Dark matter and reheating via dark glueballs

Helena Kolešová (University of Stavanger)




Joint work with Simone Biondini and Simona Procacci
arXiv: 2406.10345

ICHEP 2024 | PRAGUE

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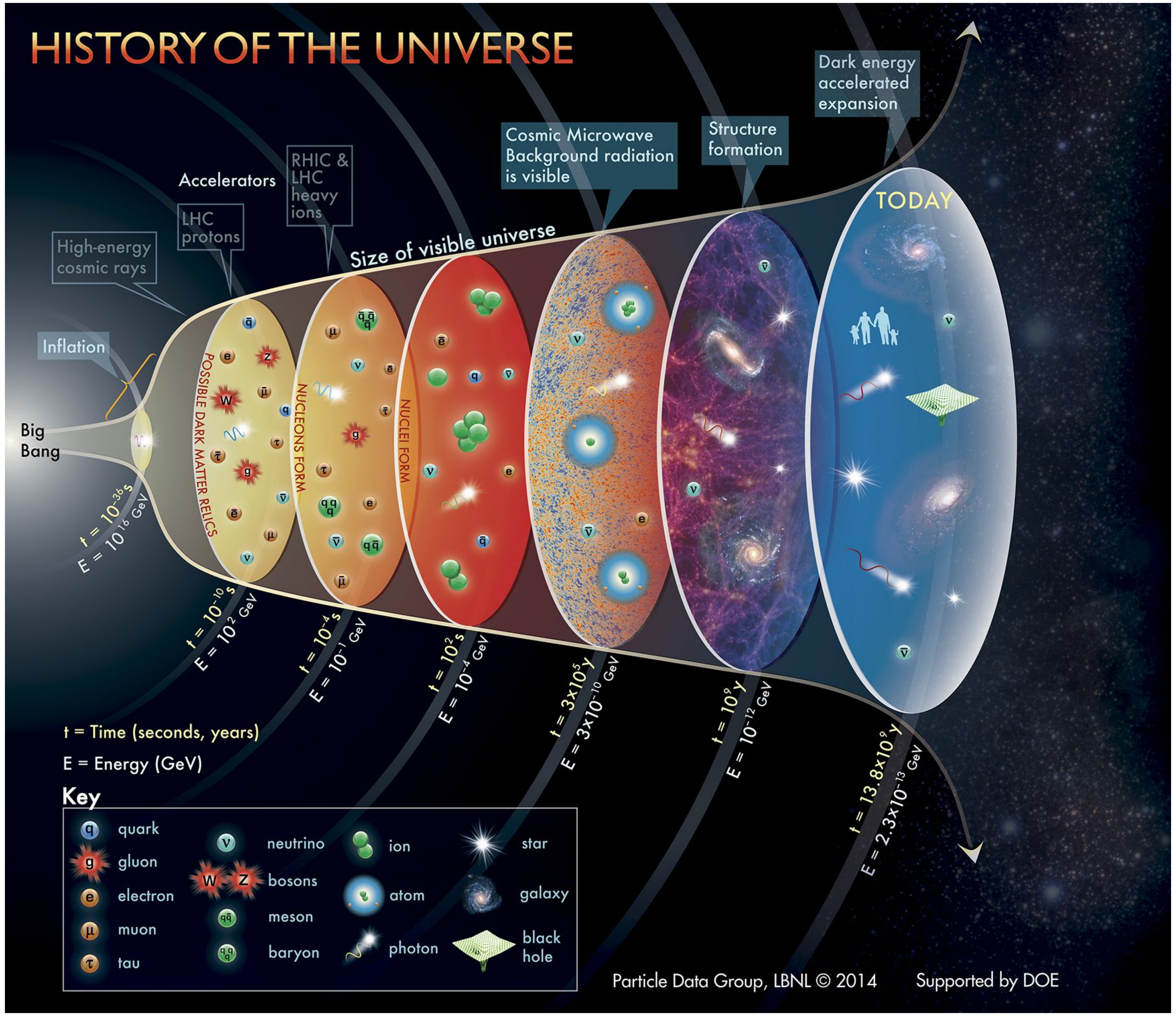
Motivation



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
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
$t = 10^{-36}$ s
$E = 10^{16}$ 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
$t = 3\text{x}10^{5}$ y
$E = 3\text{x}10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8\text{x}10^{9}$ y
$E = 2.3\text{x}10^{-13}$ 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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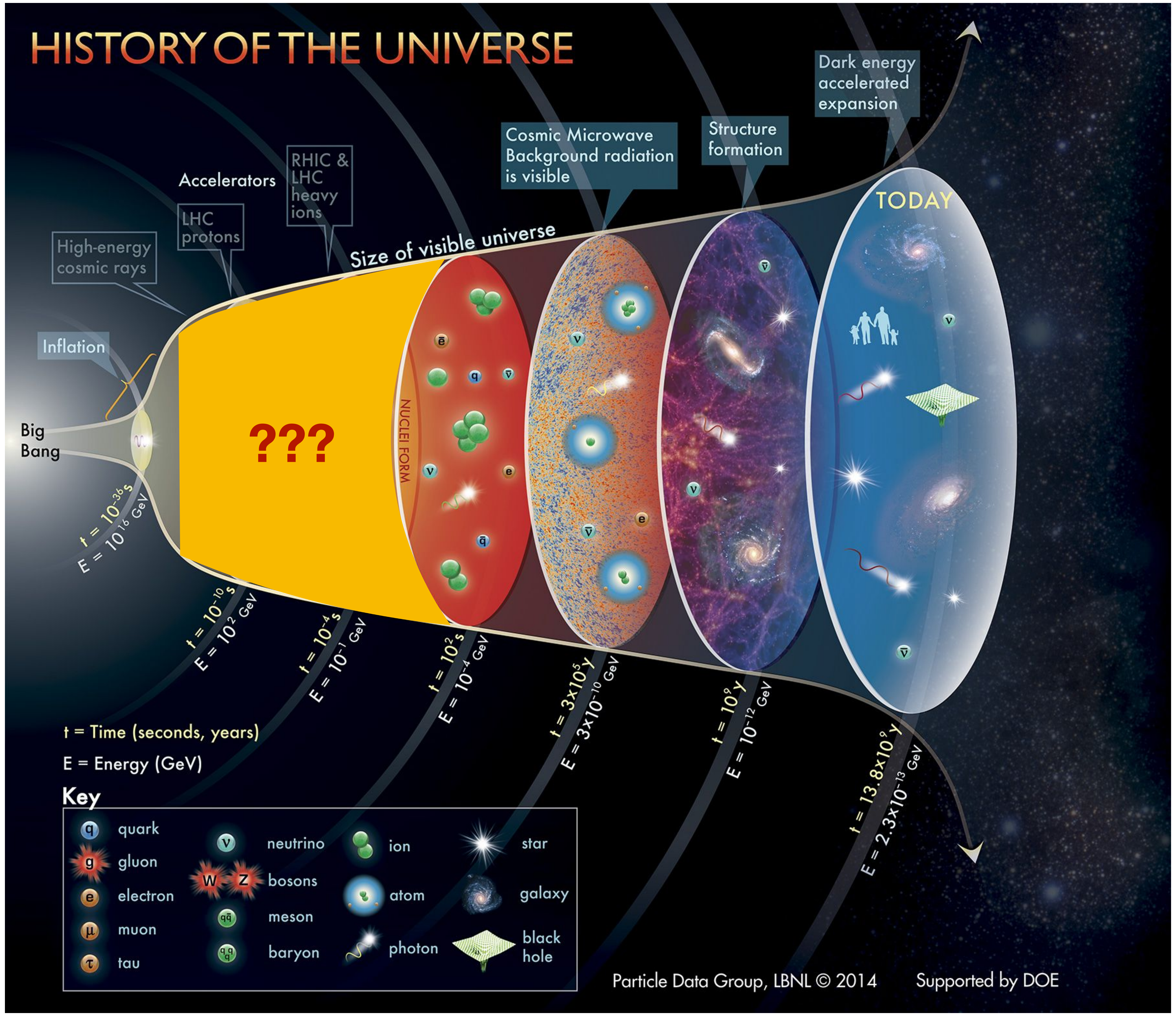
Motivation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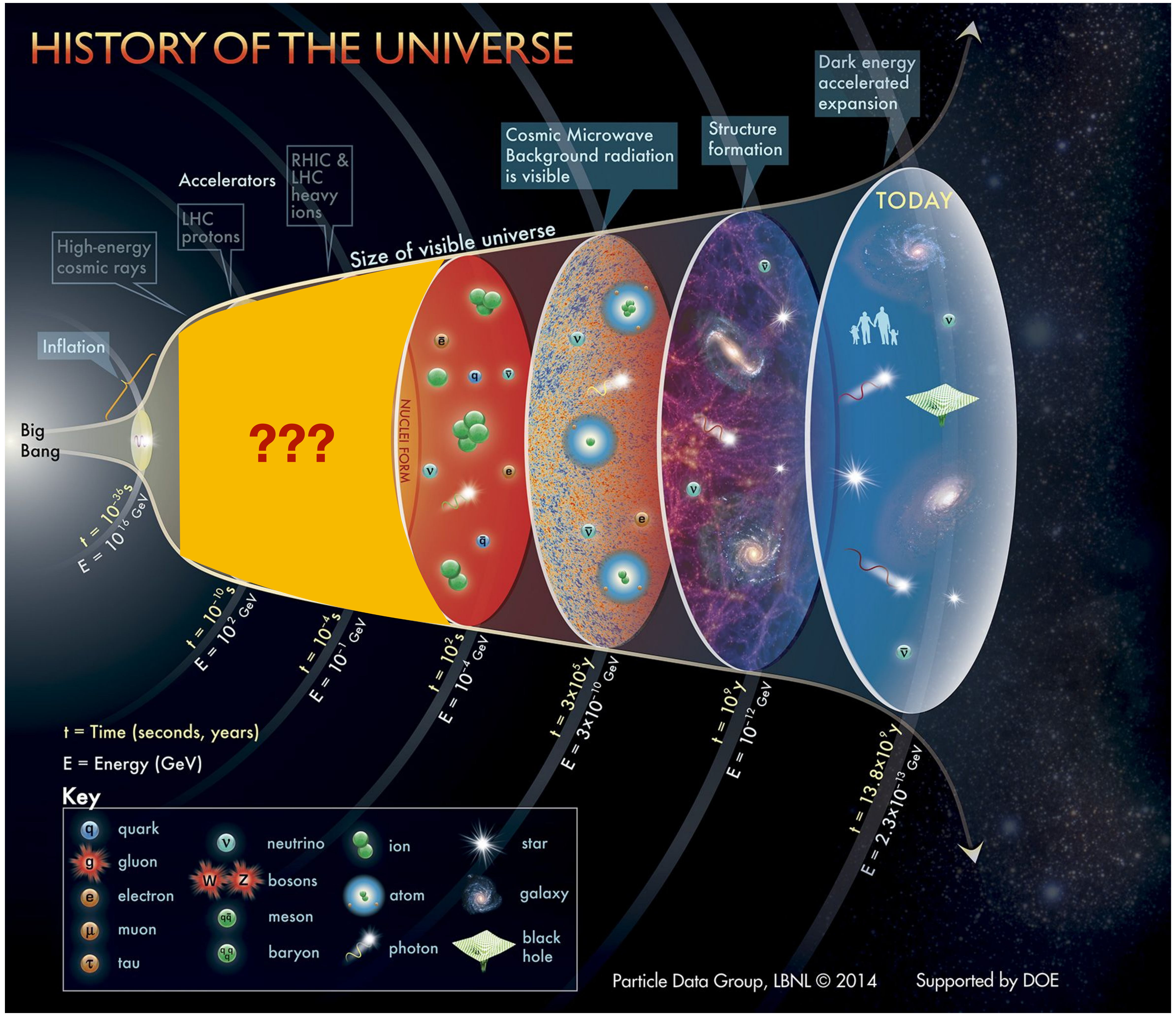
Motivation

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?



