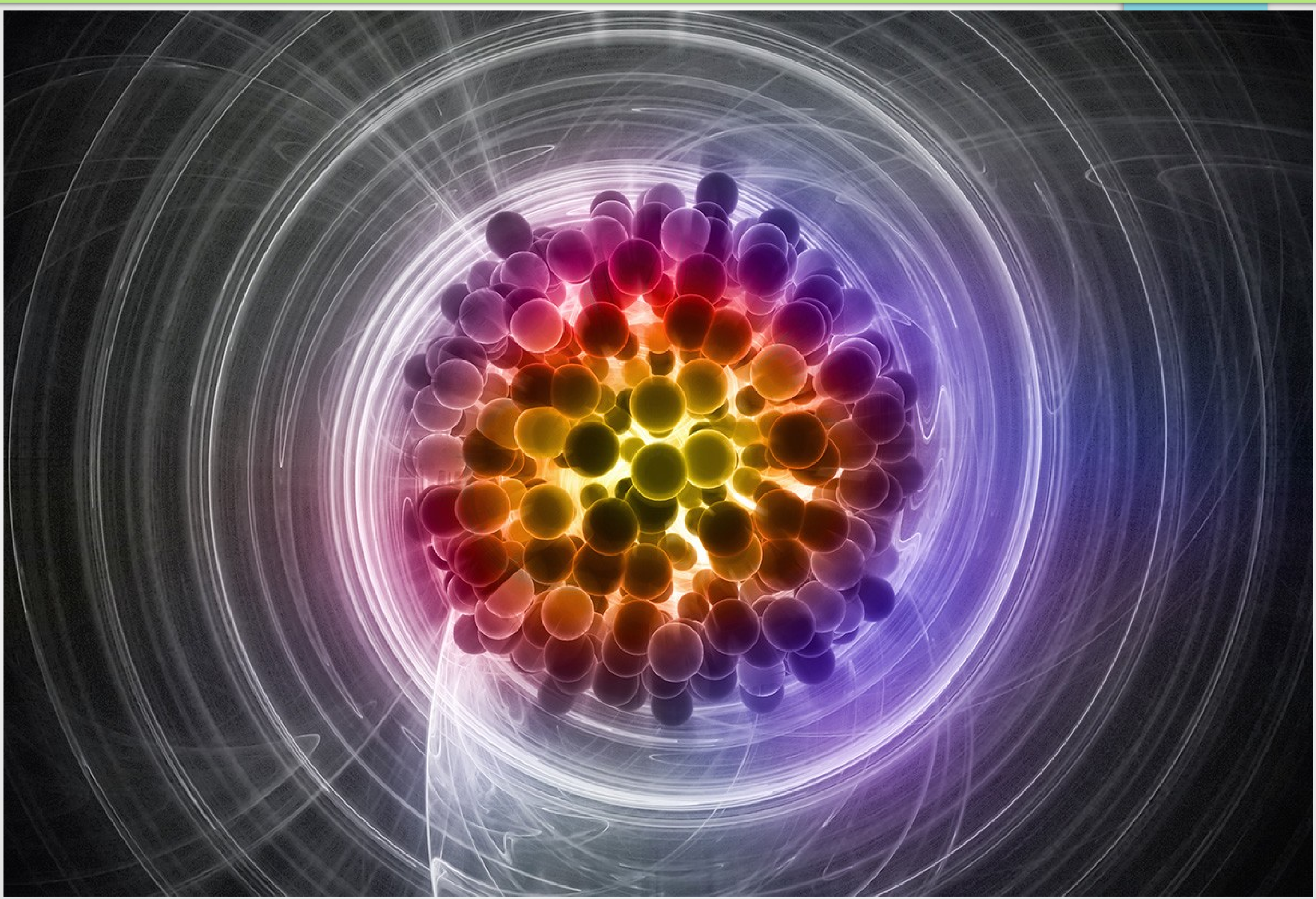
# Quark Gluon Plasma and Supersymmetry

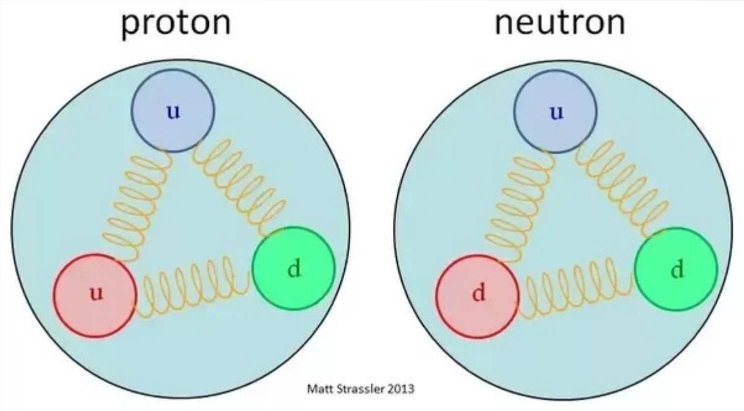


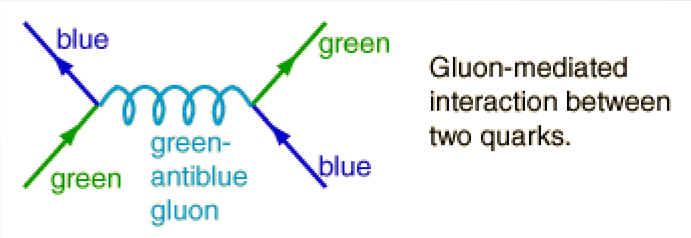
22-06-2022

Rivu Adhikary M21-192

# Theory of strong interaction

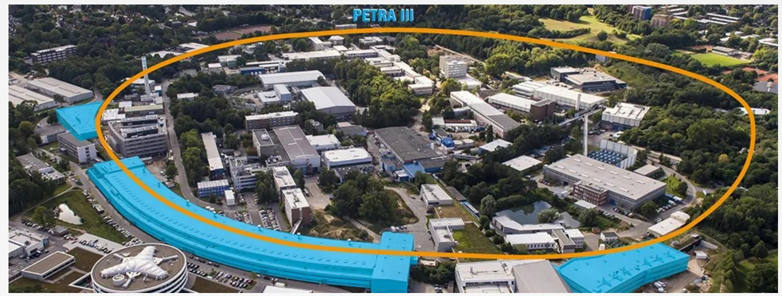
- Popularly known as Quantum Chromo Dynamics (QCD).
- Strong force describes the binding of quarks (spin 1/2) to gluons (vector boson with spin 1) to make hadrons.
- There are 3 different charges ("colors") – red , green , blue.
- There are 6 flavors of quarks – up , down , charm, strange , top and bottom.
- There are 8 different gluons. The gluons can exchange color of a quark but not its flavor.
- Main features of QCD – Confinement , Asymptotic freedom , (Hidden) chiral symmetry.
- QCD is a non-abelian gauge theory invariant under SU(3). If the symmetry group is non-commutative, then the gauge theory is referred to as non-abelian gauge theory.

