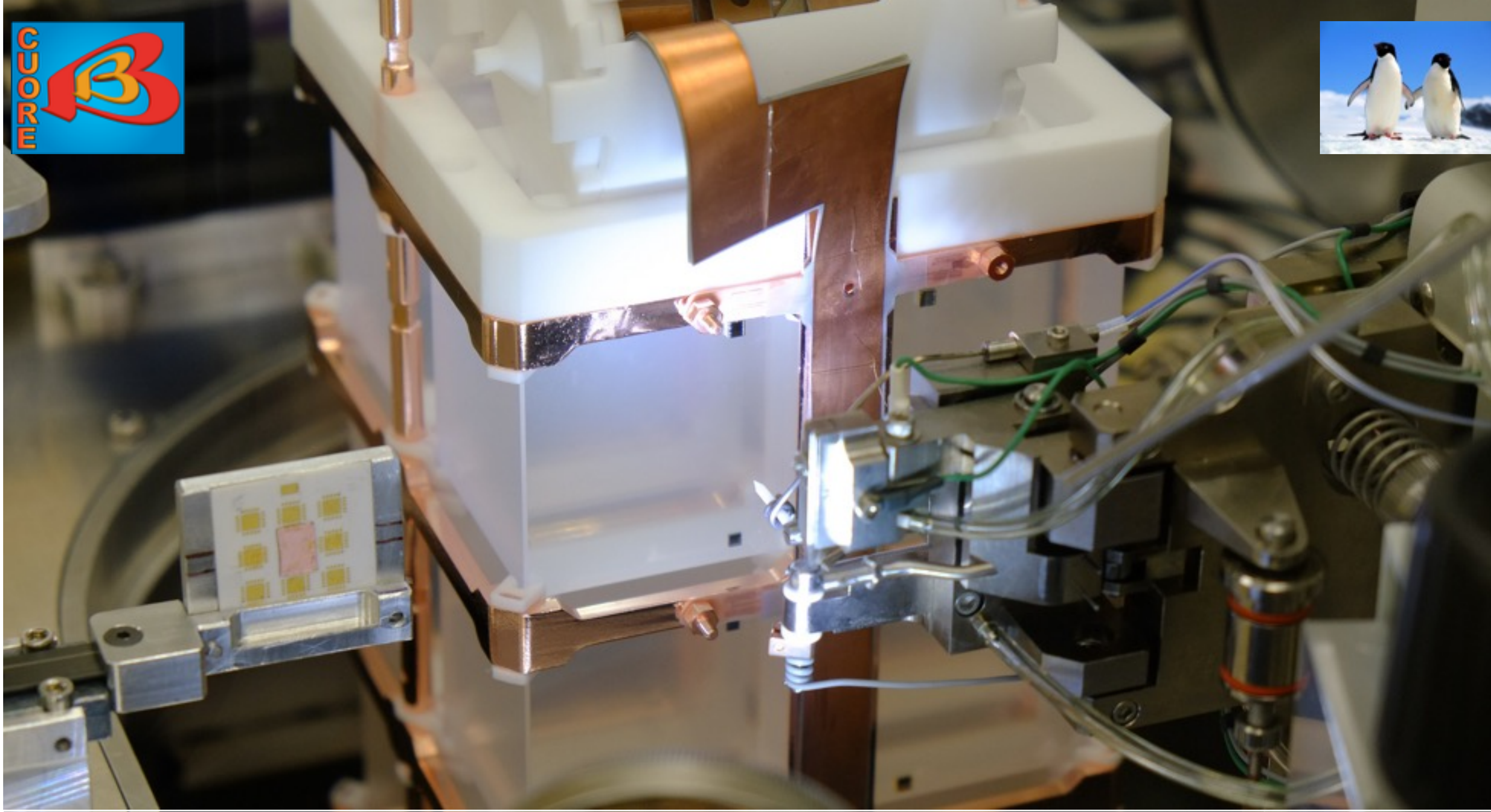


Rare Event Searches with CUORE and DM-Ice Experiments

Kyungeun E. Lim (for the CUORE and DM-Ice collaborations)

Dec. 1, 2015, High Energy Seminar, UC Davis

LUX ET VERITAS

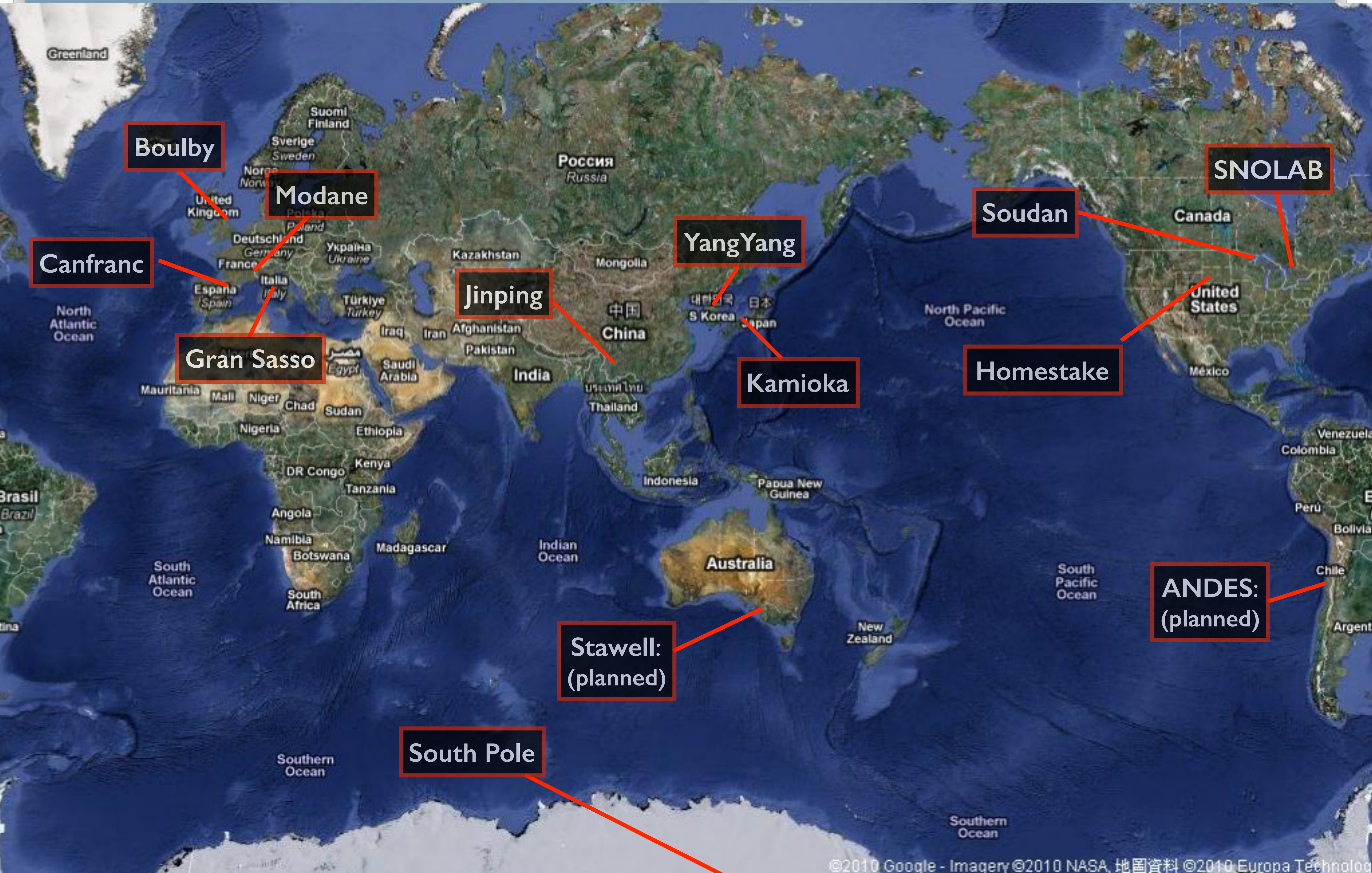
Rare Event Searches:
Finding a signal (Wally) among huge backgrounds (Crowd)

Rare Event Searches:
Need a low background environment (Less crowd)

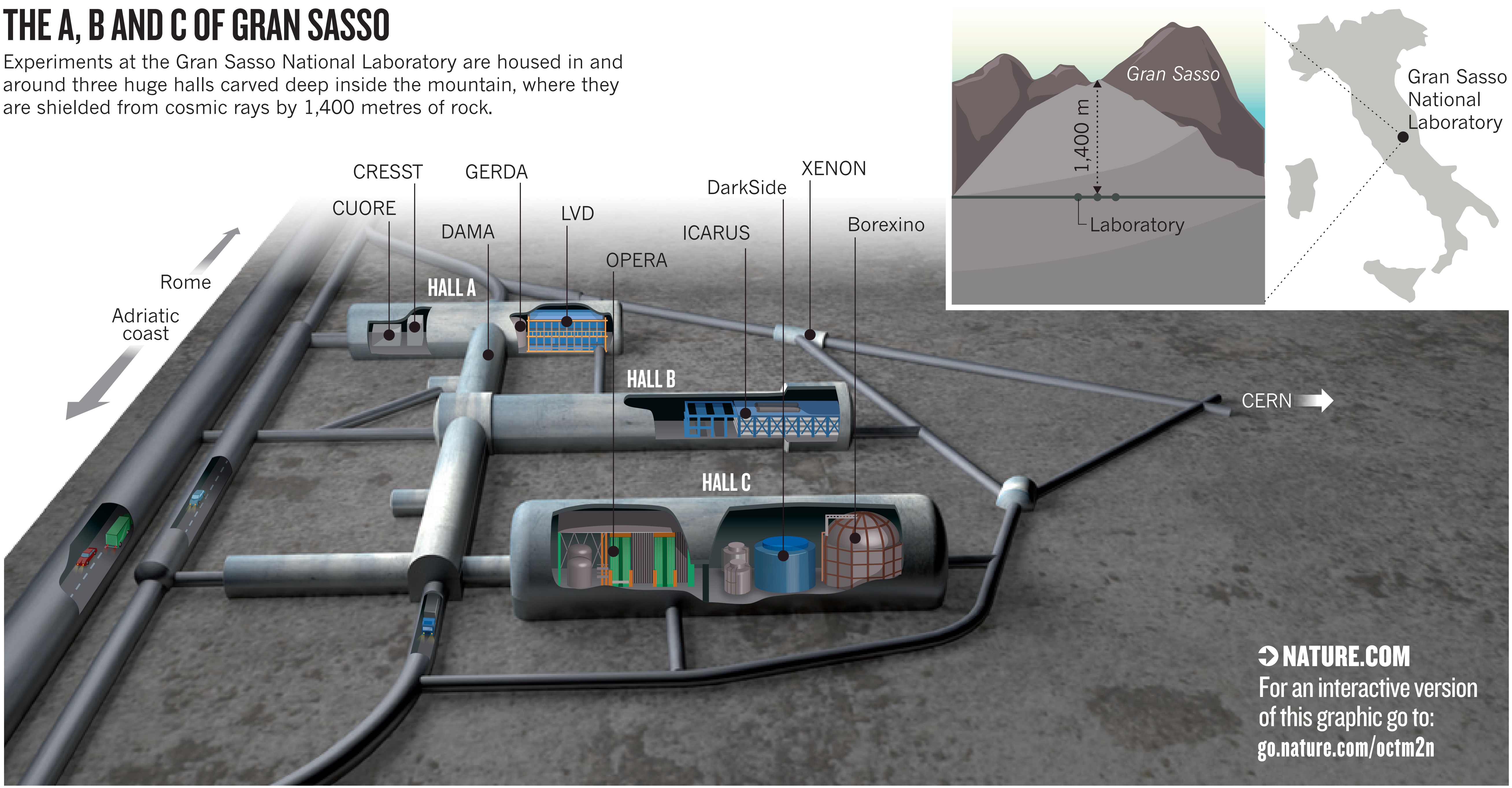
Rare Event Searches for **Nuclear-Particle-Astrophysics**:

Need a low background environment (Underground)

A World of Underground Laboratories



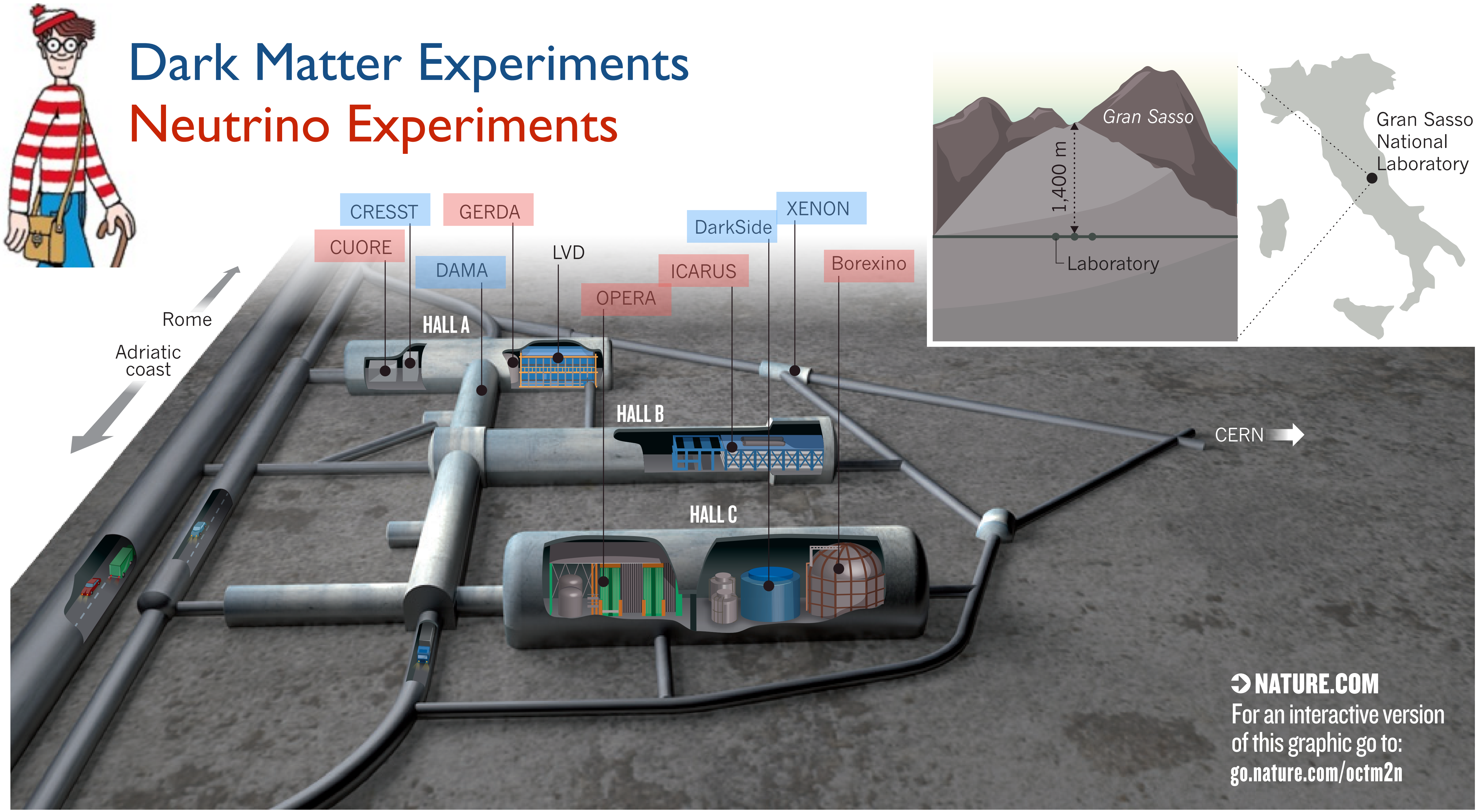
Laboratori Nazionali del Gran Sasso (LNGS)



http://www.nature.com/news/gran-sasso-chamber-of-physics-1.10696

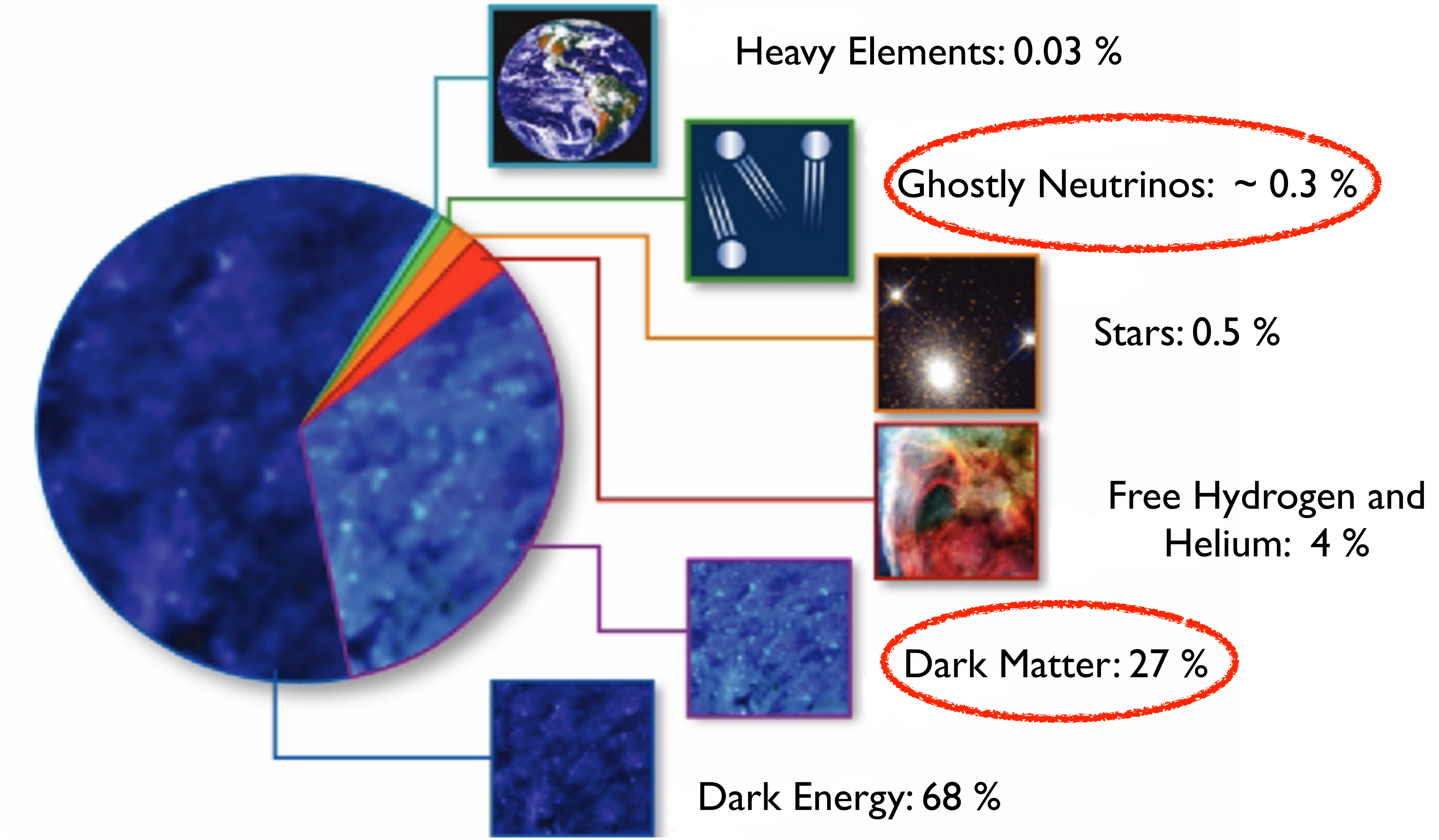
Laboratori Nazionali del Gran Sasso (LNGS)

Dark Matter Experiments
Neutrino Experiments



http://www.nature.com/news/gran-sasso-chamber-of-physics-1.10696

Why do we care about Neutrino and Dark Matter?



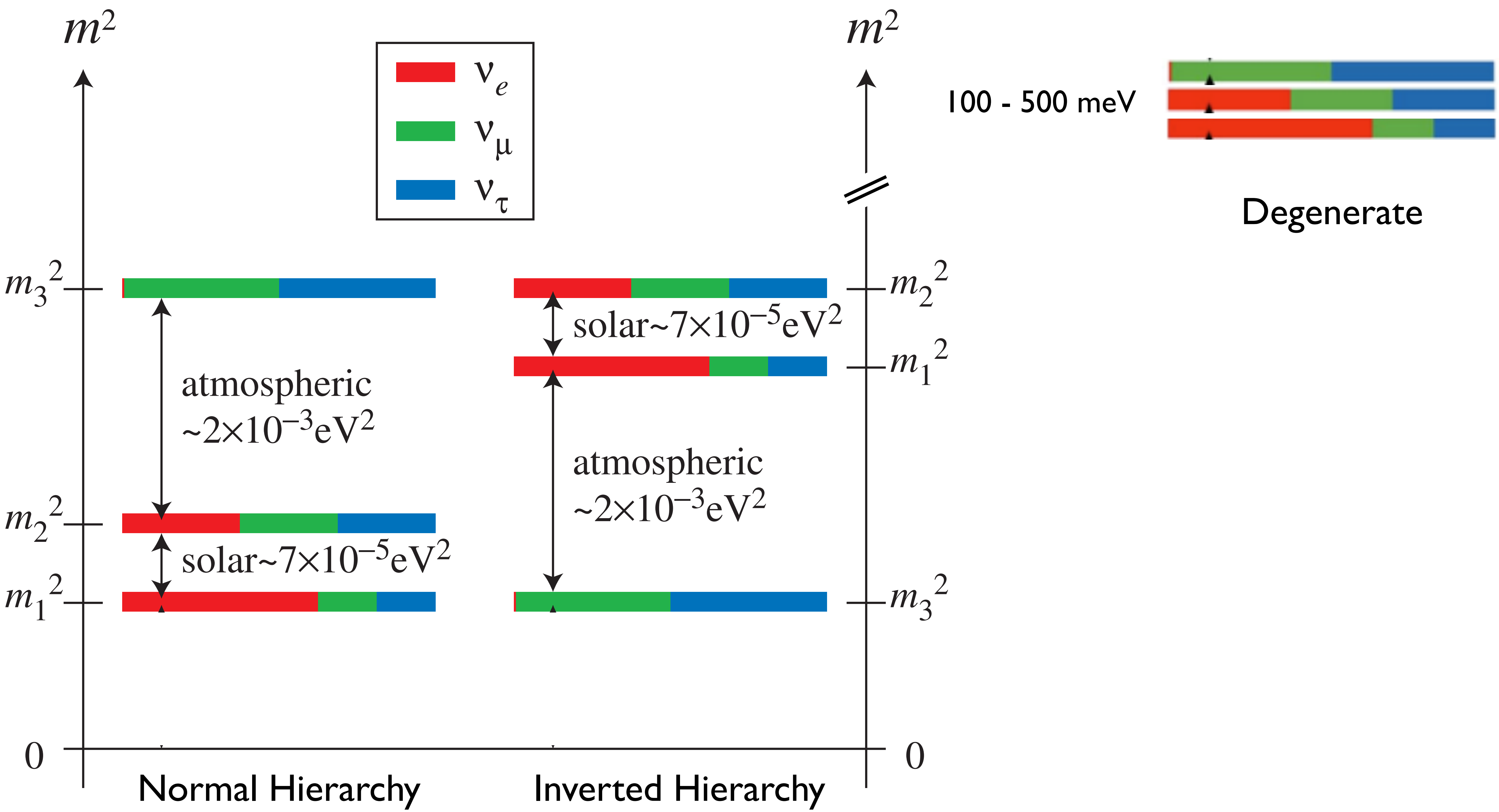
Neutrino and Dark Matter are the main drivers ask for the New Physics beyond the Standard Model of Particle Physics.

