CAP Congress 2019

Cosmological Bounds on Non-Abelian Dark Forces

PRD95, 015032, arXiv:1605.08048

PRD97, 075029, arXiv:1710.06447

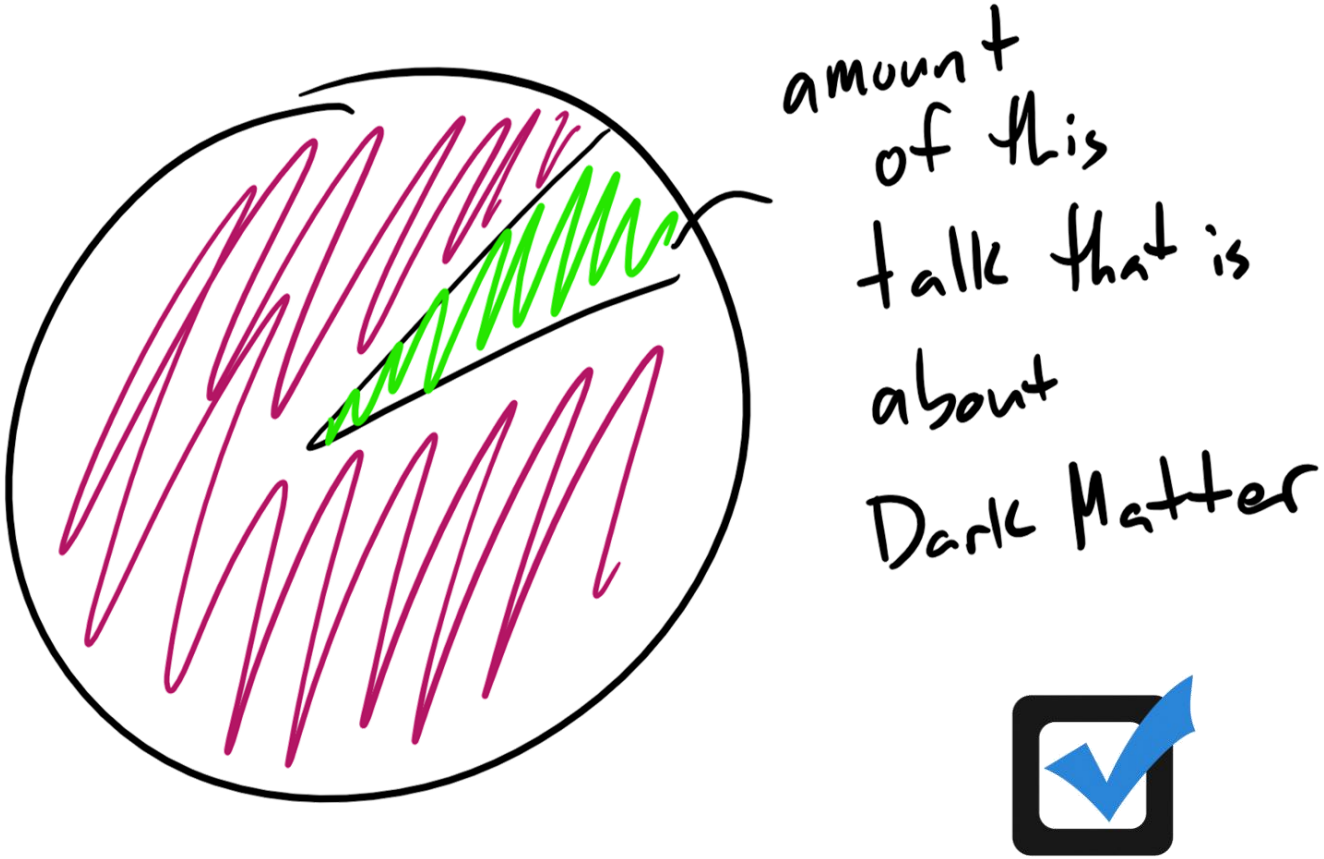
TRIUMF & UBC

Collaboration with David Morrissey & Kris Sigurdson

Lindsay Forestell

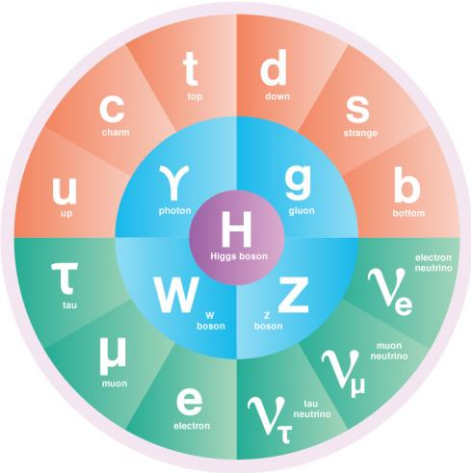
Outline

1. Motivations
2. Dark Glueballs
3. Cosmological Constraints



Standard Model(s)

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$



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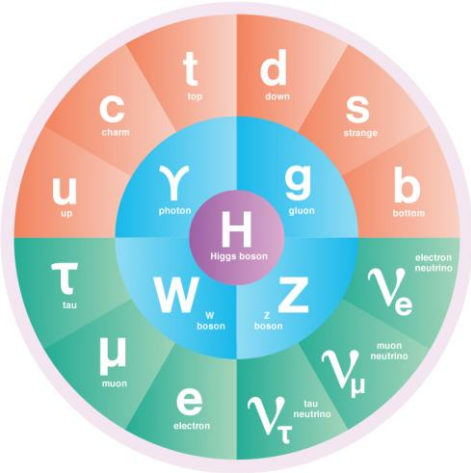
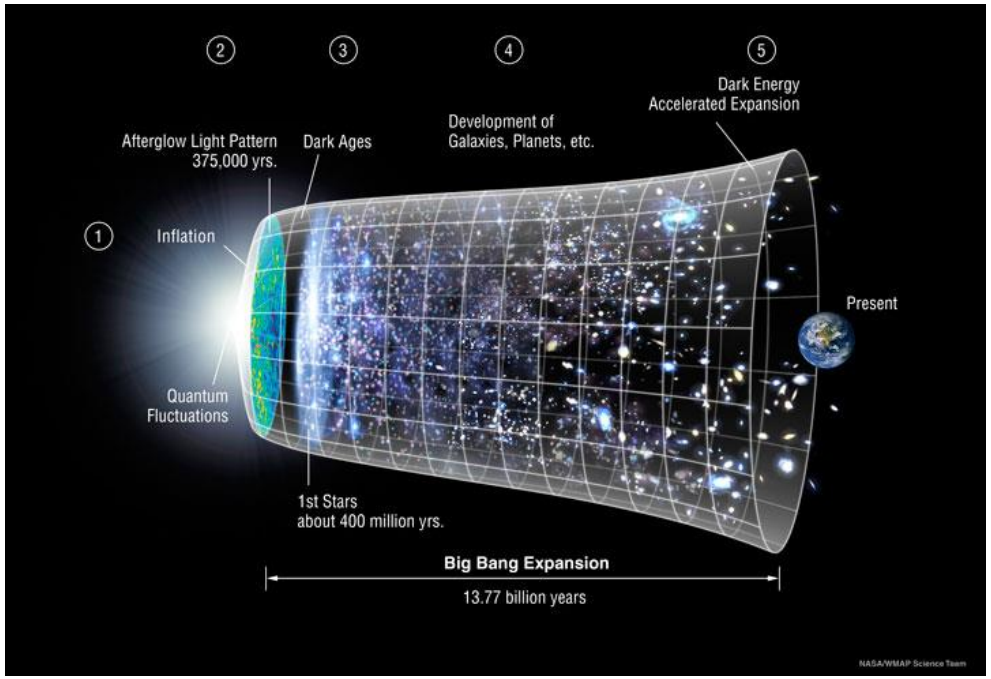
$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$+$$

$$\Lambda \times (\mathrm{C})\mathrm{DM} \times \mathrm{SM}$$





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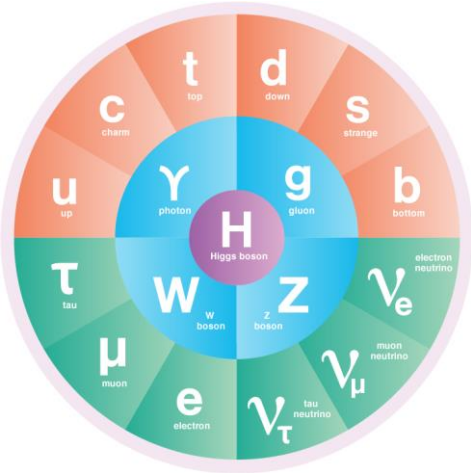
$$\mathrm{BSM}\ ???$$

