ICRANet-Minsk report

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2 Participants

2.1 ICRANet-Minsk participants

- Sergei Kilin (director)
- Ivan Siutsou (senior research fellow)
- Mikalai Prakapenia (postgraduate student)
- Stanislav Komarov (postgraduate student)
- Aksana Kurguzava (graduate student)
- Vladislav Stefanov (scientific secretary of the Center)

2.2 Ongoing collaborations

- Alexey Aksenov (ICAD, RAS, Russia)
- Gregory Vereshchagin (ICRANet-Pescara, visiting)
- Dmitry Mogilevtsev (B.I. Stepanov Institute of Physics, NASB)

3 ICRANet-Minsk center

ICRANet-Minsk center was established in 2017 following the agreement between ICRANet and the National Academy of Sciences of Republic of Belarus. It operates in areas of Relativistic Astrophysics and Cosmology, in the theoretical and observational fields, in line with ICRANet activities.

The activity of the ICRANet-Minsk include organization of schools, courses, workshops, and conferences in areas of competence of the ICRANet-Minsk combined with an active visiting program. In particular, it supports organization of the Zeldovich meetings series, the 4th meeting is planned for April 2020. In 2019 Mikalai Prakapenia visited ICRANet-Pescara, and Gregory Vereshchagin visited ICRANet-Minsk.

The Center is funded within the task 2.1.08 of subprogram ≪Microworld, plasma, and Universe≫ of the scientific research program ≪Convergence-2020≫, and by a research grant from the Belarusian Republican Foundation for Fundamental Research.

4 Scientific activities

Scientific activities of ICRANet-Minsk include research in radiation transfer in relativistic plasma, kinetics of relativistic plasma, and effects of gravity in light interaction with quantum systems.

4.1 Radiation transfer in relativistic plasma

First task is developed by Aksana Kurguzava and Ivan Siutsou. The problem of propagation of radiation in relativistic wind of finite dimension was treated previously in the paper by Ruffini, Siutsou and Vereshchagin, ApJ 772 (2013) 11. It was found that two distinct cases of photon-thick and photon-thin outflows are present at typical parameters of GRB outflows, and their photospheric emission was calculated. However, in the case of a photon-thin outflow the radius of diffusion (where most of energy radiated towards observer is originated) is quite large, of the order of $10^{14} - 10^{15}$ cm, and interaction of the outflow with the interstellar medium of typical density will deposit additional energy inside the outflow that cannot be neglected. This energy will be radiated from the photosphere of optically thick outflow, changing its observable energy and temperature from the case treated in the paper mentioned. This research is on an early stage now.

4.2 Relativistic plasma kinetics

Second task is developed by Mikalay Prakapenya and Ivan Siutsou in close collaboration with Gregory Vereshchagin. In 2019 we developed a code for simulations of relativistic plasma kinetics with parallel calculations of exact three-particle interactions rates in electron-positron-photon plasma with baryonic additions. The scheme is exact in the sense that it uses full matrix elements of quantum electrodynamics without approximations for the processes listed in the table 4.1, and it satisfies conservation laws exactly.

Table 4.1: Interactions in plasma

Two-particle interactions	Three-particle interactions
Compton scattering	Double Compton scattering
$e^{\pm}\gamma \longrightarrow e^{\pm\prime}\gamma'$	$e^{\pm}\gamma \longleftrightarrow e^{\pm\prime}\gamma'\gamma''$
$p^{+}\gamma \longrightarrow p^{+\prime}\gamma'$	$p^{+}\gamma \longleftrightarrow p^{+\prime}\gamma'\gamma''$
Coulomb, Møller and Bhabha scattering	Bremsstrahlung
$e_1^{\pm}e_2^{\pm} \longrightarrow e_1^{\pm\prime}e_2^{\pm\prime}$ $e^{+}e^{-} \longrightarrow e^{+\prime}e^{-\prime}$	$e_1^{\pm}e_2^{\pm} \longleftrightarrow e_1^{\pm\prime}e_2^{\pm\prime}\gamma$ $e^{+}e^{-} \longleftrightarrow e^{+\prime}e^{-\prime}\gamma$
$e^{\pm}p^{+} \longrightarrow e^{\pm\prime}p^{+\prime}$ $p_1^{+}p_2^{+} \longrightarrow p_1^{+\prime}p_2^{+\prime}$	$e^{\pm}p^{+} \longleftrightarrow e^{\pm\prime}p^{+\prime}\gamma$ $p_1^{+}p_2^{+} \longleftrightarrow p_1^{+\prime}p_2^{+\prime}\gamma$
Pair creation/annihilation	Three-photon pair creation/annihilation
$e^{+}e^{-} \longleftrightarrow \gamma_1\gamma_2$	$e^{+}e^{-} \longleftrightarrow \gamma_1\gamma_2\gamma_3$
	Radiative pair creation Radiative pair annihilation
	$\gamma_1\gamma_2 \longleftrightarrow e^{+}e^{-}\gamma$ $e^{\pm}\gamma \longleftrightarrow e^{\pm\prime}e^{+}e^{-}$
	$p^{+}\gamma \longleftrightarrow p^{+\prime}e^{+}e^{-}$

