Dark Matter via N SM Copies

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Summary

- Models with a large number of species are an alternative solution to the ***hierarchy problem***
- Interspecies couplings are naturally suppressed by ***perturbative unitarity***
- Could ***dark matter*** be the made of all the other weakly coupled species?

New Solution to Hierarchy Problem

- In models with N species cut off is ***lowered***
- Gravity becomes quantum/strong at a new scale

$$M_* \sim \frac{M_{\mathrm{Pl}}}{\sqrt{N}}$$

- ***Crazy idea***: if $N \sim 10^{32}$ then we have Dvali (2007)

$$M_* \sim 1\ \mathrm{TeV}$$

Non-Perturbative Argument

- BH couples ***democratically*** to ***all*** available species

$$\dot{M}_{\mathrm{BH}} \sim -\boxed{N} r_{\mathrm{Schw}}^2 T_{\mathrm{BH}}^4 = -\boxed{N} \frac{M_{\mathrm{Pl}}^4}{M_{\mathrm{BH}}^2}$$

- To be a ***semiclassical*** object $\tau \gg r_{\mathrm{Schw}}$

$$M_{\mathrm{BH}}^2 \gg N M_{\mathrm{Pl}}^2$$

$$R \sim r_{\mathrm{Schw}}^{-2} \ll \frac{M_{\mathrm{Pl}}^2}{N}$$

Peculiar Black Holes at LHC?

- A generic prediction of N-species models is the existence of unusual micro black holes
  - $M_{\mathrm{BH}} > M_{\mathrm{Pl}}\sqrt{N}$ BHs Einsteinian
  - $\dfrac{M_{\mathrm{Pl}}}{\sqrt{N}} < M_{\mathrm{BH}} < M_{\mathrm{Pl}}\sqrt{N}$ BHs undemocratic
  - Smallest BHs will form at M_* but will carry a species label

Our Idea

Content

- Take N copies of (SM + Φ)
- We are the reheating products of a ***single*** inflaton

Inflation

- Reheating leaks energy to other species

$$\Omega_{\mathrm{DM}} \sim \Omega_{\mathrm{b}} \Delta_{\mathcal{R}}^2$$

Freeze-out

- Baryons thermalise and annihilate
- DM too rare to do so $\Delta_{\mathcal{R}}^2 \sim \eta_{\mathrm{b}}$

Consistent Inflation

- Introduce inflaton potential with cross-species couplings

$$V = \sum_j V(\Phi_j) + \lambda_{22} \sum_{j_1 \neq j_2} \Phi_{j_1}^2 \Phi_{j_2}^2 + \cdots$$

  - Large field values in ***more than one*** direction give large effective mass and ***stop*** inflation
- The universe ***spontaneously*** chooses one direction in Φ-space, say Φ_1
  - Decay products in that copy become the baryons

Consistent Inflation

- Inflation generates nearly scale-free perturbations which evolve into large-scale structure

$$\Delta_{\mathcal{R}}^2 \sim \frac{H_*^2}{\epsilon M_{\mathrm{Pl}}^2} \sim 10^{-10}$$

- Curvatures and masses must remain below cut-off

$$H_* < M_*$$

- ***No enhancement*** with multiple inflatons
  - For N>10^{10} ***need*** an alternative mechanism

Modulated Reheating

Dvali, Gruzinov, Zaldarriaga (2003)

- Introduce ***light modulator*** field χ which controls decay of inflaton to matter.
  - Fluctuations in χ will perturb the reheating surface and produce curvature perturbations

$$\mathcal{R} \sim -\frac{\delta\Gamma}{6\Gamma} \sim -\frac{\delta\chi}{3\langle\chi\rangle}$$

  - VEV $\langle\chi\rangle$ determines amplitude of perturbations

$$\langle\chi\rangle \sim \frac{H_*}{\Delta_{\mathcal{R}}}$$

Reheating Products

- Lowest-order interactions for reheating:

