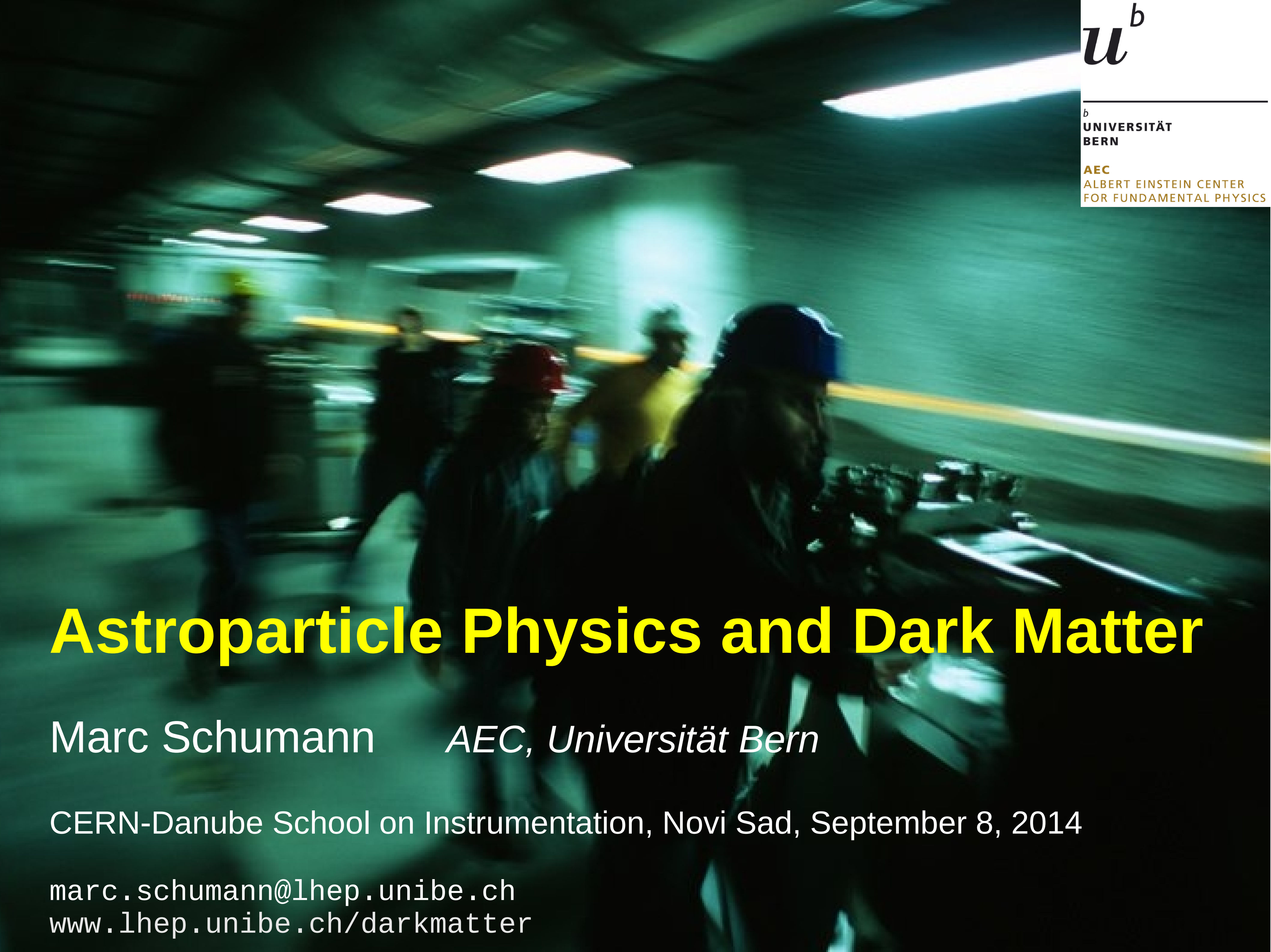

UNIVERSITÄT BERN

AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

# Astroparticle Physics and Dark Matter


Marc Schumann *AEC, Universität Bern*


CERN-Danube School on Instrumentation, Novi Sad, September 8, 2014


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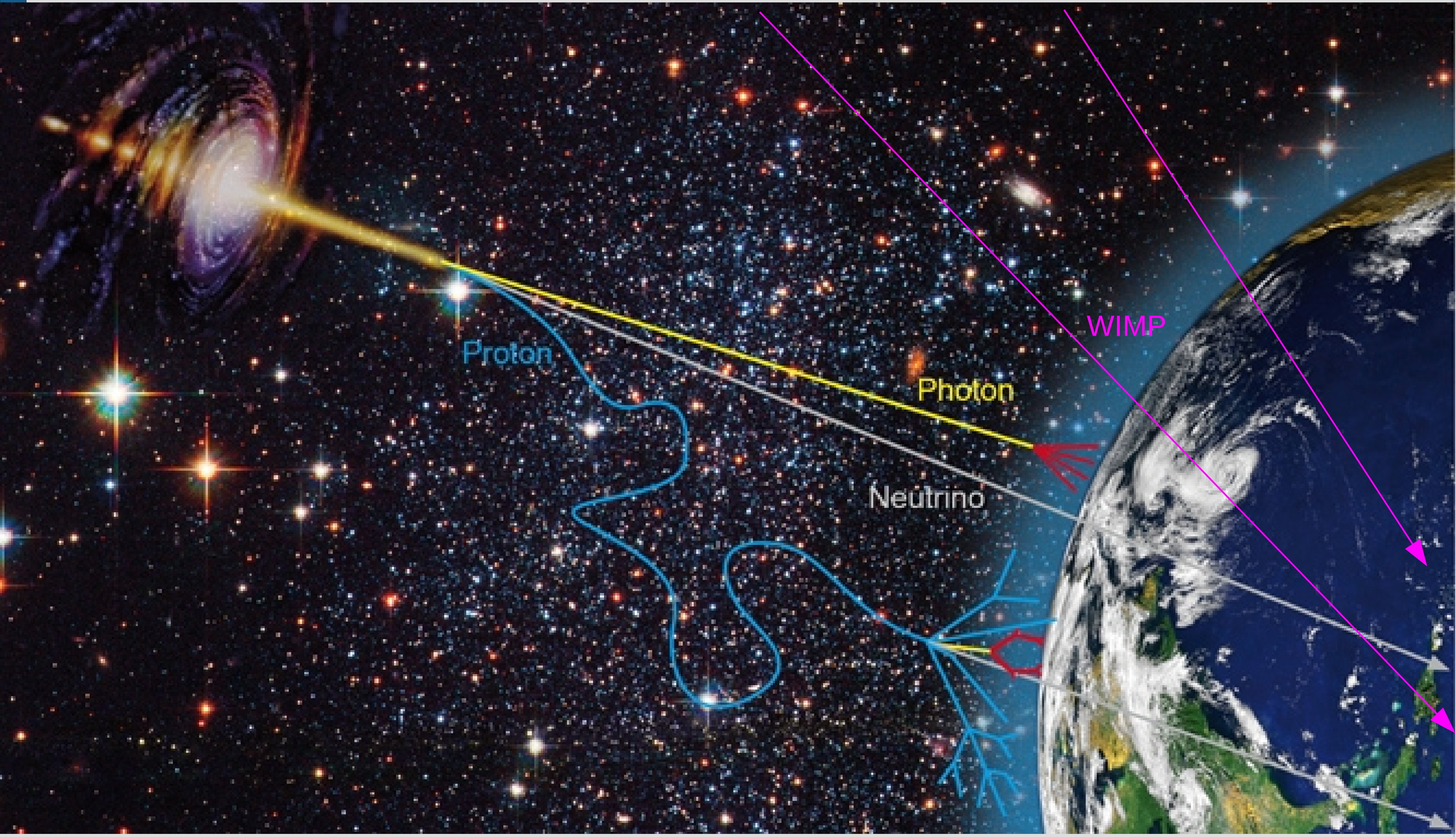
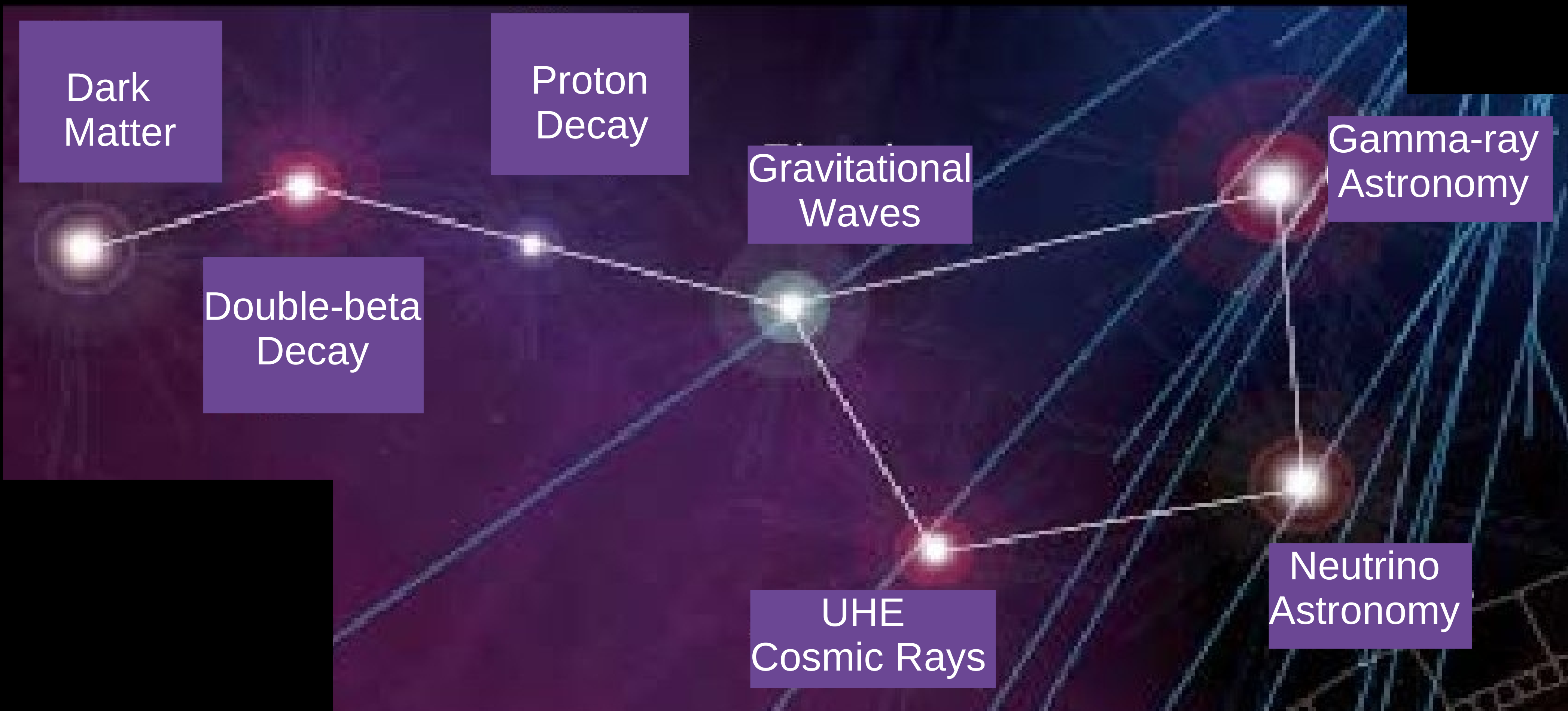
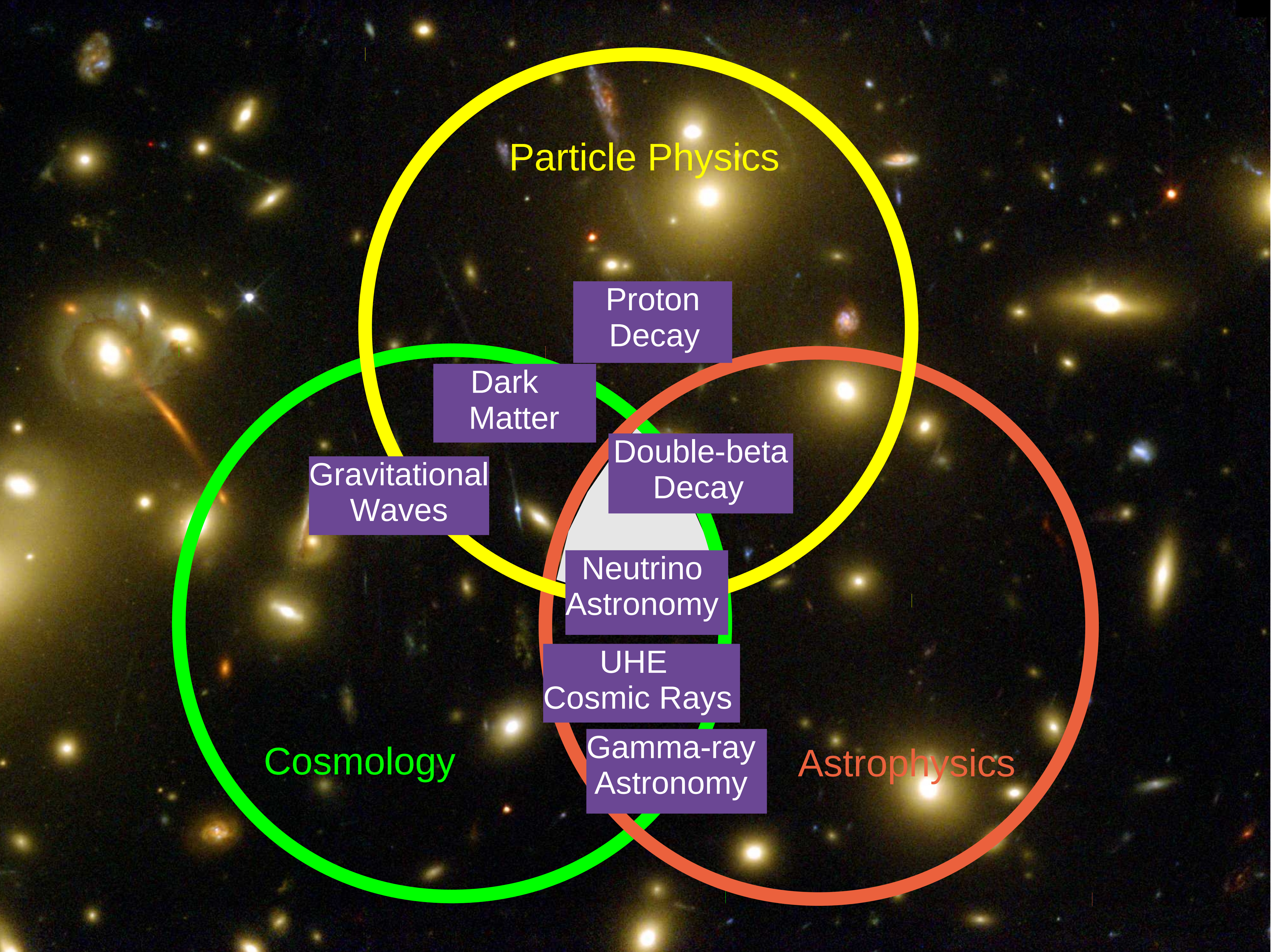
# Astroparticle Physics




Dark Matter
Proton Decay
Gravitational Waves
Gamma-ray Astronomy
Double-beta Decay
Neutrino Astronomy
UHE Cosmic Rays

ASPERA


Particle Physics
Proton Decay
Dark Matter
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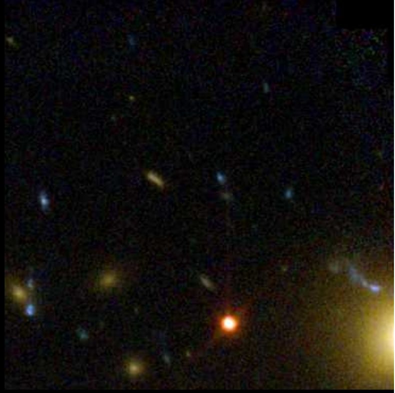
Gravitational Waves
Neutrino Astronomy
UHE Cosmic Rays
Gamma-ray Astronomy
Cosmology
Astrophysics

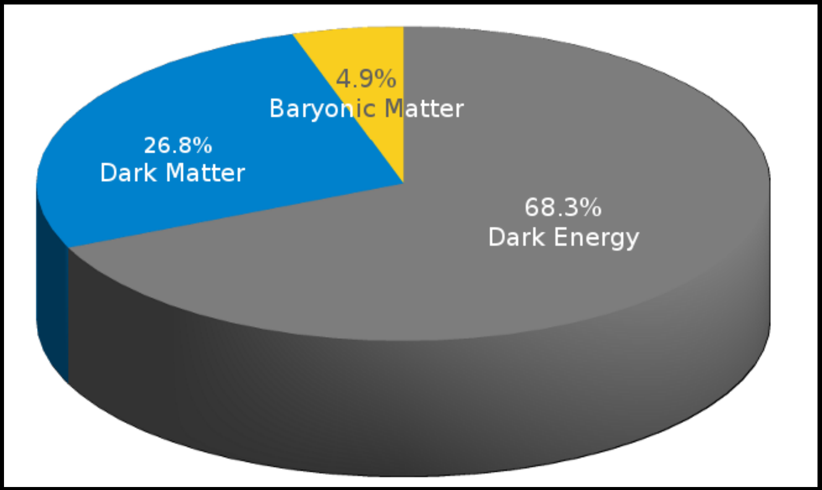


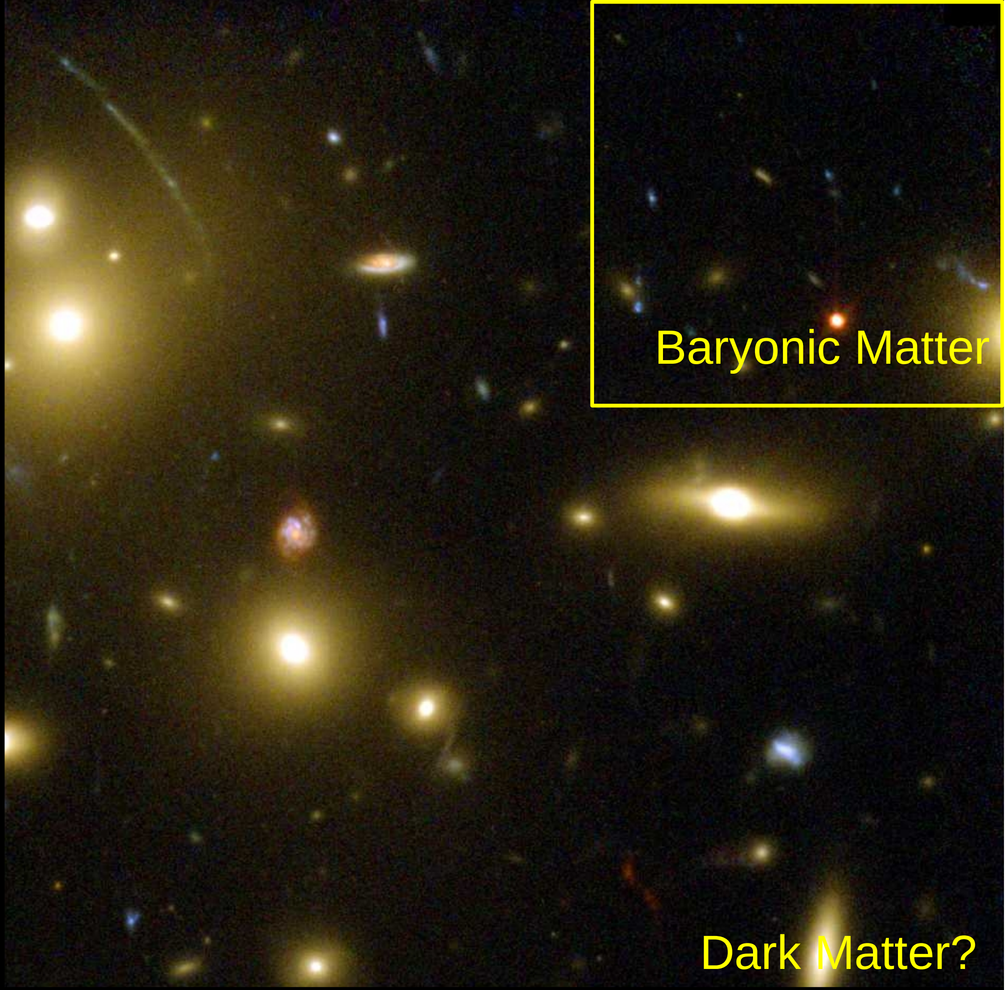
# Outline

**Dark Matter**
- Evidence
- Candidates
- Detection

**Direct Detection**

**Experiments**
- DAMA – annual modulation
- SuperCDMS – cryogenic HPGe
- LUX, XENON – noble liquid TPC
- DARWIN – the ultimate detector



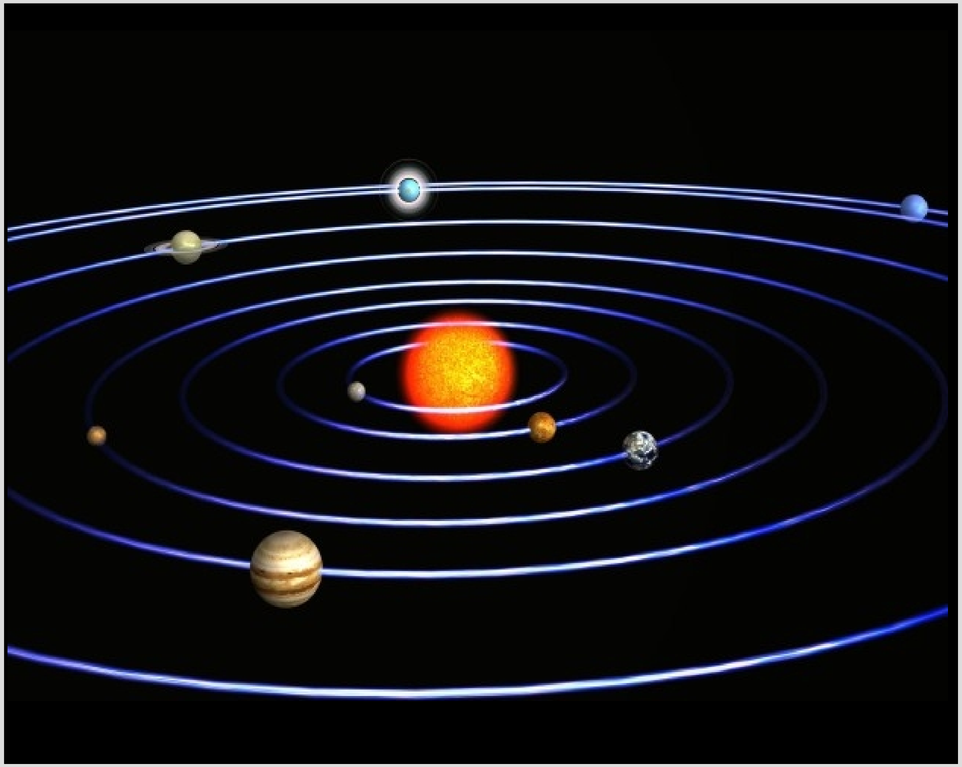




**95% of the Universe is dark!**

Dark Energy????

