Reheating and dark matter through dark glueballs

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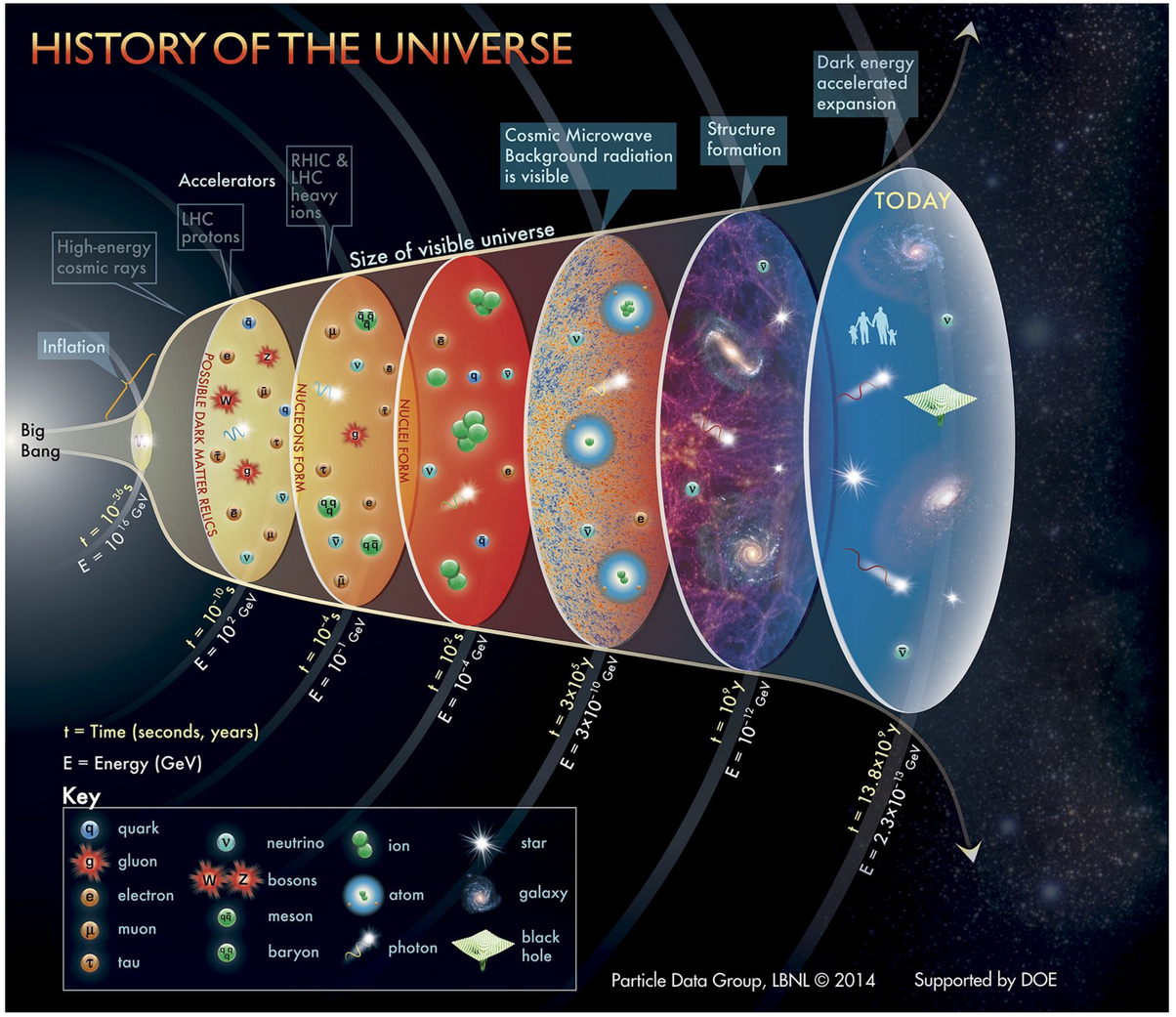
Norwegian Particle, Astroparticle & Cosmology Theory network

