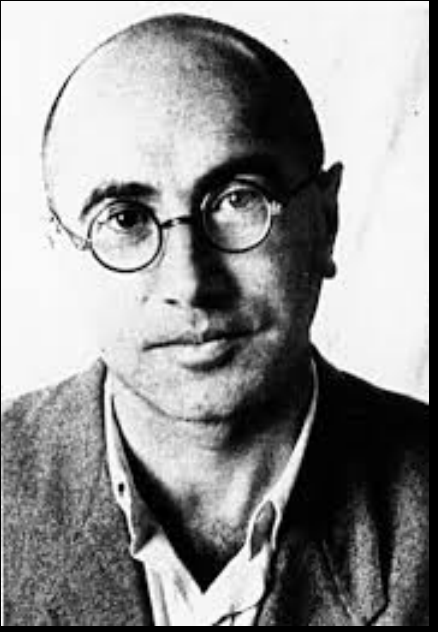


Ya. B. Zeldovich:

Chemist,

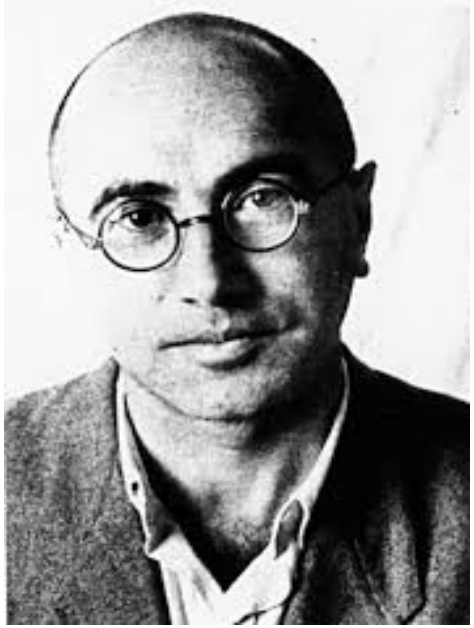
Nuclear Physicist,

Cosmologist

Varun Sahni
IUCAA
Pune, India

Yakov Borisovich Zeldovich was enormously talented !

Major contributions in:



- Chemical physics (adsorption & catalysis)
- Theory of shock waves
- Thermal explosions
- Theory of flame propogation
- Theory of combustion & detonation
- Nuclear physics
- Particle physics
- Astrophysics and Cosmology

Total scientific output includes over 500 research articles and 20 books.

Hawking: ``*Now I know you are a real person and not a group of scientists like Bourbaki*”

Remarkably, Zeldovich received no formal university education !

He graduated from high school at the age of 15 after which he joined the *Institute for Mechanical Processing of Useful Minerals* to train as a laboratory assistant.

The Soviet scientist Ioffe was very impressed by the young Zeldovich and wrote a letter to his institute requesting that Zeldovich be ``released to science''.

It is rumoured that Zeldovich was traded for a fuel pump !

Zeldovich defended his PhD in 1936 and, years later, reminiscenced of:

``the happy times when permission to defend [a PhD] was granted to people with no higher education''.

The fact that Zeldovich was primarily self-taught enormously influenced his style of doing research and also teaching.

During the 1930's, Zeldovich extensively worked on nuclear physics writing seminal papers demonstrating the possibility of controlled fission chain reactions among uranium isotopes. Soon the USSR was in the grips of WW II.

According to Andrei Sakharov:
``*from the very beginning of Soviet work on the atomic (and later thermonuclear) problem, Zeldovich was at the very epicenter of events.'*
His role there was completely exceptional."

Zeldovich's earlier work on combustion paved the way for creating the internal ballistics of solid-fuel rockets which formed the basis of the Soviet missile program during the `great patriotic war' and after.

(Sadly, much of Zeldovich's work during this period remains classified.)

Zeldovich moved to Astrophysics in 1962 when he was nearing 50 !

Almost immediately he started making pioneering contributions in key areas:

Black hole physics,
Dark matter,
Quantum field theory in curved space-time,
The cosmological constant problem,
Topological defects,
CMB, Large scale structure, etc.

In 1962 Zeldovich showed that a **black hole** could be formed not only during the course of stellar evolution, but by any process which compressed matter to sufficiently high densities. This opened up the possibility for the formation of microscopically small black holes in the early Universe.

This was Zeldovich's first paper on General Relativity.
It was also the last paper which he discussed with Lev Landau before the latter's tragic car accident in 1962.

