Symmetry Energy and Universality Classes of holographic QCD

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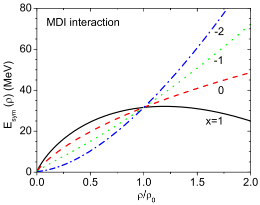

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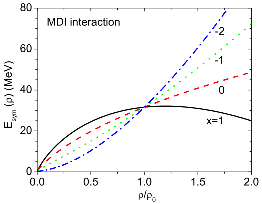

- From AdS/CFT, we can calculate the symmetry energy(D4/D6)
JHEP 1106(2011)011: Younman Kim, YS, Ik Jae Shin, Sang-Jin Sin
    - $S_2 \sim \varrho^{1/2}$
    - Is this behavior universal?

AdS/CFT correspondence

- String theory

Open Strings	Closed Strings
massless excitation Gauge Filed A_μ	massless excitation Graviton $G_{\mu\nu}$
D-branes	Curved spacetime
low energy limit $\mathcal{N} = 4,\ D = 4$ SYM	low energy limit 10d Supergravity
Large N limit Super conformal Theory	Near horizon limit $AdS_5 \times S^5$

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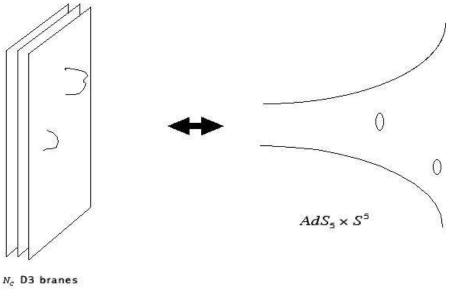
- There is Open-Closed string duality



- Weak coupling limit ($\lambda << 1$): $\mathcal{N} = 4$, $D = 4$, $SU(N_C)$ SYM
- Strong coupling limit ($\lambda >> 1$): Classical gravity in $AdS_5 \times S^5$
- From calculating classical gravity, we can obtain some quantities in gauge theory with strong coupling.

AdS/CFT correspondence

- AdS/CFT dictionary

Gauge Theory(boundary)	Gravity(bulk)
Operator $\mathcal{O}$ (Energy momentum tensor $T_{\mu\nu}$)	Field ϕ (Graviton $g_{\mu\nu}$)
Source J	Non-normailzable mode ϕ_o
Expectation value $< \mathcal{O} >$	Normalizable mode
Conformal dimension Δ_ϕ	mass of field m_ϕ
Flavor degrees	Probe brane
Global symmetry	Gauge symmetry
$\ldots$	$\ldots$

- In asymptotic region ($r \to \infty$)

$$\phi \sim J + \frac{< \mathcal{O} >}{r^\alpha} + \cdots$$

- It is far from realistic QCD, we need something more...

- Finite Temperature
  - Black Hole Geometry(In Euclidean)

$$ds^2 = f(r)dt^2 + \frac{dr^2}{f(r)} + \cdots$$

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Near horizon

$$f(r) = f(r_h) + (r - r_h)f'(r_h) + \cdots = (r - r_h)f'(r_h)$$

New coordinate

$$\rho = \frac{2\sqrt{r - r_h}}{\sqrt{f'(r_h)}}$$

$$ds^2 = \rho^2 \frac{f'(r_h)^2}{4} dt^2 + d\rho^2 = d\rho^2 + \rho^2 d\theta^2$$

$$d\theta = \frac{f'(r_h)}{2} dt$$

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To avoid conical singularity at origin, the period of θ should be 2π

$$2\pi = \frac{f'(r_h)}{2}\beta \to T = \frac{1}{\beta} = \frac{f'(r_h)}{4\pi}$$

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  - Schwartzschild black hole in flat space-time

$$f = 1 - \frac{2M}{r} \rightarrow T = \frac{1}{8\pi M}$$

Schwartzschild black hole in AdS_5

$$f = \frac{r^2}{R^2}\left(1 - \frac{r_h^4}{r^4}\right) \rightarrow T = \frac{r_h}{\pi R^2}$$

