**LOMONOSOV MOSCOW
STATE UNIVERSITY**

National Center
FOR PHYSICS AND MATHEMATICS

Status and perspectives of SATURNE
(SArov Tritium Neutrino Experiment)

Konstantin Kouzakov

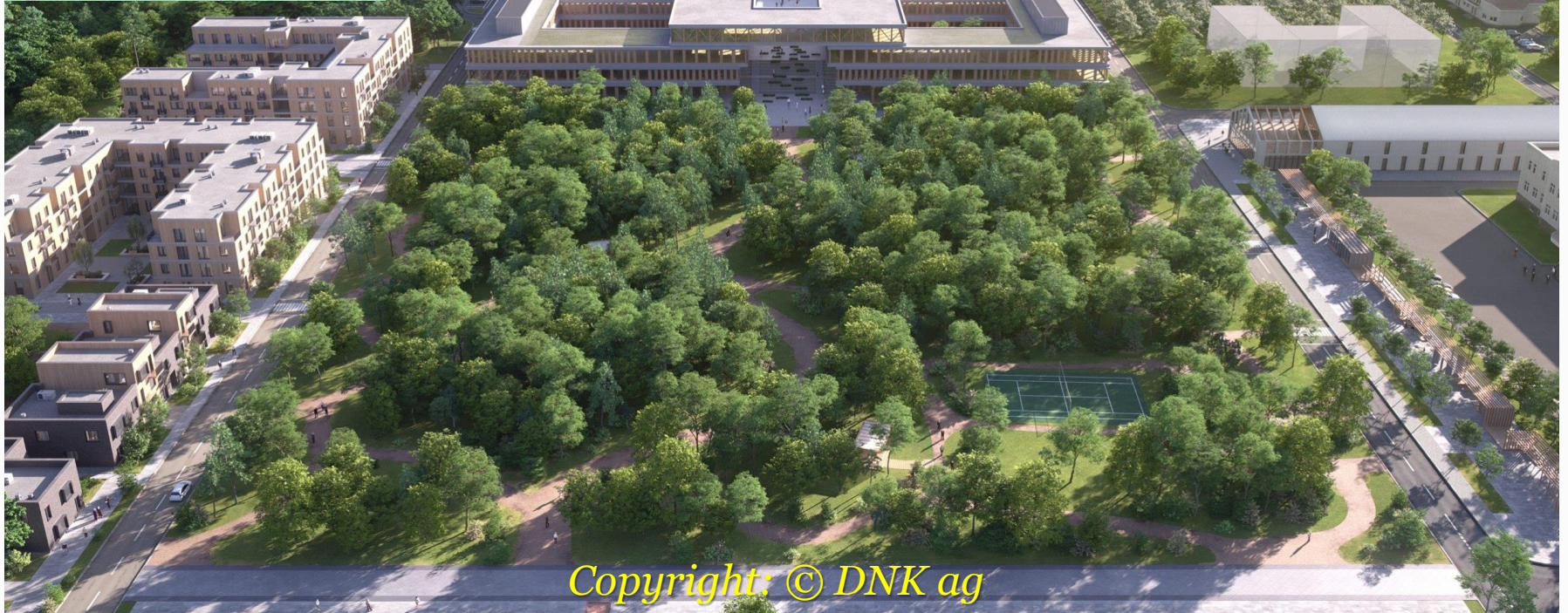*on behalf of*
The SATURNE Collaboration

QUARKS-2024

XXII INTERNATIONAL SEMINAR
ON HIGH-ENERGY PHYSICS

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$_2$**

OUTLINE

- **Physics introduction**

    - CEνAS

    - neutrino magnetic moment μ_ν

- **He II detector concept**
    - observe CEνAS channel & search for μ_ν

- **Si and SrI$_2$(Eu) detector concepts**
    - search for μ_ν with atomic ionization channel

- **Summary and outlook**

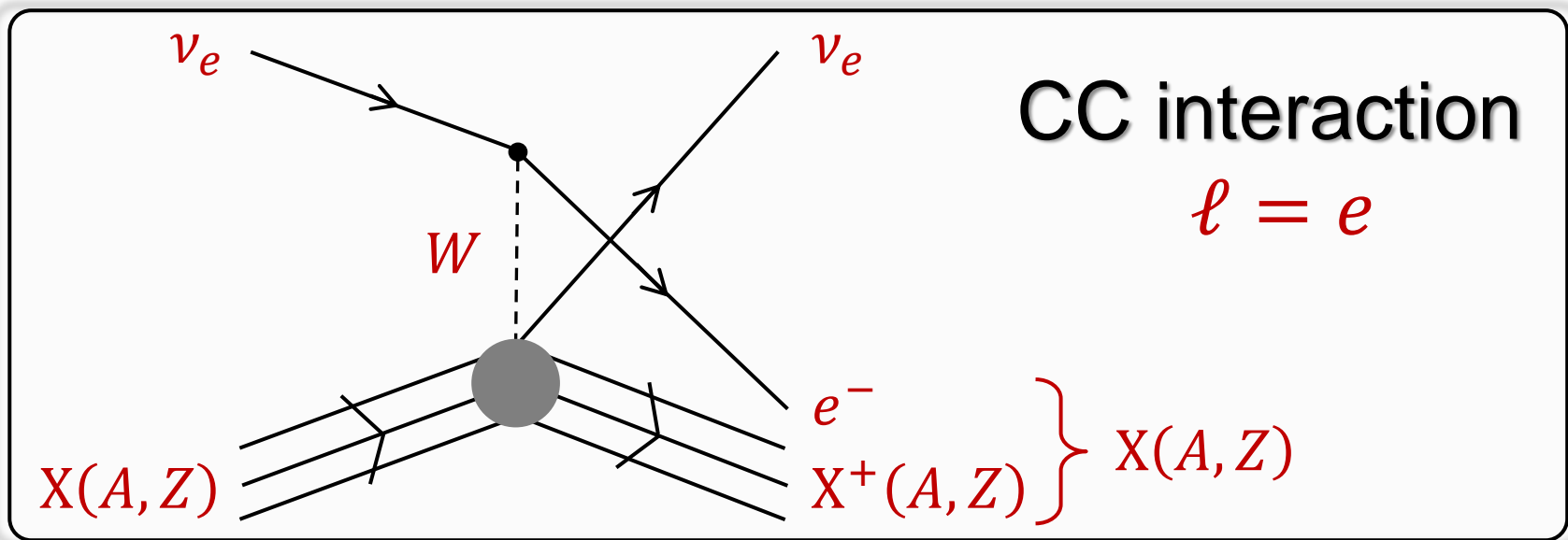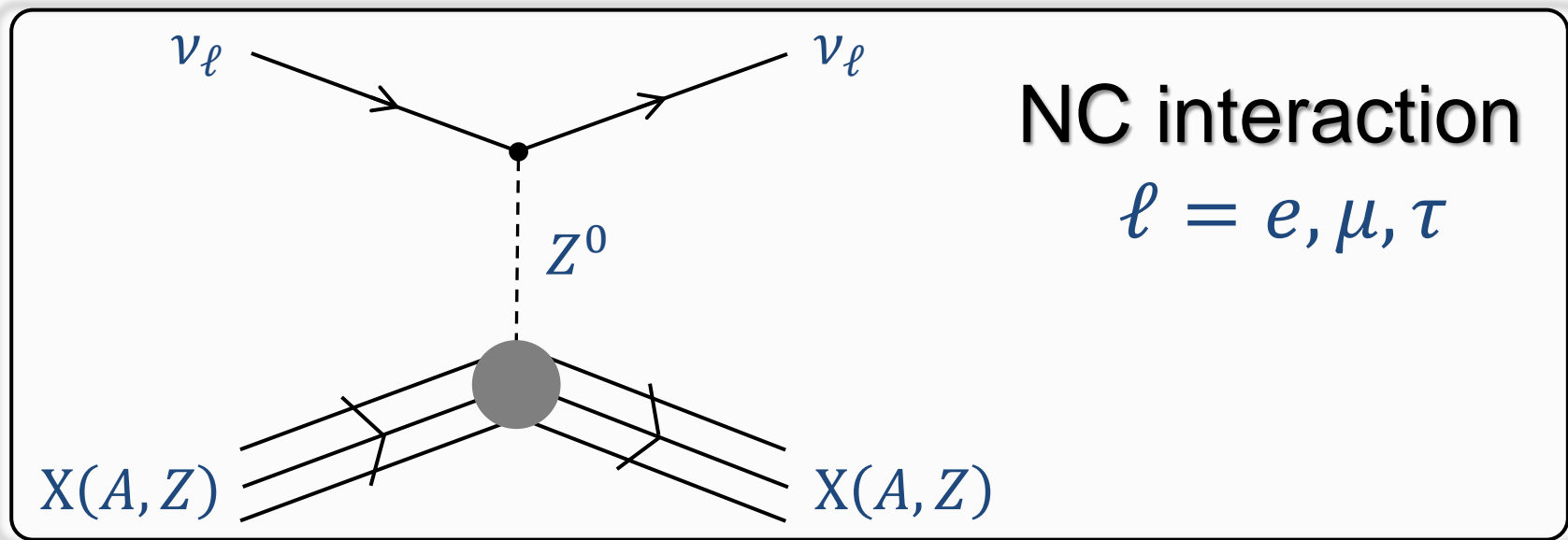# CEνAS: Coherent Elastic Neutrino-Atom Scattering

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.

Elastic neutrino-atom scattering in SM

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

CC interaction
$$\ell = e$$

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*
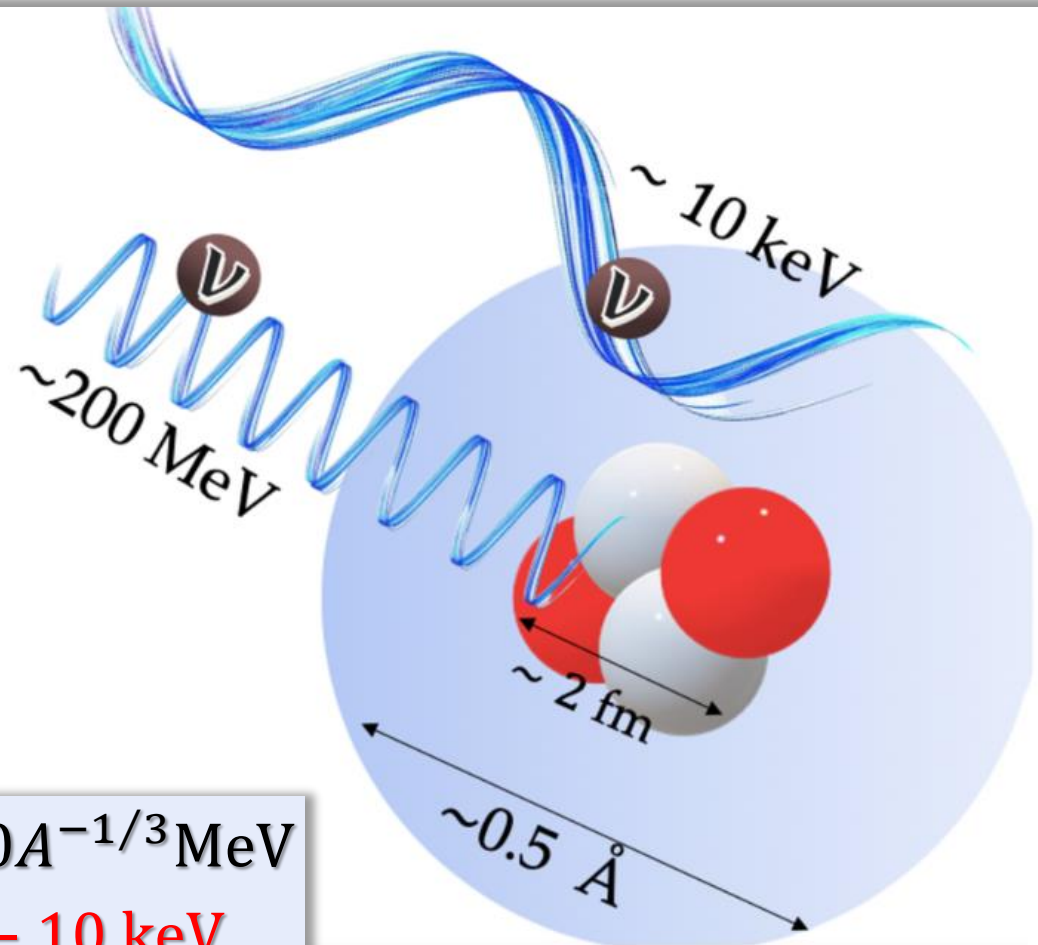*observed by D. Akimov et al. (COHERENT Collab.), Science **357** (2017) 1123*

