Gauge/Gravity duality and Nuclear Symmetry energy

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Greeks called indivisible Building block of the universe Atom

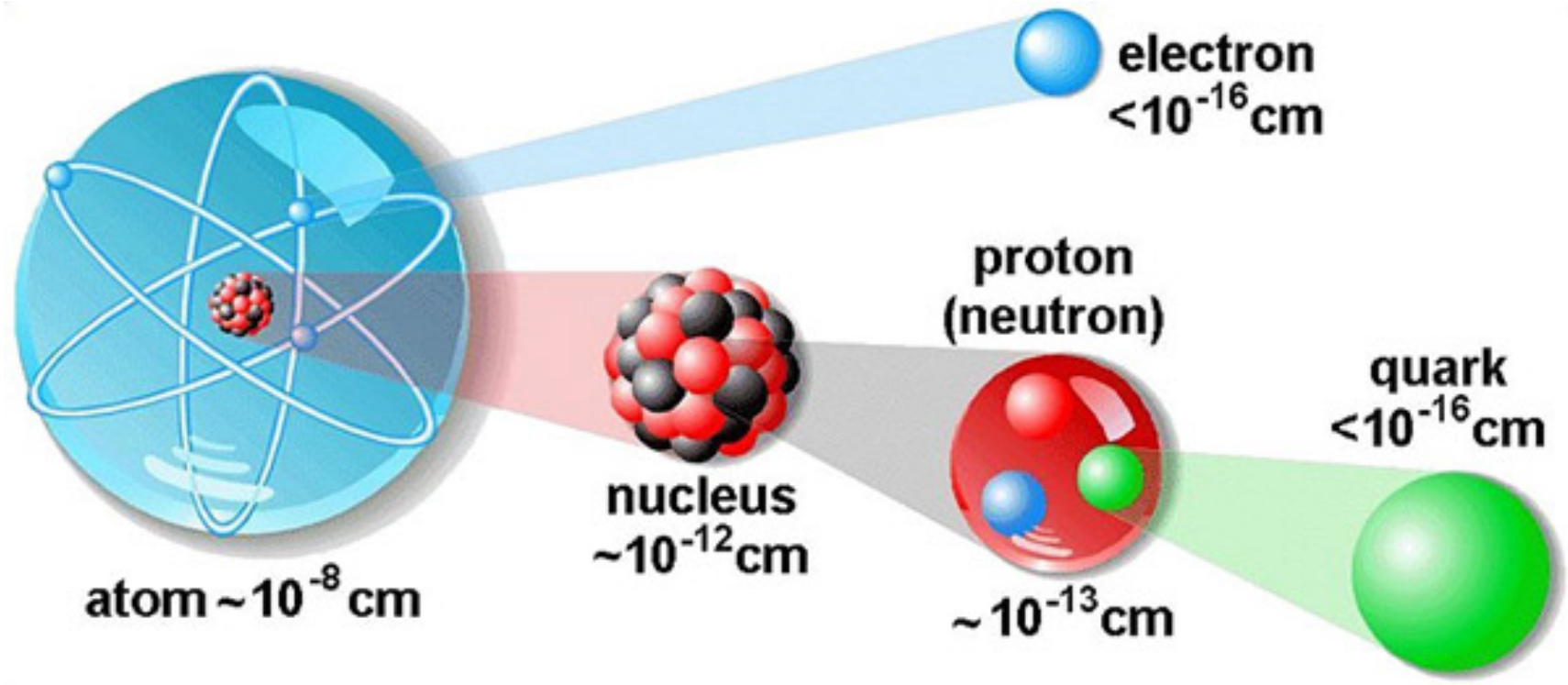
- Two most basic questions in physics are

  1. What is the Atom?

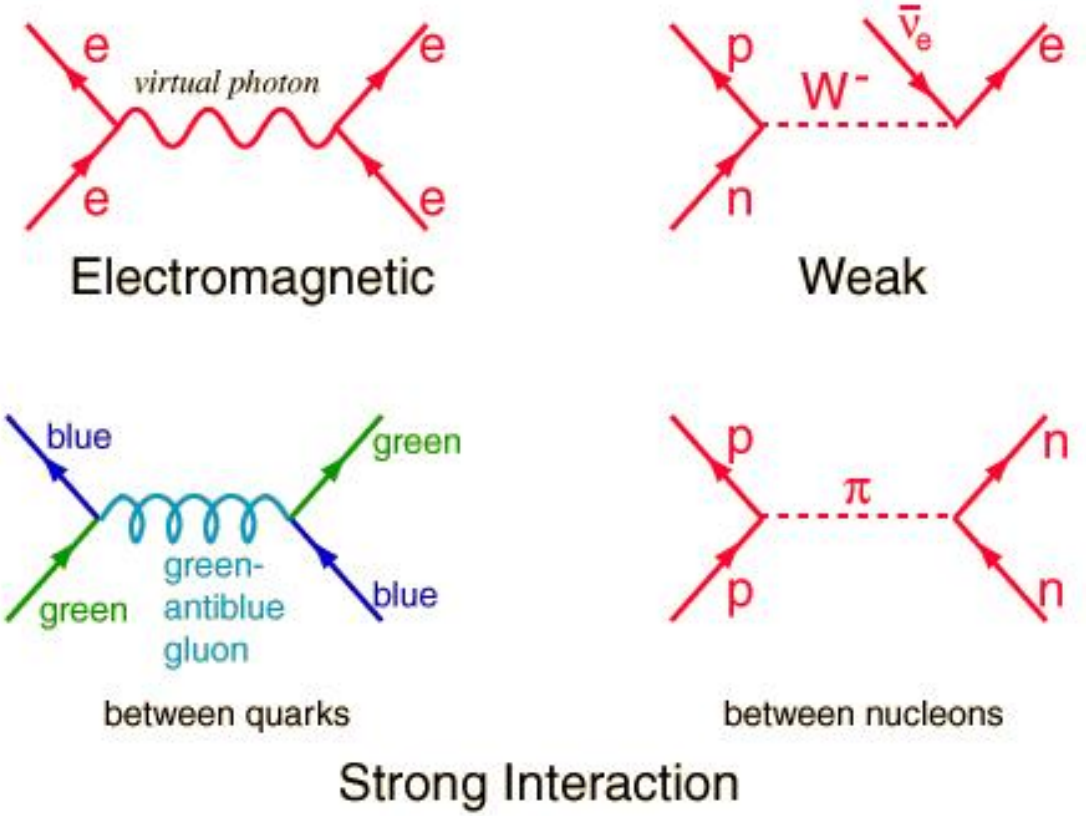
  2. What Forces glue them together to make the visible world?

Modern Theory of Atom

Dalton's story was not the end…



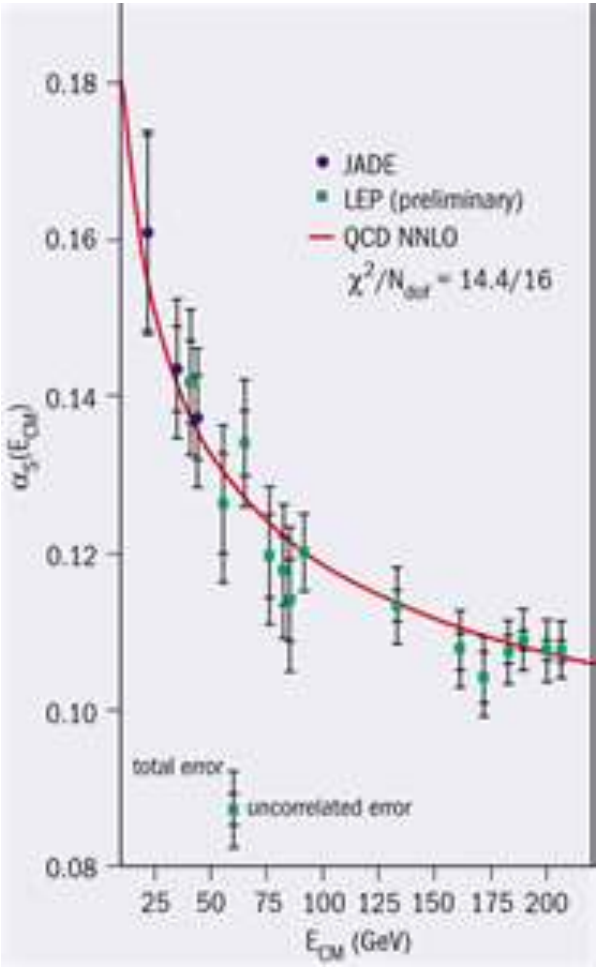
Force=exchange of glue particles

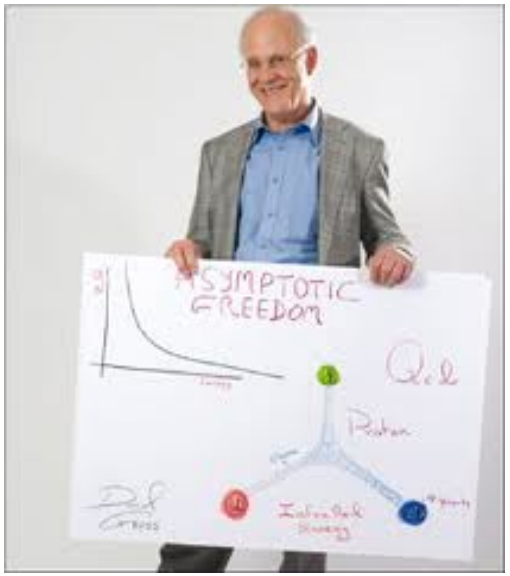


Two levels of strong force. (QCD,meson)
Gravity is very special and not included here

