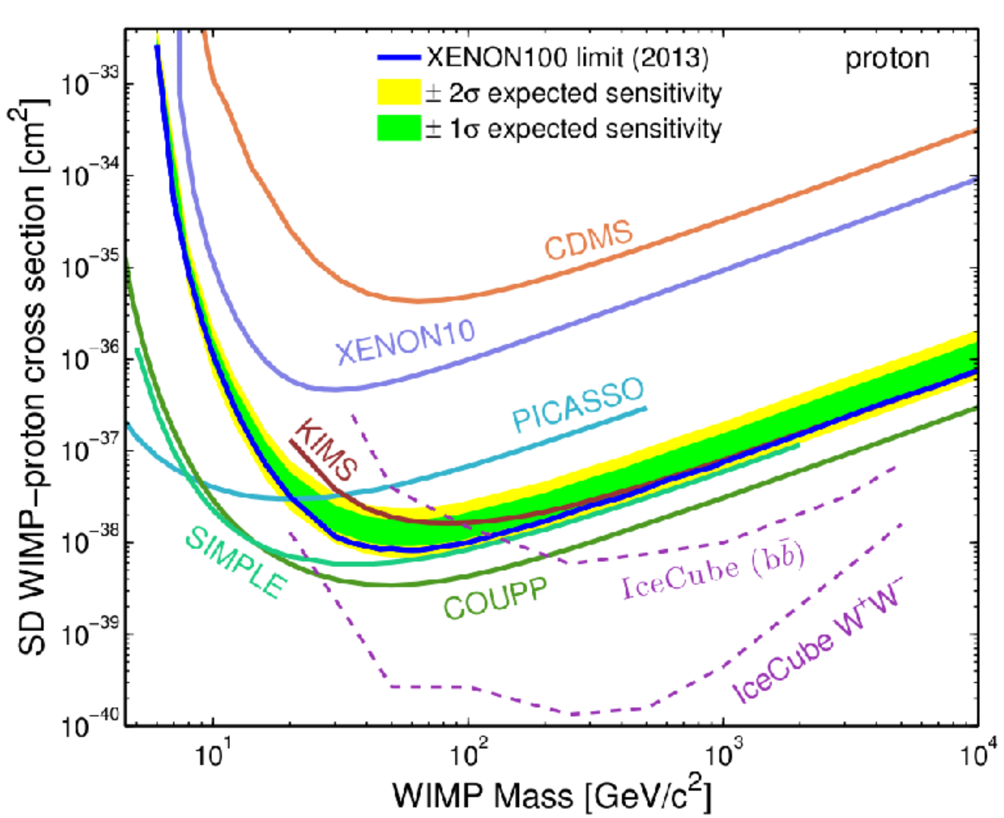
Some data selection and analysis as 225 days run 10 analysis (PRL 109 (2012) 181301)

Sensitivity to SD interaction by odd isotopes ^{129}Xe (J=1/2, 26.4%) and ^{131}Xe (J=3/2, 21.2%)

Single particle cross section limits

$$\sigma_{p,n}(q) = \frac{3}{4}\frac{\mu_{p,n}^2}{\mu_A^2}\frac{2J+1}{\pi}\frac{\sigma_{SD}(q)}{S_A^{a_0=\pm a_1}(q)}$$





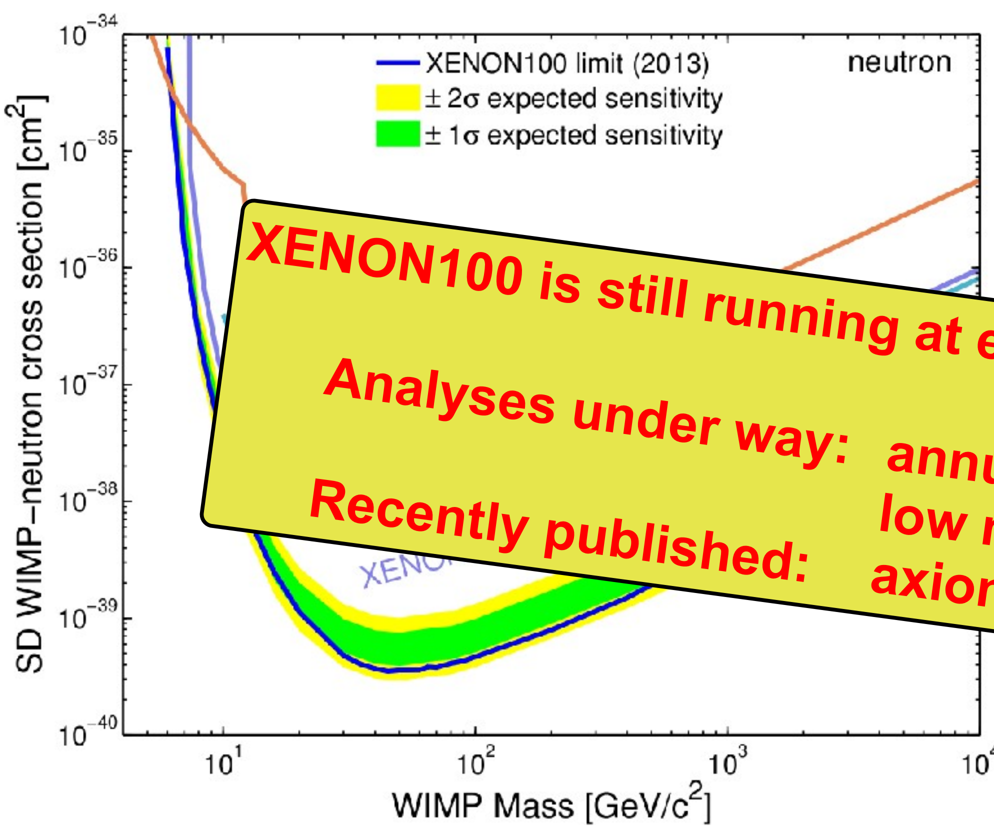
E. Aprile et al., Phys. Rev. Lett. 111 (2013) 021301

