Dark QCD Matters

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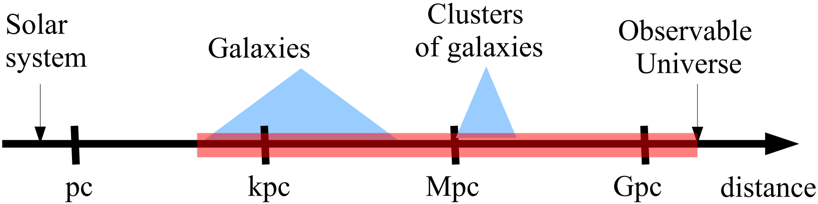
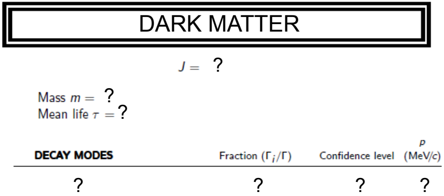
Based on
arXiv: 2105.03429
in collaboration with Michele Redi and Andrea Tesi

September 8, 2021

Evidences for Dark Matter



What do we know about Dark Matter ?



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Mass $m =$?
Mean life $\tau =$?

DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
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- No electric charge, no colour charge (Smith et al. '79, Perl et al. '01).
- Non-relativistic at the time of formation of the first structures (White, Frenk, Davis '83).
- Life time longer than the age of the Universe.

$\Longrightarrow$ Evidence for physics beyond the SM.

$\Longrightarrow$ Could be a nightmare scenario?

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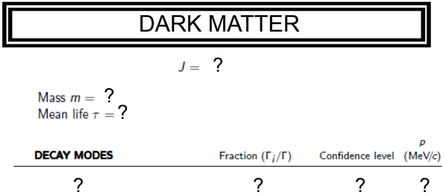

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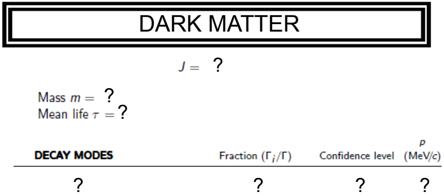

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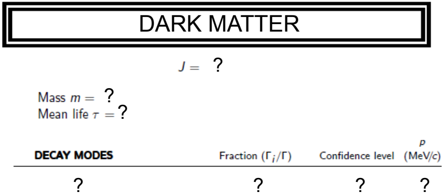

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Outline

- Introduction: Confining dark sectors and cosmological history
- Production of secluded dark sectors
    - Gravitational production
    - Inflationary production
- Phase transition and thermal history
    - Dark phase transition
    - Dark matter abundance
- Phenomenology
- Conclusions & Outlook

Introduction: Confining dark sectors and cosmological history

- Can dark matter (DM) be a baryon/pion of new confining dark sectors? $\Longrightarrow$ composite DM Bai, Hill '10 + Boddy et.al. '14 +Gresham, Lou, Zurek '17 + Bai, Long, Lu '18 + many more
- Cosmologically accidentally stable, like protons $\Longrightarrow$ dark baryon number Antipin et.al. '15 + Niel et.al. '16 + Mitradate et.al '17 + Contino et.al. '18 + Redi et.al '18
- Here we focus on

$$\int d^4x\,\sqrt{-g}\left[\mathcal{L}_{\rm SM}-\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu a}+\bar{\psi}_i\,(\not{D}-m_i)\,\psi_i+\sum\frac{\mathcal{O}_{\rm SM}\mathcal{O}_{\rm dark}}{M_{\rm Pl}^{\#}}\right].$$

with possibility of both dark-pion and -baryon DM!

