宇宙の進化と素粒子模型

平成２８年度宇宙線研究所共同利用研究成果発表会
宇宙線研究所理論グループ　伊部昌宏

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名古屋大：久野
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（合計17名）
国内旅費：10万円

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11) Simple cosmological solution to the Higgs field instability problem in chaotic inflation and the formation of primordial black holes.
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10.1103/PhysRevD.94.063509.
Phys.Rev. D94 (2016) no.6, 063509.

12) Revisiting constraints on small scale perturbations from big-bang nucleosynthesis.
By Keisuke Inomata, Masahiro Kawasaki, Yuichiro Tada.
[arXiv:1605.04646 [astro-ph.CO]].
10.1103/PhysRevD.94.043527.
Phys.Rev. D94 (2016) no.4, 043527.

13) Charged Q-ball Dark Matter from B and L direction.
By Jeong-Pyong Hong, Masahiro Kawasaki, Masaki Yamada.
[arXiv:1604.04352 [hep-ph]].
10.1088/1475-7516/2016/08/053.
JCAP 1608 (2016) no.08, 053.

14) Dark matter annihilation and decay from non-spherical dark halos in galactic dwarf satellites.
By Kohei Hayashi, Koji Ichikawa, Shigeki Matsumoto, Masahiro Ibe, Miho N. Ishigaki, Hajime Sugai.
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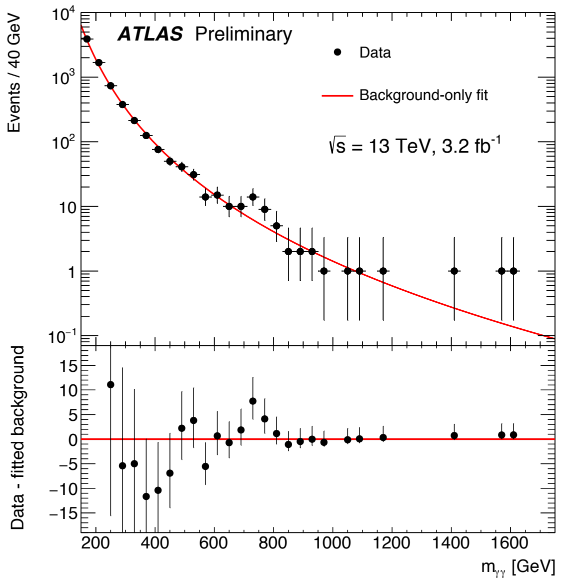
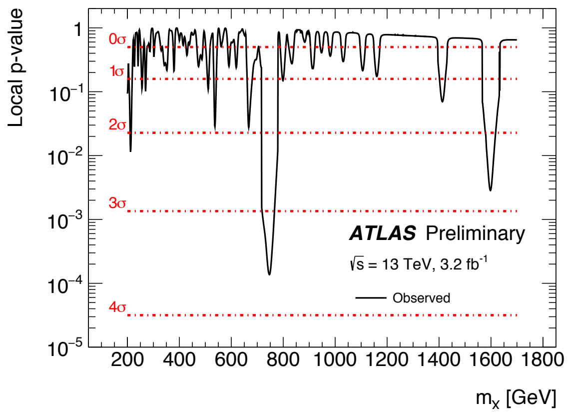
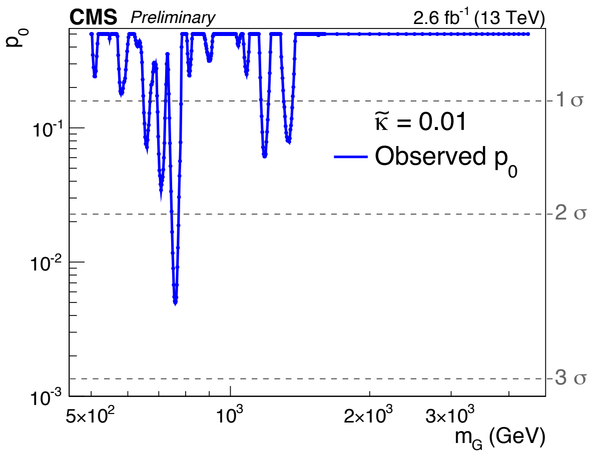
News ! ✓ Apart from the 2TeV excess, ***both*** ATLAS and CMS reported an excess at 750GeV in di-photon search (2015/12/15)!







We could have some dynamics within a TeV range?

(Our model can be tuned to explain this 750GeV signal.)

