Search for ALPs in the Apennines

ALBERTO RESSA - PHD SEMINARS

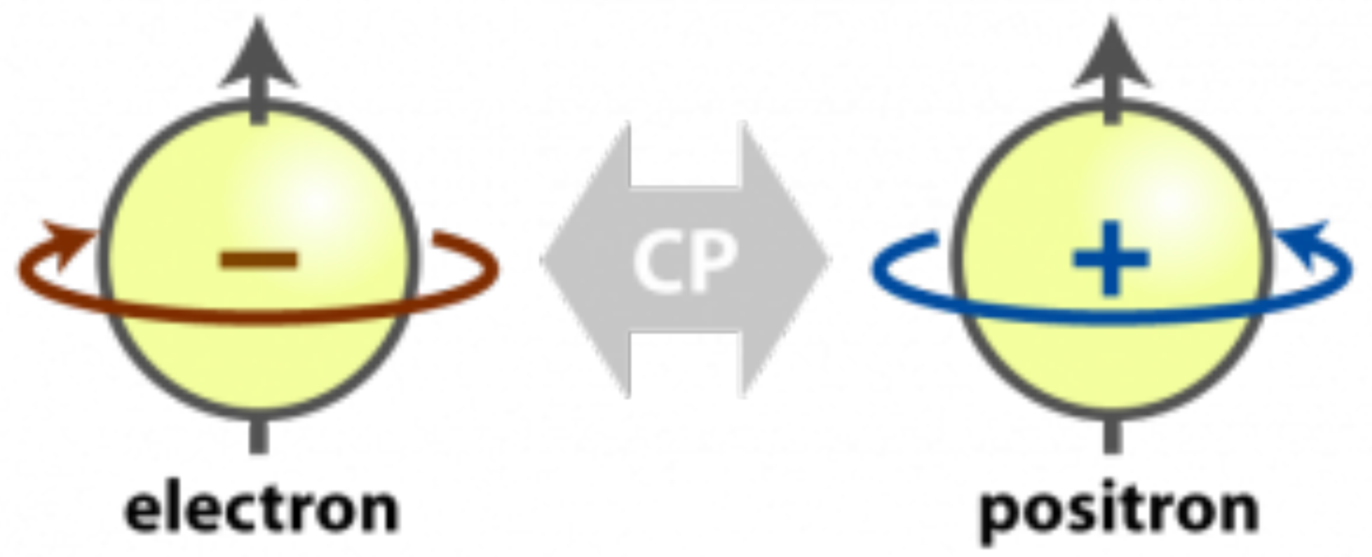
What is an ALP?

- Axion - Like Particles: so what is an axion?
- Proposed in 1977 by R. Peccei and H. Quinn
- Its name was an idea of Frank Wilczek, from a laundry detergent
- The particle is meant to “clean” the strong CP problem

What is an ALP?

- Axion - Like Particles: so what is an axion?
- Proposed in 1977 by R. Peccei and H. Quinn
- Its name was an idea of Frank Wilczek, from a laundry detergent
- The particle is meant to “clean” the strong CP problem
- But it turns out to be much more than that…

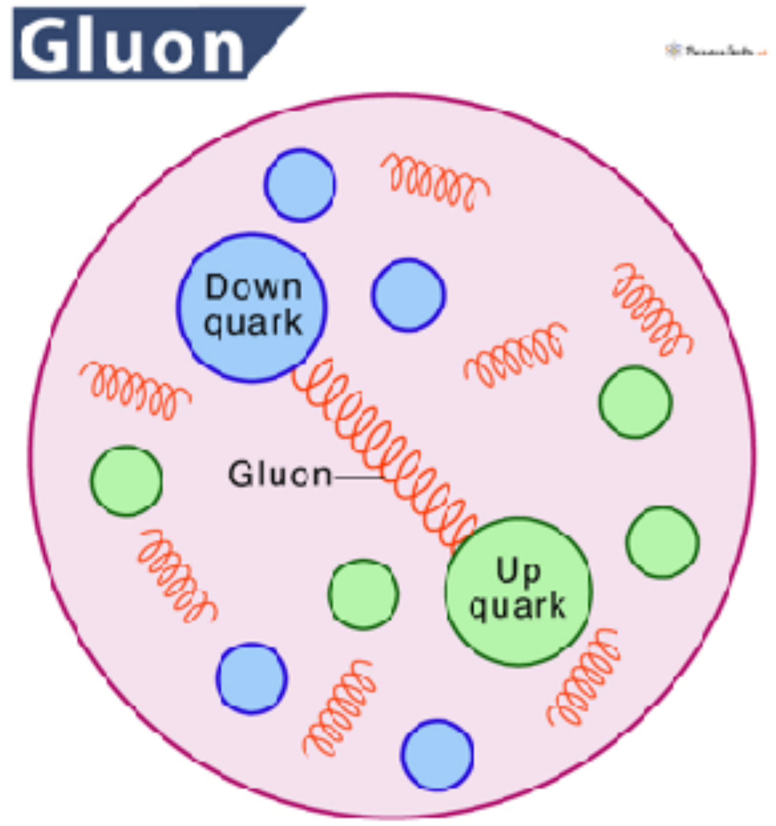
The Strong CP Problem



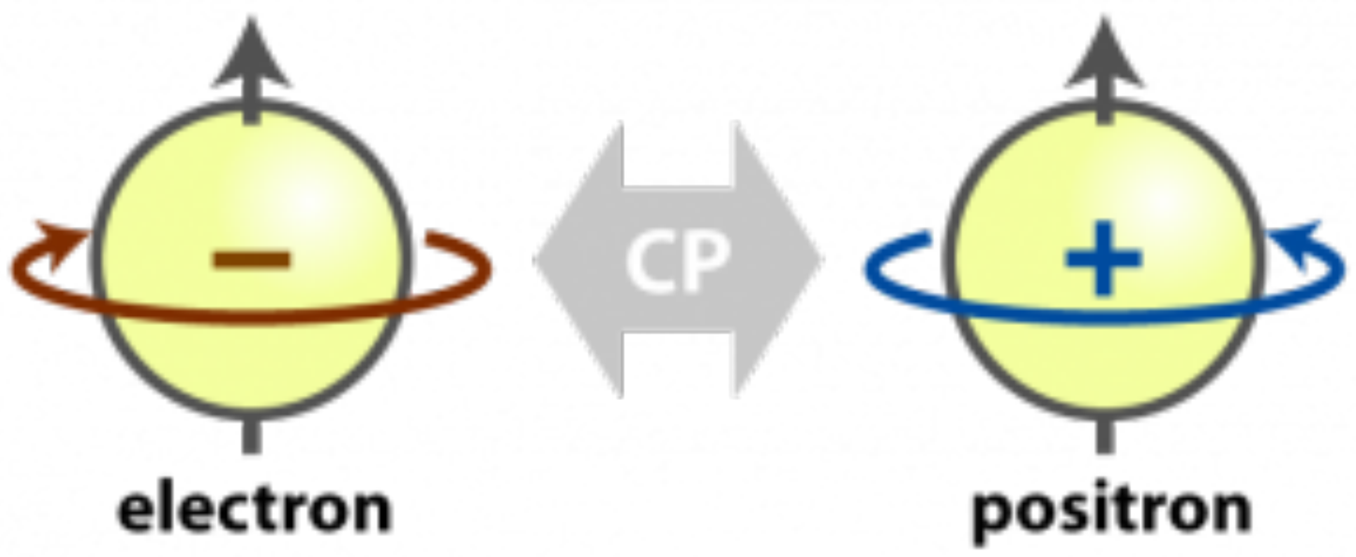
- **C**harge + **P**arity transformation turns a particle into its own antiparticle
- Standard Model predicts that it is violated by Strong Interactions