QCD: today's theme

- For High E: g<<1: Asymptotic freedom

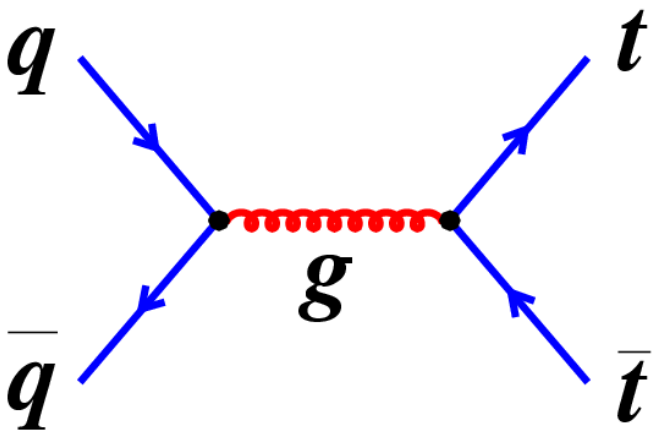


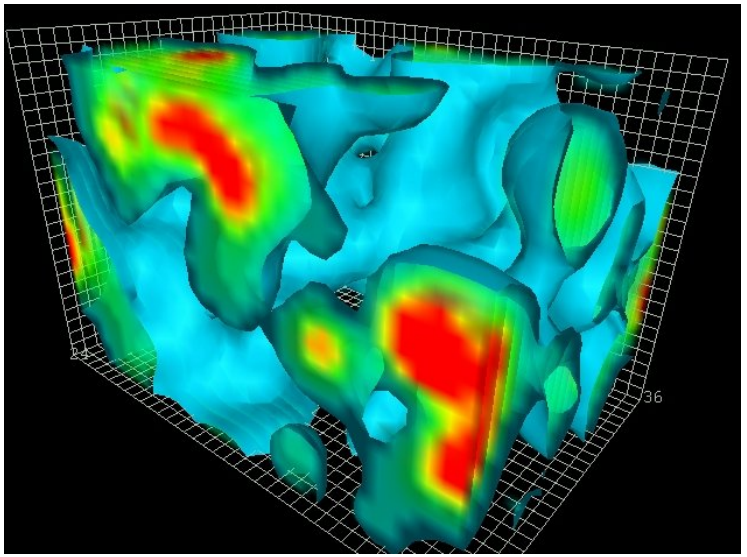


$$\beta_1(\alpha) = \frac{\alpha^2}{\pi}\left(-\frac{11N}{6} + \frac{n_f}{3}\right)$$

$$\alpha_s(k^2) \overset{\text{def}}{=} \frac{g_s^2(k^2)}{4\pi} \approx \frac{1}{\beta_0 \ln(k^2/\Lambda^2)},$$

•For Low E: QCD is still difficult
interaction strong, fluctuation large

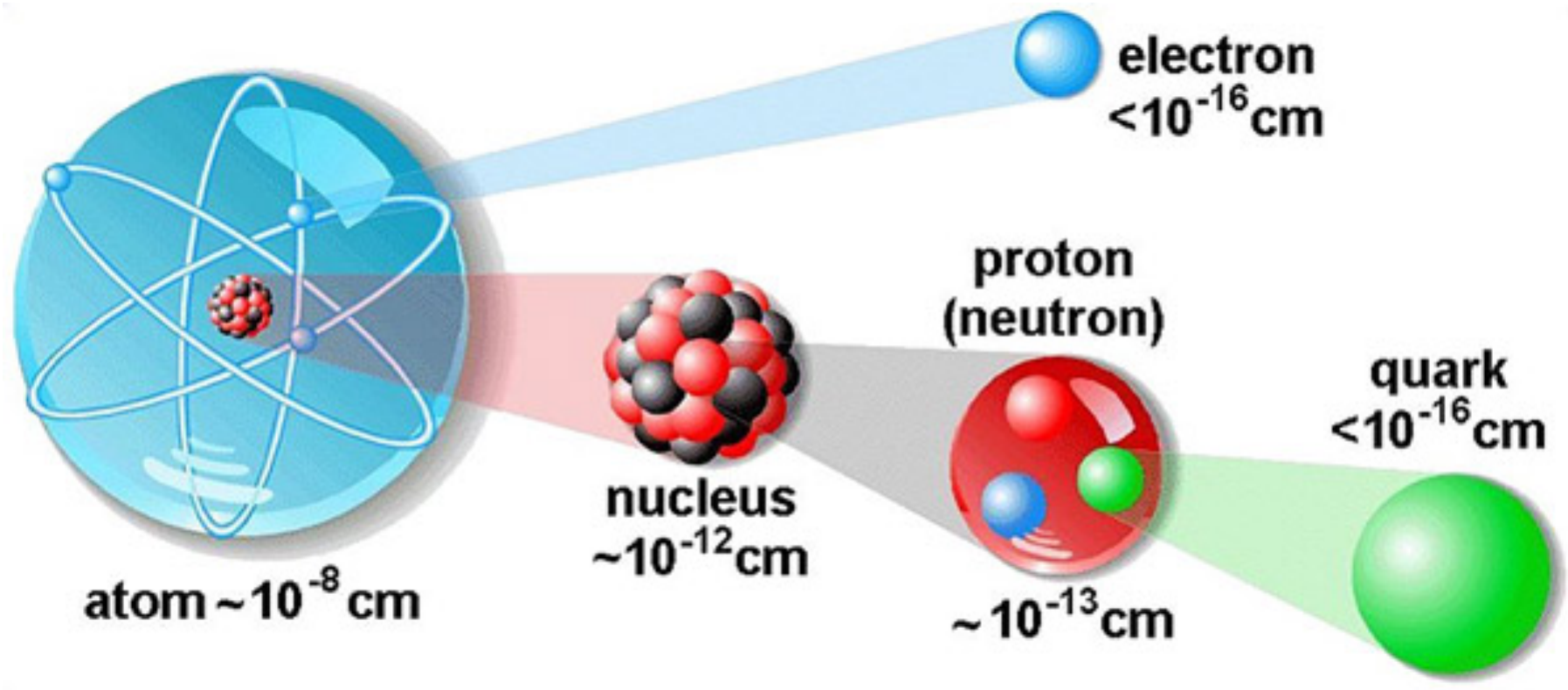




High E v.s Low E of Strong int.

For strong int. Not clear even what is particle

Asymptotic freedom and confinement



General Idea for strong int.

- Reformulate theory in terms of new degree of freedom whose interactions are weak.

Duality

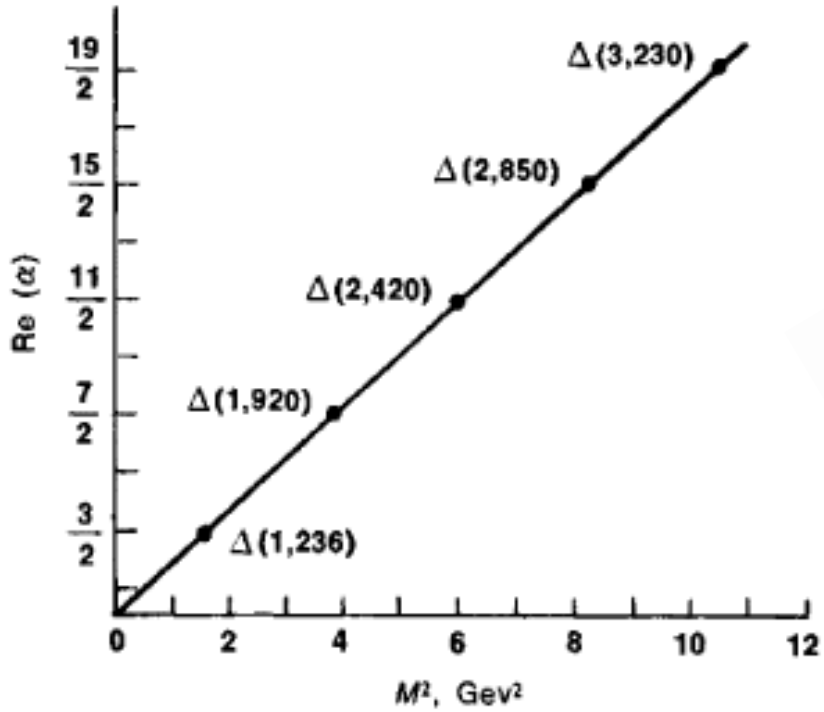
An idea from string theory

- Replace strong nuclear force by classical gravity(geometry).

- What is the string theory?

