CIPANP 2018

Cosmological Bounds on Non-Abelian Dark Forces

PRD95, 015032, arXiv:1605.08048

PRD97, 075029, arXiv:1710.06447

TRIUMF & UBC

Collaboration with David Morrissey & Kris Sigurdson

Outline

1. Motivations
2. Dark Gauge Forces
3. Dark Glueballs and Cosmology
4. Cosmological Constraints

Standard Model

$$\overbrace{SU(3)_c \times SU(2)_L \times U(1)_Y} \times STUFF$$

Missing pieces:

- How does gravity connect with the SM?
- What is dark matter?
- Baryogenesis
- Hierarchy problem
- Strong CP Violation
- …

WIMP Paradigm

G. Gelmini and P. Gondolo, *arXiv:1009.3690*

$$\chi\ \chi \leftrightarrow SM\ SM$$

Universe cools
T~m_χ

$$\chi\ \chi \rightarrow SM\ SM$$

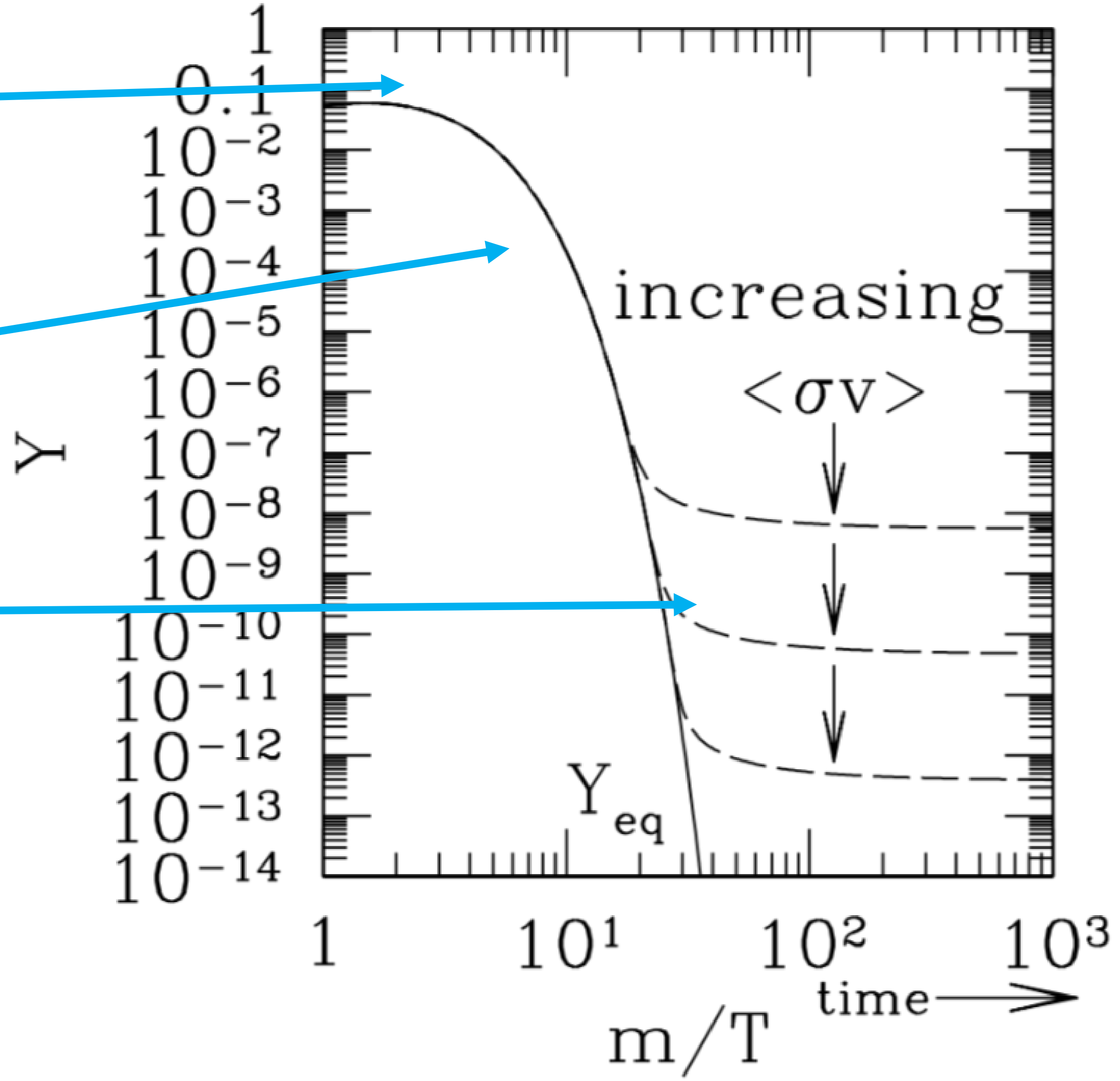
Universe cools
T~m_χ/20

$$\chi\ \chi \qquad SM\ SM$$

Production

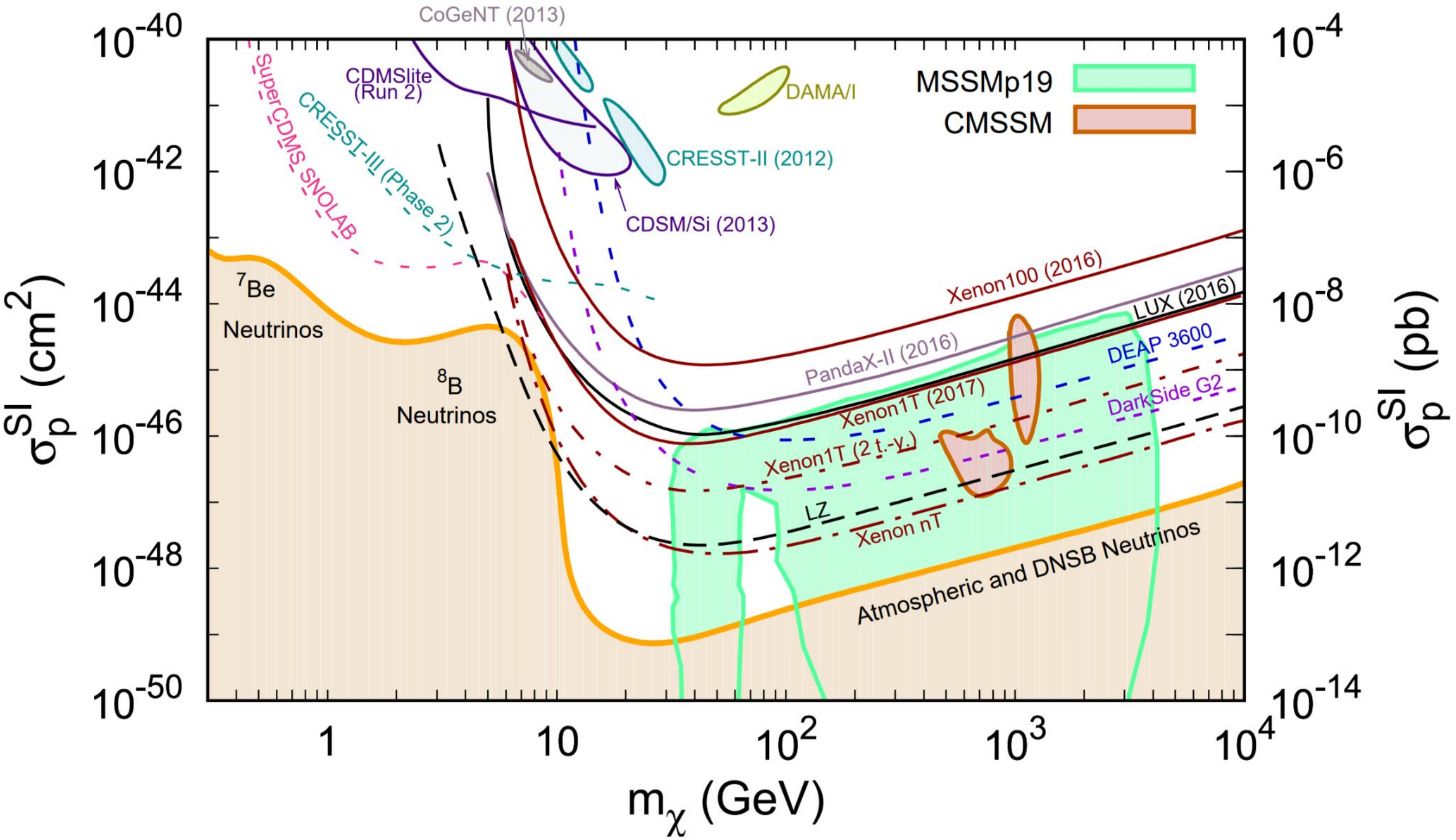
Depletion

Freeze Out



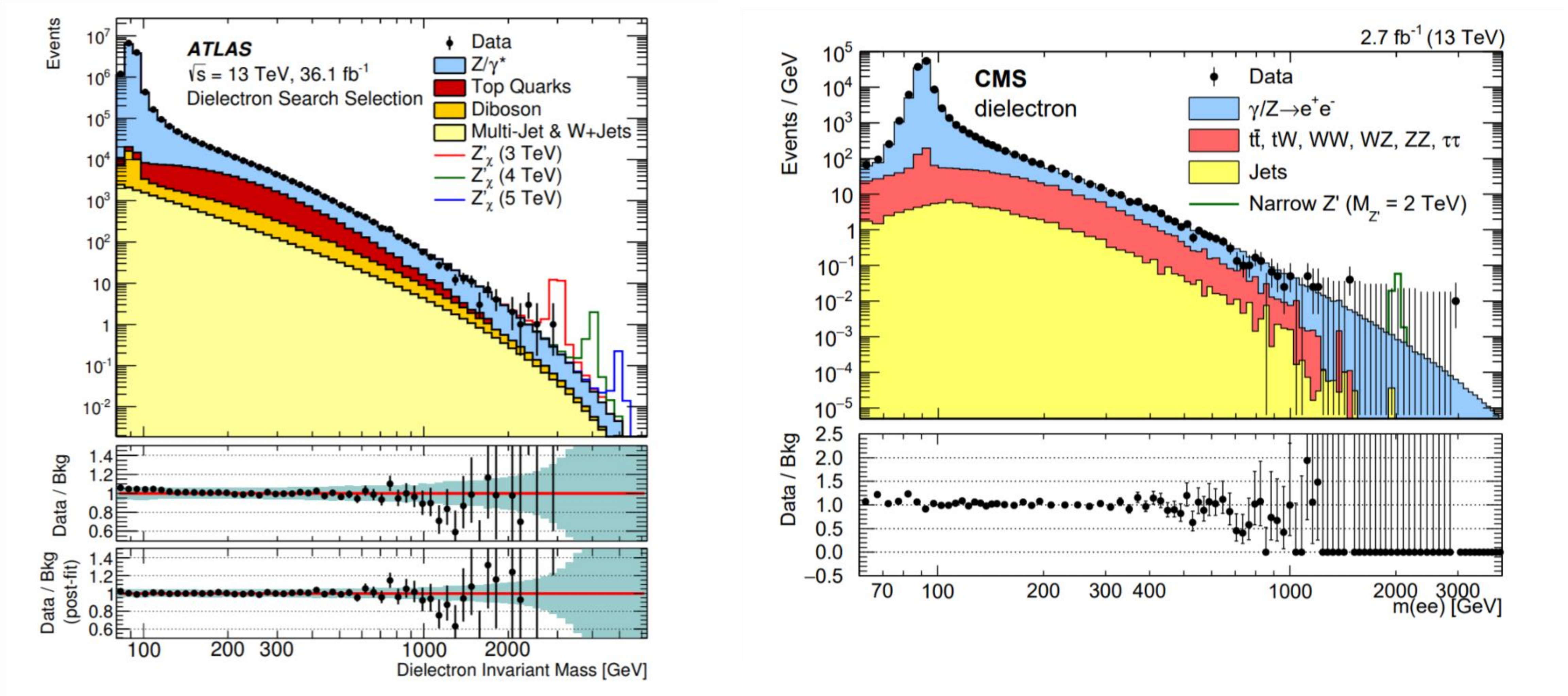
Boltzmann Equation

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{eq}^2)$$



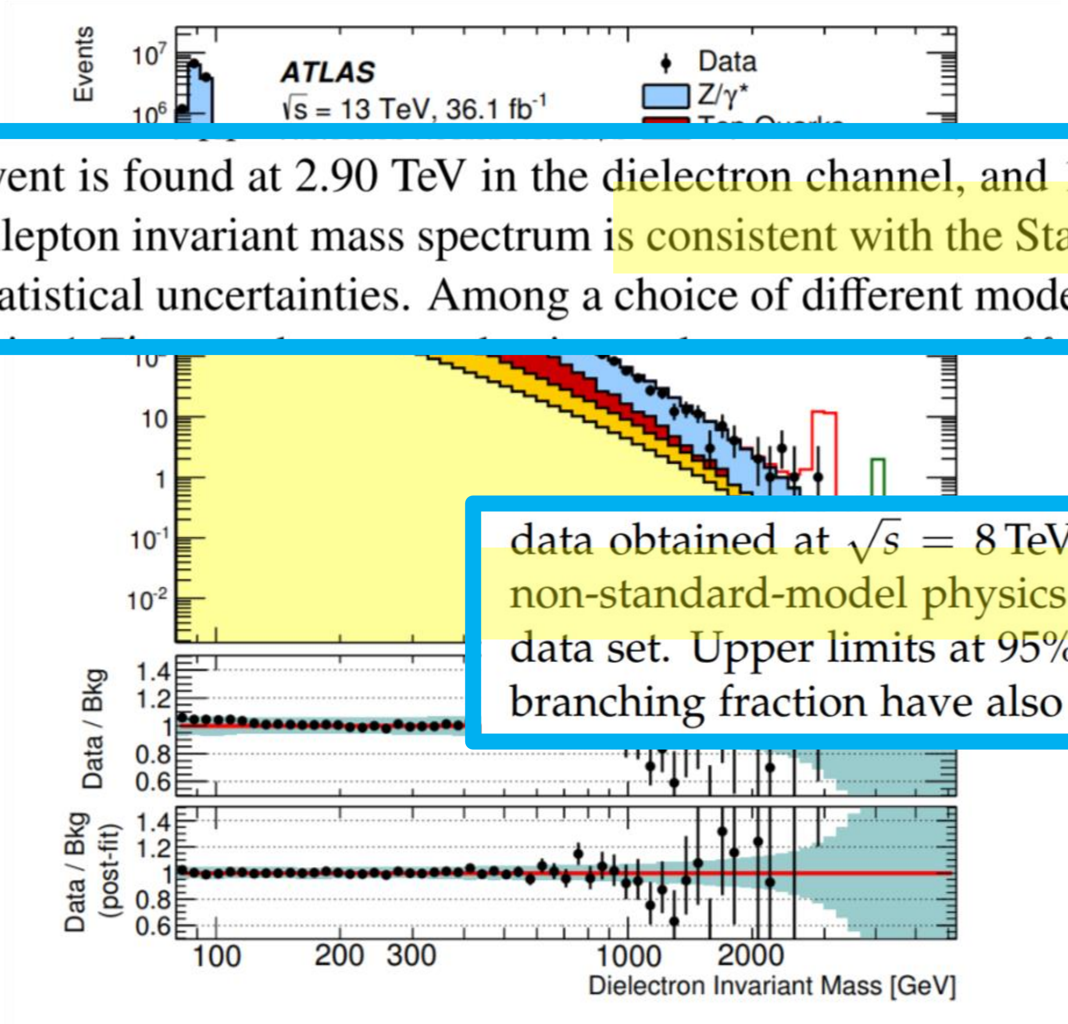
L. Roszkowski, E. M. Sessolo, and S. Trojanowski, *arXiv:1707.06277*

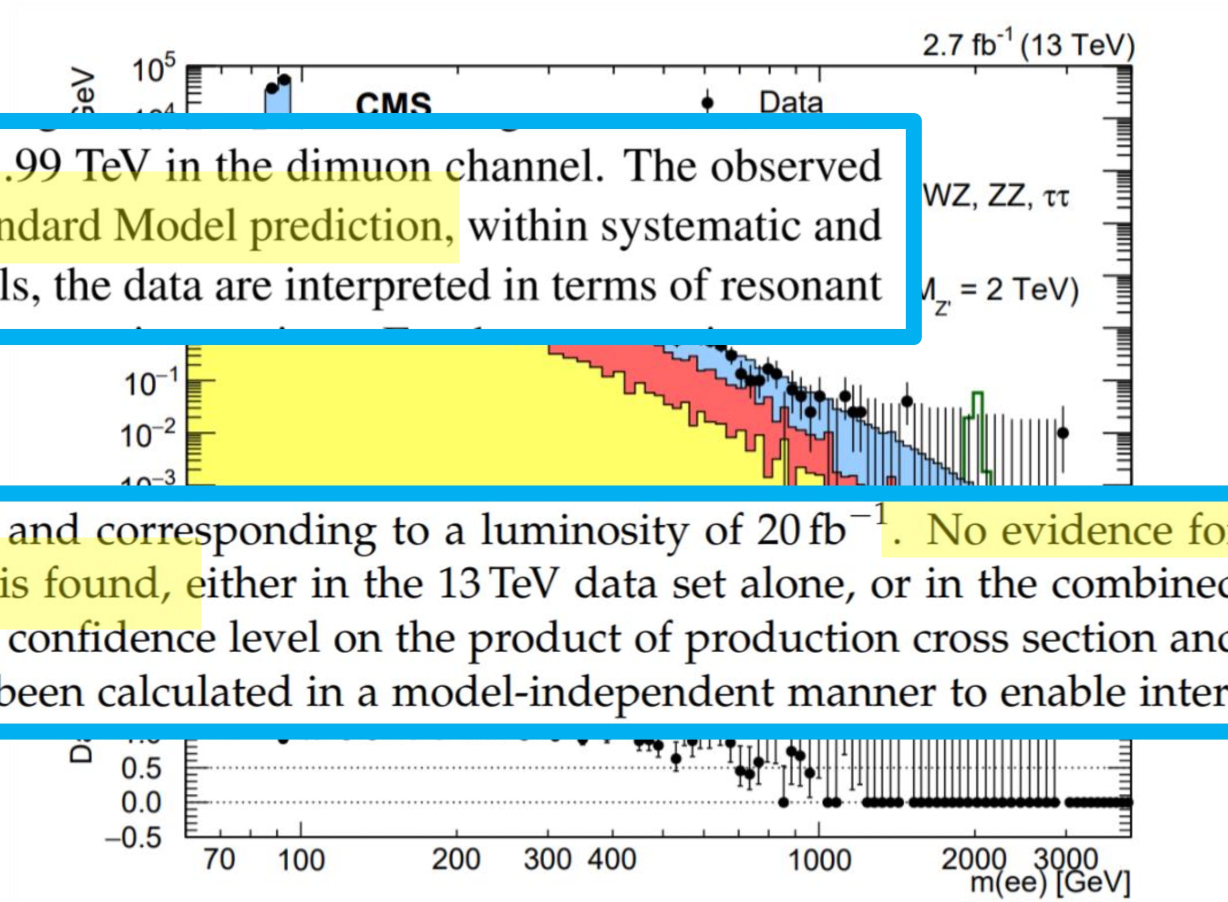
BSM at the LHC?



