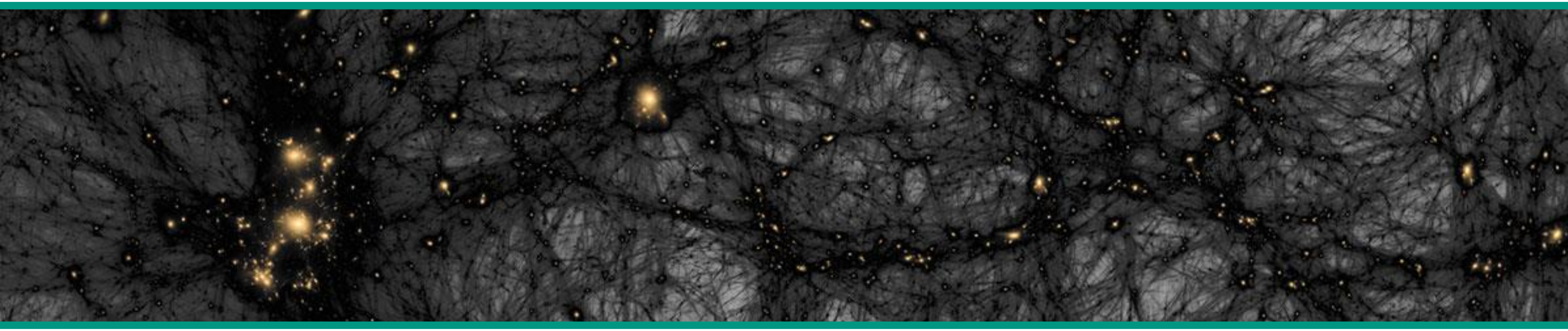
Astroparticle physics I – Dark Matter

Winter term 23/24 Lecture 12 Dec. 14, 2023



Recap of Lecture 11

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

  - $KATRIN$ experiment: precision scan of $\beta -$ **decay endpoint** 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 $\Delta L = 2$

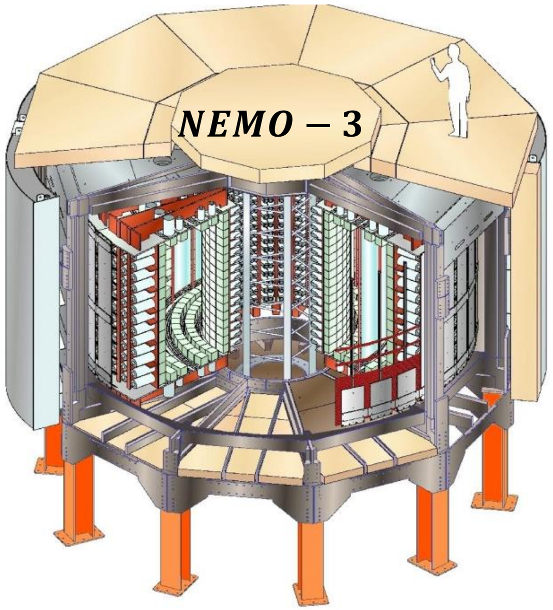
  - exchange of **virtual Majorana–ν : coherent** sum $m_{\beta\beta}$, unknown $CP -$ phases

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

Recap of Lecture 11

- **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

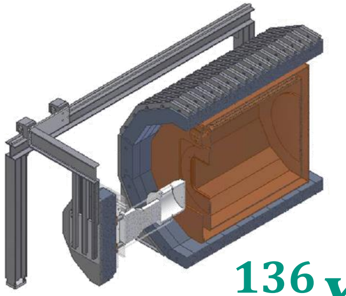
electrons result in an **ionisation signal**, or a **phonon signal** in a quantum sensor

^{76}Ge

active target

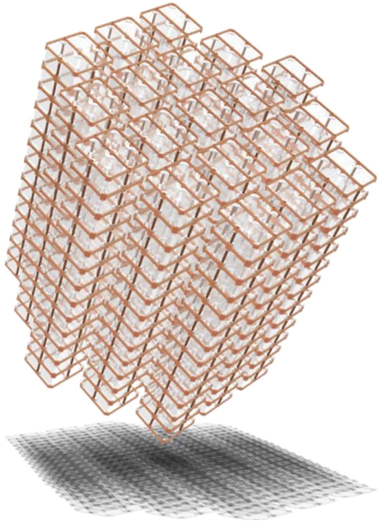
=

detector



^{136}Xe

^{130}Te



*Time Projection Chamber

Search for $0\nu\beta\beta$ – decay: exp. 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

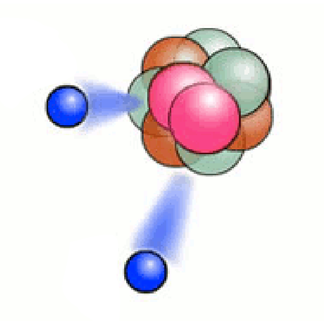
experimental
detection efficiency
$\varepsilon \le 1$

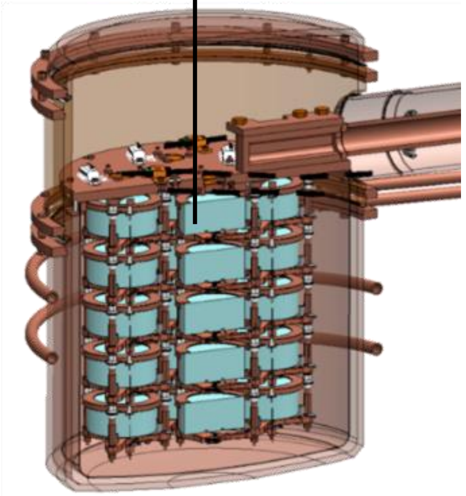
$^*1\ mole = 6.022 \cdot 10^{23}$ (atoms)

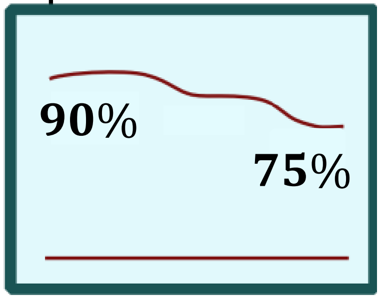
Search for $0\nu\beta\beta$ – decay: exp. observable $t_{1/2}$

- From the observed events N_{ev} to the half–life $t_{1/2}$ 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

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

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

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

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

M: mass of target in set–up

ΔE: energy resolution at endpoint (Q – value)

t: measuring time with set–up

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

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

Karlsruhe Institute of Technology

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

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

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

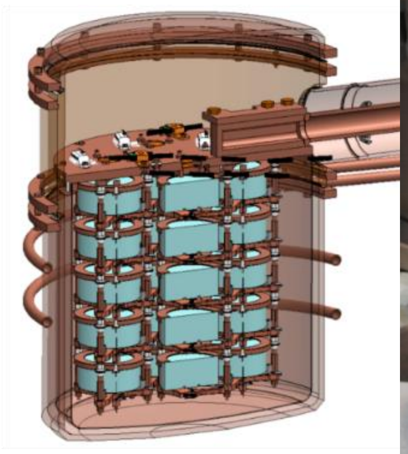
- $t_{1/2}^{0\nu\beta\beta}$ scales **linearly** with a ☑
- considerable **cost factor** ☒
  (no longer possible in Russian plants)

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

- **How do I optimize my $0\nu\beta\beta$ – set–up: use of an extended 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 $t = 1 \ldots 10\ yr$

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

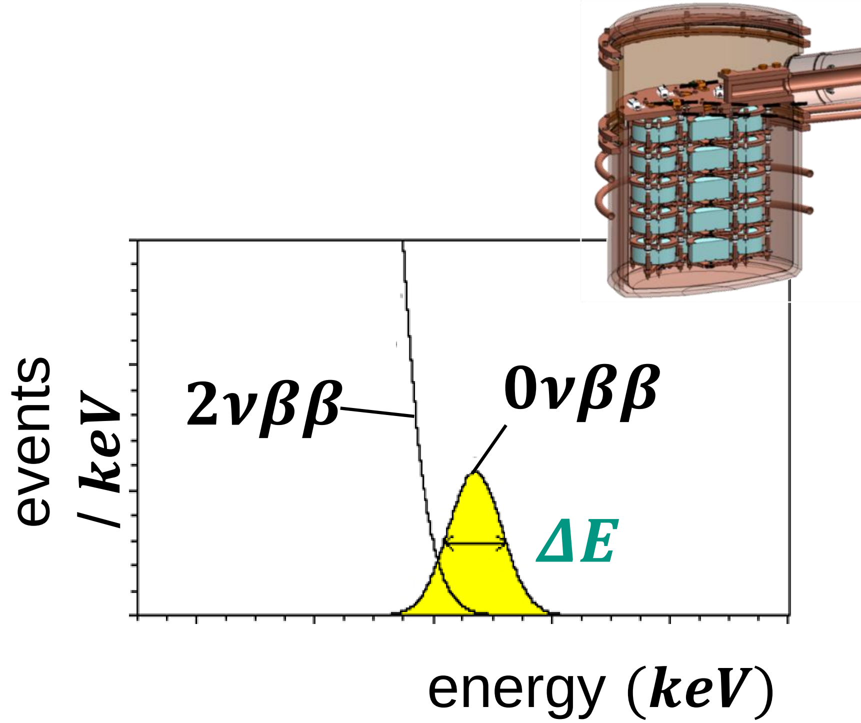
×

*see slide 13

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 keV)

- $t_{1/2}^{0\nu\beta\beta}$ 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 ($events\ keV^{-1}kg^{-1}yr^{-1}$)

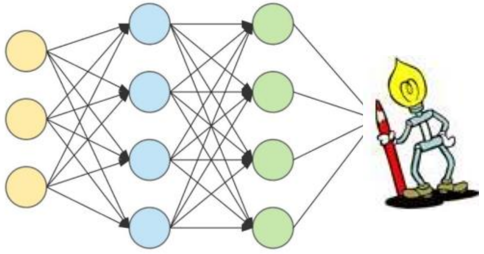
- $t_{½}^{0\nu\beta\beta}$ scales only with $\sqrt{B}$ ☑

- goal: use optimum shielding method (see ch. $2.2.2$)

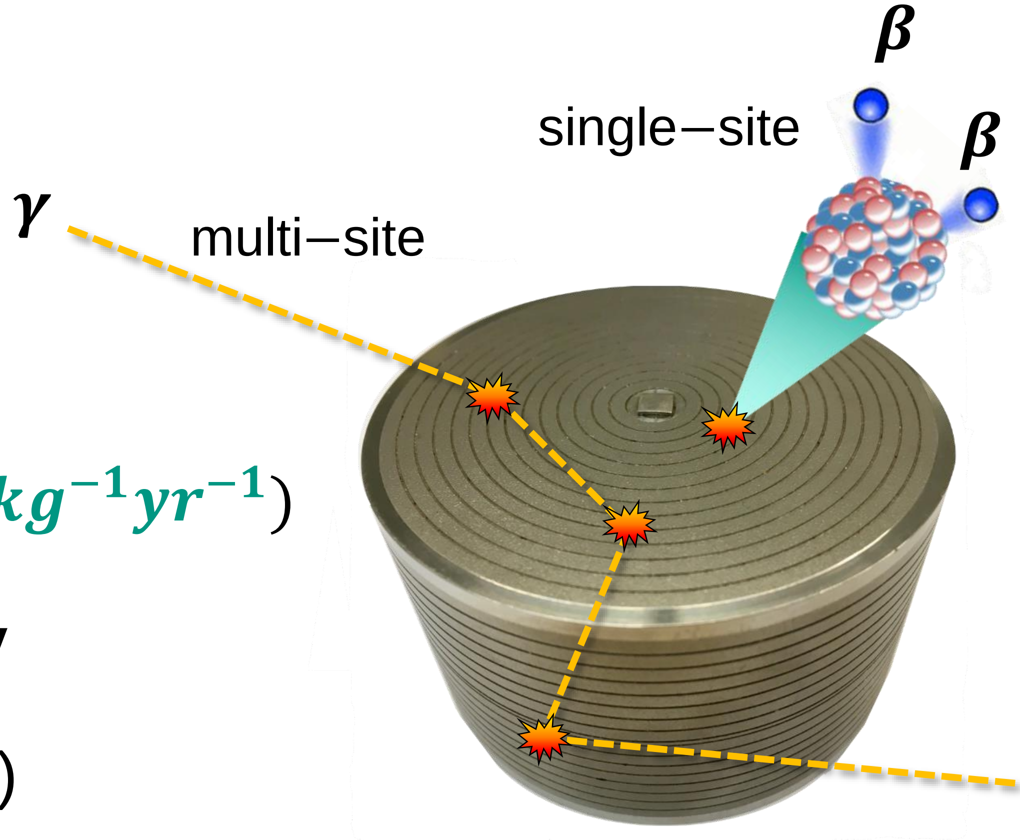
- combine passive elements (Cu) with active elements (μ – veto)

