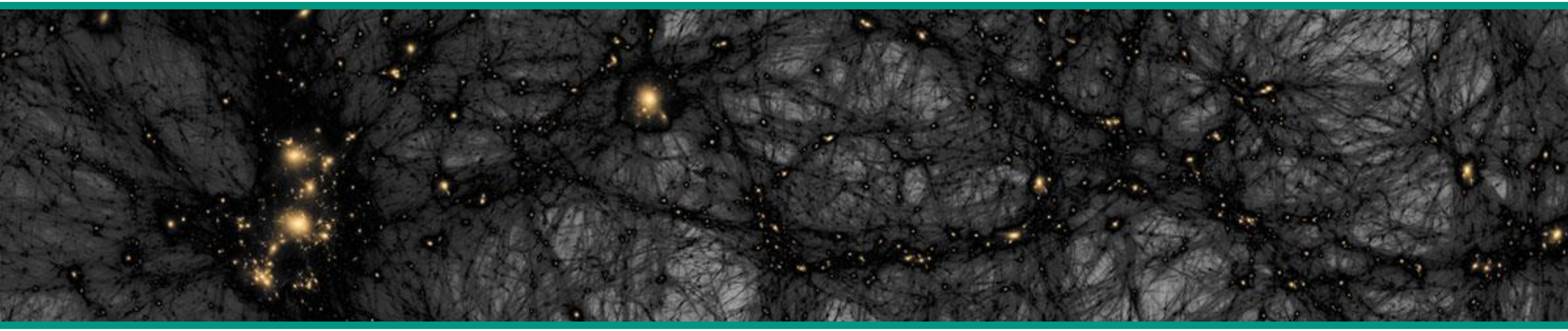
Astroparticle physics I – Dark Matter

WS22/23 Lecture 12 Dec. 15, 2022



Recap of Lecture 11

- **Neutrino properties: kinematic measurements & search for $0\nu\beta\beta$ –decay**

  - **KATRIN** experiment: scanning the β – decay endpoint region at $E_0 = 18.6\ keV$

  - combining an ultra-luminous molecular T_2 – source with a $MAC-E$ filter

  - direct kinematic experiments: **incoherent** mass sum $m(\nu_e) = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$

  - search for decay $0\nu\beta\beta$ –decay: violation of L –number with $\Delta L = 2$

  - exchange of a **virtual Majorana–ν**: **coherent** sum with (unknown) CP –phases

  - all $\beta\beta$ –isotopes are gg –nuclei: especially interesting are ^{76}Ge, ^{136}Xe, ^{130}Te

Recap of Lecture 11

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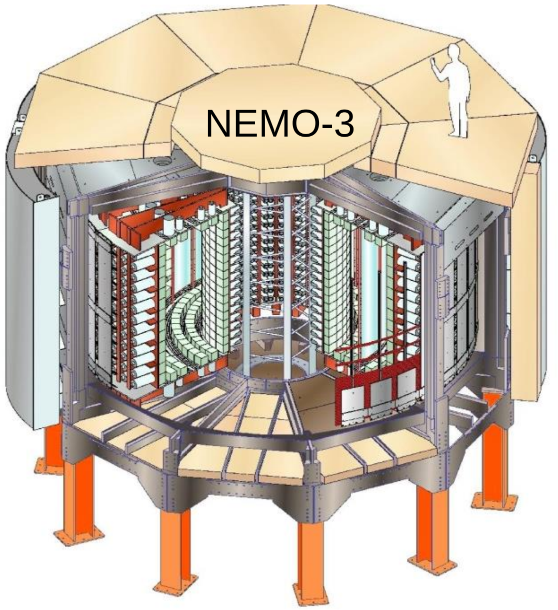
- **Hunting for $0\nu\beta\beta$ –decay events: passive vs. active techniques**

electrons leaving foil are detected via **ionisation signal** in a TPC*



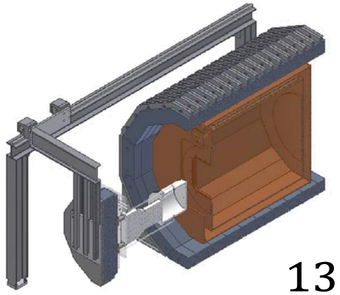
passive target = thin foil

^{100}Mo

electrons result in an **ionisation signal** or in a **heat increase** in a quantum sensor

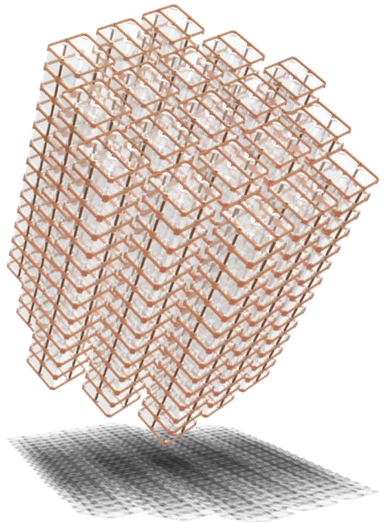
active target = detector

^{76}Ge



^{136}Xe

^{130}Te



*Time Projection Chamber

Search for $0\nu\beta\beta$ –decay: experim. observable $t_{½}$

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- **From the observed events N_{ev} to the half-life $t_{½}$ of the $0\nu\beta\beta$ –isotope**

$$N_{ev} \sim \left(t_{1/2}^{0\nu\beta\beta}\right)^{-1} \cdot N_{mol} \cdot \varepsilon \cdot t$$

measuring time t

observed $0\nu\beta\beta$ –events
or statistical upper limit
$(95\%\ C.L.)$

deduced
half-life $t_{½}$
or upper limit $(95\%\ C.L.)$

number of
$\beta\beta$ –target nuclei
(# moles)*
such as ^{76}Ge

experimental
detection efficiency
$\varepsilon \leq 1$

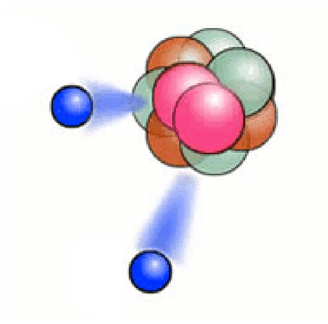
*$1\ mole = 6.022 \cdot 10^{23}$ (atoms)

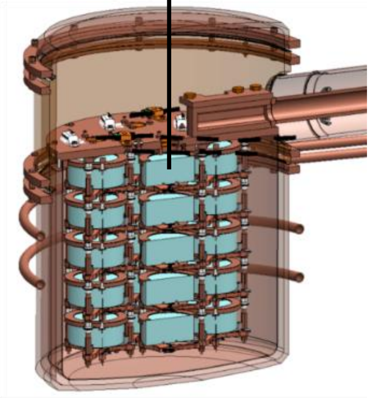
Search for $0\nu\beta\beta$ –decay: experim. observable $t_{½}$

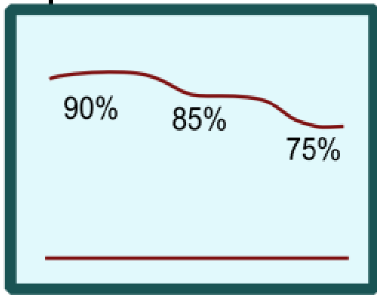
Karlsruhe Institute of Technology

- From the observed events N_{ev} to the half-life $t_{½}$ of the $0\nu\beta\beta$ –isotope

$$N_{ev} \sim \left(t_{1/2}^{0\nu\beta\beta}\right)^{-1} \cdot N_{mol} \cdot \varepsilon \cdot t$$







Search for $0\nu\beta\beta$ –decay: optimized sensitivity

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- **How do I optimize my $0\nu\beta\beta$ –set-up to be better than the competitors?**

$$t_{1/2}^{0\nu\beta\beta} \sim a \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$

$t_{1/2}^{0\nu\beta\beta}$: half-life (limit) for $0\nu\beta\beta$

$\boldsymbol{a}$: fraction of $\beta\beta$ –isotope used in set-up (natural fraction, or enrichment grade)

$\boldsymbol{M}$: mass of target in set-up

$\boldsymbol{t}$: measuring time with set-up

$\boldsymbol{\Delta E}$: energy resolution at endpoint (Q – value)

$\boldsymbol{B}$: background rate $(\text{events } keV^{-1}\, kg^{-1}\, yr^{-1})$
in region close to Q – value

Search for $0\nu\beta\beta$ –decay: optimized sensitivity

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- **How do I optimize my $0\nu\beta\beta$ –set-up : use of a highly enriched $\beta\beta$ – target!**

$$t_{½}^{0\nu\beta\beta} \sim a \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$

$t_{½}^{0\nu\beta\beta}$: half-life (limit) for $0\nu\beta\beta$

a: **fraction** of $\beta\beta$ –isotope used in set-up

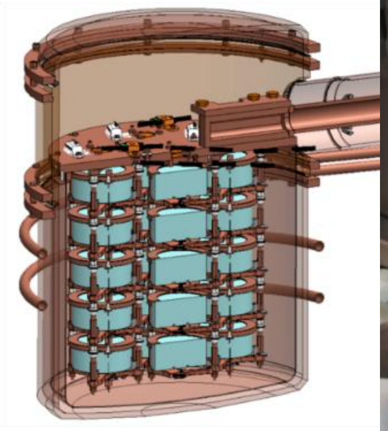
- $t_{½}^{0\nu\beta\beta}$ scales linearly with a ☑
- considerable cost factor ☒
  (no longer possible in Russian plants)

enrichment of ^{136}Xe

Search for $0\nu\beta\beta$ –decay: optimized sensitivity

- **How do I optimize my $0\nu\beta\beta$ –set-up : use of a huge target mass!**

$$t_{1/2}^{0\nu\beta\beta} \sim a \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$



M: **mass** of target in set-up

- $t_{1/2}^{0\nu\beta\beta}$ scales only with $\sqrt{M}$ ☑

- often in a modular set-up, can be scaled up

- in mid-term future we aim for a ^{76}Ge – experiment of target-mass of $M = 1\ ton$

Search for $0\nu\beta\beta$ –decay: optimized sensitivity

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- **How do I optimize my $0\nu\beta\beta$ –set-up : use of a large (long) exposure**

$$t_{1/2}^{0\nu\beta\beta} \sim a \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$

×

$M \cdot t$: **exposure** of set-up ($in\ kg \cdot yr$)

- $t_{1/2}^{0\nu\beta\beta}$ scales only with $\sqrt{M \cdot t}$ ☑

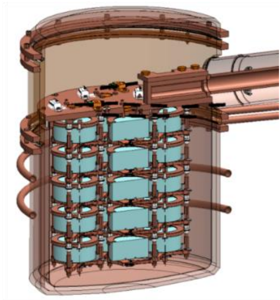
- typcial experimental time scales $t = 1 \ldots 10\ yrs$

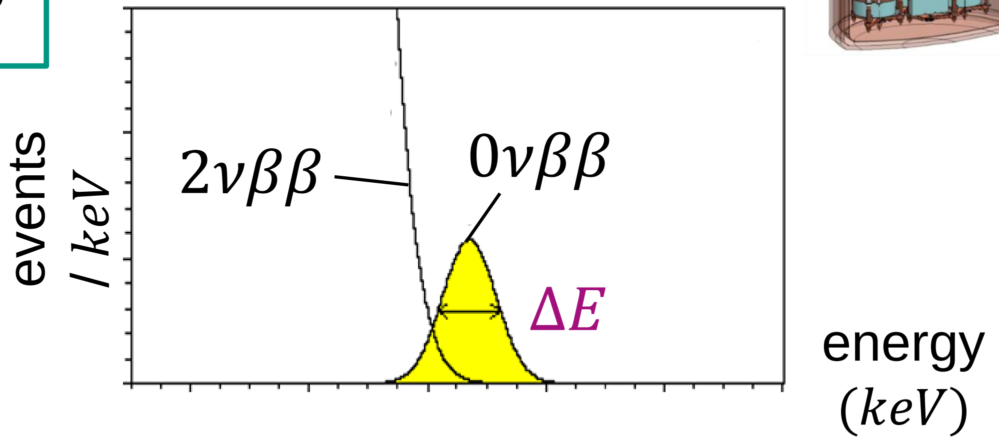
- long time scales t only useful if background rate B is small (due to fluctuations!)

