Dark Matter direct search: the XENON project

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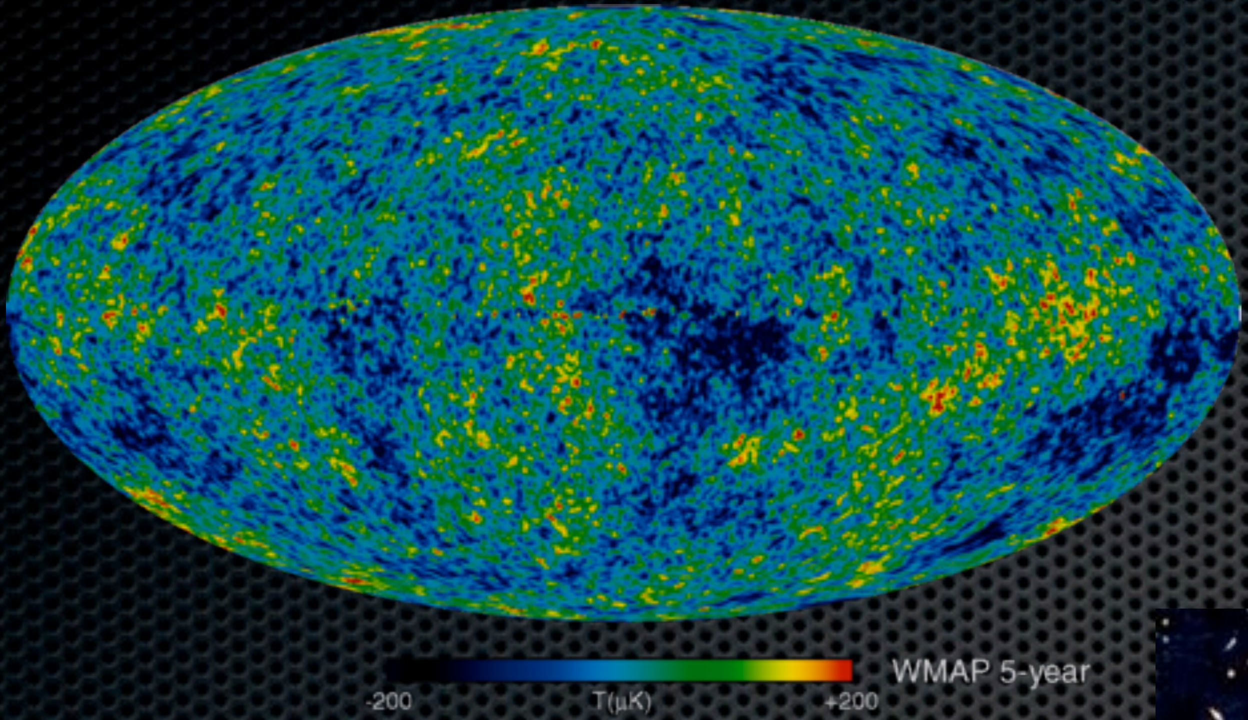
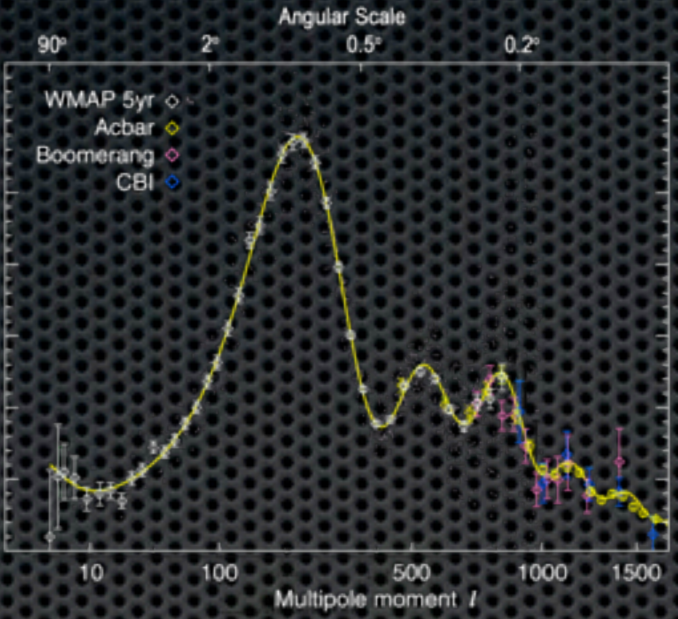
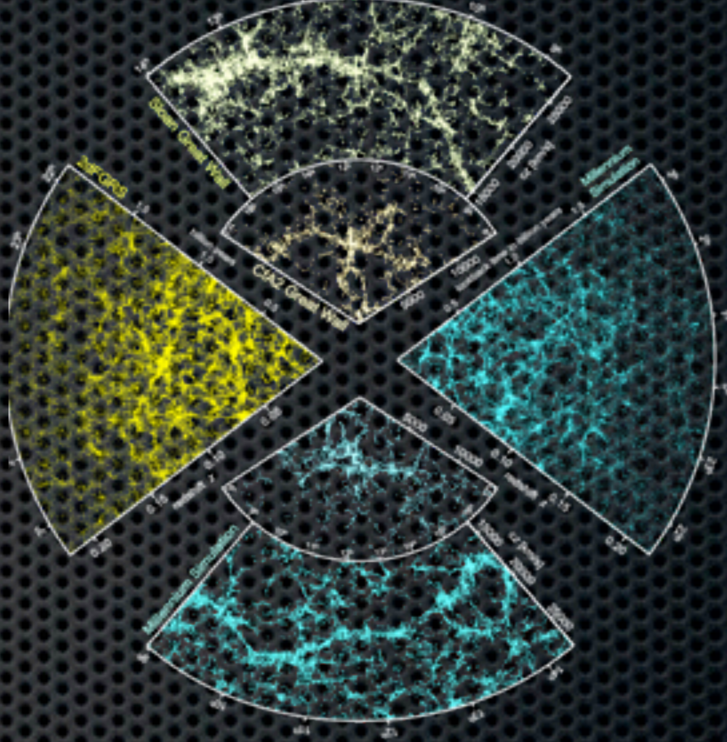
Outline

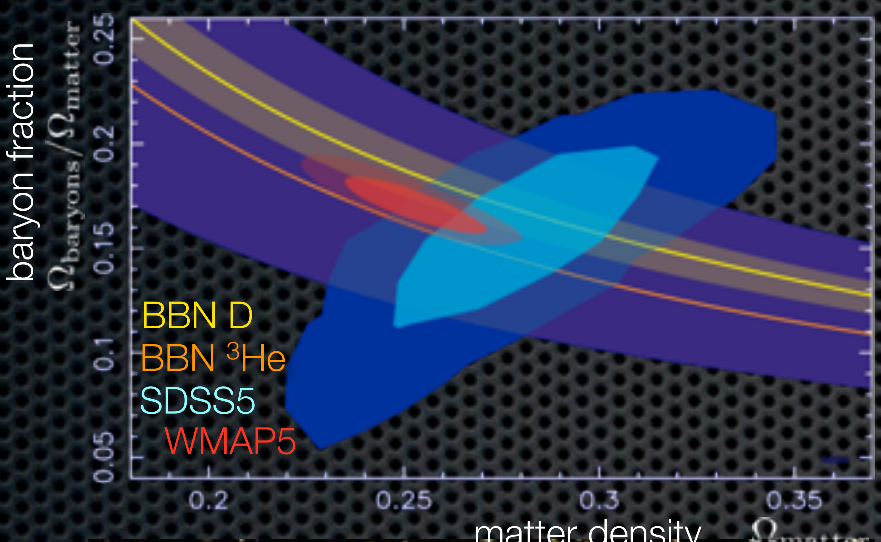
- Motivations for Dark Matter in the Universe
- The WIMP hypothesis: details of the direct search
- Generalities and requirements for DM detectors
- Principles of a double-phase TPC with Xe
- XENON100 results
- XENON1T status and sensitivity -> XENONnT

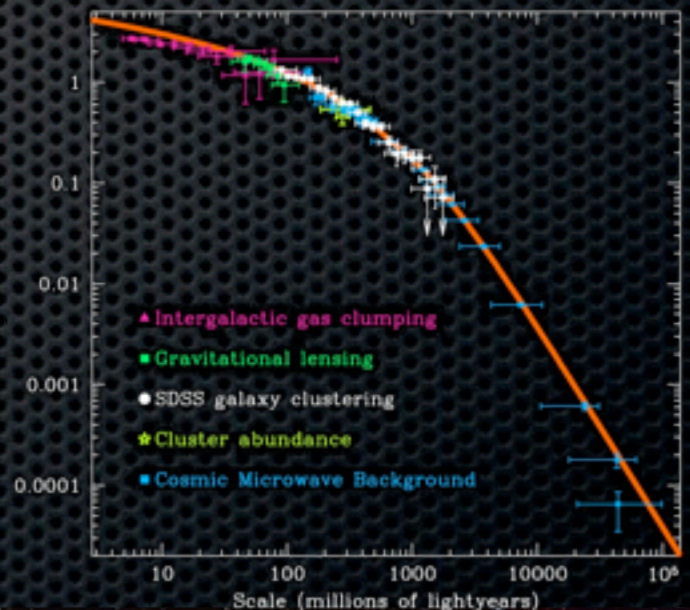
Dark Matter Exists

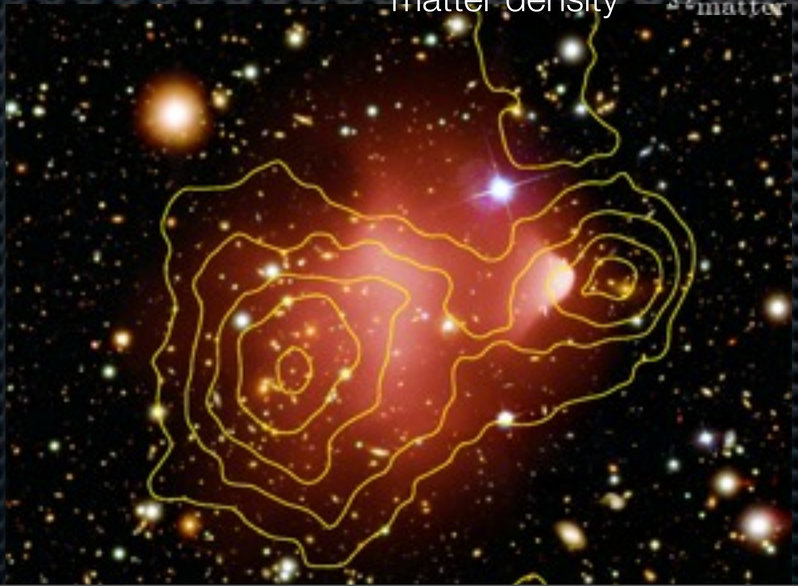


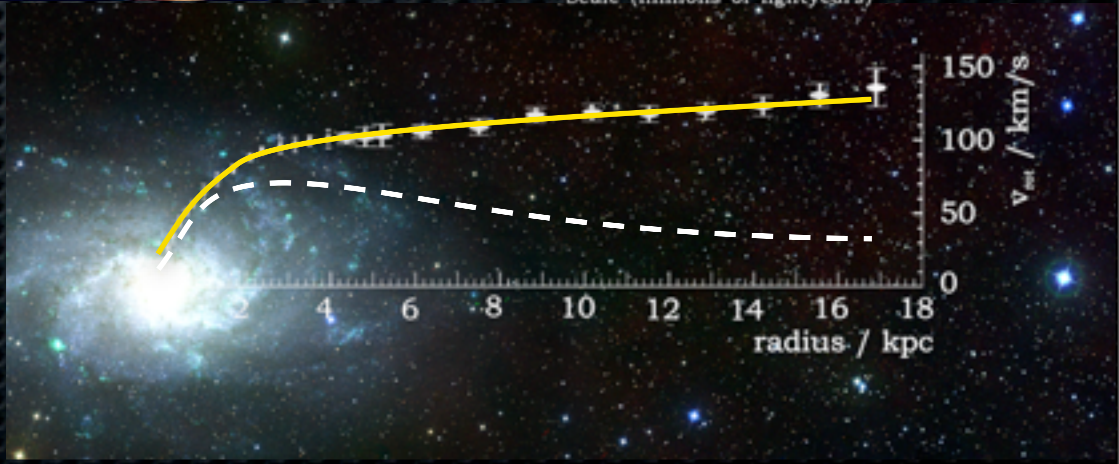




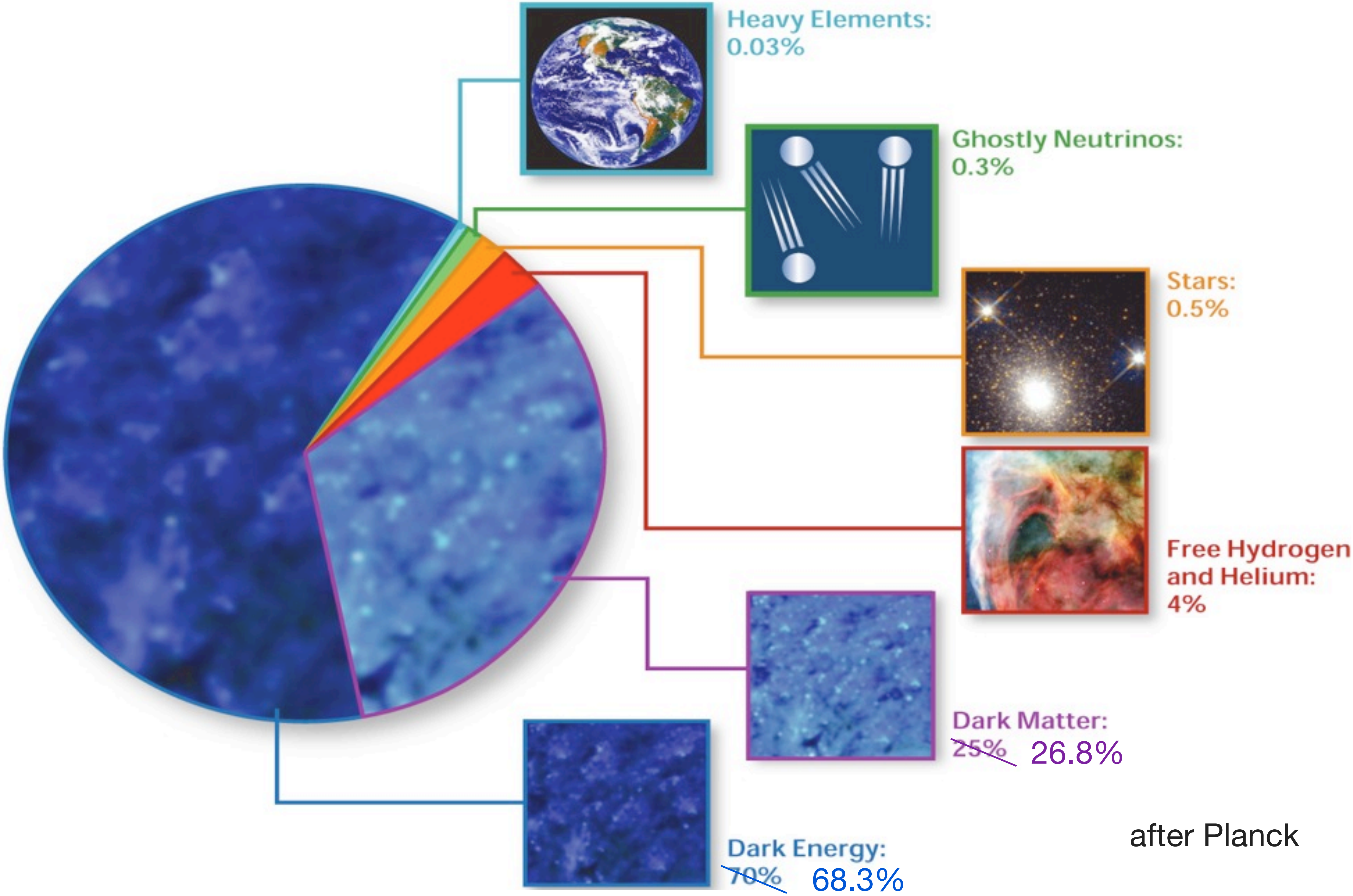








...and it dominates the Universe Matter Budget



Heavy Elements:
0.03%

Ghostly Neutrinos:
0.3%

Stars:
0.5%

Free Hydrogen and Helium:
4%

Dark Matter:
~~25%~~ 26.8%

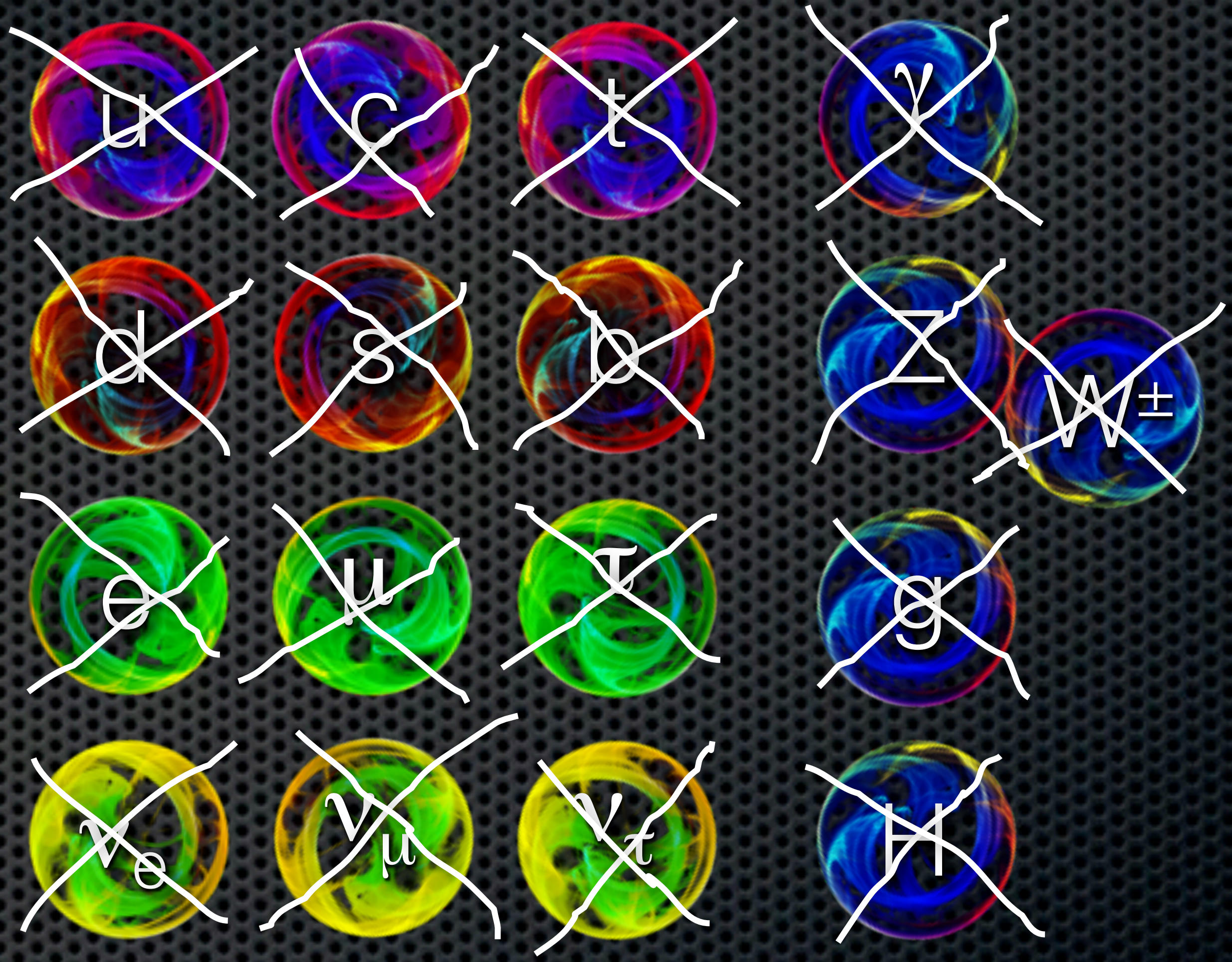
Dark Energy:
~~70%~~ 68.3%

after Planck

…but what is it made of?

We know Dark Matter has to be

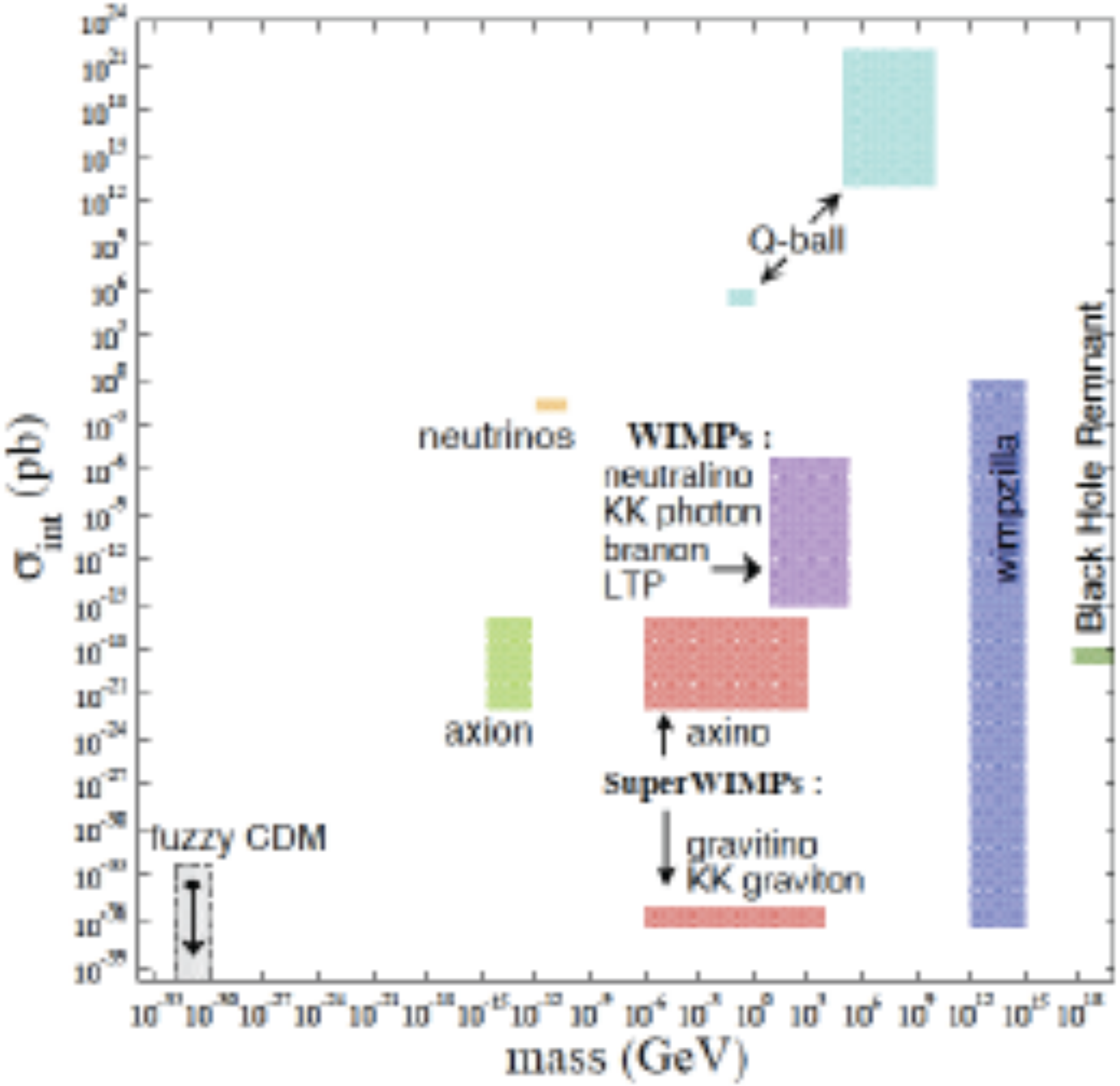
- neutral
- cold
- stable
- no EM interaction
- non-baryonic
- correct density



-> No Standard Model Candidate

Many models and a zoo of candidates

- the most convincing evidence for a particle candidate to be the dark matter is direct detection in a terrestrial experiment
- Axion and WIMPs best theoretically motivated candidates and well suited for detection with existing technologies



Weakly Interacting Masive Particles

- if a **neutral**, **massive, weakly interacting particle** (WIMP) existed in the early Universe

$$\chi + \bar{\chi} \leftrightarrow X + \bar{X}$$

- it was in equilibrium as long as the **reaction rate** was larger than the **expansion rate**

$$\Gamma \gg H$$

- after **Γ drops below H** ⇒ “freeze-out”, we are left with a **relic density**

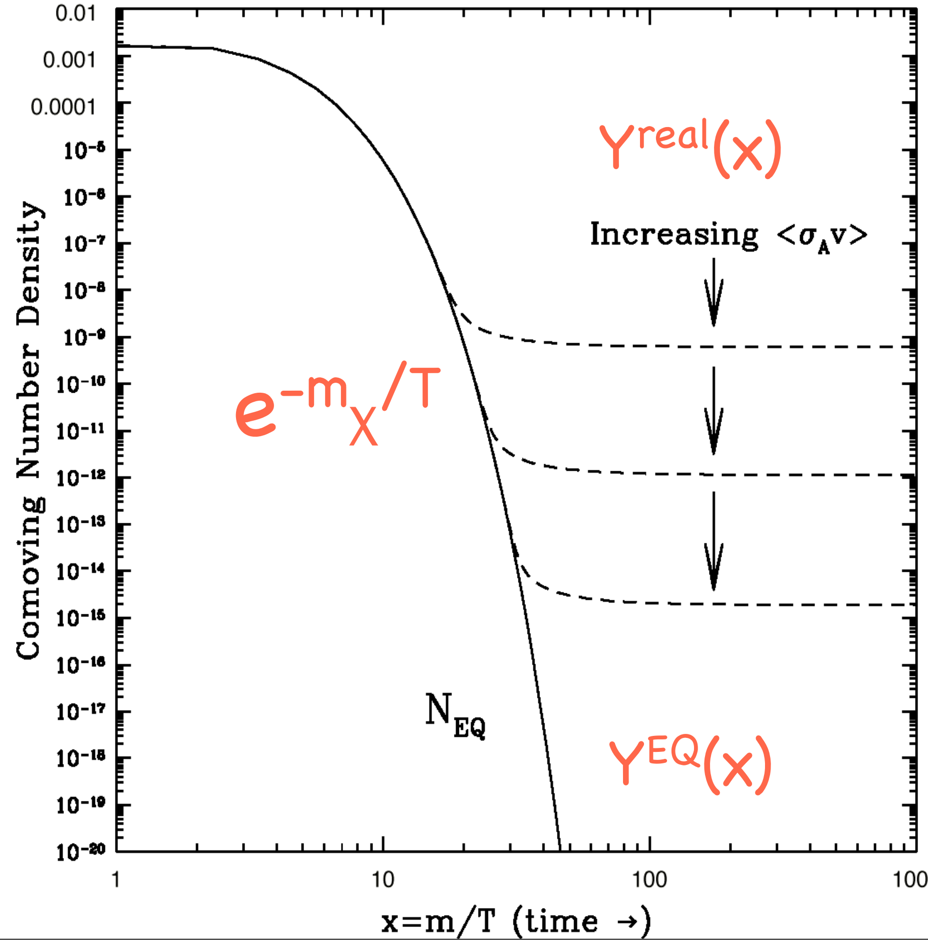
$$\frac{dn}{dt} = -3Hn - \langle \sigma_{eff} v \rangle \left(n^2 - n_{eq}^2 \right)$$

decrease due to expansion of the Universe

change due to annihilation and creation

Number density now: **integrate from freeze-out to present**

$$\Omega_\chi \propto \langle \sigma_A v \rangle^{-1}$$



Mass of a Thermal Relic Particle

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \approx \frac{3 \times 10^{-27}\, cm^3 s^{-1}}{\langle \sigma_A \mathrm{v} \rangle}$$

$$\sigma_{\mathrm{A}} \sim \frac{\alpha^2}{m_\chi^2} \Rightarrow \Omega_\chi \propto m_\chi^2$$

$$\Omega_\chi \sim 0.2$$

$$\Rightarrow \langle \sigma_A v \rangle \sim 1\ \mathrm{pb}$$

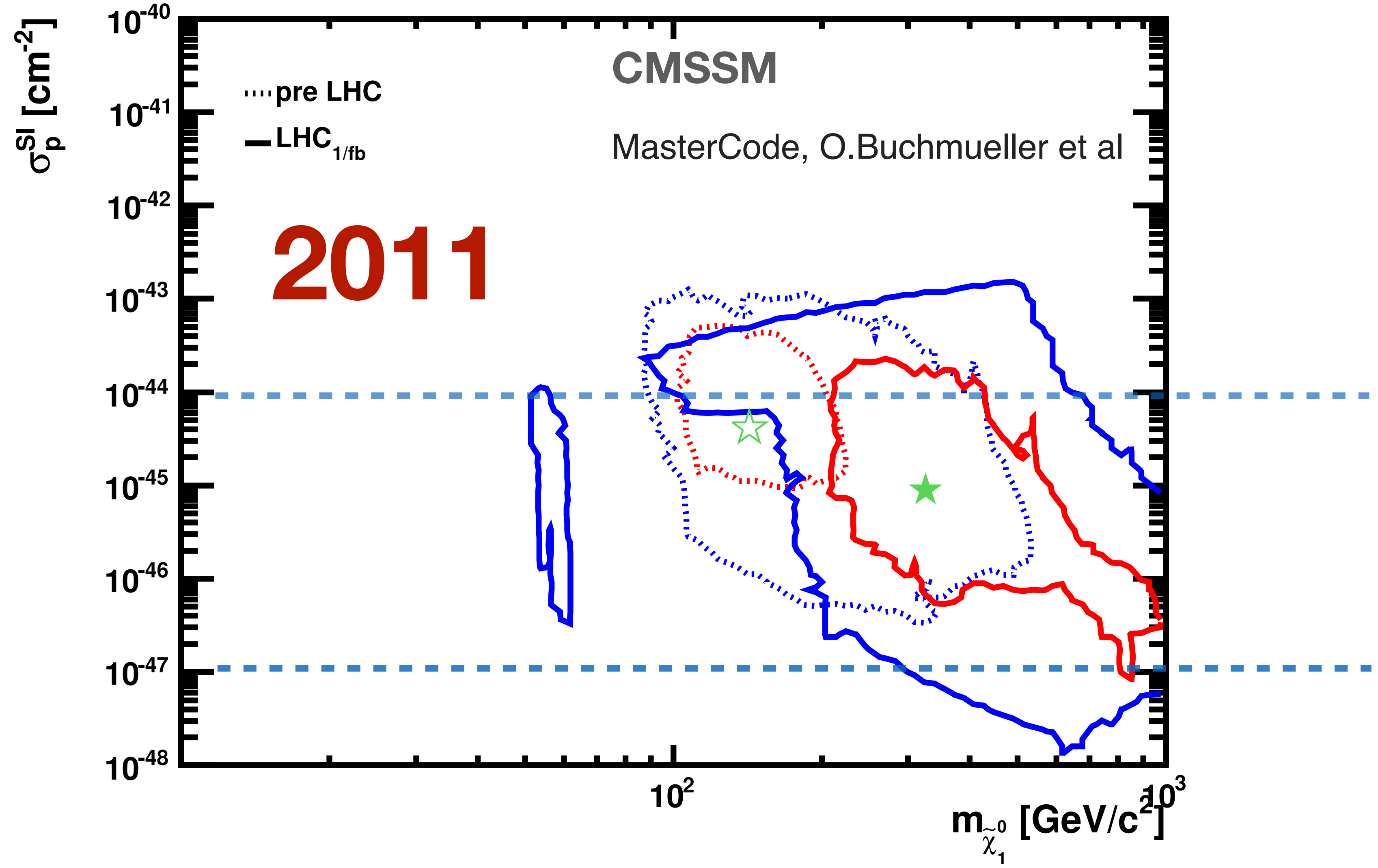
$$\Rightarrow m_\chi \sim 100\ \mathrm{GeV\ \text{-}\ 1TeV}$$