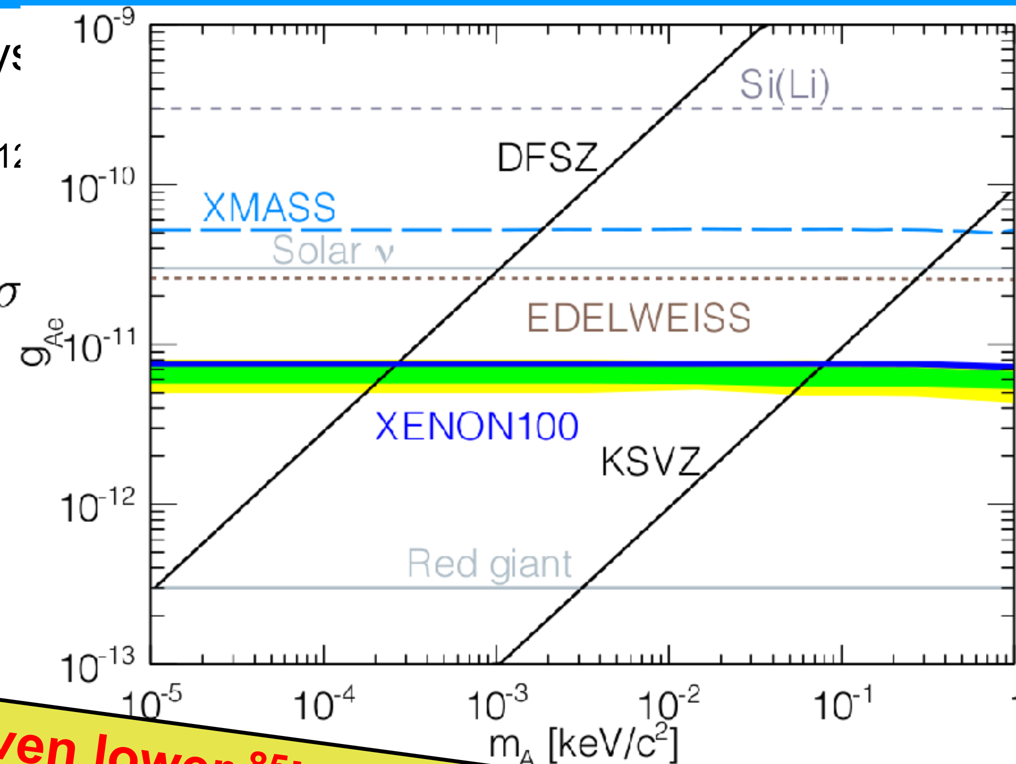
XENON100 Dark Matter run 10: Limits on spin-dependent interaction

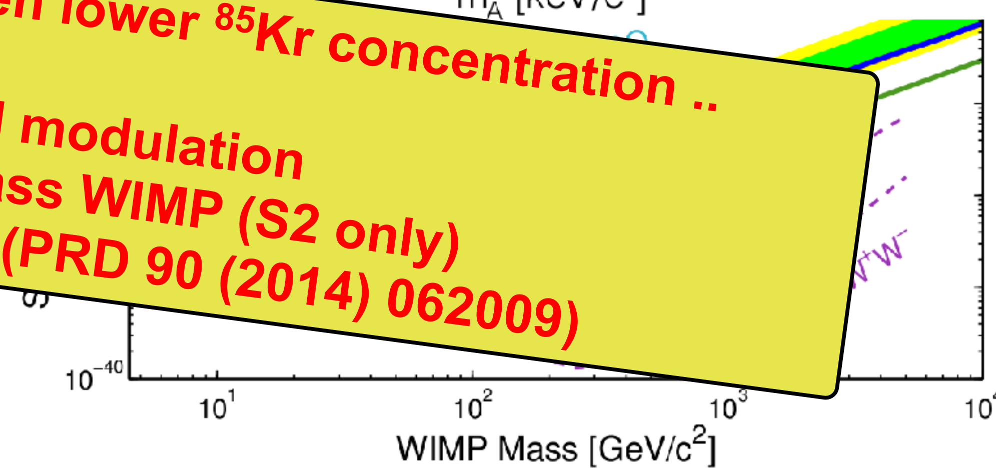
Some data selection and analysis as 225 days

Sensitivity to SD interaction by odd isotopes 1

Single particle cross section limits







XENON100 is still running at even lower ^{85}Kr concentration ..

