Dynamical Dark Matter from Strongly-Coupled Dark Sectors

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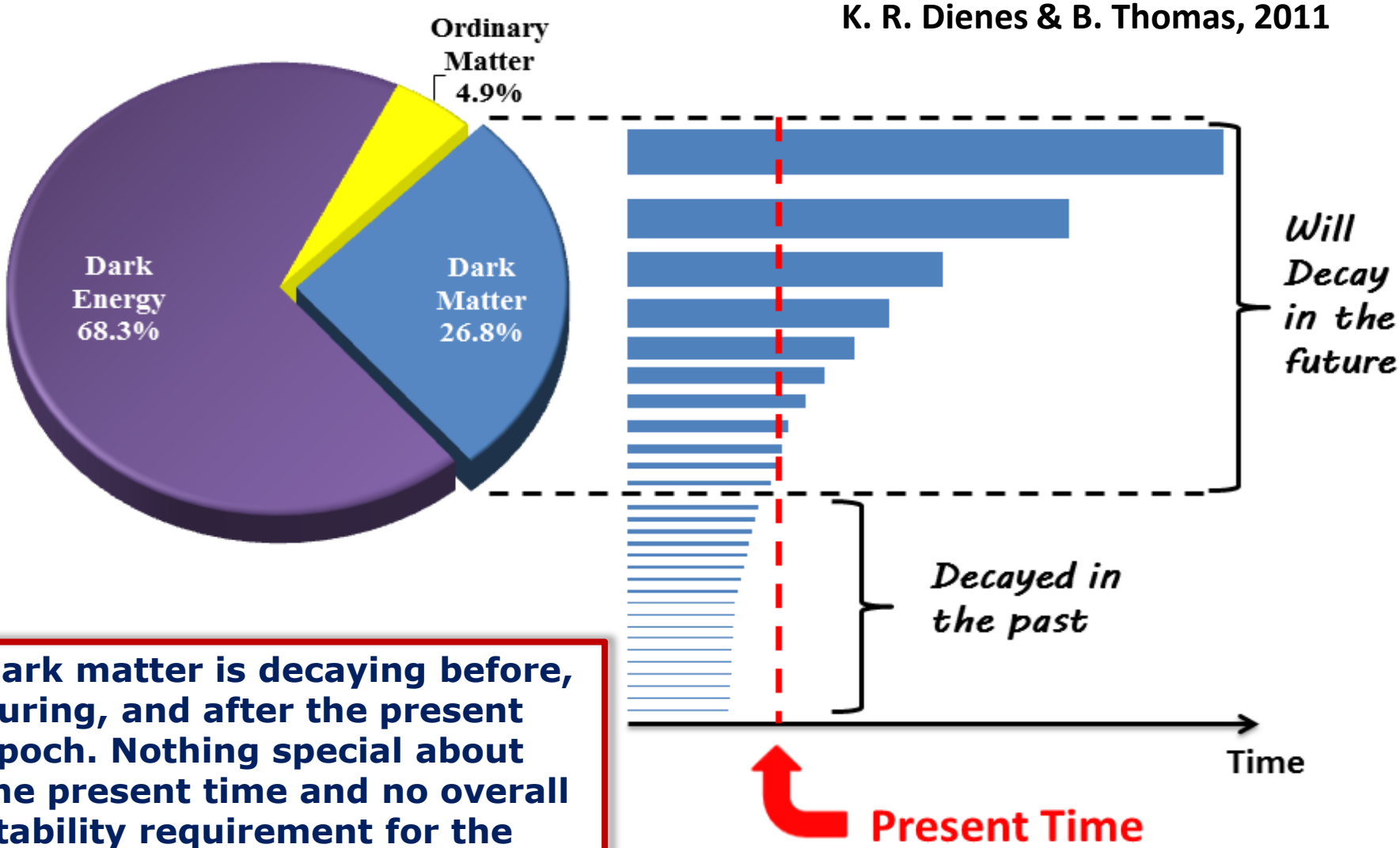
Basic Picture of Dynamical Dark Matter (DDM)

K. R. Dienes & B. Thomas, 2011



Dark matter is decaying before, during, and after the present epoch. Nothing special about the present time and no overall stability requirement for the dark sector.

DDM requires an *ENSEMBLE* of states whose lifetimes scales with their abundances. Is there any theory that can naturally provide us with such DDM ensembles?

Yes!

Previous works on DDM studied ensembles from KK towers and representations of large-hidden gauge groups.

These realizations of DDM all have polynomial scaling relations between abundances, lifetimes and masses.

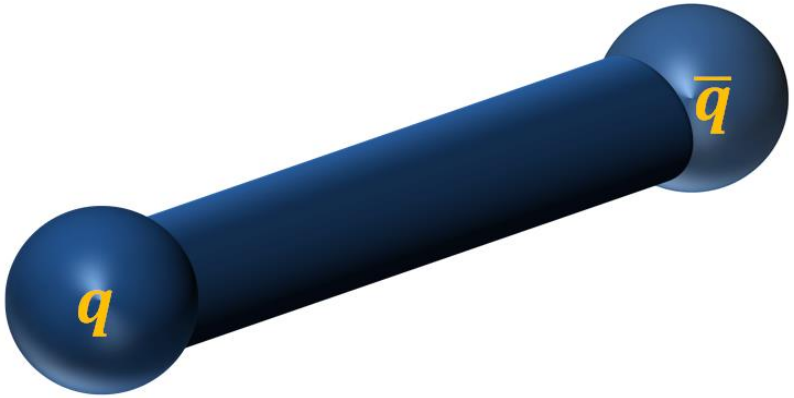
Are there other possibilities?

Yes!

