LOMONOSOV MOSCOW
STATE UNIVERSITY

Supported by the Russian Science Foundation
project #22-22-00384

National Center
FOR PHYSICS AND MATHEMATICS

Status and Physics Potential of SATURNE

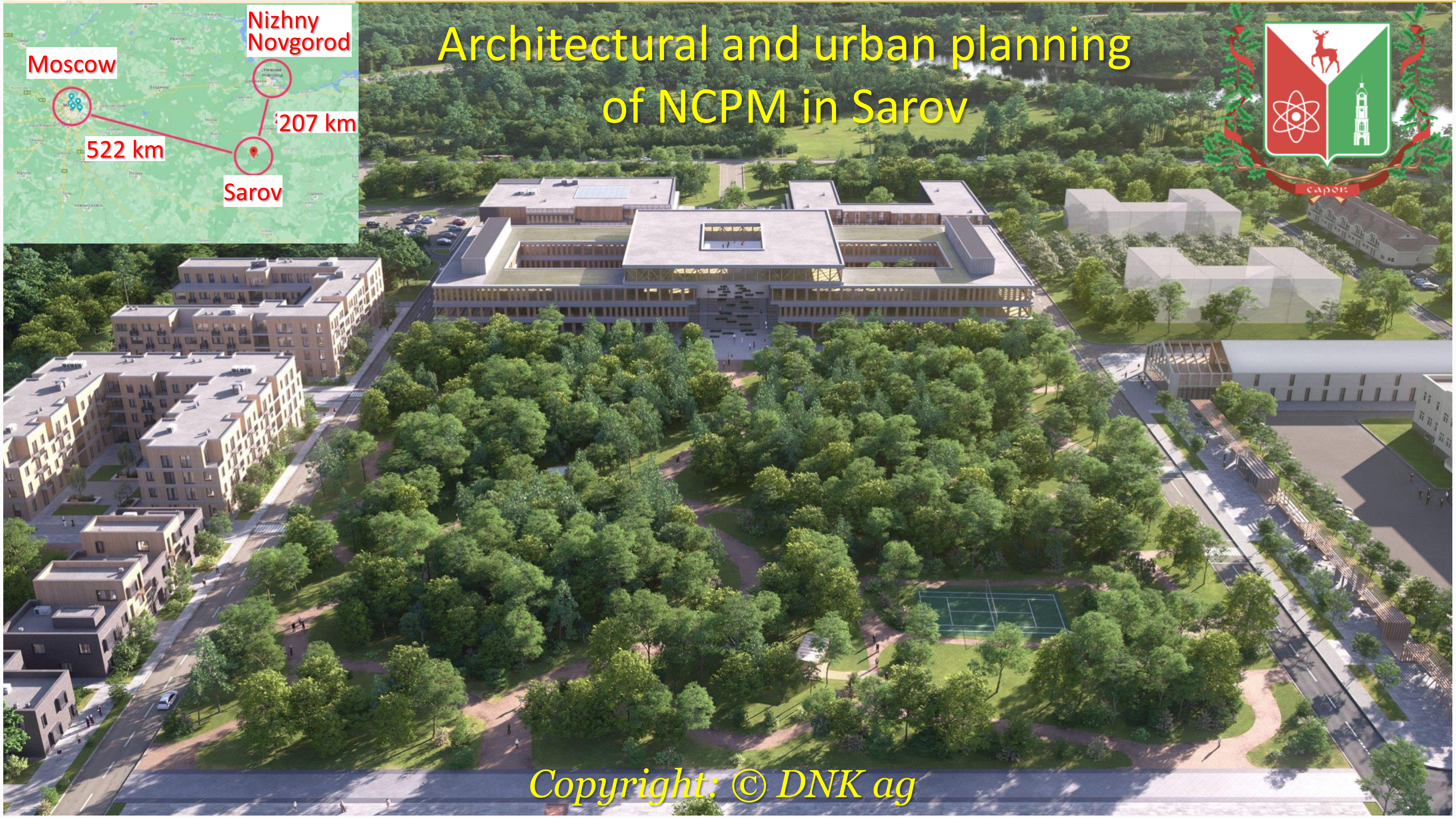
Konstantin Kouzakov

on behalf of

The SATURNE Collaboration

The 7th international conference on particle physics and astrophysics
22-25 October 2024, Moscow

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



Architectural and urban planning of NCPM in Sarov

Copyright: © DNK ag

The main goals of the experiment are

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

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

CEνAS: Coherent Elastic Neutrino-Atom Scattering

Yu. V. Gaponov and V. N. Tikhonov,
Elastic scattering of low energy neutrinos by atomic systems,
Yad. Fiz. (USSR) ***26*** *(1977) 594 (in Russian).*

Abstract. Elastic scattering of low energy neutrinos by atomic systems is treated. For the *V* variant of weak interaction scattering on the total system (on electrons, protons and neutrons) is coherent; for the *A* variant neutrino scatters coherently on using simple atomic systems. The result for an arbitrary atom is presented. The analysis shows that at neutrino energies $\lesssim$ 10 keV a region of coherent optical neutrino phenomena exists where the neutrino elastic scattering by an atom as a whole dominates.

So far there is no corresponding experimental observation. An experimental study of CEνAS could provide a unique test of the SM neutrino interactions at very low energies.

CEνAS vs CEνNS

CEνNS: Coherent Elastic Neutrino-Nucleus Scattering

predicted by *D. Z. Freedman, PRD **9** (1974) 1389;*
*V. B. Kopeliovich & L. L. Frankfurt, ZhETF Pis. Red. **19**, No. 4 (1974) 236*
observed by *D. Akimov et al. (COHERENT Collab.), Science **357** (2017) 1123*

