Cosmological Constraints on Ensembles of Unstable Particles

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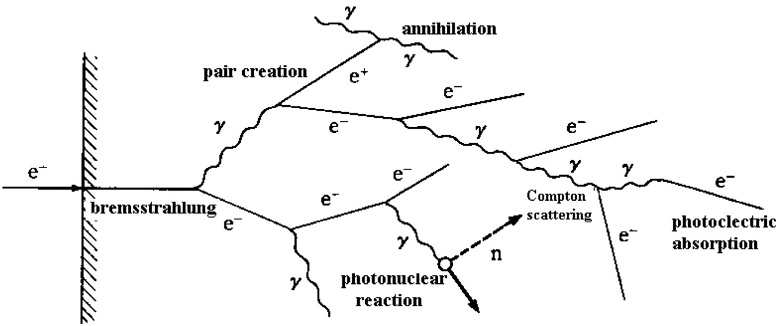
1709.maybe with Keith Dienes, Jason Kumar and Brooks Thomas

Electromagnetic processes in the early universe



Cascade processes

$\gamma\gamma_{BG} \to e^+e^-$
$e^\pm\gamma_{BG} \to e^\pm\gamma$
$\gamma\gamma_{BG} \to \gamma\gamma$

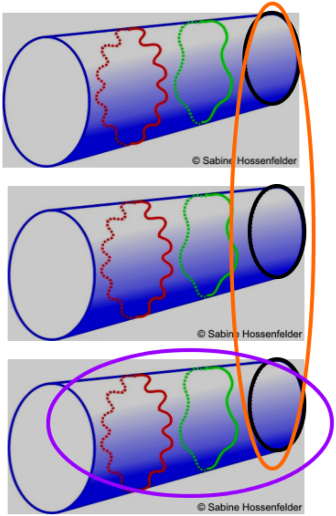
Thermalization

$\gamma N \to e^+e^- N$
$e^\pm N^\pm \to e^\pm N^\pm \gamma$
$\gamma e^\pm_{BG} \to (\gamma)\gamma e^\pm$

Injected EM particles

- ruin BBN before thermalizing
- distort CMB blackbody

Extra dimensions predict an ensmeble of decaying fields



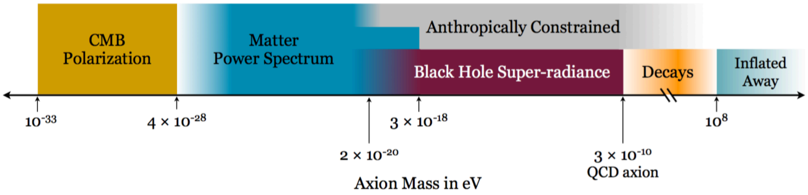
Compactification produces moduli

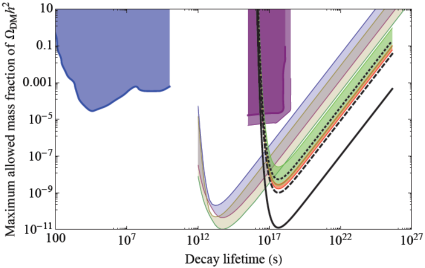
- Axion-like particles generic in string theory
- Possibly many light zero modes
- Expect logarithmic mass distribution

Higher modes can also be light

- Bulk axions yield KK tower of states
- Entire spectrum can interact with SM
- More masssive fields generally decay earlier

String axiverse can contain light fields coupling to $E \cdot B$

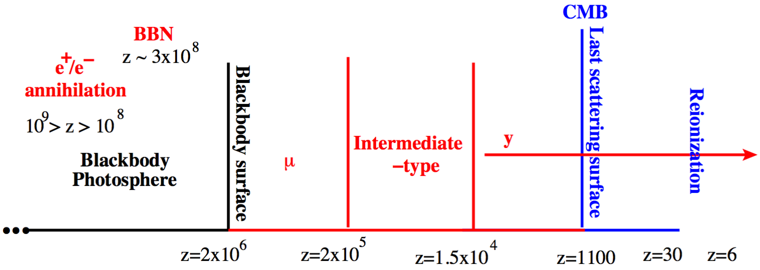




Use analytic approximations

- Estimate single component constraints from μ and y_c
- Extend to decaying ensemble
- Apply to "axiverse" example, Arvanitaki et. al. 0905.4720