Outline

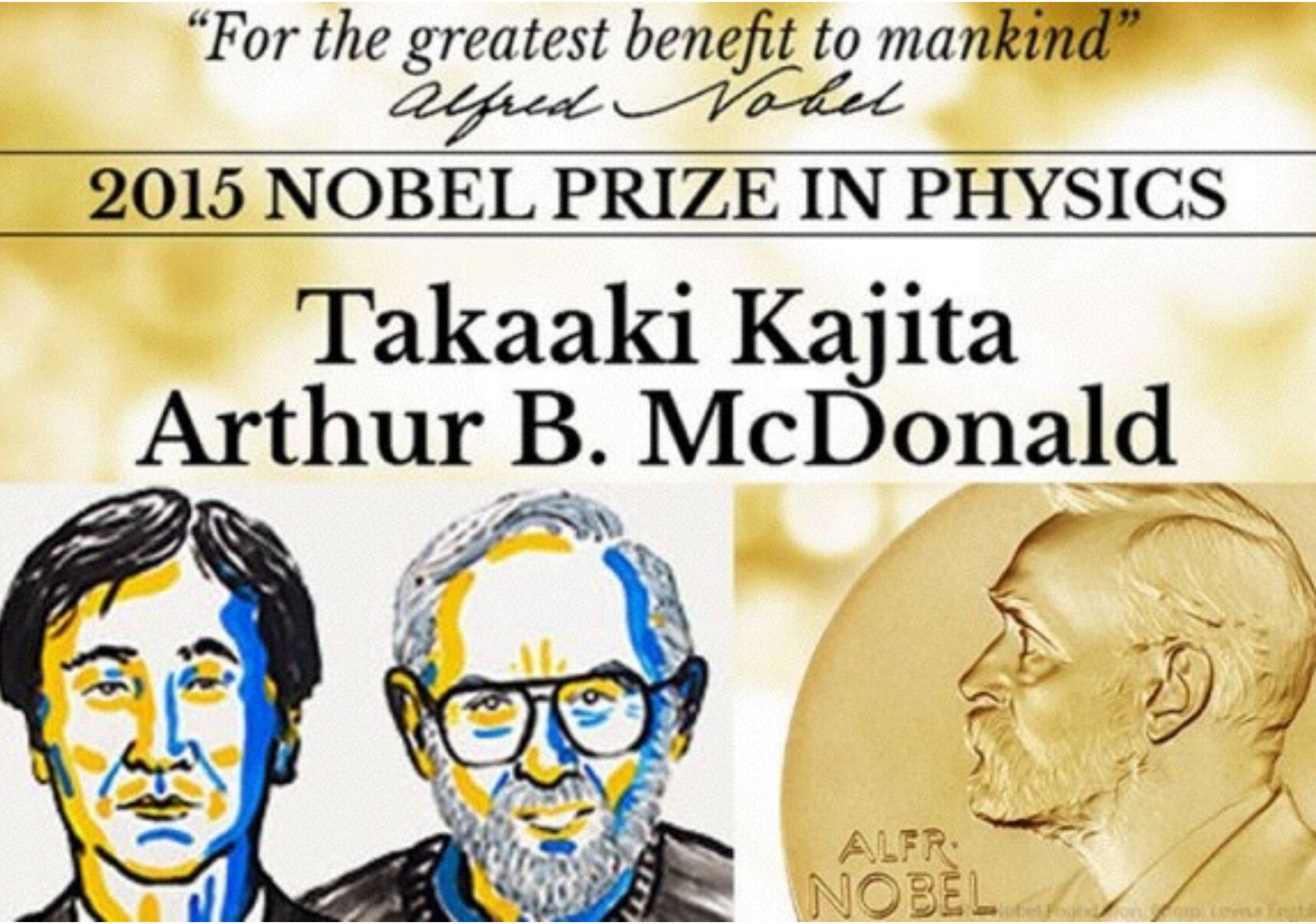
- Neutrinoless double-beta decay ($0\nu\beta\beta$) search
- CUORE : An array of TeO_2 bolometers to search for $0\nu\beta\beta$ and other rare events
- CUORE-0: $0\nu\beta\beta$ search w/ a single CUORE tower
- WIMP Dark Matter Search with CUORE
- DM-Ice : NaI(Tl) detectors to test WIMP discovery claim
- Summary

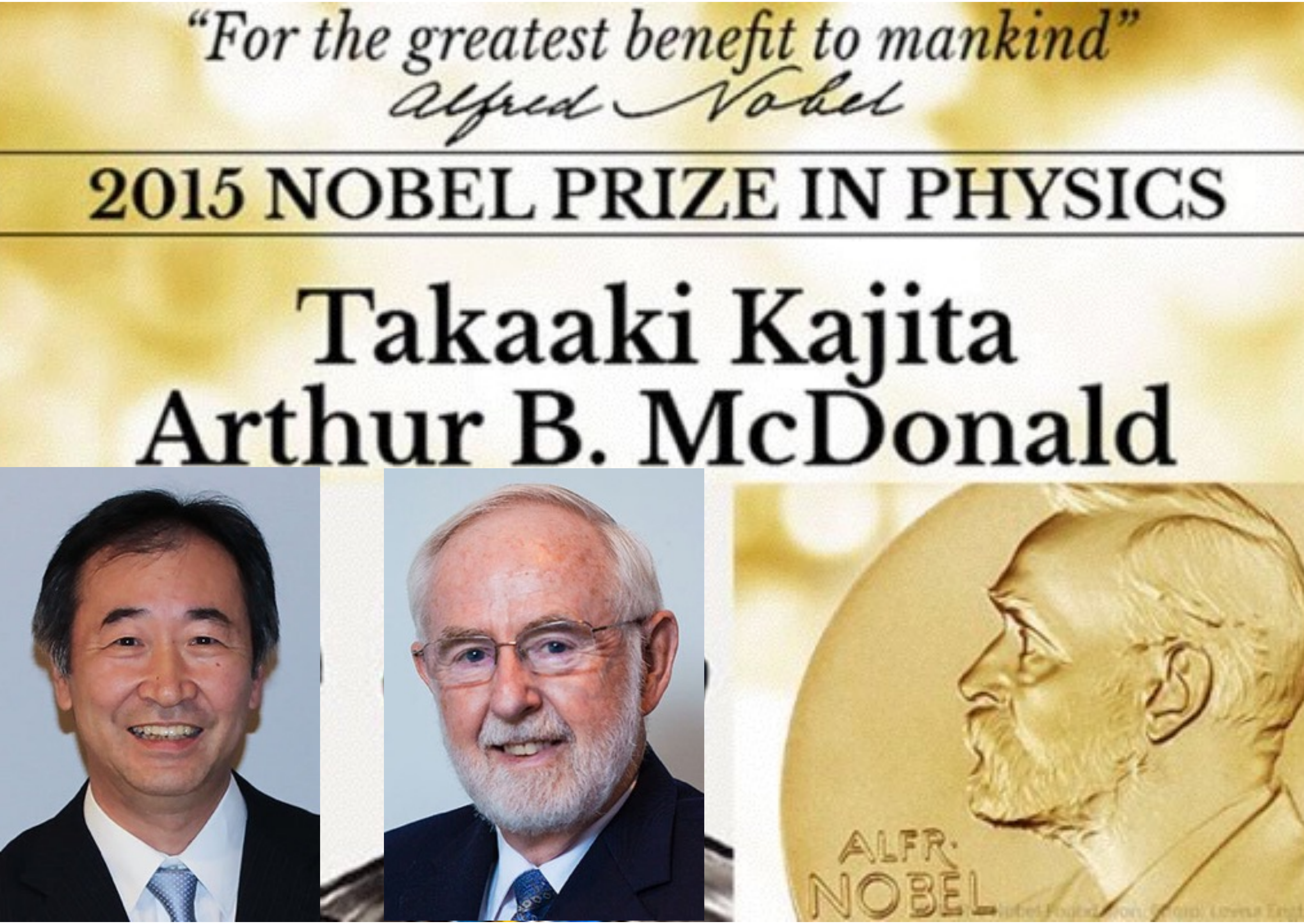
What we know about Neutrinos

Neutrino Mass Splitting



Rep. Prog. Phys. 76, 056201 (2013)


"For the greatest benefit to mankind"
Alfred Nobel
2015 NOBEL PRIZE IN PHYSICS
Takaaki Kajita
Arthur B. McDonald
ALFR.
NOBEL


"For the greatest benefit to mankind"
Alfred Nobel
2015 NOBEL PRIZE IN PHYSICS
Takaaki Kajita
Arthur B. McDonald
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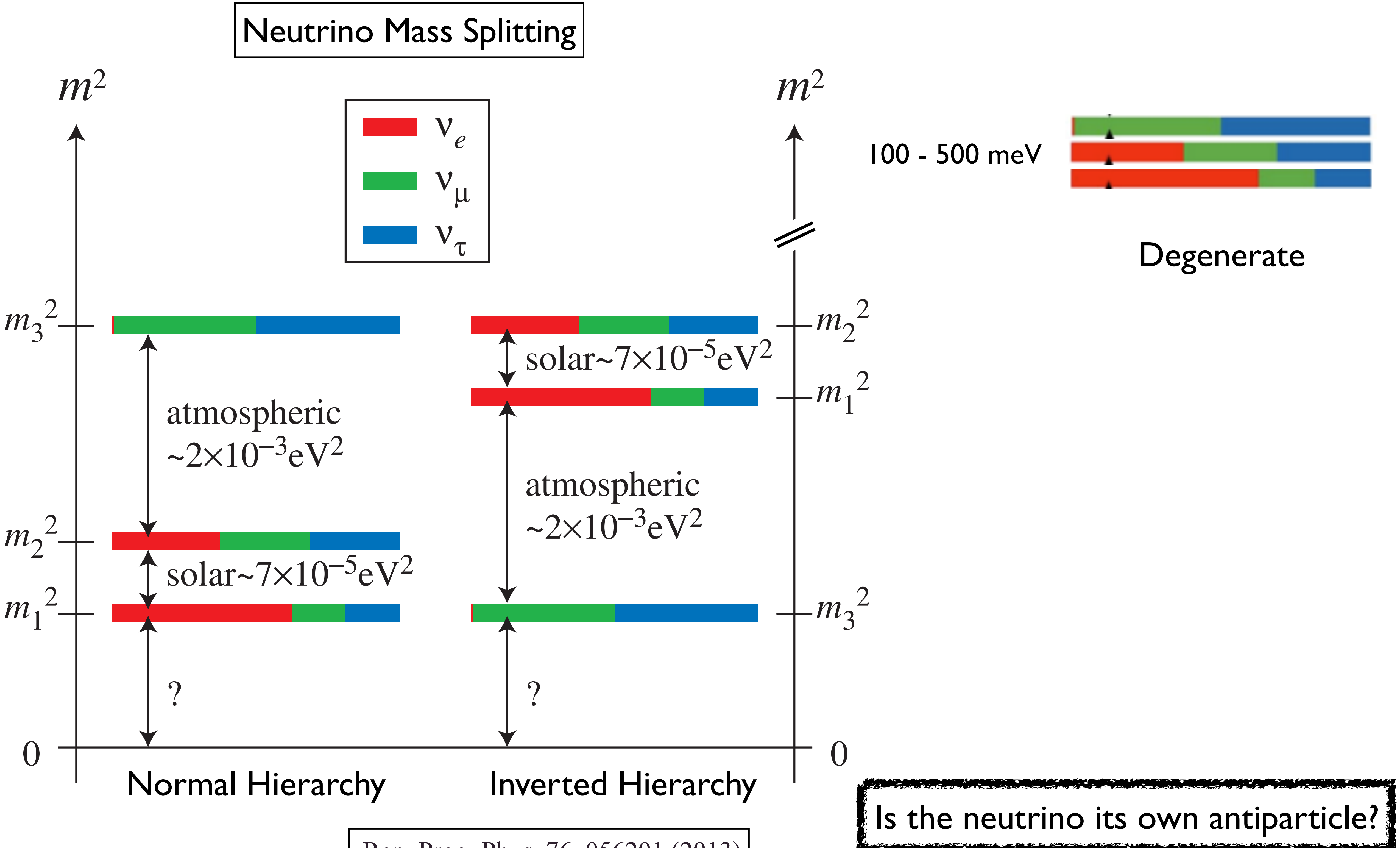
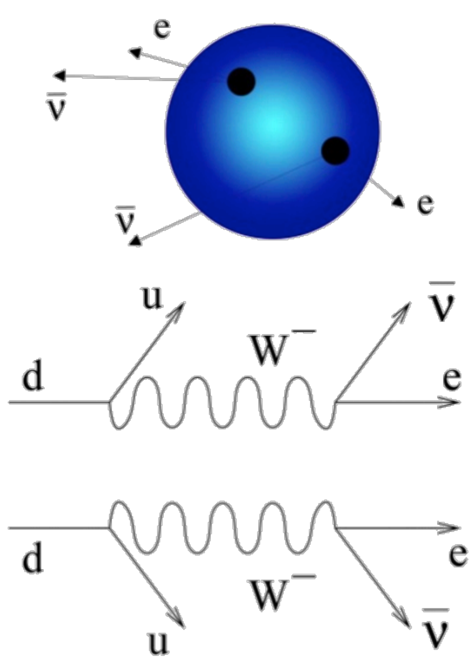
What we don’t know about Neutrinos



Rep. Prog. Phys. 76, 056201 (2013)

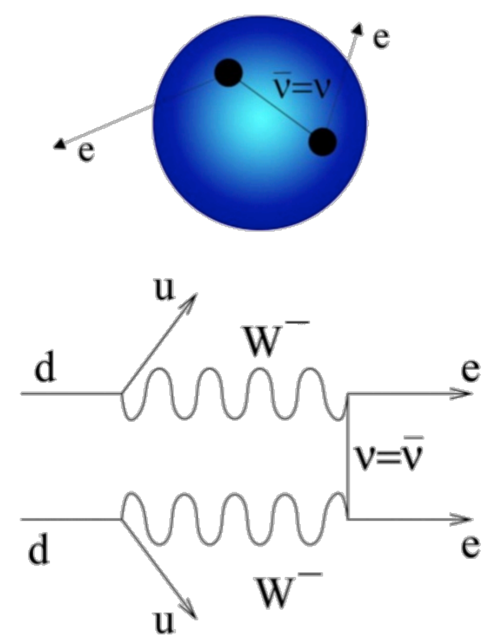
Neutrino(less) double-beta decay

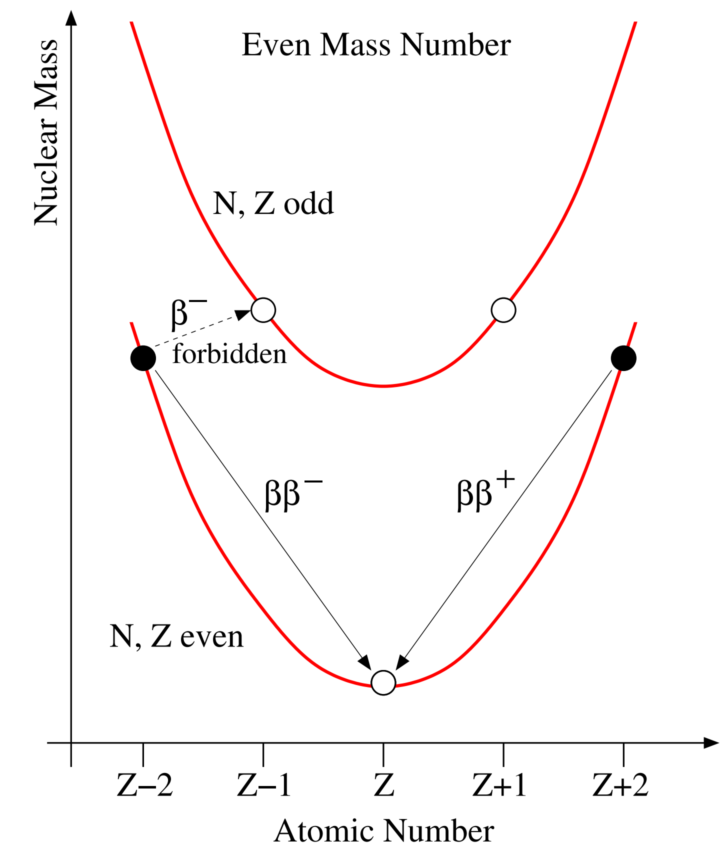
- $2\nu\beta\beta$



- Allowed in SM
- Observed in several nuclei ($T_{1/2}^{2\nu} \sim 10^{18}$-$10^{21}$ yr)

- $0\nu\beta\beta$





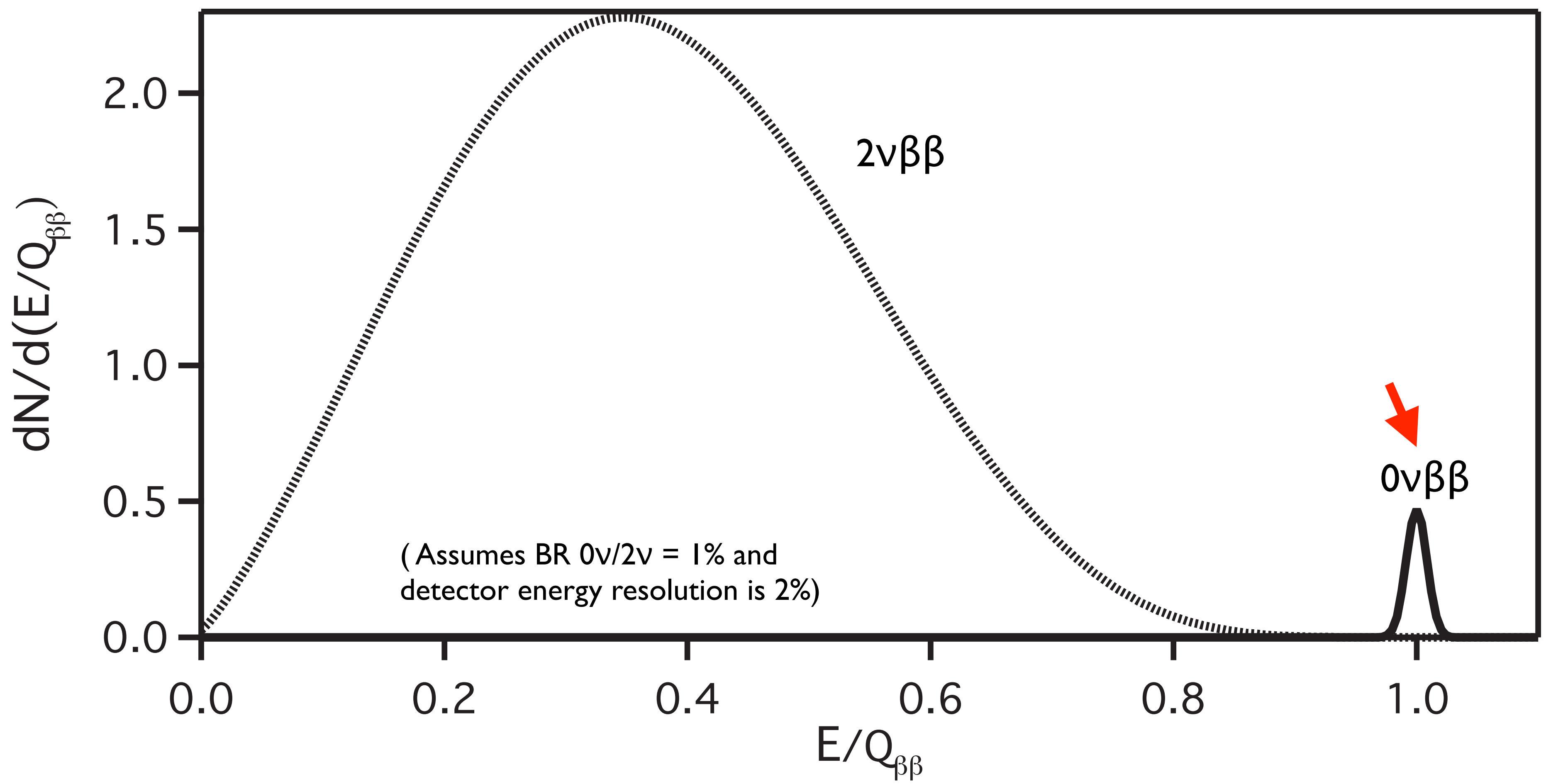
- Beyond SM
- Hypothetical process only if $\nu = \bar{\nu}$ and $m_\nu > 0$

Observation of $0\nu\beta\beta$

1. will establish that neutrinos are Majorana Particles ($\nu = \bar{\nu}$)
2. will demonstrate lepton number is not a symmetry of nature
3. will provide indirect info about the ν mass
4. may provide info about the mass hierarchy in combination with direct neutrino mass measurement

Signature of 0νββ

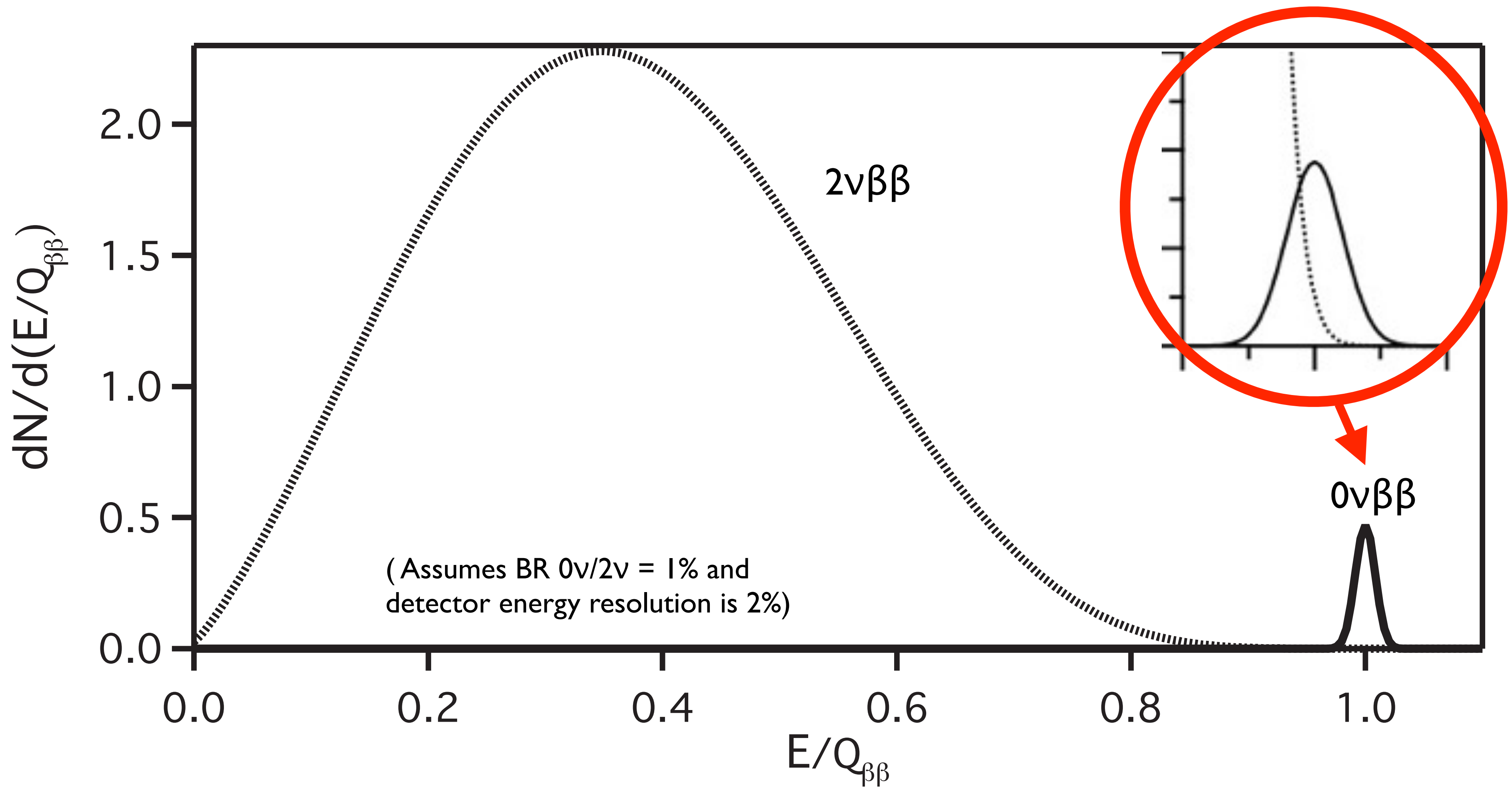
ββ summed e⁻ energy spectrum



- Look for peak in the detector at the Q-value of decay.
- Good energy resolution of a detector suppresses intrinsic background from 2νββ.

Signature of 0νββ

ββ summed e⁻ energy spectrum



- Look for peak in the detector at the Q-value of decay.
- Good energy resolution of a detector suppresses intrinsic background from 2νββ.

