Dynamical Dark Matter from Strongly-Coupled Dark Sectors

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Work done in collaboration with

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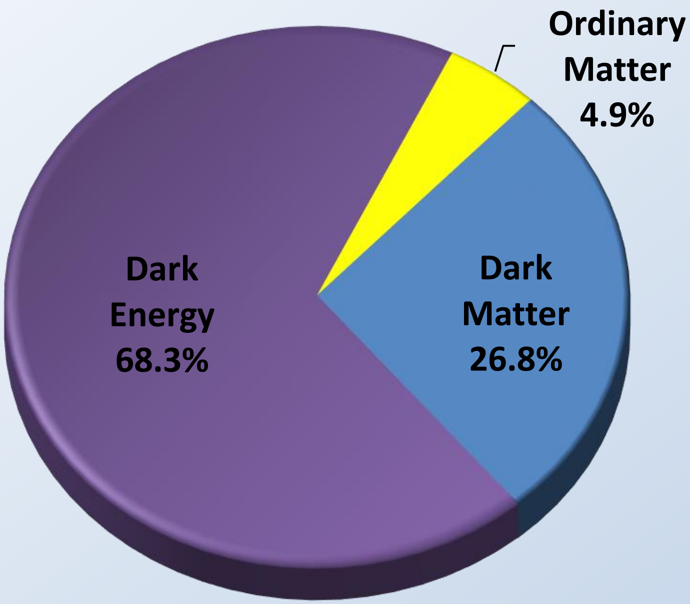
Dark Matter Properties



- **Abundance:** $\Omega_{DM} = \rho_{DM}/\rho_c = 0.268$
- **Cold**: Non-relativistic, massive.
- **Dark**: Weakly coupled to Standard Model fields.
- **Nonbaryonic**: BBN sets upper bound on baryonic matter abundance.

- Nothing in the Standard Model can explain
- Something new, beyond Standard Model

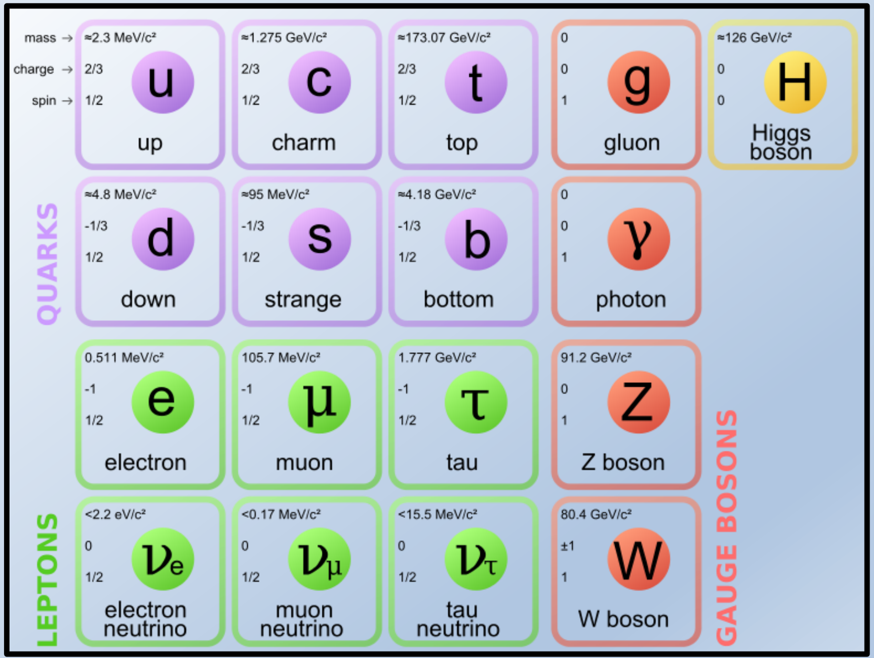
Traditional Dark Matter

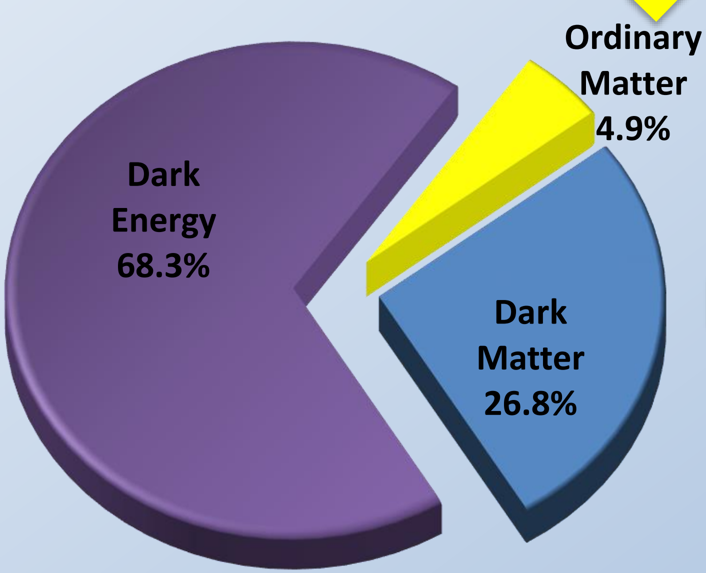
- **Single particle**, carries the entire DM abundance,
- **Hyper-stable**, $\tau_0 \approx 10^9 \times$ age of the universe

Most of the traditional Dark Matter theories are like that, stability is a necessary requirement.

What if dark sector is rich?