⇒ the relic density and mass point to the **weak scale**

⇒ the new physics responsible for EWSB likely gives rise to a **dark matter candidate**

WIMP masses and scattering cross sections

- Example for theoretical predictions from supersymmetry
- Scattering cross sections on protons/neutrons down to 10^{-48} cm^2



~ 1 event kg^{-1} yr^{-1}

~ 1 events t^{-1} yr^{-1}

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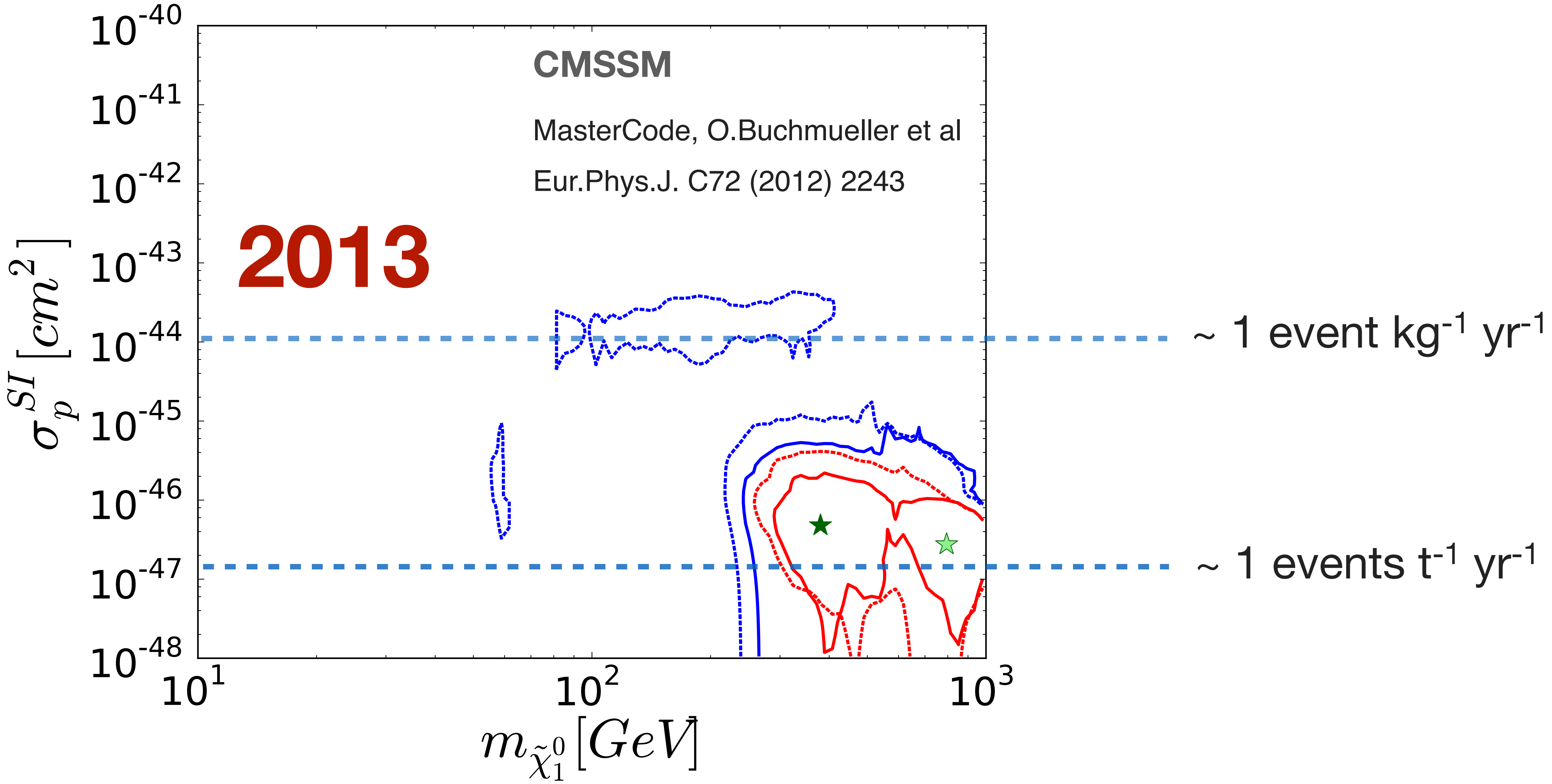
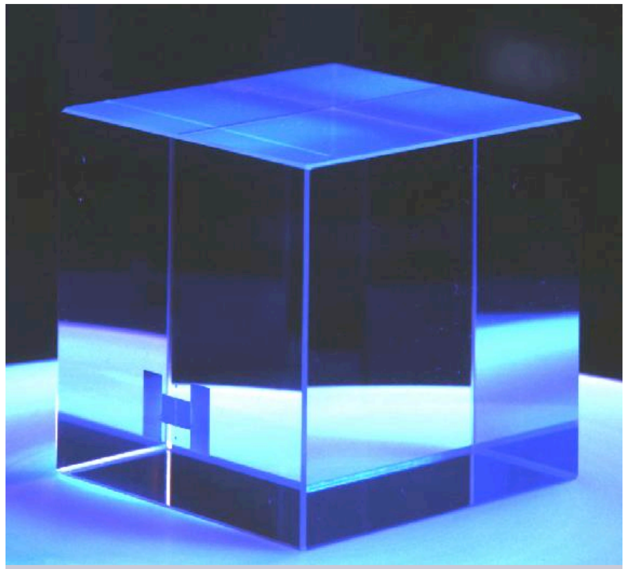


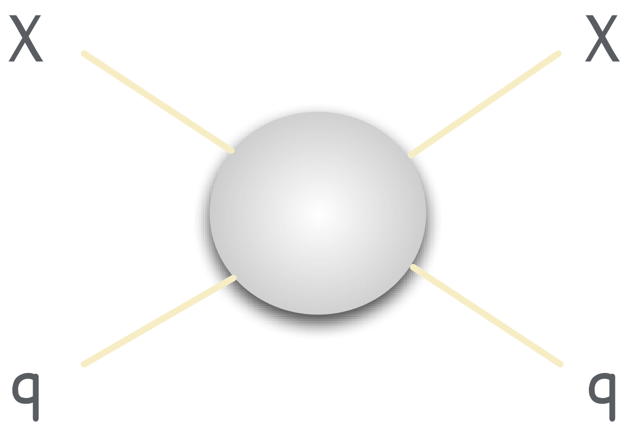
MasterCode, O.Buchmueller et al

Eur.Phys.J. C72 (2012) 2243

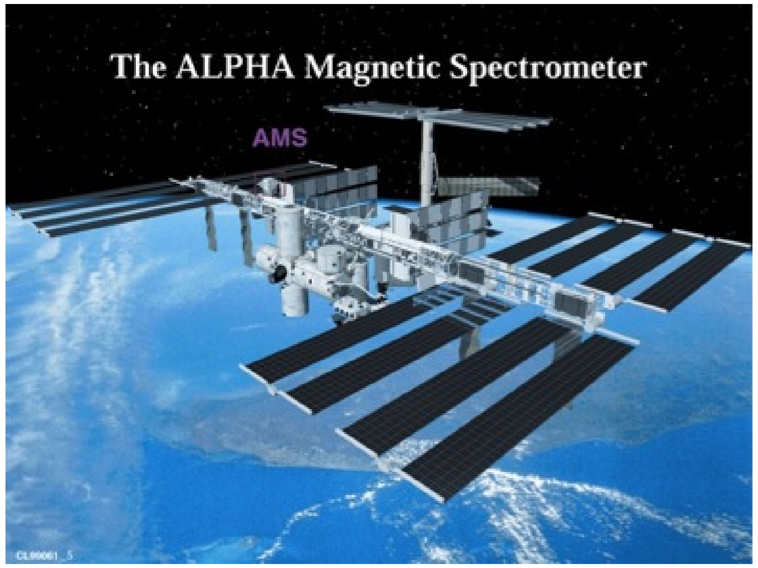
2013

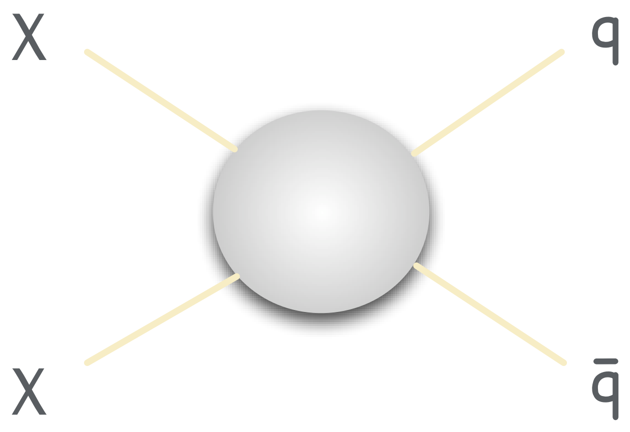
Approaches to (WIMP) Dark Matter Detection



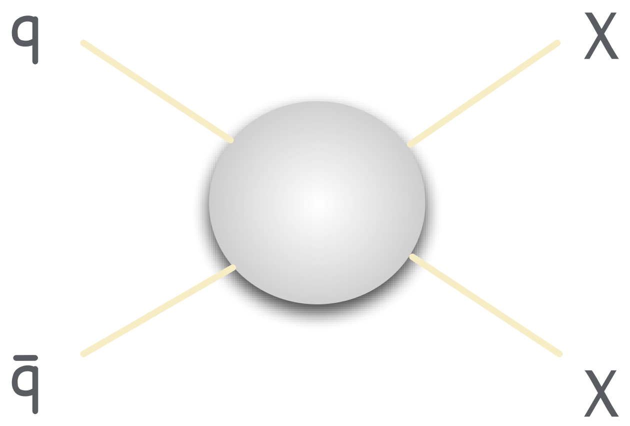


Direct



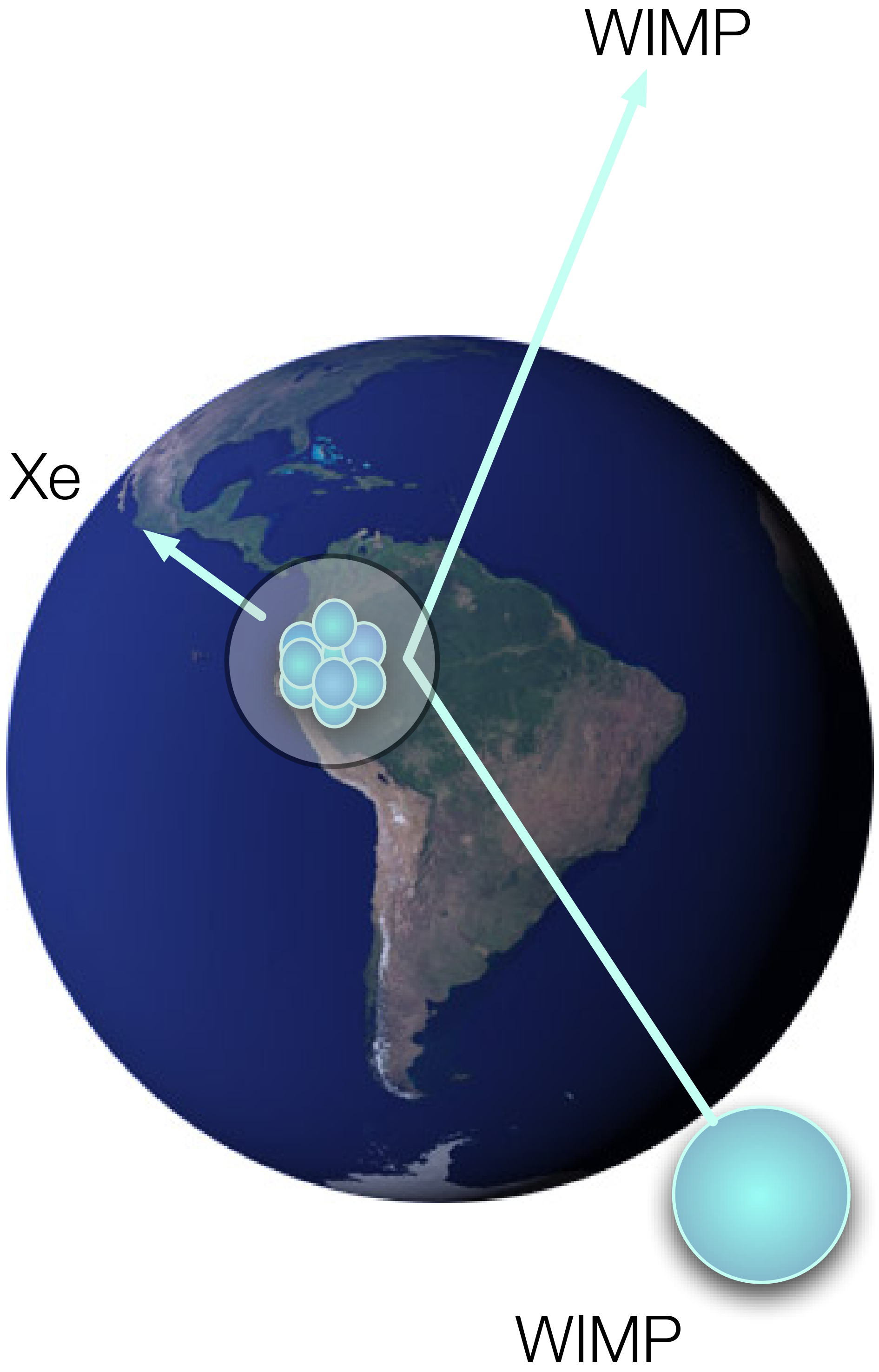


Indirect



Colliders

WIMP Detection: Scattering off Atoms



- Elastic collisions with nuclei
- The recoil energy is:

$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta) \leq 50\ keV$$

- and the expected rate:

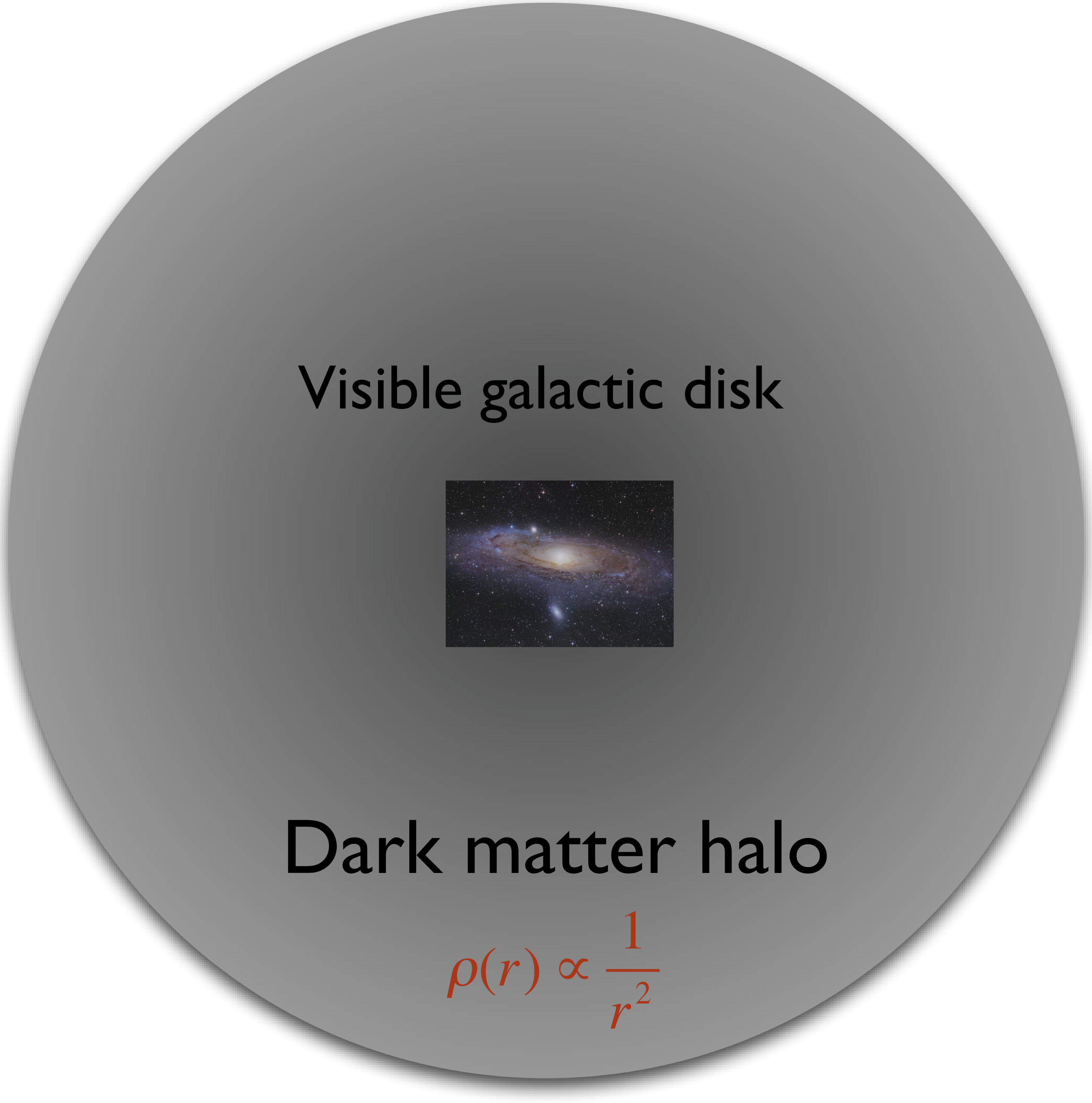
$$R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi N} \rangle \qquad \mu = \frac{m_\chi m_N}{m_\chi + m_N}$$

N = number of target nuclei in detector

ρ_χ = local WIMP density, m_χ = WIMP mass

$\langle \sigma_{\chi N} \rangle$ = scattering cross section

Dark matter in the galaxy



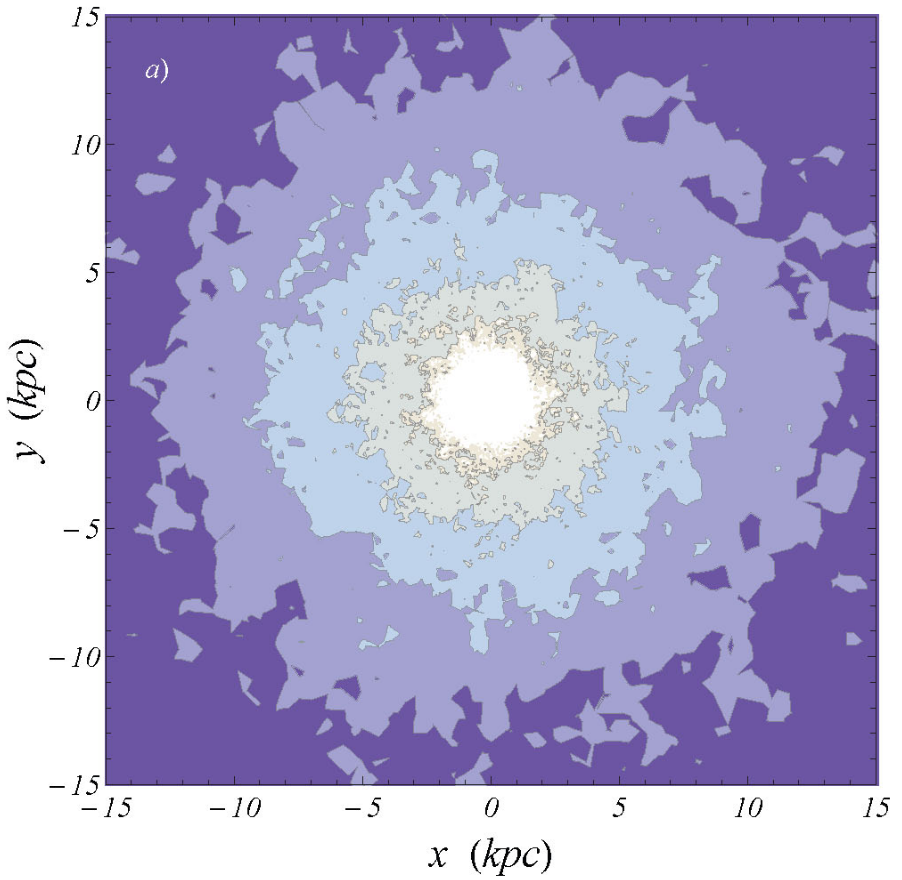
Visible galactic disk

Dark matter halo

$$\rho(r) \propto \frac{1}{r^2}$$

WIMPs in the galactic halo

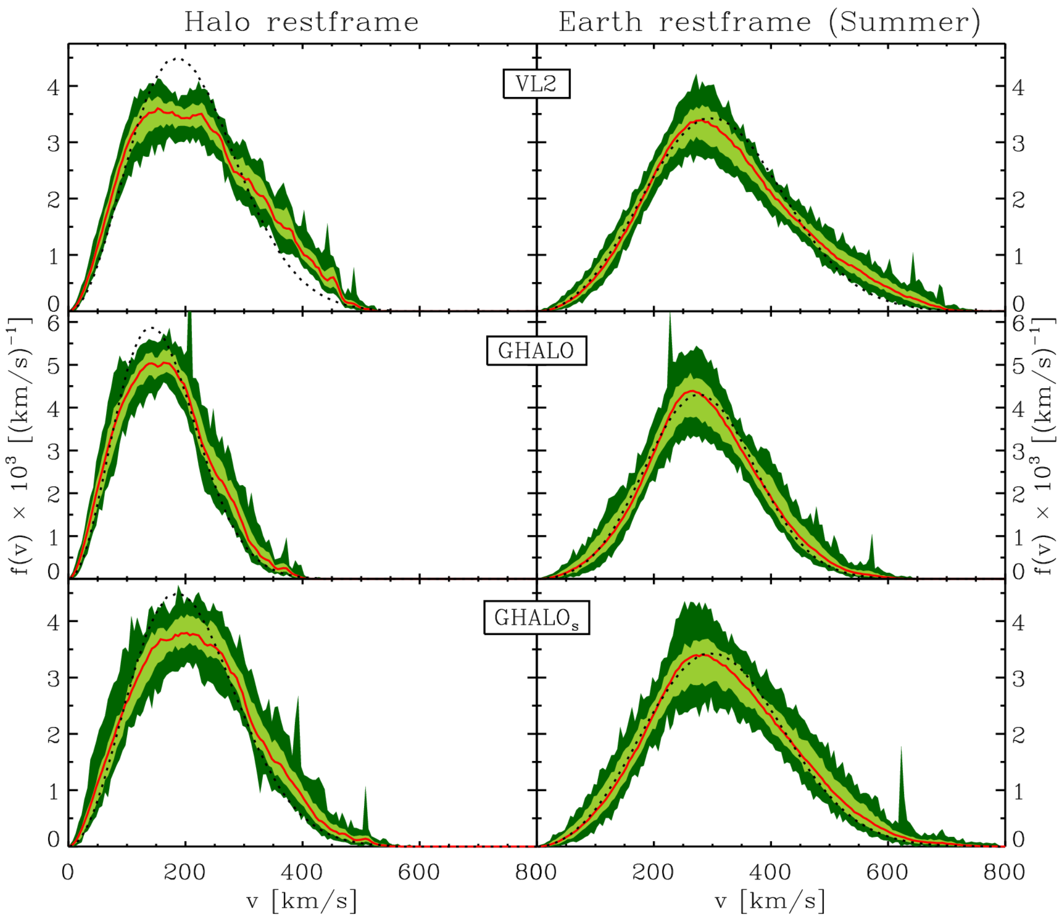
Density map of the dark matter halo
rho = [0.1, 0.3, 1.0, 3.0] GeV cm^{-3}



High-resolution cosmological simulation with baryons: F.S. Ling et al, JCAP02 (2010) 012

$$\rho_{local} \sim 0.3\,\mathrm{GeV}\cdot\mathrm{cm}^{-3}$$

Velocity distribution of WIMPs in the galaxy



M. Kuhlen et al, JCAP02 (2010) 030

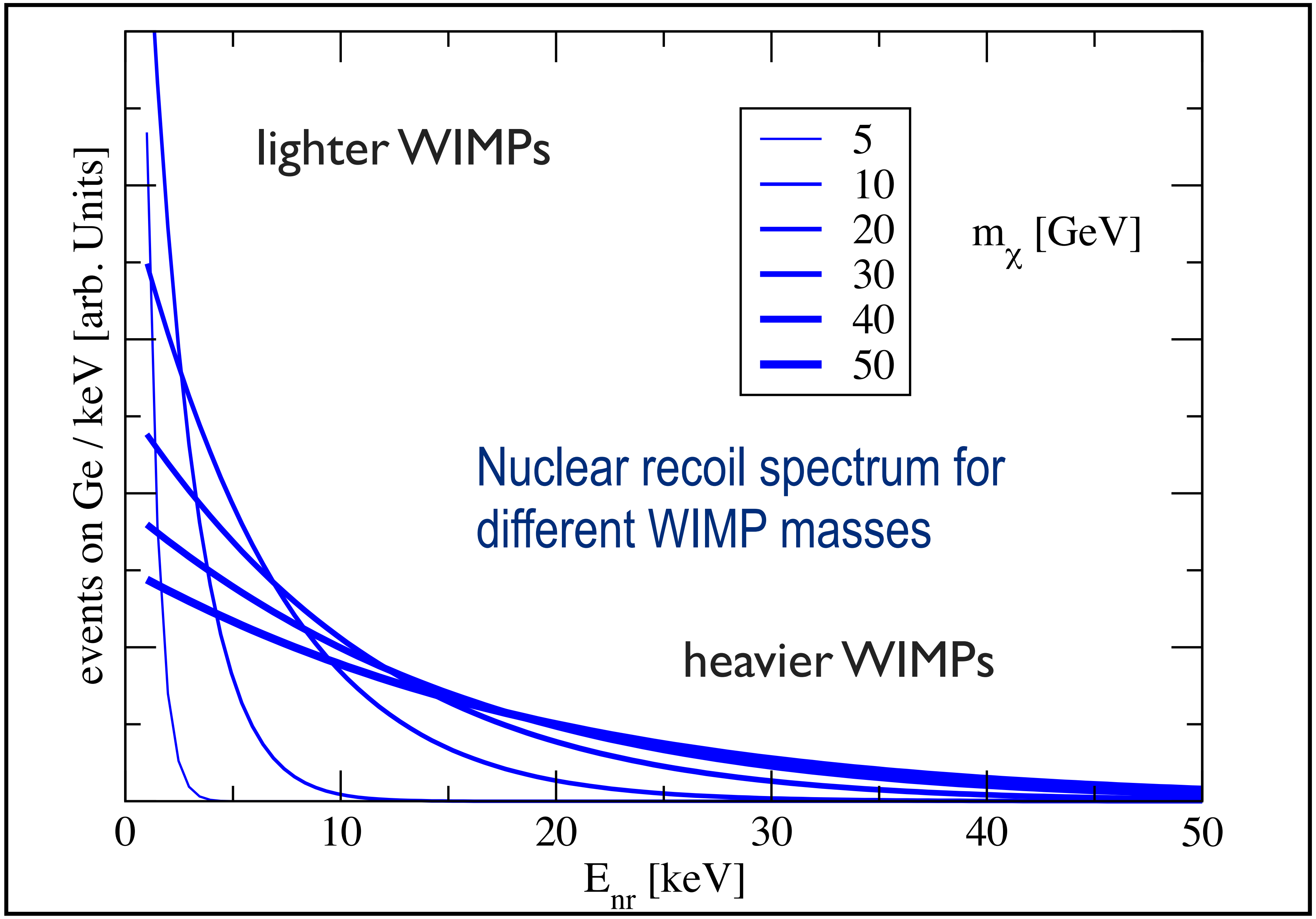
From cosmological simulations of galaxy formation: departures from the simplest case of a Maxwell-Boltzmann distribution

In direct detection experiments, mostly a simple MB distribution, truncated at v$_{esc}$, is used in the sensitivity calculation

Event Rate in a WIMP Detector

Rate after integration over WIMP velocity distribution

$$R \sim 0.13\,\frac{\text{events}}{\text{kg year}}\left[\frac{A}{100}\times\frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2}\times\frac{\langle v\rangle}{220\,\text{km}\,\text{s}^{-1}}\times\frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}}\right]$$



Nuclear recoil spectrum for different WIMP masses

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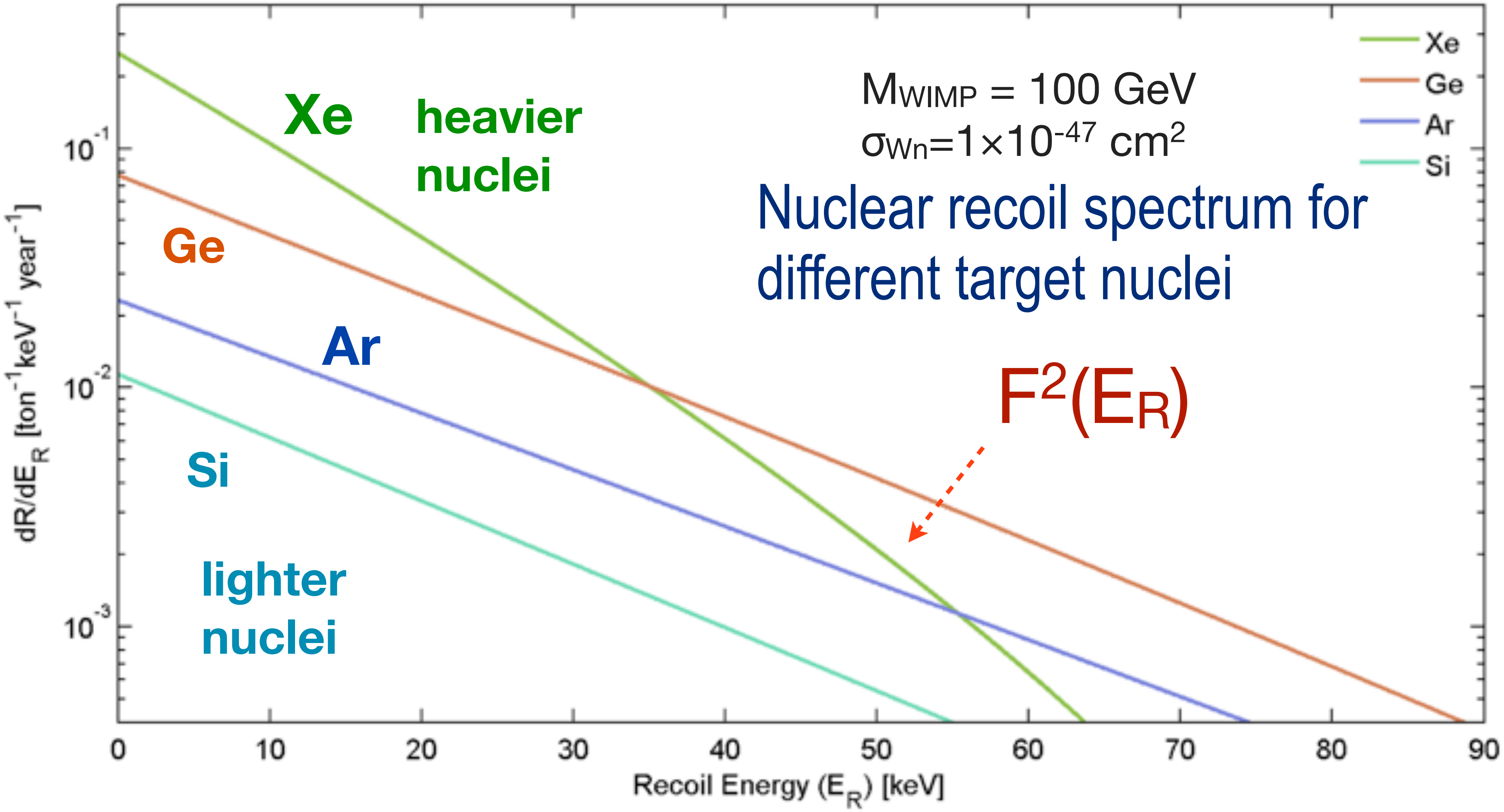