Search for $0\nu\beta\beta$ –decay: sharp energy resolution

- **How do I optimize my $0\nu\beta\beta$ –set-up : use of a high-resolution detector**

$$t_{1/2}^{0\nu\beta\beta} \sim a \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$





ΔE: energy resolution of set-up ($in\ kg \cdot yr$)

- $t_{1/2}^{0\nu\beta\beta}$ scales only with $\sqrt{\Delta E}$ ☑
- goal: use sharp ΔE ($\sim few\ keV$) to discriminate $0\nu\beta\beta$ from $2\nu\beta\beta$
- sharp ΔE requires state-of-the-art electronics & DAQ –systems

Search for $0\nu\beta\beta$ –decay: background shielding

- **How do I** **optimize my $0\nu\beta\beta$ –set-up** **: use of advanced shielding concepts**

$$t_{½}^{0\nu\beta\beta} \sim a \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$

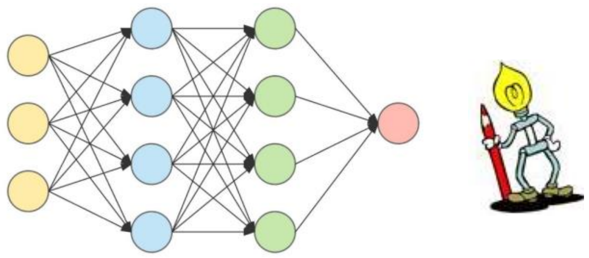
B: **background rate** of set-up $(in\ events\ keV^{-1} kg^{-1} yr^{-1})$

- $t_{½}^{0\nu\beta\beta}$ scales only with $\sqrt{B}$ ☑
- goal: use optimum shielding method (see ch. 2.2.2)
- combine passive elements (Cu) with active elements (μ –veto)

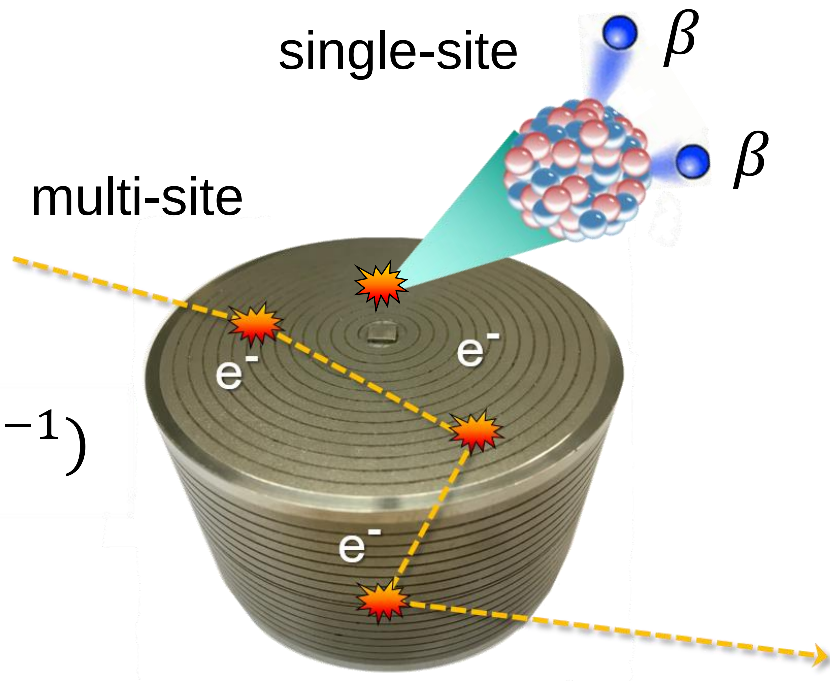
GERDA

Search for $0\nu\beta\beta$ –decay: gamma discrimination

- **How do I optimize my $0\nu\beta\beta$ –set-up : use of modern analysis techniques**



$$t_{1/2}^{0\nu\beta\beta} \sim a \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$



B: **background rate** of set-up in $(events\ keV^{-1} kg^{-1} yr^{-1})$

- $t_{1/2}^{0\nu\beta\beta}$ sensitivity improvement via **event topology**

- technique: Pulse Shape Analysis / Discrimination

- discriminate single-site event ($0\nu\beta\beta$) from multi-site (Compton e^- from γ´s)

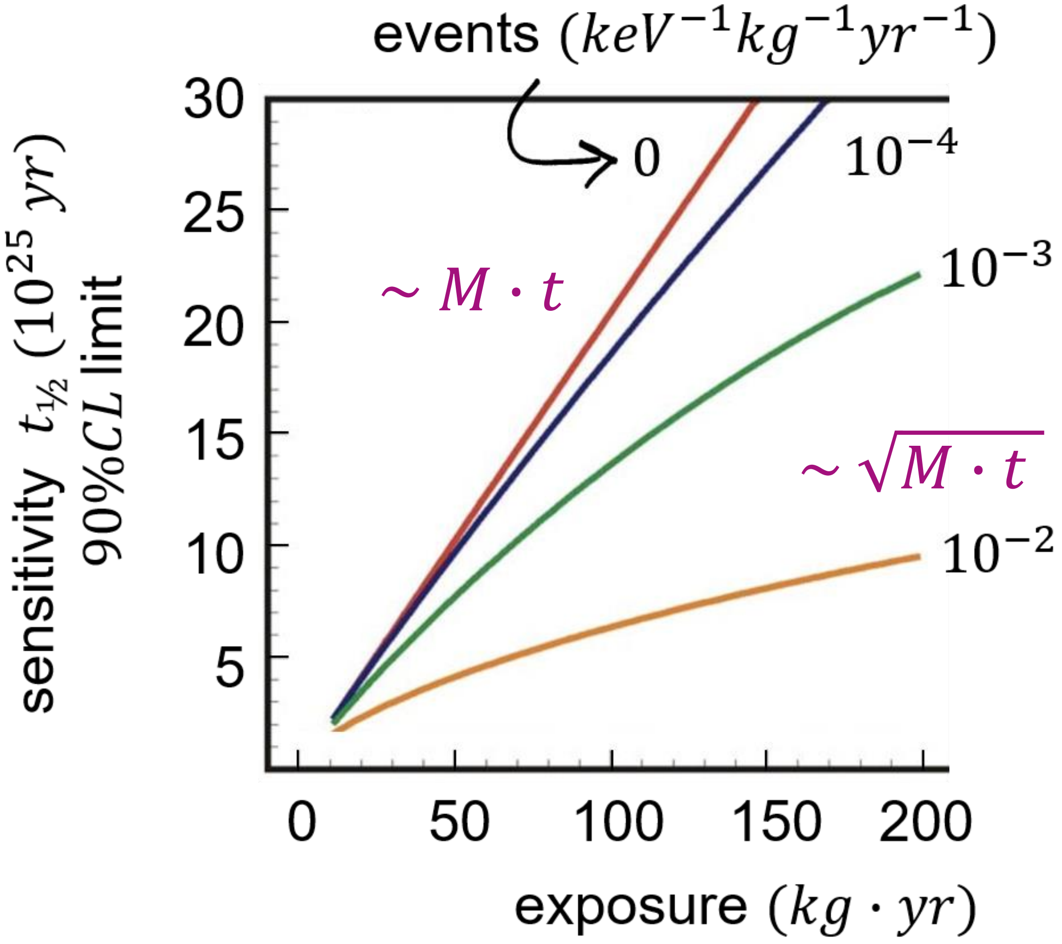
Search for $0\nu\beta\beta$ –decay: total background rate B

- **rare event search for $0\nu\beta\beta$ –decay: reduction of B**

  - the actual background rate has a major impact on the sensitivity

  - **case 1:** no background ($B = 0$)
    linear scaling of sensitivity
    with exposure $M \cdot t$

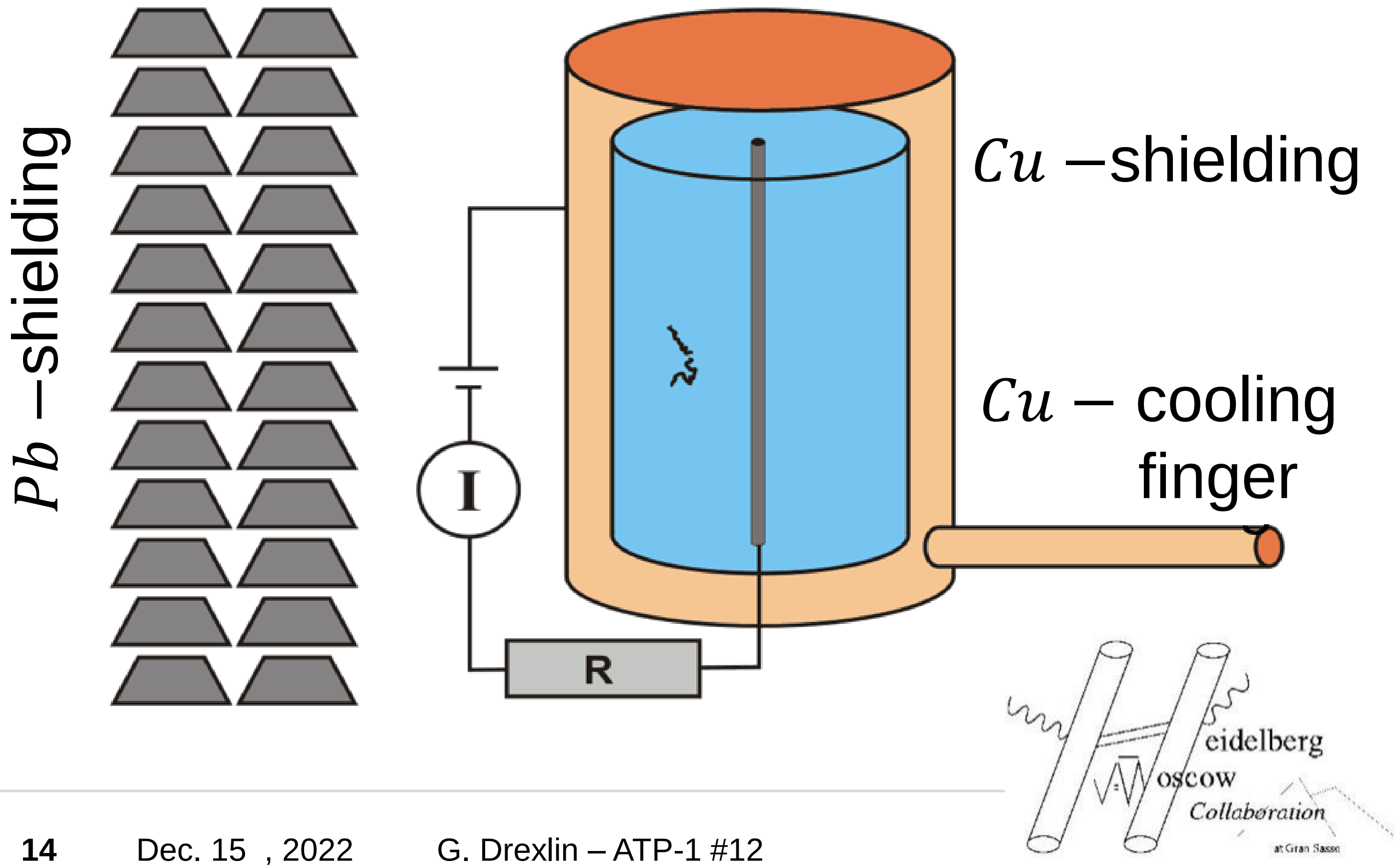
  - **case 2:** non-zero background ($B > 0$)
    scaling of sensitivity
    with exposure only as $\sqrt{M \cdot t}$
    due to Poisson fluctuations
    of background rate B

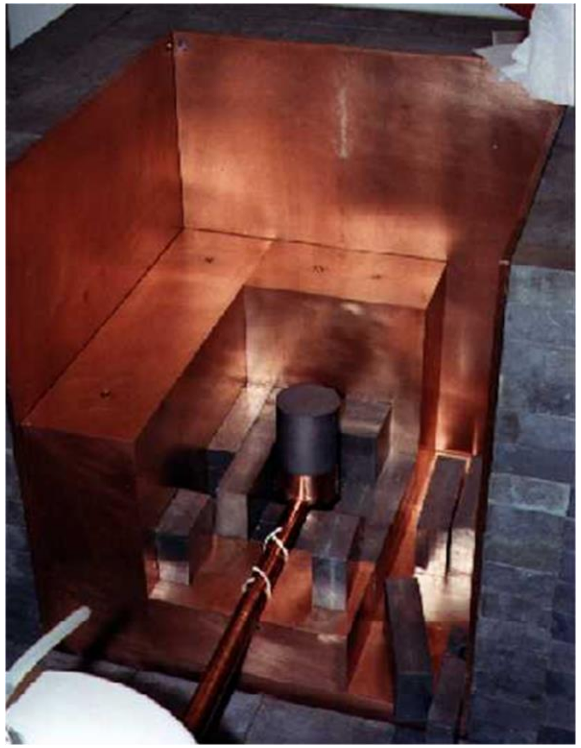


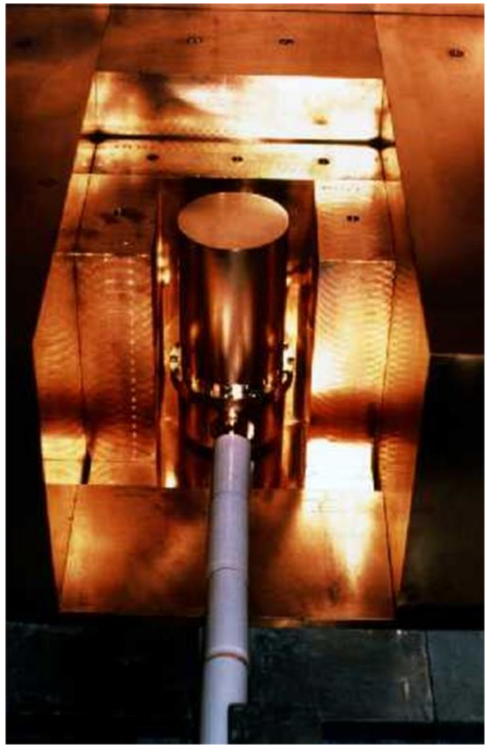
$0\nu\beta\beta$ –experiments: Heidelberg-Moscow

- A pioneering effort at LNGS $(1990-2003)$ with target mass $M = 11\ kg$

  - operation of 5 enriched Ge –diodes with enrichment grade $\boldsymbol{a} = \mathbf{0.86}$ (86%)



