FREEZE-IN OF COMPOSITE DM

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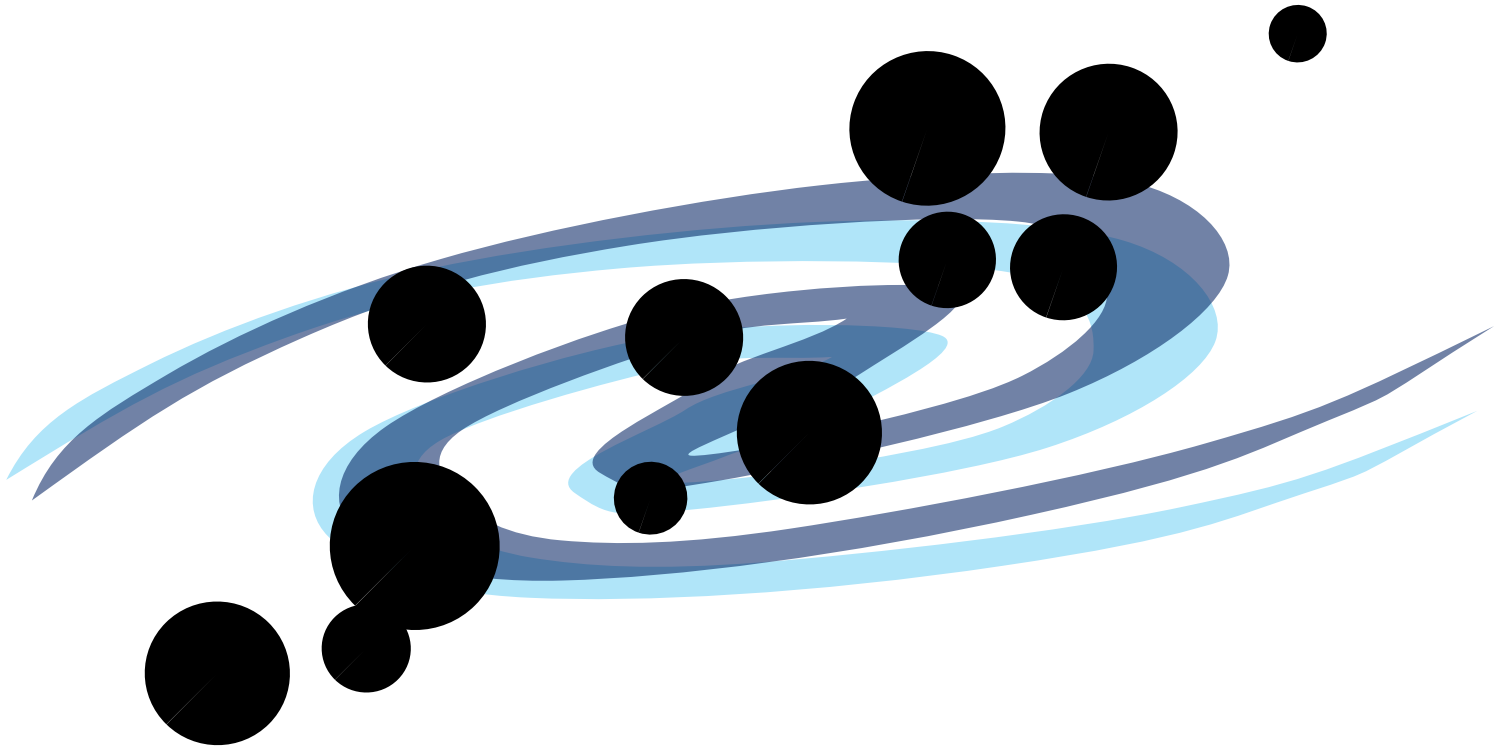
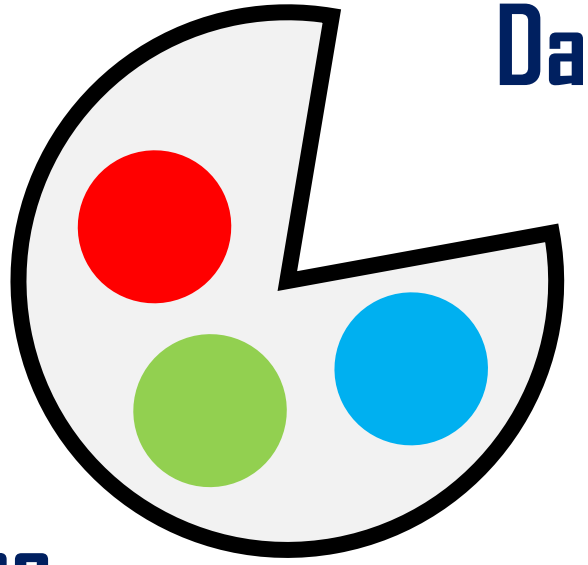