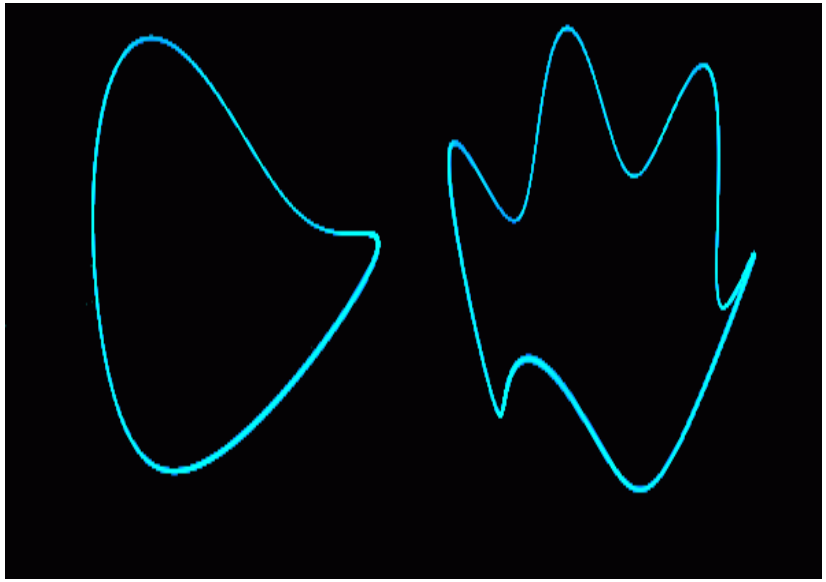
In fact, we explored something quite different…

Strongly-Coupled 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 brane states only gravitationally.
- For brane-localized observers, these states are dark matter.



Common features:

M_s: string scale
M_0: lightest mass
$B \sim D_\perp$
$C \sim$ central charge
$r \equiv M_0/M_s$

- Mass spectrum follow linear ***Regge*** trajectories:

$$M_n^2 = nM_s^2 + M_0^2$$

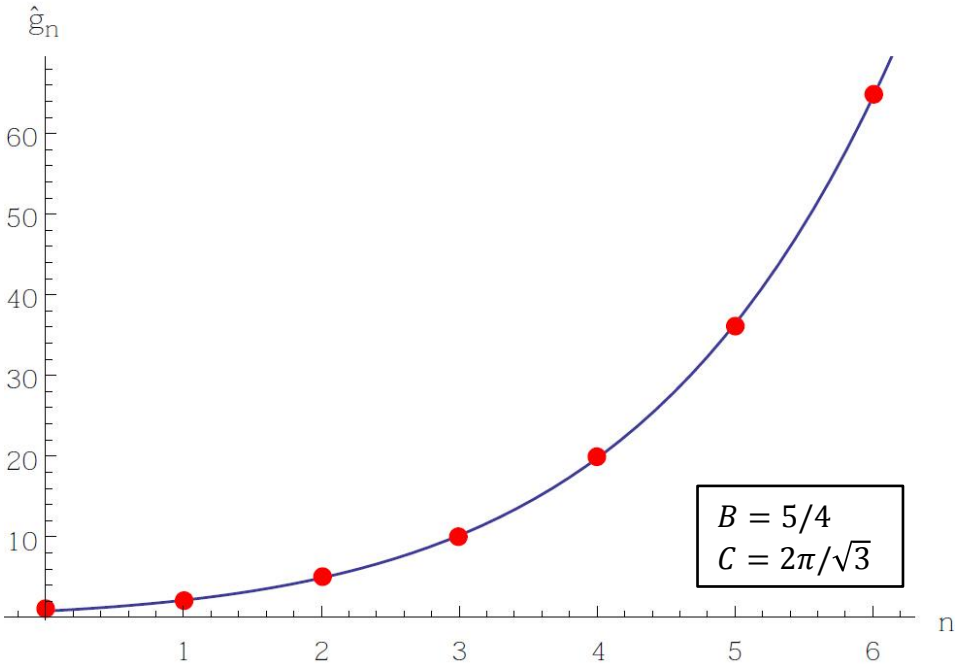
$M_s \equiv 1/\sqrt{\alpha'}$: "String scale"
M_0: Lightest mass in the spectrum

- Exponentially growing degeneracy of states(***Hagedorn*** behavior)

$$g_n \propto n^{-B} e^{C\sqrt{n}} \;\; as \;\; n \to \infty$$

$$\begin{cases} B = (3 + D_\perp)/4 \\ C = \pi\sqrt{2c/3} \end{cases}$$

$D_\perp$: Number of transverse dimensions into which string/flux tube can fluctuate
$c \equiv c_{int} + D_\perp$: Central charge



