Direct Dark Matter Search with XENON100 and XENON1t

Manfred Lindner

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

DESY

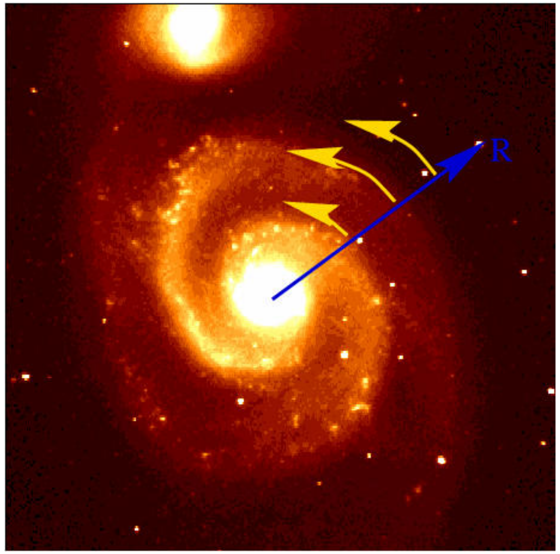
Astroteilchenphysik in Deutschland: Status und Perspektiven

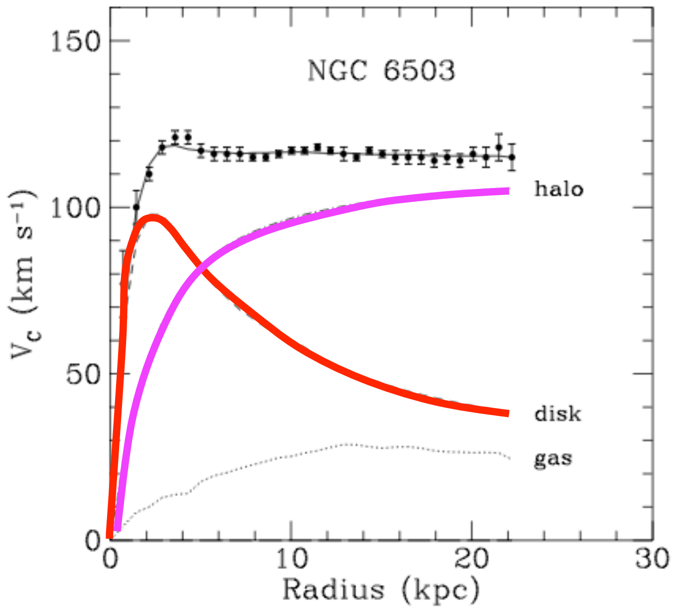
20-21 September 2012 *Zeuthen*

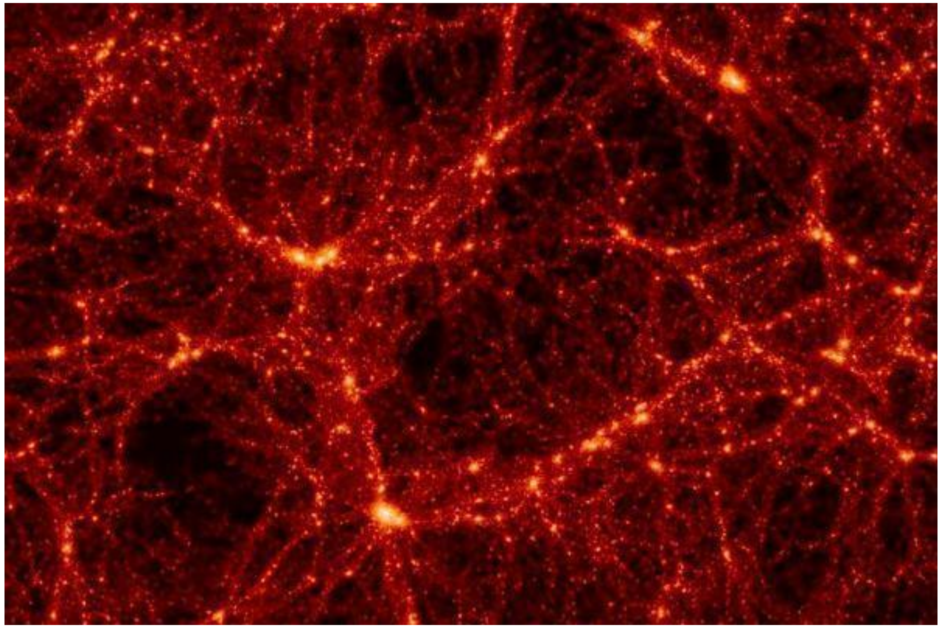
Dynamical Evidence for Dark Matter

F. Zwicky 1933
➔ proplem with galaxy clusters
➔ galaxies ➔

➔ galaxies have a large DM halo

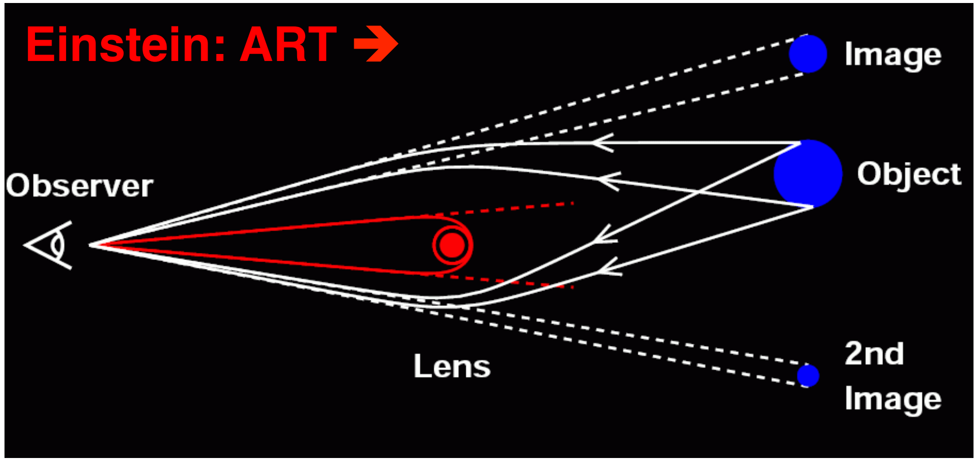




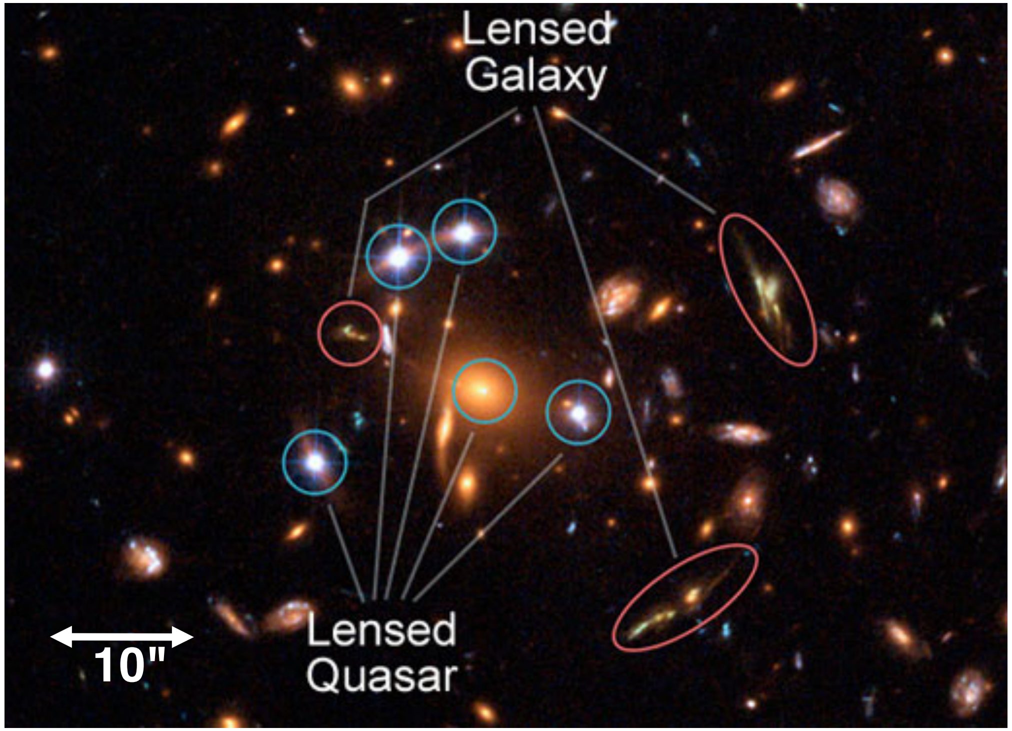


comparison of simulated and real structures
➔ cosmological DM dynamics

Static DM Distribution: Gravitational Lensing



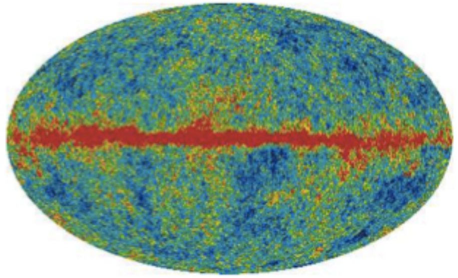
Galaxy cluster SDSS J1004+4112
HST AFT/WFC



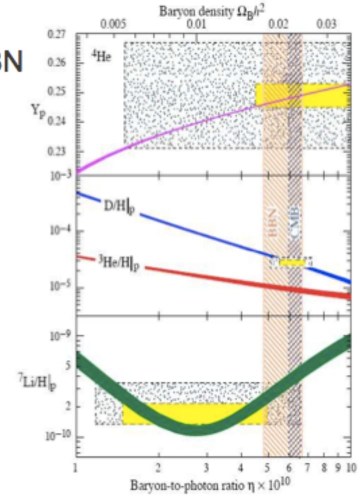
Consistent Evidences for Dark Matter

+ Galactic rotation curves
+ Galaxy clusters & GR lensing
+ Bullet Cluster
+ Velocity dispersions of galaxies
+ Cosmic microwave background
+ Sky Surveys and Baryon Acoustic Oscillations
+ Type Ia supernovae distance measurements
+ Big Bang Nucleosynthesis (BBN)
+ Lyman-alpha forest
+ Structure formation
+ …

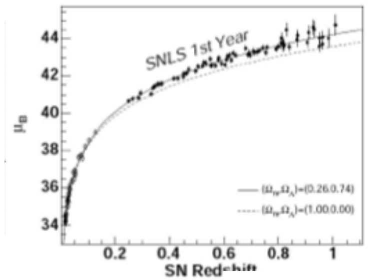
CMB (WMAP)



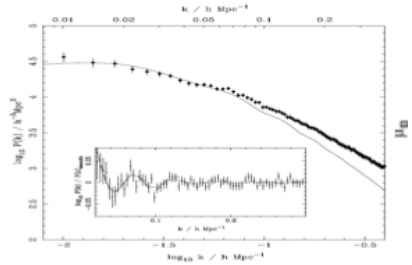
BBN



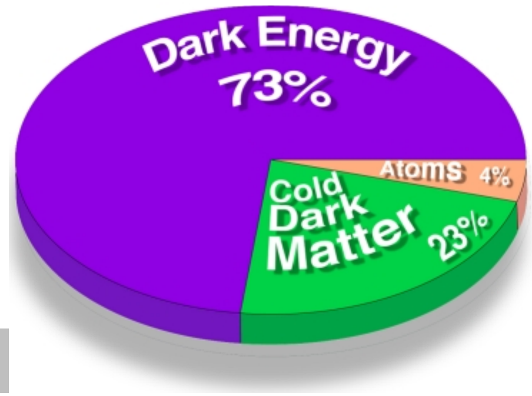
SN 1a



BAO

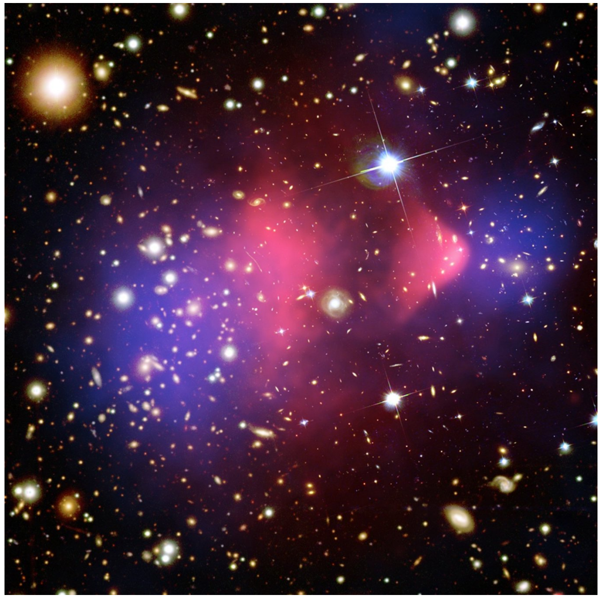


➔ **Coherent picture of the composition of the Universe: DE + DM + ordinary matter**



Is it Particles?

- **bullet cluster (1E 0657-56)**
  - colliding galaxy clusters
    = stars, gas, DM ; up to 10^6 km/h
  - x-rays from normal particle interactions
  - Dark Matter just traverses
  - displacement of visible (baryonic) and GR potential → ~ 8σ
    → large scale evidence: **DM = particles?**



- **modified gravity: MOND**
  → is just a very simple one scale modification of gravity
  → fails badly ←→ evidence for DM on many scales
  → does it imply that any conceivable modified GR fails? → NO!
  - other modifications of GR … ? ←→ conformal…

Particle Physics and Dark Matter

- **Standard Model of particle physics is most likely incomplete**
  → Beyond the Standard Model (BSM)
  → particles which are perfect DM candidates
- **Allowed interactions of new DM particles:**
  WIMP = Weakly Interacting Massive Particle
  GIMP = (only)Gravtiational Interacting Massive Particle

	WIMP	**GIMP**
electromagnetism	-	-
strong interactions	-	-
weak interactions	X	-
gravity	X	X

?

- **Candidates must be stable or long-lived ($\geq$ age of Universe)**

The WIMP Miracle

- **WIMPs have masses O(100 GeV)**
- **miracle: ~ correct abundance:**

1) Assume a new (heavy) particle χ is initially in thermal equilibrium:

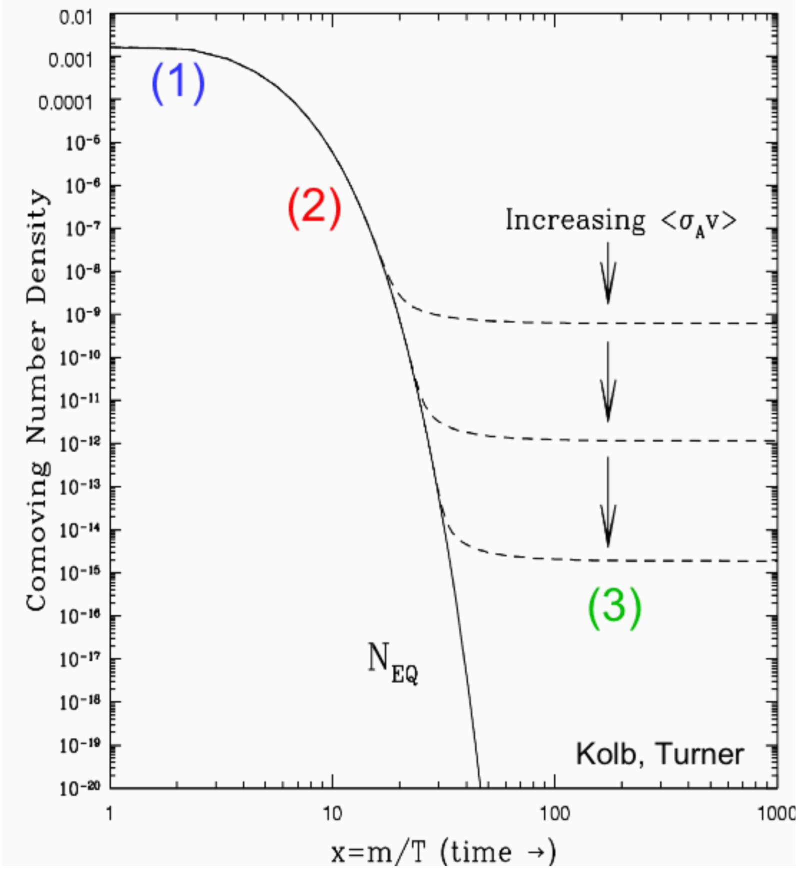
$$\chi\chi \leftrightarrow f\,f$$

2) Universe cools:

$$\chi\chi \;\substack{\rightarrow \\ \not\leftarrow}\; f\,f$$

3) "freeze out"

$$\chi\chi \;\substack{\not\rightarrow \\ \not\leftarrow}\; f\,f$$



- **Amount of DM ~ (x-section)$^{-1}$**
- **Natural x-section ~ 1/m^2**
  → abundance fixed by EW scale

➔ remarkable coincidence: Ω_{DM} ~ 0.2 for m_{WIMP} ~ 100-1000 GeV

➔ BSM AND correct abundance point towards WIMPs

The nature of Dark Matter

Gravity

MOND
one scale modification fails badly

OTHER
modifications ???

