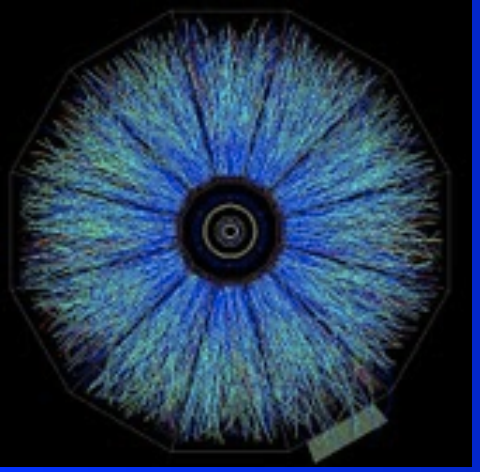


Los Alamos National Laboratory, 5/14/2015

A Beginner's Guide to Recreating the Early Universe

Xin-Nian Wang

Central China Normal University
Lawrence Berkeley National Laboratory

Forms of matter

火	水	土
(gas)	(liquid)	(solid)

Bose-Einstein condensate, fermionic condensate, superfluids, supersolids, paramagnetic, ferromagnetic, liquid crystals, …
quark-gluon plasma

Prerequisite

Convention: Natural Units

$$c = 1 \quad \hbar = 1$$

energy: $1\ eV = 1.6\,10^{-19}\mathrm{J}$

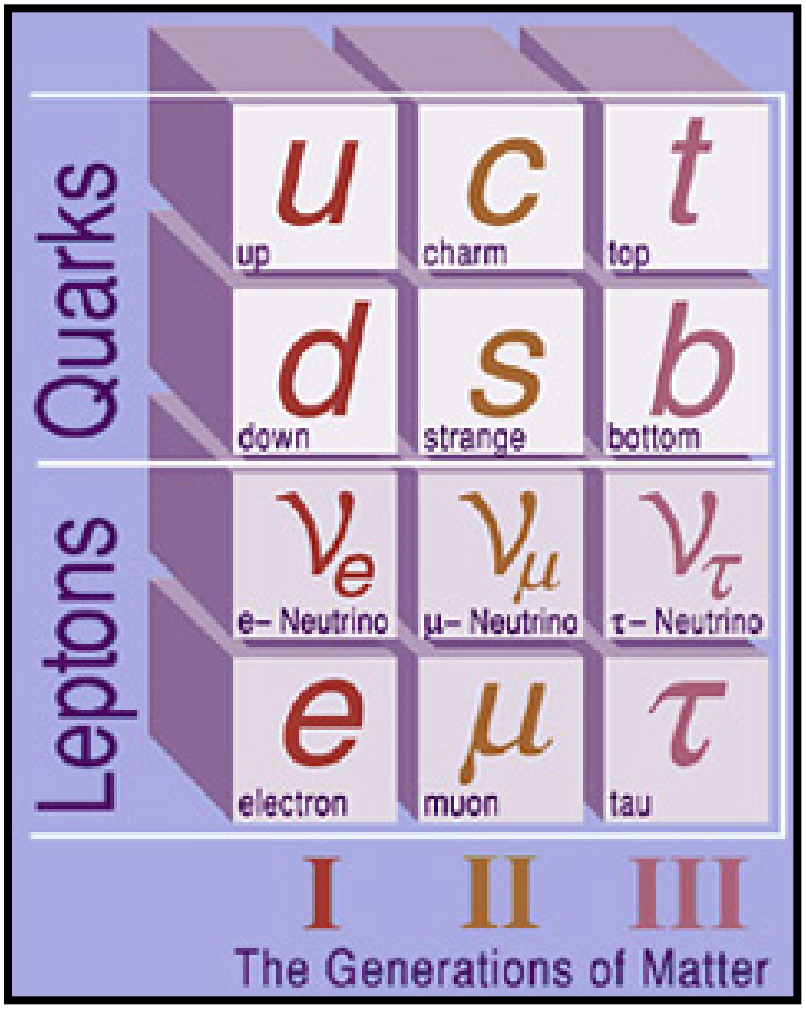
mass: $1\ eV/c^2 = 1.78\,10^{-36}\,\mathrm{kg}$

$$m_e = 0.51\ \mathrm{MeV}/c^2 \qquad m_p = 0.938\ \mathrm{GeV}/c^2$$

$$\mathrm{length}:\ fm = 10^{-15}\ m$$

$$\mathrm{time}:\ fm/c = 3.336\,10^{-24}\ s$$

Building blocks in the Standard Model



g (gluon): Strong interaction

W, Z boson: Weak interaction

γ (photon): EM interaction

Mass: Gravitation

Higgs boson:
Origin of mass

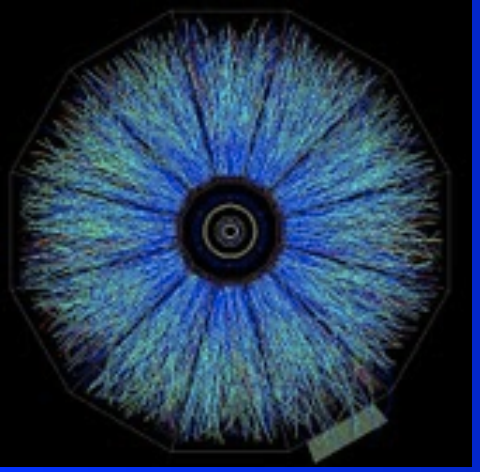
Mass in our Universe

Nucleon

$$m_u = 2.3 \;\; MeV/c^2 \qquad m_d = 4.8 \;\; MeV/c^2$$

$$m_p = 938.3 \;\; MeV/c^2 \qquad m_n = 939.6 \;\; MeV/c^2$$

(uud) $\qquad$ (udd)



Quantum Chromodynamics

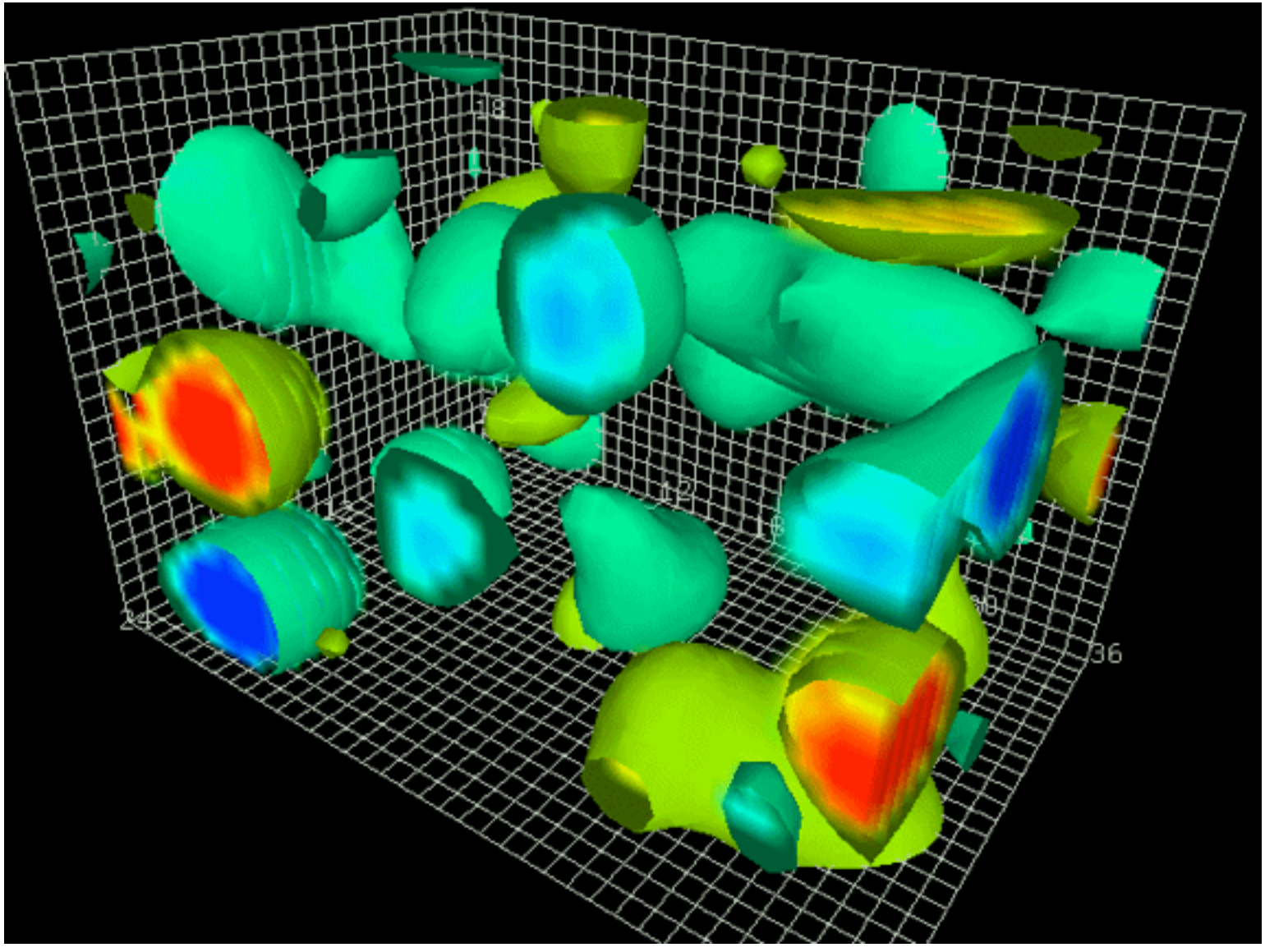
$$-\frac{1}{2g^2}\mathrm{tr}F_{\mu\nu}F^{\mu\nu}+\bar{\psi}\{i\gamma_\mu(\partial^\mu+iA_\mu)+m\}\psi$$

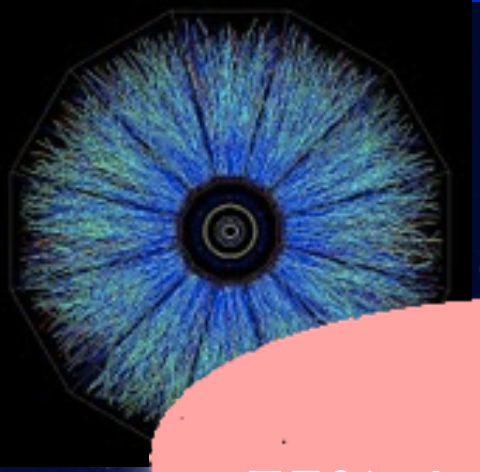
quarks: spin ½, 3 colors **gluons: spin 1, 8 colors**

Non Abelian Gauge Field => gluon-gluon interaction

Topological charge fluctuation in QCD vacuum

Derek B. Leinweber



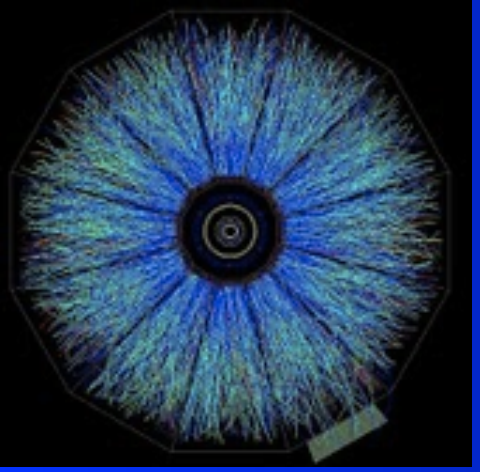


nucleon

$$m_N \bar{u}(p)u(p) = \langle N(p)|\frac{\alpha_s}{2\pi}F^a_{\mu\nu}F^{\mu\nu}_a|N(p)\rangle + \sum_{q=u,d,s} m_q \langle N(p)|\bar{\psi}_q\psi_q|N(p)\rangle$$