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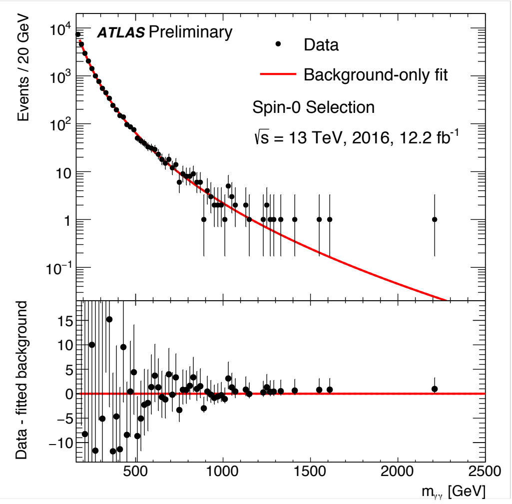
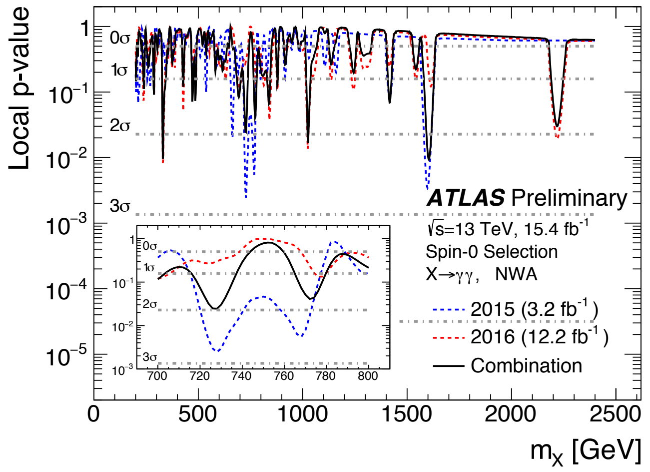
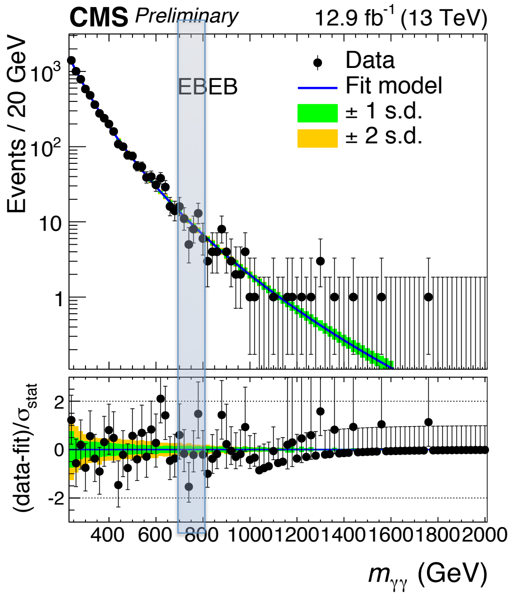
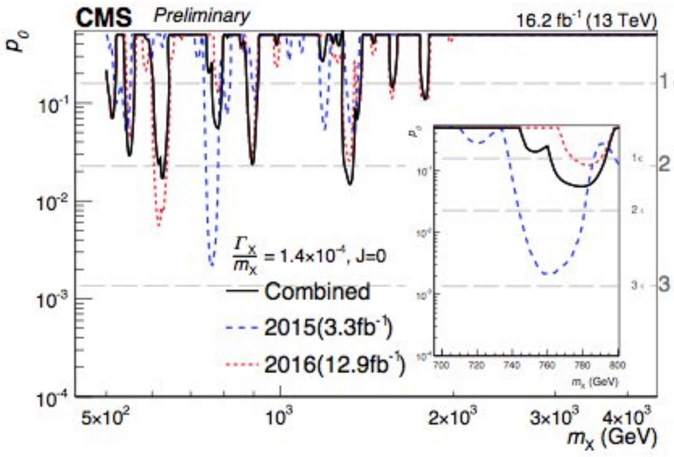
750GeV Diphoton Resonance (ICHEP 2016)

Both CMS and Atlas found no excesses from much larger data set…









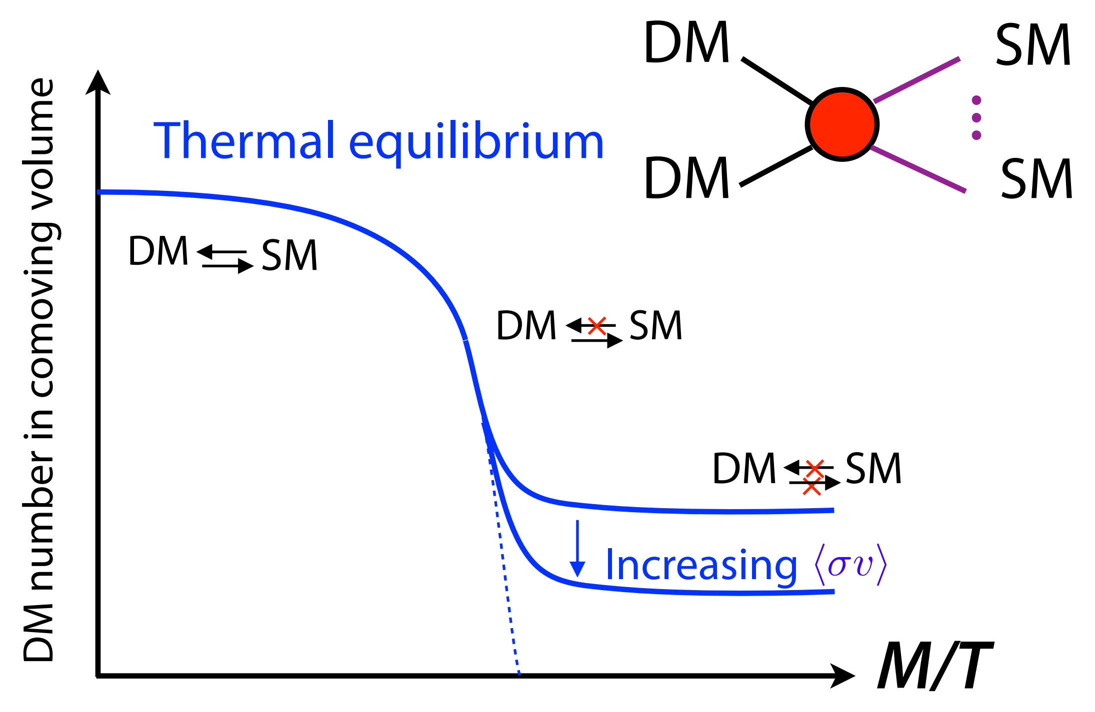
Atlas has not shown spin-2 result though…

