Thermal Relic Dark Matter Beyond the Unitarity Limit

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✓ *Known Properties of Dark Matter*

- ✓ DM makes up 27% of total energy and 85% of matter

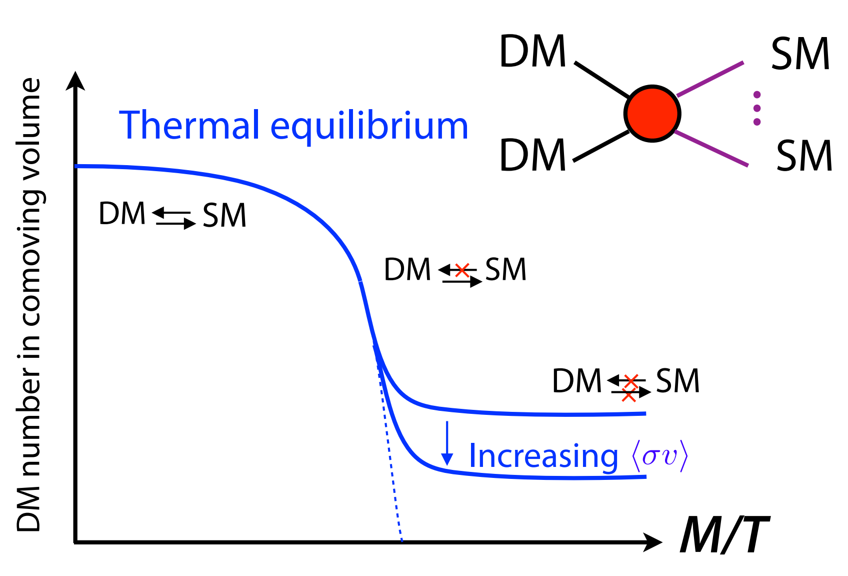
$$\Omega_{DM} h^2 = 0.1198 \pm 0.0015$$
$$\Omega_B h^2 = 0.02222 \pm 0.00023$$
$$(h = 0.6726 \pm 0.0098) \quad \textit{PLANCK 2015 Results}$$

- ✓ Neutral (does not emit light)
- ✓ Cold (slow at well before the CMB formation)
- ✓ Stable / very long lived (lifetime >> 10^{17} sec)

→ ***New Particle not in the Standard Model !***

(So far, we only managed to restrict its mass between 10^{-31} *GeV* and 10^{50} *GeV*)

✓ *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

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

Mass Range of Thermal Relic Dark Matter

Lower Limit on thermal relic dark matter mass

Dark matter freezes-out from the thermal bath at around

$$T_F \sim M_{DM}/O(10)$$

for $\langle\sigma v\rangle \sim 10^{-9}\mathrm{GeV}^{-2}$.

Freeze-out should complete before the neutrino decoupling and BBN

$$M_{DM} \gg O(10)\mathrm{MeV}$$

- If $m_{DM} < O(1)\mathrm{MeV}$, H is larger for a given T, and (n/p) becomes larger
  $\rightarrow$ ^4He abundance is increased compared with Hydrogen abundance.

- If freeze-out after the neutrino decoupling at $T \sim 1\mathrm{MeV}$, the DM annihilation increases or decreases effective number of the neutrino depending on the branching ratio.

Mass Range of Thermal Relic Dark Matter

Upper Limit on thermal relic dark matter mass

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

$$<\sigma v> \sim \frac{\pi \alpha^2}{m_{DM}^2} \sim 10^{-9} GeV^{-2}$$

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

Each partial wave cross section is limited from above

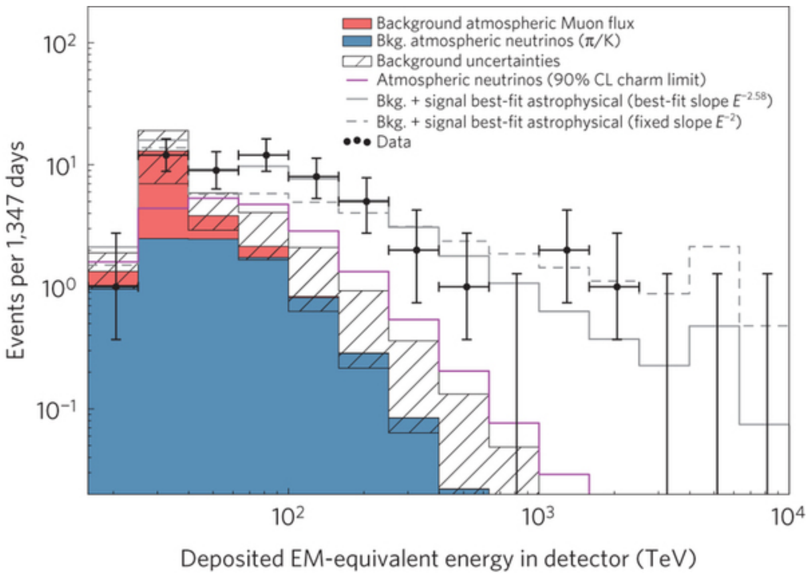
$$\sigma_\ell v_{\rm rel} \leq \frac{16\pi(2\ell+1)}{s\, v_{\rm rel}}$$