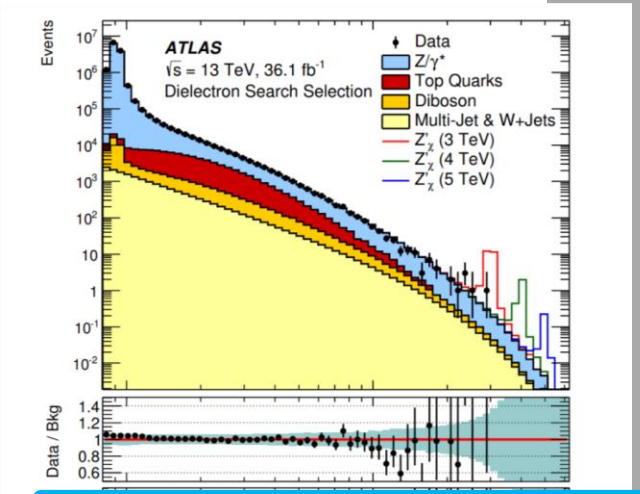


Missing pieces:

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

NASA/WMAP Science Team

BSM in Standard Searches?



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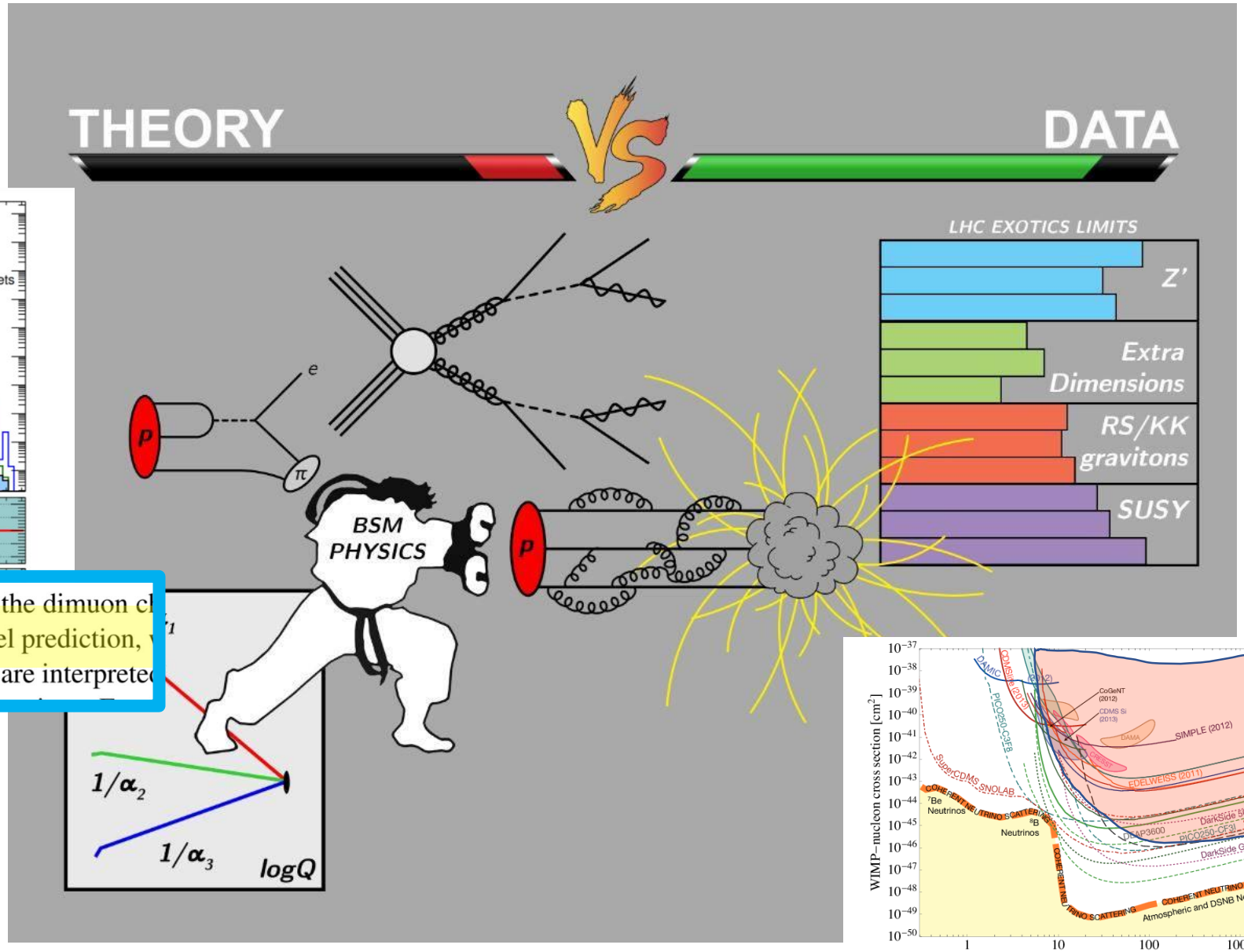
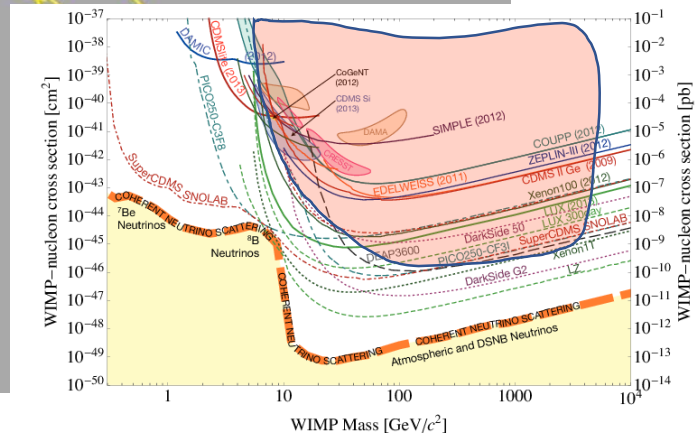




ATLAS, arXiv: 1707.02424

J. Cooley, arXiv:1410.4960

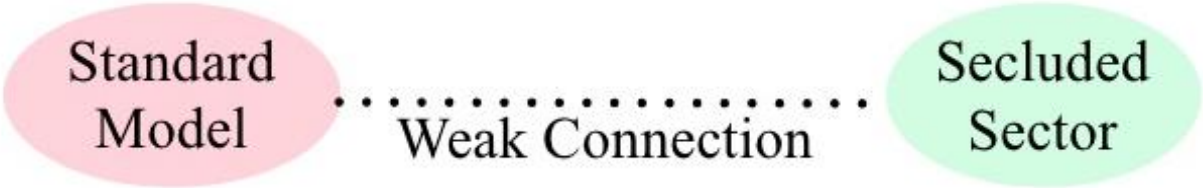
Lindsay Forestell

Move to a bigger lab?