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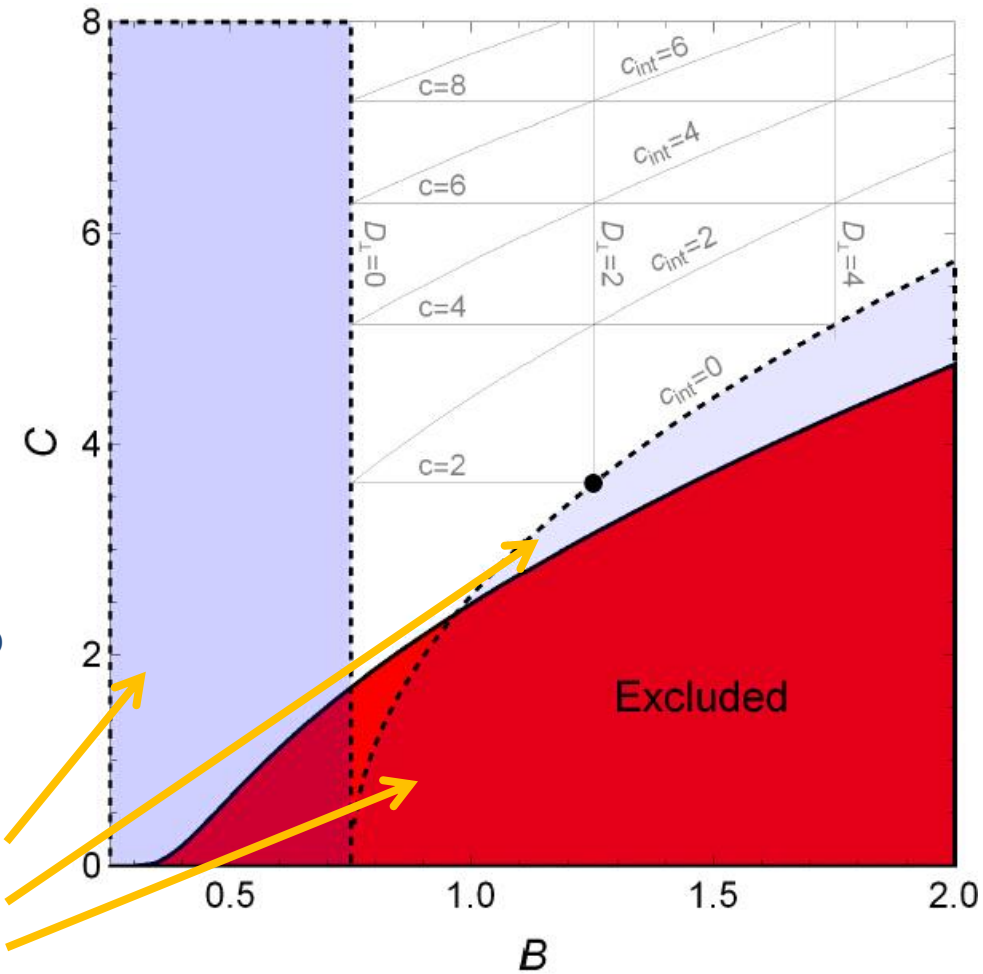


Excluded by $\begin{cases} D_\perp > 0 \\ c_{int} \geq 0 \\ g_1 > 1 \end{cases}$

Just to be self-consistent!

Cosmological Abundances

M_s: string scale
M_0: lightest mass
T_c: critical temp
$B \sim D_\perp$
$C \sim$ central charge
$r \equiv M_0/M_s$
$s \equiv T_c/M_s$

In DDM, each component has an abundance: $\Omega_n(t)$
Total dark matter abundance: $\underline{\Omega_{tot}(t)} = \sum_n \underline{g_n}\Omega_n(t)$

Finite!

Exponentially growing!

Ω_n has to fall sufficiently fast!

Assuming initial abundance distribution follows Boltzmann distribution:

$$\Omega_n(t_c) \sim e^{\underline{-M_n/T_c}}$$

Boltzmann suppression!

To have a finite total abundance:

$$\begin{cases} \Omega_n(t_c) \sim e^{-M_n/T_c} \\ g_n \sim n^{-B} e^{C\sqrt{n}} \end{cases} \Rightarrow \frac{M_s}{T_c} \equiv \frac{1}{s} \geq C$$

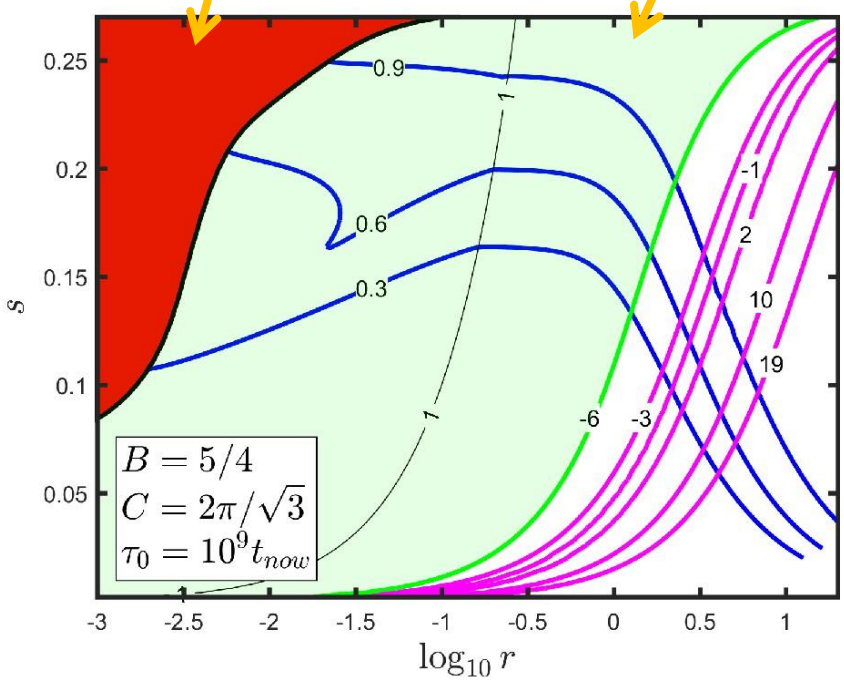
Confinement temperature must be below or at Hagedorn temperature $T_H \equiv M_s/C$

Parameter Space

M_s: string scale
M_0: lightest mass
T_c: critical temp
$B \sim D_\perp$
$C \sim$ central charge
$r \equiv M_0/M_s$
$s \equiv T_c/M_s$
τ_0: longest lifetime

Excluded by t_{LB} and EoS constraints

Excluded by BBN, structure formation constraints: $M_0 > O(keV)$



Blue lines: tower fraction, $\eta \equiv 1 - \frac{\max\{g_n \Omega_n(t)\}}{\Omega_{tot}(t)}$