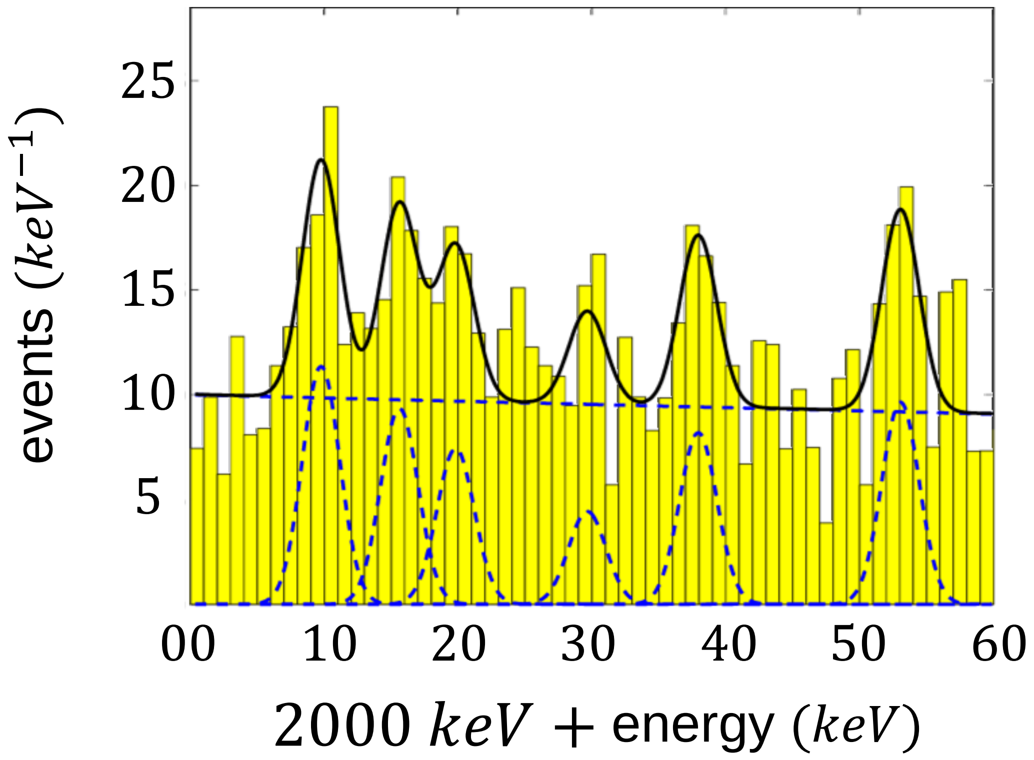




$0\nu\beta\beta$ –experiments: Heidelberg-Moscow claim

- **A pioneering effort at LNGS $(1990 - 2003)$ with target mass $M = 11\ kg$**

  - analysis of final data set *without* blinding of the signal region at Q – value



- (private) analysis performed by $\boldsymbol{PI}$*
  after calibrated energy data were available
- $0\nu\beta\beta$ – events expected at an energy
  $E_0 = (2038.7 \pm 0.44)\ keV$
- highly controversal claim for $0\nu\beta\beta$ – signal
  with $N_{ev} = (28.75 \pm 6.86)$ events $(\equiv 4.2\ \sigma)$
- this result has not been confirmed by later
  experiments (today: blind analysis methods)

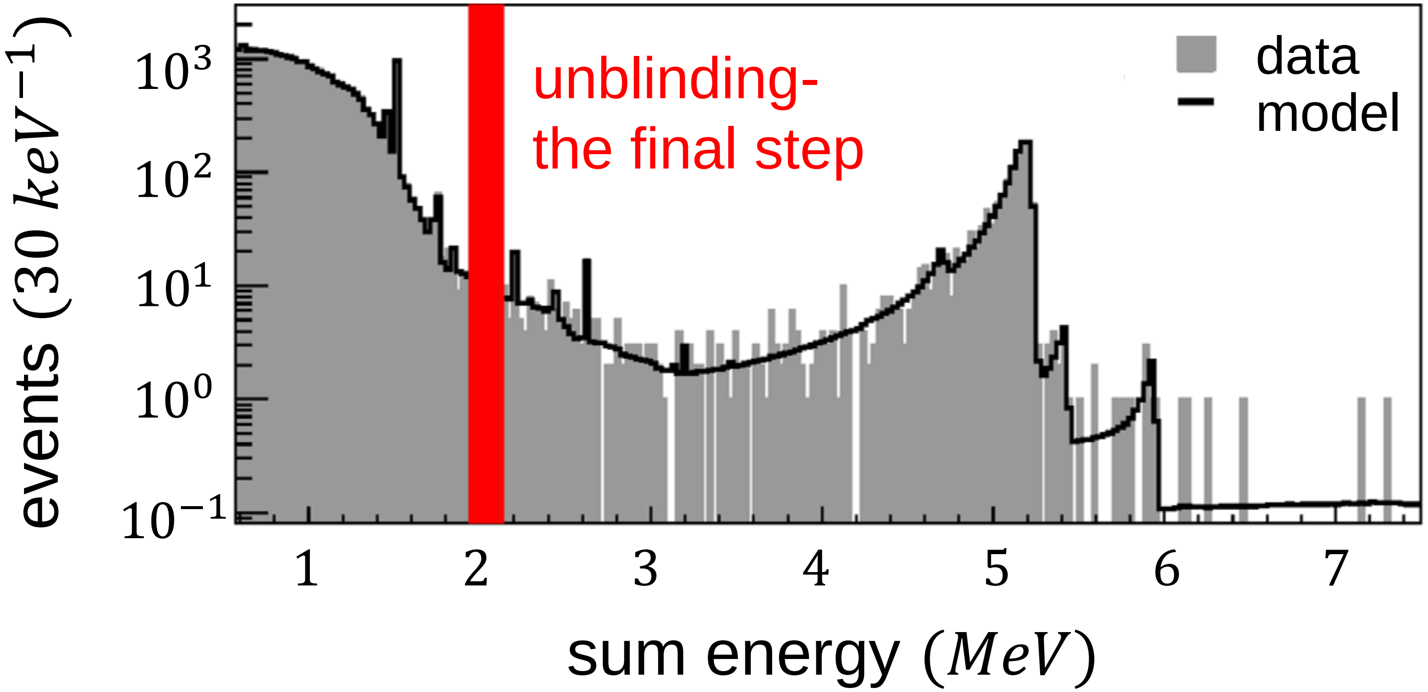
*Principal Investigator

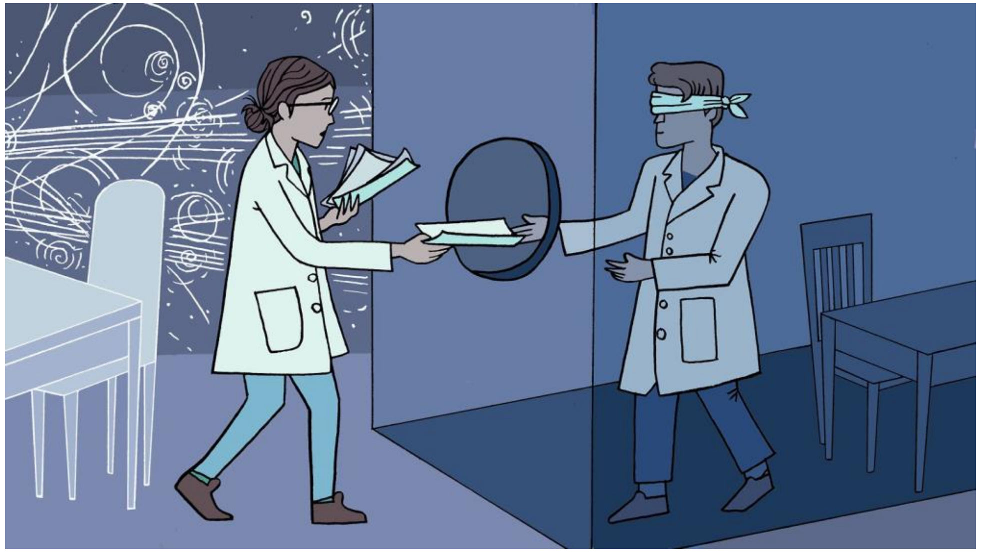
$0\nu\beta\beta$ –experiments: blind analysis method

- **Current state-of-the art analysis methods based on blocking of signal region**

  - analysis of final data set *with* blinding of the signal region at Q – value

  - **test of background model** outside of signal region: does it describe data?





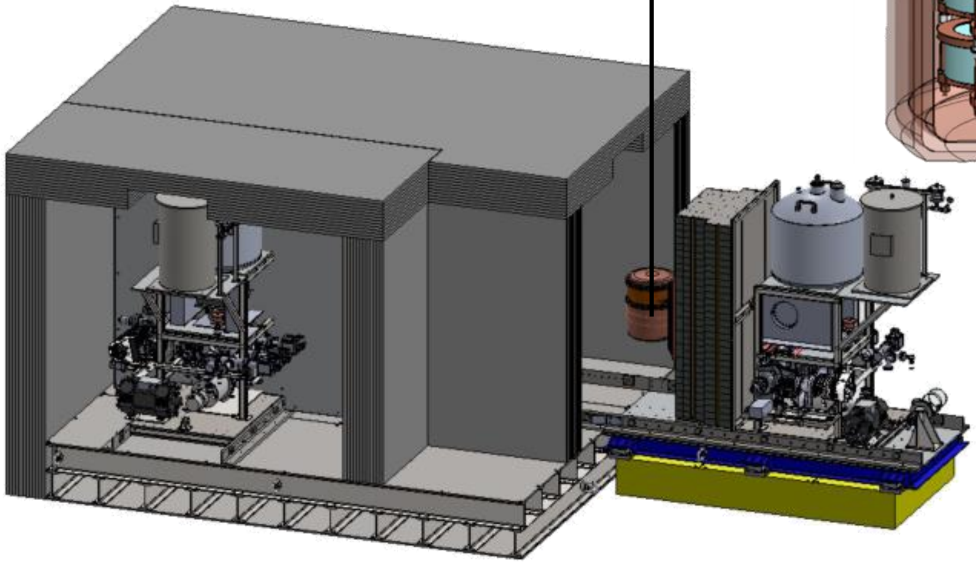
The facts and nothing but the facts

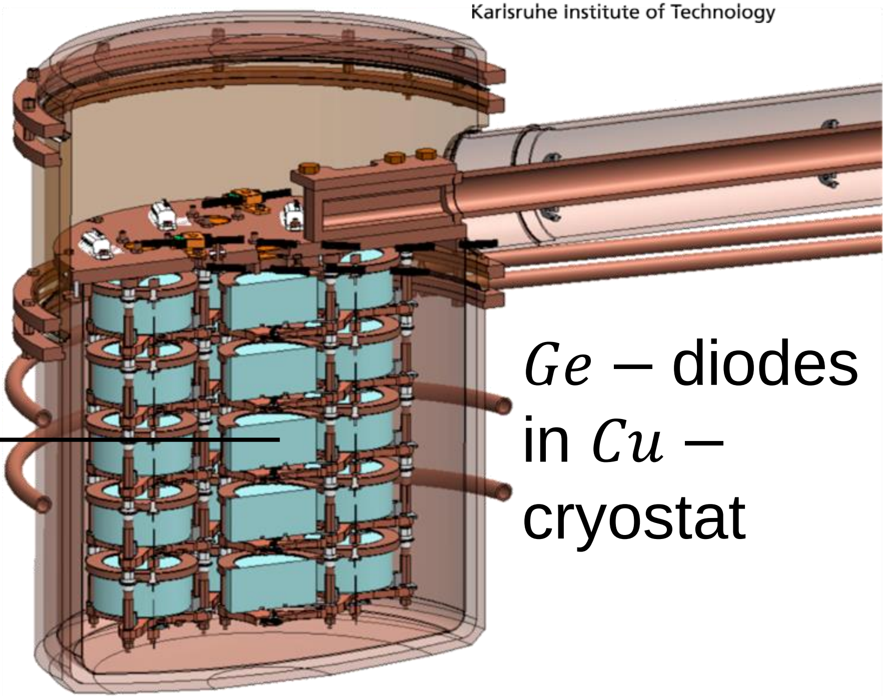
PDG 2022 on $0\nu\beta\beta$ s076.dvi (lbl.gov)