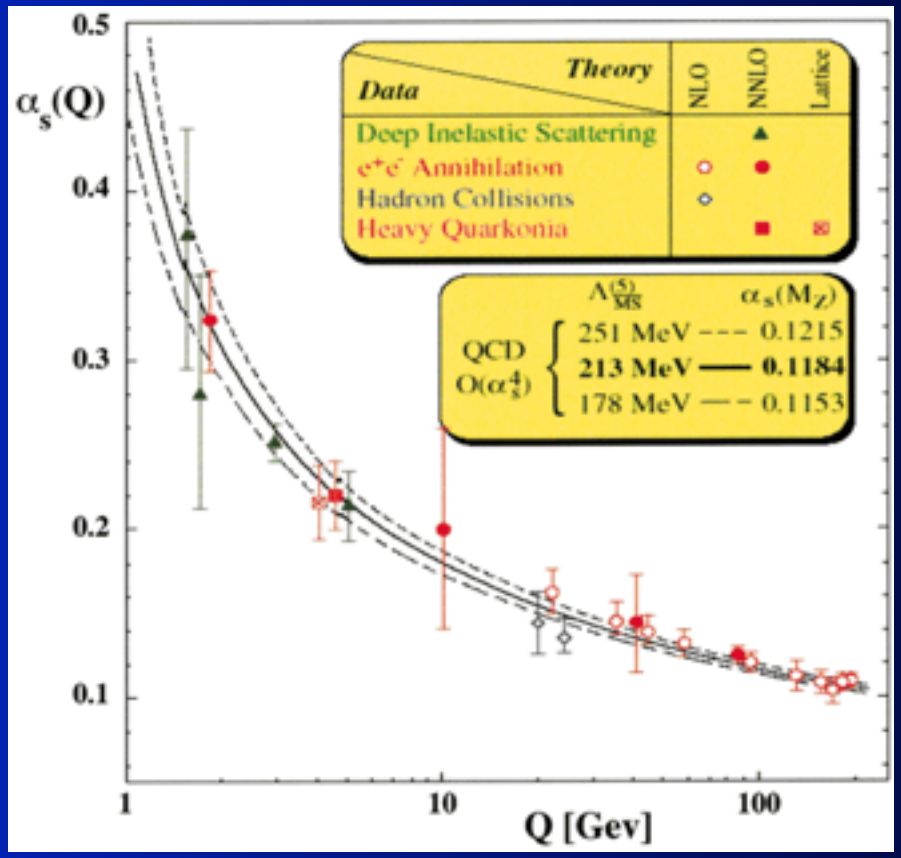
Nucleon mass = gluon (95%) + quark

origin of mass ⟷ vacuum structure

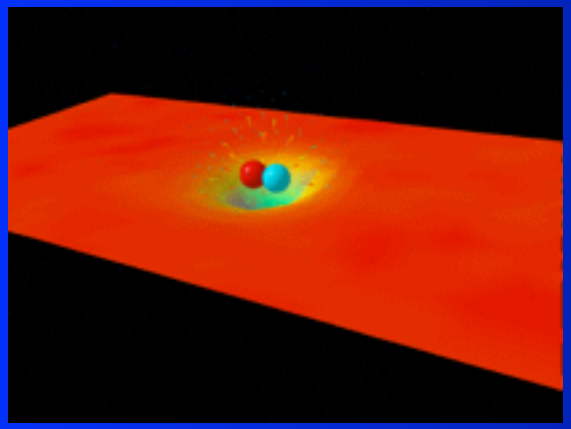


Asymptotic freedom & confinement in QCD

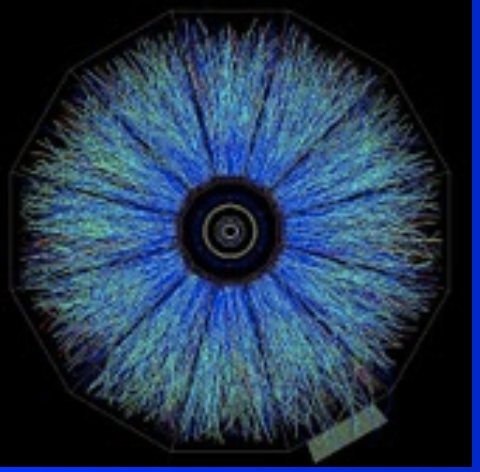
Strong Coupling constant



Derek B. Leinweber

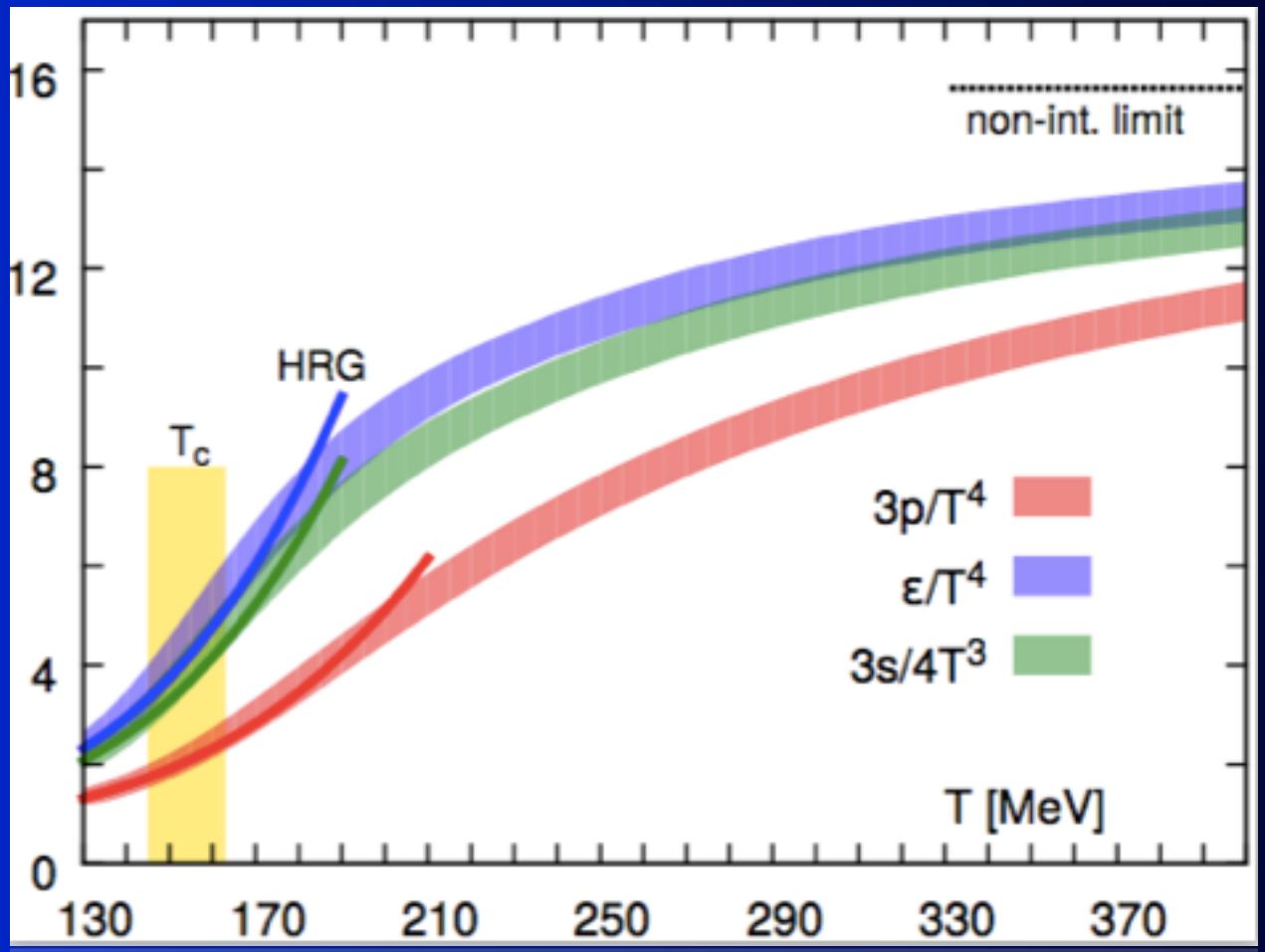


(2004 Nobel



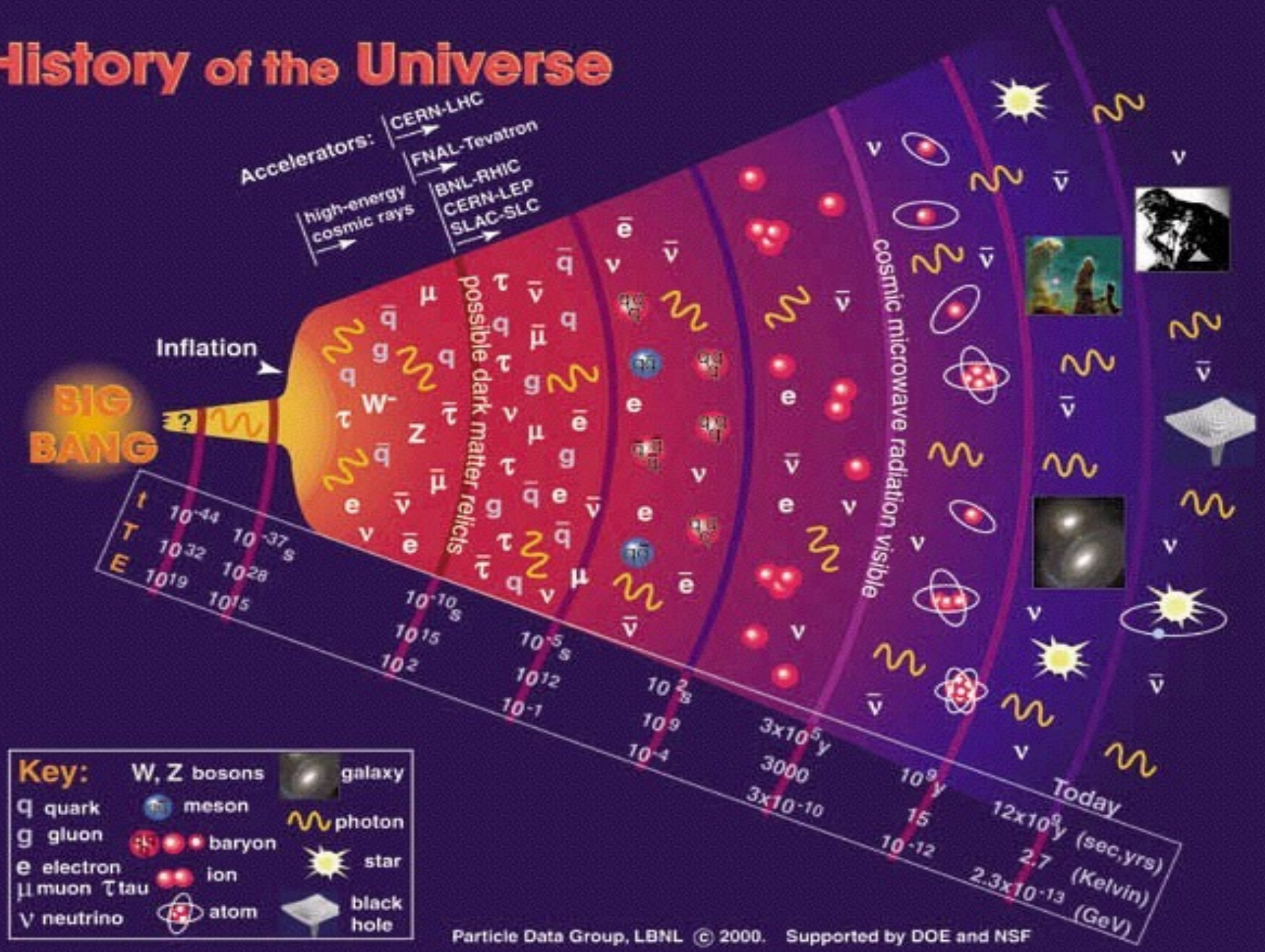
Phase transition in QCD

$$\epsilon_{SB} = \left[6 n_f \frac{7\pi^2}{120} + 16 \frac{\pi^2}{30} \right] T^4$$

