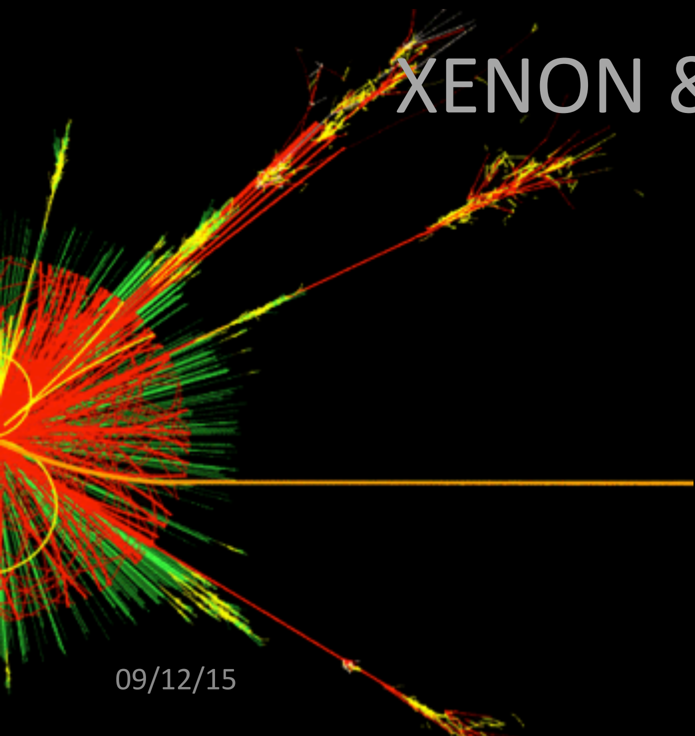
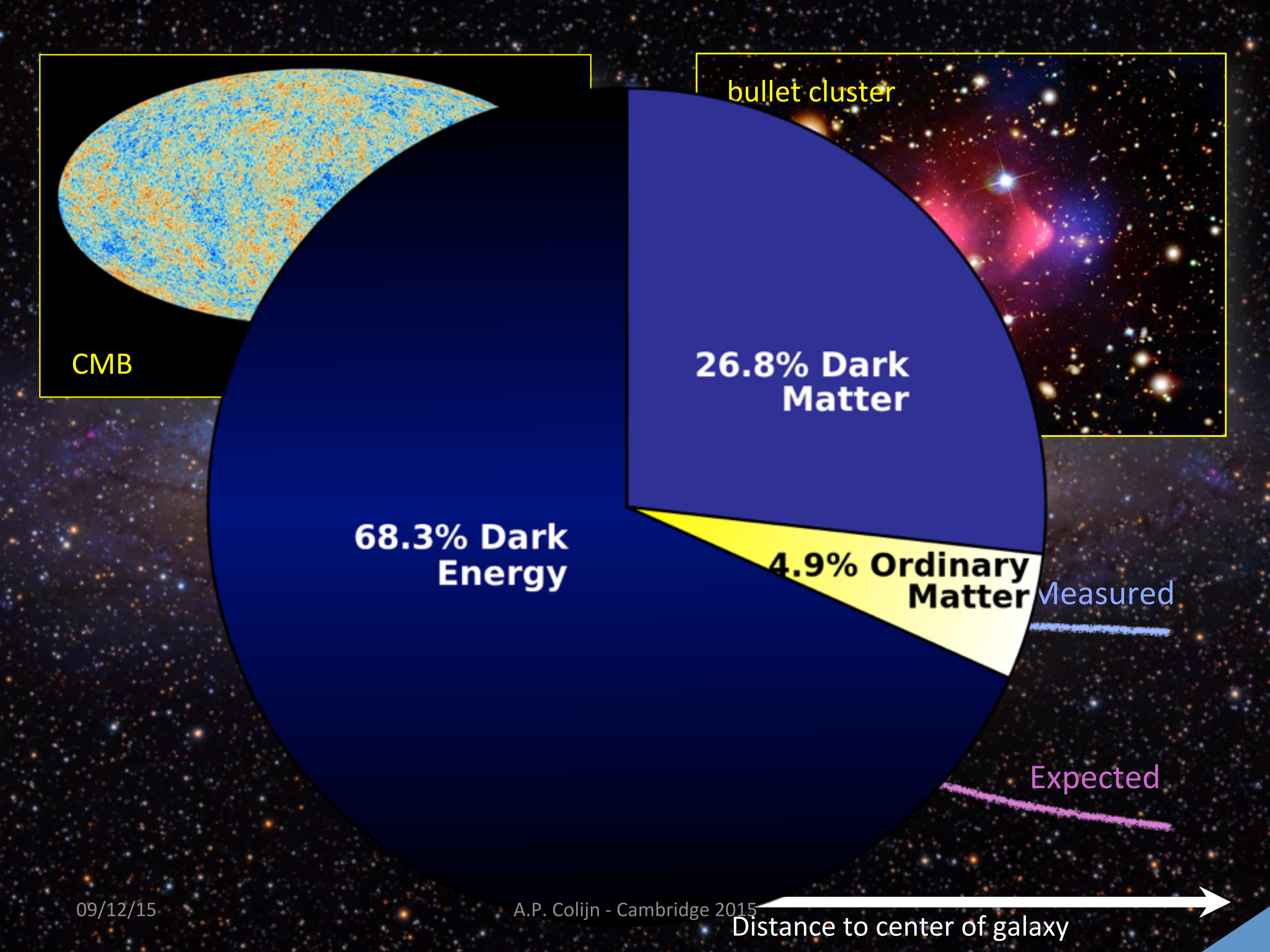
The Missing Universe



XENON & the hunt for dark matter

Auke Colijn


CMB
bullet cluster
26.8% Dark Matter
68.3% Dark Energy
4.9% Ordinary Matter
Measured
Expected
Distance to center of galaxy


I
III
u
c
t
s
b
τ
e
elektron - muon
νe
ντ

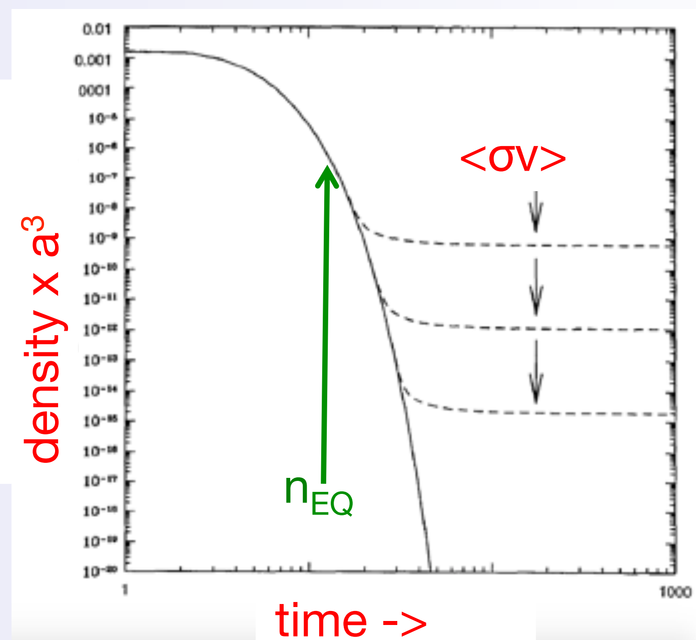
Appropriate relic density?
Is it cold?
Is it neutral?
Consistent with BBN?
Leaves stellar evol. unchgnd?
Compat. with self-interactions?
Consist. with direct DM searches?
Consist. with gamma-ray constr.?
Consist. with other astro. constr.?
Can it be probed exp.?

DM candidate	**I.** Ωh^2	**II.** Cold	**III.** Neutral	**IV.** BBN	**V.** Stars	**VI.** Self	**VII.** Direct	**VIII.** γ-rays	**IX.** Astro	**X.** Probed	**Result**
SM Neutrinos	×	×	✓	✓	✓	✓	✓	–	–	✓	×
Sterile Neutrinos	∼	∼	✓	✓	✓	✓	✓	✓	✓!	✓	∼
Neutralino	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Gravitino	✓	✓	✓	∼	✓	✓	✓	✓	✓	✓	∼
Gravitino (broken R-parity)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sneutrino $\tilde{\nu}_L$	∼	✓	✓	✓	✓	✓	×	✓!	✓!	✓	×
Sneutrino $\tilde{\nu}_R$	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Axino	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SUSY Q-balls	✓	✓	✓	✓	∼	–	✓!	✓	✓	✓	∼
B^1 **UED**	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
First level graviton UED	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×[a]
Axion	✓	✓	✓	✓	✓	✓	✓!	✓	✓	✓	✓
Heavy photon (Little Higgs)	✓	✓	✓	✓	✓	✓	✓	✓!	✓!	✓	✓
Inert Higgs model	✓	✓	✓	✓	✓	✓	✓	✓!	–	✓	✓
Champs	✓	✓	×	✓	×	–	–	–	–	✓	×
Wimpzillas	✓	✓	✓	✓	✓	✓	✓	✓	✓	∼	∼

WIMP hypothesis

Why WIMPs?

- **We have a motive**
  1. Just after Big Bang start with thermal/chemical equilibrium between matter and WIMPs: Temperature >>> all masses
  2. T drops and since $m_{WIMP} > m_{Matter}$: at some point WIMP production no longer possible. Only annihilation of WIMPs: density drops exponentially
  3. BUT: Expansion of Universe effectively stops annihilation: WIMPs no longer “meet”.
  4. Explain measured Ω_{DM} if annihilation cross section $\langle\sigma v\rangle$ around weak-scale

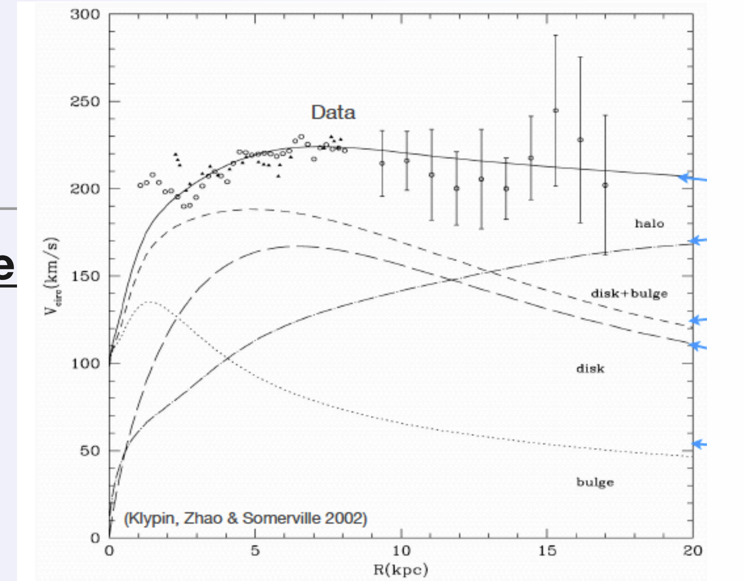


- **We have a suspect**

  ➡lightest SUSY particle

- **We have a chance to see WIMPs**

Galactic rotation & WIMPs?



- **Galactic rotation curves – experimental evidence**

  Observation of 'flat' rotation curve:

$$v(r > r_0) = v_0 \Rightarrow \rho(r) \propto \frac{1}{r^2}$$

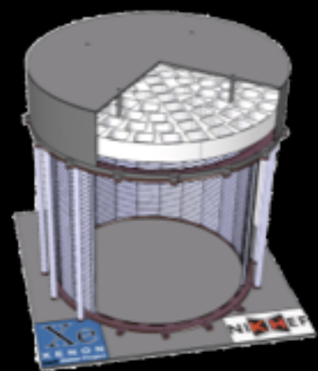
- **Dark matter particles – WIMP hypothesis**

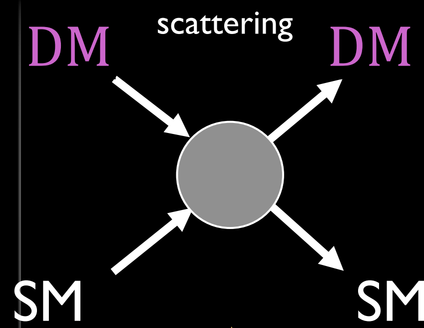
  Solution to Boltzmann equation for collisionless particles (i.e. WIMP)

$$f(\vec{v}) \propto \exp(-v^2/v_0^2) \Rightarrow \rho(r) \propto \frac{1}{r^2}$$

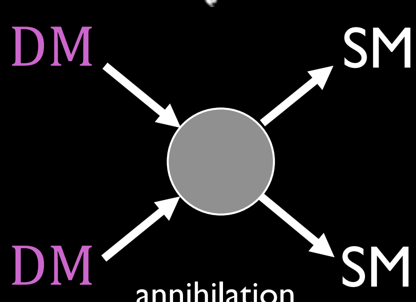
- **Implications**
  - ➡ isothermal sphere of dark matter
  - ➡ galaxy mass un-bound (!)

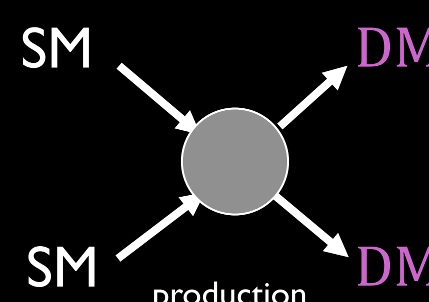
Howto find it? Matter meets Dark Matter



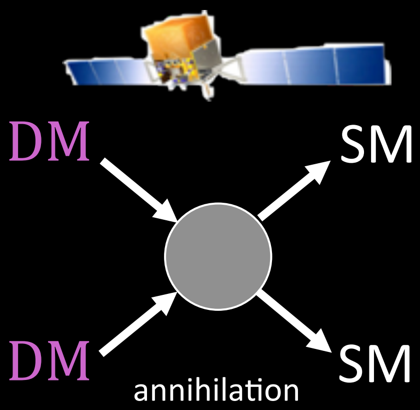


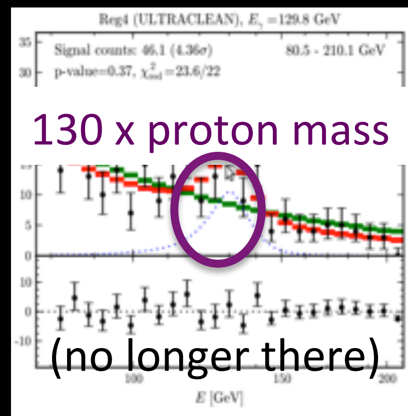
Three different ways how Dark Matter particles may interact with Normal Matter