Magenta lines: string scale, $\log_{10} M_s/GeV$

Green line: lightest mass, $\log_{10} M_0/GeV$

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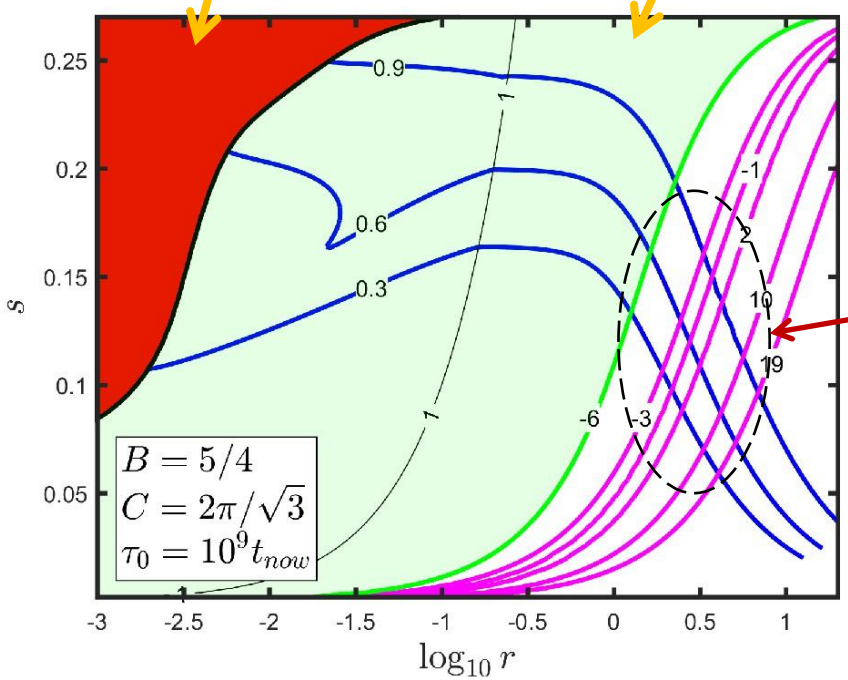

Region of interest for DDM:

- $\eta(t_{now})$ varies from 0 to 1
- M_s ranges from keV to Planck scale

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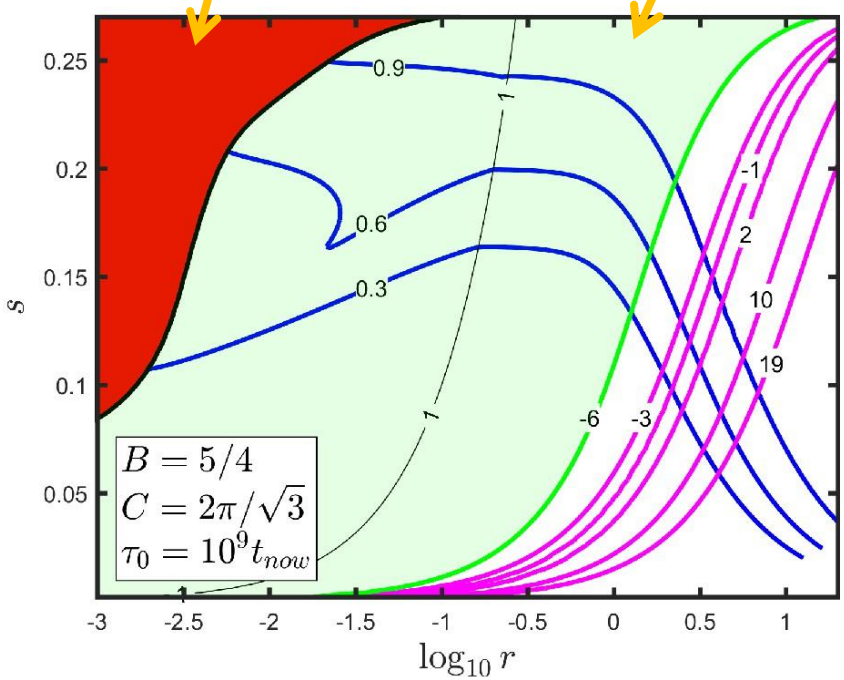

