Does the great neutrino mystery point to many missing particles?

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Monday 16 May 2022 at 11:00 A.M.

arXiv: 2106.07755 and 2110.14054

The Dark Sector

Many neutrino physicists feel as if they are wandering in a maze, not knowing which threads to follow and which ones might lead them astray.

- Wolfgang Pauli postulated the existence of neutrinos in 1930 to explain where energy goes during radioactive decay.
- There was no mass or electric charge in his theoretical design, which made him doubt that experiment would ever be able to detect it.
- “This is something no theoretician should ever do”, he wrote in his diary at that time.
- But in 1956, neutrinos were discovered in an experiment.

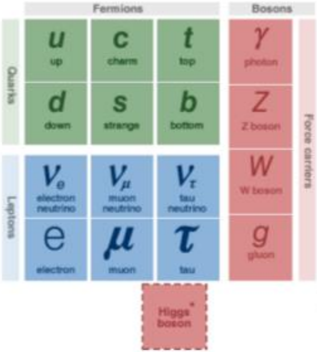
Frederick Reines and Clyde L. Cowanjun,
The Neutrino,
Nature **178***, 446–449 (1956)*

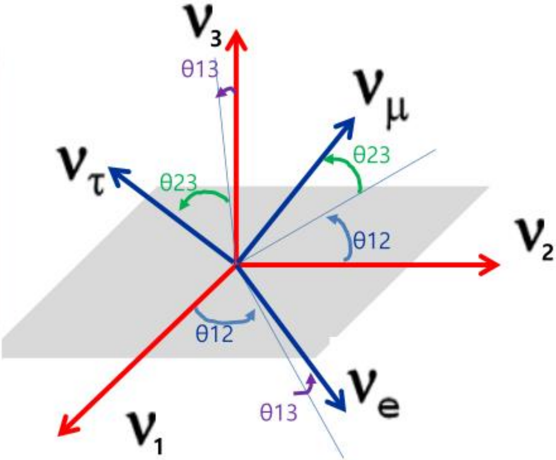
- The confusion arose when physicists discovered neutrinos coming from the sun, a natural source of particles, and found that their number was half that predicted by theoretical models of stellar nuclear reactions.
- By the 1990s, it became clear that neutrinos were behaving strangely. Mysteriously, not only solar neutrinos have disappeared, but also neutrinos falling to the Earth during the collision of cosmic rays with the upper layers of the atmosphere.
- One solution, proposed earlier by Italian physicist Bruno Pontecorvo, is for neutrinos to oscillate between three types of electrons, muons, and tau neutrinos depending on their energy and travel distance, consistent with data from the sun and sky.

Ubaldo Dore and Lucia Zanello,
Bruno Pontecorvo and neutrino physics,
arXiv: 0910.1657

1. Neutrino Oscillation

$$|\nu_\alpha(t)\rangle = U_{\alpha k} e^{-iH_k t}|E_k\rangle, \qquad |\langle E_k|\nu_\alpha(t)\rangle|^2 \neq 1, C$$





- At that time, many physicists found it difficult to accept the idea of changing the shape of the neutrino.
- The math only works if each of the three kinds of neutrinos is a quantum mechanical mixture of three different masses, in other words, the change in shape means that the neutrinos must have mass.
- But the Standard Model of particle physics, the well-tested system of equations describing known elementary particles and interactions, unambiguously considers neutrinos to be massless.
- Solar and atmospheric neutrino theories are complex, so the LSND experiment was built with a dedicated neutrino source to look for stronger evidence of shape change.
- The Liquid Scintillator Neutrino Detector (LSND) was a scintillation counter at Los Alamos National Laboratory that measured the number of neutrinos produced by the accelerator's neutrino source.