2016 業績の一例

Thermal Relic Dark Matter Beyond the Unitarity Limit

Based on JHEP 1608 (2016) 151
K.Harigaya, MI. K.Kaneta, W.Nakano, M.Suzuki

✓ *Thermal Relic Dark Matter !*



- DM is in thermal equilibrium for ***T*** > ***M***.
- For ***M*** < ***T***, DM is no more produced efficiently.
- DM is still annihilating for ***M*** < ***T*** for a while...
- DM is also diluted by the cosmic expansion
- DM cannot find each other and stop annihilating at some point
- DM number in comoving volume is frozen

✓ Dark Matter density does not depend on the initial condition!

✓ It is determined by the annihilation cross section.

ex) For s-wave annihilation mode

$$\Omega_{DM} h^2 \simeq 0.1 \times \left(\frac{10^{-9}\,\mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \right)$$

✓ *Upper Limit on thermal relic dark matter mass*

The heavier the DM is, the larger couplings are required.

$$\langle \sigma v \rangle \sim \frac{\pi \alpha^2}{m_{DM}^2} \sim 10^{-9} \mathrm{GeV}^{-2}$$

→ Unitarity Limit on WIMP mass (1990 Griest & Kamionkowski)

Each partial wave cross section is limited from above

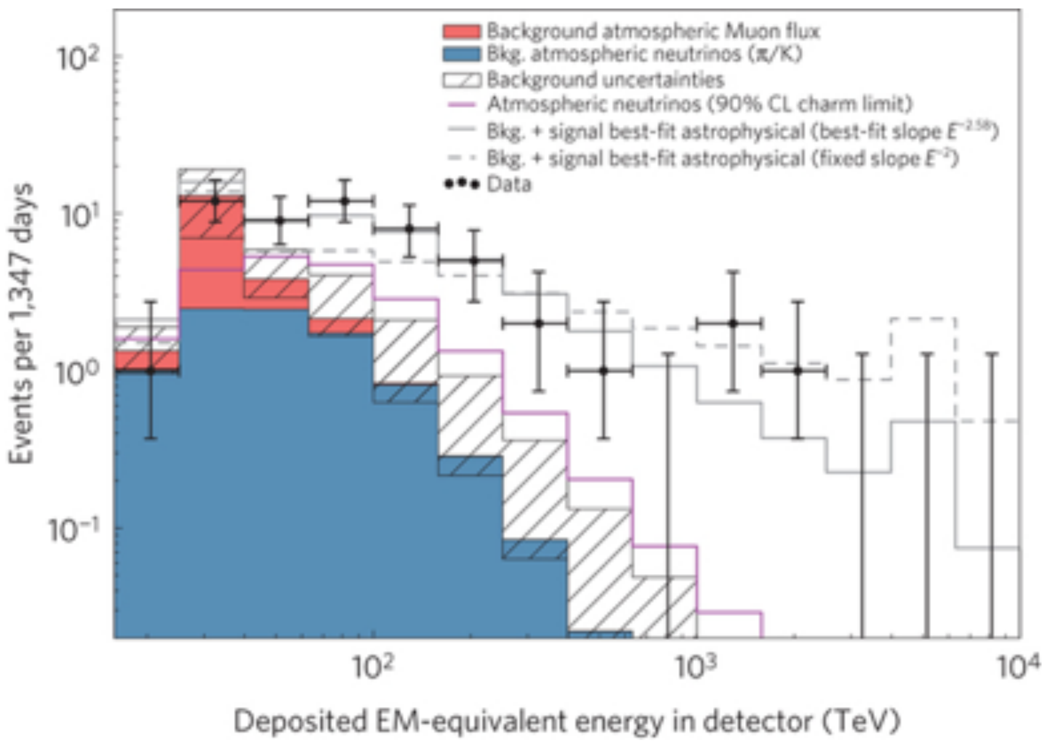
$$\sigma_\ell v_{\mathrm{rel}} \leq \frac{16\pi(2\ell+1)}{s\, v_{\mathrm{rel}}}$$

(spineless case for simplicity)

→ $M_{DM} < 300$ ***TeV***

Thermal Relic Dark Matter mass range : O(10)MeV < M_{DM} < 300TeV

Excess in PeV neutrino in IceCube neutrino spectrum



- ✓ IceCube experiment observed excesses in the PeV range.