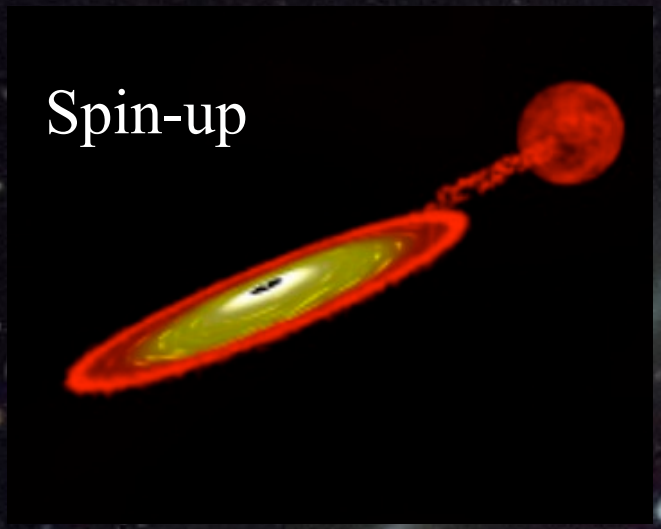


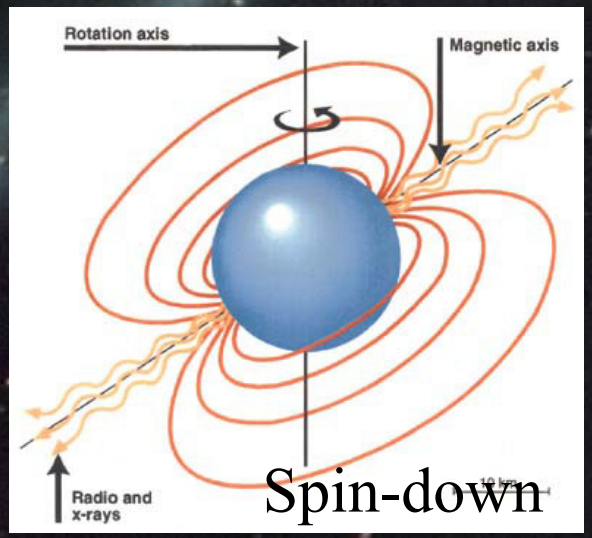
F. Karch et al., 2014

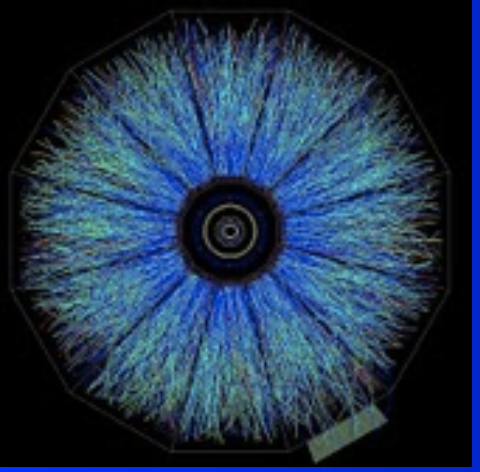
History of the Universe



Quark matter inside neutron stars

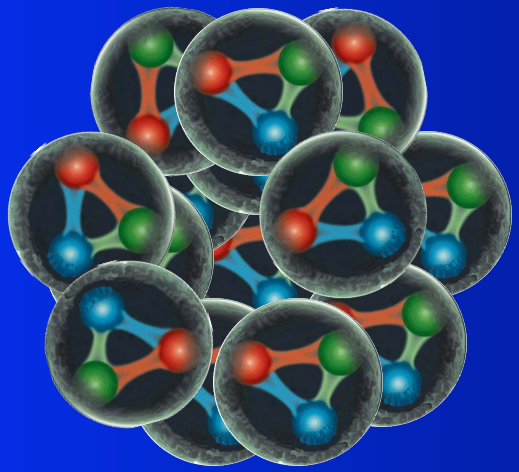






New state of matter: quark-gluon plasma (QGP)

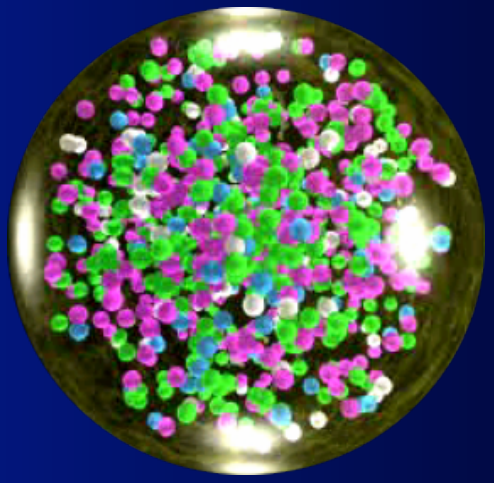
nucleus



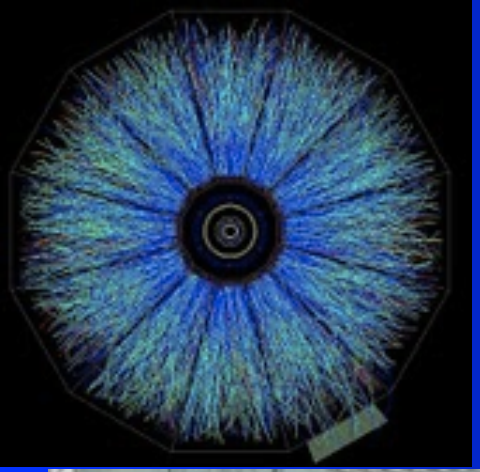
confinement

High T, μ

quark-gluon plasma (QGP)