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**

- important technique: Pulse Shape Analysis (PSA)

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

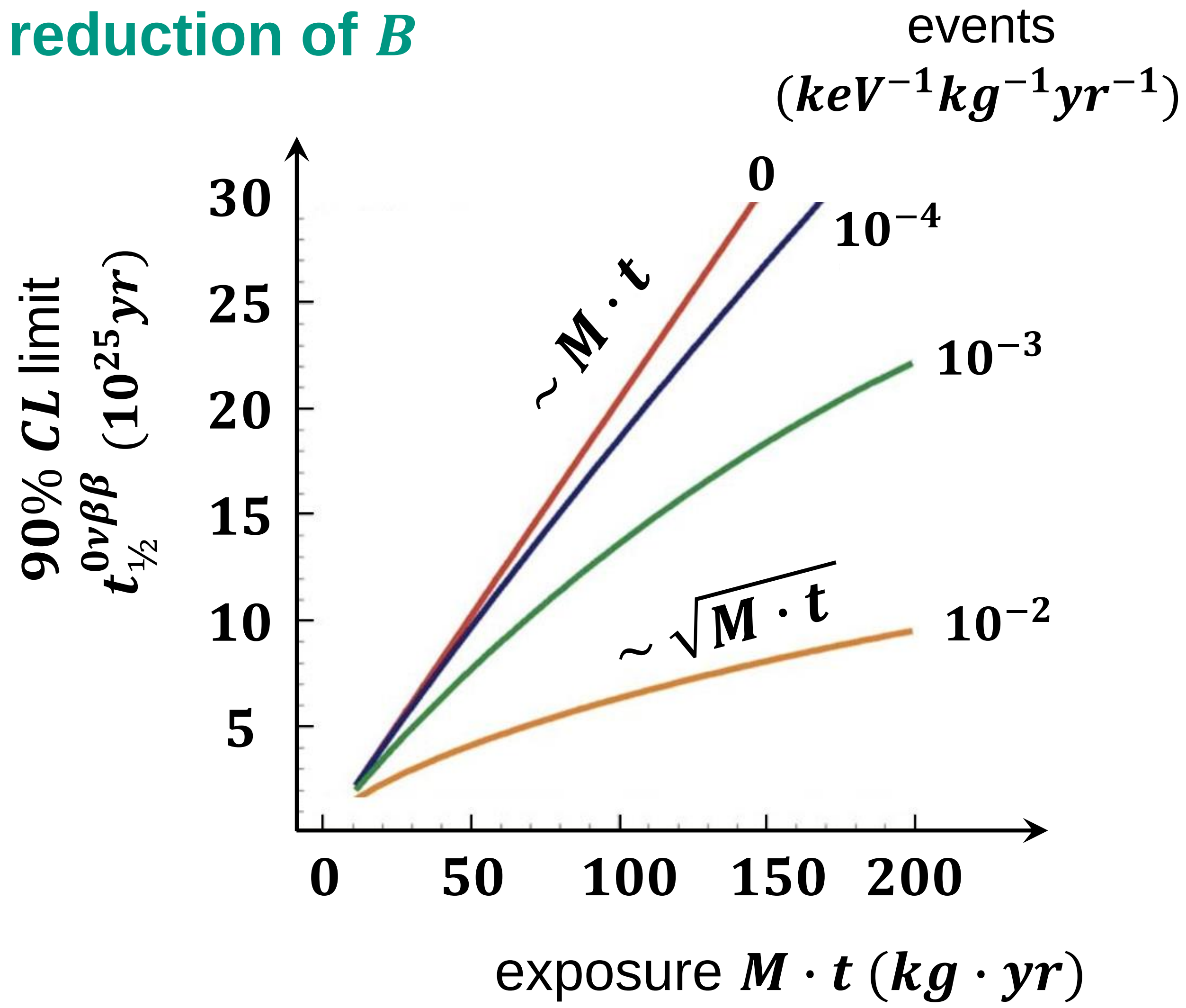
Search for $0\nu\beta\beta$ – decay: total background rate B

- **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 $M \cdot t$

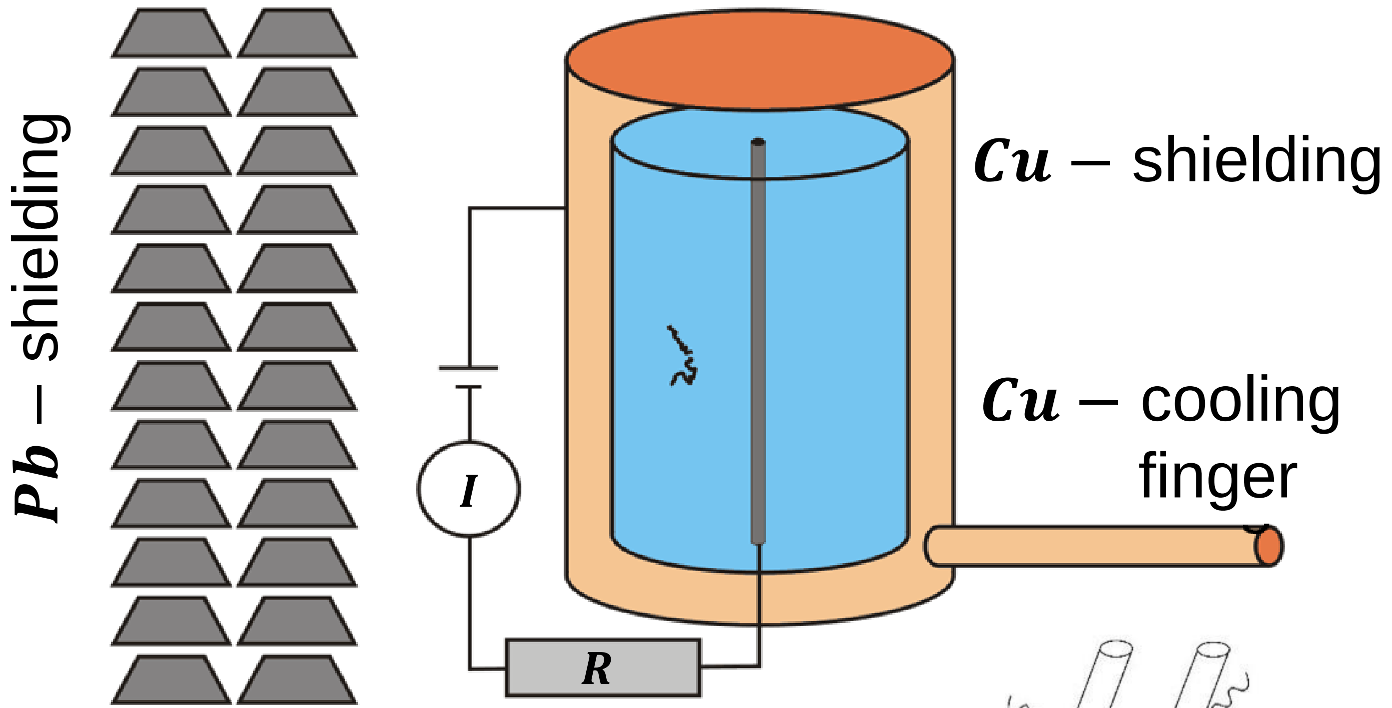
- case 2: **non–zero** background ($B > 0$)
  scaling of sensitivity
  with exposure only as $\sqrt{M \cdot t}$
  due to **Poisson fluctuations**
  of background rate B

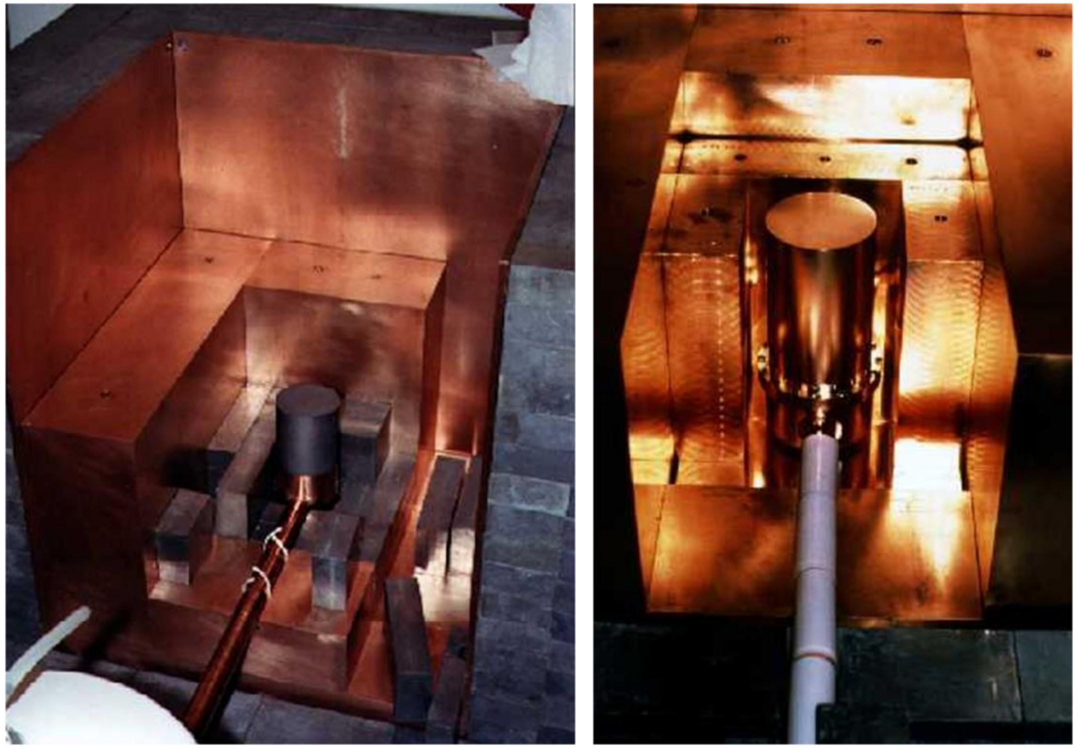


$0\nu\beta\beta$ – experiments: $Heidelberg - Moscow$

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

  - operation of 5 enriched Ge – diodes with enrichment grade $a = 0.86$ (86%)

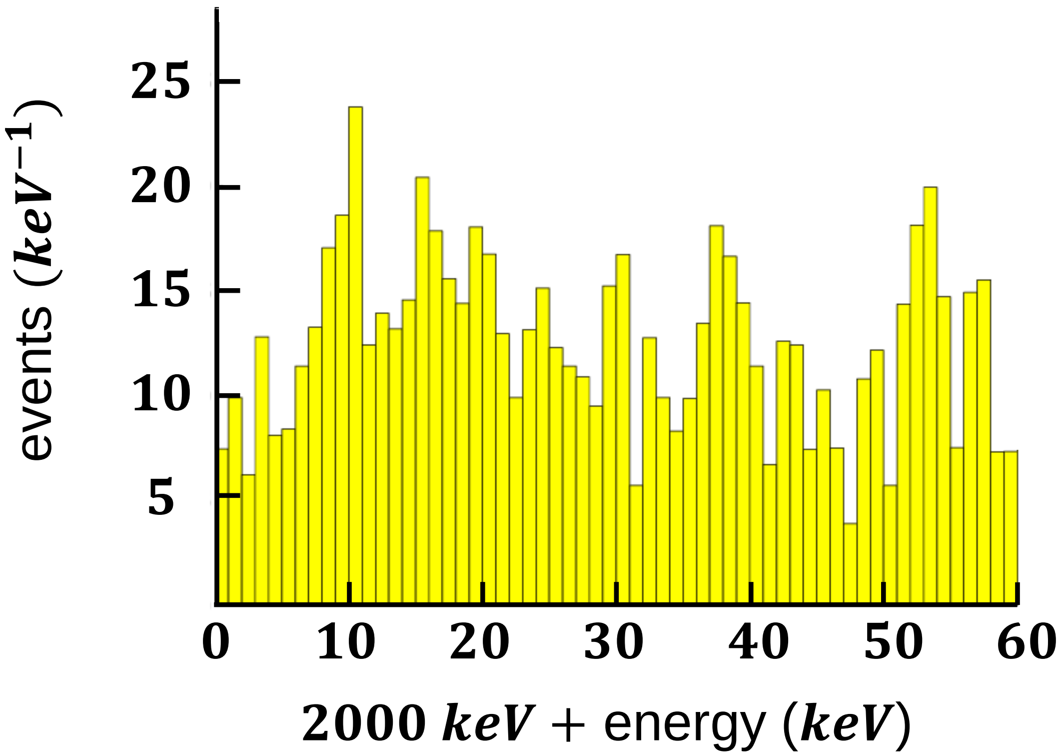




$0\nu\beta\beta$ – experiments: $Heidelberg - Moscow$ claim

- **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 PI*
  after calibrated energy data were available