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Introduction: Dark QCD Model

- Asymptotically free non-abelian theories, e.g. SO(N), Sp(N), SU(N). Here we consider SU(N) with N_F light flavours.
- Dark Baryons Antipin et.al '15: Similar to SM we choose $M_B \sim 10f$
  - for $N_F = 1$, baryons are spin $N/2$ antisymmetric combinations of N quarks.
  - For N_F even, baryons are spin 0 particles in the symmetric representation of the flavor group.
  - For N_F odd, baryons are spin 1/2 particles in the octet-like representation of flavor.
- Stability: Accidental dark-baryon number $\mathcal{Q}_i \to e^{i\alpha}\mathcal{Q}_i \implies B = \epsilon^{i_1\cdots i_n}\mathcal{Q}_{i_1}^{\{\alpha_1} \cdots \mathcal{Q}_{i_n}^{\alpha_n\}}$

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- Global chiral symmetry SU(N_F)× SU(N_F) → SU(N_F)

$$\mathcal{L}_\pi = \frac{f^2}{4}\mathrm{Tr}(\partial_\mu U)^2 + b\mathrm{Tr}[MU + h.c.] + \mathrm{WZW}, \qquad U = \exp[i\pi/f]$$

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- Stability: not absolute. Violated by

$$\frac{1}{\Lambda_5}\bar{\Psi}^i\gamma^5\Psi^j|H|^2 + \frac{1}{\Lambda_6^2}\bar{\Psi}^i\gamma^\mu\gamma^5\Psi^j\bar{f}\sigma^\mu f\,.$$

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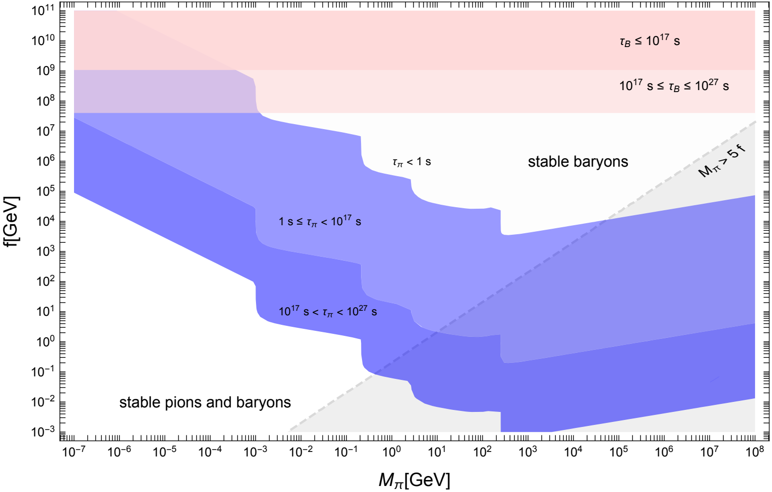
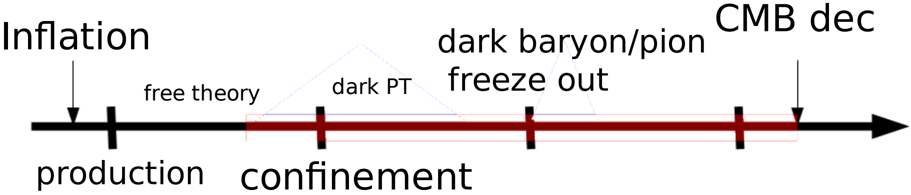


Dark QCD cosmology



Dark QCD cosmology

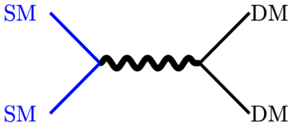
Production

Production Mechanisms

Our dQCD sector is completely secluded from SM. Only feeble interactions!

- From SM plasma: tree level gravitational production Garny et.al '16, '17 + Ema et.al. '18 + Tang et.al. '16 and from higher dimensional operators
- Inflationary production

Tree level gravitational production



$$\mathcal{A} = \frac{1}{M_p^2 s}\left(T^{\rm SM}_{\mu\nu} T^{\rm DM}_{\alpha\beta}\eta^{\mu\alpha}\eta^{\nu\beta} - \frac{1}{2}T^{\rm SM}T^{\rm DM}\right)$$