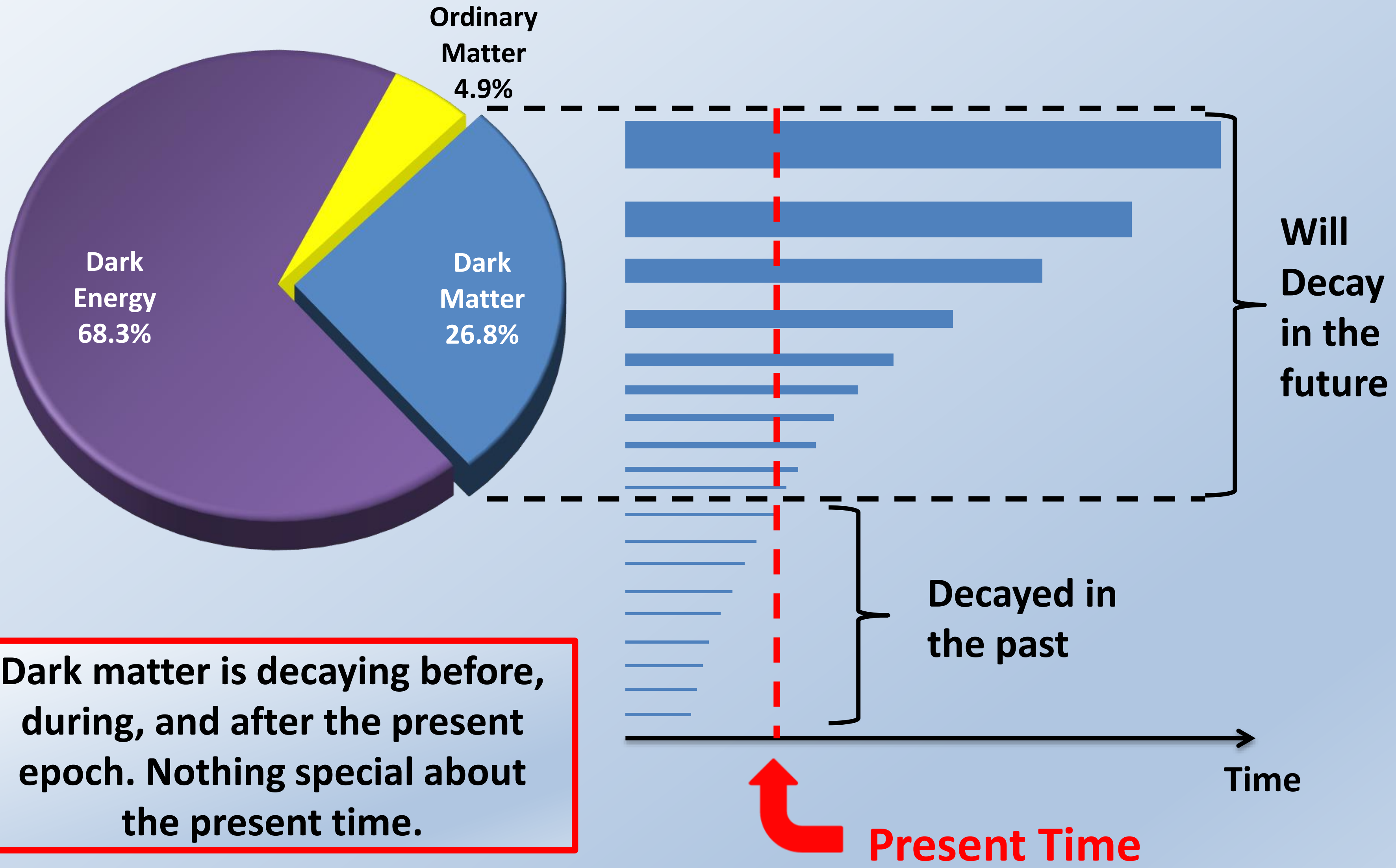
- *A given DM component need NOT to be stable if its abundance is small when decaying*
- *Balance between abundance and decay width.*
- *Stability is NO longer a necessary requirement!*





The Basic Picture

A Snapshot of the Cosmic Pie: Past, Present and Future



Dark matter is decaying before, during, and after the present epoch. Nothing special about the present time.

Dynamical Dark Matter (DDM):
A New Framework for Dark Matter Physics

K. R. Dienes & B. Thomas, 2011

- **Most general framework** for dark matter scenarios.
- **Can be reduced to single particle picture** if almost all the abundance is carried by one single dominant component.
- But, if the abundance is shared by the whole ensemble, the notion of stability is generalized to a balancing between abundance and lifetime of all the components in the ensemble. **The dark sector becomes truly dynamical!**

- With the dark sector being dynamical, in a MD universe,

$$\Omega_{tot} \neq const.$$

- Instead, have to sum over all DDM components

$$\Omega_{tot}(t) = \sum_n g_n \Omega_n(t)$$

Nontrivial time dependence because of all these decay widths.

- The usual DM EoS:

$$w = p/\rho = 0,$$

is no longer appropriate for DDM.

- Resort to effective EoS:

$$w_{eff}(t) = \frac{p_{eff}(t)}{\rho_{tot}(t)} = -\left(\frac{1}{3H}\frac{d\log\rho_{tot}(t)}{dt} + 1\right)$$

