Istituto Nazionale di Fisica Nucleare

Alla ricerca della Materia Oscura

Marco Selvi
INFN Bologna

Seminario INFN, 27 maggio 2020

Outline

- Motivations for Dark Matter
- Review of DM properties
- Generalities on signal and backgrounds
- Most effective detection techniques
- Review of recent results from direct DM detection experiments

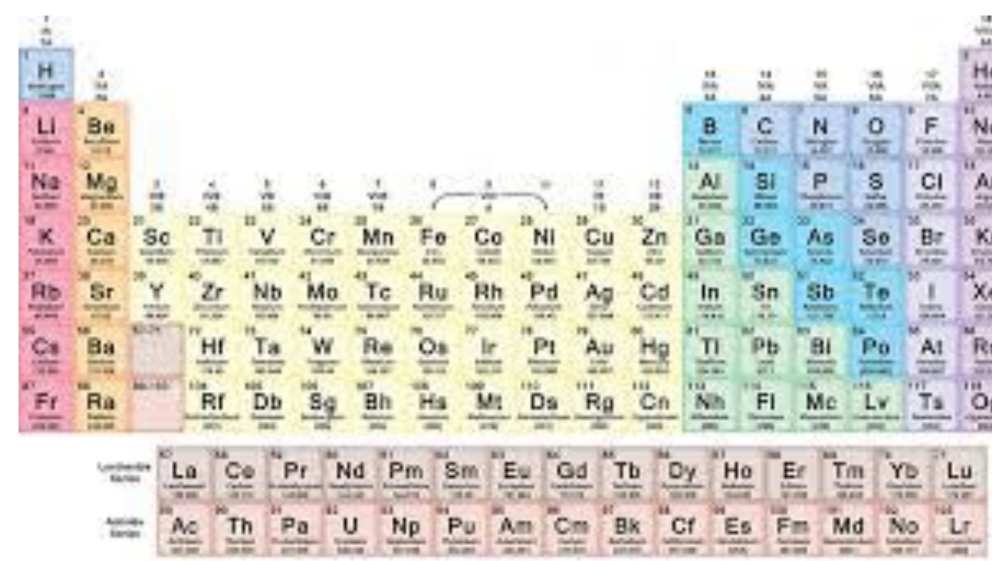
Usual disclaimers of these kinds of review talks:
not complete, biased, personal view, etc

* many thanks to
E. Aprile, L. Baudis, G. Bertone, G. Fiorillo, T. Marrodan,
K. Palladino, K. Ni, M. Schumann
for useful materials used in this review

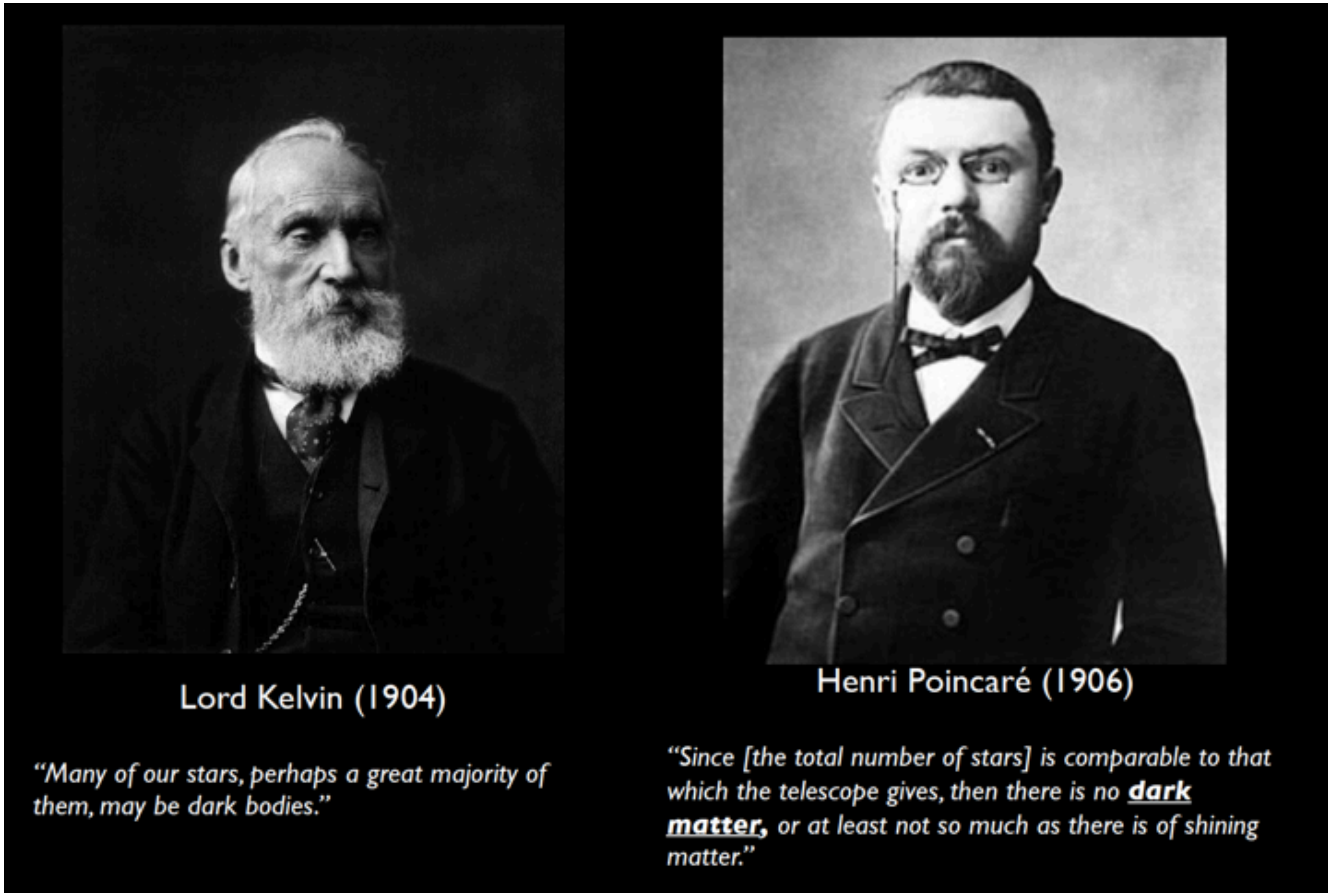
Di cosa è fatto l'universo ?

Atomi = Nuclei + Elettroni

protoni + neutroni
(quarks)



Dark Matter: a long standing “?”



Dark Matter: a long standing "?"

2019: The first **Nobel prize** for **dark matter**

PRESS RELEASE

8 October 2019

The Nobel Prize in Physics 2019

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2019

"for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos"

with one half to
James Peebles
Princeton University, USA
"for theoretical discoveries in physical cosmology"

and the other half jointly to
Michel Mayor
University of Geneva, Switzerland

Didier Queloz
University of Geneva, Switzerland
University of Cambridge, UK

"for the discovery of an exoplanet orbiting a solar-type star"

Ill. Niklas Elmehed. © Nobel Media.
James Peebles
Prize share: 1/2

Ill. Niklas Elmehed. © Nobel Media.
Michel Mayor
Prize share: 1/4

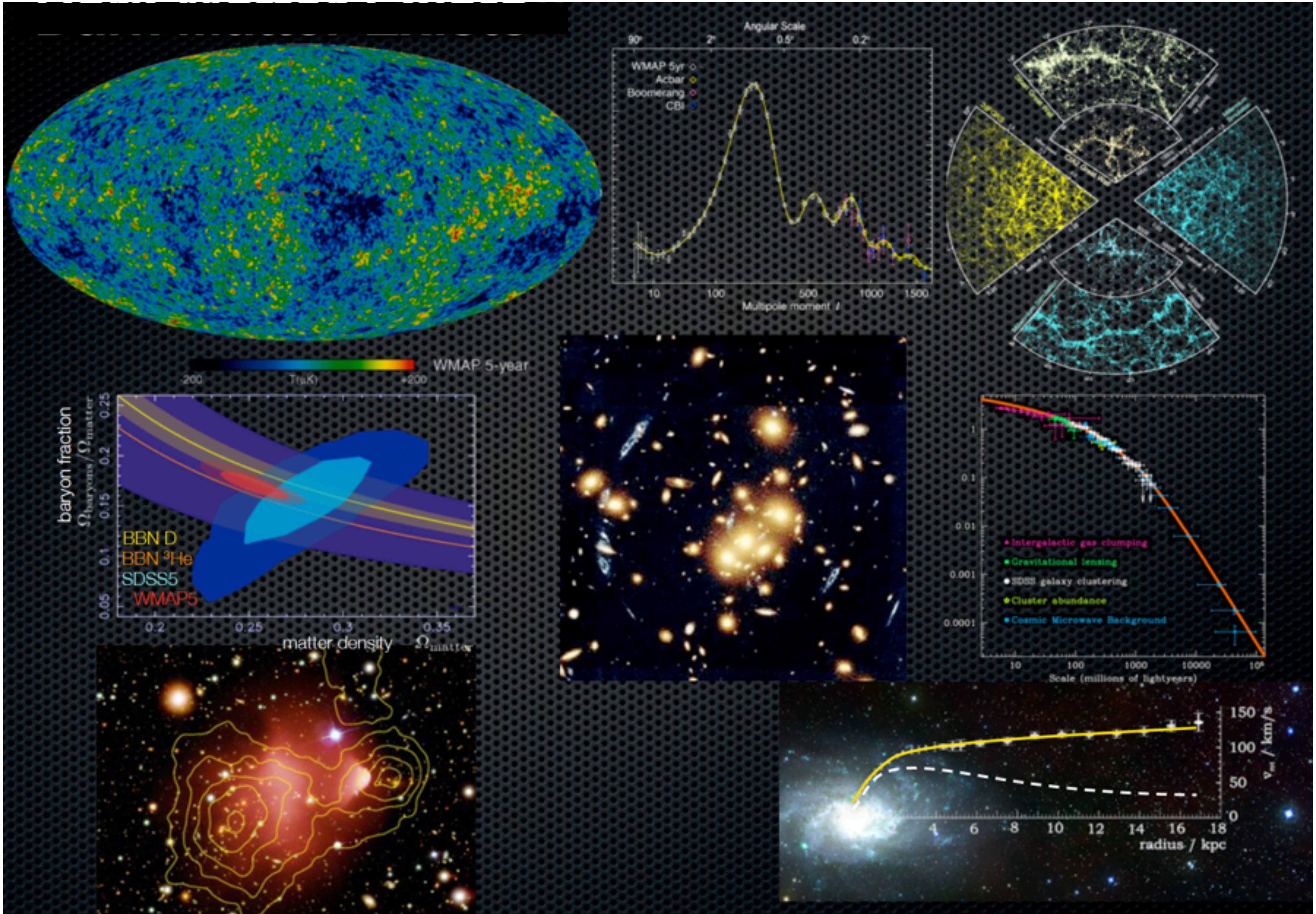
Ill. Niklas Elmehed. © Nobel Media.
Didier Queloz
Prize share: 1/4

James Peebles' insights into physical cosmology have enriched the entire field of research and laid a foundation for the transformation of cosmology over the last fifty years, from speculation to science. His theoretical framework, developed since the mid-1960s, is the basis of our contemporary ideas about the universe.

The Big Bang model describes the universe from its very first moments, almost 14 billion years ago, when it was extremely hot and dense. Since then, the universe has been expanding, becoming larger and colder. Barely 400,000 years after the Big Bang, the universe became transparent and light rays were able to travel through space. Even today, this ancient radiation is all around us and, coded into it, many of the universe's secrets are hiding. Using his theoretical tools and calculations, James Peebles was able to interpret these traces from the infancy of the universe and discover new physical processes.

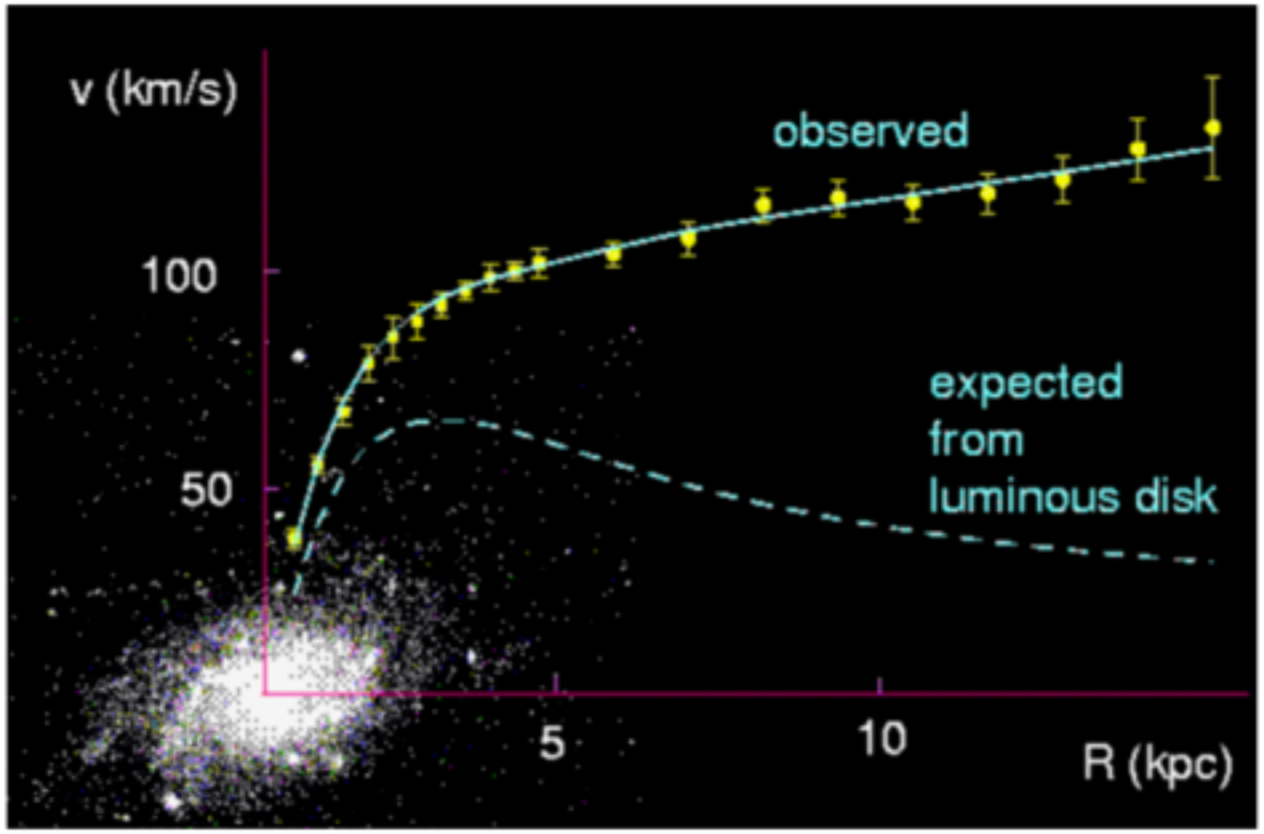
The results showed us a universe in which just five per cent of its content is known, the matter which constitutes stars, planets, trees – and us. The rest, 95 per cent, is unknown dark matter and dark energy. This is a mystery and a challenge to modern physics.

Dark Matter exists



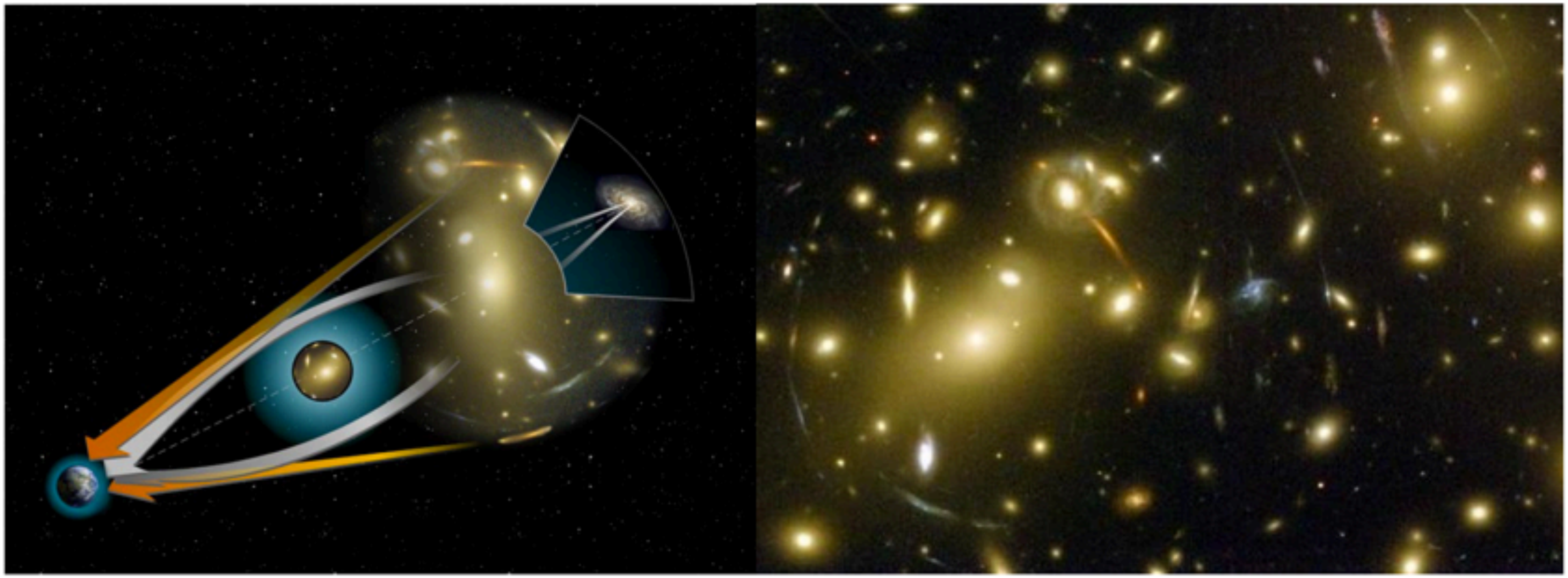
DM: indications from Astronomy

- Expectation: decrease of rotation velocity with radius
- Measurement: almost constant velocity
- Hypothesis: dark matter sphere accompanying the Galaxy



- How to measure rotation velocities?
  → doppler shift of the 21 cm hydrogen line
  Microwave line measured with radio antennas

DM: Gravitational lensing



Photon trajectories are curved around massive objects

The matter distribution between the source and the observer can be reconstructed

Gravitational lensing was proposed already in 1936 by Einstein

DM: Galaxy-cluster collision

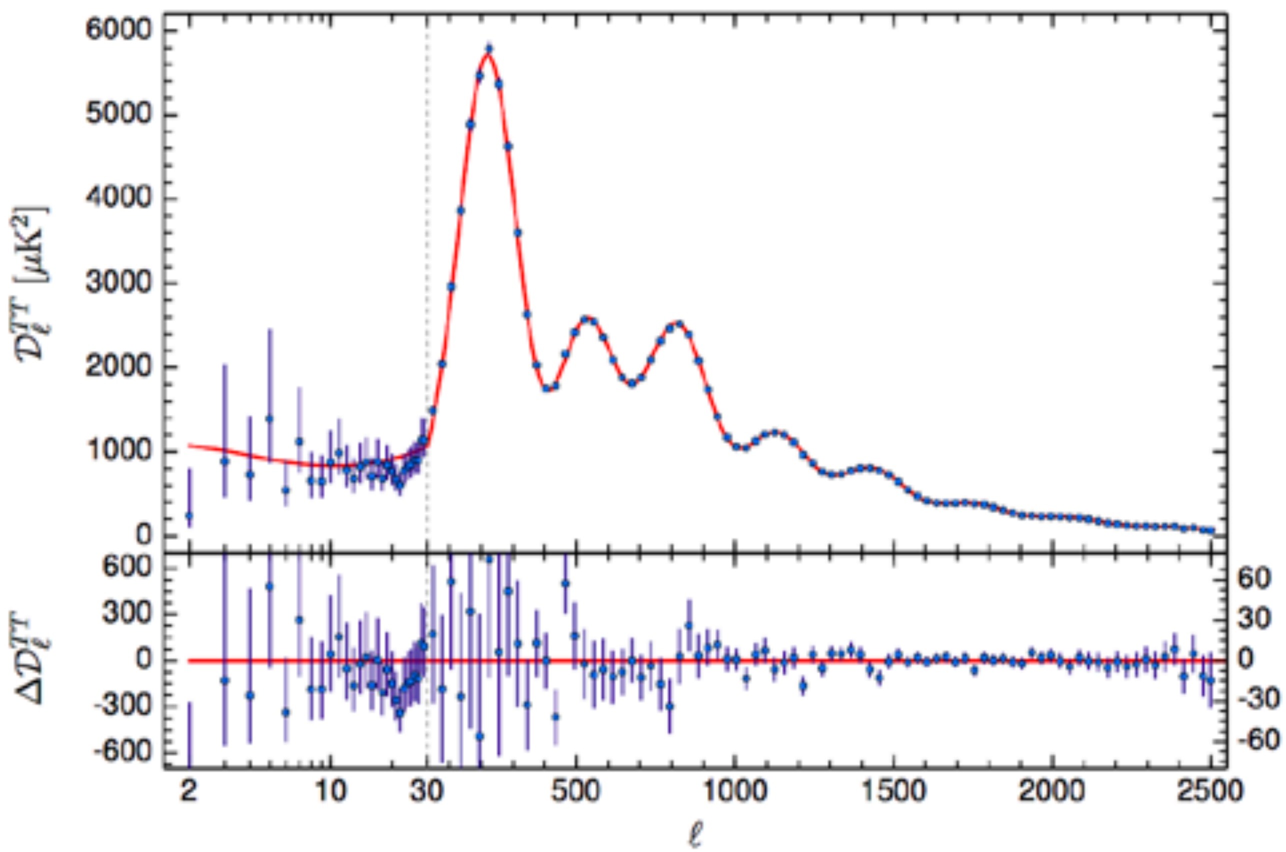
Bullet cluster, D. Clowe et al. 2004

MACSJ0025 cluster, Bradac et al. arXiv:0806.2320

→ Collision of two galaxy clusters

- Baryonic matter: X-ray production from the gas collision
- Matter distribution: reconstructed using gravitational lensing

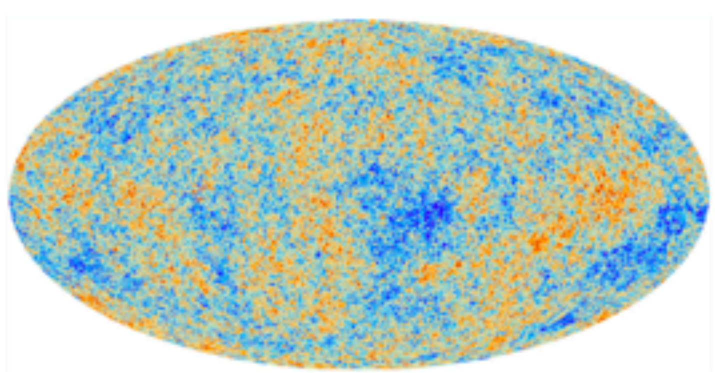
DM: indications from Cosmology



Planck Collaboration, arXiv:1502.01589

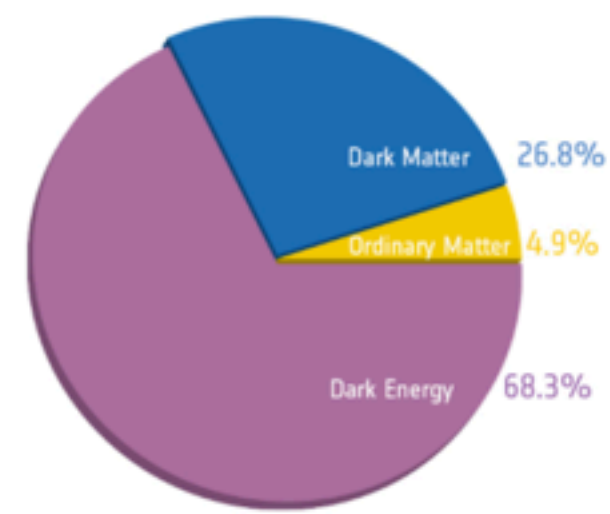
→ Cosmic microwave background

- First measurement of 2.7 K radiation in 1964 using telecommunications horn antennas
- Anisotropies (10^{-5} K) measured by the Planck satellite
- Two instruments: low and high frequency regions



Luminous matter 5%

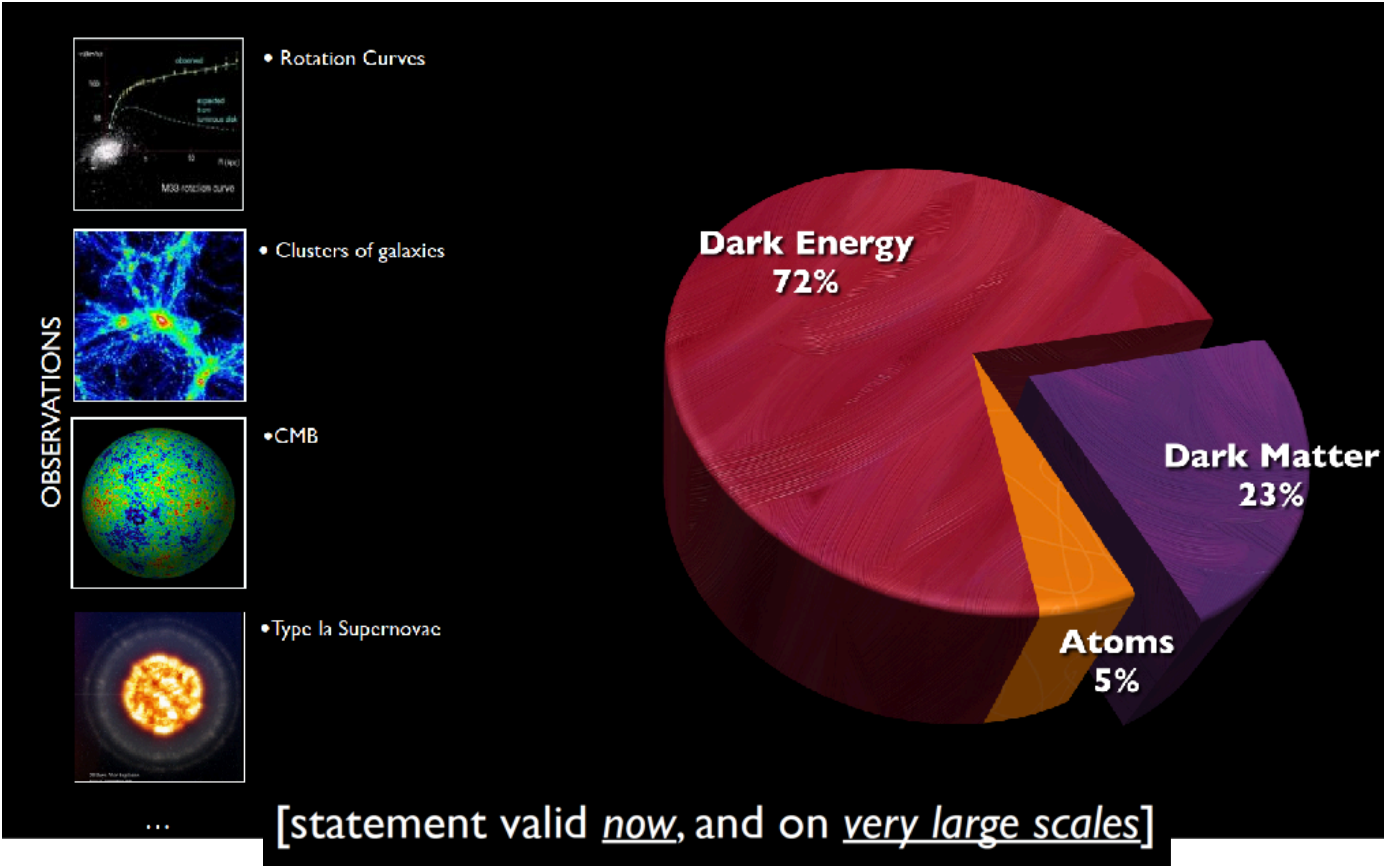
27% is dark matter



After Planck

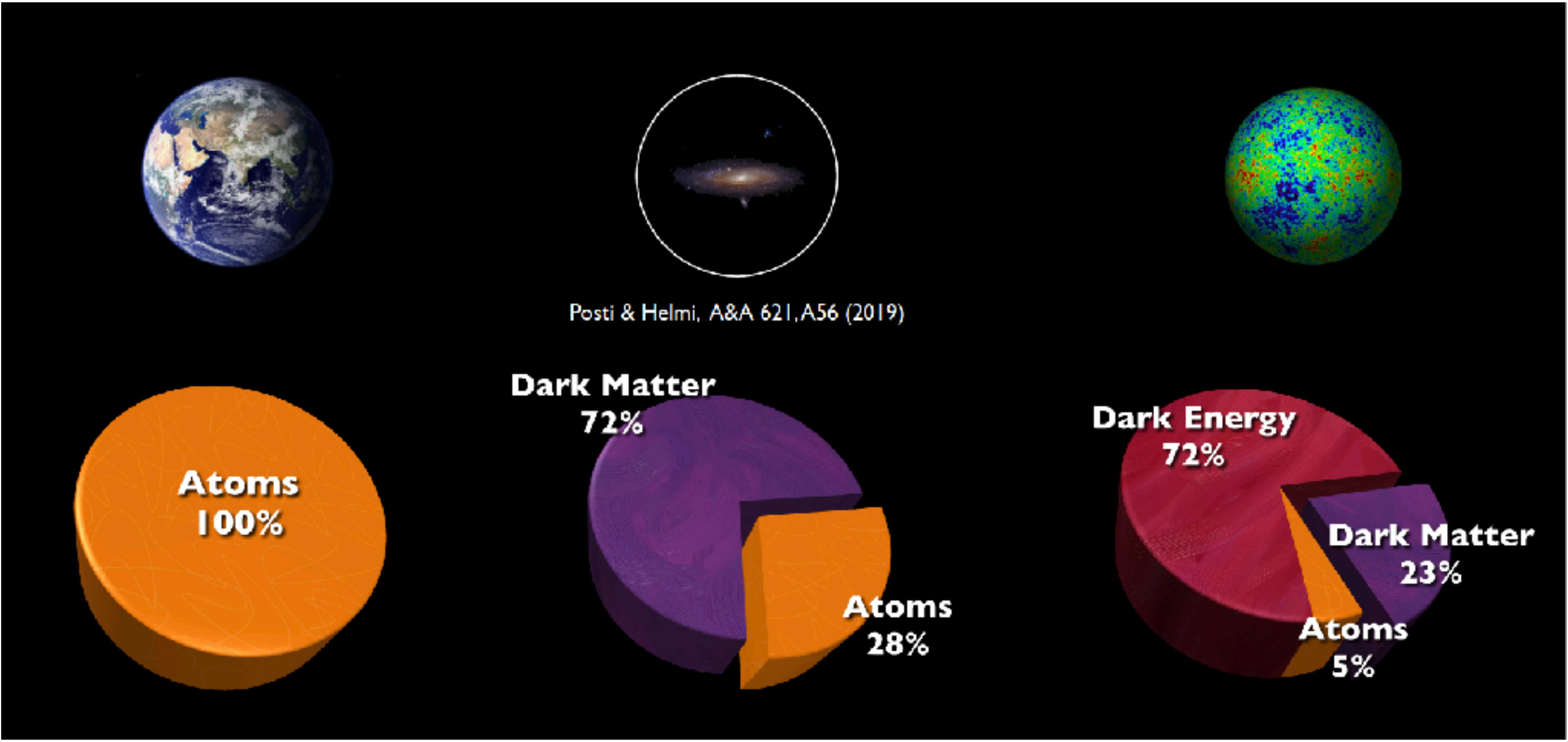
→ Further hit: structure formation

… and it dominates the Universe Matter budget



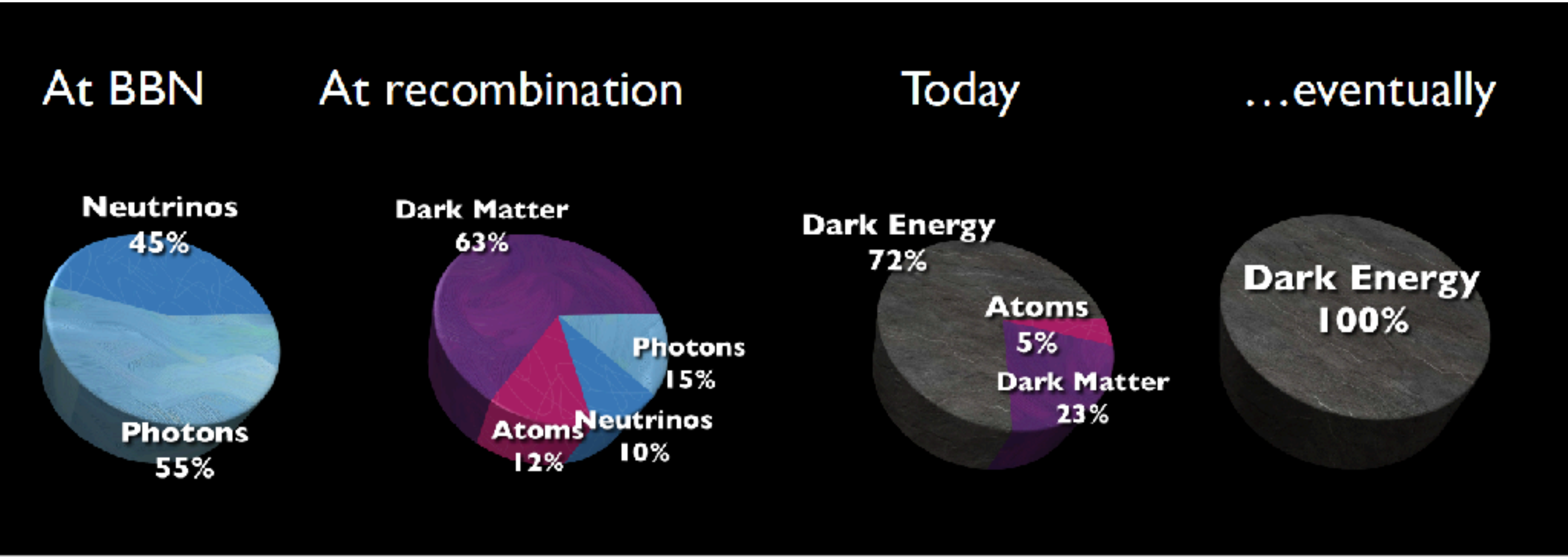
… and it dominates the Universe Matter budget

Looking at different space scales:

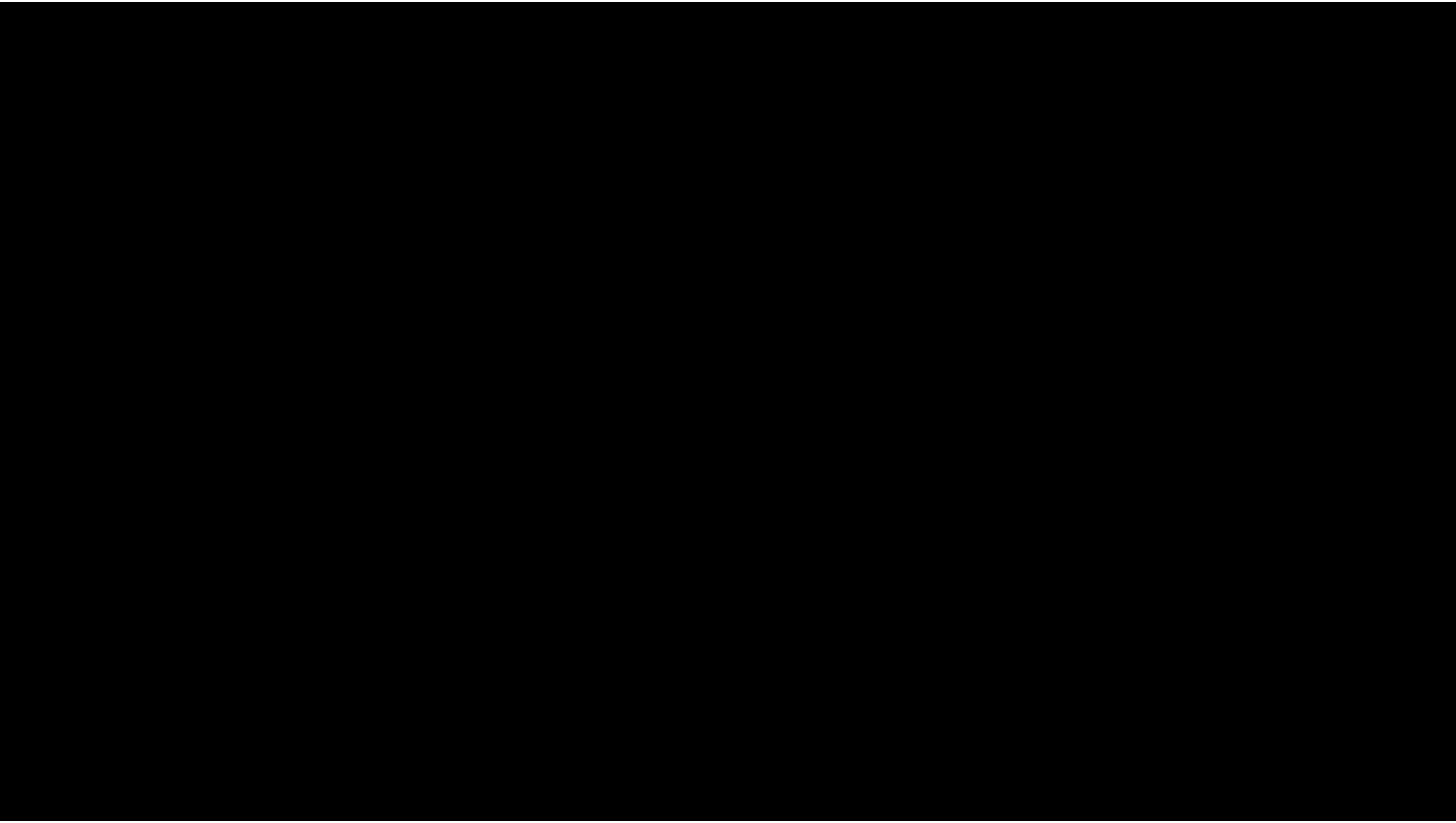


… and it dominates the Universe Matter budget

Looking at different time scales:



Universe evolution

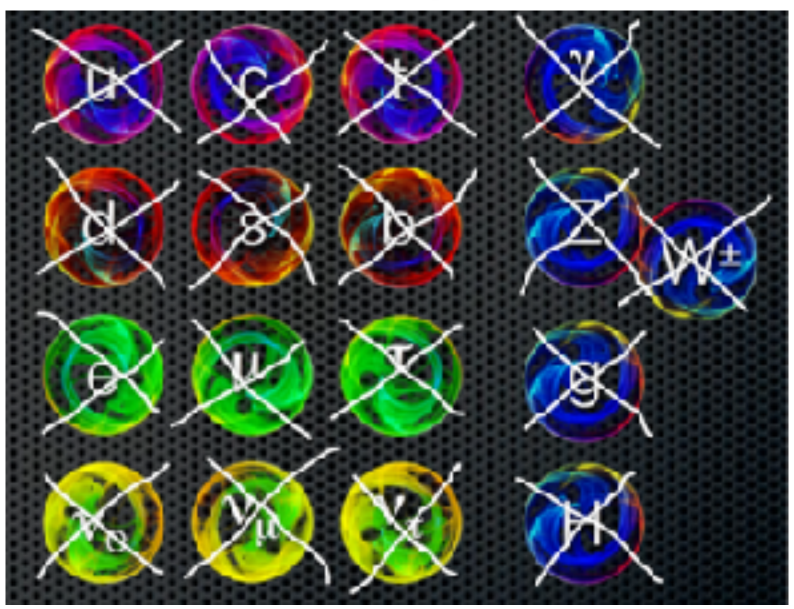


https://www.illustris-project.org/media/

What is Dark Matter made of ?