Parallelism is obtained by the code using stealing task queue for simultaneous calculations on many OpenCL devices. Three papers on the topic are in preparation now.

First significant improvement over the previous version of the code is the usage of new kinematics for integration of the rates over the angles in the isotropic plasma. As rates integral includes 4 δ-functions of energy and momentum conservation in the reaction, usual approach takes them into account excluding 3 components of momentum of one of the particles and momentum magnitude (or energy) of another particle. Excluded integration variables are represented then as functions of polar and azimuthal angles μ_i and ϕ_i of the second particle, that leads to two roots in the resulting equations, some of them spurious. As a result roots checking is needed in the innermost loop of integral calculation with corresponding drop in the code performance. New kinematics allows us to avoid it. We use energy ε_i and polar angle ϕ_i' of the first particle moment direction, taken in a coordinate system with azimuth along the direction of total momentum of the first and second particles $\vec{P} = \vec{p}_i + \vec{p}_j$, azimuthal angle being θ' and its cosine μ'. In these variables conservation laws equations can be solved without spurious roots as

$$\varepsilon_j = \varepsilon - \varepsilon_i, \quad \mu_i' = \frac{p^2 + p_i^2 - p_j^2}{2pp_i}, \quad \mu_j' = \frac{p^2 + p_j^2 - p_i^2}{2pp_j}, \quad \phi_j' = \pi + \phi_i', \tag{4.2.1}$$

$$\vec{p}_i = p_i \left(\mu_i' \vec{P}/p + \sqrt{1 - \mu_i'^2} \left[\vec{n}_1 \cos\phi_i' + \vec{n}_2 \sin\phi_i' \right] \right), \tag{4.2.2}$$

$$\vec{p}_j = p_j \left(\mu_j' \vec{P}/p + \sqrt{1 - \mu_j'^2} \left[\vec{n}_1 \cos\phi_j' + \vec{n}_2 \sin\phi_j' \right] \right), \tag{4.2.3}$$

$$p = \sqrt{\vec{P} \cdot \vec{P}}, \quad \varepsilon = \varepsilon_i + \varepsilon_j, \quad p_i = \sqrt{\varepsilon_i^2/c^2 - m_i^2 c^2}, \quad p_j = \sqrt{\varepsilon_j^2/c^2 - m_j^2 c^2}, \tag{4.2.4}$$

where $\vec{n}_1$ and $\vec{n}_2$ are two normal to each other normals to $\vec{P}$. Limits of integration are very simple in comparison to usual approach and are as follows:

$$\phi_i' \in [0, 2\pi), \qquad \varepsilon_i \in [A - B, A + B], \tag{4.2.5}$$

$$A = \frac{\varepsilon \left(\varepsilon^2 - p^2 c^2 - m_j^2 c^4 + m_i^2 c^4 \right)}{2\left(\varepsilon^2 - p^2 c^2\right)}, \tag{4.2.6}$$

$$B = \frac{pc\sqrt{\left(\varepsilon^2 - p^2 c^2 - m_j^2 c^4 - m_i^2 c^4 \right)^2 - (2 m_i m_j c^4)^2}}{2\left(\varepsilon^2 - p^2 c^2\right)}, \tag{4.2.7}$$

δ-functions give

$$\delta(\varepsilon - \varepsilon_i - \varepsilon_j)\delta^3(\vec{P} - \vec{p}_i - \vec{p}_j) = \frac{\delta(\mu_i - \mu_i^*)\delta(\varepsilon_j - \varepsilon_j^*)\delta(\mu_j' - \mu_j'^*)\delta(\phi_j' - \phi_j'^*)}{pp_ip_j}, \tag{4.2.8}$$

where asterisks denote roots of kinematics equations given by (4.2.1).