- ✓ The excess can be explained by decays of DM with a mass in the PeV range.

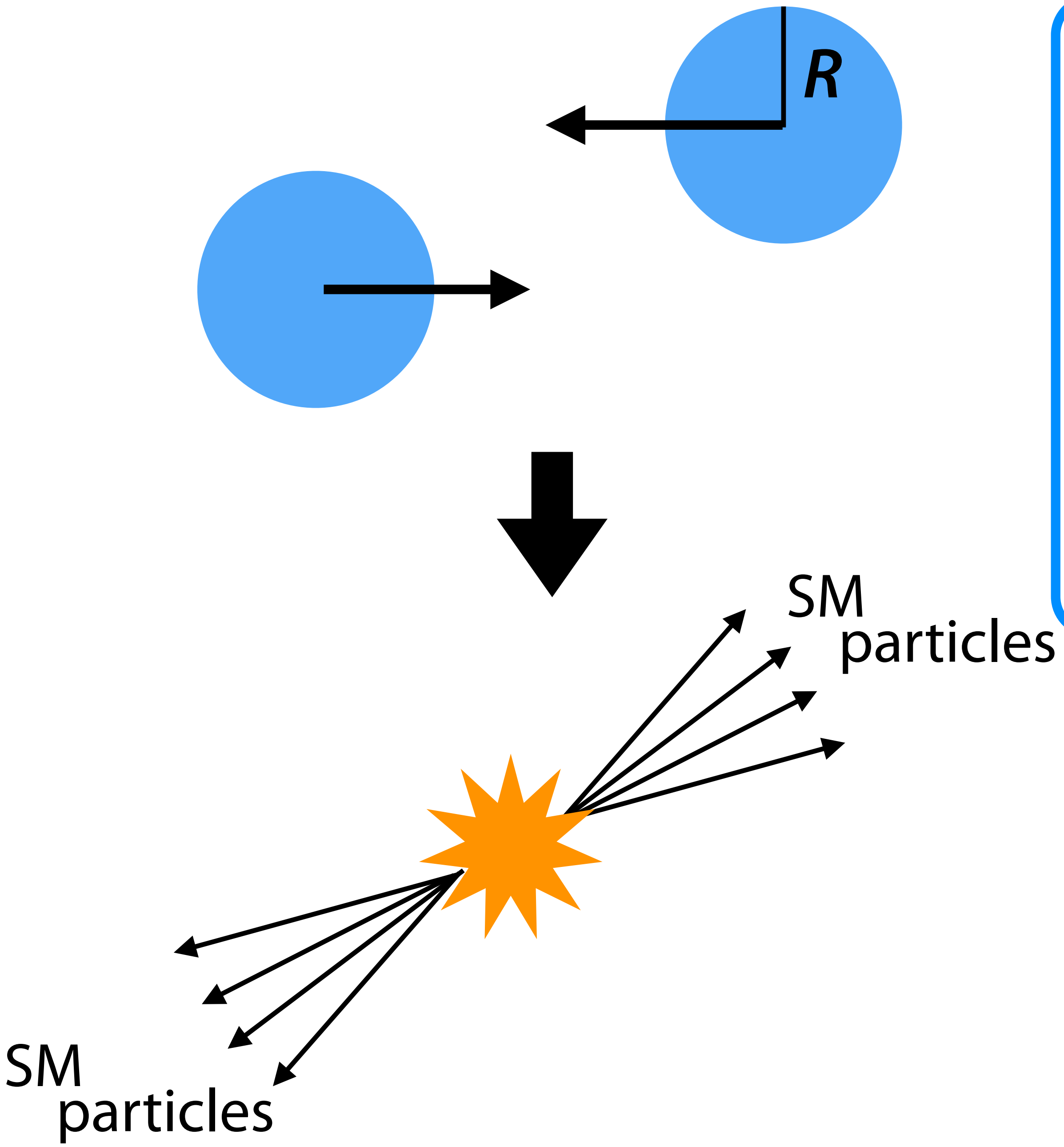
[1303.7302 : Feldstein, Kusenko, Mastumoto, Yanagida]

Thermal Relic Dark Matter mass range : O(10)MeV < M_{DM} < 300TeV

We need complicated thermal history to achieve correct abundance to explain the PeV excesses by DM ?

✓ *Can we go beyond the unitarity limit ?*

- ✓ When dark matter annihilates as ***extended objets,*** the cross section can be a geometric cross sections, ***$\sigma \sim \pi R^2$*** (1990 Griest & Kamionkowski) !



like a water balloon!

