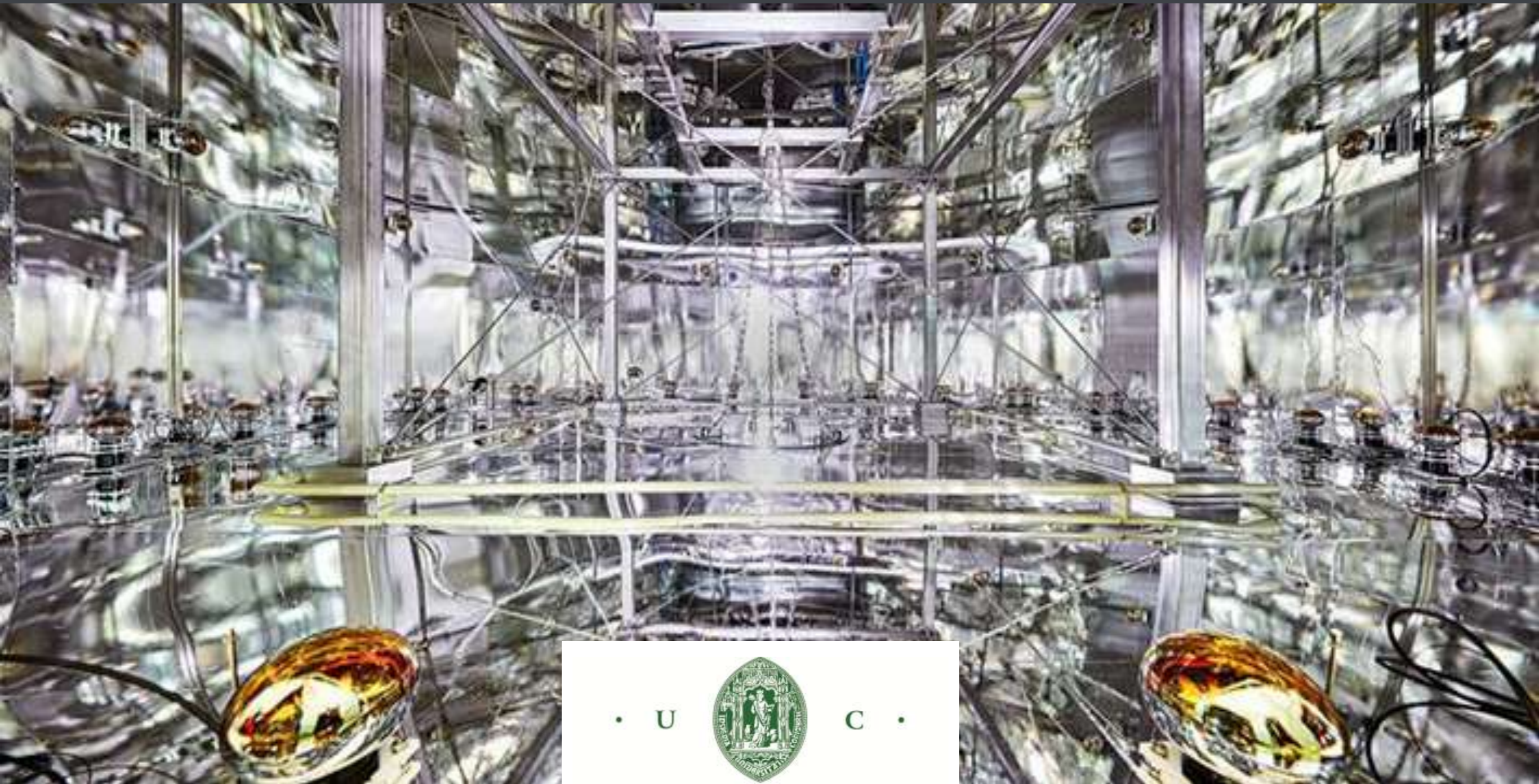


Dark matter direct detection: present scenario and future prospects

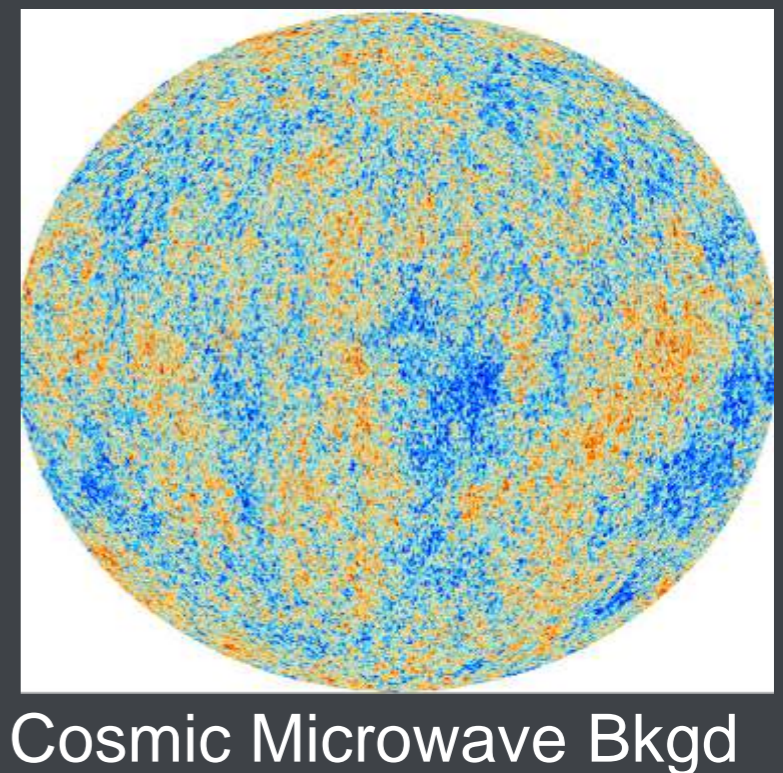
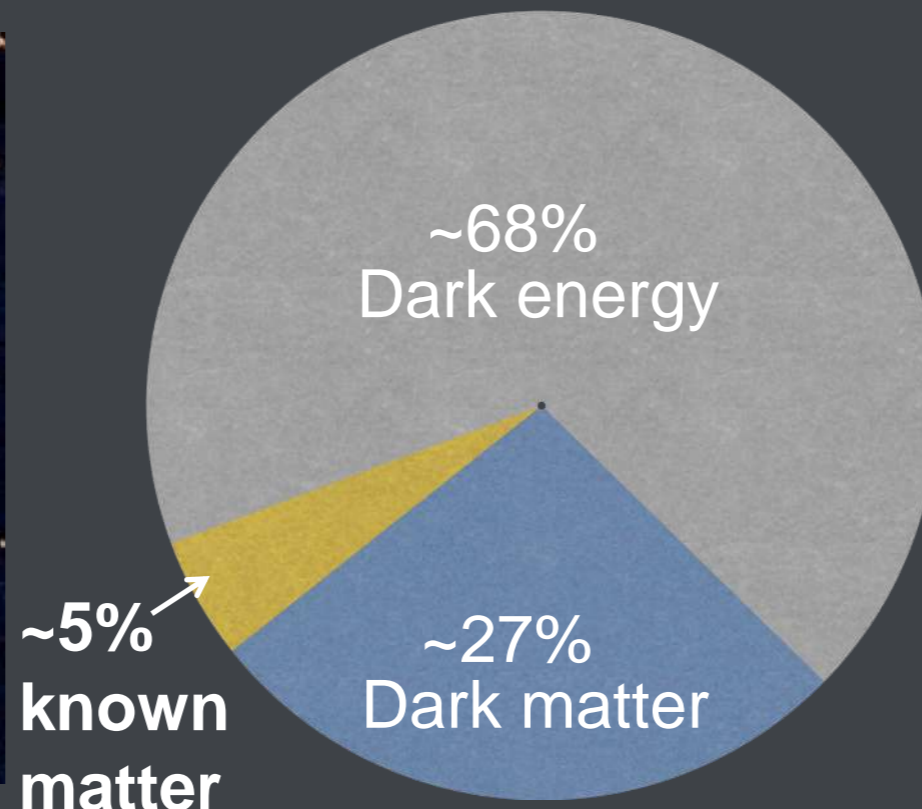
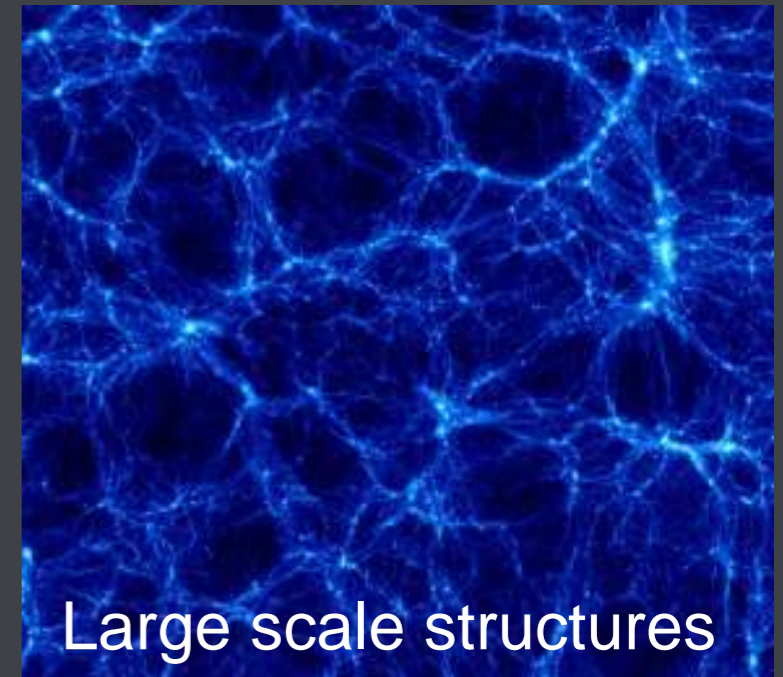


José A. Matias-Lopes



PONT, December 8, 2020

The Universe energy budget: a consistent picture from an impressive number of observations



DM existence proofs are overwhelming

100%

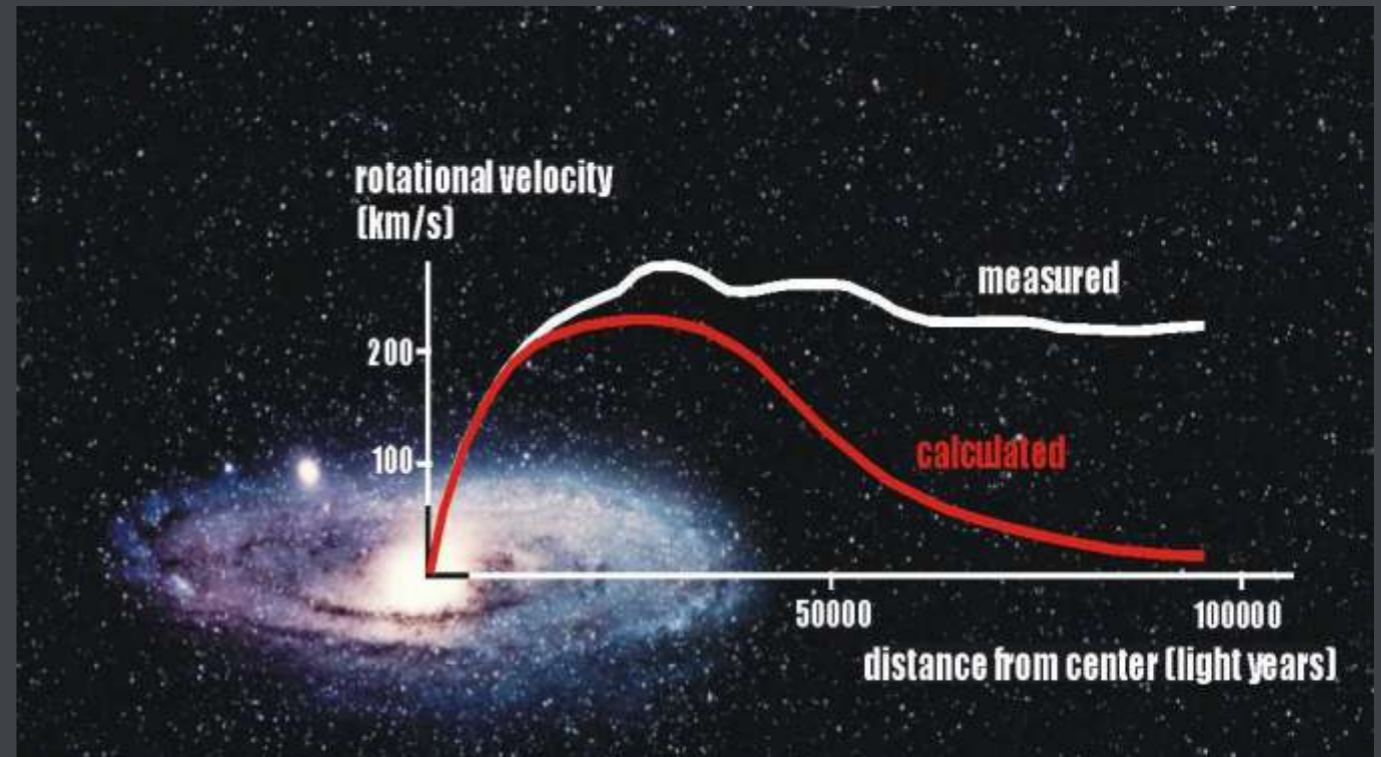
And there are many:

- Early and late cosmology (CMB, LSS)
- Clusters of galaxies
- Galactic rotation curves
- Gravitational lensing
- ...

Dark energy
68%

Dark matter
27%

Baryons
5%



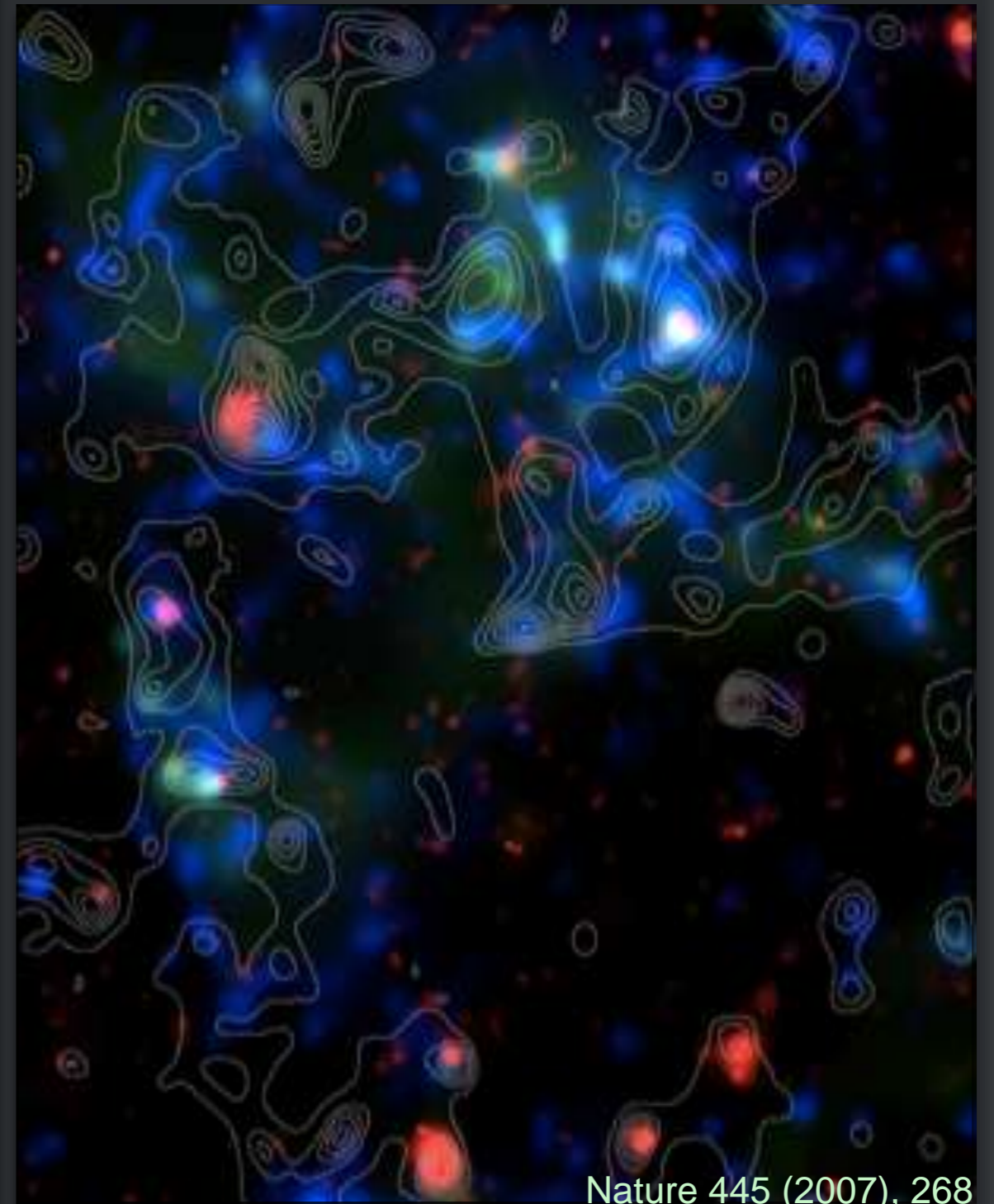
Milky Way



Dark matter: the puzzle

- Dark matter is *matter* - it leads to the formation of structure and galaxies in our universe
- We have a standard model of CDM, from 'precision cosmology' (CMB, LSS): however, *measurement \neq understanding*
- For **85% of matter in the universe is of unknown nature**

Large scale distribution of dark matter, probed through gravitational lensing



Nature 445 (2007), 268

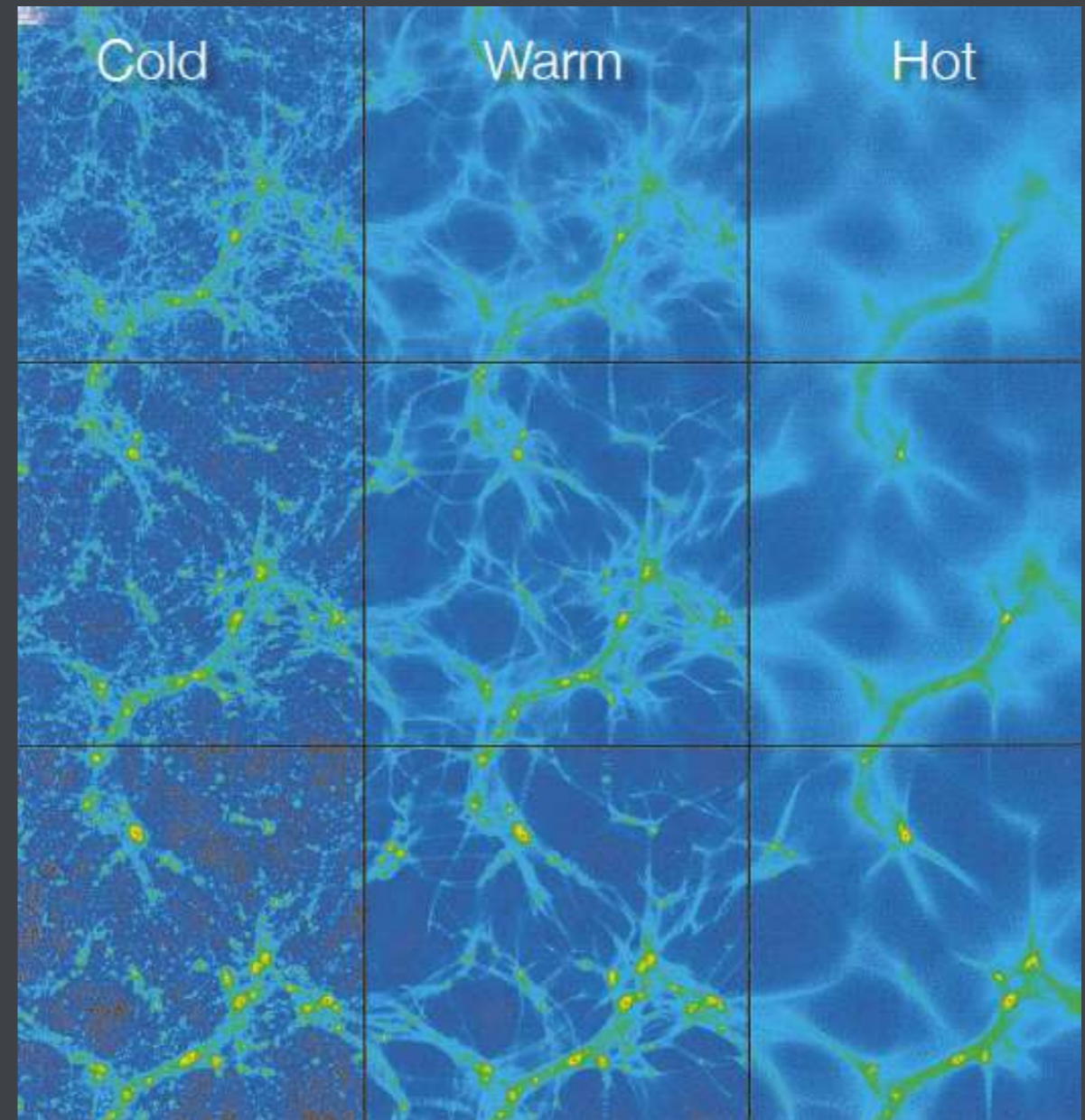
What do we know about dark matter?