"All the News That's Fit to Print"

The New York Times

NEW YORK, TUESDAY, JANUARY 31, 1995

Peso Plummets Anew on Fears Congress Won't Assist Mexico

Clinton Renews Push but Aid Plan Is Still Stalled

Car Bomb Kills 38 in Algeria

PATAKI PROPOSING DEEPEST CUTBACKS IN WELFARE PLANS

WANTS WORK INCENTIVES

Smithsonian Scales Back Exhibit Of B-29 in Atomic Bomb Attack

U.S. IN NEW PLEDGE ON ATOM TEST BAN

Biggest U.S. Terrorist Trial Begins as Arguments Clash

Gingrich Vows Total Review Of Medicare for Cost Savings

INSIDE

Dozens Killed in Floods in Northwestern Europe

Cosmos's Missing Mass: Wispy Particle Weighs In

Medicaid Repayments

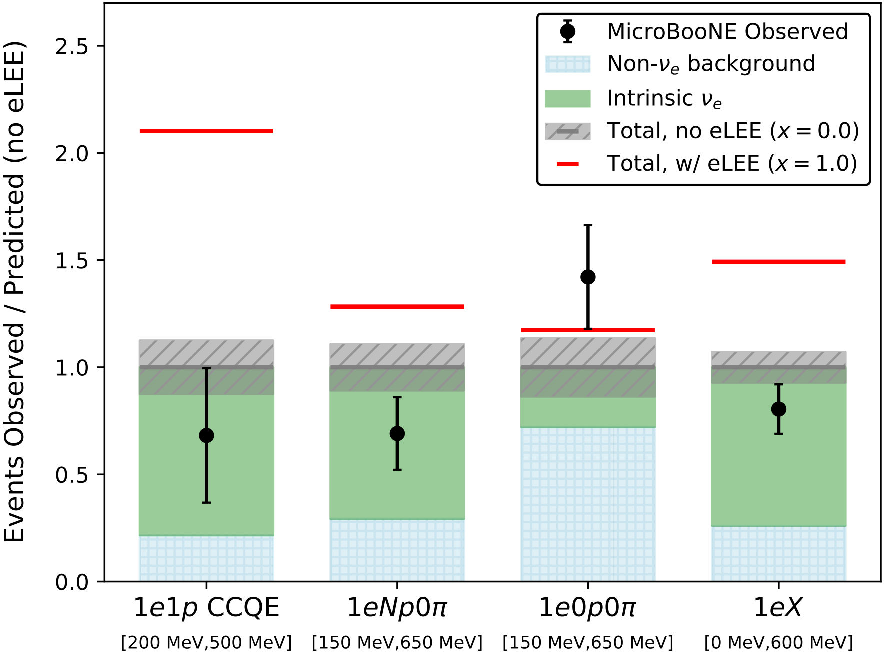
- Even the scientists who supported the idea that neutrinos oscillate and have mass, distrusted the LSND data because the supposed oscillation rate overshot the rate implied by solar and atmospheric neutrinos.
- Solar and atmospheric data suggest that neutrinos only oscillate between three known neutrino types; the addition of a fourth, sterile neutrino, so named because it doesn't need to feel the force experienced by electrons, muons, and tau neutrinos, making them detectable, fits the LSND data better.
- A series of definitive neutrino oscillation experiments in the late 1990s and early 2000s called SNO, Super-K, and KamLAND strongly supported the three-neutrino oscillation model, leading to a Nobel Prize for some of the researchers involved. A supposed fourth, sterile neutrino lurked in the shadows.
- After five years of operation, from 2002 to 2019, MiniBooNE, an improved version of LSND, began to notice a similar anomalous neutrino oscillation rate, suggesting that the LSND result was not a fluke and that a lightweight neutrino might still exist.

