# Dark Matter from Dark Confinement

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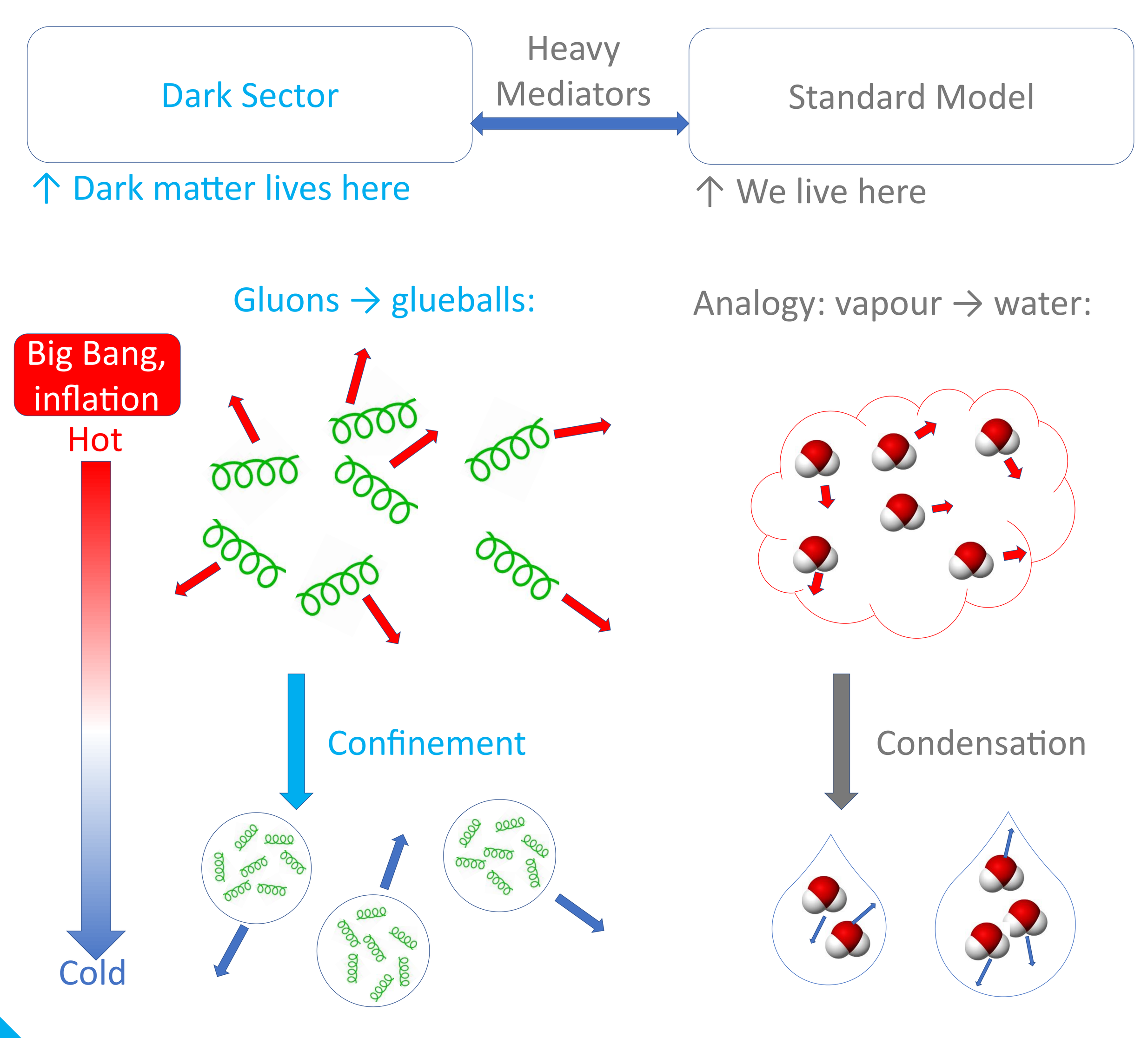
## Motivation

Astronomical observations require four times more matter than accounted for by the Standard Model (SM). This new form of matter is called dark matter (DM), but we know little about its nature; it has not been observed in laboratory yet.