ATLAS, arXiv: 1707.02424
CMS, arXiv: 1609.05391

BSM at the LHC?





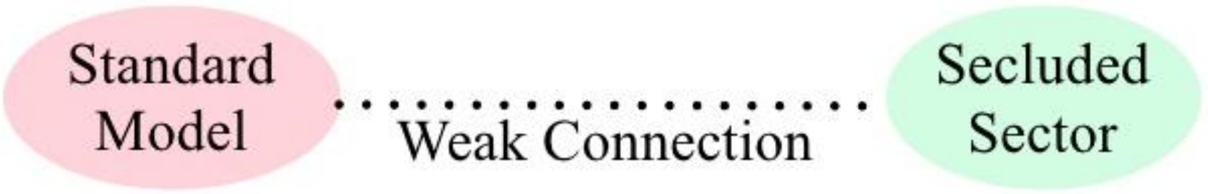
event is found at 2.90 TeV in the dielectron channel, and 1.99 TeV in the dimuon channel. The observed dilepton invariant mass spectrum is consistent with the Standard Model prediction, within systematic and statistical uncertainties. Among a choice of different models, the data are interpreted in terms of resonant

data obtained at $\sqrt{s} = 8$ TeV and corresponding to a luminosity of 20 fb^{-1}. No evidence for non-standard-model physics is found, either in the 13 TeV data set alone, or in the combined data set. Upper limits at 95% confidence level on the product of production cross section and branching fraction have also been calculated in a model-independent manner to enable inter-

ATLAS, arXiv: 1707.02424
CMS, arXiv: 1609.05391

Dark Forces

- Minimal or non-existent connections with the SM
- Evade current LHC limits
- Evade current direct detection limits
- What can we ask about it?



Dark Forces

Great session on this earlier this week!

- What type of force?
  Abelian – Dark U(1)
  Non-abelian – SU(N), SP(2N), SO(N), etc…

- What mass scale is involved?
  Confinement into massive particles
  Sets relevant energy scales

- Does it connect with the SM?
  Weak connections via particles charged under various light/dark gauge groups.

- Is it stable?
  Dark matter!

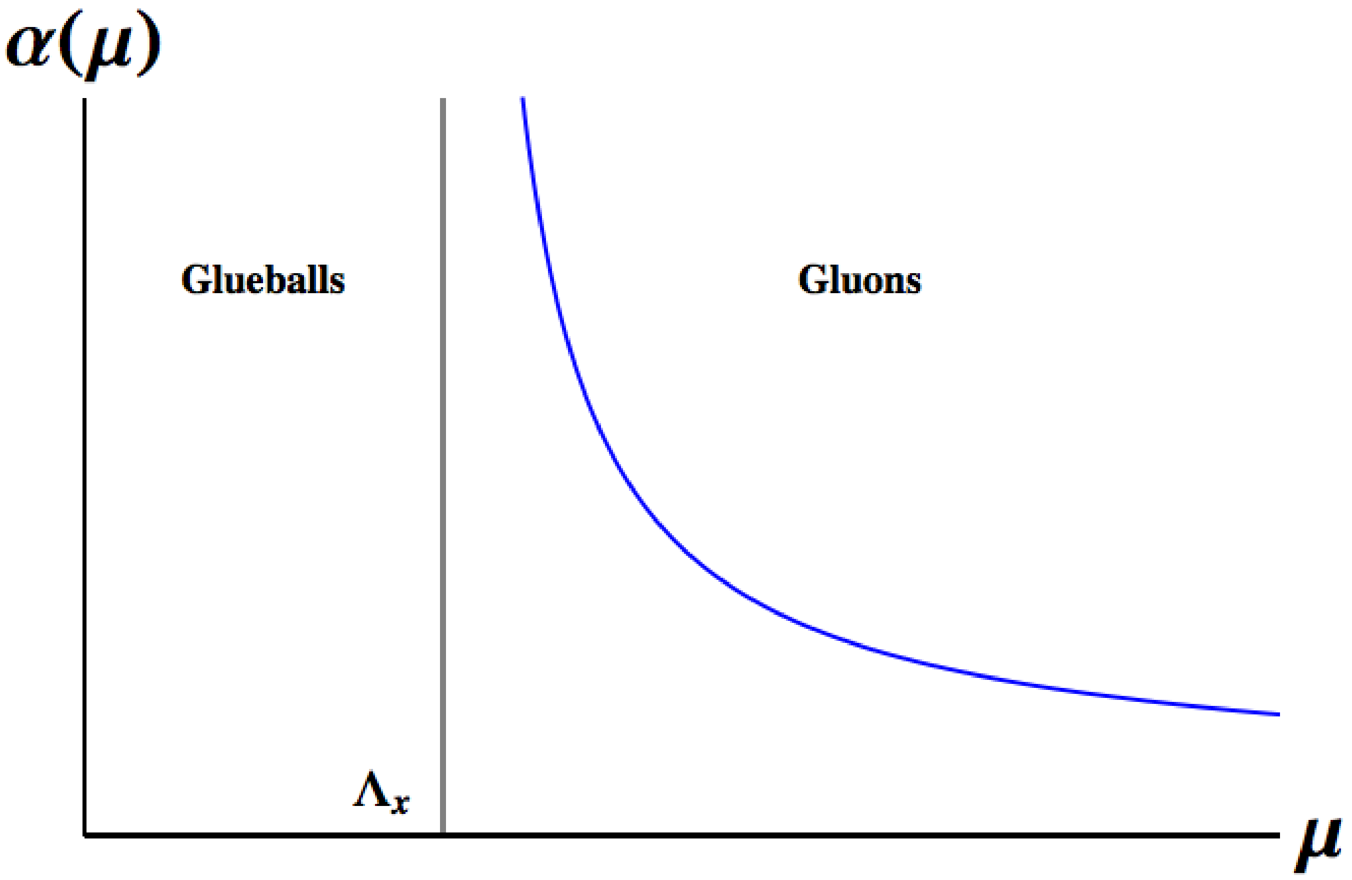
- HOW do we constrain it?

Move to a bigger lab!

Use cosmology and astrophysics to provide limits from the highest energies and earliest epochs in the Universe.