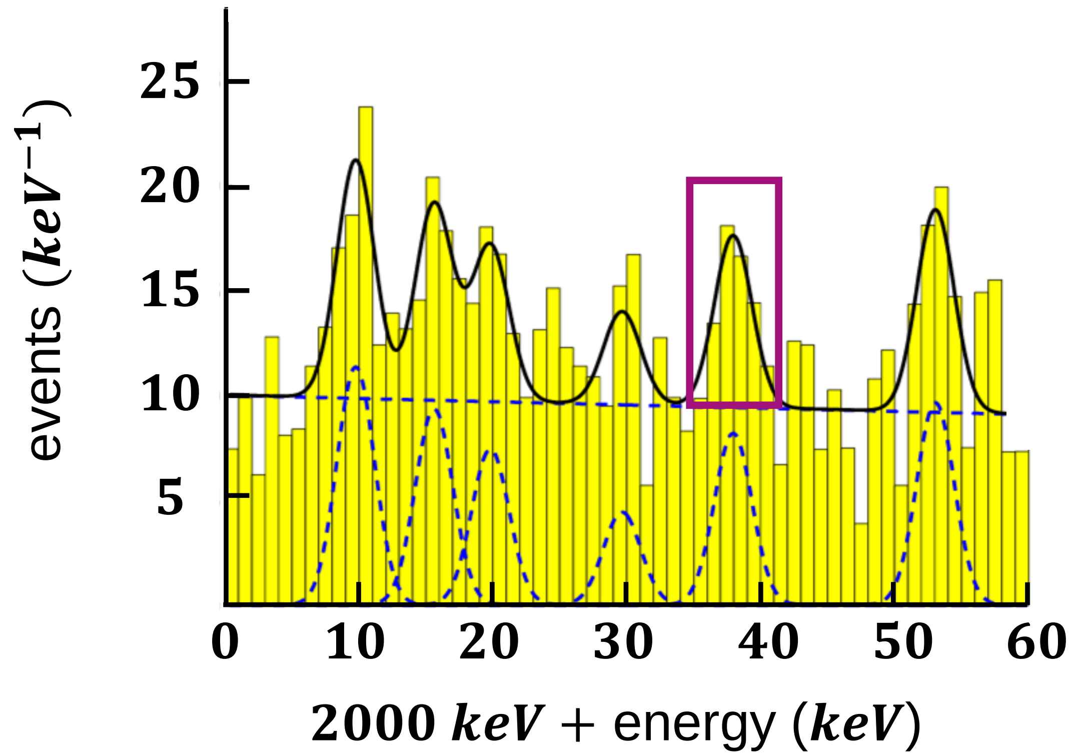
- $0\nu\beta\beta$ – events expected at an energy
  $E_0 = (2038.7 \pm 0.44)\ keV$

*Principal Investigator

$0\nu\beta\beta$ – 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 PI *after* calibrated energy data were available

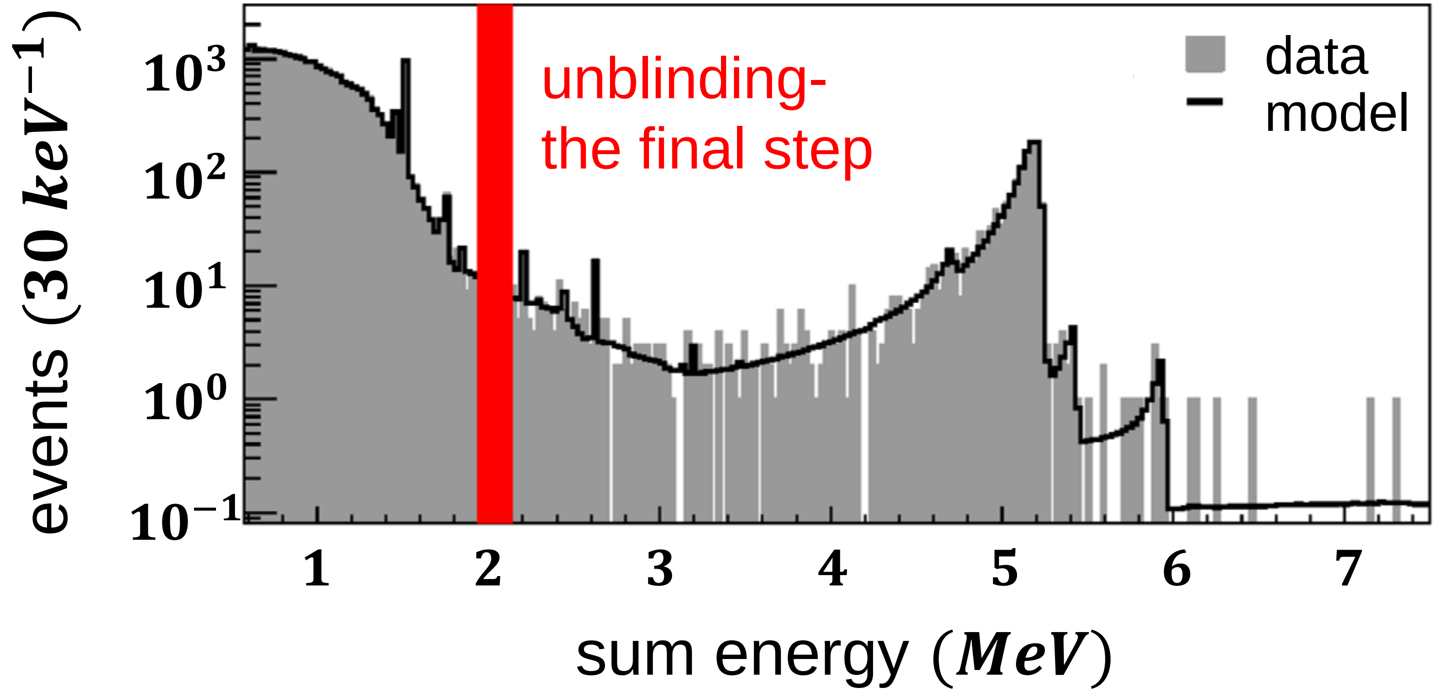
- $0\nu\beta\beta$ – events expected at an energy $E_0 = (2038.7 \pm 0.44)\ keV$

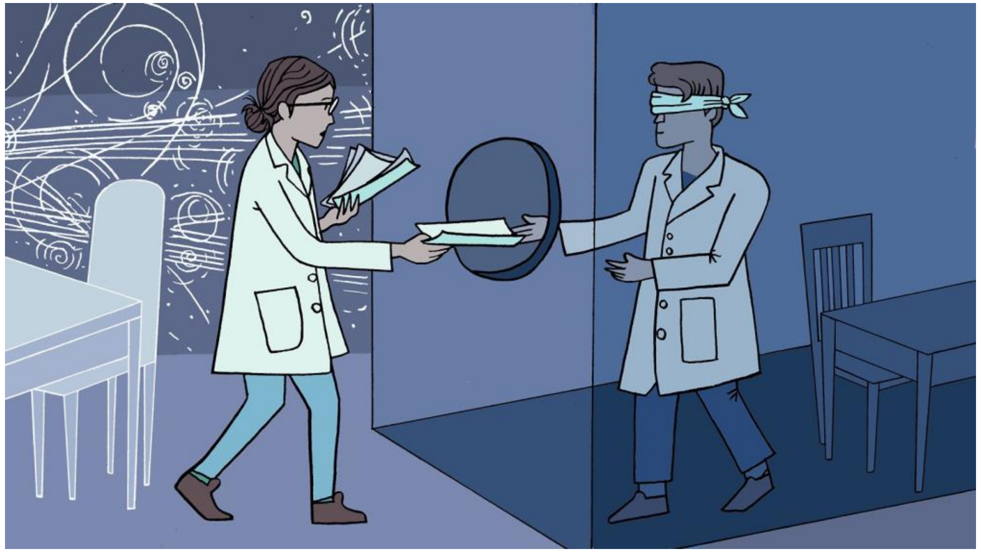
- highly **controversial claim** for $0\nu\beta\beta$ – signal with $N_{ev} = (28.75 \pm 6.86)$ events ($\equiv 4.2\ \sigma$)

- this result has **not been confirmed** by later experiments (today: **blind** analysis methods)

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

- **Current state–of–the art analysis methods: 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?



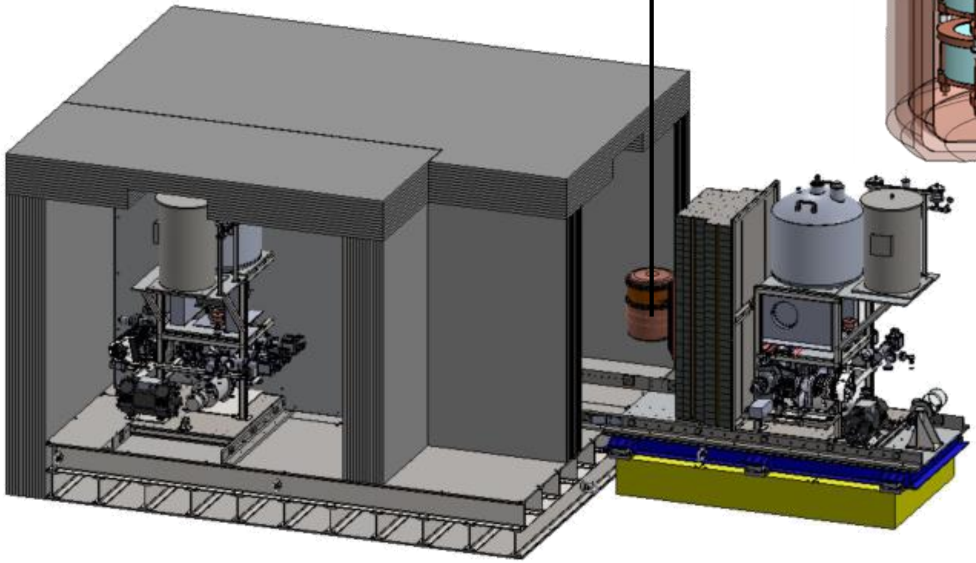


The facts and nothing but the facts

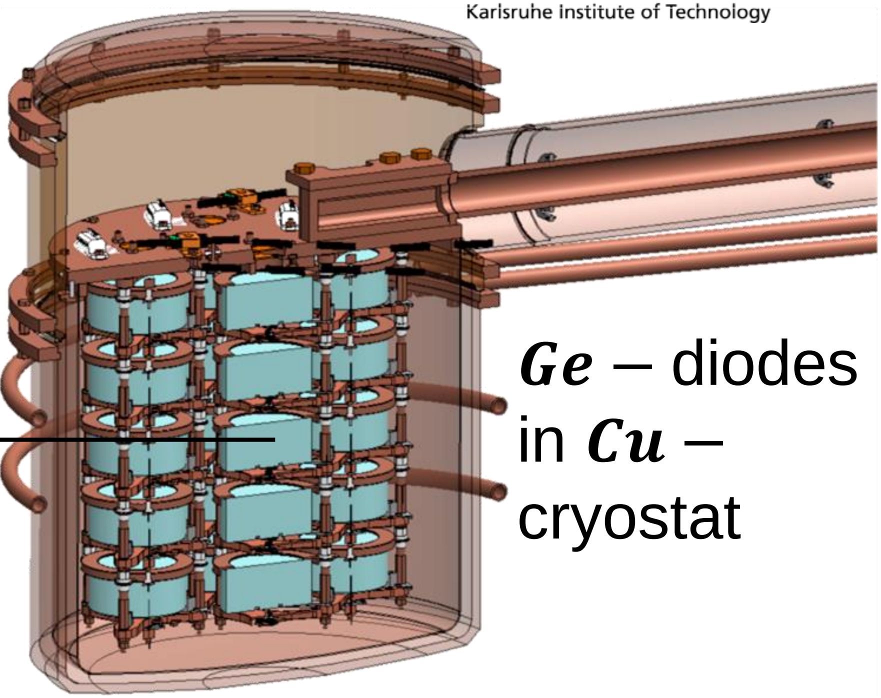
$0\nu\beta\beta$ – experiments: $MAJORANA$