Coupling constant of strong interactions

$$\mathcal{L}_\theta = \theta \frac{\alpha_s}{8\pi} Tr(G\tilde{G})$$



The Strong CP Problem



- This implies the neutron to have an electric dipole moment (which is CP odd as well)

$$|d_n| \approx |\theta| \; (0.04 - 2.0) \times 10^{-15} e\ cm$$

- But… experiments set extremely low upper limits on it, suggesting it to be 0. Therefore, 2 solutions:

ARTIFICIALLY SET θ = 0

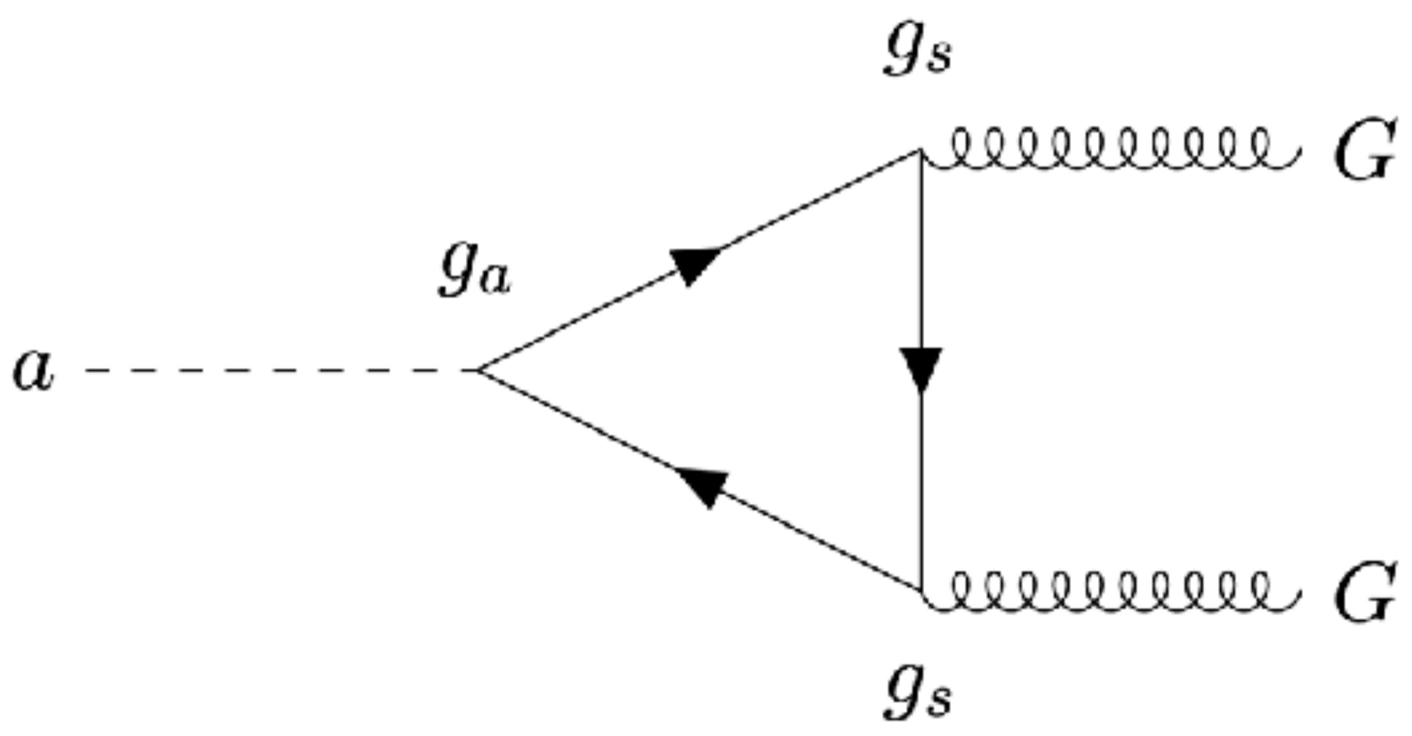
NATURALLY LET θ = 0 BY MEANS OF A NEW PARTICLE, THE AXION

Axions

It absorbs the CP violating term, letting the neutron electric dipole moment to be 0

$$\mathcal{L}_\theta = \theta \frac{\alpha_s}{8\pi} Tr(G\tilde{G}) \quad \Rightarrow \quad \mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{\alpha_s}{8\pi f_a} aG\tilde{G}$$

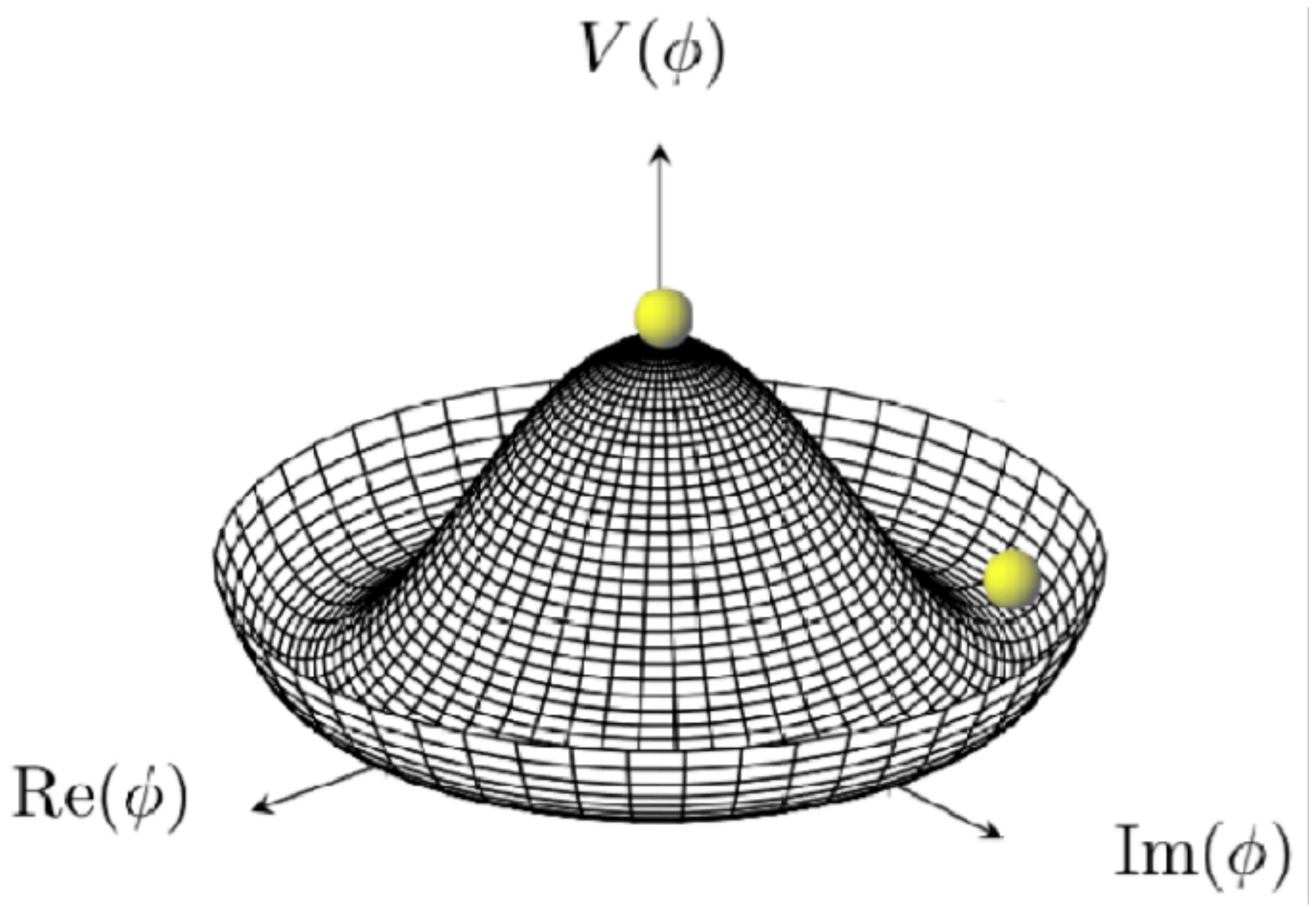
- Recipe:
  - Coupling with gluons
  - Symmetric by a constant
  - Pseudoscalar Boson