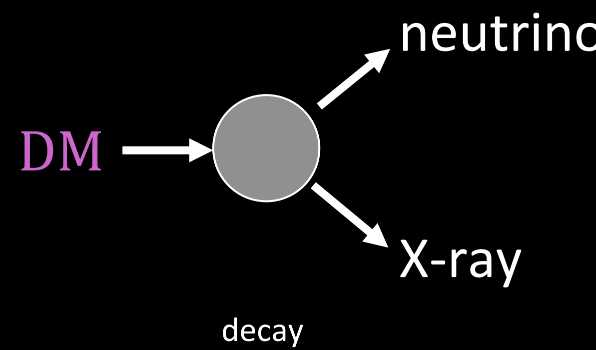


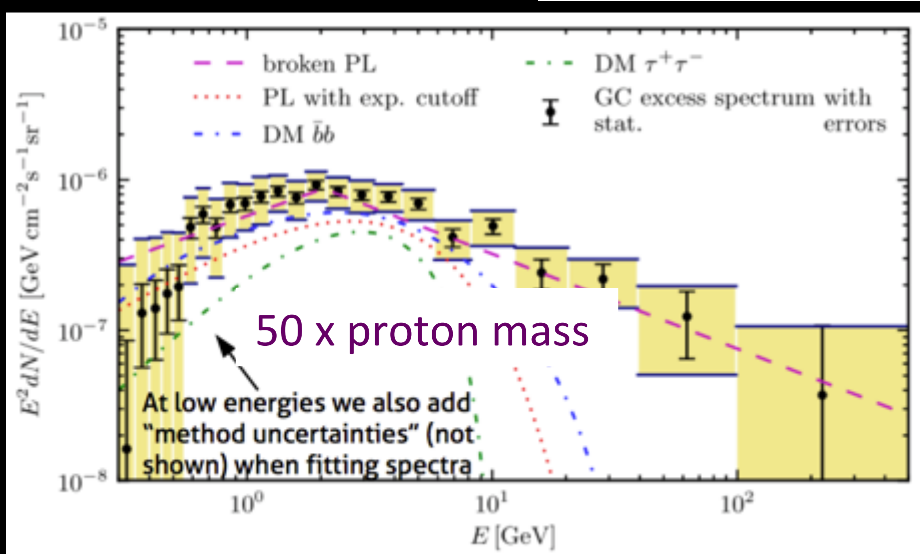


DM in the sky: γ-rays from space

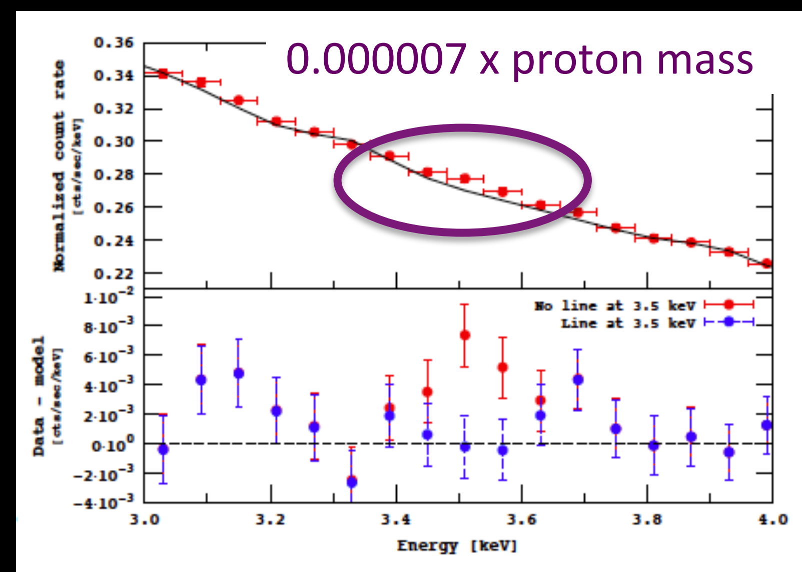








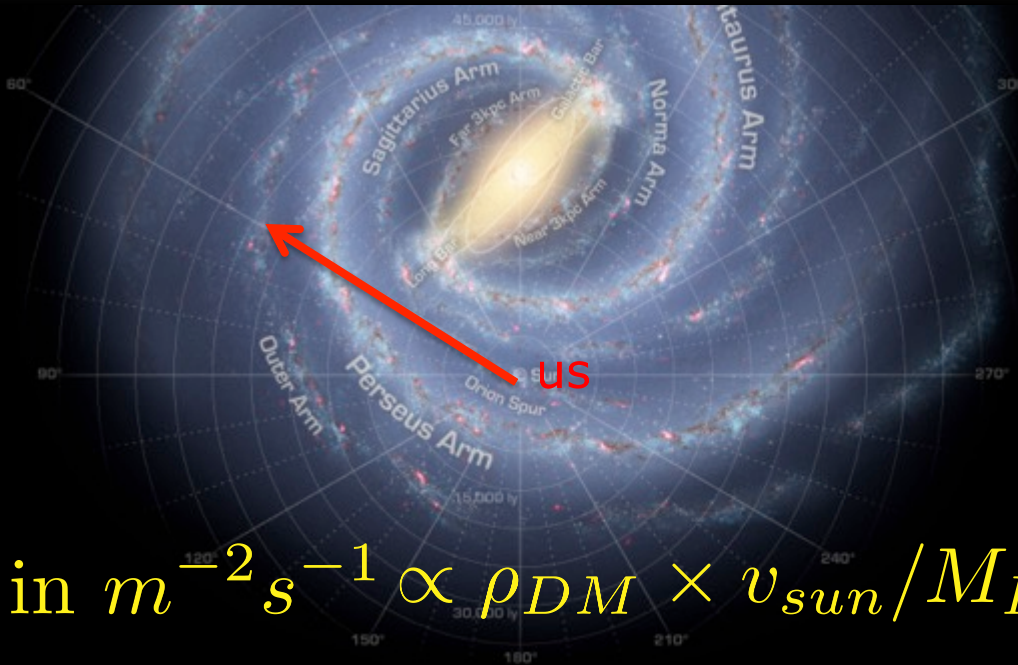
5t Int. Fermi Symposium. C. Weniger



arXiv:1402.4119

DM on earth?

Flux



$$\Phi_{DM} \text{ in } m^{-2}s^{-1} \propto \rho_{DM} \times v_{sun}/M_{DM}$$

<u>Ingredients</u>

$$\left.\begin{array}{l} \text{1. Density } \rho_{DM} \approx 0.3 \text{ GeV/cm}^3 \\ \text{2. Solar velocity } v_{sun} \approx 220 \text{ km/s} \\ \text{3. DM – WIMP mass } M_{DM} \approx 100 \text{ GeV} \end{array}\right\} \approx 10^9 m^{-2}s^{-1}$$

Nuclear recoil: interaction rate

RATE

WIMP density

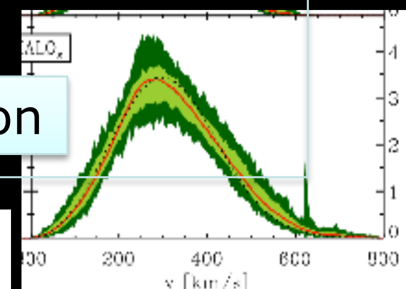
WIMP cross section

$$\frac{dR}{dE_{NR}} = \frac{M_{det}}{m_N}\frac{\rho_\chi}{m_\chi}\int_{v_{min}}^{v_{esc}} dv\, v f(v)\frac{d\sigma_N}{dE_{NR}}$$

N target

WIMP mass

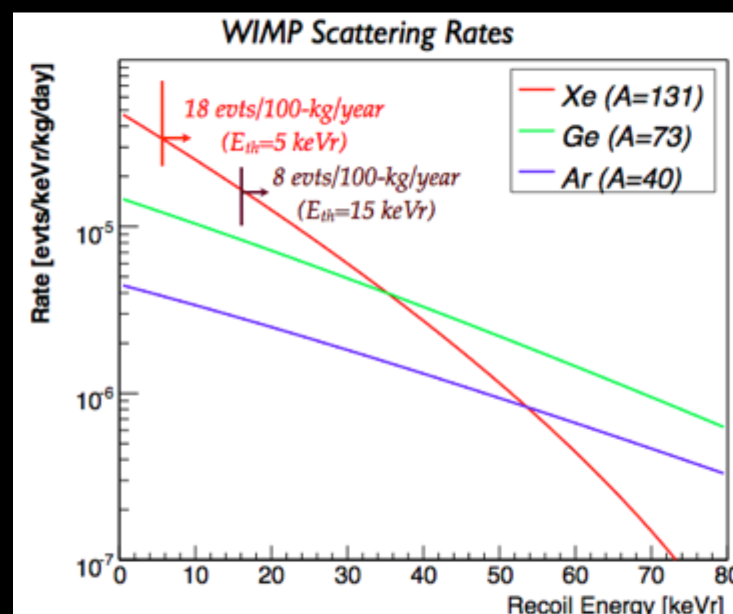
Velocity distribution



Nuclear recoil spectrum

1. O(0-100keV)
2. Featureless

E.g. 100GeV WIMP on some targets



Nuclear recoil: cross section

Spin independent

$$\frac{d\sigma_N}{dE_{NR}} = \frac{m_N \sigma_{SI} F^2(E_{NR})}{2\mu_N^2 v^2}$$

$$\sigma_{SI} = \frac{4\mu_N^2}{\pi}\left[Z f^p + (A - Z) f^n\right]^2 \propto A^2$$

$f^{p,n}$ amplitude to (p,n)

Use heavy elements for detector

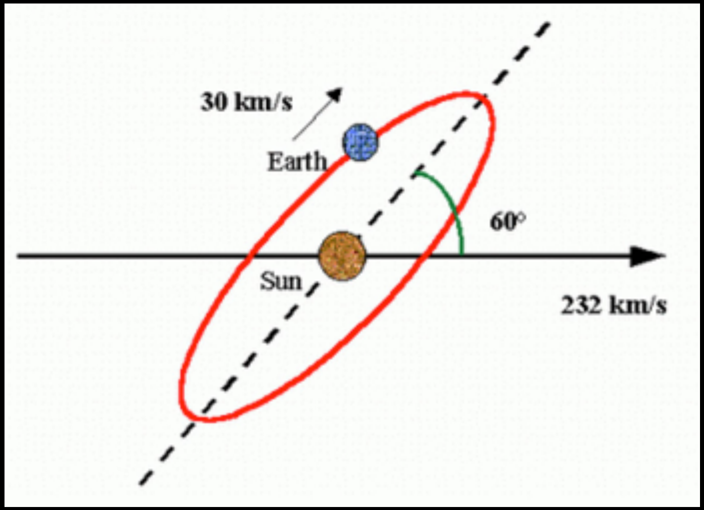
"Universal" cross section -> comparison of experiments

$$\sigma_{SI}^p = \frac{4}{\pi}\mu_p^2 f_p^2$$

Time dependence

$$\frac{dR}{dE_{NR}} = \frac{M_{det}}{m_N}\frac{\rho_\chi}{m_\chi}\underbrace{\int_{v_{min}}^{v_{esc}} dv\, v f(v)}\frac{d\sigma_N}{dE_{NR}}$$

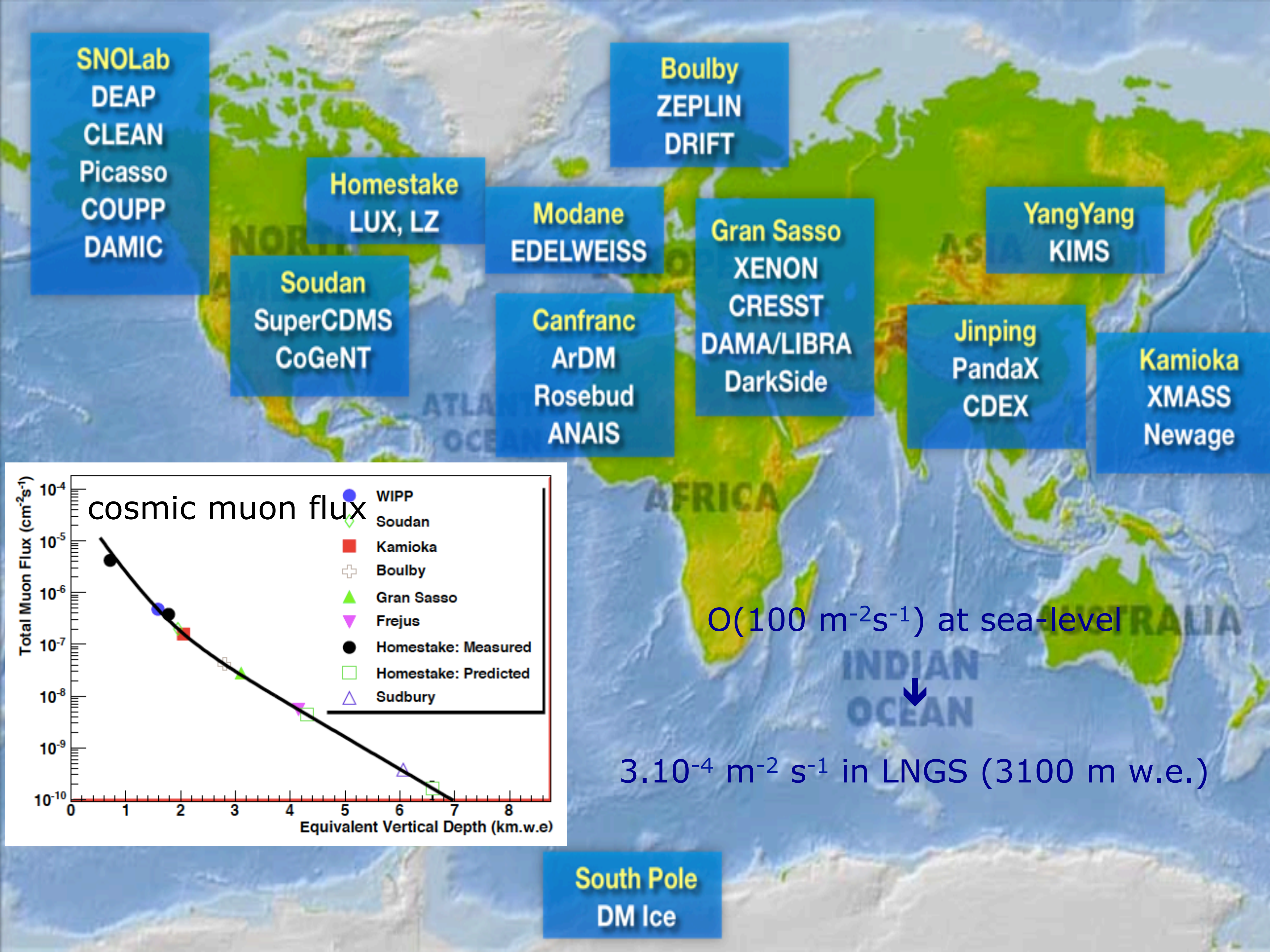
Rate oscillates with period of 1 year



Sun moves towards Vega with velocity of 220km/s

Earth around sun in one year with velocity of 30 km/s

Experiments

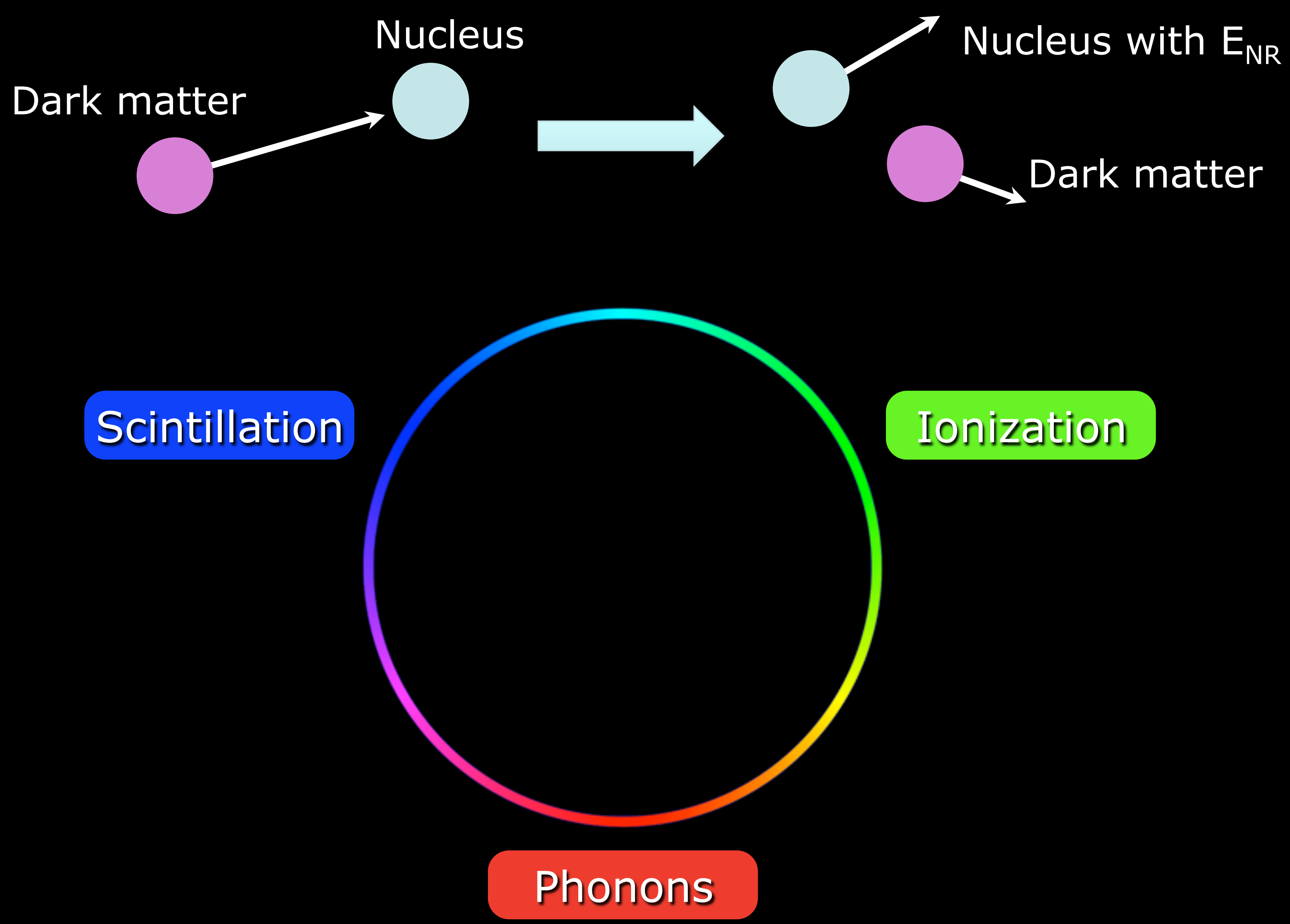


O(100 $m^{-2}s^{-1}$) at sea-level

↓

3.10^{-4} m^{-2} s^{-1} in LNGS (3100 m w.e.)

