

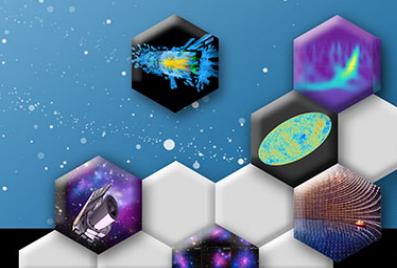
# Direct Dark Matter Searches

Manfred Lindner



**IPA**  
Interplay between Particle  
and Astroparticle Physics

LAL - Orsay, September 05 - 09, 2016

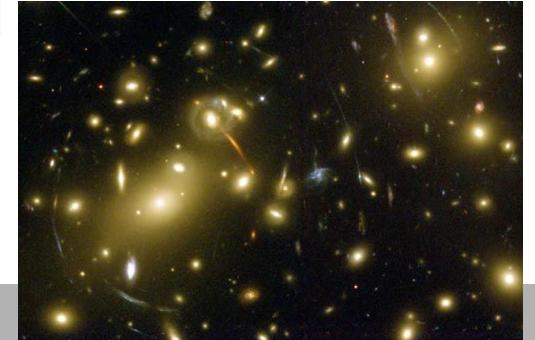
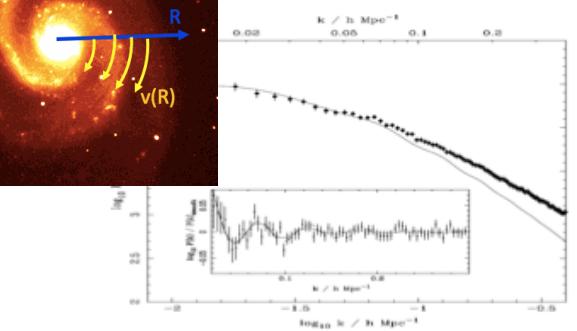
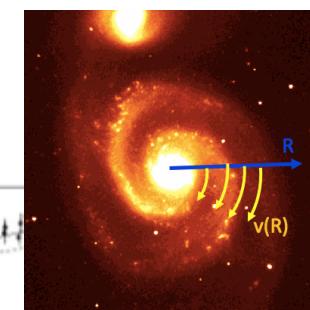
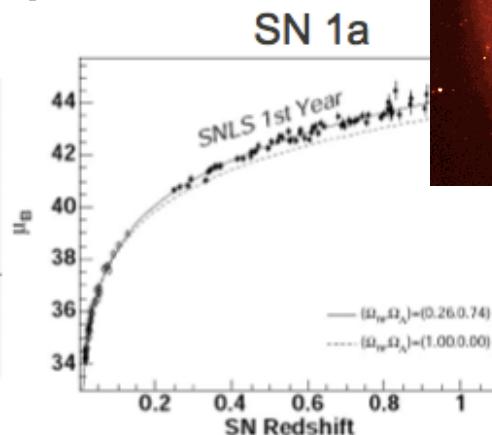
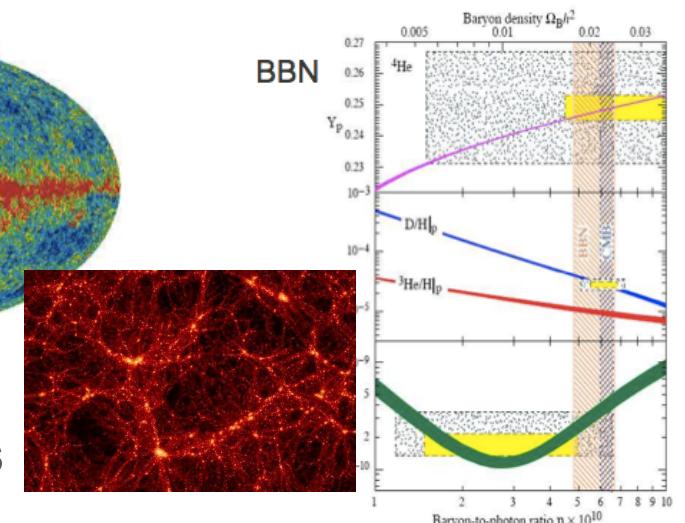
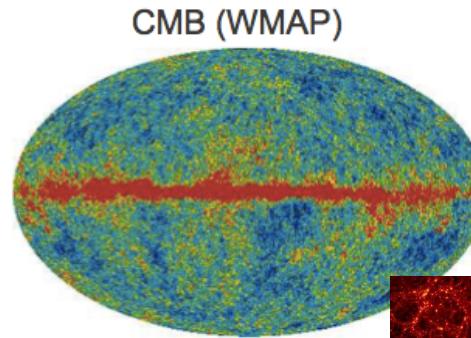


Bruno Mazoyer - LAL/Orsay

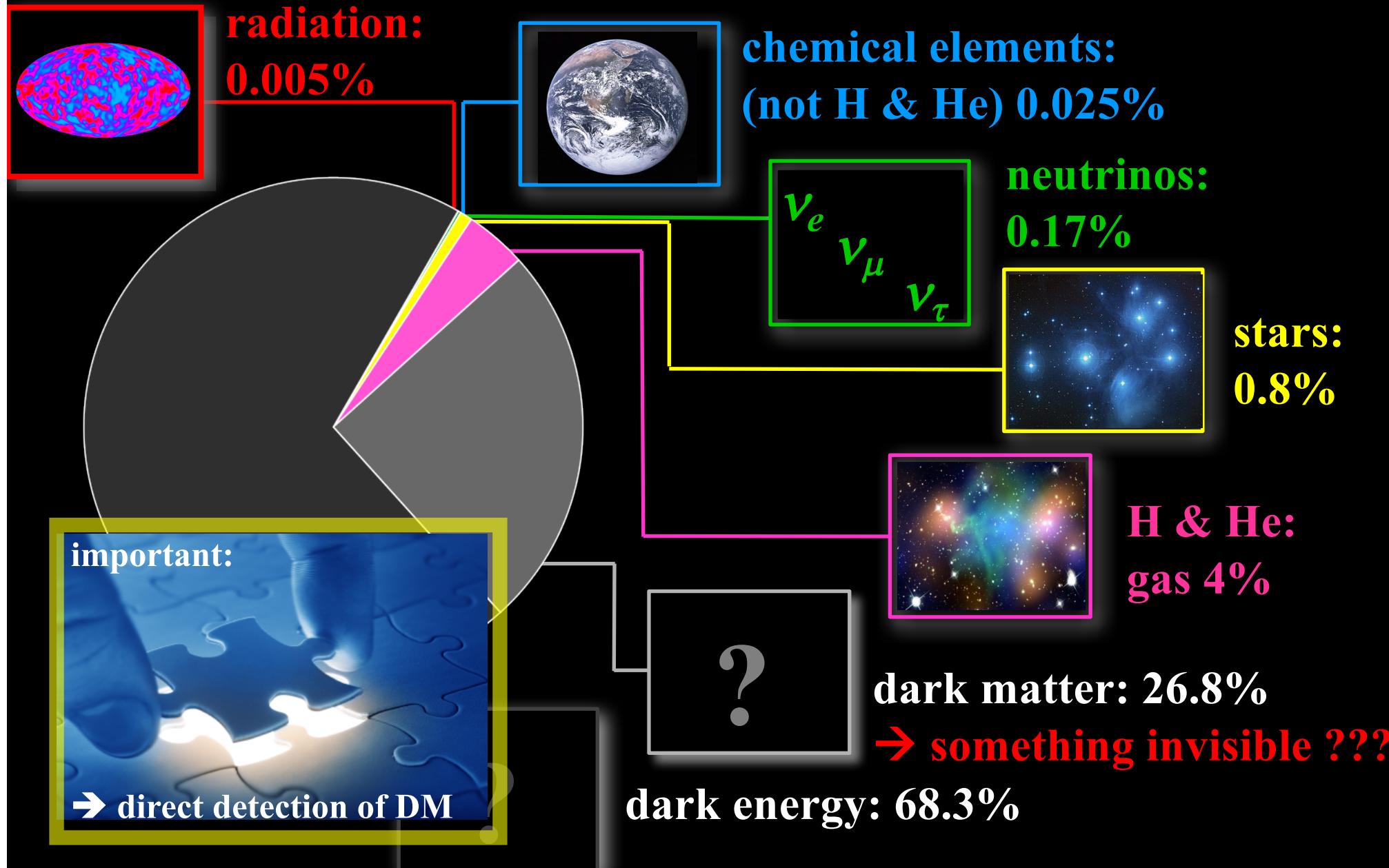
# A long List of Evidences ...

- + 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
- + ...

- Strong indirect evidence for a large dark sector
- dynamic, static, radiation, ...
- cannot be explained by ordinary matter



# The cosmic Matter Balance



# Competing Dark Matter Directions

## Gravity

**MOND**  
simple one  
scale  
modification  
→ fails badly

**Other**  
Other GR  
modifications  
→ P. Brax

or

a suitable  
population  
(mass,  
number) of  
black holes

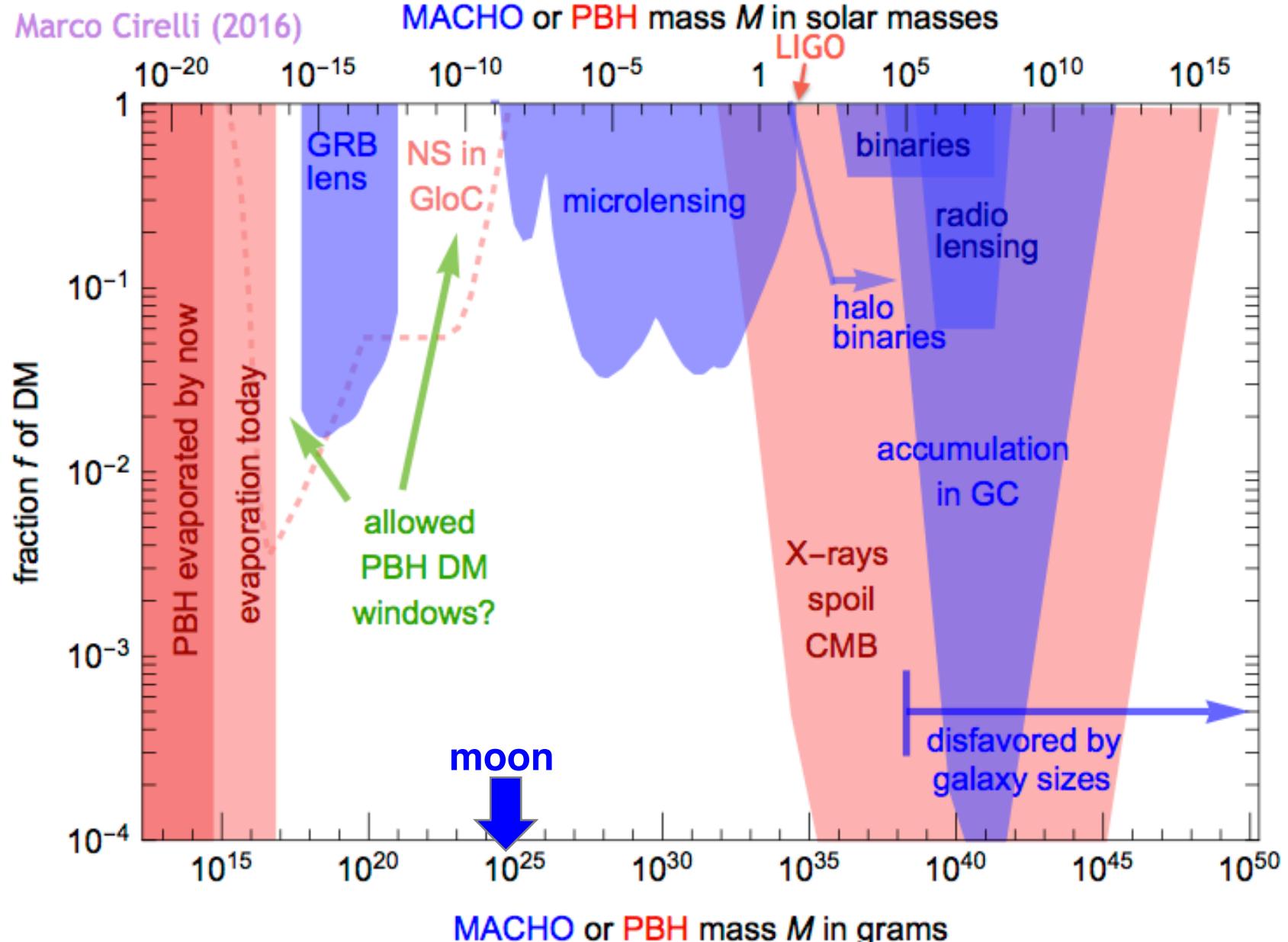
## Particles

**BSM**  
**motivated**  
(SM problems)  
- axions  
- sterile ν's  
- ...

**Abundance**  
**or model**  
**motivated**  
- various new  
particles  
→ R. Essig  
→ M. Tytgat  
- ...

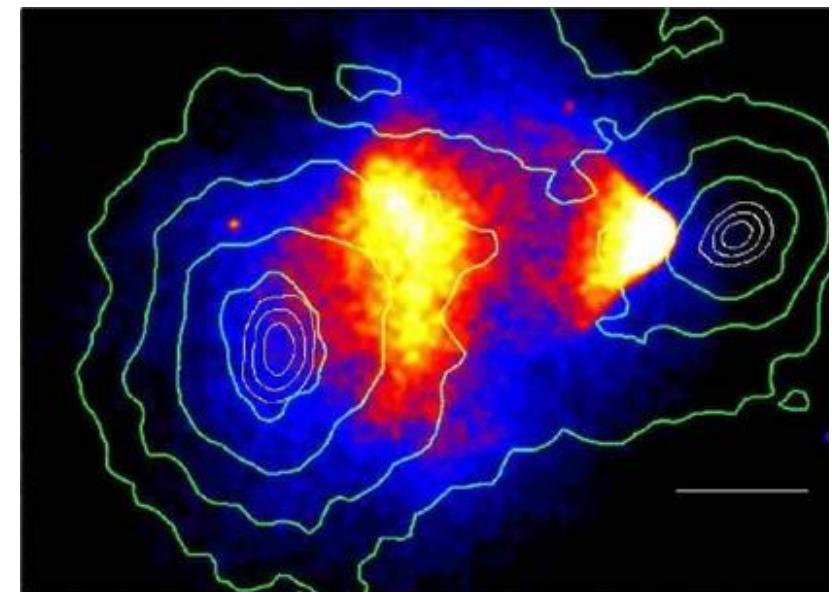
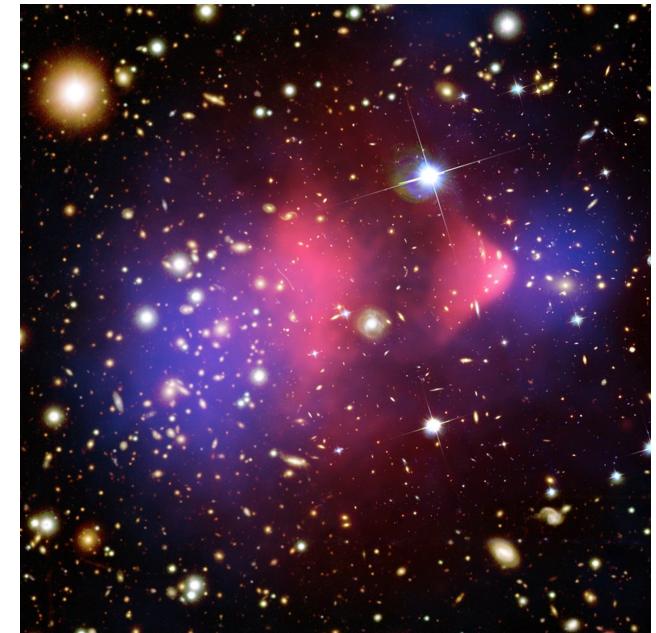
**WIMPs combine both  
aspects in an attractive  
way + WIMP miracle**

# Black Holes as Dark Matter



# Is it Particles?

- **bullet cluster (1E 0657-56)**
  - colliding galaxy clusters  
= stars, gas, DM ; up to  $10^6$  km/h
  - x-rays from charged particle interactions
  - Dark Matter just traverses w/o scattering  
→ displacement of visible matter
  - and
  - GR potential = all matter  
→ effect is  $\sim 8\sigma$
- Shows that normal particles scatter, but NOT that DM is particles

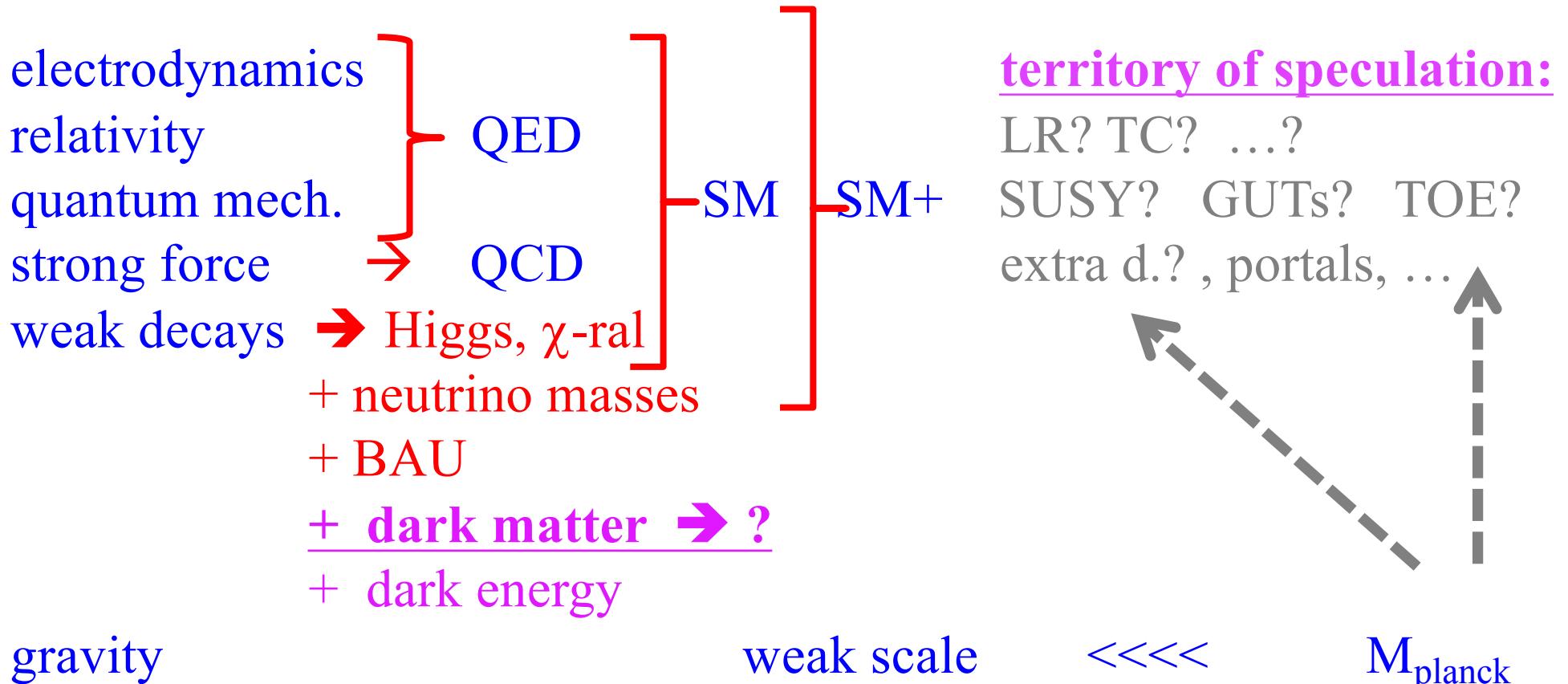


# BSM: Many Directions

d=4 QFTs:

$$\begin{array}{ccc} \text{QED} & \xrightarrow{\quad} & \text{QCD} \\ \text{U(1)}_{\text{em}} & & \text{SU(3)}_{\text{C}} \end{array} \quad \xrightarrow{\quad} \text{SM} \quad \text{SU(3)}_{\text{C}} \times \text{SU(2)}_{\text{L}} \times \text{U(1)}_{\text{Y}}$$