De-confinement

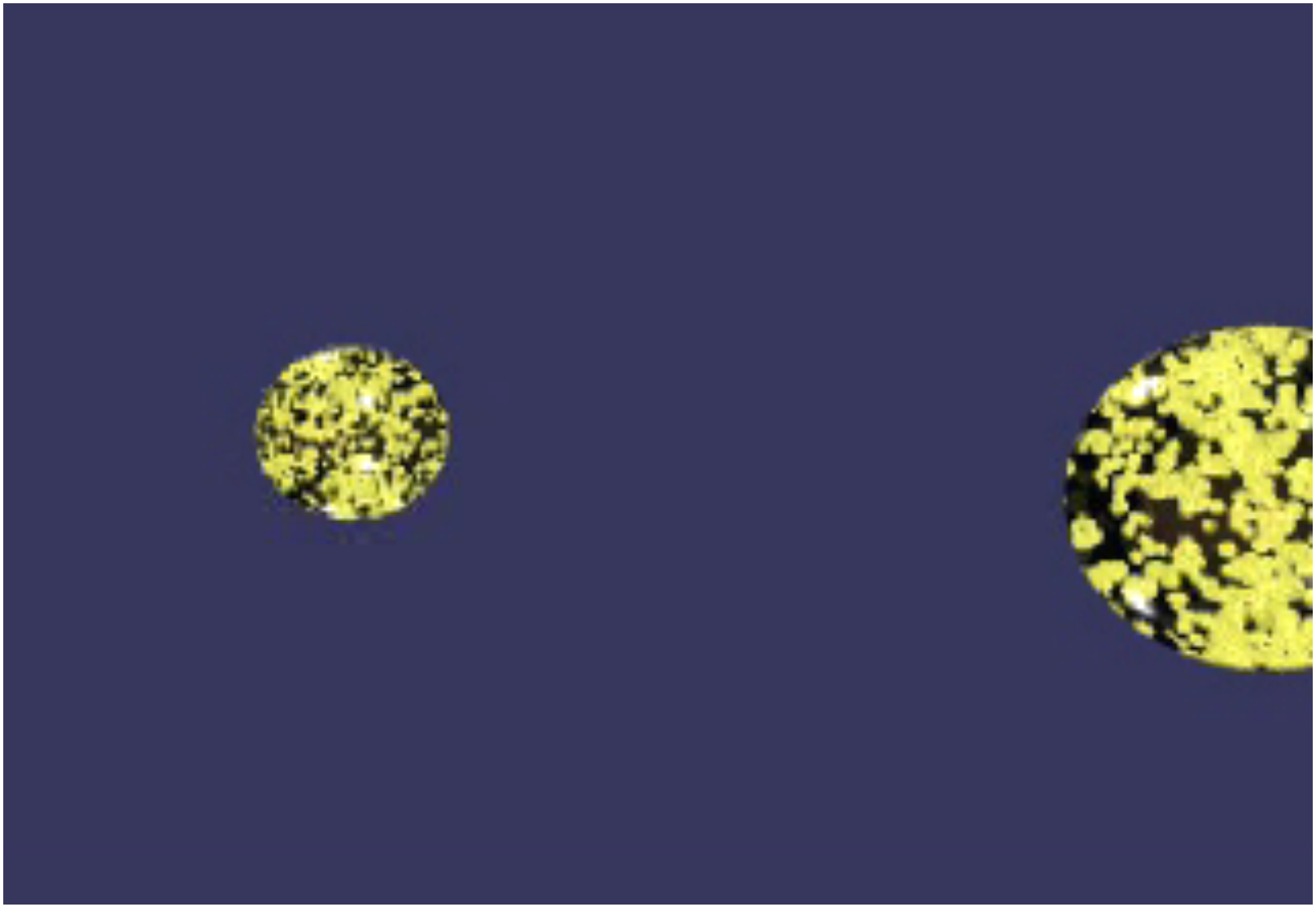


Nuclei as heavy as bulls
Through collisions
Generate new states of matter

Keran Li, T. D. Lee

Tsinghua Plaza of Science and Technology, Beijing

Anisotropic flows in non-central collisions



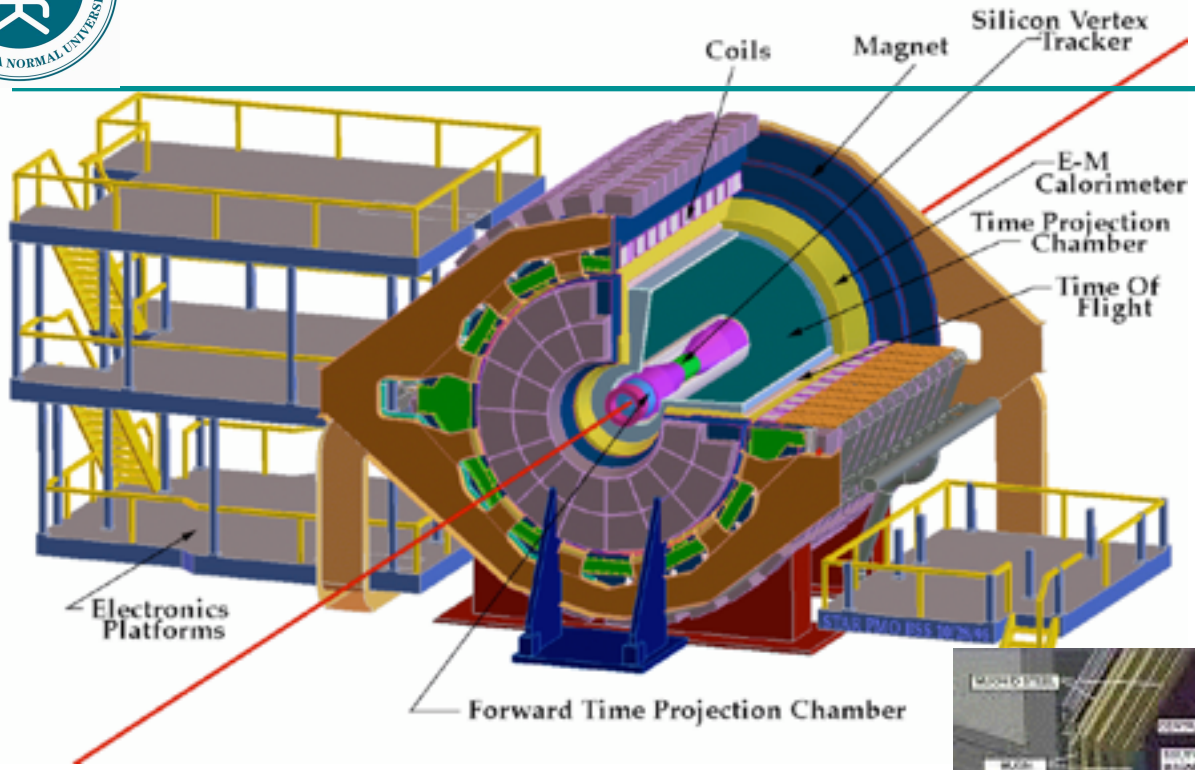
Animation by Jeffery Mitchell

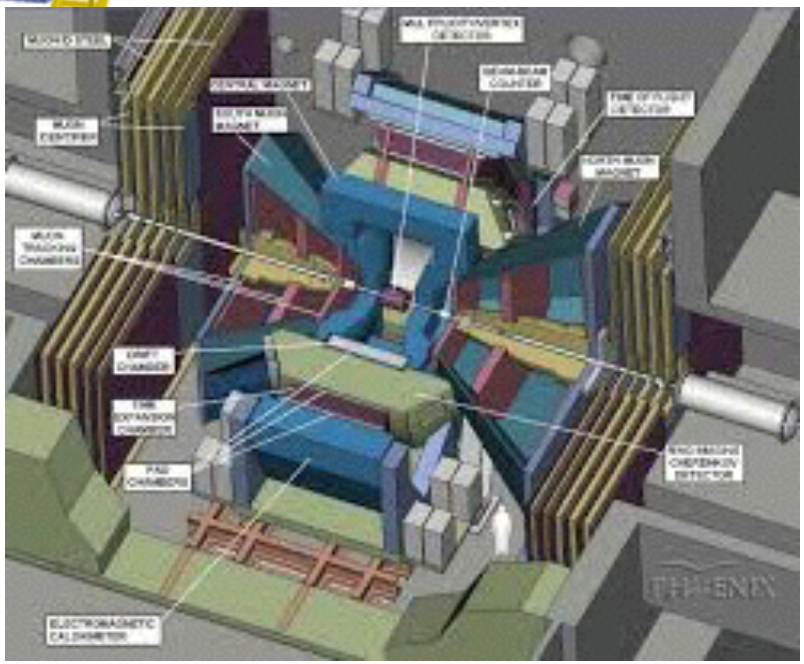
RHIC at Brookhaven

google map

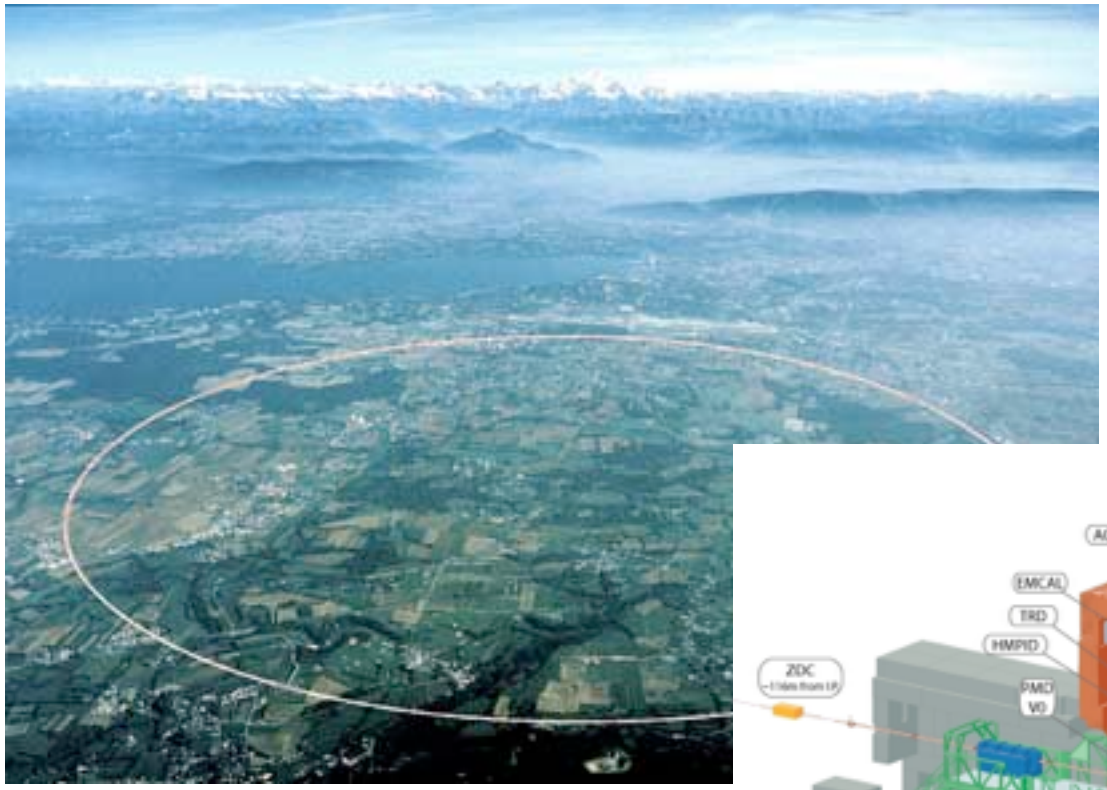
Relativistic Heavy-ion Collider