$L_{MAX} \sim M_{DM}\, v\, R$

$$\sum_{\ell=0}^{L_{\rm MAX}} \sigma_\ell < \sum_{\ell=0}^{L_{\rm MAX}} \frac{4\pi(2\ell+1)}{M_{DM}^2 v^2}$$

$$\sim \frac{4\pi L_{\rm MAX}^2}{M_{DM}^2 v^2} = 4\pi R^2$$

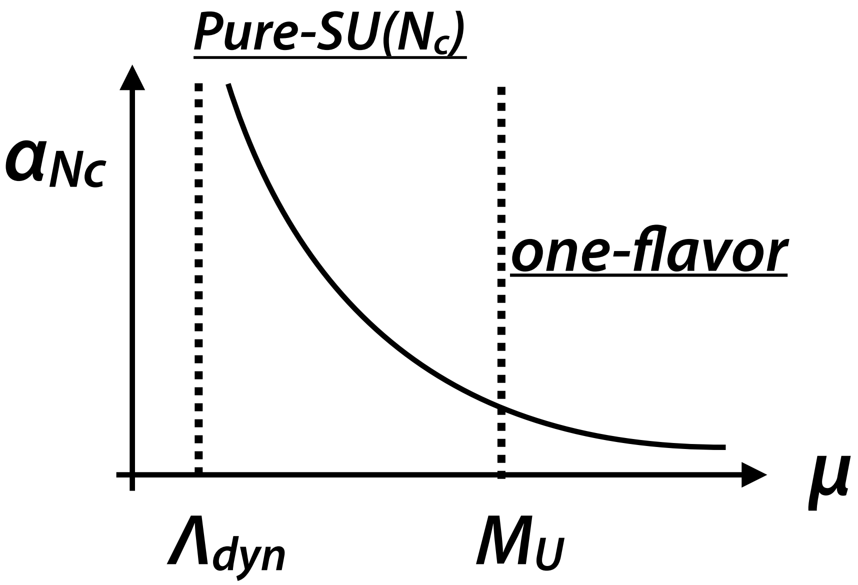
consistent with unitarity limit !

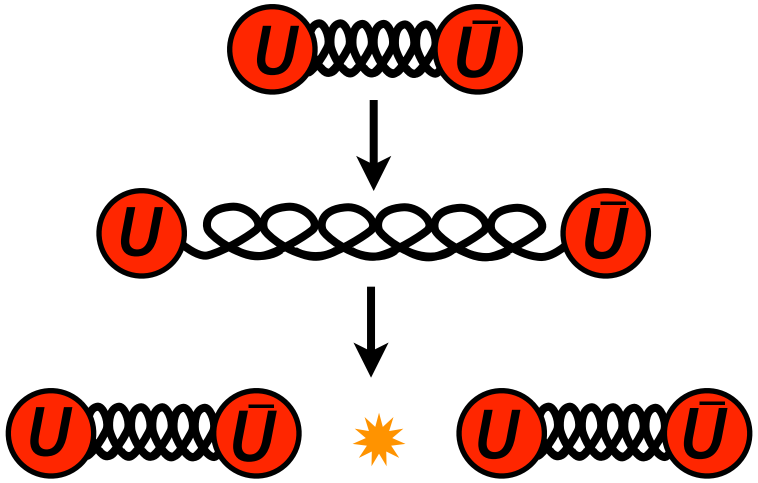
For R >> 1/(M_{DM} v), we may have thermal relic dark matter much heavier than O(100)TeV !

Can we construct a model ?

New strong interaction

- ✓ ***$SU(N_c)$*** gauge theory with one-flavor of Weyl Fermion ***$(U, \bar{U})$*** .
- ✓ Fermion ***$(U, \bar{U})$*** has a mass ***M_U*** (← ***in the PeV region)***

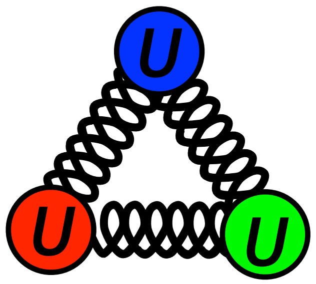




Breaks up when $L >> M_U/\Lambda_{dyn}^2$

- ✓ Baryons are the dark matter candidate !

$$\mathcal{B}_0 \propto \epsilon^{i_1 i_2 \cdots i_{N_c}} U_{i_1} U_{i_2} \cdots U_{i_{N_c}} \quad (\text{ spin } N_c/2\,)$$