Second improvement is the use of massively parallel calculations. The code initially had used only CPU and was described in M.A. Prakapenia, I.A. Siutsou, G.V. Vereshchagin "Thermalization of electron-positron plasma with quantum degeneracy", Physics Letters A 383, 2019, 306 and M.A. Prakapenia, I.A. Siutsou, G.V. Vereshchagin "Numerical scheme for treatment of Uehling-Uhlenbeck equation for two-particle interactions in relativistic plasma", Journal of Computational Physics 373, 2018, 533. Main difficulty of exact three-particle interactions rates is the amount of calculations needed, as main integration is 8-dimensional in this case. For example, number of individual collision integrals for $n_e = 60$ energy zones is of the order of $9 \cdot 10^7$, and their calculations on angular grid of $n_\mu \times n_\phi = 64 \times 128$ needs to run over $1.5 \cdot 10^{15}$ individual particle configurations. Number of configurations grows as $n_e^4 \times n_\mu^2 \times n_\phi^2$, therefore even many-core CPUs are useless in the case considered and single work-station is not enough, supercomputers needed estimation of the time needed for calculations can be obtained from nearly 1000 ticks for a configuration:

$$\sim \frac{10^3 \text{ ticks/configuration} * 10^{15} \text{ configurations}}{10^9 \text{ ticks/s/core} * 10 \text{ cores}} = 10^8 \text{ s} \simeq 10^3 \text{ days.}$$

However, in GPUs we have up to several thousands of conveyers working simultaneously, e.g. chip Tahiti from AMD in top configuration has 2048 shading units with peak performance of 4096 GigaFLOPS single precision and 1024 GigaFLOPS double precision. This allows to shorten calculation time by 1.5–2 orders of magnitude, allowing us to use laboratory-size workstation.

The code developed could use all of the OpenCL devices in a workstation. OpenCL (abbreviation of Open Computing Language) is a general framework for parallel computations on devices which can be CPUs, GPUs or FPGAs. OpenCL consists of programming language based on C99 standard (from version 2.1 OpenCL includes also another language based on C++14 standard) that is used for writing kernels running on OpenCL devices, and API to manage OpenCL devices, to send kernels and data for computations and to receive processed data from devices. Each device producer like Intel, AMD, and NVIDIA provides OpenCL runtime with its own OpenCL compiler and standardized API. OpenCL provides data and instructions parallelism and is one of the interfaces for GPGPU—general purpose calculations on graphics processing units. OpenCL is an open standard not bounded to any specific vendor, rather than CUDA that is proprietary to NVIDIA. OpenCL supports GPUs of AMD, NVIDIA, Intel, CPUs of AMD, ARM, Intel and FPGAs of Intel, Xilinx, Altera, etc.

The code includes dispatcher that first spawns some specified number of worker-threads per available OpenCL device, then defines the best options to compile OpenCL kernels of collision integral calculations on devices, after that compiles kernels and provides data structures, feeds workers with tasks to calculate, and when tasks are exhausted, finally performs stealing of tasks between workers and collection of results. Tasks granulation appears to be crucial parameter with $\sim 10^4 \div 10^5$ tasks per reaction. The code uses the most widespread OpenCL 1.2 and is tested already on OpenCL runtimes of AMD (for GPU and CPU), Intel (for GPU and CPU), and NVIDIA (for GPU and CPU). Both single and double precision was tested, the former was found to be inaccurate due to bad numerical behaviour of matrix elements.