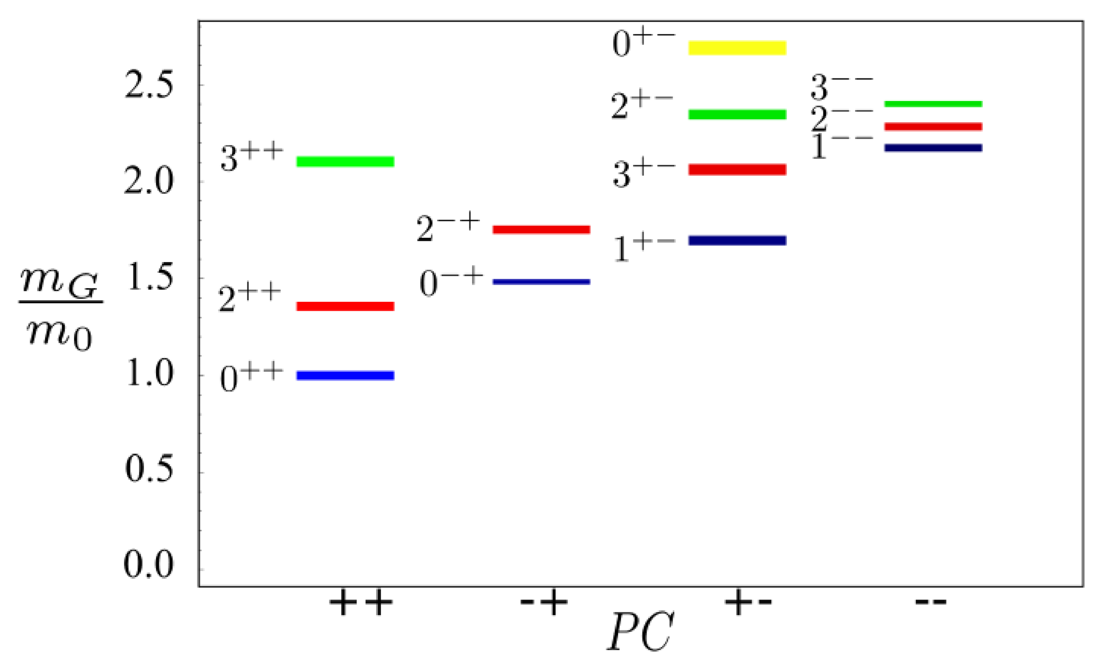
What if DM were rather a part of a new set of particles and interactions just like the SM? We consider this new set, called **dark sector**, in analogy to quantum chromodynamics (QCD) in the SM: dark-gluons get confined to their bound states called "dark glueballs" at some dark confinement scale, similar to quarks confined to protons and other baryons in QCD. Our story begins with the very early universe consisting only of the dark sector.




Schematic diagram of a dark sector and dark confinement.

## Dark Glueball Zoo (SU(N=3))

Dark glueball states are denoted by $J^{PC}$: classified by total angular momentum $J$, parity $P$, and charge conjugation $C$. We draw on existent lattice-QCD calculations for mass ratios. We identify the mass $m_0$ of the lightest glueball state ($0^{++}$) to be the dark confinement scale, and the only free parameter here.



