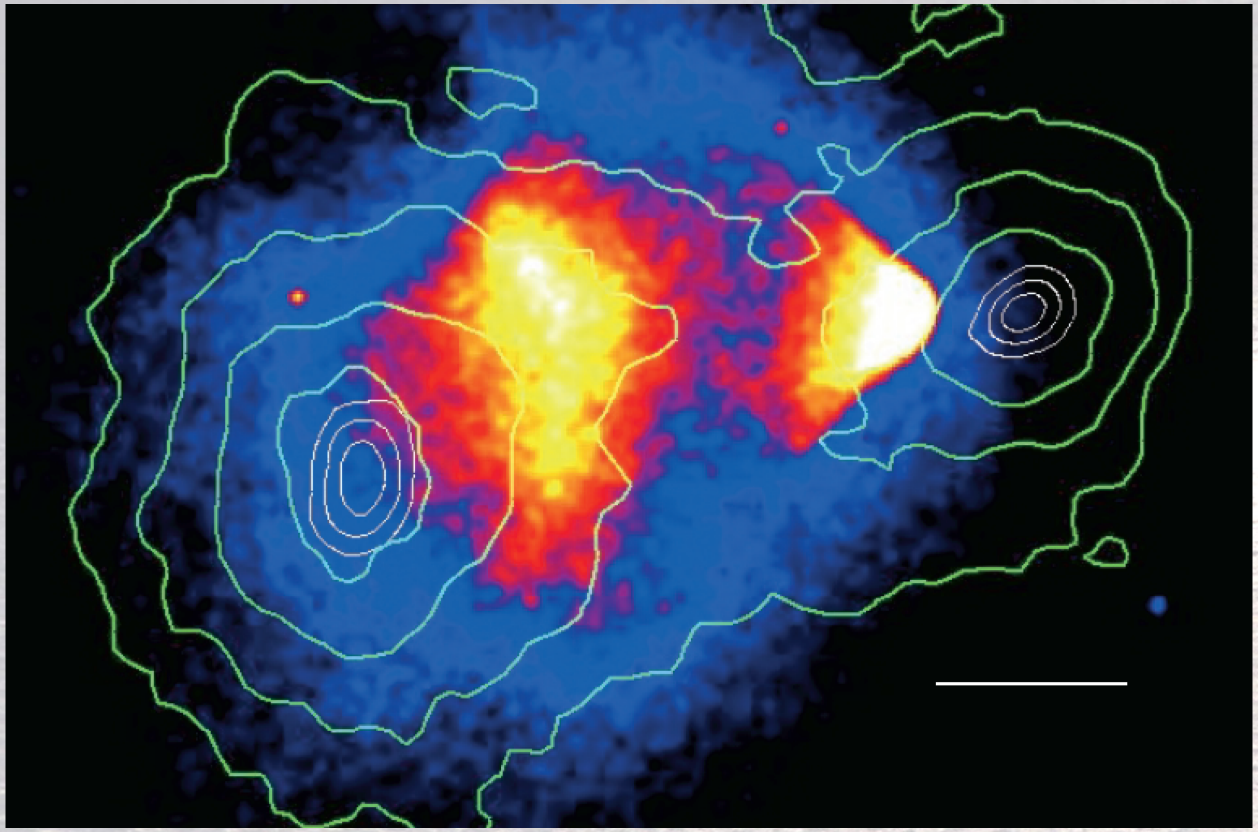


Search for Dark Matter: status of direct searches

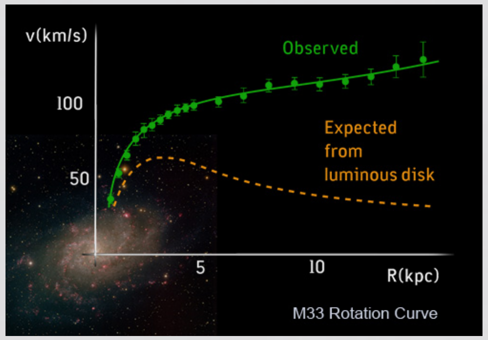
COSMOS

May 29th, 2019
Marco Pallavicini - Presidente CSN2

Istituto Nazionale di Fisica Nucleare

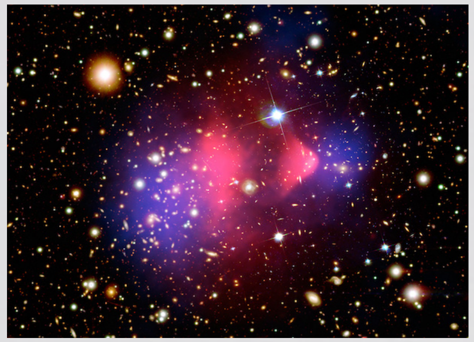
- We need dark matter to explain gravitational dynamics **at all scales**

~10 kpc



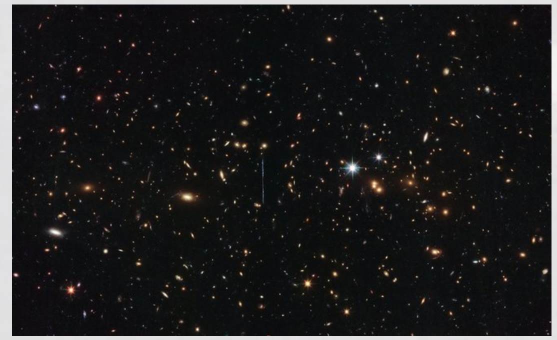
Rotation

~10 Mpc



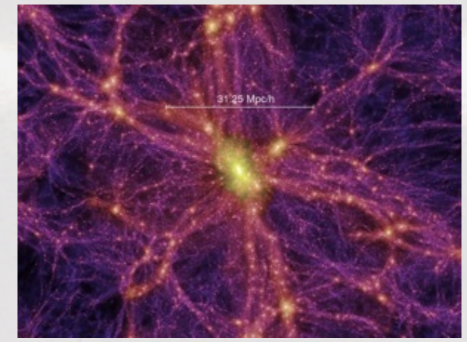
Bullet cluster

~10 Mpc



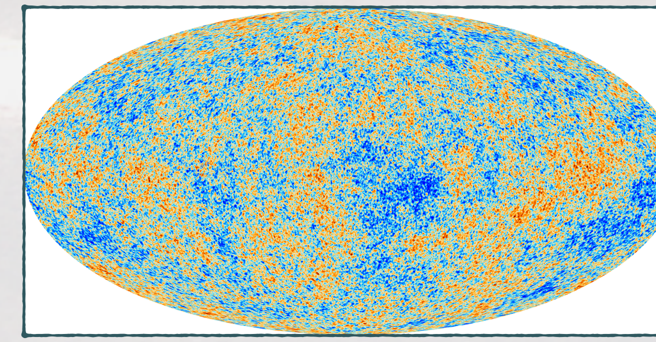
Virial

~100 Mpc



Structures

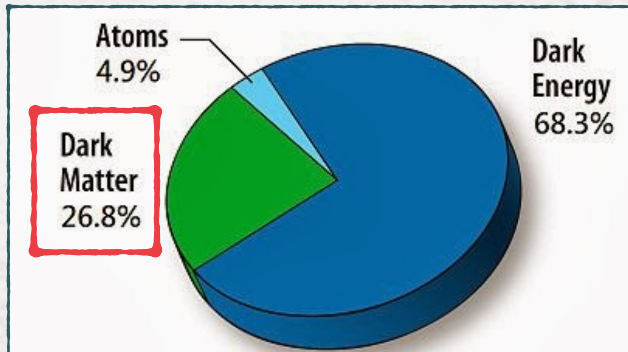
~1 Gpc



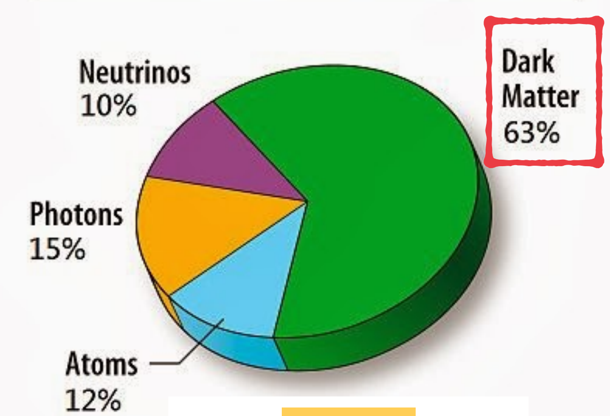
CMB

- **All based on the assumption that GR is fine at all scales**
  - A lot of effort toward MOND or Modified Gravity but (as far as I know) **no model works at all scales**

- **Average density** ~ **0.3 GeV/c² cm⁻³**
  - Local density might be different
  - Primordial BH might change the picture
  - Speed distribution often **assumed** to be a truncated Maxwell



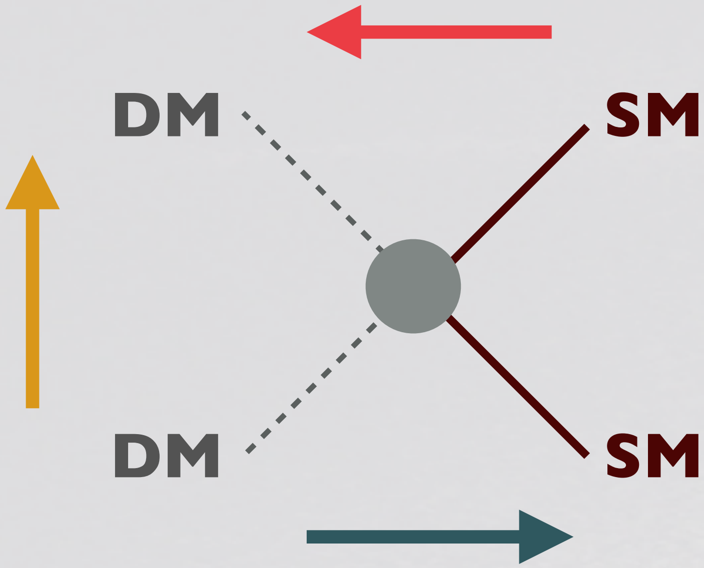
Energy density



Mass

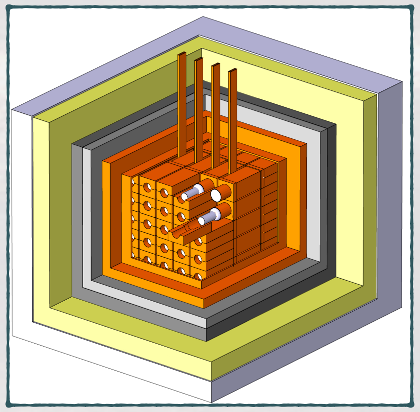
- Mostly **"cold"**, with possible **"warm" component**
- **Interactions, composition, self-interaction** and **dynamics unknown**

- Three methods: **direct**, **indirect**, **search of new particles**



Search of new particles (LHC, Beam Dumps)