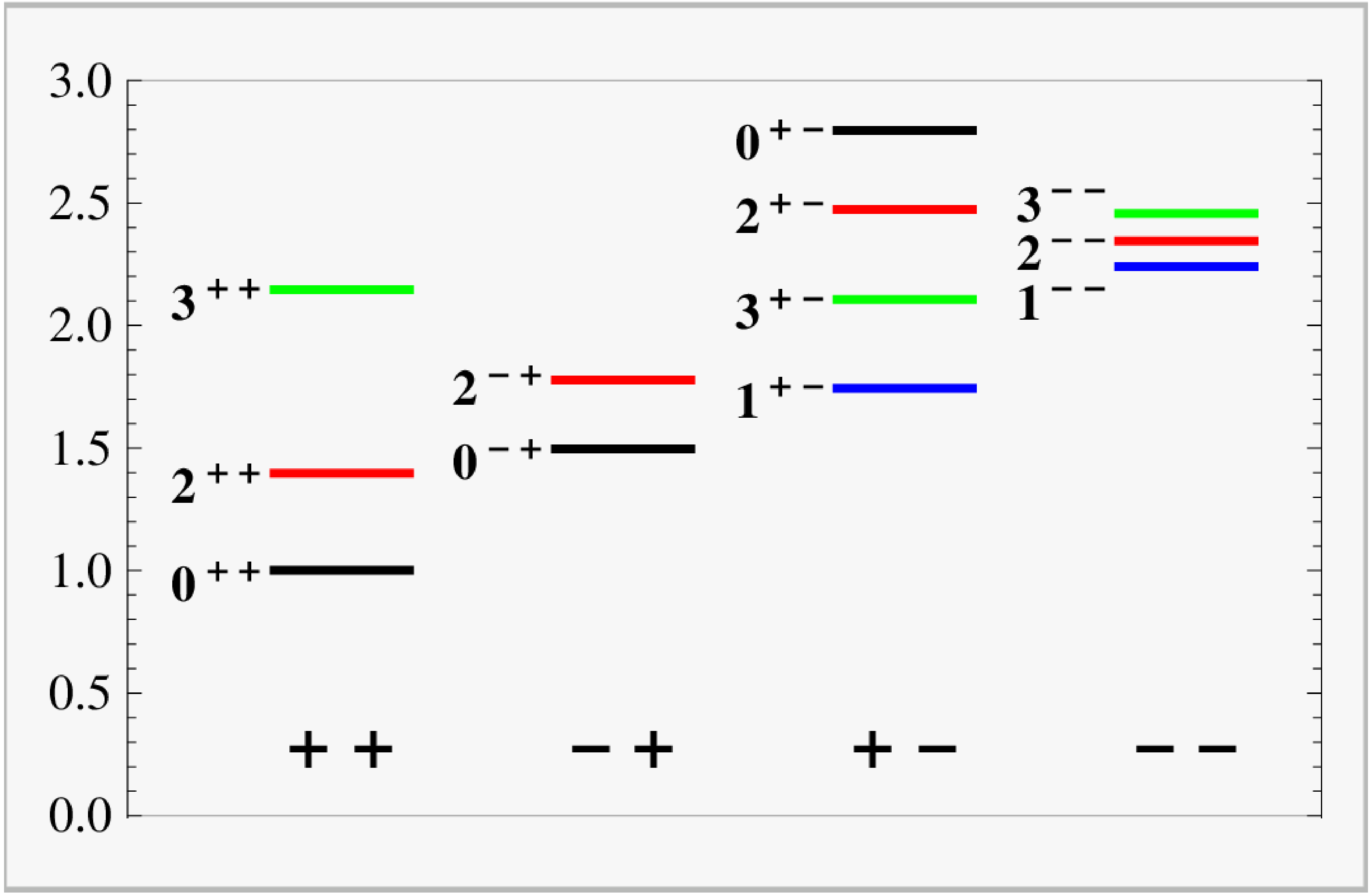
(Dark) SU(N)

$$\mathcal{L}_{eff} = -\frac{1}{16\pi\alpha_x(\mu)} X^a_{\mu\nu} X^{a\mu\nu}$$



- Focus on dark gauge SU(3)
- Evolution of the coupling with energy leads to confinement.
- At low energies, gluons confine into glueballs.

Glueball Spectrum



- Come from lattice calculations
- Classified according to J^{PC}
- Similar for larger N
- No c-odd states for SU(2)!
- Lightest is generically 0^{++}, m ~ $7\Lambda_x$

Juknevich, 2009
Morningstar, C. J. & Peardon, 1999

From Gluons to Glueballs..

$$\mathcal{L}_{eff} = -\frac{1}{16\pi\alpha_x(\mu)} X^a_{\mu\nu} X^{a\mu\nu}$$

$$\alpha_x N \rightarrow 4\pi$$

$$\frac{1}{N} X_{\mu\nu} X^{\mu\nu} \rightarrow finite$$

$$\frac{1}{N} X_{\mu\nu} X^{\mu\nu} \rightarrow F(\phi, \partial_\mu, m_x)$$

Large N Scaling

NDA

From Gluons to Glueballs..

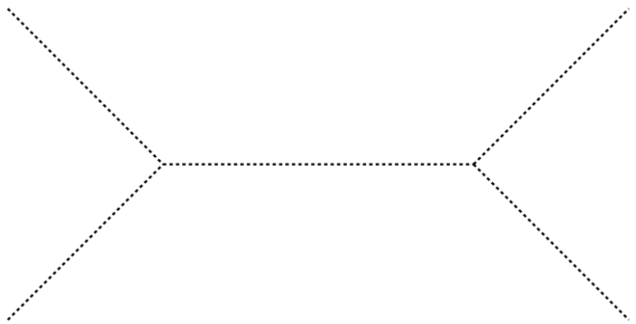
$$\mathcal{L}_{eff} = -\frac{1}{16\pi\alpha_x(\mu)} X^a_{\mu\nu} X^{a\mu\nu}$$

Identify m with the mass
of the lightest scalar field

$$\mathcal{L}_{eff} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - m^4 \sum_{n\geq 3} \frac{a_n}{n!} \left(\frac{4\pi}{N}\right)^{n-2} \left(\frac{\phi}{m}\right)^n$$

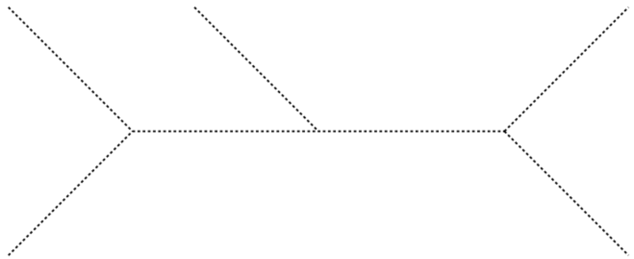
Expand function to include
all possible interactions

Glueball Interactions



$$\langle \sigma_{2\to 2} v \rangle \simeq \frac{1}{4\pi}\left(\frac{4\pi}{N}\right)^4 \frac{\beta}{s}$$

Self-interactions for glueballs today imply that m> 100 MeV.



$$\langle \sigma_{3\to 2} v^2 \rangle \simeq \frac{1}{(4\pi)^3}\left(\frac{4\pi}{N}\right)^6 \frac{1}{m_x^5}$$

Without SM interactions, only way to change the number of 0^{++} glueballs.

Multiple Glueball Interactions

Allow any interactions that conserve good symmetries : J^{PC}

$$i + j \to k + l$$

Limit to 2 to 2 interactions (3 to 2 only affects lightest state considerably).

$$C_i C_j = C_k C_l$$

C conservation implies many C-odd/even interactions will not be allowed

$$P_i P_j = (-1)^L P_k P_l$$

P conservation implies that many more interactions will be velocity suppressed for non-relativistic particles

$$\langle \sigma v \rangle_{ijkl} \sim \frac{(4\pi)^3}{N^4} \frac{\beta_{ijkl}}{s_{ij}} c_L \left(\frac{2}{x_i + x_j} \right)^L$$

Couplings   Kinematics   Velocity Suppression

Standard Model – Glueball Interactions

$$\mathcal{O}^{(6)} \sim \frac{1}{M^2} H^\dagger H tr(XX)$$

$$\mathcal{O}^{(8a)} \sim \frac{1}{M^4} tr(F_{SM} F_{SM}) tr(XX)$$

$$\mathcal{O}^{(8b)} \sim \frac{1}{M^4} B_{\mu\nu} tr(XXX)^{\mu\nu}$$

- Non-renormalizable interactions with the SM are possible.
- Integrate out massive fermions charged under both SM and dark gauge groups.
- Couple a darkly charged scalar mediator through a Higgs portal.

Standard Model – Glueball Interactions

$$tr(XXX) \to 1^{+-}$$
$$tr(XX) \to 0^{++}$$

$$\mathcal{O}^{(6)} \sim \frac{1}{M^2} H^\dagger H \, tr(XX)$$

$$\Gamma_6 \sim \frac{m_0^5}{M^4}$$

Only the 0^{++} can decay through dimension 6.

$$\mathcal{O}^{(8a)} \sim \frac{1}{M^4} tr(F_{SM} F_{SM}) tr(XX)$$

$$\Gamma_8 \sim \frac{m_0^9}{M^8}$$

Dimension 6 decays are parametrically earlier than dimension 8.

$$\mathcal{O}^{(8b)} \sim \frac{1}{M^4} B_{\mu\nu} tr(XXX)^{\mu\nu}$$

Violates C in the dark sector

If C_x is a good symmetry, then the 1^{+-} will be stable.

Glueball Cosmology

Start simple: single glueball state.

$$H^2 = \frac{1}{3M_{PL}^2}\rho = g_* \frac{\pi^2}{90}\frac{1}{M_{PL}^2}T^4$$

Yield is set by the 3 to 2 interactions.

$$\dot{n} + 3Hn = -\langle \sigma v^2 \rangle_{32}(n^3 - n^2\bar{n})$$

Hubble expansion

$3 \to 2$ dilution

$$\bar{n}_x = g_x \left(\frac{m_x T_x}{2\pi}\right)^{3/2} e^{-m_x/T_x}$$

Glueball Cosmology

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Yield is set by the 3 to 2 interactions.

$$H^2 = \frac{1}{3M_{PL}^2}\rho = g_* \frac{\pi^2}{90}\frac{1}{M_{PL}^2}T^4$$

$T_x \neq T$!