(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.

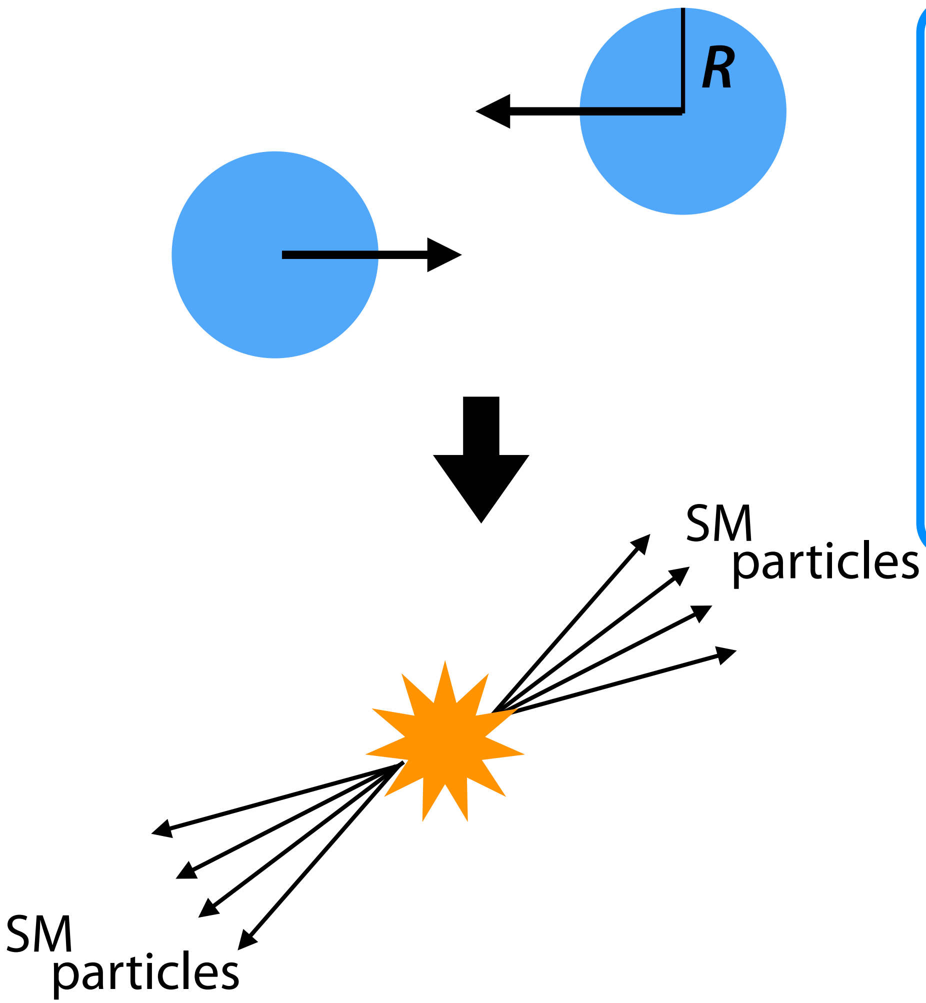
  [1303.7302 : Feldstein, Kusenko, Mastumoto, Yanagida]

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, $\boldsymbol{\sigma \sim \pi R^2}$ (1990 Griest & Kamionkowski) !



like a water balloon!

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

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

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

consistent with unitarity limit !