- **Overview: based on classical shielding concept**

  - location: Sanford Underground Laboratory
  in Lead, South Dakota



shielding & infrastructure

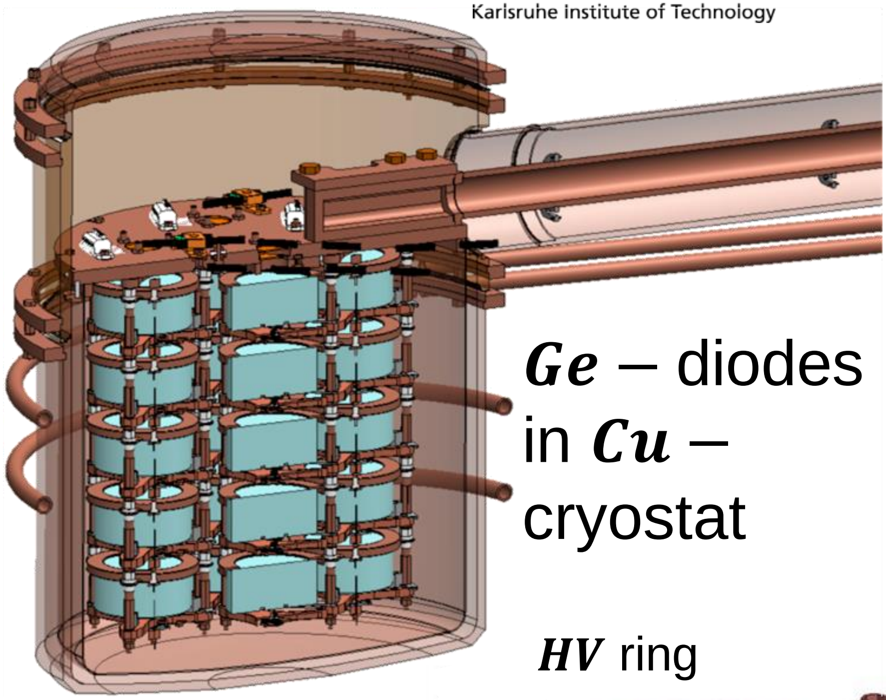


Ge – diodes in Cu – cryostat

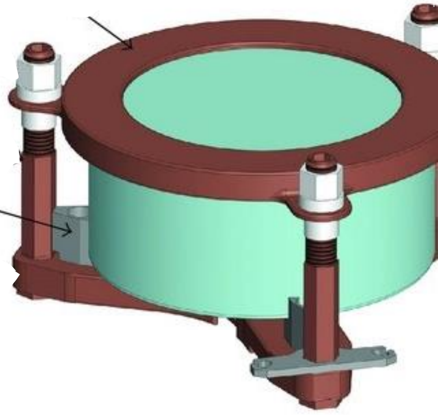
$0\nu\beta\beta$ – experiments: $MAJORANA$

- **Overview** & **shielding concept**

  - ´conventional´ set–up with ultra–clean Cu – holders (cooling of semi–conductors)



Ge – diodes in Cu – cryostat



HV ring

insulator

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

Experimental result & future plans

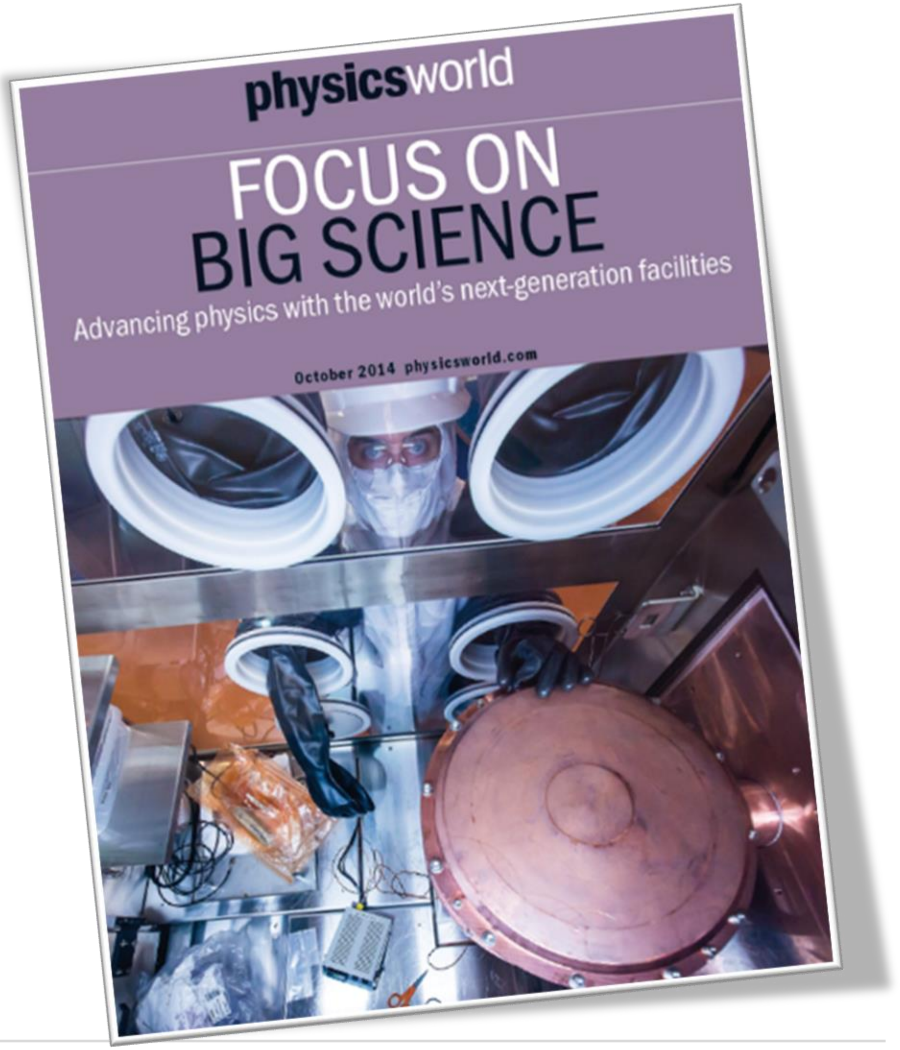
- set–up with $M = 44\ kg$ of enriched ^{76}Ge
  $M = 15\ kg$ of natural Ge

- **no** signal events observed

- published $\mathbf{2021}$ limit on $0\nu\beta\beta$ half–life of ^{76}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***



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

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

  - novel design based on ´**naked**´ 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:

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

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

GERDA

*Room Temperature

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

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- **Set–up**

clean room

diode insertion system

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

Liquid Argon $(70\ m^3)$:
ultra–pure cooling fluid + $PMTs$ for scintillation light

cryostat & internal Cu – shielding

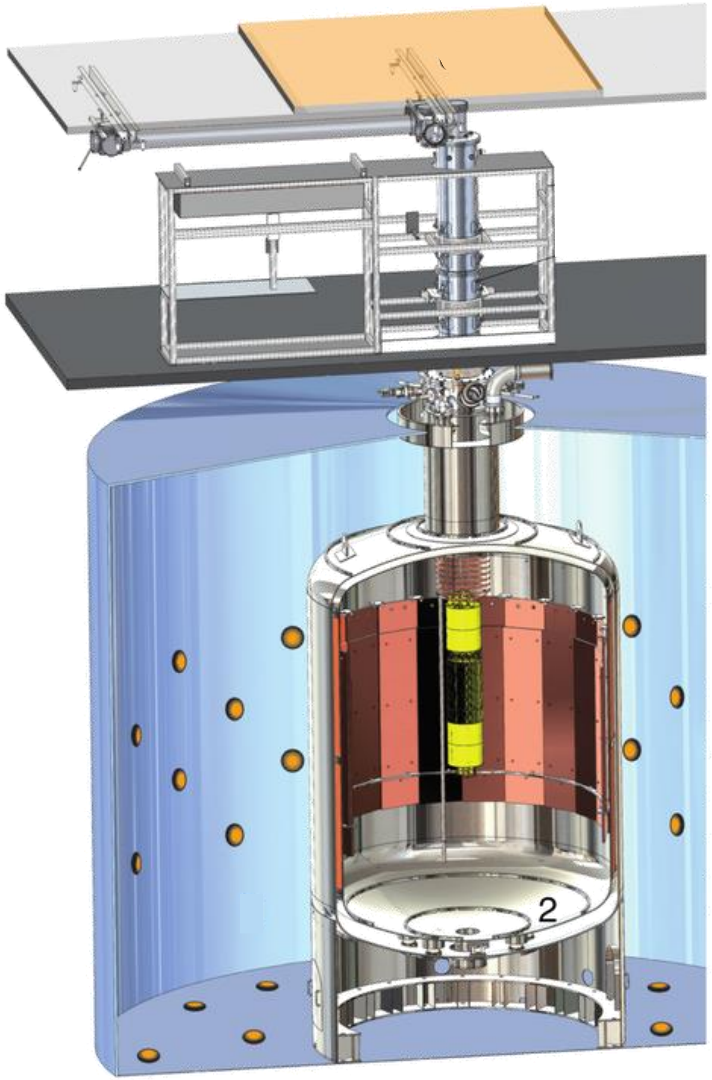
Ge – diodes
$18 \ldots 40\ kg$

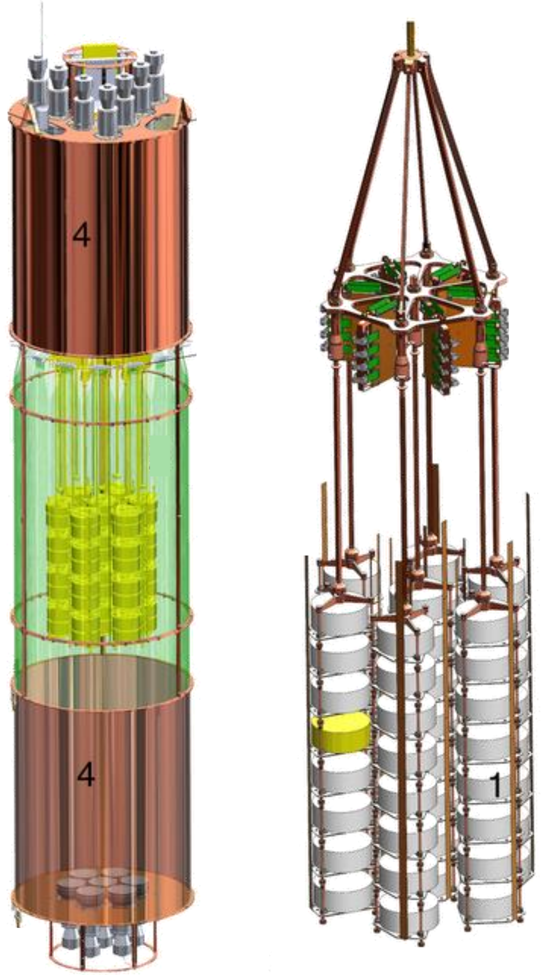
$0\nu\beta\beta$ – experiments: $GERDA$ phase II

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

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

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





*Wave–Length Shifter

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

- **Significant improvements of sensitivity**

  - energy resolution: $\Delta E \sim 3.0\ keV$

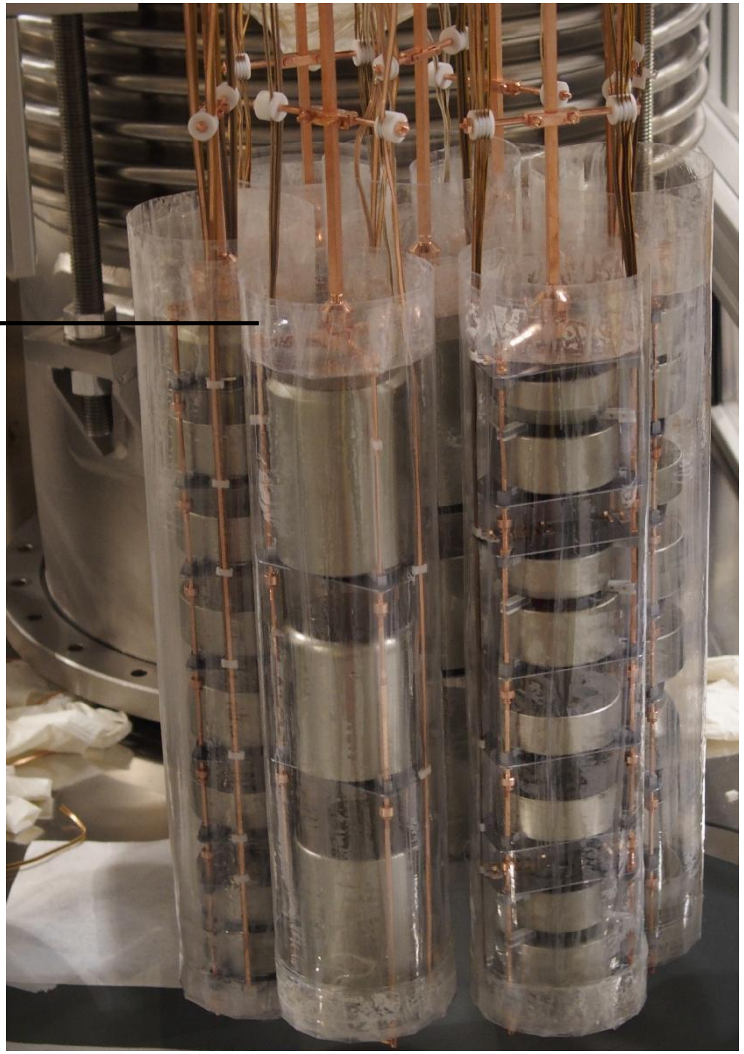
  - measurements from **12/2015 – 11/2019**