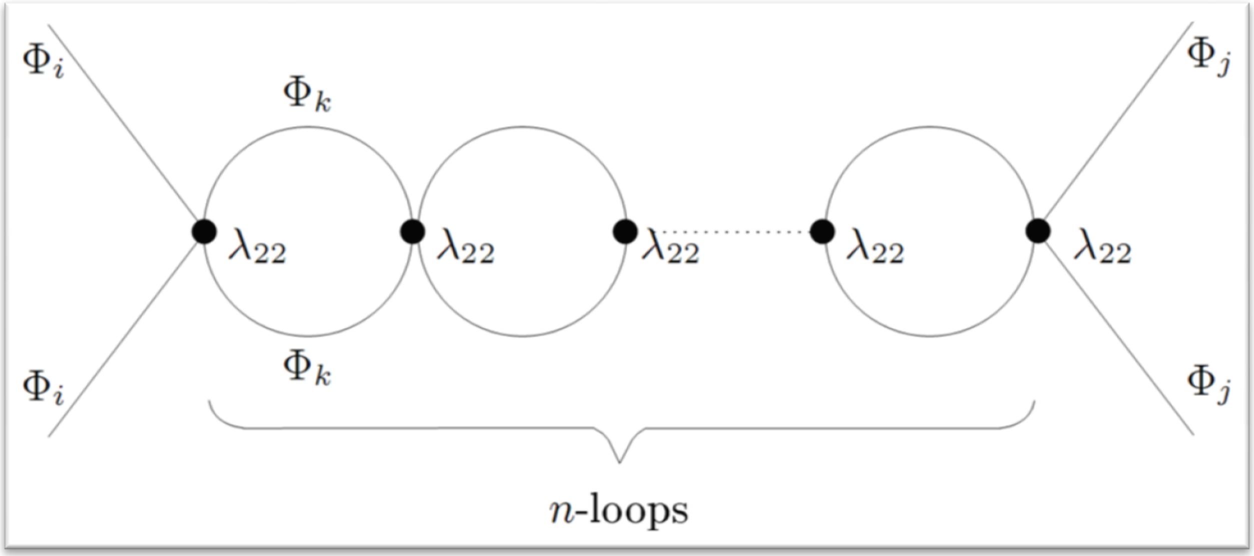
$$\frac{\Phi_i \chi}{M_*}\left(\underbrace{\boxed{g\bar{Q}_i Q_i}}_{\text{Baryons (Quarks)}} + \underbrace{\boxed{\tilde{g}\bar{Q}_j Q_j}}_{\text{Dark Matter (Quarks)}}\right)$$

- Only Φ_1 has non-zero VEV; all dark matter is produced through ***diagonal decays***