Sep. 29
BPCS 2025, Beijing

25xx.abcde w/ Sida Lu

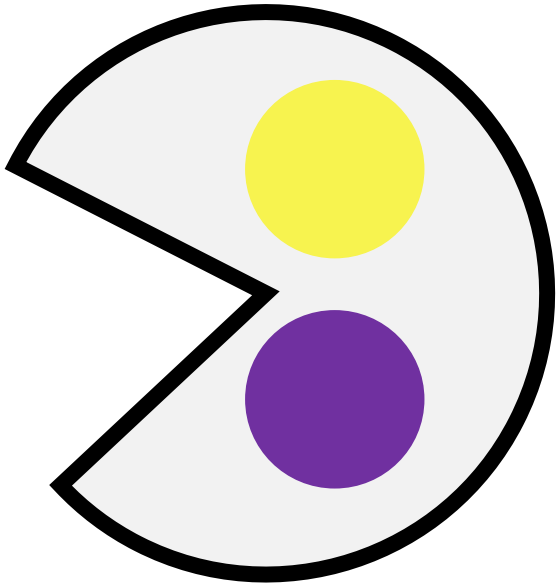
Composite DM Candidates

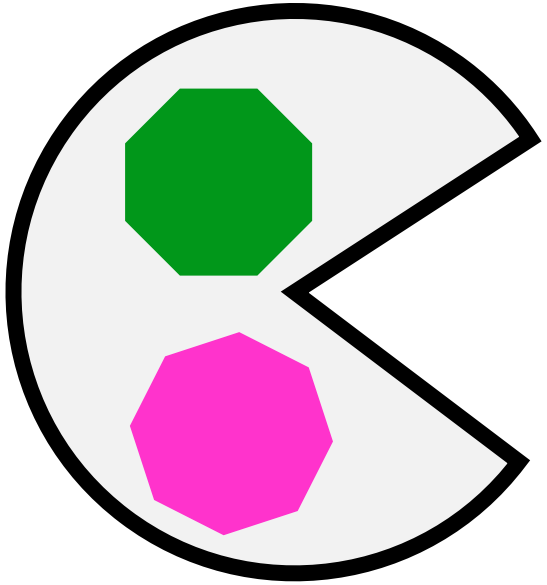


Dark Baryons

Dark Mesons

Dark R-hadrons

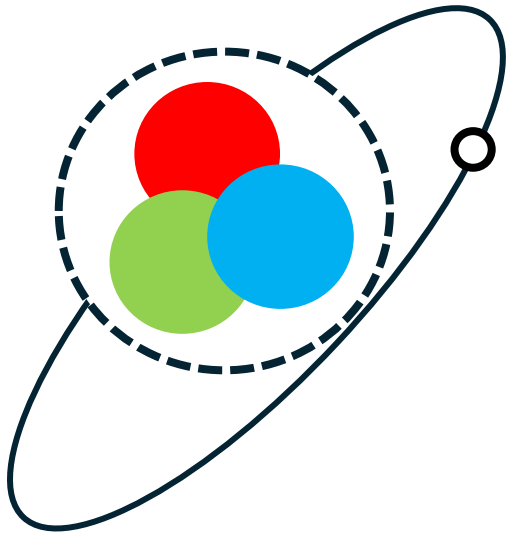


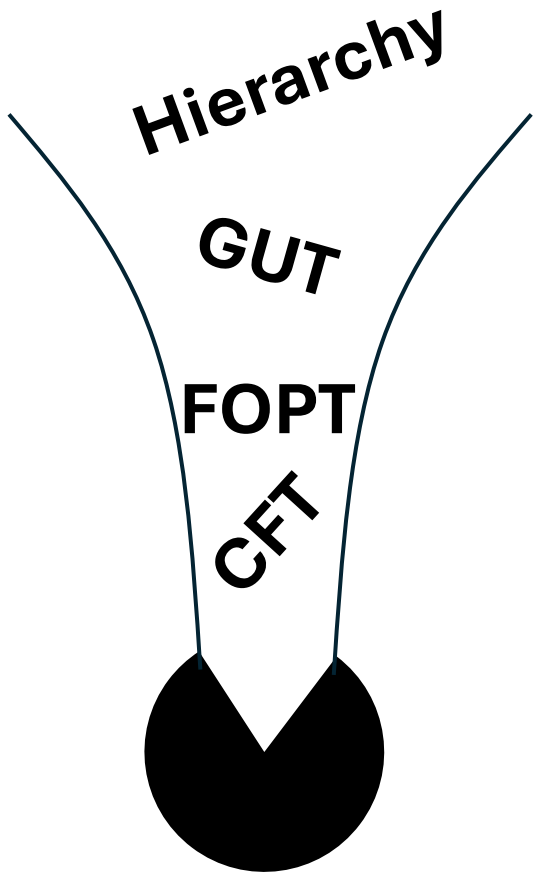


Dark Glueballs

Motivation

"Baryons" are Composite





UV Model Building

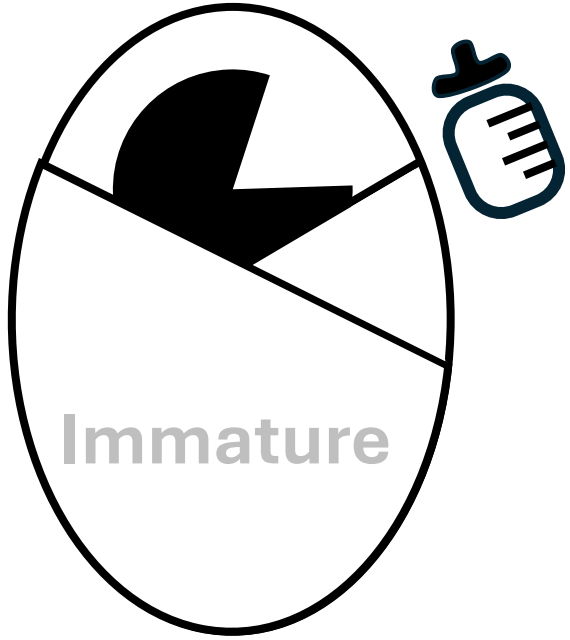
"Minimal" Setup (?)

See more in Xiaoyong Chu's talk

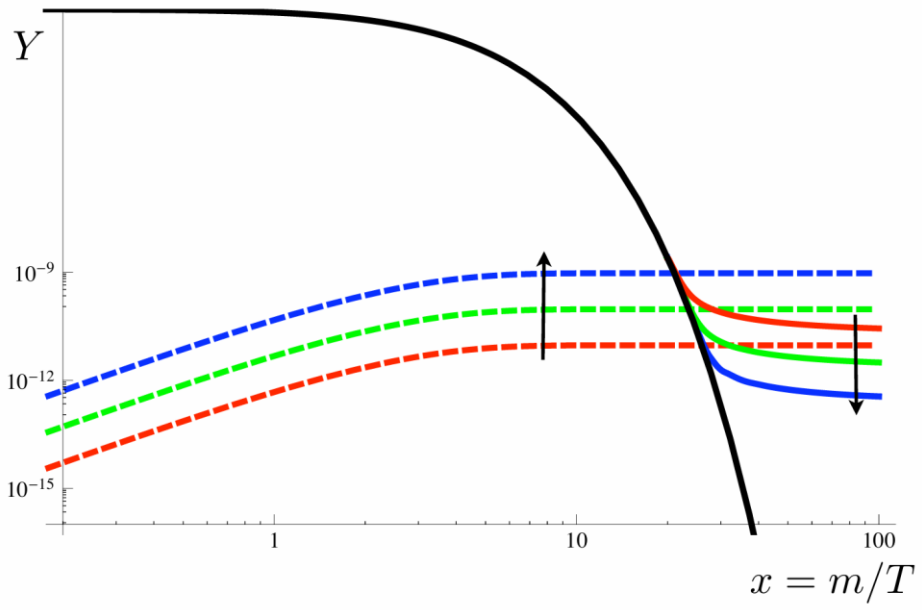
Unique Dynamics & Phenomena

DISCLAIMER:

ONGOING WORK WITH PRELIMINARY RESULTS DETAILS MAY CHANGE IN THE FUTURE

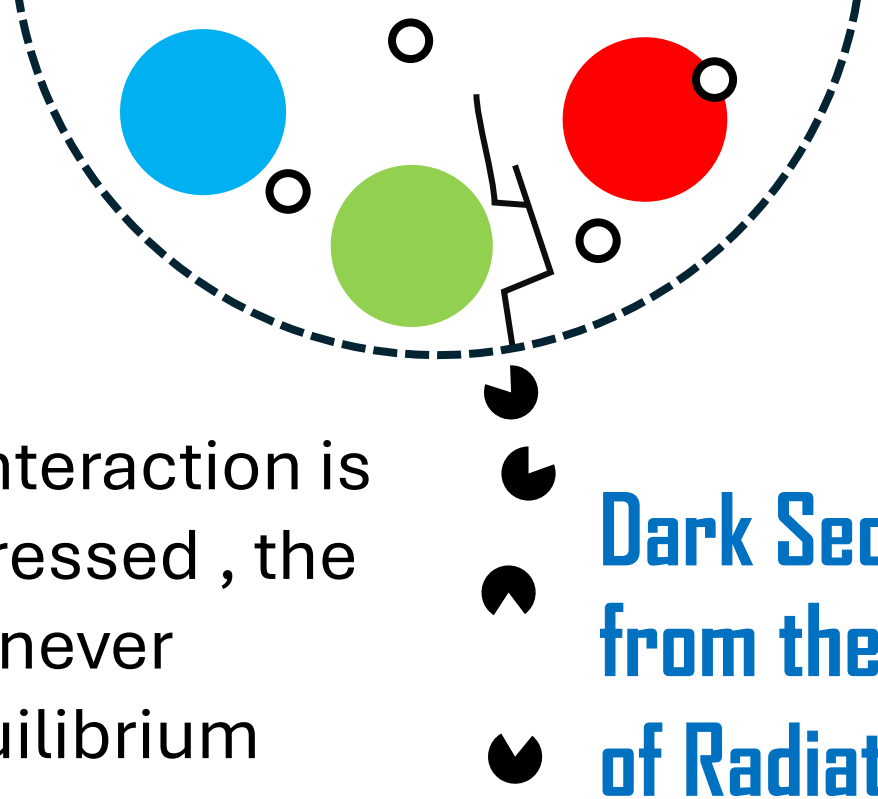


Freeze-in DM



L. J. Hall, K. Jedamzik, J. March-Russell and S. M. West, 0911.1120

The portal interaction is highly suppressed , the dark sector never reaches equilibrium



