Neutrino mass measurement and sterile neutrinos search with the KATRIN experiment

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Abstract.
In this proceeding, we report on the latest results of the KATRIN experiment on the effective electron anti-neutrino mass and the search for sterile neutrinos. KATRIN performed a high resolution and high statistics spectroscopy measurement of the tritium β-decay spectrum around its endpoint energy. The analysis of ∼1265 h of data acquired during the first two measurement campaigns of 2019 led to the most stringent limit on the neutrino mass with $m_\nu < 0.8$ eV (90% CL). We also report on the improved KATRIN exclusion limits for the eV- and keV-scale sterile neutrinos search. Finally, the future of KATRIN with the TRISTAN detector aiming at further improve the laboratory-based sensitivity to keV-scale sterile neutrino is discussed.

1 Introduction

Since the existence of neutrinos was suggested almost a hundred years ago by W. Pauli, neutrinos have benefited from an intensive research program aimed at measuring their properties. While it is now experimentally established that there are only three flavors of active neutrinos with different masses [1], the question of the mass hierarchy, but also of the absolute mass of the neutrinos and of the neutrinos nature itself remained unanswered [2]. In particular, the neutrino mass which cannot be probed by oscillation experiments, is of fundamental importance in cosmology due to its role in the evolution of the universe but also in particle physics for its role in the models beyond the SM [3]. Different types of measurement can be used to probe the neutrino mass: cosmological observation, search for neutrinoless double beta decay and kinematic study of beta decay. In this paper, we focus on the latter.

2 The KATRIN experiment

The Karlsruhe Tritium Neutrino (KATRIN) experiment [4, 5] is designed to measure the mass of the electron anti-neutrino with a sensitivity of 0.2 eV at 90% confidence using the kinematics of the tritium β-decay [6]:

$$T_2 \rightarrow {}^3\mathrm{HeT}^+ + e^- + \bar{\nu}_e. \quad (1)$$

The low Q-value of 18.6 keV of the tritium β-decay combined with its short half-life of $T_{1/2} = 12.3$ yr and its super-allowed nature make the tritium a well-suited isotope for absolute neutrino mass measurement. The neutrino mass can be measured by looking for a

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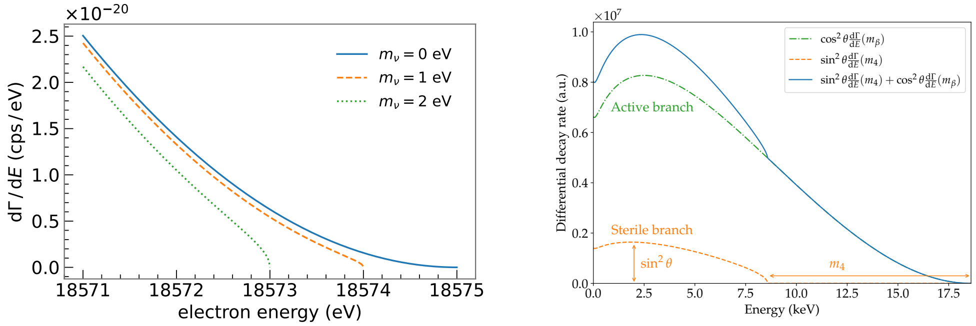

Figure 1. (Left) Illustration of the shape distortion induced by the neutrino mass on the tritium β-decay spectrum. (Right) Illustration of the sterile neutrino signature in a differential tritium β-decay spectrum. For the sake of clarity, a sterile neutrino with a mass of 10 keV and an unrealistic large mixing angle is considered.

reduction of the measured maximal electron energy as well as to a slight spectral shape distortion compared to the theoretical prediction. In the presence of mixing and for neutrinos with small mass differences the distortion of the beta spectrum is given by [6]:

$$\frac{dN}{dE} \simeq R(E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_\nu^2} \tag{2}$$

where E_0 = 18.575 keV [7] is the endpoint energy of the tritium β-decay and m_ν is the effective electron anti-neutrino mass defined as the incoherent sum of neutrino mass eigenstates: $m_\nu^2 = \sum |U_{ei}|^2 m_i^2$, where $|U_{ei}|^2$ are the elements of the Pontecorvo-Maki-Nakagawa-Sakata matrix describing the mixing of the neutrino states i. $R(E)$ contains all m_ν-independent factors. The impact of the neutrino mass on the β-decay spectrum of the tritium is illustrated in figure 1. Because of the small size of the distortion and the very small number of events expected around the endpoint energy, such measurement represents an experimental challenge. A high luminosity source and a high resolution on the electron-volt scale are thus required to address these constraints.