Search for 0νββ

Decay rate:

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2 \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Well defined

Difficult to calculate

$$\langle m_{\beta\beta}\rangle \equiv \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

- Probes absolute mass scale
- Sensitive to hierarchy

$T_{1/2}^{0\nu}$	0νββ half-life
$G^{0\nu}$ (Q,Z)	phase space factor $(\propto Q^5)$
$M^{0\nu}$	Nuclear Matrix Element (NME)
$m_{\beta\beta}$	effective Majorana mass of ν_e
m_e	electron mass

Search for 0νββ

Decay rate:

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

$T_{1/2}^{0\nu}$ sensitivity $\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$

$T_{1/2}^{0\nu}$	0νββ half-life
$G^{0\nu}$ (Q,Z)	phase space factor $(\propto Q^5)$
$M^{0\nu}$	Nuclear Matrix Element (NME)
$m_{\beta\beta}$	effective Majorana mass of ν_e
m_e	electron mass

a	isotopic abundance of source
ε	detection efficiency
M	total detector mass
b	background rate /mass/energy
t	exposure time
δE	energy resolution (spectral width)

Search for 0νββ

Decay rate:

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

$T_{1/2}^{0\nu}$ sensitivity $\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$

$T_{1/2}^{0\nu}$	0νββ half-life
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m_e	electron mass

a	isotopic abundance of source
ε	detection efficiency
M	total detector mass
b	background rate /mass/energy
t	exposure time
δE	energy resolution (spectral width)

Detector Building/
Source Selection Strategies

- Large total mass
- Ultra-low background
- Good energy resolution
- High Q-value
- High isotopic abundance
- NME

Outline

- Neutrinoless double-beta decay ($0\nu\beta\beta$) search
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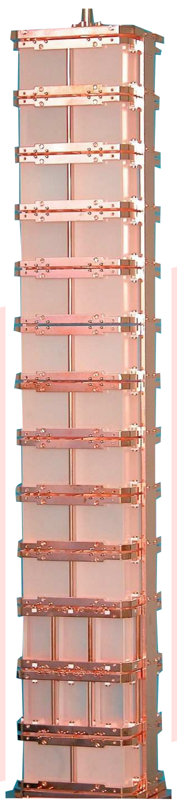
The CUORE 0νββ Search

CUORE: Cryogenic Underground Observatory for Rare Events

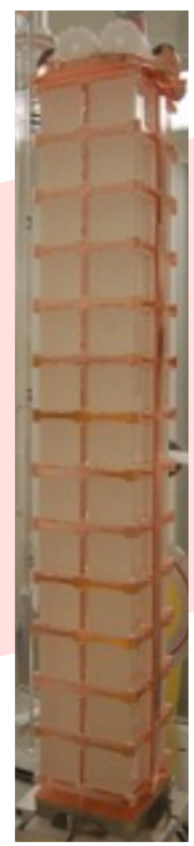
Cuoricino (2003-2008)



Achieved (2008)

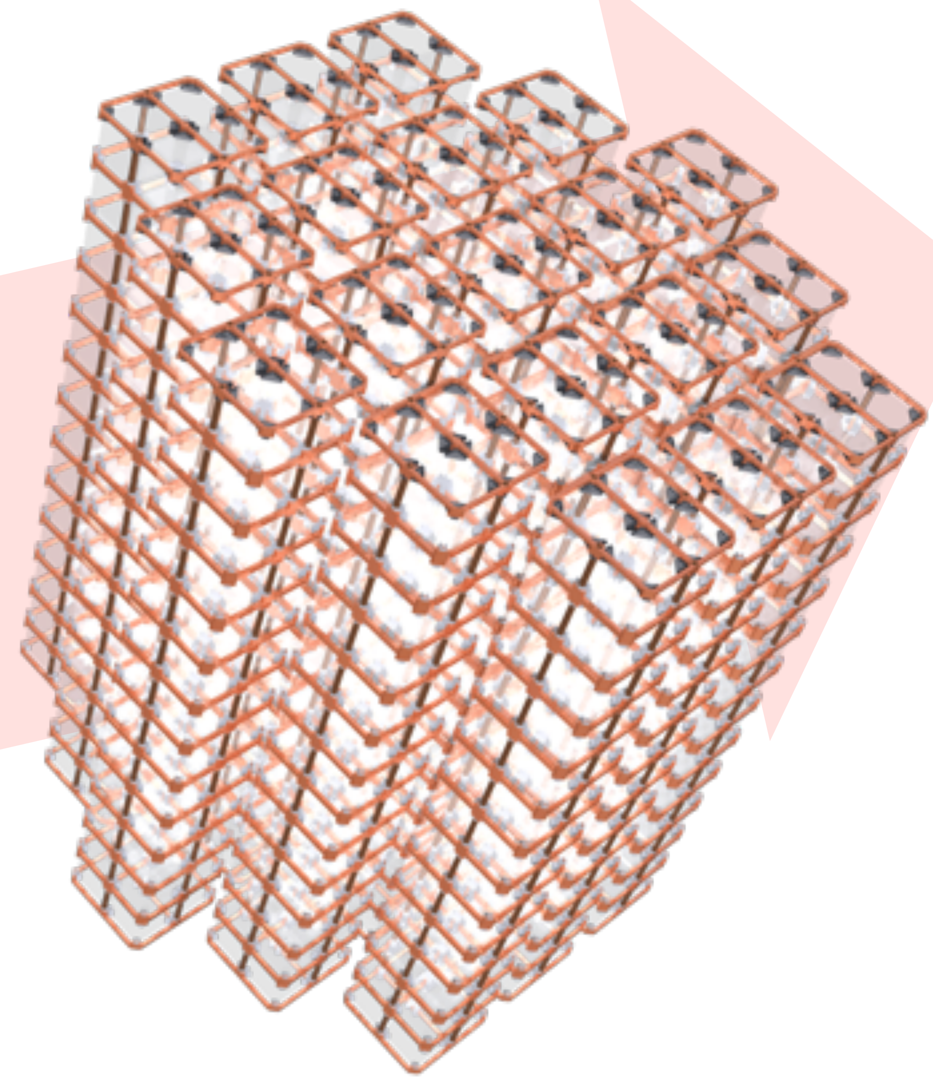
$T_{1/2}^{0\nu}$ > 2.8×10^{24} yr (90% C.L.)

CUORE-0 (2013-2015)



Achieved (2015)

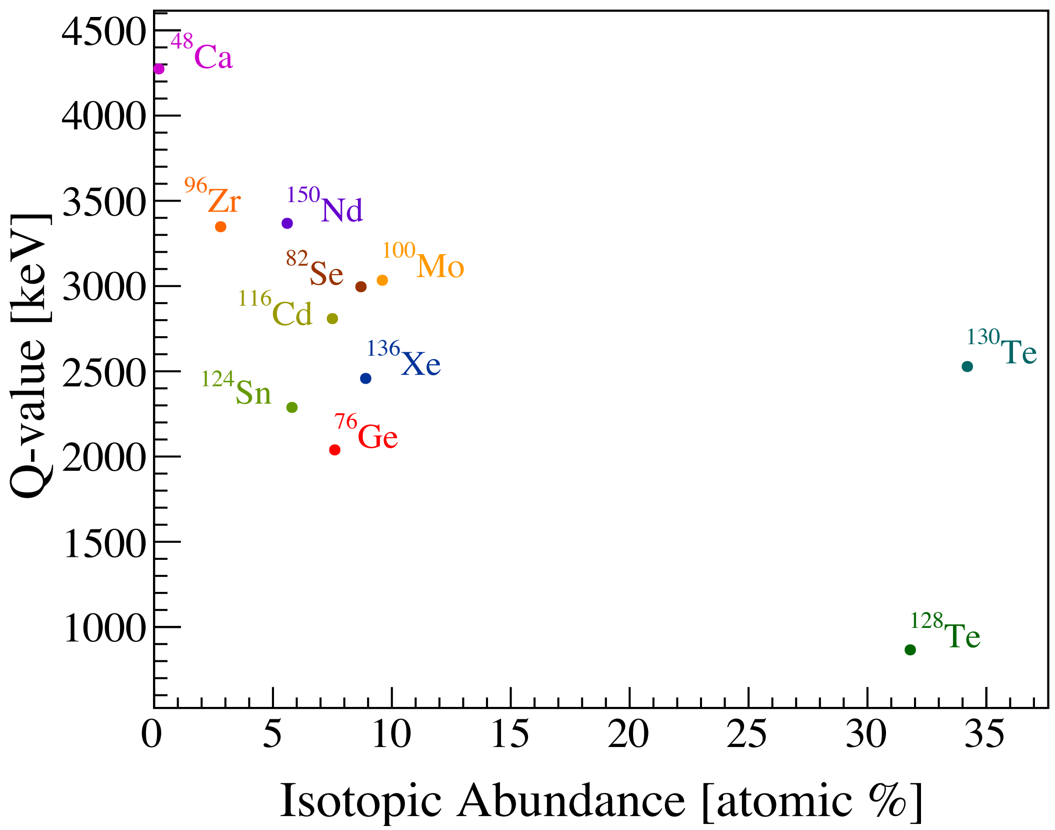
CUORE (2016-2020)

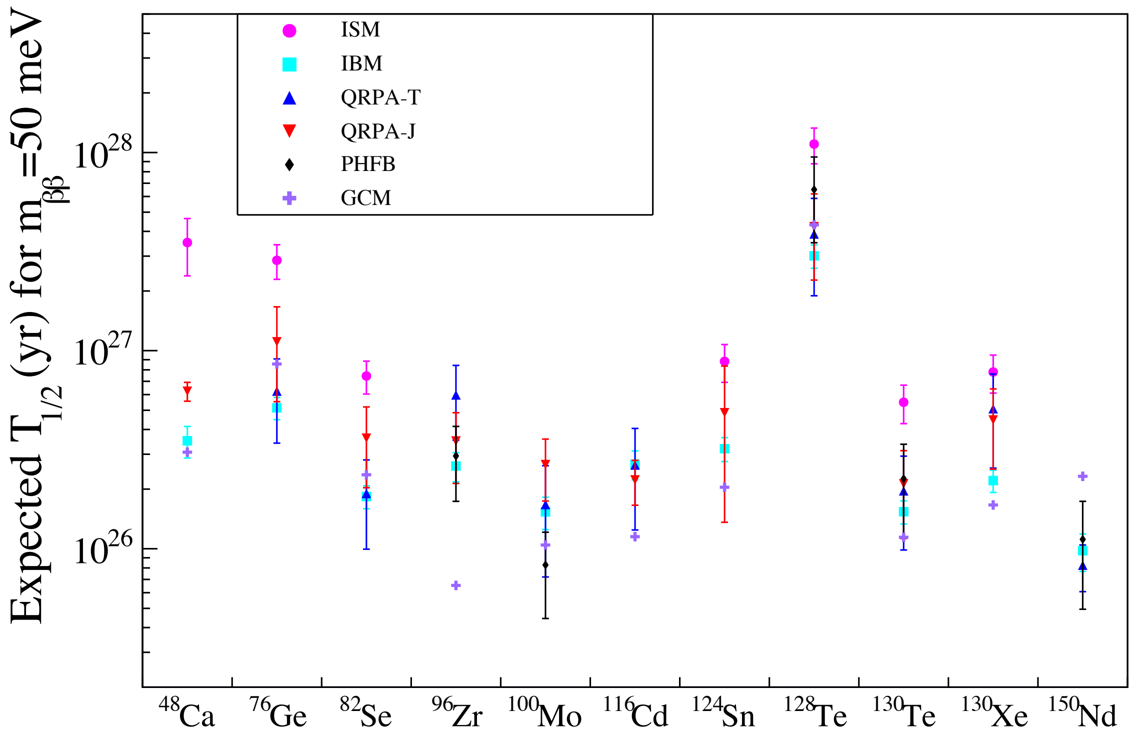


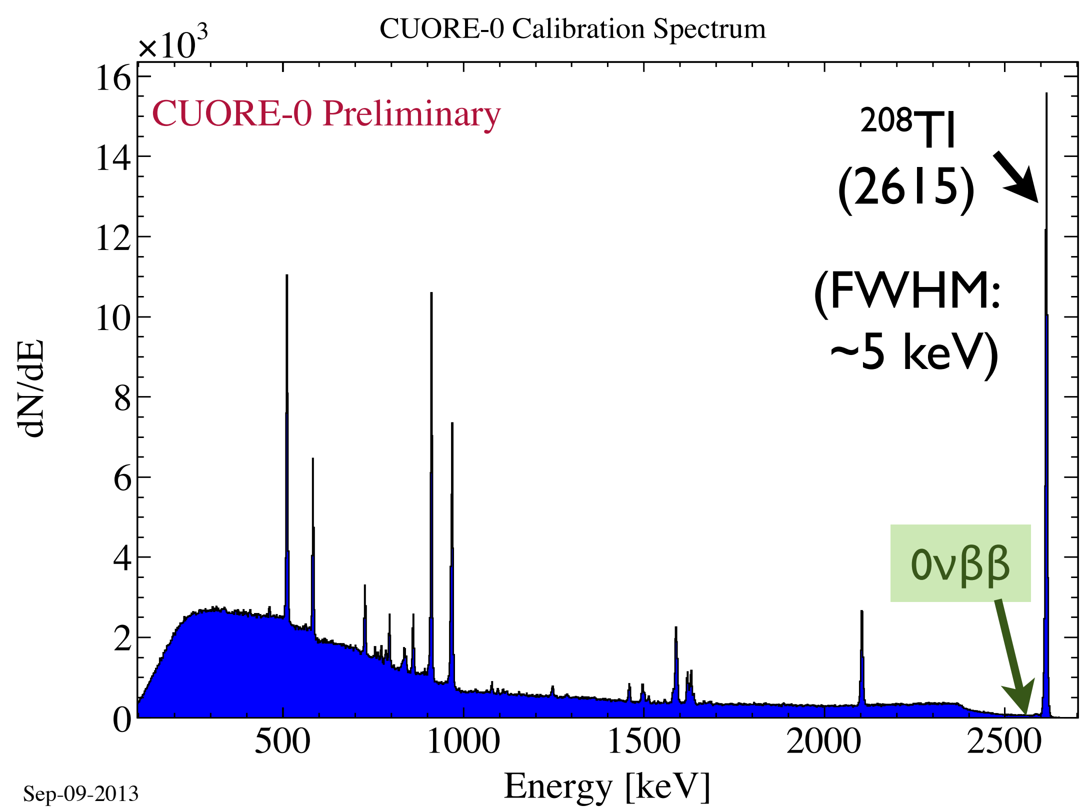
Projected (2020)

$T_{1/2}^{0\nu}$ > 9.5×10^{25} yr (90% C.L.)

Astroparticle Physics 34 (2011) 822

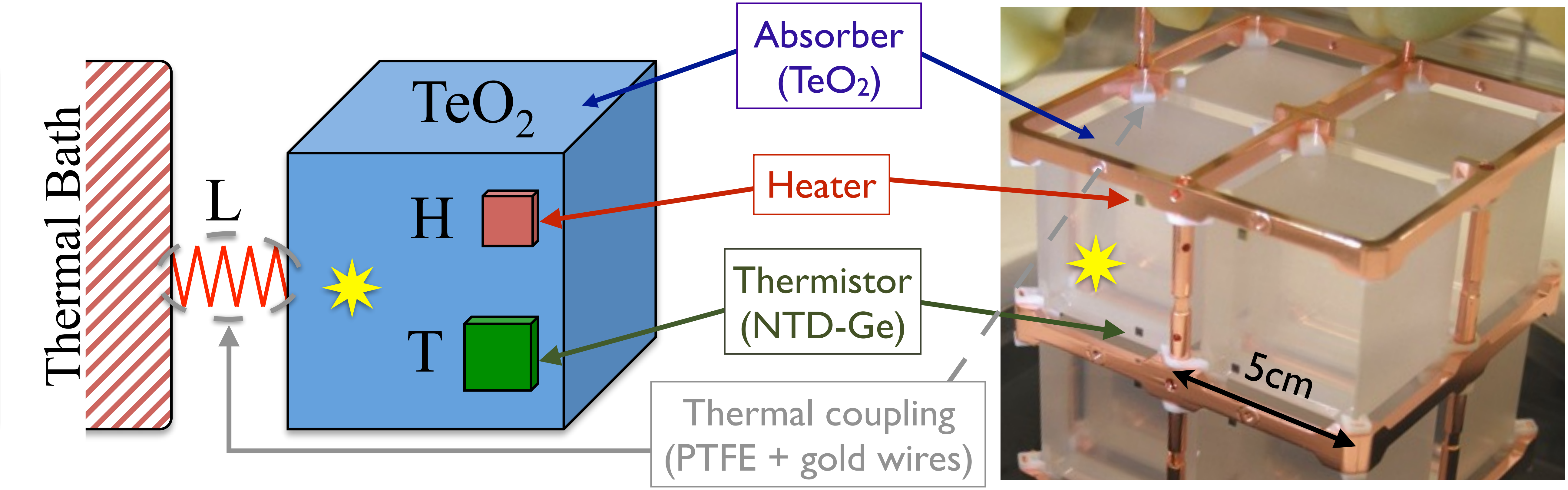




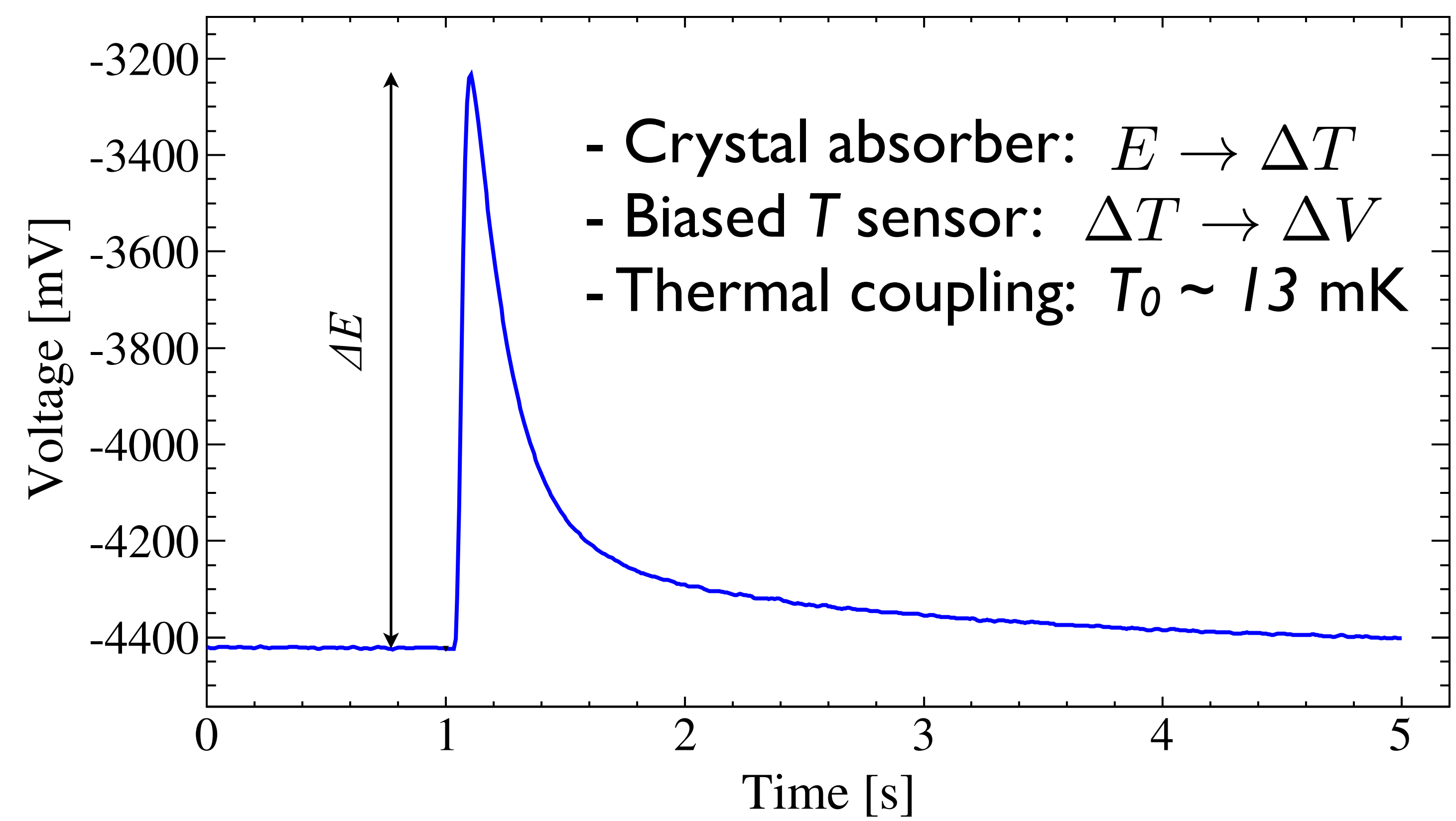


- High isotopic abundance, low background at the Q-value makes ^{130}Te appealing for 0νββ search.

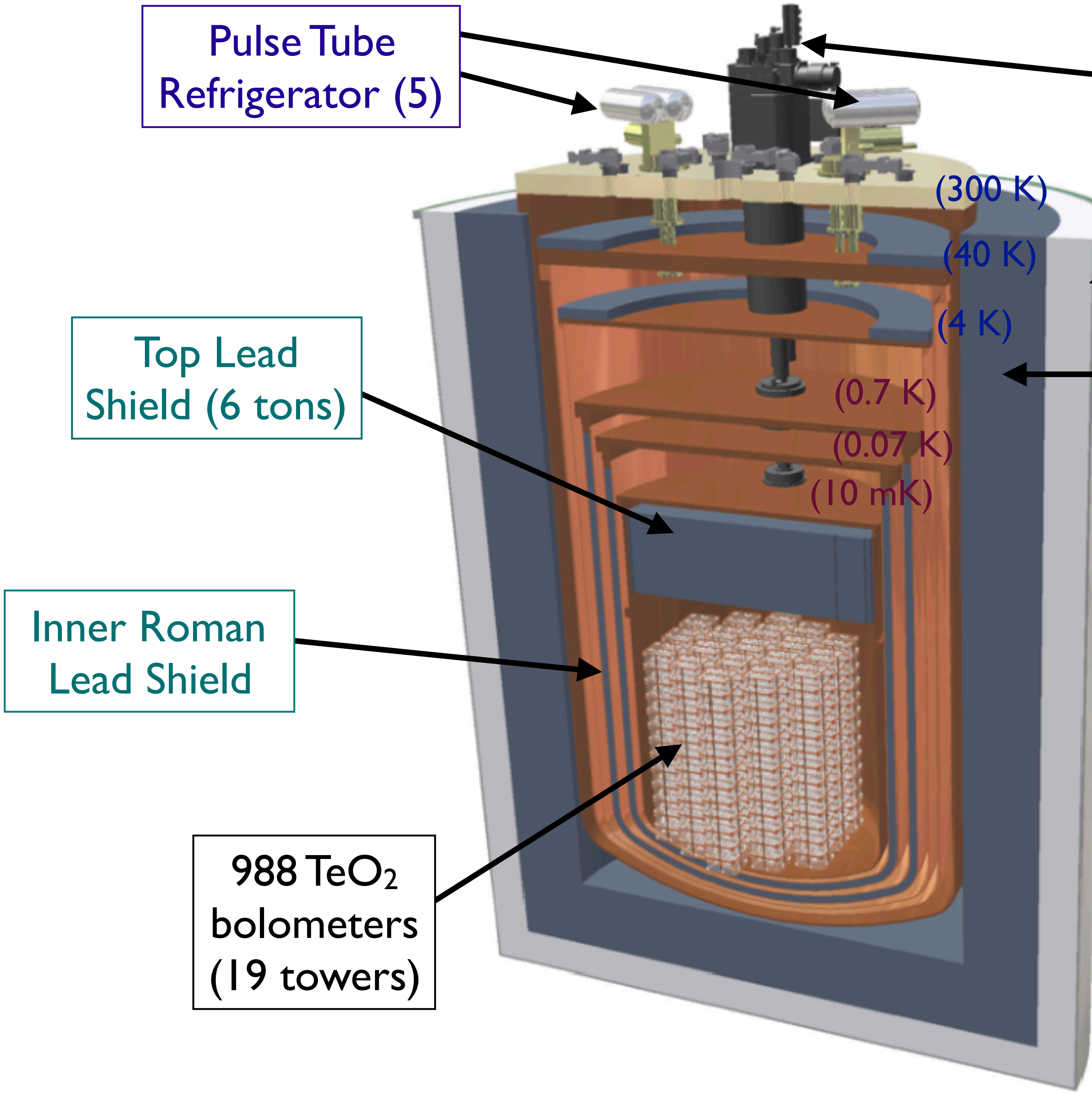
TeO_2 Bolometers



- Measure energy deposition through temperature rise.
- Provides excellent energy resolution.