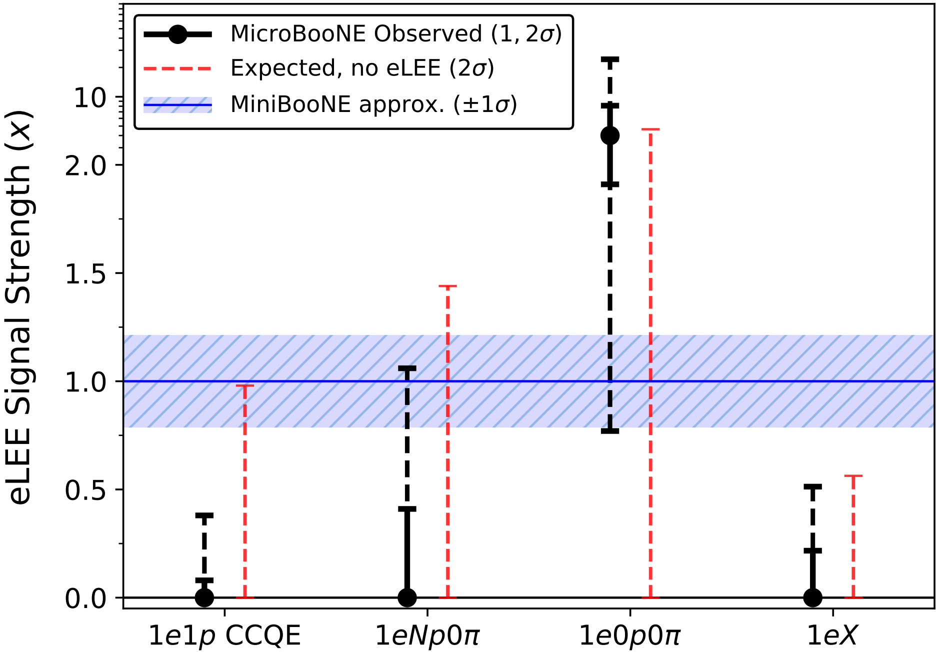
- However, while working on MiniBooNE, many other experiments began. Each examined the different distances and energies of neutrinos to see how this affects their fluctuations. Their results seem to support the three-neutrino model, contradicting not only LSND but now also MiniBooNE.
- In 2013, the Planck Space Telescope took an incredibly detailed image of the universe as it appeared shortly after the Big Bang, revealing a faint radiation from that time called the cosmic microwave background. Planck's picture of this primordial light allowed cosmologists to test their theories of the early universe in great detail.
- In the early universe, neutrinos were very energetic, which greatly influenced the rate of expansion of the universe. By deriving the expansion rate from data on Planck's cosmic microwave background, the researchers were able to estimate how many types of neutrinos filled the young cosmos. The data suggested that there were three types. This and other cosmological observations "absolutely ruled out the existence of a fourth type of neutrino", a simple, light, and sterile type of neutrino that theorists were considering.

- Fermilab's MicroBooNE experiment, a continuation of the MiniBooNE, which has been reconfigured to correct the flaw.

  MicroBooNE collaboration: P. Abratenko et. al,
  Search for an Excess of Electron Neutrino Interactions in MicroBooNE Using Multiple Final State Topologies,
  arXiv: 2110.14054

- However, the results are consistent with the possibility that only half of the MiniBooNE events are caused by neutrino oscillations.
- MicroBooNE reported that the decay of familiar Standard Model particles almost certainly cannot explain the rest of the events.
- The possibility of decay of heavy particles from the dark sector inside MiniBooNE will be determined next year in the next issue of MicroBooNE.


Events Observed / Predicted (no eLEE)
0.0
0.5
1.0
1.5
2.0
2.5
MicroBooNE Observed
Non-ν_e background
Intrinsic ν_e
Total, no eLEE ($x = 0.0$)
Total, w/ eLEE ($x = 1.0$)
1e1p CCQE
[200 MeV,500 MeV]
1eNp0π
[150 MeV,650 MeV]
1e0p0π
[150 MeV,650 MeV]
1eX
[0 MeV,600 MeV]


MicroBooNE Observed (1, 2σ)
Expected, no eLEE (2σ)
MiniBooNE approx. (±1σ)
eLEE Signal Strength (x)
10
2.0
1.5
1.0
0.5
0.0
1e1p CCQE
1eNp0π
1e0p0π
1eX

- Physicists are checking their dark sector models against existing data. The IceCube experiment, consisting of 5,000 detectors embedded in ice kilometers below the South Pole, showed that there was no sign of sterile neutrinos passing through the ice.
- But the analysis showed that if sterile neutrinos can decay into other invisible particles, then the IceCube data actually confirms their existence.

Marjon H. Moulai
Light, Unstable Sterile Neutrinos: Phenomenology, a Search in the IceCube Experiment, and a Global Picture,
arXiv: 2110.02351

- Finally, an analysis that takes into account all experiments with neutrino oscillations together also confirms the existence of decaying sterile neutrinos.

A. Diaz, C.A. Argüelles, G.H. Collin, J.M. Conrad and M.H. Shaevitz,
Where Are We With Light Sterile Neutrinos?,
arXiv: 1906.00045

NuFIT 5.1 (2021)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
	$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
	$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{\rm CP}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
	$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{\rm CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

- A dark sector model is proposed that includes three heavy neutrinos of different masses. Their model explains the LSND and MiniBooNE data as a mixture of decaying heavy neutrinos and oscillating light neutrinos; it also leaves room for explaining the origin of the neutrino mass, the asymmetry of matter and antimatter in the Universe through the seesaw mechanism and dark matter.

