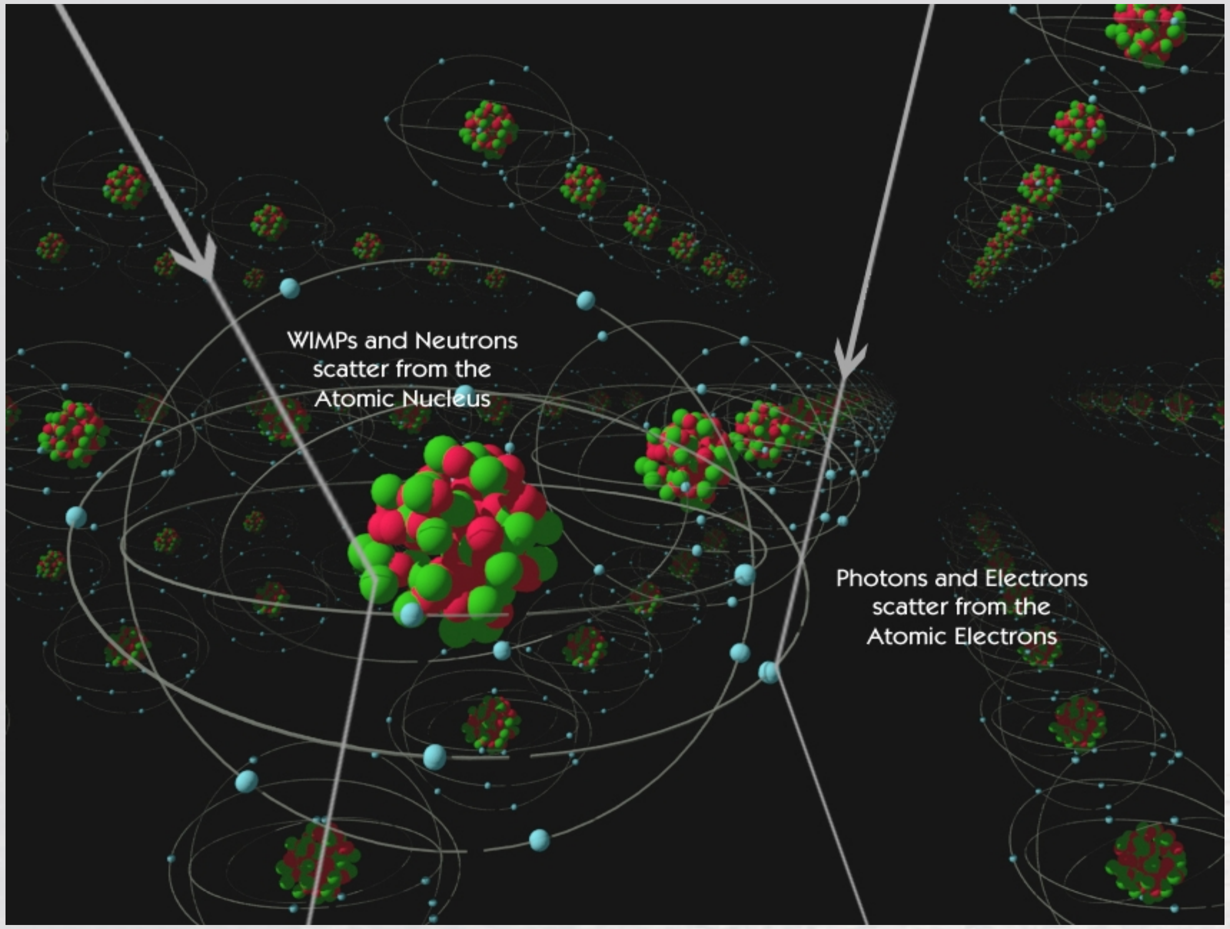
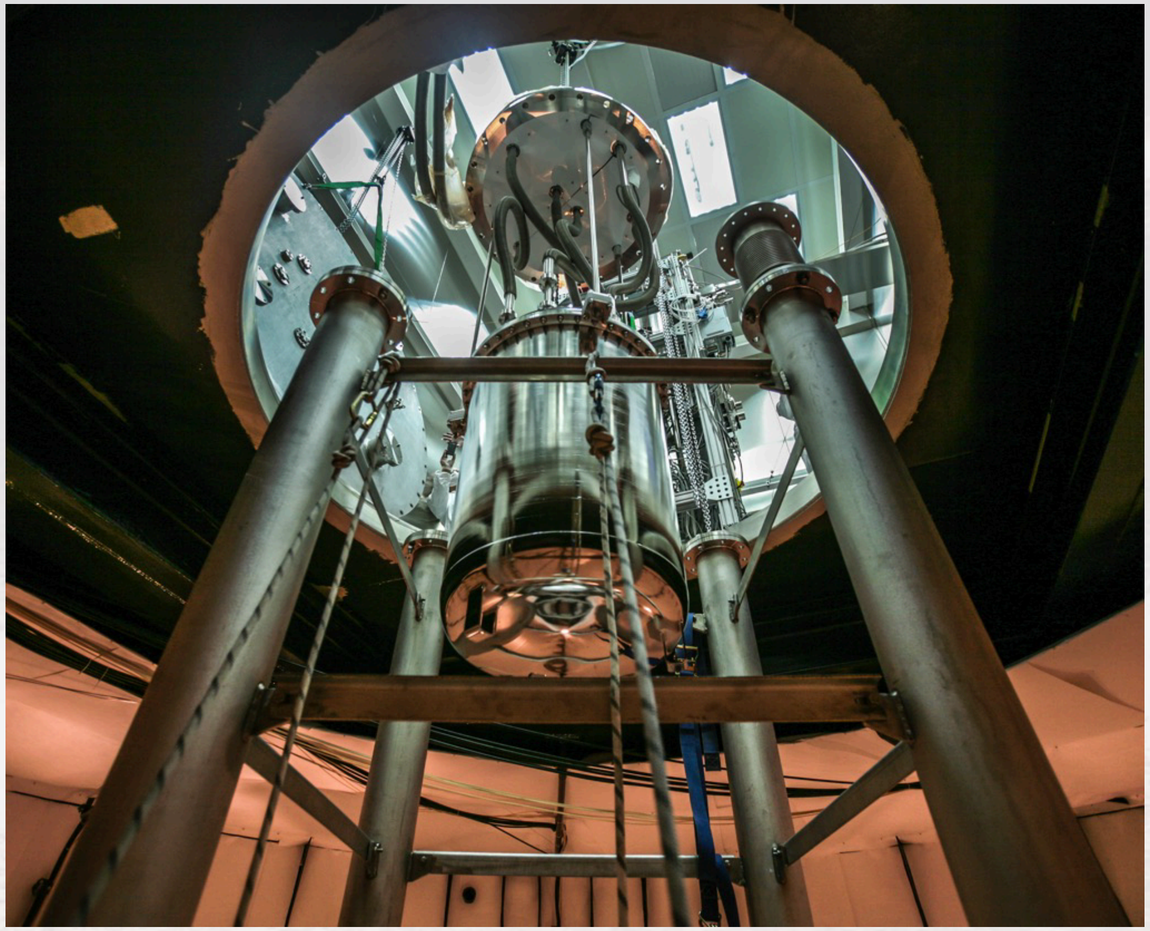




Search for dark matter and dark energy in INFN CSN2

Alghero, June 6th, 2017
Marco Pallavicini

Dipartimento di Fisica - Università di Genova
e Istituto Nazionale di Fisica Nucleare (INFN)- Genova

Bruna Bertucci's talk yesterday

ANTARES
KM3-NET

152 FTE

Neutrino Physics

266 FTE

Radiation from the Universe

AMS-02
DAMPE
PAMELA
FERMI

181 FTE

Gravitational waves, Gravity and Quantum Physics

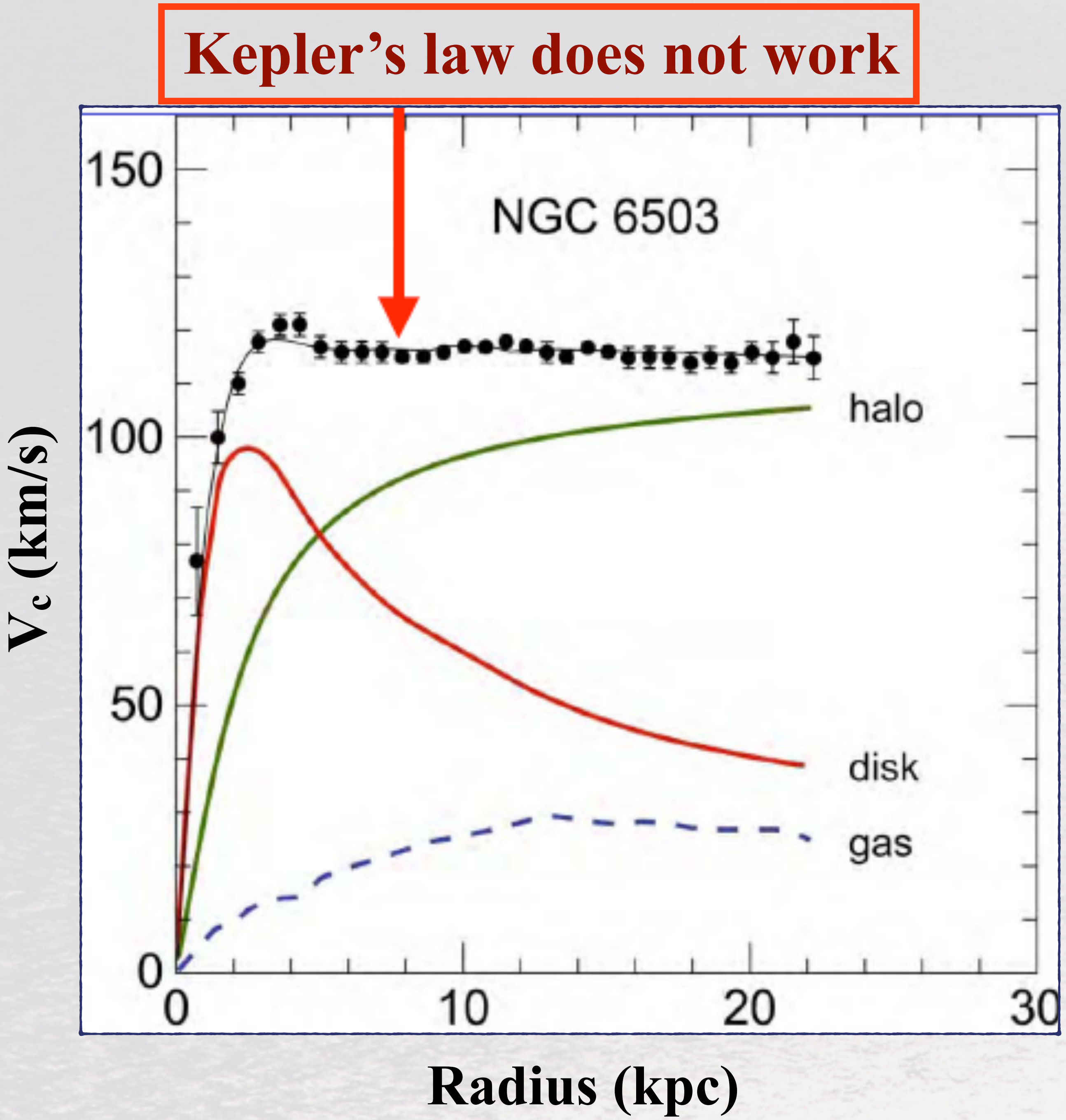
137 Full Time Equivalent

The Dark Universe

CRESST
DAMA
DARKSIDE
EUCLID
MOSCAB
NEWS
QUAX
SABRE
XENON

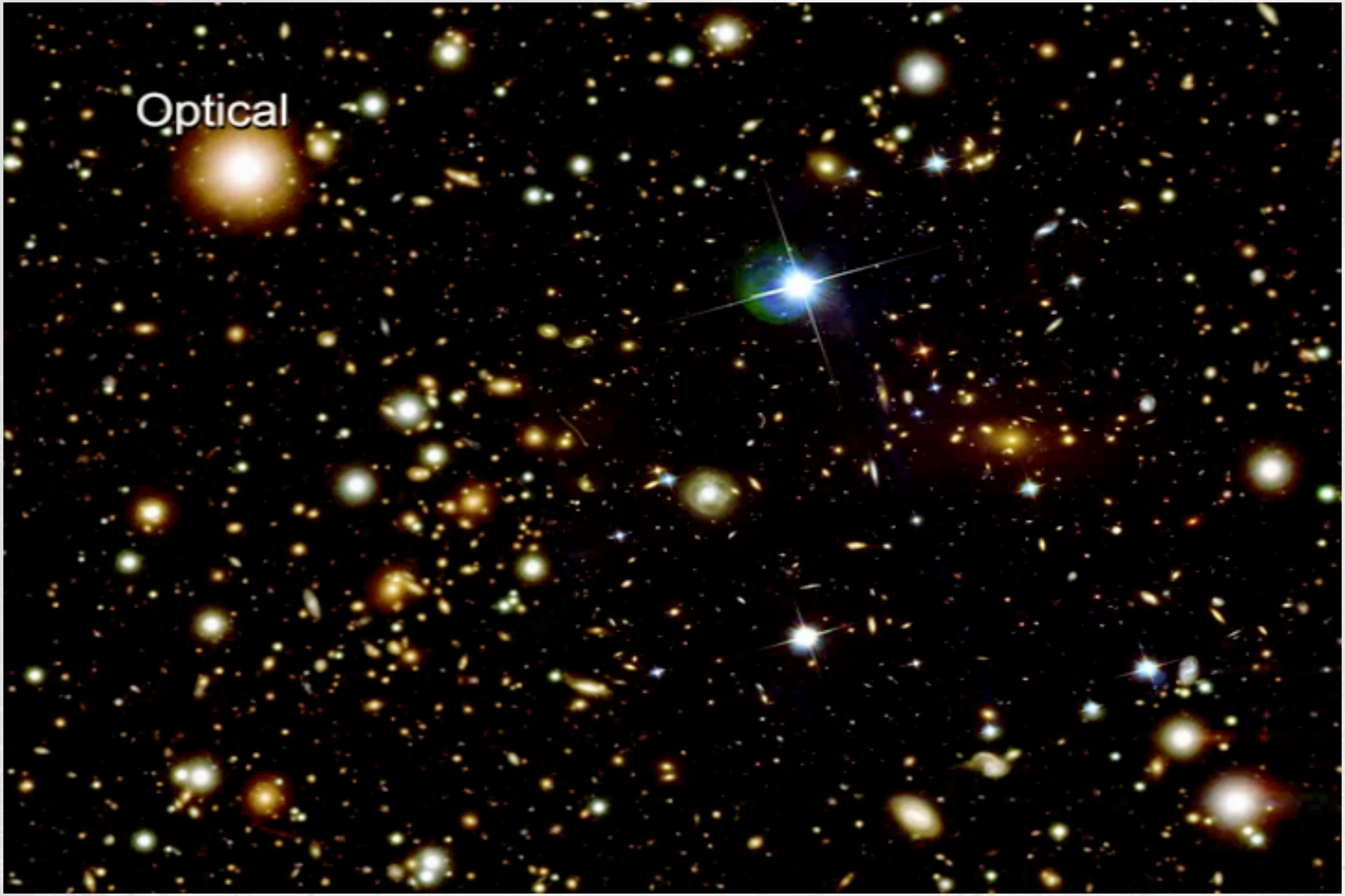
9 activities
19% of the people

- I assume astrophysical evidence for dark matter is somewhat known



EVIDENCE OF DARK MATTER (II)

- I assume astrophysical evidence for dark matter here is well known



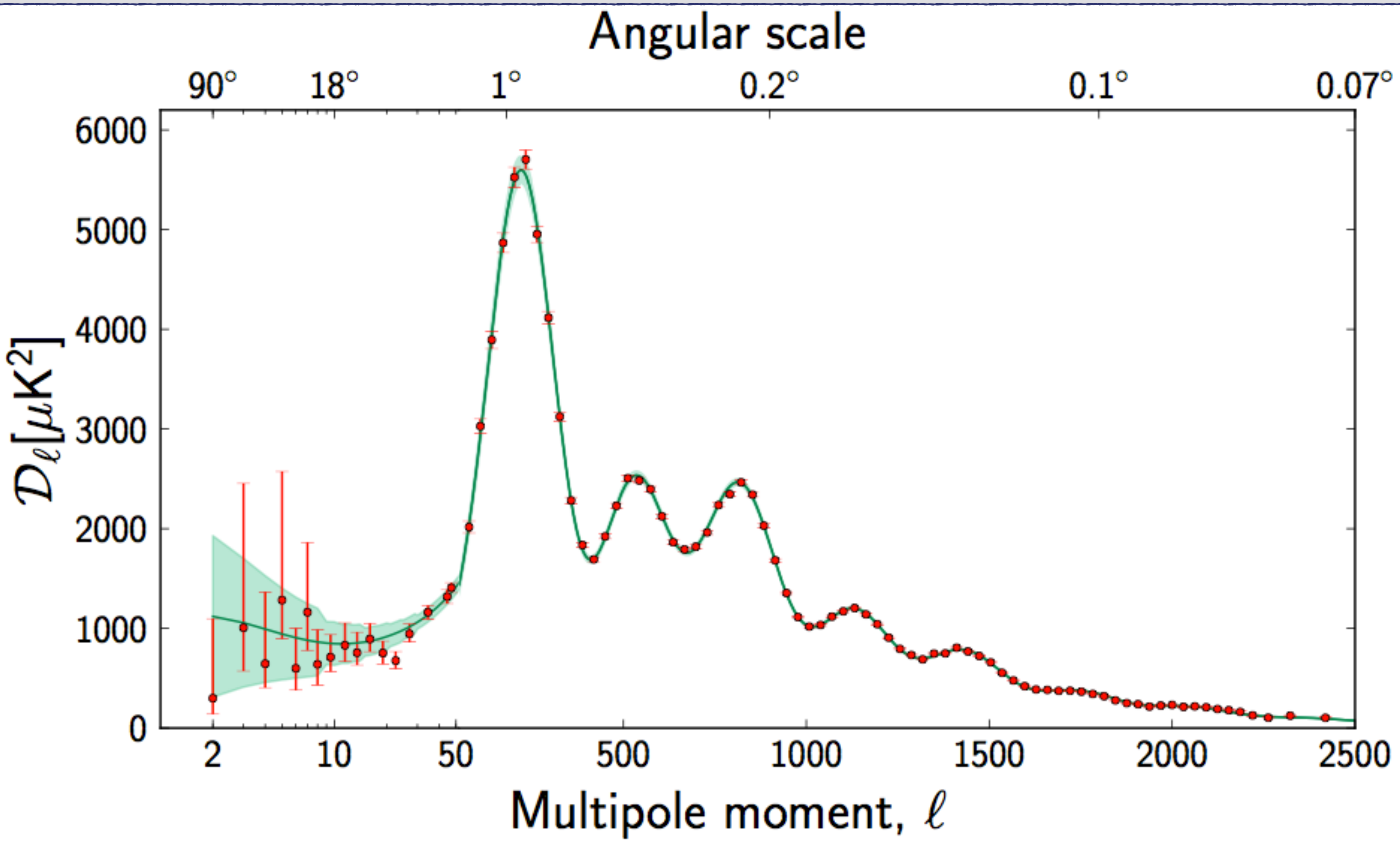
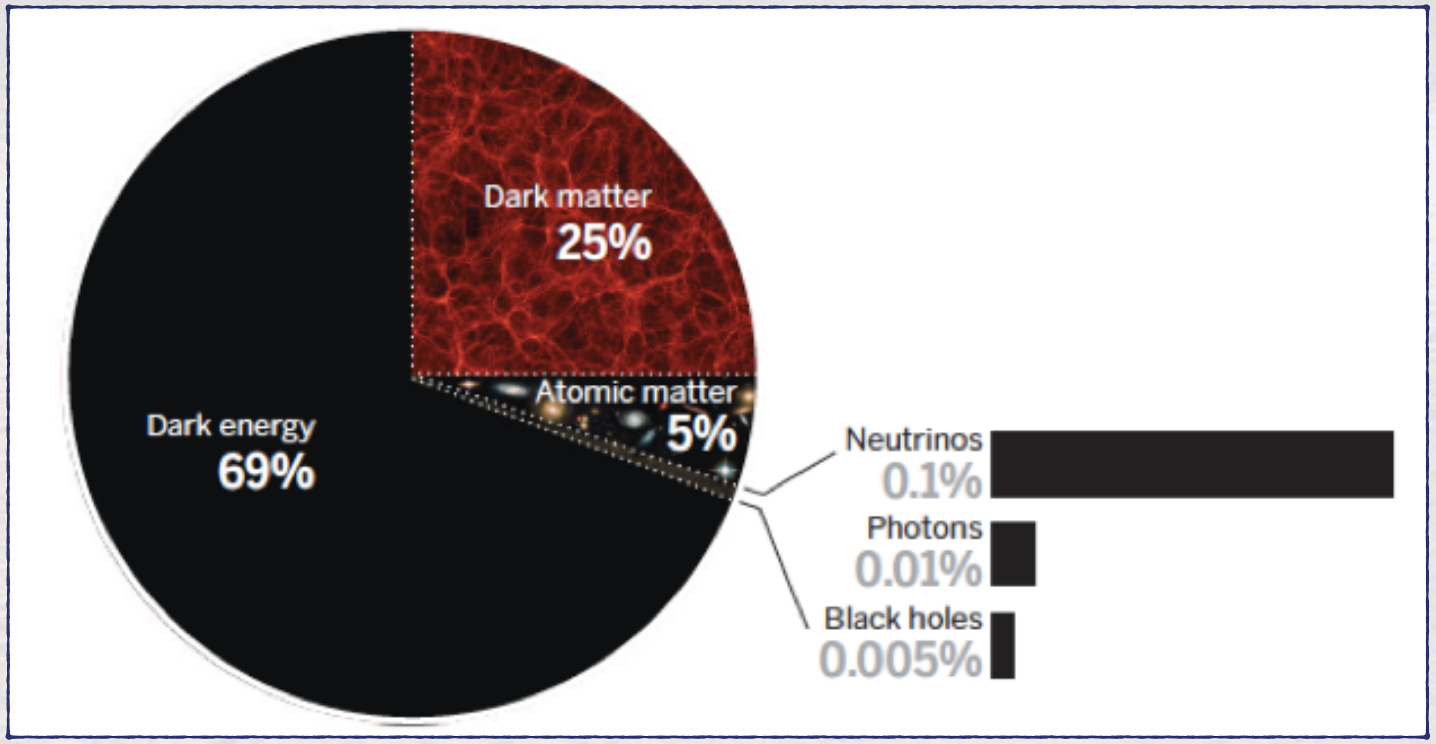


Figure 37. The 2013 *Planck* CMB temperature angular power spectrum. The error bars include cosmic variance, whose magnitude is indicated by the green shaded area around the best fit model. The low-ℓ values are plotted at 2, 3, 4, 5, 6, 7, 8, 9.5, 11.5, 13.5, 16, 19, 22.5, 27, 34.5, and 44.5.