Joint work with Simone Biondini and Simona Procacci
ArXiv: 2406.10345

Forskningsrådet

Universitetet i Stavanger

Motivation


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
TODAY
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-35 s
E = 10^15 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
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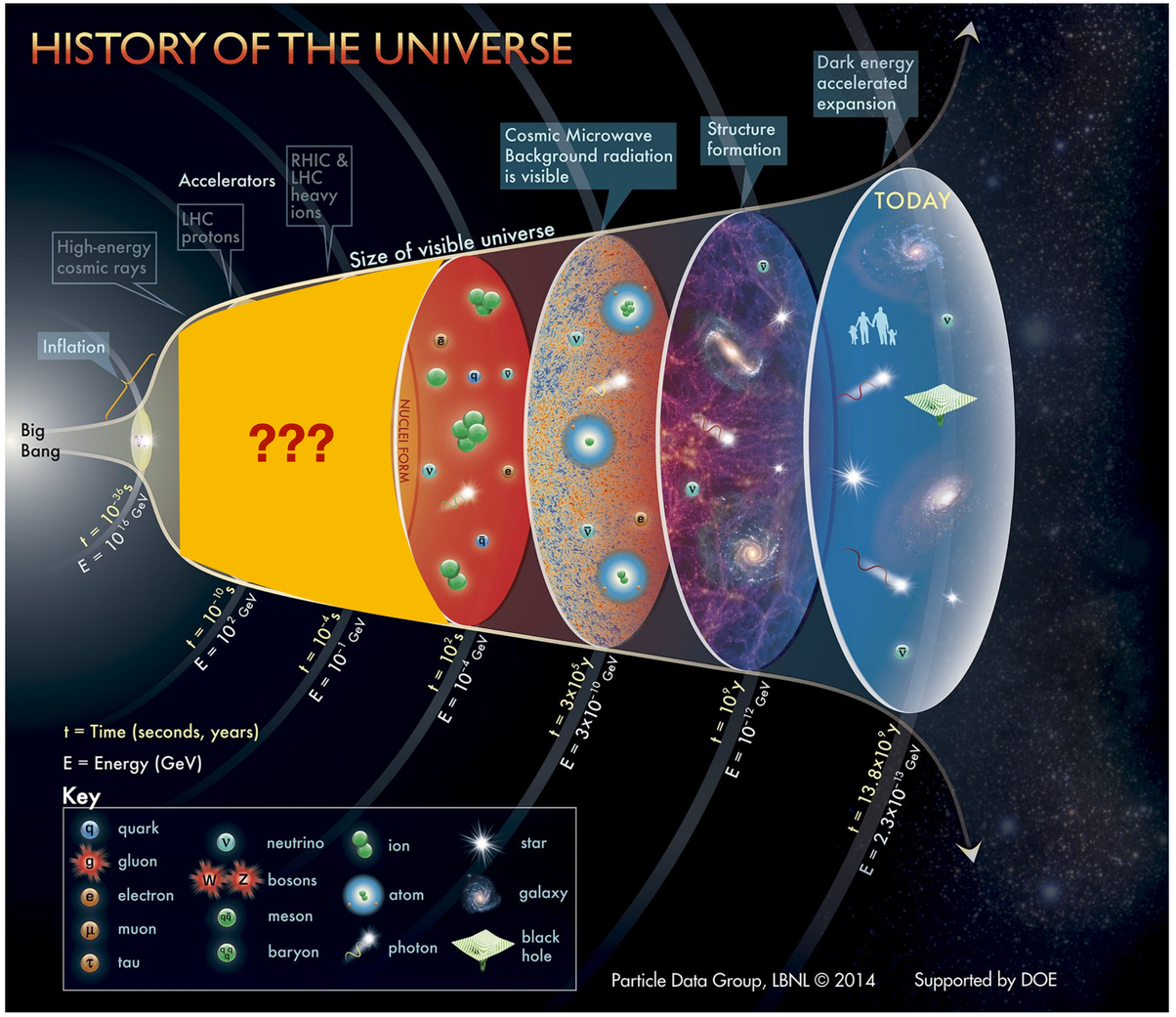
Motivation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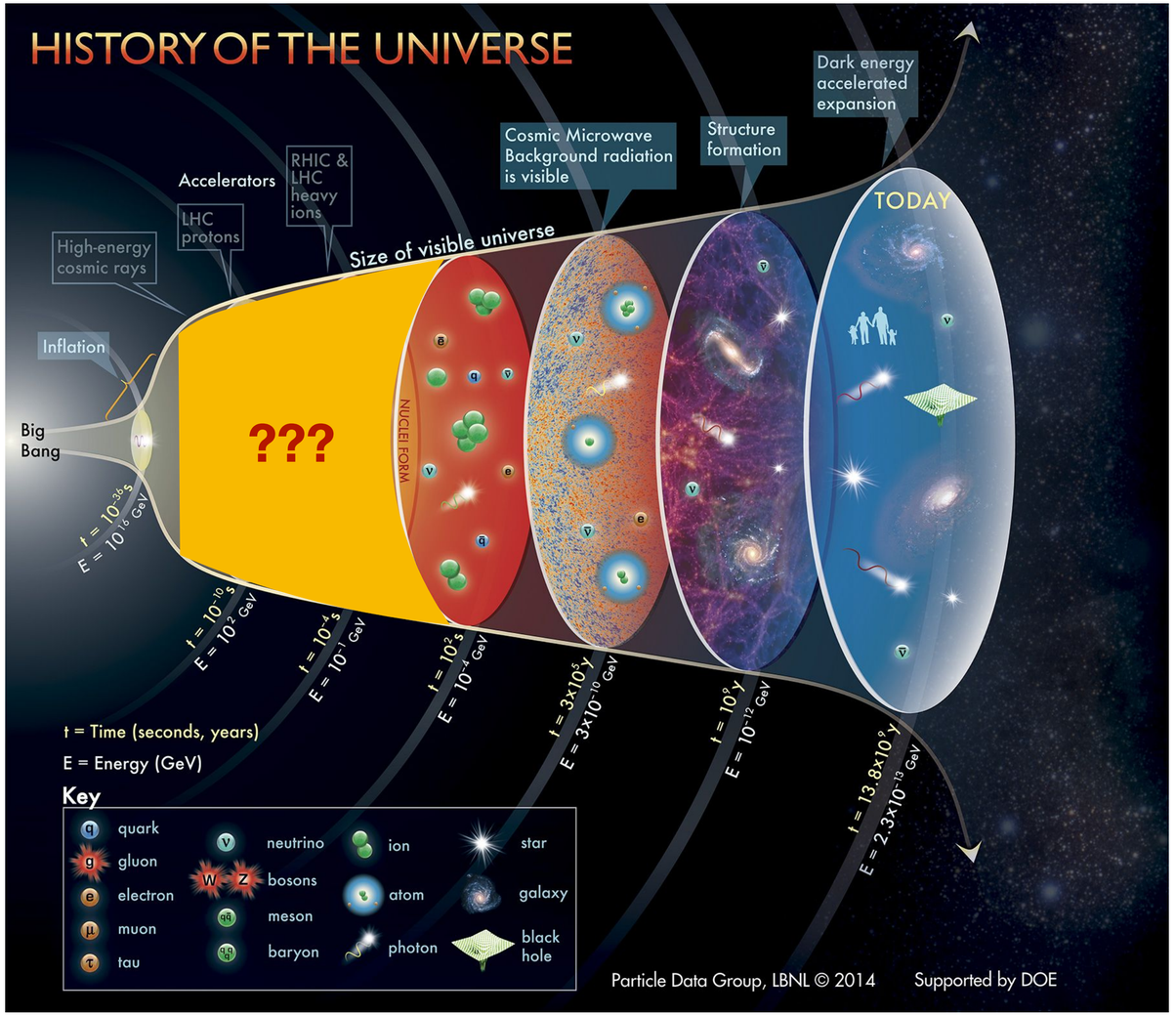
Motivation

What we “know”:

- Standard Model particles had to be reheated at least at temperatures around 4 MeV
- Dark matter had to be produced at some point?
- Perhaps inflation happened very early after Big Bang?