Particles

BSM motivated:
- axions →
- sterile ν's
- …

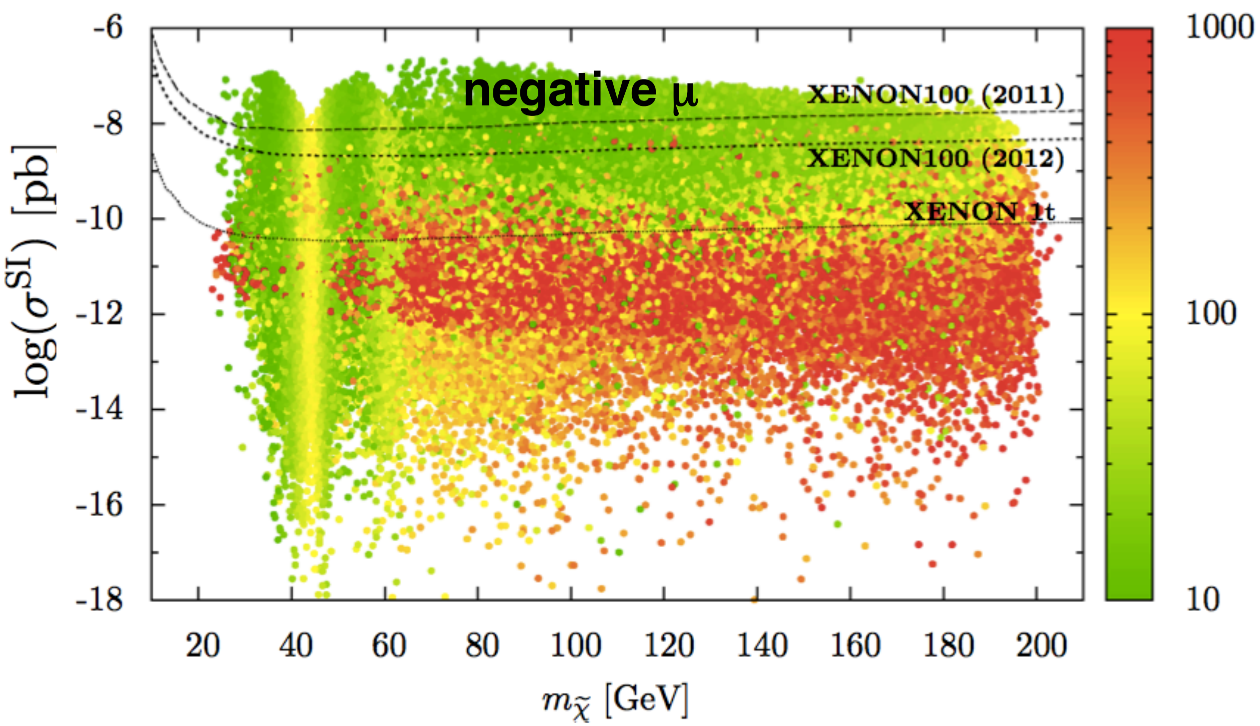
Miracle = correct abundance:
- asym. DM
- …

WIMPs combine both positive aspects →

Favoured Dark Matter: WIMPs

- Candidates in BSM models ⇔ hierarchy problem
- WIMP miracle ➔ correct abundance
- **MSSM neutralino: Level of fine-tuning ➔ Δ_{tot}**

$$\Delta p_i \equiv \left| \frac{p_i}{M_Z^2} \frac{\partial M_Z^2(p_i)}{\partial p_i} \right| = \left| \frac{\partial \ln M_Z^2(p_i)}{\partial \ln p_i} \right| \qquad \Delta_{\rm tot} \equiv \sqrt{\sum\nolimits_{p_i=\mu^2,b,m_{H_u}^2,m_{H_d}^2} \{\Delta p_i\}^2}$$



→ XENON100-2010
→ XENON100-2012
→ XENON1T

natural x-section ~1/M²
* XENON100 cuts already into expected space

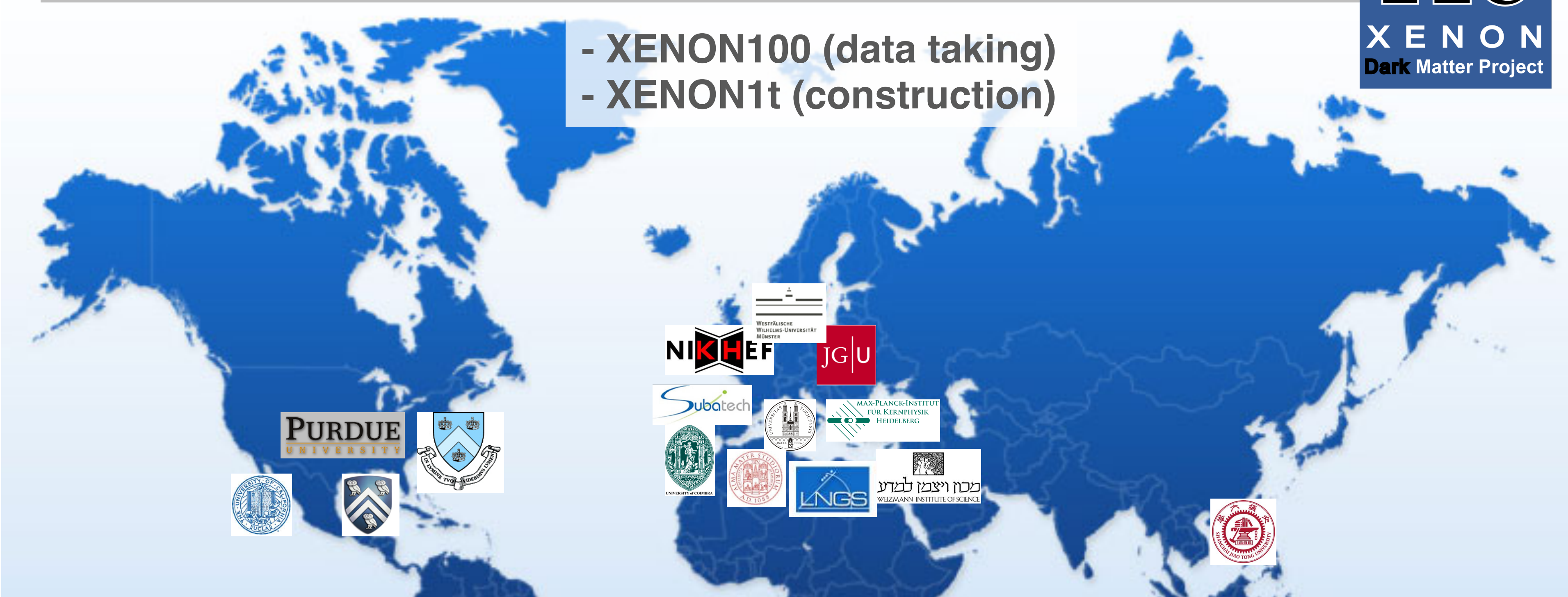
* XENON1t covers most
➔ high potential
➔ be first

Direct Dark Matter Search with XENON100

The XENON Collaboration

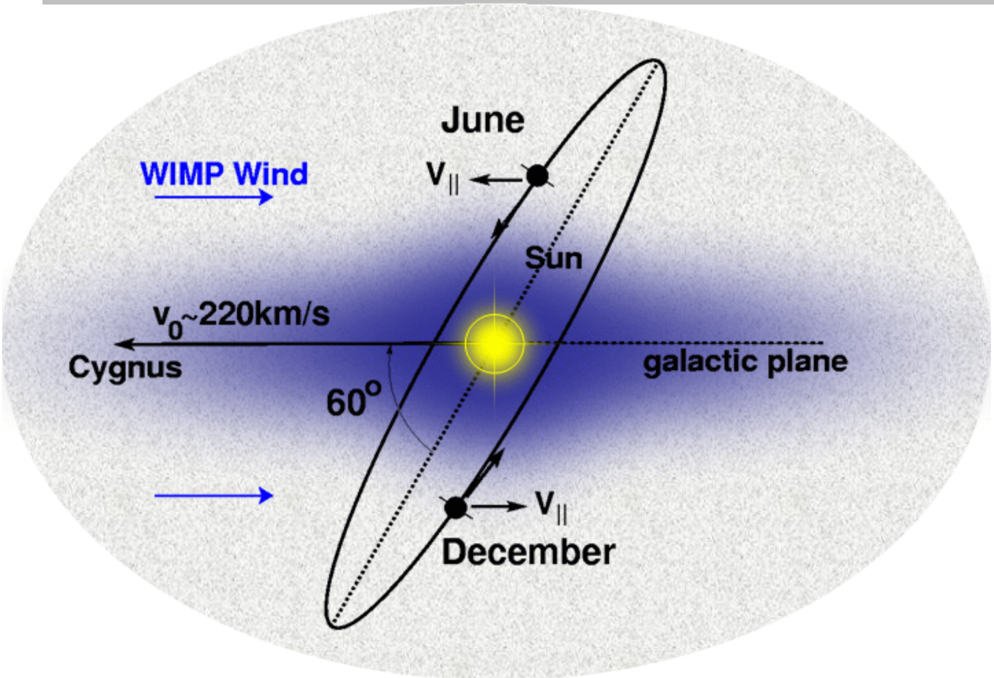
Xe
XENON
Dark Matter Project

- XENON100 (data taking)
- XENON1t (construction)



University of California Los Angeles	J. Gutenberg-Universität Mainz
Rice University Houston	Max-Planck-Institut f. Kernphysik, HD
Purdue University	Universität Zürich
Columbia University New York	Laboratori Nazionali del Gran Sasso
Universidade de Coimbra	INFN e Università di Bologna
Subatech Nantes	Weizman Institute Rehovot
NIKHEF Amsterdam	Jiao Tong University Shanghai (Xe100)
Willhelms Universität Münster	**~ 90 scientists from 15 institutions**

XENON100: Source and Detector



- sun ~ 8.5 kpc from galactic centre
- moves towards Cygnus

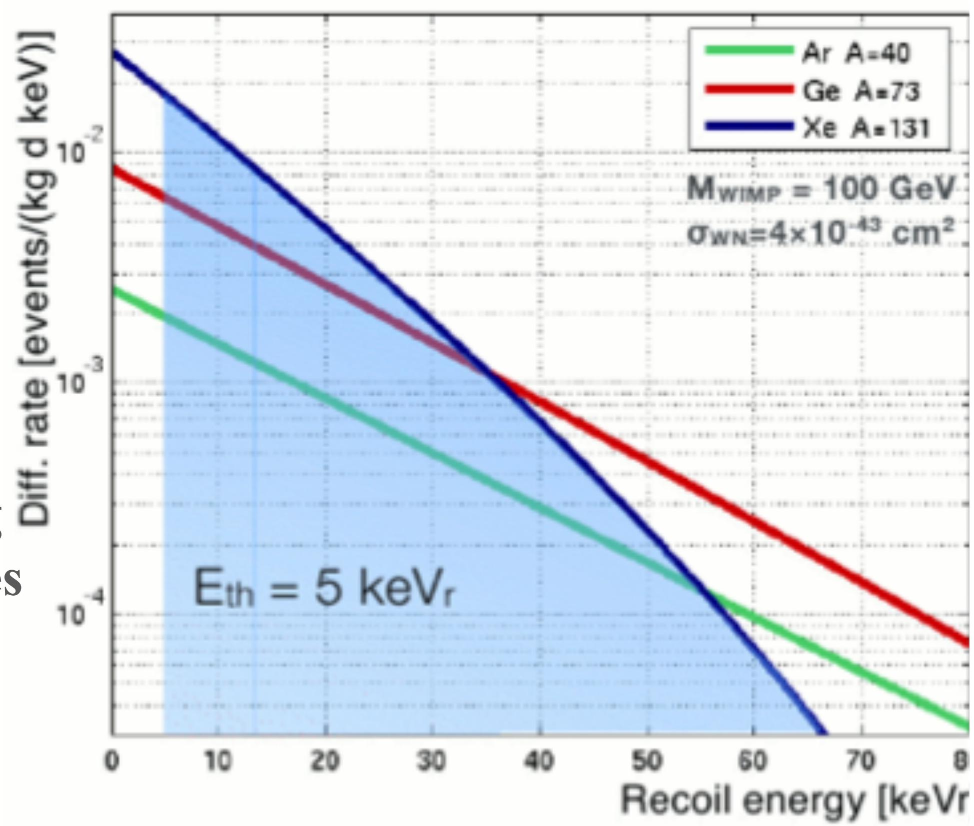
➔ "WIMP wind" <v> ~ 220 km/s
  - flux
  - dispersion
  - annual modulation

- LXe target
- avoid backgrounds:
  → rock, Cu,Pb,PE,H_2O,…
  → veto, fiducialization, …
  → radiopure materials

The Case for Liquid Xenon

Liquid noble gases (Ar, Xe) are excellent DM target materials

- good scintillation and drift properties



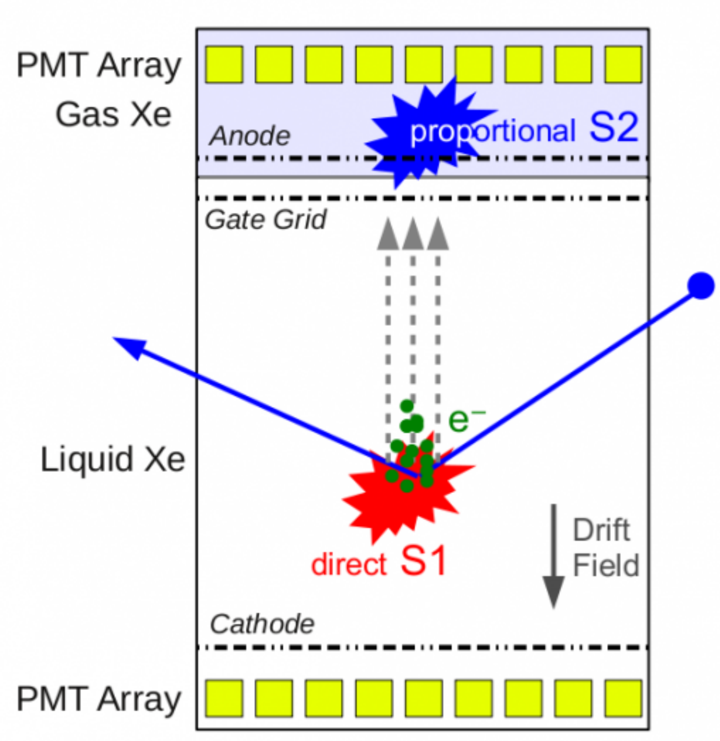
Xenon:

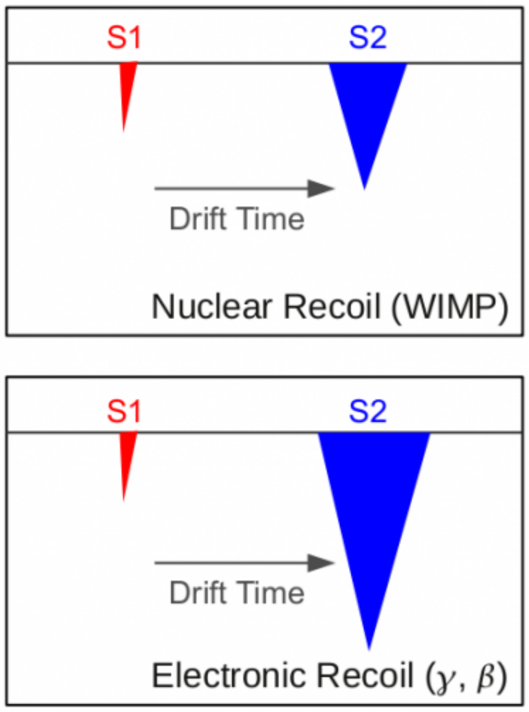
- efficient fast scintillator @ 178nm
- “easy” cryogenics @ -100 ^{o}C
- no long lived Xe isotopes
- ^{85}Kr can be removed to ppt level
- high A=131 ←→ optimal for scattering O(100 GeV) particles; 50% odd isotopes
- high Z=54 → high density → good self-shielding → compact

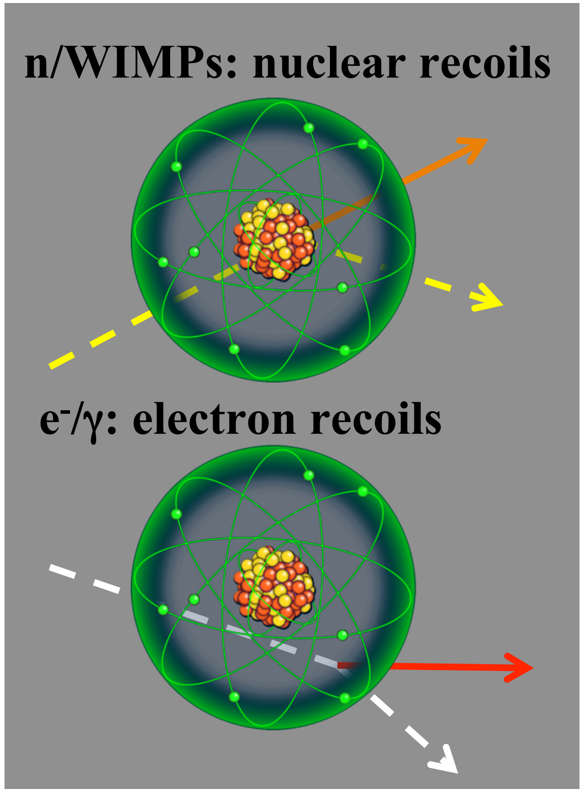
Cost: Xe >> Ar (Xe is rarest stable isotope on Earth ←→ depleting ^{39}Ar)