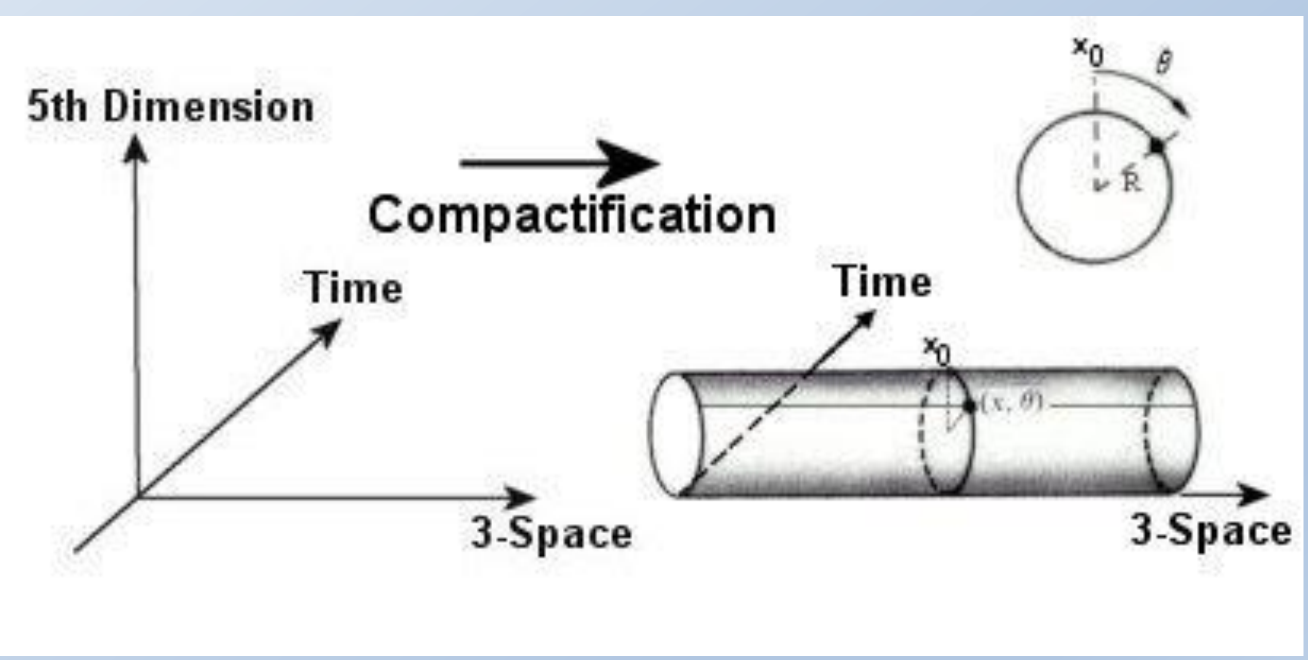
Previous Work

Phys. Rev. D85 083523
Phys. Rev. D85 083524

K. R. Dienes & B. Thomas

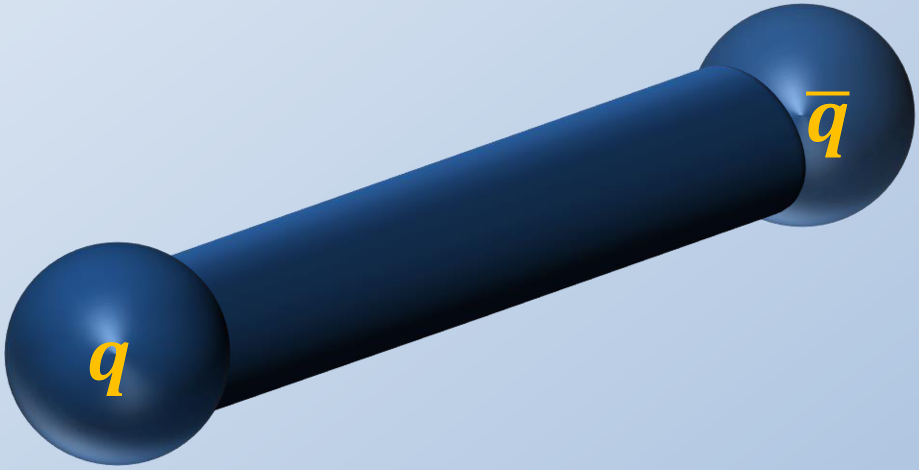
Previous work studied DDM ensembles realized by an entire tower of **Kaluza-Klein** states in which the density of states scales as **polynomials of mass**.