- Finite Temperature
  - Black Hole Geometry(D4 brane)

$$
\begin{aligned}
ds^2 &= \left(\frac{U}{R}\right)^{3/2}\left(f(U)dt^2 + d\vec{x}^2 + dx_4^2\right) + \left(\frac{R}{U}\right)^{3/2}\left(\frac{dU^2}{f(U)} + U^2 d\Omega_4^2\right) \\
e^{\phi} &= g_s\left(\frac{U}{R}\right)^{3/4}, \quad F_4 = \frac{2\pi N_c}{\Omega_4}\epsilon_4, \quad f(r) = 1 - \left(\frac{U_T}{U}\right)^3, \quad R^3 = \pi g_s N_c l_s^3
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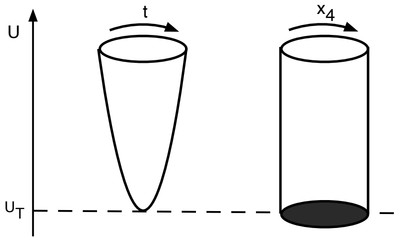
  - Geometrical structure



- $t = t + \beta$, $x_4 = x_4 + 2\pi R_4$
- Black hole horizon at $U = U_T \sim T$ (temperature)
- Deconfined phase

- Confinement
  - Double Wick rotation $t \leftrightarrow ix_4$, $x_4 \leftrightarrow i\tau$

$$
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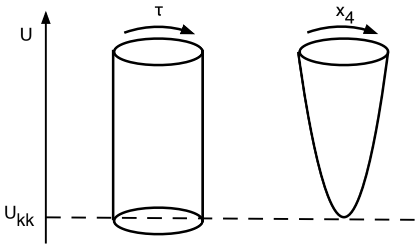

    - Arbitrary radius of time circle (zero temperature)
    - Geometry end at $U = U_{KK}$ (scale in the theory)
    - confined phase

- Adding flavor(Probe brane)
  - $y(\rho) \sim M_q + \frac{<\bar{\psi}\psi>}{\rho^2} + \cdots$

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- Adding density (or chemical potential)
  - Gauge symmetry on probe brane $\leftrightarrow$ Global symmetry
  - $U(1)$ on brane A_μ $\leftrightarrow$ Global current $< J^\mu > = < \bar{\psi}\gamma^\mu\psi >$
  - $A_0 \leftrightarrow < \bar{\psi}\gamma^0\psi > = < \psi^\dagger\psi > = < Q >$(number density)
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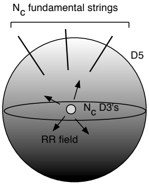
- Sources
  - End points of fundamental strings (quarks)
  - Baryon vertex



Symmetry energy in hQCD

- Energy per nucleon

$$E(\rho, \alpha) = E(\rho, \alpha = 0) + E_{\rm sym}(\rho)\alpha^2 + O(\alpha^4)$$

ρ: total baryon density, α: asymmetric parametry

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$$E_{\rm sym}(\rho) = \frac{1}{2}\frac{\partial^2 E(\rho, \alpha)}{\partial \alpha^2}\bigg|_{\alpha=0}$$

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  - D4 brane background

	0	1	2	3	4	5	6	7	8	9	q	d
D4	●	●	●	●	●							
D2	●	●				●					2	1
D4	●	●	●			●	●				4	2
D6	●	●	●	●		●	●	●			6	3

  - D3 brane background

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- Free energy

$$\mathcal{F}_{\rm total}(Q) = \mathcal{F}(Q) + \mathcal{F}^{(1)}_{Dq}(Q_1) + \mathcal{F}^{(2)}_{Dq}(Q_2),$$

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- Expansion around $\alpha = 0$

$$\mathcal{F}_{\rm total}(\tilde{Q}) = E_0 + \tilde{\alpha} E_1 + \tilde{\alpha}^2 E_2 + \cdots .$$