Dark Sector from the "Leaks" of Radiation

- DM relic abundance insensitive to DM mass

$$Y_{FI} \sim \lambda^2 \left(\frac{M_{Pl}}{m} \right)$$

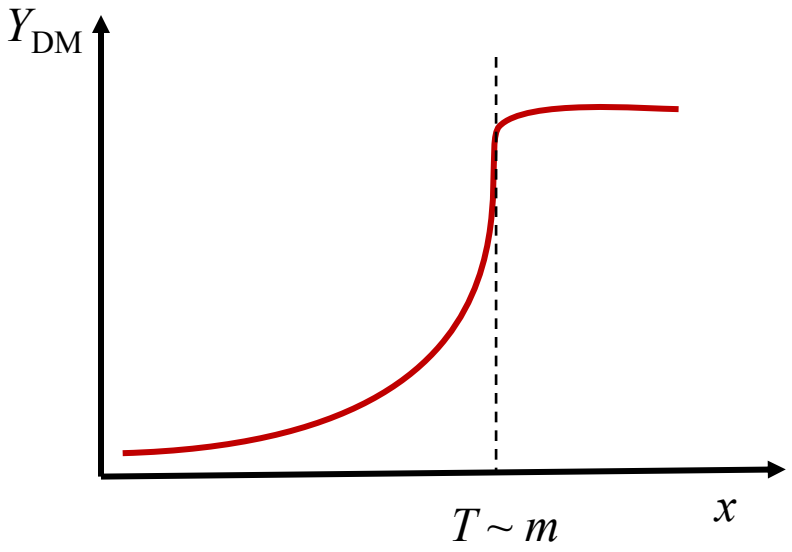
Freeze-In of Composite DM

L. J. Hall, K. Jedamzik, J. March-Russell and S. M. West, 0911.1120

F. Elahi, C. Kolda and J. Unwin, 1410.6157

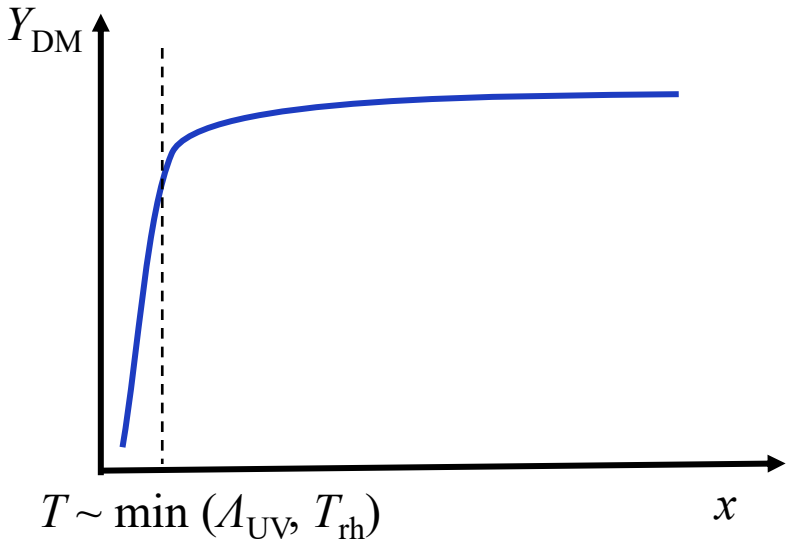
(IR) Freeze-in

$$\langle \sigma v \rangle \sim \Lambda_{\rm IR}^{n} T^{-2-n}$$



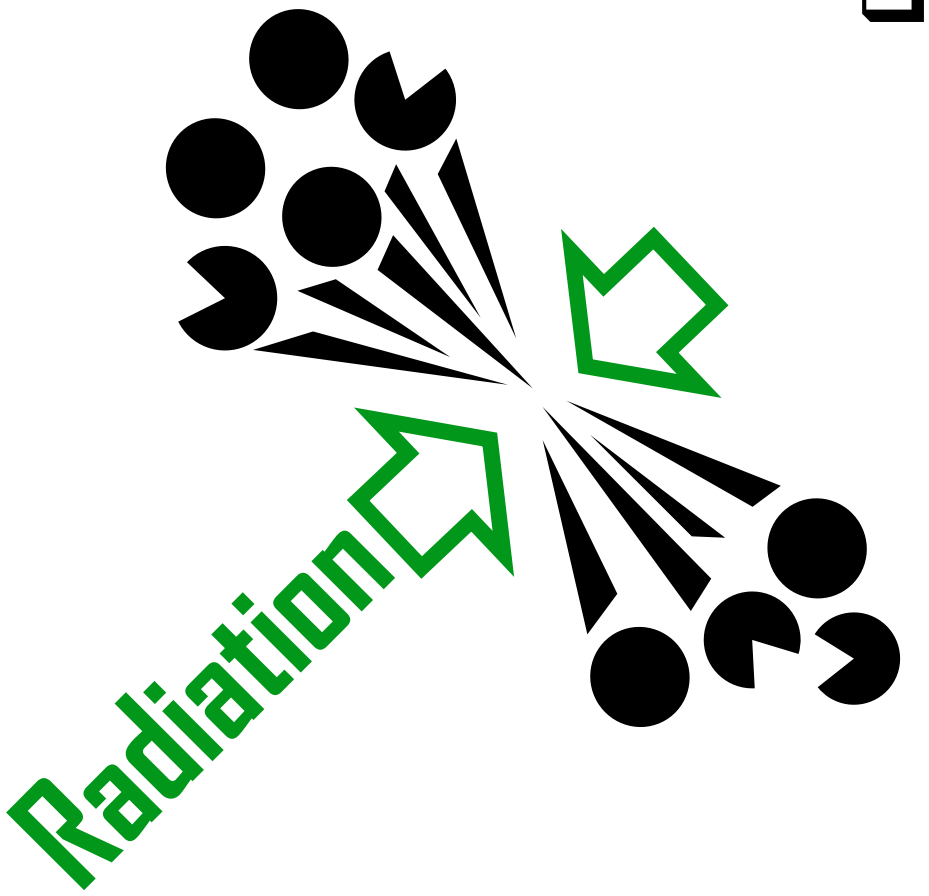
UV Freeze-in

$$\langle \sigma v \rangle \sim T^{n+4} \Lambda_{\rm UV}^{-n}$$



Dark Hadron Production

Phenomenology: 25xx.abcde
H-C. Cheng, X. Jiang, LFL, E. Salvioni 2408.13304;
H-C.Cheng, LFL, E. Salvioni, 2110.10691 ……