In 1964 Zeldovich suggested that a black hole may be detected by its Influence on the surrounding gas which would accrete onto the hole.

In 1966 (with Gusinov) he also suggested that one could look for a Black hole in a binary star system through the BH's influence on the motion of its bright stellar companion.

These papers helped create a paradigm shift in which black holes were elevated from `passive objects which were impossible to observe' to objects which created very significant activity around them.

Thus Zeldovich helped start a thriving area in astrophysics,
in which black hole candidates are being looked for within our galaxy as also in other galaxies and QSO's.

1967 – 1976: Particle production near black holes and in the early Universe.

• Zeldovich (1971) and his PhD student Starobinsky (1973) showed that the vacuum near black holes was unstable and that rotating black holes could create particle-antiparticle pairs in their vicinity.

• Precursor to `Hawking radiation (1975)'

• Particles could be copiously produced in the early universe.
If the universe was anisotropic to begin with, then particle production might isotropize it resulting in an isotropic FRW expansion !
(Zeldovich & Starobinsky, 1971)

Zeldovich's papers on particle production and his seminal work on the cosmological constant problem, laid the foundations for the important discipline of
`Quantum field theory in curved space-time'.

1966 -- 1978: Relic abundances – dark matter & topological defects.

In 1966 Gershtein and Zeldovich showed that massive relic neutrino's could very easily be the dominant matter component of the universe.

Subsequently used to explain dark matter by Marx & Szalay (1972)

In 1980 he discussed the problem of structure formation in a Hot dark matter Universe.

Zeldovich, Kobzarev and Okun (1974) and Zeldovich and Khlopov (1978) emphasized the enormous impact that topological defects, created in the early universe, could have on cosmology.
Monopoles and domain walls were disastrous, but cosmic strings were fine !

These early papers defined the dawn of a new field:
Astroparticle physics !

The CMB and large scale structure

• In 1970 Zeldovich suggested his famous `Zeldovich approximation' which describes the formation of filaments and pancakes from general initial conditions.

• In 1972 Zeldovich suggested the scale-invariant spectrum for primordial density fluctuations.

A decade later, a firm theoretical underpinning for this spectrum was provided by Inflationary Cosmology.

• 1972 also witnessed the publication of the famous `Sunyaev-Zeldovich' paper.

Also, influential papers on: percolation theory, superclusters and voids, catastrophe theory, etc. (with Arnold, Einasto, Shandarin and others)

1962-1966: Observational signatures of black holes.
BH's can be observed in binary stars and through accretion of matter !

• Paradigm shift: BH's are no longer passive objects !

1966: massive neutrino's can close the universe; paved the way for notion of non-baryonic dark matter.

1967: Cosmological constant problem: vacuum energy behaves just like Λ

$\langle T_{ik} \rangle_{\rm vac} = \Lambda g_{ik}$ Key idea for understanding Inflation and dark energy

1970: The *Zeldovich approximation*: new paradigm for LSS

1971: Particle creation near black holes and in early universe (with Starobinsky).

• Laid the foundations for the discipline of Quantum fields in curved space and precursor to Hawking radiation (1975)

1972: Suggested the scale-invariant spectrum for primordial fluctuations.

1972: Sunyaev-Zeldovich effect

1974: Paper on topological defects – paved the way for Astroparticle physics

THE COSMOLOGICAL CONSTANT AND THE THEORY OF ELEMENTARY PARTICLES

Ya. B. ZEL'DOVICH

Institute of Applied Mathematics, USSR Academy of Sciences

Usp. Fiz. Nauk 95, 209–230 (May, 1968)

Interest in gravitation theory with a cosmological constant was revived in 1967. Three papers were published, by Petrosian, Salpeter, and Szekeres in the USA[1] and by Shklovskii[2] and Kardashev[3] in the USSR, in which evolutionary universe models[1] in such a theory (the Λ models) are considered. The stimulus for the revival of the theory was provided by new observational data on remote quasistellar sources (quasars and quasags, QSR and QSG in the English-language literature).* It turned out, first of all, that for these objects the connection between the brightness and the red shift does not fit the simple models without a cosmological constant (and without assumptions concerning the evolution of the quasars!). In addition, as noted by the Burbidges[4], in ten quasars whose spectra have revealed absorption lines the red shift of these lines $z = (\lambda - \lambda_0)/\lambda_0$ lies in the narrow range $1.94 < z < 1.96$ or even $1.945 < z < 1.955$. This phenomenon will henceforth be referred to briefly as $z = 1.95$.

