HIDDeν

Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Glue-ball Dark Matter

Giacomo Landini

25/04/2023

IFIC INSTITUT DE FÍSICA CORPUSCULAR

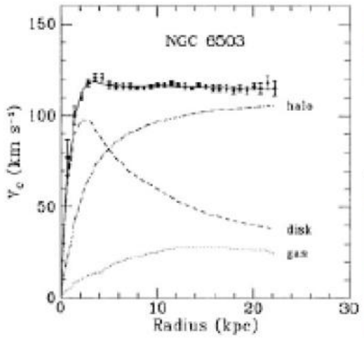
C. Gross, S. Karamitsos, GL, A. Strumia

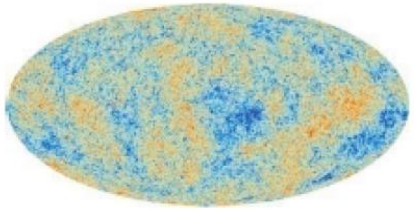
arxiv [2012.12087]

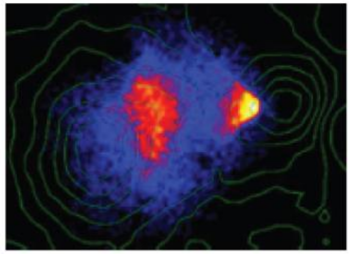
VNIVERSITAT DE VALÈNCIA

Dark Matter summary

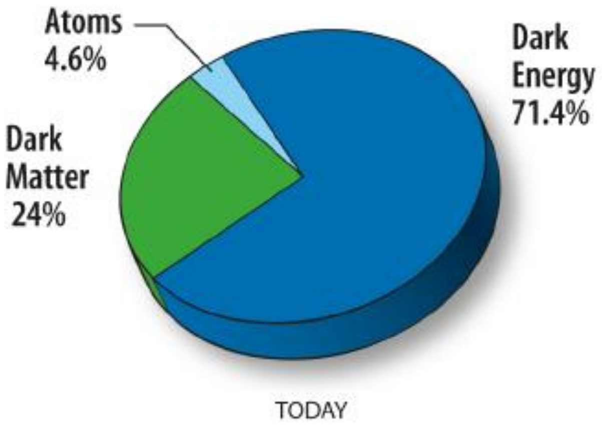
Dark Matter existence is supported by astrophysical and cosmological evidence







Today most of the Universe is dark



- Neutral and weakly interacting with SM
- **(Cosmologically) stable**
- Cold (non-relativistic at structure formation)

Gravitational DM

All the evidence for DM comes from its gravitational interactions

No evidence of non-gravitational couplings to the SM sector until now!!

We assume that DM has only gravitational couplings to the SM sector

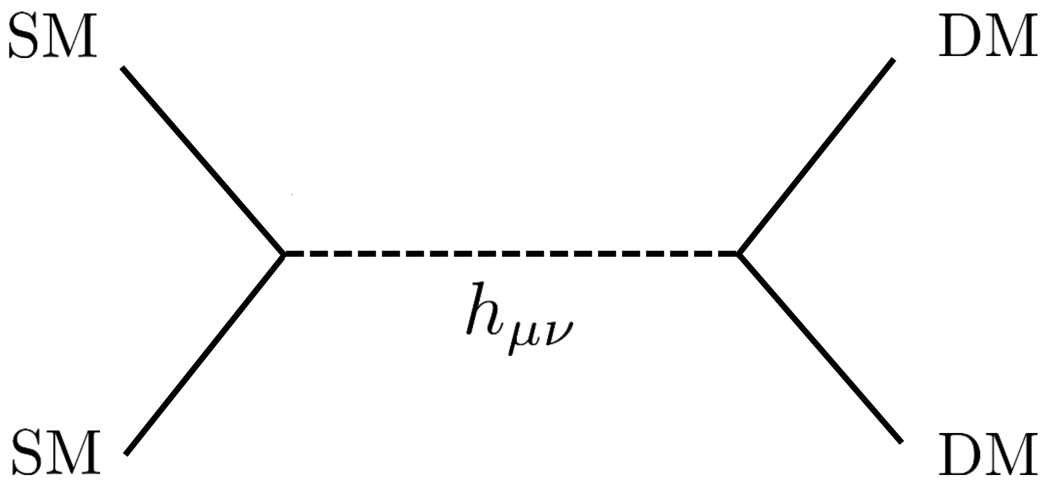
Gravitational Dark Matter

In any case the gravitational production is always present:
unavoidable background of DM population