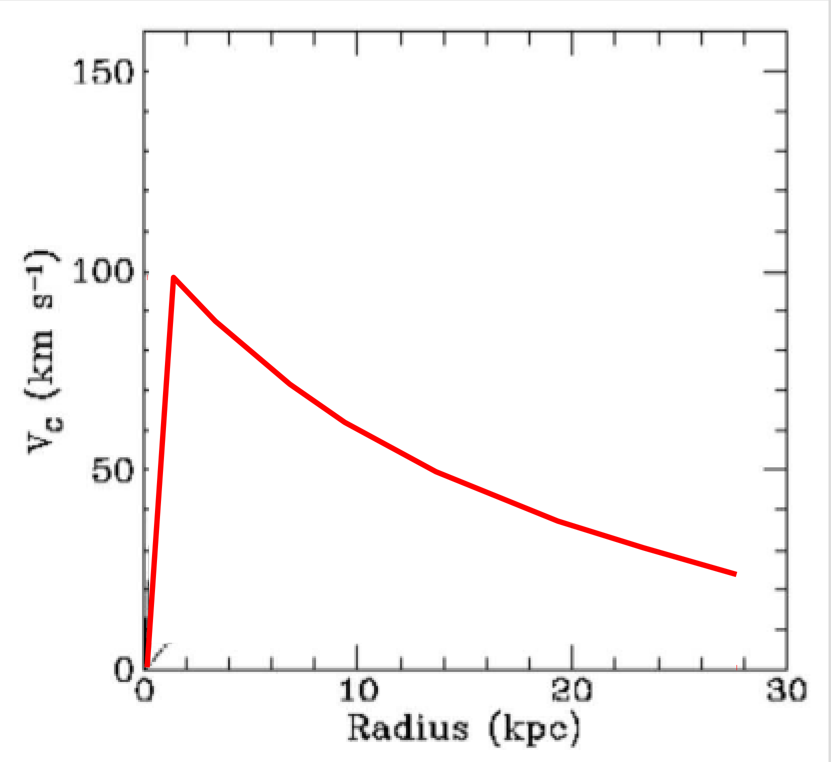
# Galactic Rotation Curves

Expect: Kepler Rotation (as in solar system)



# Galactic Rotation Curves

Expect: Kepler Rotation (as in solar system)

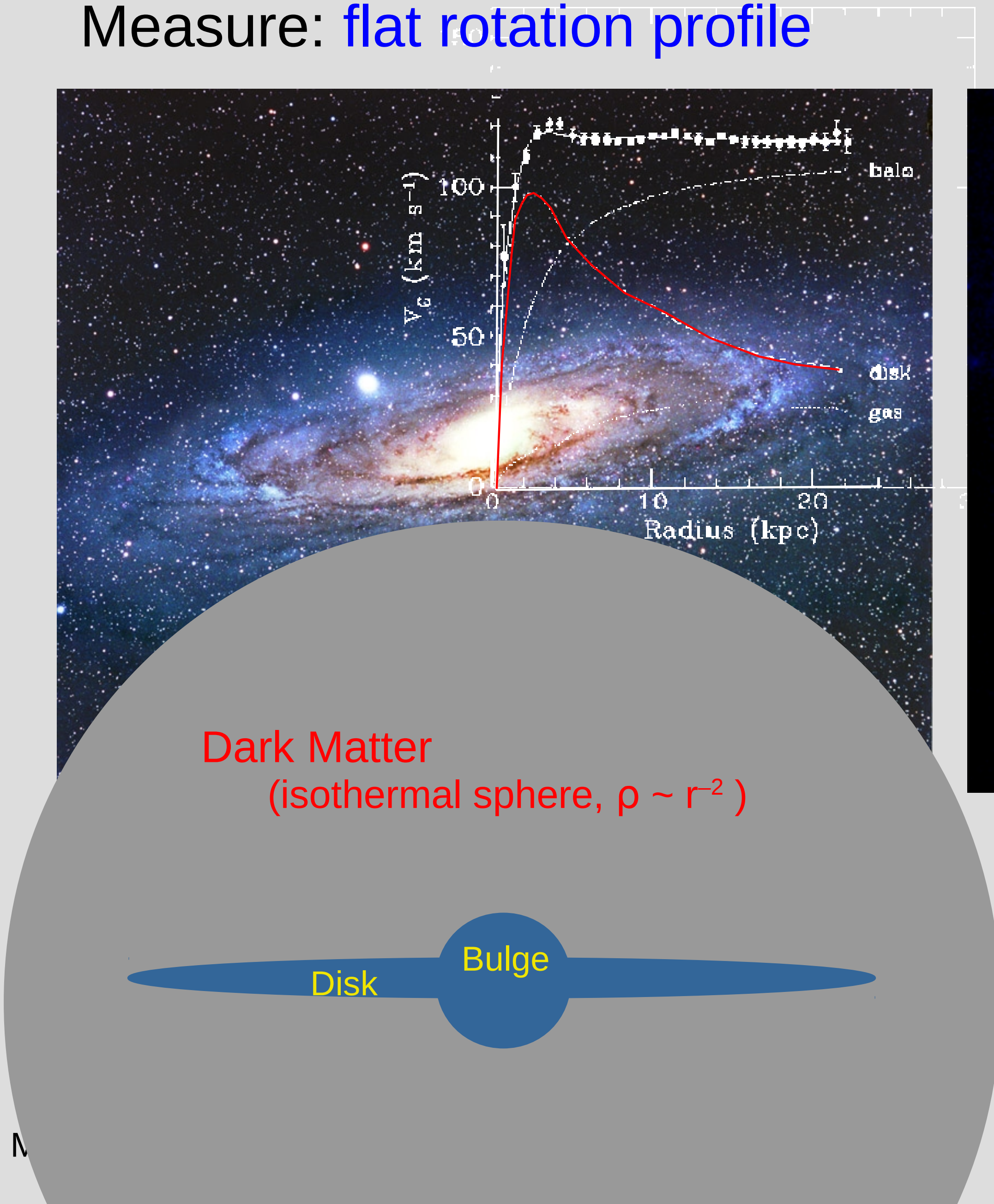


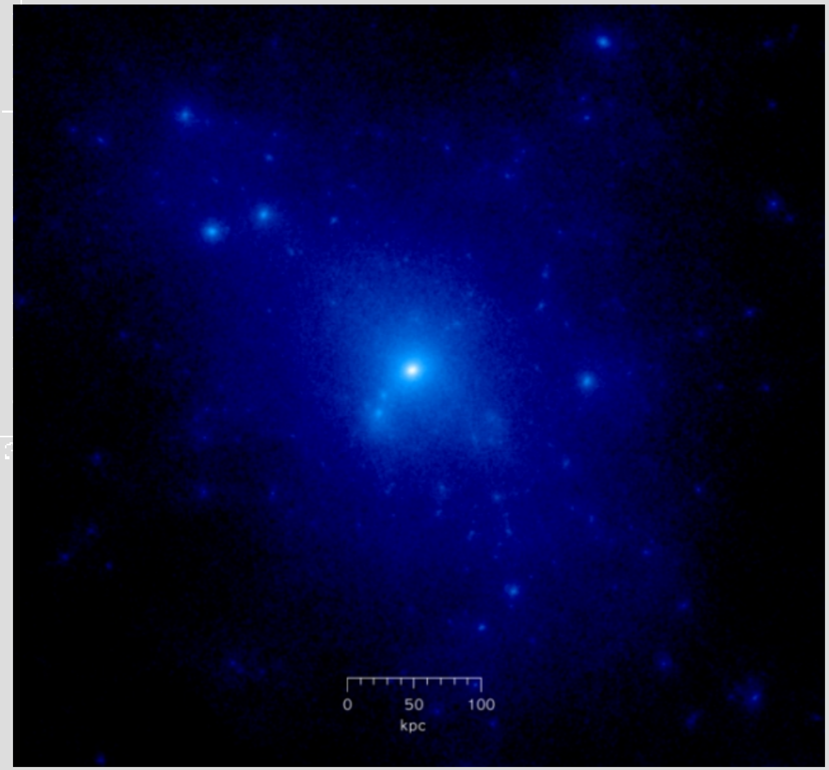


$$v^2 = \frac{G\ M(r)}{r}$$

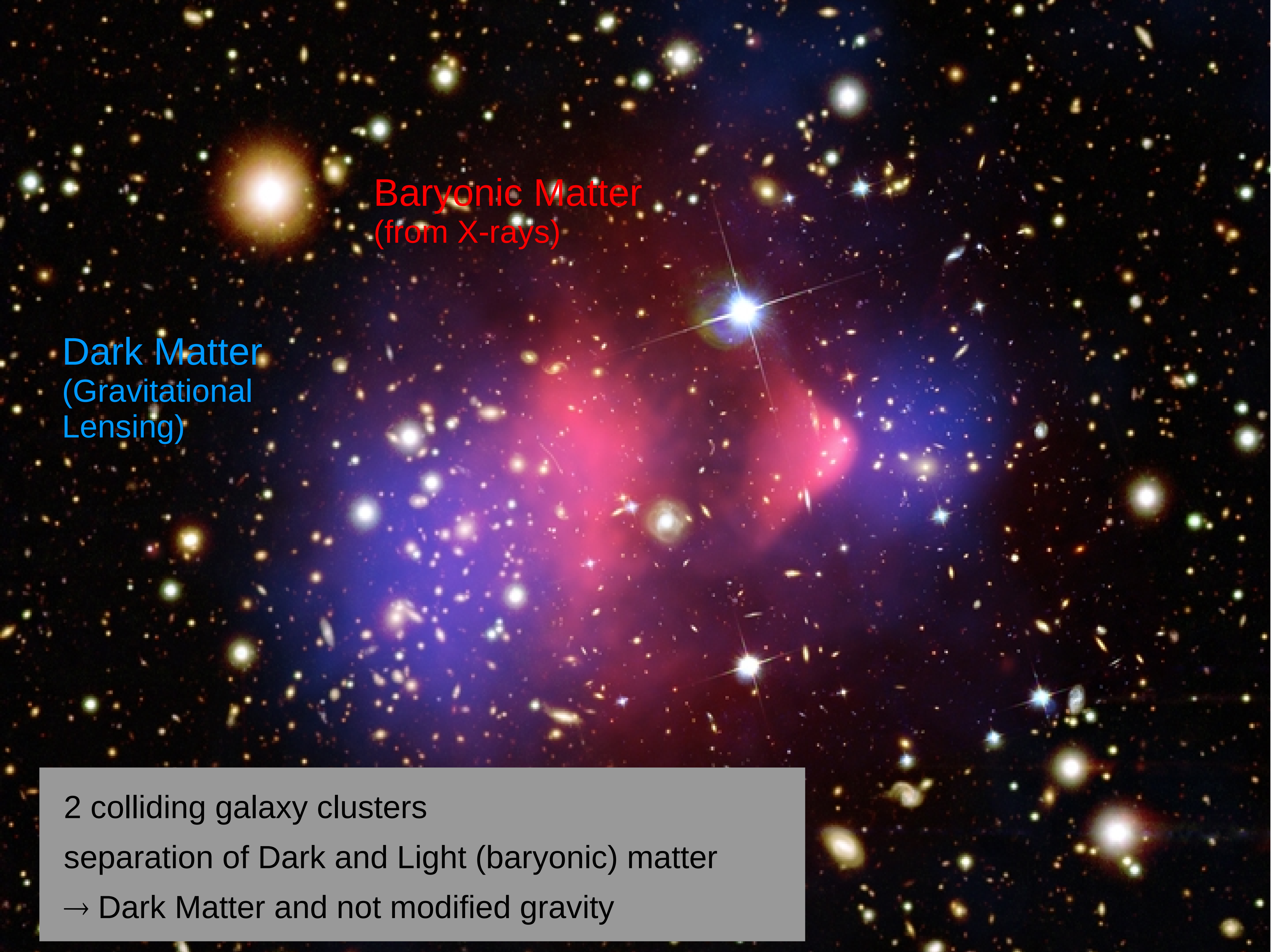
# Galactic Rotation Curves

Measure: flat rotation profile




N-body simulation result

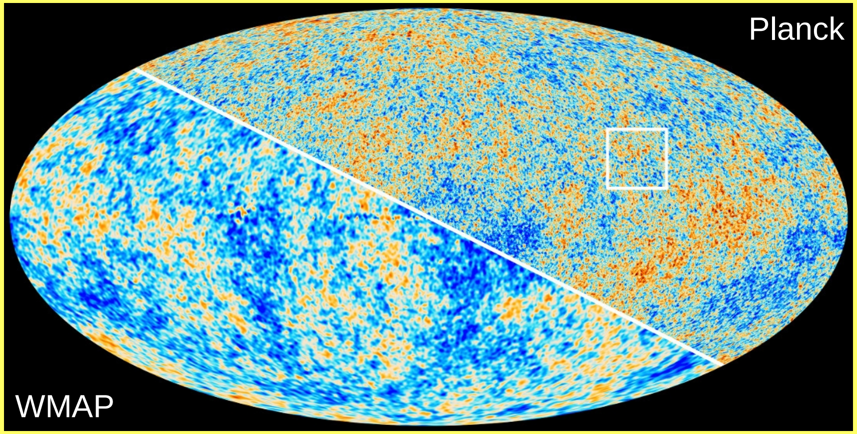



2 colliding galaxy clusters

separation of Dark and Light (baryonic) matter

→ Dark Matter and not modified gravity

# Cosmic Microwave Background

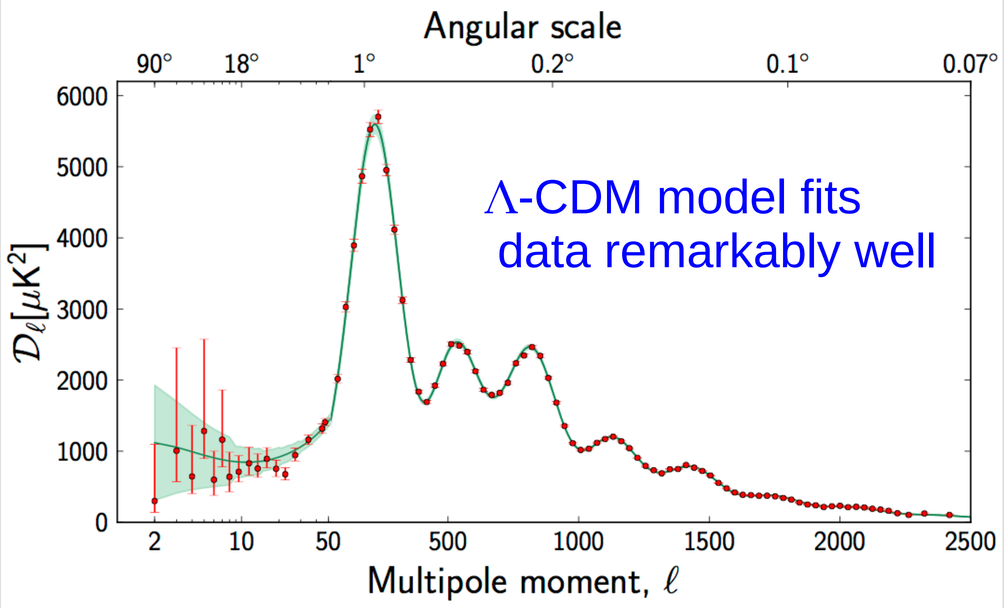



generated when radiation and matter decouple and photons can propagate freely

get information about structures in early universe

power spectrum of $\Delta T$

„typical variation at typical distance“




→ **Cold Dark Matter:**

- invisible
- cold ($v < 10^{-8}\ c$)
- collisionless
- stable
- from „new physics“

$\Omega = \rho/\rho_{crit} = 1.00(1)$

$H = 67.80(77)$ km/s/Mpc

$t_0 = 13.798(37)$ Gyr

$\Omega_\Lambda = 0.692(10)$

$\Omega_b = 0.048(1)$

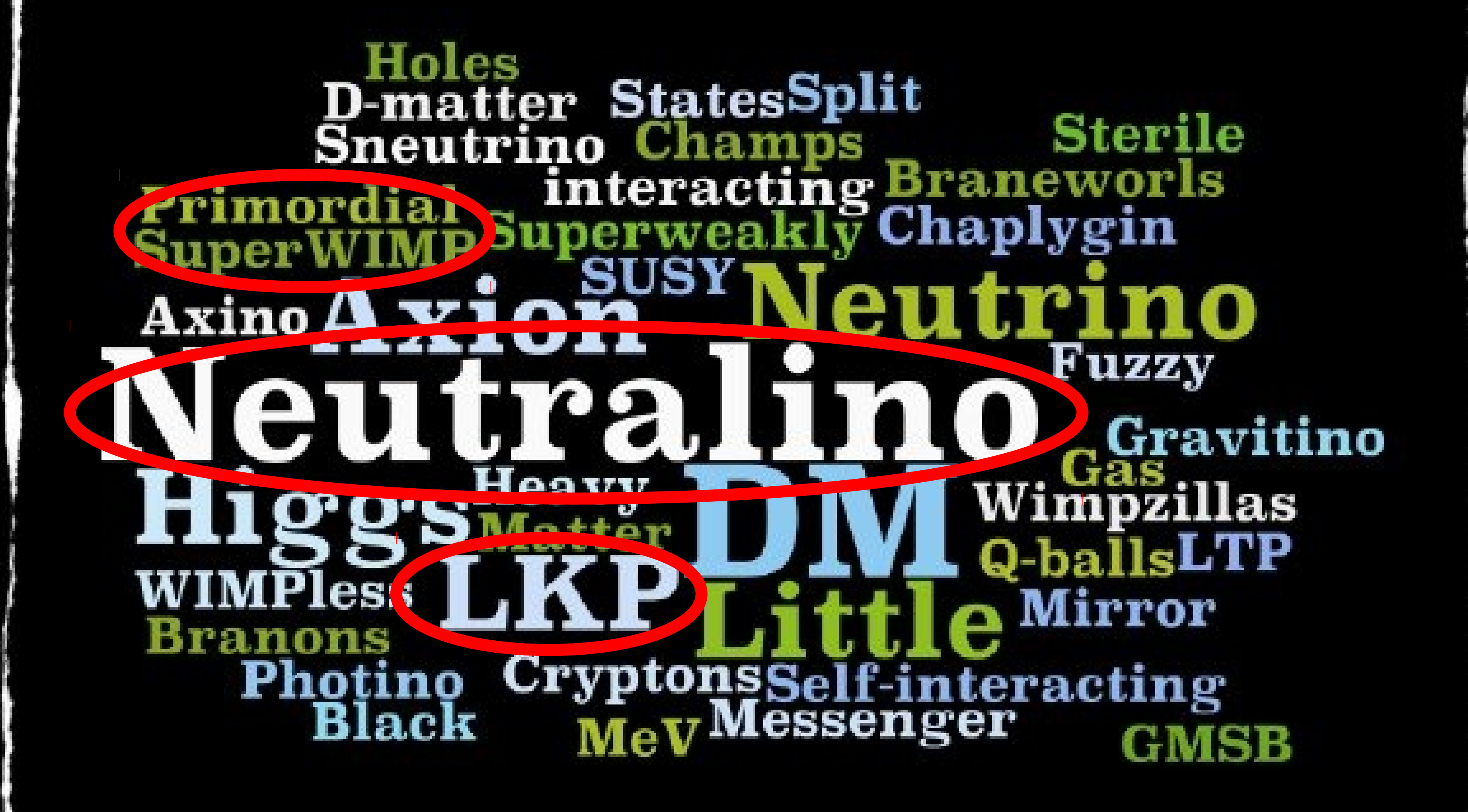
$\Omega_{cdm} = 0.258(7)$

*Planck 2013*

# The DM candidates Zoo

**WIMPs**

= weakly interacting massive particles




*stolen from G. Bertone*

# The WIMP Miracle

## In early Universe:

WIMPs in thermal equilibrium
creation ↔ annihilation

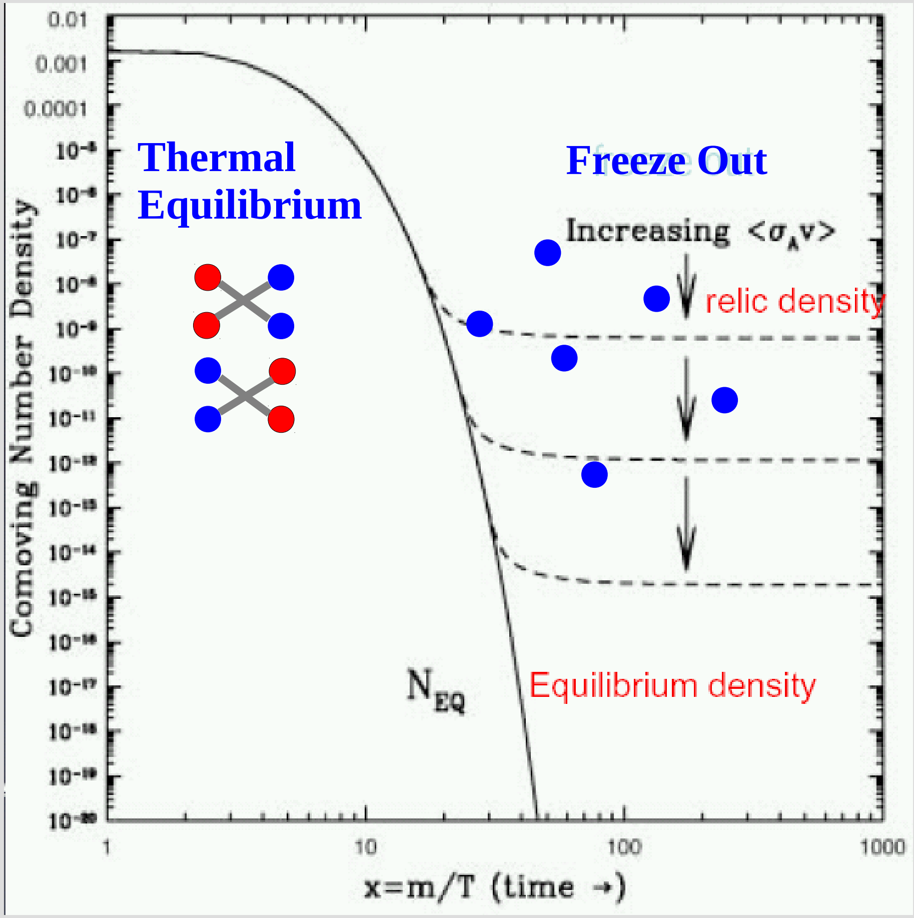
$$p(E) \propto \exp\left(-\frac{E}{k_B T}\right)$$

## expanding Universe: „freeze out“

WIMPs fall out of equilibrium, cannot annihilate anymore

$$k_B T \sim \frac{m_\chi c^2}{20}$$

→ non relativistic when decoupling from thermal plasma
→ constant DM relic density
→ relic density depends on $\sigma_A$




## WIMP relic density:

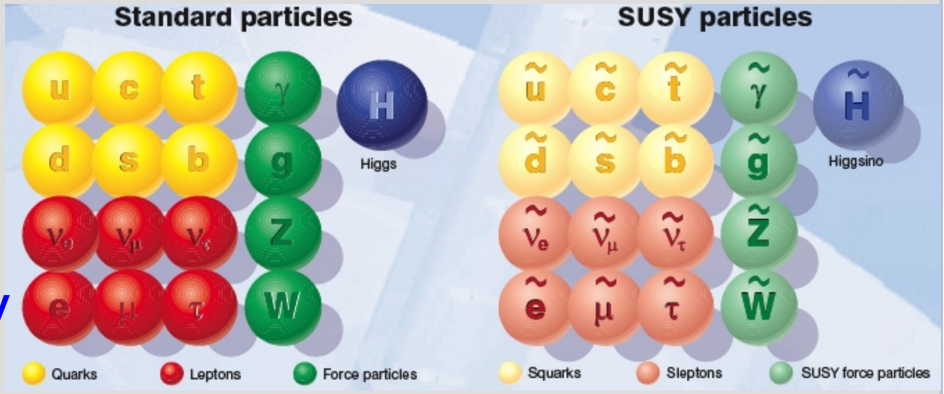
$$\Omega_\chi h^2 \approx \text{const.} \frac{T_0^3}{M_{Pl}^3 \langle \sigma_A v \rangle} \approx \frac{0.1\text{pb}}{\langle \sigma_A \; v/c \rangle}$$

O(1) when $\sigma_A \sim 10^{-36}$ cm² → weak scale

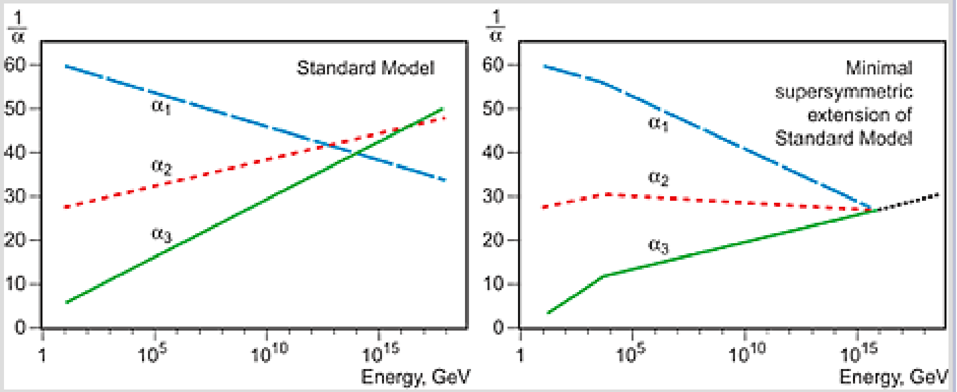
# SUSY and the WIMP

SUSY was introduced to solve Standard Model problems
(i.e. hierarchy problem, Higgs mass)

New fundamental space-time symmetry between fermions and bosons

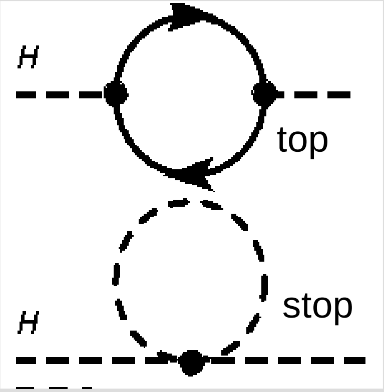



R-parity avoids B/L number violation:



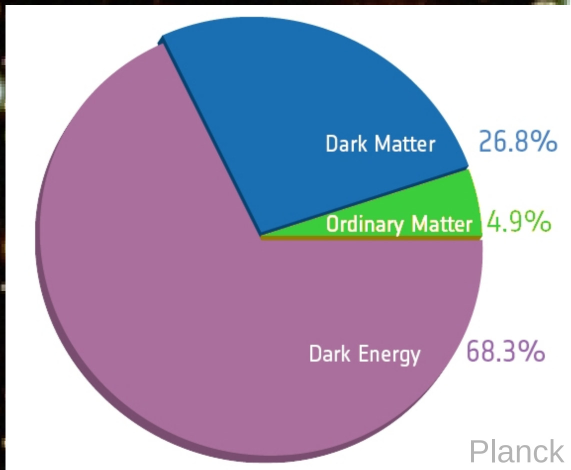

$$R = (-1)^{(3B+L+2S)}$$

→ lightest supersymmetric particle (LSP) is stable → cold DM candidate:
WIMP = weakly interacting massive particle

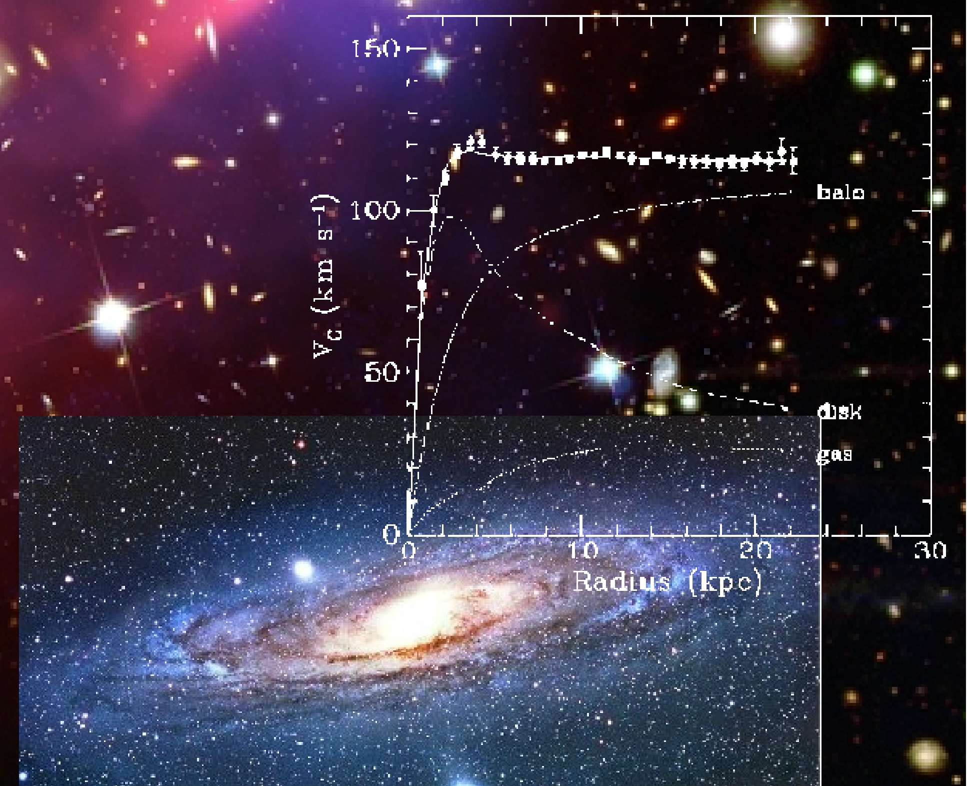


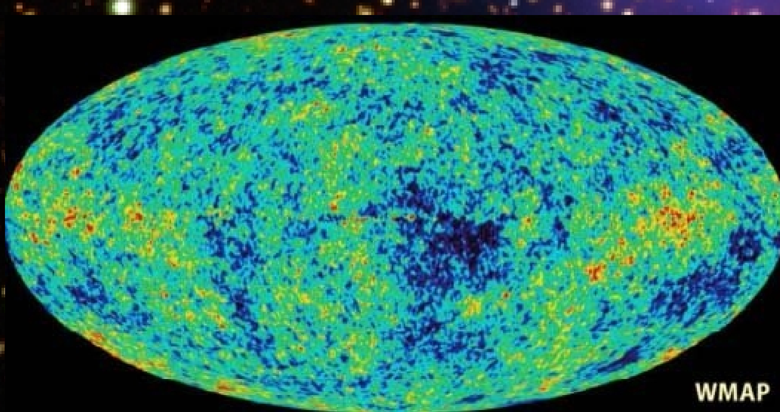

Neutralino: $$\tilde{\chi}_1^0 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}_3^0 + N_{13}\tilde{H}_d^0 + N_{14}\tilde{H}_u^0$$

# Dark Matter: (indirect) Evidence

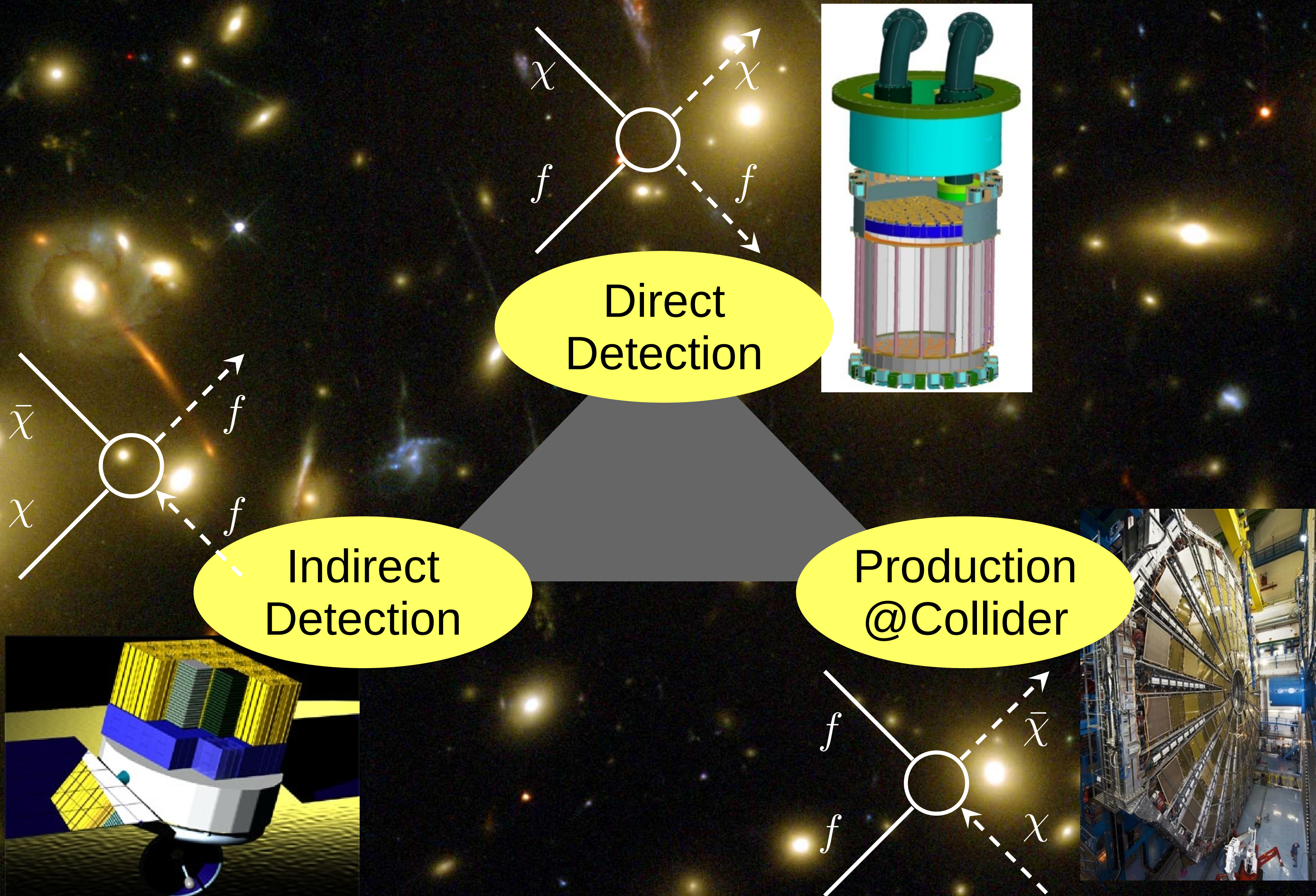



Particle Dark Matter Candidates:
– WIMP → *„WIMP miracle“*
– Axion
– SuperWIMPs
– sterile neutrinos
– WIMPless dark matter
– Gravitino
– ...