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: $E_\nu \lesssim 1/R_{\mathrm{nuc}} \sim 200 A^{-1/3} \mathrm{MeV}$
CEνAS: $E_\nu \lesssim 1/R_{\mathrm{atom}} \sim 1 - 10 \ \mathrm{keV}$

[C. Bonifazi, Neutrino 2022]

Tritium neutrinos

$$^3\text{H} \rightarrow\ ^3\text{He} + e^- + \bar{\nu}_e$$
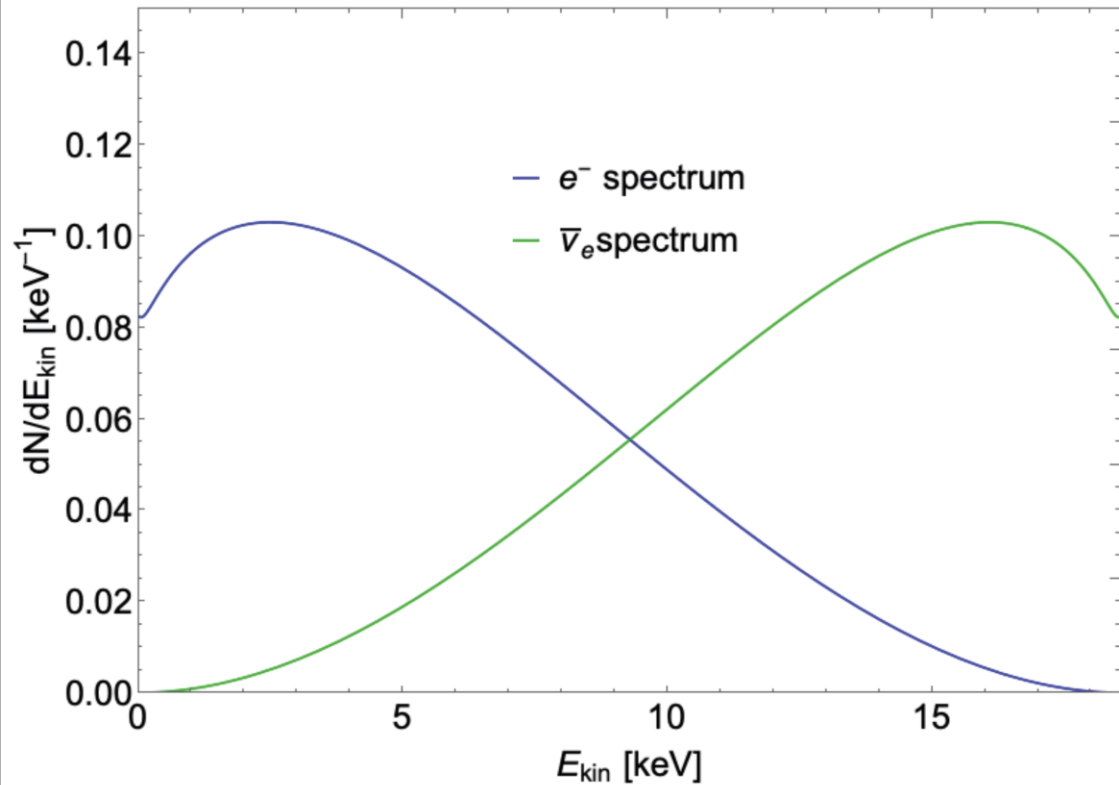
$$Q = 18.6 \text{ keV}$$

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

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

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
$m \approx A\,\text{GeV}$ is atomic mass

If $E_\nu \sim 10\,\text{keV}$: $\quad T_R \lesssim \dfrac{200}{A}\,\text{meV}$

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

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

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
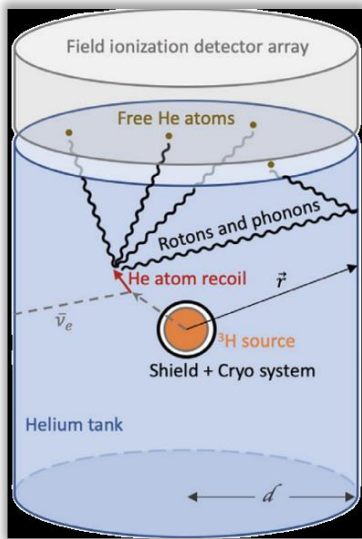
*S.A. Hertel et al., PRD **100** (2019) 092007*
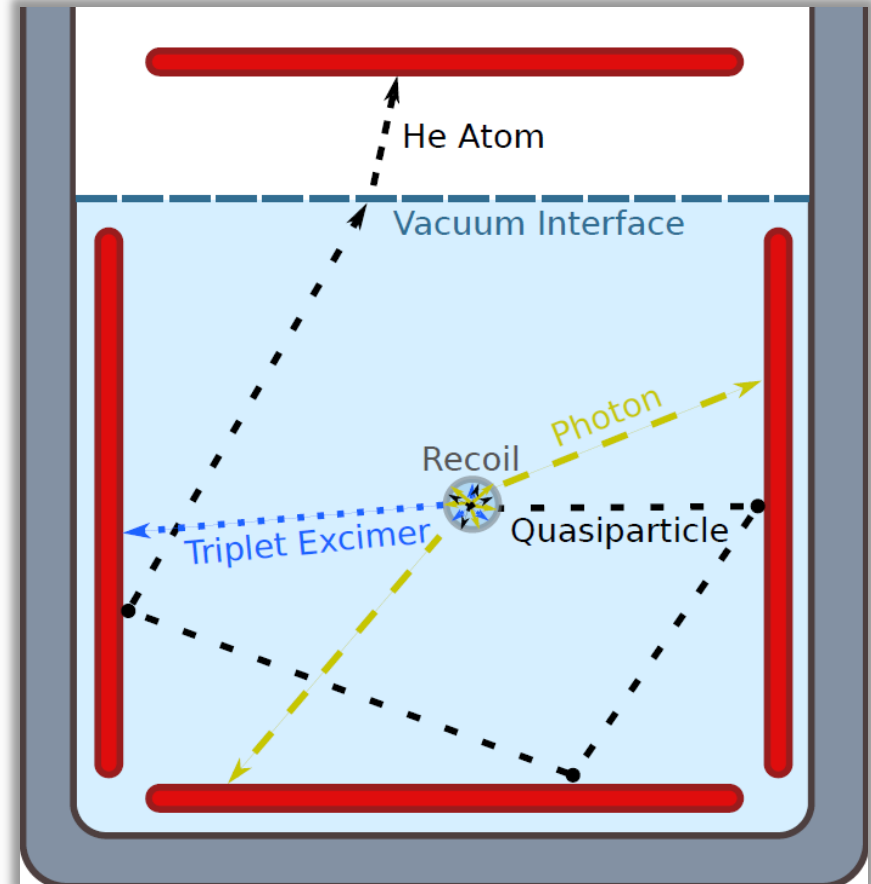
Fig. Simplified detector layout
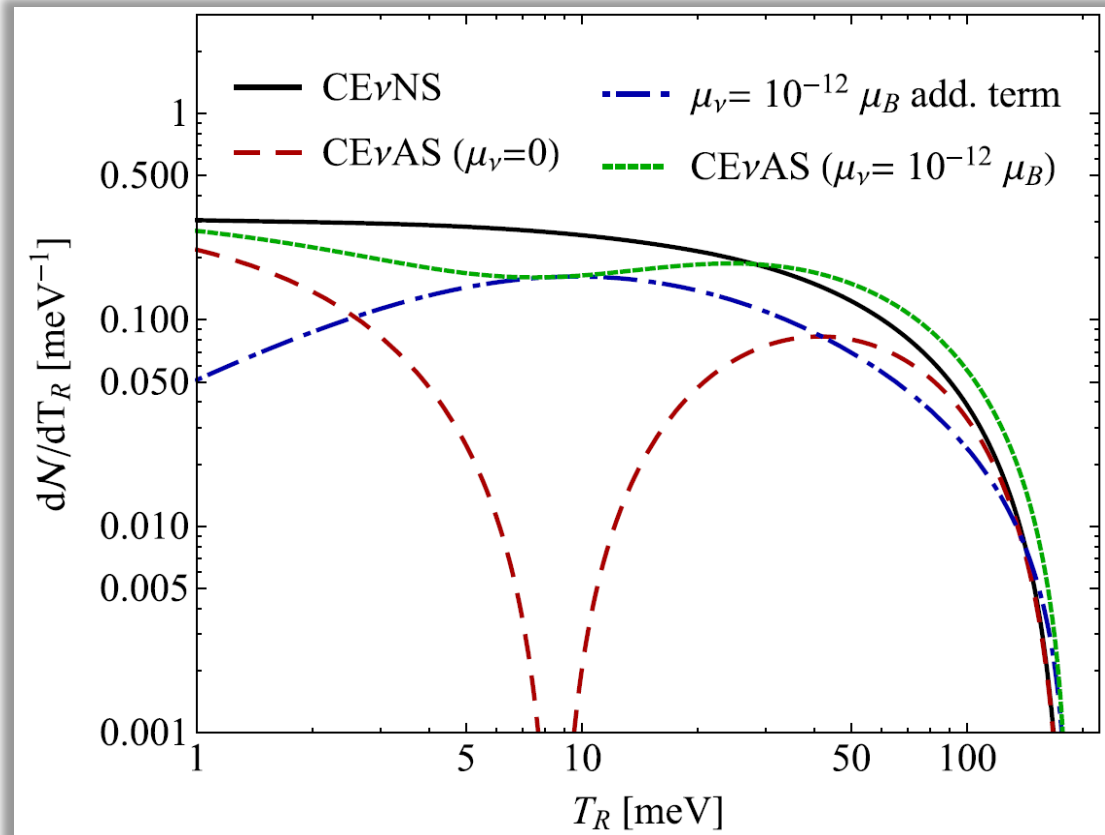
He-4 atomic-recoil spectrum with tritium $\bar{\nu}_e$

$$\frac{d\sigma_{\text{SM}}}{dT_R} = \frac{G_F^2 m}{\pi} \left[Z\left(\frac{1}{2} - 2\sin^2\theta_W\right) - \frac{1}{2}N + Z\left(\frac{1}{2} + 2\sin^2\theta_W\right)F_{\text{el}}(q^2) \right]^2 \left(1 - \frac{mT_R}{2E_\nu^2}\right)$$
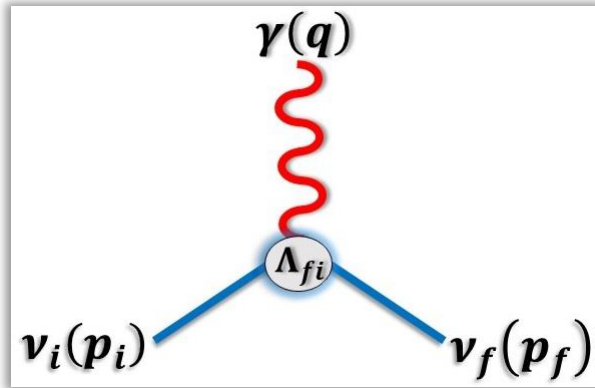
$$\frac{d\sigma_{\mu\nu}}{dT_R} = \frac{\pi\alpha^2 Z^2}{m_e^2} |\mu_\nu|^2 \left(\frac{1}{T_R} - \frac{1}{E_\nu}\right) [1 - F_{\text{el}}(q^2)]^2 \qquad \text{with} \quad q^2 = 2mT_R$$