→ Xe: low threshold E_{th} = few keV → Xe is ~ x5 better per mass

XENON100: A dual Phase TPC

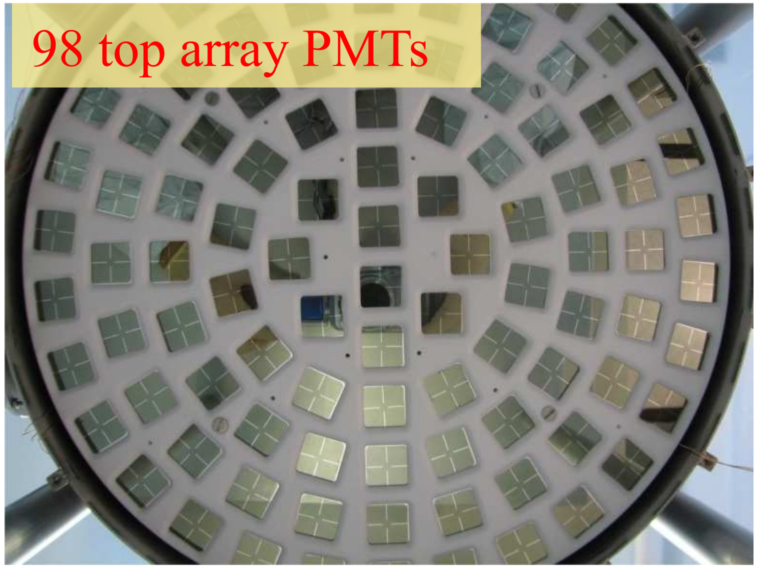






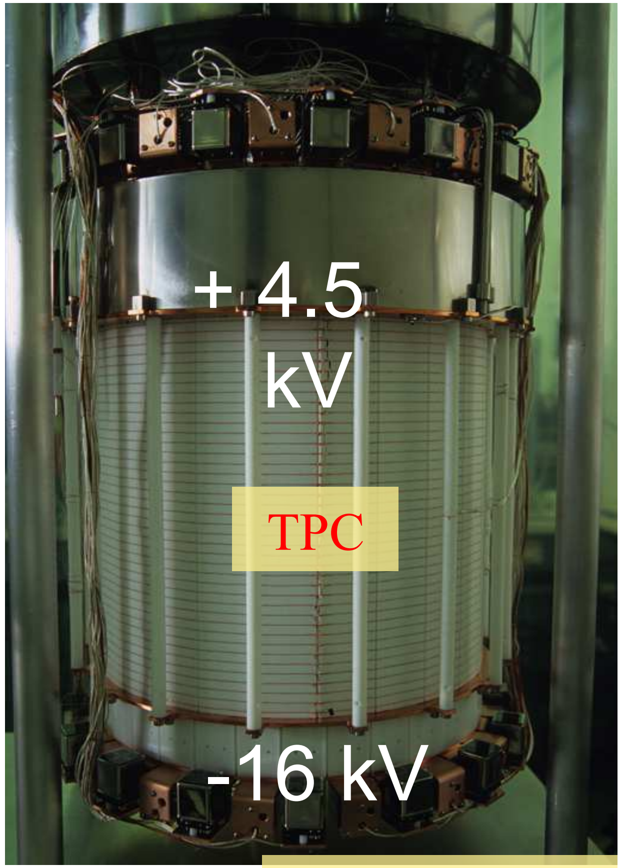
- Discrimination of e^-/γ and nuclear recoils: **$(S2/S1)_{n,WIMP} \ll (S2/S1)_{e,\gamma}$**
- 3D position sensitivity: drift time → z; PMT pattern → x,y
  - ➔ **precise fiducial inner volume** (avoid outer volume)
- Discrimination of single/multiple scattering
  - ➔ **background reduction**

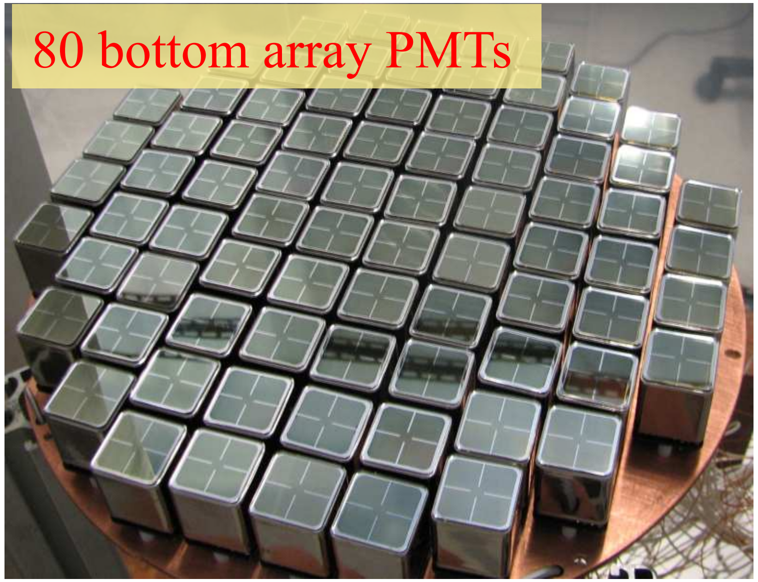
242 low activity PMTs 1x1" (Hamamatsu R8520, QE>32% @175nm



gamma event localized

Top PMT array





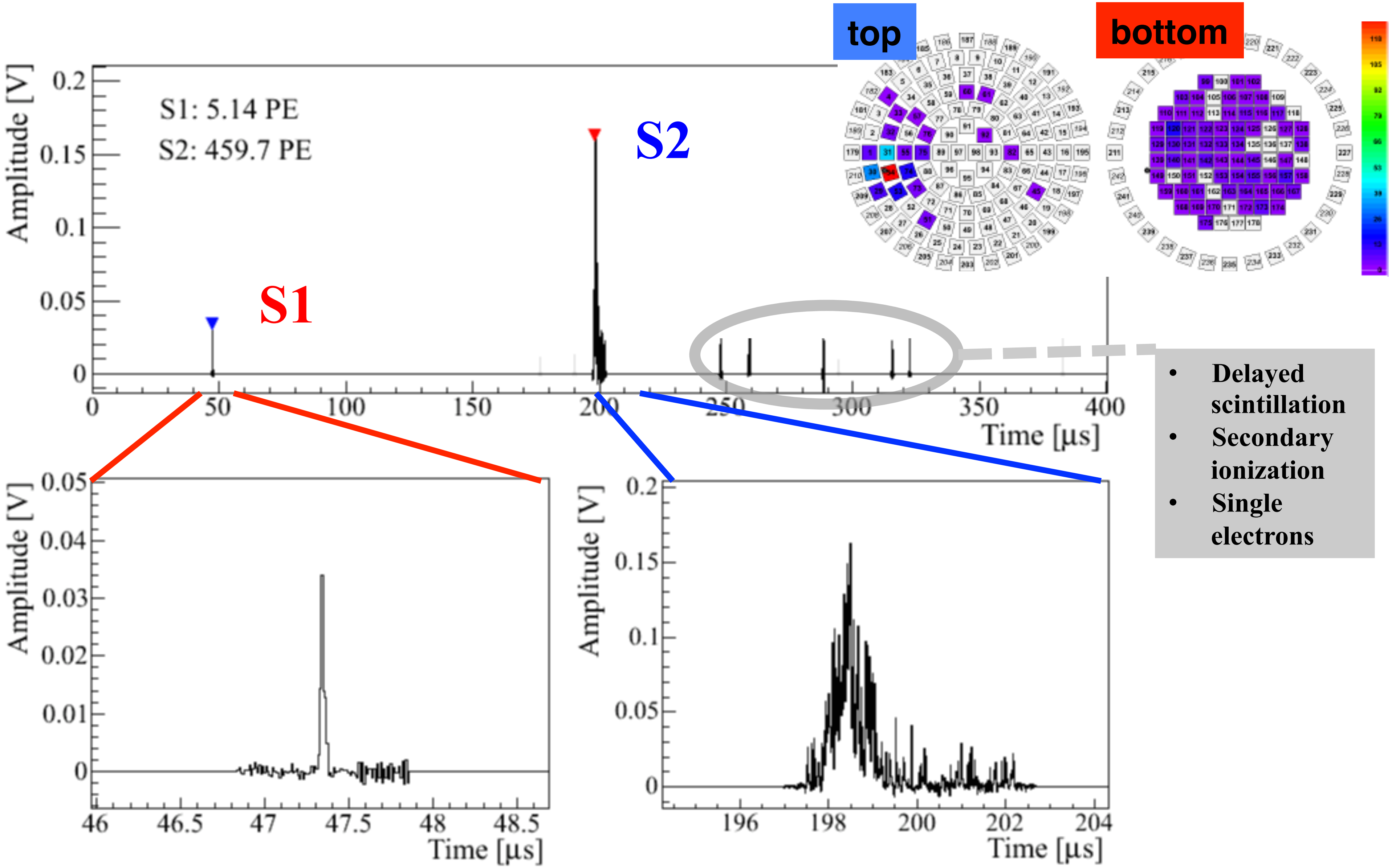
radio-purity
→ material screening

^{85}Kr → dedicated distillation column

^{222}Rn emanation
→ avoid/monitor

+passive shield: water, lead, PE, copper

The TPC at Work



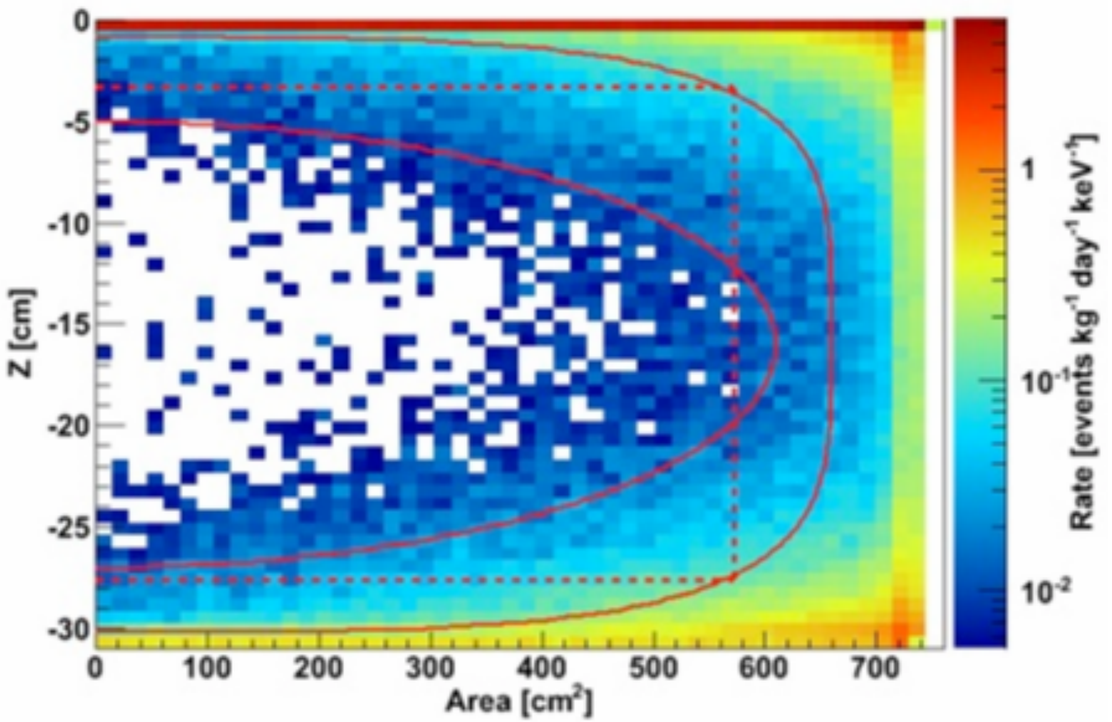
- Delayed scintillation
- Secondary ionization
- Single electrons

Fiducialization and BG Reduction

Precise spacial information:

- **S2 hit pattern: Δr < 3 mm**
- **Drift time: Δz < 2 mm**

→ avoid 'dirty' surface by selecting a fiducial volume



Optimization of fiducial volume with Monte Carlo:

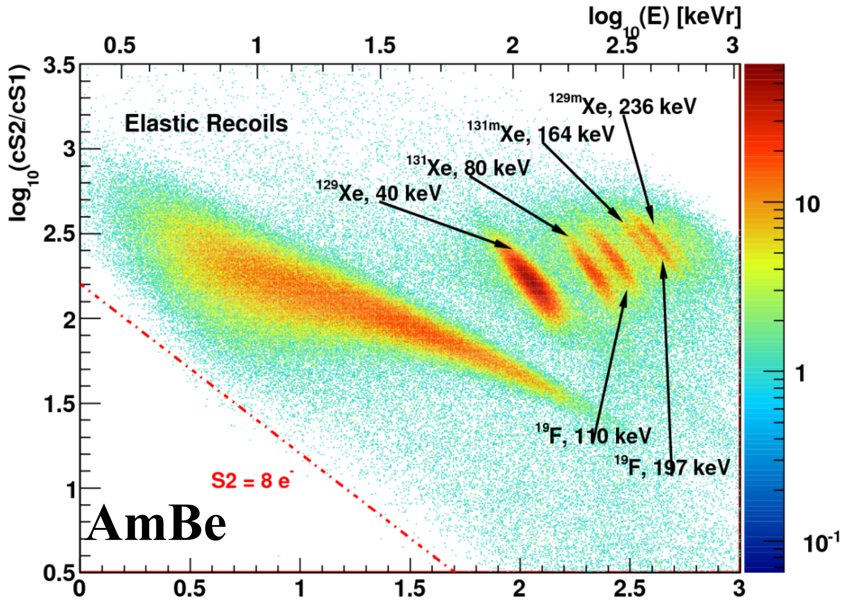
- high background rejection efficiency

- large target mass

Calibration and n/γ Discrimination

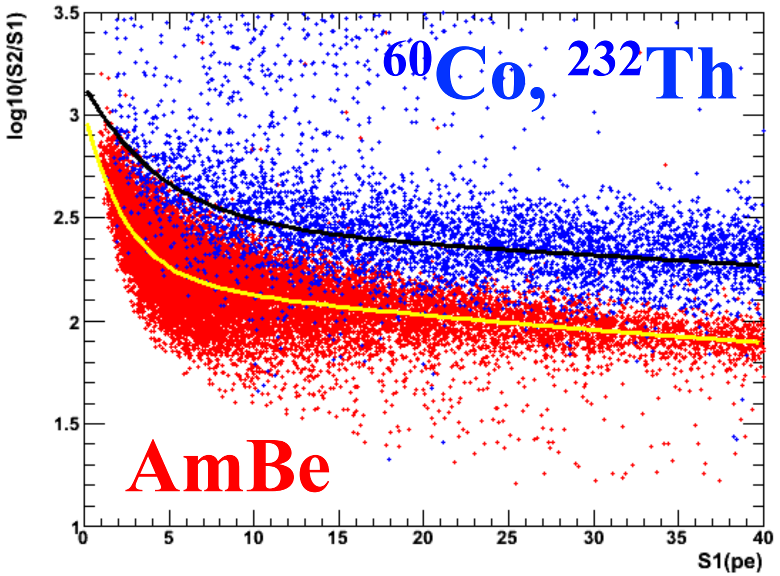
Periodically: LEDs and sources
➔ **Position dep. corrections**
Cs-137, AmBe inelastic (40 keV),
Xe* (164 keV) Kr-83m (planned)

➔ agreement better than few %

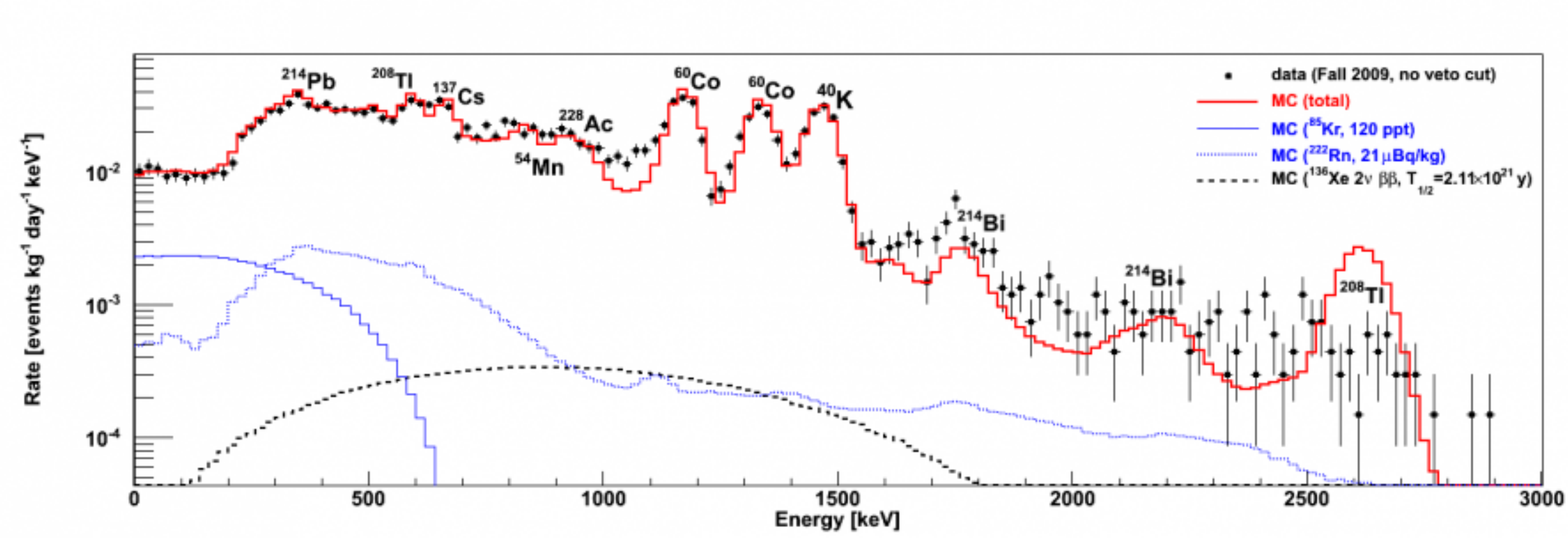


- **Electron Lifetime:** Cs-137
- **Electron Recoil Band** (backgrd.):
  Co-60, Cs-137, Th-228
- **Nuclear Recoil Band** (signal):
  neutrons: AmBe

➔ **nuclear / electronic recoil** ➔
➔ definition of WIMP search region
➔ Discrimination power: 99.5% at low energies for 50% acceptance



Background



- MC simulations and background in good agreement
- Background very well understood in full energy range

