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LOMONOSOV MOSCOW STATE UNIVERSITY

National Center FOR PHYSICS AND MATHEMATICS

The SATURNE experiment

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TWENTY-SECOND LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS

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MOSCOW STATE UNIVERSITY

The **Sarov Tritium Neutrino Experiment (SATURNE)** is part of the research program of the **National Center for Physics and Mathematics** founded in 2021

The main goals of SATURNE are

- **first observation of coherent elastic neutrino-atom scattering (CEνAS)**
- **search for neutrino magnetic moment with neutrino-atom scattering**

using a high-intensity tritium neutrino source: at least **1 kg, possibly up to 4 kg of T_2**

OUTLINE

- Physics introduction
  - Coherent elastic neutrino atom scattering (CEνAS) and its potential
- Detector concepts
  - He II detector to search for CEνAS & μ_ν
  - Si detector to search for μ_ν
  - CsI(pure) detector to search for μ_ν
- Summary and outlook

CEνAS vs CEνNS

CEνAS: Coherent Elastic Neutrino-Atom Scattering

predicted by *Yu. V. Gaponov and V. N. Tikhonov, Yad. Fiz. (USSR)* ***26*** *(1977) 594 (in Russian);* ***no experimental observation so far***

CEνNS

- $|\vec{q}|R_{\mathrm{nuc}} \ll 1$

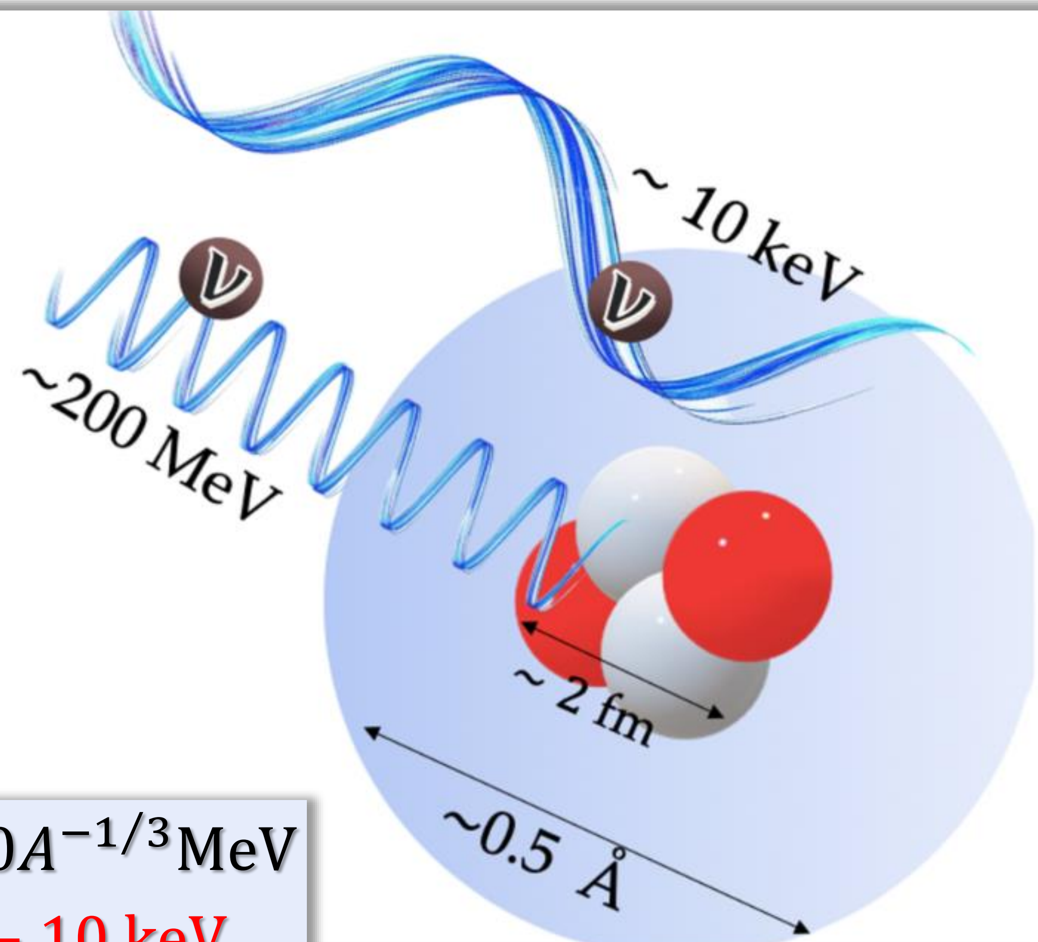
$\vec{q}$ is the momentum transfer

R_{nuc} is the nuclear radius

CEνAS

- $|\vec{q}|R_{\mathrm{atom}} \ll 1$

R_{atom} is the atomic radius

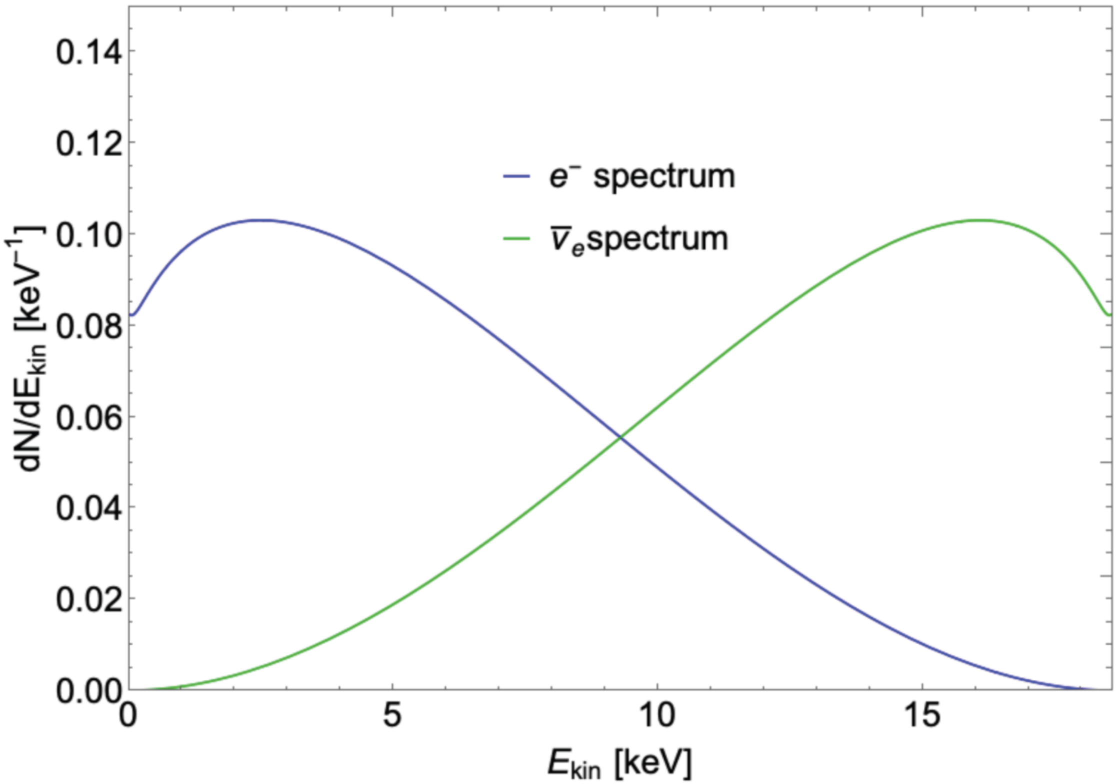


CEνNS: $E_\nu \lesssim 1/R_{\mathrm{nuc}} \sim 200A^{-1/3}\mathrm{MeV}$

CEνAS: $E_\nu \lesssim 1/R_{\mathrm{atom}} \sim 1-10\ \mathrm{keV}$

Tritium neutrinos

$$^{3}\mathrm{H} \rightarrow \; ^{3}\mathrm{He} + e^{-} + \bar{\nu}_e$$



$$Q = 18.6 \text{ keV}$$

$$t_{1/2} = 12.3 \text{ yrs}$$

$$\langle E_{\bar{\nu}_e} \rangle = 12.9 \text{ keV}$$

With 1-4 kg of tritium the neutrino flux in SATURNE will be $\Phi_{\bar{\nu}_e} \sim 10^{13}$-$10^{14}$ $sm^{-2}s^{-1}$

In contrast to stopped-pion beams ($\langle E_\nu \rangle \sim 30$ MeV) and nuclear reactors ($\langle E_\nu \rangle \sim 1$ MeV), **with a tritium neutrino source it is possible to fulfill the coherence condition in elastic neutrino-atom scattering**

Atomic recoil energy scale in CEνAS

From conservation of energy and momentum:

$$T_R \leq \frac{2E_\nu^2}{m}$$

T_R is atomic recoil energy

$m \approx A$ GeV is atomic mass

In the reactor CEνNS experiment CONNIE: Threshold is 15 eV$_{ee}$ (with CCD sensors)

Aguilar-Arevalo et al., arXiv:2403.15976v1 [hep-ex]

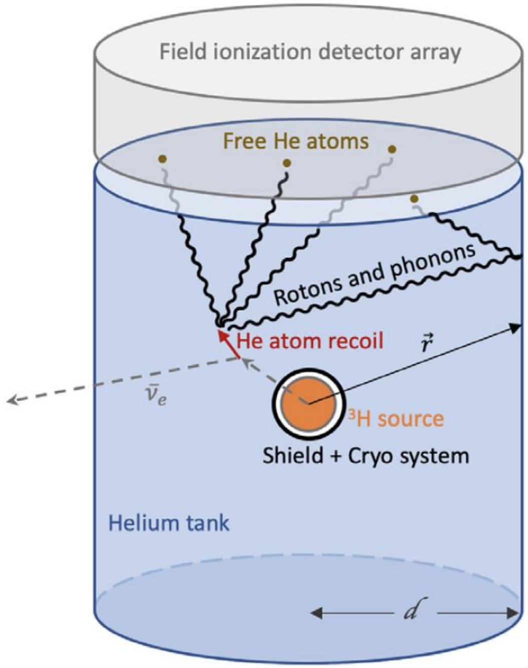
If E_ν~10 keV: $T_R \lesssim \frac{200}{A}$ meV

For the lightest atom (A=1): $T_R \lesssim 200$ meV

Light atomic targets, such as H or He, and new detector technologies are needed to observe CEνAS

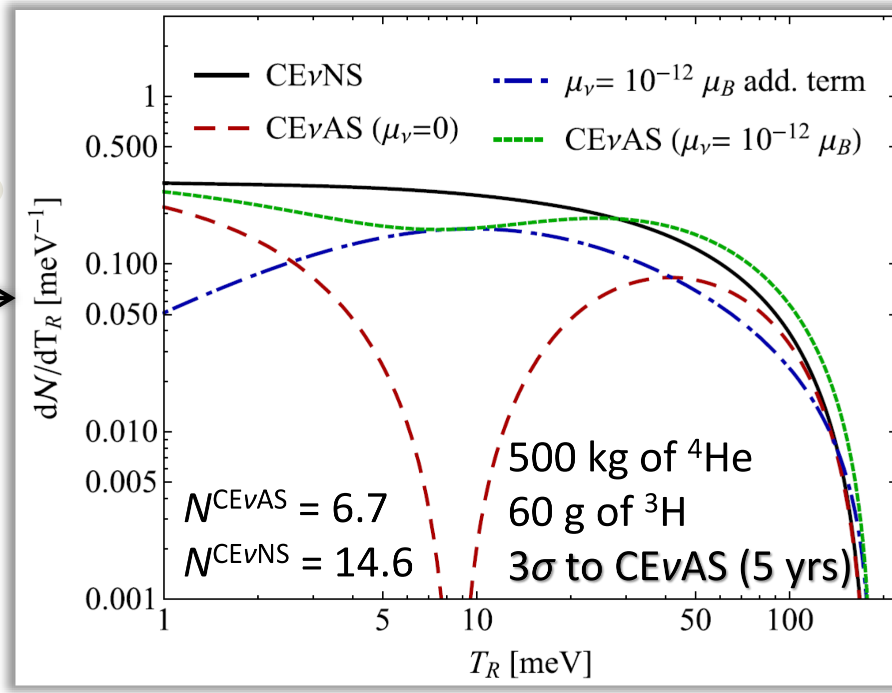
Potential of a low-energy detector based on ^{4}He evaporation