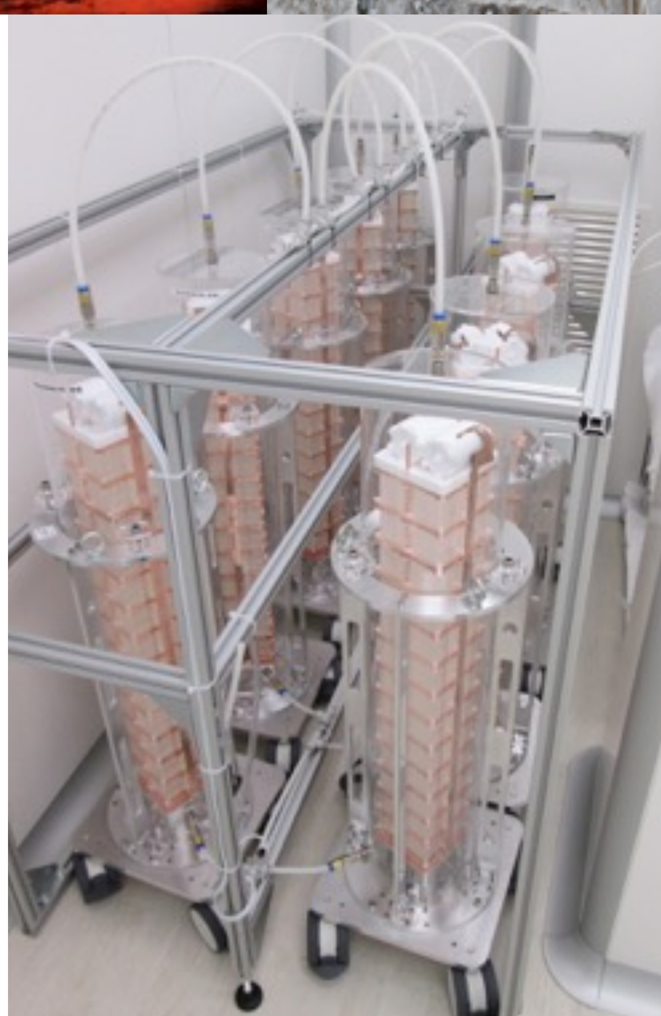


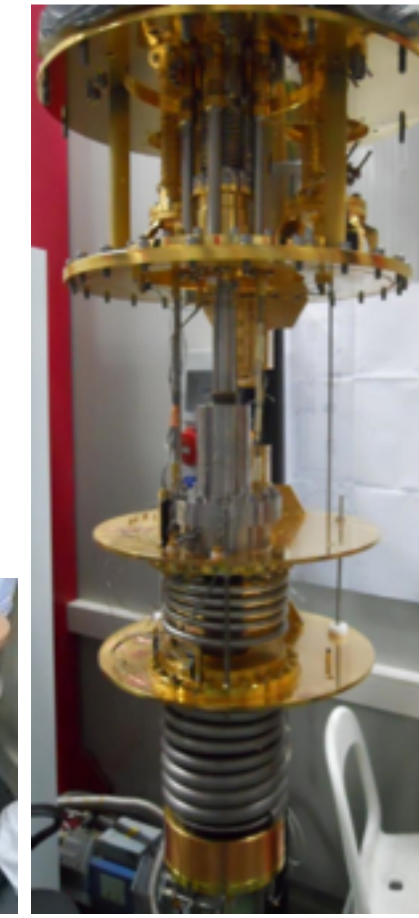
The CUORE Detector

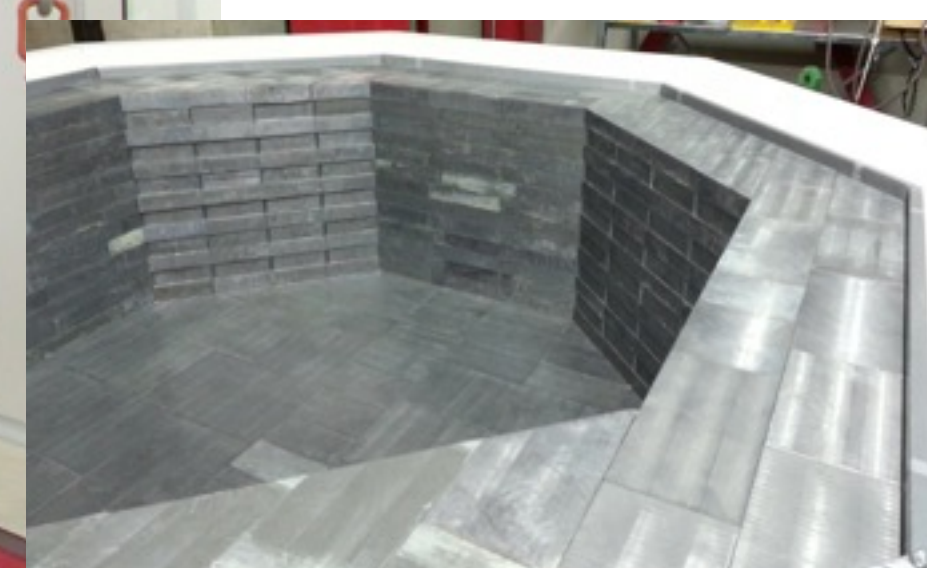


The CUORE Detector

doi:10.1038/news.2010.186 (natu







The Coldest ~ m^3 in the Known Universe

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Interactions NewsWire #71-14
21 October 2014 http://www.interactions.org
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Source: INFN
Content: Press Release
Date Issued: 21 October 2014
****

2
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CUORE: The Coldest Heart in the Known Universe

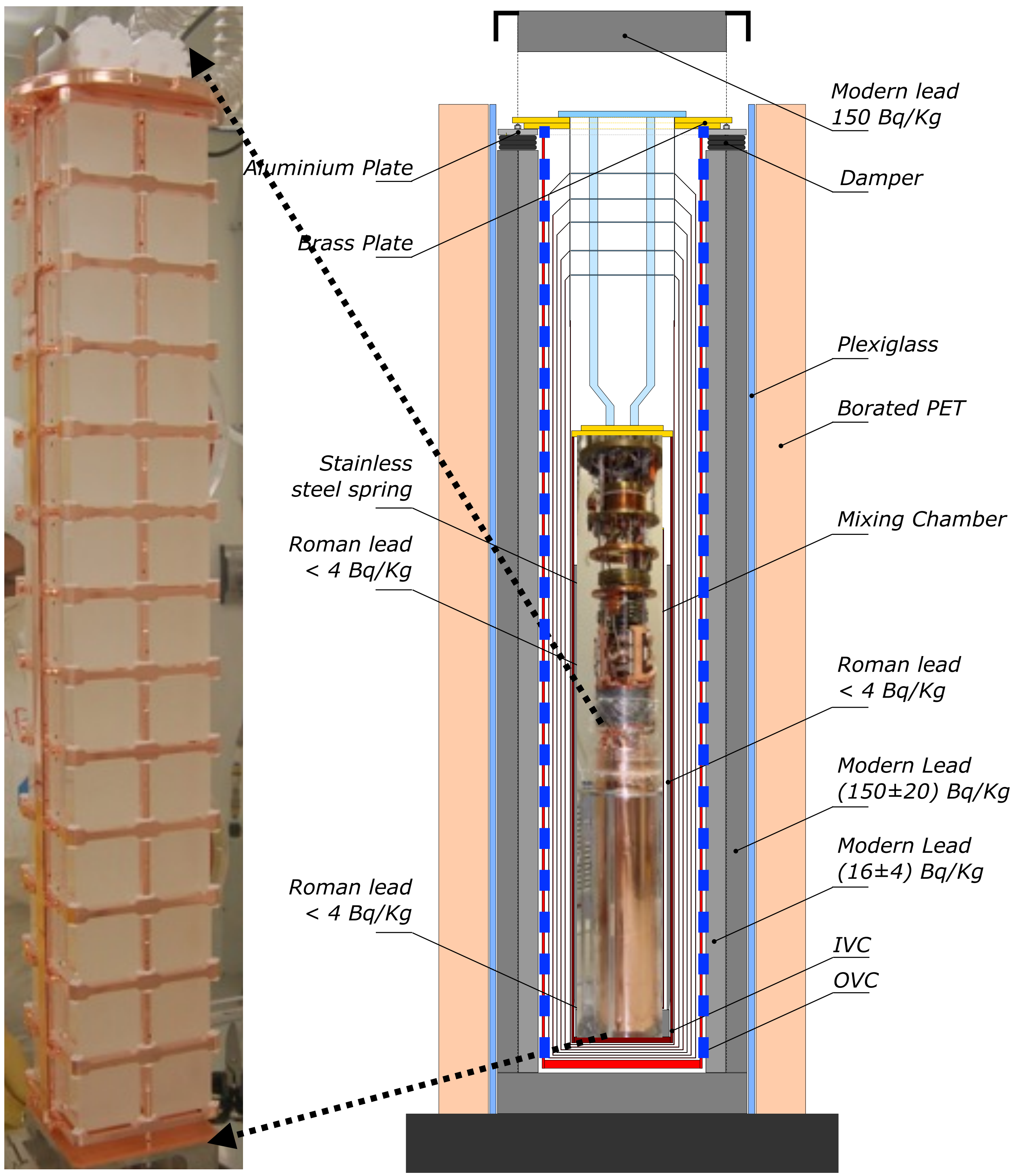
The CUORE collaboration at the INFN Gran Sasso National Laboratory has set a world record by cooling a copper vessel with the volume of a cubic meter to a temperature of 6 milliKelvins: it is the first experiment ever to cool a mass and a volume of this size to a temperature this close to absolute zero (0 Kelvin). The cooled copper mass, weighing approx. 400 kg, was the coldest cubic meter in the universe for over 15 days.

CUORE is an international collaboration involving some 130 scientists mainly from Italy, USA, China, Spain, and France. CUORE is supported by the Istituto Nazionale di Fisica Nucleare (INFN) in Italy; the Department of Energy Office of Science (Office of Nuclear Physics), the National Science Foundation, and Alfred P. Sloan Foundation in the United States.

Outline

- Neutrinoless double-beta decay ($0\nu\beta\beta$) search
- CUORE: An array of TeO_2 bolometers to search for $0\nu\beta\beta$ and other rare events
- CUORE-0: $0\nu\beta\beta$ search w/ a single CUORE tower
- WIMP Dark Matter Search with CUORE
- DM-Ice: NaI(Tl) detectors to test WIMP discovery claim
- Summary

The CUORE-0 Experiment



- 52 (13 x 4) crystals, 39 kg of TeO_2 (*11 kg of* ^{130}*Te*), 4 kg of copper structure.
- Validated new cleaning and assembly procedures for CUORE.
- Verified understanding on the background sources.

Eur. Phys. J. C 74, 2956 (2014)

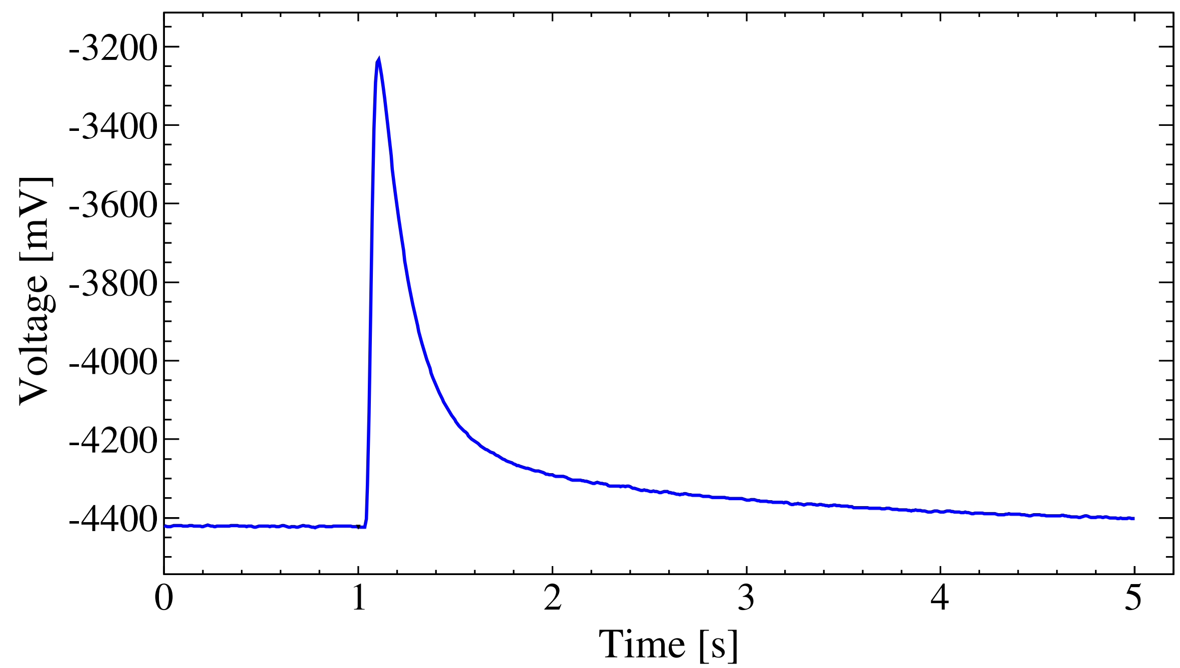
- Tested DAQ & Analysis framework for CUORE.
- Reported the limit on the half-life of $0\nu\beta\beta$ with 9.8 kg-yr of ^{130}Te exposure.

Phys. Rev. Lett. 115, 102502 (2015)

Analysis Procedure: Experimental Input

Data Acquisition
continuously sample and record the bolometer signal @ 125 S/s

Bolometer Pulse



Raw Data Processing
- software trigger thresholds (30-120 keV)
- signal, noise, pulser events
- filter pulse to optimize energy resolution
- signal (thermal) gain correction
- energy calibration (V ⟶ keV)

Blinding

ROOT
Data Trees

Event Selection
- remove low quality events
- single pulse in 7.1s window
- require pulse shape to be expected signal
- no other pulse in coincidence in other bolometers

Analysis efficiency!

Reduced Data

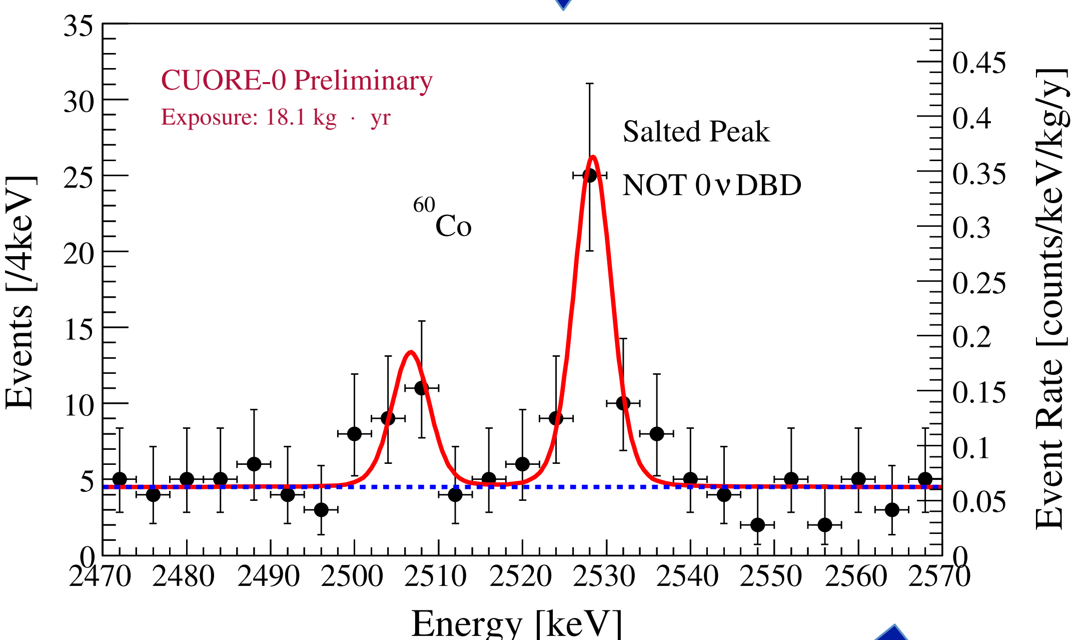
Experimental Input

calibration,
$0\nu\beta\beta$ data

background estimation,
energy resolution

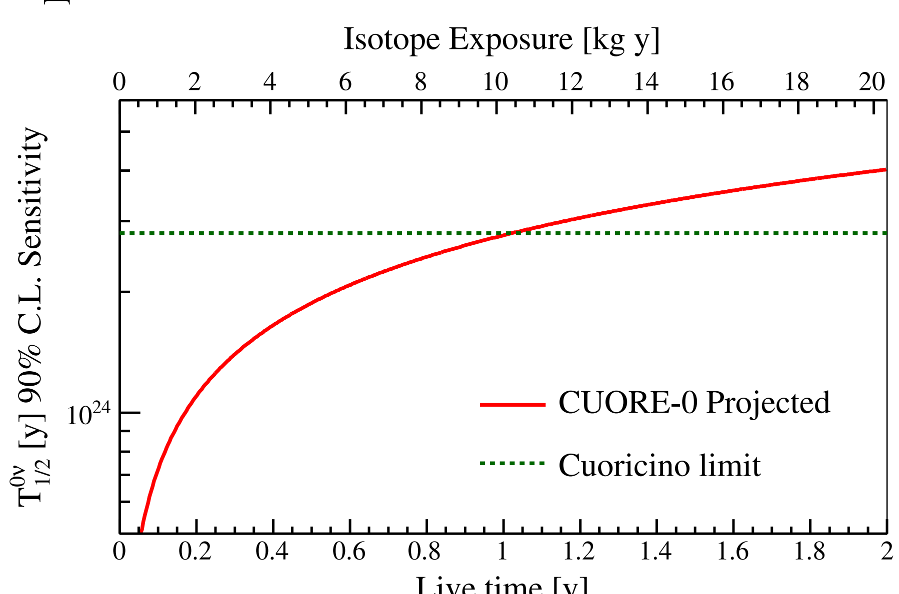
Analysis Procedure: Results & Interpretation

Data Acquisition → **Raw Data Processing** → **Event Selection** → **Experimental Input**

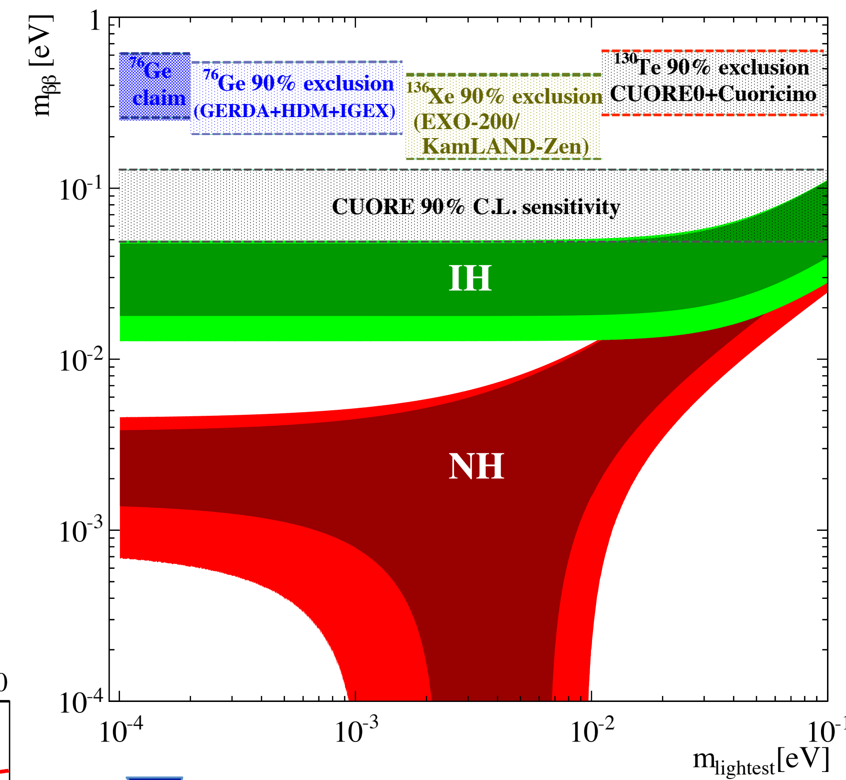


Statistical Treatment

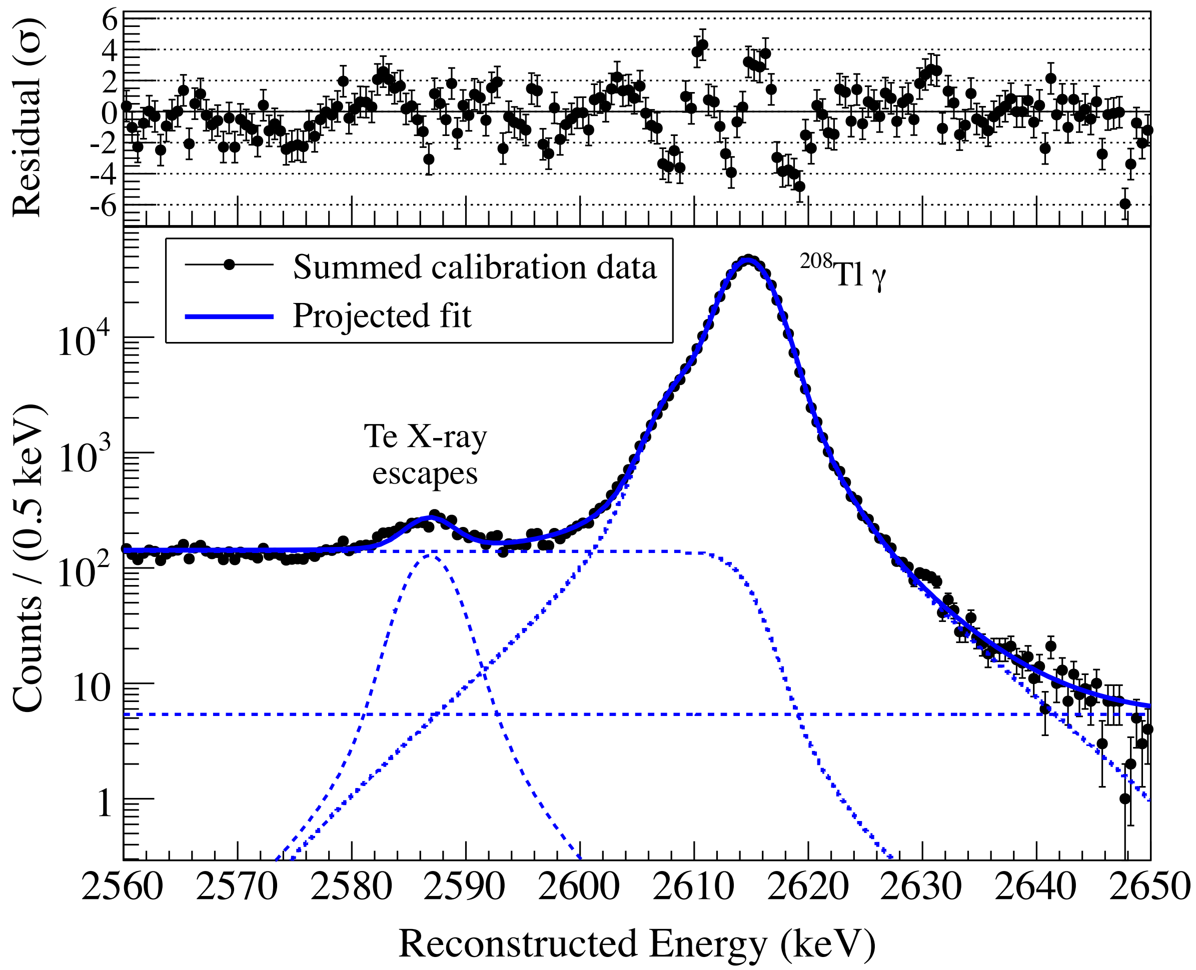
Unbinned likelihood (UEML) fit
Bayesian approach