CEνNS

- ▶ $|\vec{q}|R_{\mathrm{nuc}} \ll 1$

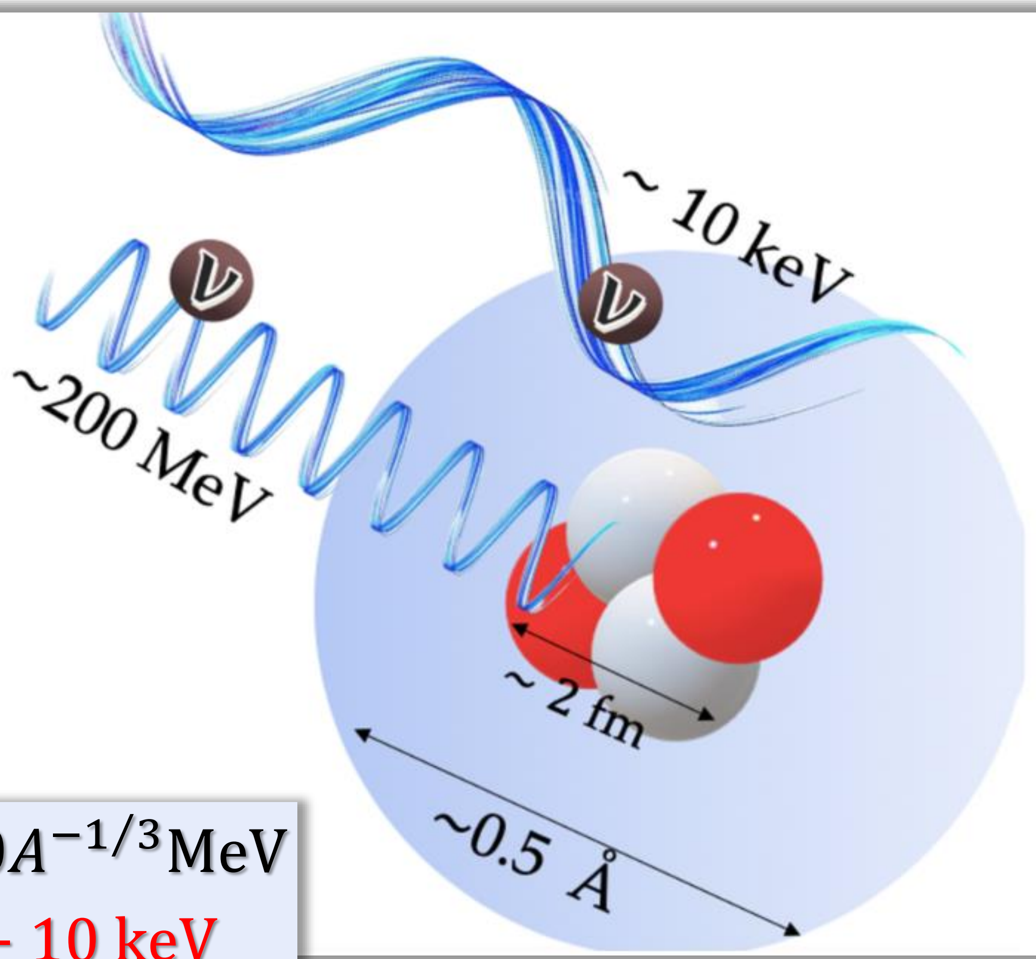
$\vec{q}$ is the momentum transfer

R_{nuc} is the nuclear radius

CEνAS

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

R_{atom} is the atomic radius

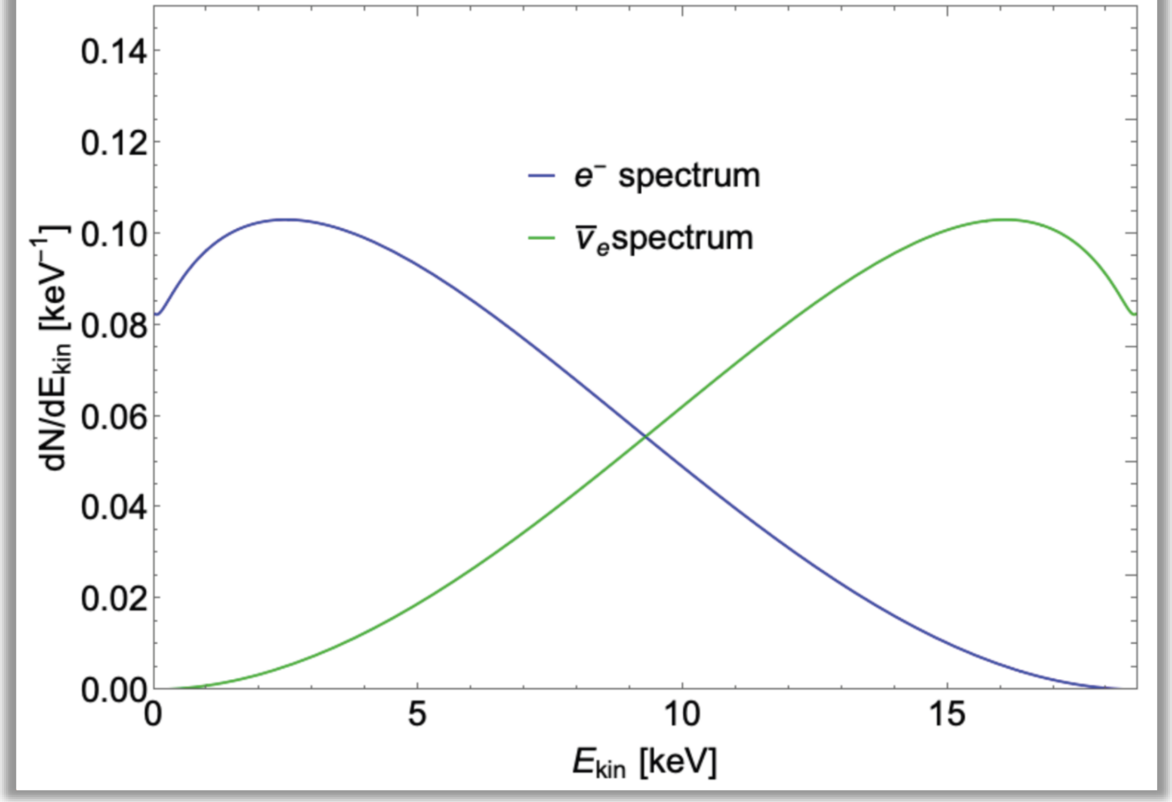


CEνNS: $E_\nu \lesssim 1/R_{\mathrm{nuc}} \sim 200A^{-1/3}\mathrm{MeV}$

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

Tritium neutrinos

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



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

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

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

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 energy-momentum conservation it follows that

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

T_R is energy transfer, or atomic recoil energy

$m \approx A$ GeV is atomic mass

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

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

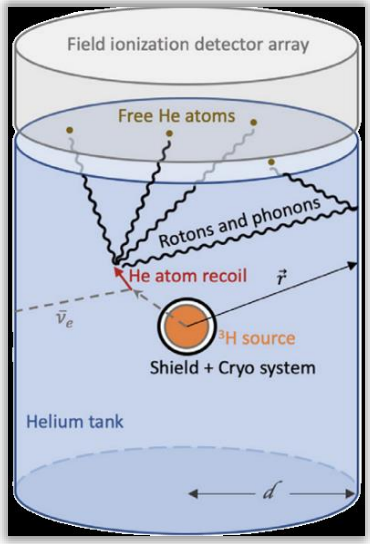
Light atomic targets, such as H or He, are needed to observe CEνAS

He-4 atomic recoil spectrum with tritium $\bar{\nu}_e$

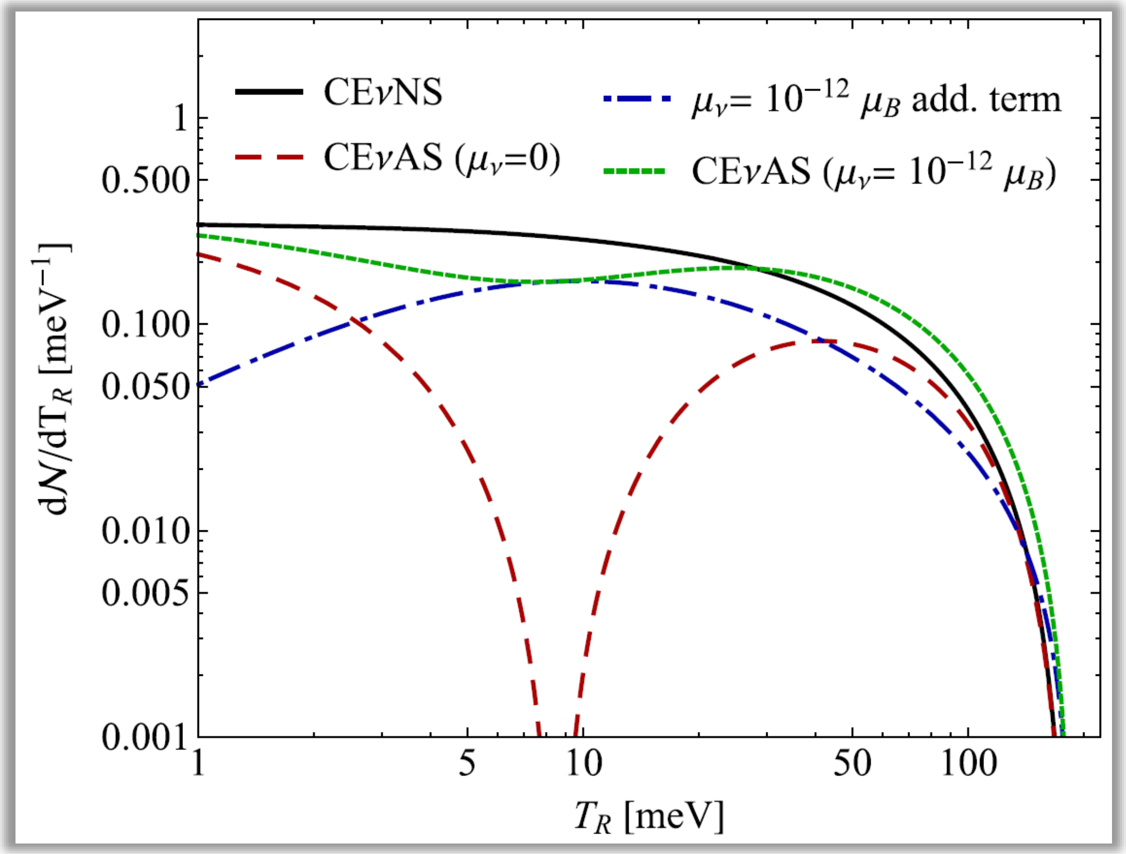
M. Cadeddu, F. Dordei, C. Giunti, K. Kouzakov, E. Picciau, A. Studenikin, PRD ***100*** *(2019) 073014*

$$\frac{d\sigma_{\rm SM}}{dT_R} = \frac{G_F^2 m}{\pi}\left[Z\left(\tfrac{1}{2} - 2\sin^2\theta_W\right) - \tfrac{1}{2}N + Z\left(\tfrac{1}{2} + 2\sin^2\theta_W\right)F_{\rm el}(q^2)\right]^2\left(1 - \frac{mT_R}{2E_\nu^2}\right)$$

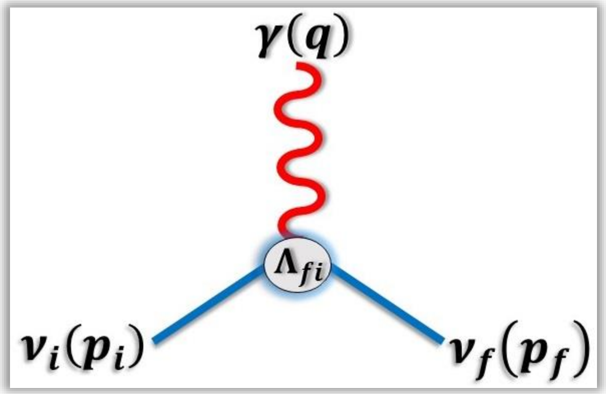
$$\frac{d\sigma_{\mu_\nu}}{dT_R} = \frac{\pi\alpha^2 Z^2}{m_e^2}|\mu_\nu|^2\left(\frac{1}{T_R} - \frac{1}{E_\nu}\right)[1 - F_{\rm el}(q^2)]^2 \qquad \text{with} \qquad q^2 = 2mT_R$$



500 kg of helium
60 g of tritium
5 yrs of taking data



Neutrino magnetic moment μ_ν



C. Giunti and A. Studenikin,
Neutrino electromagnetic interactions:
A window to new physics,
Rev. Mod. Phys. ***87*** *(2015) 531; arXiv:1403.6344*

[Alexander Studenikin, ICPPA-2024]

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

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

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),
arXiv:2406.13516v1 [nucl-ex]

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*

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

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

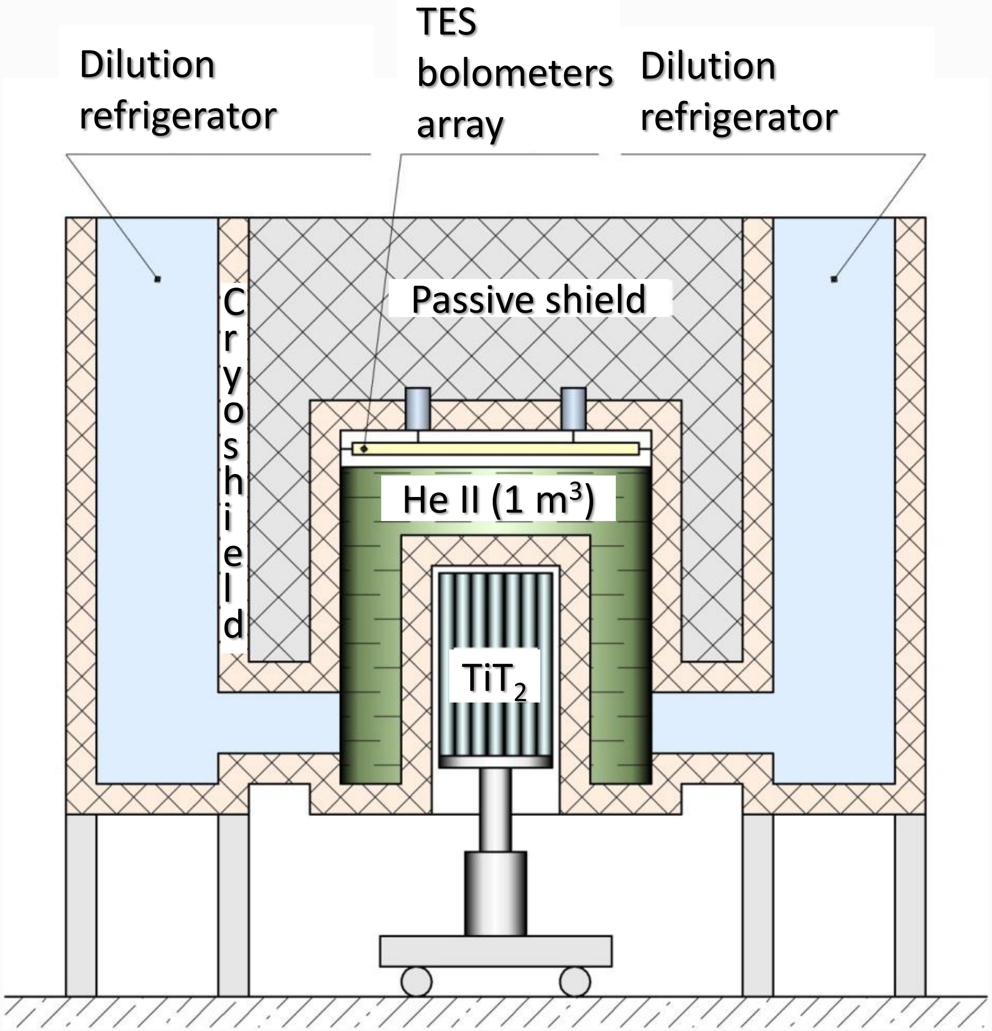
Astrophysical bounds (luminosity of globular star clusters)

