

Direct Dark Matter Searches

Manfred Lindner

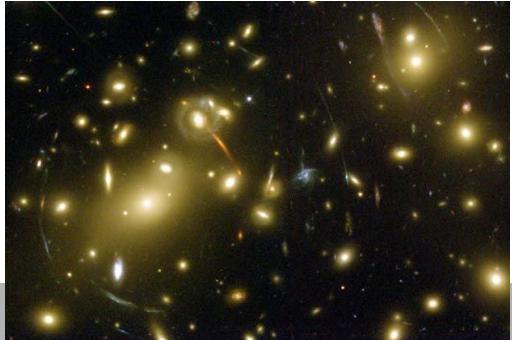
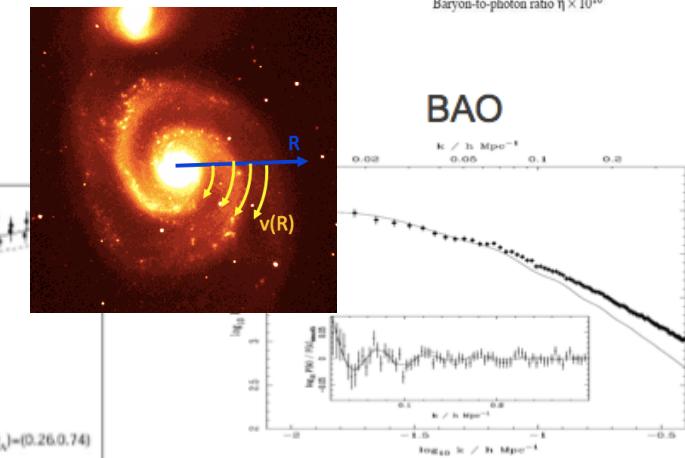
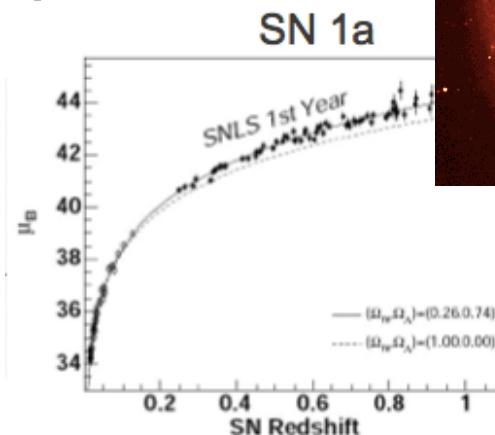
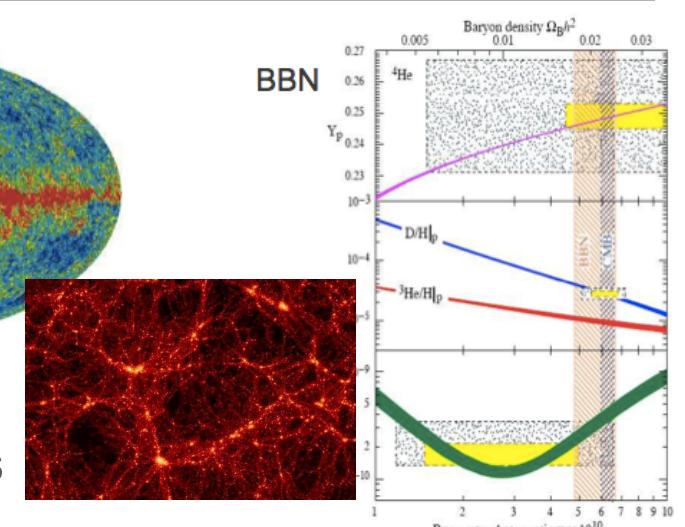
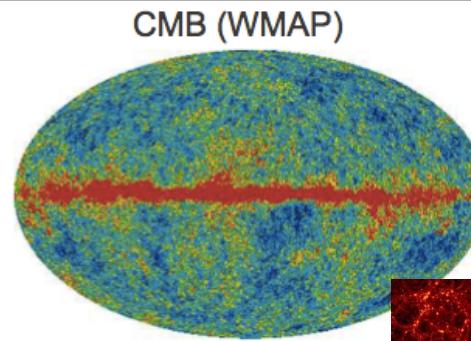


CosPA 2016
8 Nov. to 2 Dec. 2016
Sydney, Australia



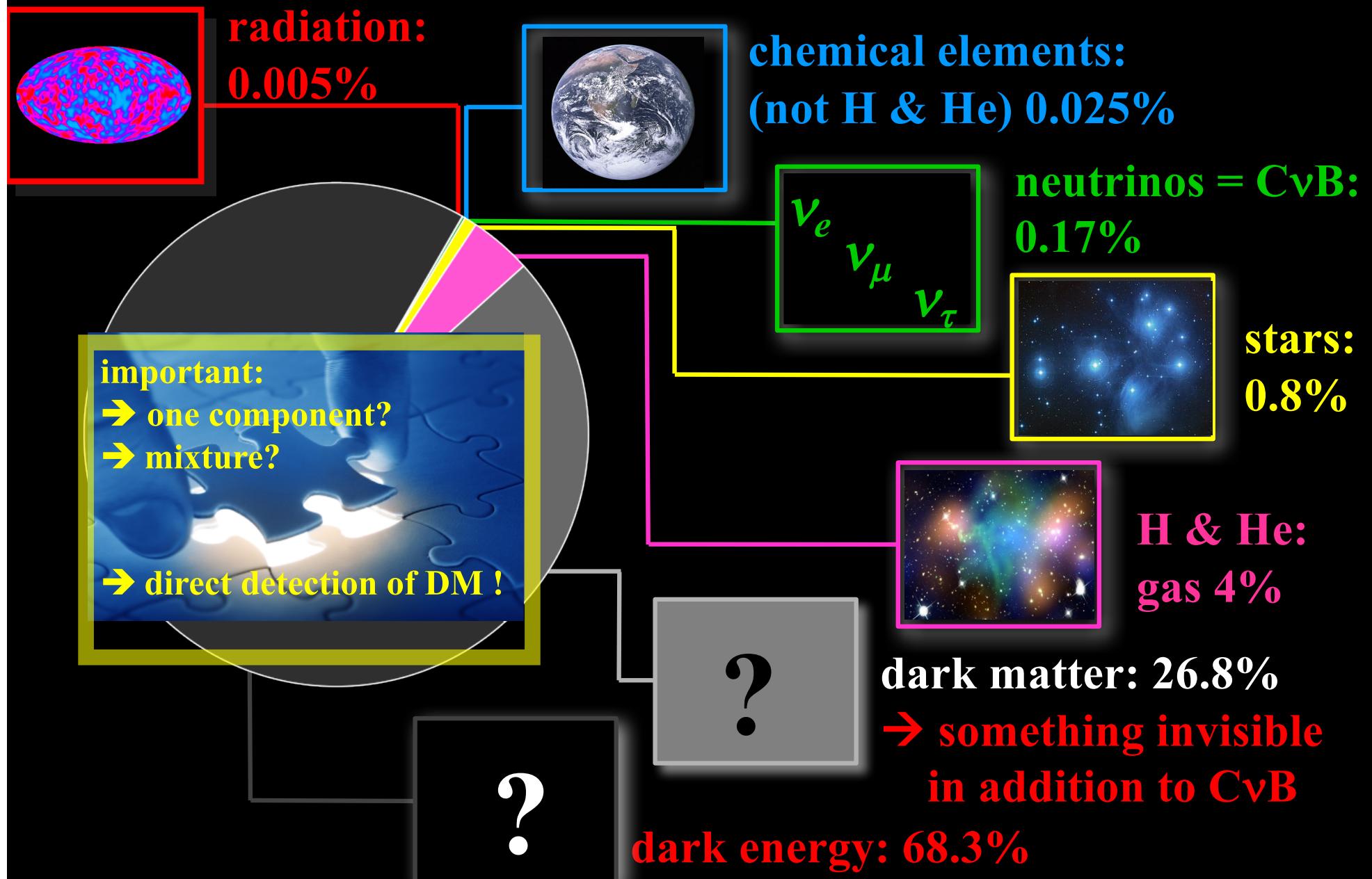
A long List of Evidences ...

- + 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

or

a suitable
population
(mass,
number) of
black holes

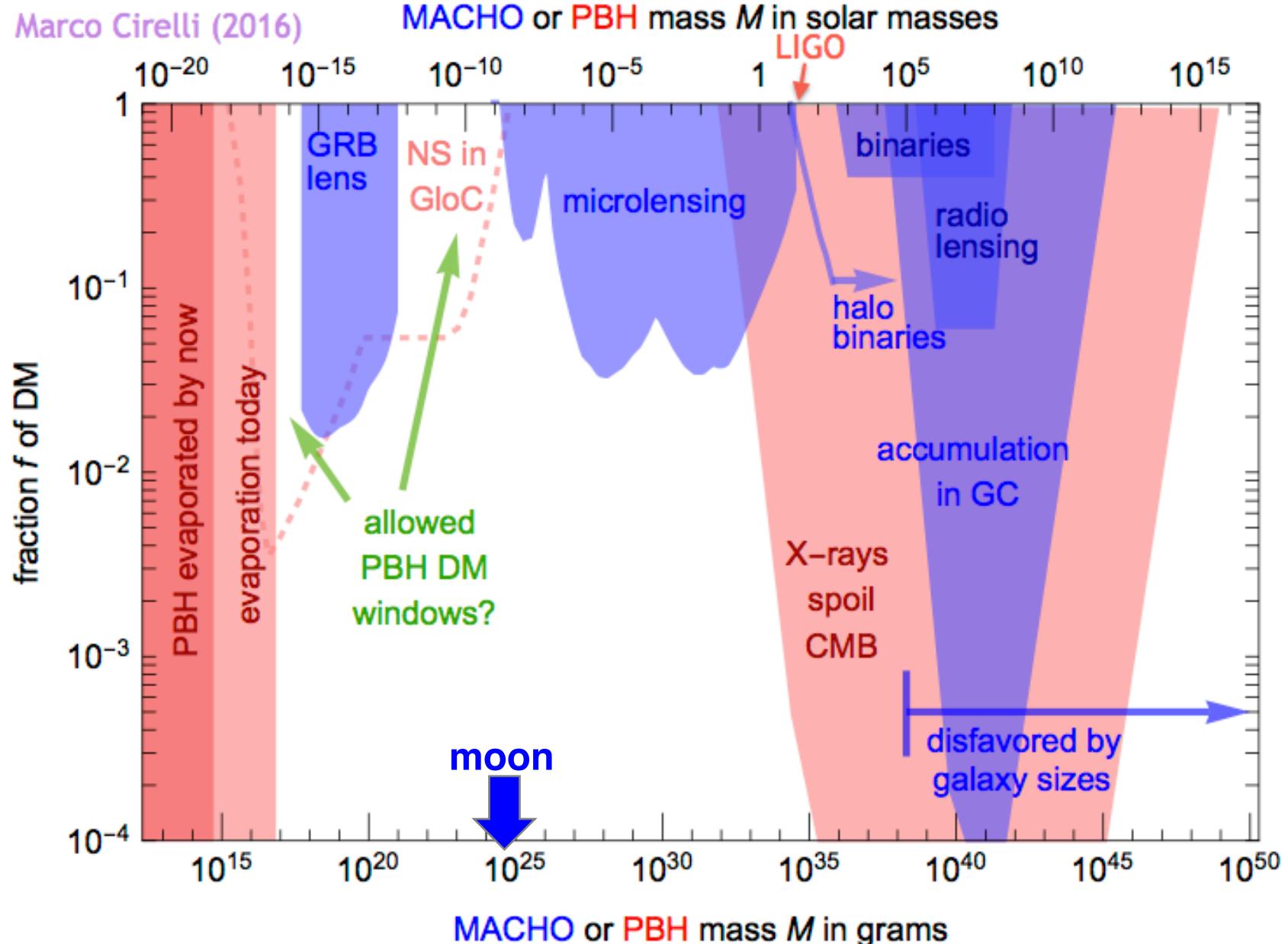
Particles

BSM
motivated
(SM problems)
- axions
- sterile ν's
- many other
particles
- ...

Abundance
or model
motivated
- various
candidates
- ...

**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

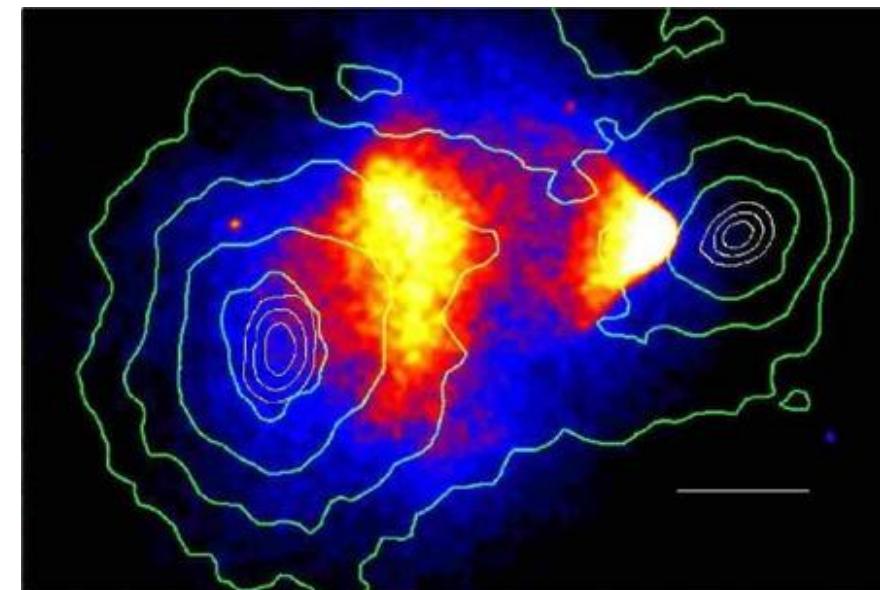
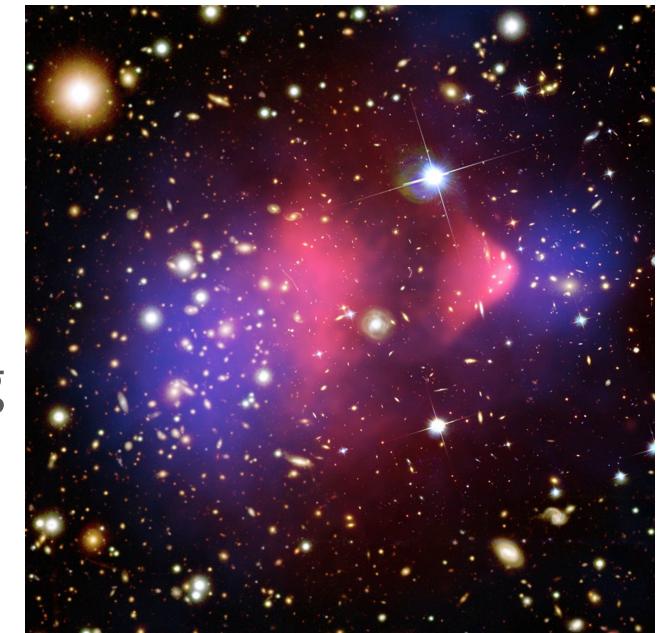
- displacement of visible matter