3 Experimental setup

The KATRIN experiment consists in a 70-m-long beamline located at the Karlsruhe Institute of Technology (see figure 2). The beamline is divided into the tritium-containing source and transport section (STS) and the tritium-free section containing the spectrometers and detector system (SDS). Electrons are produced in a 10 m long windowless gaseous tritium source (WGTS) in which a highly purified molecular tritium gas is continuously injected. The gas diffuses towards both ends of the tube where it is pumped out and fed back to the tritium loop system. The WGTS is designed to provide an extremely high activity of up to 10^{11} Bq. It is cooled at 30 K to minimize the thermal gas motion and measured stable at the 0.2% level [8]. Electrons are magnetically guided from the source to a pre- and a main spectrometer through a transport section. Between the source and the spectrometers, the differential tritium pressure is reduced by more than 14 orders of magnitude thanks to several pumping sections. The two spectrometers rely on the MAC-E principle and act as high-pass filters that allow only electrons with kinetic energies larger than the applied retarding energy qU to be transmitted. By applying a magnetic field gradually reduced toward the

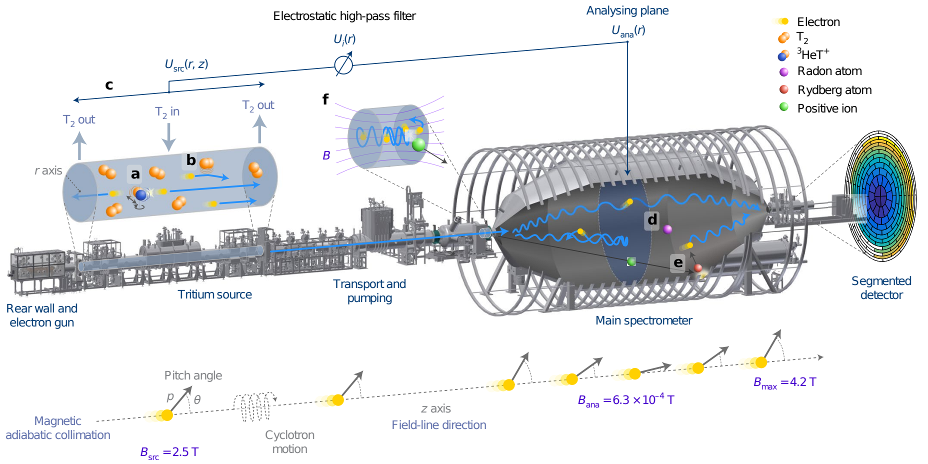

Figure 2. Illustration of the KATRIN beamline [8]. The 70-m-long beamline is composed of a rear wall section, a tritium source, a transport and pumping section, a pre- and a main spectrometer and a segmented focal plane detector.

analysing plane, electrons are adiabatically guided through the spectrometers. The MAC-E filter technology has the advantages of combining a large angle acceptance of 51° with an energy resolution at the eV-scale. The pre-spectrometer is used to reduce the flux of electrons into the main spectrometer by transmitting only electrons with an energy above 10 keV. Electrons transmitted through the main spectrometer are finally counted at the focal plane detector (FPD) as a function of the retarding potential . At the other end of the setup is located the rear section. It contains a gold-plated rear wall absorbing the non-transmitted electrons and defines the electric ground potential relative to the high voltage of the main spectrometer. It also contains an electron gun for calibration measurements.

4 Neutrino mass measurement

The integral beta spectrum is acquired by repetitively recording the detector count rate at different retarding potential. A complete sequence of such points being termed a scan. The scans are performed in an interval of 40 eV below the endpoint and 135 eV above. About 40 scans with dwell times at each point chosen to optimize the neutrino-mass sensitivity are used. The scans above the endpoint are used to measure the background. The most recently published results of KATRIN use the data acquired in 2019 during the first two measurement campaigns KNM1 and KNM2 [8]. A total of 1.48×10^6 (3.68×10^6) β-electrons were collected in the range of interest during a 521.7 h (743.7 h) period of data taking for KNM1 (KNM2).