- No longer pair produced but hadronize

$$\frac{N(\mu)}{N(\mu_0) \equiv N_0} = \exp\left[\int_{\mu_0}^{\mu} \gamma(\mu) d\log\mu\right]$$

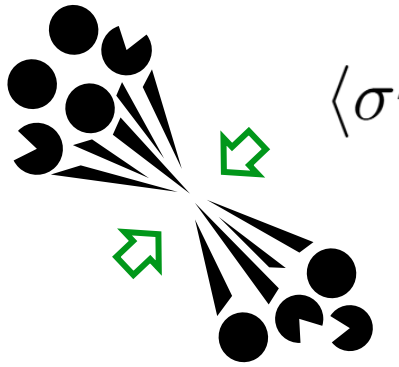
$$\gamma = \sqrt{2N_D \frac{\alpha_D}{\pi}} - \frac{\alpha_D}{2\pi}\left(\frac{\beta_0}{4} + \frac{10N_{f,D}}{3N_D^2}\right)$$

B.R. Webber, 1984

- With a limited range of energy/temperature, simplifies as:

$$N(\mu) = N_0 \left(\frac{\mu}{\mu_0}\right)^{\bar{\gamma}}$$

Dynamics of (IR) Freeze-in

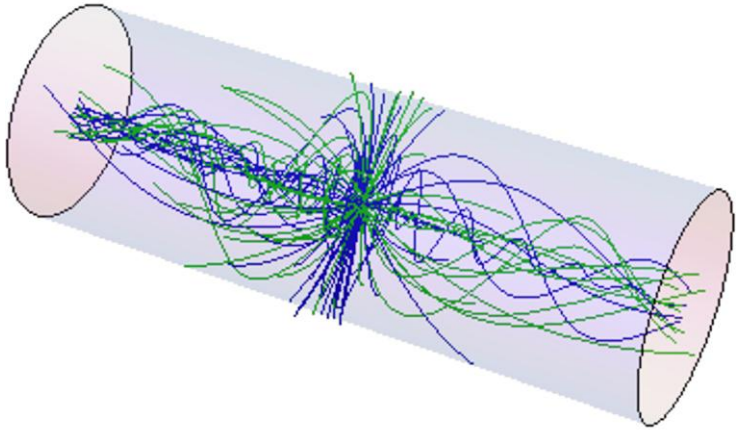


$$\langle \sigma v \rangle \sim \Lambda_{\rm IR}^{n} T^{-2-n}$$

$$N(\mu) = N_0 \left(\frac{\mu}{\mu_0}\right)^{\bar{\gamma}}$$

Extremal anomalous dimension γ → ~1 for the "soft bomb" case

S. Knapen, S. Pagan Griso, M. Papucci and D. J. Robinson, 1612.00850



- Becomes more UV than before

$$Y_D \sim 2\sqrt{\frac{2}{5}} g_D \sqrt{g_*} \frac{\lambda^2 M_{PL} \Lambda_{\rm IR}^{n} N_0 \Lambda_D^{-n-1}}{3\pi(1+n-\bar{\gamma})}$$

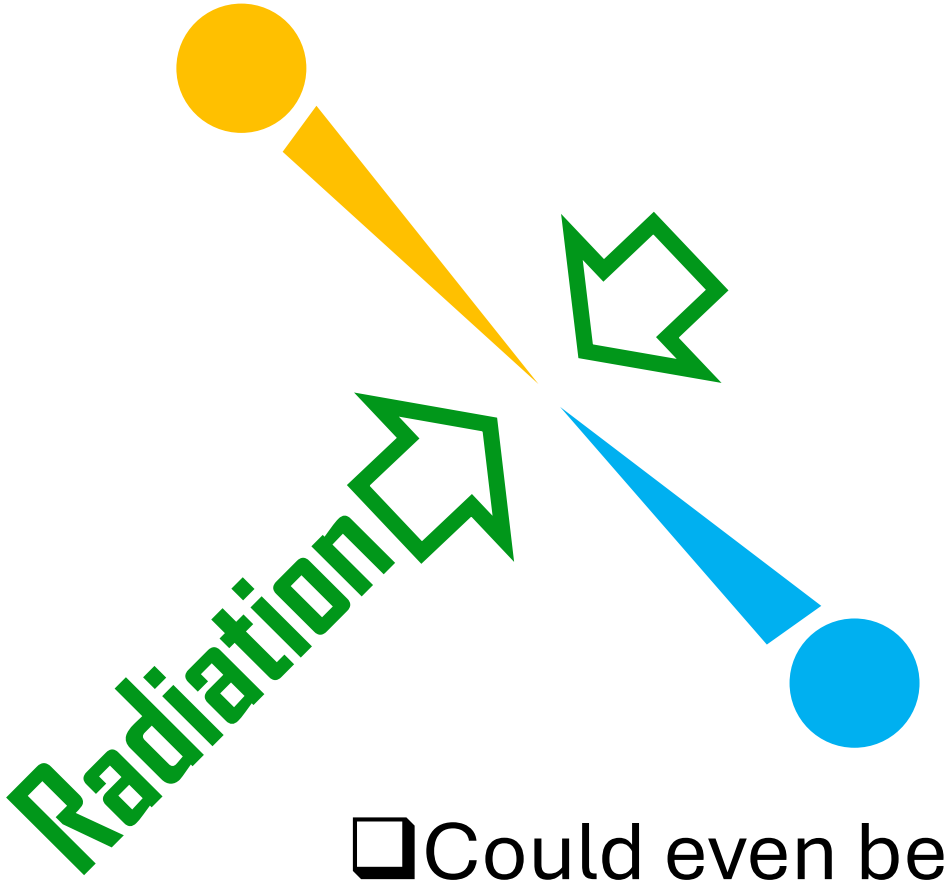
- Recover the result of weakly-interacting results when $N_0 \sim 2$ and $\gamma \sim 0$

See also:

S. Hong, G. Kurup, and M. Perelstein, 1910.10160; W. H. Chiu, S. Hong, and L.-T. Wang, 2209.10563

UV Freeze-in

- Assuming the UV d.o.f. are produced instead



$$\langle \sigma v \rangle \sim c_n^2 \frac{T^{4+n}}{\Lambda_{\rm UV}^n}$$

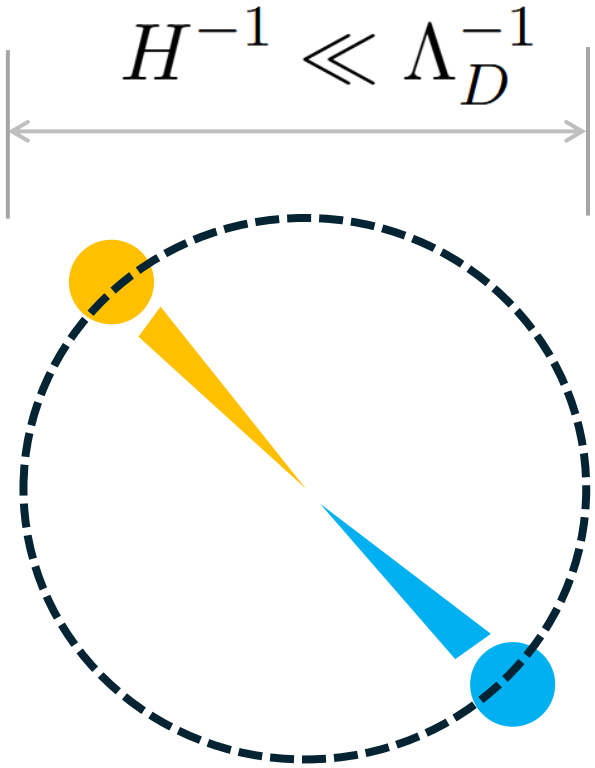
$$Y_{D,i} \approx \begin{cases} 7.6 \times 10^{-6} \dfrac{c_n^2 M_{\rm pl} T_{\rm RH}}{\Lambda_{\rm UV}^2} \left(\dfrac{g_*}{106.5}\right)^{-3/2} & n = 2 \\ 6.1 \times 10^{-5} \dfrac{c_n^2 M_{\rm pl} T_{\rm RH}^3}{\Lambda_{\rm UV}^4} \left(\dfrac{g_*}{106.5}\right)^{-3/2} & n = 4 \\ 1.7 \times 10^{-3} \dfrac{c_n^2 M_{\rm pl} T_{\rm RH}^5}{\Lambda_{\rm UV}^6} \left(\dfrac{g_*}{106.5}\right)^{-3/2} & n = 6 \end{cases} .$$

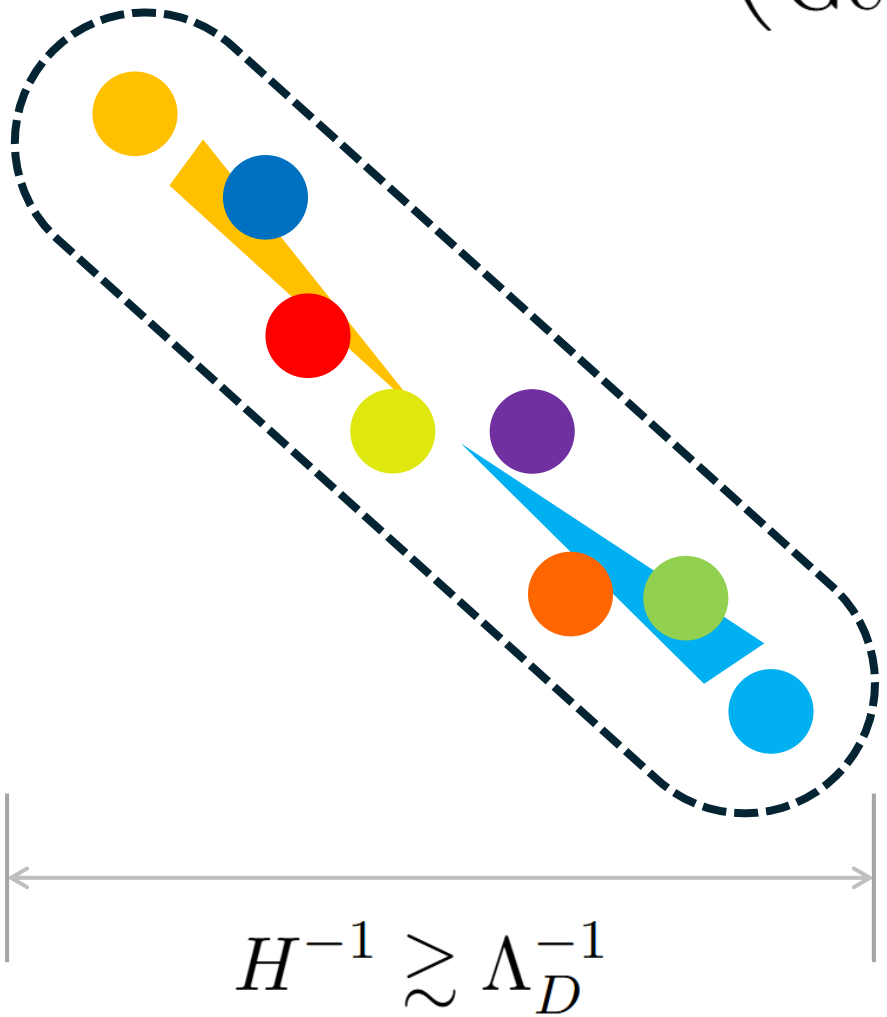
- Could even be gravity-only when we assign $\Lambda_{\rm UV} \sim M_{\rm pl}$

M. Redi, A. Tesi and H. Tillim, 2011.10565

The First Hadronization

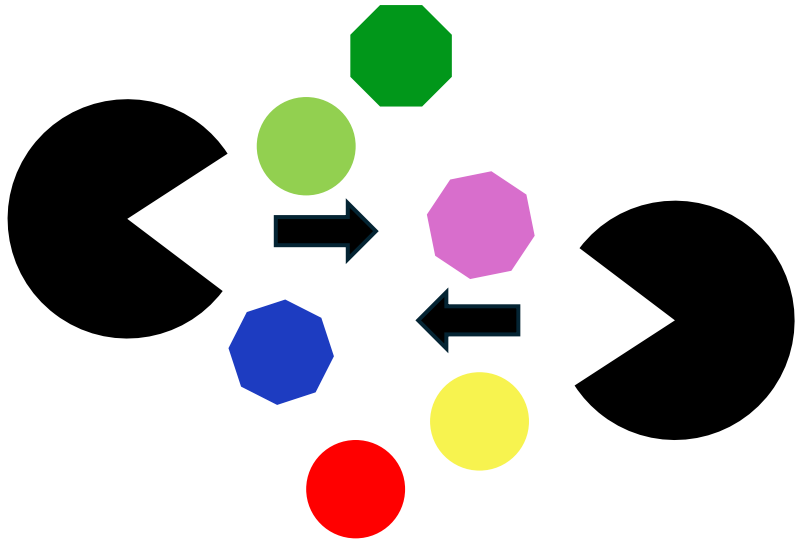
$$T_{\rm had} \simeq 10^9 \left(\frac{\Lambda_D}{\rm GeV} \right)^{\frac{1}{2}}$$





Only when the horizon size is large enough, the color string can form (and break)

Necessary Condition of Quark-Gluon Plasma (non-) Formation



- Inelastic cross section reaches geometric ones

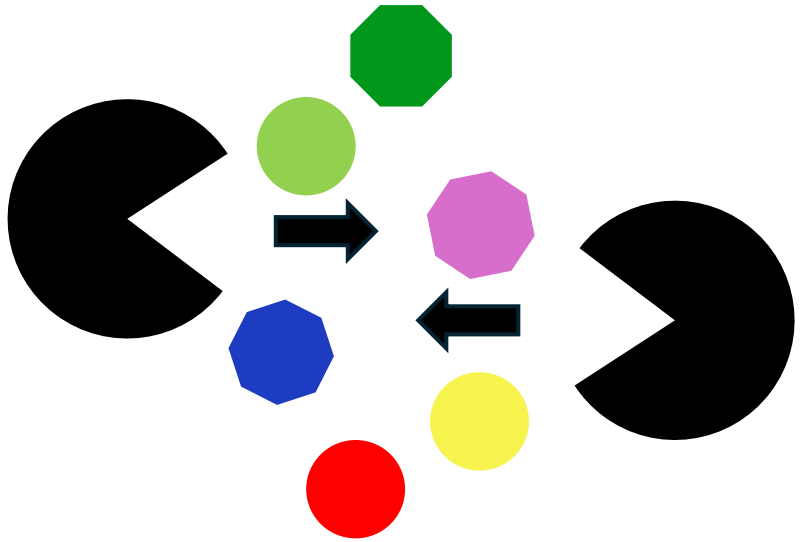
$$\langle \sigma v \rangle \sim \mathcal{O}\left(\frac{1}{\Lambda_D^2}\right)$$