$0\nu\beta\beta$ –experiments: MAJORANA

Overview & classical hielding concept

- location: Sanford Underground Laboratory
  in Lead, South Dakota





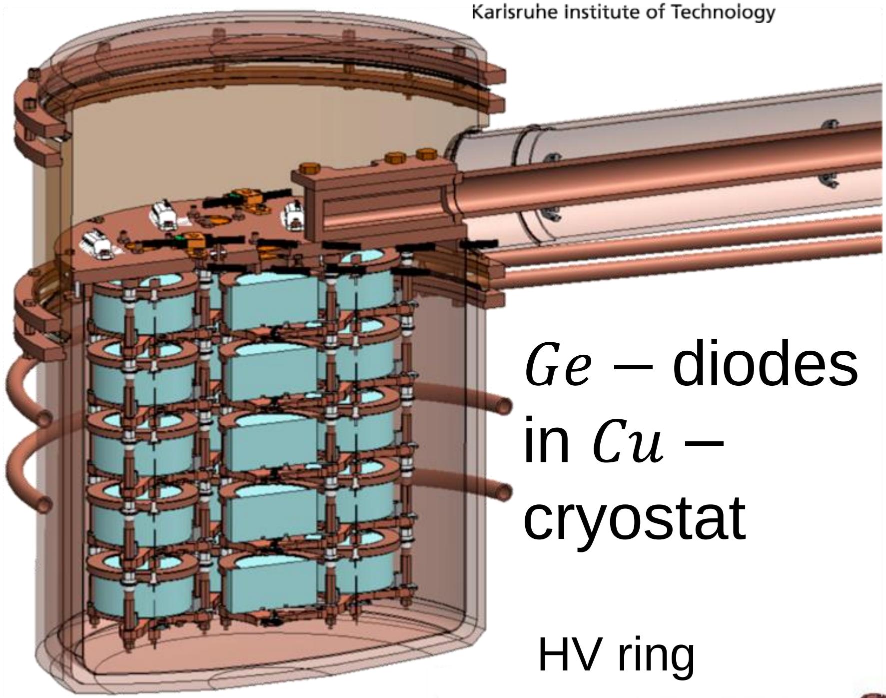
Ge – diodes in Cu – cryostat

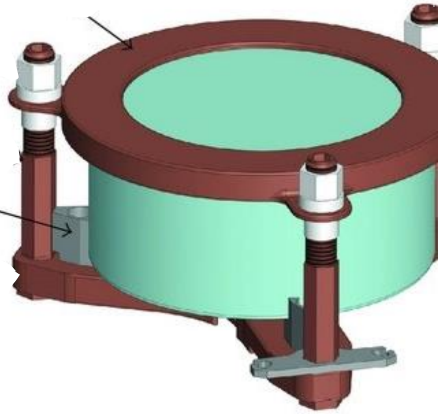
shielding & infrastructure

$0\nu\beta\beta$ –experiments: MAJORANA

- **Overview & shielding concept**

  - ´conventional´ set-up with ultra-clean Cu –holders





$0\nu\beta\beta$ –experiments: MAJORANA

Experimental result & future plans

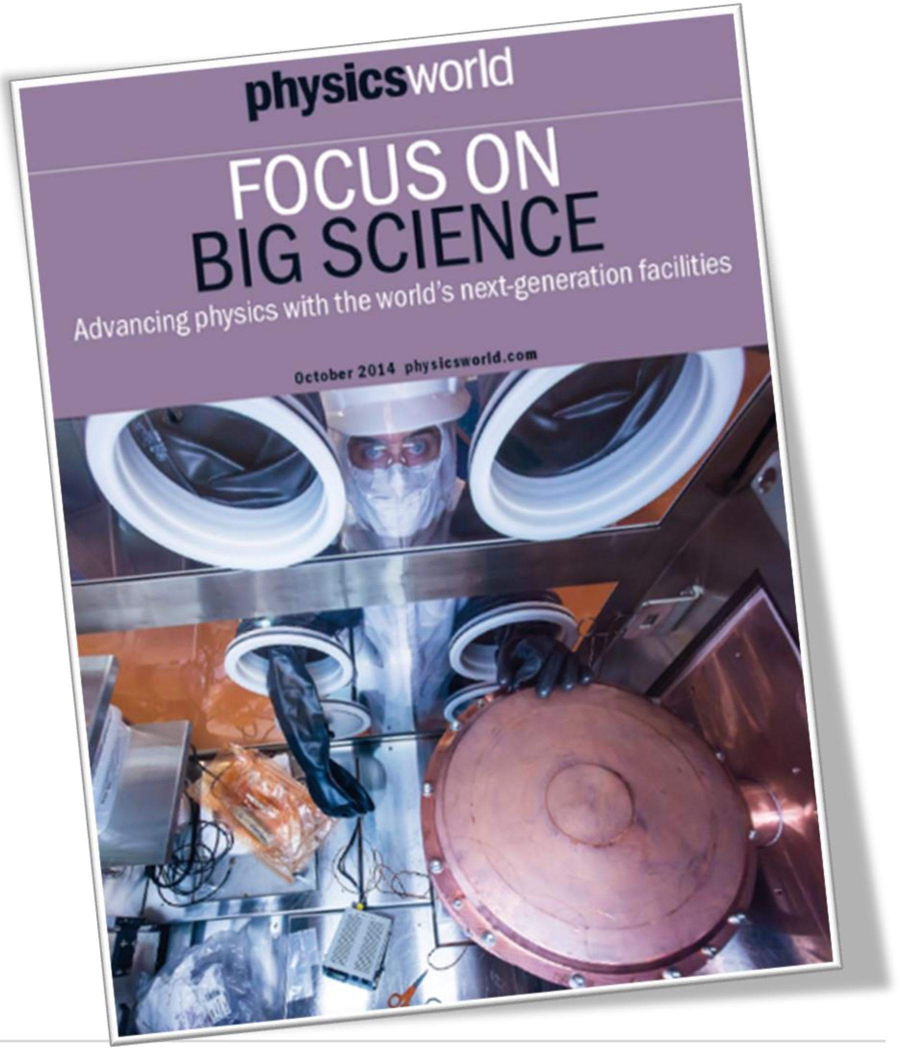
- set-up with $M = 44\ kg$ of enriched $^{76}\boldsymbol{Ge}$
  $M = 15\ kg$ of natural $\boldsymbol{Ge}$

- no signal events observed

- published 2021 limit on $0\nu\beta\beta$ half-life of $^{76}\boldsymbol{Ge}$

$$t_{1/2}^{0\nu\beta\beta} > 39.9 \cdot 10^{23}\ yr\ (90\%\ C.L.)$$

- MAJORANA (US project) will merge with GERDA (EU project) into LEGEND



evaluation period – Dec. 5 – 16, 2022

- Please take your time to evaluate the ATP lectures & exercises/tutorials

lectures: QR-code & link

https://onlineumfrage.kit.edu/evasys/public/online/index/index?online_php=&p=WYU4G&ONLINEID=4182527920698284911404837563680216893431 5

exercises & tutorials: QR-code & link

https://onlineumfrage.kit.edu/evasys/public/online/index/index?online_php=&p=D6CZR&ONLINEID=653147976830278787680879409014532250250735

$0\nu\beta\beta$ –experiments: GERDA

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- **The GERmanium Detector Array – novel technologies**

  - novel design based on ´**naked**´ $\boldsymbol{Ge}$ – **diodes** housed in large-volume liquid-argon-cryostat (surrounded by a large-scale water Cherenkov detector at RT*)

  - site: LNGS, hall A $(3400\, m.w.e.)$

  - novel (improved) shielding concept based on:

    a) avoid any structural materials in close proximity to Ge –diodes, plus rigorous material selection

    b) active μ –veto-detector with **LAr = Liquid Argon**)

*room temperature

$0\nu\beta\beta$ –experiments: GERDA

- **Set-up**

H_2O – veto
$(650\ m^3)$:
μ –identification
plus shielding
against $\gamma's$ and
neutrons

Liquid Argon
$(70\ m^3)$:
ultra-pure
Cooling fluid +
PMTs for scint. light

clean room

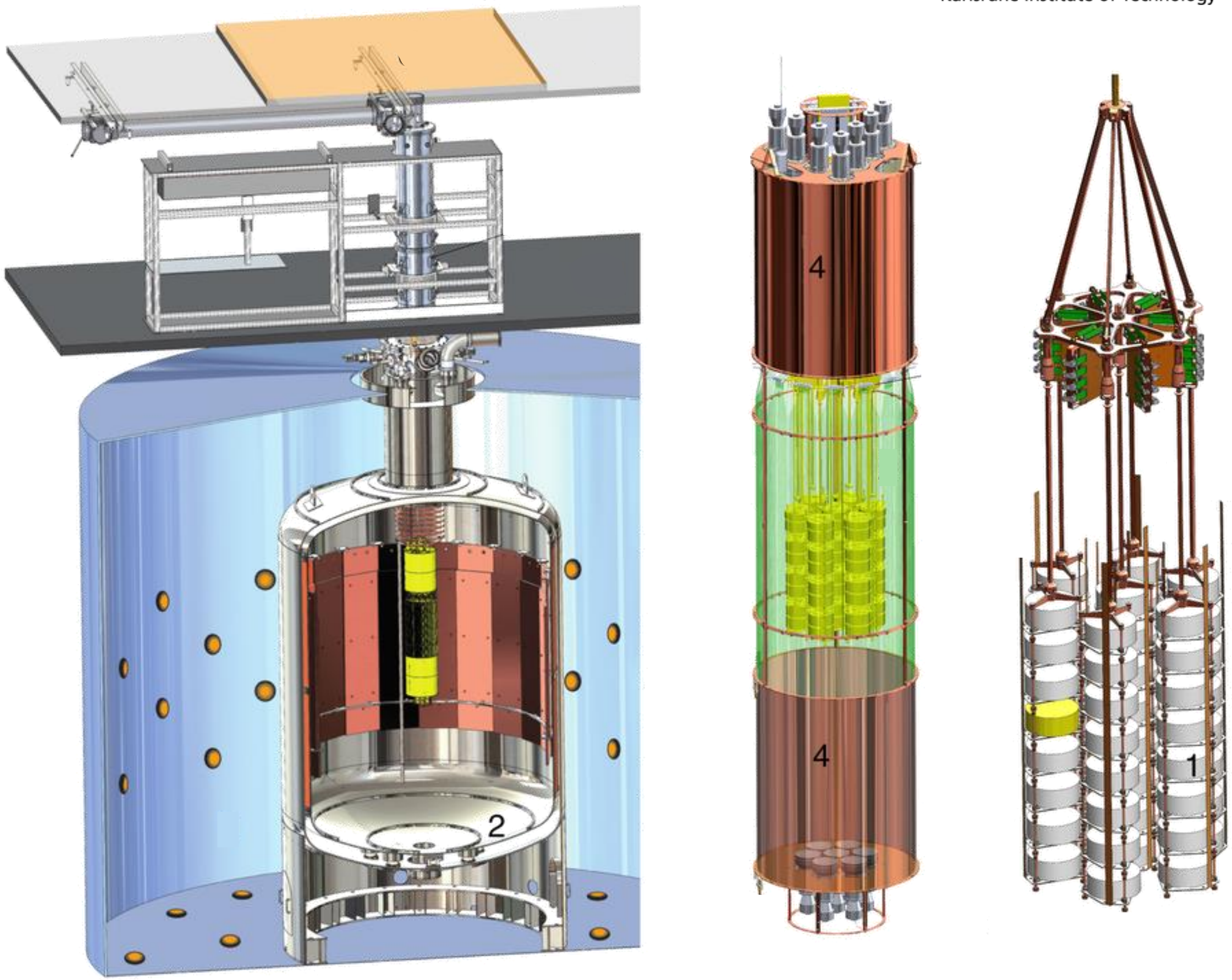
diode insertion system

cryostat &
internal
Cu – shielding

Ge – diodes
$18 \ldots 40\ kg$

$0\nu\beta\beta$ –experiments: GERDA phase II

- **Set-up: modifications for further background reduction**



\- **novel element**:
Ge –diodes surrounded by
a) nylon bag against Ar-ions
b) fibres with WLS* and
readout by $Si - PMTs$

\- **strings with $41\ Ge$ –diodes**:
$35.6\ kg$ enriched ^{76}Ge
$7.6\ kg$ natural Ge

*wavelength shifter

$0\nu\beta\beta$ –experiments: GERDA phase II

- **Significant improvements of sensitivity**

  - energy resolution: ΔE ~ 3.0 keV

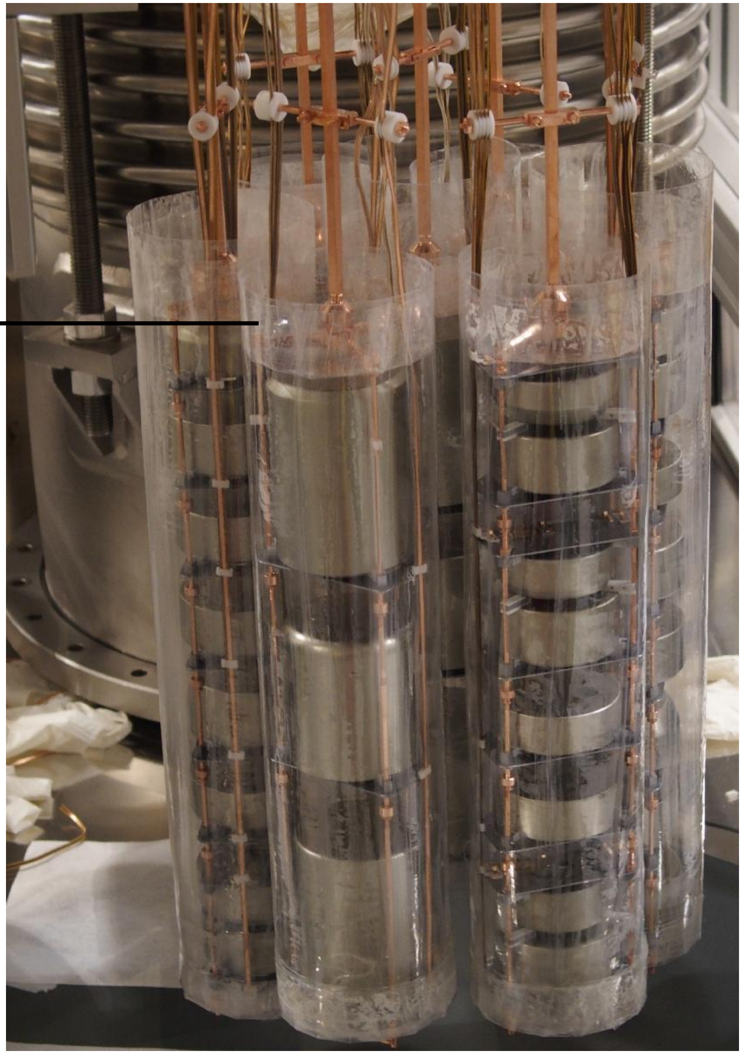
  - measurements from 12/2015 – 11/2019

  - corresponding exposure
    $M \cdot t = 127.2\ kg \cdot yr$

  - achieved (world-leading!) background rate
    $B = 0.00052$ events $keV^{-1} kg^{-1} yr^{-1}$