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

Dark Forces

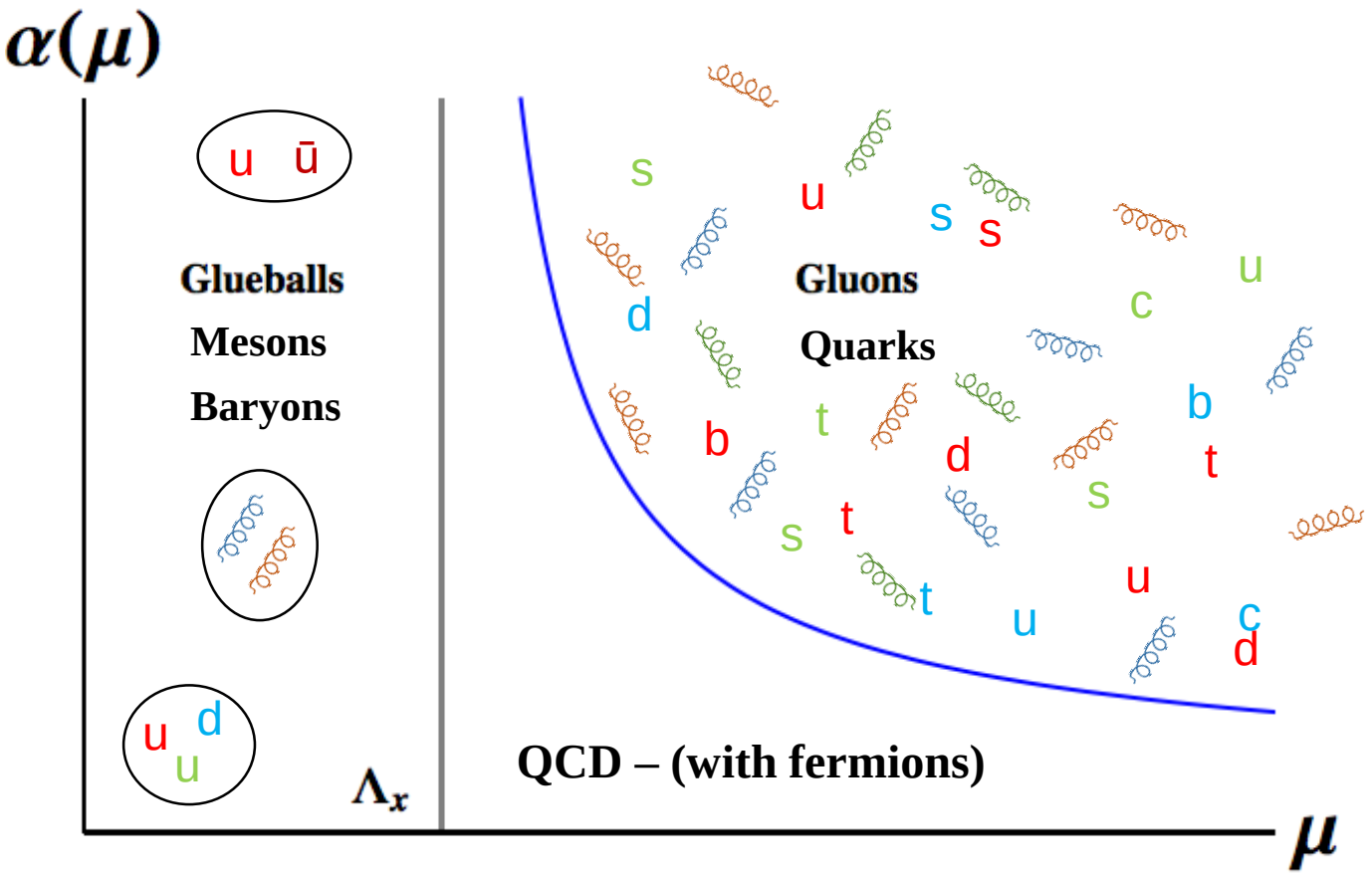
- Minimal or non-existent connections with the SM
- Evade current LHC limits
- Evade current direct detection limits
- What can we ask about it?
- **How do we constrain it?**



(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.



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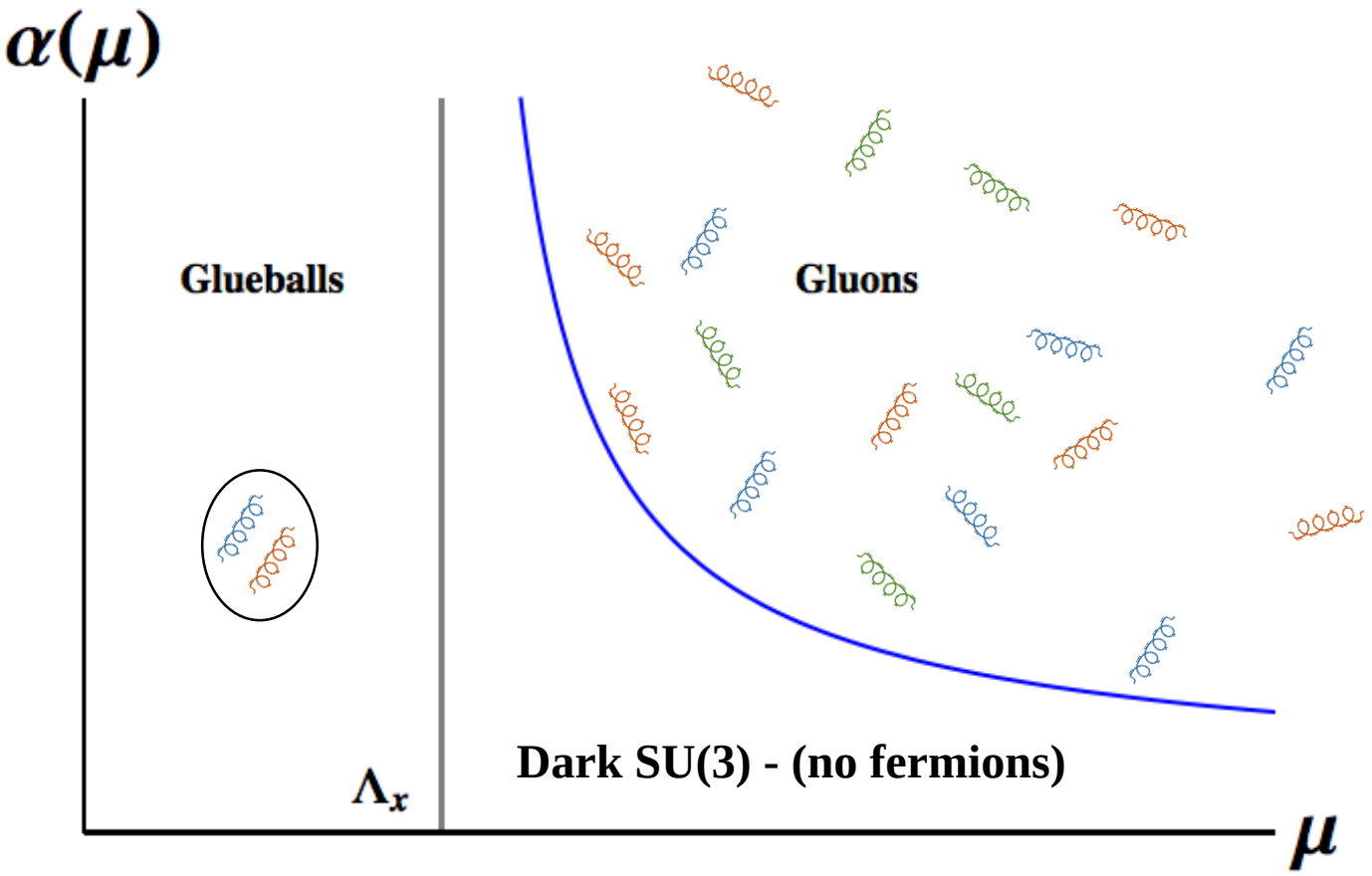
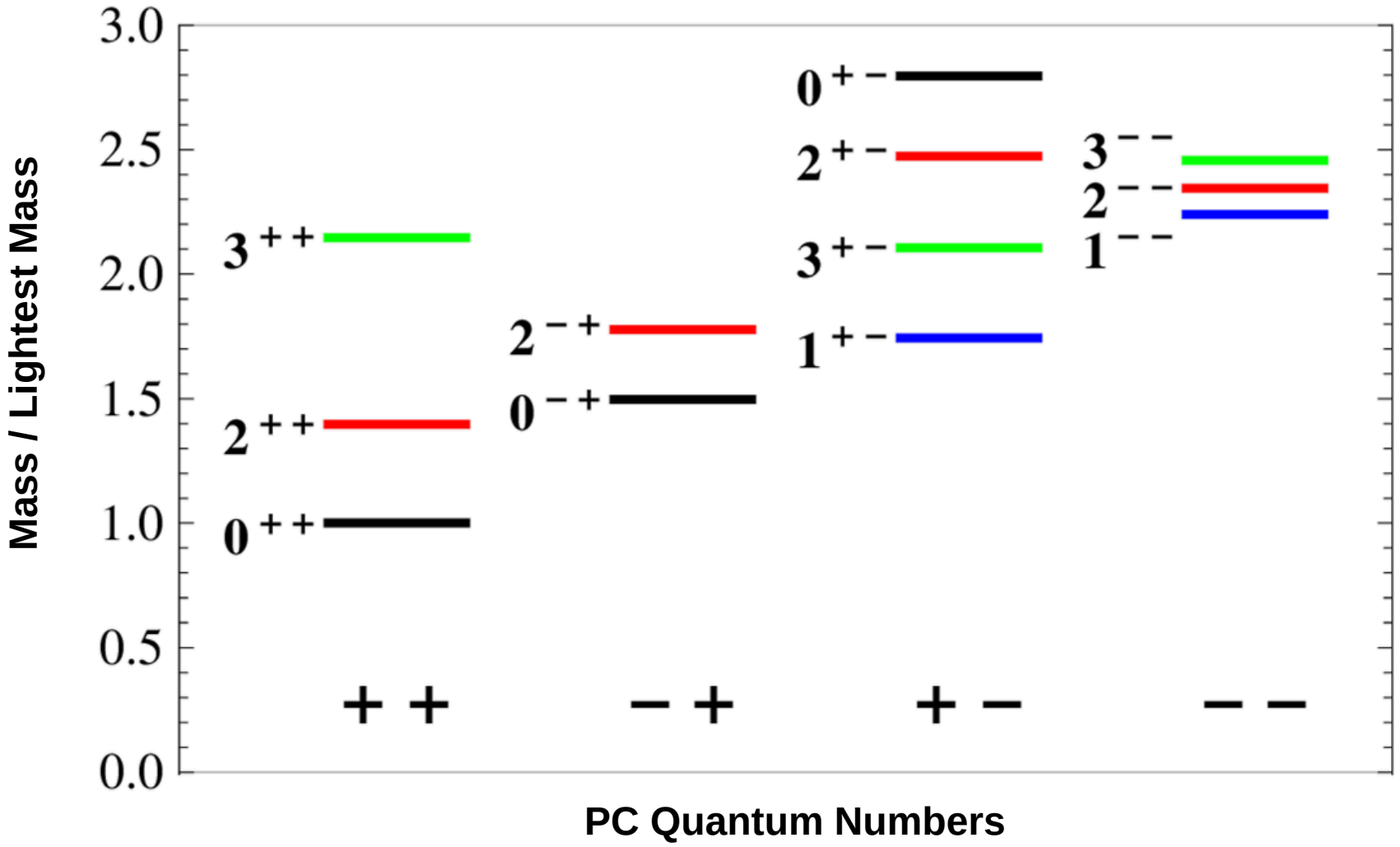