$$\frac{\rho_j}{\rho_1} = \frac{\Gamma_j}{\Gamma_1} = \frac{\tilde{g}^2}{g^2}$$

Perturbative Unitarity

- Cross-species couplings are constrained

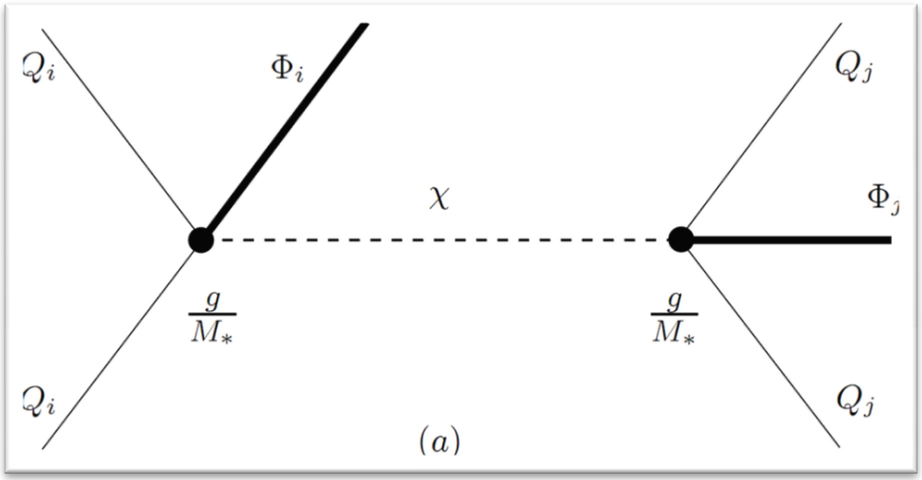


- Convergence requires that

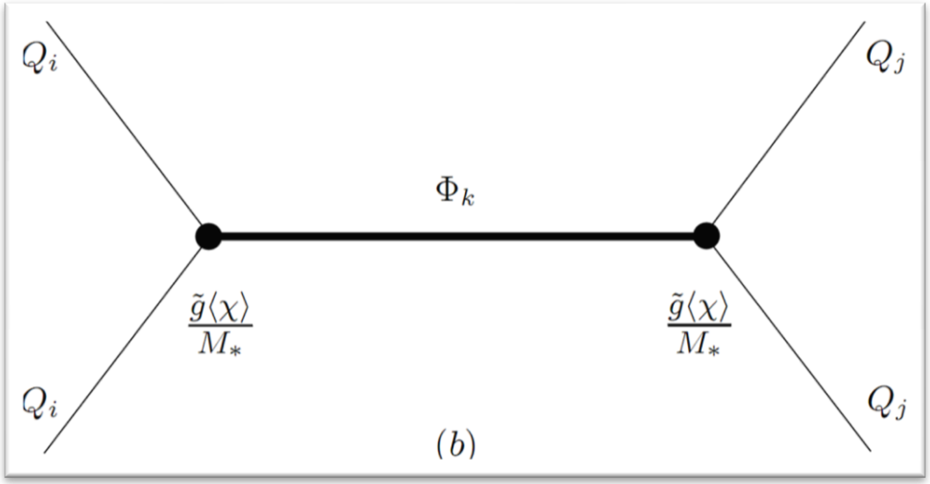
$$\lambda_{22} < N^{-1}$$

- Weak coupling between species for the same reason

Perturbative Unitarity (cont'd)



$$g < N^{-1/2}$$



$$\tilde{g} < \Delta_{\mathcal{R}} N^{-1} \left(\frac{M_*}{H_*}\right)$$

Dark-Matter Density

- Consistency forces a hierarchy in the couplings, giving a hierarchy in the densities

$$\frac{\rho_j}{\rho_1} = \frac{\tilde{g}^2}{g^2} = \left(\frac{M_*}{H_*}\right)^2 \Delta_{\mathcal{R}}^2 N^{-1}$$

- Following reheating, the total energy density in dark sector is tiny and ***independent of N***