An elementary particle?

- Massive → explain gravitational effects
- Neutral → no EM interaction & Weakly interacting at most
- Stable or long-lived → not to have decayed by now
- Cold (moving non-relativistically) or warm → structure formation



In the standard model of particle physics:
Neutrino fulfil most
but it is a hot dark matter candidate

→ Models beyond SM typically predict NEW particles

Neutralino in Supersymmetry, gravitino, Axion, LKP in extra dimensions,
Sterile neutrino, Super-heavy dark matter and many others

WIMPs

Well motivated theoretical approach:

WIMP

(**W**eakly **I**nteracting **M**assive **P**article)

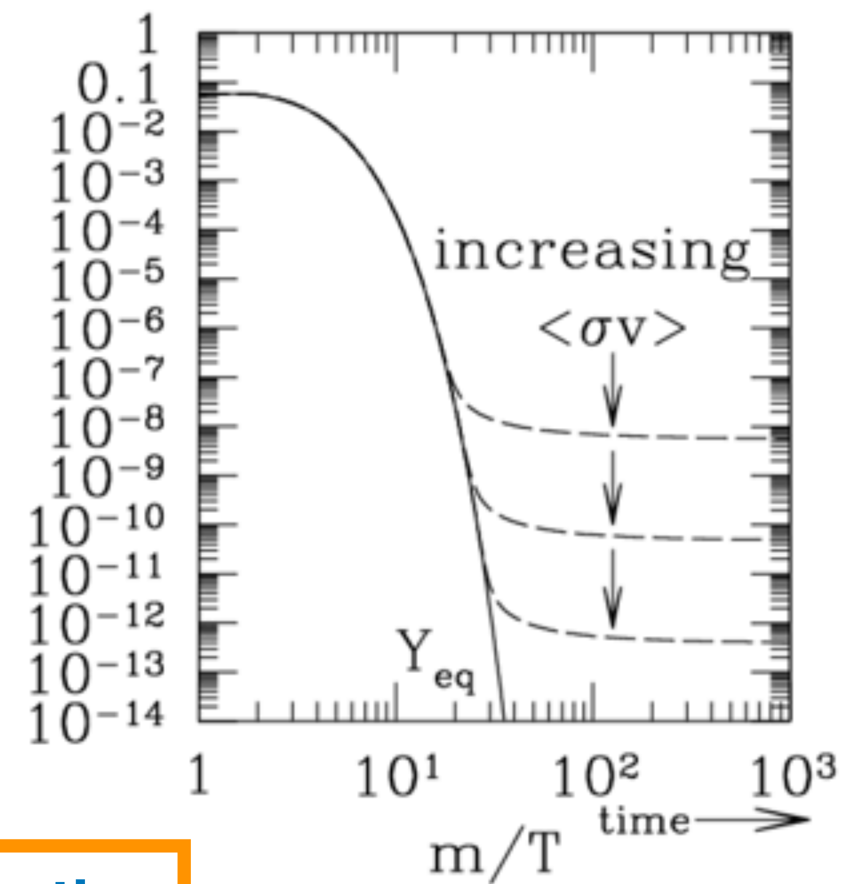
- In the early Universe particles are in thermal equilibrium:

  creation ↔ annihilation

  $\chi\bar{\chi} \leftrightarrow e^+e^-, \mu^+\mu^-, q\bar{q}, W^+W^-, ZZ\ldots$

- When annihilation rate ≪ Universe expansion rate → 'freeze out'

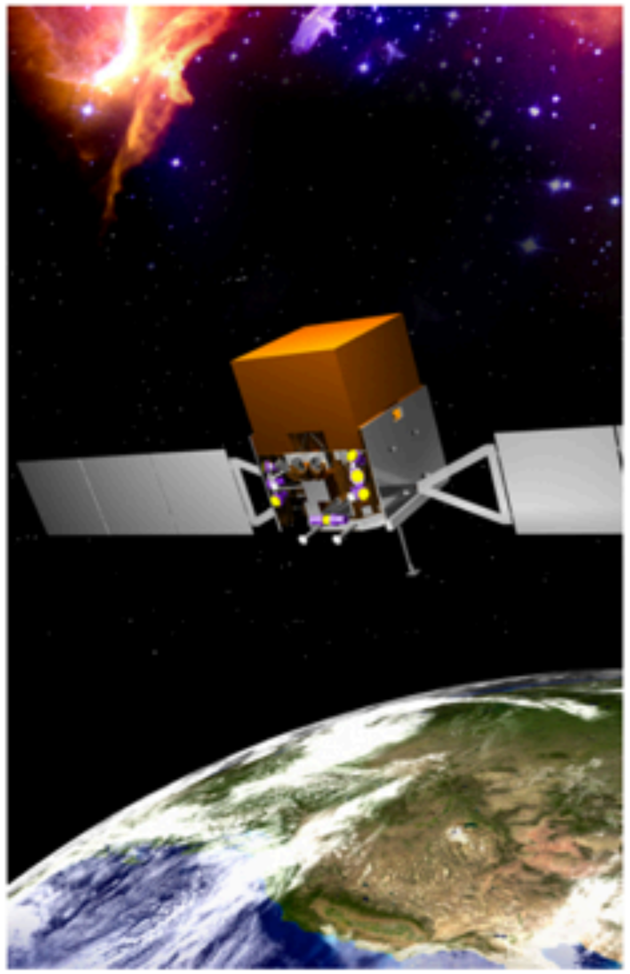
- Correct relic density for an annihilation rate ~ weak scale

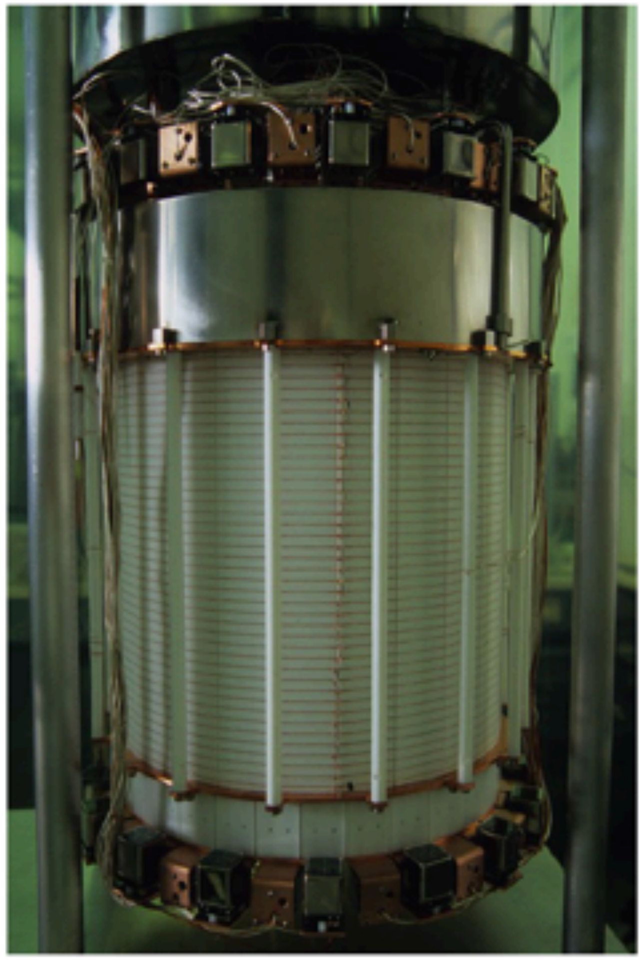


In this talk I will focus mostly on WIMP direct detection

Dark Matter searches

- Production at LHC
- Indirect detection
- Direct detection



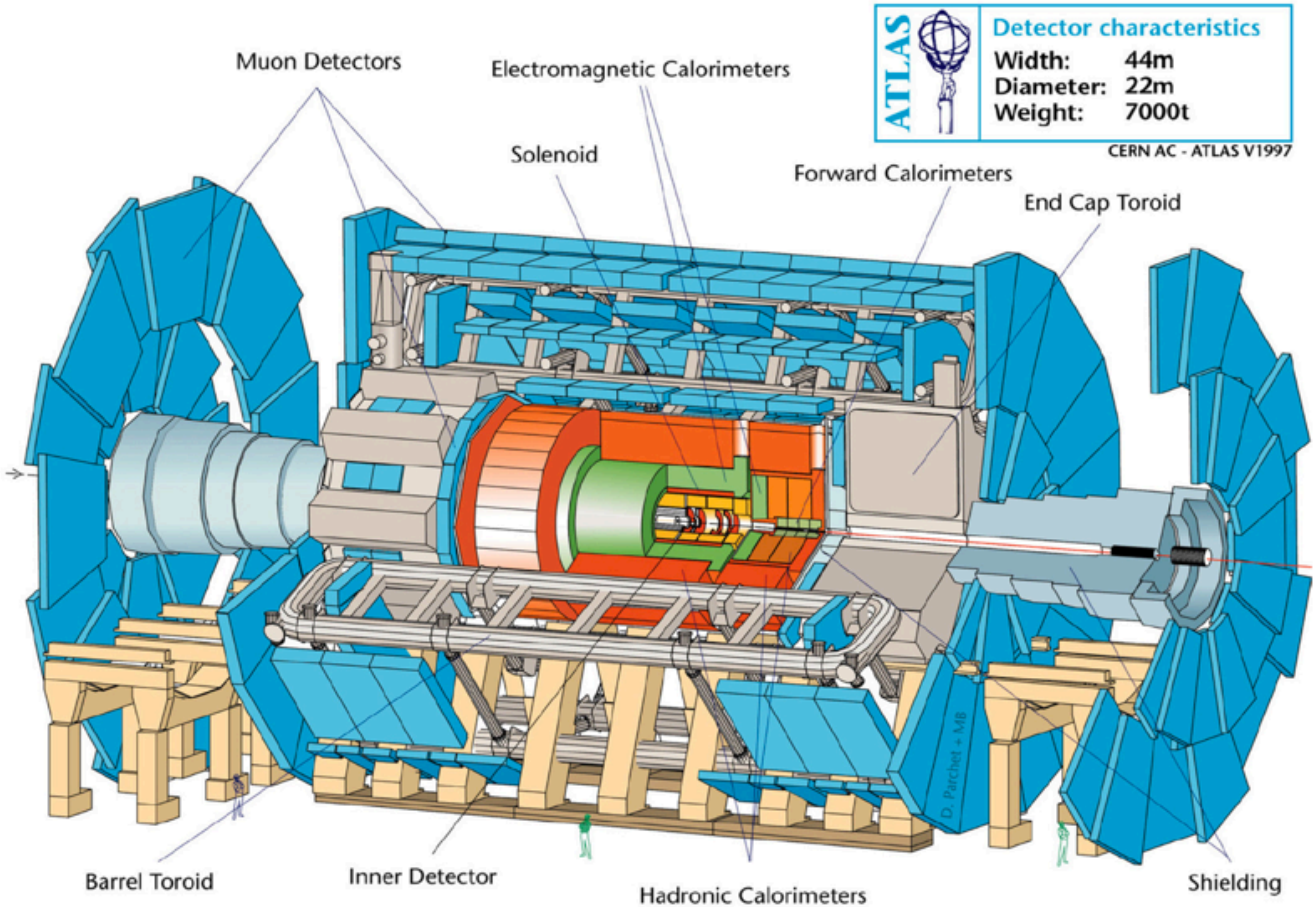


$\mathrm{p} + \mathrm{p} \rightarrow \chi\overline{\chi} + \text{a lot}$

$\chi\chi \rightarrow \gamma\gamma, q\overline{q}, \ldots$

$\chi\,\mathrm{N} \rightarrow \chi\,\mathrm{N}$

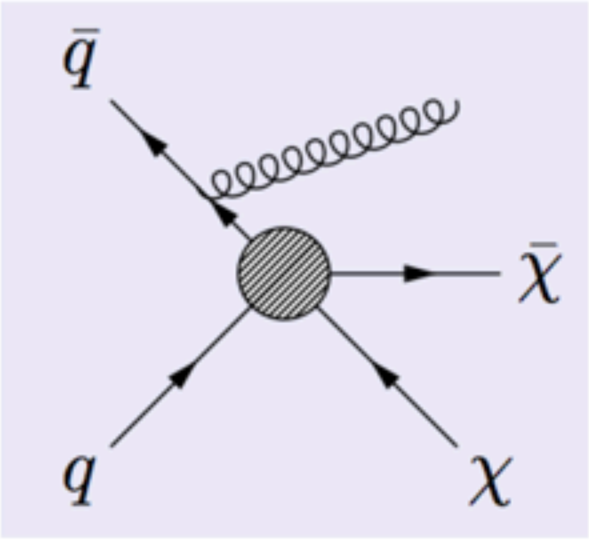
A detector @ LHC collider

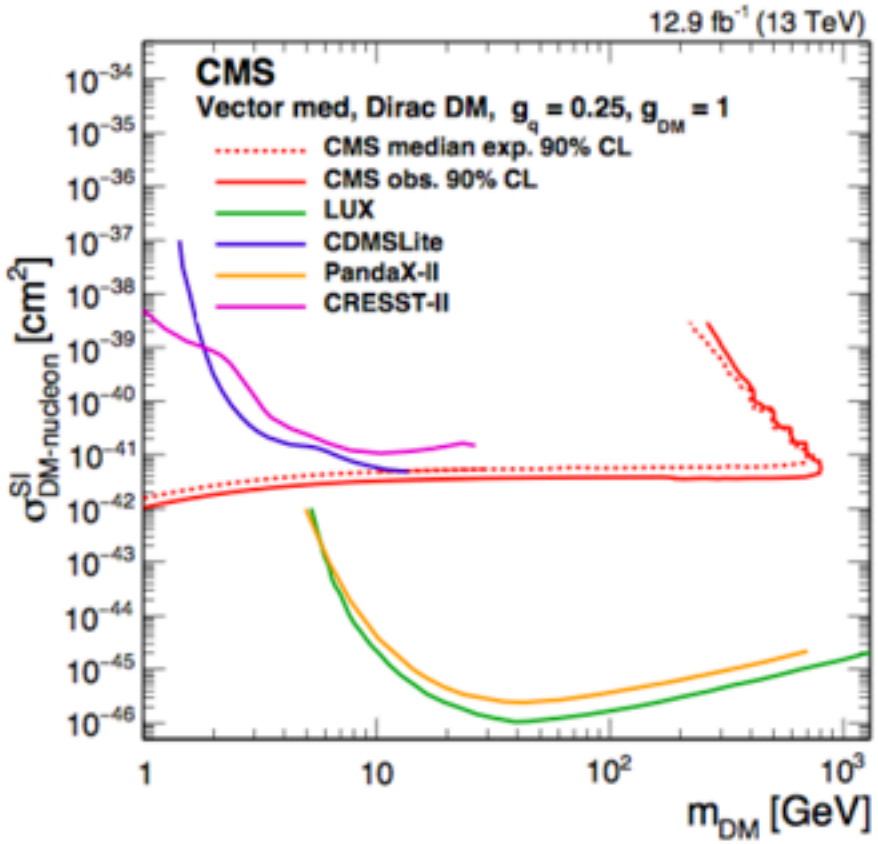


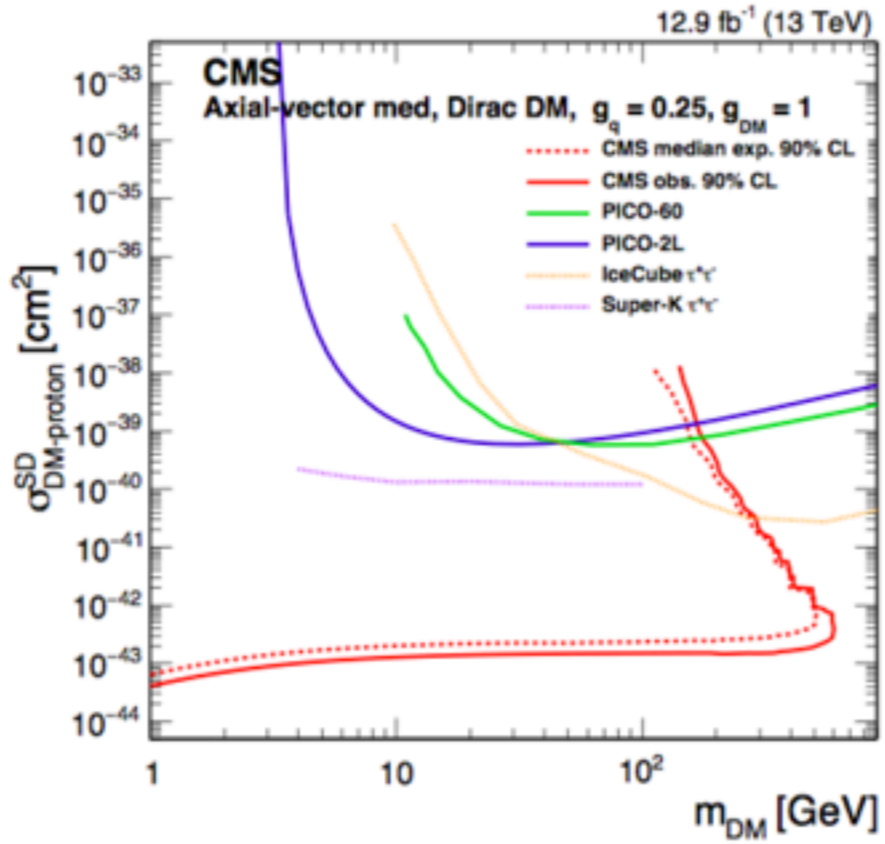
The ATLAS Detector

DM searches @ LHC

- Signatures: χ in cascades or $\chi\bar{\chi}$ accompanied by a mono-signature $p + p \to \chi\bar{\chi} + X$
  - Large missing momentum from $\chi\bar{\chi}$
  - X can be a hadronic jet, a photon or a *W* or *Z* decaying hadronically
- Comparison of results with direct detection is model dependent







Figures from CMS, arXiv:1703.01651

Indirect DM detection

- Where? → location
  - Galactic center, galactic halo
  - Subhaloes, dwarf spheroidals, the Sun ..
- Into what? → particles produced
  - $\chi\chi \to \gamma\gamma, \gamma Z, \gamma H$
  - $\chi\chi \to q\overline{q}, W^+W^-$ fragmentation into $\to e^+e^-, p\overline{p}, \nu$'s
- How measured? → detector technology
  - Satellites or balloons measuring charged particles, γ's or X-rays
  - Cherenkov telescopes and large neutrino observatories

Expected particle flux:

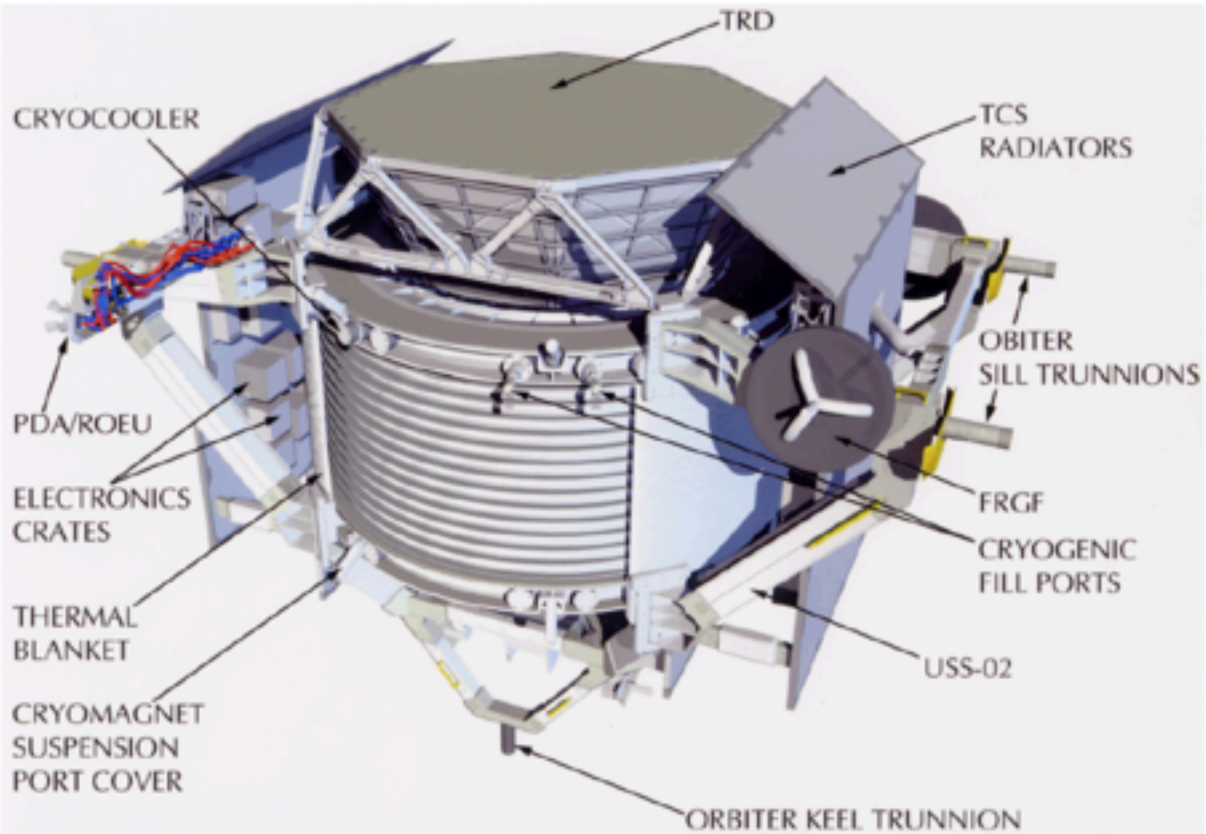
$$\frac{d\Phi_p}{dE} = \frac{<\sigma_A v>}{4\pi 2 m_\chi^2} \cdot \frac{dN_p}{dE} \cdot J(\Delta\Omega), \qquad J(\Delta\Omega) = \int d\Omega \int \rho^2(\ell) d\ell$$

with ℓ the coordinate along the line of sight

Approaches for indirect DM

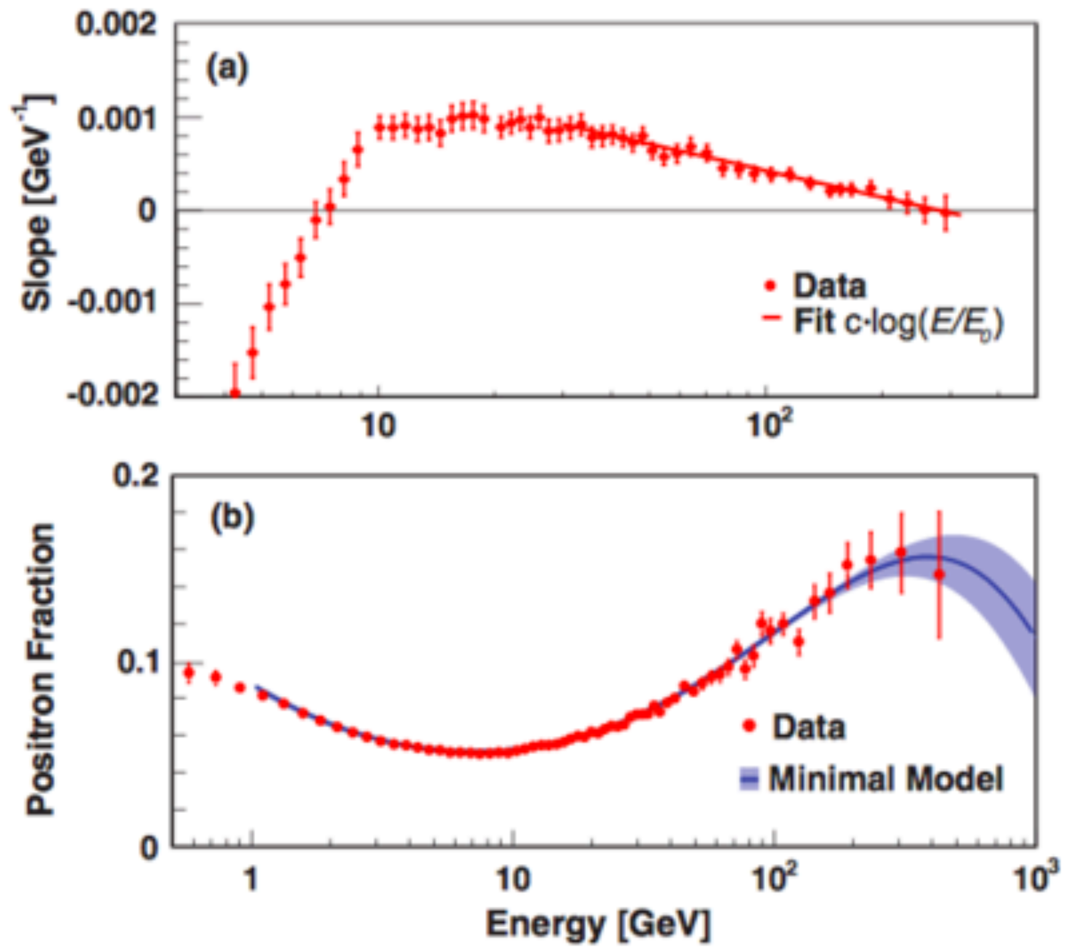
- Ground-based:
  - Large neutrino detectors
  - Cherenkov imaging telescopes
- Measuring in space:
  - Gamma-ray satellites
  - X-ray satellites
  - Charge particle detectors in space

Anti-matter search in space: AMS



- AMS: Alpha Magnetic Spectrometer
- Operating at ISS since 2011
- e^+ and e^- from $(0.5 - 500)$ GeV

- Results based on 10.9×10^6 e^+ and e^- events
- Sign of new phenomena: astrophysics or particle physics



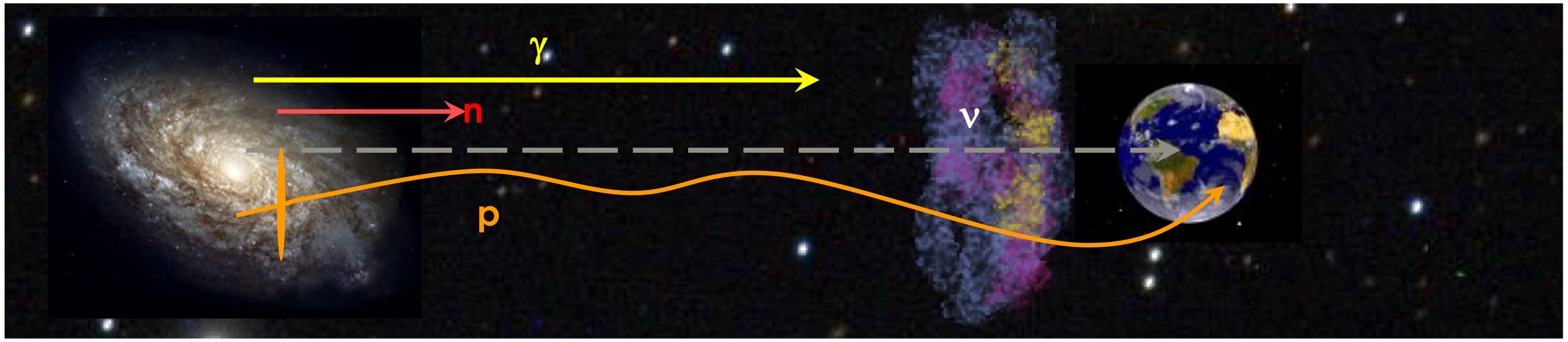
Newest positron fraction from AMS,
Phys. Rev. Lett. 113 (2014) 121101

Increase observed in the past by Fermi, Pamela, etc

Neutrino Astronomy

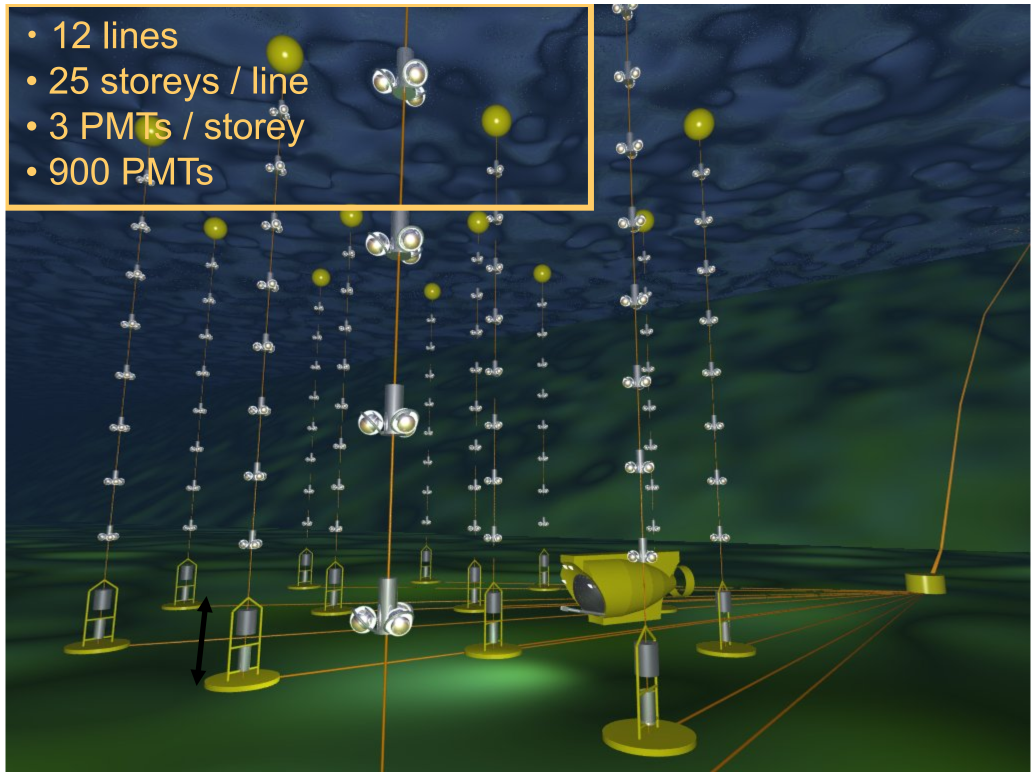
- **Obiettivo principale ricerca di sorgenti dei Raggi Cosmici**

Fotoni: interagiscono con la materia e la radiazione
Protoni : deflessi da campi magnetici
Neutroni: non sono stabili



Neutrini: piccola sezione d'urto → enormi rivelatori (~Gton)

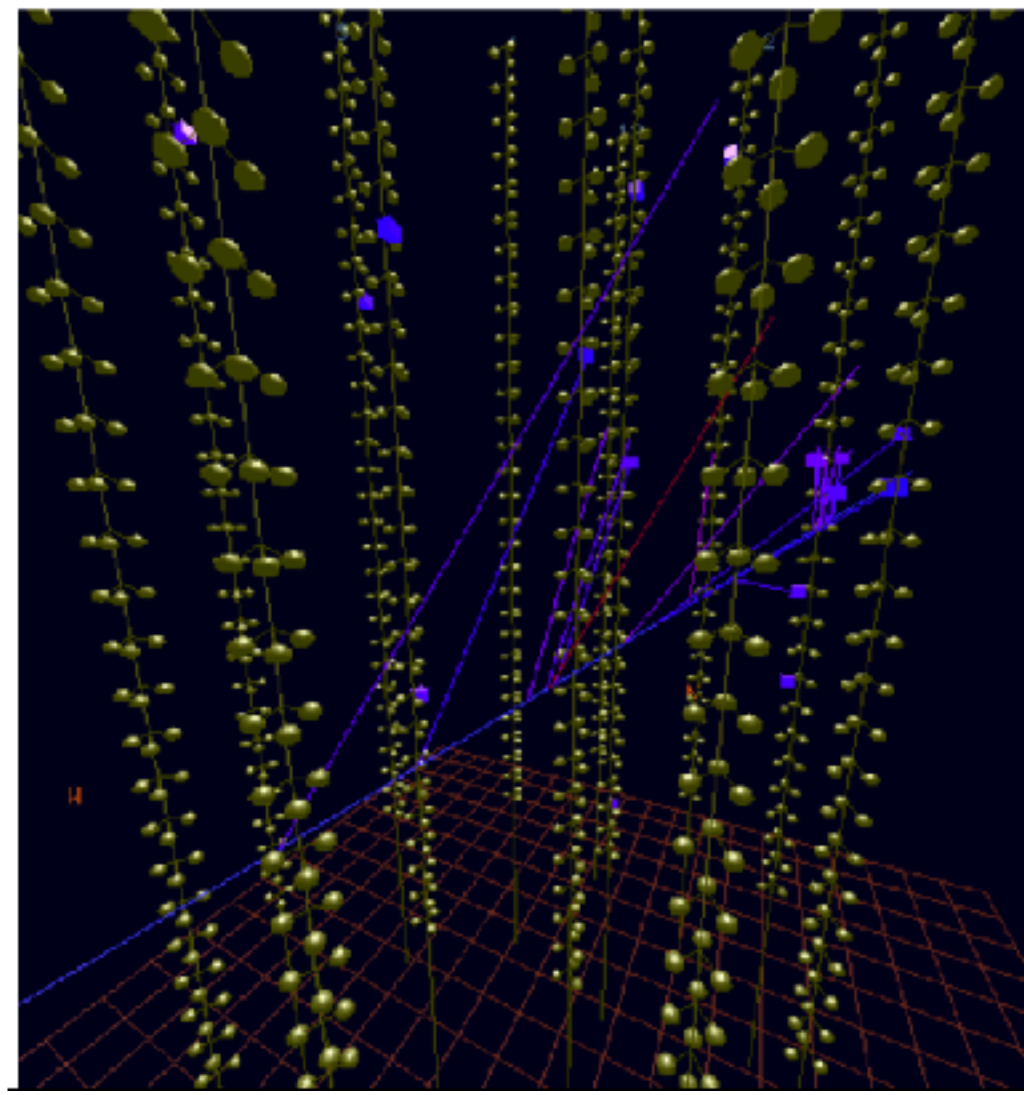
Neutrino Astronomy



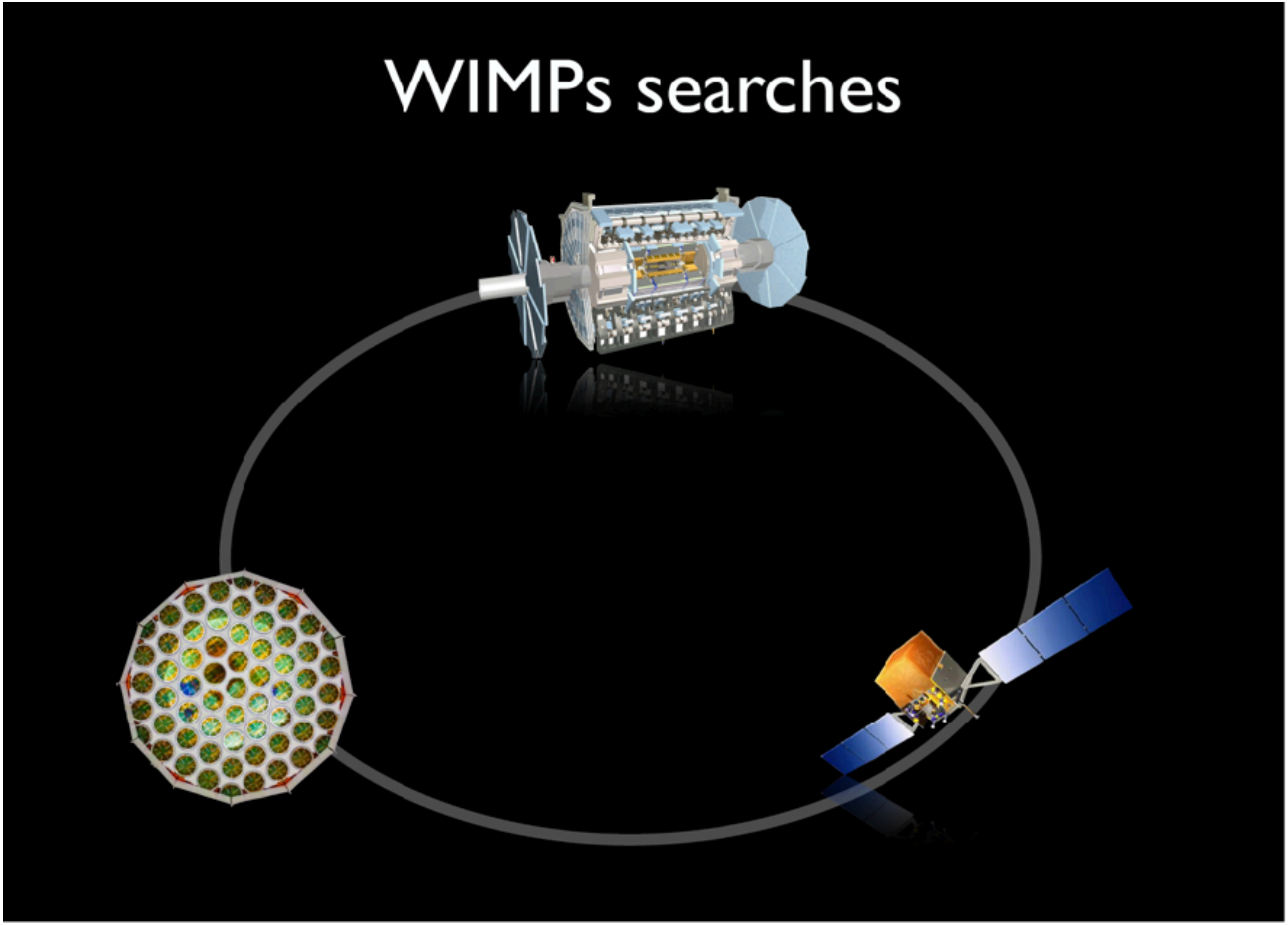
FUTURO :KM3 (rivelatore di 1km³)
In installazione al largo della Sicilia

Tipico "telescopio" marino:
ANTARES a 2500 m di profondità
(al largo di Tolone ,Costa Azzurra)

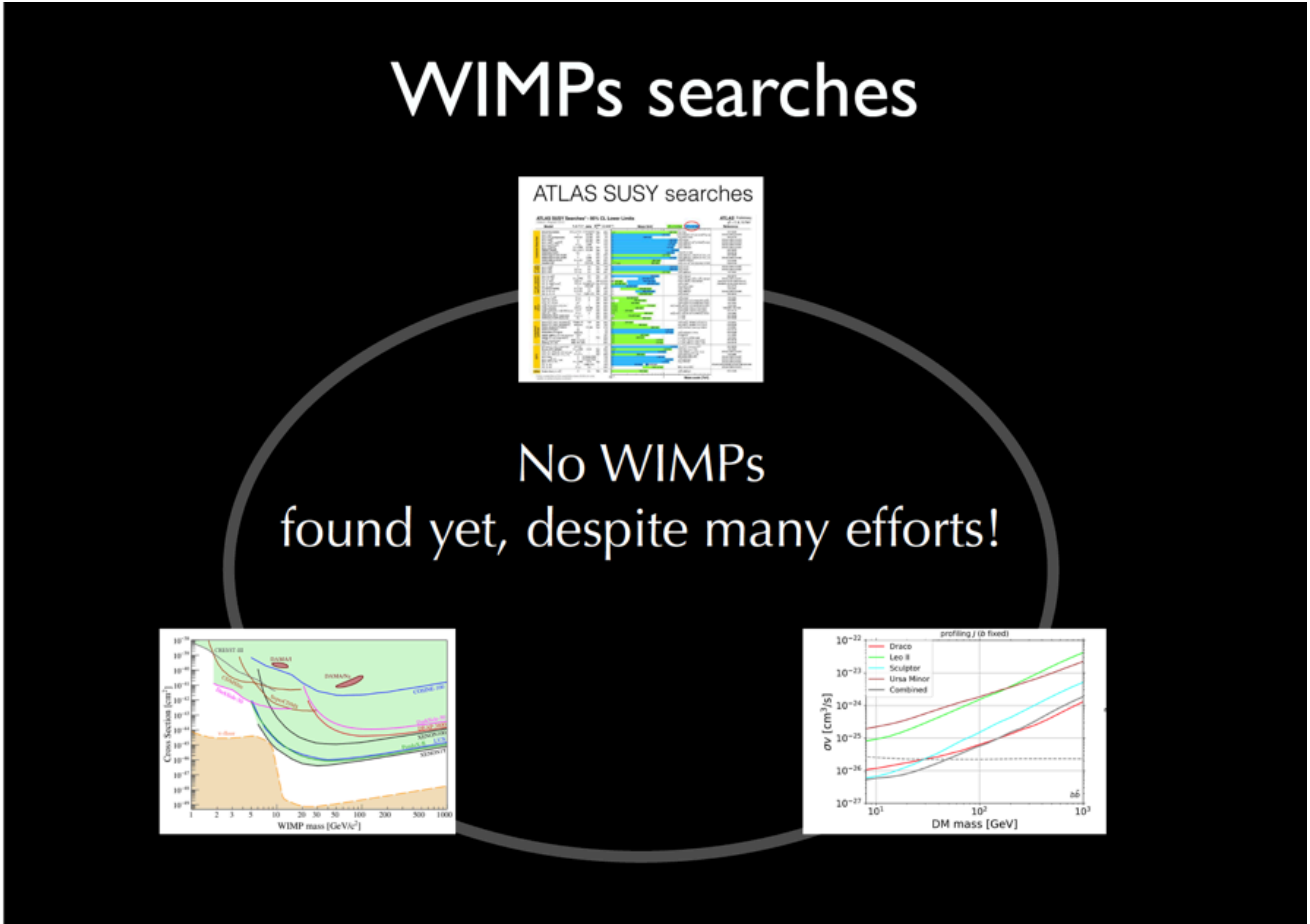
un muone da 1.2 TeV che attraversa il rivelatore



Spoiler: no WIMP detected yet !