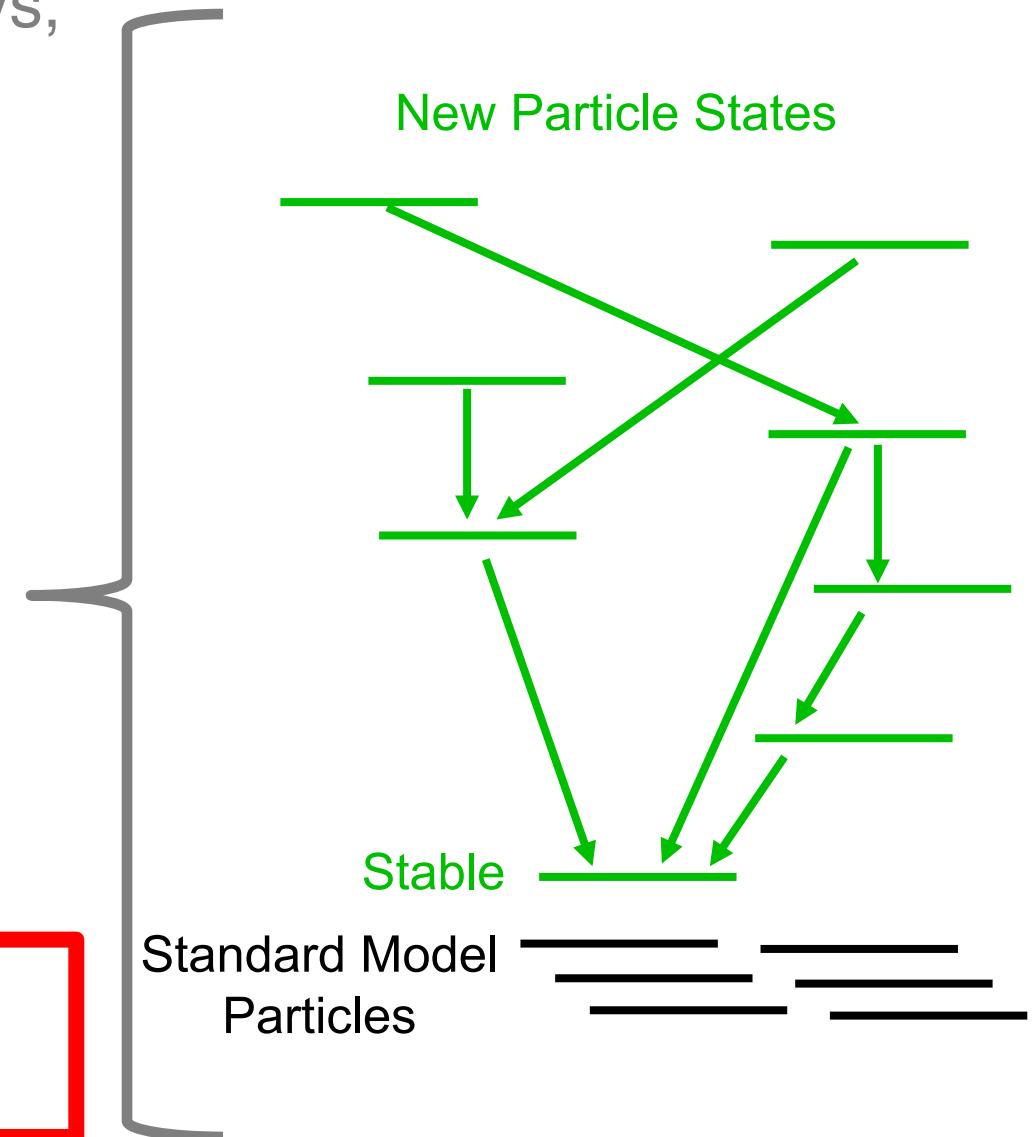
Physics: concepts (variables)  $\oplus$  equations / principles  
initial conditions  $\rightarrow$  predictions



# New DM Particle must be stable

- All existing particles produced in Big Bang and later (decays, ...)
- Some particles are stable since further decays are forbidden  $\leftrightarrow$  symmetry
- Very long-lived due to small parameters  $\rightarrow$  natural?
- The unstable extra particles have also effects  
 $\rightarrow$  on the early Universe  
 $\rightarrow$  on collider physics

**WIMPs: well motivated by BSM + WIMP miracle**

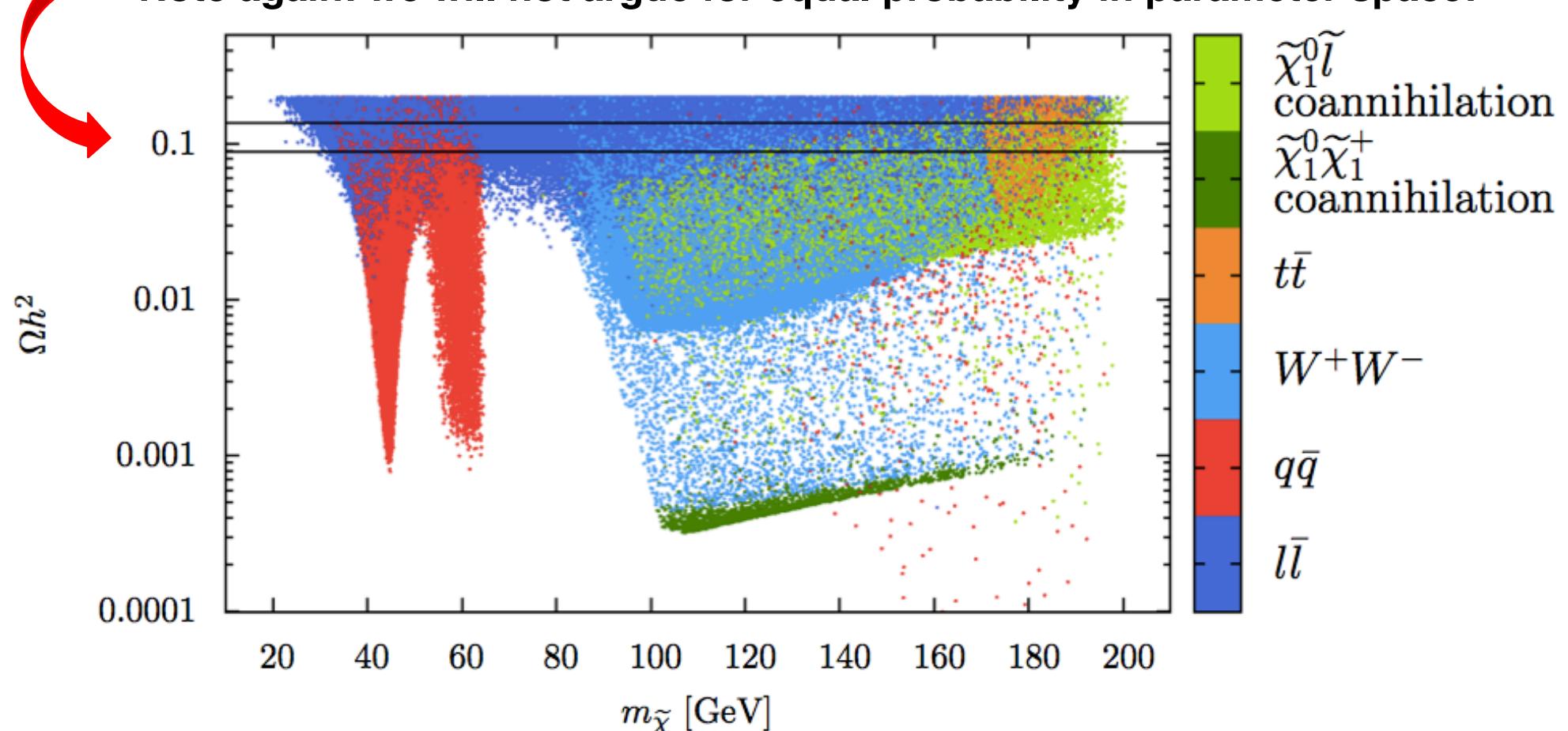


# Hierarchy Problem → MSSM → DM

- LSP=Neutralino → WIMP miracle → correct abundance

Scan parameter space for different annihilation channels →  $\Omega h^2$

Note again: we will not argue for equal probability in parameter space!



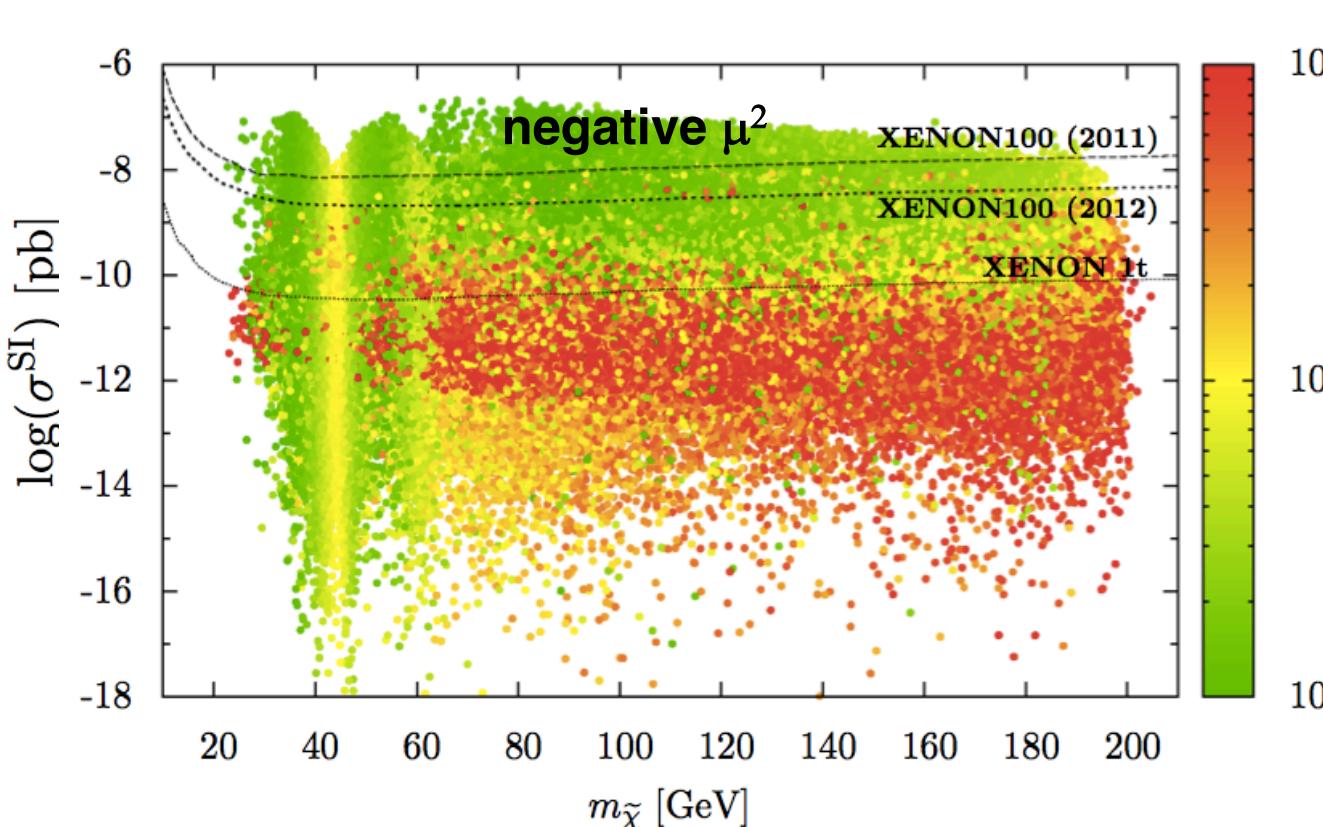
→ Select correct range of  $\Omega h^2$  → constrains parameter ranges

# How fine-tuned are the parameters?

- MSSM neutralino: Level of fine-tuning  $\rightarrow \Delta_{\text{tot}}$

$$\Delta p_i \equiv \left| \frac{p_i}{M_Z^2} \frac{\partial M_Z^2(p_i)}{\partial p_i} \right| = \left| \frac{\partial \ln M_Z^2(p_i)}{\partial \ln p_i} \right|$$

$$\Delta_{\text{tot}} \equiv \sqrt{\sum_{p_i=\mu^2,b,m_{H_u}^2,m_{H_d}^2} \{\Delta p_i\}^2}$$

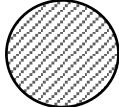


$\rightarrow$  XENON100-2010  
 $\rightarrow$  XENON100-2012  
 $\rightarrow$  XENON1T

- XENON100 cuts already into expected space
- XENON1T covers a much larger part
- \* XENONnT covers most
  - high potential
  - be first!

LMSSM: x-section down  
 $\longleftrightarrow$  WIMP miracle?

# Generic WIMP Crossection

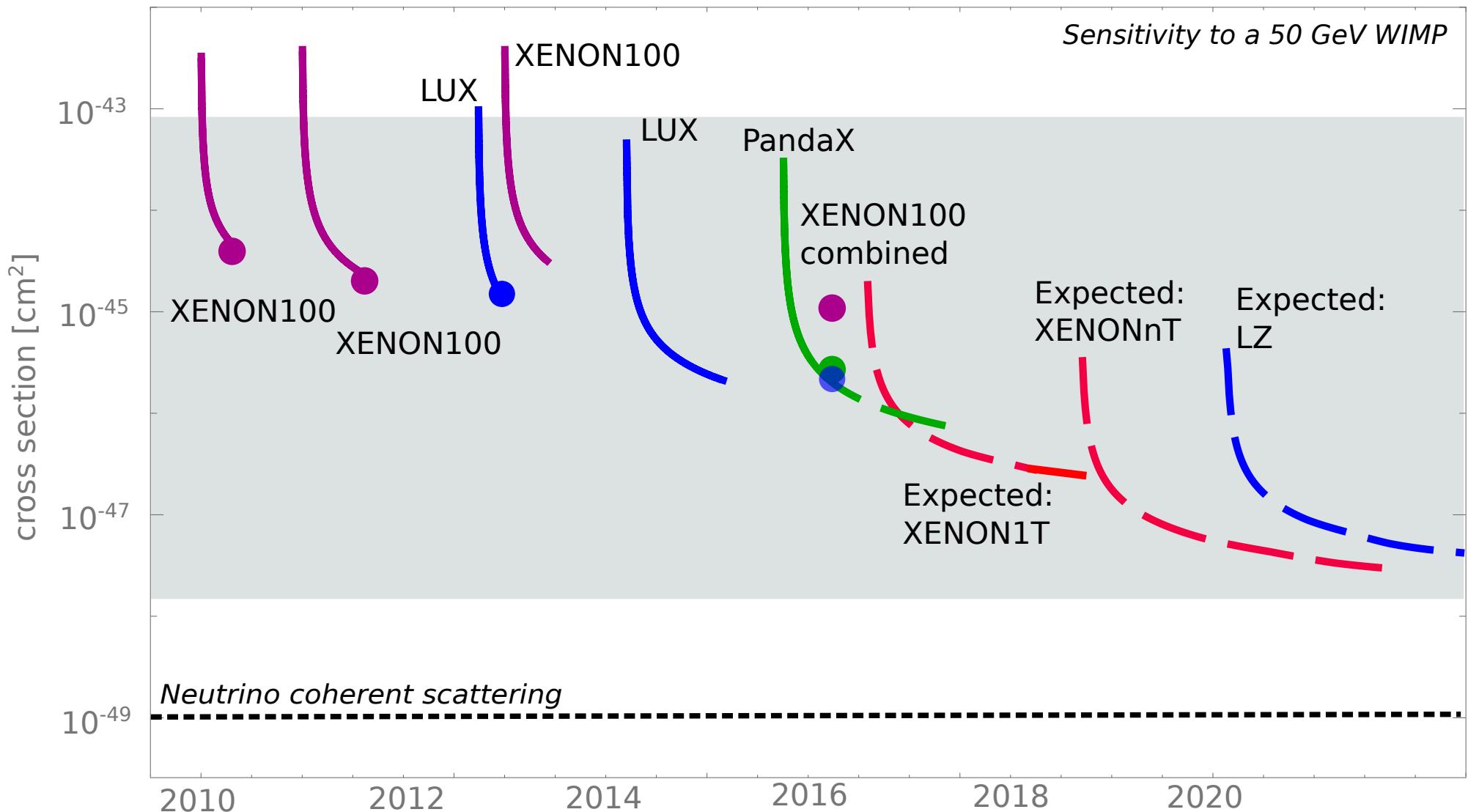
- Quantum mechanics: wavelength  $\lambda \sim 1/\text{mass}$
-  “size/area” of a particle:  $\pi\lambda^2 = \pi/m^2$
- scattering crossection = area times coupling strength
- $\sigma \sim O(0.001\text{-}1.0)^2 g_2^2 \pi/m^2$  or tuning, symmetry, ...  
model weak area  $\longleftrightarrow$  abundance  
parameters coupling

→ the natural / expected range for a 50GeV WIMP:  
 $\sigma \sim 10^{-42} - 10^{-48} \text{ cm}^2$

known amount of DM → ~WIMP flux → event rate

→ we know size/sensitivity of a detector which can cover the most interesting natural WIMP space

# Compared to Direct WIMP Search Timeline



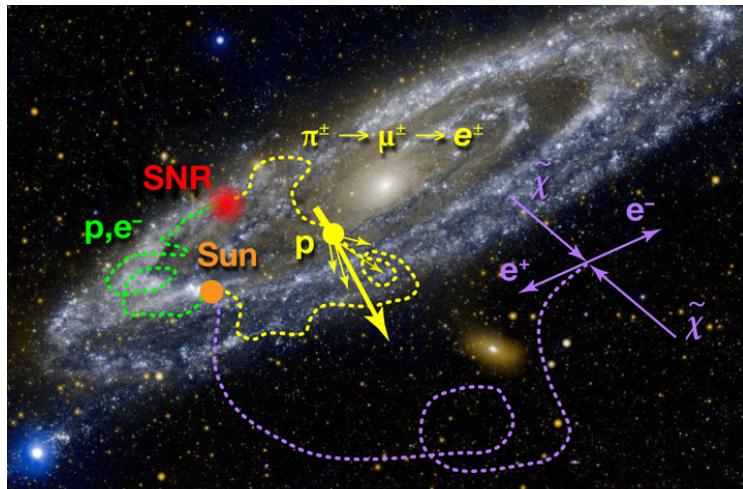
**Generic WIMP parameter space will be covered in the next years**

Systematically lowering the x-section (symmetry, tuning,...)?  $\leftrightarrow$  WIMP miracle?

# Hunting WIMPS in different Ways

known Standard Model (SM) particles interact with WIMPs : assumptions...

## indirect detection



FERMI, PAMELA, AMS, HESS,  
IceCube, ...

astronomical uncertainties...