The neutrino mass is inferred by comparing the measured integral spectrum to the expected one. The expectation is obtained by coupling a very accurate theoretical prediction of the tritium beta spectrum [9] with the experimental response obtained through calibration. This expectation is fitted to the data with four free parameters: the signal amplitude, the endpoint, the background rate and the neutrino mass. Systematic uncertainties are propagated using the covariance matrix approach. A simultaneous fit of both datasets yields $m_\nu^2 = (0.1 \pm 0.3)\ eV^2$ and a corresponding upper limit of $m_\nu < 0.8$ eV at 90% CL. This results supersedes

 https://doi.org/10.1051/epjconf/202328201011

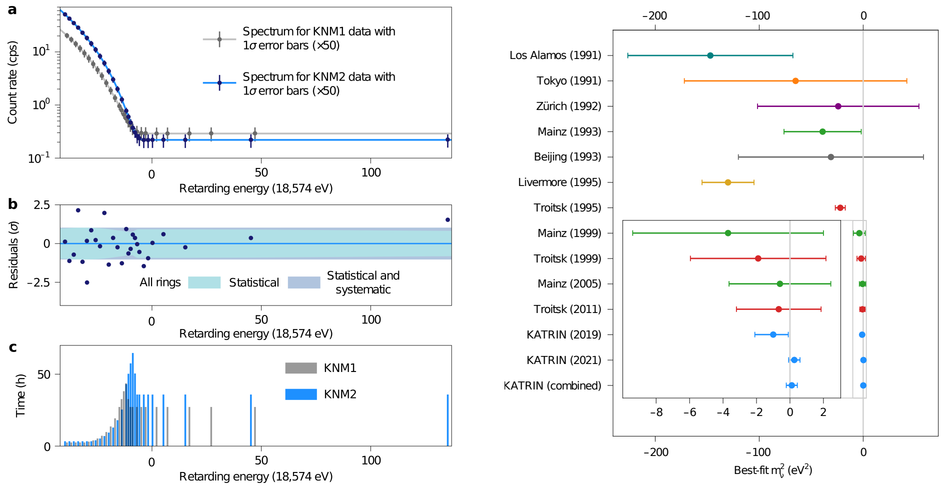

Figure 3. (Right): Measurement rate at each retarding energy for the first two KATRIN campaigns KNM1 and KNM2 [8]. (a) Data points for the count rate over all the detector rings. Error bars represent the statistical uncertainties multiplied by a factor of 50. Best-fit models for each campaign are represented by the colored lines. A reduced background rate, higher signal strength and overall higher statistics can be observed for the second campaign. (b) Normalized residuals for the fit to the data from KNM2. The shaded areas represent the statistical and total uncertainties. (c) Measurement time distribution for the two campaigns. (Left): Comparison of KATRIN results for the neutrino mass with past measurements [8]. The error bars represent the combined statistical and systematic uncertainties.

the previous KATRIN limit of $m_\nu < 1.1$ eV at 90% CL [10] and is to date the most stringent experimental constraint on the neutrino mass. The neutrino-mass result is dominated by statistical uncertainty and the largest systematic uncertainties are related to the background properties and the source electric potential. Correlated systematic uncertainties between both campaigns are negligible as both datasets are dominated by statistics. The data and best-fit models for the first two KATRIN campaigns as well as a comparison of KATRIN neutrino mass results with past measurements are presented in figure 3.

5 Sterile neutrino search

If it is well established that there are only three active neutrinos [1], the existence of one or more sterile neutrino that could only interact through gravitation has been proposed to explain some unexpected experimental results. On one hand, a light sterile neutrino [11] with a eV-scale mass could alleviate the anomalies observed in short-baseline neutrino oscillation experiments such as the gallium anomaly (GA) characterised by a deficit of ν_e from ^{37}Ar and ^{51}Cr electron capture decays [12–14] and the reactor antineutrinos anomaly (RAA) characterised by a deficit of $\bar{\nu}_e$ from nuclear reactors [15]. On the other hand, a sterile neutrino with a keV mass scale would be a viable candidate to the dark matter and could help to explain the observed pulsar velocities [3]. The existence of eV and keV neutrinos has not yet been ruled out and KATRIN appear to be very suitable as a complementary laboratory based experiment to investigate this hypothesis.