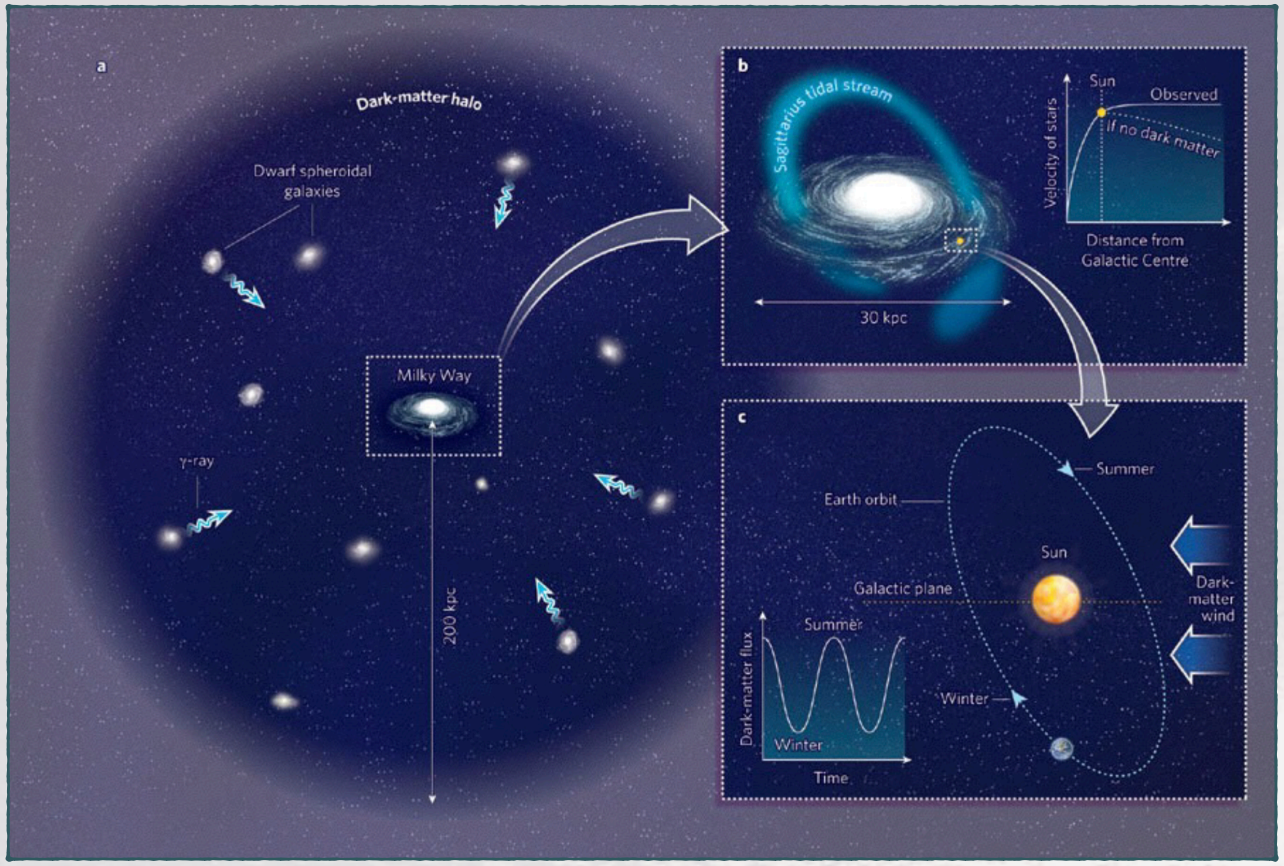
Indirect: Decay or annihilation



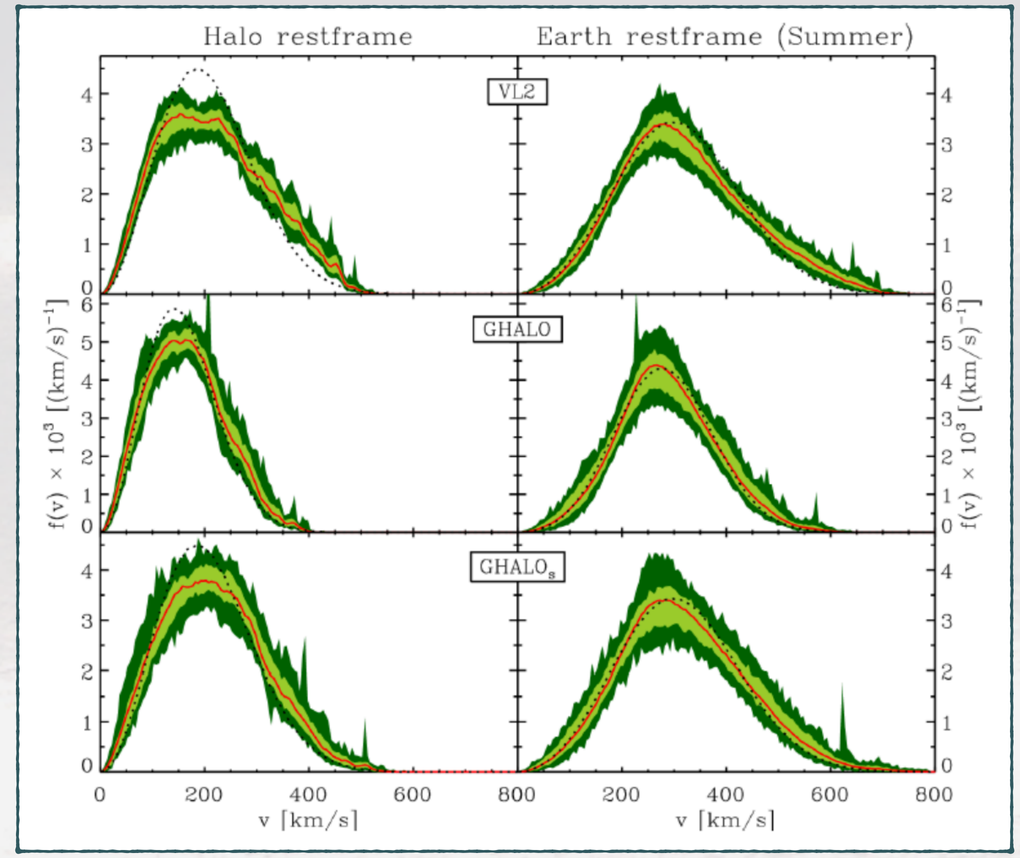
Direct

$$\frac{dR}{dE}(E > E_{thr}) = n_0 N_b \epsilon(E) \int v f(\vec{v}, t) \frac{d\sigma}{dE}(E, v) d^3\vec{v}$$

- Total rate in a detector
  - **n_0: *local* density** (unknown). For WIMPs: **$n_0 = \rho_0 / M_\chi$ (model dependent)**
  - **N_b:** number of ***targets*** (nuclei, electrons, atoms, individual nucleons)
  - **v: *relative speed*** between candidate and target. **Model dependent and variable in time**
  - **$d\sigma(E,v)/dE$: *cross section, E energy deposit*. Unknown, might depend on v**
  - **E:** deposited energy. ***$E>E_{thr}$ detection threshold.***



R. Caldwell et al - Nature 458 (2 Apr 2009)



M. Kuhlen et al., JCAP 02 (2010) 030

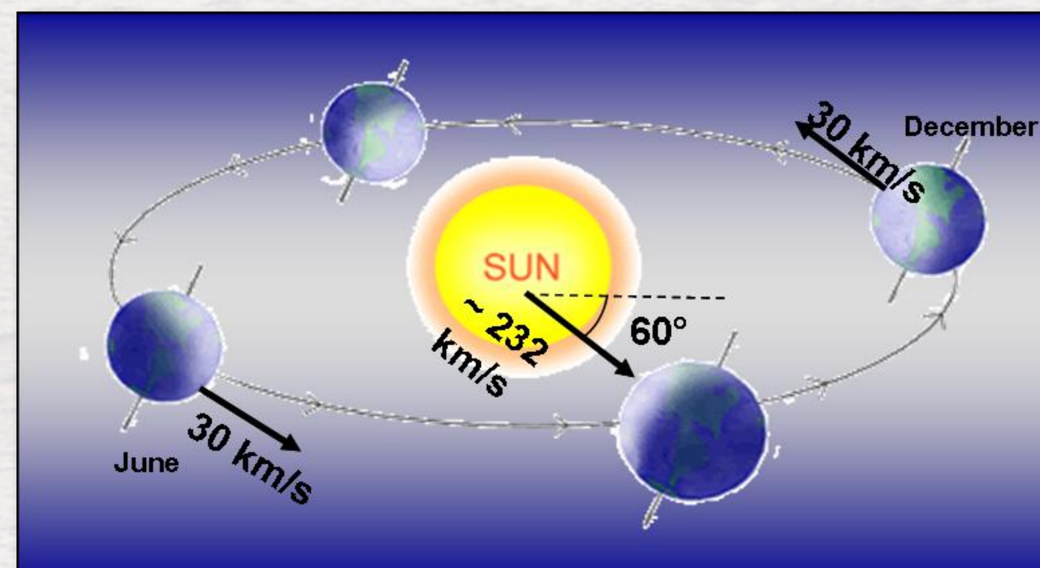
"Standard Parametrization"

(CM Alo)

$$f(v) = \begin{cases} N exp\left(-\frac{3v^2}{2\sigma^2}\right) & v < v_{esc} \\ 0 & v > v_{esc} \end{cases}$$

v_c = 220 km/s $\sigma_r = v_c$ / sqrt(2)

v_{esc} ~ 544 km/s



$$R = B + S_0 + S_m \cos(\omega t + \delta)$$

S_m e S_0 independent δ ~ June 2nd

WHAT ABOUT THE CANDIDATE ?

- ***We do not know at all,*** but we have a few "golden channel", mostly motivated by theoretical arguments and/or prejudices
  - N.B.: the assumption that DM is ***one particle*** is totally arbitrary; we might discover a rich dark sector

- **WIMP: W**eakly **I**nteracting **M**assive **P**article, of which the ***Neutralino*** (mixture of super-symmetric partners of the photon, the Z_0 and Higgs(s))
  - Mass scale unknown, but the theory calls for ~ few GeV - few TeV

- **AXION:** the Goldstone boson of a Peccei-Quinn-like broken symmetry, postulated to solve the so called ***strong CP problem,*** i.e. the "unnatural" absence of CP violation in QCD
  - Range of mass scale very broad, but quite light ~ 10^{-7} eV - 10^{-1} eV
  - **A**xion **L**ike **P**articles (ALPs) are also a common target

- **STERILE NEUTRINOS:** they must exist, mass completely unknown (from very light to super-heavy)

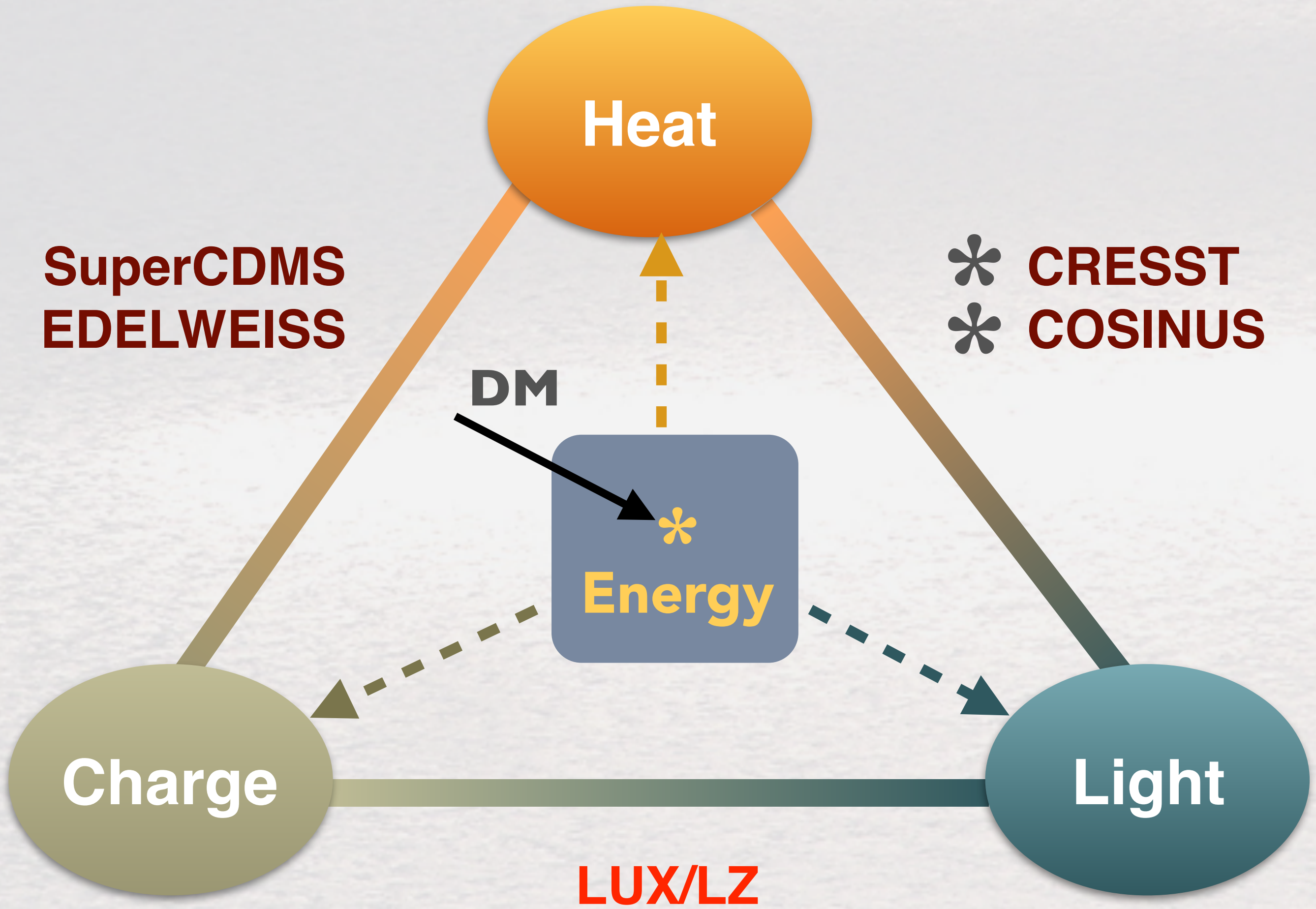
Kaluza-Klein DM
Axion
Axino
Gravitino
Photino
SM Neutrino
Sterile Neutrino
Sneutrino
Light DM
Little Higgs DM
Wimp-zillas
Q-balls
Mirror matter
Cryptons
Heavy Neutrino
Neutralino
Branos
Primordial black holes
Split SUSY

DIRECT DETECTION TECHNIQUES

- Liquid Argon
- Liquid Xenon
- R&D directional
- Low threshold
- Bubble chambers
- Bolometers
- Modulation

* @LNGS

SIMPLE
PICASSO
COUPP
PICO,
* MOSCA-B



SuperCDMS
EDELWEISS

* CRESST
* COSINUS

CoGeNT
CDEX
DAMIC
SENSEI
NEWS-G
DRIFT
MIMAC
DMTPC
* NEWS

LUX/LZ
PandaX
* XENON

ArDM
* DarkSide

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

- It seems a normal "counting experiment", but give a look at the numbers:
  - Assume a signal rate of 0.001 count kg^{-1} d^{-1} (quite high….)
  - This means **1.16 10^{-8} Bq/kg**

- **BUT:**
  - **Good mineral water: ~10 Bq/kg** **^{40}K, ^{238}U, ^{232}Th**
  - **Air: ~10 Bq/kg** **^{222}Rn, ^{39}Ar, ^{85}Kr**
  - **Typical rock ~100-1000 Bq/kg** **^{40}K, ^{238}U, ^{232}Th, + many others**

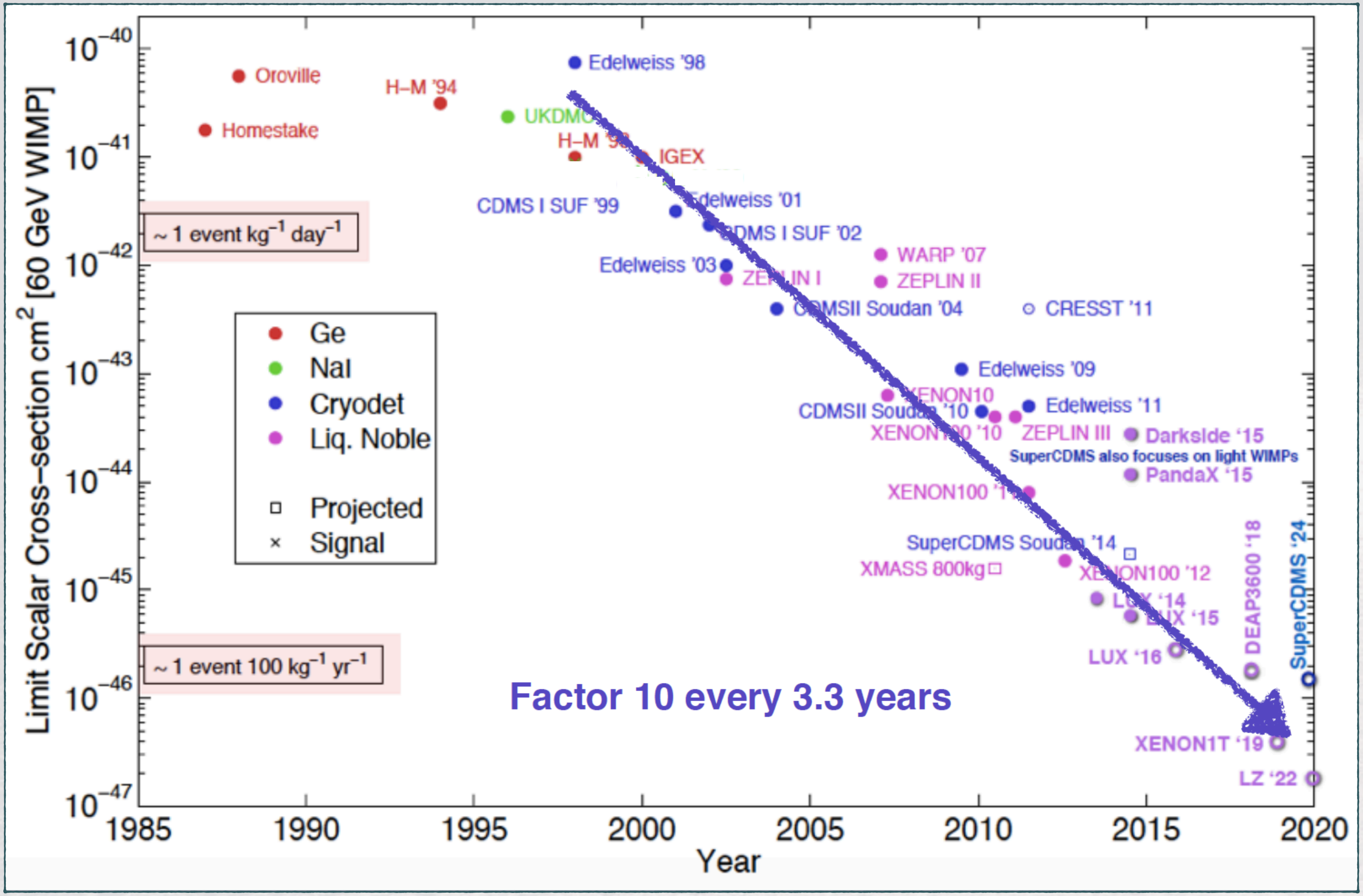
- Radioactivity is mostly higher energy than dark matter recoil
  - This helps !