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

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*
Talk by Alexander Studenikin, May 23 at 18:05

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

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

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

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

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

$m_\nu < 0.8$ eV at 90% CL
*M. Aker et al. (The KATRIN Collaboration), Nature Physics **18** (2022) 160*

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*

$\mu_\nu < 6.3 \times 10^{-12}\, \mu_B$

reactor neutrinos (GEMMA)

*A. Beda et al., Adv. High Energy Phys. **2012** (2012) 350150*
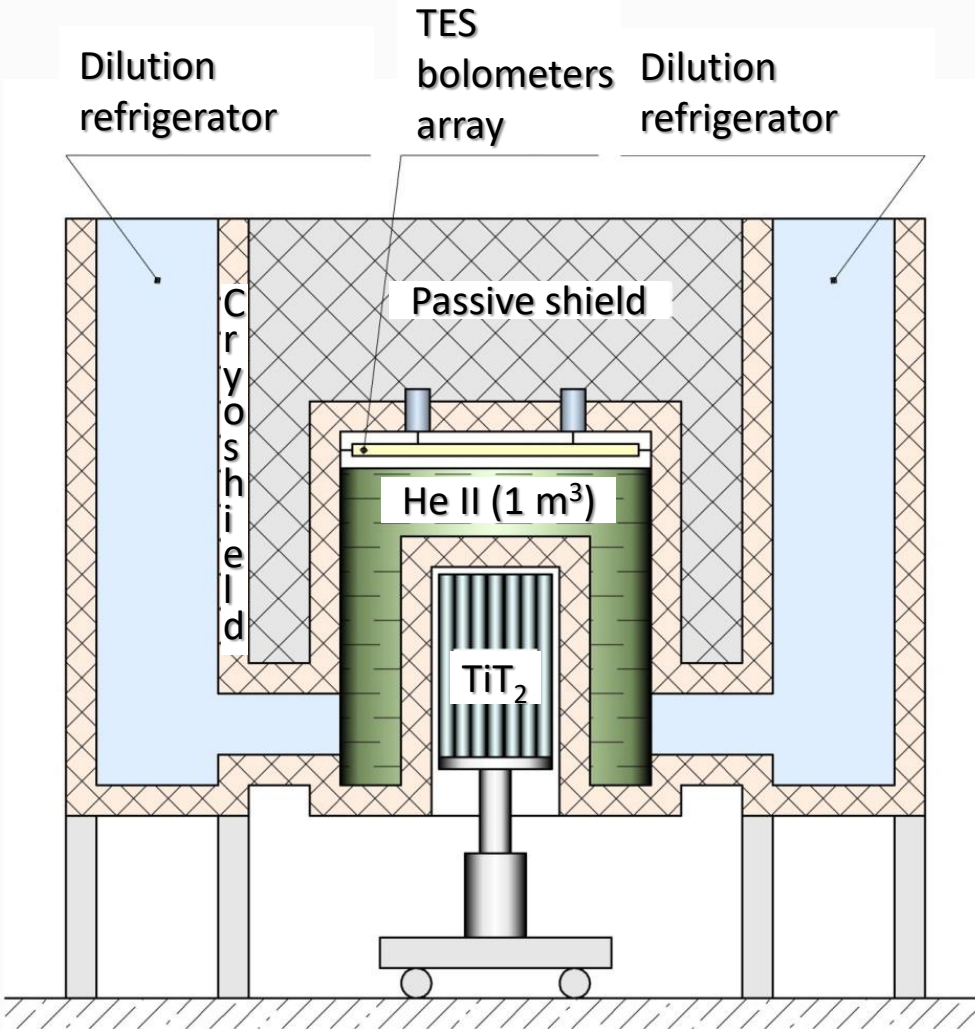
$\mu_{\nu_e} < 2.9 \times 10^{-11}\, \mu_B$

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*

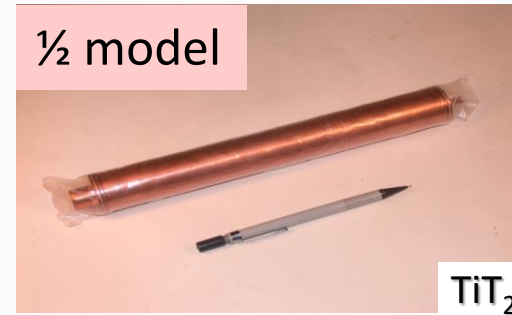$\mu_\nu < (1.2{-}2.6) \times 10^{-12}\, \mu_B$

CEνNS bounds

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

$\mu_{\nu_e} < 3.8 \times 10^{-9}\, \mu_B$

$\mu_{\nu_\mu} < 2.6 \times 10^{-9}\, \mu_B$

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

Dilution refrigerator

TES bolometers array

Dilution refrigerator

Cryoshield

Passive shield

He II (1 m^3)

TiT$_2$

Tritium neutrino source (1-4 kg, 10-40 MCi)

- Tubular copper elements with TiT$_2$

½ model

TiT$_2$

Helium II detector (1000 L)

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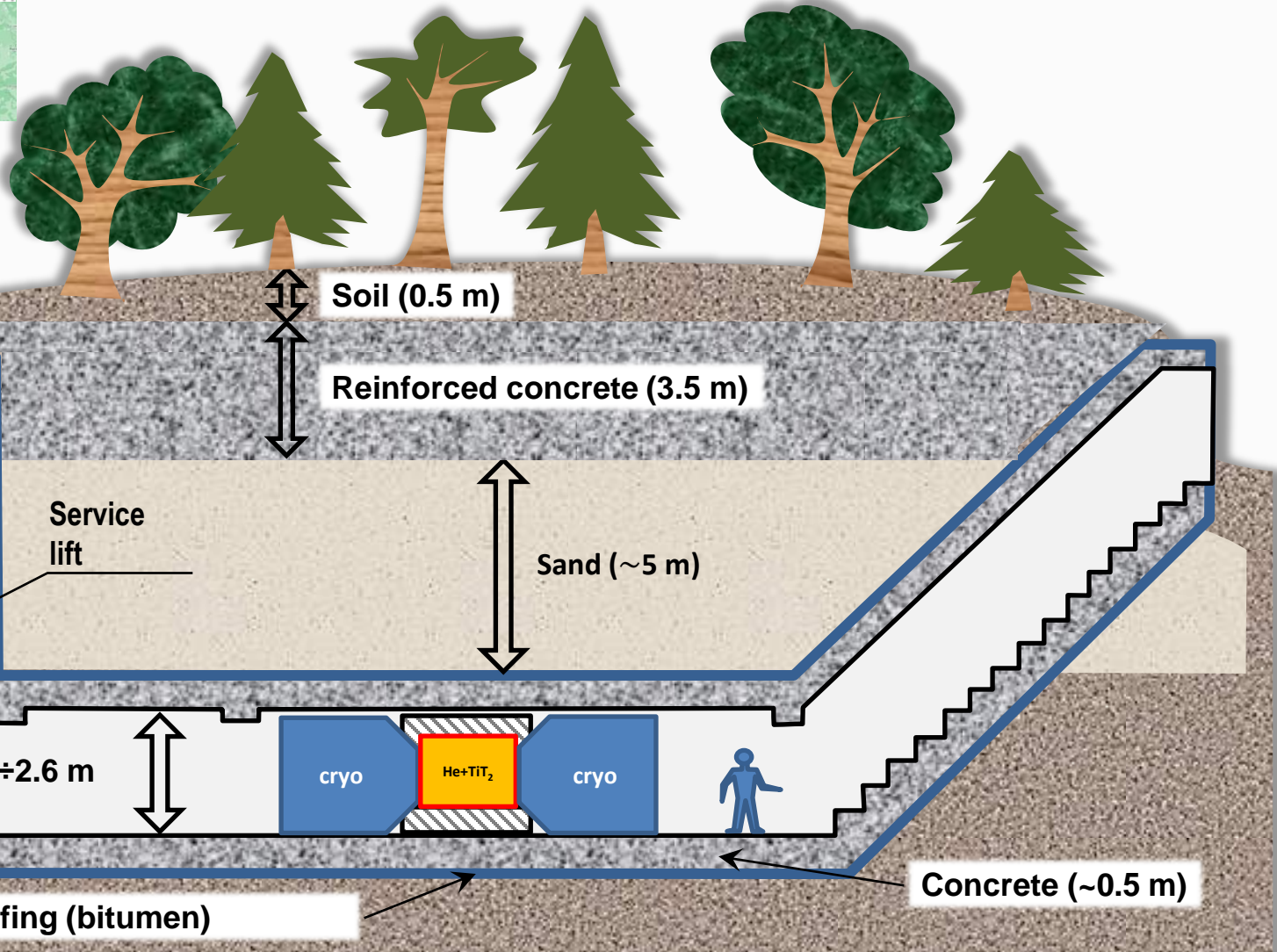- Array of 1000 TESs (transition edge sensors)
- 1000-channel SQUID readout

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: $\mu_\nu \sim$ **(2-4)x10^{-13}** μ_B at 90% C.L.

Moscow

Nizhny Novgorod

522 km

207 km

Sarov

Soil (0.5 m)

Reinforced concrete (3.5 m)

Service lift

Sand (~5 m)

2.2÷2.6 m

cryo

He+TiT$_2$

cryo

Concrete (~0.5 m)

Waterproofing (bitumen)

The overburden of ~18 m.w.e. (~7 m of standard rock) stops the soft and hadronic components of cosmic radiation