5.1 eV-sterile neutrino search

Beta decay can be used to investigate the existence of eV-sterile neutrinos. The signal signature would consist in a kink-like spectral distortion at $E = E_0 - m_4$, where E_0 is the endpoint energy of the tritium and m_4 the mass of the fourth neutrino state. The distortion of the β-decay spectrum can be expressed as:

$$R_\beta(E) = \cos^2\theta \cdot R_\beta(E, m_\nu^2) + \sin^2\theta \cdot R_\beta(E, m_4^2), \tag{3}$$

where $R_\beta(E, m_\nu^2)$ and $R_\beta(E, m_4^2)$ correspond respectively to the active and sterile decay branches and θ is the active-sterile neutrino mixing angle. R_β denotes here the tritium beta spectrum. The size of the signal is determined by the admixture $\sin^2\theta$ of the new mass eigenstate to the electron neutrino flavor. An illustration of the sterile neutrino imprint in a differential beta spectrum is illustrated in figure 1.

Using the same datasets as for the active neutrino mass, KATRIN investigated the existence of a fourth neutrino mass eigenstate [16]. The same energy range of [E_0 - 40 eV, E_0 + 135 eV] was used. The sterile fit was achieved by inferring the two parameters of interest m_4^2 and $|U_{e4}|^2$ ($|U_{e4}|^2 = \sin^2\theta$) in addition to the original fit parameters used to measure the neutrino mass. Similarly, systematic uncertainties were propagated using the covariance matrix approach. This analysis is sensitive to the fourth neutrino mass eigenstate $m_4^2 \lesssim 1600$ eV^2 and active-to-sterile mixing $|U_{e4}|^2 \gtrsim 6 \times 10^{-3}$ in the $3\nu + 1$ framework. The measurement is statistics dominated over the whole analysed energy range with $\sigma_{stat}^2/\sigma_{tot}^2 > 0.5$ for all m_4^2. No significant eV-sterile neutrino signal was observed and an improved exclusion limit was reported (see figure 4). More stringent constraints than both Mainz and Troitsk experiments for $m_{41}^2 \lessapprox 300$ eV^2 were obtained and large δm_{41}^2 solutions of the RAA and of BEST+GA anomalies are now excluded. Notably, this new result disfavors the Neutrino-4 hint of a signal for $\sin^2(2\theta_{ee}) \gtrsim 0.4$ [17] and improves the exclusion bounds set by short-baseline oscillation experiments for $m_{41}^2 \gtrapprox 10$ eV^2.

5.2 keV-sterile neutrino search

Like eV-sterile neutrinos, keV-sterile neutrinos can be investigated by searching for a kink-like distortion in the tritium β-decay spectrum. Because of the unconstrained mass, such sterile signature would lie far away from the endpoint and would require a measurement of the spectral shape deep into the spectrum. Thanks to its high-luminosity source and the high endpoint value of the tritium, KATRIN exhibits a high potential to search for keV sterile neutrinos with mass $m_4 < E_0 \simeq 18.6$ keV. However, scanning the entire spectrum with the full source activity would lead to an increase of the signal rate by several orders of magnitude compared to the standard KATRIN measurement. The current detector system is not designed to handle such high count rates. In 2018, KATRIN acquired its first data during a commissioning campaign aiming at demonstrating the stability of the operation of the experiment. This campaign was realized with a reduced isotopic abundance of 0.5% of the tritium in the deuterium carrier gas. Thanks to this reduced activity and a higher retarding potential, this data set provided a unique opportunity to search for sterile neutrinos in the 0.01 - 1.6 keV mass range [18]. No keV-sterile neutrino signal was observed and KATRIN reported exclusion limits competitive with previous laboratory-based searches. In particular, an active-sterile mixing amplitude of $\sin^2\theta < 5 \times 10^{-4}$ for a sterile neutrino mass of $m_4 = 300$ eV was excluded and the currently leading laboratory-based bounds in a mass range of 0.1 keV $< m_4 <$ 1.0 keV were improved. As well as for the neutrino mass and the eV-sterile search, this result is dominated by statistical uncertainties.