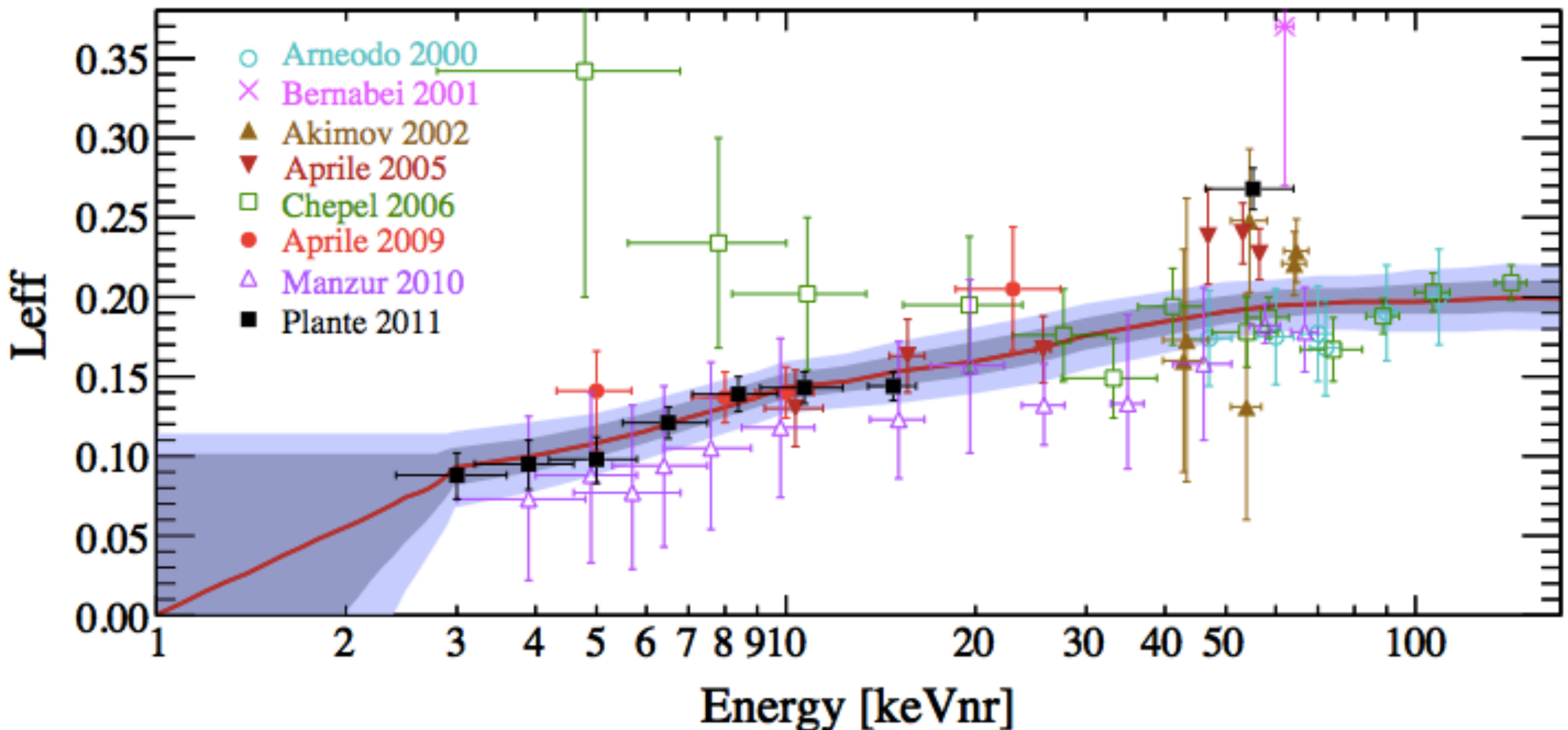
Nuclear Recoil equivalent Energy

S1 ←→ nuclear recoil energy: $E_{NR} = S_1/L_y/L_{eff} \times S_e / S_r$

S_1: in p.e.

L_y : LY for 122 keV γ in p.e./keV

S_e/S_r: quenching for 122 keV γ/NR due to drift field



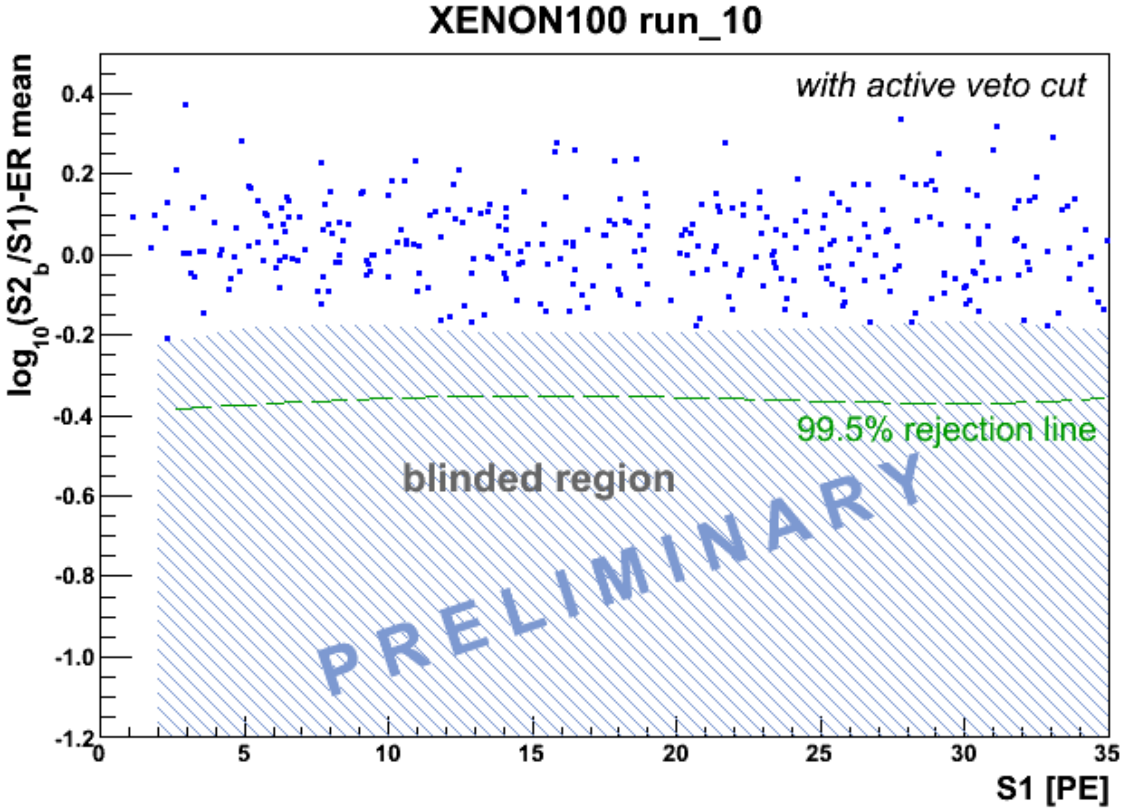
Blind WIMP Analysis

Data below the 10% quantile of the e-recoil band blinded
➔ cuts defined by background events outside WIM region

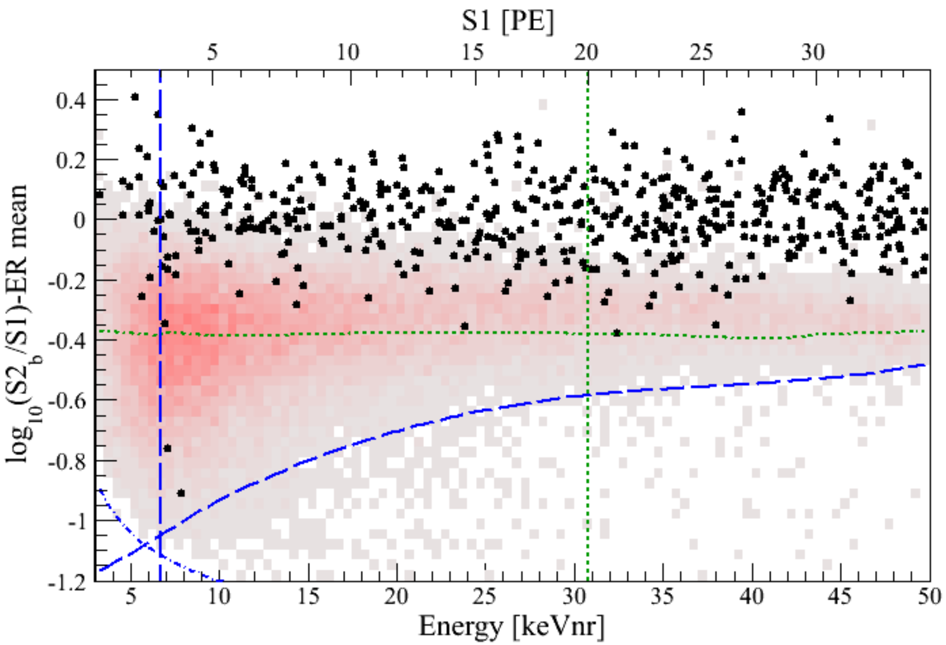
Selection cuts:

Data quality
- only stable detector periods
- …

Energy cuts
Single event selection
Consistency
NR/ER discrimination
Fiducialization:
- events must be in in FV

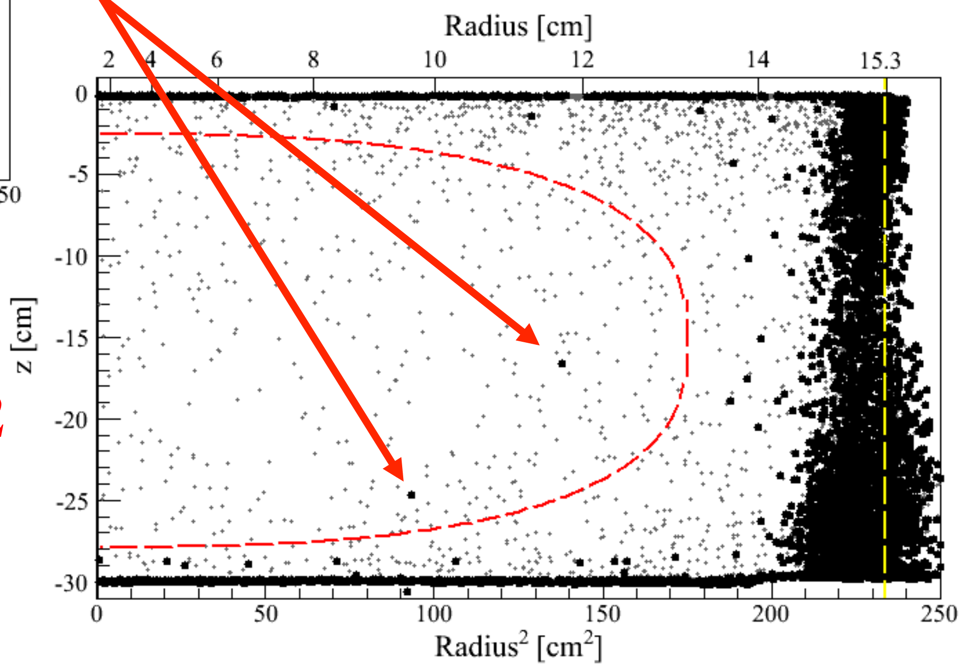


Unblinding



The two events are in good data quality by visual inspection

Position of the two events in the fiducial region with an expected background of 1.0 ± 0.2

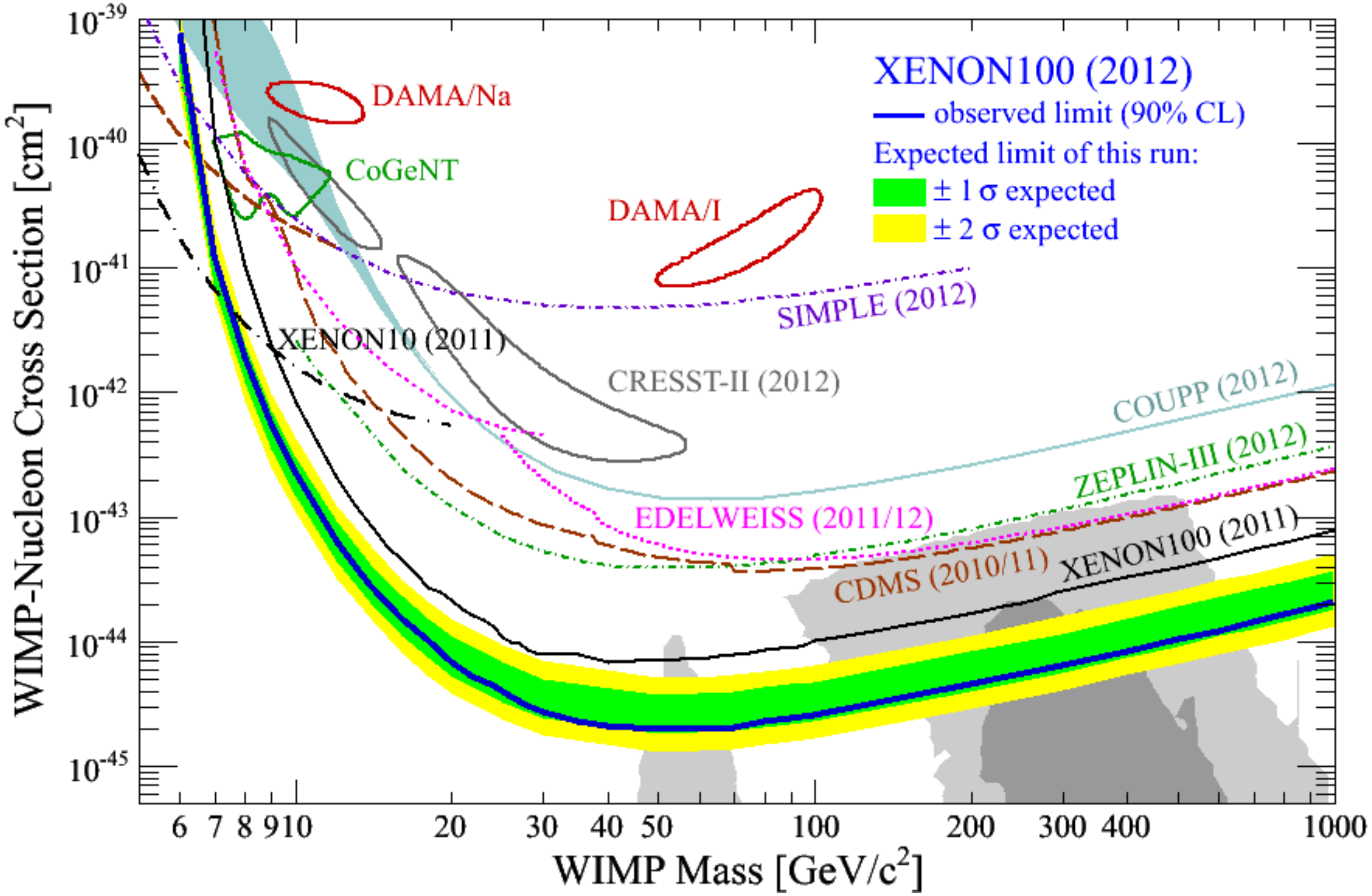


Results:

- **2 events in fiducial volume**
- **Expected background 1.0 + 0.2**
- **probability for a fluctuation from 1 to 2 events: 26.4%**
- **No significant excess seen**

➔ **improved WIMP limits**

The 2012 Result of XENON100



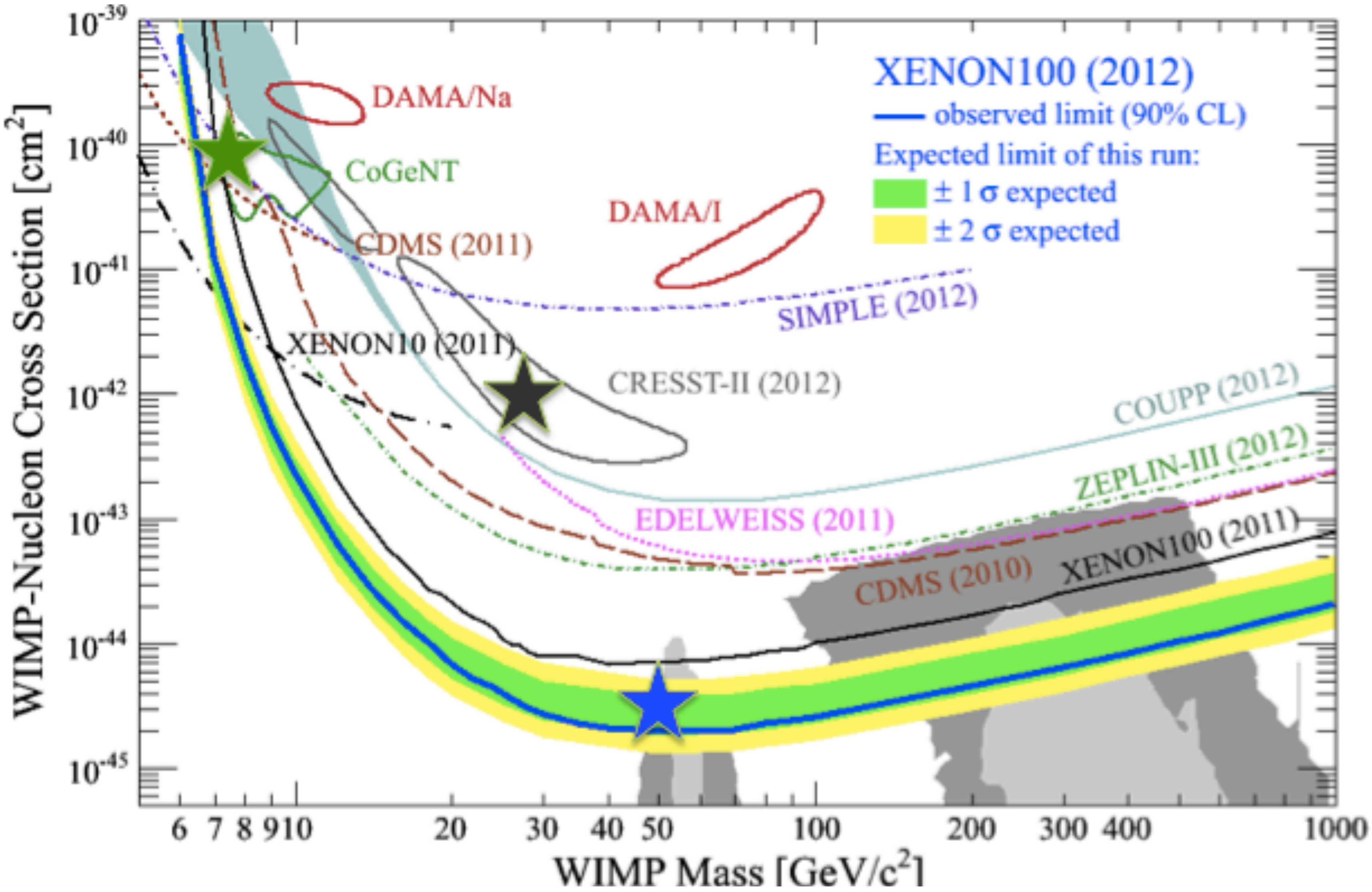
➔ **profile likelihood:**
arXiv:1103:0303