Constraints from astrophysics and searches for new particles:

- No electric charge
- No strong self-interaction

Exists since the early Universe

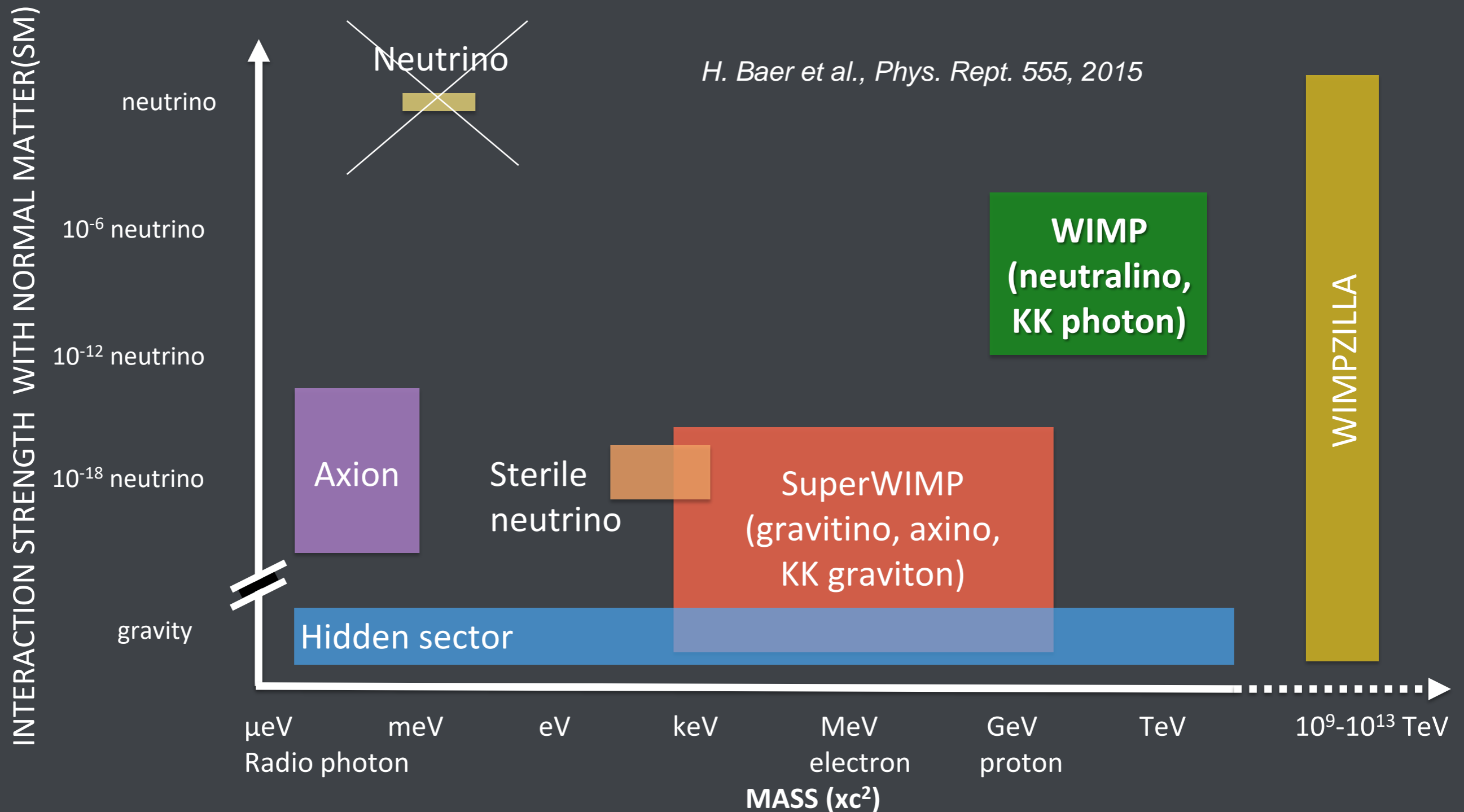
Stable, or very long-lived



Probing dark matter through gravity

Possible DM particles

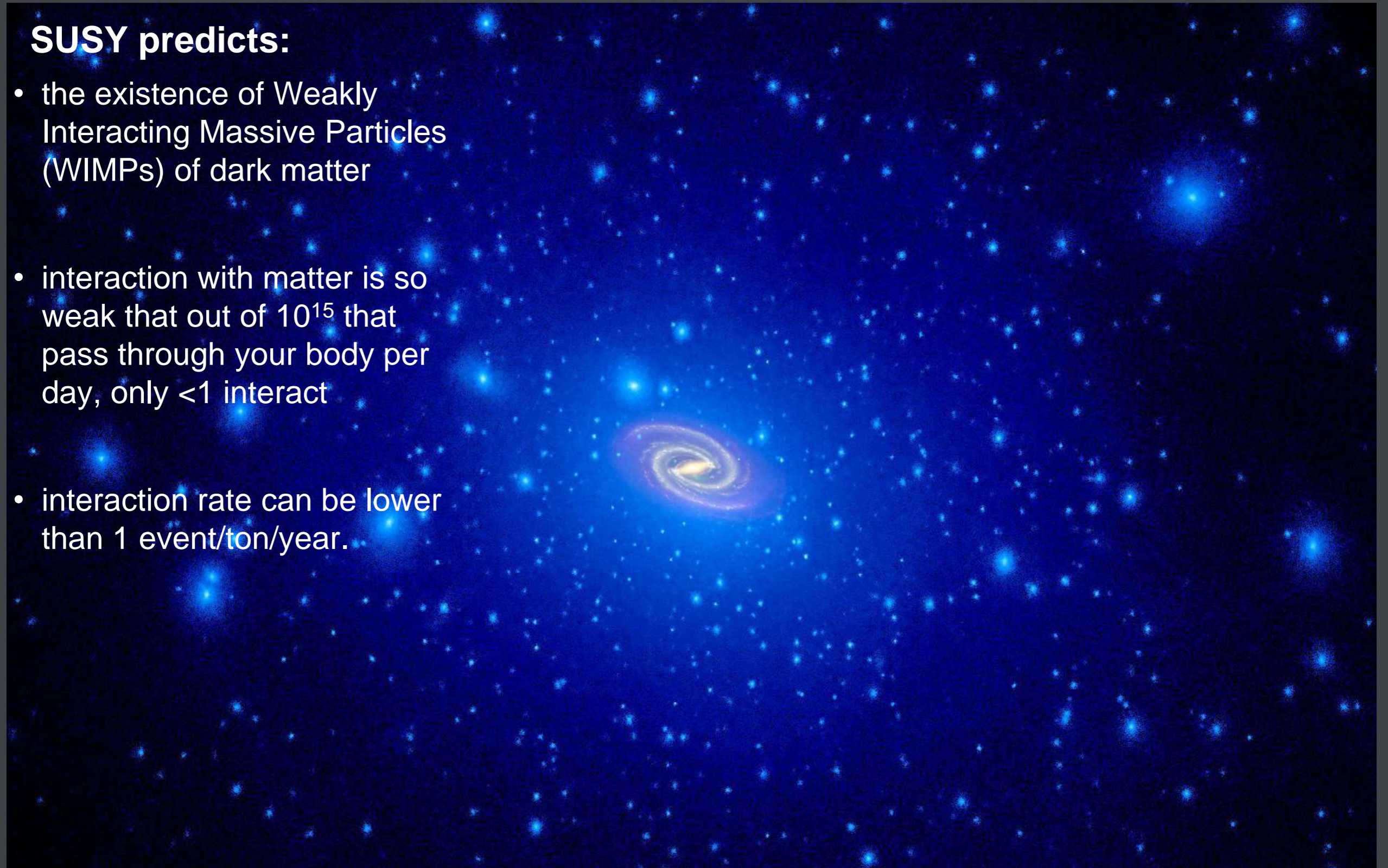
no particle of the Standard Model is a good dark matter candidate



Super Symmetry theory and Dark Matter

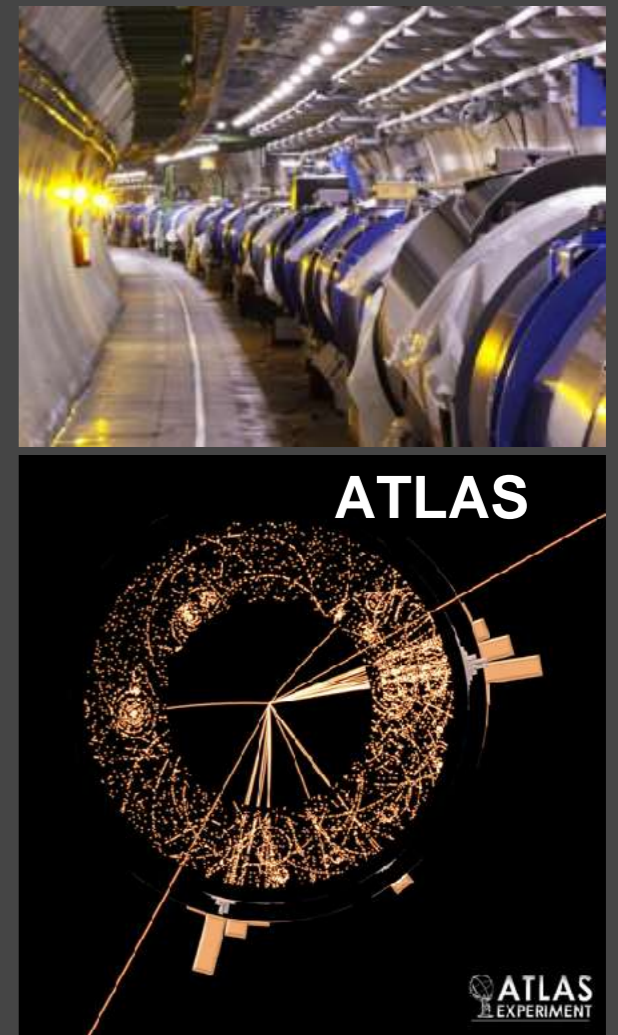
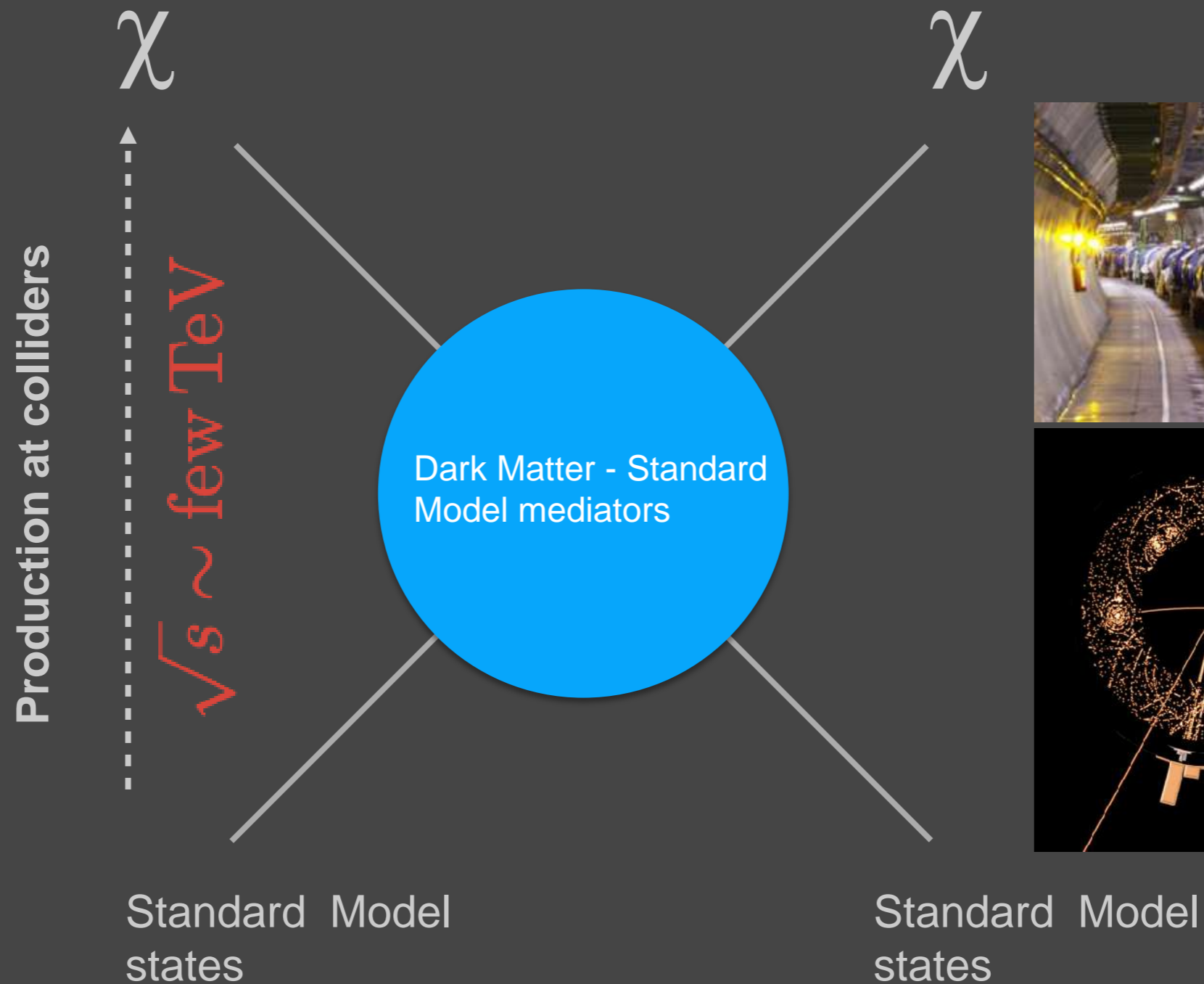
SUSY predicts:

- the existence of Weakly Interacting Massive Particles (WIMPs) of dark matter
- interaction with matter is so weak that out of 10^{15} that pass through your body per day, only <1 interact
- interaction rate can be lower than 1 event/ton/year.