$$n_\Gamma(\Gamma) \propto M^\alpha$$

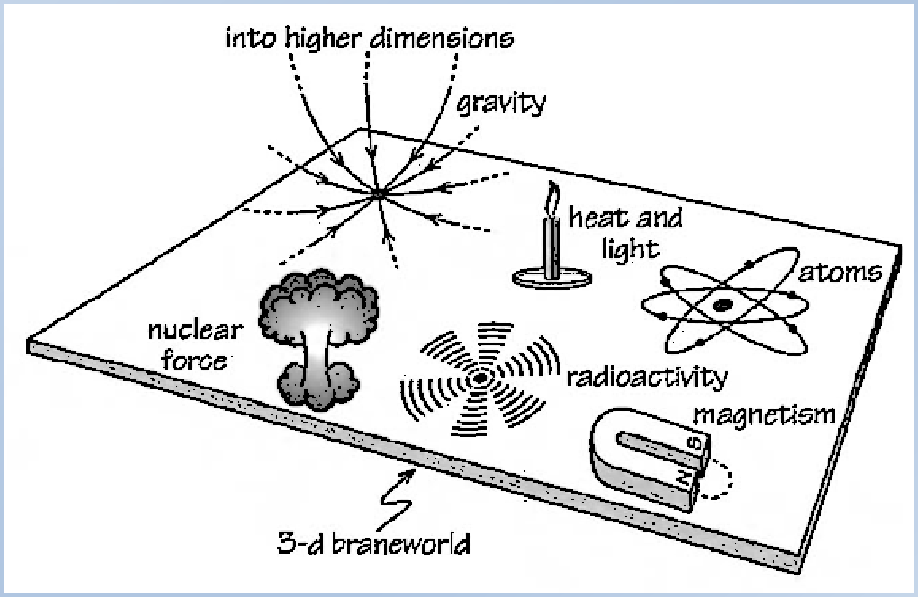


Other kinds of DDM ensembles

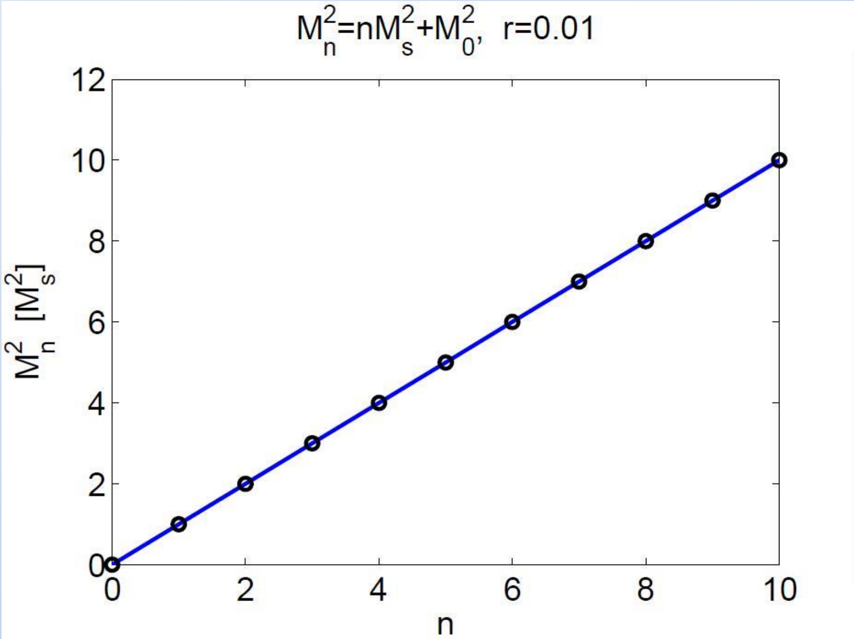
- Fermions(dark quarks) attached on the ends of a flux tube, charged under a non-Abelian gauge group G.
- In the confining phase below T_c, physical d.o.f are composite states (dark “hadrons”).



- Bulk states in Type I string theories.
- Typically neutral with respect to all brane gauge symmetries
- Interact with those brane states only gravitationally.
- For brane-localized observers, these states are dark matter.

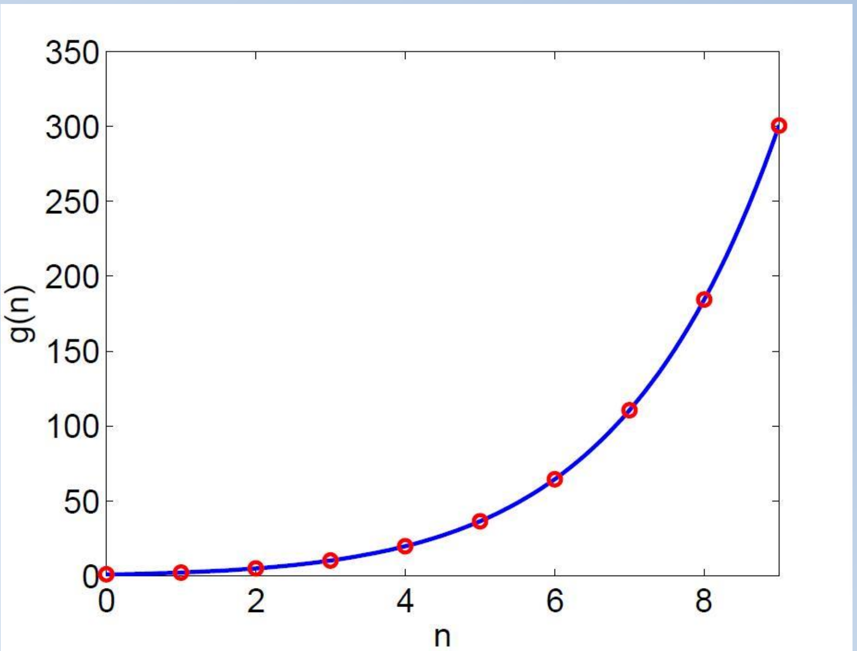


These two distinct realizations of DDM ensemble share some common features…



Mass distributions follow linear Regge trajectories:

$$M_n^2 \propto n$$



Hagedorn Behavior: (Exponentially growing, degeneracy of states)

$$g_n \sim n^{-B} e^{C\sqrt{n}}$$

Recall the total DDM abundance

Exponentially growing!

Has to be finite!

$$\Omega_{tot}(t) = \sum_{n=0}^{\infty} g_n \Omega_n(t)$$

To ensure finiteness (i.e. $\Omega_{tot}(t_{now}) \approx 0.268$), Ω_n has to take some form to suppress the exponential growth in degeneracy.

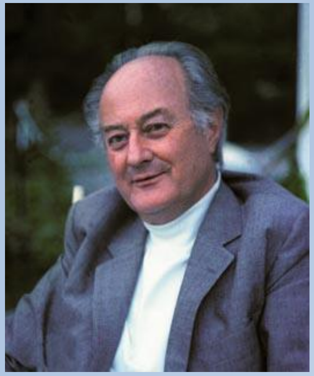
Fortunately, assume ***Boltzmann distribution*** right after DM components are created, exponential suppression factor is naturally obtained:

$$\Omega_n(t_c) \equiv \frac{\rho_n(t_c)}{\rho_{crit}(t_c)} = \frac{1}{3\widetilde{M}_P^2 H(t_c)^2} \int \frac{d^3\boldsymbol{p}}{(2\pi)^3} E_{\boldsymbol{p}} \underline{e^{-E_{\boldsymbol{p}}/T_c}}$$