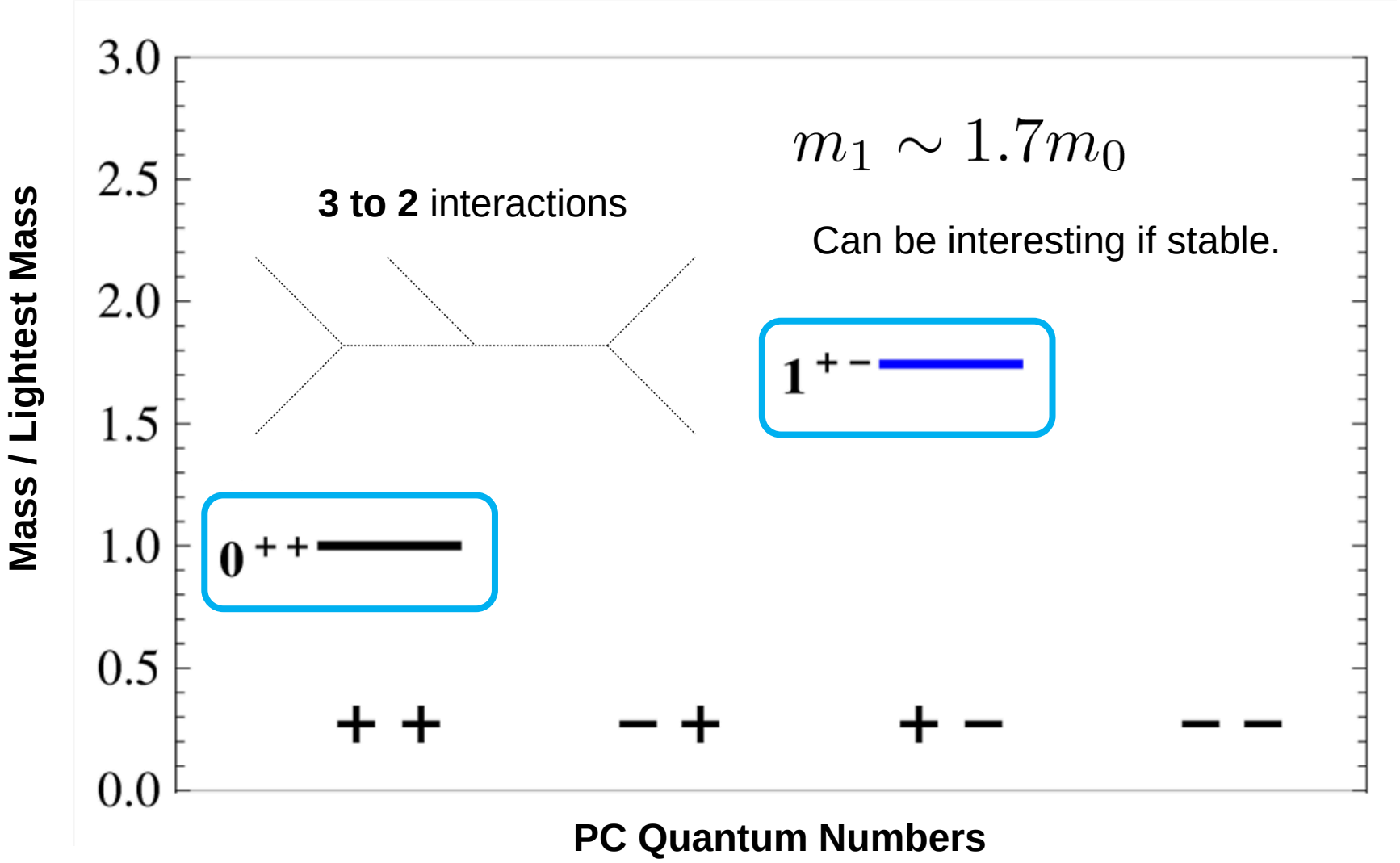
Glueball Spectrum



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

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

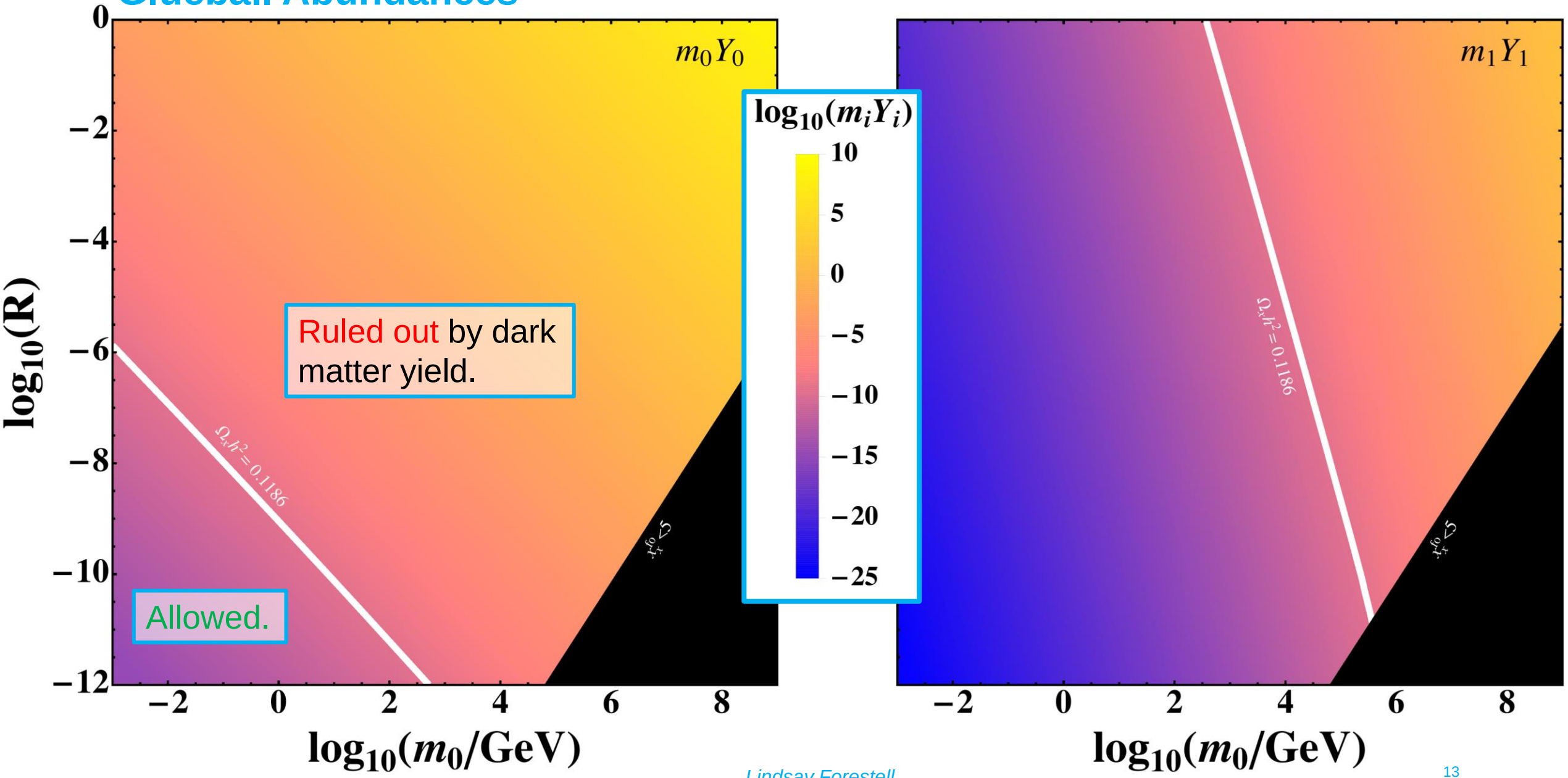
Glueball Spectrum



- Although we compute abundances with a large spectrum of glueballs, find only two states matter:
  - 0^{++} : most abundant. Has a unique **3 to 2** interaction that sets the relic yield.
  - 1^{+-} : may have important cosmological consequences if stable.

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

Glueball Abundances



Forestell, Morrissey, Sigurdson, 2018

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

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

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

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