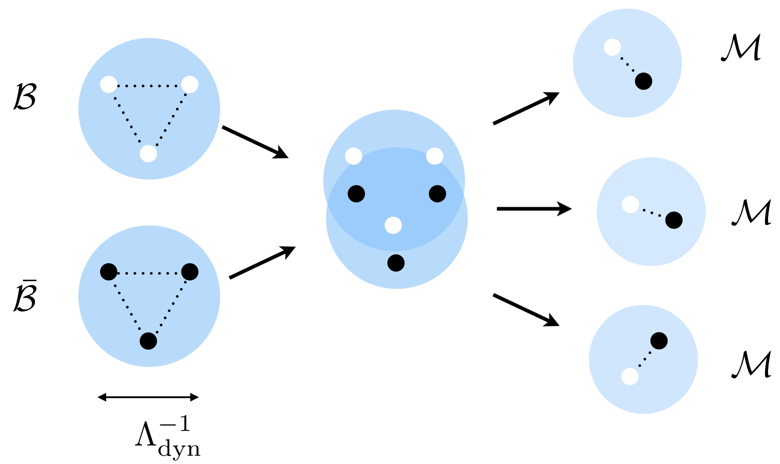
For R >> 1/(M_{DM} v), we may have thermal relic dark matter much heavier than O(100)TeV !

Can we construct a model ?

A model which goes beyond the unitarity limit on the DM mass

In our model :

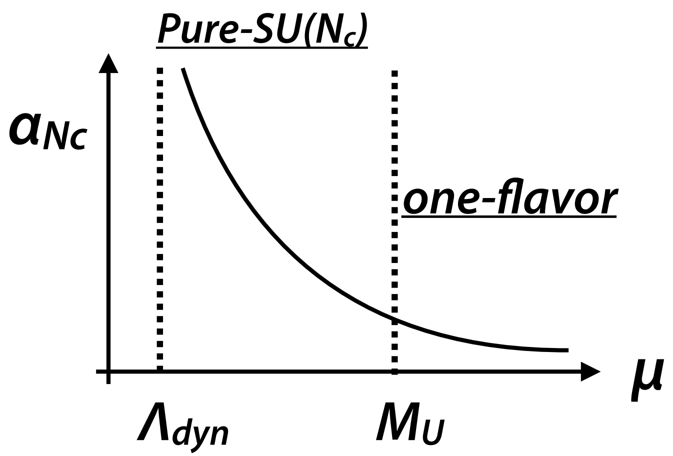
- Dark Matter is a ***bound state*** (baryon of new strong interaction).
- Baryonic Dark Matter has ***a large radius*** of ***$O(\Lambda_{dyn}^{-1})$*** much larger than the de Broglie length ***when it annihilates into mesons.***
- Mesons decay into the SM particles immediately.

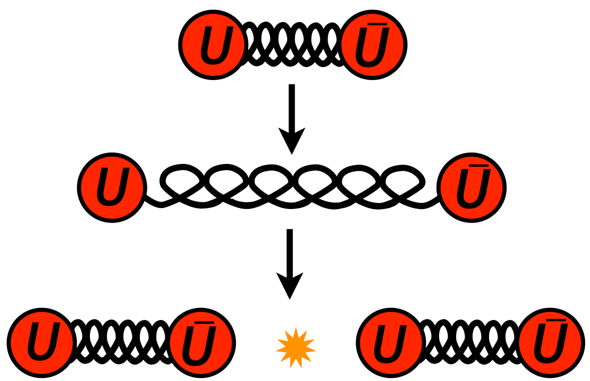


Due to a large geometric cross section, PeV thermal relic dark matter is possible!

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)***
- We arrange the dynamical scale of ***$SU(N_c)$, Λ_{dyn},*** much smaller than ***M_U*** .
- Below ***$T_c \sim \Lambda_{dyn}$,*** theory exhibits ***confinement***.





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

New strong interaction

✔ We assume baryon symmetry $U(1)_B$: $U(+1)$, $\bar{U}(-1)$.

→ $(U,\bar{U})$ are stable and hence dark matter candidates

✔ Below T_c , $(U, \bar{U})$ are confined into ***mesons*** and ***baryons*** and $U(1)_B$ charges are inherited to ***baryons***.

✔ Baryons are stable as long as $U(1)_B$ is respected while the mesons can decay → The lightest baryon is the dark matter candidate.