*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

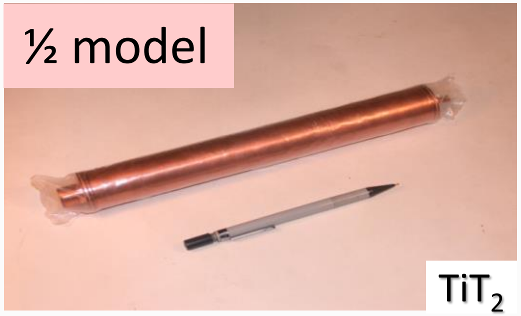
He II detector concept to study CEνAS



Tritium neutrino source

(1-4 kg, 10-40 MCi)

- Tubular copper elements with TiT_2



Helium II detector (1000 L)

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

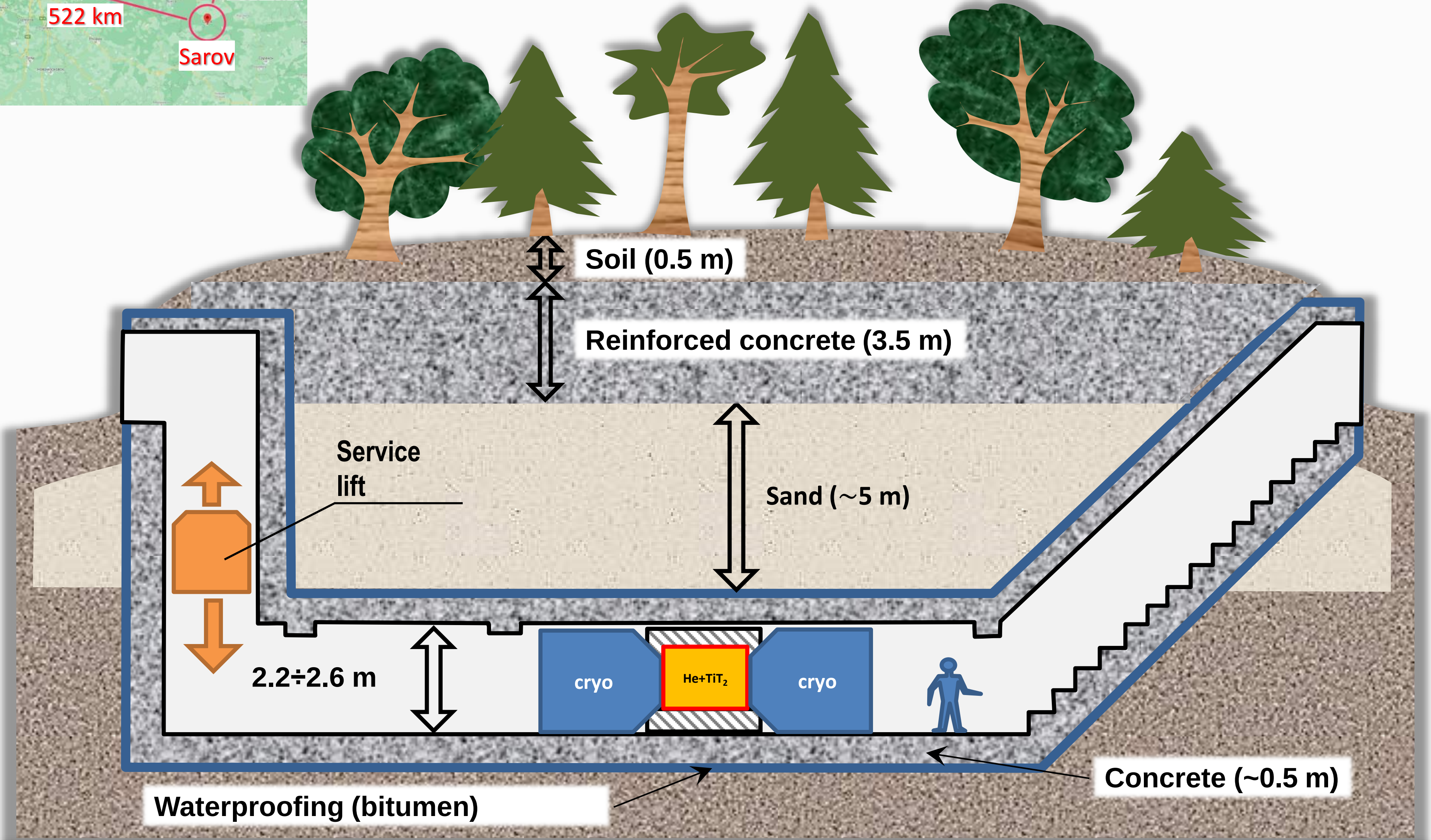
Expected results after 5 years of data collection

Number of CEνAS events within SM: **60 for 1 kg of T_2** and **200 for 4 kg of T_2**

Sensitivity to neutrino magnetic moment: μ_ν~**(2-4)x10^{-13}** μ_B at 90% C.L.

Low-background neutrino laboratory in Sarov

@ All-Russian Research Institute of Experimental Physics, RFNC



The overburden of 20-25 m.w.e. stops the soft and hadronic components of cosmic radiation

Search for μ_ν with atomic ionization channel

Inelastic channels:

$$\nu + \mathrm{X} \longrightarrow \mathrm{X}^* + \nu \qquad (T \geq \mathcal{E}_\mathrm{X}, \text{ excitation})$$

$$\nu + \mathrm{X} \longrightarrow \mathrm{X}^+ + e^- + \nu \qquad (T \geq I_\mathrm{X}, \text{ ionization})$$

$\mathcal{E}_\mathrm{X}$ and I_X are atomic excitation and ionization energies

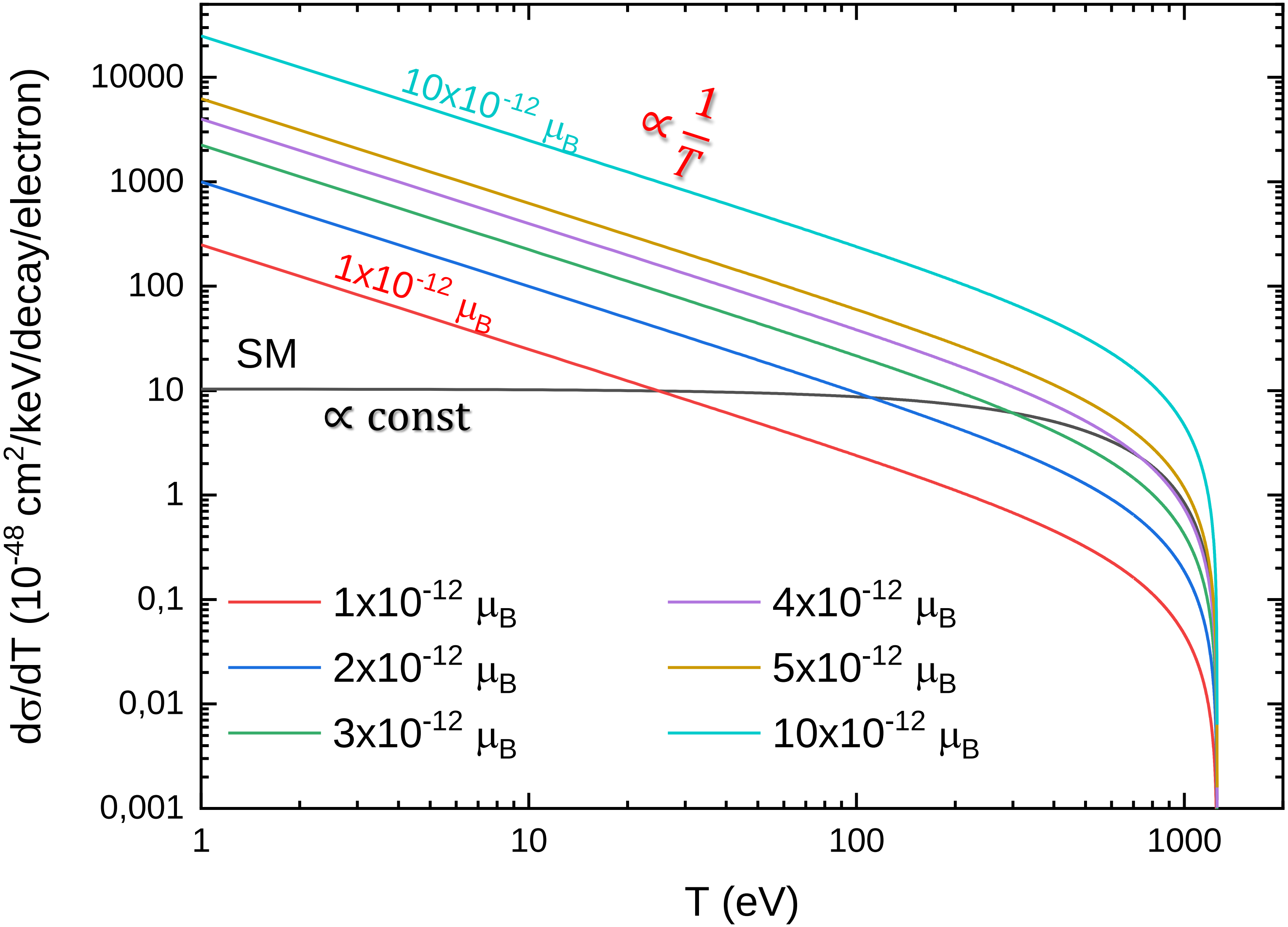
World leading laboratory constraints on μ_ν, like those from XENNONnT and GEMMA, are obtained by studying the atomic ionization channel (elastic $\nu - e^-$ scattering)