# Dark Matter Search

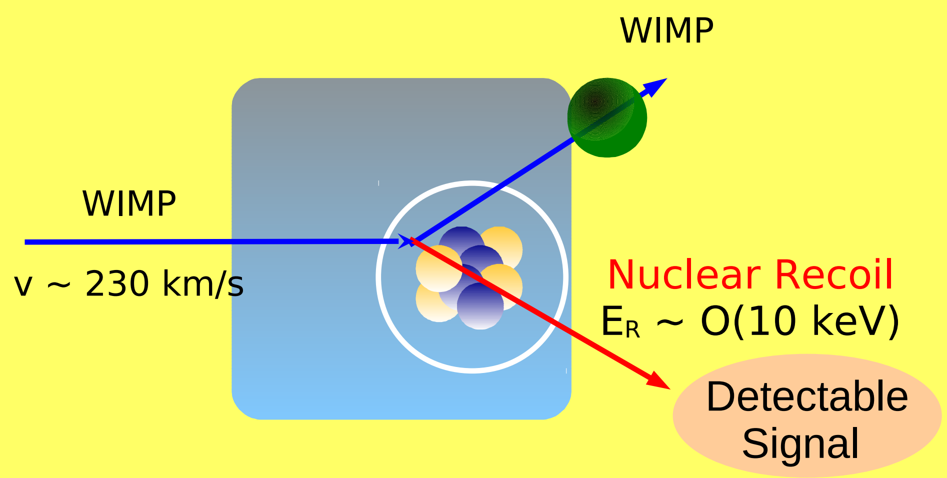


# Direct WIMP Search

Elastic Scattering of
WIMPs off target nuclei

# Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil




Recoil Energy: $$E_r = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1-\cos\theta) \sim \mathcal{O}(10\ \mathrm{keV})$$

Event Rate: $$R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi-N} \rangle$$

$N$ number of target nuclei
$\rho_\chi/m_\chi$ local WIMP number density
$\langle\sigma\rangle$ velocity-averaged scatt. X-section

Detector

Local DM Density

$\rho_\chi \sim 0.3$ GeV/$c^2$

Physics

# Direct WIMP Search

**Summary:** Tiny Rates

$R$ < 0.01 evt/kg/day

$E_R$ < 100 keV

Recoil Energy: $E_r \sim \mathcal{O}(10\ \mathrm{keV})$

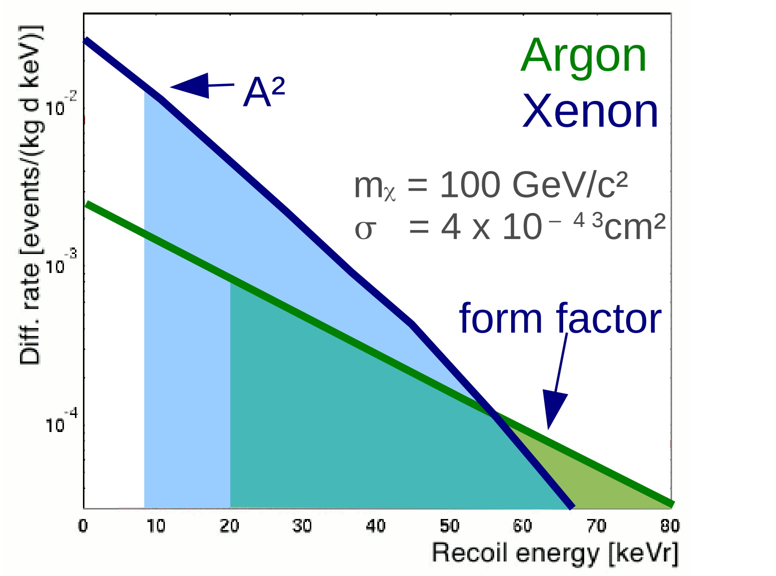
Event Rate: $R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi-N} \rangle$

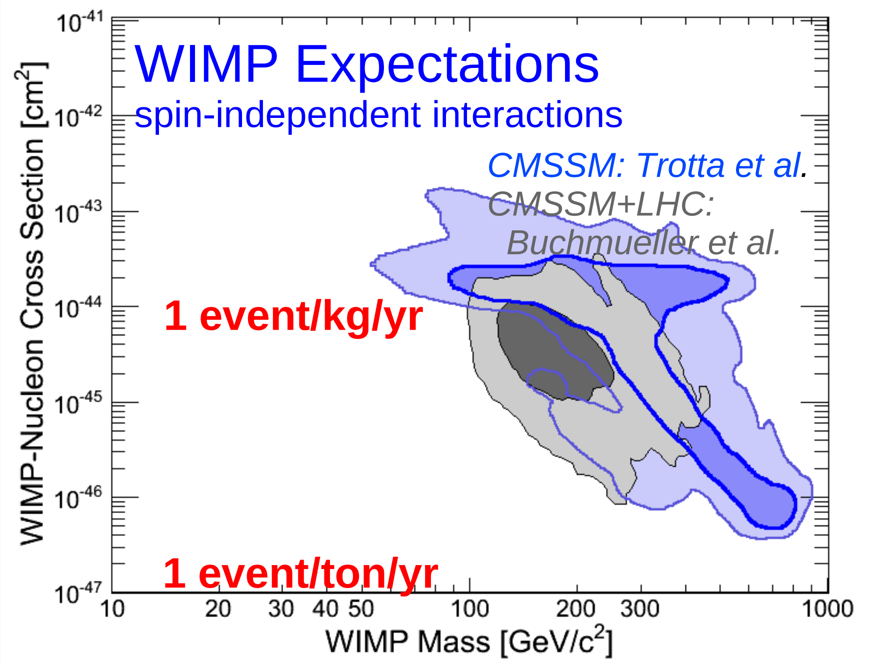
Detector

Local DM Density

$\rho_\chi$~0.3 GeV/c²

Physics



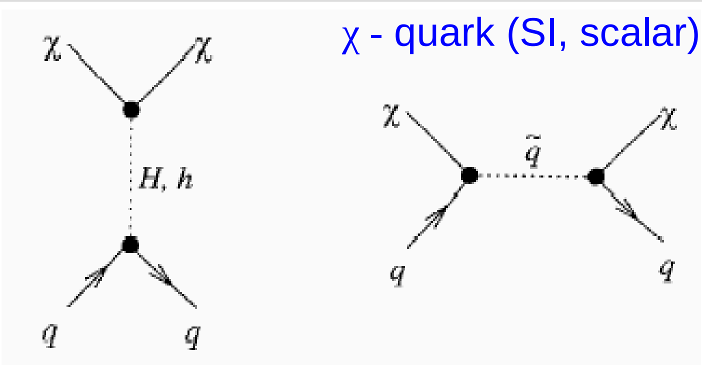



# WIMP-Nucleon Interactions

For this talk, we assume that the dark matter particle is a
**WIMP = weakly interacting massive particle**

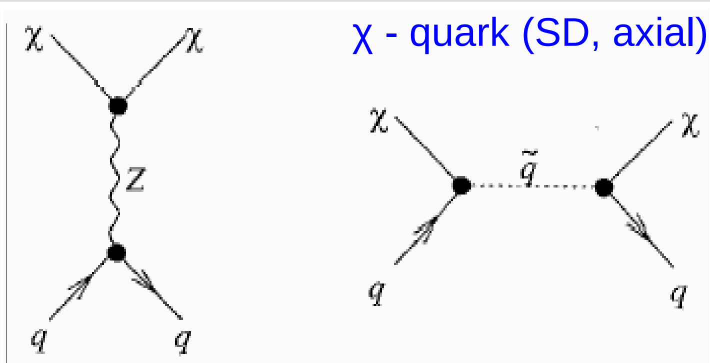
A priori, we do not know how dark matter WIMPs interact with ordinary matter (detector, Sun, ...)

## Spin independent




$$\mathcal{L}_S \sim \tilde{\chi}\chi\bar{q}q \quad \propto A^2$$

## Spin dependent




$$\mathcal{L}_A \sim \tilde{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu\gamma_5 q \quad \propto J(J+1)$$

Jungmann et al. '96 Phys.Rep.

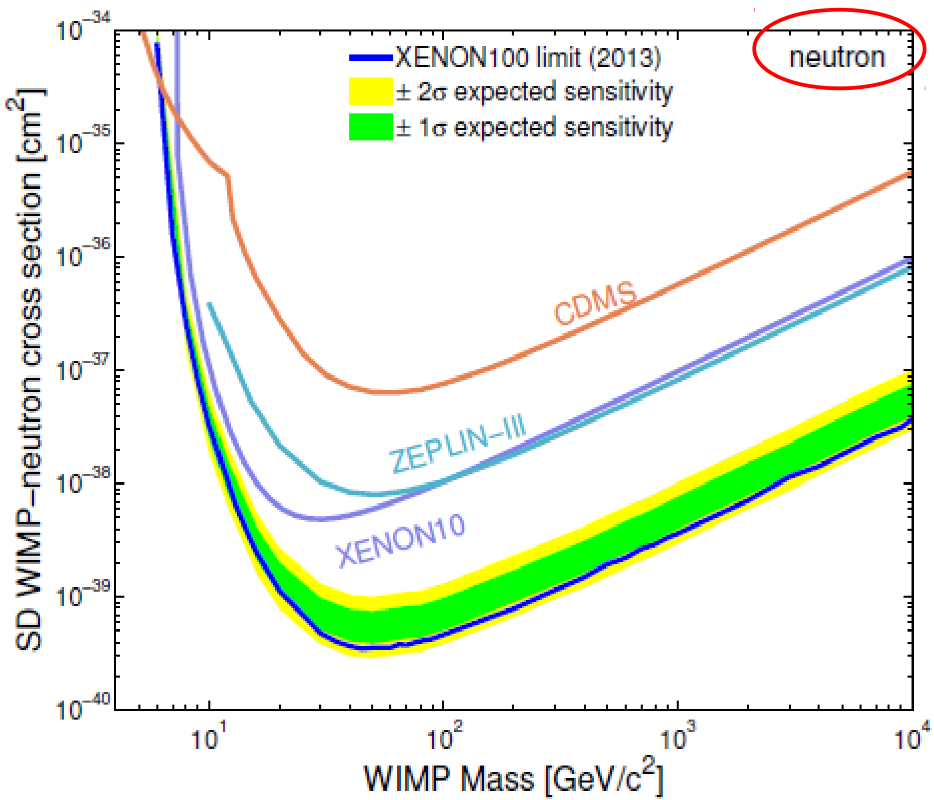
$$\frac{d\sigma}{d|\mathbf{q}|^2} = \frac{C_{spin}}{v^2} G_F^2 \frac{S(|\mathbf{q}|)}{S(0)}$$

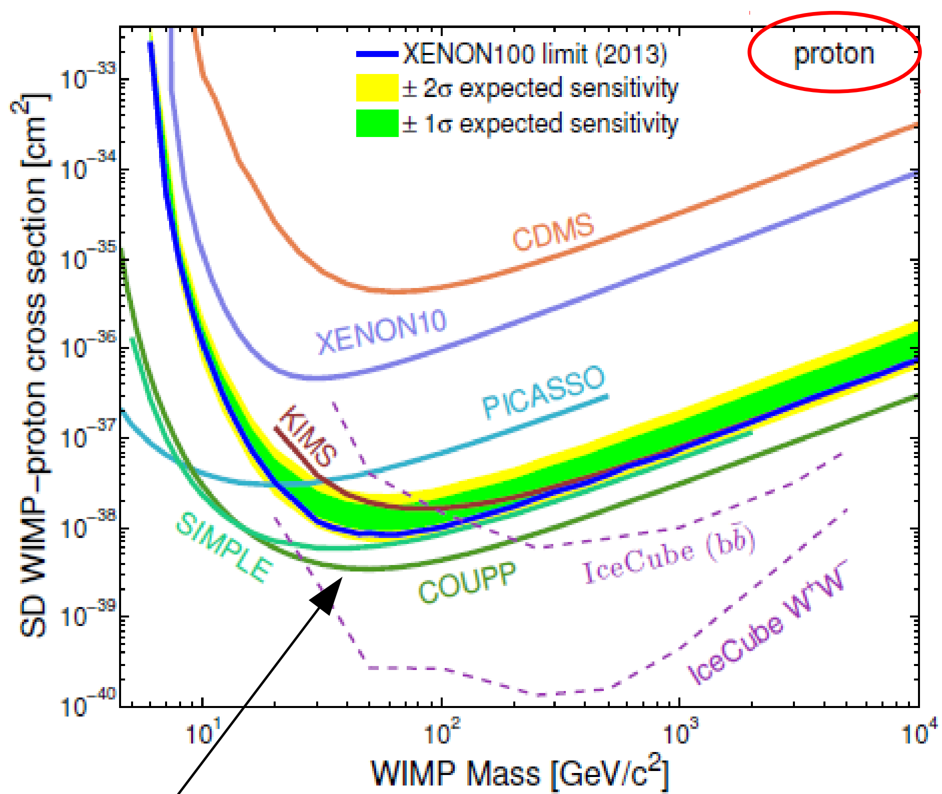
$$C_{spin} = \frac{8}{\pi}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2 \frac{J+1}{J}$$

often: express SD results in proton-only or neutron-only

# Spin-dependent Sensitivity

spin-dependent, elastic interactions

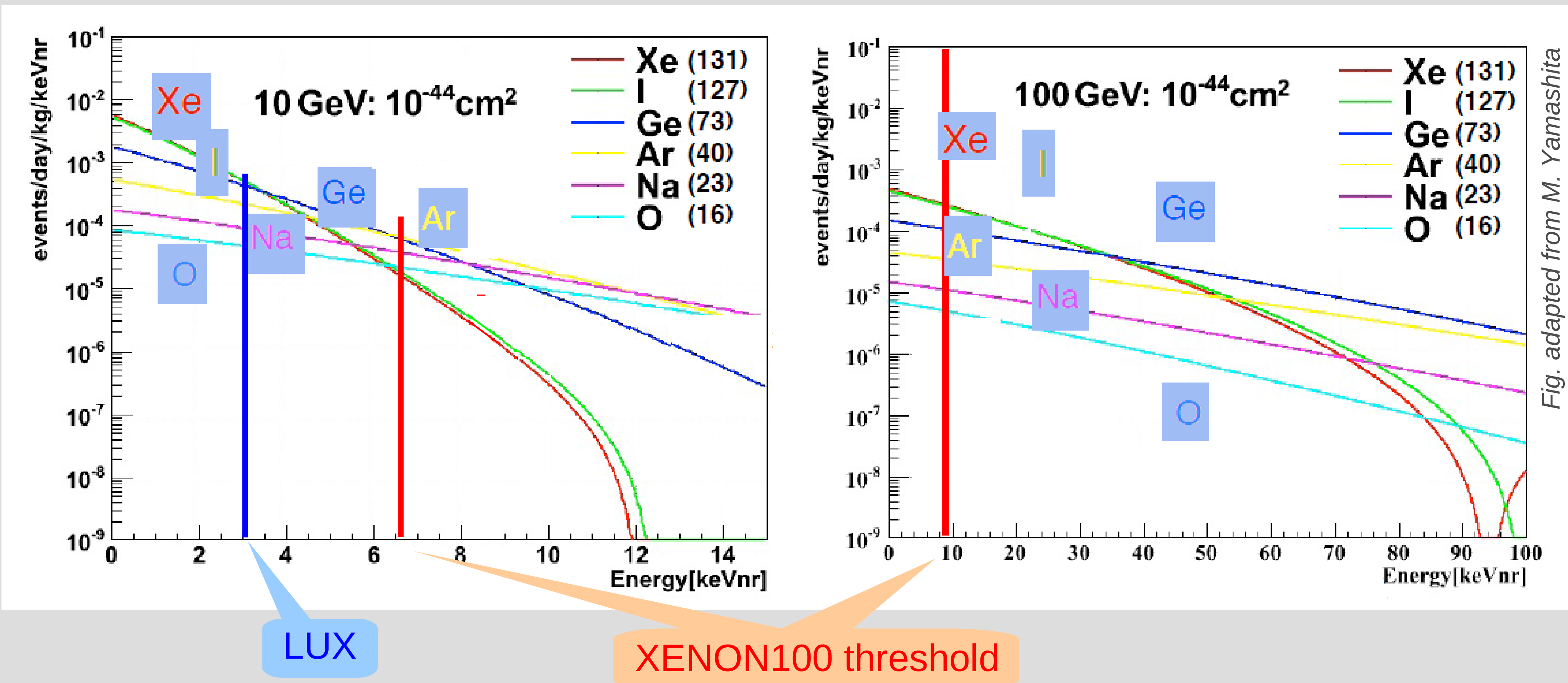



*PRL 111, 021301 (2013)*

$^{19}$F targets

# Light and heavy WIMPs




At a given $E_{nr}$, sensitivity to low mass WIMPs is higher for light targets

→ need low threshold

→ lower sensitivity can be (to some extent) compensated by target mass

(CoGeNT: 0.33 kg, XENON100: 34.0 kg → factor ~100)

# Direct WIMP Search

**Summary: Tiny Rates**

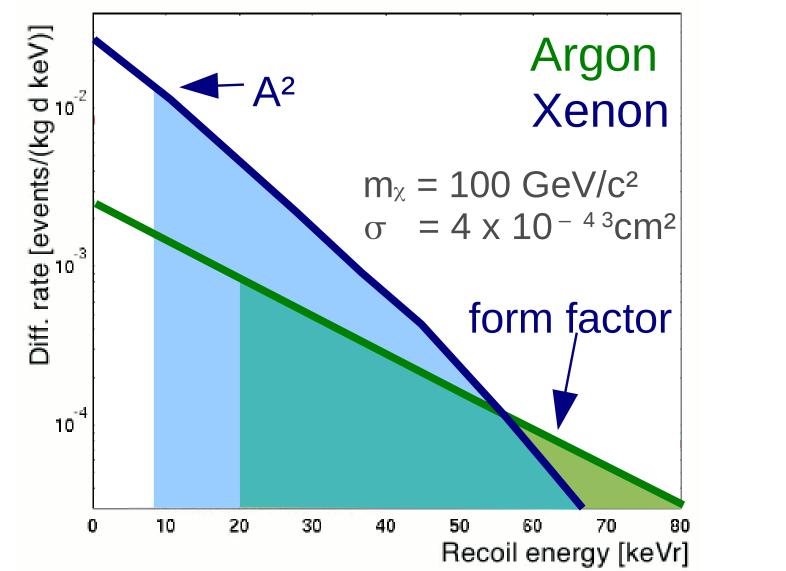
$R < 0.01$ evt/kg/day

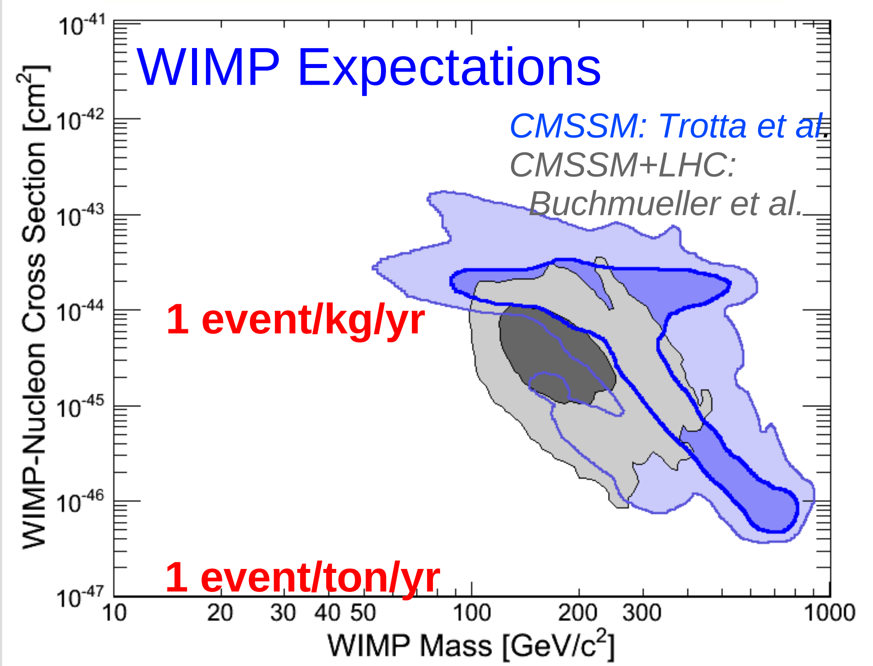
$E_R < 100$ keV

## How to build a WIMP detector?

- large total mass, high *A*
- low energy threshold
- ultra low background
- good background discrimination

We are dealing with
- extremely **low rates** (1 – 1000 Hz)
- extremely **low thresholds** (2 keV)
- extremely **low radioactive** backgrounds



# Backgrounds

## Experimental Sensitivity

without background: $\propto (mt)^{-1}$
with background: $\propto (mt)^{-1/2}$

## Background Sources

environment: U, Th chains, K

$^{238}U \xrightarrow[\alpha]{} {}^{234}Th \xrightarrow[\beta]{} {}^{234m}Pa \xrightarrow[\beta]{} {}^{234}U \xrightarrow[\alpha]{} {}^{230}Th \xrightarrow[\alpha]{} {}^{226}Ra \xrightarrow[\alpha]{} {}^{222}Rn \xrightarrow[\alpha]{} {}^{218}Po \ldots$

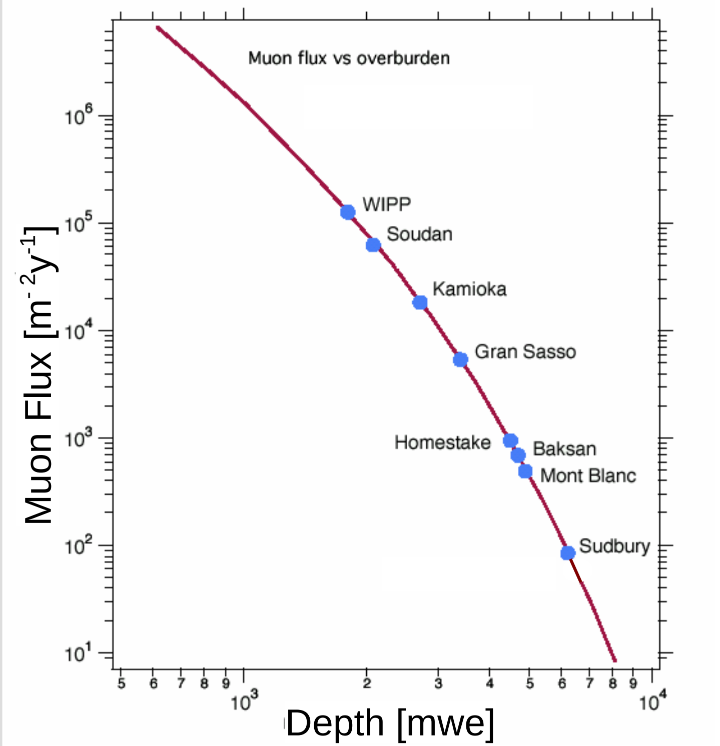
$^{232}Th \xrightarrow[\alpha]{} {}^{228}Ra \xrightarrow[\beta]{} {}^{228m}Ac \xrightarrow[\beta]{} {}^{228}Th \xrightarrow[\alpha]{} {}^{224}Ra \xrightarrow[\alpha]{} {}^{220}Rn \xrightarrow[\alpha]{} {}^{216}Po \ldots$