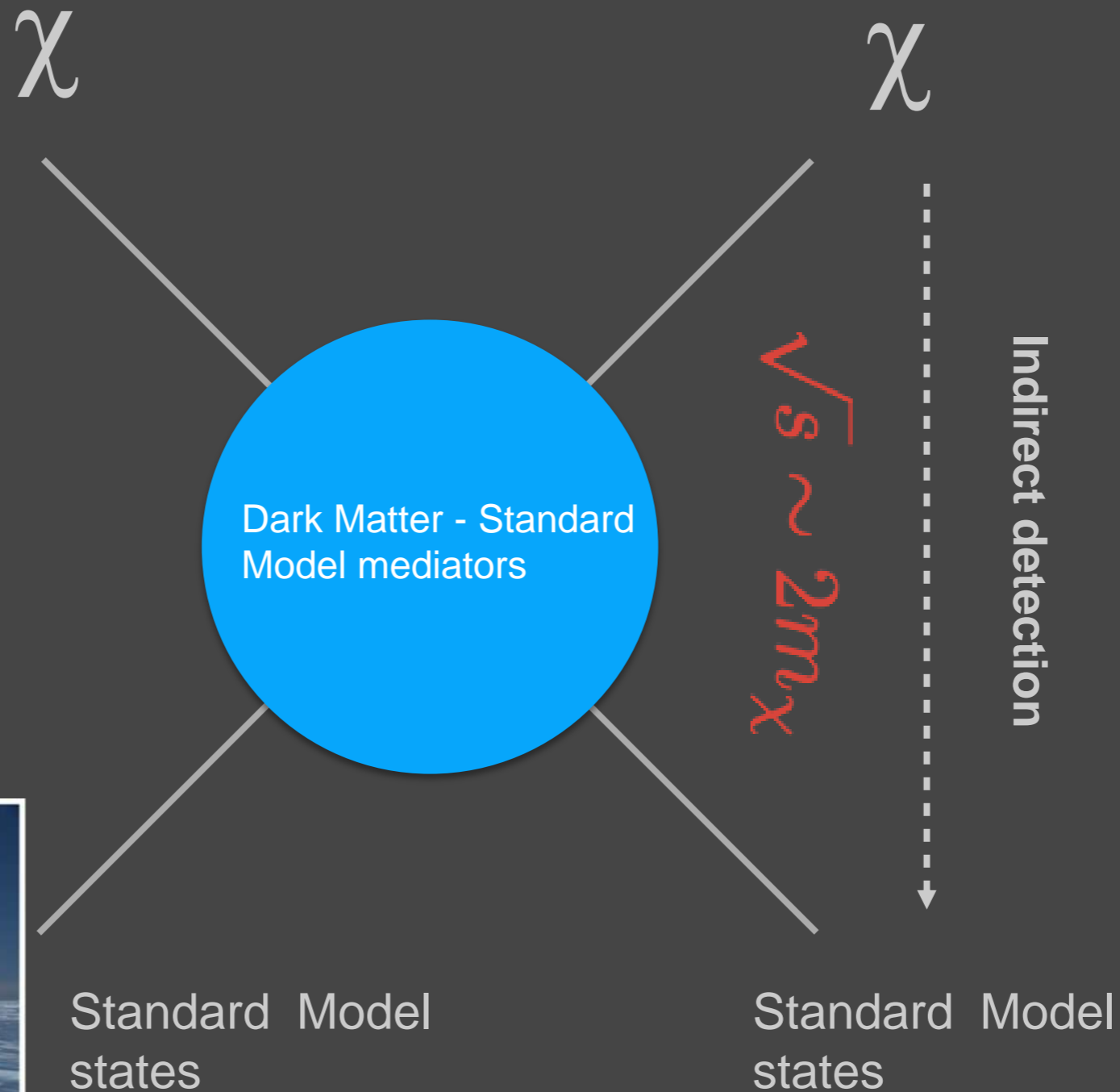


Milky Way dark matter halo

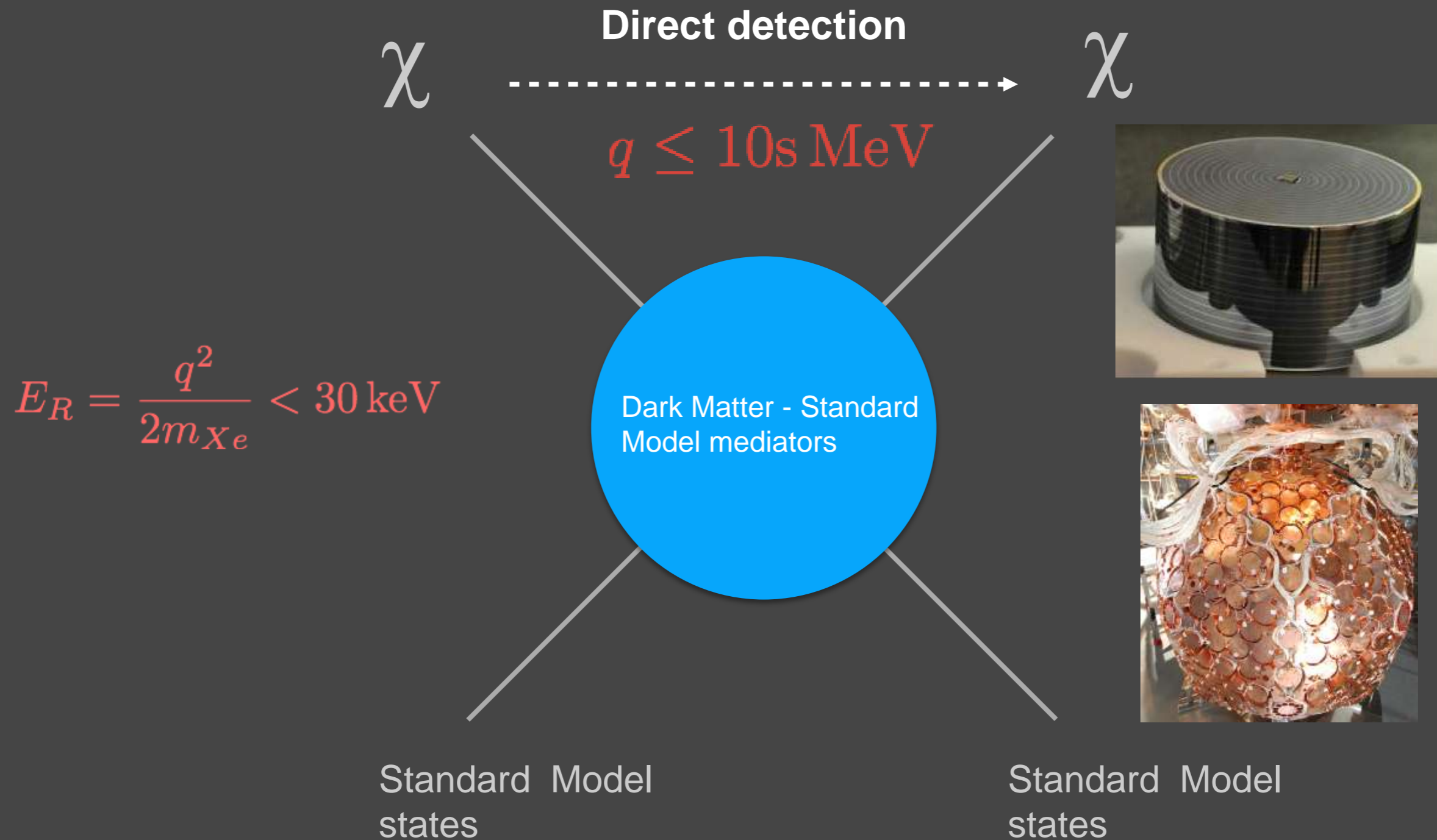
How to look for dark matter



How to look for dark matter

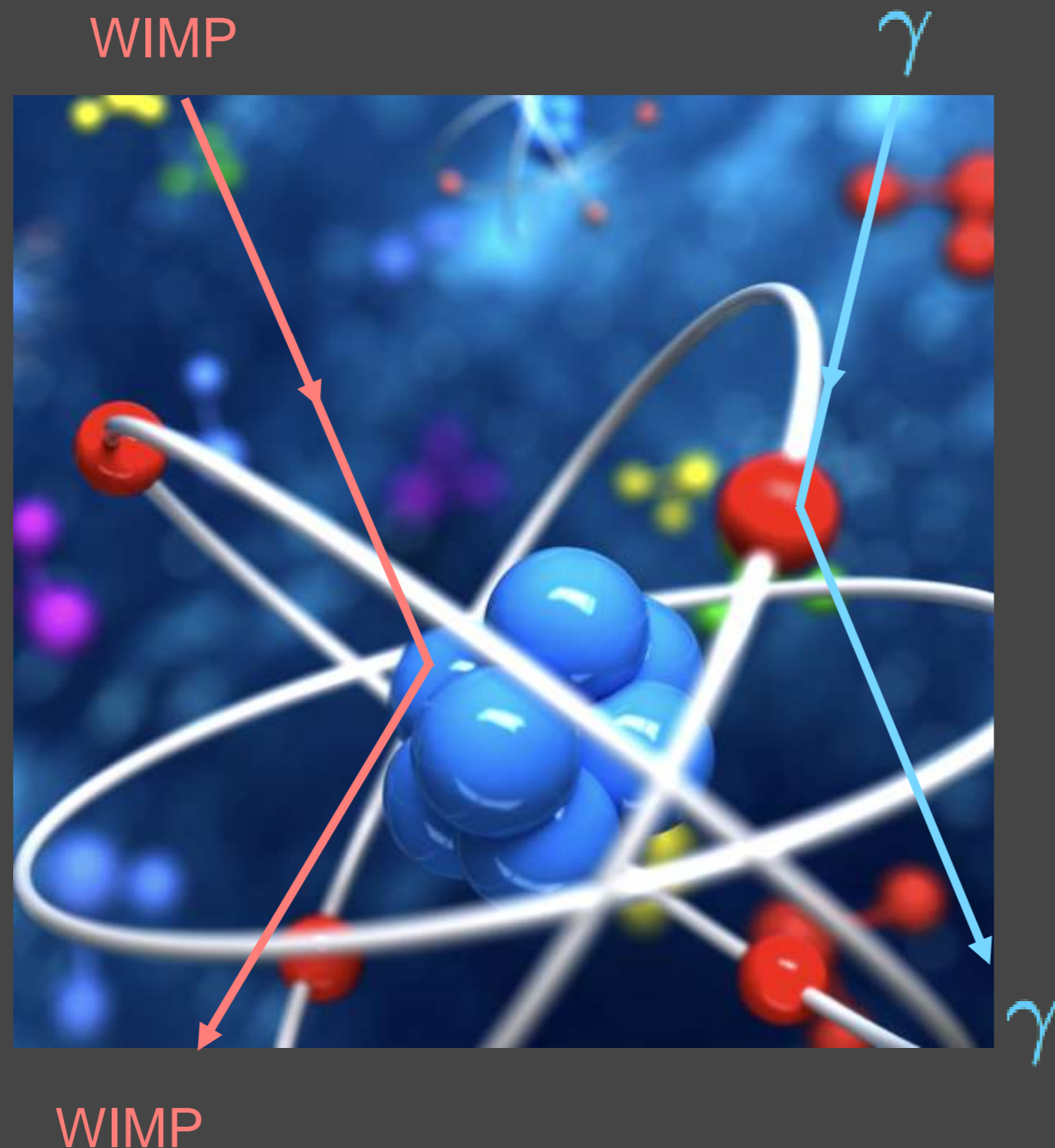


How to look for dark matter



DM direct detection principle

- Nuclear recoils

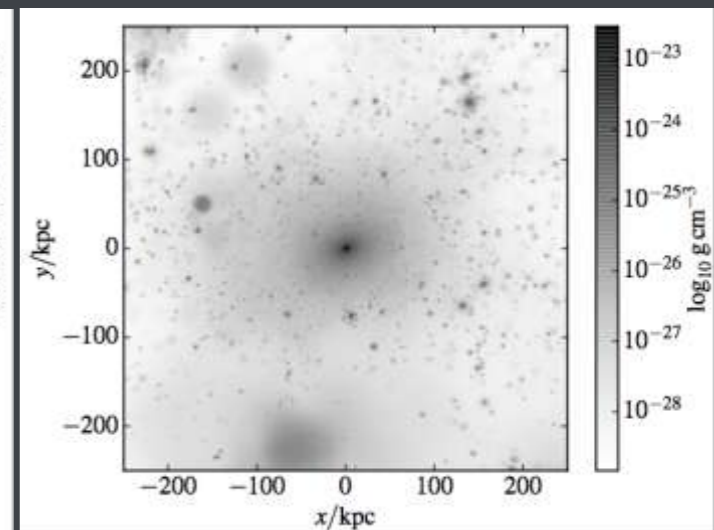
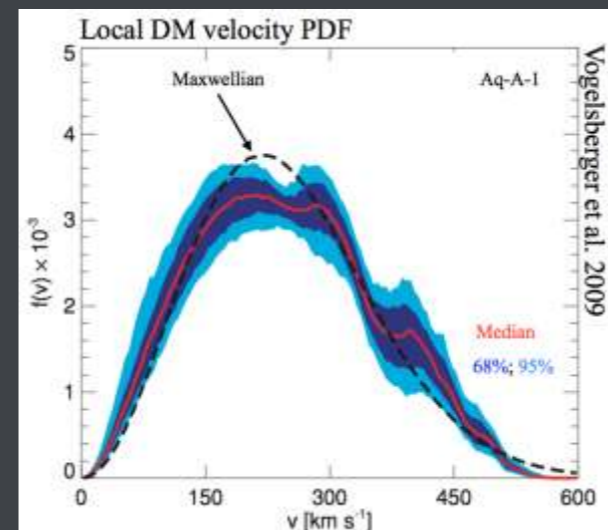
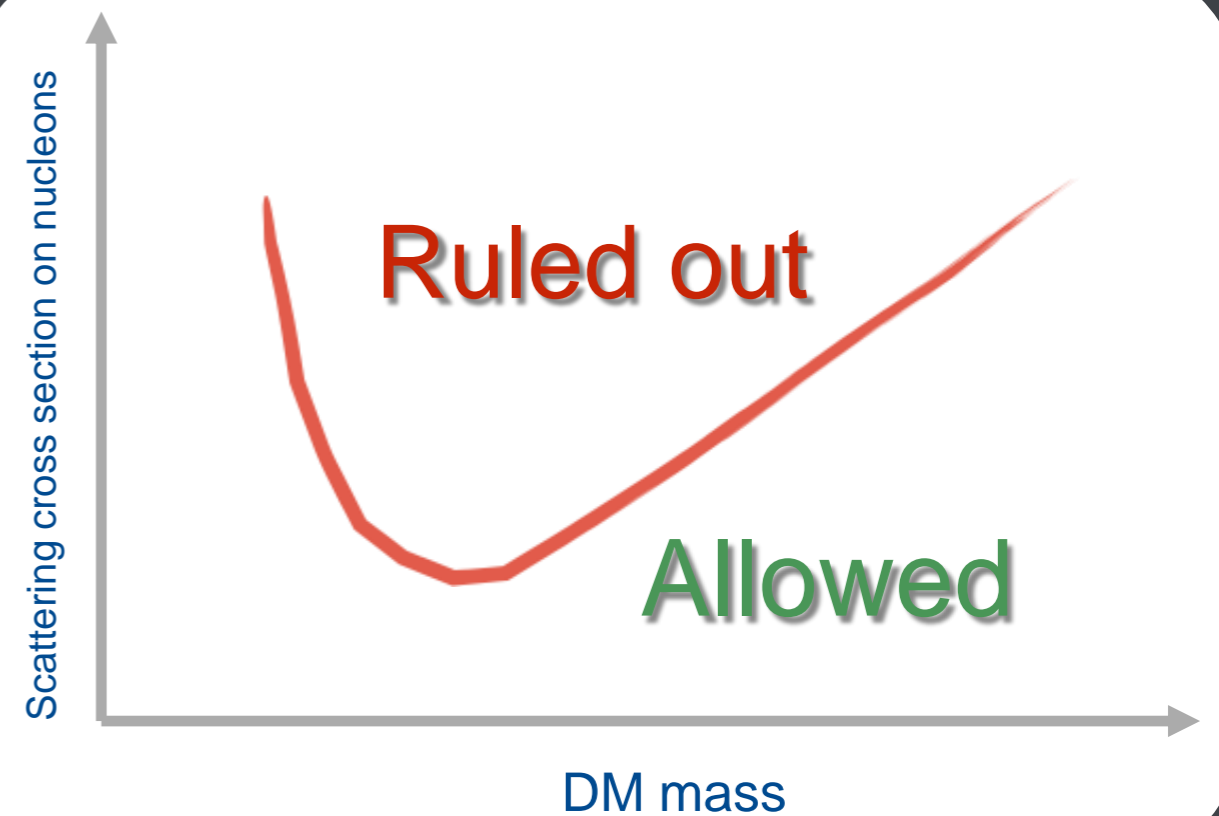
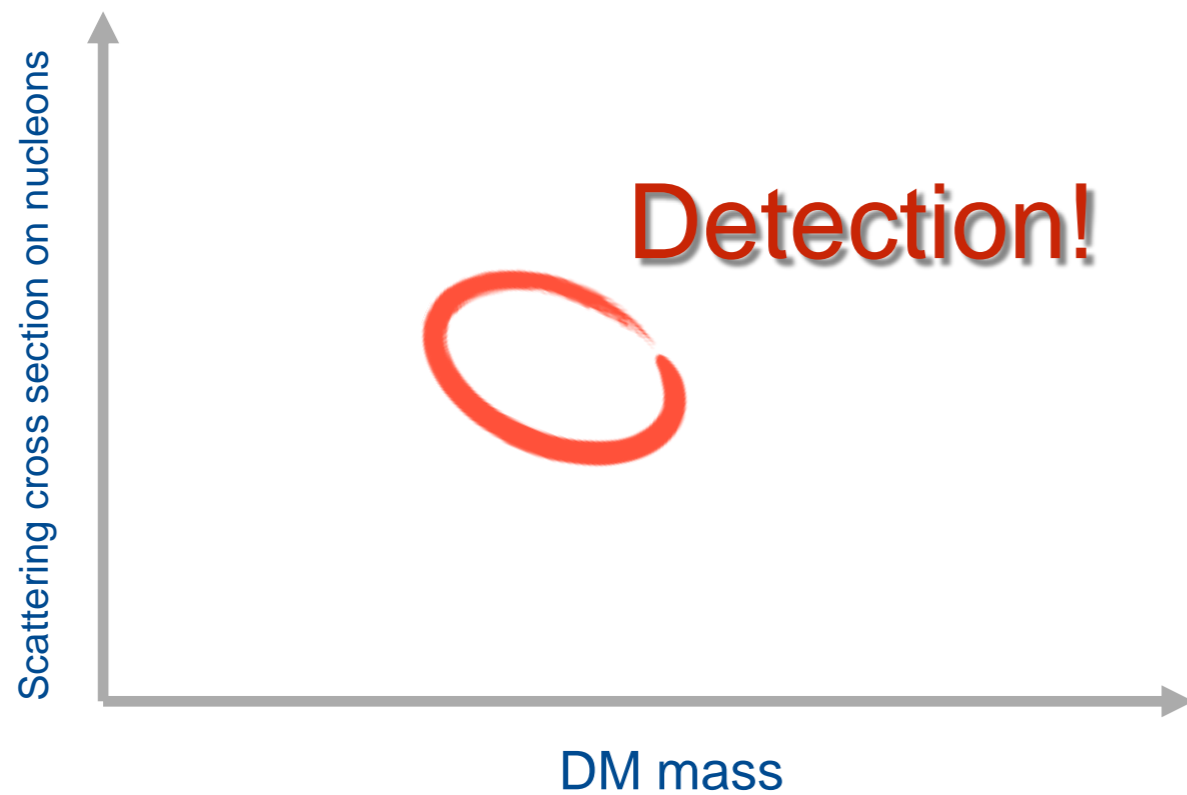


- + collisions with electrons in the atomic shell, or absorption of light bosons via the axio-electric effect
- + Bremsstrahlung from polarised atoms; e^- emission due to so-called Migdal effect

What can we learn about DM?

- Constraints on the mass and scattering cross section

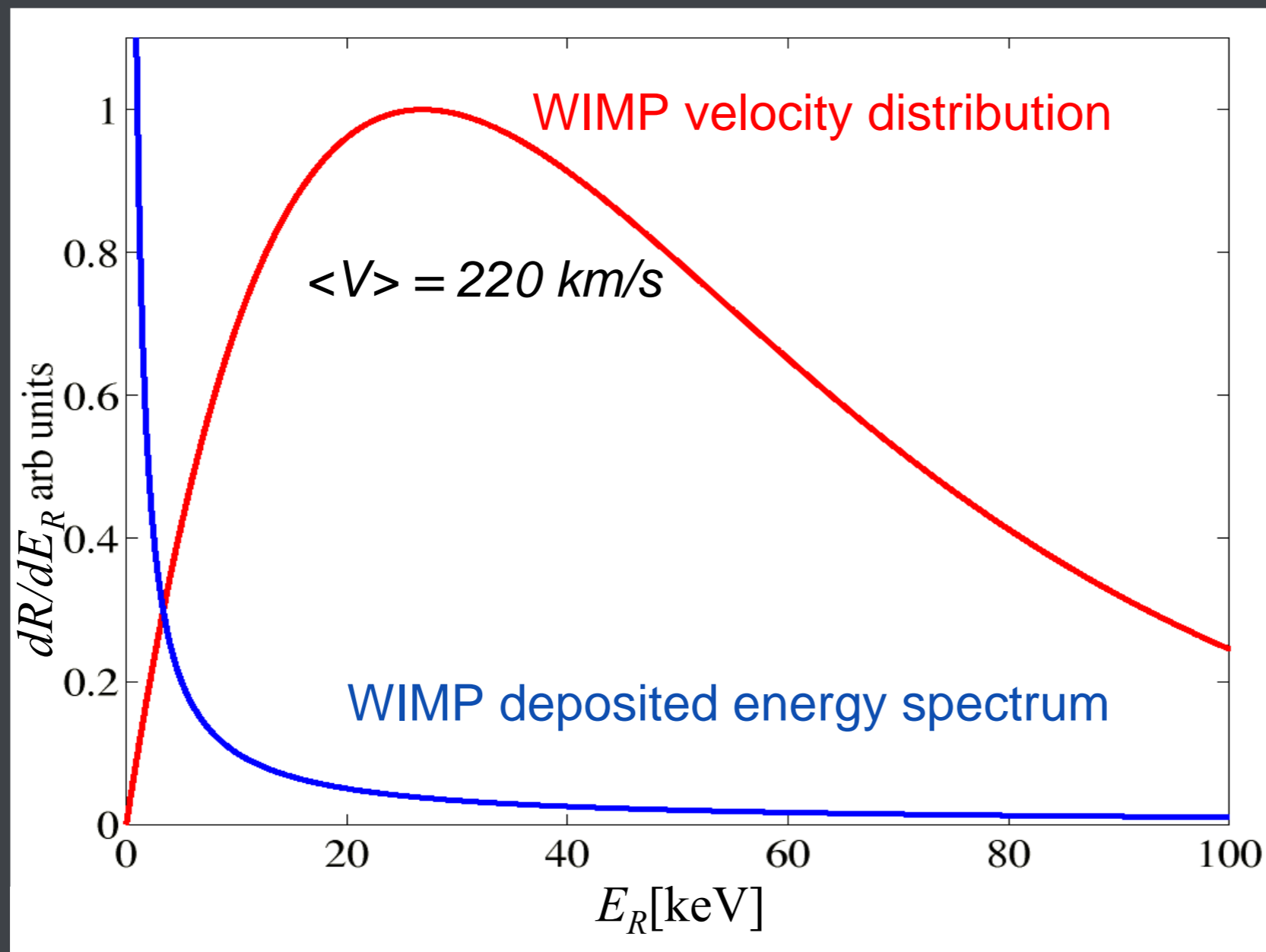
$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{min}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$



WIMP detection on Earth

Differential
event rate:

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{\sqrt{(m_N E_{th})/(2\mu^2)}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$



Astrophysics

$$\rho_0, f(v)$$

Detector physics

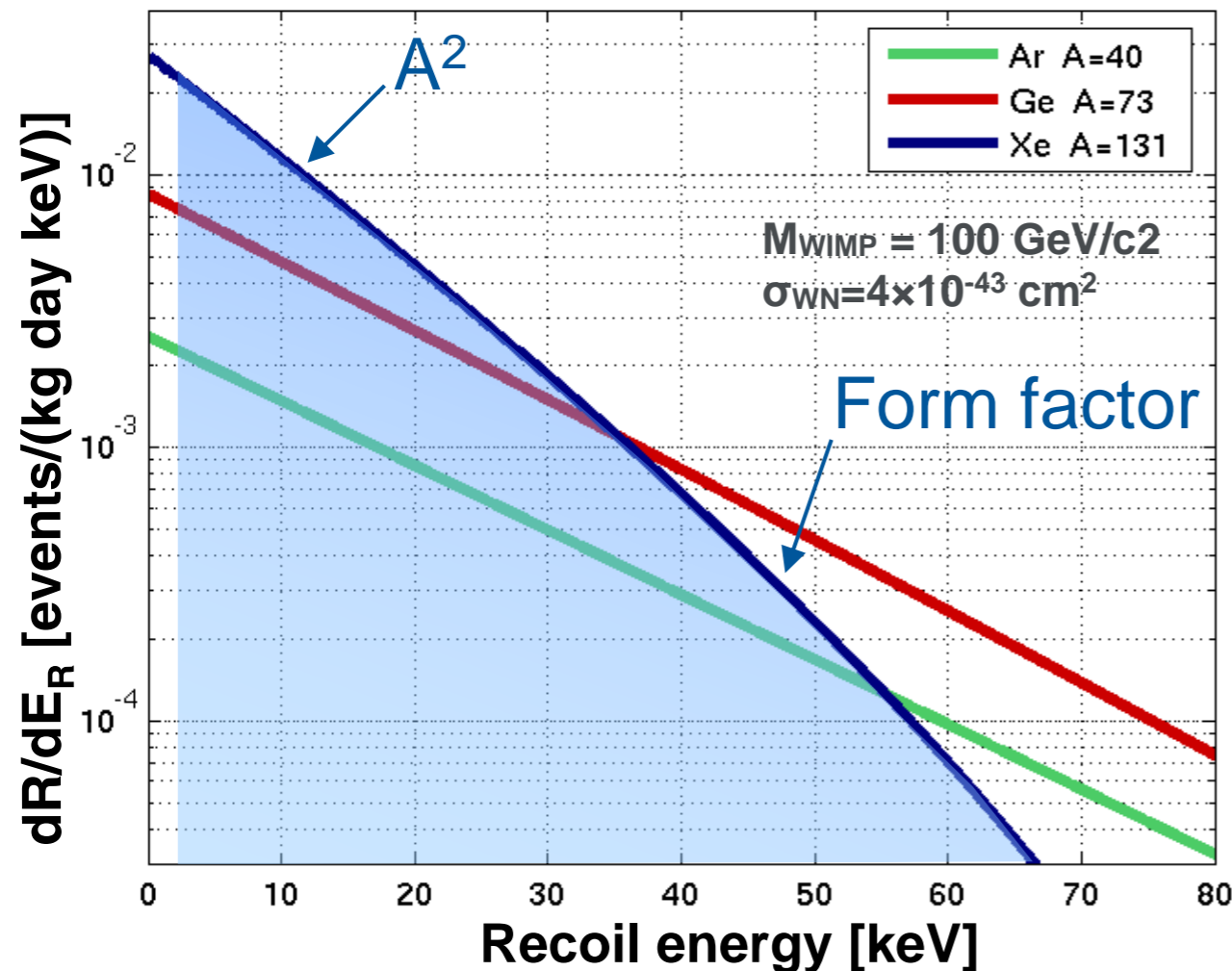
$$N_N, E_{th}$$

Particle/nuclear physics

$$m_W, d\sigma/dE_R$$

DM direct detection challenges

$$\frac{d\sigma^{SI}}{dE_R}(E_R) \propto A^2 \times F_{SI}^2(E_R)$$



Small deposited energies \Rightarrow

1) very low energy thresholds
(~ keV)

Extremely low event rates \Rightarrow

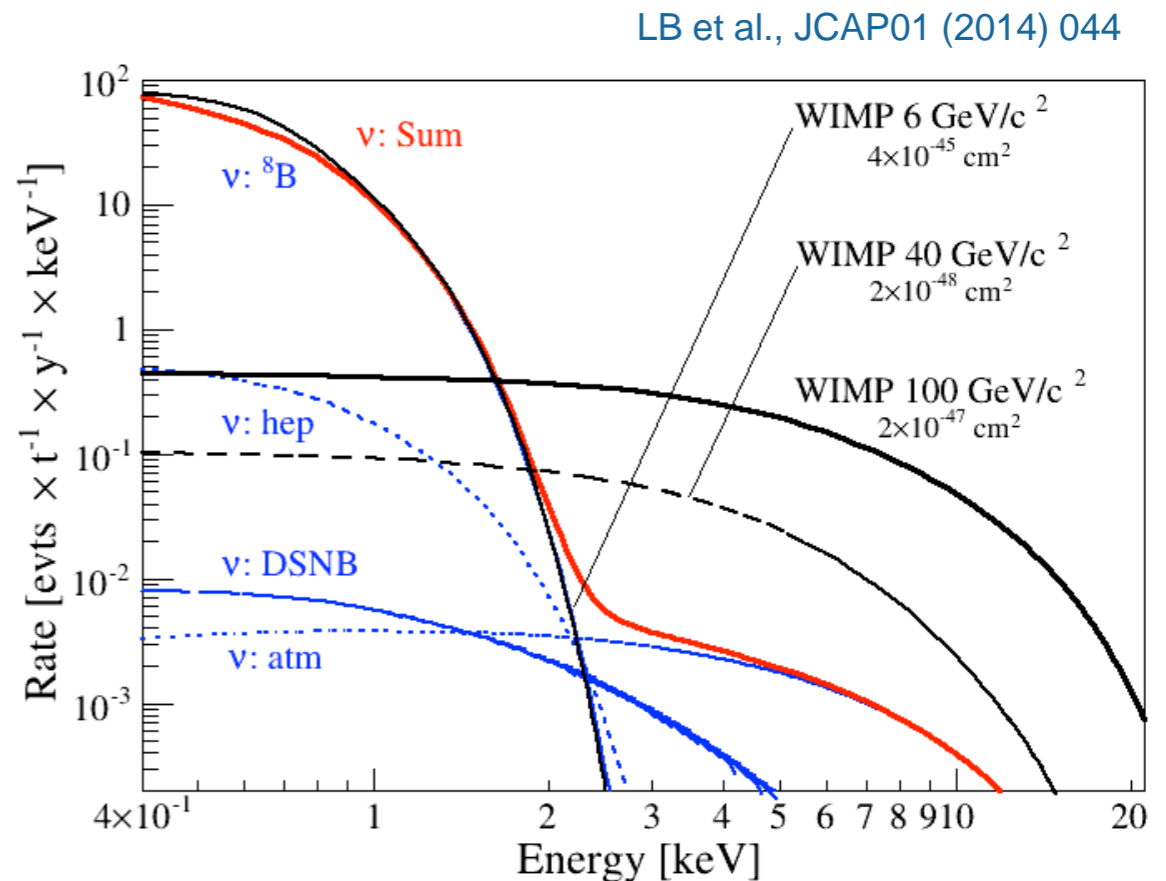
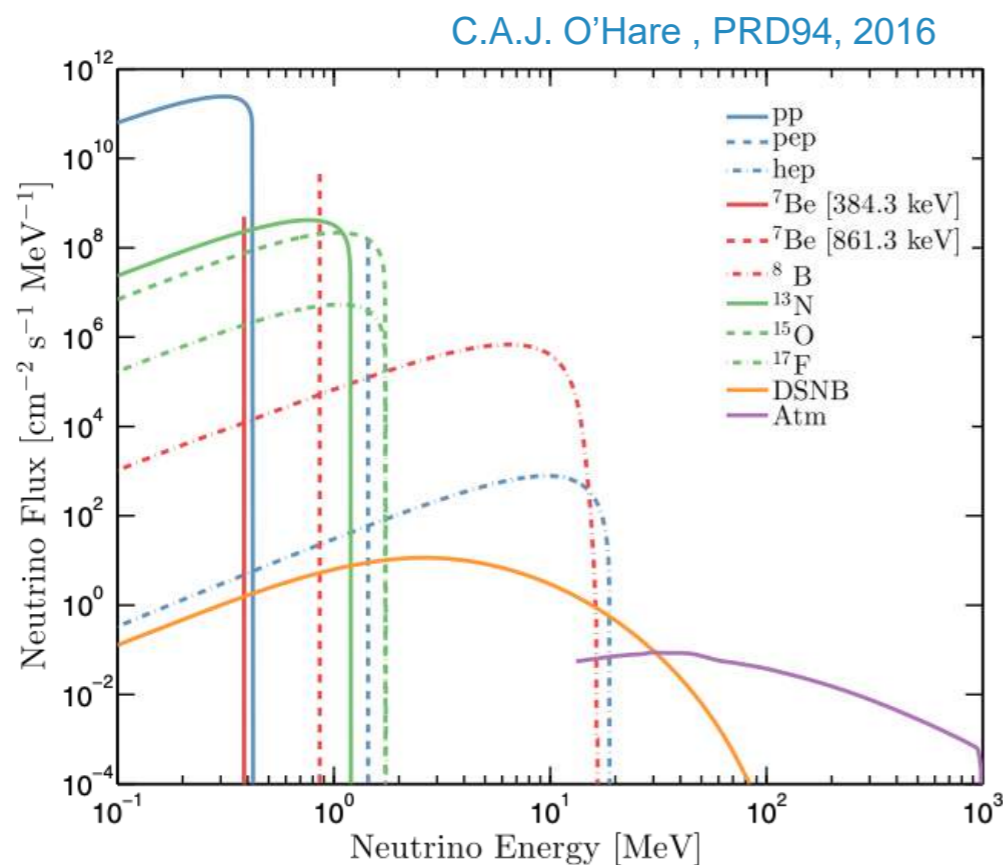
2) ultra-low backgrounds
good background
understanding

3) good background
discrimination

4) large detector masses

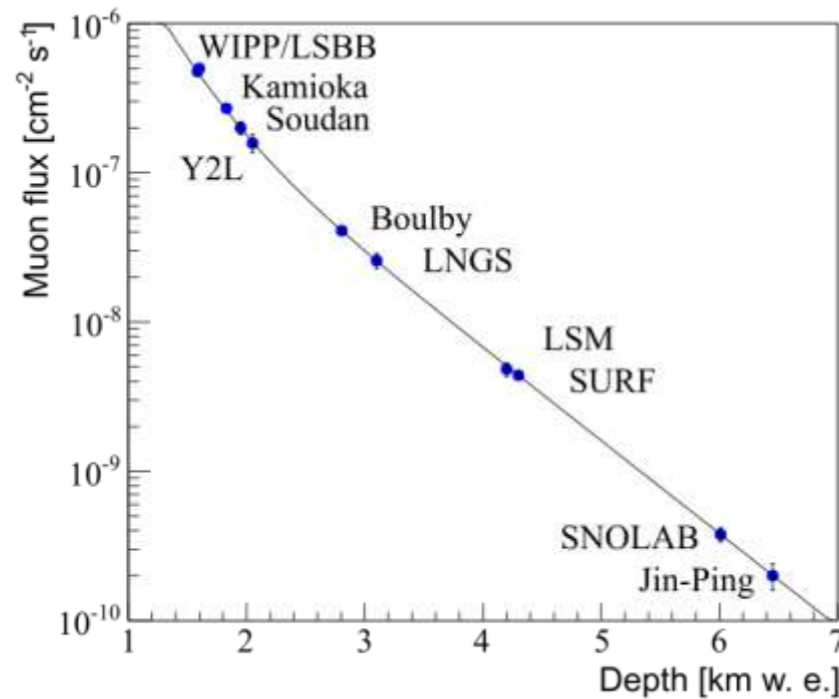
Backgrounds

- ▶ In the ideal case: below the expected signal
 - ▶ Muons & associated showers; cosmogenic activation of detector materials
 - ▶ Natural and anthropogenic radioactivity
 - ▶ Neutrinos! Coherent neutrino-nucleus scattering was observed