  - $E_0 = \mathcal{F}(Q) + 2\mathcal{F}_{Dq}\left(\frac{Q}{2}\right)$: Free energy for symmetric matter
  - $E_1 = 0$
  - $$E_2(Q) = \left(\frac{Q^2}{4}\right) \cdot \left.\frac{\partial^2 \mathcal{F}^{(1)}_{Dq}(Q_1)}{\partial Q_1^2}\right|_{Q_1 = Q/2}.$$

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- Symmetry energy in hQCD

$$S_2 \equiv \frac{E_2(Q)}{Q}.$$

- DBI action of D_q brane

$$S_{Dq} = \mu_q \int d\sigma^{q+1} e^{-\phi} \sqrt{\det(g + 2\pi\alpha' F)},$$

- Induced metric on D_q brane

$$ds^2_{Dq} = -G_{tt}dt^2 + G_{xx}d\vec{x}_d^2 + G_{\rho\rho}d\rho^2 + G_{\Omega\Omega}d\Omega^2_{q-d-1}.$$

- Legendre transformation

$$\mathcal{F}_{Dq}(\tilde{Q}) = \tau_q \int d\rho \sqrt{G_{tt}G_{\rho\rho}} \sqrt{\tilde{Q}^2 + e^{-2\phi} G^d_{xx} G^n_{\Omega\Omega}},$$

$(n = q - d - 1)$

- Symmetry energy

$$S_2 = 2\tau_q \int d\rho \frac{\tilde{Q}\sqrt{G_{tt}G_{\rho\rho}} e^{-2\phi} G^d_{xx} G^n_{\Omega\Omega}}{\left(\tilde{Q}^2 + 4e^{-2\phi} G^d_{xx} G^n_{\Omega\Omega}\right)^{3/2}}.$$

- Confining geoemtry
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Symmetry energy in nuclear matter system

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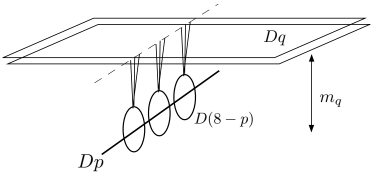

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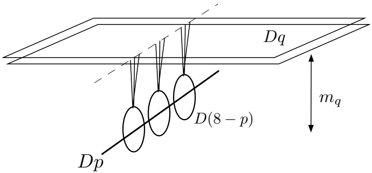

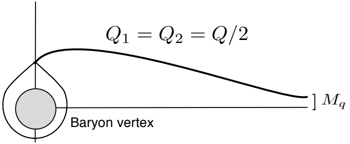

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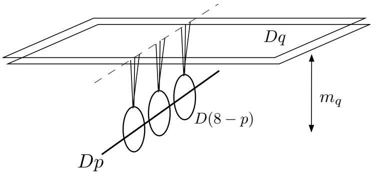
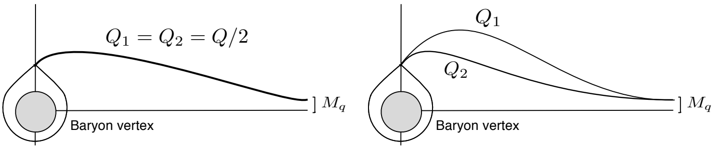




- D4 brane background

$$\begin{aligned} ds^2_{D4} &= \left(\frac{U}{R}\right)^{3/2}\left(\eta_{\mu\nu}dx^\mu dx^\nu + f(U)dx_4^2\right) + \left(\frac{R}{U}\right)^{3/2}\left(\frac{dU^2}{f(U)} + U^2 d\Omega_4^2\right) \\ e^\phi &= g_s\left(\frac{U}{R}\right)^{3/4}, \quad F_4 = \frac{2\pi N_c}{\Omega_4}\epsilon_4, \quad f(U) = 1 - \left(\frac{U_{KK}}{U}\right)^3, \quad R^3 = \pi g_s N_c l_s^3. \end{aligned} \tag{1}$$

$$g_s = \frac{\lambda}{2\pi l_s N_c M_{KK}}, \quad U_{KK} = \frac{2}{9}\lambda M_{KK} l_s^2, \quad R^3 = \frac{\lambda l_s^2}{2M_{KK}}, \quad \lambda = g_{YM}^2 N_c.$$