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.

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

Violates C in the dark sector

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

Explicit Decay Scenarios

1. Dimension-8 decays with broken C_x
   All glueballs decay with parametrically similar rates.

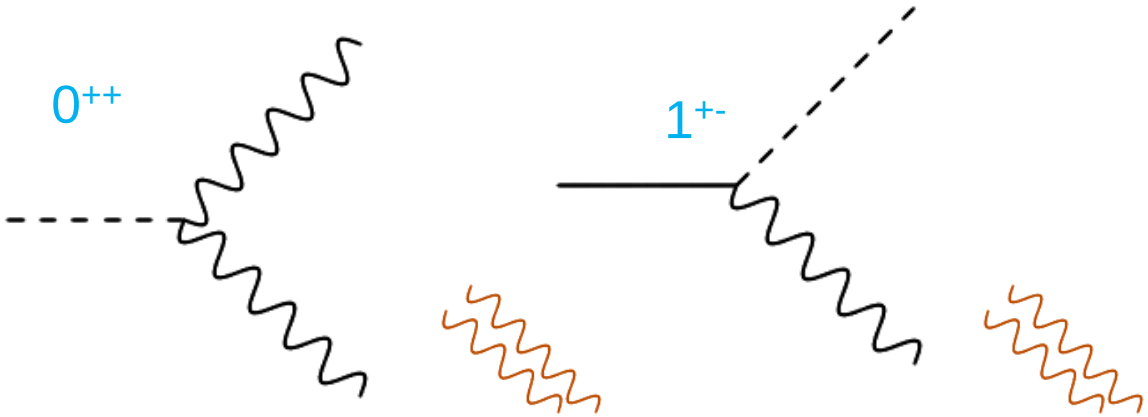
2. Dimension-8 decays with exact C_x
   1^{+-} is stable.

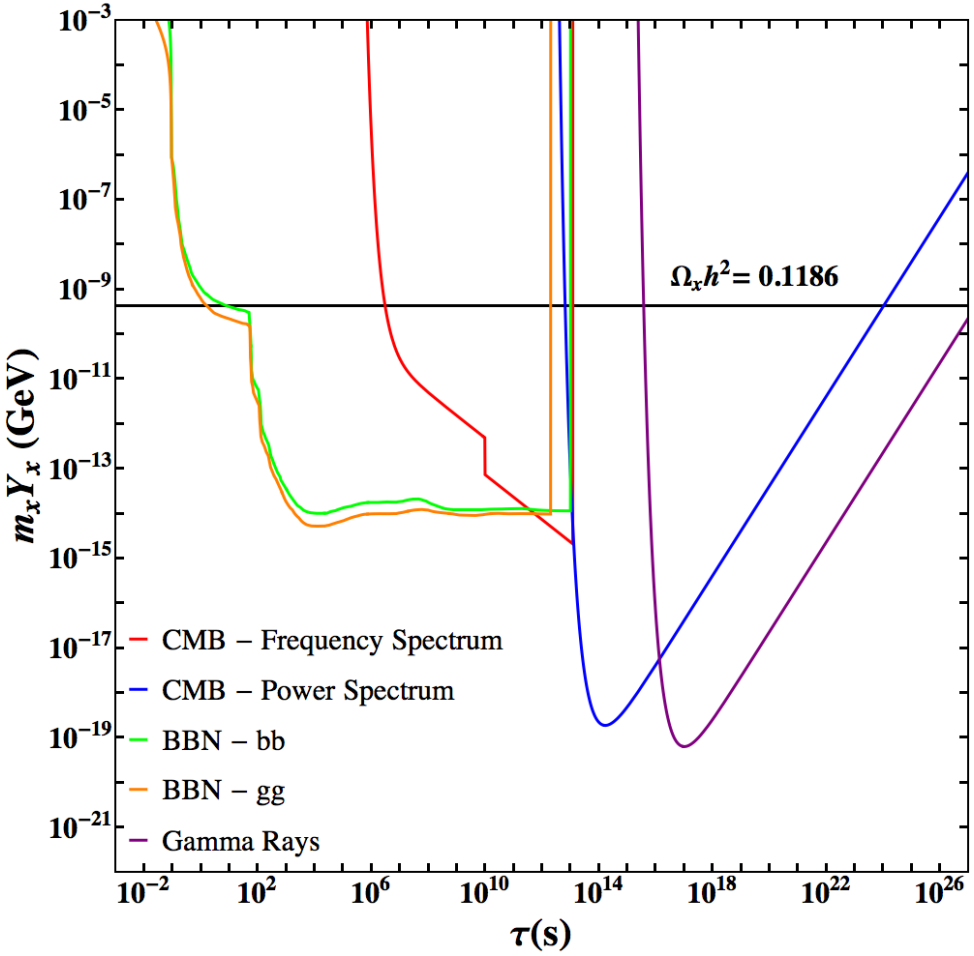
3. Dimension-6 decays with broken C_x
   Glueballs decay through the dimension-6 operator except for the C-odd 1^{+-} state, making it longer lived.

4. Dimension-6 decays with exact C_x
   1^{+-} is stable.

Cosmological Constraints

- As glueballs can decay over many different lifetimes, many various epochs of the Universe can be used to place constraints.