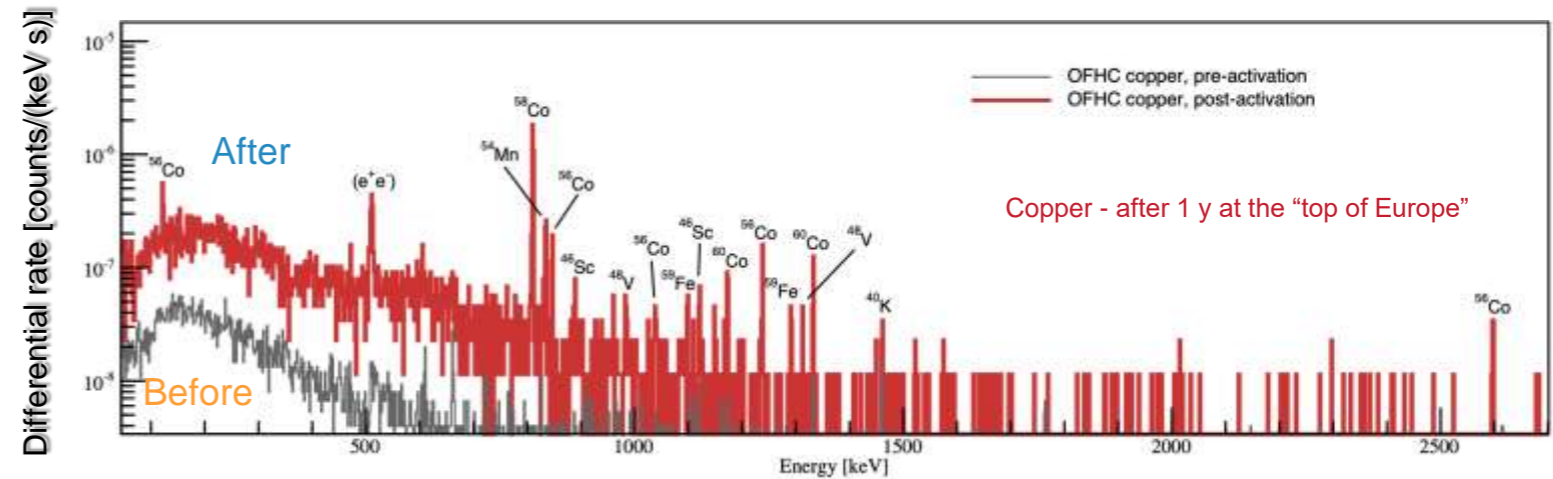
Background reduction

Go deep underground

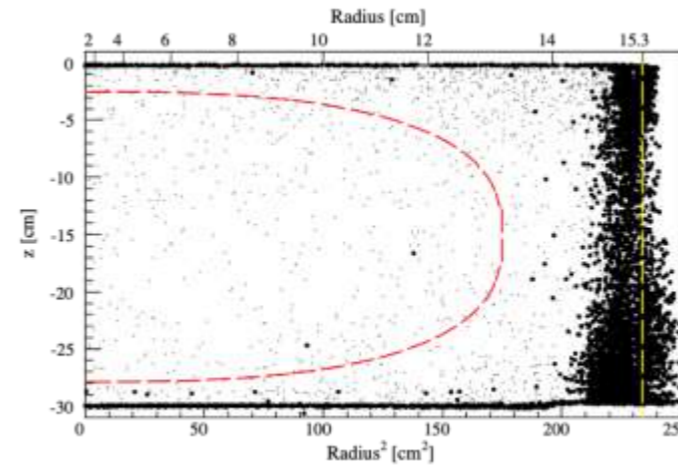


Avoid cosmic activation

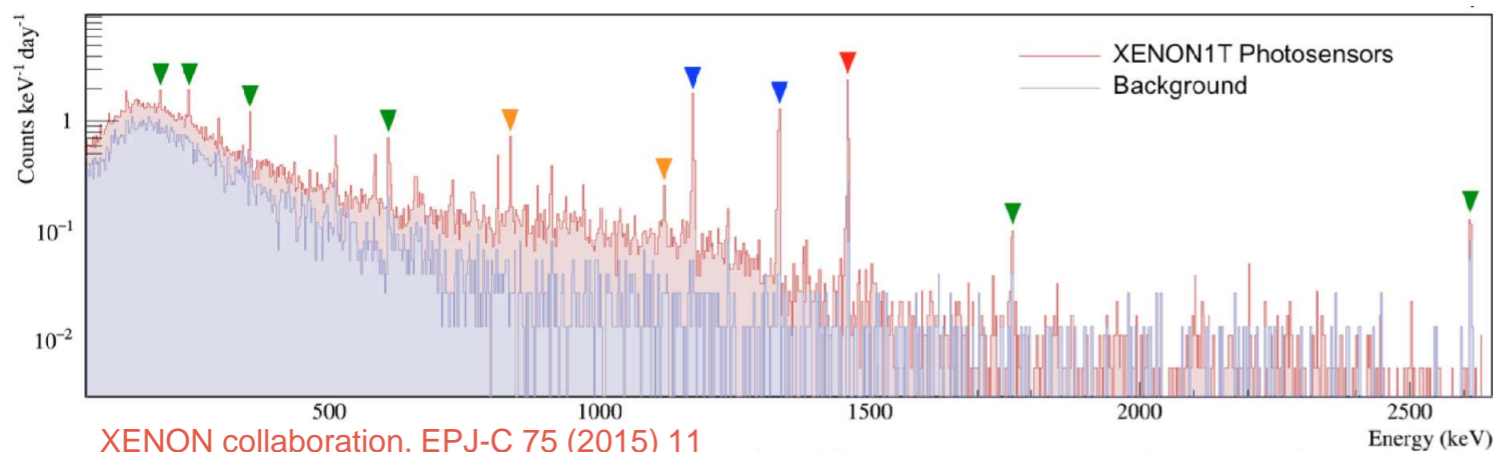
LB et al., Eur. Phys. J. C75 2015



Fiducialize



Select low-radioactivity materials



XENON collaboration, EPJ-C 75 (2015) 11

Use active shields

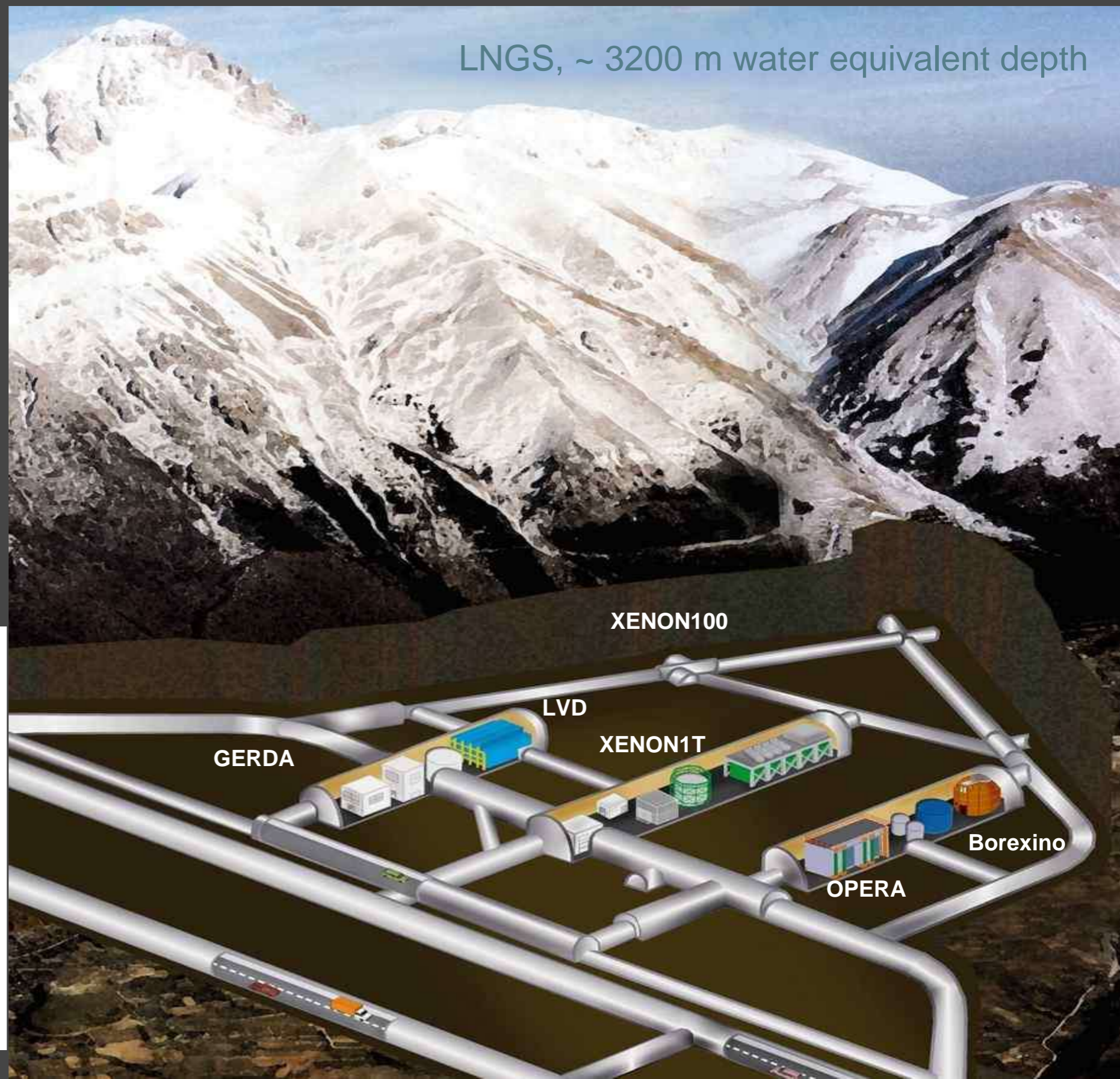
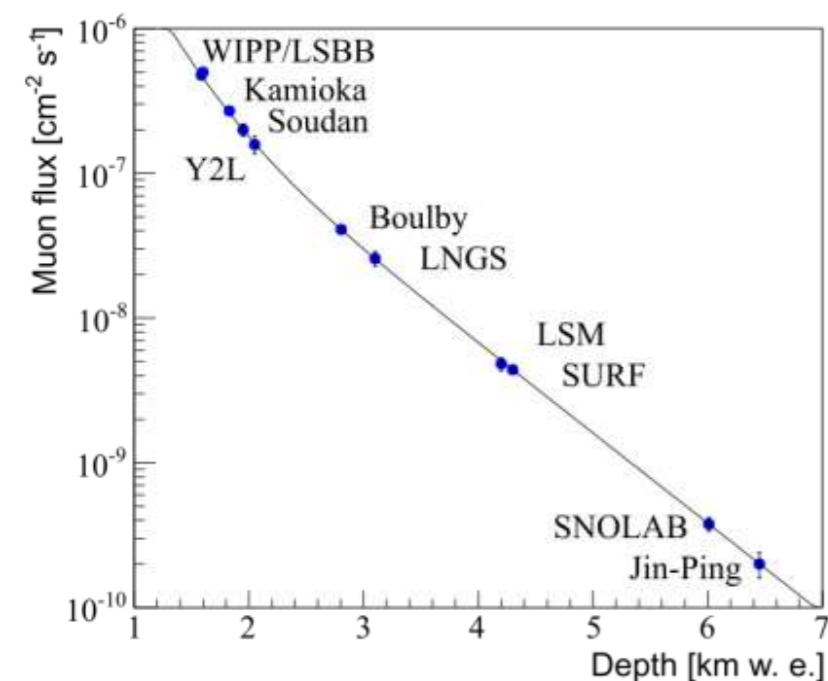


Cosmic radiation shielding

- ▶ Go underground
- ▶ Bad news: you can't shield neutrinos

- ▶ Good news: eventually these will be one of your signals:

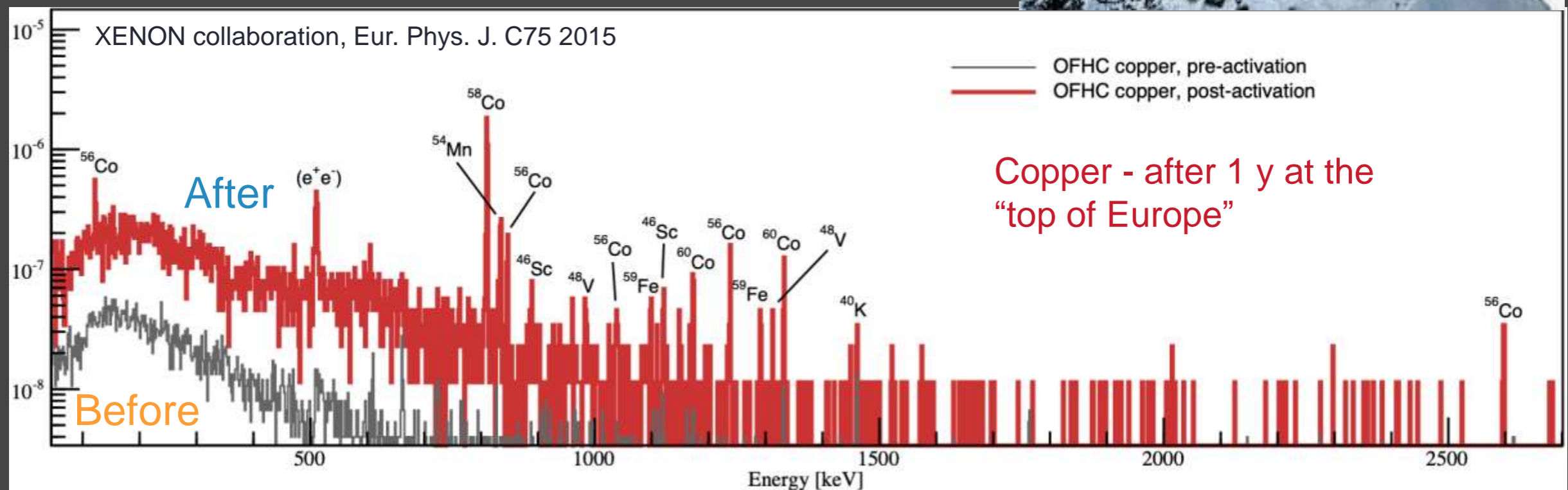
pp , ${}^7\text{Be}$, ${}^8\text{B}$, DSNB,...



Cosmogenic backgrounds

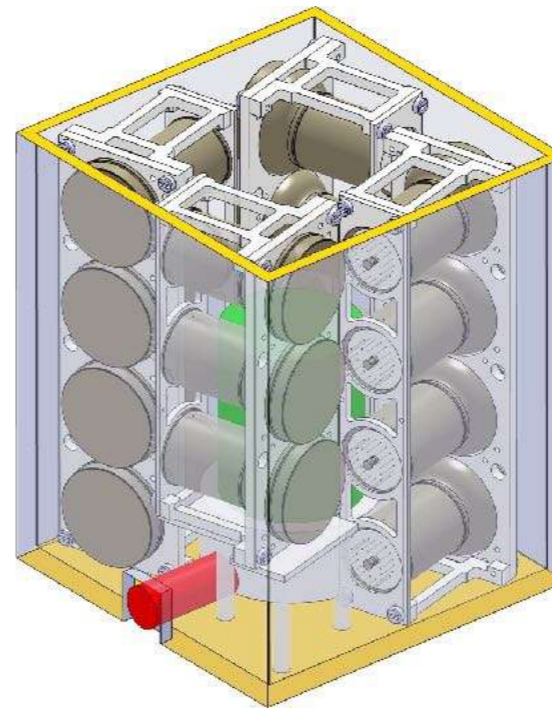
- ▶ Avoid detector components exposure to cosmic rays
- ▶ Spallation reactions can produce long-lived isotopes

Jungfrauoch, 3454 m



Material screening and selection

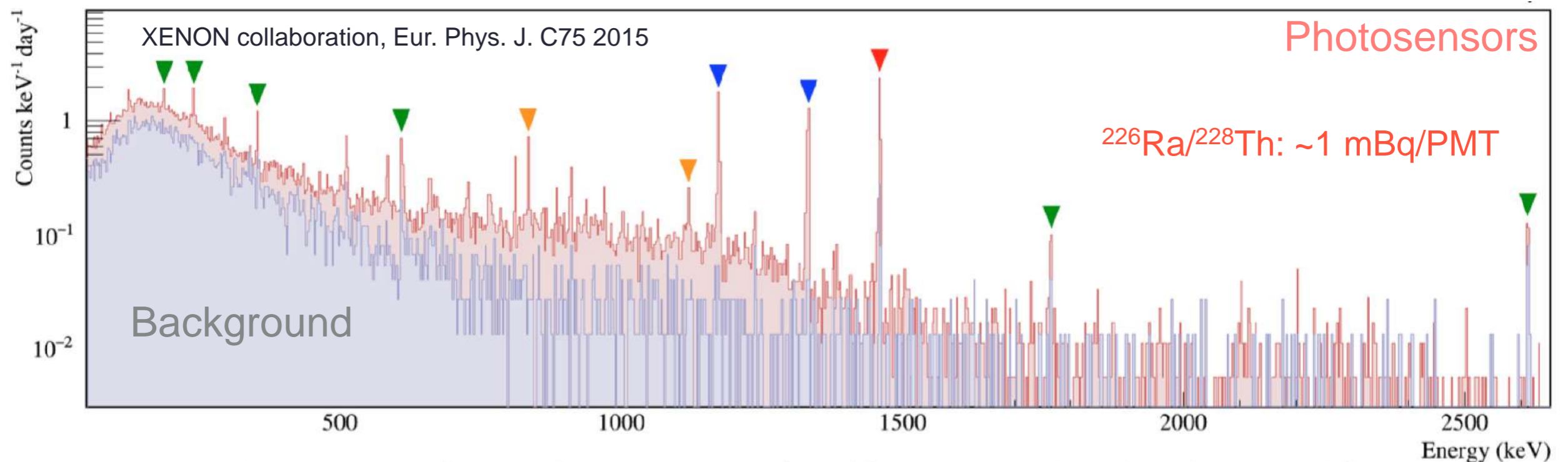
- ▶ Ultra-low background HPGe detectors
- ▶ Purification and distillation of LXe
- ▶ Radon emanation facilities
- ▶ Surface contamination



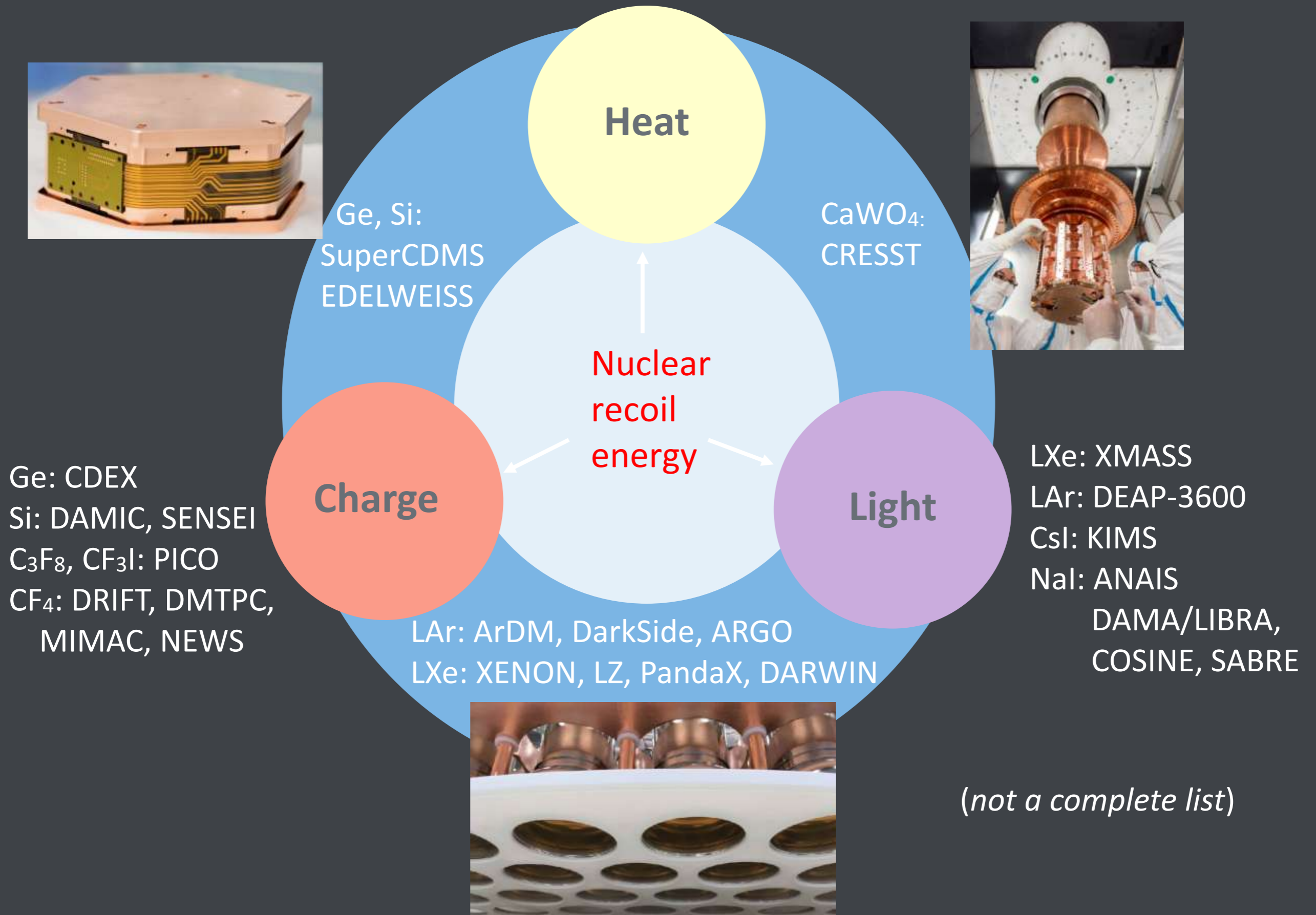
Gator HPGe detector at LNGS



L. Baudis et al., JINST 6, 2011

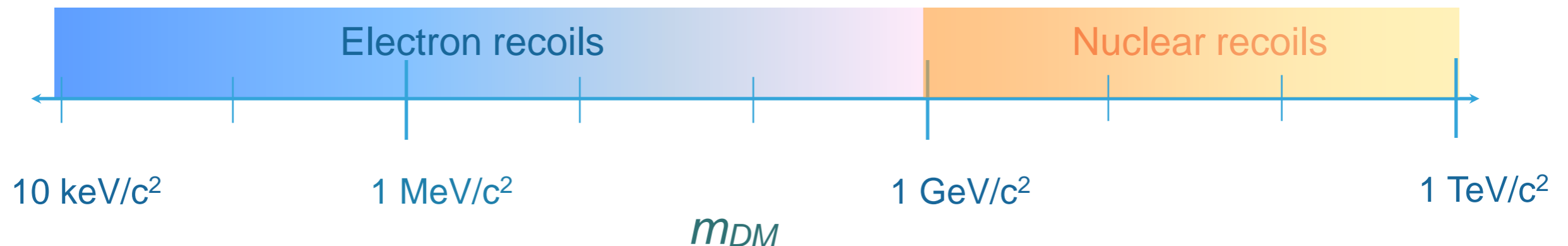


WIMP direct detection experiments



Kinematics and DM mass

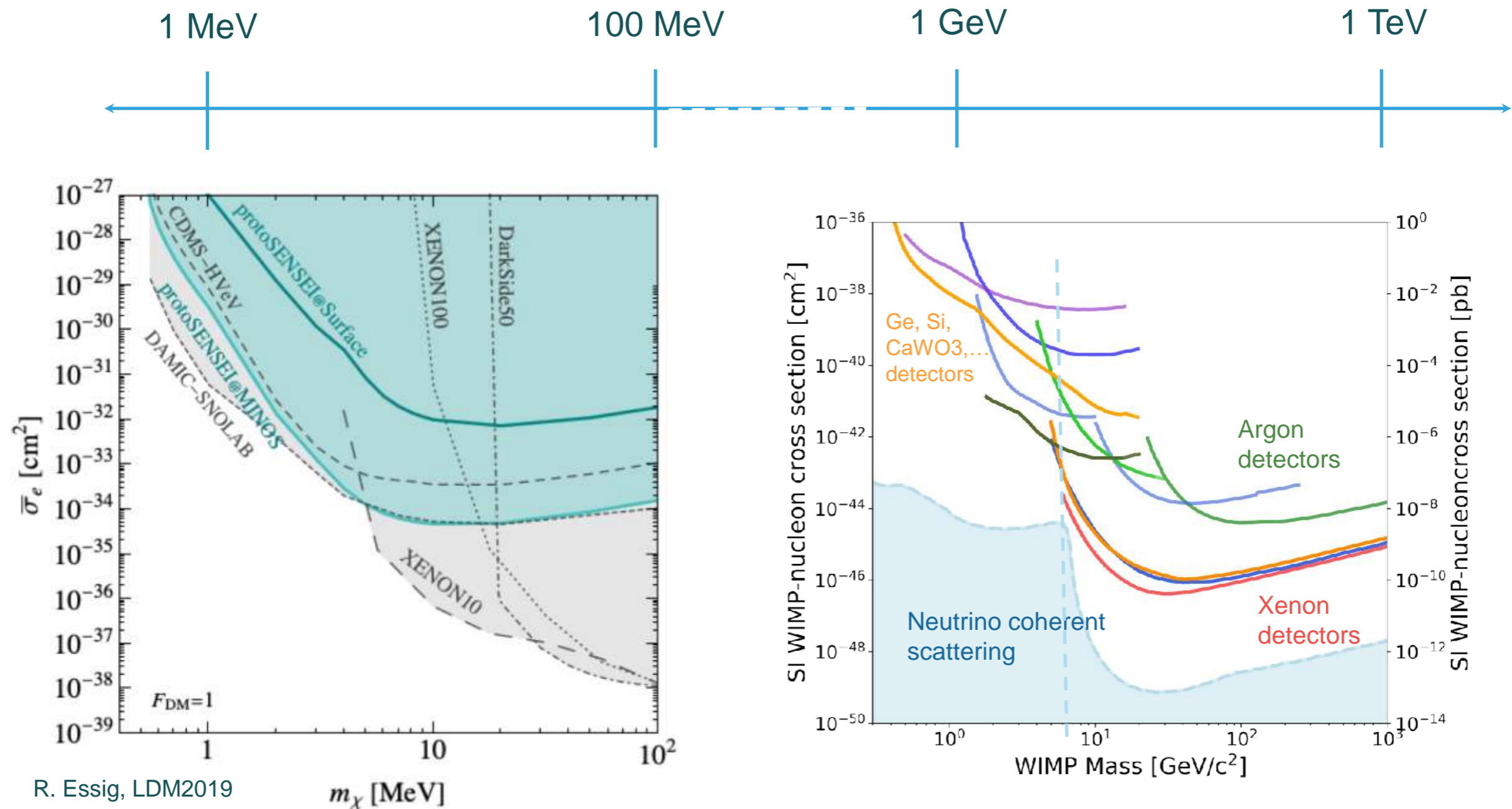
- ▶ Light DM: nuclear recoil energy - well below the threshold of most experiments
- ▶ Total energy in scattering: larger, and can induce inelastic atomic processes -> visible signals