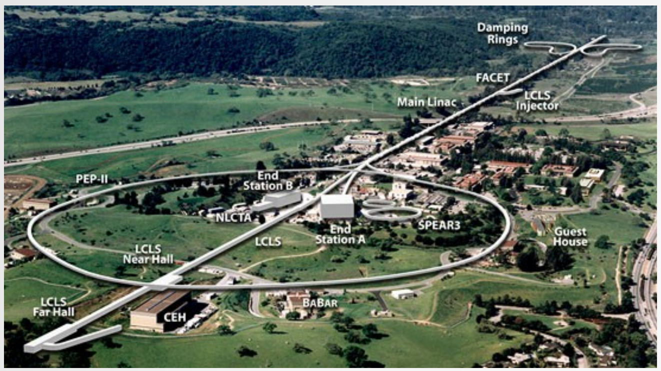


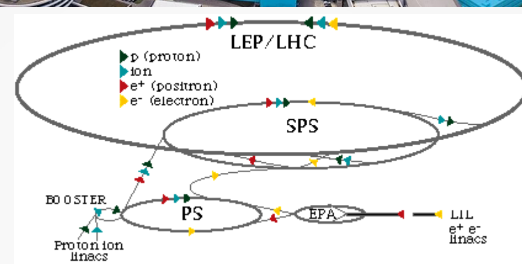
# Experimental Evidences

*PETRA DESY*

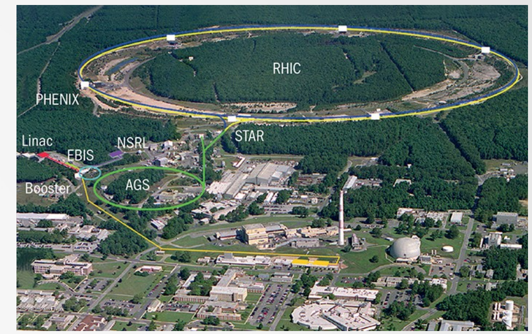



*SLAC*




*SPS CERN*

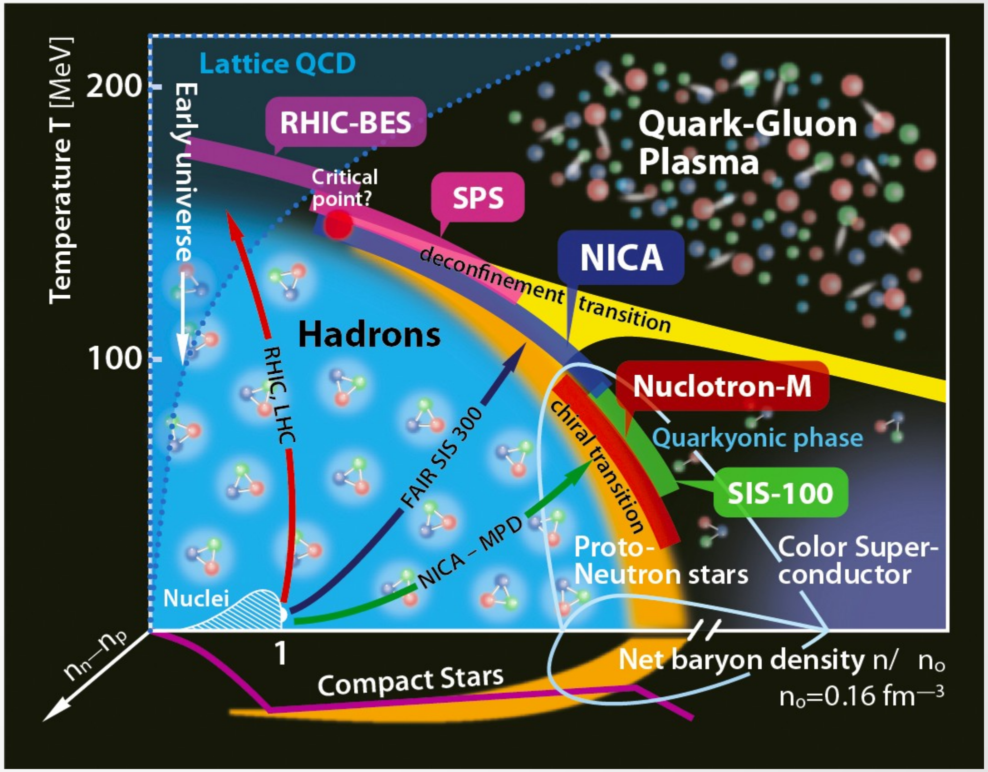



*RHIC*

- Key evidence of **quark**’s existence came from a series of inelastic electron-nucleon scattering experiments at SLAC (Stanford Linear Accelerator Centre), USA between 1967 – 73.
- Existence of **gluons** was confirmed forty years ago, in 1979, from the experiments of electron–positron annihilation by the TASSO experiment at PETRA, DESY laboratory in Germany.
- Electron–positron annihilation would occasionally produce three “jets” of particles, one of which being generated by a gluon radiated by a quark–antiquark pair.
- The first signature of strange quarks and dip in the number of J/Ψ mesons reaching the detectors at the Super Proton Synchrotron (SPS) in CERN few decades ago,hinted to the formation of a new state of matter.
- Further Experiments at RHIC, BNL revealed comprehensive iinformation about  the properties of this extreme matter , termed as the **Quark Gluon Plasma** (QGP).

