Search for ALPs in the Apennines

ALBERTO RESSA - YOUNG@INFN 2024

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

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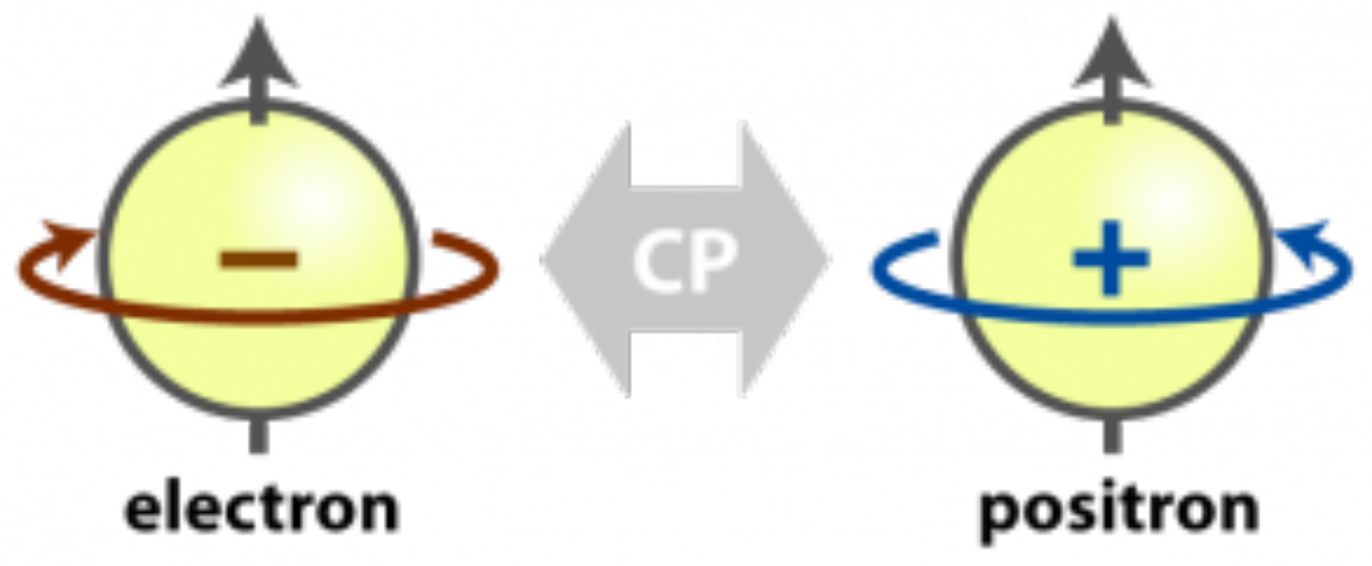
- The particle is meant to “clean” the strong CP problem
- But it turns out to be much more than that…

The Strong CP Problem



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

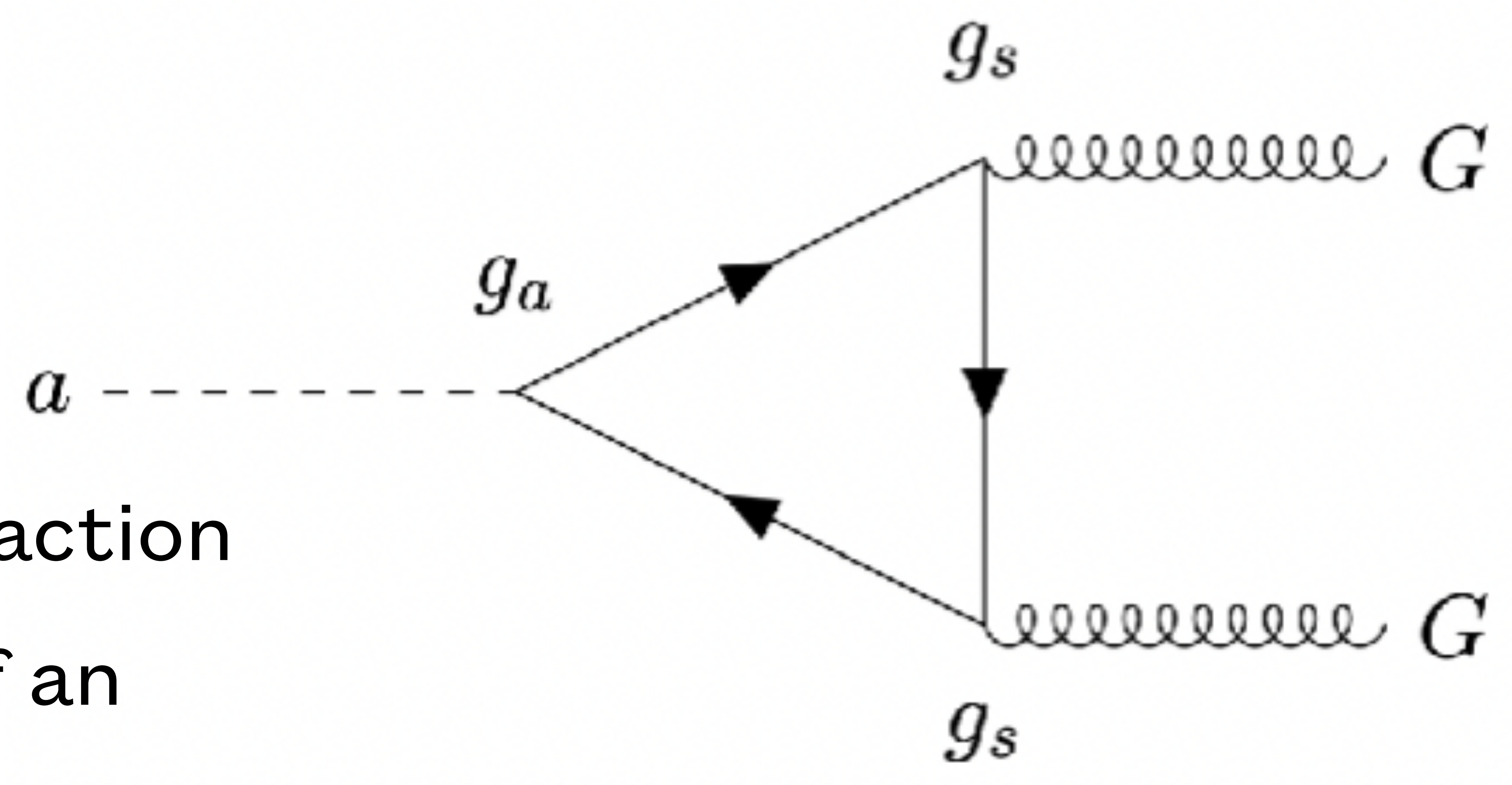
$$|d_n| \approx |\theta| \; (0.04 - 2.0) \times 10^{-15} e \; cm$$

