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Pure Glue Dark Sector Cosmology

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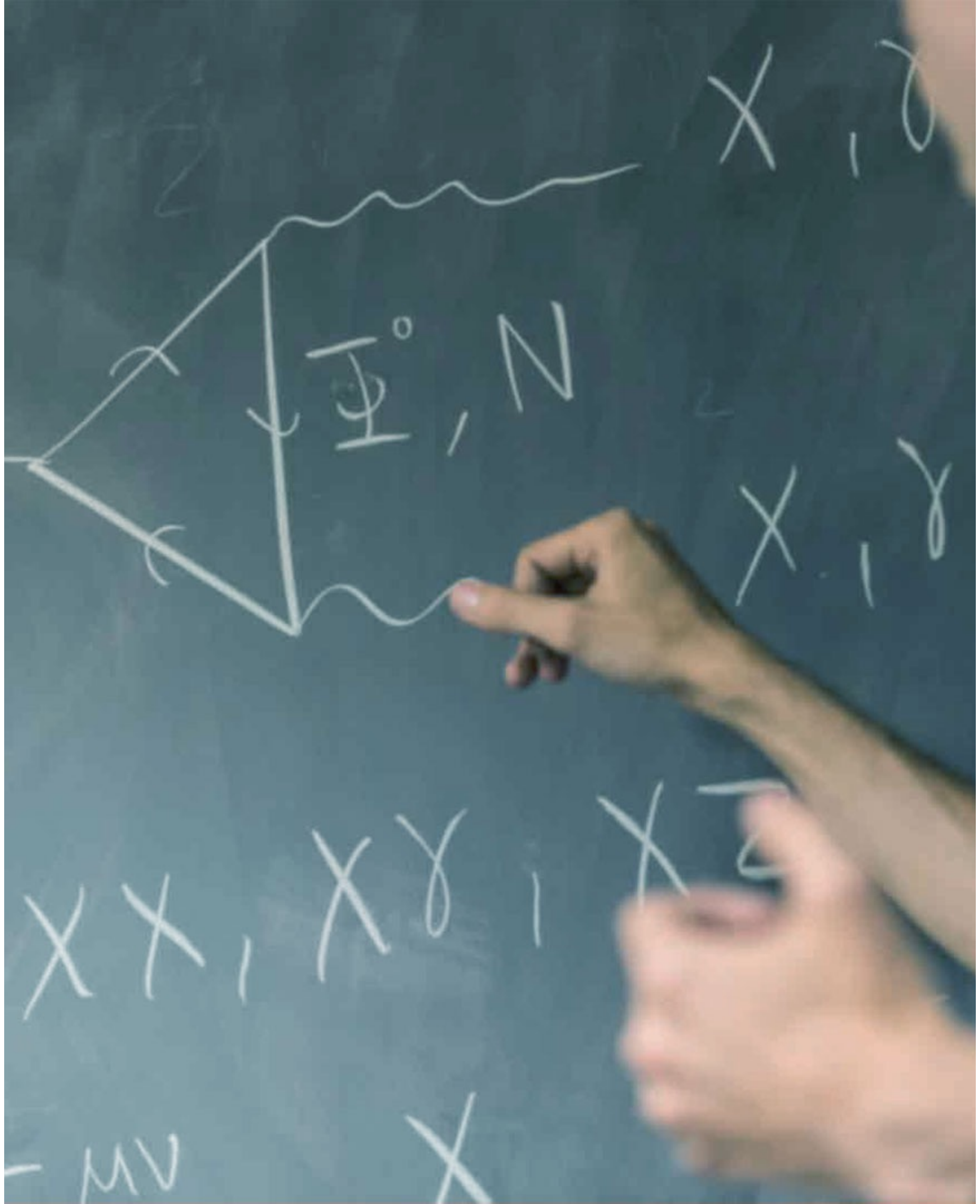
Working with D. McKeen, D. Morrissey, M. Shamma

arXiv: 2405.xxxxx (soon!)

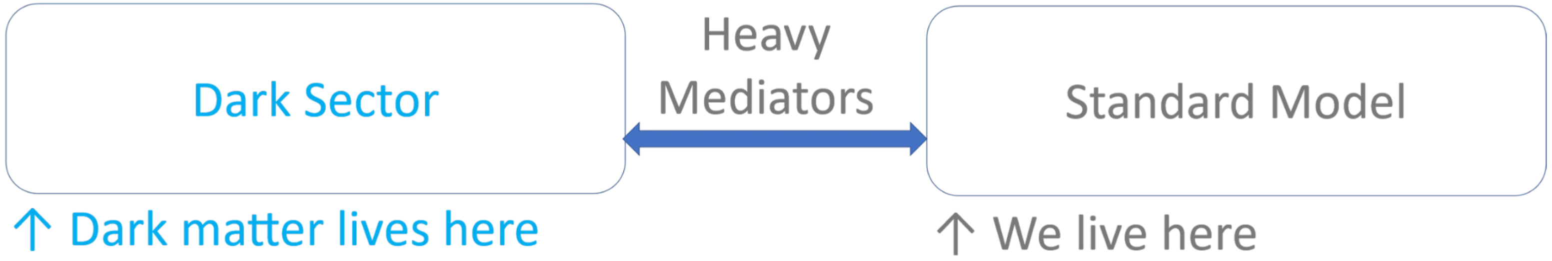
@Pheno 2024 on May 14, 2024



Discovery, accelerated

Motivation

- What if dark matter comes from a new set of interactions and particle species? → dark sector



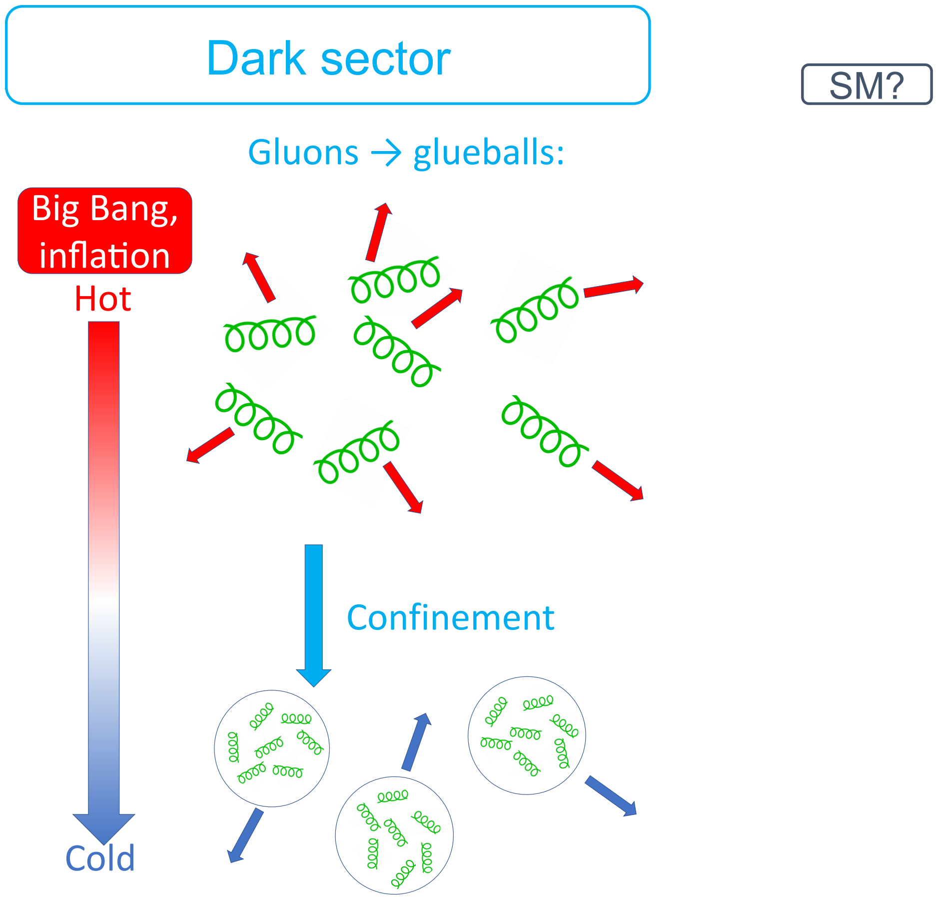
- E&M analogy: dark photons
  - Phenomenologically explored and searched

Pure Yang-Mills theory *SU*(*N*) with dark reheating

<u>DS content:</u>

$$\mathscr{L}_x = -\frac{1}{4} X^a_{\mu\nu} X^{a\,\mu\nu}$$

- Consists of dark gluons, but *no* light flavours
- Dark gluons get confined to "glueballs" at some dark confinement scale
- Considered as viable DM candidates (Boddy+ '15, Soni & Chang '16, Yamanaka+ '14, Forestell+ '17 & '18,…)



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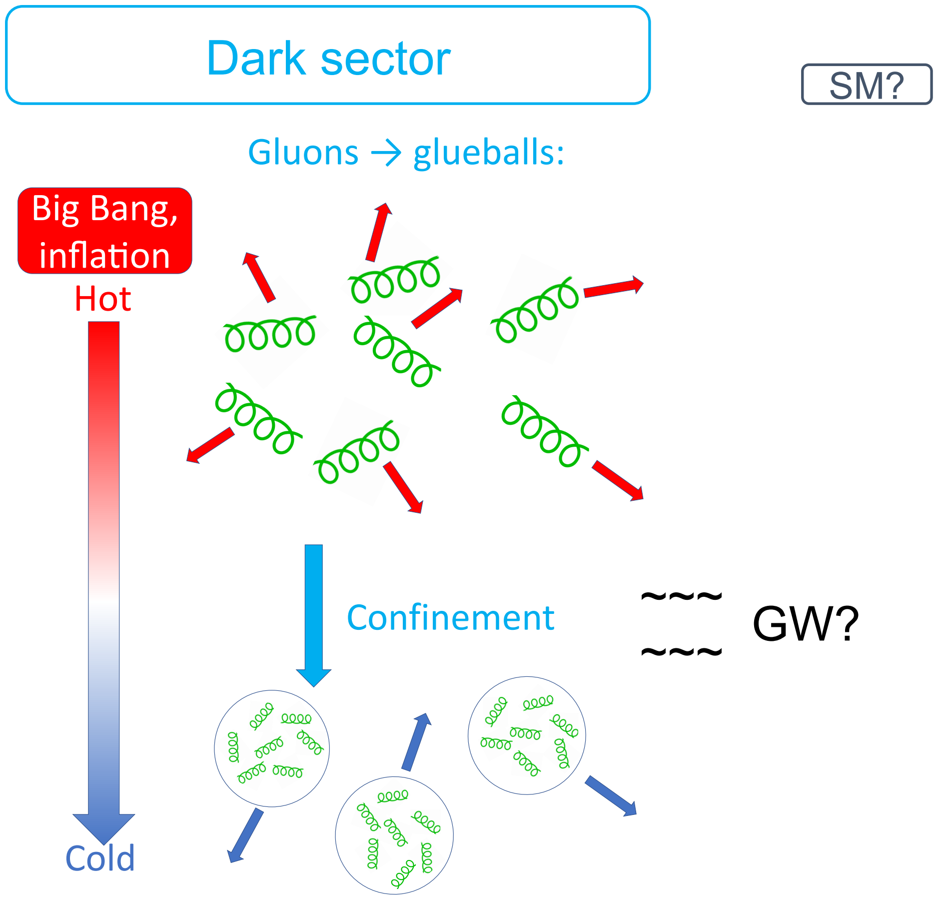
Dark reheating:

- We consider a scenario where **DS is dominantly reheated** after inflation
- Motivated from gravitational wave signals (Halverson+ '21, Huang+ '21, Kang & Chu '24, …)