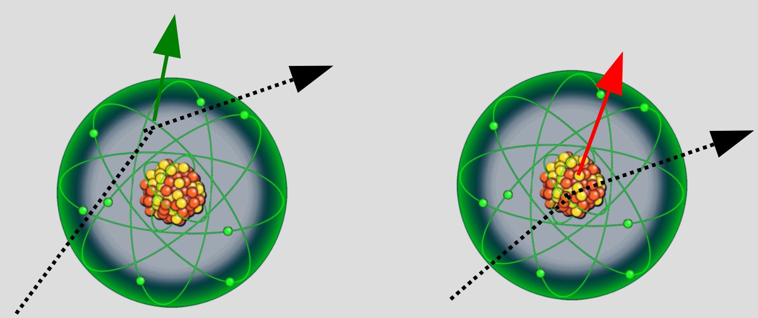
- $\gamma$ and $\beta$ Decays (electronic recoil)
  → „intrinsic“ bg most dangerous (Kr85, Rn222)

- neutrons from ($\alpha$,n) and sf in rocks and detector parts

- neutrons from cosmic ray muons

Muon reduction in underground laboratory

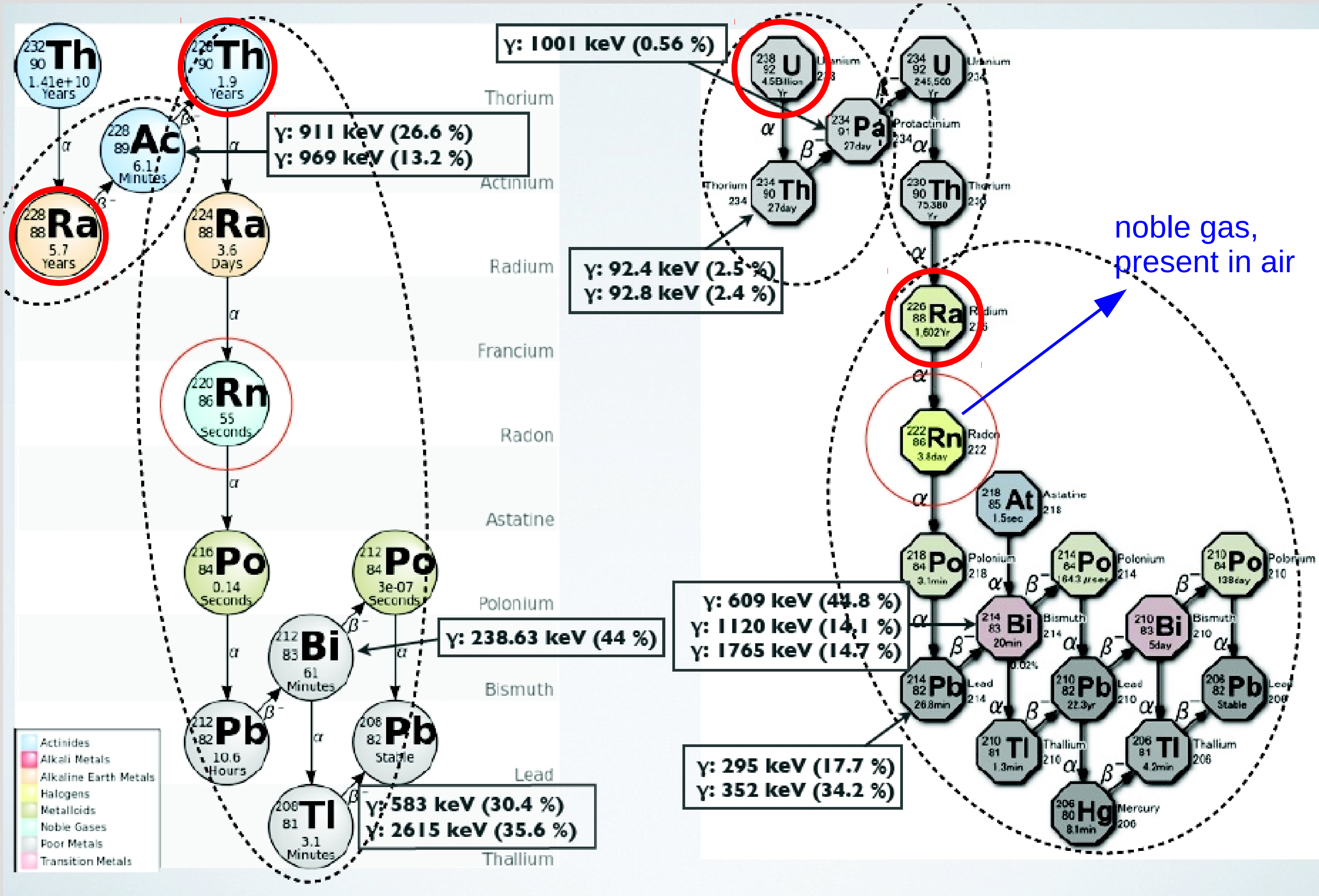


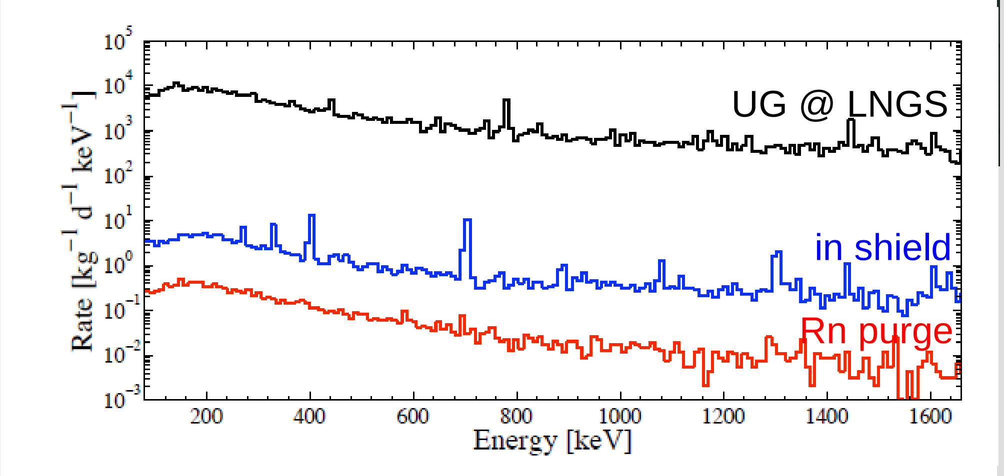
**Electronic Recoils** (gamma, beta)

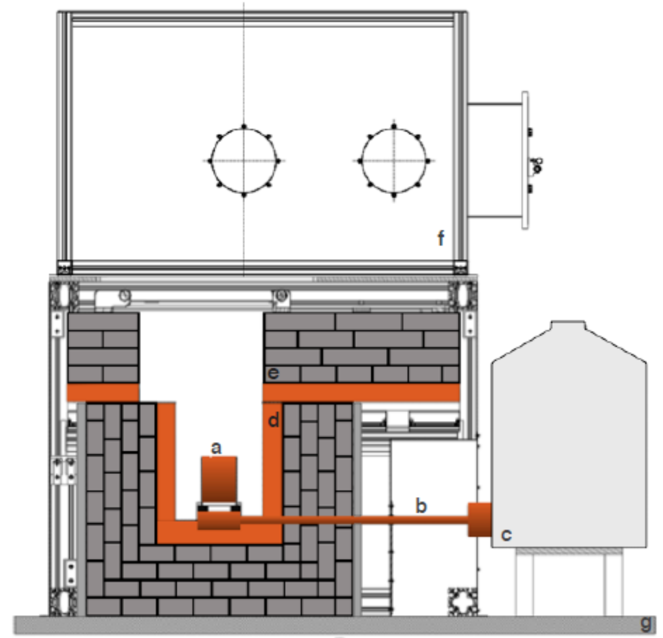
**Nuclear Recoils** (neutron, WIMPs)

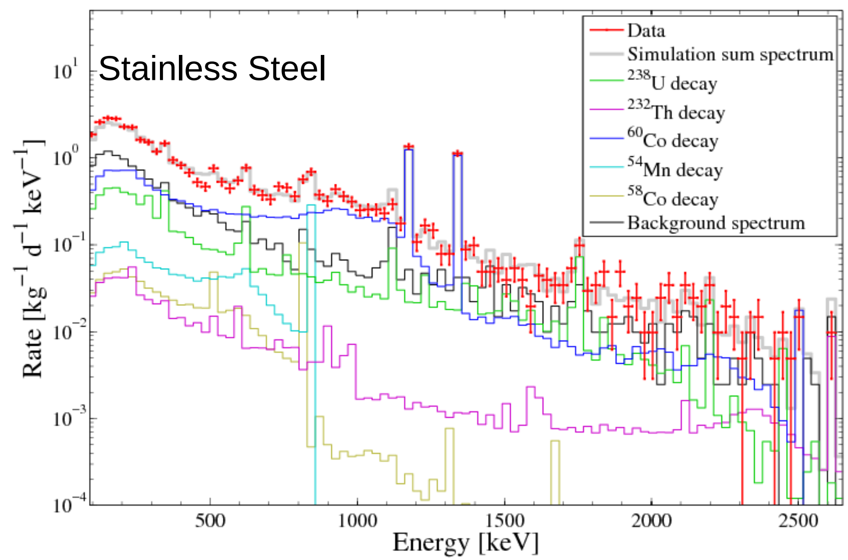
# The U and Th Chains



# Gamma Ray Screening

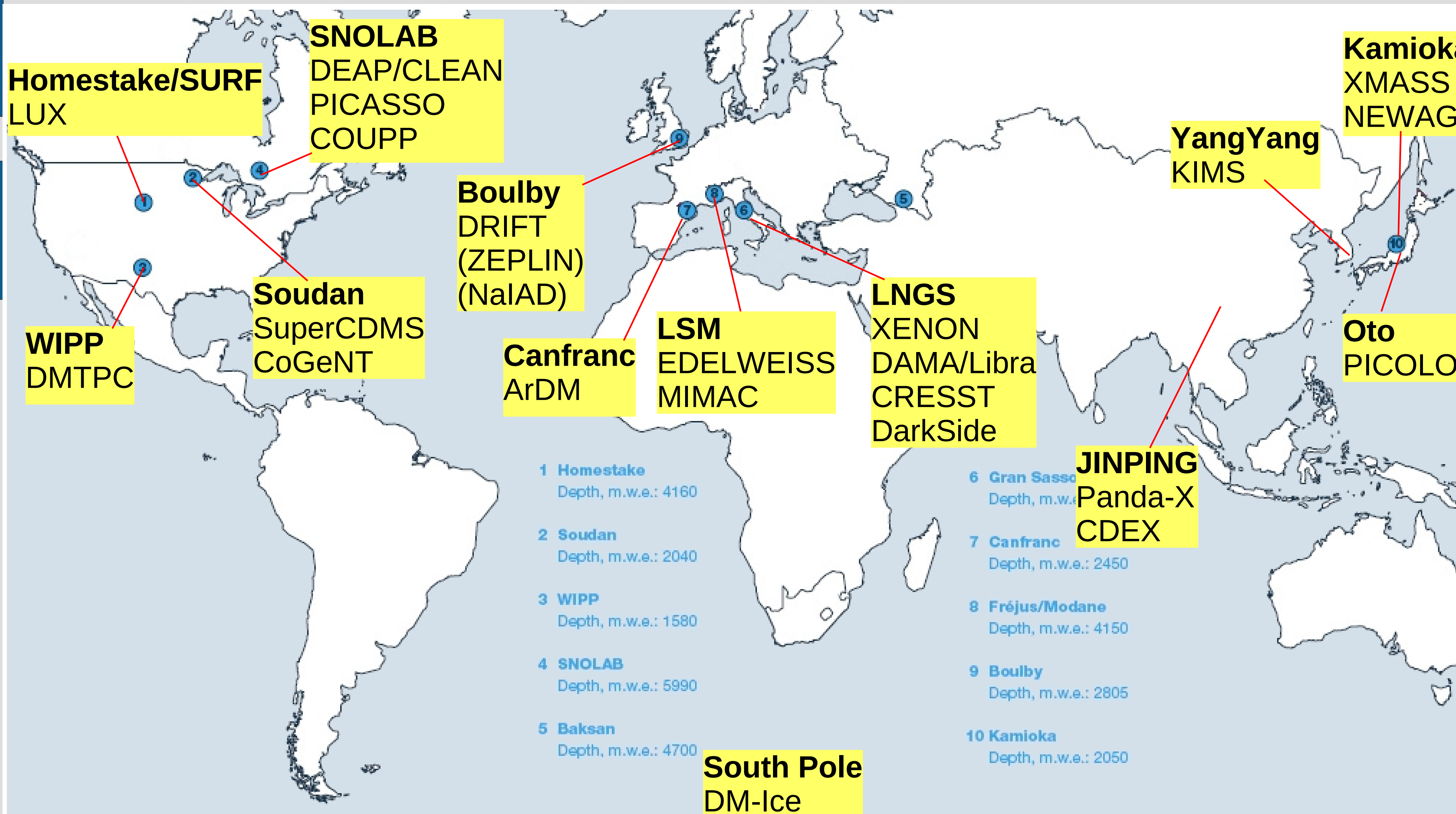




JINST 6, P08010 (2011)


ALARM
OSSIGENO OXYGEN
LVD ZONE

# Laboratori Nazionali del Gran Sasso


# World-wide Efforts



# Background Suppression

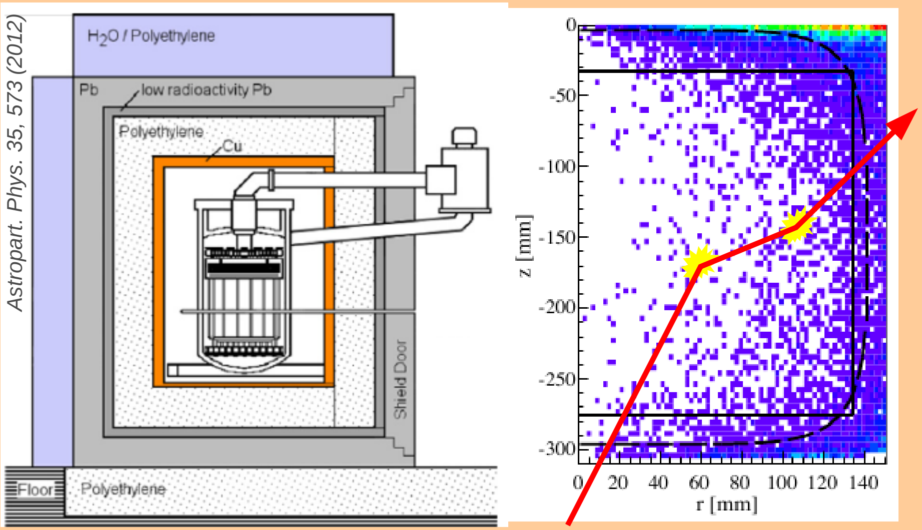
A Avoid Backgrounds

Use of radiopure materials

Shielding

deep underground location
large shield (Pb, water, poly)
active veto (μ, γ coincidence)

self shielding → fiducialization




B Use knowledge about expected WIMP signal

WIMPs interact only once

→ single scatter selection
require some position resolution

WIMPs interact with target nuclei

→ nuclear recoils
exploit different d*E*/d*x* from
signal and background

Current State-of-the-Art:
<1 evt/kg/year

Goal for future experiments:
~1 evt/ton/year

# Direct WIMP Detection

Crystals (NaI, Ge)
Cryogenic Detectors
Liquid Noble Gases

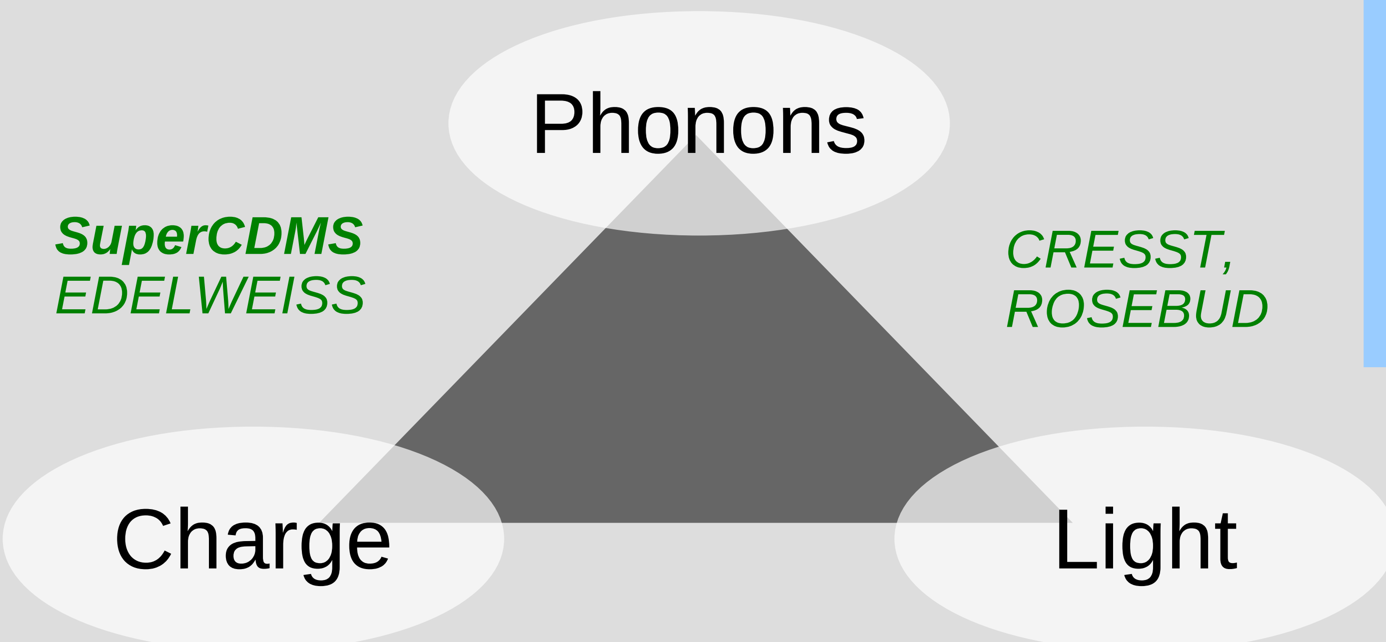
Tracking:
*DRIFT, DMTPC*
*MIMAC,*
*NEWAGE*

Superheated Liquids:
COUPP
PICASSO
PICO
SIMPLE

*CRESST-I*
*CUORE*

***SuperCDMS***
*EDELWEISS*

*CRESST,*
*ROSEBUD*



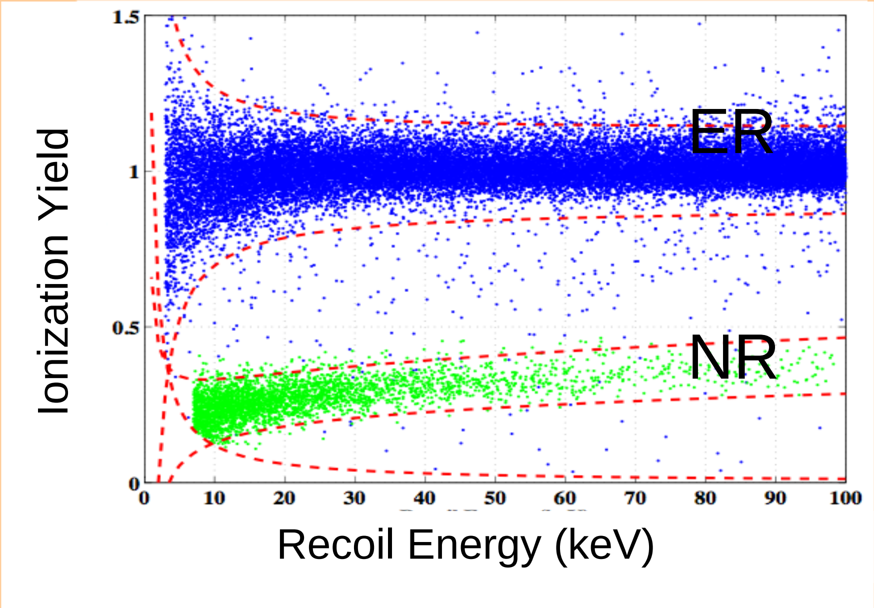

*CoGeNT*
*CDEX*
*Texono*
*Malbek*

***XENON**, **LUX***
*ArDM, Panda-X*
*ZEPLIN, Darkside*

*DEAP/CLEAN*
***DAMA**, KIMS*
*XMASS, DM-Ice,*
*Sabre*

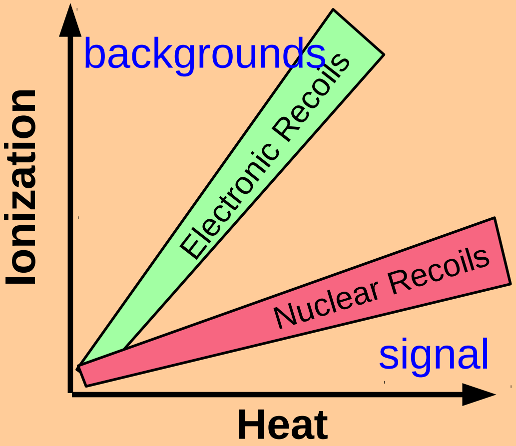
# 2 Observables for Discrimination

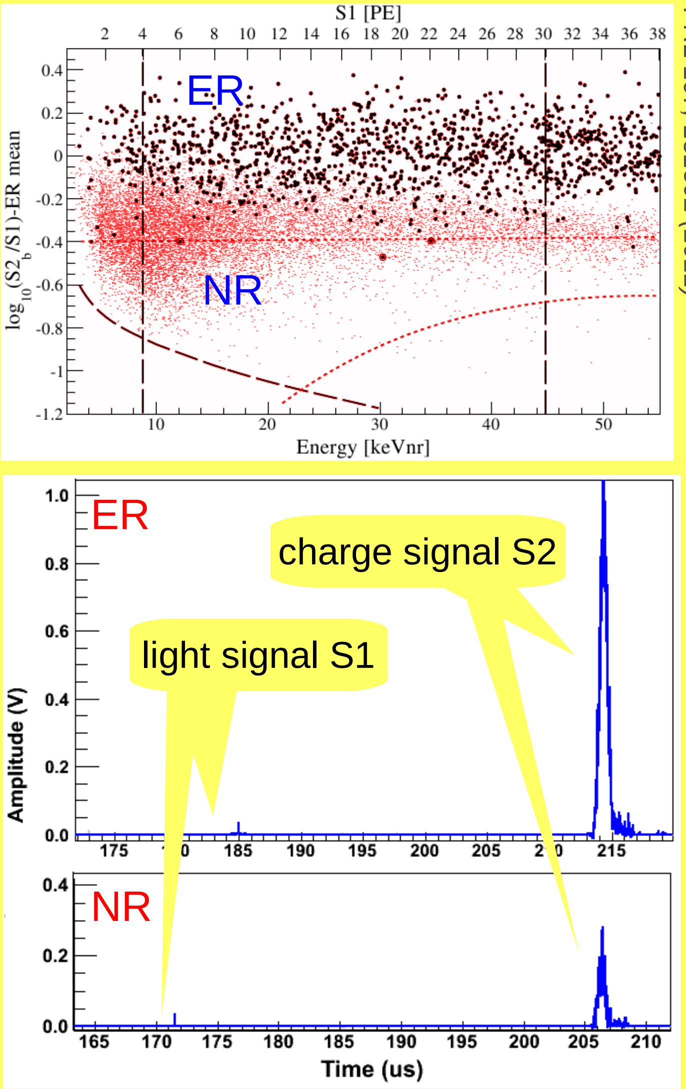
Ionization yield and Charge/Light ratio
depend on d*E*/d*x* → discrimination