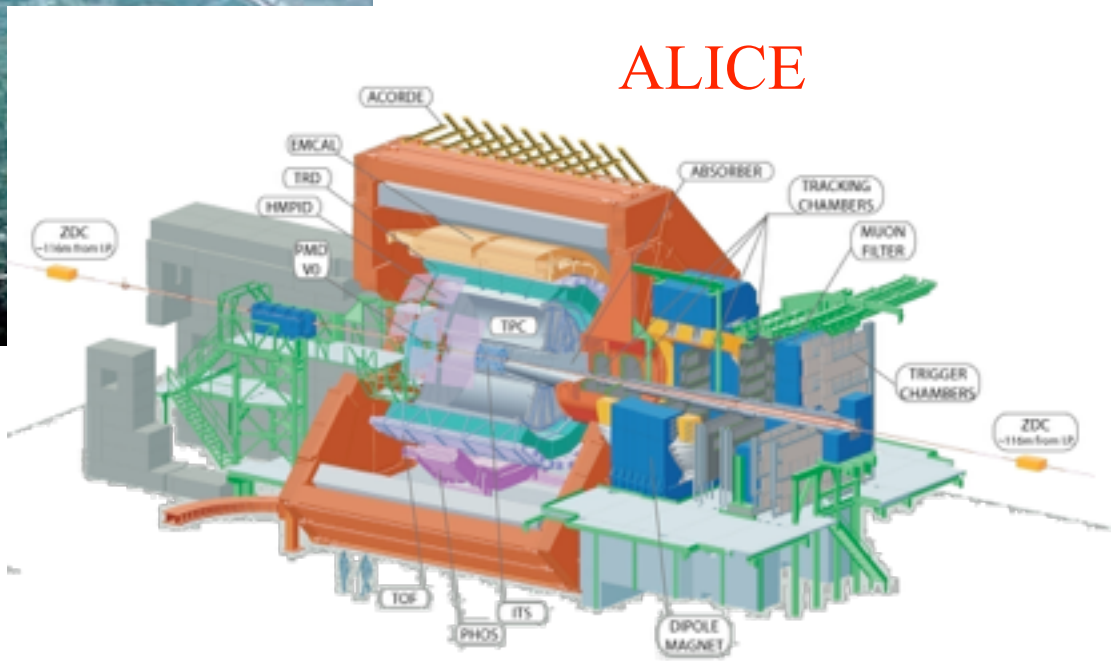
STAR Detector



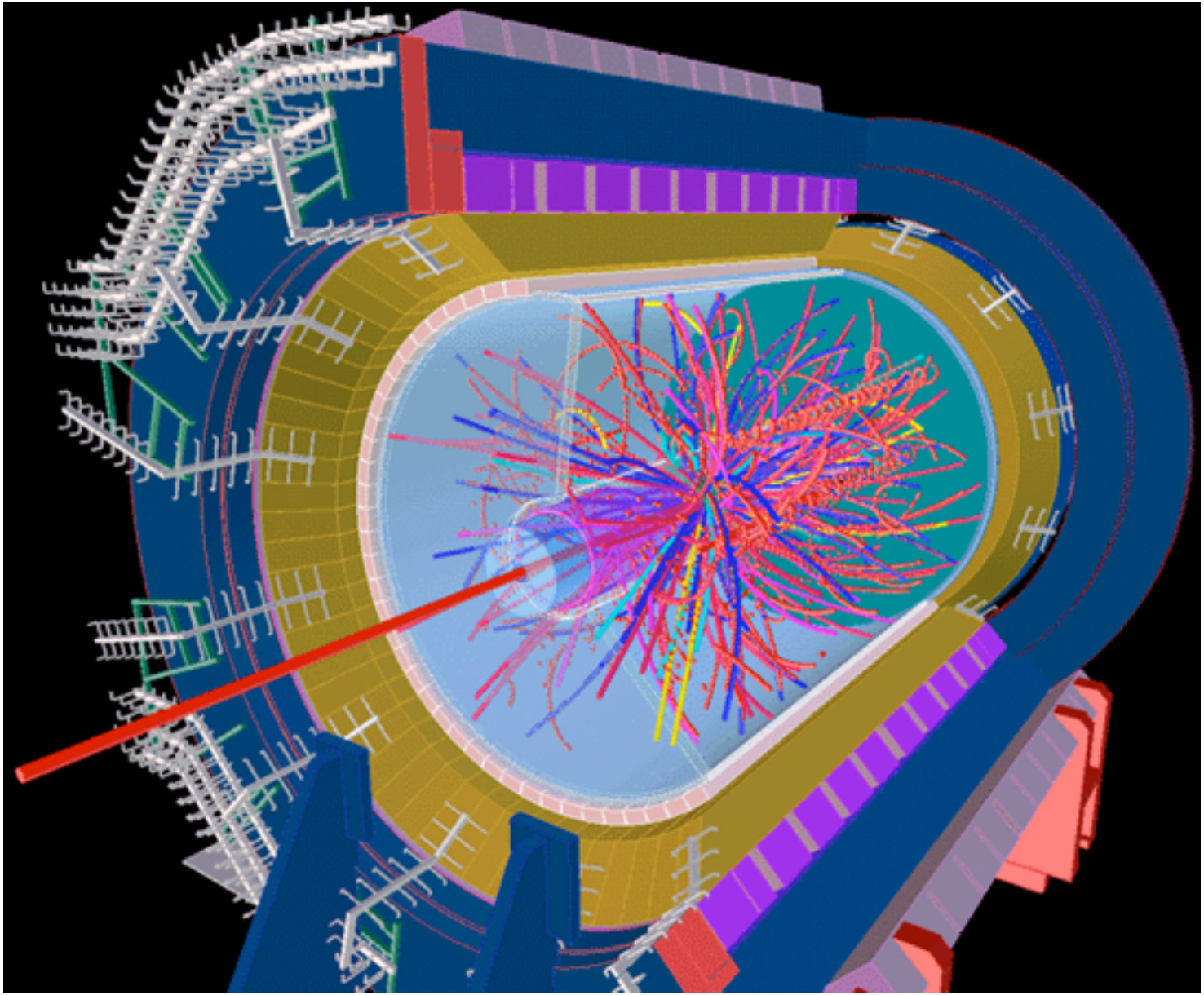


LHC: Large Hadron Collider

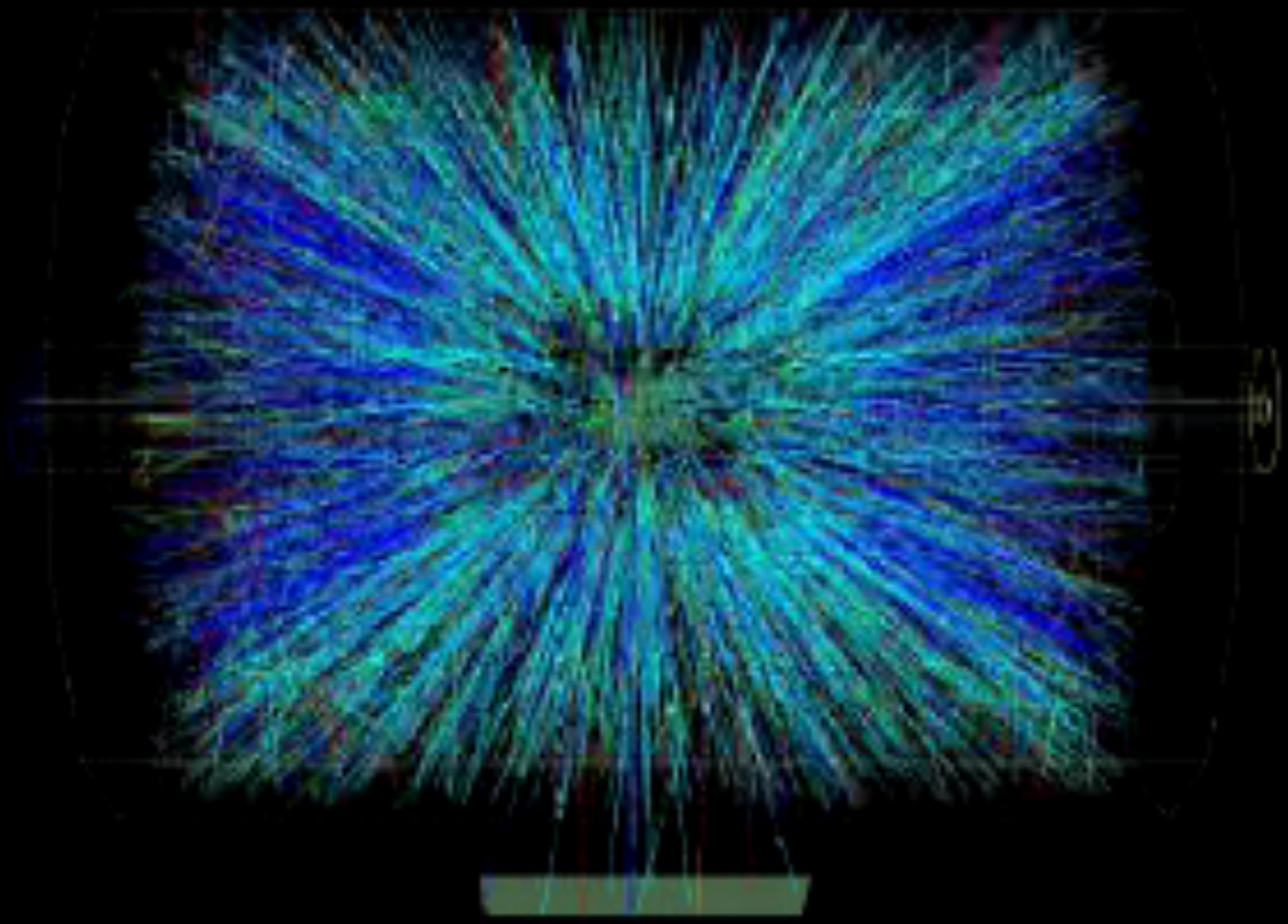




STAR:Time Projection Chamber



Au+Au Event at RHIC

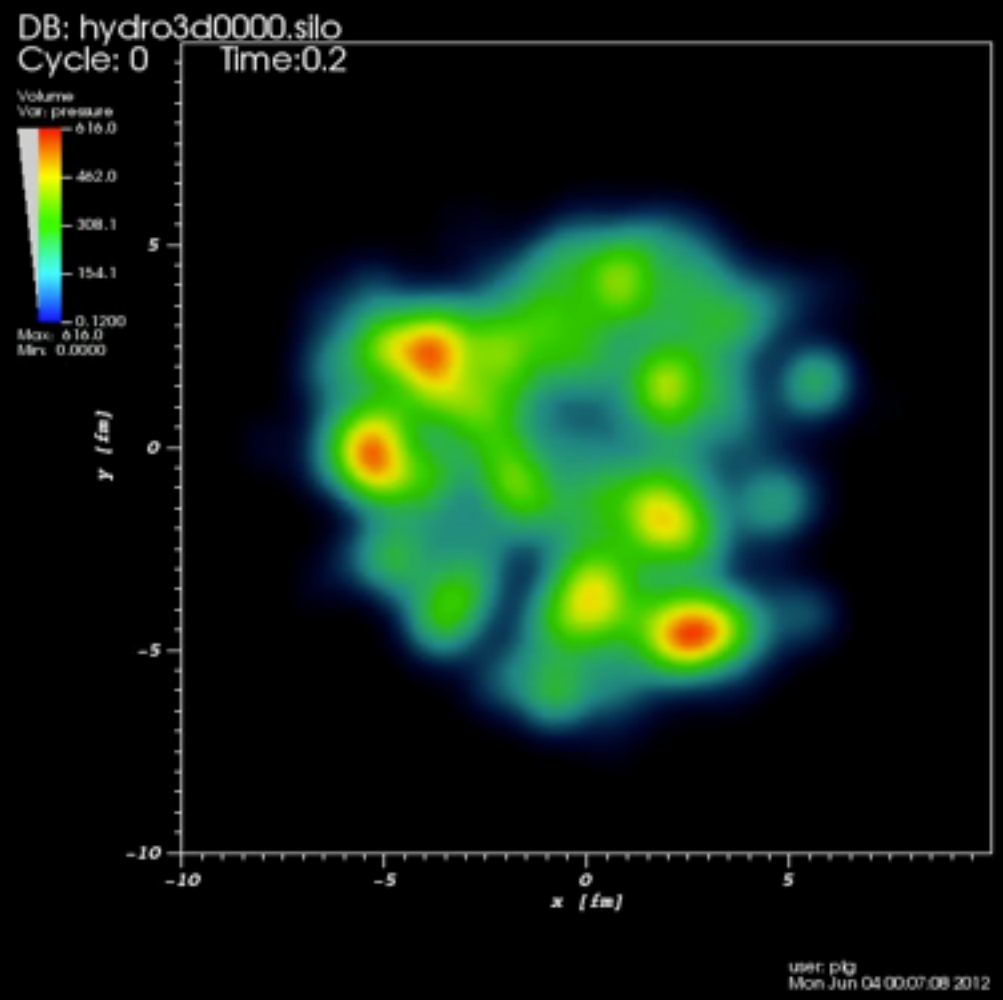


QGP in high-energy heavy-ion collisions

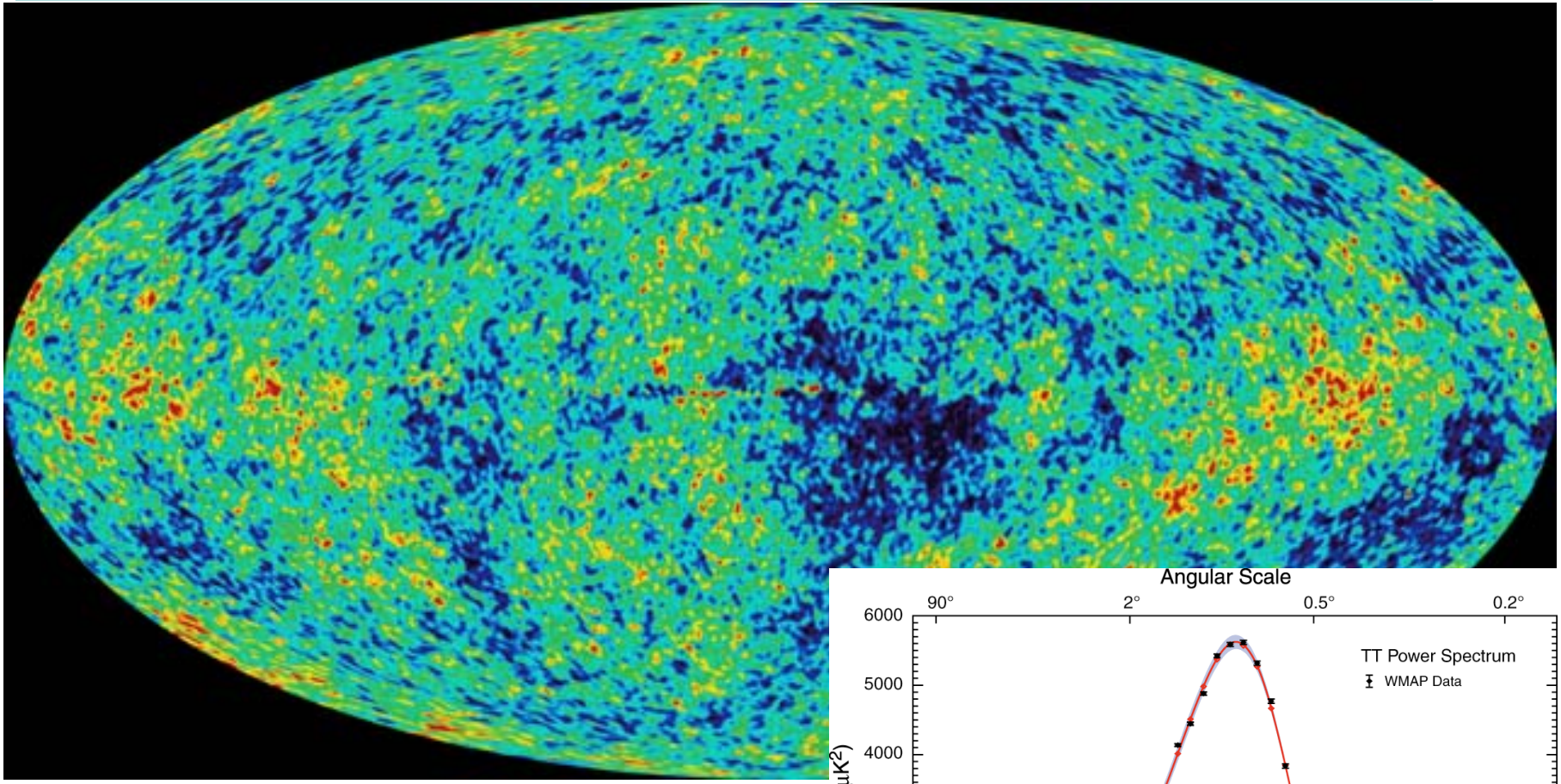
Hatsuda

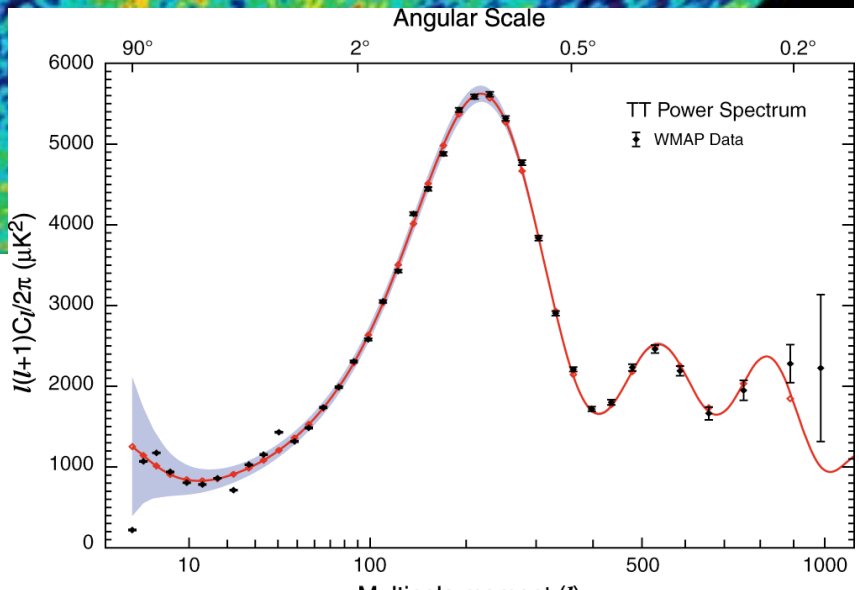
QGP evolution in heavy-ion collisions