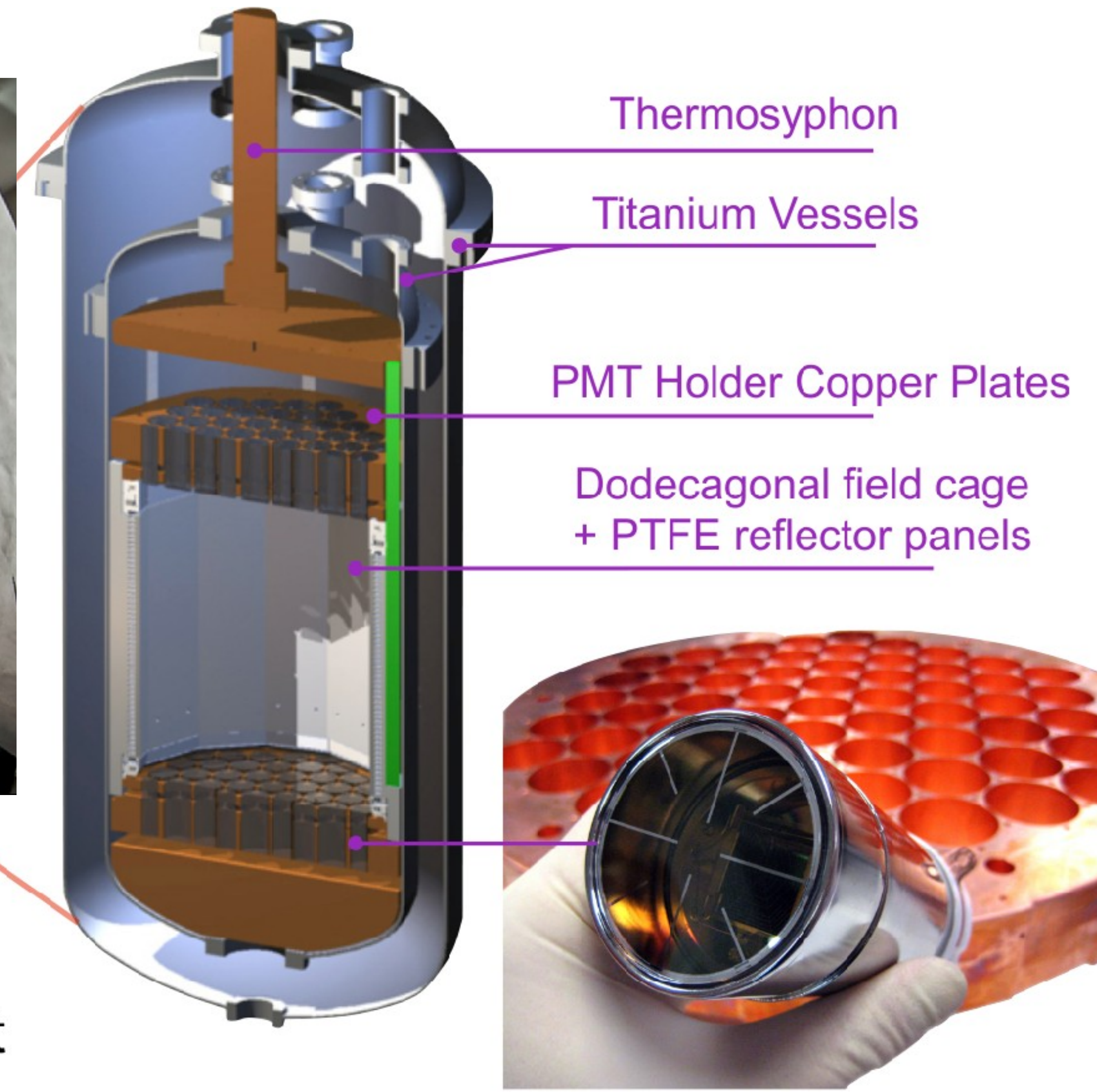
Analyses under way: annual modulation
low mass WIMP (S2 only)

Recently published: axions (PRD 90 (2014) 062009)

E. Aprile et al., Phys. Rev. Lett. 111 (2013) 021301

LUX: 2-phase Xe, measurement started in Homestake mine, aim: $\sigma = 2\ 10^{-46}\ cm^2$

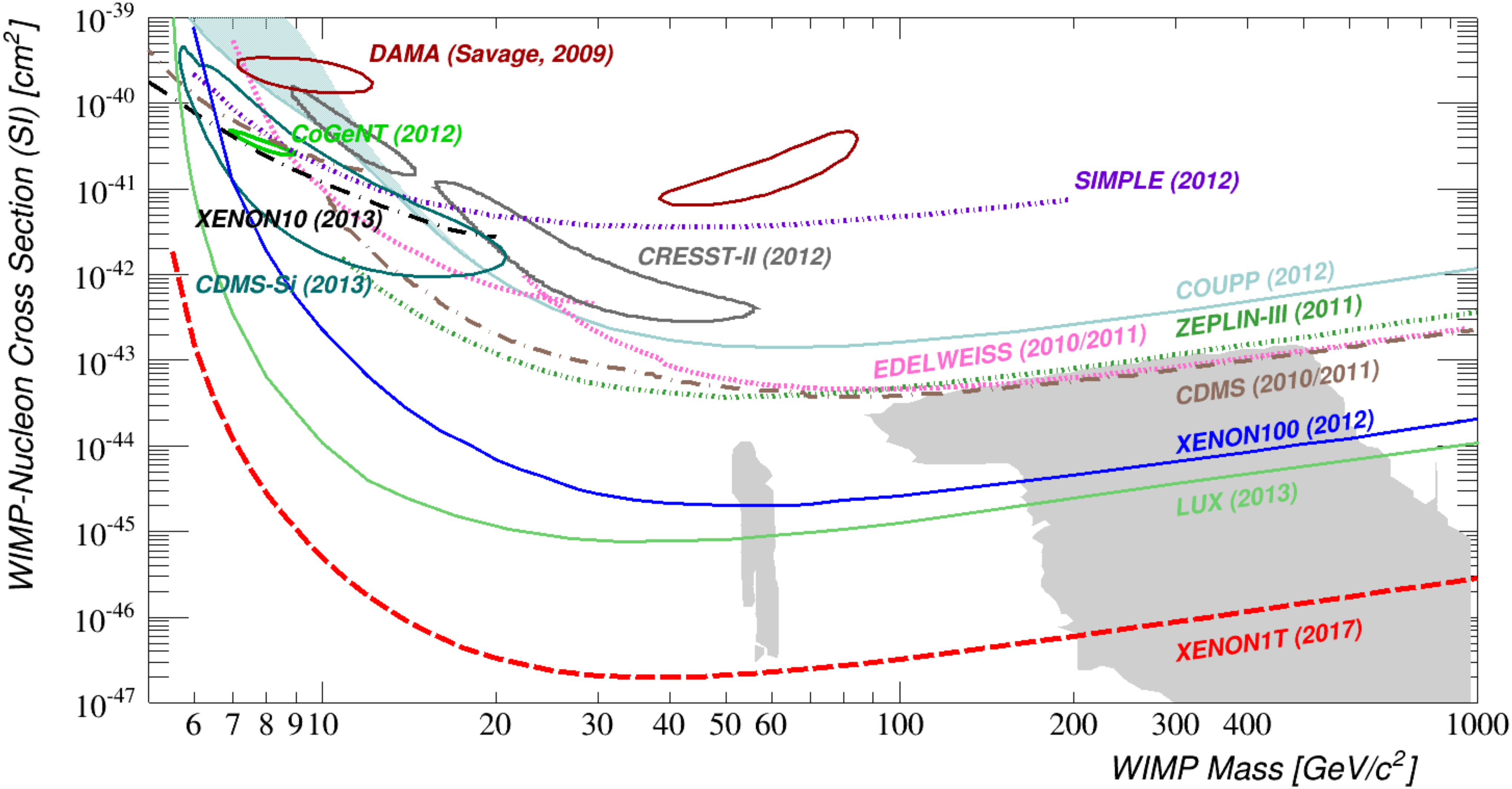
from R. Gaitskell, Aspen 2013



2" Hamamatsu R8778
Photomultiplier Tubes (PMTs)