Old String theory

- Regge trajectory→ spectrum of string



Difficulty of old string theory

- Hard to explain the quark's free behavior.
- abandoned and re-incardnated as a quantum gravity, which is a BIG deal!
- Why? qm gravity is difficult! puzzle

Specialty of Quantum gravity

- Force = - grad (potential Energy)

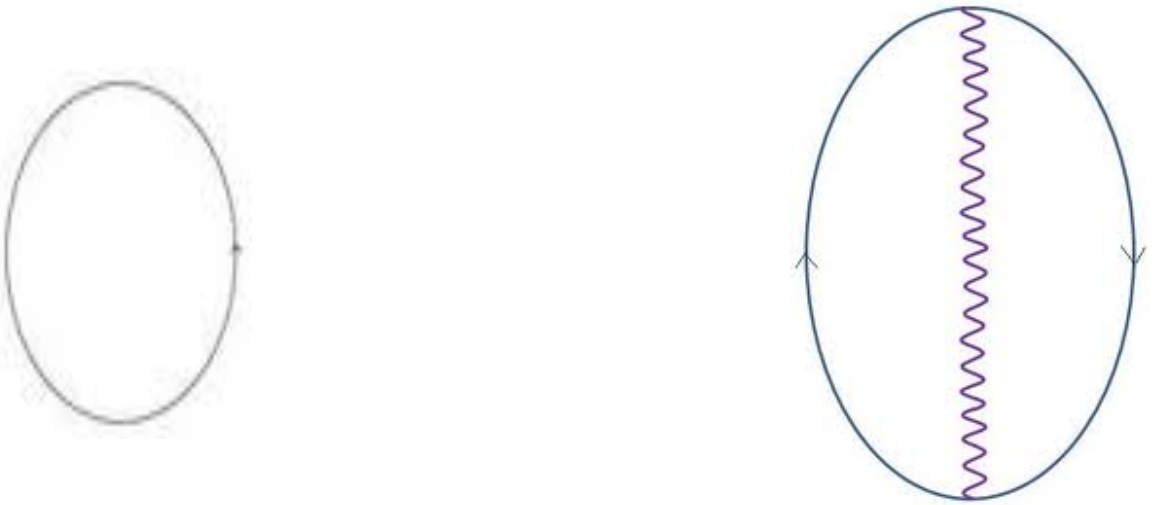
- Einstein: gravity is not a force but a curvature.

Curvature = k (Energy (mass))

- Quantum fluctuation of any field generate infinite Energy ➔infinite gravity
  essential difficulty

Origin of the vacuum energy

- Uncertainty principle. $\Delta p \sim \frac{\hbar}{\Delta x}$



- in a particle theory, any large energy is possible (Delta x→0)

Finiteness of String theory

- stringy uncertainty principle

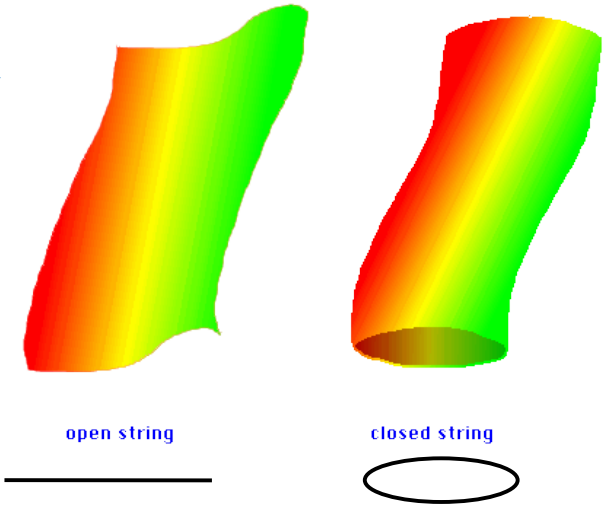
$$\Delta x \sim \frac{\hbar}{\Delta p} + \alpha' \Delta p \geq \sqrt{\alpha'} = l_{\text{string}}$$

energy of the string per unit length is constant➔ E up means length up

- Minimal length
  → UV divergence disappear

Open – closed duality

- Open String : gauge theory
  Theory of Matter
- Closed string: gravity
  Theory of space-time



- Two are dual to each other through D-brane:

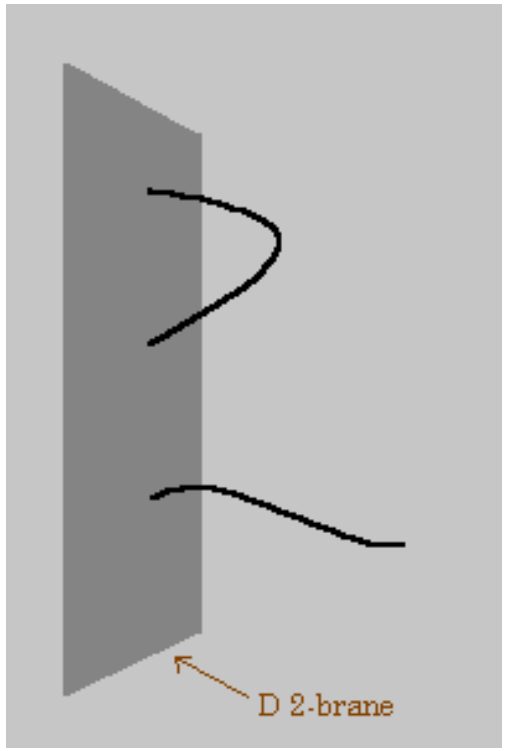
D-branes

- Closed string soliton
- That this object has dual description by dynamics of open string ending on it, is the major discovery of 90'. (Polchinski)

- vibration of D brane

=The low energy dynamics SU(N) SYM

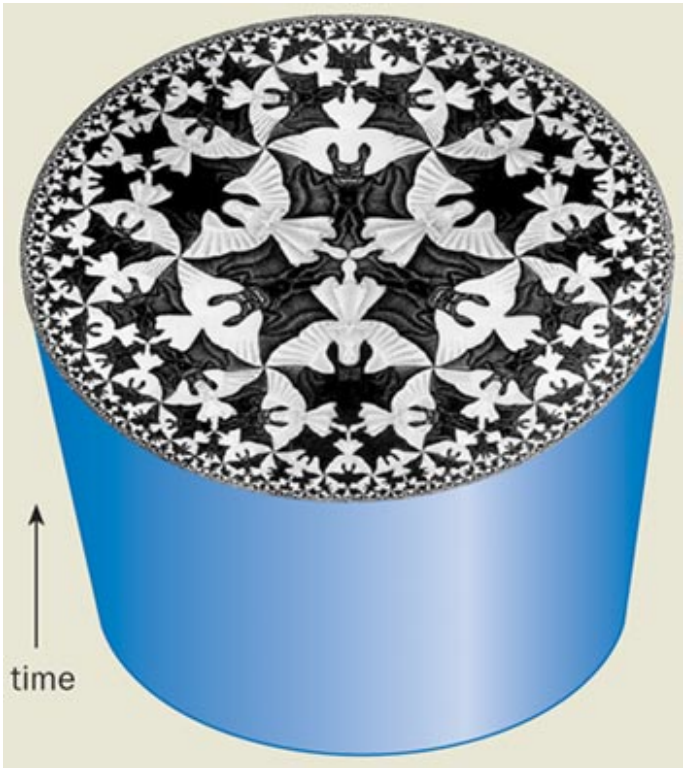
=string theory at warped geometry.



D-brane & gravity

- Stack of D-brane

  → space time warp due to the tension.
  →(AdS).



Eschers's "Angels and devils"

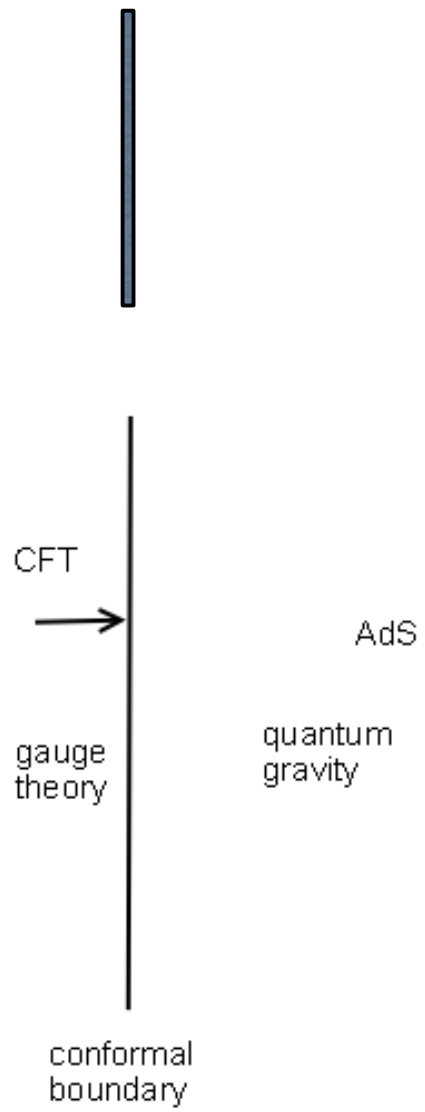
AdS/CFT duality

– String in AdS5 is dual to SYM in 4d.

– 5d v.s 4d → Holographic corr.