  S. Vergani, N.W. Kamp, A. Diaz, C.A. Arguelles, J.M. Conrad, M.H. Shaevitz and M.A. Uchida,
  Explaining the MiniBooNE excess through a mixed model of neutrino oscillation and decay,
  Phys. Rev. D **104**, *095005 (2021)*

- The idea of an invisible but fruitful dark sector is not new, but number of models are.

Basudeb Dasgupta and Joachim Kopp,
Sterile Neutrinos,
Phys. Rept. **928** *(2021) 1-63*

- The research brings together the disparate problems of dark matter and neutrino anomalies under one roof.
- Adding dark forces to the model could avoid the obstacles associated with the Planck telescope by suppressing the number of neutrinos that should have appeared in the early universe.

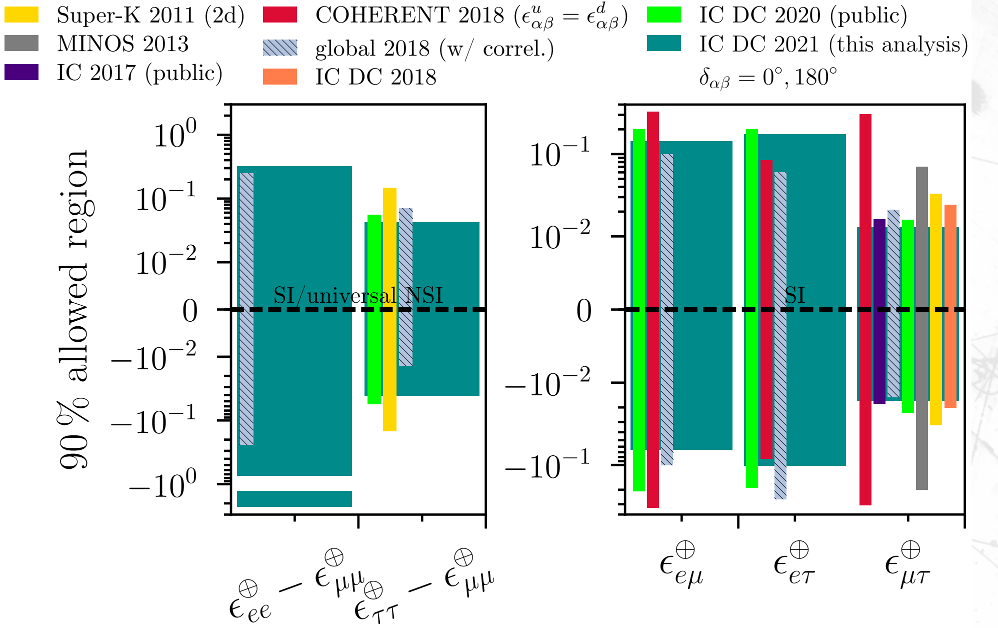
Basudeb Dasgupta and Joachim Kopp,
A ménage à trois of eV-scale sterile neutrinos, cosmology, and structure formation,
Phys. Rev. Lett. **112**, *031803 (2014)*

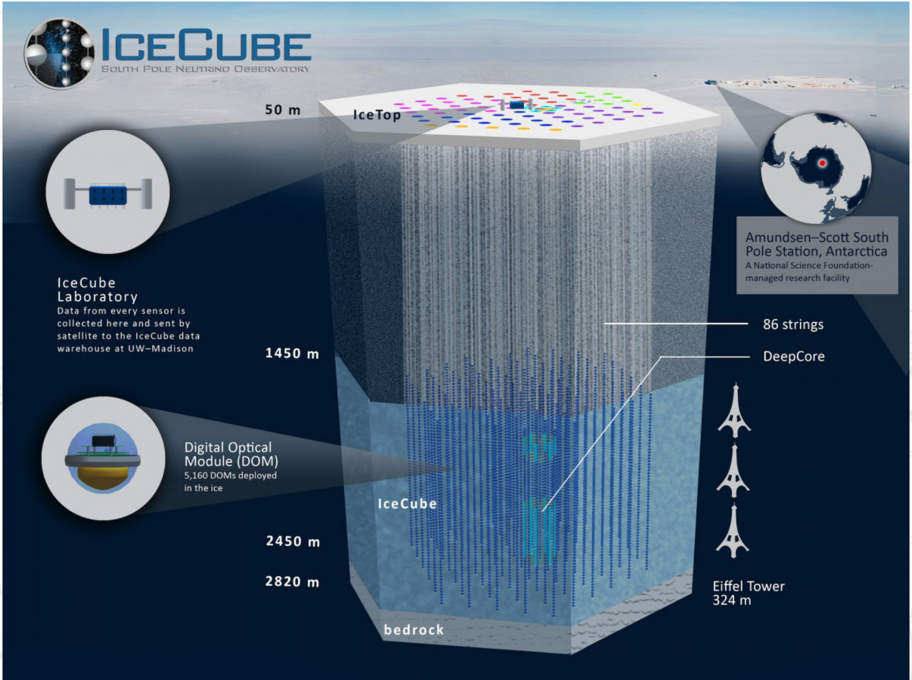
- The rich, complex dark sector may offer a solution to why the current universe seems to be expanding faster than expected, a phenomenon known as Hubble stress, and why galaxies don't seem to cluster as much as they should if dark matter were single and inert particle. A change in the dark matter physics here could indeed affect this type of cosmological stress.