- 370 kg (300 kg active) LXe
- 122 PMTs (2" round)
- Low-background Ti cryostat
- PTFE reflector cage
- Thermosyphon used for cooling (>1 kW)

LUX: 2-phase Xe, first results → no signal found (arXiv:1310.8214)



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XENON1T at LNGS

XENON Dark Matter Project

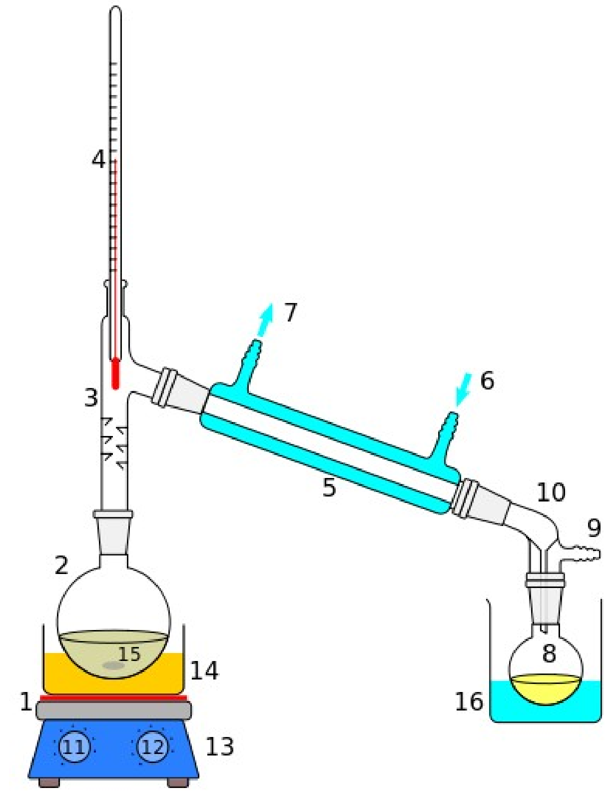
- 1 m drift TPC with 2.4 ton (1 ton fiducial) LXe
- 10 m water shield as Cherenkov Muon Veto
- 100 x less background than XENON100
- Approved by INFN for installation at LNGS
- Fully funded
- construction start in LNGS Hall B in 2012
- Science Data projected to start in 2015
- Sensitivity: 2×10^{-47} cm^2 after 2 years of data

XENON1T infrastructure meeting at MS/Jan. 2013

XENON1T in hall B at LNGS

XENON1T at LNGS: Removal of radioactive noble gases

Cryogenic distillation



^{85}Kr:

10^{-8} - 10^{-5} in commercial xenon gas,
$2*10^{-11}$ fraction of ^{85}Kr in ^{nat}Kr,
→ need very efficient purification method

up to now Kr in Xe concentrations reached in LUX, PandaX, XENON100, XMASS: 1-3 ppt