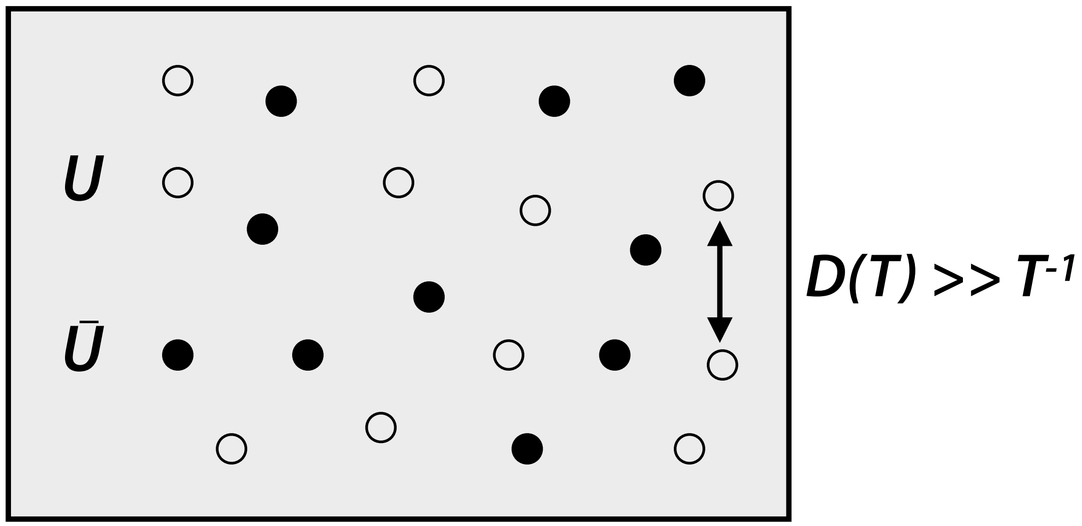
(cost of parallel spins : $\alpha_{N_c}^4 M_U$)
(cost of spacial excitation : $\alpha_{N_c}^2 M_U$)

Thermal History (early stage)

- ✓ At the very early universe, ***U***’s are in the thermal equilibrium.

- ✓ At $T \sim M_U/O(10)$, ***U***’s decouple from the thermal bath as in the usual thermal relic dark matter.

After decoupling, typical distance between Quarks are much longer than T^{-1} .

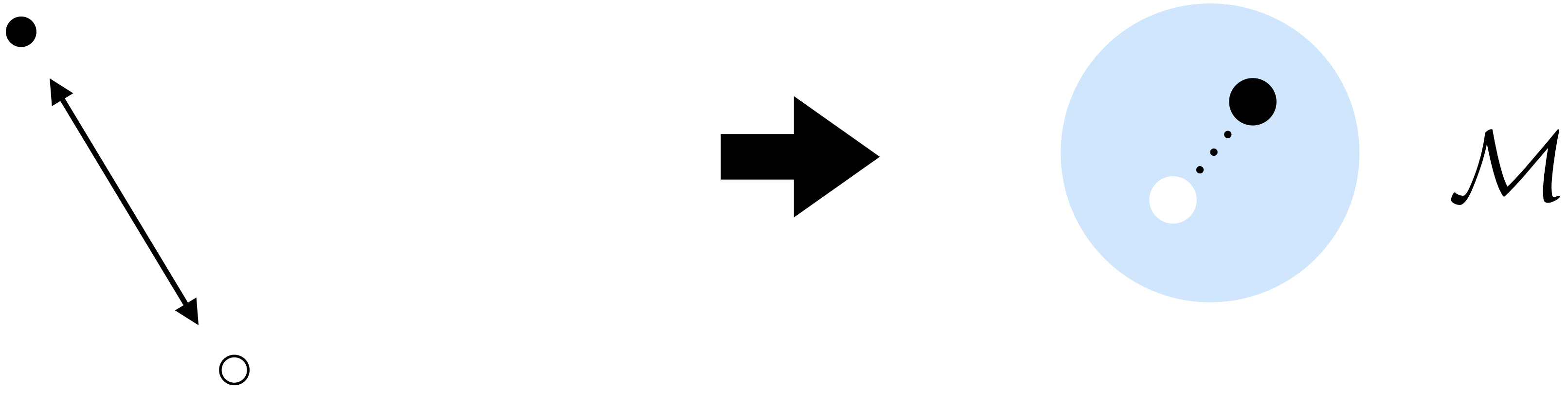


Thermal History (at around T_c)

✓ Below the critical temperature $T_c \sim \Lambda_{dyn}$, $SU(N_c)$ becomes strong .

→ U's are confined into Hadrons !

Below the critical temperature $T_c \sim \Lambda_{dyn}$, U's are pulled by the flux-tube and form the bound states.

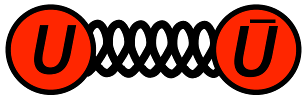


[When they are pulled by they lose their potential energies by the friction of the gluons (glueballs) in the thermal bath.]