- More evidence from smaller scale studies, structure formation

- **Astrophysics and Cosmology suggest that dark matter is:**
  - **COLD:** made of particles that were non relativistic at the time of decoupling (at least mostly)
  - **WEAKLY INTERACTING**
    - They would have been already observed otherwise

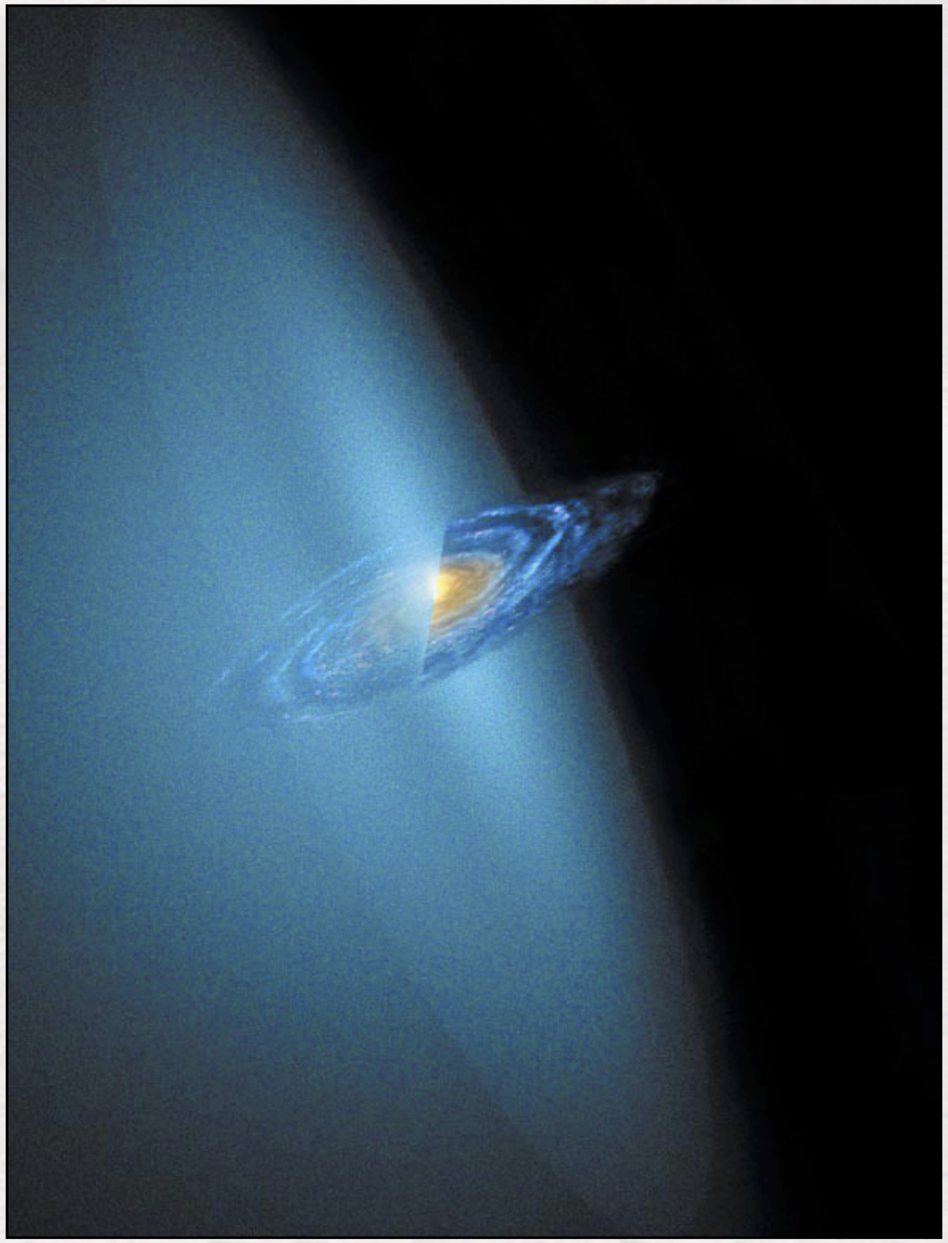


- **and that:**
  - **MASS DENSITY**
    - Local: 0.3 GeV cm^{-3}
    - Possible enhancement inside massive bodies (Sun, Earth ?)
  - **SPEED DISTRIBUTION**
    - Gravitational (Maxwell velocity distribution)

- Dark matter candidates are many
  - Essentially a measure of theoreticians' imagination
- Axion and Neutralino deserve more respect
  - Theoretically better understood
  - Some prediction about couplings and signatures
  - Motivated by theoretical reasons independent of DM
- Is DM origin coupled to Dark Energy origin ?
  - We do not know
- Should Dark Matter be a particle coupled to matter ?
  - We do not know

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
....

- Dark matter is supposed to be the main actor in the formation of **structures,** and particularly of galaxies

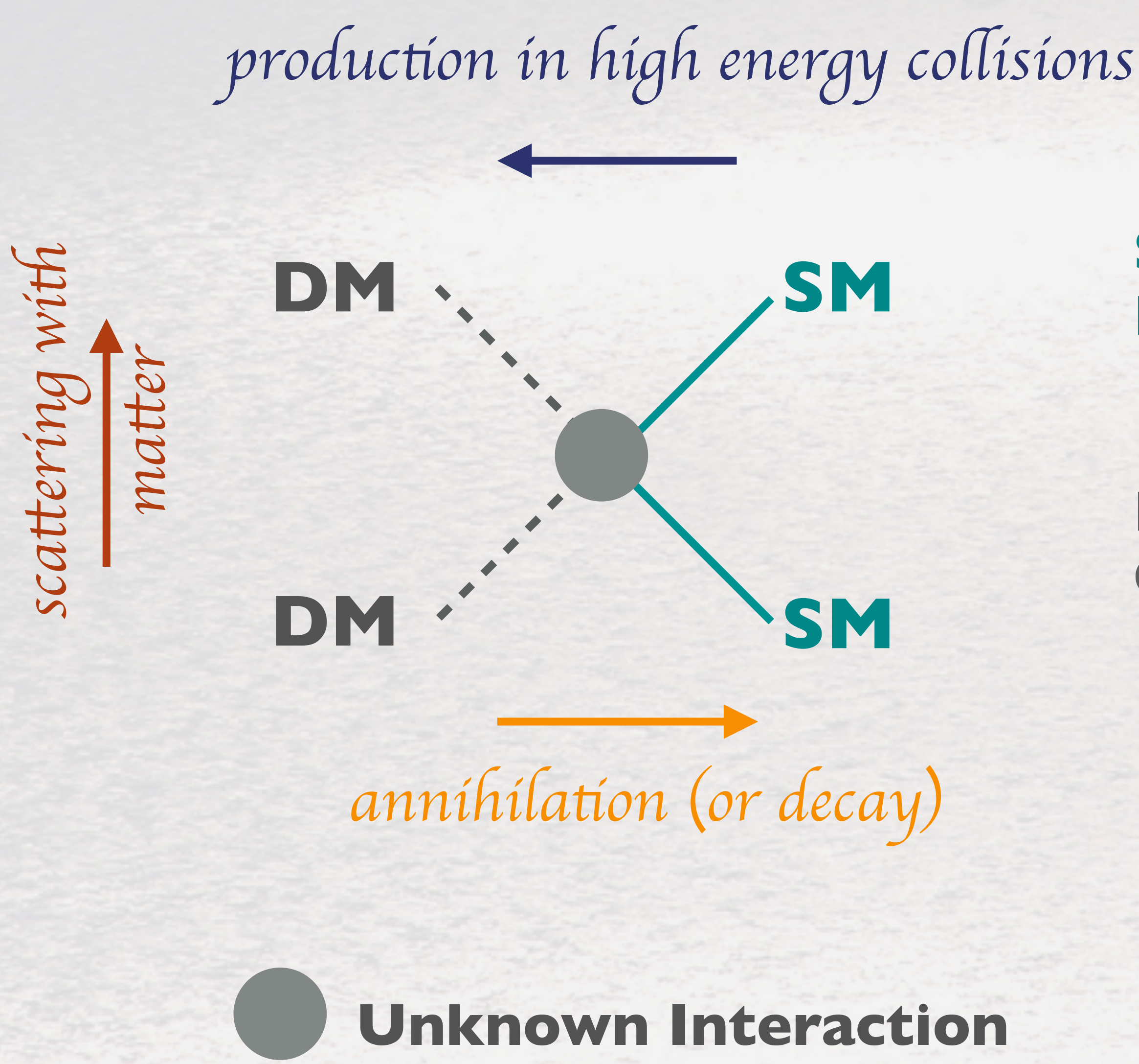


- Data is consistent with the hypothesis that a **spherical DM halo** is present in spiral galaxies
  - Supported by indirect evidence (e.g. gravitational lensing)

- Typical parameters:
  - Local density: ρ_0 = 0.3 GeV/cm^3
  - Maxwell speed distribution with:
    - r.m.s. v_0=230 km/s
    - escape velocity (cut-off) v_x=650 km/s

  - Example: M=100 GeV ---> E ~ 250 keV with v=500 km/s

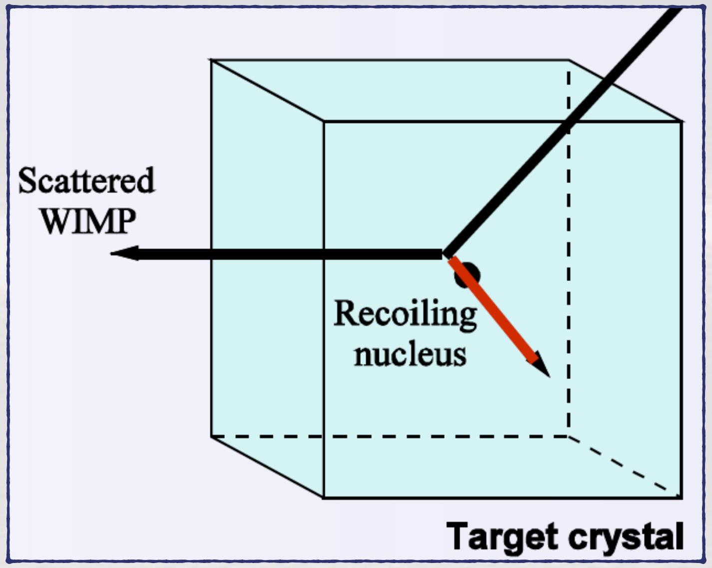
- **Three ways to search for Dark Matter**
  - **Direct**
  - **Indirect**
  - **Production (LHC)**



SM: Standard Model Particle

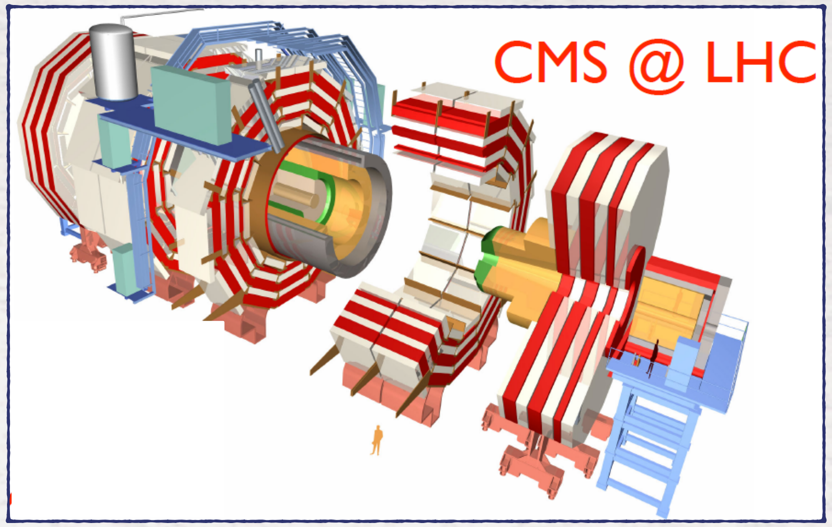
DM: Dark Matter Candidate

- Three fold way:



  - **Direct detection**
    - Build a detector capable to measure the **interaction rate** of Dark Matter particles with **ordinary matter**

  - **Indirect detection**
    - Dark Matter particles might annihilate producing photons, or electrons, or hadrons, or neutrinos, which might be detected by CR detectors in space or on ground



  - **Production @ accelerators**
    - DM particles might be produced at LHC (missing mass)
    - Even if discovered, **you can't prove that it is indeed THE dark matter. One of the above still needed.**
      - As far as I know, there is no way LHC can prove that the particle is stable.

DARK MATTER SEARCH IN INFN : AERIAL VIEW

Indirect

AMS-02	p,pbar, $e^{\pm}$
Dampe	γ,p,pbar, $e^{\pm}$
Fermi	γ, $e^{\pm}$
Pamela (end)	p,p,γ, $e^{\pm}$
Antares-Km3	heavy DM

Dark Matter

Direct

CRESST	WIMPs
DAMA-Libra	Model Independent
DarkSide-50 (20t)	WIMPs
Xenon1t (multi-ton)	WIMPs, E.M. model dep.
QUAX (R&D)	Axions, spin coupling

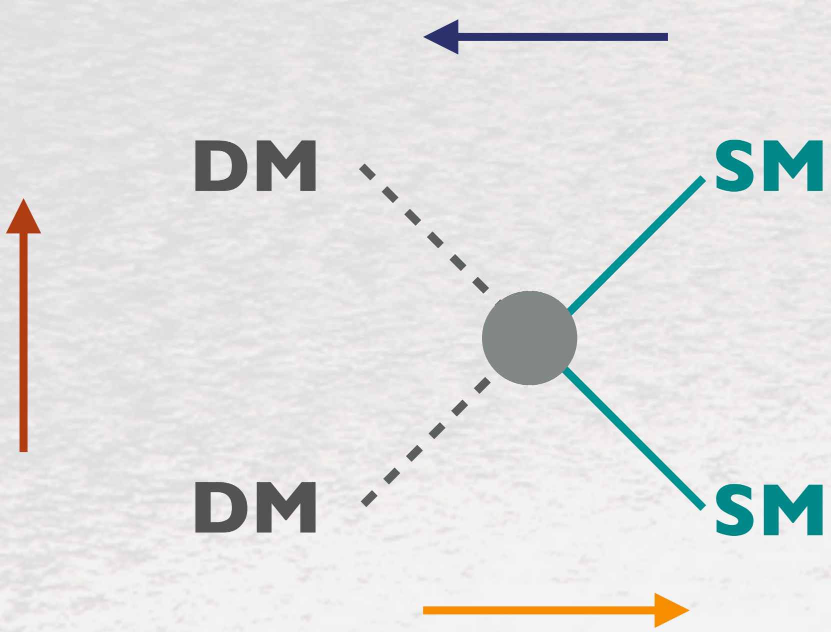
New techniques R&D

CRESST2	low mass WIMPs
SABRE	confirm Dama
NEWS	directionality
MOSCAB	new technology

Production

@LHC Experiments

search for new particles



SM: Standard Model Particle

DM: Dark Matter Candidate

- We do not know what dark matter is, so we should be prepared to many possibilities:

  - **Elastic scattering on nucleus:** the **"golden channel"**, many experiments

  - **Inelastic scattering on nucleus**
    - Including inelastic dark matter: W + N --> W* + N (W has 2 mass states)

  - Excitations of bound electrons during scattering on nuclei
    - Electromagnetic energy is added

  - Conversion of particles **(e.g. axions)** to photons

Many processes would escape experiments with pulse shape cuts

- **Expected signal rate** (with zero energy threshold!) for Wimp of mass m_χ, density ρ_χ, velocity v_χ and scattering cross section $\sigma_{\chi A}$

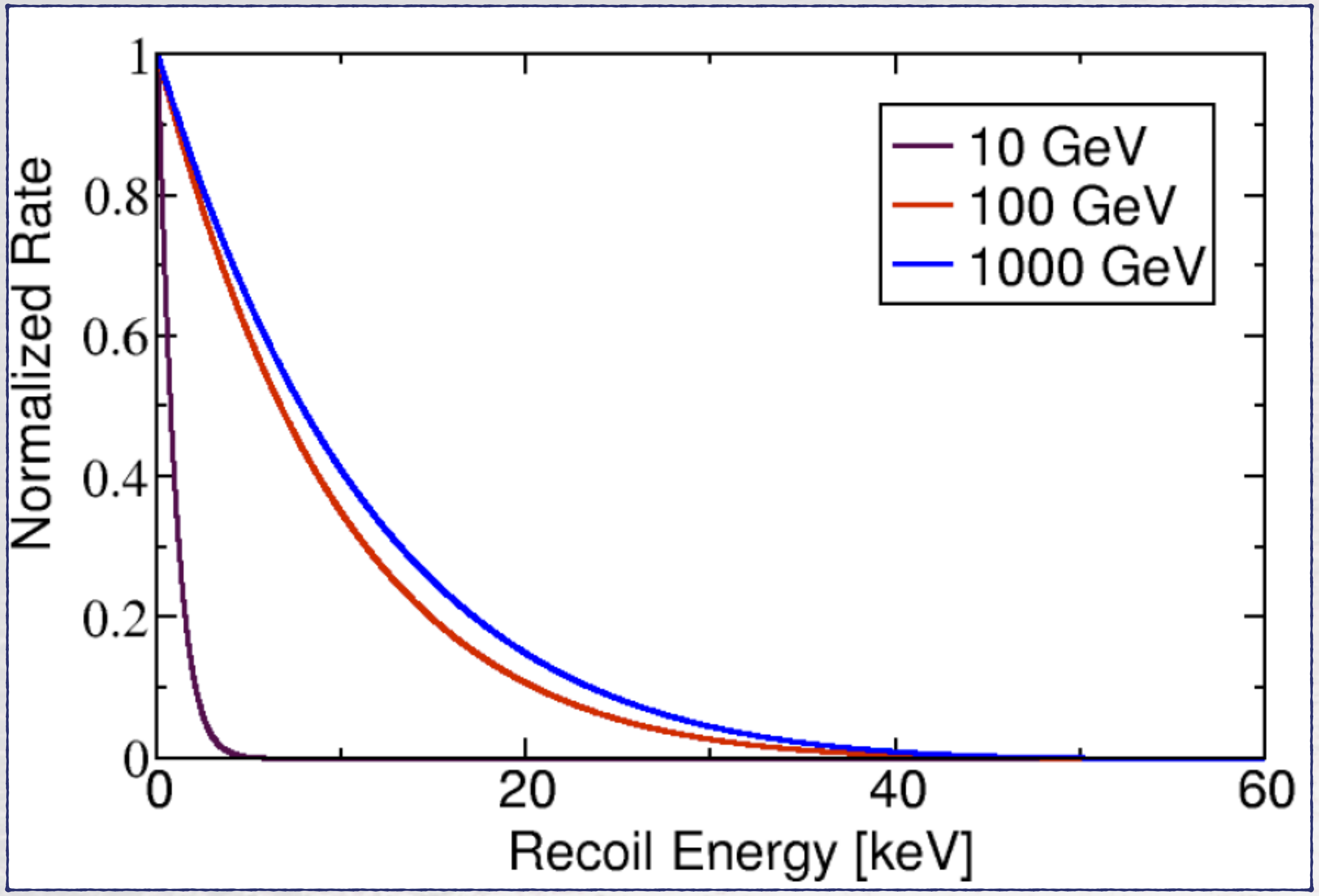
$$R \simeq \frac{\rho_\chi}{m_\chi} < v_\chi > \frac{\sigma_{\chi A}}{A}$$

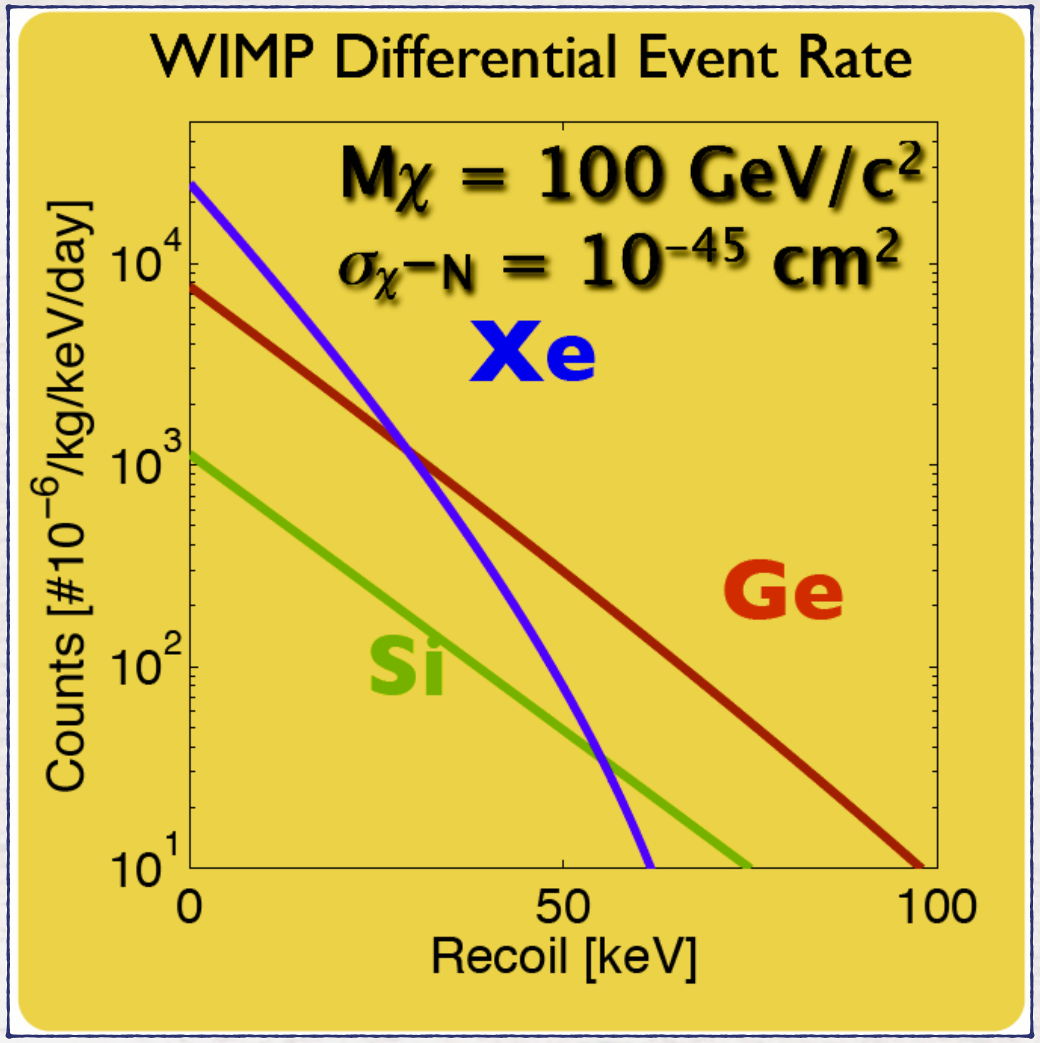
$$\simeq \frac{3.6}{A} \frac{GeV}{m_\chi} \frac{\rho_\chi}{0.3\ GeV/cm^3} \frac{< v_\chi >}{230 km/s} \frac{\sigma_{\chi A}}{10^{-38} cm^2} \frac{events}{kg \cdot day}$$

- With reasonable parameters, very small signal rate, 0.1 or less events/ton/day
  - Actually, now a factor 100 smaller at least for many candidates
  - This rate is larger than other rare events search (e.g. solar neutrinos or neutrino-less double beta decay), but they are very difficult to detect

- The recoil energy is just kinematics:

$$E_R = E\frac{4\ m_A\ m_\chi}{(m_\chi + m_A)^2}\frac{1 - cos\theta}{2}$$

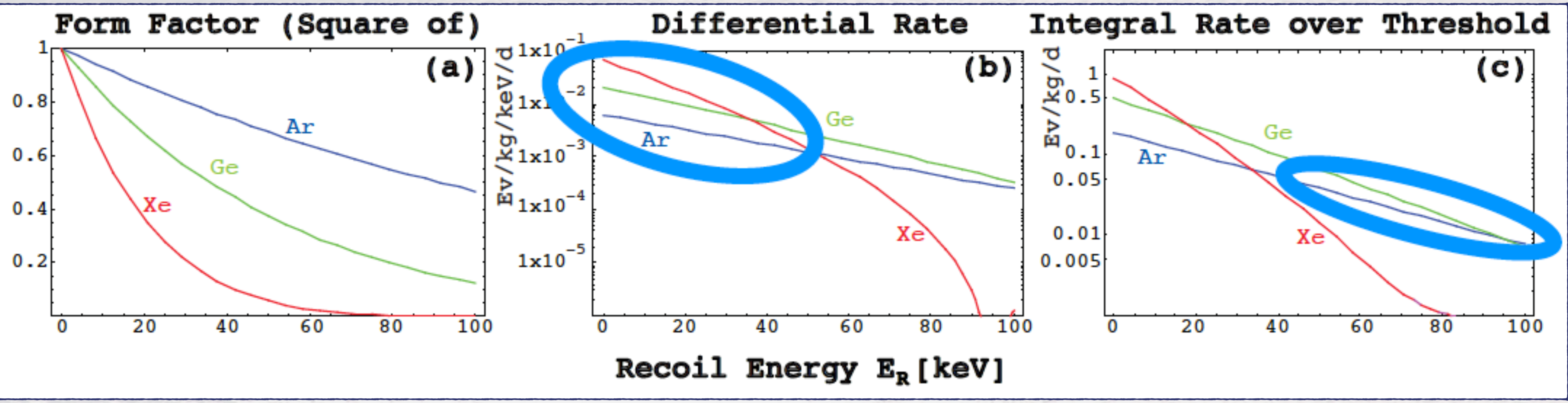




- The true recoil spectrum depends on many unknowns
  - [Lewin and Smith Astrop. Phys **6**, 87 (1996)]:

$$\frac{dR}{dE} = \frac{R_0}{E_0 r} exp(-\frac{E}{E_0 r})F(q^2(E)) \qquad E_0 = \frac{1}{2}mv^2 \qquad r = \frac{4M_N M_\chi}{(M_N + M_\chi)^2}$$

- Form factor from nuclear physics, tentative....
  - The cross section can be spin dependent (incoherent) or spin-independent (in this case coherent, cross section enhanced)



- It seems a normal "counting experiment", but give a look at the numbers:
  - Assume a signal rate of 0.01 count kg^{-1} d^{-1}
  - This means **1.16 10^{-7} 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 !