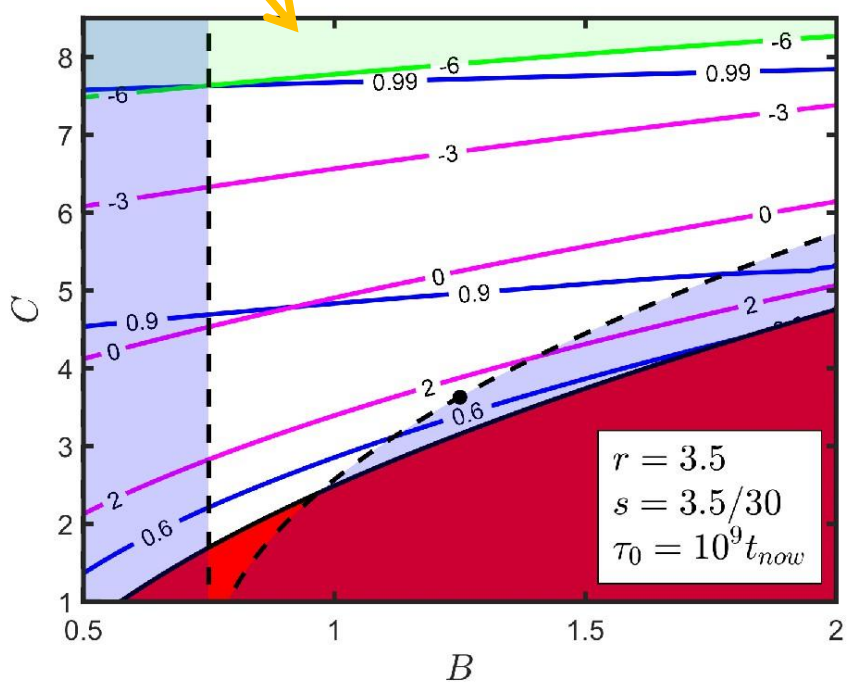

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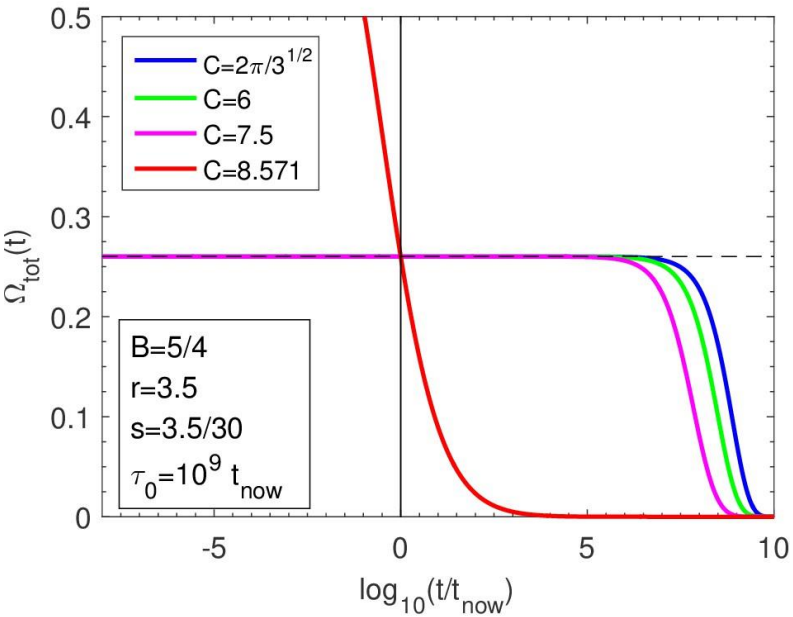
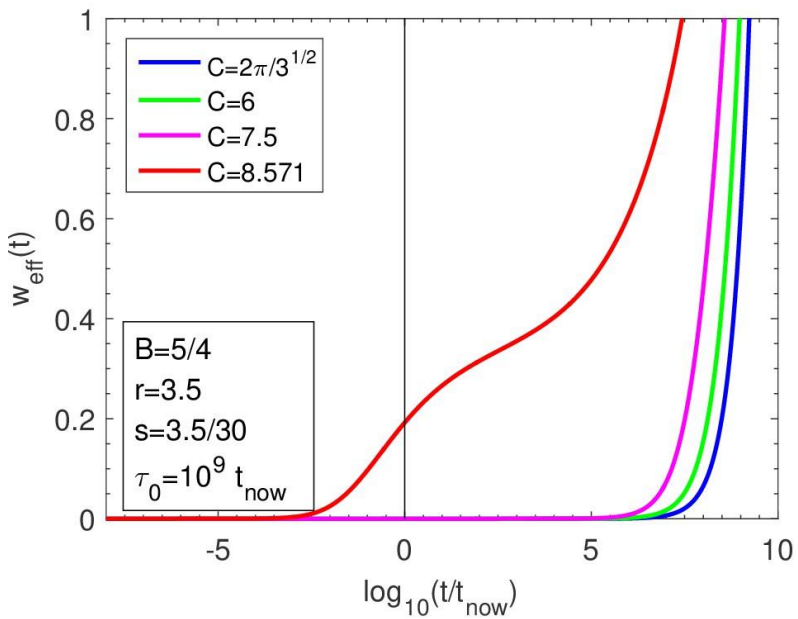
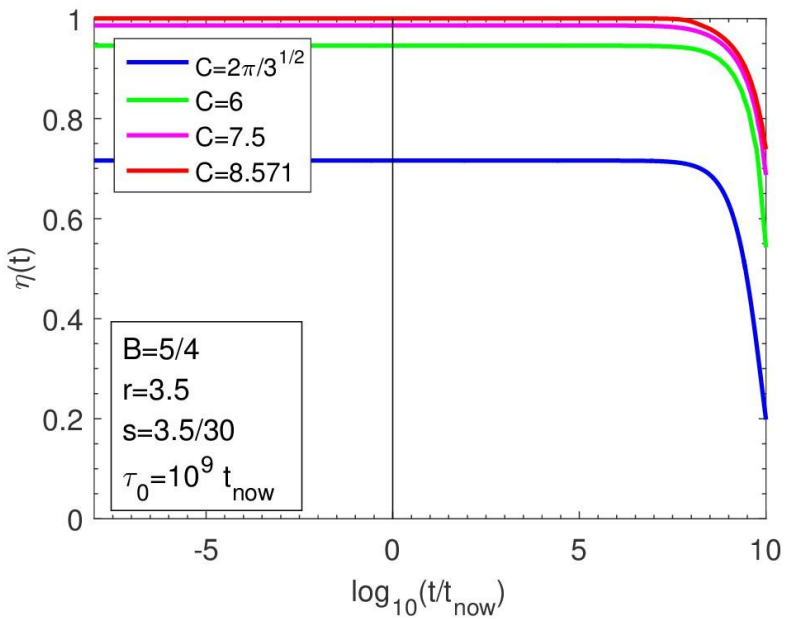
Large portion of parameter space that satisfies internal consistency requirements is also viable under the phenomenological constraints!