Spoiler: no WIMP detected yet !



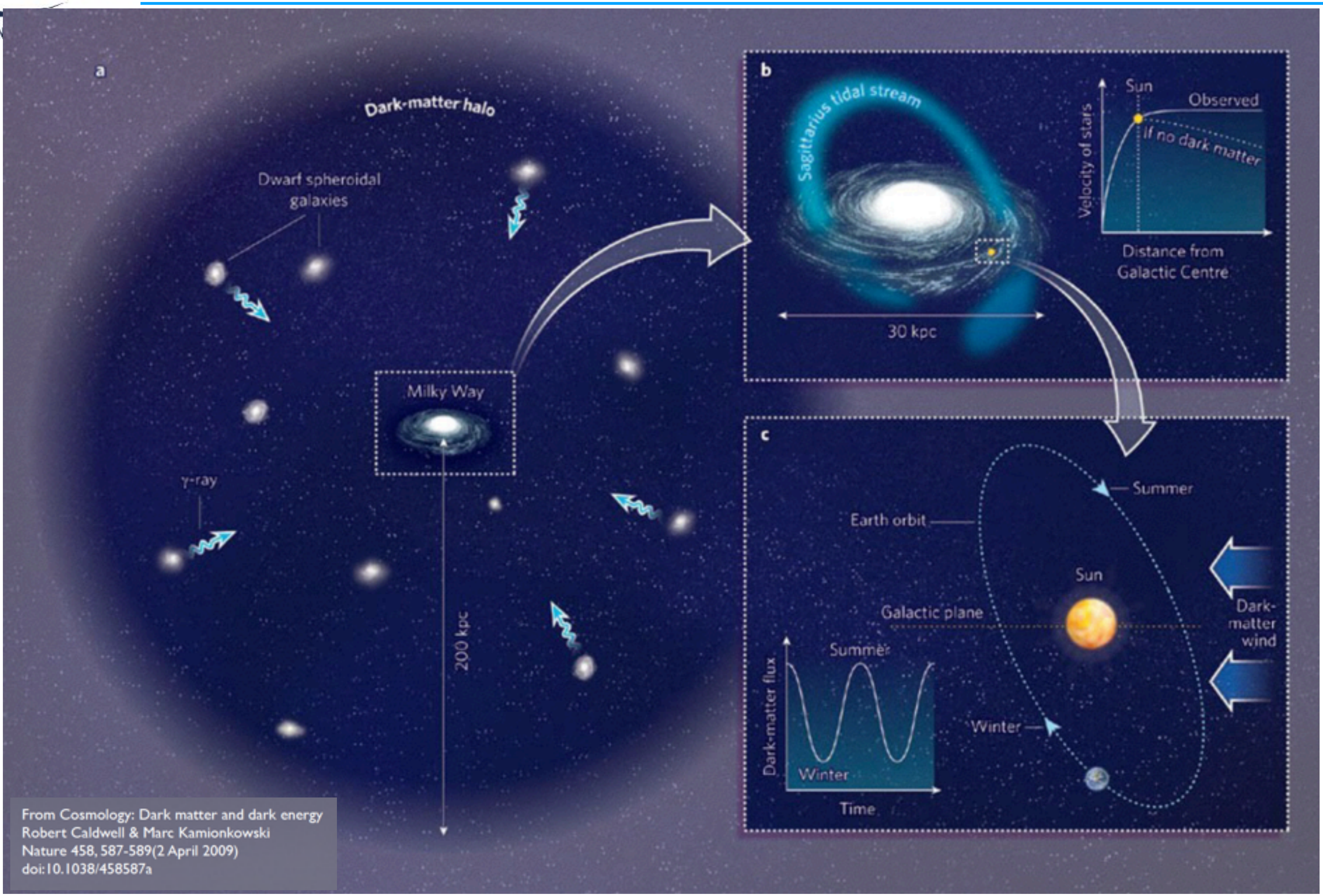
Spoiler: no WIMP detected yet !

Are WIMPs ruled out?

NO

absence of evidence ≠ evidence of absence

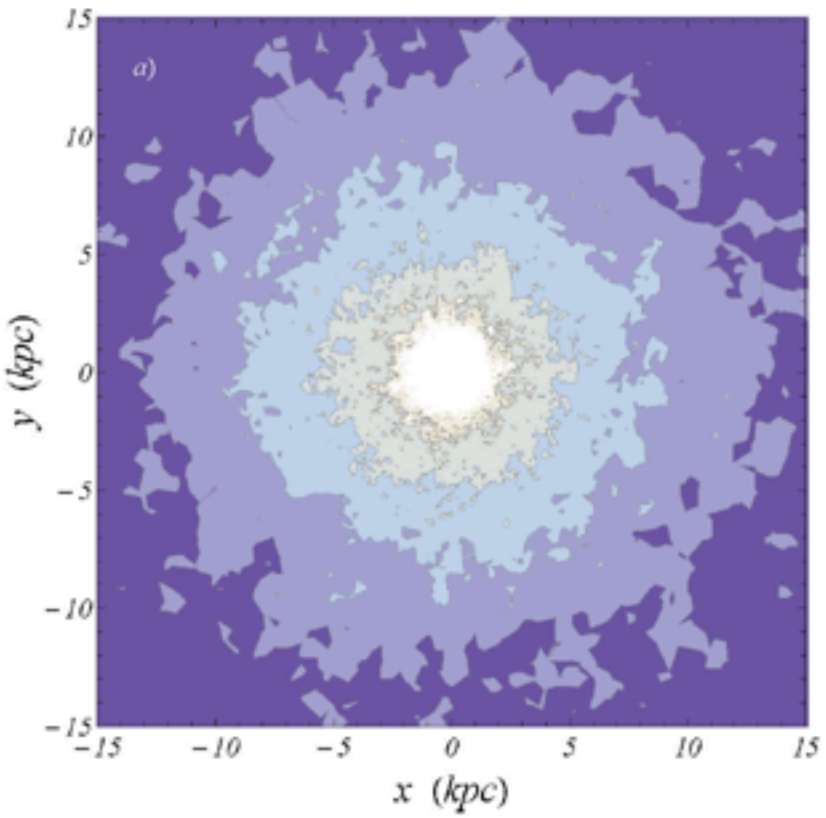
We live in a dark matter halo



WIMP density and velocity distribution

WIMPs in the galactic halo

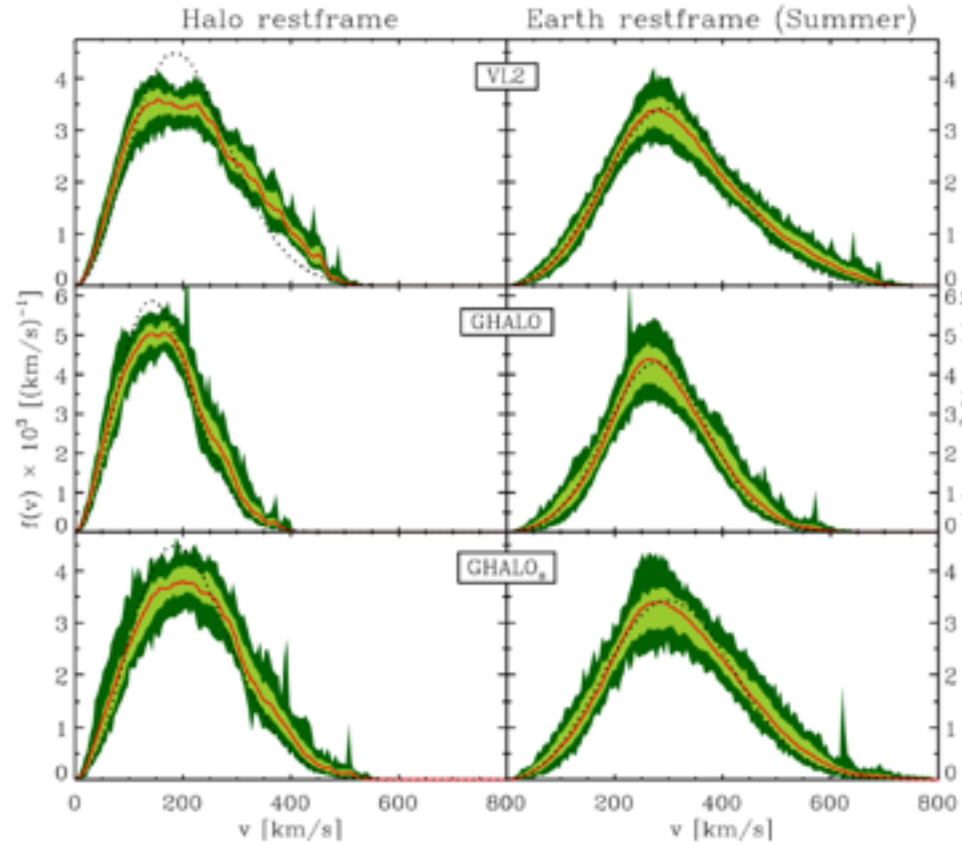
Density map of the dark matter halo
rho = [0.1, 0.3, 1.0, 3.0] GeV cm^{-3}



High-resolution cosmological simulation with baryons: F.S. Ling et al, JCAP02 (2010) 012

$$\rho_{local} \sim 0.3\,\mathrm{GeV} \cdot \mathrm{cm}^{-3}$$

Velocity distribution of WIMPs in the galaxy

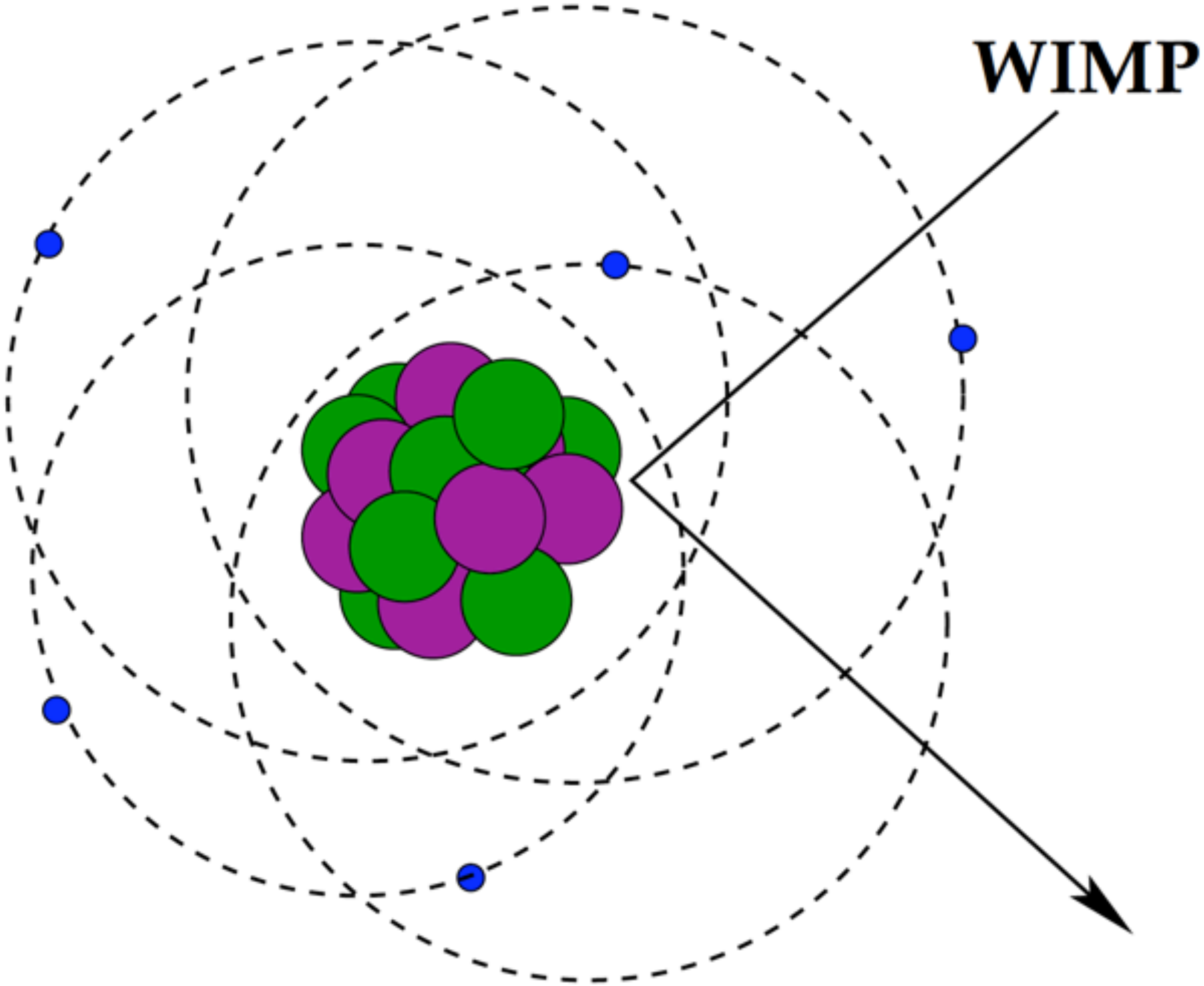


M. Kuhlen et al, JCAP02 (2010) 030

From cosmological simulations of galaxy formation: departures from the simplest case of a Maxwell-Boltzmann distribution

In direct detection experiments, mostly a simple MB distribution, truncated at v_{esc}, is used in the sensitivity calculation

Direct Dark Matter Detection



$$E_R \sim \mathcal{O}(10\,\mathrm{keV})$$

$$R \propto N_T \, \frac{\rho_0}{m_X} \, \sigma \langle v \rangle$$

Istituto Nazi

The standard halo model

Isotropic, isothermal sphere with a Maxwellian velocity distribution

$$f(v) = N \cdot \exp\left(\frac{-3|v|^2}{2\sigma^2}\right)$$

usually truncated $f(v) = 0$ for $|v| > v_{esc}$

Local density $\rho_0 = 0.3\,\mathrm{GeV/cm^3} = 0.008\,M_\odot/pc^3 = 5 \cdot 10^{-23}\,\mathrm{g/cm^3}$
determined via mass modelling of the Milky Way

About 1 WIMP in a coffee cup (assuming $m_\chi \sim 100\,\mathrm{GeV}/c^2$)

Circular velocity $v_c = 220\,\mathrm{km/s}$
with radial dispersion velocity $\sigma_r = v_c/\sqrt{2}$

Escape velocity $v_{esc} = 544\,\mathrm{km/s}$
determined from the speed of high velocity stars (RAVE)

Expected Rates

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v)\, \mathrm{d}^3 v$$

Astrophysical parameters:

- ρ_0 = local density of the dark matter in the Milky Way
- $f(\mathbf{v},t)$ = WIMP velocity distribution

Parameters of interest:

- m_χ = WIMP mass ($\sim 100\,\mathrm{GeV}/c^2$)
- σ = WIMP-nucleus elastic scattering cross section
  - Spin-independent interactions: coupling to nuclear mass
  - Spin-dependent interactions: coupling to nuclear spin

Scattering Cross Section

- In general, interactions leading to WIMP-nucleus scattering are parameterized as:
  - **scalar interactions** (coupling to WIMP mass, from scalar, vector, tensor part of L)

$$\sigma_{SI} \sim \frac{\mu^2}{m_\chi^2}[Zf_p + (A-Z)f_n]^2$$

f_p, f_n: scalar 4-fermion couplings to p and n

=> nuclei with large A favourable (but nuclear form factor corrections)

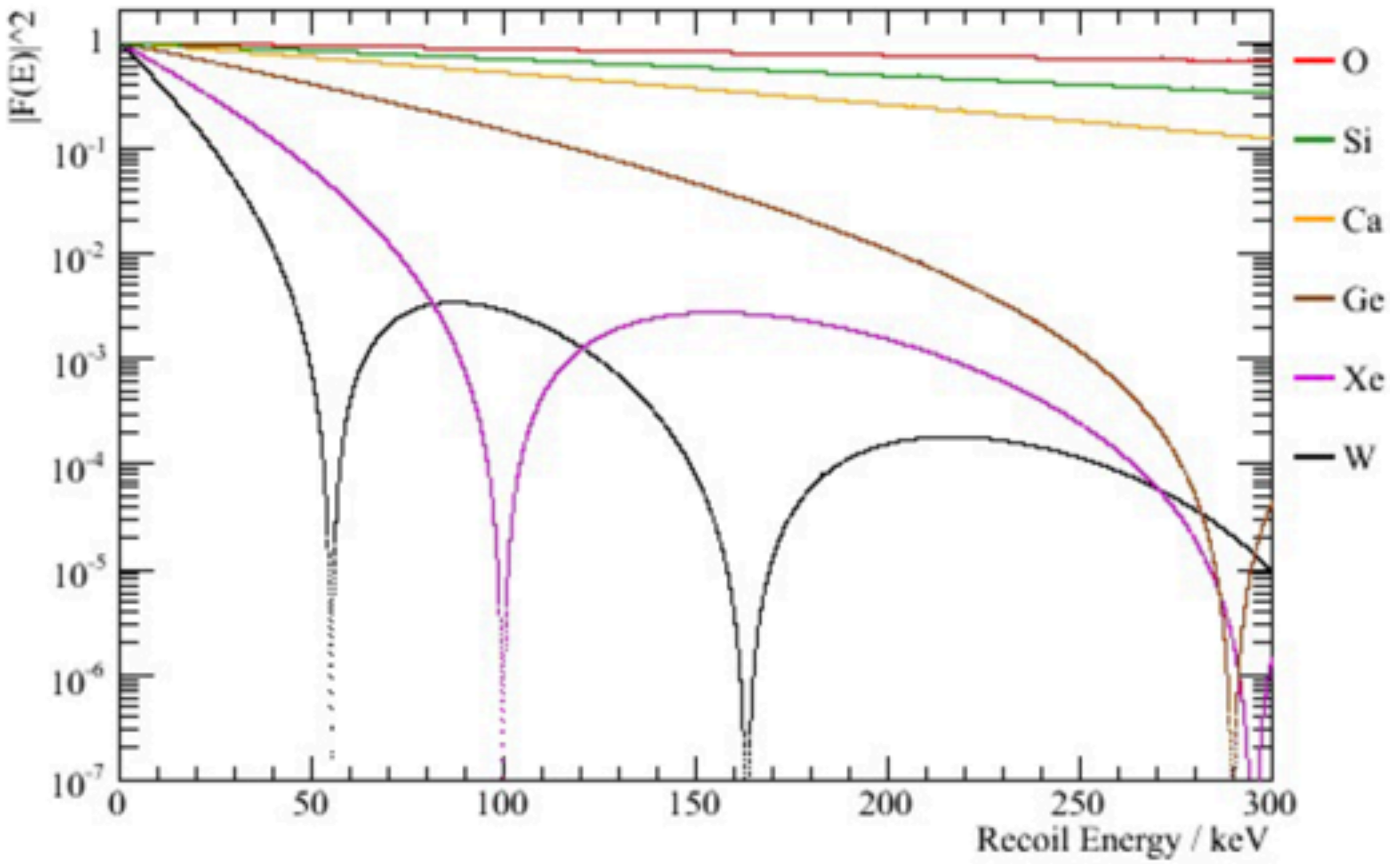
  - **spin-spin interactions** (coupling to the nuclear spin J_N, from axial-vector part of L)

$$\sigma_{SD} \sim \mu^2 \frac{J_N+1}{J_N}(a_p\langle S_p\rangle + a_n\langle S_n\rangle)^2$$

a_p, a_n: effective couplings to p and n; $\langle S_p\rangle$ and $\langle S_n\rangle$ expectation values of the p and n spins within the nucleus

=> nuclei with non-zero angular momentum (corrections due to spin structure functions)

Correction: the Form Factor



With the Helm parametrization for the nuclear density the form factor is

$$F^2(Q) = [\frac{3j_1(qR_1)}{qR_1}]^2 e^{-(qs)^2}$$

J = 1st Bessel function

s = nuclear skin thickness ~1 fm

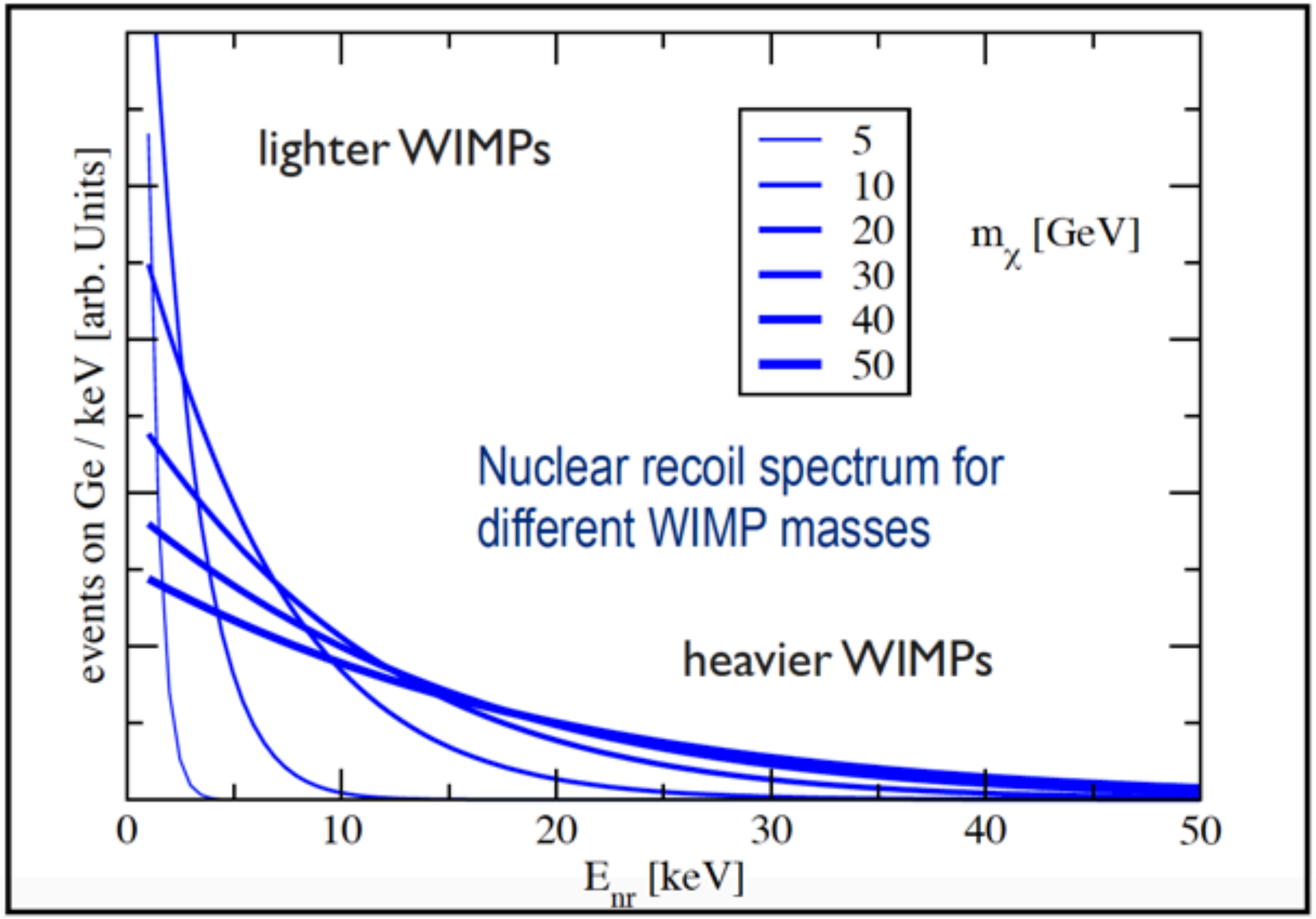
$R_1 \propto 1.14\,A^{1/3} \sim 7A^{1/3}\ \mathrm{GeV}^{-1}$

Form factor is important for large nuclei, such as Xe, W, etc.
For these targets, a low energy threshold is essential to minimize Form factor suppression of rate
At the same time, the coherence of the scattering favors large nuclei

Nuclear Recoil Energy Spectrum

Rate after integration over WIMP velocity distribution

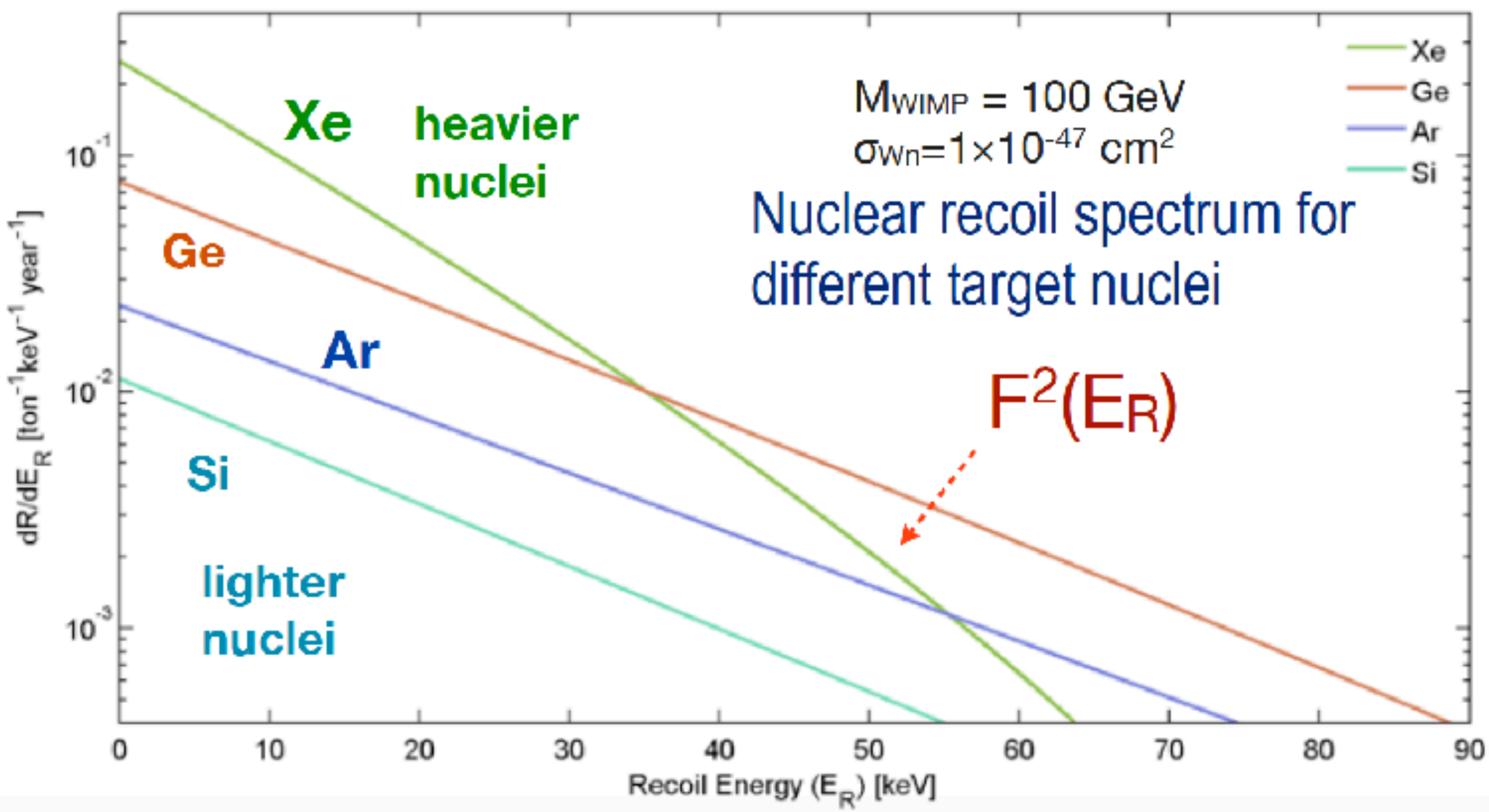
$$R \sim 0.13 \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$



Nuclear Recoil Energy Spectrum

Rate after integration over WIMP velocity distribution

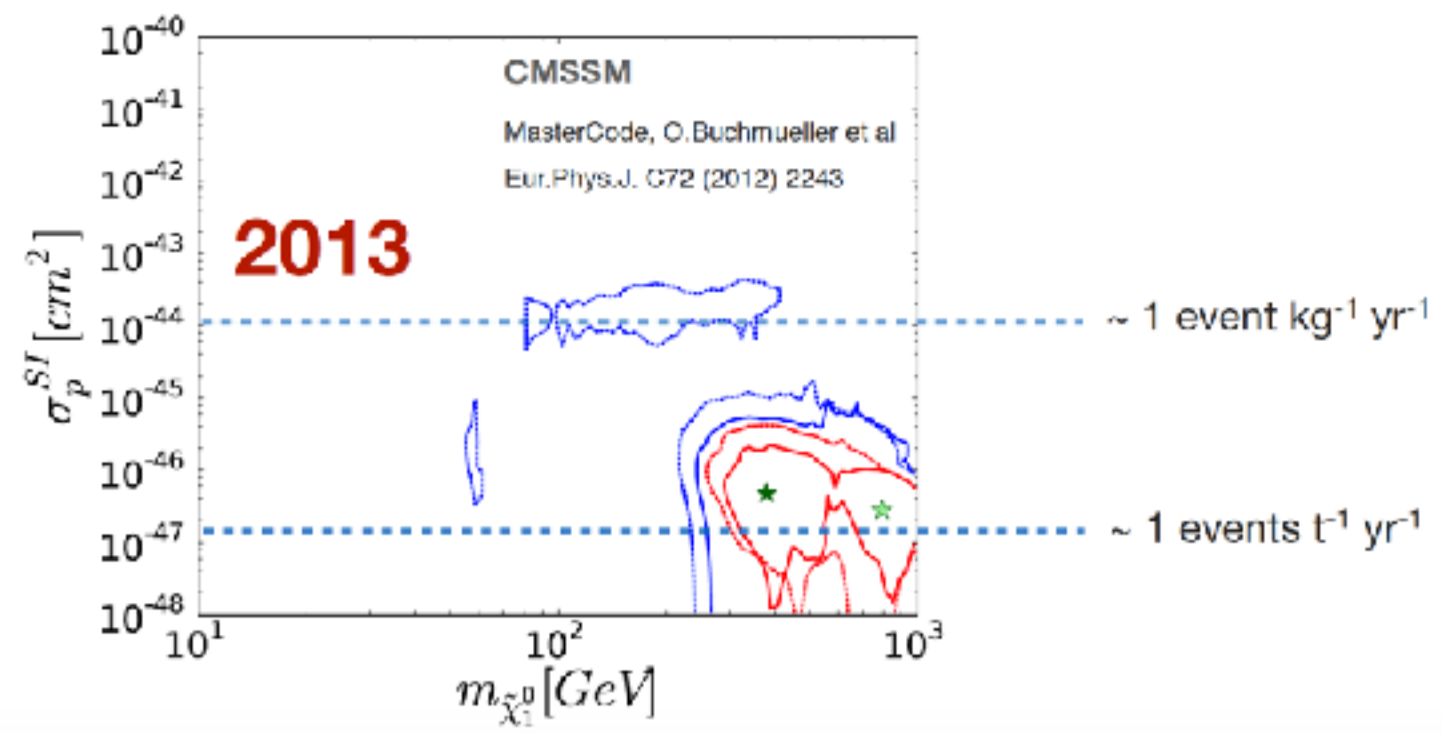
$$R \sim 0.13 \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$



Detector requirements and signatures

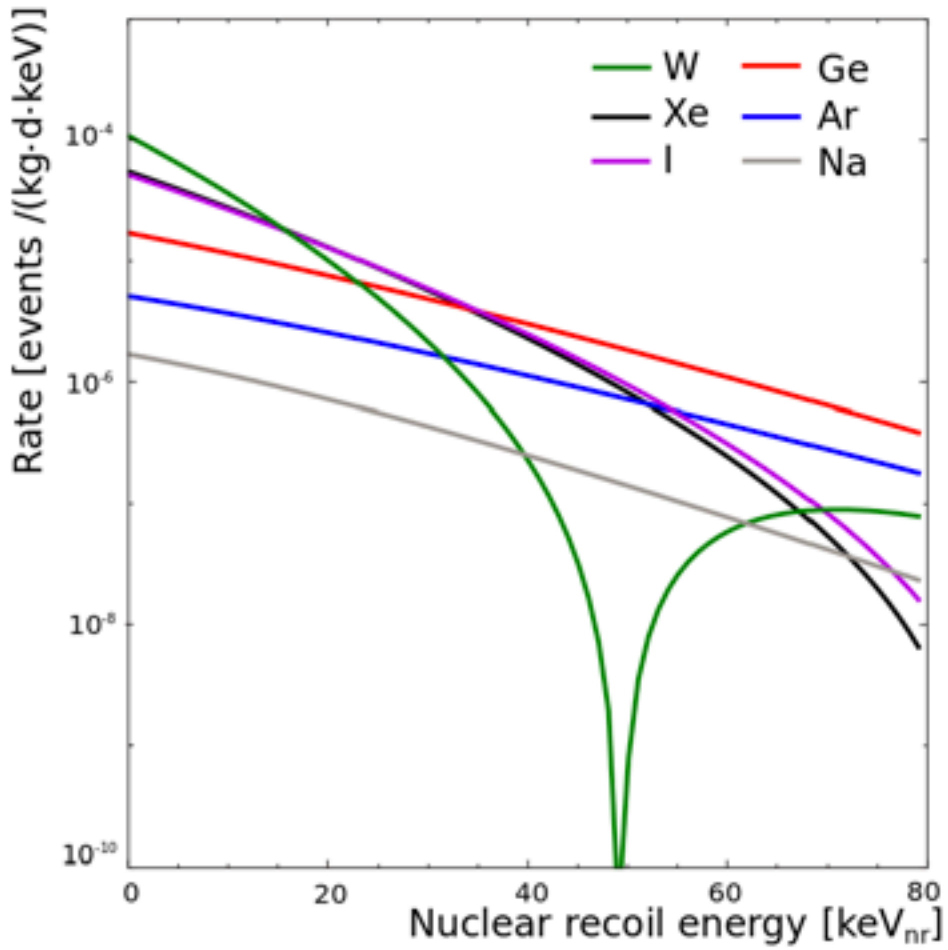
- Requirements for a dark matter detector
  - Large detector mass
  - Low energy threshold ~ sub-keV to few keV's
  - Very low background and/or background discrimination
  - Long term stability