➔ **new L_{eff}:**
arXiv:1104.2587

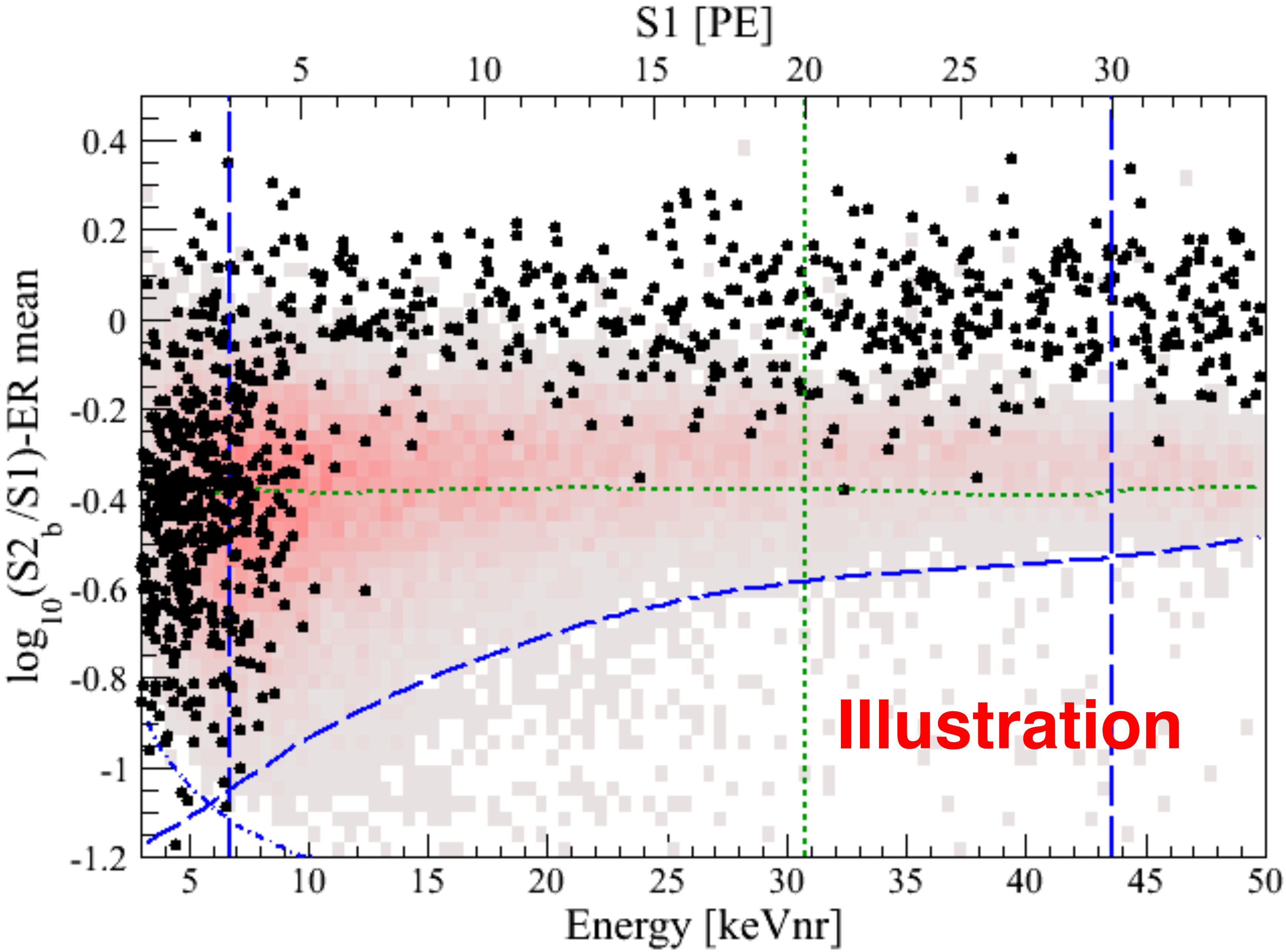
➔ **WIMP velocity:**
v_0 = 220 km/s
v_{esc} = 544 km/s

- **best limit on spin independent DM: 2 10^{-45}cm² at 50 GeV/c²**
- **excludes part of the predicted region for SUSY candidates**
- **excludes other WIMP solutions above**

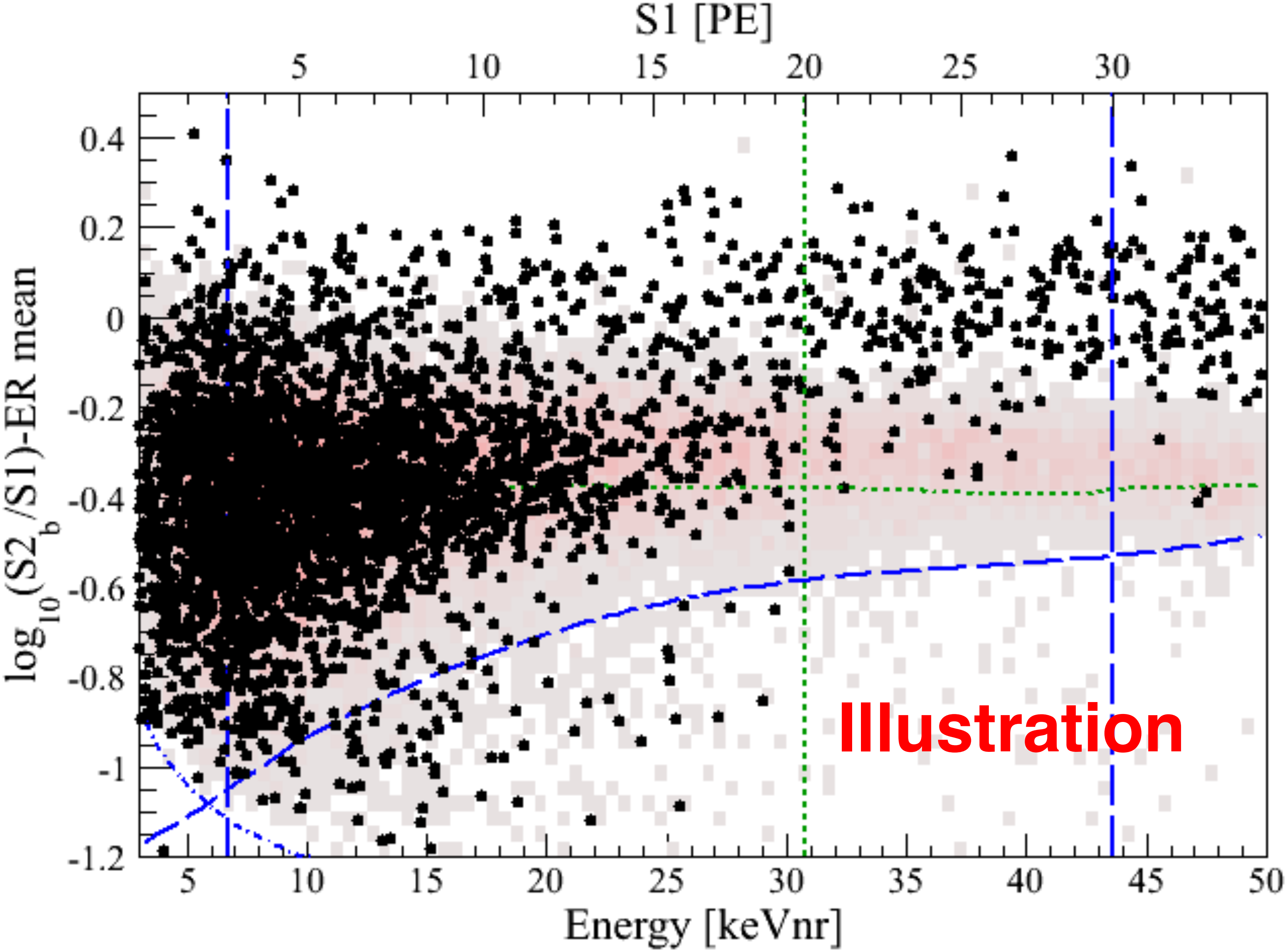
What XENON100 would see if…



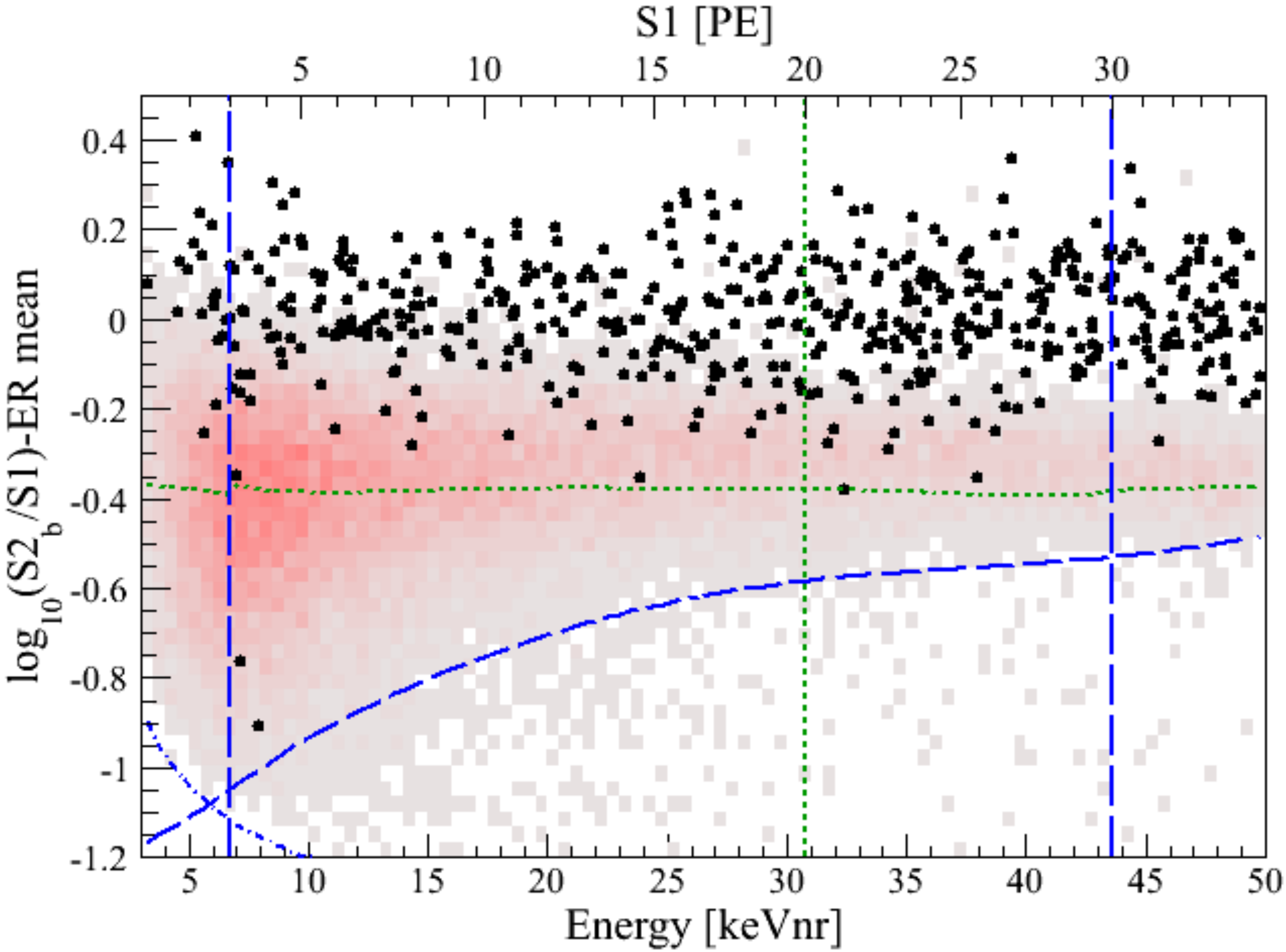
Assume "CoGeNT" (3e-41 cm²)



Assume: "CRESST" (1.6e-42 cm²)

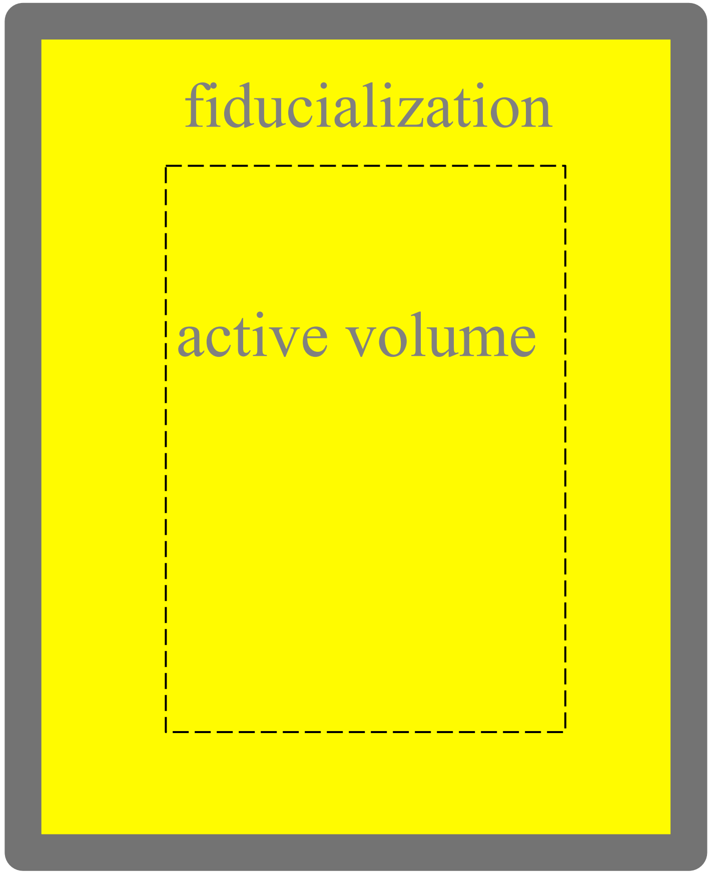


What XENON100 sees



The Future: XENON1t

Basic Scaling Considerations



- surfaces (cryostat, PMTs, …)
- volume (impurities)

Better sensitivity ➔ more exposure
➔ running time x detector size

Volume ~r^3 ←→ Surface ~r^2

BUT: More demanding background req.

1) cleaner 'surface'
2) more fiducialization (or both)
3) cleaner Xe

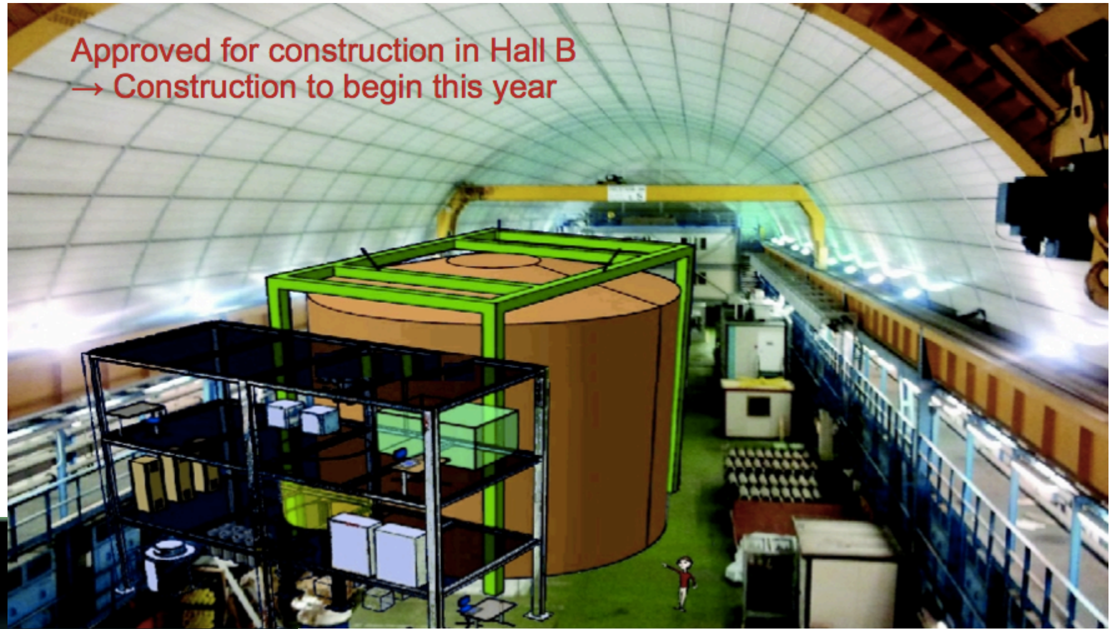
➔ requires:
a) screening of all detector materials
b) ultra clean Xe→ distillation column
c) improved online background reduction
d) improved background monitoring