The Λ models were introduced in[1] to explain the observed relation between the red shift and the brightness; the explanation of $z = 1.95$ in the absorption spectrum was touched upon casually. References 2 and 3 are devoted entirely to the explanation of $z = 1.95$: the absorption lines are ascribed to galaxies lying along the path of the light ray arriving from the quasar. The predominant appearance of one value of z is attributed by the authors to the fact that with this z[2] the expansion of the universe was greatly slowed down both compared with the preceding period ($z > 1.95$) and compared with the succeeding period ($z < 1.95$ up to $z = 0$, corresponding to the present time). The slowed-down expansion leads to an increase of the path traversed by the ray in the corresponding interval of z, and increases the probability that the quasar light ray will encounter a galaxy and that absorption lines with precisely this value of z, i.e. about 1.95, will be imprinted in it.[3]

An expansion law with a sharp deceleration at a definite value of z is possible only for the Λ models; it is necessary here to satisfy with great accuracy the relation between the total amount of matter in the universe and the value of the cosmological constant Λ. The discussed model is closed in its three dimensional geometrical structure. As shown by Kardashev[3], the assumption

The cosmological constant was placed on a firm physical foundation by Zeldovich who showed that

$$\langle T_{ik} \rangle_{\rm vac} = \Lambda g_{ik}$$

ie. the vacuum had properties reminiscent of a Λ term !

Prescient statement which paved the way for future advances including Inflation (1980's) and Dark energy (2000).

``The Genie [cosmological constant] has been let out of the bottle, and it is no longer possible to force it back in''. – Zeldovich (1968)

Personal Reminiscences

My first meeting with Zeldovich took place in 1978.

Despite his busy schedule Zeldovich taught courses at Moscow State. He alternated between cosmology and stellar structure.

His lectures were remarkable !
He supported formal proof's with
Intuitive explanations, which made
his lectures a lot of fun !

A science magician….

His lectures were attended not only of students but also by senior scientists, who frequently stayed back to discuss ideas with Z.

A remarkable quality of Z was his willingness to learn from others and to publicly acknowledge the mistakes he had made.

In his cosmology class he admitted to us how he had misread the CMB data in the 1960's and so had inititially advocated the cold big bang instead of hot BB.

Z’s manner of conducting exams was also unusual !
There was no formal time table for a written test – instead Z met me outside his office, scribbled two problems and walked away...

It took me six months to find the answers !

What would life be without friends……..

Lev Kofman

Tallinn, Tartu …. Hawaii …. Toronto

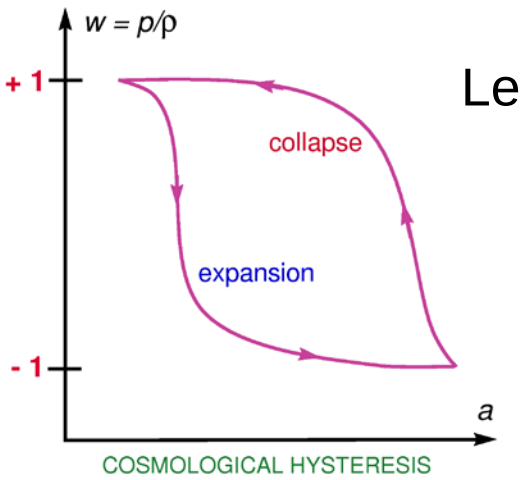
Zeldovich continuously modified and expanded his course material……

Upon attending his cosmology lectures 4 years later (1982) I found that a third of the material was new !

Inflation, phase transitions, topological defects, symmetry breaking…..

Zeldovich never pushed idea's simply because they were his own…..

Inflation:



COSMOLOGICAL HYSTERESIS

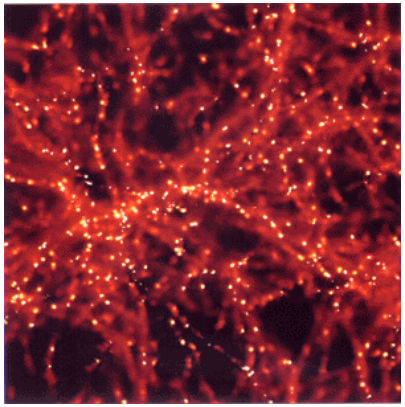
``There is a moral to be learned from these simple calculations. The result by and large conforms to Le Chatelier's principle, which also holds in human relations: Every system resists an outside force.'' –Ya.B.

A great sense of humour !