$$\dot{n} + 3Hn = -\langle \sigma v^2 \rangle_{32}(n^3 - n^2\bar{n})$$

Hubble expansion

$3 \rightarrow 2$ dilution

$$\bar{n}_x = g_x \left(\frac{m_x T_x}{2\pi}\right)^{3/2} e^{-m_x/T_x}$$

Assumptions

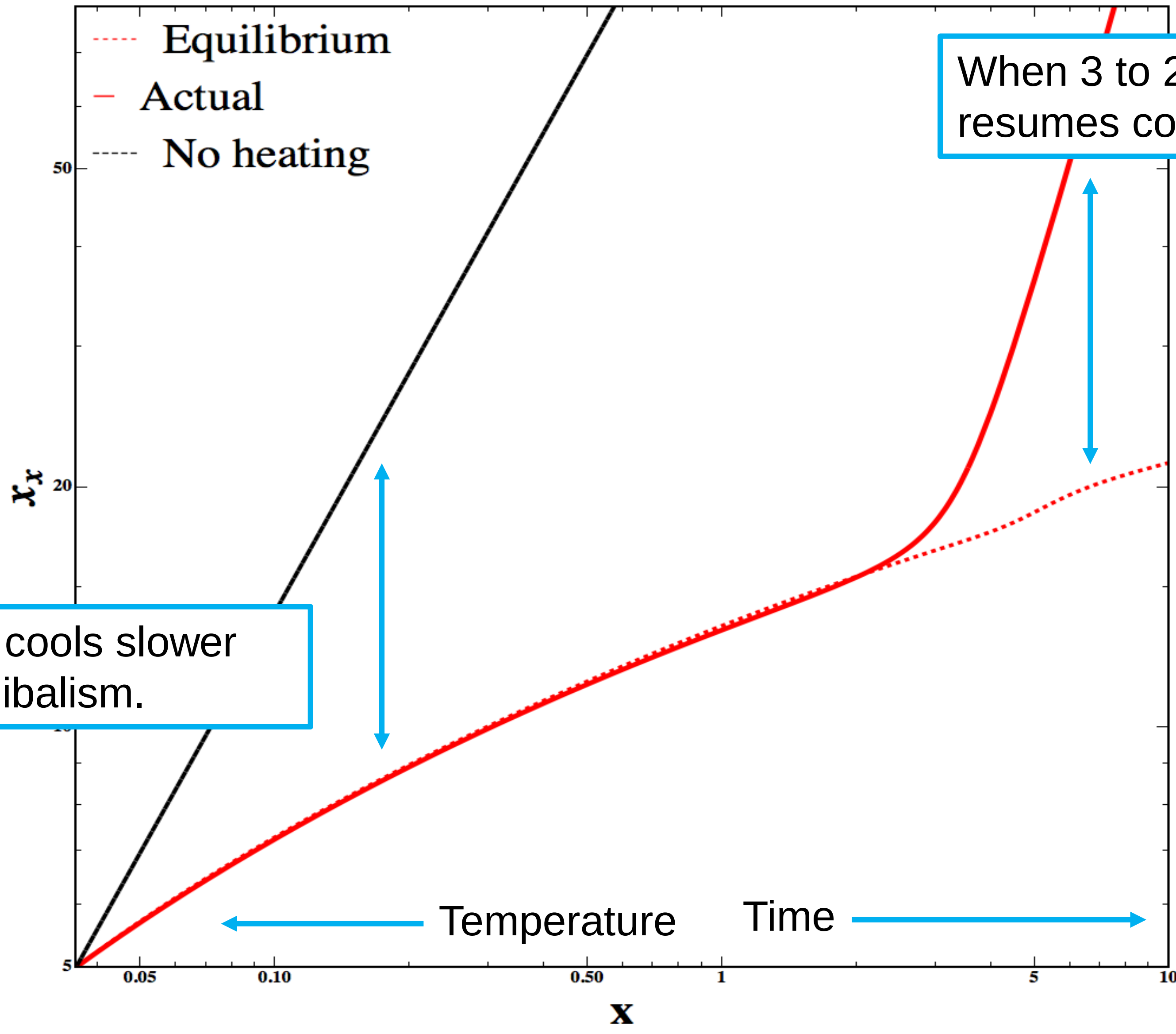
- Dark sector is thermally decoupled
- Inflation (or something like it) and reheating occurred
  - Heats the two sectors independently: $T > T_x > m$
- Glueballs self-thermalize
- Both sectors evolve adiabatically
  - Use variable, R, as a parameter in the model
- This gives us enough information to solve for the dynamical evolution
  - Can determine $T_x(T)$

Entropy Conservation:

$$R = \frac{s_x(T_x)}{s(T)} = constant$$

$$T_x s_x = \rho_x + P_x - \mu_x n_x$$

Temperature Evolution



When 3 to 2 interactions turn off, resumes cooling as normal.

Dark temperature cools slower due to 3 to 2 cannibalism.

Adding More Glueballs: C-Even

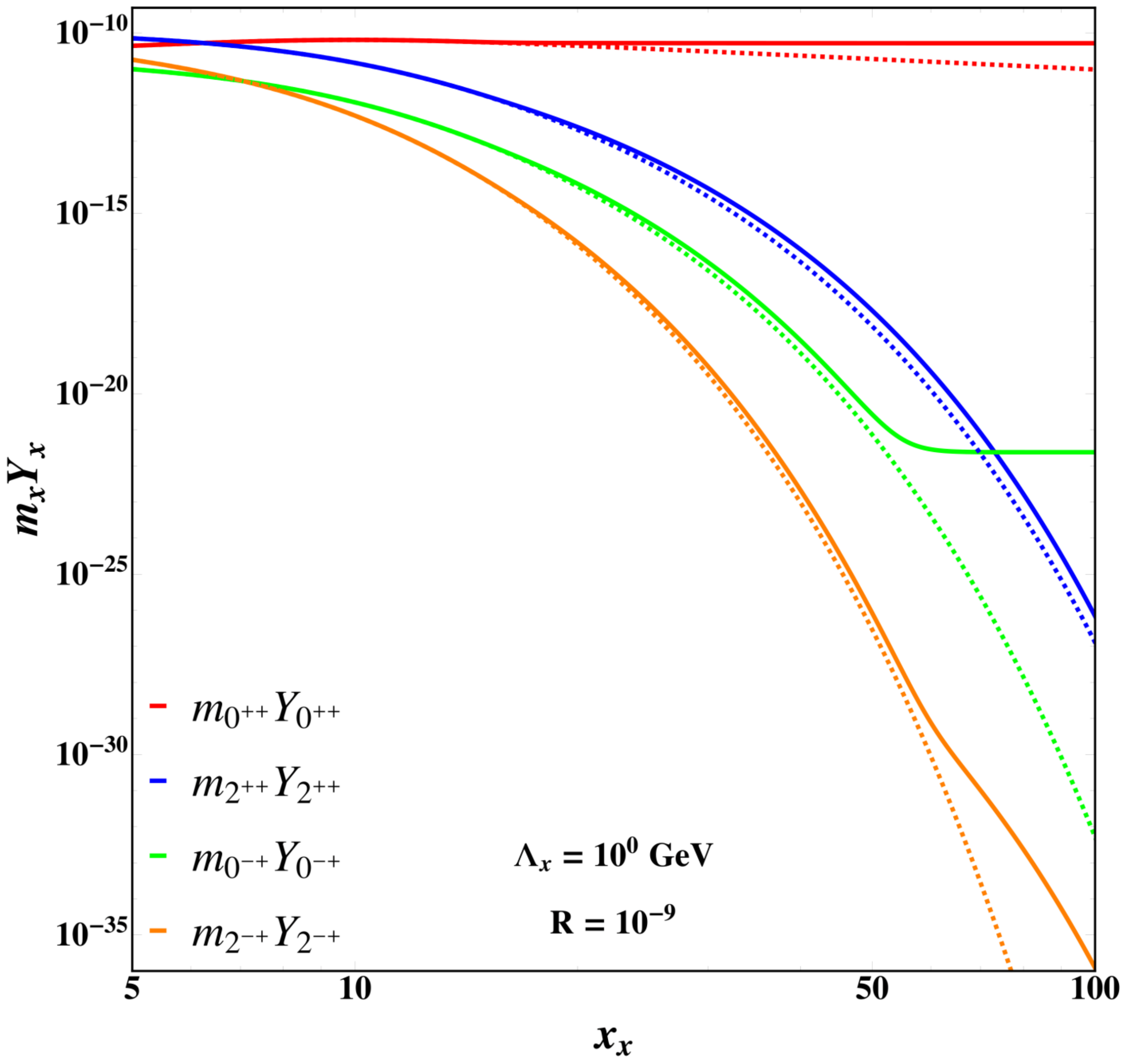
$$\begin{aligned}
\dot{n}_1 + 3Hn_1 = & -\langle\sigma_{32}v^2\rangle n_1^2(n_1 - \bar{n}_1) \\
& -\frac{1}{2}\langle\sigma v\rangle_{2111}\left[\frac{\bar{n}_2}{\bar{n}_1}n_1 n_2 - n_2^2\right] \\
& -\langle\sigma v\rangle_{2211}\left[\frac{\bar{n}_2}{\bar{n}_1}^2 n_1^2 - n_2^2\right] \\
& -\frac{1}{2}\langle\sigma v\rangle_{2214}\left[\frac{\bar{n}_2^2}{\bar{n}_1\bar{n}_4}n_1 n_4 - n_2^2\right] \\
& -\frac{1}{2}\langle\sigma v\rangle_{2415}\left[\frac{\bar{n}_2\bar{n}_4}{\bar{n}_1\bar{n}_5}n_1 n_5 - n_2 n_4\right] \\
\dot{n}_2 + 3Hn_2 = & +\frac{1}{2}\langle\sigma v\rangle_{2111}\left[\frac{\bar{n}_2}{\bar{n}_1}n_1 n_2 - n_2^2\right] \\
& +\langle\sigma v\rangle_{2211}\left[\frac{\bar{n}_2}{\bar{n}_1}^2 n_1^2 - n_2^2\right] \\
& +\langle\sigma v\rangle_{2214}\left[\frac{\bar{n}_2^2}{\bar{n}_1\bar{n}_4}n_1 n_4 - n_2^2\right] \\
& +\frac{1}{2}\langle\sigma v\rangle_{2415}\left[\frac{\bar{n}_2\bar{n}_4}{\bar{n}_1\bar{n}_5}n_1 n_5 - n_2 n_4\right] \\
& -\frac{1}{2}\langle\sigma v\rangle_{1512}\left[\frac{\bar{n}_1\bar{n}_5}{\bar{n}_1\bar{n}_2}n_1 n_2 - n_1 n_5\right] \\
\dot{n}_4 + 3Hn_4 = & -\frac{1}{2}\langle\sigma v\rangle_{2214}\left[\frac{\bar{n}_2^2}{\bar{n}_1\bar{n}_4}n_1 n_4 - n_2^2\right] \\
& +\frac{1}{2}\langle\sigma v\rangle_{2415}\left[\frac{\bar{n}_2\bar{n}_4}{\bar{n}_1\bar{n}_5}n_1 n_5 - n_2 n_4\right] \\
\dot{n}_5 + 3Hn_5 = & -\frac{1}{2}\langle\sigma v\rangle_{2415}\left[\frac{\bar{n}_2\bar{n}_4}{\bar{n}_1\bar{n}_5}n_1 n_5 - n_2 n_4\right] \\
& +\frac{1}{2}\langle\sigma v\rangle_{1512}\left[\frac{\bar{n}_1\bar{n}_5}{\bar{n}_1\bar{n}_2}n_1 n_2 - n_1 n_5\right]
\end{aligned}$$