Motivation

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- Standard Model particles had to be reheated at least at temperatures around 4 MeV
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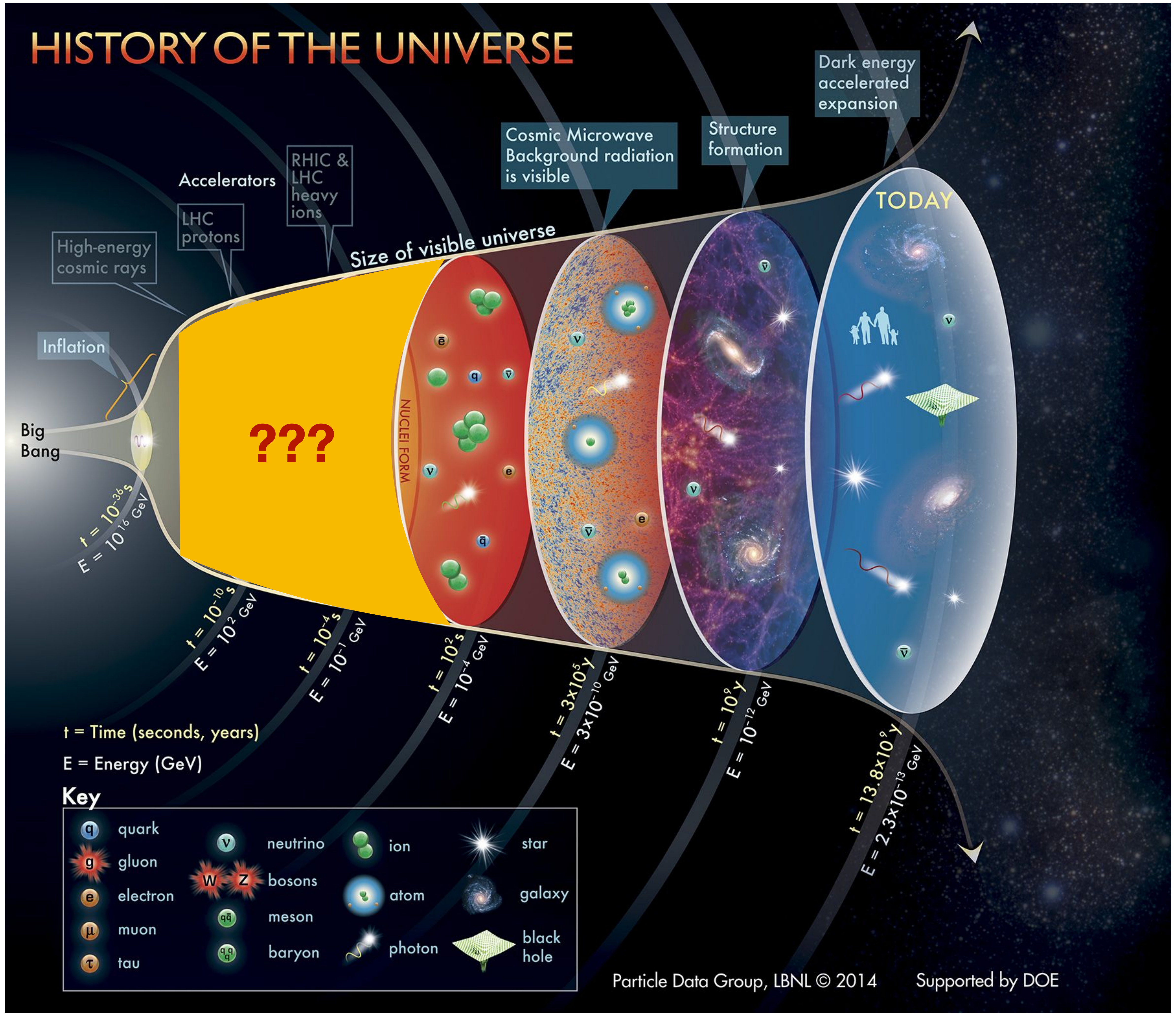
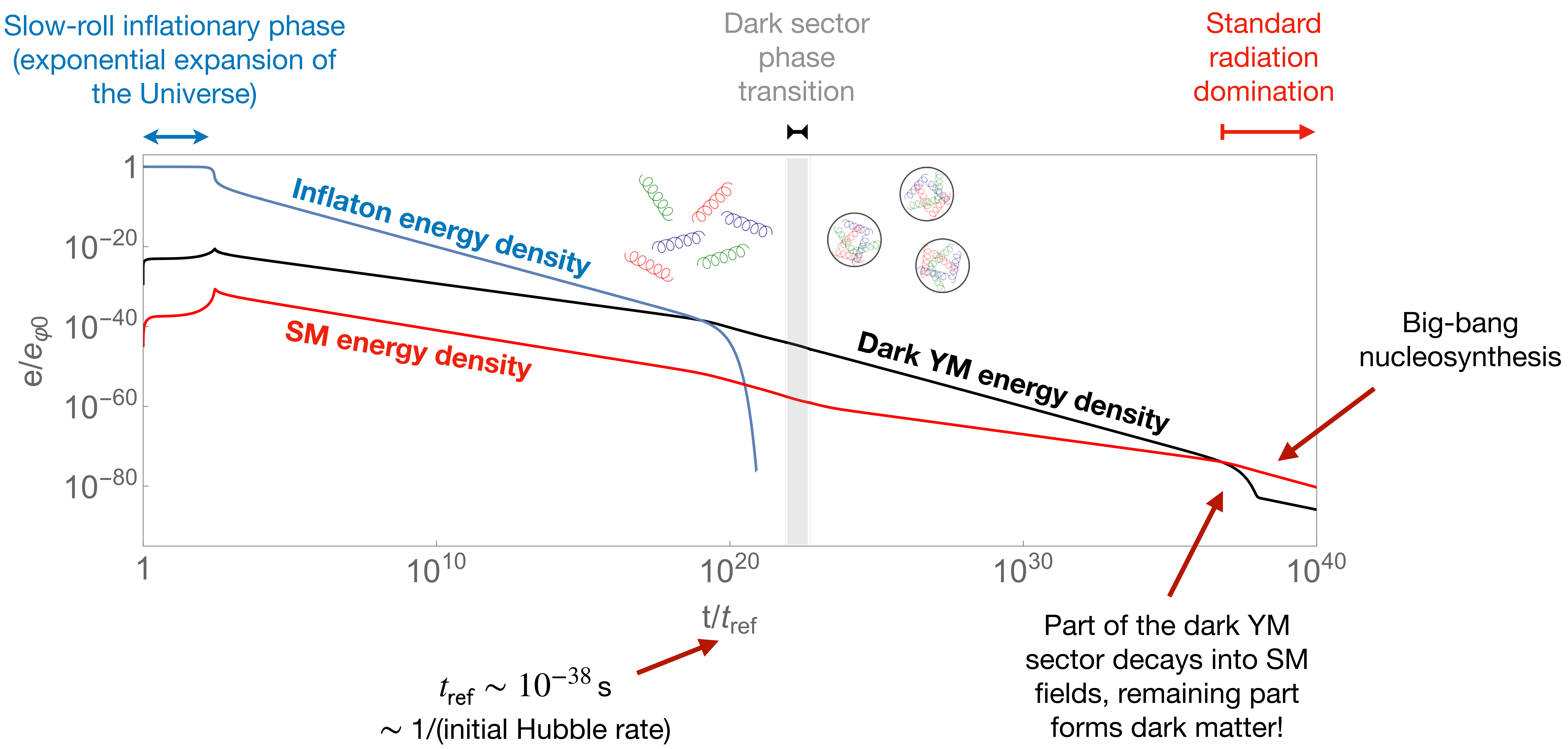


A dark Yang-Mills sector could provide both dark matter and a link between the inflation and SM reheating!