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

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

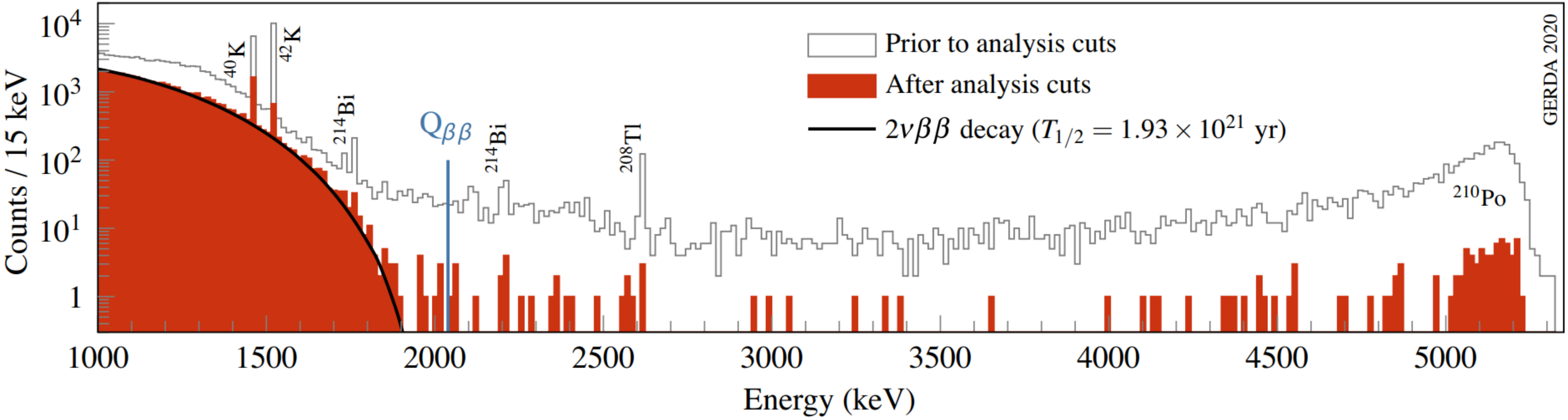
$$t_{½}^{0\nu\beta\beta} > 1.8 \cdot 10^{26}\ yr\ (90\%\ C.L.)$$

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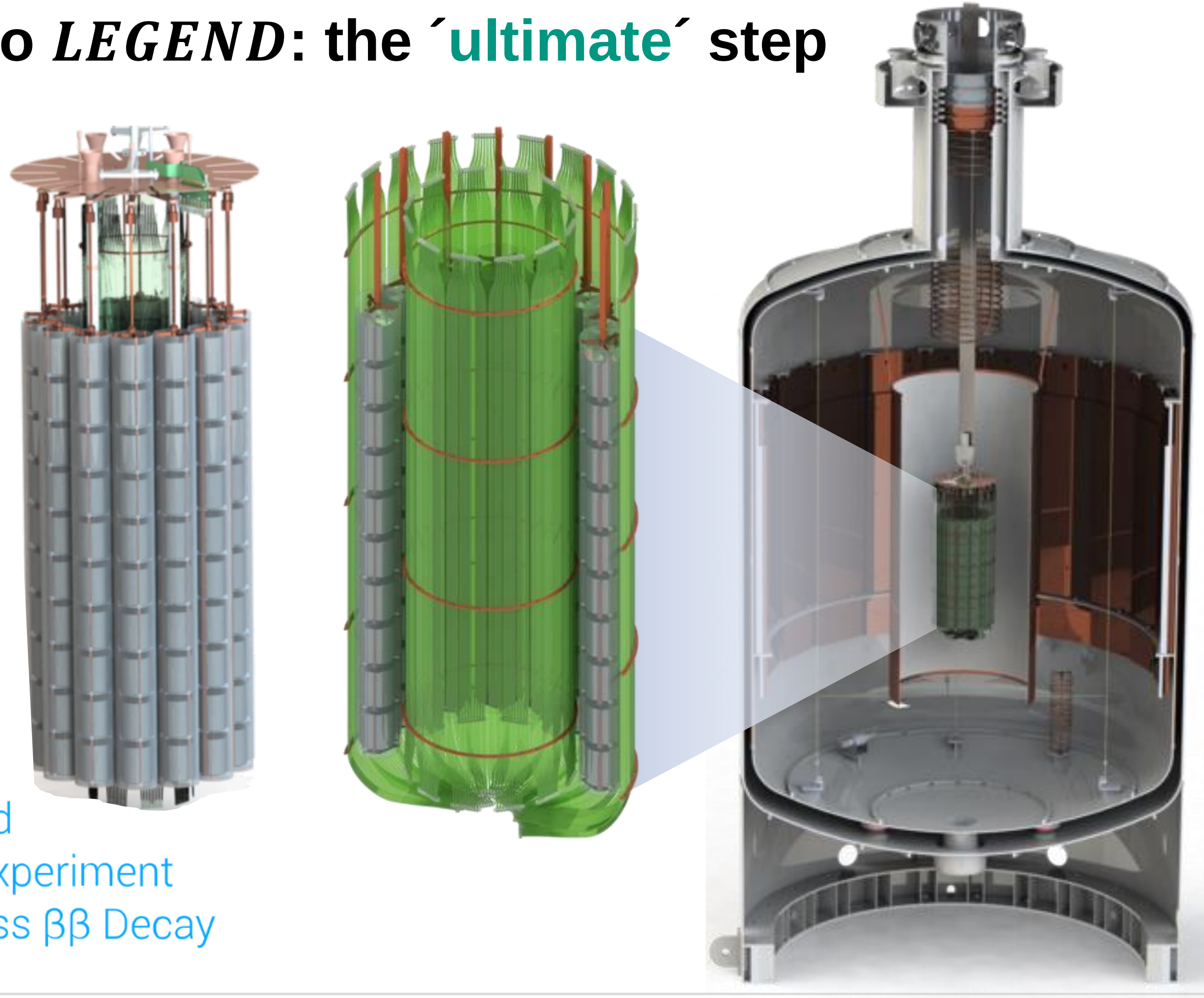
- $GERDA$ and $MAJORANA$ merge to $LEGEND$: the ´ultimate´ step

  - first stage:
    $LEGEND - 200$

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

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

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



LEGEND
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

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

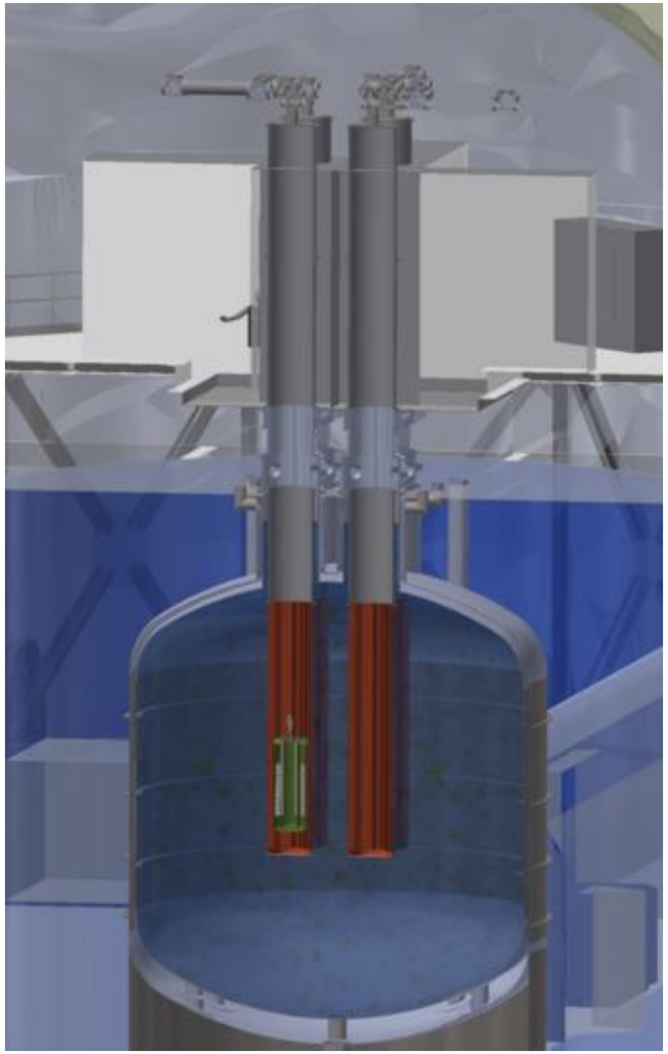
- $LEGEND - 1000$: the ´ultimate´ sensitivity

  - final stage:
    $LEGEND - 1000$

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

  - expected sensitivity
    after an exposure of
    $M \cdot t = 10\ ton \cdot yr$:

$$t_{1/2}^{0\nu\beta\beta} > 1 \cdot 10^{28}\ yr\ (90\%\ C.L.)$$



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

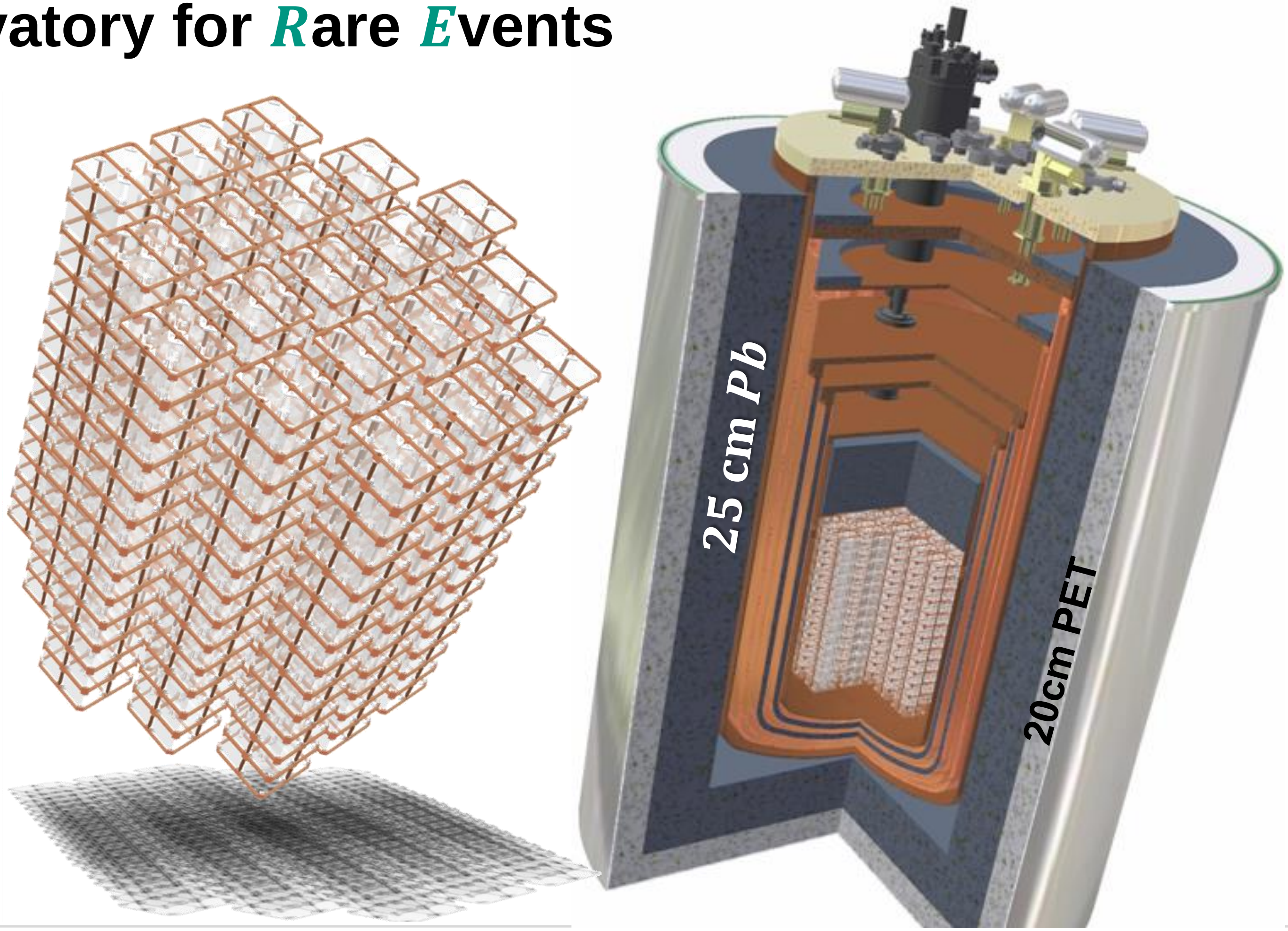
- **The coldest heart in the universe: $CUORE$ – the Cryogenic Underground Observatory for $R$are Events**