- Baryon vertex (spherical D4)

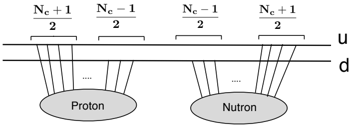
$$\mathcal{F}_{BV} = \tau_4 \int d\theta \sqrt{\omega_+^{4/3}(\xi^2 + \xi'^2)}\sqrt{\tilde{D}(\theta)^2 + \sin^6\theta},$$

- Probe brane

$$\mathcal{F}_{D_q} = \hat{\tau}_q \int d\rho \sqrt{\omega_+^{4/3}(1 + \dot{Y}^2)}\sqrt{\hat{Q}^2 + \rho^{2n}\omega_+^{\frac{4}{3}(d-1)}},$$

$n = q - d - 1$, $q = 6, 4, 2$, $d = 3, 2, 1$

- Proton and Neutron for $N_c \geq 3$



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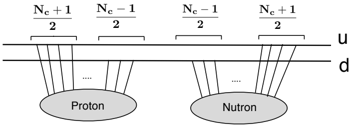


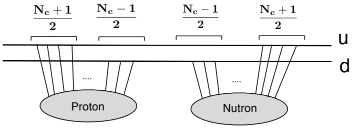
$$Q_1 - Q_2 = N_p - N_n, \qquad Q_1 + Q_2 = Q = N_B N_C,$$

$$\tilde{\alpha} = \frac{Q_1 - Q_2}{Q_1 + Q_2} = \frac{N_p - N_n}{N_C N_B},$$

$$\tilde{\alpha}^2 E_2 = \left(\frac{N_p - N_n}{N_C N_B}\right)^2 E_2 = \left(\frac{N_p - N_n}{N_B}\right)^2 \cdot \frac{E_2}{N_C^2}.$$

Symmetry energy in nuclear matter system

- Proton and Neutron for $N_c \geq 3$



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- Symmetry energy

$$S_2 = \frac{\bar{\xi}_{KK}}{\pi\alpha'} \cdot \frac{1}{N_C} \int d\rho \frac{\hat{Q}\sqrt{\omega_+^{4/3}(1+\dot{Y}^2)}\ \rho^{2n}\omega_+^{\frac{4}{3}(d-1)}}{\left(\hat{Q}^2 + 4\rho^{2n}\omega_+^{\frac{4}{3}(d-1)}\right)^{3/2}}.$$

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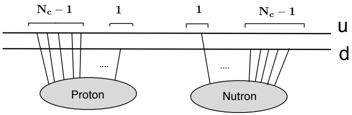

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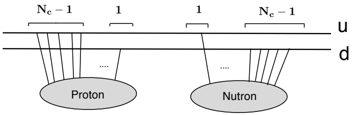

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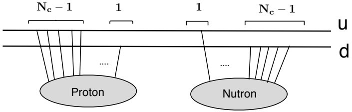
$$\tilde{\alpha}^2 E_2 = \left(\frac{N_p - N_n}{N_B}\right)^2 \cdot \frac{(N_C - 2)^2}{N_C^2} E_2.$$

- Proton and Neutron for $N_c \geq 3$



$$Q_1 - Q_2 = (N_C - 2)(N_p - N_n), \qquad Q_1 + Q_2 = N_C N_B.$$

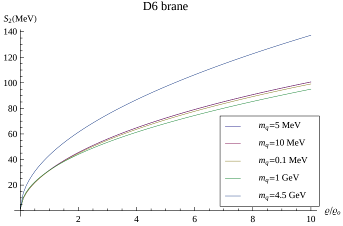
$$\tilde{\alpha} = \frac{Q_1 - Q_2}{Q_1 + Q_2} = \frac{(N_C - 2)(N_p - N_n)}{N_C N_B},$$