Thermalization freezes out ⇒ heating alters blackbody



Photon occupation number

$$n_x = \frac{1}{e^{x+\mu(x)}-1} + \Delta n_x^y$$

$$n_x \simeq n_x^{pl} + \Delta n_x^\mu + \Delta n_x^y,$$

Distortion type depends on injection time

$$\Delta n_x^y = y\frac{xe^x}{(e^x-1)^2}\left[x\coth\left(\frac{x}{2}\right) - 4\right]$$

$$\Delta n_x^\mu \simeq \mu\frac{e^x}{(e^x-1)^2}\left[\frac{x}{2.19} - 1\right], \text{ for } \mu \ll 1$$

Electromagnetic injection heats e^-_{BG}, which then heat γ_{BG}

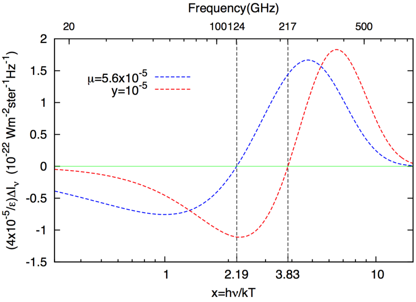


Figure: $\Delta I_\nu = I_\nu^{\mu,y} - I_\nu^{pl} \propto x^3 \Delta n$, see Khatri and Sunyaev 1207.6654.

Compton scattering maintains kinetic equilibrium as DC and BR freeze out

$$\frac{d\mu}{dt} = \frac{d\mu_{inj}}{dt} - \mu(\Gamma_{DC} + \Gamma_{BR})$$

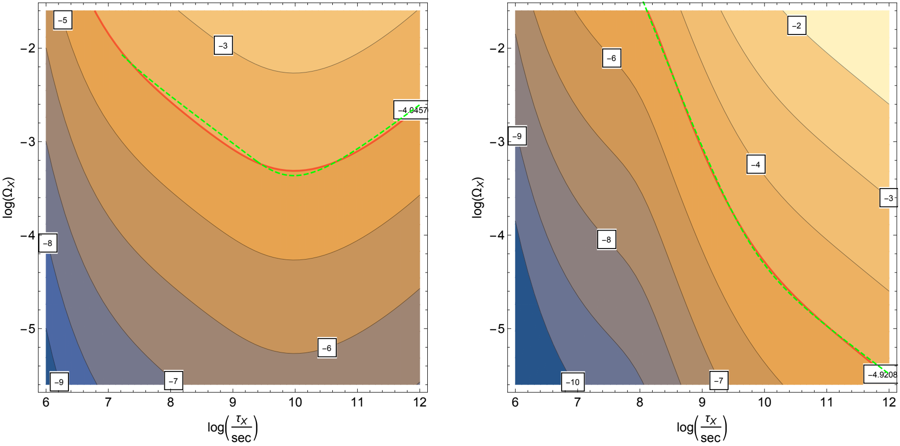
y_c-type distortion after Compton scattering becomes inefficient

$$\frac{dy_c}{dt} \sim \frac{1}{\rho_\gamma}\Gamma_0 \rho_0 \sim \frac{d\mu_{inj}}{dt}$$

Assuming $\mu, y_c \ll 1$ and $x_{inj} \gg 1$

Analytic approximations are valid and uniform decay is accurate

Use Greens functions to calculate $\mu \lesssim 10^{-4}$, $y_c \lesssim 10^{-5}$



Need subdominant μ, y_c regions for multipe decays

μ from uniform decay

$$\delta\mu\left(\tau \lesssim t_{EC}\right) \sim \Omega\tau^{1/2} e^{-(t_0/\tau)^{5/4}}$$

Add intermediate and late regions, take $t_{EC} \to t_B$ and fit seperately

$$\delta\mu\left(t_B \lesssim \tau \lesssim t_{MRE}\right) \sim \Omega\tau^{1/2}$$
$$\delta\mu\left(t_{MRE} \lesssim \tau \lesssim t_{LS}\right) \sim \Omega\tau^{2/3}$$