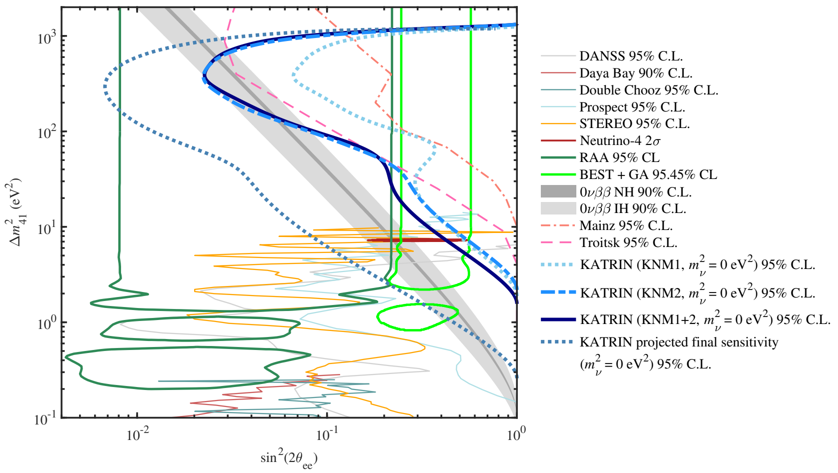

Figure 4. eV-scale sterile neutrino exclusion contours at 95% C.L. for the first and second campaign of KATRIN [16]. The combined results of the two campaigns as well the projected final sensitivity are also shown. These exclusions are compared to the most recent results from reactor, gallium, beta decay and double beta decay experiments. References for the different experimental results used in this plot can be found in [16].

This result represents an important milestone for the experiment as it demonstrates the feasibility of using KATRIN to search for keV-sterile neutrinos. In order to handle the high counting rate that would arise by measuring the full tritium spectrum with a higher source activity, a new detector system is currently being developed. The TRISTAN (TRitium Investigation on STerile to Active Neutrino mixing) detector aims at using the full KATRIN source strength and reach a statistical sensitivity at the level of $\sin^2\theta \sim 10^{-6}$ in the ~7 keV region. It was demonstrated that the observation of a kink-like structure requires an energy resolution in the order of 300 eV at 30 keV [19]. Silicon drift detectors (SDD) meet such requirement while also exhibiting low energy threshold (< 2 keV) and being able to handle high counting rate (~10^5 cps for 3 mm pixel [19]). The development of the TRISTAN detector system follows a staged approach. First, a 7-pixels detector prototype was used to investigate the general detector system properties. The system was then scaled up with modules of 47 and 166 pixels in a monolithic chips. Extensive tests and characterisation of the different detector systems are conducted. This includes among others quantities the energy resolution, the linearity and the electronic noise. For this purpose, a large variety of calibration sources such as X-ray lines from ^{55}Fe, conversion electron lines from ^{83m}Kr, laser and electron beam have been used. These extensive testing have already demonstrated the good performance of the detectors and their ability to fullfill requirements for TRISTAN [19–21]. Ultimately, TRISTAN will consist in a focal plane array composed of respectively 9 and 21 detector modules for the first and the second phase of the keV-sterile search. Each module is composed of 166 pixels for a total of respectively ~1500 and ~3500 pixels for the first and second phase. An illustration of the TRISTAN detector for the second phase is presented in figure 5.

In addition to the detector development, the modelling of the expected spectrum at the detector over the full energy range is also an ongoing effort. The model includes non-trivial effects such as electrons backscattered at the rear wall and electrons backscattered and back-reflected at the detector due to the beamline magnetic fields. This model is used to investigate the impact of the different systematic effects and their associated uncertainties on the keV-