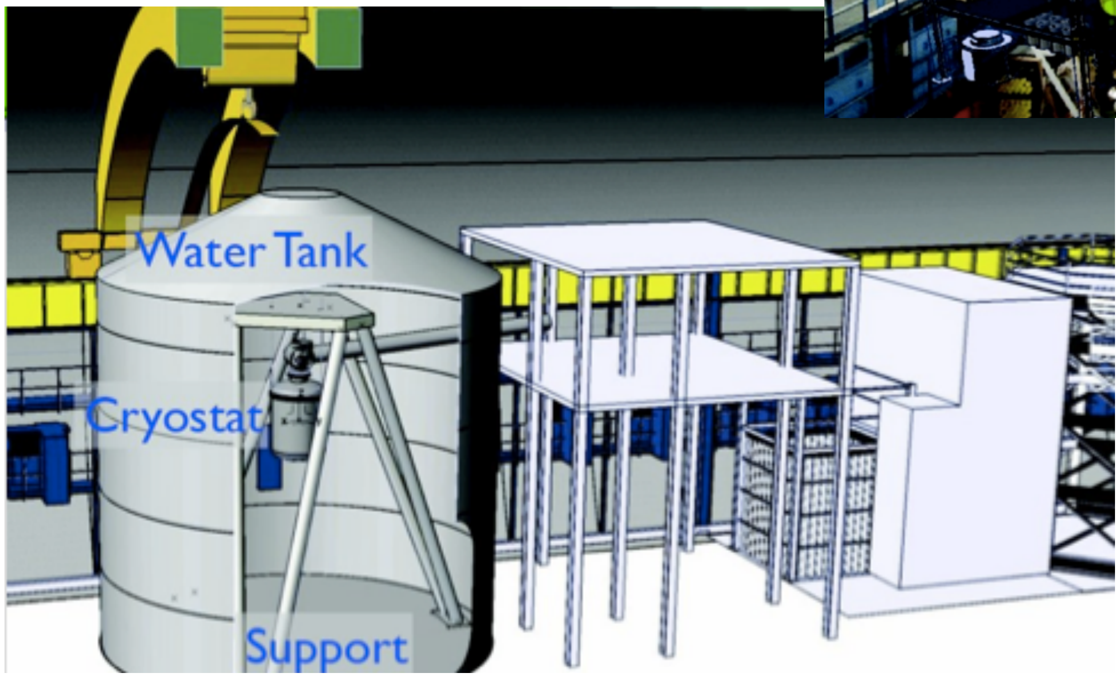
^{238}U, ^{235}U, ^{228}Th, ^{226}Ra, ^{60}Co, ^{222}Rn, ^{85}Kr …

➔ low background expertise from GALLEX, Borexino, KATRIN, Double Chooz, Gerda ➔ …

The XENON1t Project

- approved for hall B @ LNGS
- ~ all of funding in place
- construction starts soon
  ➔ detector completion until late 2014/2015





Water Cherenkov Muon Veto

Concept:

- Water tank: ~10 m high and 9.6 m in diameter
- 84 high QE 8" PMTs Hamamatsu R5912 with water-tight base
- Specular Reflector: foil DF2000MA by 3M

Trigger requirements:

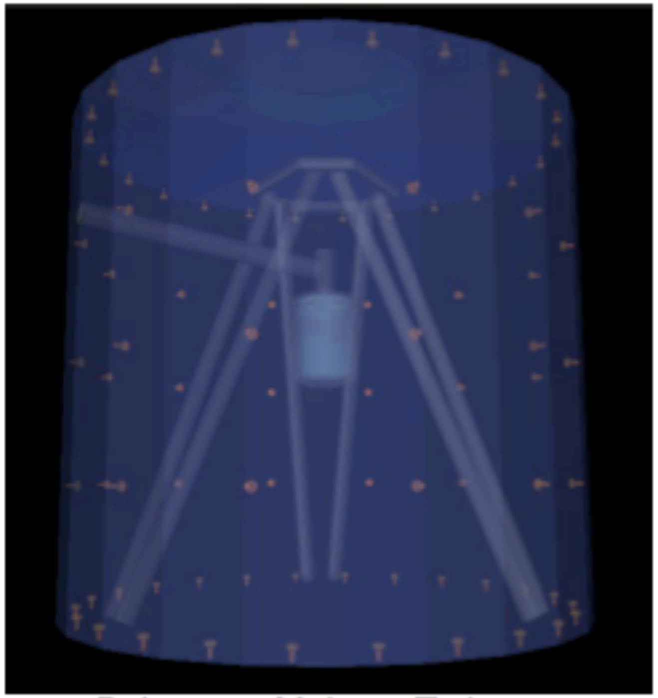
- single photoelectron
- 4 fold coincidence
- time window: 300 ns

Trigger efficiency

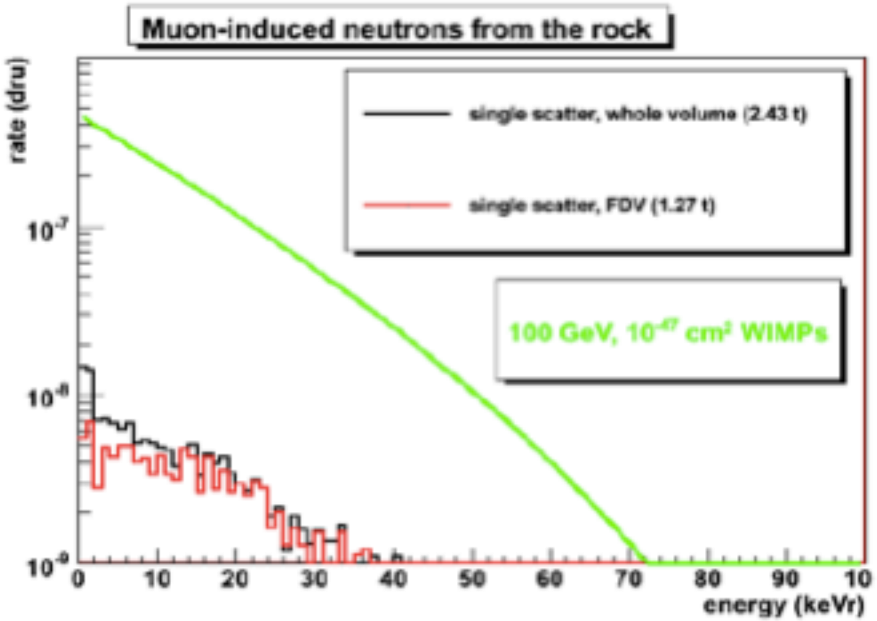
- > 99.5% for neutrons with muons in WT
- ~ 78% for neutrons with μ's outside WT

μ-induced neutron background

- 0.01 per year
- ≪ WIMP signal



Bologna – Mainz – Torino

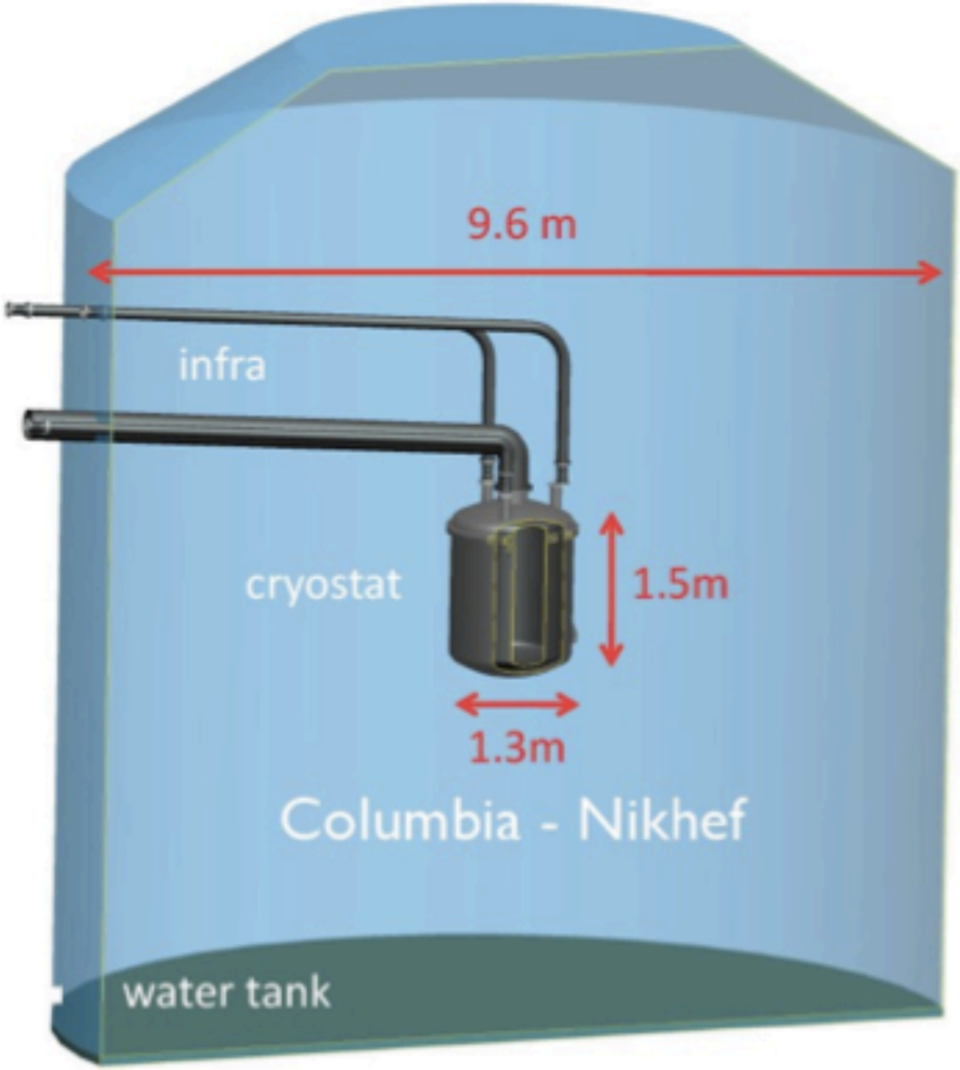


Cryostat

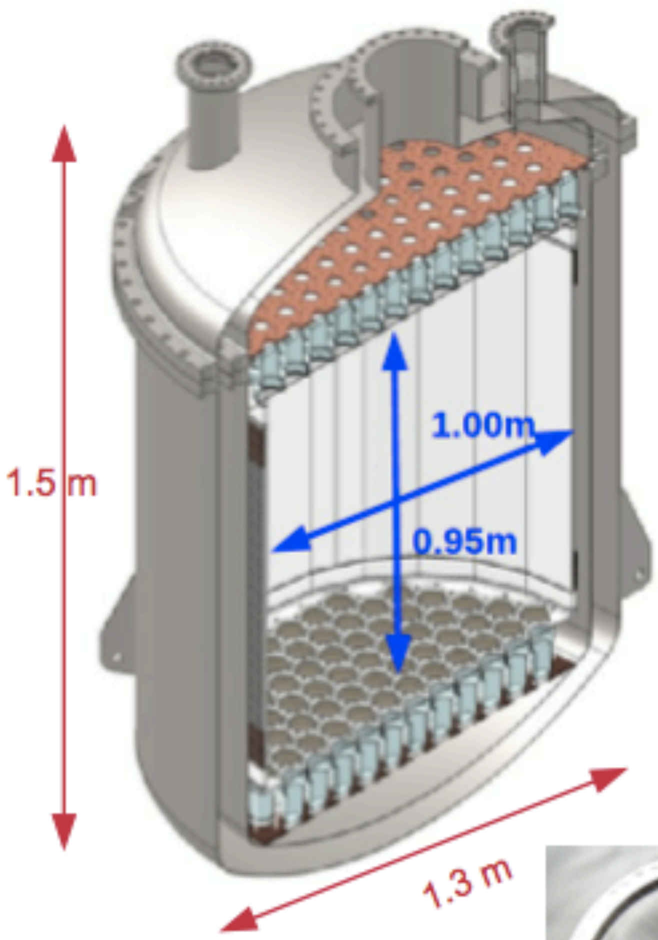
Baseline design

- Ti grade 1 double-walled cryostat
- UHV compatible, low outgas rate
- Heat load < 50 W
- Immersed in water shield
- Buoyancy load
- LNGS seismic environment
- Safety review currently ongoing

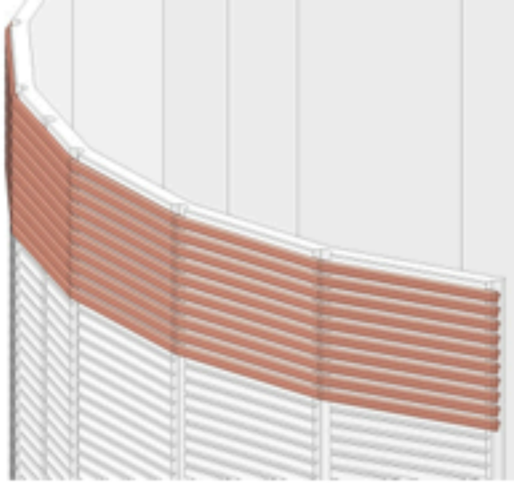
Columbia – Nikhef

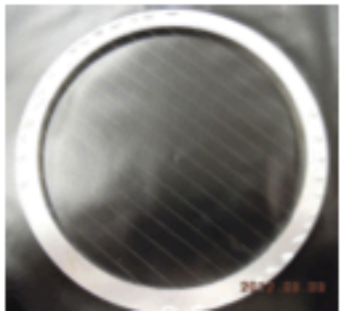


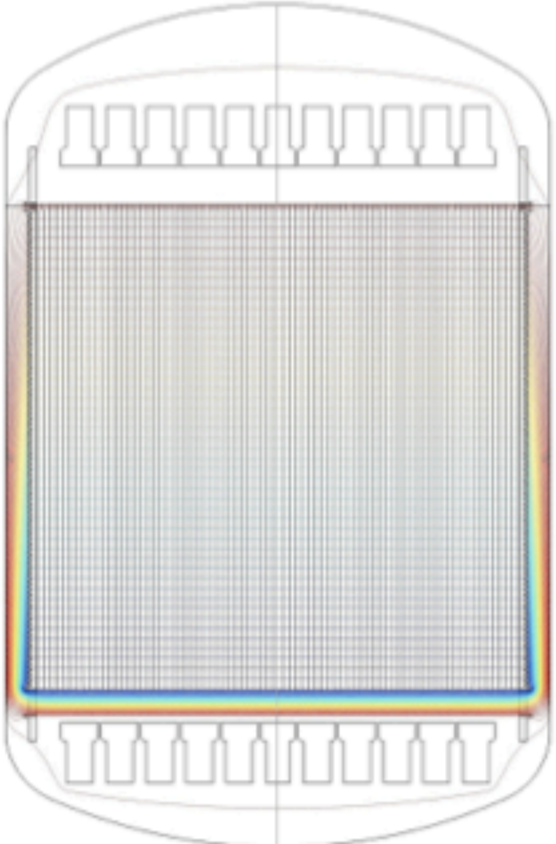
TPC



Columbia-Rice-UCLA-Zurich

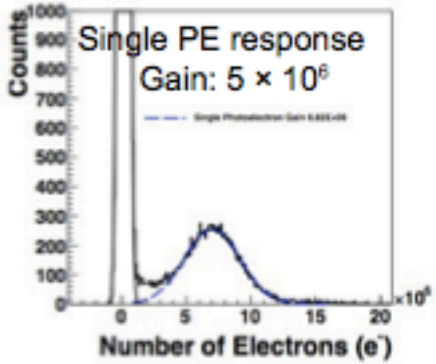


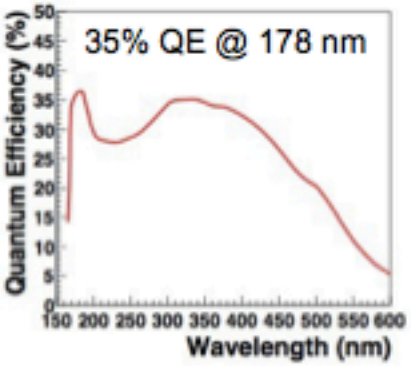


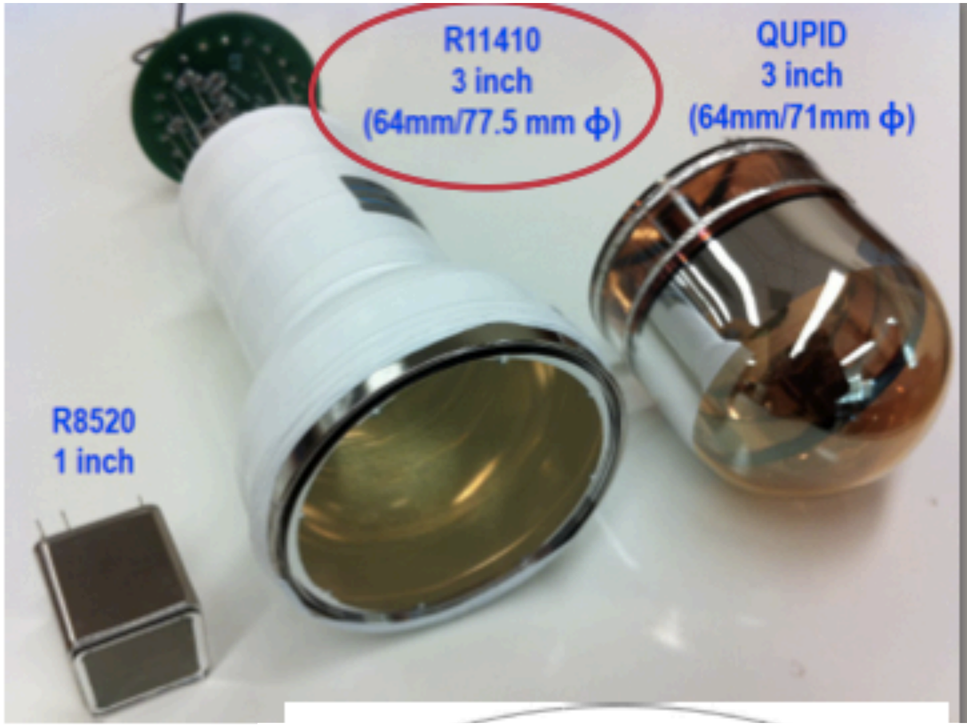


PMTs

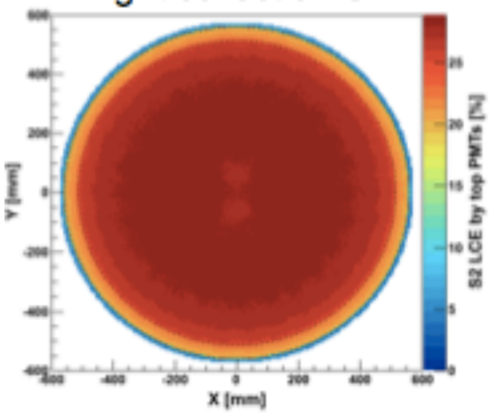
- 2 × 121 3" PMTs by Hamamatsu
- QE: 30% min., >35% achieved
- Ongoing screening program to further reduce radioactivity