Nuclear recoil spectrum for different target nuclei

WIMP Scattering Cross Sections

- A general WIMP candidate: fermion (Dirac or Majorana), boson or scalar particle
- The most general, Lorentz invariant Lagrangian has 5 types of interactions
- In the extreme NR limit relevant for galactic WIMPs (10^{-3} c) interactions classified as
  - **scalar interaction** (WIMP couples to nuclear mass from the scalar, vector, tensor part of L)

$$\sigma_{SI} \sim \frac{\mu^2}{m_\chi^2}\left[Z f_p + (A-Z) f_n\right]^2$$

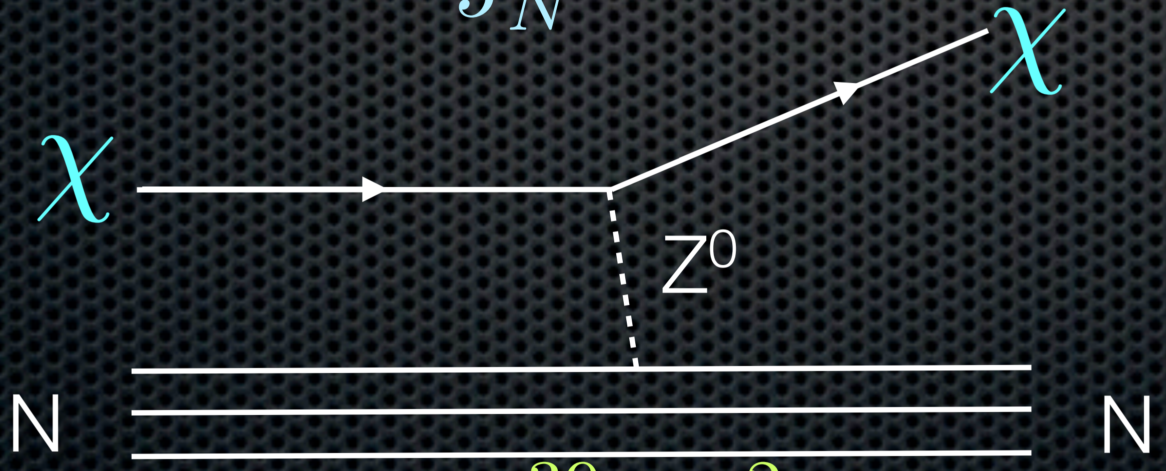
f_p, f_n: effective couplings to protons and neutrons

  - **spin-spin interaction** (WIMP couples to the nuclear spin, from the axial part of L)

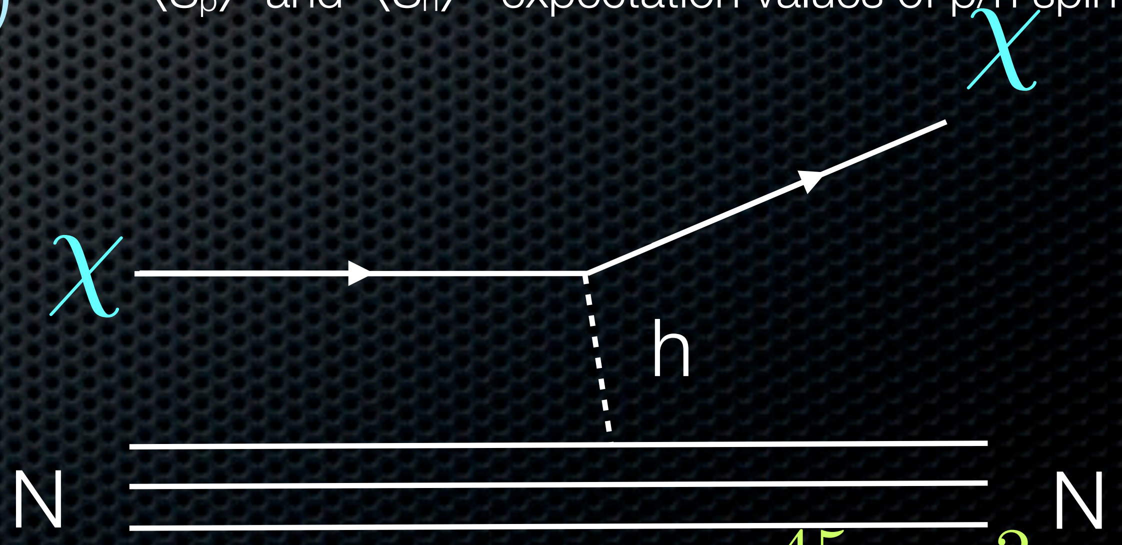
$$\sigma_{SD} \sim \mu^2 \frac{J_N+1}{J_N}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2$$

a_p, a_n: effective couplings to p/n

$\langle S_p\rangle$ and $\langle S_n\rangle$ expectation values of p/n spin



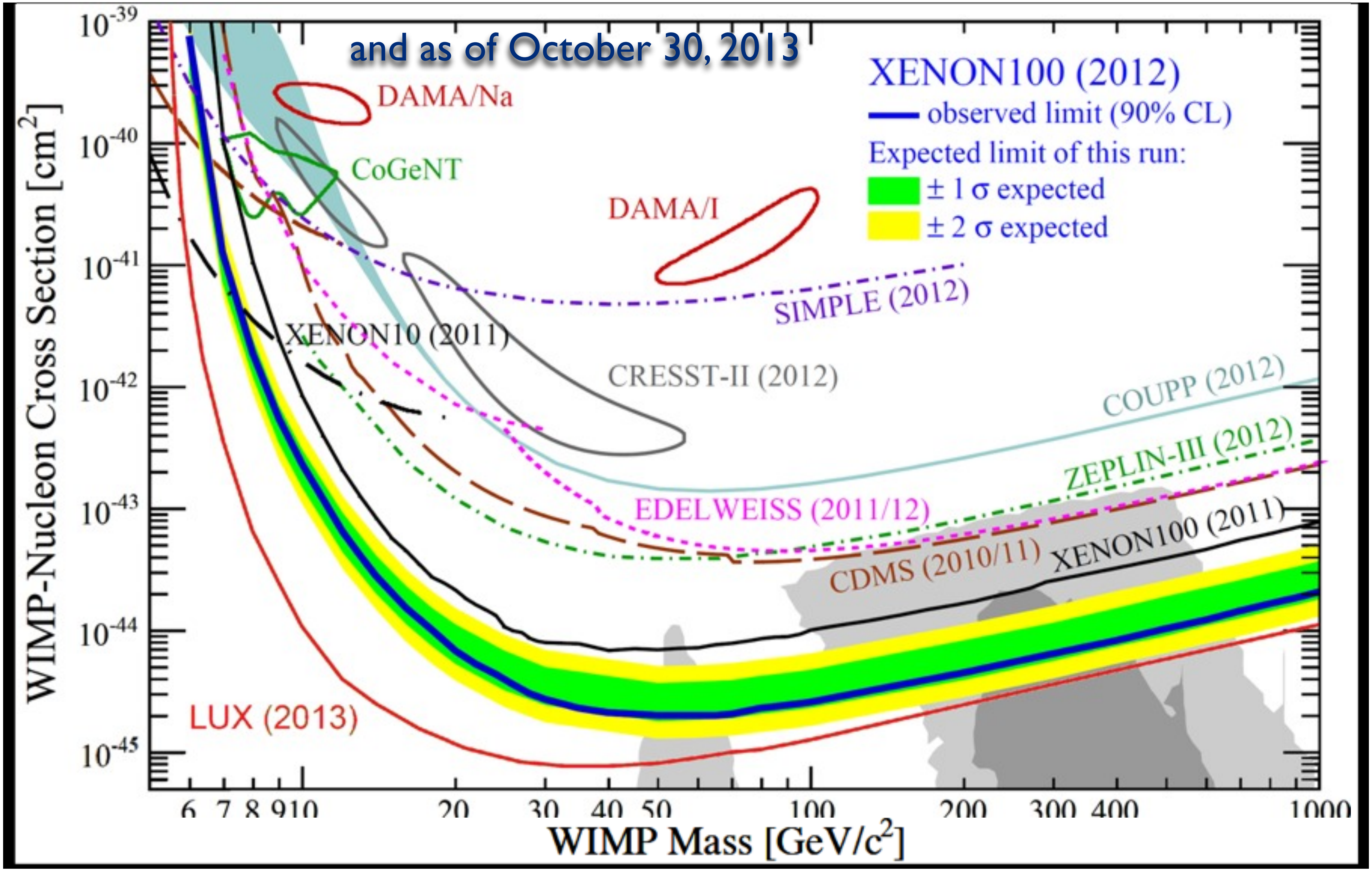
$$\sigma_0 \sim 10^{-39}\ \text{cm}^2$$



$$\sigma_0 \sim 10^{-45}\ \text{cm}^2$$

The State-of-the-Art: Spin Independent

Aprile et al.(XENON100),Phys. Rev. Lett. 109 (2012)



The State-of-the-Art : Spin Dependent

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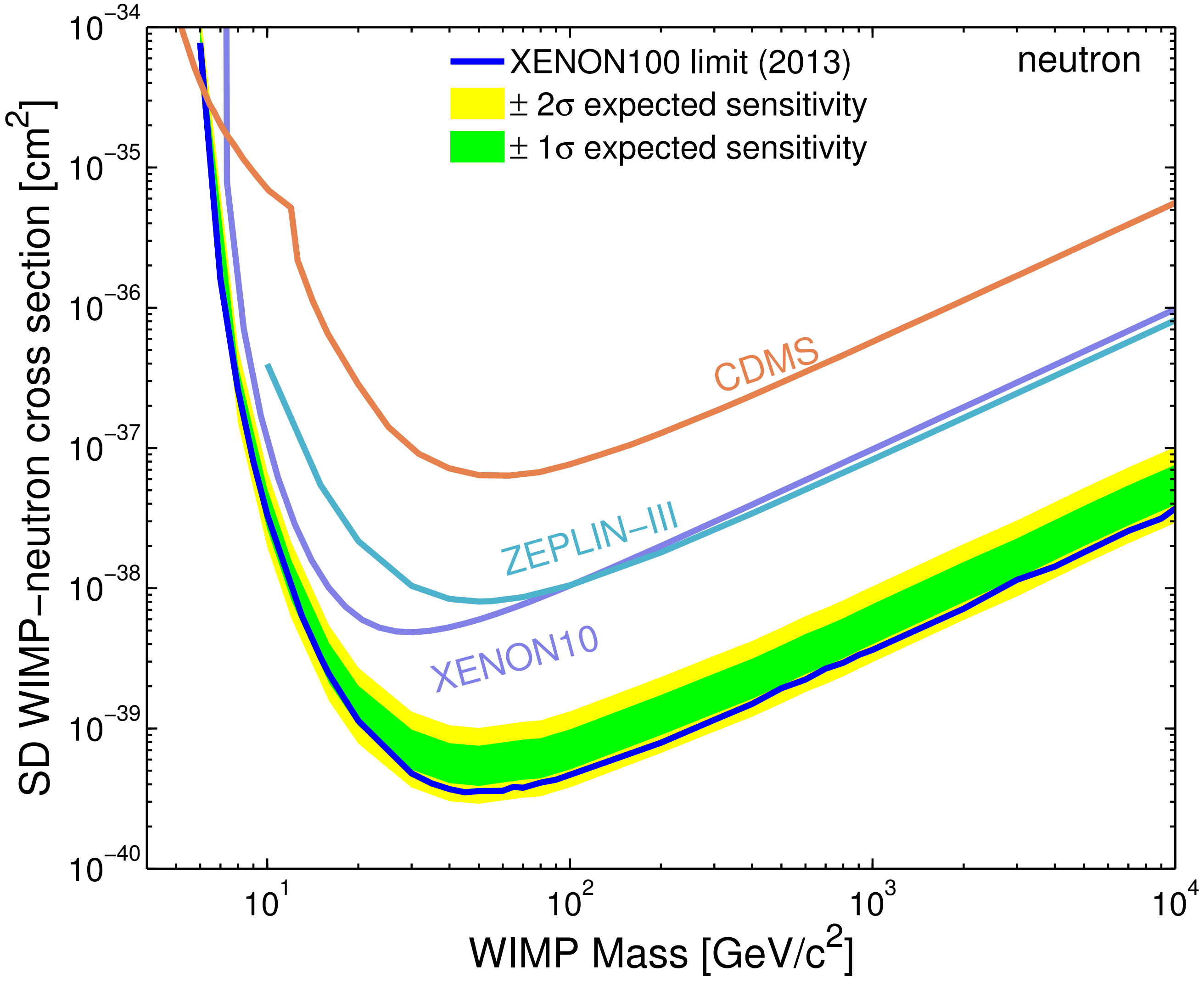
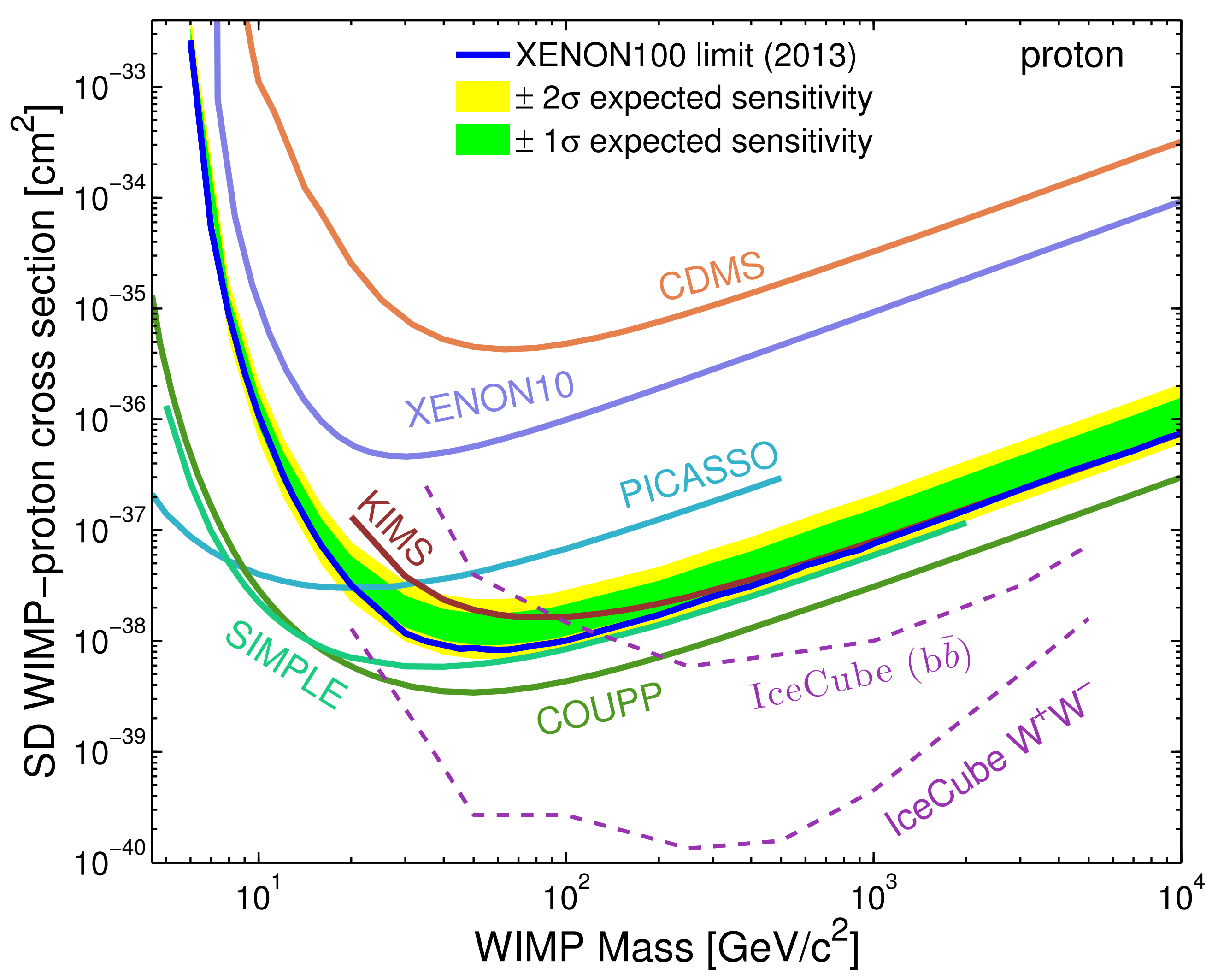


WIMP-neutron coupling



WIMP-proton coupling

Requirements for a WIMP Detector

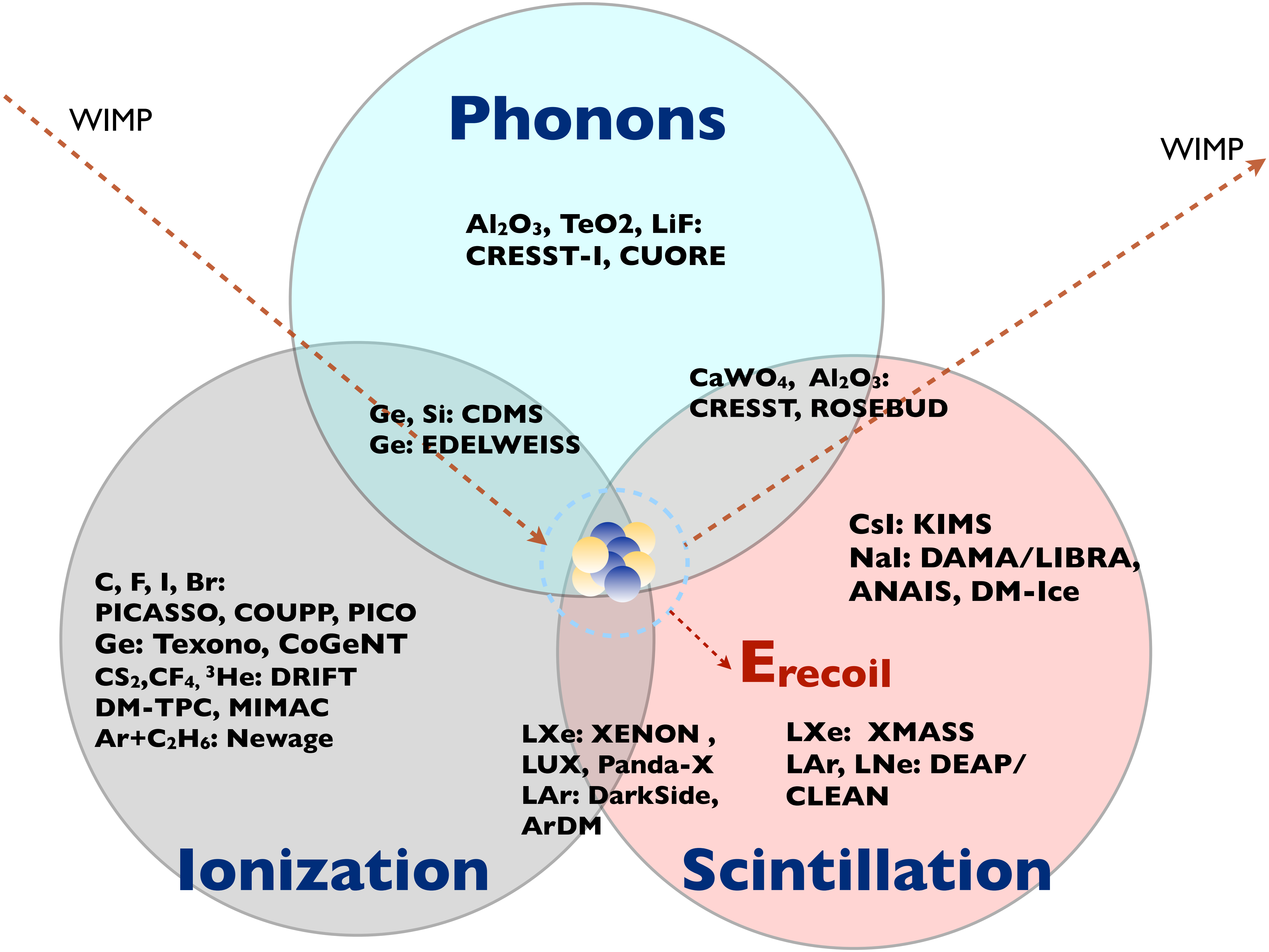
- Detector must have very low energy threshold as the energy deposited into the recoiling nucleus by WIMP scattering is as low as a few keV

- Detector must have a large target mass and long term stability of operation as signal event rate is extremely rare (1 per ton per year)

- Detector must be built with ultra-low background materials and operated deep underground

- Given that background from radioactivity and the environment cannot be eliminated completely, detector must have effective S/N discrimination

WIMP Direct Detection Techniques



WIMP

Phonons

WIMP

Al_2O_3, TeO2, LiF:
CRESST-I, CUORE

$CaWO_4$, Al_2O_3:
CRESST, ROSEBUD

Ge, Si: CDMS
Ge: EDELWEISS

CsI: KIMS
NaI: DAMA/LIBRA,
ANAIS, DM-Ice

C, F, I, Br:
PICASSO, COUPP, PICO
Ge: Texono, CoGeNT
CS_2,CF_4, ^3He: DRIFT
DM-TPC, MIMAC
$Ar+C_2H_6$: Newage

E_{recoil}

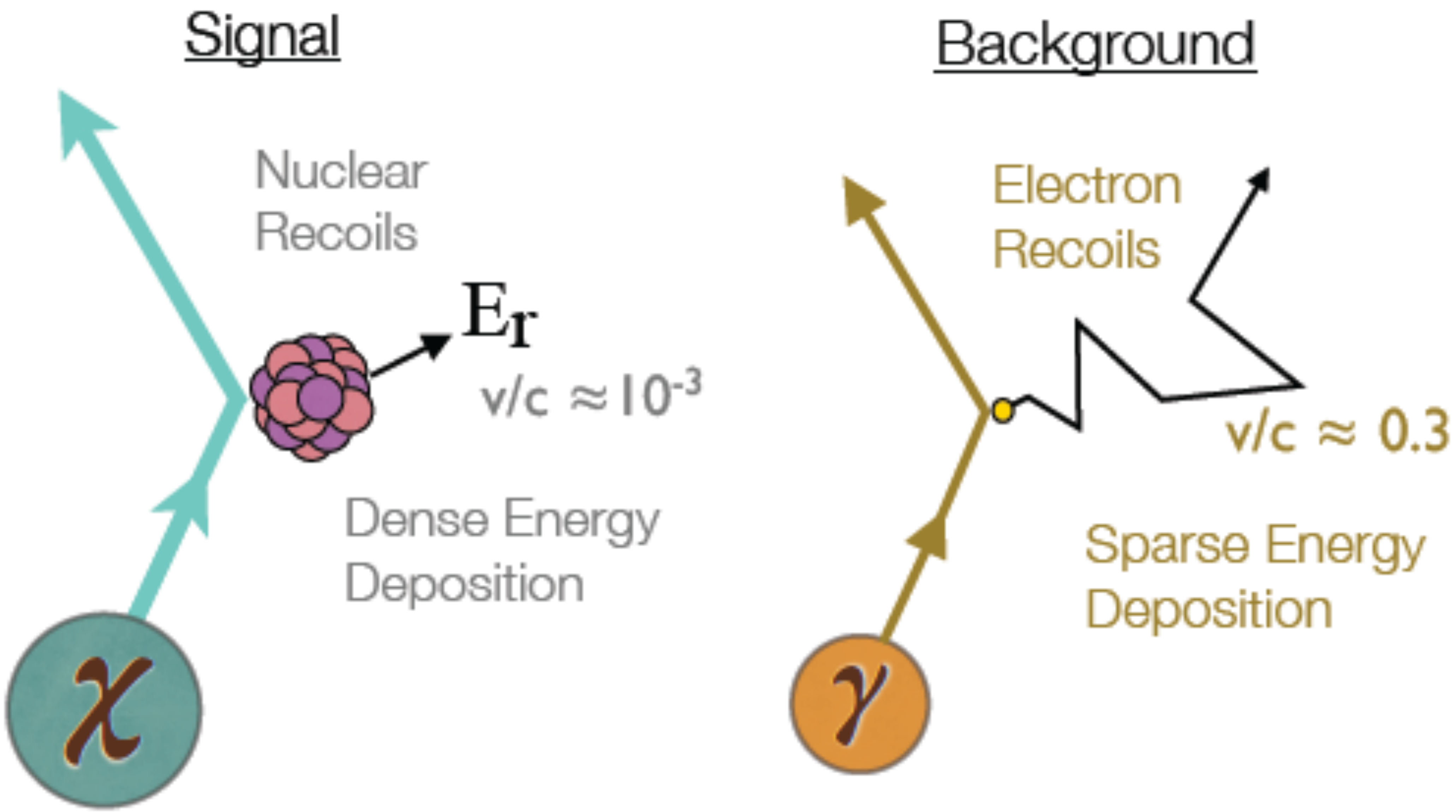
LXe: XENON ,
LUX, Panda-X
LAr: DarkSide,
ArDM

LXe: XMASS
LAr, LNe: DEAP/
CLEAN

Ionization

Scintillation

Discriminating Signal from Background



- Scattering from an atomic nucleus leads to different response in most materials than scattering from an electron
- Detectors which can measure this difference can effectively reduce the dominant EM background
- Neutrons however scatter also off nuclei but unlike WIMPs they scatter in multiple sites hence can be recognized with position sensitive detectors large enough compared to the typical mean free path of order 10 cm

Quenching factor and discrimination

the quenching allows to distinguish between electron and nuclear recoils if two simultaneous detection mechanisms are used

example:

charge and phonons in Ge

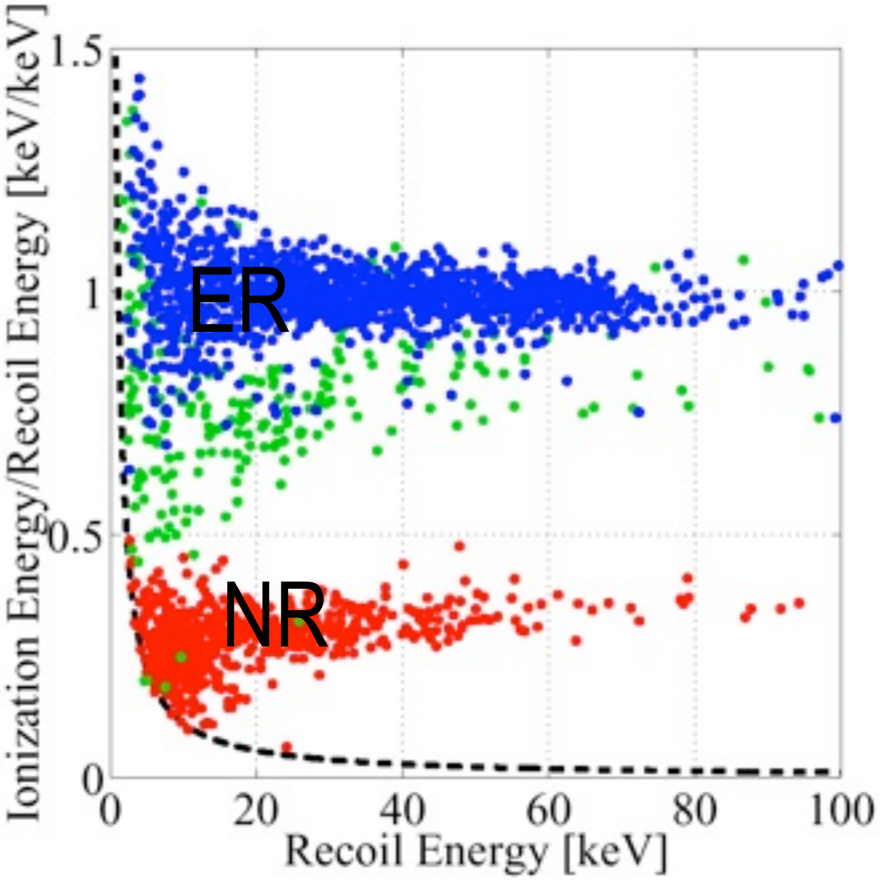
$E_{visible} \sim 1/3 \, E_{recoil}$ for NR

(=> QF ~ 30% in Ge)

ER = background

NR = WIMPs or neutrons (background)