Essig, Mardon, Volanski,
PRD85, 2012

US Cosmic Visions,
arXiv:1707.04591

Present DM direct detection scenario



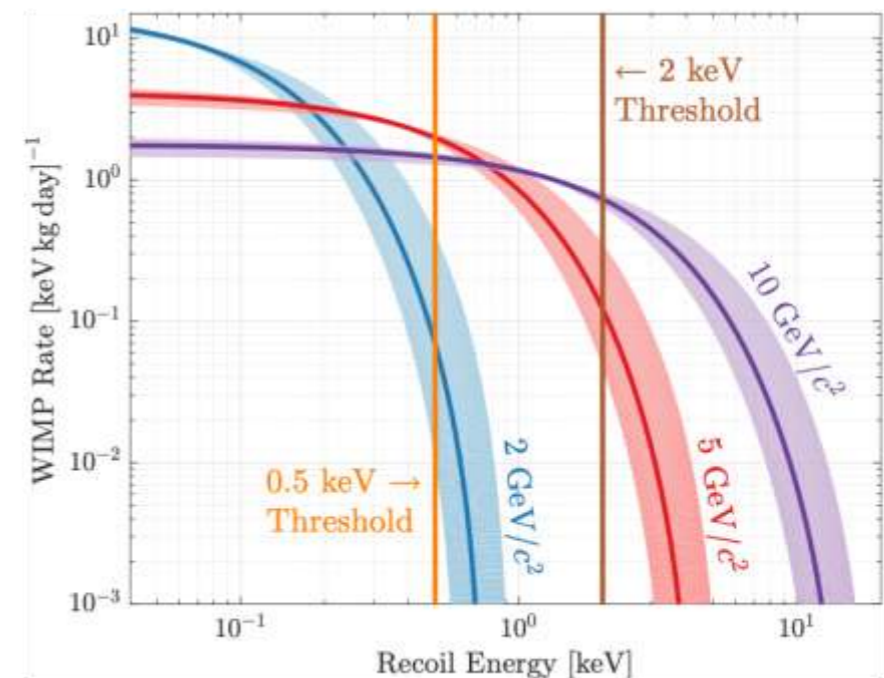
Scattering off electrons

Nuclear recoils

Low mass searches - phonon detection at $T \sim \text{mK}$

- ▶ Sub-keV energy thresholds
- ▶ Probe sub-GeV particle masses
- ▶ Phonons and ionization or light; ionization

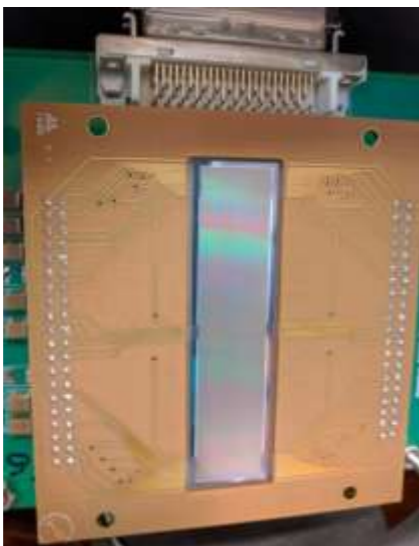
Super-CDMS nuclear recoils



CRESST



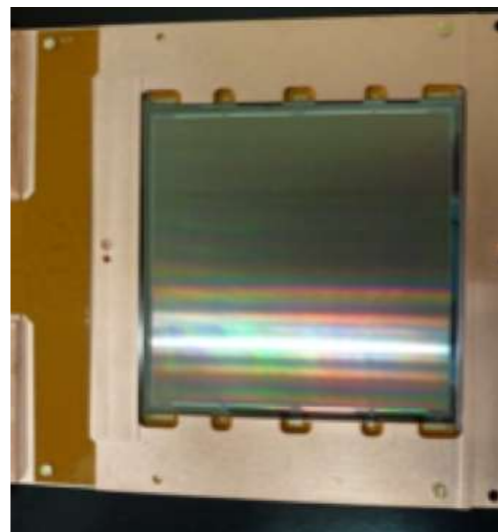
SENSEI



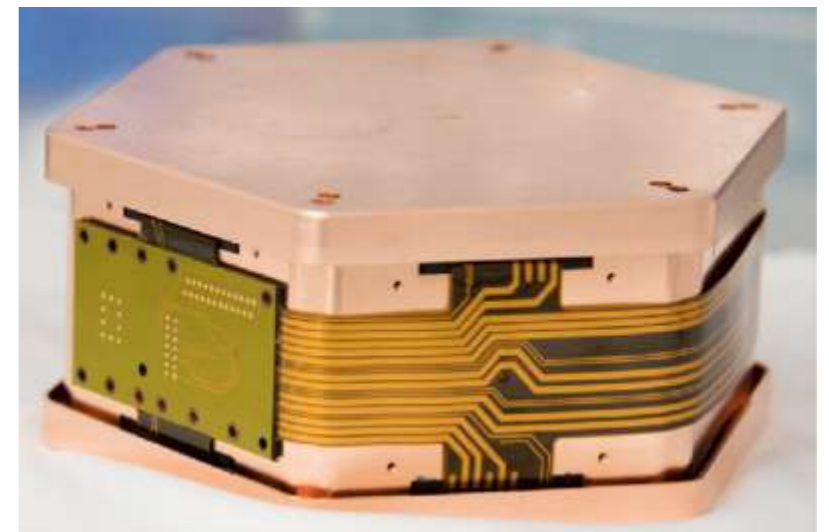
EDELWEISS



DAMIC

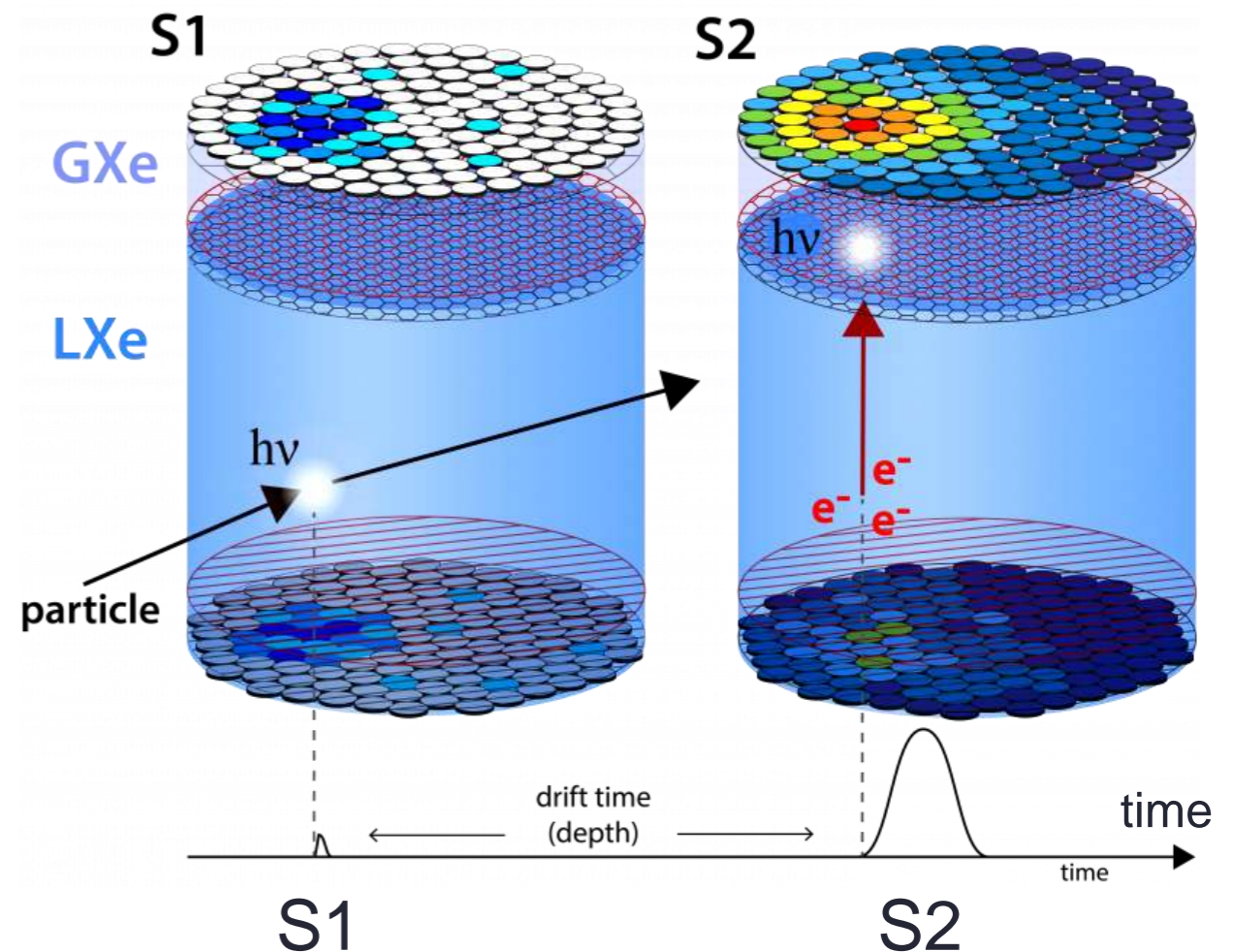


Super-CDMS



High mass searches – liquefied noble gases

- ▶ Single (liquid) and two-phase **Ar & Xe** detectors
- ▶ Two-phase: time projection chambers
 - 3D position resolution via light (S1) & charge (S2): fiducialisation
 - S2/S1 \rightarrow particle ID
 - Single (DM) versus multiple (bkgd) interactions



XMASS



DEAP-3600



XENON1T



LUX



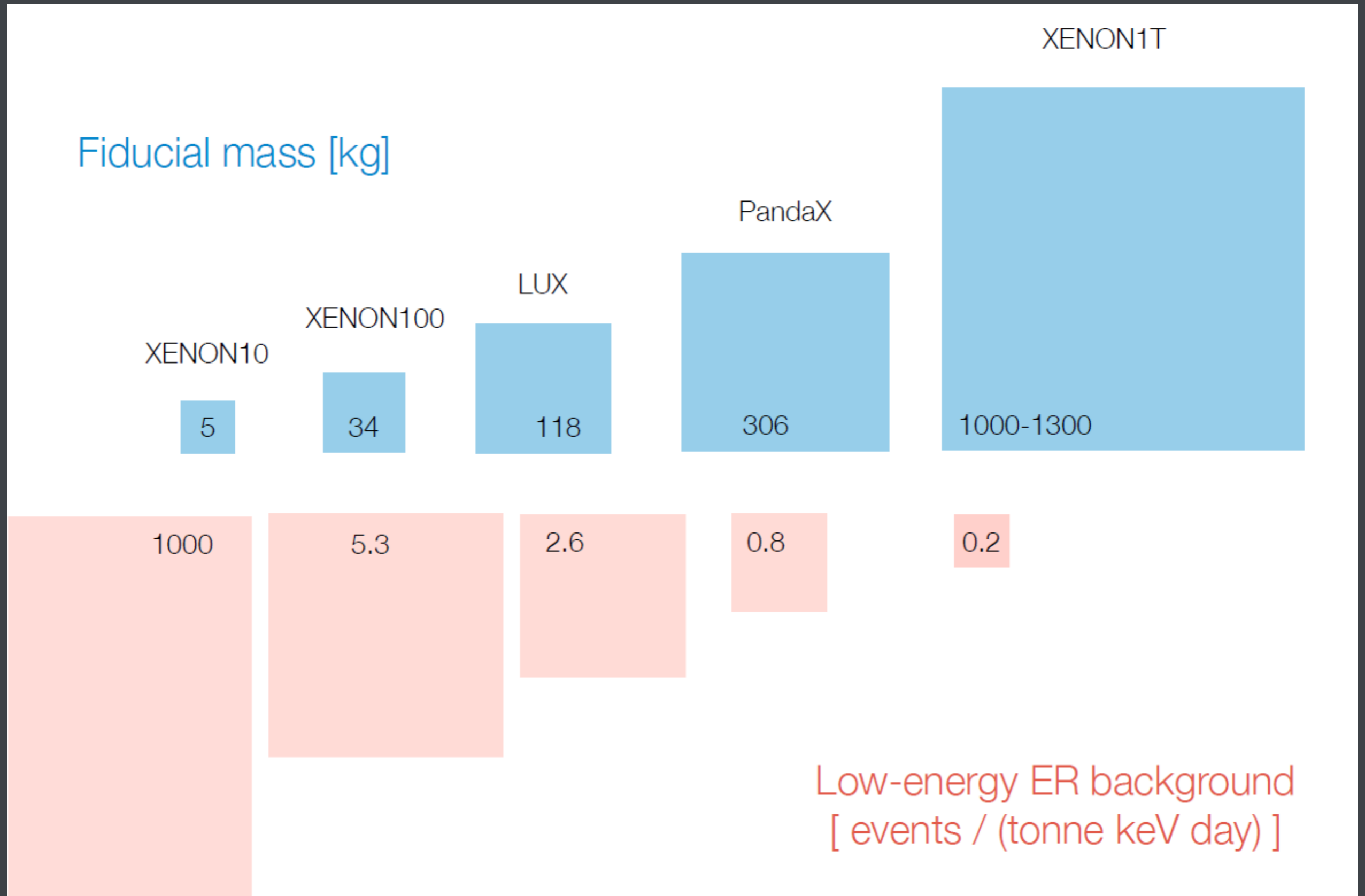
DarkSide-50



PandaX-II



The impressive evolution of LXe WIMP TPCs



The XENON1T Experiment



- 3.2 t LXe
- Largest LXe TPC ever operated: $\sim 1\text{m}$ drift \times $\sim 1\text{m}$ diameter
- Most stringent exclusion limits for WIMP masses $> 6\text{ GeV}/c^2$

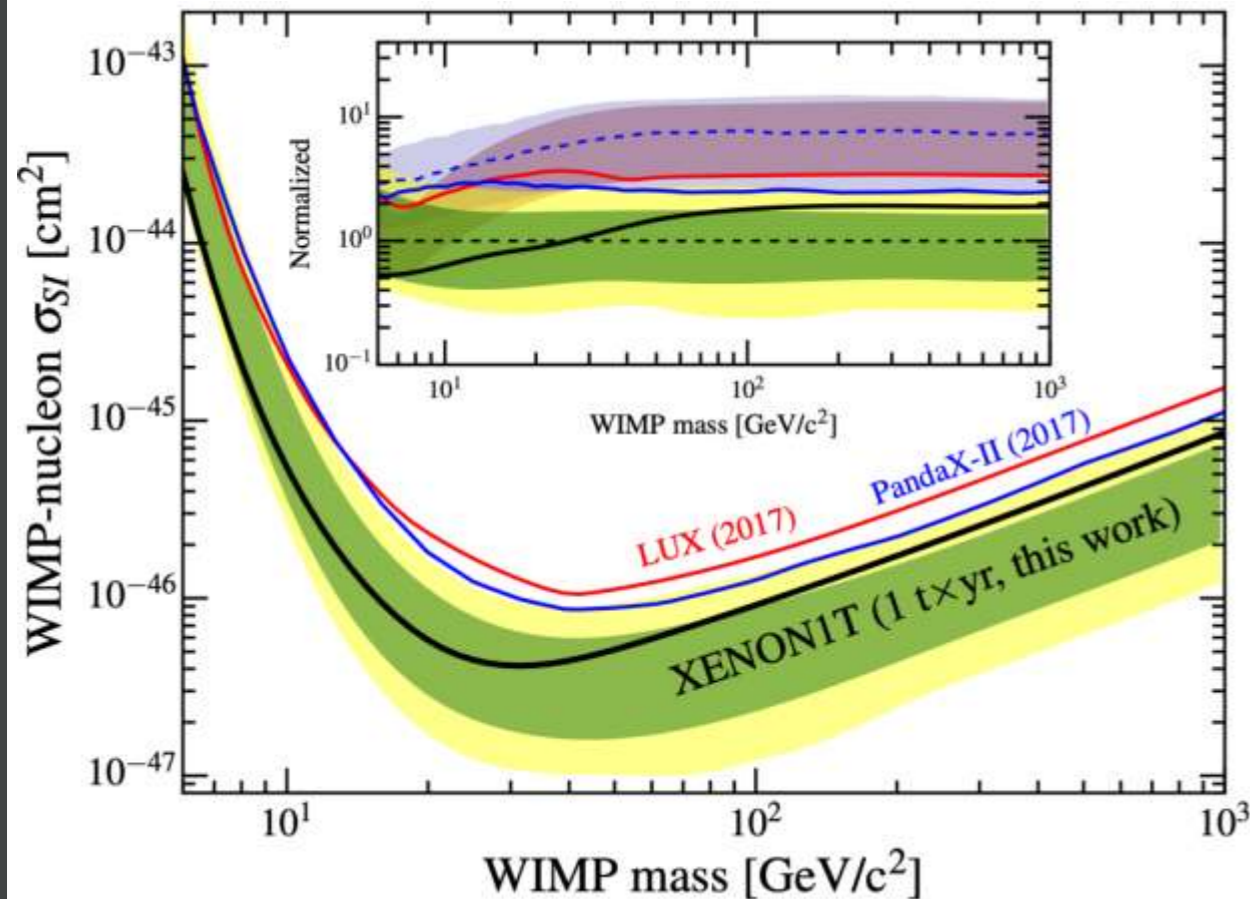


XENON1T results:

nuclear recoils and electronic recoils WIMP Searches

- Strongest limit on SI WIMP-nucleon cross sections $> 6 \text{ GeV}/c^2$

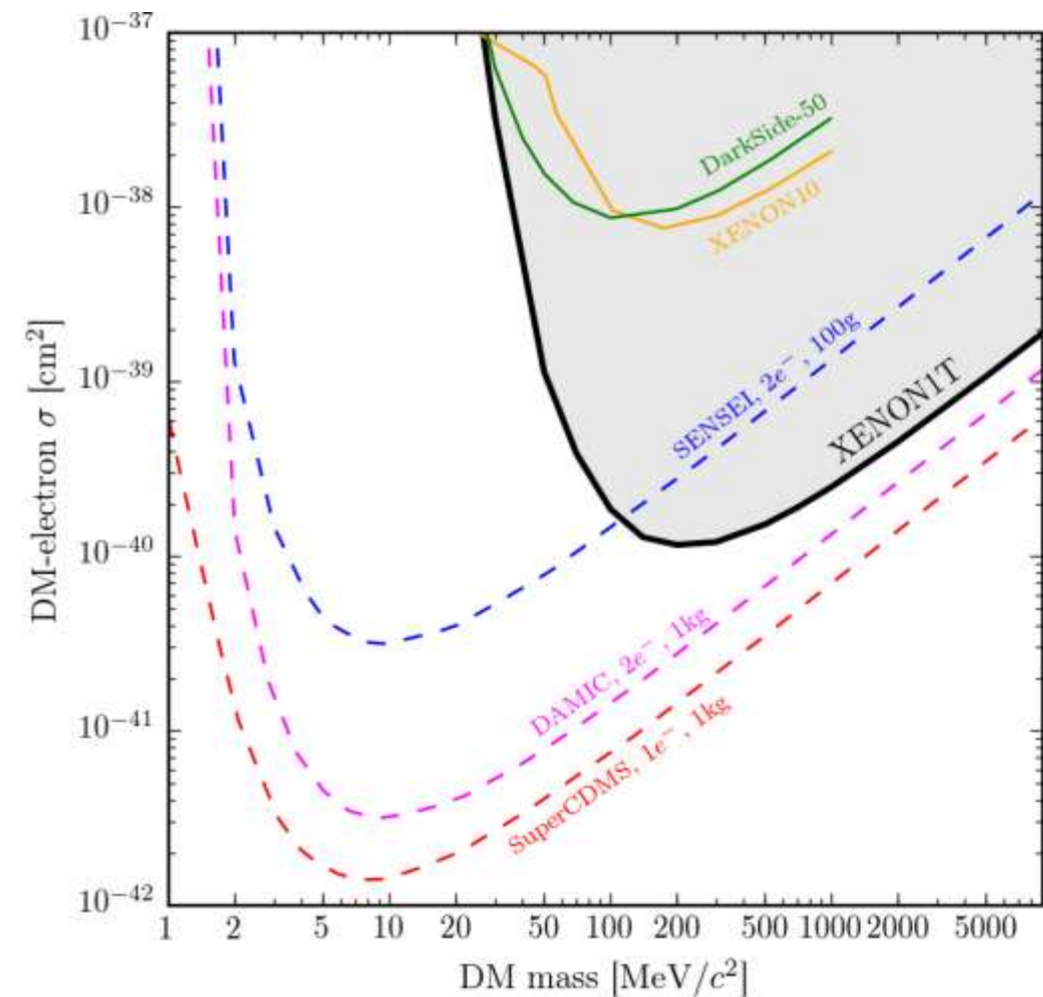
$$\sigma_{\text{SI}} < 4.1 \times 10^{-47} \text{ cm}^2 \text{ at } 30 \text{ GeV}/c^2$$