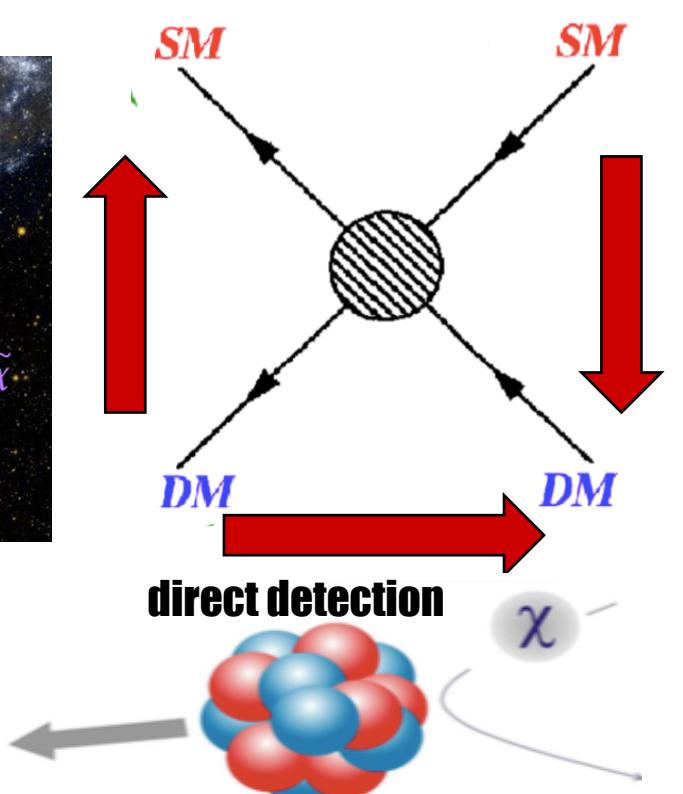
→ signal without doubt

from DM?

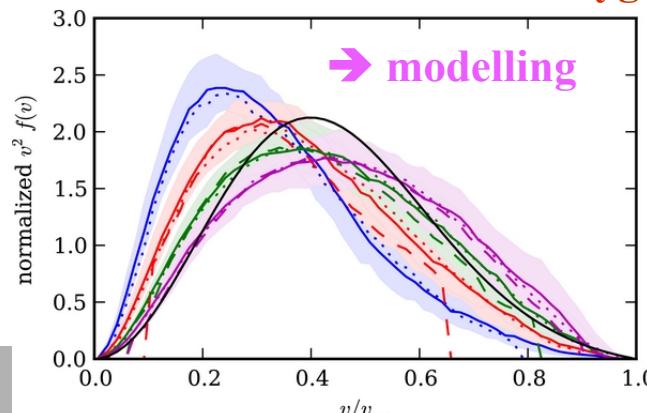
→ J. Biteau

→ G. Zaharijas

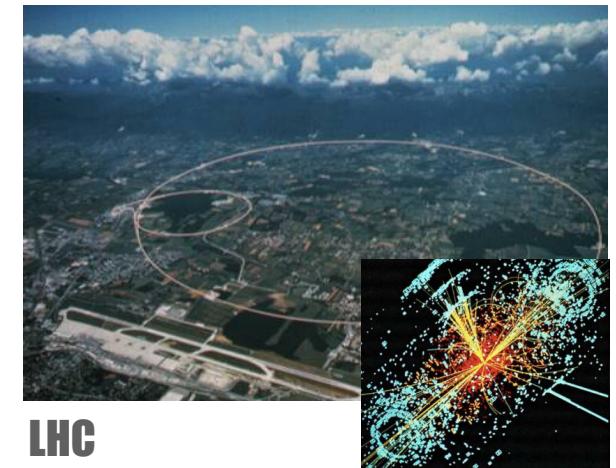
keV lines ↔ atomic physics



WIMP wind : 220km/s from Cygnus



## colliders



may detect new particles, but  
is it DM (lifetime, abundance)?  
ICHEP2016: Nothing seen...

- impact on theory...
- SUSY → higher scale
- other SB motivated WIMPs
- new ideas/candidates
- F. Kahlhöfer
- M. Jeitler
- ...

# keV Lines, Hitomi & Charge Exchange Reactions

Hitomi X-ray satellite (failed March 26, 2016)

Before: look at the Perseus galaxy cluster @232Mly

→ no sign of the previously reported X-rays **1607.07420**

Charge exchange explanation of 3.5 keV line **1608.04751**

Highly charged ions in and between galaxies

→ completely ionized sulfur ( $S^{16+}$ )

( $S^{16+}$ ) coming close to H

→ charge exchange reaction → excited ( $S^{15+}$ )

→ de-excitation by emission of 3.5 keV photon

→ 3.5 keV gamma line...

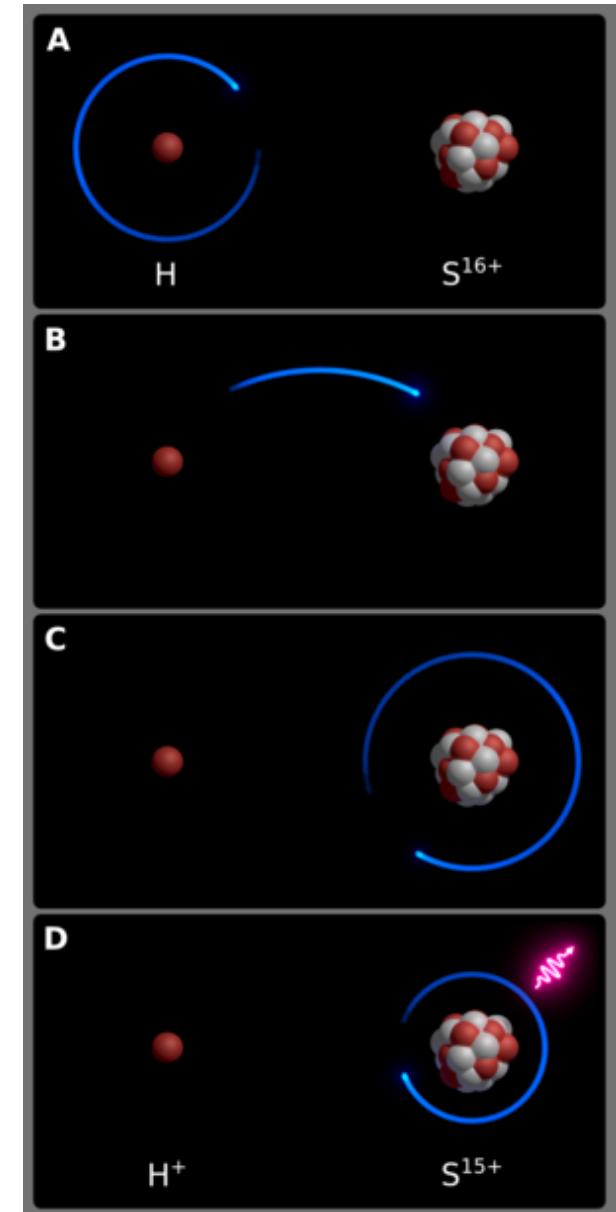
Intensity ↔ fits typical abundance

→ **3.5 keV lines not from dark matter**

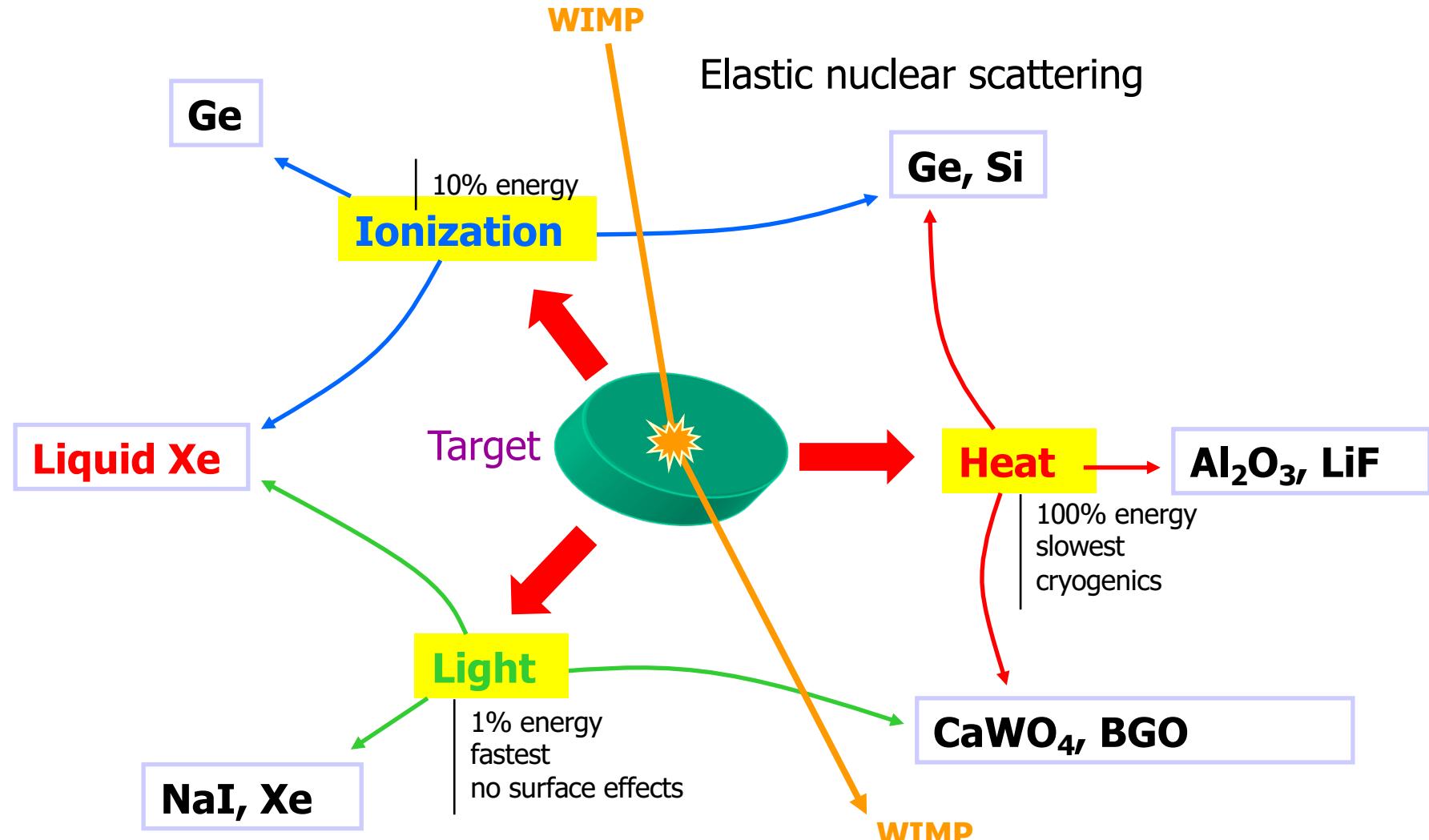
lesson: there may be other keV lines ...

... and other charge exchange reactions

→ unambiguous detection is difficult

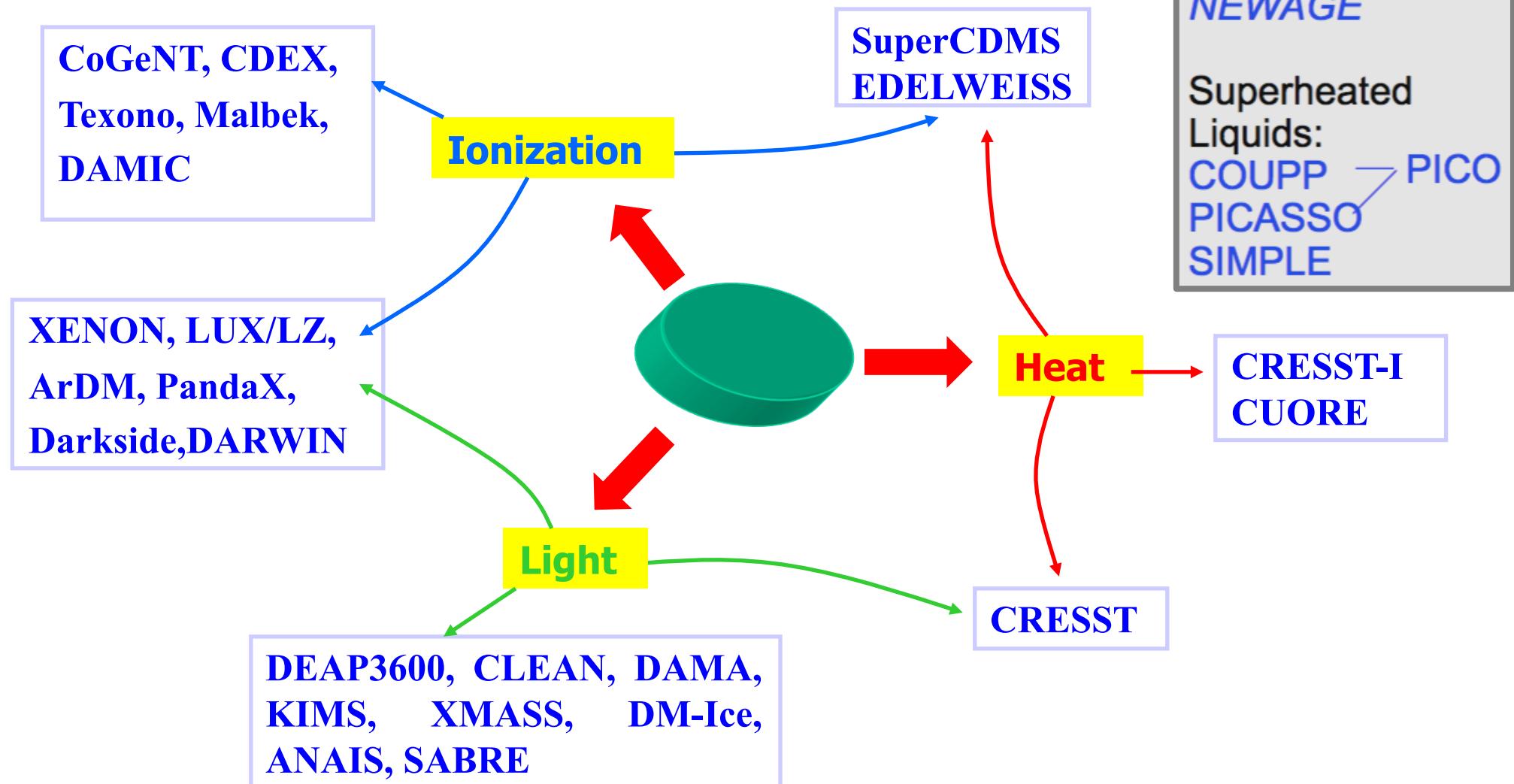


# Different direct Detection Techniques

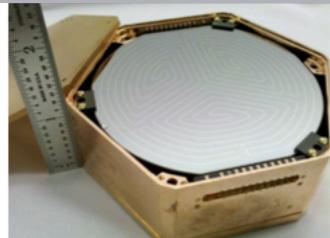


# Different direct Detection Techniques

Detection methods: Crystals (NaI, Ge, Si),  
Cryogenic Detectors, Liquid Noble Gases



# Light WIMPs: SuperCDMS - EDELWEISS - CRESST



SuperCDMS: Ge, Si

**phonons (heat) + ionization**

## SuperCDMS @SNOLAB

Aim: 50 kg-scale (cryostat up to 400kg)  
low threshold, less bg: deeper, cleaner,  
upgraded electronics, data taking 2020+



EDELWEISS-III (Ge)

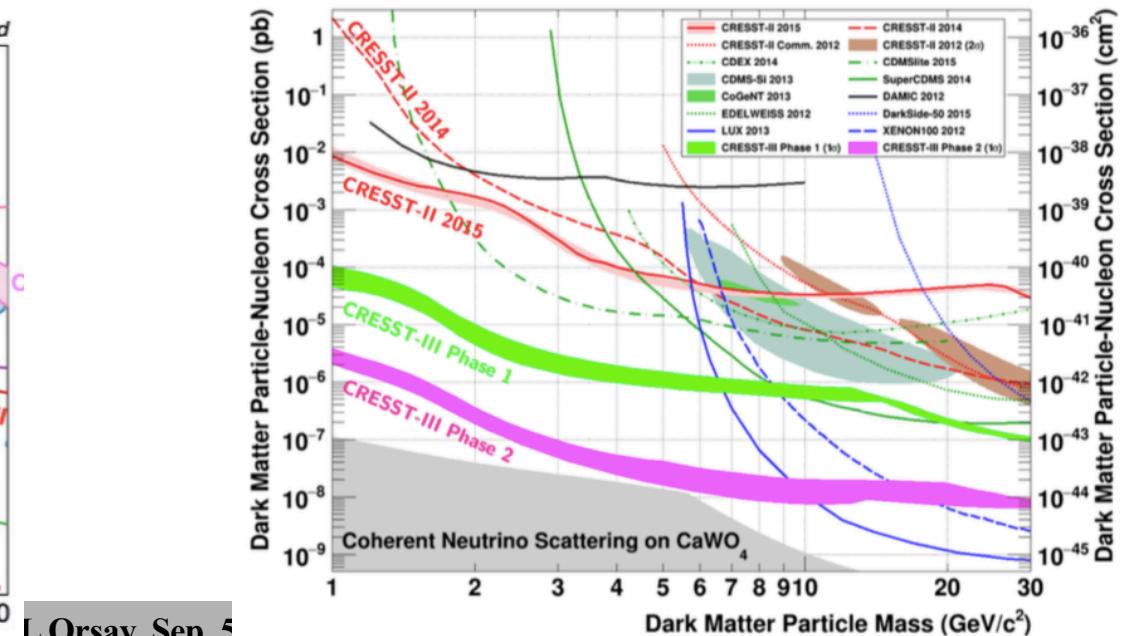
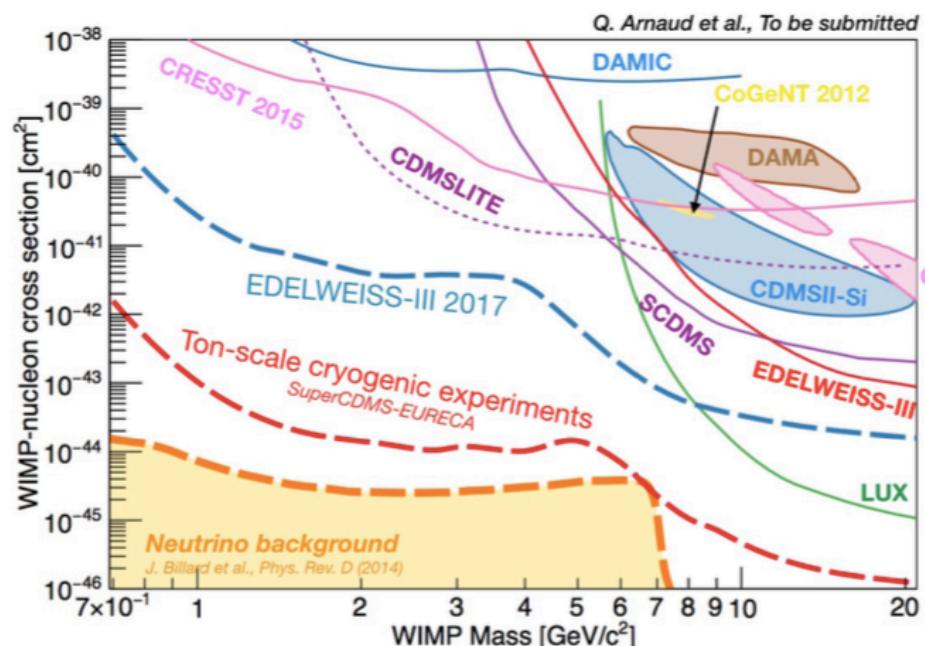


CRESST (CaWO<sub>4</sub>)