Similarly in noble liquids..discussed later

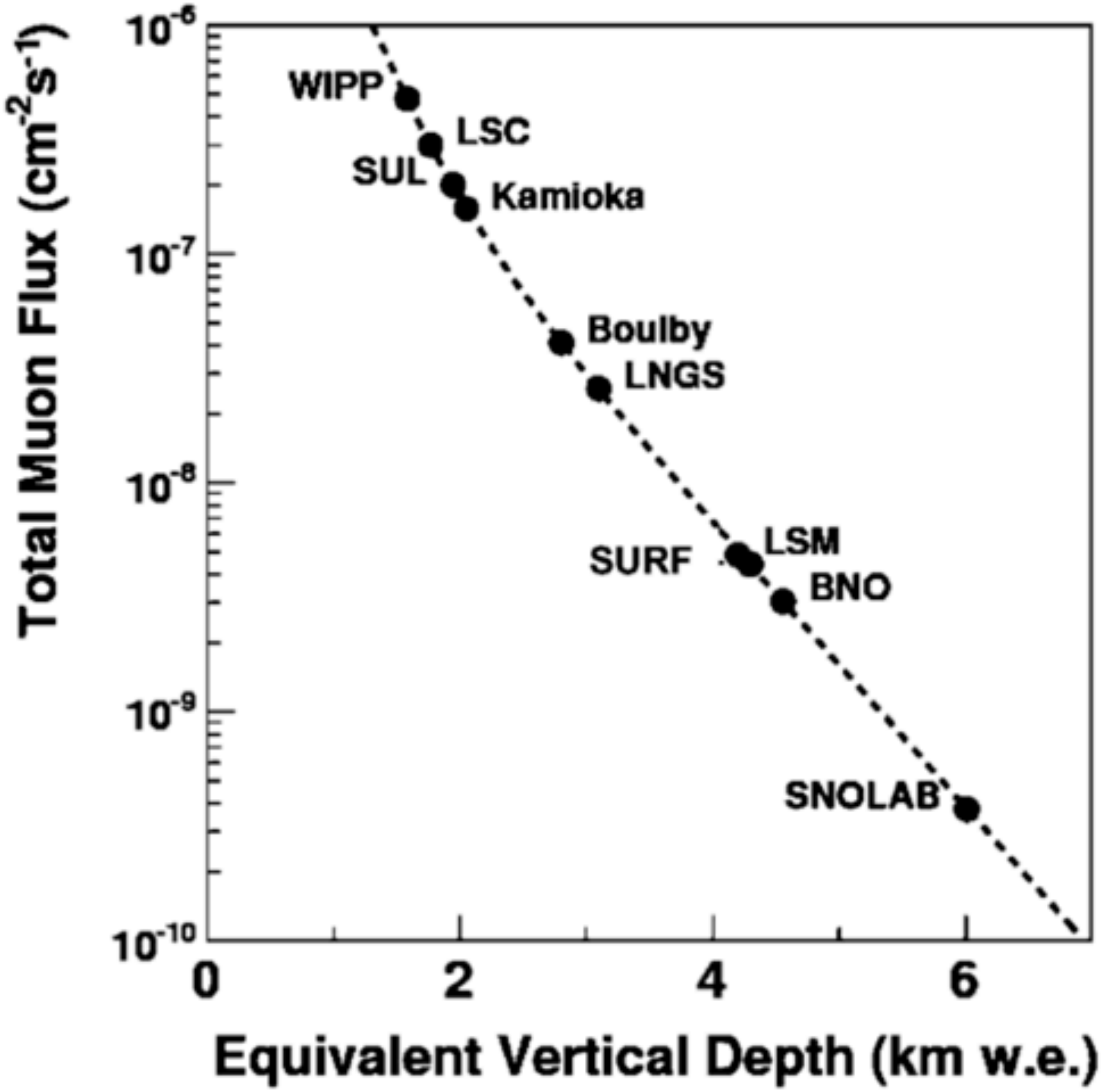


Backgrounds

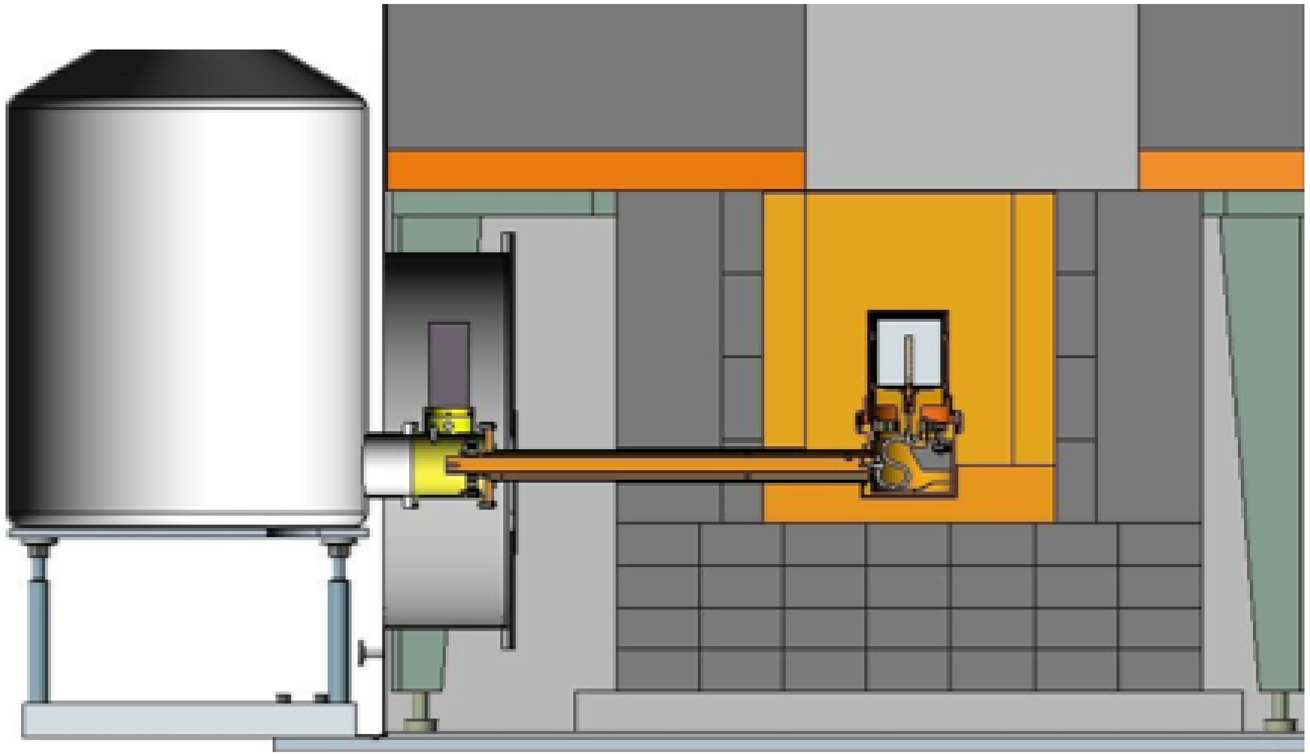
Electromagnetic radiation
- natural radioactivity in detector and shield materials
- airborne radon (^{222}Rn)
- cosmic activation of materials during storage/ transport

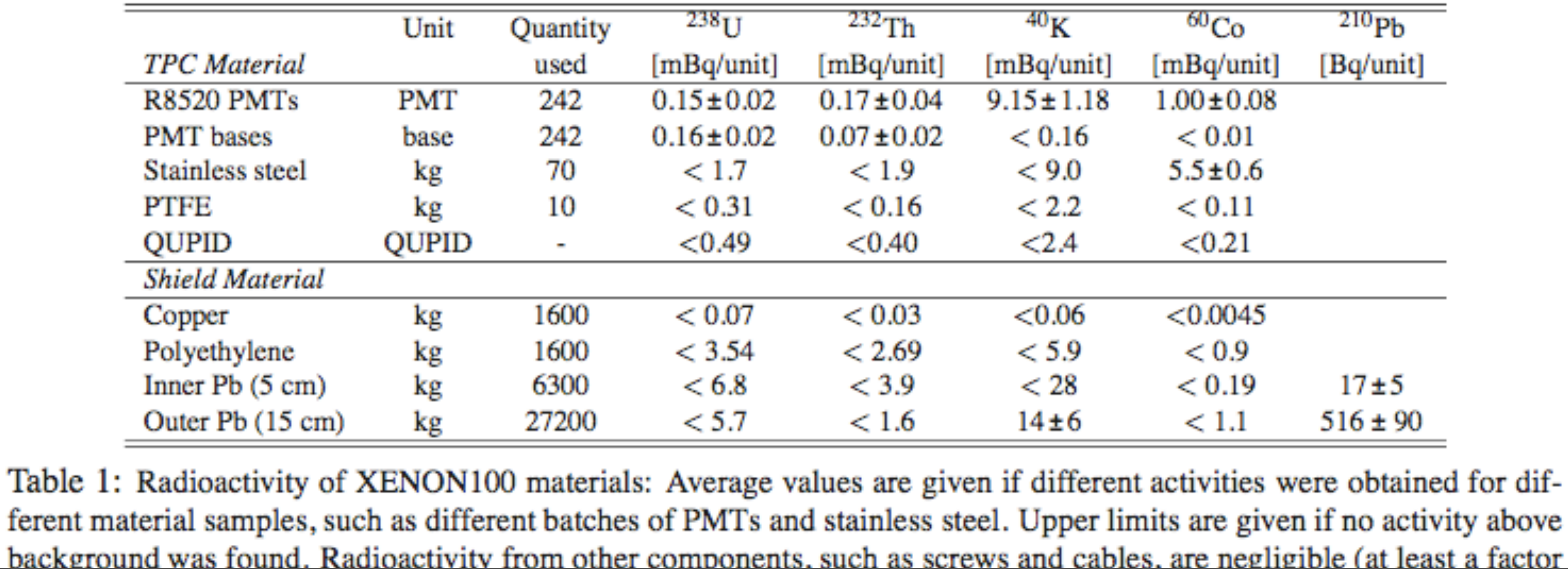
Neutrons
- slow/low energy neutrons from materials radioactivity: (α,n) and fission reactions. Can be reduced by shielding
- fast/energetic neutrons from spallation of nuclei in materials by cosmic muons. Cannot be shielded. Detectors must operate deep underground to reduce muon flux

Alpha particles
- ^{210}Pb decays at the detector surfaces
- nuclear recoils from the Rn daughters



Minimize Backgrounds through Materials Screening Example: the XENON100 Counting Facility





TPC Material	Unit	Quantity used	^{238}U [mBq/unit]	^{232}Th [mBq/unit]	^{40}K [mBq/unit]	^{60}Co [mBq/unit]	^{210}Pb [Bq/unit]
R8520 PMTs	PMT	242	0.15±0.02	0.17±0.04	9.15±1.18	1.00±0.08	
PMT bases	base	242	0.16±0.02	0.07±0.02	< 0.16	< 0.01	
Stainless steel	kg	70	< 1.7	< 1.9	< 9.0	5.5±0.6	
PTFE	kg	10	< 0.31	< 0.16	< 2.2	< 0.11	
QUPID	QUPID	-	<0.49	<0.40	<2.4	<0.21	
Shield Material							
Copper	kg	1600	< 0.07	< 0.03	<0.06	<0.0045	
Polyethylene	kg	1600	< 3.54	< 2.69	< 5.9	< 0.9	
Inner Pb (5 cm)	kg	6300	< 6.8	< 3.9	< 28	< 0.19	17±5
Outer Pb (15 cm)	kg	27200	< 5.7	< 1.6	14±6	< 1.1	516 ± 90

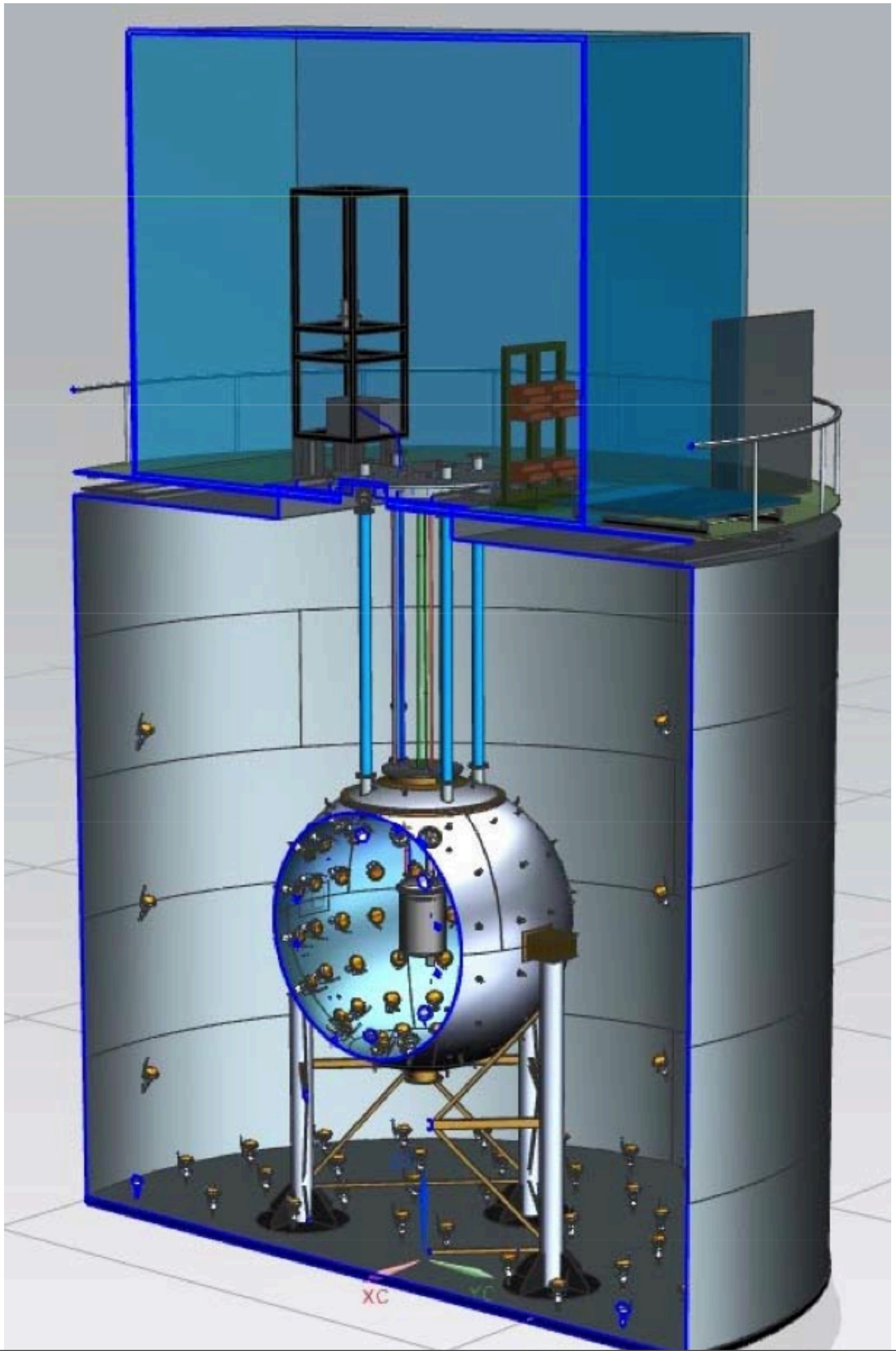
Table 1: Radioactivity of XENON100 materials: Average values are given if different activities were obtained for different material samples, such as different batches of PMTs and stainless steel. Upper limits are given if no activity above background was found. Radioactivity from other components, such as screws and cables, are negligible (at least a factor

Minimize Backgrounds through Shielding
Example: the XENON100 Passive Shield

- 20 cm of water (to stop neutrons from rock)
- 20 cm of lead (to stop gammas from radioactivity in rock): 15 cm of normal lead in the external part and 5 cm of low-activity lead closer to detector
- 20 cm of polyethylene (to moderate neutrons from fission decays and from (alpha,n) interactions resulting from U/Th decays in materials)
- 5 cm of copper (to attenuate gammas from residual radioactivity in polyethylene)

Minimize Backgrounds through Shielding Example: the DarkSide Active Shield

- External Water Tank (5.5 m radius - 10 m high instrumented with 80 PMTs) acts as muon veto and cosmogenic neutrons veto. Also provides passive gamma and neutron shielding
- Borated Liquid Scintillator as Neutron Veto (2 m radius instrumented with 110 PMTs) allows coincident veto of neutrons in TPC and provides in situ measurement of the n-background rate
- Water tank Muon Veto + Neutron Veto expected to reduce total cosmogenic neutron background by more than a factor 1000
- Both radiogenic neutrons (a few MeV) from natural radioactivity mostly in PMTs and Steel cryostat and support structures and cosmogenic neutrons from muons (flux at LNGS is 2.4 / m-2 day-1



Signals

- We have seen that the recoil rate is energy dependent due to the kinematics of elastic scattering and the WIMP velocity distribution

- In addition the recoil rate is time- and direction-dependent due to the motion of the Earth with respect to the galactic rest frame

- Variation can occur in the: Energy Spectrum, in the Event Rate and in the Recoil Direction

Signal: Energy Dependence

For the standard halo model, we can write the differential event rate as:

$$\frac{dR}{dE_R} \approx (\frac{dR}{dE_R})_0 F^2(E_R) exp(\frac{-E_R}{E_c})$$

event rate in
limit E --> 0

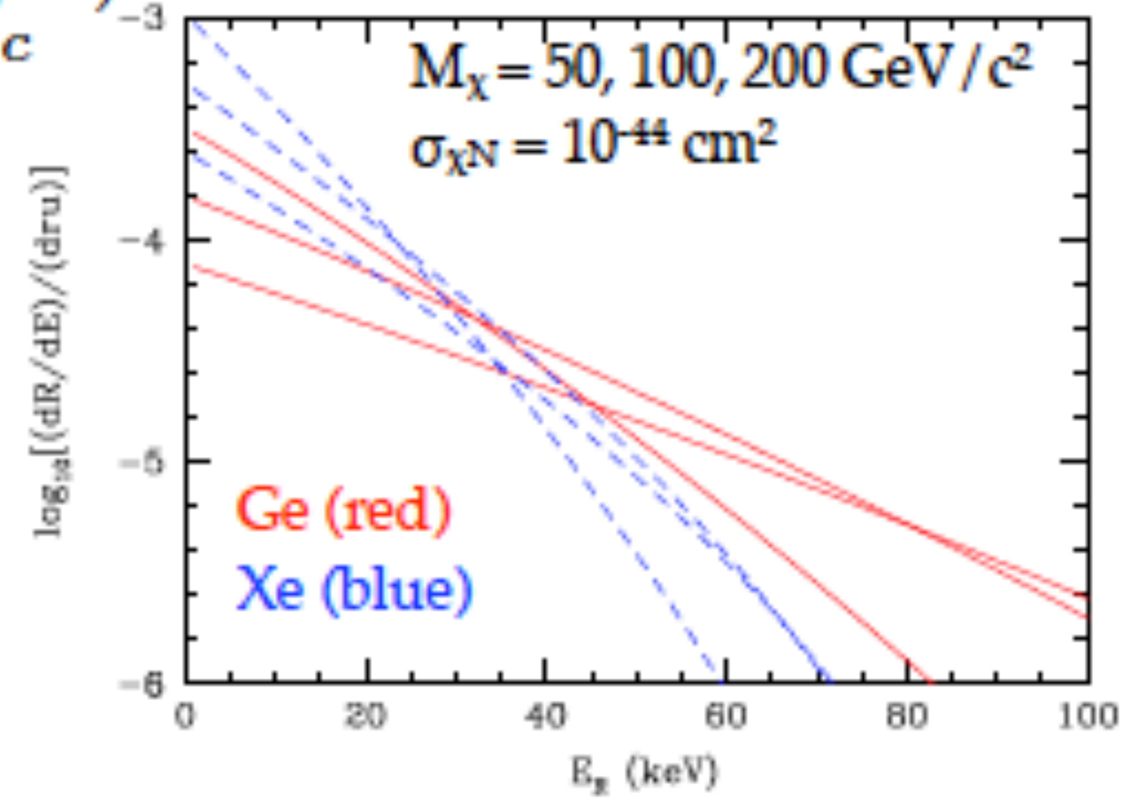
Characteristic energy scale given by:

parameter that
depends on target

$$E_c = \frac{c_1 2\mu_N^2 v_c^2}{m_N}$$

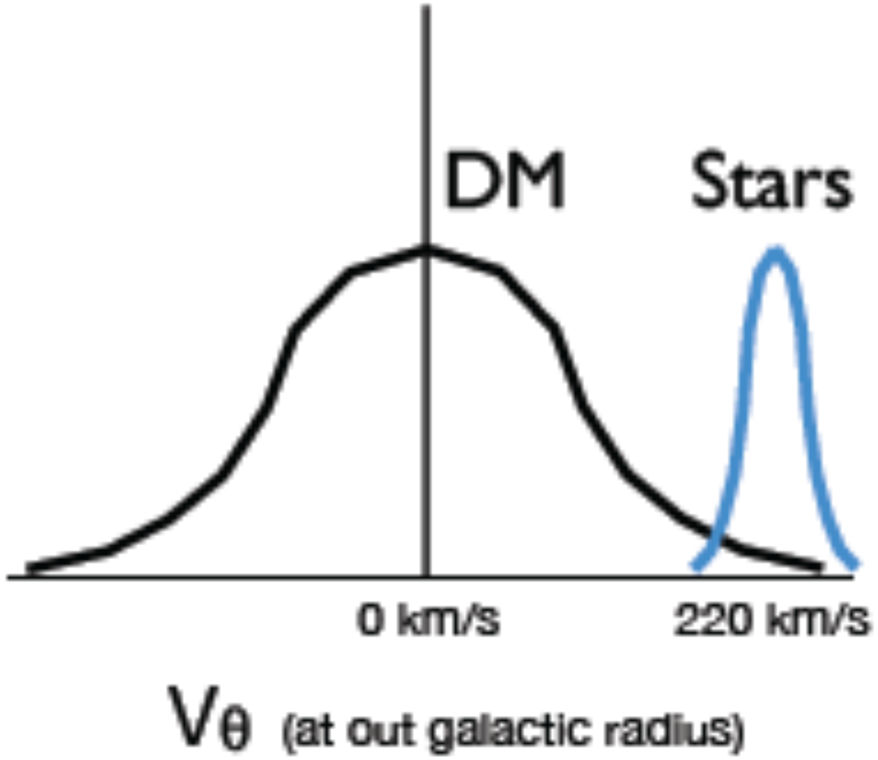
$$m_\chi << m_N \rightarrow E_c \propto \frac{m_\chi^2}{m_N}$$

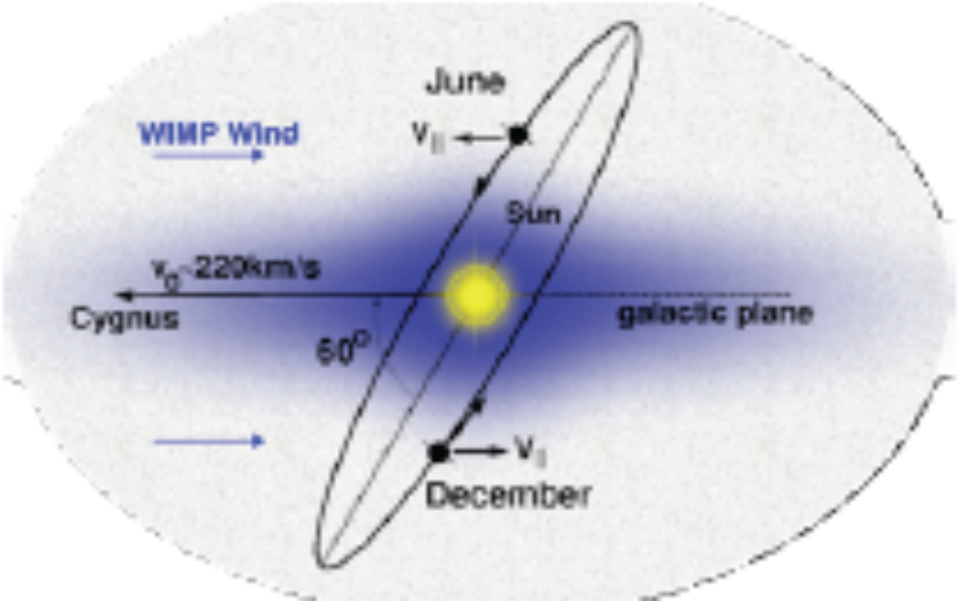
$$m_\chi >> m_N \rightarrow E_c \propto m_N$$



Total recoil rate is proportional to WIMP number density

Signal: Annual Modulation

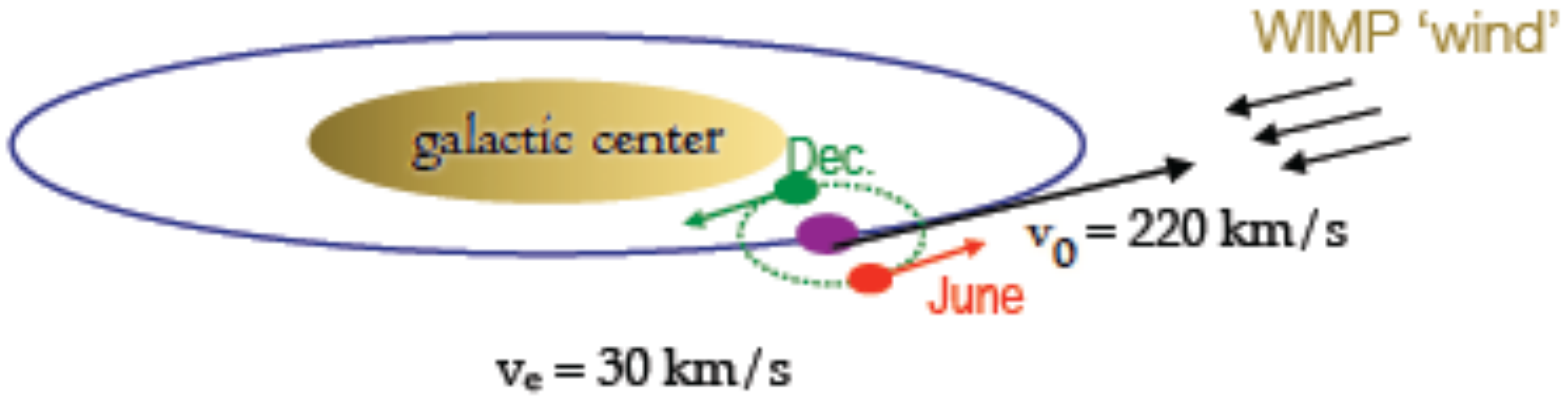




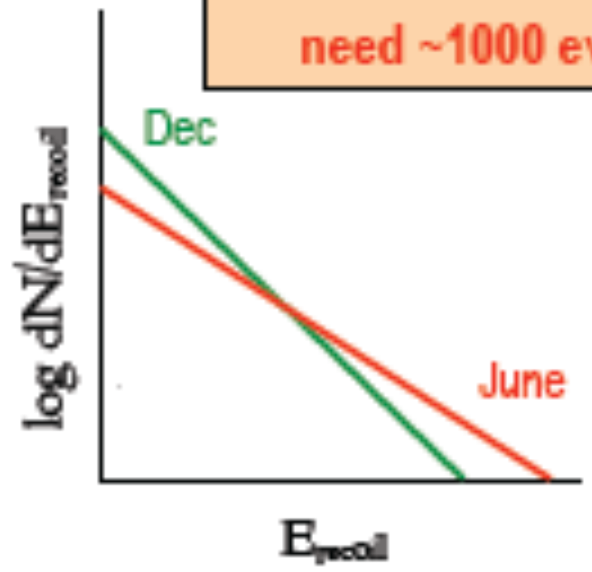
- Baryons travel together in roughly circular orbits with small velocity dispersion
- Dark matter particles travel individually with no circular dependence and large velocity dispersion
- As a result, the flux of WIMPs passing through Earth modulate over the course of a year as Earth rotates around the sun.

Signal Modulation: Rate

Assume WIMP Isothermal Halo:



~2% seasonal effect - need ~1000 events

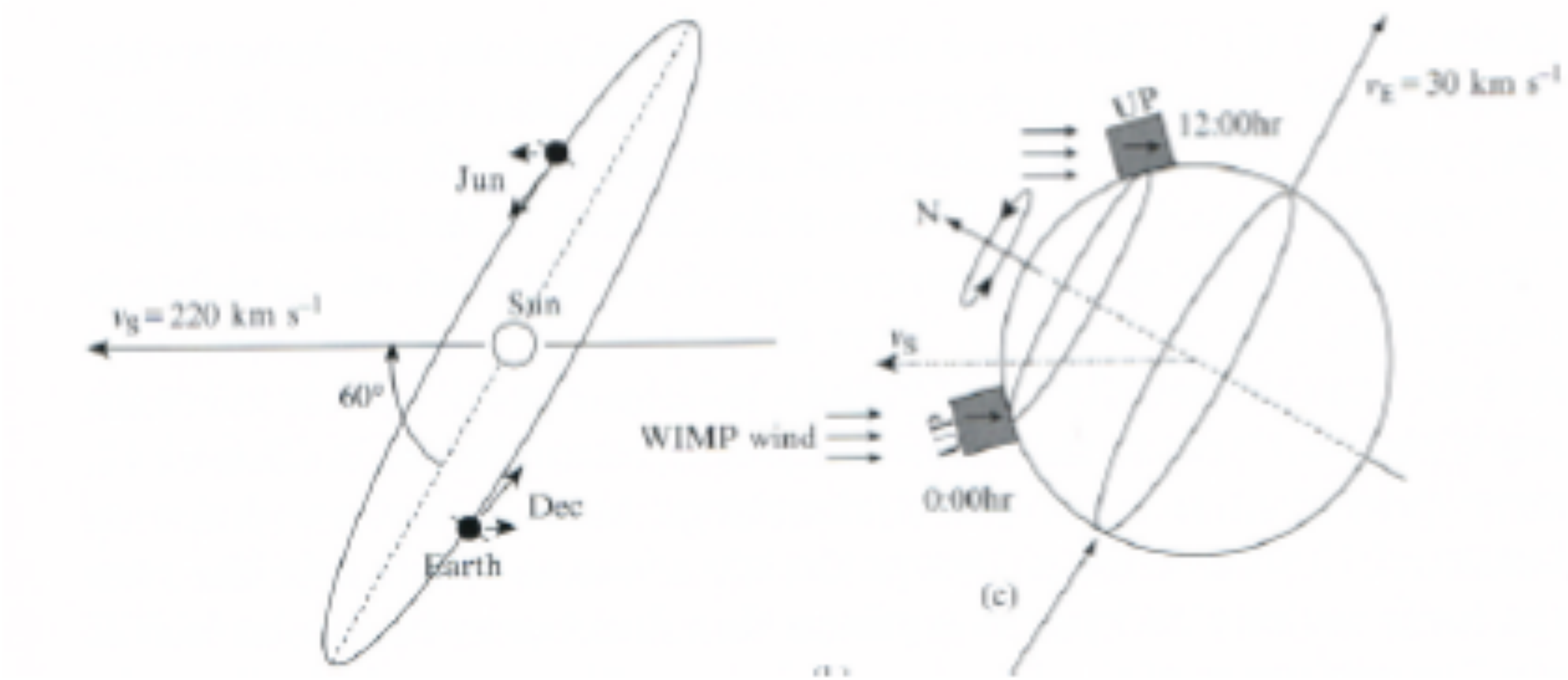


Since Earth's orbital speed around the sun is significantly smaller than the Sun's circular speed, the amplitude of the modulation is small and can be written as a Taylor Series.

$$\frac{dR}{dE_R} \approx \left(\frac{d\bar{R}}{dE_R}\right)[1 + \Delta(E_R)\cos\alpha(t)]$$

where $\alpha(t) = 2\pi(t - t_0)/T$ and $T = 1$ year, $t_0 = 150$ days

Signal Modulation: Direction



- A detector at 45 degree latitude will see the dark matter wind oscillate in direction over the course of a day.
- This is a sidereal (tied to stars) effect, not diurnal (tied to sun).

Double-phase Xe TPC

Which Target ?

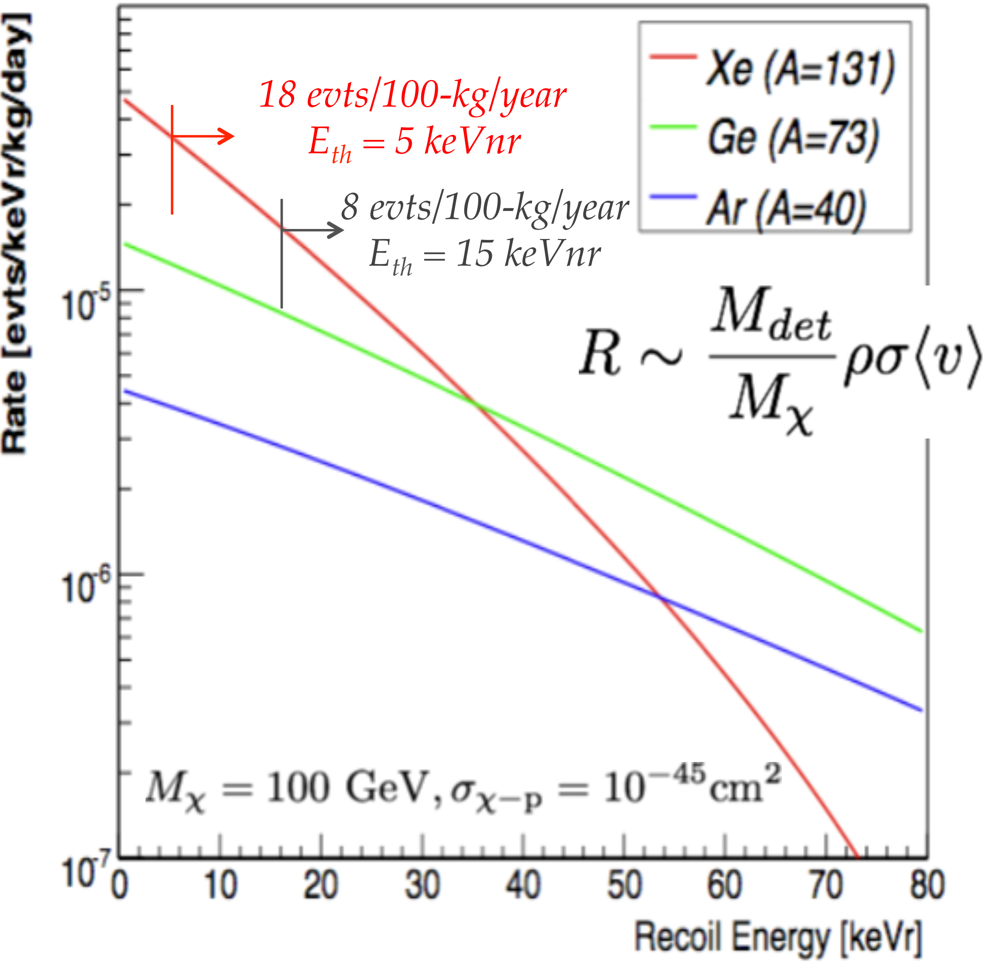
Use Xenon !