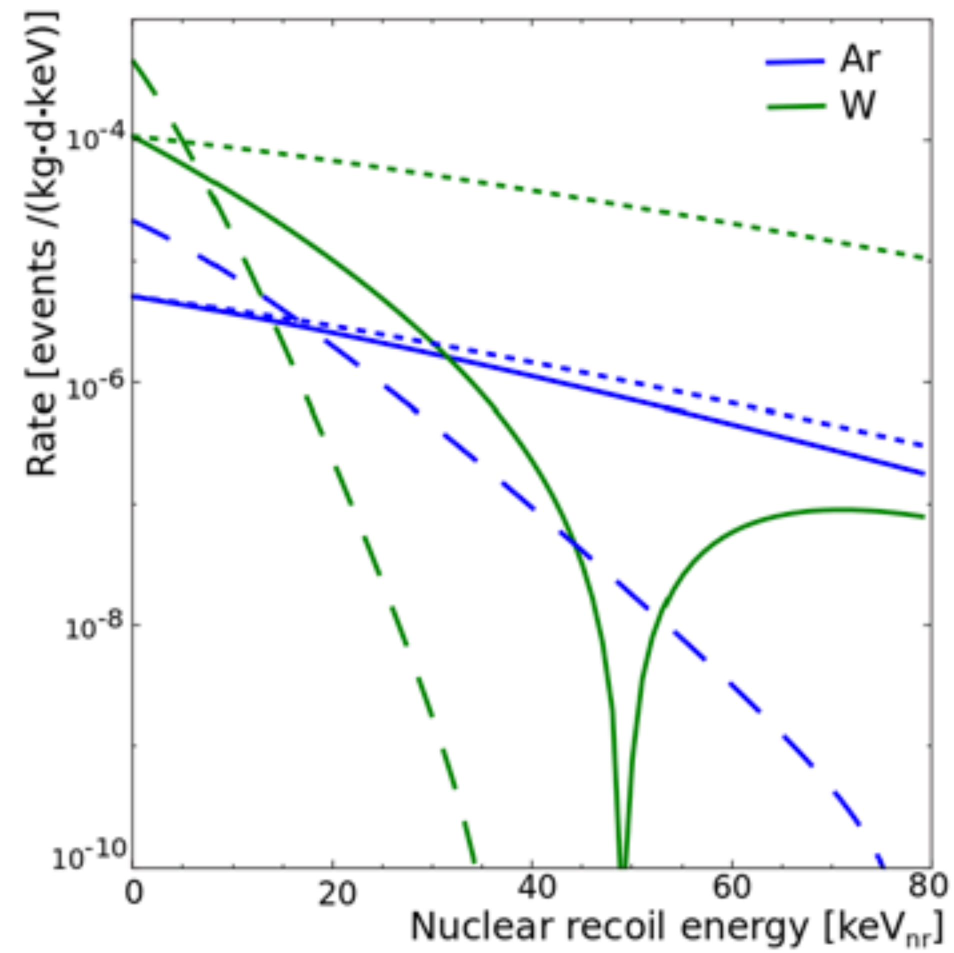
- Possible signatures of dark matter
  - Spectral shape of the recoil spectrum
  - Annual modulated rate
  - Directional dependance



Signature: spectral shape

$$\frac{dR}{dE}(E) \approx \left(\frac{dR}{dE}\right)_0 F^2(E)\exp\left(-\frac{E}{E_c}\right)$$





J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

m_W = 50 GeV

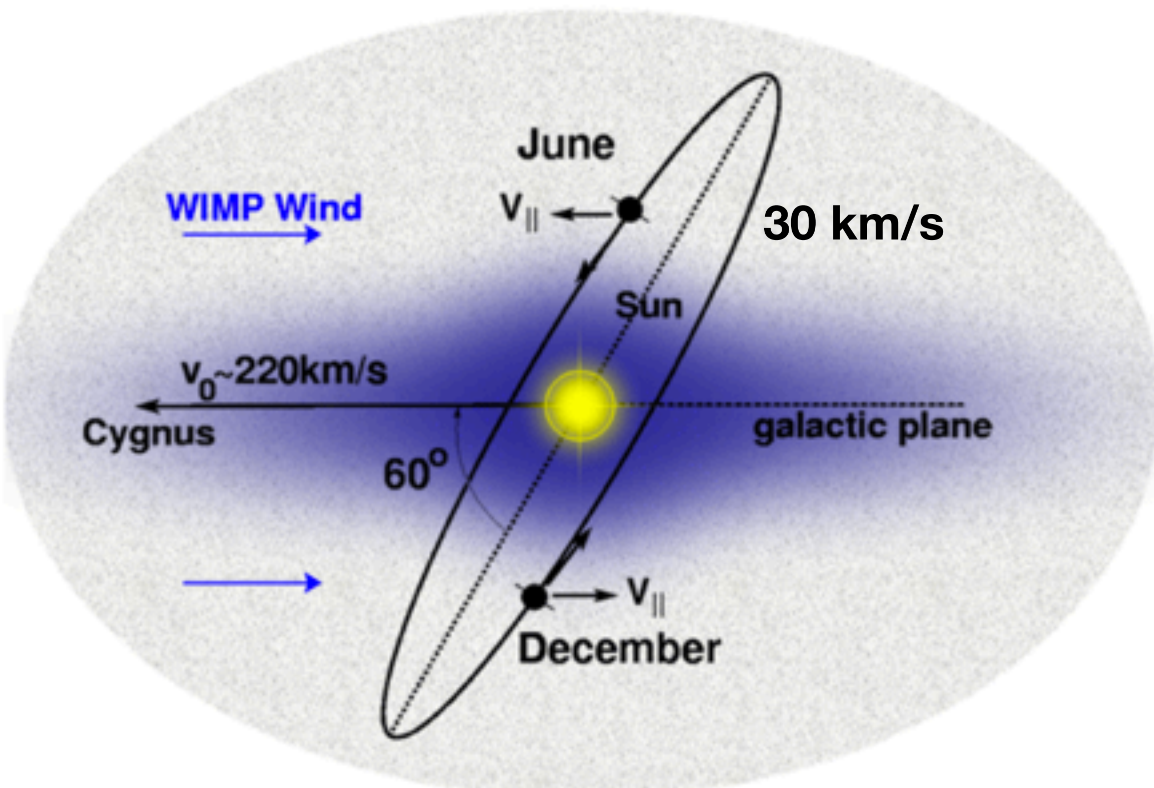
Event rates as function of nuclear recoil energy for different target materials

Dotted line: no form factor correction

Dashed line: for a 25 GeV/c^2 WIMP mass

Signature: annual modulation

$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E)\cdot\cos\left(\frac{2\pi(t-t_0)}{T}\right)$$



- Earth rotation around the Sun
- Relative speed of DM particles larger in summer
- Larger number of nuclear recoils above threshold in summer

Signature: directionality

$$\frac{dR}{dE\, d\cos\gamma} \propto \exp\left[\frac{-[(v_E + v_\odot)\cos\gamma - v_{min}]^2}{v_c^2}\right]$$

γ: NR direction relative to the mean direction of solar motion
v_E and $v_\odot$: the Earth and Sun motions
$v_c = \sqrt{3/2}v_\odot$: halo circular velocity

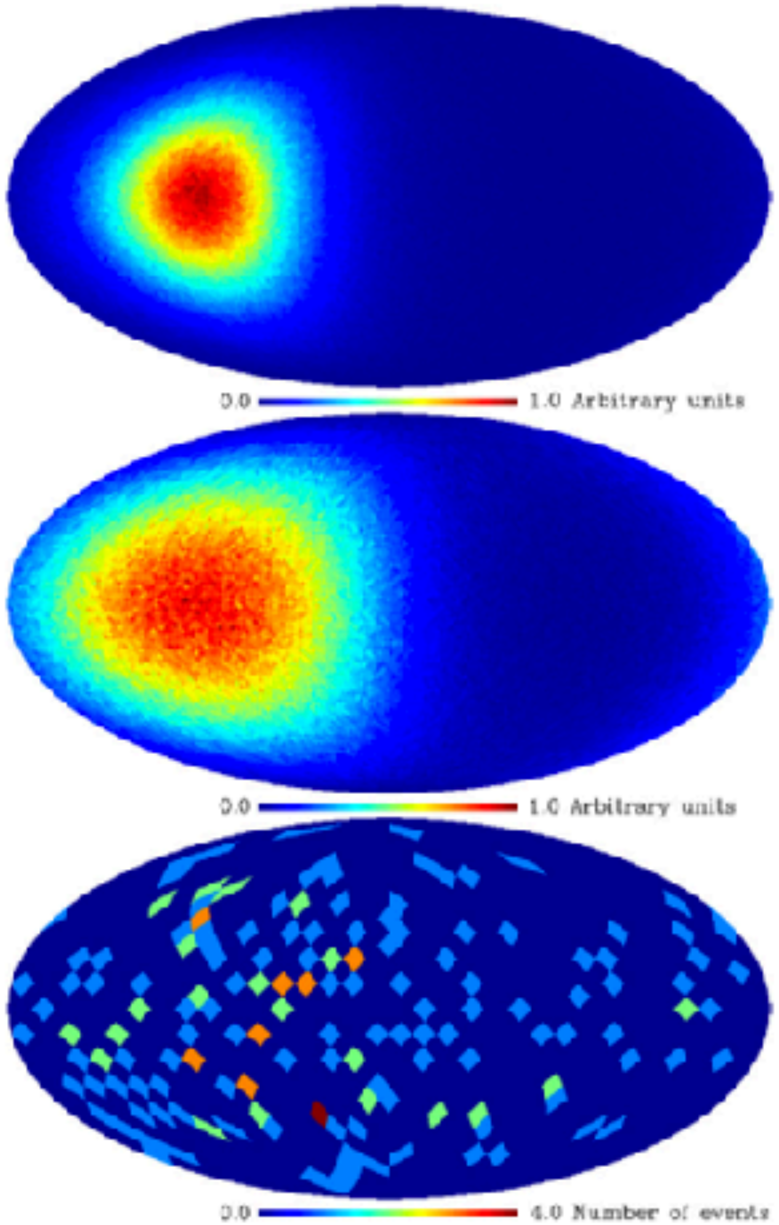
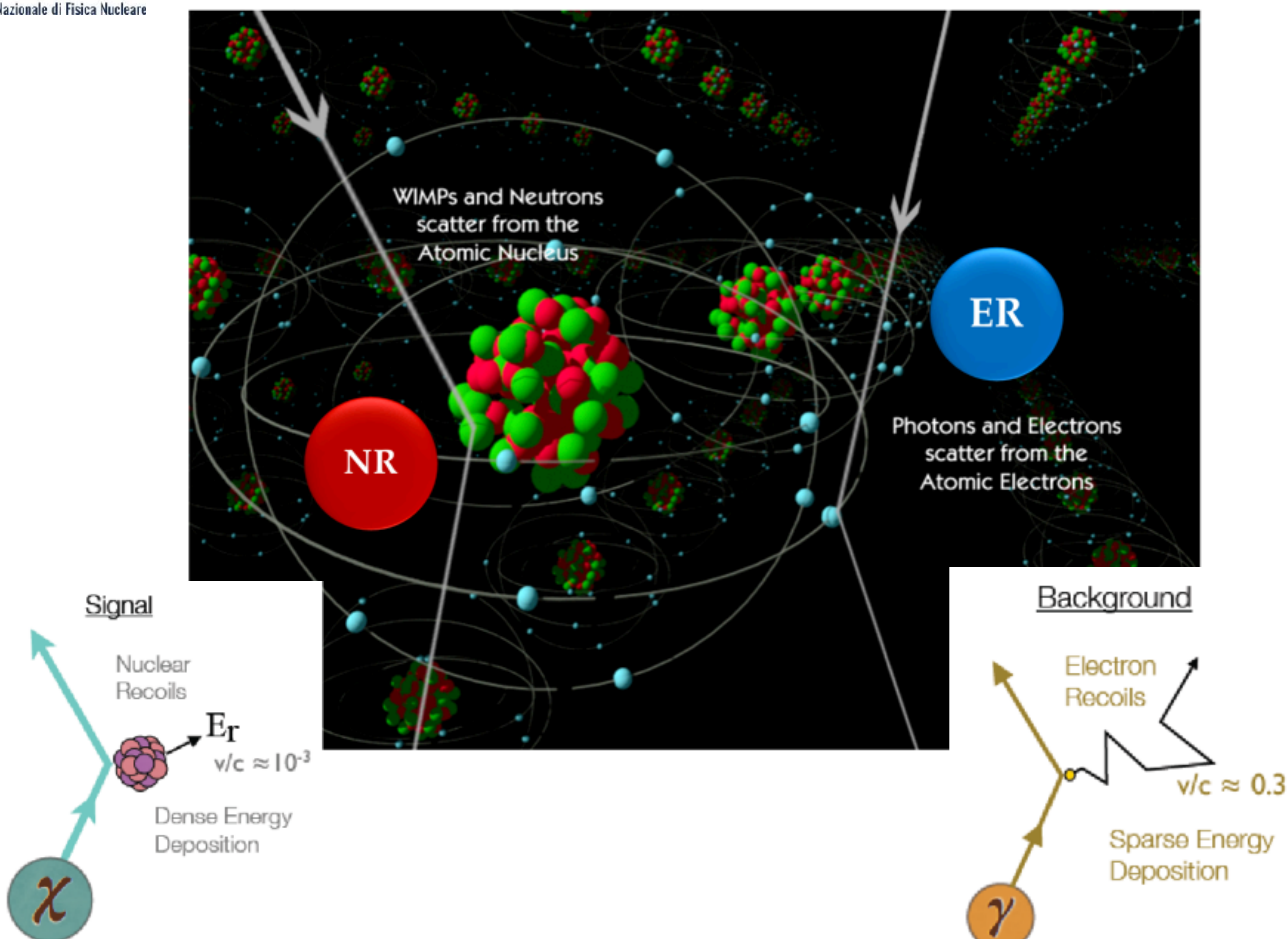


Figure from J. Billard *et al.* 2010

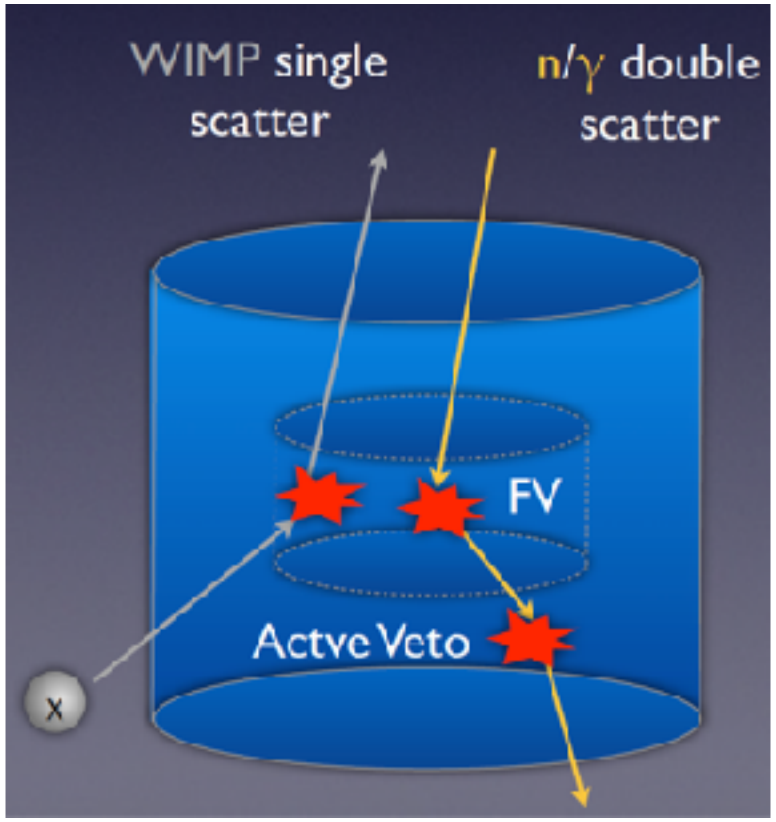
- WIMP flux in the case of an isothermal spherical halo
- WIMP-induced recoil distribution
- A typical simulated measurement: 100 WIMP recoils and 100 background events (low angular resolution)

Backgrounds: Electron & Nuclear Recoils



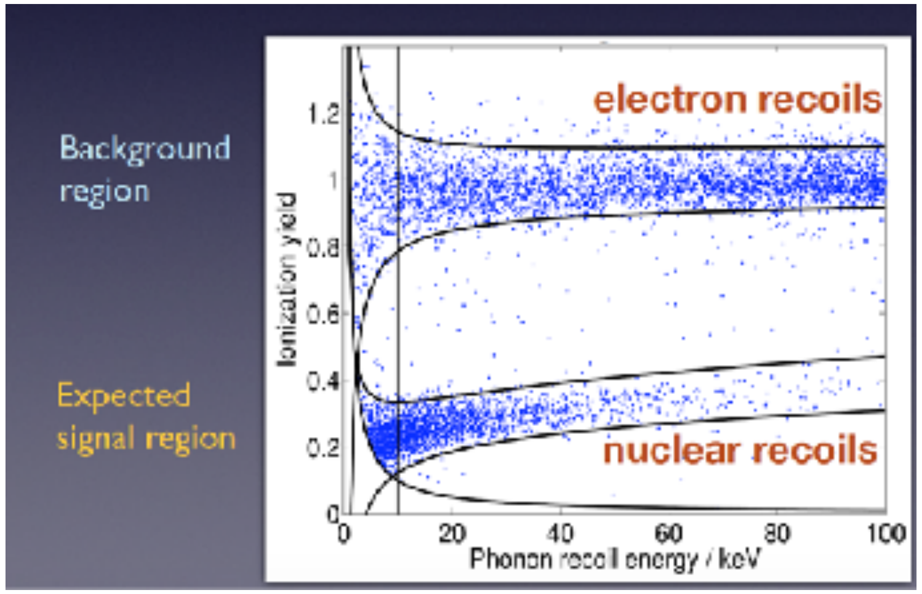
Backgrounds: external sources

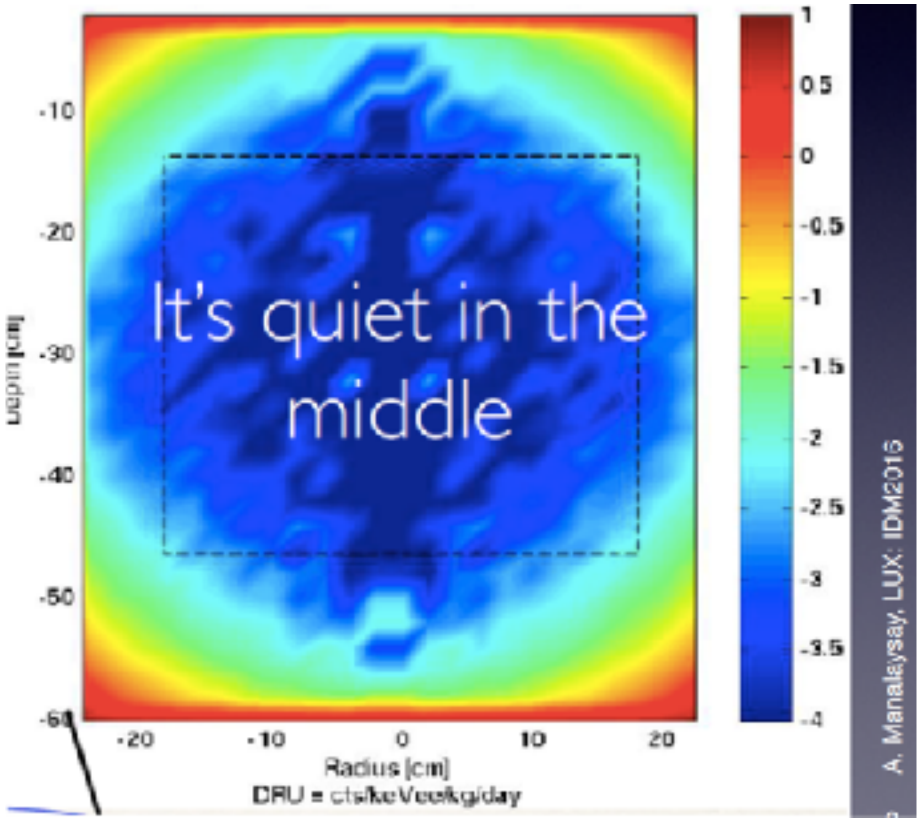
- External γ's from natural radioactivity:
  - Suppression via self-shielding of the target
  - Material screening and selection
  - Rejection of multiple scatters & discrimination



- External neutrons:
  muon-induced, (α, n) and from fission reactions
  - Go underground!
  - Shield: passive (polyethylene) or active (water/scintillator vetoes)
  - material selection for low U and Th contaminations

- Neutrinos:
  from the Sun, atmospheric and from supernovae
  - Elastic neutrino-electron scattering
  - Coherent neutrino-nucleus scattering





Natural Radioactivity

- Radioactivity is everywhere:

  Q: Radioactivity of a human body?

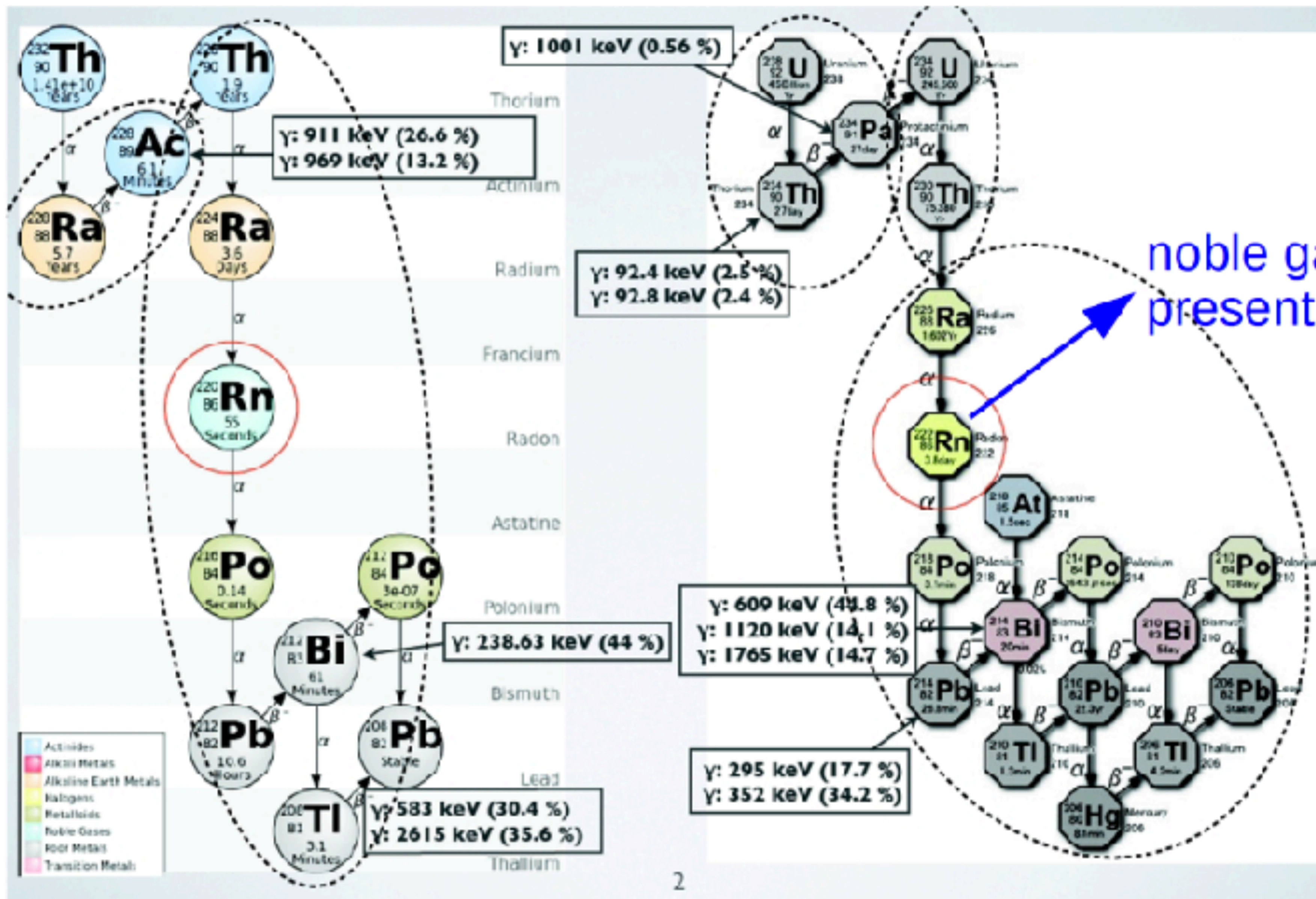
  → 4 kBq (C-14), 4 kBq (K-40: e^- + 400 γ [1.4 MeV], +8000ν)

  Q: Rn atoms escaping the ground?

  → 7000 s^{-1} m^{-2}

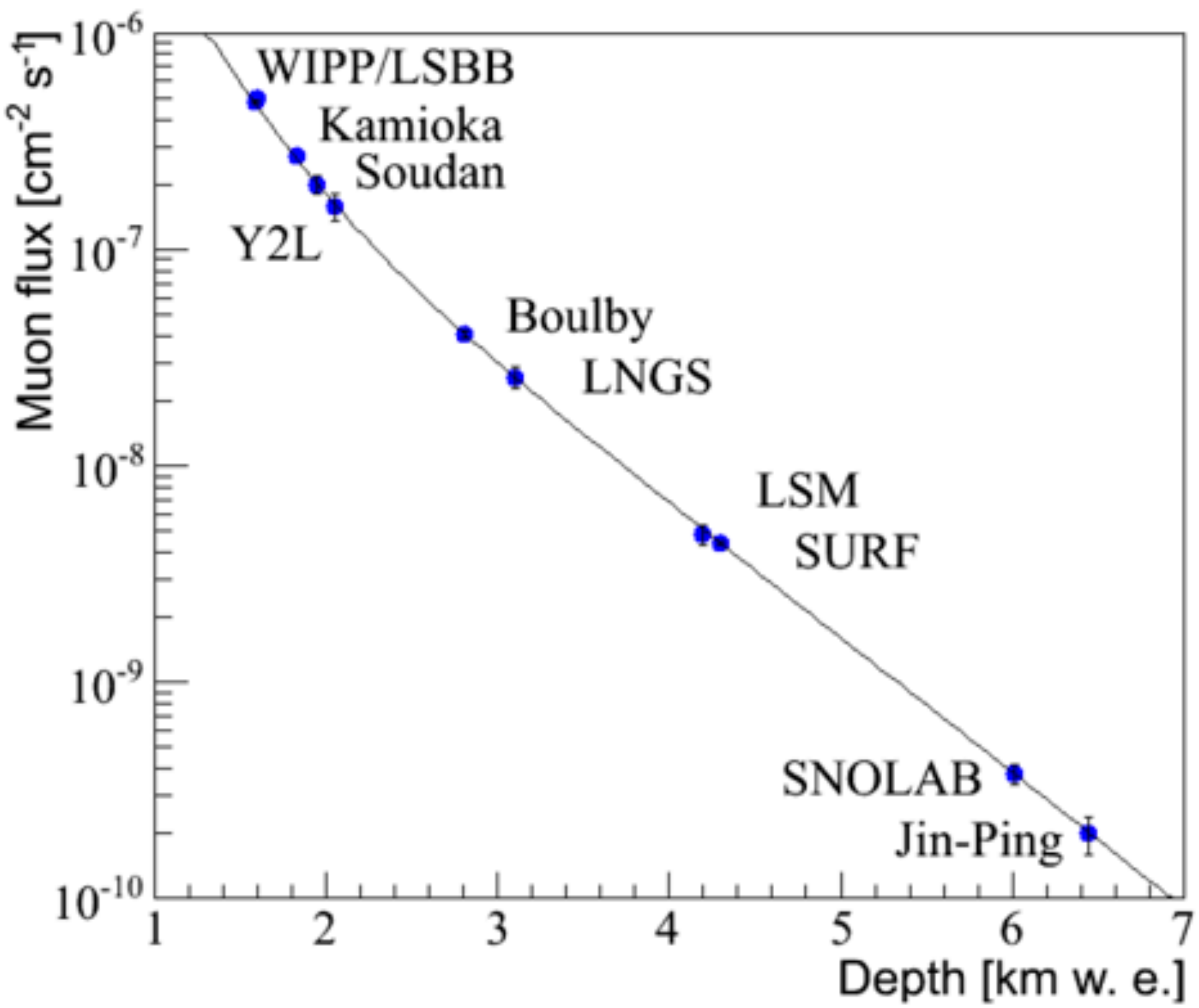
Q: Number of Pu atoms in 1kg of soil?

→ 10 million (transmutation of U-238 by CR neutrons)



noble gas, present in air

Underground laboratories



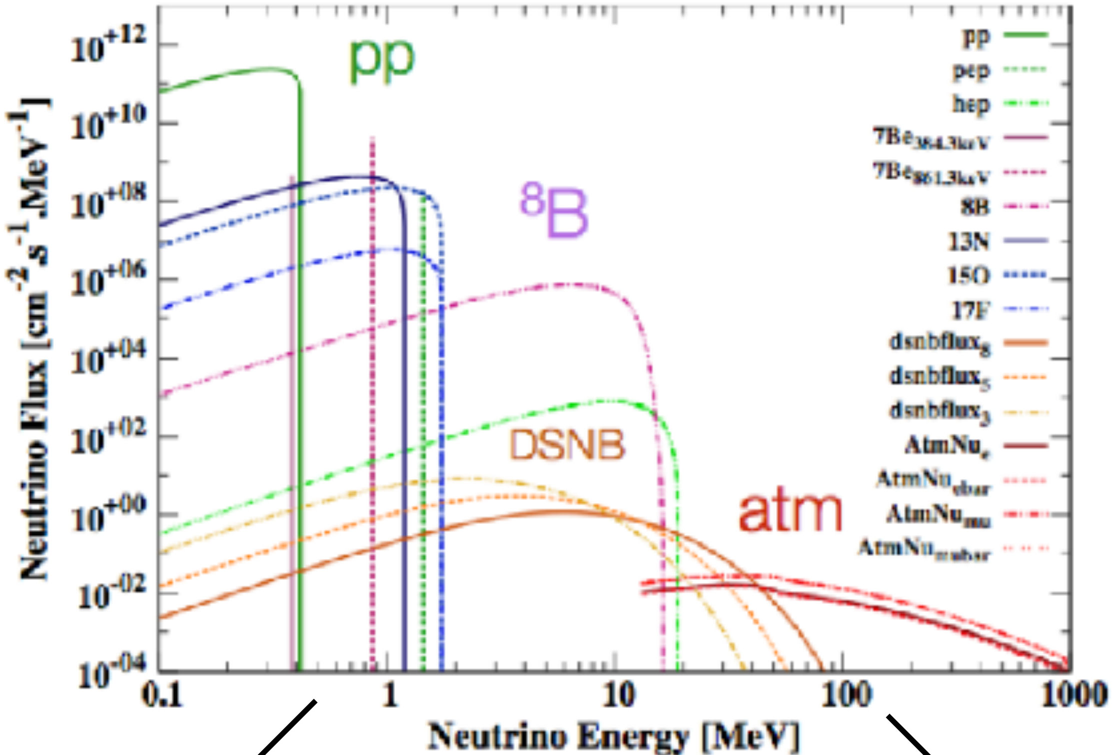
- WIPP in USA (DMTPC)
- LSBB in France (SIMPLE)
- Kamioka in Japan (XMASS, NEWAGE)
- Soudan in USA (SuperCDMS, GoGeNT)
- Y2L in Corea (KIMS)
- Boulby in UK (DRIFT, ZEPLIN)
- LNGS in Italy (XENON, DAMA, Cresst, DarkSide)
- LSM in France (Edelweiss, MIMAC)
- SURF in USA (LUX)
- SNOLAB in Canada (DEAP/CLEAN, PICASSO, COUPP)
- Jin-Ping in China (PandaX, CDEX)

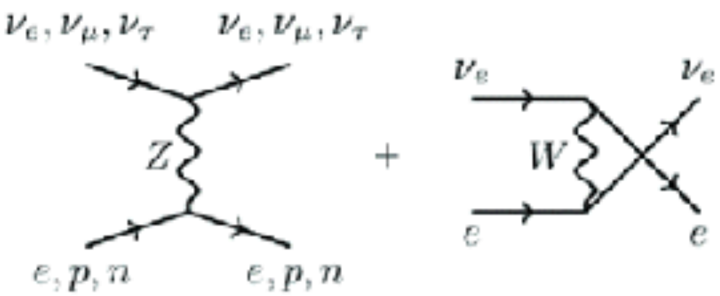
Underground laboratories

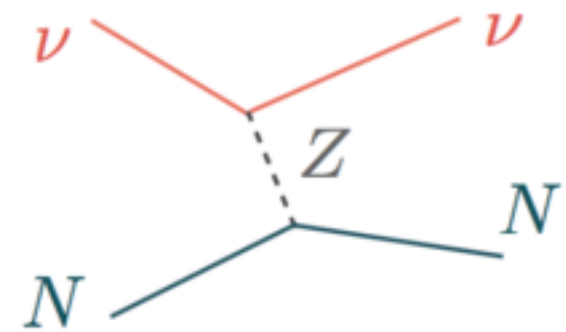
Backgrounds: internal and surface sources

- Internal contamination in liquids:
  - ^{85}Kr: removal by cryogenic distillation/chromatography/centrifuges
  - Rn: removal using activated carbon, distillation, dust removal
  - Argon: ^{39}Ar (565 keV endpoint, 1 Bq/kg), ^{42}Ar
  - Xenon: ^{136}Xe $\beta\beta$ decay ($T_{1/2} = 2.2 \times 10^{21}$ y) *long lifetime!*
- Surface background in solids:
  - Germanium detectors or solid scintillators grown out of high purity powders or melts → low intrinsic background
  - Cosmic activation
  - Surface events from α or β-decays

The ultimate background from neutrinos



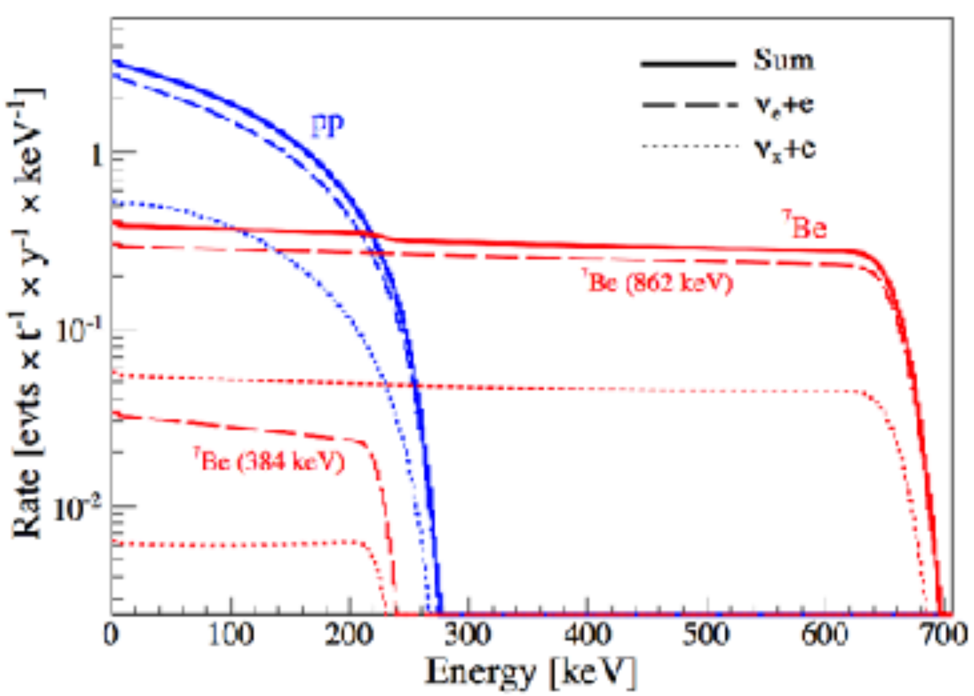


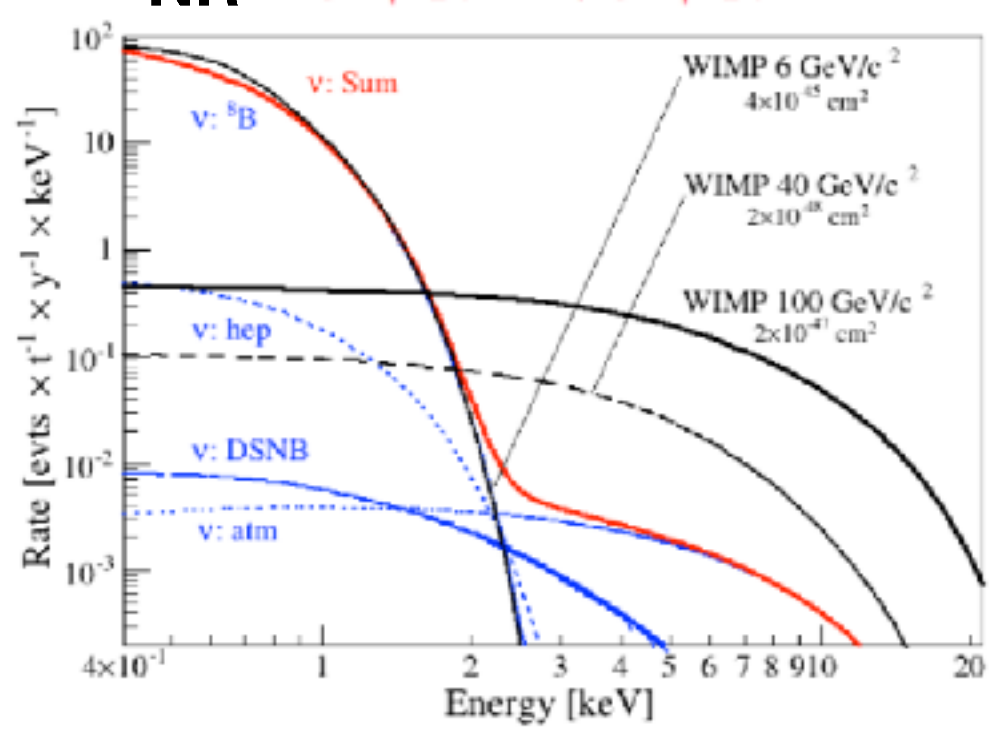


F. Ruppin et al., 1408.

ER

NR $\nu + N \longrightarrow \nu + N$





LB et al., JCAP01 (2014) 044

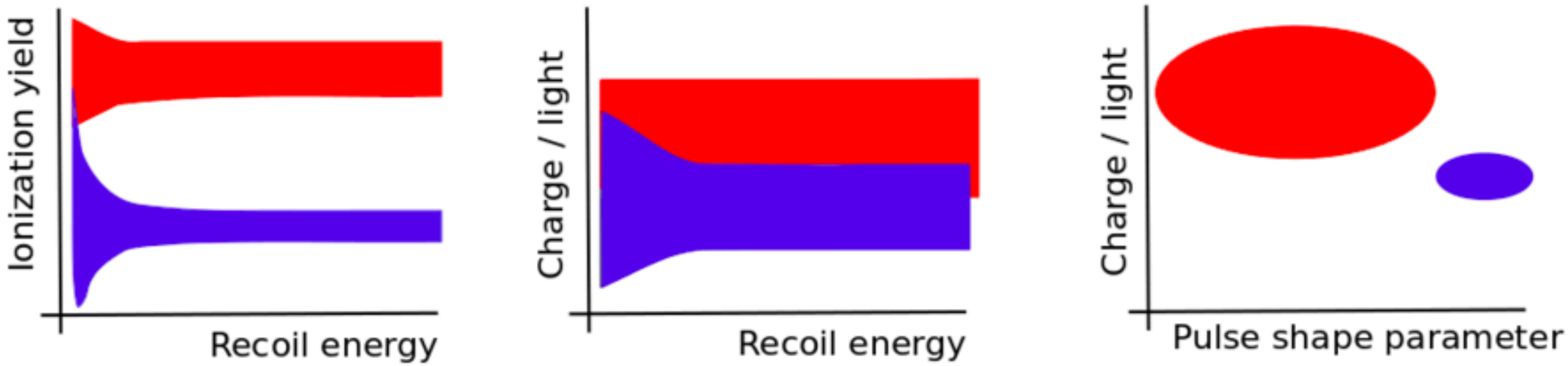
Detector Calibration

Purposes of detector calibration:

- Data stability:
  monitoring of detector parameters (amplification of signals, slow control parameters, ..) and of the related electronics
- Determination of energy scale:
  detector signals are photoelectrons, charges or heat
  → need to convert to keV_{nr}
- Determination of signal and background regions:
  description of nuclear and electronic recoil regions

INFN Istituto Nazionale di Fisica Nucleare

Detector Calibration: Signal & Background

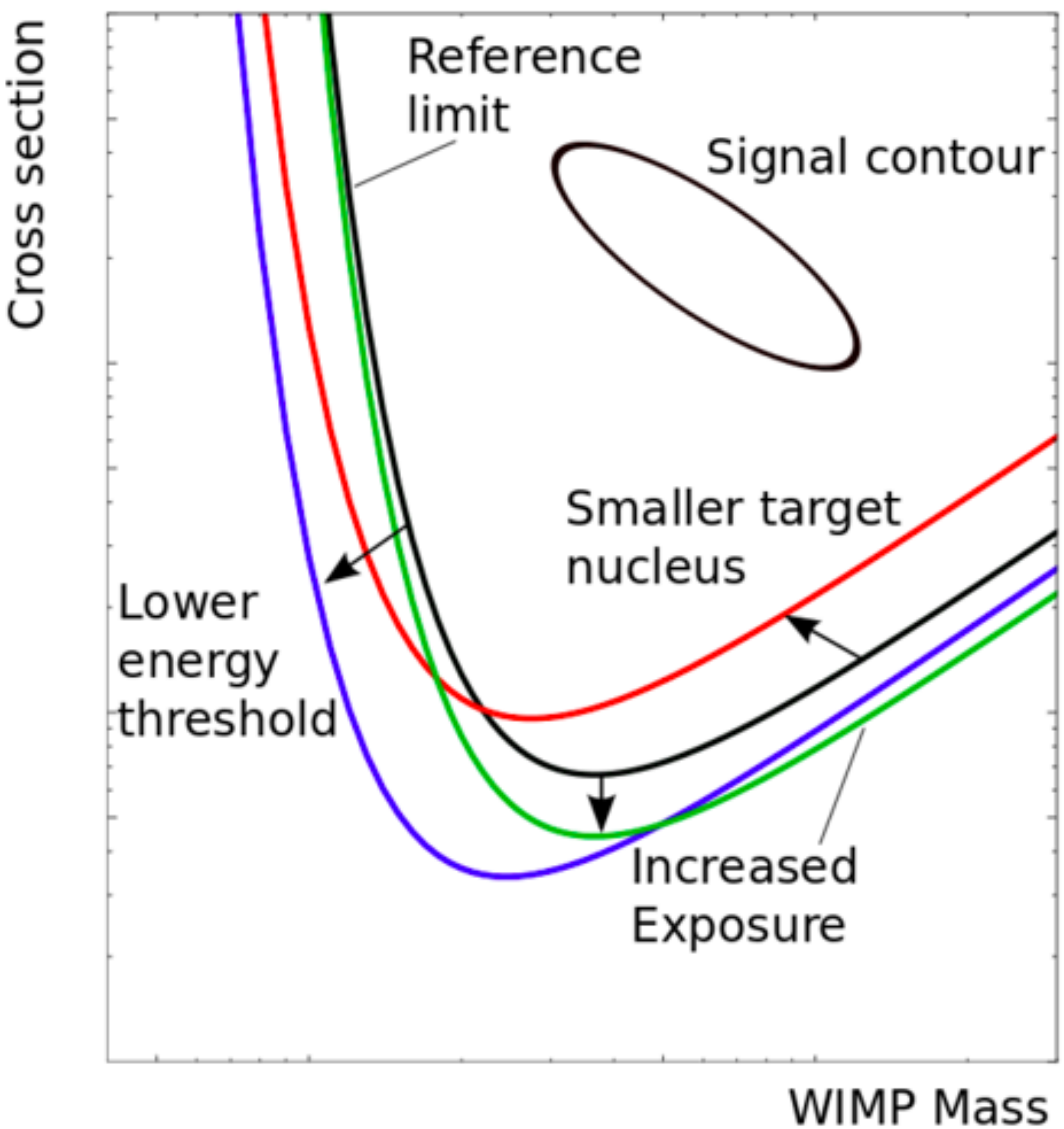


- Discrimination in a cryogenic germanium detector (left)
  No surface events included!
- Discrimination in a liquid xenon detector (middle)
- Discrimination in a liquid argon detector (right)
  Two parameters available for discrimination

Sensitivity plot in direct DM experiments

→ Statistical significance of signal over expected background?

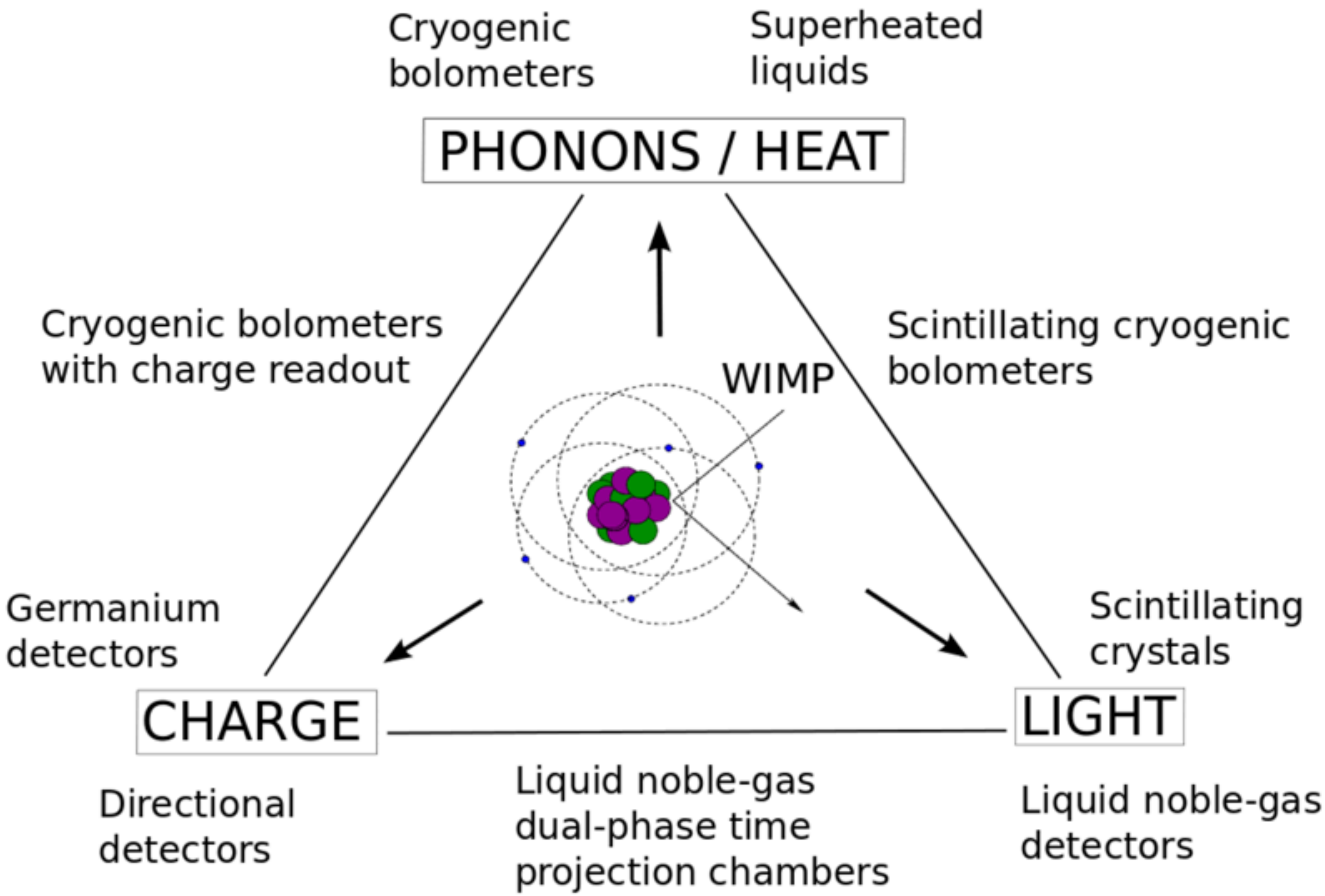
J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767



- **Positive signal**
  - Region in σ_χ versus m_χ
- **Zero signal**
  - Exclusion of a parameter region

  - Low WIMP masses: detector threshold matters
  - Minimum of the curve: depends on target nuclei
  - High WIMP masses: exposure matters $\epsilon = m \times t$

Direct detection Techniques



J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

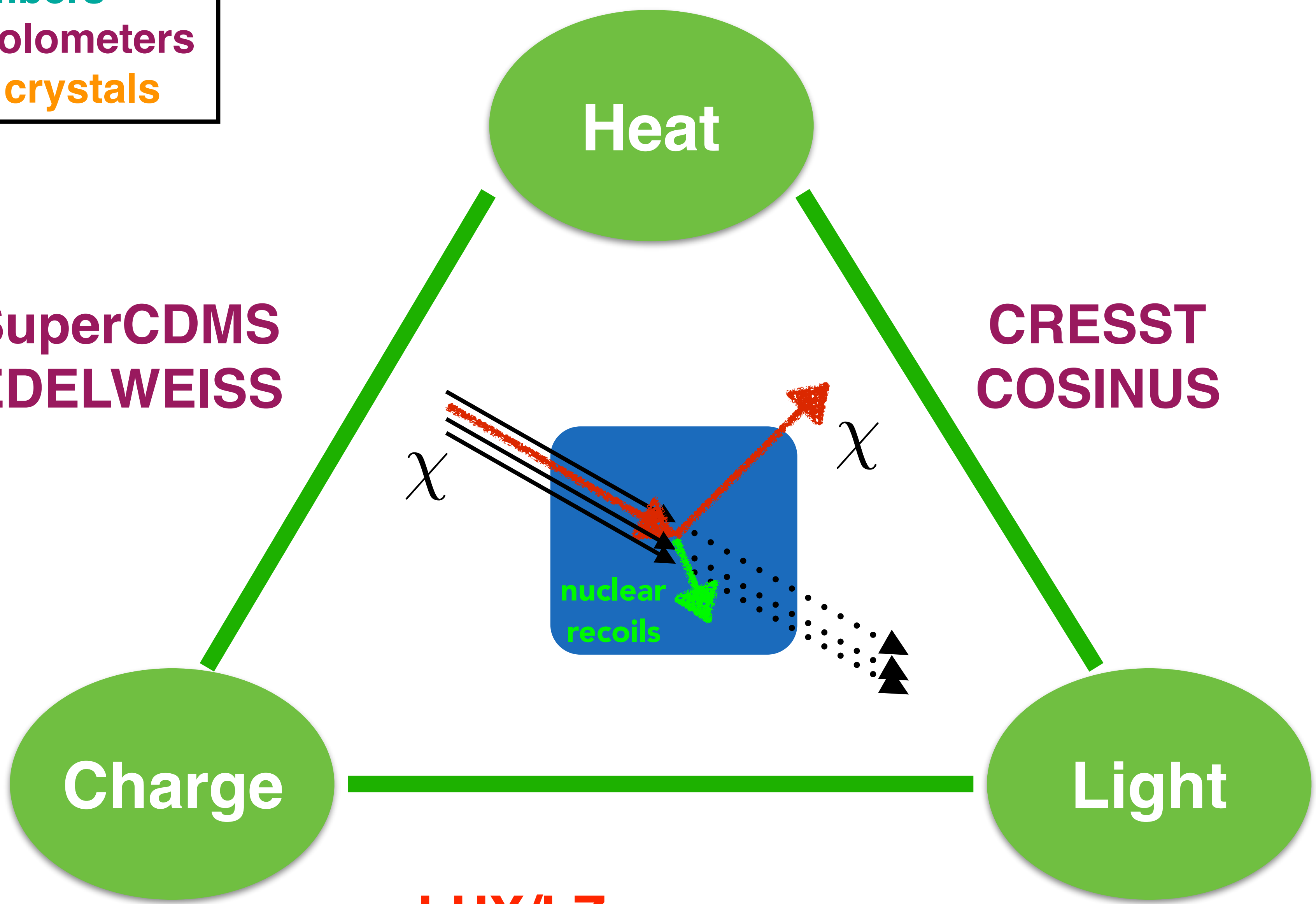
Direct Detection Techniques

- Liquid argon
- Liquid xenon
- Directional detectors
- Low-threshold
- Bubble chambers
- Cryogenic bolometers
- Scintillating crystals

SIMPLE
PICASSO
COUPP
PICO

SuperCDMS
EDELWEISS

CRESST
COSINUS



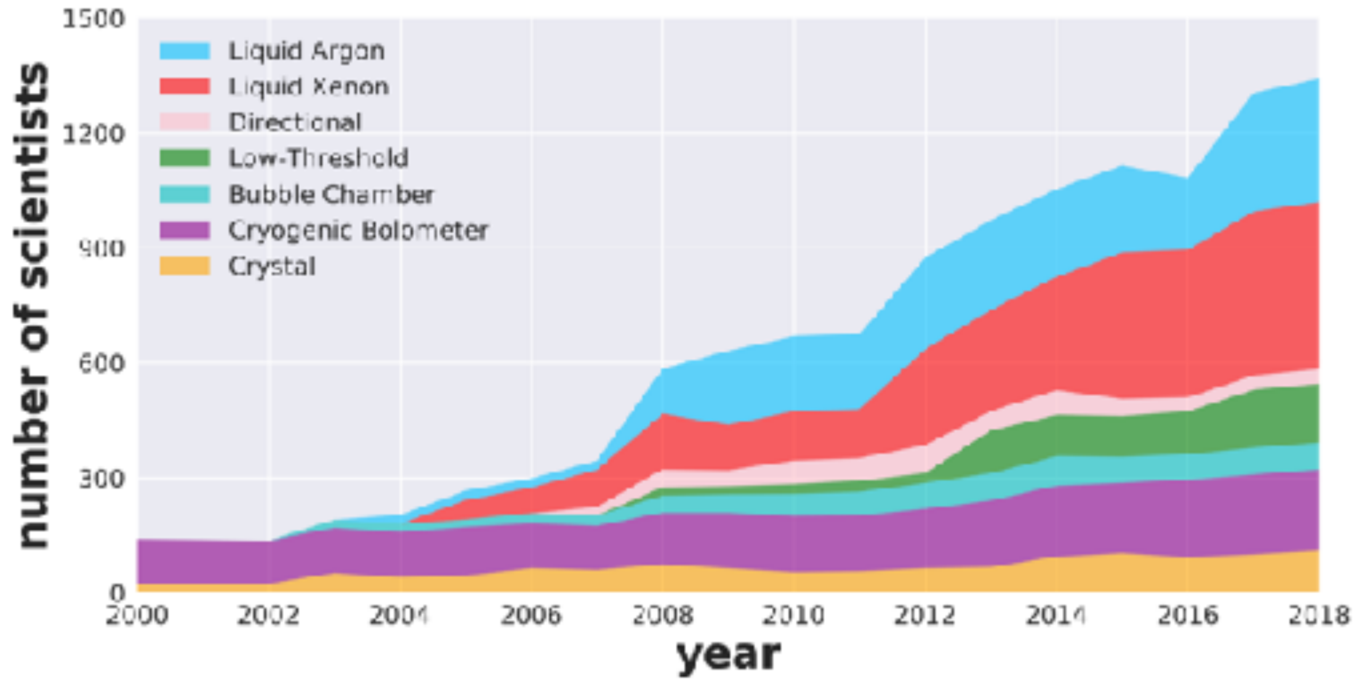
CoGeNT
CDEX
DAMIC
SENSEI
NEWS-G
DRIFT
MIMAC
DMTPC

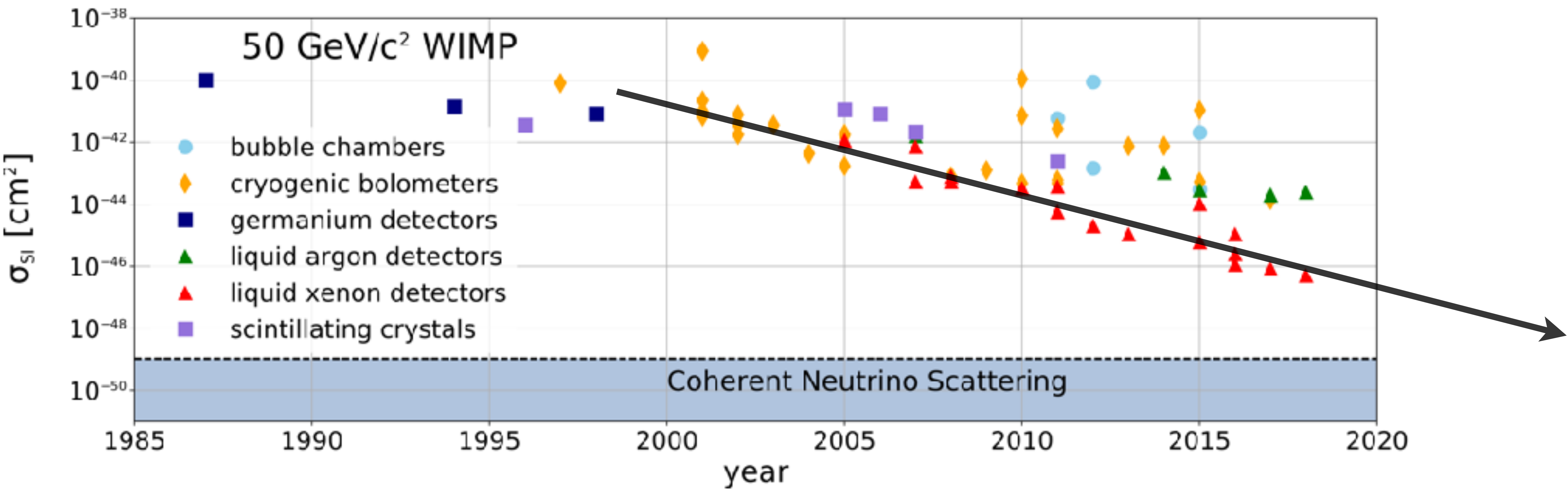
LUX/LZ
PandaX
XENON

ArDM
DarkSide

DAMA
DM-Ice
COSINE
SABRE
ANAIS
PICO-LON
DEAP
XMASS

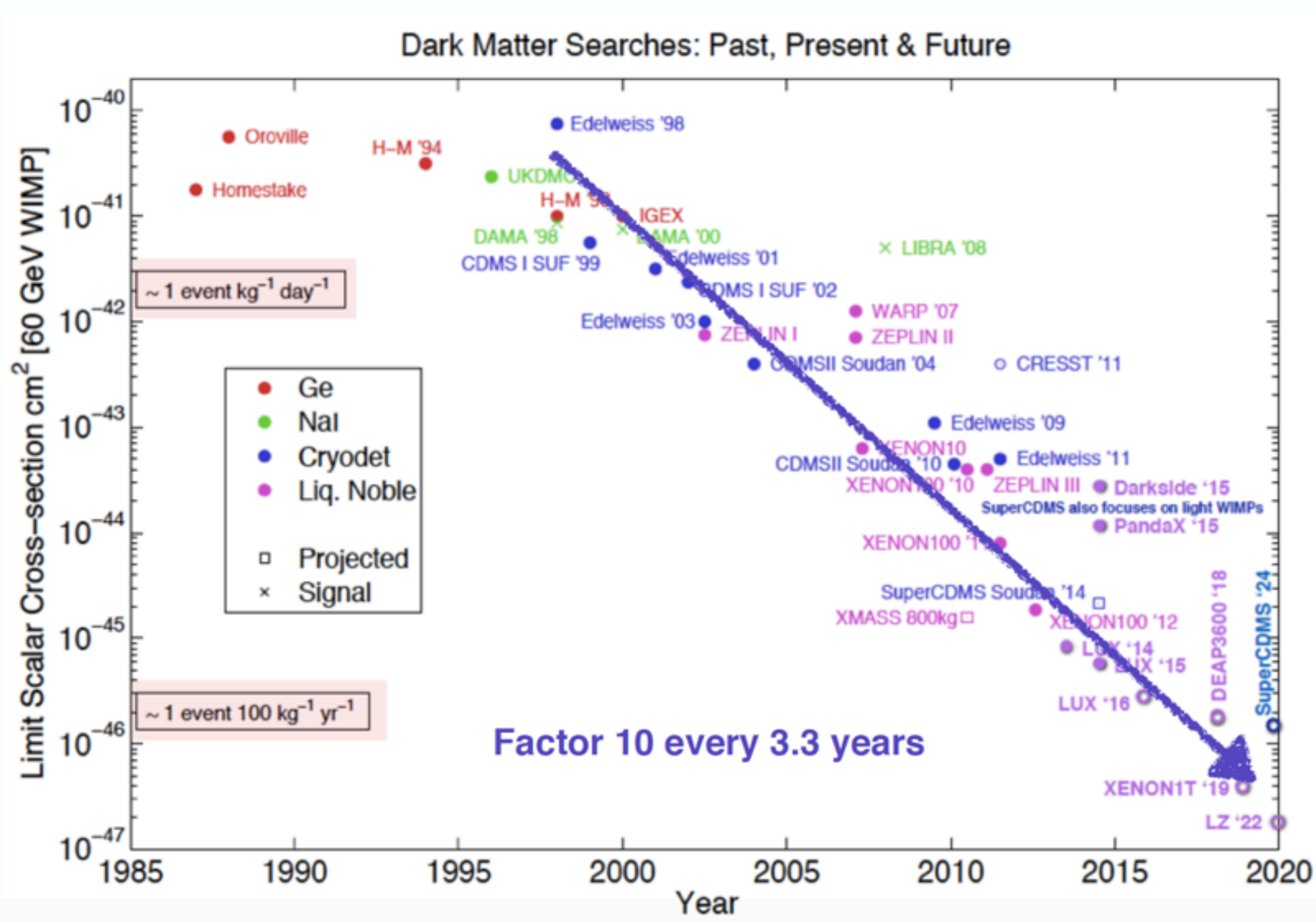
Competitive field, rapid progress





detector sensitivity improved by ~5 orders of magnitude in the last 20 years

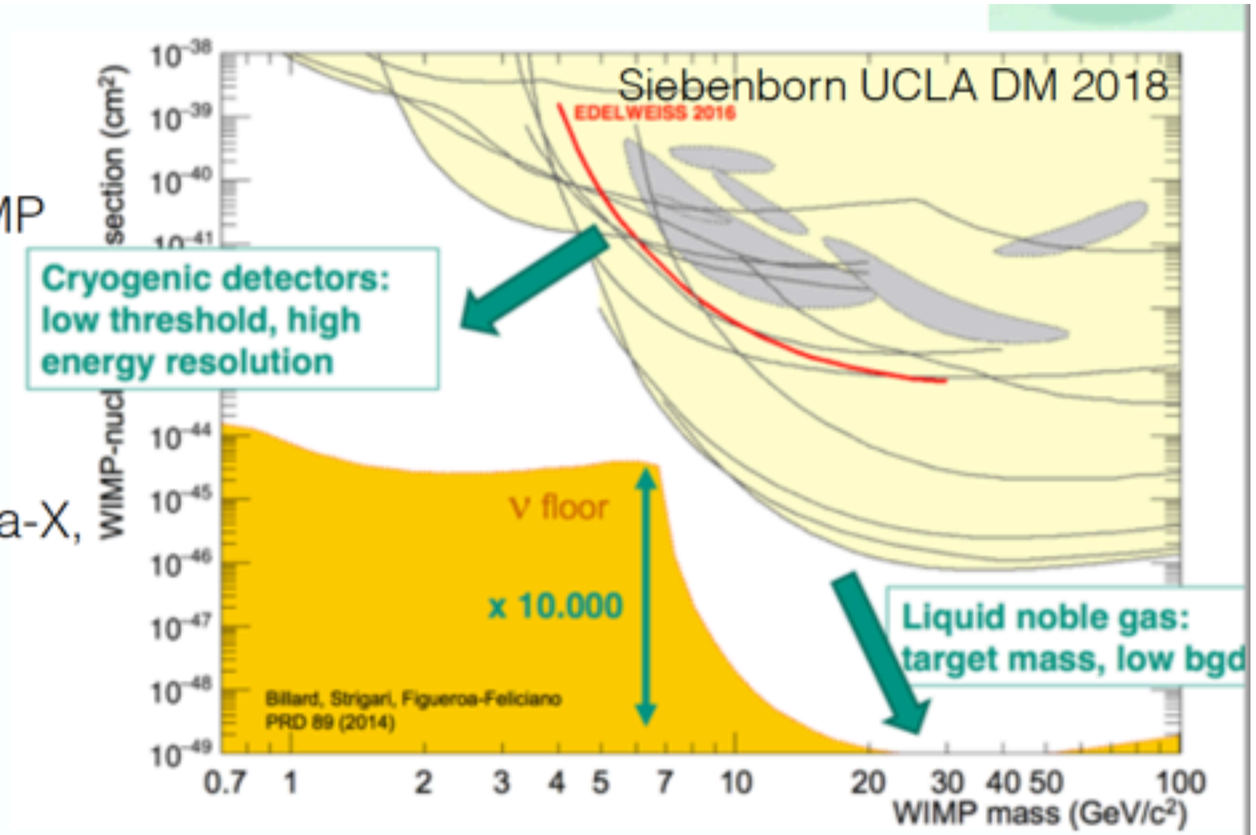
Competitive field, rapid progress

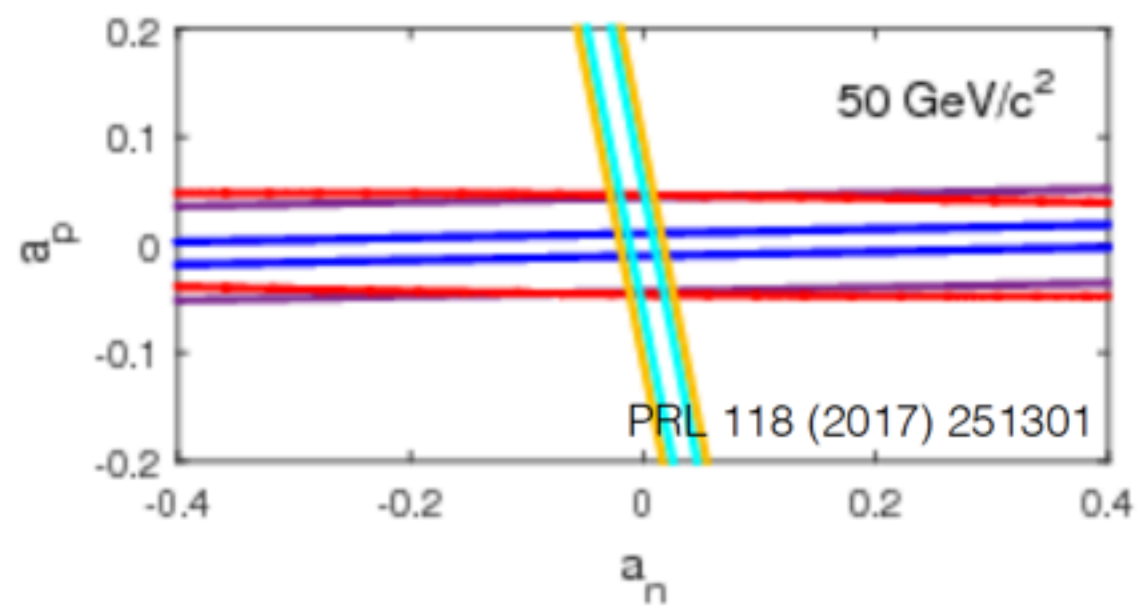


detector sensitivity improved by ~5 orders of magnitude in the last 20 years

Two main lines of improvements (+ others)

- **Liquid Noble targets**
  - Largest and most sensitive over the widest WIMP range
  - 5 GeV-1 TeV WIMP masses probed
  - Darkside, DARWIN, DEAP3600, LUX, LZ, Panda-X, XENON1T, XENONnT
- **Cryogenic crystal targets**
  - Oldest technology, with new innovations
  - 1-10 GeV WIMP masses probed
  - CRESST, EDELWEISS, SuperCDMS,
- **Alternate targets with unique properties**
  - NaI crystals, bubble chambers
  - ANAIS, COSINE, DAMA/LIBRA, SABRE, PICO



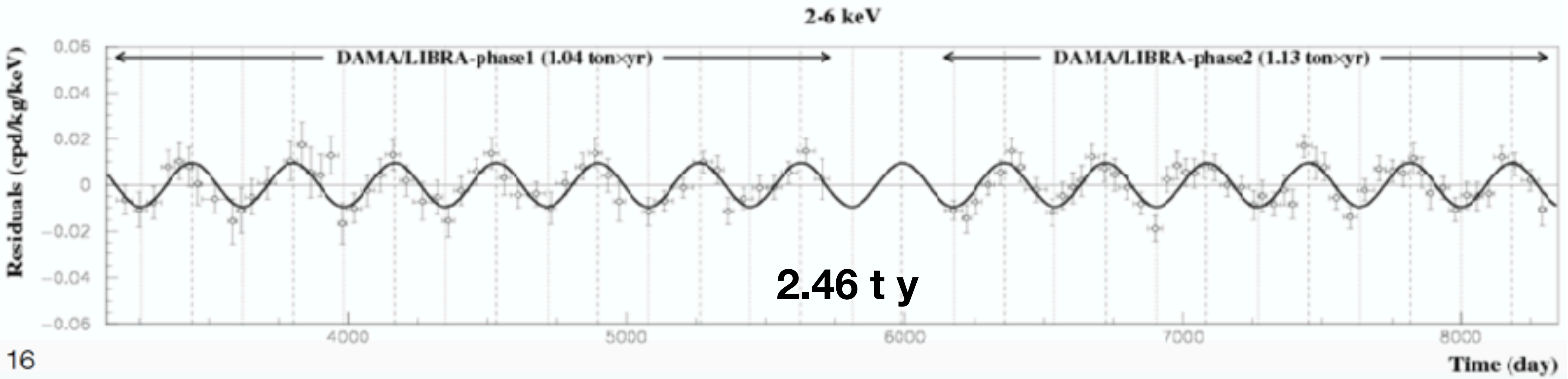


Scintillating crystals

- Mostly NaI (Tl) and CsI (Tl) used in dark matter searches
- Arrays of several crystals at room temperature
  → simple operation, important for long-term stability
- No particle discrimination
  → Low radioactivity of the target material
  → Rejection of multiple scatters in different crystals

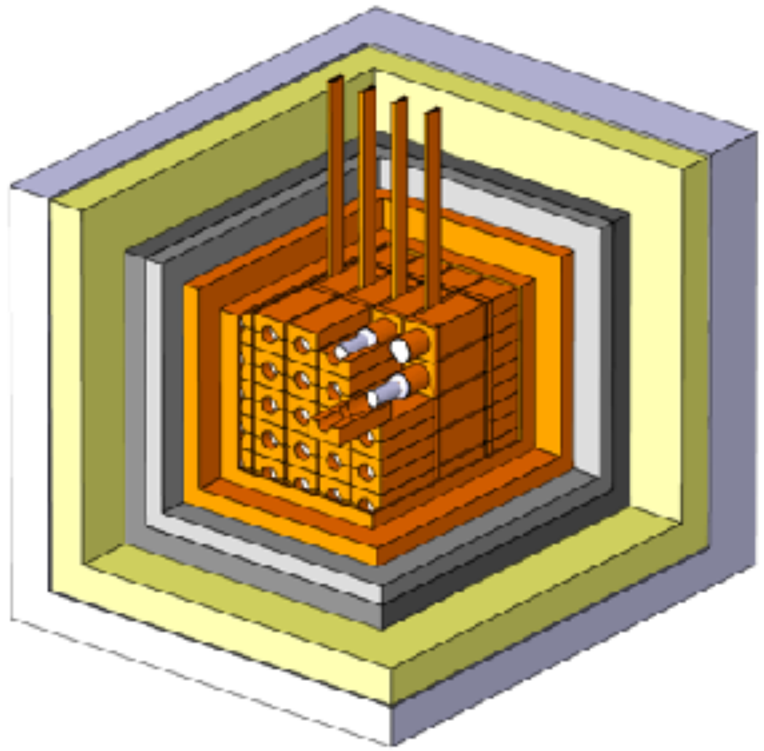
DAMA-LIBRA new results

- DAMA and DAMA/LIBRA phase 1
  - 250-kg high-purity NaI(Tl) array collected data for 14 solar cycles
  - observed ~0.01 cpd/kg/keV modulation in 2 - 6 keV energy range
  - over 9 σ stat. significant; WIMP signal interpretation in tension with other experiments
- DAMA/LIBRA phase 2 arXiv:1805.10486
  - 250-kg high-purity NaI(Tl) array collected data for 6 solar cycles
  - 2-6 keV range combined now gives 12.9 σ stat. significant
  - Modulation clearly evident in lowest energy bins now too (1-3 keV)