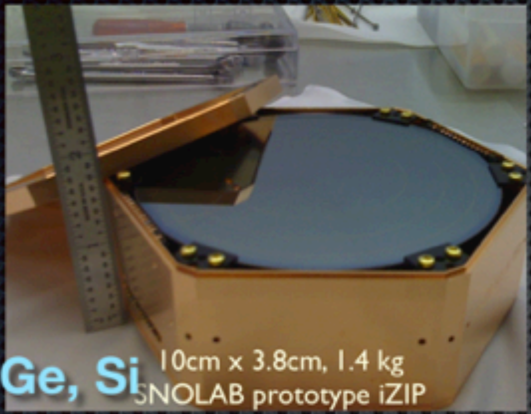
Many detectors – 1 mechanism



New data from cryogenic experiments

- Absorber masses from ~ 100 g to 1400 g

phonon + ionization

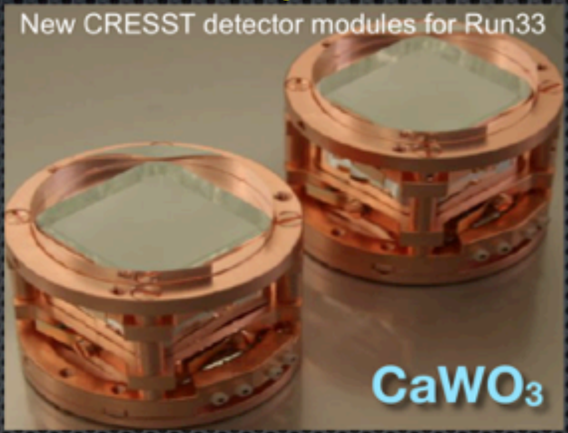


SuperCDMS

new, leading results at low masses

proposed for SNOLAB:
Std: ~92 kg Ge, 11 kg Si
Lite: 5 kg Ge, 1.2 kg Si

phonon + light

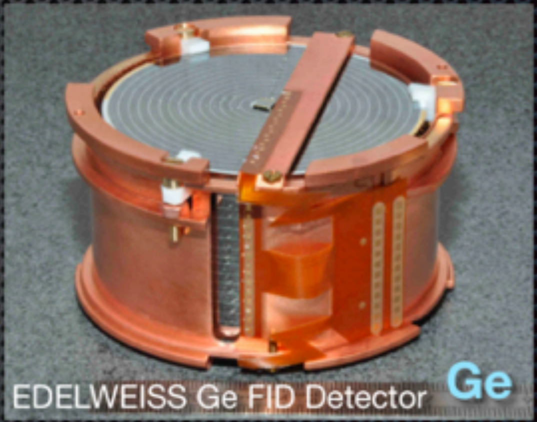


CRESST

18 $CaWO_3$ detector modules (5 kg) installed at LNGS in 2013

low-background run in 2014, recent results and taking more data

phonon + ionization



EDELWEISS-III

new run with 36 Ge FID800 (~ 30 kg) detectors since June 2014

End 2014/early 2015: reach 3000 kg x d (125 live days)

2016: reach 1.2 ton x days (500 live days)

New data from Ar and Xe TPCs

XENON100 at LNGS:

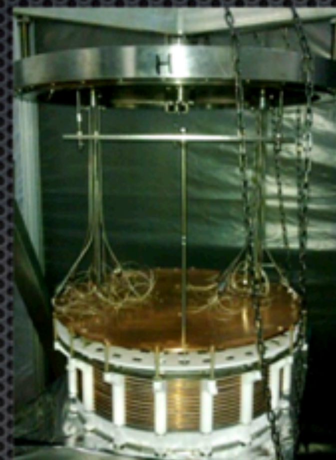
161 kg LXe
(~50 kg fiducial)

242 1-inch PMTs
close to unblinding of new data set

LUX at SURF:

370 kg LXe
(100 kg fiducial)

122 2-inch PMTs
physics run and first results in 2013
new run in 2014



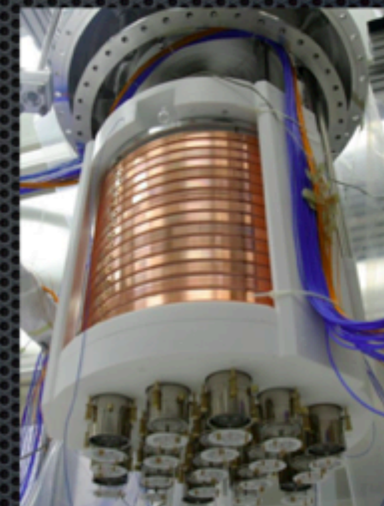
PandaX at CJPL:

125 kg LXe
(37 kg fiducial)
arXiv:1408.5114v2
143 1-inch PMTs
37 3-inch PMTs
first results in August 2014

ArDM at Canfranc:

850 kg LAr
(100 kg fiducial)

28 3-inch PMTs
in commissioning
to run 2014



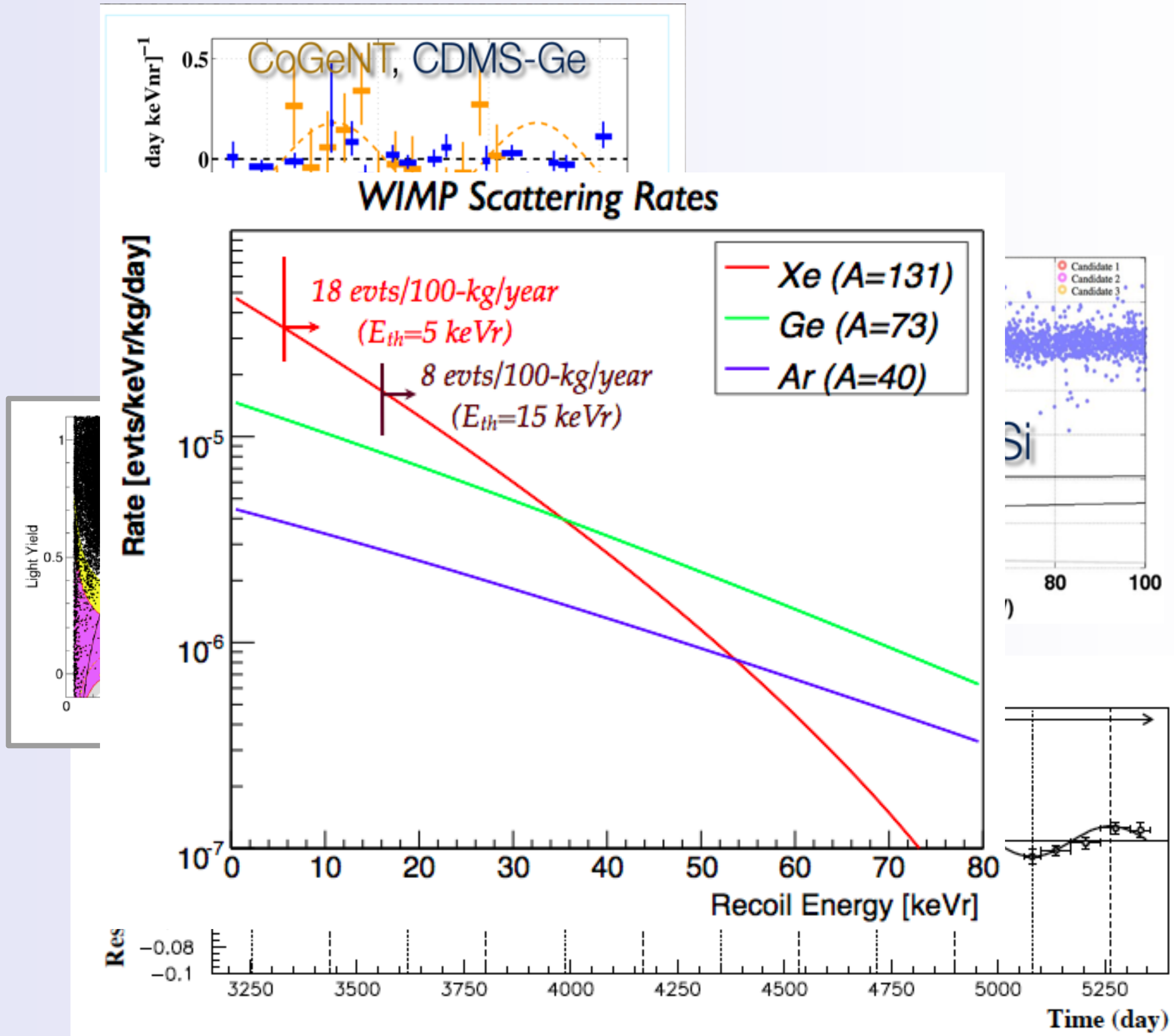
DarkSide at LNGS:

50 kg LAr (dep in ^{39}Ar)
(33 kg fiducial)
arXiv:1510.00702v2
38 3-inch PMTs
first data with non-depl Ar in 2014

WIMPs observed?

Low mass observations:

- ➡ CRESST
  - arXiv:1109.0702
  - arXiv:1407.3146
- ➡ CDMS
  - arXiv:1304.4279
  - arXiv:1410.1003
- ➡ CoGeNT:
  - arXiv:1106.0650
  - (arXiv:1405.0495 by others)
- ➡ DAMA
  - Still there

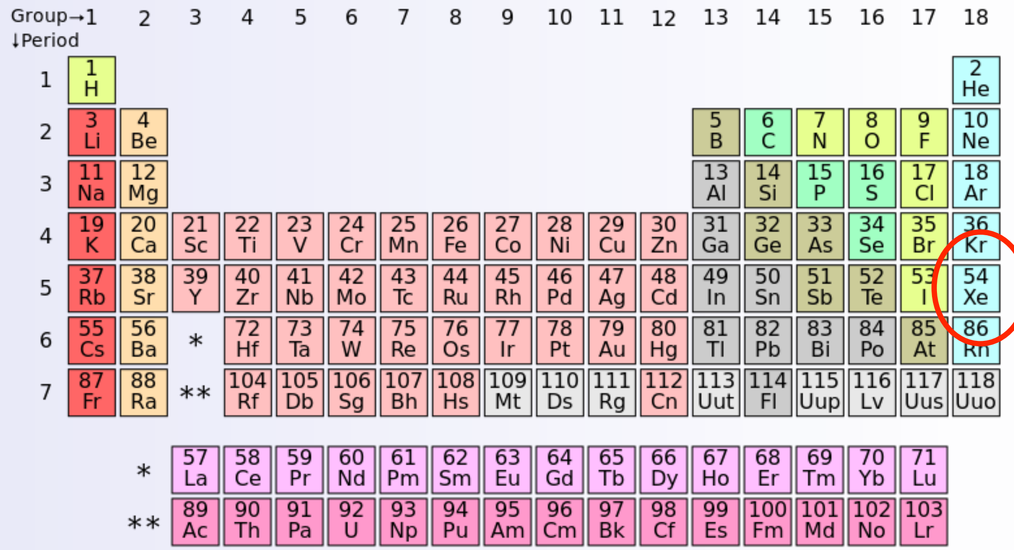


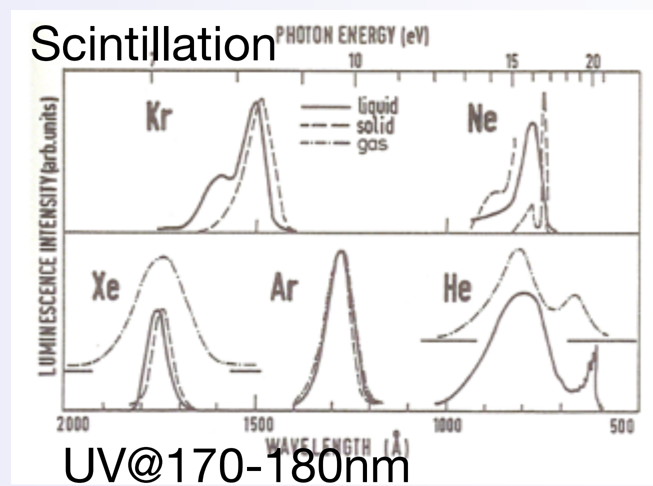
- Recoil spectrum conspires with threshold effects.

Xenon TPC

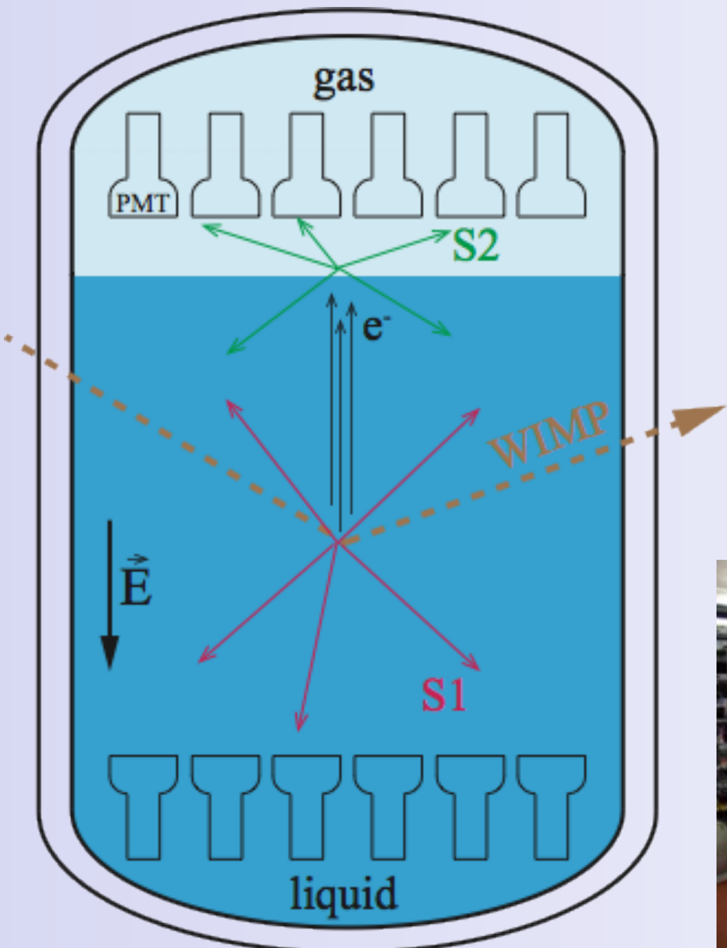
Why use liquid xenon?

- Heavy element
  - ➡SI scattering scales with A^2
  - ➡SD scattering from odd isotopes
- Good detector material
  - ➡Scintillator
  - ➡Ionization
- Scalability
  - ➡2x bigger detector > 2x better
  - ➡may be expensive ☹
- No long-lived isotopes
  - ➡except $^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba} + 2\nu 2\beta$
  - ➡except $^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba} + 0\nu 2\beta$

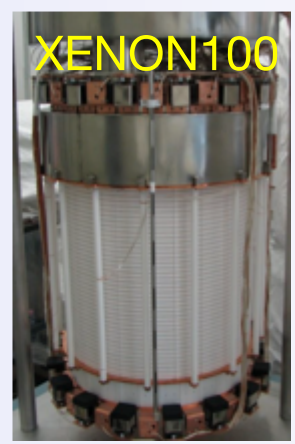




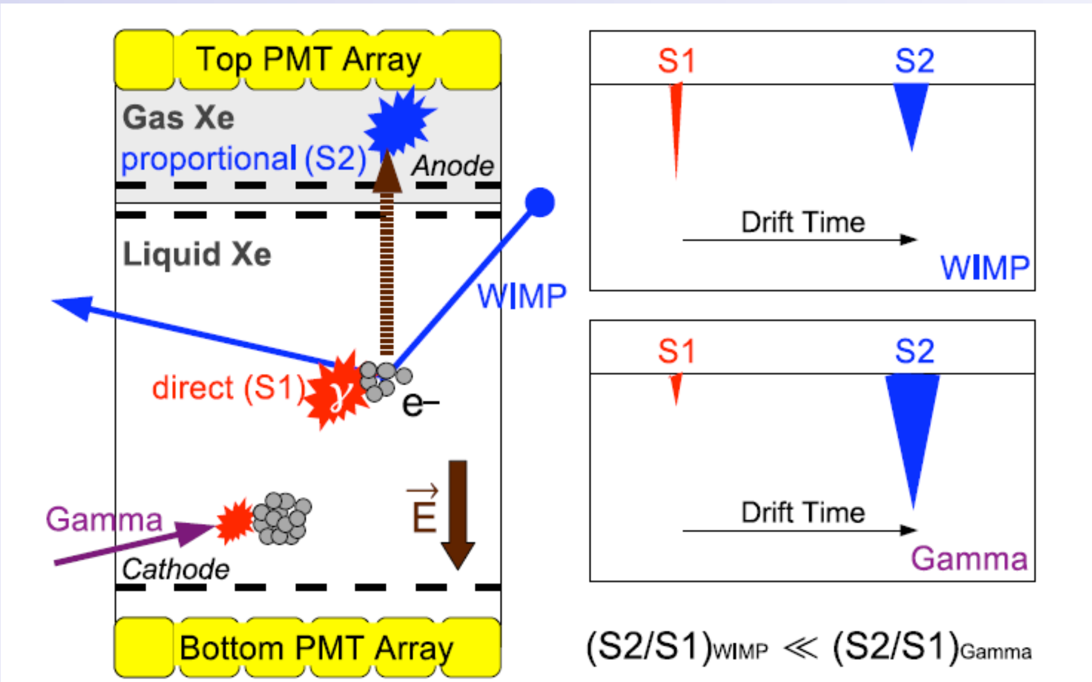
XENON TPC: Calorimeter & 3D position detector



- From "any" recoil in xenon:
  - ➡S1 = scintillation
  - ➡S2 = ionization
- **Energy** from S1 and/or S2
- **3D position**
  - ➡ z-coordinate from $t_{drift} = t_{S2}-t_{S1}$
  - ➡ xy-coordinate from S2 pattern

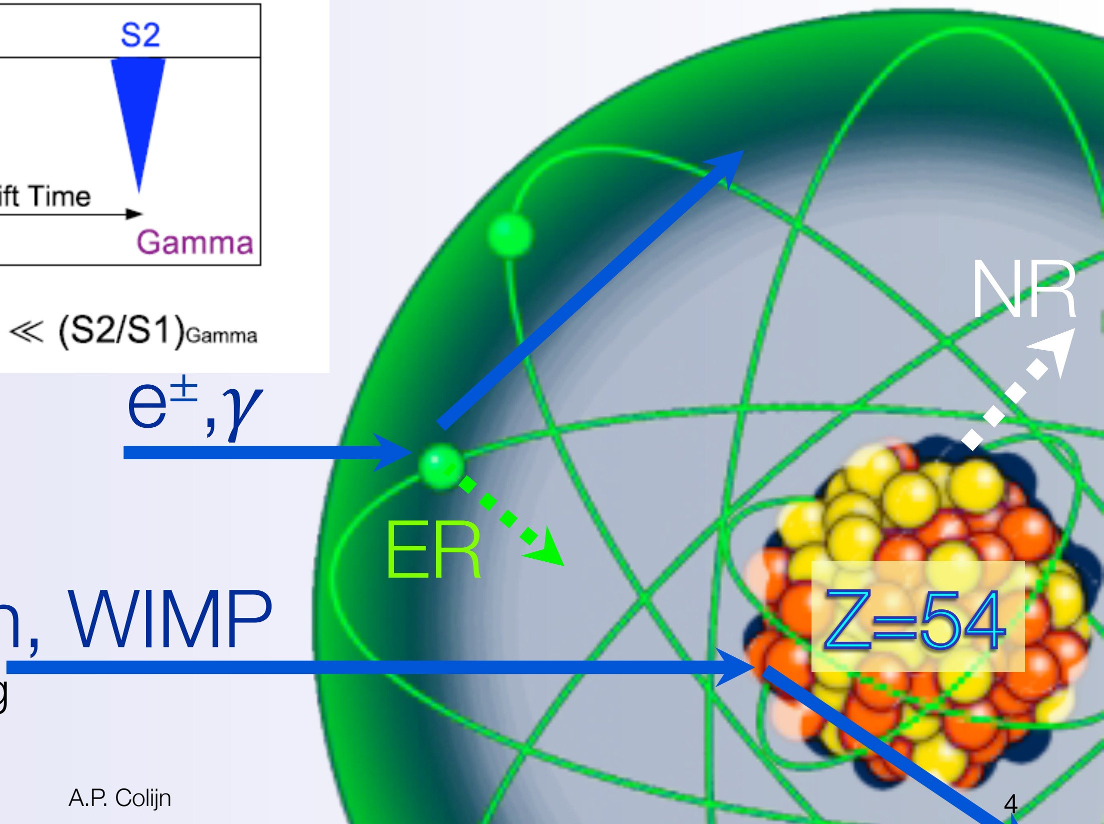


XENON TPC: “particle identification”