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

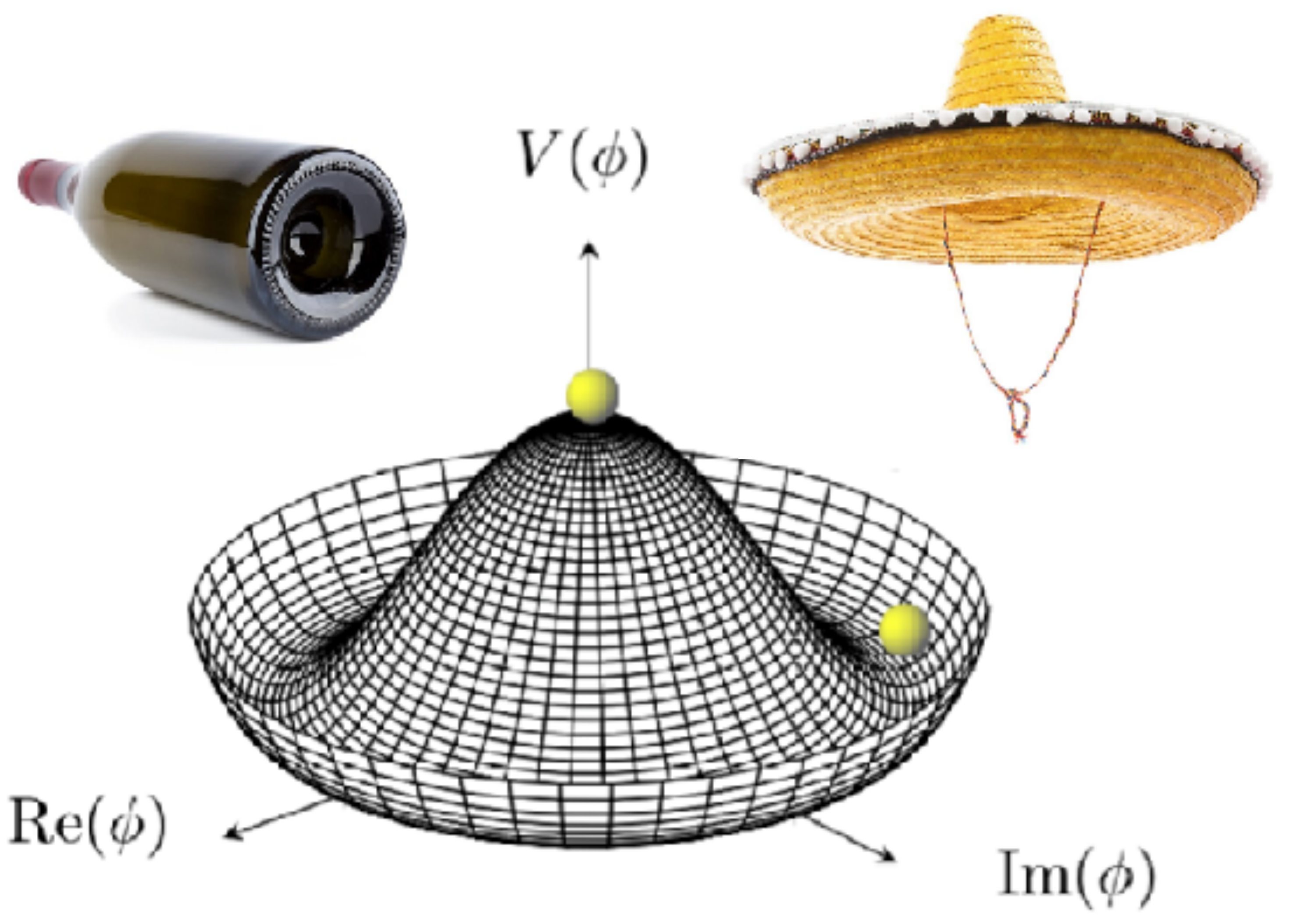
ARTIFICIALLY SET θ = 0

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

Axions



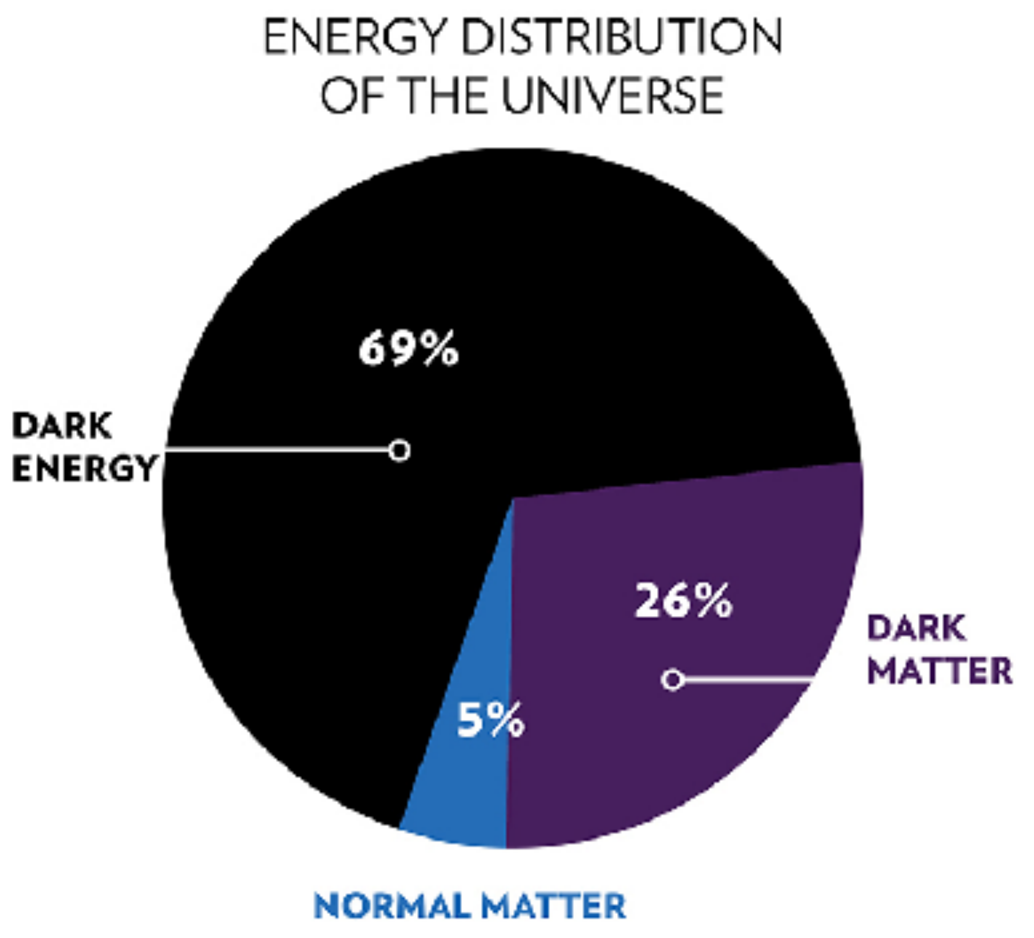
- Pseudoscalar bosons coupling to gluons
- They “absorb” the CP violating term in strong interaction
- They arise from spontaneous symmetry breaking of an exotic scalar field