Relativistic hydrodynamics $\partial_\mu T^{\mu\nu} = 0$



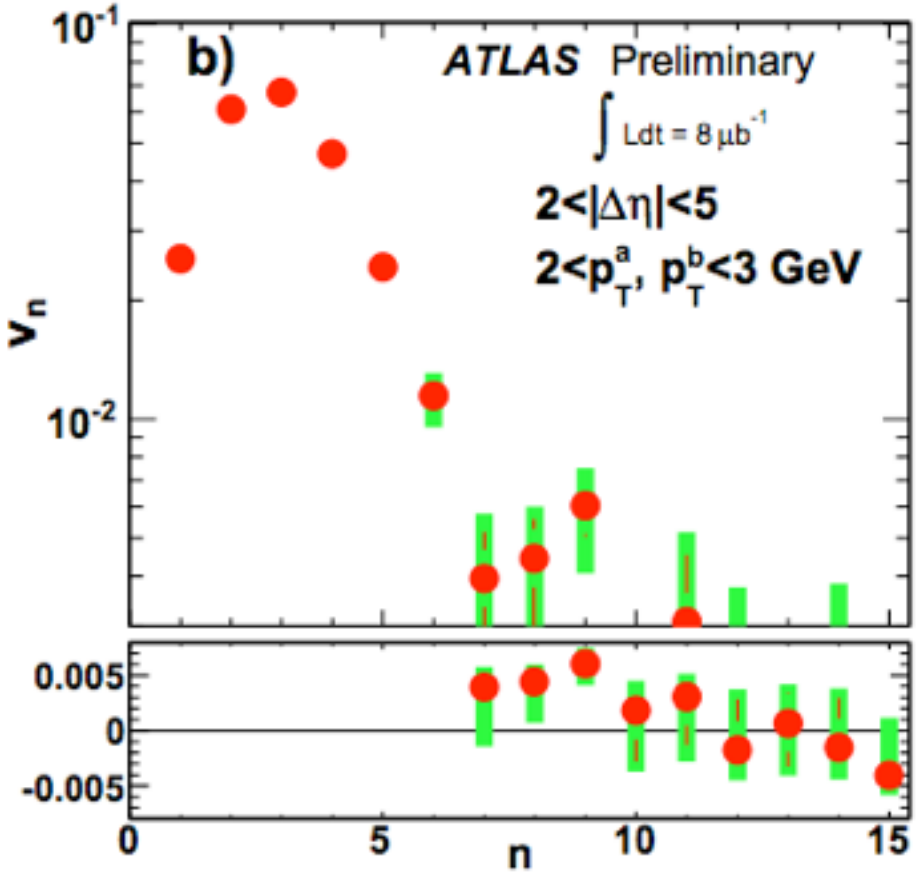
Fluctuation in CMB

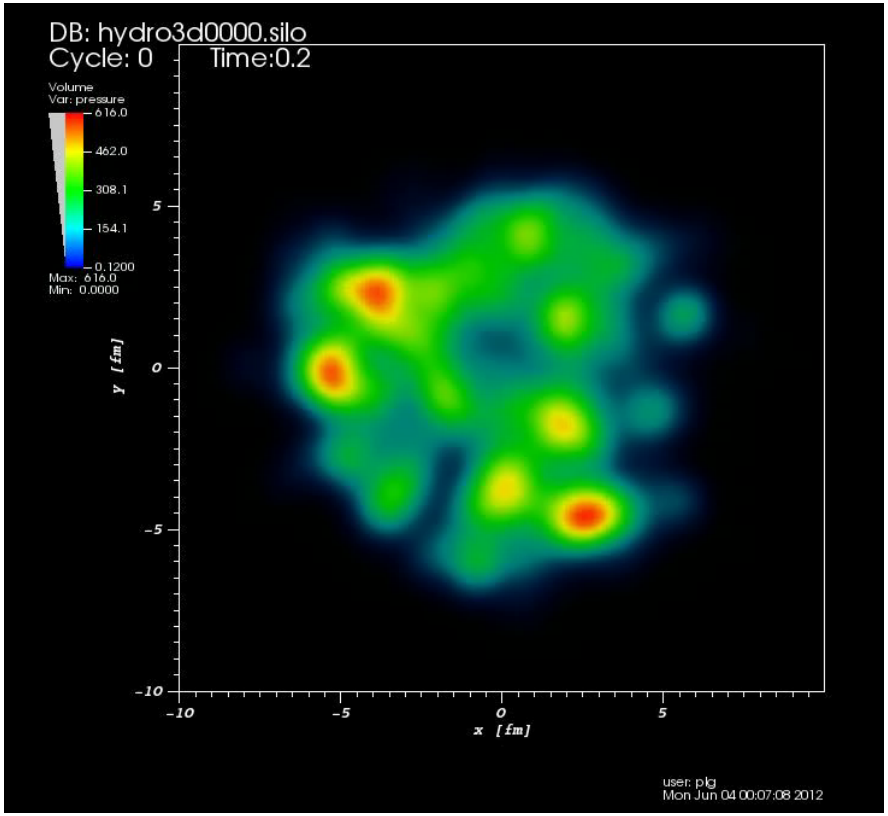




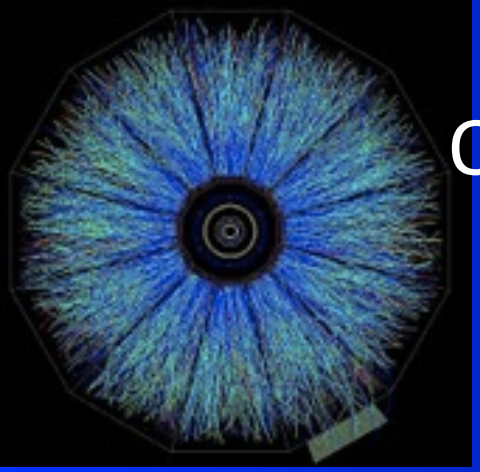
Anisotropy of hadron spectra

$$f(\phi) = f_0[1 + 2\sum_n v_n \cos(\phi - \Psi_n)]$$



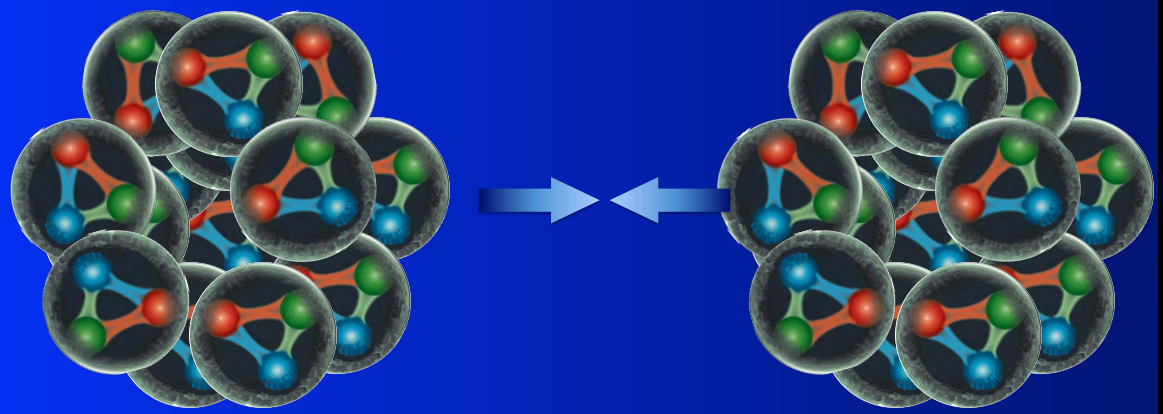


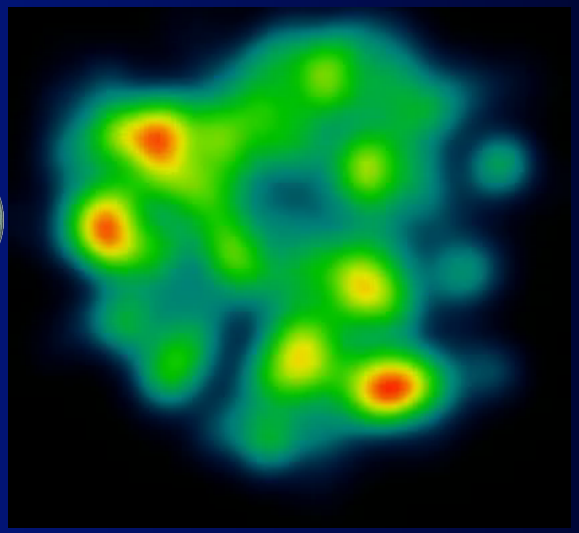
η/s=0.08-0.25



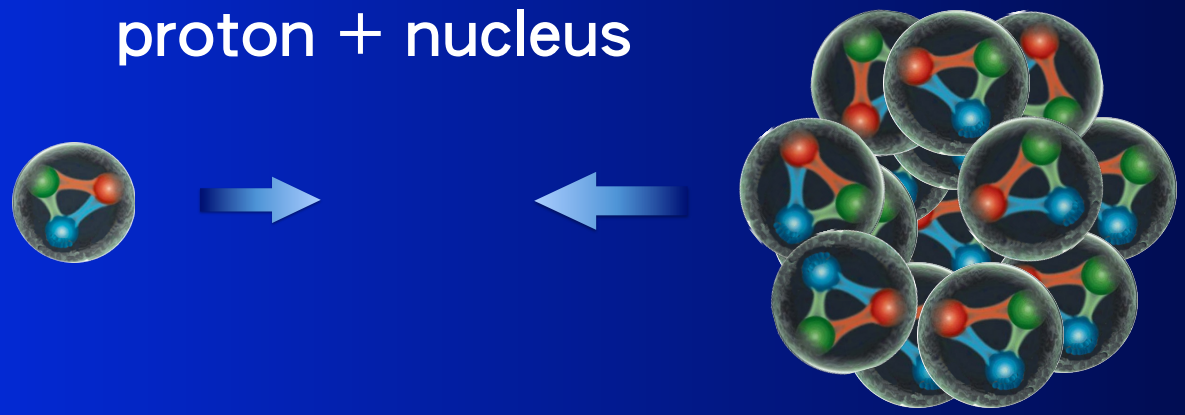
Quantum fluctuation in a nuclei (nucleon)