Z succeeded in explaining difficult ideas simply and with a lot of humour
-- a Science Magician !

Sometimes this got him into trouble.

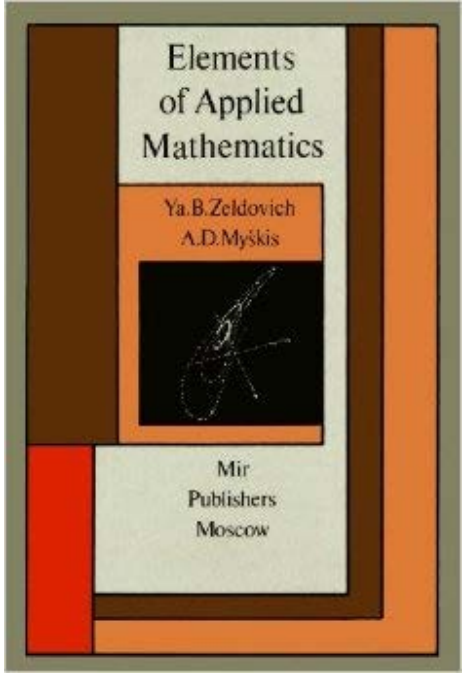
``The poor get poorer and the rich get richer'' – Ya B

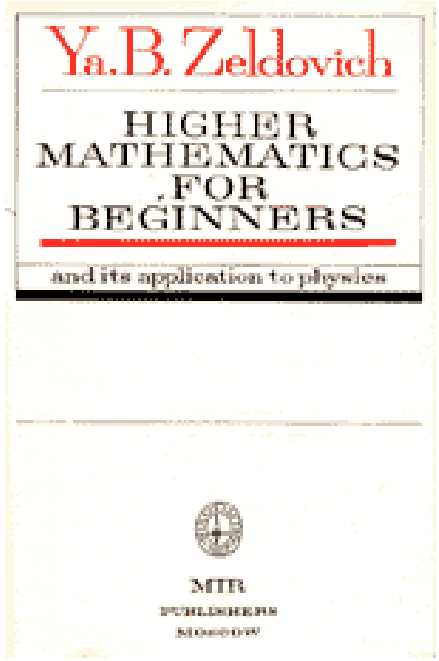


``Comrade, how dare you ascribe the laws of capitalism to the whole Universe ?''
-- Communist party

Zeldovich's ``effect on his pupils was remarkable; he often discovered in them a capacity for scientific creativity which, without him, would not have been realized or could have been realized in part and with great difficulty.''
-- Andrei Sakharov

His keen insight into what the student really needed made Z write monographs on several subjects including mathematics !





Mir publishers played a great role in acquainting Indian students with the Russian classics.

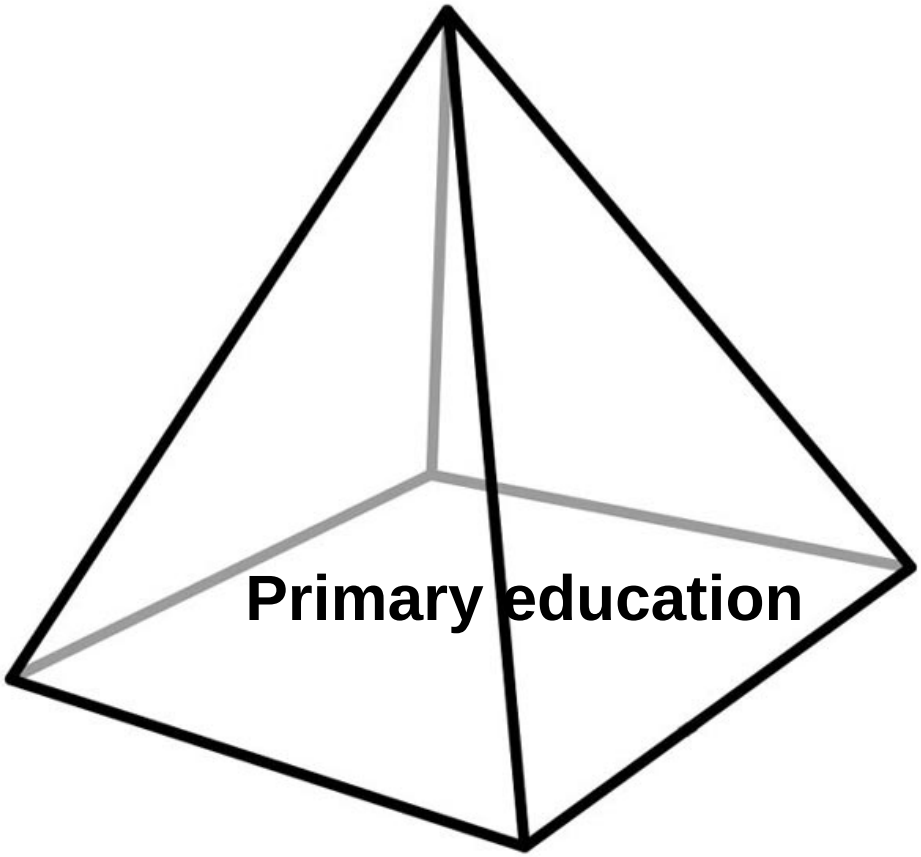
From Russian into English, Hindi, Urdu, Marathi,….