- and

- GR potential = all matter

- effect is $\sim 8\sigma$

- **Shows that normal particles scatter, but NOT that DM is particles**

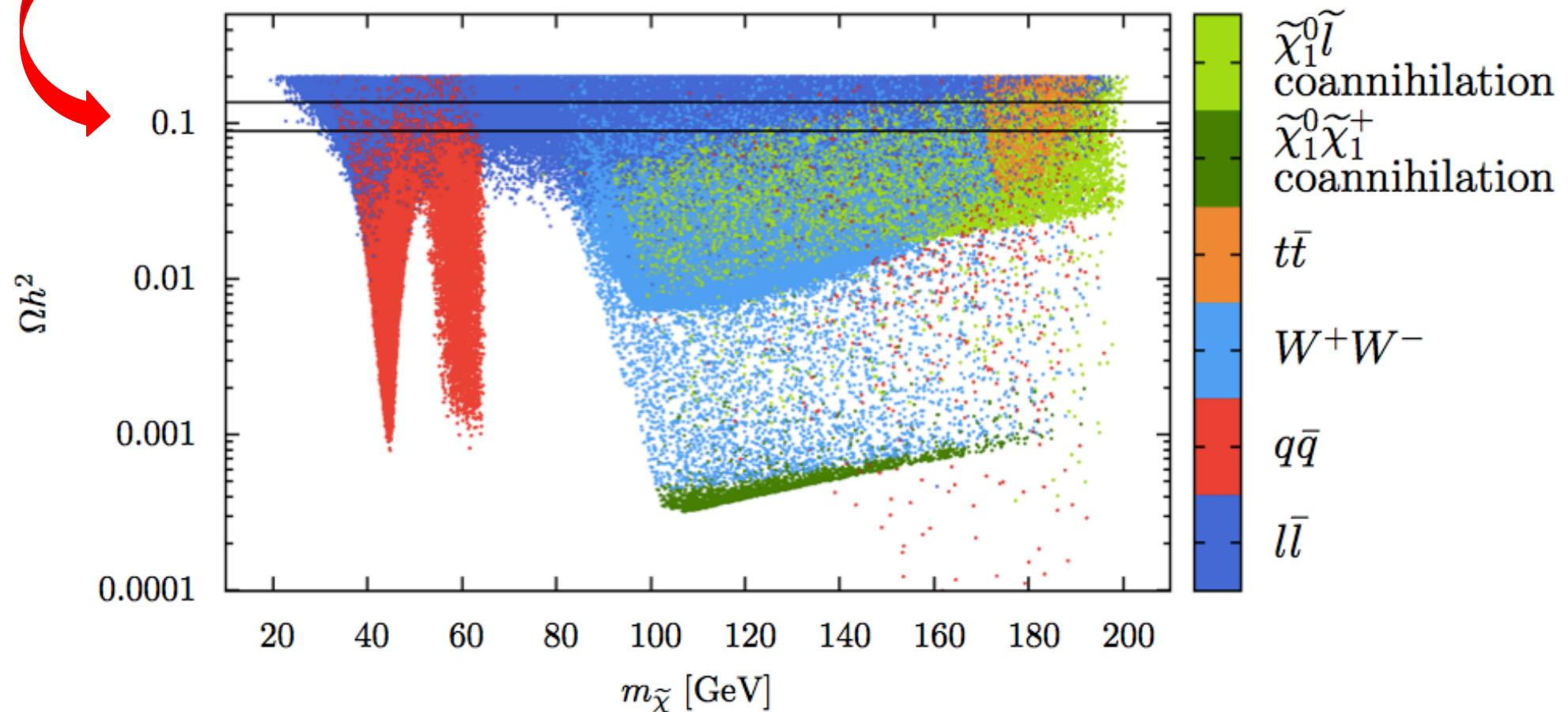


Hierarchy Problem → MSSM → DM

- LSP=Neutralino → WIMP miracle → correct abundance

Scan parameter space for different annihilation channels → Ωh^2

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

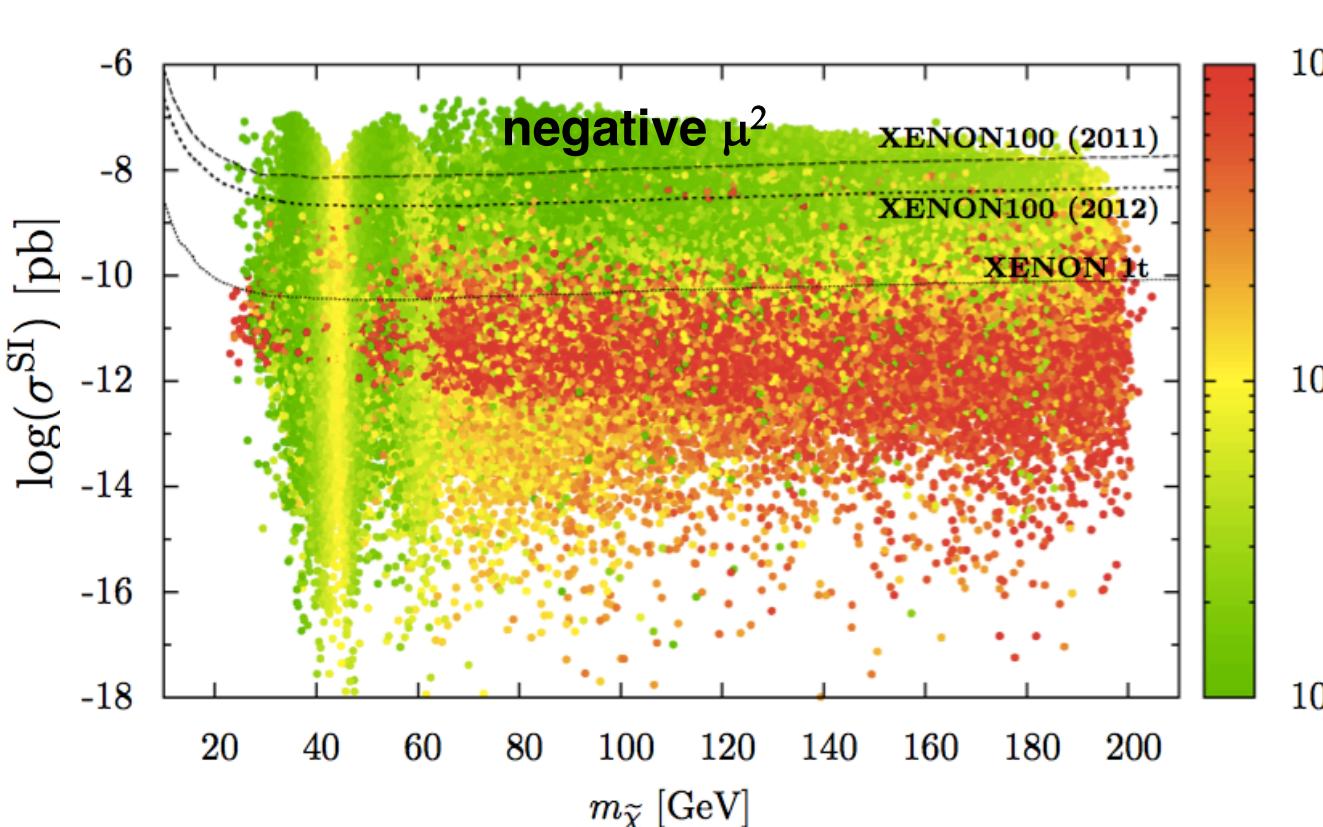


How fine-tuned are the parameters?

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

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

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



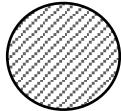
→ XENON100-2010
→ XENON100-2012
→ XENON1T

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

LMSSM: x-section down
↔ WIMP miracle?

Grothaus, ML, Takanishi: full MSSM, not cMSSM, pMSSM, NMSSM...

Generic WIMP Crossection

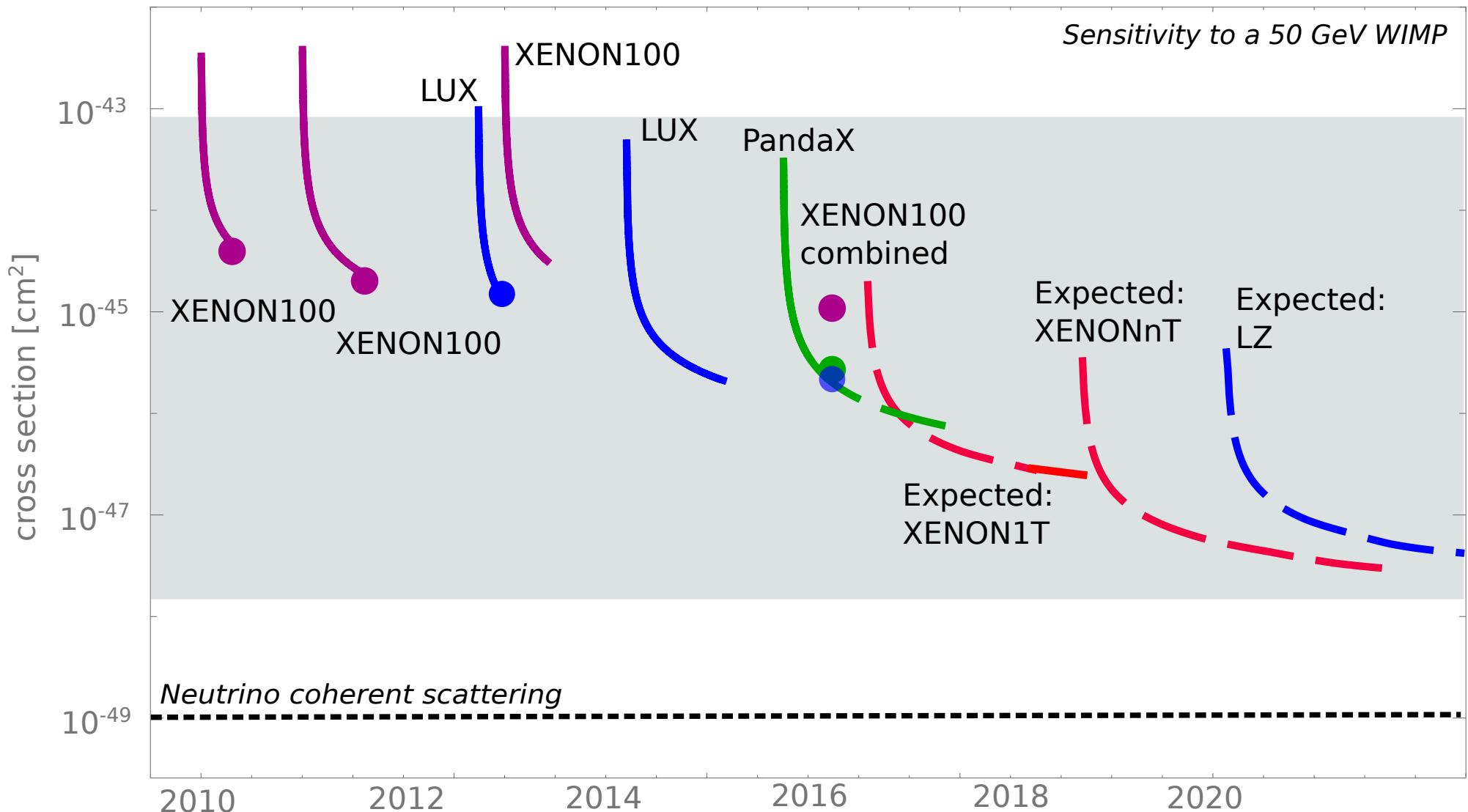
- Quantum mechanics: wavelength $\lambda \sim 1/\text{mass}$
-  “size/area” of a particle: $\pi\lambda^2 = \pi/m^2$
- scattering crossection = area times coupling strength
- $\sigma \sim O(0.001\text{-}1.0)^2 g_2^2 \pi/m^2$ or tuning, symmetry, ...
model weak area
parameters coupling \leftrightarrow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

→ 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



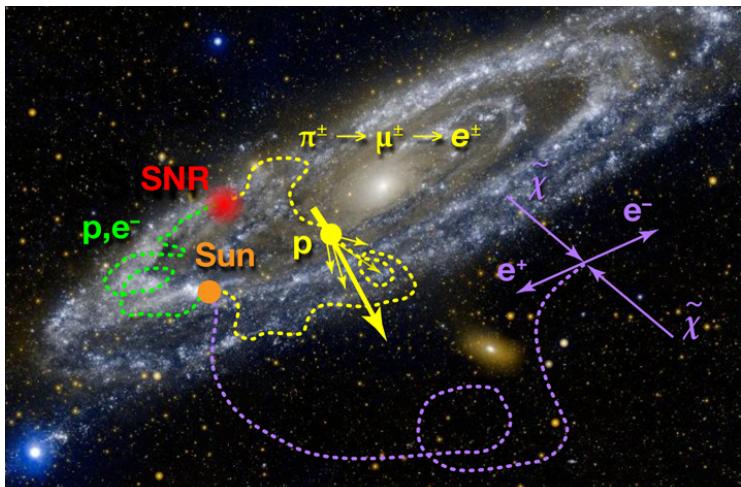
Generic WIMP parameter space will be covered in the next years

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



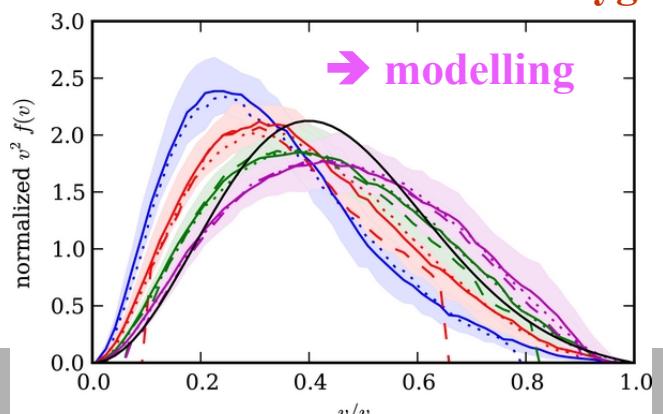
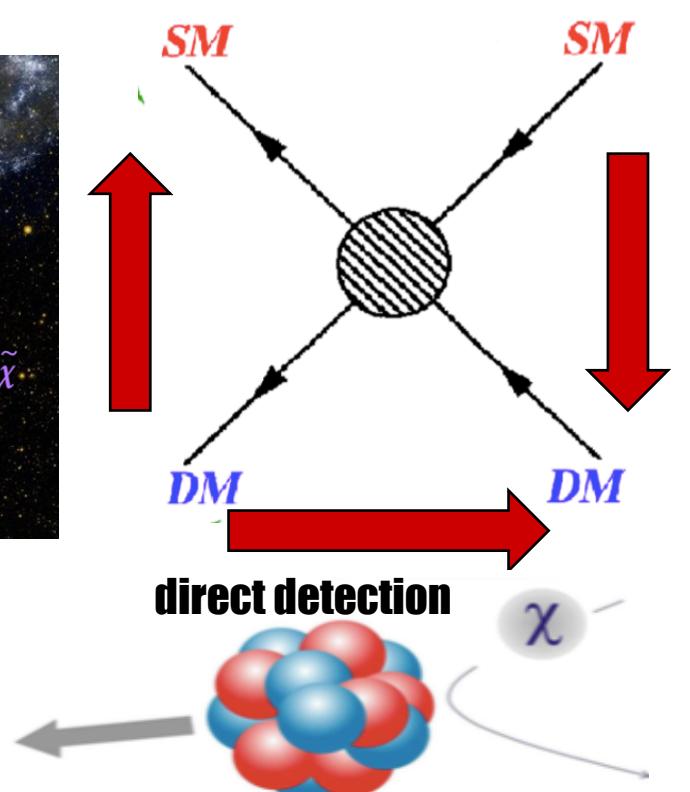
FERMI, PAMELA, AMS, HESS,
IceCube, ...

astronomical uncertainties...