3→2

Coannihilations

Smaller number changing processes

- Can model independently of the c-odd states.
- Get a host of different freeze-out processes at play.



0^{++} dominates, and is largely unaffected by underlying states. (Relic density entirely set by 3 →2 process).

2^{++} depletes more efficiently relative to others due to coannihilation effects.

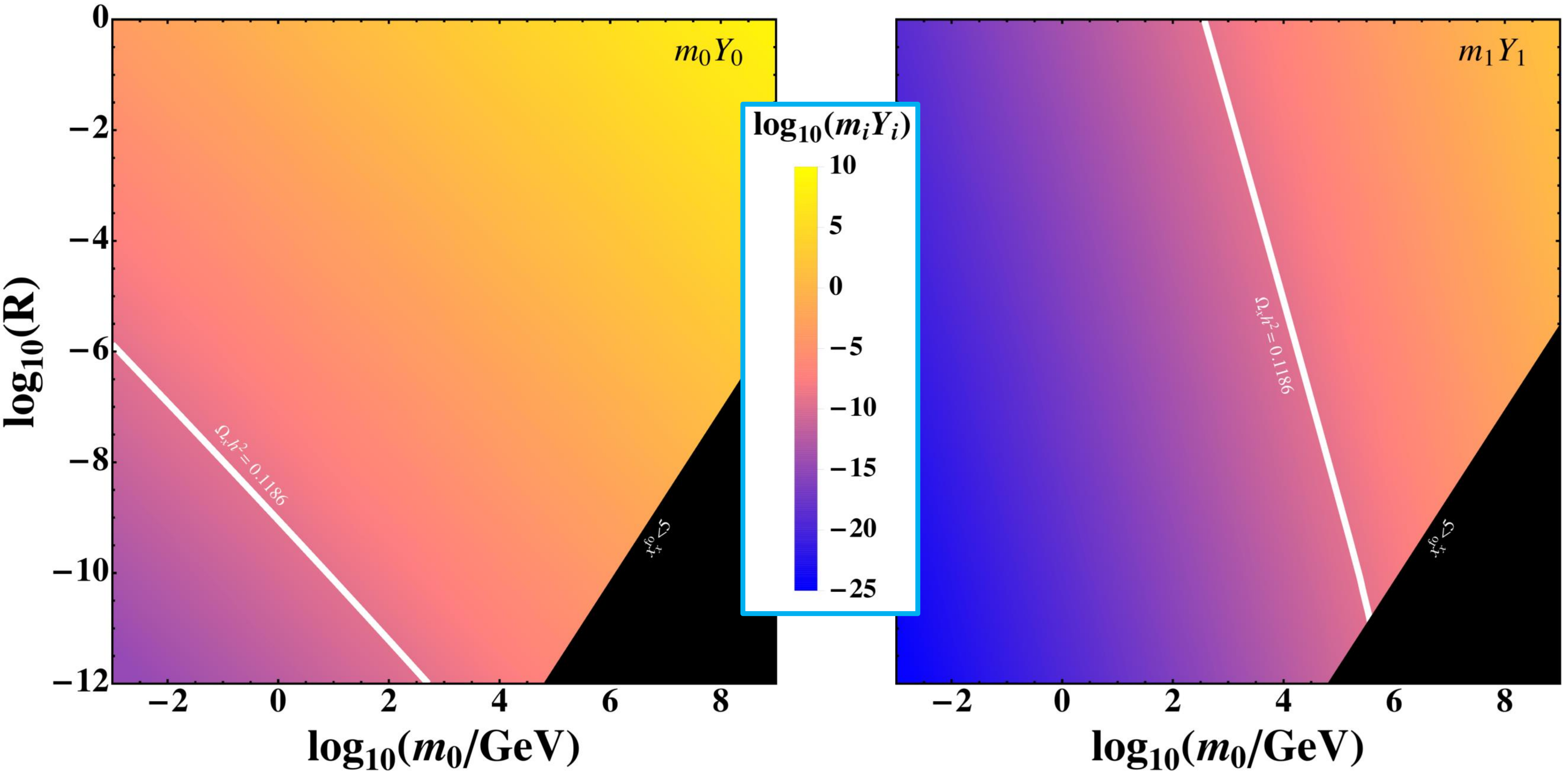
Forestell, Morrissey, Sigurdson, 2017

Adding More Glueballs: C-Odd

- Can model independently of the C-even states.
- Like the 0^{++} state, the 1^{+-} state largely dominates the C-odd relic yield.
- Coannihilations of heavier C-odd states reduce these heavier state yields.
- Sufficient to use a 2 state system consisting of only the 0^{++} and 1^{+-}

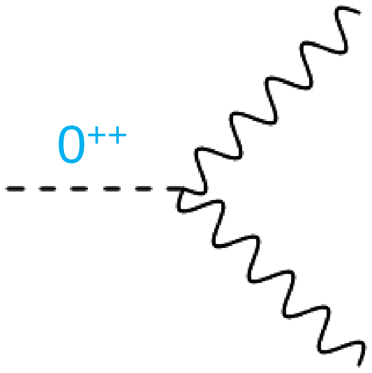
$$\begin{aligned}\dot{n}_0 + 3Hn_0 = &\ -\langle \sigma_{32} v^2 \rangle n_0^2 (n_0 - \bar{n}_1) \\ &+ \langle \sigma v \rangle_{1100} \left[n_1^2 - \left(\frac{n_0}{\bar{n}_0} \right)^2 \bar{n}_1^2 \right]\end{aligned}$$

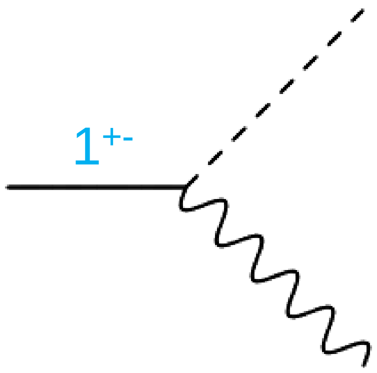
$$\dot{n}_1 + 3Hn_1 = -\langle \sigma v \rangle_{1100} \left[n_1^2 - \left(\frac{n_0}{\bar{n}_0} \right)^2 \bar{n}_1^2 \right]$$