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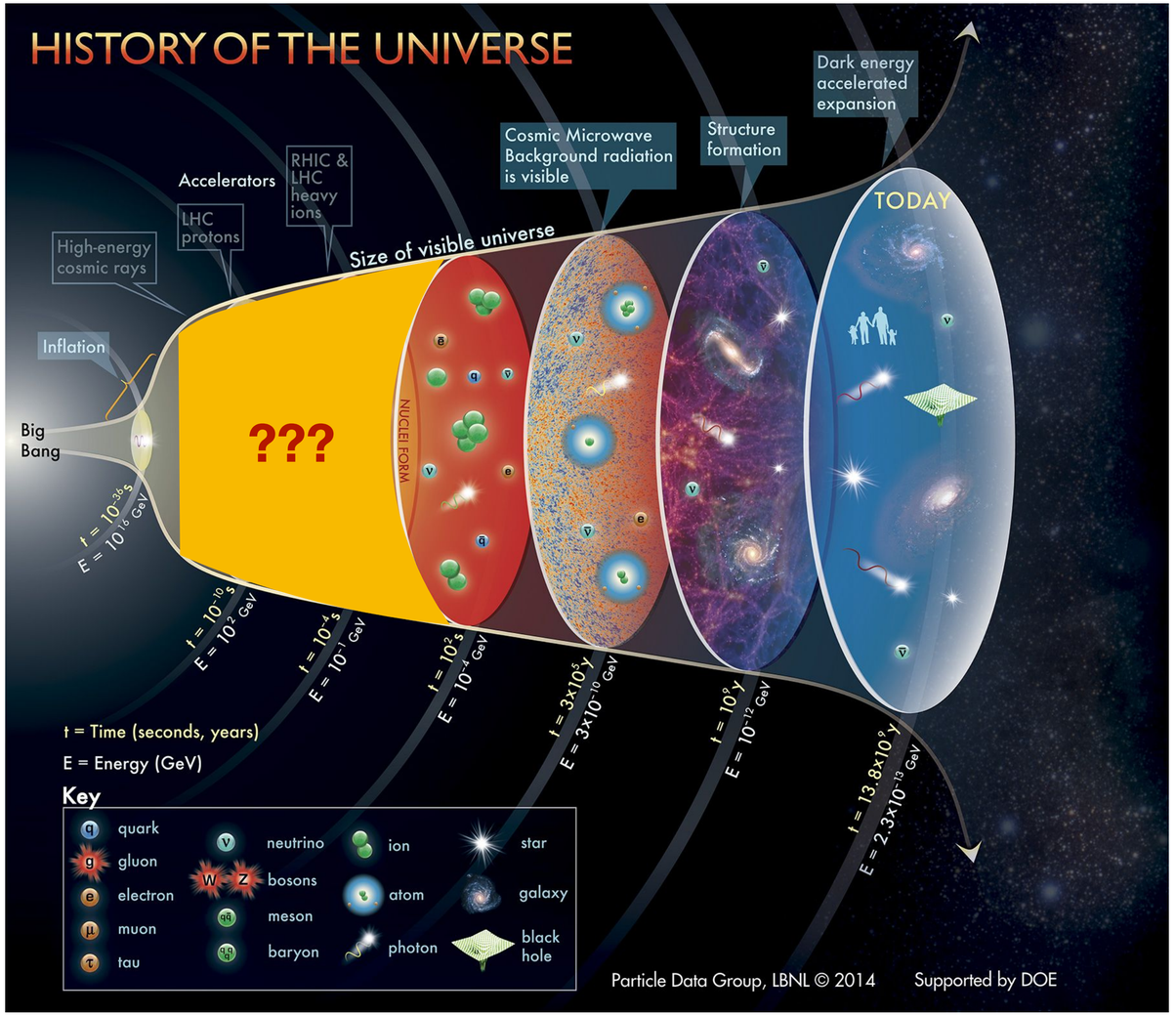
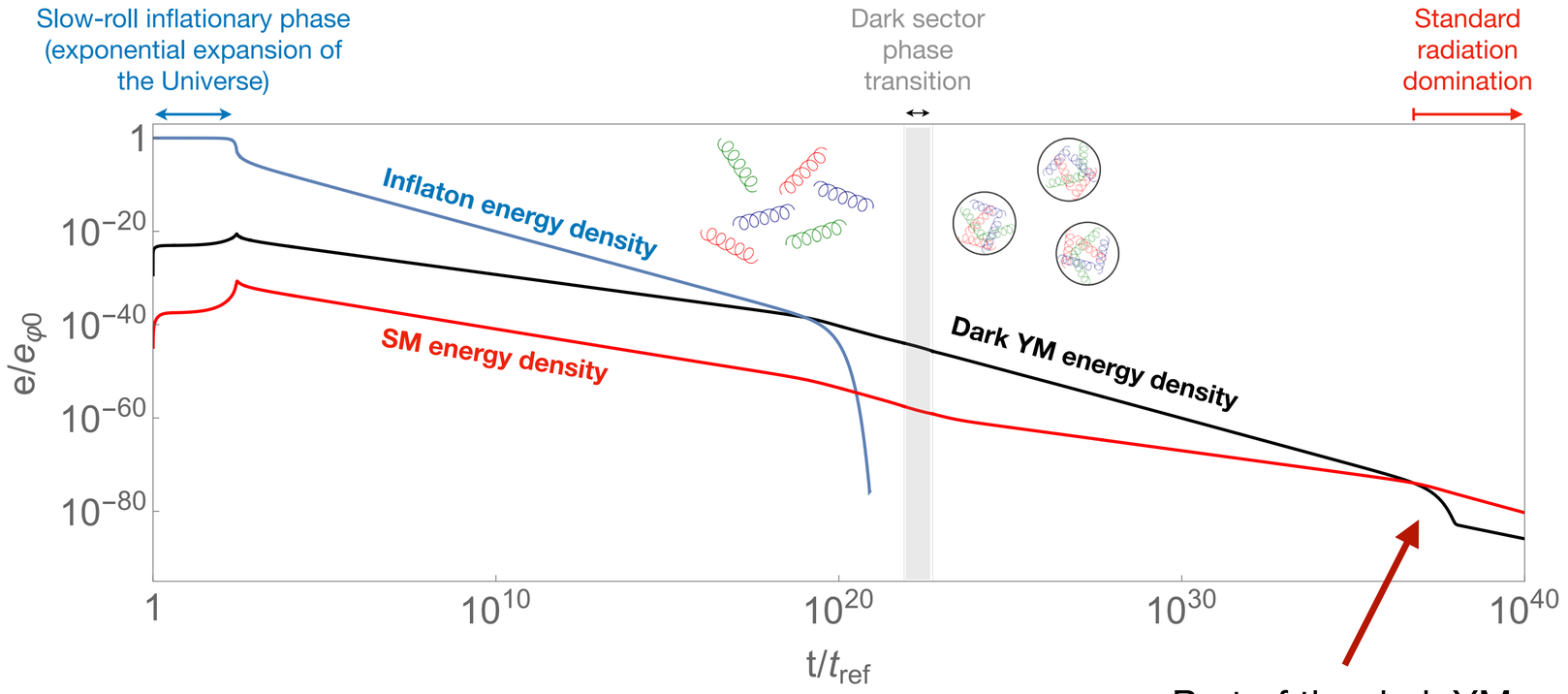


Could a dark Yang-Mills sector provide both dark matter and a link between the inflation and SM reheating?