In **SATURNE** we develop

- Cryogenic Si crystal detector
- $\mathrm{SrI_2(Eu)}$ scintillation detector

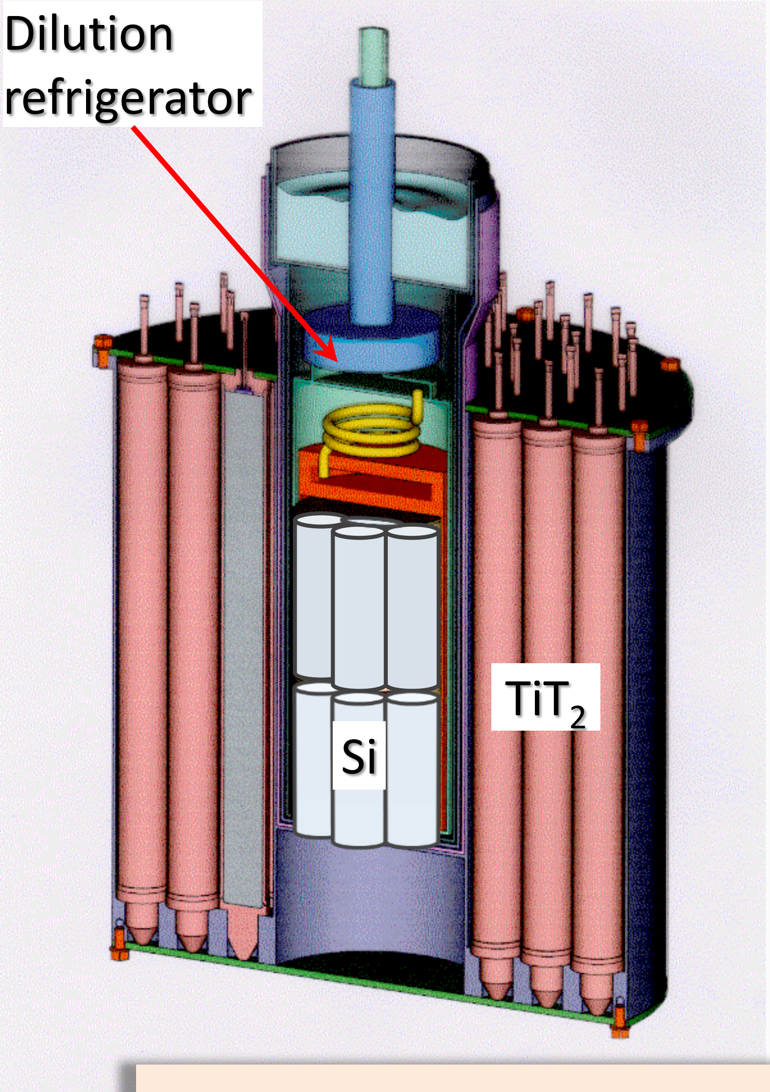
Electron recoil spectrum for tritium $\bar{\nu}_e$ on Si

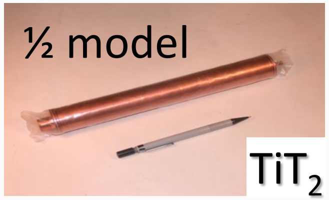
SM predicts a flat spectrum at small T, and the μ_ν contribution $\propto \frac{1}{T}$



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

Si detector concept





Tritium neutrino source (1-4 kg)

- tubular copper elements with TiT$_2$

Silicon cryodetectors (T=10-50 mK)
14×125 cm^3, M=4 kg

- TES 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)*

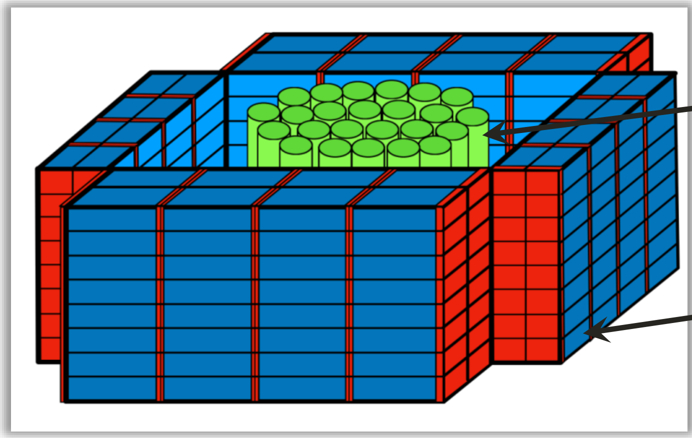
*B. Neganov and V. Trofimov, USSR patent no. 1037771, Otkrytia i Izobreteniya **146** (1985) 215; P. N. Luke, J. Appl. Phys. **64** (1988) 6858.*

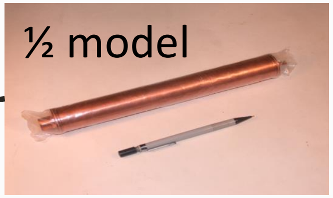
Expected results after 1 year of data collection

Number of events within SM: **10 for 1 kg of T$_2$** and **40 for 4 kg of T$_2$**

Sensitivity to neutrino magnetic moment: μ_ν~**(1-1.5)x10^{-12}** μ_B at 90% C.L.

$SrI_2(Eu)$ scintillation detector concept



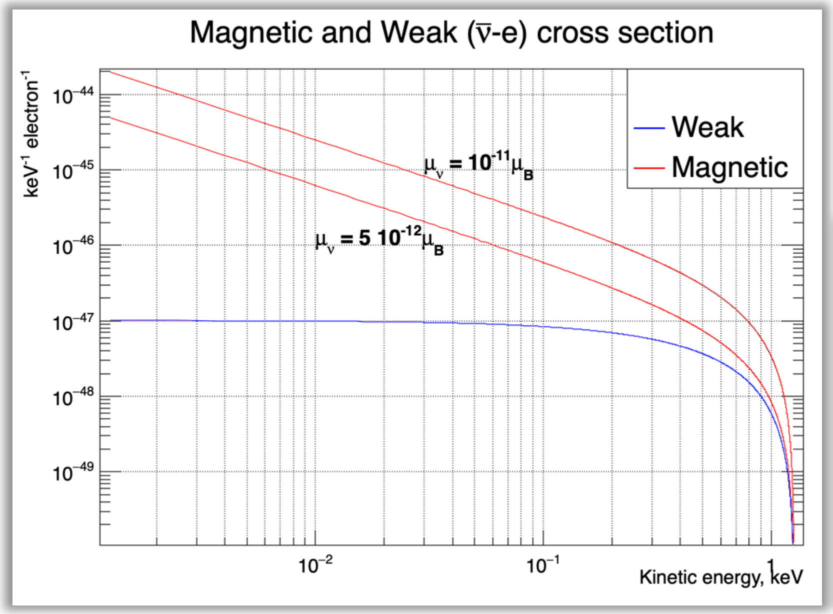


Tritium neutrino source (1-4 kg)

Tubular copper elements with TiT_2

15x15x25 mm^3 $SrI_2(Eu)$ crystals operating at T from -60 to -40 °C, total mass is M=14 kg

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



- SiPM readout

  (4 SiPMs per each crystal)
- Light collection at a level of 50 p.e./keV
- Energy threshold is E_{th}~100 eV

Expected results after 1 year of data collection

Number of events within SM:

25 for 1 kg of T_2 and **100 for 4 kg of T_2**

Sensitivity to neutrino magnetic moment:

$\mu_\nu \sim (1.5\text{-}2)\times10^{-12}\ \mu_B$

Summary and outlook

The Sarov tritium neutrino experiment aims at

(i) first observation of **coherent elastic neutrino-atom scattering** to test SM neutrino interactions at unprecedentedly low energies

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

A high-intensity tritium neutrino source is being prepared

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

A 1000-L He II detector is being developed (to be **ready by 2027**)

- observation of **CEνAS (2032)**
- sensitivity to $\mu_\nu \sim$**(2-4)x**10^{-13} μ_B **(2032)**