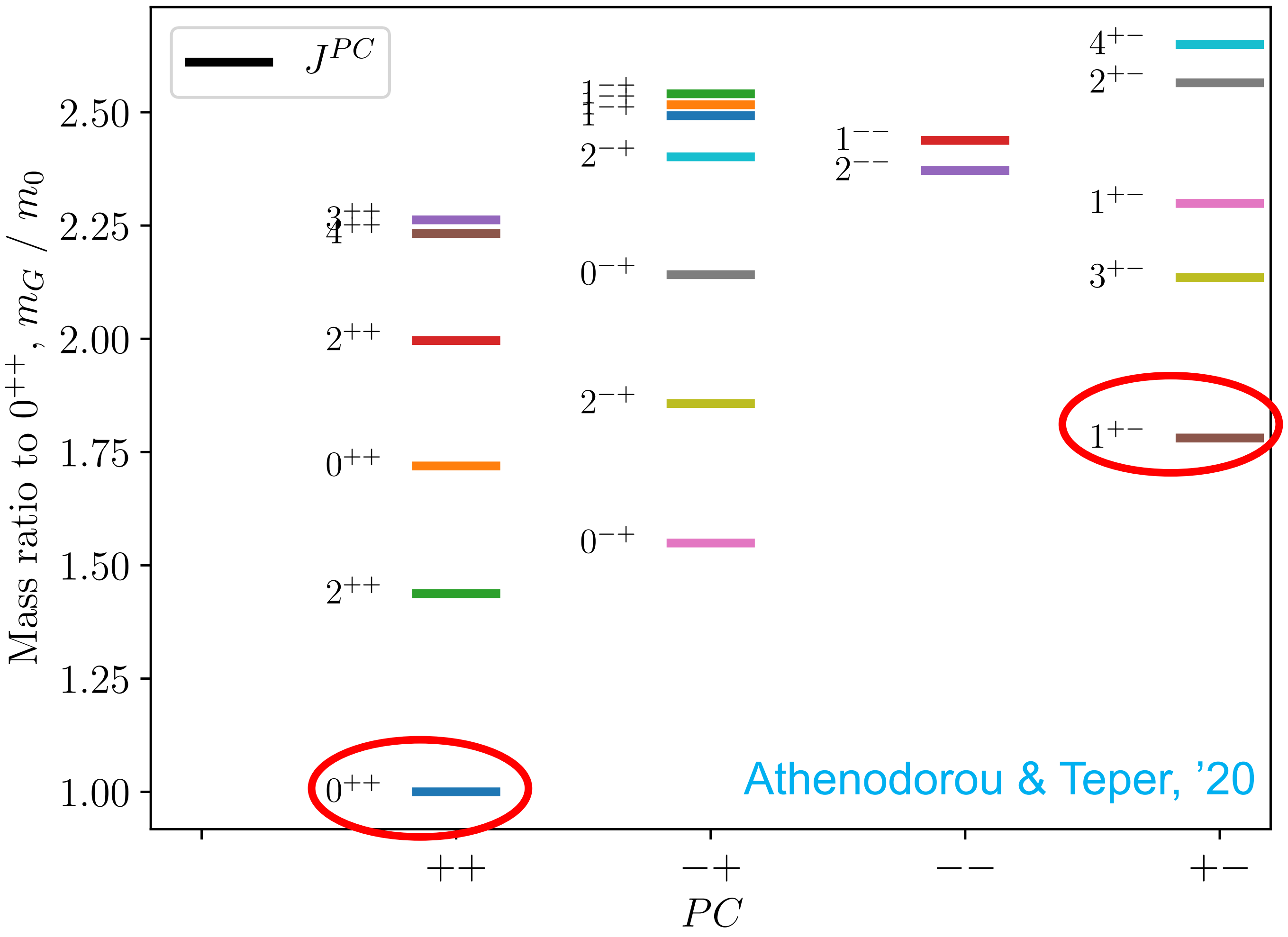
Dark glueball spectrum

We draw on Lattice QCD calculations:

- Glueballs are classified by J^{PC}
- The output is the mass ratio
  - m_0 as the free parameter
- $SU(N > 3)$ has a similar mass spectrum!

States of interest: 0^{++} and 1^{+-}

$N = 3$:



Evolution of DS alone

0^{++} freezes-out first

- forms a massive bath

  $0^{++} + 0^{++} + 0^{++} \to 0^{++} + 0^{++}$

1^{+-} freezes-out next

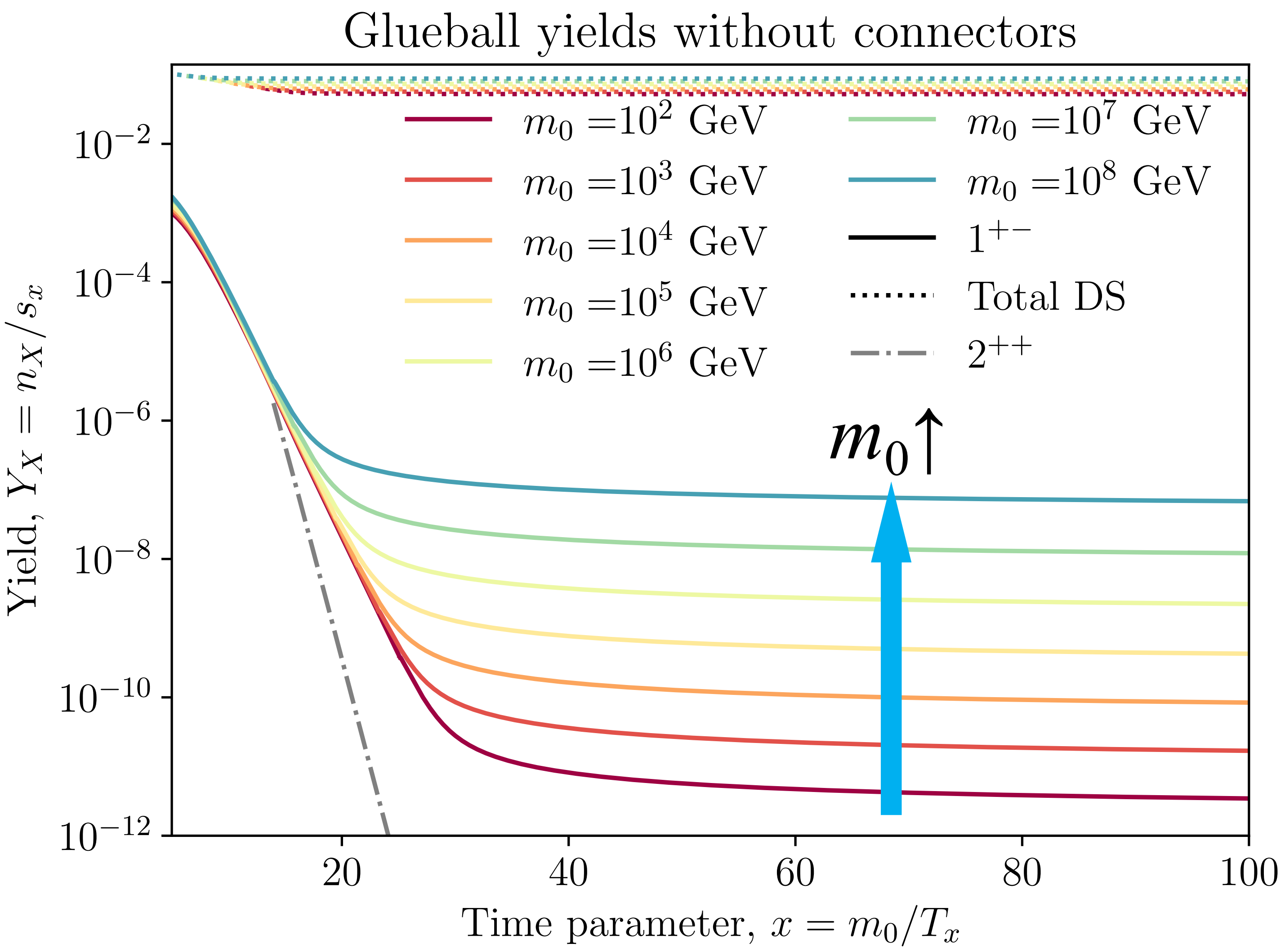
- Abundance comparable to DM

  $1^{+-} + 1^{+-} \to 0^{++} + 0^{++}$

Other states stay in thermal equilibrium with 0^{++}

- Abundance is negligible

  Ex: $2^{++} + 0^{++} \rightleftarrows 0^{++} + 0^{++}$



Connectors

- To recover standard cosmology, we need to introduce connectors:

- We consider EFT operators with heavy mediator mass scale M:

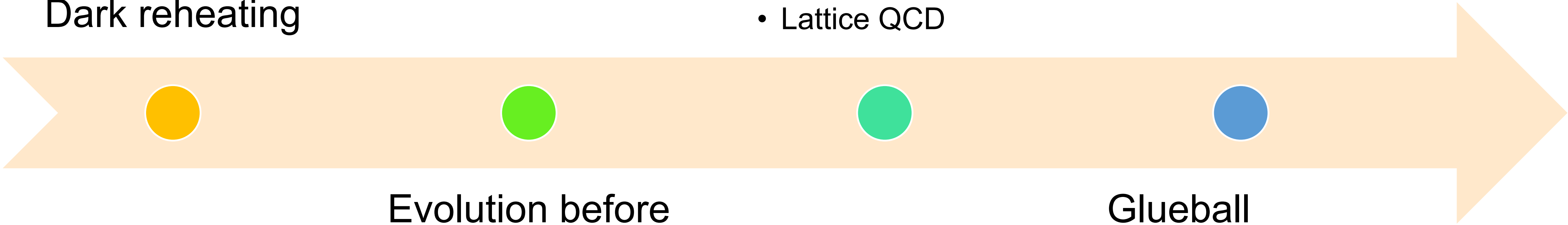
$$-\mathscr{L}_{tr} = \frac{\kappa_6}{M^2}|H|^2 X^a_{\mu\nu} X^{a\mu\nu} + \frac{\kappa_8}{M^4} B_{\mu\nu} tr(XXX)^{\mu\nu} + \ldots$$

Cosmological timelines

Dark reheating

Confinement

- Equation of State
- Lattice QCD



Evolution before confinement

Glueball evolution and decays

- in presence of SM

Forestell+ ’18

Borsanyi+ ’12
Caselle+ ’18
Trotti+ ’23

Juknevich+ 10

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- Equation of State
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D-6 operator

- Dark charge (C_x)-even
- Induces decays to most glueballs, including 0^{++} bath
- Populates SM
- **Cannot decay 1^{+-}!**
  - 1^{+-} : lightest C_x -odd

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D-8 operator

- Leading C_x-odd term if C_x is broken
- Induces decays to 1^{+-}:

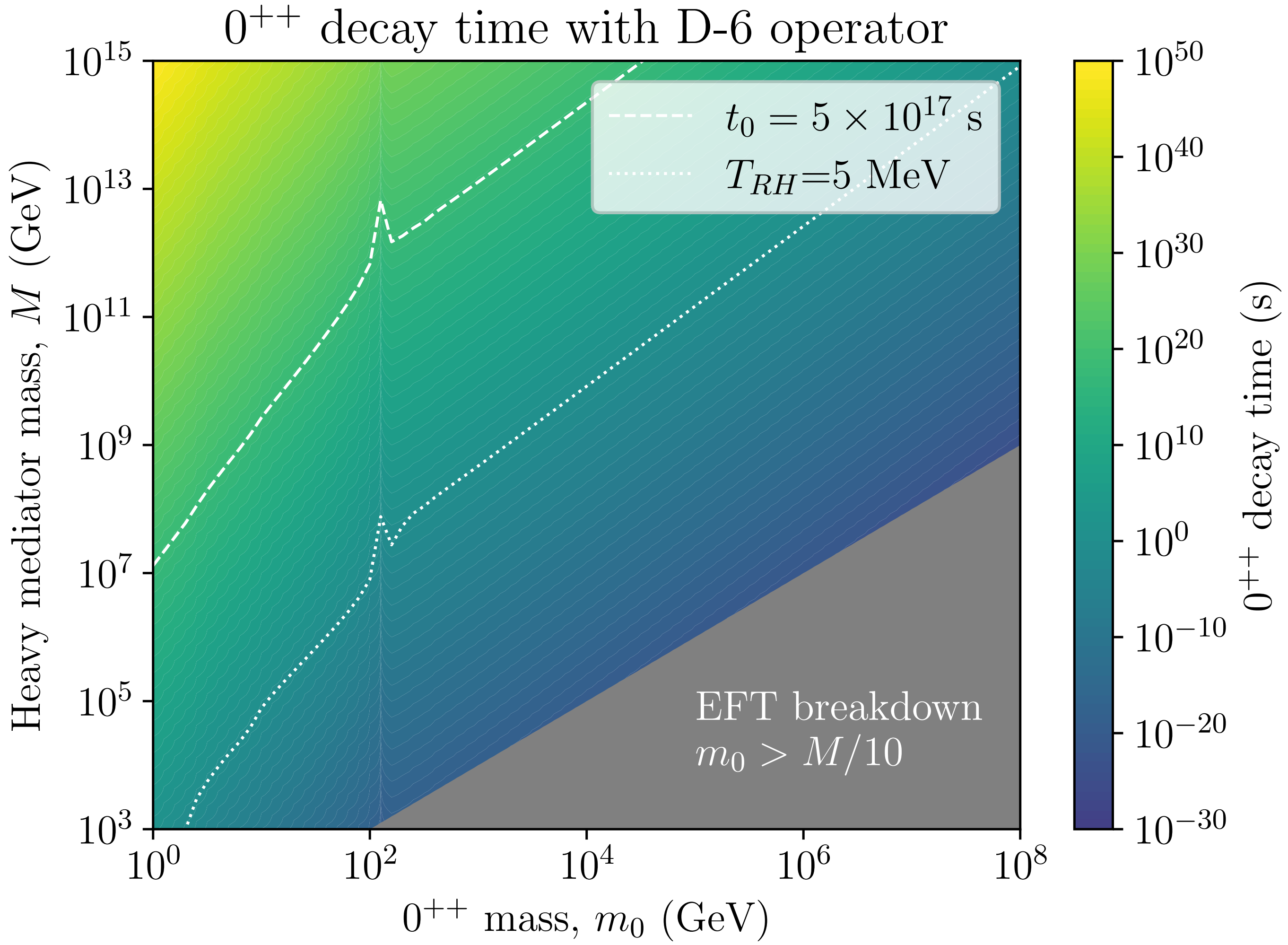
  $1^{+-} \rightarrow 0^{++} + Z/\gamma$

- If C_x is conserved, 1^{+-} is stable!

0^{++} decays and SM reheating

$$-\mathcal{L}_{tr} \supset \frac{\kappa_6}{M^2}|H|^2 X^a_{\mu\nu} X^{a\mu\nu}$$

- Decay time ~ M^4 / m_0^5
- We require that SM is sourced before BBN



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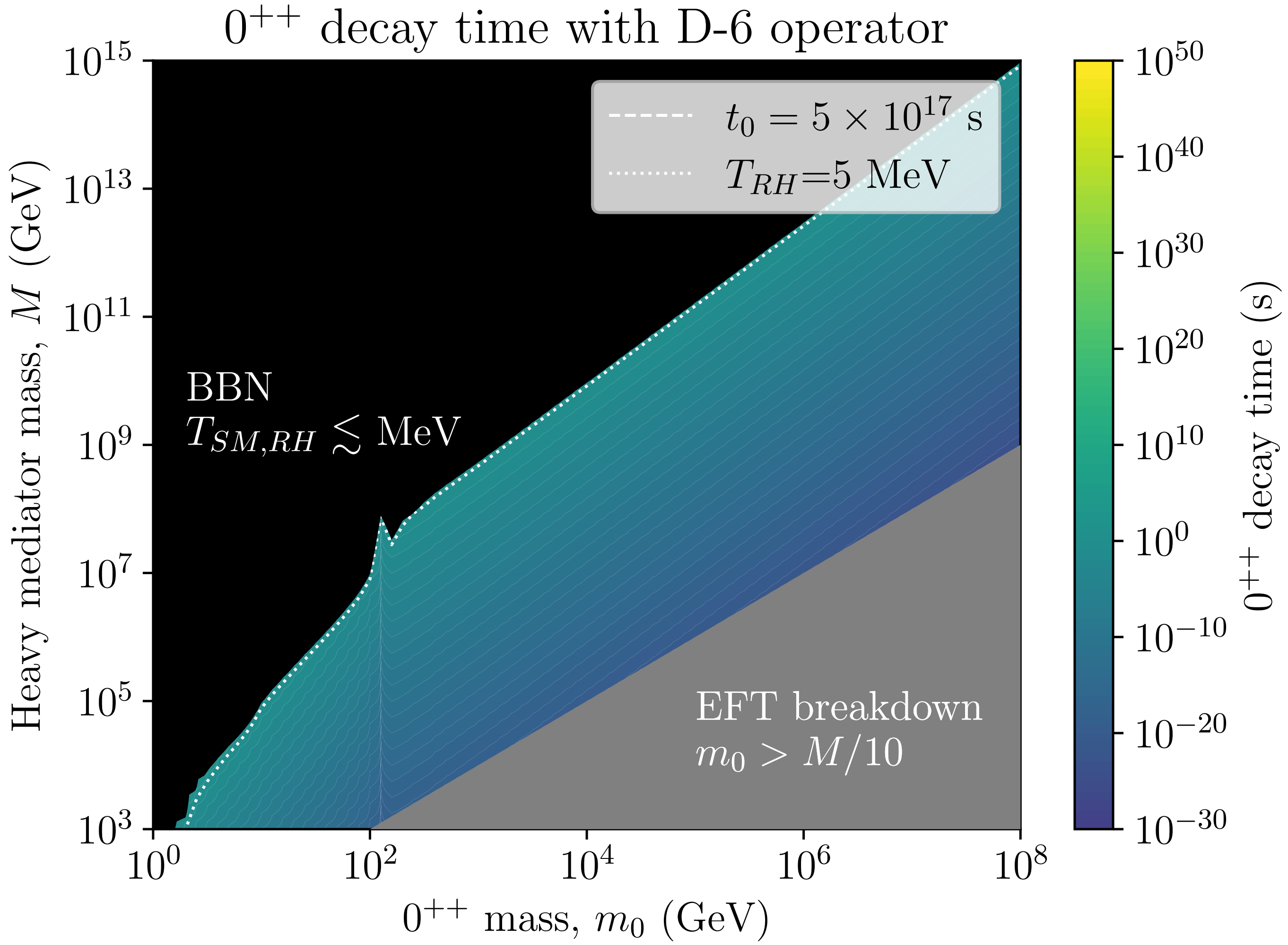
- Decays can dilute the abundance of 1^{+-}

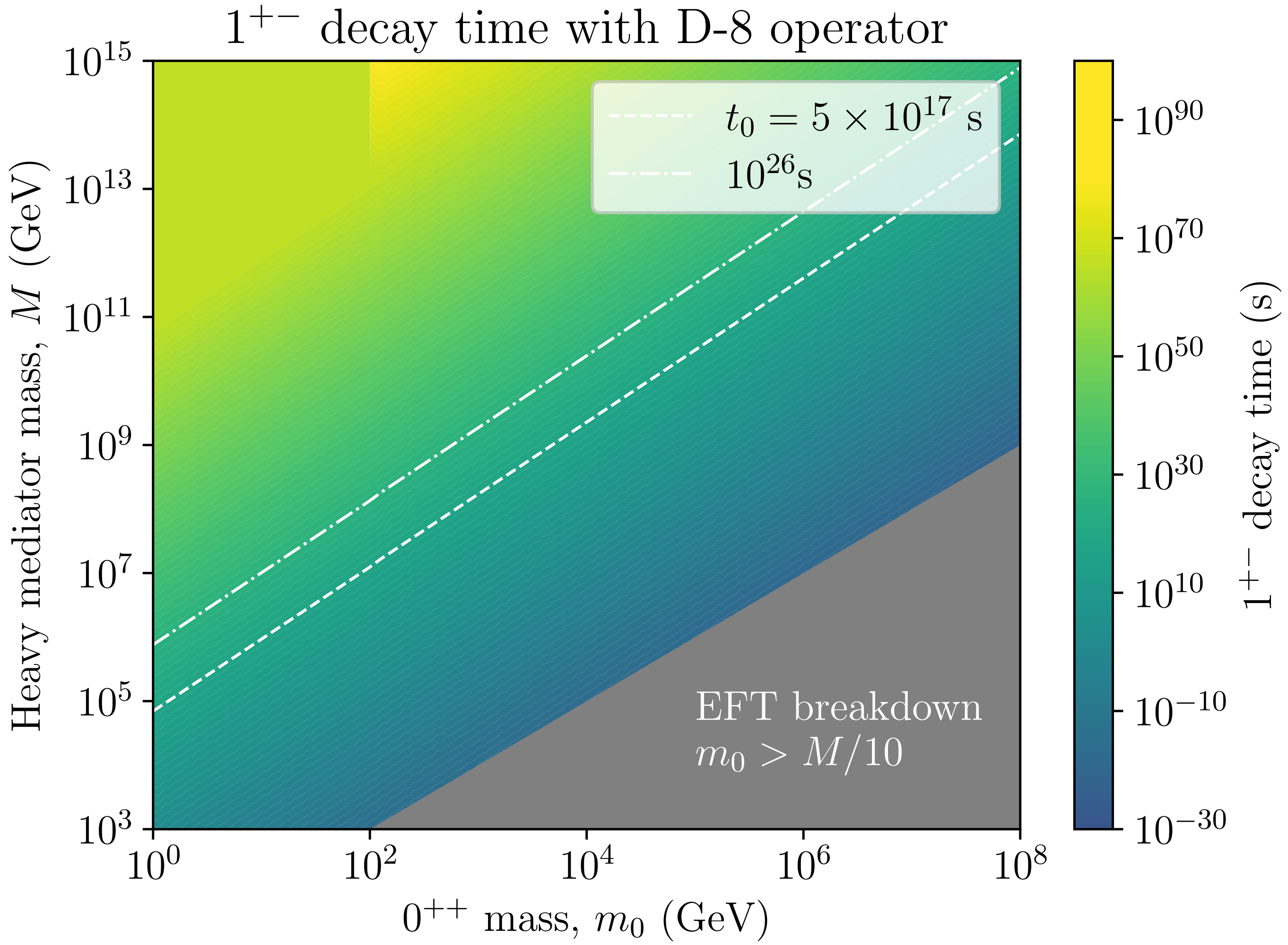


1^{+-} decays in C_x-broken Universe

$$-\mathscr{L}_{tr} \supset \frac{\kappa_8}{M^4} B_{\mu\nu} tr(XXX)^{\mu\nu}$$

- Decay time ~ M^8 / m_0^9
- 1^{+-} is parametrically longer-lived
  - Potential DM candidate!
- 1^{+-} has a monochromatic photon channel:

$$1^{+-} \to 0^{++} + \gamma$$



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Parameter space for 1^{+-} as DM

Discovery, accelerated

Cosmological abundance of 1^{+-}

Small *M* (vertical line):