Discrimination of background events

General view of the cryostat

Detector volume

Tritium source

GM cryocooler

Gas shock absorber

~1000 Al-foil cells
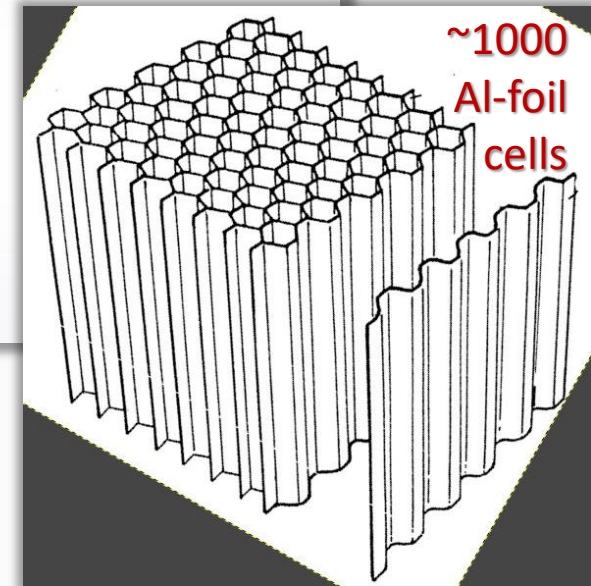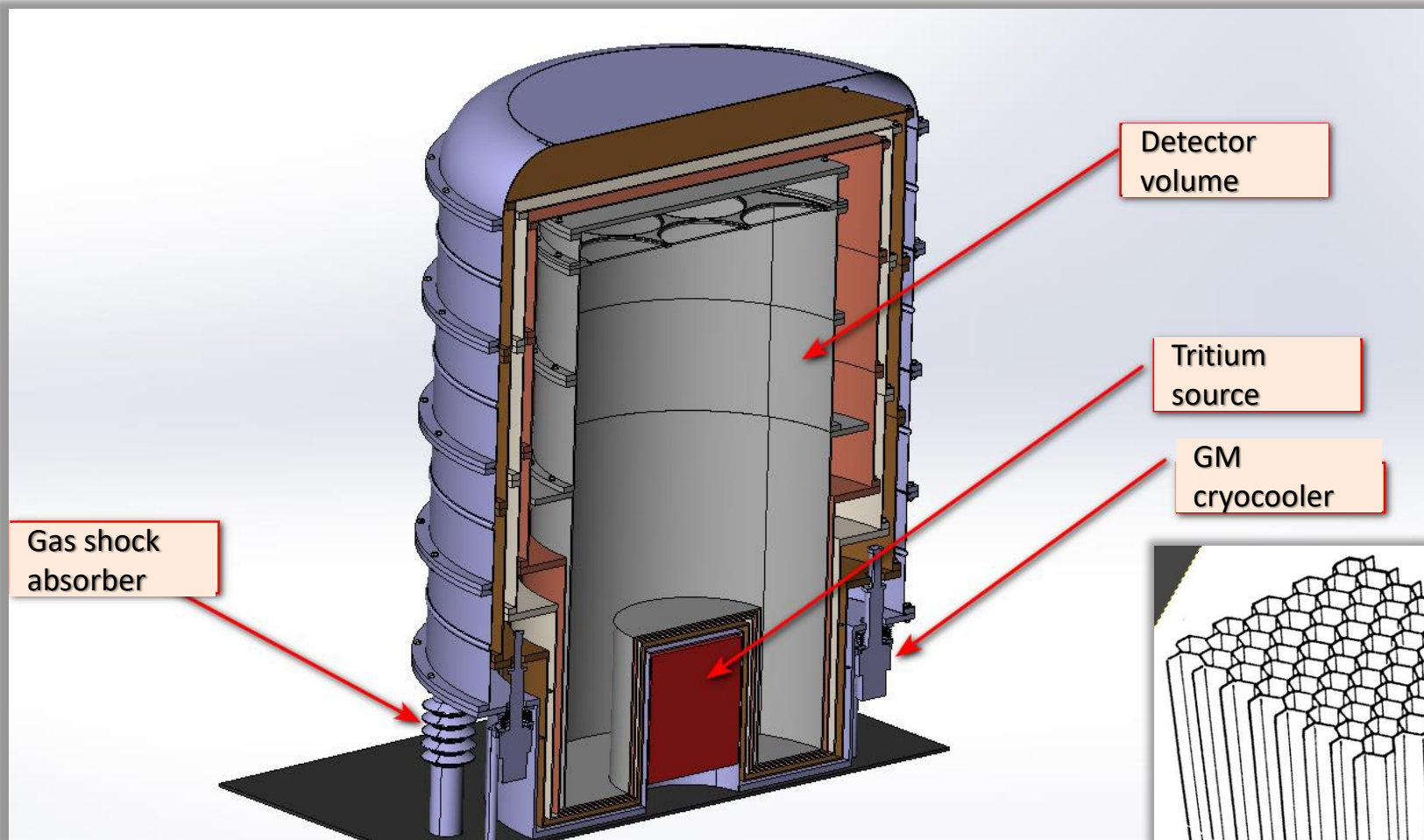
Segmentation of the He detector is the key to background discrimination

Atomic ionization channel

When the energy transfer *T* exceeds the maximal atomic recoil energy

$$T > T_R^{\max} = \frac{2E_\nu^2}{m}$$

the elastic neutrino-atom scattering channel $\nu + \mathrm{X} \longrightarrow \mathrm{X} + \nu$ **is closed**

Open channels:

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

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

$\mathcal{E}_\mathrm{X}$ 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)

Ionizing neutrino-atom interactions
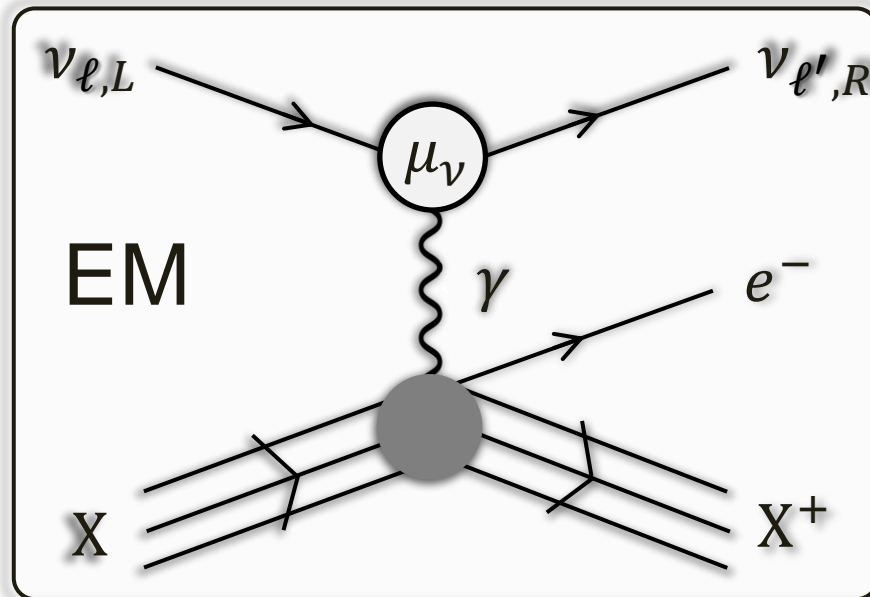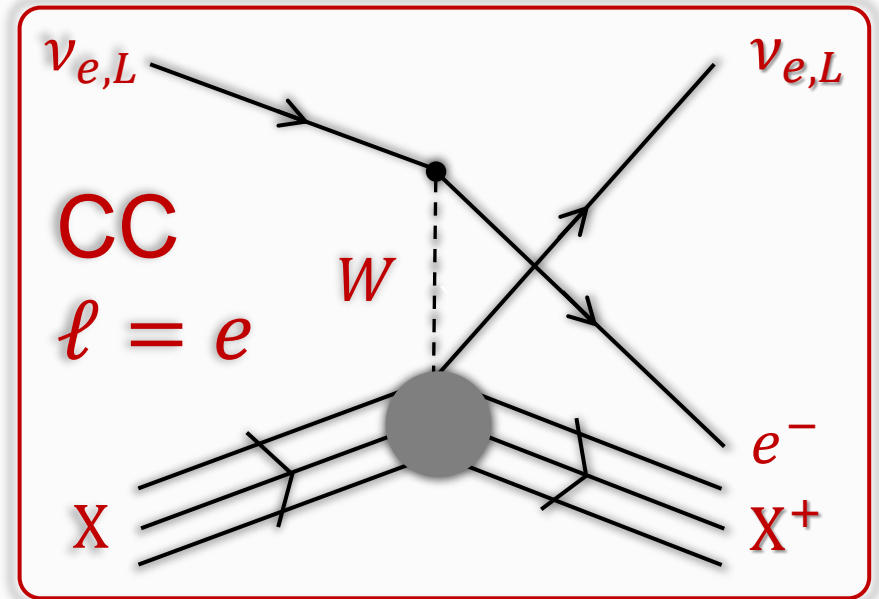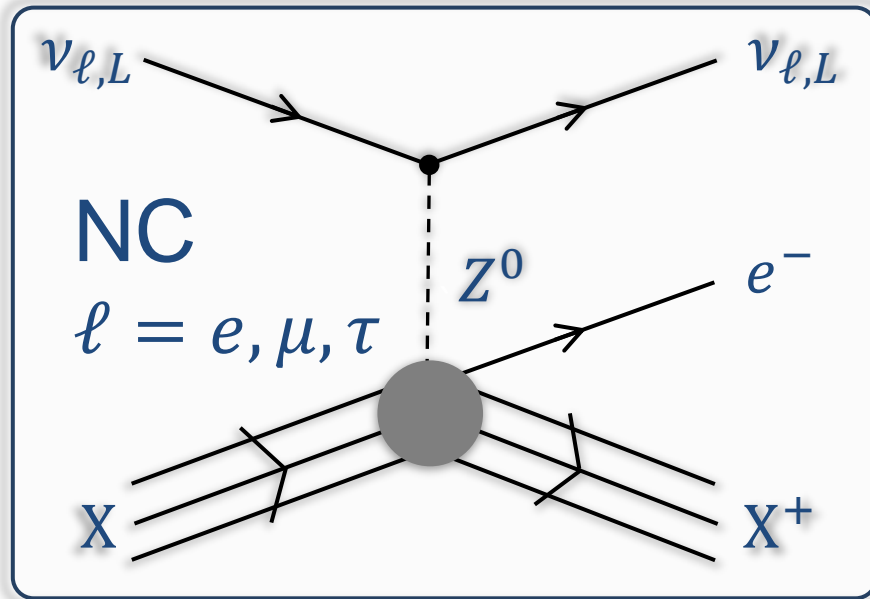
Unlike the SM weak NC and CC interactions, the μ_ν interaction flips the neutrino helicity ($L \rightarrow R$) and can change the neutrino flavor if the transition magnetic moment ($\ell \neq \ell'$) is nonzero.

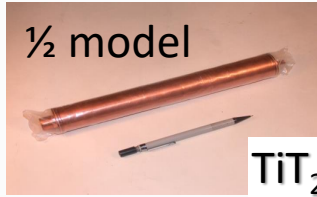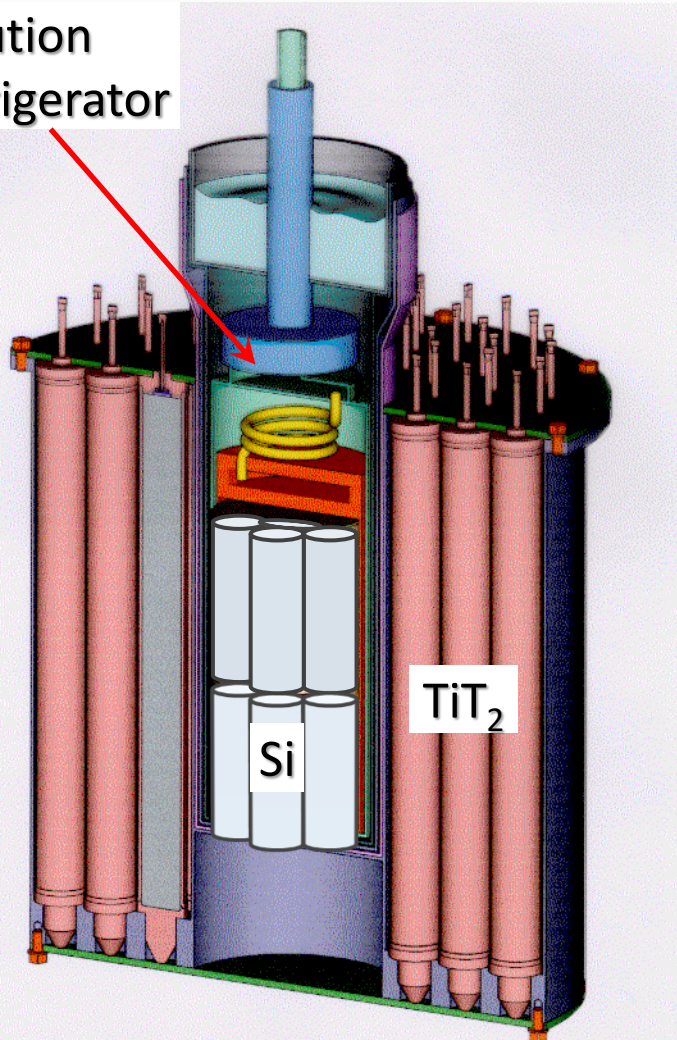# Electron-recoil spectrum for tritium $\bar{\nu}_e$ on Si