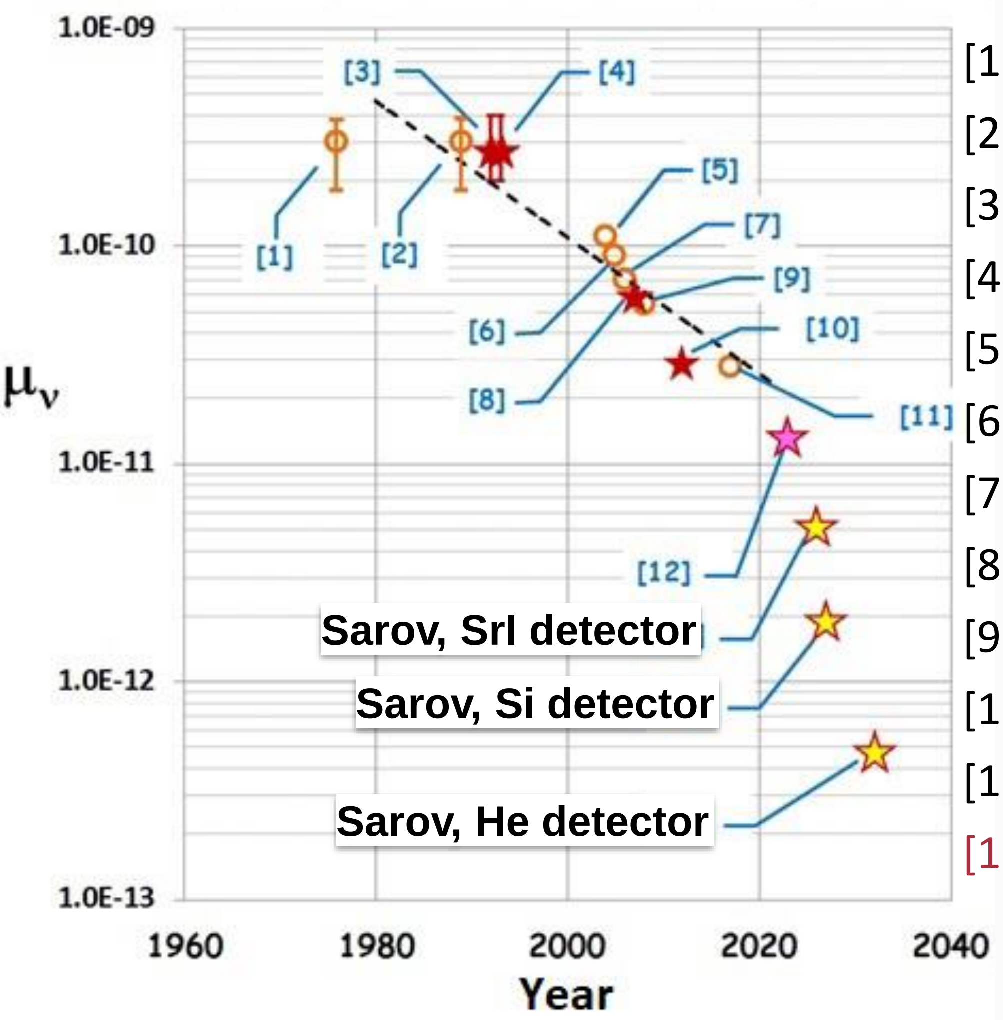
A 4-kg Si detector is being developed (to be **ready by 2026**)

- sensitivity to $\mu_\nu \sim$**(1-1.5)x**10^{-12} μ_B **(2027)**

A 14-kg SrI_2**(Eu) detector** is being developed (to be **ready by 2025**)

- sensitivity to $\mu_\nu \sim$**(1.5-2)x**10^{-12} μ_B **(2026)**

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…2024)

Thank you for your attention!

Backup

The SATURNE Collaboration

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

PRODUCTION
ASSOCIATION
MAYAK

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

1755
LOMONOSOV MOSCOW
STATE UNIVERSITY

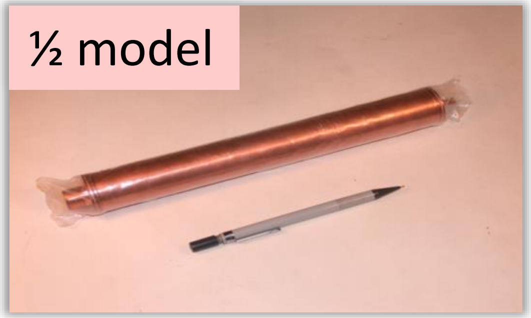
LOBACHEVSKY
UNIVERSITY

JOINT INSTITUTE
FOR NUCLEAR RESEARCH

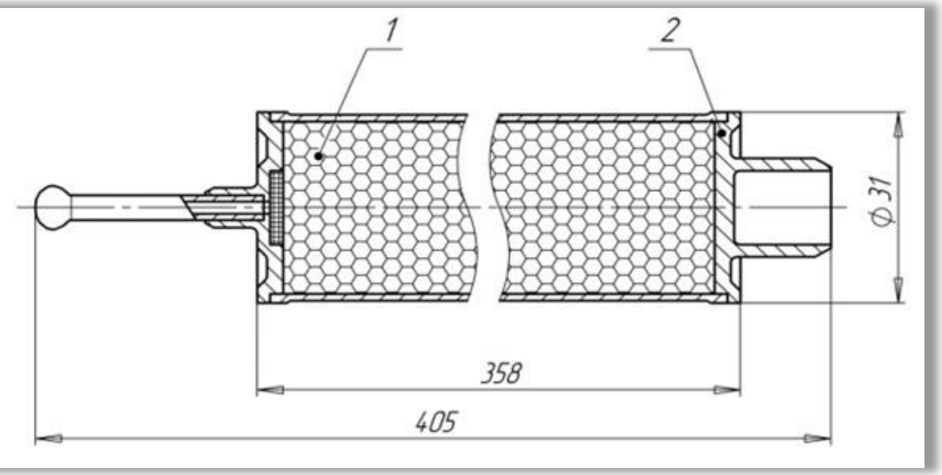
IPM RAS

Ioffe
Physical-
Technical
Institute

Tritium neutrino source (TNS)



Construction of a tubular tritium element



1 – titanium tritide; 2 – body

The basic design scheme of a tritium neutrino source (TNS) has been worked out in *A.A. Yukhimchuk et al. Fusion Science and Technology* ***48****, No.1 (2005) 731-736.*

TNS is a set of tritium elements in which tritium is in a chemically bound state on titanium.

Titanium powder in bulk is placed in the tritium element. Then the titanium powder is thermally activated and saturated with tritium, after which the tritium element is sealed.

Proposals for light dark matter searches with He II

SPICE/HeRALD [*R. Anthony-Petersen et al., arXiv:2307.11877v1 [physics.ins-det]*]

DELight [*B. von Krosigk et al., arXiv:2209.10950v1 [hep-ex]*]

Advantages of superufluid 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*

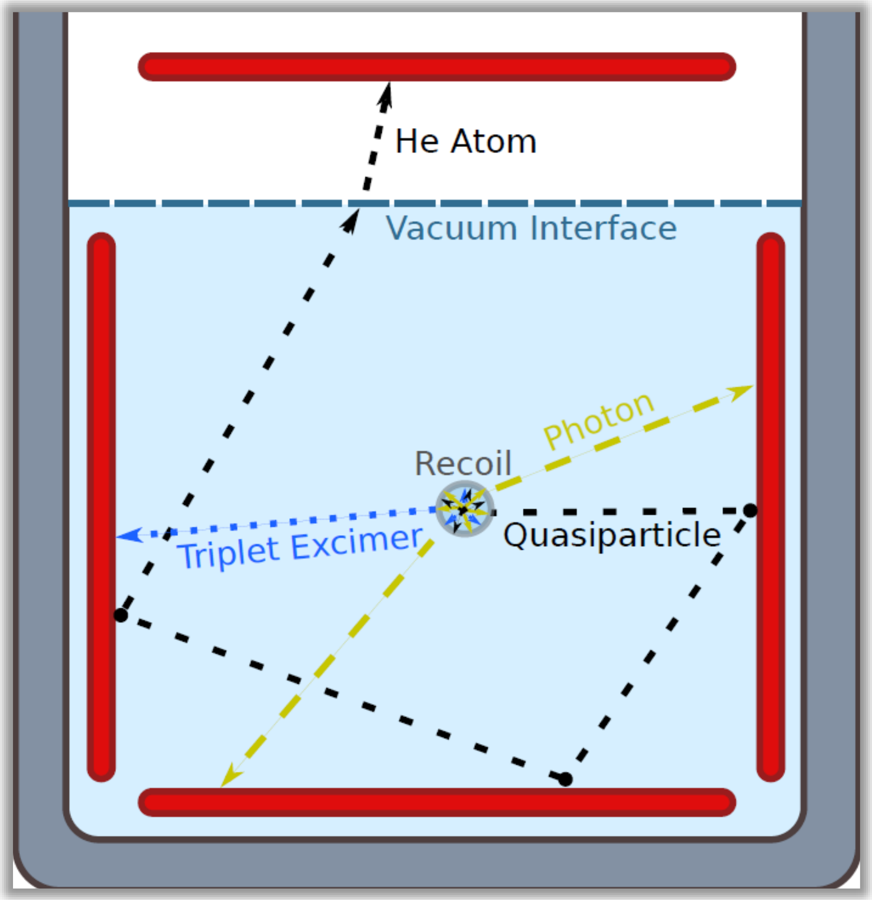
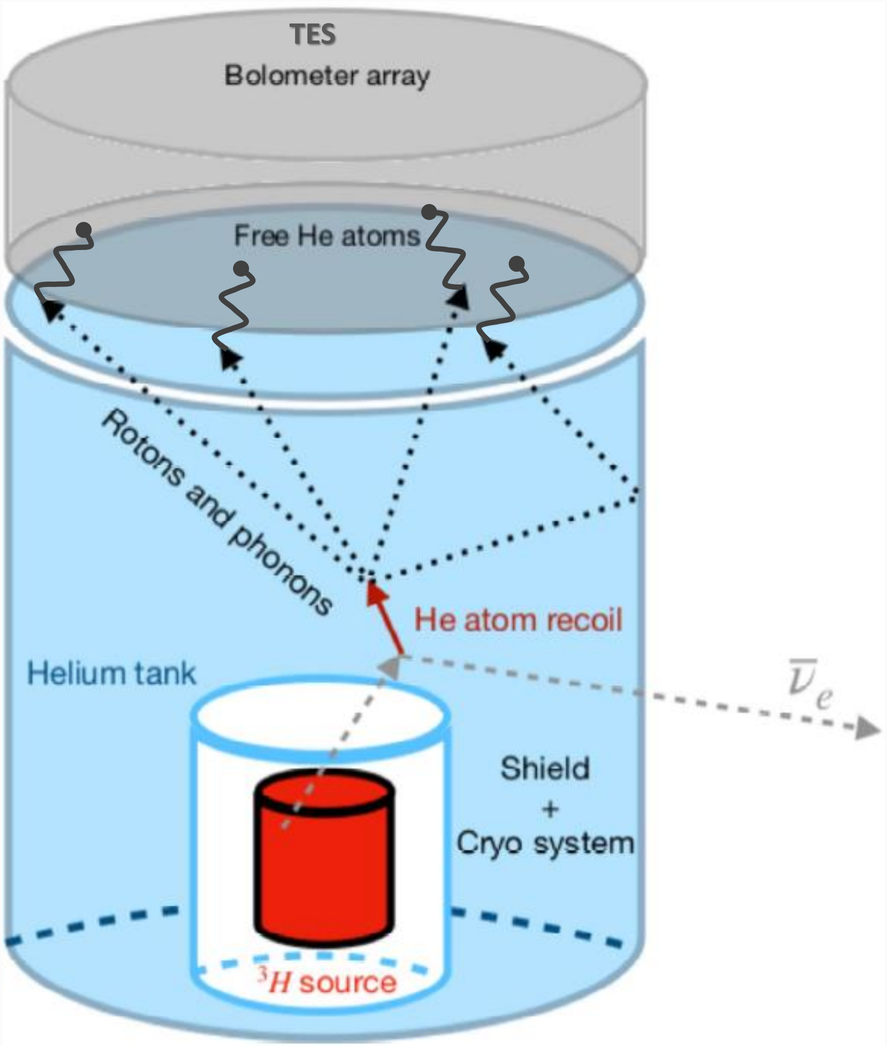