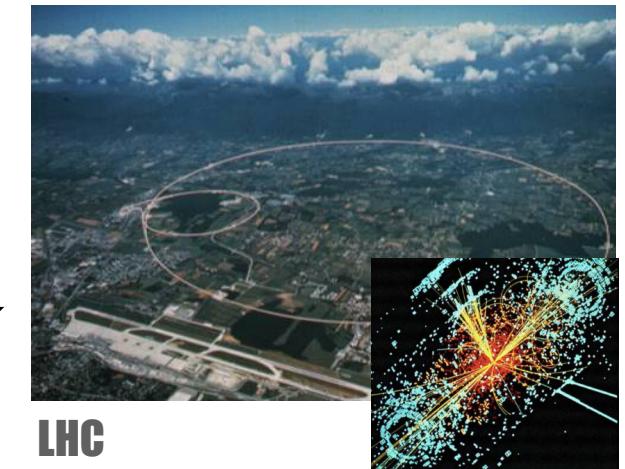
→ signal without doubt

from DM?

keV lines ↔ atomic physics



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

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...

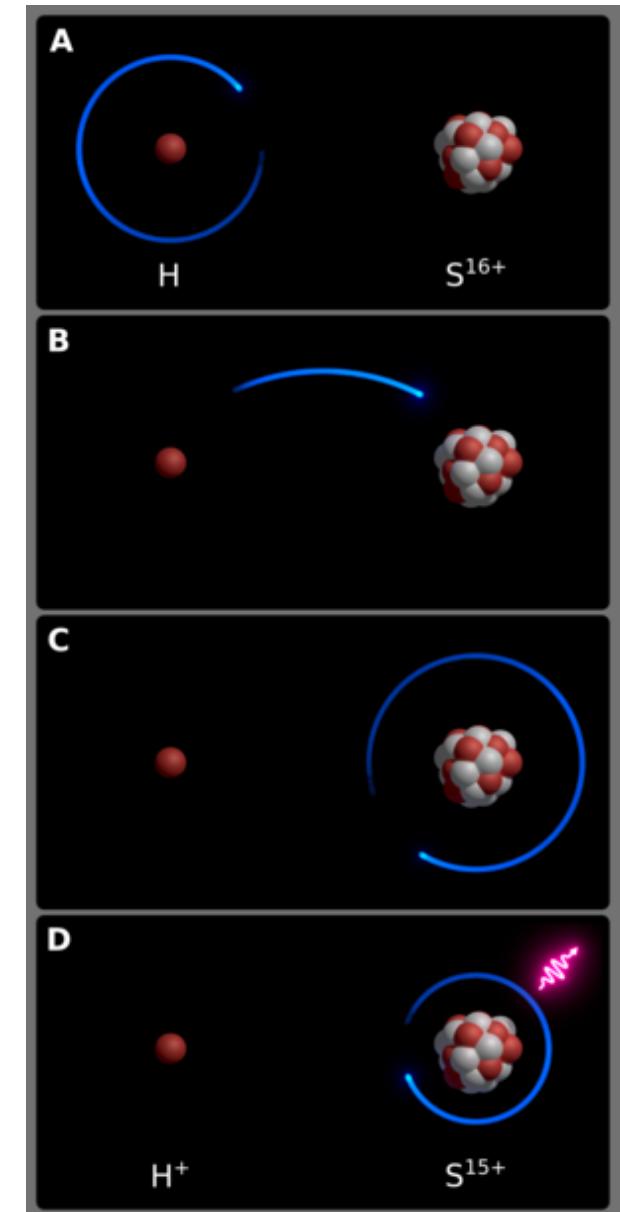
Intensity ↔ fits typical abundance

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

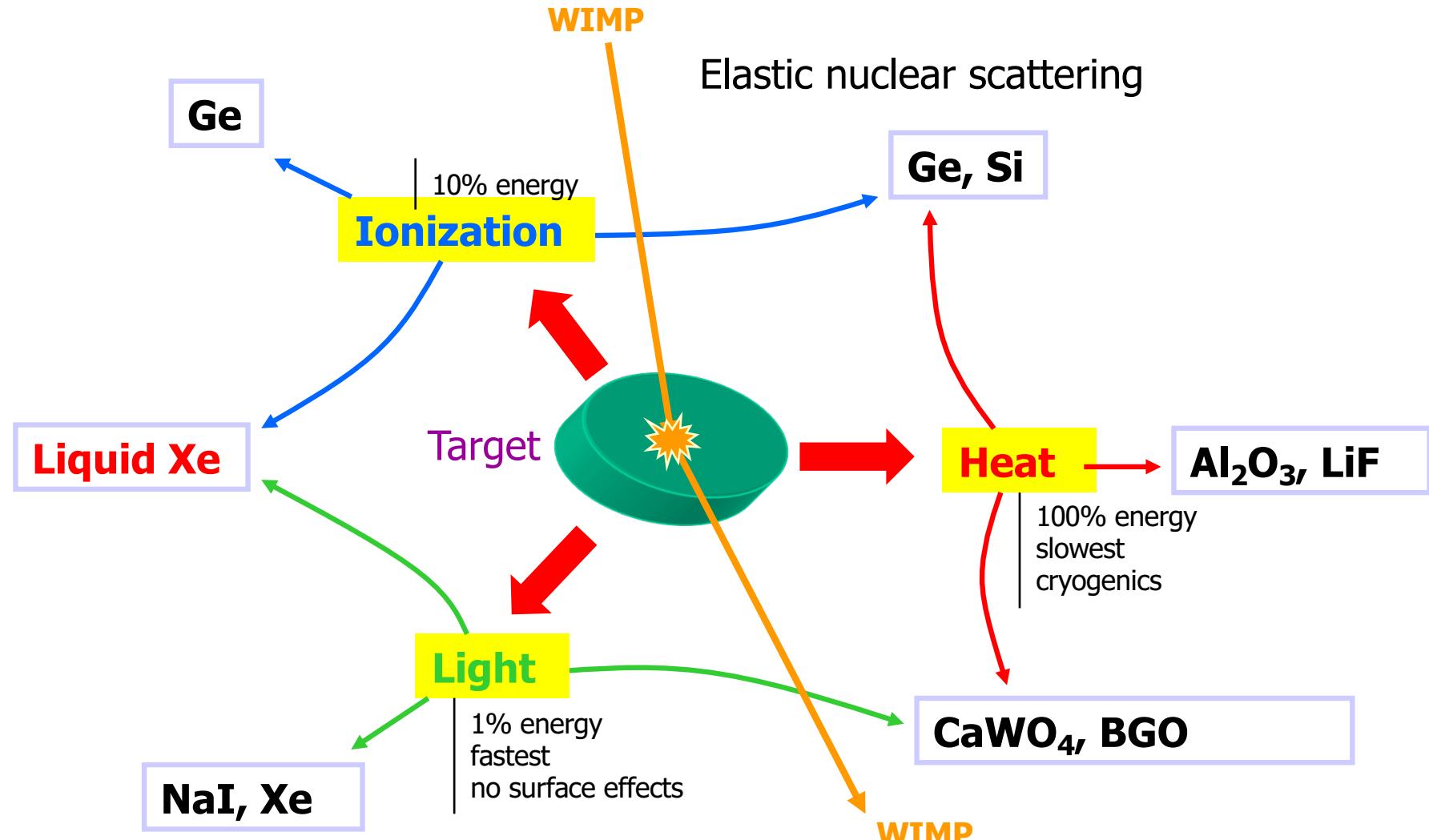
lesson: there may be other keV lines ...

... and other charge exchange reactions

→ unambiguous detection is difficult

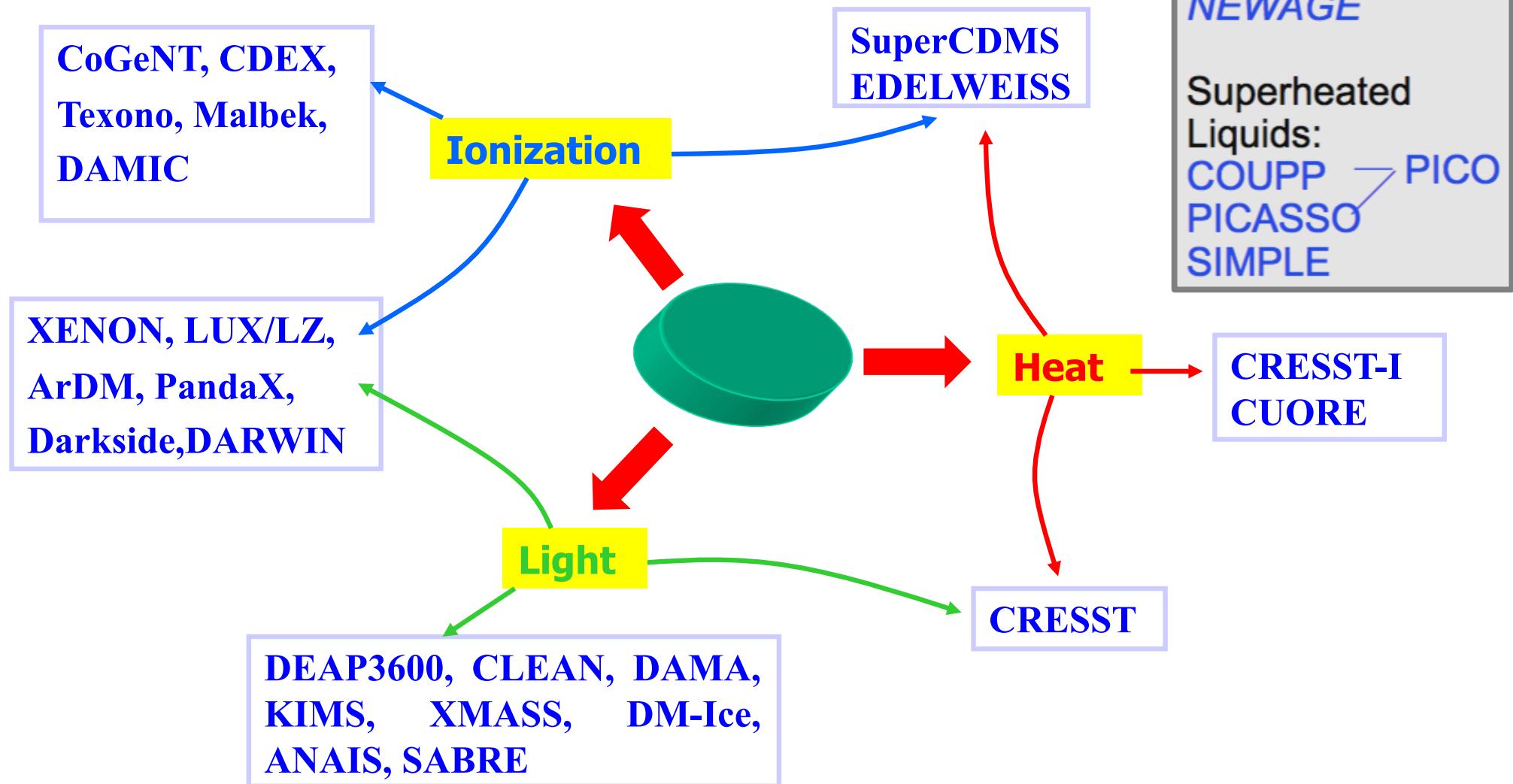


Different direct Detection Techniques

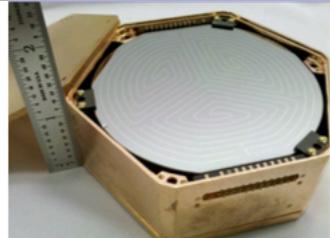


Different direct Detection Techniques

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



Light WIMPs: SuperCDMS - EDELWEISS - CRESST

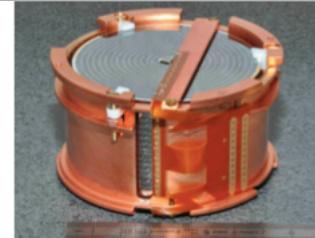


SuperCDMS: Ge, Si

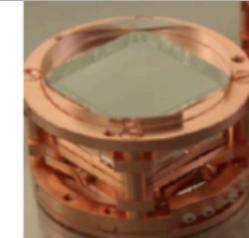
phonons (heat) + ionization

SuperCDMS @SNOLAB

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



EDELWEISS-III (Ge)

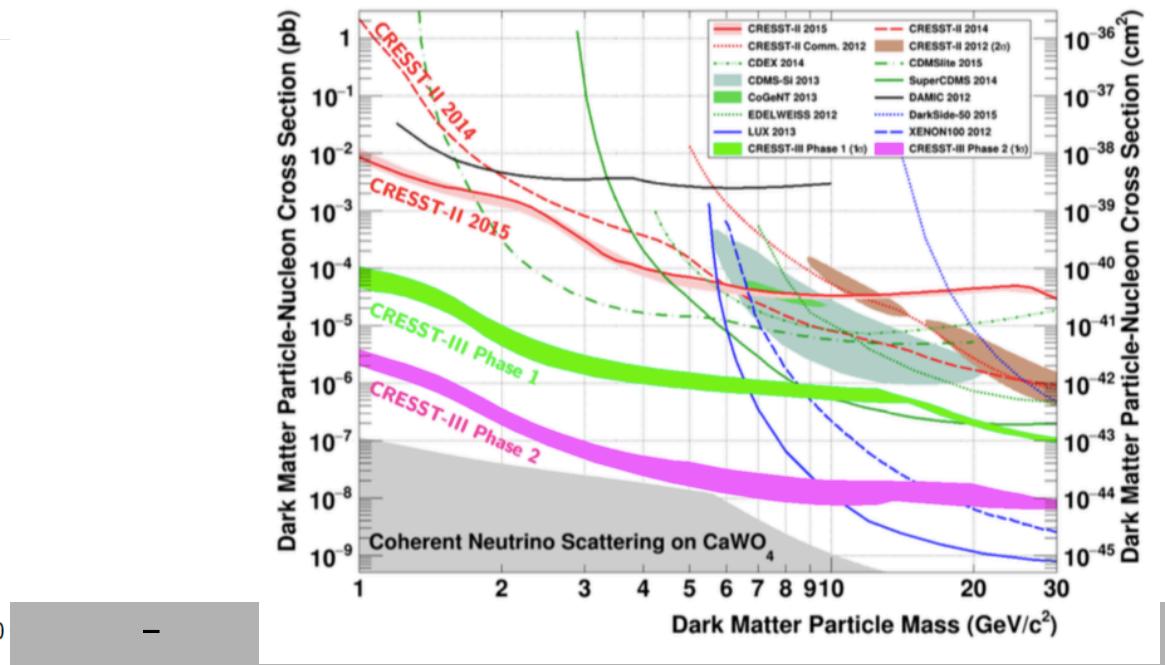
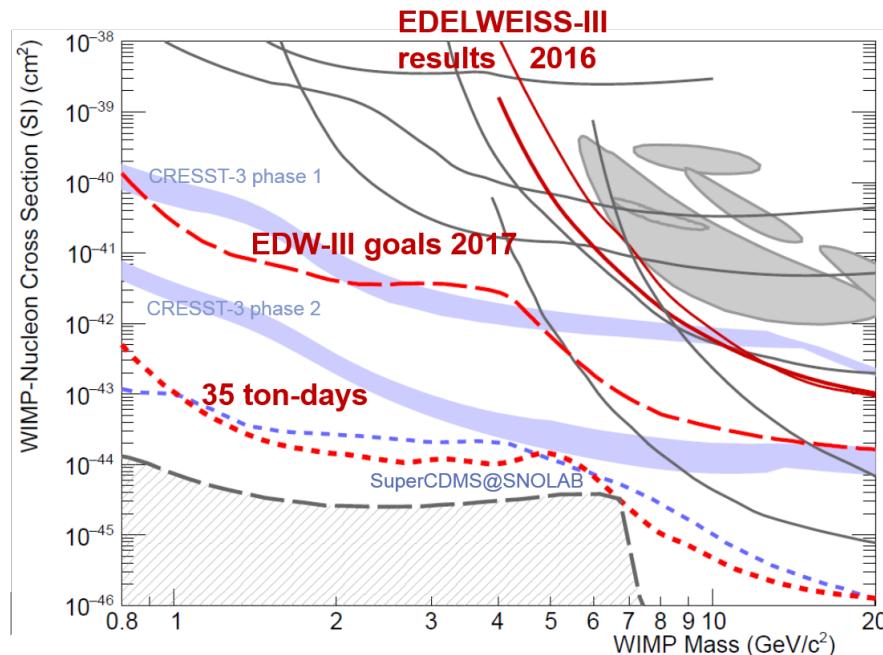