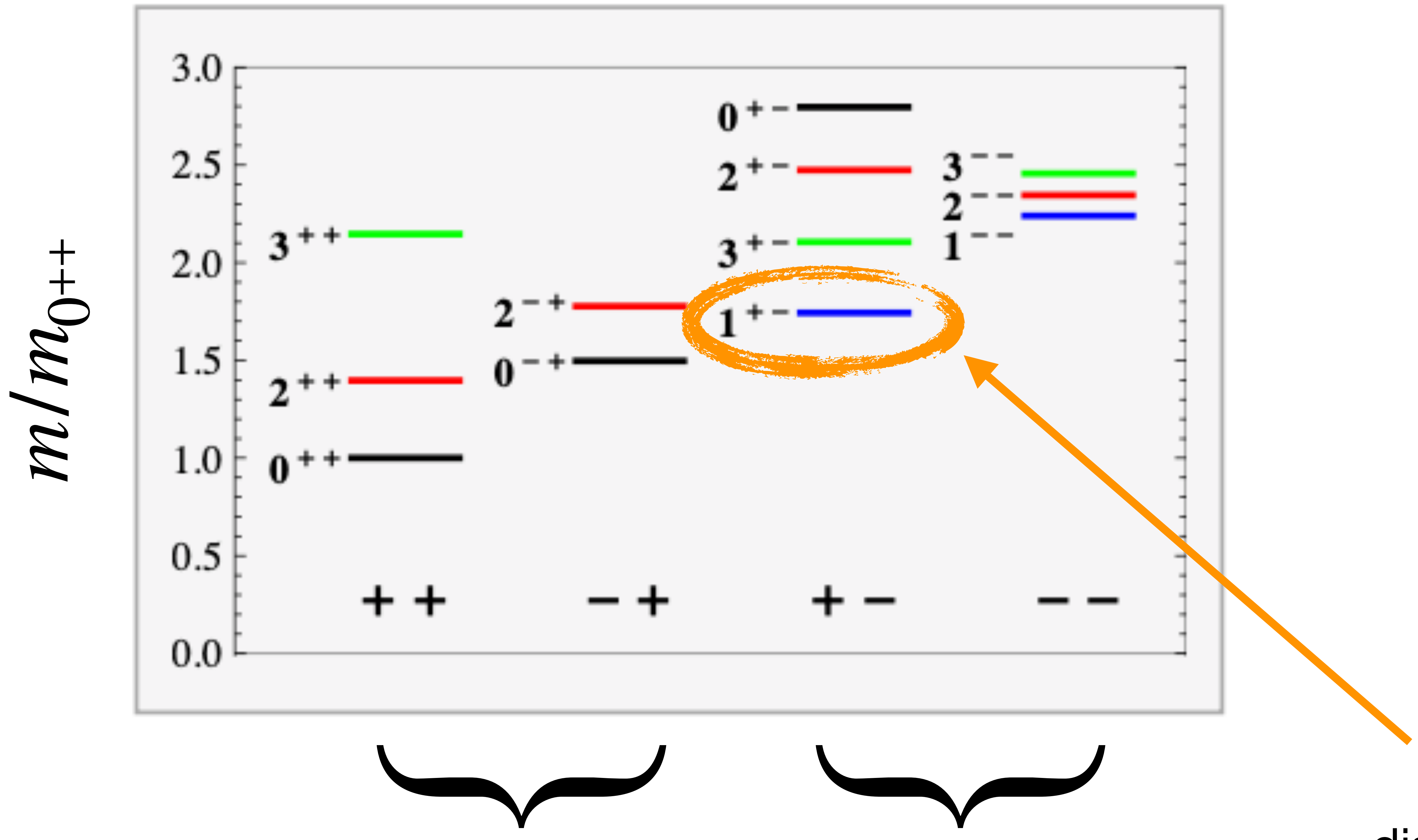
History of the Universe à la 2406.10345

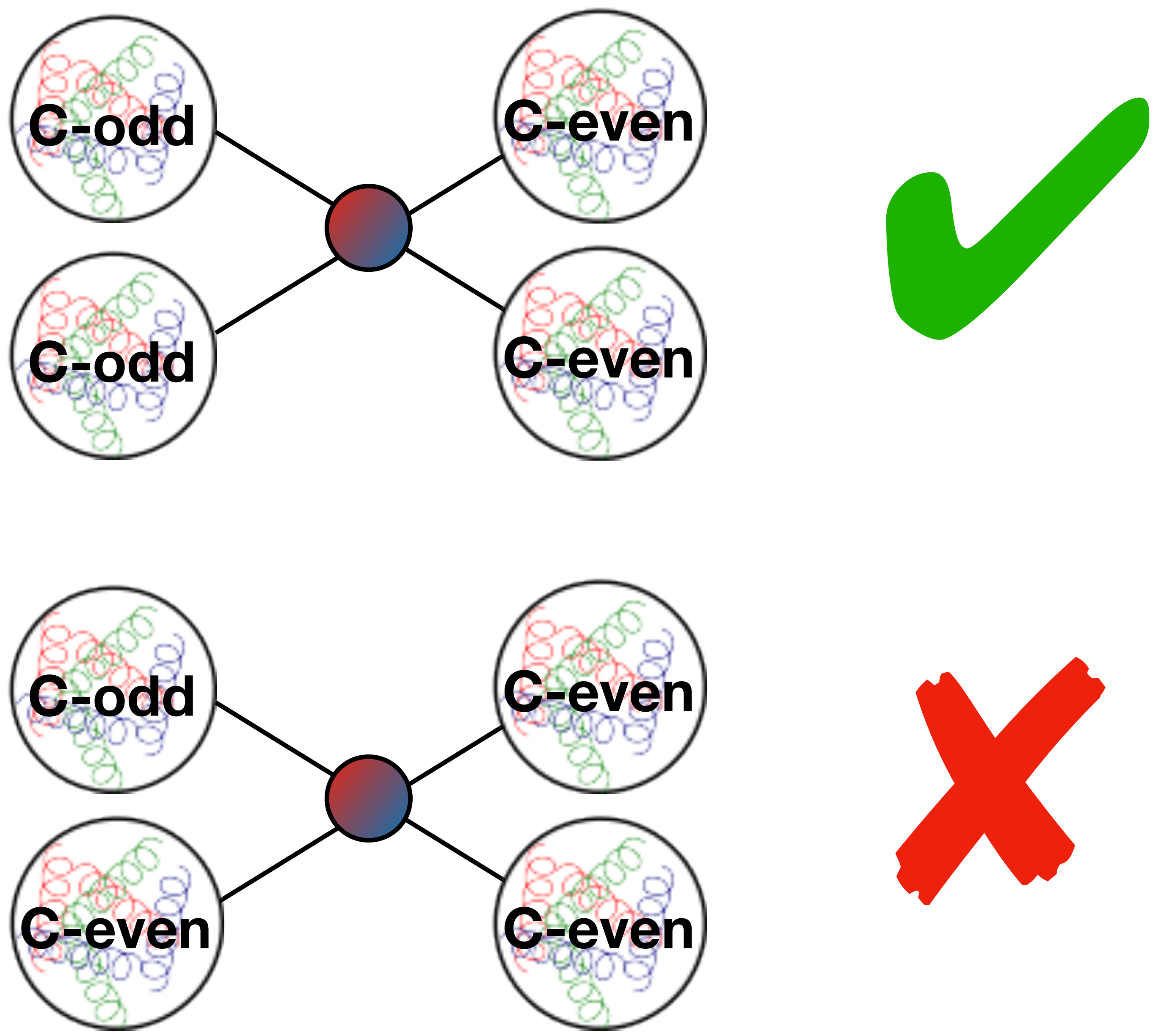


Glueball dark matter

[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] [McKeen, Mizuta, Morrissey, Shamma: 2406.18635]…