**heat + light**

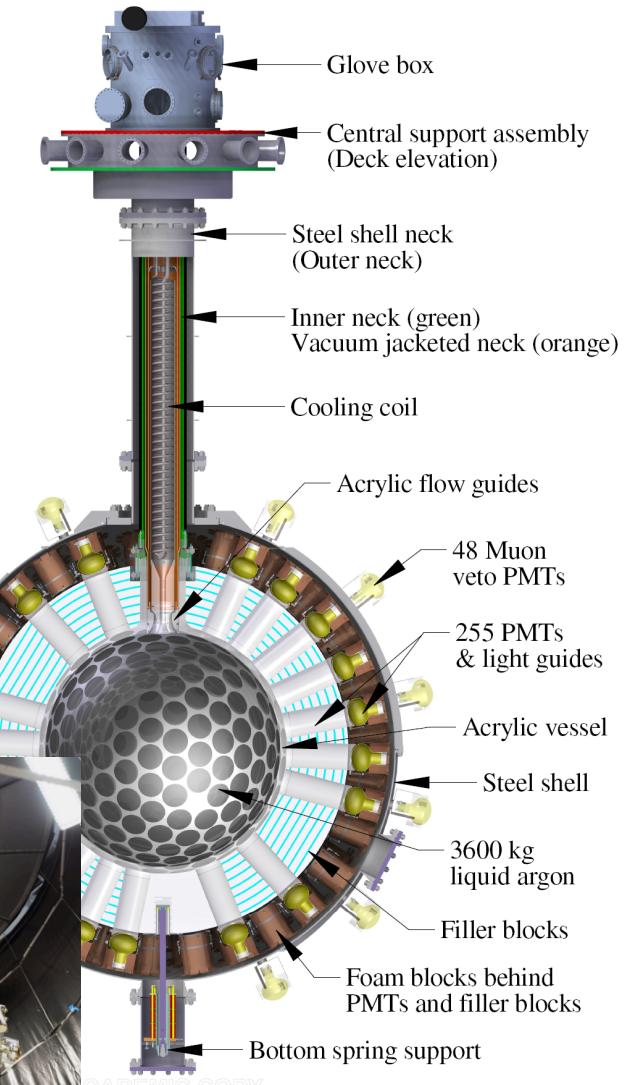
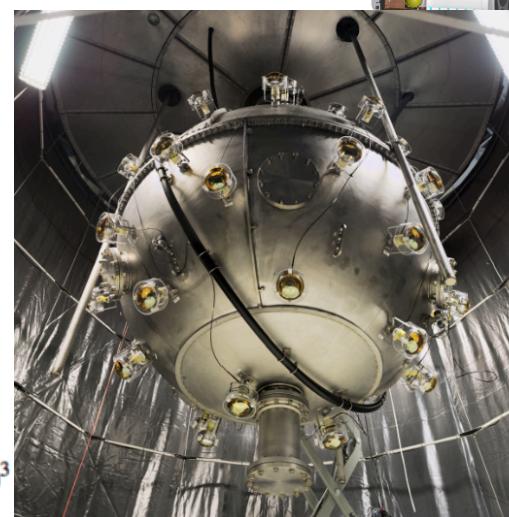
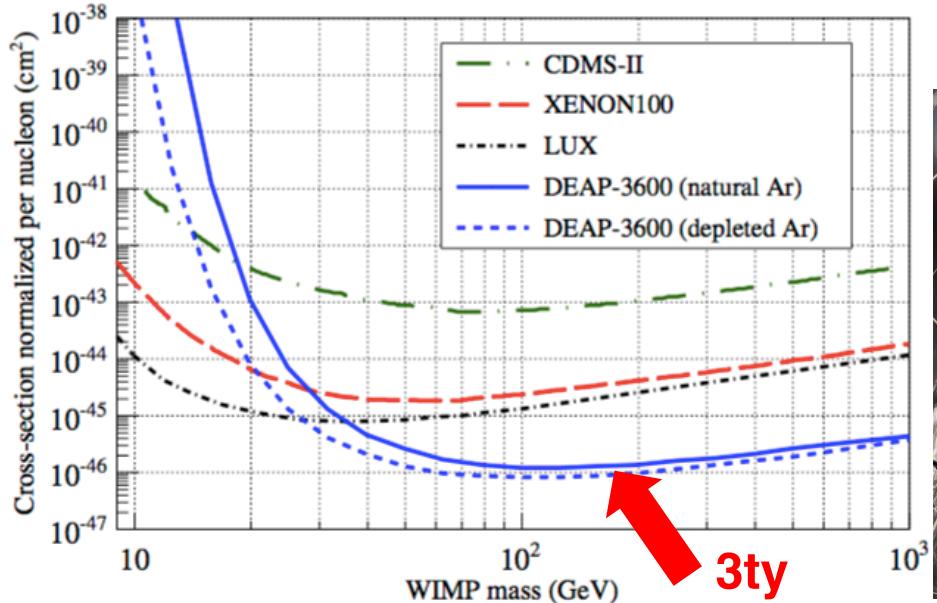
## CRESST @LNGS

2013-2015, 52 kg × d  
now: best threshold 300 eVnr  
excellent sensitivity  
for small WIMP mass  
→ CRESST-III

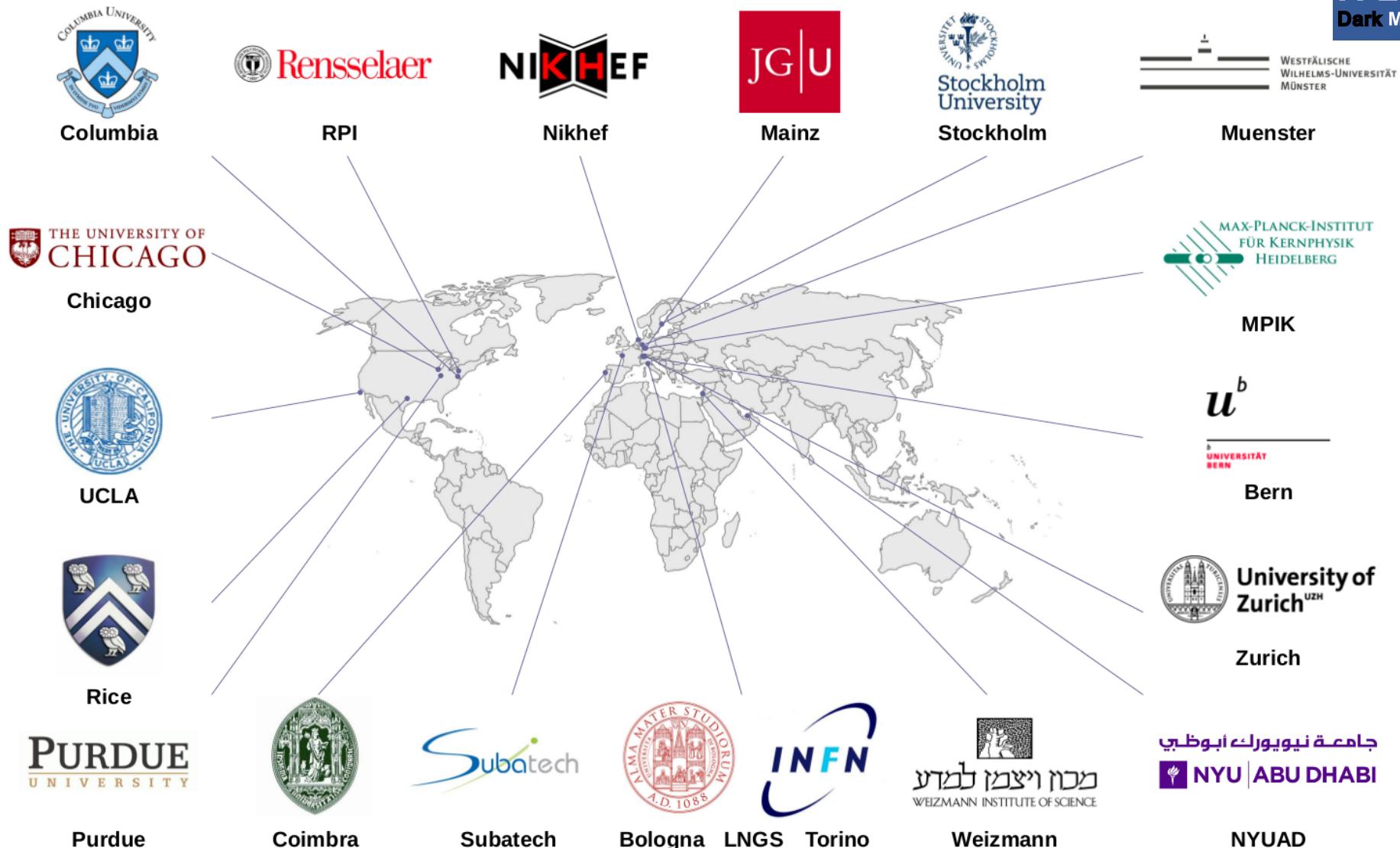


# DEAP-3600 @ SNOLAB

- Single phase LAr TPC, 3.6t (1t fiducial)
- Spherical ultra pure acrylic vessel
- 255 PMTs, extra shielding (foam, PE)
- TPB wavelength shifter → 128nm scintillation light into visible light
- Water tank + veto PMTs
- Ready for physics run ~filled → physics run

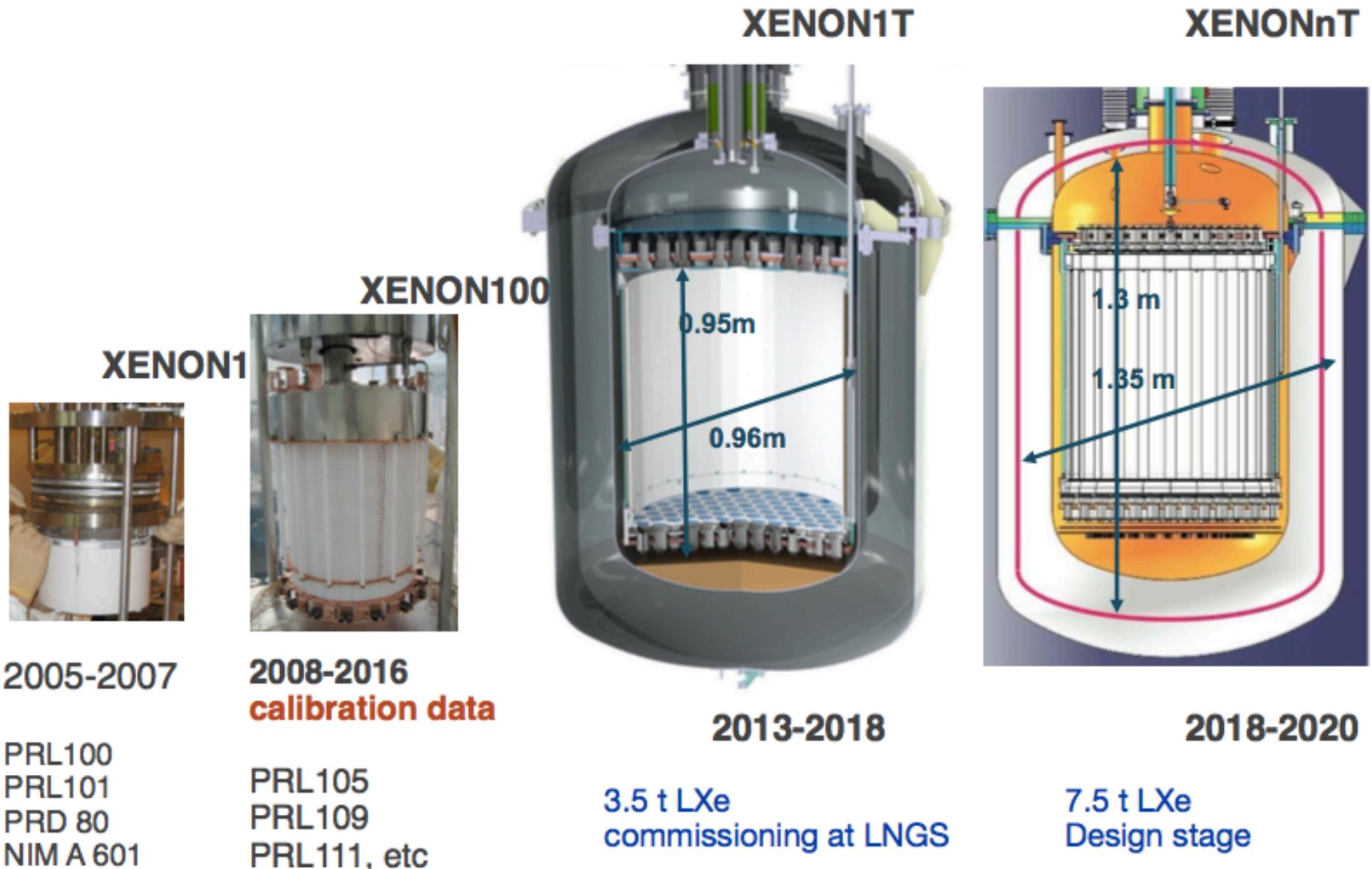


# The XENON Collaboration



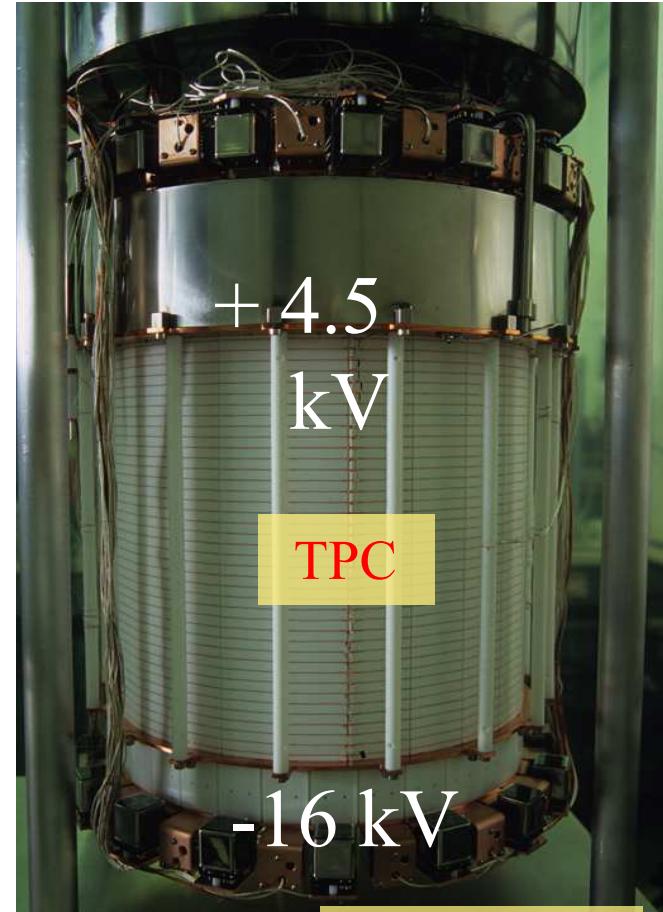
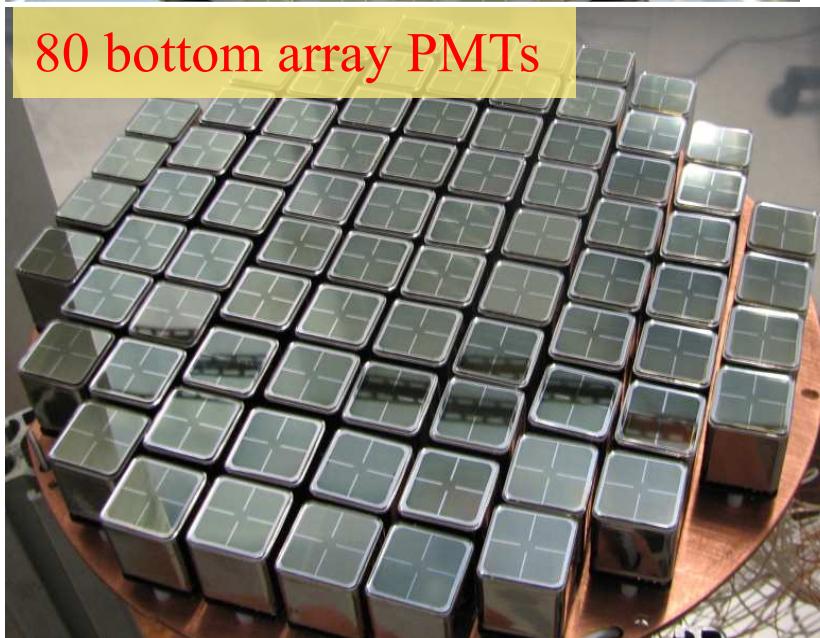
21 institutes, ~130 people

# The XENON-Program @ LNGS



# XENON100:

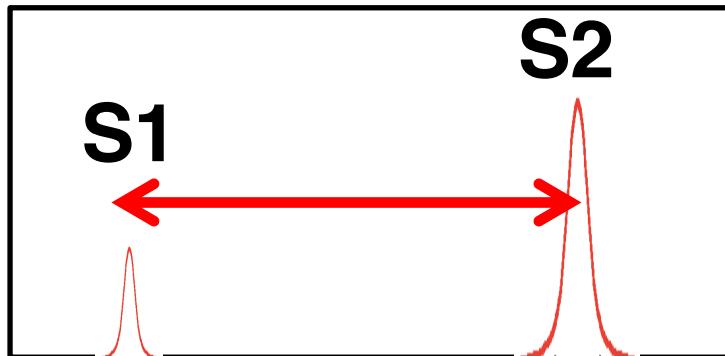
**242 low activity PMTs 1x1" (Hamamatsu R8520, QE>32% @175nm**



# XENON100: Dual-Phase TPC

WIMP-scattering:

- 1) direct light signal  $\rightarrow S_1$
- 2) drift of electrons to gas phase
- 3) 2<sup>nd</sup> light signal  $\rightarrow S_2$



- Drift-time  $\rightarrow z$
- PMT-signal distribution  $\rightarrow x,y$
- Pulse height, shape, ...