- Mean free path greater than the horizon size, otherwise thin+hot hadron gas instead of QGP

$$l \sim \left(\langle \sigma v \rangle n_D\right)^{-1} \ll H^{-1}$$

Need to reach critical abundance to make it happen

Necessary Condition of Quark-Gluon Plasma (non-) Formation

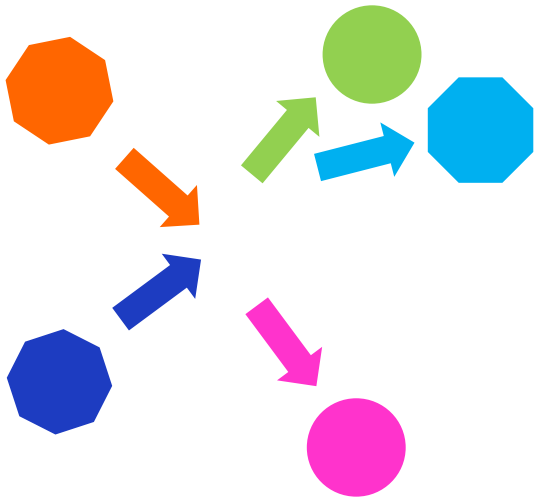


- (Very) high energy confined d.o.f. instead of elementary ones during radiation dominance

$$Y \gtrsim \frac{g_D \Lambda_D^2}{g_* M_{\rm pl} T}$$

Hot, thin hadron "gas" instead of quark gluon "plasma"

Sufficient Condition of Quark-Gluon Plasma (non-) Formation



- For QGP to be formed, the mean free path for UV d.o.f. scattering with radiation shall be less than the horizon size

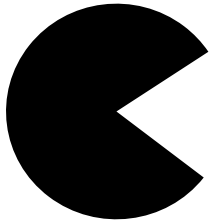
$$n\langle\sigma v\rangle \gtrsim H \qquad\qquad \langle\sigma v\rangle \sim \alpha^3/\widetilde{T}^2$$

The critical density

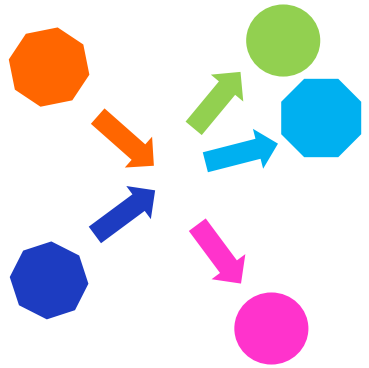
$$Y_{\rm QGP} \sim \frac{\widetilde{T}^2}{\alpha_D^3 g_*^{1/2} T M_{\rm pl}} \gg \frac{g_D \Lambda_D^2}{g_* M_{\rm pl} T}$$

Dark Sector Population

$$Y \sim \frac{g_D \Lambda_D^2}{g_* M_{\rm pl} T}$$



"Self Populating Gas"



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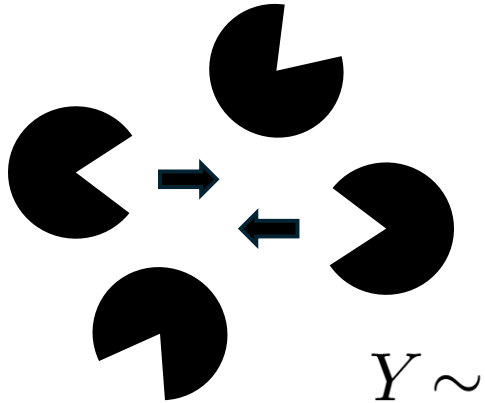
"Free Gas"



"Dark QGP"

Y_D

Dark Population density

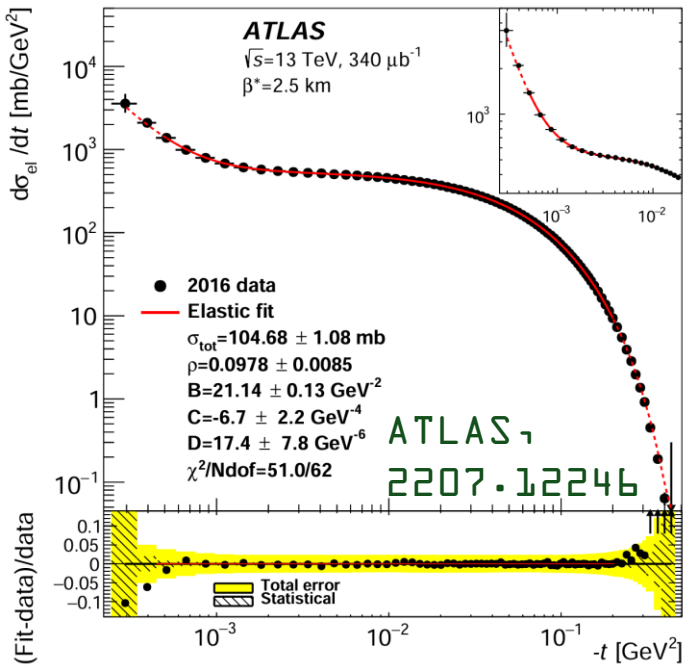
$$Y \sim \frac{\widetilde{T}^2}{\alpha_D^3 g_*^{1/2} T M_{\rm pl}}$$

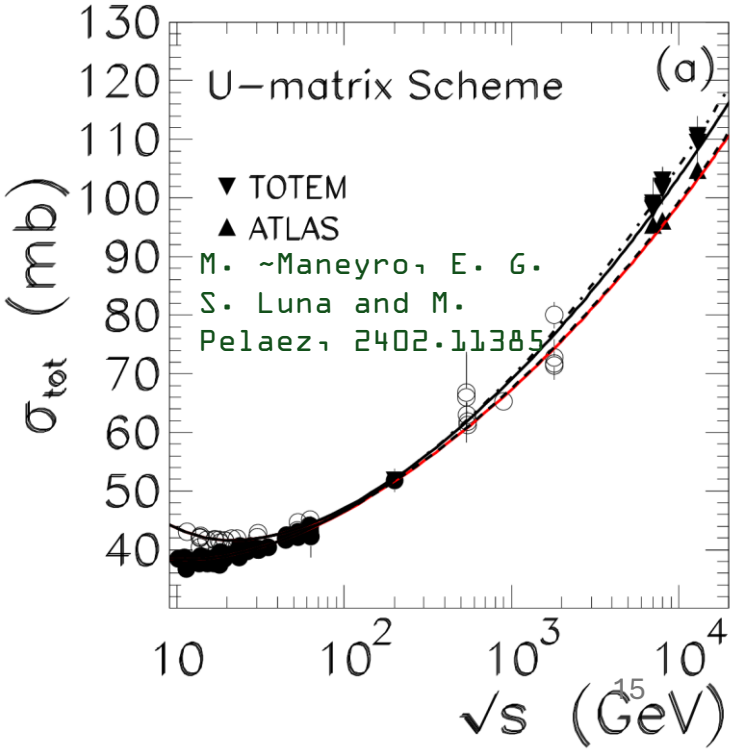
Dark Sector Self-Population

- At late times, sparce dark hadrons with high energy scatter with each other and reproduce J. March-Russell, H. Tillim and S. M. West, 2007.14688