Xe
Xenon
Kα
Lα
Rn
Radon
85
210
Astatine
11.4270
Iodine
83
208.980
Bismuth
Antimony
26.359
3.604
10.8390
2.4197
Re
TAXIS

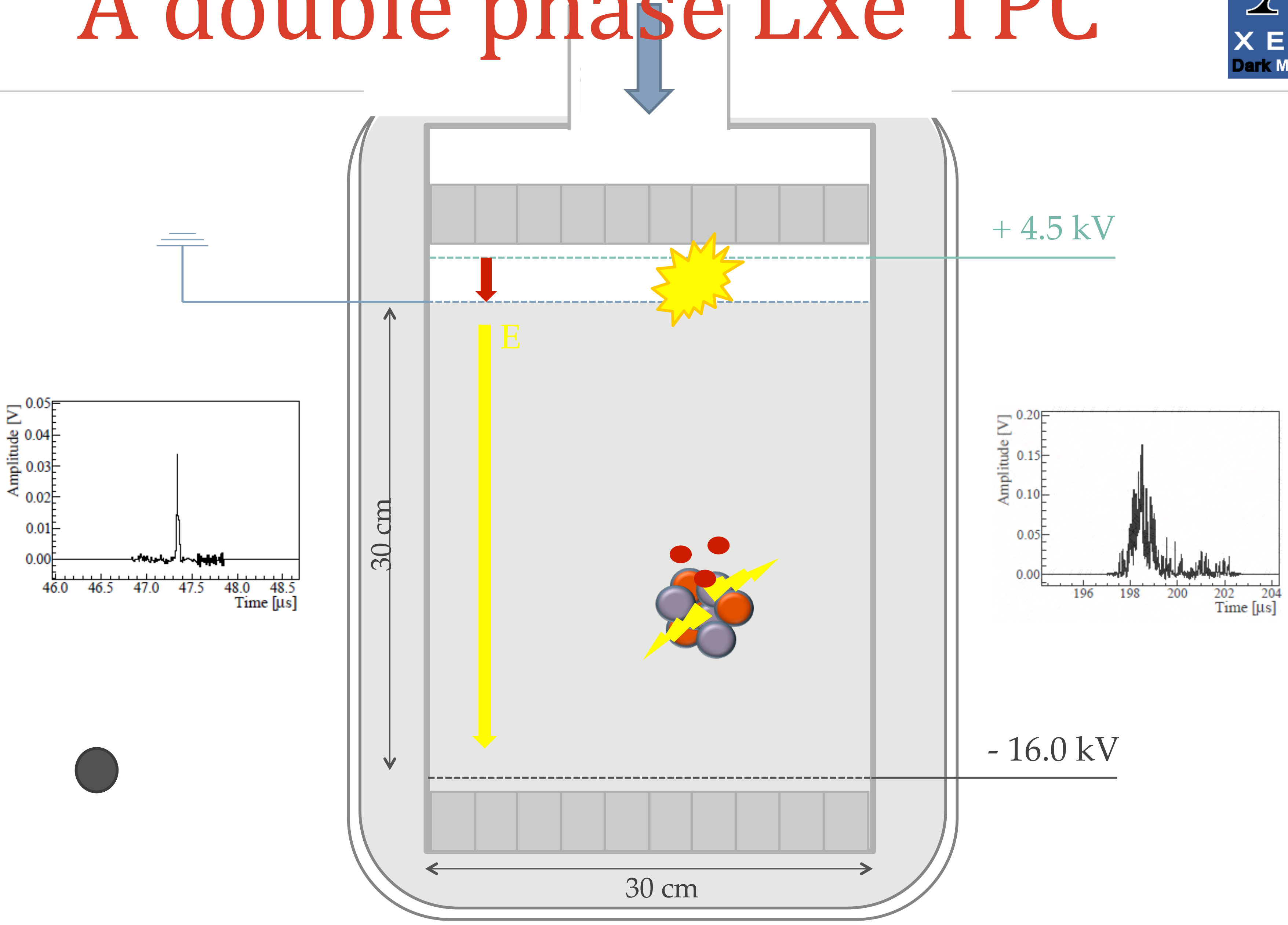
and... beware of Rn (and Kr) !

Xenon intrinsic properties

- High A: large number of SI interactions
- Self shielding: high Z=54 and and high density ρ=2.83 kg/l
- Scalability: possibility to build compact detectors, scalable to larger dimensions
- Odd-nucleon isotopes: high A=131 with ~50% of odd isotopes. Good for SD.
- Wavelength 178 nm: no need for a wave-length shifter
- Intrinsically pure: ^{136}Xe has very small decay rate; Kr can be removed to ~ppt
- Charge & light: highest yield among the noble liquids
- “Easy” cryogenics: -100 °C

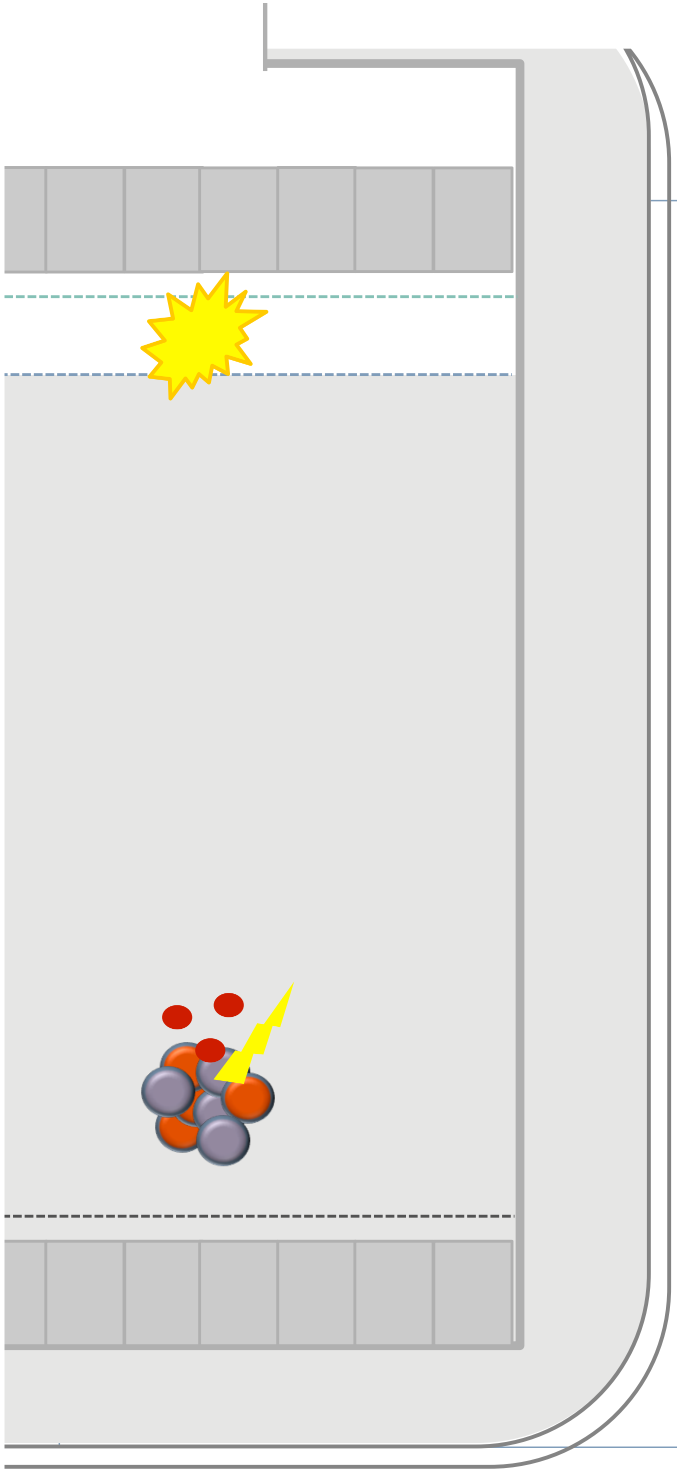


A double phase LXe TPC

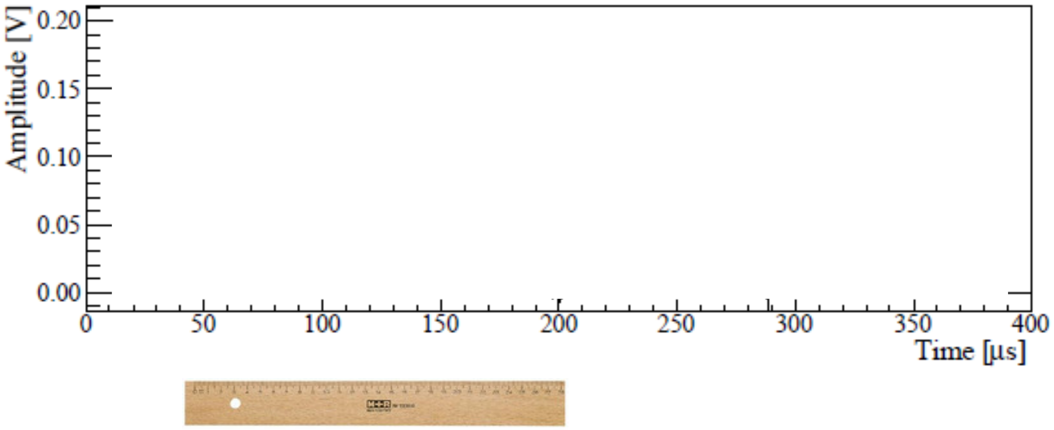


161 kg LXe in total
thereof 62 kg inside TPC

Vertex reconstruction in Z …



● Rec



$z(dt) = v_{drift}$ x dt ; $v_{drift} \approx 1.74$ mm/µs

Resolution $\sigma_z < 0.3$ mm

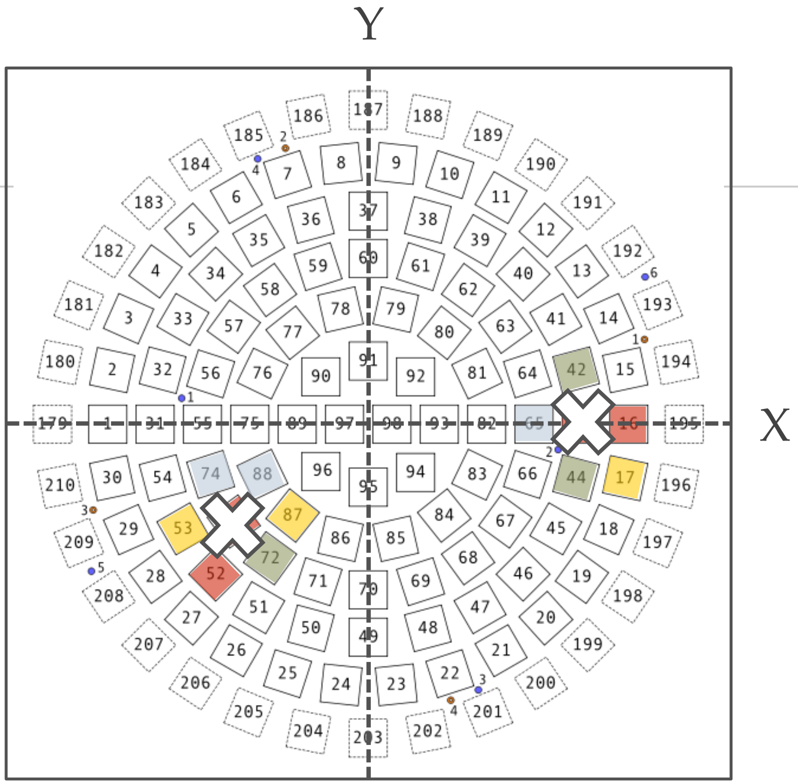
Capability to distinguish two events along Z: ~ 3 mm

… and X,Y position

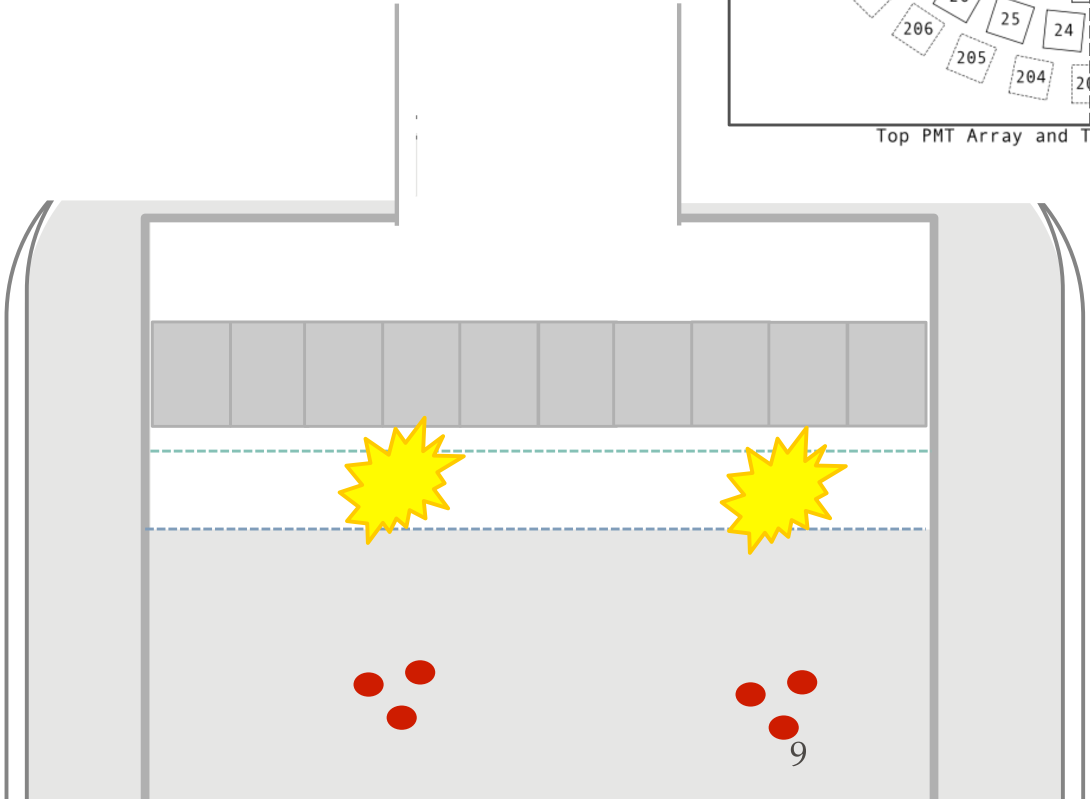
Computed and cross-checked by

- Neural network algorithm
  - χ^2 minimization
- Support Vector Machine

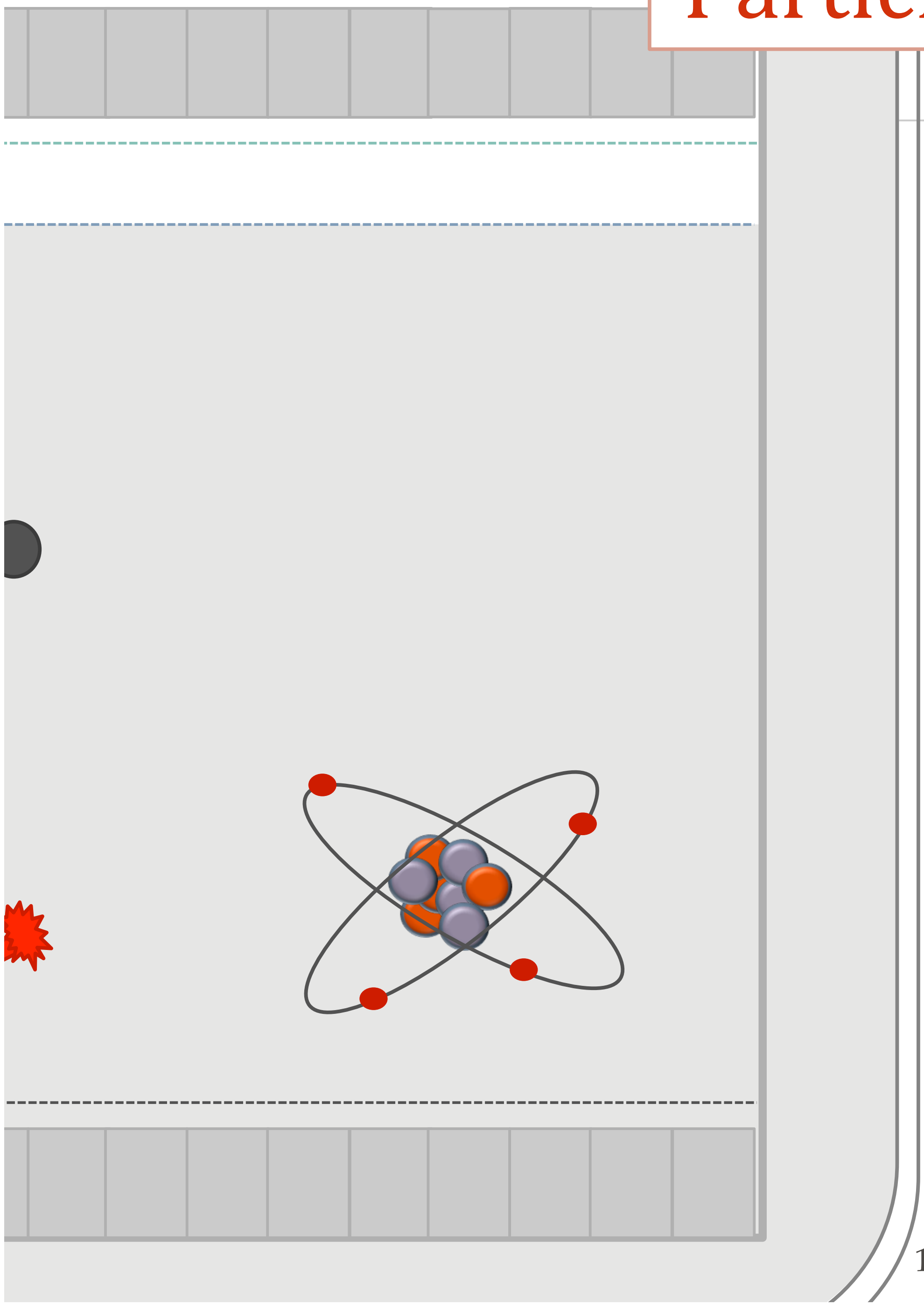
Resolution $\sigma_{X,Y} < 3$ mm



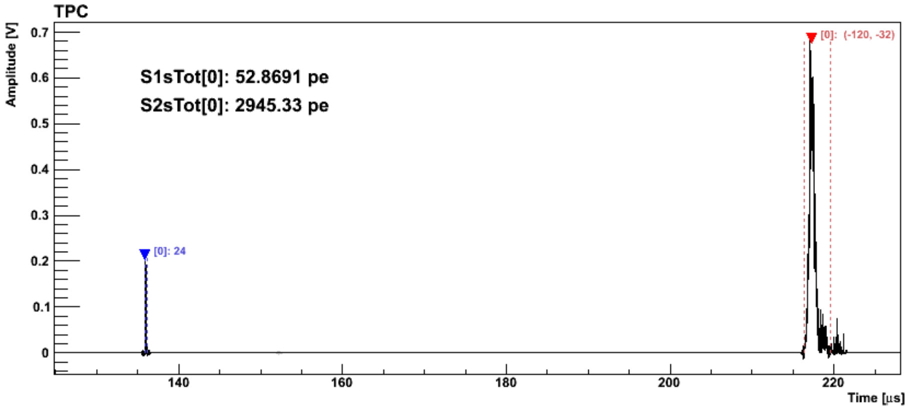
Top PMT Array and Top Shield PMT Array



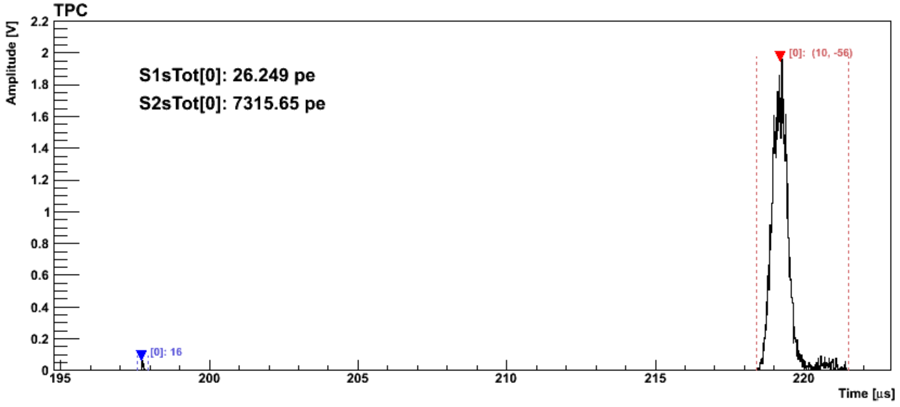
Particle discrimination



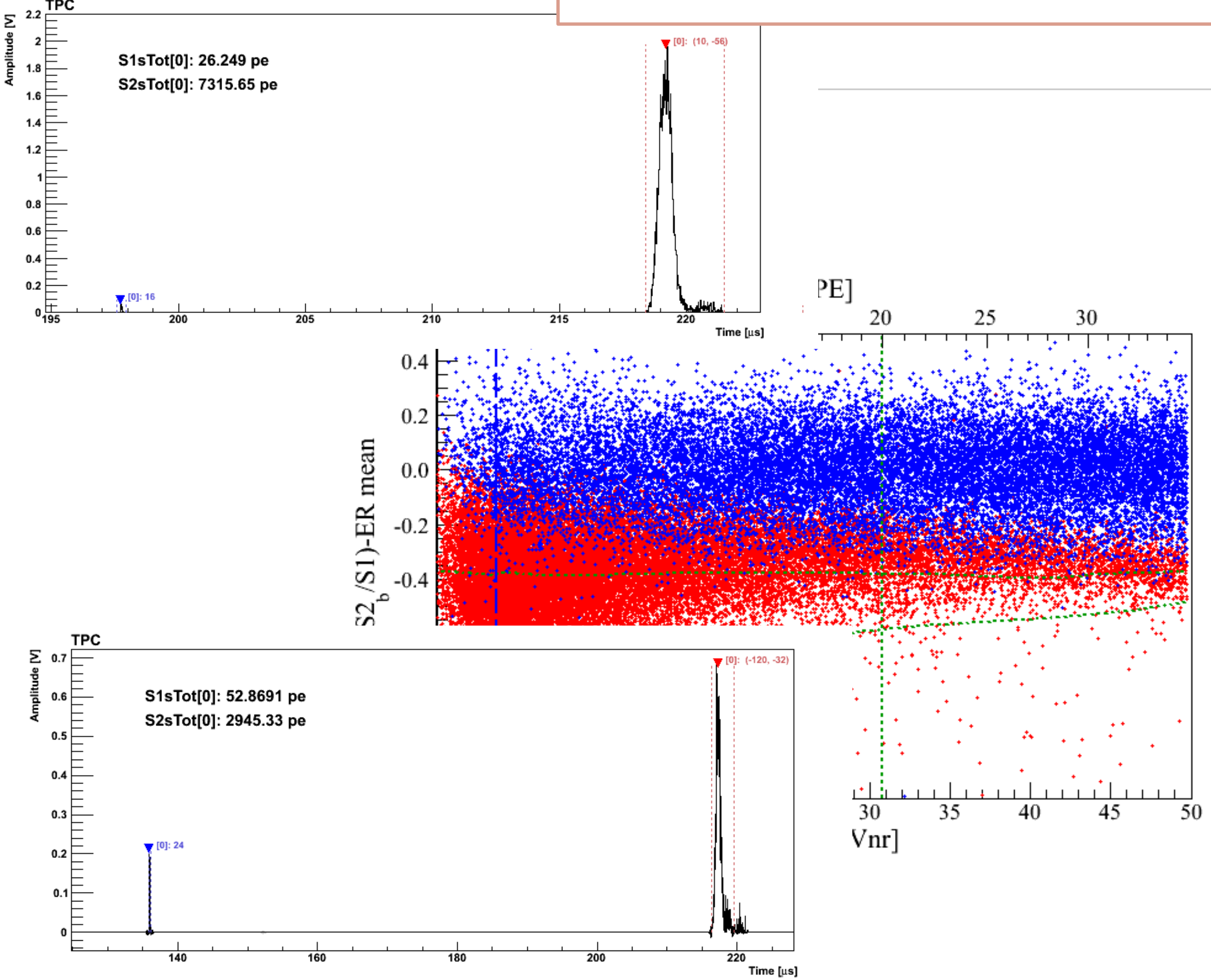
nuclear recoil



electronic recoil



Particle discrimination



electronic recoils
(^{60}Co, ^{232}Th)

nuclear recoils
(n from AmBe)

XENON Collaboration

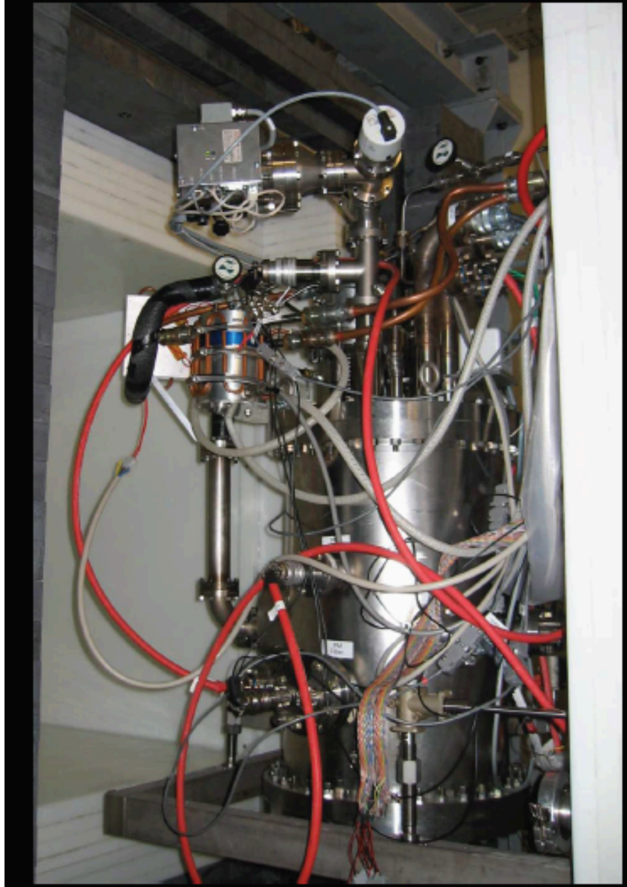
~130 scientists from 19 institutions

Laboratori Nazionali del Gran Sasso (LNGS), Italy

The XENON Dark Matter Program

Xe XENON Dark Matter Project

2005-2007



XENON10

15 cm drift TPC - 25 kg

~10^{-43} cm^2

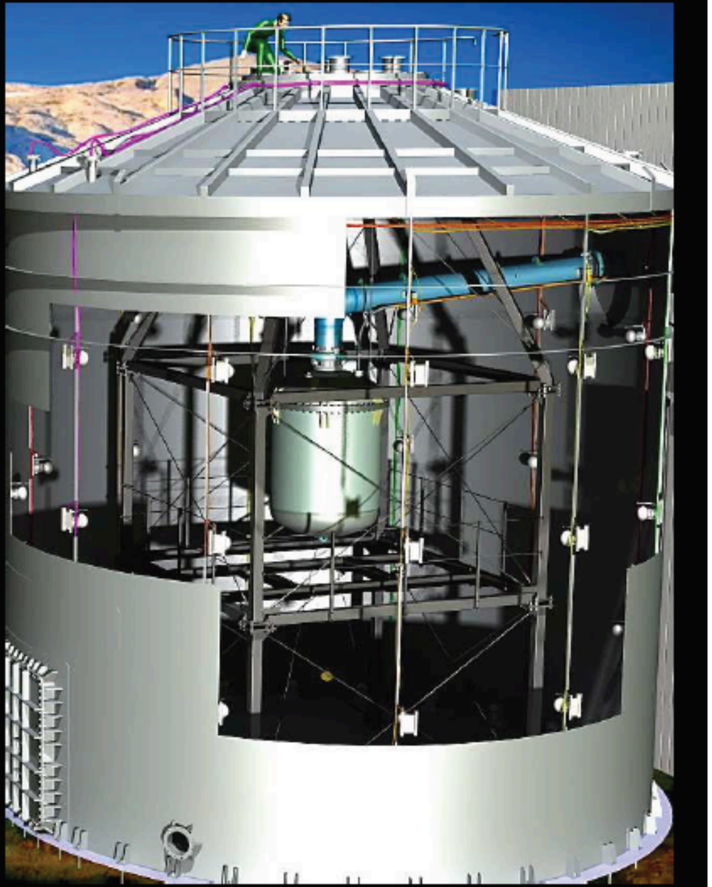
2007-2015

XENON100

30 cm drift TPC - 161 kg

~10^{-45} cm^2

2012-2022

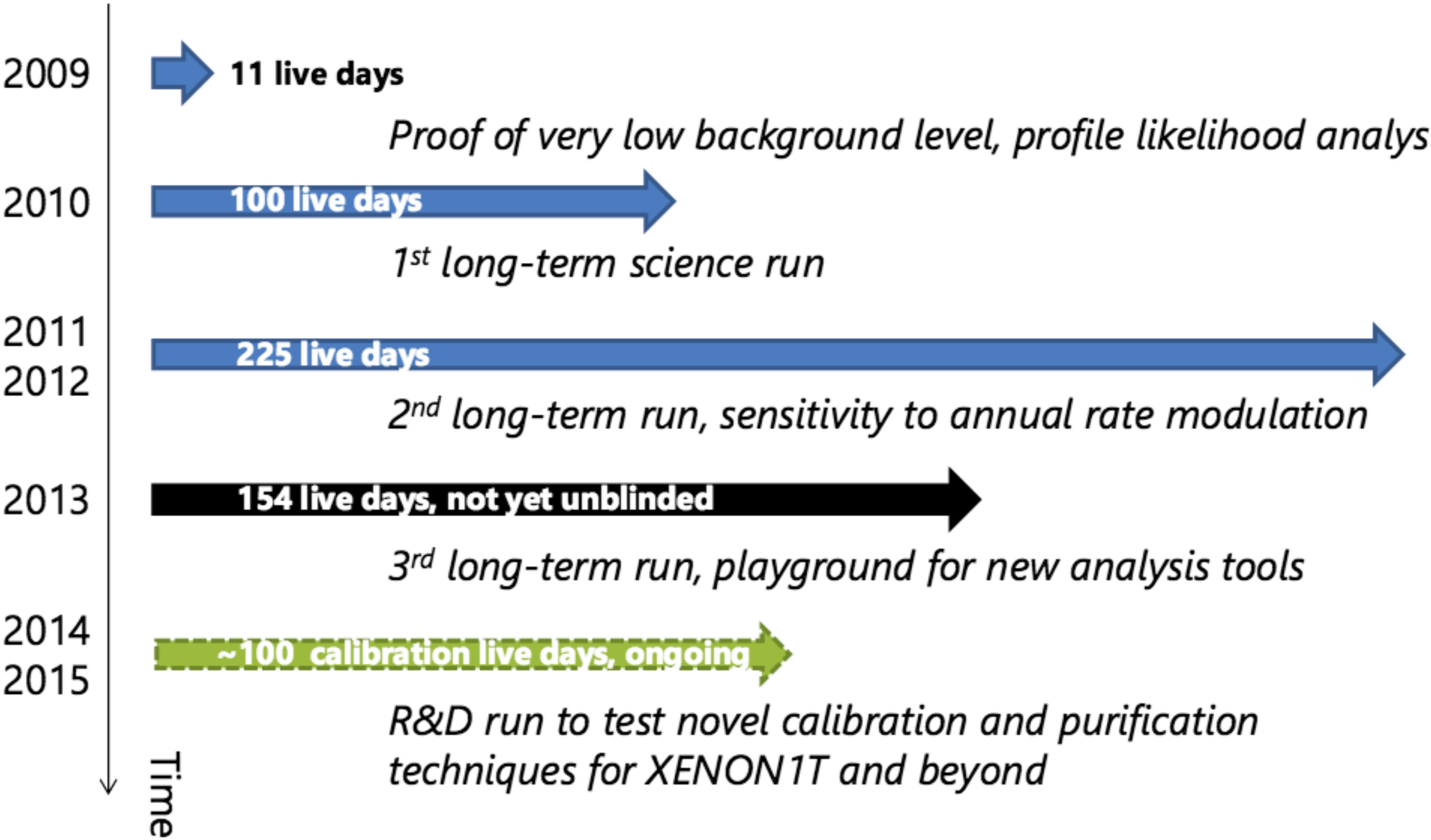


XENON1T/XENONnT

100 cm drift TPC - 3500 kg/7000 kg

~10^{-47} cm^2 / 10^{-48} cm^2

XENON100 Timeline



2009 **11 live days**

Proof of very low background level, profile likelihood analysis

2010 **100 live days**

1st long-term science run

2011
2012 **225 live days**

2nd long-term run, sensitivity to annual rate modulation

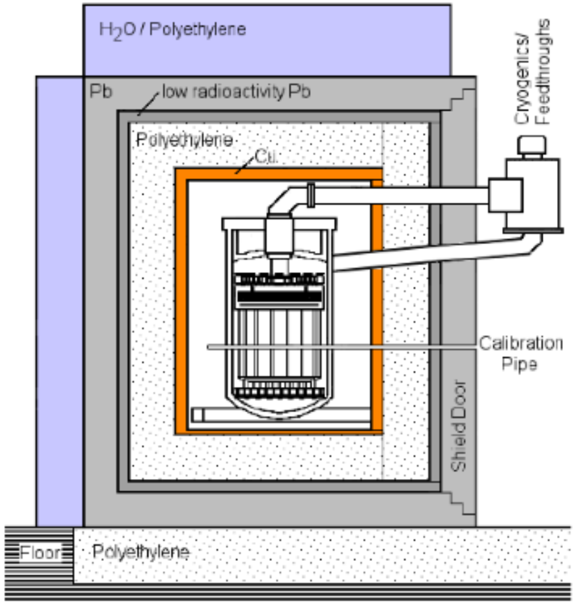
2013 **154 live days, not yet unblinded**