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

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

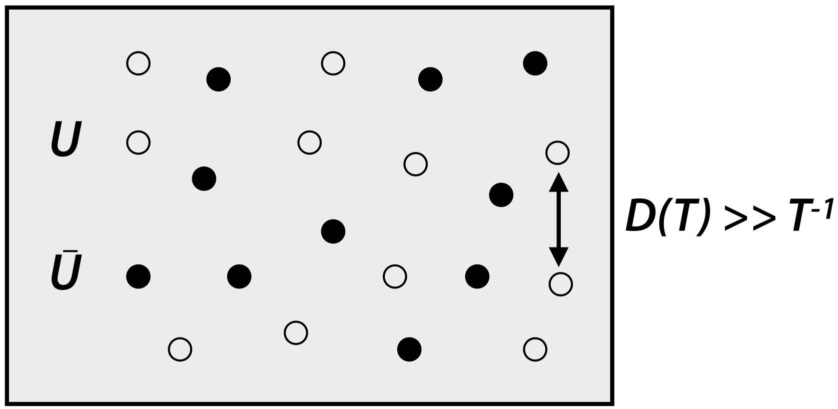
(We also introduce a portal so that the mesons decay into the SM particles.)

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} .

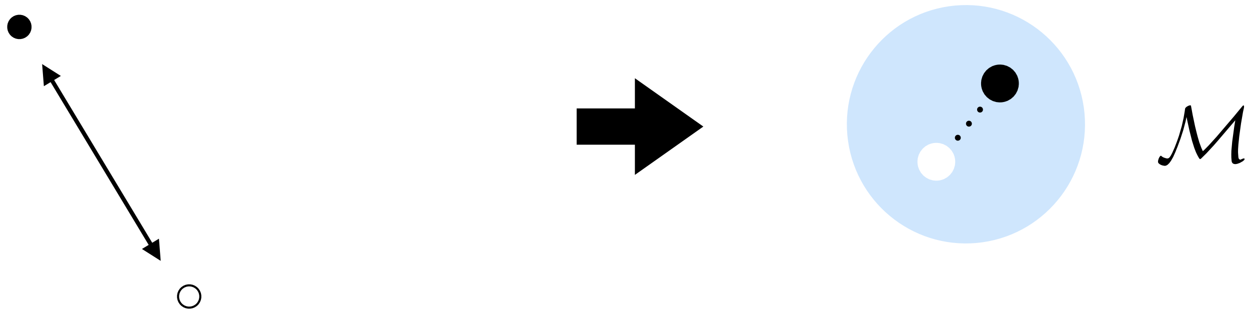


Thematic History (at around T_c)

✓ 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.

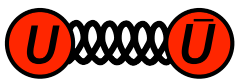


[When they are pulled by they lose their potential energies by the friction of the gluons (glueballs) in the thermal bath.]

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

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

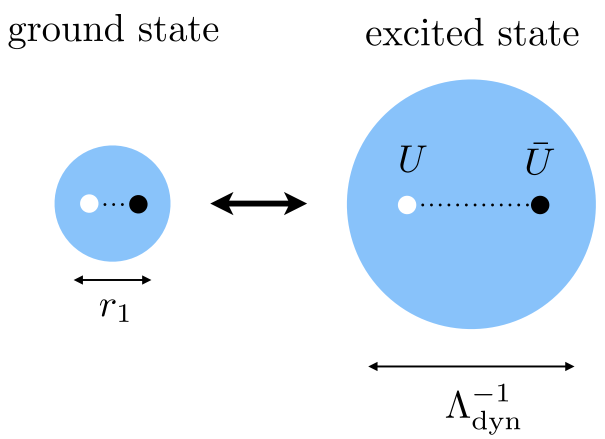
F_{Nc} : tension of flux tube



Thermal History (at around T_c)

- ✓ The size of the bound state is not very large as required…
  ($R \sim 1/M_U$)

- ✓ The bound states are not in the ground state at ***T_c***!



excitation rate :

$$\Gamma_{\rm ex}(T) \sim \frac{\alpha_{N_c}^2}{E_{\rm ex}^2} \times T^3 e^{-\frac{E_{\rm ex}}{T}}$$

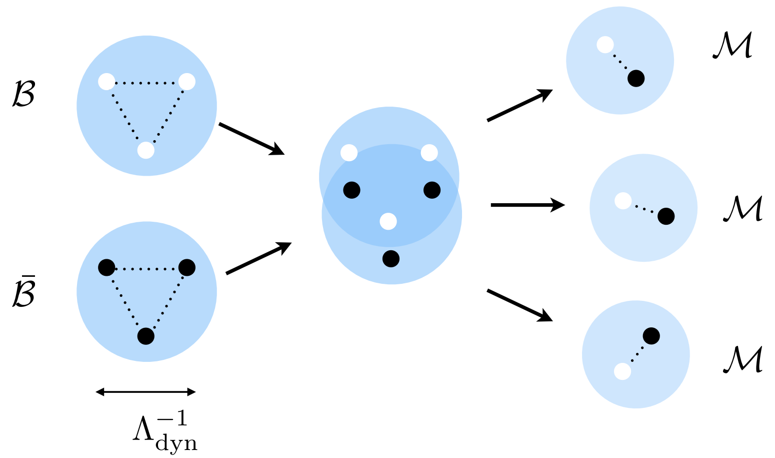
E_{ex} ~ Binding Energy
($B \sim \kappa^2 \alpha_{N_c}^2 M_U/4$)

$\Gamma_{ex}(T_c) >> H(T_c)$

The each bound state transits between the ground state and the excited states as long as ***$M_U \lesssim 10^3 \Lambda_{dyn}$***!