CRESST (CaWO₄)

heat + light

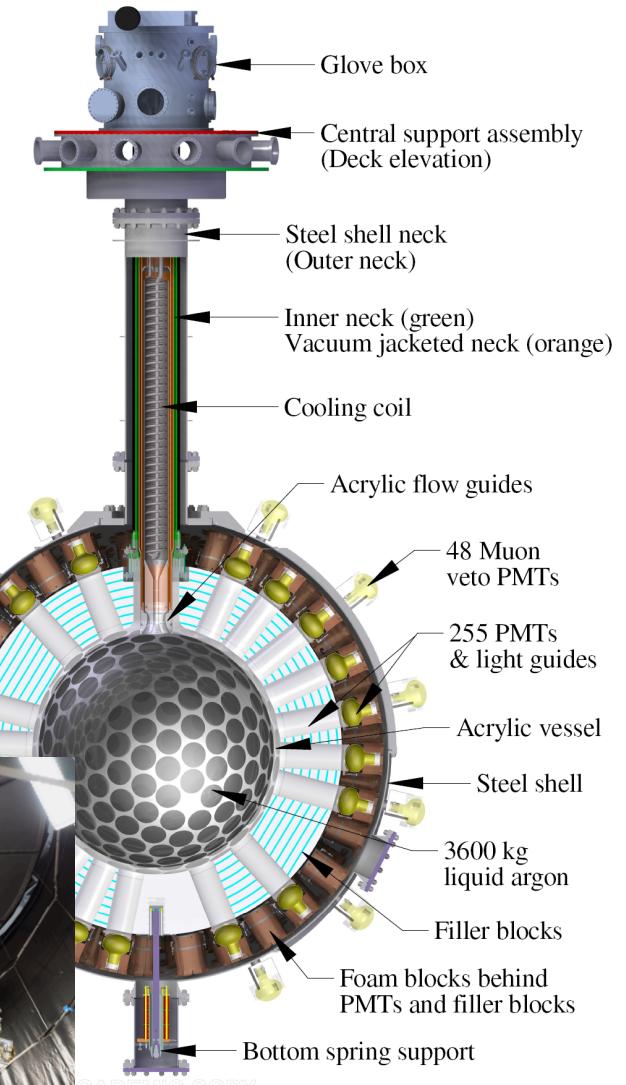
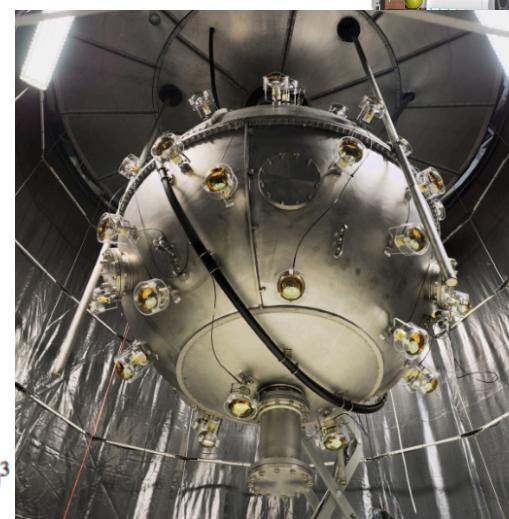
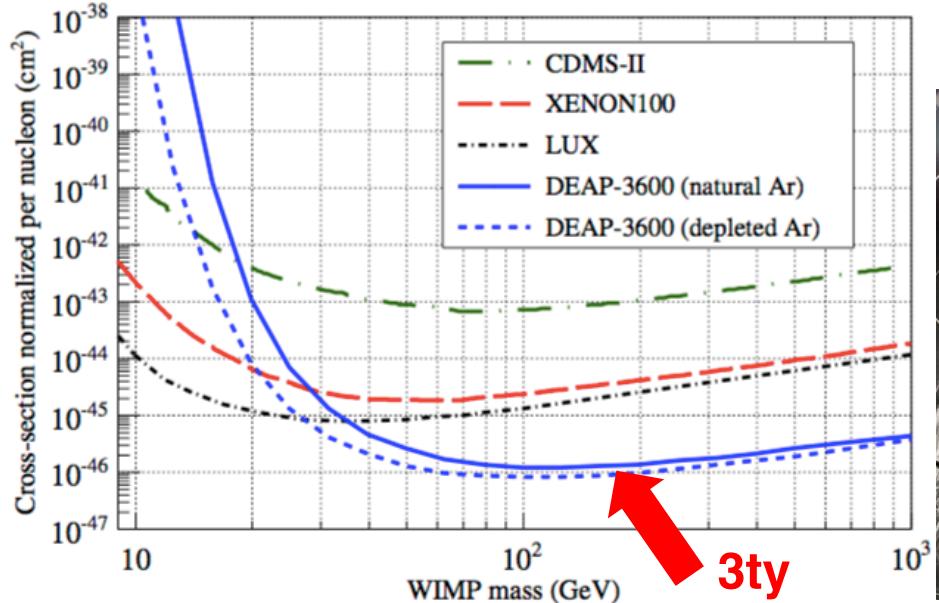
CRESST @LNGS

2013-2015, 52 kg × d
now: best threshold 300 eV_{nr}
excellent sensitivity
for small WIMP mass
→ CRESST-III ↔ bg?



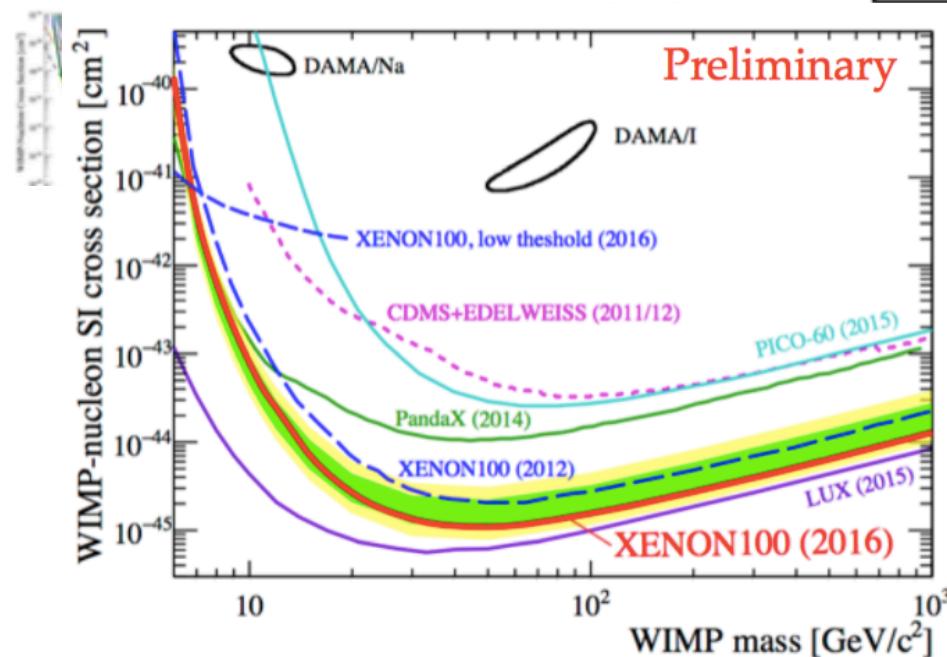
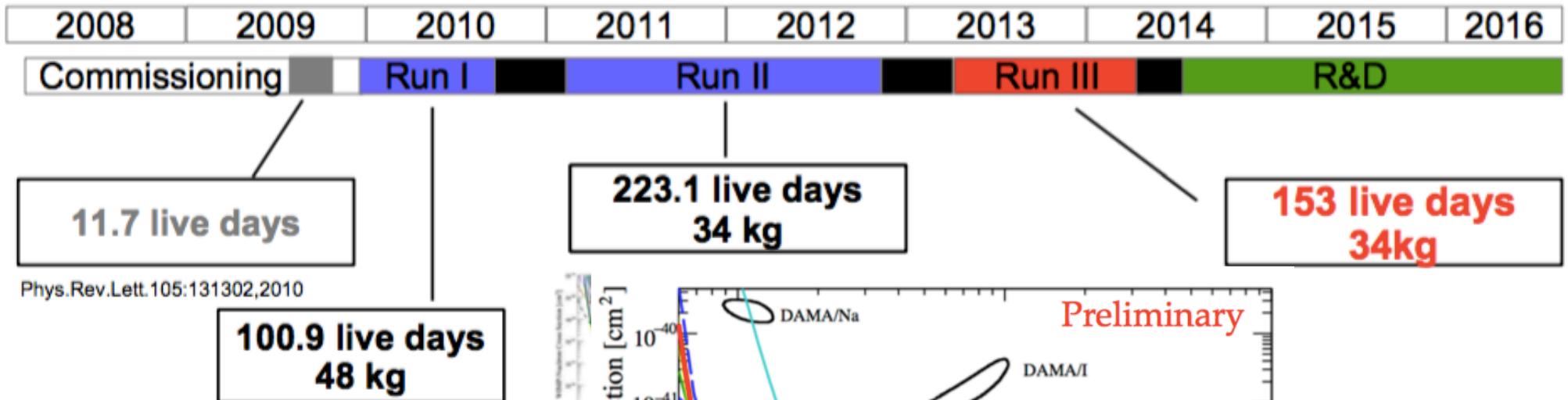
DEAP-3600 @ SNOLAB

- 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



Dual Phase TPCs: XENON100, LUX, PandaX → Recent Results

XENON100: Combination of Runs



Improvement of SI limit with respect to Run II by a factor of 1.7 @50 GeV/c² and 1.09 10⁻⁴⁵ cm²

...while we were building XENON1T...

DAMA's Modulation

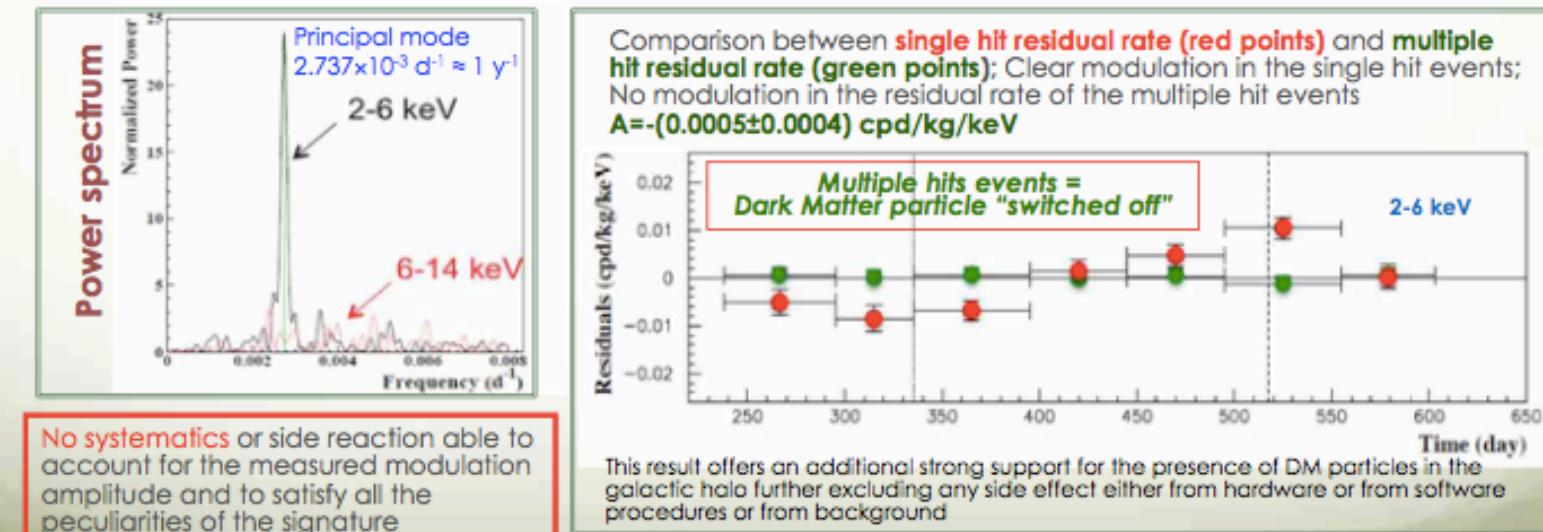
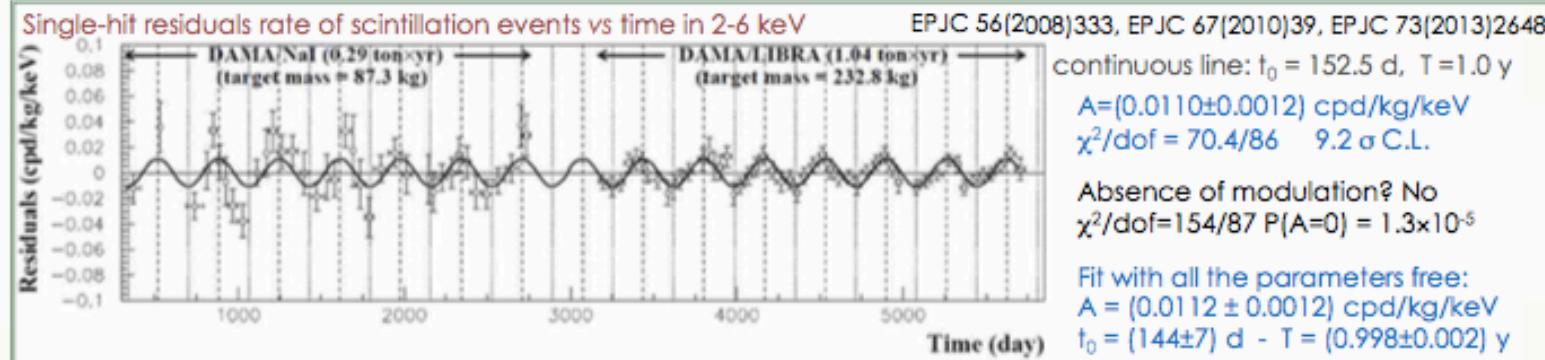
Belli
IDM 2016

DAMA/Libra
phase 2
is running

9.2 σ → ?