- However, if you want to detect dark matter with single counts, you must be **6-7 orders of magnitude more pure than anything on earth**

WORLD EFFORT

- In the following:
  - ***A personal selection*** of results and experiments to give a feeling of the current understanding (or lack thereof….)
  - Impossible to give credit to all world effort
  - Mainly covering
    - Modulation experiments, a.k.a. model independent searches
    - Search of WIMP-induced nuclear recoil
    - Search for AXIONS
    - Final remarks

STANDARD WIMPS: FIELD DEVELOPMENT



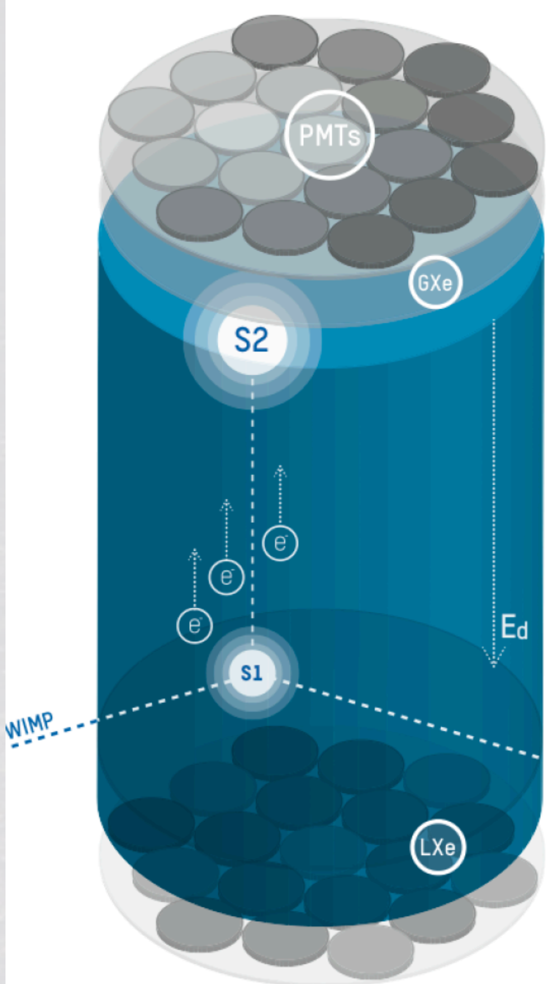
Sensitivity to a "standard" WIMP as a function of time

(useful as benchmark, but it works ONLY for experiments searching for elastic nuclear recoils in some WIMP mass range)

Credito: M. Selvi

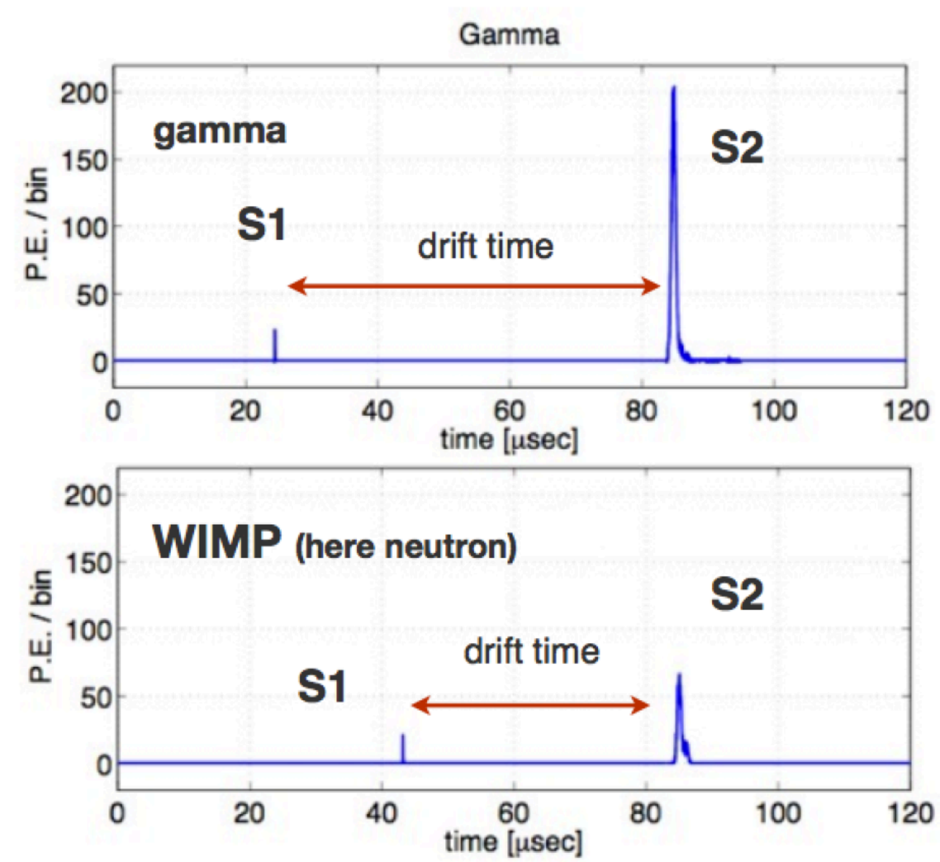
STANDARD WIMPS

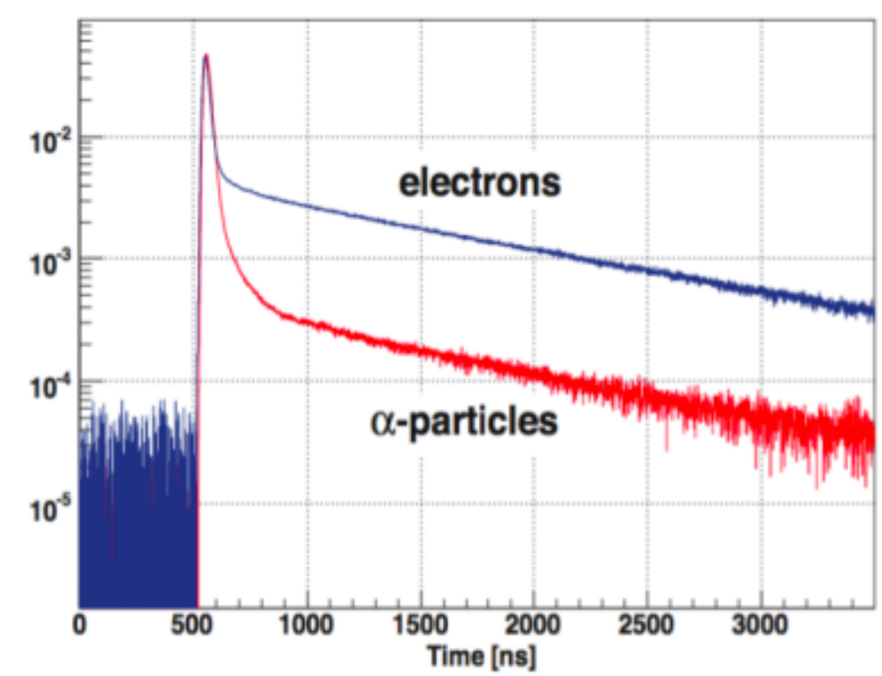
- Main efforts:
  - Noble liquid detectors with either Xenon or Argon
  - Either double phase TPCs (e.g. DarkSide, LUX, Xenon, LZ, PANDAX) or single phase detectors (e.g. DEAP, XMASS)



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

→ Electron- /nuclear recoil discrimination



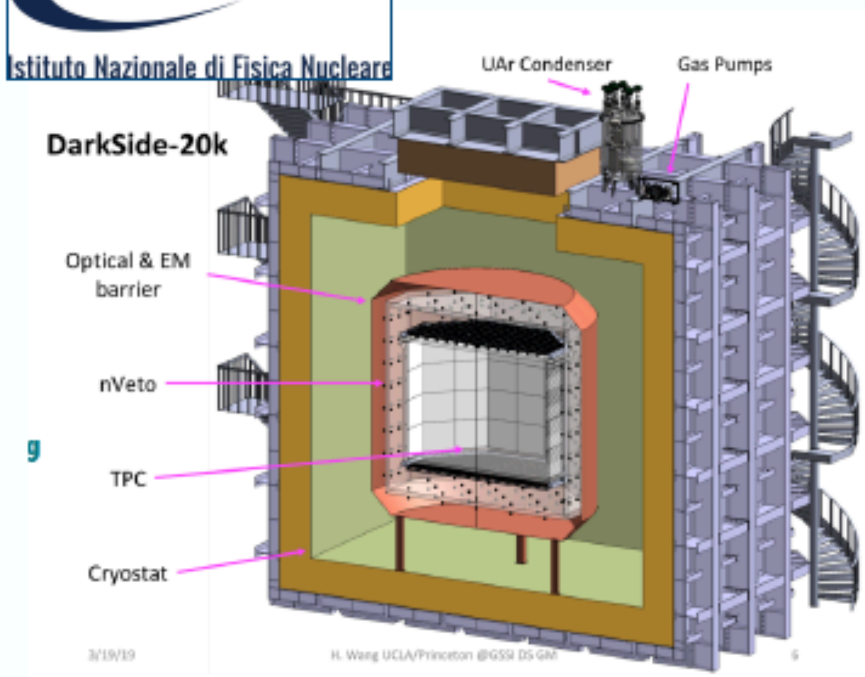


Scintillation decay constants of argon measured by ArDM

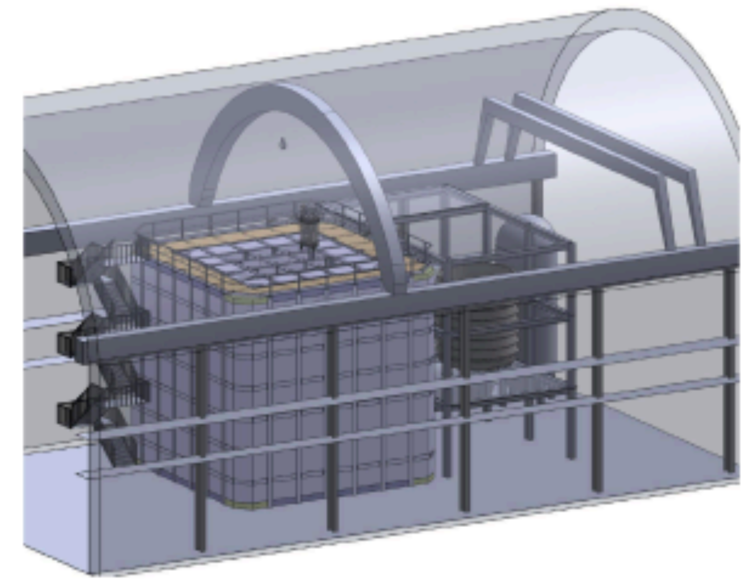
- Drift field
- Electronegative purity
- Position resolution

INFN
Istituto Nazionale di Fisica Nucleare

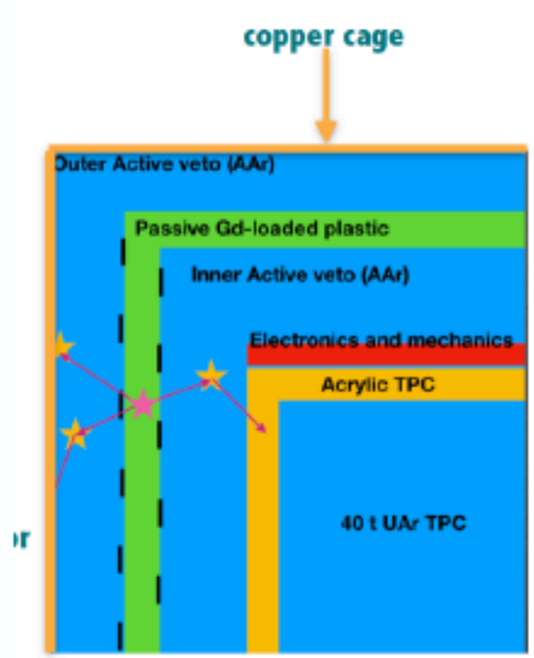
DarkSide-20k



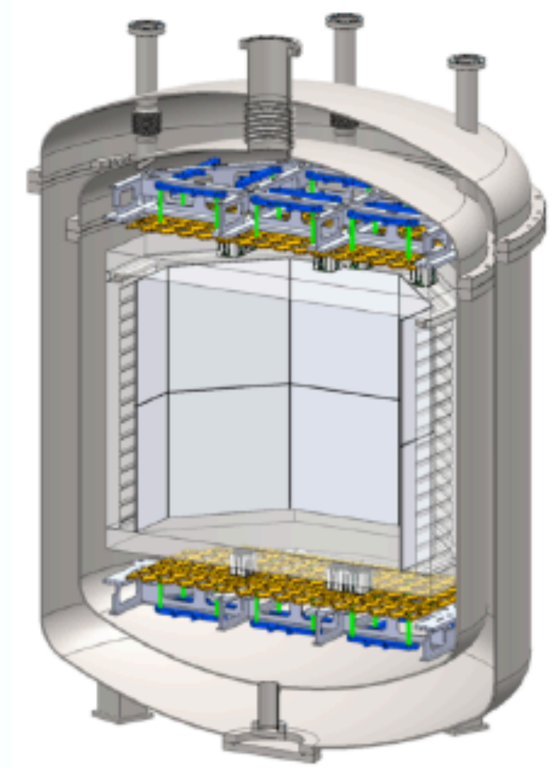
- 8280 PDM's
- drift length 3.5m
- 50tons of depleted argon
- 40tons fiducial mass with 5cm from the walls
- 70% of background from top and bottom
- optimisation of further z cut for DM search ongoing