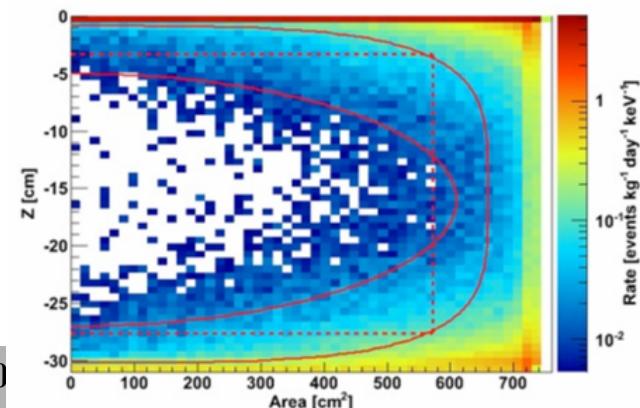
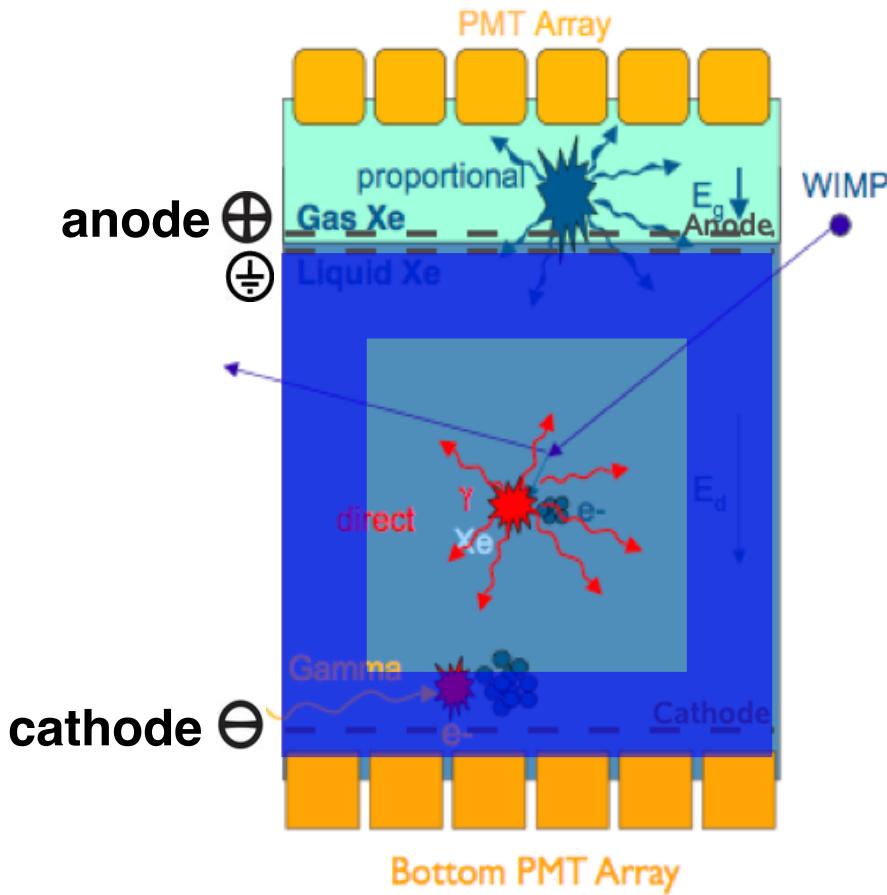
→ excellent 3D position reconstruction

$$\Delta r < 3 \text{ mm}; \Delta z < 0.3 \text{ mm}$$

→ fiducialization = exclude known backgrounds from 'dirty' surfaces

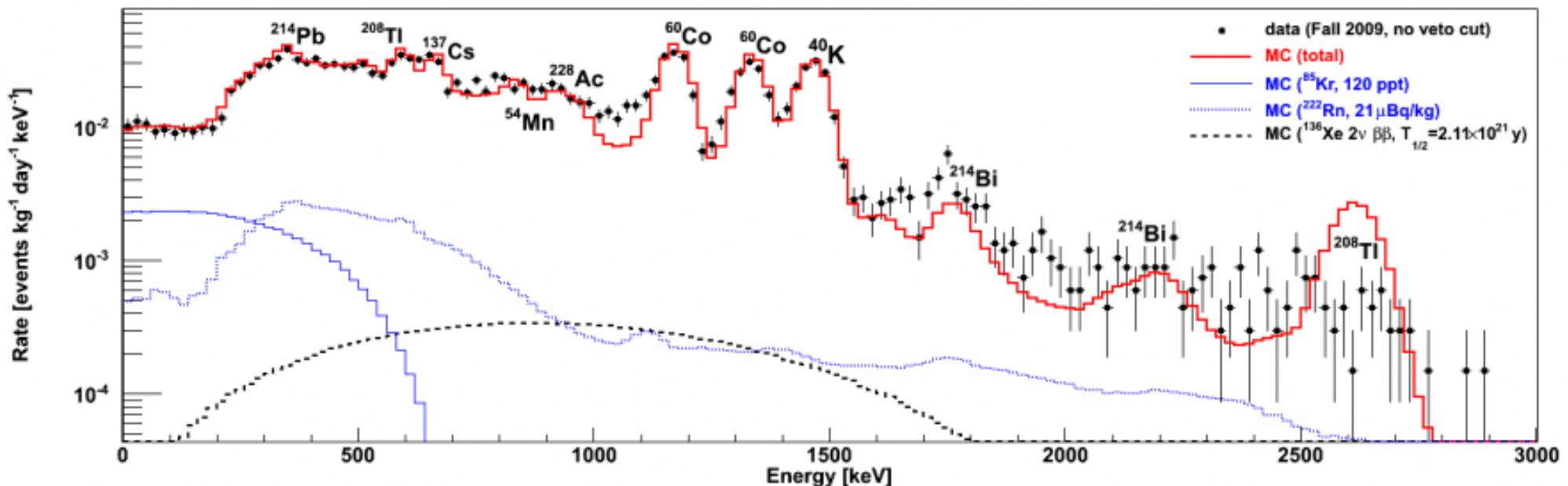
→ cuts: NR/ER/other, pulse shapes, ...

→ calibration



# Detailed Background Understanding

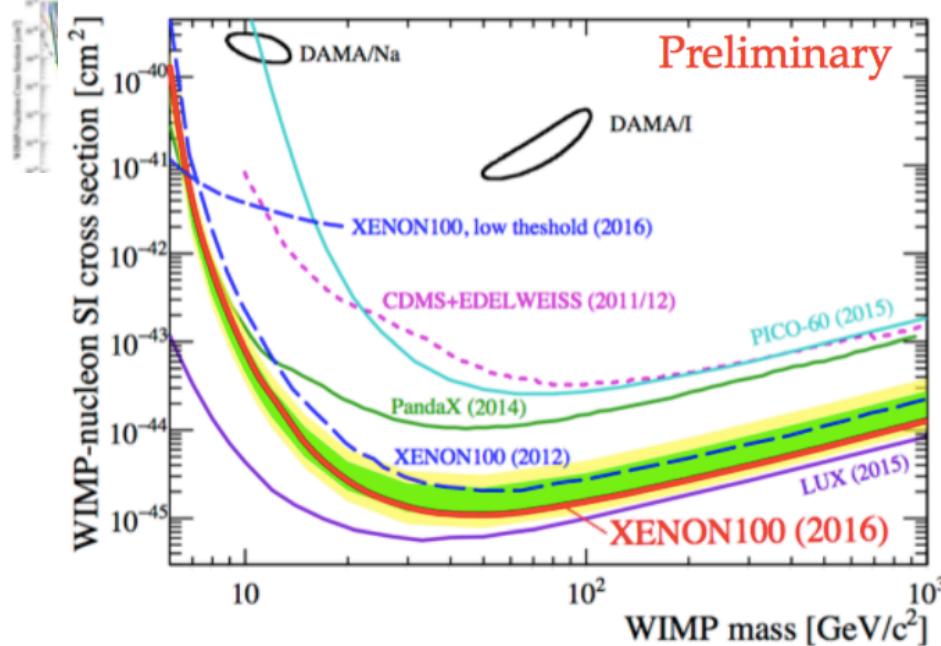
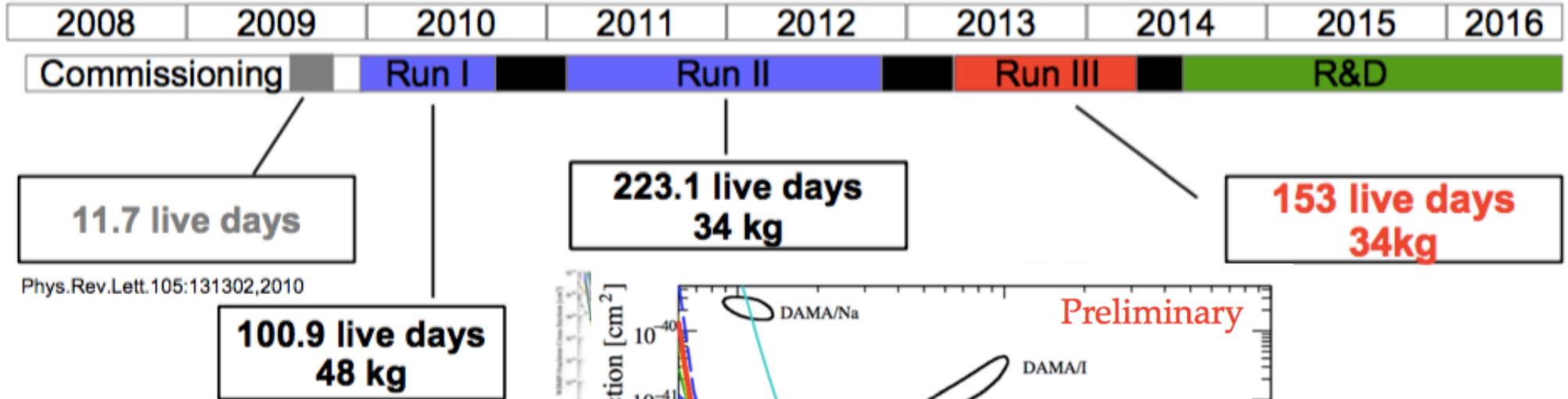
PRD 83, 082001 (2011)



- MC simulations and background in good agreement
- Background very well understood in full energy range
- $5 \leq 10^{-3}$  evts/kg/keV/d after the veto cut
  - achieved design goal of factor 100 lower than in XENON10! (and than any other search...)

+ LUX, PandaX  
→ Recent Results

# XENON100: Combination of Runs



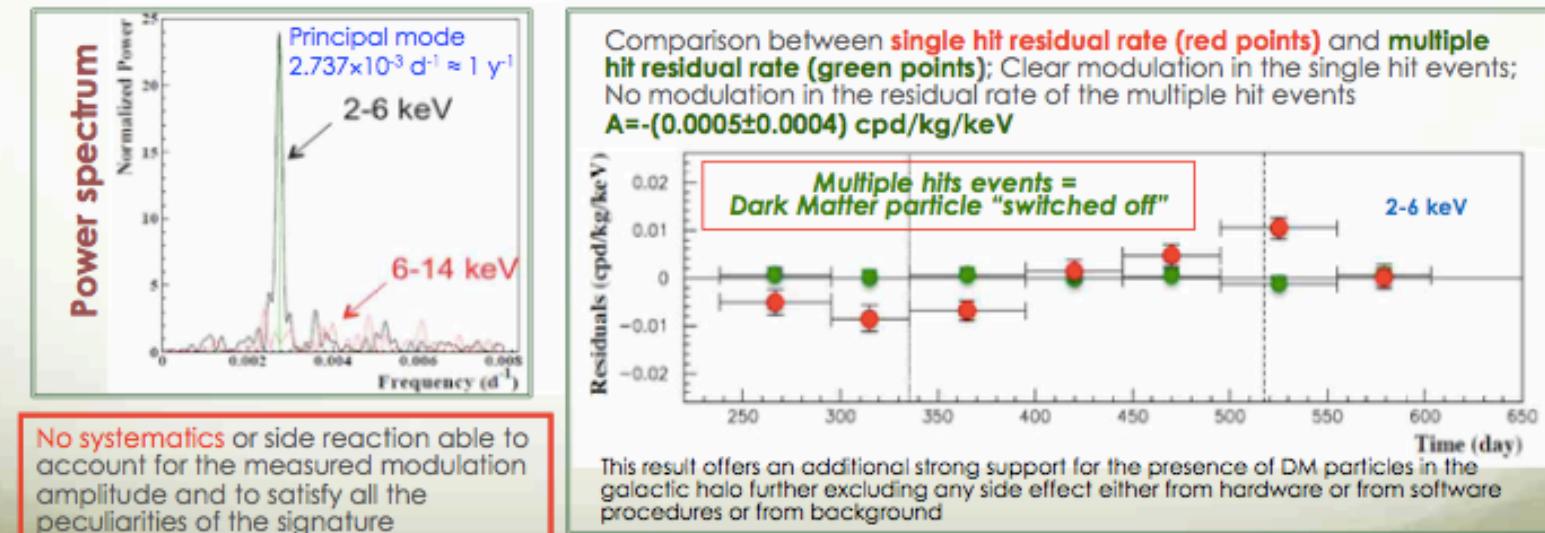
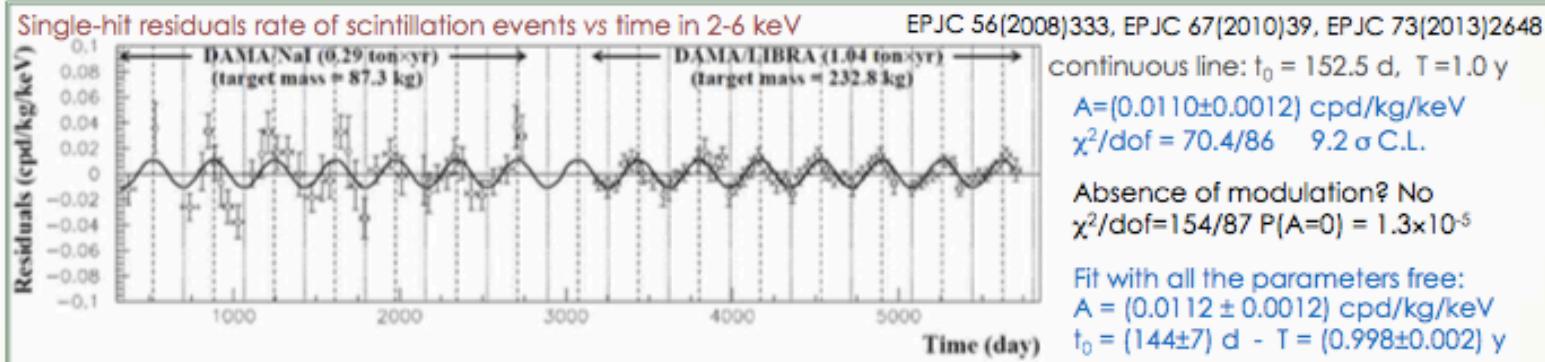
NEW: Improvement of SI limit with respect to Run II by a factor of 1.7 @50 GeV/c<sup>2</sup> and 1.09 10<sup>-45</sup> cm<sup>2</sup>  
...while we were building XENON1T → soon

# DAMA's Modulation

Belli  
IDM 2016

## Model Independent Annual Modulation Result

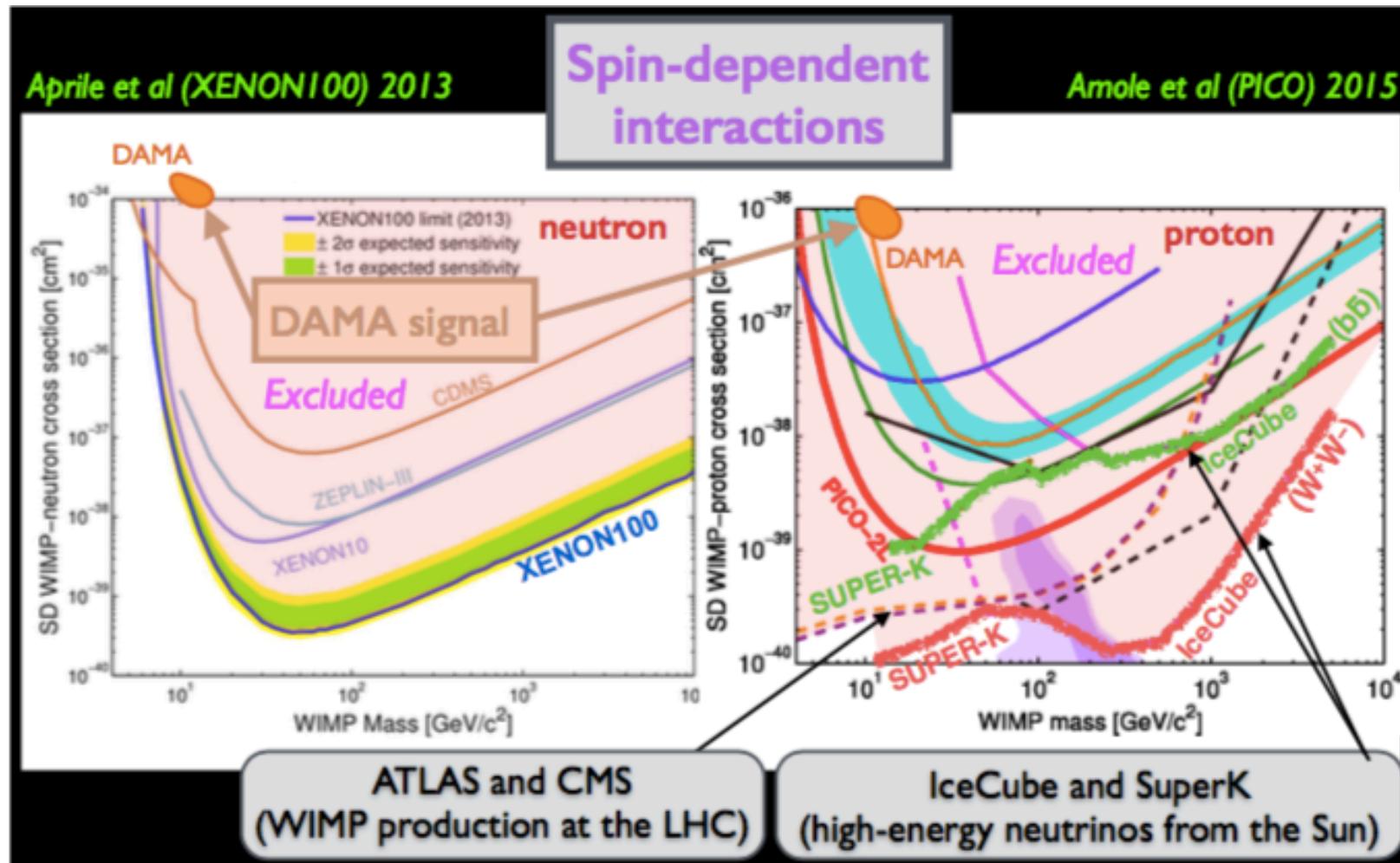
DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = 1.33 ton×yr



The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about  $9.2\sigma$  C.L.