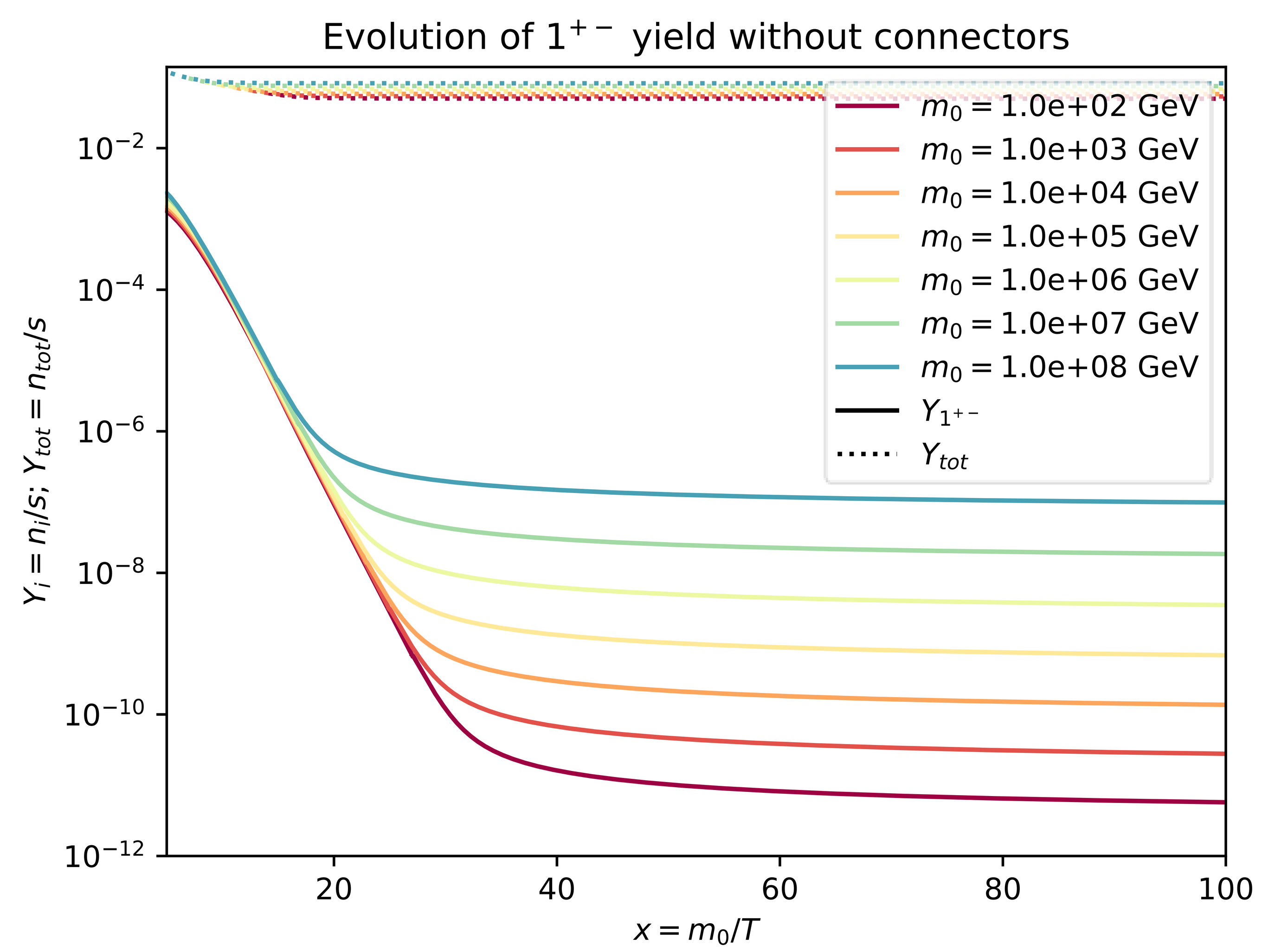

Adapted from Juknevich, 2020 [hep-ph: 0911.5616]

## Evolution of Glueball Densities

- When glueballs are formed, the universe would be hot and dense. Different states would actively react with each other such as:
  - $0^{++} + 0^{++} + 0^{++} \rightleftarrows 0^{++} + 0^{++}$ …(1)
  - $1^{+-} + 1^{+-} \rightleftarrows 0^{++} + 0^{++}$ …(2)
- As the universe expanded and cooled down, reactions would occur too slowly to keep up with cosmic expansion, and eventually shut off, making the abundance almost constant. This process is called **freeze-out**.
- Precise freeze-out calculations would require complete reaction networks for each state. We found a systematic way to incorporate all reactions for the dark sector abundance as dotted lines on the right plot.
- We also numerically showed that heavier glueball states (solid lines) freeze-out parametrically later than $0^{++}$, making $0^{++}$ abundant in the dark sector.