Model Independent Annual Modulation Result

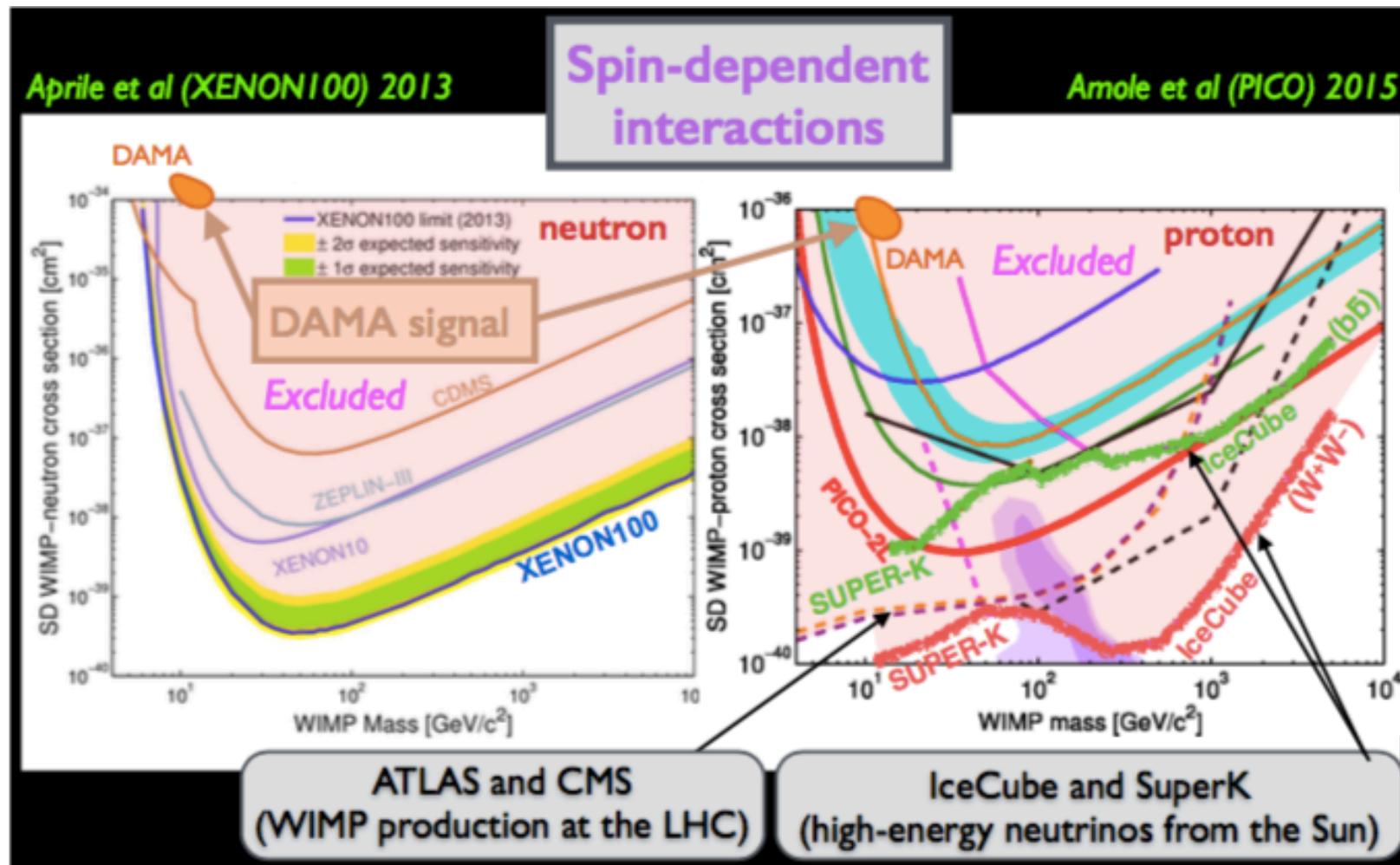
DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = 1.33 ton×yr



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

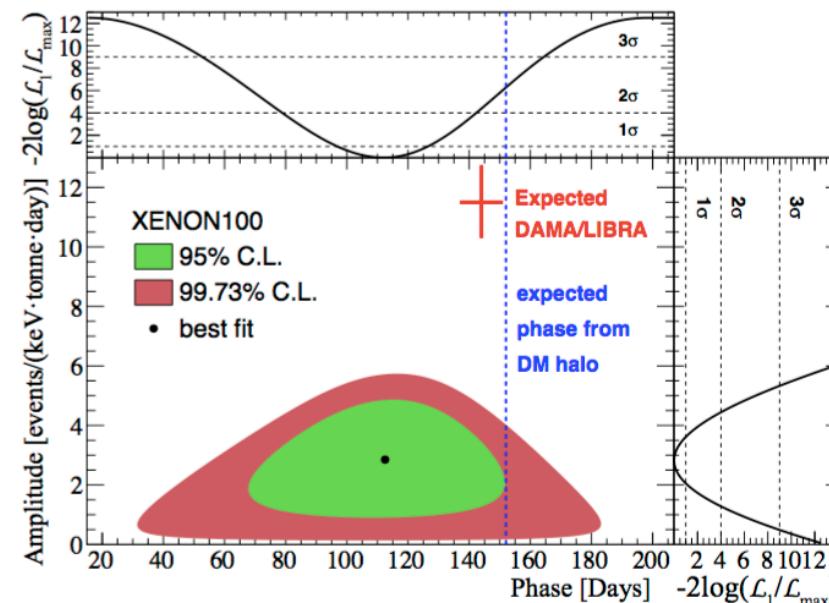
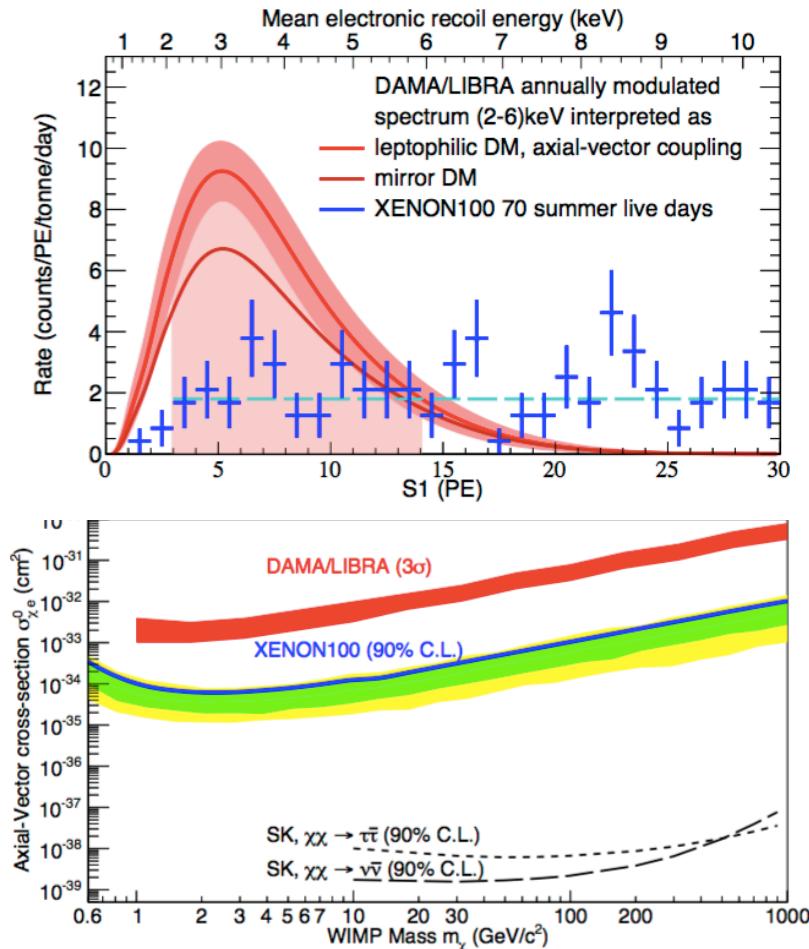
Incompatible with other Results

- 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

LUX (SI Limits FSR + SSR)

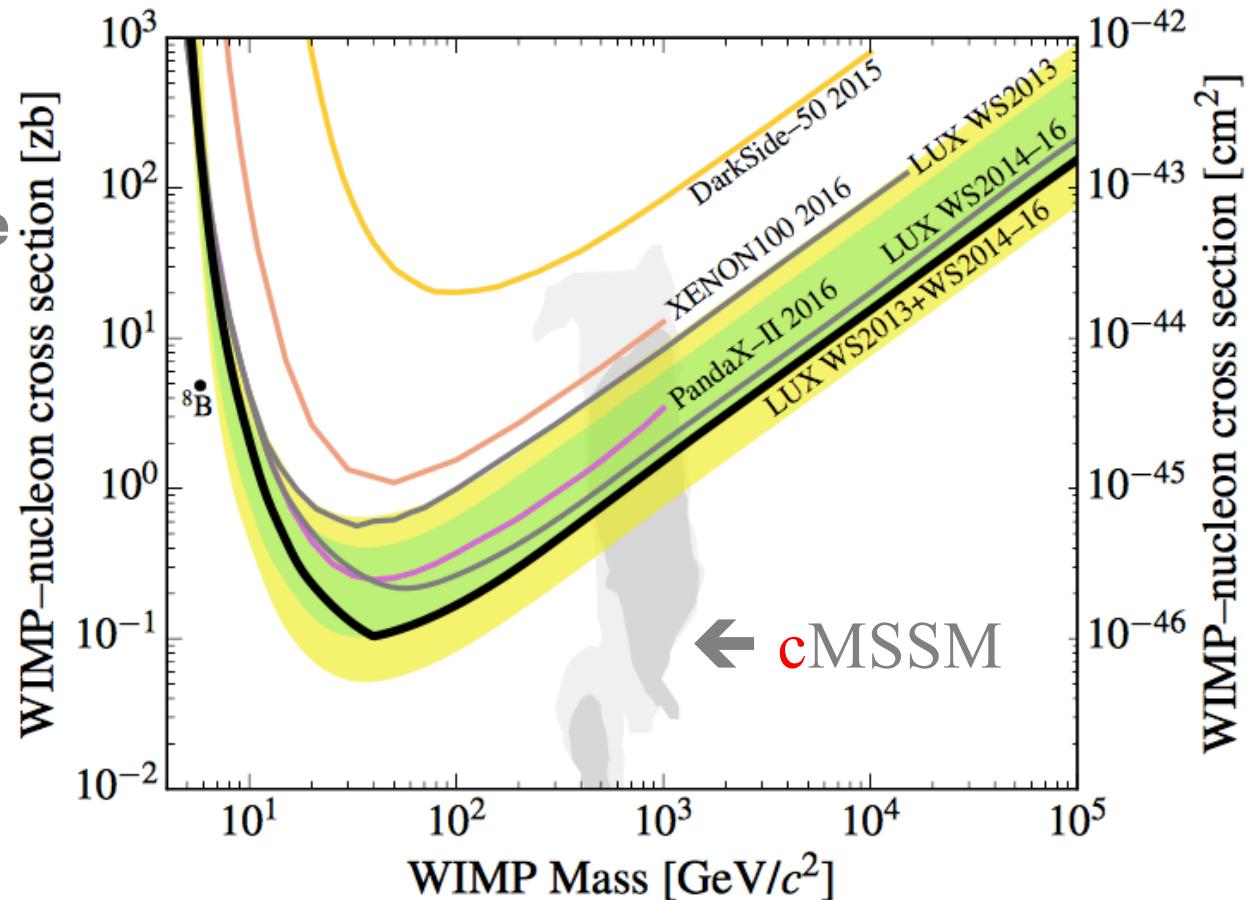
arXiv:1608.07648

Both LUX runs combined

3.35×10^4 kg-day exposure

At $m_{\text{WIMP}} = 50$ GeV:

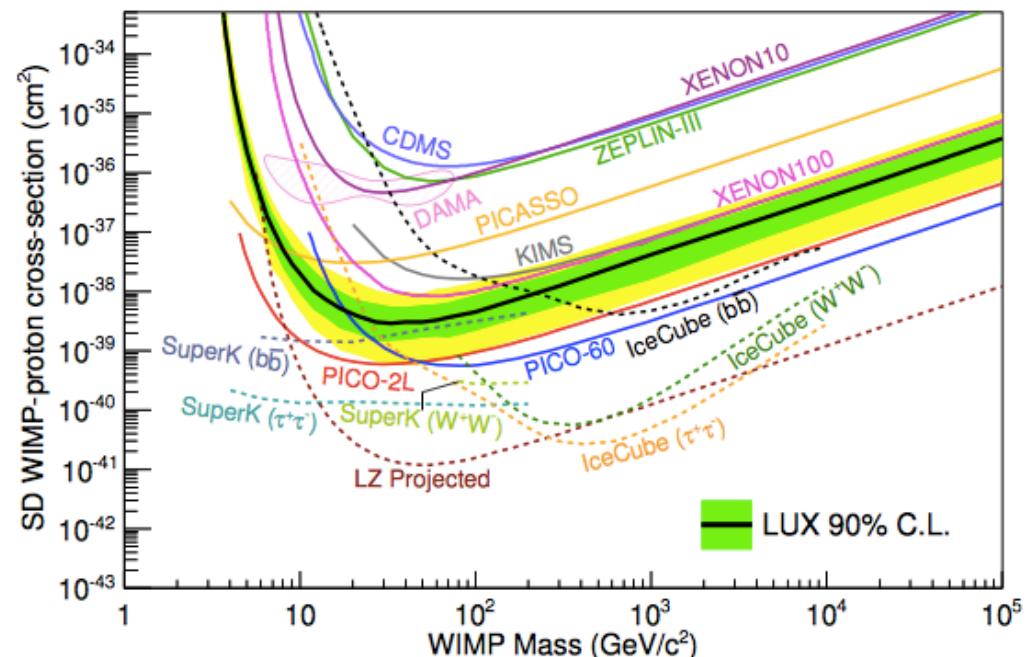
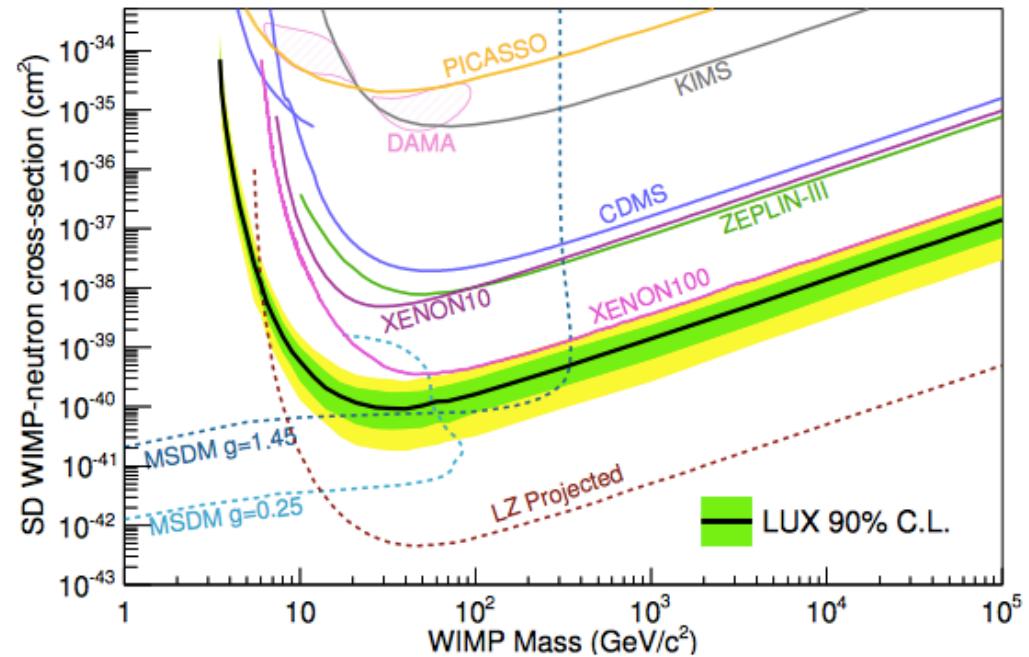
$2.2 \times 10^{-46} \text{ cm}^2$ @90%CL