- At high energies well approximated by relativistic CFTs. Computed in terms of 2-point function of the stress energy tensorRedi, Tesi, Tillim '21
- yield is controlled by reheating temperature:

$$Y_{\rm D} = 6\times 10^{-6}\, c_D \left(\frac{T_R}{M_{\rm Pl}}\right)^3 .$$

and

$$f_D(T,p) \approx \frac{2\pi^4 g_*}{135}\, Y_D\, \frac{p\, e^{-p/T}}{T} ,$$

Planck suppressed operators

Can be more important than gravitational production depending on dimensionality

- phenomenologically relevant operators:

$$\frac{1}{\Lambda_{\mathrm{UV}}^{d-2}}|H|^2\mathcal{O}\,, \qquad\qquad [\mathcal{O}] = d\,,$$

- yield is controlled by reheating temperature and the effective scale:

$$Y_D = \int_0^{T_R} \frac{dT}{T}\frac{\langle\sigma v\rangle s}{H} Y_{\mathrm{eq}}^2 = a_{\mathcal{O}} \frac{135\sqrt{5/2}}{4(2d-5)g_*^{3/2}\pi^7}\left(\frac{T_R}{\Lambda_{\mathrm{UV}}}\right)^{2d-5}\frac{M_{\mathrm{Pl}}}{T_R}\,.$$

with

$$\langle\sigma v\rangle = \frac{1}{g_i^2}\frac{a_{\mathcal{O}}}{4\pi}\frac{T^{2d-6}}{\Lambda_{\mathrm{UV}}^{2d-4}}\,.$$

Phase transition

Phase Transition and Thermal History

Thermal history

After production the dark sector is in the deconfined phase, renormalizable interactions such as strong gauge interactions keep the dark sector in thermal equilibrium among themselves Arnold et.al. '02 and Kurkela et.al. '14

- conserving energy we find initial dark sector temperature

$$\xi^0 \equiv \frac{T_D}{T} = \left(\frac{g_* \rho_D}{g_D \rho_{SM}} \right)^{\frac{1}{4}} \quad ,$$

- graviton exchange

$$\xi^0_{gr} \approx 0.3 \left(\frac{T_R}{M_{\mathrm{Pl}}} \right)^{\frac{3}{4}} \quad .$$

- dimension 5 operator

$$\xi^0_{|H|^2} \approx 0.2 \left(\frac{a_{\bar{\Psi}\Psi}}{g_D} \frac{M_{\mathrm{Pl}} T_R}{\Lambda^2_{\mathrm{UV}}} \right)^{\frac{1}{4}} \sim 0.1 \left(\frac{T_R}{\Lambda_{\mathrm{UV}}} \right)^{\frac{1}{4}} \quad .$$

Dark phase transition I

- First order or cross over? depends on N and N_F
- pure gluonic theories: first order Paneoro '09 + Lucini et.al. '12 and Brambilla et.al. '14
- with light fermions: weakly first order for $3 \leq N_F \lesssim 4N$ for $N > 3$ Brambilla et.al. '14, which is expected to be adiabatic with the critical temperature $T_c \simeq \mathcal{O}(1)\, f$ Borsanyi '12

Dark phase transition II

- The system reorganizes in color neutral states. SM temperature when this happens is T_Λ
- In confined phase baryons and pions are the physical degrees of freedom. As pions are light $M_\pi < 5f$, they are relativistic at production.
- Baryons are heavy $M_B \sim 10f$. Both pions and baryons are in thermal eqbn with the dark plasma
- Ratio of temperatures $\xi \equiv T_D/T|_{T_\Lambda}$ right after the phase transition

$$\frac{\xi}{\xi_0} \approx \left(\frac{2(N^2-1)+4NN_F}{N_F^2-1}\right)^{\frac{1}{3}} .$$

(assuming cross-over and adiabatic)

Dark sector temperature evolution

- Temperature of i-th species

$$T_i \equiv \frac{P_i(T_i)}{n_i(T_i)} = \frac{g_i}{n_i(T_i)} \int \frac{d^3 p_i}{(2\pi)^3} \frac{p_i^2}{3E_i} f_i(T_i)\,.$$