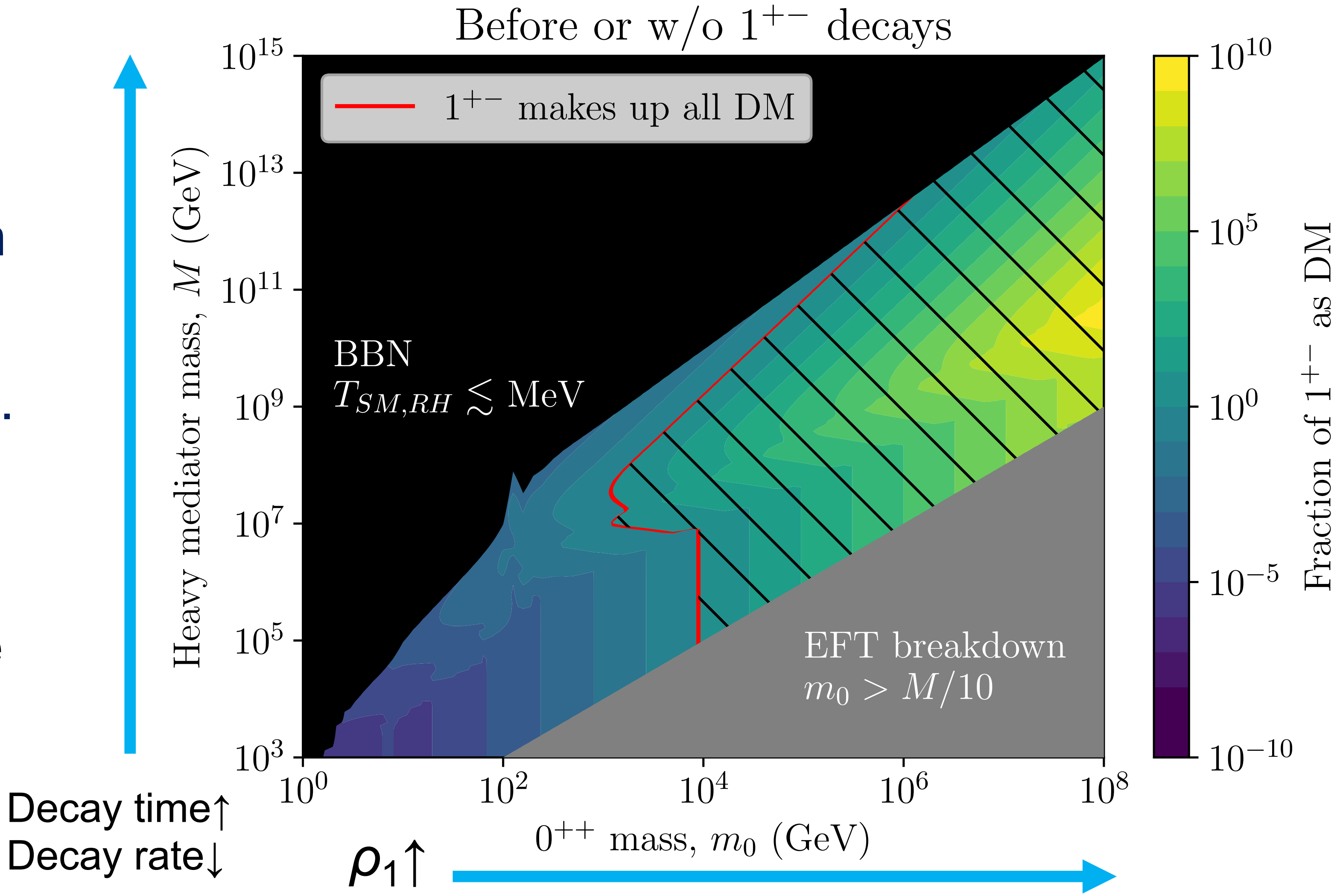
- 0^{++} bath thermalized with SM
- 1^{+-} freezes-out (f.o.) in SM bath

Medium *M*:

- 0^{++} decays compete with 1^{+-} f.o.

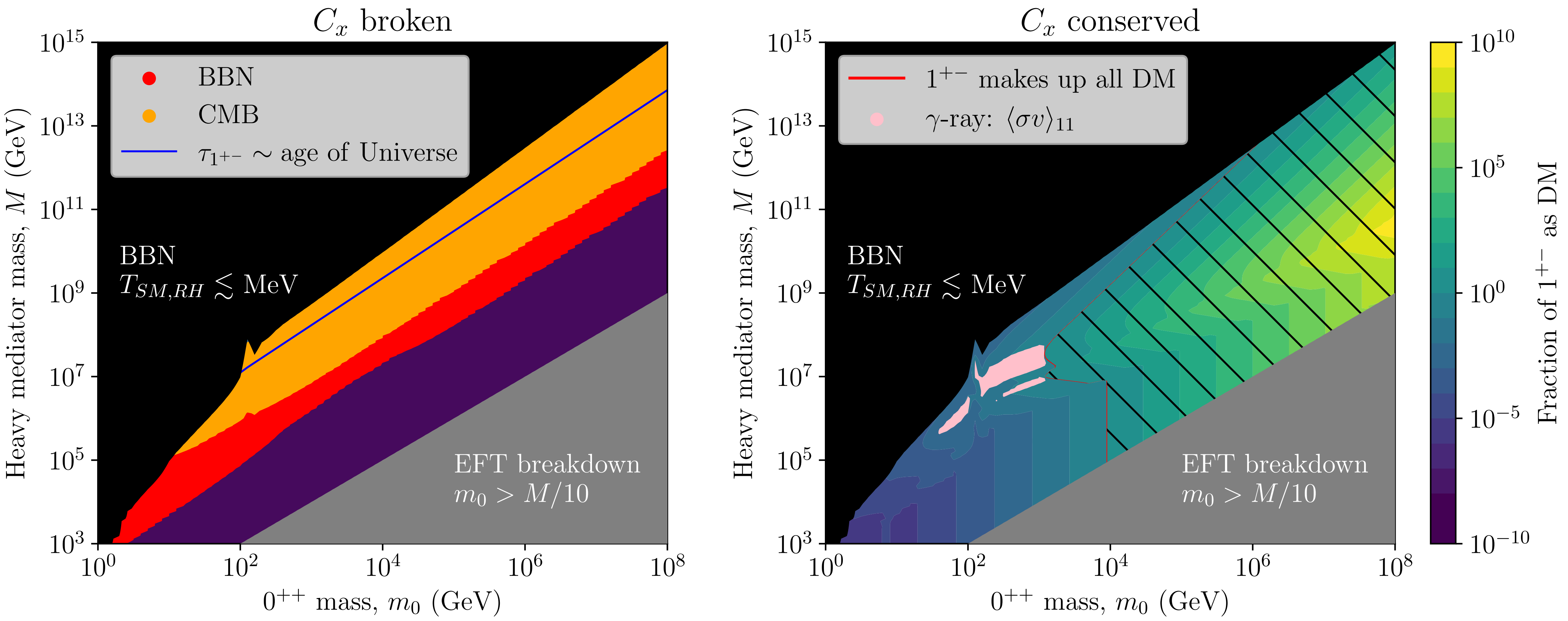
Large *M* (slope):

- 1^{+-} f.o. in 0^{++} bath
- 0^{++} decays dilute 1^{+-} abundance



C_x-broken vs. C_x-conserved cosmology

CMB: Slatyer, '12
BBN: Kawasaki+, '18
γ-ray: Armand+, '21



Conclusions

1. Pure SU(N) dark sector
   a. Dark gluons confine to a spectrum of glueball states
   b. We start with the DS-dominated Universe
   c. Within DS, 1^{+-} freezes-out in 0^{++} massive bath
2. Connectors to recover standard cosmology
   a. Dominant 0^{++} decay into SM and could dilute the abundance of 1^{+-}
   b. 1^{+-} is either stable or long-lived
3. 1^{+-} as DM
   a. C_x-broken: ruled out by CMB and BBN
   b. C_x-conserved: still large parameter space

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Thank you for listening!

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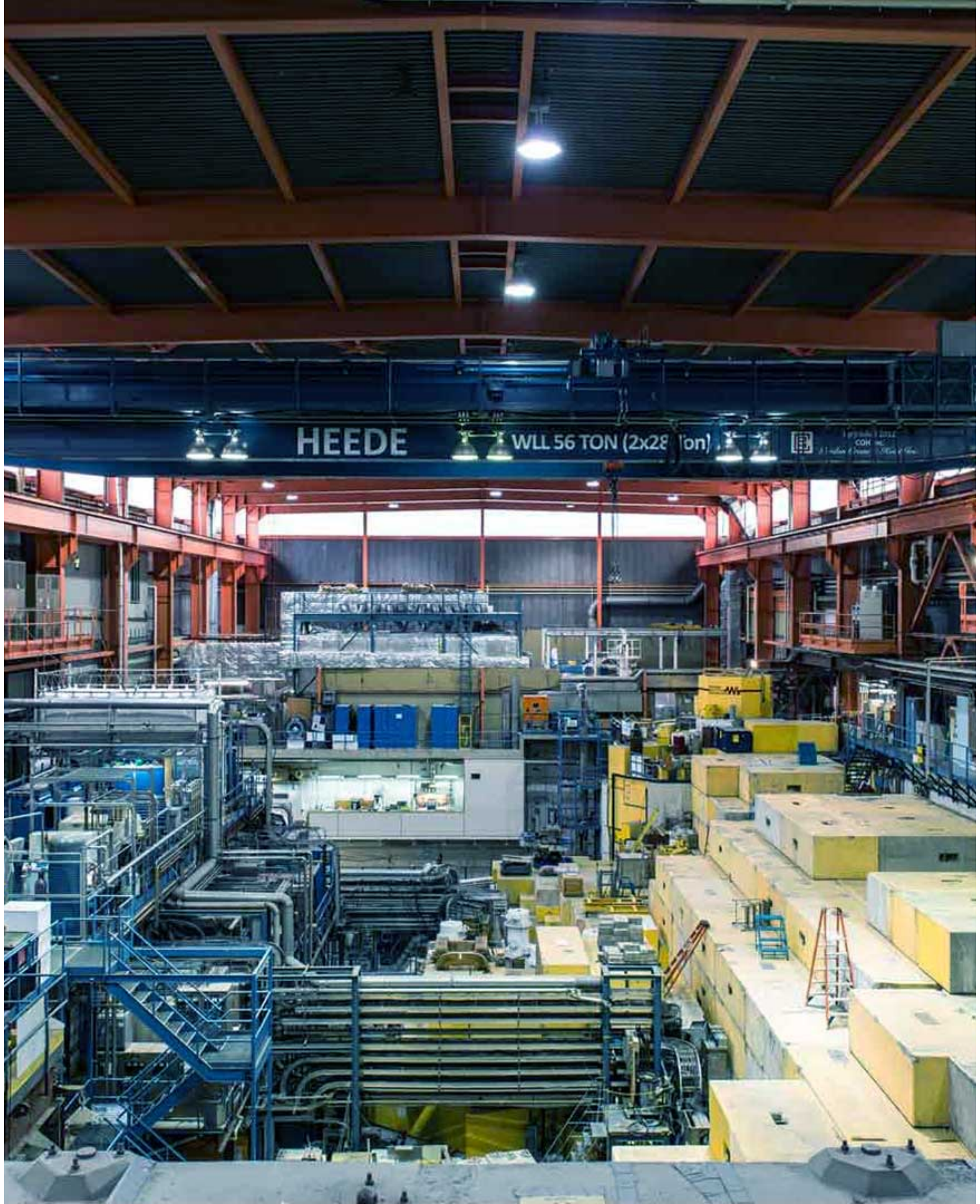
Backup slides



Discovery, accelerated

Backup: glueball decays

Dim-8 operator

Juknevich '10

$$\mathscr{L}_{eff} \supset \frac{\alpha_x}{M^4}\left(\alpha_1\chi_1 B_{\mu\nu}B_{\alpha\beta} + \alpha_2\chi_2 W^c_{\mu\nu}W^c_{\alpha\beta} + \alpha_3\chi_3 G^a_{\mu\nu}G^a_{\alpha\beta}\right)$$
$$\times\left(\frac{1}{60}S\,\eta^{\mu\nu}\eta^{\alpha\beta} + \frac{1}{45}P\,\epsilon^{\mu\nu\alpha\beta} + \ldots\right)$$
$$+\ \frac{\alpha_x^{3/2}\alpha_1^{1/2}}{M^4}\chi_Y\,B_{\mu\nu}\,\frac{14}{45}\left(\Omega^{(1)}_{\mu\nu} - \frac{5}{14}\Omega^{(2)}_{\mu\nu}\right)\ .$$

$$\mathcal{O}^{(8a)} \sim \frac{1}{M^4}tr(F_{SM}F_{SM})\,tr(XX)\ ,$$
$$\mathcal{O}^{(8b)} \sim \frac{1}{M^4}B_{\mu\nu}\,tr(XXX)^{\mu\nu}\ ,$$
$$\mathcal{O}^{(6)} \sim \frac{1}{M^2}H^\dagger H\,tr(XX)\ ,$$

$$\chi_i = \sum_r d(r_i)T_2(r_i)/\rho_r^4$$
$$\chi_Y = \sum_r d(r_i)Y_r/\rho_r^4\ ,$$