**CDMS-II**
Discrimination O($10^{-5}$), large acceptance

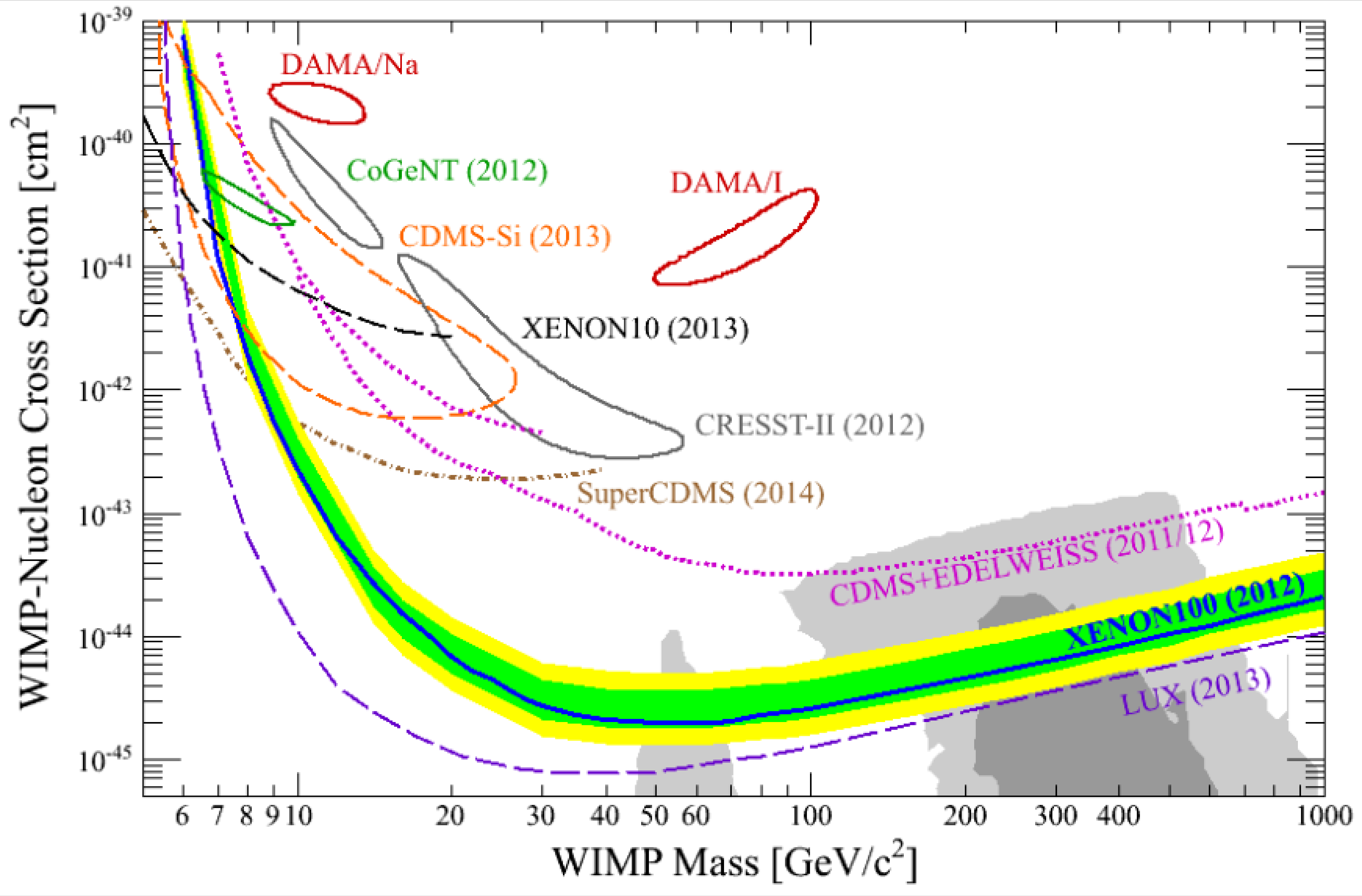
BUT: „surface events“
→ timing cut



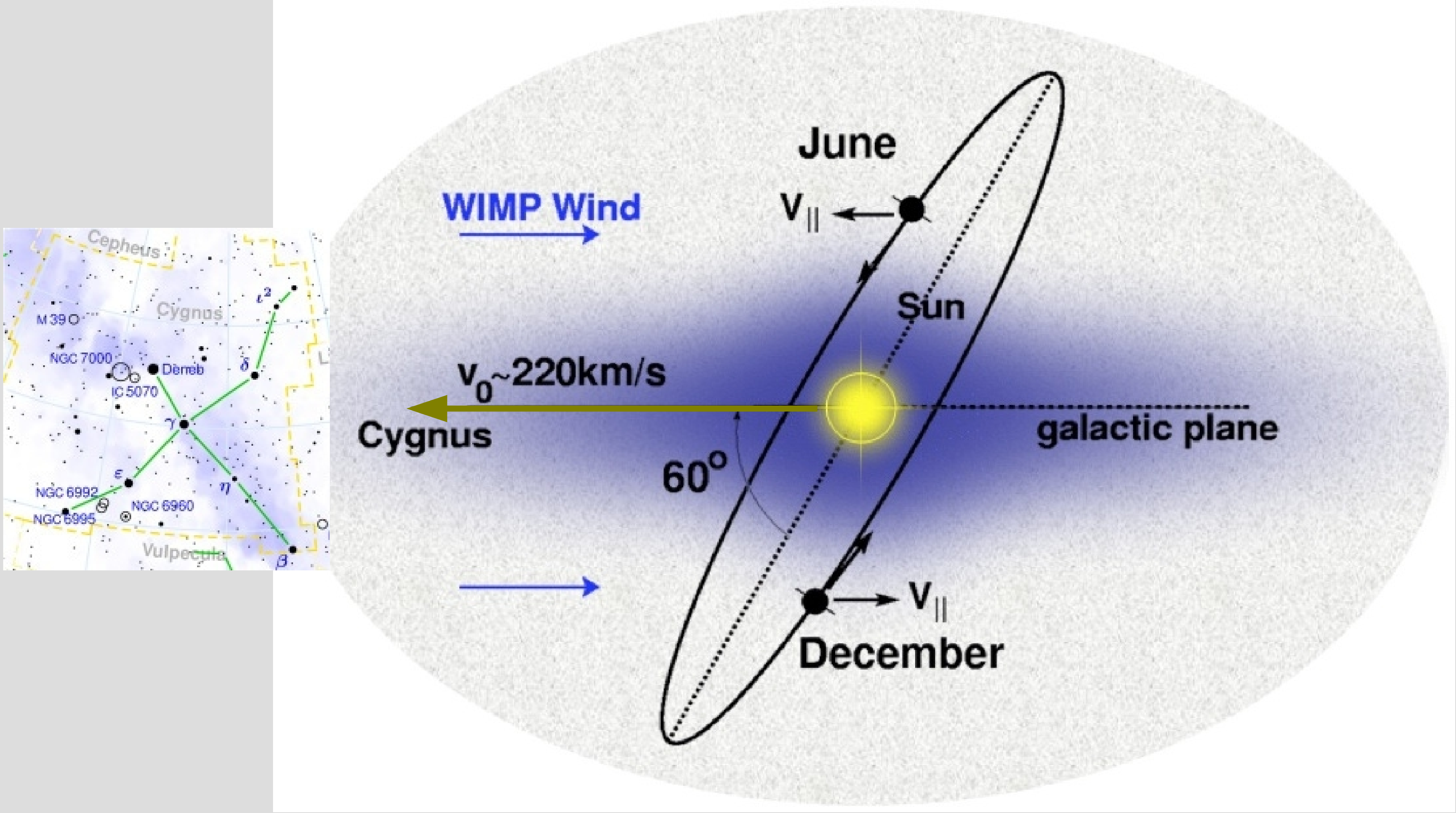




**XENON100**
~99.5% rejection @ 50% acceptance

# The current WIMP Landscape



# Annual Modulation

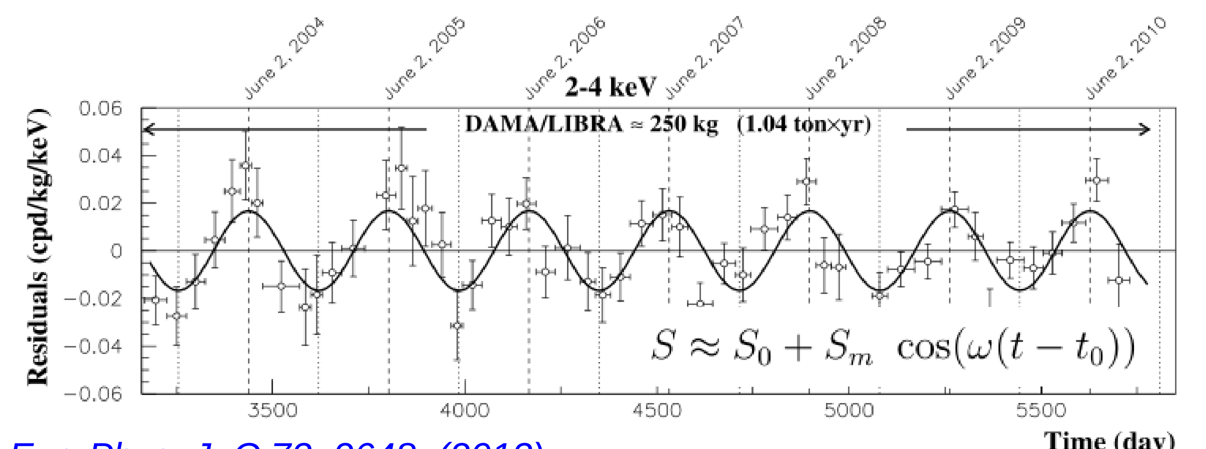



→recoil spectrum gets harder and softer during the year
→ search for annually modulating signal (3% effect)
→does not require many physical assumptions

# Annual Modulation: DAMA/Libra

- PMTs coupled to **NaI(Tl)** Scintillators @ LNGS
  → extremely clean background necessary
- looks for annual modulation (~3% effect)
- large mass and exposure: 1.17 ton years

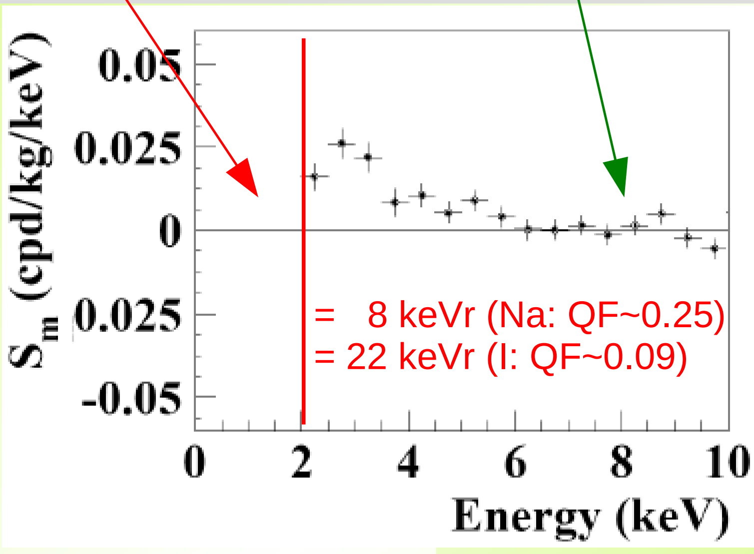
- DAMA finds annual modulation @ 8.9σ C.L.
- BUT: no ER/NR discrimination!




*Eur. Phys. J. C 73, 2648 (2013)*

what is here?

no modulation above 6 keV

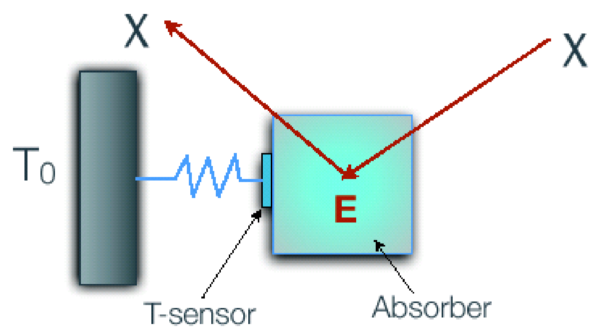


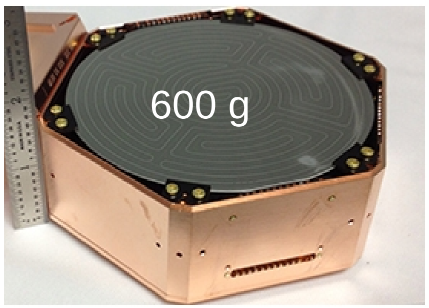

Interpretation as Dark Matter interaction
is in conflict with numerous other experiments

# SuperCDMS

@ Soudan Lab, Minnesota (USA) → later: SNOLAB

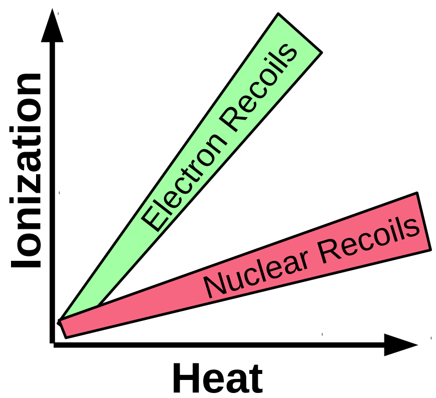
measure charge and heat (phonons):
  *E* deposition → temperature rise *ΔT*



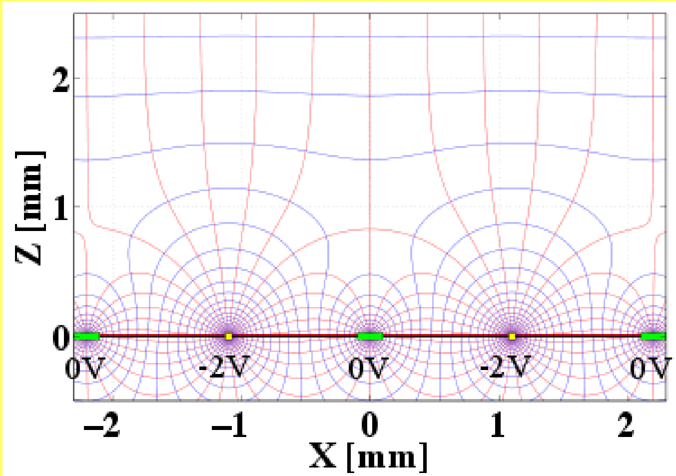

Crystals: **Ge**, **(Si)** cooled to few mK
– low heat capacity
– Δ*T* ~ μK

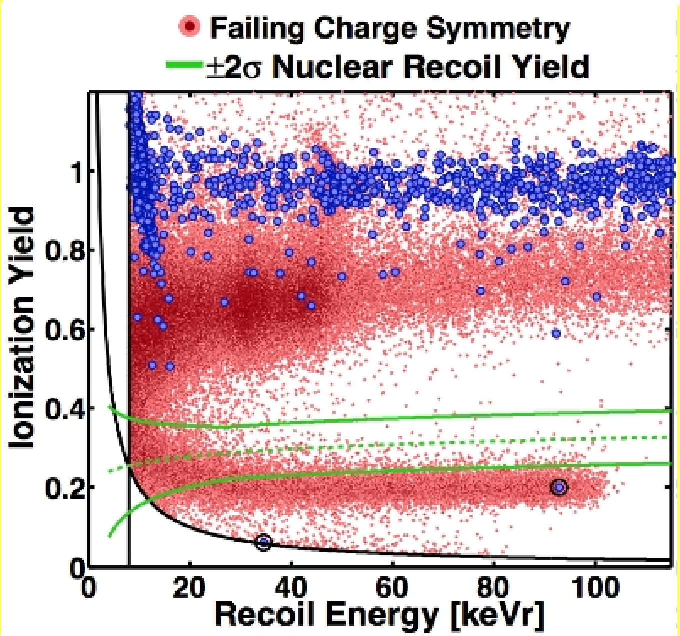
Very good discrimination
→ BUT: need to reject surface events




*similar: EDELWEISS (F)*
*combined result with CDMS-II: PRD 84, 011102 (2011)*

## Rejection of Surface Events

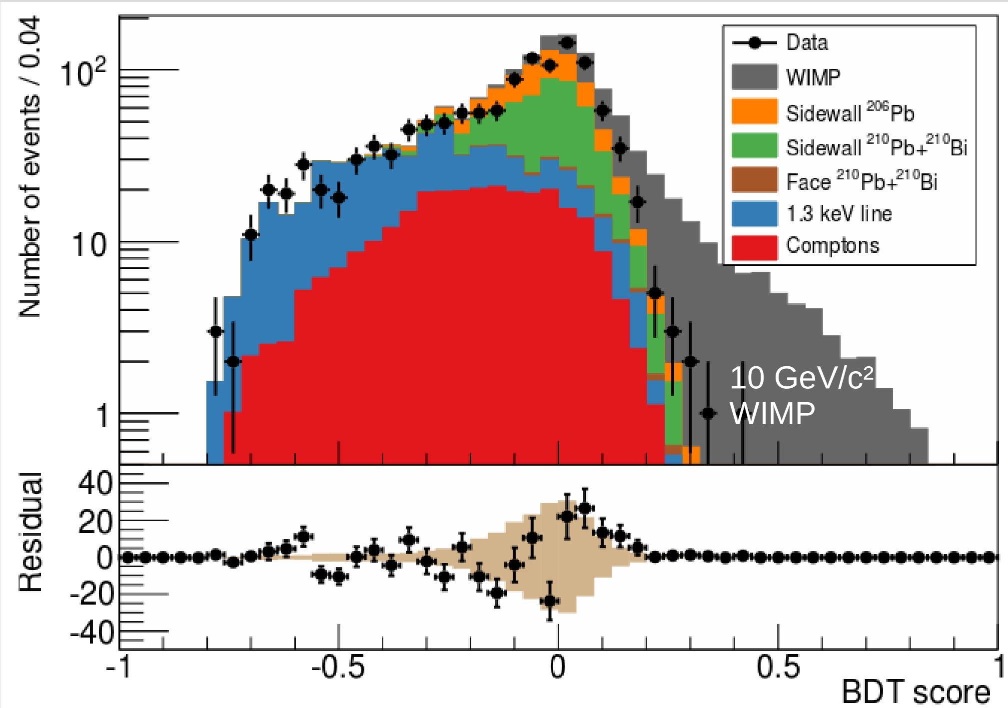


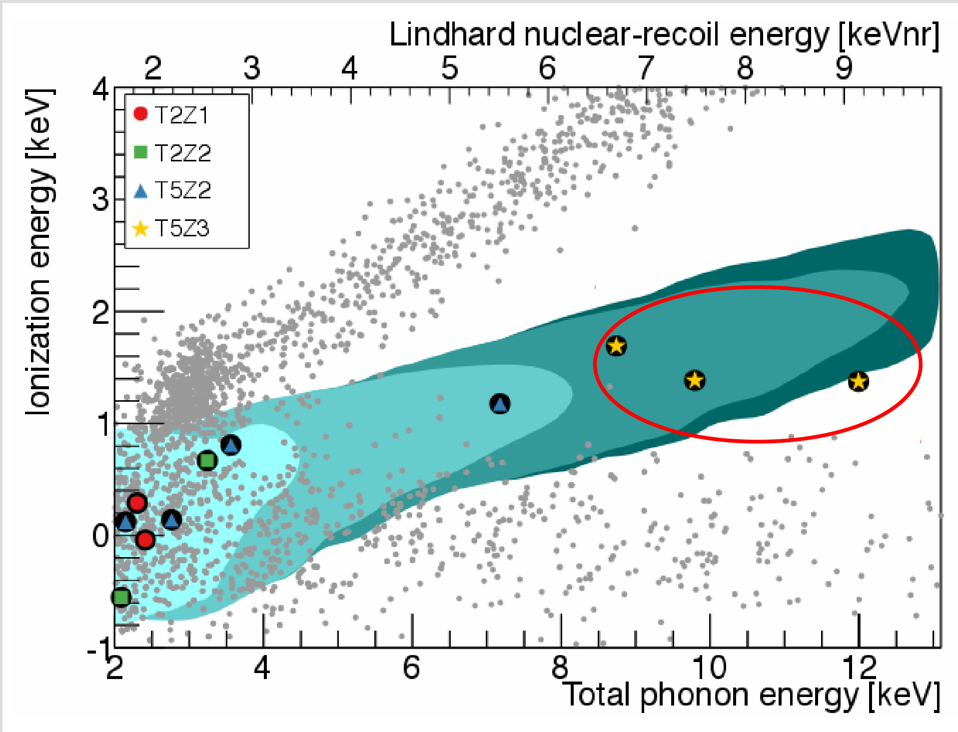




*Appl.Phys.Lett. 103 (2013) 164105*

# SuperCDMS: Results

*PRL 112, 241302 (2014)*



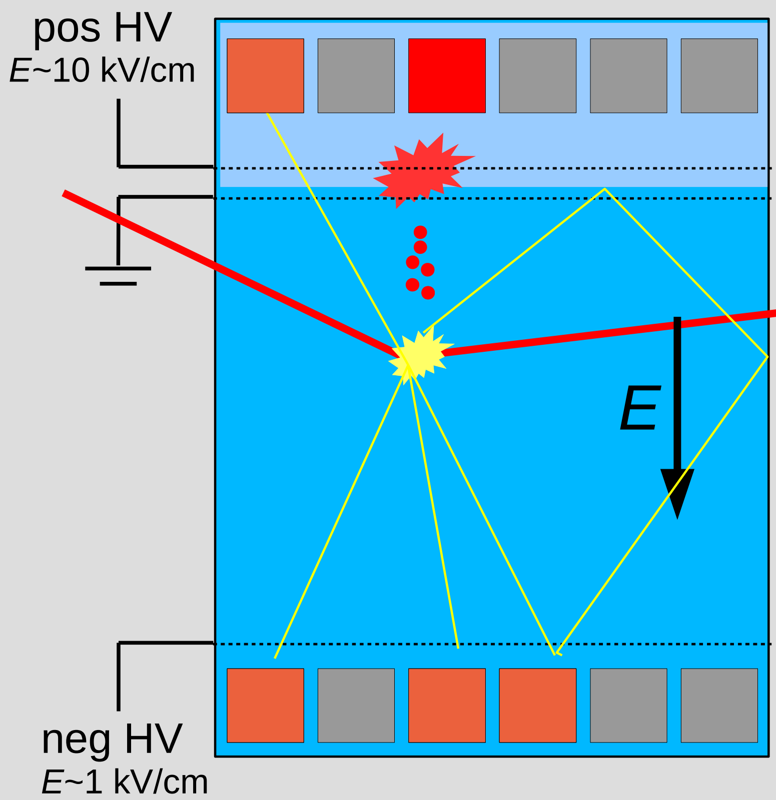



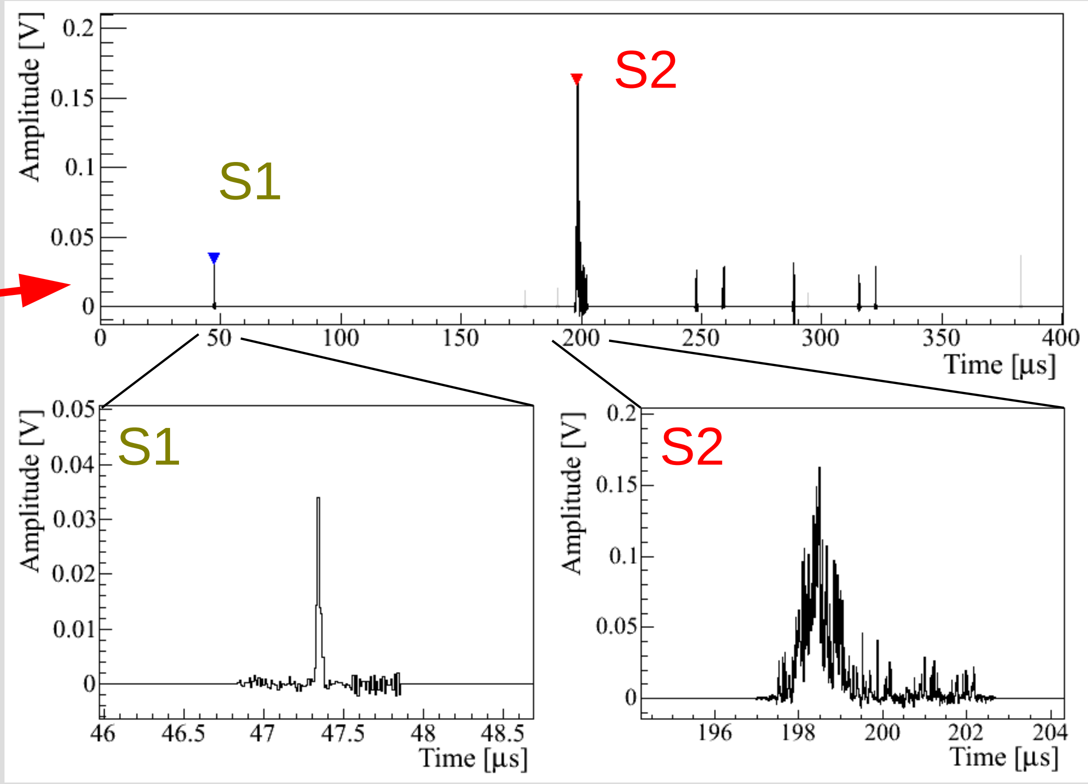

- 7 (out of 15) Ge detectors, 577 kg x day exposure
- 11 events observed after unblinding, 6.1 expected from (blind) background model
- lowest *E*-event is probably noise, 3 high-*E* events in same detector are suspicious
  (maybe non-perfect background model for this detector)
- still consider all events as candidate events and calculate a limit
  → weaker than expected at higher masses but very good at low masses

# Dual Phase TPC

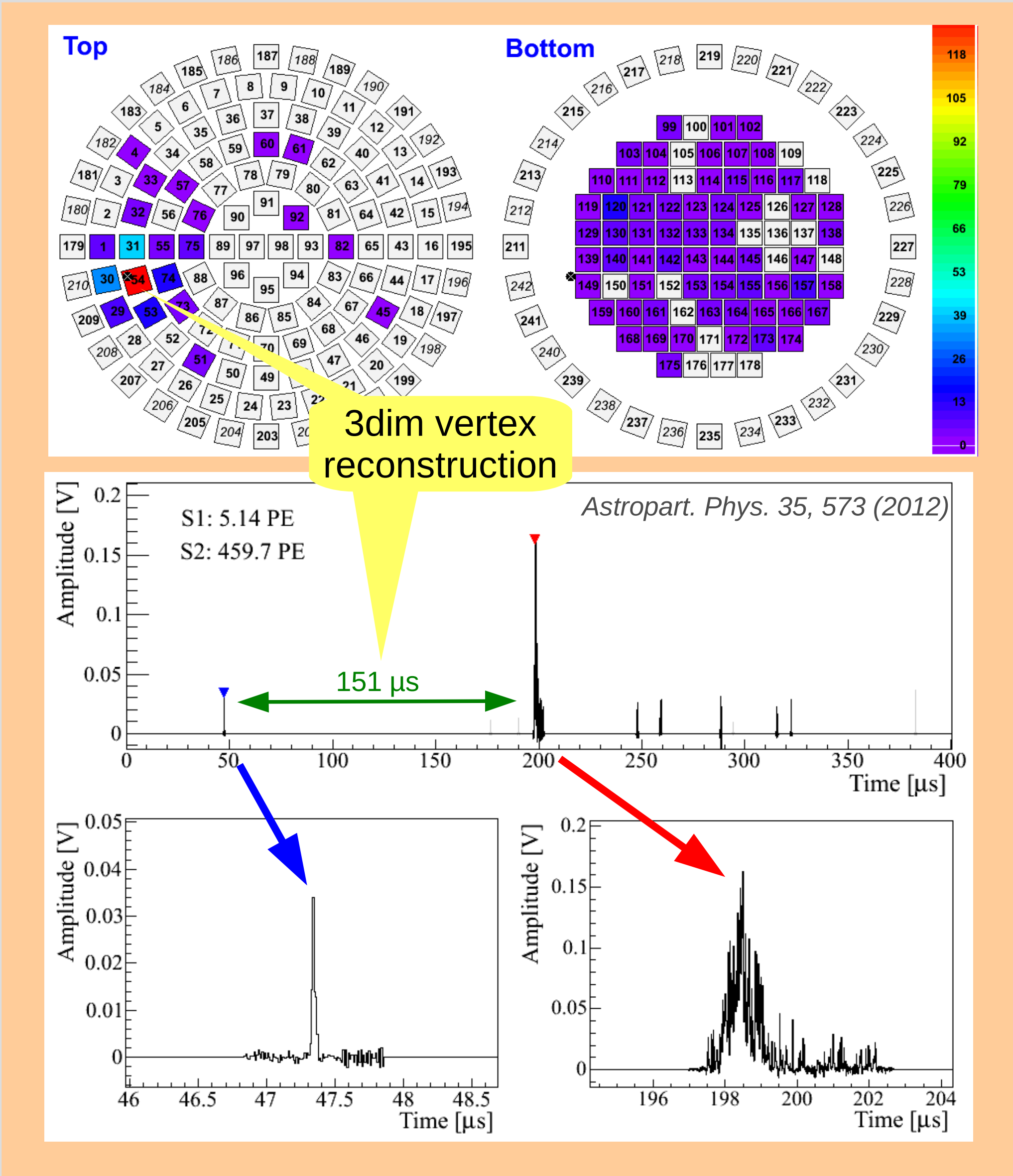
*Dolgoshein, Lebedenko, Rodionov, JETP Lett. 11, 513 (1970)*