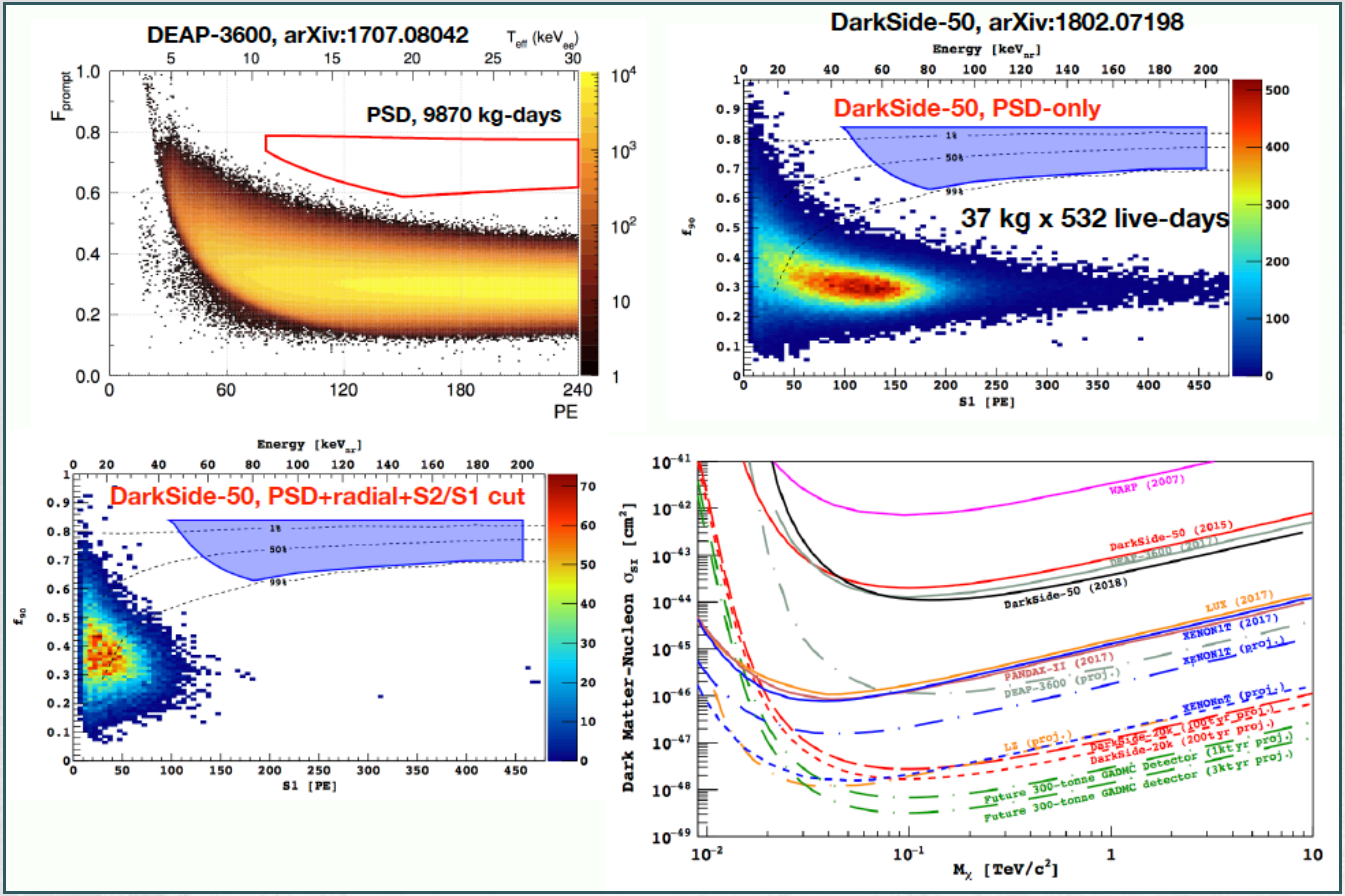
Organic scintillator-free design: the only liquid around is argon (and nitrogen). Most of the TPC and VETO material is acrylic (PMMA). Gadolinium (2% in mass) in the VETO is embedded in a solid matrix of PMMA.



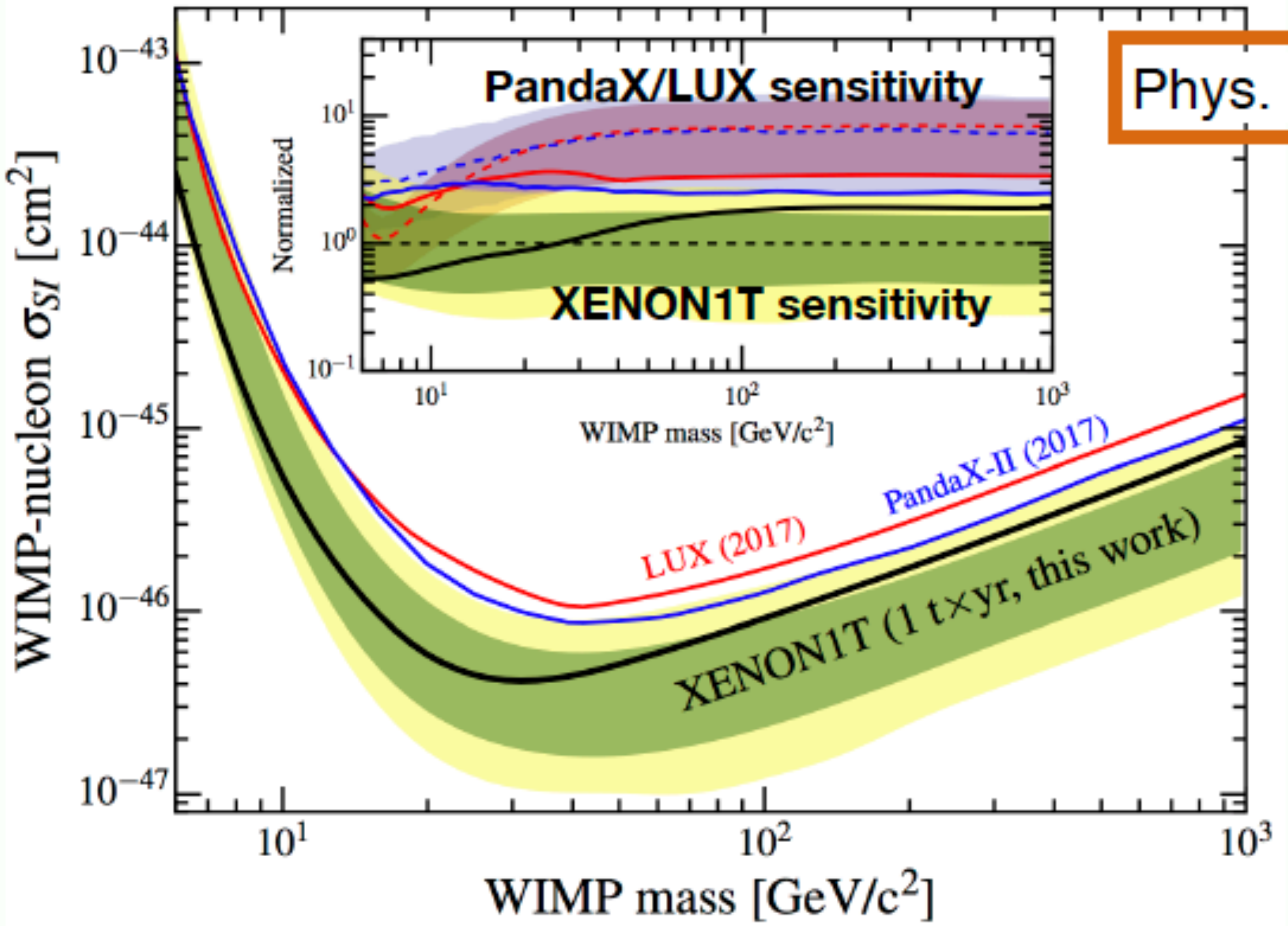
Proto-1t



LIQUID ARGON RESULTS: DEEP 3600 AND DARKSIDE-50

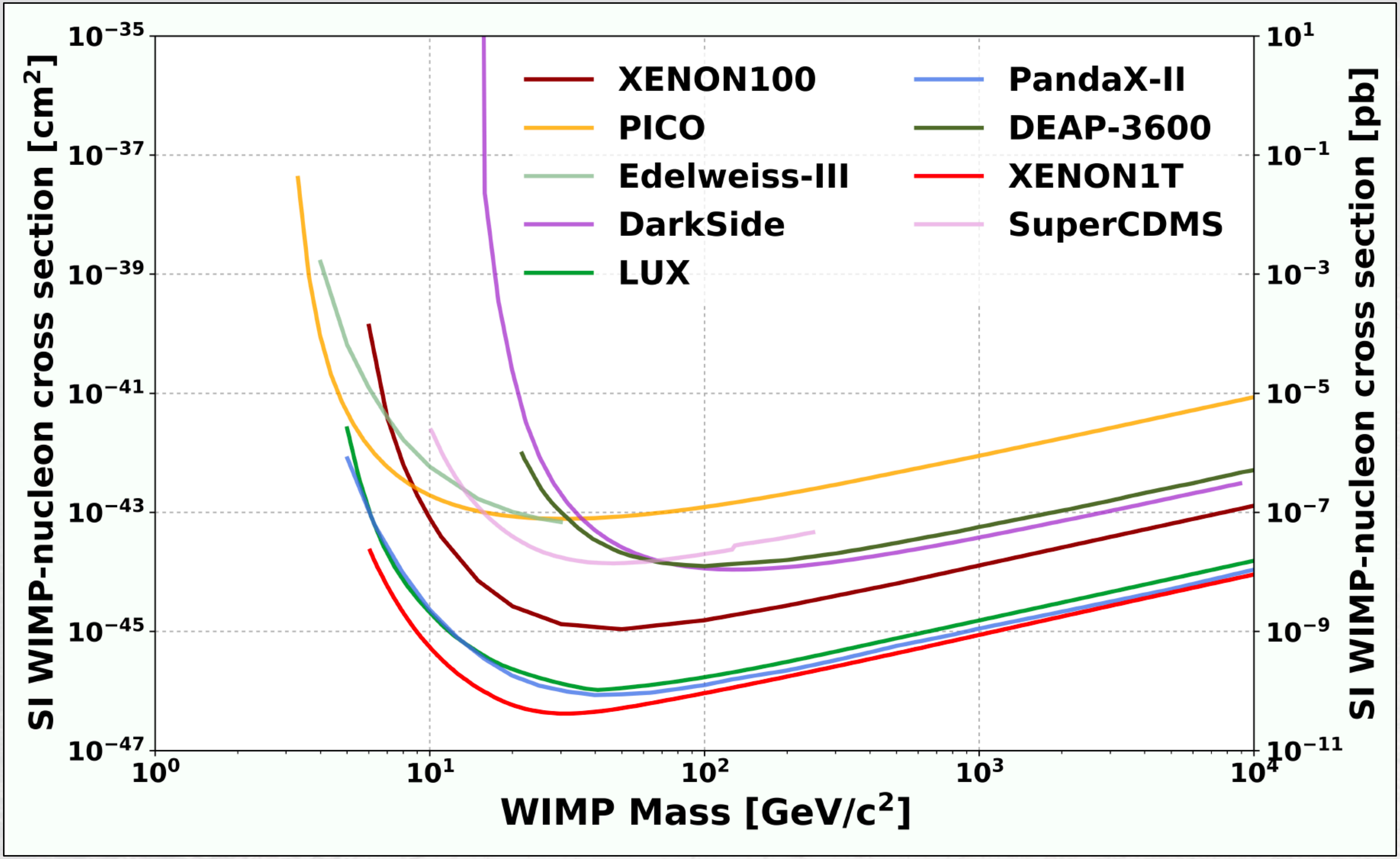


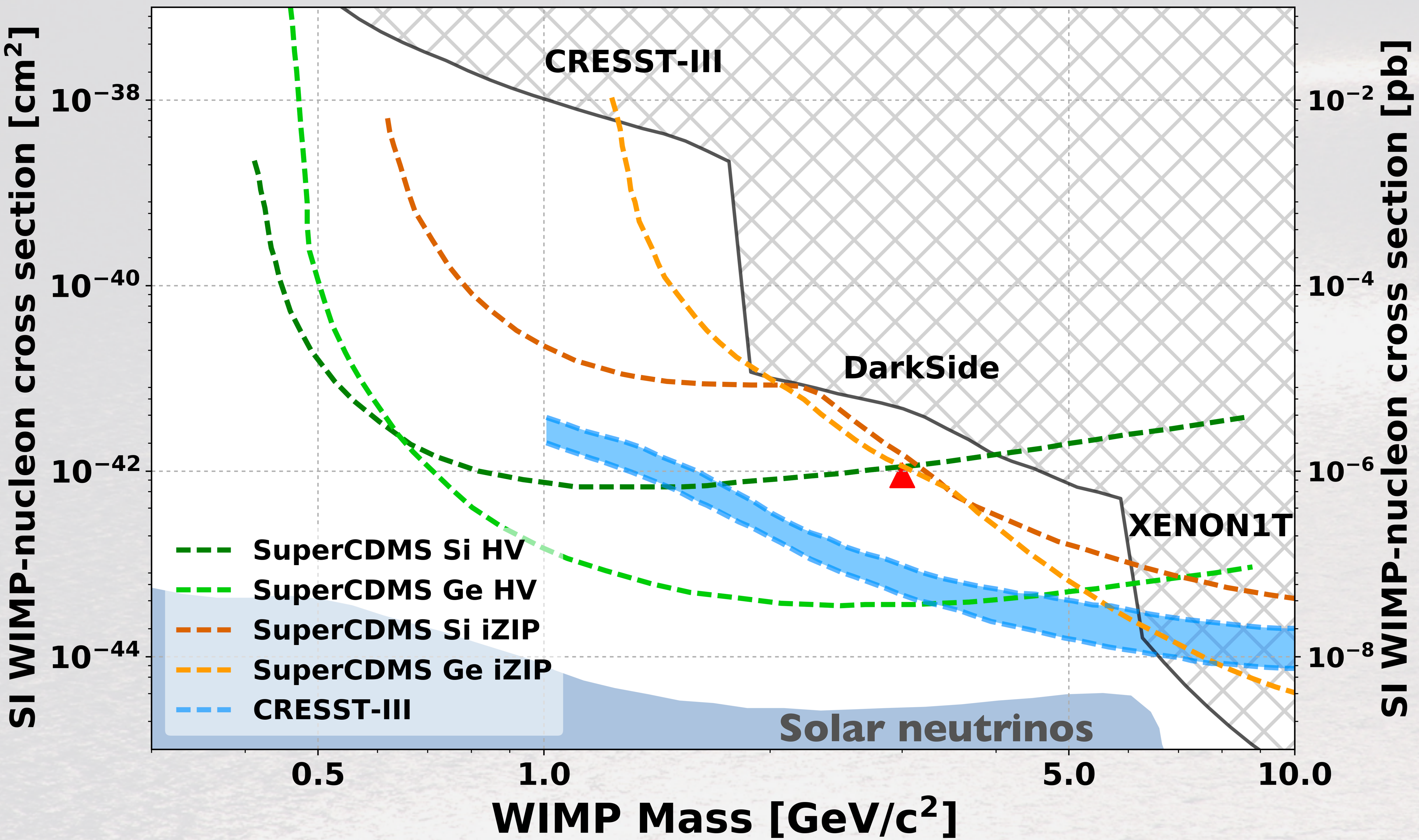
- **No significant (>3 sigma) excess at any scanned WIMP mass**
- **p-value for background-only hypothesis: ~0.2 at high WIMP mass**
- **Rate plot shows best-fit cross-section of 4.7x10^{-47} cm^2 assuming 200 GeV/c^2 WIMPs**
- **Relevance of a unified statistical approach among direct DM experiments (Neyman construction, unified approach 1,2-sided confidence interval, protection agains under-fluctuations, ...)**