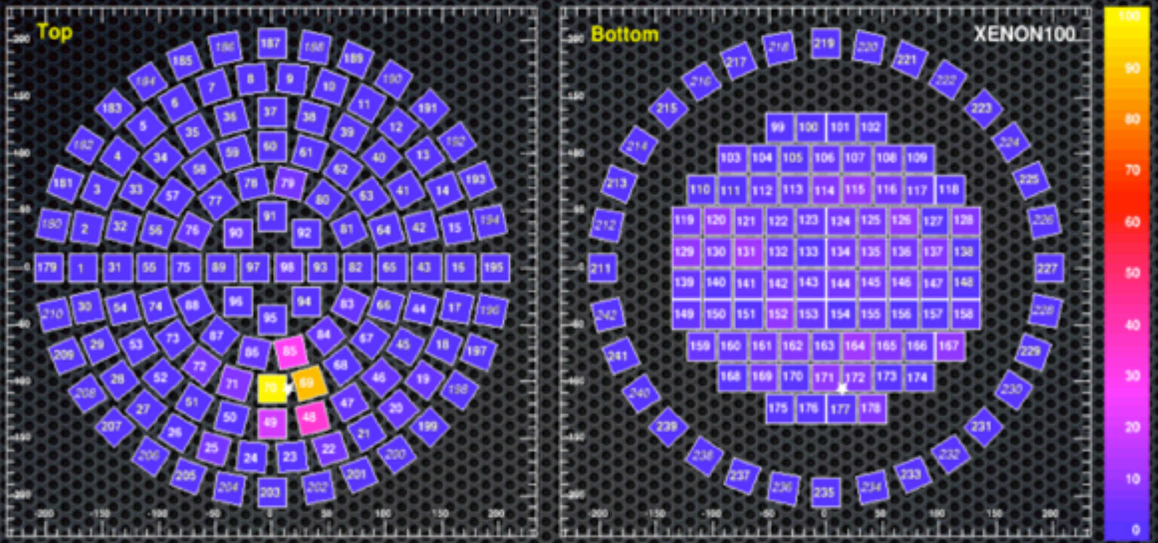
$(S2/S1)_{ER}$ > $(S2/S1)_{NR}$

In XENON100 99.75% of electronic recoils (ER) are rejected, while keeping 50% of the nuclear recoils (NR).



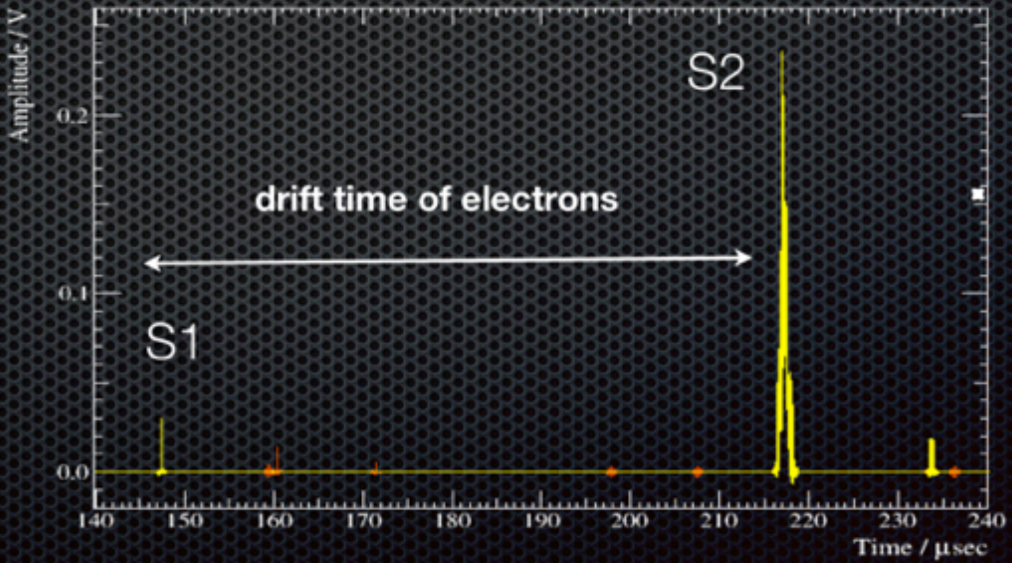
Example of a 9 keV nuclear recoil event

XENON100
top
PMT array



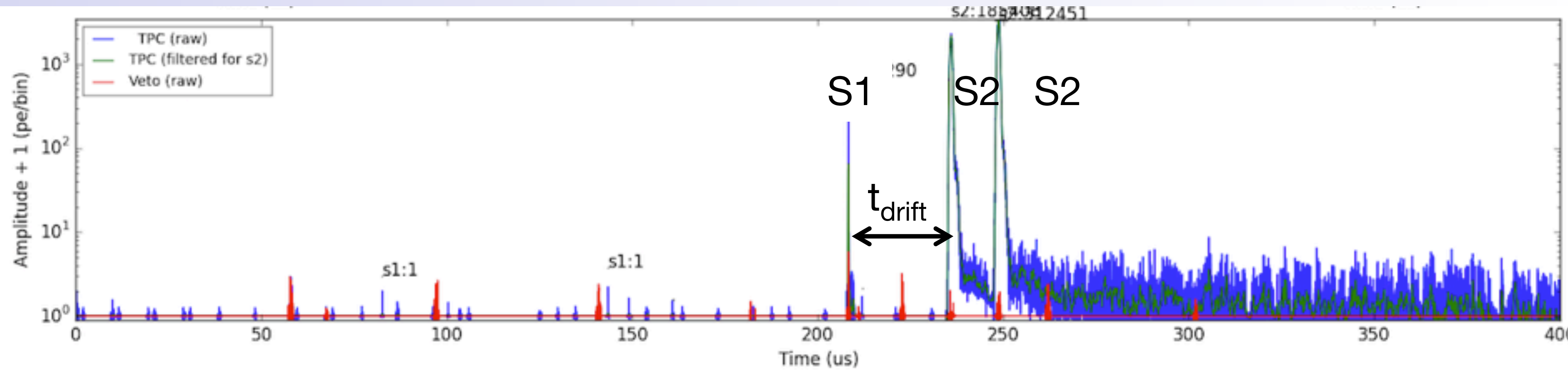
XENON100
bottom
PMT array

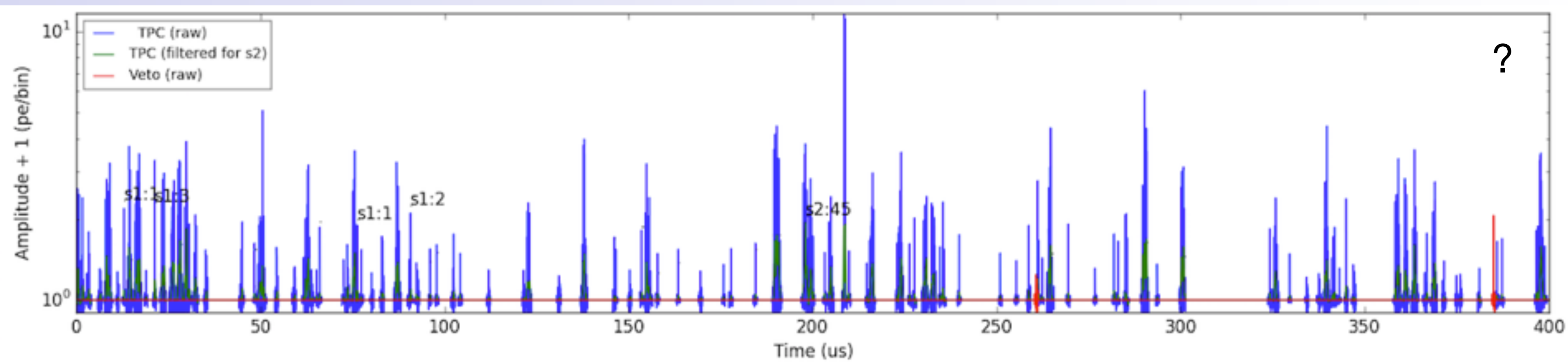
S1: 4 photoelectrons detected from about 100 S1 photons



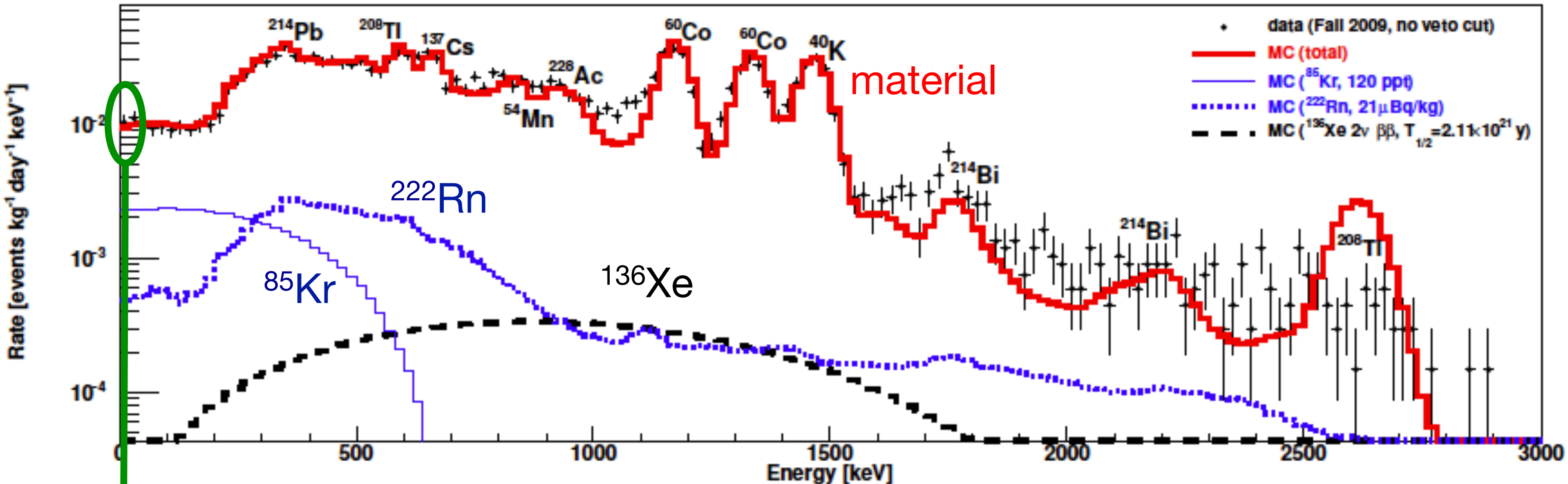
S2: 645 photoelectrons detected from 32 ionization electrons which generated about 3000 S2 photons

XENON100: Example – neutrons from AmBe



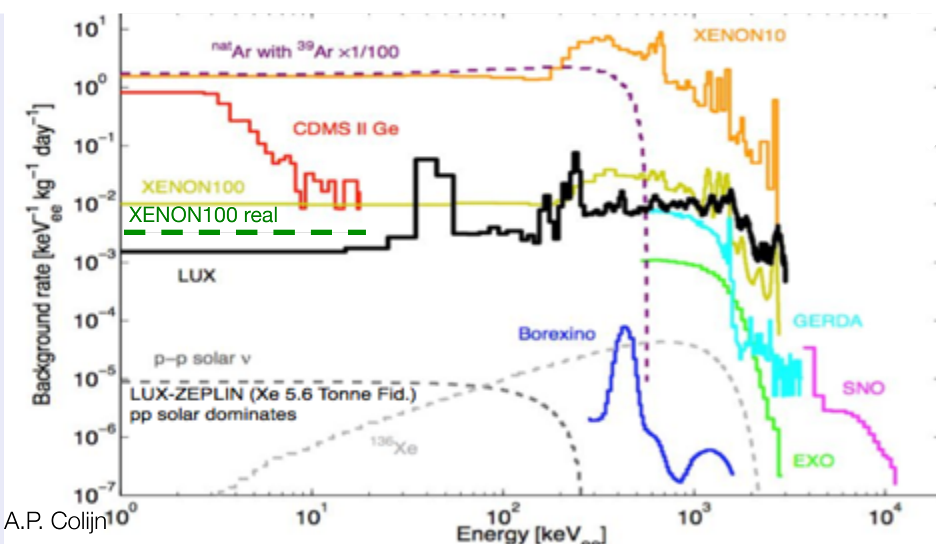


XENON100: electronic recoil spectrum …..



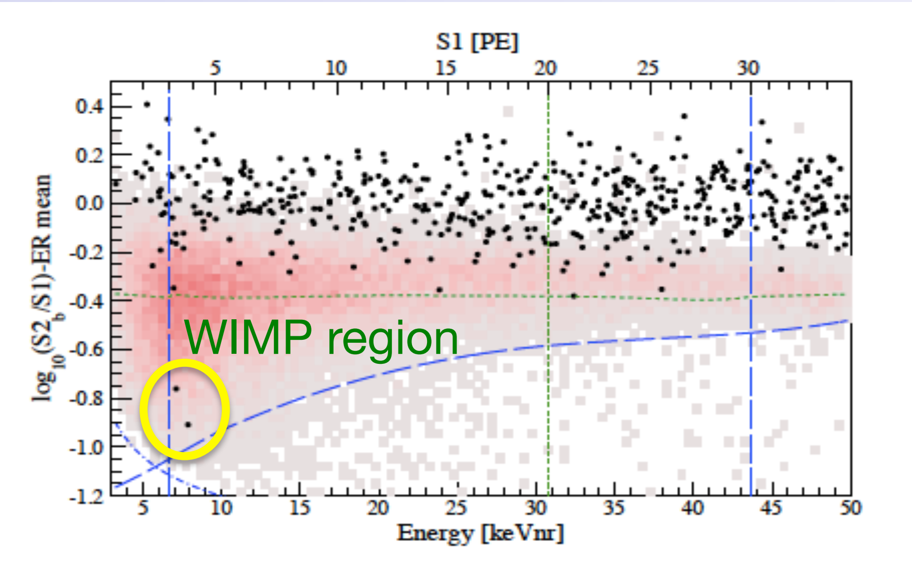
Phys.Rev.D83:082001,2011

Region of interest. Also region of biggest improvement with new detector.