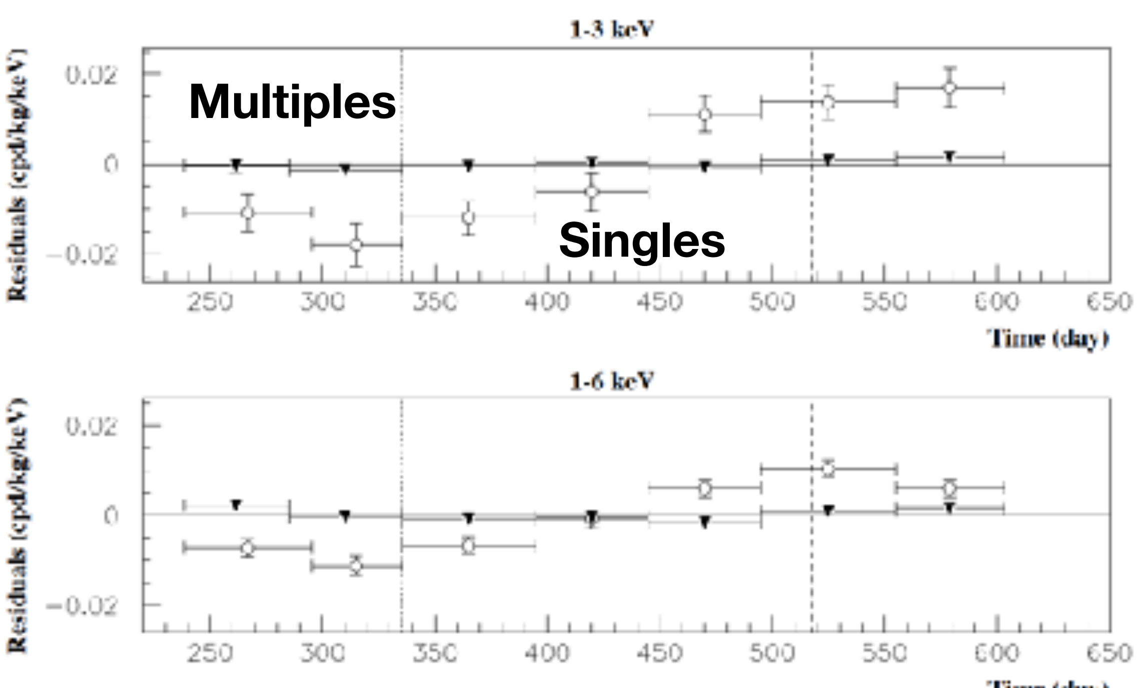


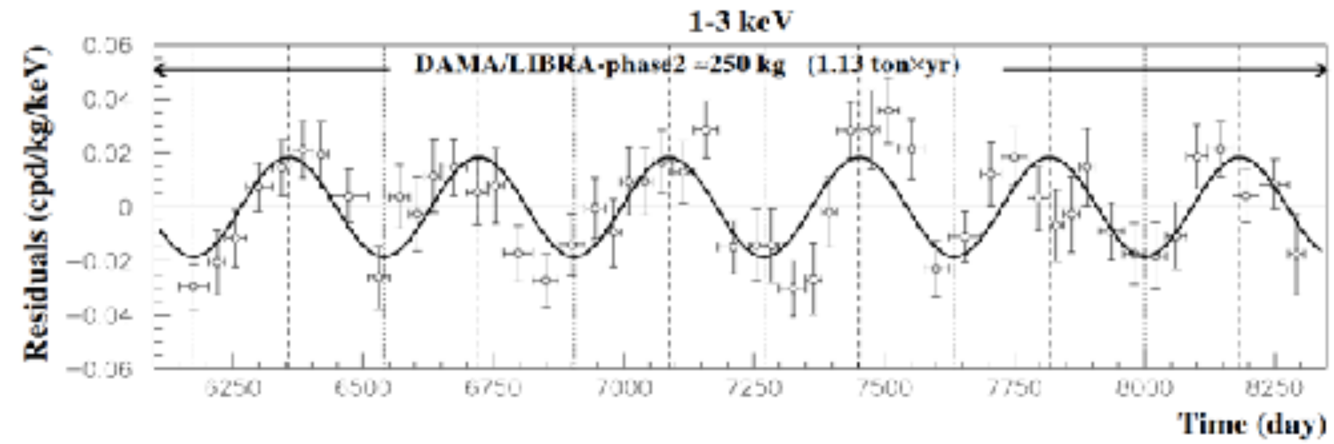
INFN
Istituto Nazionale (

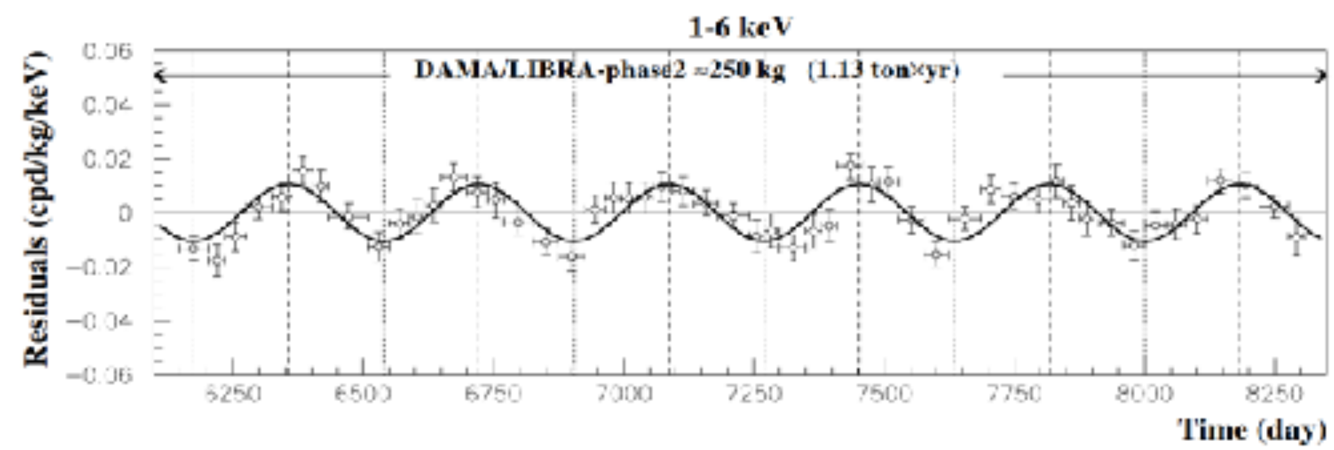
DAMA-LIBRA new results

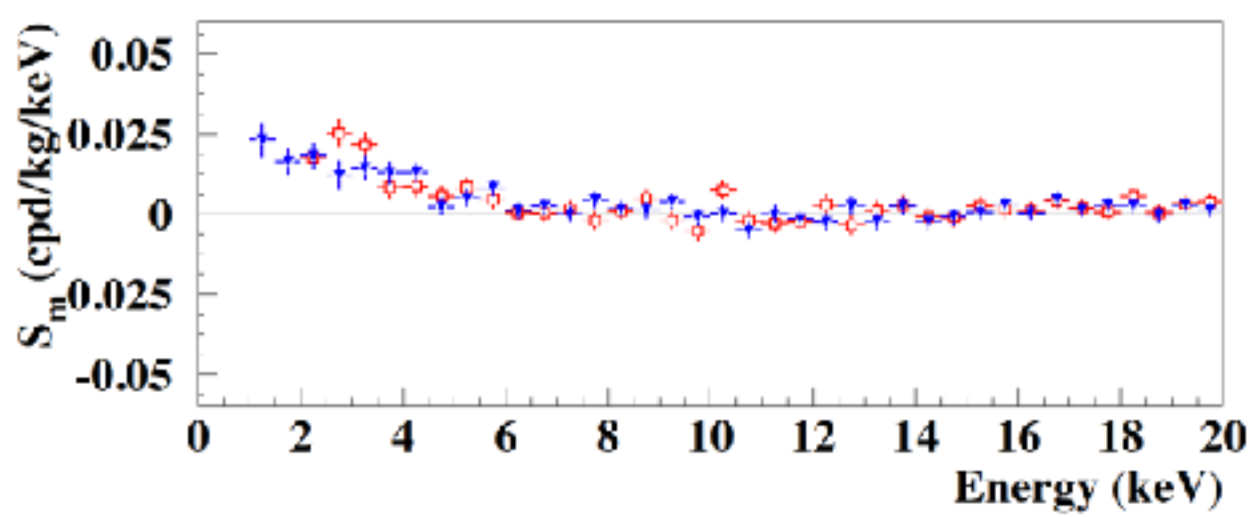


a) b)





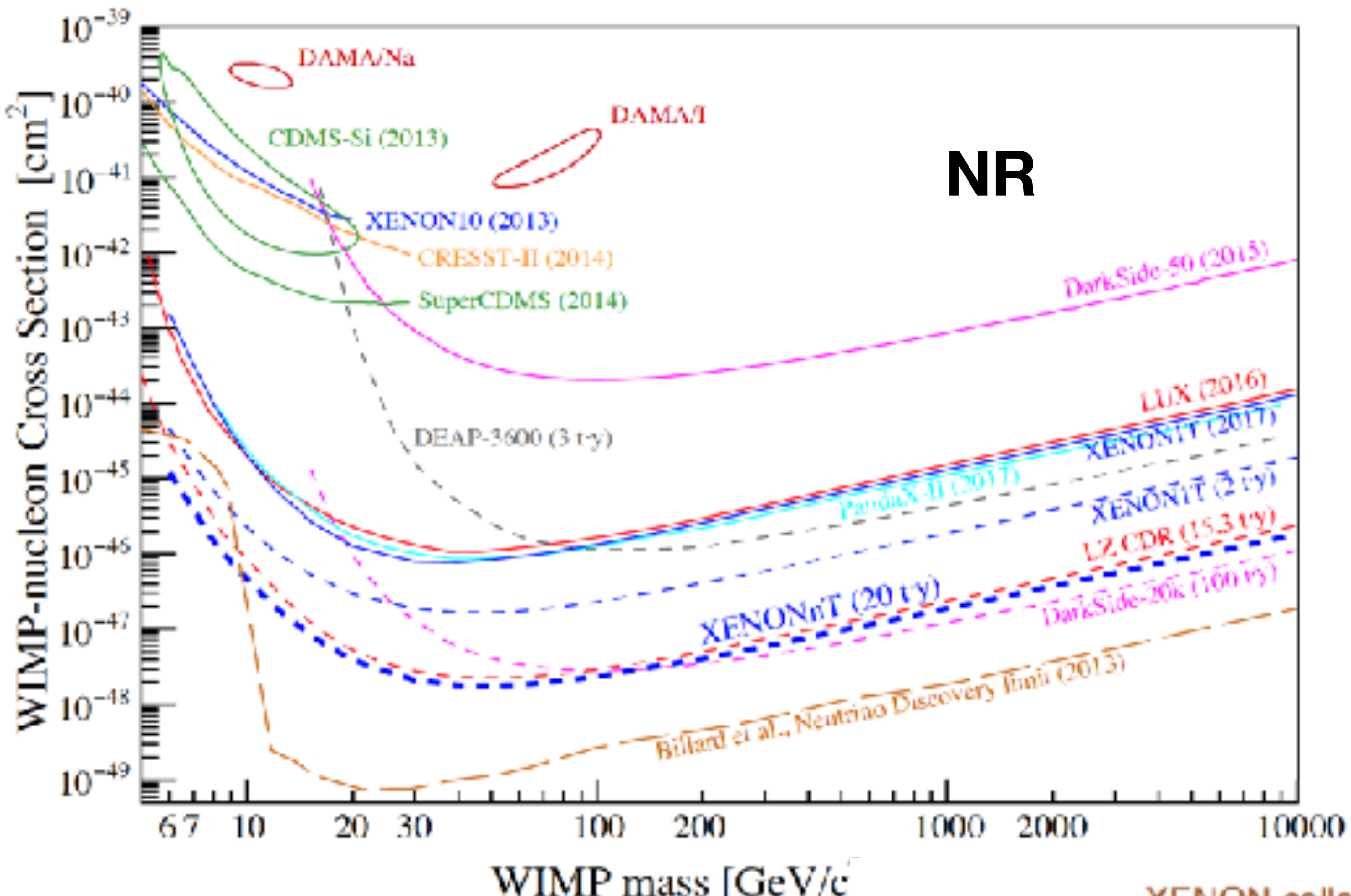




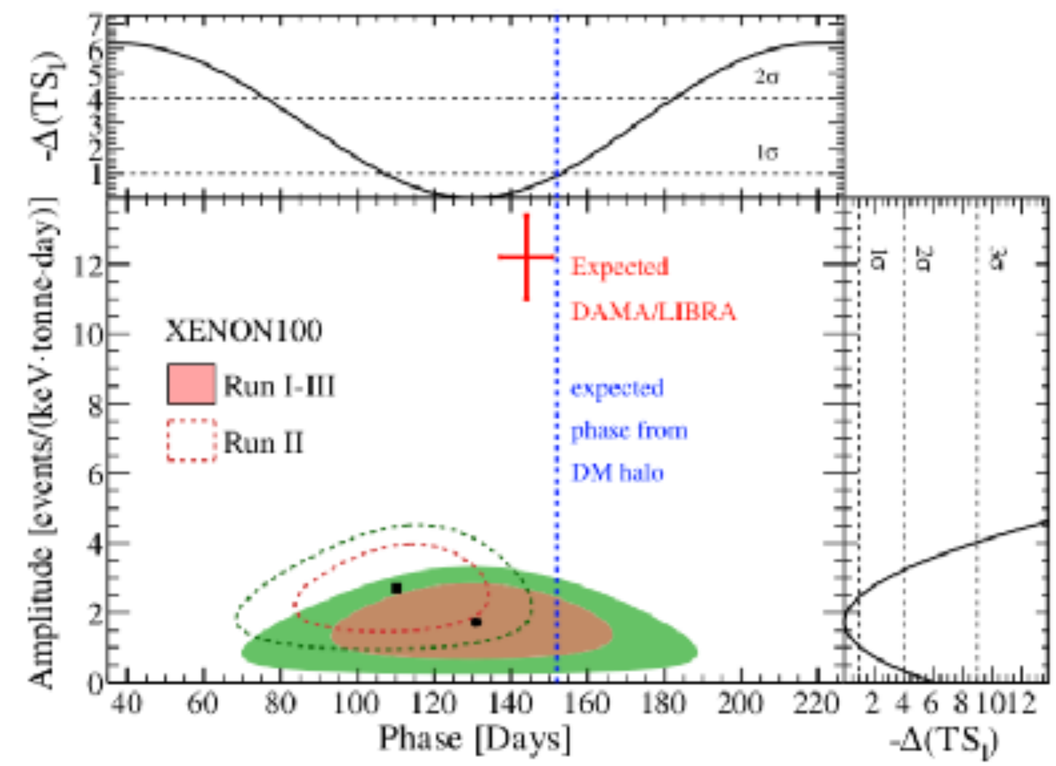
Very hard to attribute it to neutrons, muons, or worst … neutrinos !!!

Comparing DAMA with others

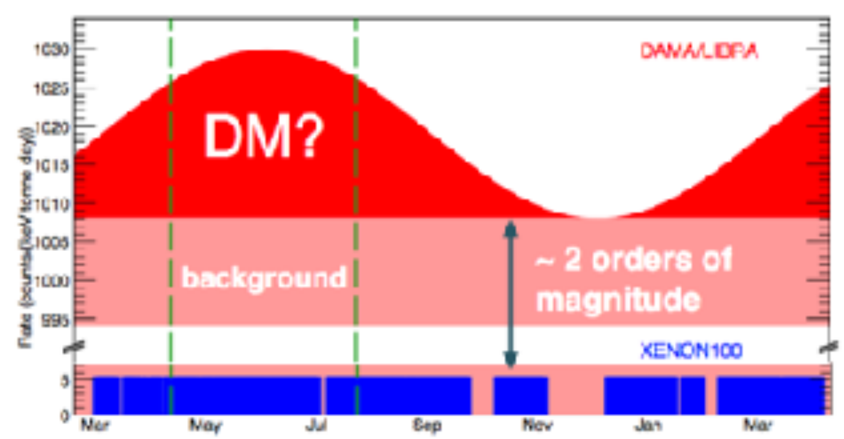
- not compatible with experiments with other targets



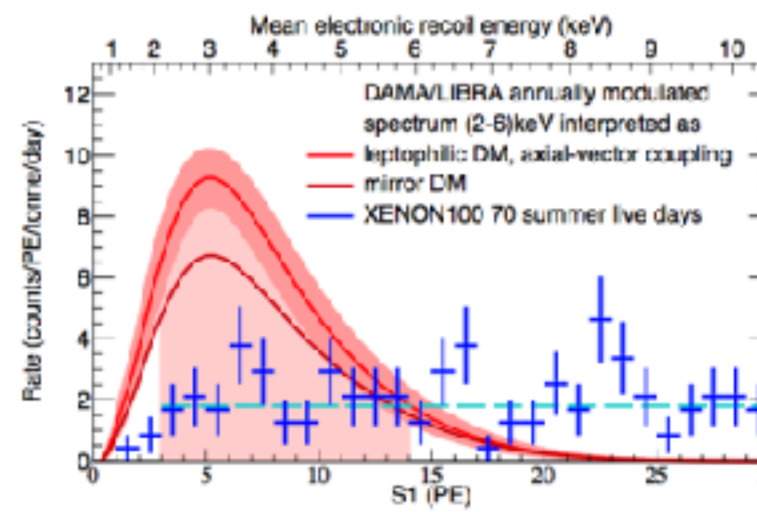
XENON100 4-year ER modulation study, PRL 118, 101101 (2017)



XENON collaboration, arXiv: 1507.07747, Science 349, 2015



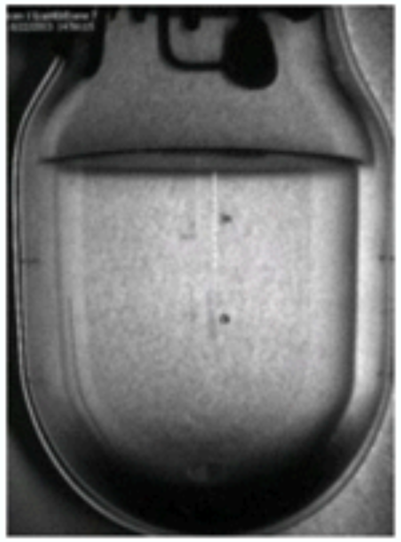
Consider the 70 days with the largest signal



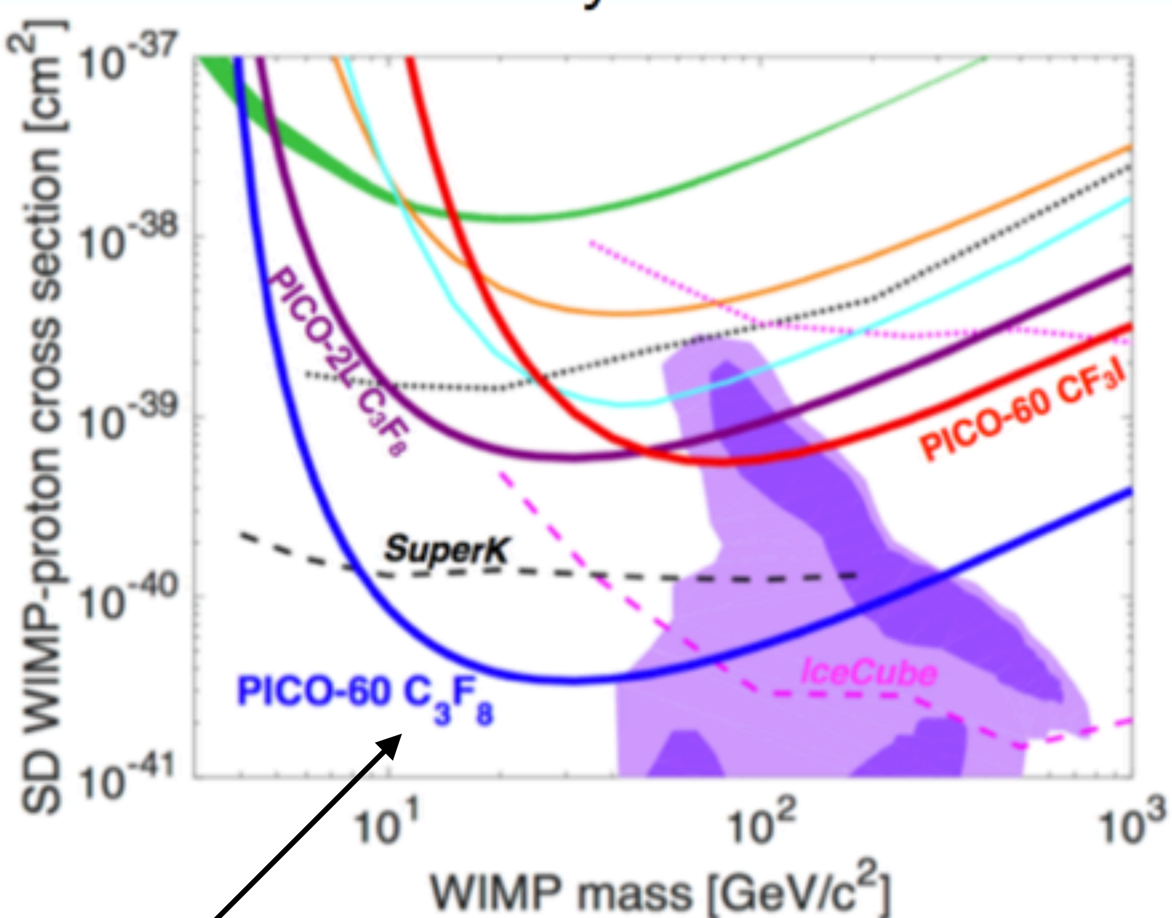
DAMA/LIBRA modulated spectrum as would be seen in XENON100 (for axial-vector WIMP-e scattering)

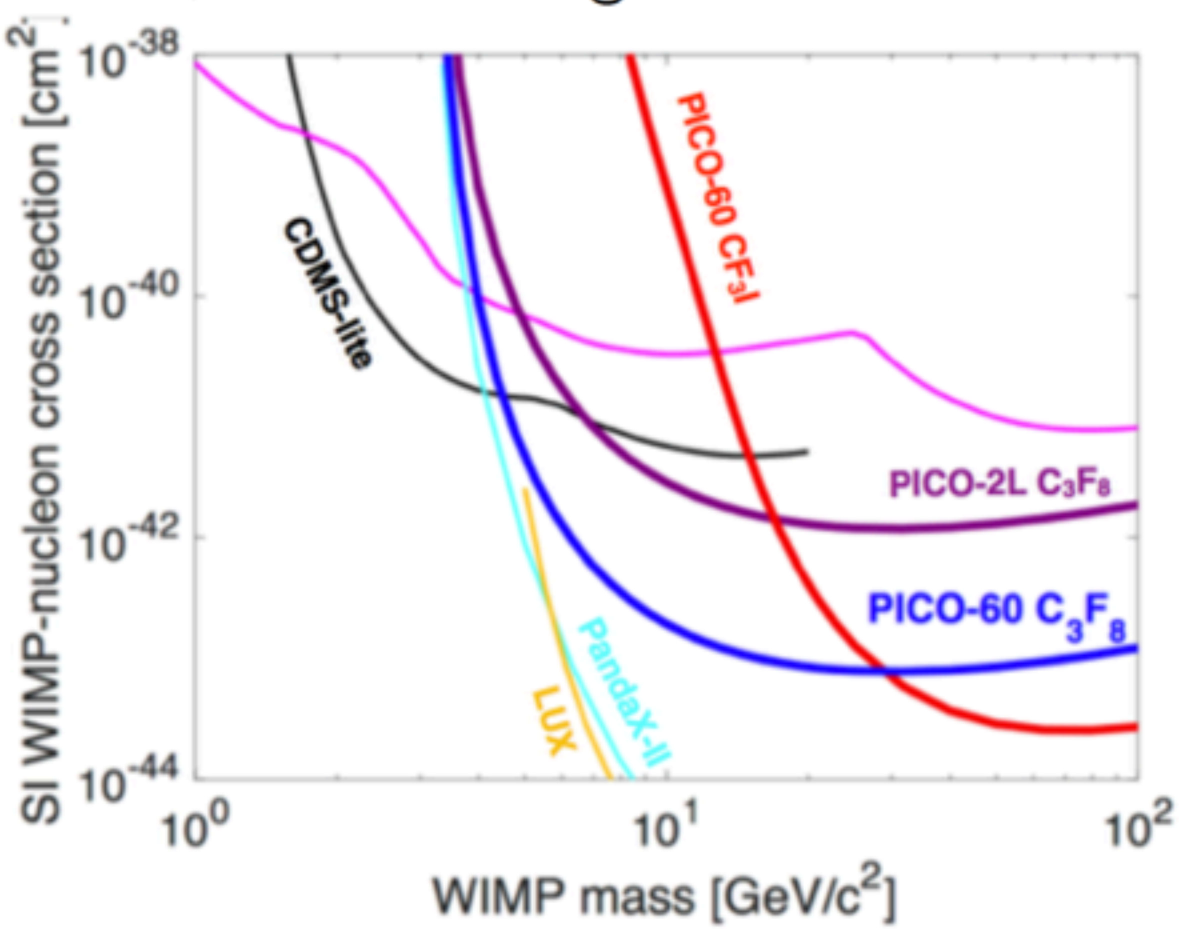
...but also with ER models, i.e. leptophilic

Bubble chambers



- Bubble nucleation in superheated liquids, target can include spin-dependent proton targets (F)
- Gammas and betas do not cause bubbles, alphas discriminated with acoustic signal
- PICO 60 6-2017 run 201results with 52 kg active, 30 days at 3.3 keV threshold, then background limited

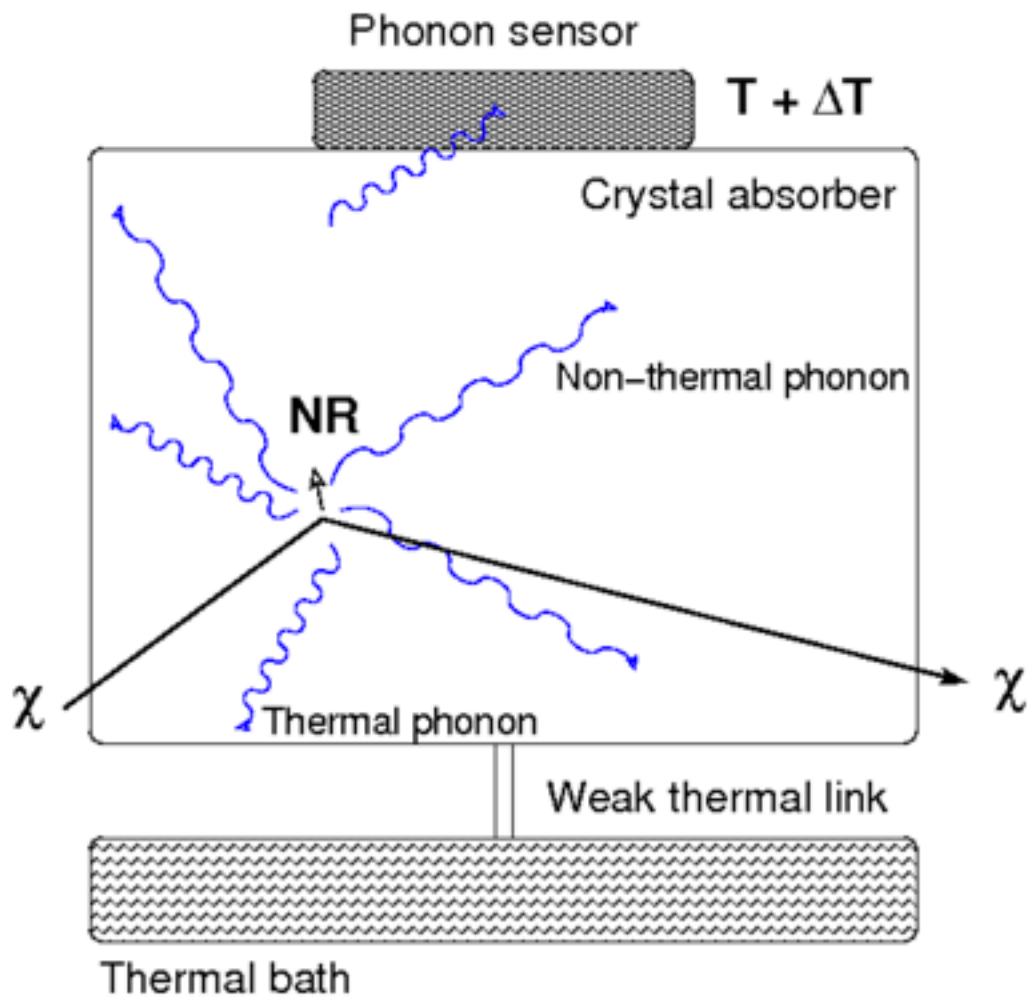


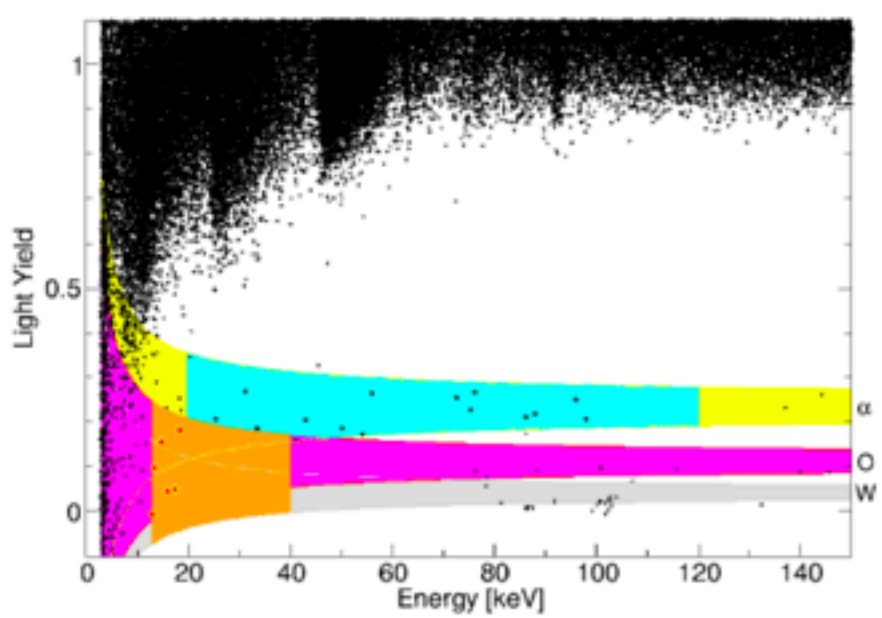


Phys. Rev. Lett. **118**, 251301 (2017)

- best SD WIMP-proton limit: 3.4e-41 cm^2 at 30 GeV/c^2

Cryogenic bolometers

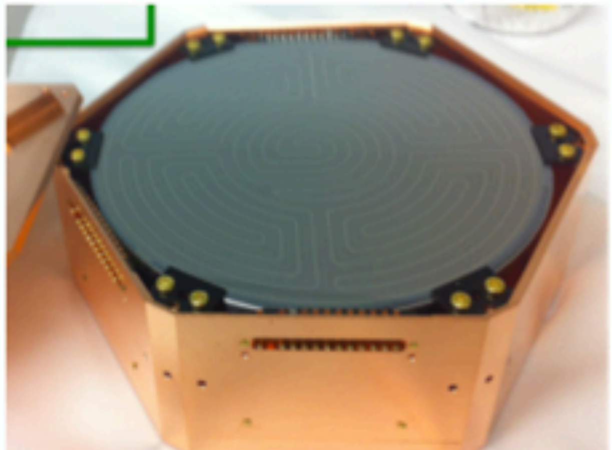


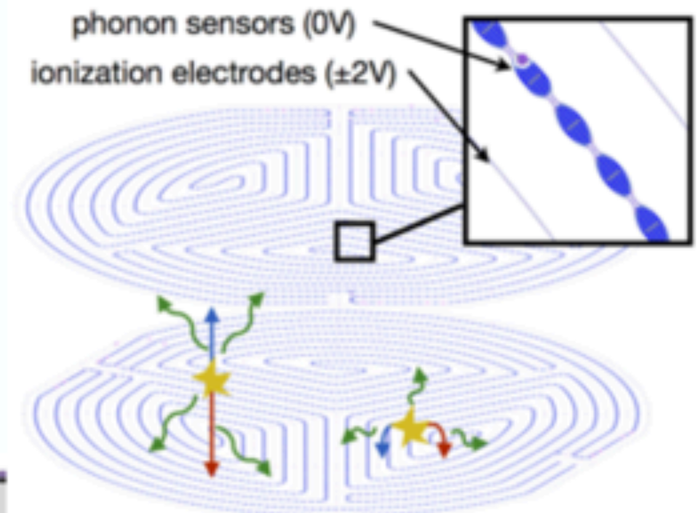


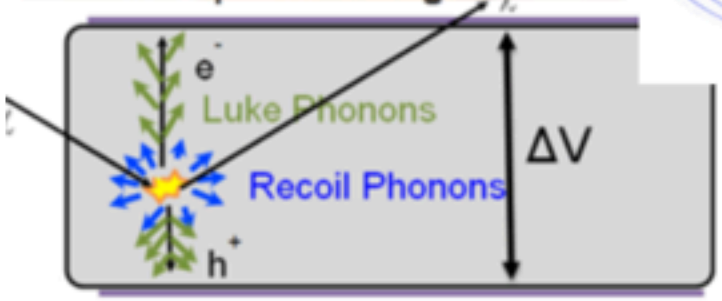
- Crystals at $(10 - 100)$ mK
- Temperature rise:
  $\Delta T = E/C(T)$
  E.g. Ge at 20 mK, $\Delta T = 20\,\mu$K for few keV recoil
- Measurements of ΔT
  NTD: neutron transmutation-doped Ge sensors
  TES: Transition edge sensors
- Discrimination: combination with light or charge read-out
- Large separation of electronic and nuclear recoil bands

Example from CRESST, EPJC 72 (2012) 1971

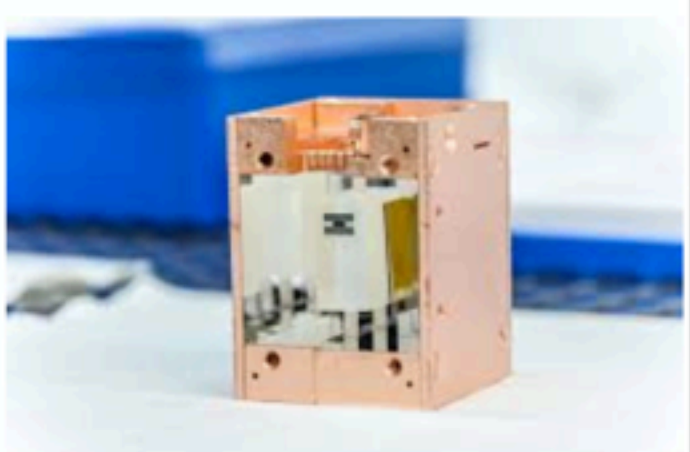
Cryogenic bolometers

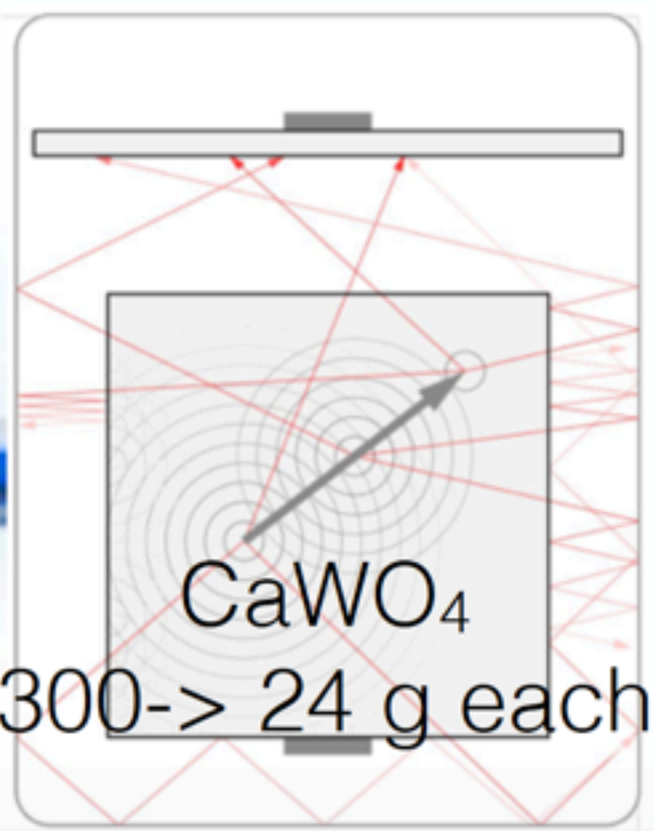






Ge, Si ~1 kg each





300-> 24 g each

- SuperCDMS/EDELWEISS 2 techniques
  - HV (CDMSlite): Luke phonons: low threshold, but no discrimination
  - iZIP/FID: ionization and phonon signals with interleaved sensors discriminate against electronic recoils and surface events
- CRESST
  - $CaWO_4$ crystals for phonons and scintillation
- DAMIC
  - Si CCD

Liquid Noble Detectors

- Large masses and homegeneous targets (LNe, LAr & LXe)

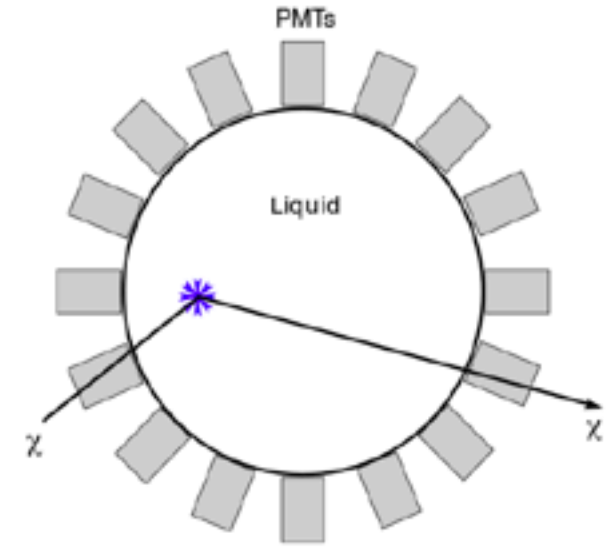
  Two detector concepts: single & double phase
- 3D position reconstruction → fiducialization
- Transparent to their own scintillation light

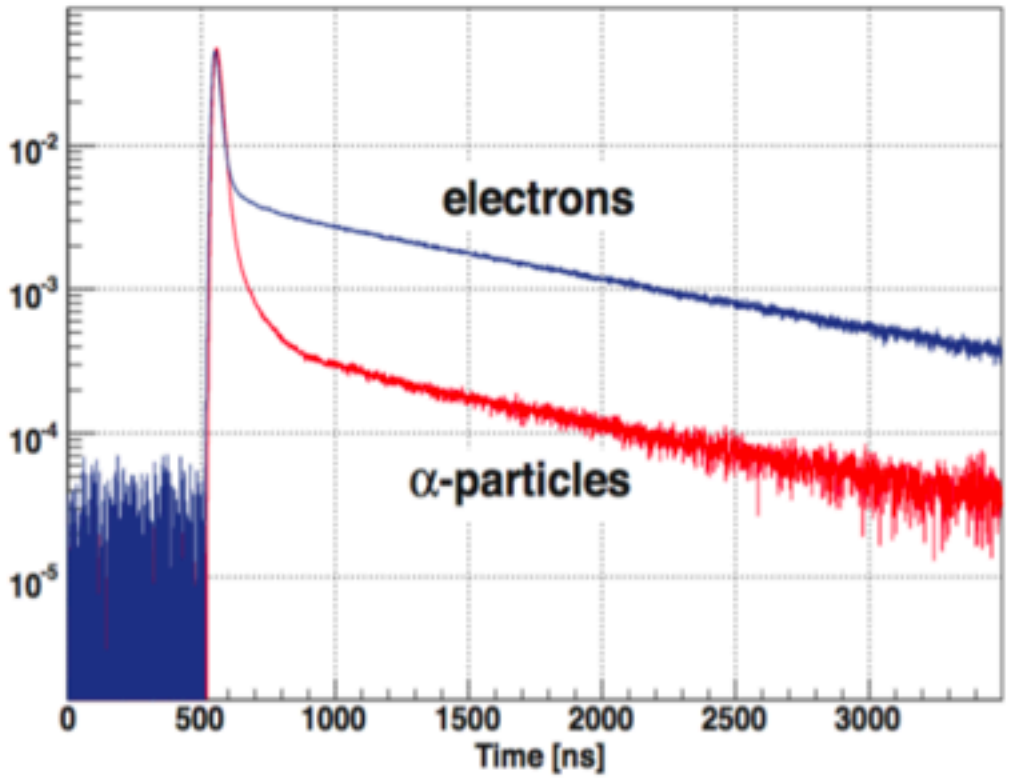
	LNe	LAr	LXe
Z (A)	10 (20)	18 (40)	54 (131)
Density [g/cm^3]	1.2	1.4	3.0
Scintillation λ	78 nm	125 nm	178 nm
BP [K] at 1 atm	27	87	165
Ionization [e$^-$/keV]*	46	42	64
Scintillation [γ/keV]*	7	40	46

* for electronic recoils

Liquid Noble Detectors: Single Phase

- High light yield using 4π photosensor coverage
- Position resolution in the cm range
- Pulse shape discrimination (PSD) from scintillation