XENON collaboration, PRL121 (2018) 111302

Light DM

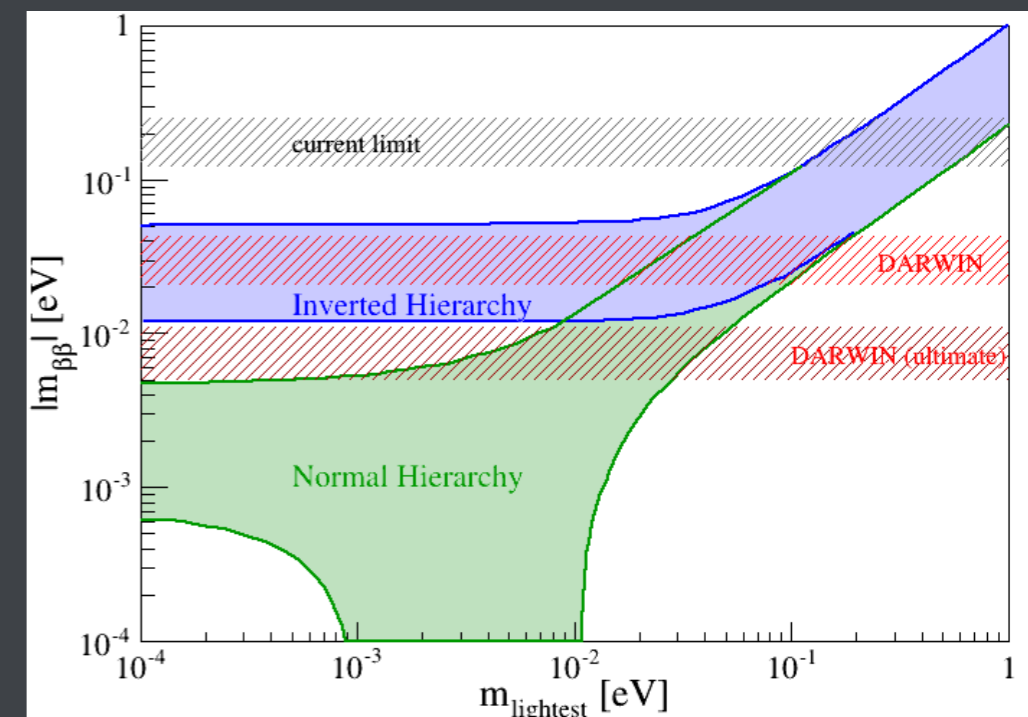
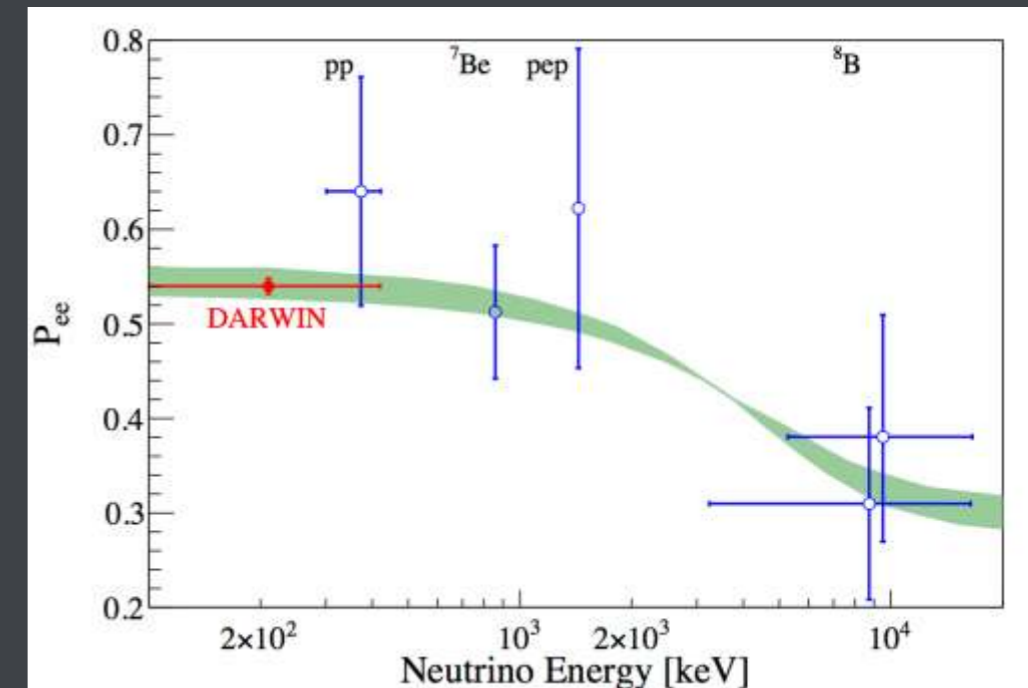
- Use charge signal (S2) only
- Achieve lower energy threshold (at the expense of higher backgrounds)



XENON collaboration, PRL 123 (2019) 251801

XENON1T: an extremely sensitive system that allows for non-WIMP Physics

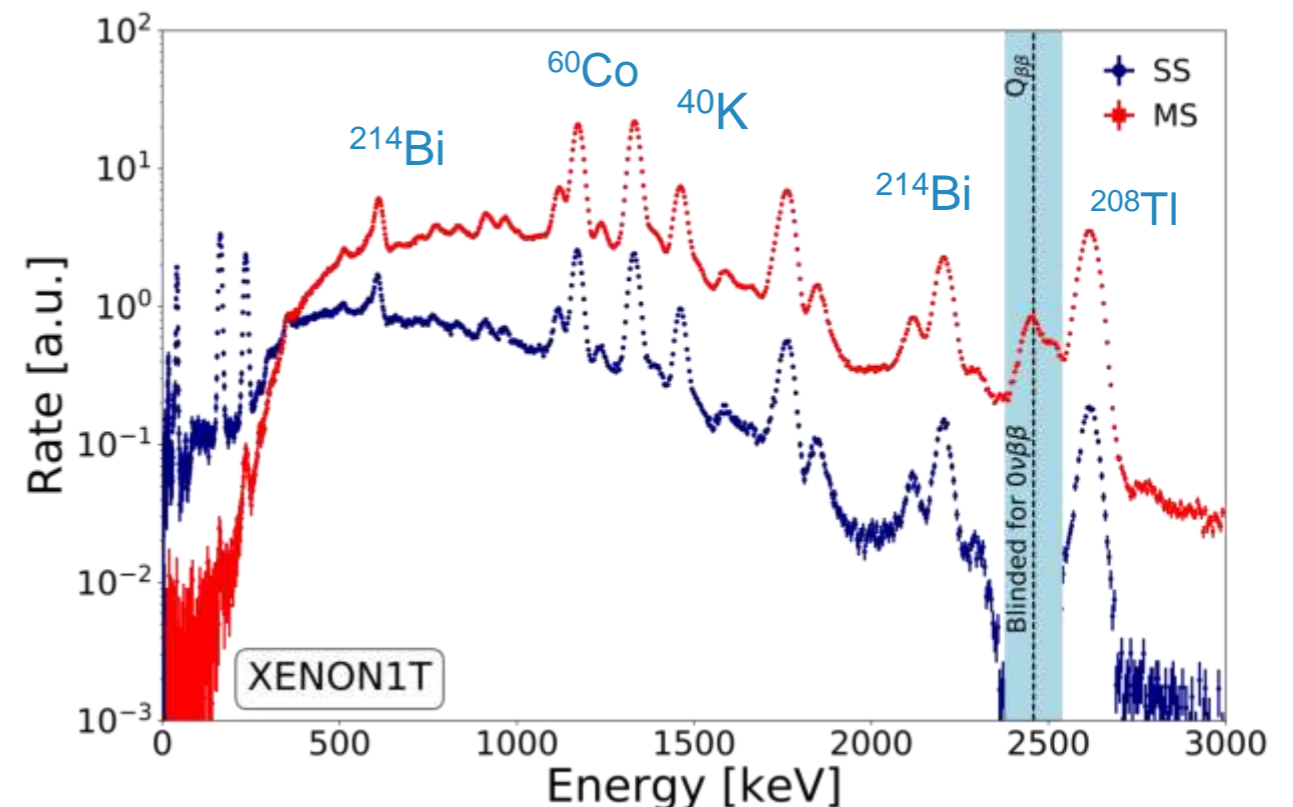
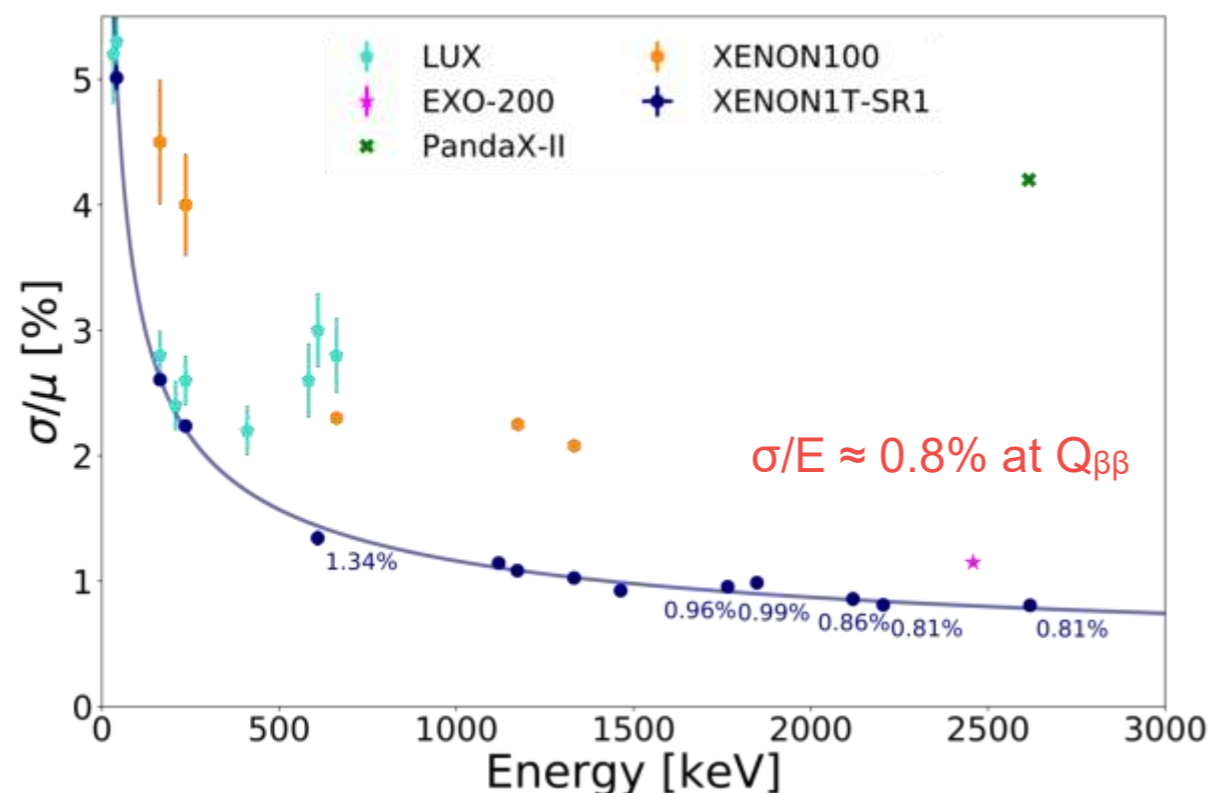
- pp solar neutrinos (ν - e^- scattering)
- ^8B neutrinos (coherent ν - nucleus scattering)
- Supernova neutrinos
- Neutrinoless double beta decay in ^{136}Xe
- Double electron capture in ^{124}Xe
- Solar axions and axion-like particles (via axio-electric effect)
- Heavy sterile neutrinos (masses in the > 10 keV range)
- Bosonic SuperWIMPs (via absorption by Xe atoms)
- ...



XENON1T results:

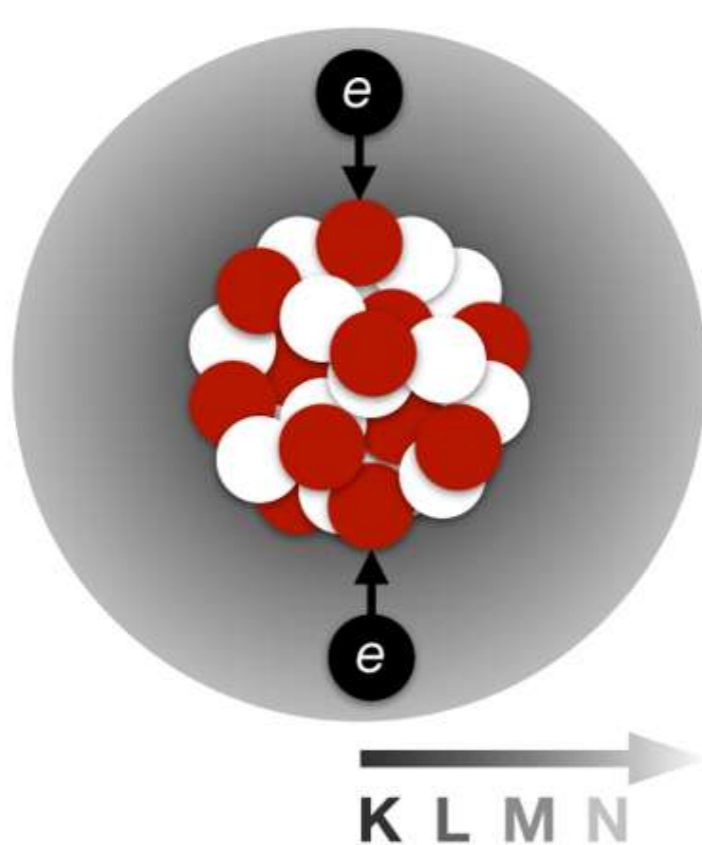
Neutrino less double beta decay

- ▶ Search for $0\nu\beta\beta$ -decay of ^{136}Xe , at $Q_{\beta\beta} = 2.458 \text{ MeV}$
- ▶ Correct for signal saturation, determine event multiplicity, energy scale, resolution
- ▶ Achieved $\sigma/E \sim 0.8\%$; $0\nu\beta\beta$ -decay data analysis and data/MC matching in progress

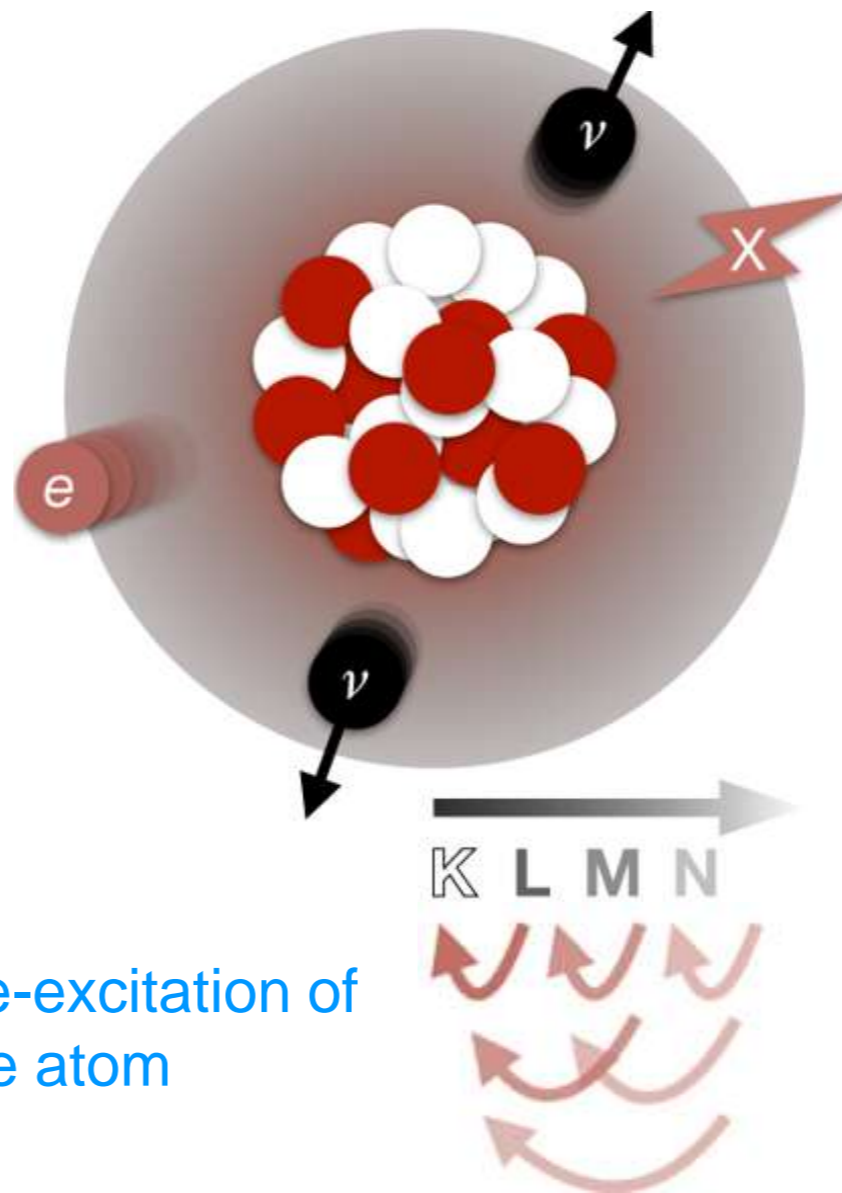


XENON1T results:

Double electron capture



2 electrons are captured from the atomic shell



De-excitation of the atom

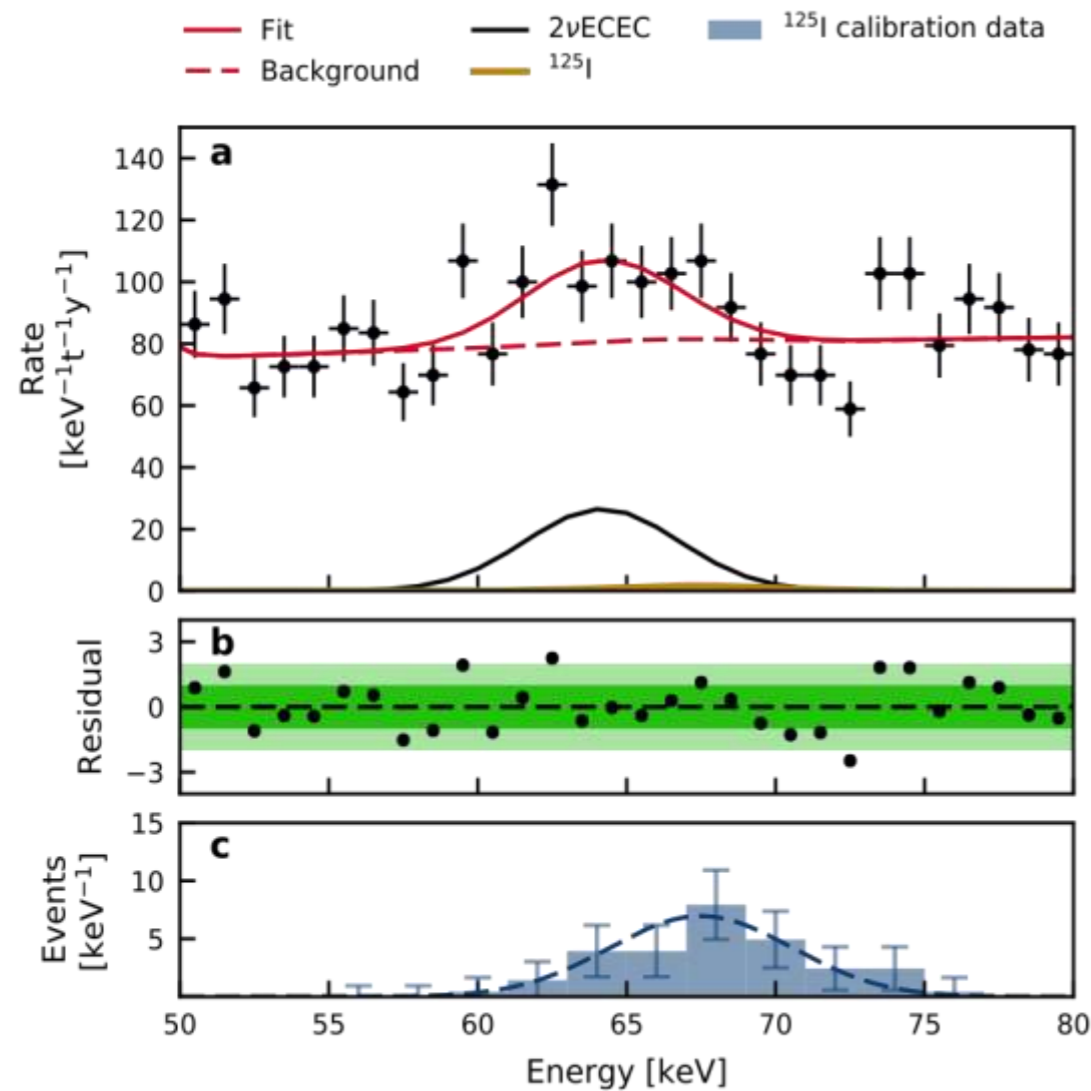
The 2 neutrinos leave the detectors unnoticed

X-rays with at ~ 64 keV are observed (Q-value: 2.96 MeV)

$$\sigma/E = (4.1 \pm 0.4)\% \text{ at } 64 \text{ keV}$$

XENON1T results:

Double electron capture



$$T_{1/2} = (1.8 \pm 0.5_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22} \text{ y}$$

**longest half life ever
measured directly**

nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE



SEX AND GENDER
TRANSITIONAL INSIGHTS
The world's largest study of transgender people
PAGE 446

ENVIRONMENT
IN THE DARK
How high-rise living deprives urban centres of natural light
PAGE 451

NEUROSCIENCE
SPEECH SYNTHESIZER
Implant gives voice to brain signals that control movement
PAGES 466 & 493