+ $a \rightarrow a + a_0$ + $\not{CP}$

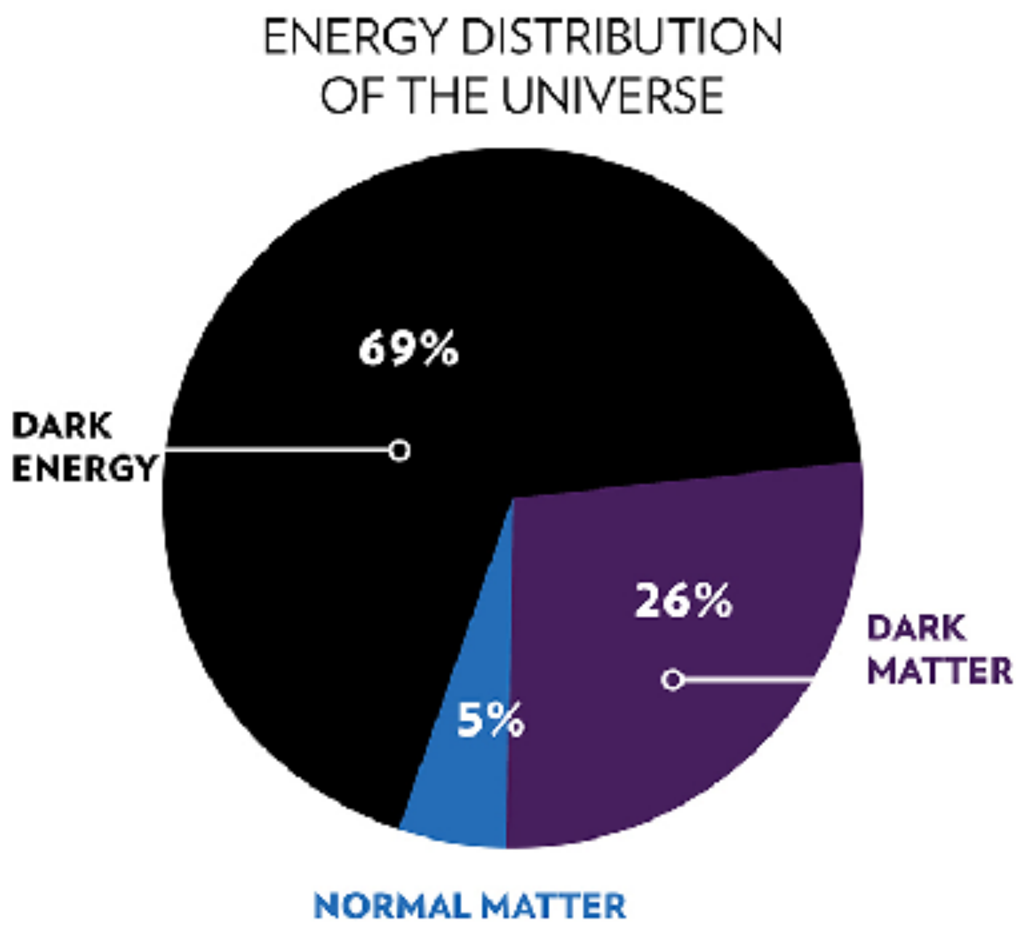
Axions

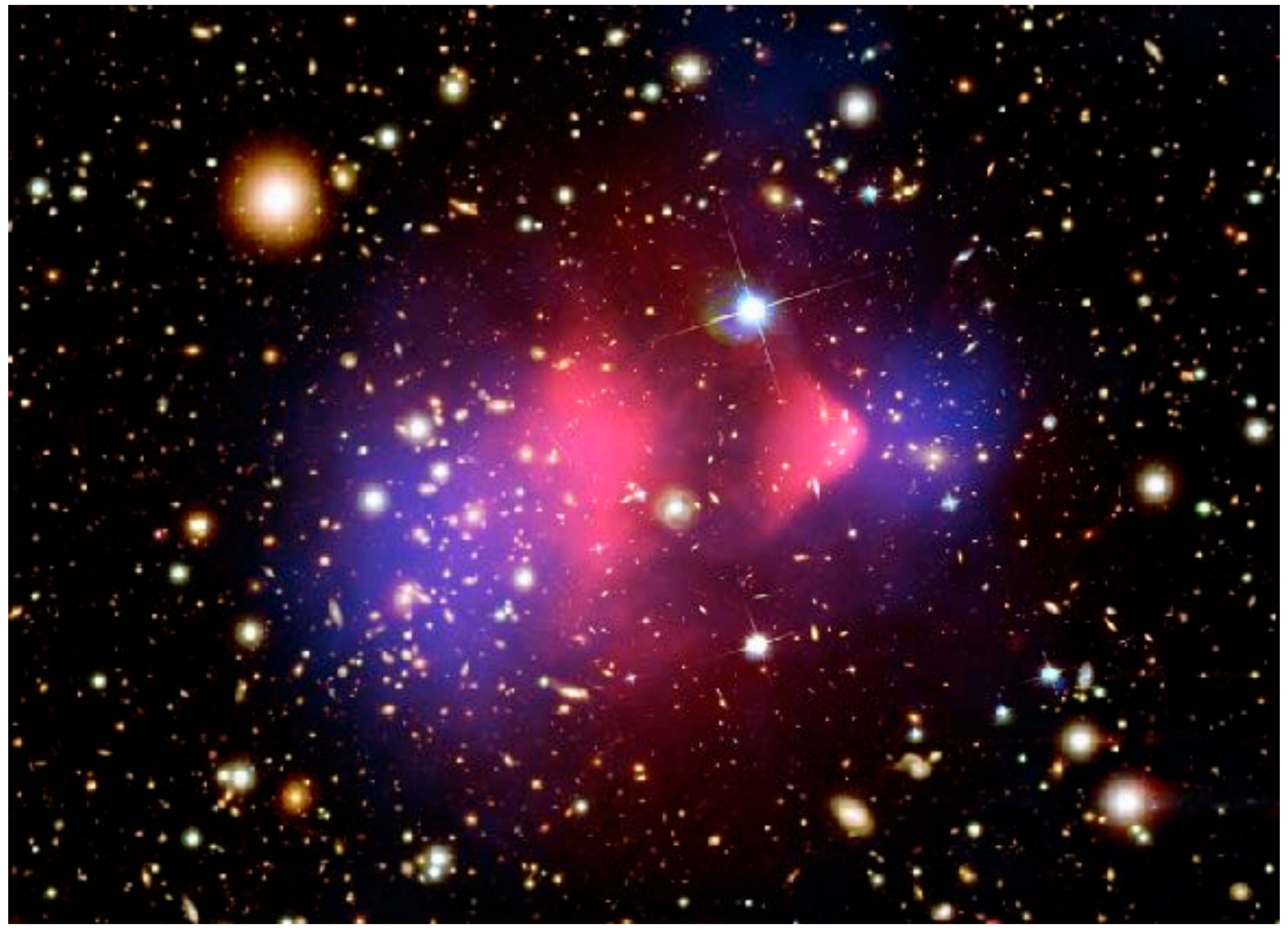
- Such a particle can be achieved by Spontaneous symmetry breaking (an old friend of Standard Model)
  - Take a scalar field with Mexican Hat (or bottle bottom?) potential
  - Let the vacuum state to break the symmetry spontaneously below a given energy
  - The resulting angular “excitations” (or degrees of freedom) are the Nambu-Goldstone bosons