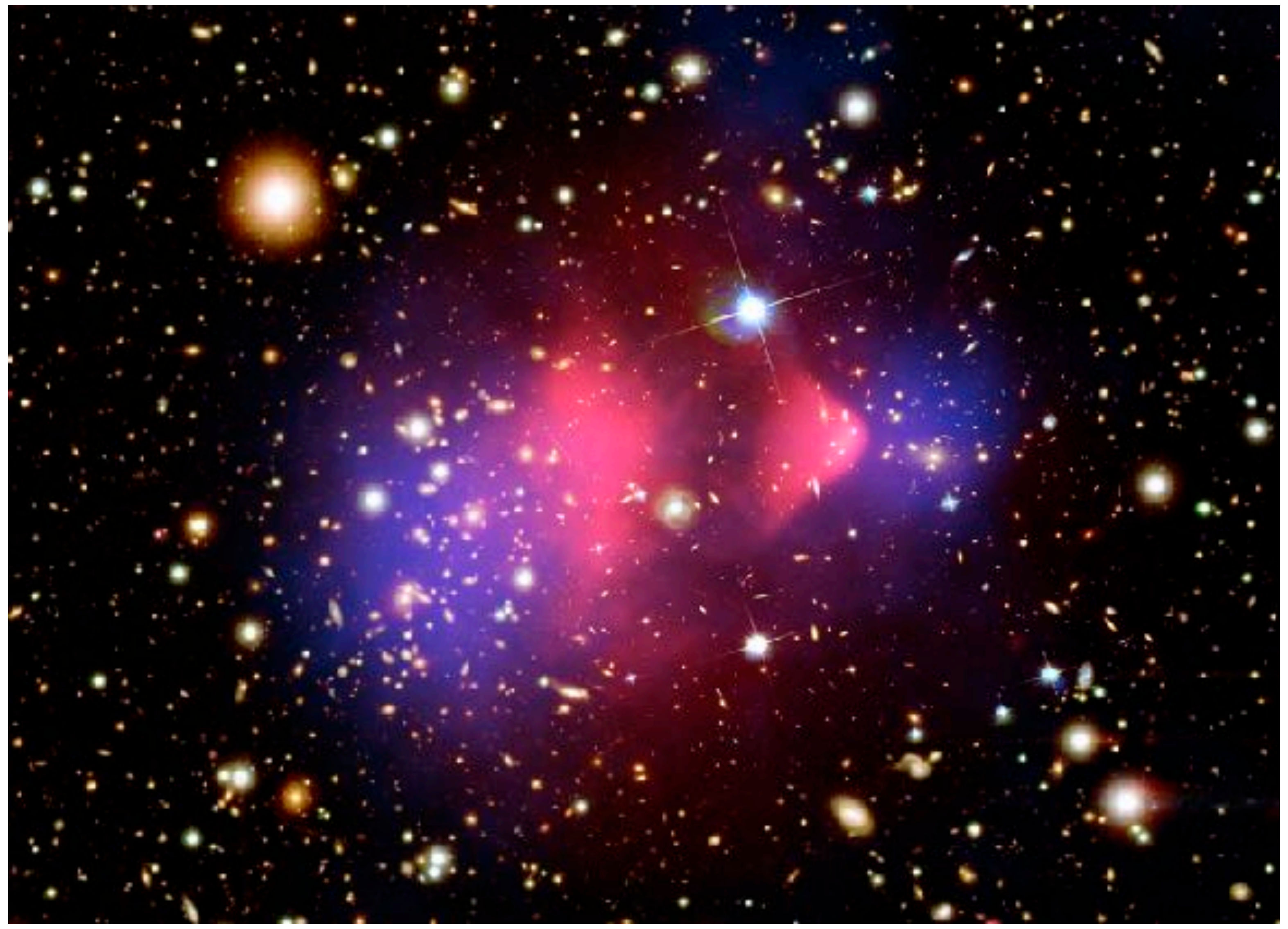


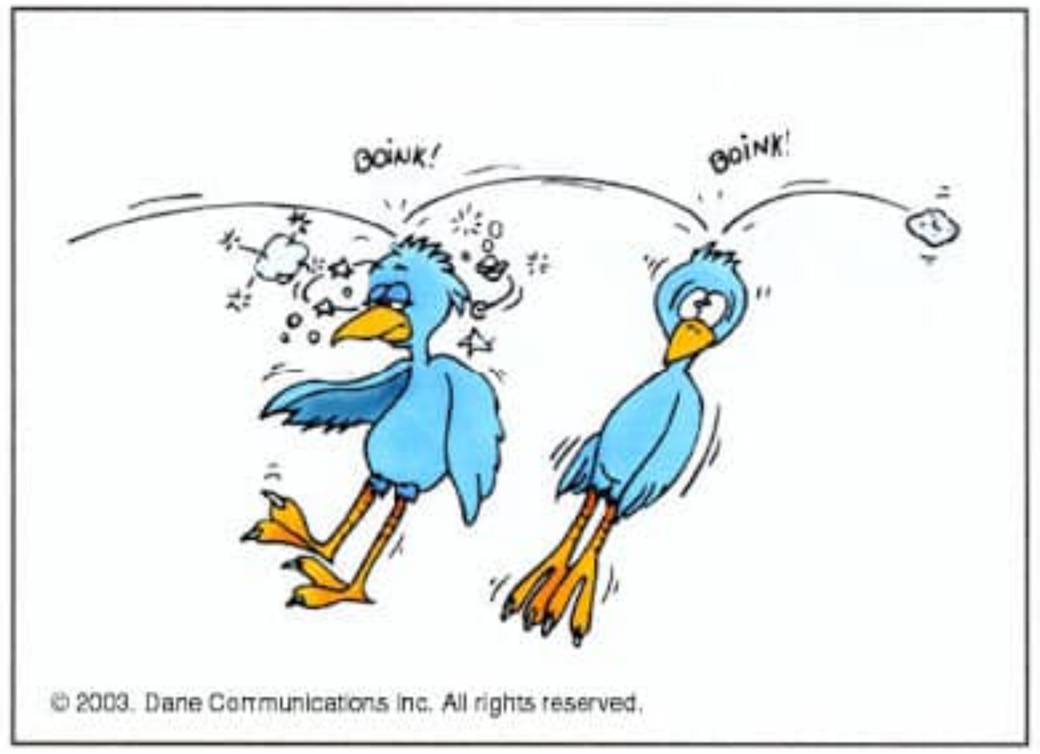
- Being bosons, they act coherently as a macroscopic wave in the early universe
  - Contribute to gravity
  - Do not (or only feebly) interact with radiation