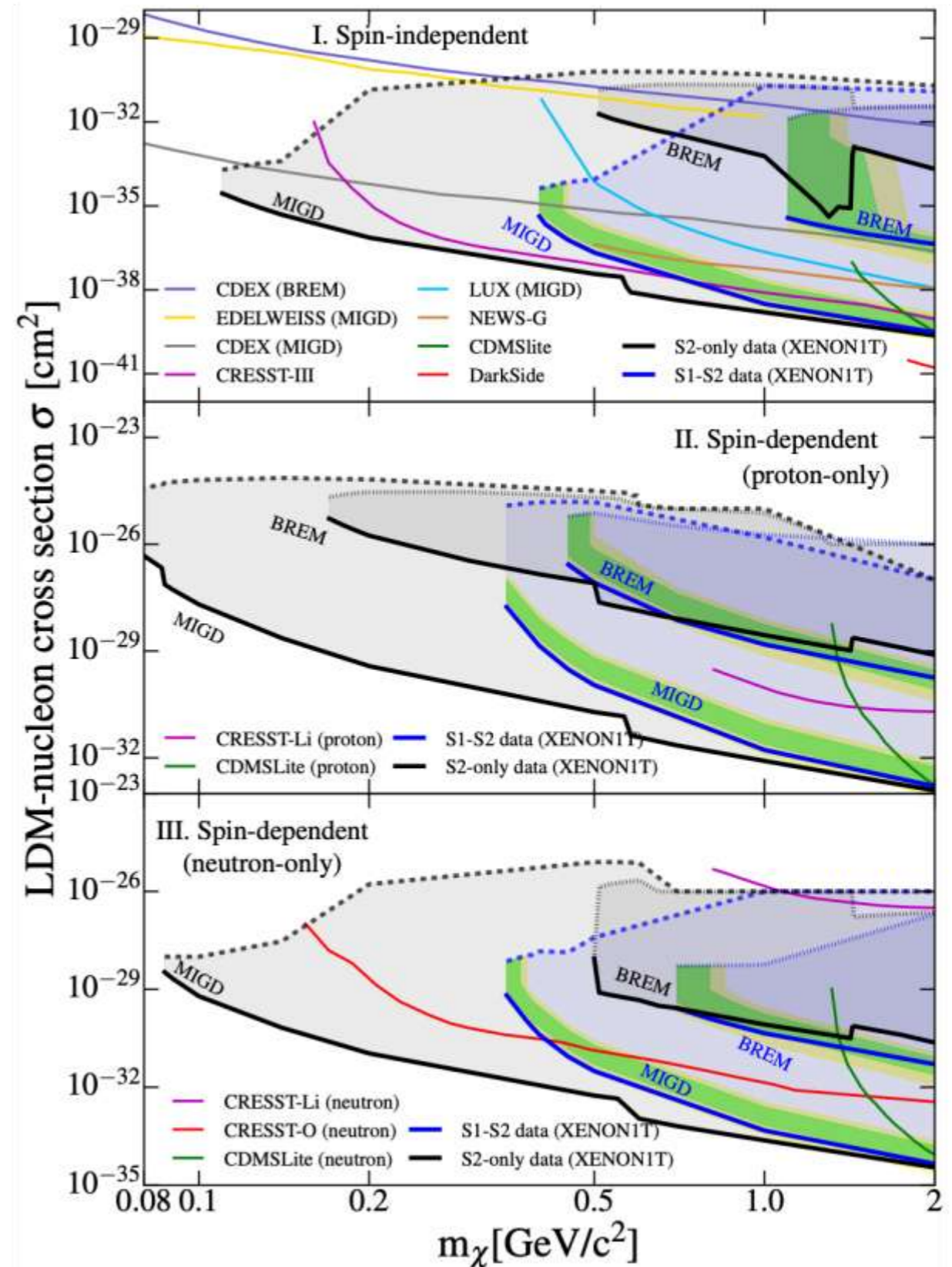
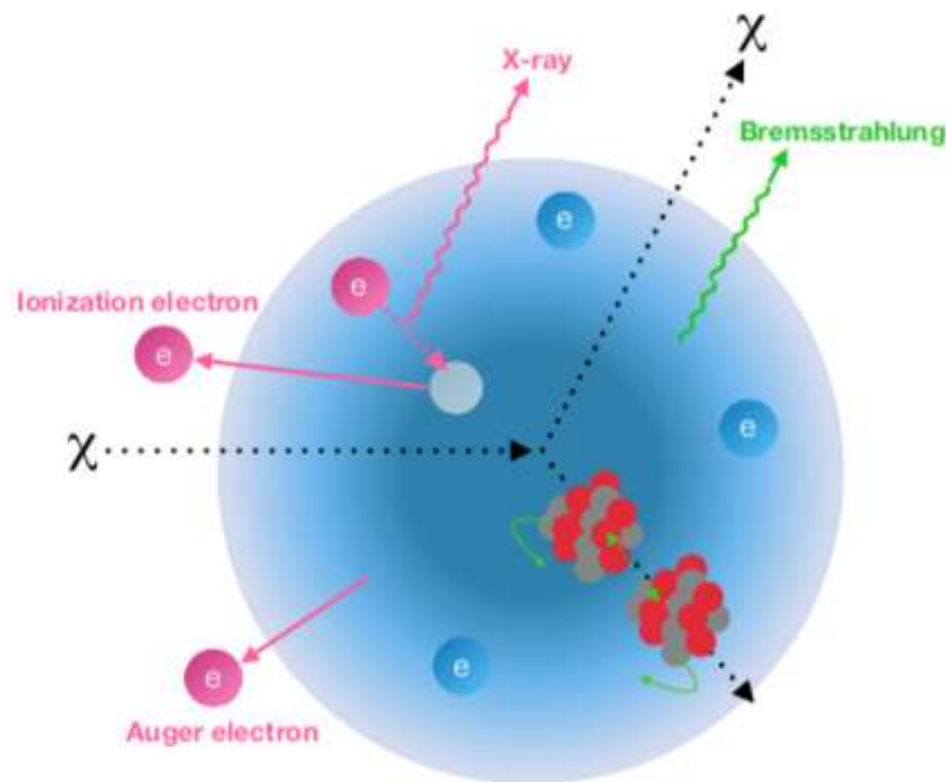
NATURE.COM
25 April 2019
Vol. 568, No. 7751

XENON collab., Nature 568, 2019

XENON1T results: Light DM through Migdal effect

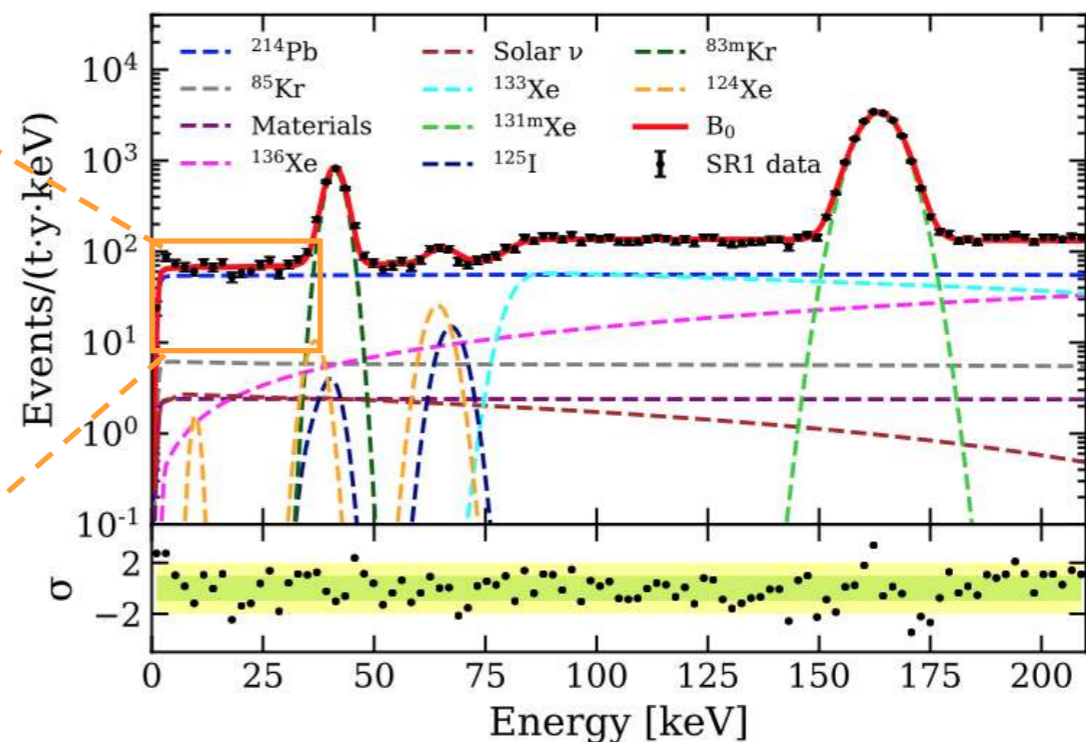
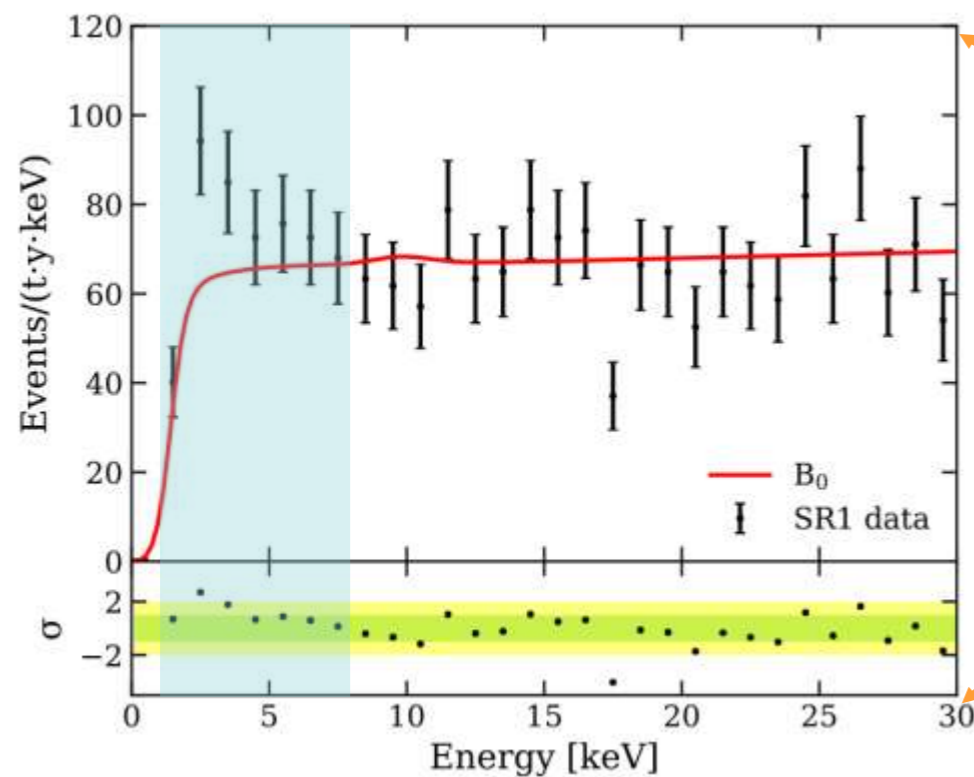
XENON collaboration, PRL 123 (2019) 241803

- ▶ Exploit the Migdal effect
- ▶ Sudden nuclear momentum change (with respect to e^-) after NR
- ▶ Kinematic boost of e^-

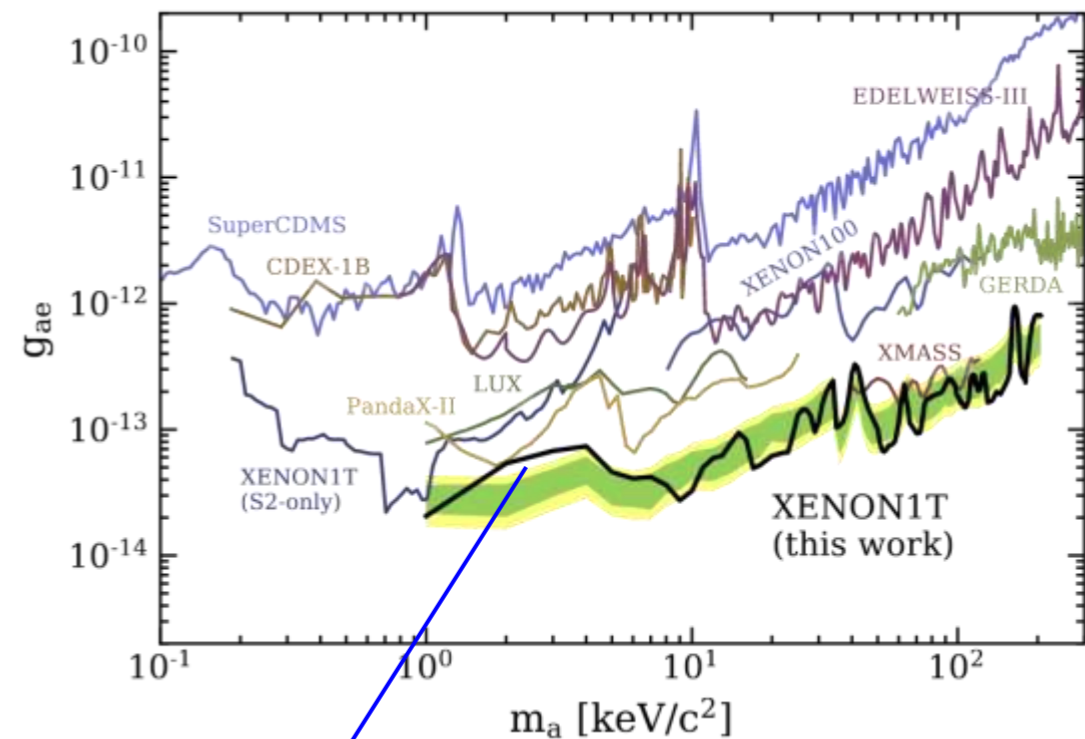
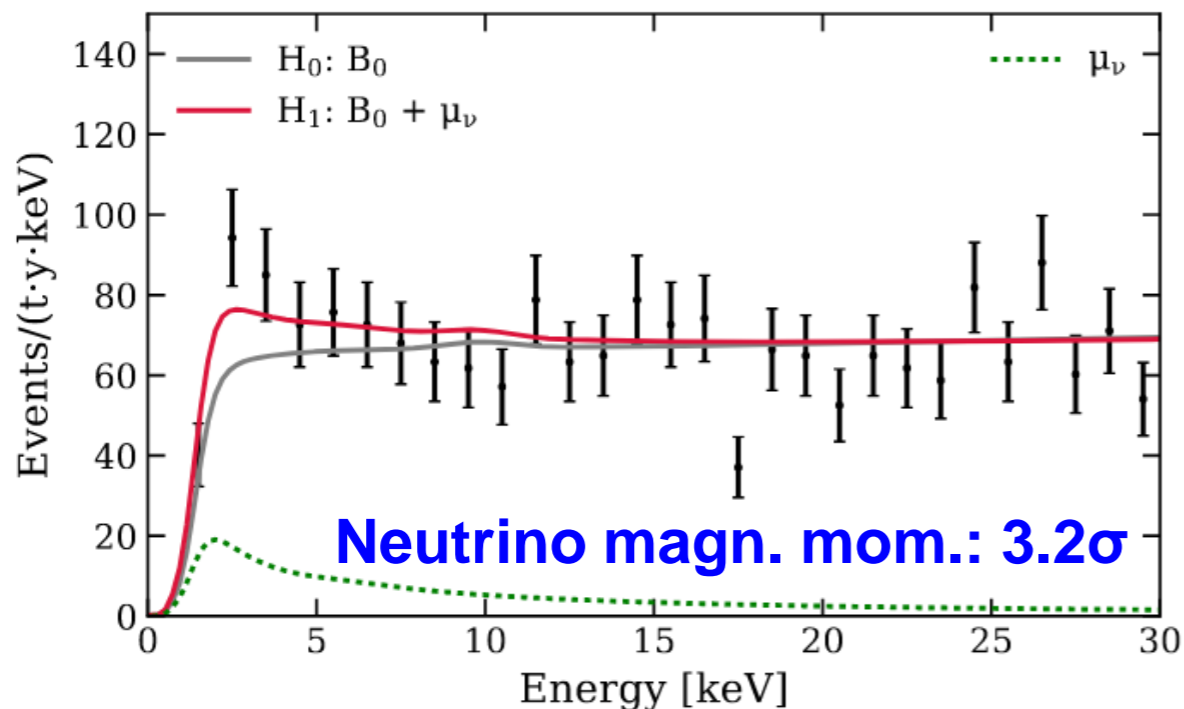
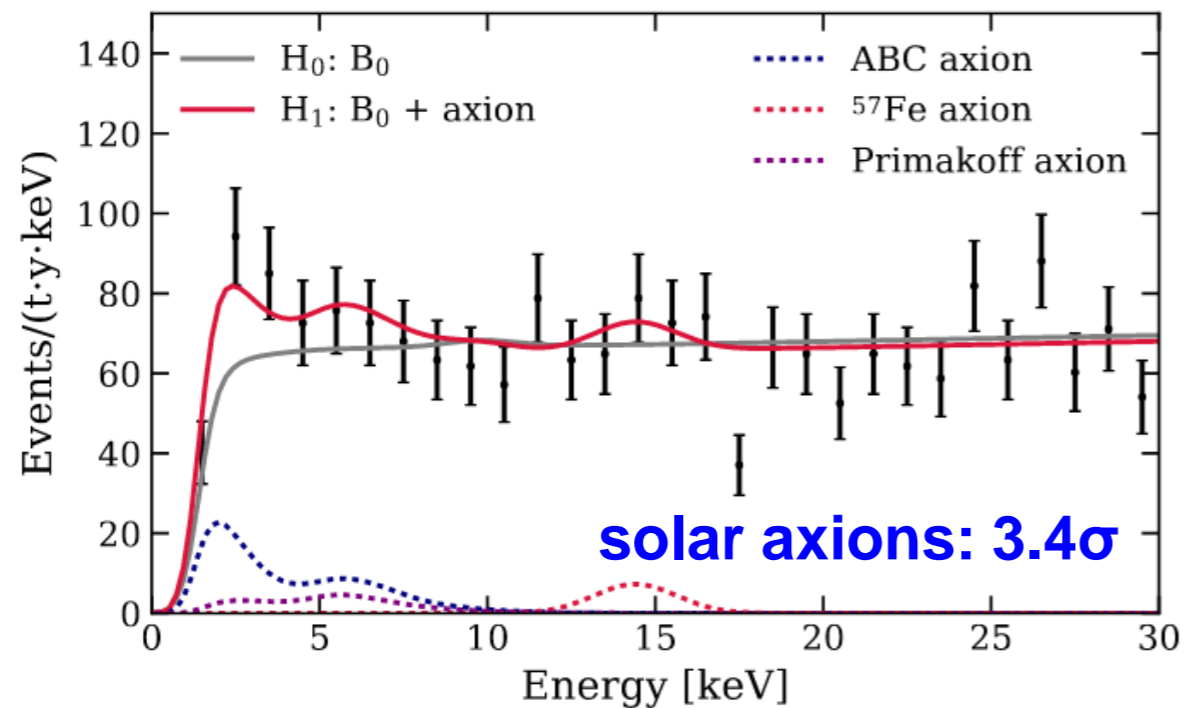


XENON1T results: Low energy excess

- ▶ Energy region: (1, 210) keV; background model good fit over most of the energy region; excess between (1,7) keV: number of observed events: 285, expected from background: (232 ± 15) events
- ▶ **Lowest background in history - (1,30) keV: 76 ± 2 events/(t y keV)**



XENON1T results: Low energy excess



Bosonic ALPs

3.0σ global (4.0σ local)

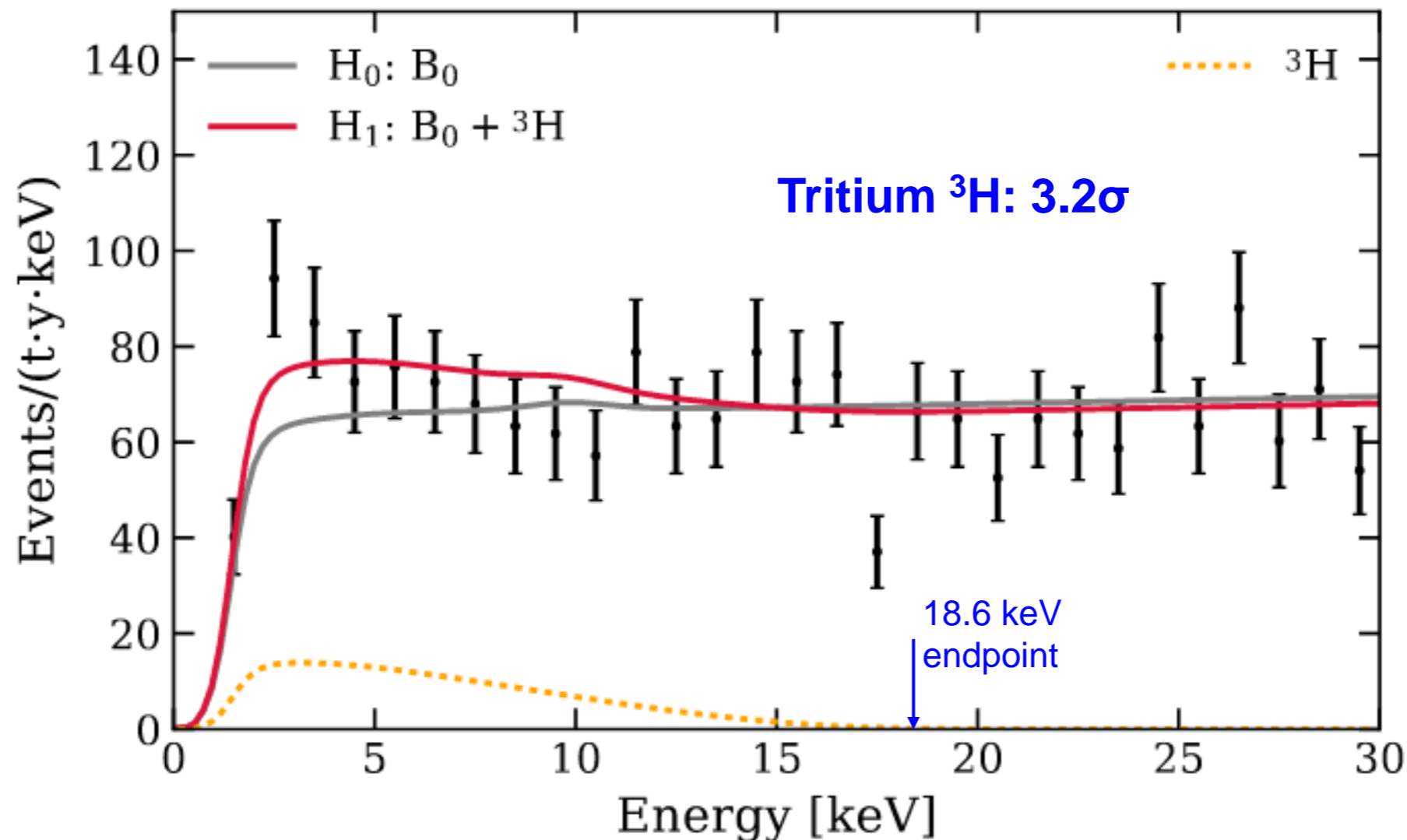
@ $m_a = 2.3 \pm 0.2 \text{ keV}$

... and many others since we made our result public.