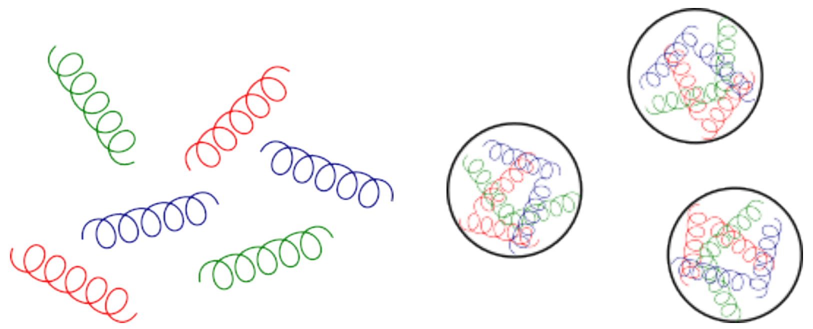
Spectrum of SU(3) glueballs J^{PC}





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



Dark Yang-Mills sector

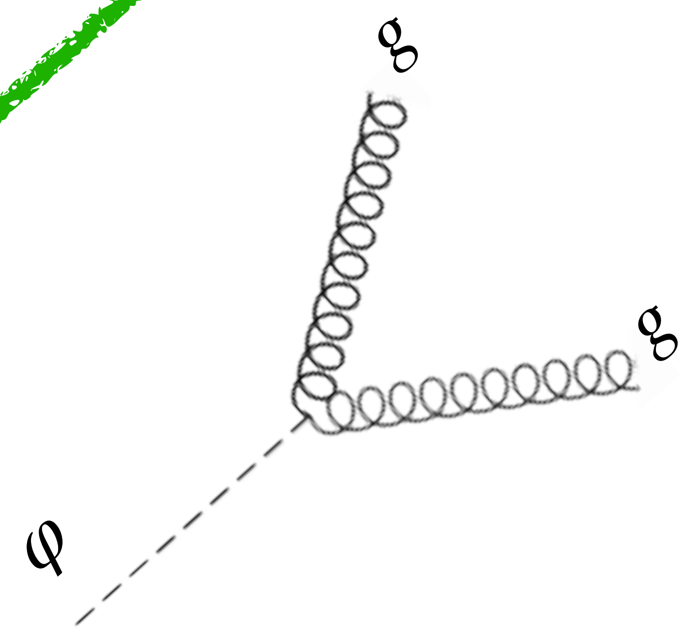
Gauge coupling

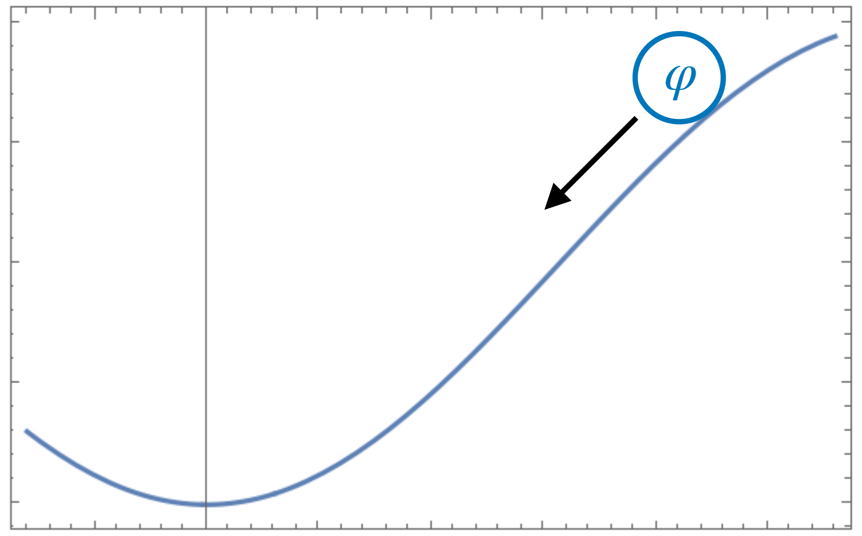
Yang-Mills field strength

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

Axion decay constant

Axion-like inflaton

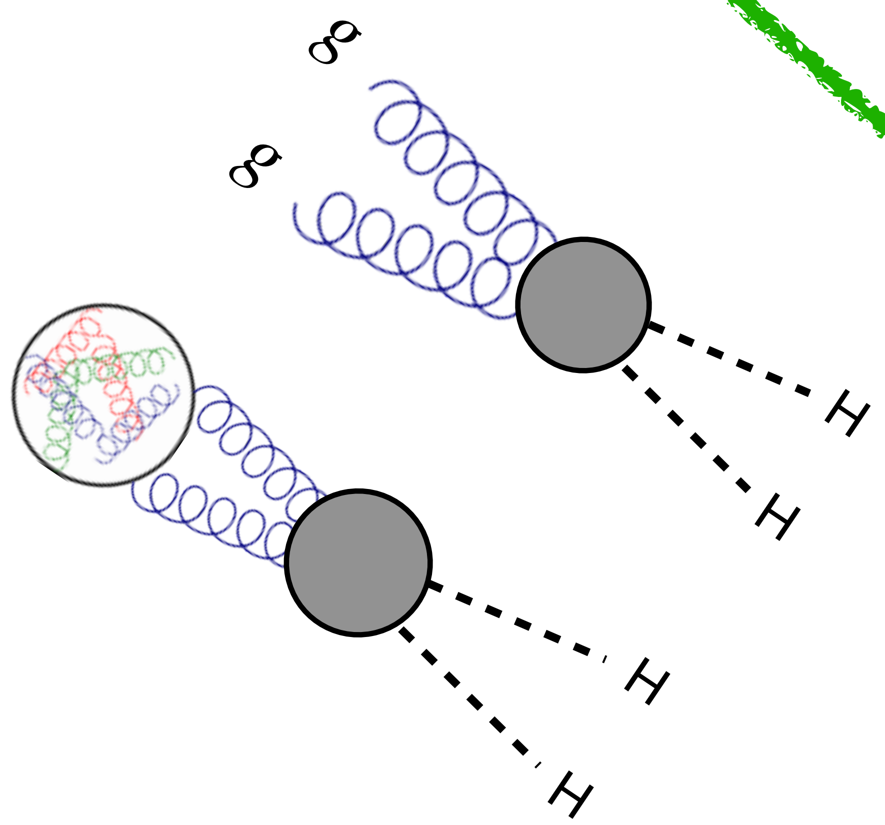




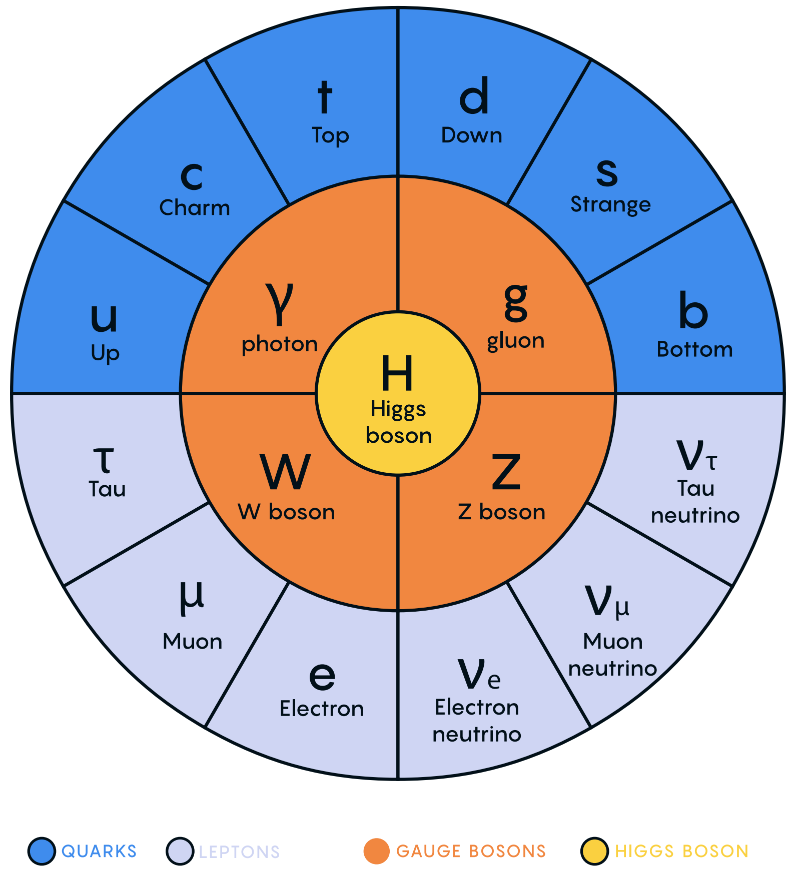
[Berghaus, Graham, Kaplan: 1910.07525]
[Laine, Procacci: 2102.09913]
[Klose, Laine, Procacci: 2201.02317]
[Klose, Laine, Procacci: 2210.11710]
[HK, Laine, Procacci: 2303.17973]

Example of an effective operator either for gravitational interaction (then $M = m_{\rm pl}$) or for interaction via portal particles with large mass M (e.g. heavy fermions)

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



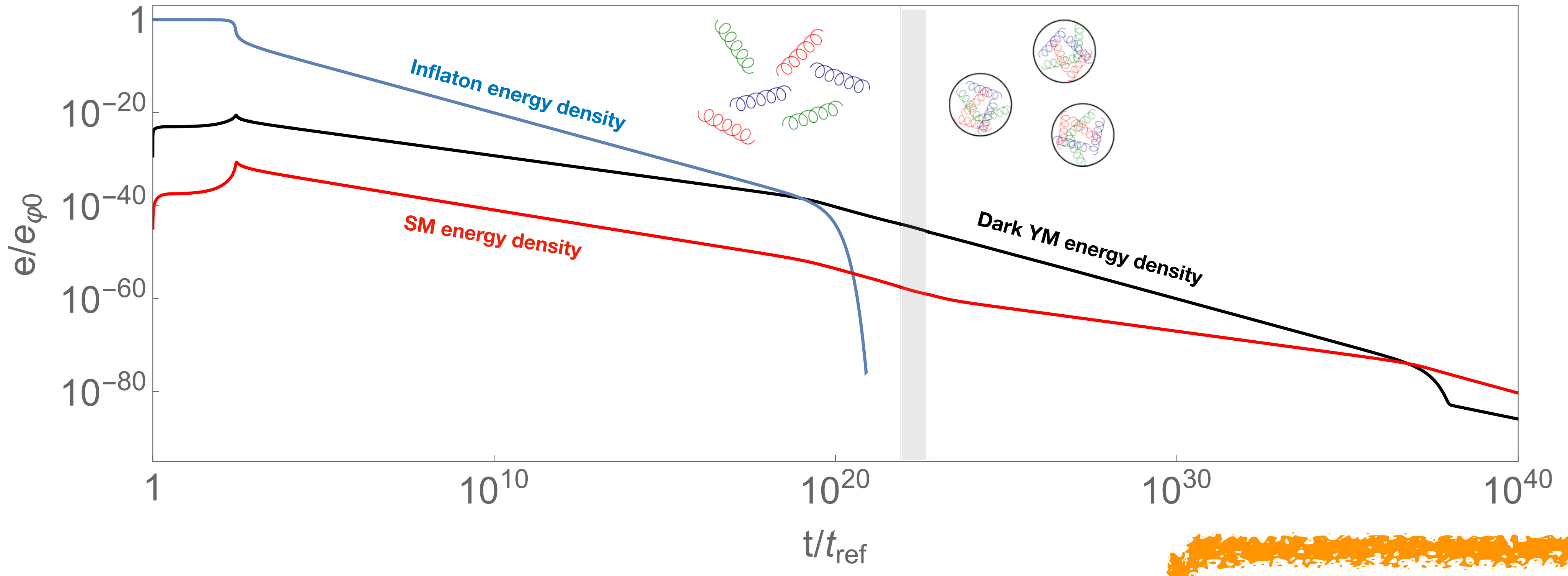
Standard Model



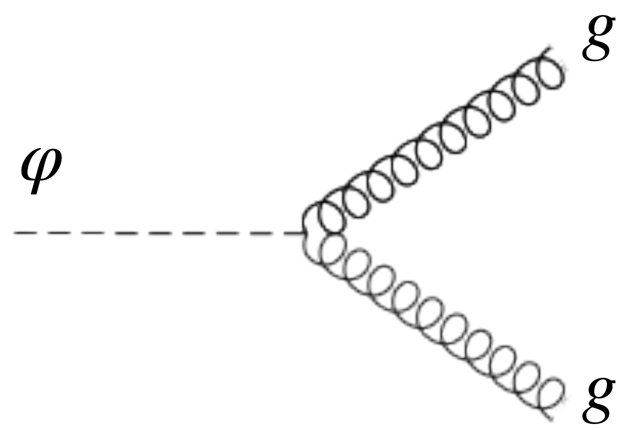
Credit: quantamagazine.org

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

Evolution equations



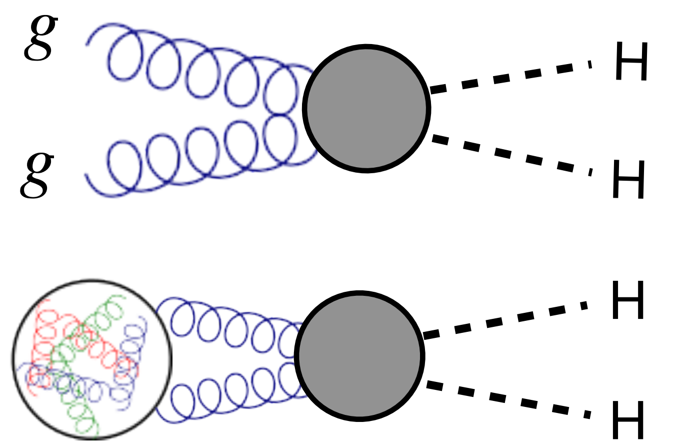
Inflaton decay rate: $\Upsilon \simeq \alpha^2 m_\varphi^3/(32\pi^3 f_a^2)$ if $T_{\mathrm{DS}} \ll m_\varphi$,
lattice input available for SU(3)
[Moore,Tassler: 1011.1167] [Laine, Niemi, Procacci, Rummukainen: 2209.13804]



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

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

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



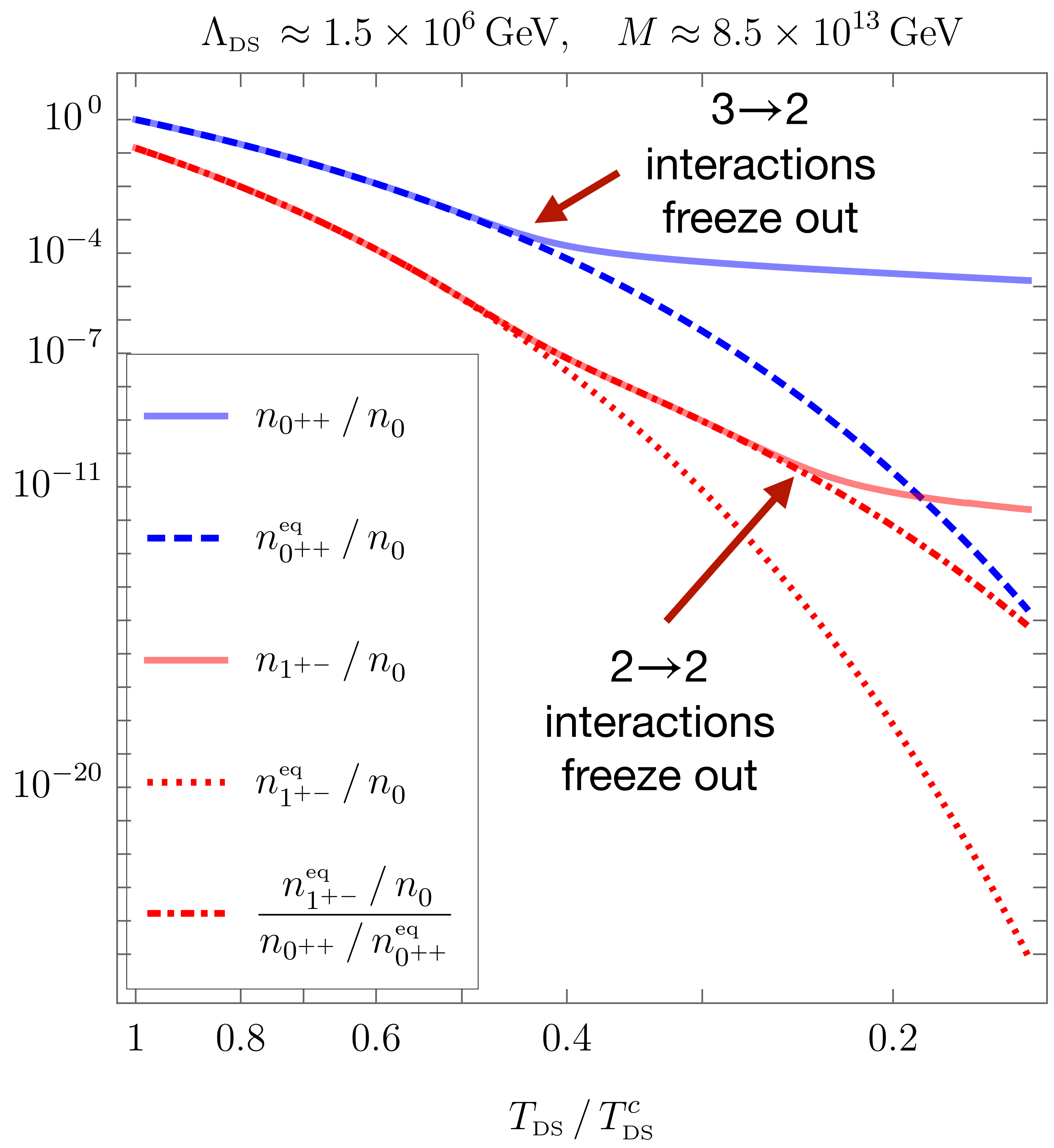
Dark sector energy and pressure densities parameterised by temperature.
SU(3) equation of state:
[Giusti, Pepe: 1612.00265]
[Meyer: 0905.422]

Hubble rate:

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

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

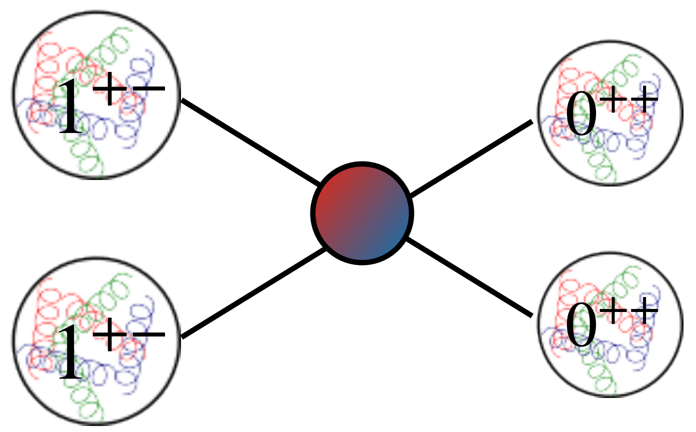
Dark matter relic abundance?