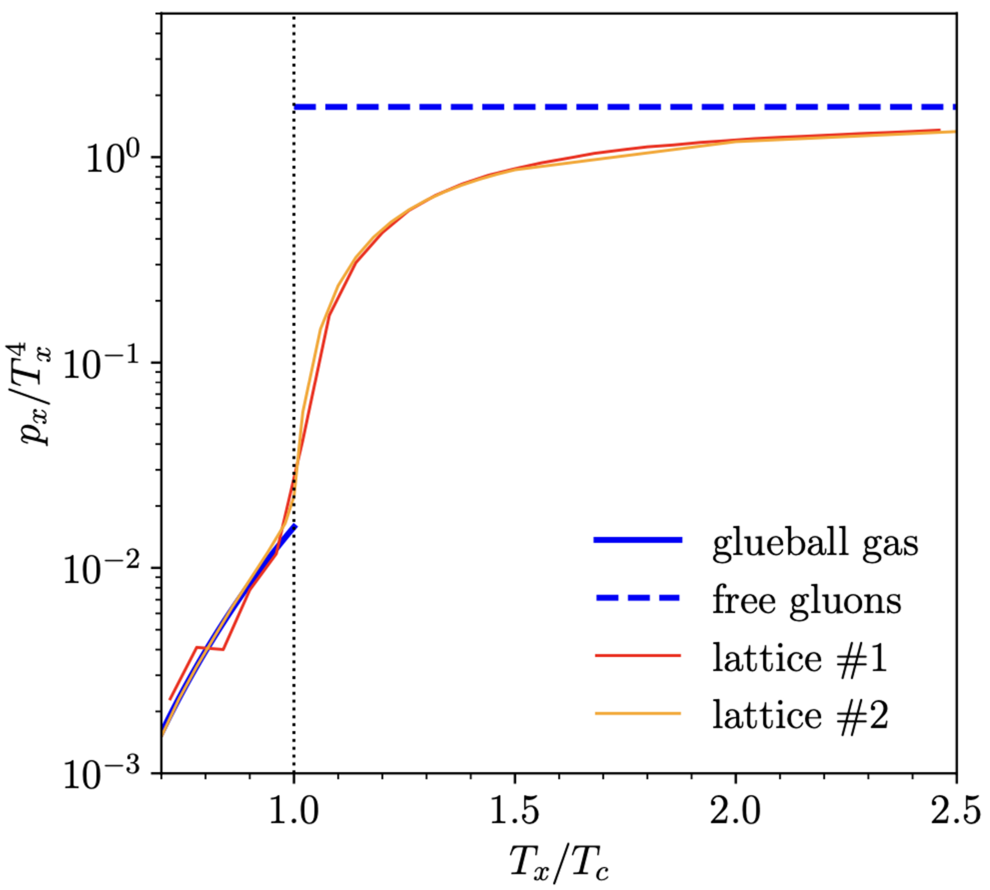
Glueball decay summary

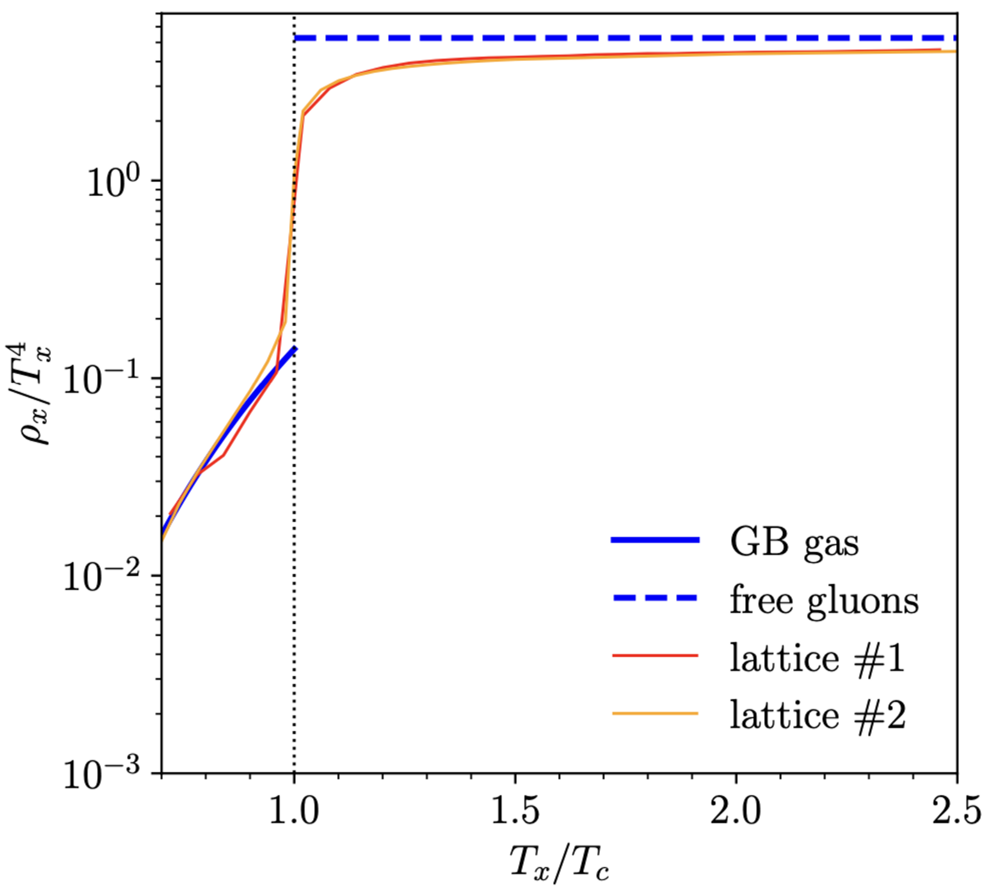
Juknevich '10

State	$D = 6$ operators	$D = 8$ operators
0^{++}	bb, W^+W^-, ZZ, hh	gg, WW, ZZ, $Z\gamma$, $\gamma\gamma$
$2^{\pm +}$	$0^{\pm +}h(h^*)$	gg, WW, ZZ, $Z\gamma$, $\gamma\gamma$
0^{-+}	-	gg, WW, ZZ, $Z\gamma$, $\gamma\gamma$
3^{++}	$0^{-+}h$, $2^{\pm +}h(h^*)$	$0^{-+}gg$ $2^{++}gg$, $1^{+-}\gamma$
1^{+-}	-	$0^{\pm +}\gamma$, $2^{-+}\gamma$
1^{--}	$1^{+-}h(h^*)$	$0^{\pm +}\gamma$, $2^{\pm +}\gamma$, ff
0^{+-}, 2^{+-}, 3^{+-} 2^{--}, 3^{--}	$J^{P-}h(h^*)$	$0^{\pm +}\gamma$, $2^{\pm +}\gamma$

Backup: confinement

Through dark confinement

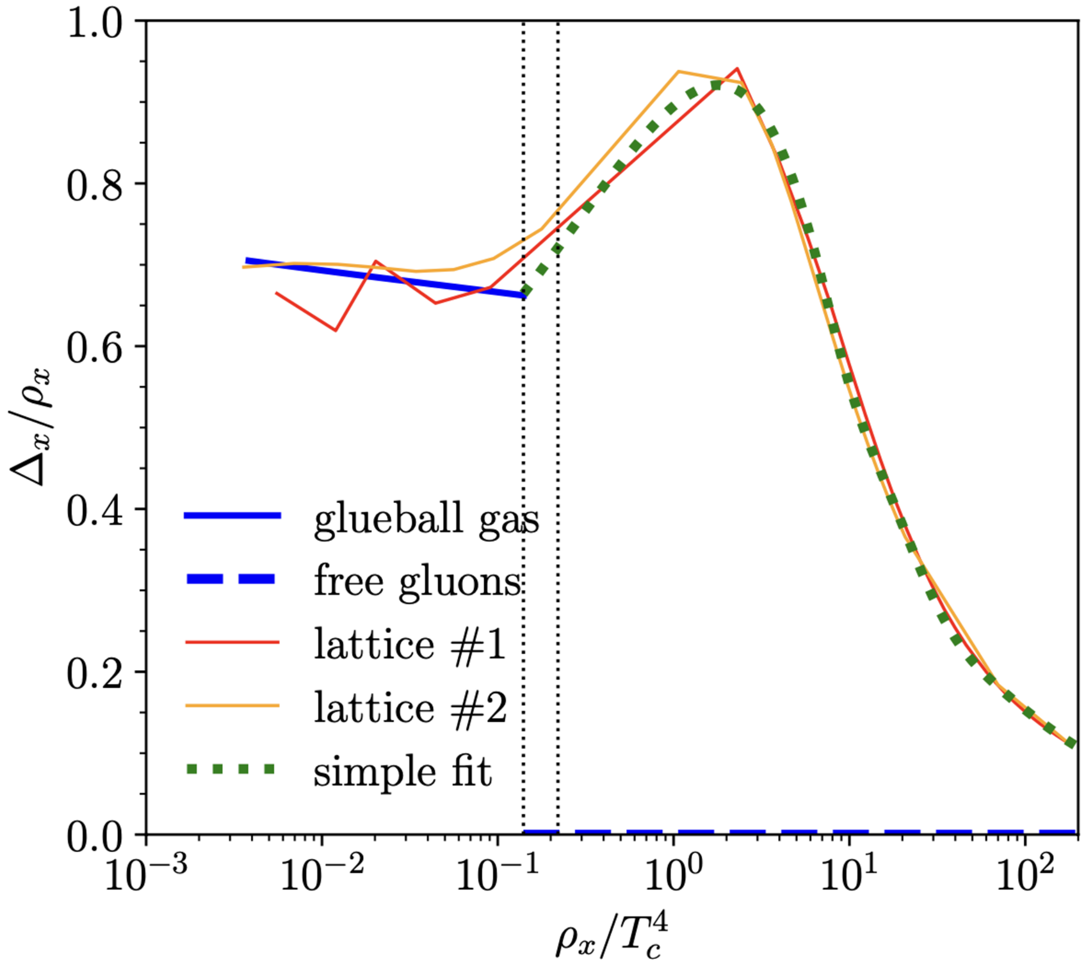




Courtesy: David
lattice #1: Nada and Panero 2018; #2: Borsanyi et al. 2012

Equation of state during transition

- Lattice studies match up well with glueball gas' EOS
- During the confinement, we can use a data fit for EOS