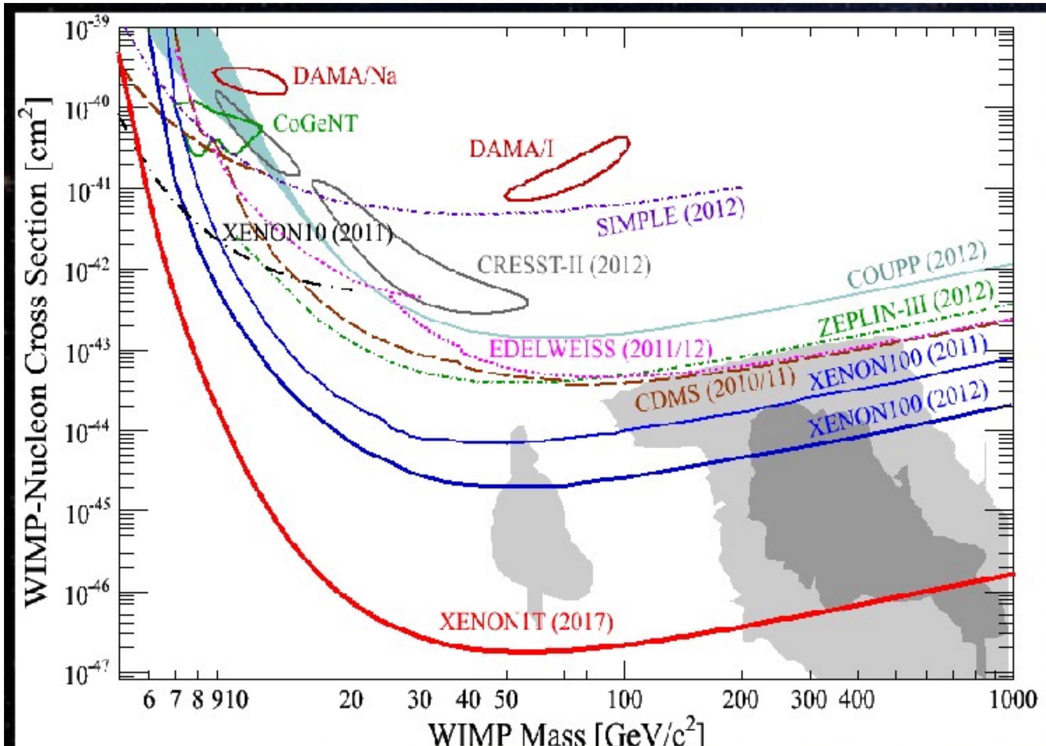
XENON1T requires < 0,5 ppt

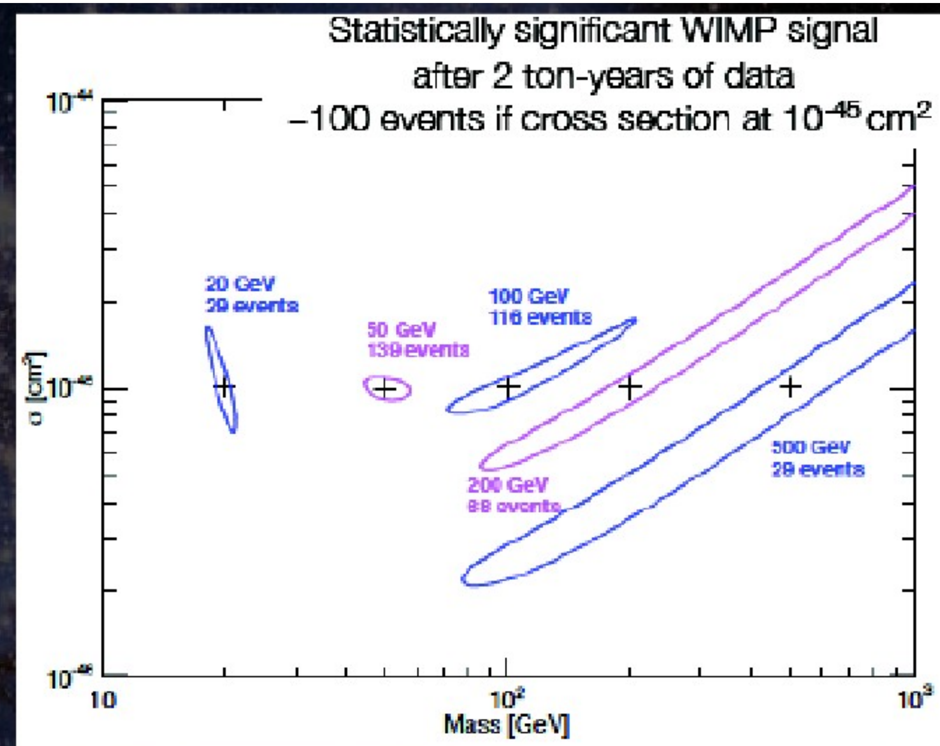
cryogenic distillation with Münster column (3kg/h):
< 0.026 ppt (MPIK measurement)

^{219}Rn, ^{220}Rn, ^{222}Rn:

comes from walls, weldings, ..
→ purification by absorption (e.g. on cold charcoal)
or by cryogenic distillation (never demonstrated yet)

XENON1T at LNGS: Sensitivity





Example of discovery

σ_{SI} = 2 x 10^{-47} cm^2 for 50 GeV/c^2 WIMP

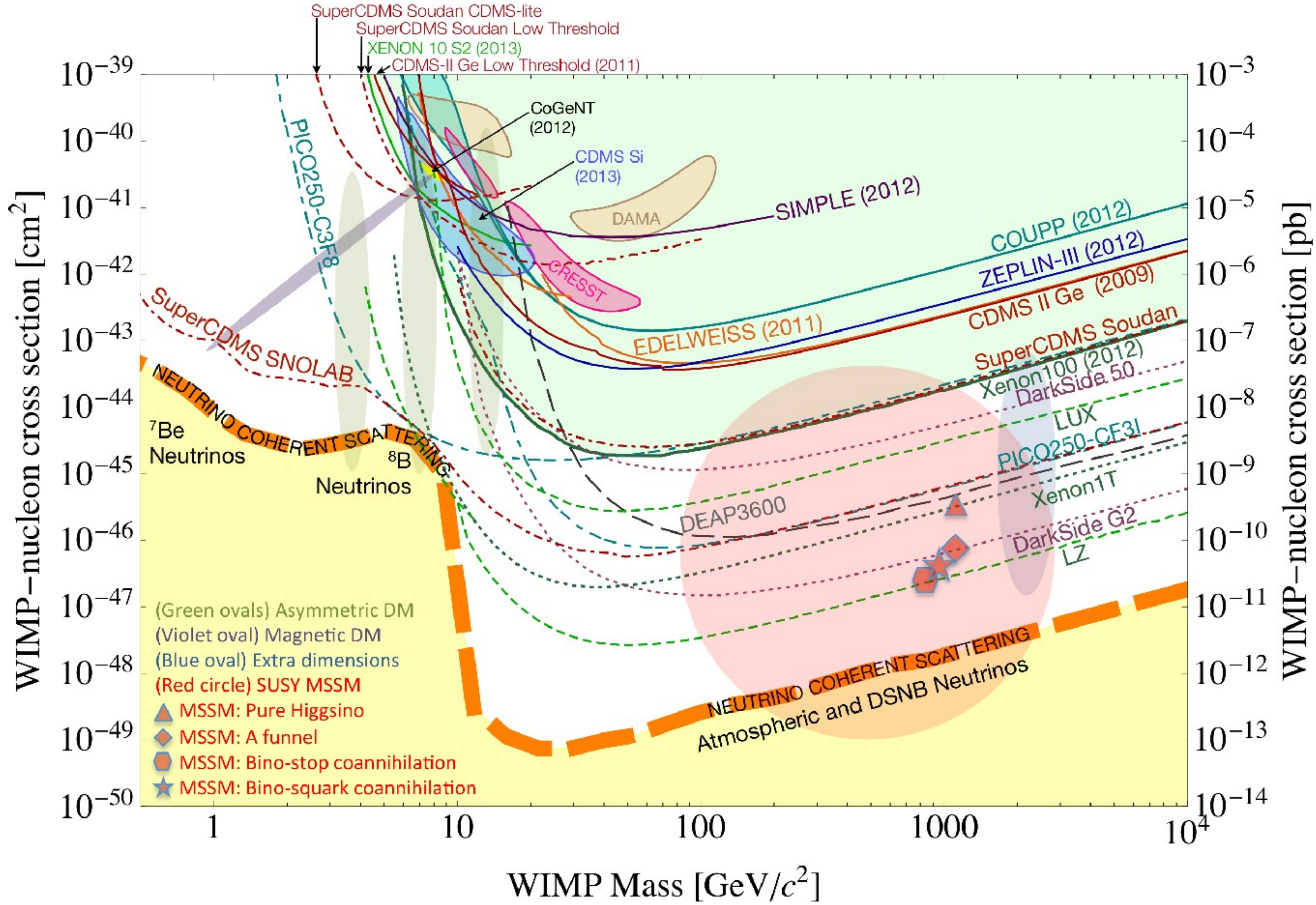
Probe majority of SUSY-favored phase space