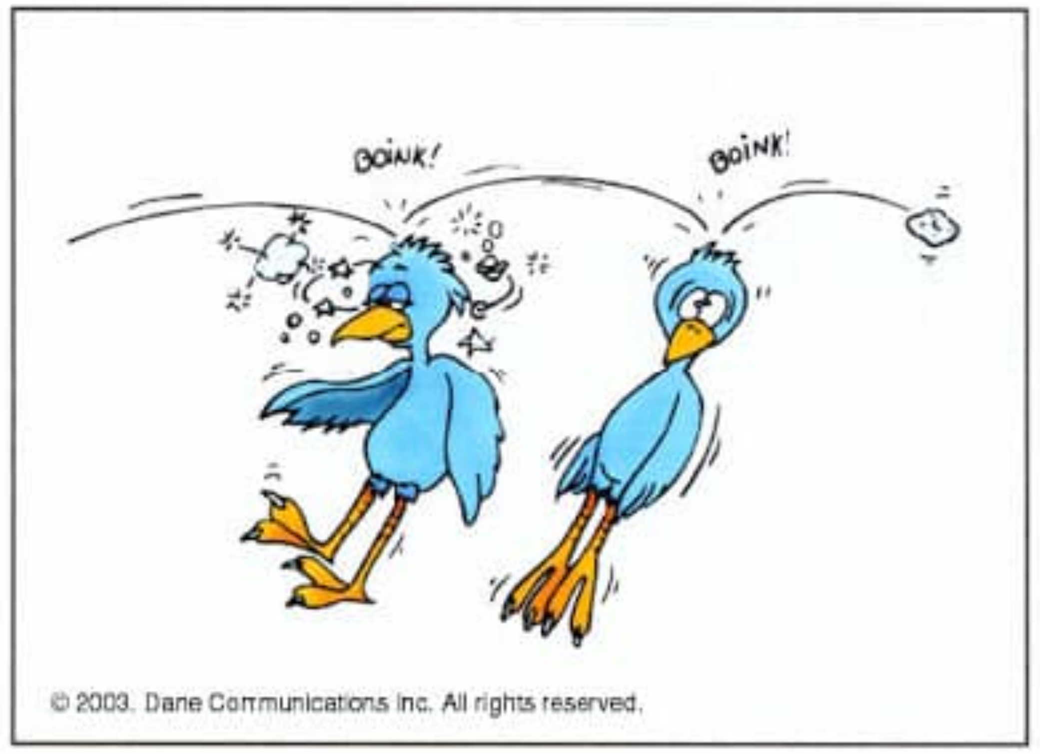


Axions as Dark Matter?!

- Yes, they can also solve another particle physics puzzle!
- We have several astrophysical and cosmological proves for dark matter existence, but we only know few things about it:
  - Interact gravitationally on macroscale (galaxies, galaxies clusters ...)
  - Very weakly interacting with ordinary particles (if it does...)
  - Distributed as a halo in the galaxies





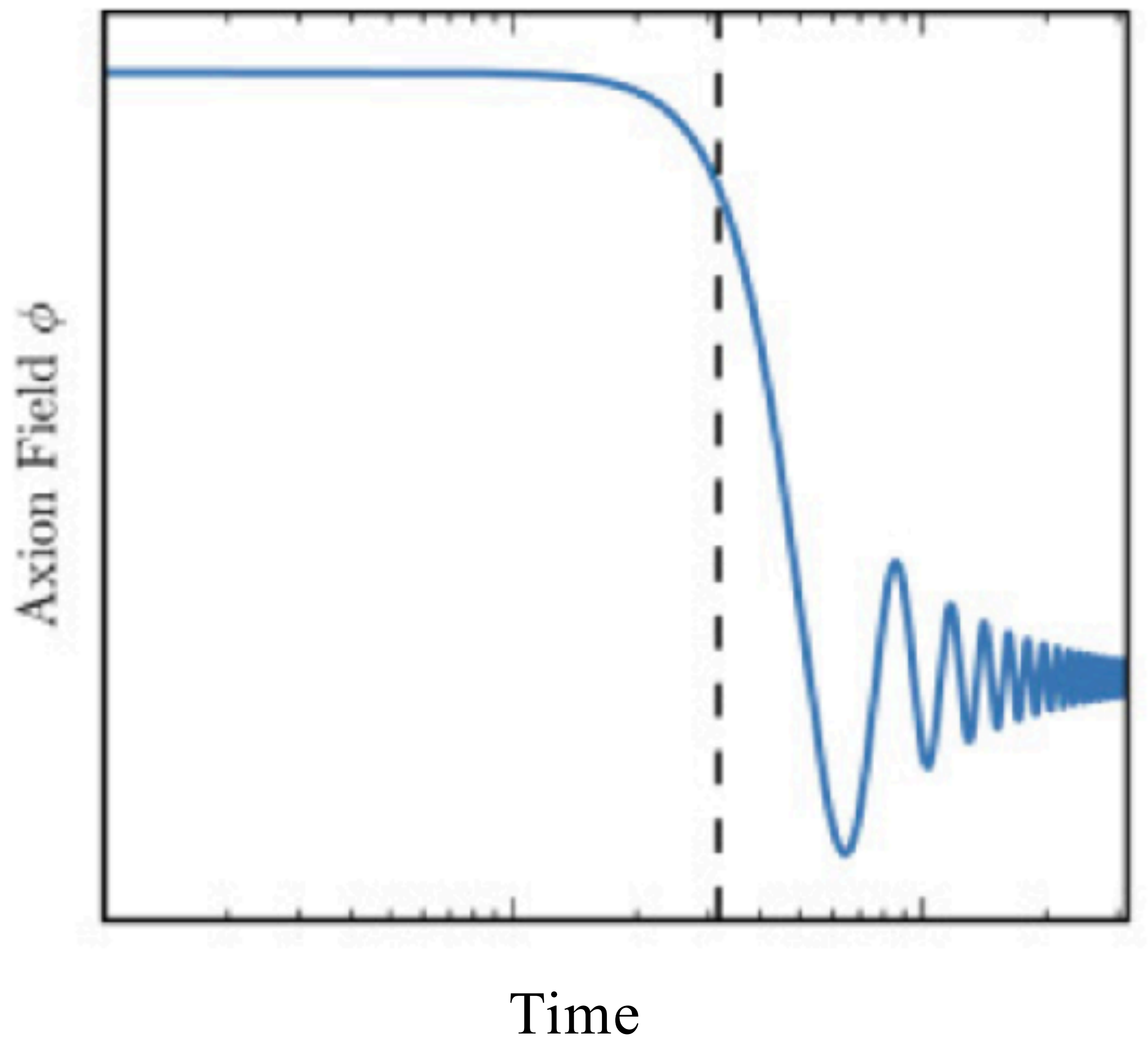


Axions as Dark Matter?!