Gravitational freeze-in

We assume that DM has only gravitational couplings to the SM sector

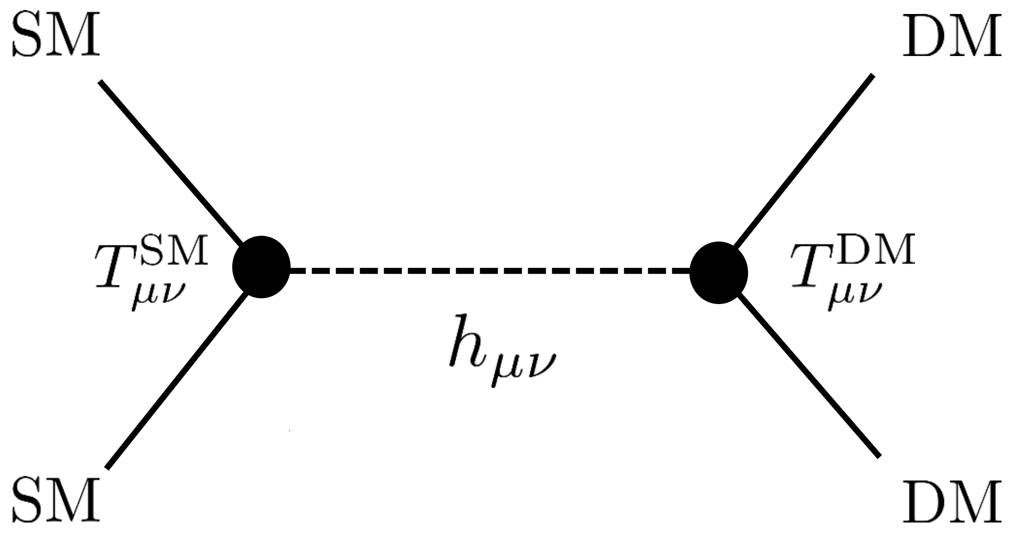
Gravity is weak: DM does not thermalize with the SM thermal bath

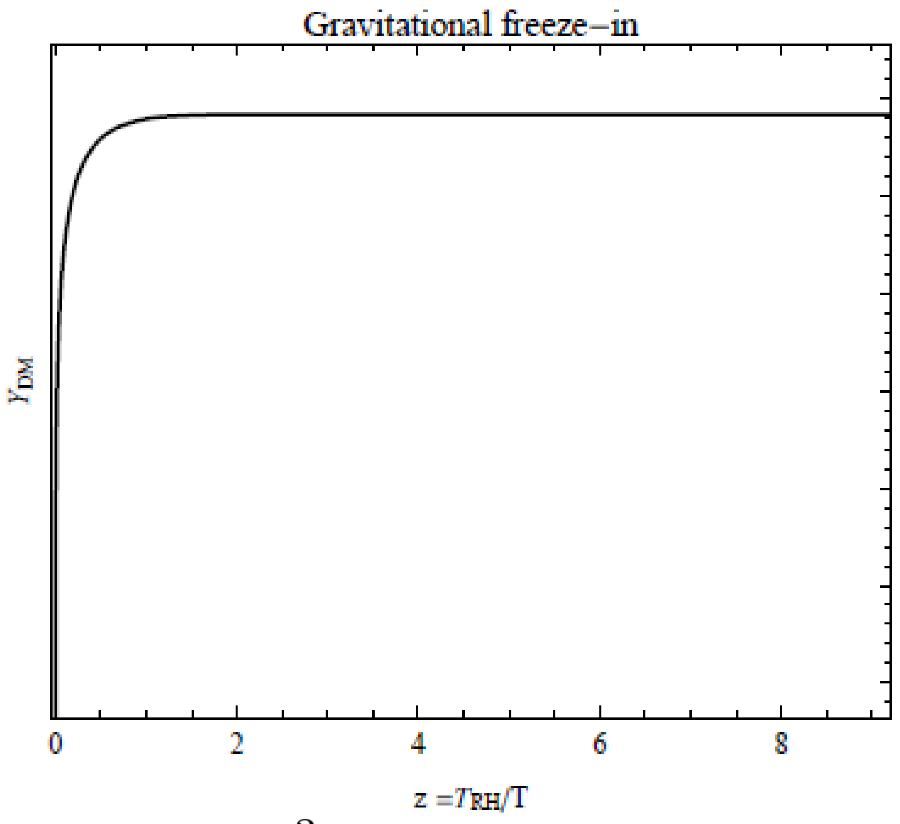


We assume a vanishing DM initial abundance

Gravitational freeze-in

The production is peaked at the highest temperature $T_{\rm RH} \equiv \max_{\rm RD}[T]$