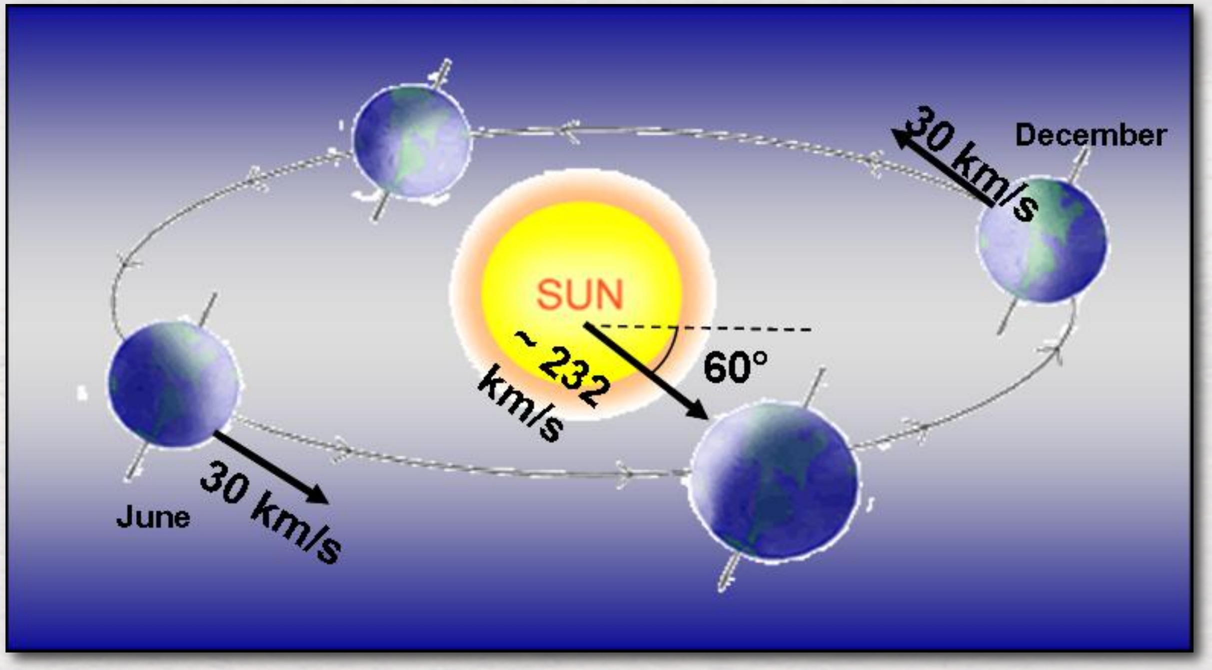
- However, if you want to detect dark matter with single counts, you must be **5-6 orders of magnitude more pure than anything on earth**

- There are two strategies used by experiments:
  - 1. Make an assumption about D.M. nature (e.g. Wimp or axion or other), and build a (almost) background free detector that search for the expected interactions

Background: CRITICAL !

  - 2. Make no assumption and search for annual or daily modulations
    - The Solar systems moves in the Galaxy frame with typical free fall speed 232 km/s, the same average speed of Wimps
    - Earth rotates around the Sun at 30 km/s
    - The detector rotates around the Earth axis at 0.5 km/s (at the equator)

Background less critical



  - The detector sees a **Wimp flux** that is **modulated yearly** and also **daily**. The effect depends on the velocity distribution assumed for the Wimps, and also on the cross section dependence on speed (which may be relevant in some models)
    - **The amplitude of the modulation is model dependent**

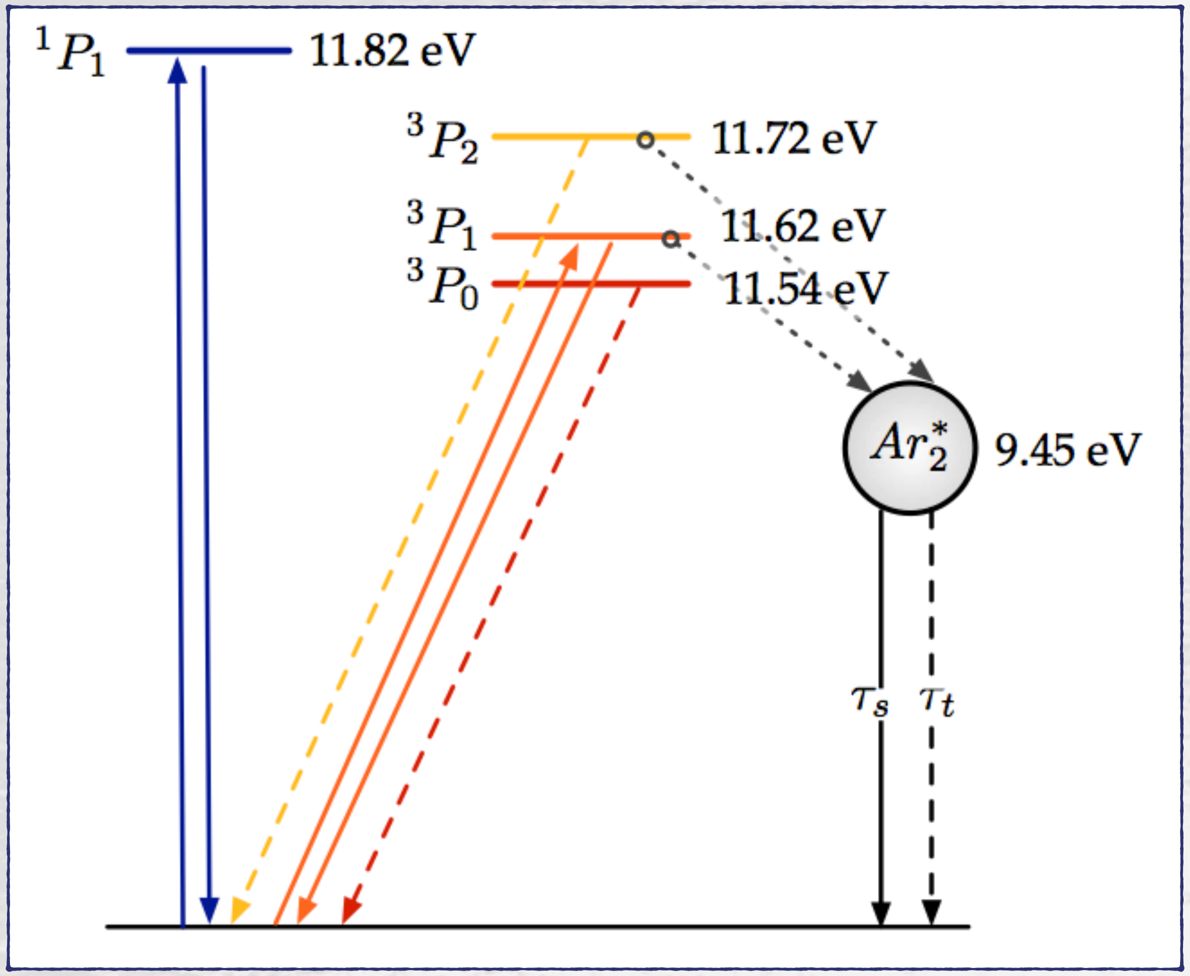
- The kinetic energy of the recoiled nucleus (somewhere between a few keV up to ~ 100 keV) might be detected in several ways, **possibly concurring:**

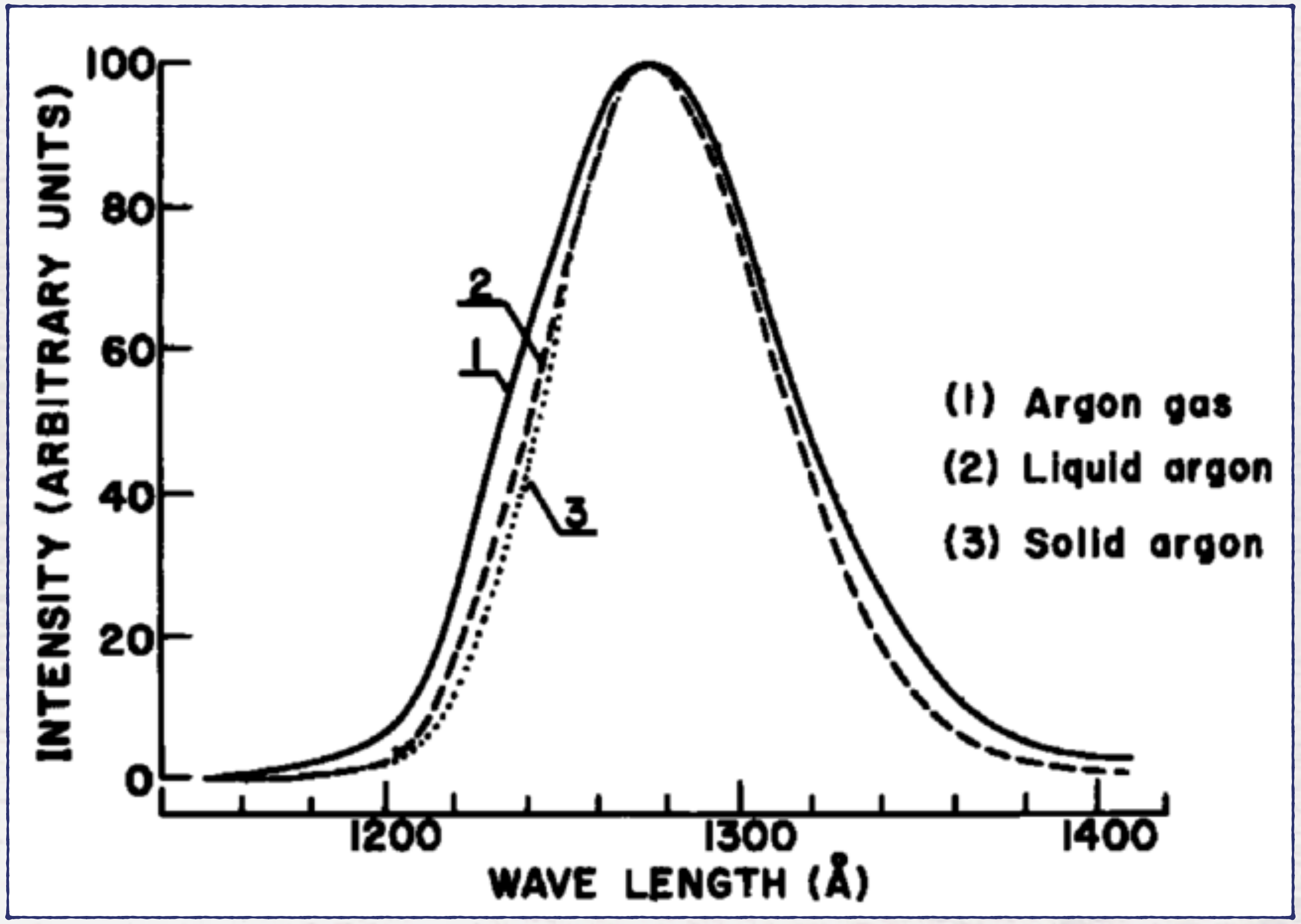
- **Scintillation light**
  - Solid scintillators (inorganic crystals): light from excitons
  - Liquid scintillators (noble gas/liquids): light from molecular excited states

- **Ionization**
  - Noble liquids or gas (argon, xenon): **e - ion pairs**
  - Crystals (germanium diodes, silicon diodes or similar): **e-p pairs**

- **Heat (phonons)**
  - Bolometers
  - Can use thermal or a-thermal phonons

- An Argon atom, when excited by the passage of a charge particle in gas or liquid produce **excimers** Ar_2^* or ionised Argon molecules Ar_2^+
  - The spectrum is **peaked in UV,** very difficult to detect directly even with special cathodes
    - Suitable materials must be used to convert UV light to larger wavelength photons which can be more easily detected with PMTs





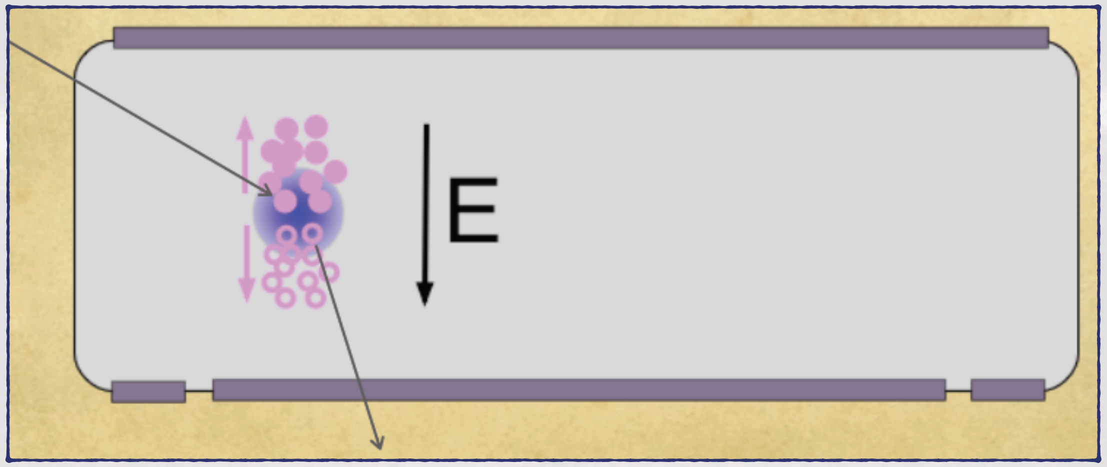
- **Crystals** are well known in many applications in nuclear and particle physics, but:
  - You need **extremely radio-pure crystals**
  - You need extremely high-yield crystals to reach low energy threshold
  - You need < 1% stability over several years if you search for annual modulations

- In order to get good enough crystals you must:
  - Measure and select the powders with high sensitivity
    - Low background underground Ge detectors
    - Neutron activation, mass spectrometry
  - Clean and selected growing process
  - Chemical and physical purification of all materials
  - Protocols for growing, handling, stocking, transporting

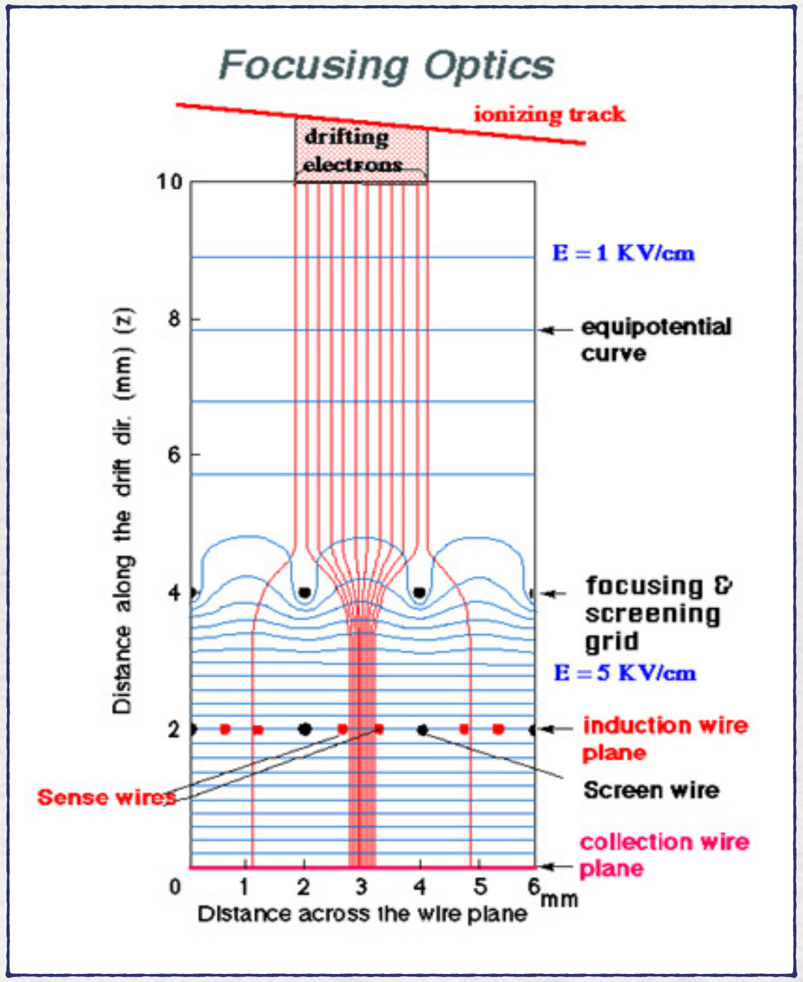
  - Typically, many years of R&D even for already experienced people

- In all scintillators the amount of light produced is proportional to the deposited energy, but the constant depends on particle type
  - Usually, a 1 MeV electron will release more light that a 1 MeV alpha, or 1 MeV recoiled nucleus
  - This phenomenon is called **QUENCHING**
- Generally, the heavier is the particle the more is quenched, but for some scintillators is the other way around
  - For Argon, Xenon, NaI is normal way: heavier particles yield less light
- **The light can identify the particle, if energy is measured in another way**
  - **Double readout detectors can identify particle type**
- Also **the time distribution of the light pulse may depend on particle type**

- A charged particle in motion produce e-p pairs in a solid
  - With an electric field this signal can be collected
  - The charge depends on particle total energy but also on particle type
  - Ge and Si crystals are standard examples

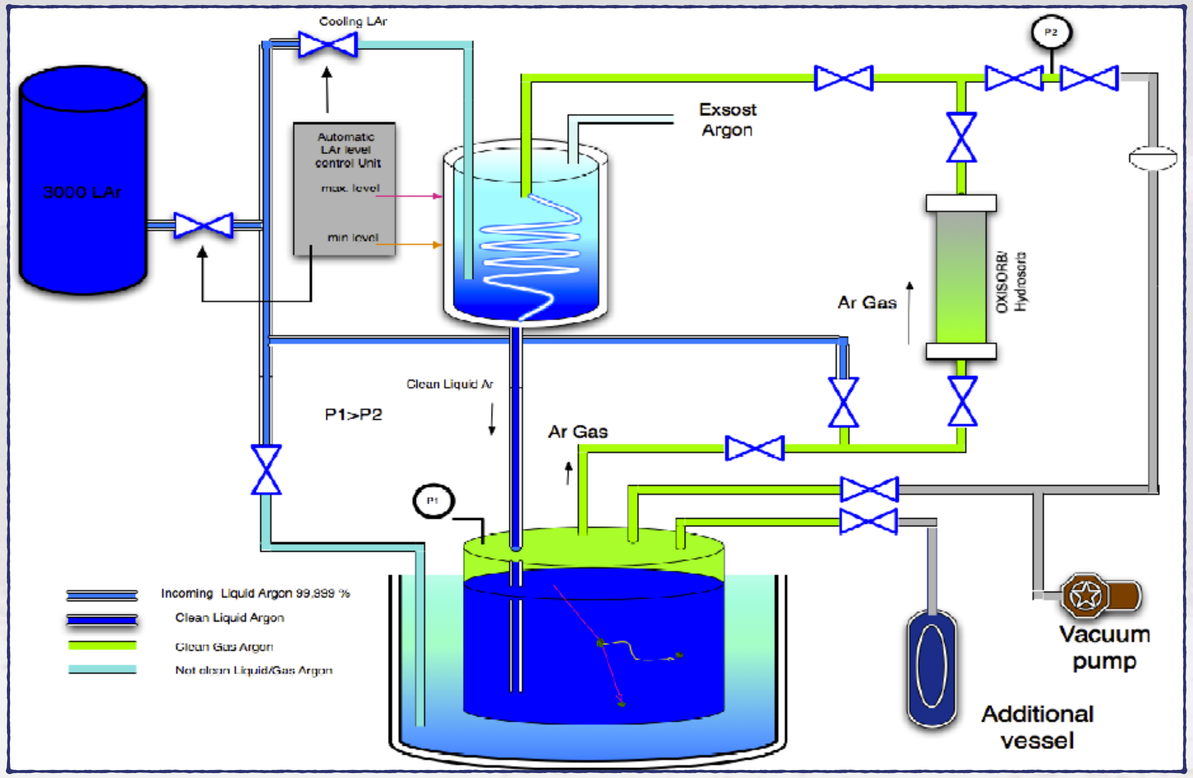


- Ionisation happens in liquid and gas as well
  - Same concept
  - In case of liquid, extreme care is needed to guarantee a sufficient life-time to bring this charge over long distance
    - Very high purity levels in water and oxygen contamination