Boltzmann Suppression

VS

Hagedorn Behavior

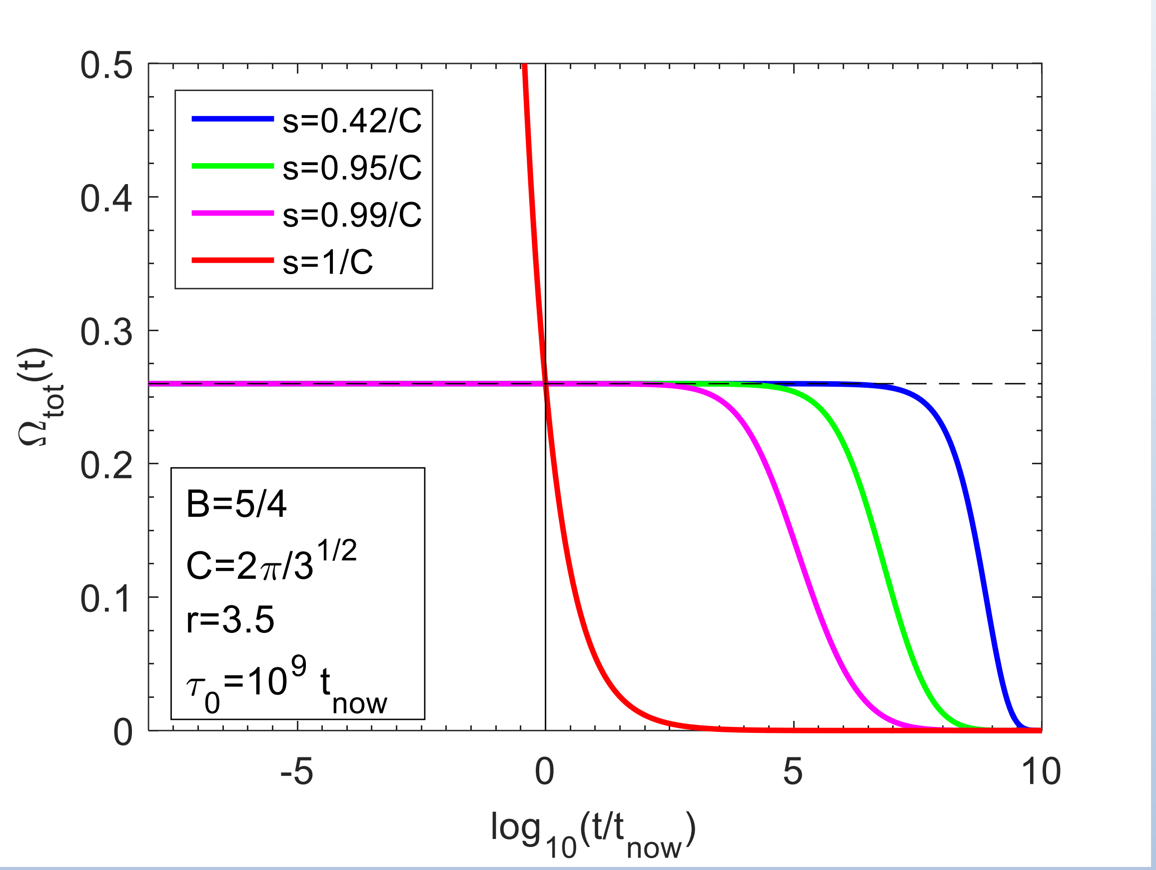


DDM abundance will be finite if Boltzmann suppression is strong!

Abundance Evolution

Since all the components are decaying, total DDM abundance reaches zero eventually.

When Boltzmann suppression is stronger, abundance is close to present value over a long period in cosmological history, as required!
(Red curve shows the case when Hagedorn behavior is stronger)



Look-back-time constraint:

- Go back from t_{now} to $10^{-6}t_{now}$, total dark matter abundance changes no more than 5%, i.e., ***there is no significant change in total dark matter abundance***

Equation of State

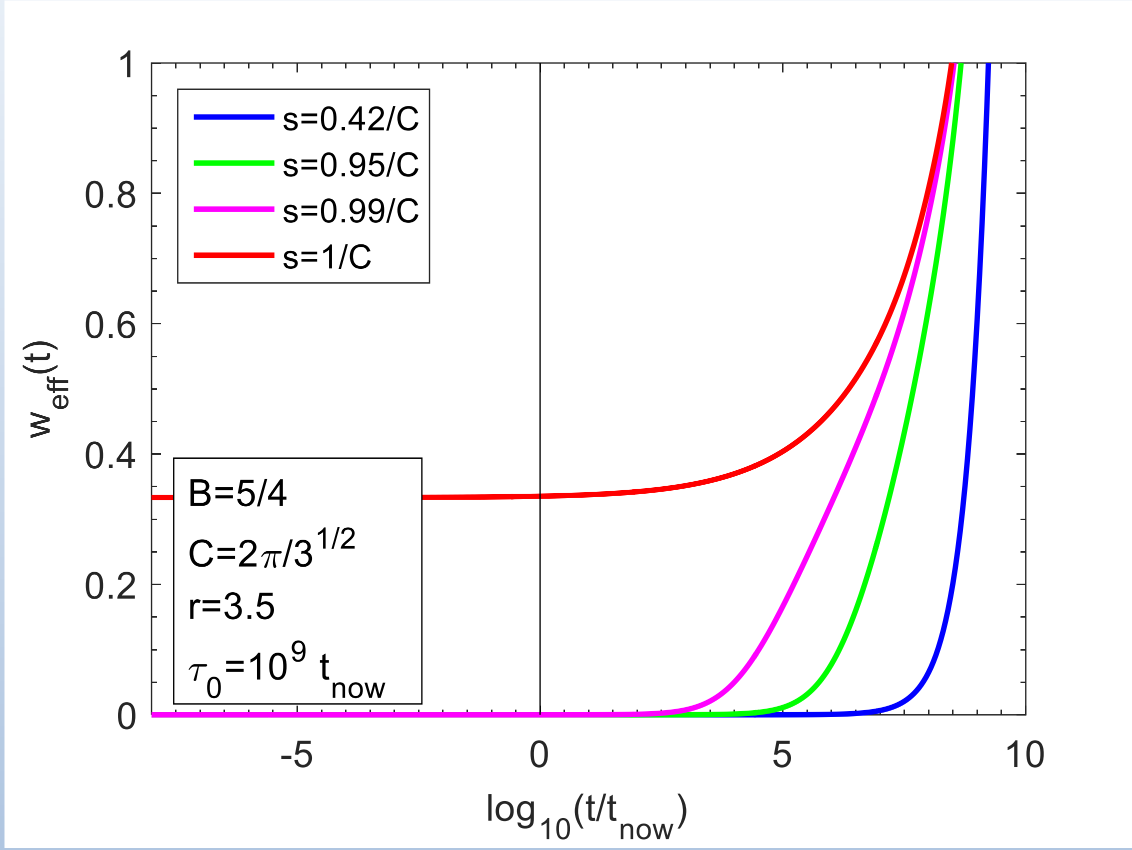
$$w_{eff}(t) = -\left(\frac{1}{3H}\frac{d\log\rho_{tot}}{dt} + 1\right)$$