(however in strong tension with stellar cooling constraints, see e.g. 2006.12487)

XENON1T results: Low energy excess

Considering a new type of background

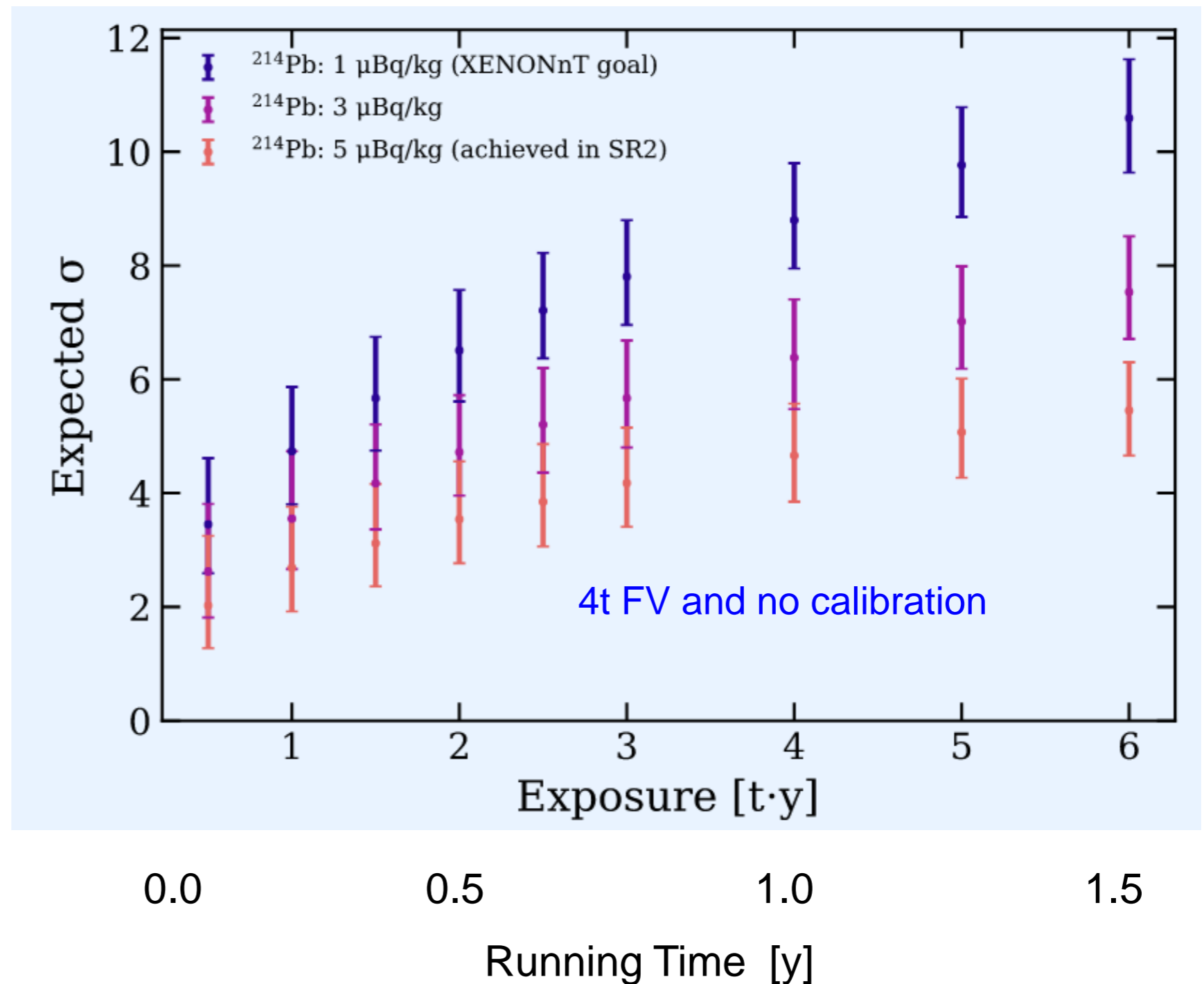


- less than 3 ³H atoms per kg of Xe
- cosmogenic production by Xe-spallation or H₂O adsorption in walls
- **we can neither confirm nor exclude the Tritium hypothesis at this point**

Axions vs. Tritium in XENONnT

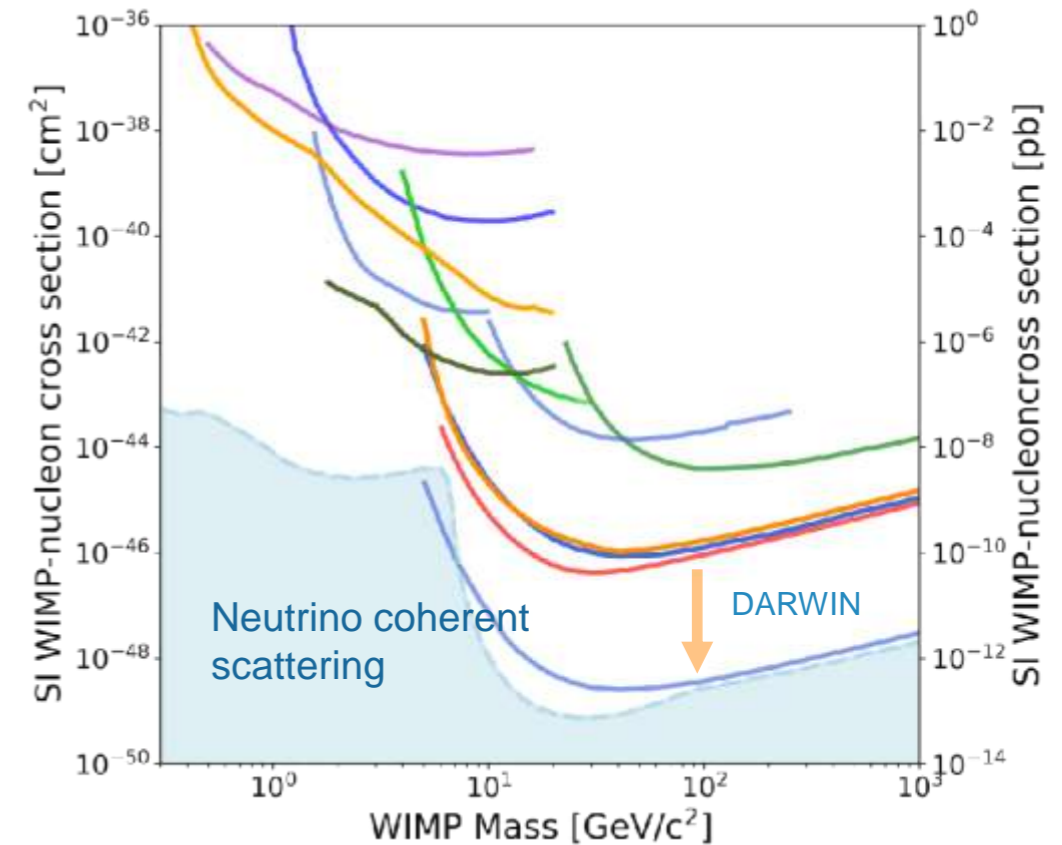
Assuming that the excess persists and is from solar axions

How much data is needed to distinguish it from ^3H ?

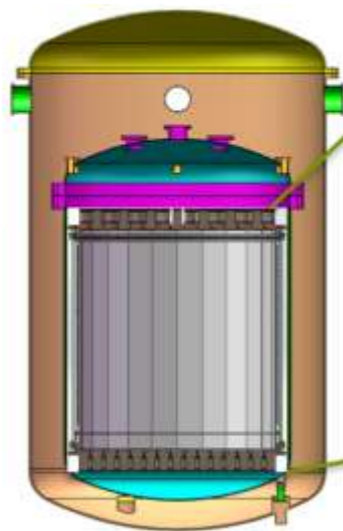


Future liquefied noble gases detectors

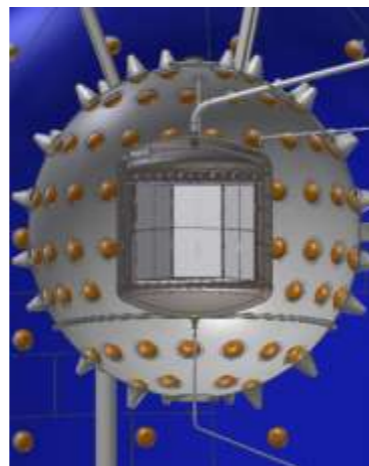
- ▶ About to start data taking
 - ▶ XENONnT
- ▶ In construction
 - ▶ LUX-ZEPLIN, DarkSide-20k, PandaX-4t
- ▶ Planned (design and R&D stage)
 - ▶ DARWIN (50 t LXe), ARGO (300 t LAr)



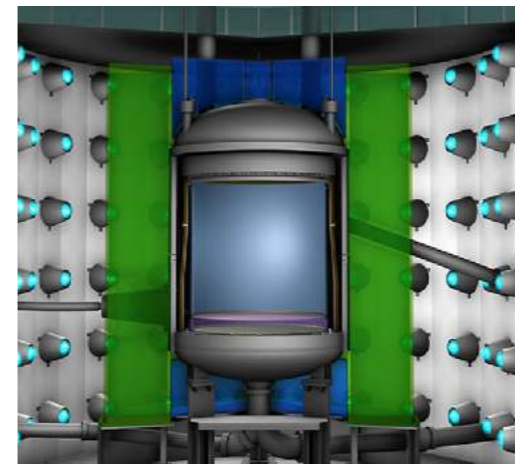
XENONnT: 8t LXe
Data taking 2020



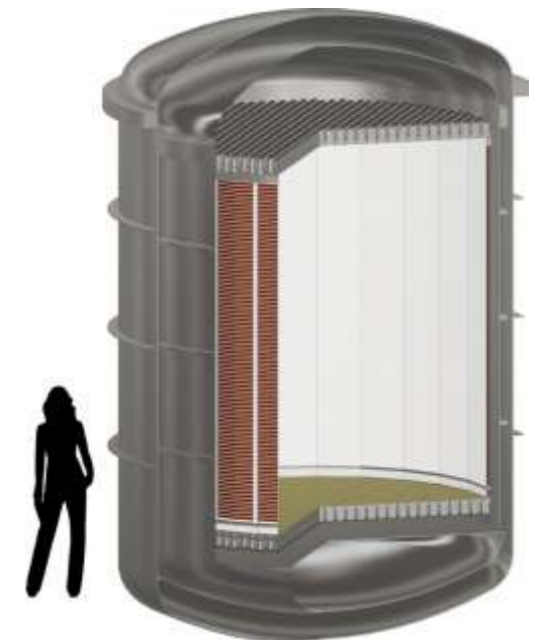
PandaX-4t LXe
Data taking 2021



DarkSide: 20 t LAr
Data taking 2021



LUX-ZEPLIN: 8 t LXe
Data taking 2021

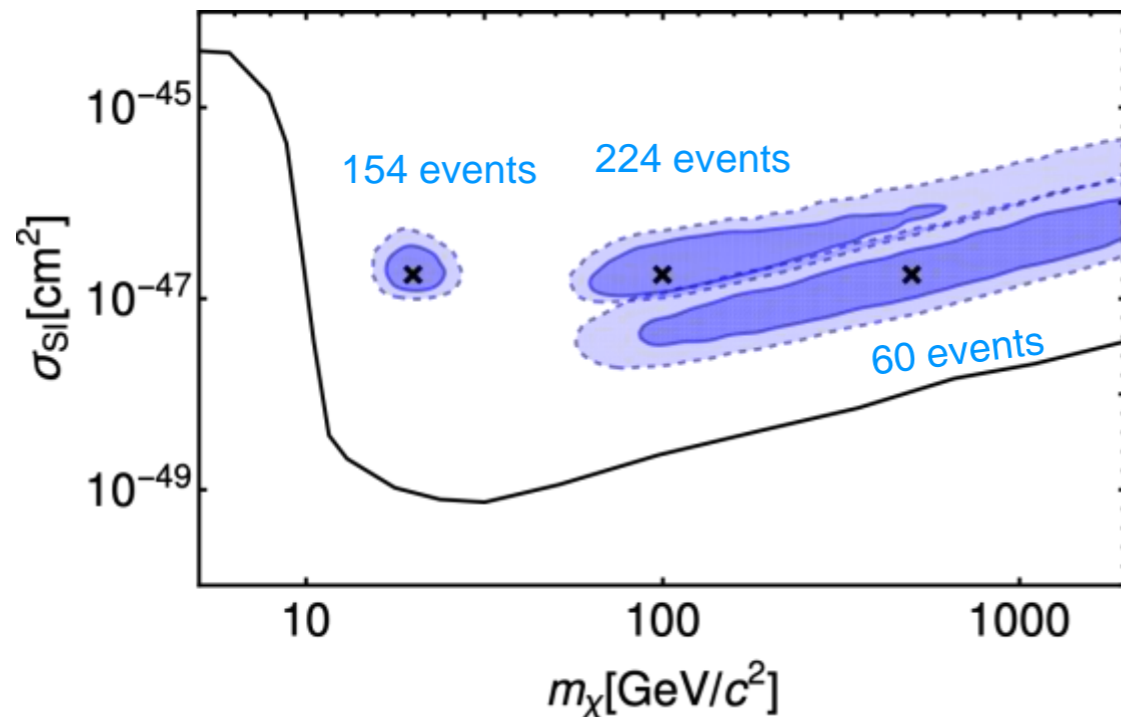


DARWIN: 50 t LXe
Data taking ~2027

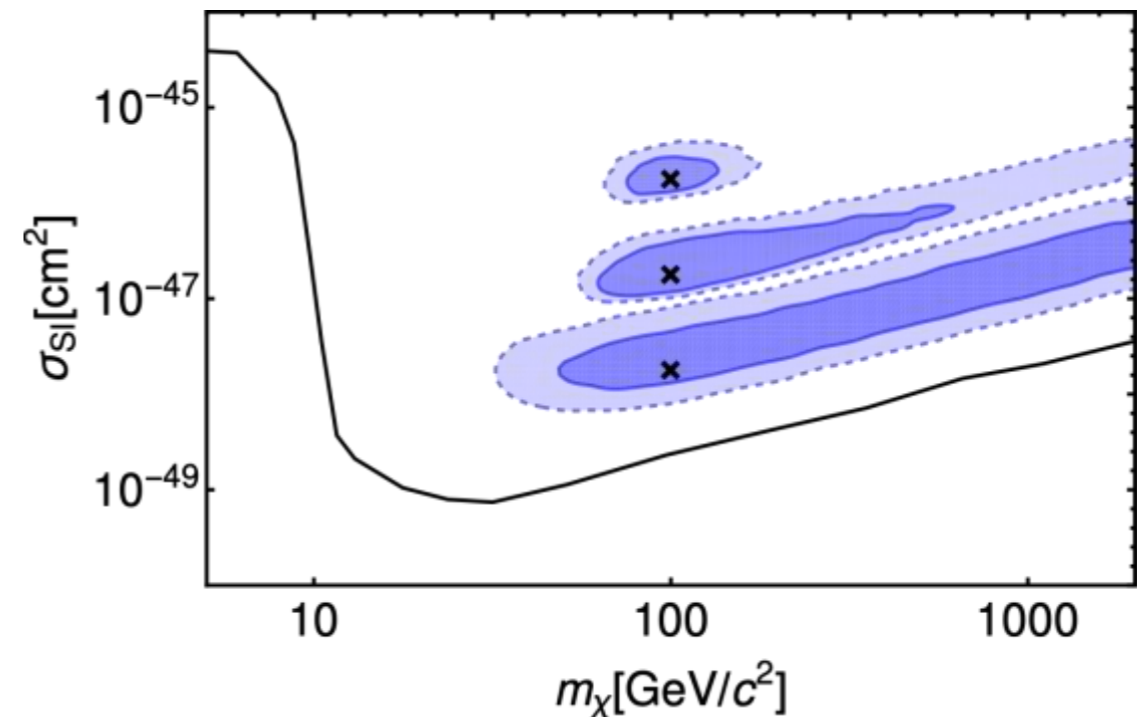
How well do we expect to measure DM?

- DM mass and cross section reconstruction for various masses (20, 100, 500 GeV/c²) and cross sections

Exposure: 200 t y



Exposure: 200 t y



1 σ and 2 σ confidence level regions, marginalized over astrophysical parameters

$$v_{esc} = 544 \pm 40 \text{ km/s}$$

$$v_0 = 220 \pm 20 \text{ km/s}$$

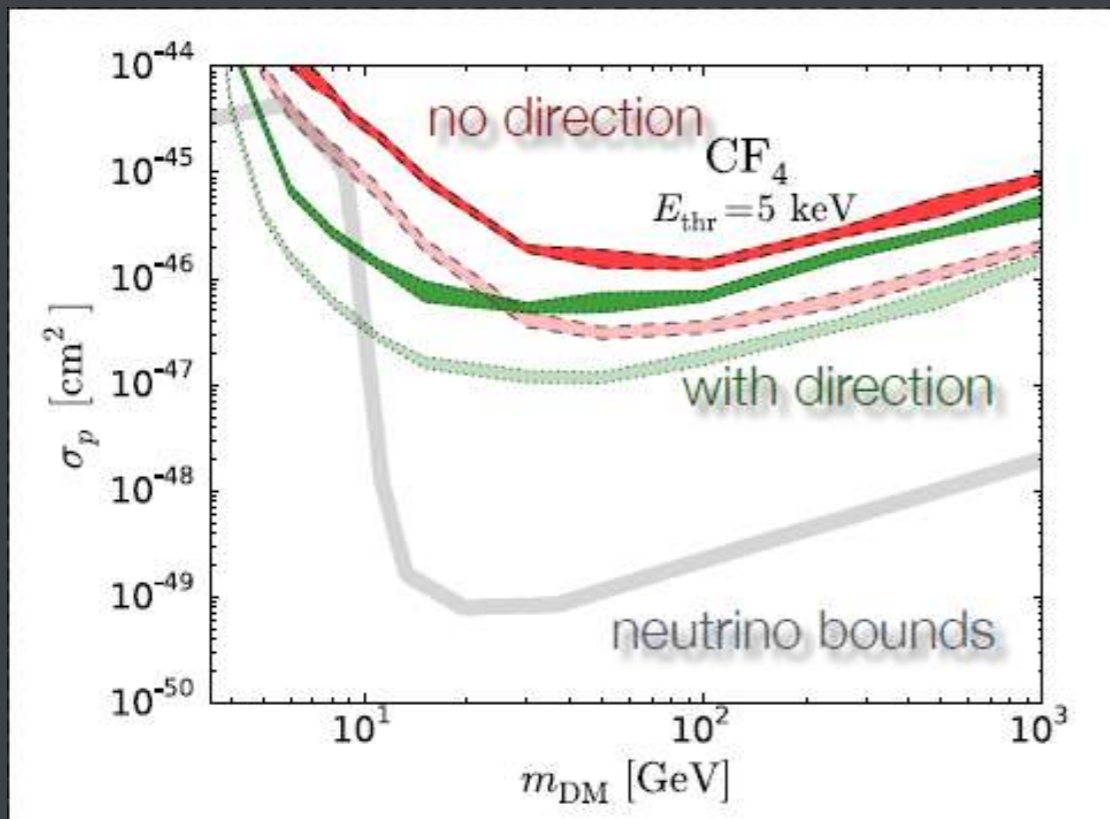
$$\rho_\chi = 0.3 \pm 0.1 \text{ GeV/cm}^3$$

DARWIN collaboration, JCAP 1611 (2016) 017

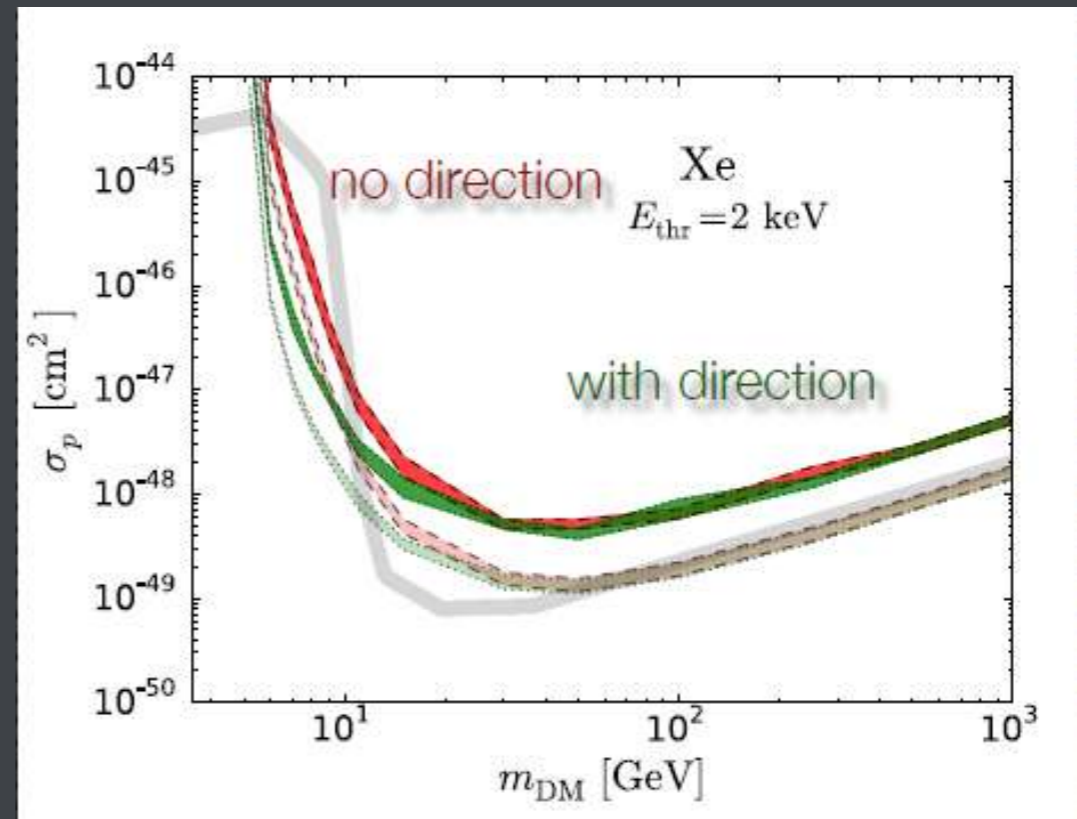
Will directional information help?

- Yes, but mostly for low WIMP masses
- Several directional techniques currently in R&D phase
- Might be difficult to reach the 10^{-48} - 10^{-49} cm^2 cross sections

36.6 t yr exposure, 500 events

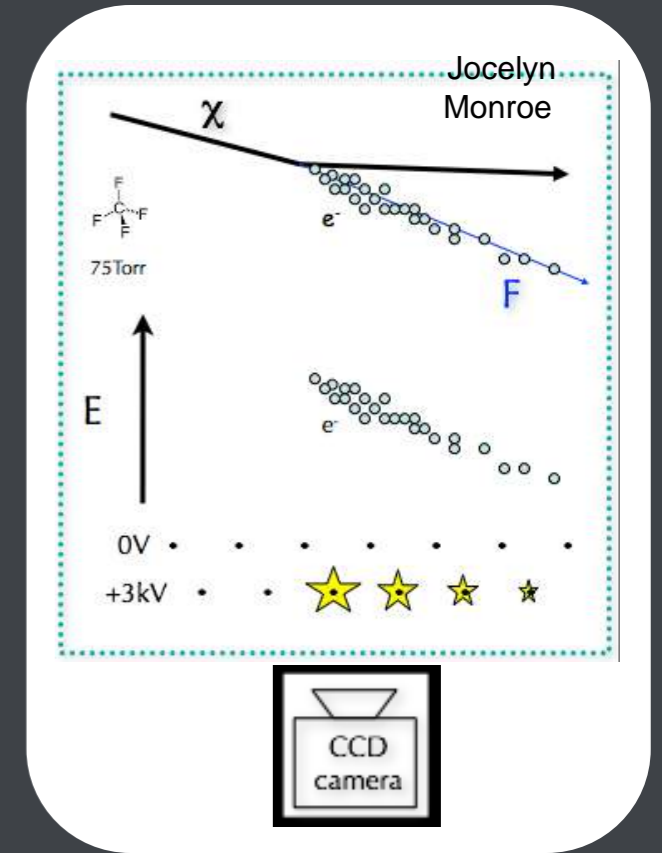


367 t yr exposure, 500 events



Directional detectors

- Low-pressure (~ 0.1 atm) gas and **nuclear emulsion** detectors to measure the recoil direction (30° and **13°** resolution), correlated to the galactic motion towards Cygnus
- Challenge: good angular resolution plus head/tails at 30-50 keV nuclear recoil
- CYGNUS aiming at converging the gas detectors efforts to a single consortium ($\text{He} + \text{SF}_6$, 1000 m^3)



DRIFT, Boulby
Mine
1 m³ prototype
CS₂ + CF₄ gas



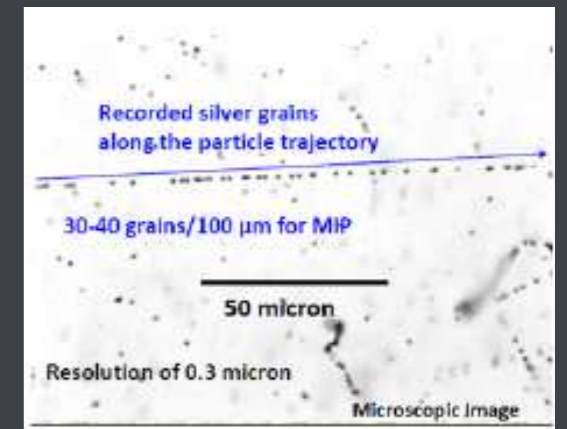
DMTPC, WIPP
1 m³ prototype
CF₄ gas



MIMAC, Modane
5l chamber
CF₄ gas



NEWAGE, Kamioka
50 keV threshold
CF₄ gas



NEWSdm, LNGS
nuclear emulsion
a few kg detector in
preparation

Summary

- ▶ A variety of technologies employed for DM detection
- ▶ *We have mostly learned what dark matter is not...* we have been narrowing down the options; tremendous progress over the past decades, and expected for next
- ▶ Rich non-WIMP physics programme (neutrinos, axions/ALPs, dark photons, etc)
- ▶ Keep in mind that today's background might be tomorrow's signal!

Thank you for your attention!