Scintillation decay constants of argon measured by ArDM

- Very different singlet and triplet lifetimes in argon & neon
- Relative amplitudes depend on particle type → discrimination

DEAP-I obtained 10^{-8} discrimination in LAr above 25 keV_{ee} (50% acceptance)

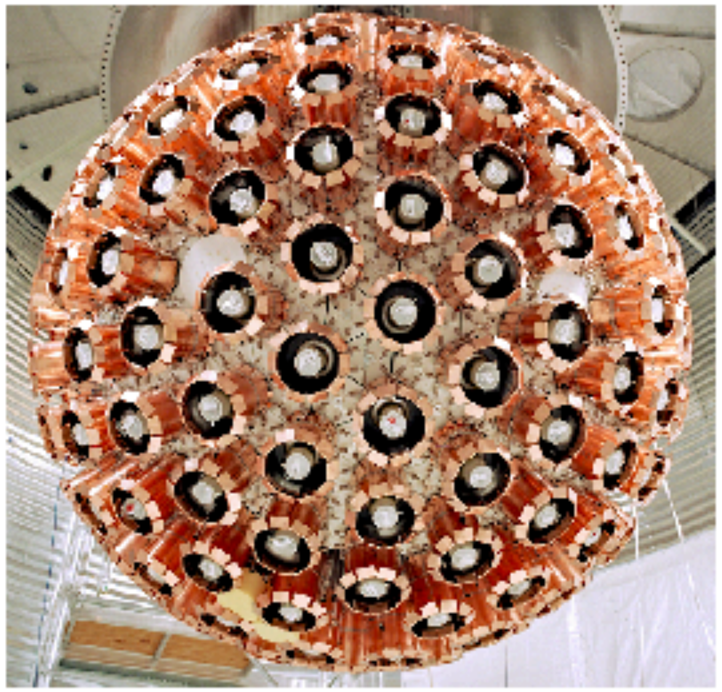
M. G. Boulay *et al.*, arXiv:0904.2930

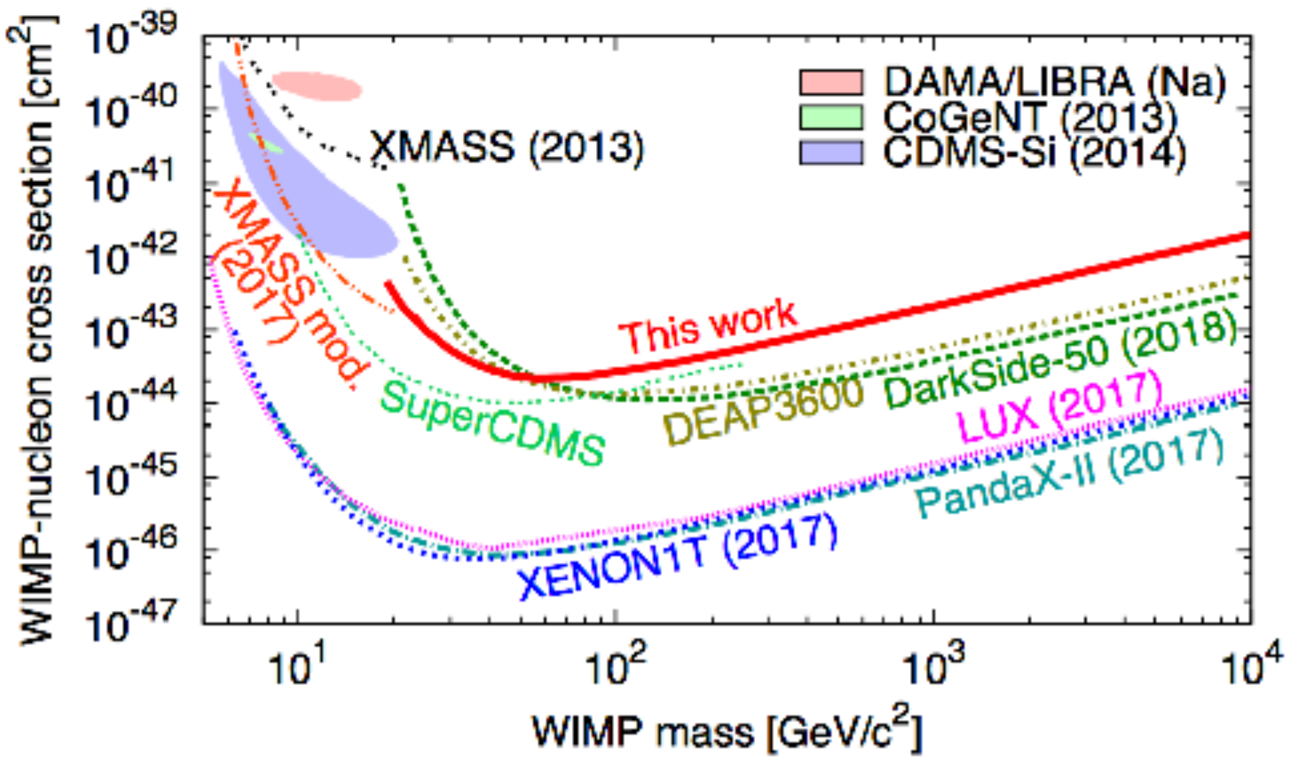
→ PSD less powerful in LXe: similar decay constants XMASS, NIM. A659 (2011) 161

Liquid Noble Detectors: Single Phase

DEAP - LAr detector at SNOLAB, Canada
Dark matter **E**xperiment with **A**rgon and **P**ulse shape discrimination

- 3 600 kg total mass & 1 ton FV
- 2-inch thick ultraclean acrylic vessel
- Wavelength-shifter inside the vessel
- Light guides to the PMTs



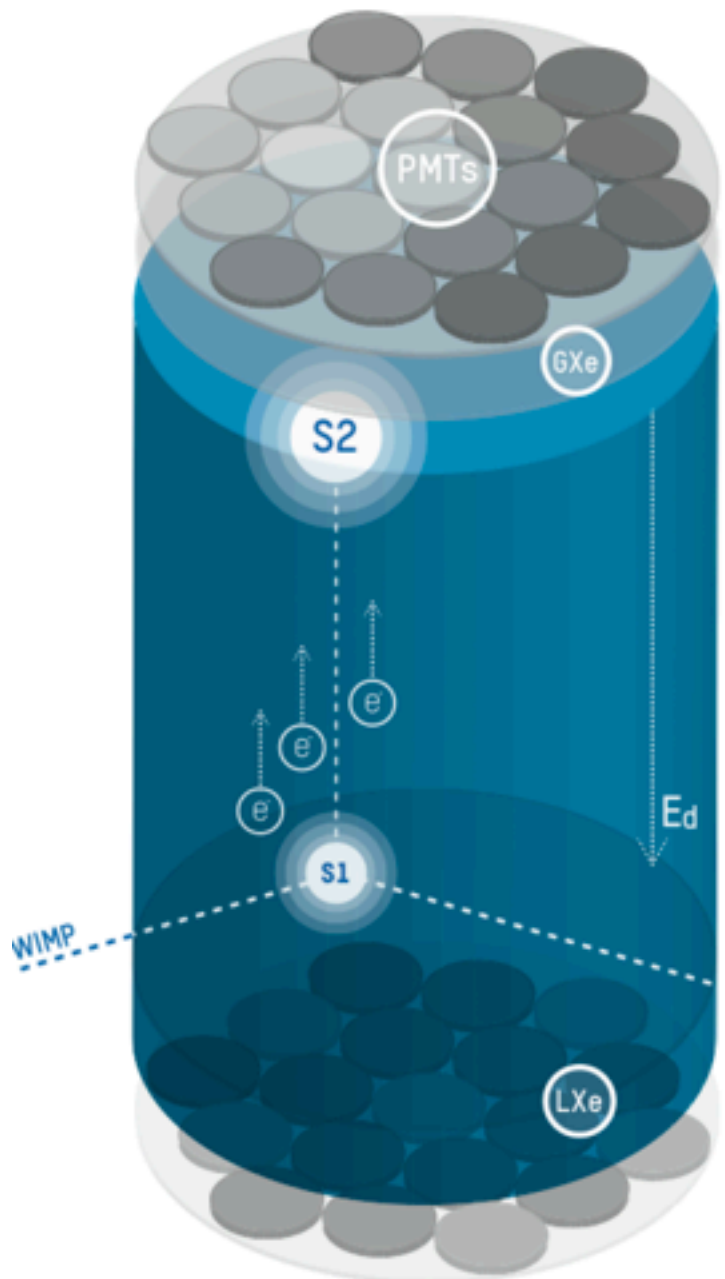


n

the

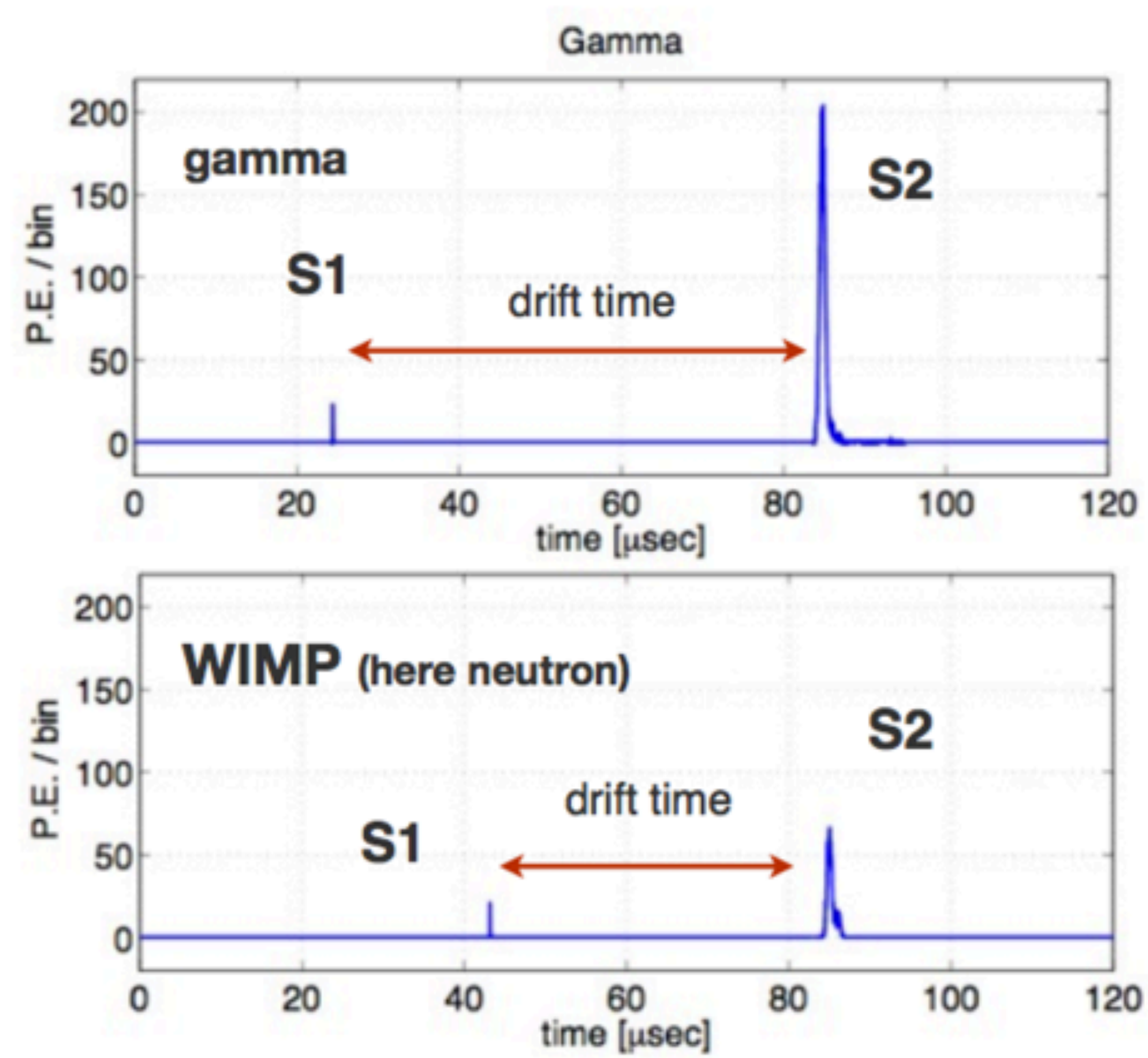
e

Liquid Noble Detectors: Double Phase TPC



- Scintillation signal (S1)
- Charges drift to the liquid-gas surface
- Proportional signal (S2)

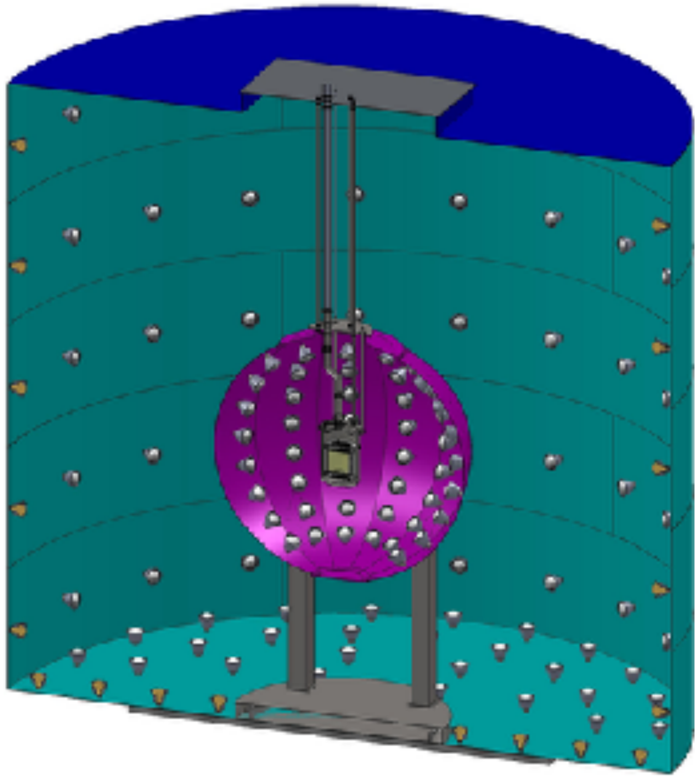
→ Electron- /nuclear recoil discrimination



- Drift field
- Electronegative purity
- Position resolution

DarkSide-50 and -20k

DarkSide-50



- Detector inside Borexino counting facility at LNGS (Italy)
- 50 kg depleted argon from underground sources

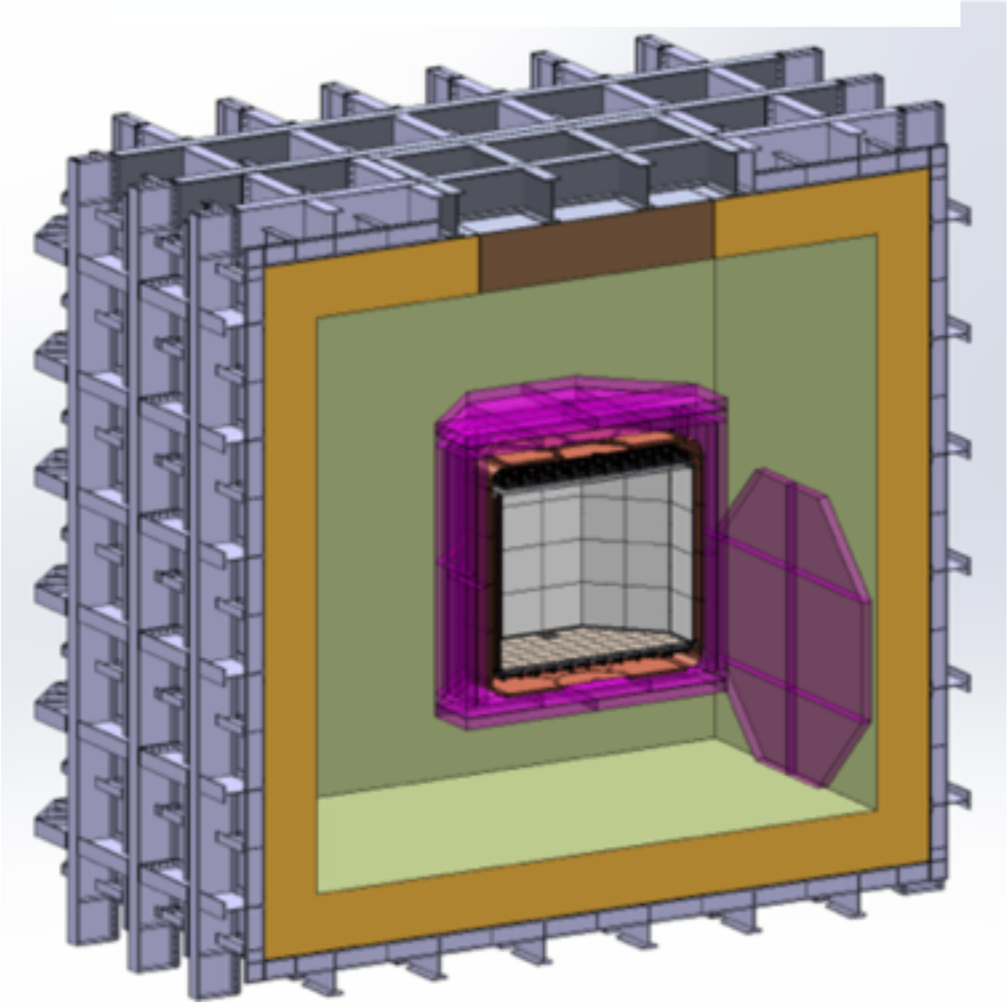
  > 1000 reduction in ^{39}Ar level
- Pulse shape & charge/light ratio for particle discrimination

  Pulse-shape separation > 10^7
- Hamamatsu R11065 as photosensor

  Challenge: operation of PMTs at LAr temperatures

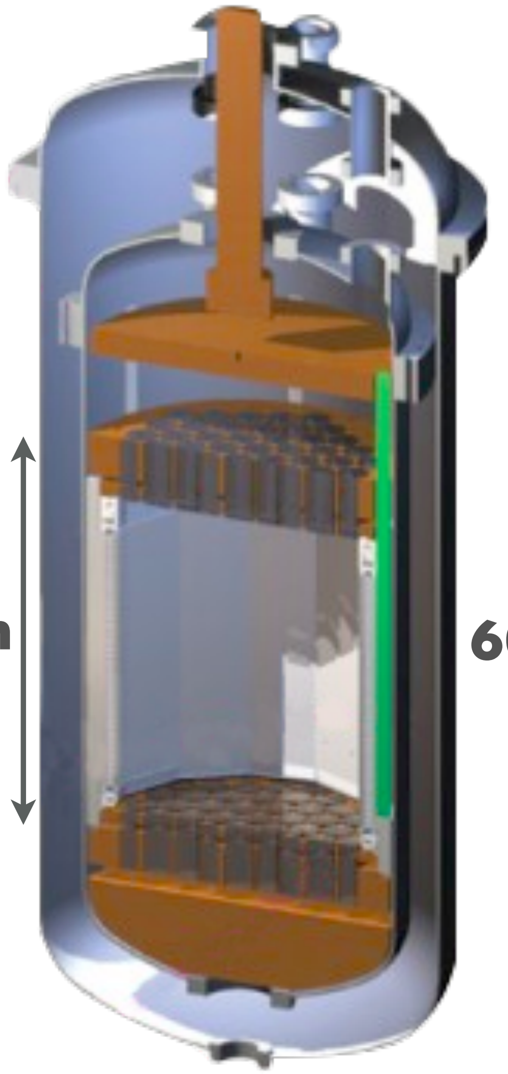
  → plan to use SiPMs in the next generation detector

- **DarkSide-20k**
  - Scheduled for 2021
  - Utilizing underground argon
  - Atmospheric LAr veto, DUNE style cryostat possible
  - Background free
- Global Argon Dark Matter Collaboration
  - 300 t in 2027

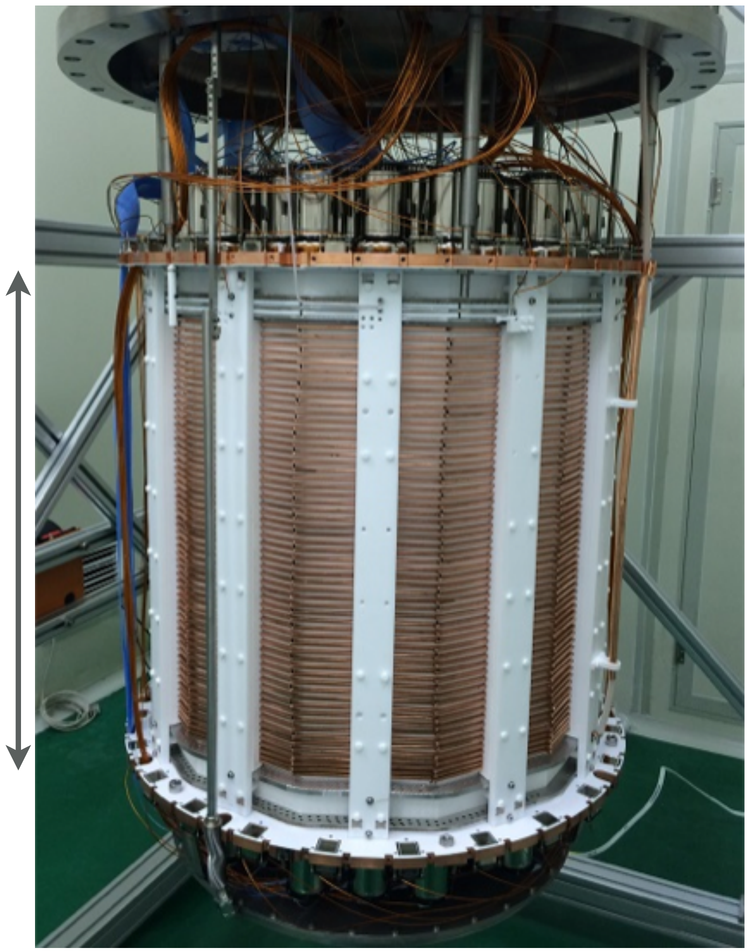


(previous) detectors using the LXeTPC

48 cm



60 cm



100 cm

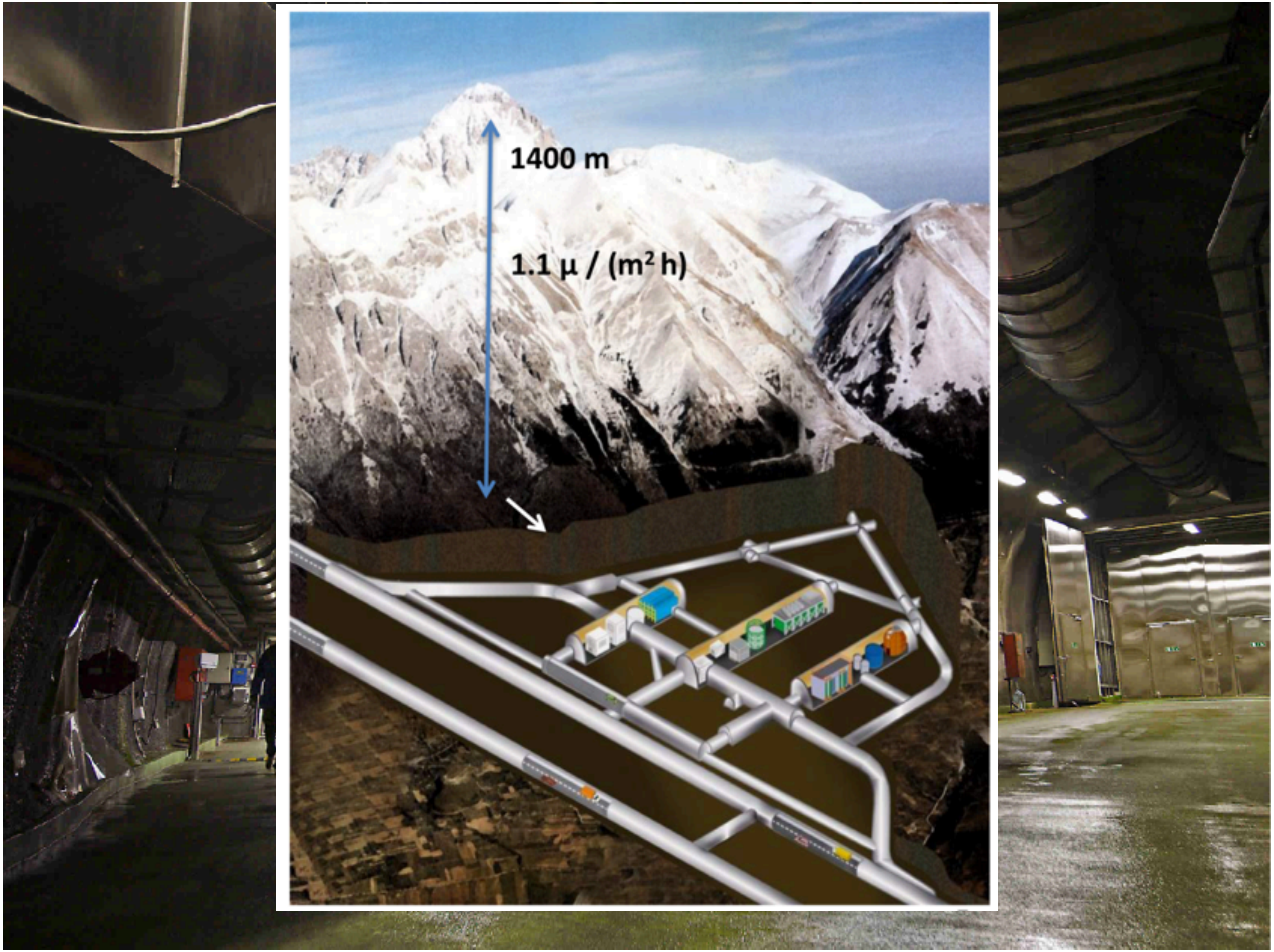
LUX
Active Target: ~250 kg
completed

PandaX-II
Active Target: ~580 kg
completed

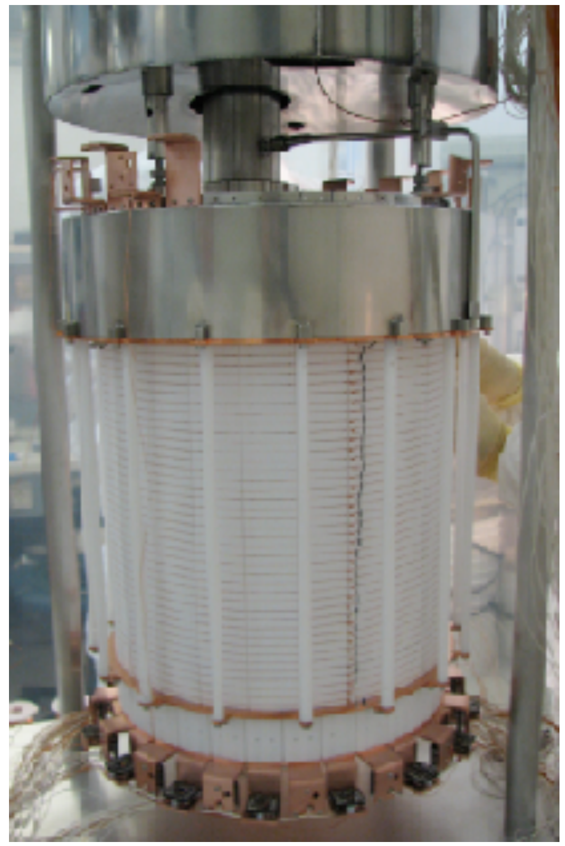
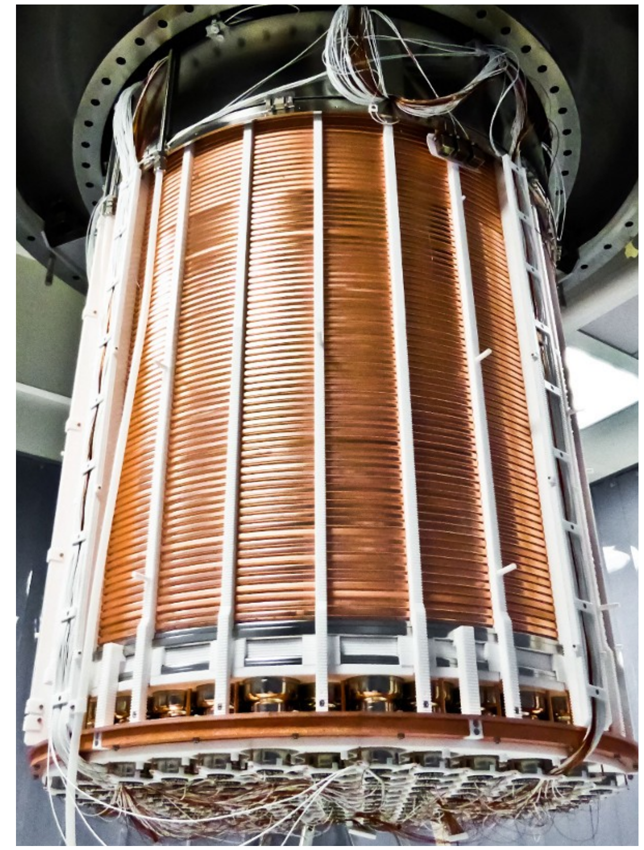
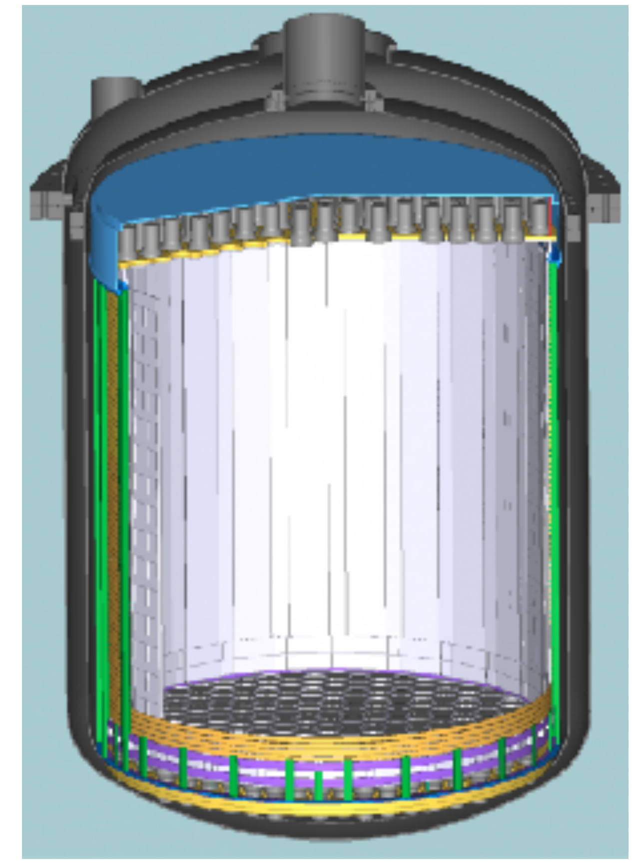
XENON1T
Active Target: 2000 kg
completed in 2018

LNGS

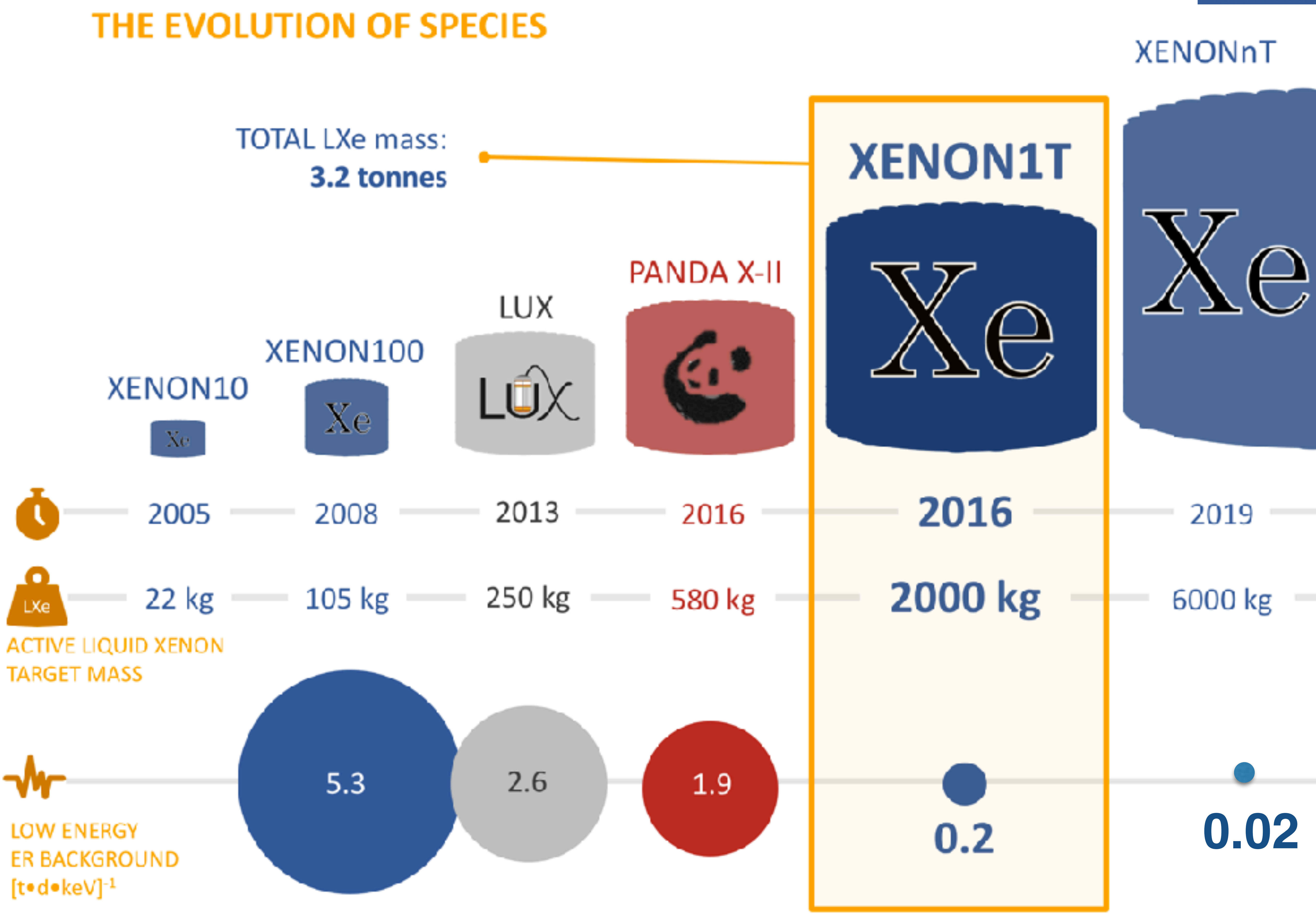
LNGS



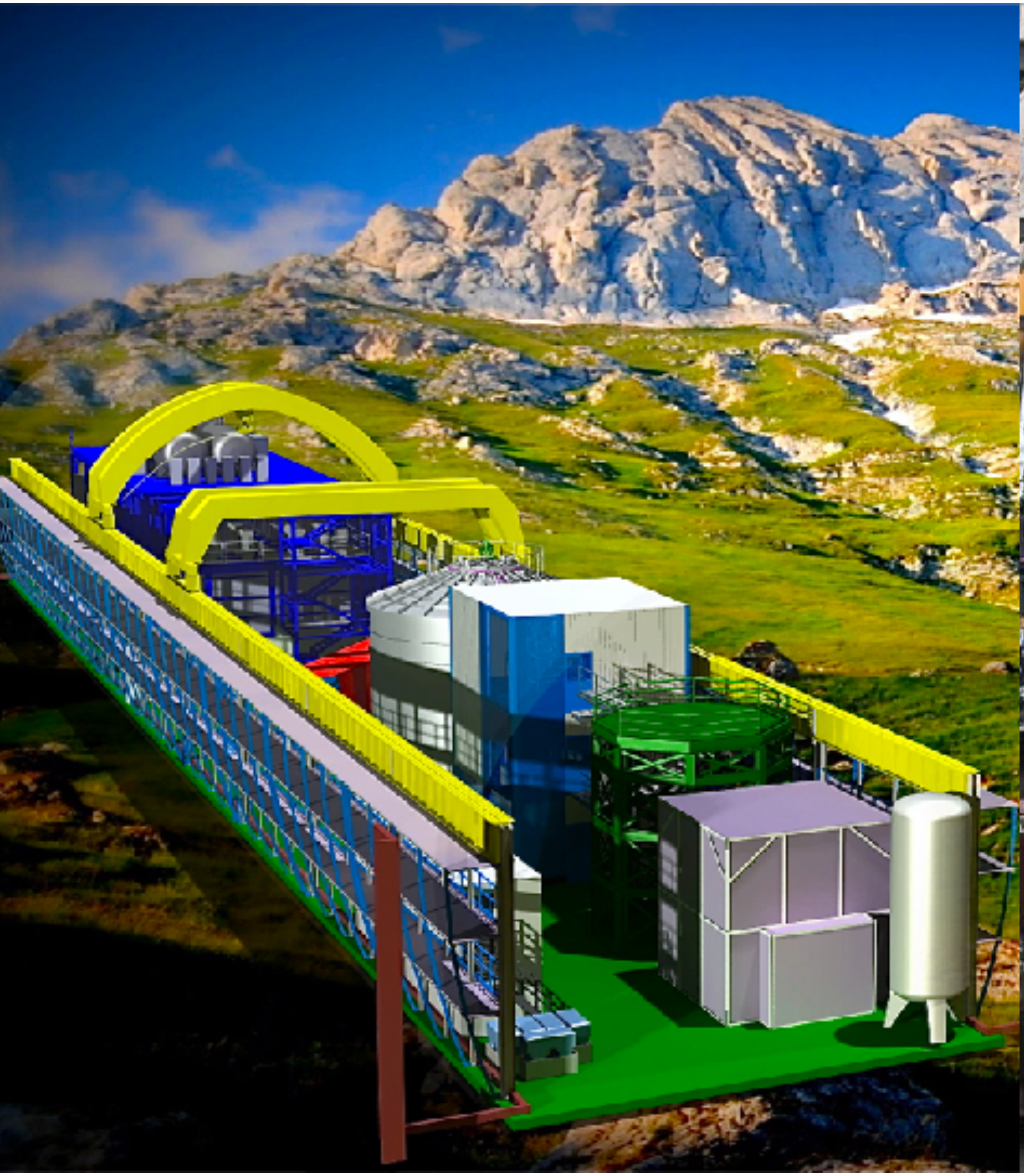
WIMP detectors from the XENON-series

XENON10	XENON100	XENON1T	XENONnT
			
2005-2007	2008-2016	2012-2018	2020-2025
25 kg - 15cm drift	161 kg - 30 cm drift	3.2 ton - 1 m drift	8 ton - 1.5 m drift
$\sim 10^{-43}$ cm^2	$\sim 10^{-45}$ cm^2	$\sim 10^{-47}$ cm^2	$\sim 10^{-48}$ cm^2