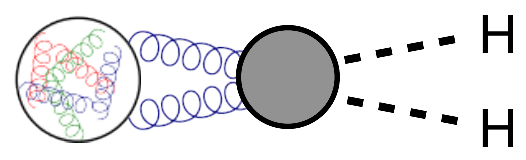
Boltzmann equations for the number densities of the lightest C-even and lightest C-odd glueballs:

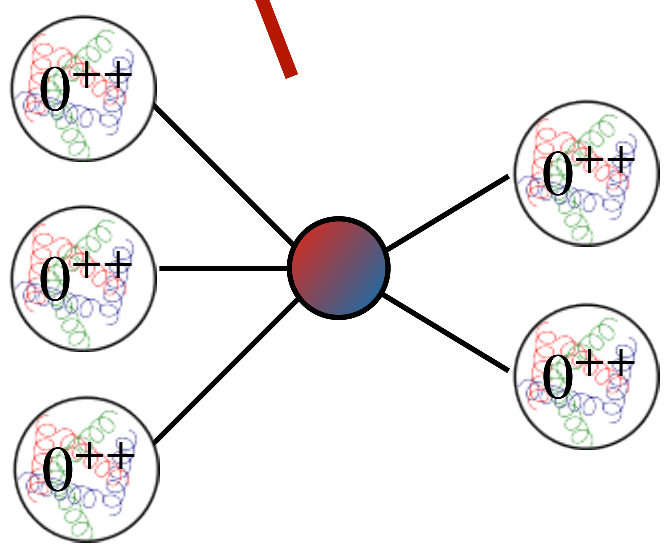
$$\dot n_{1^{+-}} + 3Hn_{1^{+-}} = B_\varphi^{1^{+-}}\Upsilon \frac{e_\varphi}{m_{1^{+-}}} - \langle\sigma_{2\to2}v\rangle \left(n_{1^{+-}}^2 - \left(\frac{n_{0^{++}}}{n_{0^{++}}^{eq}}\right)^2 (n_{1^{+-}}^{eq})^2\right)$$

$$\dot n_{0^{++}} + 3Hn_{0^{++}} = B_\varphi^{0^{++}}\Upsilon \frac{e_\varphi}{m_{0^{++}}} + \langle\sigma_{2\to2}v\rangle \left(n_{1^{+-}}^2 - \left(\frac{n_{0^{++}}}{n_{0^{++}}^{eq}}\right)^2 (n_{1^{+-}}^{eq})^2\right)$$



$$- n_{0^{++}}\Gamma - \langle\sigma_{3\to2}v^2\rangle\, n_{0^{++}}^2 (n_{0^{++}} - n_{0^{++}}^{eq})$$





Inspired by [Forestell, Morrissey, Sigurdson: 1605.08048]
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: open parameter space

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

$$m_\varphi = 1.09 \times 10^{-6}\, m_{\text{pl}},$$

$$f_a = 1.25\, m_{\text{pl}}$$

Too much dark matter

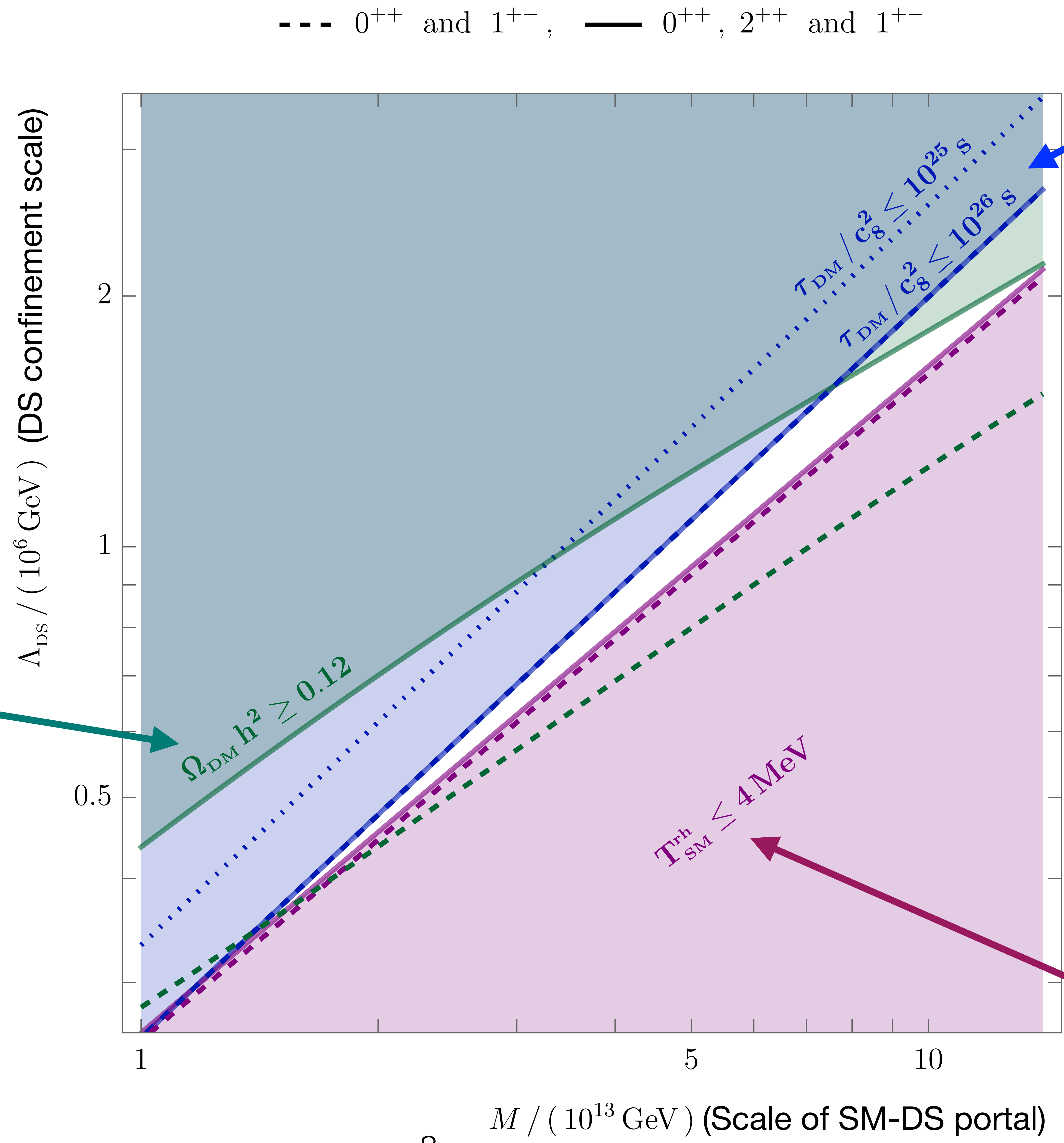
⇔

Too early freeze-out

⇔

Too weak interactions:

$$\langle \sigma_{2\to 2} v\rangle \propto 1/\Lambda_{\text{DS}}^2$$

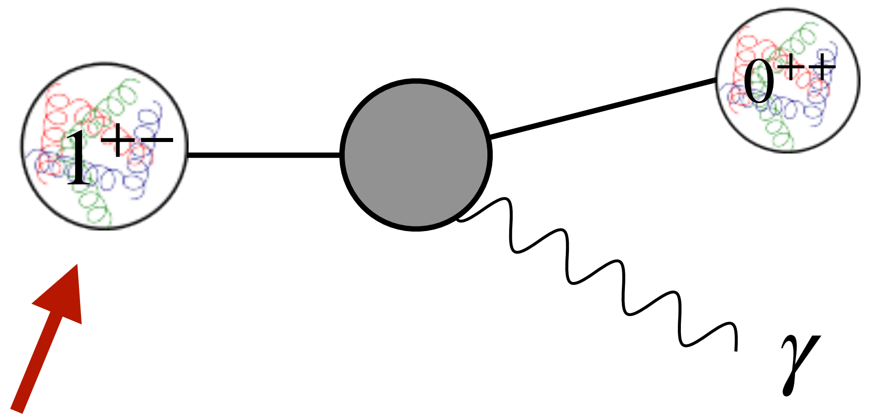


Too large DM decay rate

$$\Gamma_{\text{DM}} \propto \Lambda_{\text{DS}}^9 / M^8$$

NB: C-odd glueballs decay through operators like

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



Dark matter particle: lightest C-odd glueball

$$m_{1^{+-}} \simeq 11\, \Lambda_{\text{DS}}$$

Lightest glueball (unstable):

$$m_{0^{++}} \simeq 7\, \Lambda_{\text{DS}}$$

SM not reheated efficiently enough

$\Leftrightarrow \Gamma \propto \Lambda_{\text{DS}}^5 / M^4$ too small

Conclusions & Outlook

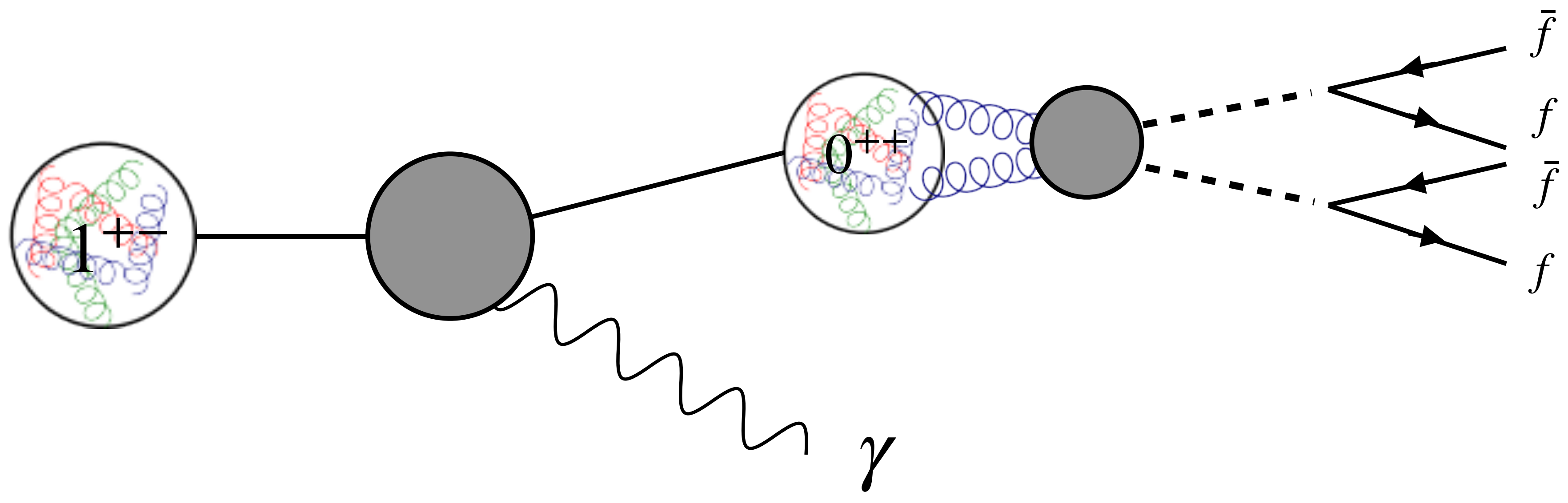
- A general scenario linking dark matter production with inflation and SM reheating provided