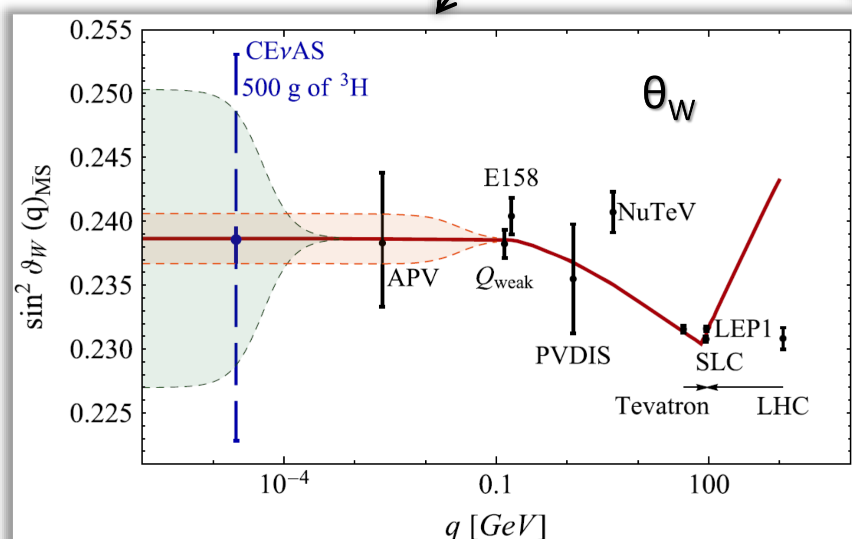
*M. Cadeddu, F. Dordei, C. Giunti, K. Kouzakov, E. Picciau, A. Studenikin, PRD **100** (2019) 073014*

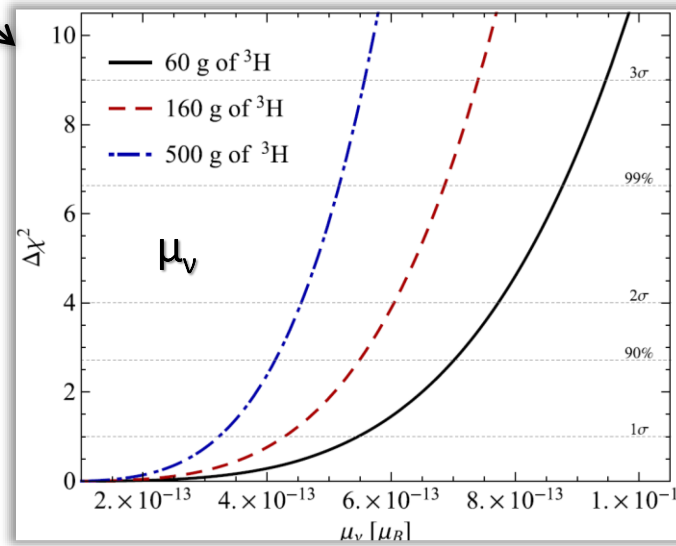


We can study:

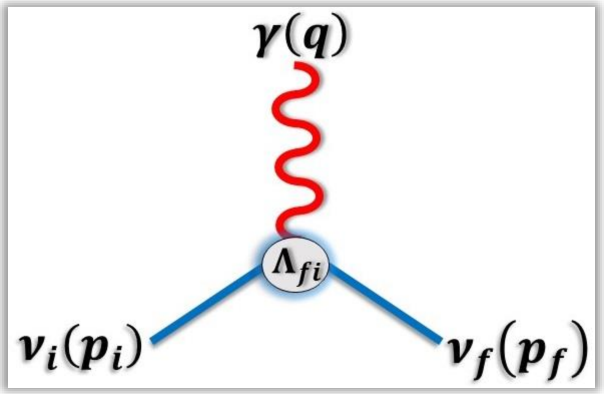
- CEνAS
- θ_W
- μ_ν







Neutrino magnetic moment



*C. Giunti and A. Studenikin, **Neutrino electromagnetic interactions: A window to new physics**, Rev. Mod. Phys. **87** (2015) 531; arXiv:1403.6344 [hep-ph]*
*C. Giunti, K. Kouzakov, Y.-F. Li, and A. Studenikin, **Neutrino electromagnetic properties**, Annu. Rev. Nucl. Part. Sci. **75** (2025); arXiv:2411.03122 [hep-ph]*

The effective neutrino electromagnetic vertex under the Lorentz and gauge invariance:

$$\Lambda_{\mu}^{(\mathrm{EM};\nu)fi}(q) = \left(\gamma_\mu - \frac{q_\mu q}{q^2}\right)\left[f_Q^{fi}(q^2) - q^2\, f_A^{fi}(q^2)\gamma_5\right] - i\sigma_{\mu\nu}q^\nu \left[f_M^{fi}(q^2) + if_E^{fi}(q^2)\gamma_5\right]$$

In the minimally extended SM with addition of right-handed massive Dirac neutrinos:

$$\mu_\nu \simeq 3.2 \times 10^{-19}\mu_B \left(\frac{m_\nu}{1\ \mathrm{eV}}\right)$$

*K. Fujikawa and R. Shrock, PRL **45** (1980) 963*

$m_\nu < 0.45$ eV at 90% CL
*M. Aker et al. (The KATRIN Collaboration), Science **388** (2025) 180; arxiv:2406.13516*

Much greater μ_ν values are predicted beyond the minimally extended SM

World leading upper bounds on μ_ν

Laboratory bounds (elastic $\nu - e^-$ scattering)

solar neutrinos (XENONnT)

A. Khan, Phys. Lett. B ***837*** *(2023) 137650*

$\mu_\nu < 6.3\times10^{-12}\,\mu_B$

reactor neutrinos (GEMMA)

A. Beda et al., Adv. High Energy Phys. ***2012*** *(2012) 350150*

$\mu_{\nu_e} < 2.9\times10^{-11}\,\mu_B$

CEνNS bounds

V. De Romeri et al., JHEP ***04*** *(2023) 035*

$\mu_{\nu_e} < 3.8\times10^{-9}\,\mu_B$

$\mu_{\nu_\mu} < 2.6\times10^{-9}\,\mu_B$

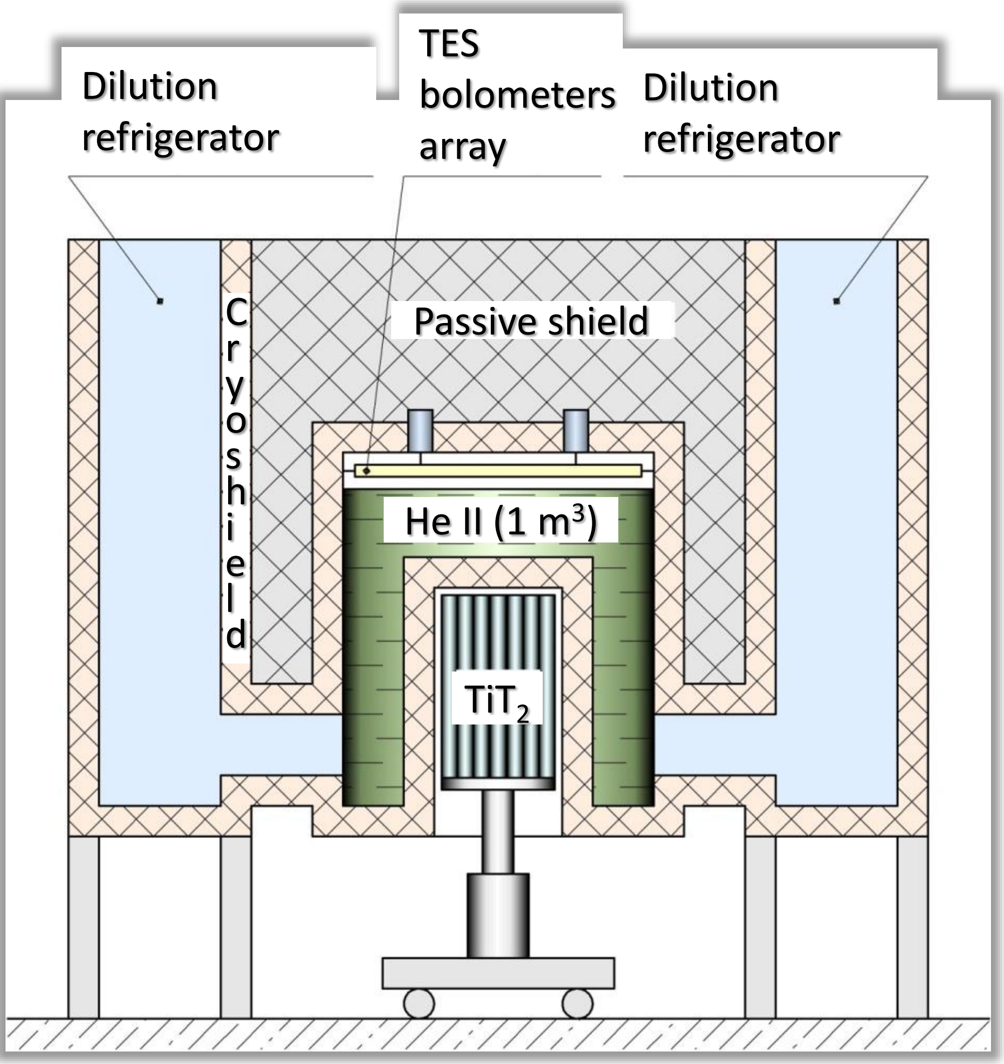
Astrophysical bounds (luminosity of globular star clusters)

N. Viaux et al., Astron. & Astrophys. ***558*** *(2013) A12; S. Arceo-Diaz et al, Astropart. Phys.* ***70*** *(2015) 1; F. Capozzi and G. Raffelt, Phys. Rev. D* ***102*** *(2020) 083007*

$\mu_\nu < (1.2-2.6)\times10^{-12}\,\mu_B$

With CEνAS, we could improve the CEνNS limits by four orders of magnitude, and the world leading limits by an order of magnitude

He II detector concept to study CEνAS



Helium II detector (1000 L)

- Liquid He-4 at 40-60 mK
- Array of 1000 TESs (transition edge sensors)
- 1000-channel SQUID readout