Zeldovich strove to explain complicated ideas simply through numerous entertaining articles and text books. He once wrote ``the so-called strict proofs and definitions are far more complicated than the intuitive approach to derivatives and integrals. As a result, the mathematical ideas necessary for an understanding of physics reach school-pupils too late. Its like serving the salt and pepper not for lunch but later – for afternoon tea''.

``I have this undergraduate level mathematical physics book written by Zeldovich that reads like a story.
One of the finds from the Daryaganj roadside Sunday market
that I used to frequent in Delhi.'' – Dr. Prava (Indian Inst. of Astrophysics)

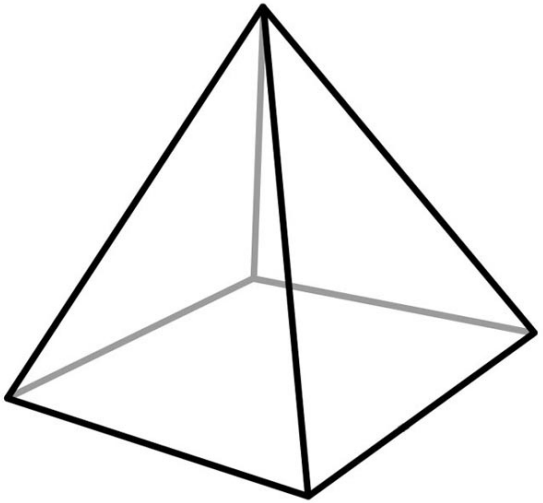
Soviet science school

Landau, Zeldovich, Kolmogorov, etc.



Soviet chess school

Taal, Karpov, Kasparov, etc.



Chess clubs in every town and city

Math and astronomy hobby circles were very widespread, books were extremely cheap !

Although extremely talented and very fond of travel
Zeldovich faced numerous travel restrictions.

In 1982 I was about to leave for India on holiday and was very keen that Zeldovich visit India as well…

Sadly, Z's India visit never did materialize and the following year I was a witness to the very bizarre policies of the Soviet government with respect to foreign travel by eminent scientists…..

Z was finally allowed to travel outside of the Soviet block in 1982, when at the age of 68 he spoke at the IAU in Greece.
When asked by Ostriker when he was last out of the Soviet Union Zeldovich replied ``sixty eight years ago'' -- in a previous life !

But if `Muhammed cannot go to the mountain then the mountain must come to Muhammed', and so many eminent scientists visited Moscow to meet Zeldovich (Hawking, Chandra,….)

PhD defence in Moscow in 1985 with my two Guru's !

Post-doc's in UK and Canada (CITA) before joining IUCAA in 1991.

No IUCAA back in 1991, just trees and snakes and scorpions...
Built a beautiful institution from scratch ! (J.V. Narlikar – founding director)

The first **Zeldovich meeting** in Cosmology at IUCAA (1995)

(organized by VS & Sergei Shandarin)