Third improvement is the use of numerically exact quadrature for the innermost integral of matrix element on ϕ'_i (Jacobian (4.2.8) does not depend on ϕ'_i). Matrix element is some complicated rational function of kinematic invariants that are 4-products of particle's momenta. In three-particle reaction $I_1 + II_2 \longrightarrow III_3 + IV_4 + V_5$ there are just two kinds of these invariants in relation to ϕ'_i: $p_I p_{II}, p_I p_{III}, p_{II} p_{III}, p_{IV} p_V$ do not depend on this polar angle, and $p_I p_{IV}, p_I p_V, p_{II} p_{IV}, p_{II} p_V, p_{III} p_{IV}, p_{III} p_V$ do depend on ϕ'_i, but in the same way (see (4.2.1)):

$$p_a p_i = \varepsilon_a \varepsilon_i - c^2 p_i \left(\mu'_i \vec{p}_a \vec{P}/p + \sqrt{1-\mu'^2_i} \left[\vec{p}_a \vec{n}_1 \cos\phi'_i + \vec{p}_a \vec{n}_2 \sin\phi'_i \right] \right) = \\ = (p_a p_i)_{\vec{P}} + (p_a p_i)_{\vec{n}_1} \cos\phi'_i + (p_a p_i)_{\vec{n}_2} \sin\phi'_i \quad (4.2.9)$$

(for j-particle we have just change in trigonometric functions sighs as $\phi'_j = \pi + \phi'_i$). It means that we have here the integral of rational function on $\cos\phi, \sin\phi$ along the full circle of ϕ (from here on we omit primes and other specifications of the angles when they can be easily recovered from context).

For such kind of integrals there is a technique of exact numerical quadrature by taking appropriately weighted sum of the function in a small number of points on the circle. Positions of the points and corresponding weights are defined by the poles of the integrated rational function, this technique is known as Szegö rational quadrature [Bultheel, A. et al., Numerical Algorithms 3 (1992) 105 and Mathematics of Computation, 78(266) (2009) 1031.].

To use this method first let us change variable of integration as

$$\cos\phi = \frac{z+1/z}{2}, \quad \sin\phi = \frac{z-1/z}{2i}, \quad z = e^{i\phi}, \quad d\phi = \frac{dz}{iz}.$$

Then we define number of quadrature points. If the function has the form of $P_{2n}(z)/(Q_n(z)Q^*_n(z))$, where lower indices denote maximal powers of z in corresponding polynomials, and $Q^*_n(z)$ is a polynomial with roots α^*_i complexly conjugated to roots α_i of polynomial $Q_n(z)$ (i.e. $\alpha^*_i = 1/\bar{\alpha}_i$), it can

Table 4.2: Number of quadrature points for different three-particle processes

Process	Direct reaction	Inverse reaction
Double Compton scattering	9	8 (1 zero)
Bremsstrahlung $e^{\pm}e^{\pm}$	13	13
Bremsstrahlung $e^{\pm}e^{\mp}$	11 (2 zeros)	11 (2 zeros)
Three-photon annihilation	9	13
Radiative pair production $\gamma e^{\pm}$	13	13 (2 zeros)
Radiative pair production $\gamma\gamma$	13	9

be proved that $n+1$ quadrature point is enough, therefore one point can account for two poles of integrated function positioned at α_i and $1/\bar{\alpha}_i$ (using this property, we will take $|\alpha_i| < 1$, else we can redefine $\alpha_i \leftrightarrow 1/\bar{\alpha}_i$). As invariants depend on ϕ through (4.2.9), nearly all the poles of matrix elements appear exactly in these pairs, with addition of some poles at 0 and infinity. Depending on the reaction, it appears that we need to use from 8 to 13 quadrature points, see Table 4.2. To get these numbers we need to gather matrix element into a single fraction with polynomials in z in numerator and denominator, this is the task that is virtually impossible to do by hand. We made it by system of computer algebra Mathematica 11.2, each transformation has taken from hours (for double Compton-related processes) to days (for bremsstrahlung-related processes) on Intel i7-7740K CPU.