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



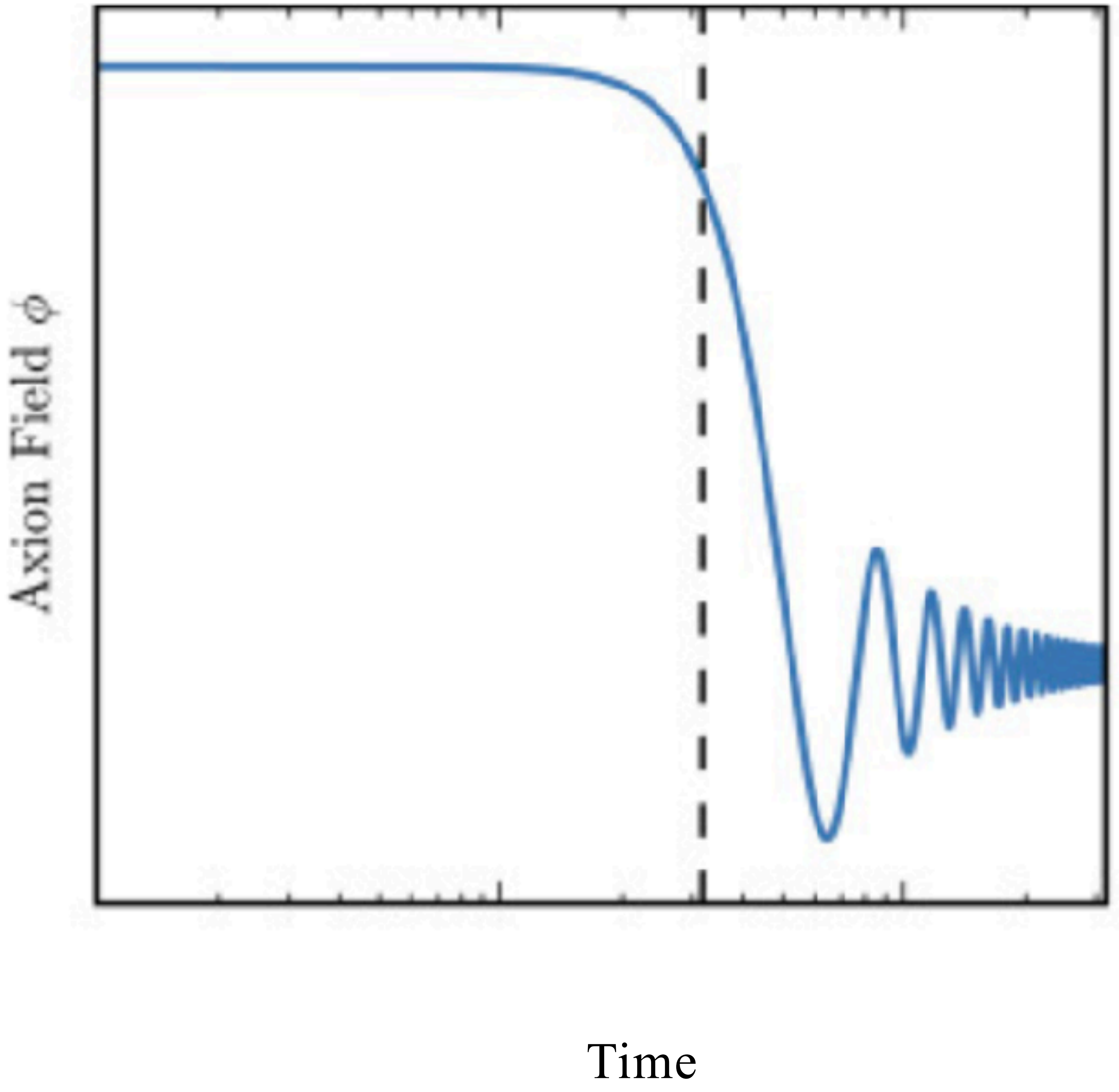




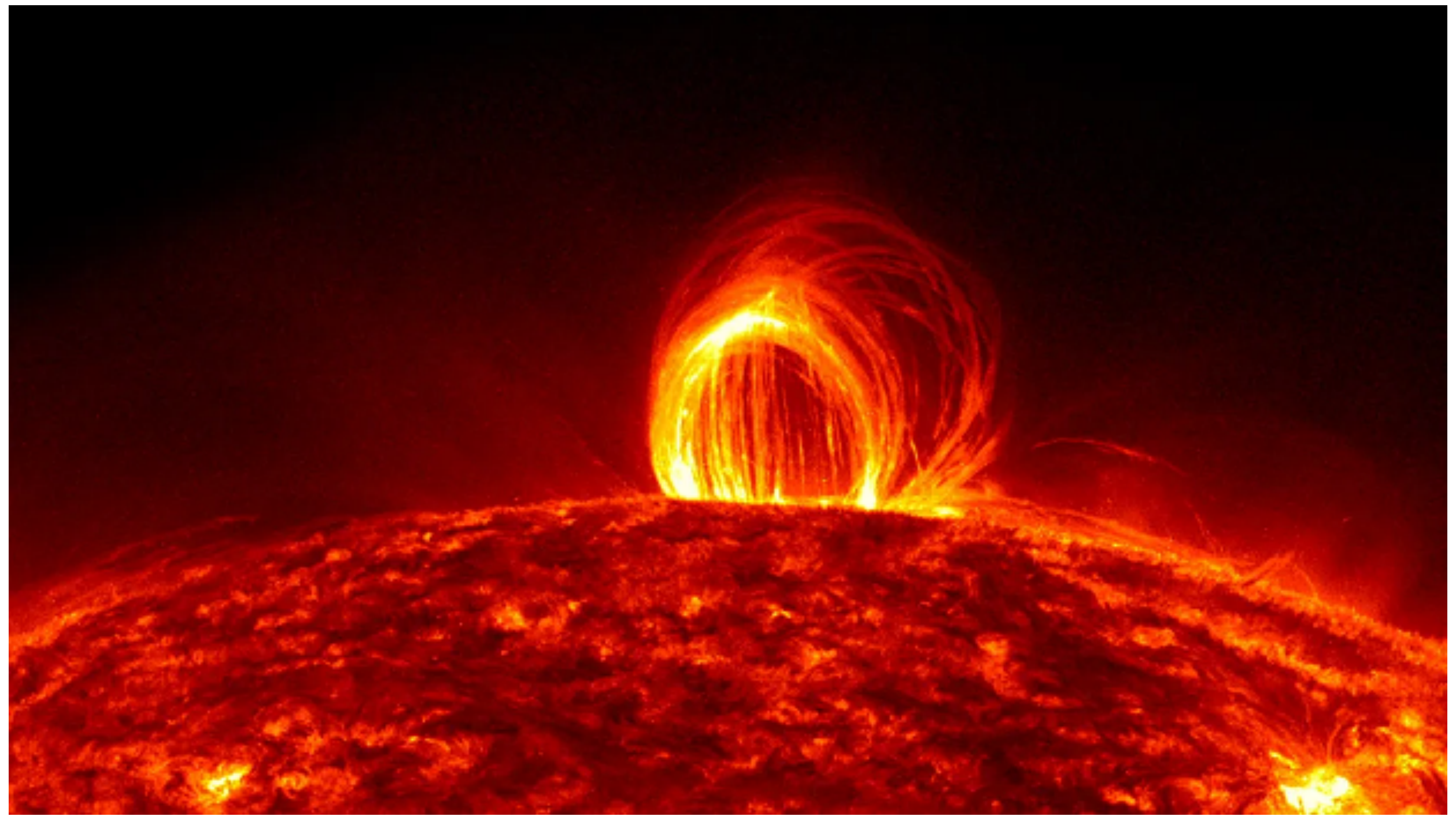
Axions as Dark Matter?!

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

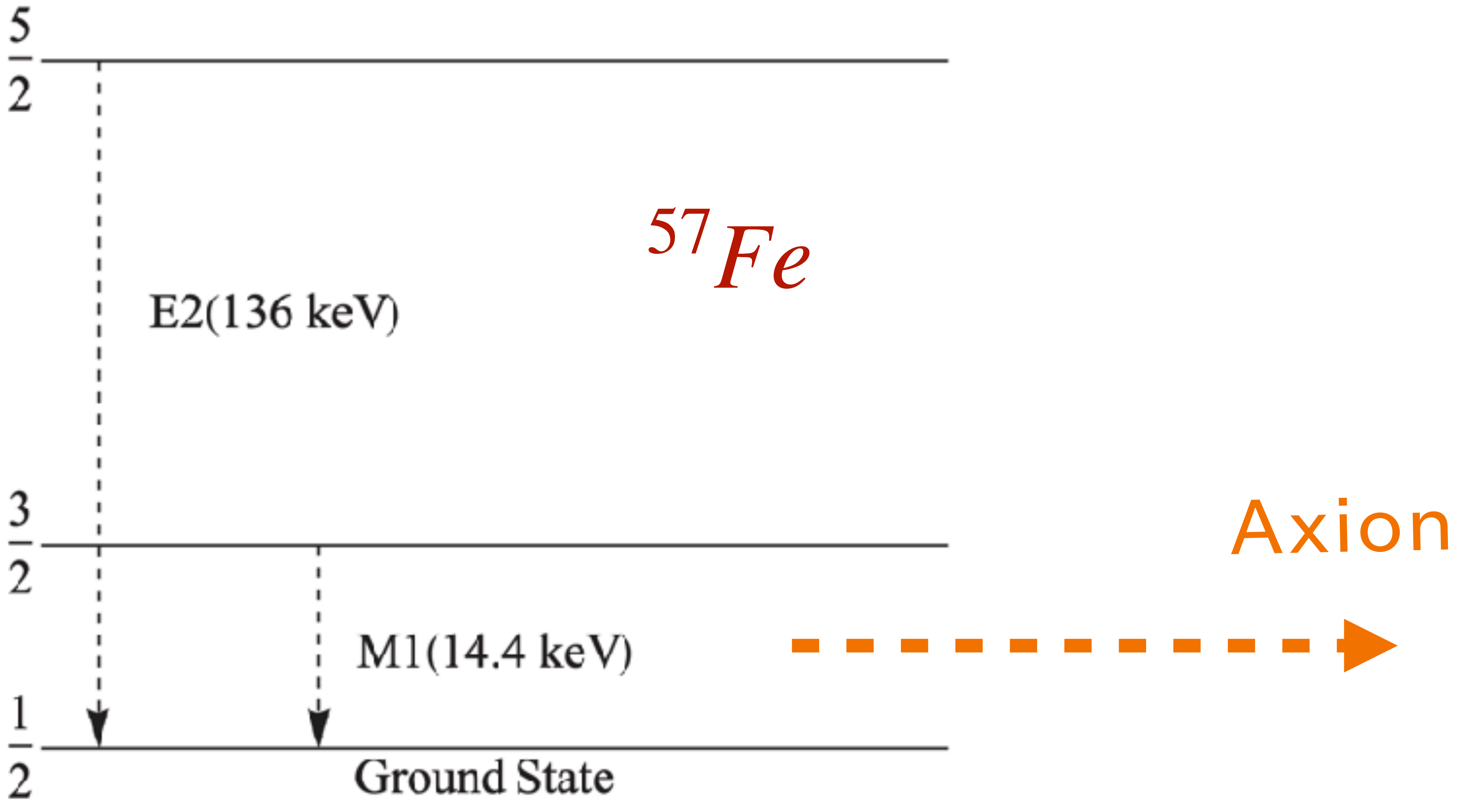
$$\frac{d^2\phi}{dt^2} + 3H(t)\frac{d\phi}{dt} + m_a^2\phi = 0$$