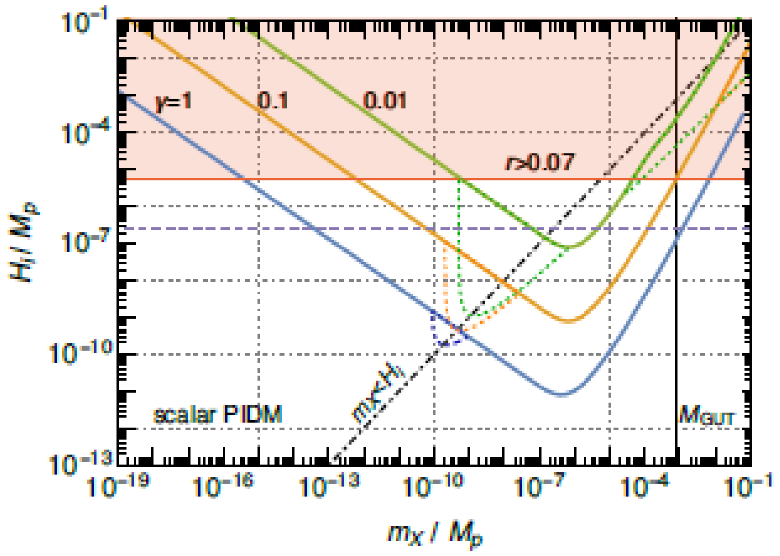


$$Y_{\rm DM} = n_{\rm DM}/s \sim (T/M_{\rm Pl})^3 \sim (T_{\rm RH}/M_{\rm Pl})^3$$

$$\frac{\Omega_{\rm DM} h^2}{0.12} = \frac{m_{\rm DM} Y_{\rm DM}}{T_{\rm eq}} \quad \Rightarrow \quad m_{\rm DM} \sim 10^8 \ {\rm GeV} \left(\frac{10^{13}\ {\rm GeV}}{T_{\rm RH}}\right)^3$$

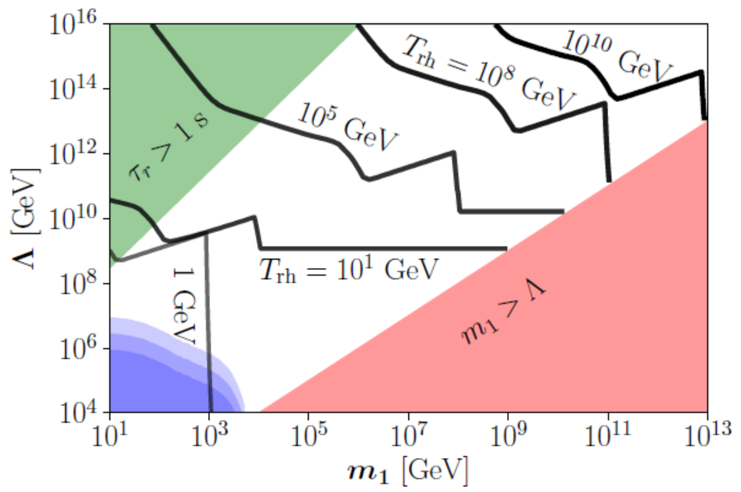
Gravitational freeze-in: status

Gravitational freeze-in has been studied for scalar, fermion and massive vector DM



Garny,Palessandro,Sandora,Sloth, JCAP 02 [1709.09688]
Tang, Wu, Phys.Lett.B 774 [1708.05138]

Bernal,Donini,Folgado,Rius, JHEP 09 [2004.14403]



Gravitational freeze-in: status

Gravitational freeze-in has been studied for scalar, fermion and massive vector DM

Scalar and fermion DM have renormalizable couplings

$$|S|^2|H|^2, S|H|^2 \qquad\qquad LHN$$

Larger contribution to DM production or fine-tuned couplings

A massive vector alone is not a complete theory (extra states and interactions, most likely stronger than gravity)