- To explain the large scale structure (i.e. galaxies, galaxies clusters…) we observe today, we need matter that do not interact with radiation

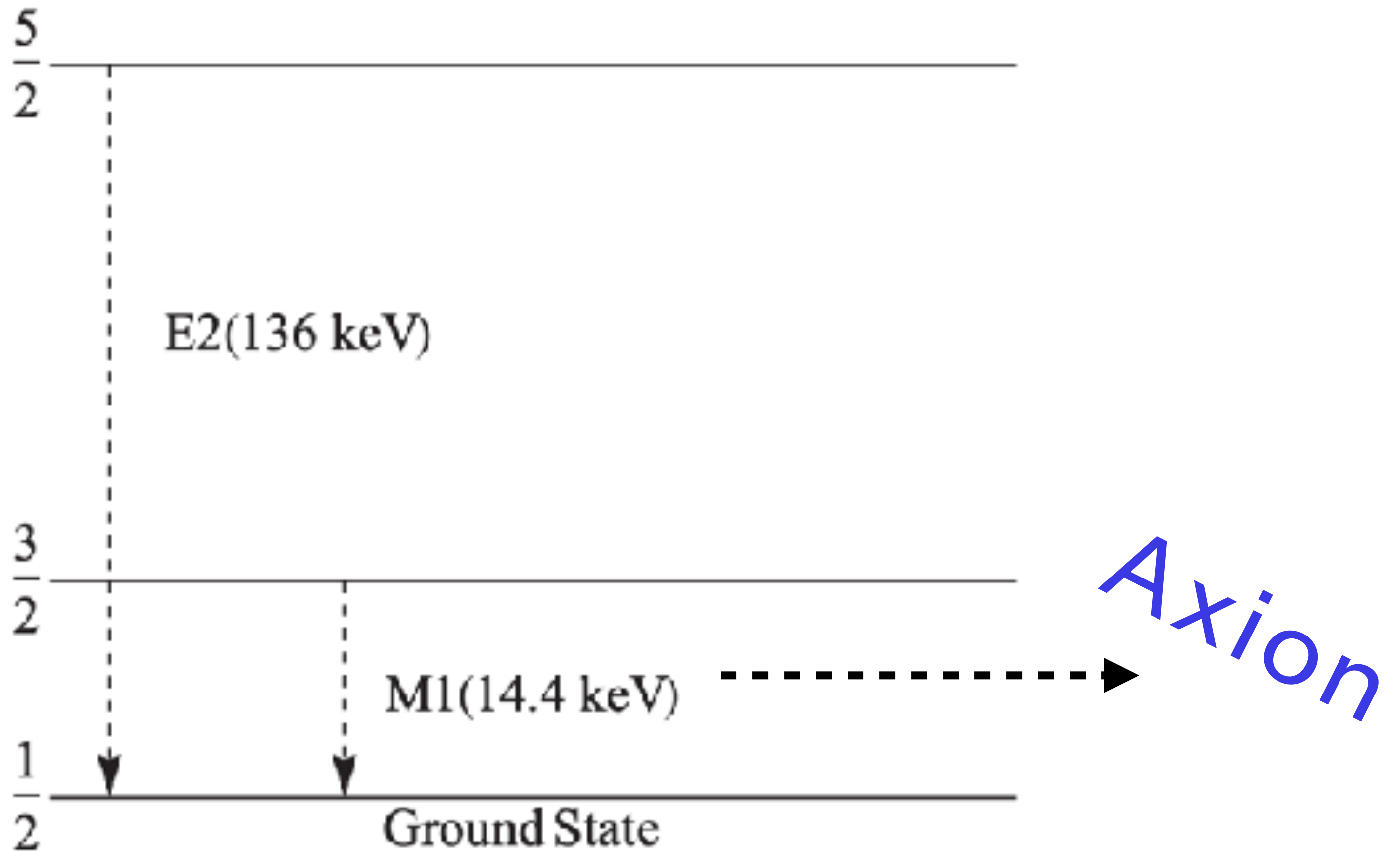
- Being bosons, early universe axions act coherently like a macroscopic wave
- They account for macroscopic gravitational effect even if their mass can be extremely low (from keV down to μeV or neV)
- The oscillation are ruled by Universe expansion (Hubble constant) and axion mass
- The resulting energy density contributing to the structure formation is the same as of the ordinary matter

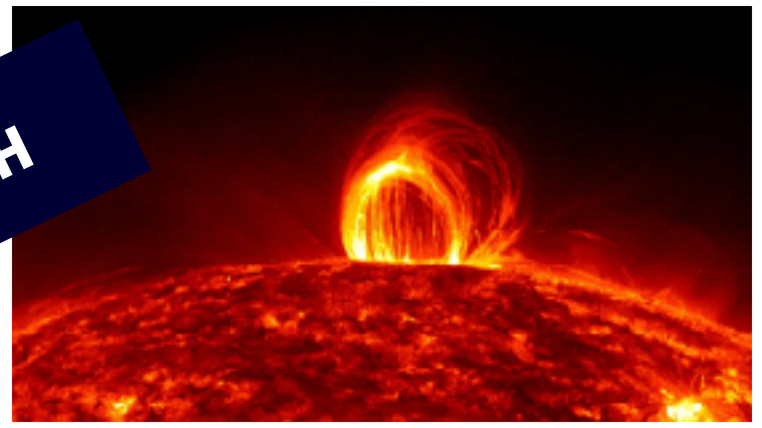
$$\frac{d^2\phi}{dt^2} + 3H(t)\frac{d\phi}{dt} + m_a^2\phi = 0$$