Positions of quadrature points z_i are defined as roots of parametric polynomial equation

$$Poly(z) = z\prod_{j=1}^{n+1}(z-\alpha_j) + \tau\prod_{j=1}^{n+1}(1-z\bar{\alpha}_j) = 0 \tag{4.2.10}$$

with parameter τ belonging to the circle, $|\tau| = 1$. We can fix then one of the roots at $z_1 = 1$, it gives

$$\tau = \frac{-\prod_{j=1}^{n+1}(1-\alpha_j)}{\prod_{j=1}^{n+1}(1-\bar{\alpha}_j)}$$

. To find other roots we use accelerated Gauss-Seidel variant of iterative WDK-method (corresponding to 4.10 Comparison of Efficiencies] this method provides faster-than-quadratic convergence with very high numerical performance, and it works in place, not requiring two tables of roots that is important in the case of GPU with limited number of available registers)

$$z_j^{(i)} = z_j^{(i-1)} - \frac{Poly(z_j^{(i-1)})}{\prod_{k=1}^{j-1}(z_j^{(i-1)} - z_k^{(i)}) \prod_{k=j+1}^{n+1}(z_j^{(i-1)} - z_k^{(i-1)})}, \quad j = 2, \cdots, n+1. \tag{4.2.11}$$

At the beginning we start from equidistant points $z_j^{(0)} = \exp\left(i\frac{2\pi(j-1)}{n+1}\right)$ and iterate up to the point when $\sum_j |Poly(z_j^{(i-1)})|^2$ and $\sum_j(|z_j^{(i)}|^2 - 1)$ drop below specialized thresholds (typically 10^{-24} and 10^{-14} for double precision), that takes 3-6 iterations. The only problem was found when some of the points during iterations try to get far away from $z = 0$, as polynomial of 13-th power overflows at even not-so-large z, so that in such a case the point is just not iterated, and convergence to the circle is usually restored at the next iteration step. As poles positions move slowly during integration on ε, we reuse z_j obtained on the previous integration as initials for iterations for the next integral, it gives substantial reduction of the execution time. After quadrature points determination we find their associated weights

$$A_j = 2\pi \Bigg/ \left(1 + \sum_{j=1}^{n+1} \frac{1 - |\alpha_j|^2}{|z_j - \alpha_j|^2}\right), \tag{4.2.12}$$

and integral itself is found as

$$\int_0^{2\pi} X d\phi = \sum_{j=1}^{n+1} A_j X(\phi_j), \quad z_j = e^{i\phi_j}. \tag{4.2.13}$$

All the procedure is realized in the code in OpenCL language. It effectively reduces dimension of integration by 1, to 7D, replacing $O(n_\phi)$ complexity of the innermost integration with $O(1)$, that gives lower execution time from $n_\phi = 64$ on.

Fourth improvement is underway. It was found that the described scheme of the numerically exact quadrature is quite involved and provides difficulties for OpenCL compilers. For example, it appears that it compiles incorrectly on AMD Adrenalin drivers from 19.5.1 version on, the compiler bug was confirmed by AMD and will be fixed in the future updates. Another problem arisen is high register pressure of the OpenCL kernels, leading to leakage of variables from vector general purpose registers (VGPR) into scratch memory—part of global memory to store each workitem private values. As memory throughput of global memory reads and writes are somewhat 100 times slower than registers, it leads to a huge drop in processing power of GPU on such kernels. So the decision was taken to rewrite the kernels into an assembler language of GCN architecture still using OpenCL API to interact with the CPU code. For that purpose an open-source software CLRadeonExtender of version 5000 (November 16, 2019) was implied, that can compile binaries with Radeon Adrenalin OpenCL 1.2 format. It gives more than 10 times increase in kernel performance, for example, time of kinetic coefficients calculations on a grid of $n_\mu \times n_\phi = 32 \times 64$ for inverse electron-electron bremsstrahlung drops down from 191 s to 13.3 s. The assembler kernels in fact use so few VGPRs that it is possible to introduce adaptive integration scheme in energy ε without getting out of registers. These kernels, as well as assembler kernels of some reactions are under test now.

4.3 Photon condensation in relativistic plasma

Third task is the application of the code to plasma kinetics that was developed by Mikalay Prakapenya in close collaboration with Gregory Vereshchagin. Results are presented in a manuscript under review now.