SM predicts a flat spectrum at small T, and the μ_ν contribution $\propto \dfrac{1}{T}$
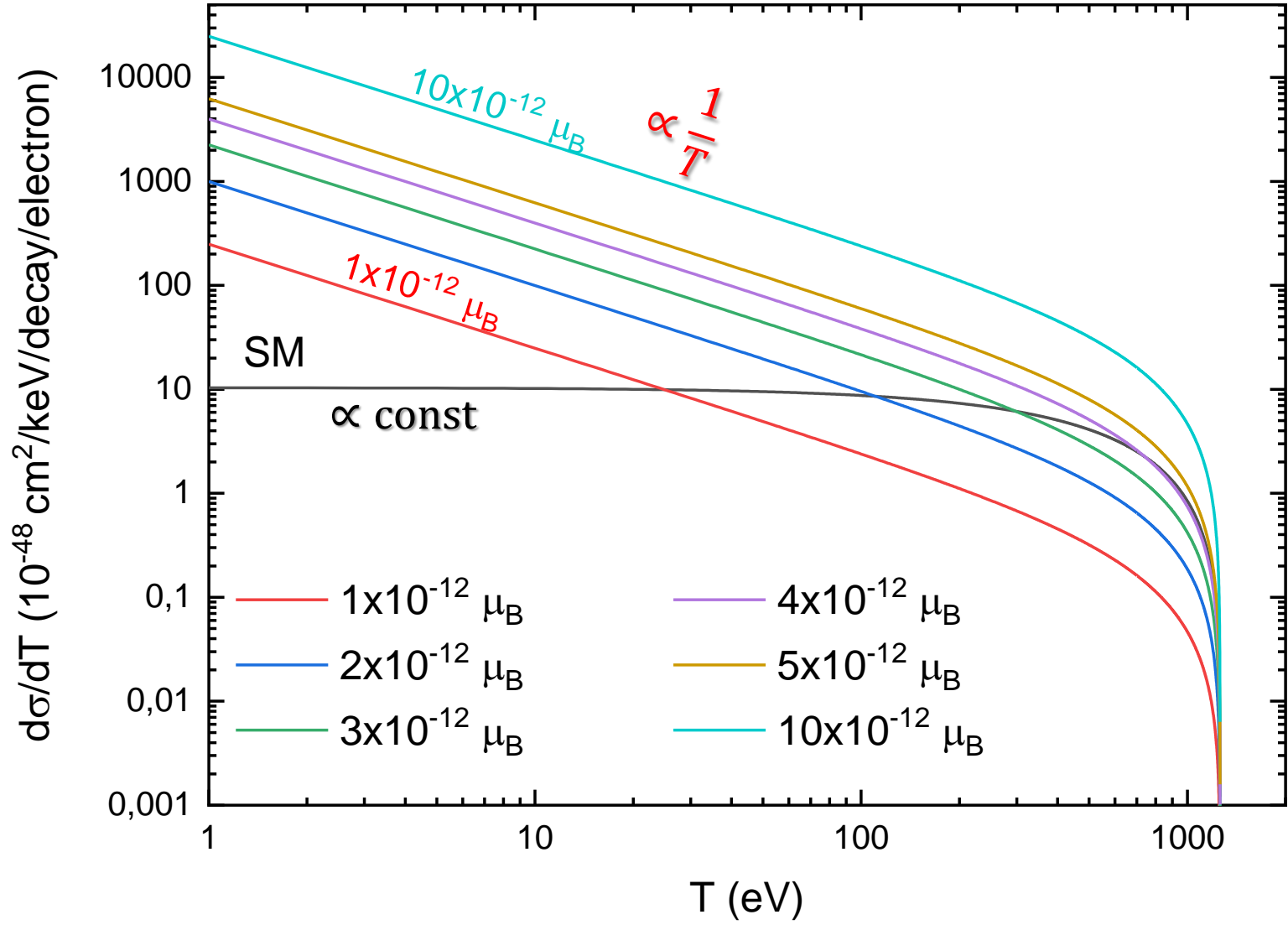
The detector's energy threshold needs to be as low as possible

Si detector concept

Dilution refrigerator

TiT$_2$

Si

½ model

TiT$_2$

Tritium neutrino source (1-4 kg)
- tubular copper elements with TiT$_2$

Si

Silicon cryodetectors (T=10-50 mK)
14×125 cm³, 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: **30 for 1 kg of T$_2$** and **120 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


½ model
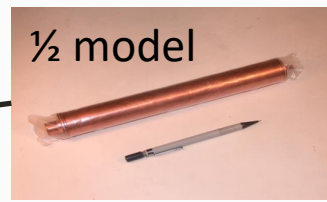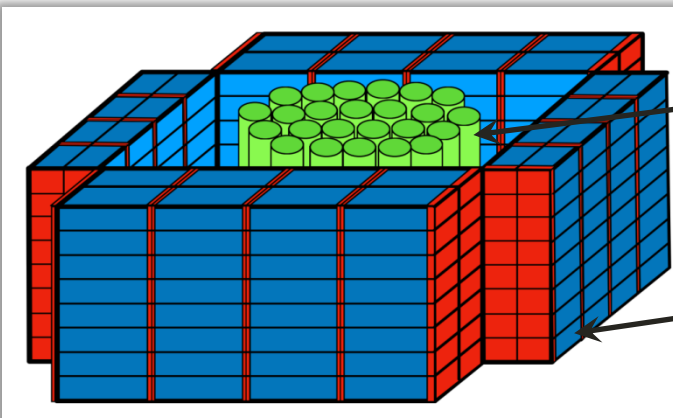
Tritium neutrino source (1-4 kg)

Tubular copper elements with TiT$_2$

15x15x50 mm^3 SrI$_2$(Eu) crystals at T from -60 to -40 °C, total mass is M=14 kg

- SiPM readout

  (two SiPMs per each crystal)

- Light collection at a level of

  50 photoelectrons/keV

- Energy threshold is

  E$_{th}$~100 eV

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

Magnetic and Weak ($\bar{\nu}$-e) cross section
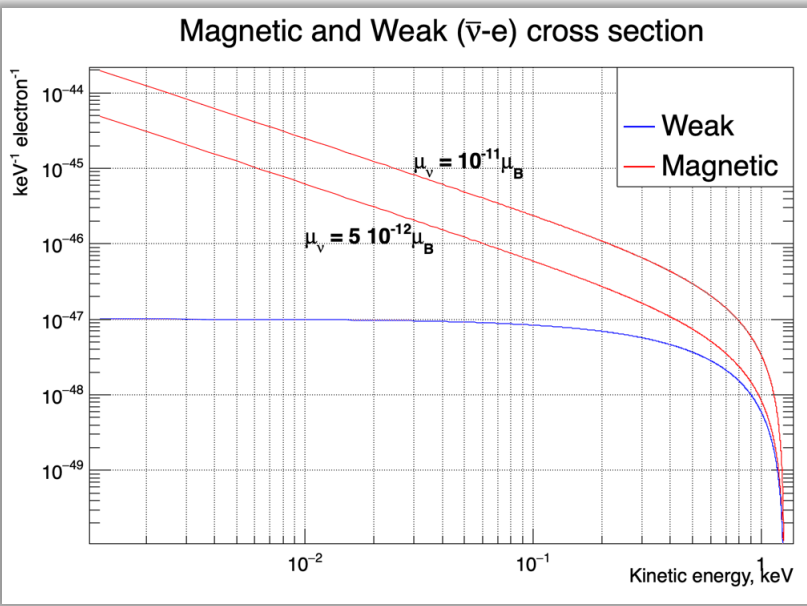
Expected results after 1 year of data collection

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:

μ_ν~(1.5-2)x10^{-12} μ_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**)

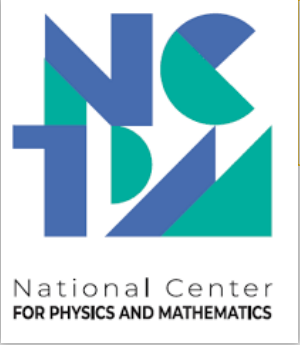**A 1000-L He II detector** is being developed (to be **ready by 2027**)
- observation of **CEνAS (2032)**
- sensitivity to $\mu_\nu \sim$**(2-4)x10^{-13} μ_B (2032)**

A 4-kg Si detector is being developed (to be **ready by 2026**)
- sensitivity to $\mu_\nu \sim$**(1-1.5)x10^{-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)x10^{-12} μ_B (2026)**