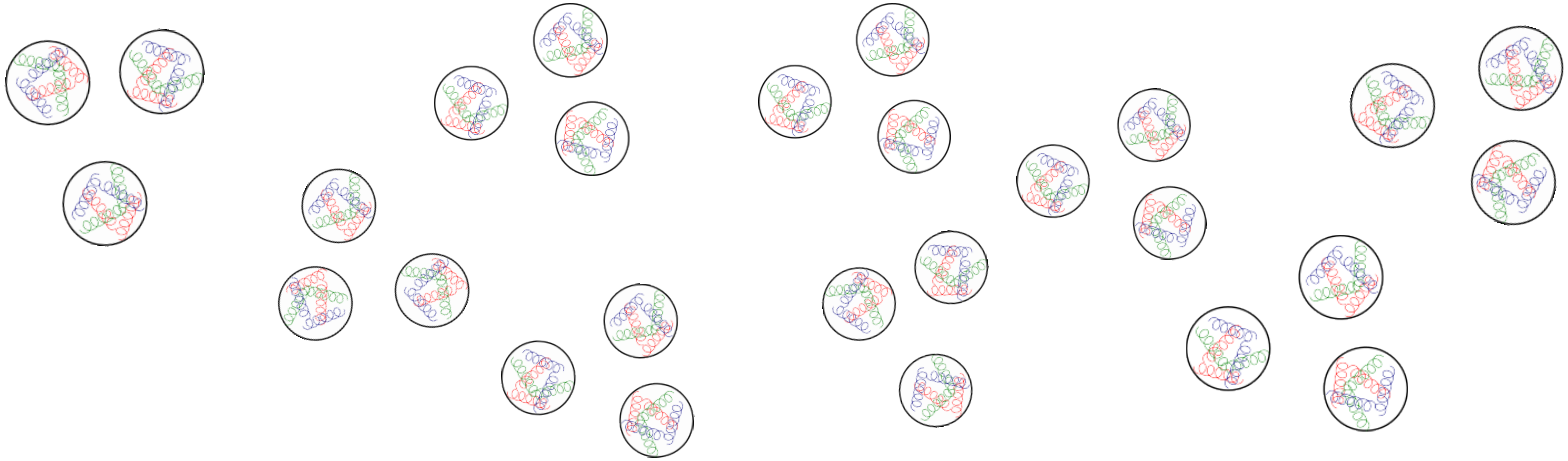
- Dark matter relic abundance independent of the details of the inflationary scenario ⇒ generalisations beyond axion-like inflation possible

- 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?

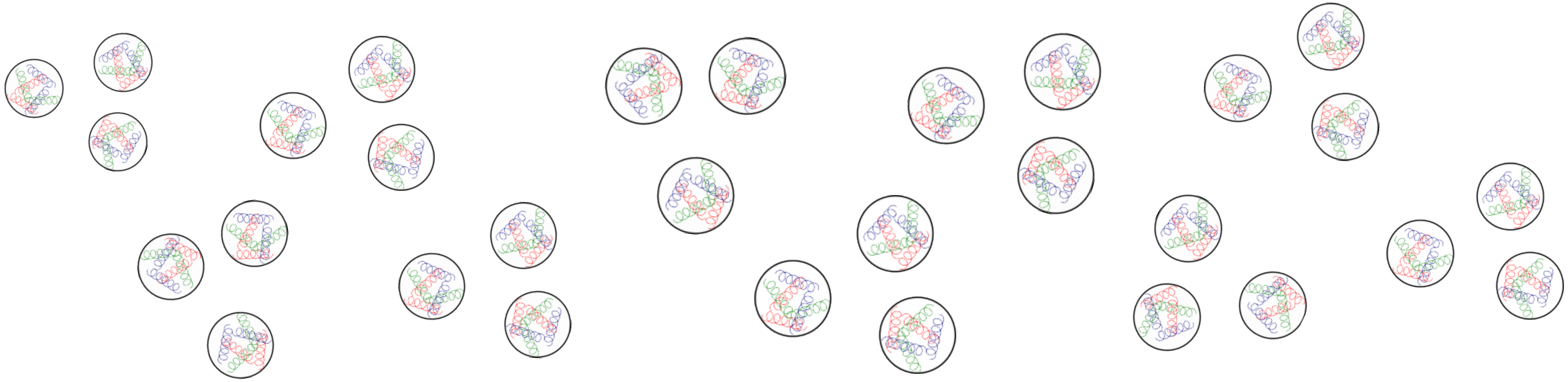
- Larger open parameter space can be obtained for theories where the “protected” glueballs are more long-lived. E.g., for SO(N) with $N \geq 8$: $\Gamma_{\mathrm{DM}} \propto \Lambda_{\mathrm{DS}}^{2N-3}/M^{2N-4}$

- Concrete indirect detection signal to be predicted!



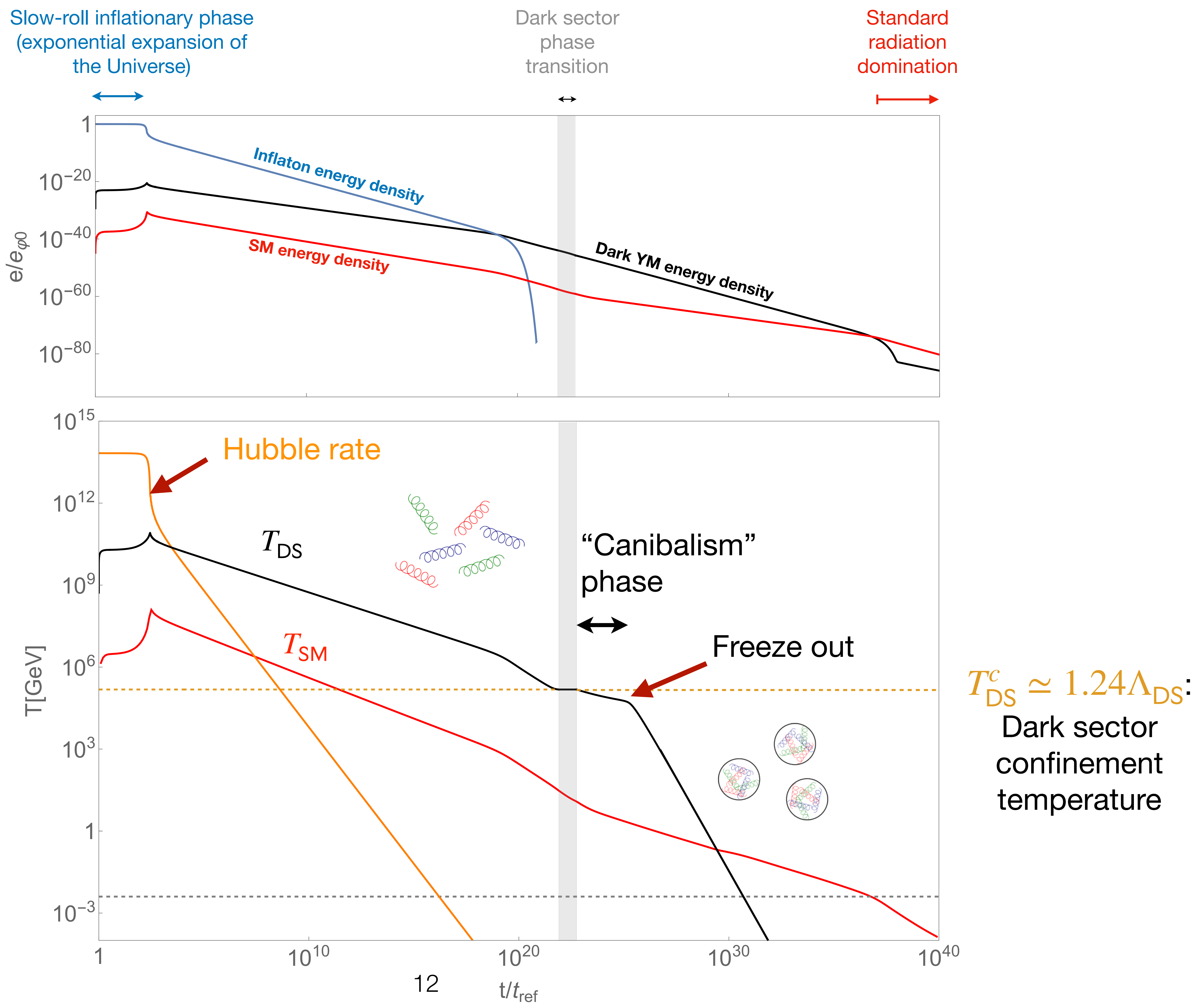


Thanks for your attention!