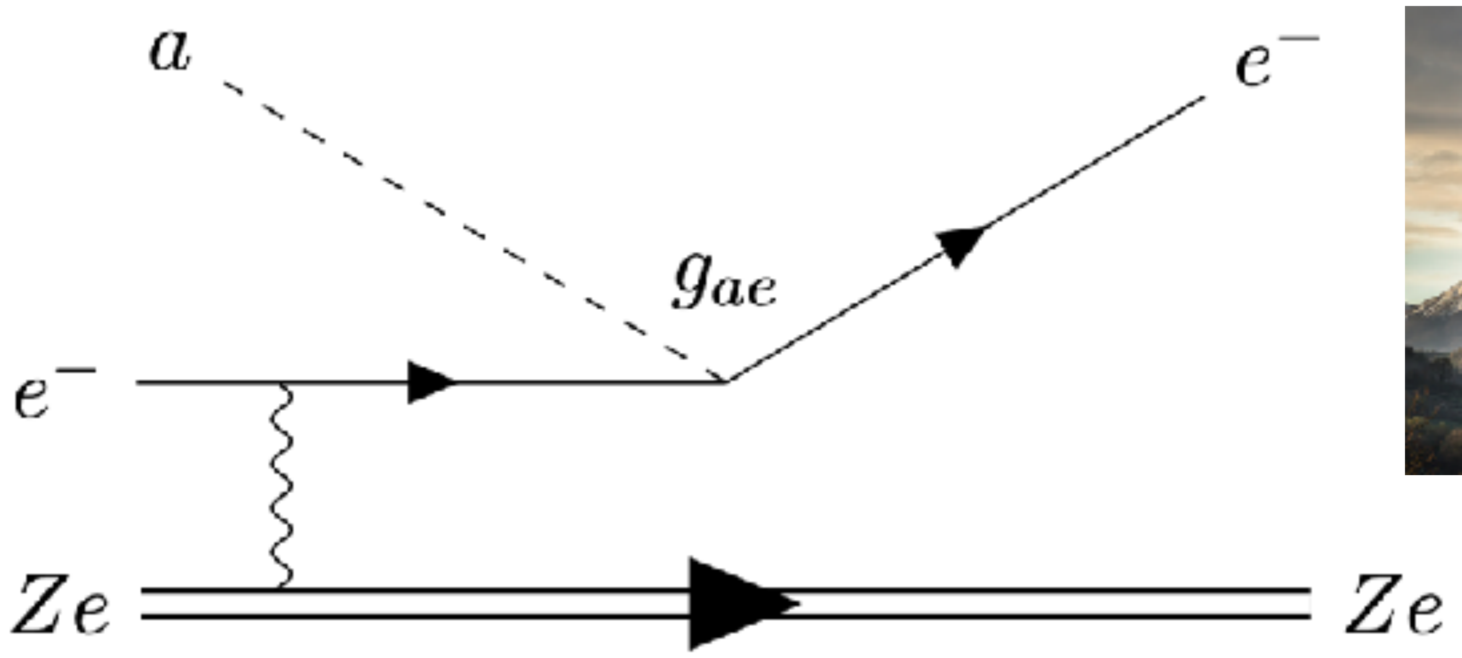


Solar Axions

- Axions are predicted to feebly interact with ordinary matter
- Emitted as a competing branch from deexcitation of 57Fe in the core of the Sun
- The temperature (about 3 keV) let the first level to be enough thermally populated







- Axions hit the detector absorbing material and converts to electrons by axis-electric effect
- It works as the photo electric one but with axions

Why in the Apennines?

What do we need to search for feebly interacting particles or rare events?

LOW BACKGROUND

LARGE EXPOSURE (MASS X TIME)

GOOD ENERGY RESOLUTION

Experiments at Laboratori Nazionali del Gran Sasso largely satisfy these requirements

Why in the Apennines?

LOW BACKGROUND

LARGE EXPOSURE (MASS X TIME)

GOOD ENERGY RESOLUTION

- Laboratori Nazionali del Gran Sasso are located under 3600 meters of water equivalent (i.e. if the mountain density were water)

- Natural shielding against cosmic rays:
  - $\sim$ 1 muon / (cm^2 min) $\rightarrow$ 3×10^{-8} muons / (cm^2 s)
  - $< 4 \times 10^{-6}$ neutrons / (cm^2 s)
  - < 1 gamma / (cm^2 s)

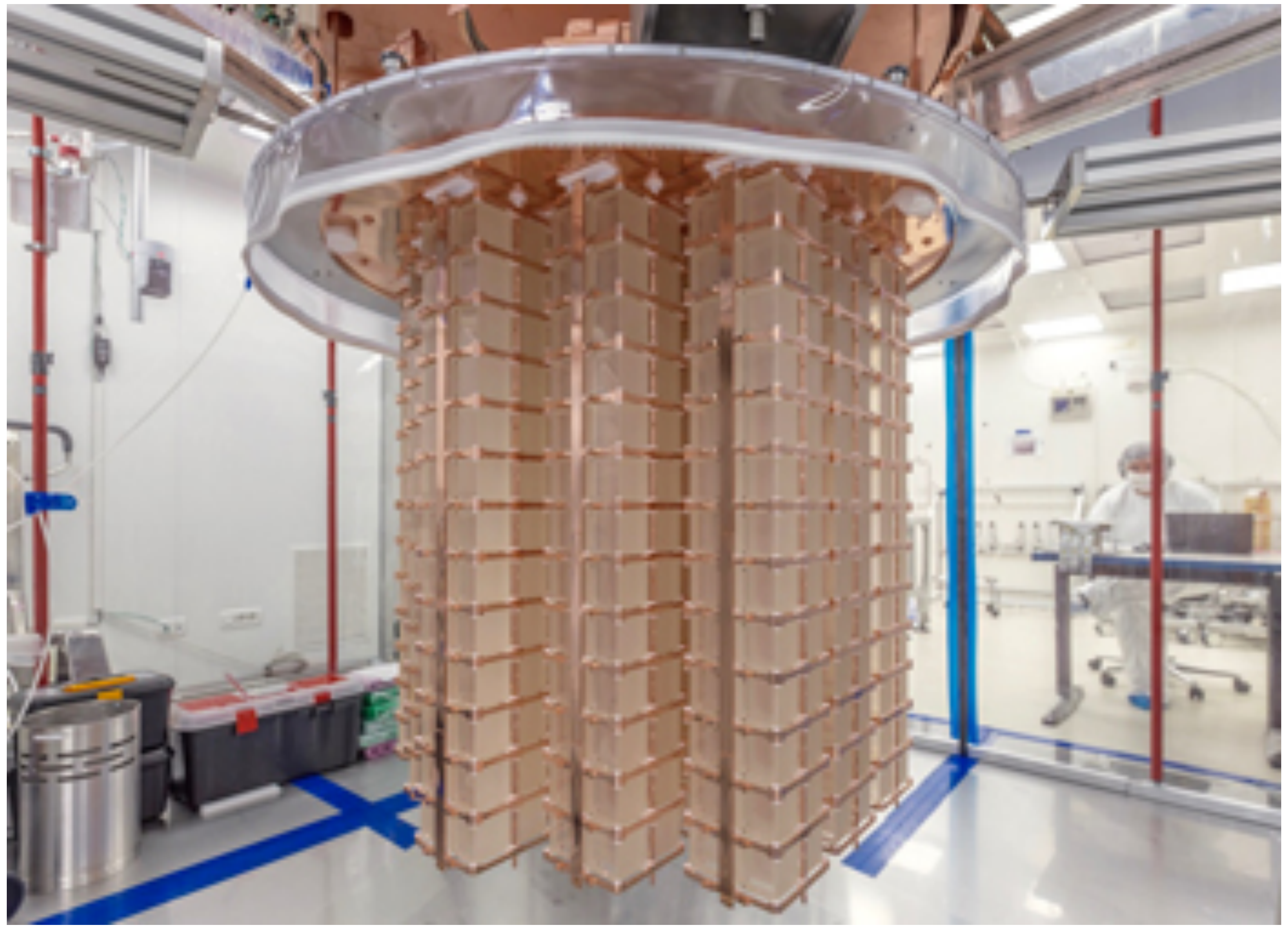
CUORE Experiment

Cryogenic Underground Observatory for Rare Events

LOW BACKGROUND

LARGE EXPOSURE (MASS X TIME)

GOOD ENERGY RESOLUTION



- Array of 988 detectors/absorbing material (TeO_2 crystals)
- About 1 ton of material kept at 10 mK by a world leading cryostat
- Stable for a 5 years operation... so far!
- Collected more than 2 ton x years of exposure
- First large scale experiment using cryogenic calorimeters