→ Strong discovery potential

Buchmueller et. al, arXiv:1112.3564 (2011)
A Fowli et. al, arXiv:1112.3564 (2012)

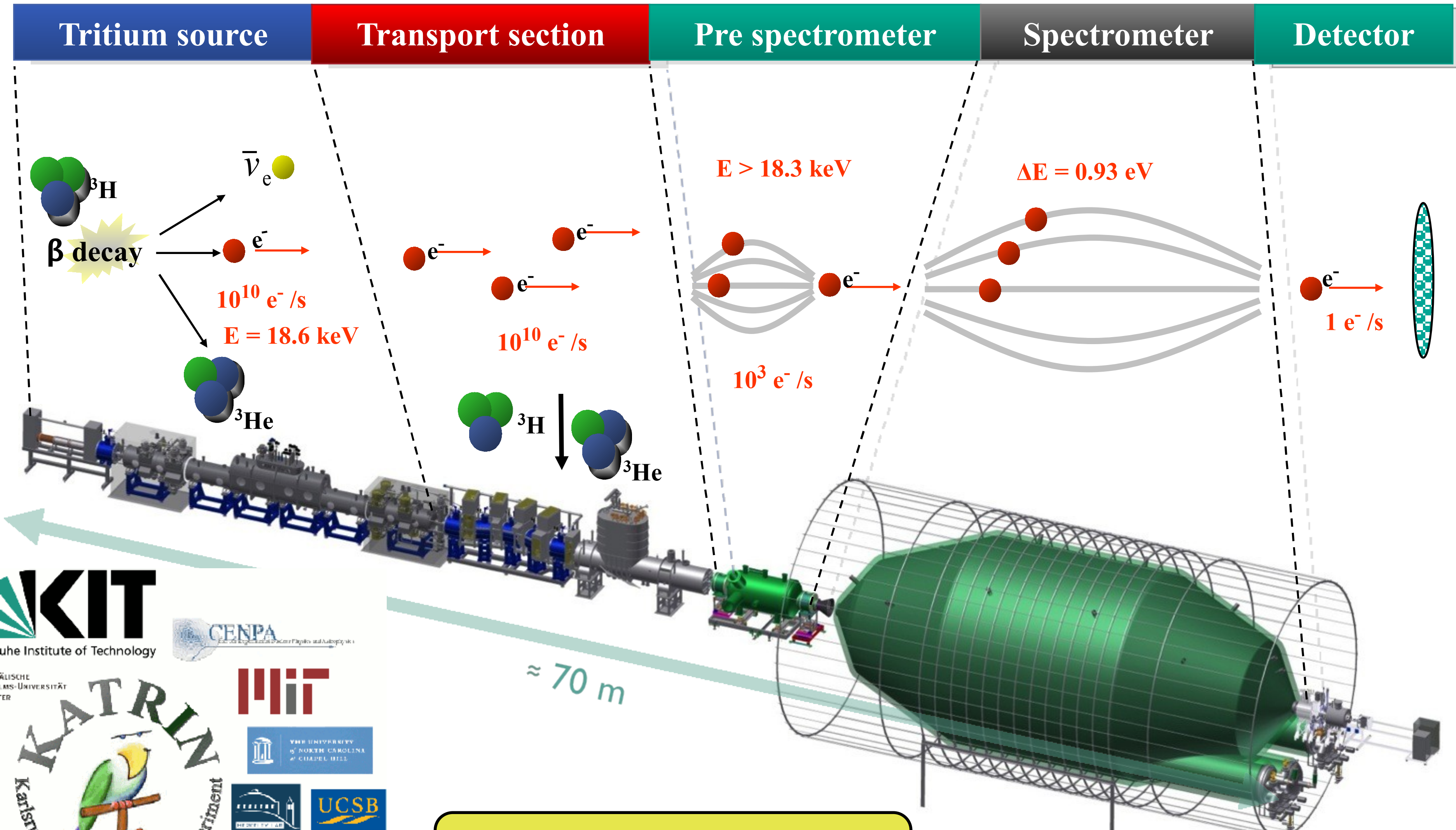
Ethan Brown TAUP, Sept 8 - 13 2013 18/20

Finally, the sensitivity will be limited by neutrino background !