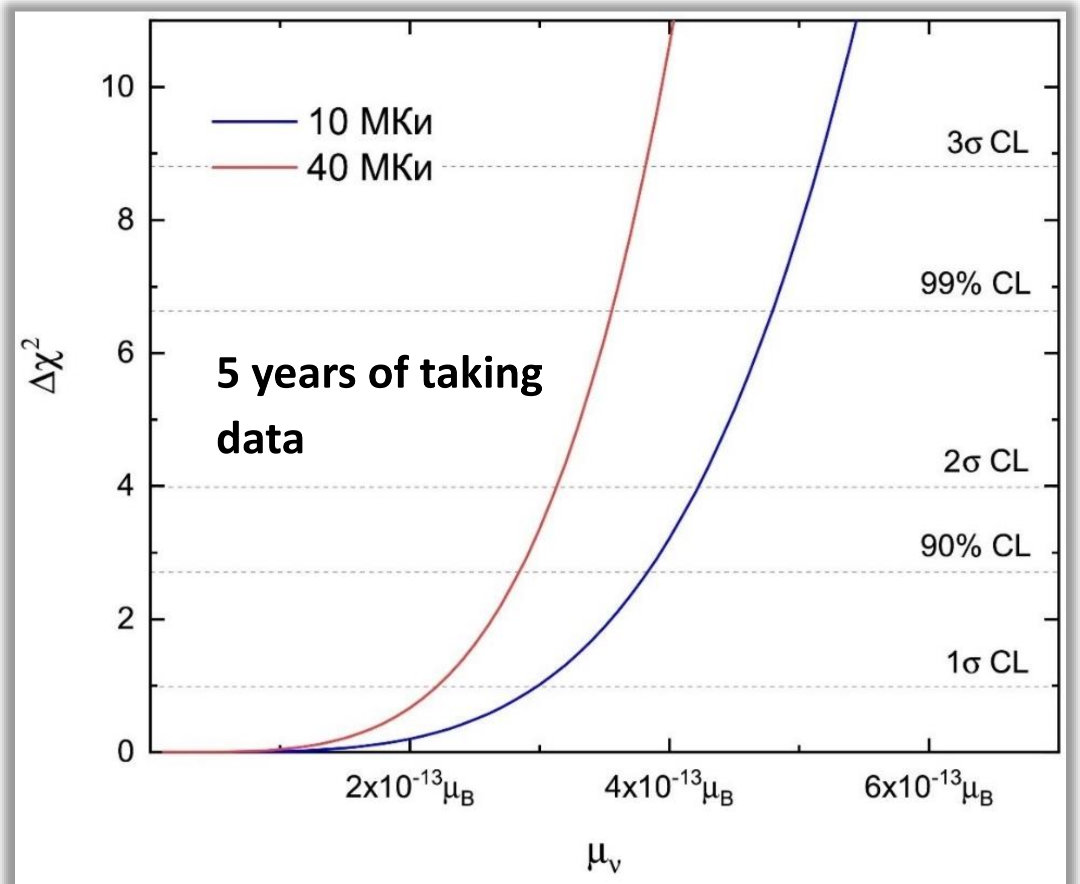
Tritium neutrino source

1-4 kg, 10-40 MCi

- Tubular elements with TiT_2

*A.A. Yukhimchuk et al. Fusion Science & Technology **48**, No.1 (2005) 731-736*

Projected μ_ν-sensitivity of He-4 detector



Tritium mass is

(i) 1 kg (10 MCi)

(ii) 4 kg (40 MCi)

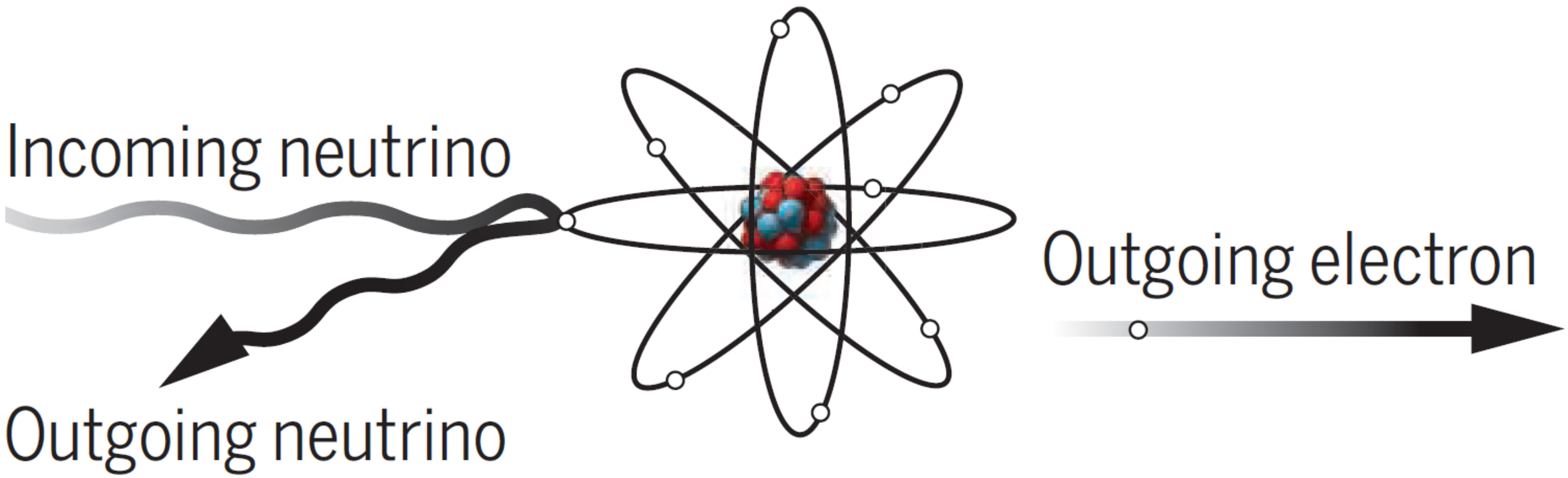
$$\Delta\chi^2 = \chi^2 - \chi^2_{\min}$$

$$\chi^2 = \left(\frac{N_{SM} - N}{\sqrt{N_{SM}}}\right)^2$$

$$N = N_{SM} + N_{\mu_\nu}$$

Initial tritium activity	N_{SM}	N_{μ_ν}, $3\times10^{-13}\mu_B$	N_{μ_ν}, $10^{-12}\mu_B$
10 MCi	53.7	7.1	82.1
40 MCi	177.1	24.6	271.1

Atomic ionization channel



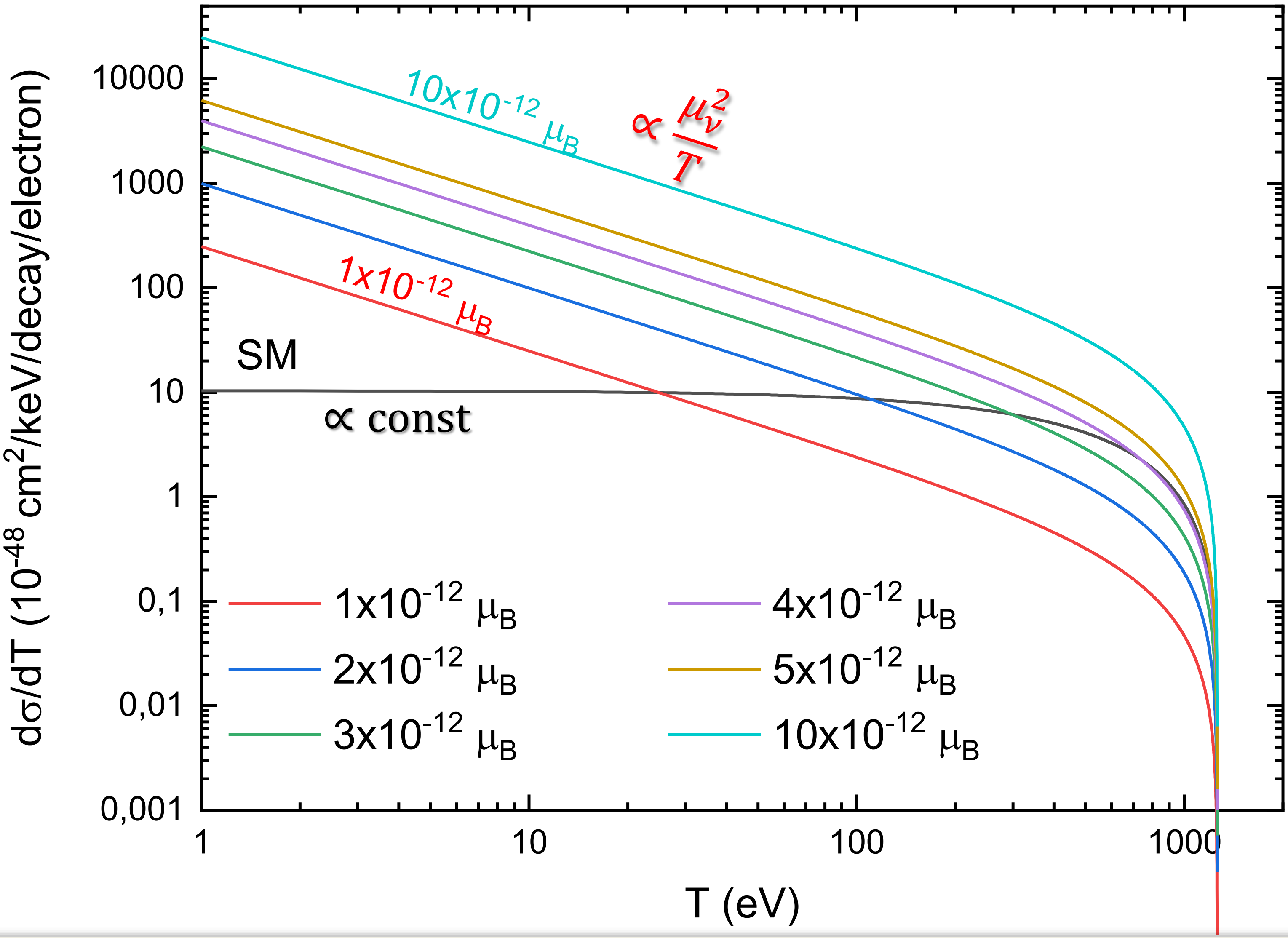
World leading laboratory constraints on μ_ν, like those from XENNONnT and GEMMA, are obtained by studying the atomic ionization channel (elastic $\nu - e^-$ scattering)

In **SATURNE** we develop

- Si crystal detector
- CsI(pure) scintillation detector

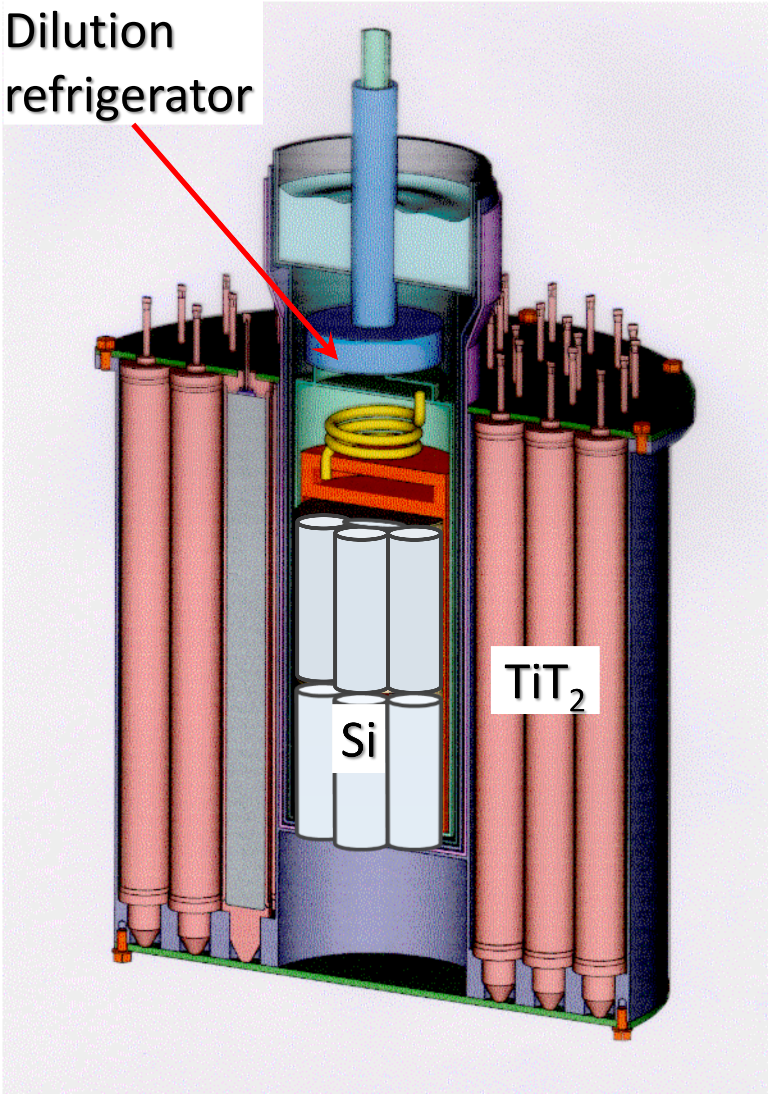
Differential cross sections for ionization of Si by tritium $\bar{\nu}_e$