– For large coupling, ,
AdS/CFT → gravity/gauge dualtiy

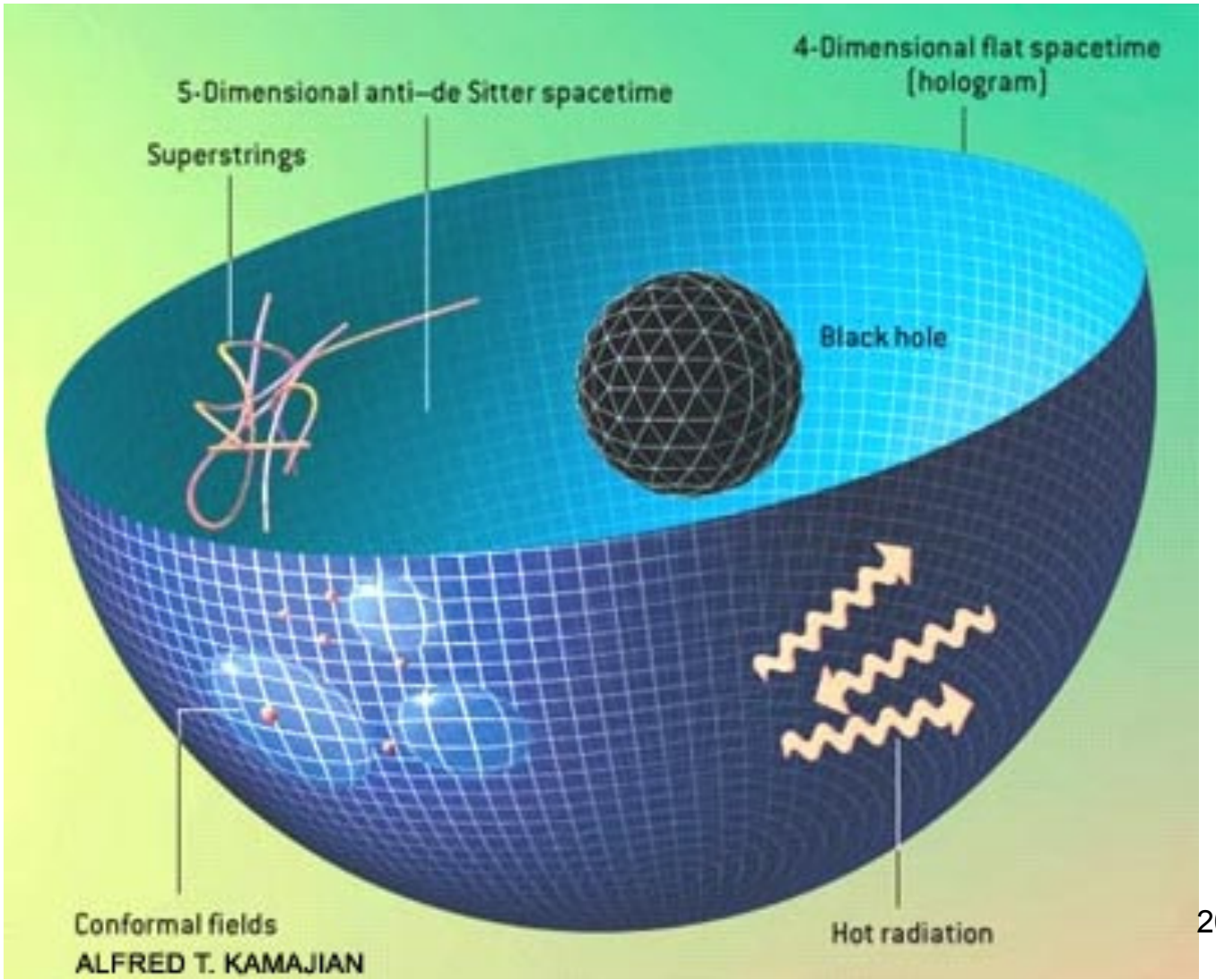
$$\lambda = g_s N_c$$



Consequence of duality

- Gluon dynamics is replaced by ads gravity.
- For large N_c, gravity is weakly coupled.
- Correlation function in 4d can be calculated by the classical dynamics at the ads bulk.

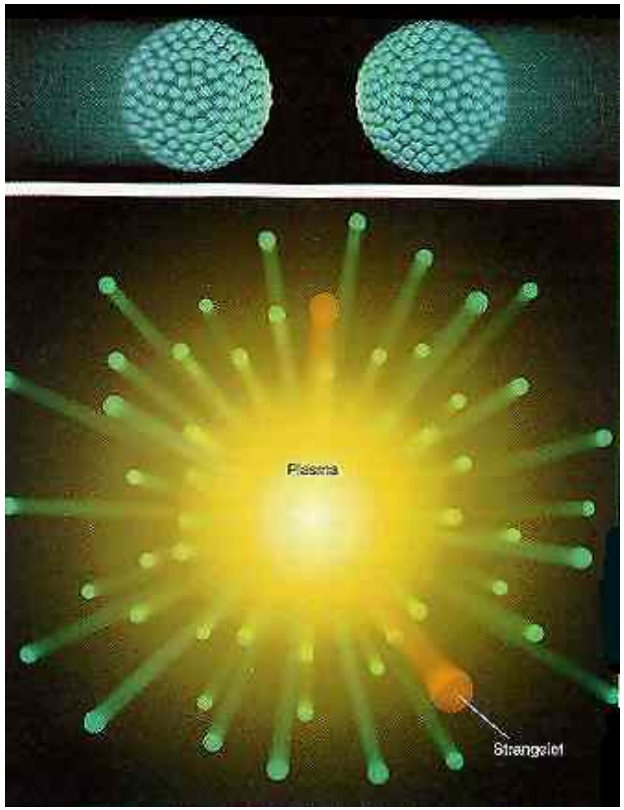
AdS/CFT at finite T



II. String theory in RHIC/LHC collider

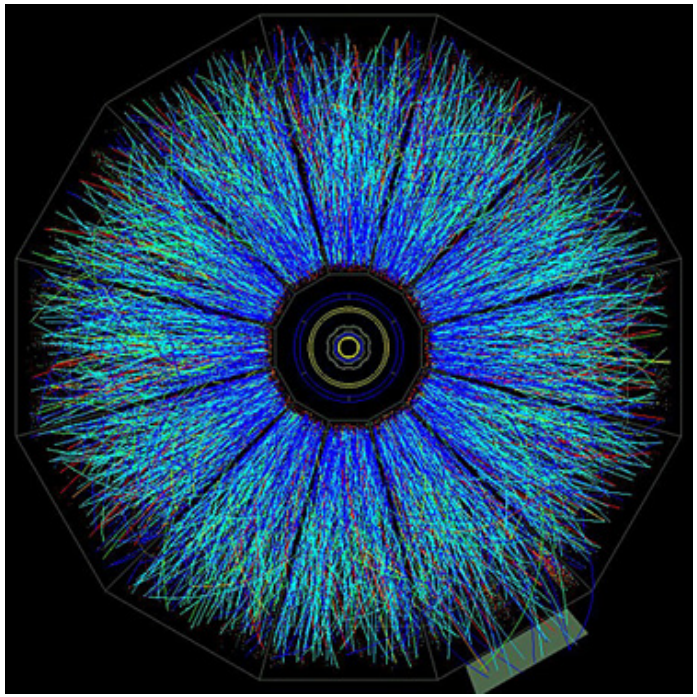
Relativistic Heavy Ion Collider (Brookhaven N.L)

- Au-Au collision
- E~200 GeV/nucleon
- Seek quark-gluon plasma(QGP)



Detectors

star



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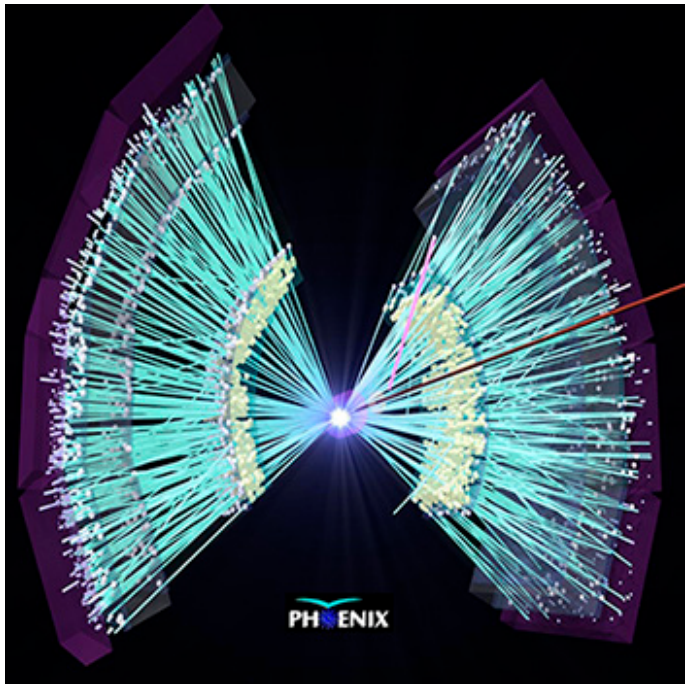
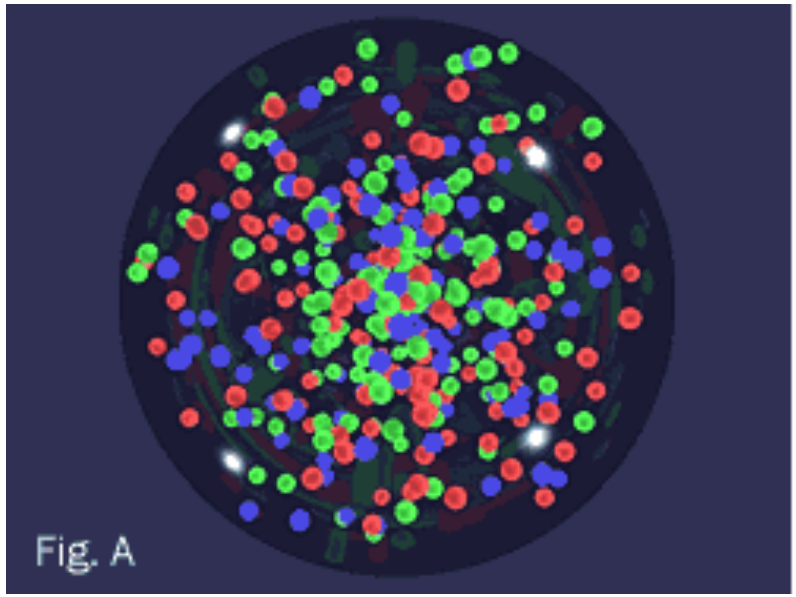