Gravitational freeze-in: status

A pure gauge theory (= massless vector) does not suffer from these issues

The model

(i) a non-Abelian dark gauge group **G** (SU(N), SO(N), Sp(N),...)
(ii) gauge vectors (gluons)
(iii) no additional matter content (no scalars, no fermions)

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + \theta_{\rm DC} \frac{g^2_{\rm DC}}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu a}$$

UV-complete

Minimal

No renormalizable coupling with the Standard Model

No fine-tuning

The model

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Simplest realization of Gravitational Dark Matter*

*also studied in Redi, Tesi, Tillim, JHEP 05 [2011.10565]

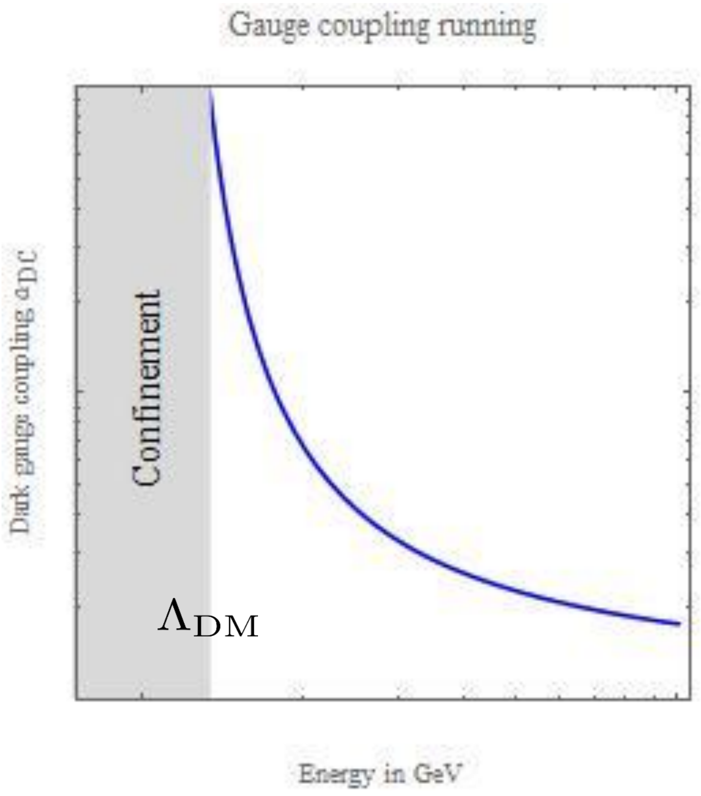
Gauge confinement

The dark gauge coupling grows at low energy and the theory confines

$$\alpha_{\rm DC}(\mu) \approx \frac{6\pi}{11 C_G}\frac{1}{\ln \mu/\Lambda_{\rm DM}}$$

$$C_G = N \qquad SU(N)$$

$$C_G = 2(N-2) \quad SO(N)$$



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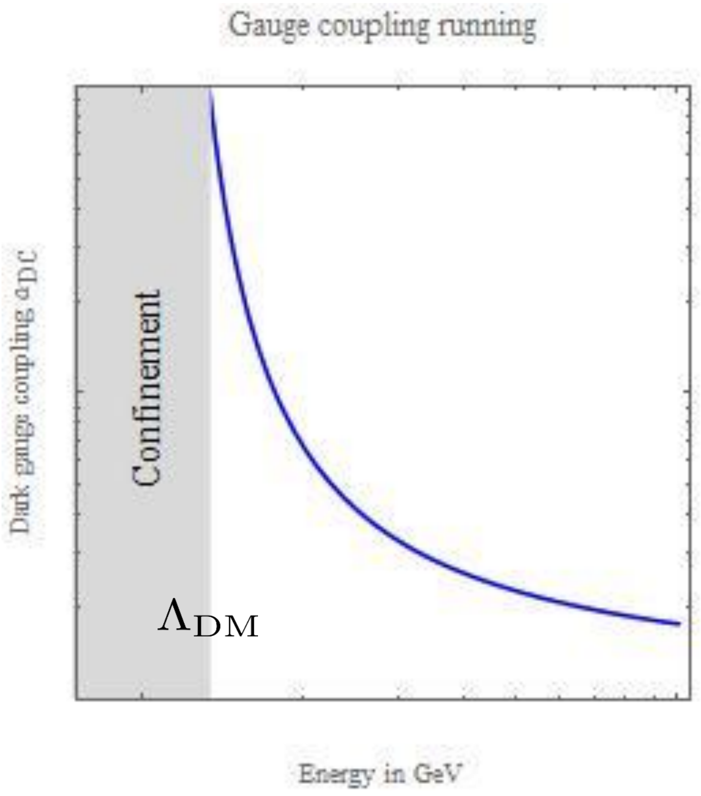
Fundamental energy scale of the theory