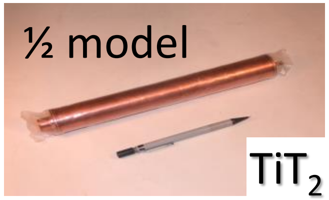
At small T values: $\frac{d\sigma_{SM}}{dT} \propto \mathrm{const}$, and $\frac{d\sigma_{(\mu)}}{dT} \propto \frac{\mu_\nu^2}{T}$



The detector's energy threshold is to be as low as possible

Si detector concept





Tritium neutrino source (1-4 kg)

- tubular elements with TiT_2

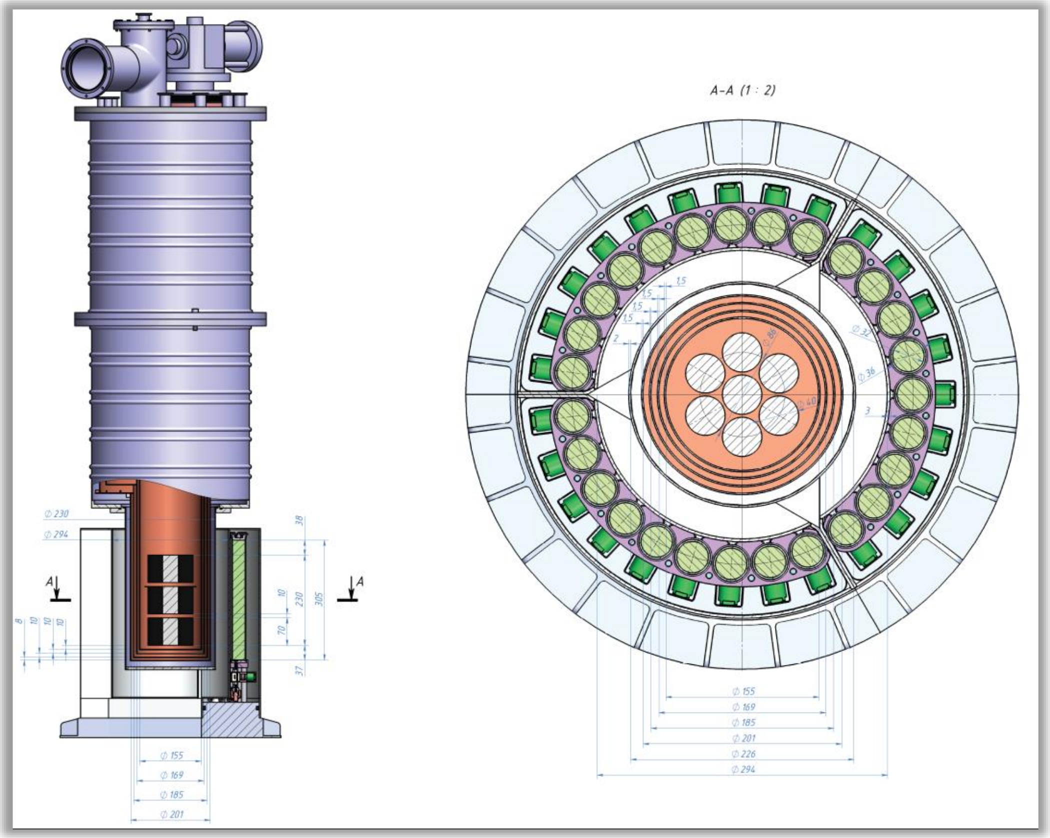
Silicon cryodetectors (T=10-50 mK)
(14-28)×125 cm³, M=2.9-5.7 kg
with TES or CEB mounted on each Si crystal

The Si detector with an ultra-low threshold E_{th}~10 eV or even E_{th}~1 eV owing to the Neganov-Trofimov-Luke effect *(heat amplification of ionization signal)*

*B. Neganov and V. Trofimov, USSR patent no. 1037771, Otkrytia i Izobreteniya **146** (1985) 215;*

*P. N. Luke, J. Appl. Phys. **64** (1988) 6858.*

Projected μ_ν-sensitivity of Si detector



Tritium mass is 1 kg (10 MCi)

$$\Delta\chi^2 = \chi^2 - \chi^2_{\min}$$

$$\chi^2 = \left(\frac{N_{SM} - N}{\sqrt{N_{SM}}}\right)^2$$

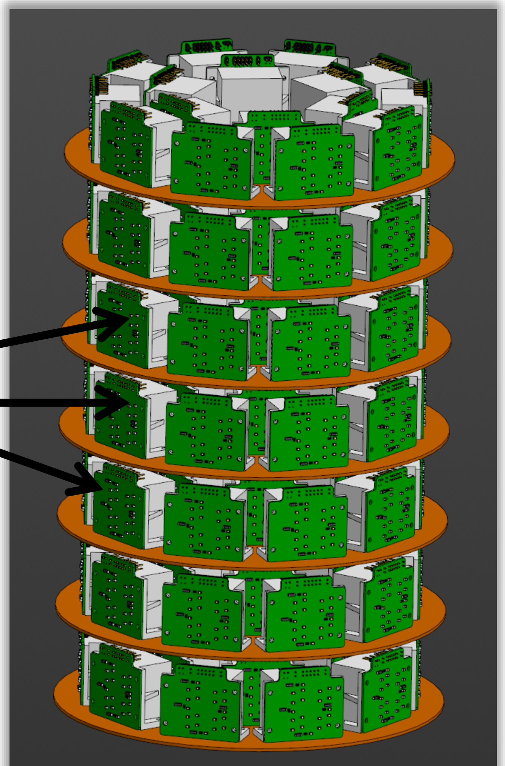
$$N = N_{SM} + N_{\mu_\nu}$$

1 year of taking data	14 cylinders, 2.9 kg		21 cylinders, 4.3 kg		28 cylinders, 5.7 kg	
	1 эВ	10 эВ	1 эВ	10 эВ	1 эВ	10 эВ
N_{SM}	7.96	7.94	11.52	11.49	14.61	14.57
μ_ν, $10^{-12}\mu_B$ 90% CL	1.76	2.03	1.61	1.85	1.51	1.74

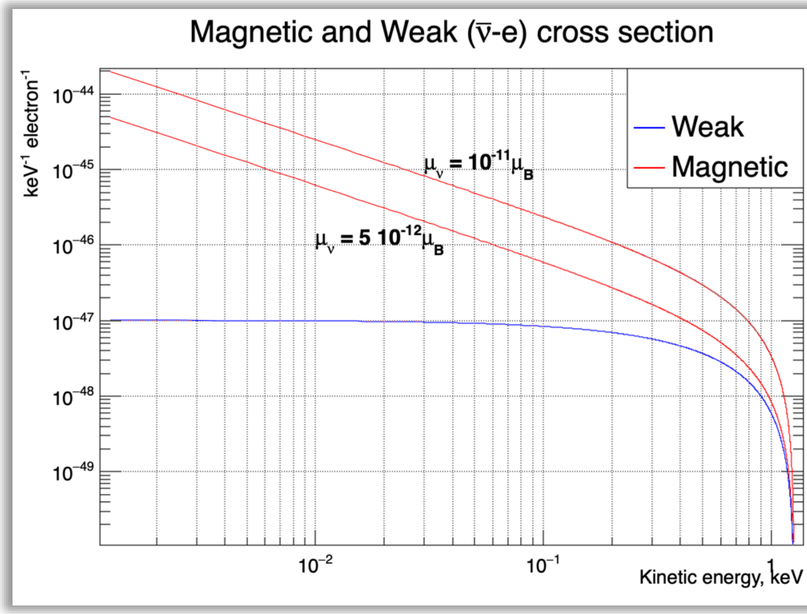
CsI(pure) detector concept

Detector assembly

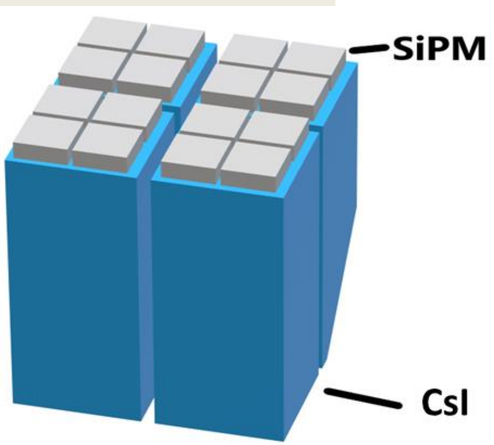
Layers of modules



Abdurashitov, Vlasenko, Ivashkin, Silaeva, Sinev, Phys. Atom. Nuclei ***85*** *(2022) 701*



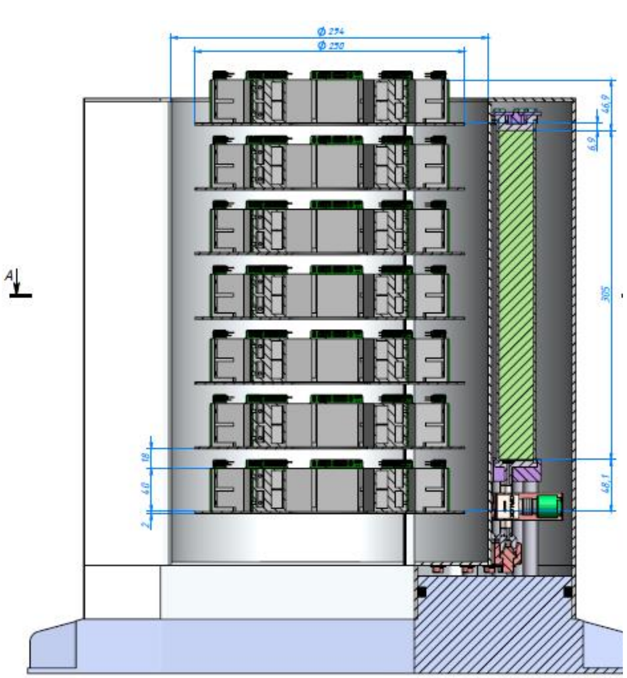
Detector module

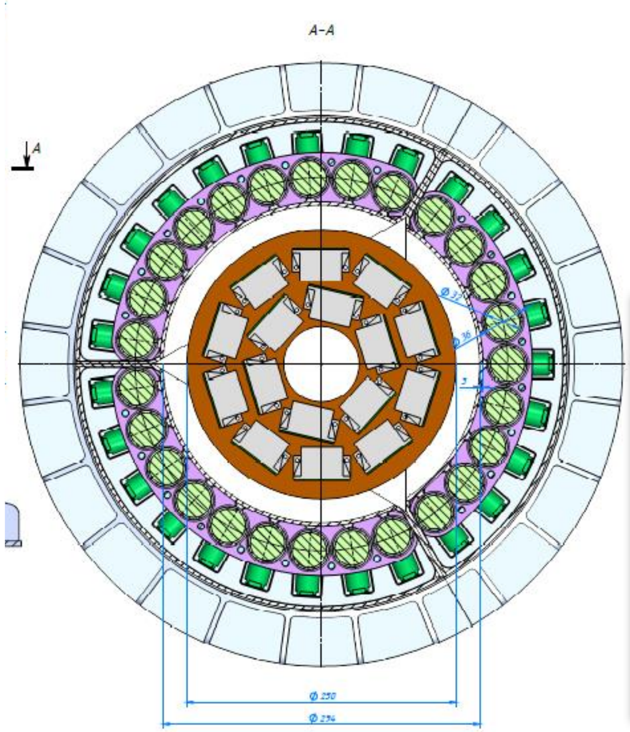


15x15x25 mm^3 CsI(pure) crystals at T=77 K, total mass is M=7.5-10.5 kg

- SiPM readout (two SiPMs per each crystal)
- Light collection at a level of ~30 photoelectrons/keV
- Energy threshold is E_{th}~100 eV