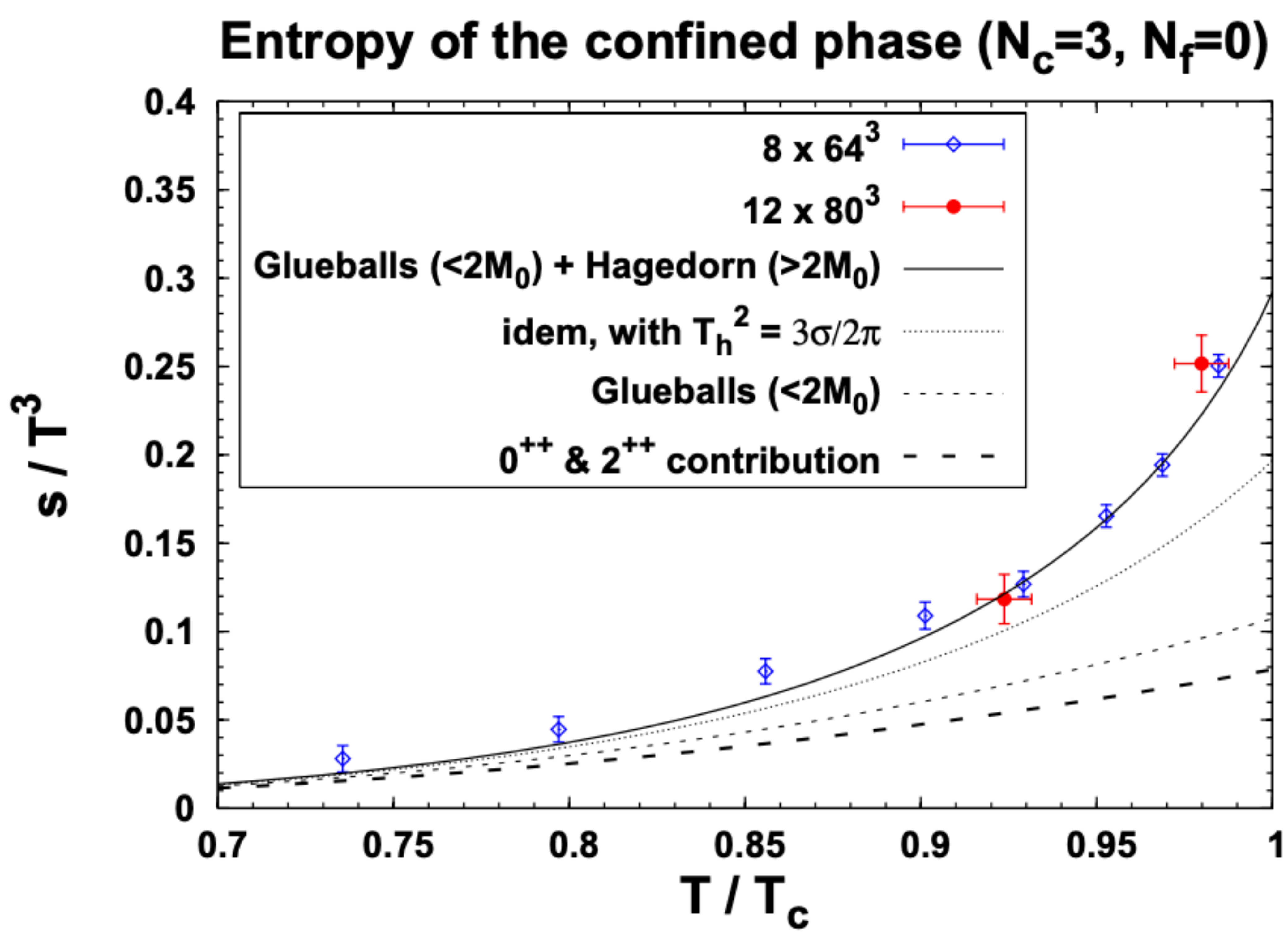


Backup

History of the Universe à la 2406.10345

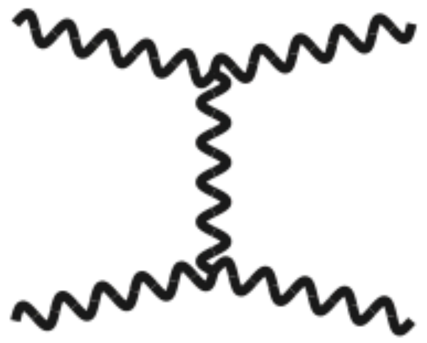


Thermodynamics of a YM theory below confinement scale might be indeed described as an ensemble of glueballs!

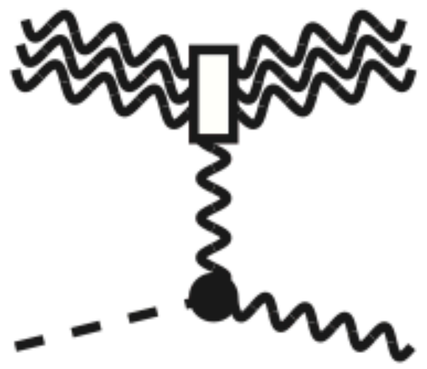


[Meyer: 0905.4229]

Thermalisation?



(a)



(b)

Thermalisation rate:

$$\Gamma_g \sim \alpha^2 T$$

$$\Gamma_a \sim \Upsilon$$

Glueball dark matter

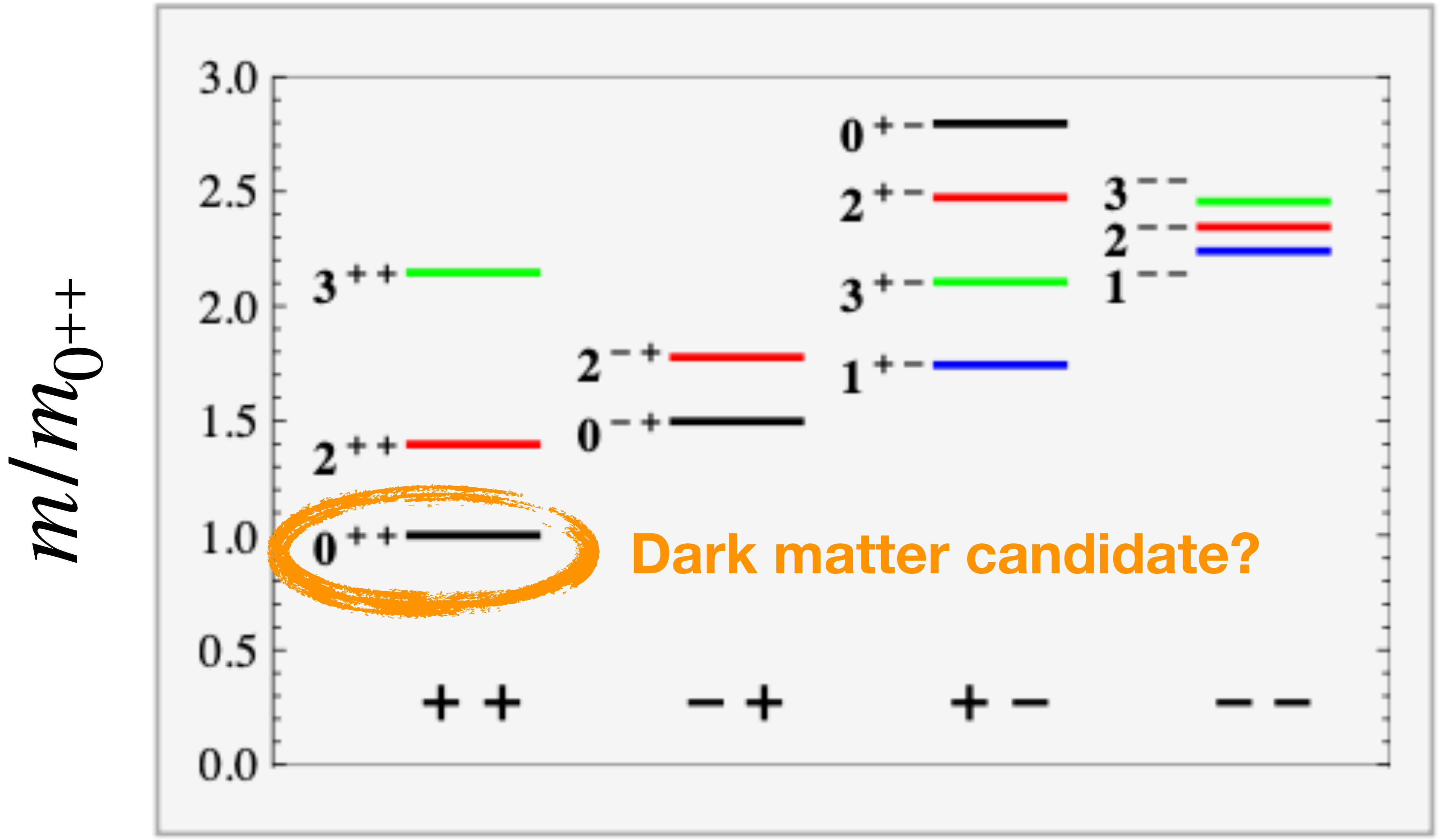
[Boddy et al.:1402.3629] [Soni, Zhang: 1602.00714] [Forestell, Morrissey, Sigurdson: 1605.08048, 1710.06447] [Carenza, Pasechnik, Wang et al.: 2207.13716, 2306.09510]…

- Self-interacting dark matter: $\sigma_{GB} \propto m_{GB}^{-2}$
  $\sigma_{GB}/m_{GB} \sim 1$ cm^2/g if $\Lambda \sim$ 100 MeV
- Example of the lowest order effective operator for the decay of the lightest 0^{++} glueball to SM fields:

$$\frac{|H|^2 \mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu}}{M^2} \Rightarrow \Gamma_{0^{++}} \sim \frac{\Lambda^5}{M^4}$$

- If the lightest glueball forms dark matter: $1/\Gamma_{0^{++}} \gtrsim 10^{26}$ s
- Even if $M \sim m_{\mathrm{pl}}$ this translates to $\Lambda \lesssim 10^6$ GeV

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

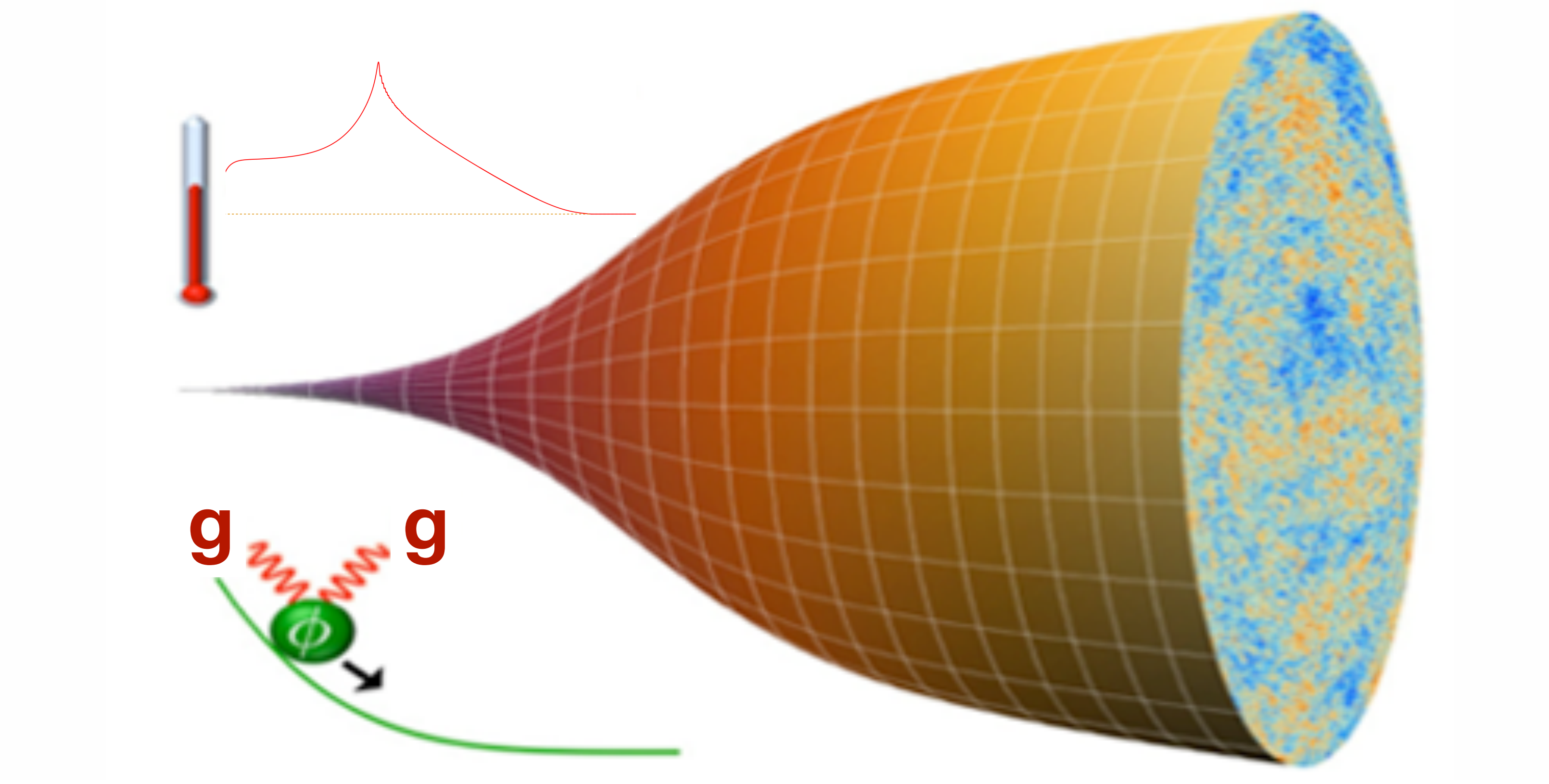


[Juknevich, Melnikov, Strassler: 0903.0883]