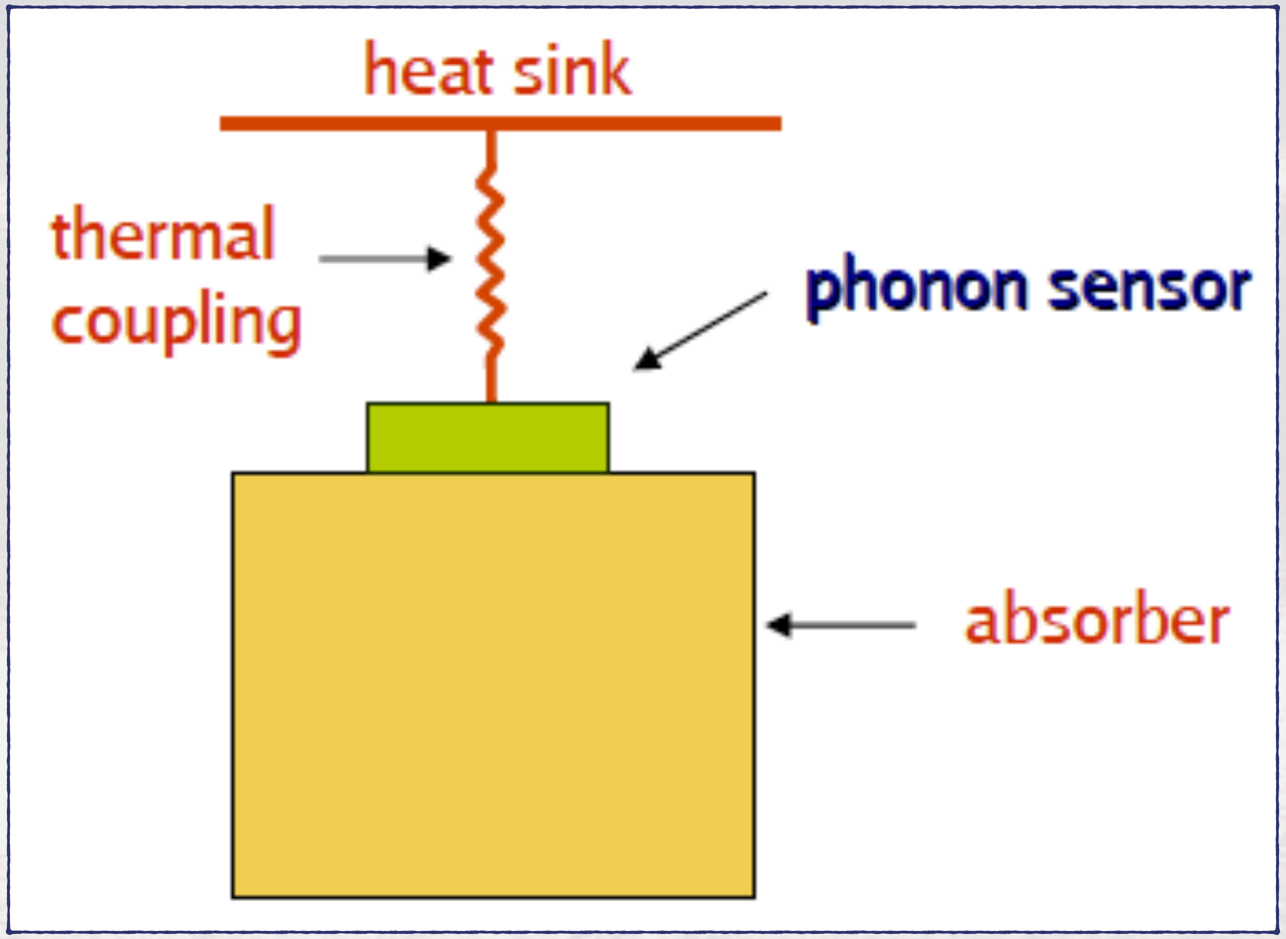
- As for light, **ionisation can be used to identify the particle if energy is known in an independent way**

- The drift velocity of charge particles is of the order of m / ms with 500 V/m field
- This requires **life-time** of **several 100 μs** for relatively small detectors (this generation of dark matter experiments) or **even ms** for **ton-scale future detectors**



- **Icarus** have opened the way
  - tens of ms achieved
- This requires **impurity levels of the order of 10^{-10}** or less
  - Very difficult, especially for **water and oxygen**, which are everywhere
    - Purification methods
    - Cleaning
    - Material selection
    - A lot of experience needed

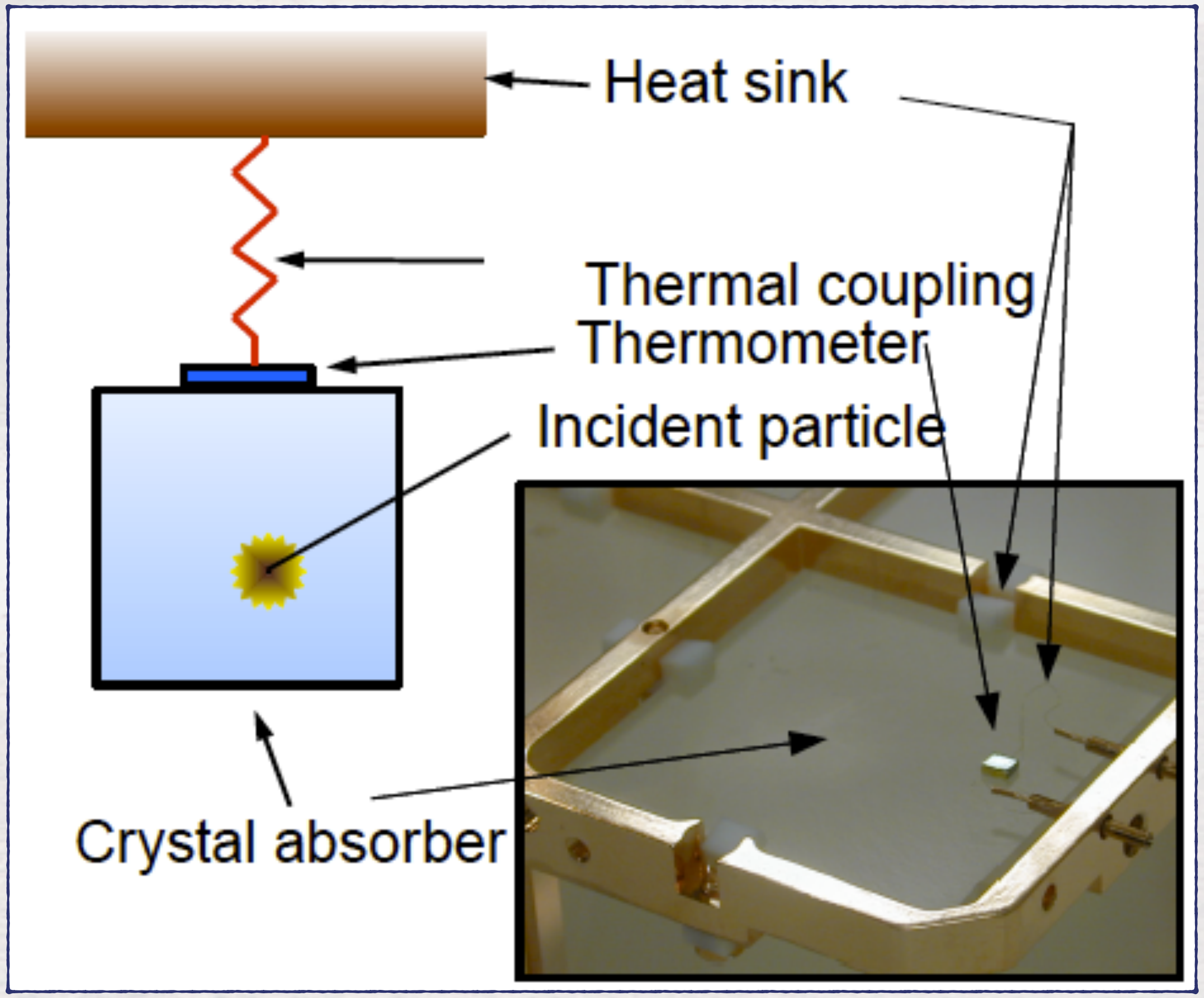
- A sufficiently cold crystal has a **thermal capacitance** low enough to cause a measurable T rise when a radioactive decay occurs



- More specifically, fast (a-thermal) phonons are produced, which slowly degraded into thermal ones

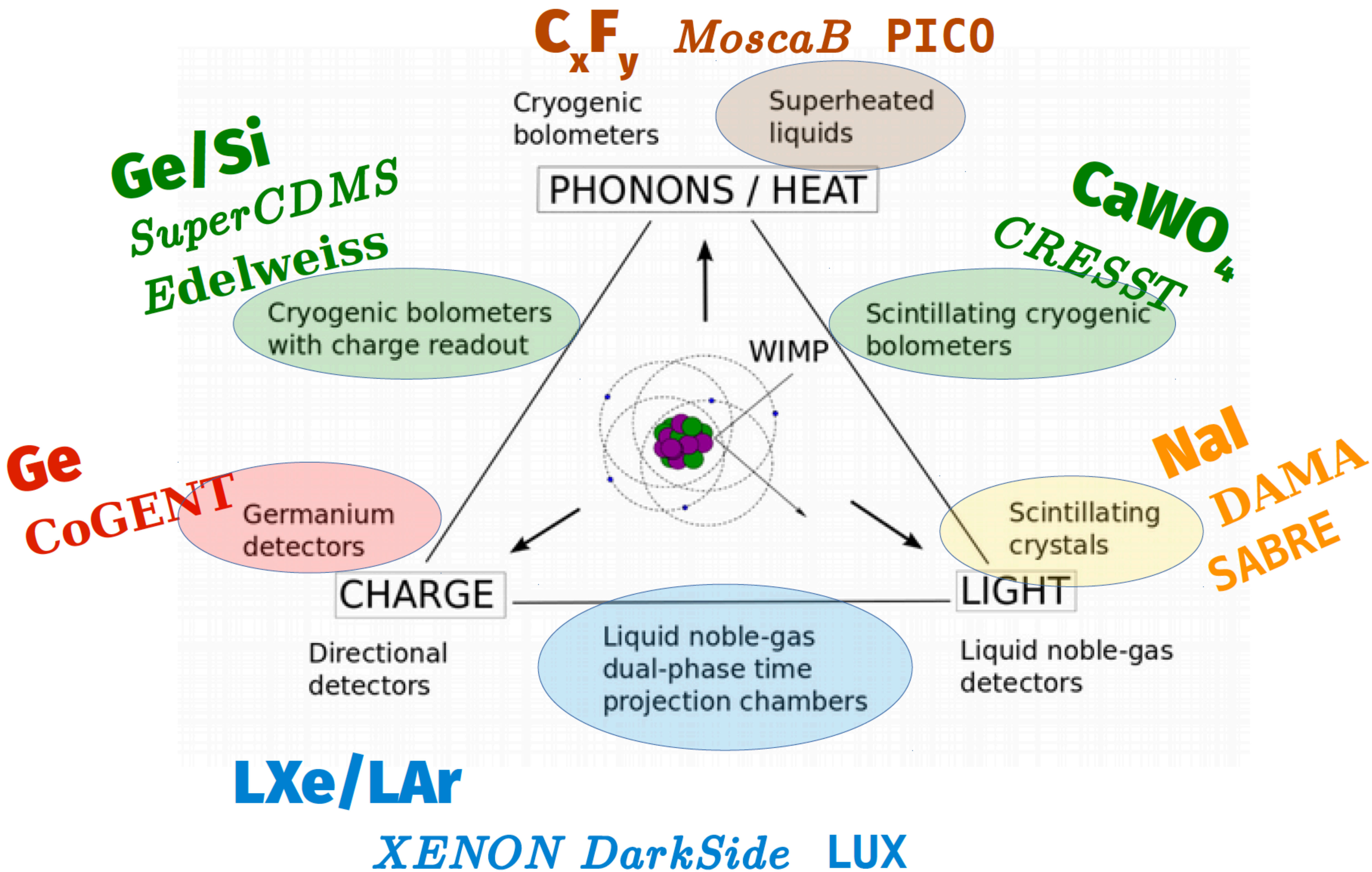
- With suitable sensors, both types can be used to detect the particle
  - Bolometer: phonon detector sensitive to thermal phonons (a.k.a. heat!)
  - In bolometers, no sensitivity to position of the event (thermalisation)
    - A-thermal phonons should be used to get more info

- GOOD
  - Many materials can be used
  - Very good energy resolution
  - Large mass possible

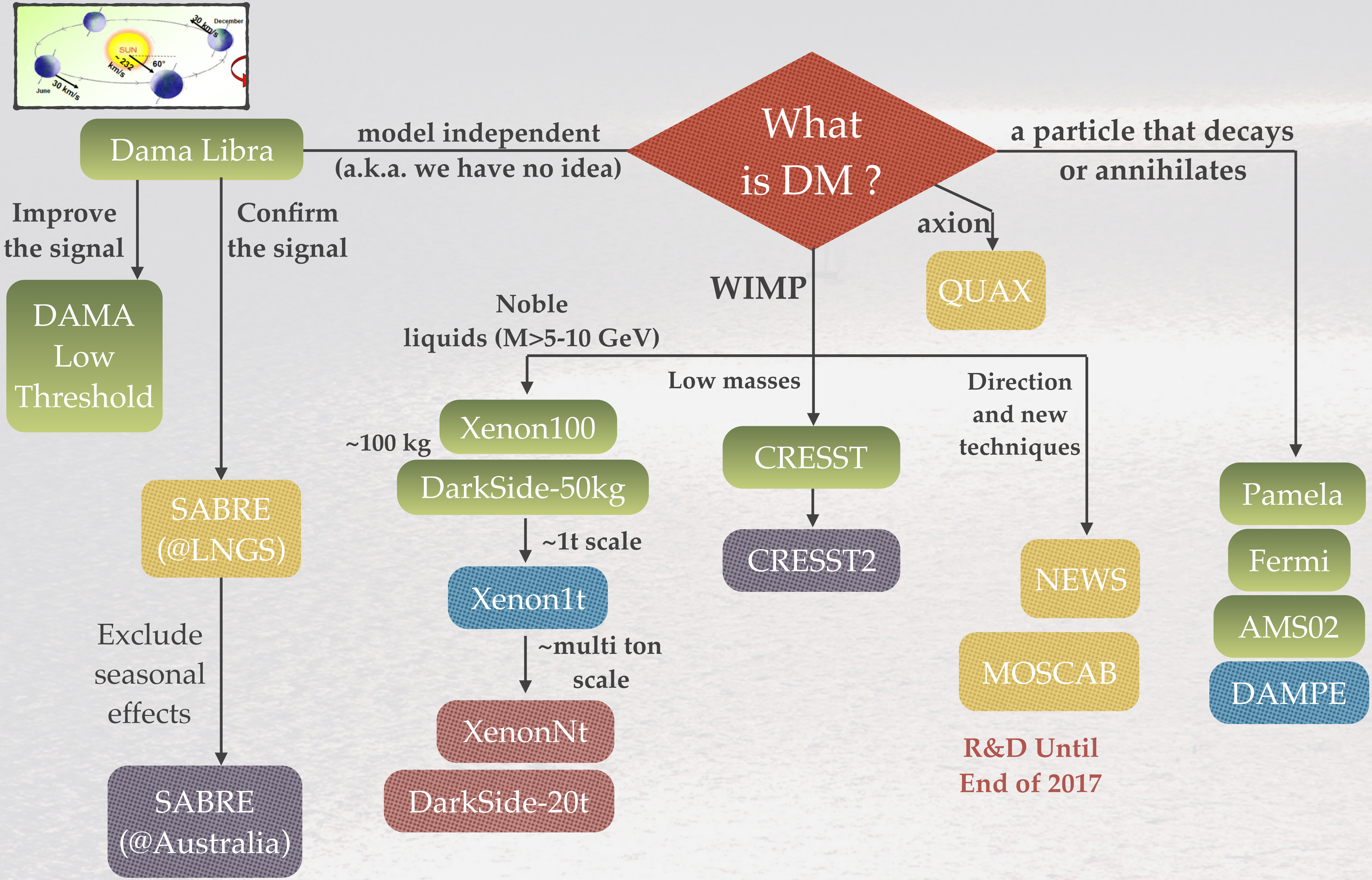


- PROBLEM
  - Stability
  - Complexity
  - Unusual behaviours
  - Shielding not easy because of criogenics

EXPERIMENTS' DIAGRAM (NOT ONLY INFN)



DARK MATTER: STRATEGIC FLOW

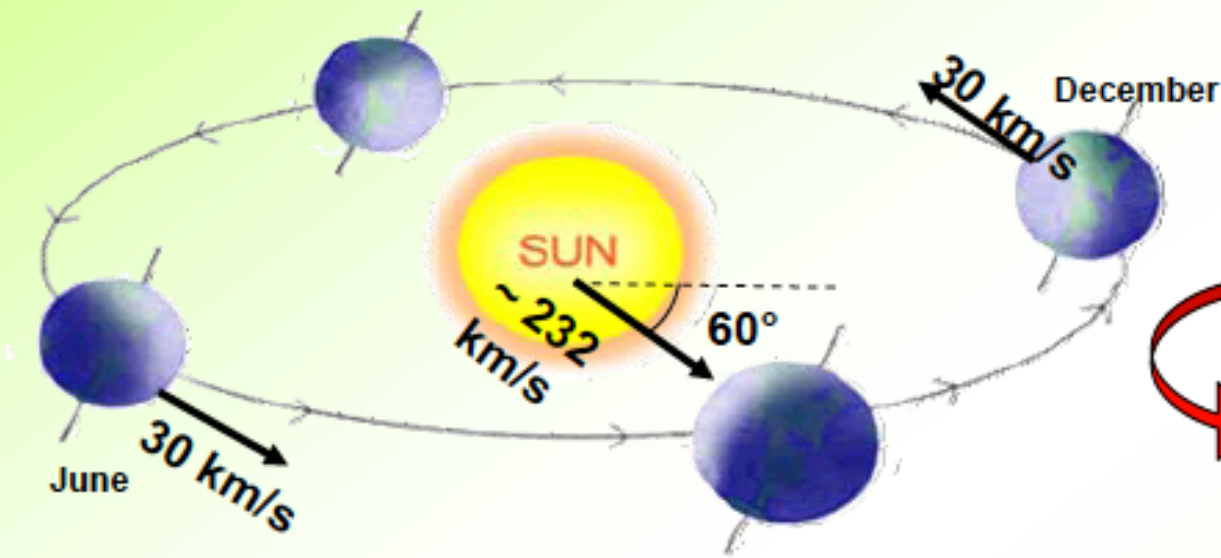


- The only experiment that claims discovery of dark matter
  - A large mass **NaI** detector (250 kg), much more than others
  - **Many years of data taking** in very stable conditions
  - **Model independent analysis of annual modulations**
    - **No cuts,** no assumption on DM particle nor interaction process
- The evidence of the modulation is beyond doubt
- Many checks against all suggest source of background have been done, with negative result
  - No explanation exists for the observed modulation except DM signal

The annual modulation: a model independent signature for the investigation of Dark Matter particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small **a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions would point out its presence.**

Drukier, Freese, Spergel PRD86
Freese et al. PRD88



- v_{sun} ~ 232 km/s (Sun velocity in the halo)
- v_{orb} = 30 km/s (Earth velocity around the Sun)
- $\gamma = \pi/3$
- $\omega = 2\pi/T$ T = 1 year
- t_0 = 2nd June (when $v_\oplus$ is maximum)

$$v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma \cos[\omega(t-t_0)]$$

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

Expected rate in given energy bin changes because the annual motion of the Earth around the Sun moving in the Galaxy

Requirements of the annual modulation

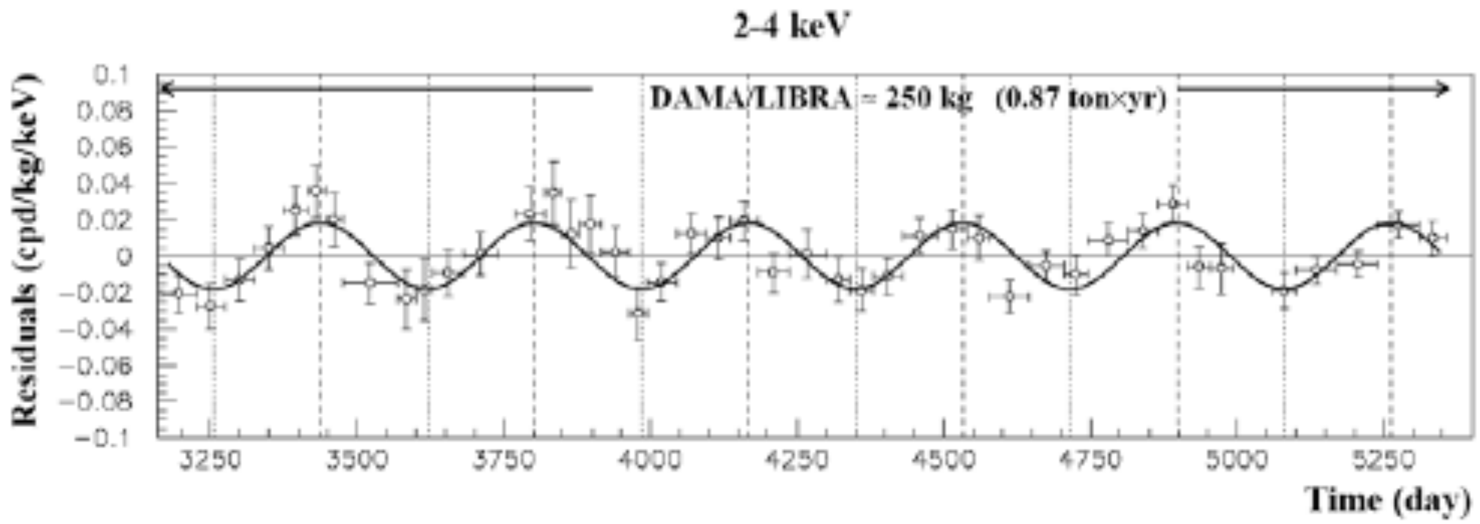
1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) Just for single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios

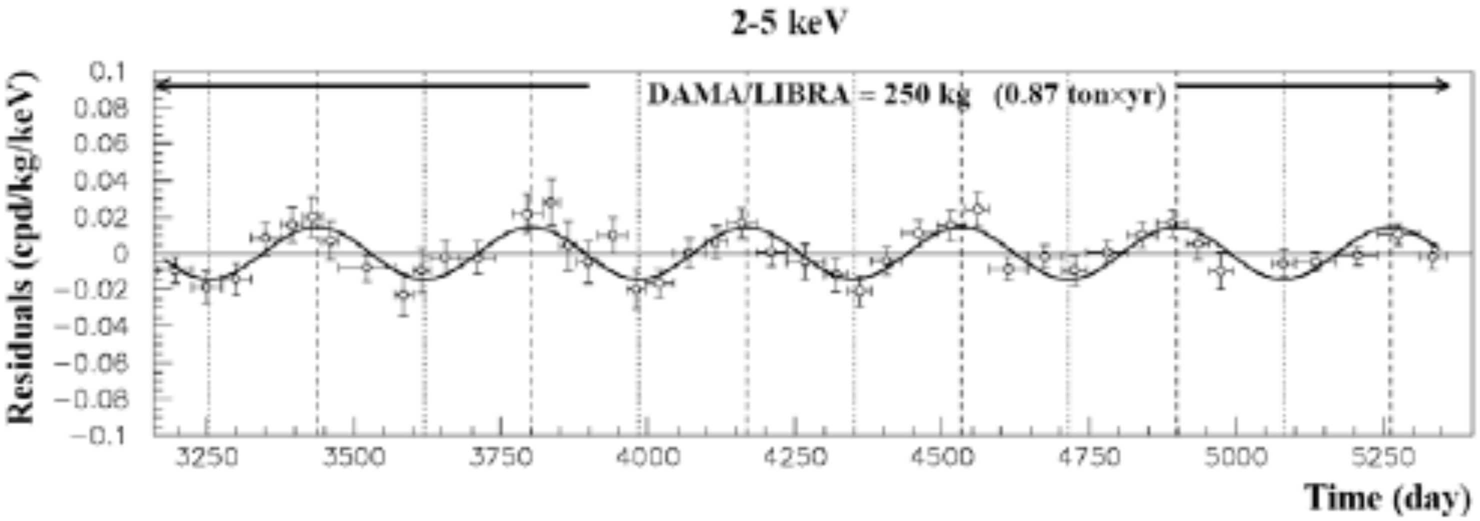
To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