Projected μ_ν-sensitivity of CsI detector





Tritium mass is 1 kg (10 MCi)

$$\Delta\chi^2 = \chi^2 - \chi^2_{\min}$$

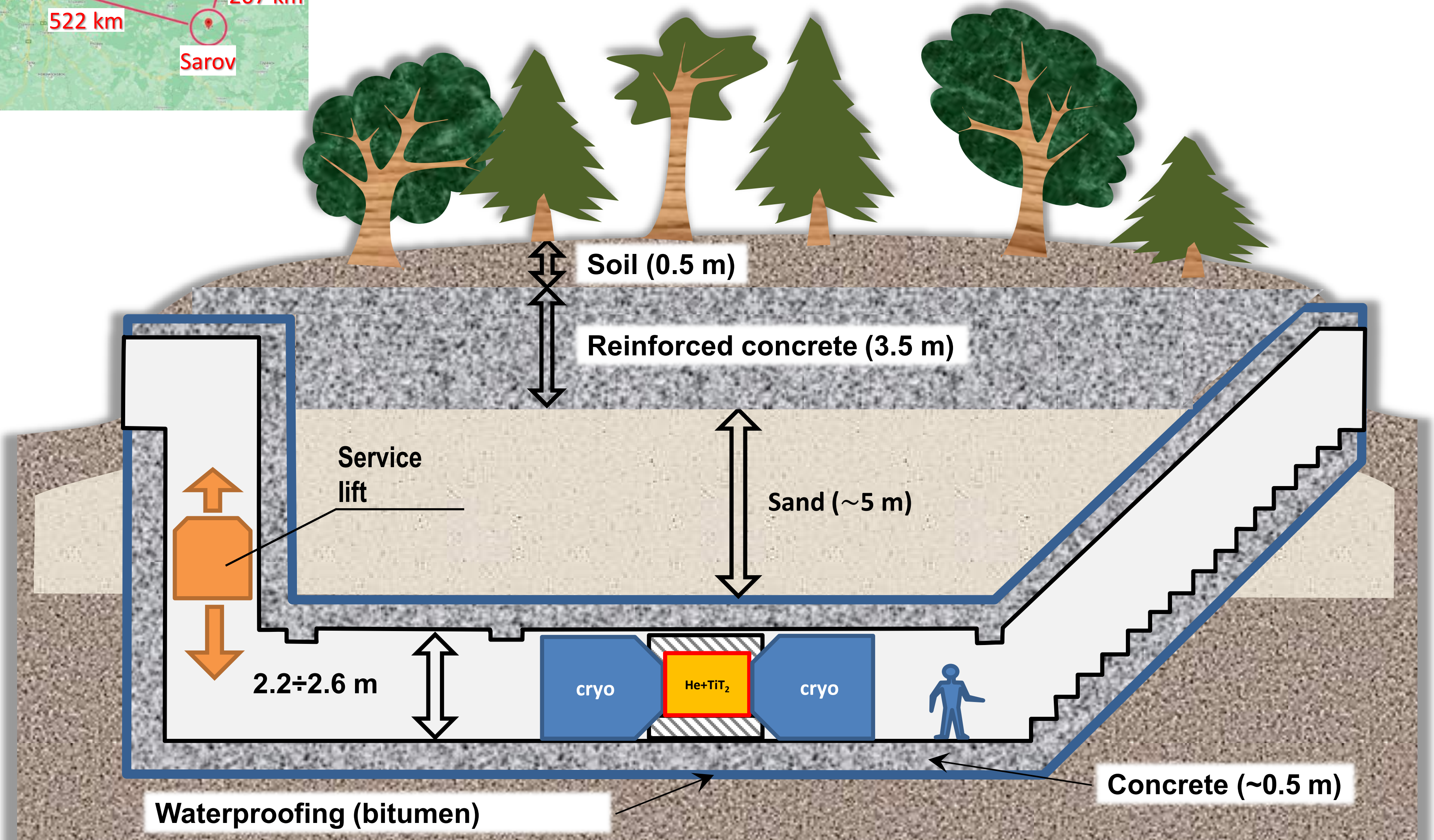
$$\chi^2 = \left(\frac{N_{SM} - N}{\sqrt{N_{SM}}}\right)^2$$

$$N = N_{SM} + N_{\mu_\nu}$$

1 year of taking data	**5 layers, 7.5 kg**				**7 layers, 10.5 kg**			
	100 эВ	200 эВ	300 эВ	400 эВ	100 эВ	200 эВ	300 эВ	400 эВ
N_{SM}	12.48	11.53	10.52	9.50	15.71	14.51	13.24	11.96
μ_ν, $10^{-12}\mu_B$ 90% CL	2.31	2.66	2.91	3.11	2.18	2.51	2.75	2.93

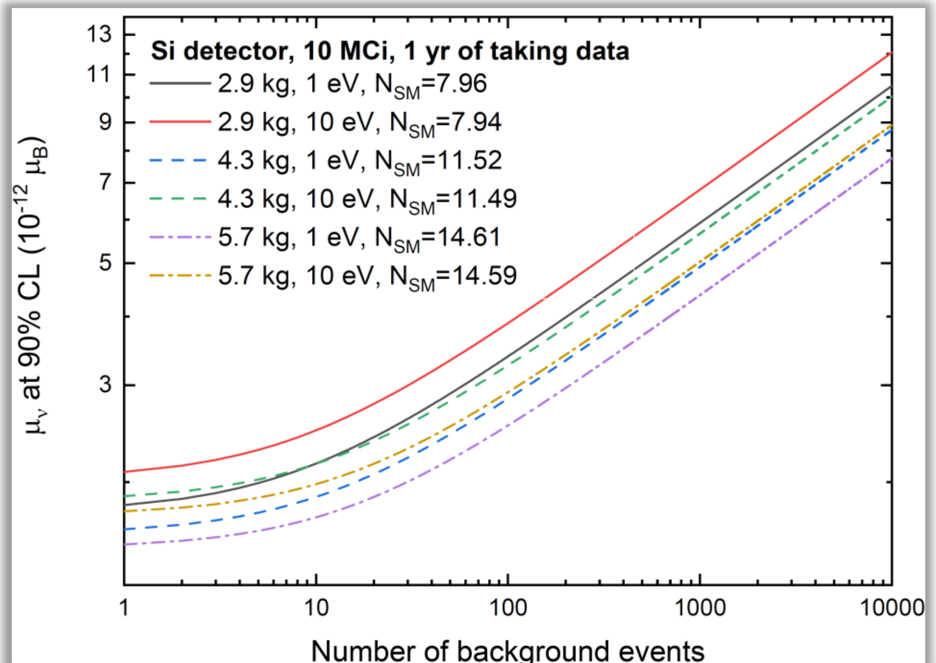
Low-background neutrino laboratory in Sarov

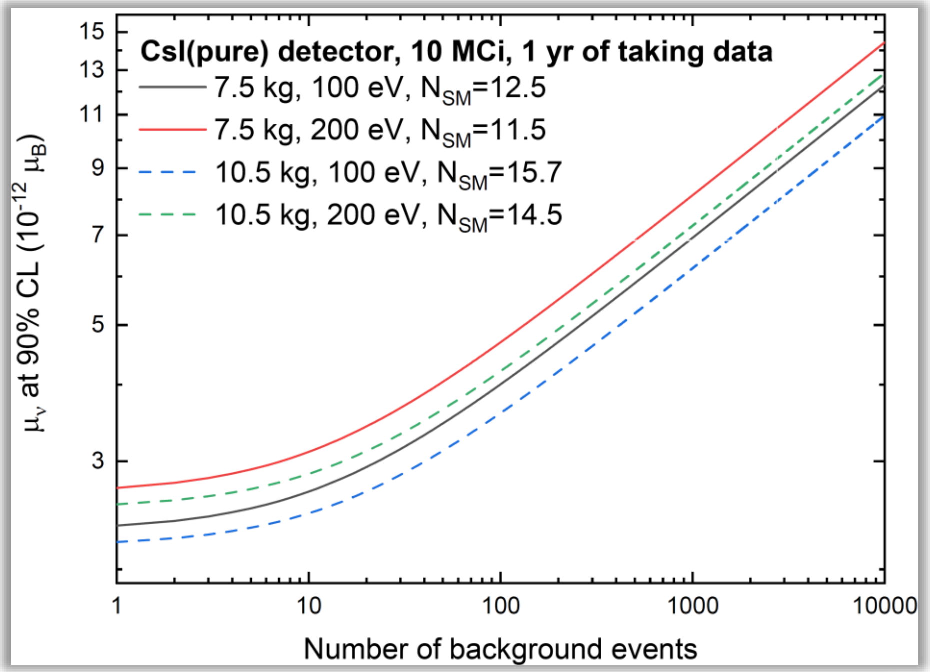
@ All-Russian Research Institute of Experimental Physics, RFNC

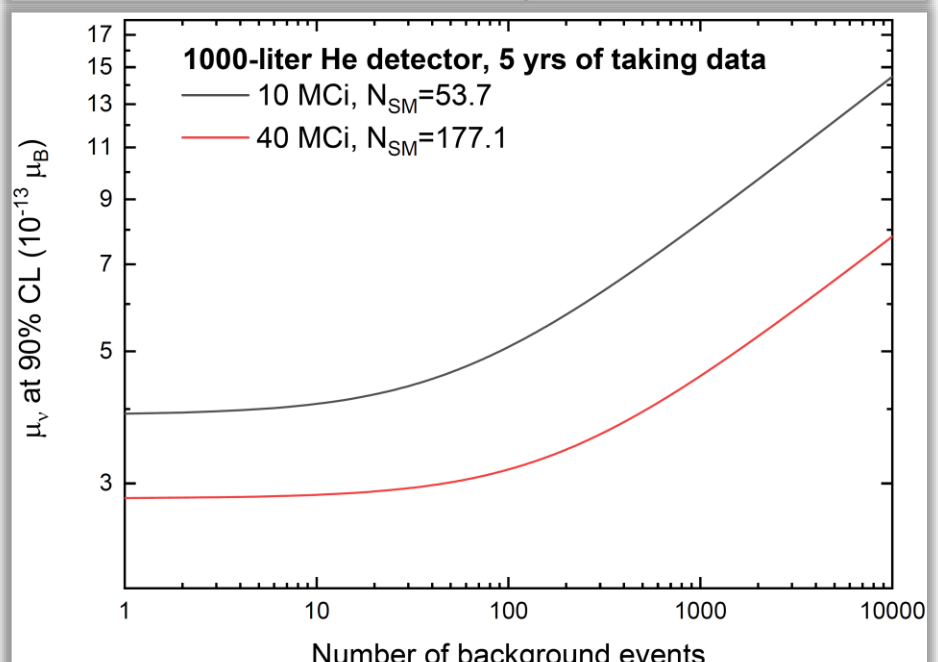


The overburden of 20-25 m.w.e. (7.5-9.5 m of standard rock) stops the soft and hadronic components of cosmic radiation