$$\sum_{j \neq 1} \rho_j \sim 10^{-10} \rho_1$$

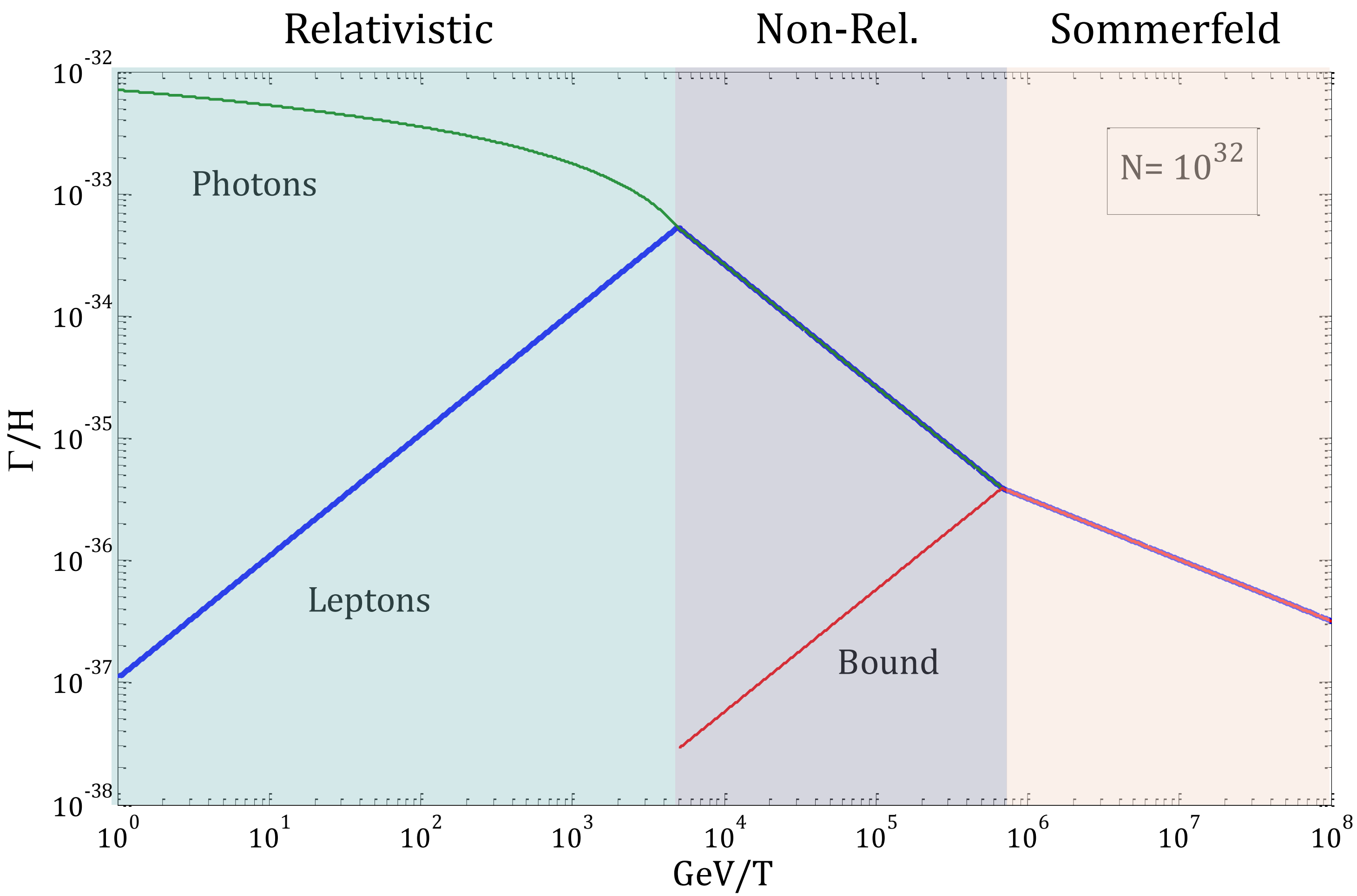
Freeze-Out

- ***Our sector*** dense: thermal history normal
- Require DM ***annihilation*** to remain frozen-out ***at all times***

$$1 \gg \frac{\Gamma_j^A}{H} \sim \frac{n_j \sigma v}{H}$$

- Achieve this by making n_j small
    - For large N, partial densities are so small that protons of the same species ***never meet***

Annihilation Freeze-Out



Final Abundance

- Immediately following reheating we had

$$\frac{\Omega_{\mathrm{DM}}}{\Omega_{\mathrm{b}}} = \frac{M_*^2}{\langle\chi\rangle^2} = \Delta_{\mathcal{R}}^2 \left(\frac{M_*}{H_*}\right)$$

- Allowing inflation to occur around the cut-off and accounting for annihilation

$$\frac{\Omega_{\mathrm{DM}}}{\Omega_{\mathrm{b}}} > \frac{\Delta_{\mathcal{R}}^2}{\eta_{\mathrm{b}}} = 4$$

Comment

- Only the freeze-out mechanism depends on a large number of species
  - It works if $N > 10^{11}$
- There is no need to keep all the copies identical
  - Generations are effectively such copies already
  - Maybe there are more generations, but just decoupled and stable?
- Is there some way of relating the baryon asymmetry to the amplitude of perturbations?