The SATURNE Collaboration

National Center FOR PHYSICS AND MATHEMATICS

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

PRODUCTION ASSOCIATION MAYAK

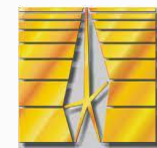NIZHNY NOVGOROD STATE TECHNICAL UNIVERSITY N.A. R.E. ALEKSEEV

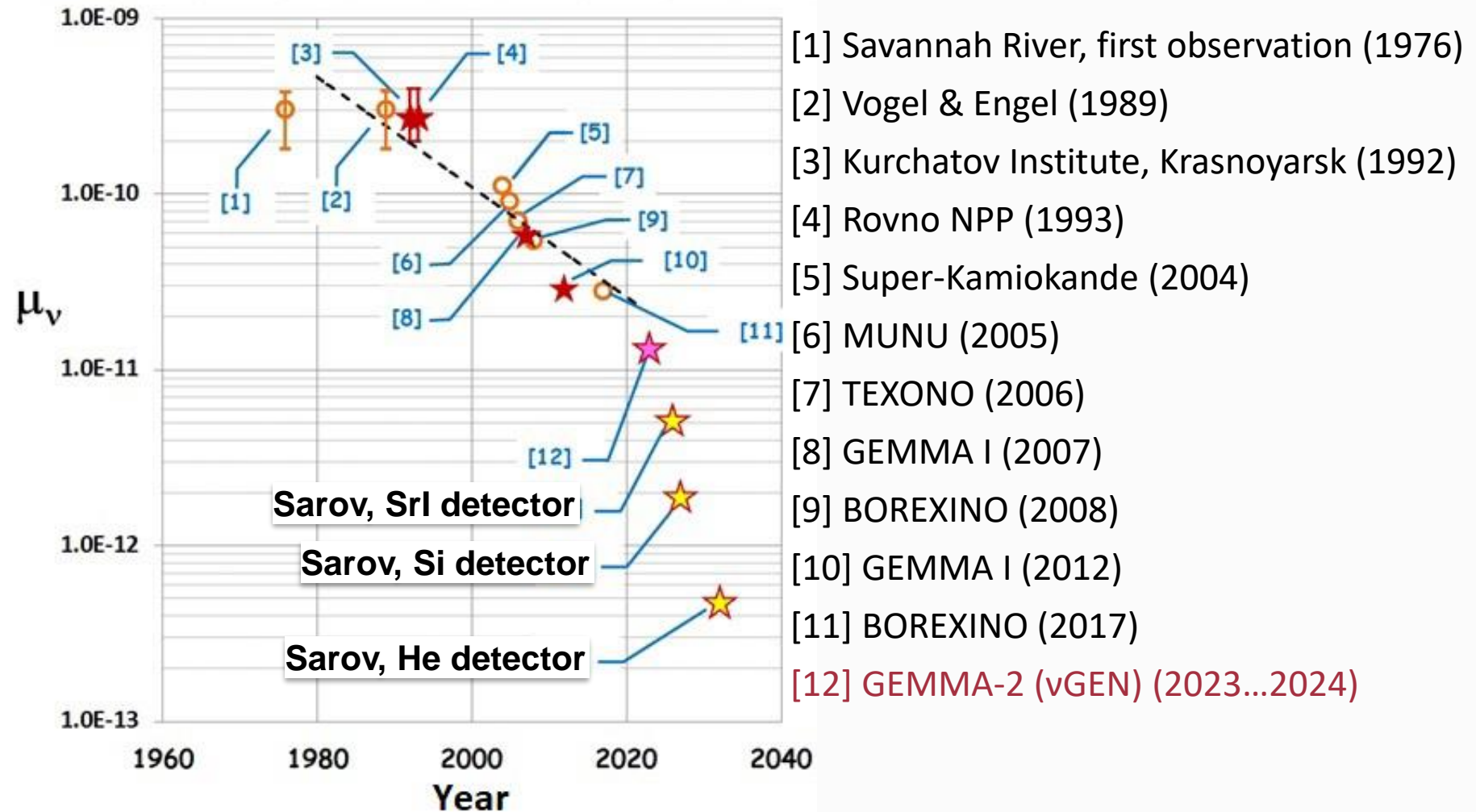LOMONOSOV MOSCOW STATE UNIVERSITY

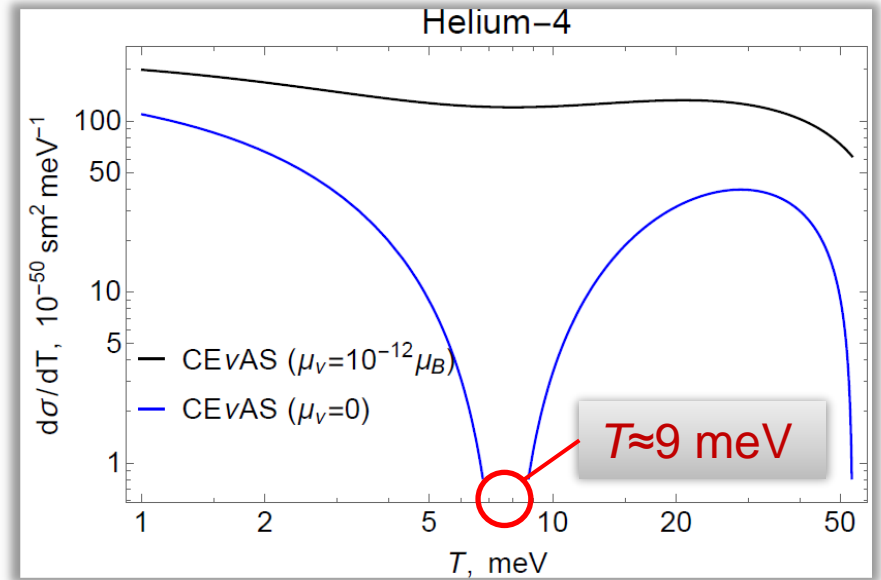LOBACHEVSKY UNIVERSITY

JOINT INSTITUTE FOR NUCLEAR RESEARCH
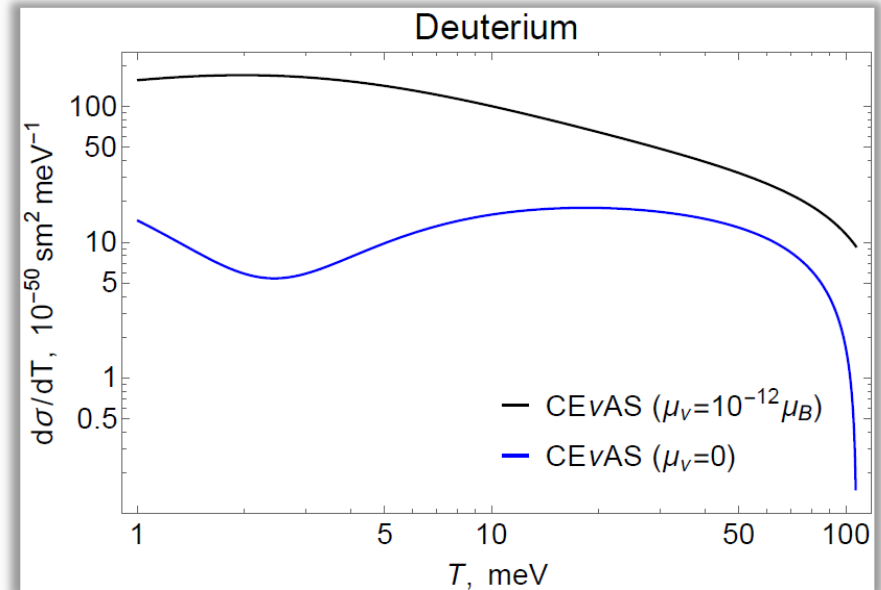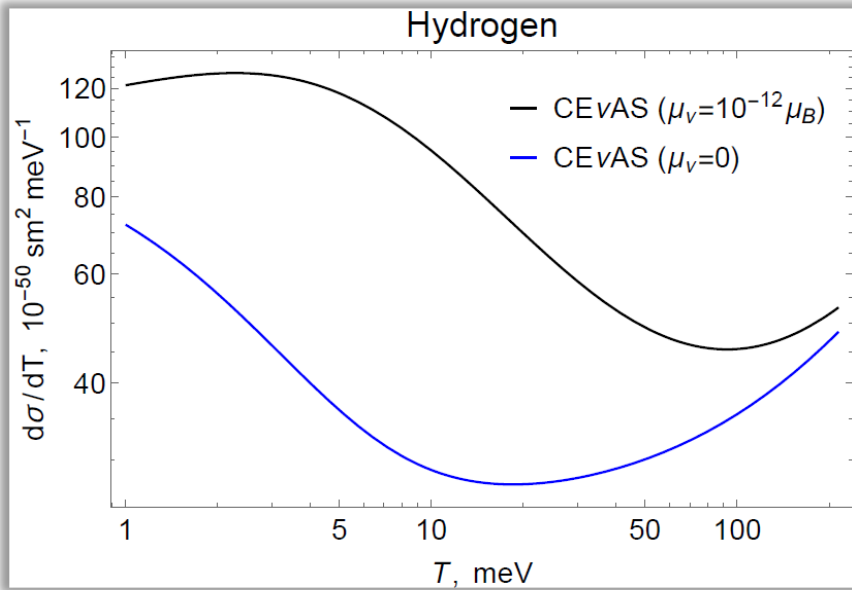
IPM RAS

Ioffe Physical-Technical Institute

Progress of experimental sensitivity to μ_ν

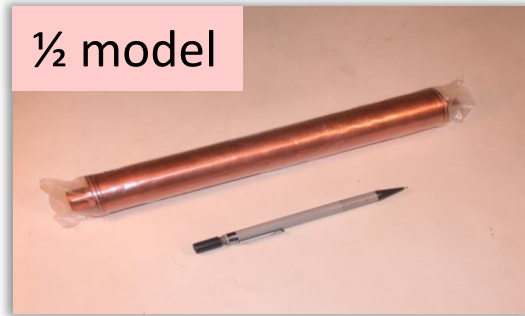

[1] Savannah River, first observation (1976)

[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 (vGEN) (2023...2024)

Thank you for your attention!

Backup slides

CEνAS cross sections for $\bar{\nu}_e$ with E_ν=10 keV

*Donchenko, Kouzakov, Studenikin, JETP Lett. **117**, 879 (2023)*

Tritium neutrino source (TNS)

½ model

Construction of a tubular tritium element
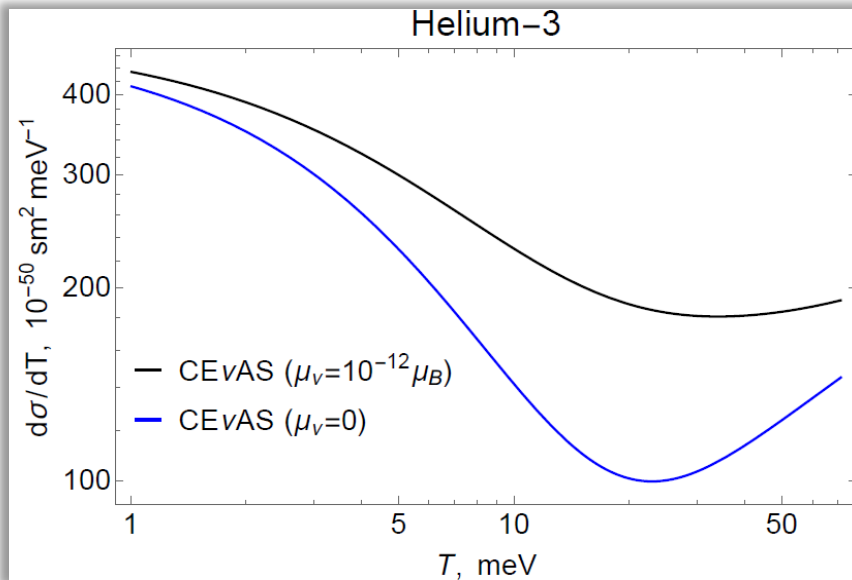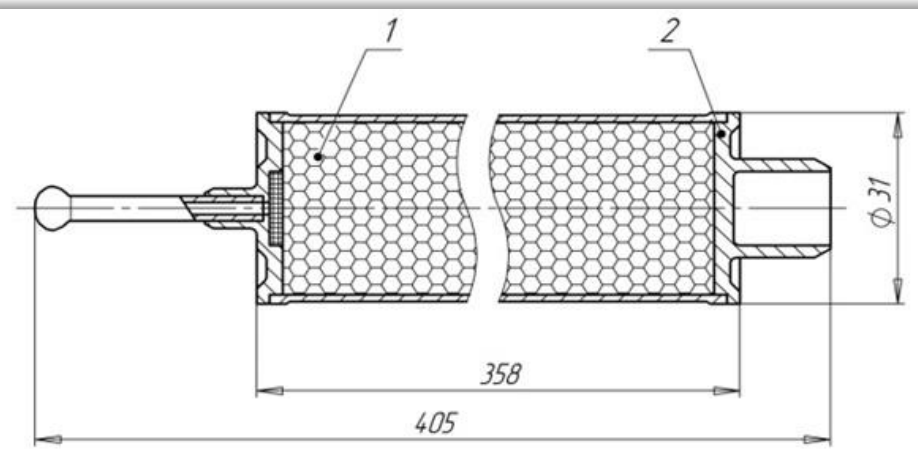
1 – titanium tritide; 2 – body

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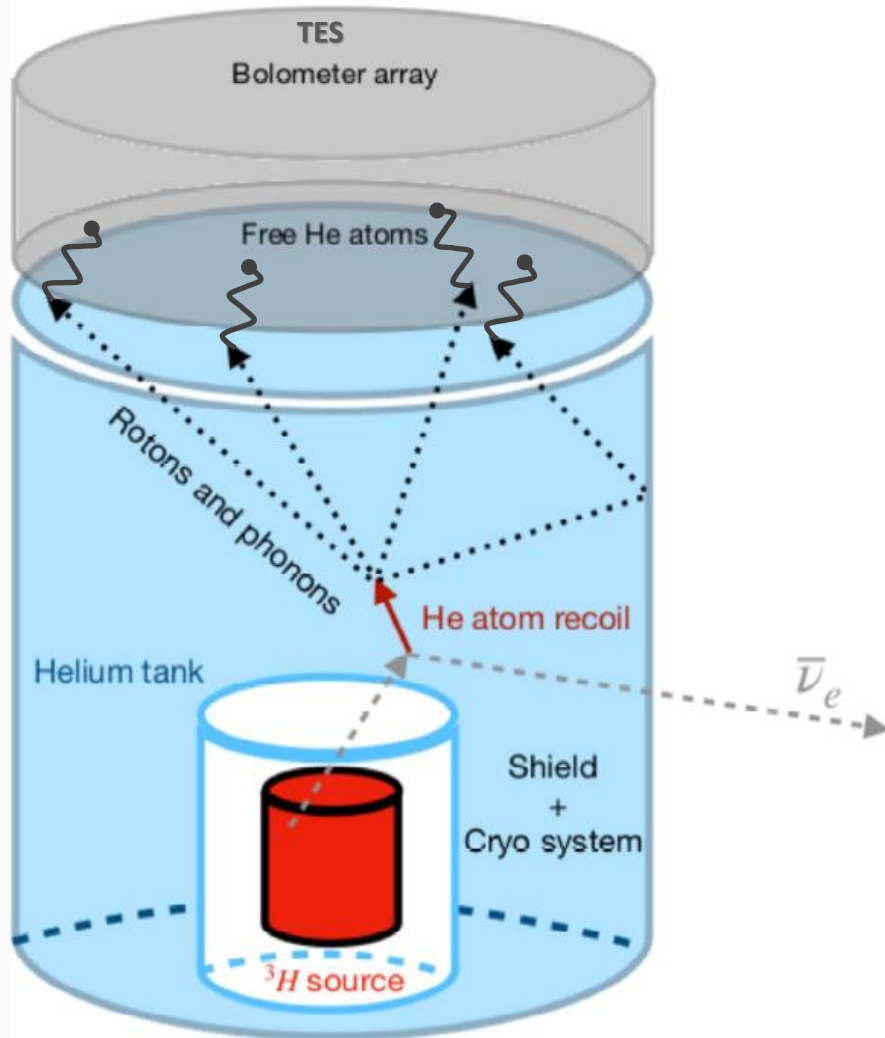
TNS is a set of tritium elements in which tritium is in a chemically bound state on titanium.