Required background conditions







To provide background conditions necessary to achieve the world-leading sensitivities to the neutrino magnetic moment, some measurements may be performed in the Baksan Neutrino Observatory

Summary and outlook for SATURNE

Sarov tritium neutrino experiment (SATURNE) aims at

(i) first ever observation of **CEνAS** to test SM neutrino interactions at unprecedentedly low energies

(ii) search for **neutrino magnetic moment**

High-intensity tritium neutrino source is being prepared

- at least **1 kg, 10 MCi** (possibly up to **4 kg, 40 MCi**)

He II detector is being developed

- observation of **CEνAS at 5σ (2028-2033)**
- sensitivity to $\mu_\nu \sim$**(3-4)x**10^{-13} μ_B **at 90% CL (2033)**

Si detector is being developed

- sensitivity to $\mu_\nu \sim$**(1.5-2.0)x**10^{-12} μ_B **at 90% CL (2027-2028)**

CsI(pure) detector is being developed

- sensitivity to $\mu_\nu \sim$**(2-3)x**10^{-12} μ_B **at 90% CL (2026-2027)**

National Center
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The SATURNE Collaboration

RUSSIAN FEDERAL NUCLEAR CENTER
ALL-RUSSIAN RESEARCH INSTITUTE OF EXPERIMENTAL PHYSICS

PRODUCTION ASSOCIATION
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NIZHNY NOVGOROD STATE TECHNICAL UNIVERSITY N.A. R.E. ALEKSEEV

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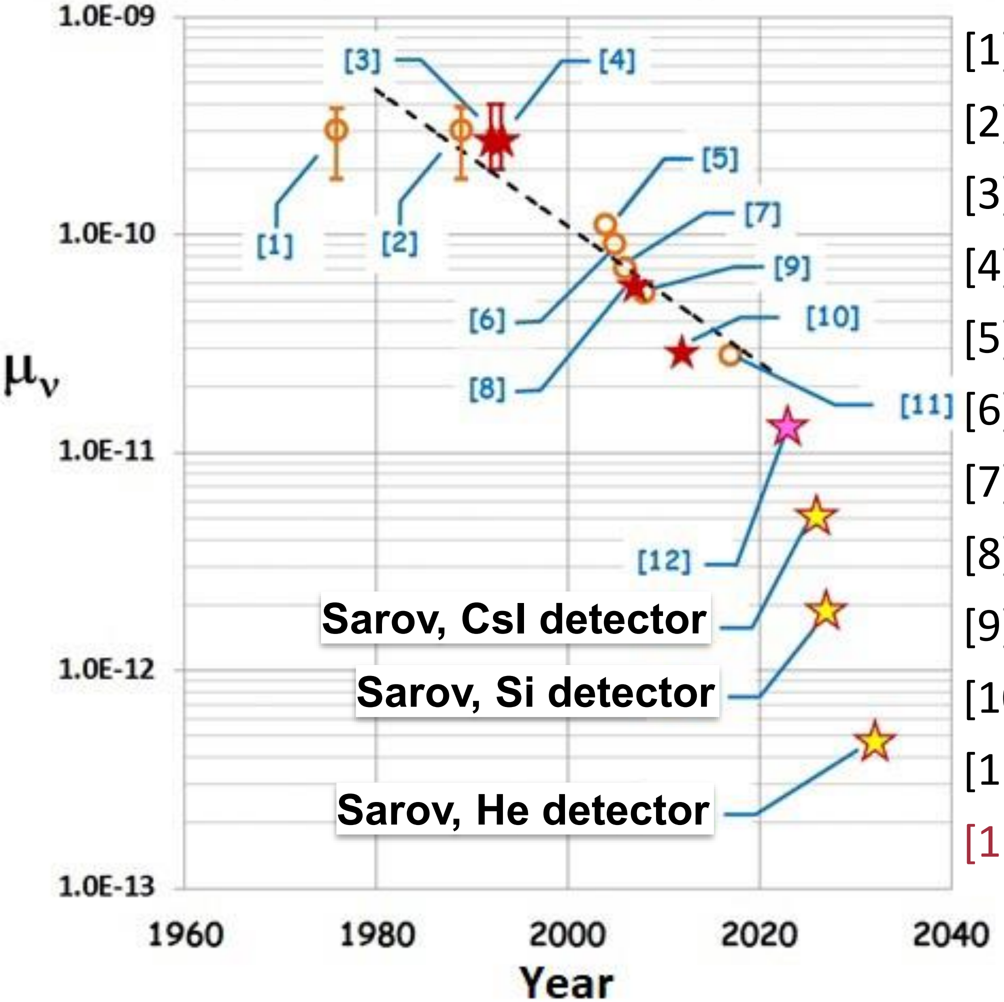
Progress of experimental sensitivity to μ_ν

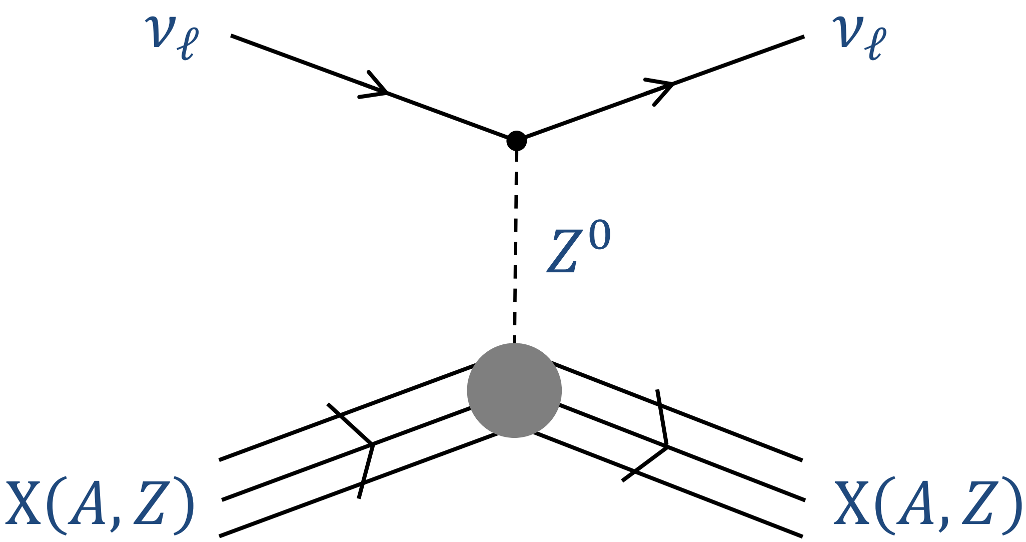


[1] Savannah River, first observation (1976)
[2] Vogel & Engel (1989)
[3] Kurchatov Institute, Krasnoyarsk (1992)
[4] Rovno NPP (1993)
[5] Super-Kamiokande (2004)
[6] MUNU (2005)
[7] TEXONO (2006)
[8] GEMMA I (2007)
[9] BOREXINO (2008)
[10] GEMMA I (2012)
[11] BOREXINO (2017)
[12] GEMMA-2 (νGEN) (2023-…)

Thank you for your attention!

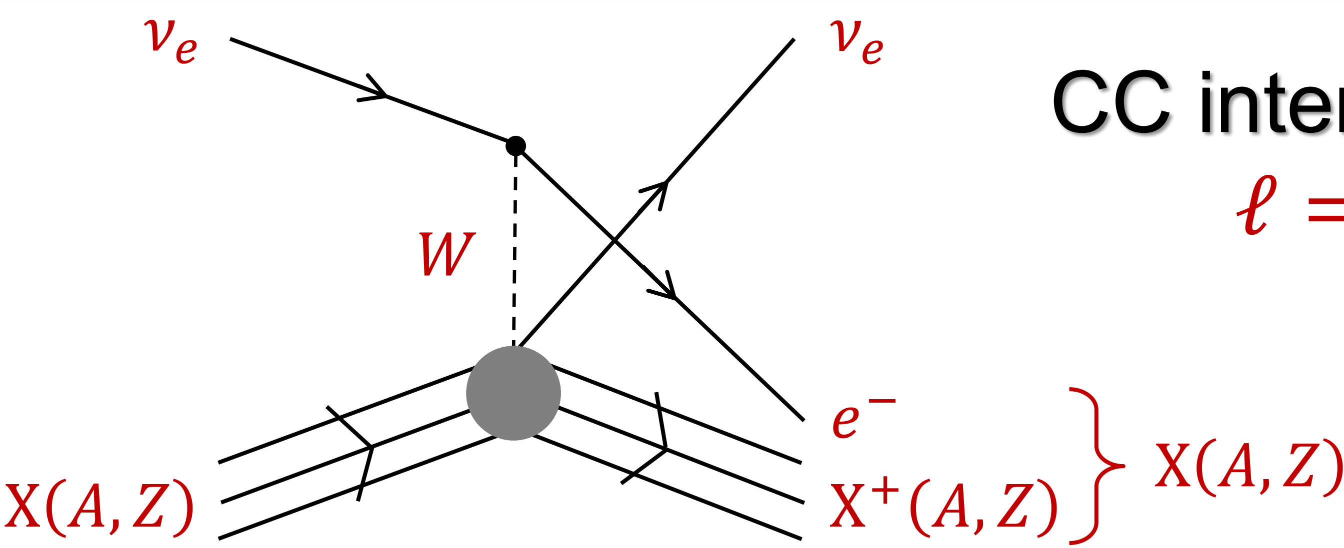
BACKUP

Elastic neutrino-atom scattering in SM



NC interaction

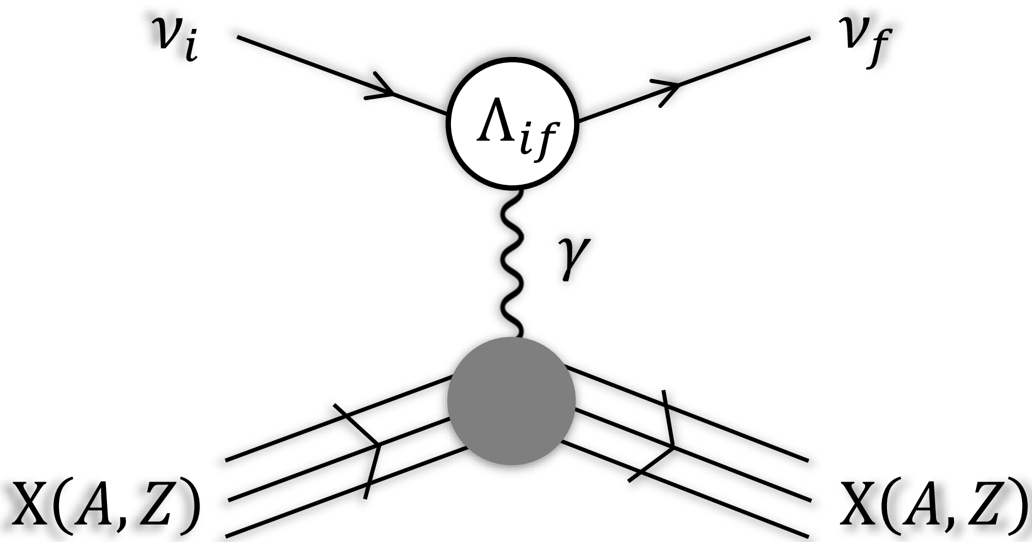
$\ell = e, \mu, \tau$



CC interaction

$\ell = e$

Electromagnetic interactions in CEνAS



$$\Lambda_\mu^{(\mathrm{EM};\nu)fi}(q) = \left(\gamma_\mu - \frac{q_\mu q}{q^2}\right)\left[f_Q^{fi}(q^2) - q^2\, f_A^{fi}(q^2)\gamma_5\right] - i\sigma_{\mu\nu}q^\nu\left[f_M^{fi}(q^2) + if_E^{fi}(q^2)\gamma_5\right]$$

$$\sigma_{\mu\nu} = \frac{i}{2}(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)$$