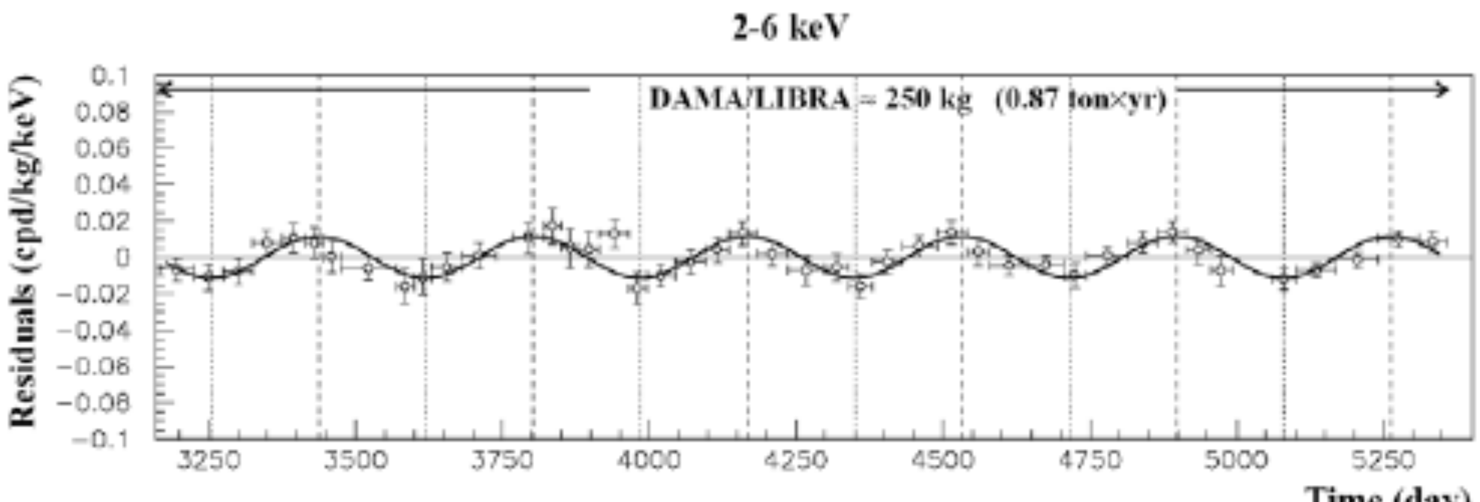
The DM annual modulation signature has a different origin and, thus, different peculiarities (e.g. the phase) with respect to those effects connected with the seasons instead

$A\cos[\omega(t-t_0)]$; continuous lines: t_0 = 152.5 d, T = 1.00 y

DAMA/LIBRA-1,2,3,4,5,6 (0.87 ton × yr)







The fit has been done on the DAMA/NaI & DAMA/LIBRA data (1.17 ton × yr)

2-4 keV

A=(0.0183±0.0022) cpd/kg/keV

χ^2/dof = 75.7/79 **8.3 σ C.L.**

Absence of modulation? No

χ^2/dof=147/80 ⇒ P(A=0) = 7×10^{-6}

2-5 keV

A=(0.0144±0.0016) cpd/kg/keV

χ^2/dof = 56.6/79 **9.0 σ C.L.**

Absence of modulation? No

χ^2/dof=135/80 ⇒ P(A=0) = 1.1×10^{-4}

2-6 keV

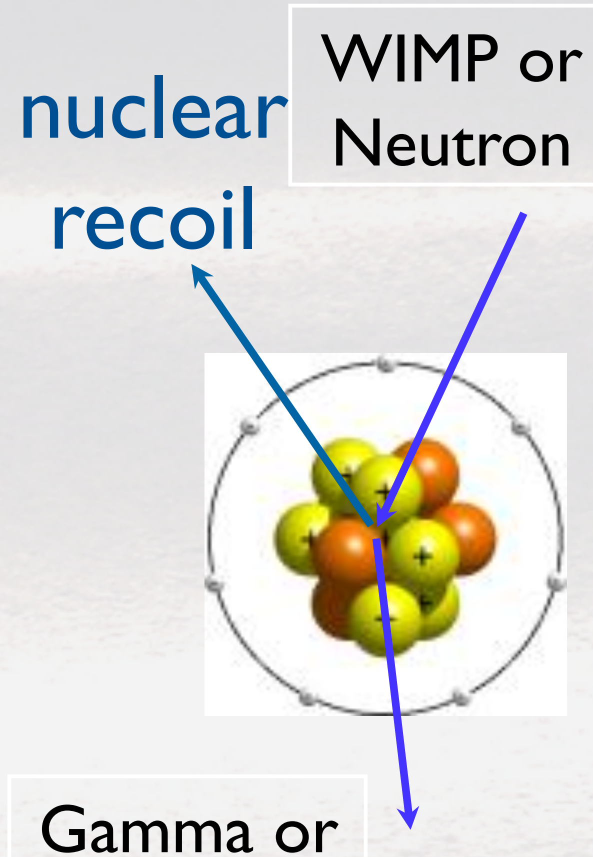
A=(0.0114±0.0013) cpd/kg/keV

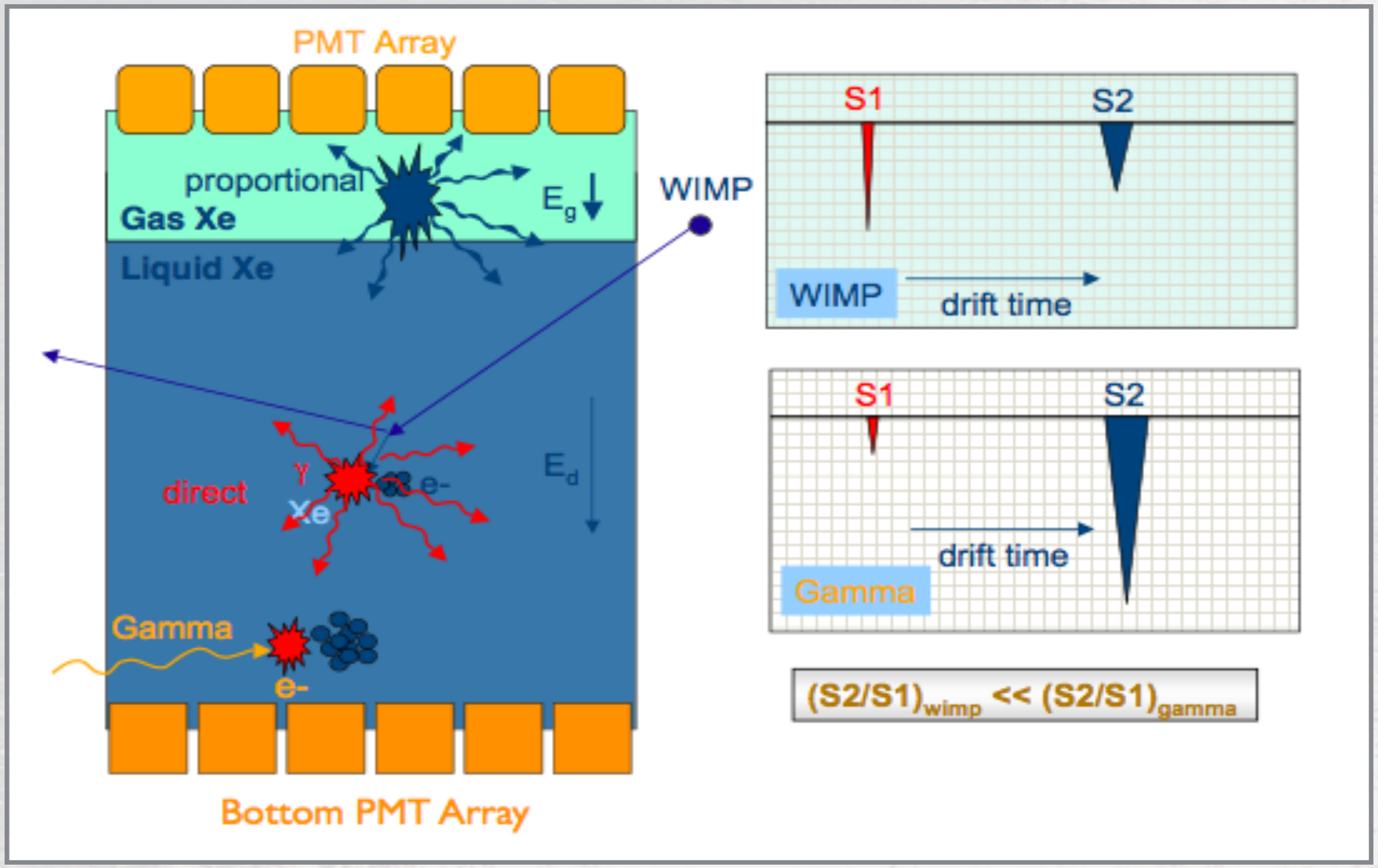
χ^2/dof = 64.7/79 **8.8 σ C.L.**

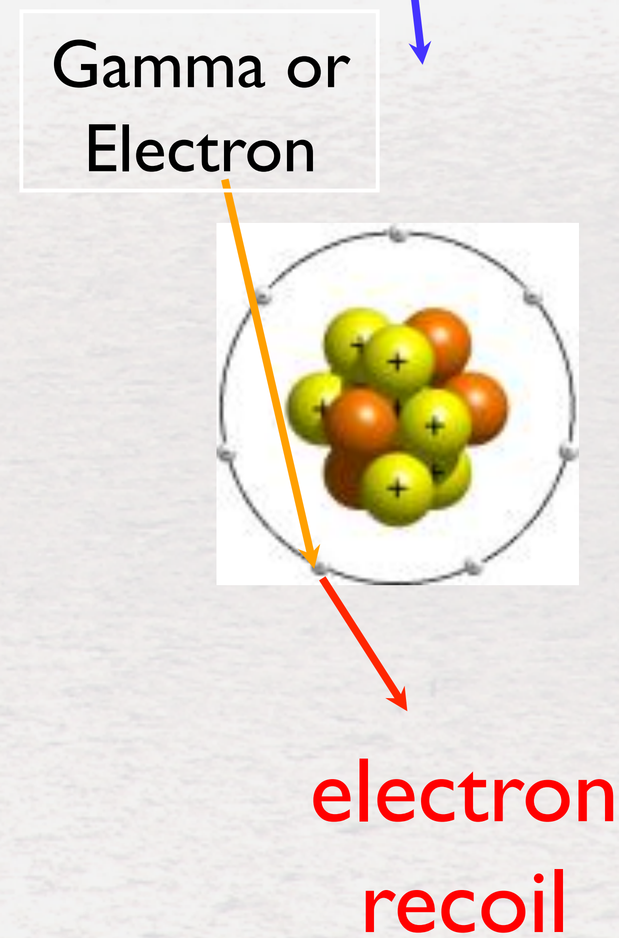
Absence of modulation? No

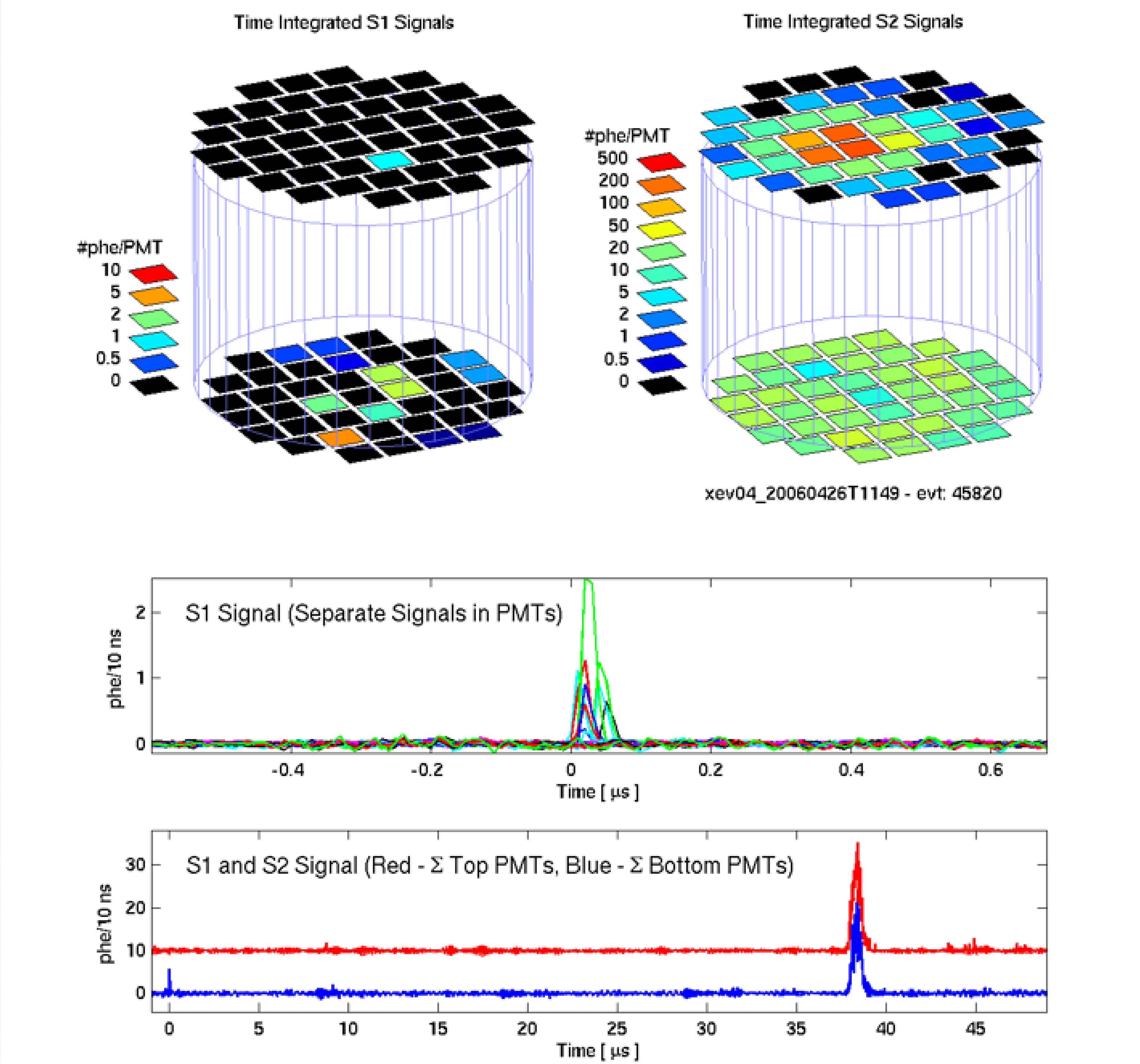
χ^2/dof=140/80 ⇒ P(A=0) = 4.3×10^{-5}

- two- phase Time Projection Chamber with 3D event imaging with millimeter resolution. Simultaneously measure the ionization and scintillation produced by low energy recoils in pure LXe (~5 keVr threshold) to achieve >99.5% gamma/beta background rejection. Additional background rejection provided by 3D event localization, LXe self-shielding, multiple scatter signature, plus external shielding.



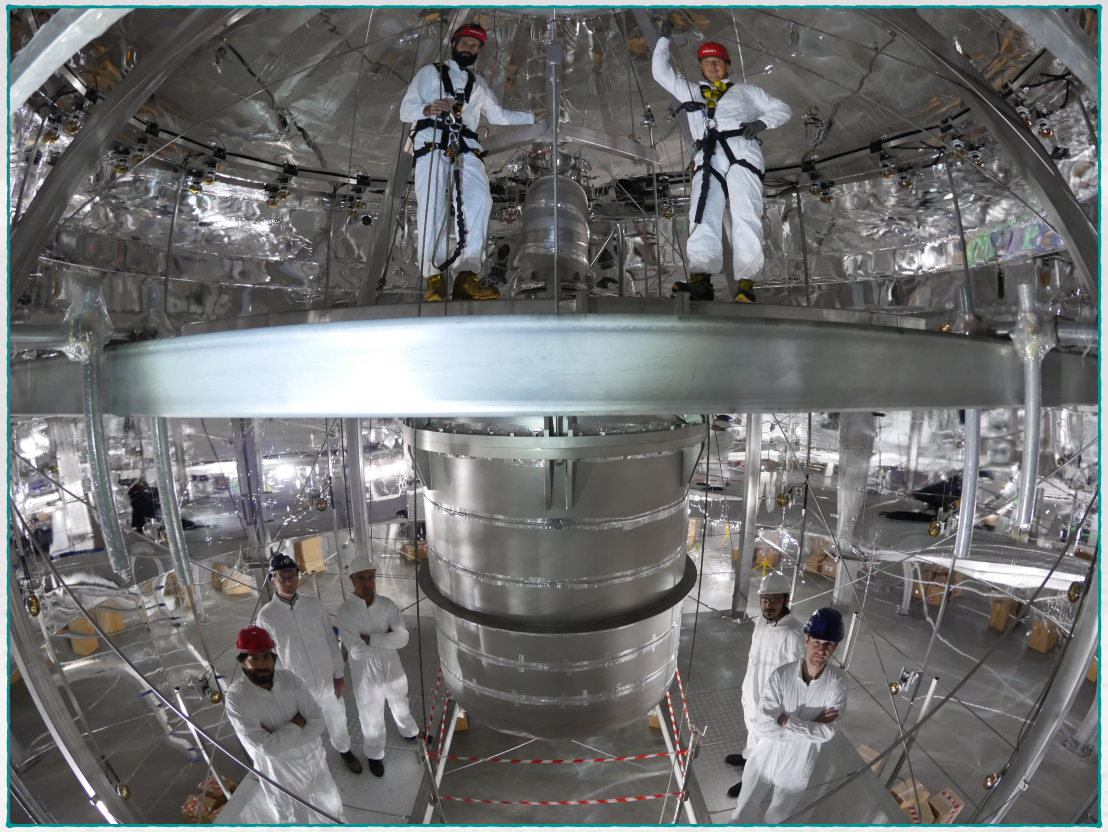




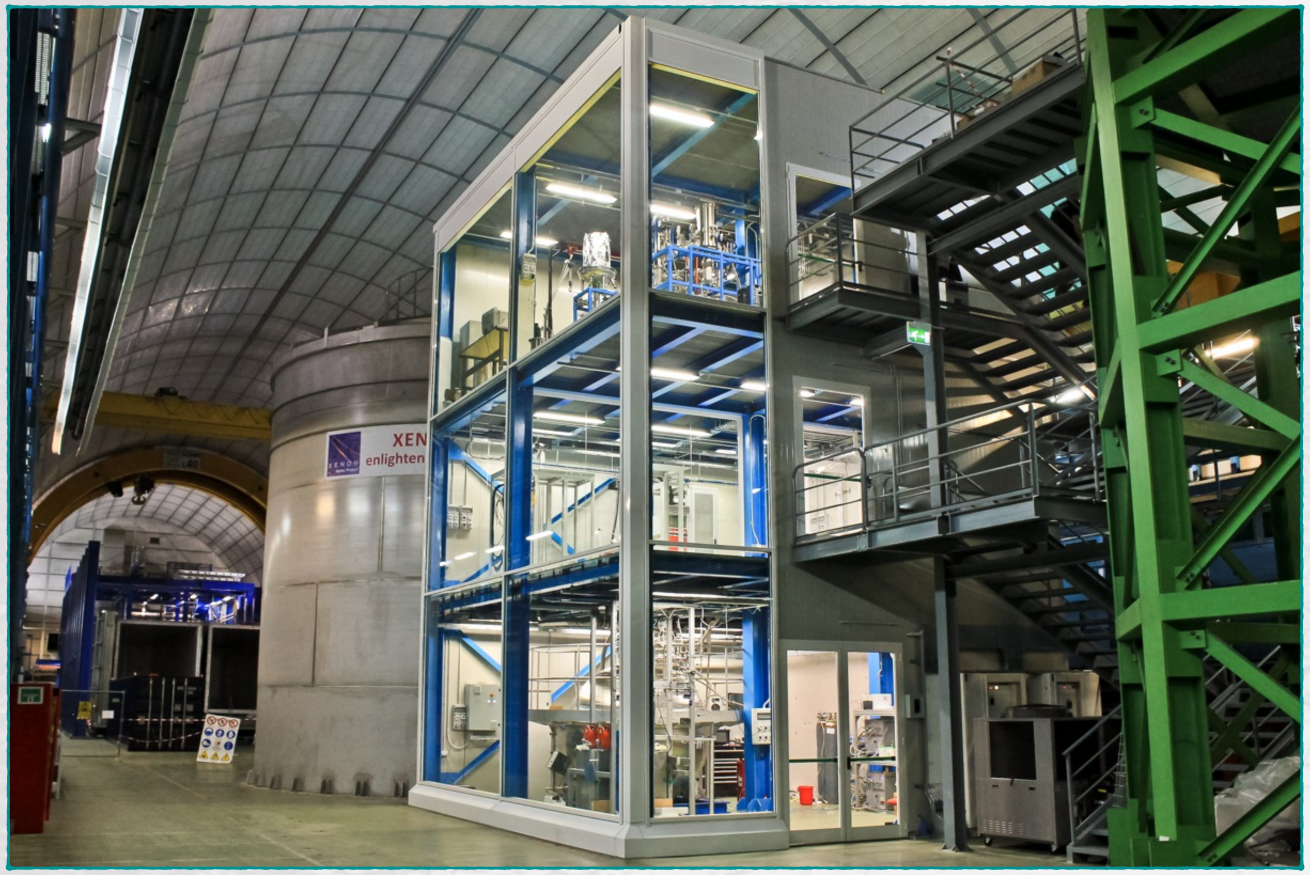


Example: Xenon-10

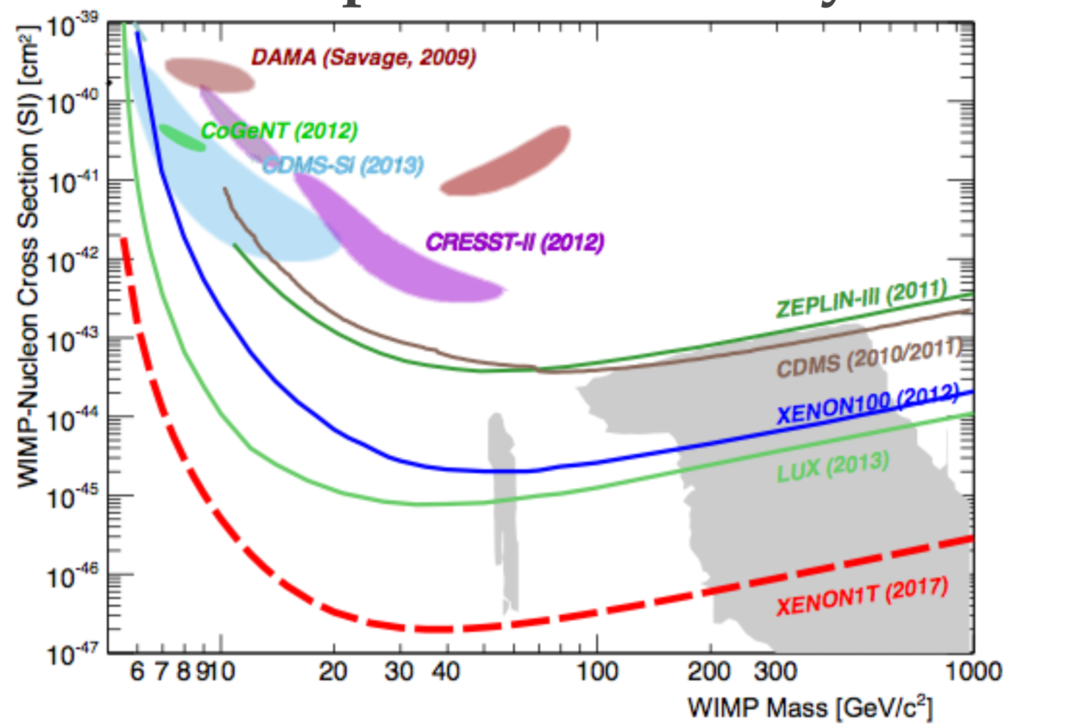
- **Construction completed**
  - **Data taking in progress**
  - **First D.M. results a few days ago**