Solar Axions

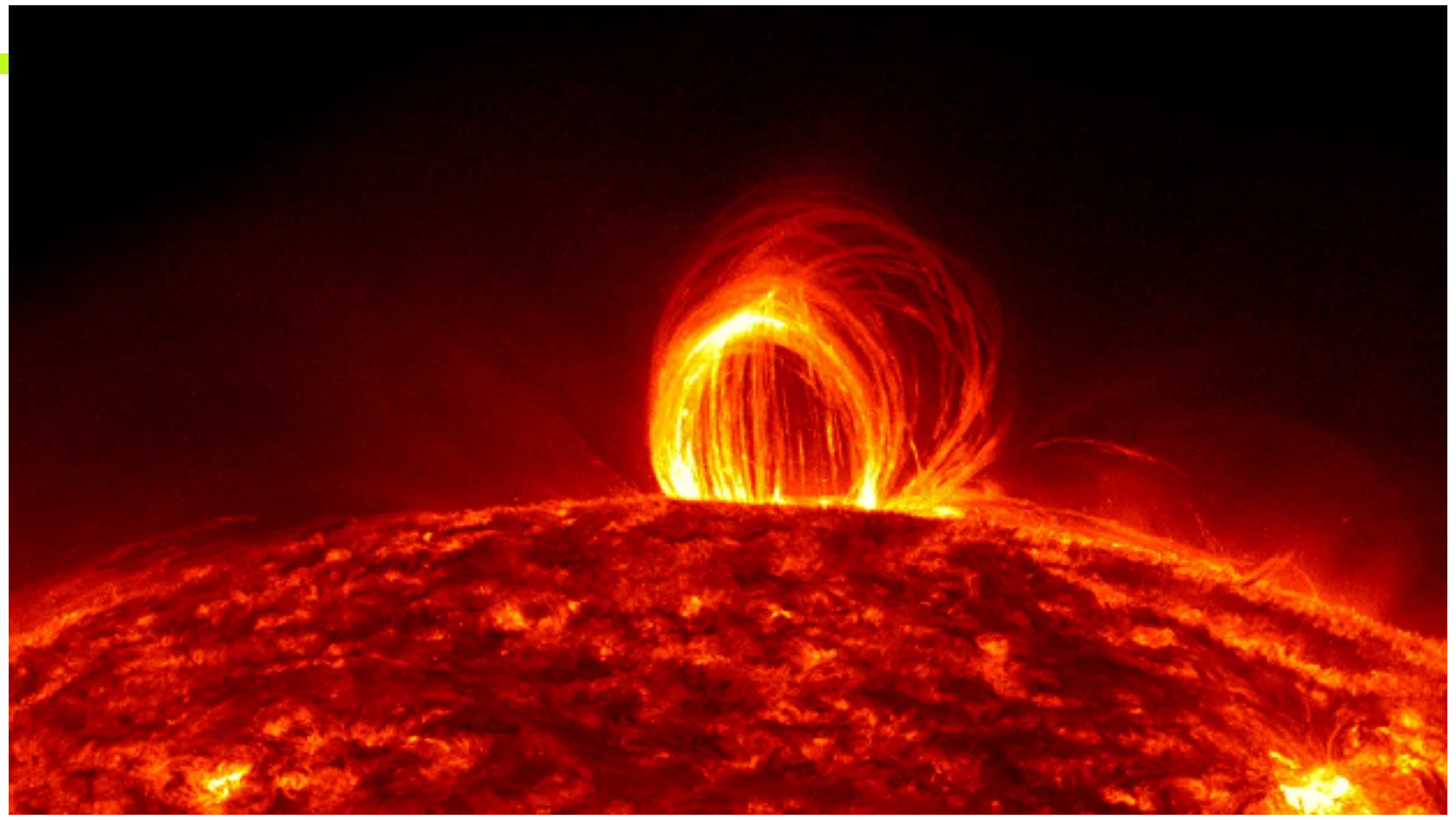


- Axions are predicted to feebly interact with ordinary particles
- The Sun's high temperature, high density, and proximity make it an optimal axion flux source.

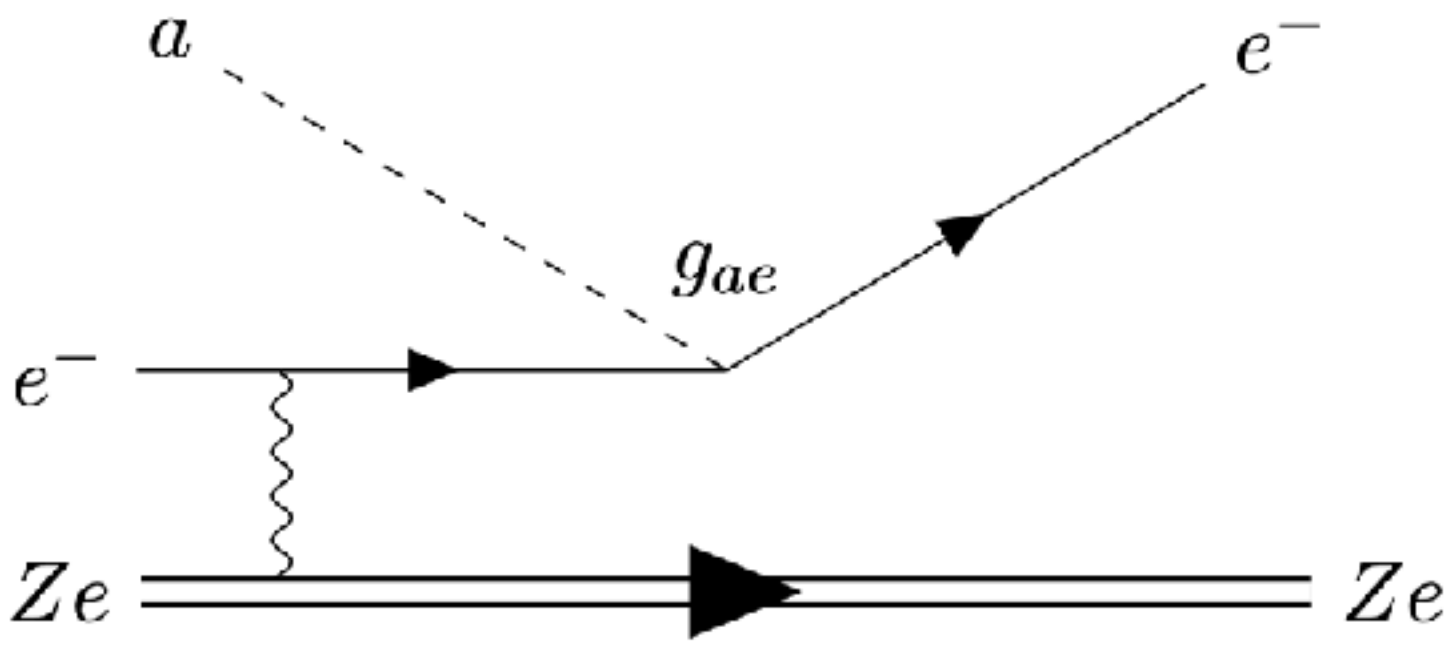


- We focus on the simplest signature: flux from ^{57}Fe de-excitation
  - First excited level is thermally populated in the core of the Sun
  - Axions could be emitted as a competing branch by coupling to nucleons
  - Produce a monochromatic flux at 14.4 keV

Solar Axions



AXIONS TRAVEL TO EARTH



- The flux eventually hits a particle detector absorbing material
- The axion converts into an electron though the axio-electric effect (analogous to the photo-electric one)
- The 14.4 keV electron is detected, giving rise to a monochromatic peak

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?

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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

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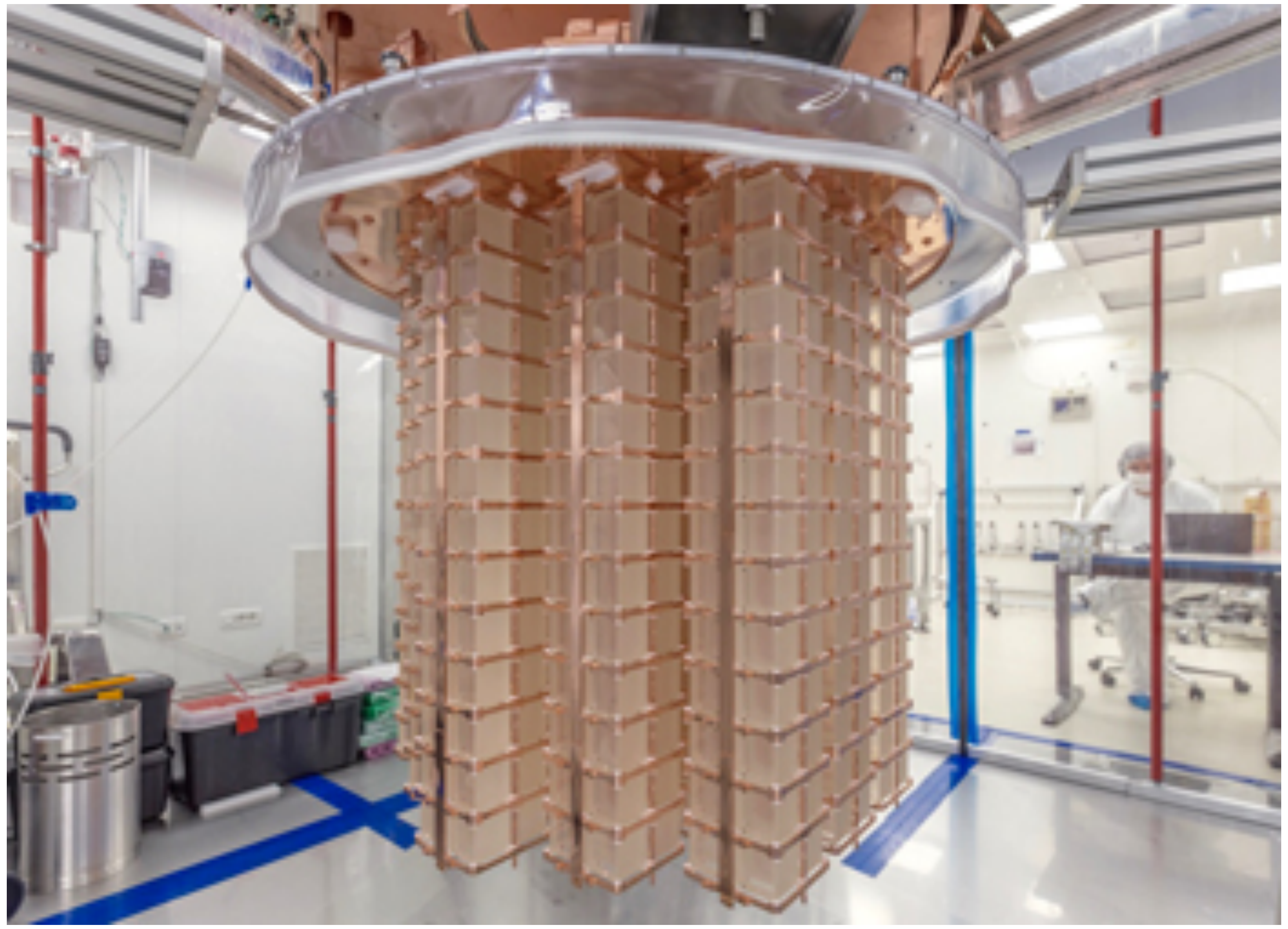