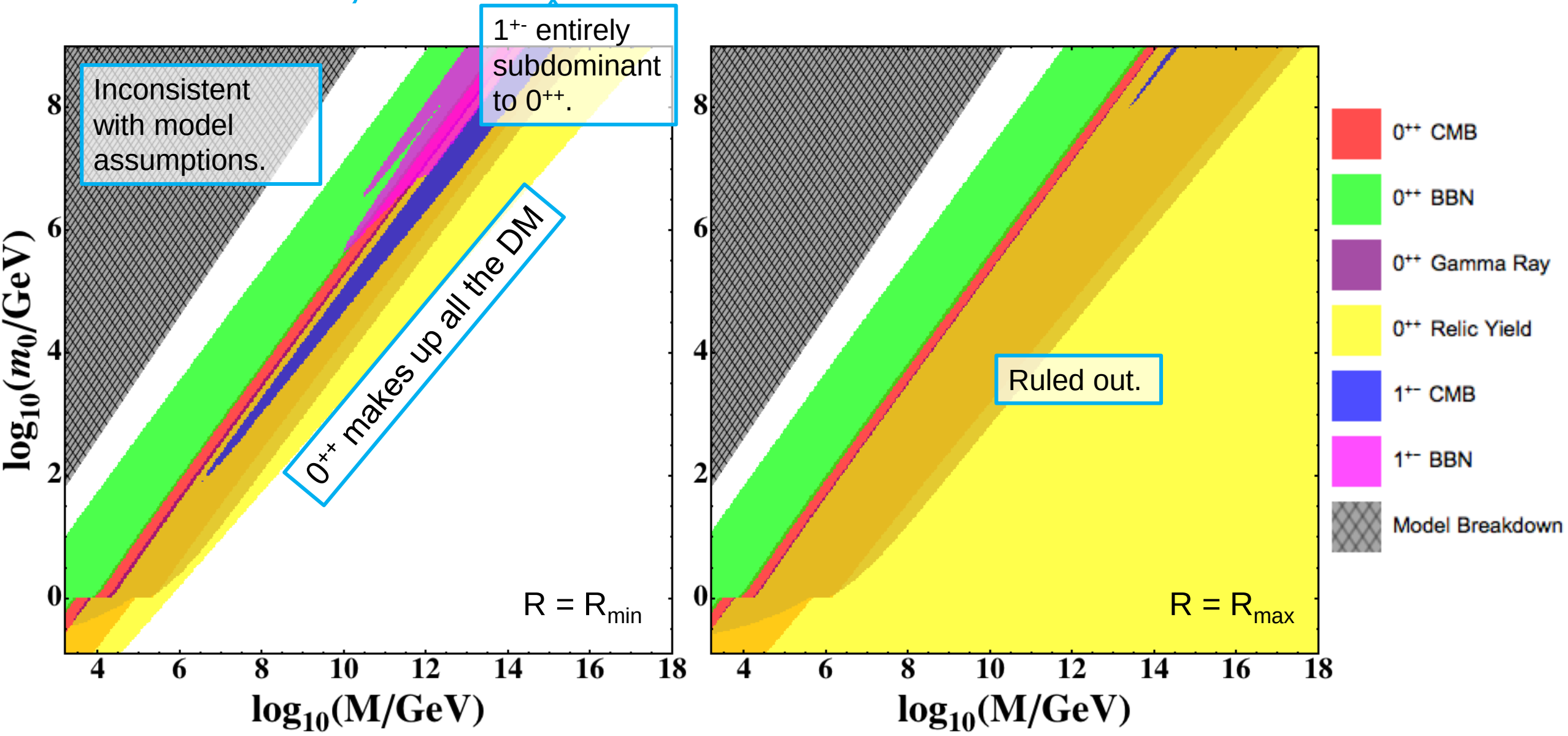
Big Bang? → BBN → Recombination → Today

~MeV (3 min.)
Light elements form

~eV (380, 000 years)
CMB forms

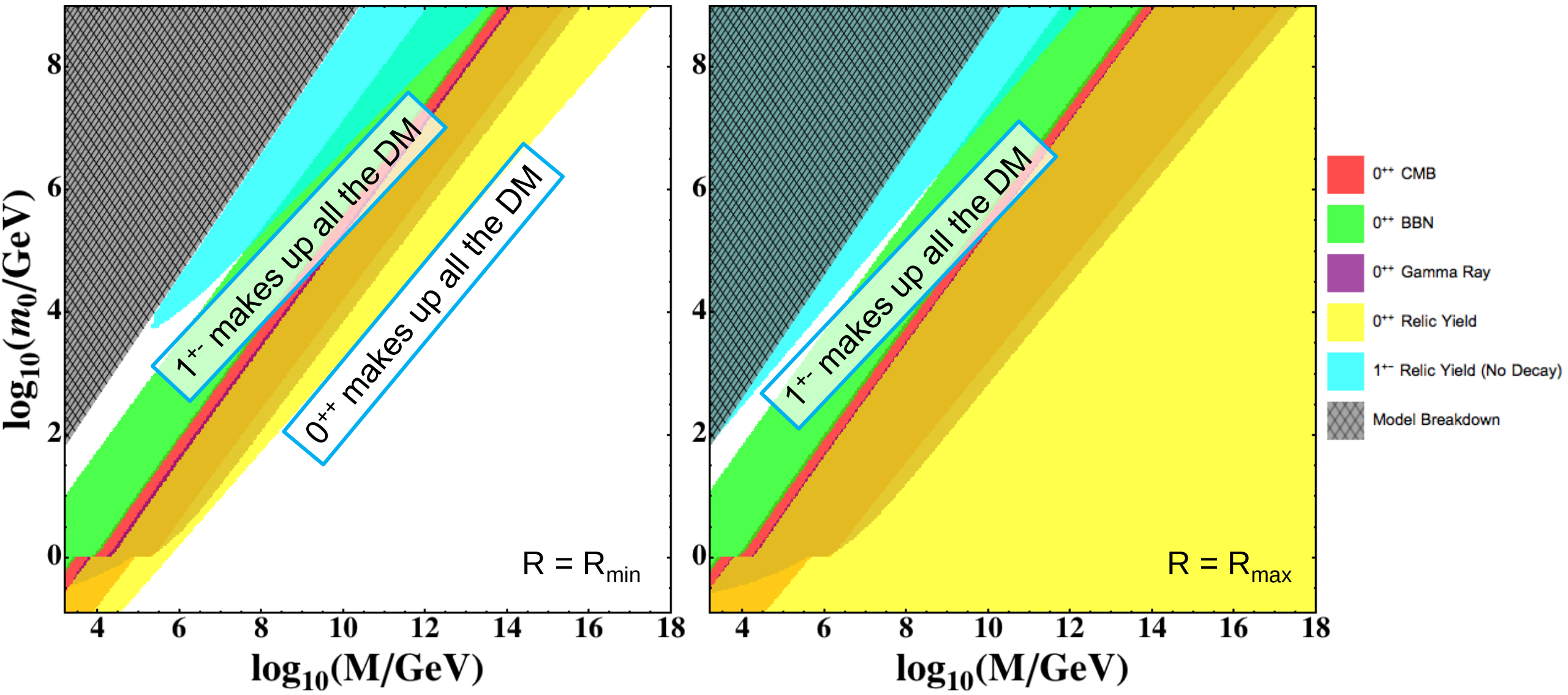
~14 Gyr

Dimension 8, Broken C_x



Forestell, Morrissey, Sigurdson, 2018

Dimension 8, Exact C_x (stable 1^{+-})



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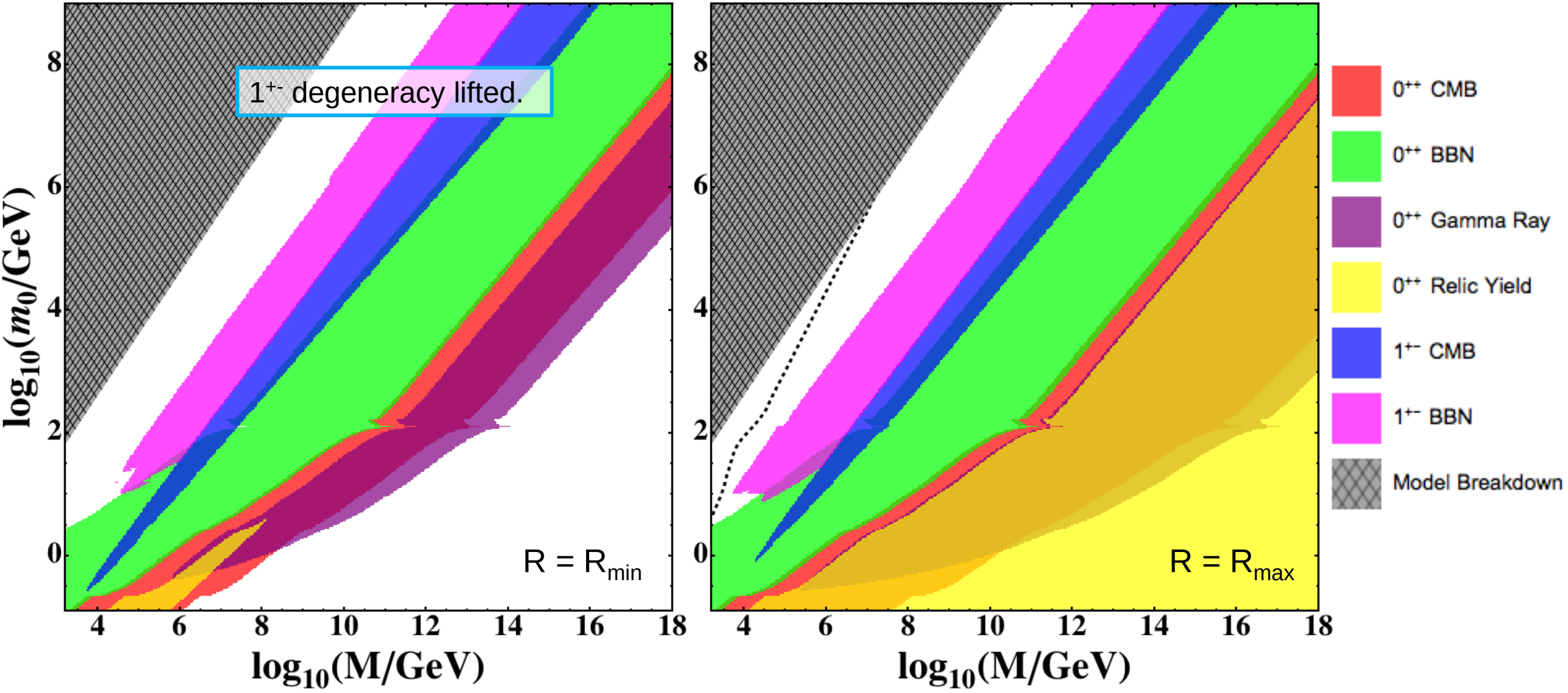
Dimension 6, Broken C_x