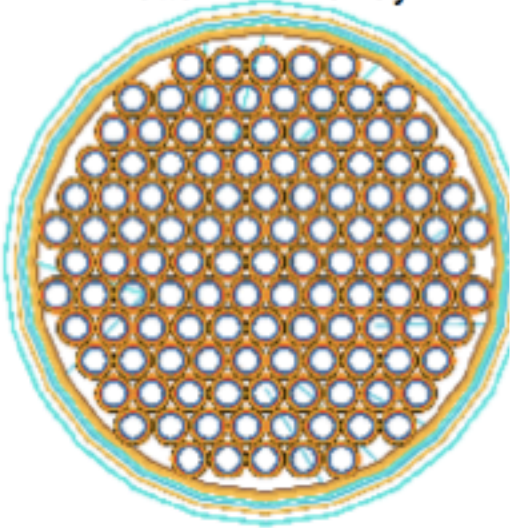


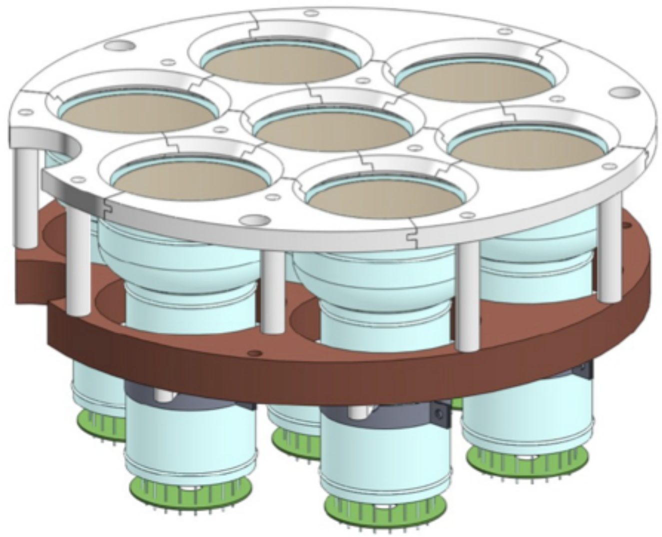
light collection S2



UCLA – Columbia – MPIK – Zurich

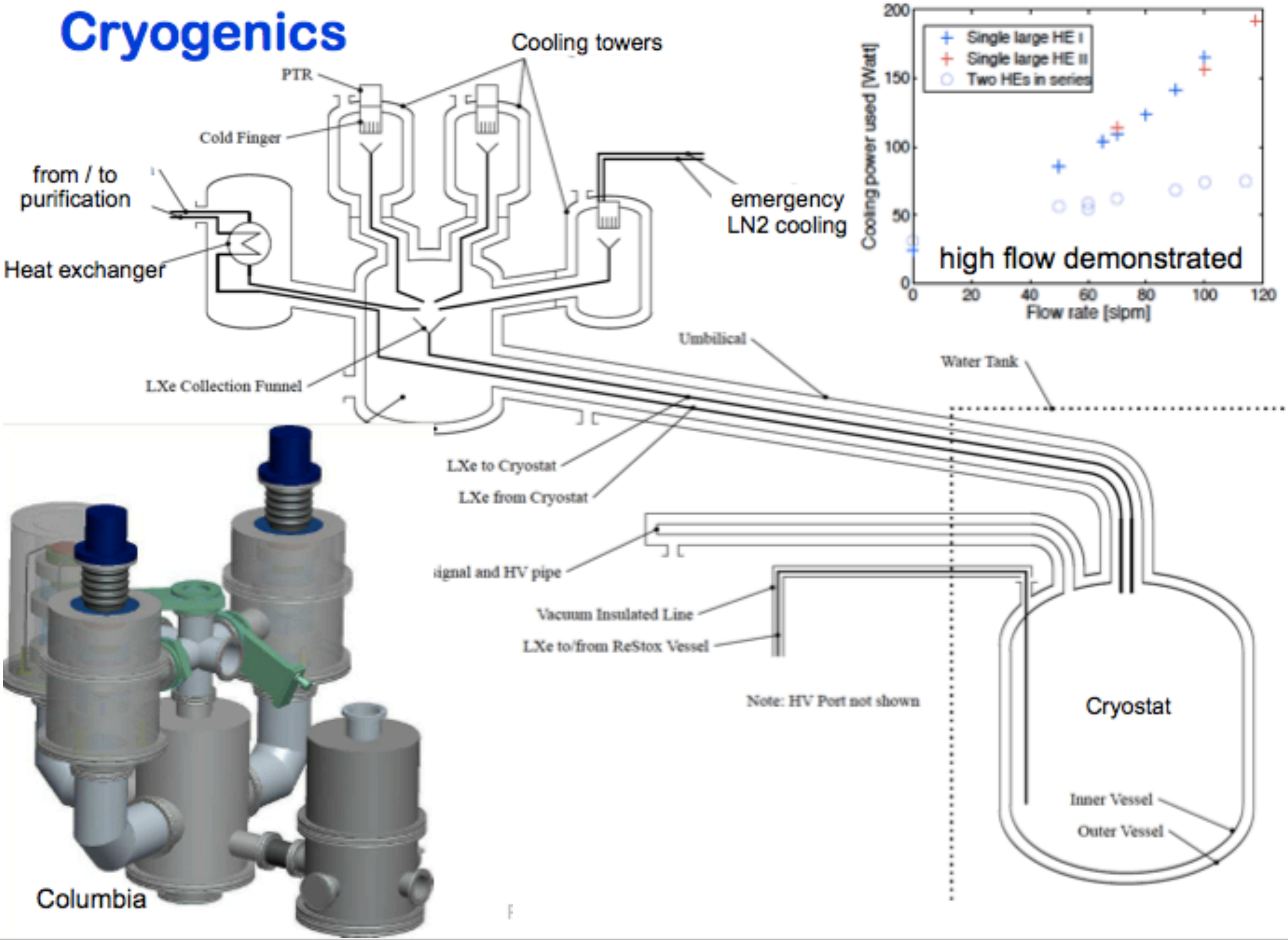
Bottom PMT array





Prototype PMT mounting

Cryogenics

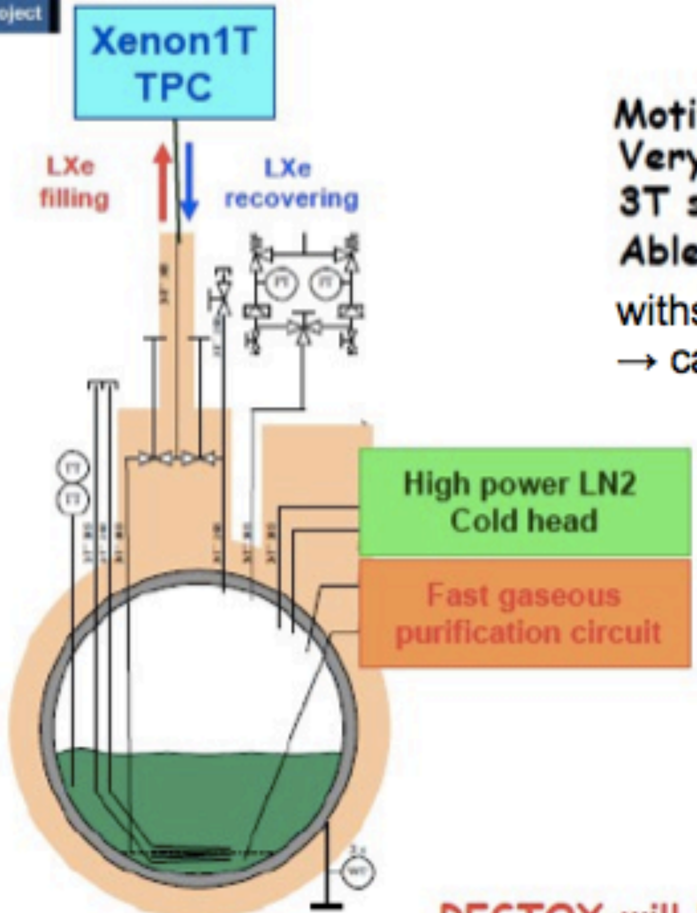


Cooling towers
PTR
Cold Finger
from / to
purification
Heat exchanger
emergency
LN2 cooling
LXe Collection Funnel
Umbilical
Water Tank
LXe to Cryostat
LXe from Cryostat
ignal and HV pipe
Vacuum Insulated Line
LXe to/from ReStox Vessel
Note: HV Port not shown
Cryostat
Inner Vessel
Outer Vessel
Single large HE I
Single large HE II
Two HEs in series
Cooling power used [Watt]
Flow rate [slpm]
high flow demonstrated
0
50
100
150
200
0
20
40
60
80
100
120
Columbia

Xenon Storage

RESTOX : A Liquid Xenon station

(REcovering and STOrage system of Xenon1T)



Motivations :
Very compact station
3T storage capacity from 20°to -108°C
Able to keep high purity all the time
withstands 65 bar
→ can also keep Xe at room temperature

Time schedule:
Construction will start in summer 2012
Installation for end of 2013

RESTOX will be easily scalable to larger sizes

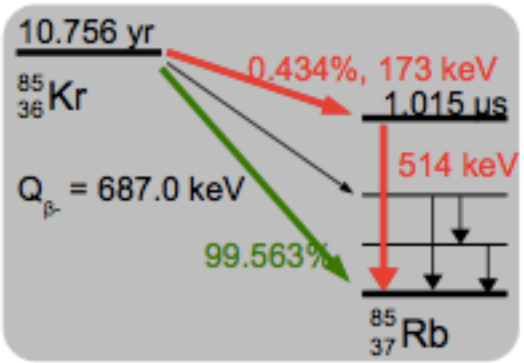
Subatech

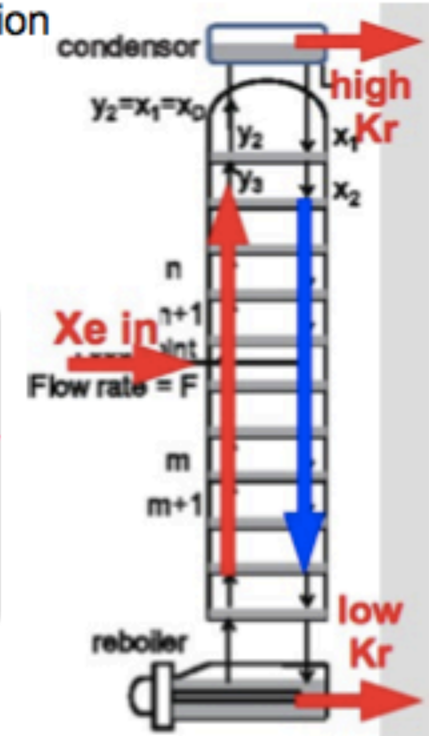
Krypton Removal

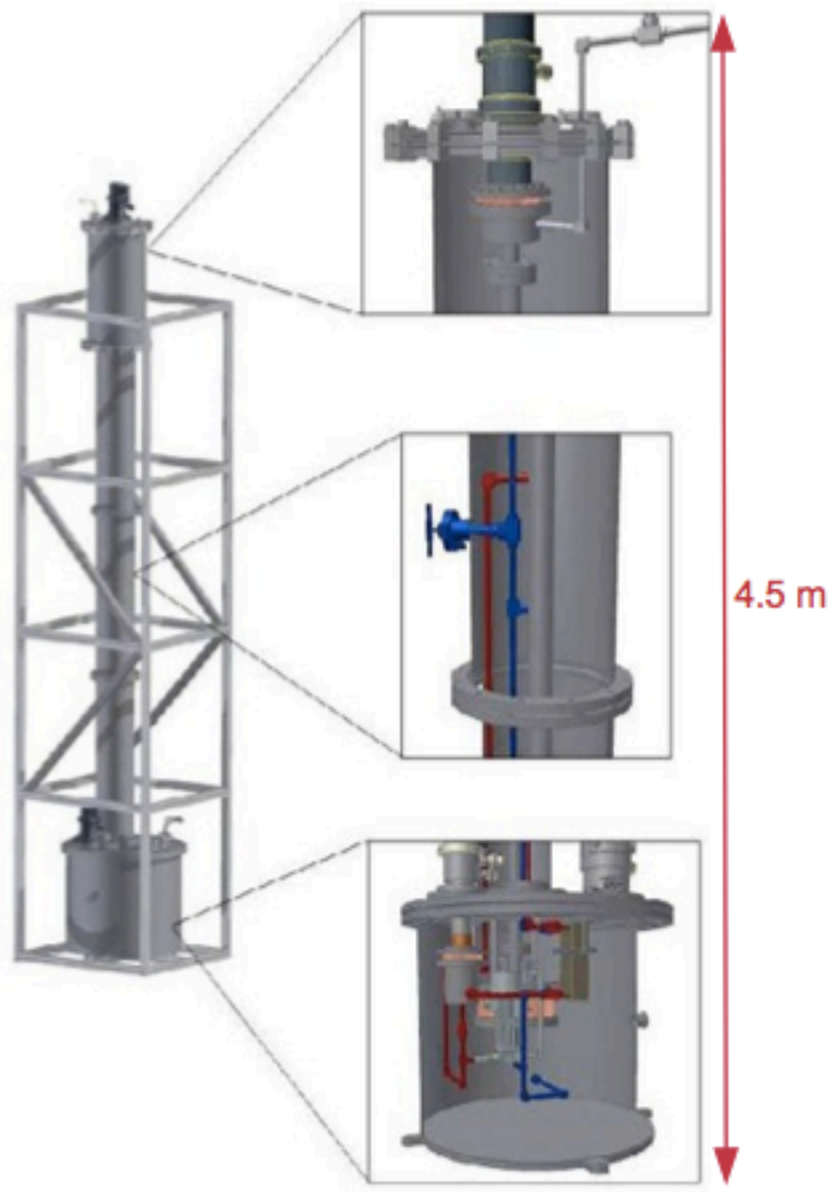
- Cryogenic distillation
- Reduce ppb Kr traces in Xe gas to ppt
- proven technique,
  achieved (19 +- 1) ppt in XENON100

Design Parameters for XENON1T

- through-put: 3 kg/hr
- factor of 10^4-10^5 separation
- final Kr/Xe < 1 ppt





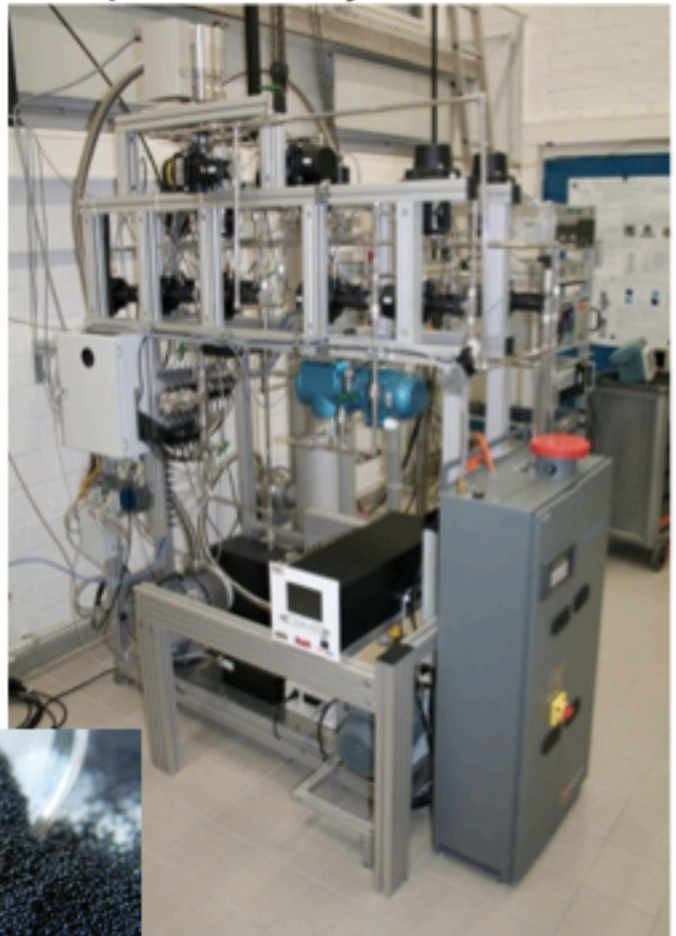


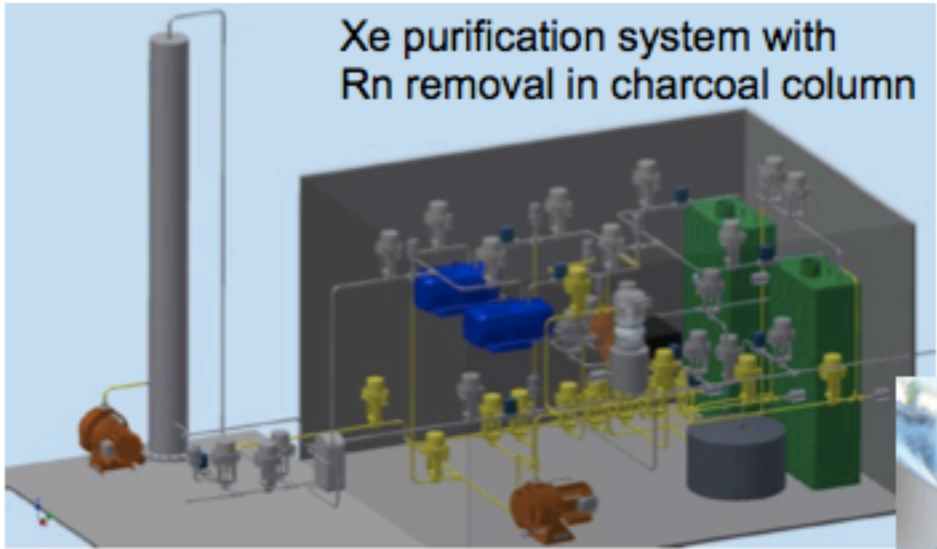
Münster

Xenon Purification & Rn-Removal

- ½ inch gas lines, VCR connections
- Orbitally welded
- Pneumatic valves
- SAES PS4-MT50 getter
- QDrive and KNF pumps
- Dedicated monitors for ppb-level impurities (H_2O, O_2, Kr)