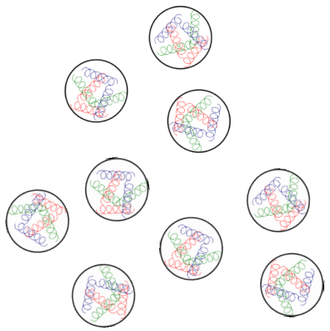
History of the Universe à la 2406.10345



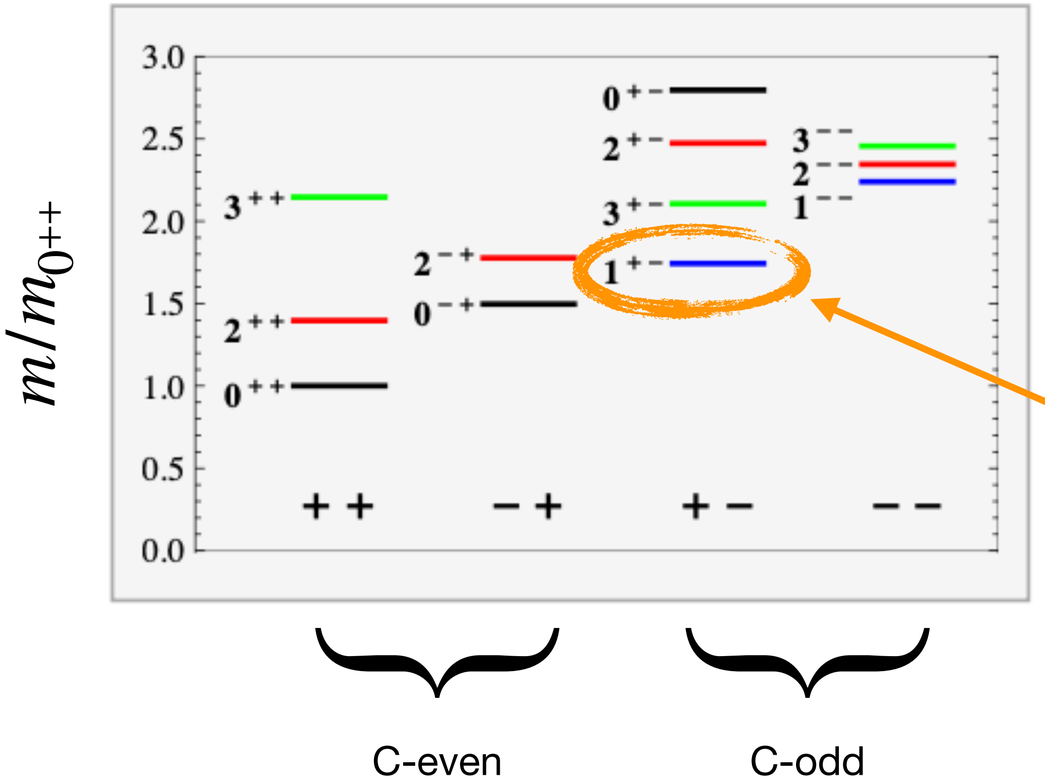
Part of the dark YM sector decays into SM fields, another part forms dark matter!

Glueball dark matter

[Boddy et al.:1402.3629] [Soni, Zhang: 1602.00714] [Forestell, Morrissey, Sigurdson: 1605.08048, 1710.06447]
[Carenza, Pasechnik, Wang et al.: 2207.13716, 2306.09510] [Gross, Karamitos, Landini, Strumia: 2012.12087]…



Spectrum of SU(3) glueballs J^{PC}



The lightest C-odd glueball is protected by the discrete symmetry and can be sufficiently stable even if the C-even glueballs decay fast into SM fields!

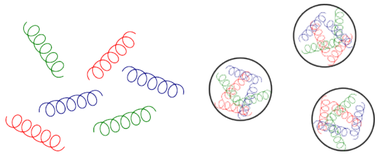
Ingredients

Yang-Mills field strength

Gauge coupling

$$\frac{\alpha\,\varphi\,\epsilon^{\mu\nu\rho\sigma}F^c_{\mu\nu}F^c_{\rho\sigma}}{16\pi f_a}$$

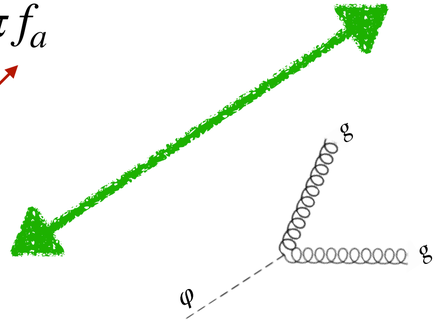
Axion decay constant

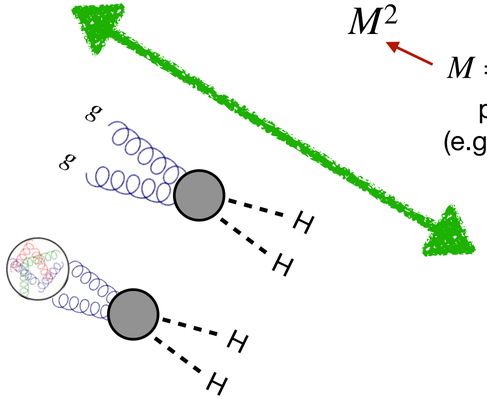


Dark Yang-Mills sector

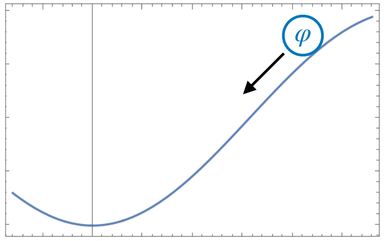
$$\frac{|H|^2\,\mathrm{Tr}\,F_{\mu\nu}F^{\mu\nu}}{M^2}$$

$M = m_{\rm pl}$ or mass of portal particles (e.g. heavy fermions)





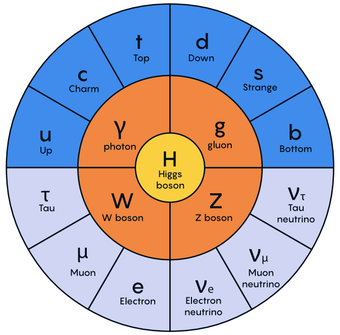
Axion-like inflaton



[Berghaus, Graham, Kaplan: 1910.07525]
[Laine, Procacci: 2102.09913]
[Klose, Laine, Procacci: 2201.02317]
[Klose, Laine, Procacci: 2210.11710]