# Quark Gluon Plasma

- Also known as Quark Matter, QGP is an interacting localized assembly of quarks and gluons at thermal (local kinetic) and (close to) chemical (abundance) equilibrium.
- The word plasma signals that color charged particles (quarks and/or gluons) are able to move in the volume occupied by the plasma.
- The temperature is above Hagedorn temperature Th=150 MeV (of order 10^12 kelvins) .
- The density rises to the point where the average inter-quark separation is less than 1 fm (quark chemical potential μ around 400 MeV).
- This QGP fireball is in the so-called (color) deconfined phase of matter.
- This form of matter preceded in time in the early Universe, when it was 10-30 microseconds "old".



# Space Time and Internal Symmetries

***Continuous*** spacetime symmetries are symmetries involving transformations of space and time :

- *Time translation* ( eg: gravitational potential energy )
- *Spatial translation* (temperature)
- *Spatial rotation* (rotational symmetry)
- *Poincaré transformations* (full symmetry of special relativity : translations, rotations and boosts)
- *Projective symmetries* (preserve the geodesic structure of spacetime)
- *Inversion transformations* (conformal one-to-one transformations on the space-time coordinates)

***Discrete symmetry*** is a symmetry that describes non-continuous changes in a system

- *CPT symmetry*
- *Supersymmetry*

| Class | Invariance | Conserved quantity |
|---|---|---|
| Proper orthochronous Lorentz symmetry | translation in time (homogeneity) | energy |
| | translation in space (homogeneity) | linear momentum |
| | rotation in space (isotropy) | angular momentum |
| | Lorentz-boost (isotropy) | mass moment $\mathbf{N} = t\mathbf{p} - E\mathbf{r}$ |
| Discrete symmetry | P, coordinate inversion | spatial parity |
| | C, charge conjugation | charge parity |
| | T, time reversal | time parity |
| | CPT | product of parities |
| Internal symmetry (independent of spacetime coordinates) | U(1) gauge transformation | electric charge |
| | U(1) gauge transformation | lepton generation number |
| | U(1) gauge transformation | hypercharge |
| | $U(1)_Y$ gauge transformation | weak hypercharge |
| | U(2) [ U(1) × SU(2) ] | electroweak force |
| | SU(2) gauge transformation | isospin |
| | $SU(2)_L$ gauge transformation | weak isospin |
| | P × SU(2) | G-parity |
| | SU(3) "winding number" | baryon number |
| | SU(3) gauge transformation | quark color |
| | SU(3) (approximate) | quark flavor |
| | S(U(2) × U(3)) [ U(1) × SU(2) × SU(3) ] | Standard Model |