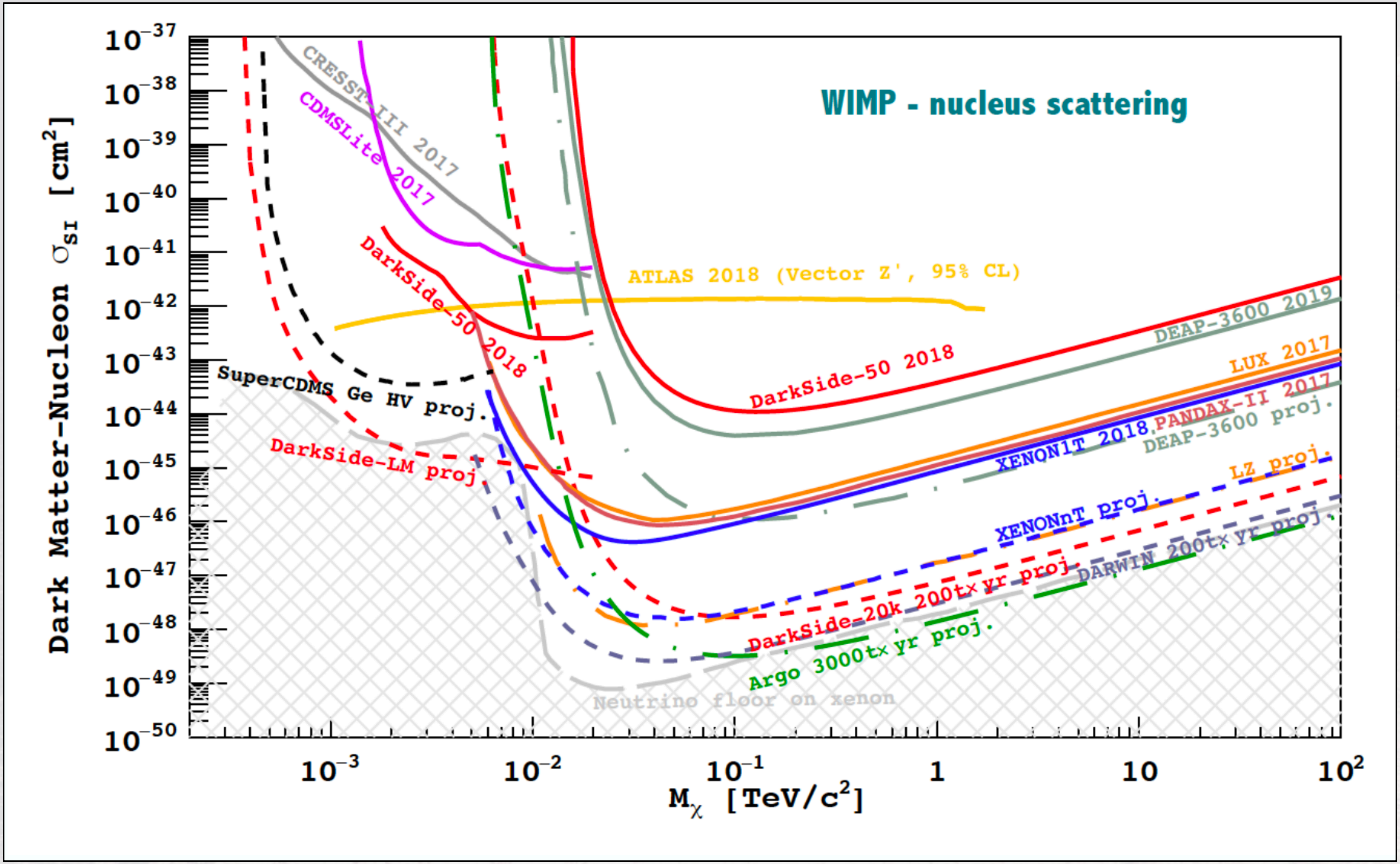
Phys. Rev. Lett. **121**, 111302

HEAVY WIMP SUMMARY

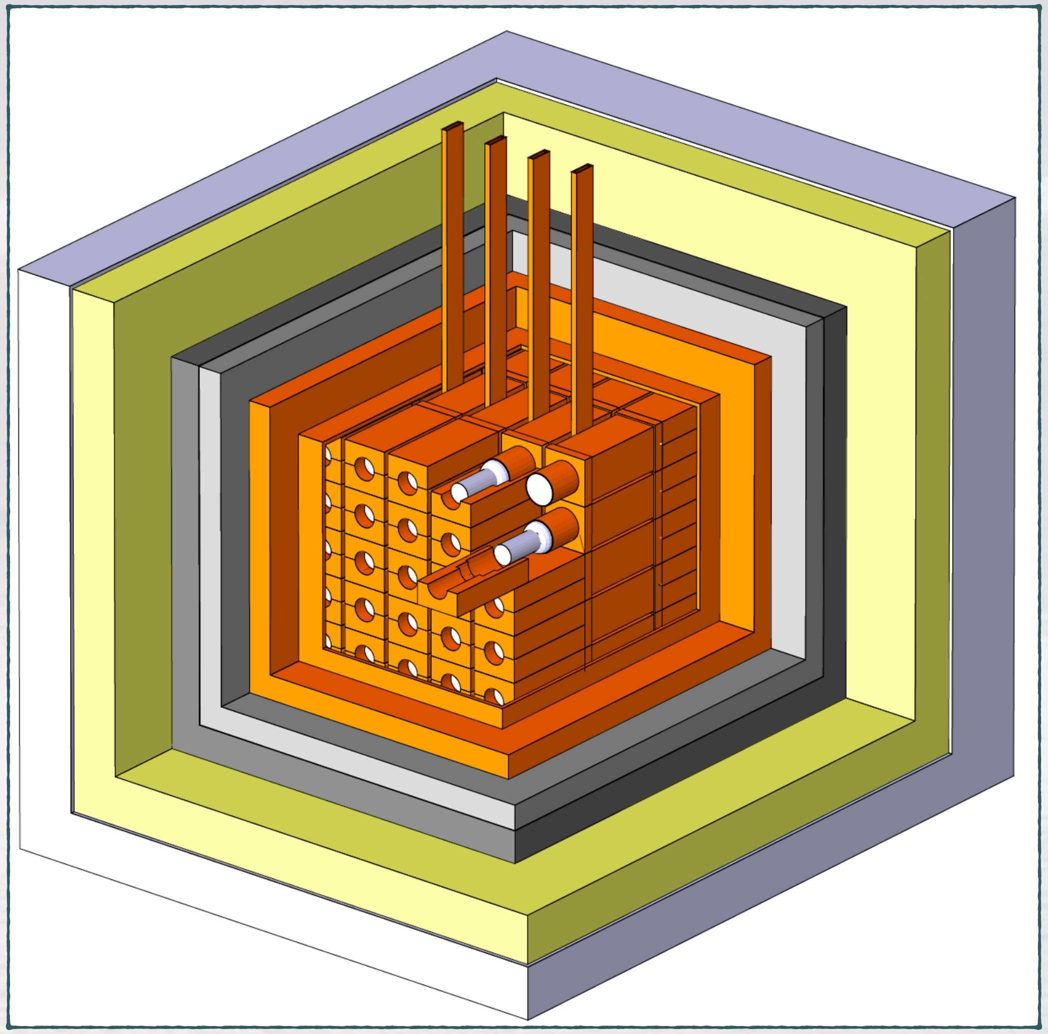



CRESST-III
DarkSide
XENON1T
Solar neutrinos
SuperCDMS Si HV
SuperCDMS Ge HV
SuperCDMS Si iZIP
SuperCDMS Ge iZIP
CRESST-III
SI WIMP-nucleon cross section [cm²]
SI WIMP-nucleon cross section [pb]
WIMP Mass [GeV/c²]
10⁻³⁸
10⁻⁴⁰
10⁻⁴²
10⁻⁴⁴
10⁻²
10⁻⁴
10⁻⁶
10⁻⁸
0.5
1.0
5.0
10.0

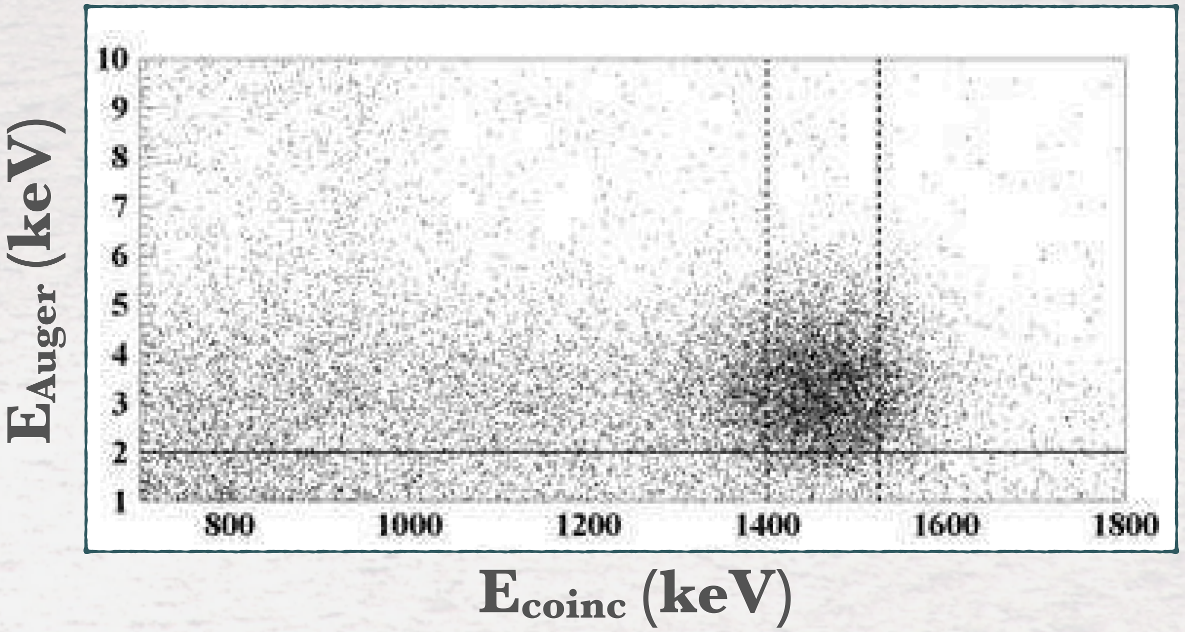
STANDARD WIMP: HORIZON 2020-2030

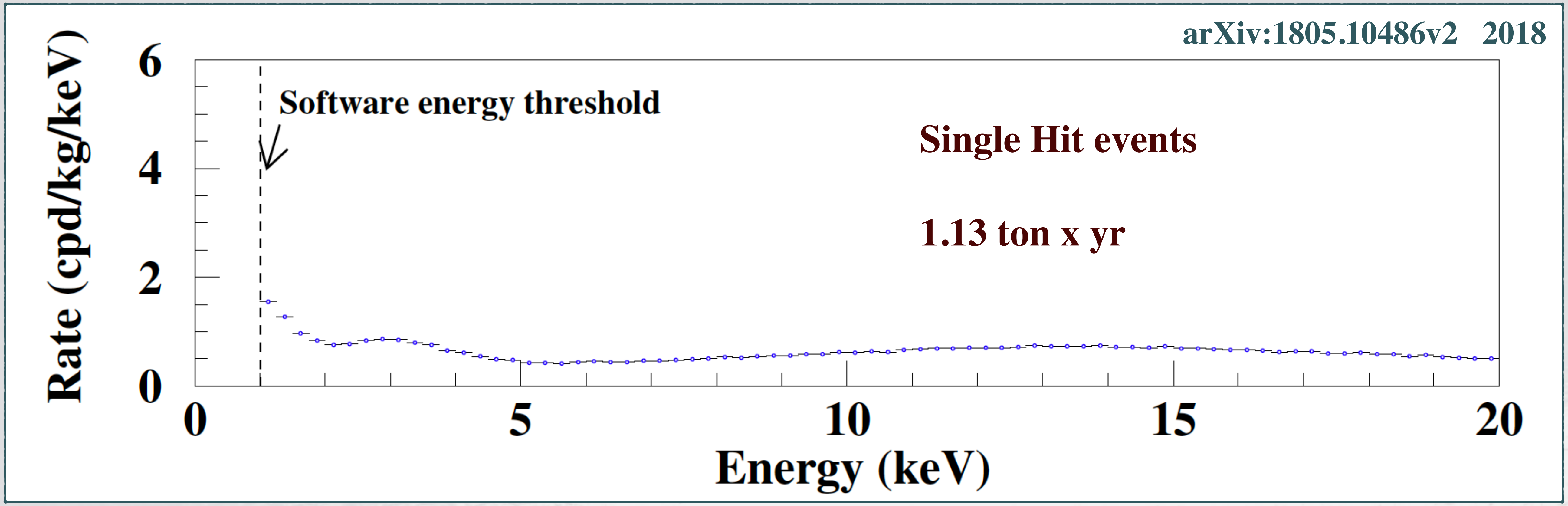


- **Geometry**
  - **~250** kg NaI(Tl), 9.70 kg, 10.2x10.2x25.4 cm^3 **(25)**
  - Shielding against γ, **neutrons, Rn,** with stability monitor at the level of **~ 1%**
- **PMTs**
  - Phase 1: ETL at low radioactivity
  - Phase 2: Hamamatsu at low radioactivity
    - **Q.E.: 33-39%** at 420 nm (emission peak NaI(Tl)), **36-44%** at efficiency peak
    - **Dark Noise ~ 100 Hz**
- **Record purity** with NaI(Tl) of such a mass
  - ^{nat}**K < 20 ppb** (measured)
    - Natural calibration line at **3.2 keV**
  - ^{238}**U: 0.7-10 ppt** (broken chain)
  - ^{232}**Th: 0.5 - 7.5 ppt** (equilibrium)