- Array of 988 detectors/absorbing material (TeO_2 crystals)
- About 1 ton of material kept at 10 mK by a world leading cryostat
- Stable for a 5 years operation… so far!
- Collected more than 2 ton x years of exposure
- First large scale experiment using cryogenic calorimeters

CUORE Experiment

Cryogenic Underground Observatory for Rare Events

State of art of large scale cryogenic calorimeters:

- Crystal (abrostine material)
- Very sensitive thermometer $R(T) = R_0 e^{\sqrt{T_0/T}}$
- Heat Bath

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

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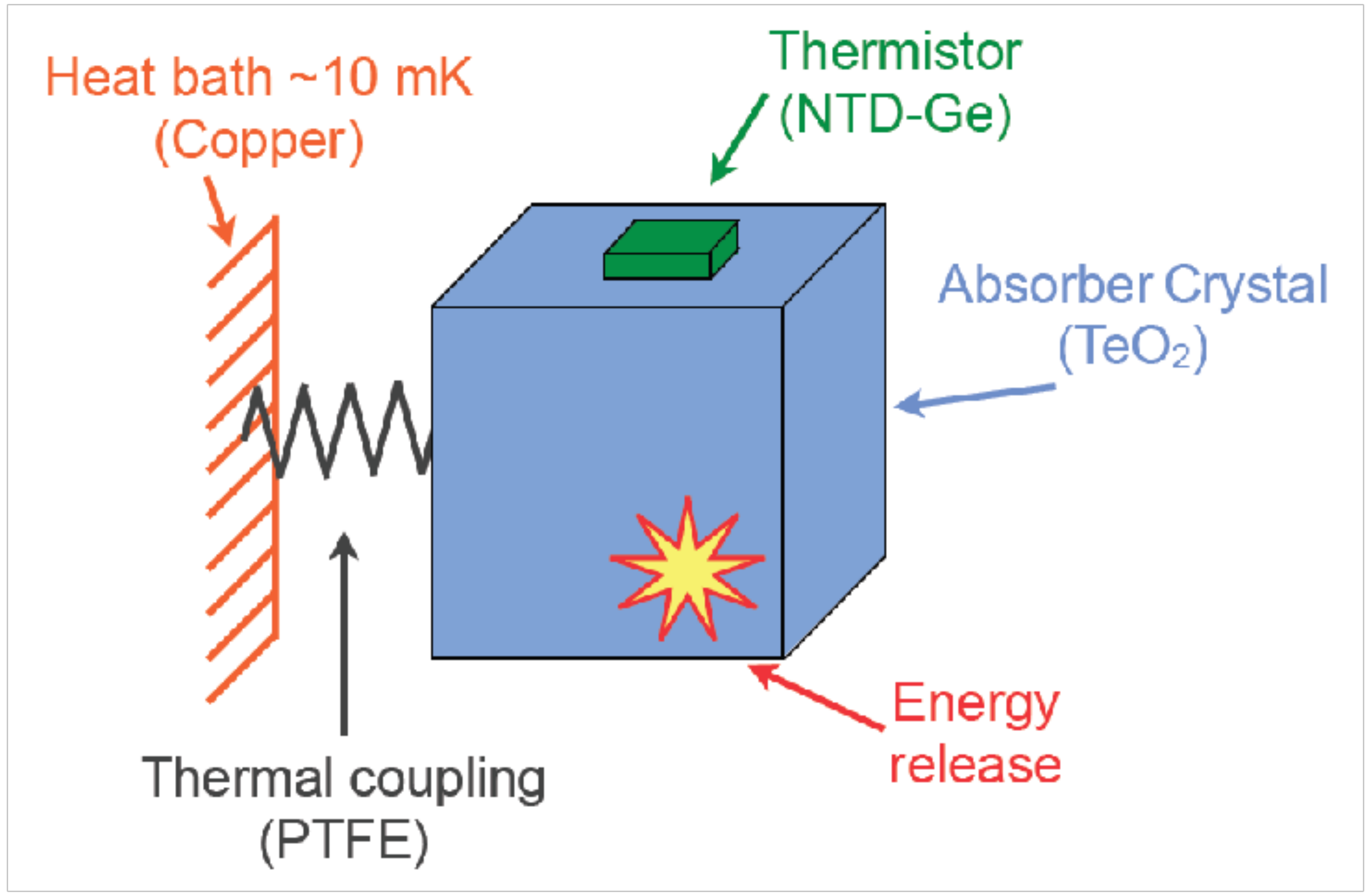

CUORE Experiment

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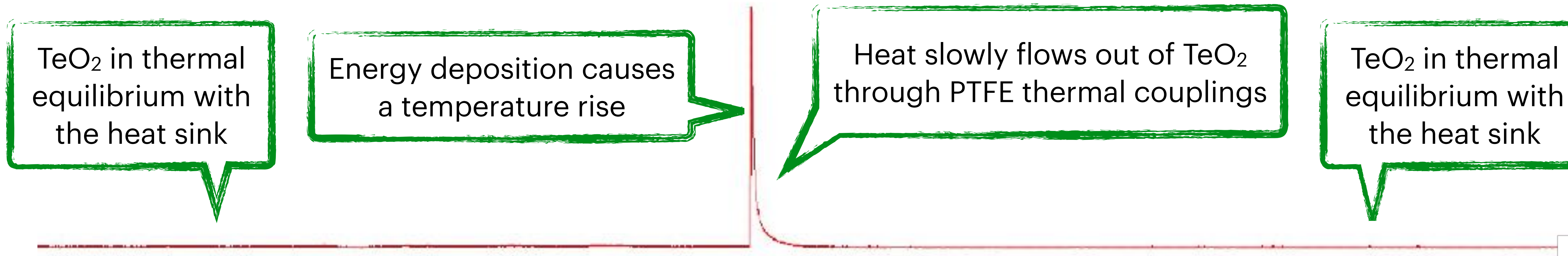
GOOD ENERGY RESOLUTION

Example of CUORE data stream



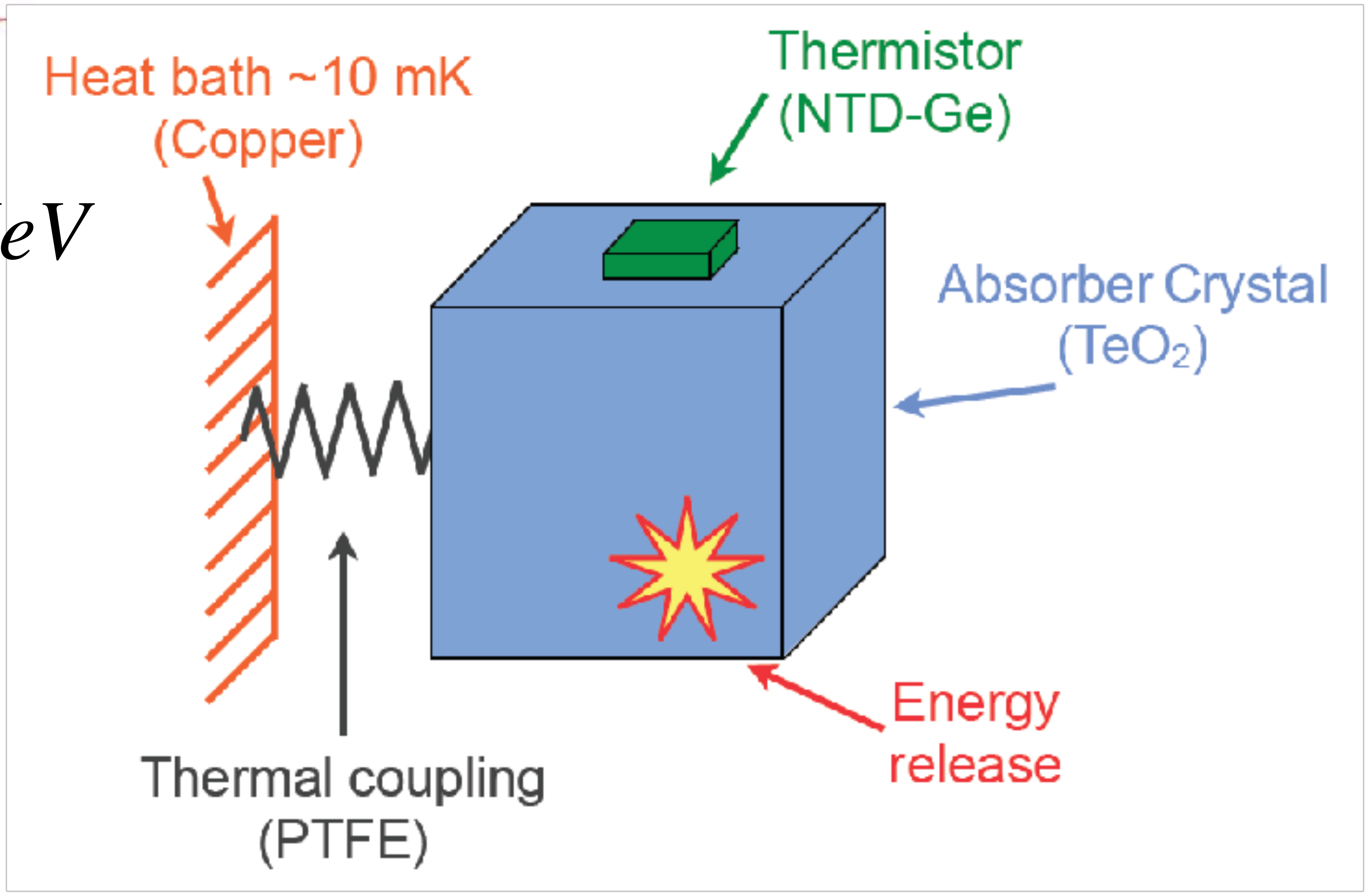
- Cryogenic Temperatures (10mK): need low heat capacity