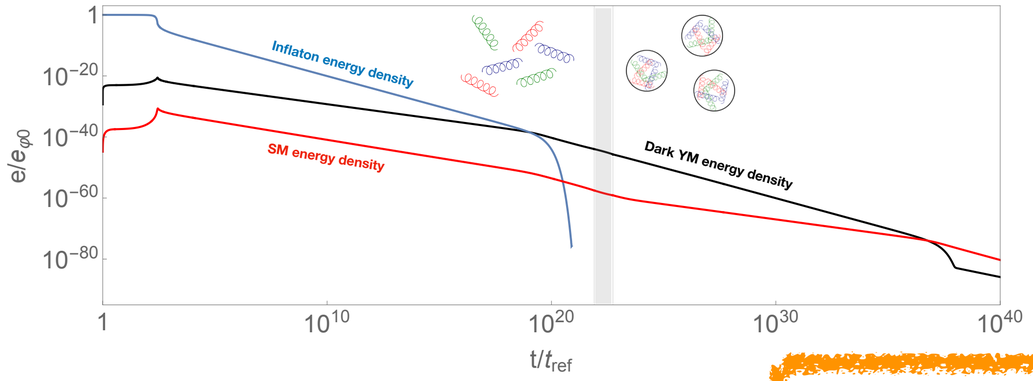
[Juknevich: 0911.5616]
[Forestell, Morrissey, Sigurdson: 1605.08048, 1710.06447]

Standard Model

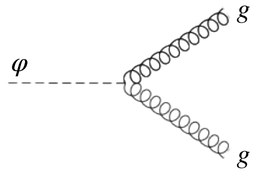


Credit: quantamagazine.org

Evolution equations



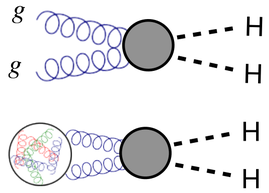
Inflaton decay rate: $\Upsilon \simeq \alpha^2 m_\varphi^3/(32\pi^3 f_a^2)$ if $T_{\rm DS} \ll m_\varphi$,
lattice input available for SU(3)
[Moore,Tassler: 1011.1167] [Laine, Niemi, Procacci, Rummukainen: 2209.13804]



$$\dot{e}_\varphi + 3He_\varphi = -\Upsilon e_\varphi$$

$$\dot{e}_{\rm DS} + 3H(e_{\rm DS} + p_{\rm DS}) = \Upsilon e_\varphi - \Gamma e_{\rm DS}$$

$$\dot{e}_{\rm SM} + 4H e_{\rm SM} = \Gamma e_{\rm DS}$$



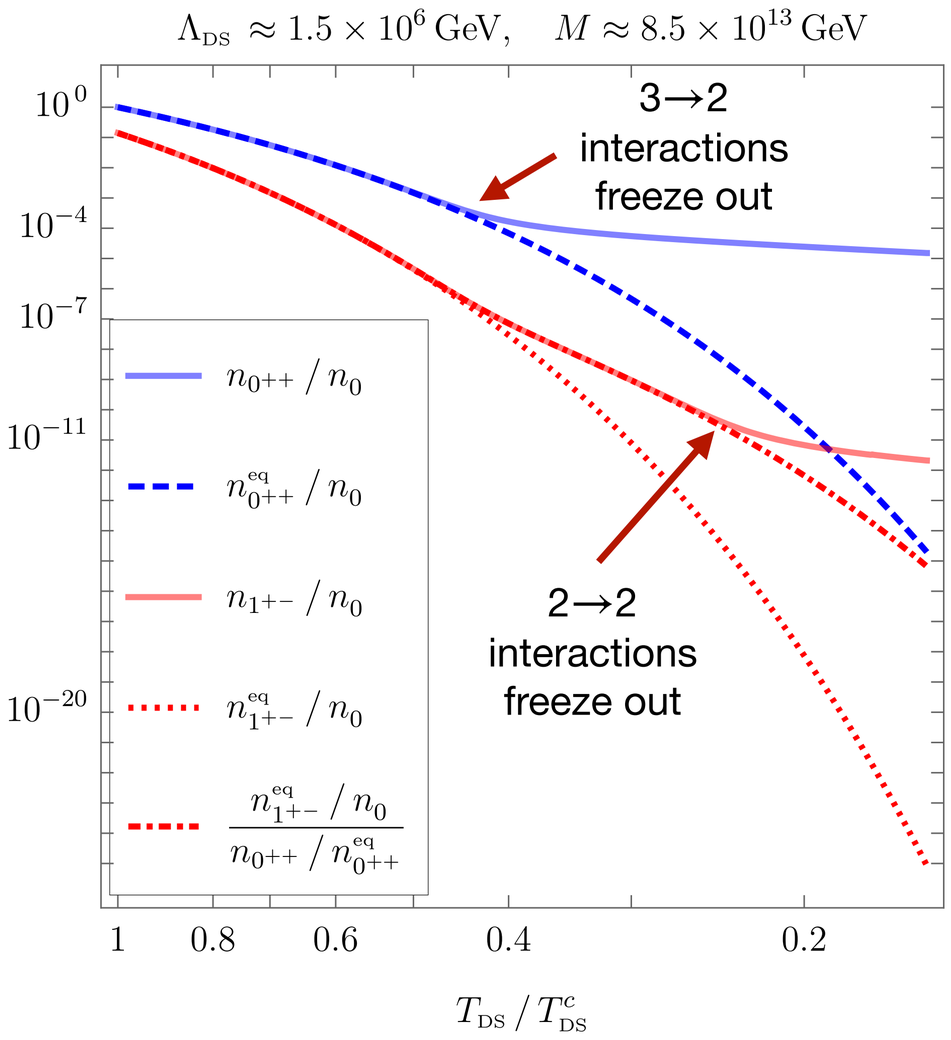
Dark sector energy and pressure densities parameterised by temperature.
SU(3) equation of state:
[Giusti, Pepe: 1612.00265]
[Meyer: 0905.422]

Hubble rate:

$$H = \sqrt{\frac{8\pi}{3m_{\rm pl}^2}\left(e_\varphi + e_{\rm SM} + e_{\rm YM}\right)}$$

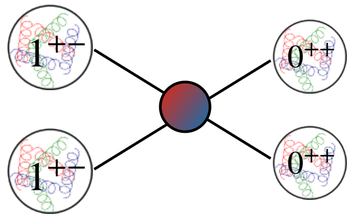
Gluon annihilation rate:
$\Gamma \propto T_{\rm DS}^5/M^4$
or glueball decay rate
$\Gamma \propto \Lambda_{\rm DS}^5/M^4$,
$\Lambda_{\rm DS}$: Dark YM confinement scale

Dark matter relic abundance?