Firstly we use the code to investigate condensation of photons in norelativistic electron-photon plasma. There is no reactions of pair creation/annihilation in such a plasma. A series of simulations of thermalization process was performed for different final temperatures of the plasma and different initial states. Photon initial state was chosen to be Plank distribution with temperature much higher than final temperature of the system, so there is an excess of photons, possibly leading to their condensation. Initial state of electrons is fully degenerate to maximally suppress photon absorption (namely, inverse double Compton and bremsstrahlung processes). Then there is a threshold near the peak of initial Plank distribution for bremsstrahlung process, and double Compton absorption process has rate lower than rate of ordinary Compton scattering. During thermalization process electron degeneracy decreases by energy transfer from photons due to Compton scattering, i.e. electron distribution spread out into free higher energy states. This leads to vanishing of threshold in bremsstrahlung and photon number decreases before condensation can occur. That shows impossibility of photon condensation in nonrelativistic electron plasma starting from initial Plank spectrum, which was predicted by Zel'dovich and Levich in 1969 on the base of plasma model with Compton scattering on Maxwellian electrons only. Results of calculations show that three-particle interactions play significant role even in non-relativistic plasma, both degenerate and not.

Secondly we study photon condensation in pair plasma in non-relativistic and relativistic cases. Another series of simulations of plasma thermalization for different final temperatures of 0.1, 0.2, and 0.3 $m_e c^2/k$ was performed for different initial states of pairs and photons. We find that Bose-condensation of photons in non-relativistic plasma appears as an intermediate state before full thermodynamic equilibrium. Condensate is represented by excess of photons over Plank distribution. For the condensation to occur initial spectrum of the photons should be narrow, while initial pair spectrum form is unimportant. Initial number density of photons should be higher than final thermal one. Simulations performed for 3-, 5-, 7- and 10-fold excess of photon number over final one shows no dependence of condensation on the initial excess (degeneracy). Additional series of simulations with relativistic temperatures of plasma was performed using kinetic coefficients calculated earlier (energy grid is from 0.1 to 150 $m_e c^2$). Bose-condensation appeared to occur for a state with final temperature of 3 $m_e c^2/k$, however the form of photon spectrum is different from non-relativistic case due to difference in reaction rates.

4.4 Gravitationally induced dephasing in timed Dicke state decay

Fourth line of research is pushed by Vlad Stefanov and Ivan Siutsou together with Dmitriy Mogilevtsev of Center of Quantum Optics and Quantum Information of B.I. Stepanov Institute of Physics (National Academy of Sciences of Belarus). We recovered an effect of dephasing induced by a weak gravitational field on the collective radiation dynamics of atomic system in timed single-photon Dicke states. We show that a photon absorbed by the stationary system of randomly placed stationary atoms is no more spontaneously emitted in the direction of the impinging photon. The influence of gravity leads to broadening of the angular distribution of emission. This result is under second round of review at Physical Review D (arXiv:1905.12301).

Curiously, it appears that basic features of the effect are retained in the presence of gravity: a pure entangled gravity-affected timed Dicke state is formed after photon absorption, emitted field does not depend on the size of the atomic system. However, different time-dilation in different parts of the system leads to the broadening of the angular distribution of the emitted photon. This broadening is asymmetric with respect to the direction of the gravity gradient: we have a finite width distribution of directions around the vector of initial photon $\vec{k}_0$. The spread of wave-vectors around the wave-vector of the impinging photon is defined by the quantity $a\nu/\Gamma$, distribution of k_z being

$$G_{k_z} = \frac{-i}{a\nu} \exp\left[-(k_{0z} - k_z)\frac{\Gamma}{a\nu}\right] \Theta[k_{0z} - k_z], \tag{4.4.1}$$

where $\Theta[k_{0z} - k_z]$ is the Heaviside step function. Notice that this spread is asymmetric, the photon tends to deviate toward the direction of gravitational attraction. Also, not only the emission direction is "blurred". The photon energy is changed, so the external observer will see the superposition of photon wave-packets with frequencies different from the original one, with the width of this frequency spread being

$$\delta\nu \approx \frac{ac\nu}{\Gamma} \cos\theta_0, \tag{4.4.2}$$

here θ_0 is the angle between z-direction and $\vec{k}_0$. Eq. (4.4.2) demonstrates that indeed the gravitation influence quantum interference in the process of spontaneous emission of a delocalized collective single-excitation state. As the result, for the emitted field this influence looks like dephasing. Of course, it is not large. Near the Earth surface $a = 2 \cdot 10^{-16}$ 1/m, for typical values of the spontaneous emission rate $\Gamma \approx 10^8$ Hz and optical frequencies $\nu \approx 10^{15}$ Hz, the frequency spread (4.4.2) is about several Hz. But near the stronger gravitating bodies (especially in the vicinity of black holes) this effect will be considerably more pronounced.