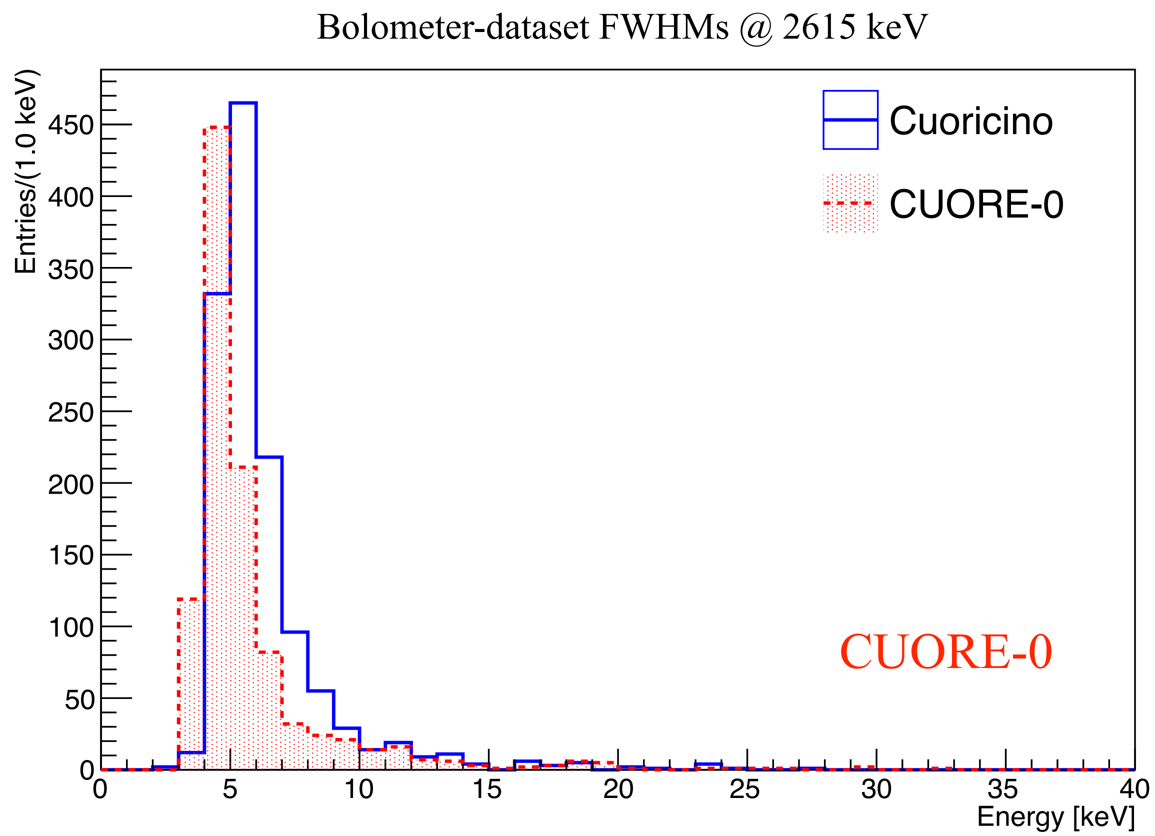


Nuclear Physics



Calibration Energy Resolution



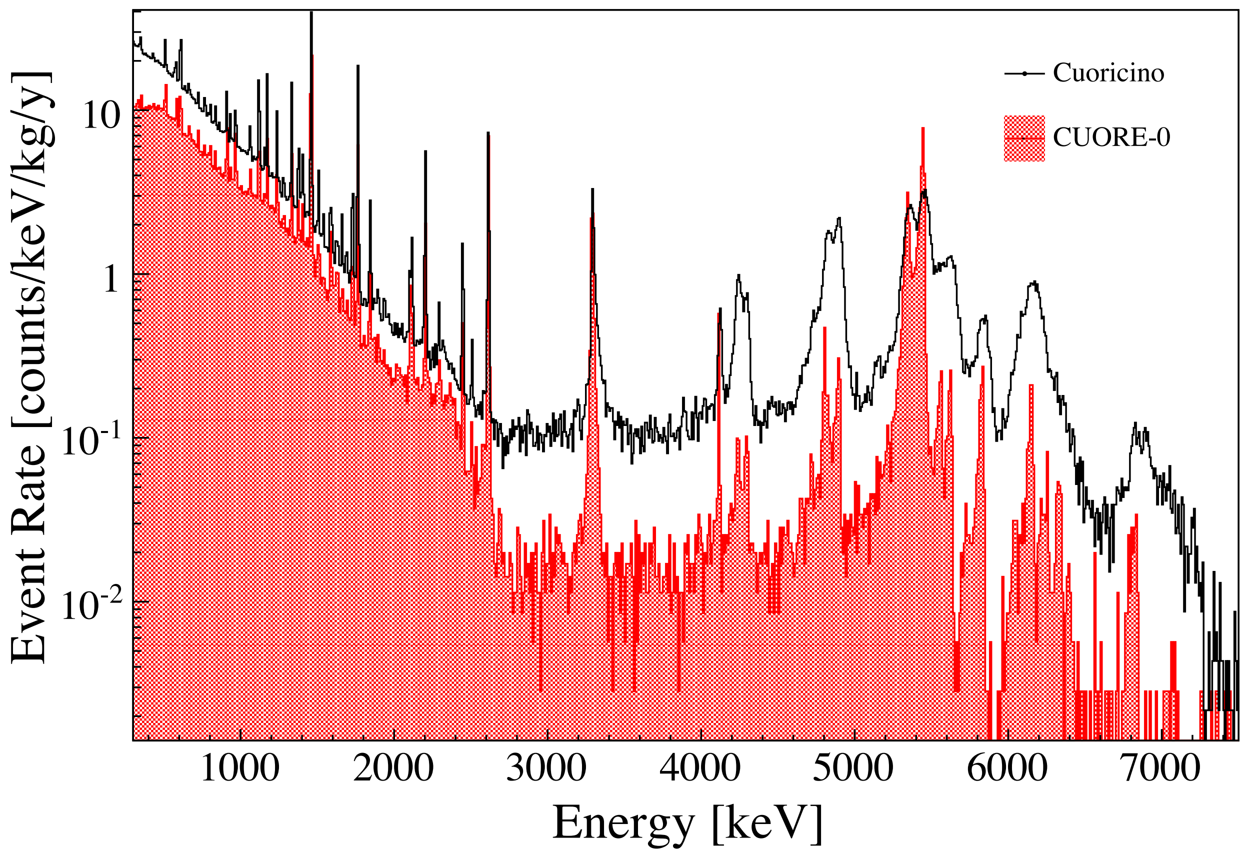


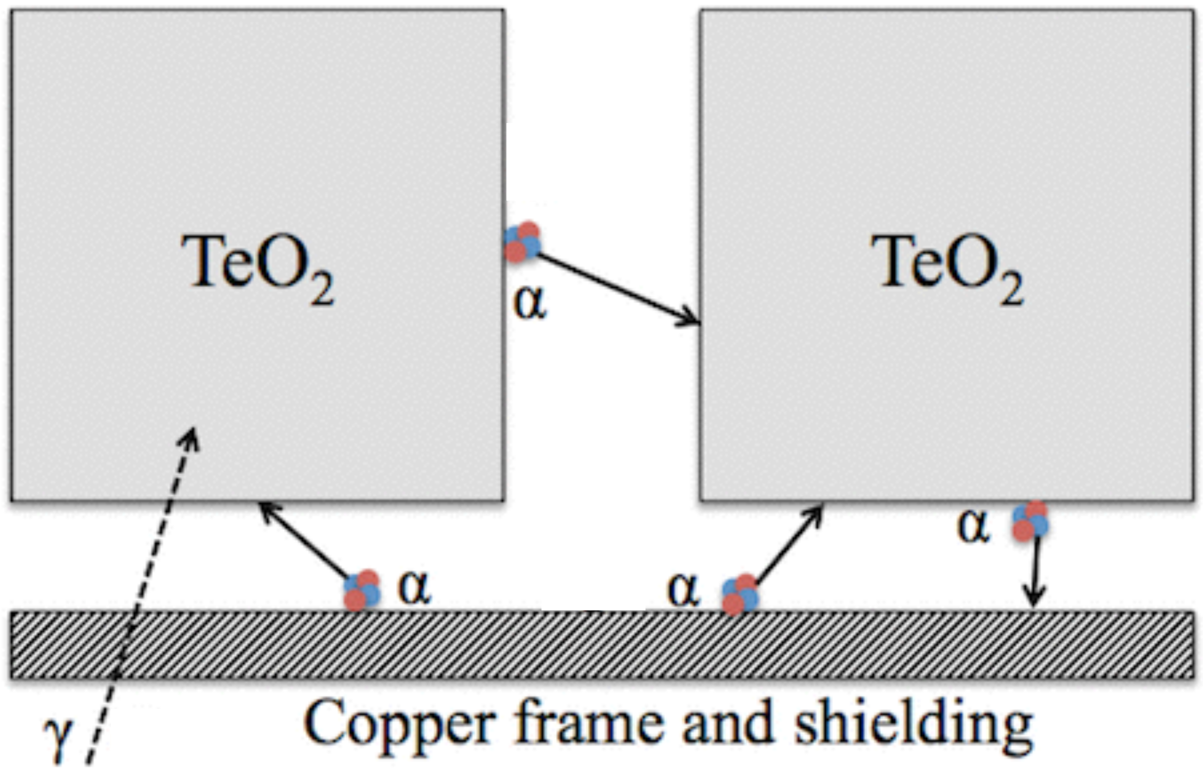
Weight FWHMs by corresponding exposure

	FWHM harmonic mean [keV]	FWHM dist RMS [keV]
Cuoricino	5.8	2.1
CUORE-0	4.9	2.9

- Energy resolution is evaluated for each bolometer and dataset by fitting the 2615 keV peak from ^{208}Tl in the calibration data.
- The obtained resolution is < 5 keV, which is the CUORE goal.

Background Comparison with Cuoricino

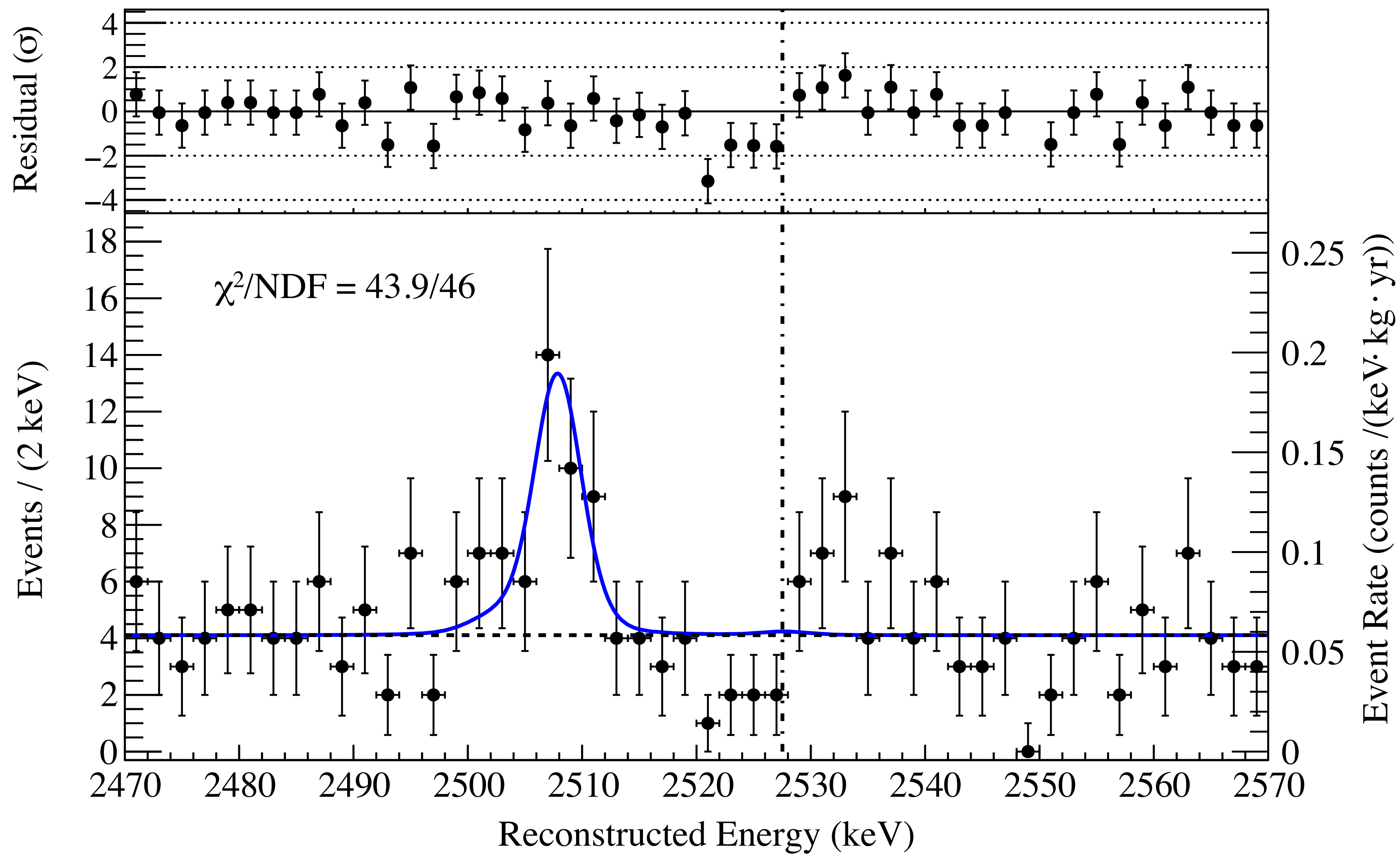




- γ background (from ^{232}Th) was not reduced since the cryostat remained the same.
- γ background (from ^{238}U chain) was reduced by a factor of 2.5 due to better radon control.
- α background from copper surface and crystal surface was reduced by a factor of 6.5 thanks to the new detector surface treatment.
- Demonstrate CUORE sensitivity goal is within reach.

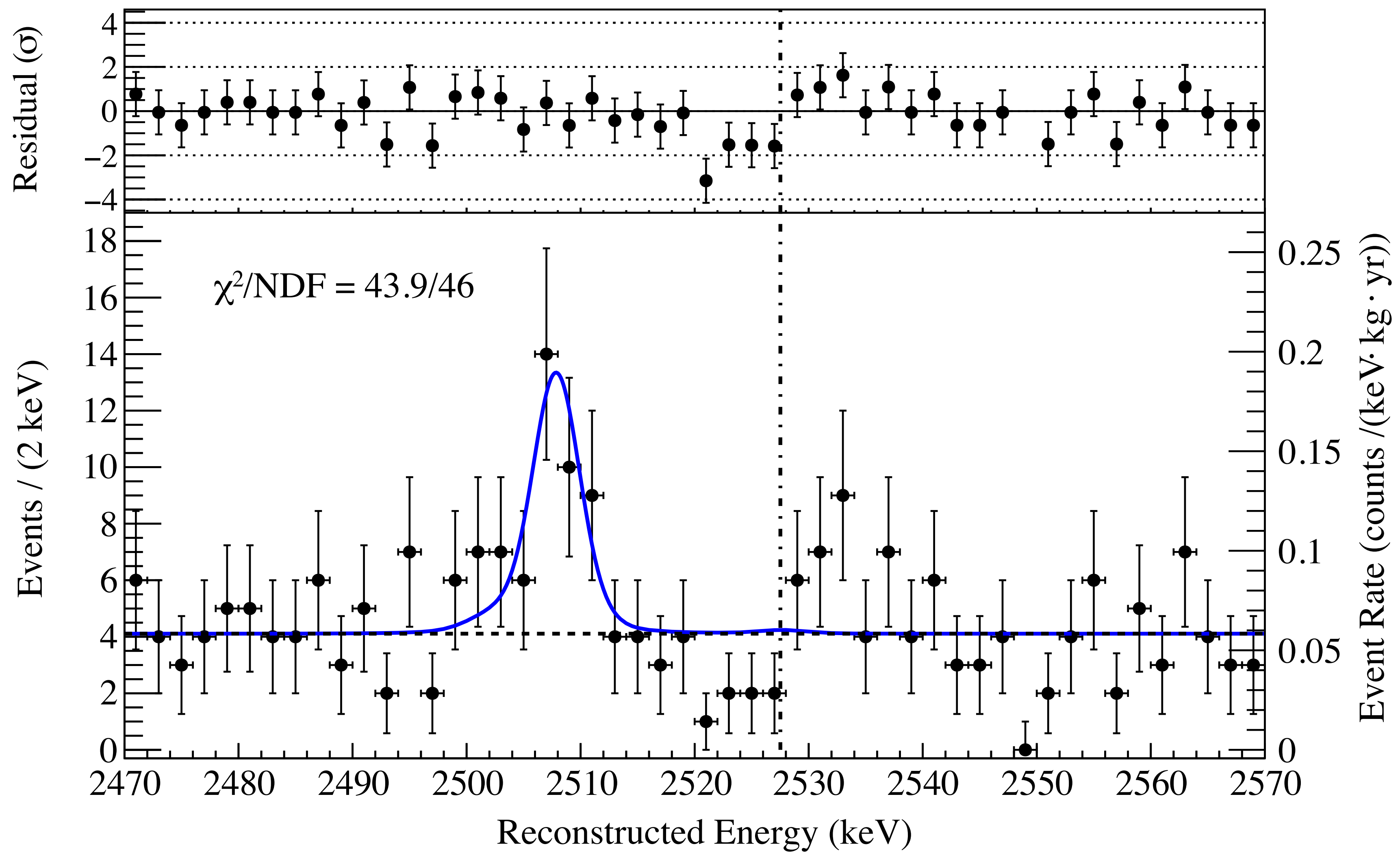
Background paper in preparation!

Fit to the Unblinded ROI



- Simultaneous unbinned extended ML fit to range [2470,2570] keV
- Fit function has 3 components:
  1. Calibration-derived lineshape modeling posited fixed at 2527.5 keV
  2. Calibration-derived lineshape modeling Co peak floated around 2505 keV
  3. Continuum flat background

Fit to the Unblinded ROI

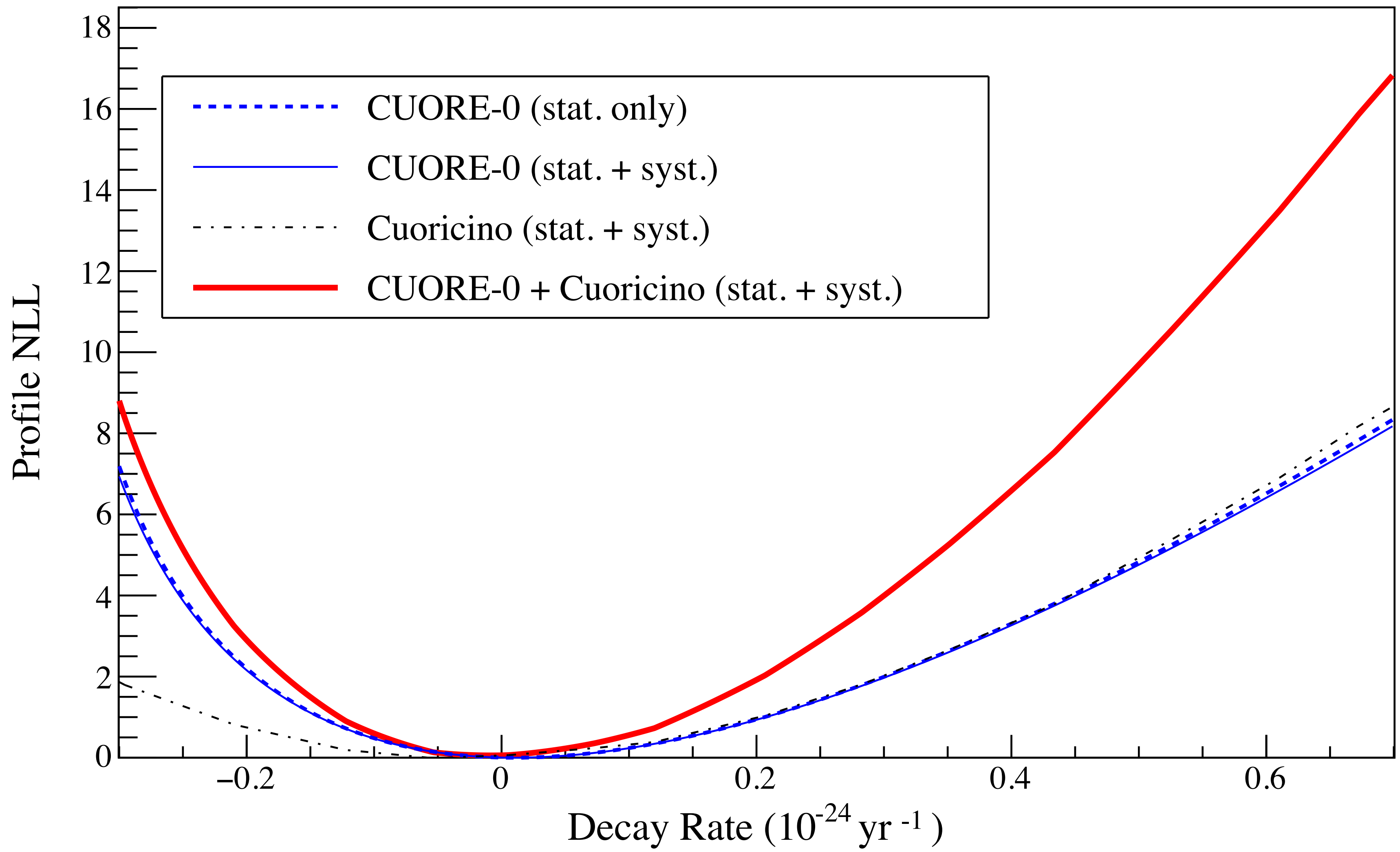


We find **no evidence** for 0νββ of ^{130}Te (report the Bayesian limits)

$$\Gamma^{0\nu\beta\beta}(^{130}\mathrm{Te}) < 0.25 \times 10^{-24}\ \mathrm{yr}^{-1}\ (90\%\ \mathrm{C.L., stat.+sys.})$$

$$T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) > 2.7 \times 10^{24}\ \mathrm{yr}\ (90\%\ \mathrm{C.L., stat.+sys.})$$

Combining Cuoricino & CUORE-0

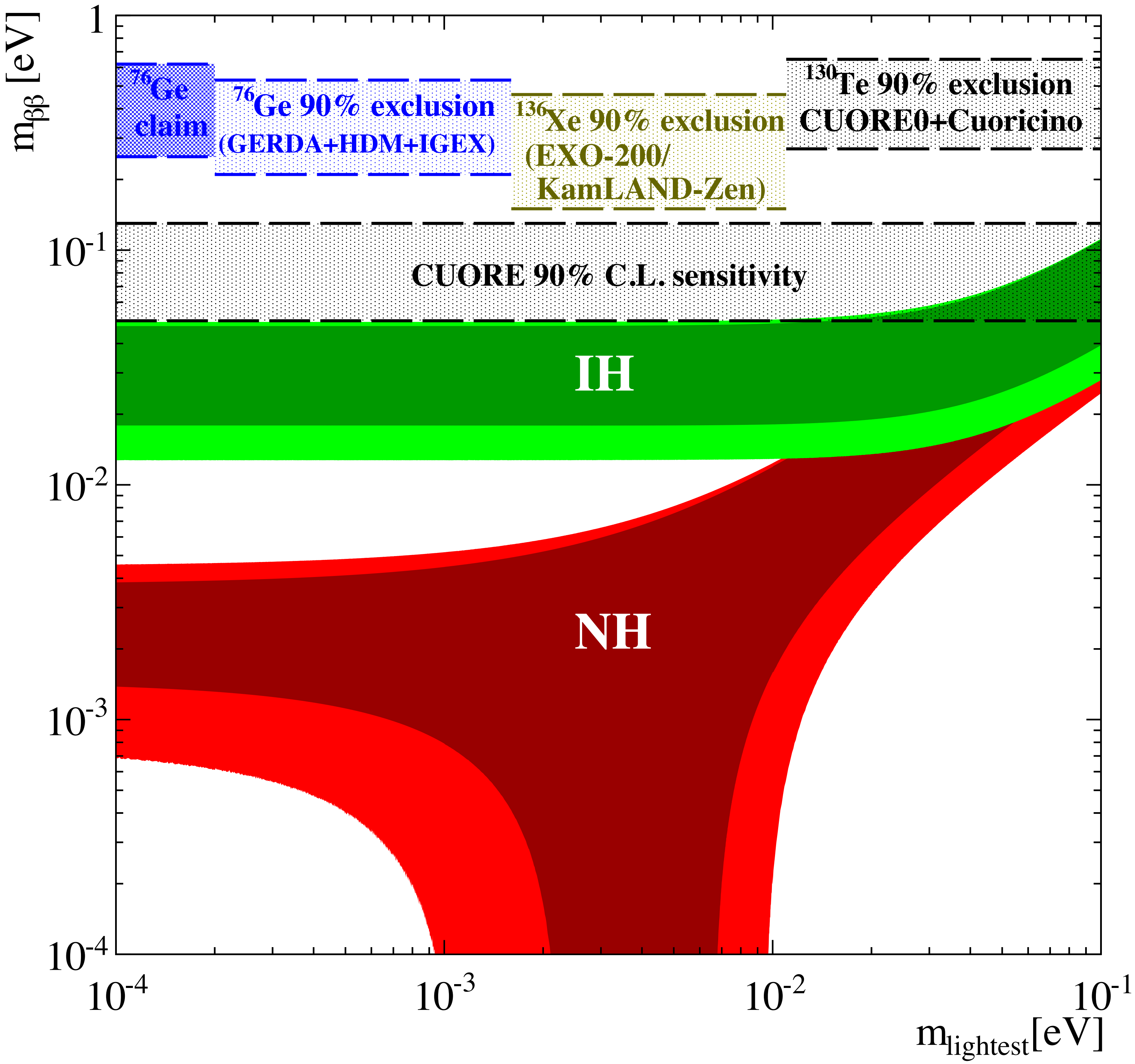


Combining the CUORE-0 result with the Cuoricino result from 19.75 kg-yr of ^{130}Te exposure yields the Bayesian lower limit:

$T_{1/2}^{0\nu\beta\beta}(^{130}\text{Te}) > 4.0 \times 10^{24}$ yr (90% C.L., stat.+sys.)

Phys. Rev. Lett. 115, 102502 (2015)

Effective Majorana Mass



$\langle m_{\beta\beta} \rangle < 270 – 650$ meV

1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015)
4) ISM (NPA 818, 139 (2009))
5) EDF (PRL 105, 252503 (2010))

Including additional Shell-Model NME

$\langle m_{\beta\beta} \rangle < 270 – 760$ meV

1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015)
4) Shell Model (PRC 91, 024309 (2015))
5) ISM (NPA 818, 139 (2009))
6) EDF (PRL 105, 252503 (2010))

Where is the field going?