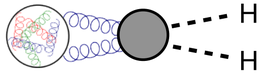
Boltzmann equations for the number densities of the lightest C-even and lightest C-odd glueballs:

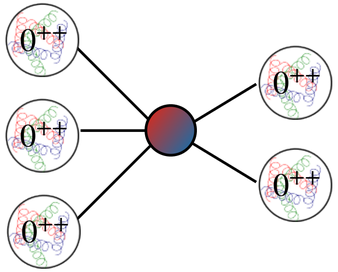
$$\dot{n}_{1^{+-}} + 3Hn_{1^{+-}} = B_\varphi^{1^{+-}} \Upsilon \frac{e_\varphi}{m_{1^{+-}}} - \langle \sigma_{2\to 2} v \rangle \left(n_{1^{+-}}^2 - \left(\frac{n_{0^{++}}}{n_{0^{++}}^{\rm eq}} \right)^2 (n_{1^{+-}}^{\rm eq})^2 \right)$$



$$\dot{n}_{0^{++}} + 3Hn_{0^{++}} = B_\varphi^{0^{++}} \Upsilon \frac{e_\varphi}{m_{0^{++}}} + \langle \sigma_{2\to 2} v \rangle \left(n_{1^{+-}}^2 - \left(\frac{n_{0^{++}}}{n_{0^{++}}^{\rm eq}} \right)^2 (n_{1^{+-}}^{\rm eq})^2 \right)$$

$$- n_{0^{++}} \Gamma - \langle \sigma_{3\to 2} v^2 \rangle \, n_{0^{++}}^2 (n_{0^{++}} - n_{0^{++}}^{\rm eq})$$



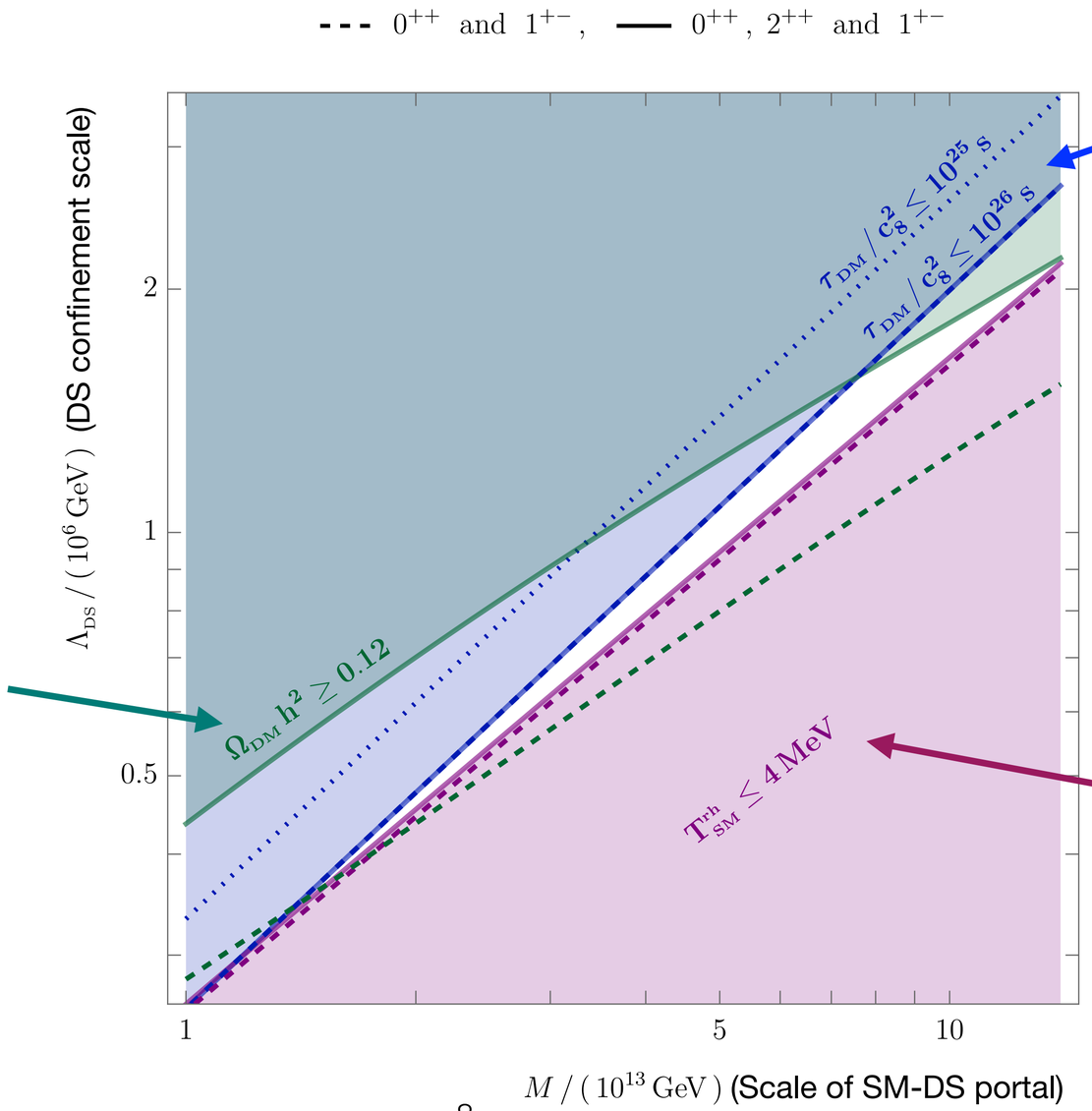


Inspired by [Forestell, Morrissey, Sigurdson: 1605.08048, 1710.06447]
NB: The second lightest glueball 2^{++} included as well in order to capture better the thermodynamic quantities, but the full equations wouldn't fit this slide :)

Results: parameter space

NB: Inflaton parameters fixed based on CMB constraints [Klose, Laine, Procacci: 2201.02317]:

$$m_\varphi = 1.09 \times 10^{-6}\, m_{\rm pl},$$
$$f_a = 1.25\, m_{\rm pl}$$

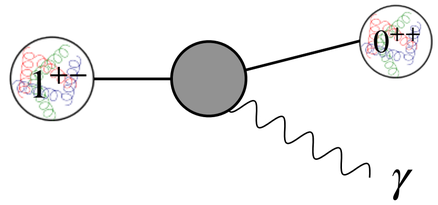


Too much dark matter
⇔
Too early freeze-out
⇔
Too weak interactions:
$\langle \sigma_{2\to 2} v \rangle \propto 1/\Lambda^2_{\rm DS}$