Heavy quarks are bounded by (see e.g. hep-ph/0001312)

$$V(r) \sim -\frac{\kappa\, \alpha_{N_c}}{r} + F_{N_c}(T)\, r \qquad \kappa = C_F = (N_c^2 - 1)/(2N_c)$$

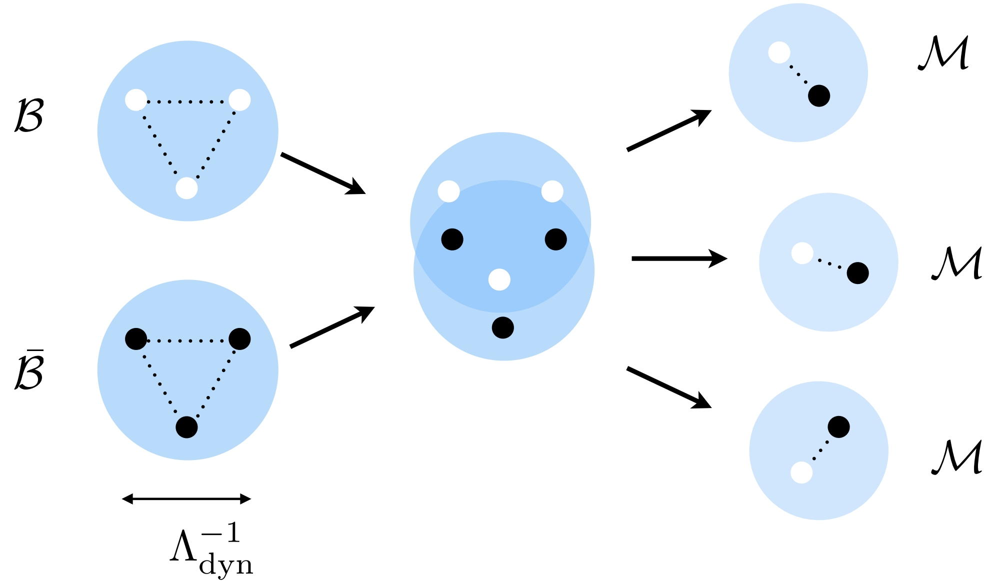
F_{Nc} : tension of flux tube



Fate of Baryons

✓ Baryons spend most of their time as excited states.

✓ Baryons collide with each other with a geometric cross section.



quark velocity at $T \sim \Lambda_{dyn}$

$$v_U \sim (\Lambda_{dyn}/M_U)^{1/2}$$

quark stays in the overlapped region

$$\Delta t \sim R/v_U \sim (M_U/\Lambda_{dyn}^3)^{1/2}$$

bound states are well stirred

$$\Delta v_U \sim F_{Nc}/M_U\, \Delta t \sim (\Lambda_{dyn}/M_U)^{1/2}$$

[see also '06 Kang, Luty, Nasri]

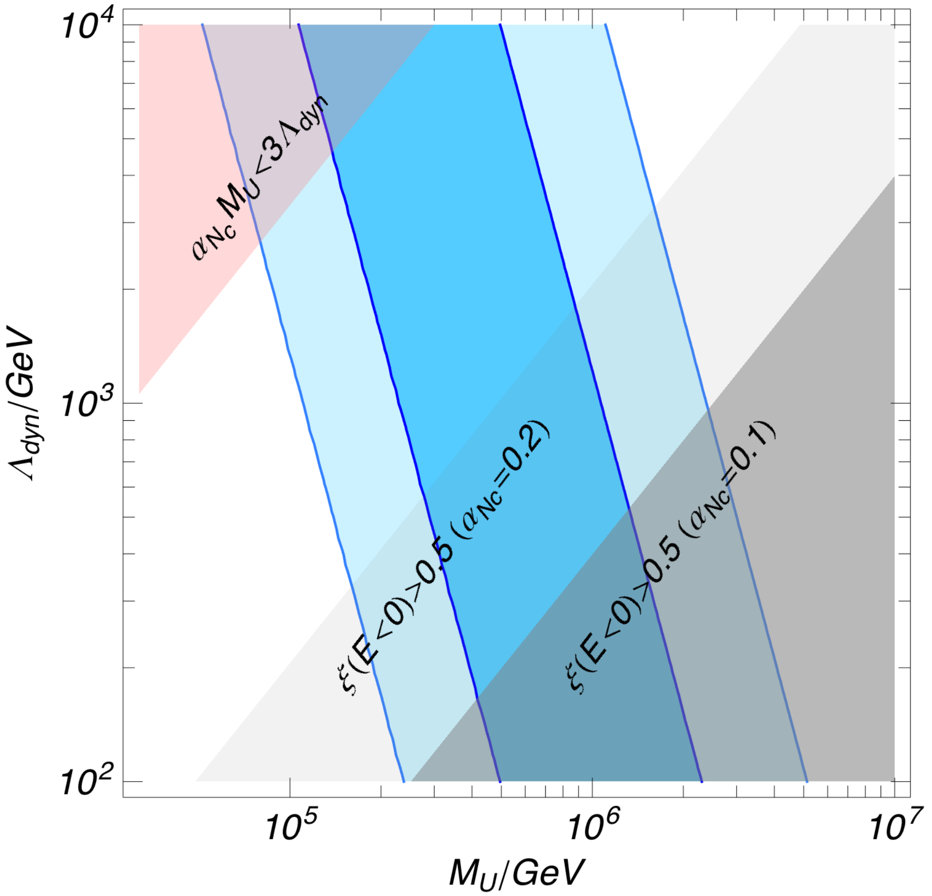
✓ We expect the annihilation into mesons occurs with ***O(1)*** probability at each collision!

$$\mathcal{B} + \bar{\mathcal{B}} \to \mathcal{M} + \mathcal{M} + \mathcal{M} + (\mathcal{S}) + \cdots$$

The inverse process is negligible since ***M decays*** immediately!