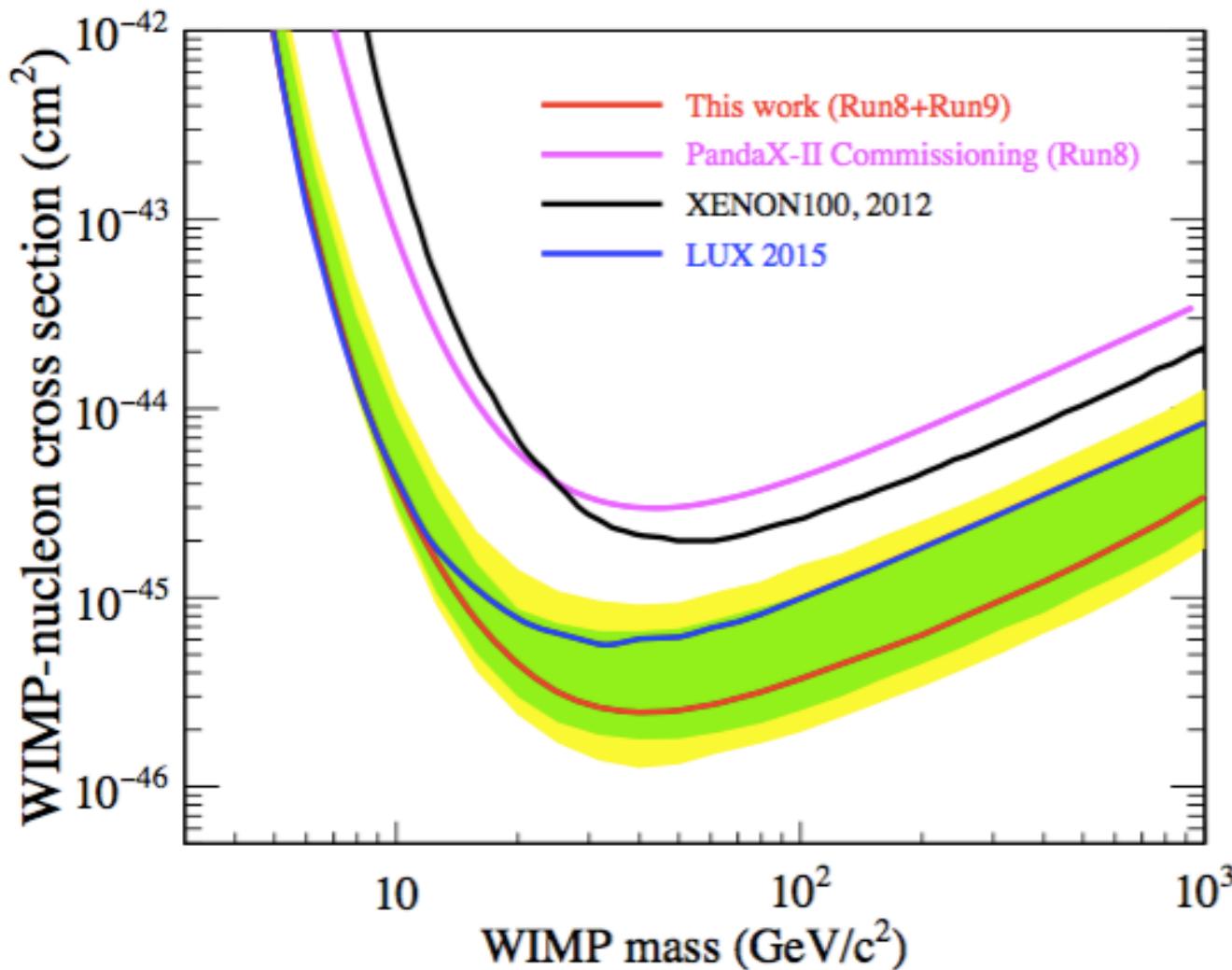
LUX SD (FSR)

PhysRevLett.116.161302

95 live days (1.4×10^4 kg·days)



PandaX: SI Result



[arXiv:1607.07400](https://arxiv.org/abs/1607.07400)
Results from 98.7 days of PandaX-II

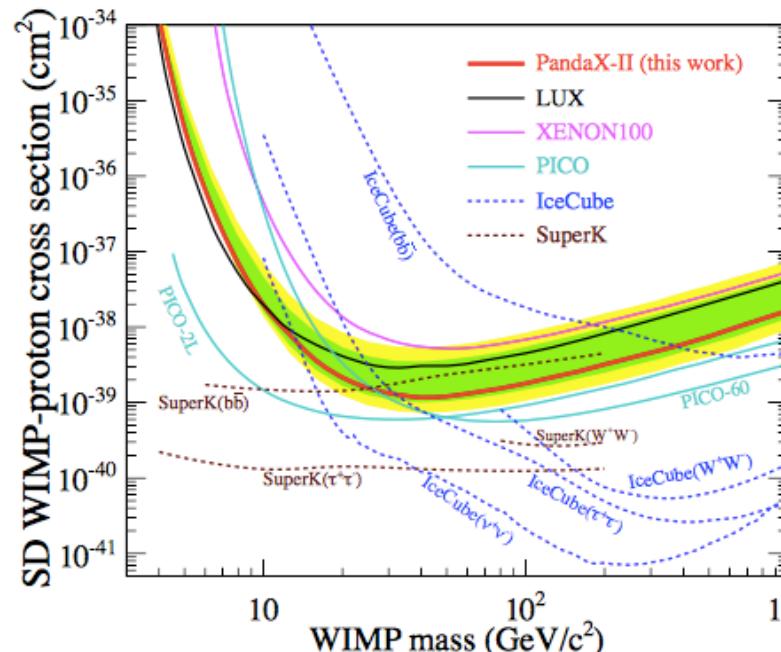
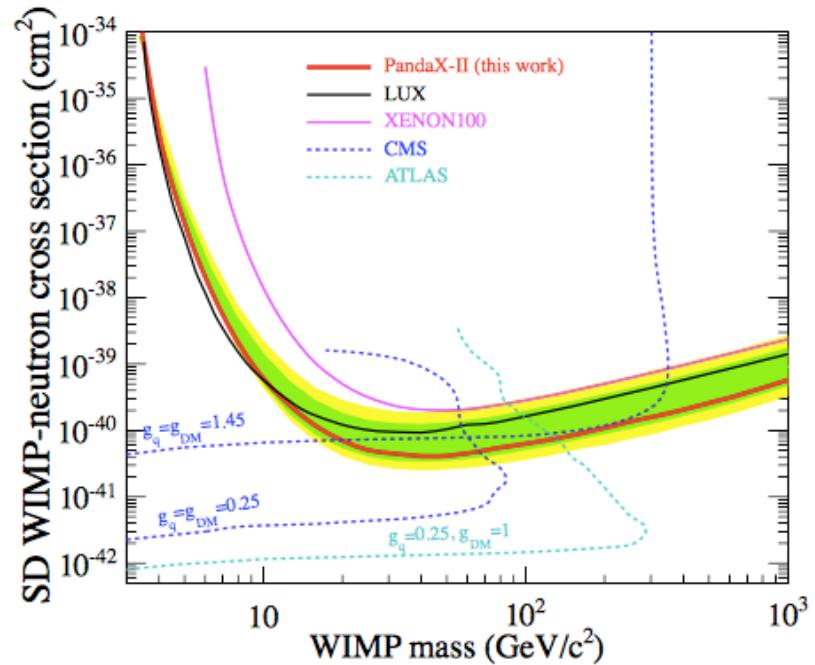
Panda-X SD

arXiv:1611.06553

exposure of 3.3×10^4 kg-day

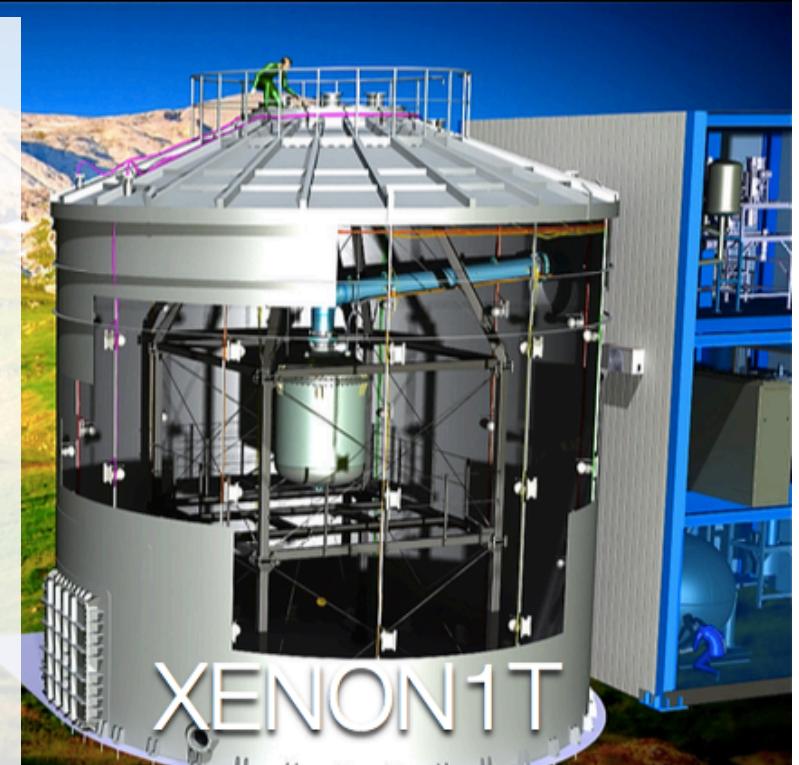
→ most stringent limits
above $10 \text{ GeV}/c^2$

+ limits from LHC for
low WIMP masses.



Meanwhile: Construction of 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
 - data taking starts ~ now
- goal: $2 \times 10^{-47} \text{ cm}^2$
@50 GeV for 2ty



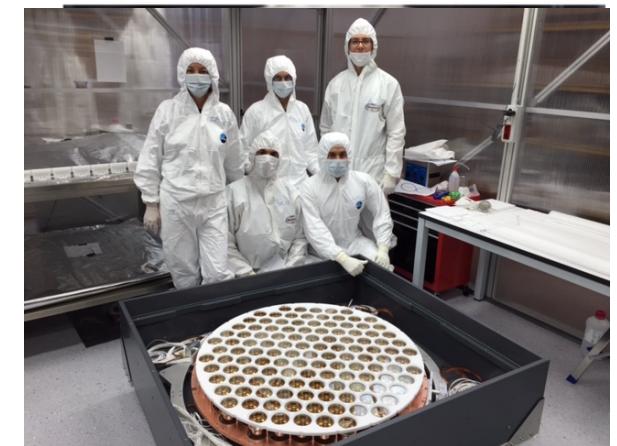
The XENON1T inner Detector



The TPC



TPC installation underground

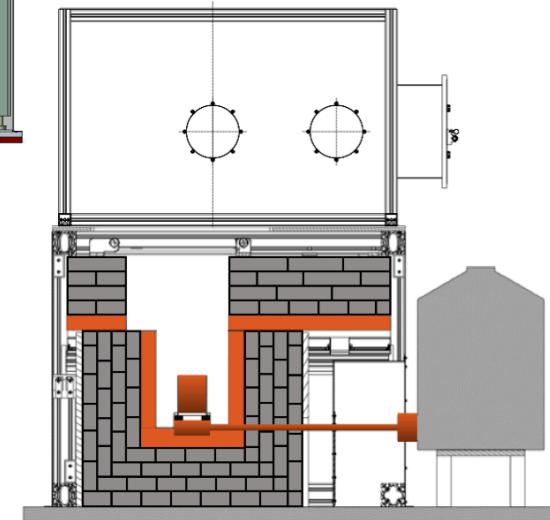
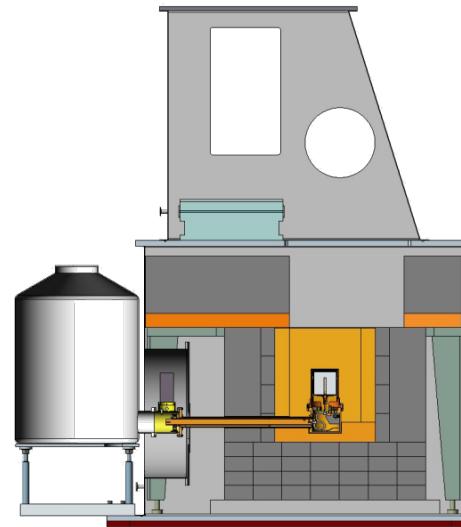