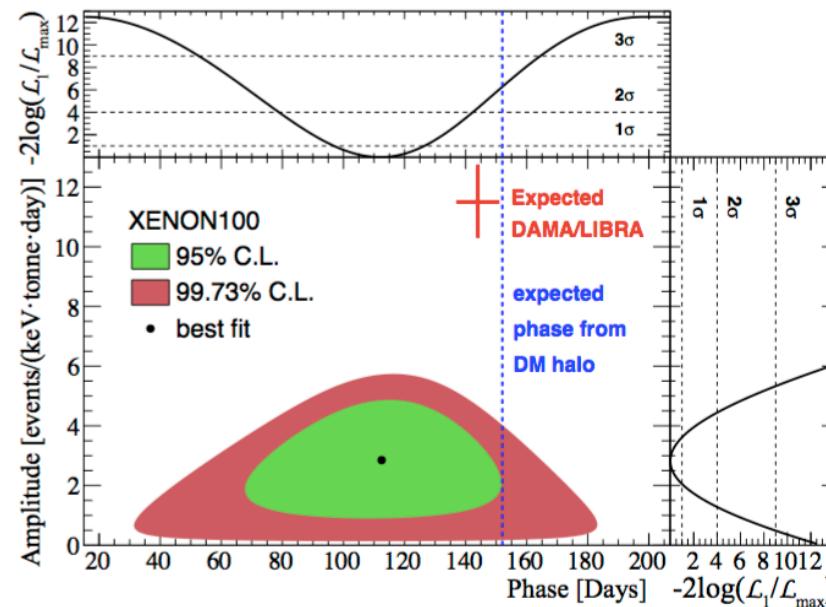
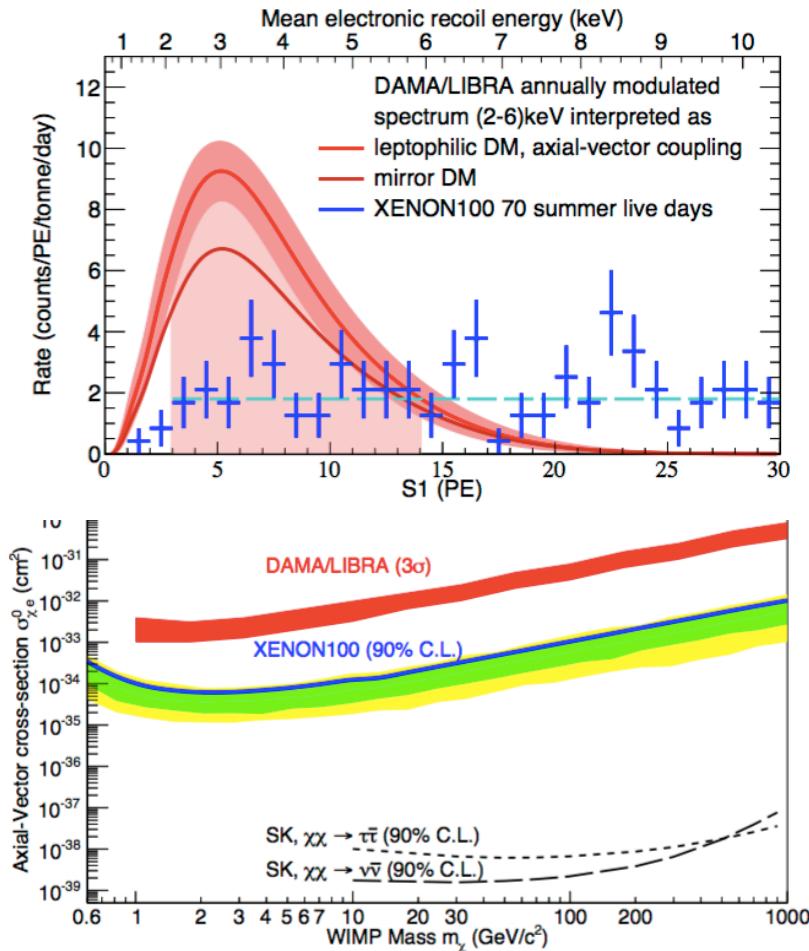
# Incompatible with other Results

- Spin-independent interactions Standard halo model
- Spin dependent



# More: Electronic Recoil in XENON100

E. Aprile et al. Science 349 (2015) no.6250, 851-854; Phys.Rev.Lett. 115 (2015), 091302



**Conclusion:** Leptophilic models excluded; annual modulation must have another origin \*or\* sophisticated models with a signal in DAMA and nowhere else

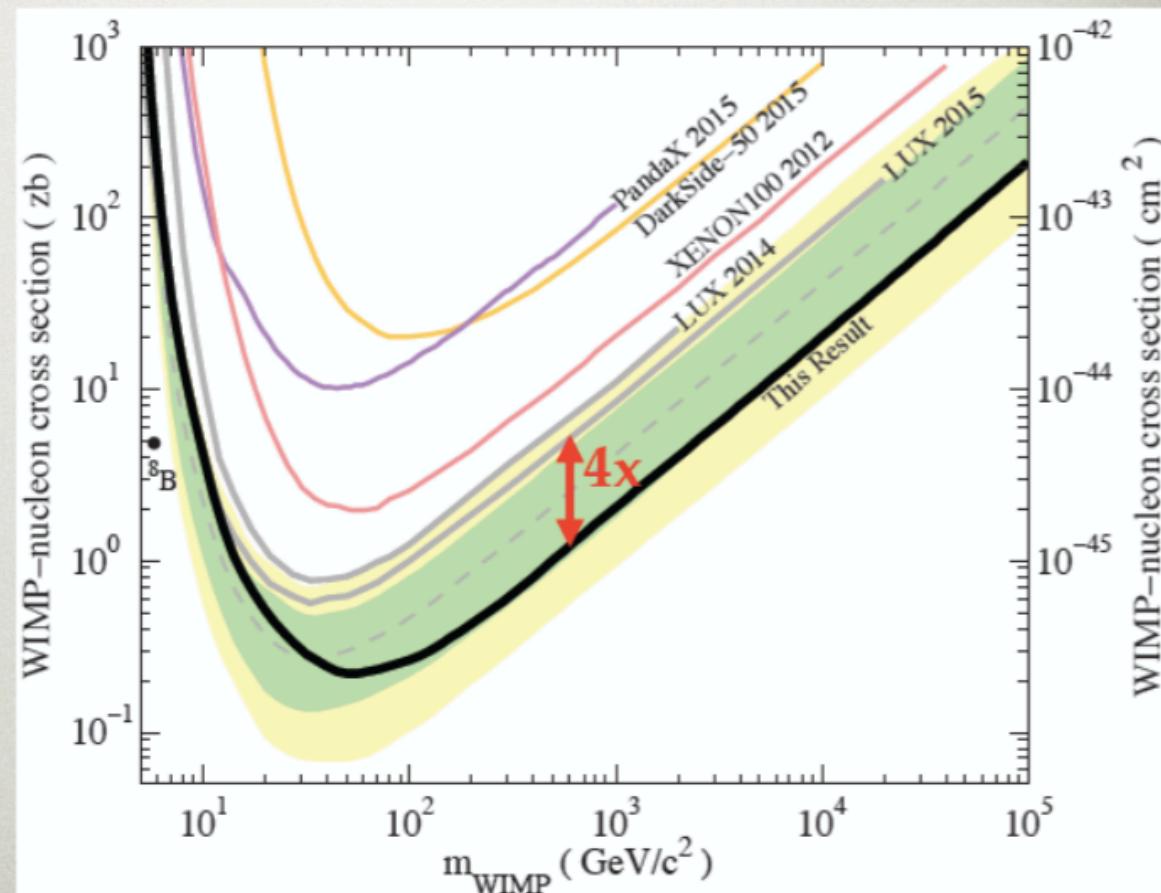
In addition: New NaI Projects to directly test DAMA → clarify the modulation signal  
**SABRE@LNGS, COSINE-100 (DM-Ice+KIMS) @Yangyang , ANAIS @Canfranc**

# New LUX Result

Dark-matter results from 332 new live days of LUX data

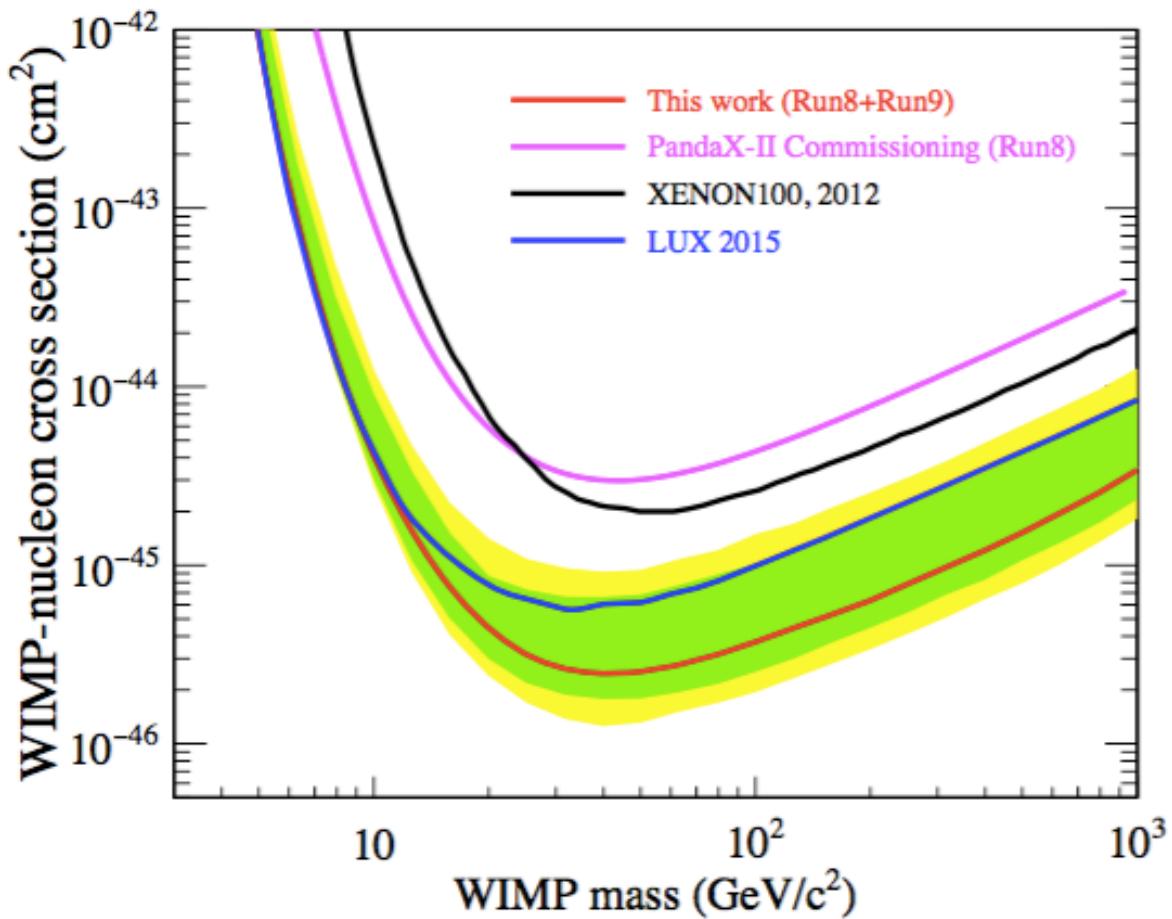
## SI WIMP-nucleon exclusion

- Brazil bands show the 1- and 2-sigma range of expected sensitivities, based on random BG-only experiments.
- Factor of 4 improvement over the previous LUX result in the high WIMP masses
- Minimum exclusion of  $2.2 \times 10^{-46} \text{ cm}^2$  at 50 GeV



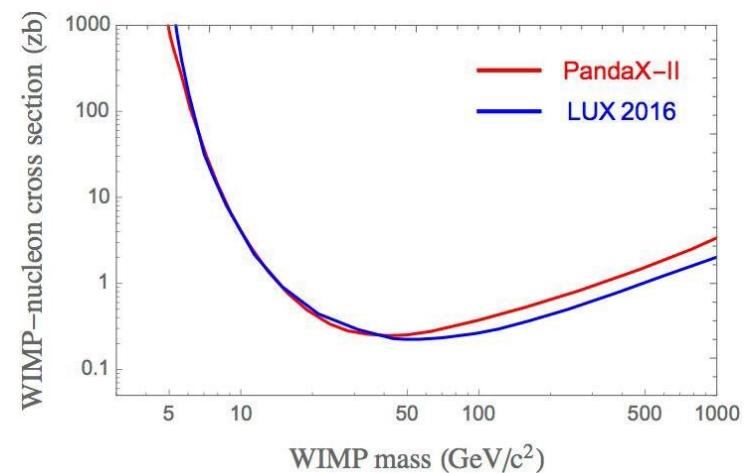
A. Manalaysay  
IDM 2016

# New PandaX Result (Run 8+9)

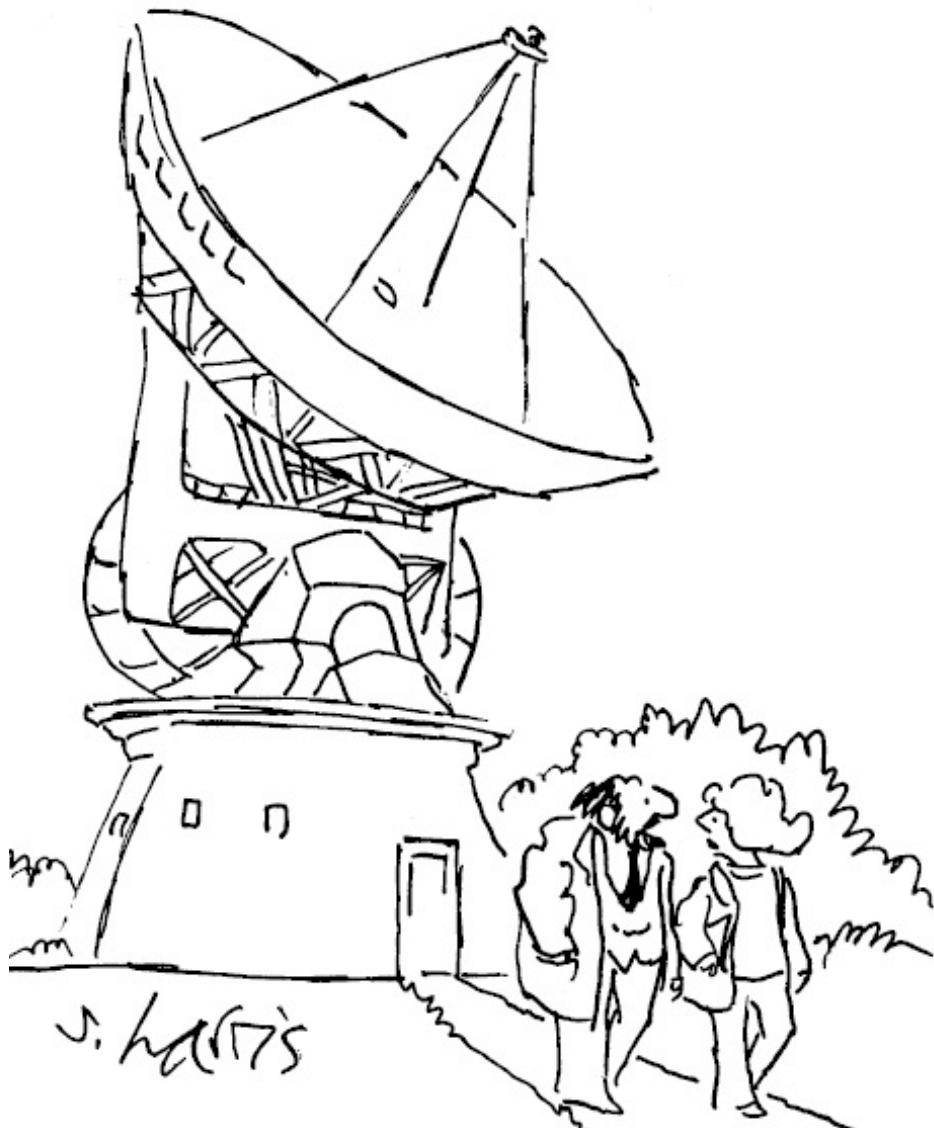


Compared to new LUX result →

A. Tan et al. arXiv:1607.07400  
Results from 98.7 days  
of PandaX-II



"I'LL BE WORKING ON THE LARGEST AND SMALLEST OBJECTS IN THE UNIVERSE — SUPERCLUSTERS AND NEUTRINOS. I'D LIKE YOU TO HANDLE EVERYTHING IN BETWEEN."

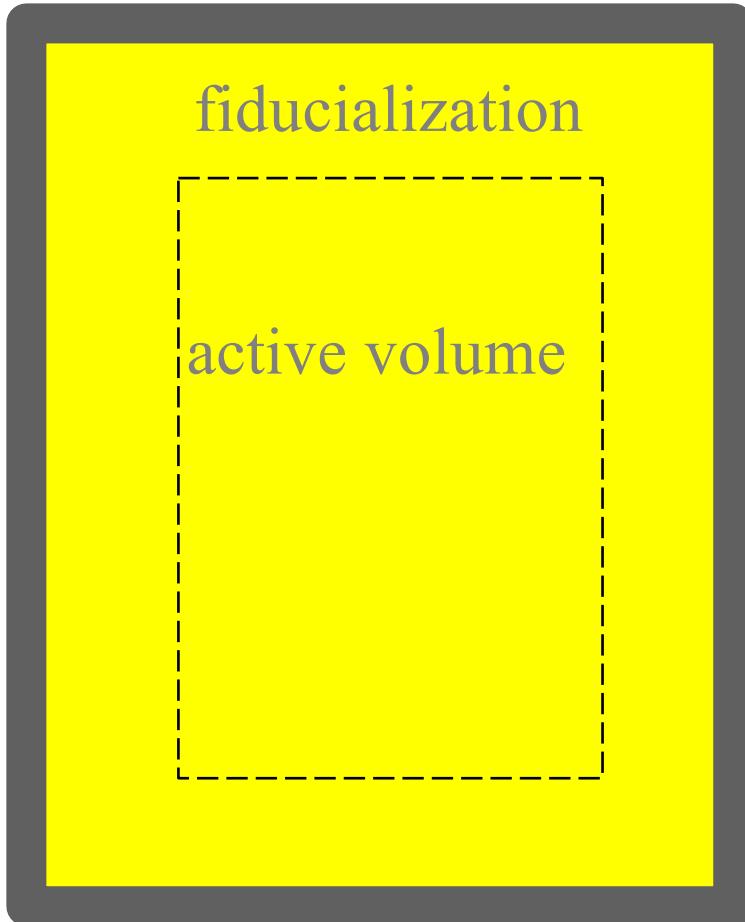


**while XENON100 was  
producing important  
results:**

**Fainter signals require**  
**- bigger detectors**  
**- more suppression**  
**of backgrounds**

**→ build XENON1T while  
others catch up**

# Next generation Scaling Considerations



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

Better sensitivity → more exposure  
→ bigger running time  $\propto$  detector size  
 $\text{Volume} \sim r^3 \leftrightarrow \text{Surface} \sim r^2$

**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 bg. reduction & monitoring

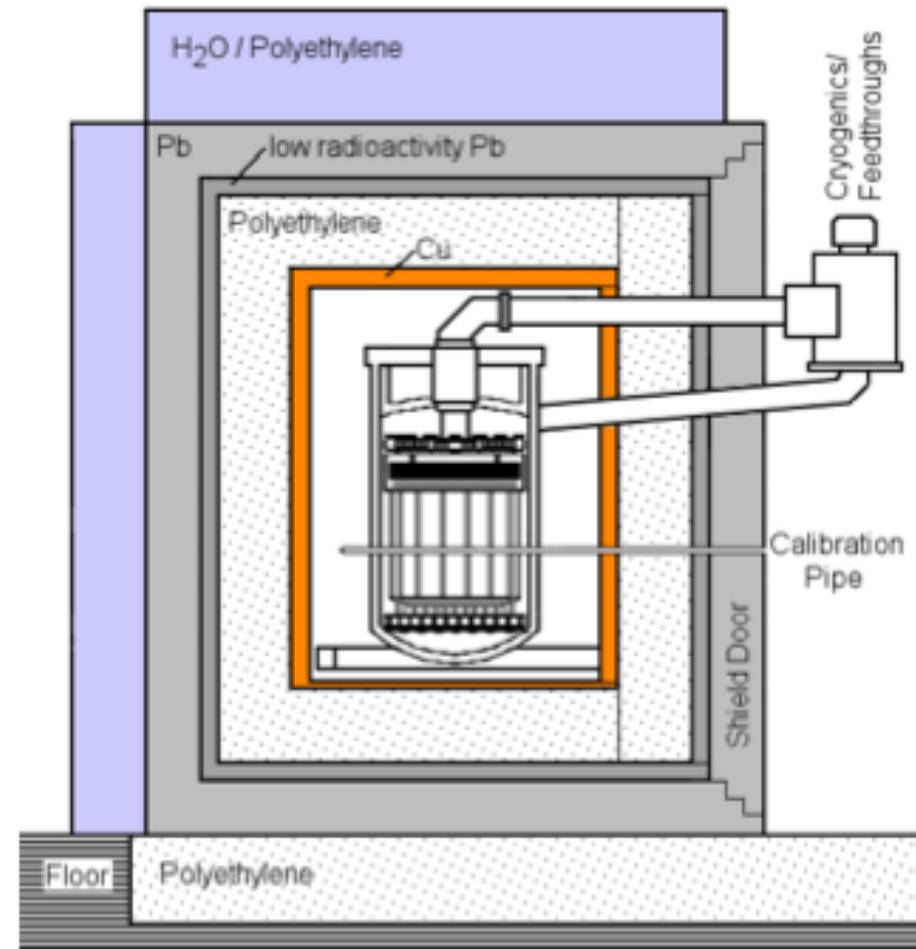
$^{238}\text{U}$ ,  $^{235}\text{U}$ ,  $^{228}\text{Th}$ ,  $^{226}\text{Ra}$ ,  $^{60}\text{Co}$ ,  $^{222}\text{Rn}$ ,  $^{85}\text{Kr}$  ...