Tank and Building in Hall B



Expected sensitivity



First Dark Matter Search Results from the XENON1T Experiment

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May 2017

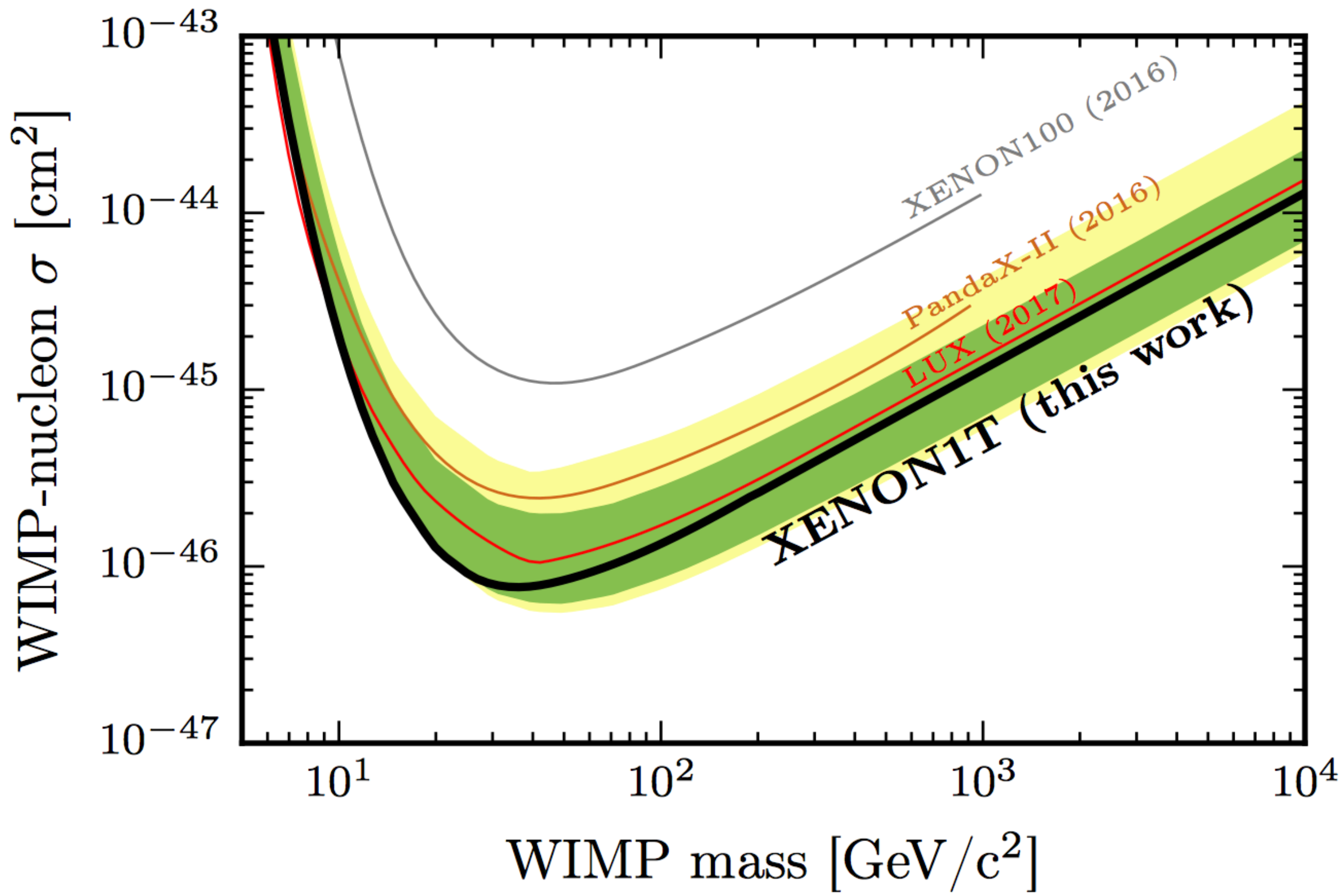
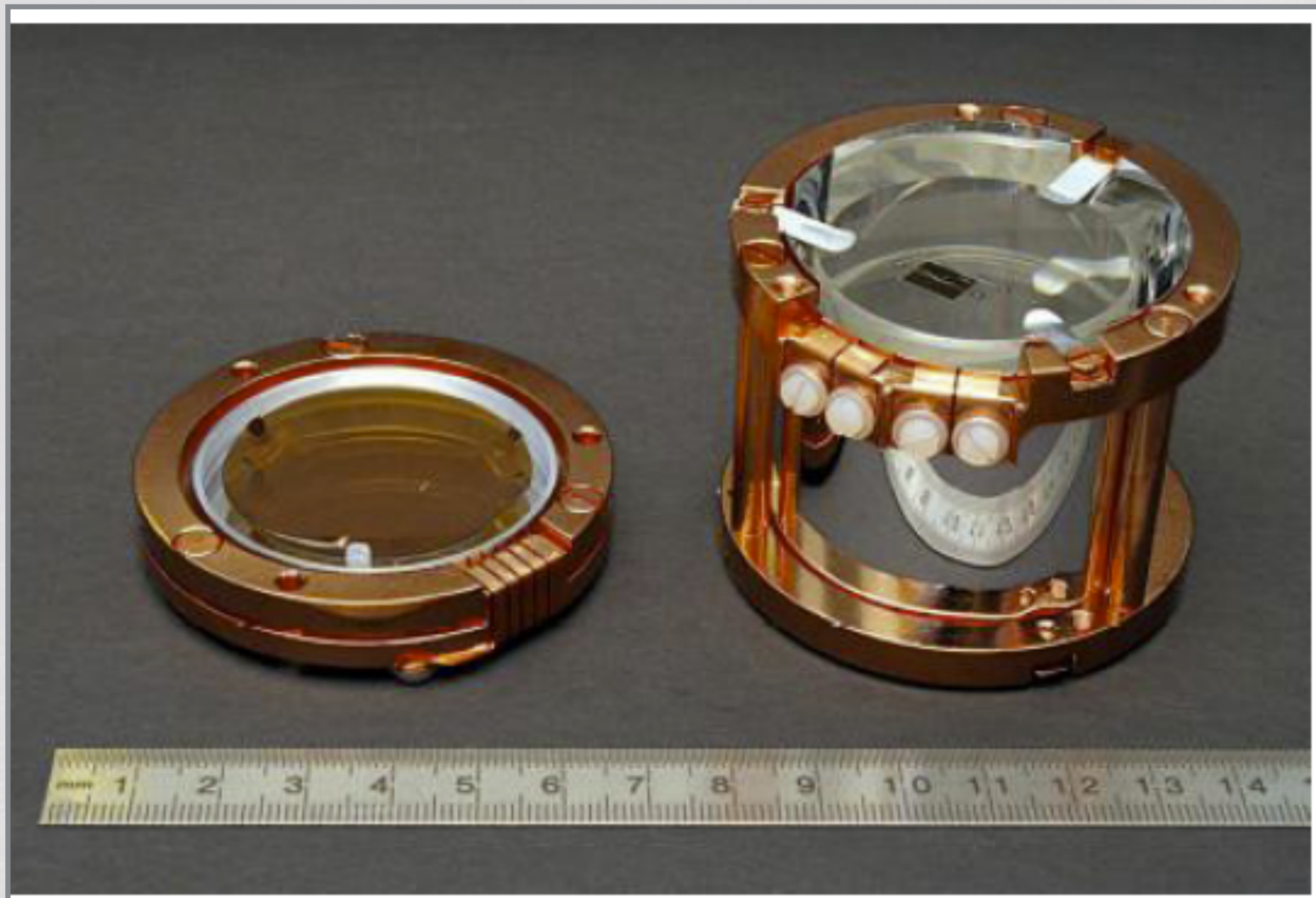


FIG. 4: The spin-independent WIMP-nucleon cross section limits as a function of WIMP mass at 90% confidence level (black) for this run of XENON1T. In green and yellow are the 1- and 2σ sensitivity bands. Results from LUX [26] (red), PandaX-II [27] (brown), and XENON100 [23] (gray) are shown for reference.

- Measurement of phonons and light in CaWO4 crystals



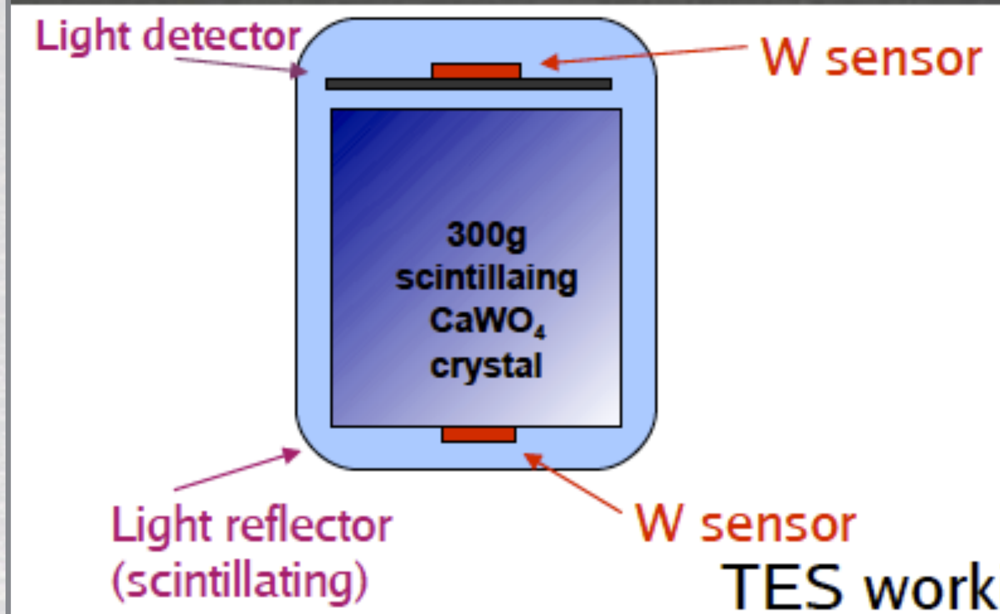
Tungsten (W) thin films (200nm respectively 120nm) as Transition Edge Sensors (TESs)

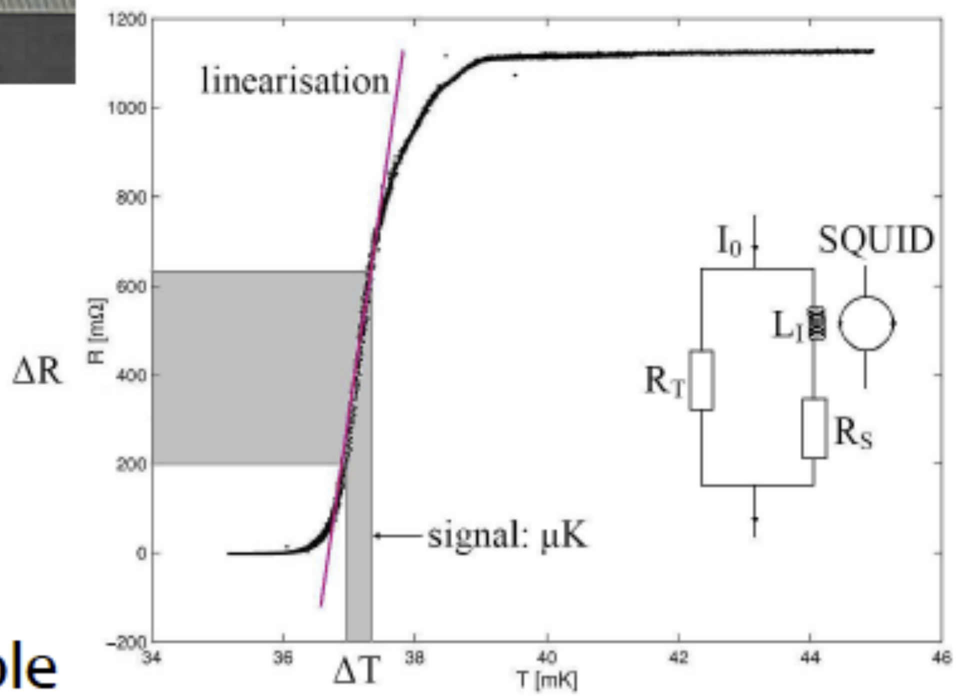
Phonon channel

Scintillating $CaWO_4$-crystal (300g, height=40mm) as target with W-TES on top

Light channel

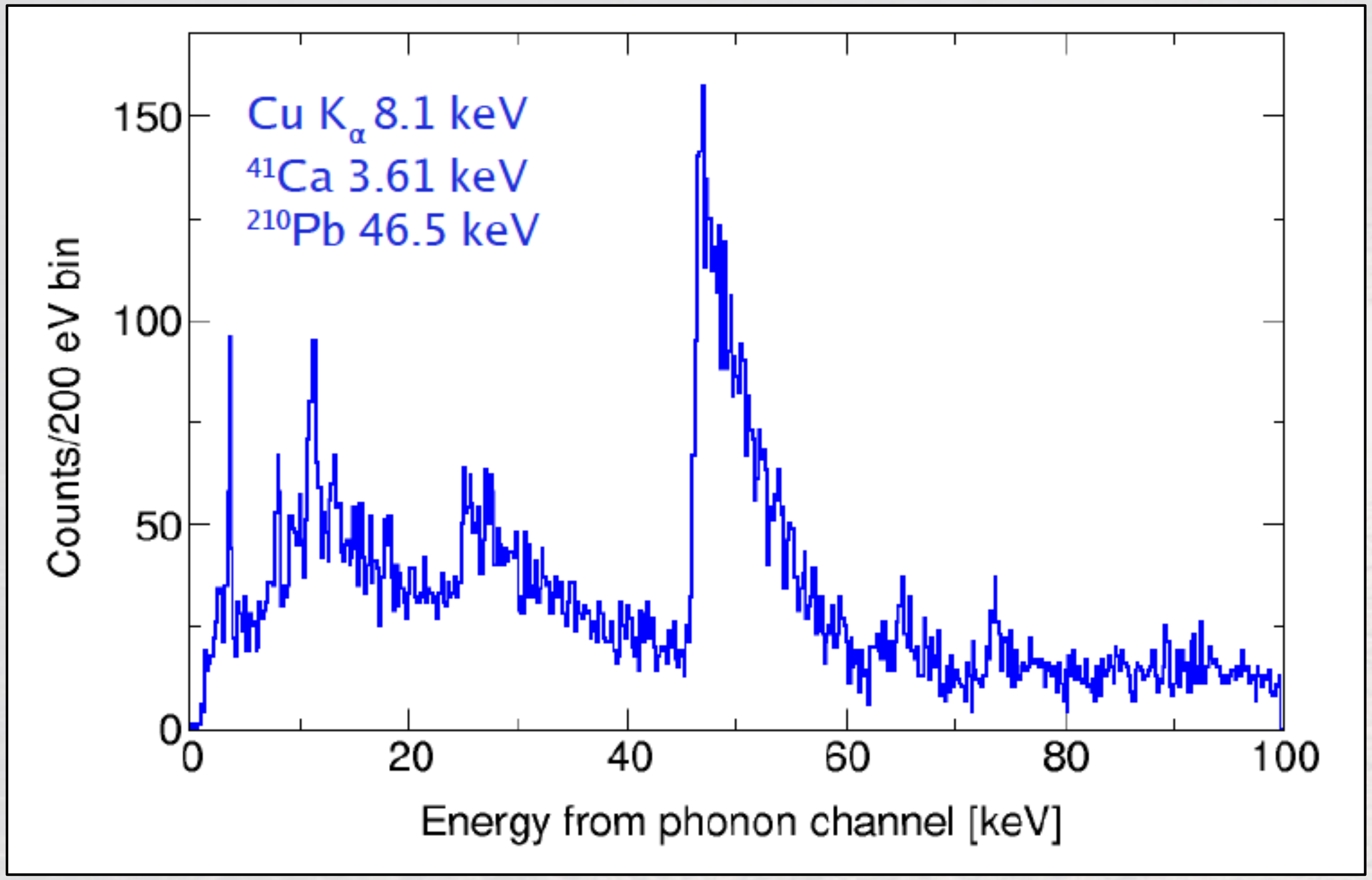
SOS (Silicon on Sapphire) crystal (=40mm) with W-TES on top

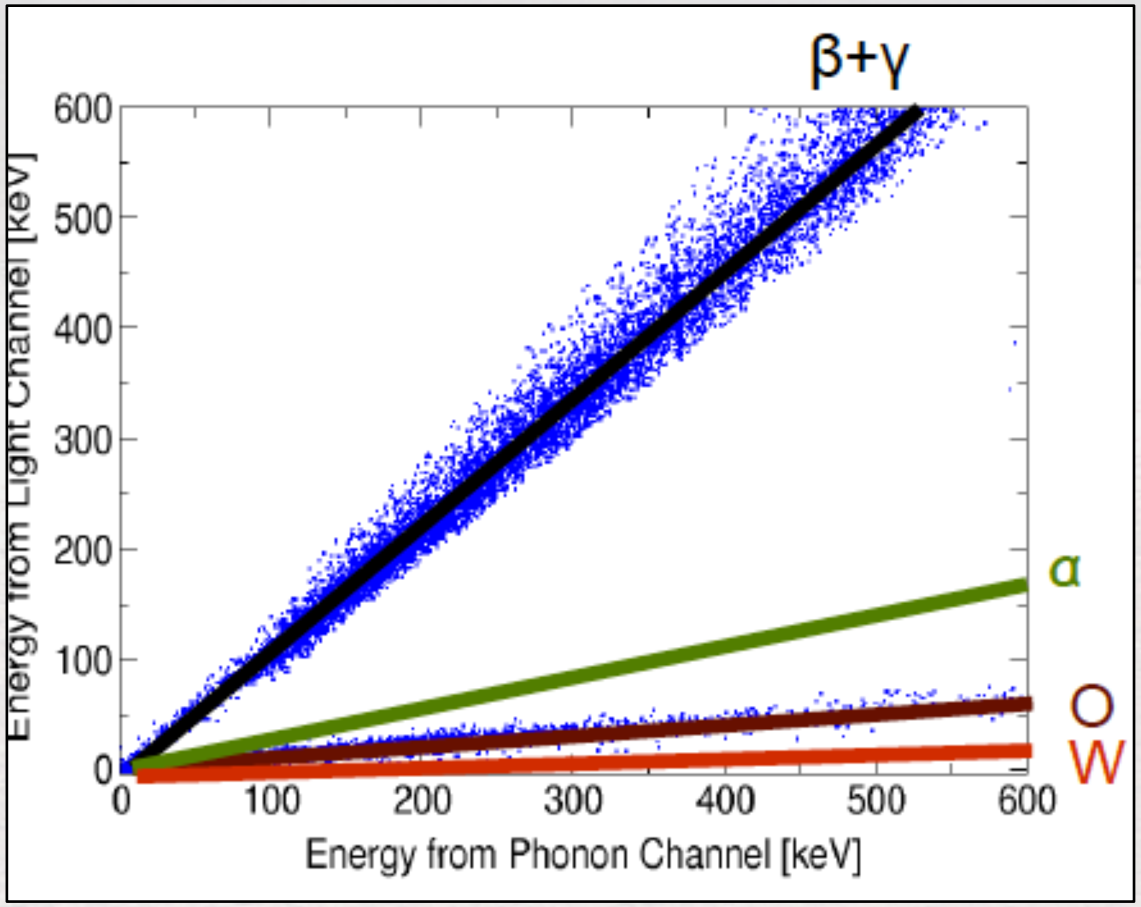


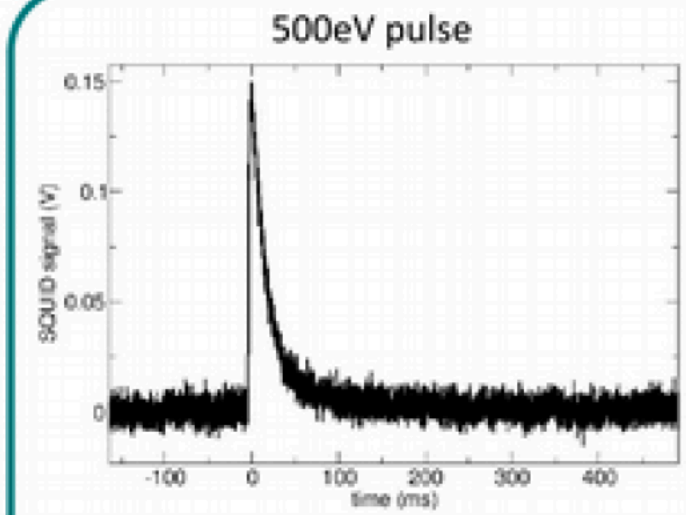


TES working principle

- Very precise even at very low energy
- Nuclear recoil discrimination

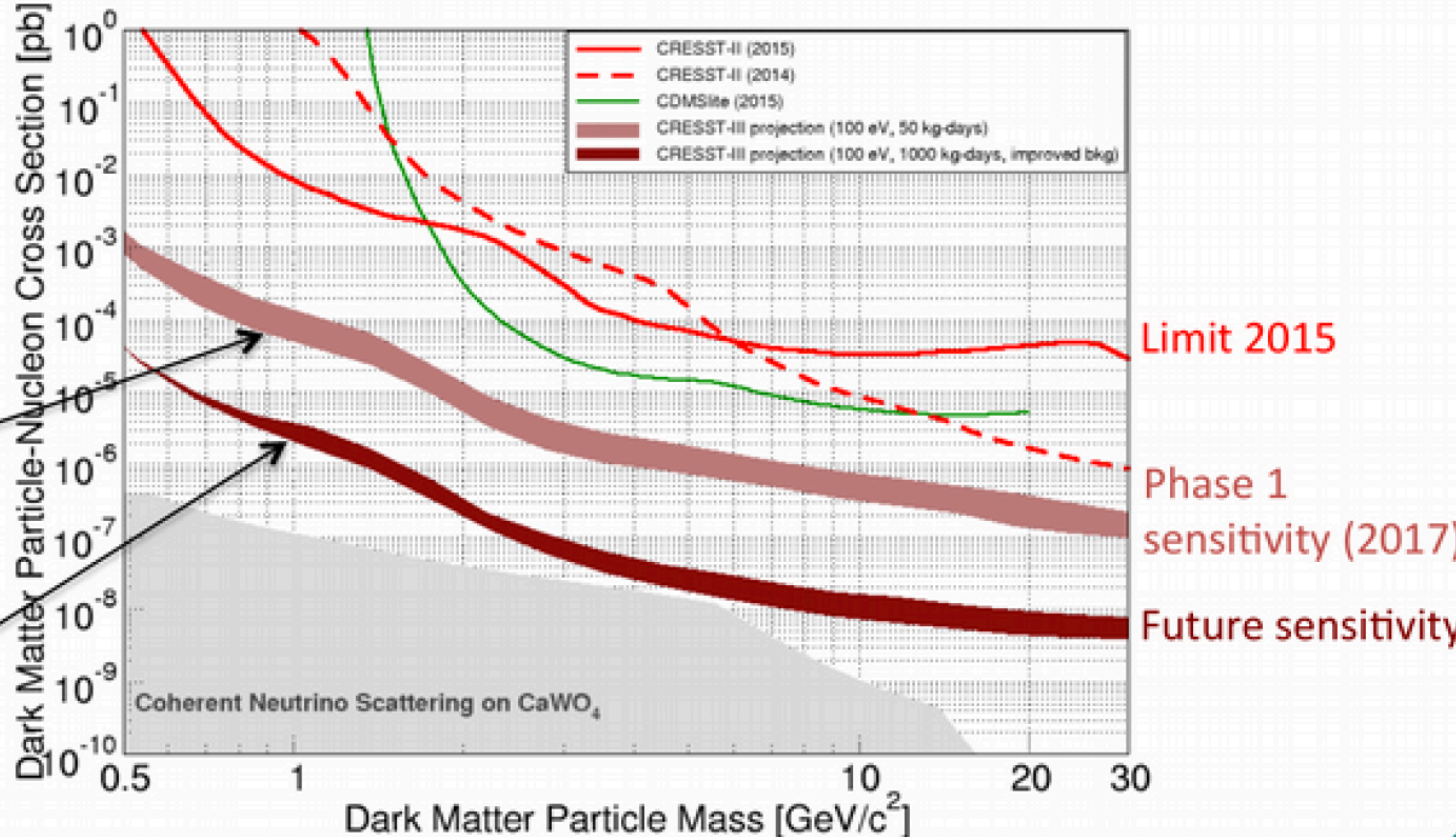






Projected sensitivity for 50kg days (1 year) with design goal threshold (100eV)