Multiply correction for $\tau \gtrsim t_B$

$$\left(1 - \exp\left[-\left(t_{1,2}/\tau\right)^{\alpha_{1,2}}\right]\right)$$

y_c from uniform decay

$$\delta y_c\left(t_{EC} \lesssim \tau \lesssim t_{MRE}\right) \sim \Omega\tau^{1/2}$$
$$\delta y_c\left(t_{MRE} \lesssim \tau \lesssim t_{LS}\right) \sim \Omega\tau^{2/3}$$

Add early region, take $t_{EC} \to t_B$

$$\delta y_c\left(\tau \lesssim t_B\right) \sim \Omega\tau^{1/2} e^{-(t_0/\tau)^{5/4}}$$

Multiply correction for $\tau \gtrsim t_B$

$$\left(1 + \left(t_{1,2}/\tau\right)^{\alpha_{1,2}}\right)^{-1}$$

Intermediate Greens functions suggested in Chluba 1304.6120

Analytic contstraints on multiple decaying particles

$$
\begin{aligned}
D_\mu &> \sum_{t_e<\tau_i<t_{B\mu}} A_\mu \Omega_i (\tau_i/t_{0\mu})^{1/2} \exp\left[-\left(t_{0\mu}/\tau_i\right)^{5/4}\right] \\
&+ \sum_{t_{B\mu}<\tau_j<t_{MRE}} B_\mu \Omega_j (\tau_j/t_{1\mu})^{1/2} \left(1-\exp\left[-\left(t_{1\mu}/\tau_j\right)^{\alpha_{1\mu}}\right]\right) \\
&+ \sum_{t_{MRE}<\tau_k<t_{LS}} C_\mu \Omega_k (\tau_k/t_{2\mu})^{2/3} \left(1-\exp\left[-\left(t_{2\mu}/\tau_k\right)^{\alpha_{2\mu}}\right]\right), \\
D_y &> \sum_{t_e<\tau_i<t_{By}} A_y \Omega_i (\tau_i/t_{0y})^{1/2} \exp\left[-\left(t_{0y}/\tau_i\right)^{5/4}\right] \\
&+ \sum_{t_{By}<\tau_j<t_{MRE}} B_y \Omega_j (\tau_j/t_{1y})^{1/2} \left(1+\left(t_{1y}/\tau_j\right)^{\alpha_{1y}}\right)^{-1} \\
&+ \sum_{t_{MRE}<\tau_k<t_{LS}} C_y \Omega_k (\tau_k/t_{2y})^{2/3} \left(1+\left(t_{2y}/\tau_k\right)^{\alpha_{2y}}\right)^{-1}
\end{aligned}
$$

Can reporoduce single component limits with analytic fits

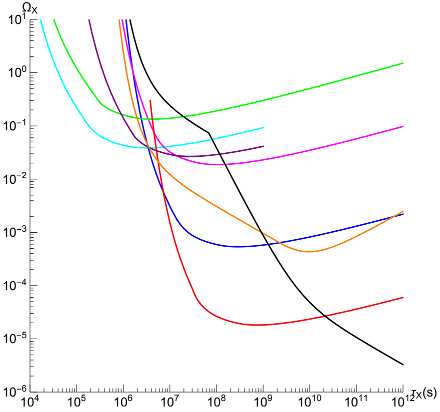


Figure: Limits on EM injection from μ-type distortion and **y-type distortion**.

Consider log mass spacing, thermally produced ensemble

$$m_i = m_0 \left(\frac{\Delta m}{\mathrm{GeV}}\right)^i \quad \Omega_i = \frac{f_{EM}}{C_X}\Omega_{DM}\sigma_{DM} m_i^2 \quad \Gamma_i = \frac{m_i^3}{\Lambda^2}$$