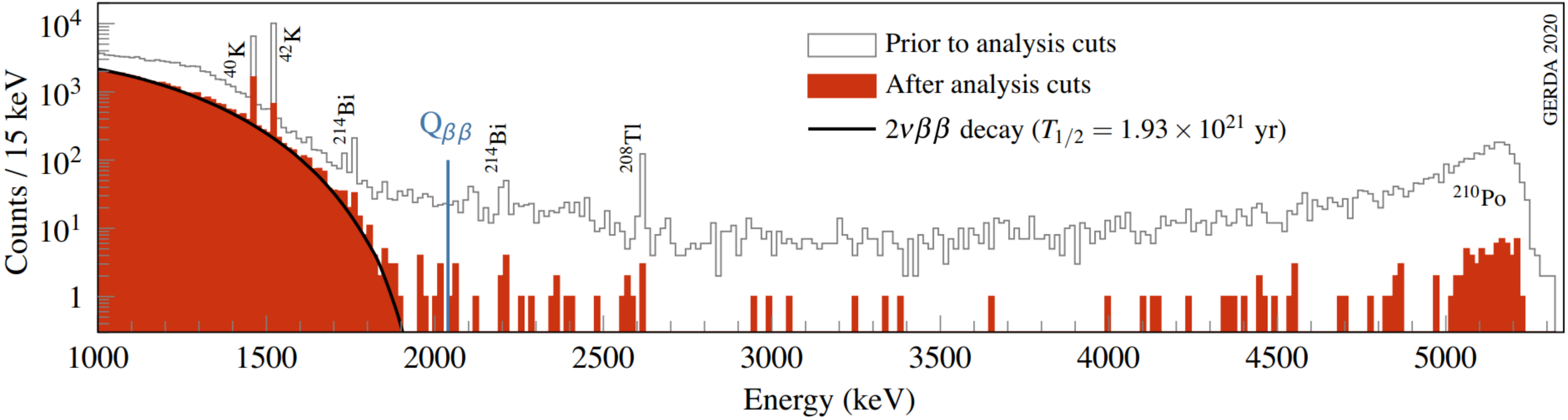
$$t_{1/2}^{0\nu\beta\beta} > 1.8 \cdot 10^{26}\ yr\ (90\%\ C.L.)$$

nylon bag against ions



$0\nu\beta\beta$ –experiments: GERDA phase II

- **Significant improvements of sensitivity**



$$t_{½}^{0\nu\beta\beta} > 1.8 \cdot 10^{26}\, yr\ (90\%\ C.L.)$$

[Final Results of GERDA on the Search for Neutrinoless Double-β Decay (aps.org)]

$0\nu\beta\beta$ –experiments: LEGEND

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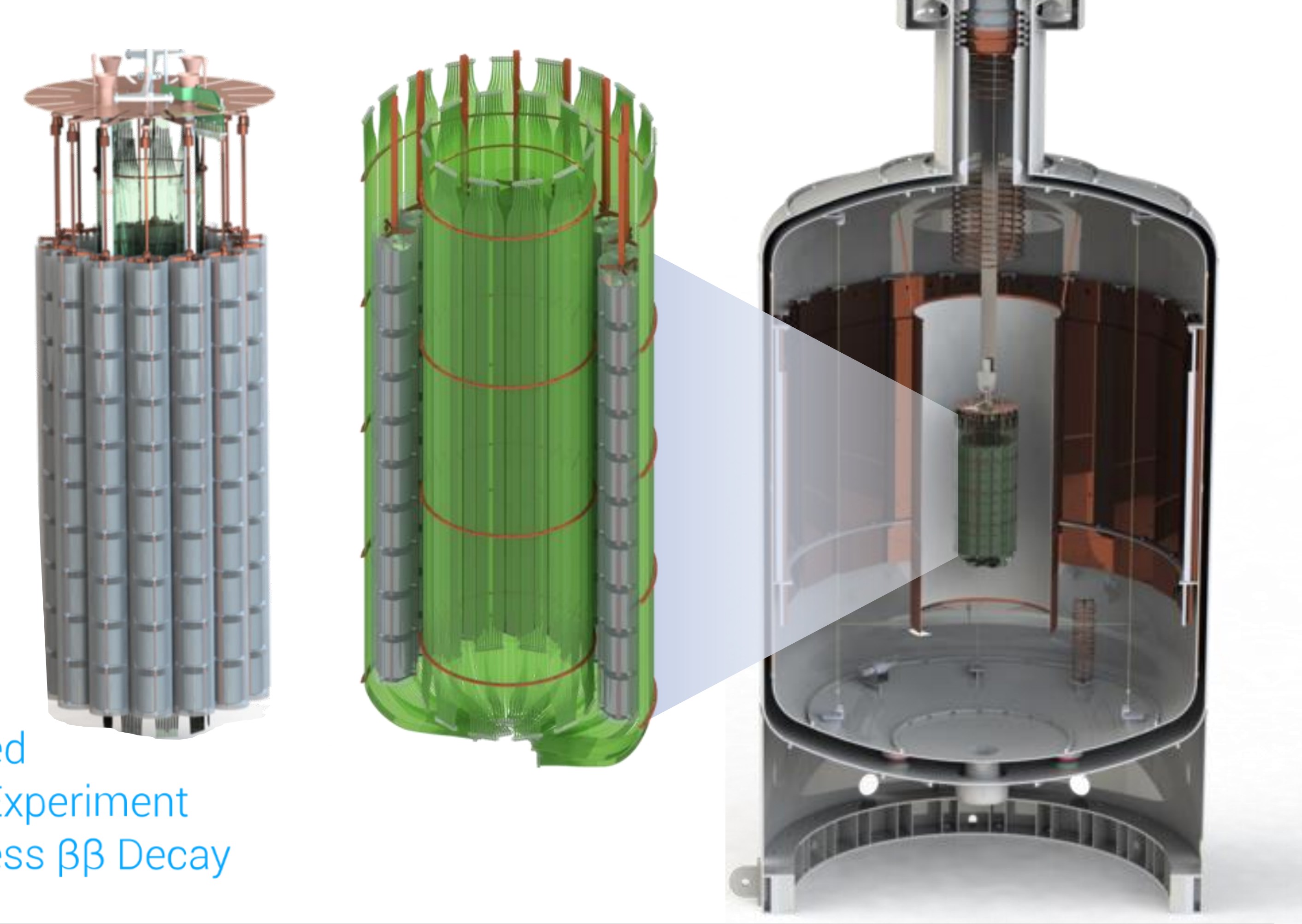
- **GERDA and MAJORANA merge to LEGEND: the ´ultimate´ step**

  - first stage:
    LEGEND-200

  - 14 strings with $^{76}\boldsymbol{Ge}$ – diodes
    total mass $\boldsymbol{M = 200\ kg}$

  - expected sensitivity $(1\ ton \cdot yr)$:

$$t_{½}^{0\nu\beta\beta} > 1\ \cdot 10^{27}\ yr\ (90\%\ C.L.)$$



Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

$0\nu\beta\beta$ –experiments: LEGEND

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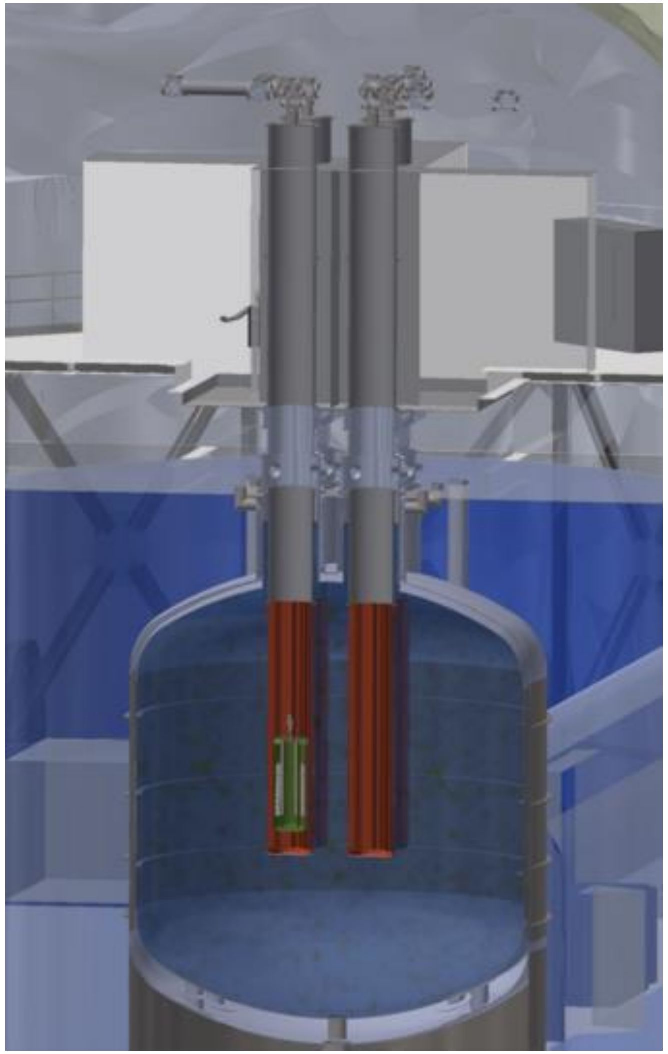
- **LEGEND-1000: the ´ultimate´ sensitivity**

  - final stage:
    LEGEND-1000

  - strings with $^{76}\boldsymbol{Ge}$ – diodes
    total mass $\boldsymbol{M = 1000\ kg}$

  - expected sensitivity $(10\ ton \cdot yr)$:

$$t_{½}^{0\nu\beta\beta} > 1\ \cdot 10^{28}\ yr\ (90\%\ C.L.)$$



LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

$0\nu\beta\beta$ –experiments: CUORE

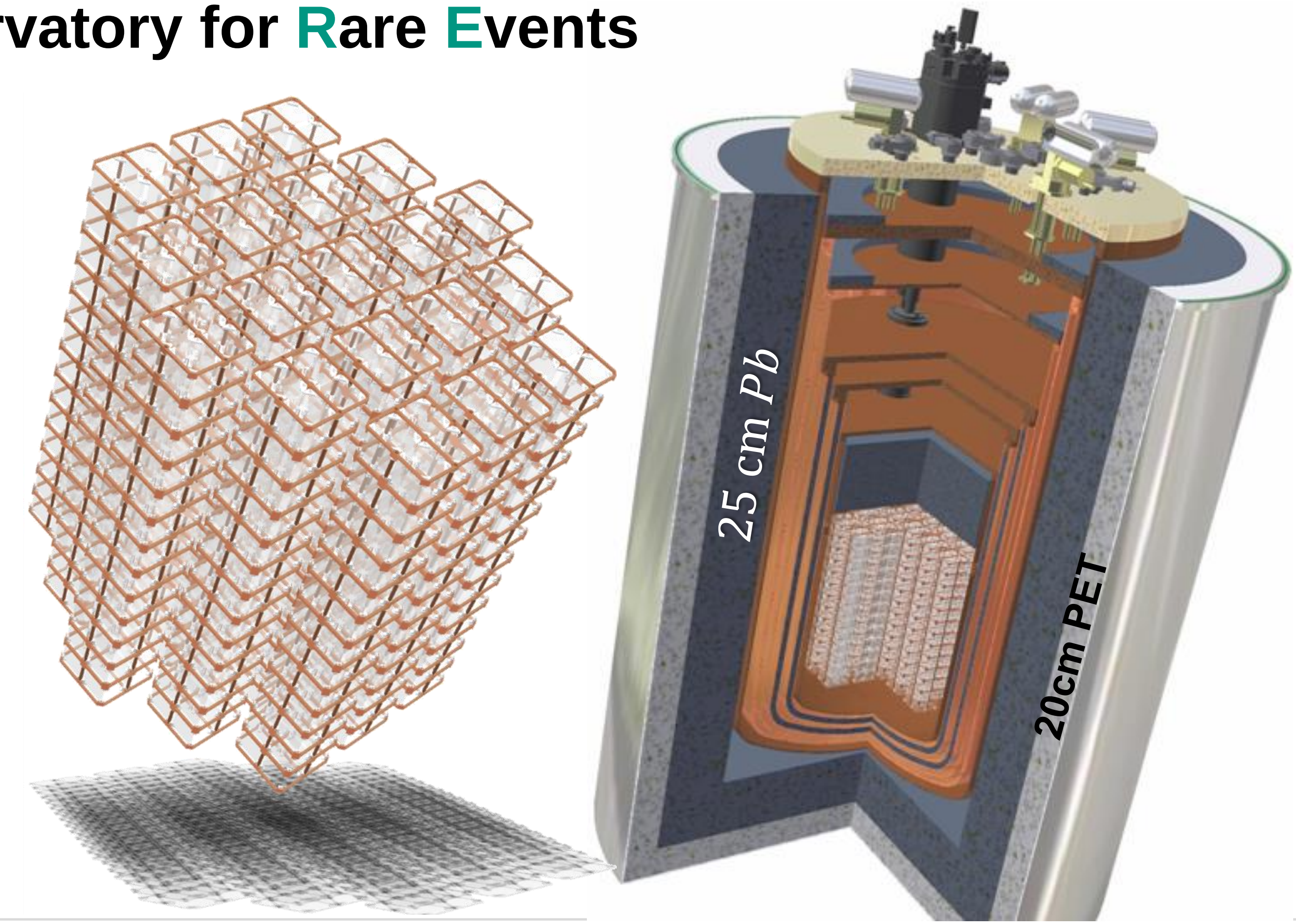
- **The coldest heart in the universe: CUORE - the Cryogenic Underground Observatory for Rare Events**