from R. Gaitskell

The Karlsruhe Tritium Neutrino Experiment KATRIN - overview

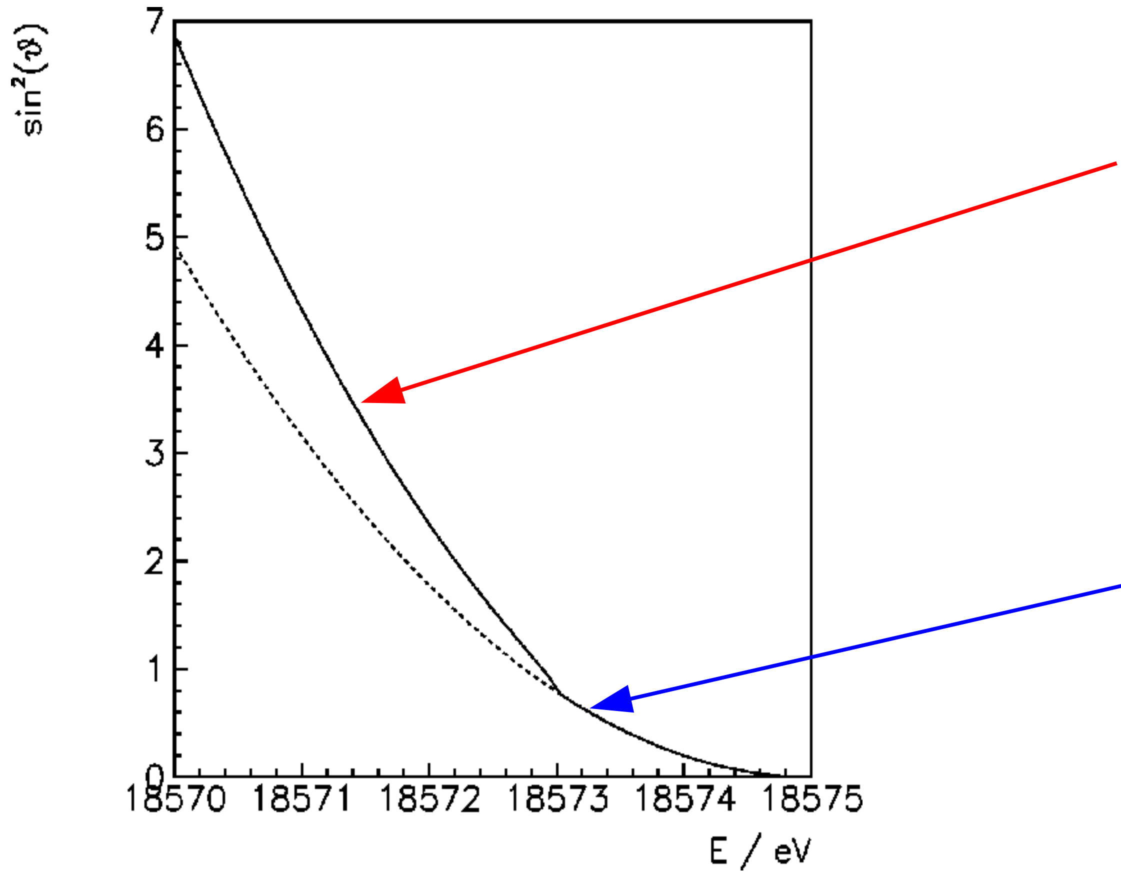


Sensitivity on $m(\nu_e)$:

$2\ eV/c^2 \rightarrow 200\ meV/c^2$

Influence of a 4th sterile neutrino near the endpoint E_0

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e) \left(\cos^2(\theta) \sqrt{(E_0-E_e)^2 - m(\nu_{1,2,3})^2} + \sin^2(\theta) \sqrt{(E_0-E_e)^2 - m(\nu_4)^2} \right)$$



e.g.

$m(\nu_4) = 2$ eV

$\sin^2(\theta) = 0.3$

e.g.

$m(\nu_{123}) \approx 0$ eV

$\cos^2(\theta) = 0.7$

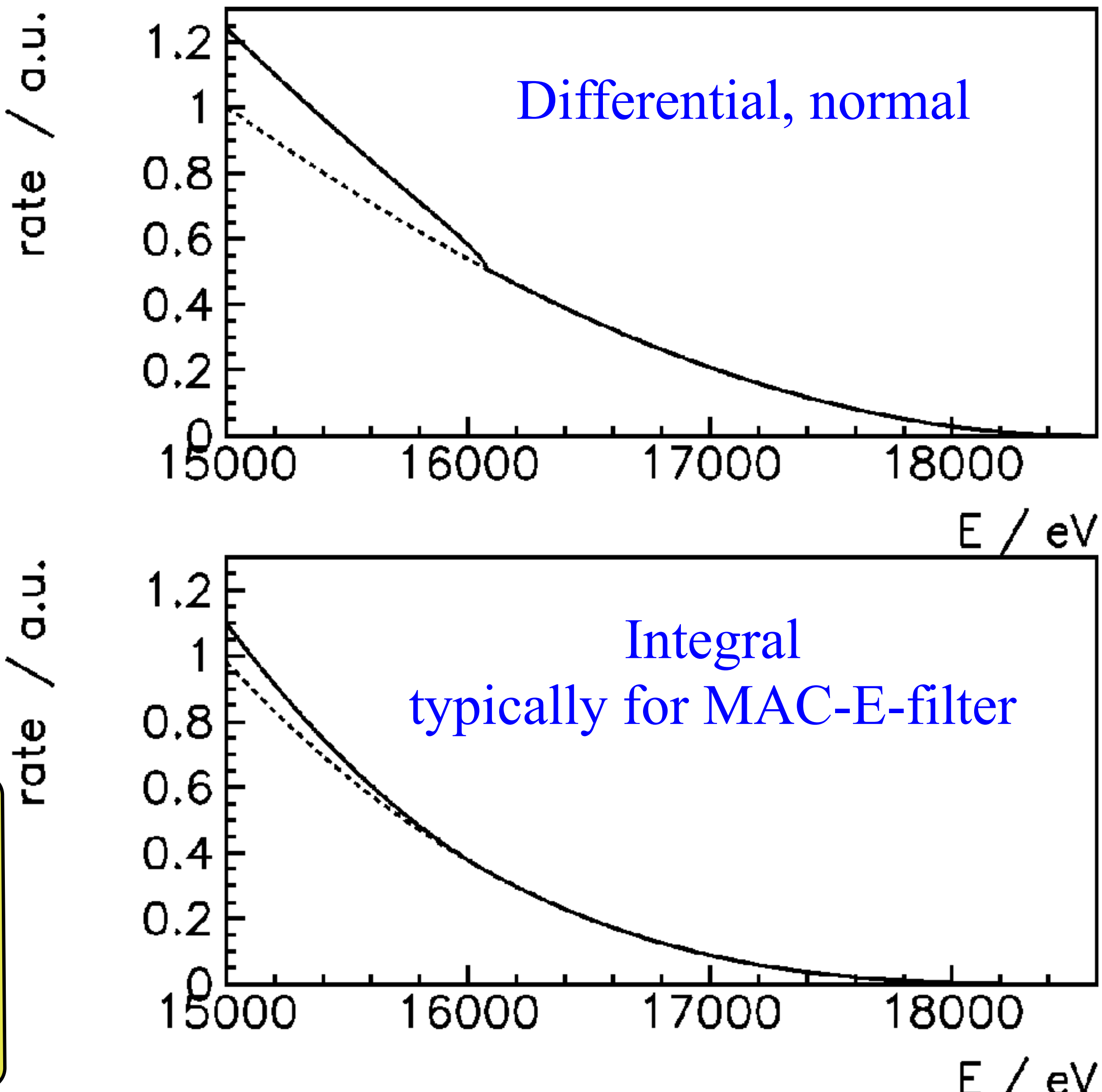
Normal ("differential") or integral β-spectrum