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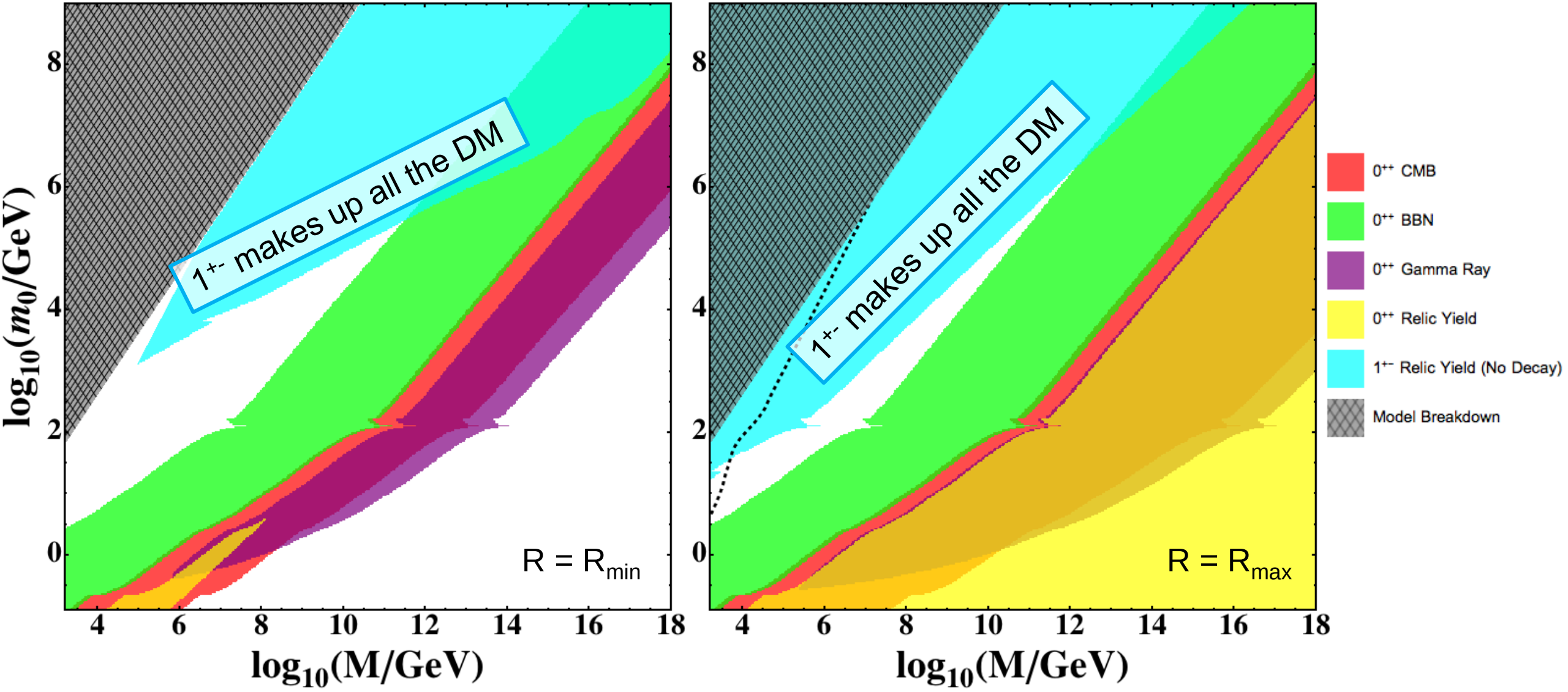
Dimension 6, Exact C_x (stable 1^{+-})



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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→2 cannibalism phase.
- Constrain the gauge based on lifetimes, using various cosmological laboratories.
- Constraints are placed on m, M, R.

Thank You!

Backup Slides…

Dark Forces

- 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?

From Gluons to Glueballs..

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

$$\alpha_x N \to 4\pi$$

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

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

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

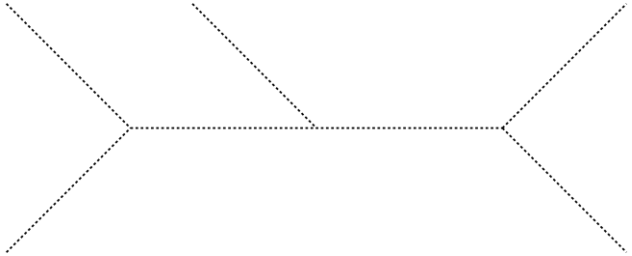
$$\mathcal{L}_{eff} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - m^4 \sum_{n\geq 3} \frac{a_n}{n!} \left(\frac{4\pi}{N}\right)^{n-2} \left(\frac{\phi}{m}\right)^n$$

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.

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 → 2 dilution

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

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$T_x \neq T$!

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Hubble expansion

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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:

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

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

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

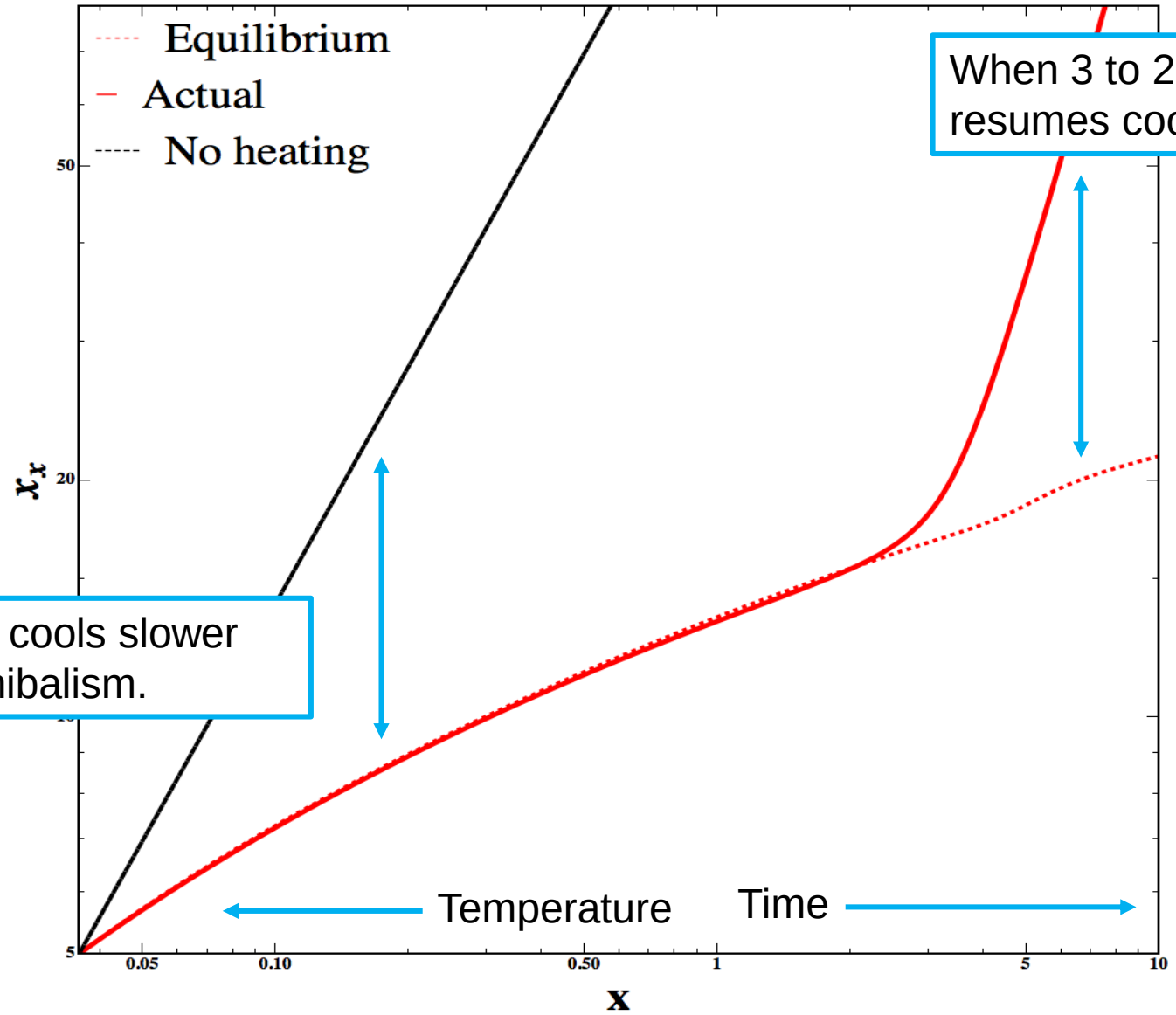
$$\langle \sigma v \rangle_{ijkl} \sim \frac{(4\pi)^3}{N^4} \frac{\beta_{ijkl}}{s_{ij}} c_L \left(\frac{2}{x_i + x_j} \right)^L$$