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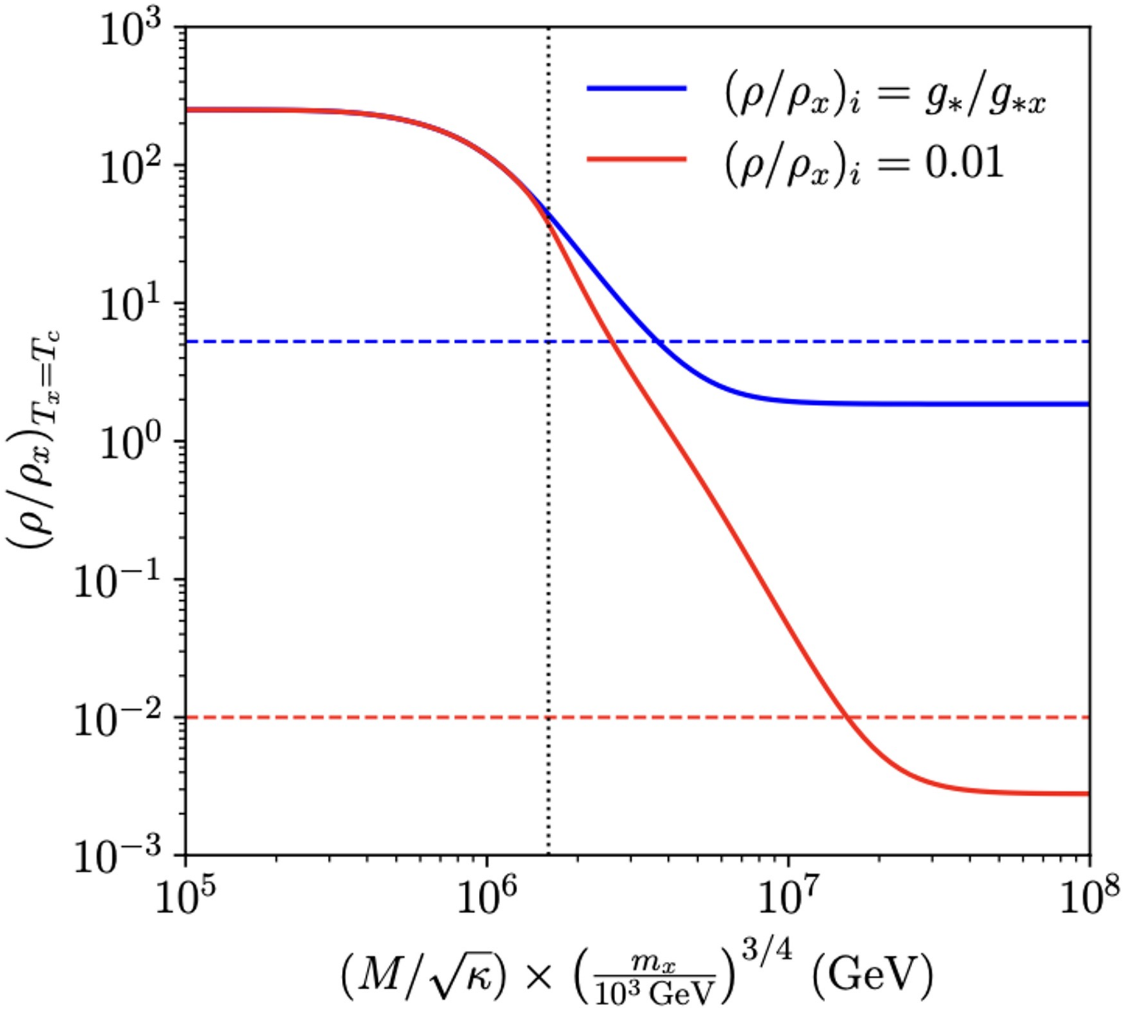
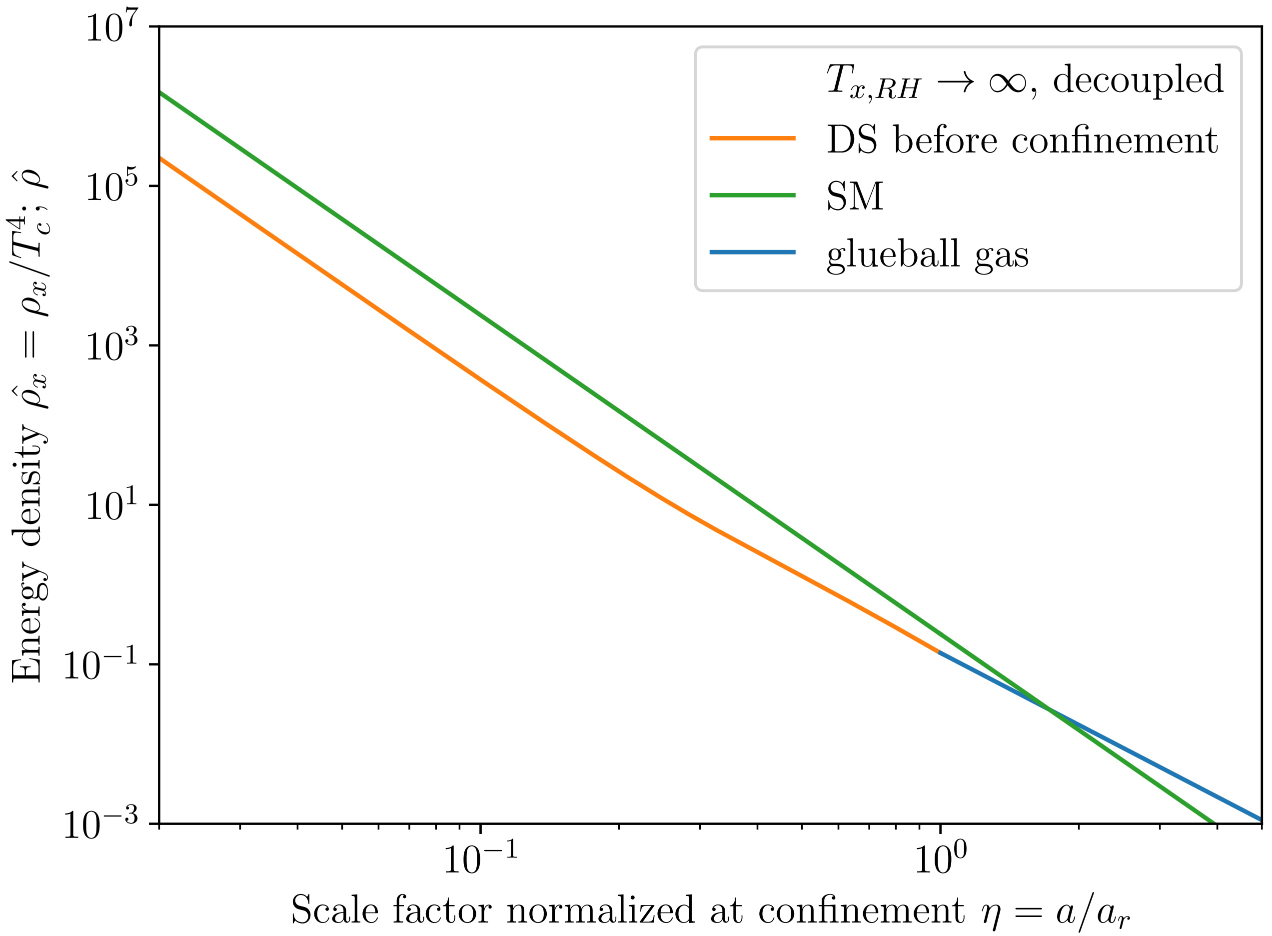
Backup: initial conditions

Initial conditions; gluons & SM evolution

- y-axis: energy density ratio of SM to DS at confinement temperature
- Dashed lines: initial density ratio
- Left from dotted lines:
  - Both sectors are kept thermalized
  - independent of initial SM fraction
- Right from dotted lines:
  - DS and SM are decoupled
  - SM radiation is more diluted (a^{-4}) than newly formed glueballs (a^{-3})



SM dilution during dark confinemnet



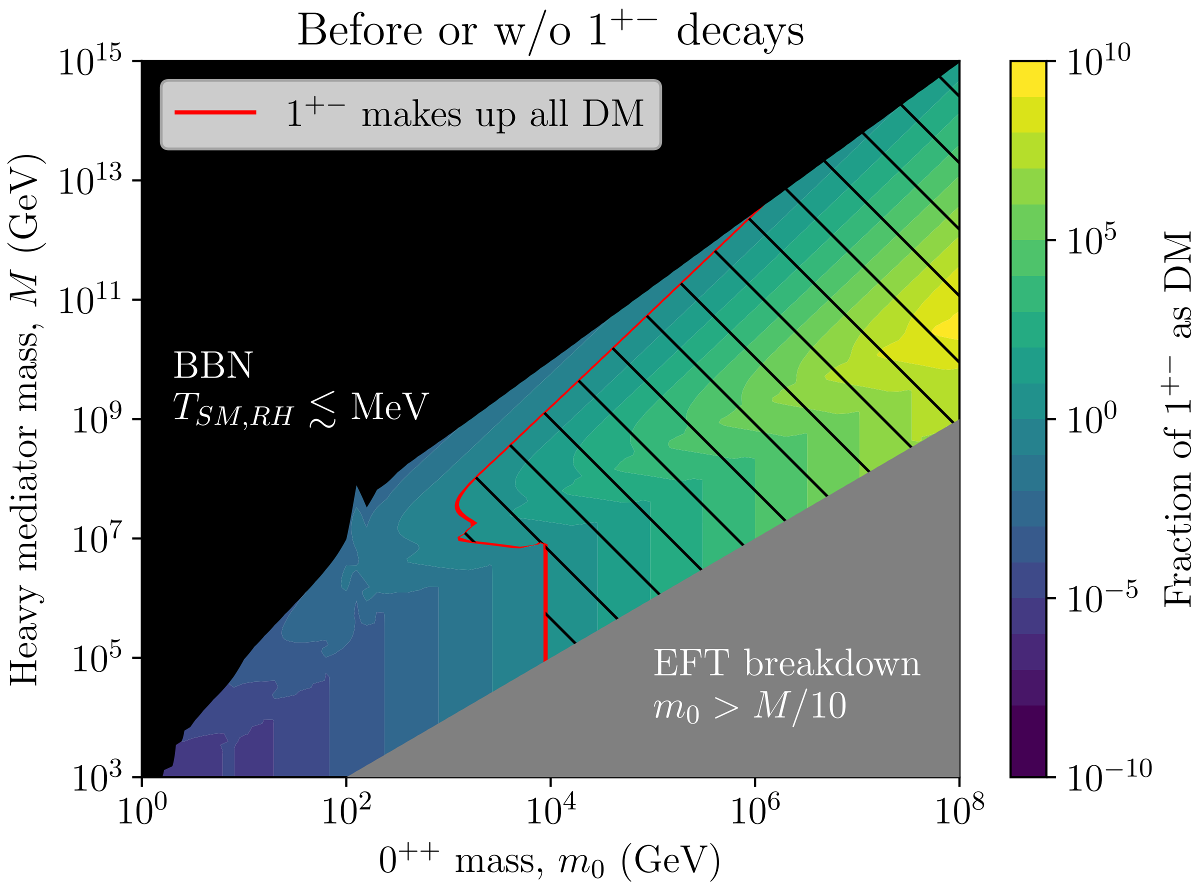
Dark gluon-SM Higgs interactions

Initial T_x at the end of inflation can lie in $[m_0, \infty]$

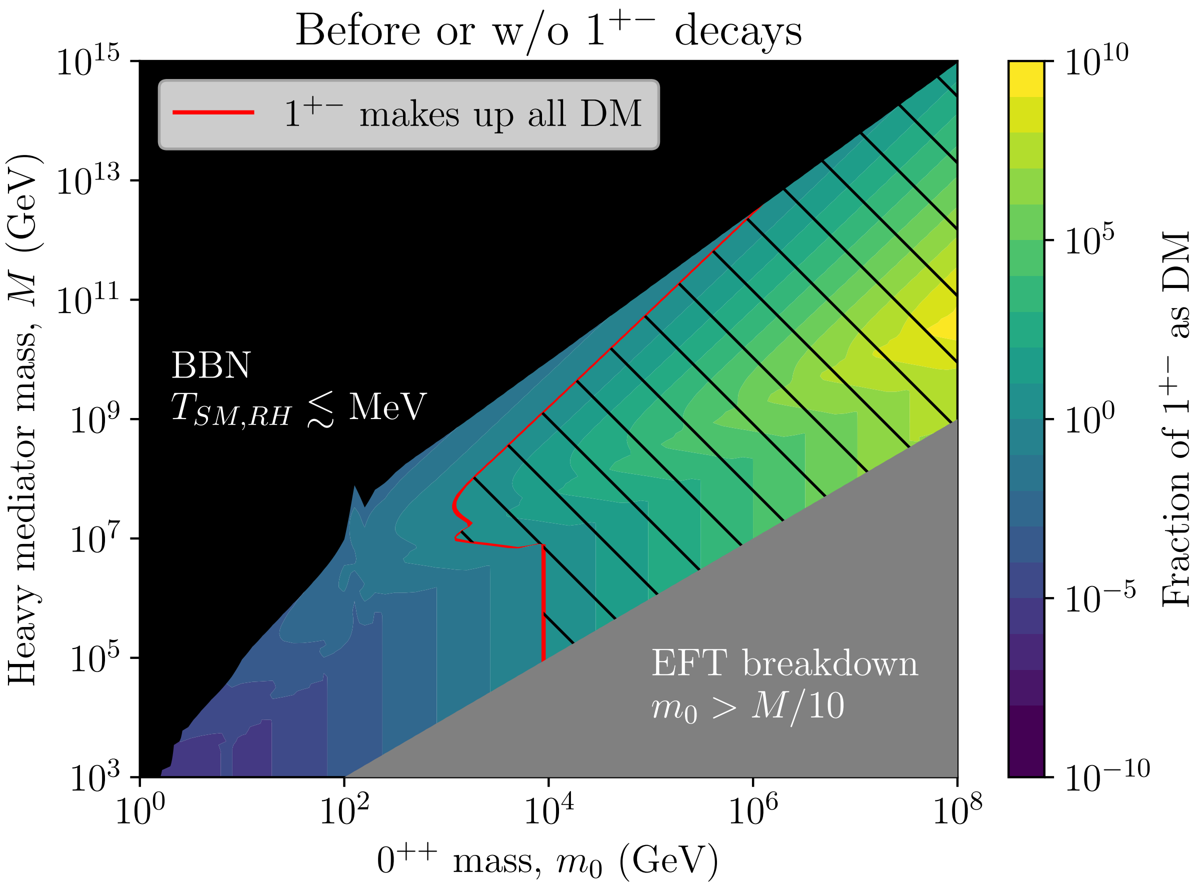
	$T_{x,i} \to \infty$	$T_{x,i} \to m_0$ (confinement)
$M\uparrow$ (rate $\downarrow$)	Thermalized $\to$ decoupled	No time for thermalization
$M\downarrow\downarrow$ (rate $\uparrow\uparrow$)	Thermalized	Thermalized