- final stage:
  988 TeO_2 bolometers
  in 19 towers

- total mass $M = 754\ kg$
  thereof ^{130}Te: $M = 206\ kg$

- Q –value: $2.572\ MeV$

- massive shielding outside of
  cryostat by Roman Lead



$0\nu\beta\beta$ –experiments: CUORE

- TeO_2 –bolometers: a novel technology to observe $0\nu\beta\beta$ –events

- bolometer: low-temperature-detector (crystal) operated at $T = 6\,mK$

- $\beta\beta$ –decay leads to local energy deposition in a crystal:

⇨ small **increase of the detector temperature T**

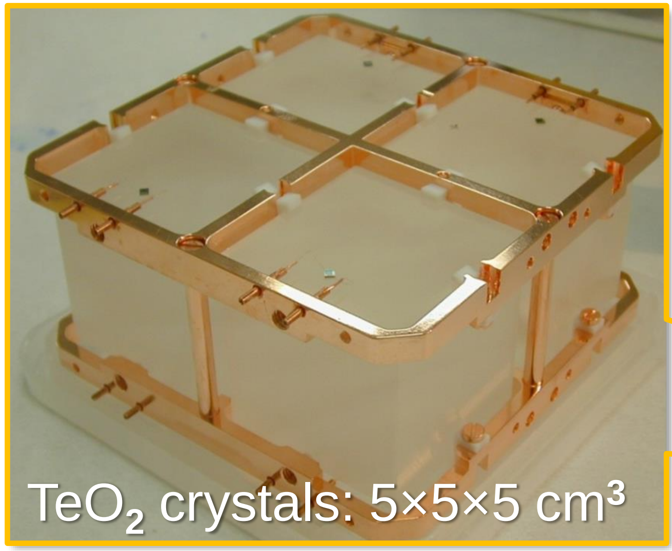
⇨ read-out via quantum sensor **thermistor***

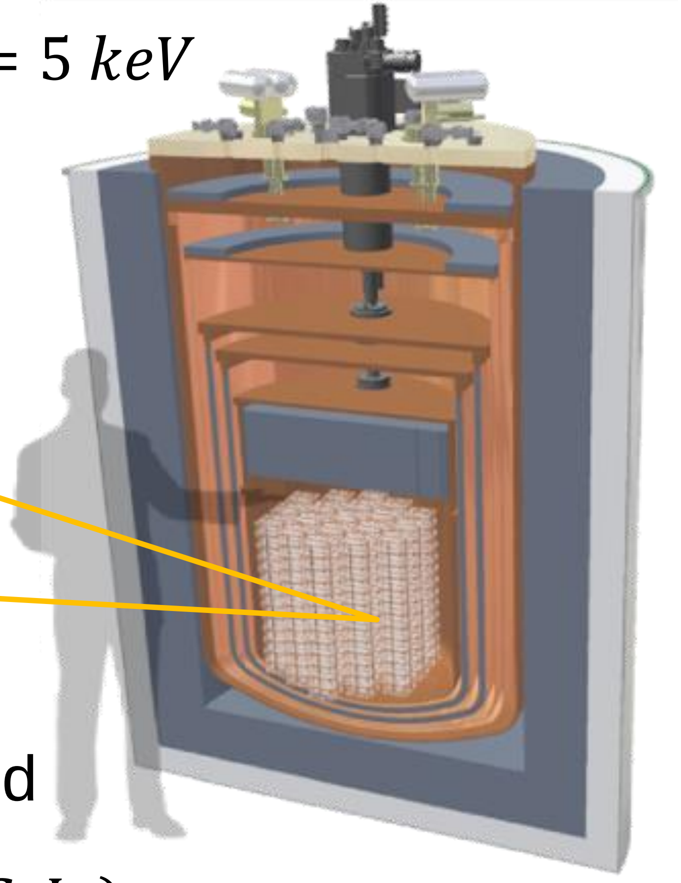
*thermistors: see chapter 4.5.2

$0\nu\beta\beta$ –experiments: CUORE

- TeO_2 –bolometers: results

  - bolometer energy resolution $\Delta E = 5\ keV$





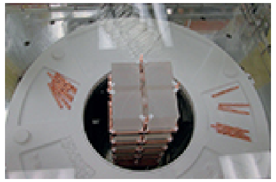
  - no ^{130}Te – signal events observed

$$t_{1/2}^{0\nu\beta\beta} > 1.5 \cdot 10^{25}\ yr\ (90\%\ C.L.)$$

CERN COURIER

Nov 27, 2014

CUORE has the coldest heart in the known universe



The CUORE experiment

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 metre to a temperature of 6 mK. It is the first experiment to cool a mass and a volume of this size to a temperature this close to absolute zero. The cooled copper mass, weighing approximately 400 kg, was the coldest cubic metre in the universe for more than 15 days. No experiment on Earth has ever cooled a similar mass or volume to temperatures this low. Similar conditions are also not expected to arise in nature.

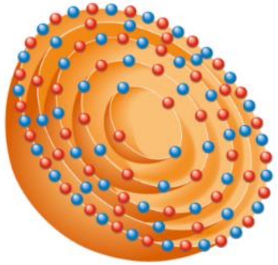
CUORE - which stands for Cryogenic Underground Observatory for Rare Events, but is also Italian for heart - is an experiment being built by an international collaboration at Gran Sasso to study the properties of neutrinos and search for rare processes, in particular the hypothesized neutrinoless double-beta decay. The experiment is designed to work in ultra-cold conditions at temperatures of around 10 mK. It consists of tellurium-dioxide crystals serving as bolometers, which measure energy by recording tiny fluctuations in the crystal's temperature. When complete, CUORE will contain some 1000 instrumented crystals and will be covered by shielding

$0\nu\beta\beta$ –experiments: from $t_{½}^{0\nu\beta\beta}$ to $m_{\beta\beta}$

- **How does my half-life limit transform into the Majorana neutrino mass?**

  - we need nuclear theory (***maxtrix elements*** $M_{F,GT}^{0\nu\beta\beta}$) to obtain this, uncertainties for various nuclei typically very large (up to ~200%)

$$\langle m_{\beta\beta}\rangle^2 = \left(T_{1/2}^{0\nu\beta\beta}\cdot G^{0\nu\beta\beta}(E_0,Z)\cdot\left|M_{GT}^{0\nu\beta\beta}-\frac{g_V^2}{g_A^2}M_F^{0\nu\beta\beta}\right|^2\right)^{-1}$$

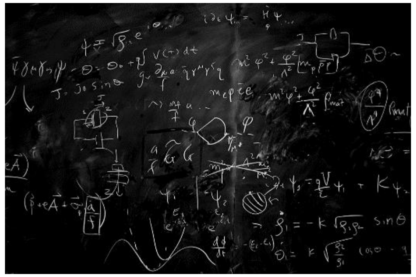


phase space

matrix elements (F Fermi, GT Gamow-Teller)

EXPERIMENT

×



THEORY

$0\nu\beta\beta$ –experiments: from $t_{1/2}^{0\nu\beta\beta}$ to $m_{\beta\beta}$

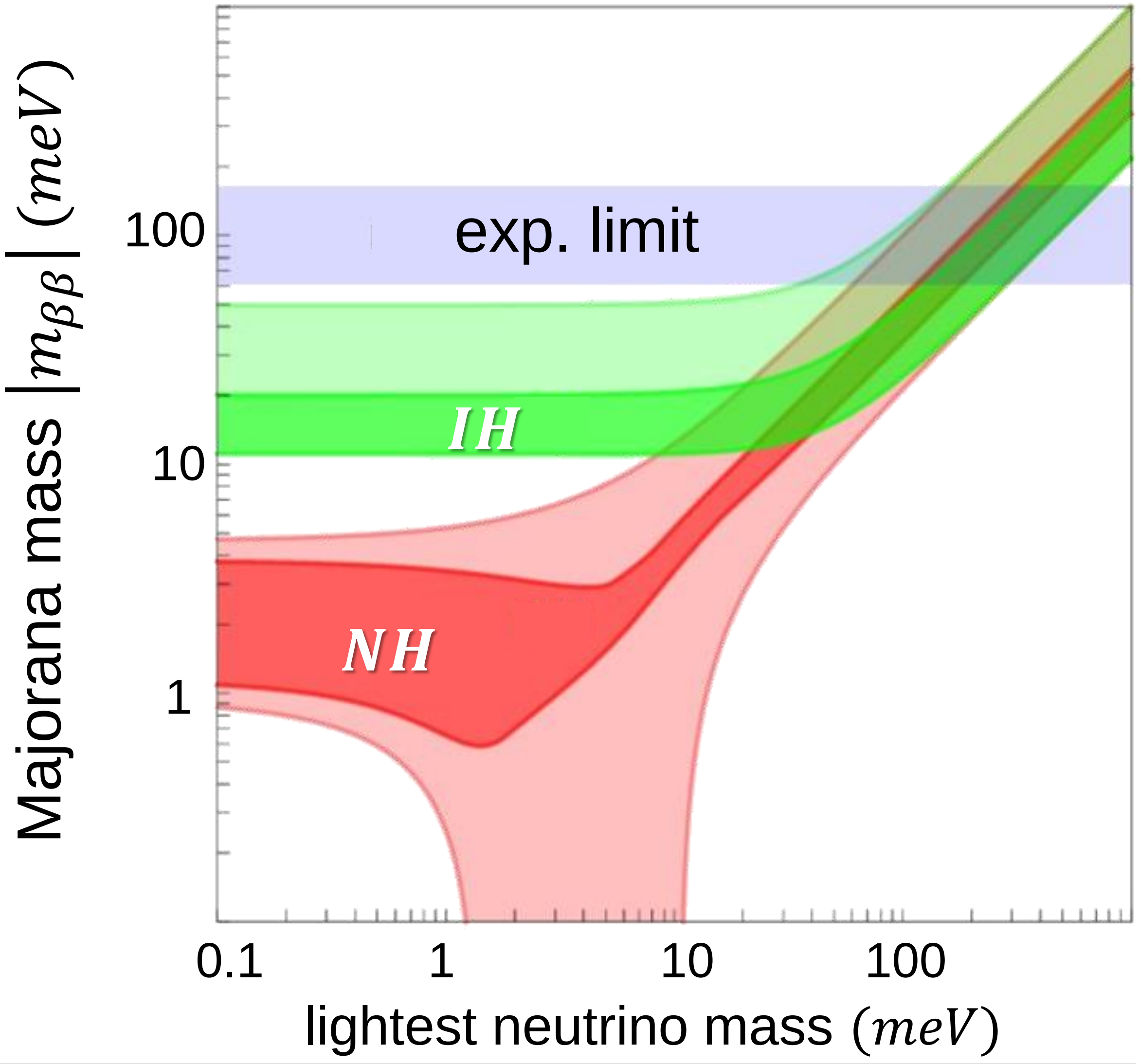
- **How large is the effective Majorana neutrino mass $m_{\beta\beta}$?**

- comparison of a typical upper limit from experiment on $m_{\beta\beta}$

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} \left| U_{e,i} \right|^2 m_i \cdot e^{i\alpha_i} \right|$$

to different theoretical models of neutrino masses:

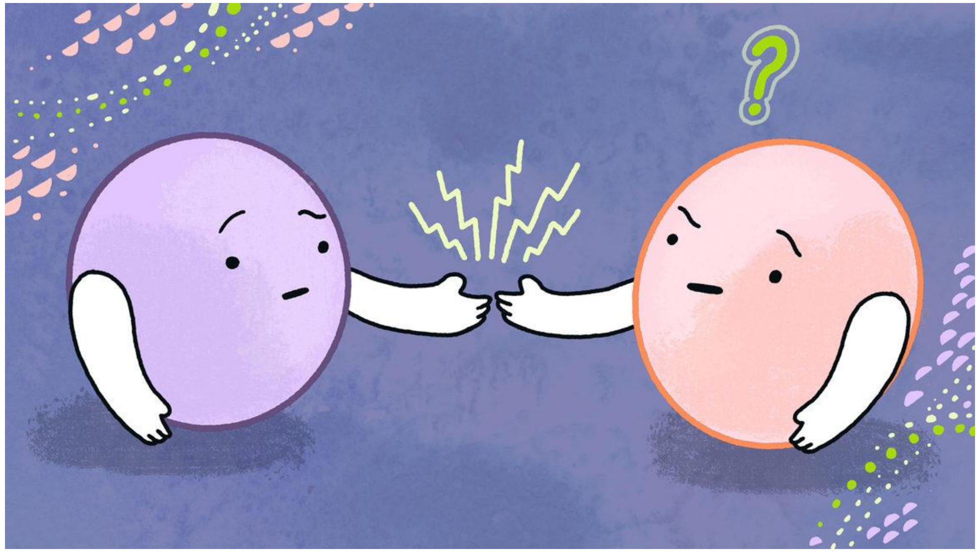
- NH normal hierarchy: $m_1 < m_2 < m_3$
- IH inverted hierarchy: $m_3 < m_{1,2}$



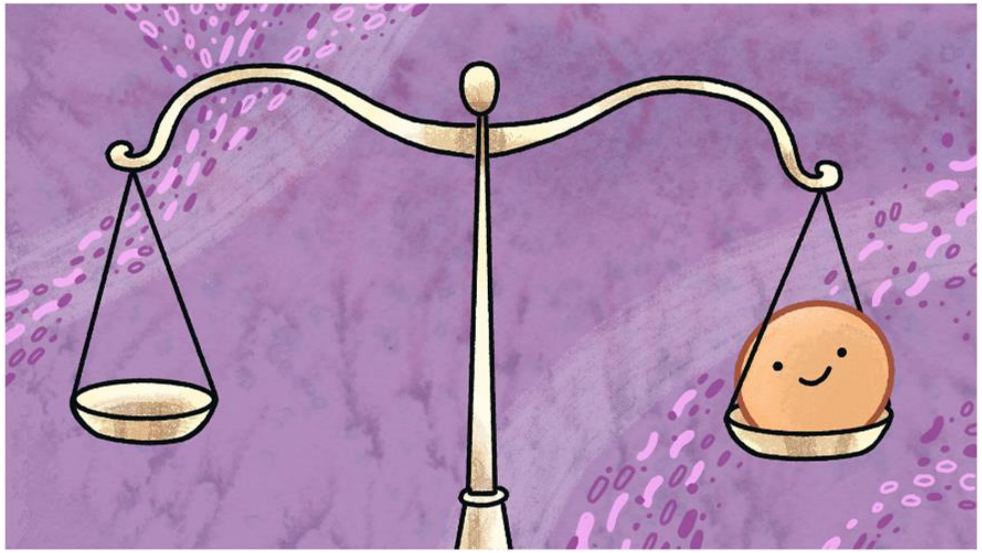
Neutrino physics: a most fascinating topic…

- Many fundamental open questions in neutrino physics remain!