# Coleman-Mandula Theorem

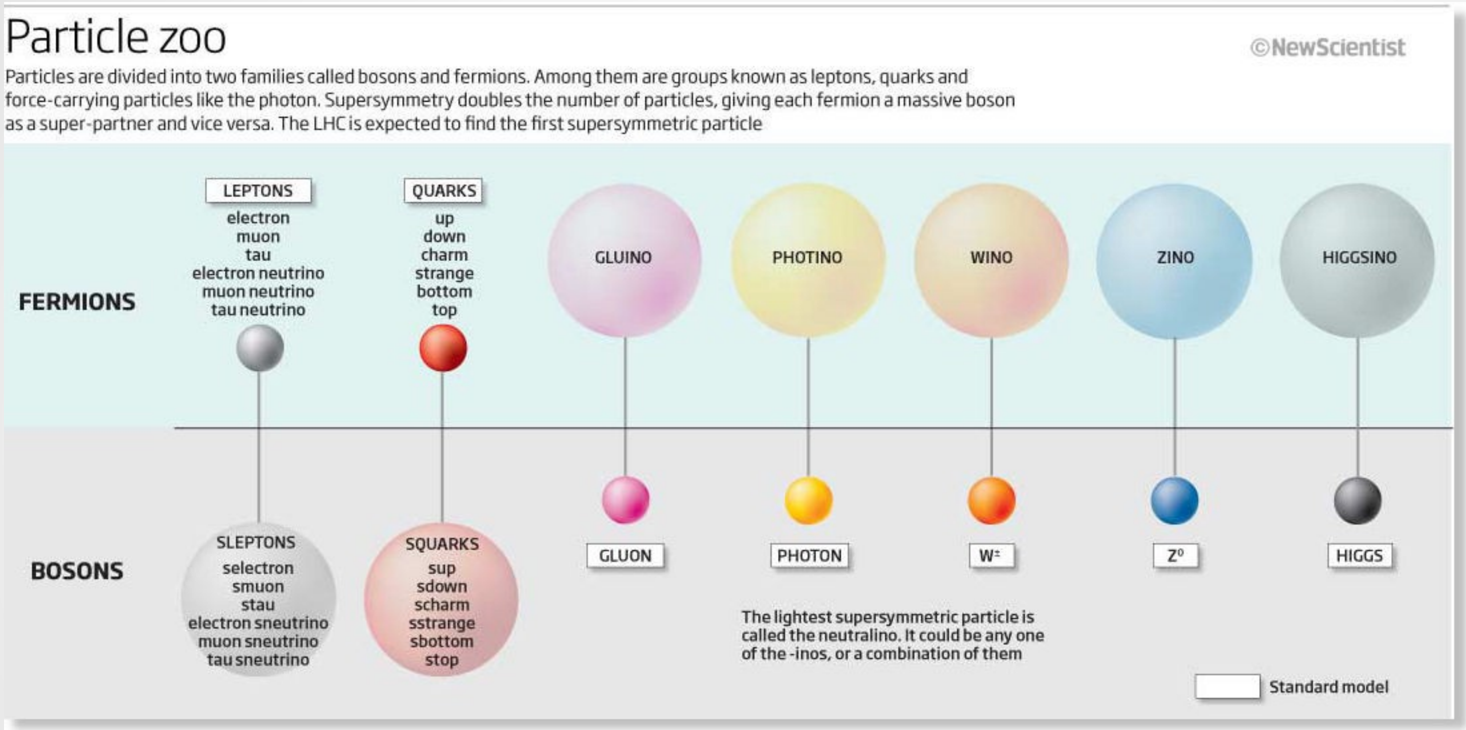
- A no-go theorem (when a particular situation is not physically possible) in theoretical physics.
- Authored by Sidney Coleman and Jeffrey Mandula, the Coleman-Mandula theorem states that space-time and internal symmetries cannot be combined in any but a trivial way.
- In other words, the symmetry group of a consistent 4-dimensional quantum field theory is the direct product of the internal symmetry group and the Poincaré group.
- Few limitations :

***a)*** The theorem only makes a statement about the unification of the Poincare group with an internal symmetry group. Different consequences will occur if it is applied to other space time symmetries.

***b****)* It only constrains the symmetries of the S-matrix itself. It places no constraints on spontaneously broken symmetries .

***c****)* It only applies to discrete Lie algebras and not continuous Lie groups.

# SuperSymmetry




***Supersymmetry*** (SUSY) is a spacetime symmetry between two basic classes of particles: **bosons**, which have an integer-valued spin and follow *Bose–Einstein statistics*, and **fermions**, which have a half-integer-valued spin and follow *Fermi–Dirac statistics*.

The Minimal Supersymmetric Standard Model (MSSM) is an extension to the Standard Model. This model proposes the presence of neutralinos, a (WIMP) dark matter candidate, which could provide evidence for grand unification or the viability of string theory.