5 Hardware development for scientific computing

Due to requirement of heavy parallel computing the main focus in hardware development in 2019 was the construction of the workstation of ICRANet-Minsk. Research of market shows that the most cost-effective solution for double precision computations currently is Tahiti chips of AMD production with prices on secondary market of $\sim$50 €. A growing collection of them has reached 23 pieces at the end of the year, with 14 already working in the ICRANet-Minsk workstation providing 14 TFLOPS of peak processing power in double precision (which is about 1 per cent of the most powerful supercomputer in Belarus SKIF-SOYUZ). It uses ASUS B250-MINING-EXPERT motherboard, 2-core processor Intel i3-7100 with 32 Gb of DDR4 non-ECC Hynix memory, system SSD and storage HDD, and 2 power supplies: Aerocool ACPS-1800W ATX and HAFF-2000, within a special framed case. The workstation is depicted on Fig. 5.1. Partial funds for the workstation are provided by Ivan Siutsou.

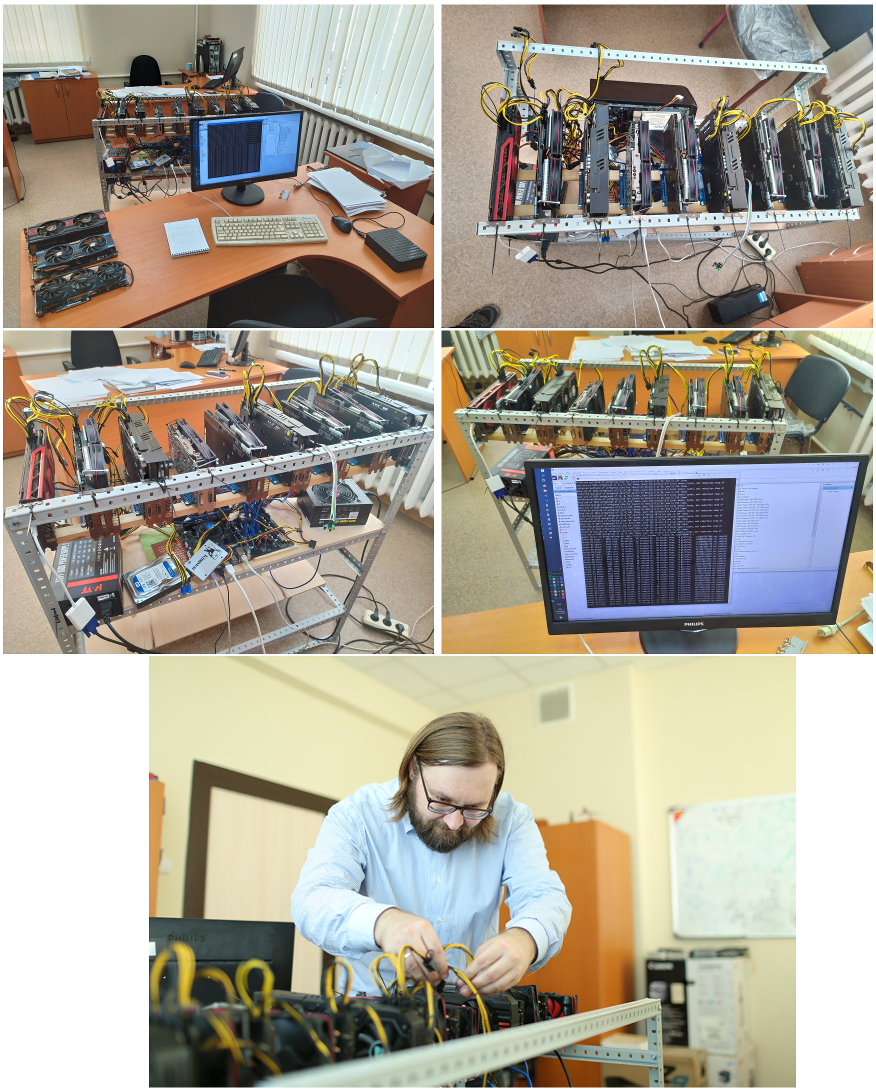

Figure 5.1: Workstation of ICRANet-Minsk center: 14 Tahiti chips, 14 TFLOPS in double precision