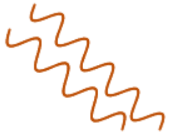


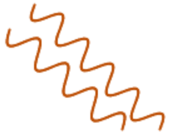
Forestell, Morrissey, Sigurdson, 2018

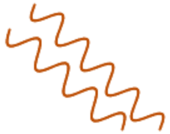
Cosmological Constraints









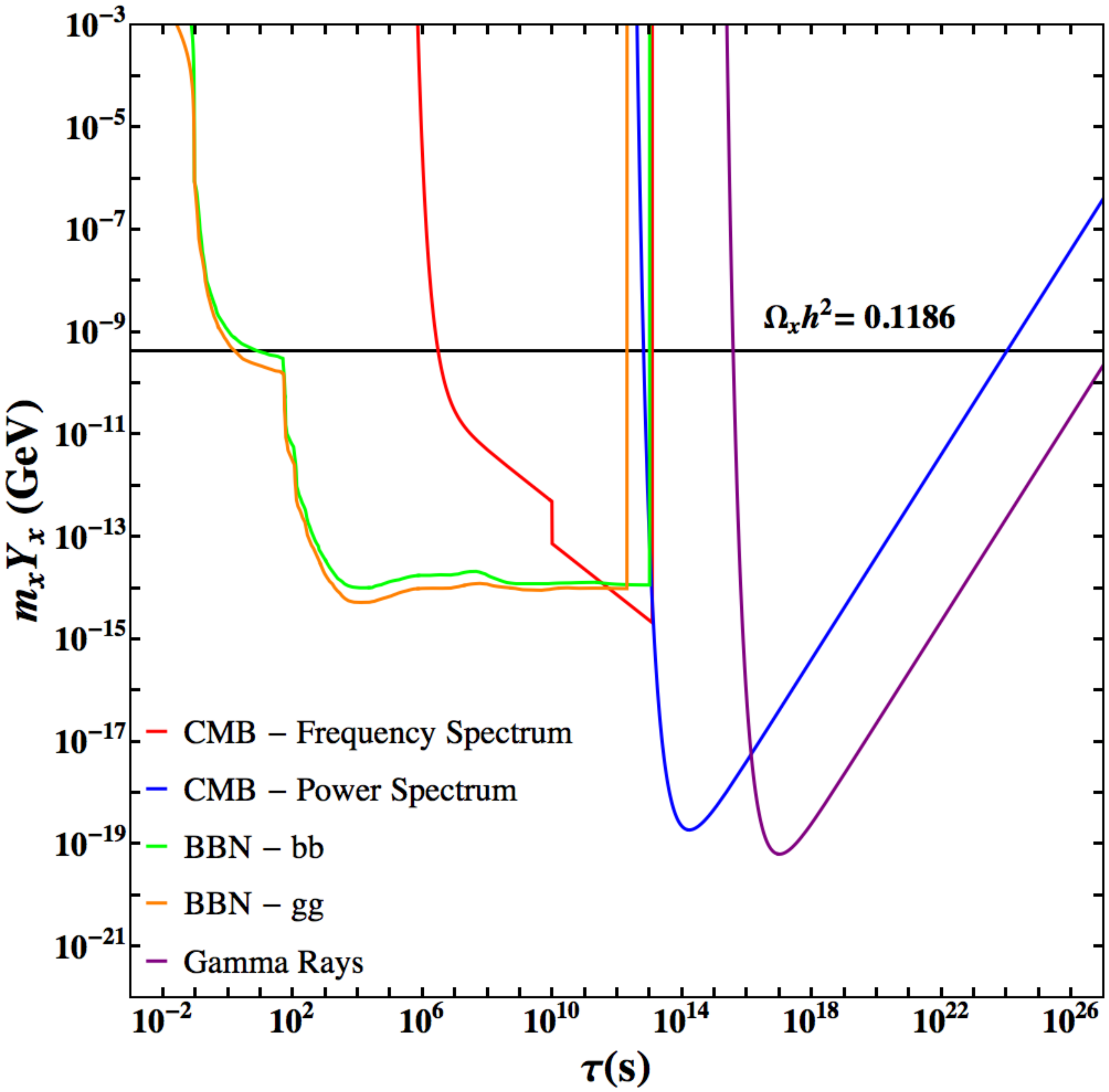


Big Bang → BBN → Recombination → Structure Formation → Today

~MeV
Light elements form

~eV
CMB forms

~meV
First stars, galaxies form



Kawasaki, 2004
Hu & Silk, 1993
Fradette, 2014
Cohen, 2016

Explicit Decay Scenarios

1. Dimension-8 decays with broken C_x

   All glueballs decay with parametrically similar rates.

2. Dimension-8 decays with exact C_x

   1^{+-} is stable.

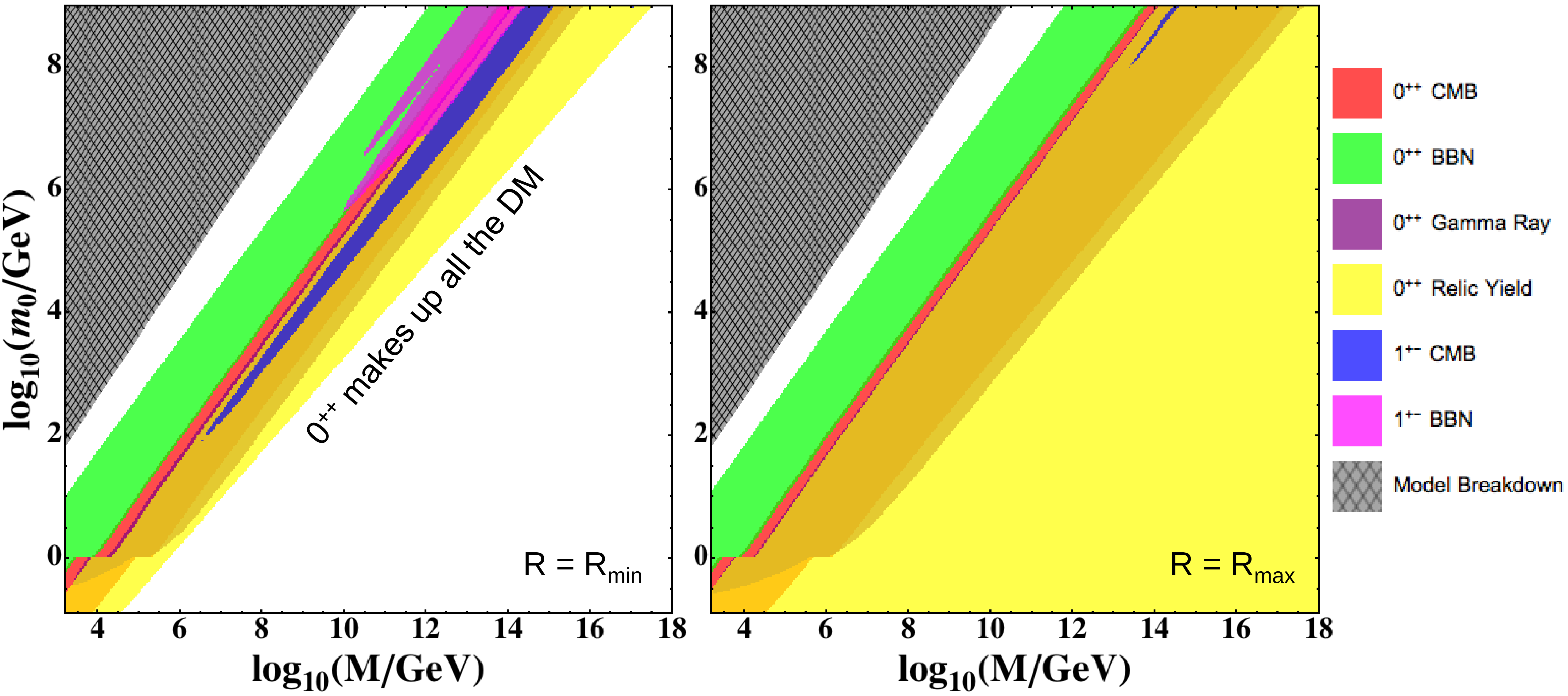
3. Dimension-6 decays with broken C_x

   Glueballs decay through the dimension-6 operator except for the C-odd 1^{+-} state, making it longer lived.

4. Dimension-6 decays with exact C_x

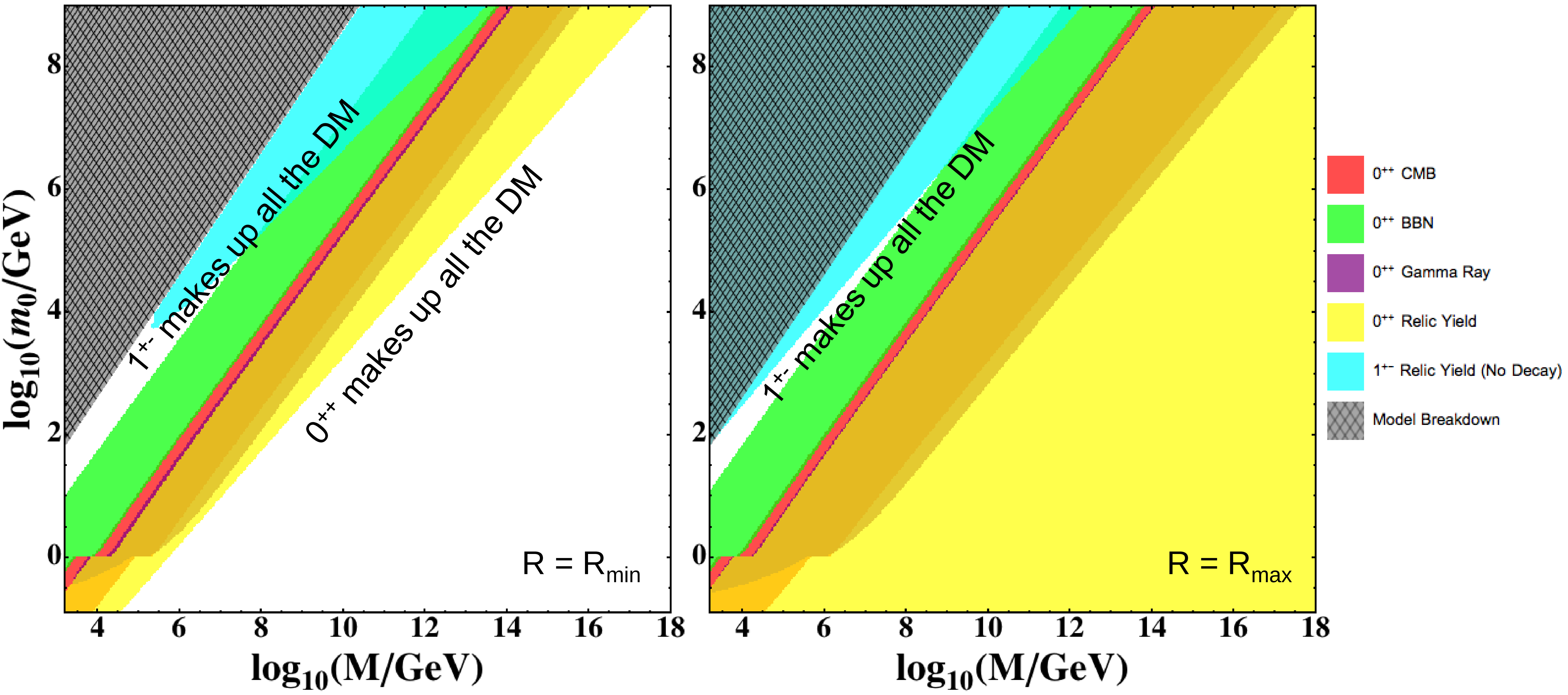
   1^{+-} is stable.