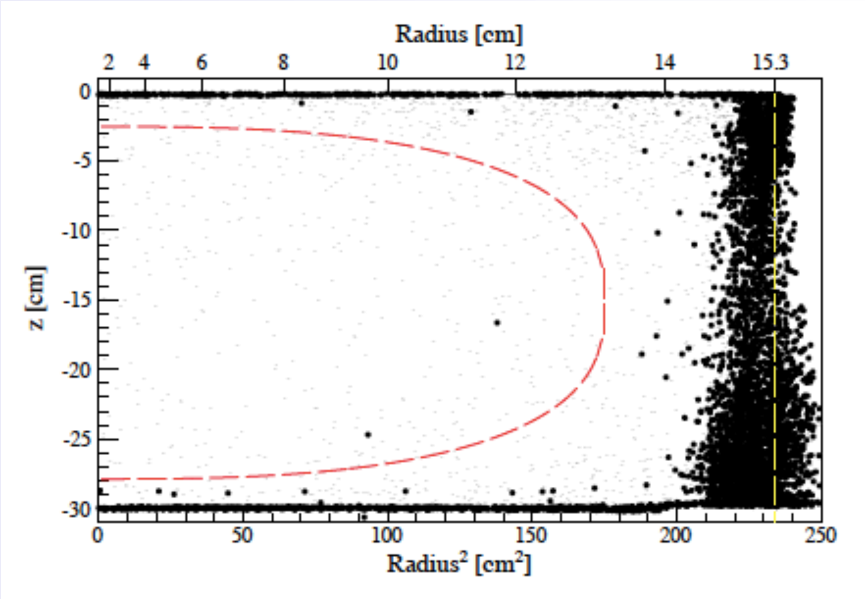


XENON100: Seen “nothing” for 225 days…

Phys. Rev. Lett. 109, 181301 (2012)



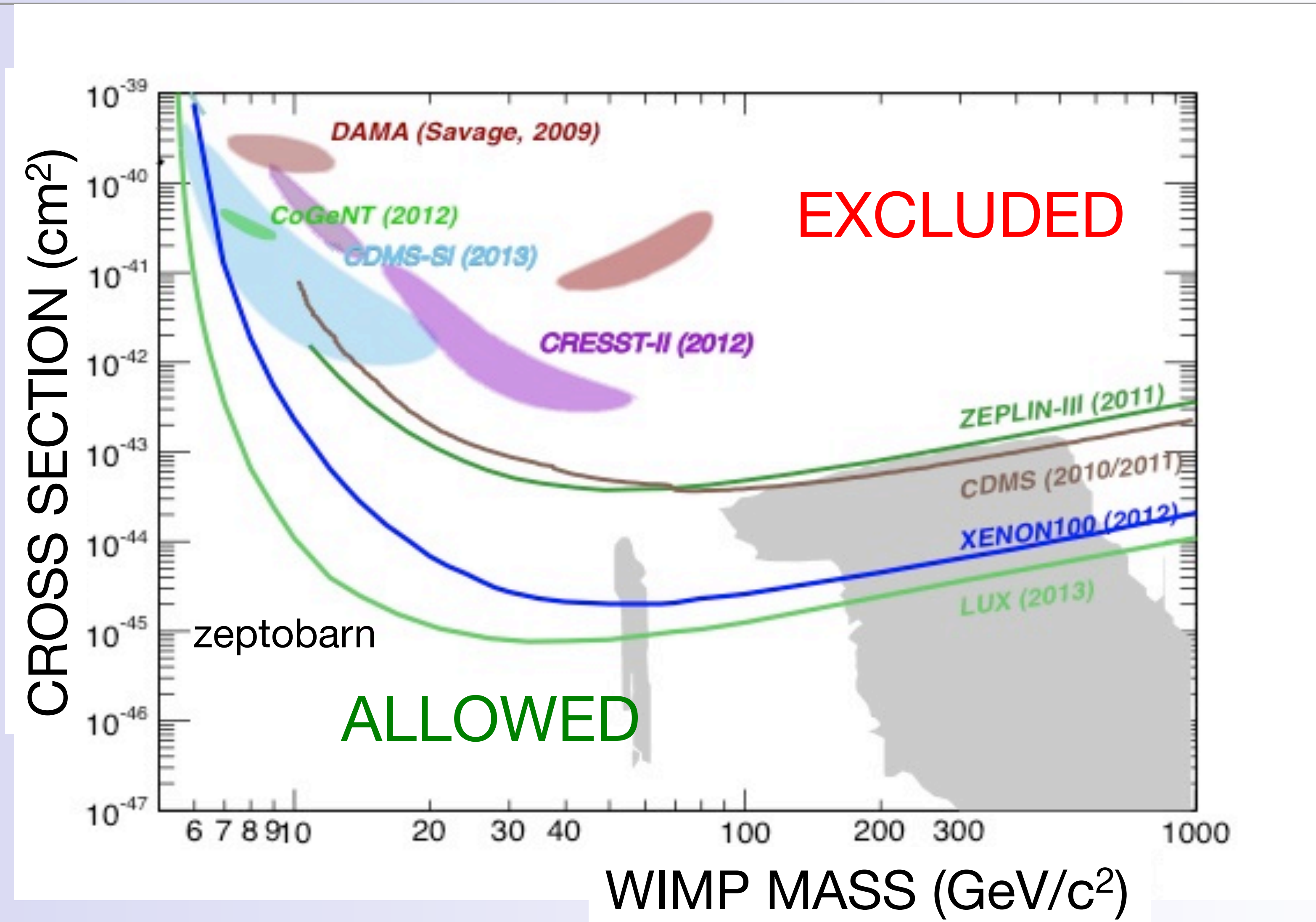
[Fiducialization](#)



- 2 events observed
- 1.0±0.2 events expected from background

…… and many other results
[arxiv:1507.07748](#)
[arxiv:1507.07747](#)
[arxiv:1404.1455](#)
[arXiv:1311.1088](#)
…….

XENON: LUX leading the pack…..

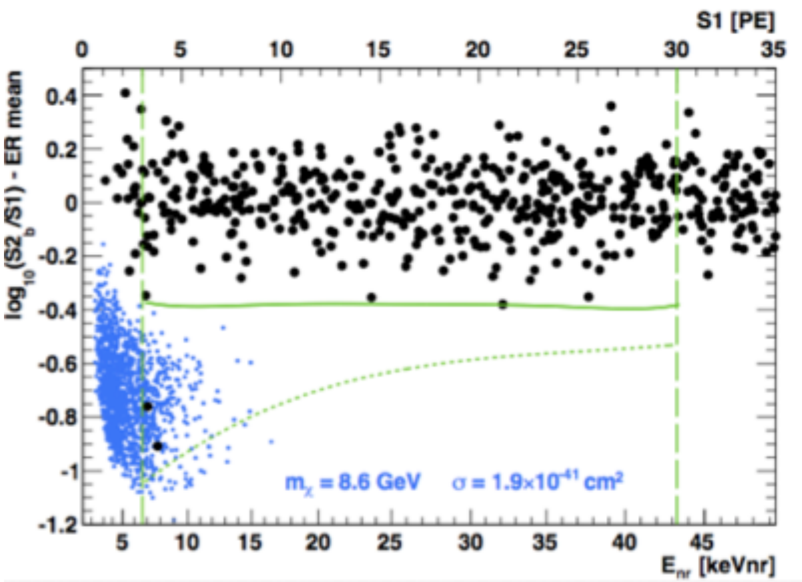


(Baudis)

What would low-mass WIMPs look like in Xenon TPCs?