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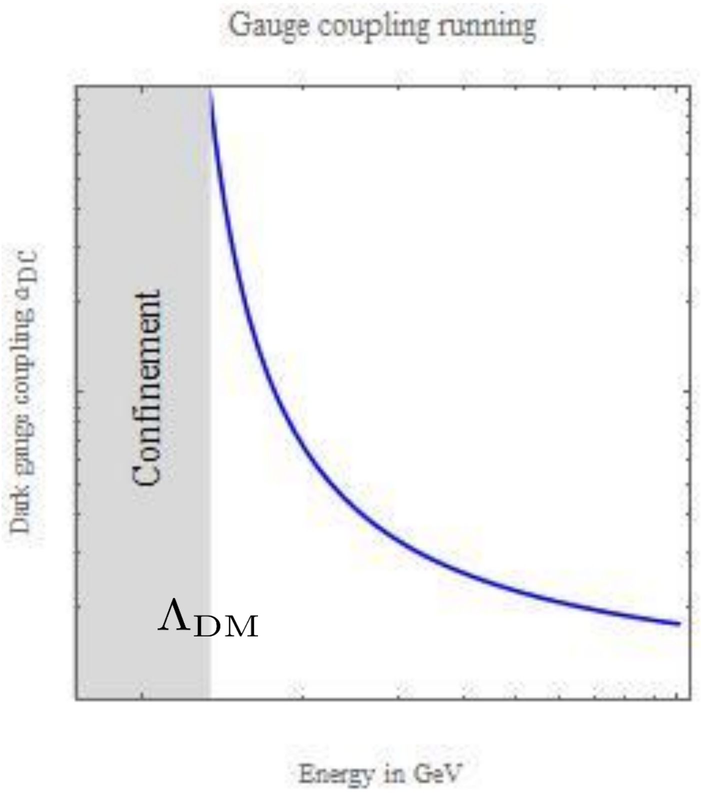

The dark vectors must combine into *gauge-invariant bound states*:
dark glue-balls!

Glue-ball bound states

Glue-ball spectrum can be computed on the lattice for simple groups

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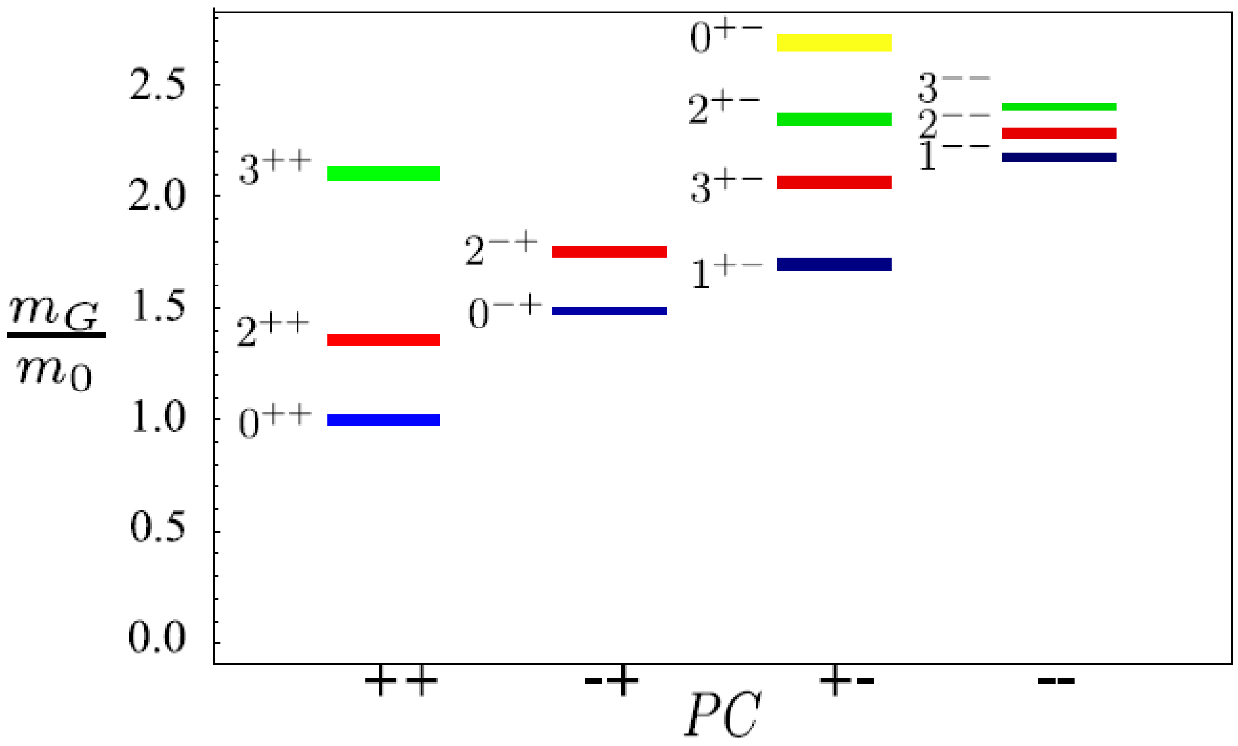
Glue-ball spectrum can be computed on the lattice for simple groups