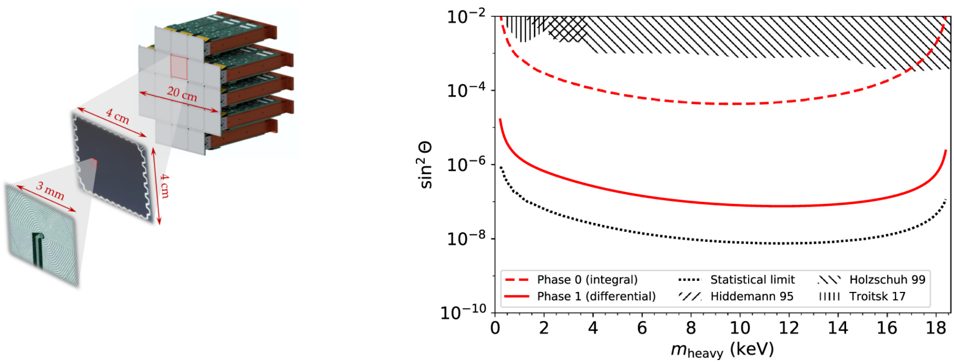

Figure 5. (Left) TRISTAN detector design for the second phase of the keV-sterile search. The full detector will consist of an array of 21 identical modules each consisting of 166 pixels. (Right) Expected 95% CL statistical sensitivity of the KATRIN experiment to keV-scale sterile neutrinos for different stages with the TRISTAN detector [19]. Phase-0 (dashed red line): integral measurement with a total statistics of $6{\times}10^{11}$ electrons. This could be achieved with a 7 d measurement campaign at a reduced signal rate of 10^6 cps. This rate can be obtained with a reduced amount of tritium. Phase-1 (solid red line): differential measurement with a total statistics of 10^{16} electrons. This could be achieved with a 3 years measurement campaign and a signal rate of 10^8 cps. This signal rate can be obtained with a 100-fold reduced tritium column density (with respect to nominal KATRIN operation). The statistical limit (dashed black line) for a differential measurement with a total statistics of 10^{18} electrons is also reported. This limit represent the most optimistic scenario for which a measurement of 3 years with the full source strength of the KATRIN experiment can be achieved. The grey dashed area depicts the current laboratory-based limits [22–24].

sterile sensitivity. As of now, systematic effects are estimated to reduce by at least one order of magnitude the statistical limit. An illustration of KATRIN sensitivity expected for the keV-sterile search is presented in figure 5.

6 Conclusion

In early 2022, the KATRIN experiment reported its results on the neutrino mass and the search for eV- and keV sterile neutrinos. The analyses were performed on the data taken during the first two measurement campaigns conducted in 2019 for which a total of $\sim 6 \times 10^6$ β-electrons have been collected. The combination of the first two campaigns results gives an improved uper limit on the neutrino mass of $m_\nu < 0.8$ eV (90% CL). This result constitutes the best neutrino-mass sensitivity for direct neutrino-mass measurement. KATRIN also reported an updated analysis of its light sterile neutrino search. This analysis is sensitive to the fourth neutrino mass eigenstate $m_4^2 \lesssim 1600$ eV^2 and active-to-sterile mixing $|U_{e4}|^2 \gtrsim 6 \times 10^{-3}$ in the $3\nu + 1$ framework. No significant eV-sterile neutrino signal was observed and an improved exclusion limit was reported. Notably, this improved result disfavors the Neutrino-4 hint of a signal for $\sin^2(2\theta_{ee}) \gtrsim 0.4$. These two analysis are dominated by statistical uncertainties. KATRIN is currently analysing the data of three additional measurement campaigns corresponding to a statistical increase of $\sim$5 compared to the analysis reported here. By the end of the data taking, a total statistic of about $\sim 70 \times 10^6$ electrons is expected for a target sensitivity on the neutrino mass of $m_\nu < 0.2 - 0.3$ eV (90% CL).

Moreover, KATRIN reported the results of its first keV-scale sterile-neutrino search using first tritium data acquired in the commissioning run. No significant keV-sterile neutrino signal was observed and exclusion limits were reported. This result improves the current laboratory limits on the active-to-sterile mixing amplitude in a mass range of 0.1 keV < m_4 < 1.0 keV by up to an order of magnitude. After completion of the neutrino-mass campaigns in 2025, KATRIN is planning to further improve the sensitivity to keV-scale sterile neutrinos. For this purpose, a novel detector system relying on the SDD technology is under development.

We acknowledge the support of Helmholtz Association, Ministry for Education and Research BMBF (5A17PDA, 05A17PM3, 05A17PX3, 05A17VK2, and 05A17WO3), Helmholtz Alliance for Astroparticle Physics (HAP), Helmholtz Young Investigator Group (VH-NG-1055), and Deutsche Forschungsgemeinschaft DFG (Research Training Groups GRK 1694 and GRK 2149, and Graduate School GSC 1085 - KSETA) in Germany; Ministry of Education, Youth and Sport (CANAM-LM2011019, LTT19005) in the Czech Republic; and the United States Department of Energy through grants DE-FG02-97ER41020, DE-FG02-94ER40818, DE-SC0004036, DE-FG02-97ER41033, DE-FG02-97ER41041, DE-AC02-05CH11231, DE-SC0011091, and DE-SC0019304, and the National Energy Research Scientific Computing Center.

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