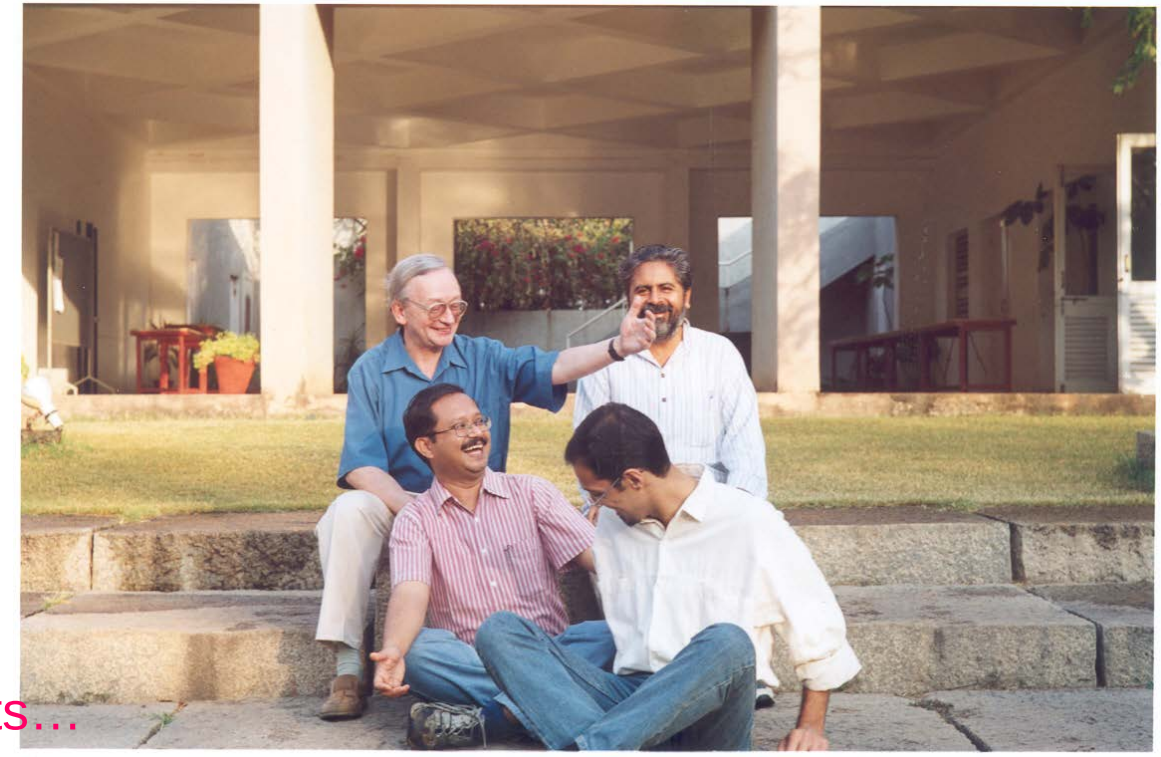
Zeldovich & Starobinsky school in India:

Alexei Starobinsky with **Varun Sahni**
Jatush Sheth, **Tarun Souradeep**,
Ujjaini Alam, Sanjit Mitra, Amir Hajian

The way ahead…….

Also: Dipak Munshi,
Tarun Saini,
Arman Shafieloo,
Rajib Saha, Tuhin Ghosh,
Moumita Aich, Nidhi Joshi
Amir Aghamousa,
Gaurav Goswami,
Aditya Rotti, Santanu Das,
Satadru Bag,
Suvodip Mukherjee, etc.

Zeldovich's great-grand students…



Thank You !!

The significant problems we have cannot be solved at the same level of thinking with which we created them.

--- Albert Einstein

Perhaps this is also true for Dark Energy !

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A remarkable quality of Z was his willingness to learn from others and to publicly acknowledge the mistakes he had made.

In his cosmology class he admitted to us how he had misread the CMB data in the 1960's and so had inititially advocated the cold big bang instead of hot BB.

His great gift was of being able to explain complex ideas very simply.

True for other members of the Landau school as well !

Those were the days my friend…….

Memories of Moscow Days …..

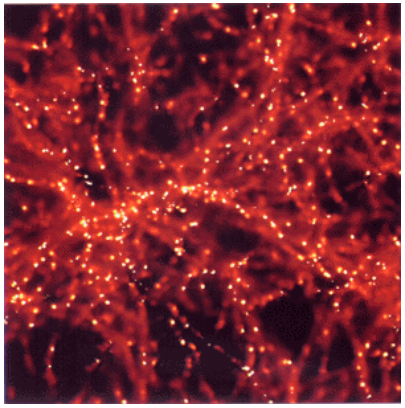
Of Ya.B. Zeldovich…

and of his school !

Varun Sahni
IUCAA
Pune, India

The formation of high density regions in the distribution of matter on the cosmic web is similar to the formation of caustics in light !

Caustics form on the Cosmic Web



Trajectories of matter intersect to form the Cosmic web

After passing through glass/water neighboring light trajectories intersect to form caustics where the intensity of light is exceedingly bright !

Caustics in the distribution of light

Zeldovich, 1970

Shandarin and Zeldovich Rev Mod Phys 1989