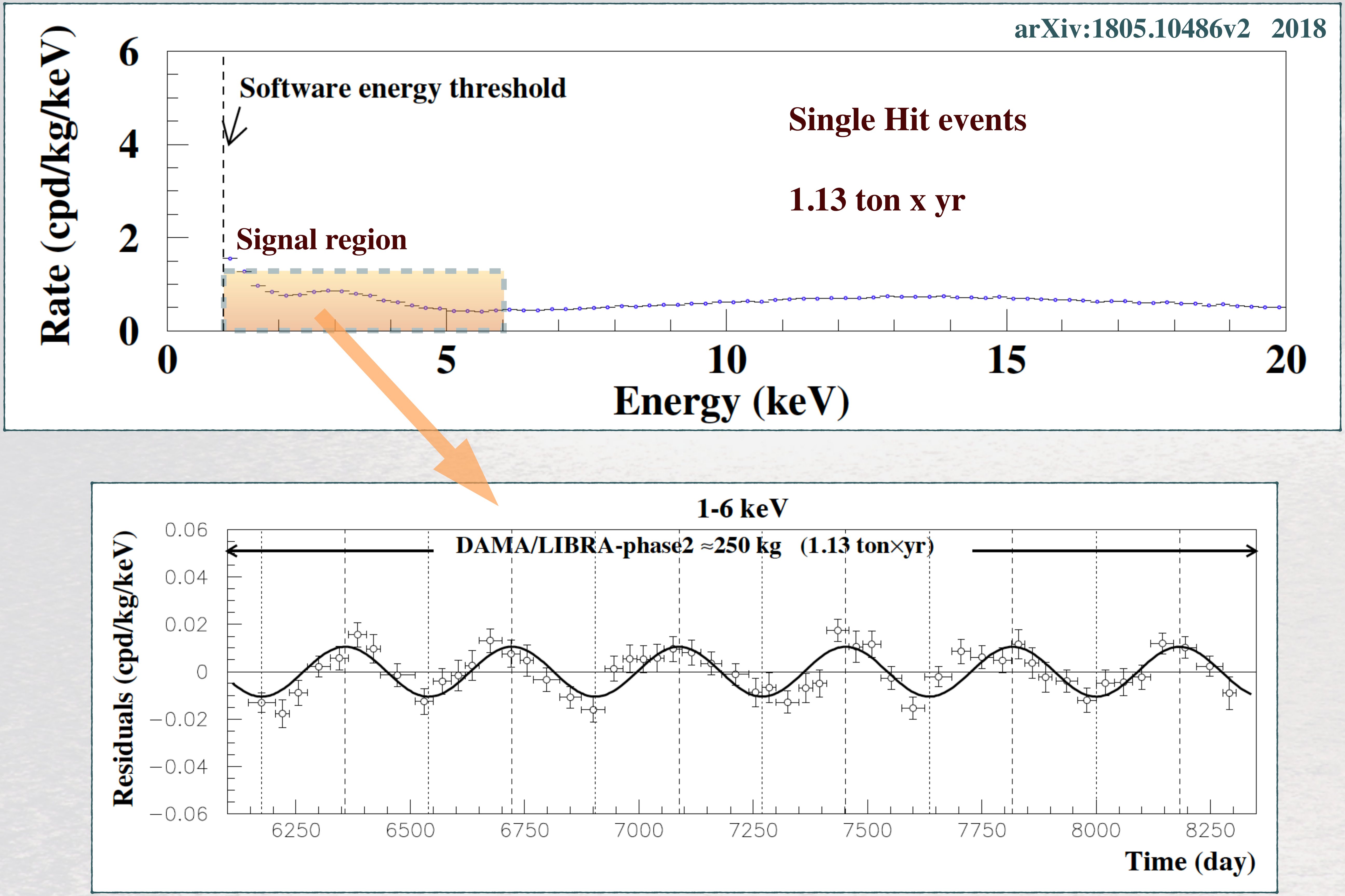


Direct measurement of ^{40}K 3.2 keV line

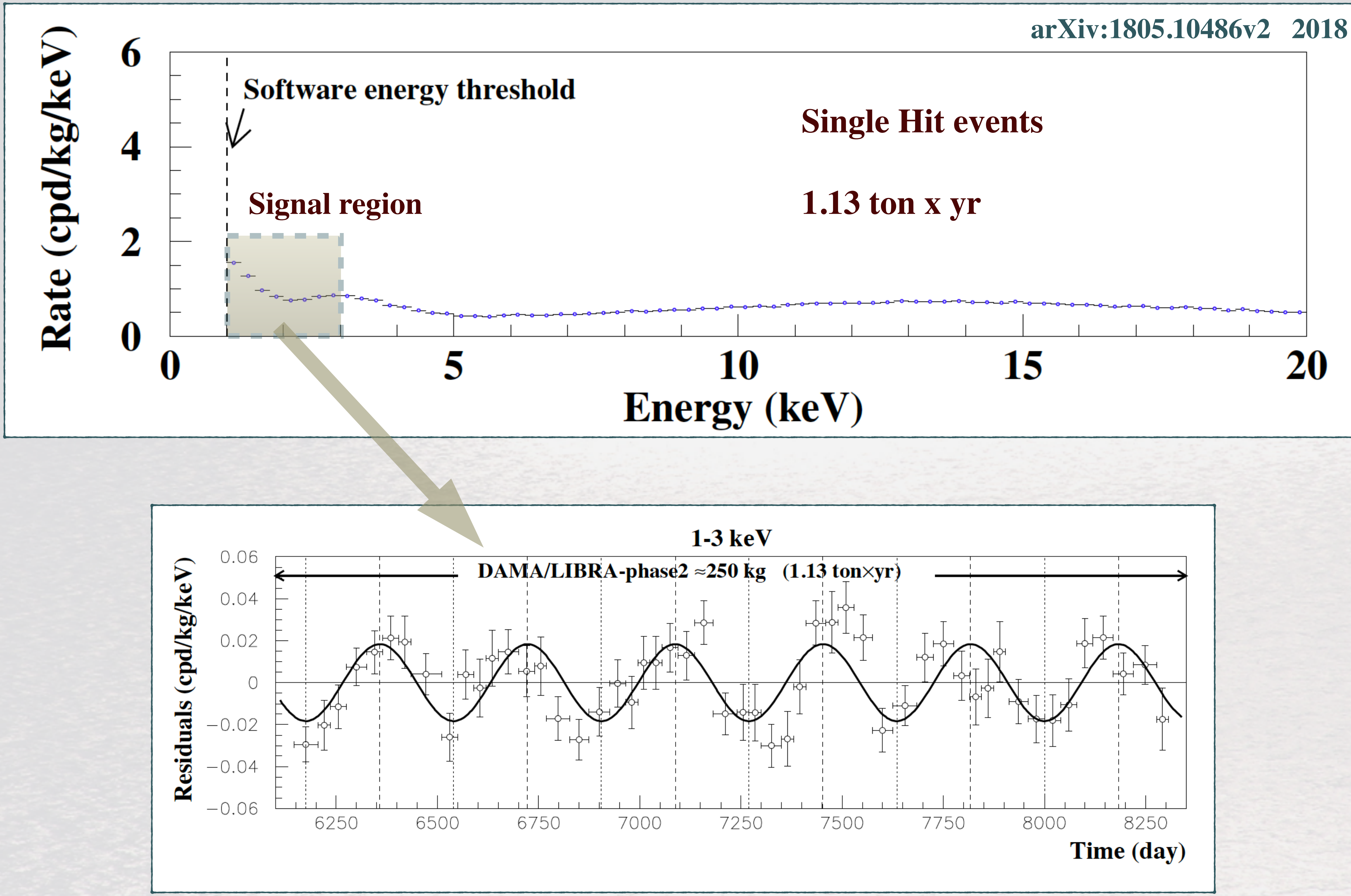



arXiv:1805.10486v2 2018
Rate (cpd/kg/keV)
Software energy threshold
Single Hit events
1.13 ton x yr
0
2
4
6
0
5
10
15
20
Energy (keV)

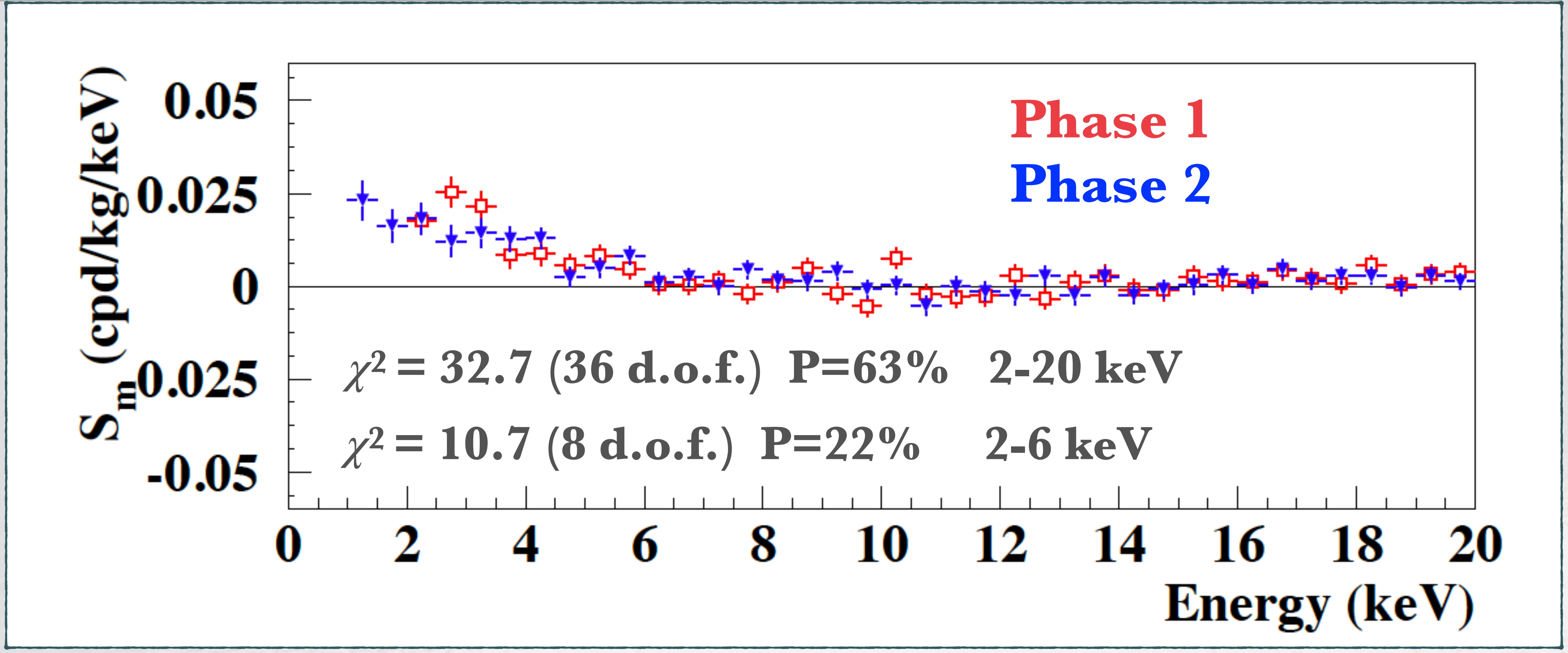
RESULT 2018


arXiv:1805.10486v2 2018
Software energy threshold
Single Hit events
1.13 ton x yr
Signal region
Rate (cpd/kg/keV)
Energy (keV)
1-6 keV
DAMA/LIBRA-phase2 ≈250 kg (1.13 ton×yr)
Residuals (cpd/kg/keV)
Time (day)

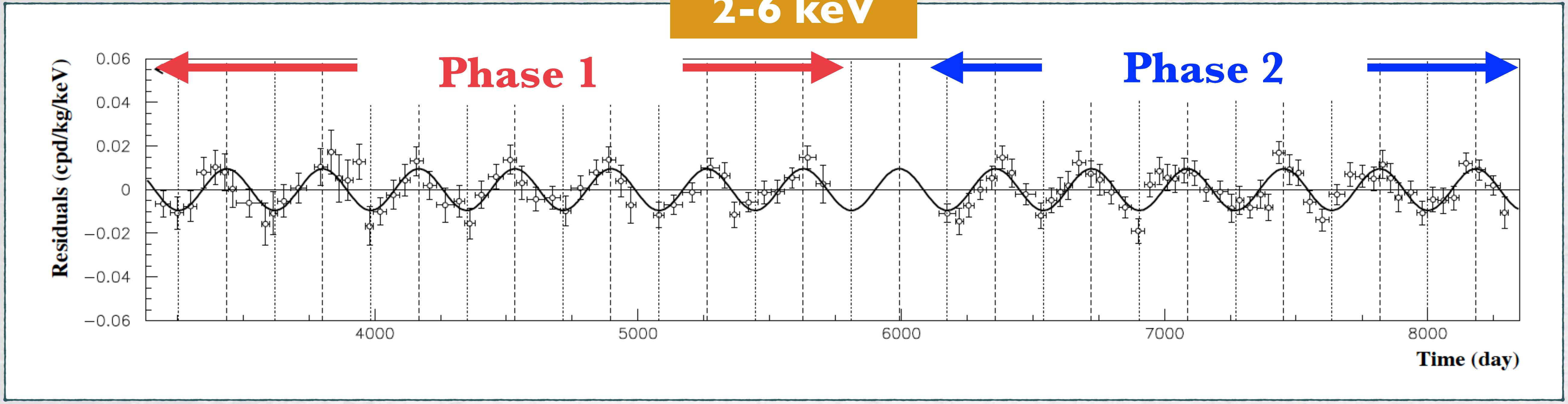
RESULT 2018


arXiv:1805.10486v2 2018
Software energy threshold
Single Hit events
Signal region
1.13 ton x yr
Rate (cpd/kg/keV)
Energy (keV)
0
2
4
6
0
5
10
15
20
1-3 keV
DAMA/LIBRA-phase2 ≈250 kg (1.13 ton×yr)
Residuals (cpd/kg/keV)
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
6250
6500
6750
7000
7250
7500
7750
8000
8250
Time (day)