Time-Evolution of $\Omega_{\rm tot}(t)$, $w_{eff}(t)$ and $\eta(t)$

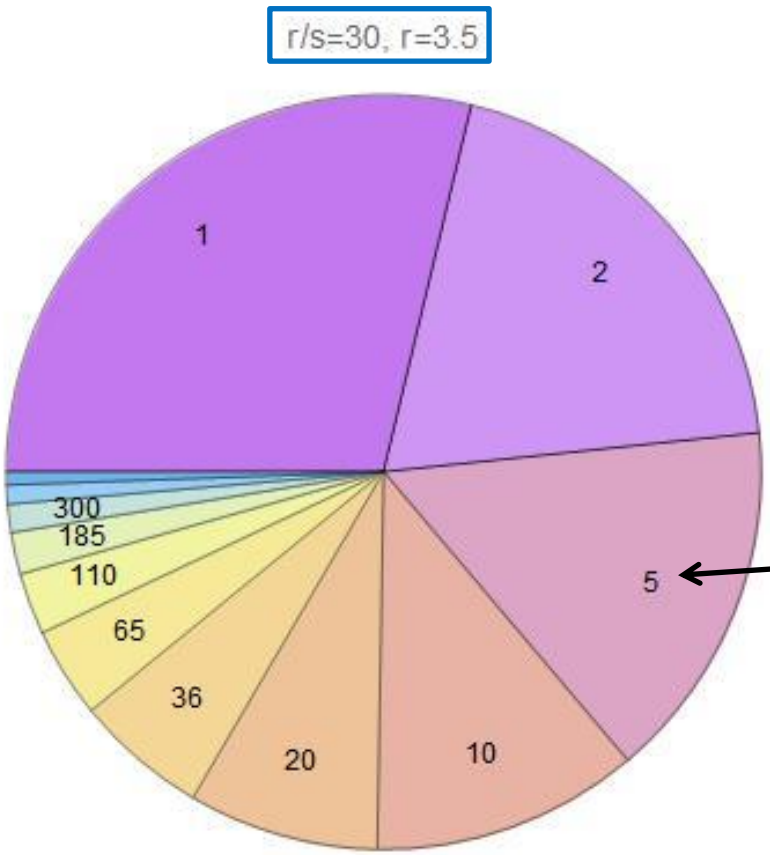
- $\Omega_{tot}(t_{now}) = 0.26$, all states eventually decay
- Larger C → higher degeneracy → more shorter-lived excited states → more decays
- Evolution well behaved($\Omega_{\rm tot}$ changes little when going back in time, $w_{\rm eff}(t_{now})$ close to zero) if Boltzmann suppression is stronger than Hagedorn behavior. Red curve shows the opposite situation.
- η significantly above zero, really ***DDM-like***, with many states in the ensemble carrying significant abundance.