Higgs-Mechanism vs. see-saw, Lepton number violation?



Are there right-handed neutrinos?

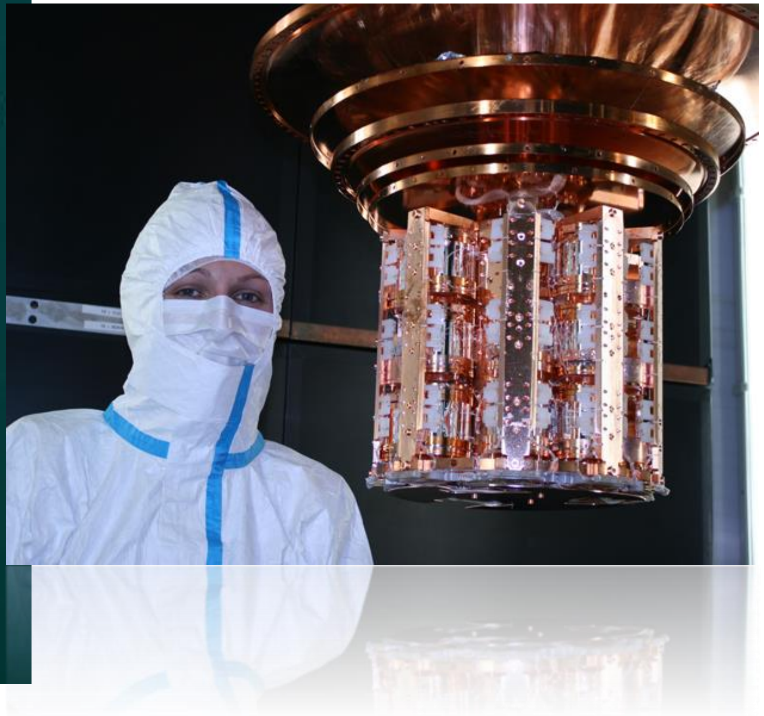


Info-Graphic by Sandbox Studio, Chicago with Corinne Mucha

How do neutrinos get their mass?

06/09/20 | By Jessica Romeo

Neutrinos don't seem to get their mass in the same way as other particles in the Standard Model.



CHAPTER 4 – DARK MATTER

4.1 Introduction

- **Evidences for Dark Matter (DM) from Cosmology & astrophysics**

  - cosmology*: physics of the early universe, analysis of CMB, structure formation

  - astrophysics: galaxy clusters, rotation curves of galaxies

  - evidences for DM are (up to now) only based on their gravitational action due to **Newtonian gravity**

  - possible (but unlikeky) alternative: theories based on **MOdified Newtonian Dynamics (MOND)**

  - searches for DM in astroparticle physics: particle interaction with nucleons/electrons, annihilation, or DM-production (LHC)

*see my lectures on cosmology

Searches for Dark Matter

- **DM-Triangle**

production at collider

direct detection

Indirect detection

Evidences for Dark Matter

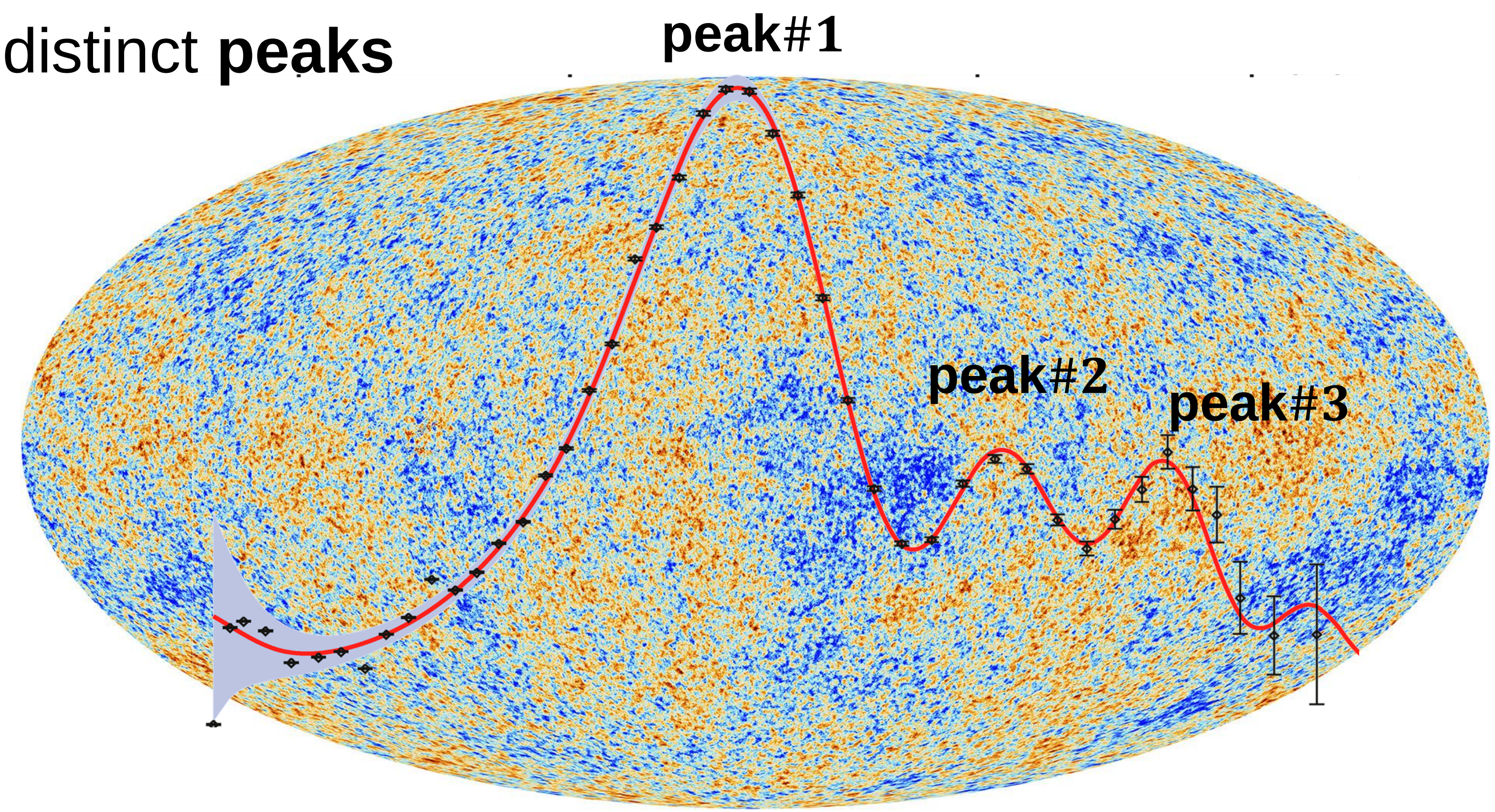
- **Cosmology: signatures in the $3K$ cosmic background radiation (CMB)**

  - CMB shows characterisitic very small **temperature fluctuations ΔT**

  - multipole analysis reveals distinct **peaks** $(\#1, \#2, \#3, \ldots)$

  - peak height of #2 : #3 gives $\boldsymbol{\Omega_{DM} \sim 0.27}$

  - popular scenario: **DM-production in the very early universe by thermal processes**



Evidences for Dark Matter

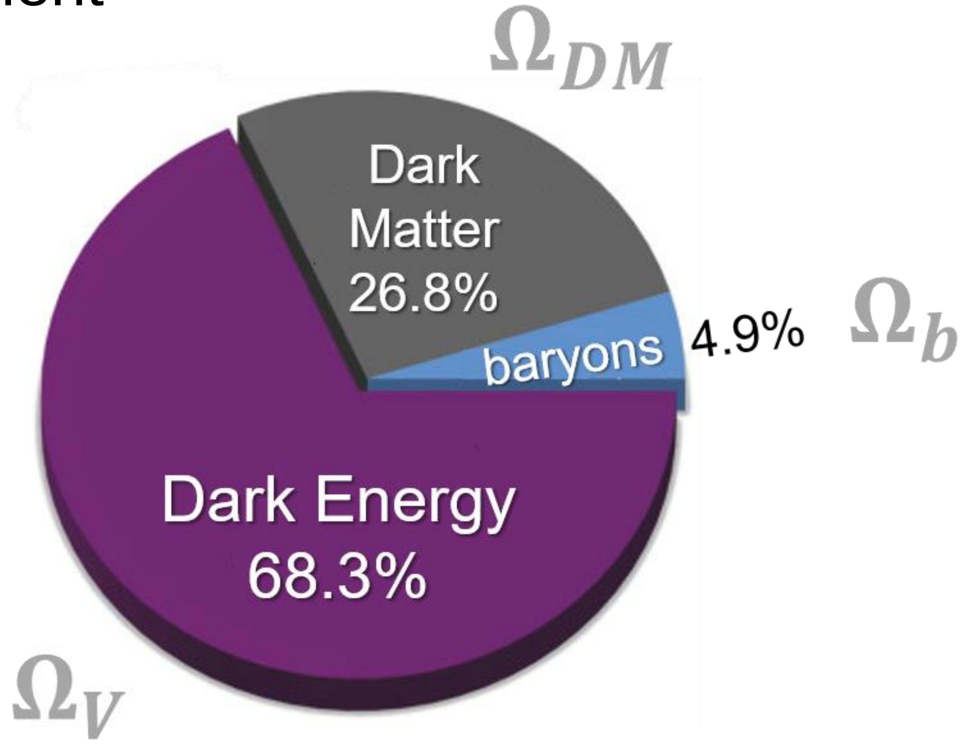
- **Cosmology: Dark Matter fraction Ω_{DM} on the overall matter-/energy- budget**

  - ΛCDM ´concordance´ model of cosmology consists of (beyond baryons):

    a) dark matter Ω_{DM} : non-baryonic component with Newtonian gravitational attraction cosmological density $\sim 1\ GeV/m^3$

    b) dark energy Ω_V : component due to properties of vacuum (Einstein´s famous cosm

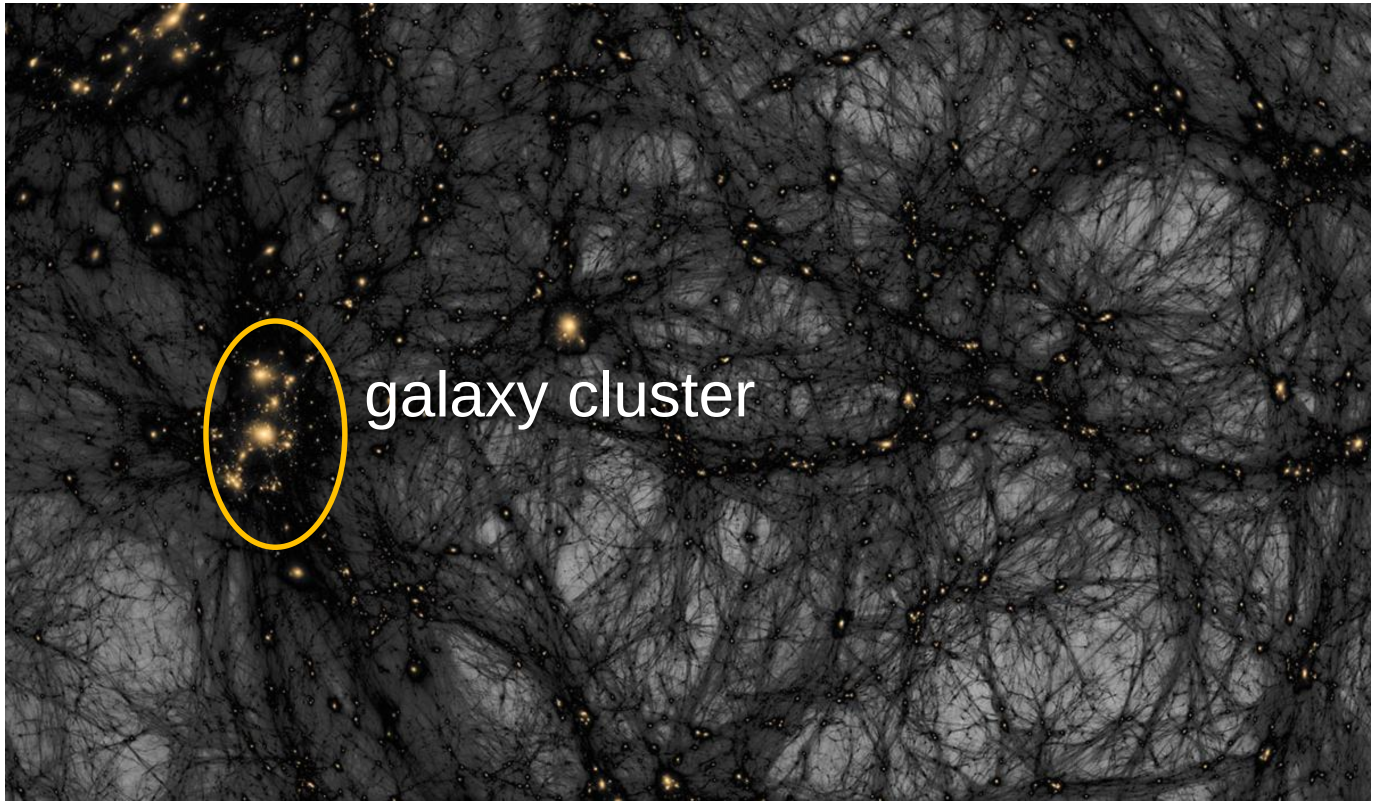
  - DM: large local overdensities ($e.g.$ center of Milky Way)