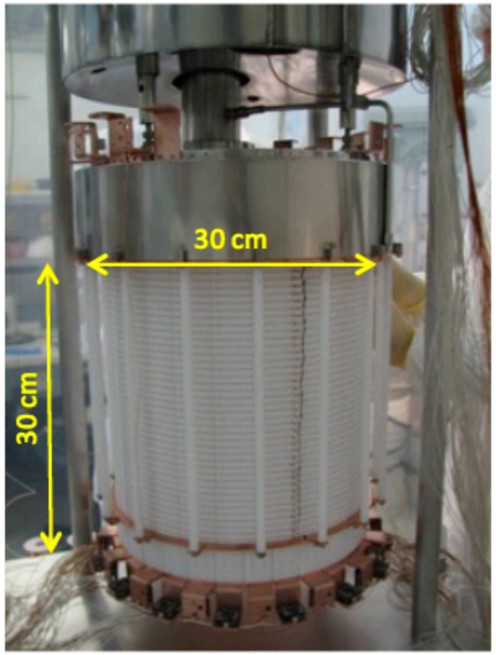
3rd long-term run, playground for new analysis tools

2014
2015 **~100 calibration live days, ongoing**

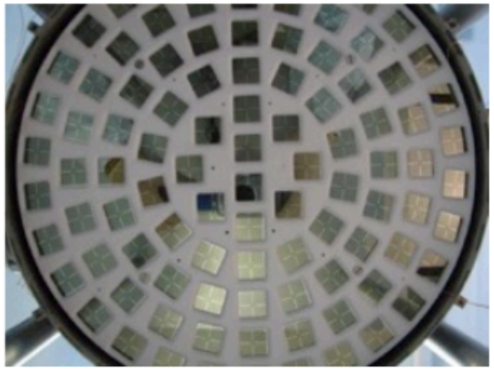
R&D run to test novel calibration and purification techniques for XENON1T and beyond

The XENON100 detector



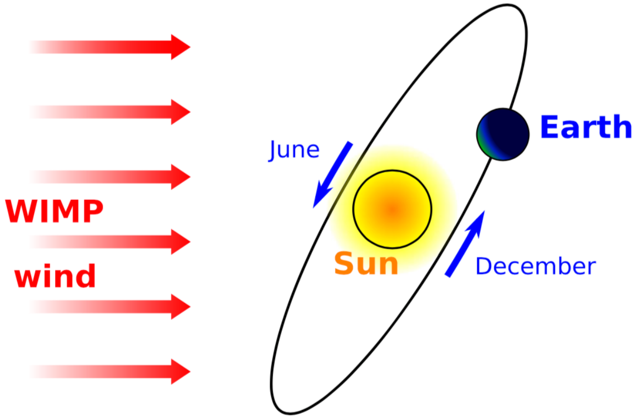


- 161 kg liquid xenon (62kg in TPC, 99kg active veto)
- 242 low activity Hamamatsu R8520-06 1“ square PMTs
- Surrounded by passive neutron and gamma radiation shield
- Comprehensive material screening of all inner parts
- Purification through hot getter and Kr distillation column

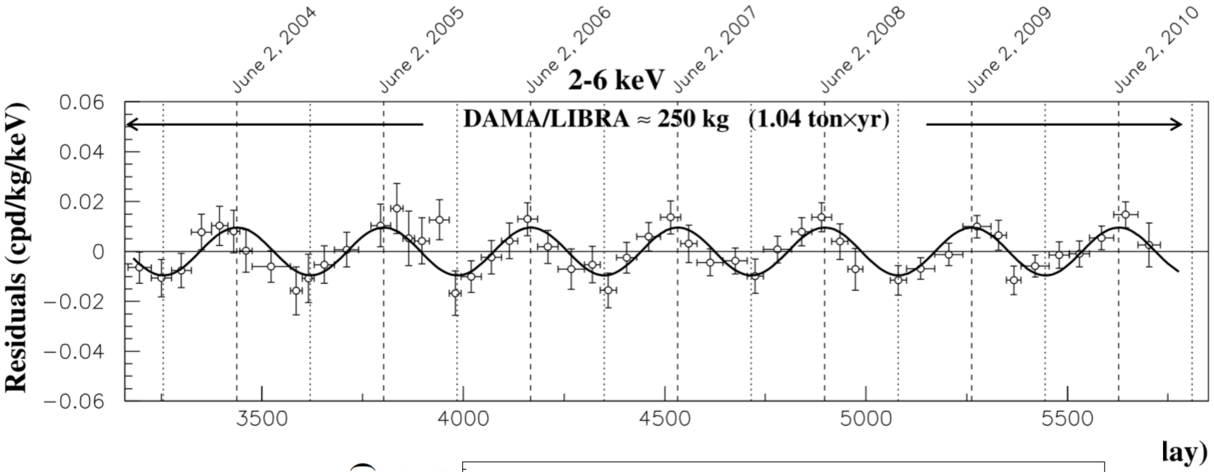


Annual modulation: DAMA/LIBRA

- Dark matter (DM) signal rate is expected to be annually modulating
- Peak phase 152 days (June 1)



Freese *et al.*, Rev. Mod. Phys. 85, 1561 (2013)



DAMA/LIBRA:

9.3 sigma significance

only for single hit

Phase (144 +- 7) days

No signal above 6 keV

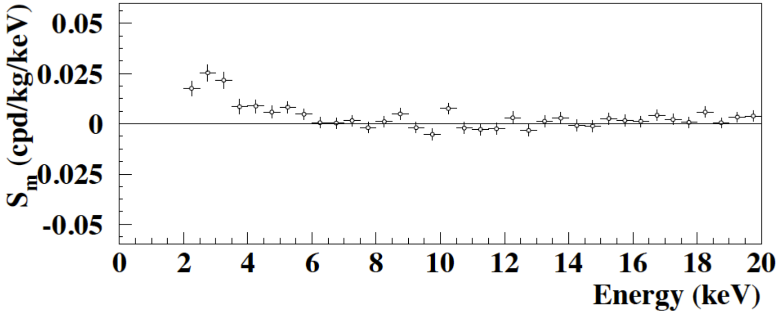


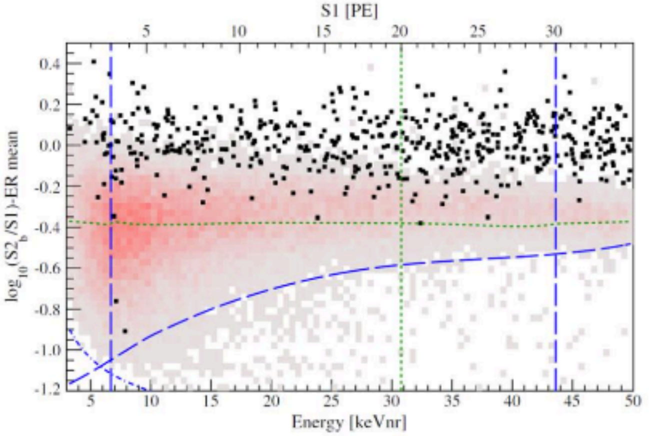
Figure 8: Energy distribution of the S_m variable for the total cumulative exposure 1.33 ton×yr. The energy bin is 0.5 keV. A clear modulation is present in the lowest energy region, while S_m values compatible with zero are present just above. In fact, the S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 35.8 for 28 degrees of freedom (upper tail probability of 15%).

Bernabei *et al.*, Eur. Phys. J. C 73, 12 (2013)

A very strong model-independent signal, let's interpret it with a model.

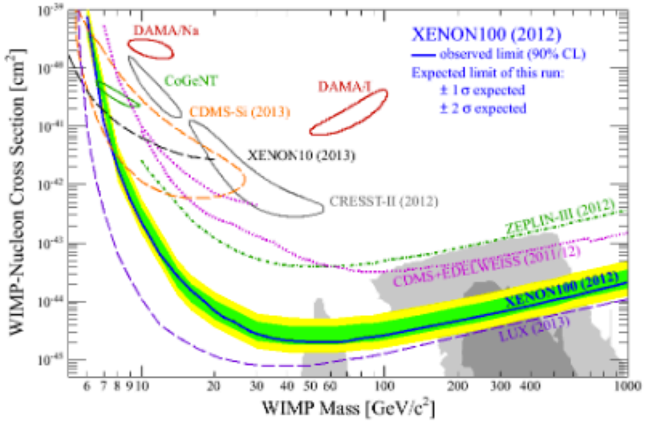
Nuclear Recoil Interpretation

Particle discrimination

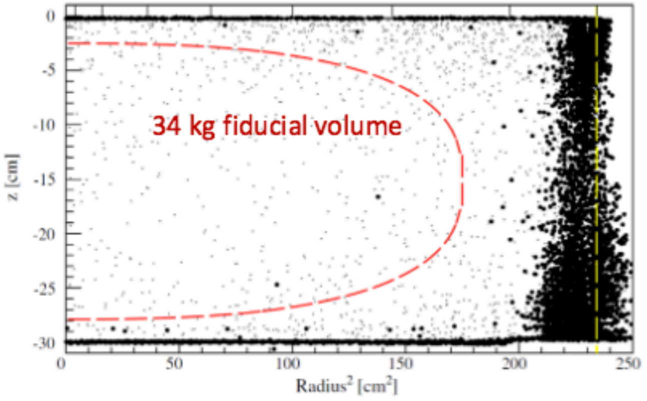


Spin-independent WIMP-nucleon coupling

E. Aprile et al. (XENON100), Phys. Rev. Lett. 109, 181301 (2012)

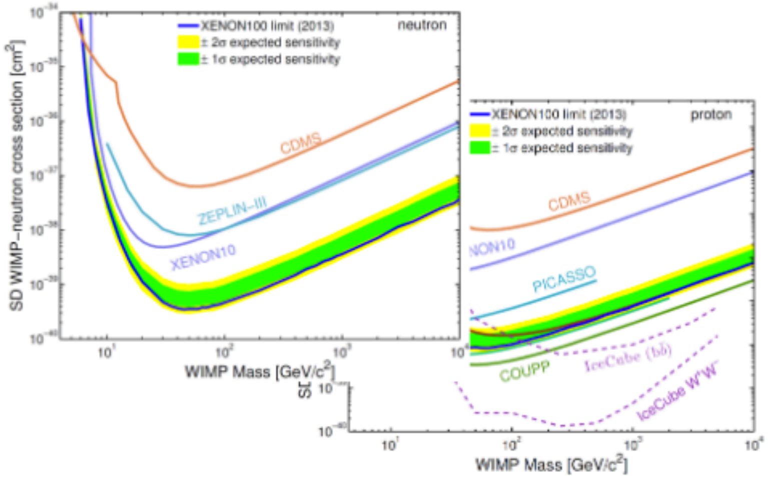


Spatial event distribution



Spin-dependent WIMP-nucleon coupling

E. Aprile et al. (XENON100), Phys. Rev. Lett. 111, 021301 (2013)



How about Leptophilic DM?

- DAMA/LIBRA annual modulation can be interpreted as signals from Leptophilic DM models

- We tested three representative models in XENON100 using the electronic recoil data:

- 1, DM-electron scattering through axial-vector coupling

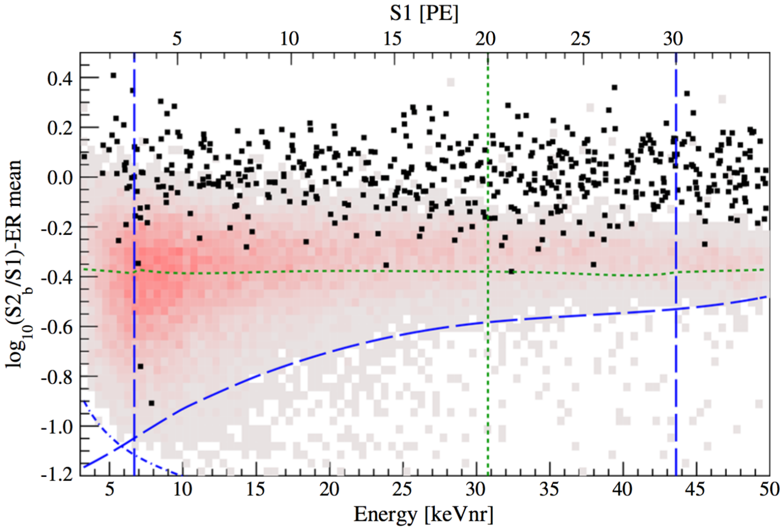
  J. Kopp et.al, Phys.Rev. D80, 083502 (2009)

- 2, Mirror DM model

  . R. Foot, Int.J.Mod.Phys. A29, 1430013 (2014)

- 3, Luminous DM model

  . B. Feldstein et.al, Phys.Rev. D82, 075019 (2010)



ER energy scale

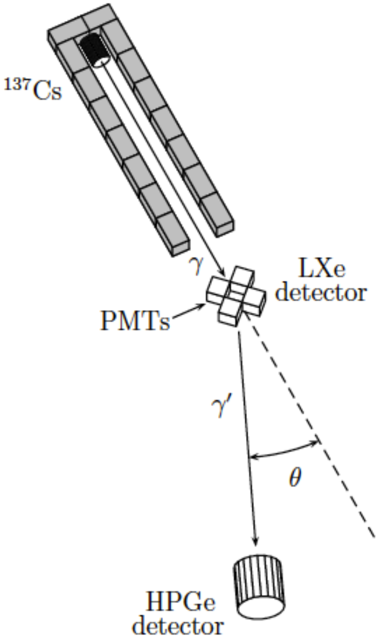
- Knowledge of the response of LXe to low energy ER is of course crucial.
- ^{83m}Kr provides 32.1 and 9.4 keV lines; but this is still a “high” energy (DAMA annual modulation signal is in the 2-6 keV energy window)

Measurements using the “Compton coincidence technique“

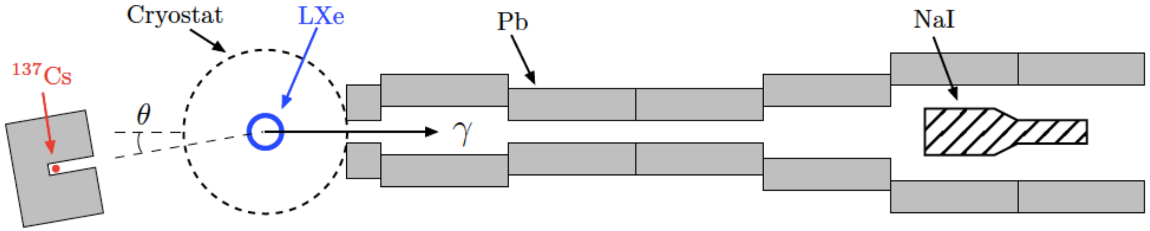
$$\begin{aligned} E_{\rm er} &= E_\gamma - E'_\gamma \\ &= E_\gamma - \frac{E_\gamma}{1+\frac{E_\gamma}{m_e c^2}(1-\cos\theta)} \end{aligned}$$

Two different setups:

Columbia: Aprile et al., Phys. Rev. D 86, 112004 (2012)

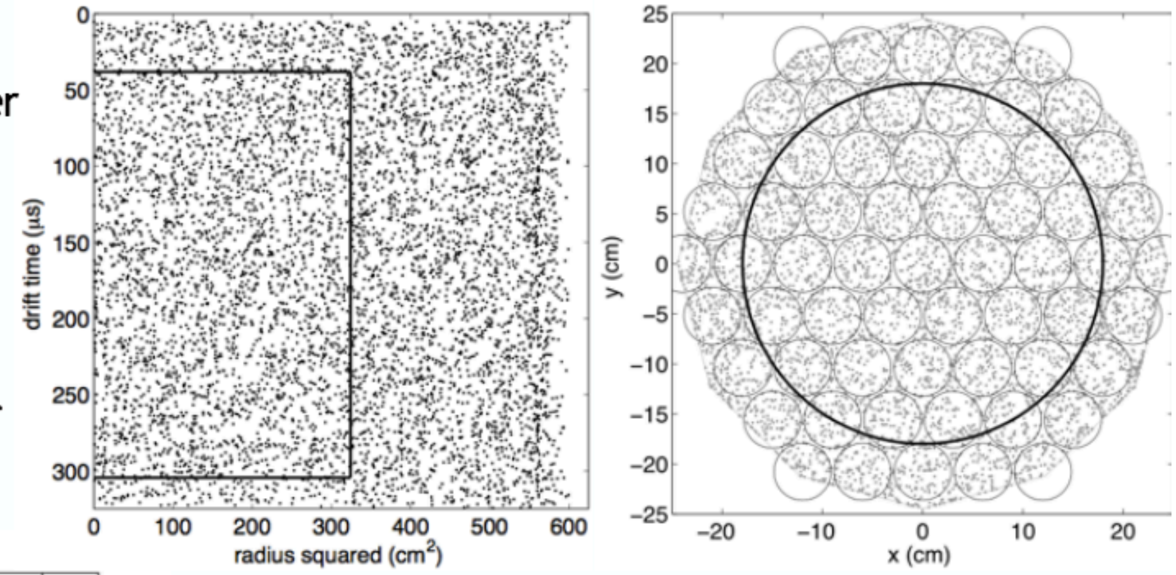


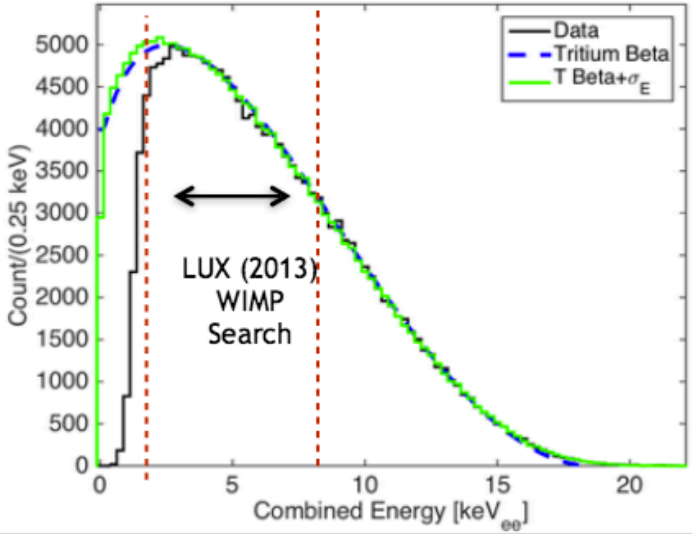
Zurich: Baudis et al., Phys. Rev. D 87, 115015 (2013)



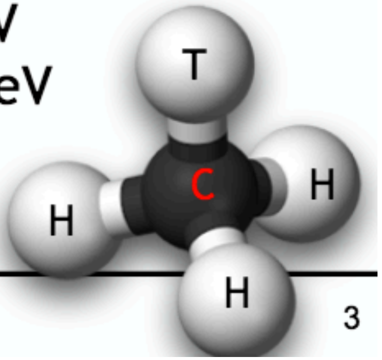
Tritiated methane (from LUX)

- Methane diffuses much slower than bare tritium.
- Dissolved uniformly in the xenon.
- Removed with standard purification technology.
- Used to calibrate the fiducial volume.





- Single Scatter ER events in energy region of interest: 0.1 keV to 18 keV
- Mean energy: 5 keV
- Peak energy: 2.5 keV

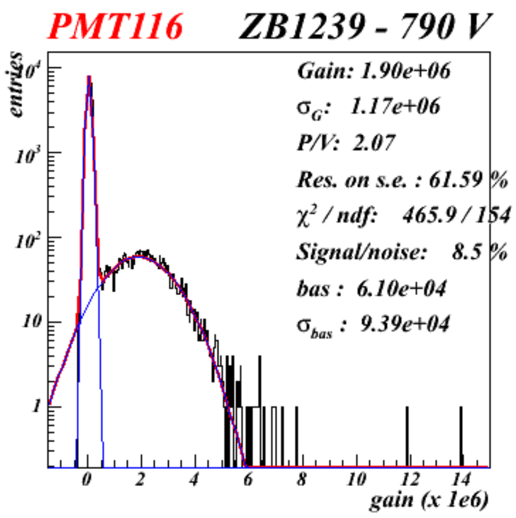


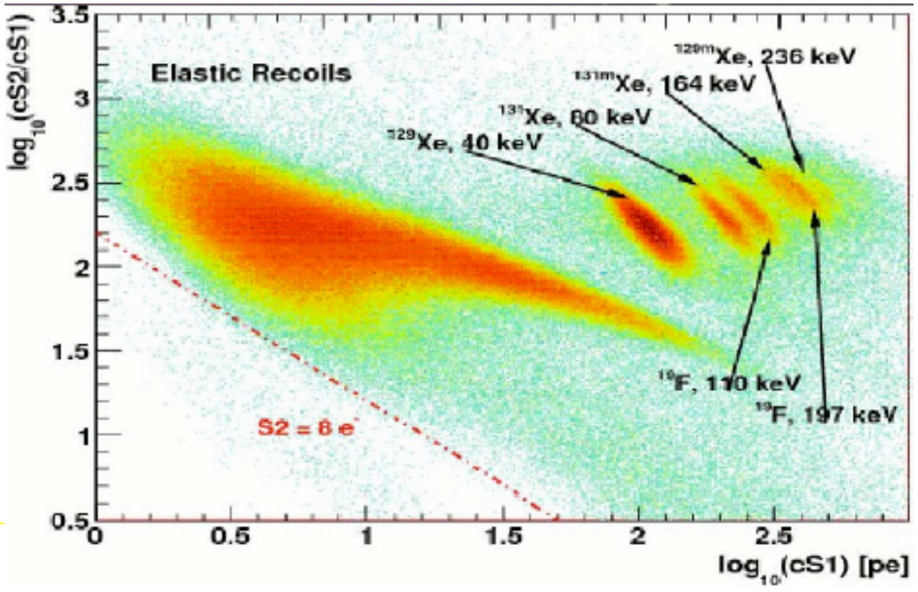
XENON100 Light Calibration

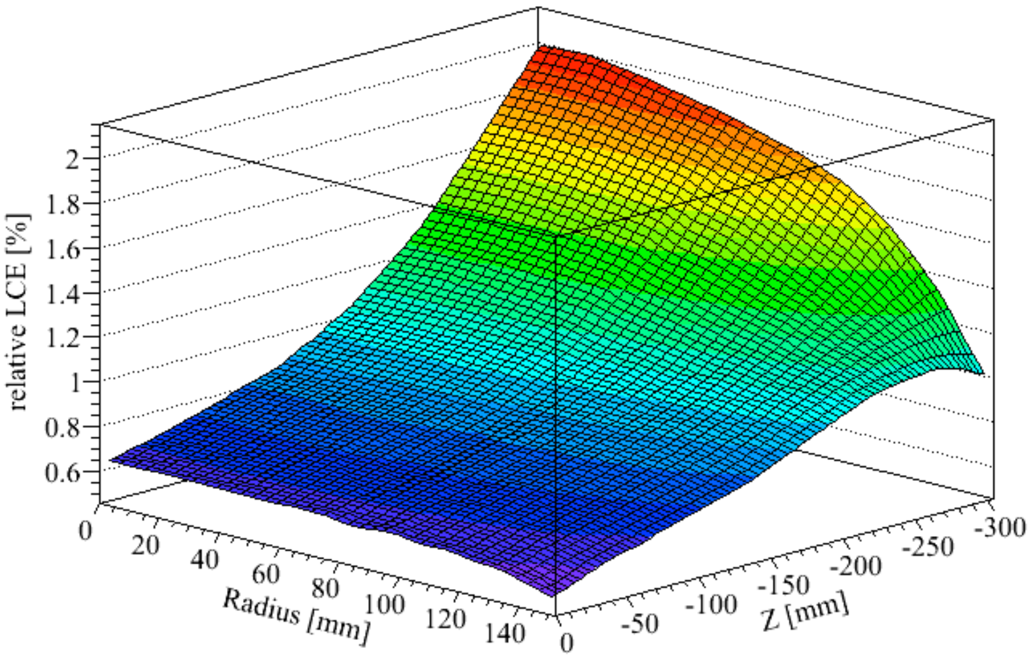
The light response of each PMT is periodically calibrated with LED light.

A map of the light collection efficiency for the detector has been measured, so that we can correct our results with high accuracy thanks to the ~mm position resolution of the TPC.

Measurements from different sources (AmBe, ^{137}Cs, ^{83m}Kr) with different energies give the same result.

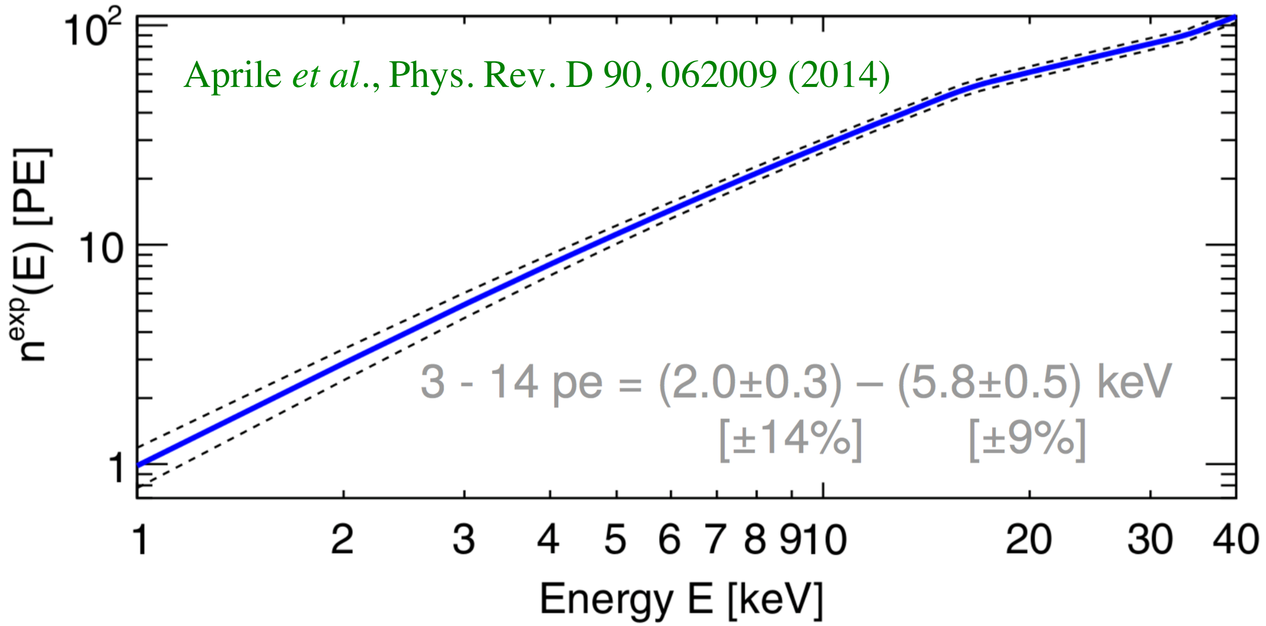






Light vs ER energy in LXe

DAMA/LIBRA 2-6 keV Electronic recoil (ER) corresponds to 3-14 PE in XENON100

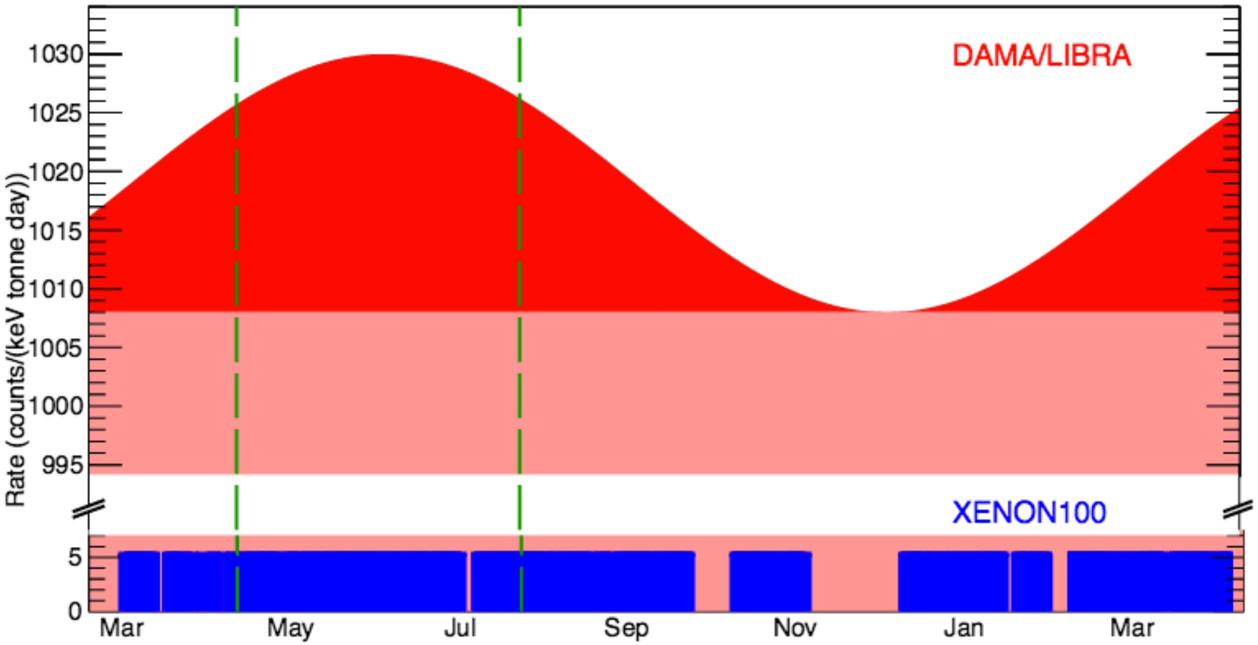


- Energy (keV) -> (Energy Scale) -> Expected average S1 signal (PE)
- Expected average S1 signal (PE) -> (Poissonian fluctuations + PMT response) -> Real S1 signal
- Real S1 signal -> (S1 Acceptance) -> S1 rate detected in XENON100