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.

Detection method to study CEνAS

Tritium neutrino

⬇

Elastic neutrino-atom scattering

⬇

He atom recoil
(1-185 meV)

⬇

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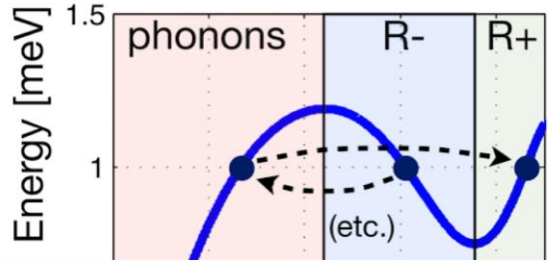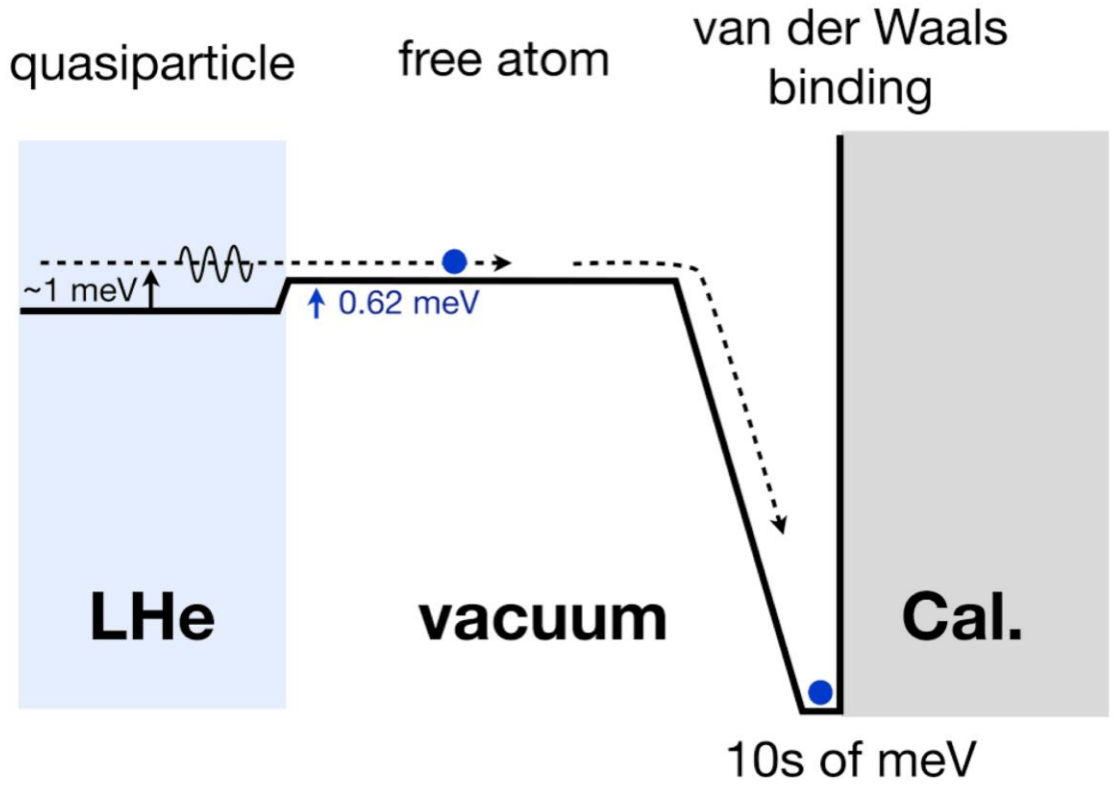(0.7-1.2 meV per q. p.)
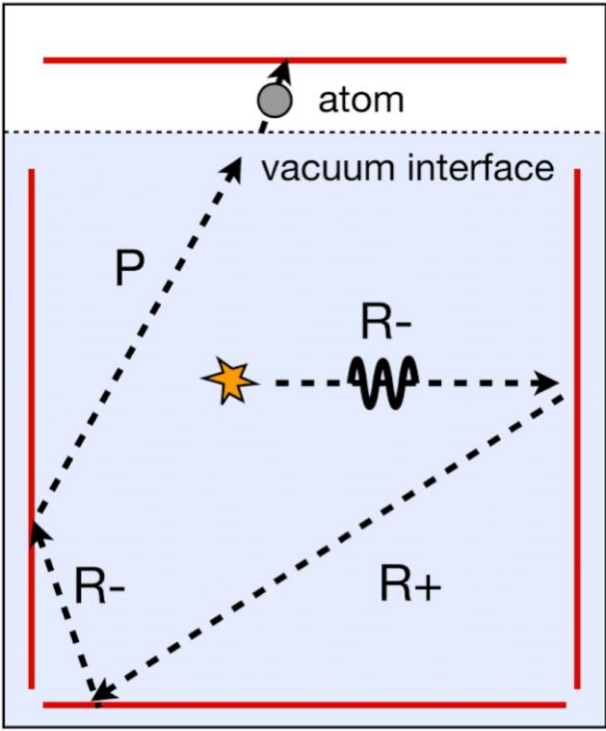
⬇

Quantum evaporation
(0.6 meV per atom)

⬇

Adsorption onto TES
(6-50 meV per adatom)

⬇

Signal

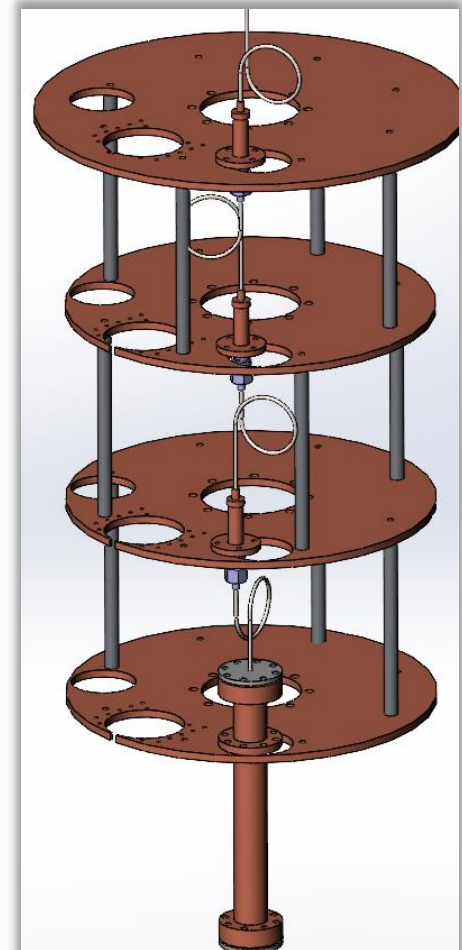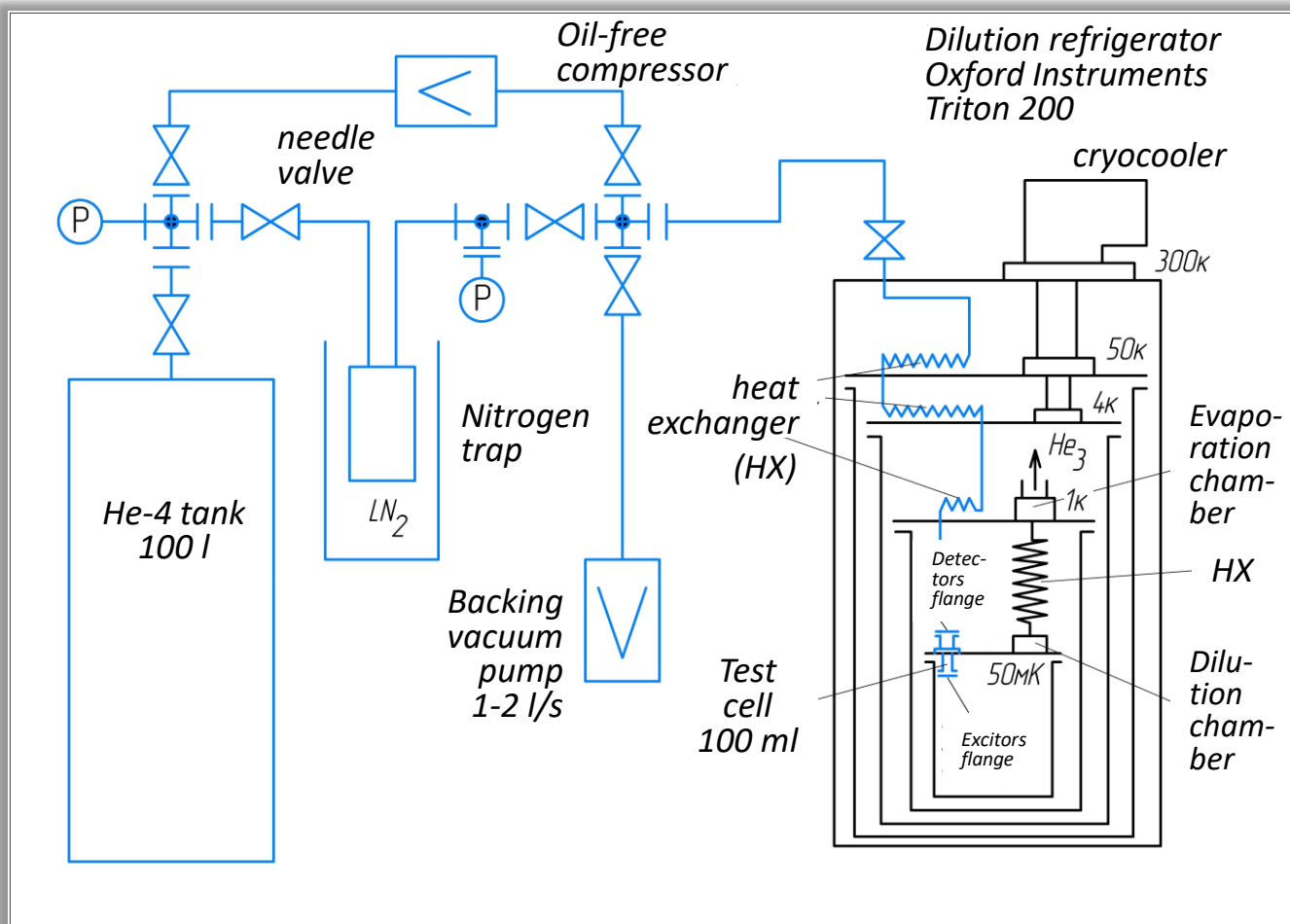# Quasiparticle readout: Quantum evaporation of He atom