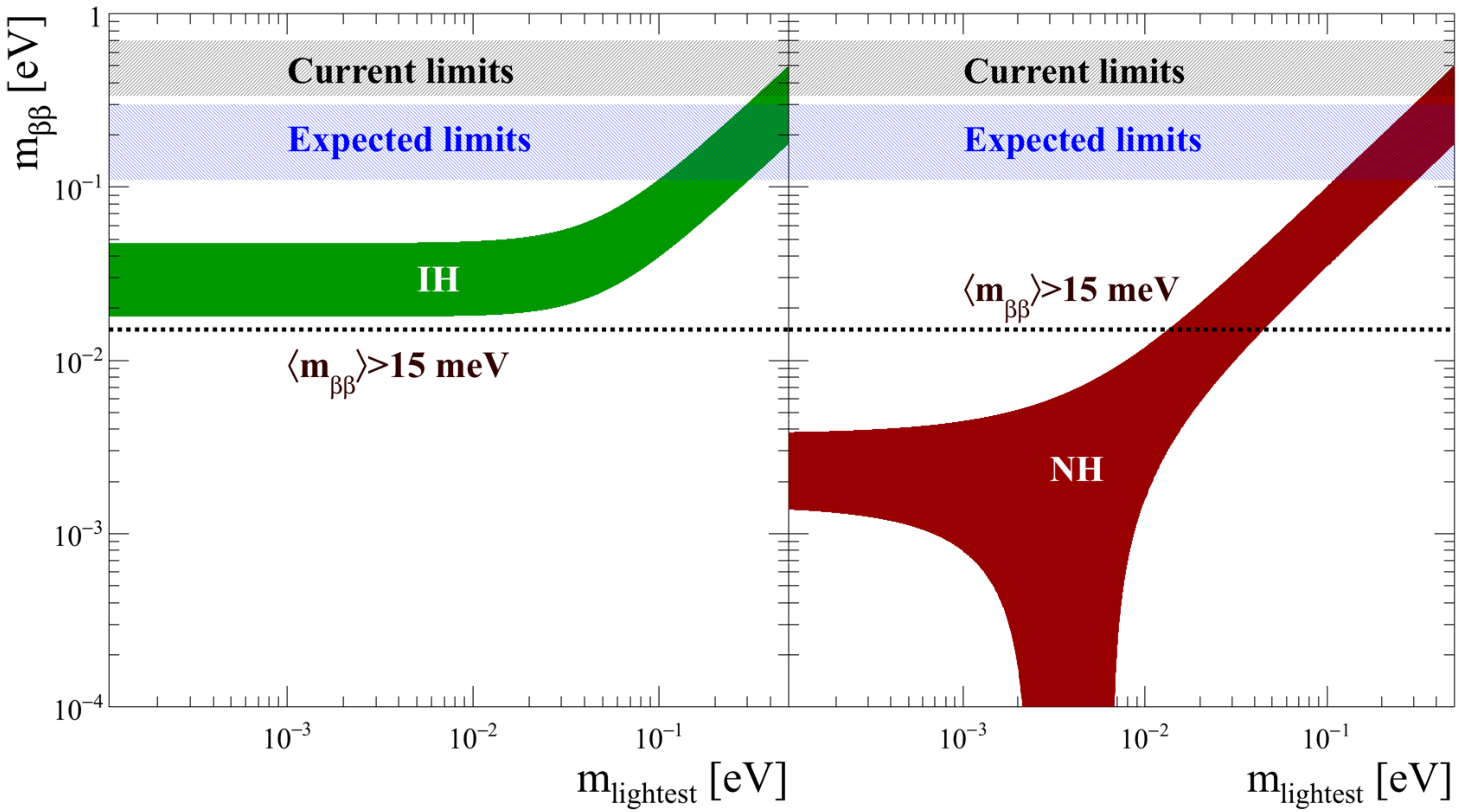


Figure 5.2: *Effective average neutrino mass from neutrinoless double beta decay vs. the mass of the lightest neutrino. Current limits and expected limits from ongoing experiments are shown as gray and blue horizontal bands. The green (for inverted hierarchy) and red (for normal hierarchy) bands show the expected ranges within the light Majorana neutrino exchange mechanism. Next-generation ton-scale experiments aim to probe effective Majorana neutrino masses down to 15 meV, shown as the horizontal dashed line.*

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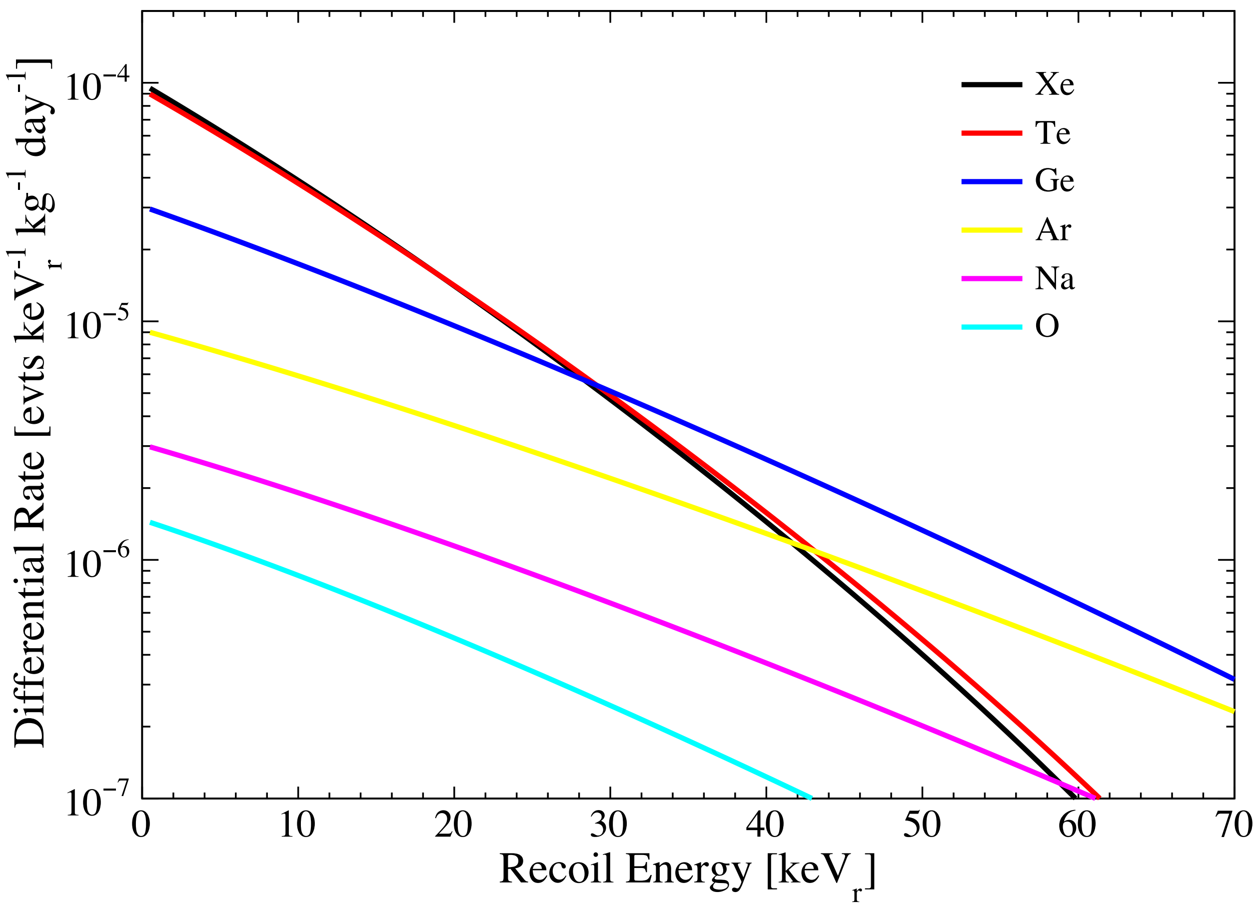
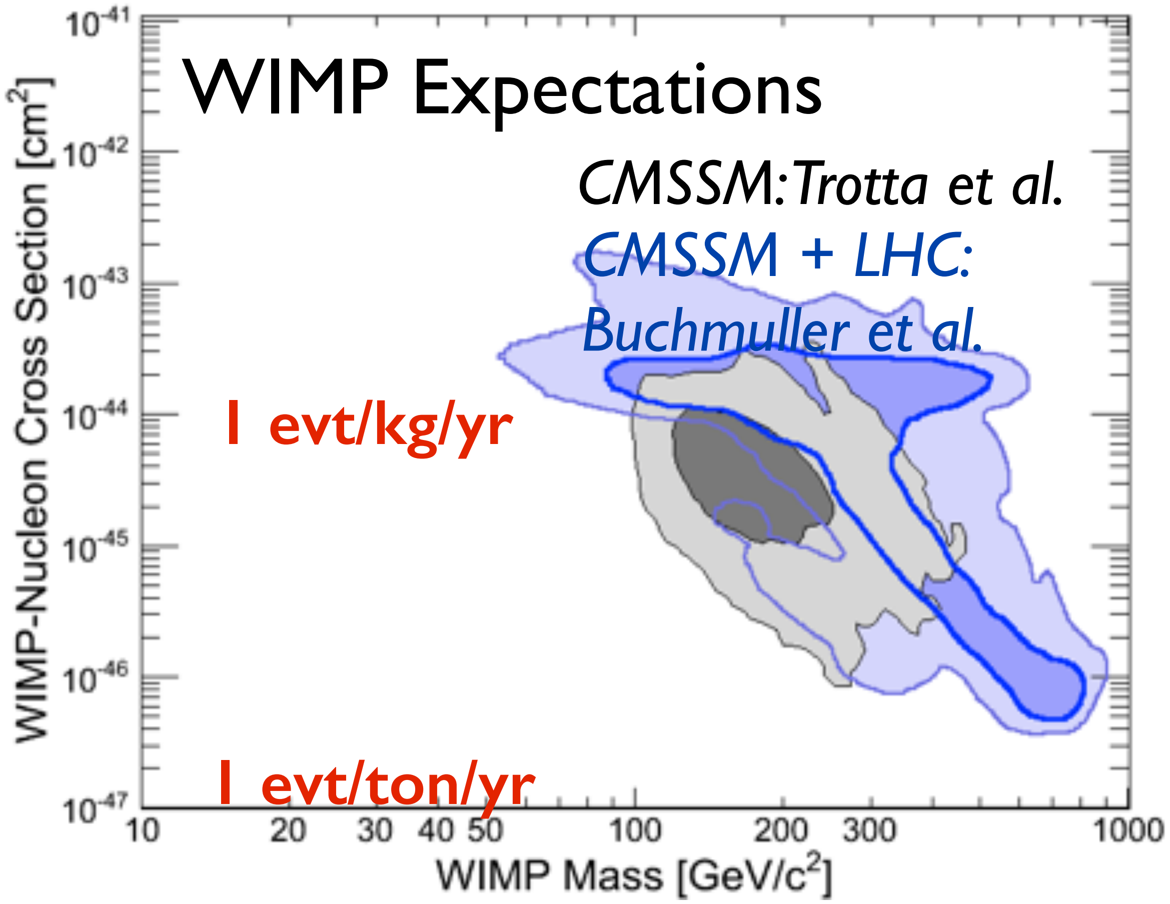
- Summary

WIMP Direct Detection Search

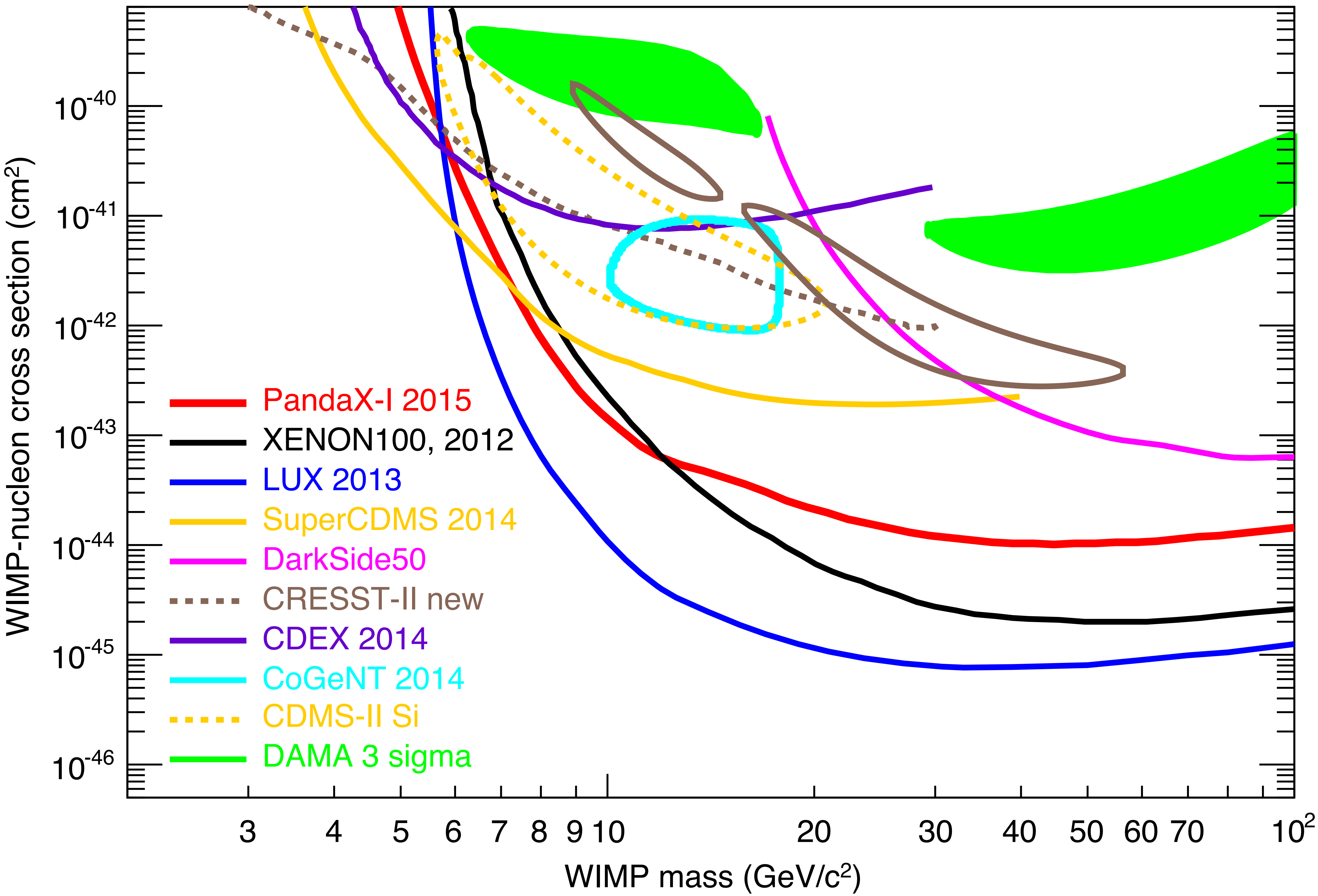




Summary:
Exponentially Falling
Tiny Rates

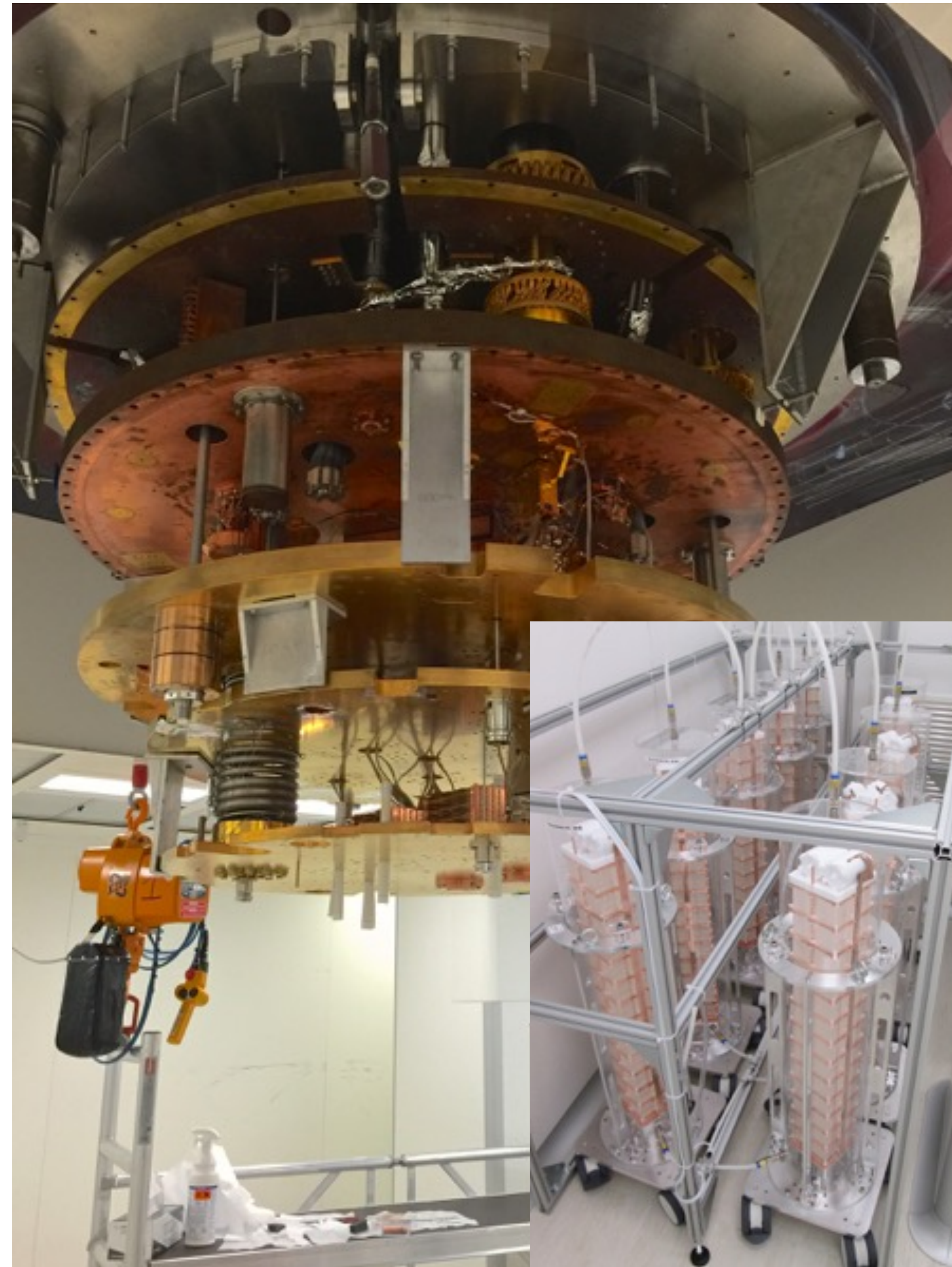
- Large total mass
- Stable detector operation
- Low energy threshold
- Very low background

Status of the WIMP Direct Detection Searches



WIMP Search with CUORE

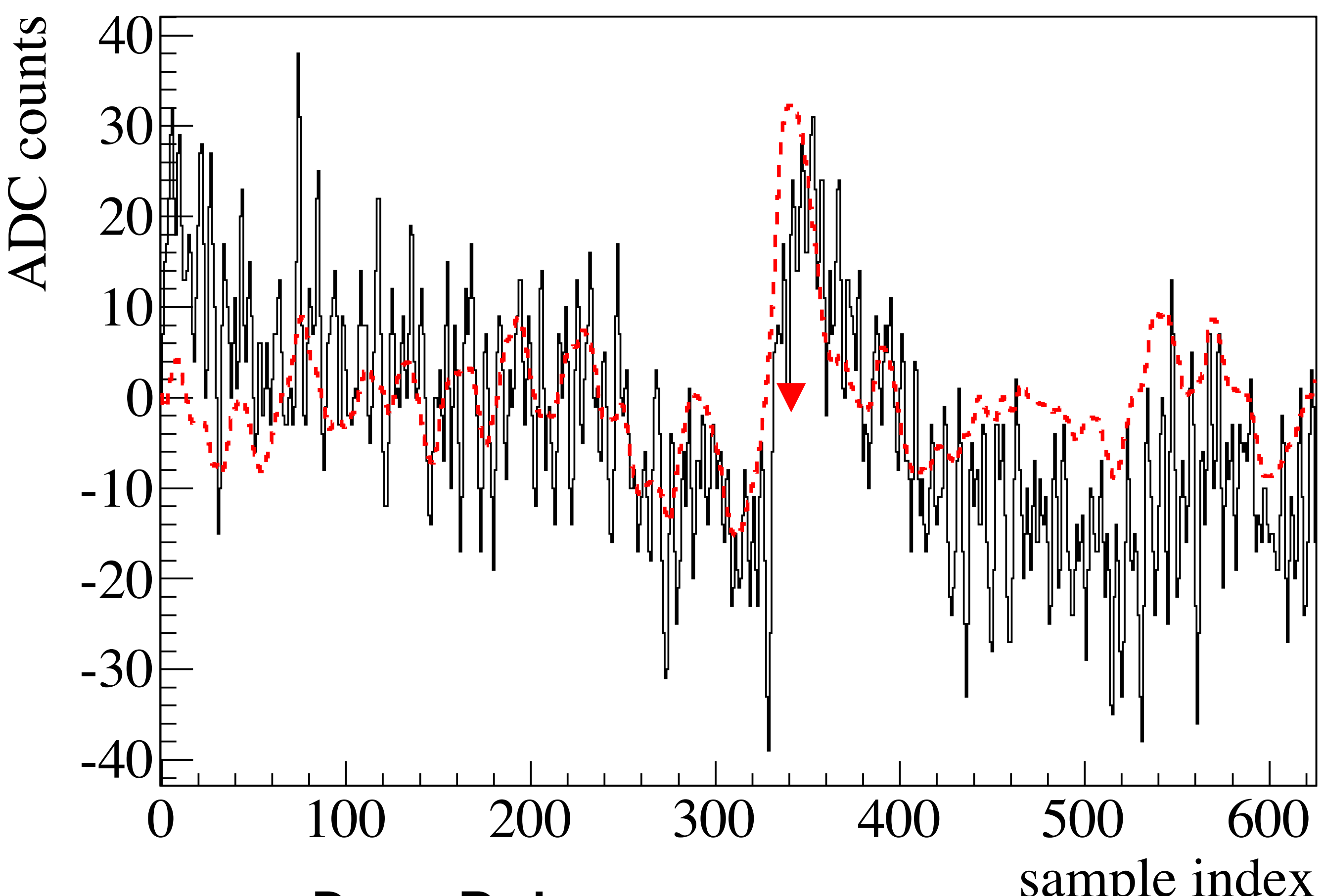
- Total target mass of 741 kg
- Stable detector operation expected with pulse tube and dilution refrigerators
- Bolometer offers low energy threshold and good energy resolution
- Quenching factor ~ 1 benefits detection of nuclear recoil events
- **First dark matter search to test DAMA with Te**



WIMP Search with CUORE: Energy Threshold

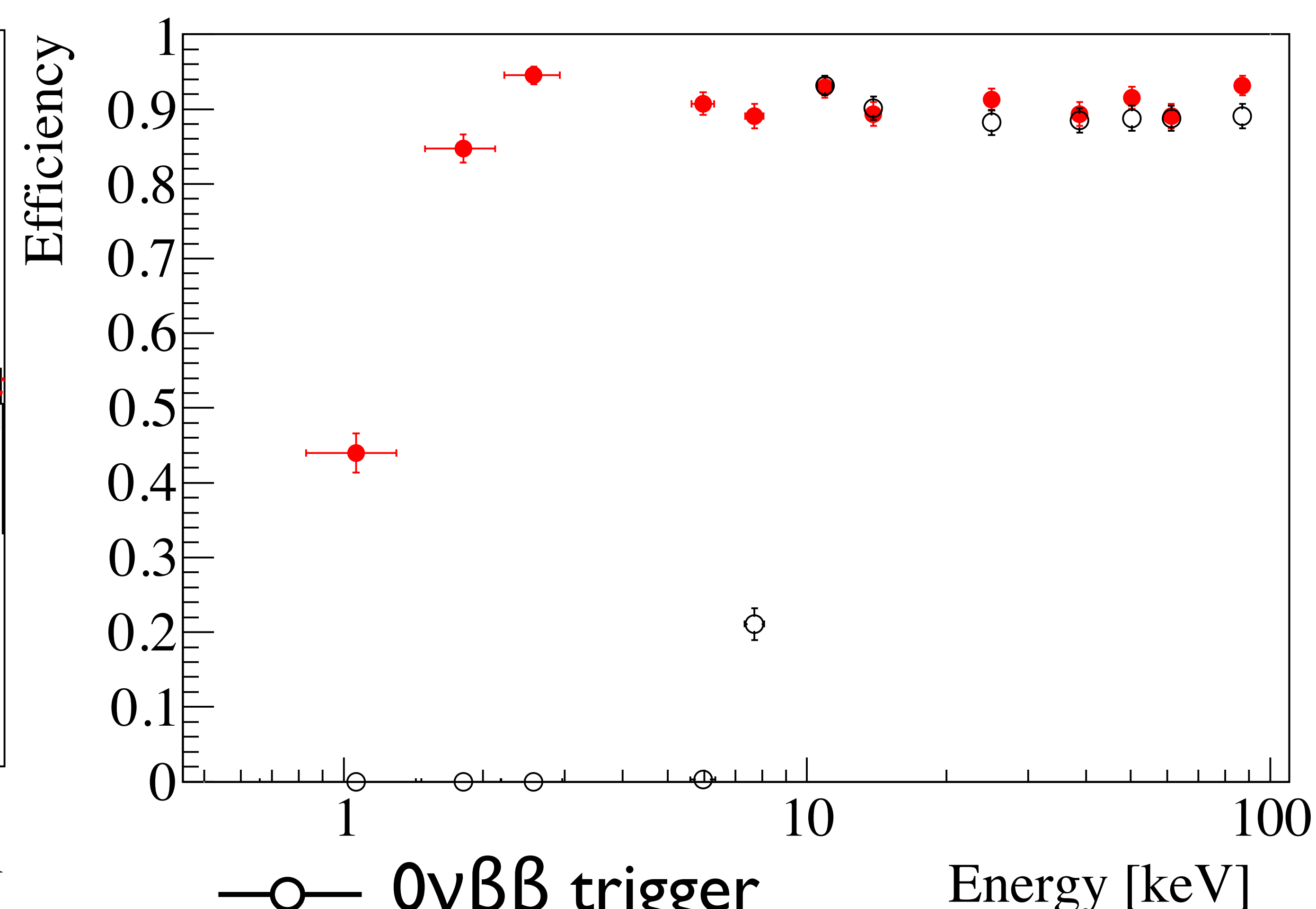
- Continuous Data Acquisition provides access to the low energy events
- Optimal Filter can identify low energy events