  - final stage:
    $\mathbf{988}\ TeO_2$ bolometers
    in $\mathbf{19}$ towers

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

  - Q – value: $2.572\ MeV$

  - massive shielding outside of cryostat via **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 $T = 6\ mK$

- radiation ($\beta\beta, \ldots$) leads to local energy deposition in a crystal

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

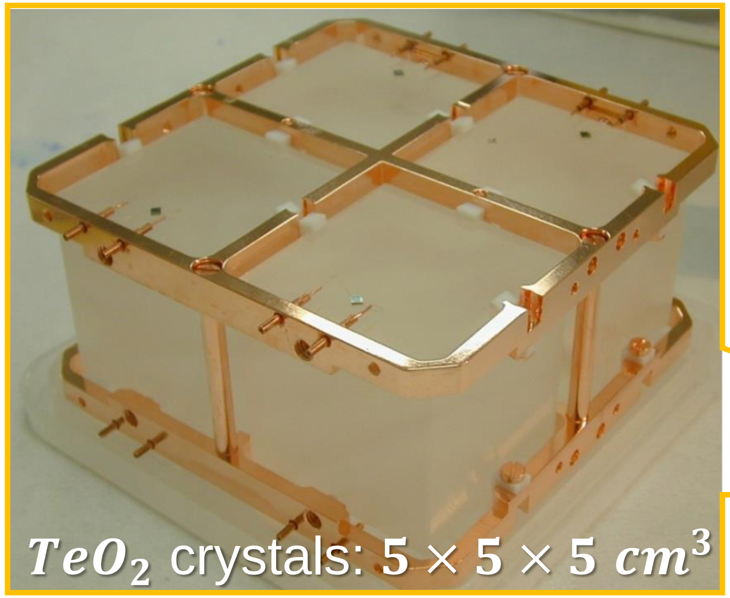
  ⇨ read–out of ΔT via quantum sensor (**thermistor***)

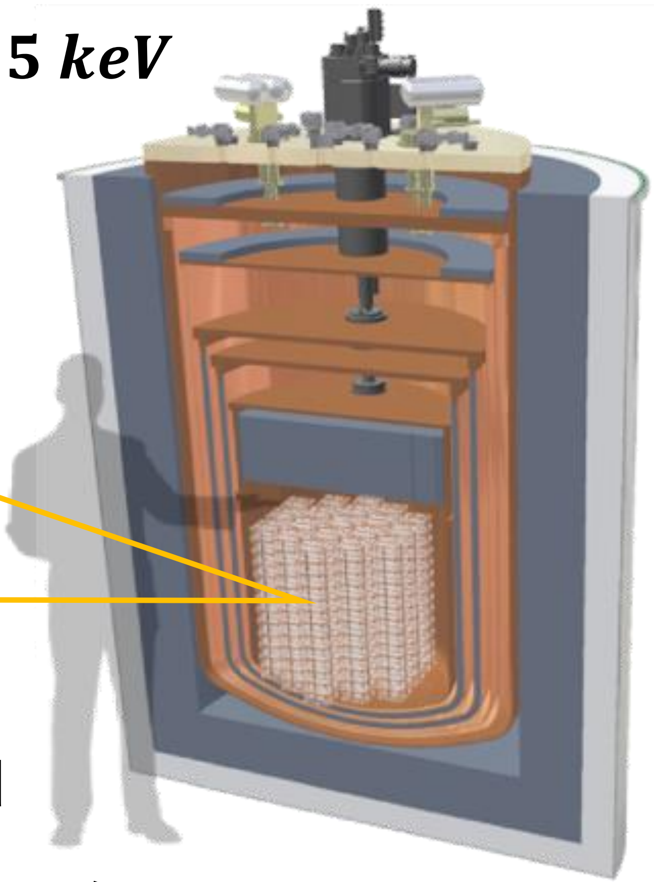
*thermistor principle: see chapter $4.5.2$

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

- TeO_2 – bolometers: results

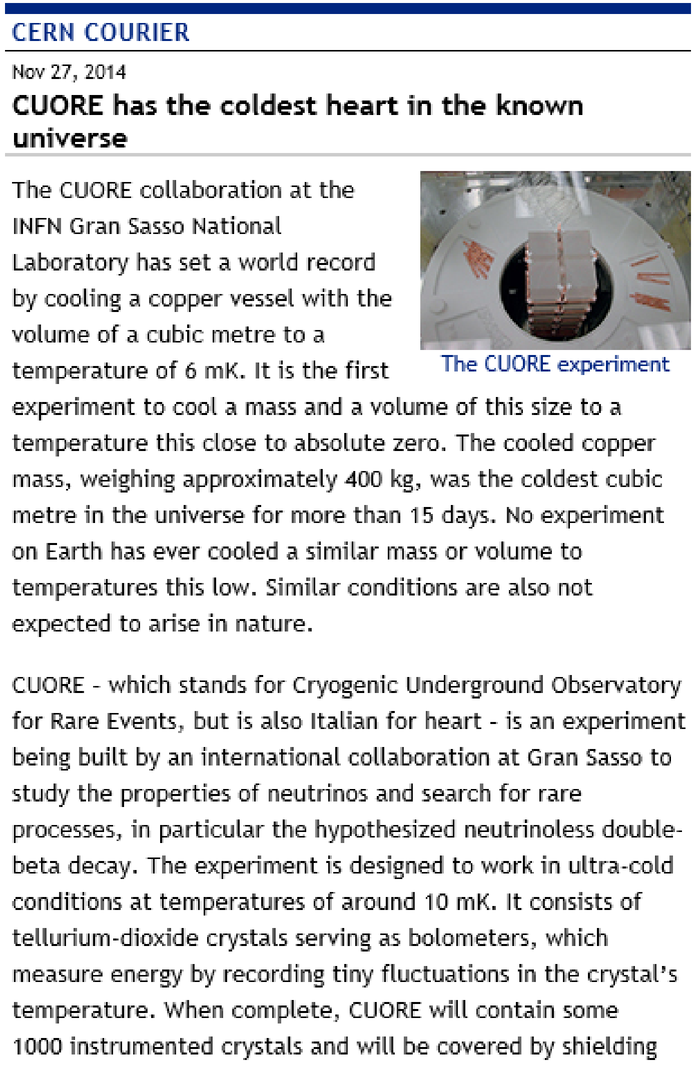
- bolometer energy resolution $\Delta E = 5\ keV$





- 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 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.

The CUORE experiment

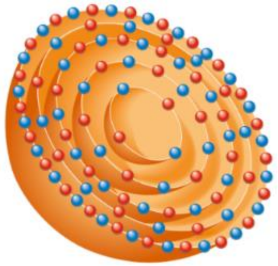
CUORE - which stands for Cryogenic Underground Observatory for Rare Events, but is also Italian for heart - is an experiment being built by an international collaboration at Gran Sasso to study the properties of neutrinos and search for rare processes, in particular the hypothesized neutrinoless double-beta 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 $t_{1/2}^{0\nu\beta\beta}$ to $m_{\beta\beta}$

- **How does my half–life value 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 are very large (up to ~$\mathbf{200}$ %)

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

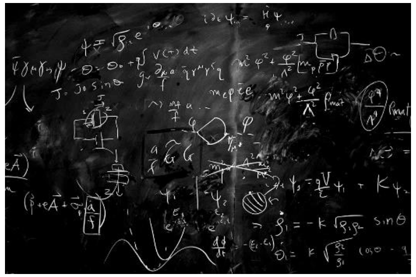


phase space

matrix elements (*GT* Gamow–Teller, *F* Fermi)

EXPERIMENT

×



THEORY

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

Karlsruhe Institute of Technology

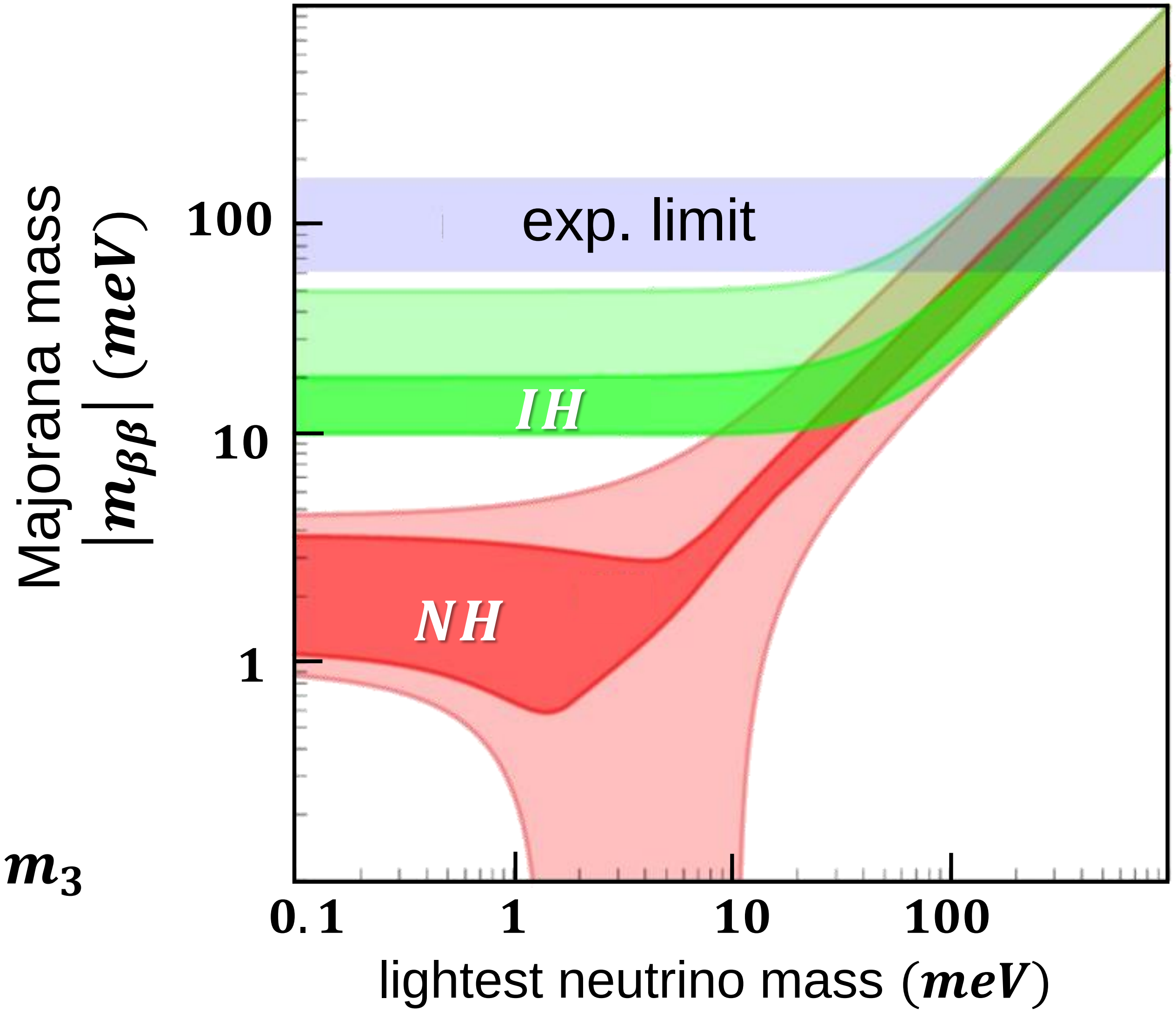
- **How large is the effective Majorana neutrino mass $m_{\beta\beta}$?**

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

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

to different theoretical models of neutrino masses:

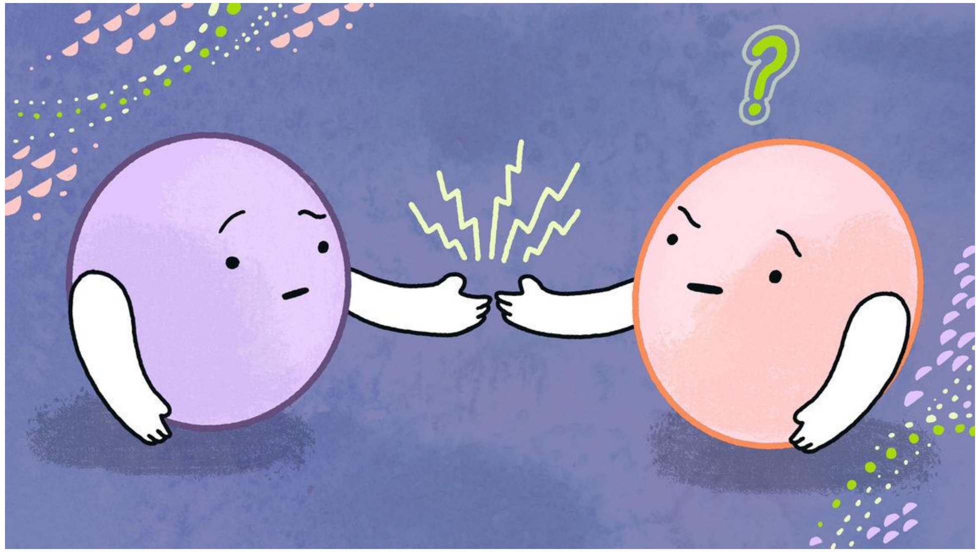
- NH **N**ormal **H**ierarchy: $m_1 < m_2 < m_3$
- IH **I**nverted **H**ierarchy: $m_3 < m_{1,2}$