Impressive evolution of LXeTPCs



The XENON1T Experiment @ LNGS

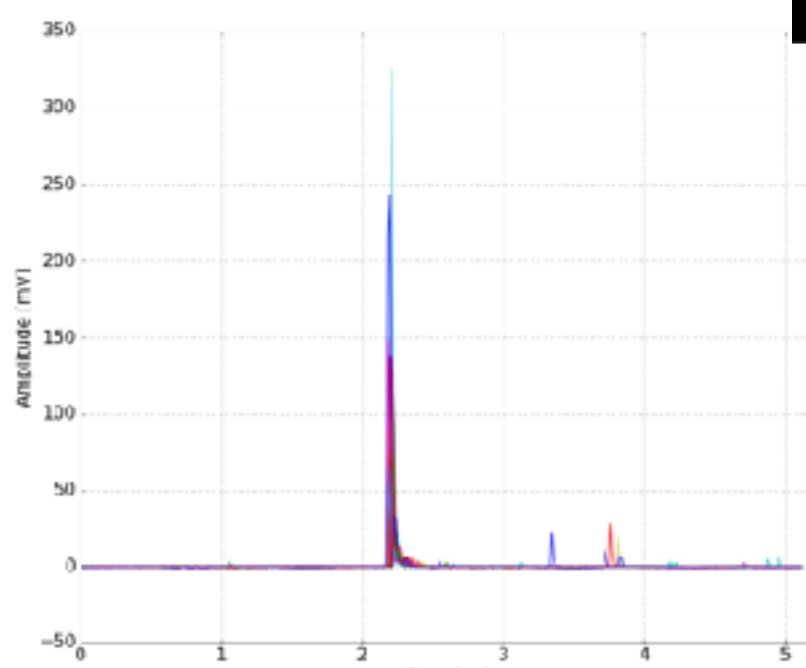


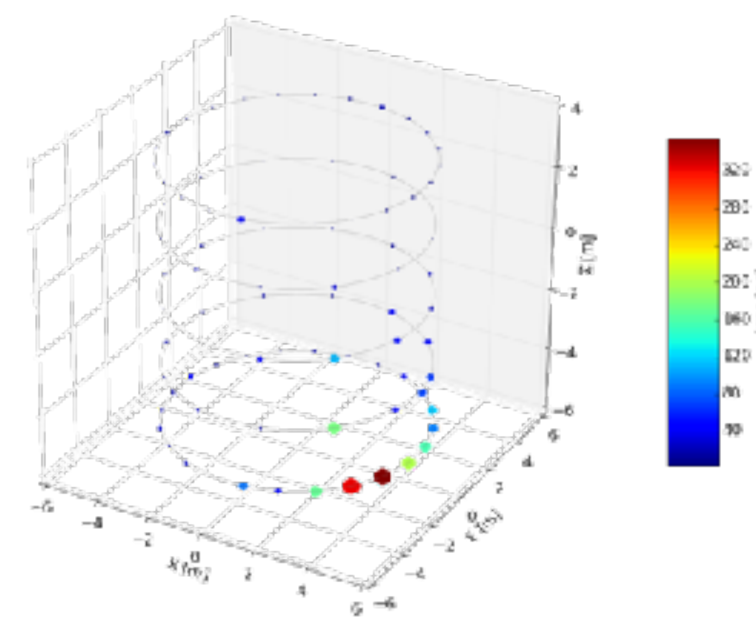

XENON1T: All Systems

E. Aprile et al.,
"The XENON1T Dark Matter Experiment",
EPJ C 77, 881 (2017).

Gd-Water Cherenkov Muon and Neutron Veto

- 700 ton pure water instrumented with 84 high-QE 8" PMTs
- Trigger efficiency > 99.5% for muons in water tank
- Cosmogenic neutron background suppressed to <0.01 events/ton/yr
- For XENONnT, 120 more PMTs, inner reflective region, and Gd-doping to reduce neutron background

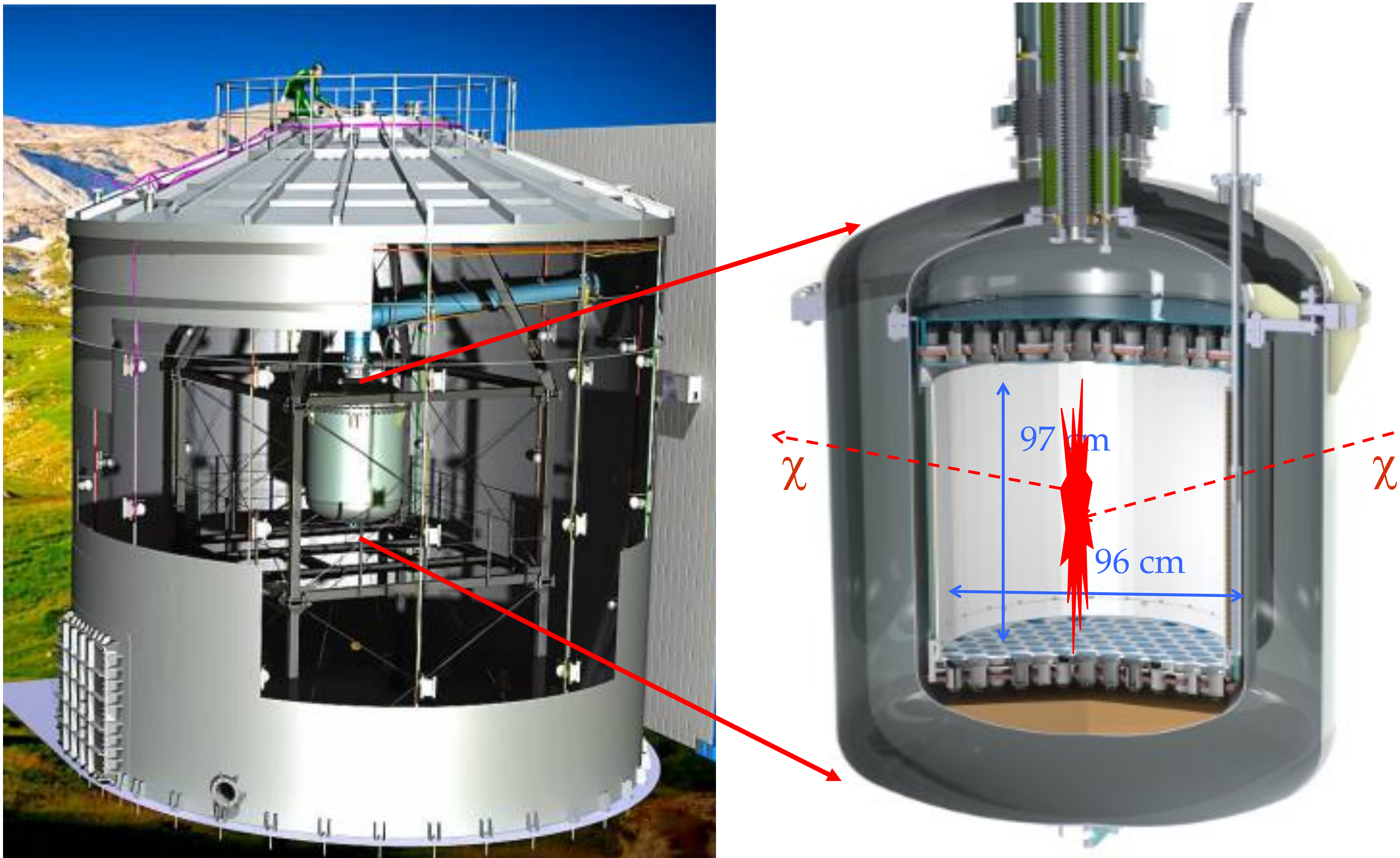




Key contribution of INFN-Bologna researcher and technical staff

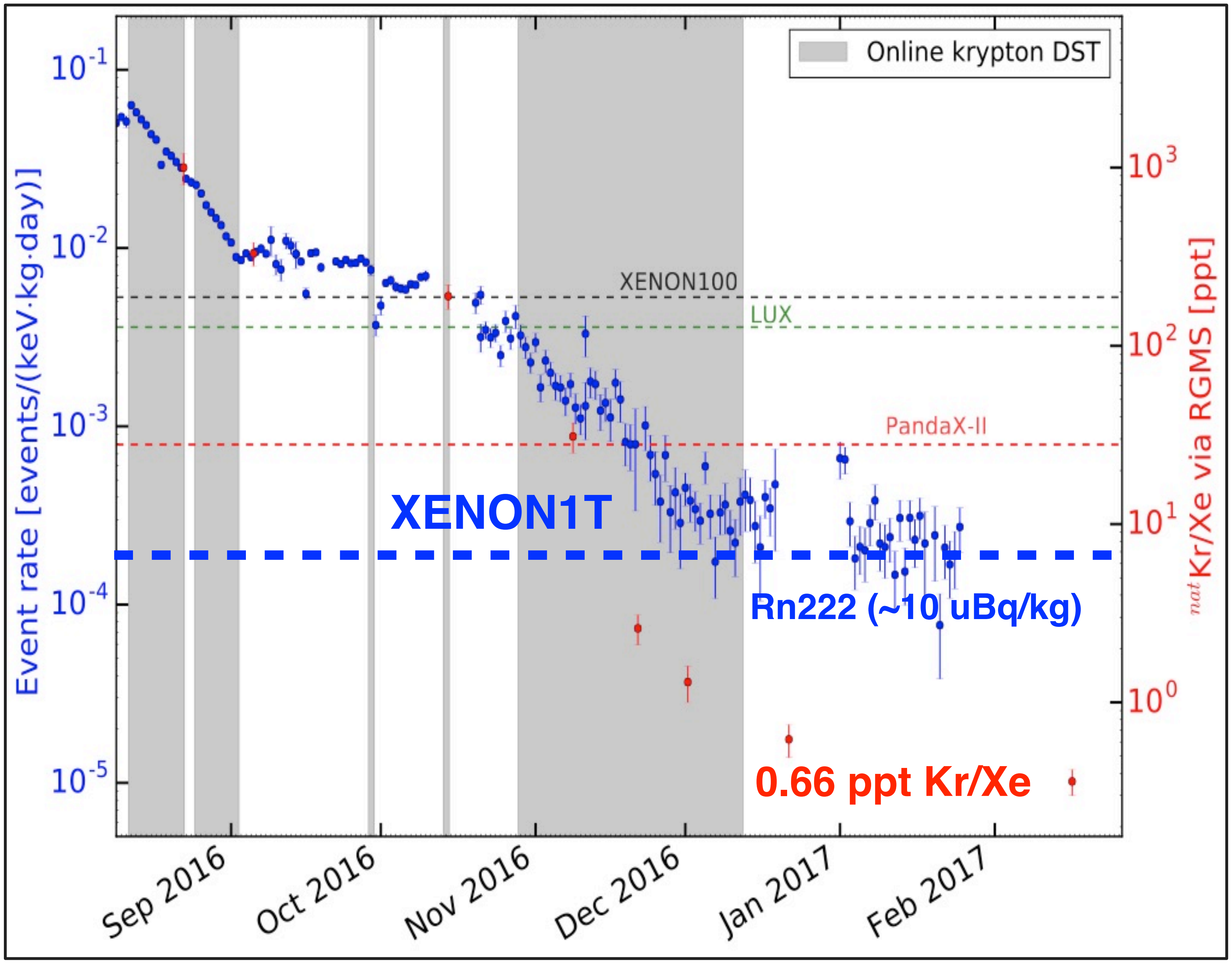
JINST 9, 11007 (2014)

The XENON1T experiment



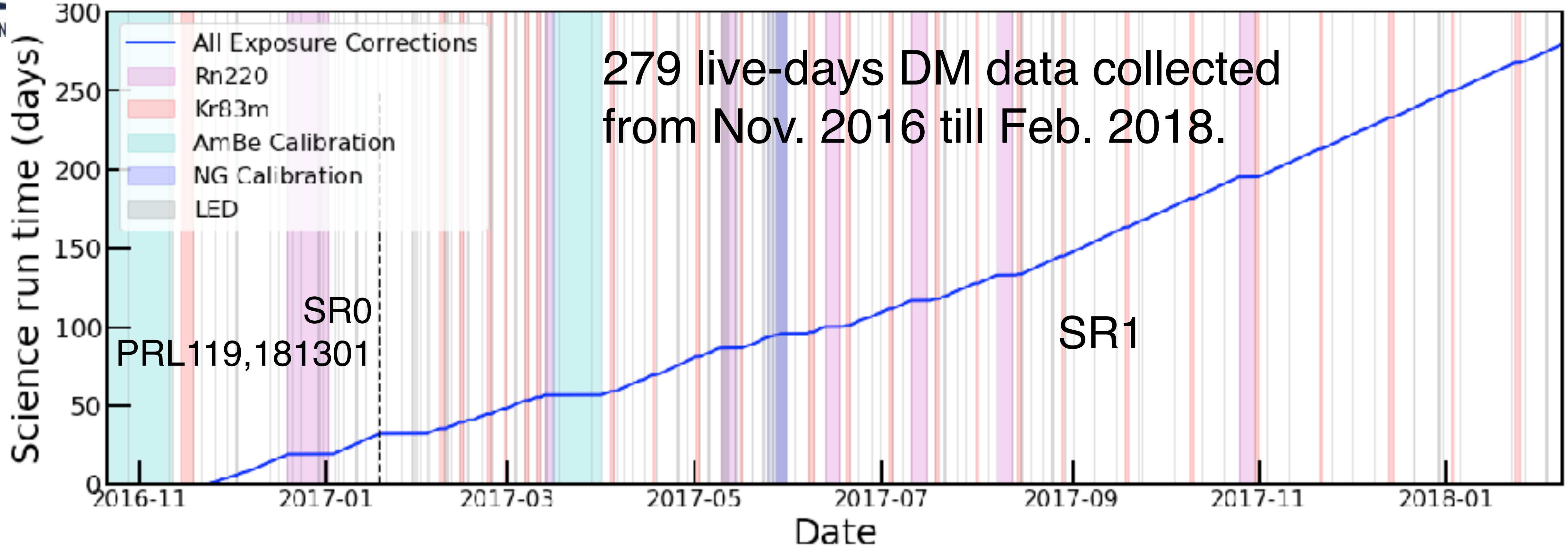
The XENON1T Time Projection Chamber

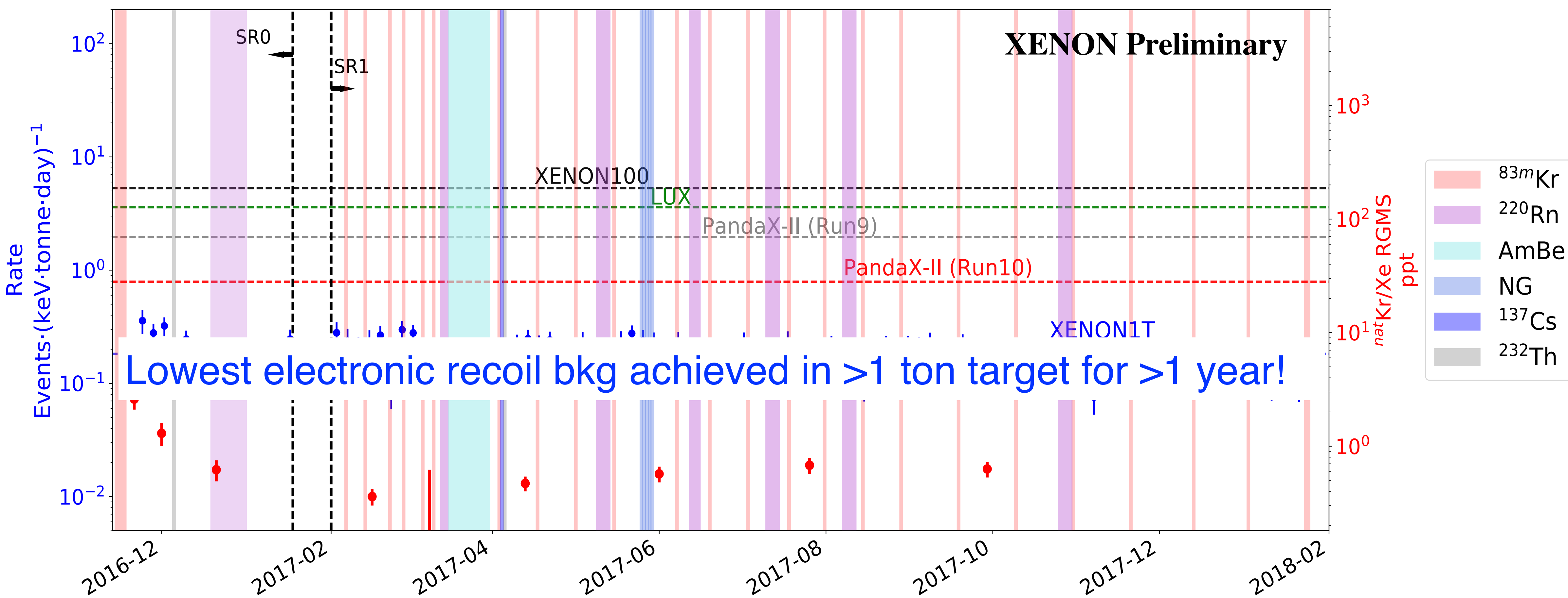
Key issue: reduce the intrinsic radio-contaminants



XENON1T Distillation Column

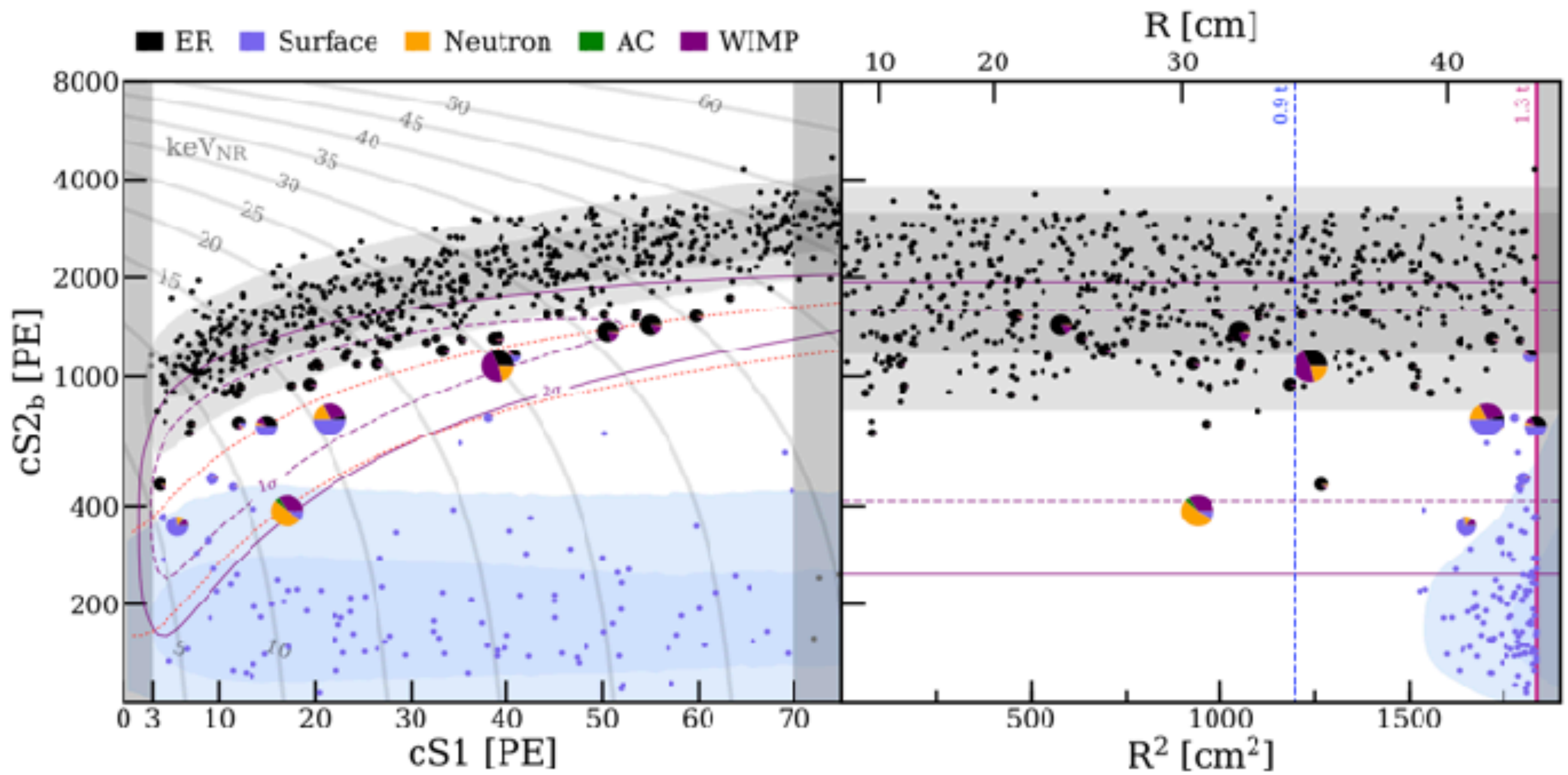
XENON1T Data taking

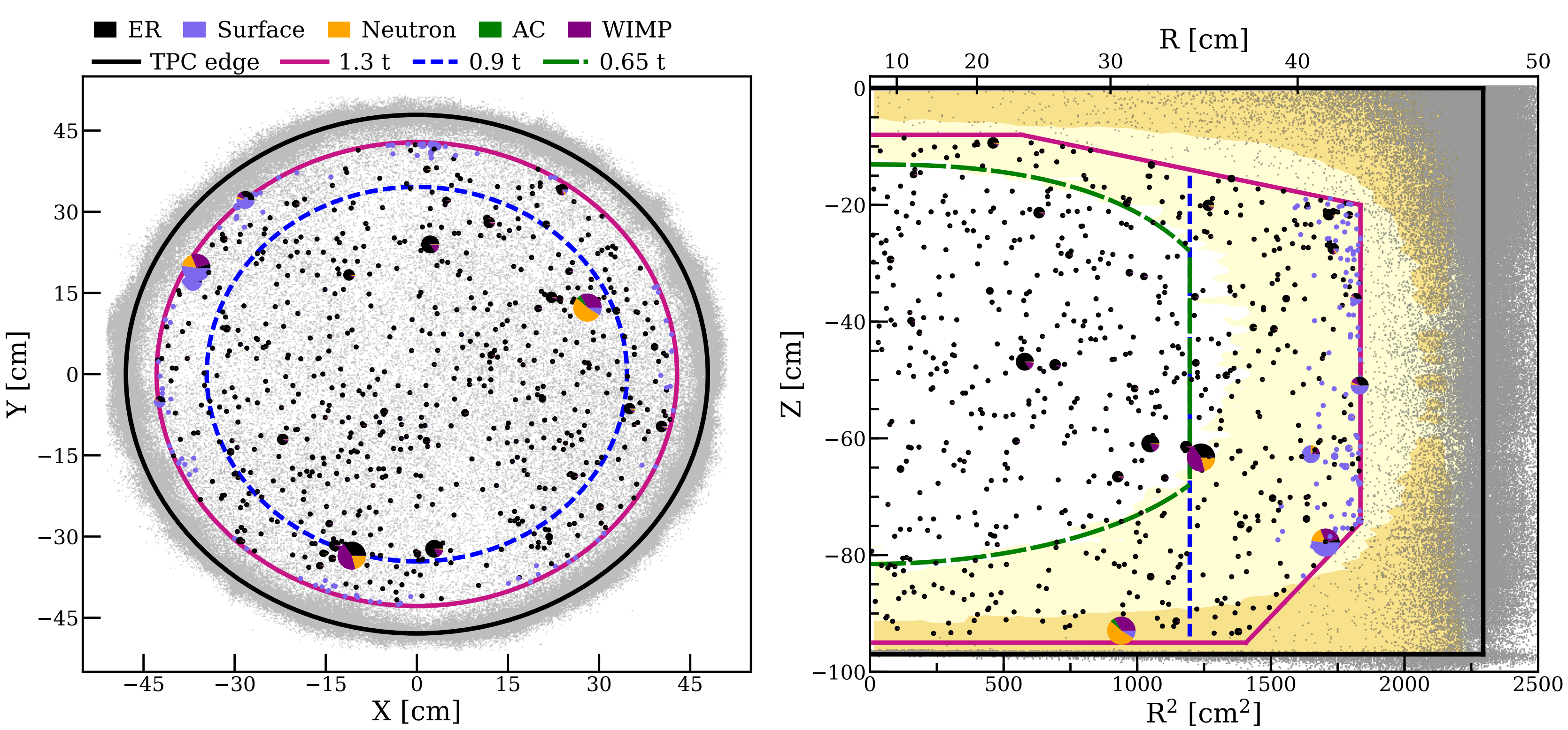




Lowest electronic recoil bkg achieved in >1 ton target for >1 year!

XENON1T results

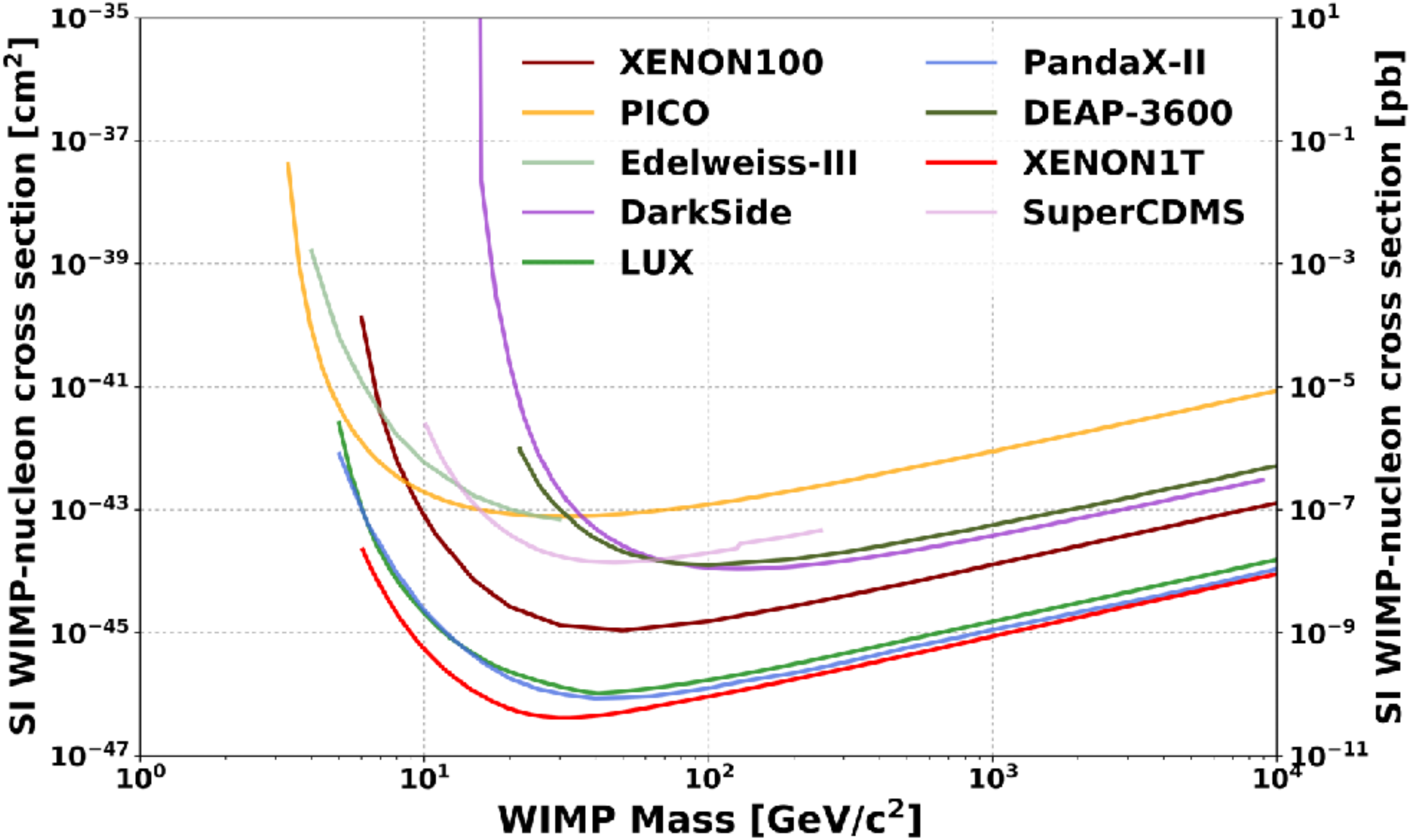




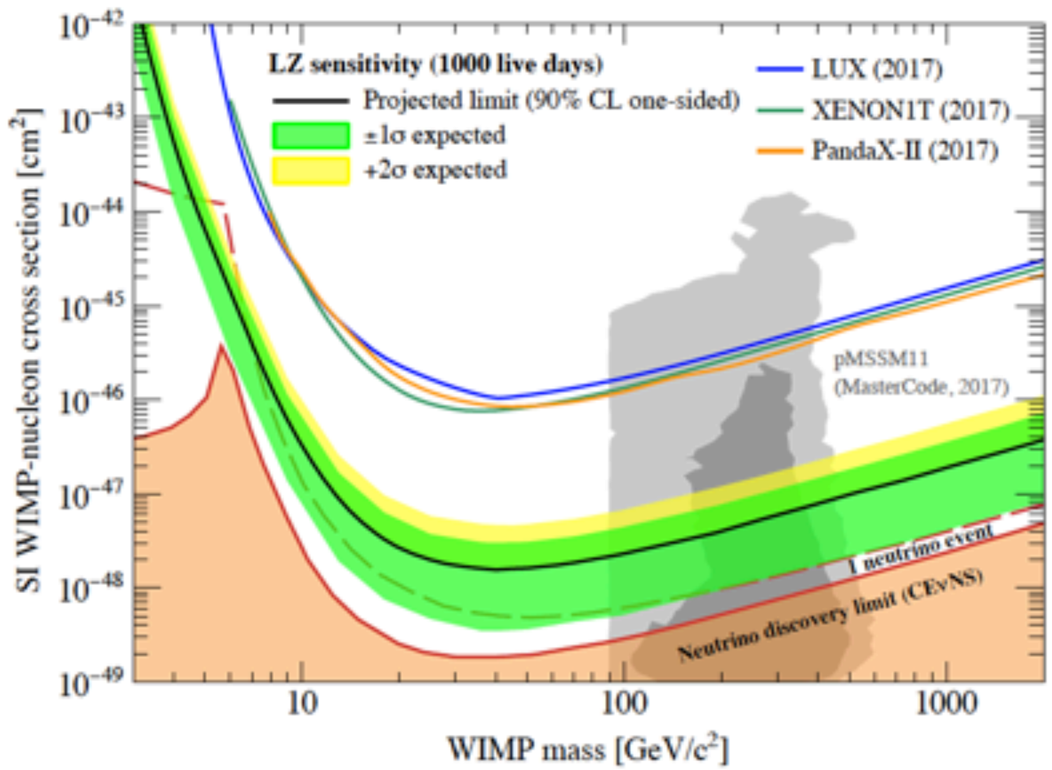
- **Results interpreted with unbinned profile likelihood analysis in cS1, cS2, R space**
- **Piecharts indicate the relative PDF from the best fit (assuming 200 GeV/c² WIMPs at cross-section of 4.7x10⁻⁴⁷ cm²)**

INFN Istituto Nazionale di Fisica Nucleare

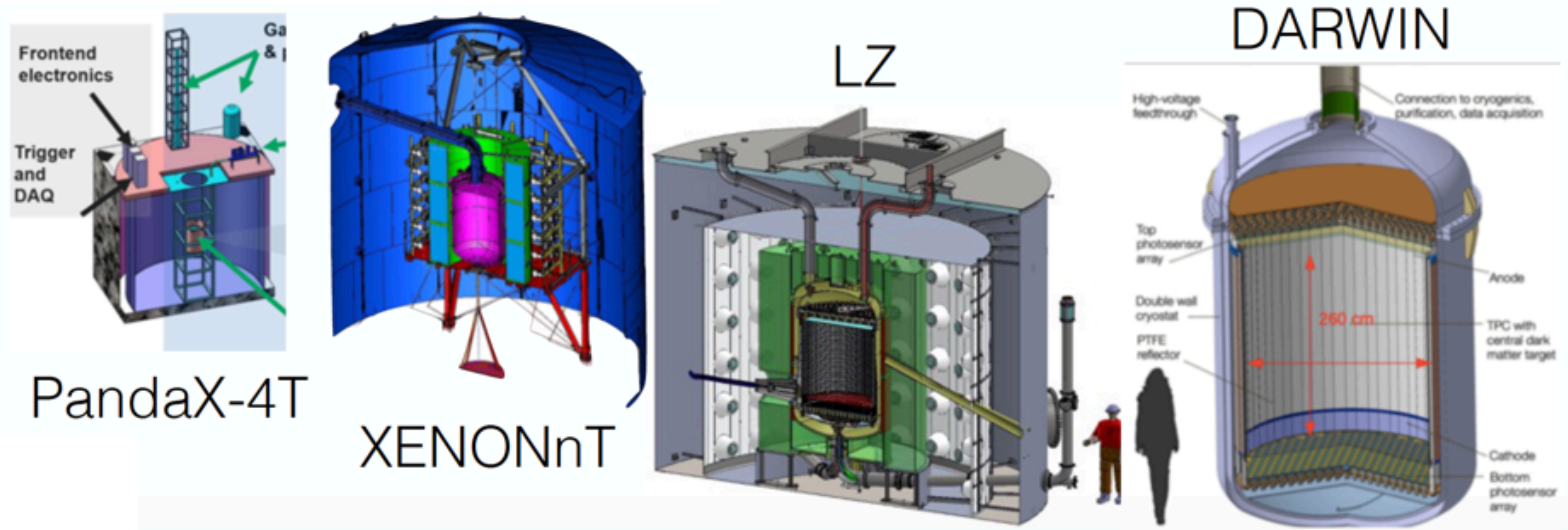
Heavy WIMPs search: current status



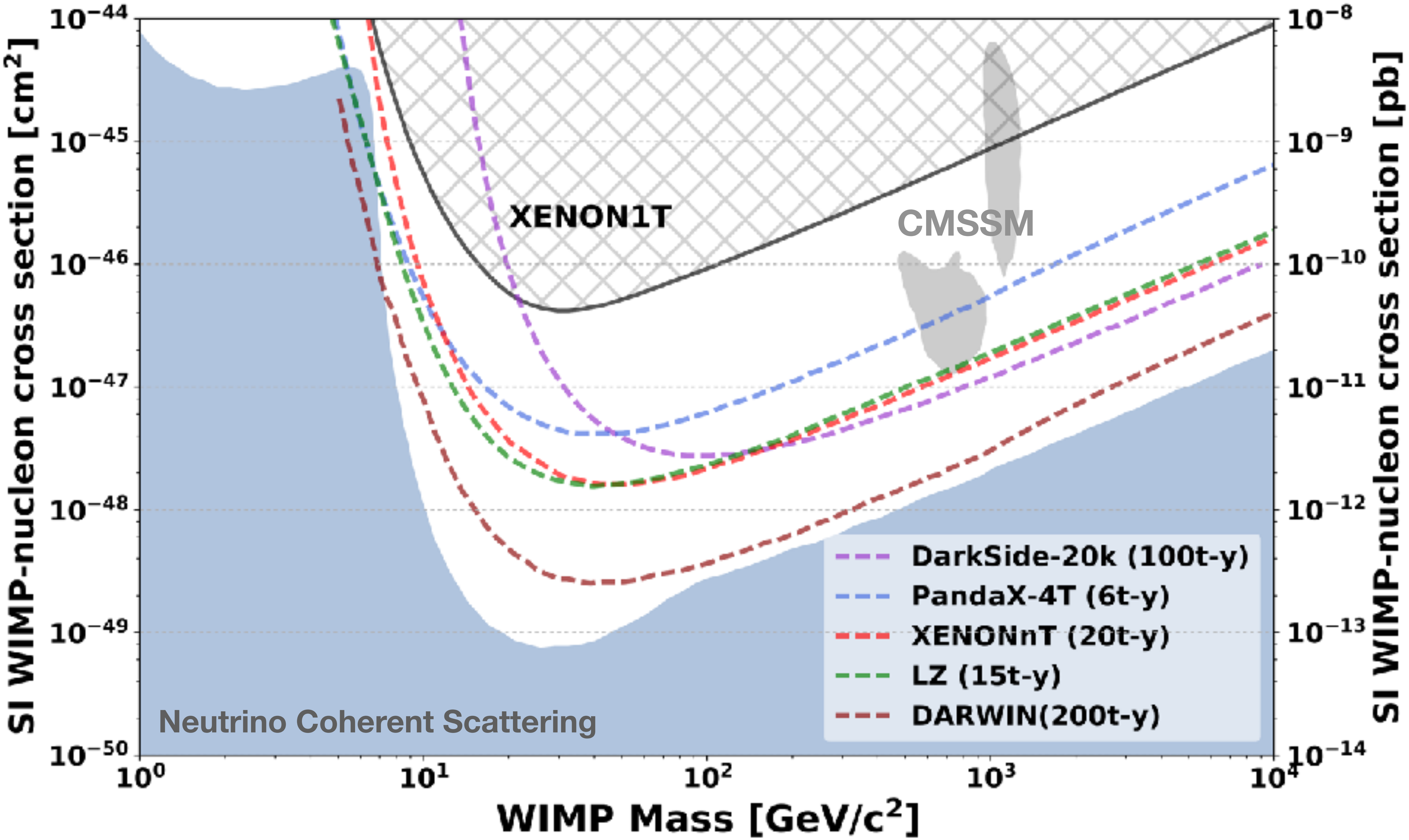
LXe TPCs: the future



- Results from running experiments and secondary results from completed ones
- XENONnT: 2019 8t, 4t fiducial
- PandaX-4T: 2020 4t
- LZ:2020 10t, 5.6t fiducial
- DARWIN:2024 50t



Direct Detection of WIMPs by 2025?



INFN
Istituto Nazionale di Fisica Nucleare

Thanks !

Marco Selvi
INFN Bologna