Couplings

Kinematics

Velocity Suppression

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

$$\dot{n}_1 + 3Hn_1 = -\langle\sigma_{32}v^2\rangle n_1^2(n_1 - \bar{n}_1) - \frac{1}{2}\langle\sigma v\rangle_{2111}\left[\frac{\bar{n}_2}{\bar{n}_1}n_1n_2 - n_2^2\right] - \langle\sigma v\rangle_{2211}\left[\frac{\bar{n}_2}{\bar{n}_1}^2 n_1^2 - n_2^2\right] - \frac{1}{2}\langle\sigma v\rangle_{2214}\left[\frac{\bar{n}_2^2}{\bar{n}_1\bar{n}_4}n_1n_4 - n_2^2\right] - \frac{1}{2}\langle\sigma v\rangle_{2415}\left[\frac{\bar{n}_2\bar{n}_4}{\bar{n}_1\bar{n}_5}n_1n_5 - n_2n_4\right]$$

3→2

$$\dot{n}_2 + 3Hn_2 = +\frac{1}{2}\langle\sigma v\rangle_{2111}\left[\frac{\bar{n}_2}{\bar{n}_1}n_1n_2 - n_2^2\right] + \langle\sigma v\rangle_{2211}\left[\frac{\bar{n}_2}{\bar{n}_1}^2 n_1^2 - n_2^2\right] + \langle\sigma v\rangle_{2214}\left[\frac{\bar{n}_2^2}{\bar{n}_1\bar{n}_4}n_1n_4 - n_2^2\right] + \frac{1}{2}\langle\sigma v\rangle_{2415}\left[\frac{\bar{n}_2\bar{n}_4}{\bar{n}_1\bar{n}_5}n_1n_5 - n_2n_4\right] - \frac{1}{2}\langle\sigma v\rangle_{1512}\left[\frac{\bar{n}_1\bar{n}_5}{\bar{n}_1\bar{n}_2}n_1n_2 - n_1n_5\right]$$

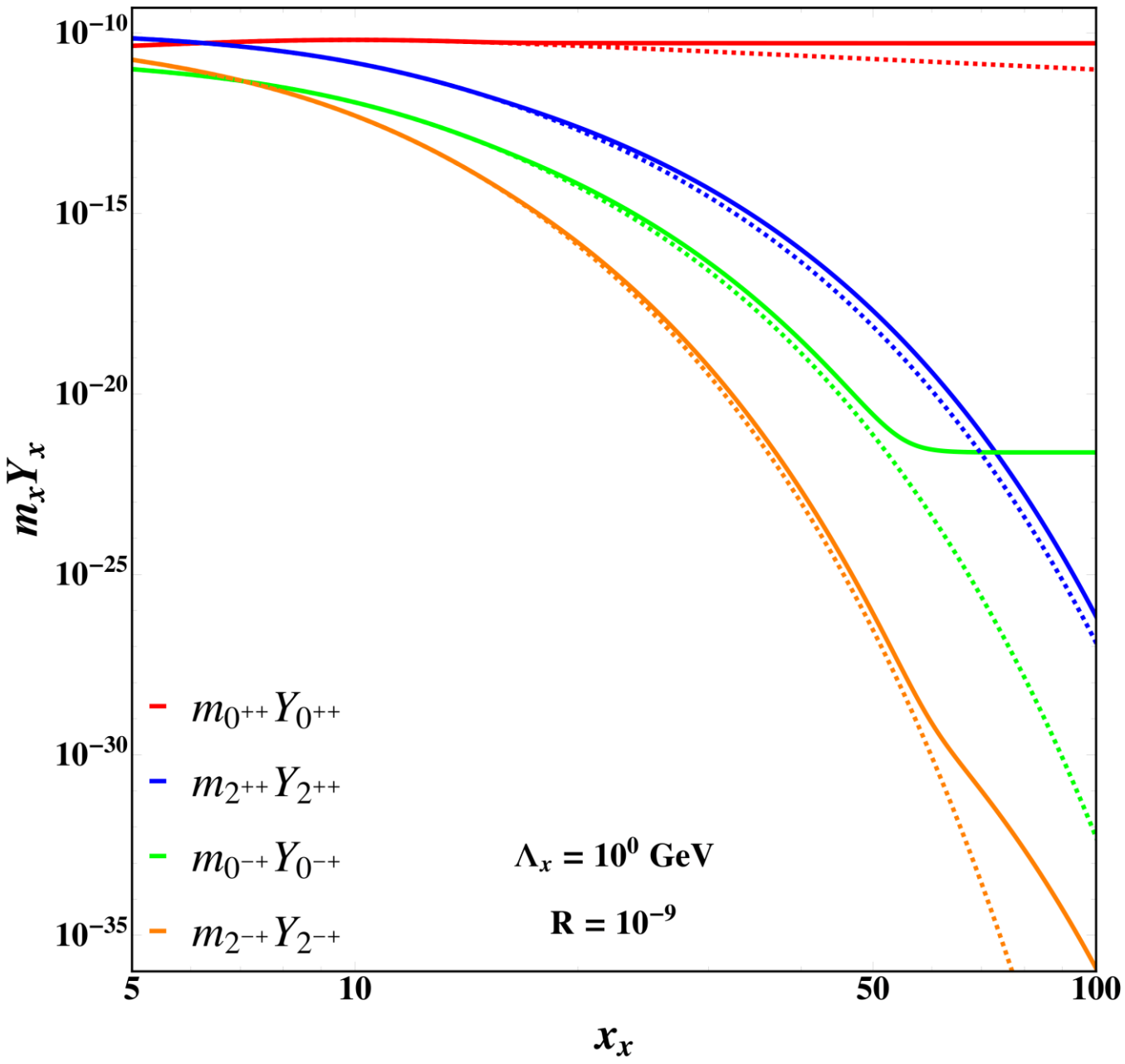
Coannihilations

$$\dot{n}_4 + 3Hn_4 = -\frac{1}{2}\langle\sigma v\rangle_{2214}\left[\frac{\bar{n}_2^2}{\bar{n}_1\bar{n}_4}n_1n_4 - n_2^2\right] + \frac{1}{2}\langle\sigma v\rangle_{2415}\left[\frac{\bar{n}_2\bar{n}_4}{\bar{n}_1\bar{n}_5}n_1n_5 - n_2n_4\right]$$

$$\dot{n}_5 + 3Hn_5 = -\frac{1}{2}\langle\sigma v\rangle_{2415}\left[\frac{\bar{n}_2\bar{n}_4}{\bar{n}_1\bar{n}_5}n_1n_5 - n_2n_4\right] + \frac{1}{2}\langle\sigma v\rangle_{1512}\left[\frac{\bar{n}_1\bar{n}_5}{\bar{n}_1\bar{n}_2}n_1n_2 - n_1n_5\right]$$

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.

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