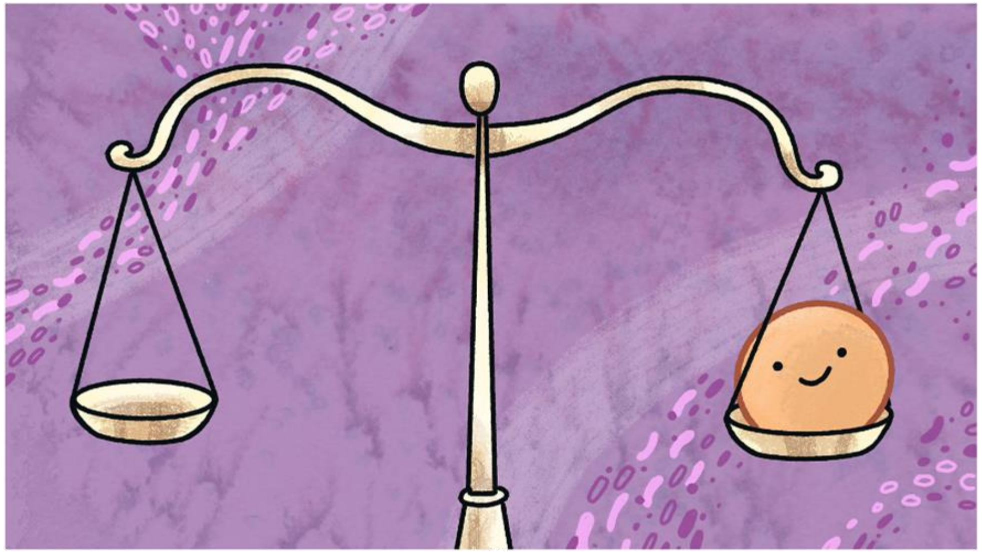
Neutrino physics: a most fascinating topic…

- **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 its **gravitational action** due to **Newtonian gravity**

  - possible (but rather 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 lectures on cosmology

Searches for Dark Matter

- DM – Triangle

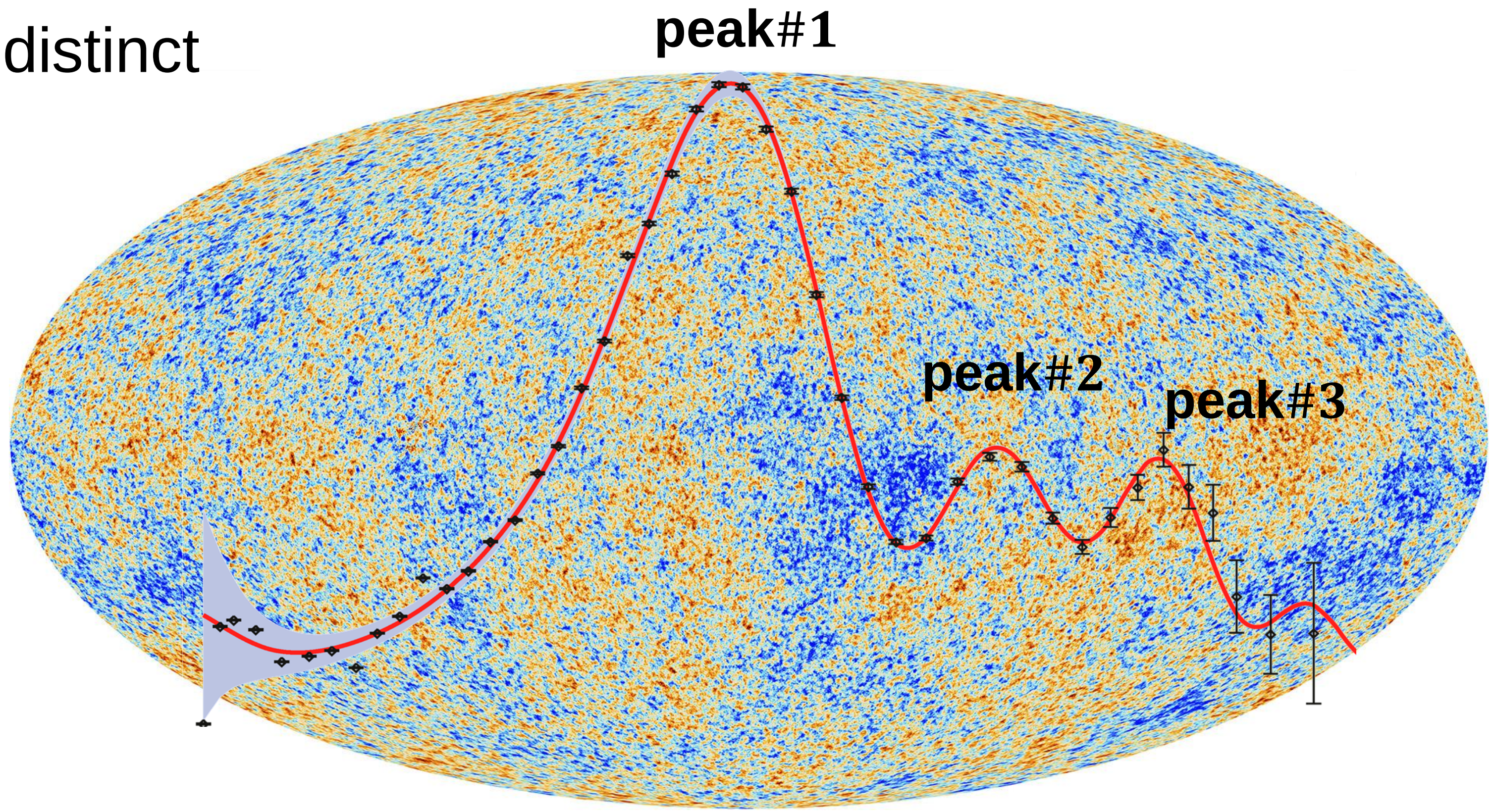
production at collider

direct detection

indirect detection

Evidences for Dark Matter: cosmology

- **Signature of DM in the $3K$ cosmic background radiation (CMB)**
  - CMB shows characteristic, very small **temperature fluctuations ΔT**
  - **multipole** analysis reveals distinct **peaks** $(\#1, \#2, \#3, \ldots)$
  - ratio of peak height $\#2 : \#3$ gives $\Omega_{DM} \sim 0.27$
  - popular scenario: **DM – production in the very early universe by thermal processes**



Evidences for Dark Matter: cosmology

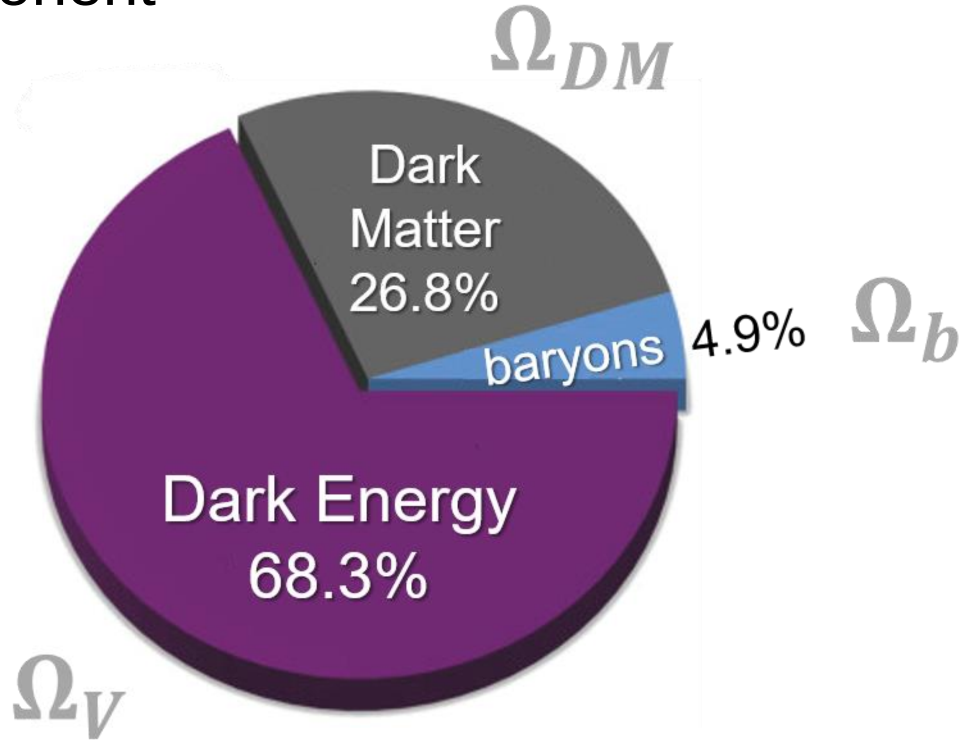
- DM **fraction** Ω_{DM} **relative to the overall matter−/energy− budget**

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

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

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

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



Evidences for Dark Matter: simulations

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

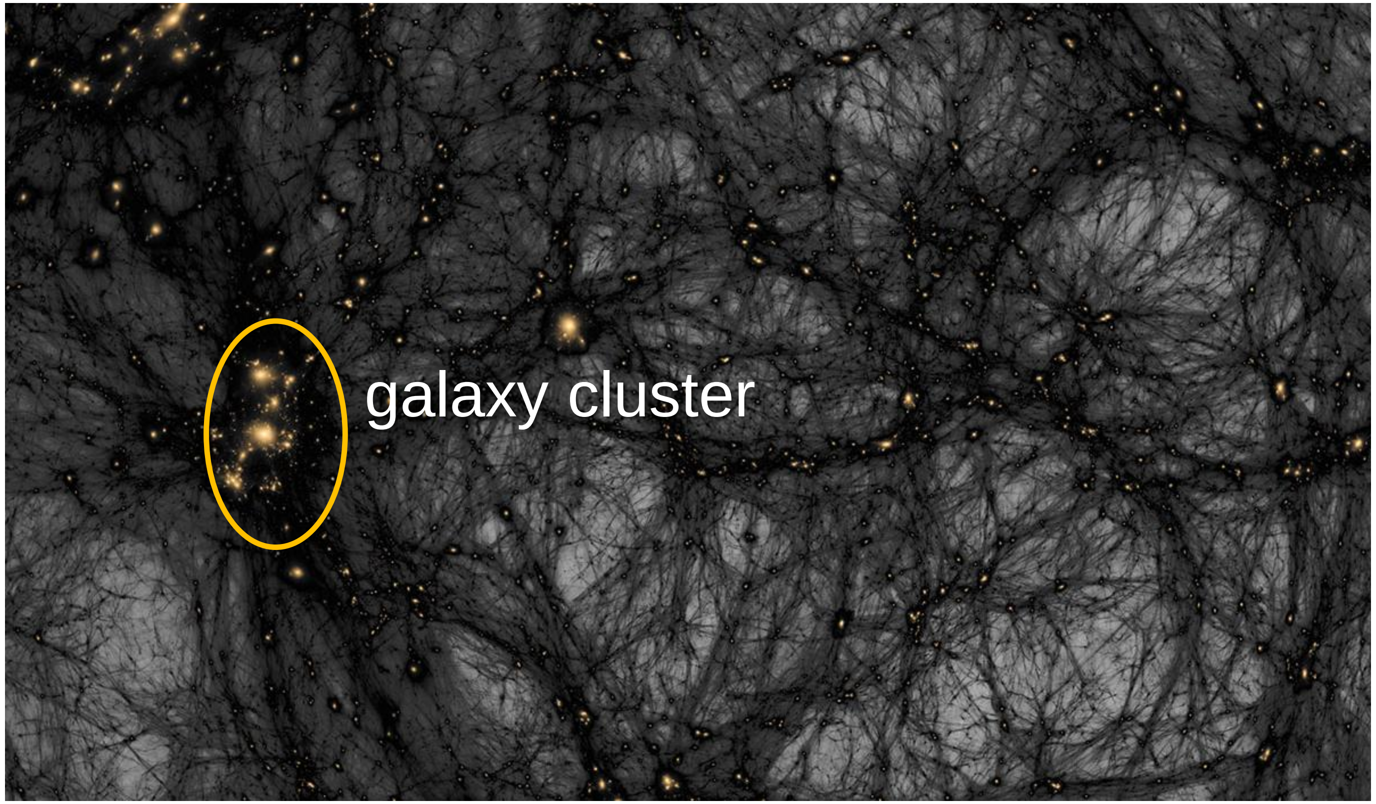
  - details are provided by large–scale N – **body simulations**