PHASE 1 - PHASE 2 COMPARISON



2-6 keV

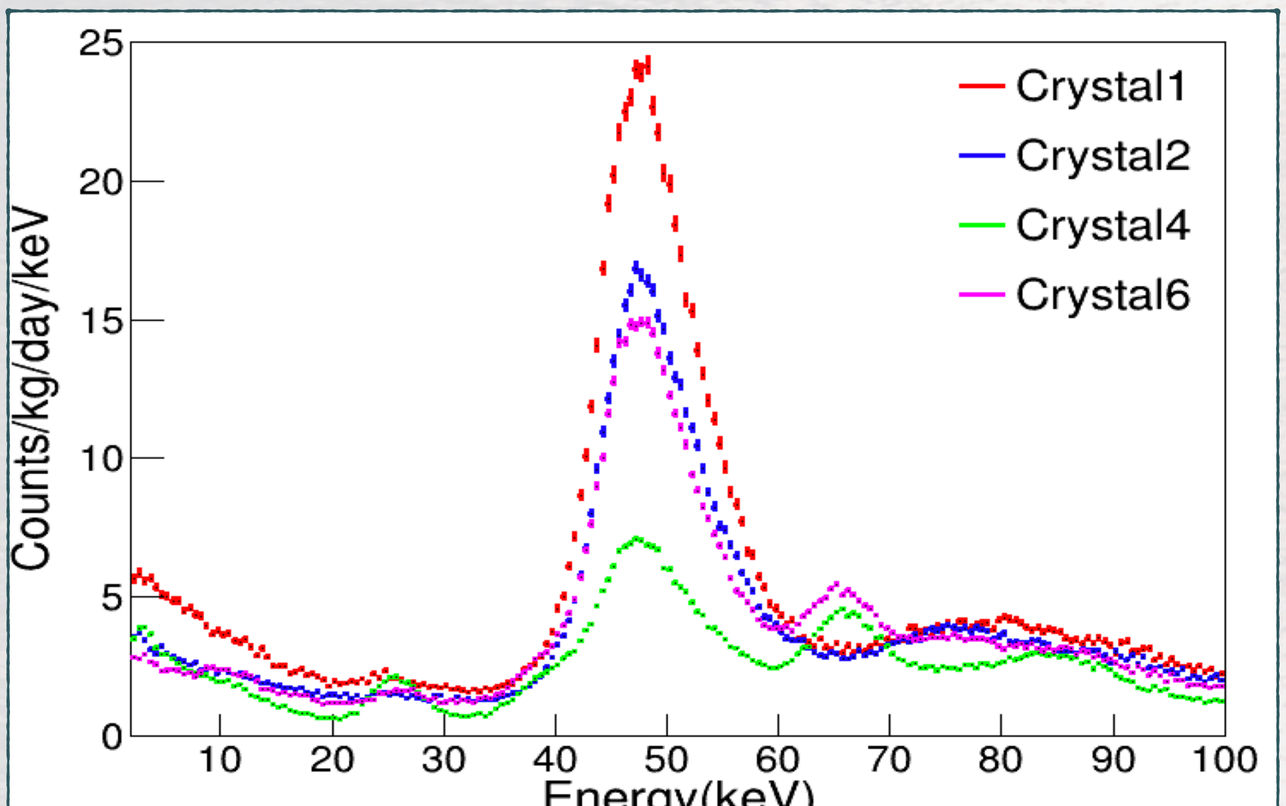


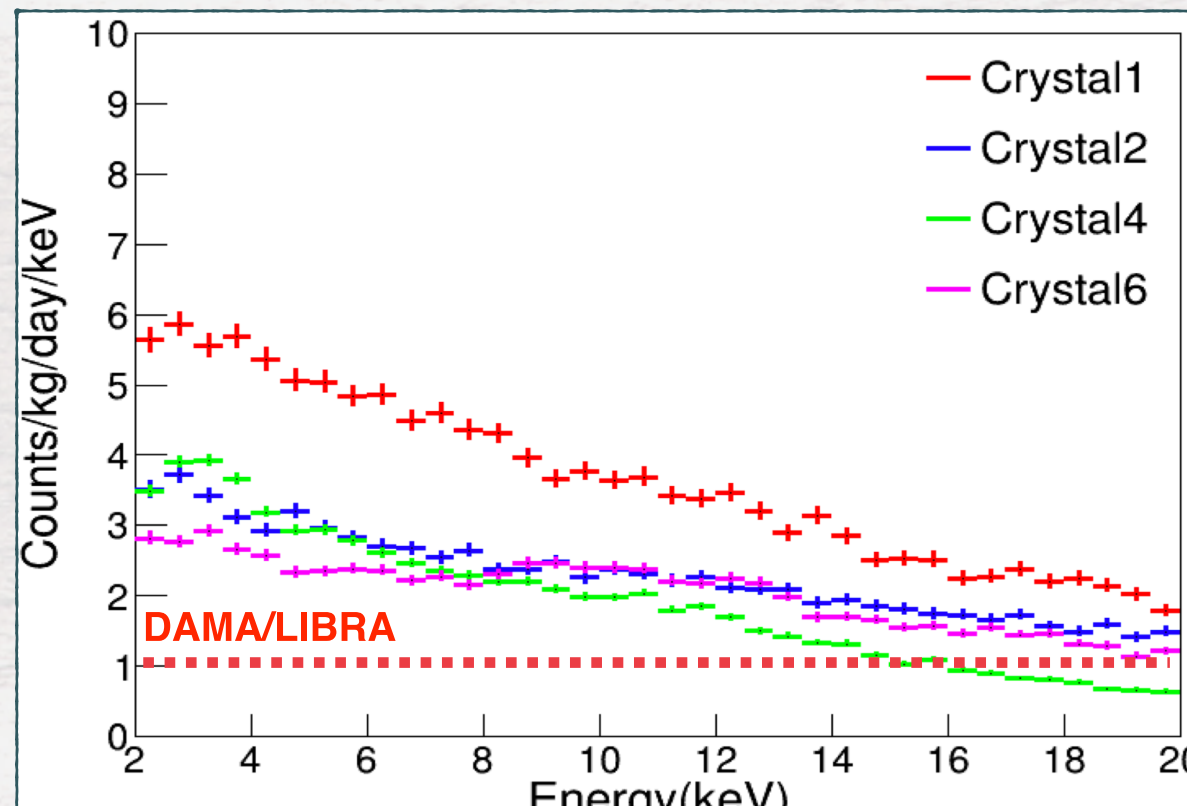
2004 2006 2008 2010 2012 2014 2016

Eur. Phys. J. C 78 (2018) 107

- **8** crystals, **106 kg**
  - Higher background for **^{210}Pb e *α***
    - ^{238}U, ^{232}Th better, ***^{40}K worse***
  - Liquid scintillator veto (LAB) for ^{40}K

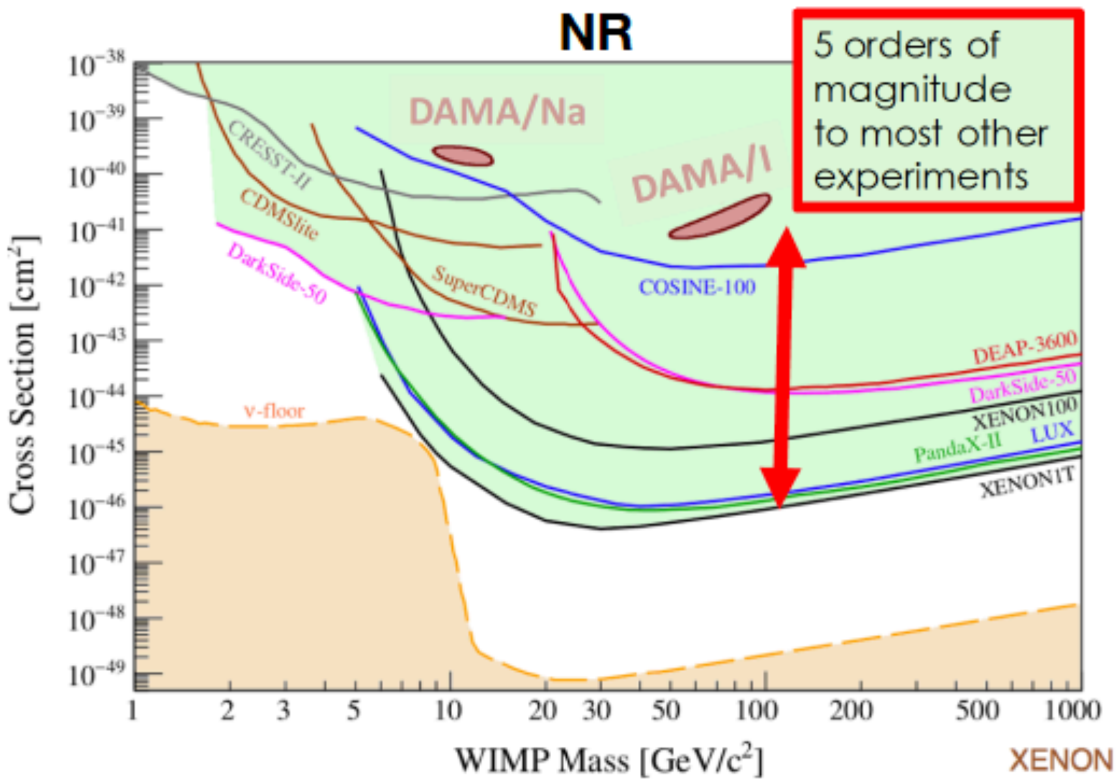
Crystal	Mass (kg)	Powder	Alpha rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light yield (p.e./keV)
Crystal 1	8.3	AS-B	3.20 ± 0.08	43.4 ± 13.7	< 0.02	1.31 ± 0.35	14.88 ± 1.49
Crystal 2	9.2	AS-C	2.06 ± 0.06	82.7 ± 12.7	< 0.12	< 0.63	14.61 ± 1.45
Crystal 3	9.2	AS-WS II	0.76 ± 0.02	41.1 ± 6.8	< 0.04	0.44 ± 0.19	15.50 ± 1.64
Crystal 4	18.0	AS-WS II	0.74 ± 0.02	39.5 ± 8.3		< 0.3	14.86 ± 1.50
Crystal 5	18.0	AS-C	2.06 ± 0.05	86.8 ± 10.8		2.35 ± 0.31	7.33 ± 0.70
Crystal 6	12.5	AS-WS III	1.52 ± 0.04	12.2 ± 4.5	< 0.018	0.56 ± 0.19	14.56 ± 1.45
Crystal 7	12.5	AS-WS III	1.54 ± 0.04	18.8 ± 5.3		< 0.6	13.97 ± 1.41
Crystal 8	18.3	AS-C	2.05 ± 0.05	56.15 ± 8.1		< 1.4	3.50 ± 0.33
DAMA			< 0.5	< 20	0.7 - 10	0.5 – 7.5	5.5 – 7.5



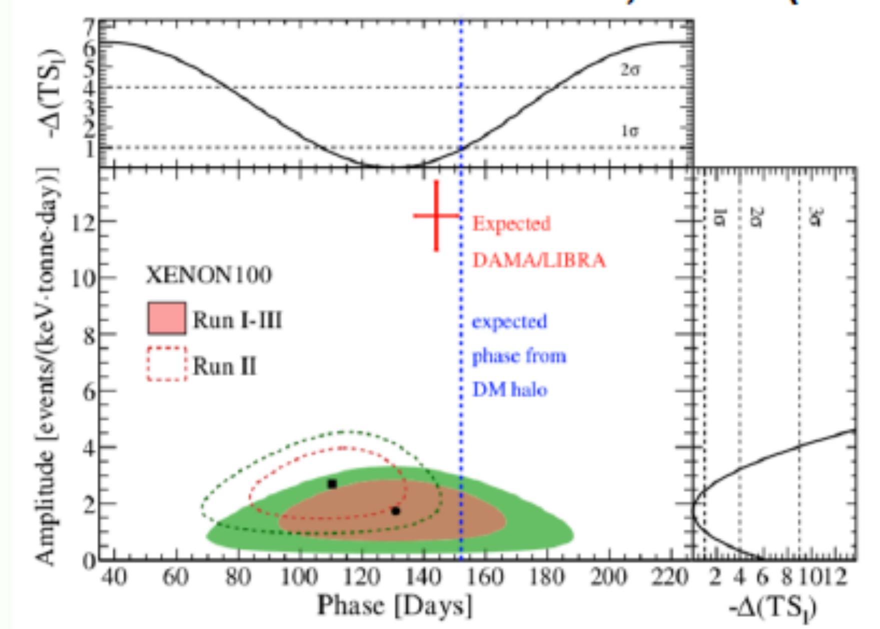


- Can you compare DAMA with other results ?
  - **Not exactly,** you can do it ***only in the framework of specific models and assumptions***

- not compatible with experiments with other targets

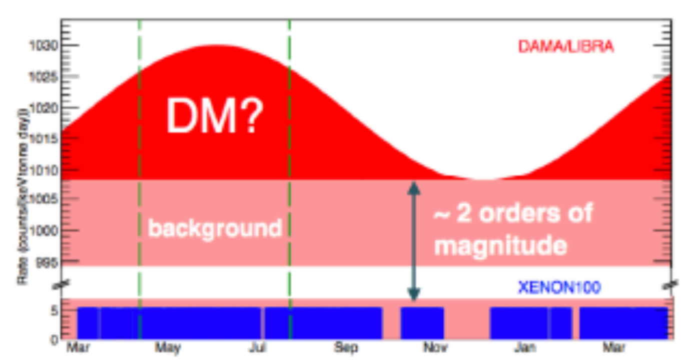


XENON100 4-year ER modulation study, PRL 118, 101101 (2017)

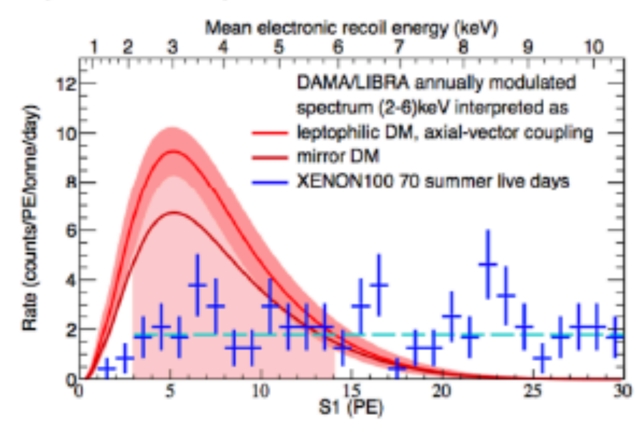


XENON collaboration, arXiv: 1507.07747, Science 349, 2015

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



Consider the 70 days with the largest signal



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

- The QCD lagrangian contains a term that foresees CP violation (CPV)

-> electric dipole moment for hadrons $d_n \neq 0$
-> there should be CP violation in the strong sector

In particular for the **neutron**

$$d_n = (2.4 \pm 1.0)\bar{\theta} \times 10^{-16} \text{ e cm}$$

$$d_n^{\text{exp}} < 3.0 \times 10^{-26} \text{ e cm (90\% C.L.)}$$

$$\bar{\theta} < 1.3 \times 10^{-10}$$

Why so small?
This angle is the sum of two a priori arbitrary phases of unrelated origin.