Xe purification system



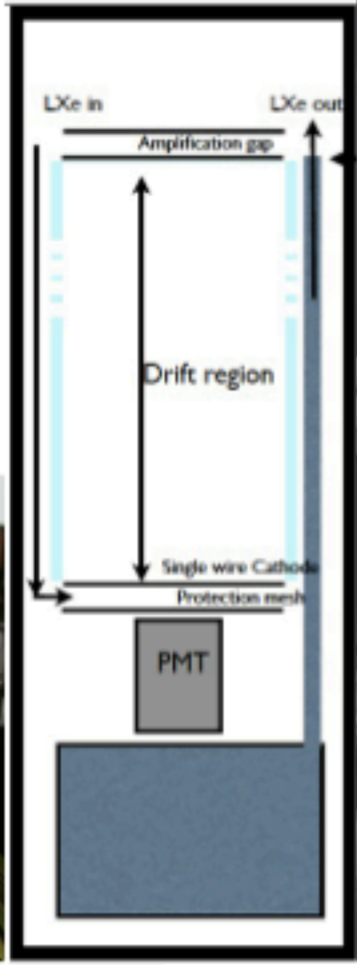


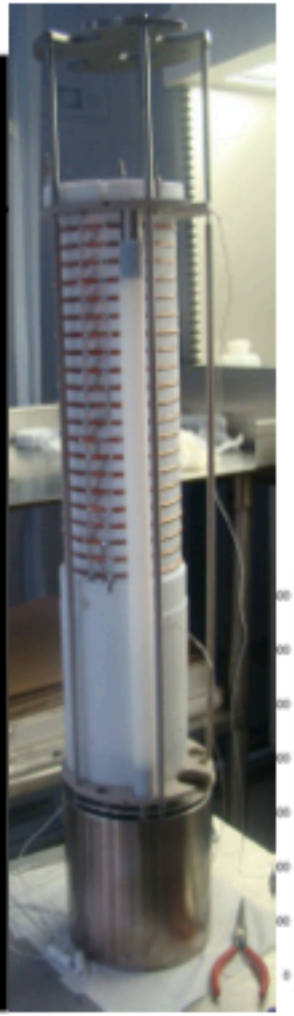
Xe purification system with
Rn removal in charcoal column

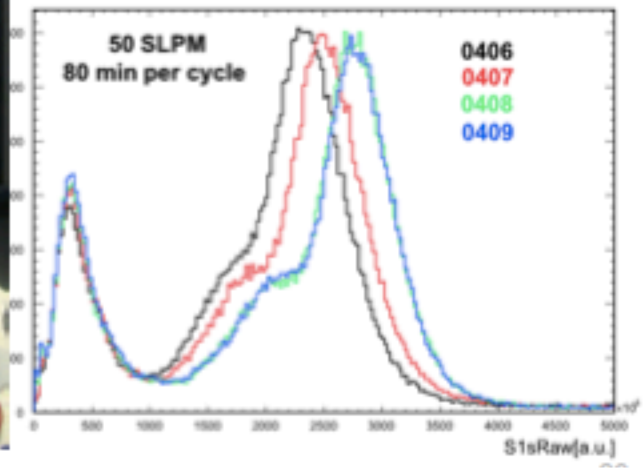
Münster (Xe purification) –
MPIK (Rn column)

XENON1T Demonstrator

- XENON purification and heat exchange at 100 slpm
- Verification of cooling concept
- Cathode HV tests: grid+feed-through goal: -100 kV
- Electron lifetime demonstrated. Next: 1 m drift



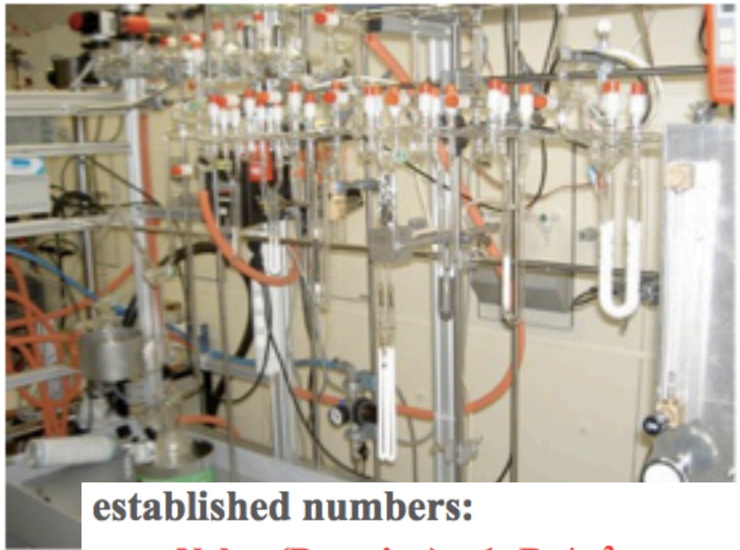




Columbia – Rice – UCLA

Material Screening

- Gamma-ray screening with sensitivity ~10 μBq/kg with GeMPIs and Gator, located at LNGS
- Gas counting systems, located at LNGS and MPIK, for ^{222}Rn measurements at few atoms sensitivity
- ICPMS @ LNGS, UCLA
  Inductively coupled plasma mass spectrometry
- Neutron activation analysis @ PSI, Mainz



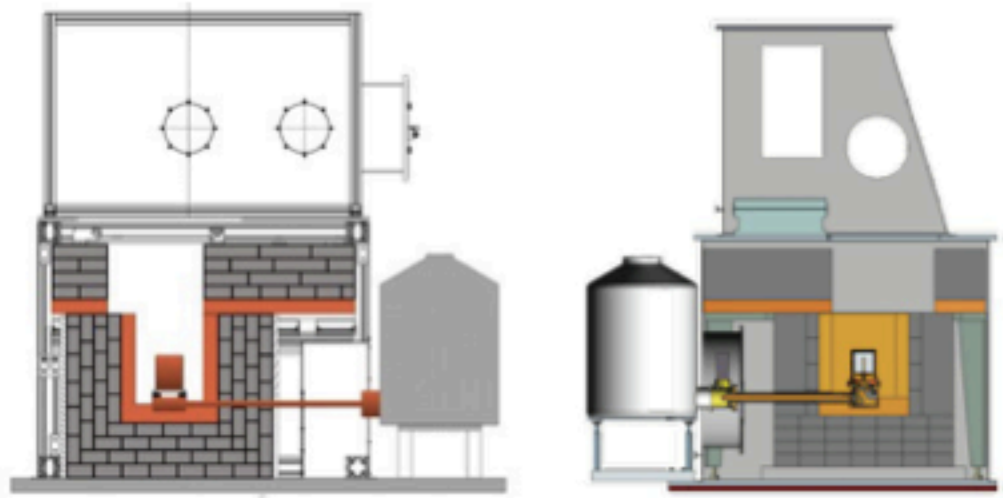
established numbers:

Nylon (Borexino) < 1μBq/m²

Copper (Gerda): 2μBq/m²

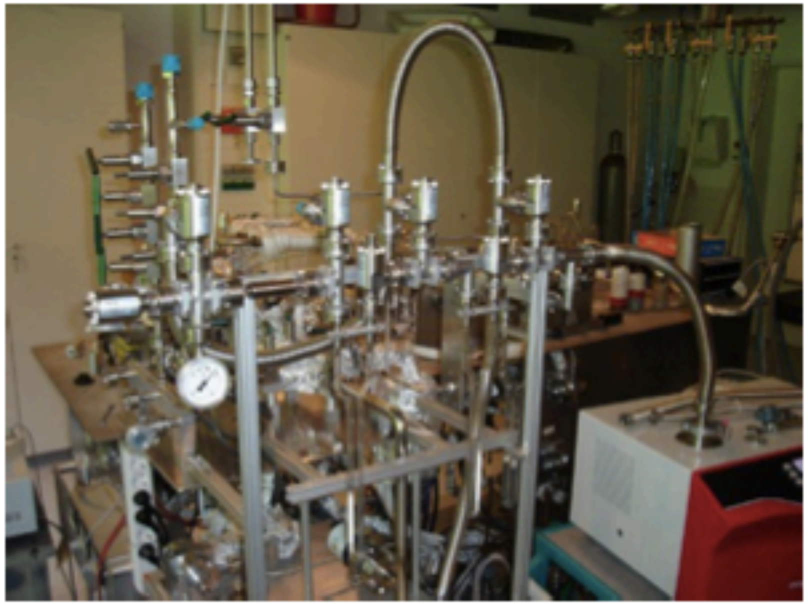
Stainless steel (Borexino): 5μBq/m²

Titanium (preliminary): (100 ± 30) μBq/m²

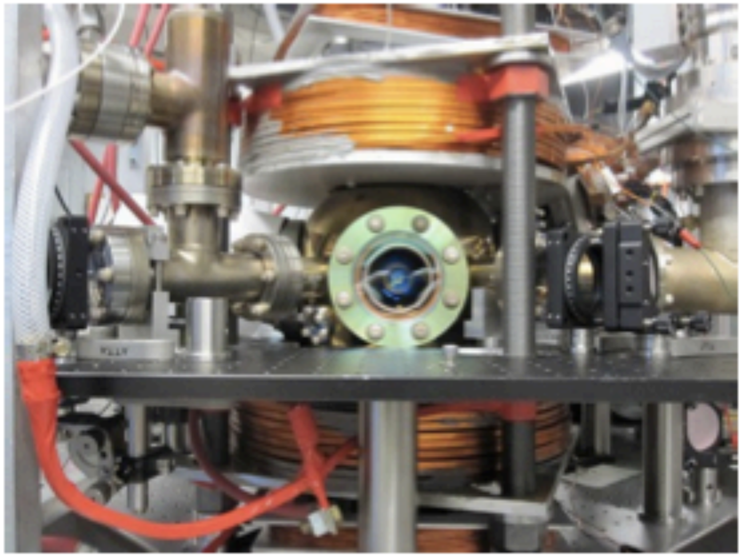


MPIK – Zurich

Krypton Analysis



- Kr measurements with gas chromatography plus Rare Gas Mass Spectroscopy RGMS
  - →measurement of ^{nat}Kr to ppt level
  - →extrapolation to ^{85}Kr from atmospheric abundance
  - →gas chromatography: Xe separation
  - →demonstrated for XENON100

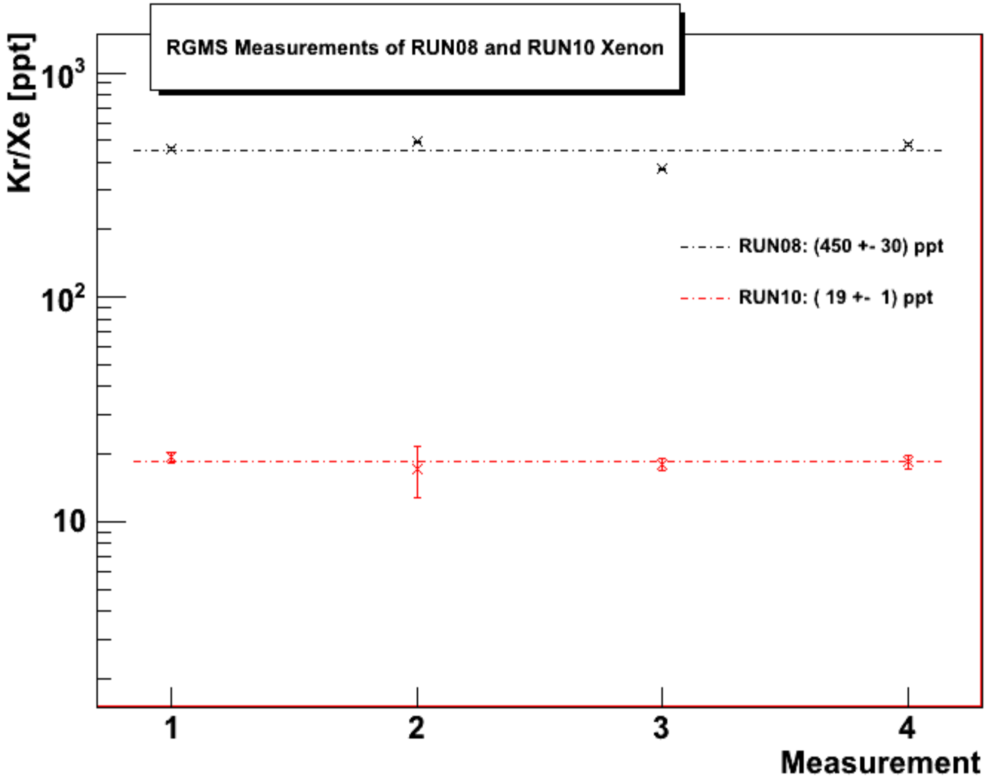


- ^{84}Kr measurement with atomic trap ATTA
  - →measurement of ^{84}Kr to ppt level
  - →extrapolation to ^{85}Kr from atmospheric abundance
  - →Atom trap operational and efficient for Ar*
  - →First Kr/Xe measurements for XENON100 by Fall 2012

MPIK (RGMS) –
Columbia (ATTA)

^{85}Kr Analytics @ppt level

- Detector improvements (Münster, …)
- New measurement technique (MPIK)
  ➔ sensitivity ≤ 1ppt = 1000ppq
  (He carrier gas with ≤ 1ppq He/Xe ~1000)



← Run08: (450 ± 30 ppt)

← Run10: (19 ± 1 ppt)

➔ Purification efforts between runs confirmed
➔ ppt precision established
➔ better bg understanding @ XENON100

Xenon Inventory

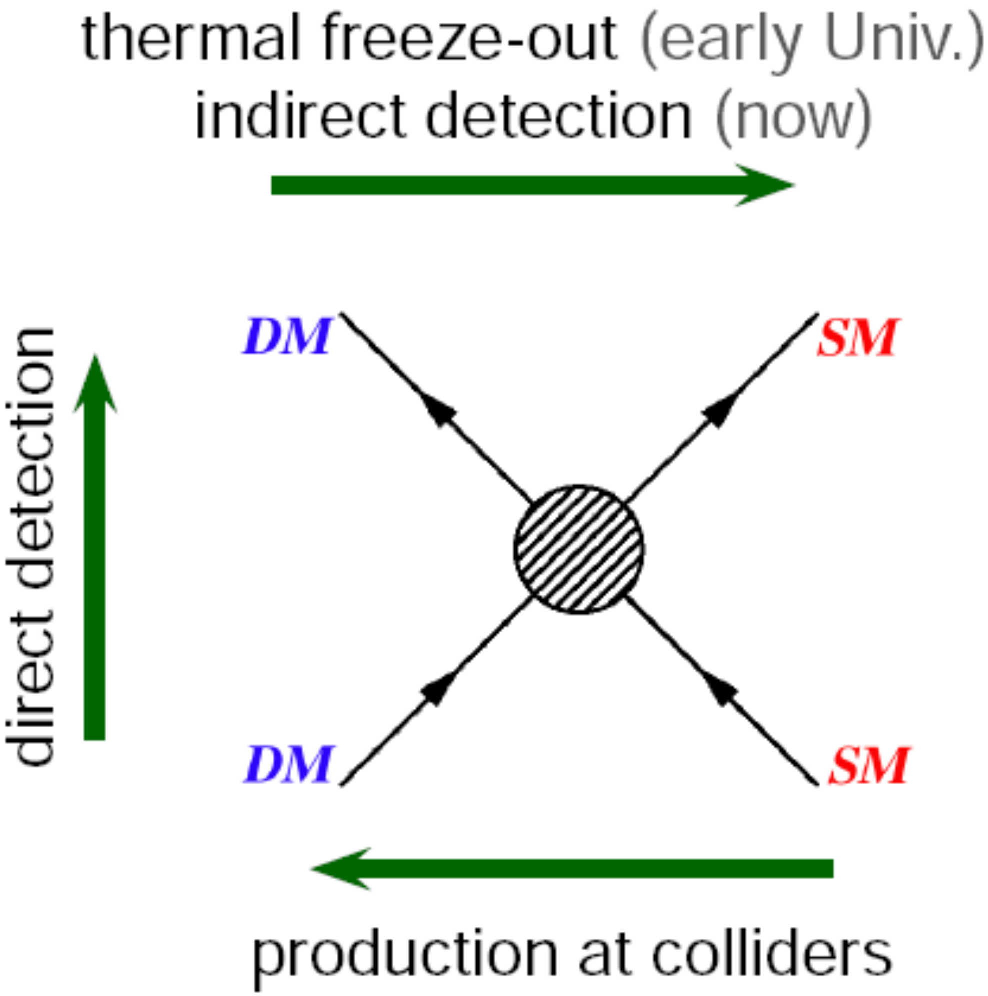
- 2.5 tons of HP Xe procured by Coll.
- All gas with <1 ppm O2 equivalent impurities and < 10 ppb Kr/Xe
- Purity level of each Xe bottle validated with dedicated measurements at MPIK
- Gas cylinders stored underground to minimize activation

The larger Context

WIMP Synergies

- SM particles must interact with WIMP DM ➔

- colliders
- early Universe & indirect
- scattering on target ➔ direct



- synergetic results:

- direct detection
  = least ambiguous
- WIMP-like particle @LHC
- astronomy/cosmology

➔ exciting times ahead!

DARWIN

Dark Matter WIMP Search with Noble Liquids

R&D and design study for a next-generation noble liquid facility in Europe

25 groups from ArDM, DarkSide, WARP, XENON

Europe: UZH, INFN, ETHZ, Subatech, Mainz, MPIK, Münster, Nikhef, KIT, TU Dresden, Israel: WIS, USA: Columbia, Princeton, UCLA, Arizona SU

similar effort in the US: MAX

Summary

- **WIMPs are the best motivated Dark Matter candidate**
- **XENON100 cuts already into typical parameter space**
  - ➔ an emerging signal would not be surprising
  - ➔ continue operation…
- **Massive R&D effort for XENON1t**
- **Construction of XENON1t at LNGS will start soon**
  - ➔ moving fast → completion end of 2014/2015
  - ➔ covers large fraction of the natural WIMP space
  - ➔ good potential
  - ➔ timely funding
- **Beyond that: DARWIN for WIMPs and more…**