Comparison of initial conditions

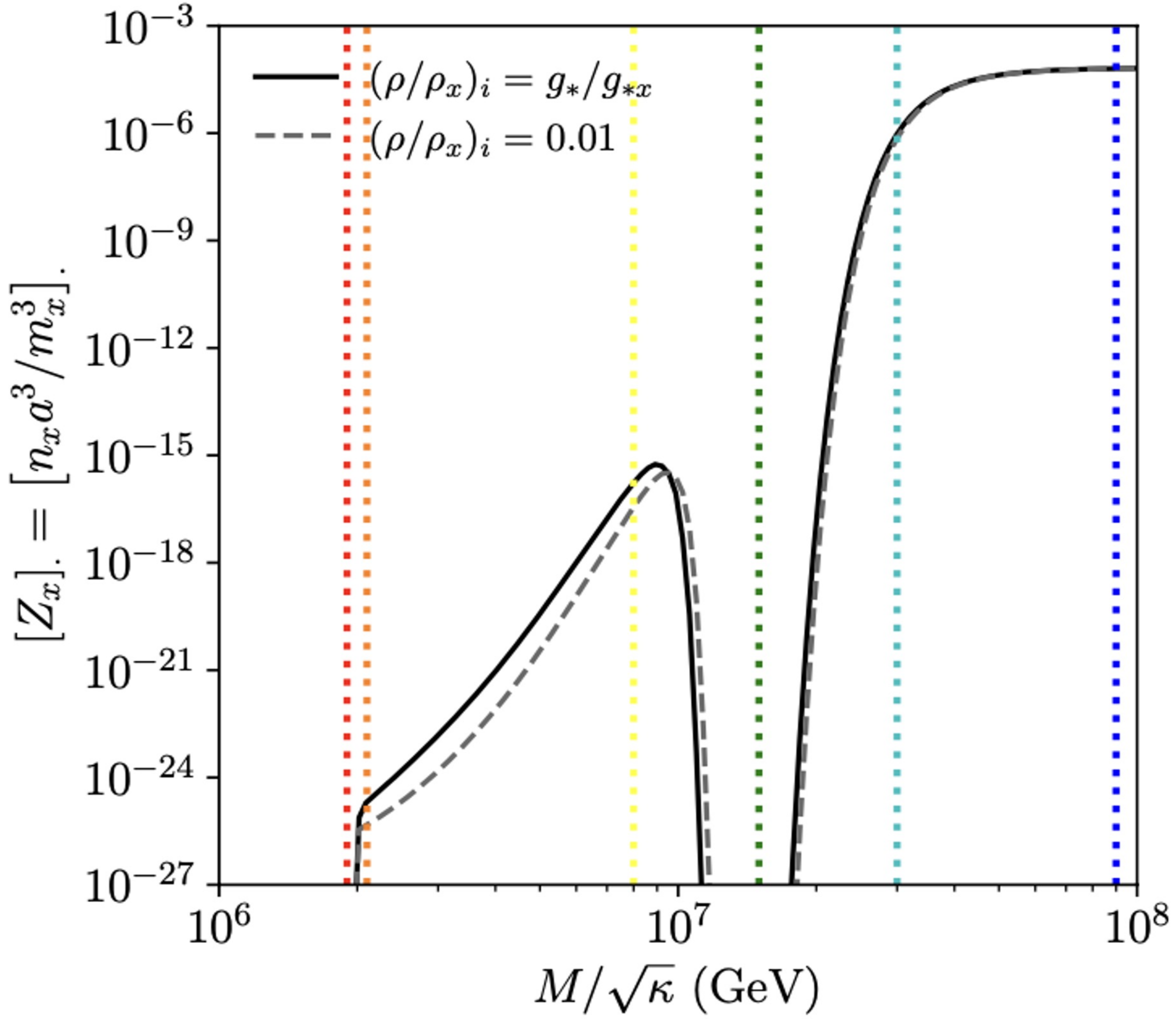
Thermalized:

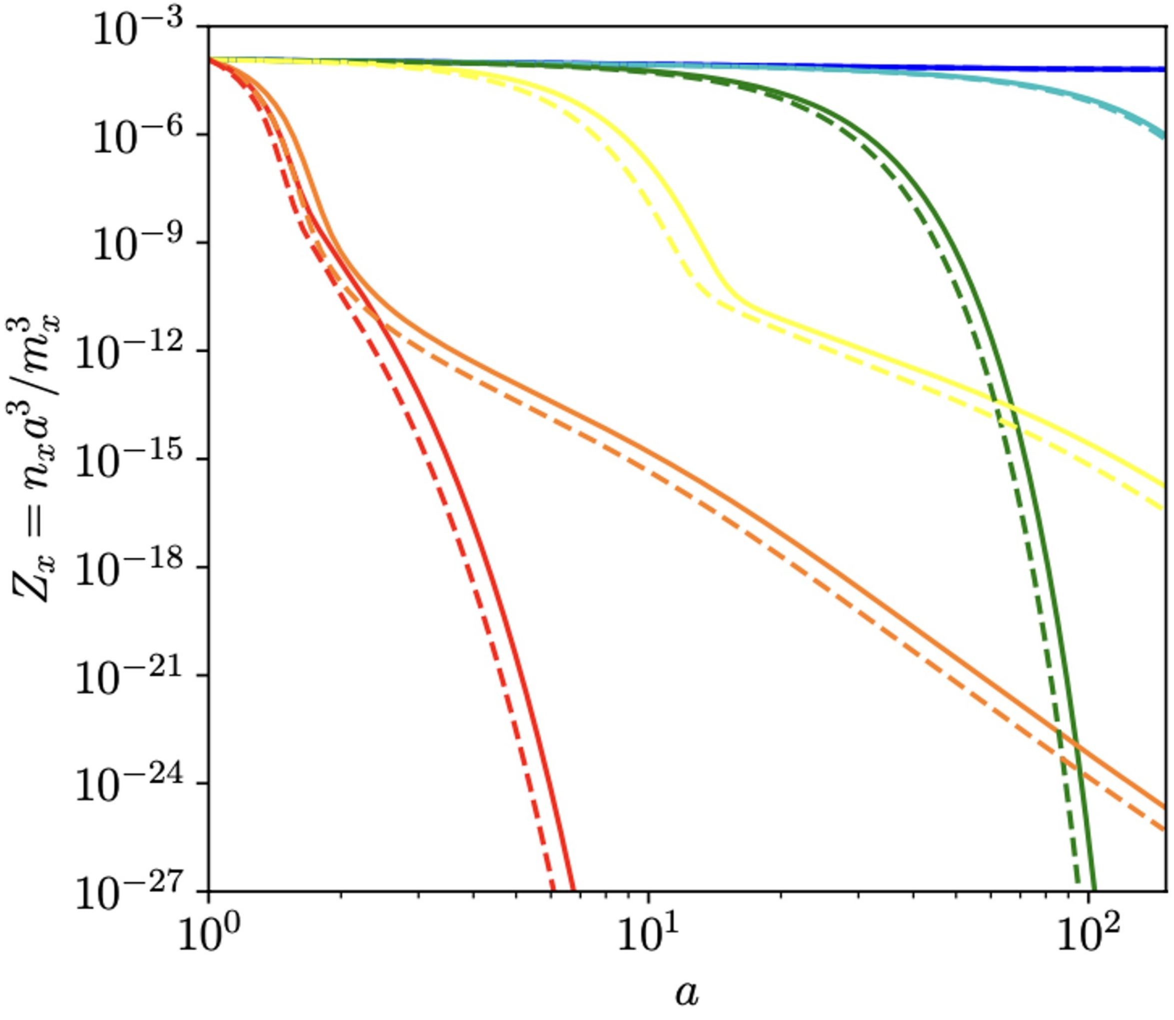


Initial SM = 1%:



Closer look to the nose

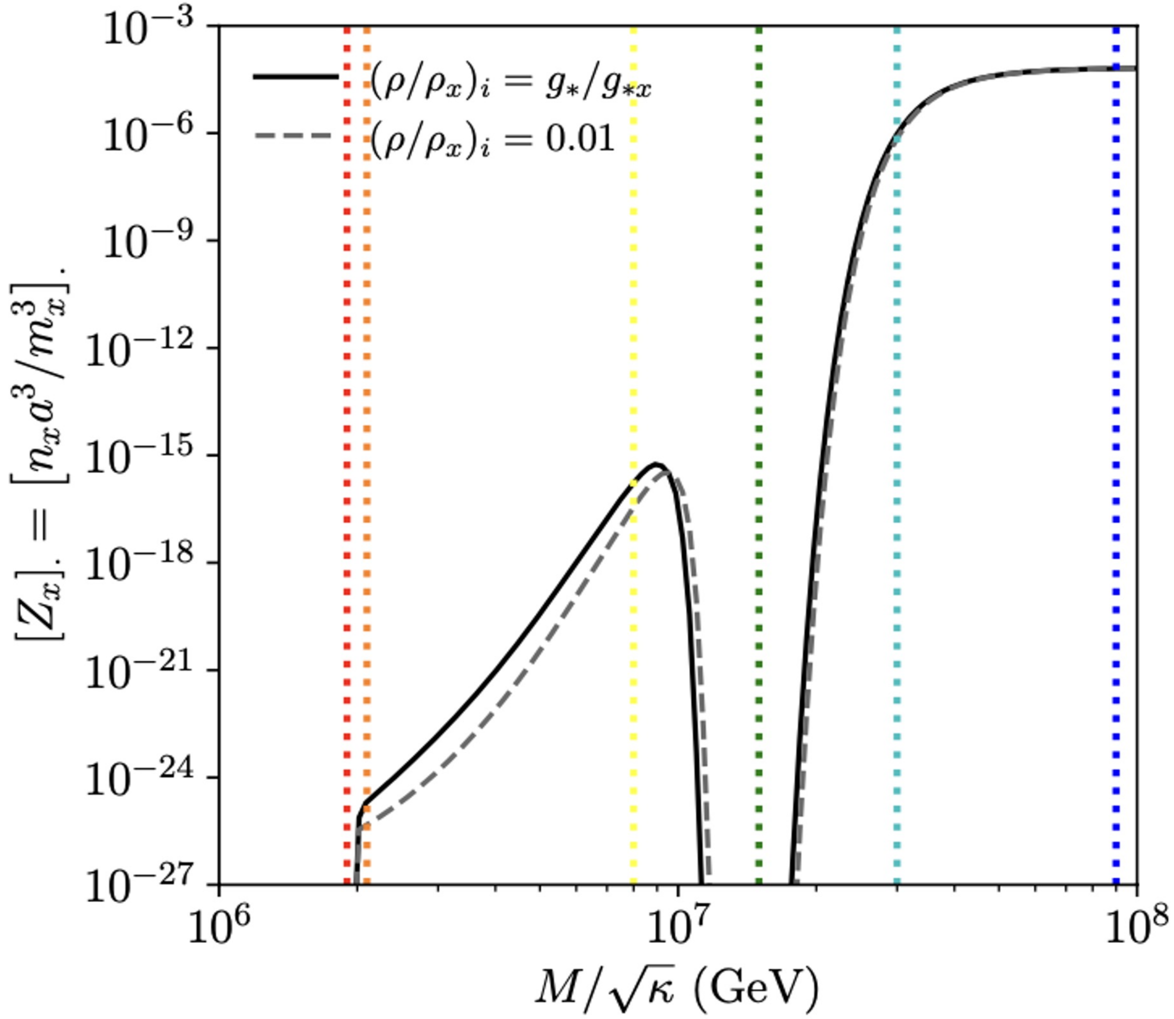


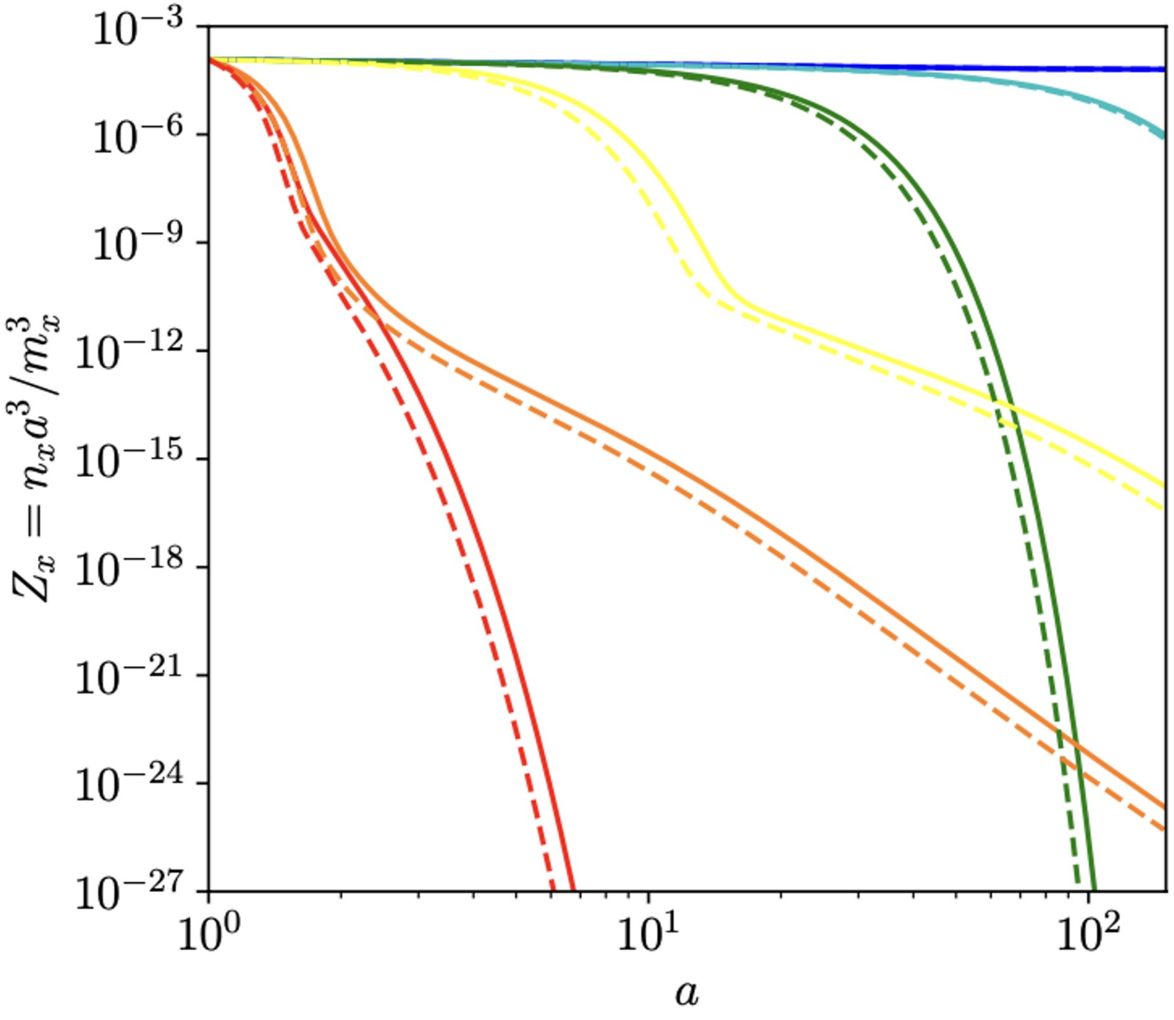


Backup: 1^{+-} evolution

Closer look

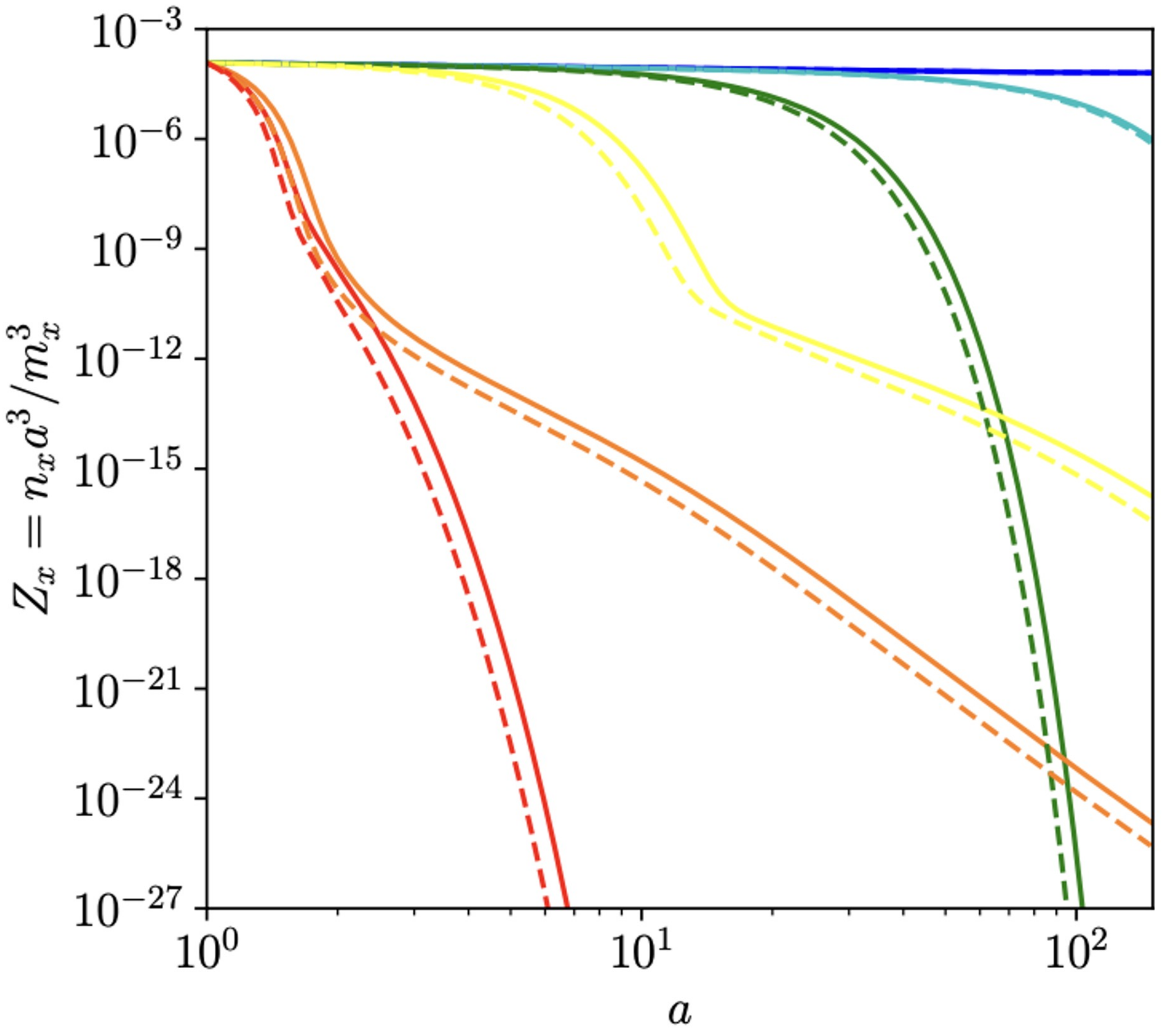
Red: 0^{++} decays before freeze-out
blue: 0^{++} decays after freeze-out

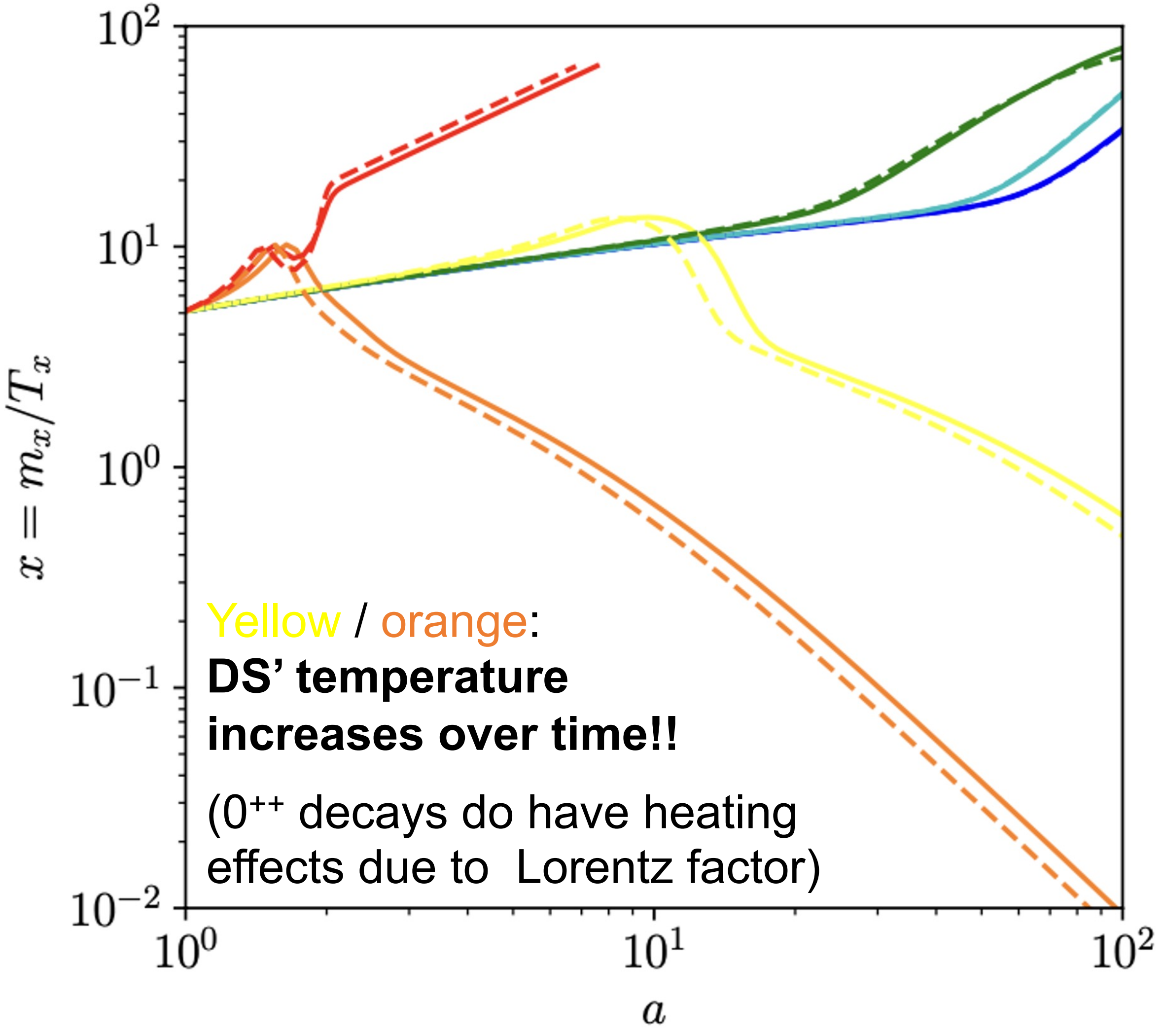




Heating effects due to decays

Red: 0^{++} decays before freeze-out
blue: 0^{++} decays after freeze-out





Yellow / orange:
DS' temperature increases over time!!

(0^{++} decays do have heating effects due to Lorentz factor)