THIS VERY FINE TUNING! → STRONG CP PROBLEM

- Peccei and Quinn (1977) proposed to solve the strong CP problem by postulating the existence of a global $U_{PQ}(1)$ *quasi*-simmetry (it is spontaneously broken).
- The **axion a** (Weinberg 1978, Wilczeck 1978) is the **pseudo Goldstone boson** associated with the spontaneous breakdown of the PQ simmetry.
- With the PQ quasi-simmetry the fine tuning problem can be solved.

The "standard" axion

- The axion is a **light pseudoscalar boson**, its properties can be derived using current algebra techniques
- The axion is the light cousin of the π^0 :

$$m_a f_a \approx m_\pi f_\pi$$

m_p = 135 MeV – pion mass
f_p = 93 MeV – pion decay constant

- The most recent calculation using lattice QCD

$$m_a = 5.70(6)(4)\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

G.Grilli di Cortona et al J. High Energy Phys. 01 (2016) 034

Axion Like Particles (ALPs)

$$L_{ALP} = \frac{1}{2}\partial^\mu a\,\partial_\mu a - \frac{1}{2}m^2_{ALP}a^2 - g_{a\gamma\gamma}\vec{E}\cdot\vec{B}a$$

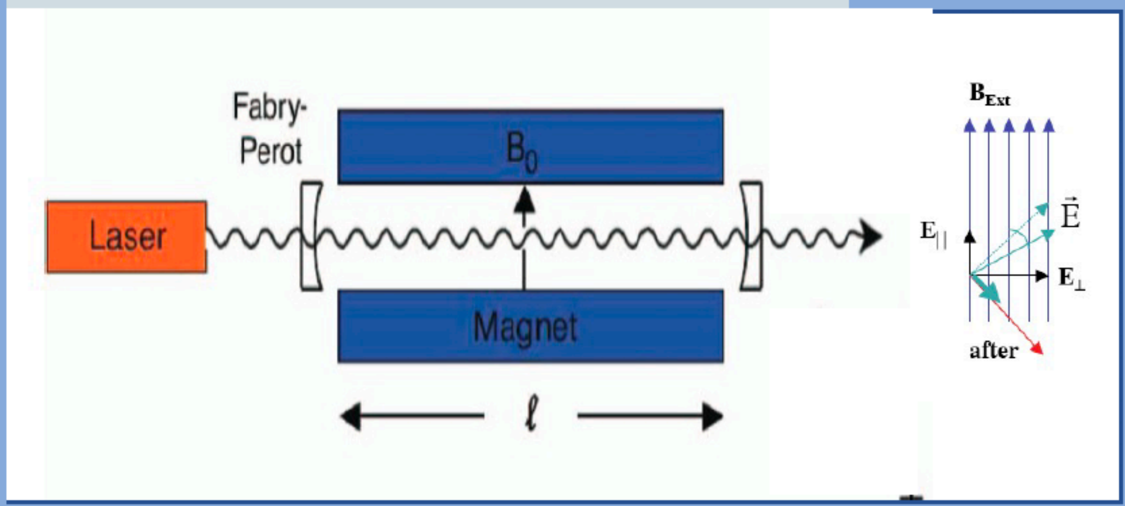
With $g_{a\gamma\gamma}$ a free parameter to be determined experimentally

- **Experimental searches are mainly directed to ALPs**, in order to relax the coupling parameter. Experiments looking for the ALPs are, in principle, sensitive also to the axions.

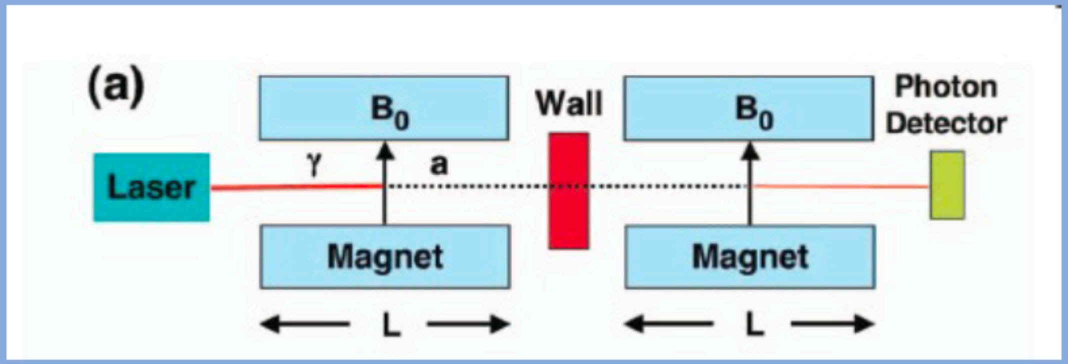
- Mainly based on ***axion-photon coupling***

A **Production and detection of axions in a terrestrial laboratory**

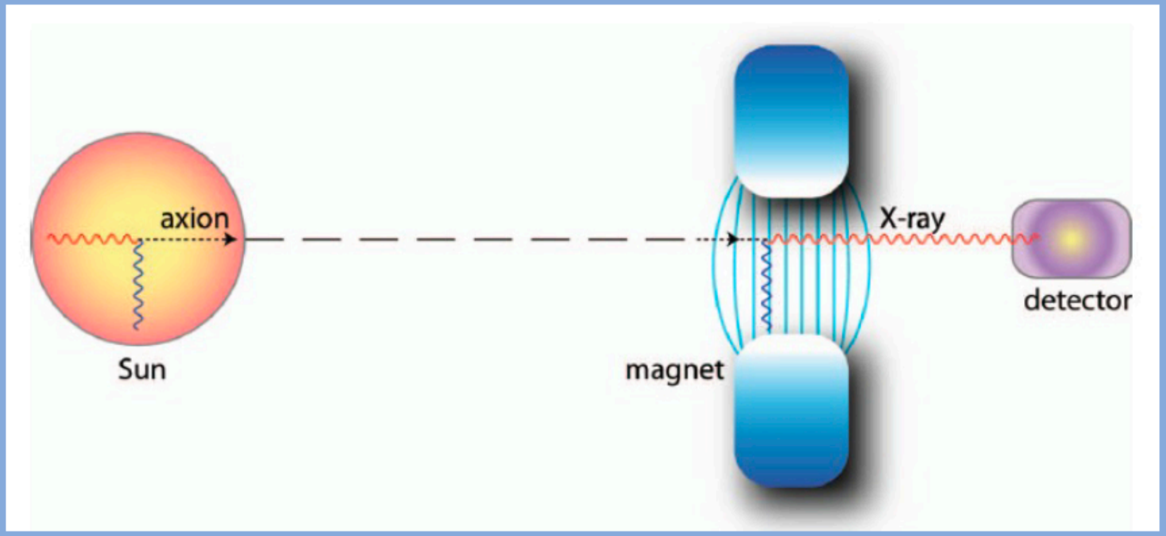
Polarization experiments



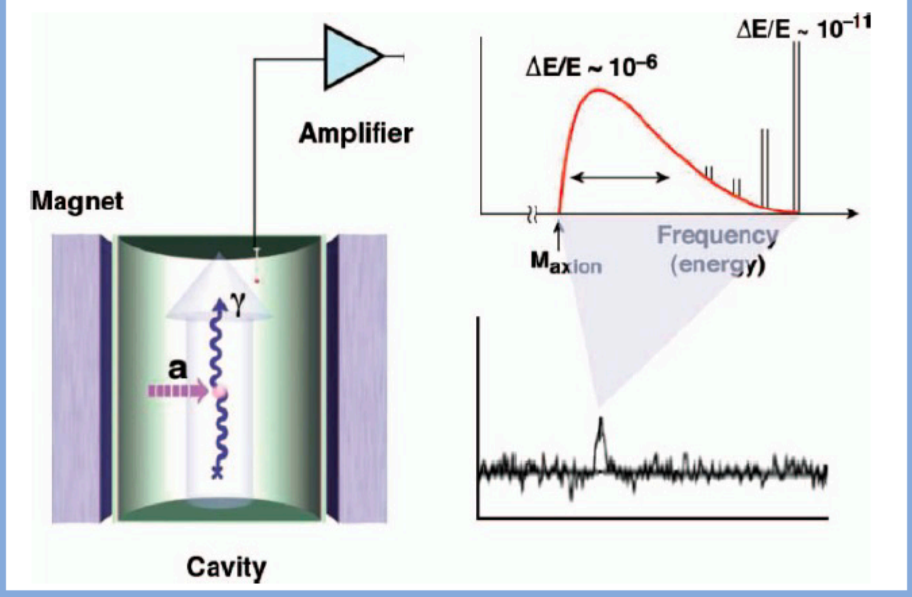
Light shining through walls



B **Detection of axions coming from external sources (Sun)- Helioscopes**

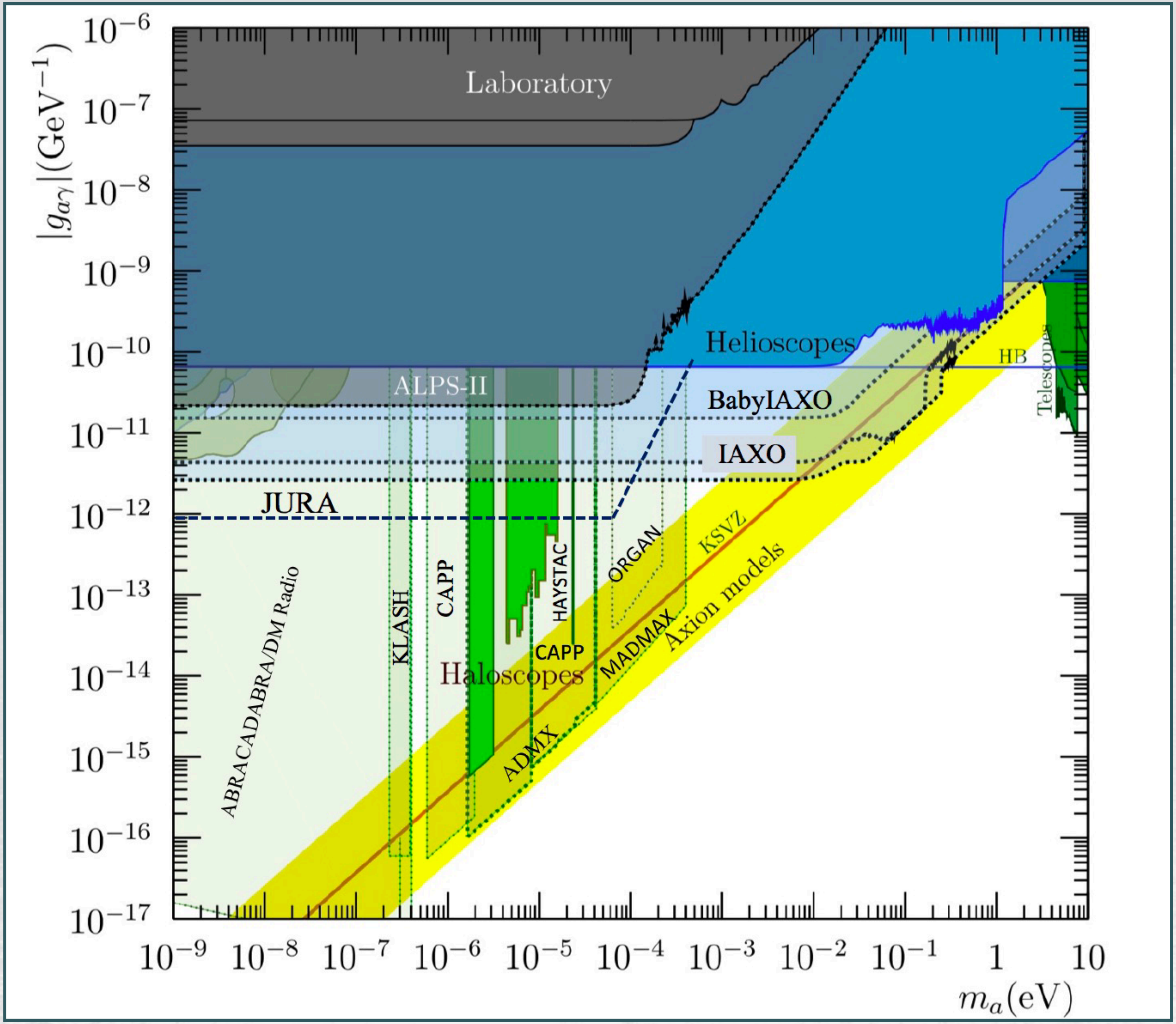


C **Detection of axions present into the Galactic Halo -Haloscopes**



All pictures from: G. Carosi et al, Contemp. Phys. 49, 281 (2008)

AXION - PHOTON COUPLING - CURRENT STATUS



CONCLUSION

- The search of Dark Matter by means of direct underground experiments is an extremely active field
  - Multi-ton scale experiments for standard WIMPs in the forthcoming years
  - Cross sections as low as 10^{-48} cm^2 within reach
  - So called neutrino floor benchmark reachable in 10 years
- DAMA result is still there.
  - No alternative explanation, but not consistent with other experiments in the framework of any known dark matter model
  - It might well be DM, but different from what we expect
- Axion search is also very active, no discovery yet