Dimension 8, Broken C_x



Forestell, Morrissey, Sigurdson, 2018

Dimension 8, Exact C_x



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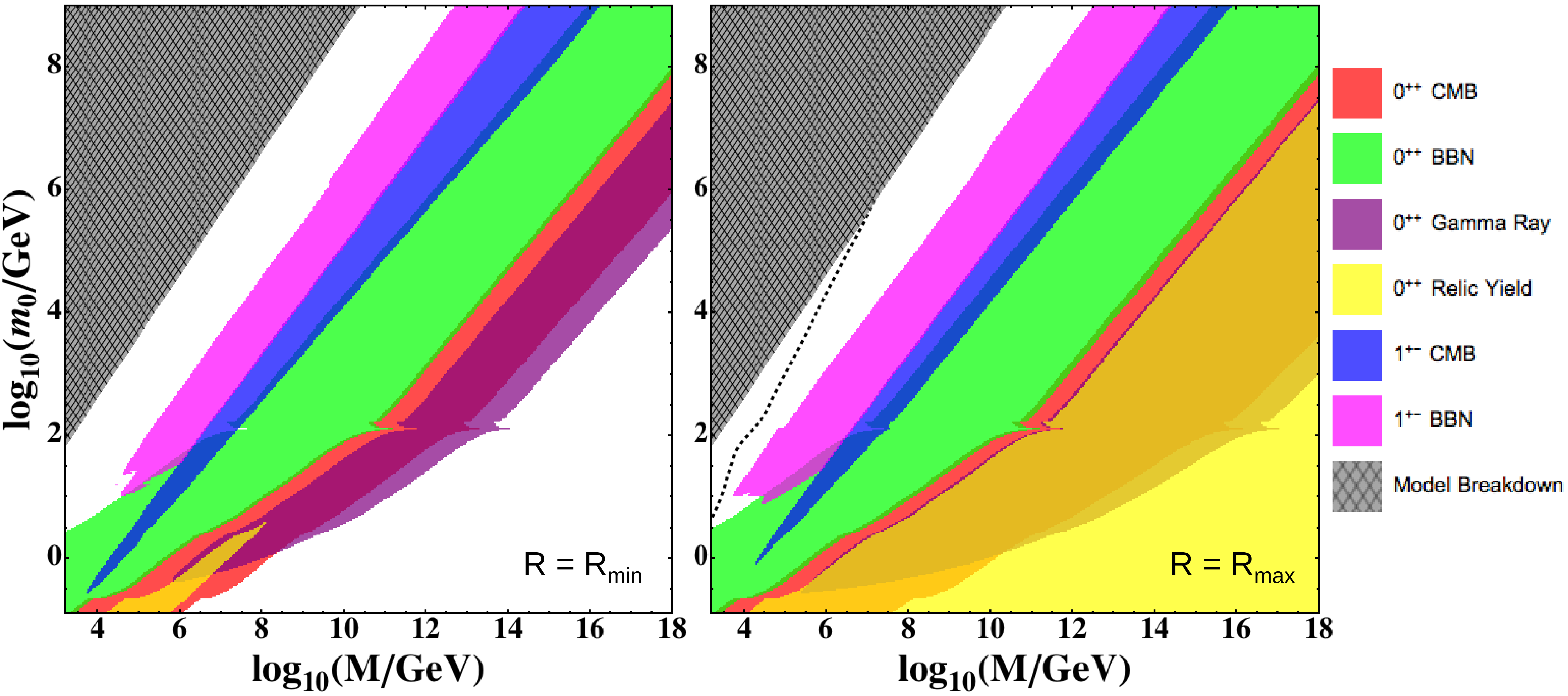
Dimension 6, Broken C_x



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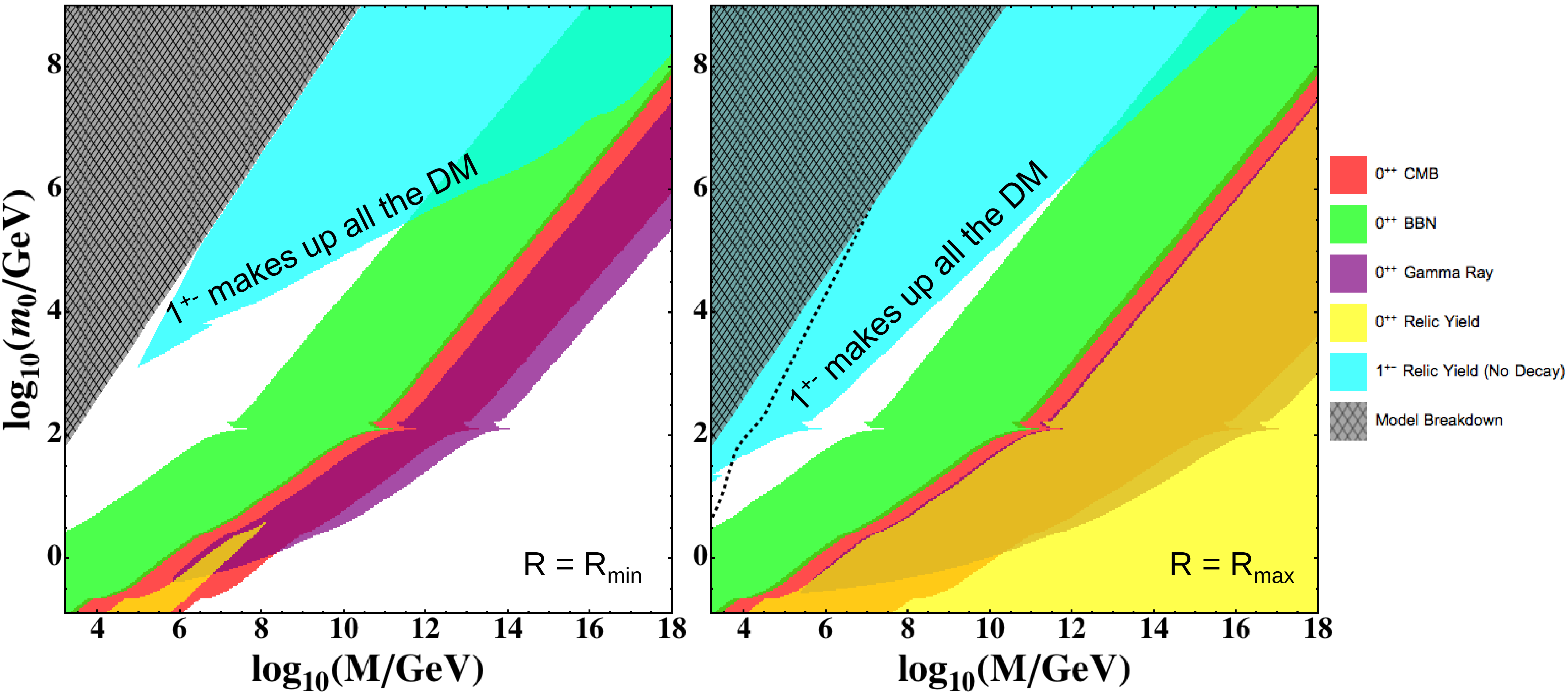
Dimension 6, Exact C_x



Forestell, Morrissey, Sigurdson, 2018

Summary

- Now is a good time to explore new dark gauge forces.
- Rich dynamics in the non-Abelian sector.
- Considered a spectrum of massive glueballs.
- Complicated freeze-out dynamics including a $3 \to 2$ cannibalism phase.
- Constrain the gauge based on lifetimes, using various cosmological laboratories.
- Constraints are placed on m, M, R.

Coming soon to a poster near you…

Phases of UV Dark Matter Freeze-In

Thank You!