Nils Schöneberg, Guillermo Franco Abellán, Andrea Pérez Sánchez, Samuel J. Witte, Vivian Poulin and Julien Lesgourgues,
The H_0 Olympics: A fair ranking of proposed models,
arXiv: 2107.10291

- In addition, limits on non-standard neutrino interactions (NSI) have been derived from observations of atmospheric neutrinos with IceCube DeepCore data.

  IceCube Collaboration: R. Abbasi et al,
  All-flavor constraints on nonstandard neutrino interactions and generalized matter potential with three years of IceCube DeepCore data,
  Phys. Rev. D **104***, 072006 (2021)*


Super-K 2011 (2d)
MINOS 2013
IC 2017 (public)
COHERENT 2018 ($\epsilon^u_{\alpha\beta} = \epsilon^d_{\alpha\beta}$)
global 2018 (w/ correl.)
IC DC 2018
IC DC 2020 (public)
IC DC 2021 (this analysis)
$\delta_{\alpha\beta} = 0^\circ, 180^\circ$
90 % allowed region
10^0
10^{-1}
10^{-2}
0
-10^{-2}
-10^{-1}
-10^0
SI/universal NSI
SI
$\epsilon^\oplus_{ee} - \epsilon^\oplus_{\mu\mu}$
$\epsilon^\oplus_{\tau\tau} - \epsilon^\oplus_{\mu\mu}$
$\epsilon^\oplus_{e\mu}$
$\epsilon^\oplus_{e\tau}$
$\epsilon^\oplus_{\mu\tau}$



ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
IceCube Laboratory
Data from every sensor is collected here and sent by satellite to the IceCube data warehouse at UW–Madison
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
86 strings
DeepCore
1450 m
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
IceCube
2450 m
2820 m
bedrock
Eiffel Tower
324 m

Out of the Maze

- The neutrino itself is a dark particle. It has the ability to interact and mix with other dark particles, which no other particle in the Standard Model can.
- New and upcoming neutrino experiments could open a portal to the dark sector. MicroBooNE will soon be followed by the Fermilab SBND and ICARUS experiments, which investigate neutrino oscillations at different distances and energies, revealing the full picture of oscillations. Meanwhile, the DUNE experiment at Fermilab will be sensitive to heavier dark sector particles. Careful observation of neutrinos emitted by radioactive sources such as lithium-8 in “decay at rest" experiments will offer an alternative view of the current hodgepodge of results.

Journal Club / Журнальный клуб

Eleventh meeting of the Journal Club

Monday 23 May 2022, 11:00 → 12:00 Europe/Moscow

Blokhintsev Conference Hall, BLTP, 4th floor

Description Speaker: *Pavel Maksimov (BLTP, JINR)*
Title: *Anyons in an exactly solved model and beyond*
Journal: *Annals of Physics, Volume 321, Issue 1, January 2006, Pages 2-111*

Venue: *Blokhintsev Conference Hall, BLTP, 4th floor*
Online: *Zoom link will be provided upon request*

More information on Journal Club

kitaev2006.pdf

Organized by Bogoliubov Laboratory of Theoretical Physics (BLTP), The Joint Institute for Nuclear Research (JINR)

Contact journal_club@theor.jinr.ru