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]

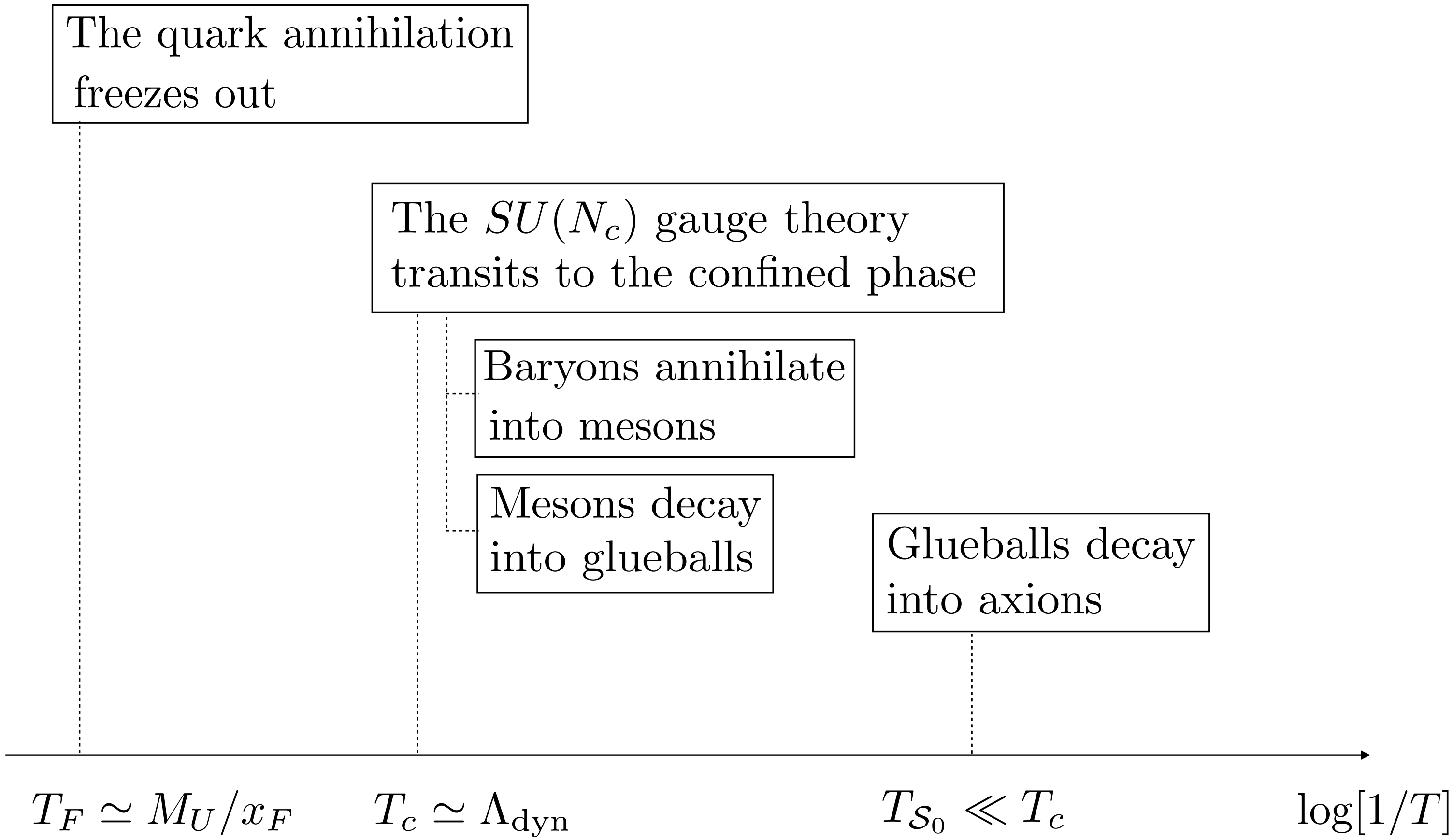
- ✓ We expect the annihilation into mesons occurs with ***O(1)*** probability at each collision!