Too large DM decay rate
$\Gamma_{\rm DM} \propto \Lambda^9_{\rm DS}/M^8$

NB: C-odd glueballs decay through operators like

$$c_8 \frac{B_{\mu\nu} \mathrm{Tr}\, G^{\mu\nu} G_{\alpha\beta} G^{\alpha\beta}}{M^4}$$

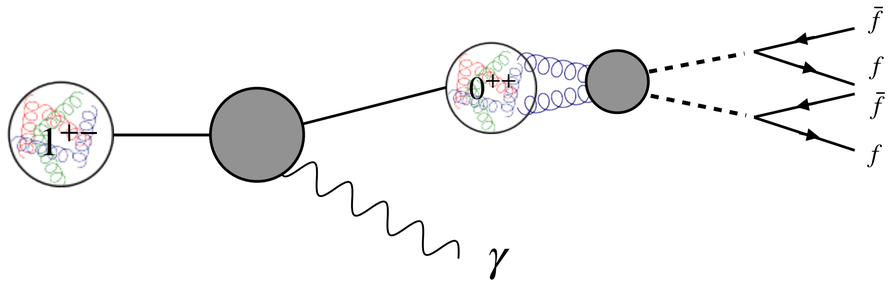


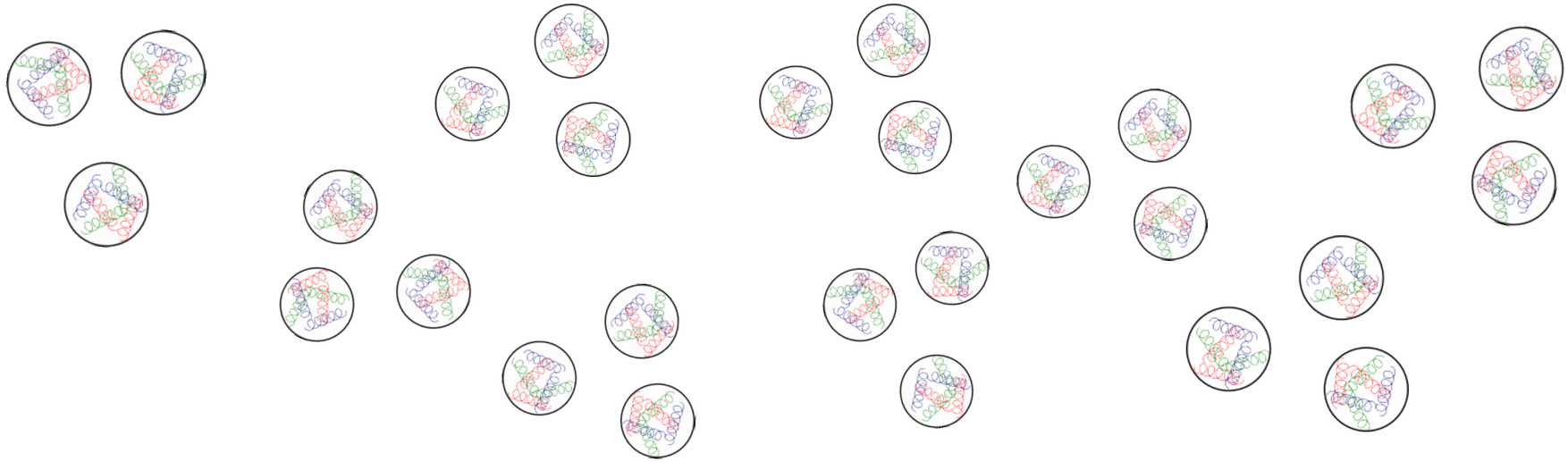
SM not reheated efficiently enough
⇔
$\Gamma \propto \Lambda^5_{\rm DS}/M^4$
too small

Conclusions & Outlook

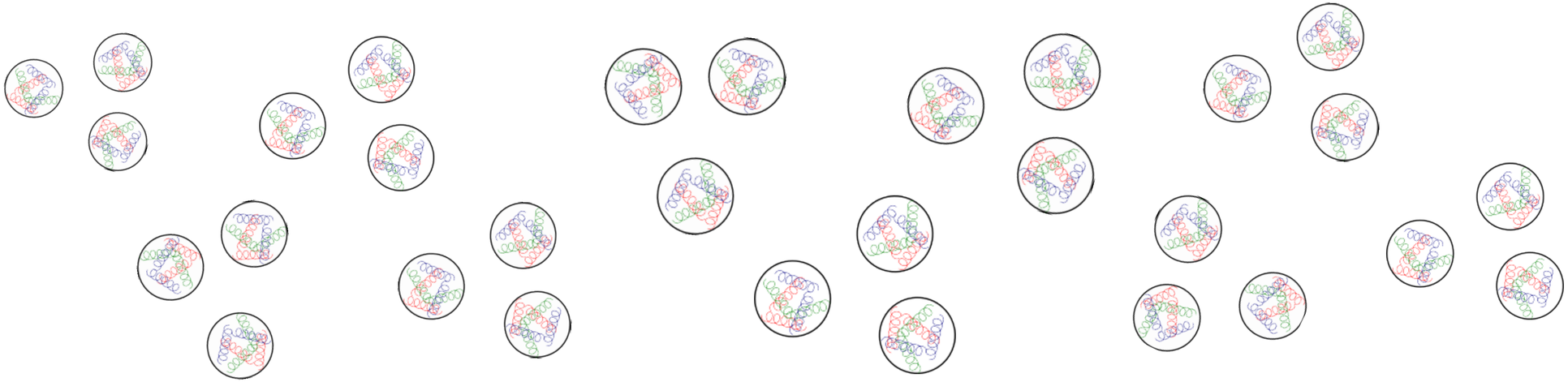
- A general scenario linking dark matter production with inflation and SM reheating provided
- Dark matter relic abundance independent of the details of the inflationary scenario ⇒ generalisations beyond axion-like inflation possible

- If SU(3) dark sector chosen, portal to SM at energies $M \sim 10^{13}$ GeV needed. Connection to other puzzles in high-energy physics?
- Larger open parameter space can be obtained for theories where the "protected" glueballs are more long-lived. E.g., for SO(N) with $N \geq 8$: $\Gamma_{\mathrm{DM}} \propto \Lambda_{\mathrm{DS}}^{2N-3}/M^{2N-4}$
- Concrete indirect detection signal to be predicted!





Thanks for your attention!