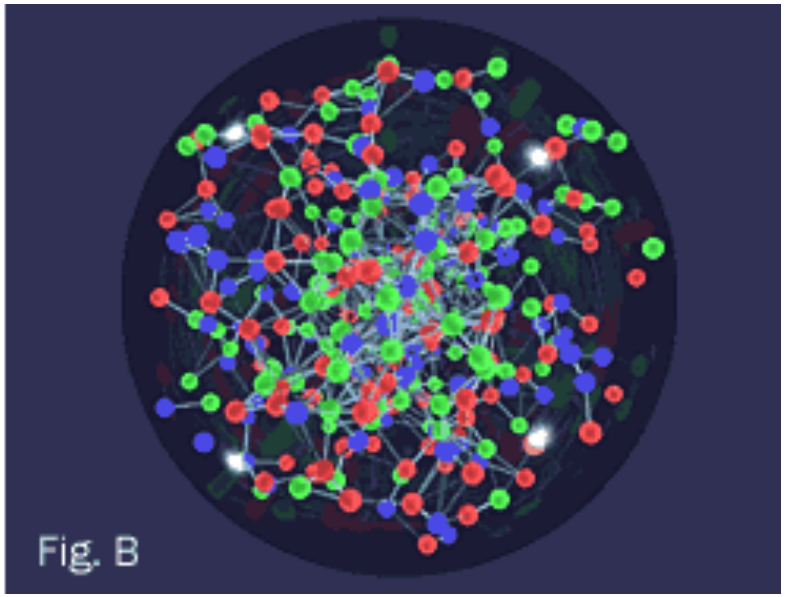
Some Puzzles（my contributions)

- Elliptic flow (hep-th/0610113)*
- Perfect fluid : (0806.4460 , 0901.0610)
- Jet quenching (hep-th/0607123)
- Early thermalization (hep-th/0511199)

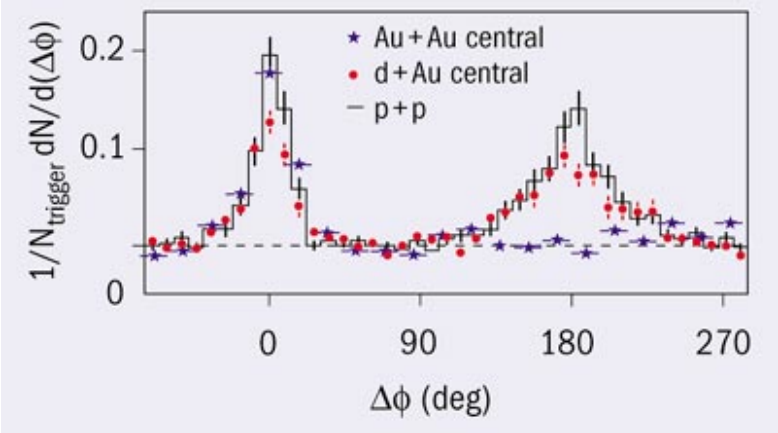
→QGP is strongly interacting

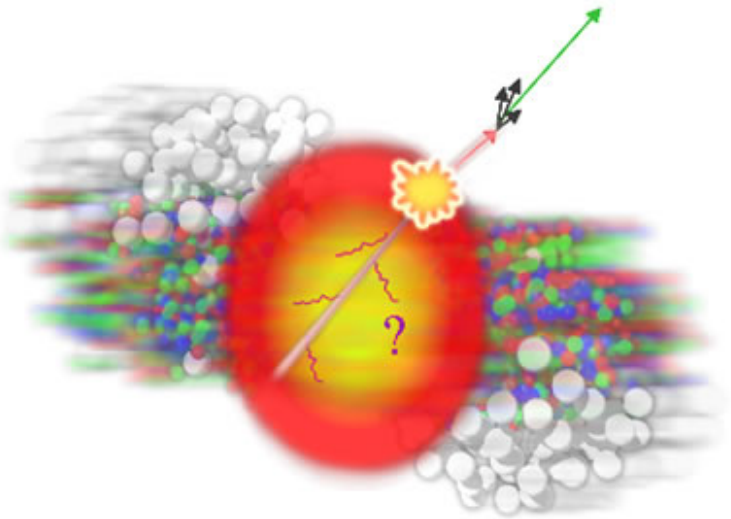
Liquid than Ga$





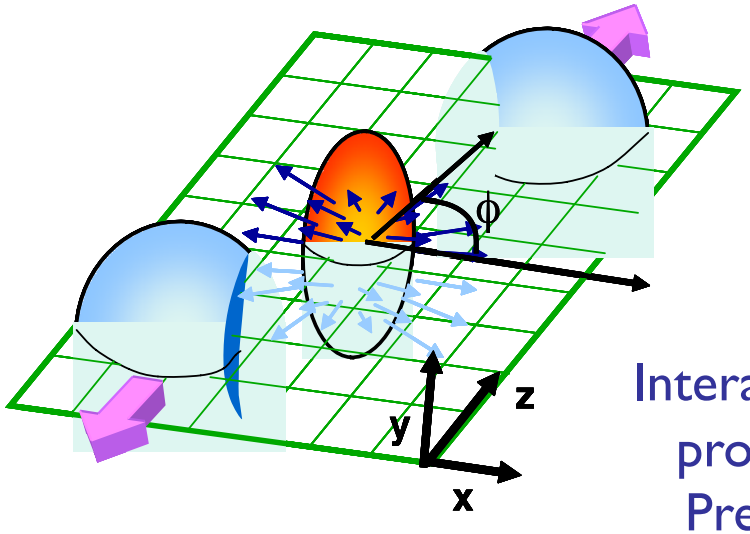
Jet-Quenching





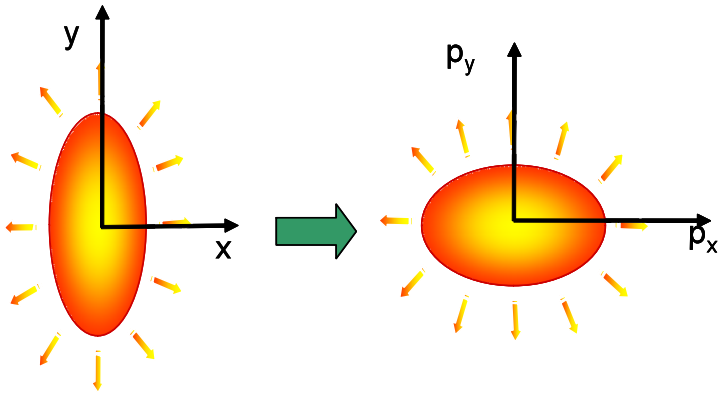
- Energy Loss Problem.

Elliptic flow v_2



$$\frac{dN}{d\varphi} = \frac{1}{2\pi}(1 + 2v_1 \cos\varphi + 2v_2 \cos 2\varphi + \ldots)$$

Interactions among the produced particles: Pressure gradients generate positive elliptic flow v_2



Early observation at RHIC:

v_2 as large as predicted by **perfect fluid dynamics**!

Perfect fluid

Exp: $\eta / s < 0.1 \times \hbar / k_B$

While perturbative evaluation ~1/g^4

ads/cft : $\dfrac{\eta}{s} = \dfrac{\hbar}{4\pi k_B}$ Universal value

Transport Coeff.