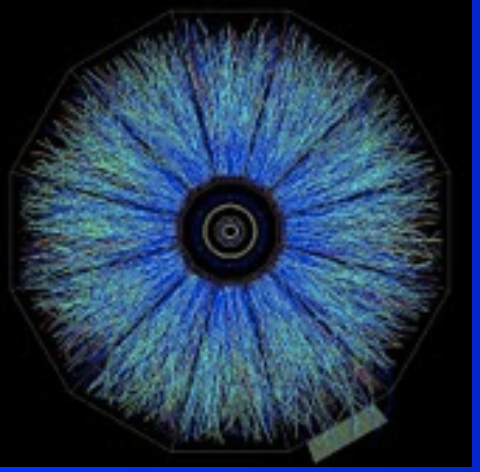
nucleus + nucleus





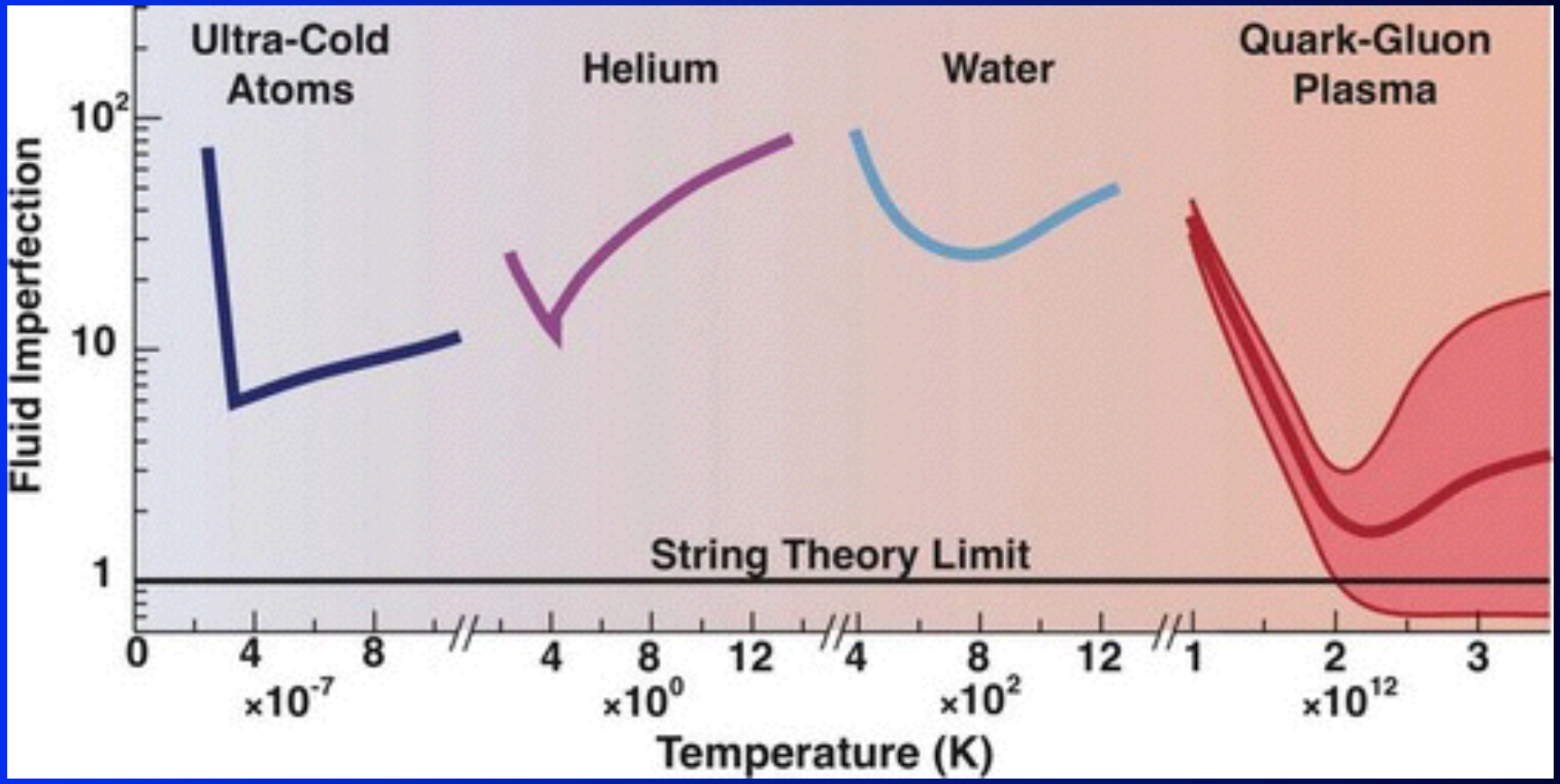
proton + nucleus





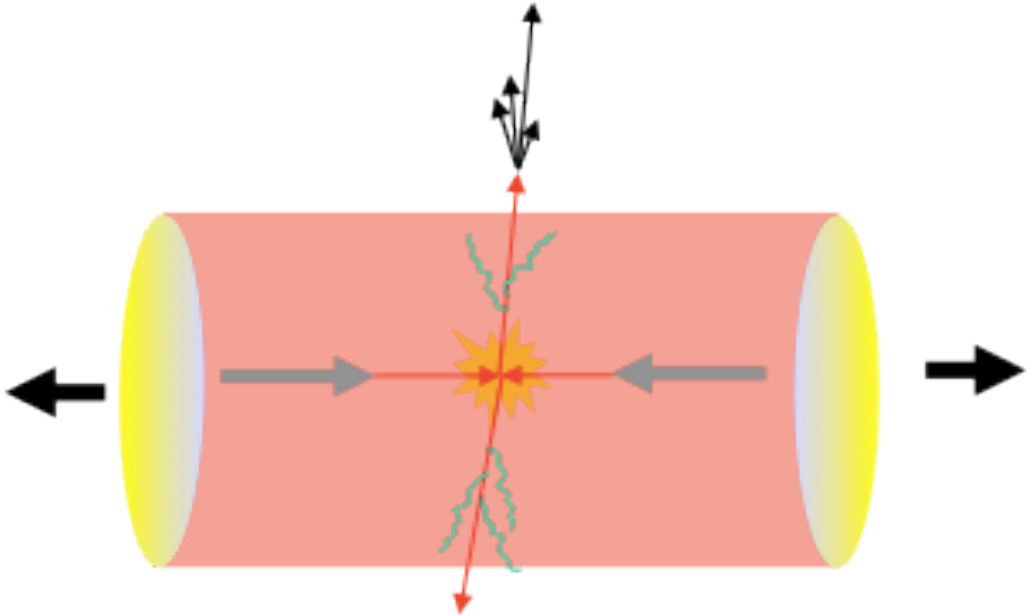
QGP: a perfect fluid

η/s



Hard Probes of QGP

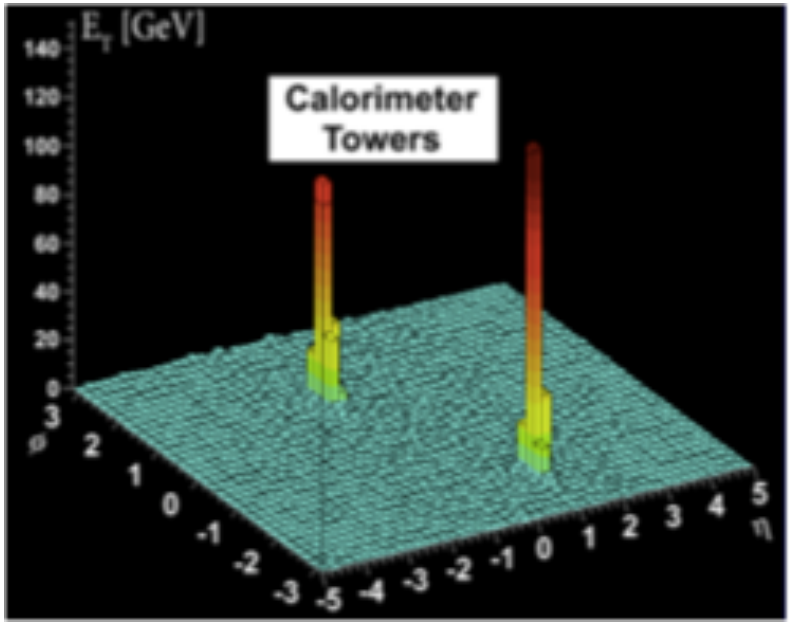
Jet quenching

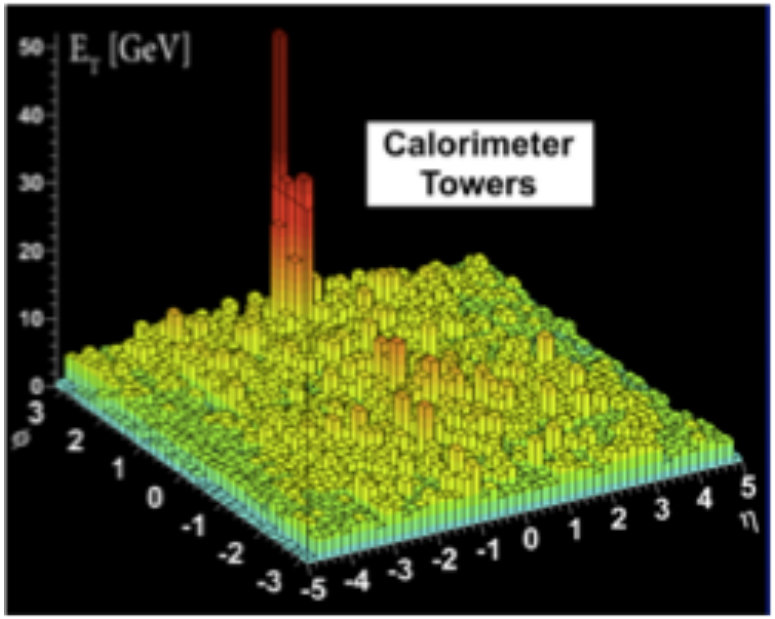


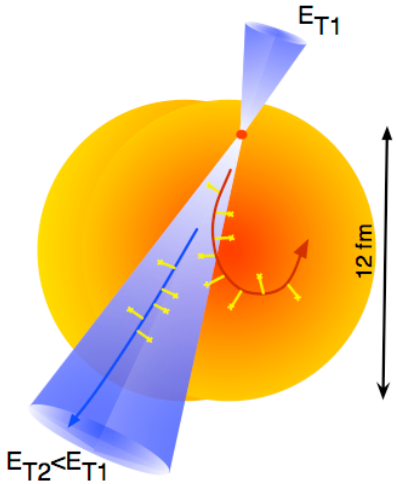
quark transport in medium: energy loss, diffusion