$q^2 \to 0$: $f_Q(q^2) - q^2 f_A(q^2)\gamma_5 = e_\nu + \dfrac{q^2}{6}(\langle r_\nu^2\rangle - 6a_\nu\gamma_5)$

$f_M(q^2) + if_E(q^2)\gamma_5 = \mu_\nu + \mathrm{i}\epsilon_\nu\gamma_5$

$\gamma_5 = -1$ for ν and $\gamma_5 = +1$ for $\bar{\nu}$

The μ_ν effect in CEνAS

$$\frac{d\sigma}{dT} = \frac{d\sigma_{\rm SM}}{dT} + \frac{d\sigma_{\mu_\nu}}{dT}$$

$$\frac{d\sigma_{\rm SM}}{dT} = \frac{G_F^2 m}{\pi}\left[C_V^2\left(1 - \frac{mT}{2E_\nu^2}\right) + C_A^2\left(1 + \frac{mT}{2E_\nu^2}\right)\right]$$

$$q^2 = 2mT$$

The μ_ν effect (μ_ν is in units of μ_B):

$$\frac{d\sigma_{\mu_\nu}}{dT} = \frac{\pi\alpha^2 Z^2}{m_e^2}|\mu_\nu|^2\left(\frac{1}{T} - \frac{1}{E_\nu}\right)[1 - F_{\rm el}(q^2)]^2$$

Proposals for light dark matter searches with He II

SPICE/HeRALD [*R. Anthony-Petersen et al., arXiv:2307.11877 [physics.ins-det]*]

DELight [*B. von Krosigk et al., arXiv:2209.10950 [hep-ex]*]

Advantages of superfluid He target:

- extreme intrinsic radiopurity
- high impedance to external vibration noise
- unique "quantum evaporation" signal channel enabling the detection of quasiparticle modes (rotons and phonons) via liberation of ^{4}He atoms into a vacuum

*S.A. Hertel et al., PRD **100** (2019) 092007*
arXiv:1810.06283 [physics.ins-det]

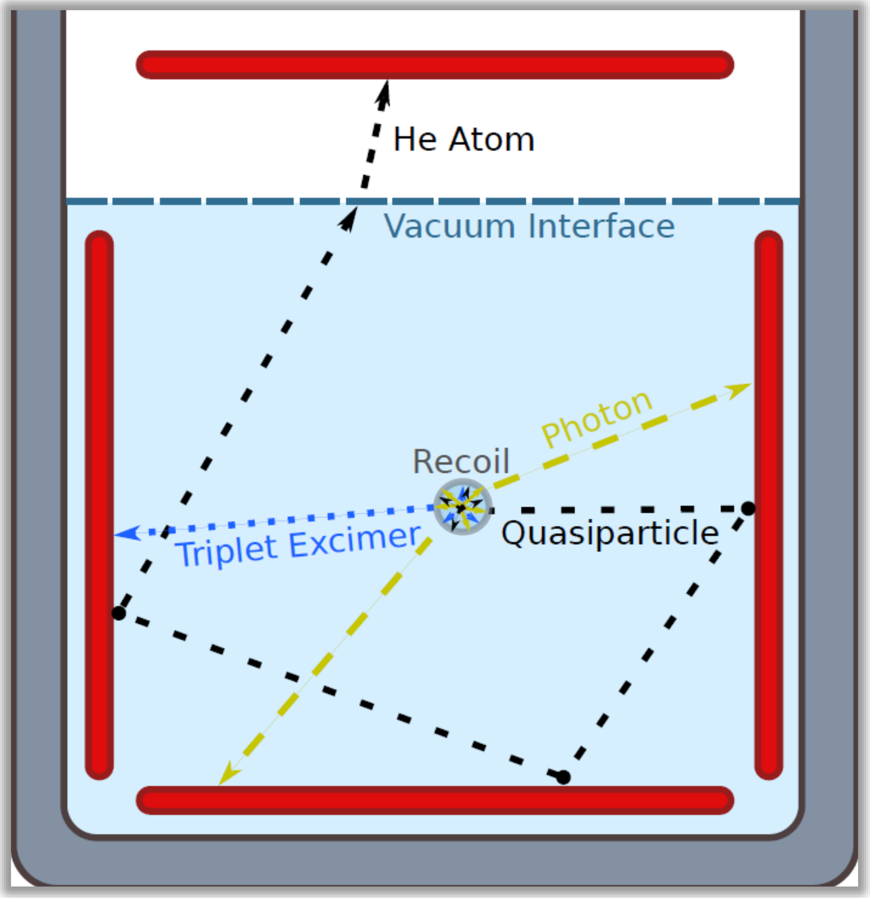
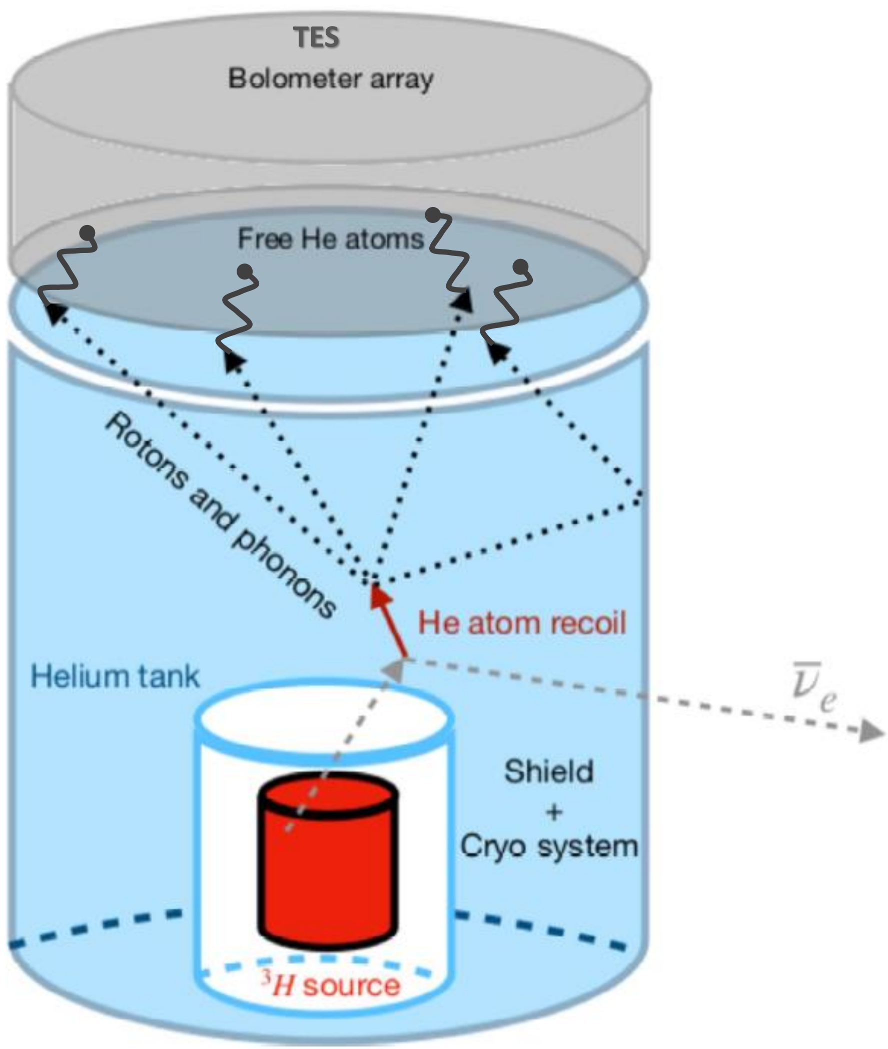


Fig. Simplified detector layout

Detection method to study CEνAS



Tritium neutrino

↓

Elastic neutrino-atom scattering

↓

He atom recoil (1-185 meV)

↓

Phonons and rotons (0.7-1.2 meV per q. p.)

↓

Quantum evaporation (0.6 meV per atom)

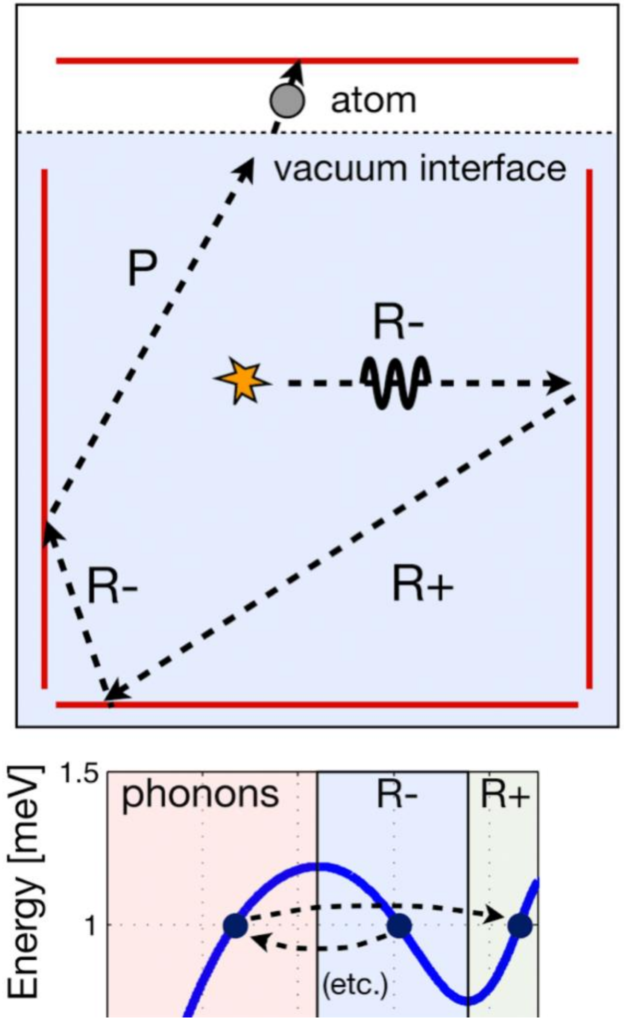
↓

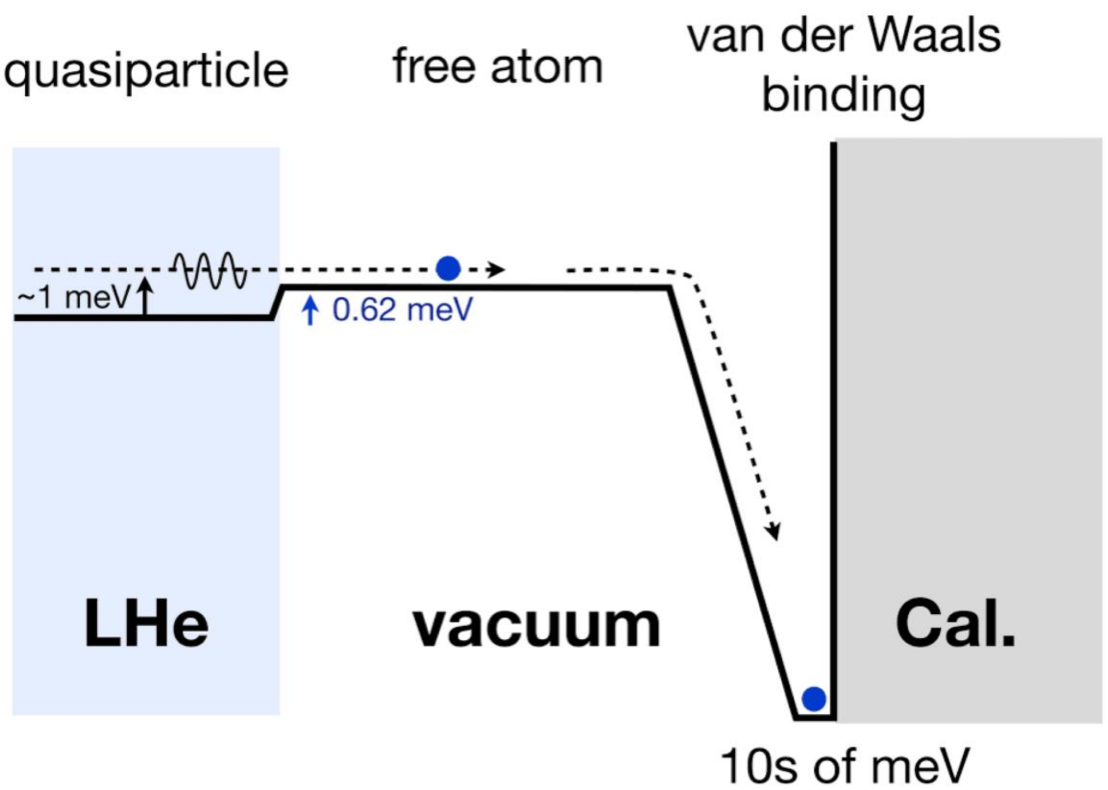
Adsorption onto TES (6-50 meV per adatom)