e.g. $m_{sterile}$ = 2.5 keV

$\sin^2(\theta) = 0.25$

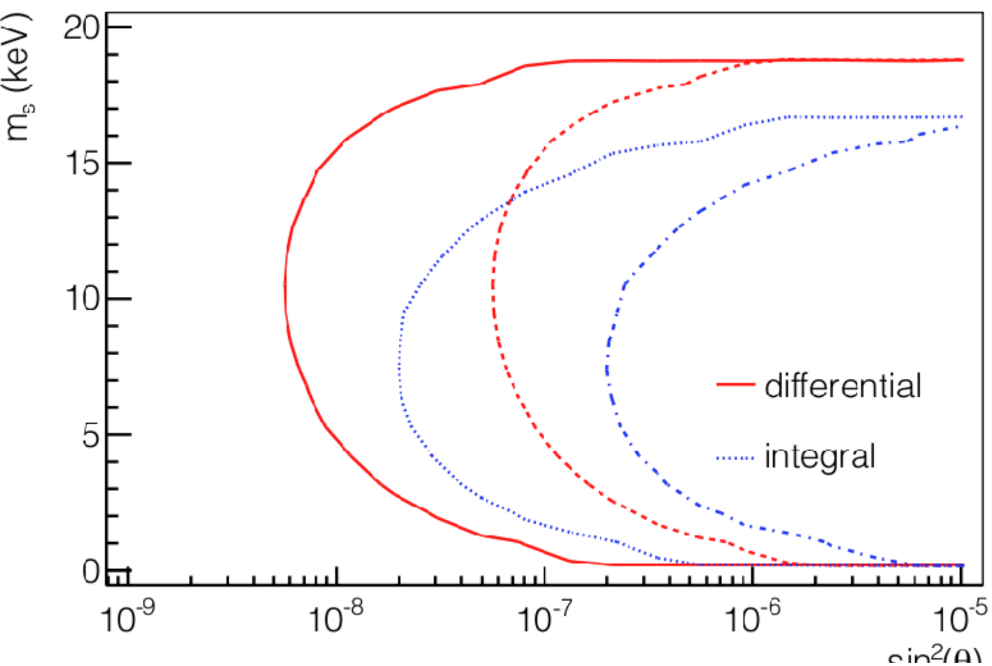
(unrealistically high

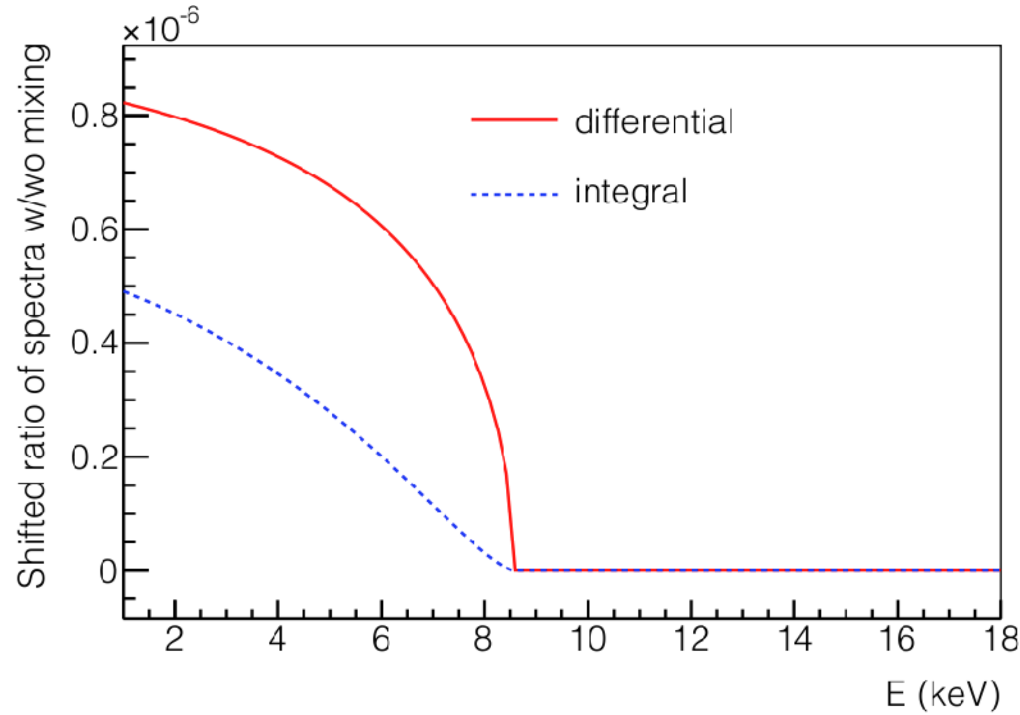
for Warm Dark Matter)



→ obviously much better signal-to-background-ratio for differential β-spectrum w.r.t. integral β-spectrum

Statistical sensitivity for integral and differential measurement





----- standard KATRIN source

- - - 1% KATRIN source

S. Mertens et al., „Sensitivity of Next Generation Tritium β-Decay Experiments for keV-Scale Sterile Neutrinos“, S. Mertens et al., arXiv:1409:0920, see also S. Mertens, proceedings of TAUP 2013

→ **statistical uncertainty is not a problem for 10^{-7} but what about the systematics !**

Summary of 4th lecture

Liquid noble gas experiments (LAr, LXe):
- combine large mass (nicely scalable to ton masses) with low background (intrinsic clean, fiducialisation, self-shielding; γ-WIMP distinction)
- well-established technology for dual phase LXe TPC

Best WIMP sensitivity by XENON100 and LUX

Many experiments under construction or commissionig (e.g. DarkSide, DEAP-3600 ...)

New projects with fiducial mass O(1t) are being constructed (e.g. XENON1T, …) aiming at a sensitivity of $O(10^{-47})$ cm^2