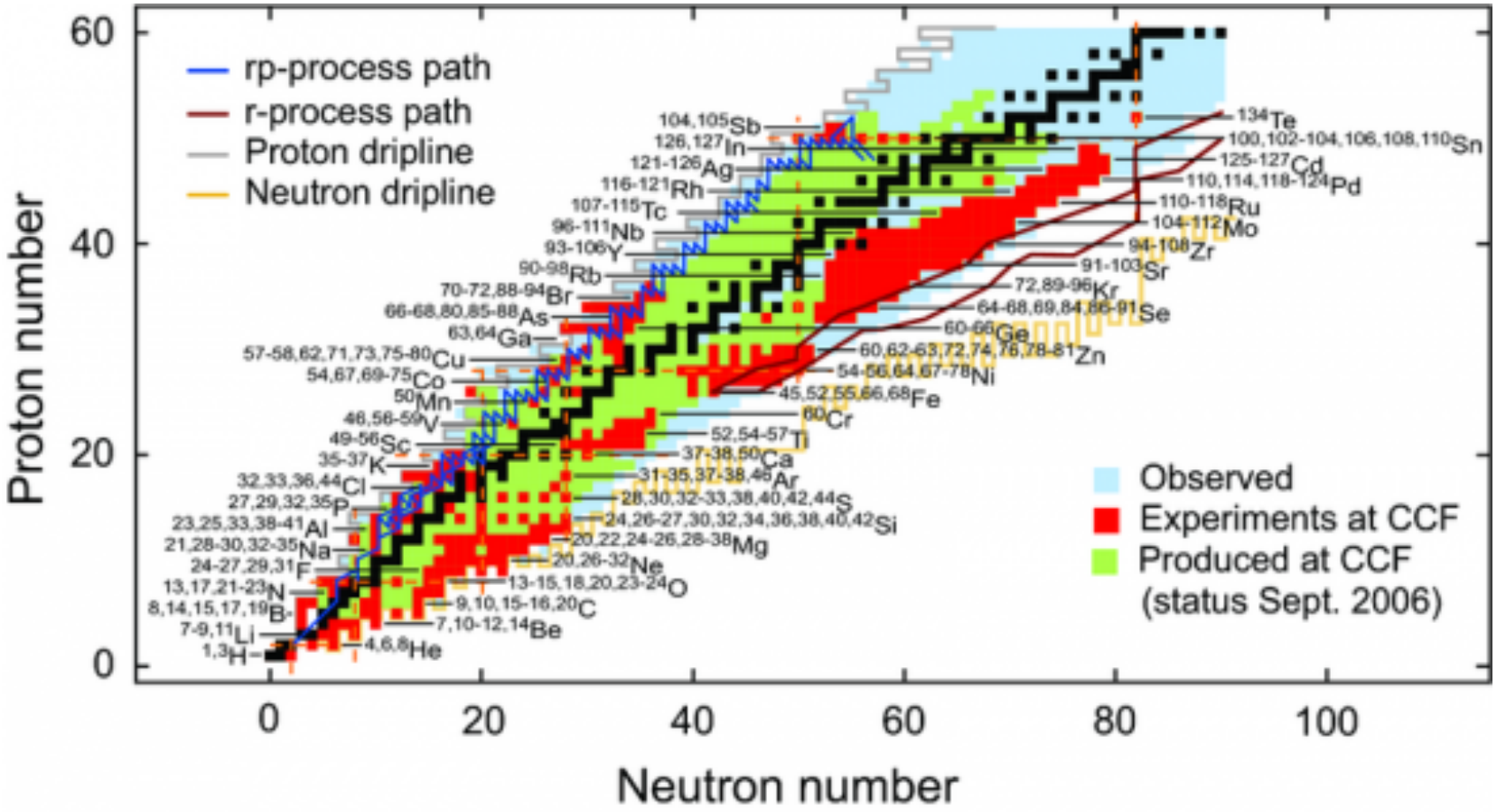
X.Ge, Y.Matsuo, F.Shu, SJS, Takuya Tsukioka , **arXiv:0806.4460**
Y. Matsuo, SJS. S.Takeuchi, T.Tsukioka, C.Yoo (APCTP**), archiv:0901.0610**

- Linear response theory: causal Green function→ T.C
- Ads/cft can calculate <JJ>, <TT> easily.

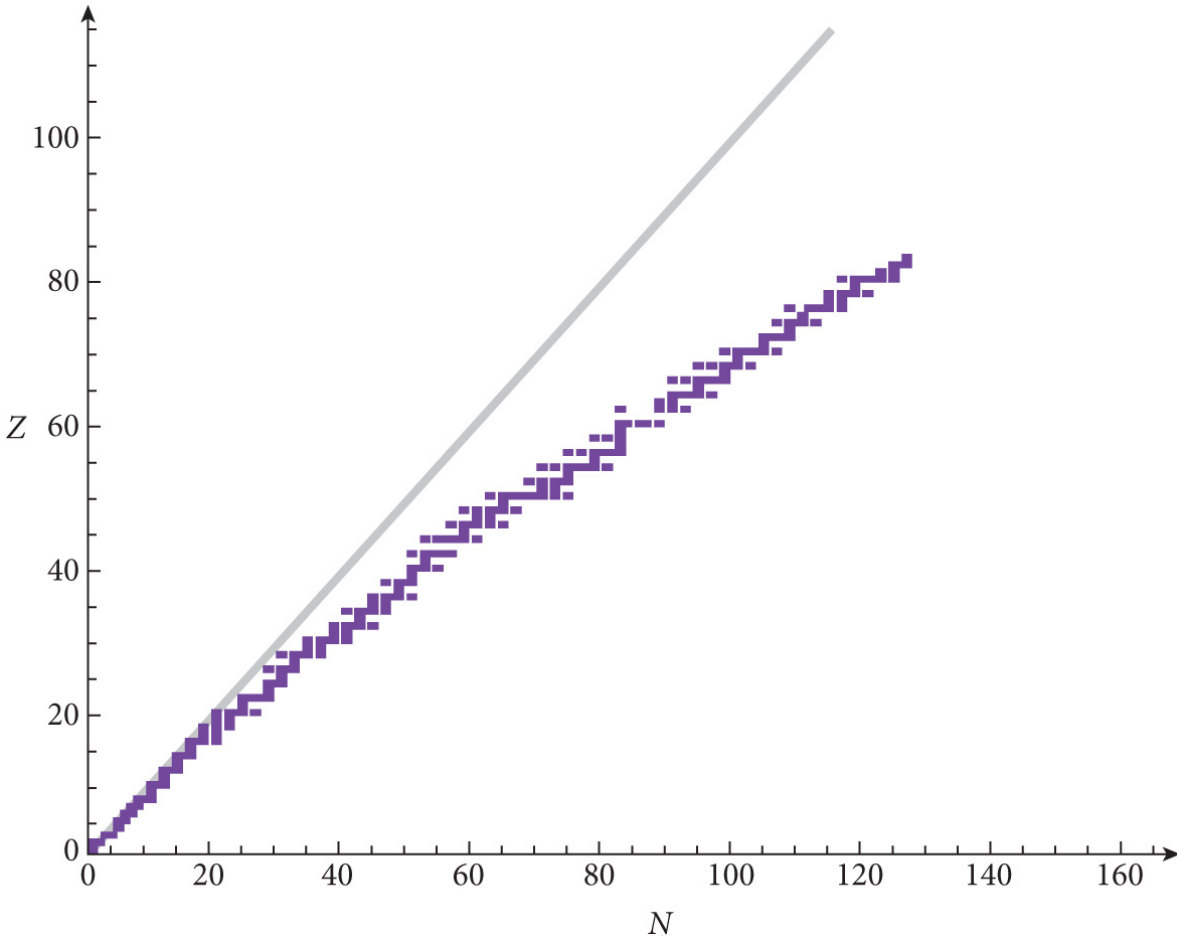
III. String theory and Nuclear Symmetry Energy.

- There will be a heavy ion collider constructed in Korea in 5 year with ~billion dollar.

KoR(are)I(sotope)A



- Valley of stability: Pauli v.s Coulomb



Symmetry Energy

- Liquid Drop Model
  Bethe-Weizsäcker formula (1935):

$$m = Zm_p + Nm_n - \frac{E_B}{c^2}$$

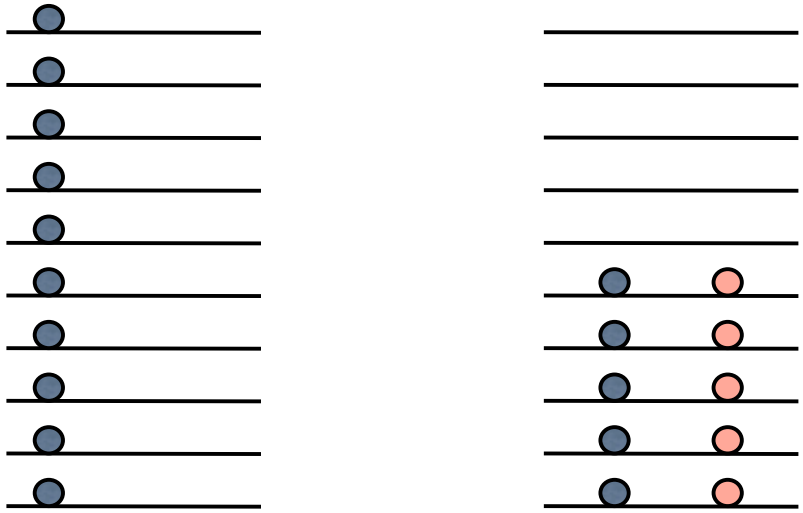
$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A,Z)$$