- Solve Boltzmann equations for the 2nd-moment Bai et.al. '19 + Mondino et.al. '20

$$n\frac{\dot{T}_D}{T_D} + nHT_D + \sum_i n_i(\delta_i - 1)HT_D \approx -(\dot{n} + 3Hn)\,.$$

- Analytical solution in limiting cases:

$$T_D(T) = \begin{cases} \left(\frac{g_*^s(T)}{g_*^s(T_\Lambda)}\right)^{\frac{1}{3}} \xi\, T, & T_D > M_\pi \quad \text{equivalent to } T_\Lambda \geq T > M_\pi/\xi \\ \left(\frac{g_*^s(T)}{g_*^s(T_\Lambda)}\right)^{\frac{2}{3}} \xi^2 \frac{T^2}{M_\pi}, & T_D < M_\pi \quad \text{equivalent to } T < M_\pi/\xi \end{cases}$$

Dark matter from dQCD

We identify four regimes

- Light pion DM
- Baryon DM
- Non-relativistic pions decoupled: B B $\rightarrow n\,\pi$
- Non-relativistic pions in equilibrium: cannibalism

Dark matter from dQCD: dark-pion DM

- Abundance of dark pions is mainly set by the phase transition. If in eqbn

$$Y_\pi = (N_F^2 - 1)\frac{45\zeta(3)}{2\pi^4 g_*}\xi^3 .$$

- For $M_\pi < \mathcal{O}(100)$ GeV, relic density today is

$$\frac{\Omega h^2}{0.12} \approx 0.6(N_F^2 - 1)\frac{M_\pi}{0.1\mathrm{GeV}}\left(\frac{\xi}{10^{-2}}\right)^3\left(\frac{106.75}{g_*}\right)$$

$$\to \quad M_\pi^{\mathrm{DM}} \approx \frac{0.14\,\mathrm{keV}}{N_F^2\xi^3}\left(\frac{g_*}{106.75}\right) .$$

Dark matter from dQCD: dark-baryon DM I

- Abundance of baryon is set by annihilation into multi-pion final states. Need to solve

$$\frac{dY_B}{dT_D} = \frac{\langle \sigma v \rangle s(T)}{H(T)\, T_D} \left[Y_B^2 - (Y_B^{\mathrm{eq}}(T_D))^2 \right] ,$$

and corresponding abundance in the light pion mass regime is

$$\frac{\Omega_B h^2}{0.12} \approx \xi \left(\frac{g_* + g_D \xi^4}{106.75} \right)^{1/2} \left(\frac{M_B}{100\,\mathrm{TeV}} \right)^2$$

$$\rightarrow \quad M_B^{\mathrm{DM}} \approx \frac{100\,\mathrm{TeV}}{\sqrt{\xi}} \left(\frac{106.75}{g_* + g_D \xi^4} \right)^{\frac{1}{4}} .$$

Dark matter from dQCD: dark-baryon DM II

- In the heavy pion regime, pions can decay via mixing with higgs for $d = 5$ scenario. Leads to early matter dominated era. Need to account for entropy dilution

$$\eta = \frac{s}{s_\Gamma} \approx \min\left[1,\ 0.8\frac{(T_\Gamma/M_\pi)^{3/4}}{Y_\pi^{3/4}}\right] \approx \min\left[1,\ \frac{1.3}{g_*^{1/4}}\left(\frac{M_{\rm Pl}^2\Gamma_\pi^2}{M_\pi^4}\right)^{1/4}\frac{1}{Y_\pi}\right].$$

resulting in baryon abundance:

$$M_B^{\rm DM} \approx \frac{100\,{\rm TeV}}{\sqrt{\xi}}\left(\frac{106.75}{g_* + g_D\xi^4}\right)^{\frac{1}{4}} \max\left[1,\ \ 10N_F\xi\left(\frac{g_* + g_D\xi^4}{106.75}\right)^{\frac{1}{8}}\left(\frac{M_\pi}{10^4\,{\rm GeV}}\right)^{3/8}\right]$$

Dark matter from dQCD: non-rel pion regimes

- Solve

$$\dot{n}_B + 3Hn_B \approx -\langle \sigma v \rangle_{n,\mathrm{max}} \left[n_B^2 - \left(\frac{n_\pi}{n_\pi^{\mathrm{eq}}(T_D)} \right)^n (n_B^{\mathrm{eq}}(T_D))^2 \right] .$$

SM nuclear physics data Amsler et.al. '97 suggests that the dominant channel is the one dominated by the largest number of pions allowed kinematically, i.e. $Q_{n,\mathrm{max}} = 2M_B - nM_\pi \to 0$.