CUORE Experiment

LOW BACKGROUND

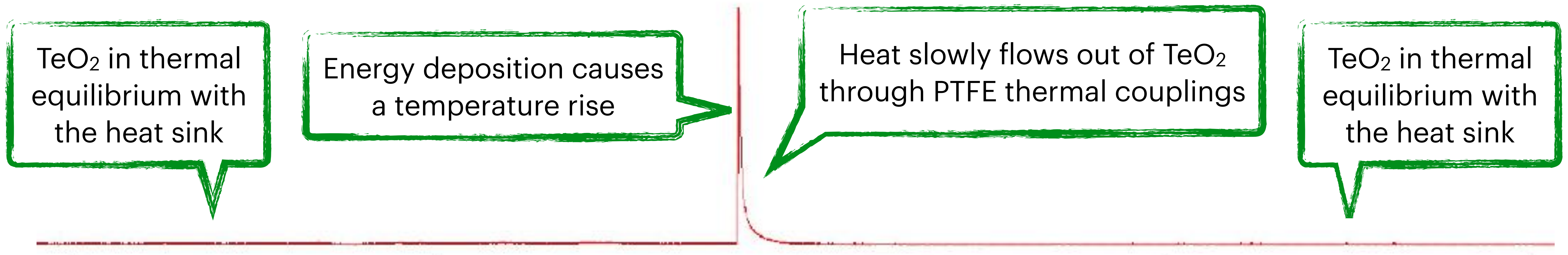
LARGE EXPOSURE (MASS X TIME)

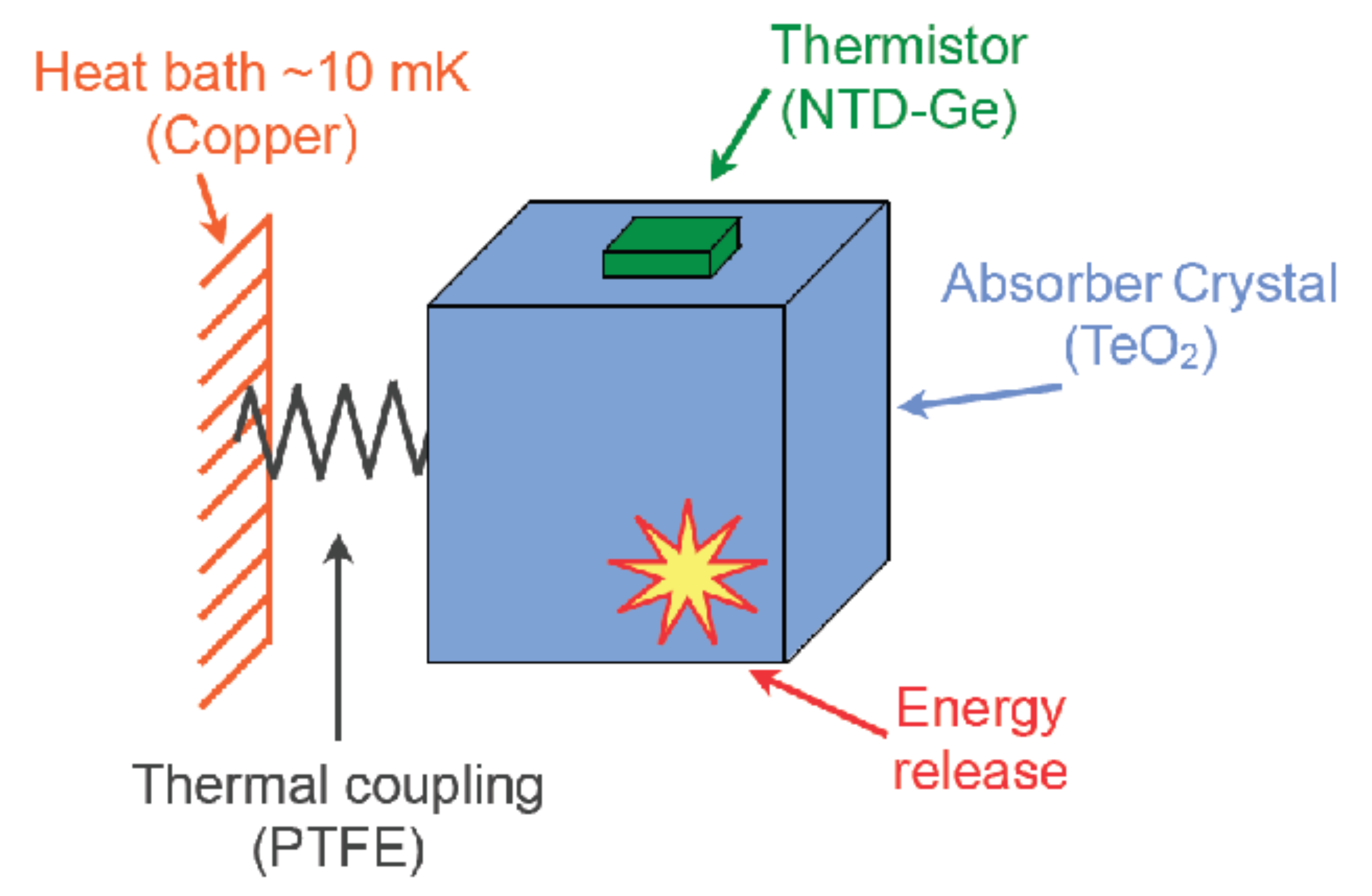
GOOD ENERGY RESOLUTION

Cryogenic Underground Observatory for Rare Events

1. A particle interacts releasing energy in a crystal
2. Energy converted into phonons, heating the crystal
3. Temperature increase converted into electrical signal

Example of CUORE data stream





The energy price to create a phonon is very small ($\sim\mu$eV to meV), allowing for an excellent energy resolution

CUORE Experiment

- Additional shieldings
  - Ancient Roman Lead against external radioactivity
  - Recovered from a roman ship off the coasts of Sardinia
  - The centuries spent under the water let all the 210Pb to decay, without re-activation due to cosmic rays
  - This make the lead intrinsically radio pure