Fig. Simplified detector layout

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)**

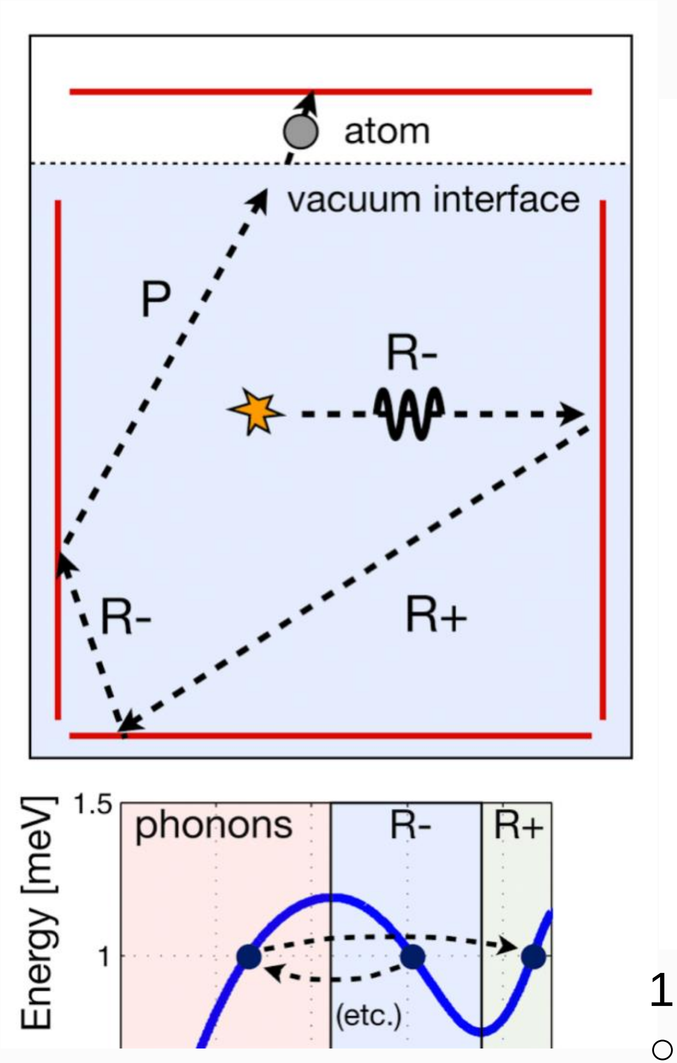
↓

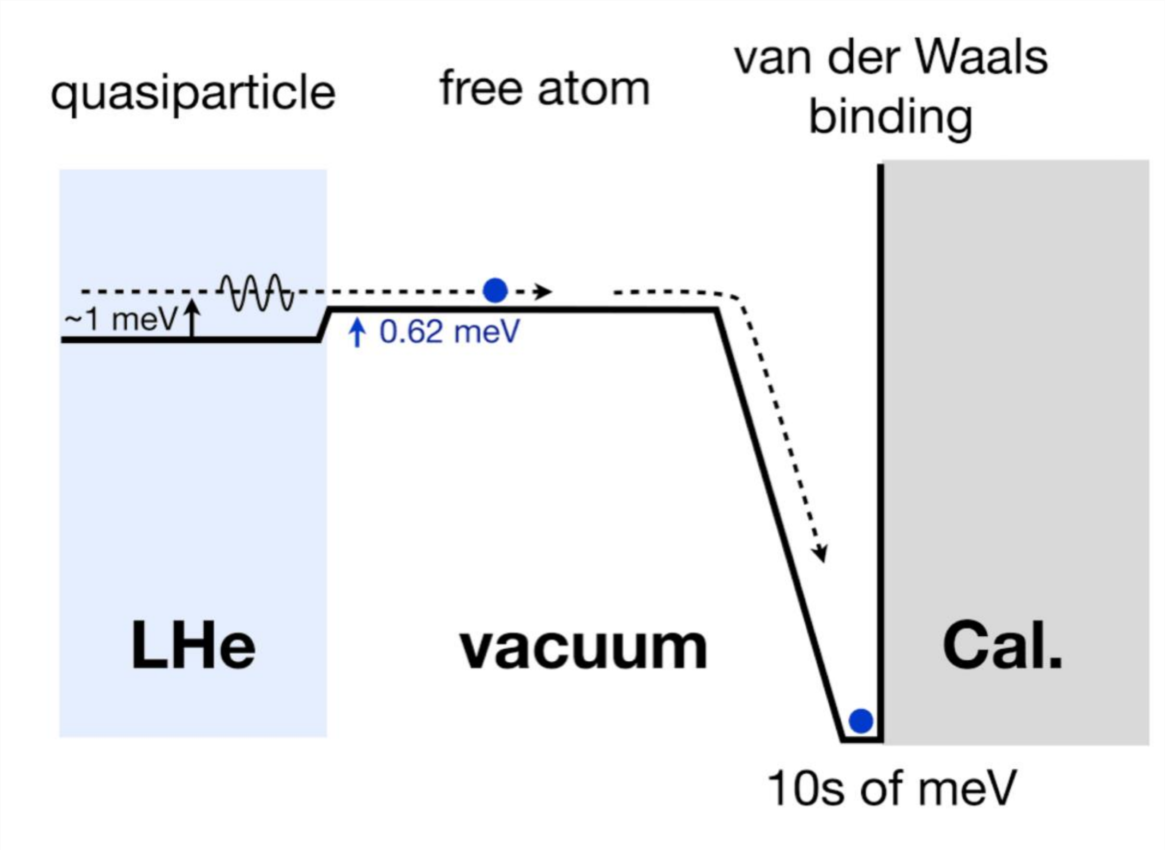
**Adsorption onto TES
(6-50 meV per adatom)**

↓

Signal

Quasiparticle readout: Quantum evaporation of He atom





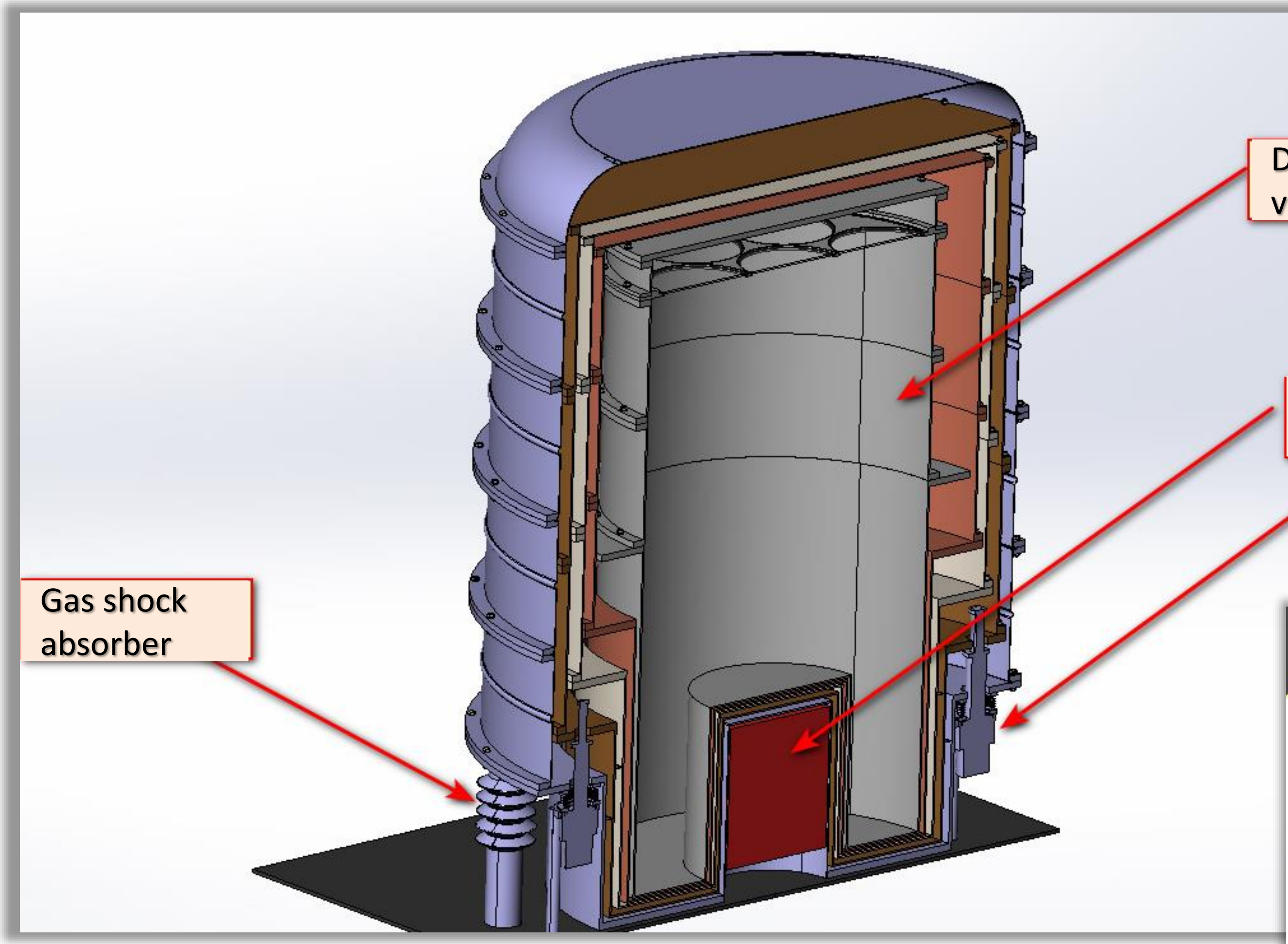
1 meV roton energy becomes up to 40 meV observable