PMT arrays

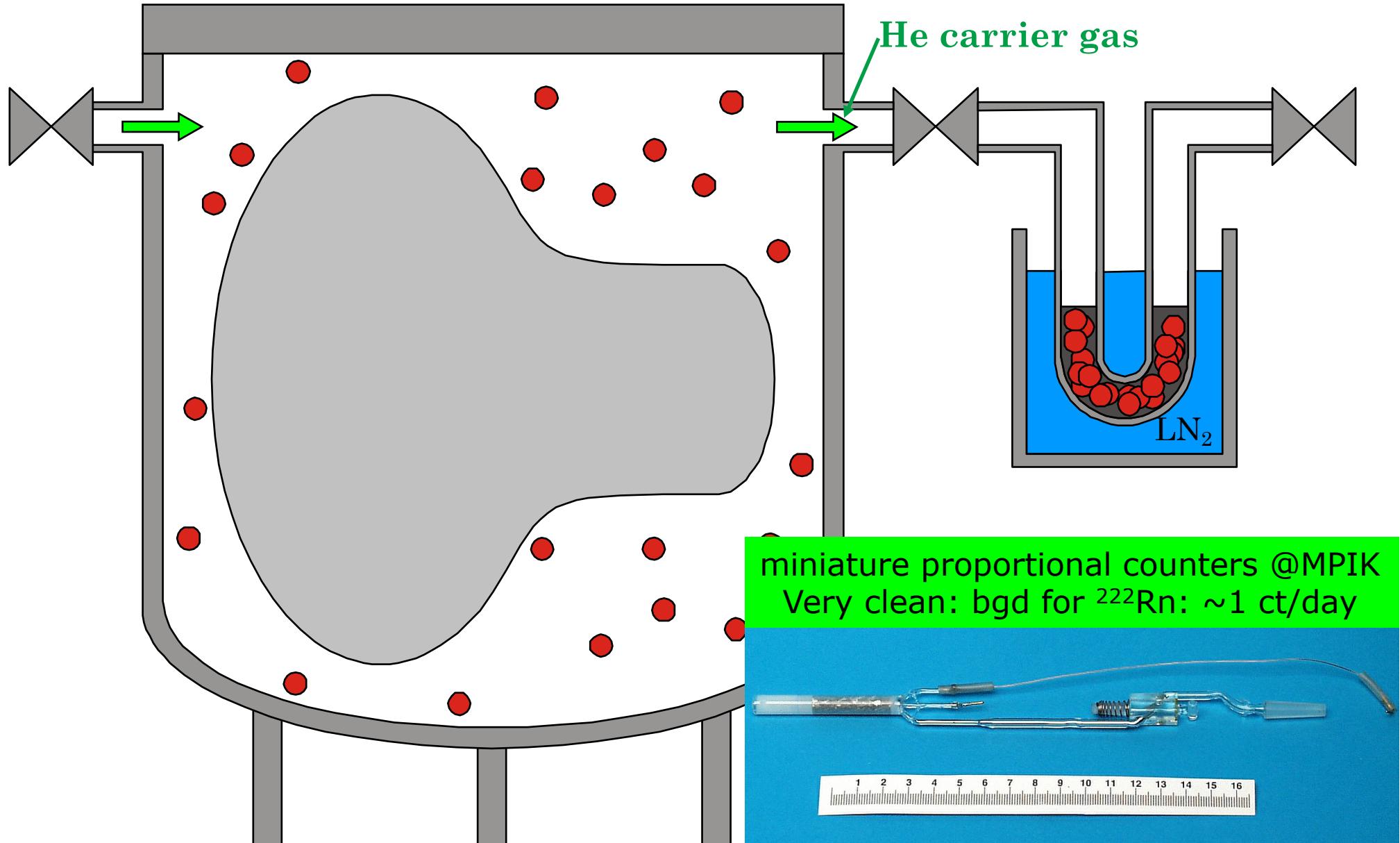
→ Space for XENONnT TPC; otherwise designed for nT
larger → significantly stronger requirements for radiopurity / backgrounds

Extremely sensitive Material γ -Screening

- Different screening stations @MPIK underground lab (1mBq/kg)
 - 4 GEMPIs of MPIK @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}Rn (α -decaying)



MPIK Rn Screening Facilities

Gas counting systems

@LNGS and @MPIK

^{222}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

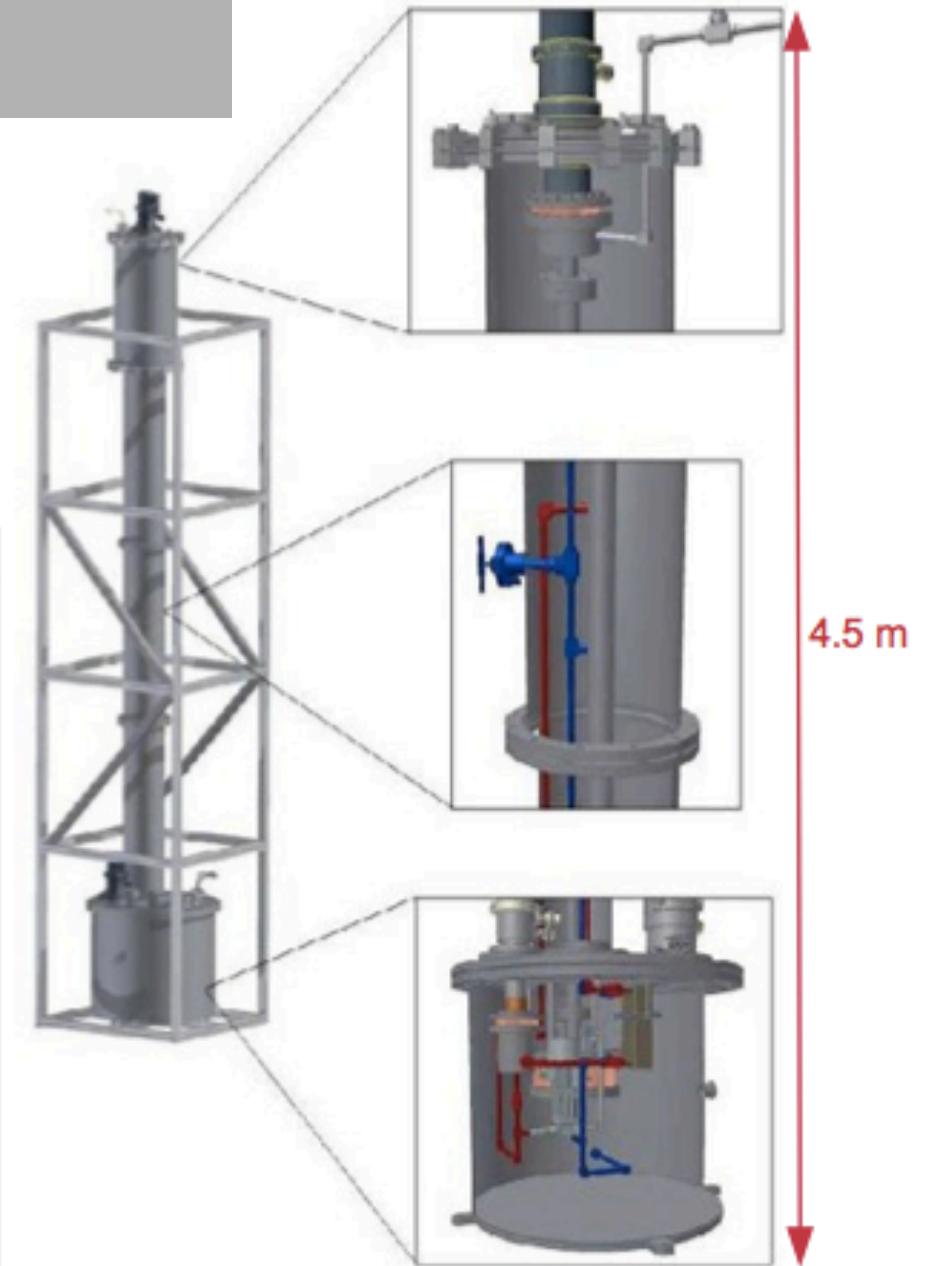
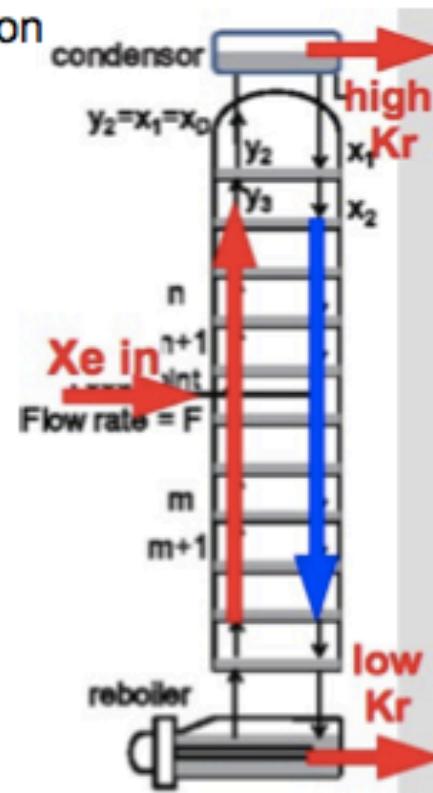
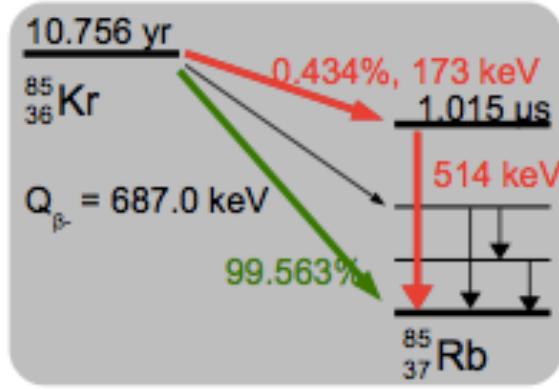


Krypton Removal

- 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 $10^4\text{-}10^5$ separation
- final Kr/Xe < 1 ppt



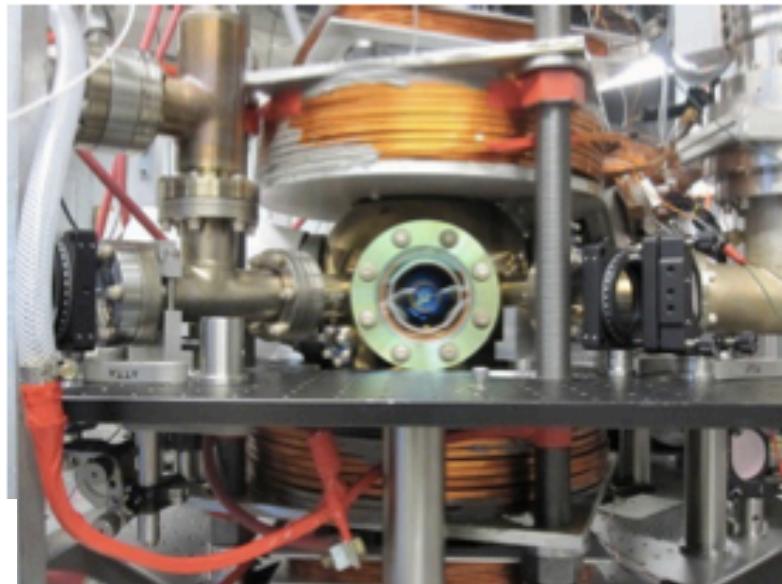
Münster for XENON1T

Krypton Analysis

- Kr measurements with gas chromatography plus Rare Gas Mass Spectroscopy RGMS
 - measurement of ^{nat}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

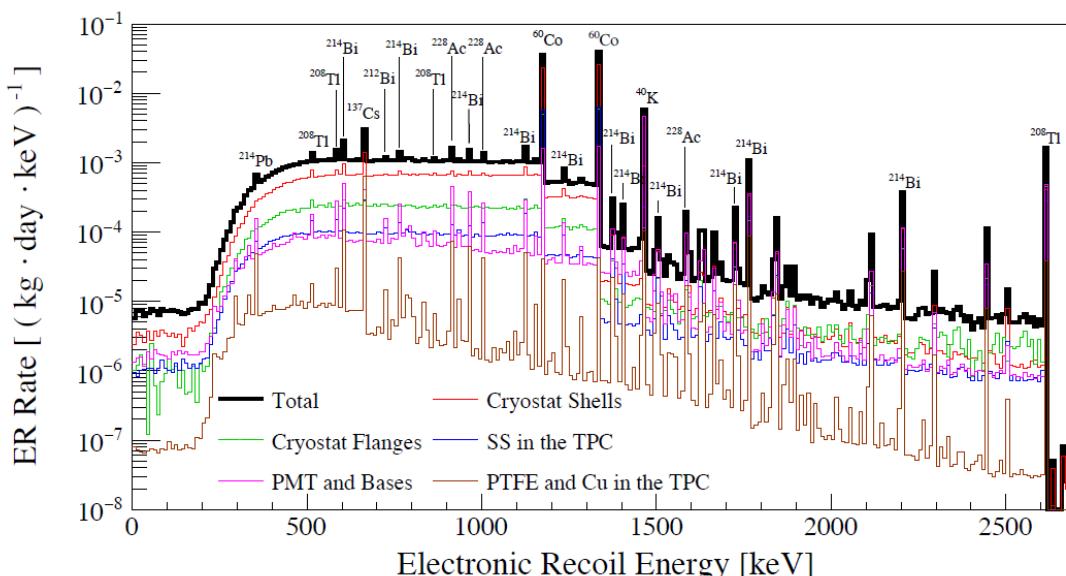
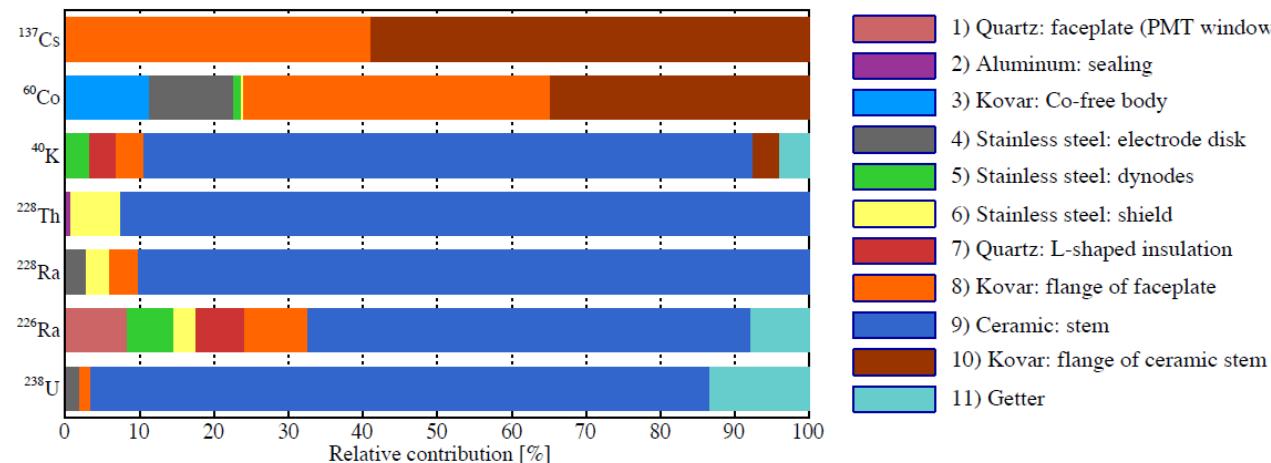


**MPIK (RGMS): ppt ... ppq sensitivity achieved
Columbia U (ATTA)**

used for XENON100 and XENON1T

A lot of Work: E.g PMTs...