Furthermore, owing to the limitations of the Coleman-Mandula theorem, **Supersymmetry** may be considered a possible "loophole" of the theorem as it supercharges that are not scalars but rather spinors.

Haag–Łopuszański–Sohnius theorem is the corresponding theorem for SUSY theories with a mass gap.

# Possibility of SUSY partners in QGP state

- SUSY can be related to QCD by using N=2 and N=4 super gravity models.
- All processes in nature are based on specific symmetries (eg . Charge of leptons or quark content of baryons).
- The interconversion between bosons and fermions during decay, annihilation or production processes points out to the connectedness of the two fields. (eg. beta decay)
- It is possible that the Universe at its earliest stages might have been supersymmetric (an unified bosonic and fermionic field, which later broke out during the inflation period).
- The massive supersymmetric partners (squarks and gluinos) were formed for about a yoctosecond before decaying into quarks and gluons in the QGP state which existed for roughly around a few microseconds before forming baryons.
- Stronger colliders exceeding the current energy scales in next few years might reveal this phenomenon and we can succeed in a better understanding of our very existence.

# References


- 1. Coleman, Sidney; Mandula, Jeffrey (1967). "All Possible Symmetries of the S Matrix". Physical Review. 159 (5): 1251. Bibcode:1967PhRv..159.1251C.doi:10.1103/PhysRev.159.1251.
- 2. Griffiths, D. Introduction to Elementary Particles. Wiley, New York, 1987.
- 3. Perkins, D. H. Introduction to High Energy Physics. Cambridge University Press, Cambridge, UK, 2000.
- 4. M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018) and 2019 update.
- 5. J. Adams, et al, [STAR Collaboration], Nucl. Phys. A 757 (2005) 102-183;nuclex/ 0501009.
- 6. K. Adcox et al, [PHENIX Collaboration], Nucl. Phys. A 757 (2005) 184-283;nuclex/0410003.
- 7. I. Arsene et al, [BRAHMS Collaboration], Nucl. Phys. A 757 (2005) 1-27; nuclex/0410020.
- 8. B. B. Back et al, [PHOBOS Collaboration], Nucl. Phys. A 757 (2005) 28-101;nuclex/ 0410022.
- 9. Niida, T., Miake, Y. Signatures of QGP at RHIC and the LHC. Association of Asia Pacific Physical Societies (AAPPS) Bulletin. Springer. 31,12 (2021). https://doi.org/10.1007/s43673-021-00014-3. Springer

10. Rafelski J. Discovery of Quark Gluon Plasma: Strangeness Diaries (2020). https://doi.org/10.1140/epjst/e2019-900263-x. Eur. Phys J. Special Topics 229, 1– 140 (2020).

11. B. Muller and J. Nagle, Annu. Rev. Nucl. And Part. Phys.1 (2006)

12. Annala, Eemeli; Gorda, Tyler; Kurkela, Aleksi; Nättilä, Joonas; Vuorinen, Aleksi (2020-06-01). "Evidence for quark-matter cores in massive neutron stars". Nature Physics. 16 (9): 907–910. arXiv:1903.09121. doi:10.1038/s41567-020-0914-9. ISSN1745-2481.

13. Khlopov M. Fundamentals of Cosmic Particle Physics. Cambridge International Science Publishing Ltd and Springer, 2012.

14. Das A., & Ferbel T. Introduction to Nuclear and Particle Physics. Singapore: World Scientific Publishing Co. Pte. Ltd, 2003.

15. N. Seiberg and E. Witten, Monopoles, duality and chiral symmetry breaking in N=2 supersymmetric QCD, Nucl. Phys. B 431, 484 (1994) [hep-th/9408099].

16. Y.-B. Yang, J. Liang, Y.-J. Bi, Y. Chen, T. Draper, K.-F. Liu, and Z. Liu, “Proton mass decomposition from the QCD energy momentum tensor,” Phys. Rev. Lett. 121, 212001 (2018).

# Thank you for your attention