When Boltzmann suppression is stronger, EoS:

$$w_{eff}(t_{now}) \approx 0,$$

as required!

Red curve shows the case when Hagedorn behavior is stronger.



EoS constraint:

- $w_{eff}(t_{now}) < 0.05$, i.e., ***dark matter particles cannot decay too fast Today!***

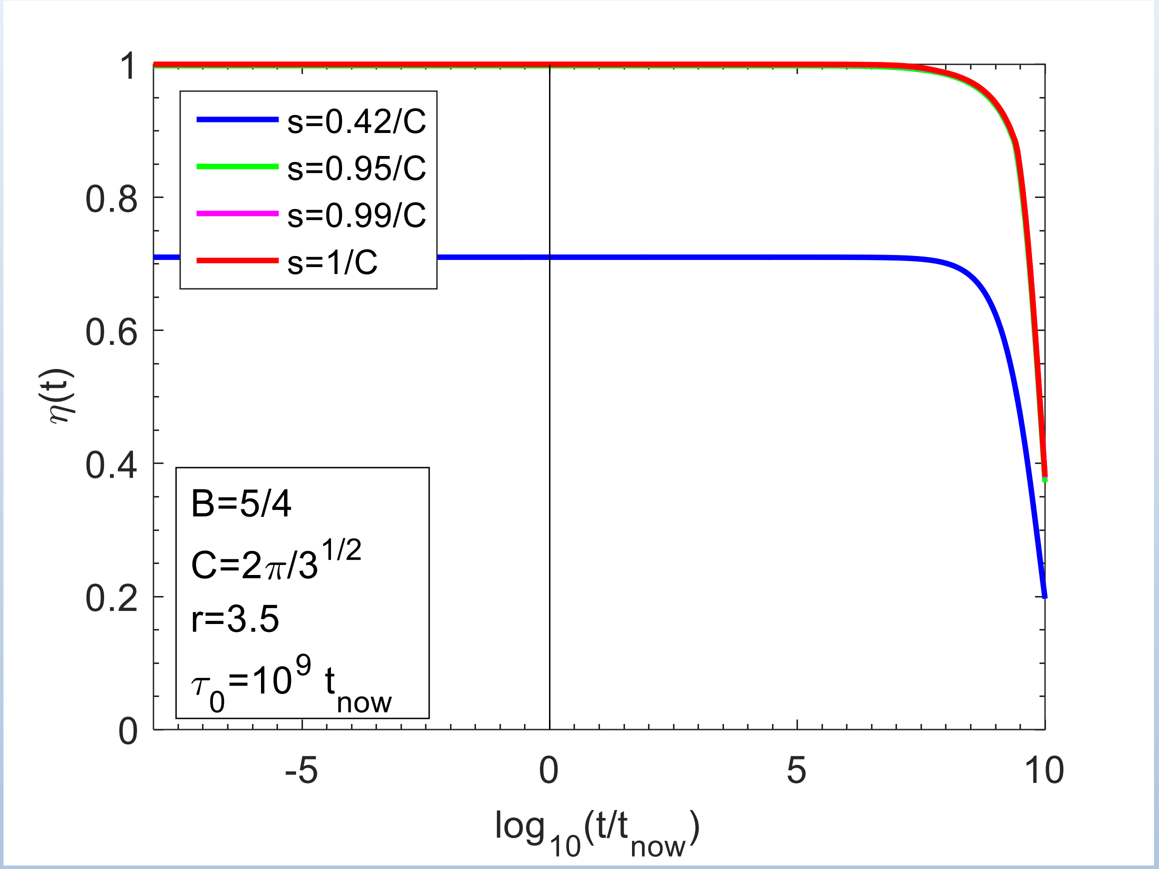
Tower Fraction

$$\eta(t) = 1 - \max_n \frac{\{\widehat{\Omega}_n(t)\}}{\Omega_{tot}(t)}$$

Fraction of DM abundance ***NOT*** carried by the dominant level.