Theoretical development since 1990: including Vitev, Kang & Xing

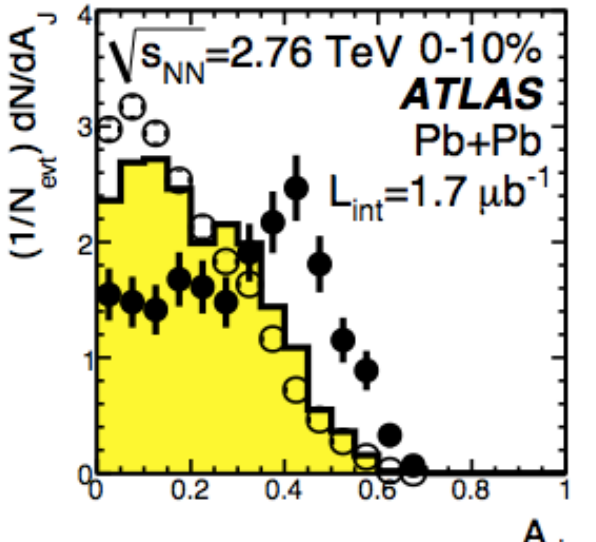
Jet quenching at LHC



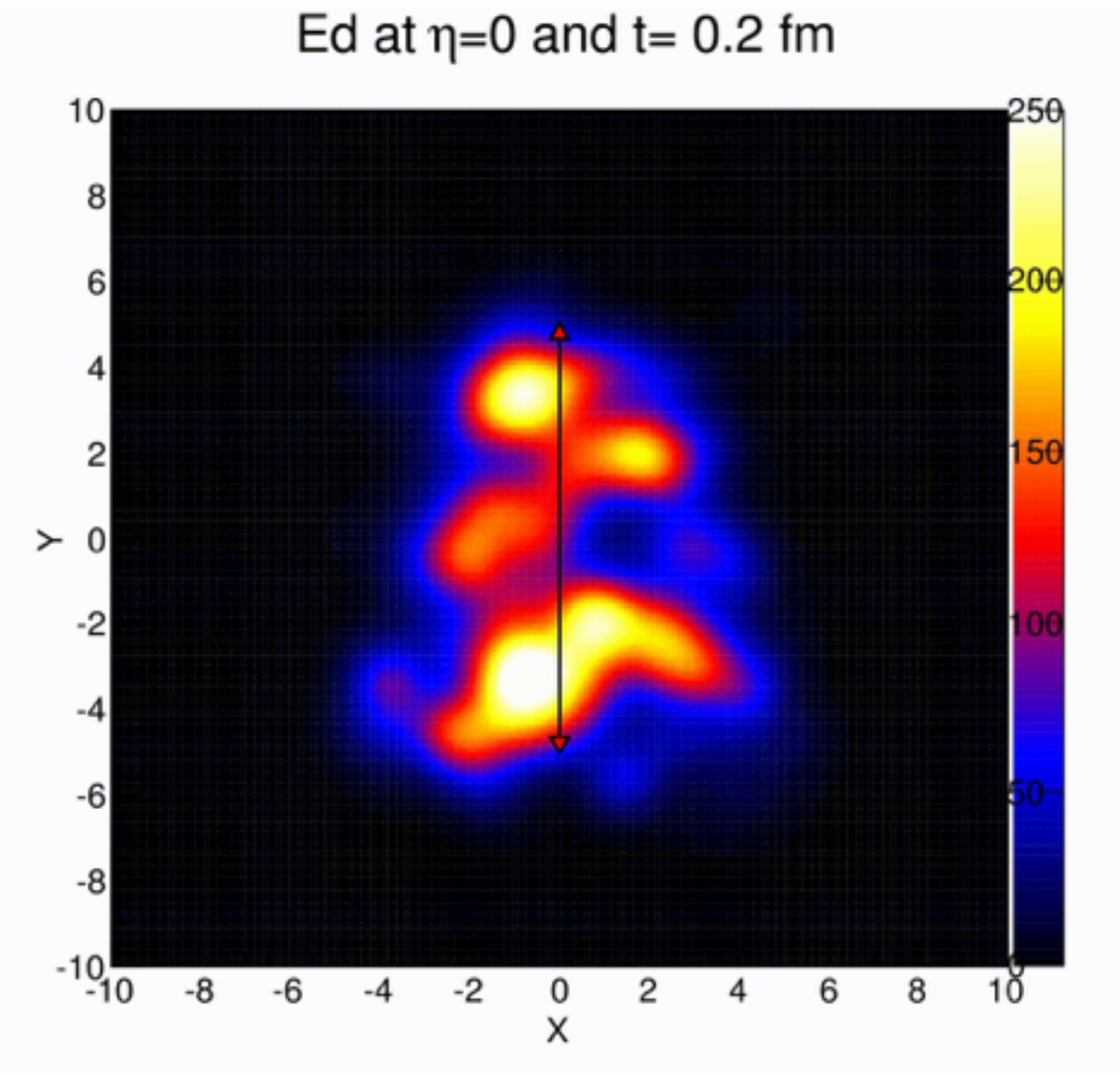




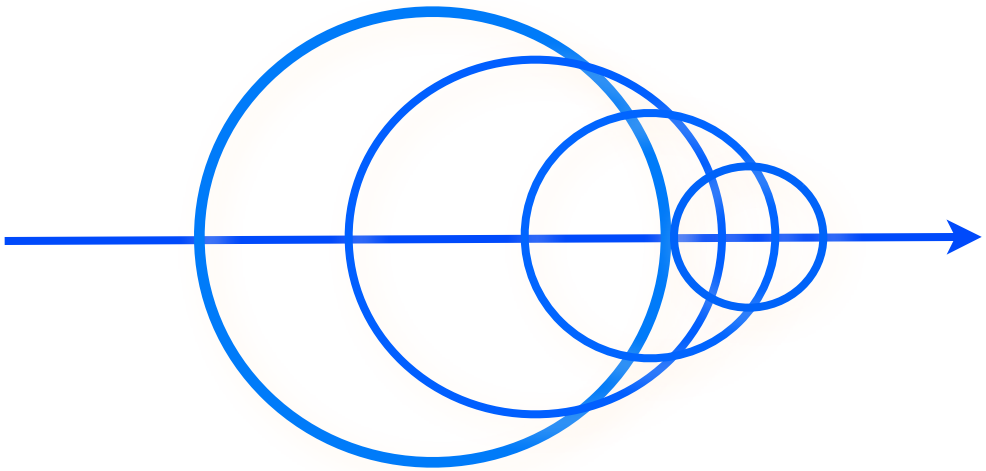
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$



Jet propagation in QGP



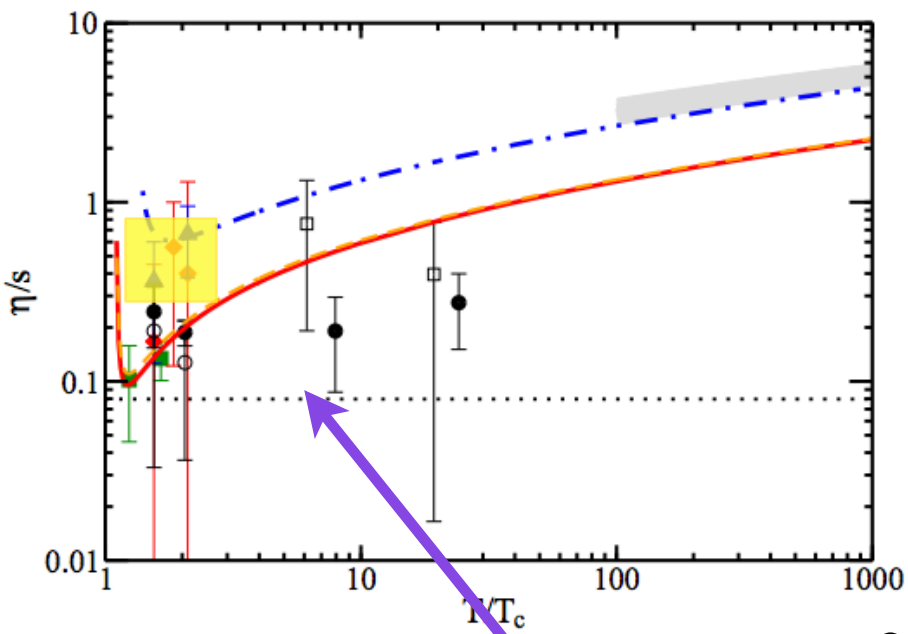
Jet Induced Mach Cone



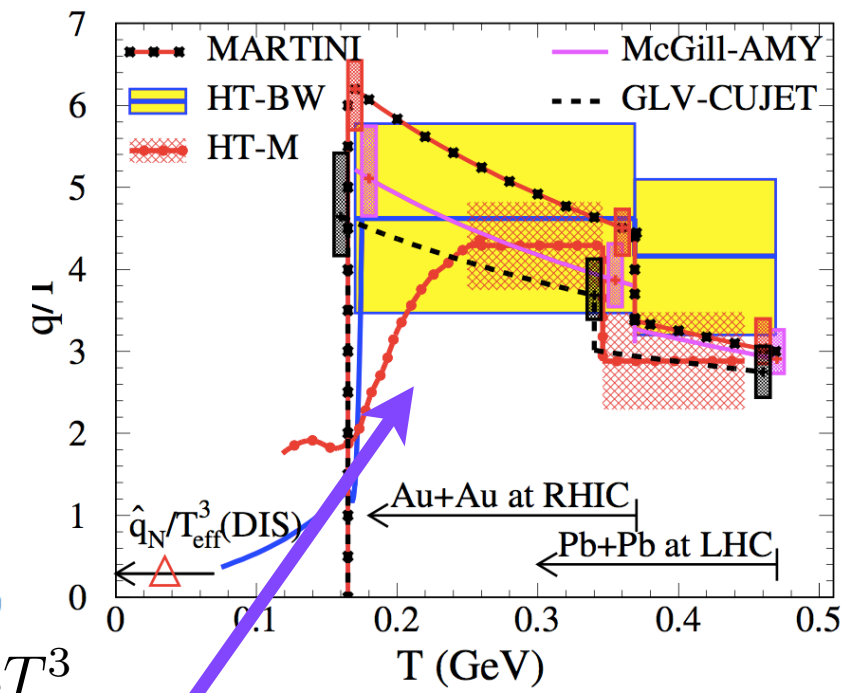
Jet and fluid transport property

PHENIX

fluid transport



jet transport

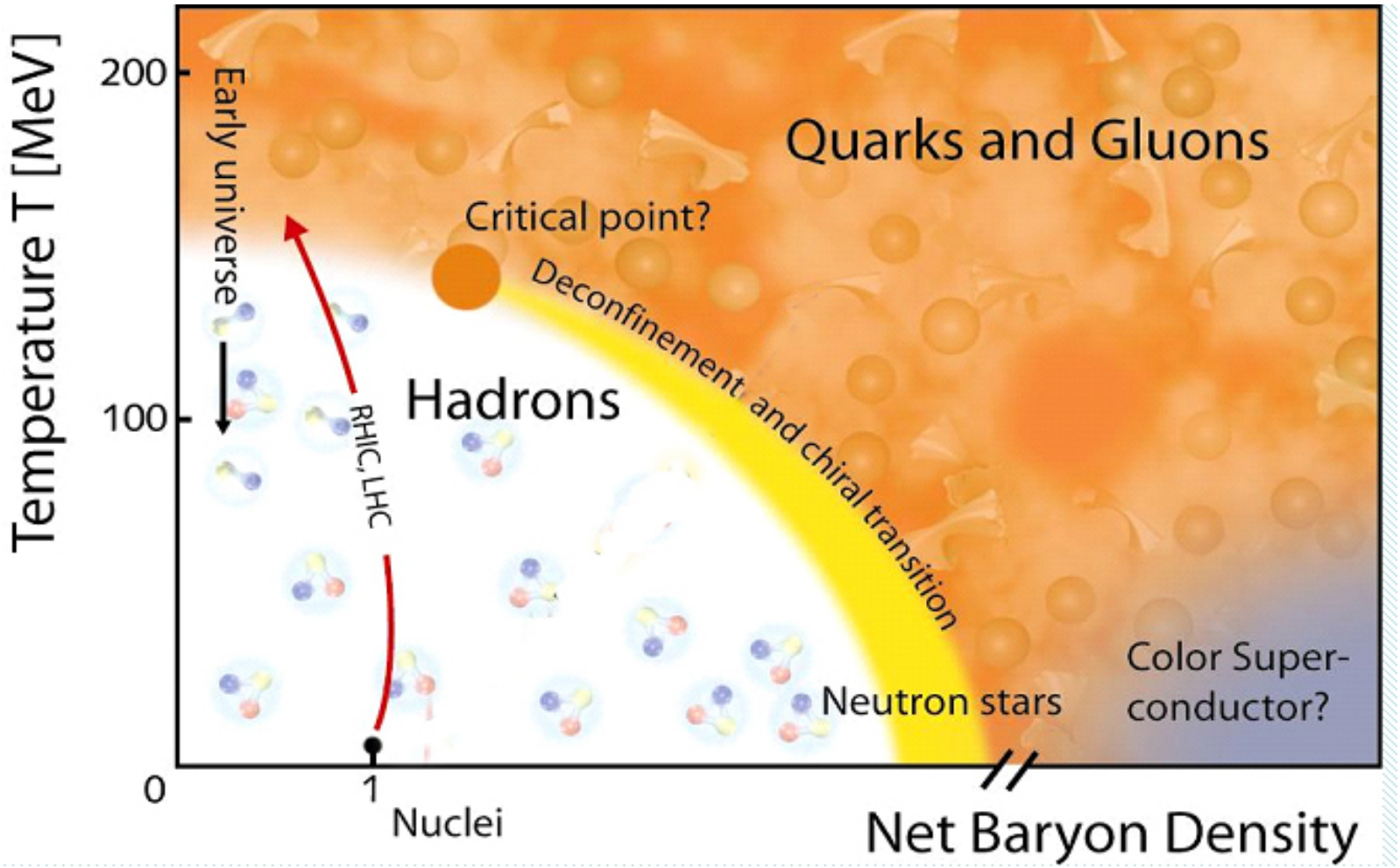


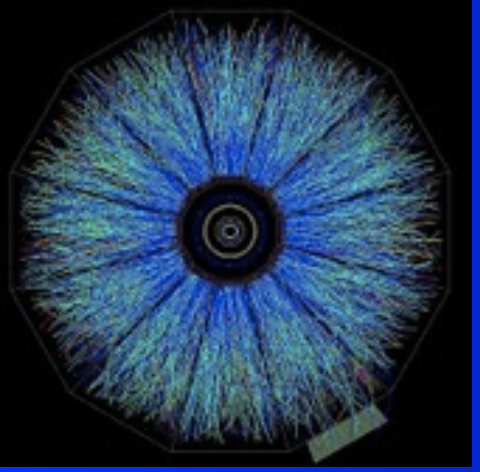
$$\frac{\eta}{s} \geq \frac{3T^3}{2\hat{q}}$$

$$\hat{q} = \langle p_T^2 \rangle / L$$

Perfect fluid? strongly

Physics goals





Thank you