↓

Signal

Quasiparticle readout: Quantum evaporation of He atom





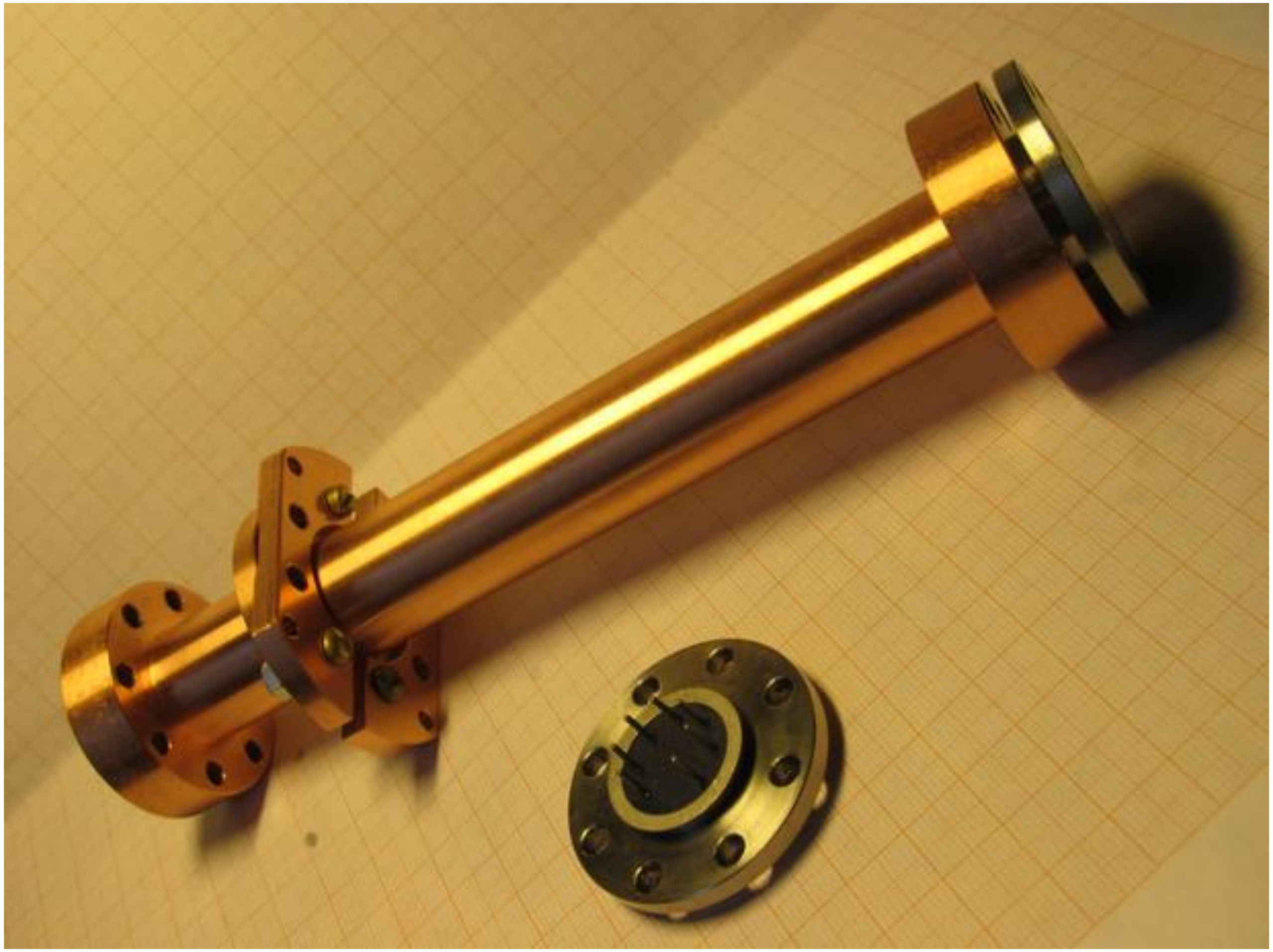
1 meV roton energy becomes up to 40 meV observable

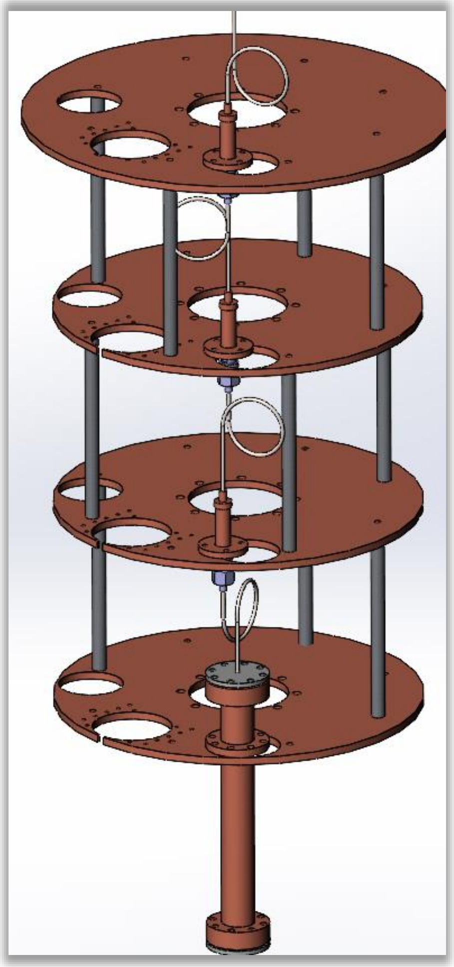
- **x** 40 amplification
- Graphene-fluorine surface

[D. McKinsey, SNOLAB Workshop 2021]

The test He II cell for TRITON 200

@ JINR & Nizhny Novgorod State Technical University

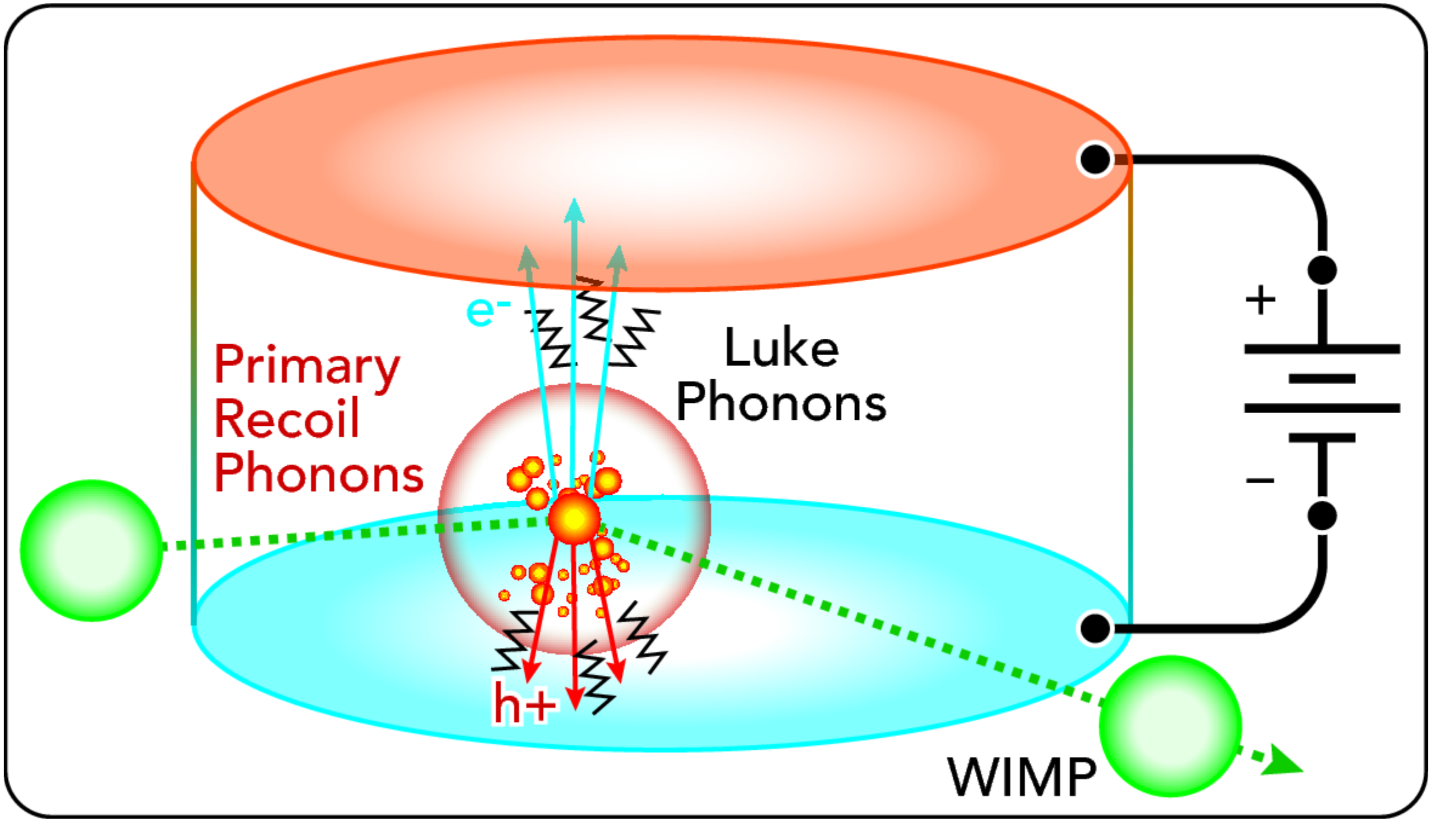




Purpose: To test the possibility of (i) generation of various excitations in helium (phonons, rotons, scintillations) by various controlled methods (thermal, mechanical, irradiation with various particles) and (ii) registration of these excitations by microcalorimetric detectors of various types

Neganov-Trofimov-Luke effect

Phonon amplification of ionization signal



Observed Phonon Energy = $E_{Recoil} + E_{NTL}$

[B. von Krosigk (on behalf of the SuperCDMS Collaboration), IDM2018]

Potentialities of detector systems

He II detector

- searches for light dark matter
- (thermal) solar neutrinos

Si detector

- CEνNS with reactor neutrinos
- searches for dark matter

CsI(pure) detector

- CEνNS with reactor neutrinos
- search for neutrinoless double beta decay
- isotope identification