3 keV signal



Raw Pulse
Optimal Filtered Pulse

Detection Efficiency

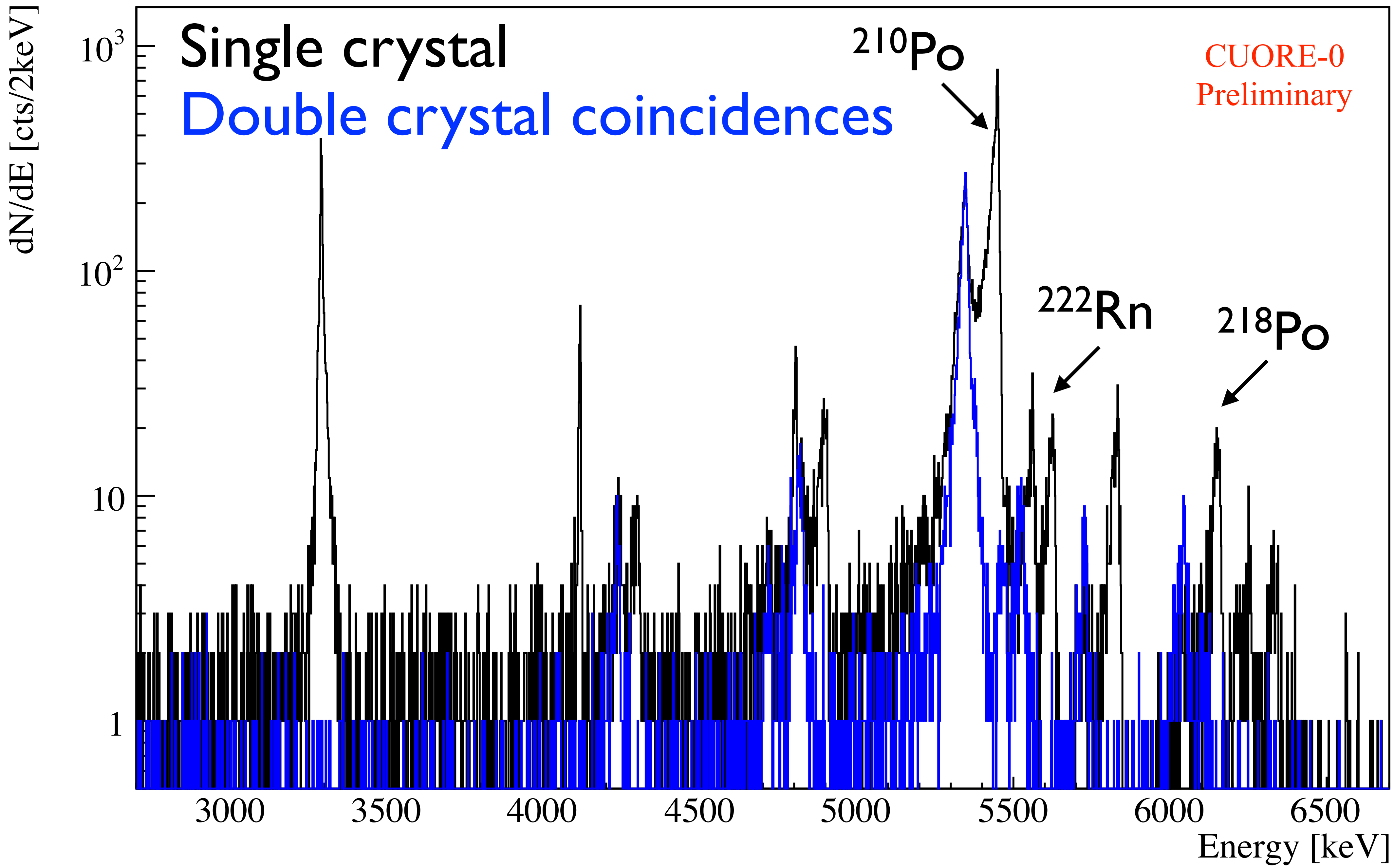


$0\nu\beta\beta$ trigger
Dark matter trigger

JINST 6 (2011) P02007

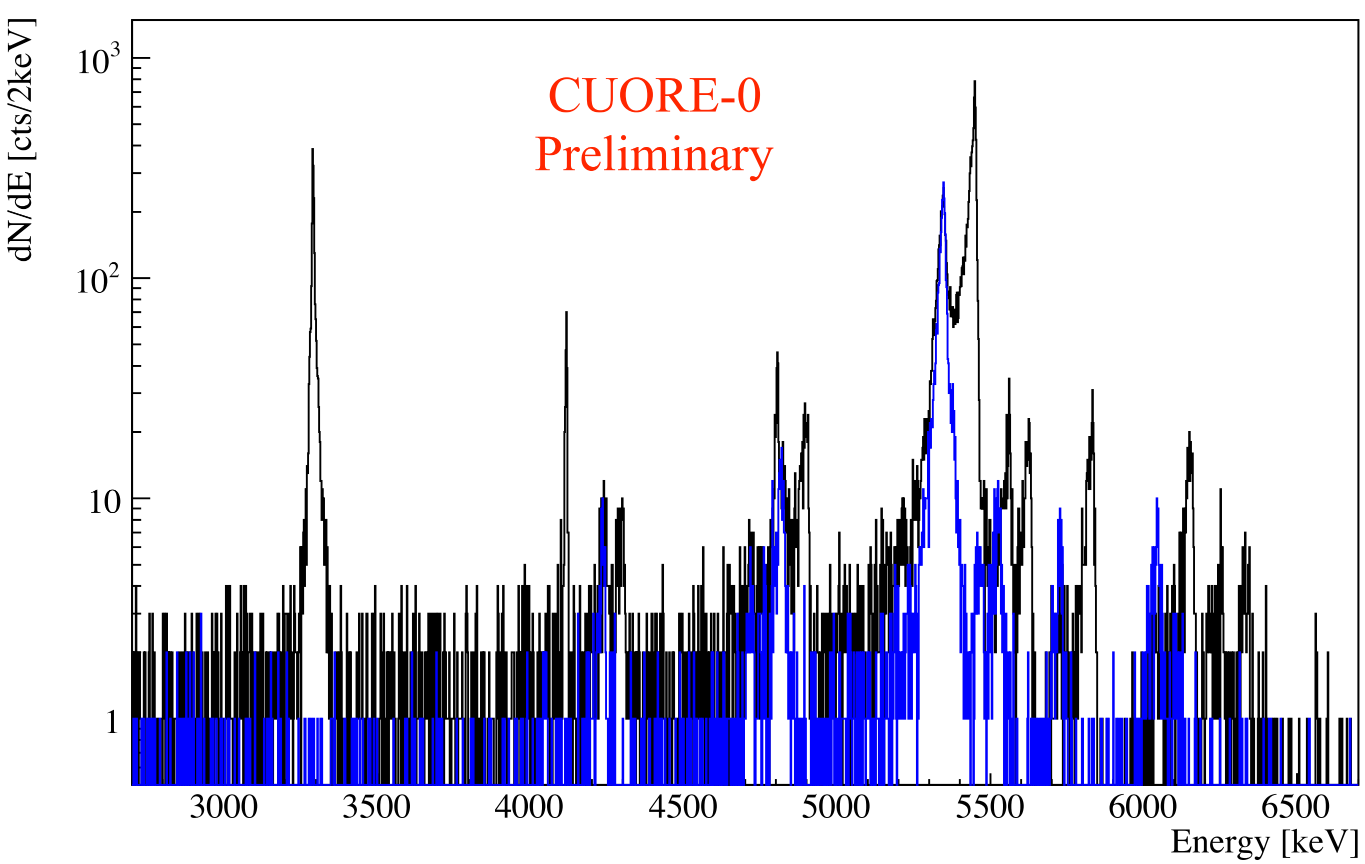
Nuclear Recoil Quenching

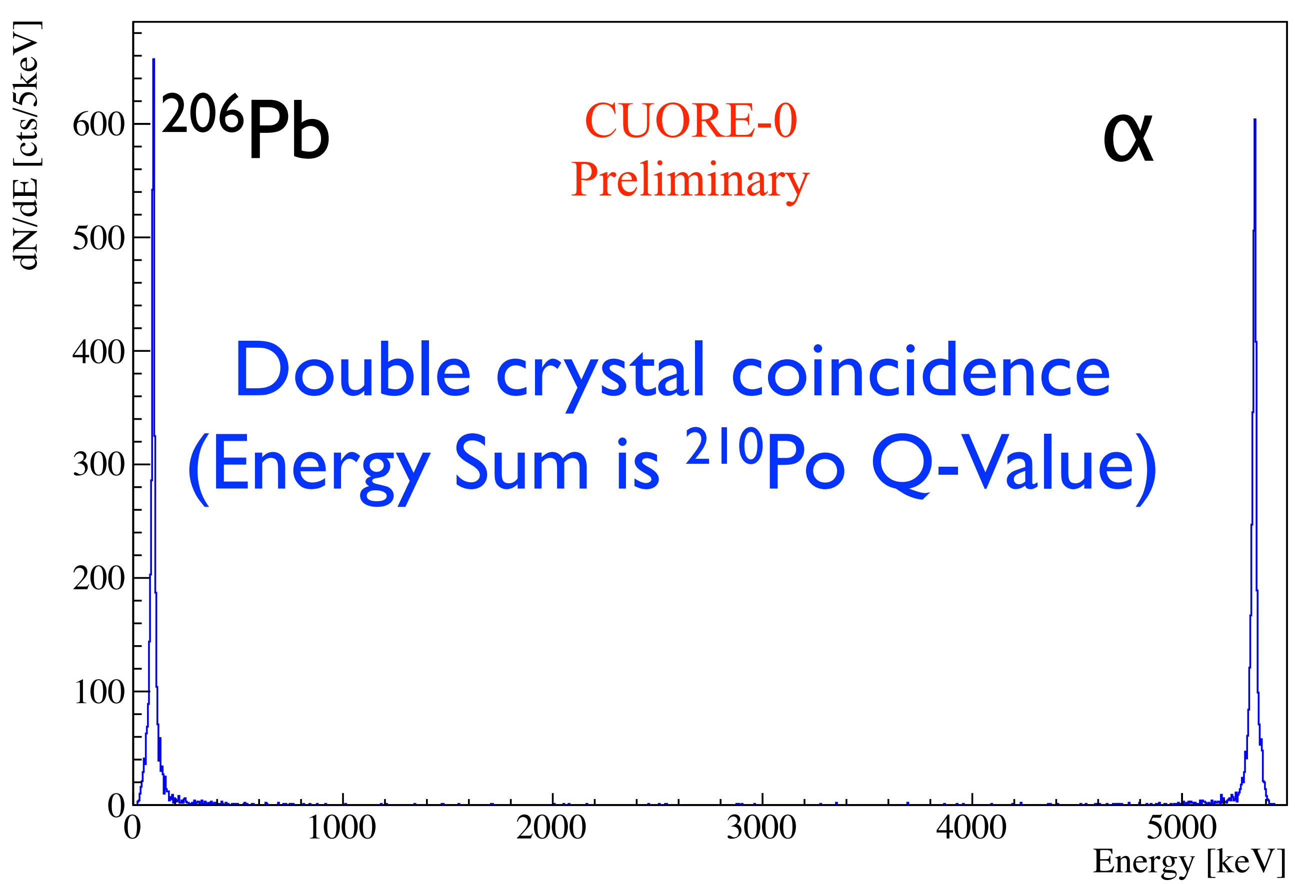
- Using surface alpha events, it is possible to measure nuclear quenching of recoiling nuclei from ^{210}Po, ^{218}Po, ^{222}Rn decays



Nuclear Recoil Quenching

- Using surface alpha events, it is possible to measure nuclear quenching of recoiling nuclei from ^{210}Po, ^{218}Po, ^{222}Rn decays
- Nuclear quenching factor of phonon detector is expected to be 1
- The largest deviation from 1 measured by ^{206}Pb was integrated as uncertainty on the nuclear recoil energy scale





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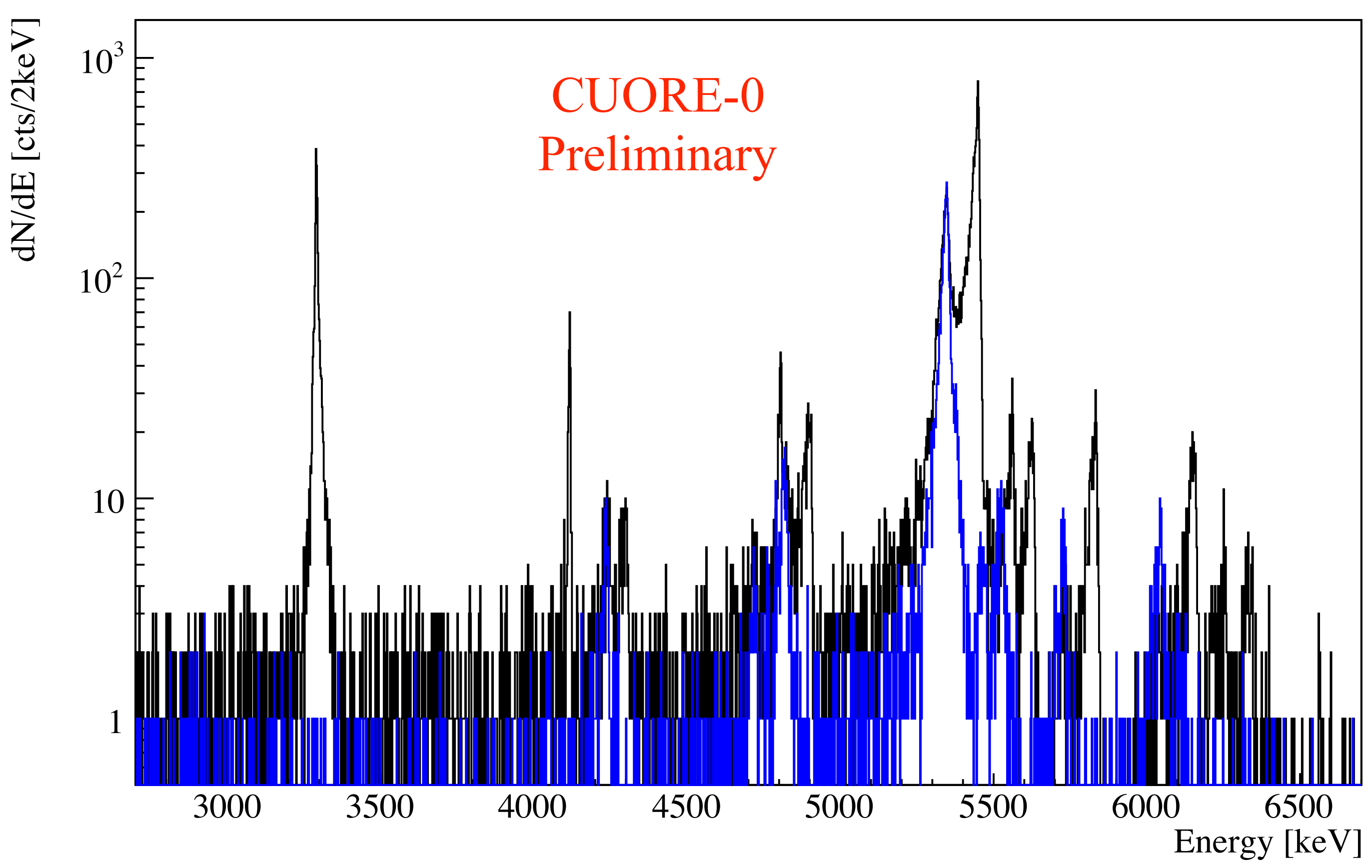
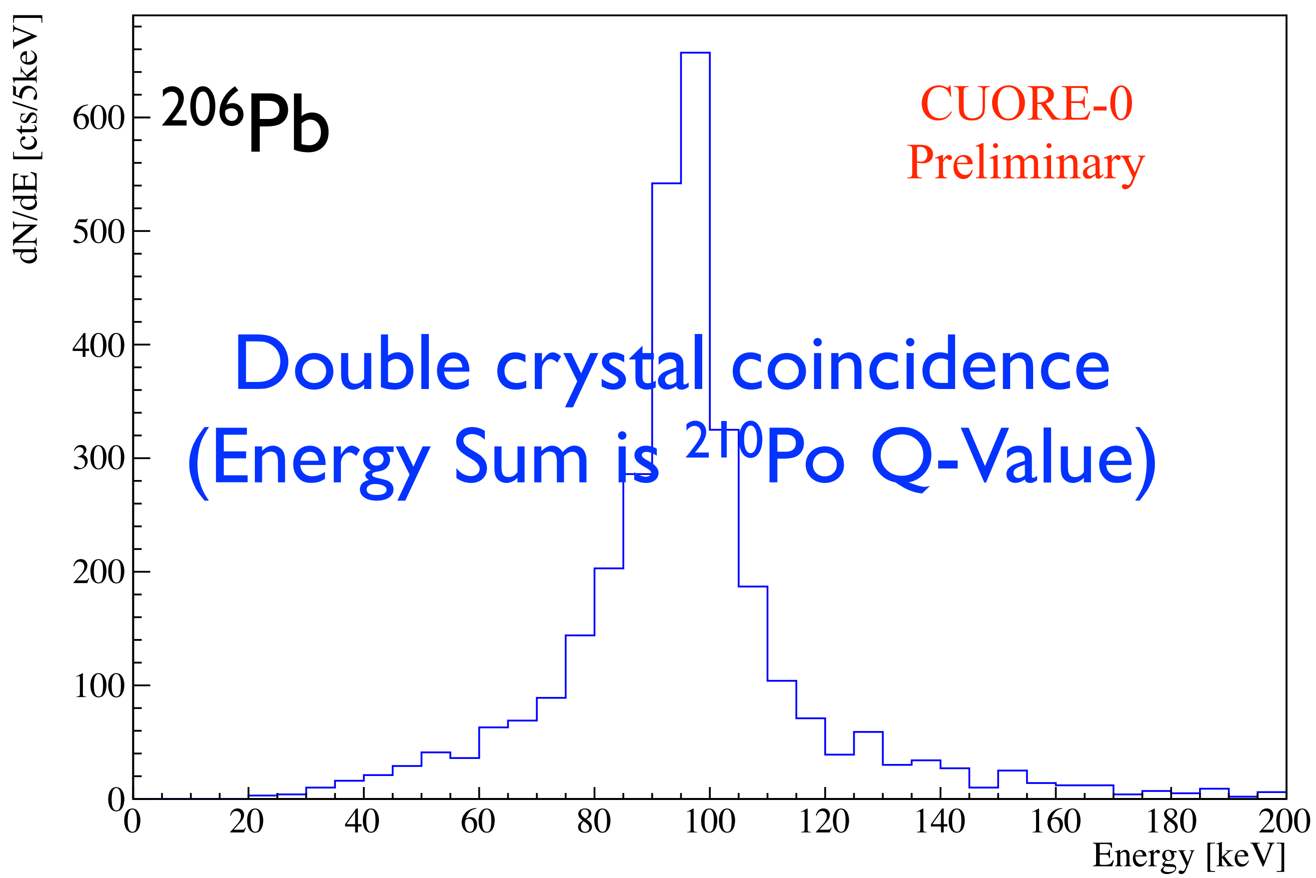
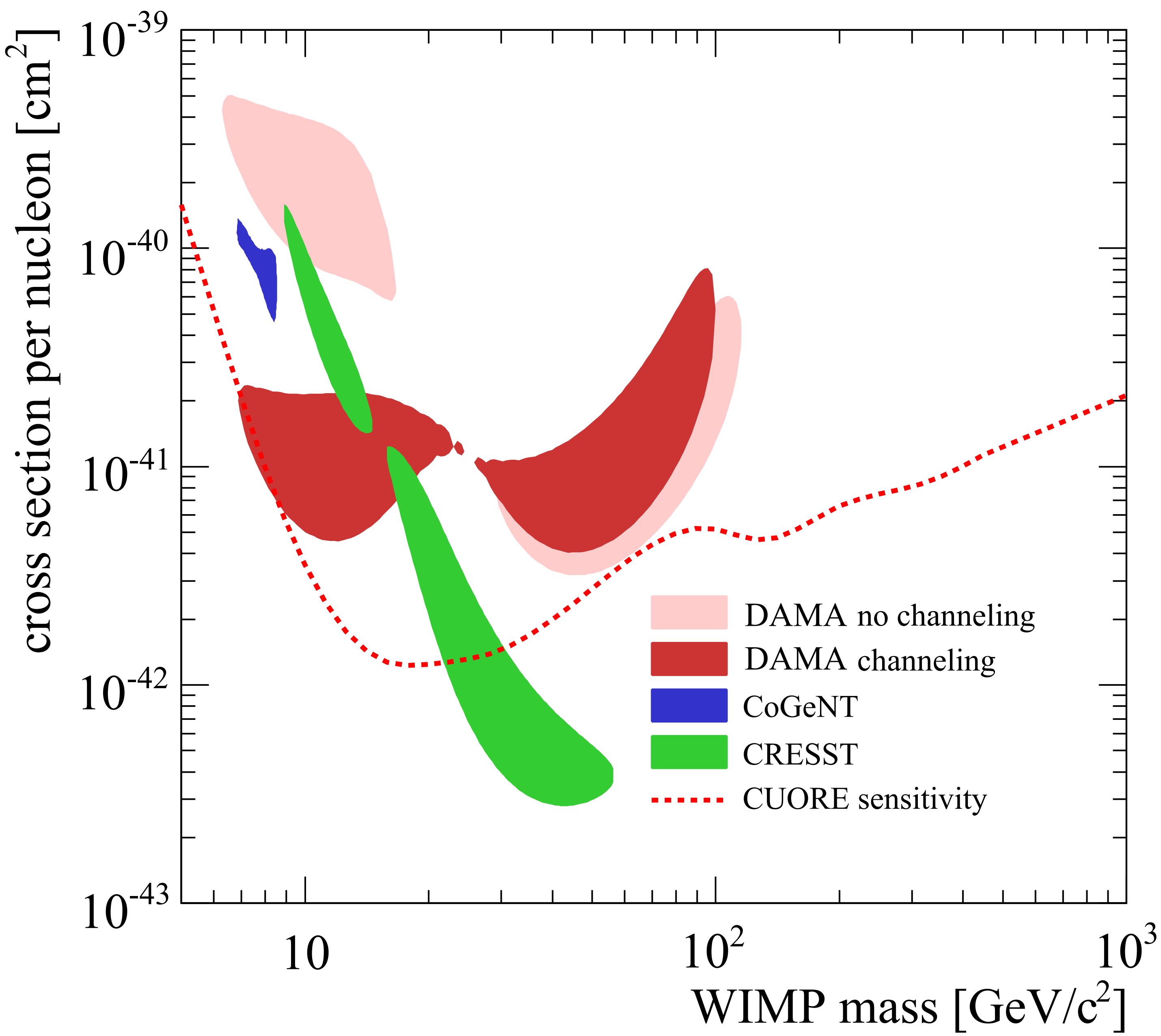




Dark Matter Perspective of CUORE



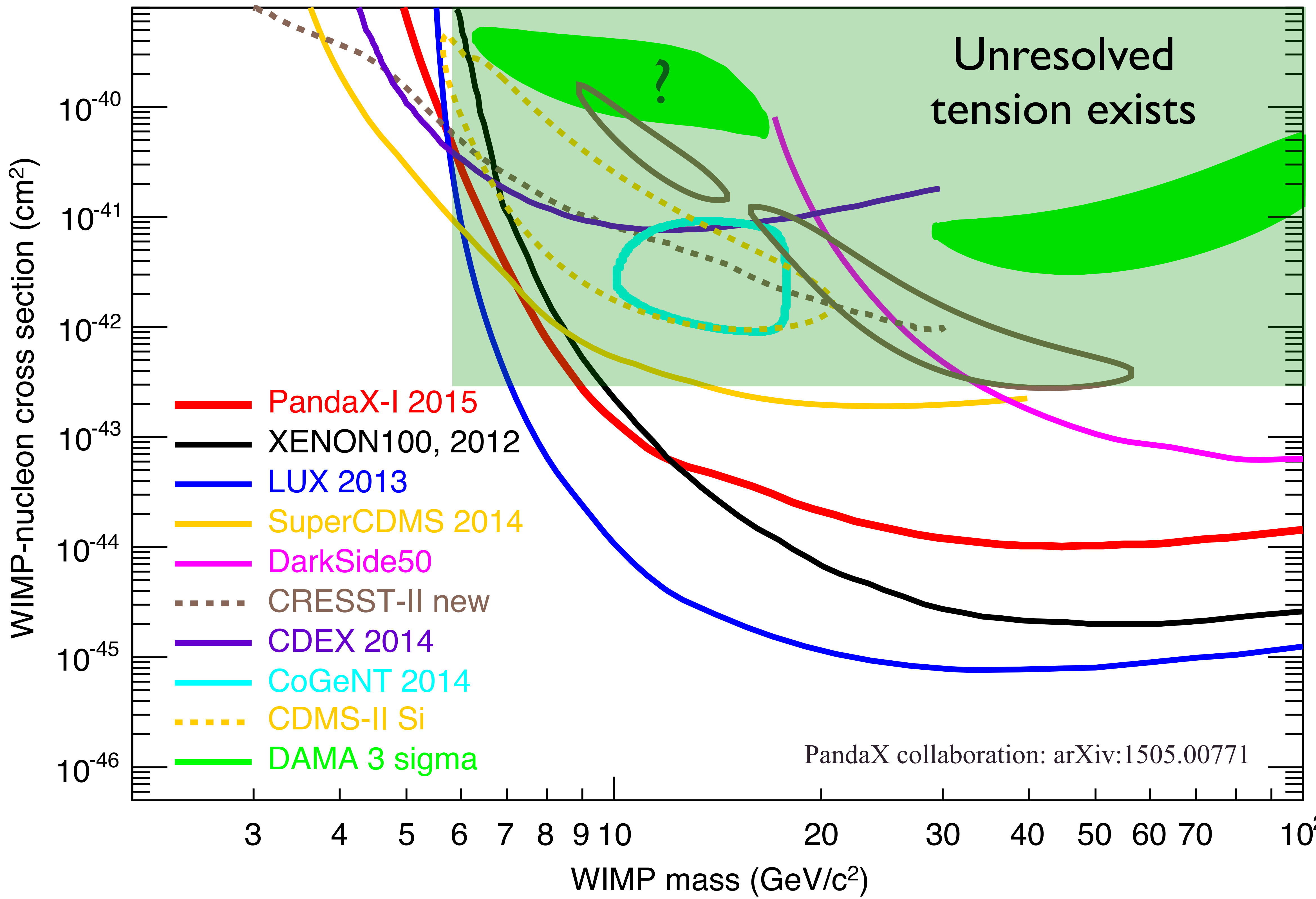
JCAP 01 (2013) 038

- CUORE is expected to test the DAMA WIMP observation claim with 5 years of data accumulation