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



Hamamatsu

R11410-21



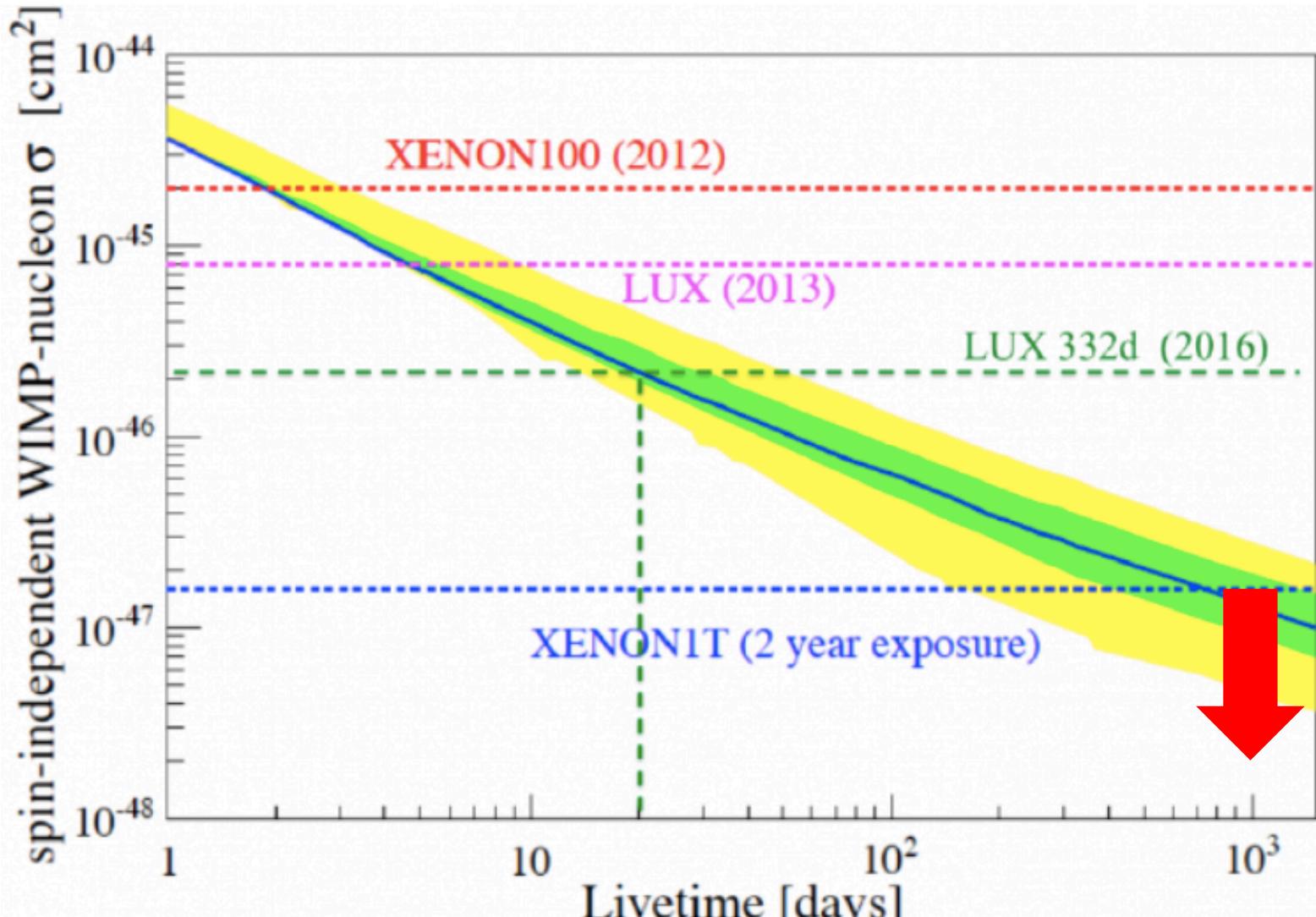
← radiopurity optimization
of PMTs together with
Hamamatsu

Material advice and control with
screening for every little piece
achieved < 1 mBq/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](https://arxiv.org/abs/1512.07501), [JCAP04\(2016\)027](https://jcap.oxfordjournals.org/content/2016/04/027)

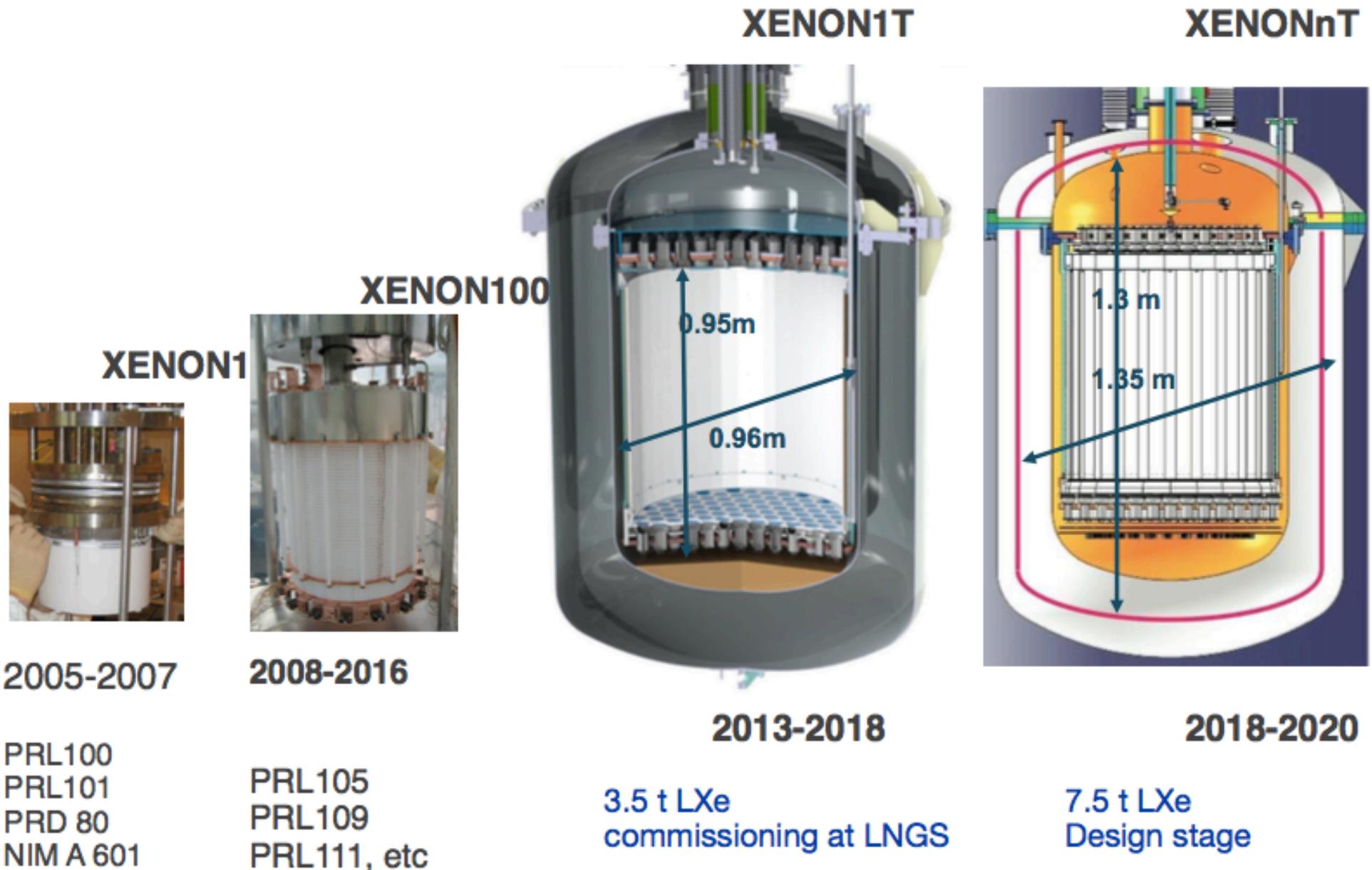
XENON1T Sensitivity Projection



and then
XENONnT
→ 20ty
→ x10

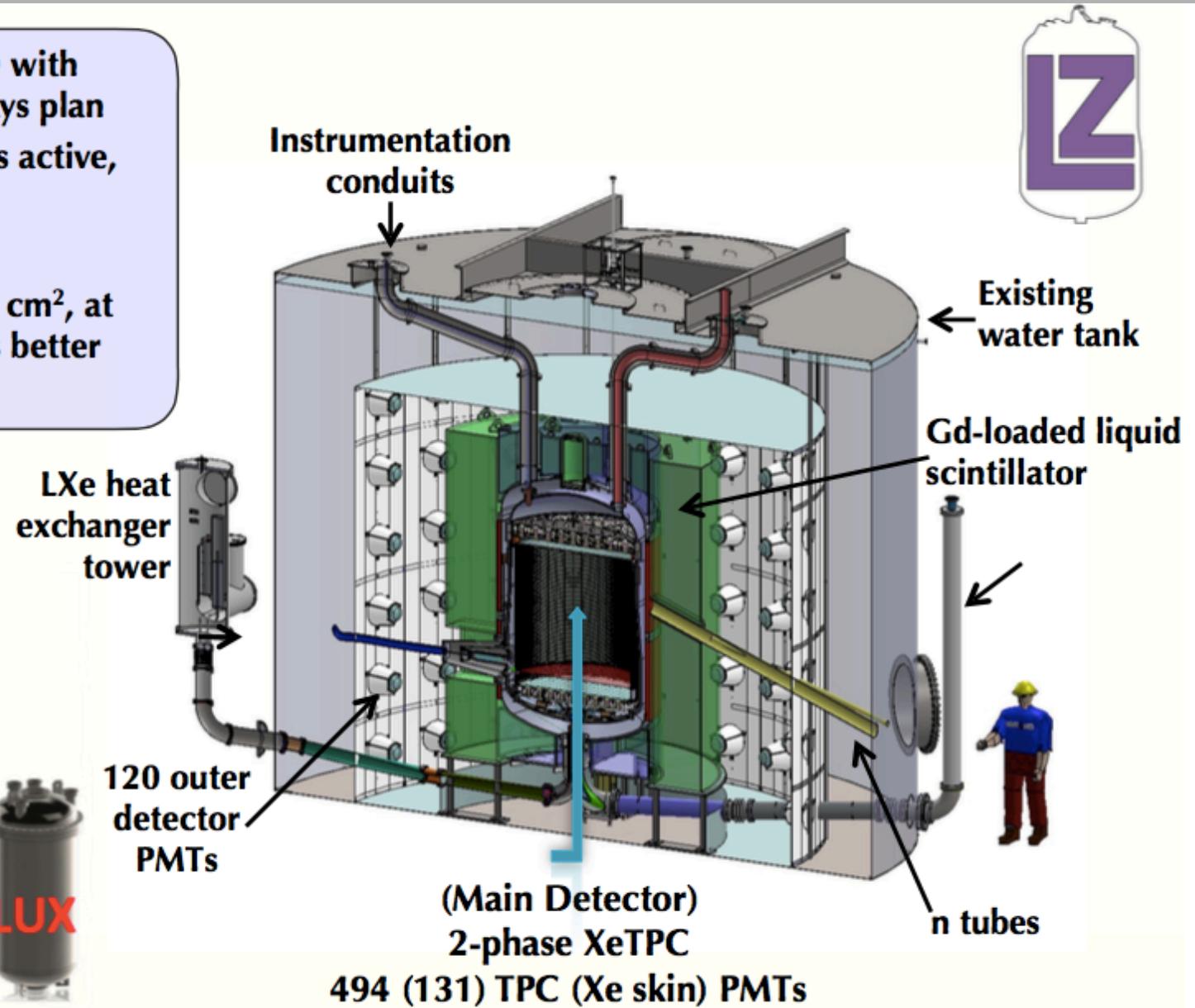
is built while
XENON1T is
running;
reuses most
parts → faster

The XENON-Program @ LNGS



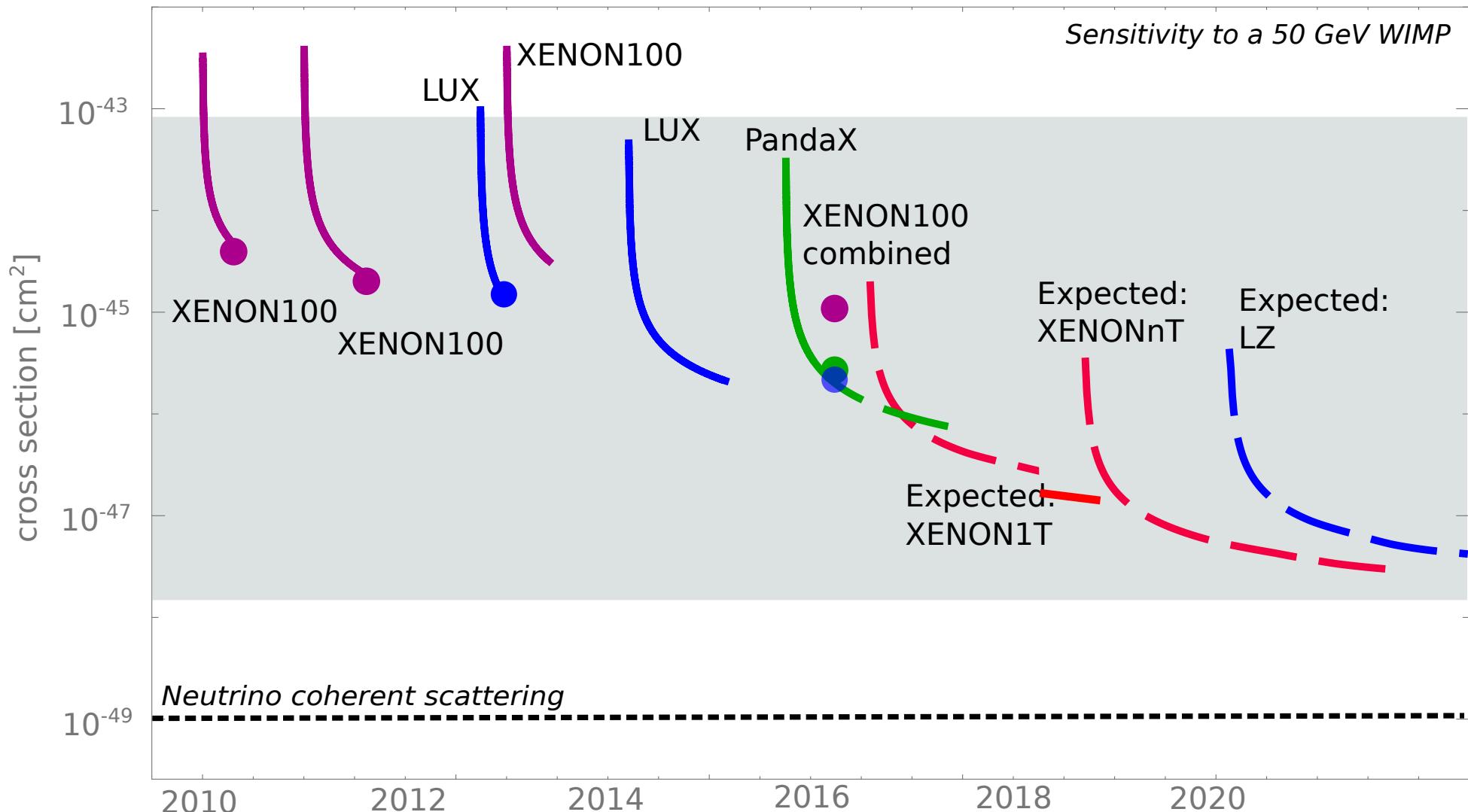
LUX-ZEPLIN (LZ)

- Turning on by 2020 with 1,000 initial live-days plan
- 10 tons total, 7 tons active, ~5.6 ton fiducial
- Unique triple veto
- GOALS: $< 2 \times 10^{-48} \text{ cm}^2$, at 40 GeV ~100 times better than LUX



Slide from C. Frederico Pascoal da Silva

Direct WIMP Search Timeline (Xe)



About 25 days of XENON1T data will be enough to catch up and then move on
In the remaining generic WIMP parameter space

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!