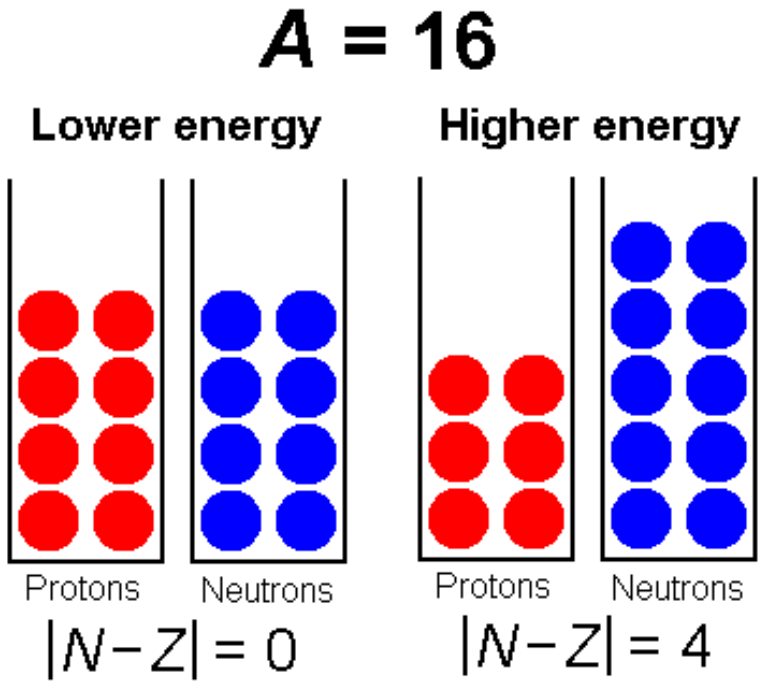
$$E(\rho,\tilde{\alpha}) \simeq E(\rho,0) + S_2(\rho)\tilde{\alpha}^2 \qquad \tilde{\alpha} \equiv (N-Z)/A$$

  It determines the curvature of valley of Stability.

Es and Pauli principle

Asymmetry term Es(N-Z)^2 is the consequence of Pauli principle. → Pauli term





Es(N-Z)^2 :

If Es→0, pure neutron star is possible.

If Es→infinity: N=P

Importance of Es

- Structure of Neutron Star
  the mass and width of neutron-star crusts.
- Properties of Exotic Nuclei
- Nucleo-Synthesis during the supernova explosion.

non-interacting fermi gas

$$E_k = \frac{3}{5}(N_p\epsilon_{Fp} + N_n\epsilon_{Fn})$$

$$E_k = \frac{3}{5}\epsilon_F(N_p+N_n)^{2/3}+\frac{1}{3}\epsilon_F\frac{(N_n-N_p)^2}{(N_p+N_n)}+O((N_n-N_p)^4) = \frac{3}{5}\epsilon_F A^{2/3}+\frac{1}{3}\epsilon_F\frac{(A-2Z)^2}{A}+O((A-2$$

$$E_{sym} = \frac{\epsilon_F}{3} \sim \rho^{2/3}$$ Non-relativistic

$$\sim \rho^{1/3}$$ Relativistic

Contribution of Pot.

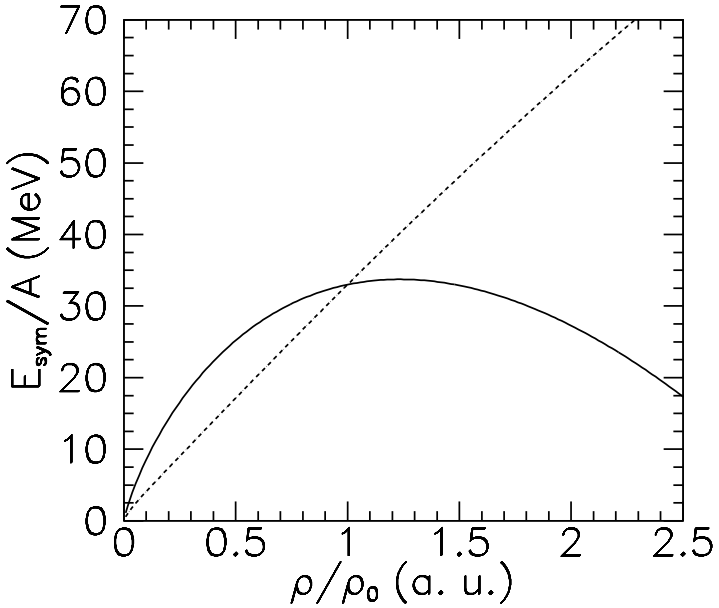
$$E_{sym} = E_{sym}(kin) + E_{sym}(pot) \equiv \frac{\epsilon_F}{3} + C_{sym}(\rho)$$

stronger density dependence,

$$E_{sym}(\rho) = a \cdot \left(\frac{\rho}{\rho_0}\right)^{2/3} + b \cdot \frac{2(\rho/\rho_0)^2}{1+(\rho/\rho_0)},$$

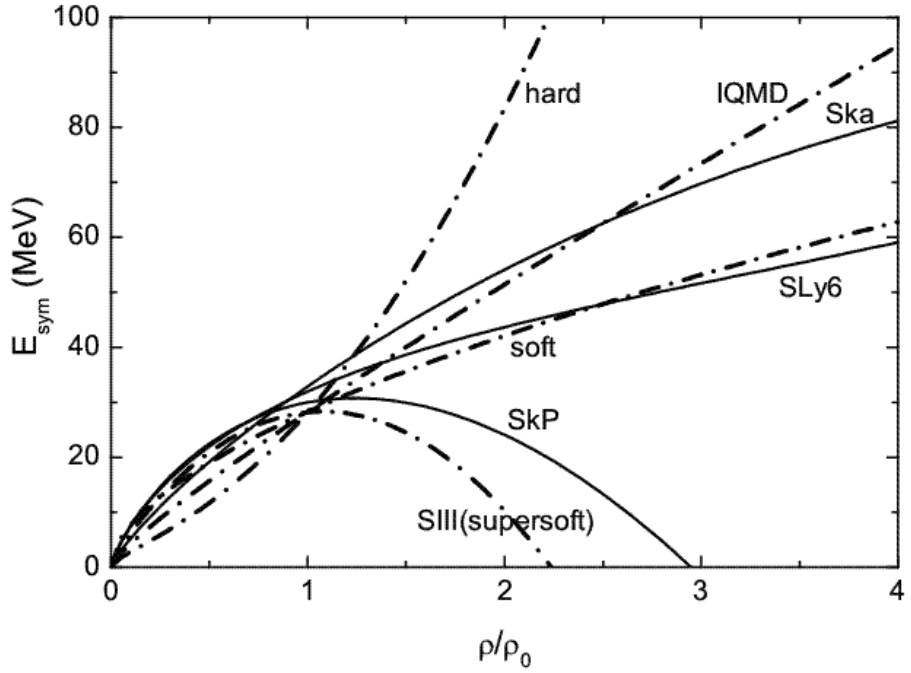
weaker density dependence

$$E_{sym}(\rho) = a \cdot \left(\frac{\rho}{\rho_0}\right)^{2/3} + 240.9\rho - 819.1\rho^2,$$



What is known for E_s ?

- Little is known for high density.
  not Exp. nor theoretical.



Even for the low density

- The separation of free part and potential part may not be valid.

So both low as well as high density regime is to be trusted.

Why difficult?

1. Strongly interacting.
   No good calculational tool in this regime.
2. Density effect: Even lattice qcd does not help much.

Repeat:
String theory idea is

- Replace Nuclear force by classical gravity

Gluon dynamics→ Geometry.