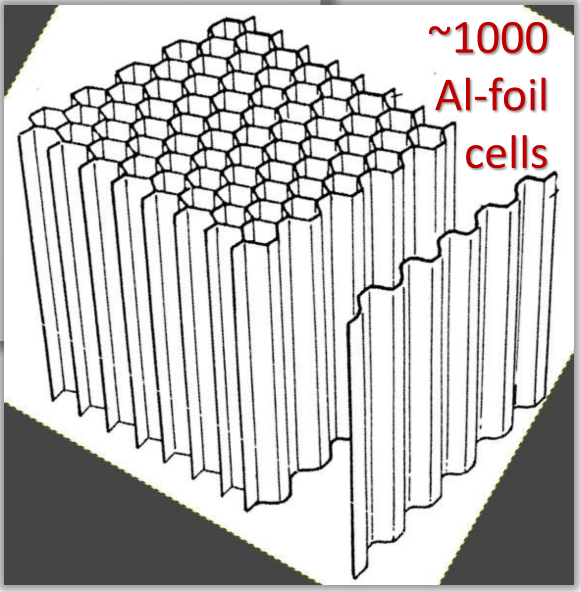
- **x** 40 amplification
- Graphene-fluorine surface

[D. McKinsey, SNOLAB Workshop 2021]

Discrimination of background events

General view of the cryostat

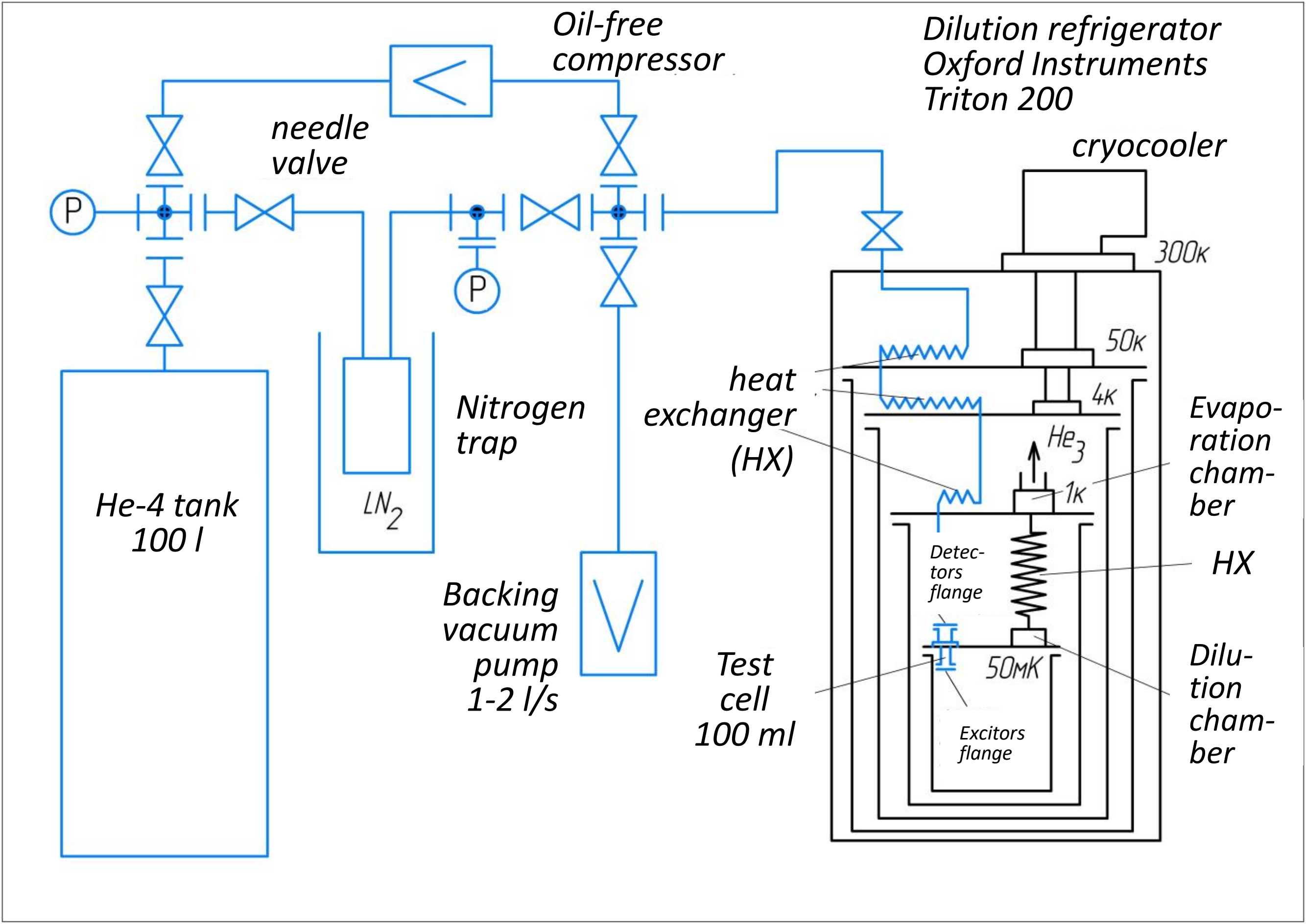


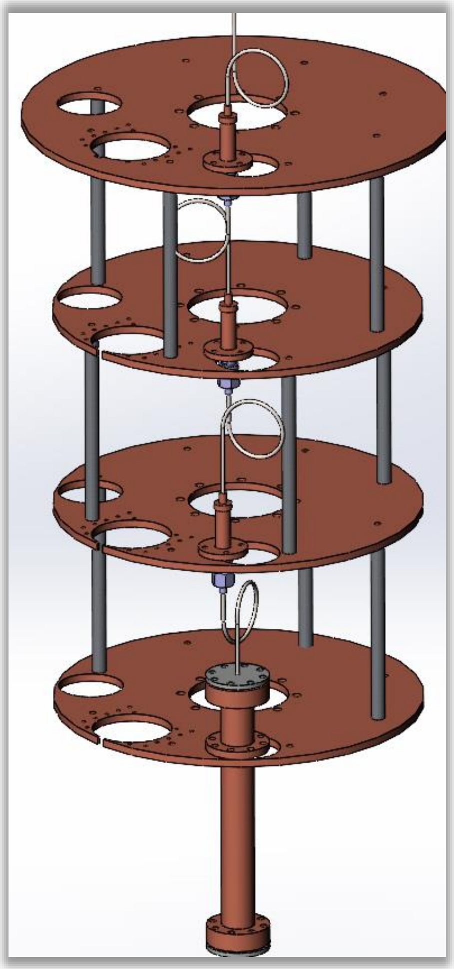


Segmentation of the He detector is the key to background discrimination

The test He II cell for TRITON 200

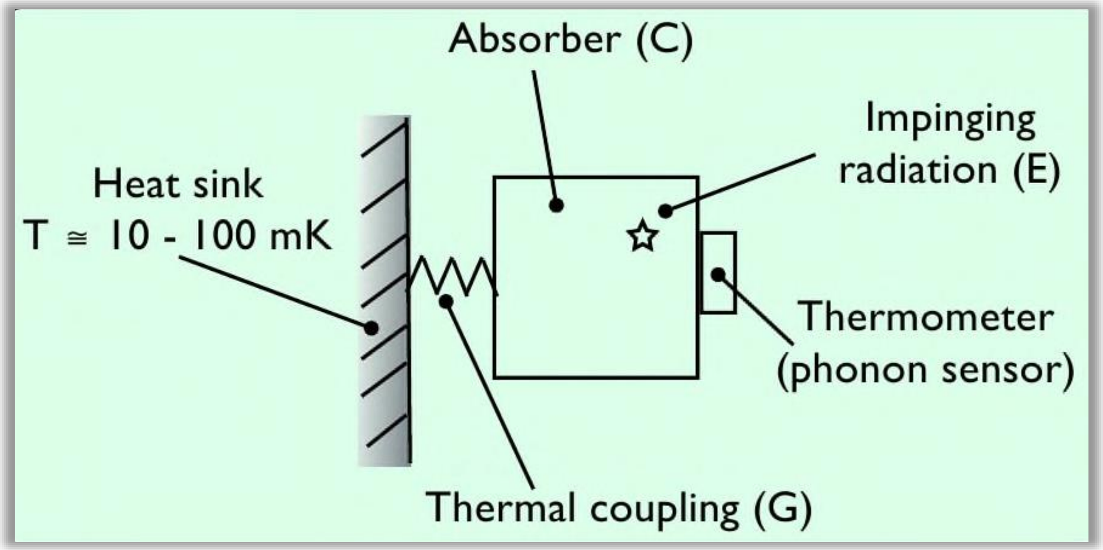
@ JINR & Nizhny Novgorod State Technical University