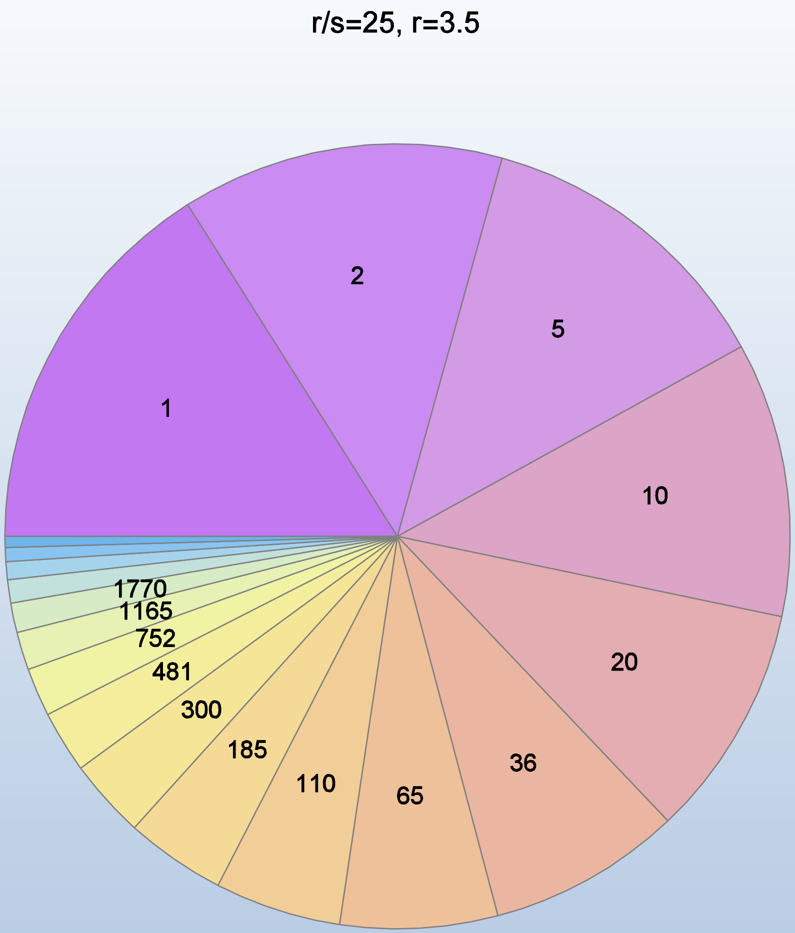
$\eta \to 0$, ***single particle scenario***

$\eta \to 1$, ***DDM scenario***

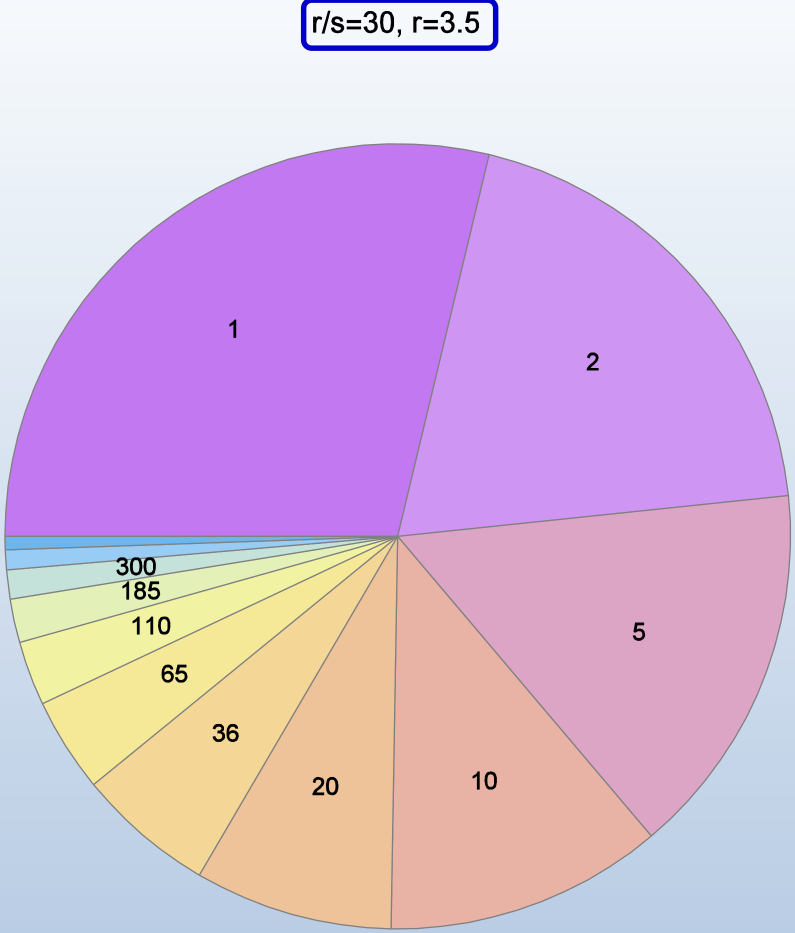


The full DDM ensemble can still be relevant today! This is ***NOT*** the standard WIMP paradigm!

(Green and magenta curves are almost overlapping on the red curve.)