Outline

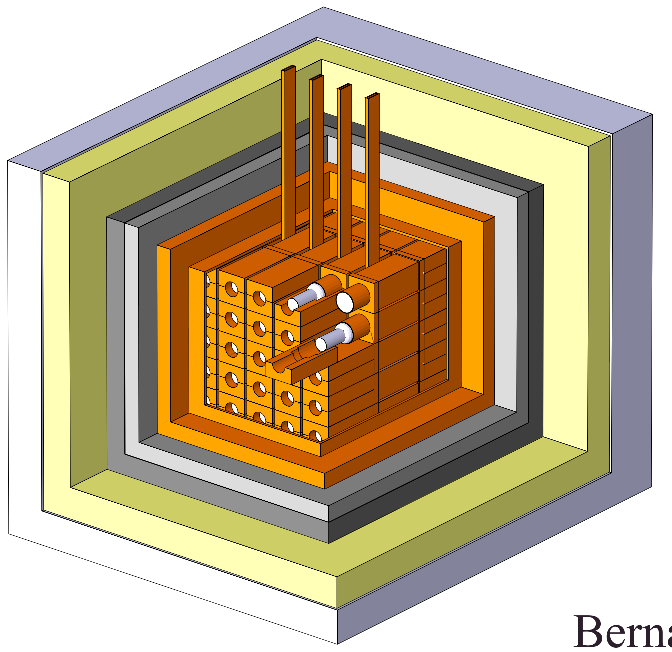
- Neutrinoless double-beta decay ($0\nu\beta\beta$) search
- CUORE : An array of TeO_2 bolometers to search for $0\nu\beta\beta$ and other rare events
- CUORE-0: $0\nu\beta\beta$ search w/ a single CUORE tower
- WIMP Dark Matter Search with CUORE
- DM-Ice : NaI(Tl) detectors to test WIMP discovery claim
- Summary

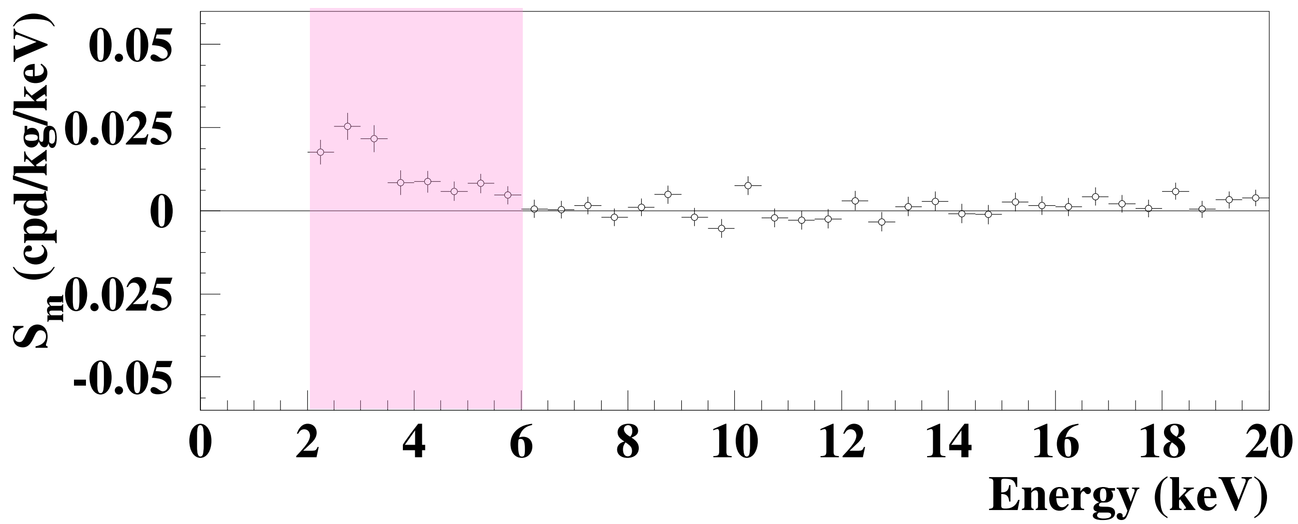
Status of the WIMP Direct Detection Searches



DAMA Modulation Signal

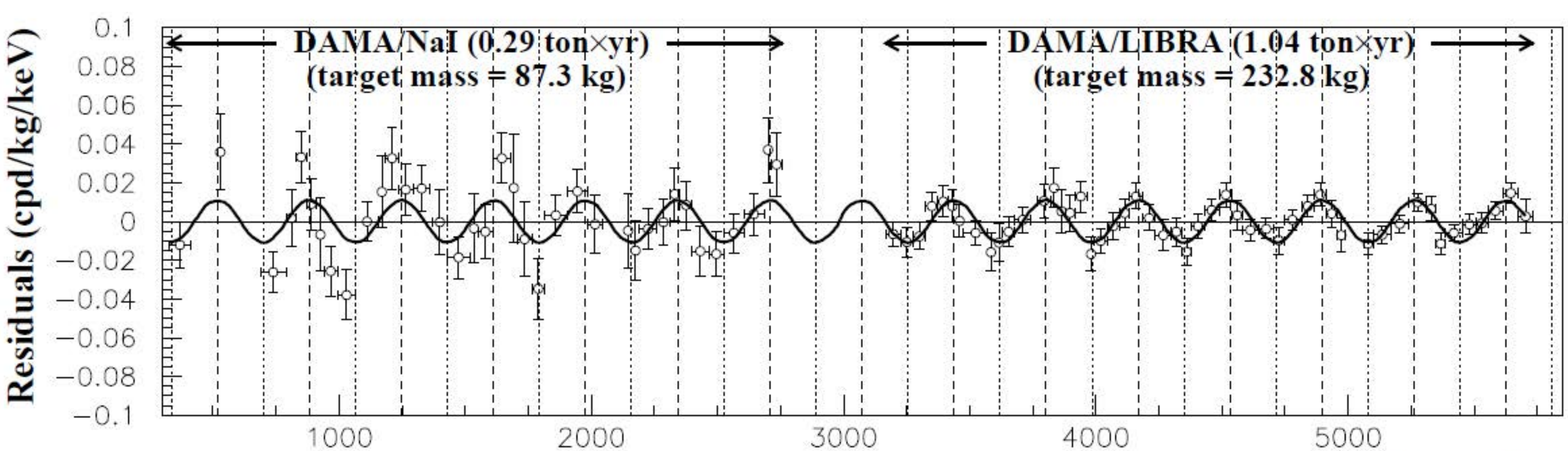
- 243 (25x9.7) kg of NaI(Tl), operated at LNGS in Italy
- Observe annual modulation only at the low energies





Bernabei *et al.*, Eur. Phys. J. C73 (2013) 2648

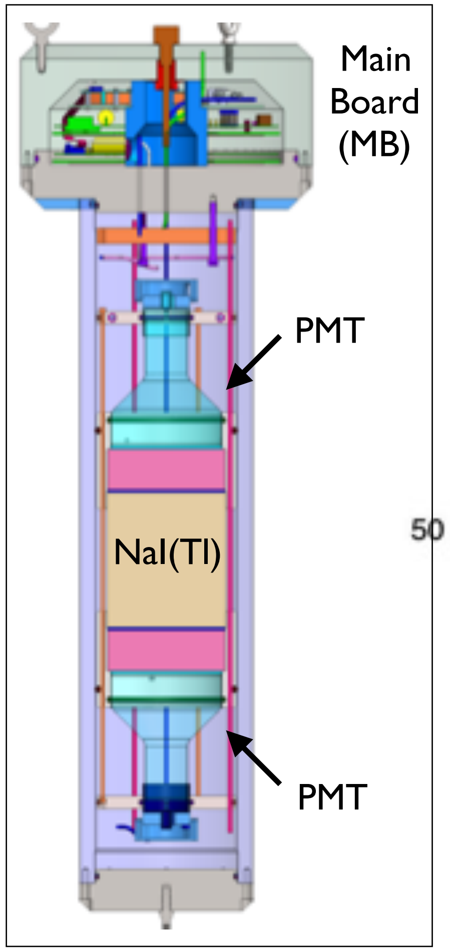
- Modulating signal w/ **9.3σ** C.L.
- Spanning 15 cycles

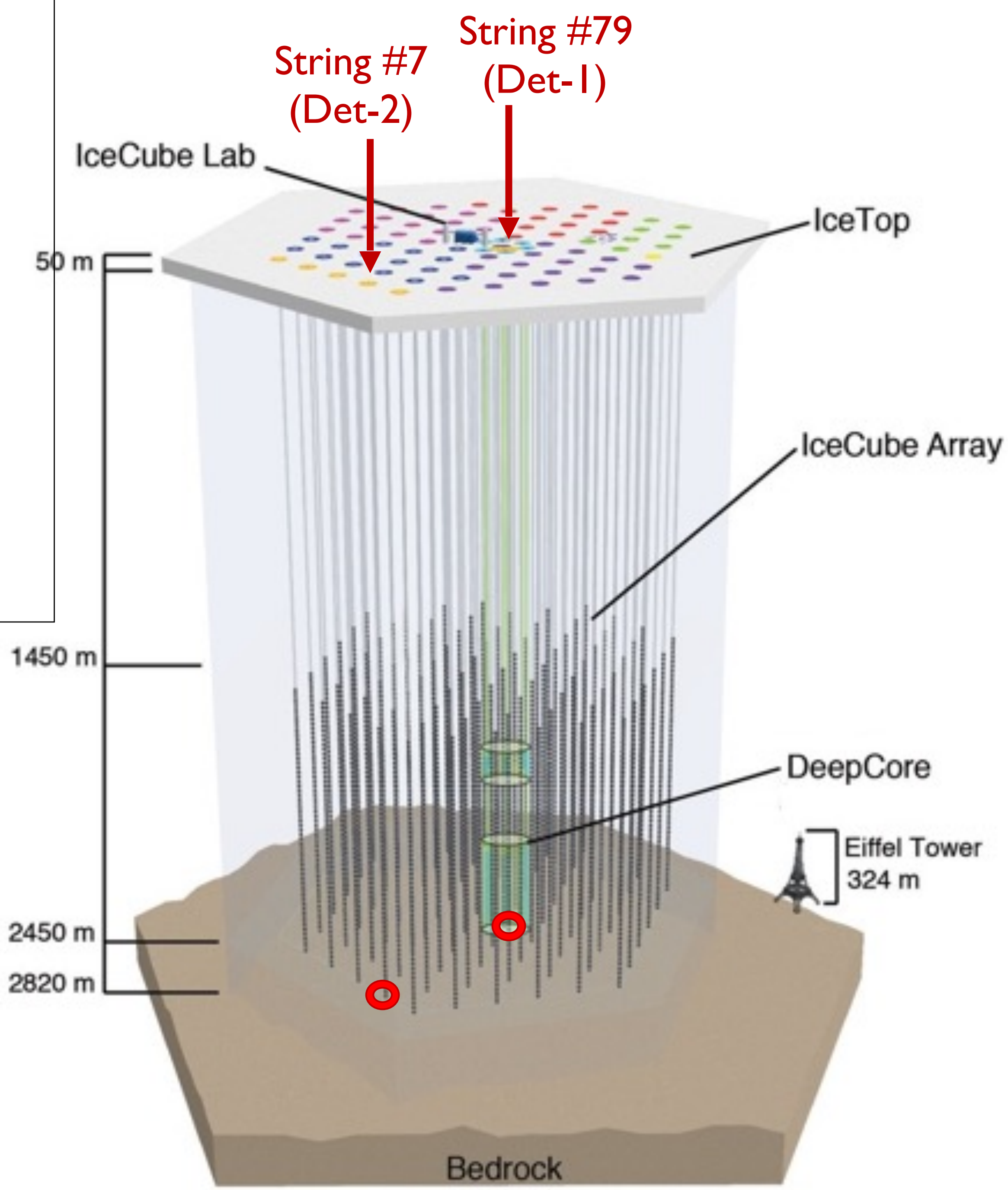


Bernabei *et al.*, arXiv:1412.6524

DM-Ice17 at the South Pole

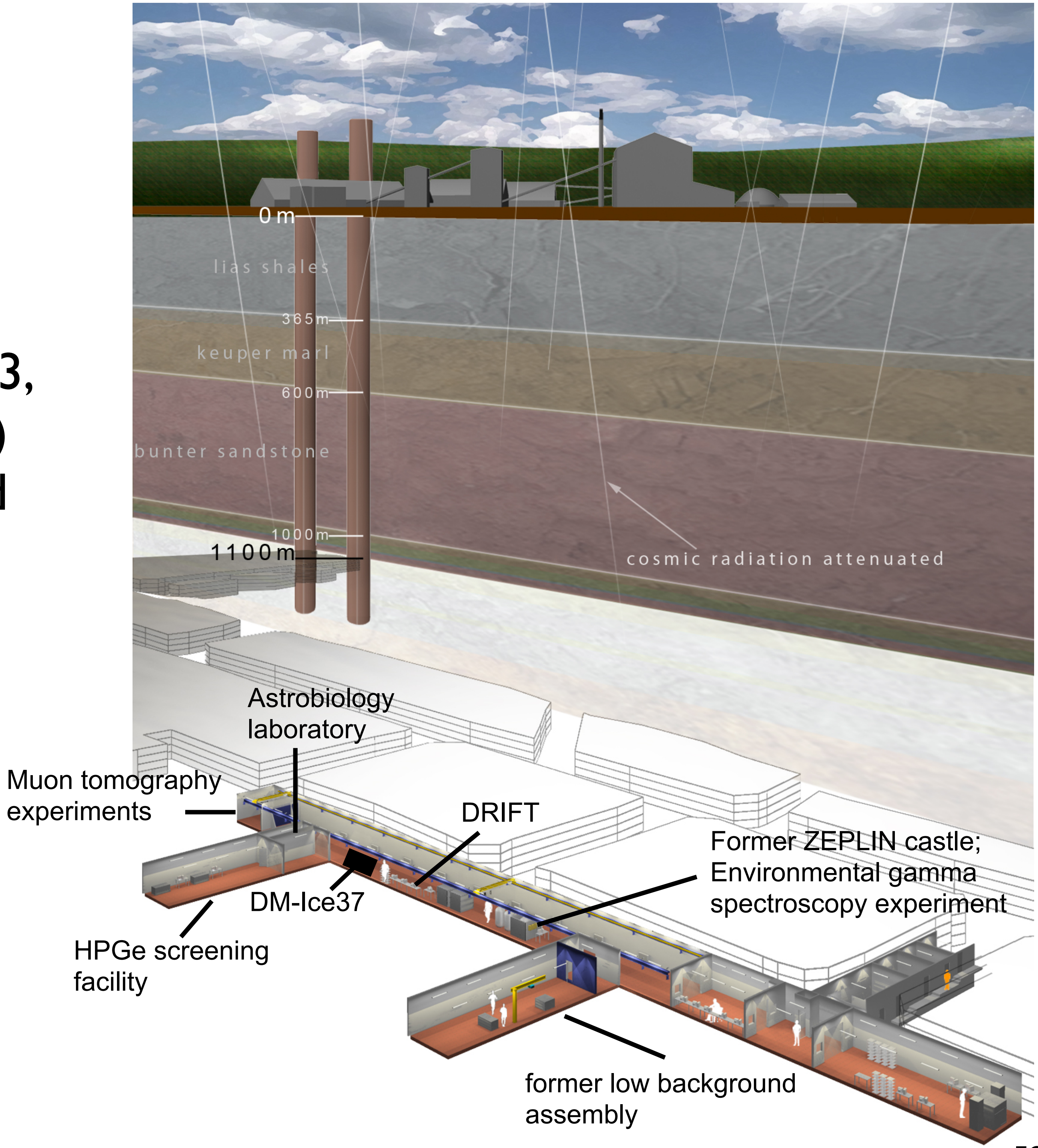
- 2x 8.5kg NaI(Tl) modules
- Data from June 2011 to present
- Demonstrated the feasibility of deploying and operating NaI(Tl) detectors in the Antarctic Ice
- Studied environment stability and the capability of IceCube to veto muon events
- *In situ* measurement of the radio purity of the surrounding ice
- First results published:
  Cherwinka *et al.*, Phys. Rev. D 90 (2014)





DM-Ice37 at Boulby Underground Lab

- Operating newly-grown NaI(Tl) crystals (2x 18.3kg) at Boulby Lab in UK
  - 2850 m.w.e overburden
  - Low Rn background (2.5 Bq/m^3, ~ x10-50 lower than other labs)
  - Housed in the copper lined lead castle

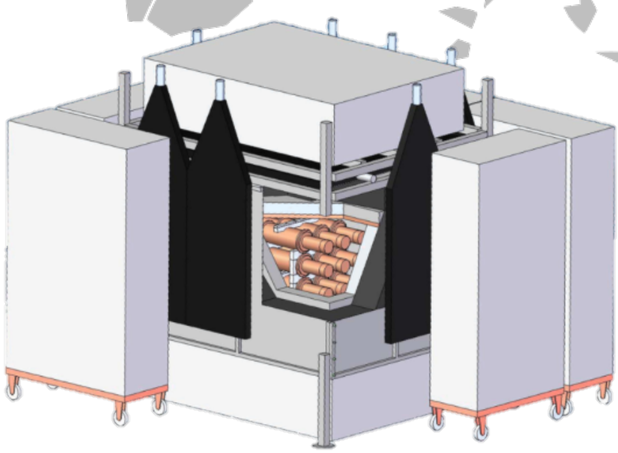


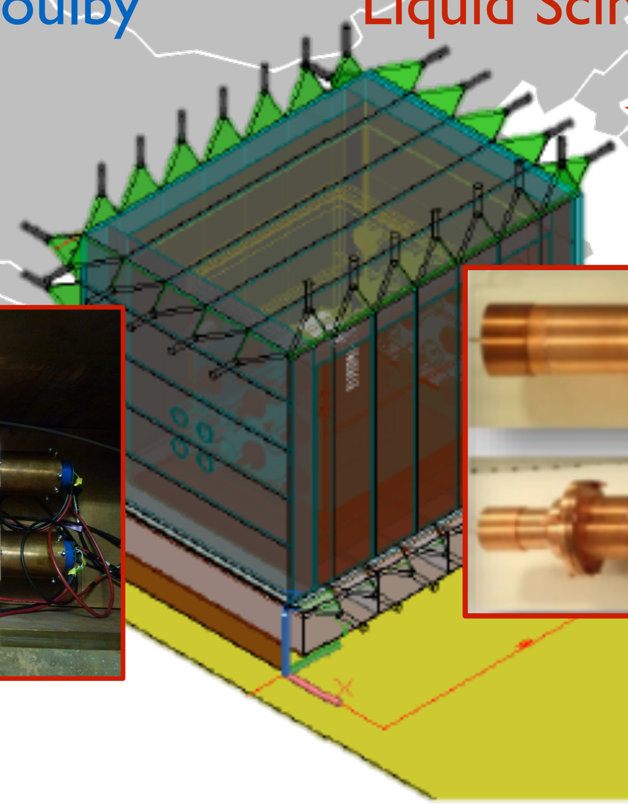
COSINE

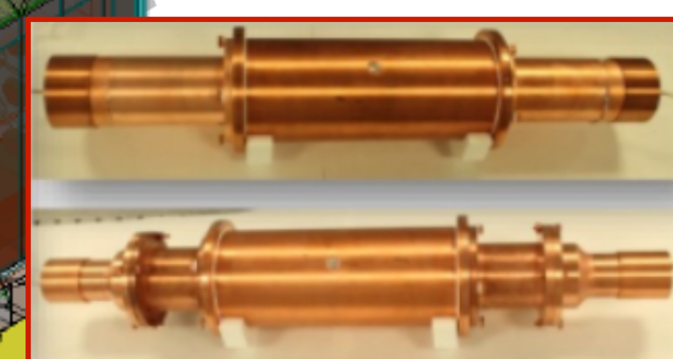
An International Consortium of Sodium Iodide Experiments

ANAIS + **DM-Ice** + **KIMS**

ANAIS	DM-Ice	KIMS
113 kg	55 kg in Yangyang	52 kg
External Muon Veto	Crystal R&D Boulby	Liquid Scintillator Veto

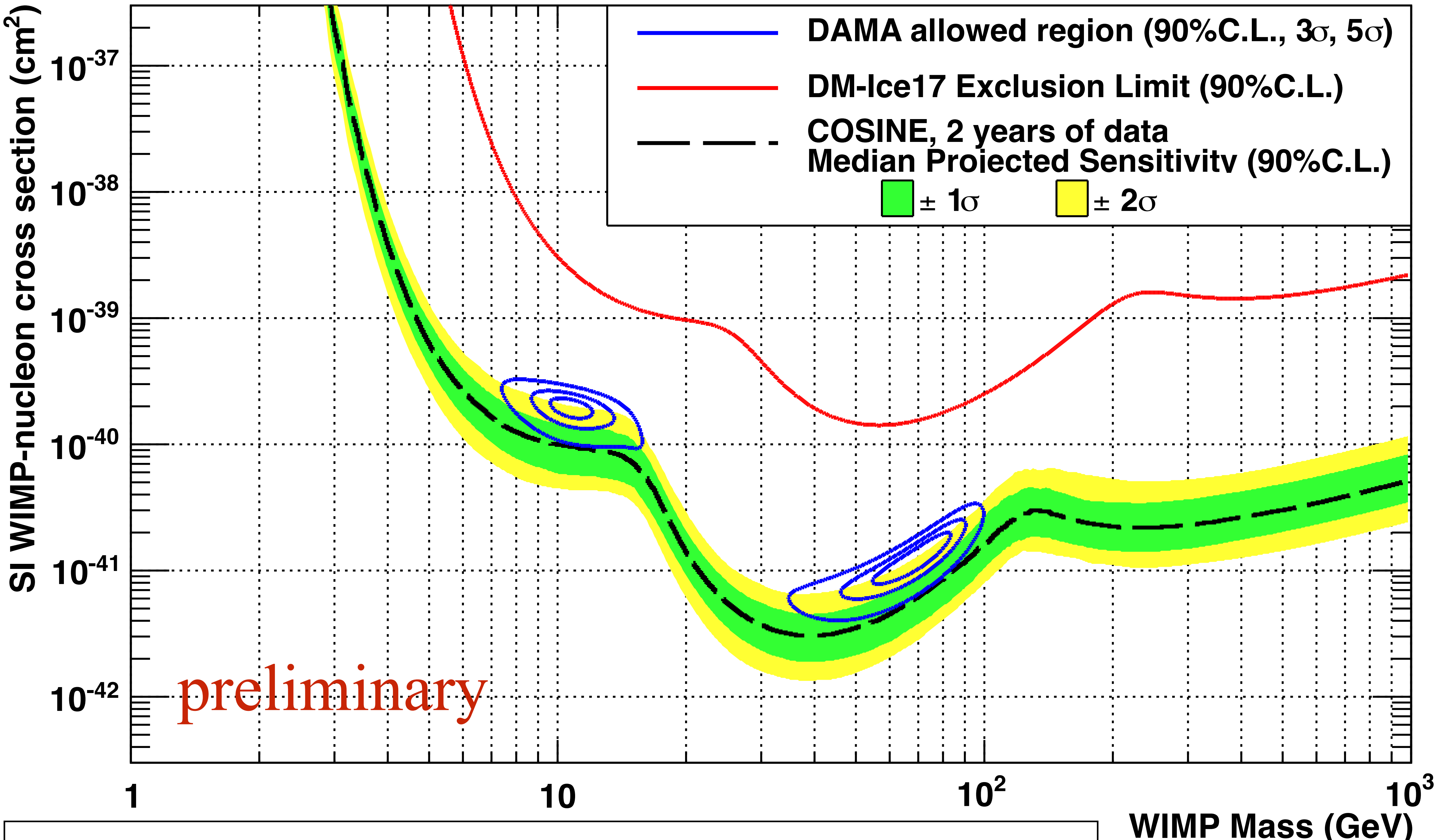






- Cross-collaboration data analysis effort
- Start data-taking by June 2016, Test DAMA in 2.5 years

COSINE



Strongest limit from the Southern Hemisphere

Summary

- $0\nu\beta\beta$ and WIMP dark matter discovery, which require new physics beyond the Standard Model would have a major impact on our understanding on the Universe.
- As experiments are getting bigger, addressing common challenges in $0\nu\beta\beta$ and WIMP dark matter searches can greatly benefit both fields.
- CUORE will be one of the most sensitive $0\nu\beta\beta$ searches world wide, using well-established and competitive techniques offered by TeO_2 bolometers.
- WIMP analysis of CUORE will be complementary to the other dark matter experiments using different target materials.
- COSINE, an international consortium of Sodium Iodide Experiments, will definitely test the DAMA claim within two and half years of data-taking starting in 2016.