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

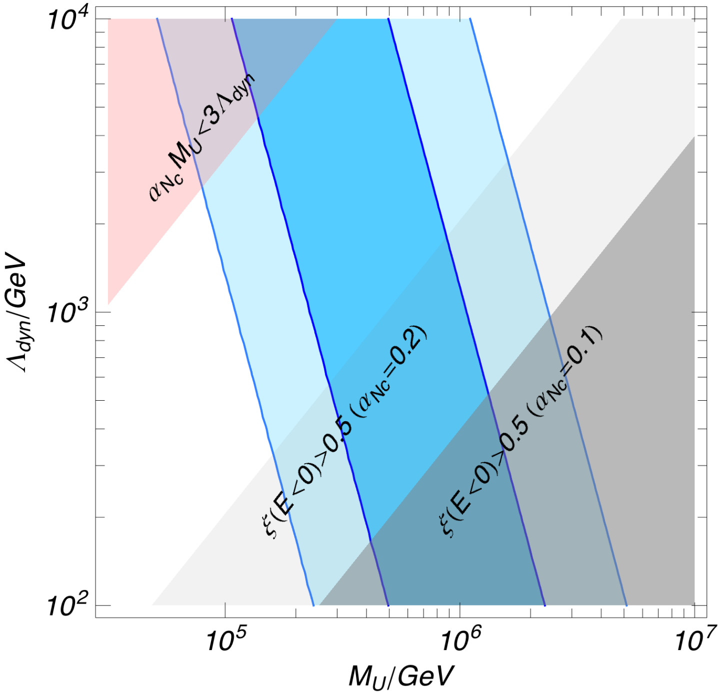
The inverse process is negligible since ***M decays*** immediately!

Fate of Baryons

✔ Outline of thermal history



Fate of Baryons



(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 $A = 0.3 - 3$

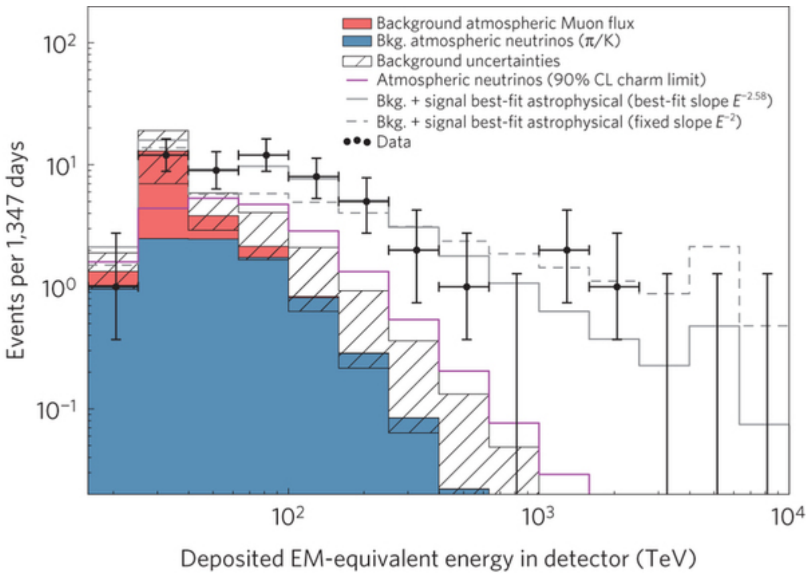
(LightBlue Shaded Region : $\Omega h^2 \sim 0.1$ for $A = 0.1 - 10$)

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

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 $\boldsymbol{N_c = 3}$***,*** the Baryonic dark matter has spin ***3/2***

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

$\boldsymbol{M_{DM} = 2.4\ \mathrm{PeV}\ (M_U = 0.8\ \mathrm{PeV}),\ M_* = 5 \times 10^{34}\ \mathrm{PeV}\ (\tau = 10^{28}\ \mathrm{sec})}$

Summary

- Thermal relic dark matter is attractive since the relic density does not depend on details of initial condition.

- If dark matter is a point-like particle, the WIMP mass is

  Mass range : $O(10)MeV << M_{DM} < 300TeV$

- If dark matter has a geometric cross section, heavier DM is possible.

- In ***$SU(N_c)$*** with one-flavor model allows baryonic dark matter annihilation with a geometric cross section !

  PeV thermal relic dark matter is possible.

  (Possible application : IceCube signal)