Projected sensitivity for 1000kg days (2 year with 100 detectors) with design goal threshold (100eV)



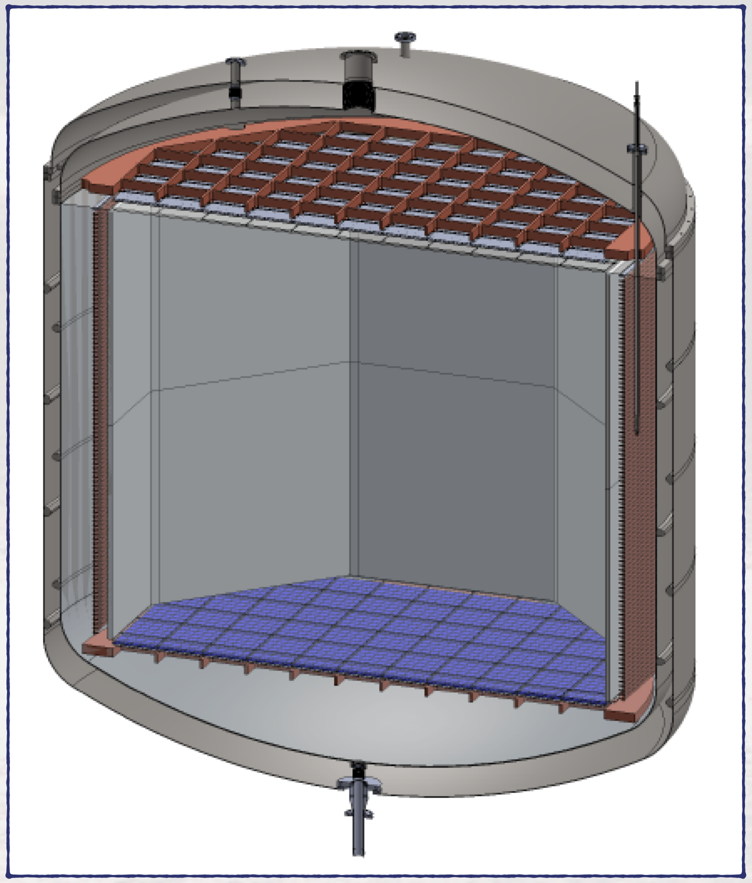
Extreme low mass sensitivity ideal for direct dark matter search and identification

Future: approach the neutrino floor

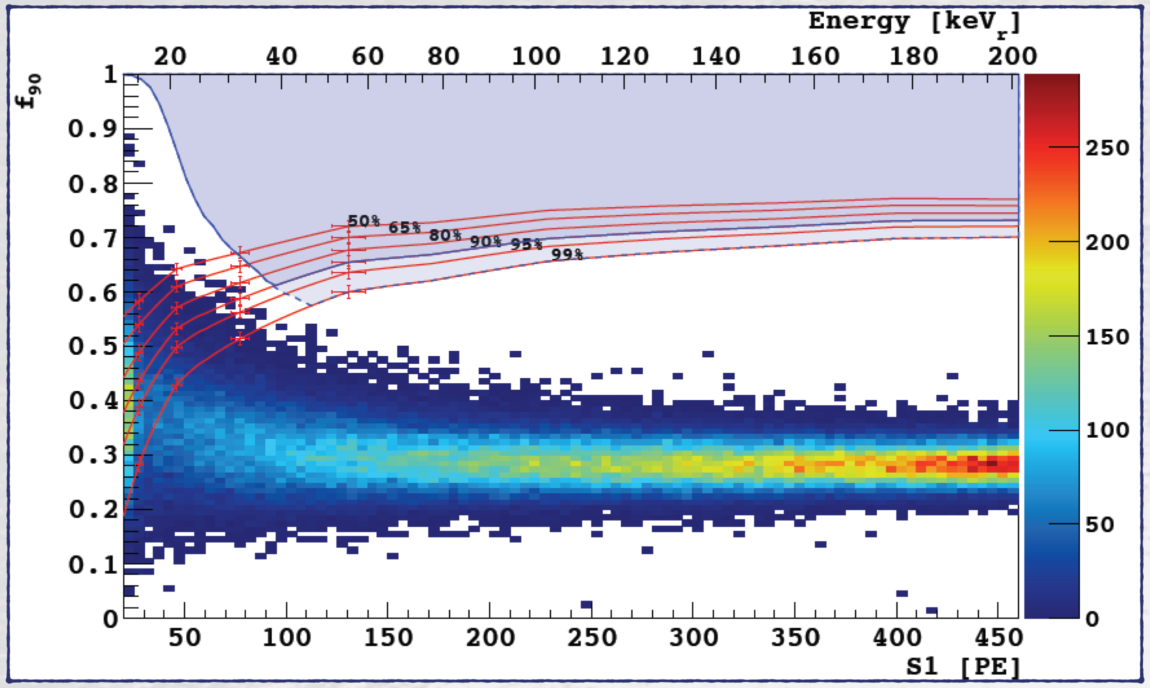
- material screening and purification of raw material for crystal production
  - factor of 100 reduction of background
- upgrade of LNGS facility to operate 100 detectors
  - 1000 kg days in 2 years

DARKSIDE-50 KG (FUTURE 20T)

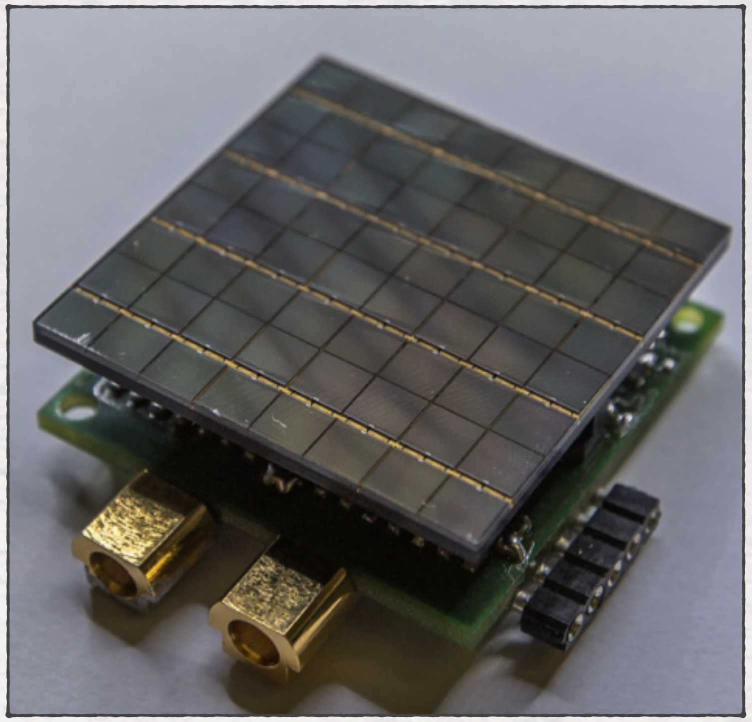
- **50 kg LAr** bi-phase detector operated with low **^{39}Ar** and liquid scintillator neutron veto
  - Zero background goal achieved
  - ***20 t phase approved by CSN2***



- Contribution from Russia: low background titanium cryostat



SiPM device under development at FBK (INFN Trento)



BCK REJECT: PULSE SHAPE DISCRIMINATION

- Two scintillation time constants:

  - singlet ~7ns

  -triplet ~1500ns

- Nuclear and electron recoils have different ratios of singlet and triplet states.

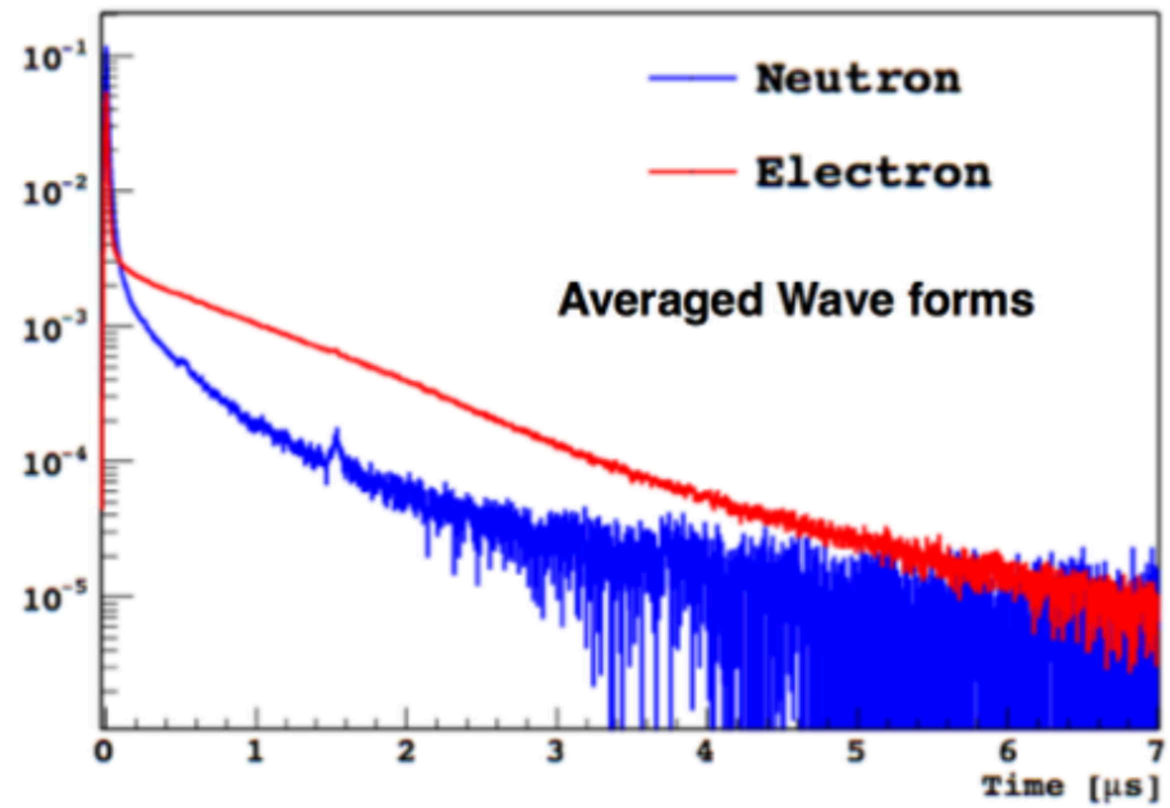
Possible discrimination between NR and ER.

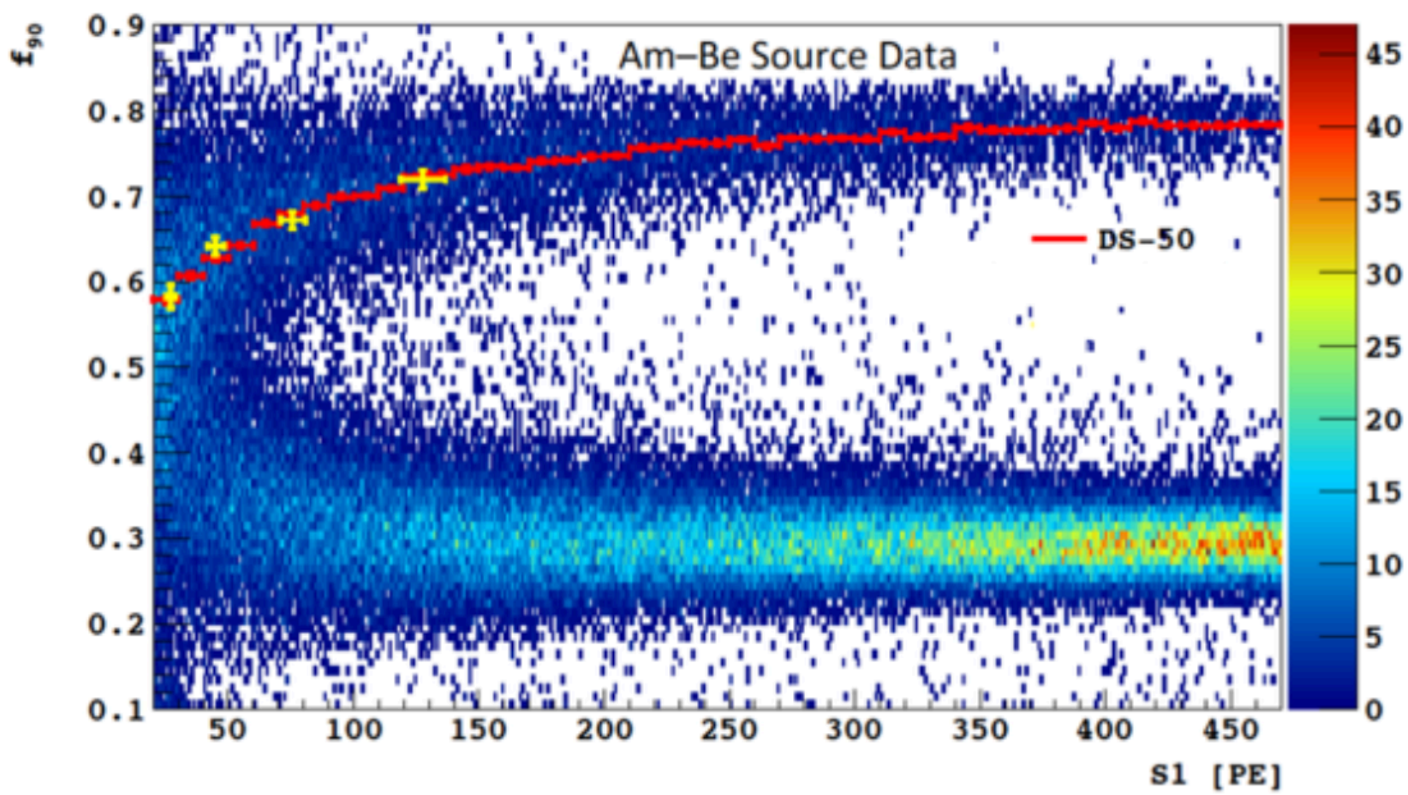
PSD parameter:

$$f90 = \frac{\text{light first 90ns}}{\text{total light}}$$

$f90 \approx 0.7$ ⟶ NR

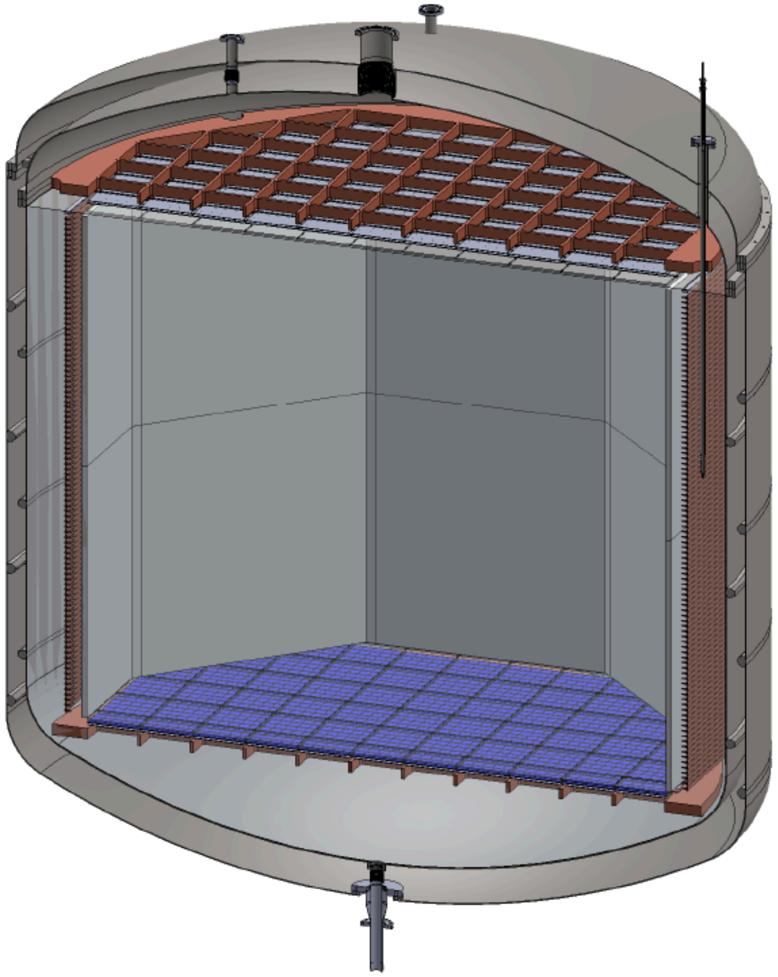
$f90 \approx 0.3$ ⟶ ER





DarkSide-50

2013-201X



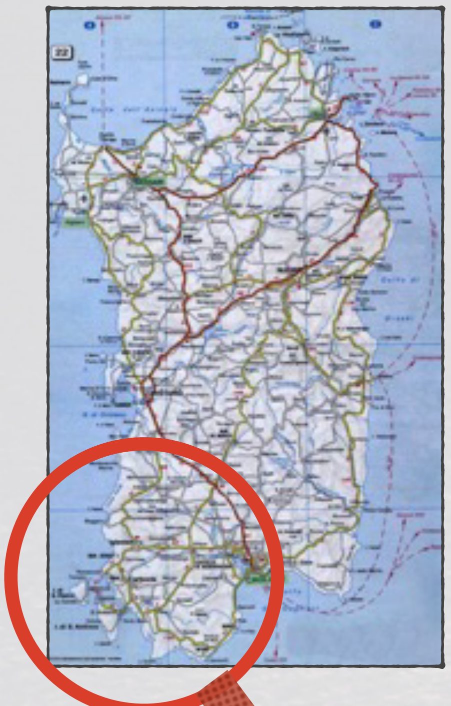
DarkSide-10

2011-2013

DarkSide-20k

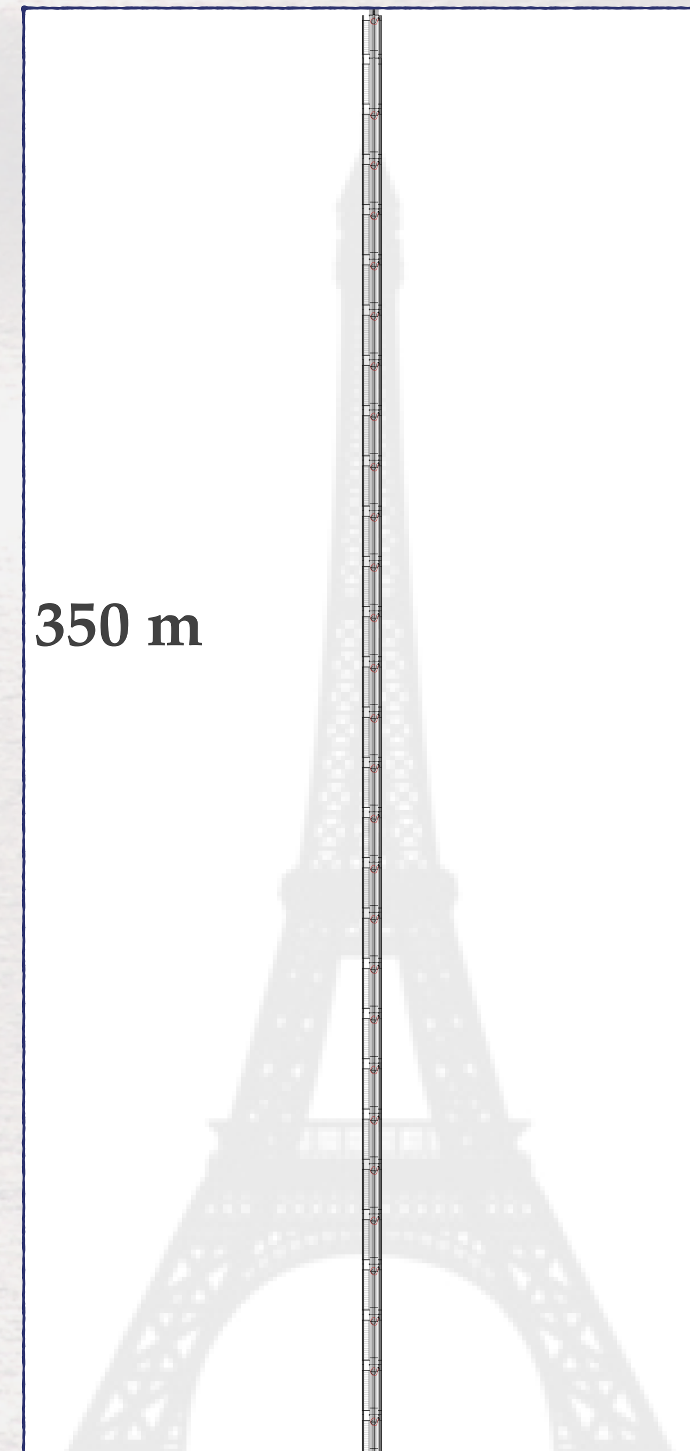
2020-202X

- Seruci **cryogenic distillation column**
  - Dark Matter goal: **separate by distillation ^{40}Ar**
  - Potential by-product
    - **A plant for isotope enrichment unique in the world**
    - **^{13}C, ^{15}N, ^{18}O** and others (Industry, Medical, **0νββ?**)
      - Studies indicate 200 M€/y market with 10% y growth




Seruci Mine in Sardinia


Existing shaft N. 1

Size comparison


- **4 pillars:**
  - **URANIA:** extraction of underground Argon in Colorado
  - **ARIA:** distillation and isotopic enrichment plant in Sardinia
  - **REGIONAL** money from **Sardinia and Abruzzo** for technological transfer from FBK
  - **DARKSIDE-20t:** An innovative detector with depleted UAr, SiPM technology, Ti cryostat
- **~100 M€ scale project.** A lot of financial, political, and programmatic issues to solve
  - **A high scientific priority, however.**

- QCD should bring a large CP violation, but apparently it does not

$$\mathcal{L}_{CPV} = -\frac{\alpha_s}{8\pi}\left(\Theta - arg\ det\ M_q\right) Tr\ \tilde{G}_{\mu\nu} G^{\mu\nu}$$

- Parameter Θ is free, no reason to be too small and induces an electric moment for the neutron, which is not observed

$$\bar{\Theta} = \Theta - arg\ det\ M_q \qquad d_n = \bar{\Theta}\ 10^{-16}\ e\ cm = \frac{\bar{\Theta}}{10^2}$$

$$d_n < 3\ 10^{-26}\ e\ cm \quad \Longrightarrow \bar{\Theta} < 10^{-10}$$

- This is called the “strong CP problem”

A DYNAMICAL SOLUTION

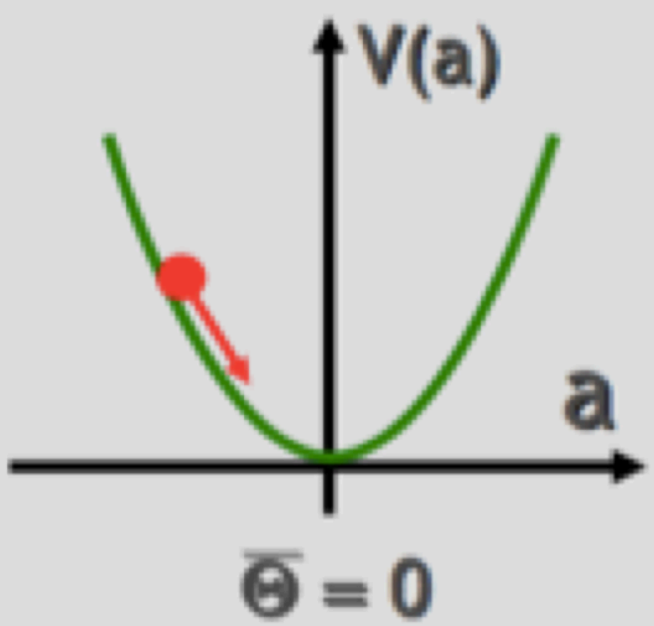
Peccei & Quinn 1977 - Wilczek 1978 - Weinberg 1978