$$C(T) \propto T^3$$

$$\Delta T = \Delta E / C \sim 100\ \mu K/MeV$$

- Extremely low energy prize to produce thermal phonons allows for negligible intrinsic energy resolution

- Main contribution from external sources (electronic and vibrations)



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

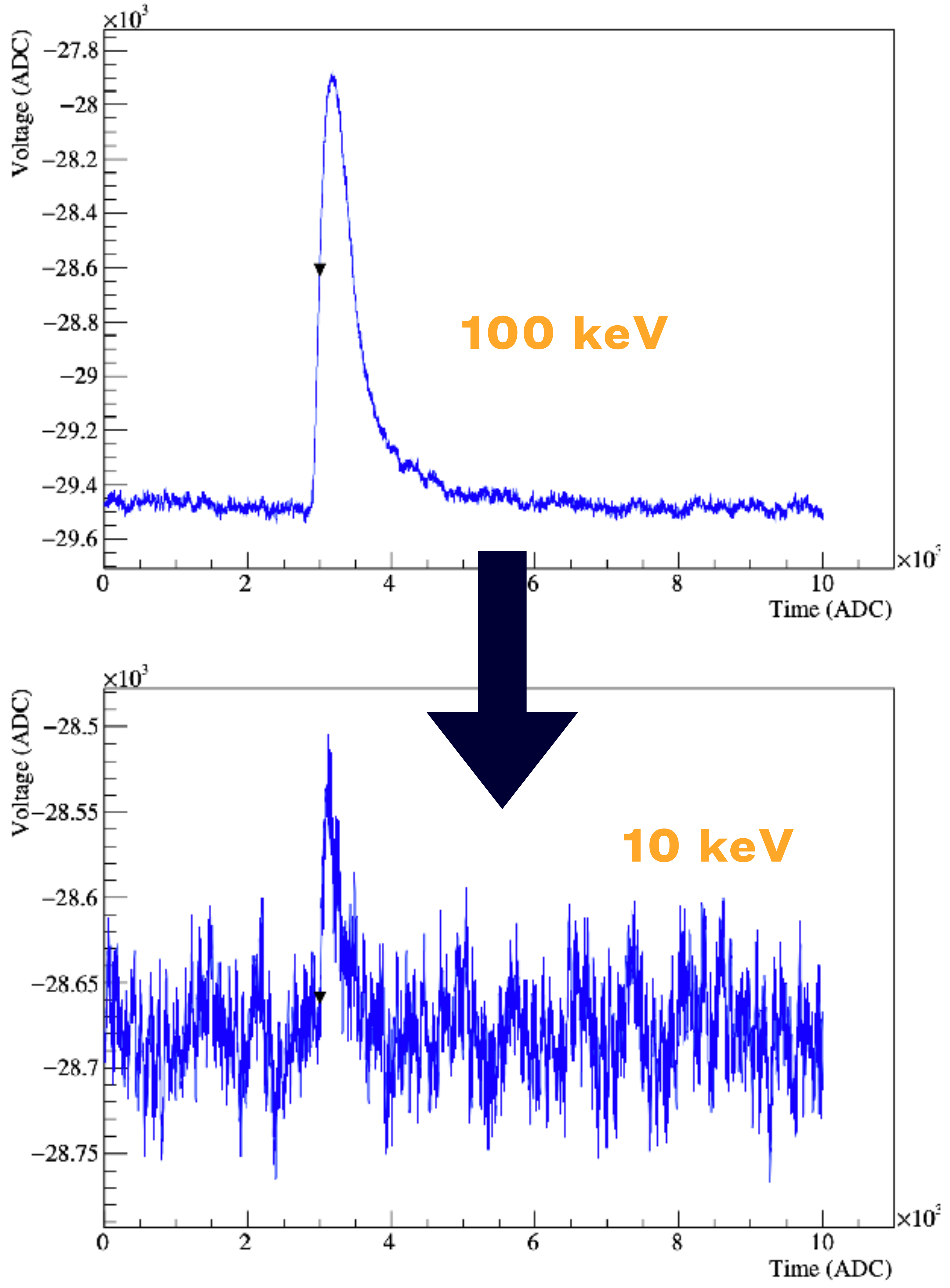
LOW BACKGROUND

LARGE EXPOSURE (MASS X TIME)