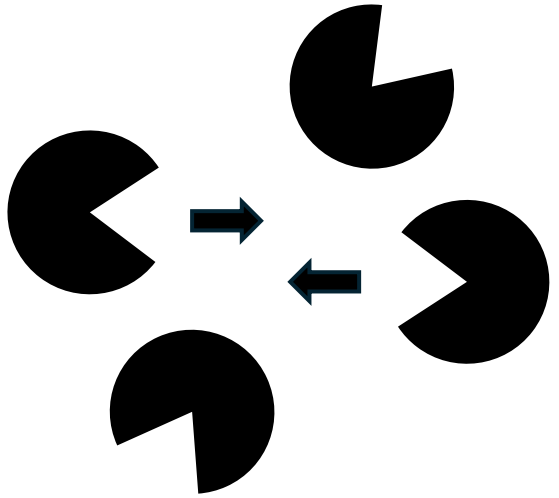
- Most interactions could be "ultra-peripheral" and "forward" (small q^2)

- Differential properties not completely known even for SM QCD





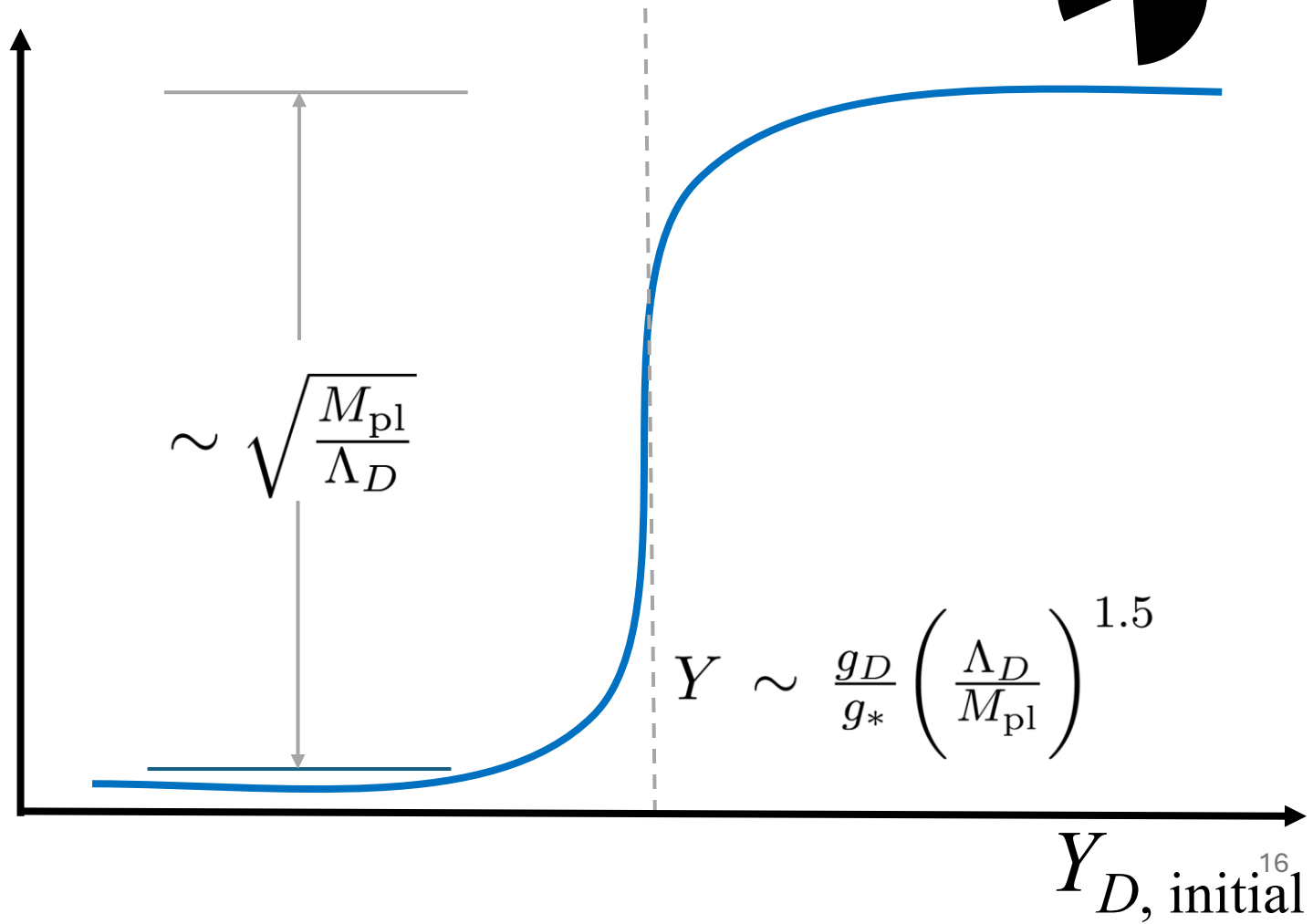
Dark Sector Self-Population



- Geometric inelastic cross section
- Moderate hadron yield

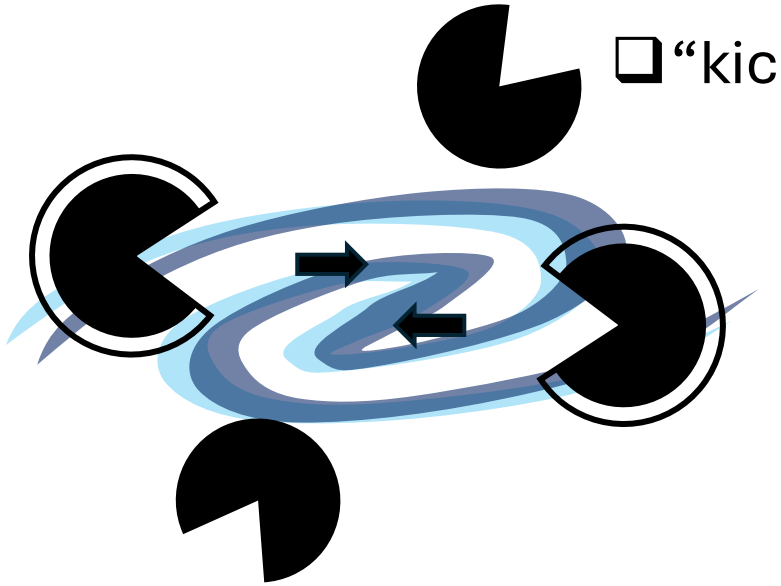
$$\frac{Y_{D,\,\mathrm{final}}}{Y_{D,\,\mathrm{initial}}}$$

Large enhancement (or nothing) across the "critical point" of the initial population



Potential Observable Effects

DM self-heating



- "kicked out"
- Higher DM components (vector mesons, heavy flavor, excited glueballs…) annihilate and heats the DS