6 Teaching and outreach

ICRANet-Minsk stuff performs teaching activities. Mikalai Prakapenia is a lecturer in theoretical mechanics and electrodynamics in the Belarusian State University, while Ivan Siutsou gives lectures on nonlinear physics, astrophysics and physical kinetics for master students of the Graduate School of the National Academy of Sciences of Belarus.

ICRANet-Minsk is active in popularization of physics and astrophysics. Ivan Siutsou provided two reports: on superluminal motion and time machines in General Relativity and on modern cosmology, for the methodological seminar of the Institute of philosophy of the National Academy of Sciences of Belarus. Three interviews of Ivan Siutsou were published in Belarusian newspapers:

- The Universe: from Big Bang to expansion,
- National astrophysicists already have the first know-how,
- To touch the stars and catch a comet by the tail.

Also Ivan Siutsou was one of three invited speakers on a public lecture in occasion of the Nobel prizes for astrophysics on December 8th, 2019, and gave three comments on TV on time in physics (first) and cosmic weather (others), broadcasted correspondingly April 11th, December 14th (ONT), December 21st (Belarus 3, Science-mania) of 2019.

7 Publications 2019

1. M. A. Prakapenia, I. A. Siutsou and G. V. Vereshchagin, “Thermalization of electron-positron plasma with quantum degeneracy”, Physics Letters A 383 (2019) pp. 306-310.

   The non-equilibrium electron-positron-photon plasma thermalization process is studied using relativistic Boltzmann solver, taking into account quantum corrections both in non-relativistic and relativistic cases. Collision integrals are computed from exact QED matrix elements for all binary and triple interactions in the plasma. It is shown that in non-relativistic case (temperatures $k_B T \leq 0.3 m_e c^2$) binary interaction rates dominate over triple ones, resulting in establishment of the kinetic equilibrium prior to final relaxation towards the thermal equilibrium, in agreement with the previous studies. On the contrary, in relativistic case (final temperatures $k_B T \geq 0.3 m_e c^2$) triple interaction rates are fast enough to prevent the establishment of kinetic equilibrium. It is shown that thermalization process strongly depends on quantum degeneracy in initial state, but does not depend on plasma composition.

2. M. A. Prakapenia and G.V. Vereshchagin, “Bose-Einstein condensation in relativistic plasma”, European Physics Letters, accepted for publication.

   The phenomenon of Bose-Einstein condensation is traditionally associated with and experimentally verified for low temperatures: either of nano-Kelvin scale for alkali atoms [1-3] or room temperatures for quasi-particles [4,5] or photons in two dimensions [6]. Here we demonstrate out of first principles that for certain initial conditions non-equilibrium plasma at relativistic temperatures of billions of Kelvin undergoes condensation, predicted by Zeldovich and Levich in their seminal work [7]. We determine the necessary conditions for the onset of condensation and discuss the possibilities to observe such a phenomenon in laboratory and astrophysical conditions.

3. V. Stefanov, I. Siutsou, D. Mogilevtsev, “Gravitational decoherence effects on spontaneous emission of atomic ensembles in timed Dicke

state", submitted for publication, arXiv:1905.12301.

Here we discuss an effect of gravitational decoherence due to time dilation on the collective radiation dynamics of atomic system in timed single-photon Dicke states. We show that a photon absorbed by the stationary system of randomly placed stationary atoms is no more spontaneously emitted in the direction of the impinging photon. Time-dilation effect leads to broadening of the angular distribution of the emitted photon. Even for the spherically symmetric gravitational field, the broadening has specific non-symmetrical character.