Model setup: Example of a “warm inflation”

- Axion inflation coupled to non-abelian dark sector

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



Credit: João G. Rosa/University of Aveiro; ESA and the Planck collaboration

$$\mathscr{L} \supset \frac{1}{2}\partial^\mu \varphi\, \partial_\mu \varphi - V_0(\varphi) - \frac{\alpha\, \varphi\, \epsilon^{\mu\nu\rho\sigma} F^c_{\mu\nu} F^c_{\rho\sigma}}{16\pi f_a}$$

Gauge coupling; Yang-Mills field strength; Inflaton field; Axion decay constant

Inflaton potential:

$$V_0 \simeq m^2 f_a^2 \left[1 - \cos\left(\frac{\bar{\varphi}}{f_a}\right)\right]$$

“Natural/axion inflation” [Freese, Frieman, Olinto: Phys.Rev.Lett. 65 (1990)]

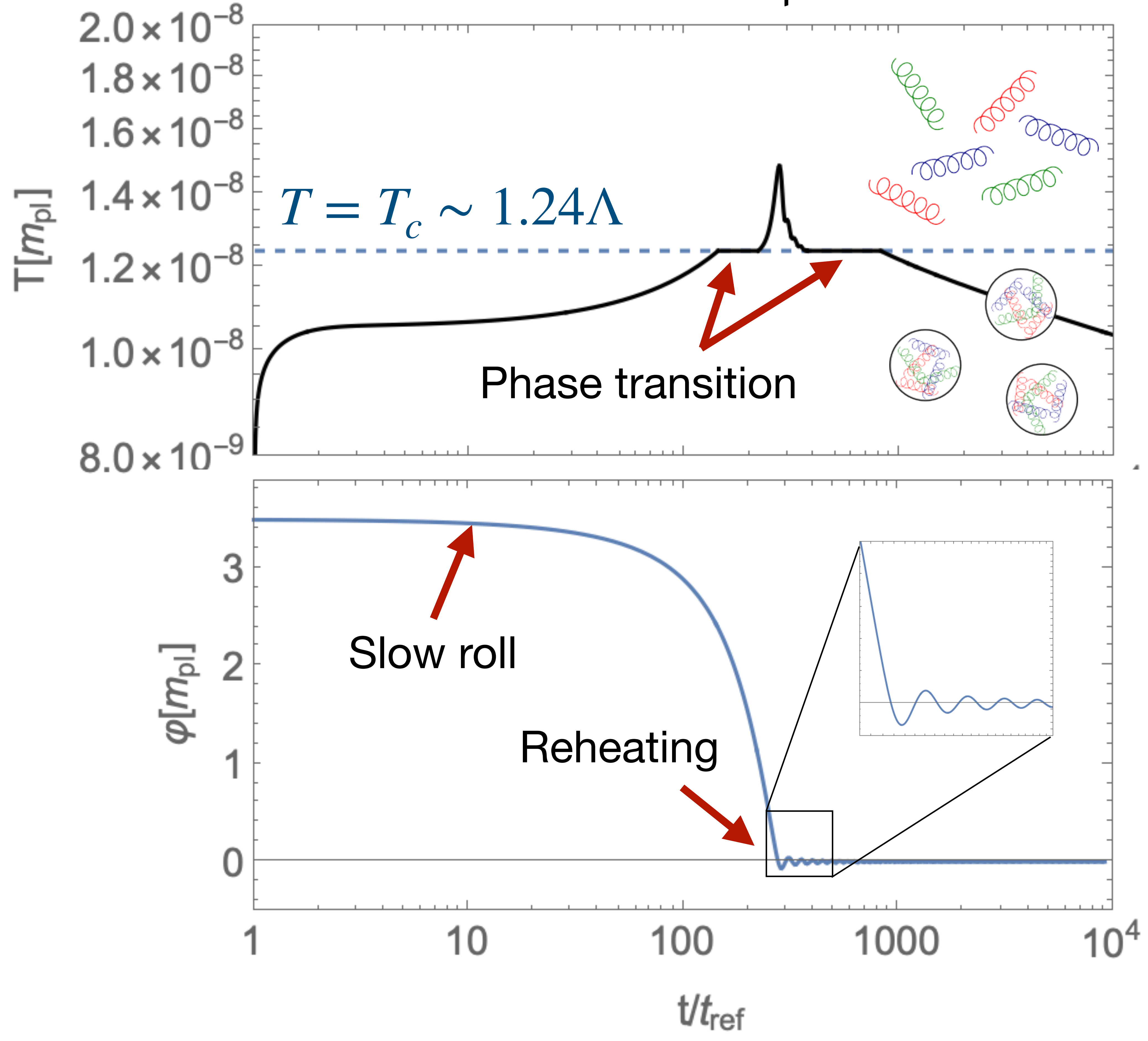
$$\ddot{\bar{\varphi}} + (3H + \Upsilon)\dot{\bar{\varphi}} + V_\varphi \simeq 0$$

$$\dot{\rho}_r + 3H(\rho_r + p_r) \simeq \Upsilon \dot{\bar{\varphi}}^2$$

Hubble rate; Friction due to inflaton coupling to dark sector; Dark radiation energy and pressure densities

Evolution of the dark sector

$\Lambda = 10^{-8} m_{\text{pl}}$



($m_{\text{pl}} = 1.22 \times 10^{19}$ GeV)

- Evolution of an SU(3) sector coupled to axion inflation studied for varying confinement scale Λ
  [HK, Laine, Procacci: 2303.17973]

Friction due to inflaton coupling to dark sector: lattice input available for SU(3)
[Moore,Tassler: 1011.1167] [Laine, Niemi, Procacci, Rummukainen: 2209.13804]

$$\ddot{\varphi} + (3H + \Upsilon)\dot{\varphi} + V_\varphi \simeq 0$$

$$\dot{\rho}_r + 3H\left(\rho_r + p_r\right) \simeq \Upsilon \dot{\varphi}^2$$

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

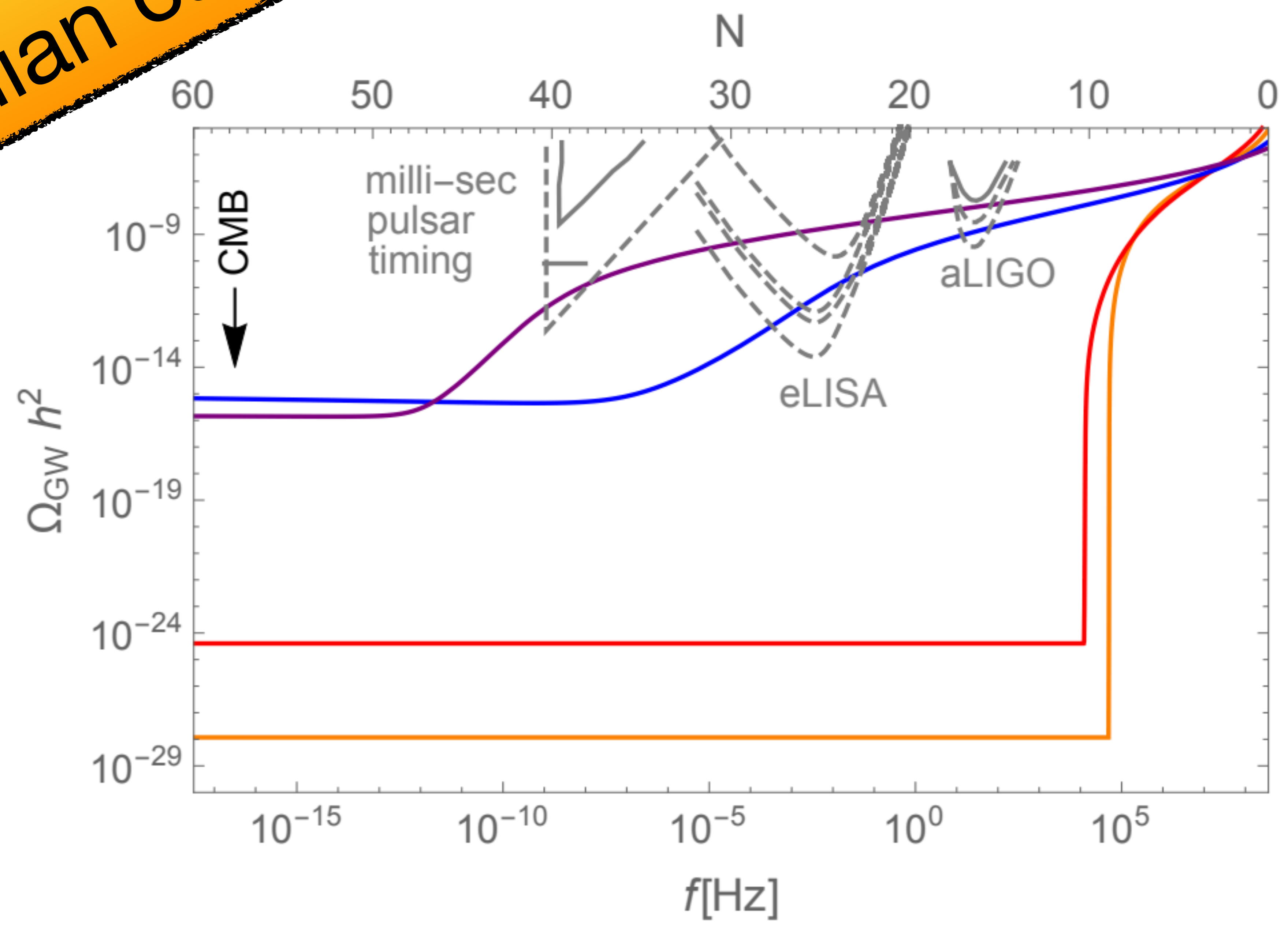
NB: abelian vs non-abelian dark sector

- Pseudoscalar inflaton coupled to gauge fields:

$$\mathscr{L} \supset -\frac{\alpha\, \varphi\, \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}}{16\pi f_a}$$

Absent in thermal non-abelian case!

- Abelian case: exponential growth of one helicity mode of the vector field ⇒ GW, PBH, CMB non-gaussianities… [Sorbo: 1101.1525; Cook, Sorbo: 1101.1525; Barnaby, Pajer, Peloso: 1110.3327; Domcke, Pieroni, Binétruy: 1603.01287…]



[Domcke: 1605.06364; Domcke, Pieroni, Binétruy: 1603.01287]

- Discussion about back-reaction [… Figueroa et al.: 2303.17436]

- Non-Abelian case: thermalisation assumption simplifies the back-reaction modeling!