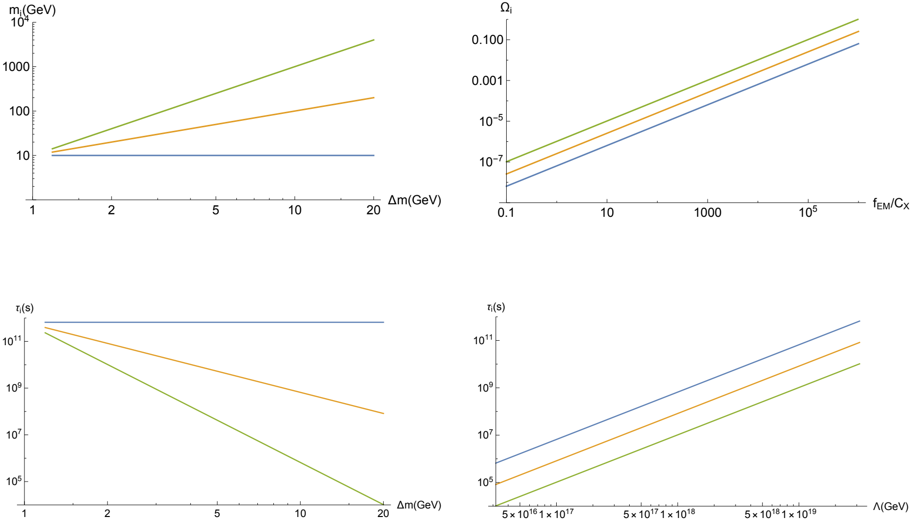
Freeze out with universal C_X

- Self annihilation cross section $\sigma_i \sim C_X/m_i^2$
- Normalized to current relic abundance $\Omega_{DM} \simeq 0.25$, with $\sigma_{DM} \simeq 1\,\mathrm{pb}$
- f_{EM} is branching fraction to EM particles

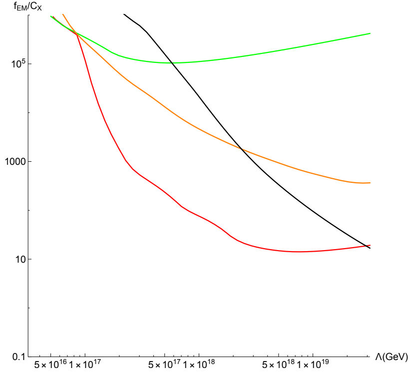
Decays $\to \gamma\gamma$, universal coupling

- Assume width $\sim m_i^3$, dimensionally need Λ^{-2}
- For simplicity, assume $m_0 = 10\,\mathrm{GeV}$, but constraints valid so long as $m_0 \gg T_{therm}$
- For ensemble of n particles, $\{\Delta m, f_{EM}/C_X, \Lambda\}$

What does an ensemble with $n = 3$ look like?



Set limits on f_{EM}/C_X as functions of Λ and Δm



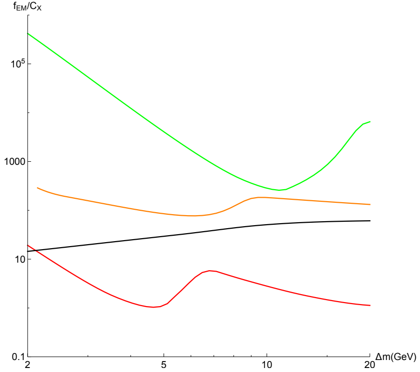


Figure: Λ with $\Delta m = 2\,\mathrm{GeV}$ constant and Δm with $\Lambda = 3 \times 10^{19}\,\mathrm{GeV}$ constant.

Now try for $n = 9$ packed into same mass range

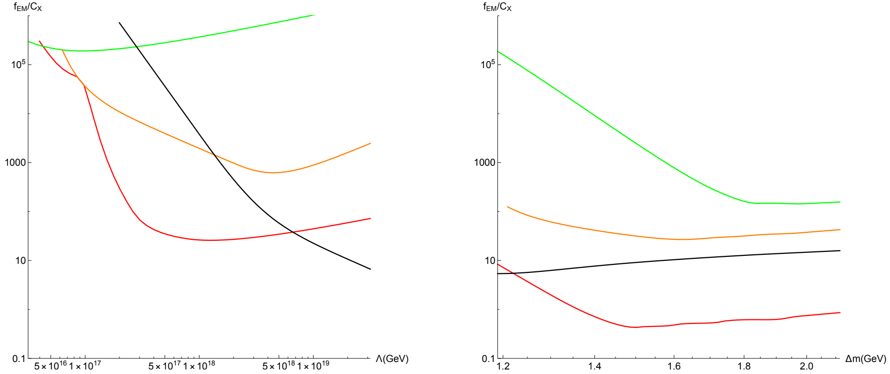


Figure: Λ with $\Delta m = 2^{1/4}\,\mathrm{GeV}$ constant and Δm with $\Lambda = 3 \times 10^{19}\,\mathrm{GeV}$ constant.