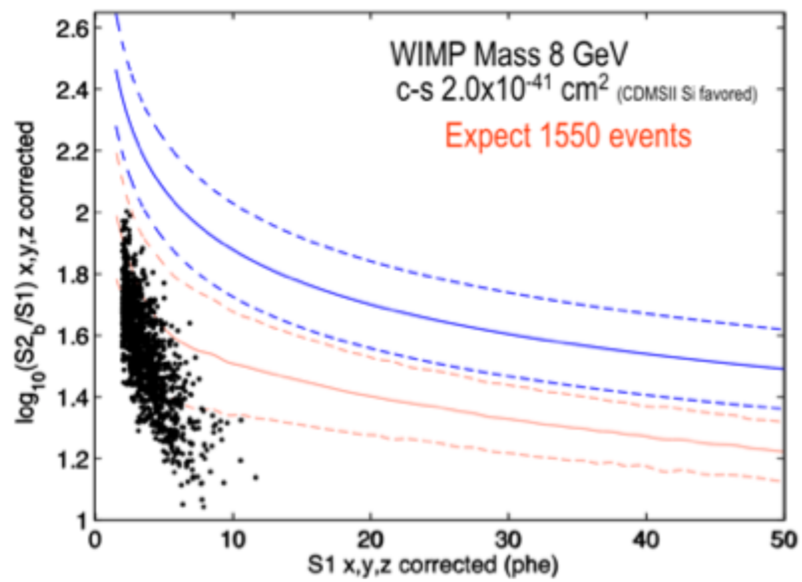
XENON100

Expected: 220 events



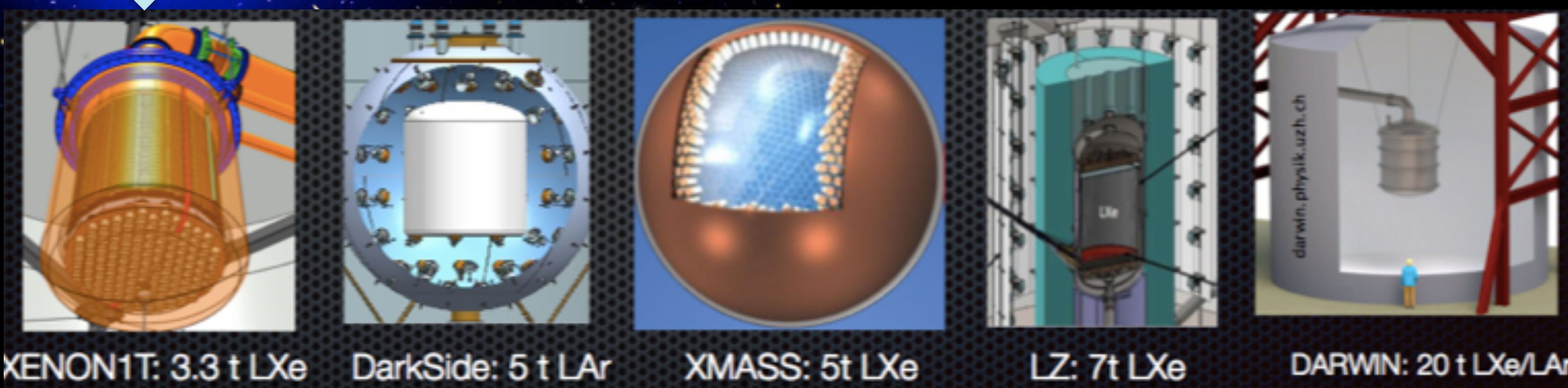
LUX

Expected: 1550 events

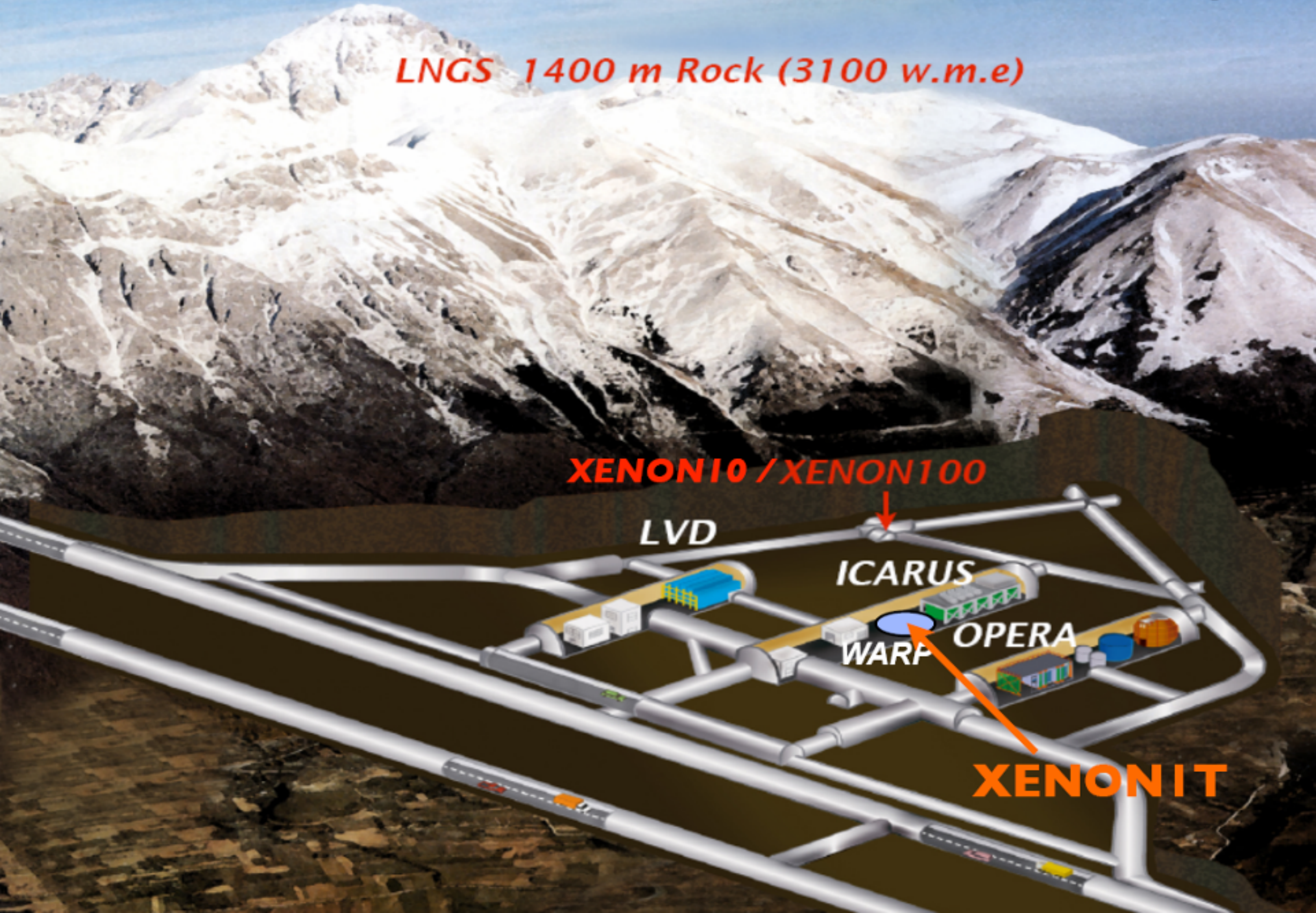


Only talk about this one…

Next generation



Laboratori Nazionali del Gran Sasso, Italy



XENON1T:Two orders of magnitude more sensitive

- **Go**

➡

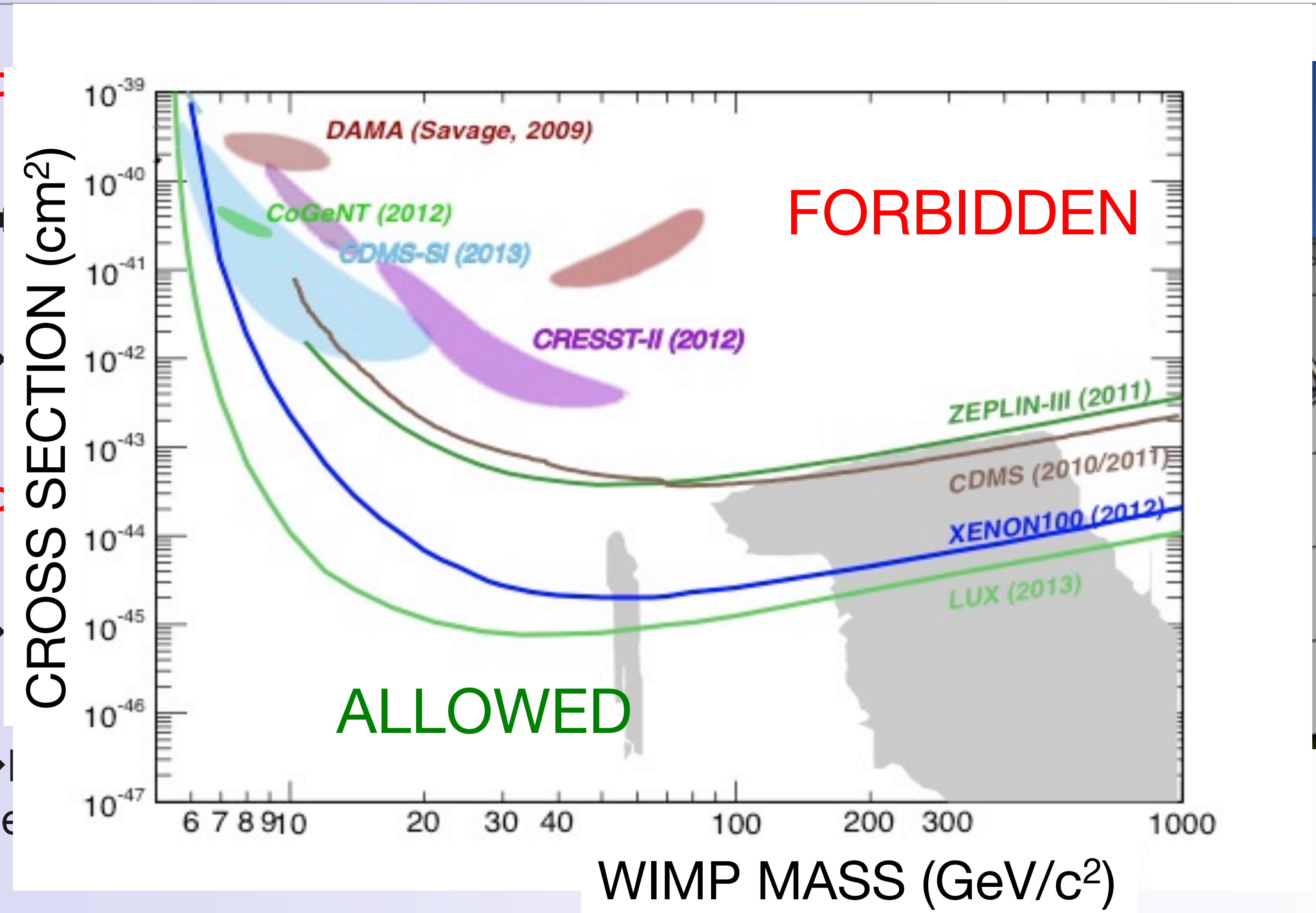
➡

- **Ho**

➡

➡I

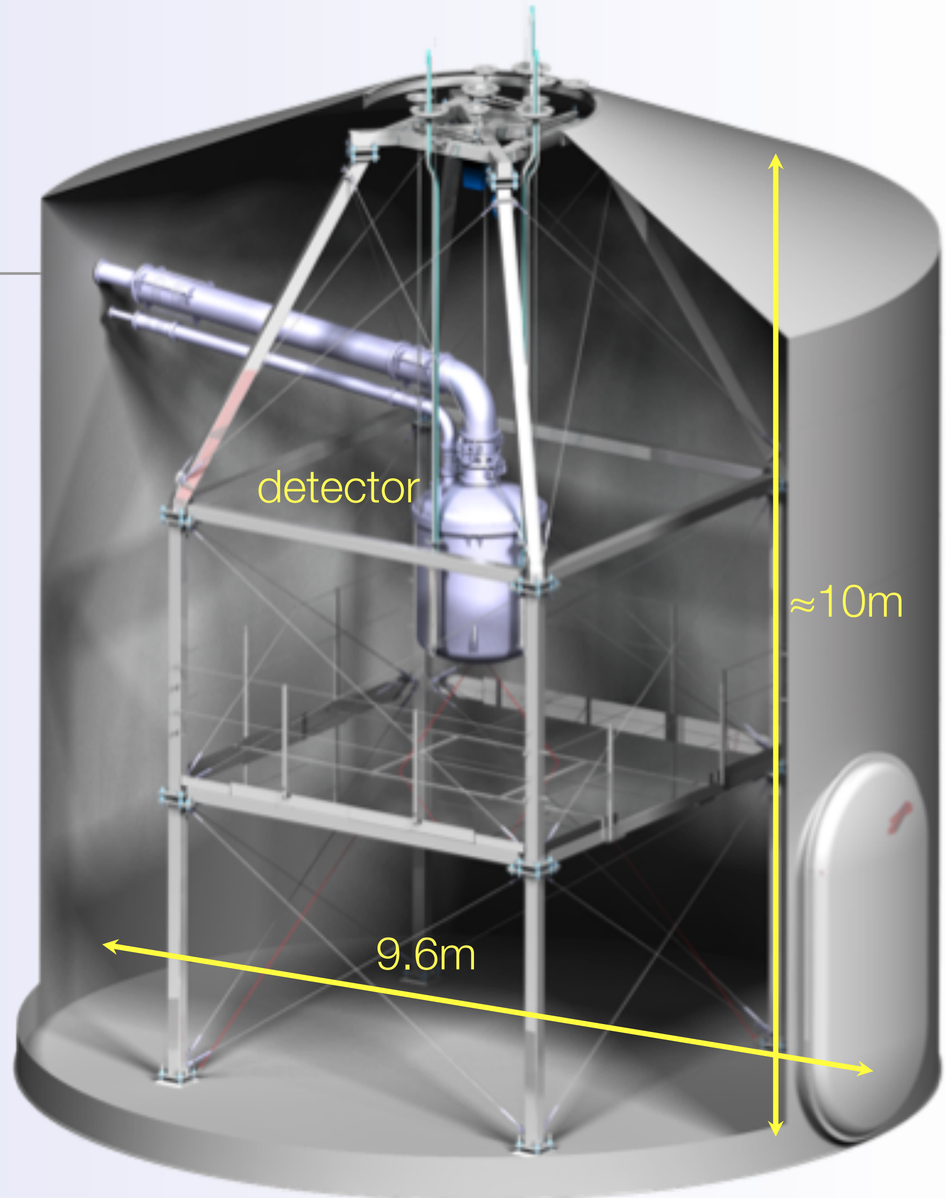
e



XENON1T: Design

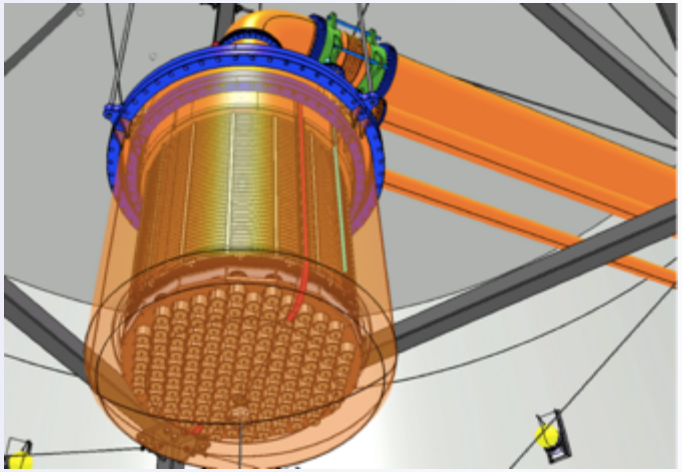
- Dark matter detector inside cryostat
- Surrounded by 10m diameter Cerenkov active shield
- Cryostat suspended from 3 rods, like a marionette

- Infrastructure outside water shield
  - ➡DAQ + HV + slow control
  - ➡Cryogenics system
  - ➡Xenon purification and handling



XENON100 on same scale

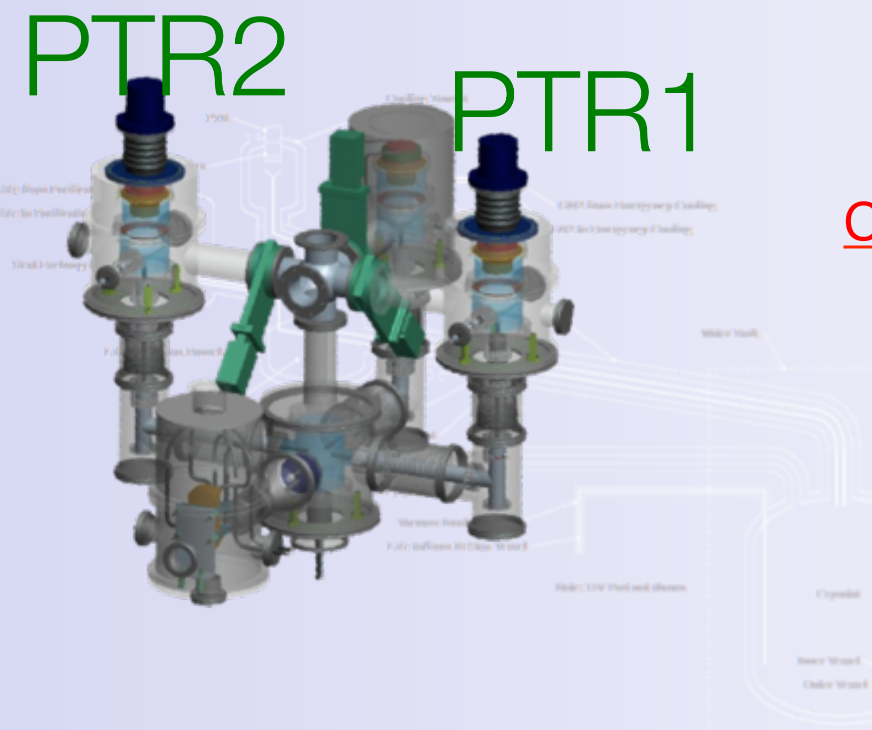
XENON1T: Cryostat & Cryogenics



Cryogenics

➡200W pulse tube refrigerator plant

➡Liquid N_2 backup for safety



Cryostat

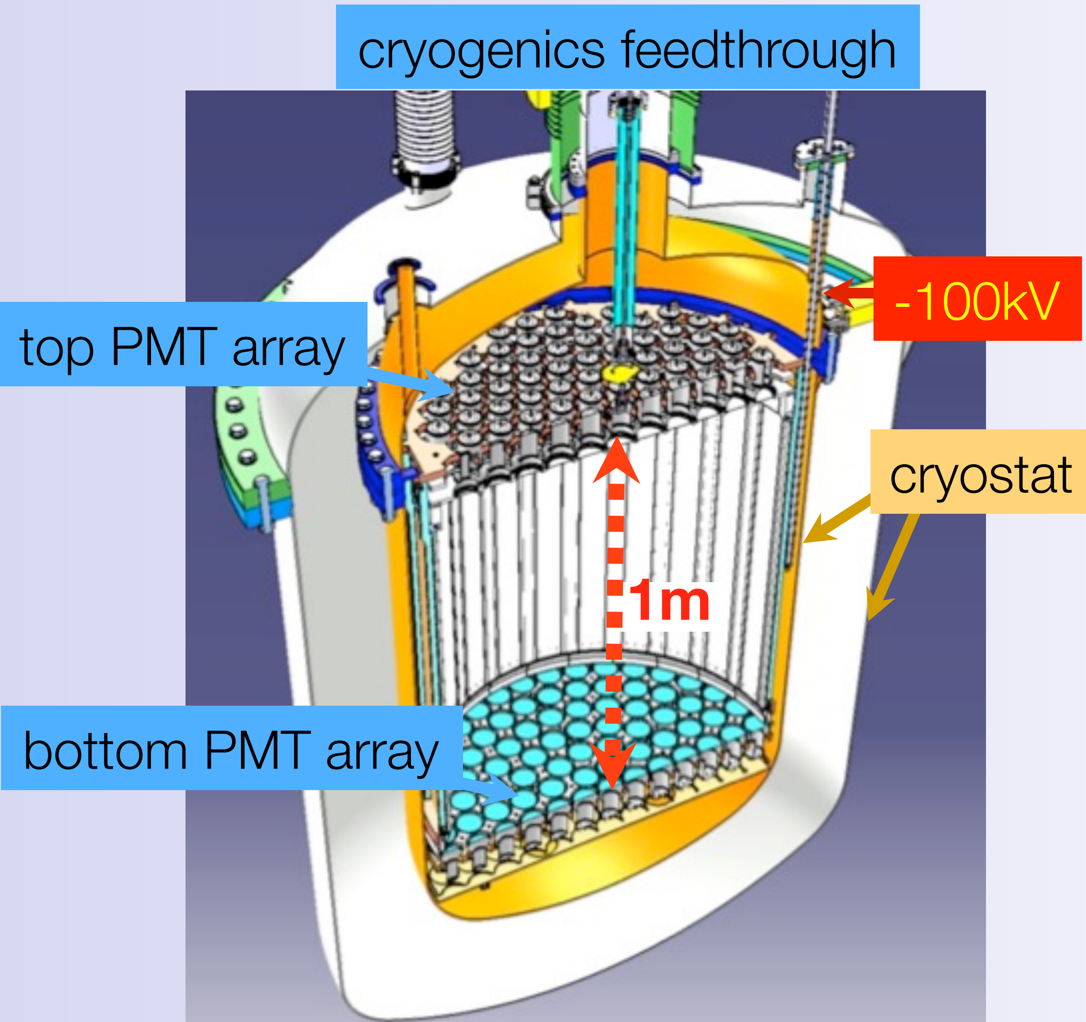
➡Two stainless steel vessels with vacuum insulation

➡Feedthroughs for PMT signal/HV, detector HV, LXe recovery

➡Connected to cryogenic system through big-pipe

➡Heat leak <50W

XENON1T: Time Projection Chamber



Xenon

- ➡>2 ton liquid xenon @ -100°C
- ➡>1.1 ton fiducial
- ➡~1m drift

Photomultipliers

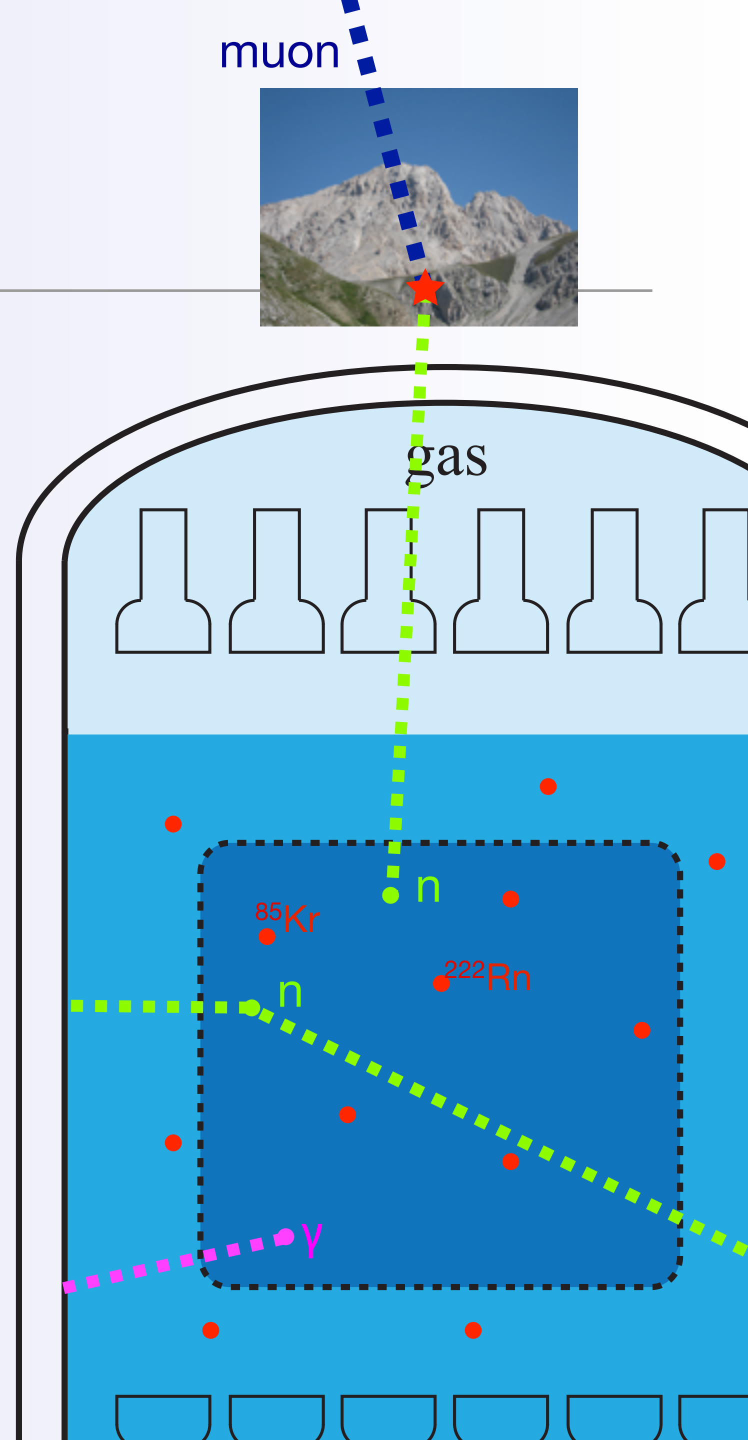
- ➡3” R11410 from Hamamatsu
- ➡127 in top array
- ➡121 in bottom array

HV = -100kV (-16kV for XENON100)

Backgrounds

- <u>External backgrounds</u>
  - ➡cosmic muons
  - ➡neutrons induced by cosmic muons
  - ➡U and Th in any material
    - neutrons from spontaneous fission
    - neutrons from (α, n) reactions
    - γ’s
  - ➡neutrinos

- <u>Internal backgrounds</u>
  - ➡^{85}Kr
  - ➡^{222}Rn
  - ➡2ν2β decay of ^{136}Xe



Backgrounds: Electronic Recoil

- XENON100

  $(5.3 \pm 0.6) \cdot 10^{-3}$ /keV/kg/day

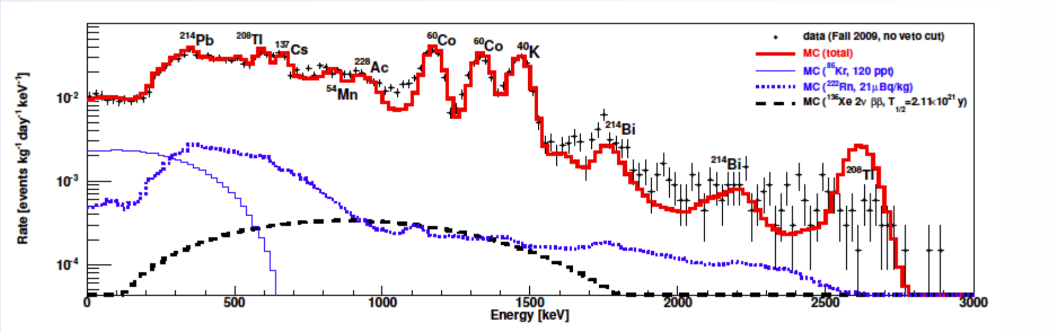
- XENON1T (2-12keV)

  $(4.2 \pm 0.4) \cdot 10^{-5}$ /keV/kg/day

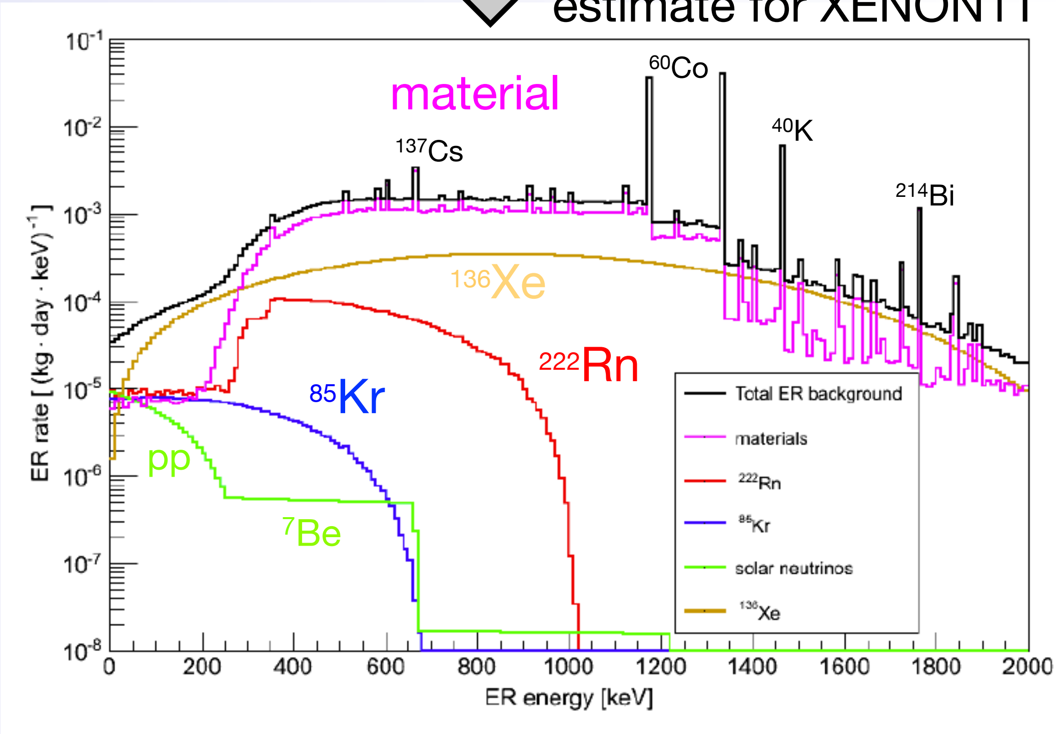
- 99.95% rejection with S2/S1 ratio. Nuclear recoil BG:

  0.1 /t/yr

- **Uncertainty: ^{222}Rn**

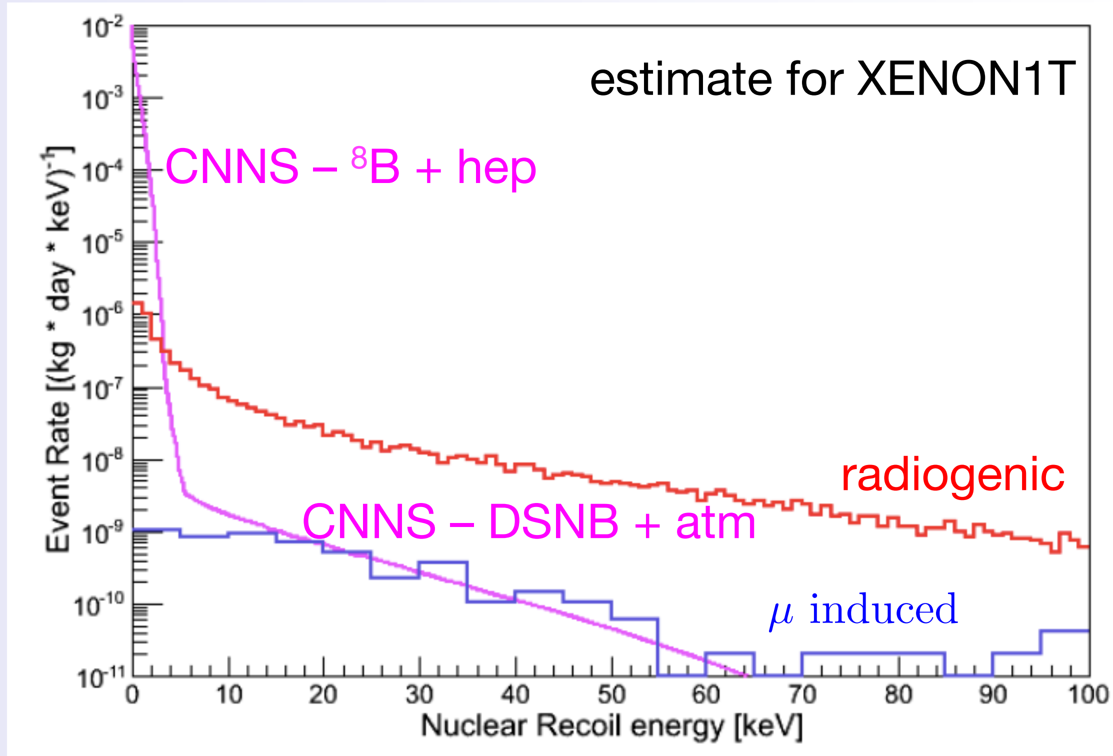


estimate for XENON1T

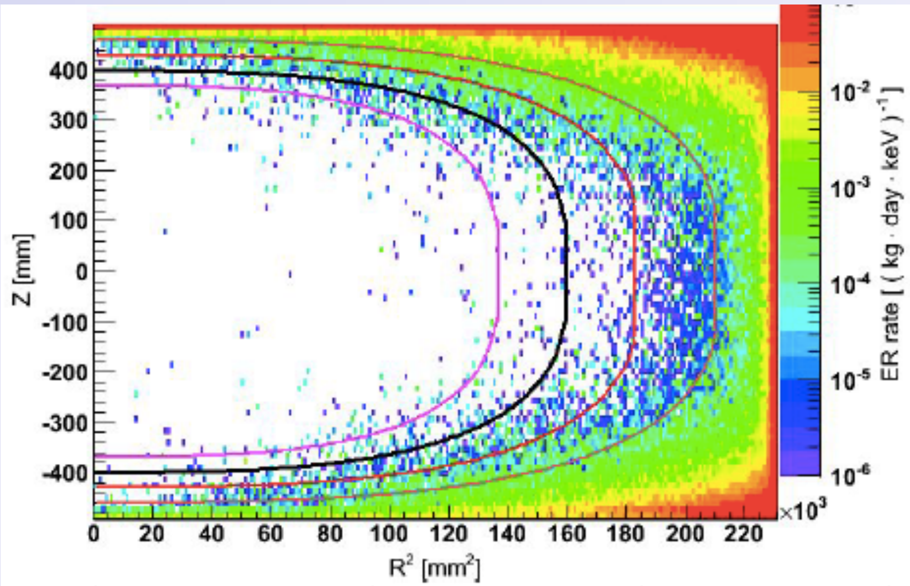


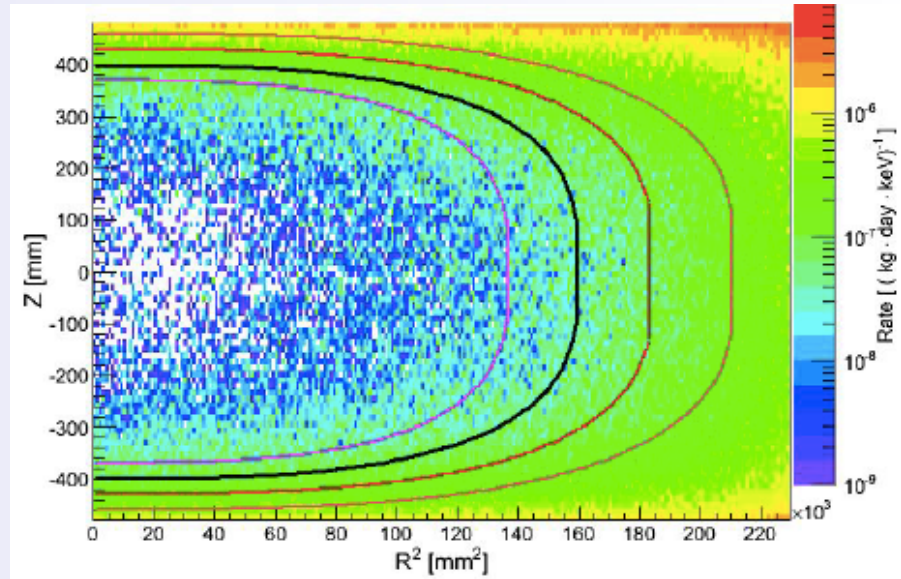
Backgrounds: Nuclear Recoil

- Irreducible background
- Still dominated by construction materials
- XENON1T
  - ➡ Expected in (5-50) keV_{nr}
    $$0.5 \pm 0.1/\mathrm{t}/\mathrm{yr}$$
  - ➡ Note steep rise of CNNS at low energy



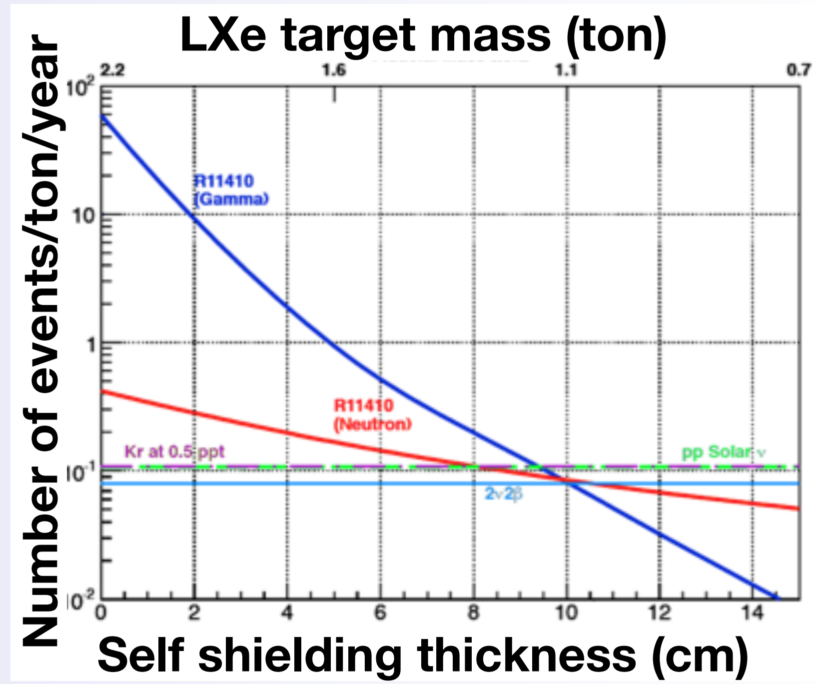
Electronic Recoil vs Nuclear Recoil





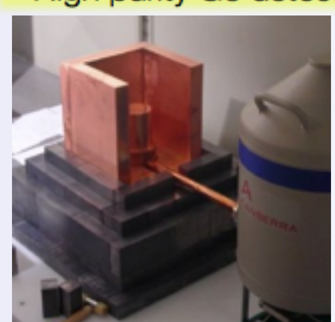
Backgrounds: How to ‘eliminate’

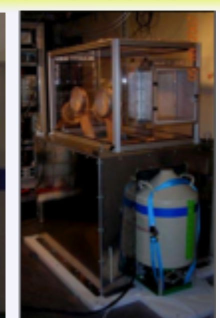
- **Strategy**
  1. **External backgrounds**: Use self-shielding of LXe to reduce external backgrounds (Z=54, ρ_{LXe}=3 g/cm^3)
  2. **Internal backgrounds:** Reduction of background atoms in LXe
  3. “Screen everything”



- Advantage in **BIG** detector
  - ➡can afford more self-shielding
  - ➡extra neutron suppression

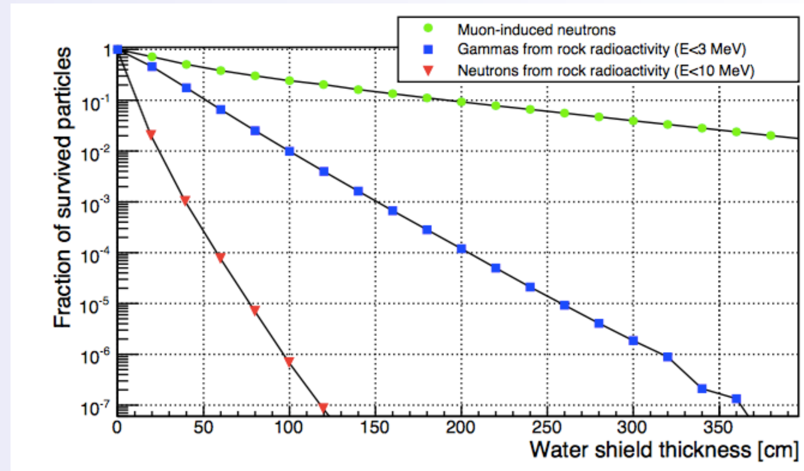
High purity Ge detector for screening



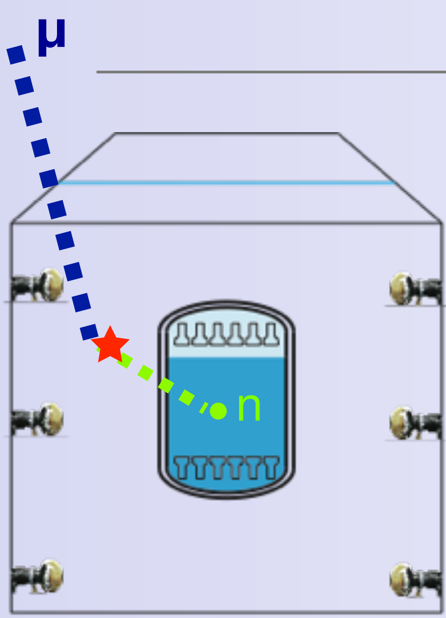


Backgrounds: cosmic muon induced

- **Water shield**
  - ➡Big difference / complication with respect to XENON100 is the ~4.5 m water shield surrounding the XENON1T cryostat
  - ➡Passive shield alone insufficient to reduce the high energy neutron flux

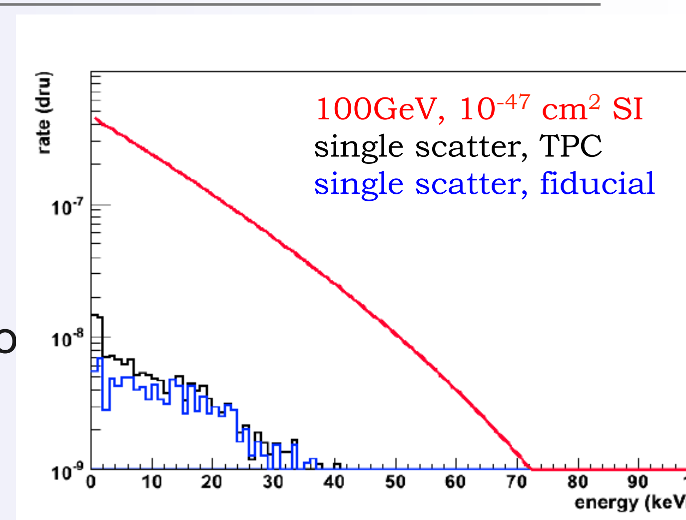


JINST9, P11006 (2014)



Active Cerenkov VETO

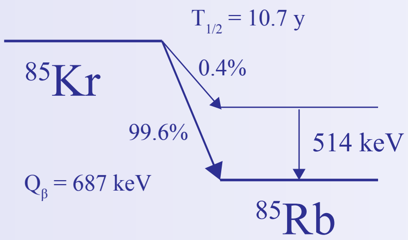
- 84 high QE Hamamatsu R5912 PMTs
- Reject 99.5% of n with μ in veto
- Reject 72% of n with μ outside veto
- μ induced n background<0.01/t/yr



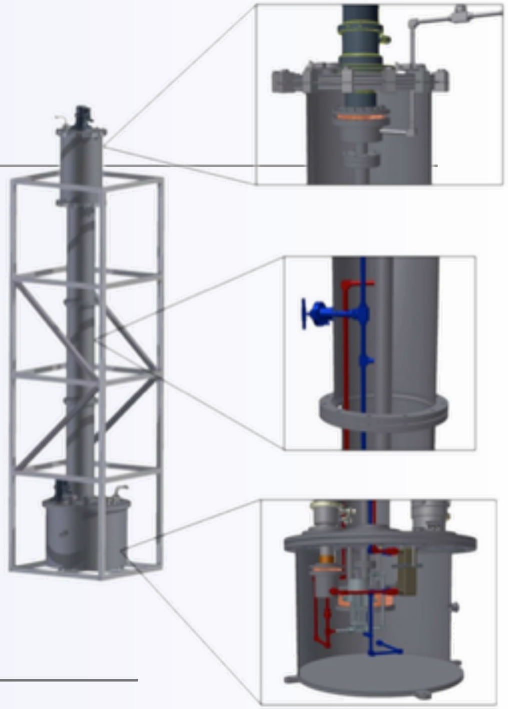
Backgrounds: ^{85}Kr and ^{222}Rn

^{85}Kr

- ^{85}Kr : ^{nat}Kr ~ 10^{-11}
- beta / gamma emitter:



- reduce ^{nat}Kr to < 0.2 ppt < 12 atoms ^{85}Kr per kg xenon
- custom built distillation column
- 3kg / h @ 10^{-4} separation



^{222}Rn

Screening: Rn emanation setup

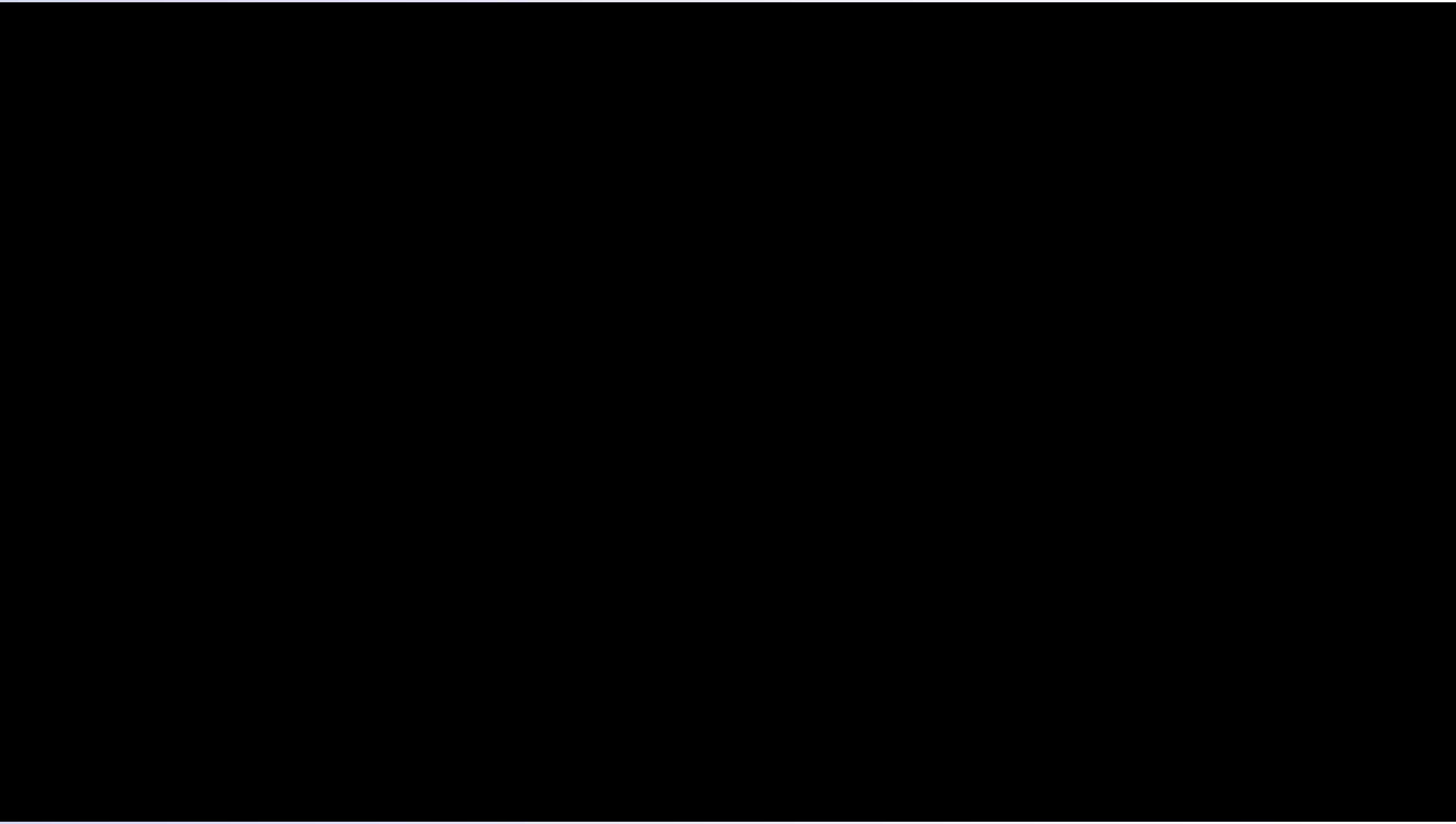
- Noble gas produced in the ^{238}U decay chain.
  - ➡ can originate from any surface (in unpredictable way)
  - ➡ dissolves well in LXe
  - ➡ $t_{1/2}$ = 3.8 days, with shortlived daughters and longlived ^{210}Pb
- Strategy for elimination
  - ➡ avoid surfaces that emanate a lot-> screening
  - ➡ more work

XENON1T: what does it look like today?