Re-interpret $\bar{\Theta}$ as a dynamical variable (scalar field)

$$\bar{\Theta} \rightarrow \frac{a(x)}{f_a}$$

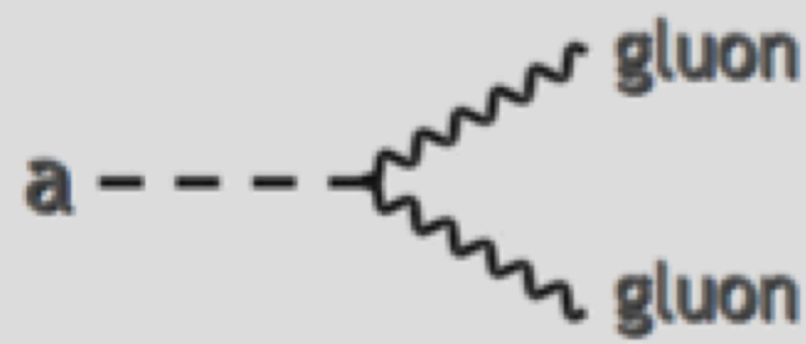
- $a(x)$: Pseudo-scalar axion field
- f_a: Peccei-Quinn scale, Axion decay constant

$$L_{CP} = -\frac{\alpha_s}{8\pi}\bar{\Theta}\,\mathrm{Tr}(G\tilde{G}) \quad \Rightarrow \quad L_{CP} = -\frac{\alpha_s}{8\pi}\frac{a(x)}{f_a}\,\mathrm{Tr}(G\tilde{G})$$



Potential (mass term) induced by L_{CP} drives a(x) to CP-conserving minimum

CP-symmetry dynamically restored

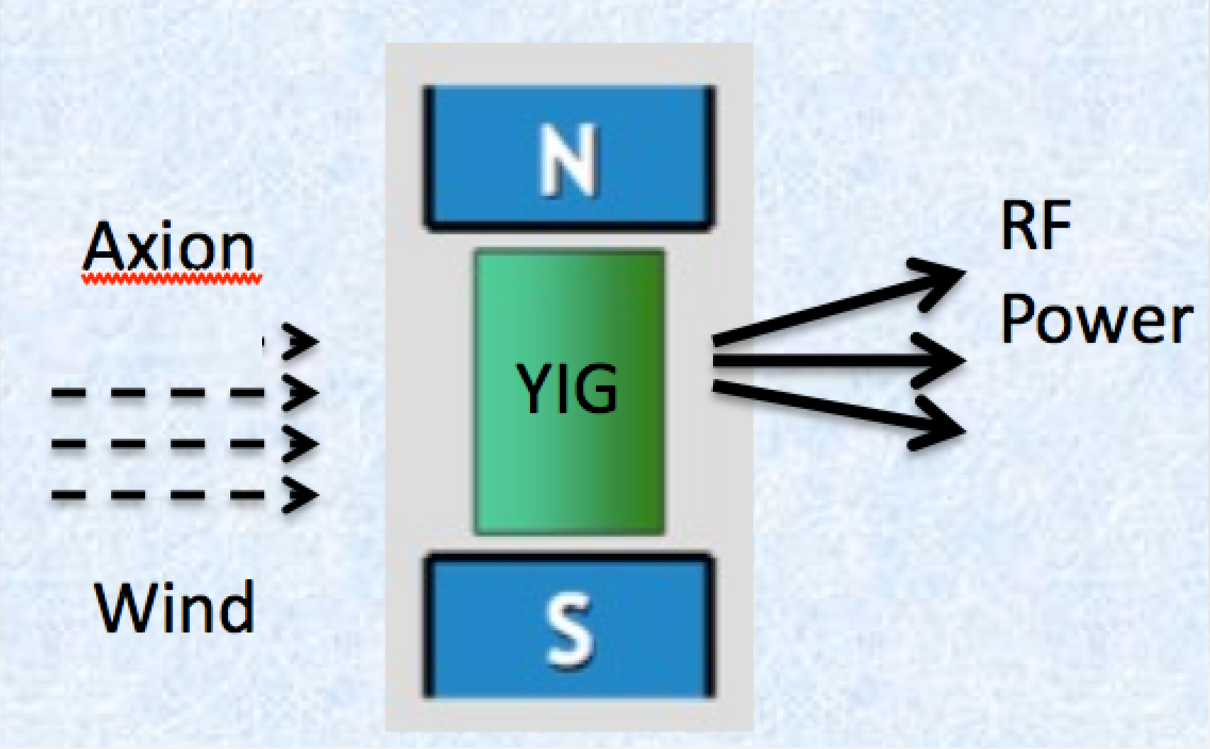


Axions generically couple to gluons and mix with π^0

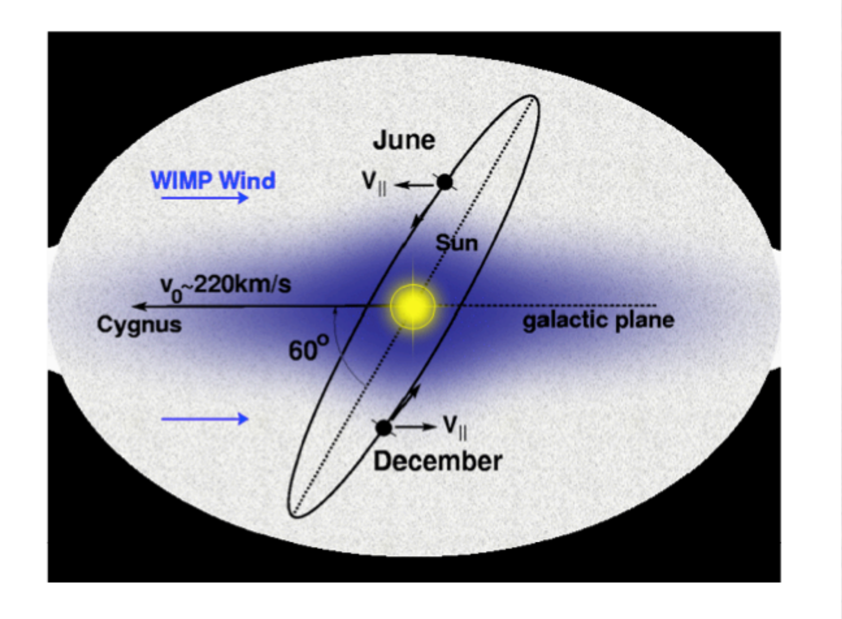
$$\begin{pmatrix}\text{Axion mass} \\ \text{\& couplings}\end{pmatrix} \sim \begin{pmatrix}\text{Pion mass} \\ \text{\& couplings}\end{pmatrix} \times \frac{f_\pi}{f_a}$$

$f_\pi \approx 93$ MeV
Pion decay constant

- **Main idea:**
  - Use axion spin coupling
  - The axion field may act as an effective magnetic field on electron spin
  - It may induce ferromagnetic transitions in magnetised sample and emit μ-waves



  - R&D is in progress 2015-2017
    - Noise budget unknown
    - Collaboration with INRIM
    - Magnet uniformity and stability: a challenge
    - Group: PD, LNL, TO



Directionality between axion wind and spin

FLYING DETECTORS

PAMELA, 15-6-2006
e+, e-, nuclei, anti-p, anti-He

FERMI, 11-6-2008
Brand new γ sky, but also electrons

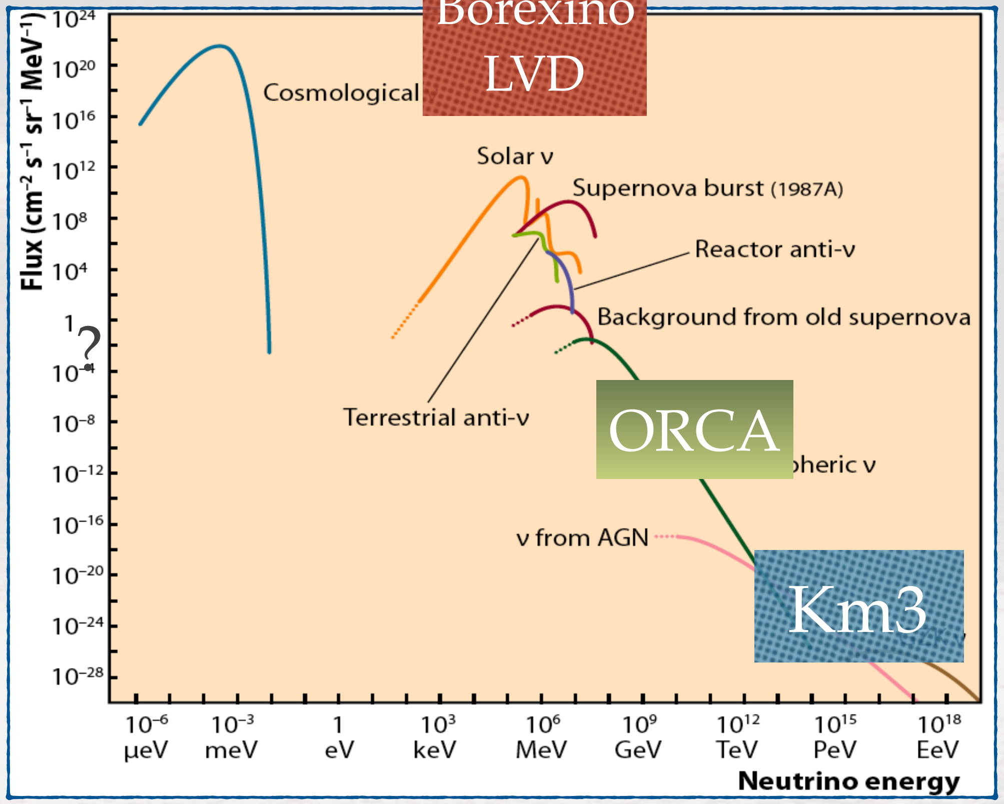
AMS-02, 11-6-2011
Charged particles up to 1 TeV

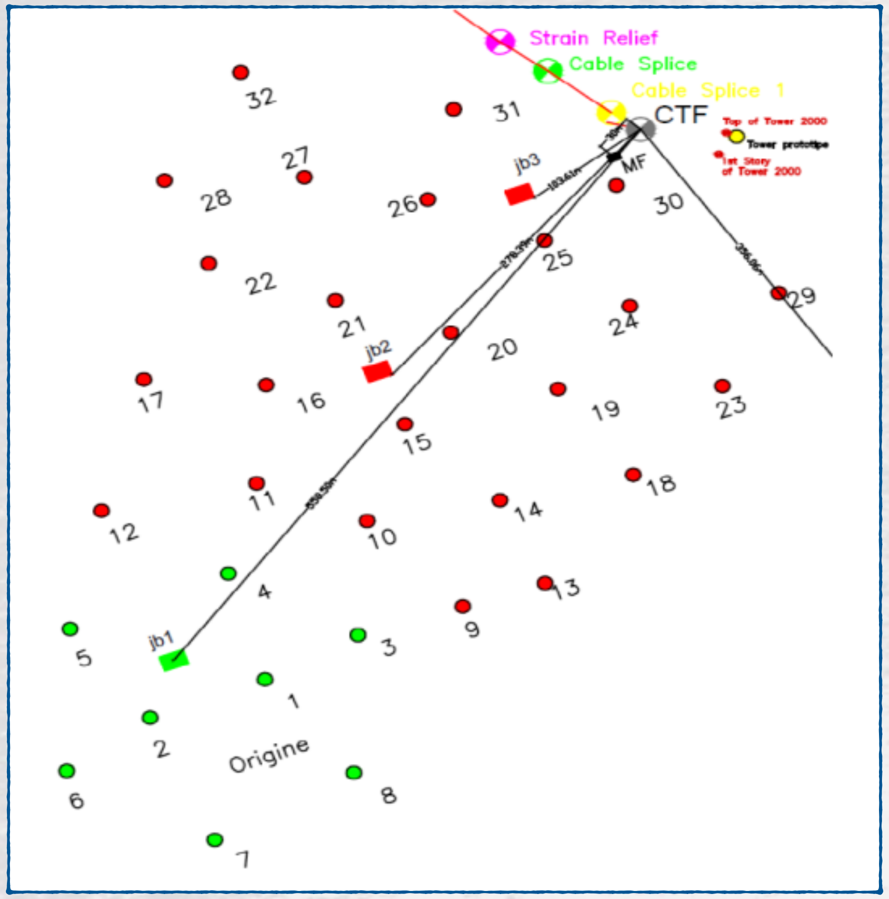
DAMPE, 18-12-2015
Charged particles and photons up to 10 TeV (500 TeV protons)

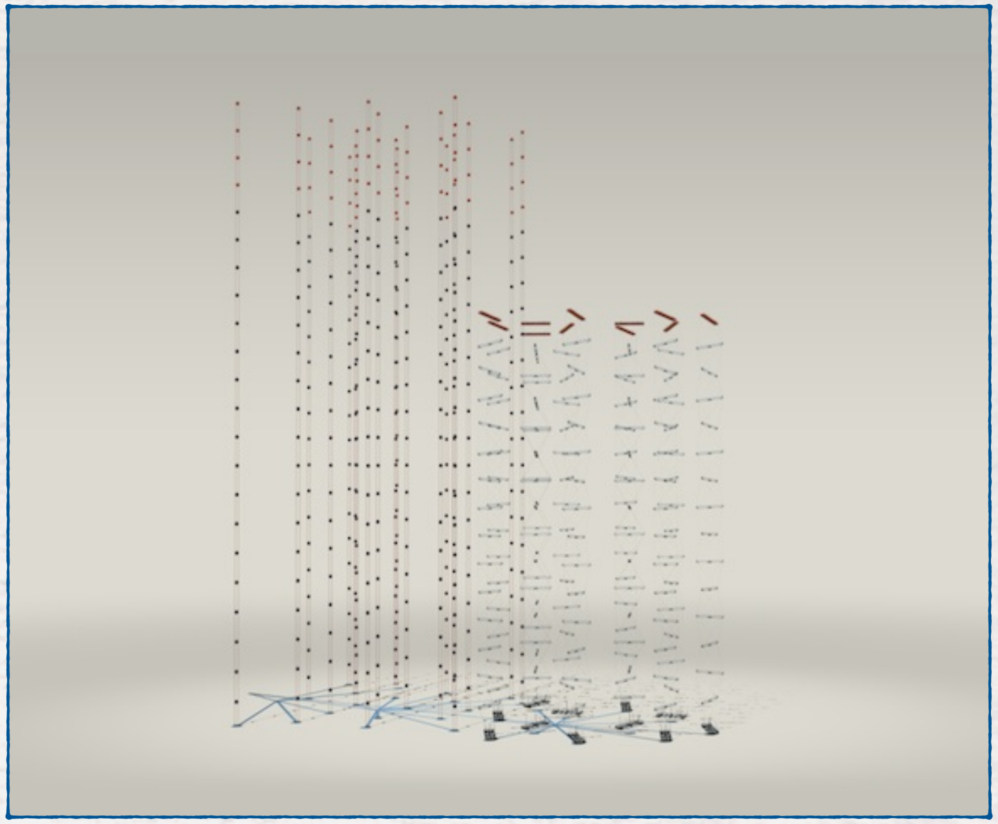
- **PAMELA:** to be **closed** at the ***end of 2017***
- **AMS-02:** continuation approved until 2020. A few technical issues (broken pumps) to address and see what happens
- **FERMI:** continuation approved until 2018, option until 2020. Main reason: transients with GW detections.
- **DAMPE** (now WUKONG): Flying since Dec. 2015

Bruna Bertucci's talk yesterday

- **Deep sea detectors for:**
  - Neutrino astronomy in the Mediterranean: **Km3Net**
  - Atmospheric neutrinos (hierarchy): **ORCA**
- Both **high priority,** but only partially funded
  - Work in progress





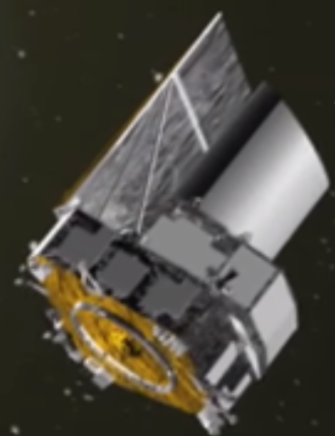


Euclid

esa

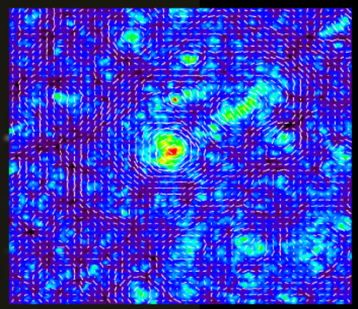
Mapping the Geometry of the Dark Universe
(DE, DM, Gravity, Inflation)

- Launch 2020
- Mission 6 years
- Orbit point L2
  1.5 M km from Earth

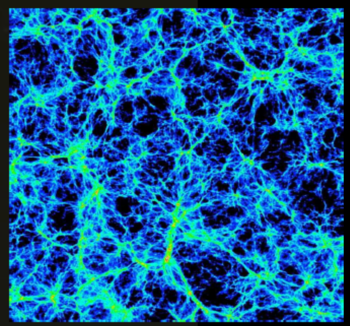


1.2 m Ø telescope
15,000 deg^2 survey

2 Probes



Weak Gravitational Lensing
Imaging



Large Scale Structure
Spectroscopy

INFN → HARDWARE

NISP Control Unit

NISP Data Processing Unit

Responsible of the NISP Warm Electronics Integration & Validation

INFN → SCIENCE

WG on Cross-Correlation between Euclid and CMB results

2 Instruments on board
VISual Imager - 36 CCDs

Near-Infrared Spectrometer & Photometer - 16 H2RG

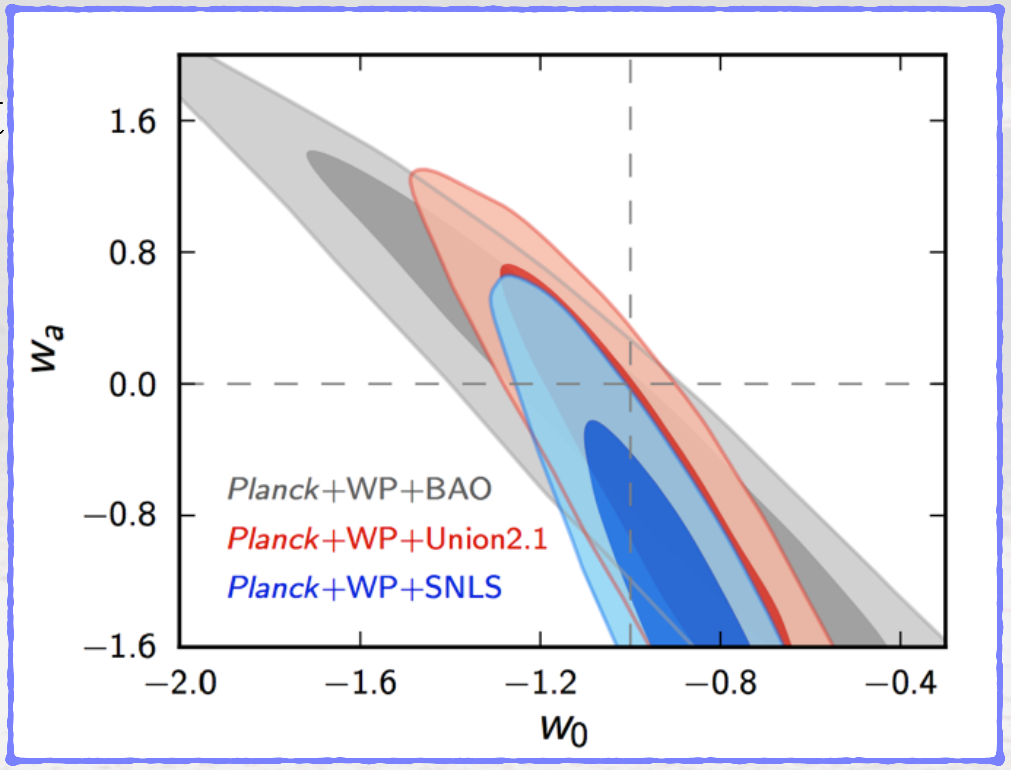
Euclid Consortium
15 Countries 1200 Members
ITALY : ASI INAF, Universities,
+ INFN (25 people/ 10 FTE)

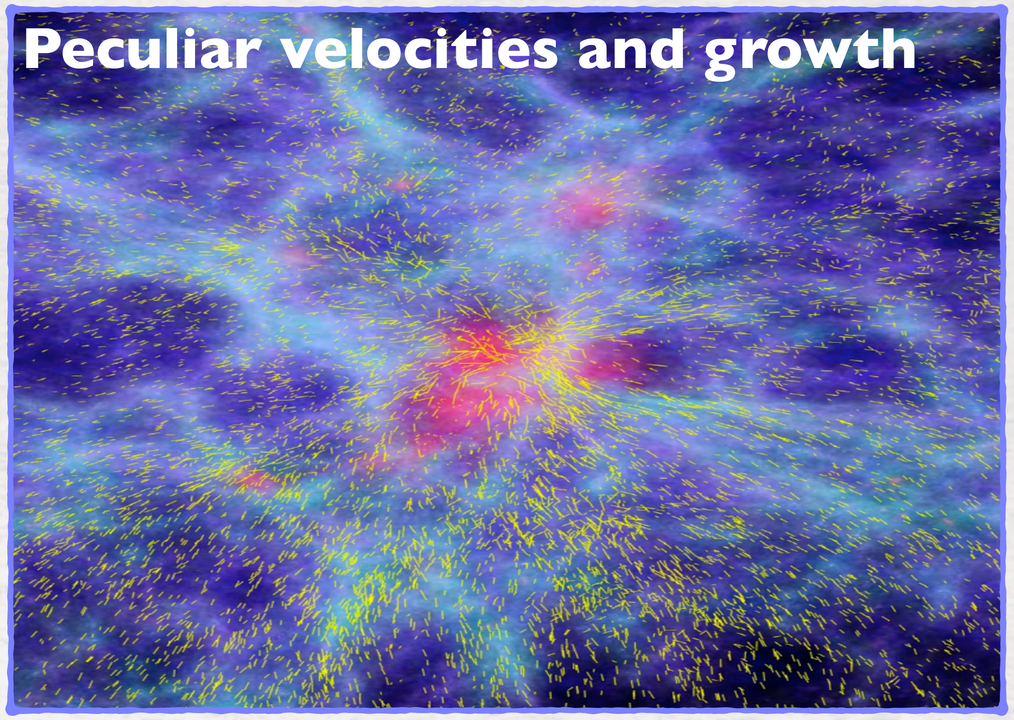
- **EUCLID:** mapping the universe with sufficient precision to disentangle different dark energy models (and much more)

  - High precision Barionic Acoustic Oscillations
  - High precision weak gravitational lensing
  - Measure the growth of structures
  - Launch: ~ 2021

  - Among the main fundamental scientific questions for the next decades

$$w(a) = w_0 + w_a (1 - a)$$





CONCLUSION (NOT REALLY… JUST THE BEGINNING)