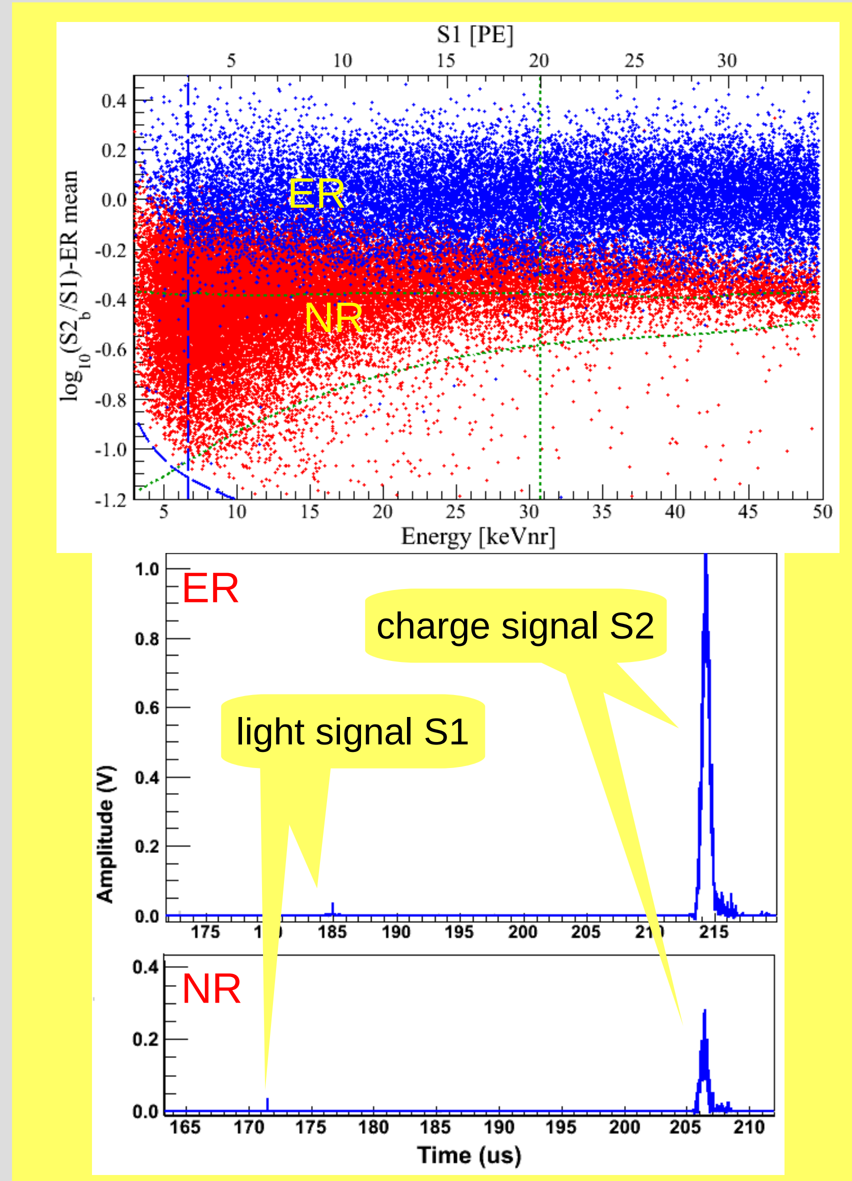
TPC = time projection chamber



# Dual Phase TPC

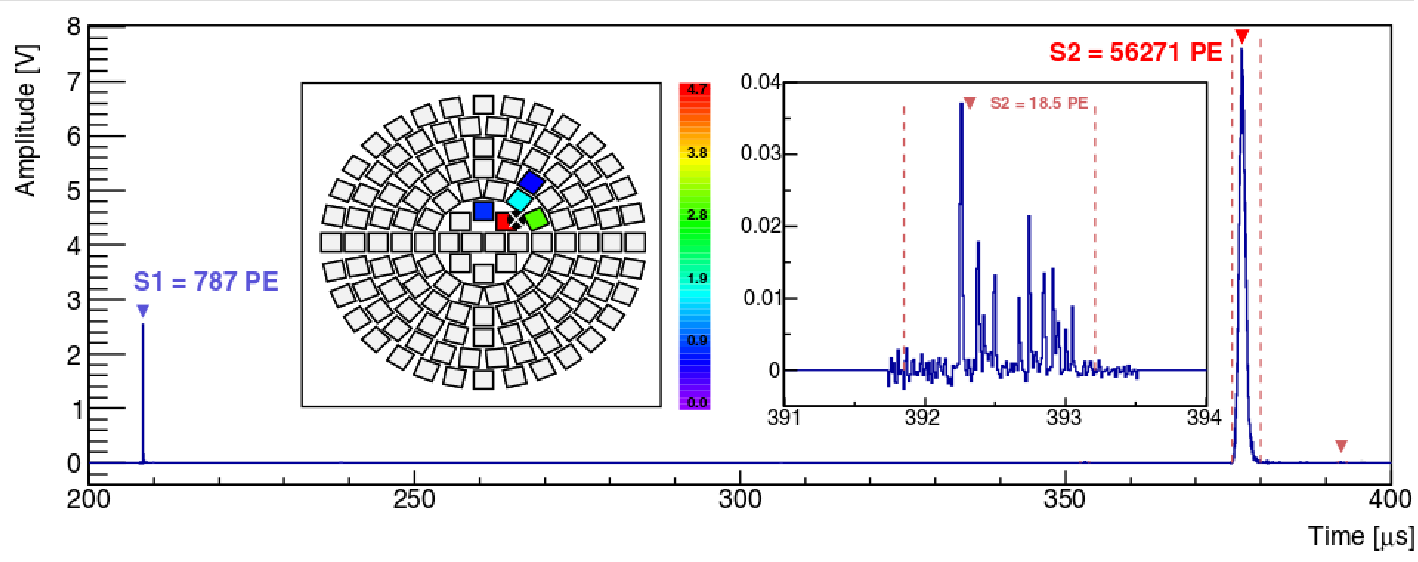


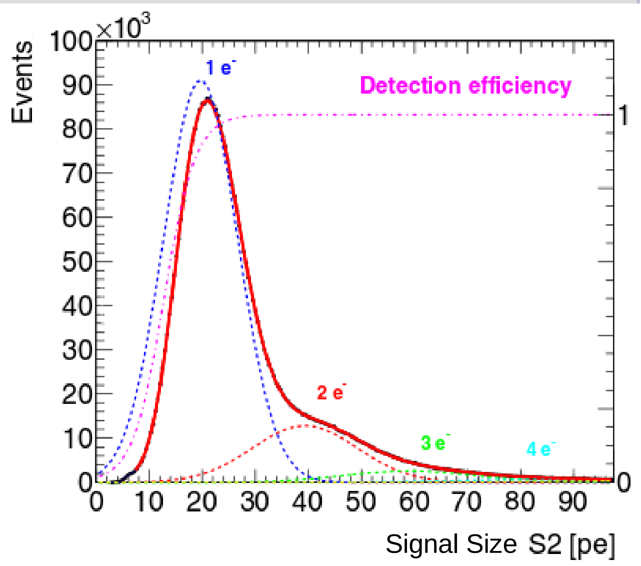



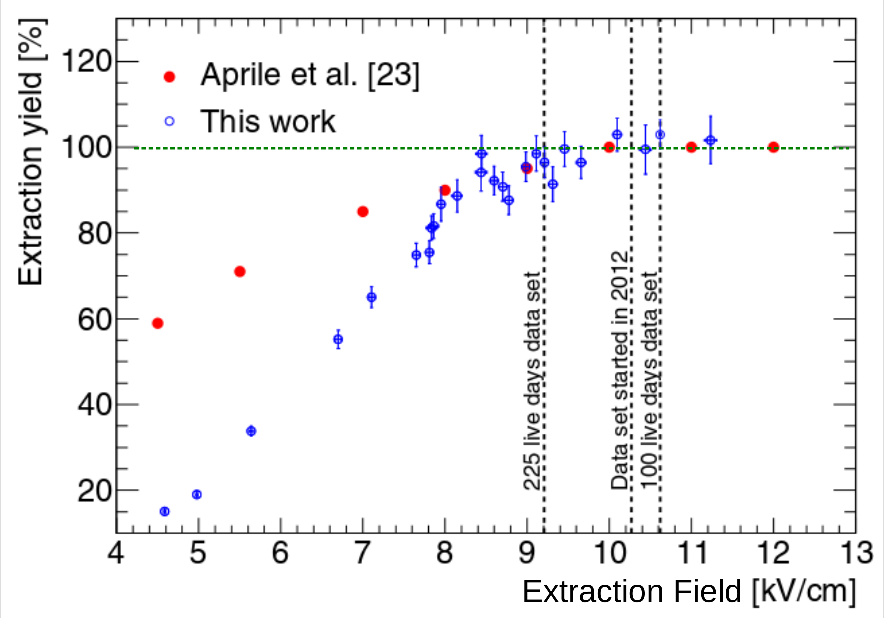

*Figures from XENON100*

# Single electron sensitivity

*J. Phys. G 41, 035201 (2014)*

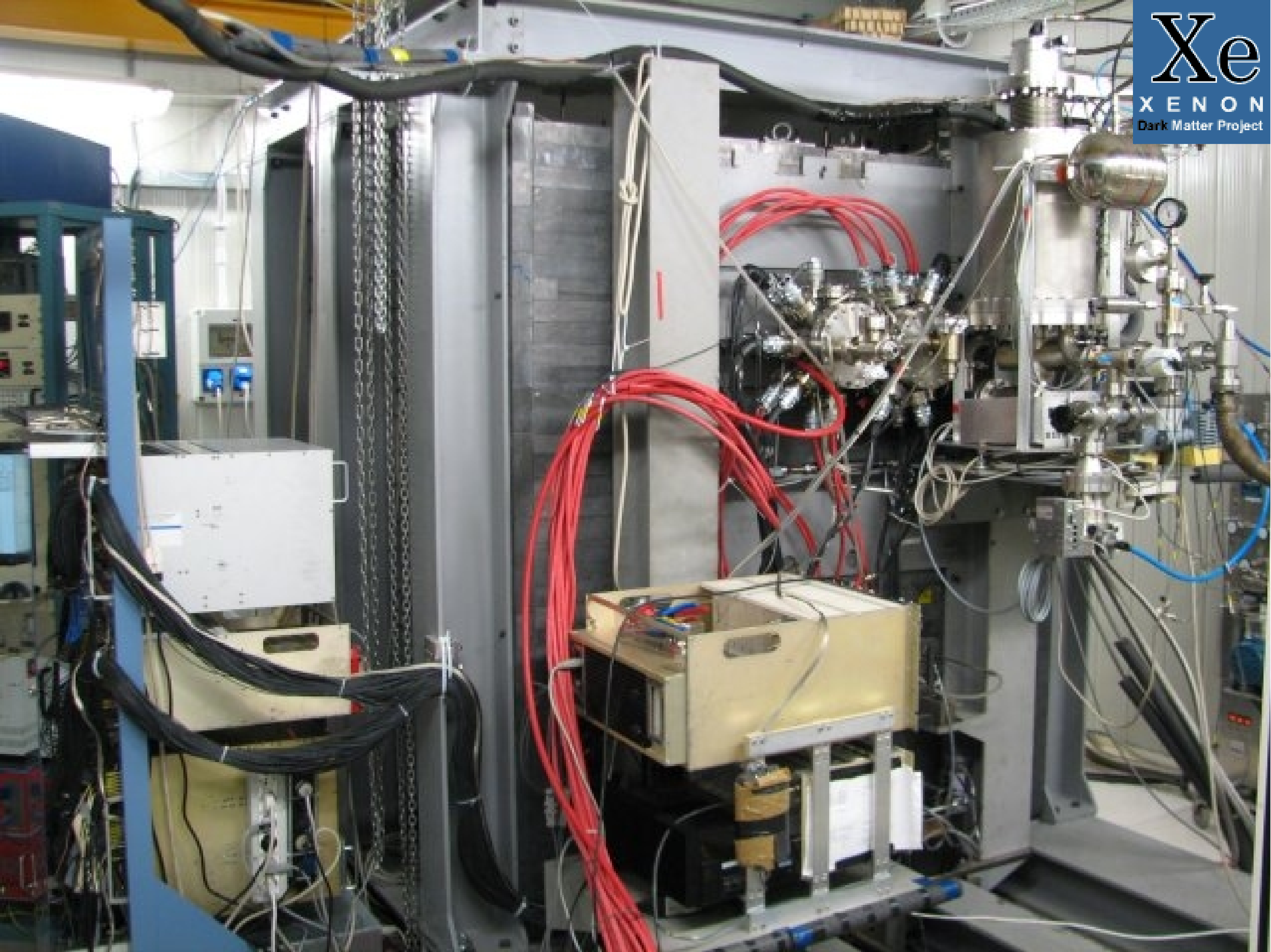



## Single electron signals

- the path towards an extremely low threshold
  → XENON10 low-mass limit *PRL 110, 249901 (2013)*
- observed signals are mainly from photo-ionization of surfaces and impurities
  → depends on LXe purity
  → rate correlated to large S2 signal
  → few e⁻ signals are accidental coincidences
- high stats sample to monitor detector stability
- allows for measurement of instrument parameters

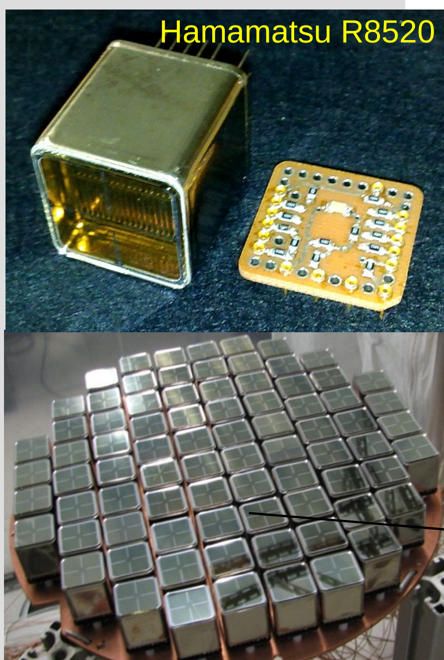

Xe
XENON
Dark Matter Project

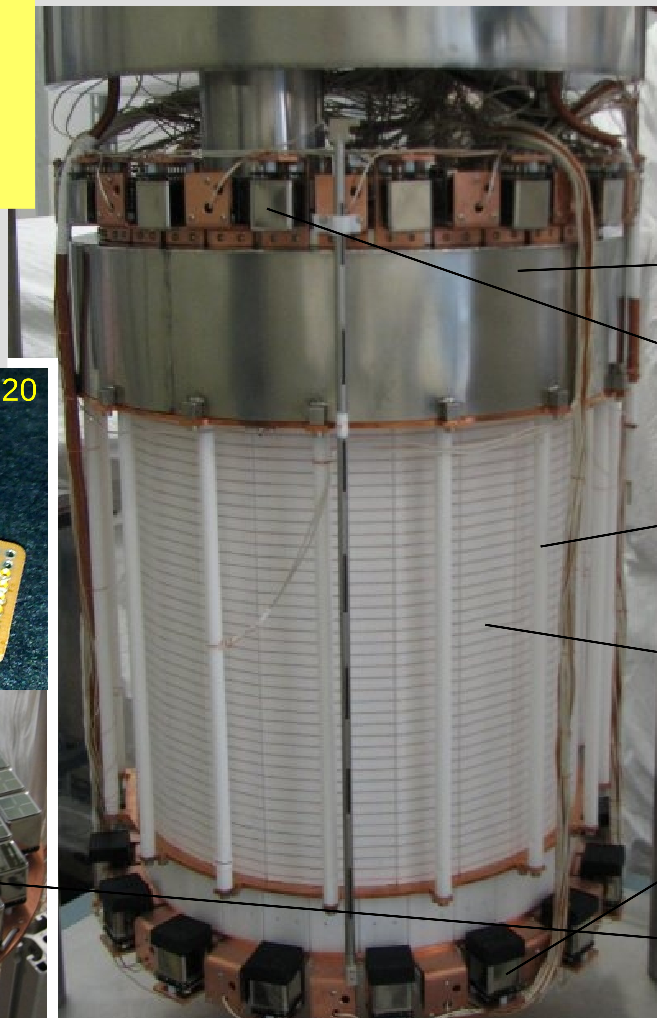

Xe
XENON
Dark Matter Project

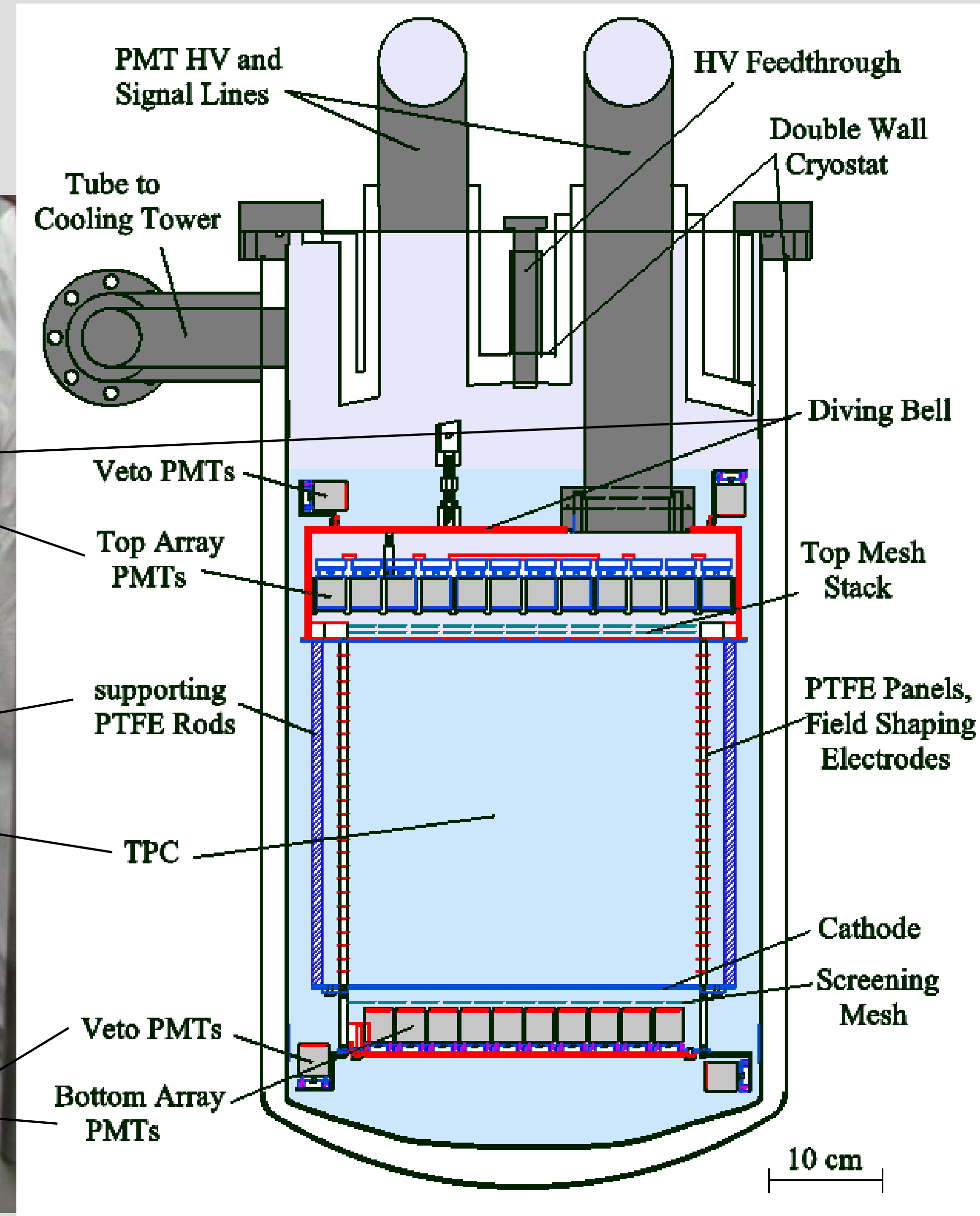
# The XENON100 Detector

*Astropart. Phys. 35, 573 (2012)*

Quick Facts
- 62 kg **LXe** target
- dual phase TPC
- active LXe veto
- 242 PMTs
- running
  @ LNGS (IT)



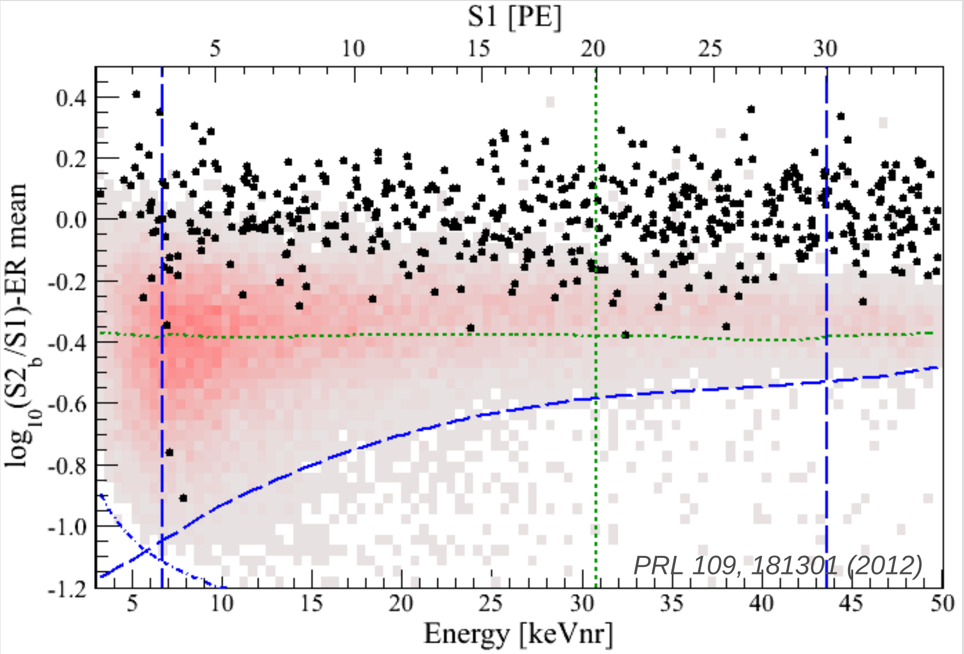


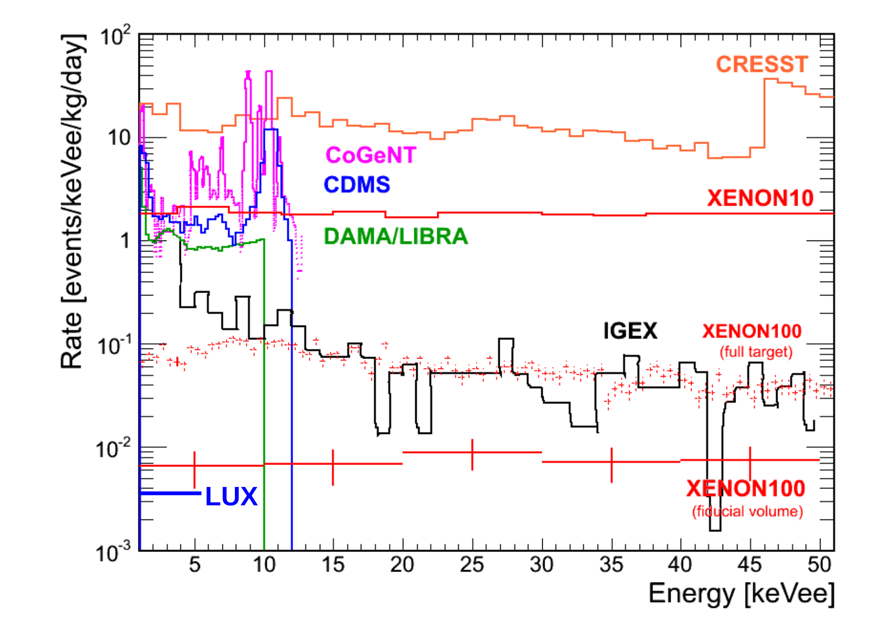
# XENON100 Results

**Background**
among the lowest of all DM experiments

electronic recoils („background like“)
rate = 0.0053 evts/$keV_{ee}$/kg/day (in FV)
*PRD 83, 082001 (2011)*

nuclear recoils („signal like“)
rate = 0.000003 evts/$keV_{ee}$/kg/day (in FV)
*J. Phys G 40, 115201 (2013)*



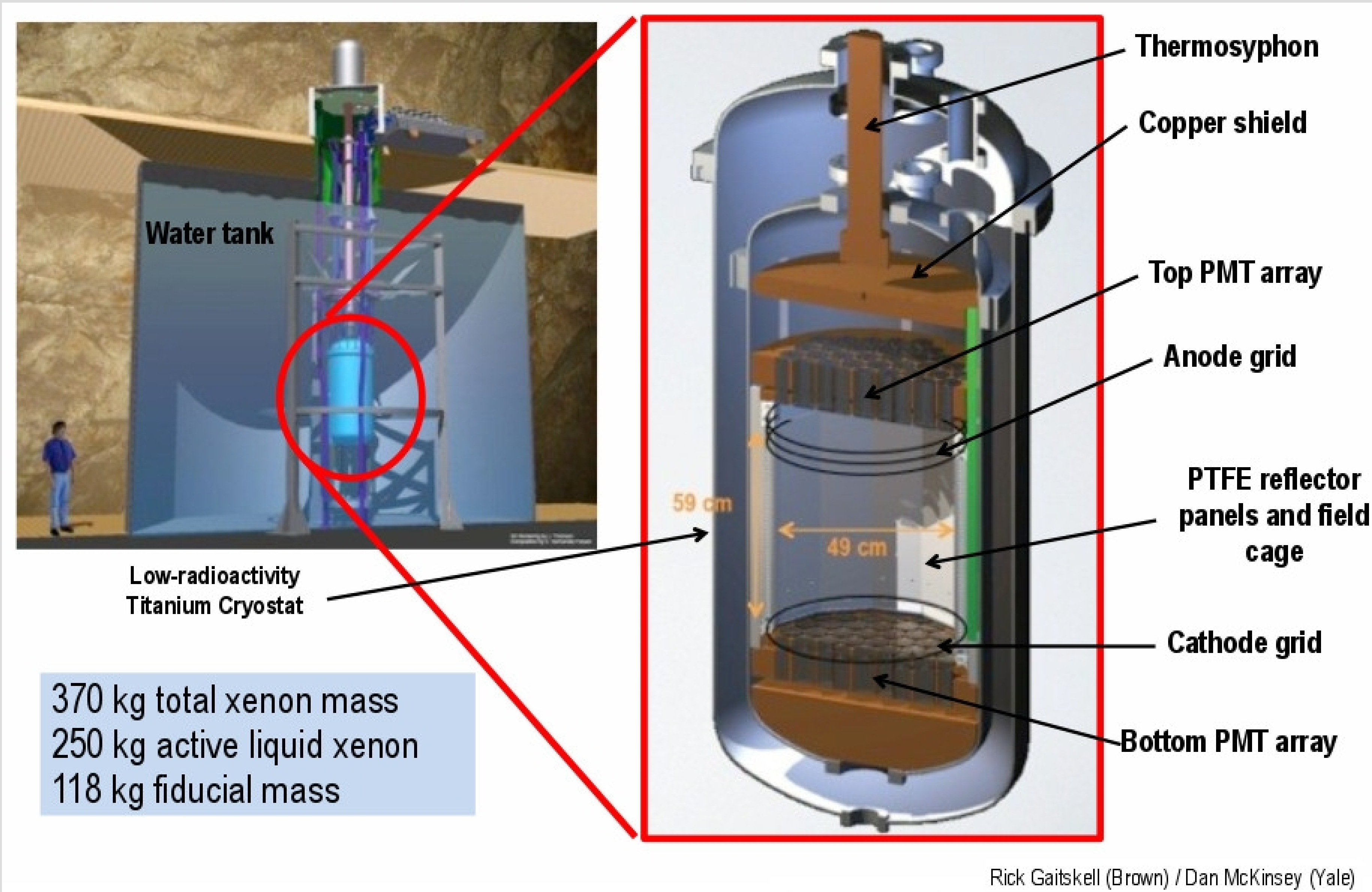




**Last science run** *PRL 109, 181301 (2012)*

7636 kg x d raw exposure
2324 kg x d acpt. corrected (100 GeV/c²)