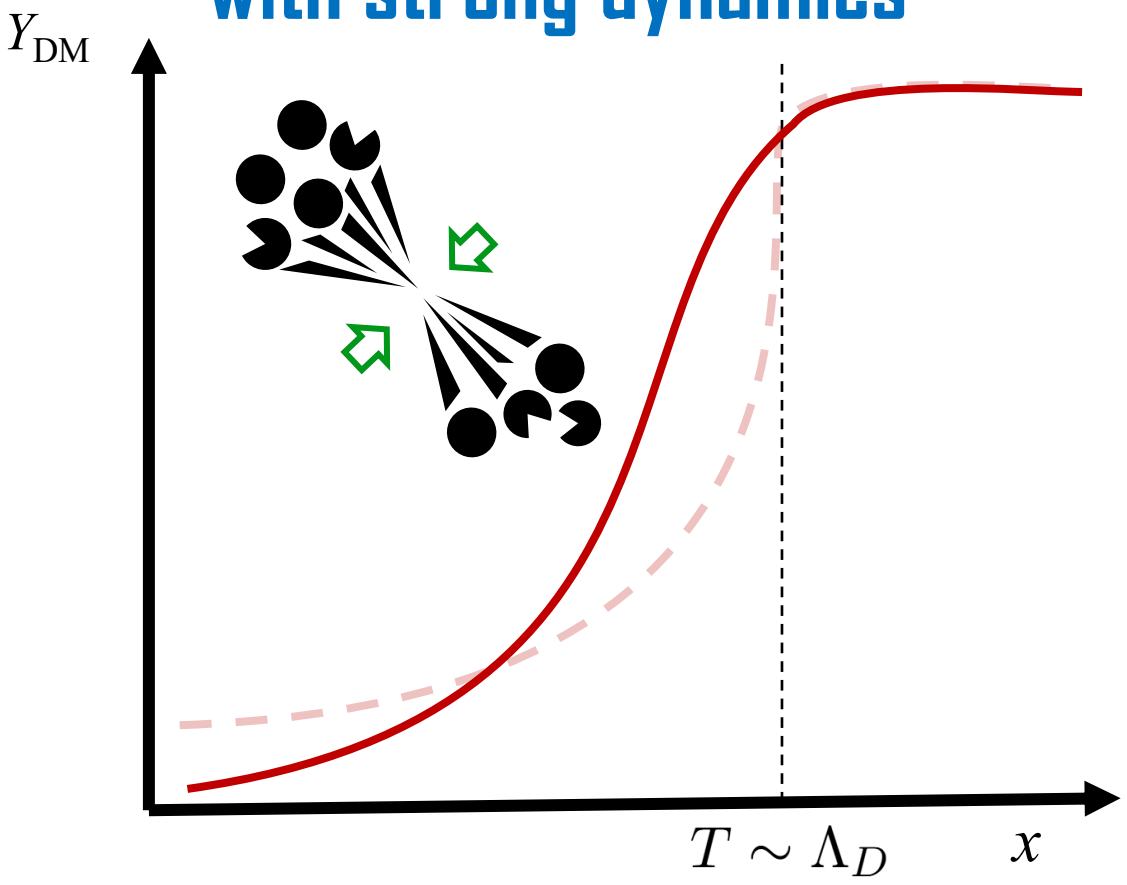
Other Possibilities

- Gravitational waves?
- Small-scale structure?

  See more in Xiaoyong Chu's talk
- Phenomenology?

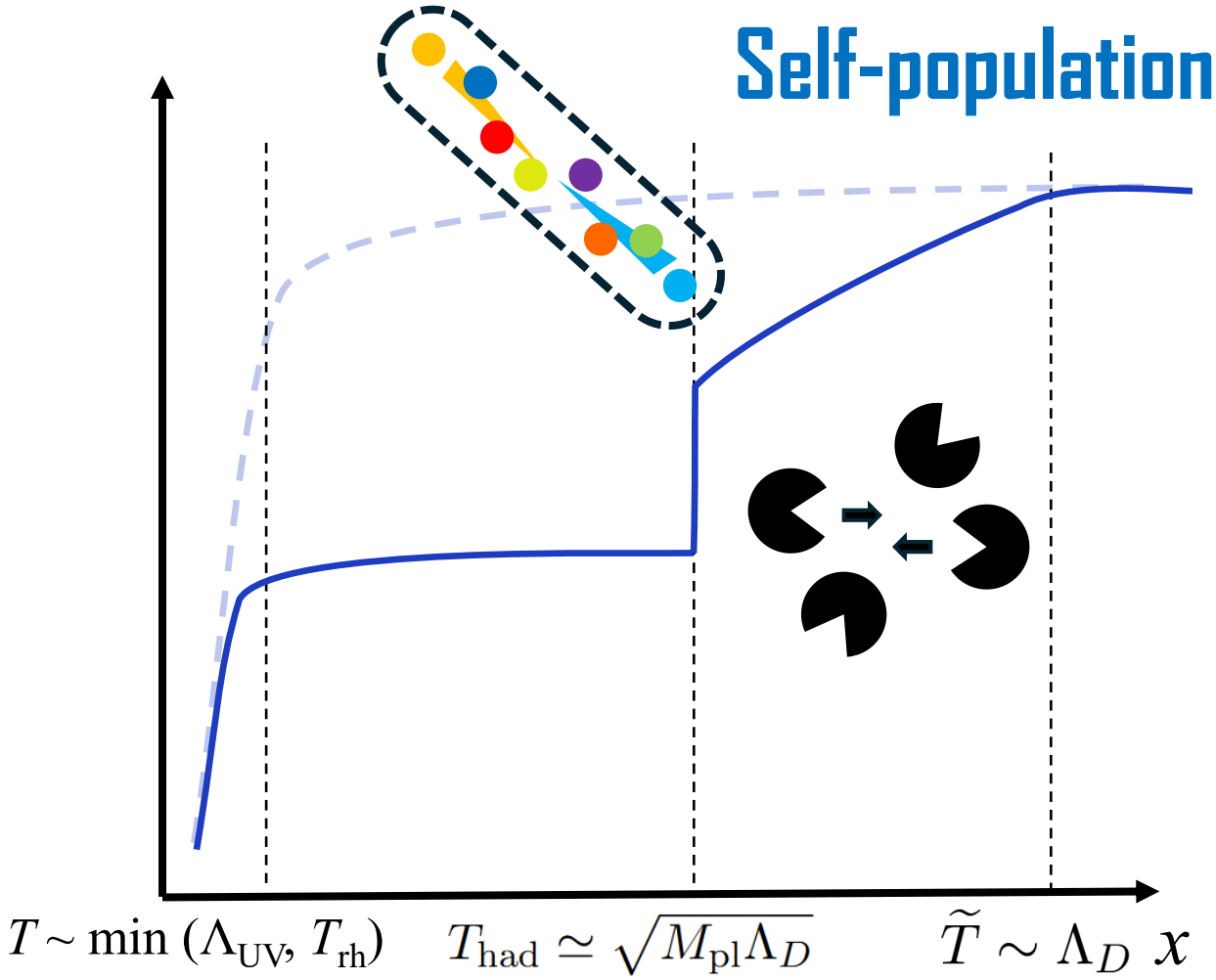
Summary (I)

Make freeze-in more UV with strong dynamics



First hadronization

Self-population



Summary (II)

- ❖We study the case of generic dark sector with strong dynamics
- ❖Both type of freeze-in scenario work as expected, but more feature granted by the DM self-interactions
- ❖The IR case becomes more UV and produces more DM
- ❖The UV case can be of gravitational interaction only (depending on the reheating temperature)
- ❖Hadronization and self-population of DM possible