Can look at light elements and/or DDM in more detail

Dedicated light element code

- Uniform decay can map onto arbitrary injection history
- Include hadronic decays
- Make code publicly available

Look at DDM ensembles

- Indirect detection and CMB ionization become dominant
- Highly depedent on decay channels
- Use direct detection and this work to constrain DDM

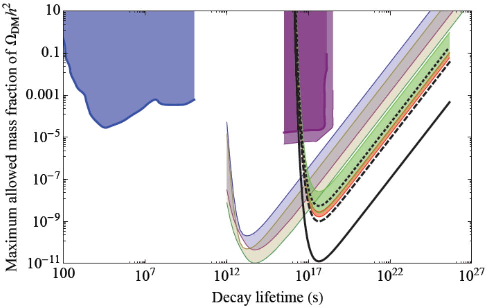
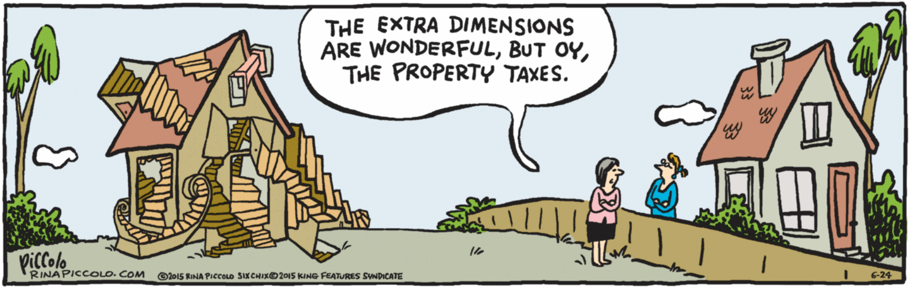


Figure: Limits on abundances of EM decaying particles, see Slatyer 1211.0283.

Thank you!


THE EXTRA DIMENSIONS ARE WONDERFUL, BUT OY, THE PROPERTY TAXES.
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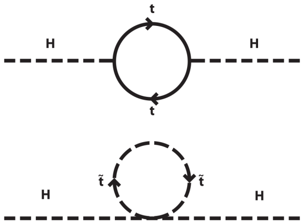
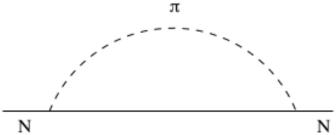
Interaction rates suppressed by new physics at high scales



$$\mathcal{L}_{QCD} \in \frac{\theta}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu a}$$



Gravity mediated SUSY breaking

- Stable neutralino LSP is WIMP dark matter candidate
- Weak scale gravitino NLSP
- Decays through $\tilde{G} \to \tilde{\chi}\gamma$

Break PQ symmetry to cancel θ

- Axion field left over from solving strong CP problem
- Can take almost any mass
- Decays through $a \to \gamma\gamma$

Decays before matter domination underconstrained

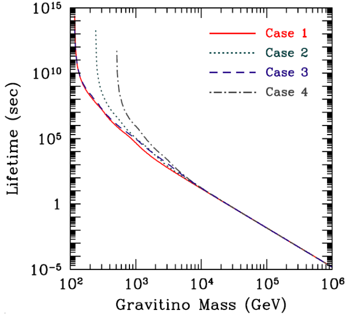


Figure: Gravitino lifetimes for several canonical mSUGRA cases, see Kawasaki et. al. 0804.3745.

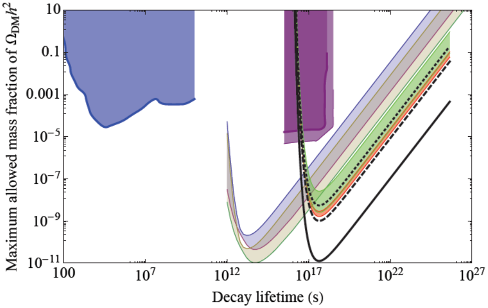


Figure: Limits on abundances of EM decaying particles, see Slatyer 1211.0283.

Multicomponent ensemble that balances Γ_X and Ω_X