2 events observed
→ compatible with background expectation of (1.0±0.2) evt
→ best WIMP limit over large mass range (at time of publication)

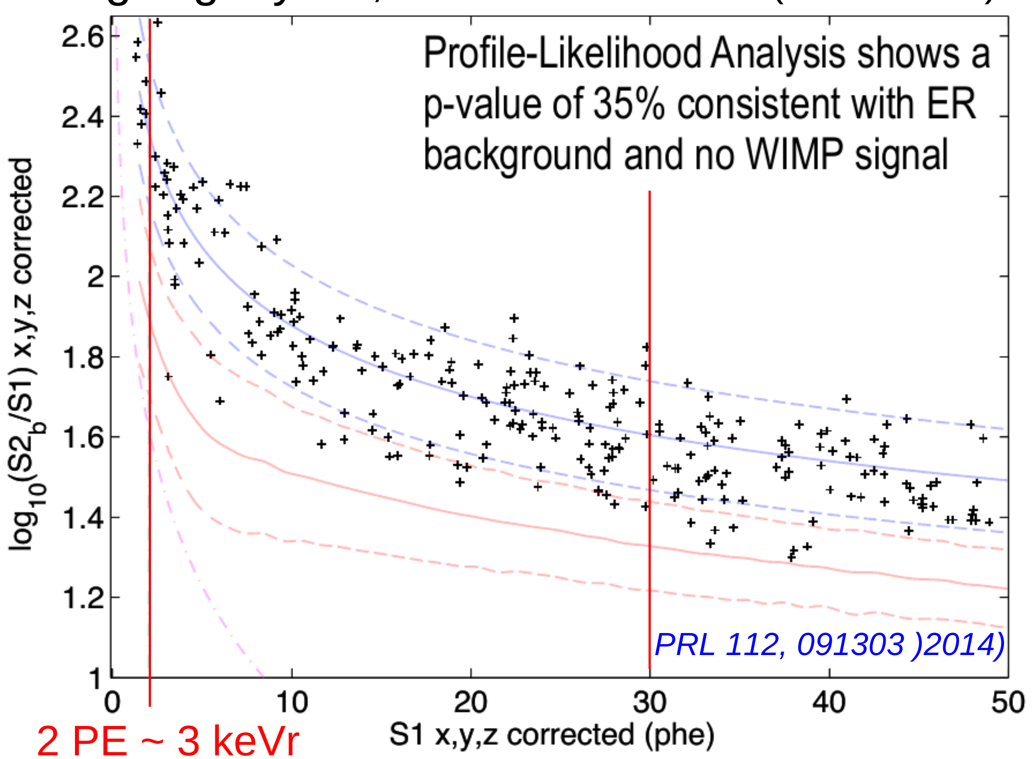
# LUX

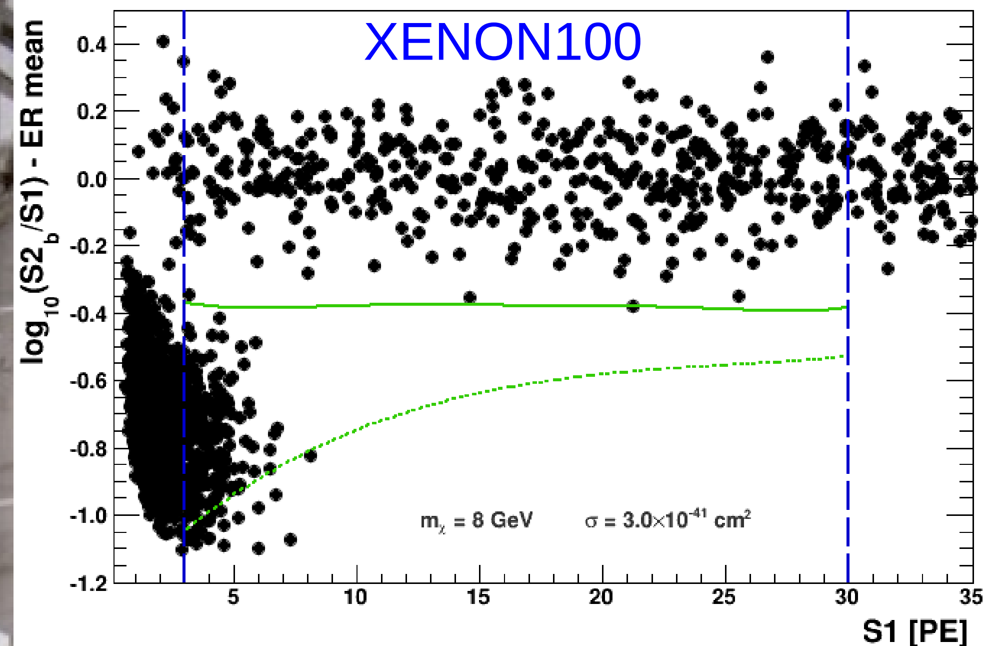

Water tank
Low-radioactivity
Titanium Cryostat
370 kg total xenon mass
250 kg active liquid xenon
118 kg fiducial mass
Thermosyphon
Copper shield
Top PMT array
Anode grid
PTFE reflector
panels and field
cage
Cathode grid
Bottom PMT array
59 cm
49 cm
Rick Gaitskell (Brown) / Dan McKinsey (Yale)

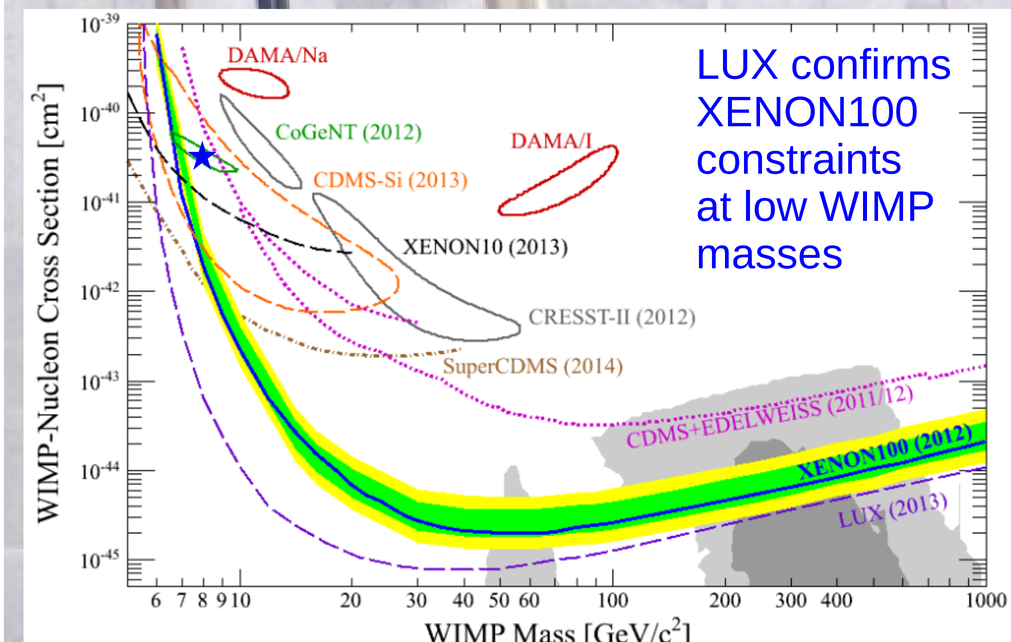
# LUX @ SURF

Raw exposure: 118 kg x 85.3 d = 10065 kg d
*(XENON100): 34 kg x 224.6 d = 7636 kg d*

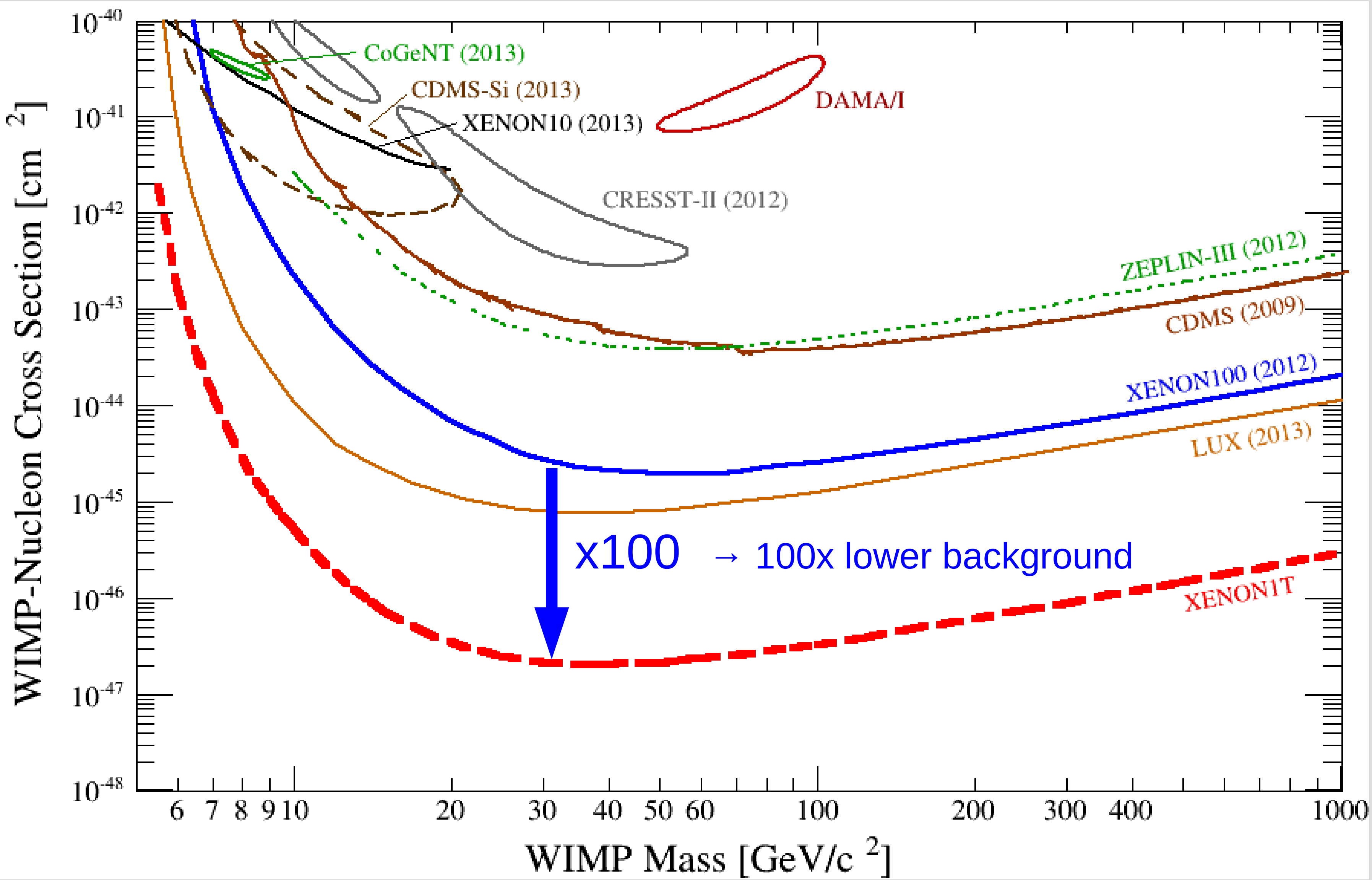
Non-blind analysis, only a few cuts
High light yield, rather low E-field (0.18 kV/cm)



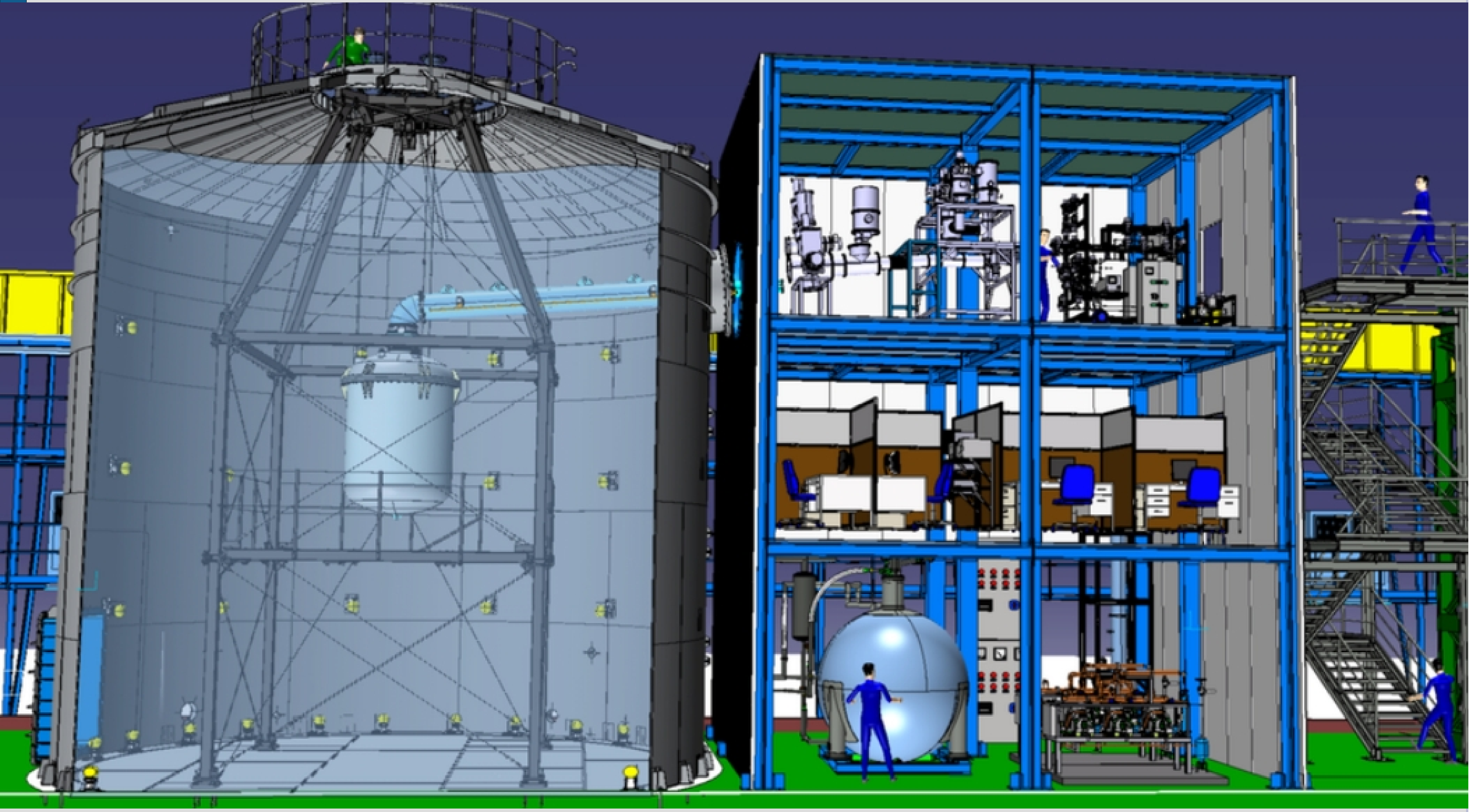



# The XENON Future



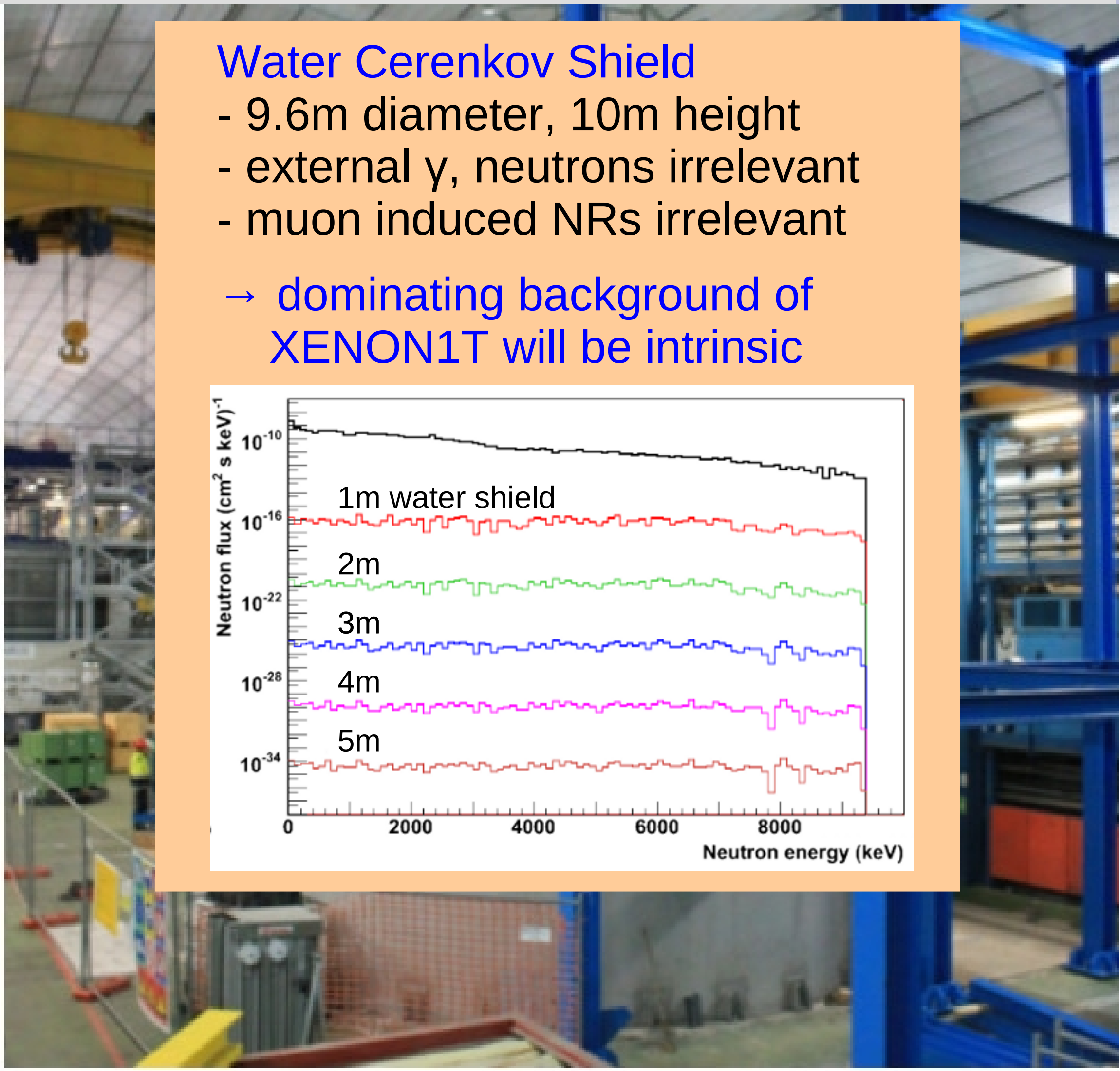
# XENON1T in Hall B @ LNGS



# XENON1T in Hall B @ LNGS

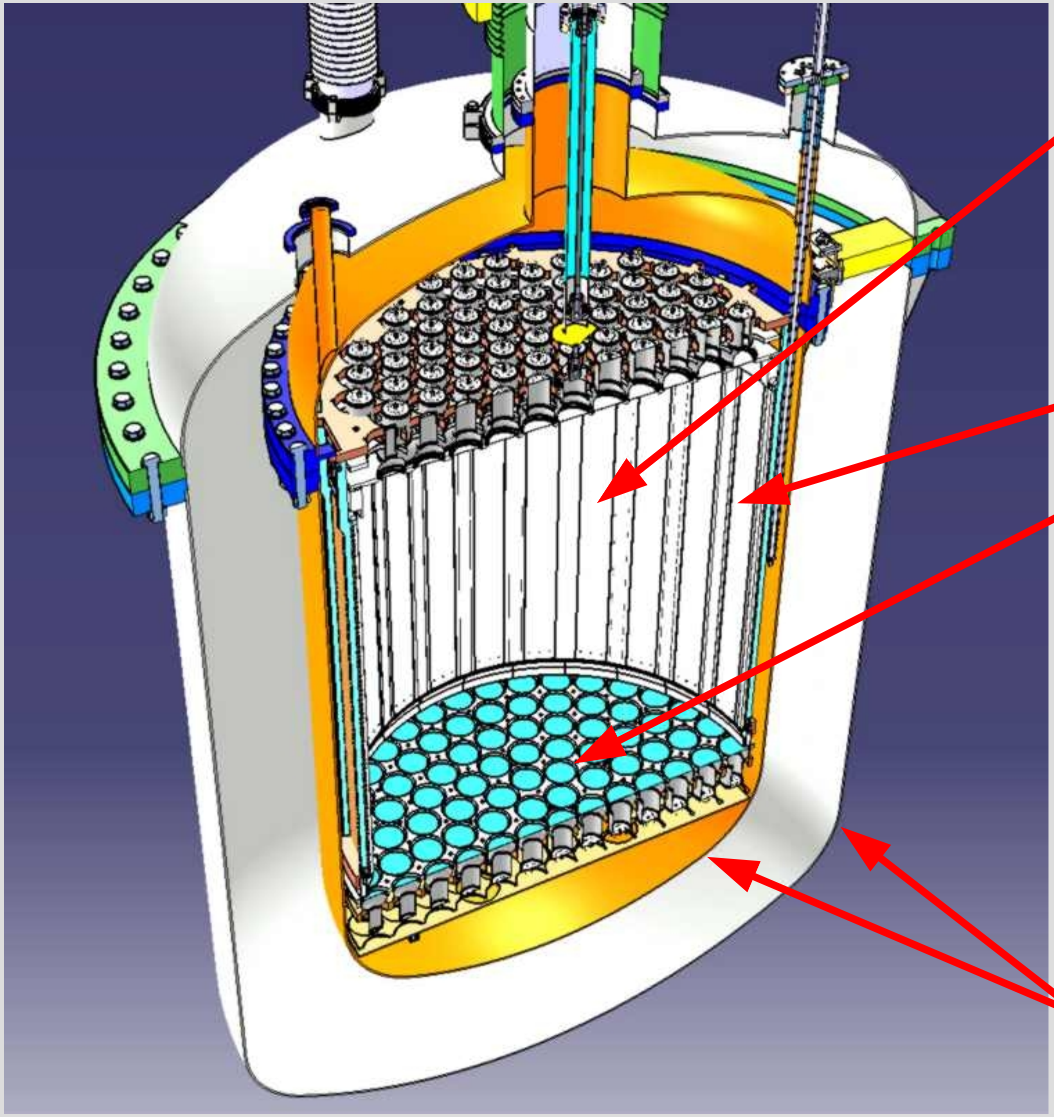
Water Cerenkov Shield
- 9.6m diameter, 10m height
- external γ, neutrons irrelevant
- muon induced NRs irrelevant

→ dominating background of XENON1T will be intrinsic




XEN
enlighten
XENON

# XENON1T



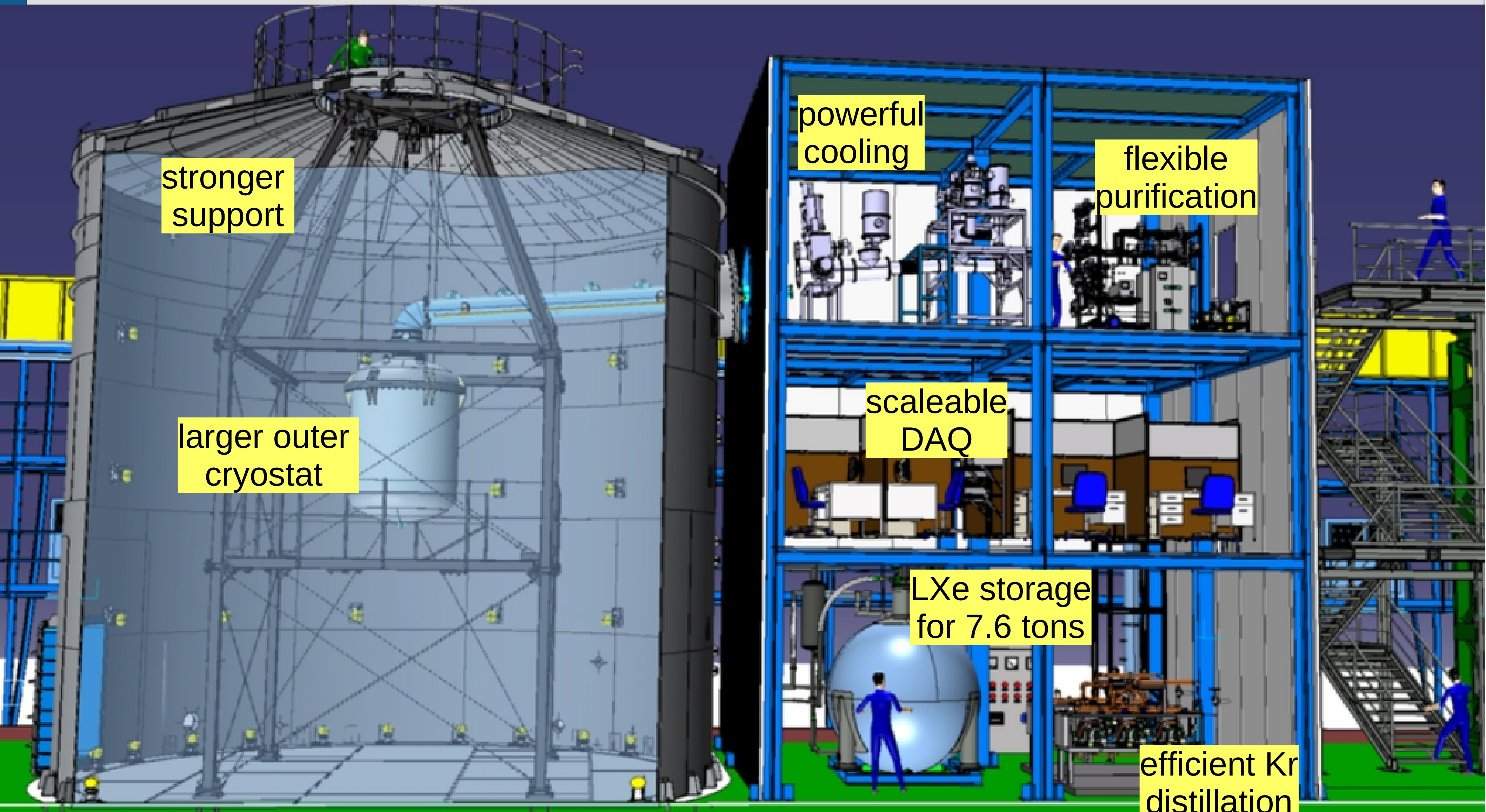
dual-phase LXe TPC
- total mass ~3.2 t
- active mass ~2.0 t
- fiducial mass: ~1 t