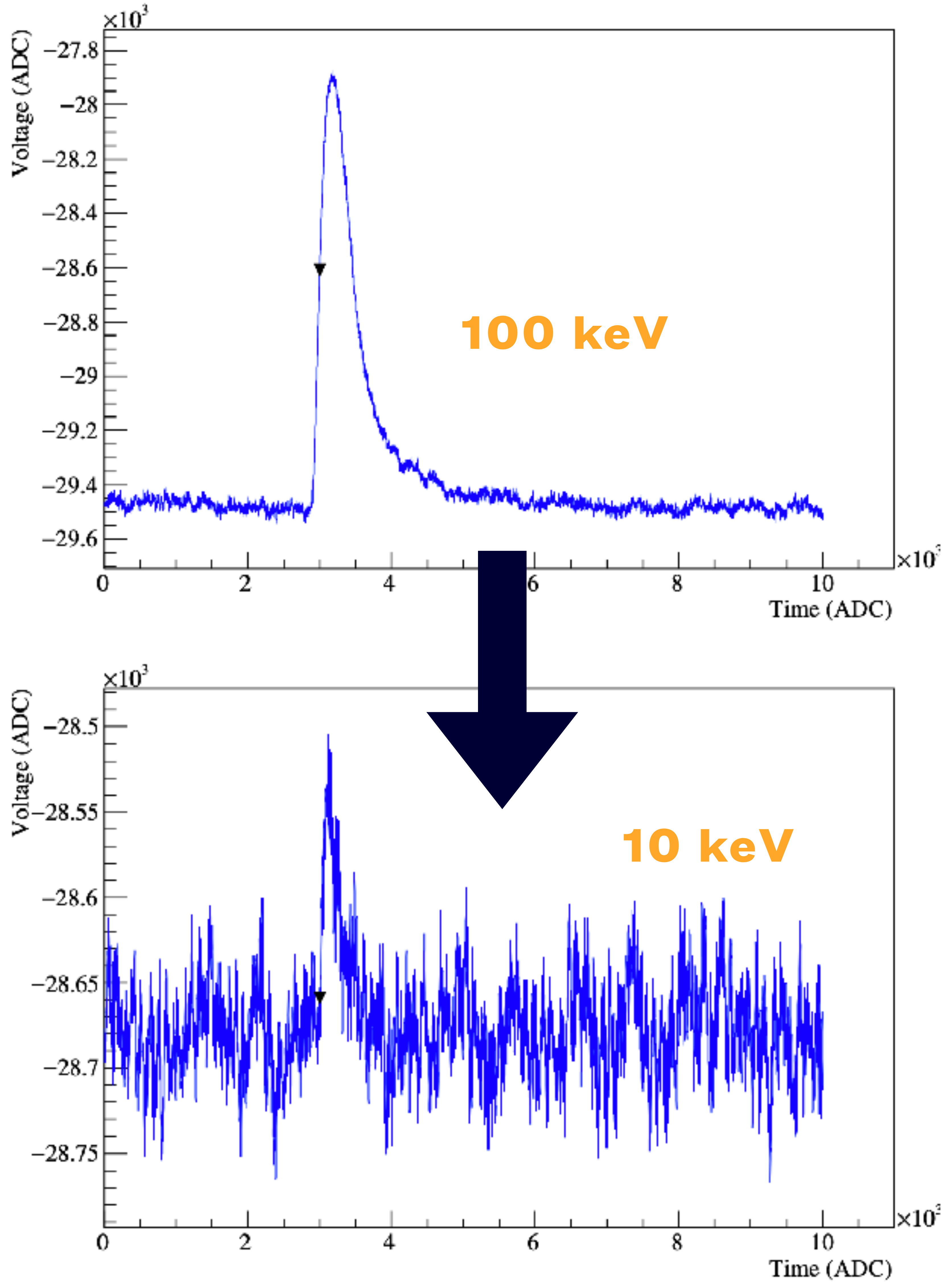
LOW BACKGROUND

LARGE EXPOSURE (MASS X TIME)

GOOD ENERGY RESOLUTION

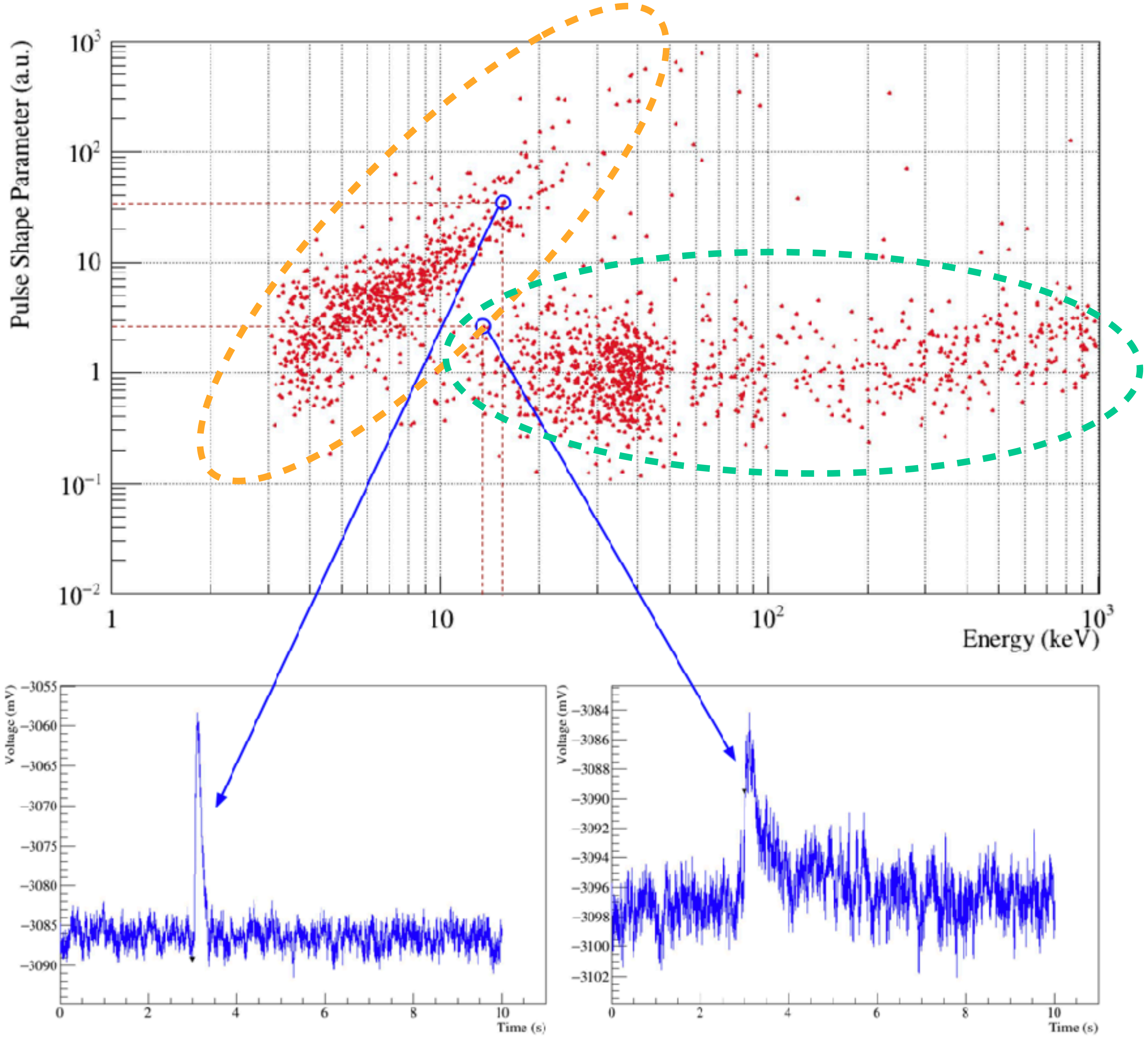
Low Energy CUORE

- Detection of thermal phonons has a wide energy range of operation (keV to MeV)
- Axions events are expected at 14.4 keV, which is near the detector threshold (few keV), i.e. where noise gets more relevant than signal
- CUORE main purpose is to search for Majorana neutrino at few MeV
- But we want to fully exploit the data taking!
- Nevertheless it is hard to optimize such a large array so close to the detector threshold (**from great exposure comes great responsibility…**)



Low Energy CUORE

- The temperature rise can be due not only to particle interactions, but to a variety of other non-physical phenomena (especially vibrations)
- CUORE is sensitive to far earthquakes as well! (And we have to reject data because of that)
- Down to what energy are we able to identify particles from vibrations?
- We look at the pulses shape, and perform a strict data selection
- Only about 30% of the CUORE detectors can get down to 10 keV



Conclusions

- Axions are very cool
- Cryogenic calorimeters too
- Balancing good performance and large exposure is like "have your cake and eat it too" (or "a full barrel and a drunk wife")
- Can we still use CUORE for dark matter as well? ...Stay tuned

Thanks for your attention!