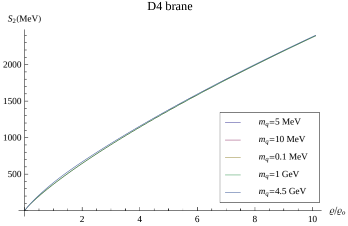
$$\tilde{\alpha}^2 E_2 = \left(\frac{N_p - N_n}{N_B}\right)^2 \cdot \frac{(N_C - 2)^2}{N_C^2} E_2.$$

- Symmetry energy

$$S_2 = \frac{\bar{\xi}_{KK}}{\pi \alpha'} \cdot \frac{(N_C - 2)^2}{N_C} \int d\rho \frac{\hat{Q}\sqrt{\omega_+^{4/3}(1 + \dot{Y}^2)}\ \rho^{2n}\omega_+^{\frac{4}{3}(d-1)}}{\left(\hat{Q}^2 + 4\rho^{2n}\omega_+^{\frac{4}{3}(d-1)}\right)^{3/2}}.$$

- $\lambda = 18,\ M_{kk} = 1GeV,\ N_c = 3$

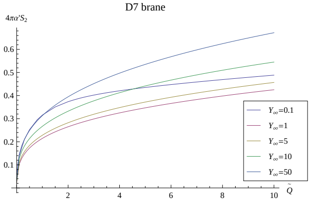


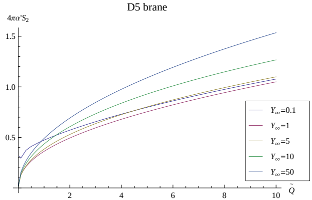


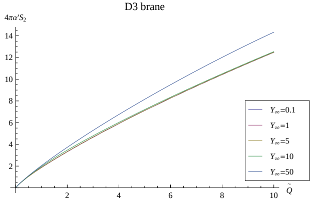
- D6 brane(3+1): $S_2 = S_0(\varrho/\varrho_0)^{1/2}$, where $27\mathrm{MeV} \le S_0 \le 36\mathrm{MeV}$
- D4 brane(2+1): linear

Symmetry energy in nuclear matter system

- D3 background







- D7 probe(3+1): $0.21\tilde{Q}^{1/3} \leq 4\pi\alpha' S_2 \leq 0.31\tilde{Q}^{1/3}$
- D5 probe(2+1):$0.34\tilde{Q}^{1/2} \leq 4\pi\alpha' S_2 \leq 0.5\tilde{Q}^{1/2}$
- D3 probe(1+1): linear

Symmetry energy in quark matter system

- Deconfining geoemtry
  - Black hole geometry

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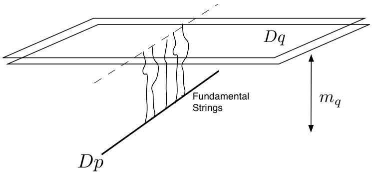

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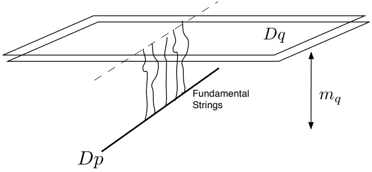