Xe

XENON

Dark Matter Project

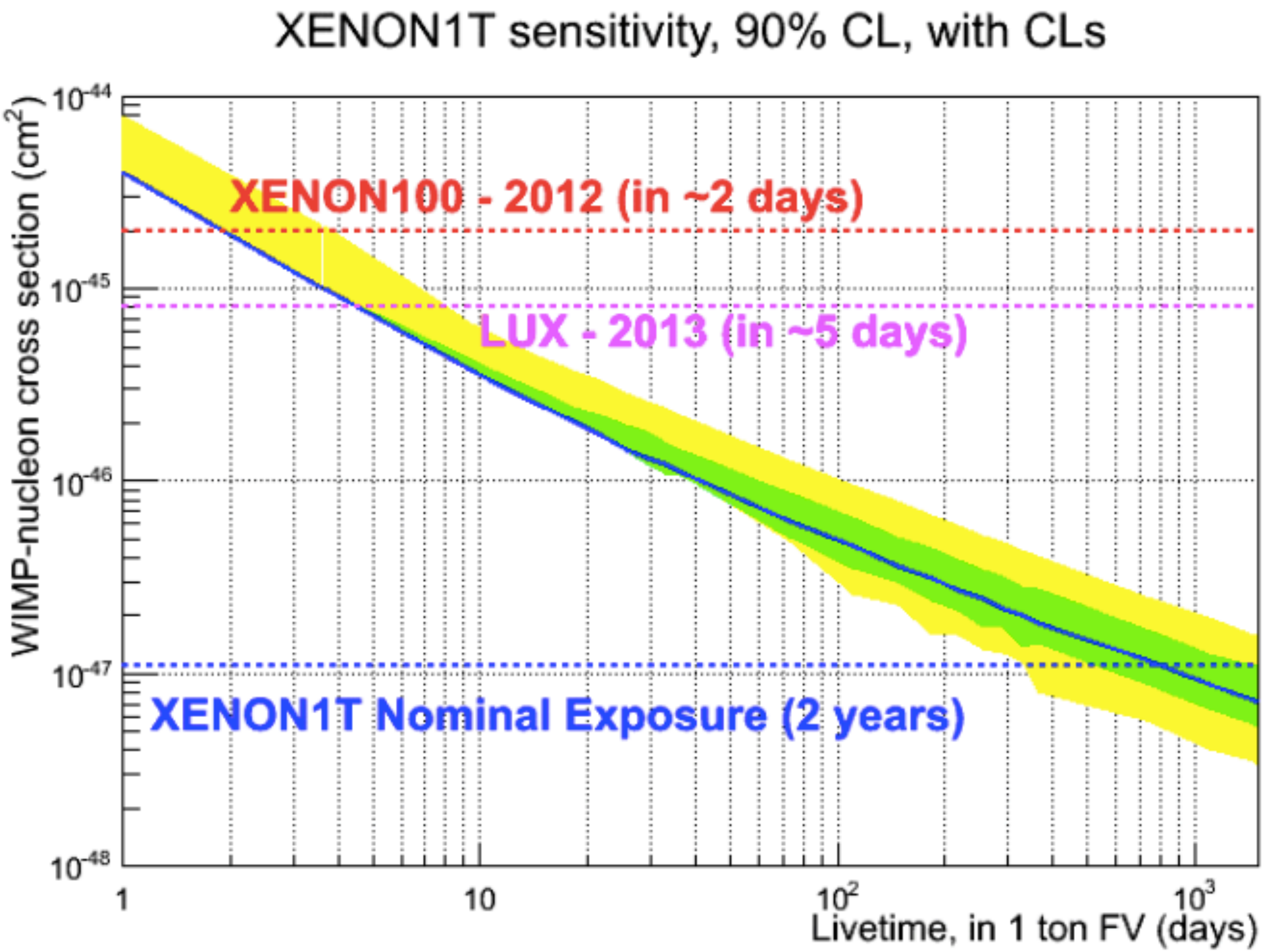


2 months ago….

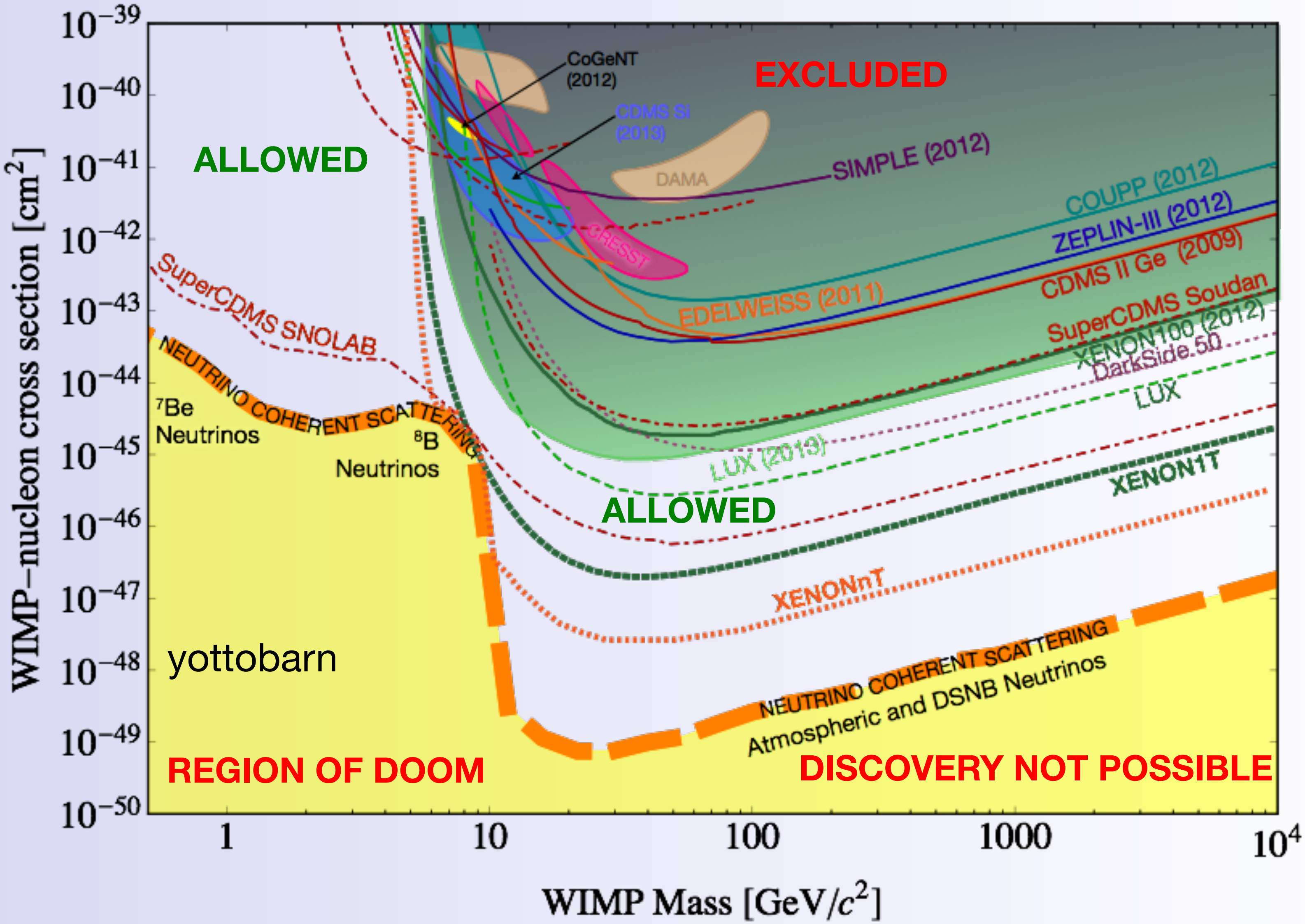
1 month ago....

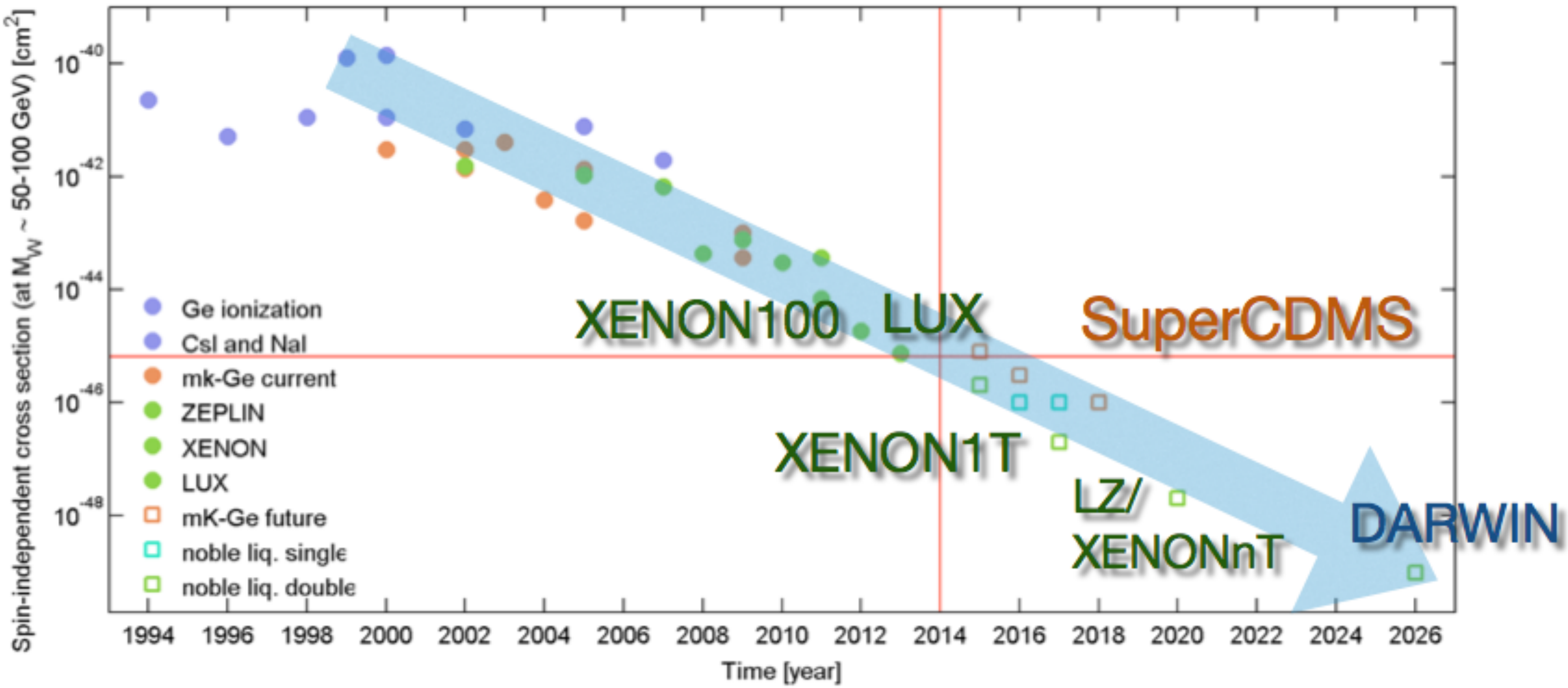
today

XENON1T Sensitivity vs Exposure



XENON1T and beyond: Bigger and bigger?





(Baudis 1408.4371, and many other slides taken from Bau

Summary

Many experiments in hot pursuit of cold DM

Within 10 years answer: yes or can't see

BONUS MATERIAL

Background Sources

ID	Component	Material	Quantity	Unit	Contamination [mBq/unit]							
					^{238}U	^{235}U	^{226}Ra	^{232}Th	^{228}Th	^{60}Co	^{40}K	^{137}Cs
1	**Cryostat Shells**	SS	870	kg	2.4 ± 0.7	$(1.1 \pm 0.3) \cdot 10^{-1}$	$< 6.4 \cdot 10^{-1}$	$(2.1 \pm 0.6) \cdot 10^{-1}$	$< 3.6 \cdot 10^{-1}$	9.7 ± 0.8	< 2.7	$< 6.4 \cdot 10^{-1}$
2	**Cryostat Flanges**	SS	560	kg	1.4 ± 0.4	$(6 \pm 2) \cdot 10^{-2}$	< 4.0	$(2.1 \pm 0.6) \cdot 10^{-1}$	4.5 ± 0.6	37.3 ± 0.9	< 5.6	< 1.5
3	**Bottom Filler**	SS	90	kg	11 ± 3	$(5 \pm 2) \cdot 10^{-1}$	1.2 ± 0.3	1.2 ± 0.4	2.0 ± 0.4	5.5 ± 0.5	< 1.3	$< 5.8 \cdot 10^{-1}$
4	**TPC Panels** (1)	PTFE	92	kg	$< 2.5 \cdot 10^{-1}$	$< 1.1 \cdot 10^{-2}$	$< 1.2 \cdot 10^{-1}$	$< 4.1 \cdot 10^{-2}$	$< 6.5 \cdot 10^{-2}$	$< 2.7 \cdot 10^{-2}$	$< 3.4 \cdot 10^{-1}$	$(1.7 \pm 0.3) \cdot 10^{-1}$
5	**TPC Plates** (2)	Cu	184	kg	< 1.2	$< 5.5 \cdot 10^{-1}$	$< 3.3 \cdot 10^{-2}$	$< 4.3 \cdot 10^{-2}$	$< 3.4 \cdot 10^{-2}$	0.10 ± 0.01	$< 2.8 \cdot 10^{-1}$	$< 1.6 \cdot 10^{-2}$
6	**Bell and Rings** (3)	SS	80	kg	2.4 ± 0.7	$(1.1 \pm 0.3) \cdot 10^{-1}$	$< 6.4 \cdot 10^{-1}$	$(2.1 \pm 0.6) \cdot 10^{-1}$	$< 3.6 \cdot 10^{-1}$	9.7 ± 0.8	< 2.7	$< 6.4 \cdot 10^{-1}$
7	**PMT Stem**	Al_2O_3	248	PMT	2.4 ± 0.4	$(1.1 \pm 0.2) \cdot 10^{-1}$	$(2.6 \pm 0.2) \cdot 10^{-1}$	$(2.3 \pm 0.3) \cdot 10^{-1}$	$(1.1 \pm 0.2) \cdot 10^{-1}$	$< 1.8 \cdot 10^{-2}$	1.1 ± 0.2	$< 2.2 \cdot 10^{-2}$
8	**PMT Window**	Quartz	248	PMT	< 1.2	$< 2.4 \cdot 10^{-2}$	$(6.5 \pm 0.7) \cdot 10^{-2}$	$< 2.9 \cdot 10^{-2}$	$< 2.5 \cdot 10^{-2}$	$< 6.7 \cdot 10^{-3}$	$< 1.5 \cdot 10^{-2}$	$< 6.8 \cdot 10^{-3}$
9	**PMT SS**	SS	248	PMT	$(2.6 \pm 0.8) \cdot 10^{-1}$	$(1.1 \pm 0.4) \cdot 10^{-2}$	$< 6.5 \cdot 10^{-2}$	$< 3.9 \cdot 10^{-2}$	$< 5.0 \cdot 10^{-2}$	$(8.0 \pm 0.7) \cdot 10^{-2}$	$< 1.6 \cdot 10^{-1}$	$< 1.9 \cdot 10^{-2}$
10	**PMT Body**	Kovar	248	PMT	$< 1.4 \cdot 10^{-1}$	$< 6.4 \cdot 10^{-3}$	$< 3.1 \cdot 10^{-1}$	$< 4.9 \cdot 10^{-2}$	$< 3.7 \cdot 10^{-1}$	$(3.2 \pm 0.3) \cdot 10^{-1}$	< 1.1	$< 1.2 \cdot 10^{-1}$
11	**PMT Bases**	Cirlex	248	PMT	$(8.2 \pm 0.3) \cdot 10^{-1}$	$(7.1 \pm 1.6) \cdot 10^{-2}$	$(3.2 \pm 0.2) \cdot 10^{-1}$	$(2.0 \pm 0.3) \cdot 10^{-1}$	$(1.53 \pm 0.13) \cdot 10^{-1}$	$< 5.2 \cdot 10^{-3}$	$(3.6 \pm 0.8) \cdot 10^{-1}$	$< 9.8 \cdot 10^{-3}$
12	**Whole PMT**	-	248	PMT	8 ± 2	$(3.6 \pm 0.8) \cdot 10^{-1}$	$(5 \pm 1) \cdot 10^{-1}$	$(5 \pm 1) \cdot 10^{-1}$	$(5.0 \pm 0.6) \cdot 10^{-1}$	$(7.1 \pm 0.3) \cdot 10^{-1}$	13 ± 2	$< 1.8 \cdot 10^{-1}$