Abundance now

$$\frac{\Omega_B^{(n,\mathrm{max})}}{\Omega_B} \approx 0.1 \frac{M_B}{\sqrt{m_\pi Q_{n,\mathrm{max}}}} \frac{\langle \sigma v \rangle}{\langle \sigma v \rangle_{n,\mathrm{max}}} .$$

$Q_{n,\mathrm{max}}/T_D|_{f.o.} \approx 2\log(\langle \sigma v \rangle_{n,\mathrm{max}} M_\pi M_{\mathrm{Pl}} \xi^2) \implies$ no substantial deviation from the previous case!

Phenomenology

Sector completely secluded!

- No direct/indirect/collider detection constraints $\Longrightarrow$ nightmare scenario
- Possible constraints from cosmology: Bullet cluster, structure formation and CMB !
- Pheno governed by only 3 parameters

$$f\,, \quad M_\pi\,, \quad \xi$$

  with dark pion decay constant f and $M_B \sim 10\, f$
- Bonus: possible stochastic gravitational wave signals

Phenomenology: constraints

- Bullet cluster: limit on DM self-interaction Spergel et.al. '99 $\sigma_{\rm el}^{DM}/M_{DM} < {\rm cm}^2/{\rm g}$.
  Easily evaded for dark baryons as $\sigma_{\rm el}^{B} \approx \frac{4\pi}{M_B^2}$

  Constrains pions Hochberg et.al. '14:

$$\sigma_{\rm el}^{\pi} \simeq \frac{1}{64\,\pi} \frac{(3N_F^4 - 2N_F^2 + 6)}{N_F^2(N_F^2-1)} \frac{M_\pi^2}{f^4} \quad \overset{N_F \to 3}{=} \quad \frac{77}{1536\,\pi} \frac{M_\pi^2}{f^4}\,.$$

- CMB: If pion mass is vanishingly small $\implies$ dark radiation

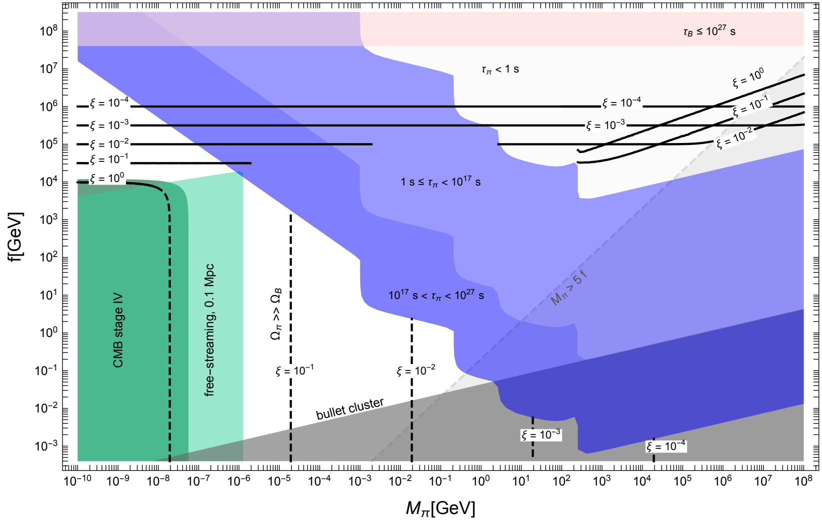
$$\Delta N_{\rm eff}\big|_{\rm CMB} = \frac{4}{7}\left(\frac{g_\nu}{g_{\rm eff}}\right)^{4/3}(N_F^2-1)\xi^4 = 0.027(N_F^2-1)\xi^4\,,$$

  exclusion obtained by taking $\Delta N_{\rm eff} \lesssim 0.25$ Fields et.al. '19