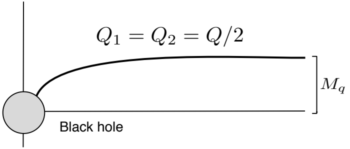

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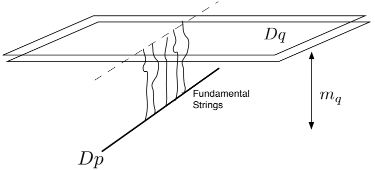
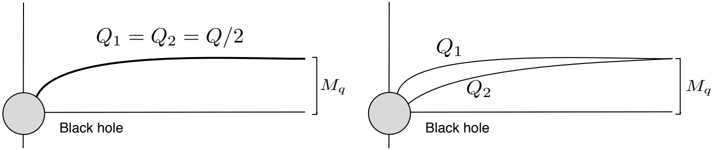
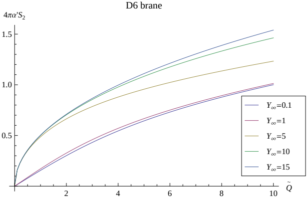
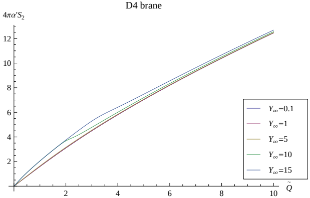




- D4 brane background





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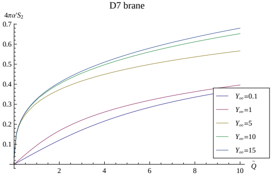

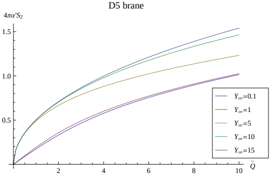

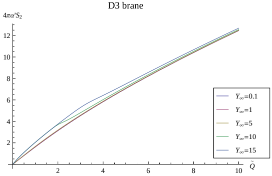

- $M_q \to \infty$, $Q \to 0$ limit
  - $\dot{Y} = 0$
  - Background geometry

$$ds_{10}^2 = Z_p^{-1/2}(-dt^2 + d\vec{x}_p^2) + Z_p^{1/2} d\vec{x}_\perp^2\,,$$

$$e^{2\phi} = Z_p^{\frac{3-p}{2}}\,.$$

  - Symmetry energy

$$S_2 \quad = \quad 2\tau_q \int d\rho \frac{\tilde{Q}\rho^{2n}}{\left(\tilde{Q}^2 + 4\rho^{2n}\right)^{3/2}} = c_n \tilde{Q}^{\frac{1}{n}}\,,$$

Table: D4 brane background

	0	1	2	3	4	5	6	7	8	9	q	d	$q-d-1$	S_2	$2\nu = n/d$
D4	•	•	•	•	•										
D2	•	•				•					2	1	0	$\mathcal{O}(1)$	-
D4	•	•	•			•	•				4	2	1	Q	$1/2$
D6	•	•	•	•		•	•	•			6	3	2	$Q^{1/2}$	$2/3$

Table: D3 brane background

	0	1	2	3	4	5	6	7	8	9	q	d	$q-d-1$	S_2	$2\nu = n/d$
D3	•	•	•	•											
D3	•	•			•	•					3	1	1	Q	1
D5	•	•	•		•	•	•				5	2	2	$Q^{1/2}$	1
D7	•	•	•	•	•	•	•	•			7	3	3	$Q^{1/3}$	1

- We calculate density dependence of symmetry energy by using D-brane configuration
  - Symmetry energy seems to have power law depends on the dimensionality of probe brane and boundary space:
    $$S_2 \sim Q^{\frac{1}{q-d-1}}$$
  - Symmetry energy is not so sensitive to the background geometry

Conclusion and Discussion

- We calculate density dependence of symmetry energy by using D-brane configuration
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- Origin of symmetry energy
  - D-brane point of view: $U(1)$ repulsion between sources
  - Boundary point of view: Palui exclusion
    JHEP 1003:074,2010: Youngman Kim, YS, Sang-Jin Sin

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    JHEP 1003:074,2010: Youngman Kim, YS, Sang-Jin Sin
- Fermi gas model for nuclei

$$E/A = \frac{3}{5}\epsilon_F + \frac{1}{3}\epsilon_F \alpha^2 + \mathcal{O}(\alpha^4),$$

If we naively extrapolate the relation $S_2 \sim \epsilon_F$, $S_2 \sim \rho^{1/n}$ means the dispersion relation becomes $\epsilon \sim k^{d/n}$

  - D3 brane background: relativistic fermions
  - D4 brane background: non-fermi liquid

Thank you !!!