Abundance Distribution at present time



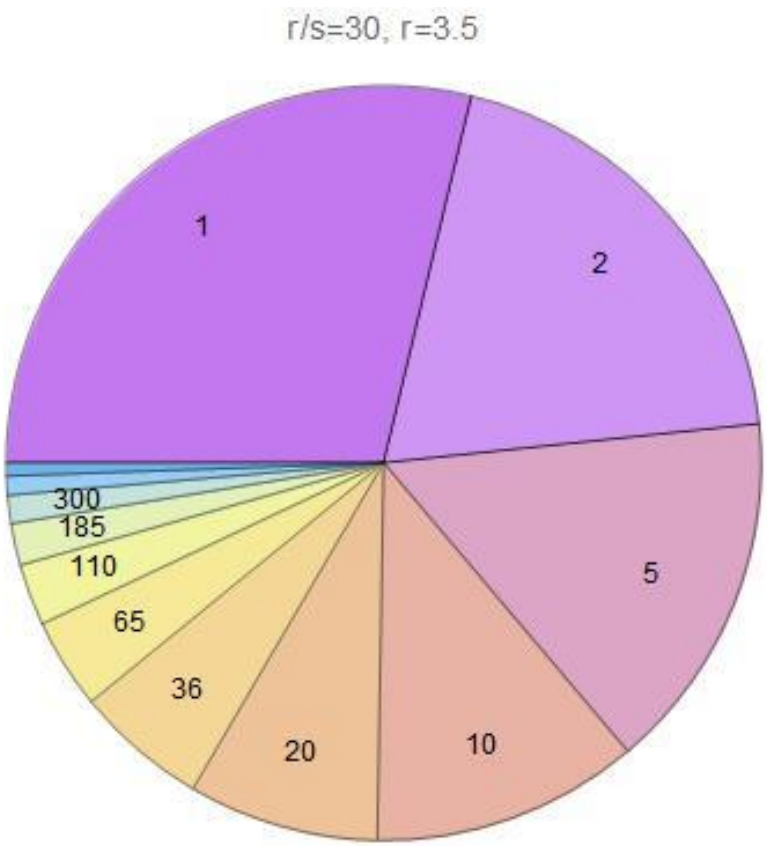
Degeneracy of states

M_0=531.9 GeV, T_c=17.7 GeV, M_s=152.0 GeV

Fundamental scales

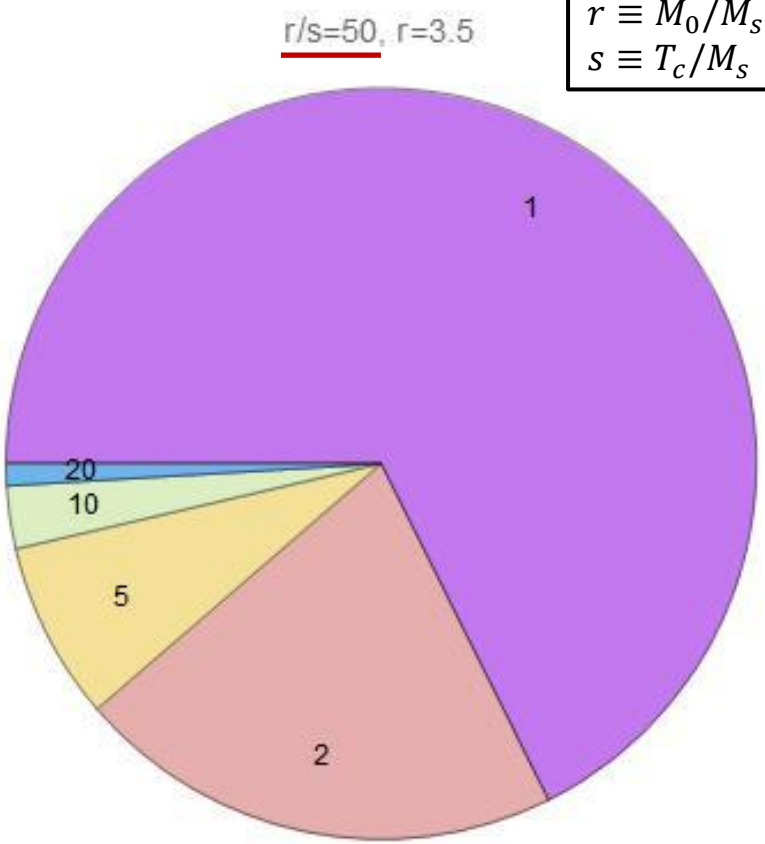
Abundance Distribution at present time

$r \equiv M_0/M_s$
$s \equiv T_c/M_s$



M_0=531.9 GeV, T_c=17.7 GeV, M_s=152.0 GeV

Increase r/s



M_0=42.9×10^{10} GeV, T_c=0.9×10^{10} GeV, M_s=12.2×10^{10} GeV

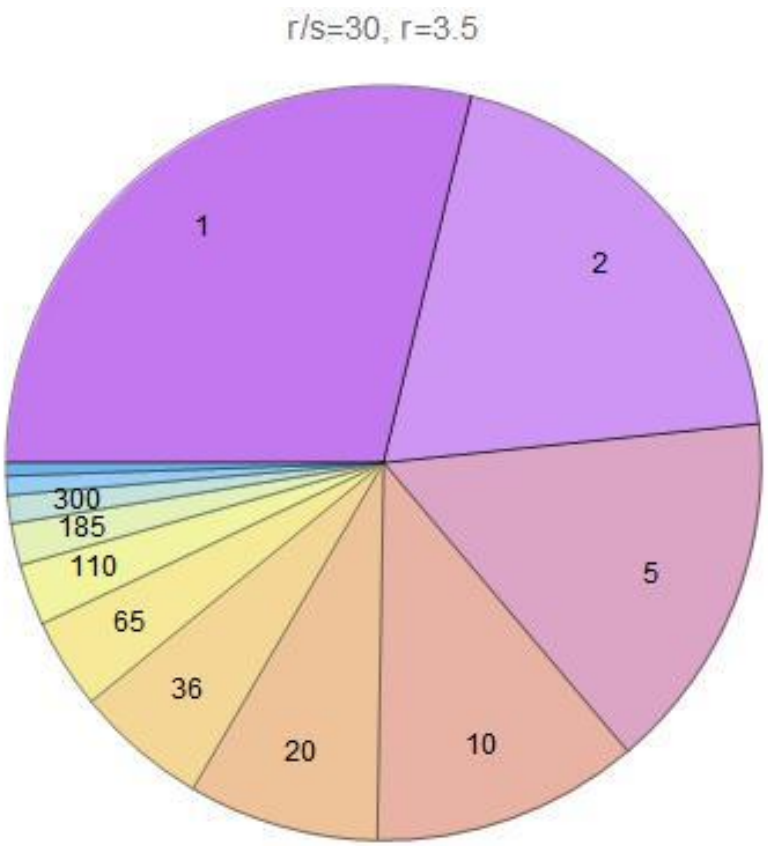
Increasing r/s while holding r fixed amounts to decreasing s, leading to a *stronger Boltzmann suppression* for heavier states, such that

- Tower fraction is *decreased*, less DDM-like
- Corresponding mass scales are *increased*

} Tower fraction and mass scales are ***INVERSELY CORRELATED!***

Abundance Distribution at present time

$r \equiv M_0/M_s$
$s \equiv T_c/M_s$



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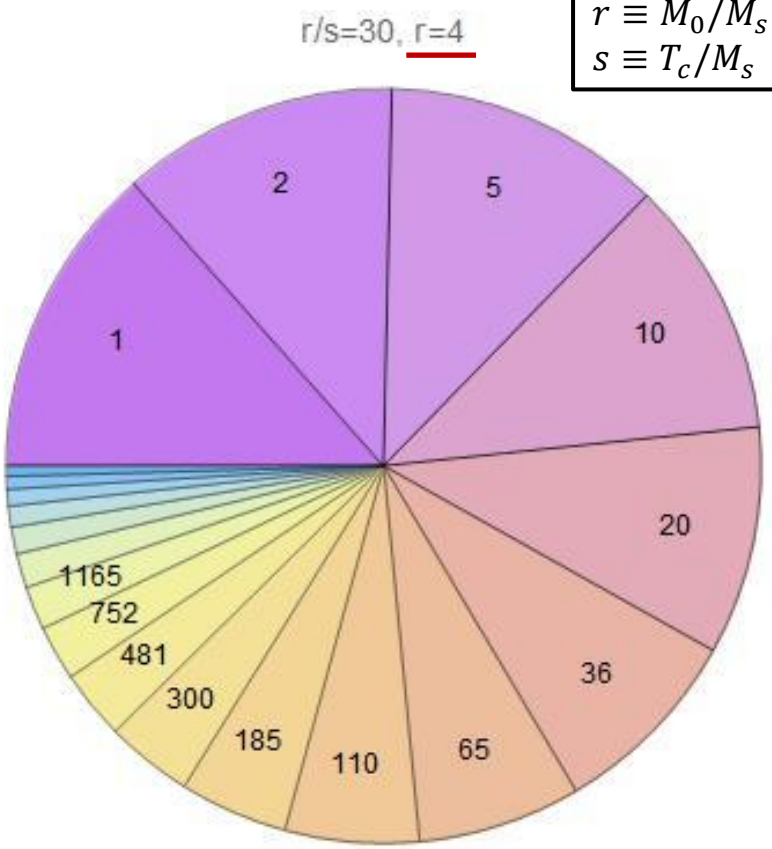
Increase r