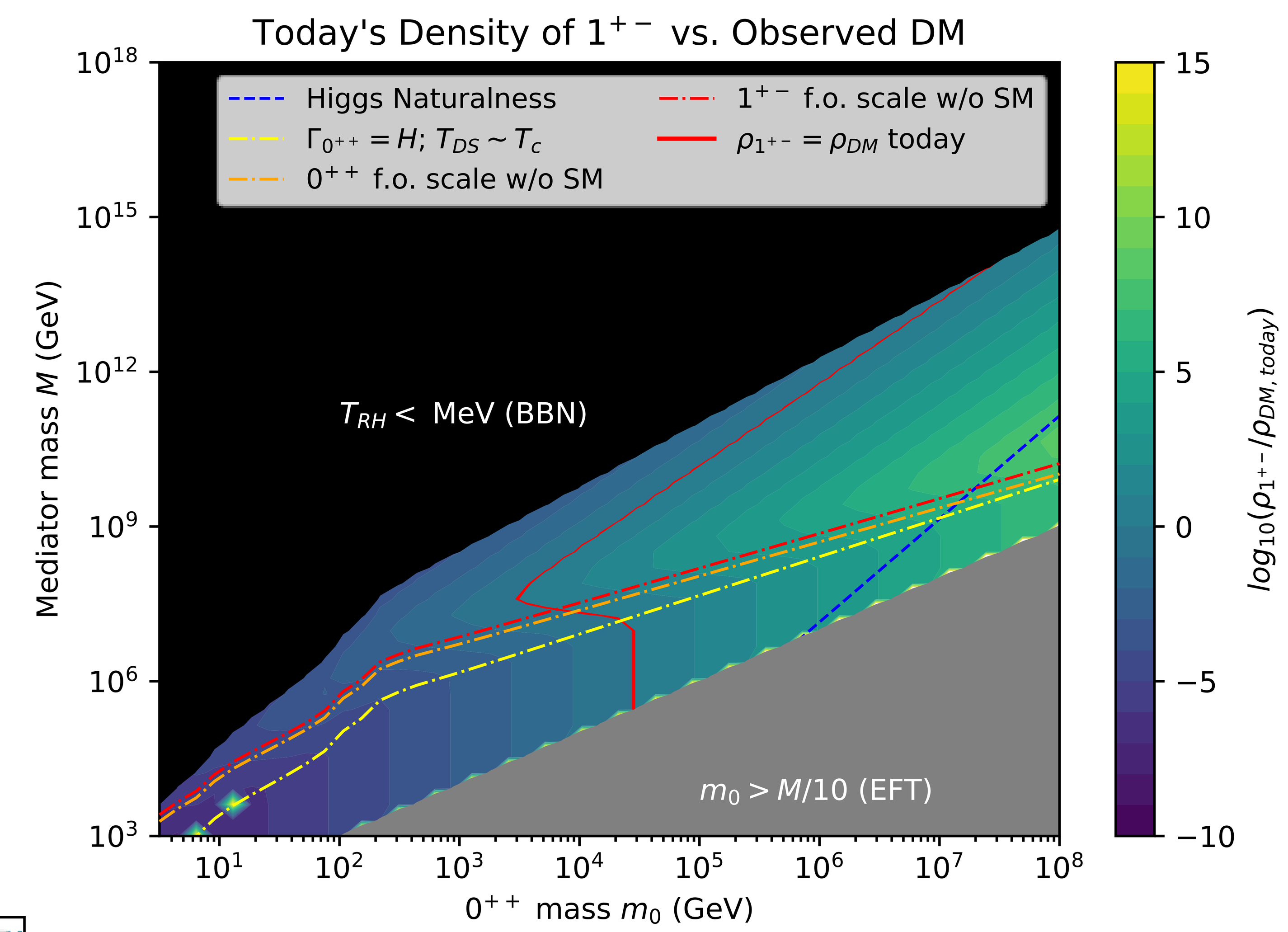
## Where is the Standard Model?

- Our story so far assumed that there is only the dark sector in the early universe, but our universe today is formed with SM particles.
- In fact, glueball states, including the dominant $0^{++}$, could decay into SM particles via very heavy dark mediators of mass $M$. These decays would source the SM sector.
- From then on, the universe would consist of the dark and SM sectors, because some glueball states are parametrically more long-lived than others. The dark sector would now contain only long-lived glueball states, and these sectors would evolve with feeble interactions with each other.
- The SM sector needs to be populated early enough for theory to agree with cosmological observations. This is assured in the parameter space under the black-shaded region on the right contour plot.
- The heaviness of the mediators allows us to compute decays in a model-independent way. The area above the gray-shaded region ensures the validity of such theory.




## Dark Matter from Dark Sector

- While the SM sector is populated, long-lived glueball states would keep evolving. In fact, $1^{+-}$ would be the most stable and abundant today, and hence a viable DM candidate.
- $1^{+-}$ can freeze-out in complex cosmic environment due to glueball decays. We computed its evolution and showed the parameter space on the left of the red solid line in the contour plot where $1^{+-}$ can be DM.




## Summary

- We started with the very early universe consisting of a QCD-like sector only, where dark gluons get confined into glueballs.
- We accounted for all reactions in the dark sector evolution; $0^{++}$ dominates the sector while heavier states are highly suppressed.
- Glueball decays would source the SM sector, and residual long-lived states would continue to evolve in the dark sector.
- $1^{+-}$ turns out long-lived and dominates the dark sector after glueball decays. We showed the parameter space where it can be DM.

**Discovery, accelerated**