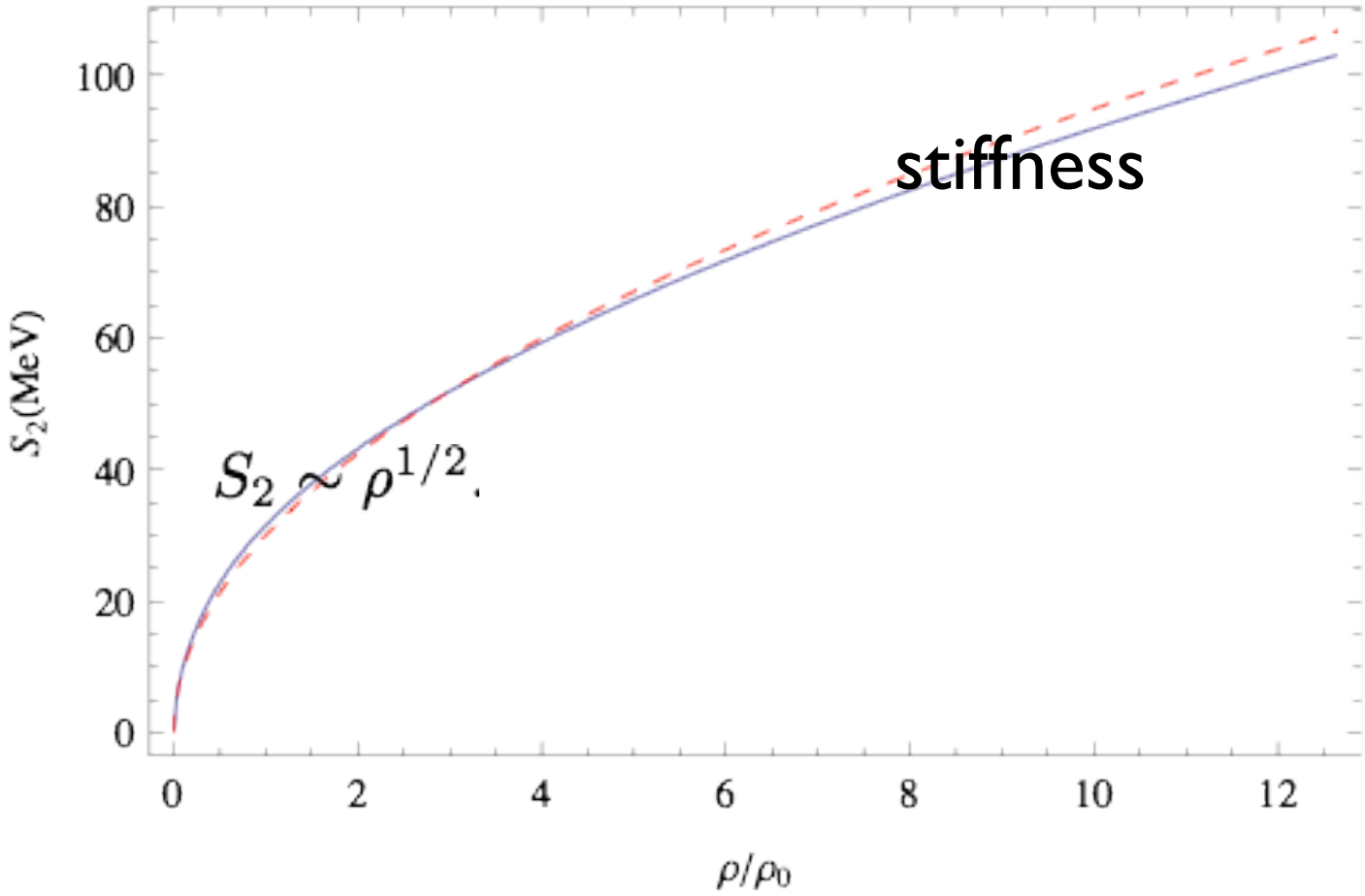
Confinement or deconfinement
depends on geometry.

Flavor dynamics by classical fields
in warped geometry.

Result

arXiv:1011.0868→ to appear in JHEP

by Y.Kim, Y.Seo, I. Shin, SJS



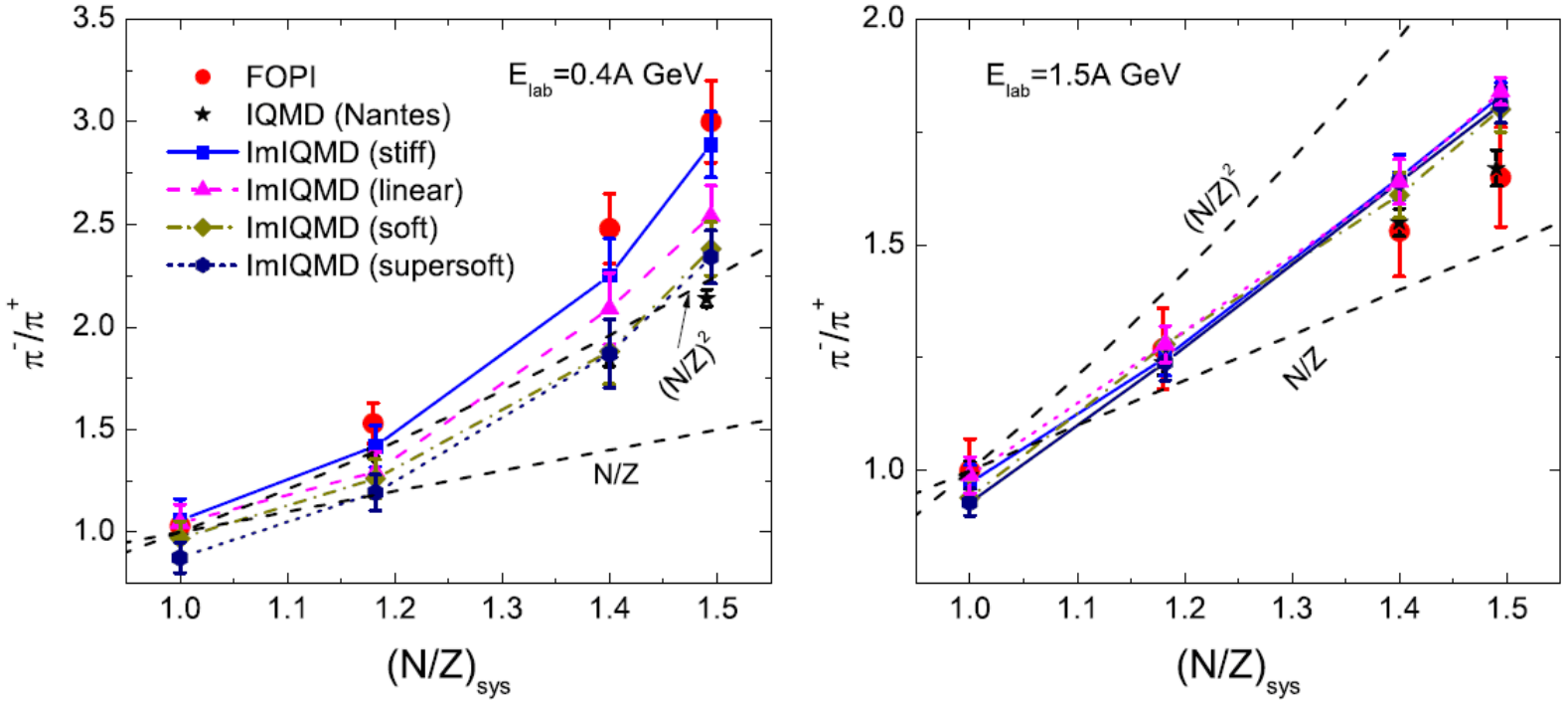
How to detect Es ?

- Asymmetry in N-P is
  ~ that in π- π+

- π-/π+ yields are sensitive to
  the stiffness of the symmetry energy
  near threshold energy.

Experiment→ stiff

Z.-Q. Feng, G.-M. Jin / Physics Letters B 683 (2010) 140–144



$^{40}Ca+^{40}Ca$, $^{96}Ru+^{96}Ru$, $^{96}Zr+^{96}Zr$ and $^{197}Au+^{197}Au$, and also plotted the ratios of N/Z and $(N/Z)^2$
as a function of N/Z at incident energy 0.4A GeV and 1.5A GeV, respectively.

Pauli principle in hQCD.

- DBI action[Q1,Q2]=f(Q)+S2(Q1-Q2)^2+ …
  Positivity of S2 is equivalent to the Pauli principle in hqcd
- Parallel to "Driving force of Z=N is Pauli principle"
- Dual of fermion number is the local U(1) in 5d.
- Coulomb repulsion of the dual E&M is responsible for the Es.

Why $S_2 \sim \rho^{1/2}$.

- analytic expression for symmetry energy.

$$S_2 = \frac{2\tau_6}{N_B}\int d\rho \frac{\sqrt{1+\dot{y}^2}\tilde{Q}^2\omega_+^{10/3}\rho^4}{(\tilde{Q}^2+4\omega_+^{8/3}\rho^4)^{3/2}},$$

- For the flat embedding approximation.

$$S_2 = \left(\Gamma(\frac{5}{4})\right)^2\sqrt{\frac{\lambda\rho_0}{2M_{KK}}}\sqrt{\frac{\rho}{\rho_0}}.$$

$S_2 \sim \rho^{1/2}$.

- Have confidence on

Dispersion relation for non-fermi-Liquid

$E_{sym} \sim \rho^{2/3}$ comes from $E = p^2$

$E_{sym} \sim \rho^{1/3}$ from $E = p$

$E_{sym} \sim \rho^{1/2} \rightarrow E = p^{3/2}$

Why interesting?

- The anomaly in dispersion relation is closely related to the fermi surface structure.
- For strongly interacting system, fermi surface is fuzzy and its implication is a big and interesting issue.
- Entire Thermodynamics as well as hydrodynamics of the strongly interacting Non-fermi liquid system will be a hot issue.

Non-fermi Liquid in Nuclear system?

$$G_R(\omega, k) = \frac{h_1}{k_\perp - \frac{1}{v_F}\omega - h_2\omega^{2\nu_{k_F}}}$$

Liu et. al
0903.2477
0907.2694

$$\text{if } \nu_{k_F} < \frac{1}{2}, \quad \omega_\star(k) \sim k_\perp^z, \qquad z = \frac{1}{2\nu_{k_F}} > 1$$

- If we choose $\nu_{k_F} = \frac{1}{3},$

  we get $E = p^{3/2} \to E_{sym} = \rho^{1/2}$

Conclusion

- String theory is useful as well as interesting.
- Symmetry Energy can be calculated using the holographic principle.
- Physics of fermi surface for strongly interacting system will be Interesting issue.
- It can make the KoRIA more interesting project.