TPC made from OFHC and PTFE

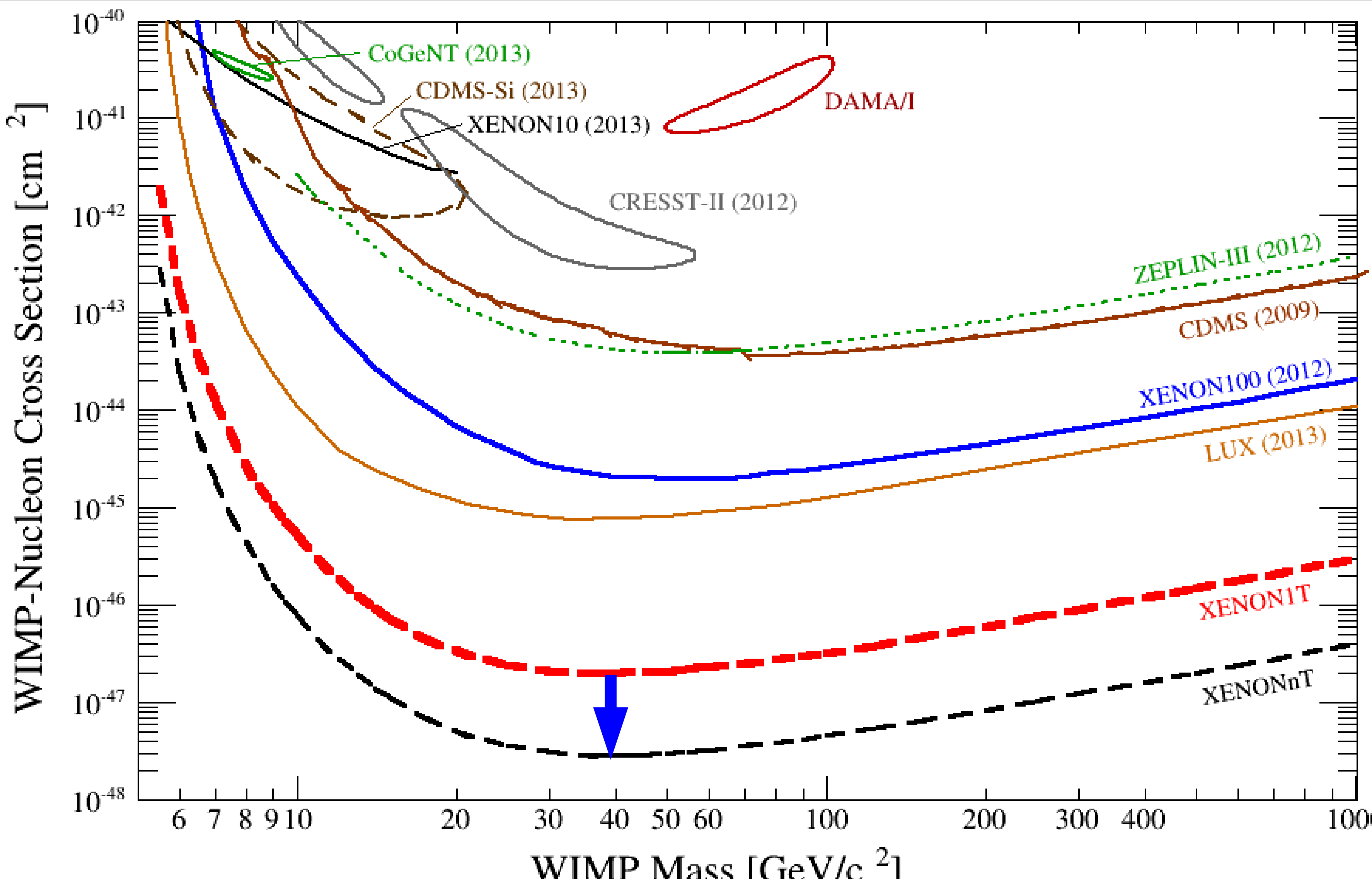
248 photomultipliers
- Hamamatsu R11410-21
- low background
- high QE (36% @ 178nm)
- extensive testing in
  cryogenic environments
  *JINST 8, P04026 (2013)*


Low-background stainless steel cryostats

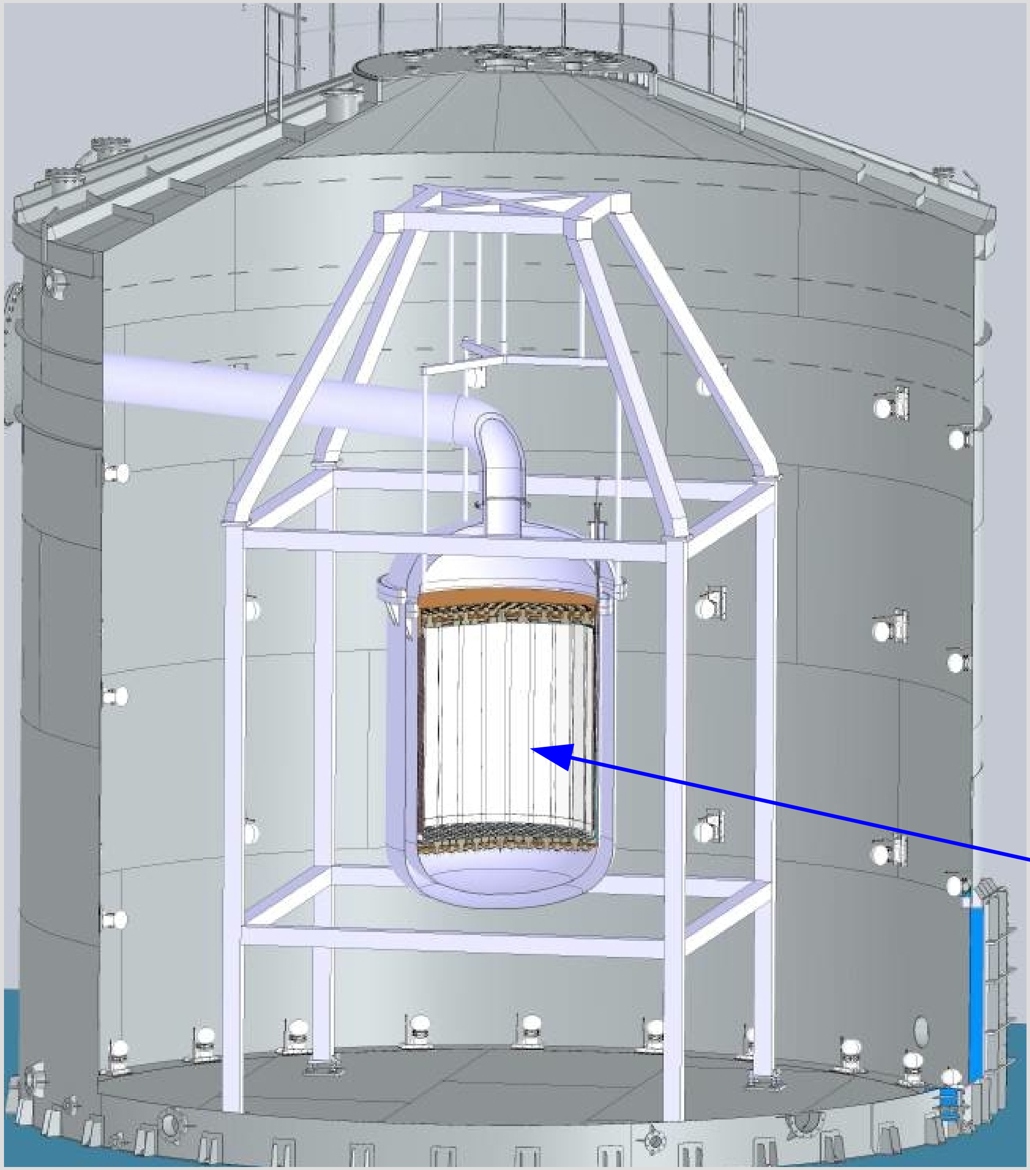
# XENONnT in Hall B @ LNGS



# The XENON Future



# DARWIN The ultimate WIMP Detector



- aim at sensitivity of a few $10^{-49}$ cm², limited by irreducible ν-backgrounds

- will measure WIMP properties (m,σ) precisely if WIMPs detected by XENONnT-scale detectors before

- design study
  - EU Aspera funded 2010-2013
  - included in the European Roadmap for Astroparticle Physics
  - CH, DE, IT, NL, FR, SE, IL, US
  - R&D ongoing

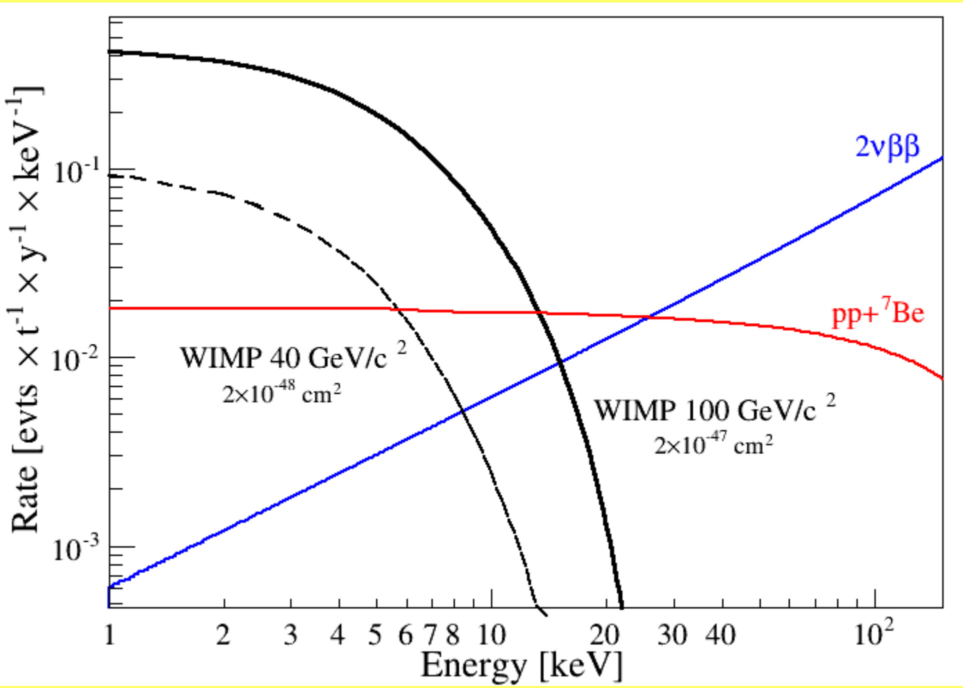
Baseline scenario
~20 t LXe TPC
~14 t fiducial mass

Timescale: start after XENONnT
(→ science run by ~2023)

# Neutrino Backgrounds

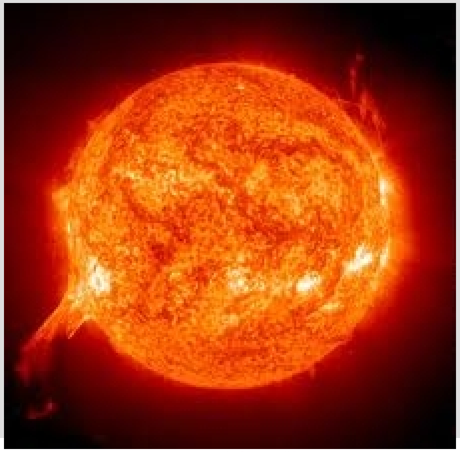
*JCAP 01, 044 (2014)*

### Low-energy solar Neutrinos: pp, $^{7}$Be




- pp-neutrinos dominating
- solar neutrinos, as well as 2νββ from $^{136}$Xe generate electronic recoils

→ can be reduced via S2/S1 discrimination



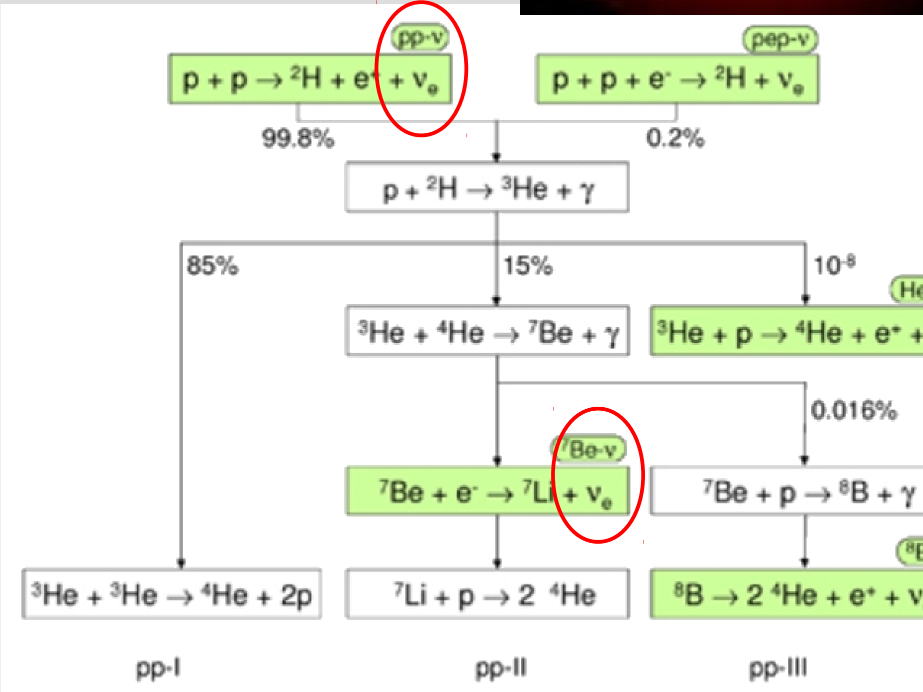
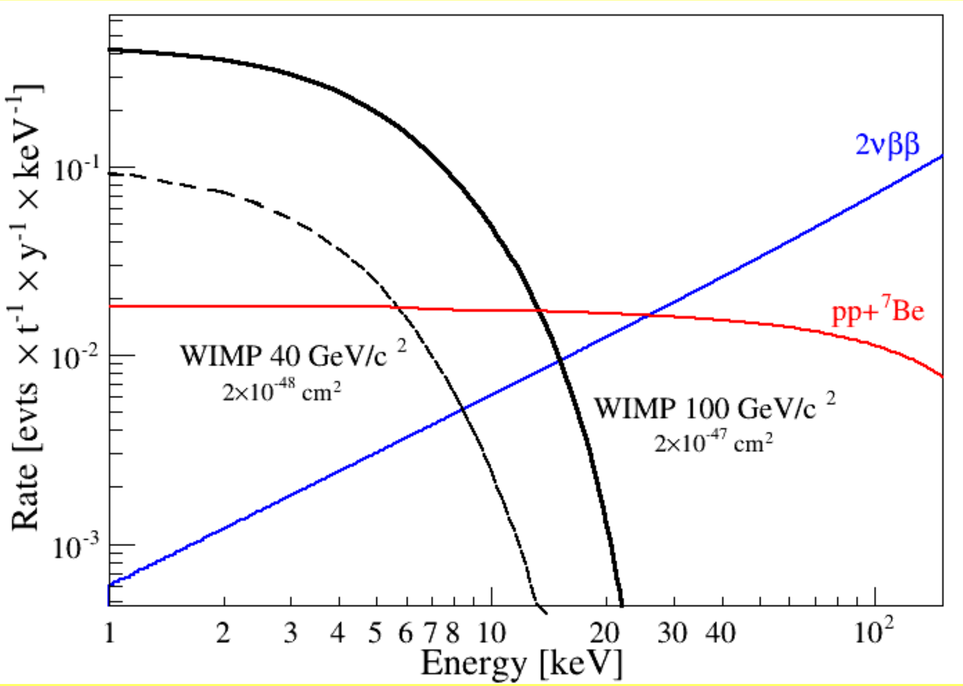



*Image: Borexino*

# Neutrino Backgrounds

*JCAP 01, 044 (2014)*

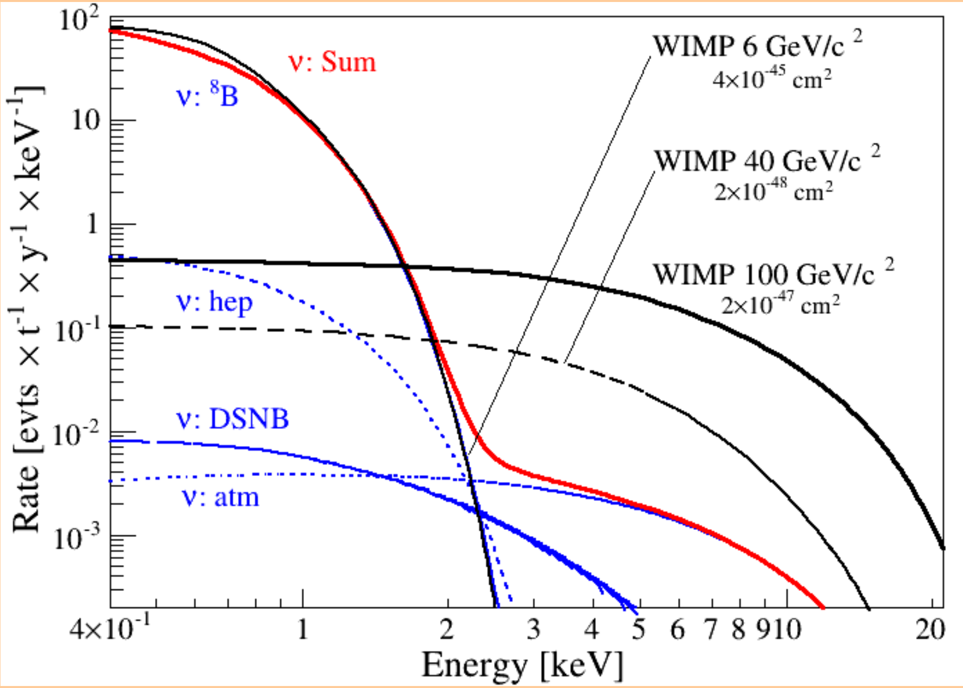
## Low-energy solar Neutrinos: pp, $^7$Be




- pp-neutrinos dominating
- solar neutrinos, as well as 2νββ from $^{136}$Xe generate electronic recoils

→ can be reduced via S2/S1 discrimination

## Coherent neutrino-nucleus scattering




- coherent interactions of solar, atmosperic, and supernova neutrinos with the Xe nuclei
- nuclear recoils

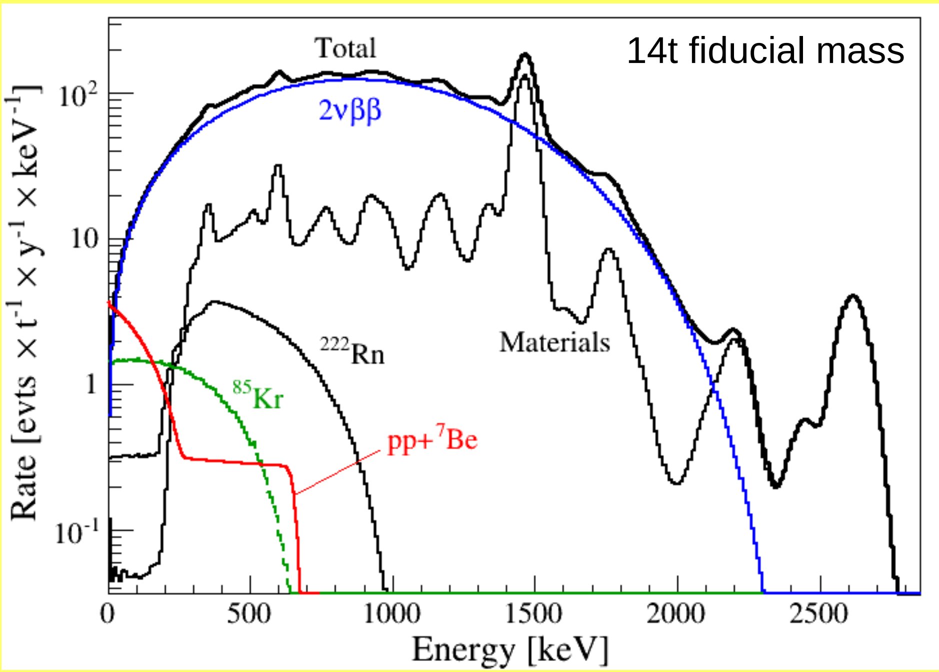
→ indistinguishable from WIMPs

→ the ultimate limit for direct searches

# DARWIN: Neutrino Physics

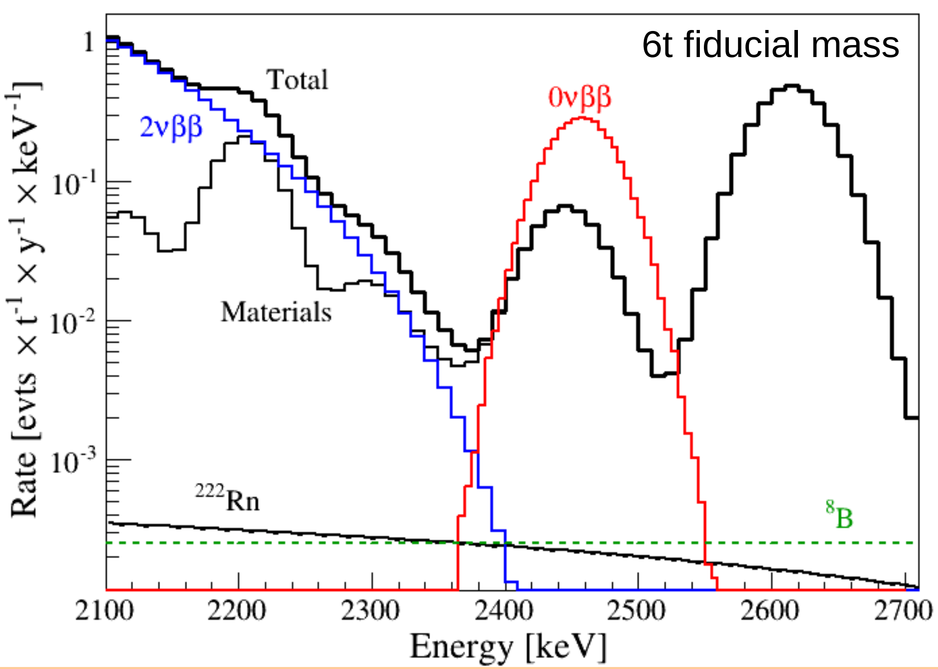
Results of a detailed DARWIN background study *JCAP 01, 044 (2014)*

## Low-energy solar Neutrinos: pp, $^7$Be



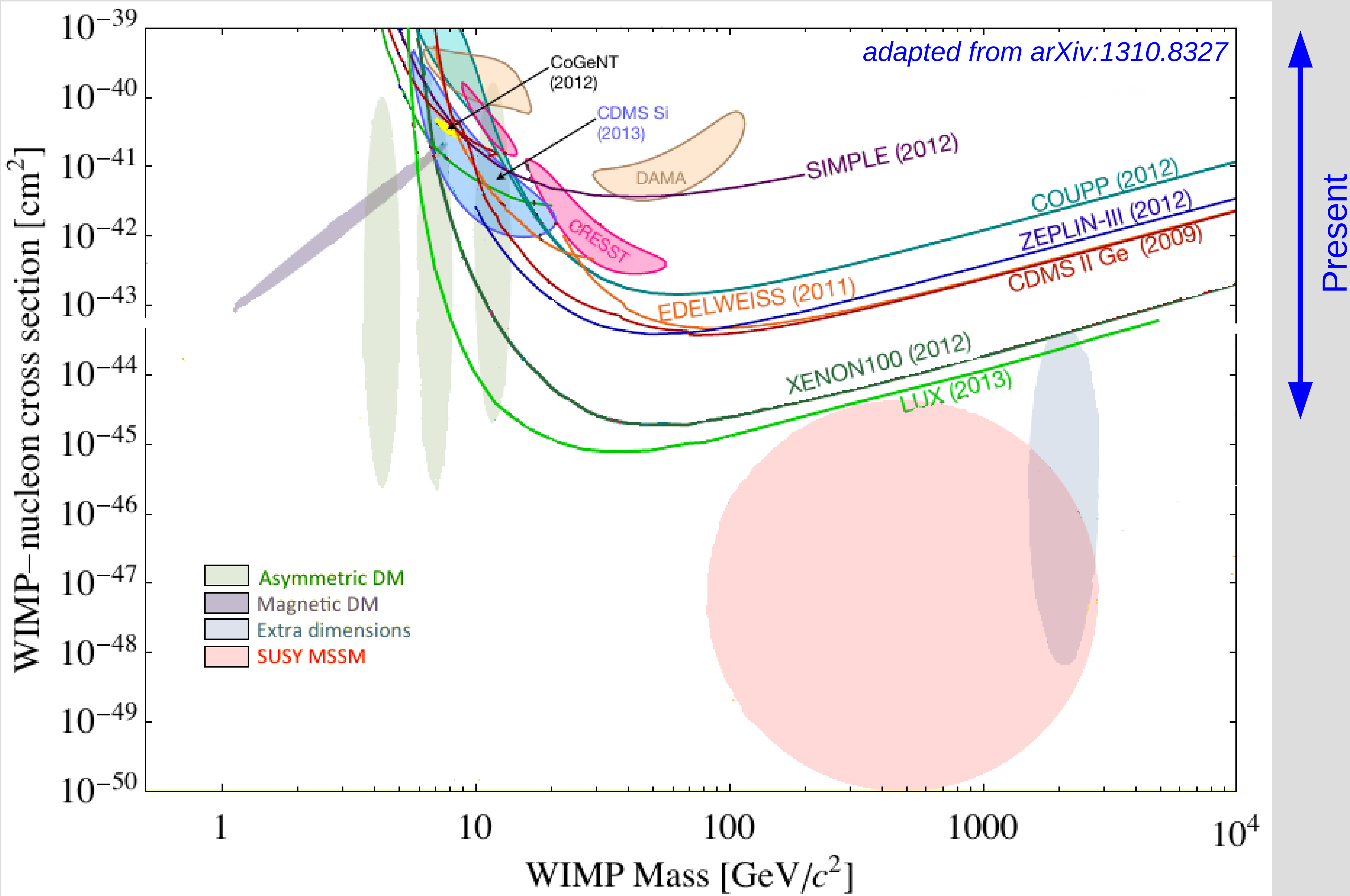

- realistic detector design (~20t LXe), all relevant backgrounds included
- 1180 pp-ν/year in [2,30] keV interval
- flux-measurement at 1% precision in 5y

## Neutrinoless double-beta decay




- natural Xe, no isotopic enrichment!
- signal in plot assumes $T_{1/2}=1.6 \times 10^{25}$ y
- ultimate sensitivity (limited by intrinsic bg): $T_{1/2}=8.5 \times 10^{27}$ y (95% CL) with 14t x 10y

# The WIMP Landscape today



# Exciting times ahead of us