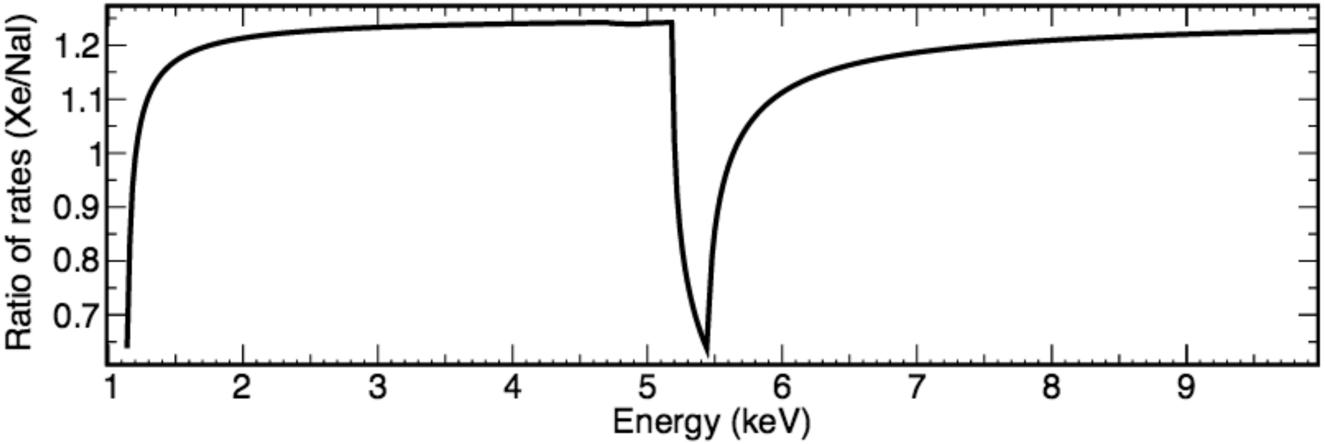
DC analysis

Comparison with DAMA/LIBRA

Pessimistic assumption
(for the exclusion):
consider as signal only the
modulated region,
and the flat one below
modulation as background

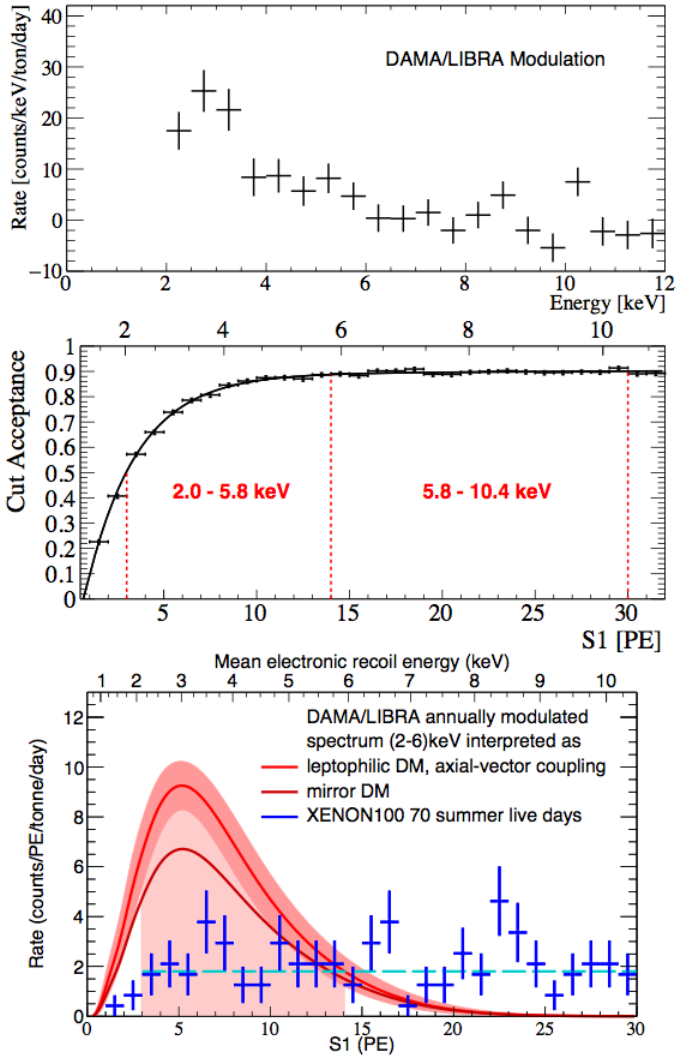


Axial vector
coupling model to
convert from NaI to
LXe



Comparison with DAMA/LIBRA

- DAMA/LIBRA rate converted to XENON100 spectrum assuming leptophilic DM model, axial vector coupling
- Energy response, resolution and cut acceptance applied
- Compare XENON100 average rate with DAMA/LIBRA modulation amplitude
- Constraints on DM interpretation of DAMA/LIBRA (assuming 100% modulation):
- WIMPs-electron scattering 4.4-sigma
- Mirror dark matter model 3.6-sigma
- Luminous dark matter model 4.6-sigma



Science 349, 851 (2015)

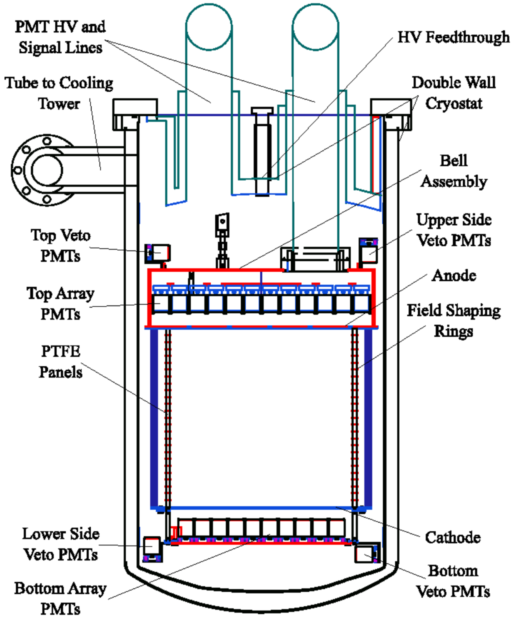
AC analysis

Search for Modulations

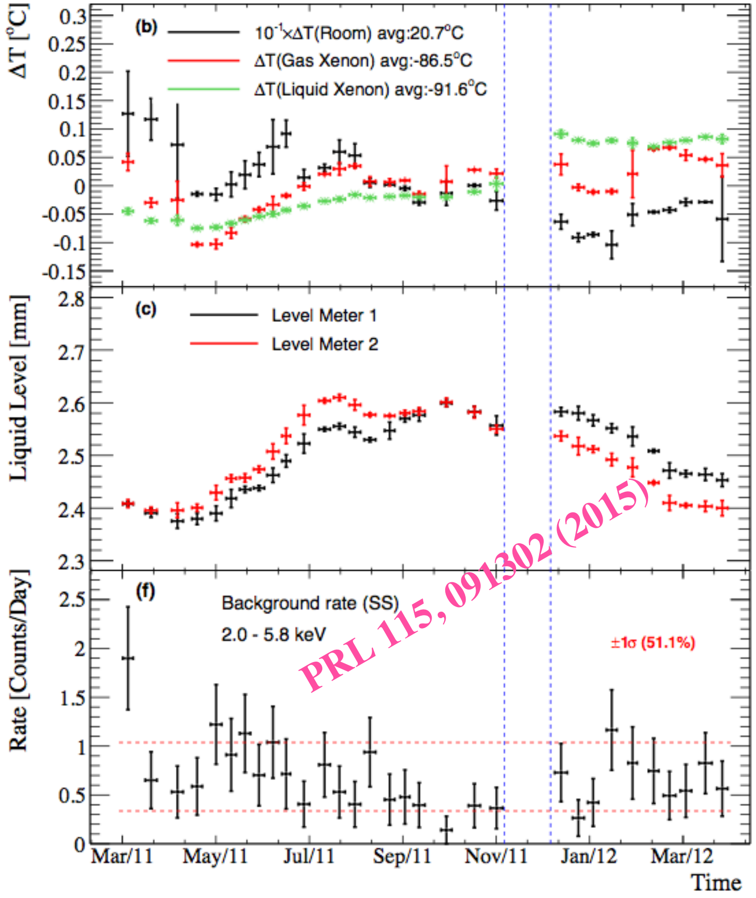
- The first LXe TPC with more than one year of stable running conditions
- The first modulation search for DM at Gran Sasso Lab after DAMA/ LIBRA
- Demonstration for future XENON modulation searches
- Search for leptophilic DM signals
- Require good understand the stability of detector and backgrounds
- 224.6 live days,
  along ~400 days, from Feb 28, 2011 till Mar 31 2012
- 153 events in the low energy region [2, 5.8] keV

Stability of the Detector

Aprile *et al.*, Astropart. Phys., 35, 573-590 (2012)



- Detector pressor (2)
- Room pressor
- LXe temperature (4)
- PTR temperature
- Room temperature
- Purification flow rate
- LXe levels (2)
- PMT gain
- Radon level (2)



PRL 115, 091302 (2015)

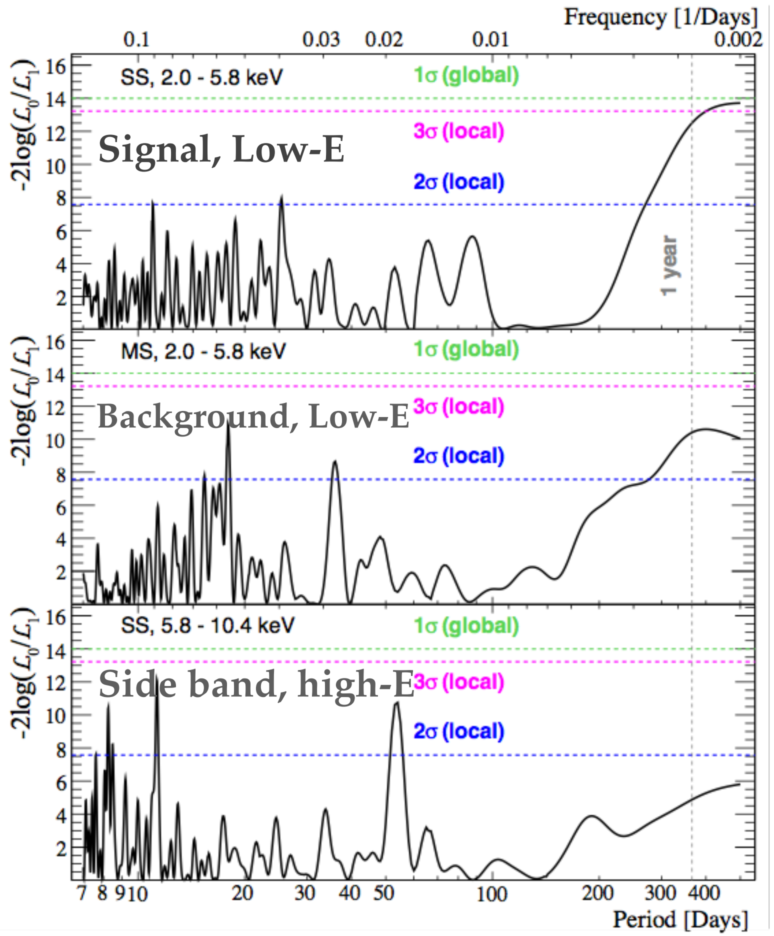
Very tiny absolute variations

No correlations with ER rate

No significant impact on ER rate!

Modulation Search Results

- No evident peak crossing the 1-sigma global significance threshold
- Single Scatter in the Low-E (2.0-5.8 keV) range shows increasing significance at long period region. 2.8-sigma local significance at one year period
- Multiple Scatter (background) control sample in Low-E range shows similar power spectrum as SS. This disfavors an WIMPs interpretation of the SS spectrum
- SS in high-E (5.8-10.4 keV) does not show high significance at long period region

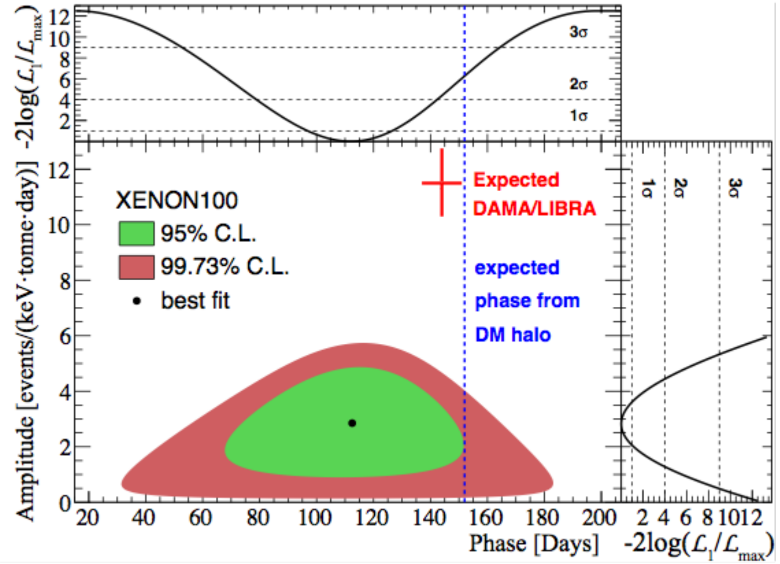


PRL 115, 091302 (2015)

DAMA/LIBRA Comparison (2D)

- The phase (112+-15) days (April 22) is not consistent with the standard halo model (June 2) at 2.6-sigma
- The amplitude of is also too small (only ~25%) compared with the expected DAMA/LIBRA modulation signal in XENON100.
- The DM interpretation of DAMA/LIBRA annual modulation as being due to WIMPs electron scattering through axial vector coupling is disfavored at 4.8-sigma from a PL analysis

PRL 115, 091302 (2015)



$$A = (2.7 \pm 0.8) \quad \text{events}/(\text{keV} \cdot \text{tonne} \cdot \text{day}),$$

$$C = (5.5 \pm 0.6) \quad \text{events}/(\text{keV} \cdot \text{tonne} \cdot \text{day}),$$

$$\phi = (112 \pm 15) \ \text{days}$$

$$DAMA/LIBRA(expected) = 11.5 \pm 1.2 stat \pm 0.7 syst$$

Summary (XENON100)

- Limit to WIMP-induced NR: 2 x 10^{-47} cm^2 at m_χ=50 GeV/c^2.
  Combination of the three main DM runs will be presented next week @IDM2016

- Leptophilic DM models to interpret DAMA/LIBRA modulation have been challenged by XENON100, with a simplified analysis (single-bin, no background subtraction). We find:
  - Axial-vector WIMPs-electron scattering disfavored at 4.4-sigma
  - Mirror dark matter model ->3.6-sigma
  - Luminous dark matter model -> 4.6-sigma

Science 349, 851 (2015)

- XENON100 is the first stable LXe TPC sufficient for modulation searches.
- No significant modulation is found globally in the XENON100 electronic recoil data.
- The local significance (~3σ) at 1-year period in both SS and MS samples does not favor a dark matter interpretation
- The interpretation of DAMA/LIBRA as due to Axial-vector WIMPs-electron scattering is disfavored at 4.8 sigma

PRL 115, 091302 (2015)

… waiting for XENON1T

XENON1T

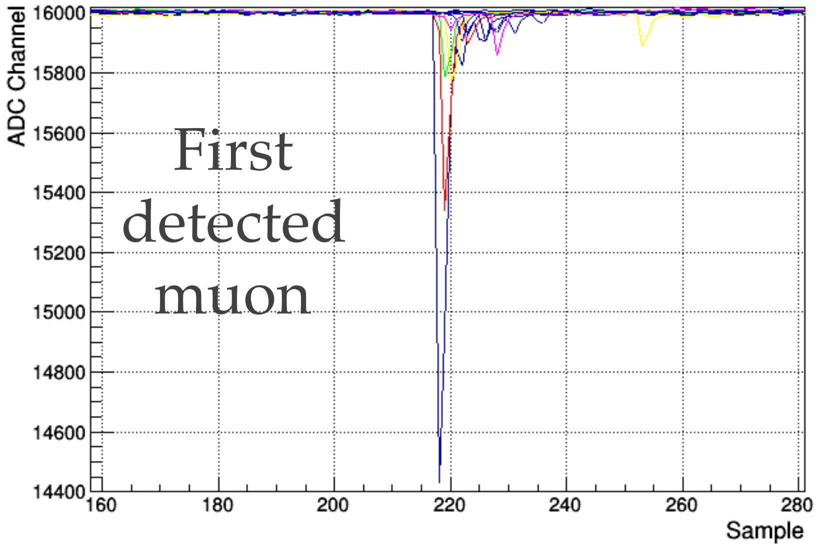
- **Science goal:** 100 times more sensitive than XENON100.
- **Target/Detector:** 3.2 tonnes of Xe/ dual-phase TPC readout by 248 PMTs.
- **Shielding:** Water Cherenkov muon veto.
- **Cryogenic Plants:** Xe cooling/ purification/distillation/storage systems designed to handle up to 10 tonne of Xe. Upgrade to a larger detector (XENONnT) planned for 2018
- **Status:** All systems successfully tested. Commissioning of detector ongoing. First science run this Fall.

XENON1T Systems

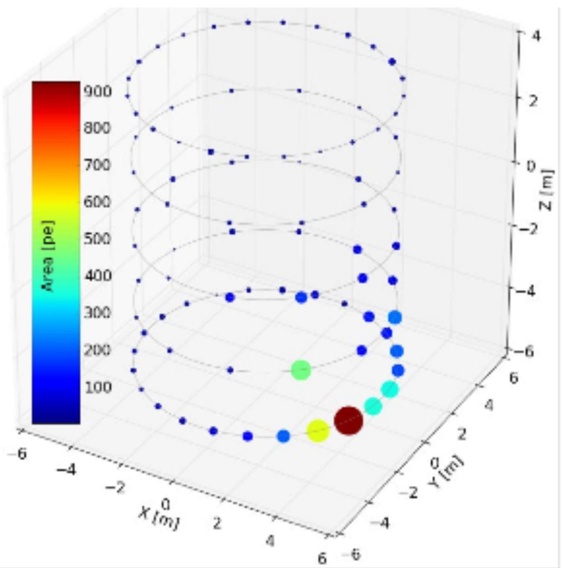
MUON VETO

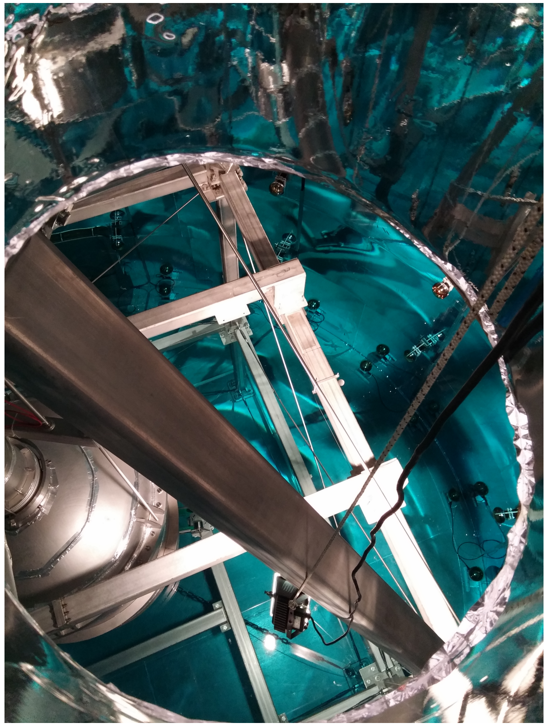
E. Aprile et al., JINST 9 P11006 (2014)

- The XENON1T cryostat is immersed in a tank filled with 700 tonnes of pure water.
- The tank is instrumented with 84 high-QE, 8″ photomultipliers in order to be used as a Water Cherenkov detector and tag cosmogenic-induced background.
- The muon veto serves also as passive shield against external radioactivity.
- The muon veto has been commissioned in March 2016.
- Muon-induced background reduced to < 0.01 ev/y

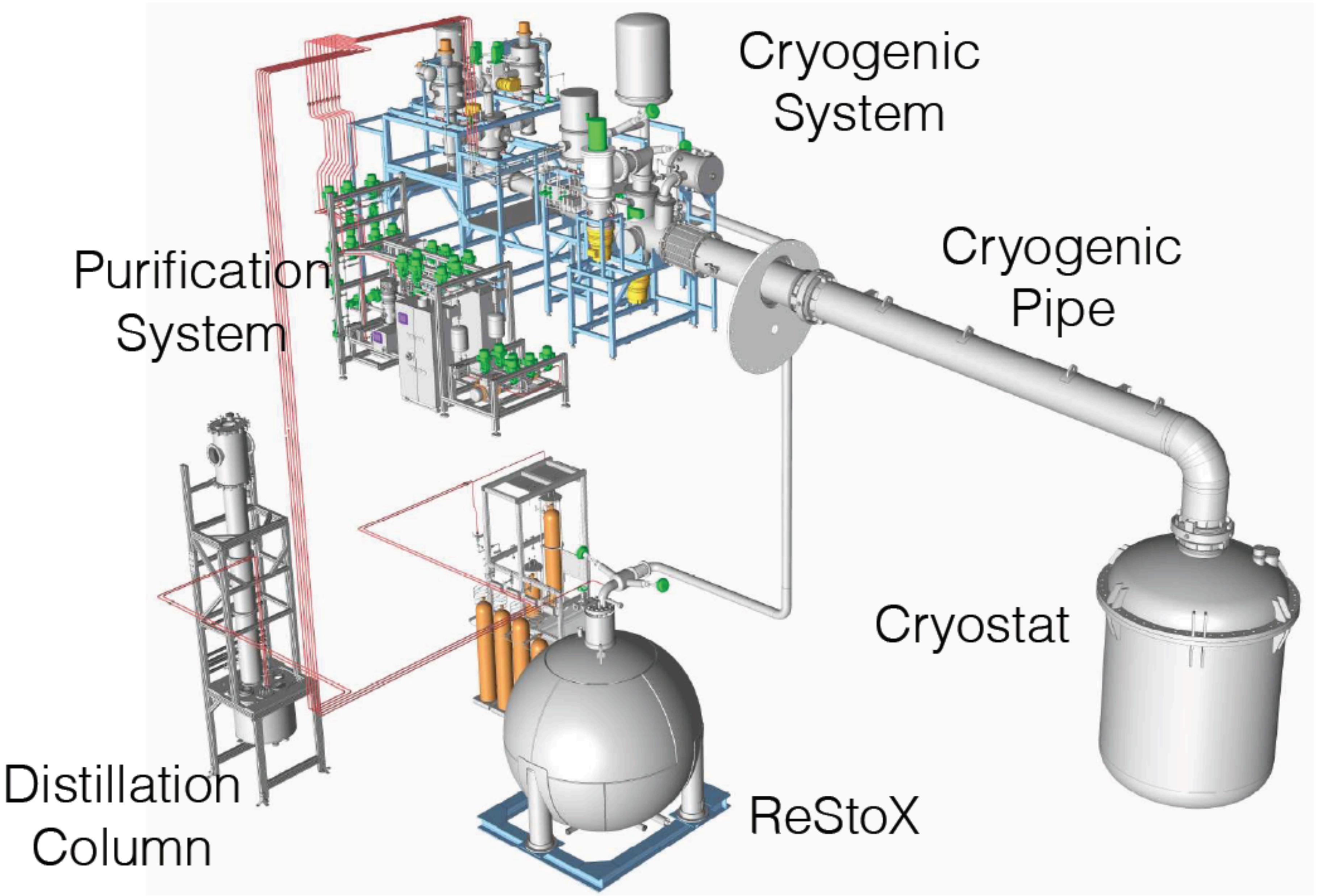


First detected muon

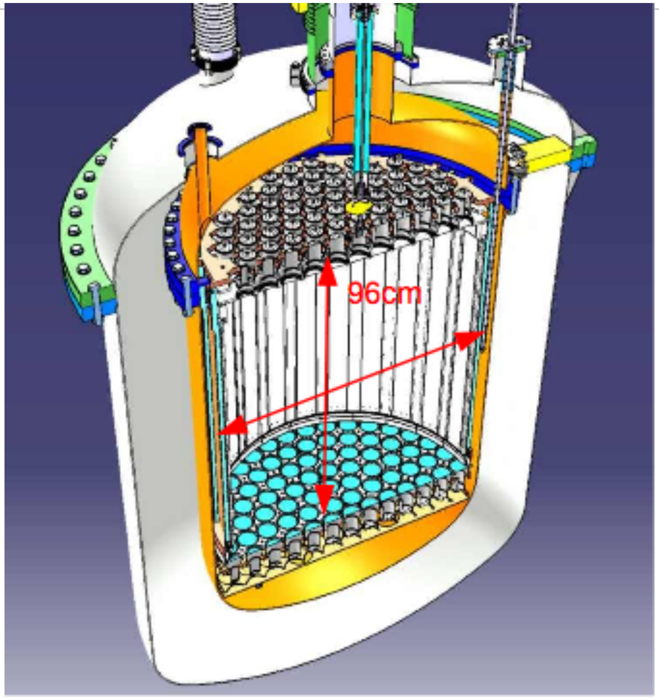




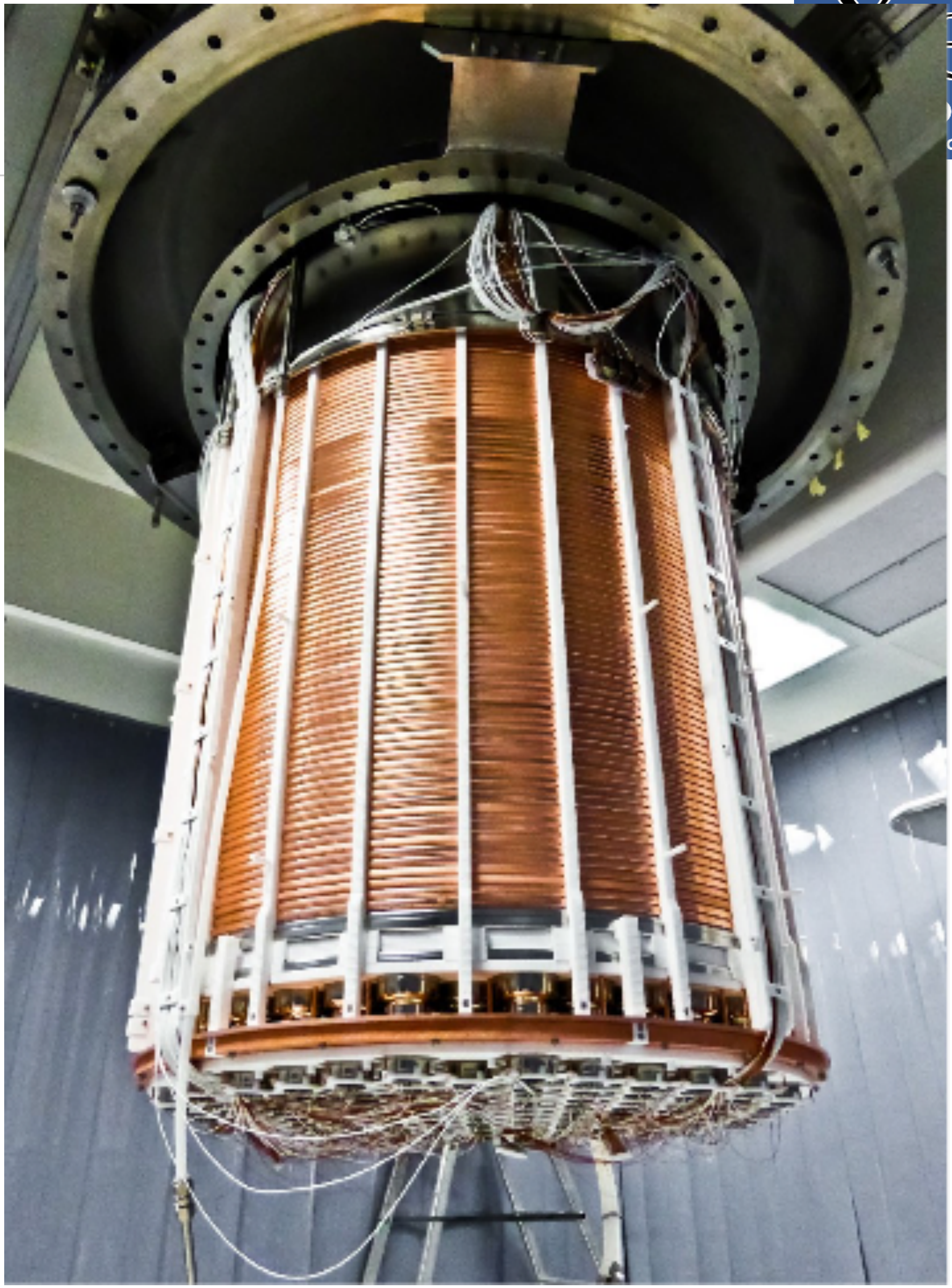
Cryogenic plants



XENON1T TPC



- The XENON1T Time Projection Chamber (TPC) is filled, since April 2016, with 3.2 tonnes of high-purity Xenon.
- 248 low-background 3"photomultipliers (Hamamatsu R11410-21) are reading out the 2-tonne active volume.