  - 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**

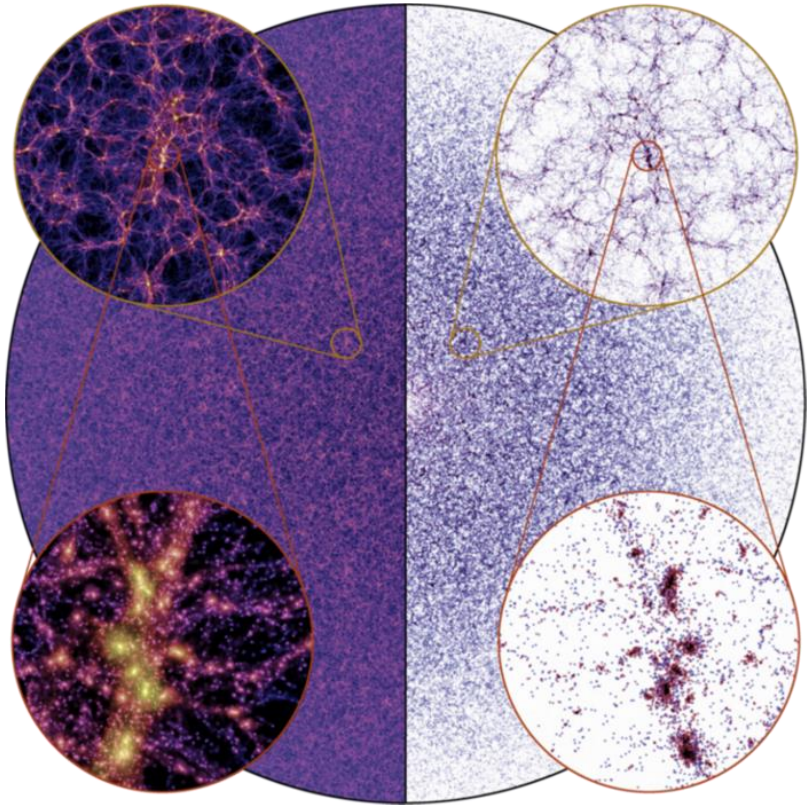
  - details are provided by large–scale N – **body simulations**

  - state–of–the–art code: $\boldsymbol{Illustris}$ $(\mathbf{2015})$

  - $\mathbf{19 \cdot 10^6}$ $\boldsymbol{CPU}$ hours

  - updated code: $\boldsymbol{Illustris - TNG}$ (release $\mathbf{2018}$)

  - updated codes: $\boldsymbol{Millennium - TNG}$
    $\boldsymbol{TNG}$ – Cluster $(\mathbf{11/2023})$



[2311.06338] Introducing the TNG-Cluster Simulation: overview and physical properties of the gaseous intracluster medium (arxiv.org)

Evidences for Dark Matter: F. Zwicky

Karlsruhe Institute of Technology

- ***Fritz Zwicky:*** $\boldsymbol{DM}$ **via the Virial theorem**

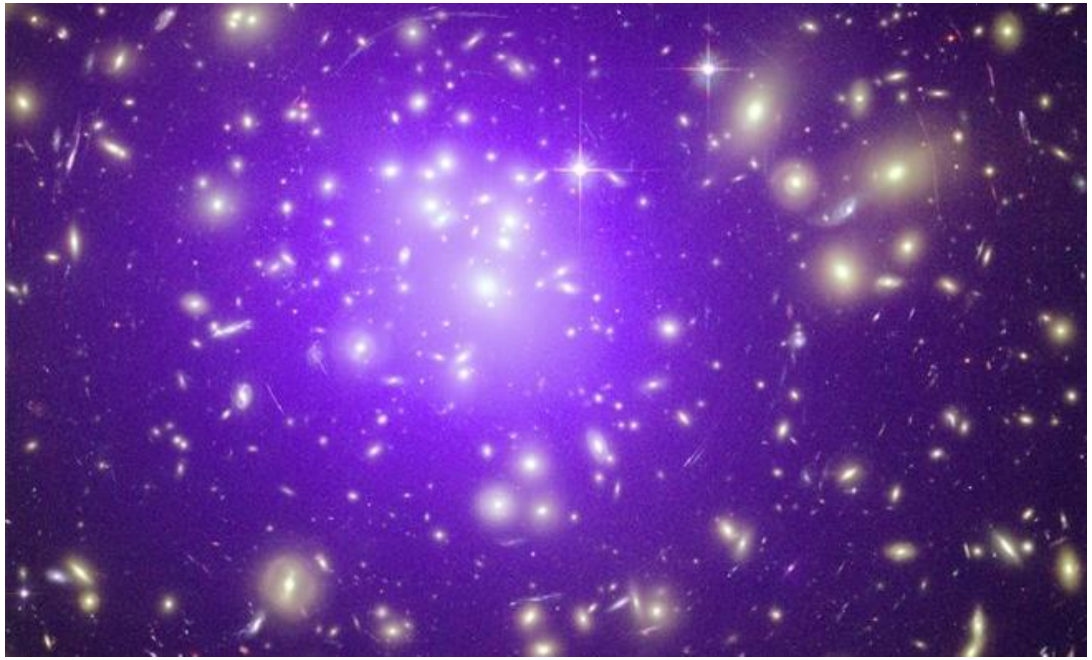
  - galaxy clusters: gravitationally bound (´**virialised**´) systems with relation $E_{kin} = -½ \cdot E_{grav}$

  - the peculiar velocities v of galaxies in a cluster (along the line–of–sight) are too large → DM

    ⇨ **´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

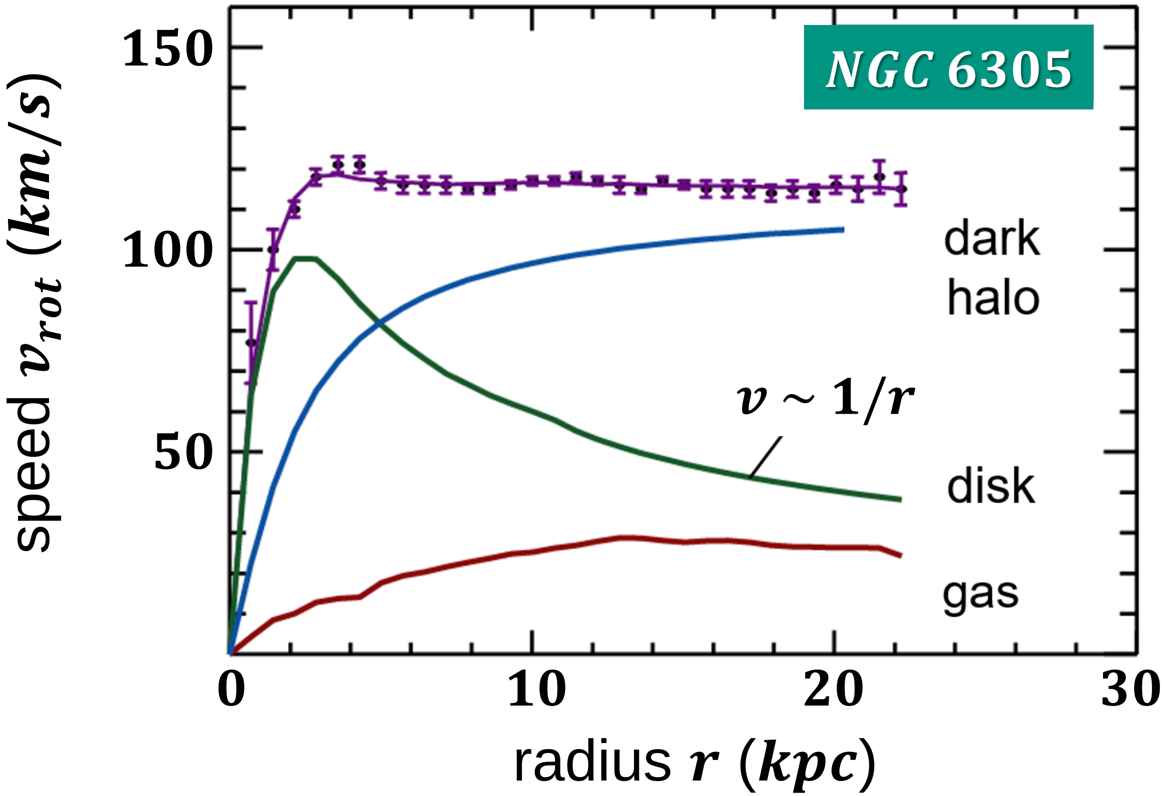
- ***Vera Rubin***: $\boldsymbol{DM}$ via galactic rotation curves

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

  - modelling requires the existence of a ´**Dark Halo**´ (due to $\boldsymbol{DM}$ particles)

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

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



Evidences for Dark Matter: V. Rubin

Karlsruhe Institute of Technology

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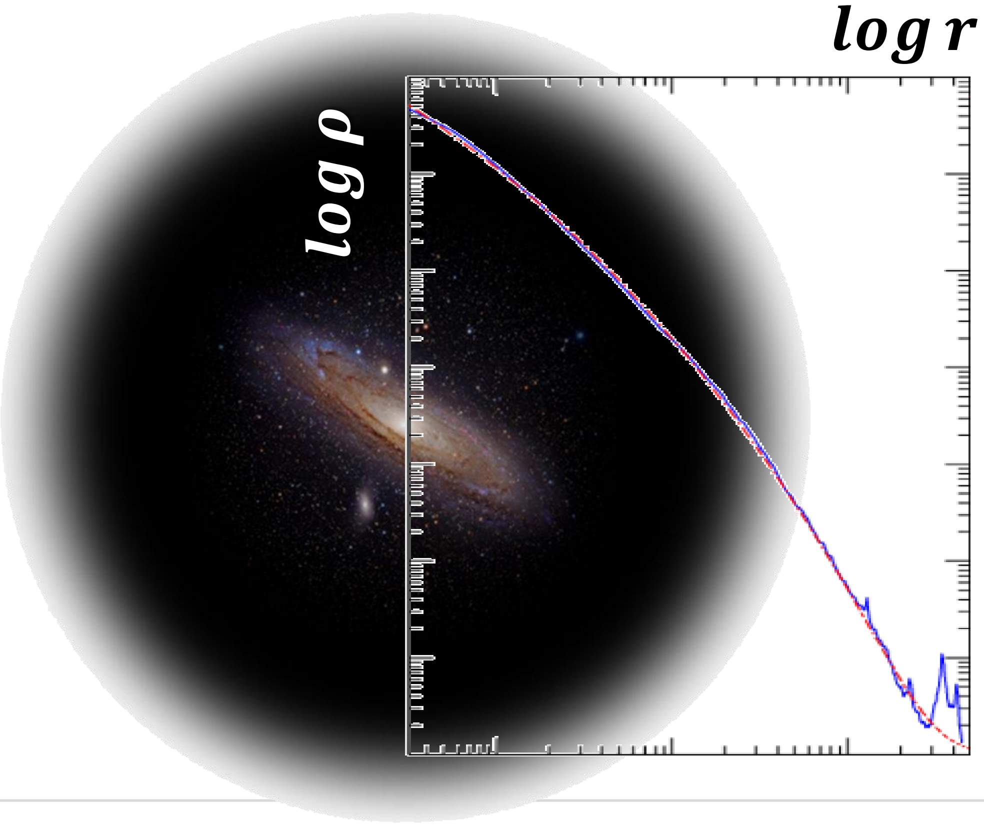
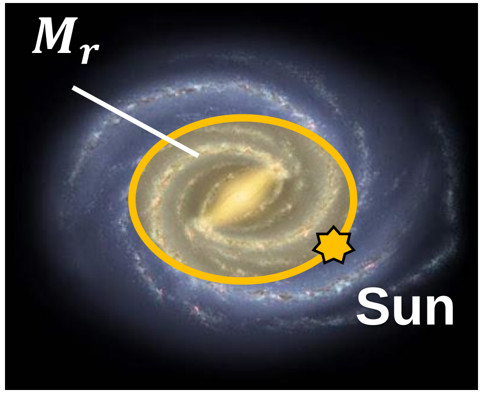


Local Density of Dark Matter

- **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 $M_r = {}^4/_3 \cdot \pi \cdot \rho \cdot r^3$

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

⇨ $\rho_{DM,local} = 0.3\ GeV/cm^3$

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 $M_r = {}^4/_3 \cdot \pi \cdot \rho \cdot r^3$

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

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

$M = 50\ GeV$

$V = 150\ cm^3$

*Weakly Interacting Massive Particle