1 meV roton energy becomes up to 40 meV observable
- **x** 40 amplification
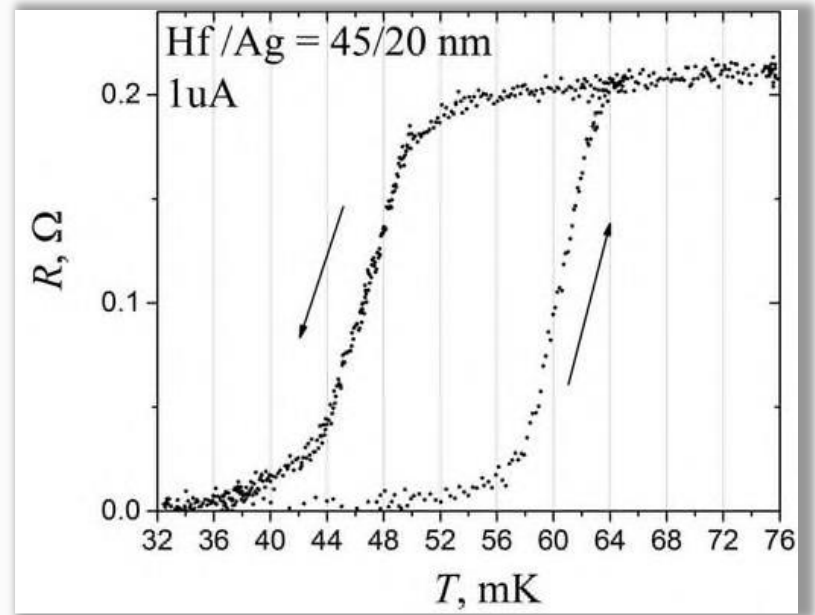- Graphene-fluorine surface
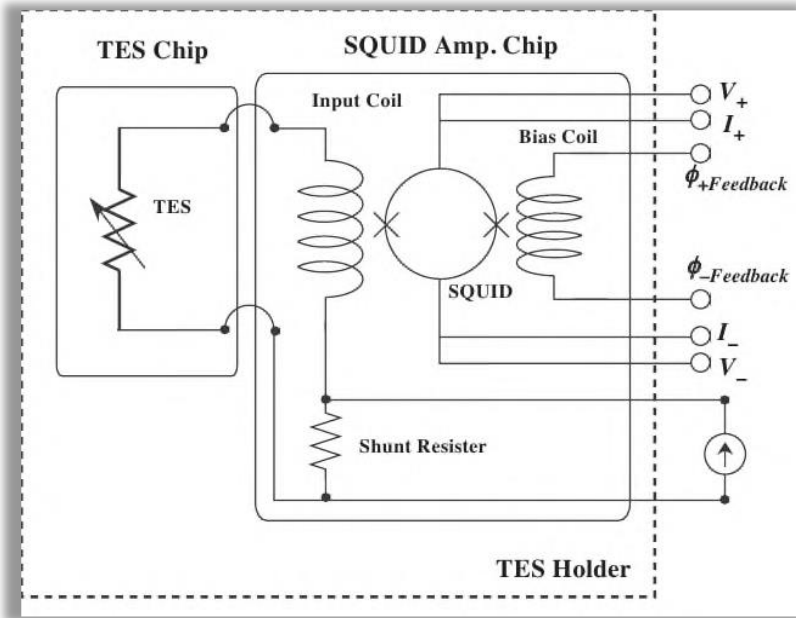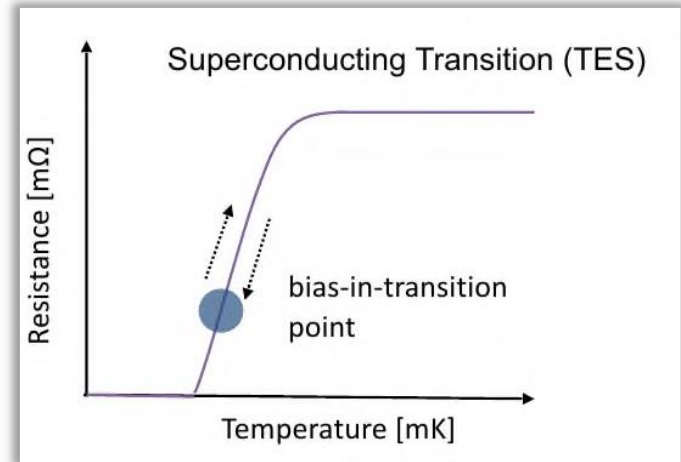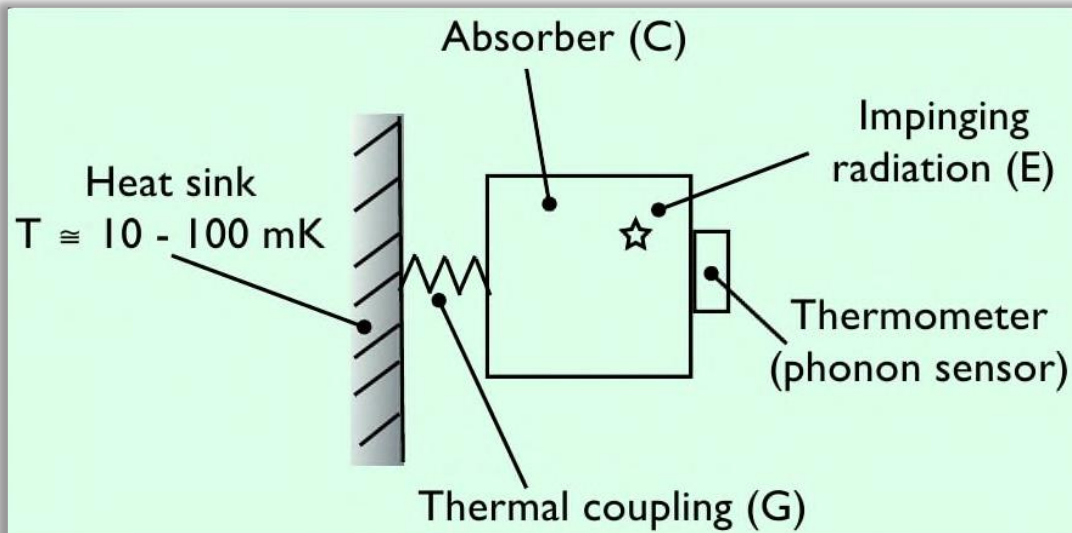
[D. McKinsey, SNOLAB Workshop 2021]

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

Transition edge sensor

Absorber (C)

Impinging radiation (E)

Heat sink
T ≅ 10 - 100 mK

Thermometer (phonon sensor)

Thermal coupling (G)

Superconducting Transition (TES)

Resistance [mΩ]

bias-in-transition point

Temperature [mK]

TES Chip

SQUID Amp. Chip

Input Coil

Bias Coil

V_+
I_+
$\phi_{+Feedback}$

TES

$\phi_{-Feedback}$

SQUID

I_-
V_-

Shunt Resister

TES Holder

Hf /Ag = 45/20 nm
1uA

R, Ω

T, mK

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 $\Delta T_c < 1$ 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$_2$O$_3$	$\alpha(\beta)$–W/Al$_2$O$_3$; 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
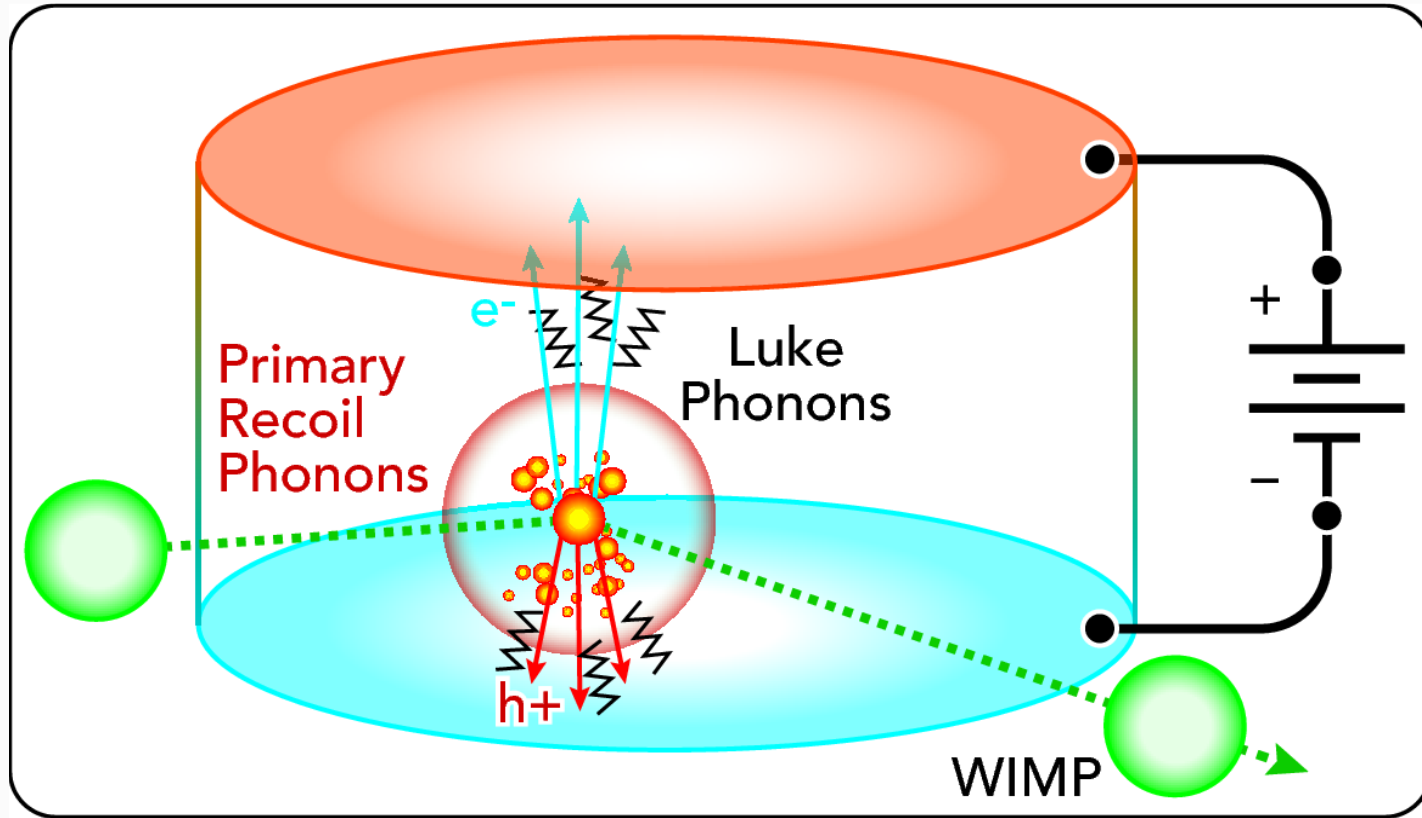
Studies of film electric properties
@ Nizhny Novgorod State Technical University
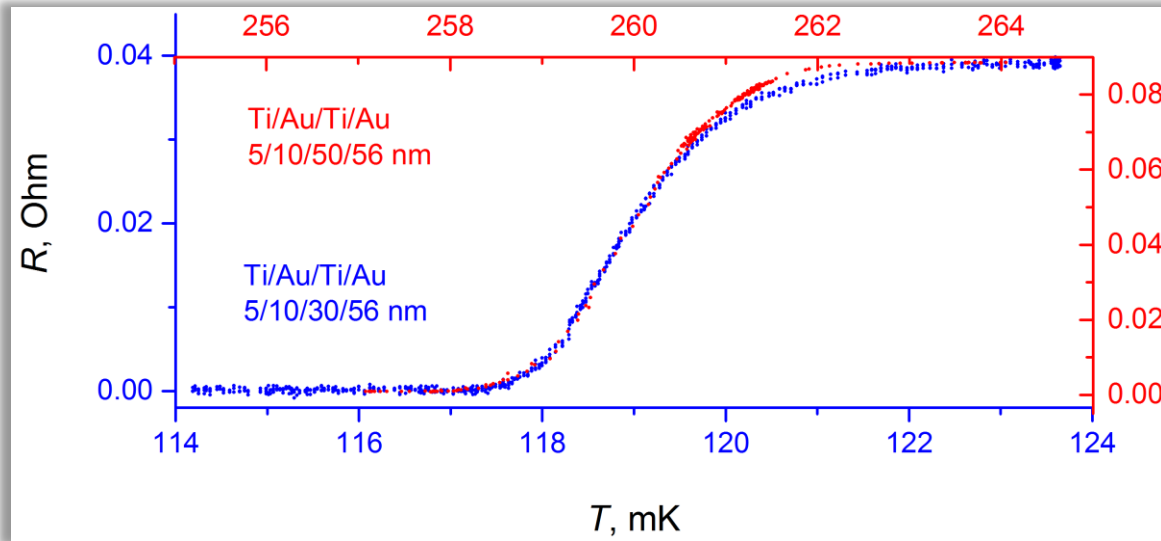
Neganov-Trofimov-Luke effect

Phonon amplification of ionization signal

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

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