Evidences for Dark Matter

- **large-scale distribution of (cold) Dark Matter: evolution over time & space**

  - details are provided by large-scale **N-body simulations**
  - filament-like DM-structures
  - galaxy clusters at intersections of DM-filaments
  - simulations in agreement with **large-scale galaxy surveys**
  - dominant form of DM is **cold** (i.e. non-relativistic)



Evidences for Dark Matter

- **large-scale distribution of (cold) Dark Matter: evolution over time & space**

  - details are provided by large-scale N-body simulations

  - state-of-the-art code: Illustris (2015)

  - $19 \cdot 10^6$ CPU hours

  - new code: Illustris-TNG (public release in 12/2018)

IllustrisTNG - Main (tng-project.org)

Evidences for Dark Matter: F. Zwicky

KIT Karlsruhe Institute of Technology

- **Fritz Zwicky ´discovers´ DM via the Virial theorem**

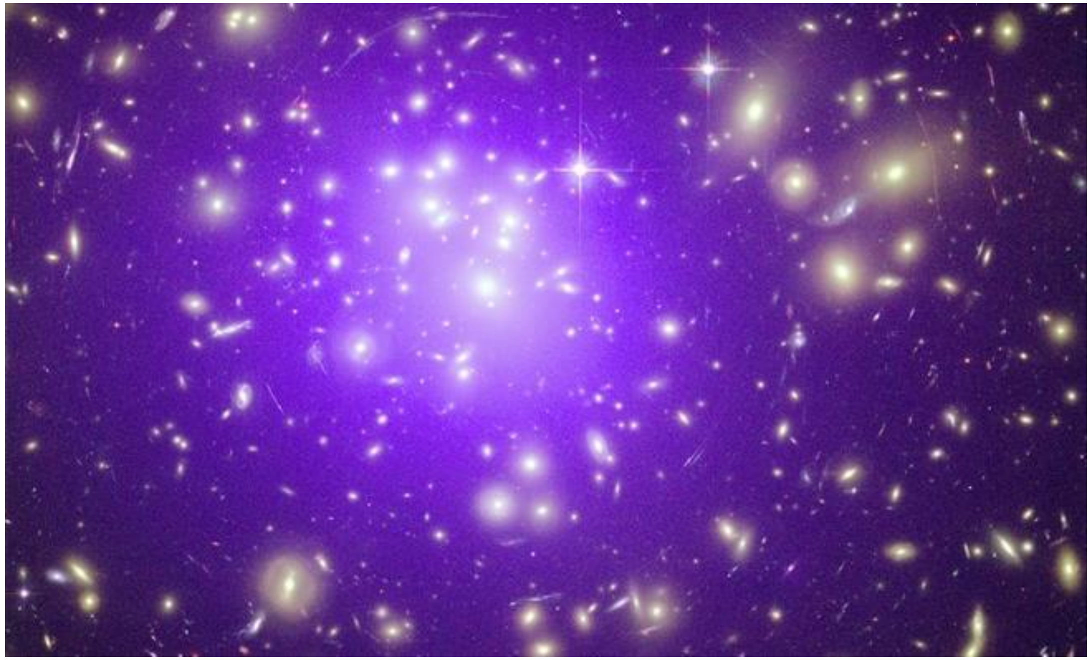
  - galaxy clusters: gravitationally bound (´virialised´) systems with relation $E_{kin} = -½ \cdot E_{grav}$

    ↓ (from E_{kin}) and ↓ (from E_{grav})

  - the peculiar velocities v (from E_{kin}) — **DM** (from E_{grav})
    of galaxies in a cluster (along the line-of-sight) are too large:
    ⇨ **´missing mass´**

  - **Dark Matter comprises ~90% of entire mass of a galaxy cluster (1933)**

Die Rotverschiebung von extragalaktischen Nebeln
von **F. Zwicky.**
(16. II. 33.)



Evidences for Dark Matter: V. Rubin

Karlsruhe Institute of Technology

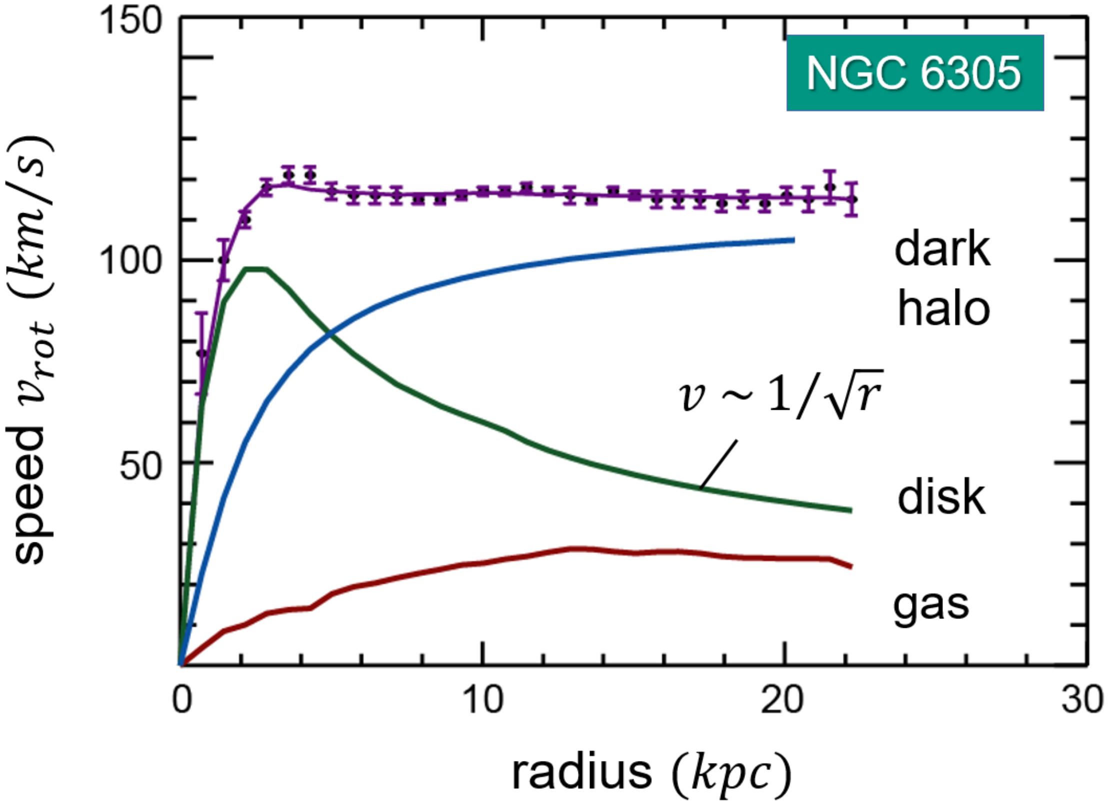
- **Vera Rubin ´discovers´ DM via rotation curves**

  - all galaxies show a **flat profile** of the rotation speed of their stars v_{rot} from center to the outer edge

  - modelling requires the existence of a ´**Dark Halo**´ (of Dark Matter particles)

  - density distribution $\rho_{DM}(r)$ of Dark Matter (important for direct/indirect detection):

$$M(r) \sim r \Rightarrow \boldsymbol{\rho_{DM}(r) \sim 1/r^2}$$



Evidences for Dark Matter: V. Rubin

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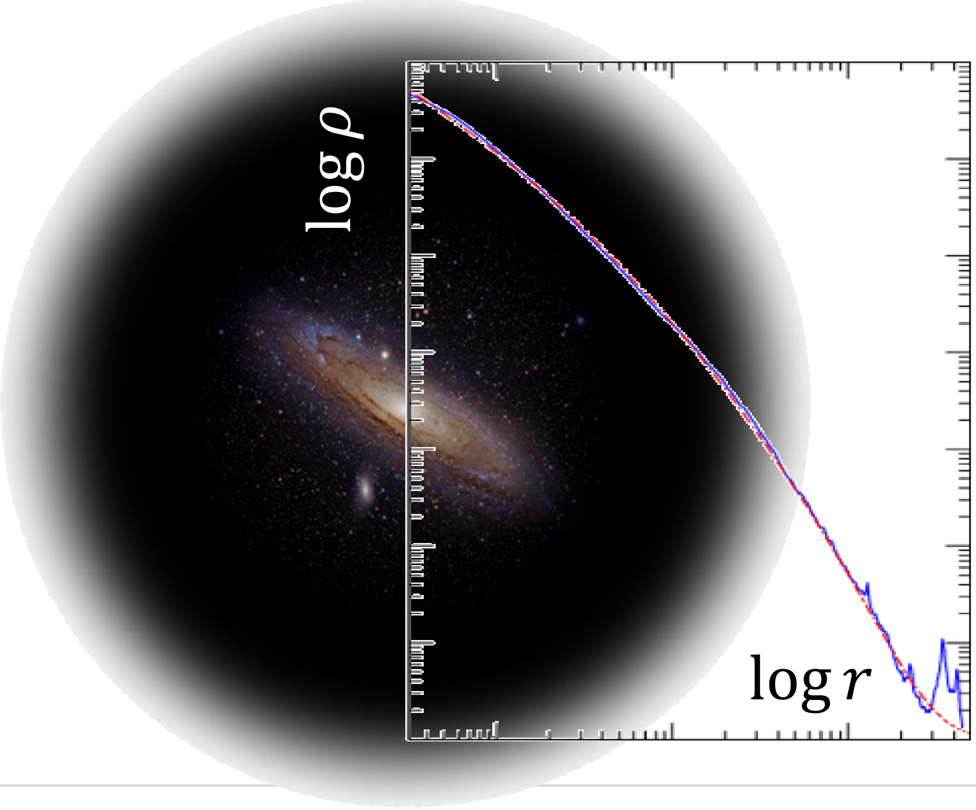
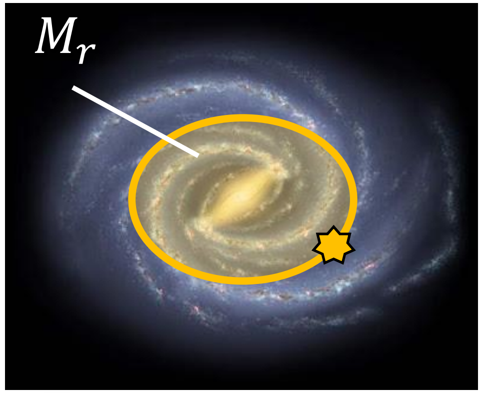


Local Density of Dark Matter

- **How many Dark Matter particles are in my cup of coffee today?**



- let´s use the rotation speed $v_{rot,sun} = 230\ km/s$ of the sun at our radius $r_{sun} = 8\,kpc$ in the galaxy to calculate it

$$\frac{v_{rot,sun}^2}{r} = \frac{G \cdot M_r}{r^2}$$

with DM-halo mass $M_r = {}^4/_3 \cdot \pi \cdot \rho \cdot r^3$

⇨ $\rho_{DM,local} = 3 \cdot v_{rot,sun}^2 \,/\, 4 \cdot \pi \cdot r_{sun}^2 \cdot G$

⇨ $\boldsymbol{\rho_{DM,local} = 0.3\ GeV/cm^3}$

Local Density of Dark Matter revealed

- **There is about 1 Dark Matter particle (WIMP*) of 50 GeV in my coffee cup**

  - let´s use the rotation speed $v_{rot,sun} = 230\ km/s$ of the sun at our radius $r_{sun} = 8\ kpc$ in the galaxy to calculate it

$$\frac{v_{rot,sun}^2}{r} = \frac{G \cdot M_r}{r^2}$$

with DM-halo mass $M_r = {}^4/_3 \cdot \pi \cdot \rho \cdot r^3$

⇨ $\rho_{DM,local} \sim \mathbf{10^5 \rho_{DM,universe}}$

⇨ $\rho_{DM,local} = \mathbf{50\ GeV/150\ cm^3}$

$M = 50\ GeV$

$V = 150\ cm^3$

*Weakly Interacting Massive Particle