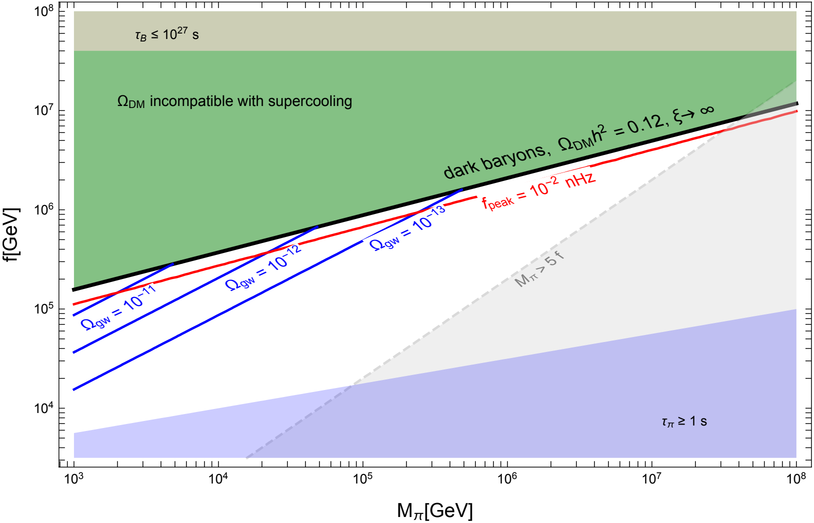
- Structure formation:

$$\lambda_{\rm FS}\big|_{\Omega_{\rm DM}} \approx 5.2\,{\rm Mpc}\,\xi^4 \left(\frac{N_F^2-1}{8}\right)\left(\frac{106.75}{g_*^s(T_\Lambda)}\right)^{\frac{1}{3}}\,.$$

Phenomenology: Results



Phenomenology: Gravitaional waves



Conclusions and Outlook

- New confining gauge theories $\implies$ accidental stable DM, if the dark sector is neutral under SM.
- In dark SU(N) theories with light fermions both the lightest pion and baryon are DM candidates. Dark baryons typically heavy $\sim$ 100 TeV and dark pion are light $\sim$ keV.
- Constraints on light pion scenario from cosmology. Dark sectors as hot or hotter than the SM plasma is excluded!
- Work in progress: refine structure formation bounds for light pions using boltzmann solver CLASS. Includes time dependent dark sector background distributions and self interactions.

Thank You !

Gravitational Waves

- If phase transistion super-cooled, maximal GW signals
- Max. amplitude

$$\Omega_{\rm gw}^{\pi-{\rm decay}} = \Omega_\gamma \frac{\rho_{\rm gw}}{\rho_\pi^*} \left(\frac{a_{\rm NR}}{a_*}\right)^{\frac{4}{3}} \left(\frac{3M_{\rm Pl}^2\Gamma_\pi^2}{\rho_\pi^*}\right)^{\frac{1}{3}} \left(\frac{g_*^s(T_0)}{g_*^s(T_{R,\pi})}\right)^{\frac{4}{3}} \frac{g_*(T_{R,\pi})}{g_*(T_0)}$$

- Peak frequency:

$$f_{\rm peak} = 3.8\times 10^{-6}\,{\rm Hz}\,\frac{f_*}{H_*}\left(\frac{g_*(T_{R,\pi})}{106.75}\right)^{\frac{1}{6}}\left(\frac{T_{R,\pi}}{100{\rm GeV}}\right)\times\left(\frac{a_{\rm NR}}{a_*}\right)^{\frac{1}{3}}\left(\frac{3M_{\rm Pl}^2\Gamma_\pi^2}{\rho_\pi^*}\right)^{\frac{1}{6}}.$$

with $T_{R,\pi} = 1.7\sqrt{\Gamma_\pi M_{\rm Pl}}/g_*(T_{R,\pi})^{1/4}$