→ low background expertise from GALLEX, Borexino, KATRIN, Double Chooz, Gerda ...

# Shielding of environmental Radioactivity

- 1) Locate detector in an underground laboratory
- 2) Increasing cleanliness towards inner part:

- Neutrons from rock
  - shields of PE, lead copper
- Radon gas
  - purged with clean nitrogen
- instable isotopes in detector material (U, Th, K, Tl, ...)
  - “screening” of construction material
- Cleanliness of the Xenon gas (both radiopure and e-lifetime)
  - distillation
  - extreme precise instruments for the measurements of Rn, Kr, ... (ppq)



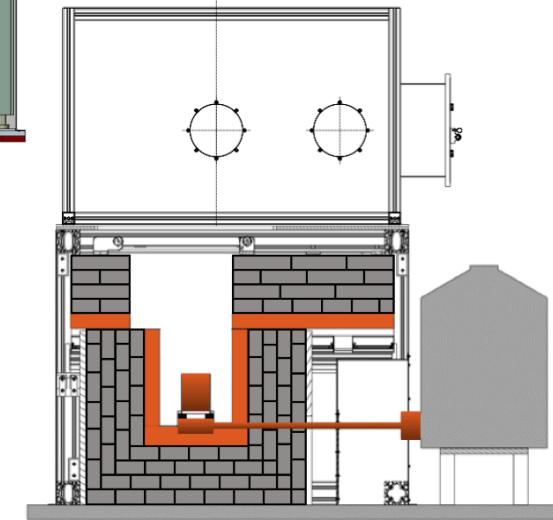
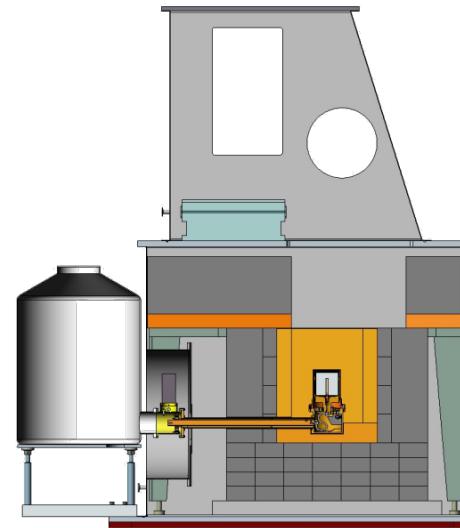
# MPIK Material $\gamma$ -Screening Facilities

- Different screening stations @MPIK underground lab ( $1\text{mBq/kg}$ )

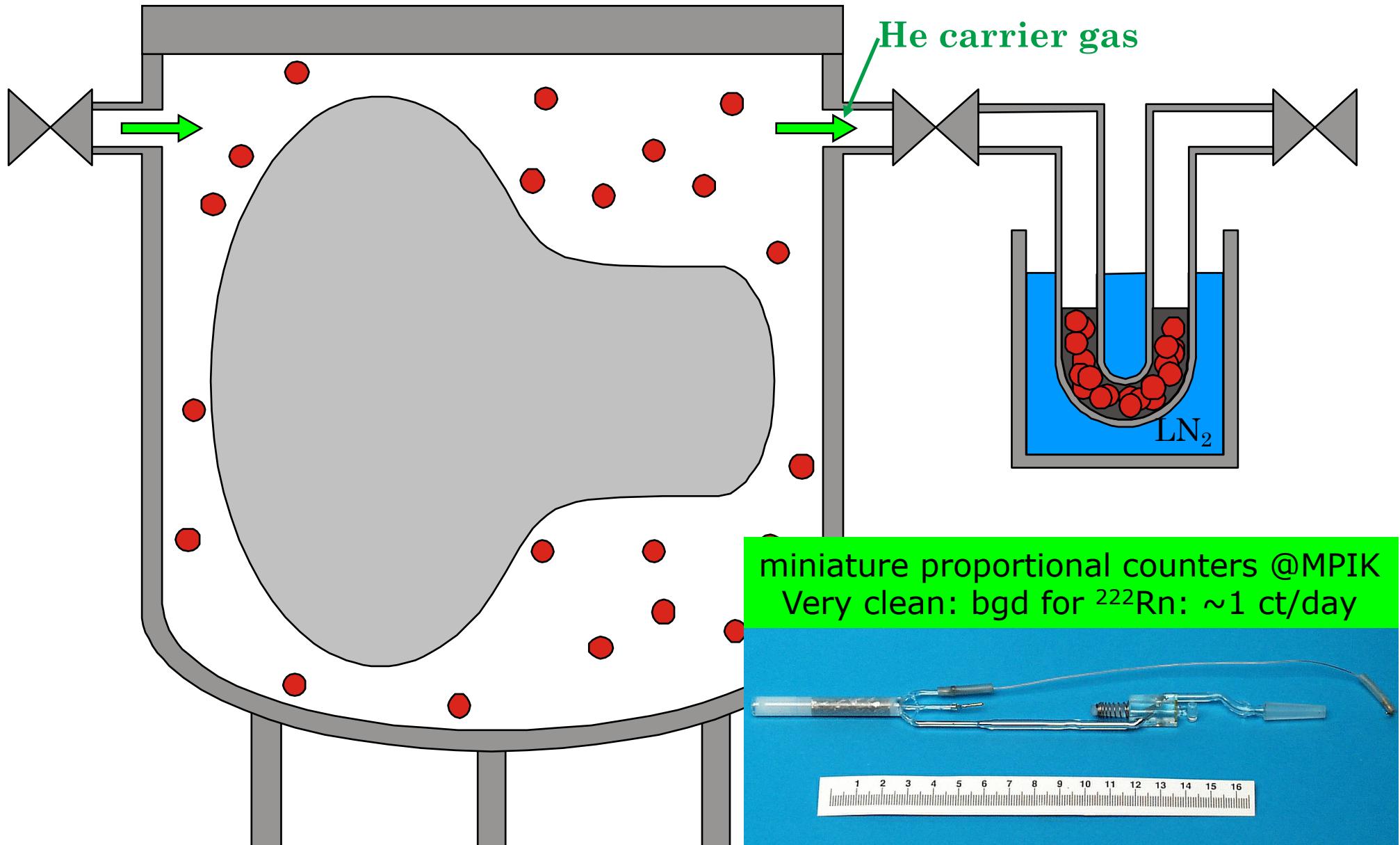
- 4 GEMPIs @LNGS ( $10\mu\text{Bq/kg}$ )

- New: GIOVE @MPIK ( $50\mu\text{Bq/kg}$ )

→ extensive task for GERDA,  
XENON and other experiments



# Rn Emanation; Avoid $^{222}\text{Rn}$ ( $\alpha$ -decaying)



# MPIK Rn Screening Facilities

## Gas counting systems

@LNGS and @MPIK

## $^{222}\text{Rn}$ emanation technique:

- sensitivity = few atoms/probe
- large samples  $\leftrightarrow$  absolute sensitivity
- non-trivial; not commonly available; routine @MPIK
- established numbers:

Nylon (Borexino)  $< 1\mu\text{Bq}/\text{m}^2$

Copper (Gerda):  $2\mu\text{Bq}/\text{m}^2$

Stainless steel (Borexino):  $5\mu\text{Bq}/\text{m}^2$

Titanium:  $(100 \pm 30) \mu\text{Bq}/\text{m}^2$

- Auto-Ema: New automated Rn screening facility at MPIK  $\rightarrow$  many samples for future experiments

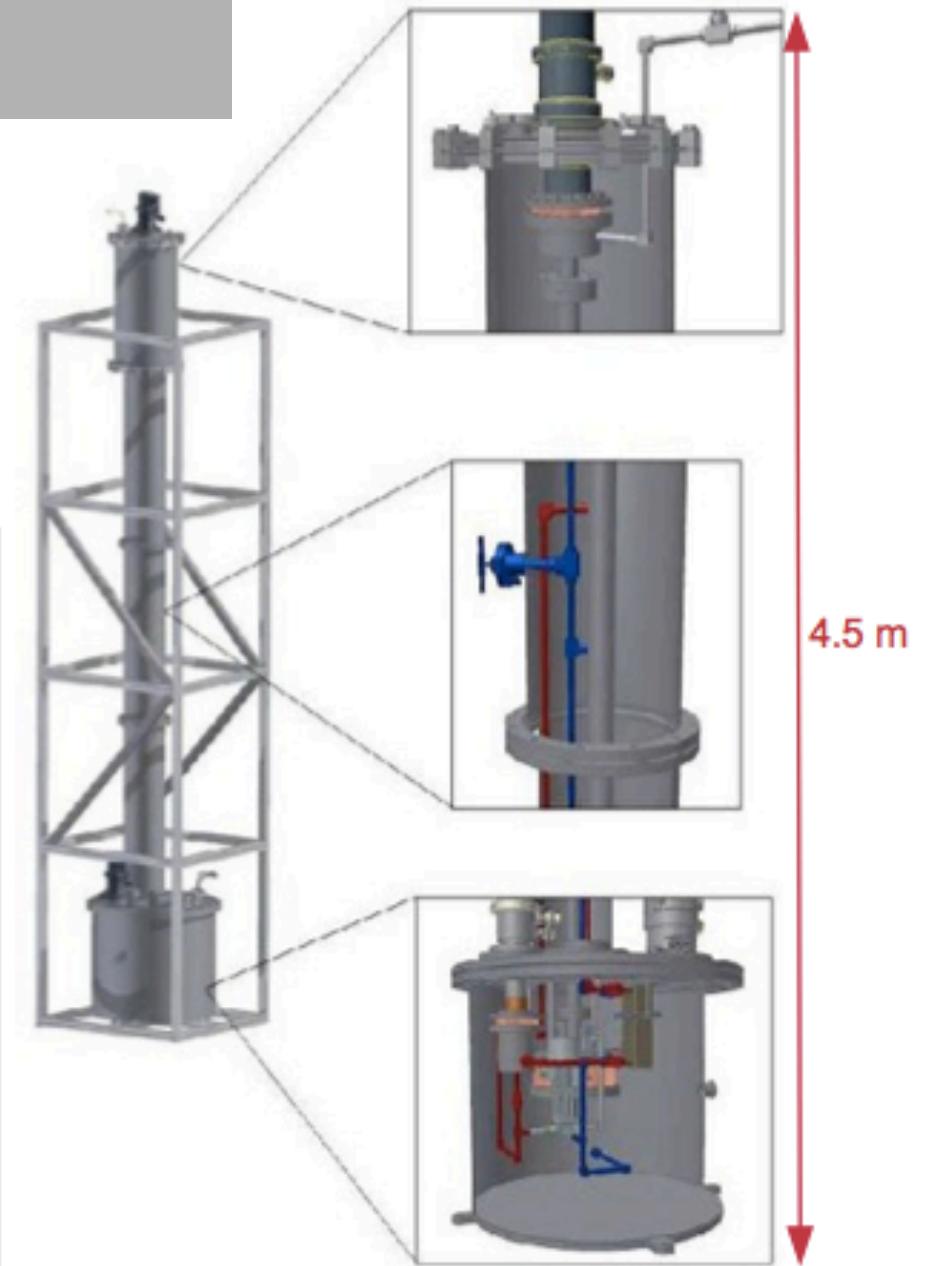
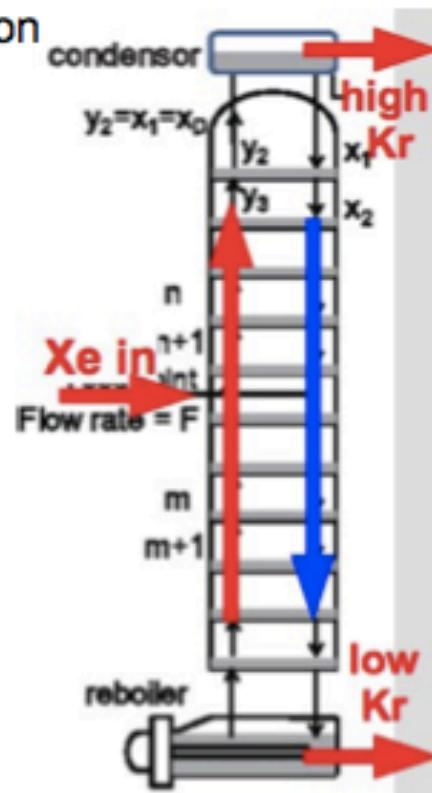
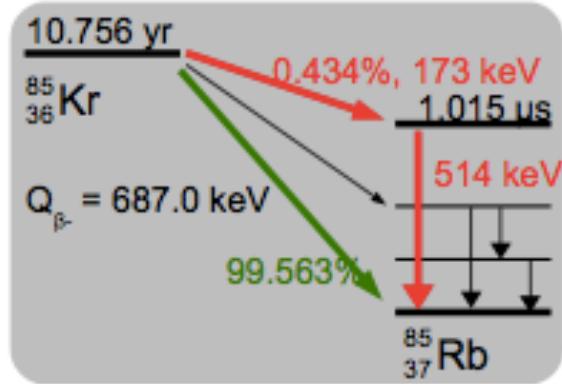


# Krypton Removal

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

## Design Parameters for XENON1T

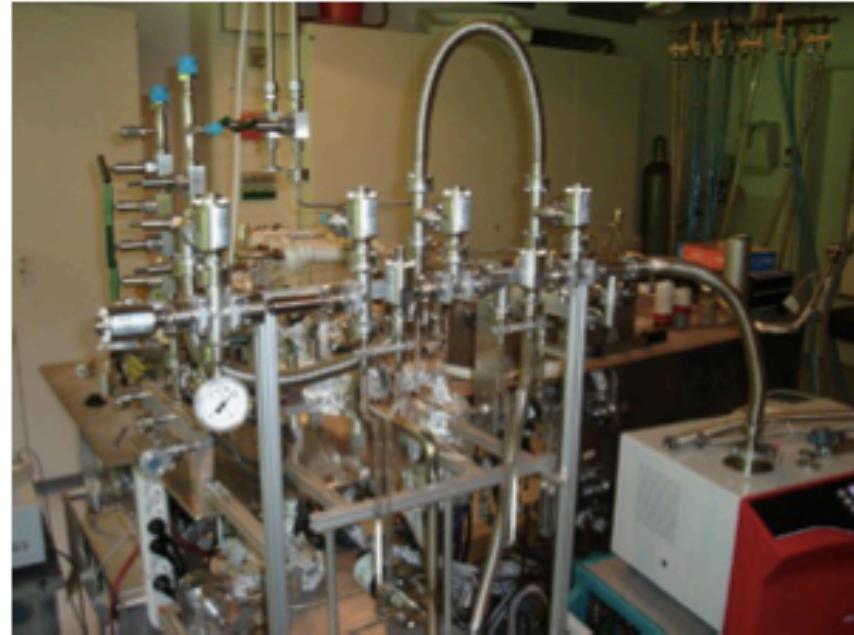
- through-put: 3 kg/hr
- factor of  $10^4\text{-}10^5$  separation
- final Kr/Xe < 1 ppt



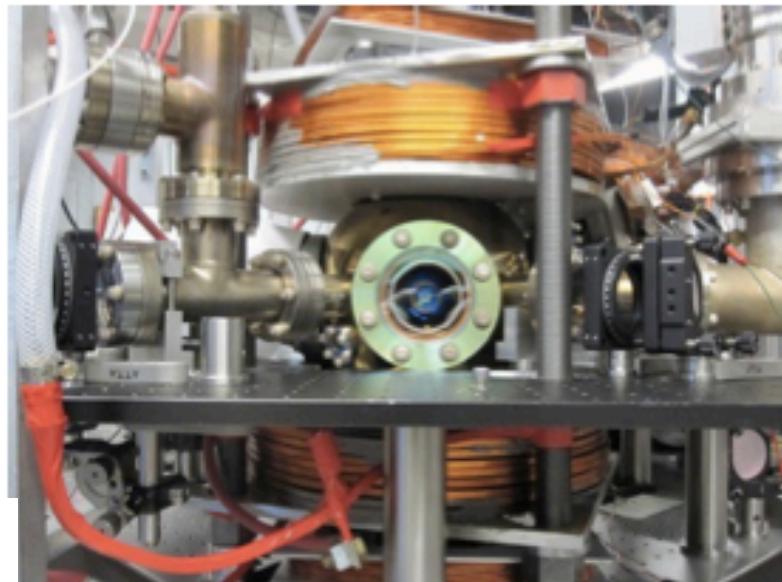
Münster for XENON1T

# Krypton Analysis

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



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

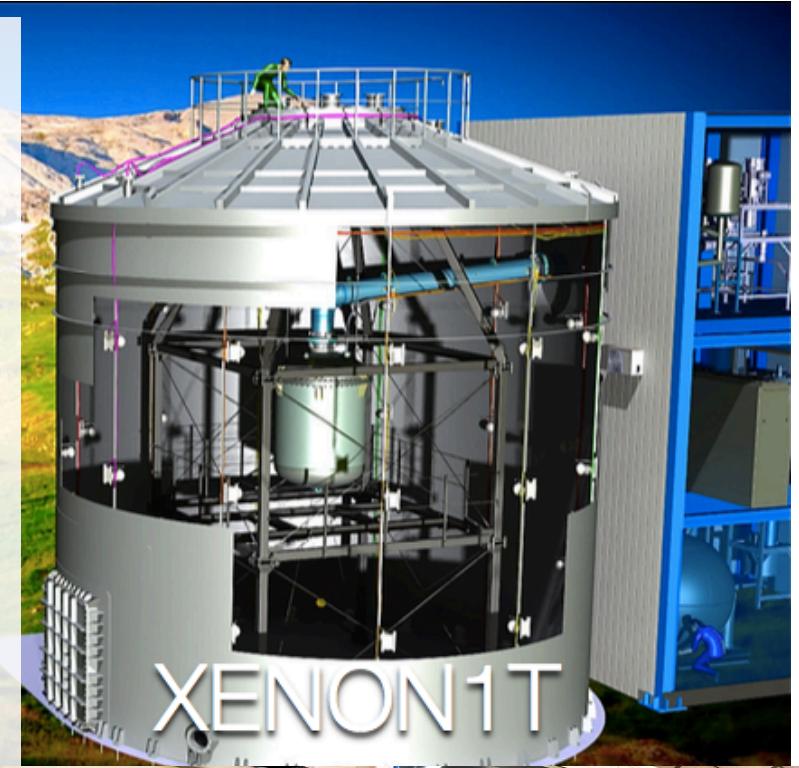


**MPIK (RGMS): ppt ... ppq sensitivity achieved  
Columbia U (ATTA)**

used for XENON100 and XENON1T

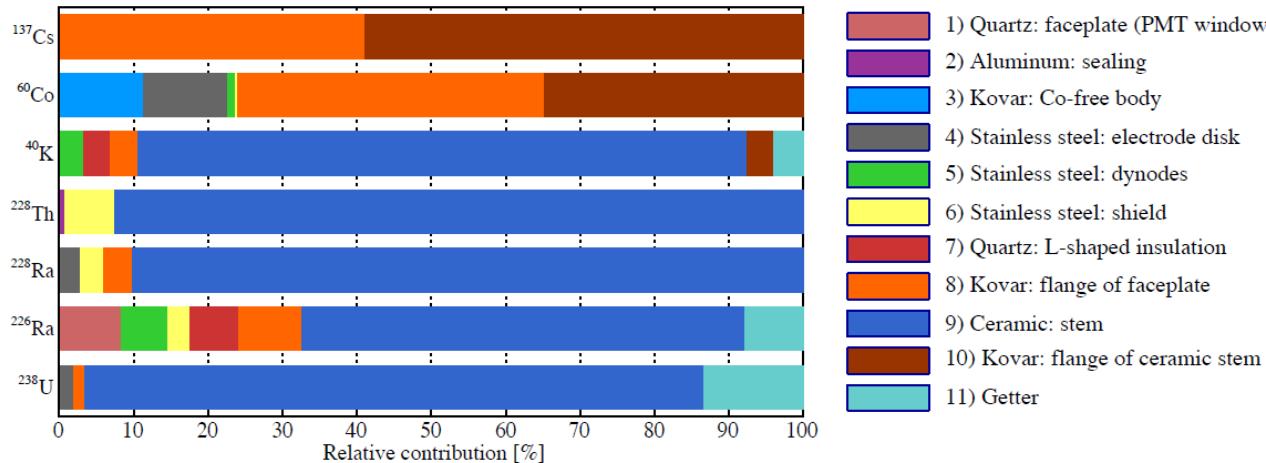
# XENON1T

- plan: x100 compared to XENON100
- target/Detector: 3.5t LXe TPC with 250 high QE low radioactivity PMTs
- water Cherenkov muon veto
- cryogenics: Xe cooling / purification / distillation / storage systems designed to handle up to 10t of LXe  
→ allows fast upgrade to XENONnT (2018) → another factor x10
- status:
  - all systems successfully tested
  - first science run this fall
- goal:  $2 \times 10^{47} \text{ cm}^2$   
@50 GeV for 2ty