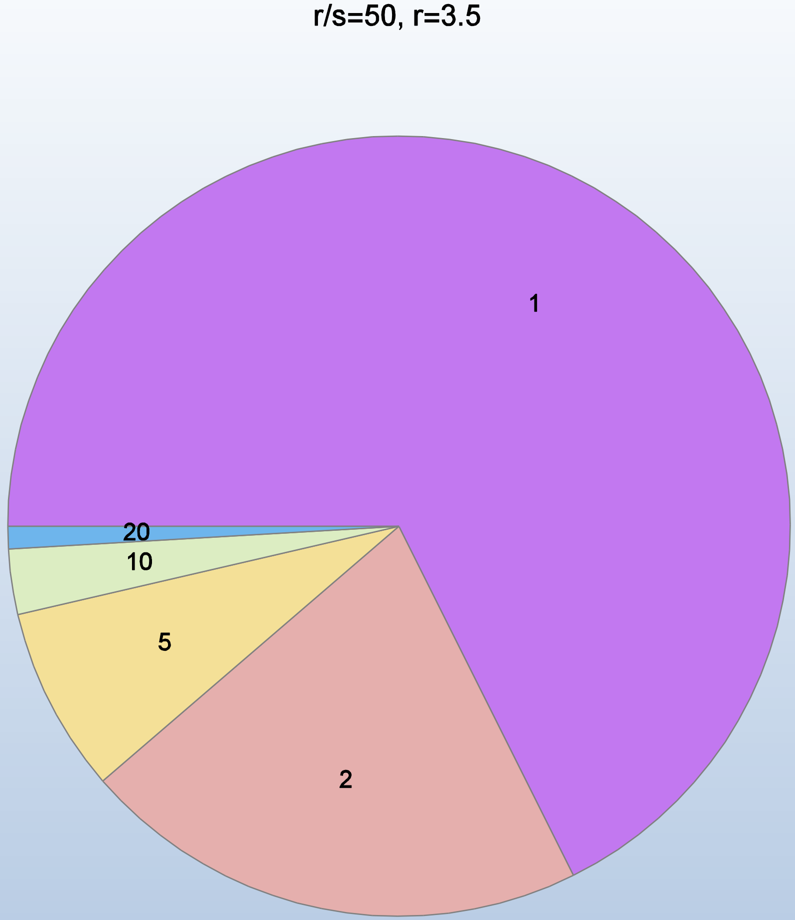
M_0=704.73MeV, T_c=28.19MeV, M_s=201.35MeV

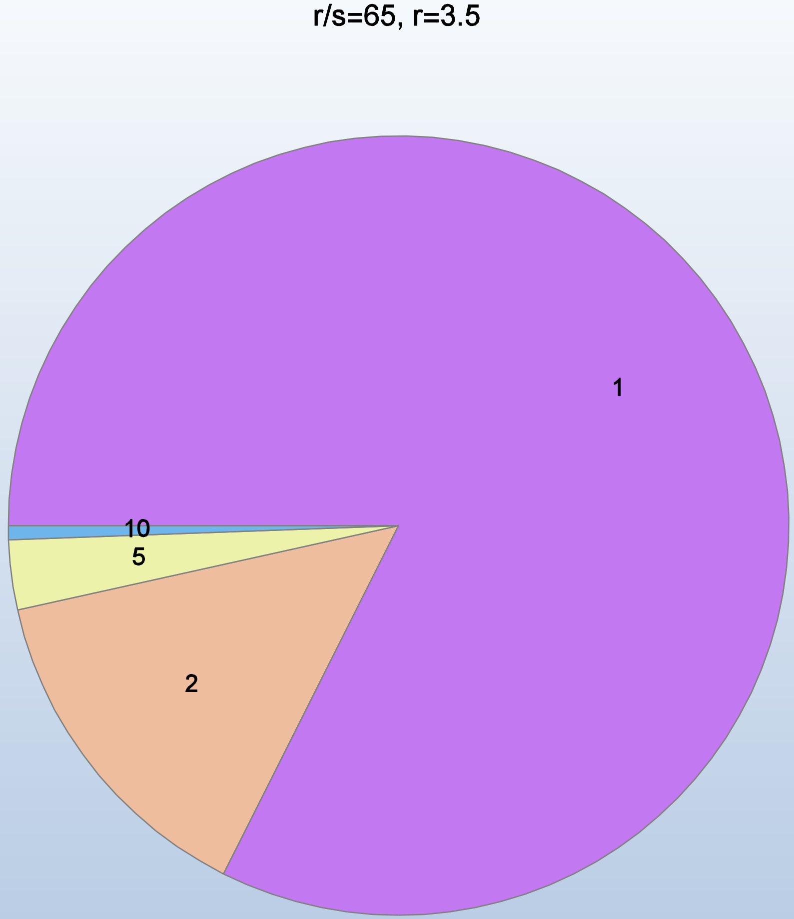


M_0=531.94GeV, T_c=17.73GeV, M_s=151.98GeV

Contributions to $\Omega_{tot}(t_{now})$ from different levels at the present time

In a <u>DDM-like</u> scenario, the whole dark matter ensemble receives nontrivial contribution from a wide variety of states. Even the lightest state need not to be the most abundant level.





$M_0=42.85\times10^{10}$GeV, $T_c=0.86\times10^{10}$GeV, $M_s=12.24\times10^{10}$GeV

$M_0=11.55\times10^{17}$GeV, $T_c=0.18\times10^{17}$GeV, $M_s=3.30\times10^{17}$GeV

Contributions to $\Omega_{tot}(t_{now})$ from different levels at the present time

Phenomenological constraints tend to favor traditional DM scenarios when fundamental scales are higher, while they favor more DDM-like scenarios when the fundamental scales are lower.

Conclusion

- With only simple assumptions, DDM from strongly coupled dark sector is ***potentially viable!***
- Ω_{tot} and w_{eff} both have ***nontrivial time dependence.***
- Natural mechanism – ***Boltzmann distribution*** keeps total DDM abundance ***finite***.
- The whole DDM ensemble can receive ***nontrivial contributions from many states***, i.e., ***Strongly coupled dark sector can naturally be DDM-like!***
  - Even the lightest state is ***NOT*** necessarily the most abundant one.
- Relationship between Fundamental ***scales*** and ***"diversity"*** of the dark sector are explored – ***scenarios with lower fundamental energy scales are more DDM-like.***