M_0=248.5 GeV, T_C=8.3 GeV, M_s=62.1 GeV

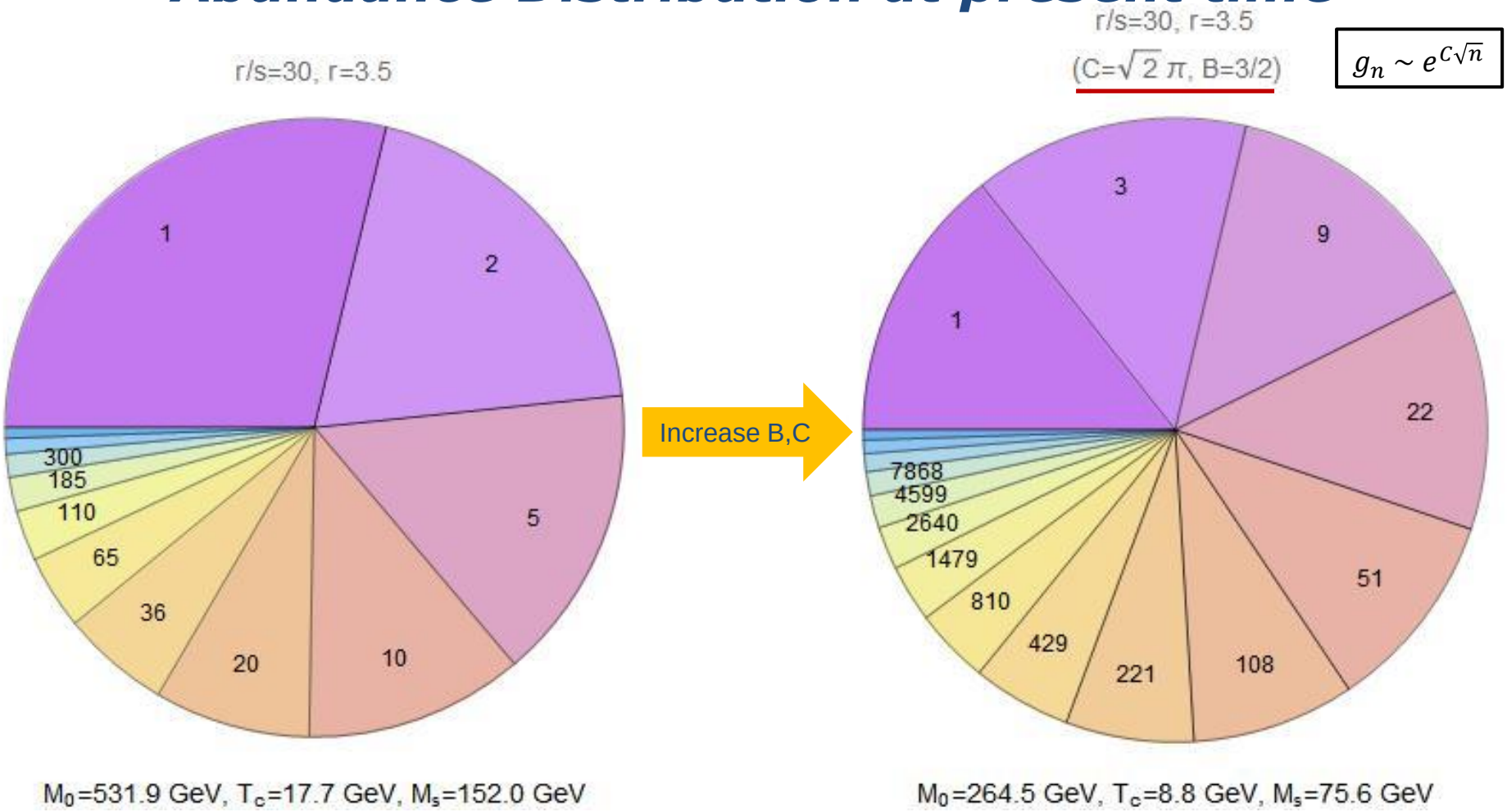
Increasing r while holding r/s fixed increases s while decreases mass ratio between heavier and lighter states, leading to *weaker Boltzmann suppression*

- Heavier states become *more abundant*, more DDM-like
- Corresponding mass scales are *decreased*

Correlation appears again!

Abundance Distribution at present time

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



Increasing C *increases degeneracy* thus allowing more states to contribute.

- Higher levels become *more abundant*, *more DDM-like*
- Corresponding mass scales are *decreased*

Still, inversely correlated!

- Ground state need *NOT* to be the most abundant one at t_{now}

Conclusions

- DDM from strongly coupled dark sector which exhibits Hagedorn behavior is potentially viable since a natural Boltzmann distribution provides an exponential suppression.
- Evolution of $\Omega_{tot}(t)$, $w_{eff}(t)$ and $\eta(t)$ show nontrivial time dependence.
- A large parameter space is explored, fundamental scales, i.e., M_0, M_s and T_c, can be dialed from keV/MeV all the way to M_{Pl}.
- Lower-mass scenarios are more DDM-like, with many states contributing.
- Higher-mass scenarios are less DDM-like, thus more traditional
- DDM framework smoothly incorporates entire transition between different behaviors

Future Prospects

- A full phenomenological study of this model.
- Including intra-ensemble decay in which heavier states can cascade down the tower and decay into lighter states.
- A detailed study of DDM freeze-out, how it affects DDM abundance distribution.
- How DDM affects small structure.