# A lot of Work behind it...

- Design, simulation, testing, ...  
screening  $\leftrightarrow$  R&D

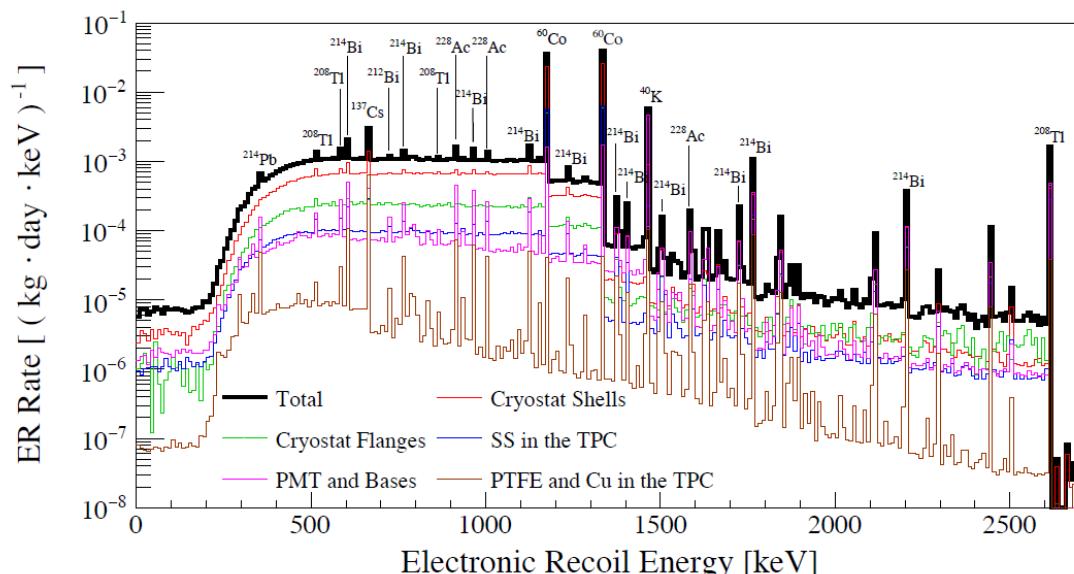


e.g. PMTs



← radiopurity optimization  
of PMTs together with  
Hamamatsu

Material advice and control with  
screening for every little piece  
achieved < 1mBq/PMT in U/Th  
Eur. Phys. J. C75 (2015) 11



Extensive tests of PMTs at  
room temperature and cryogen  
high QE, stability, tightness, ...  
→ paper to appear very soon

← Electronic recoil BG from materials  
arXiv:1512.07501, JCAP04(2016)027

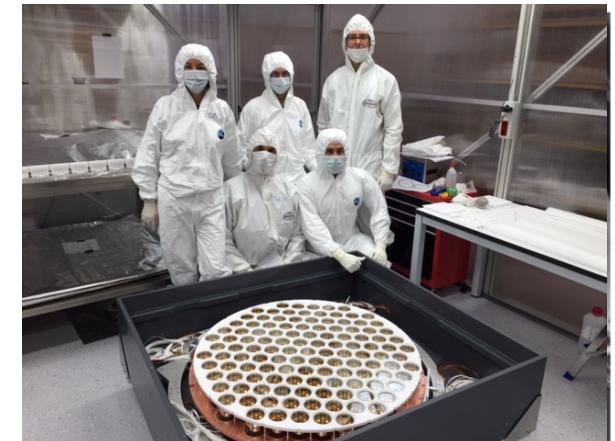
# The inner Detector



The TPC

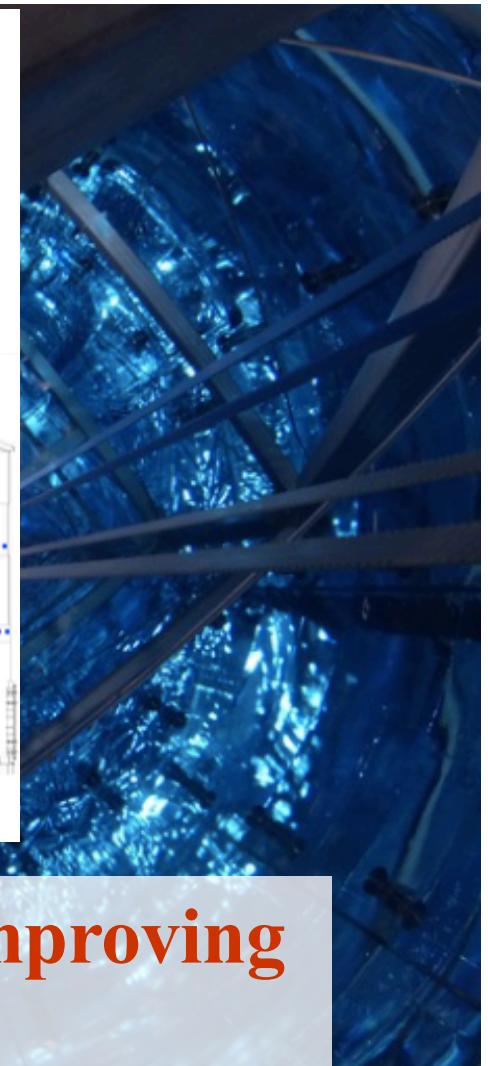
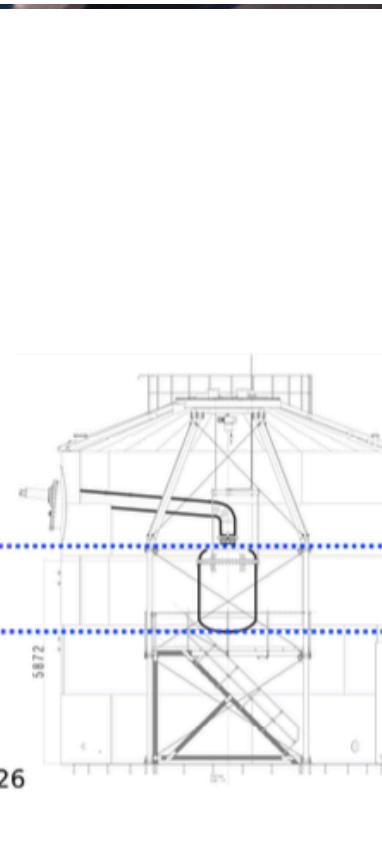
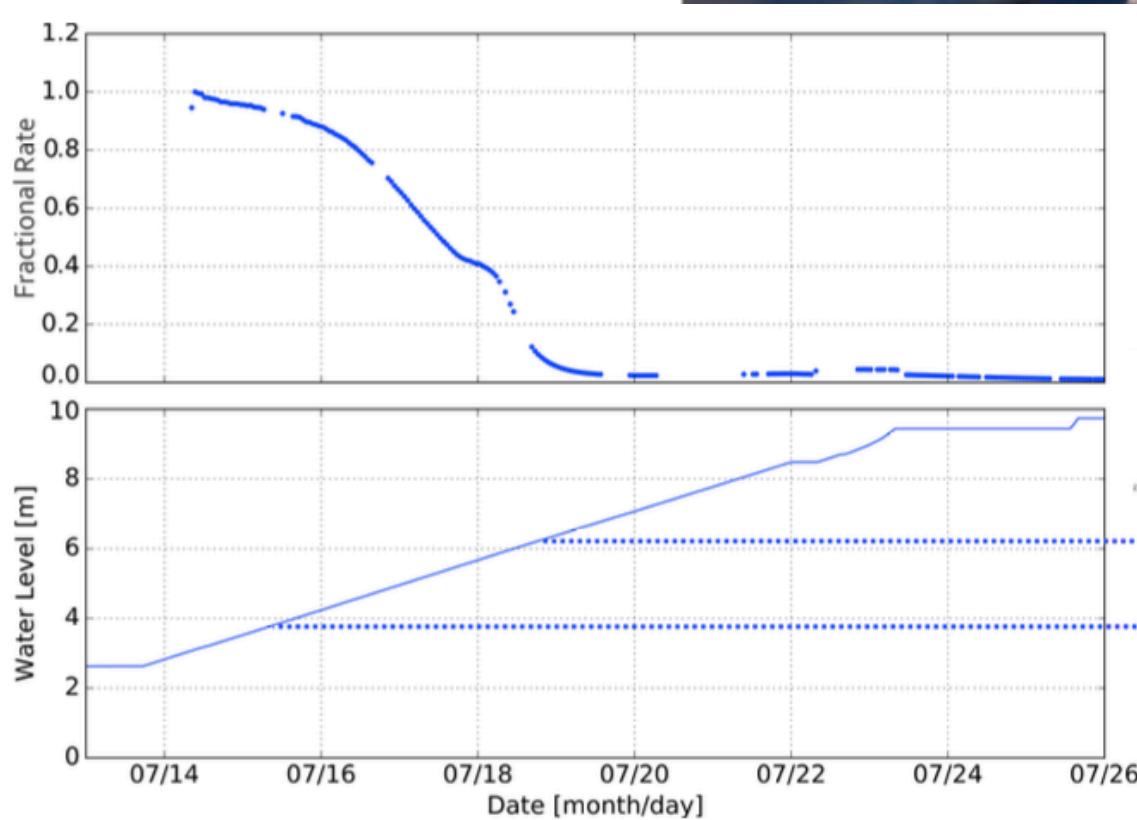


TPC installation underground



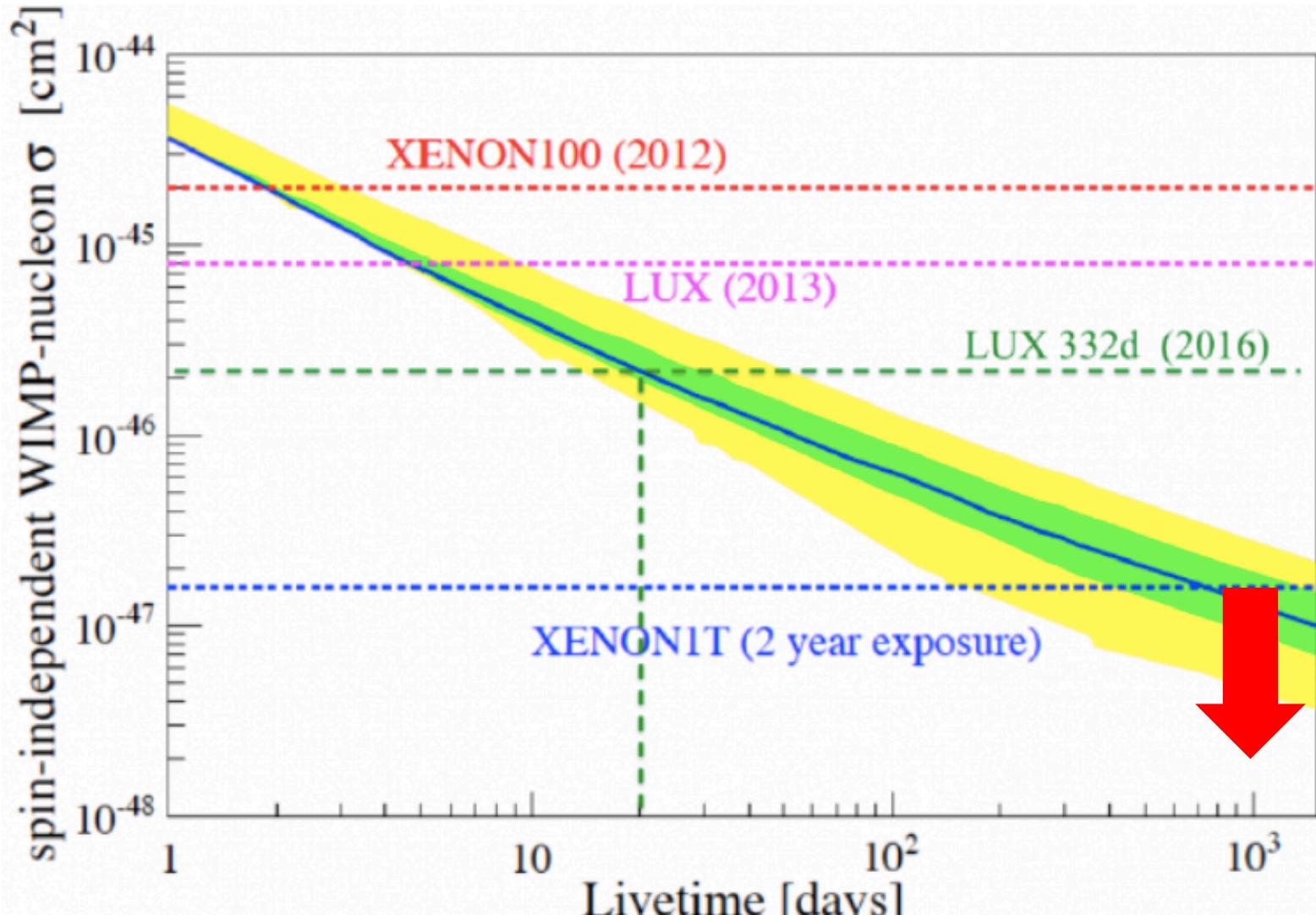
PMT arrays

# TPC filled with LXe and shielded by Water



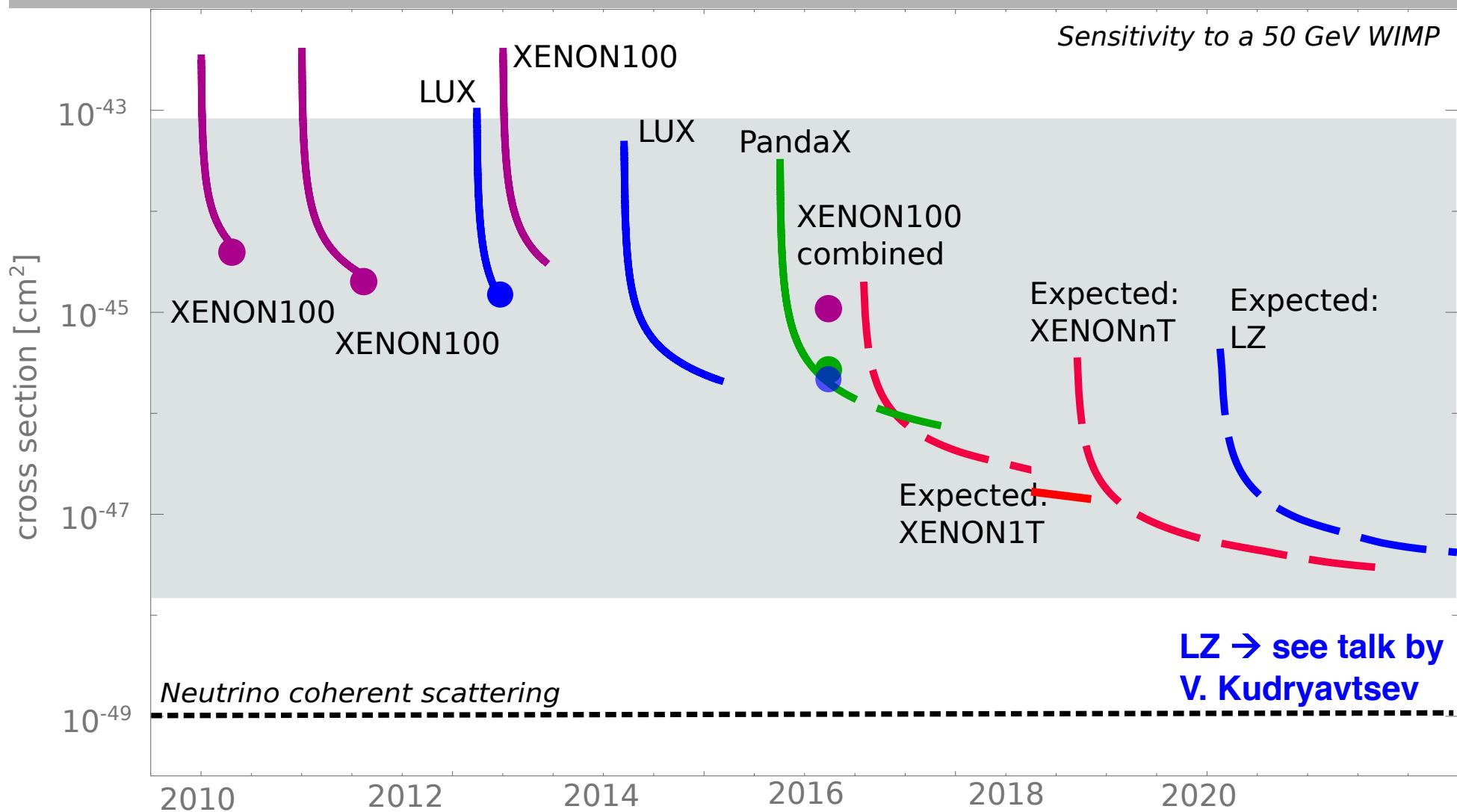
- e-lifetime & TPC performance rapidly improving
  - Kr-distillation
- getting ready for WIMPs time !!

# XENON1T Sensitivity Projection



and then  
**XENONnT**  
→ 20ty  
→ x10  
  
is built while  
**XENON1T** is  
running;  
reuses most  
parts → faster

# Direct WIMP Search Timeline (Xe)



About 25 days of data will be enough to catch up and then move on  
Generic WIMP parameter space will be covered soon → ?

Systematically lowering the x-section (symmetry, tuning,...)?  $\leftrightarrow$  WIMP miracle?

# Conclusions

**Direct detection of Dark Matter is the crucial test to prove that the Universe is full of new particles**

- Clear evidence exists for DM in the Universe
- Different options/candidates
  - WIMPs seem best motivated (don't forget others)
- Excellent opportunity to find or exclude WIMPs in the next years in the favoured / natural parameter space
  - WIMPs might be found or get under pressure
  - in any case exciting progress ahead!