GOOD ENERGY RESOLUTION

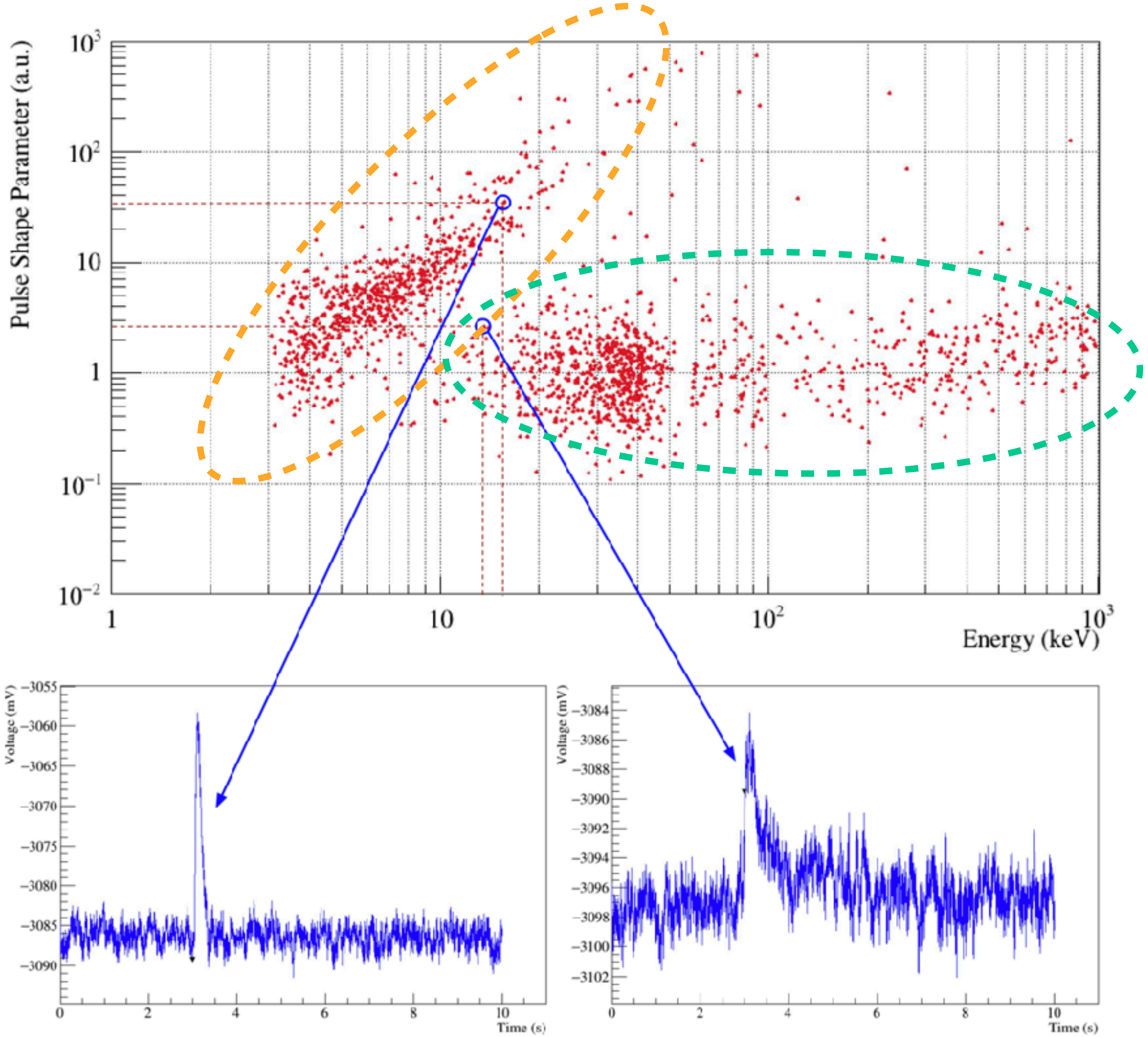
Low Energy CUORE

- Detection of thermal phonons has a wide energy range of operation (keV to MeV)
- Solar Axions (and many more new physics) expected close to energy threshold
- We want to fully exploit the CUORE data taking!
- It is hard to optimize such a large array so close to the detector threshold (**from great exposure comes great responsibility…**)
- While standard CUORE analysis is meant for MeV scale, we are developing a dedicated one for the keV



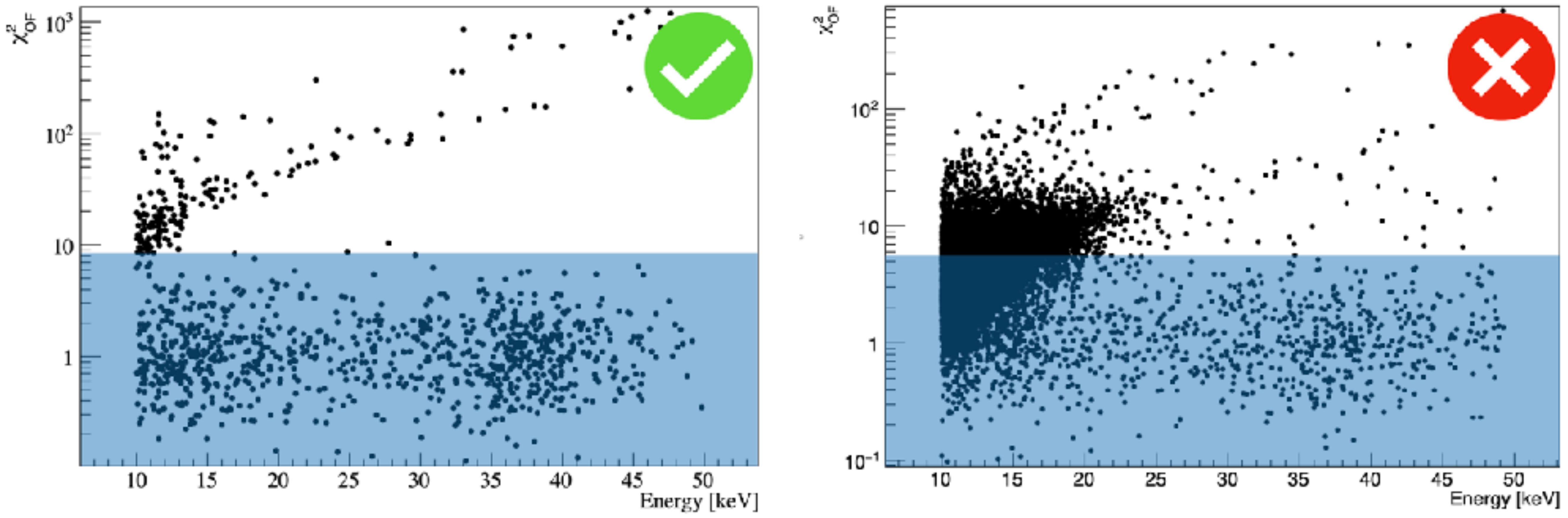
Low Energy CUORE

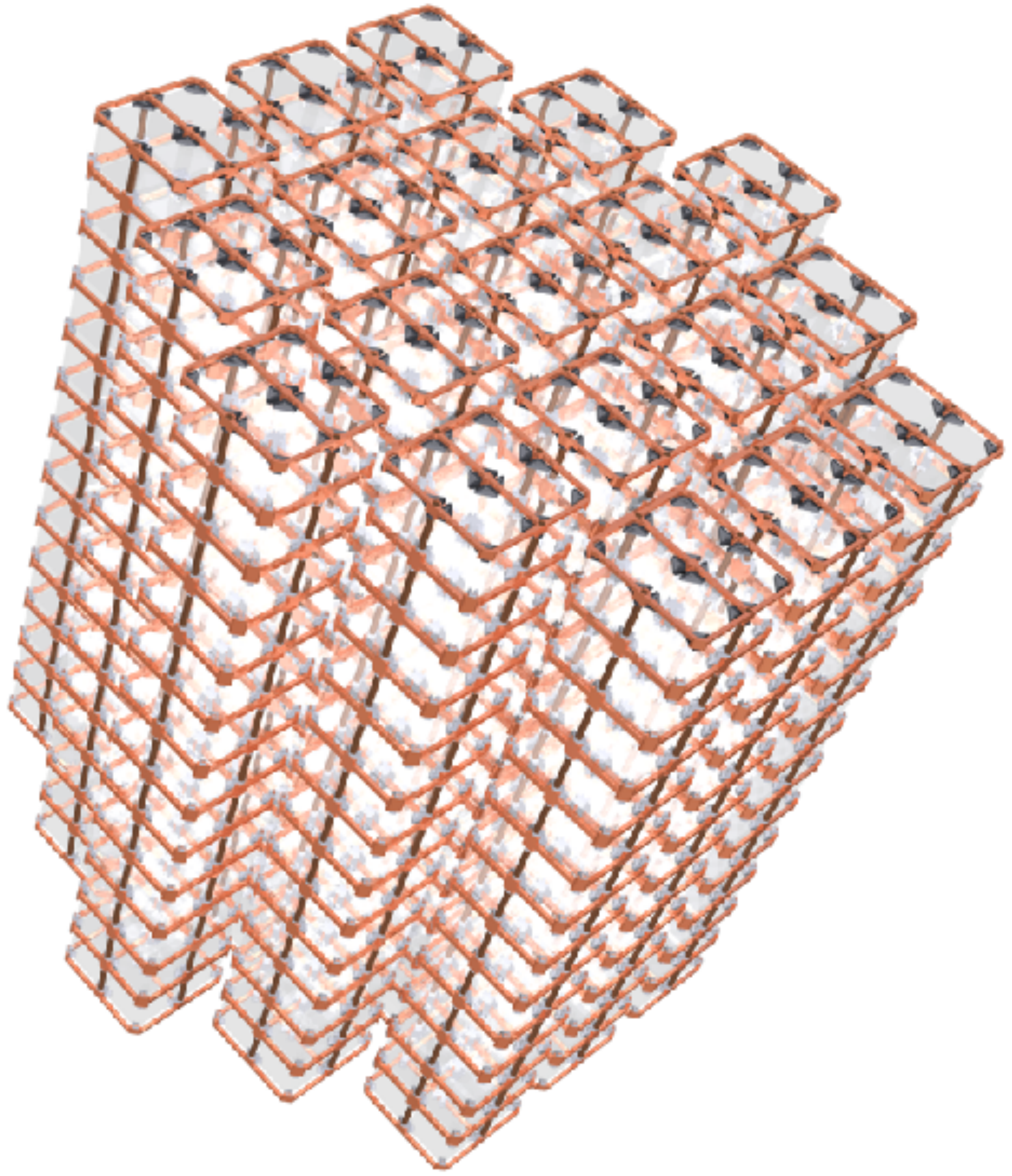
- The temperature rise can be due not only to particle interactions, but to a variety of other non-physical phenomena (especially vibrations)
- CUORE is sensitive to far earthquakes as well! (And we have to reject data because of that)
- Down to what energy are we able to identify particles from vibrations?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



Low Energy CUORE

- In what detectors of the array the pulse shape is able to reject spurious events?
- Only about 30% of the CUORE detectors can get down to 10 keV
  - a specific production batch of thermistors (lower Johnson noise)
  - inner CUORE towers (higher screening)
  - central floors (lower effect to vibrations)





Conclusions

- Axions are very appealing
- Cryogenic Calorimeters technology for large scale experiment is possible
  - just achieved >2 ton yr of exposure with CUORE
- Balancing good performance and large exposure is difficult
- Can we still use CUORE for keV searches dark matter as well? …Stay tuned

Thanks for your attention!