Fate of Baryons

$N_c = 3$



(dark matter mass $M_{DM} = 3xM_U$)

✓ Boltzmann equation :

$$\dot{n}_B + 3Hn_B \simeq -\langle \sigma_B v \rangle\, n_B^2 \ .$$

$$\sigma_B = A\pi R^2(T_c) \quad A = \mathcal{O}(1)$$

Relic Density

$$\Omega h^2 \sim 0.1 \times \frac{N_c}{A}\left(\frac{M_U}{10^6\,\mathrm{GeV}}\right)^{3/2}\left(\frac{\Lambda_{\rm dyn}}{10^3\,\mathrm{GeV}}\right)^{1/2}\left(\frac{100}{g_*}\right)^{1/2}$$

Relic density does not depend on the density at ***$T > \Lambda_{dyn}$*** .

Blue Shaded Region : ***$\Omega h^2 \sim 0.1$*** for ***$A = 0.3 - 3$***

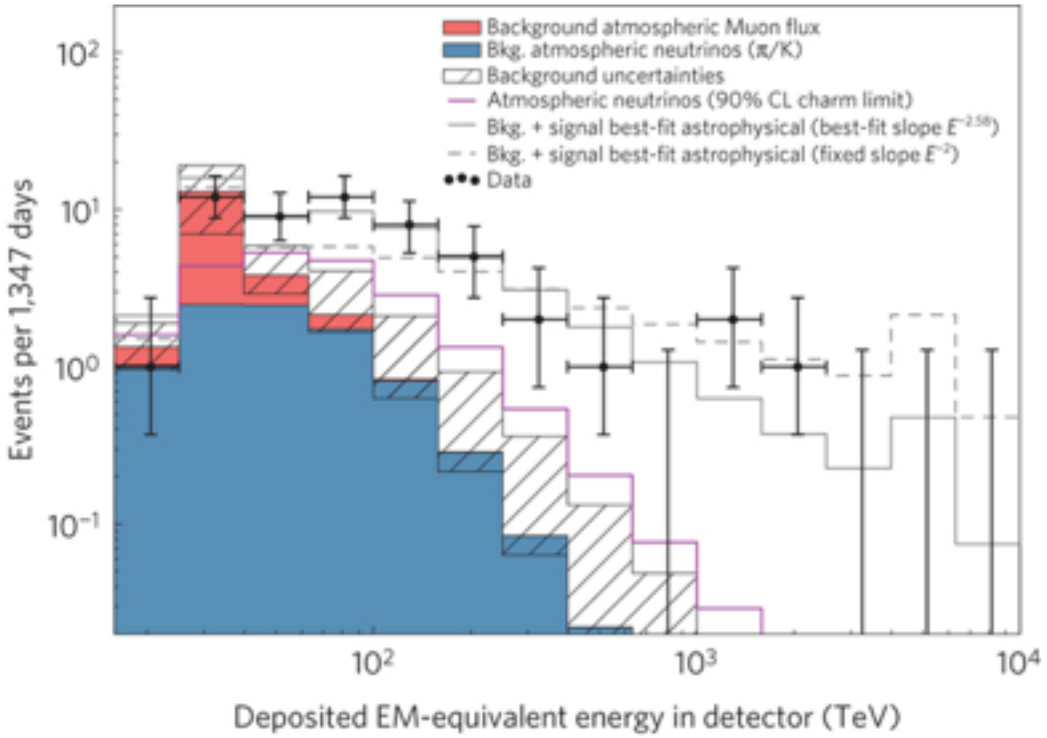
(LightBlue Shaded Region : ***$\Omega h^2 \sim 0.1$*** for ***$A = 0.1 - 10$***)

Pink Shaded Region : ***$SU(N_c)$*** is too strong at ***$\mu \sim \kappa\, \alpha_{Nc} M_U$*** .

Gray Shaded Region : most stats are in ground state : ***$n_U(E_1)/n_U > 0.5$***

PeV thermal relic dark matter is possible !

Application : Excess in IceCube neutrino spectrum



- ✓ IceCube experiment observed excesses in the PeV range.

- ✓ The excess can be explained by decays of DM with a mass in the PeV range.

[1303.7302 : Feldstein, Kusenko, Mastumoto, Yanagida]

- ✓ In our model, we can explain the IceCube excess by ***thermal relic dark matter*** !

For ***N_c = 3,*** the Baryonic dark matter has spin ***3/2***

$$\mathcal{L} = \frac{1}{M_*}(\bar{L} i D_\mu H^c)\gamma^\nu\gamma^\mu\psi_\nu$$

M_{DM} = 2.4 PeV (M_U = 0.8 PeV), M_* = 5 x 10^{34} PeV (τ = 10^{28} sec)