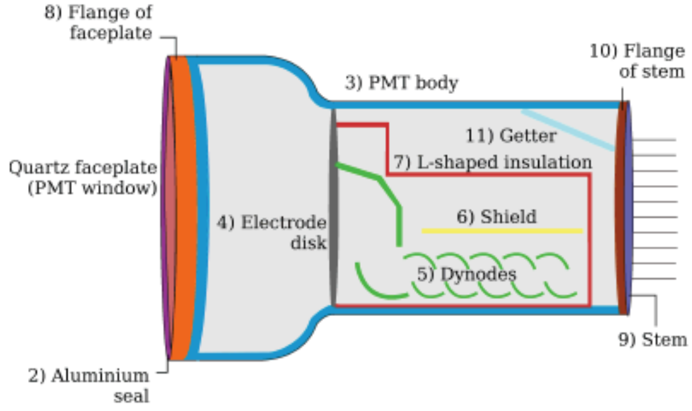


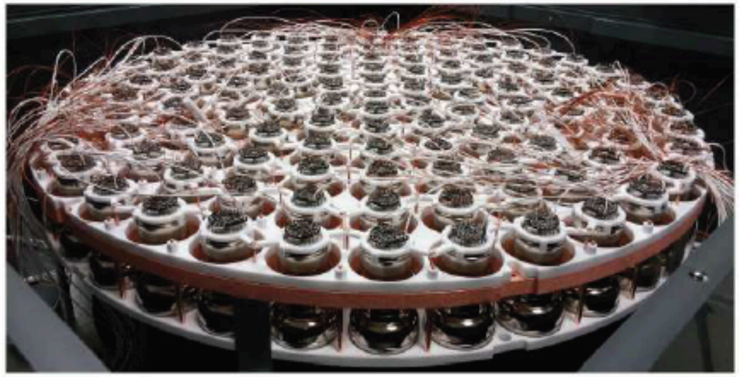
TPC assembly

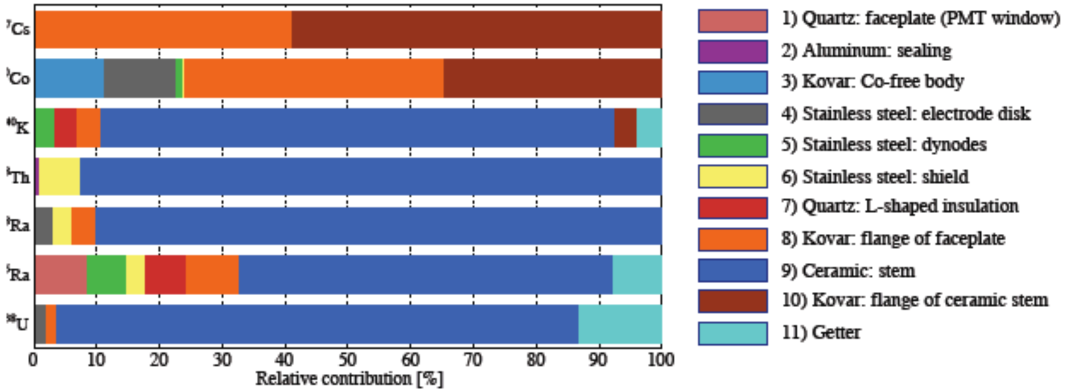
XENON Dark Matter Project

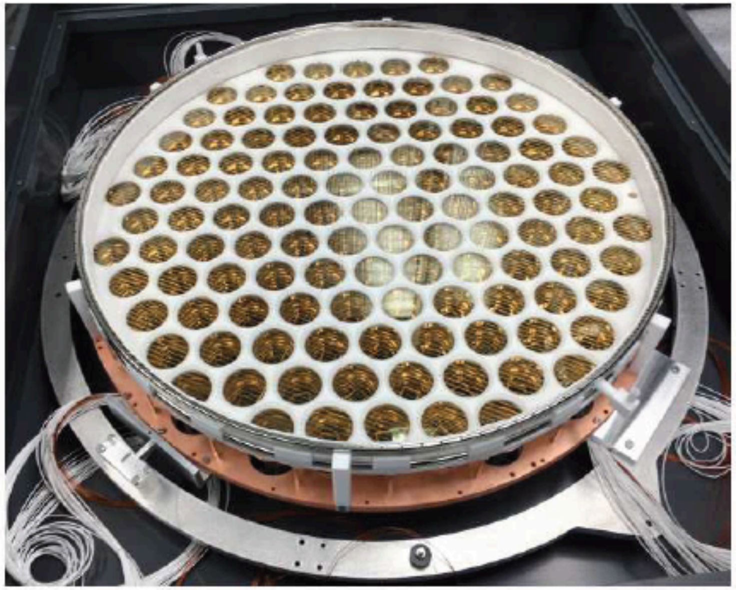
PMTs

- High QE (average 34%) , low-radioactivity, 3” PMT (R11410-21) developed for XENON1T, in close collaboration with Hamamatsu to select cleanest materials. Tested stability in LXe.
- Each PMT has been screened for radioactivity and tested at room T and low T





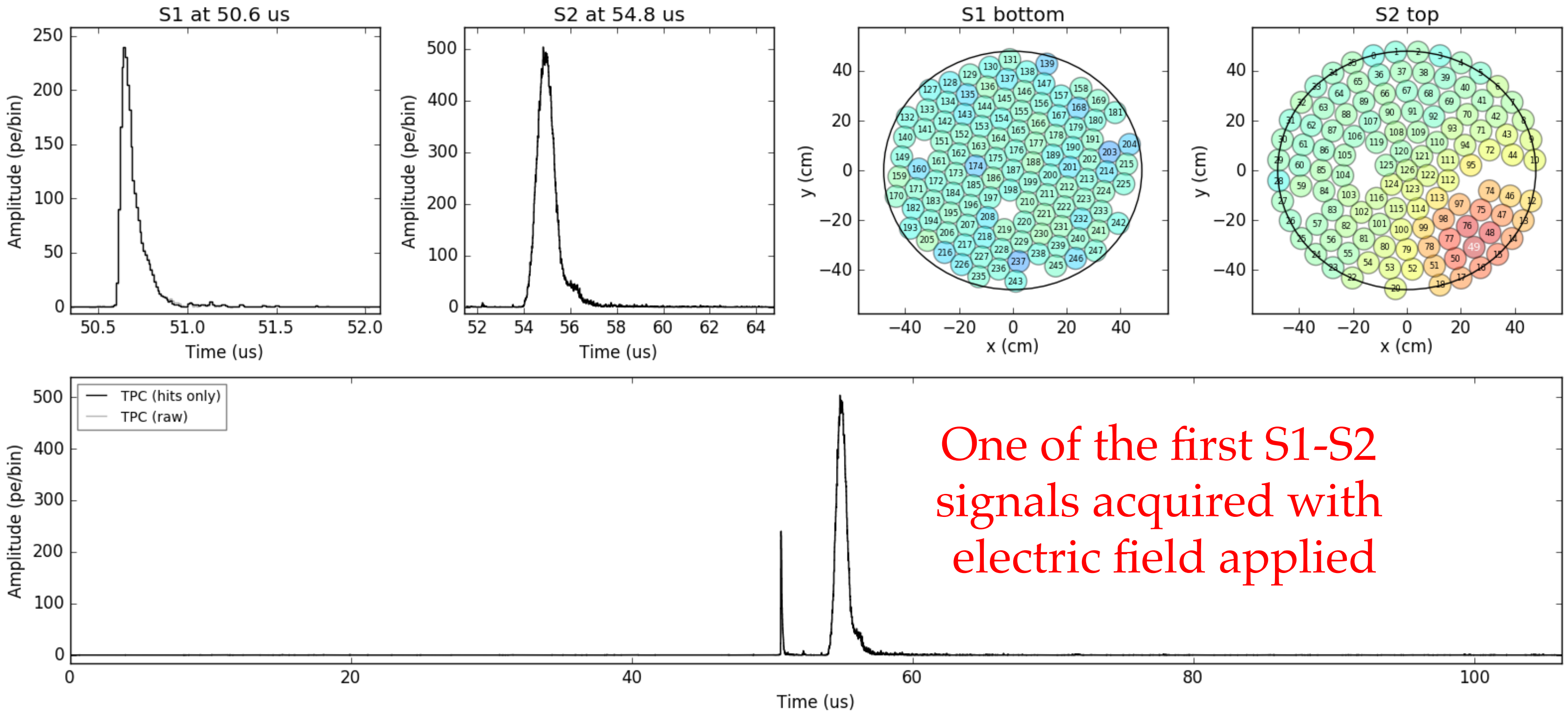




E. Aprile et al. (XENON), Eur. Phys. J. C75 (2015) 11, 546

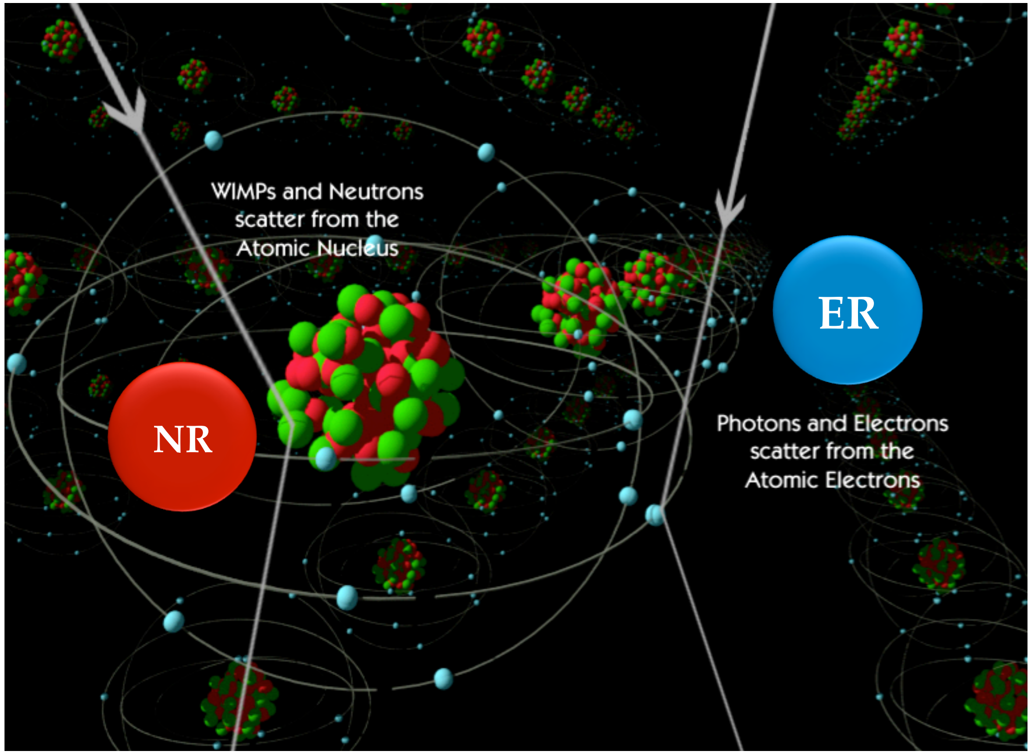
TPC commissioning

- The XENON1T Time Projection Chamber and associated cryogenic system are presently under commissioning.
- Detector is responding to radiation as expected, with both charge and light being detected. The total mass of 3.2 tonnes of LXe is being continuously purified to reach the desired charge yield at the applied field.



One of the first S1-S2 signals acquired with electric field applied

Main Backgrounds



Electron recoils (ER):

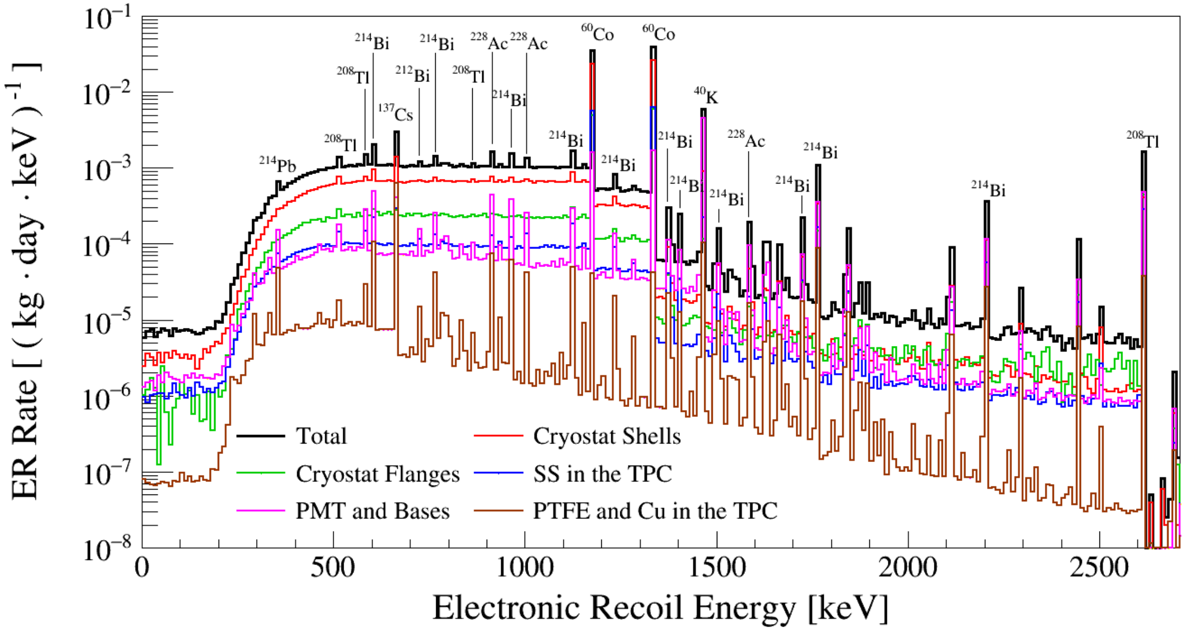
- low energy Compton scatters from the radioactive contaminants in the detector components: U and Th chains, ^{40}K, ^{60}Co, ^{137}Cs.
- Intrinsic contaminants: β decays of ^{222}Rn daughters, ^{85}Kr, ^{136}Xe.
- Elastic scattering of solar neutrinos off electrons.

Nuclear Recoils (NR):

- Radiogenic neutrons: spontaneous fission and (α, n) reaction from the U and Th chains in the detector components.
- Muon-induced neutrons.
- Coherent scattering of neutrinos (mostly solar) off the Xe nuclei.

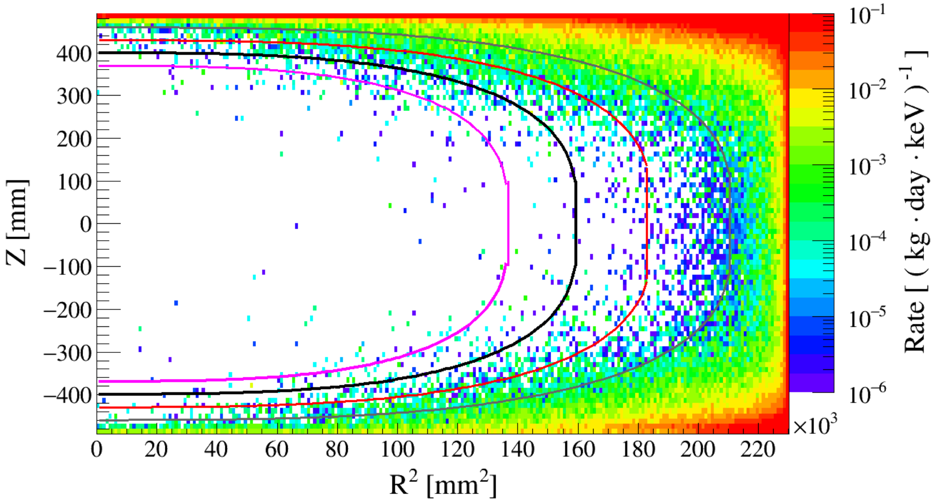
E. Aprile et al. (the XENON collaboration)
"Physics reach of the XENON1T dark matter experiment", arXiv:1512.07501, JCAP 04 (2016) 027

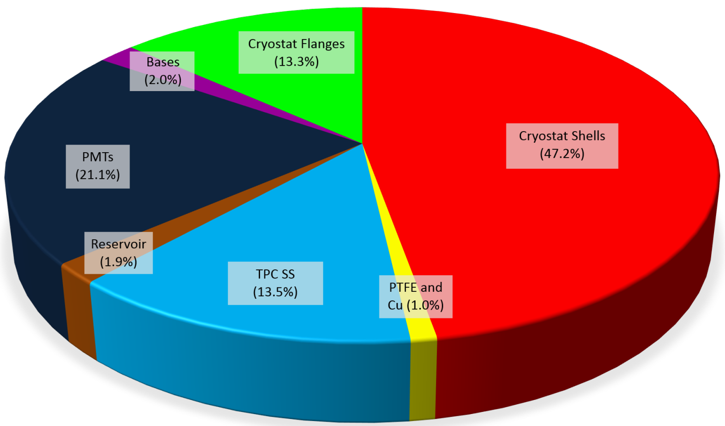
ER from the materials



Extensive screening campaign using gamma (Ge) and mass (ICP-MS) spectrometry.
Eur.Phys.J. C75 **(2015) 546**

ER background
from the materials
in 1 t Fiducial Volume,
in [1, 12] keV:
$7.3\ 10^{-6}$ $(\text{kg day keV})^{-1}$

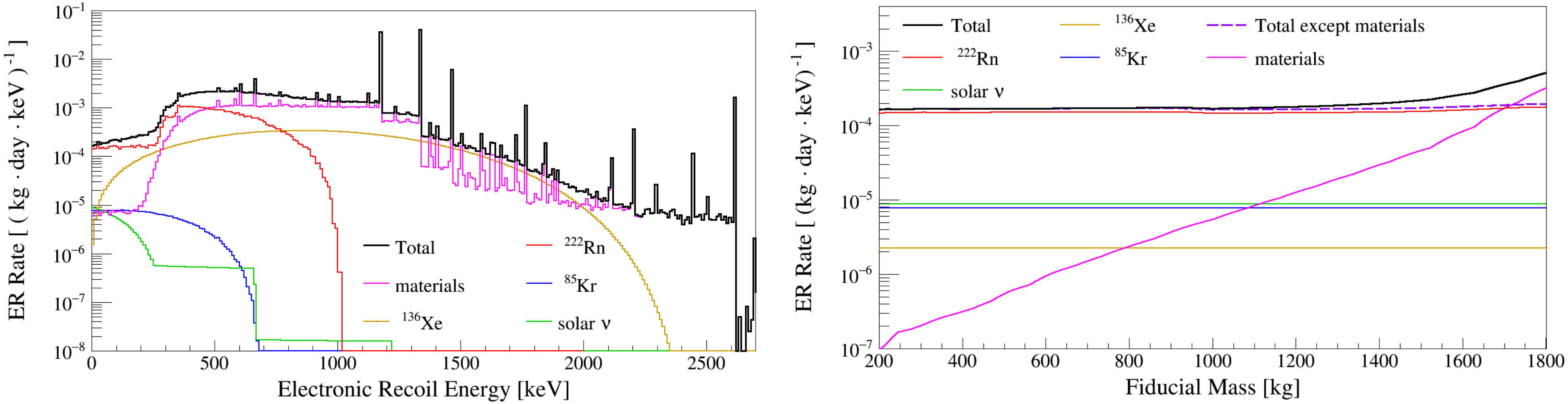




Total ER background

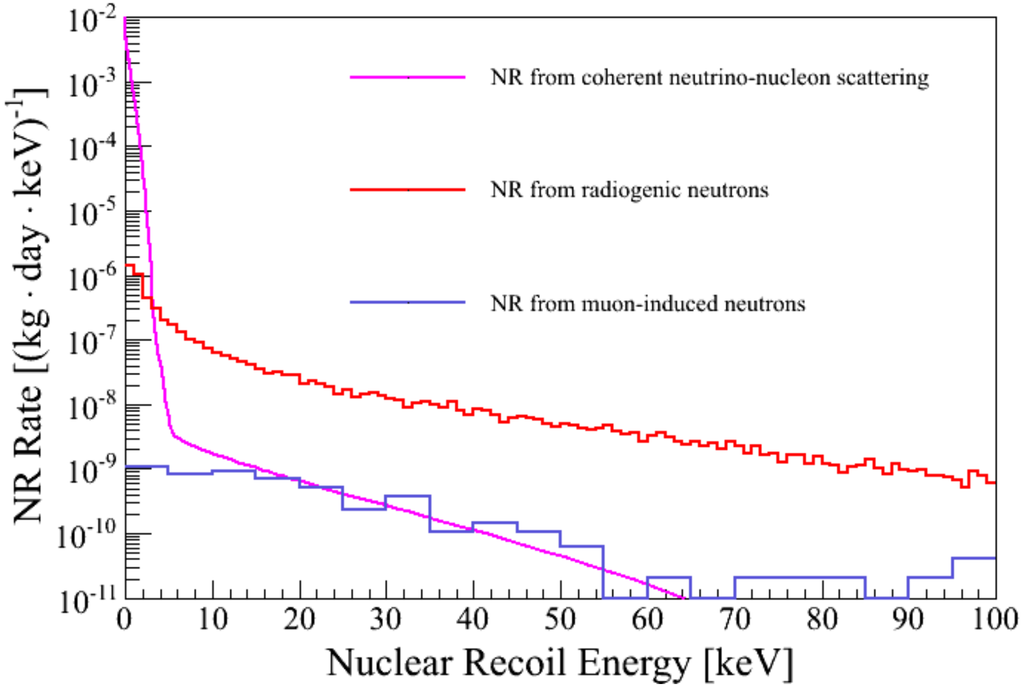
Assumptions on the intrinsic backgrounds:

- 0.2 ppt of ^{nat}Kr (already achieved in XENON1T distillation column tests),
- 10 μBq/kg of ^{222}Rn (conservative estimation based on Rn emanation measurements).



^{222}Rn (mainly from ^{214}Pb β-decay) is the most relevant source of ER background in most of the TPC.

Total NR background

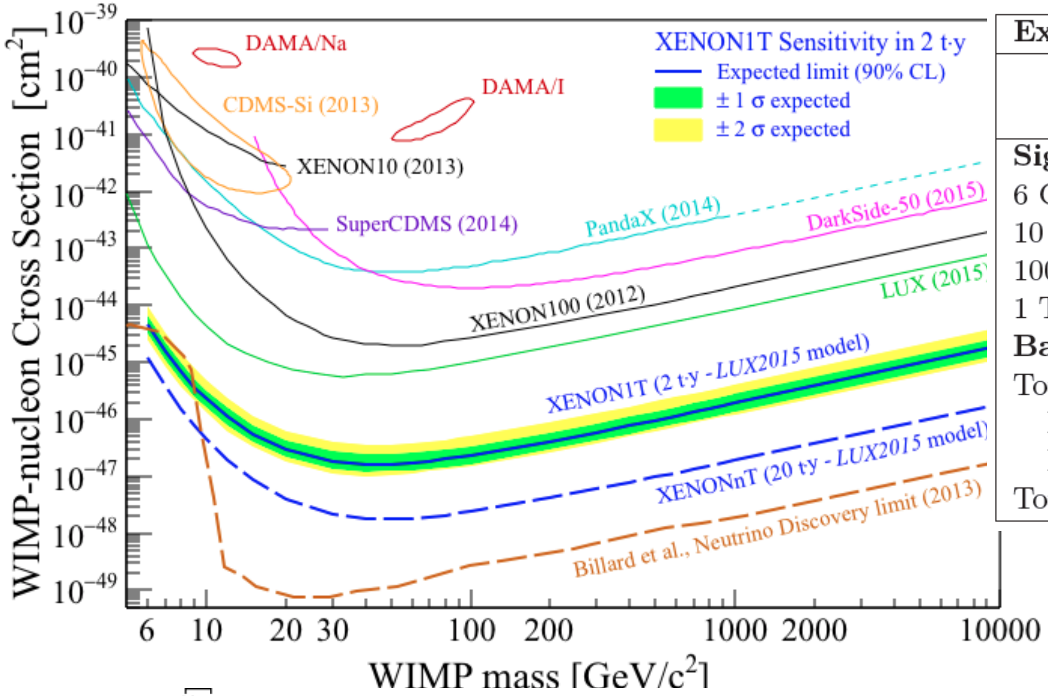


Single Scatter, 1 t Fiducial Volume,
[4, 50] keVr, 100% NR acceptance

Source	Background (ev/y)
Radiogenic neutrons	0.6 ± 20%
Muon-induced neutrons	< 0.01 (muon veto ON)
CNNS	0.02 ± 20%
Total NR	**0.62 ± 0.12**

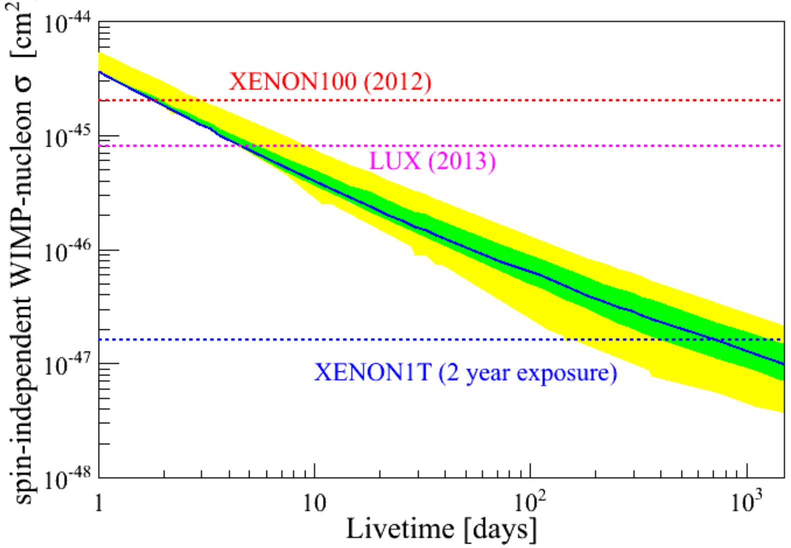
Given the very steep spectrum of NR from CNNS, its contribution will become more relevant after the conversion into the S1, S2 signals, considering the detector response and energy resolution.

XENON1T sensitivity



Expectation values of events in XENON1T, in 2 t·y exposure

	XENON100 model	*LUX2015* model
Signal (μ_s)		
6 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-45}$ cm^2)	0.68	2.72
10 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-46}$ cm^2)	4.65	5.96
100 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-47}$ cm^2)	7.13	7.13
1 TeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-46}$ cm^2)	8.85	8.85
Background		
Total ER (μ_{bER})	1300	1300
NR from neutrons	1.10	1.13
NR from CNNS	1.18	5.36
Total NR (μ_{bNR})	2.28	6.49



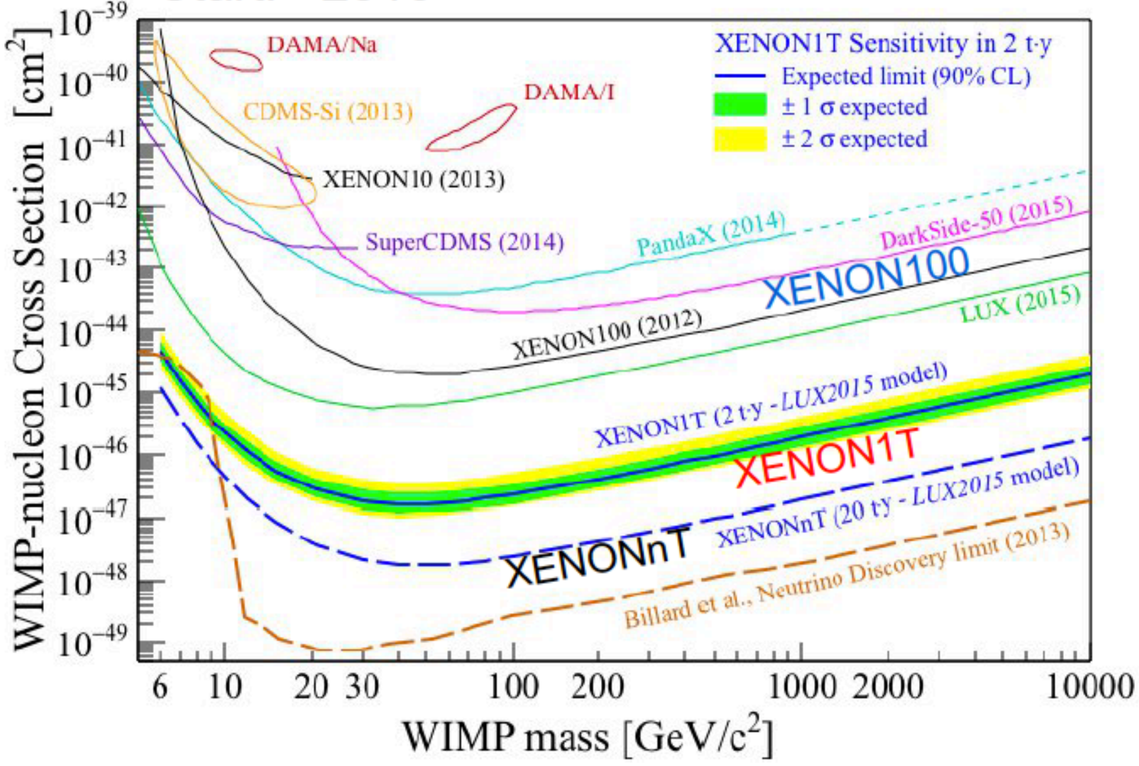
Potential to detect CNNS
from solar neutrinos.

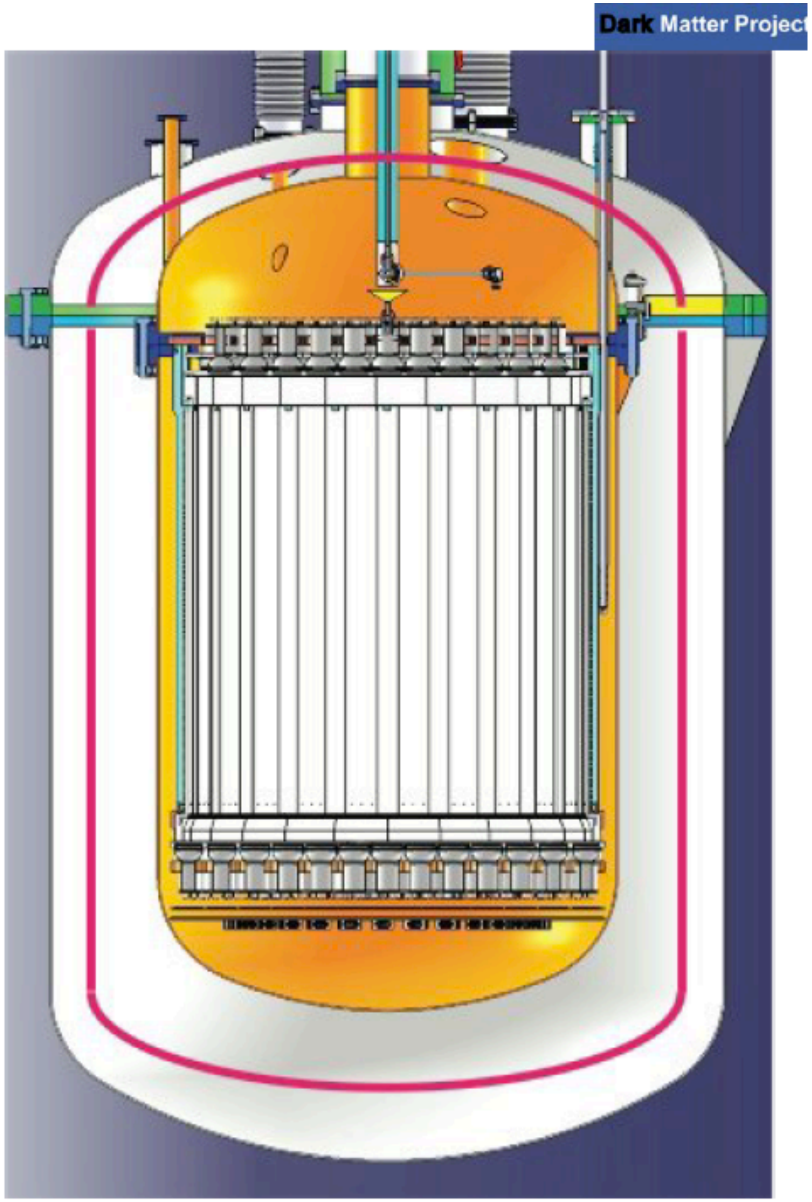
Significant improvement in sensitivity
to WIMPs
at low masses, below 10 GeV/c^2.

In less than 10 days we can reach the
sensitivity of the currently running
experiments

XENONnT

- XENONnT: larger TPC & larger inner vessel to fit inside XENON1T outer cryostat.
  Other systems will be largely reused.
- Aim: 20 ton-years exposure, reduced background to reach few 10^{-48} cm^2 sensitivity.
- Start: ~2018





Summary (XENON1T/nT)

- A new era in Dark Matter Direct Detection is about to begin with the deployment of the first multi-ton scale liquid Xenon detector, XENON1T. The experiment will start science data taking this Autumn.

- The technology of two-phase Xe TPC has already proven to yield the best sensitivity. The challenges we meet and the solutions we invent for XENON1T will inform future efforts with noble liquid targets worldwide.

- XENON1T/XENONnT will cover much of the high mass WIMP parameter space by ~2022. Coherent neutrino scattering will ultimately constraint the sensitivity but also provide the opportunity for a first discovery.

- XENON1T will take data at the same time as the LHC Run 2 and indirect searches. The complementarity of the three approaches is critical to either discover or rule out WIMPs as Dark Matter in the next few years.

Thank you !


Xe
XENON
Dark Matter Project
XENON1T
enlightening the Dark