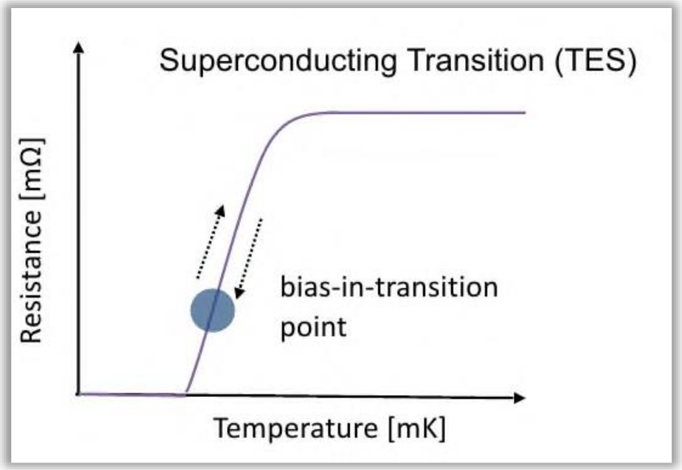


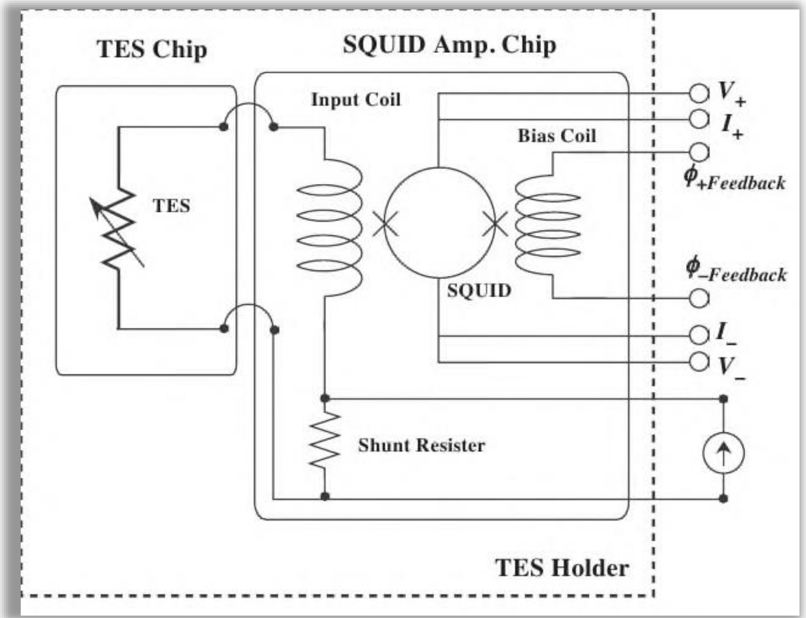


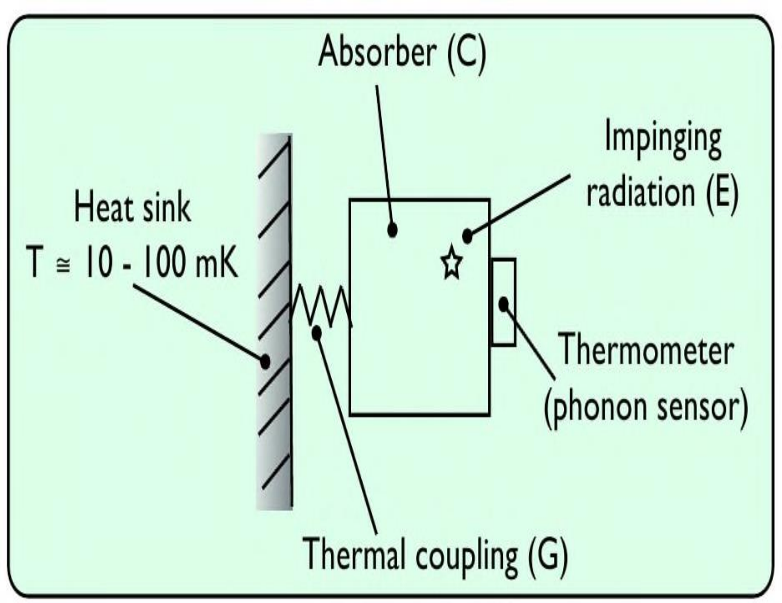
Purpose: To test the possibility of (i) generation of various excitations in helium (phonons, rotons, scintillations) by various controlled methods (thermal, mechanical, irradiation with various particles) and (ii) registration of these excitations by microcalorimetric detectors of various types

Transition edge sensor









Thin-film metal structures for microcalorimeters

@ Institute for Physics of Microstructures, RAS, Nizhny Novgorod

Goal

Obtaining superconducting films with a critical temperature T_c from 15 mK to 100 mK and a sharp transition ΔT_c<1 mK

Methods and approaches

Multilayer structures with proximity effect:

Ti(T_c=0.49 K)/Mo(T_c=0.92 K)/Au & iridium films Ir (T_c = 0.11 K)

Allotropic modifications of tungsten: α-W(T_c=12-15 mK) / β-W (T_c=1-4 K)

Growth technologies

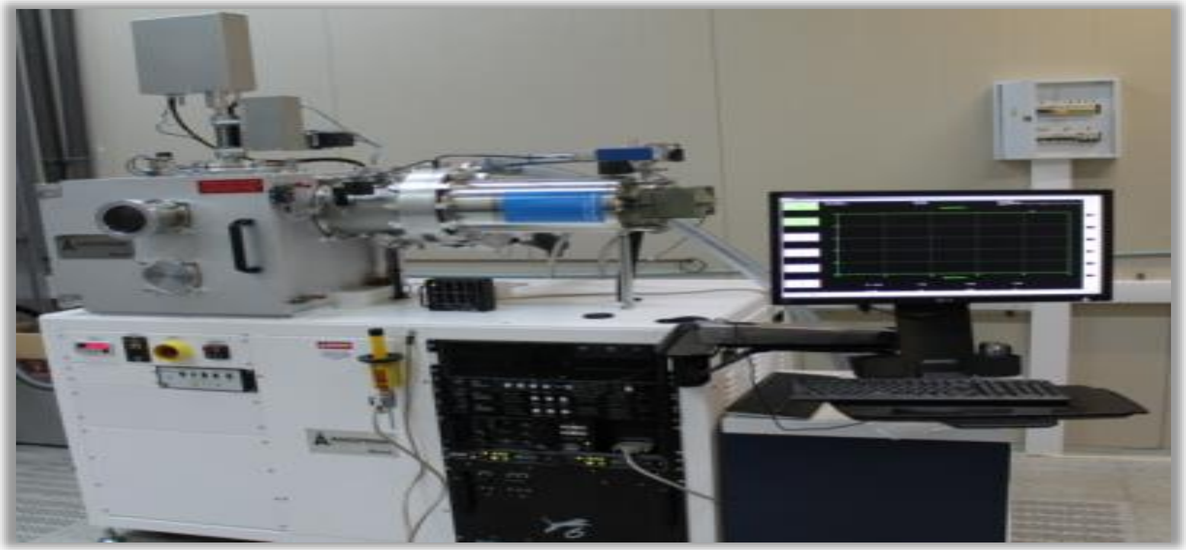
MOCVD with vertical reactor	MOCVD with horizontal reactor (EpiquipVP-502 RP)	Electron beam deposition (Amod 206)
		
α-W/Al_2O_3	α(β)–W/Al_2O_3; GaAs; Si	Ti/Mo/Au; Ir/Si

Post-growth and diagnostic methods

Ultraviolet lithography (Suss MJB4); Plasma etching (Oxford Plasmalab 8); X-Ray Diffractometry (BrukerD8 Discover); Secondary-ion mass spectrometry (TOF.SIMS-5); Atomic force microscopy

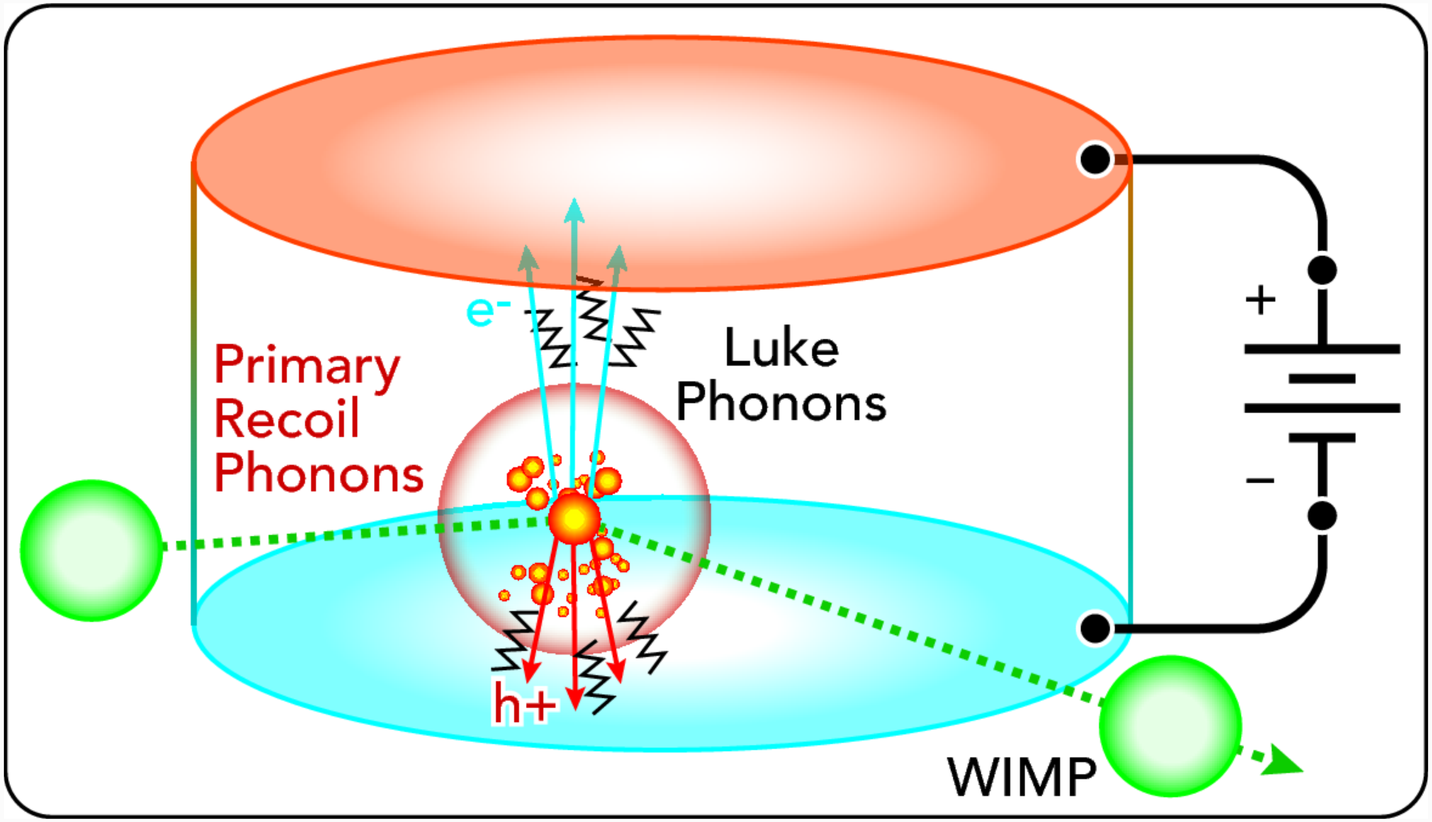
Studies of film electric properties

@ Nizhny Novgorod State Technical University



Neganov-Trofimov-Luke effect

Phonon amplification of ionization signal



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

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