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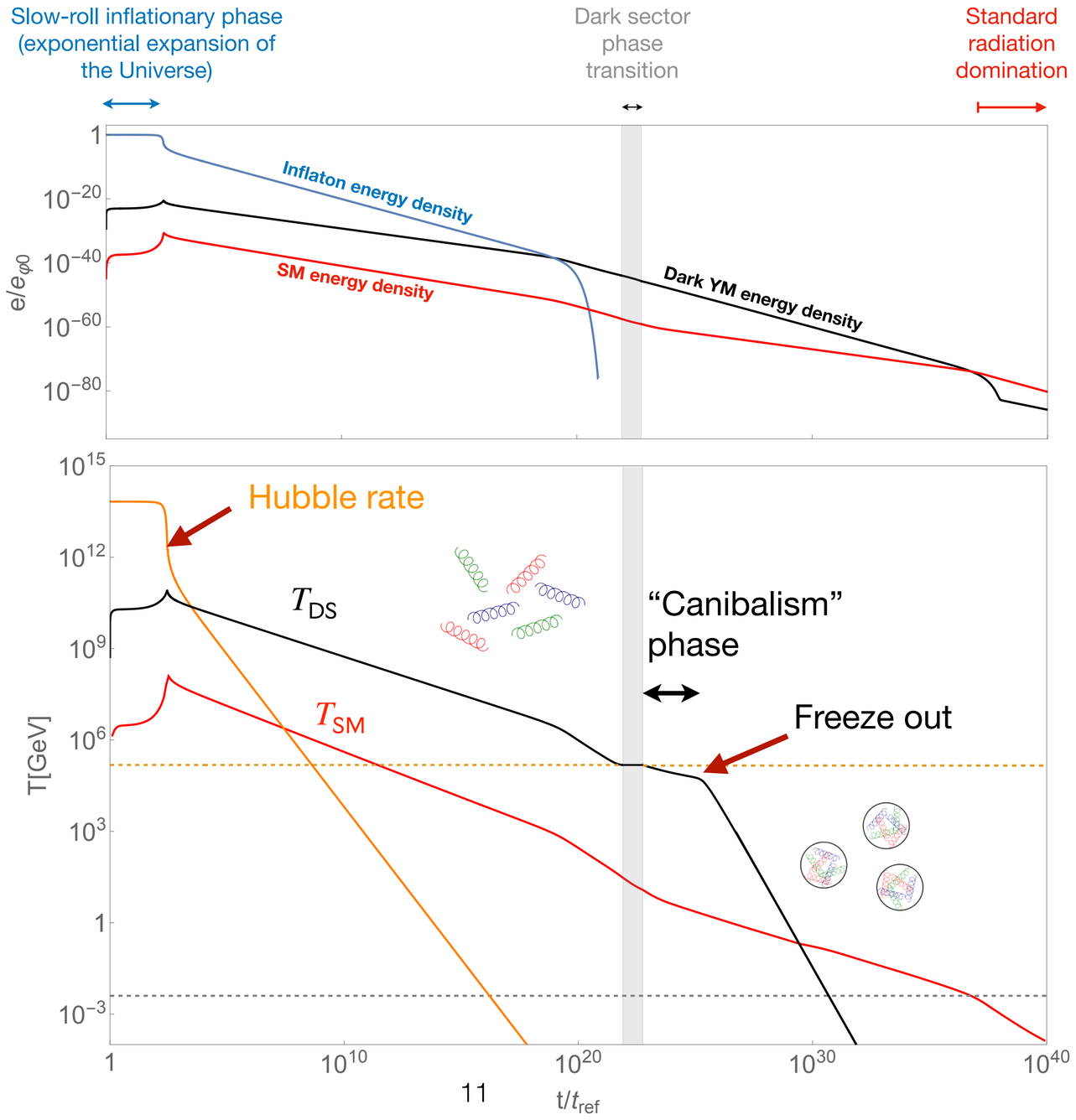
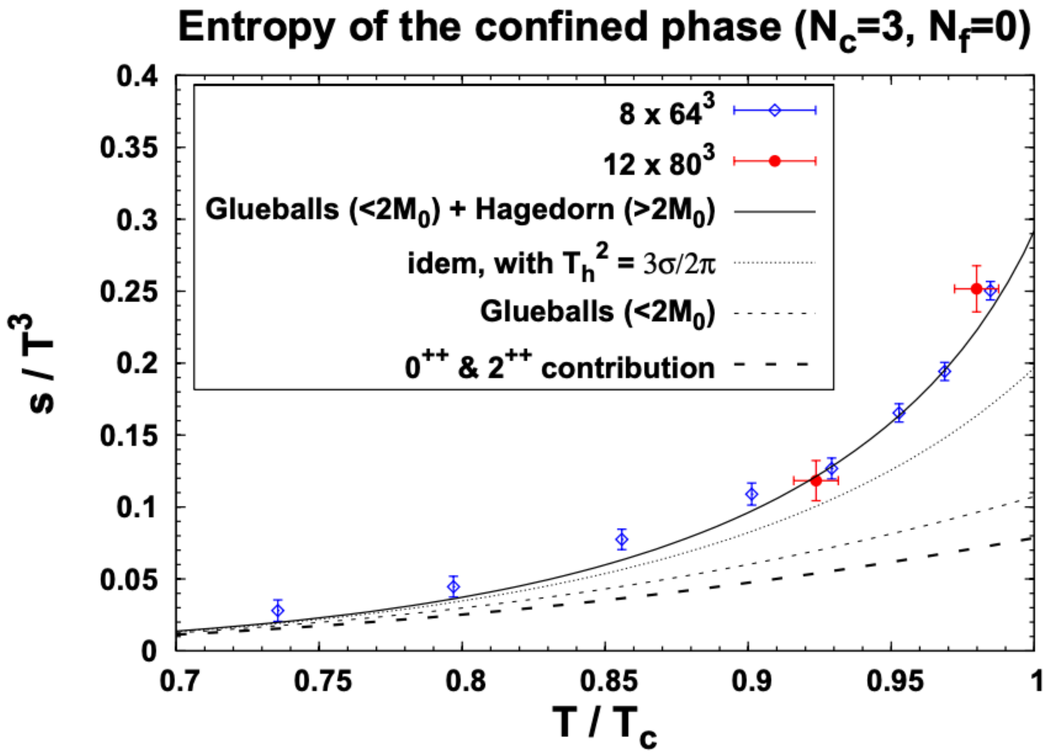


Thermodynamics of a YM theory below confinement scale might be indeed described as an ensemble of glueballs!



[Meyer: 0905.4229]