Example:
SU(3)

Juknevich, Melnikov, Strassler JHEP 07 [0903.0883]
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Morningstar,Peardon Phys.Rev.D60 [9901004]

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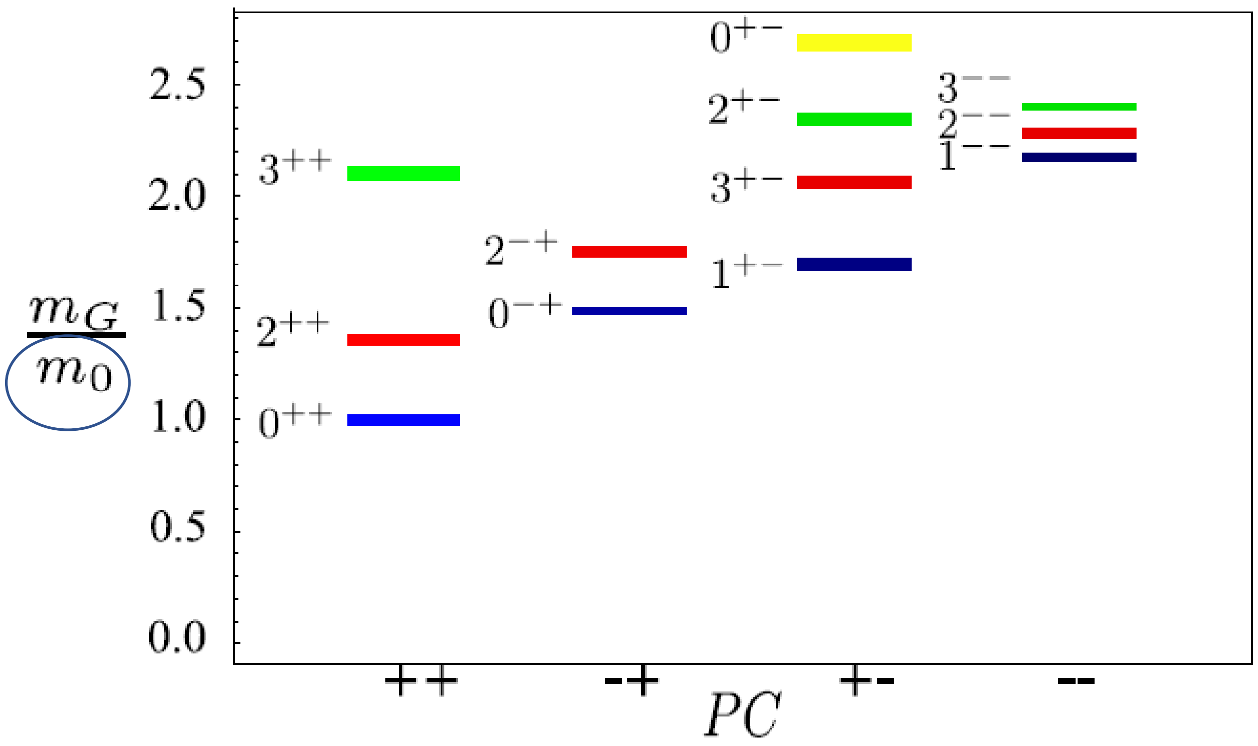

Lightest state

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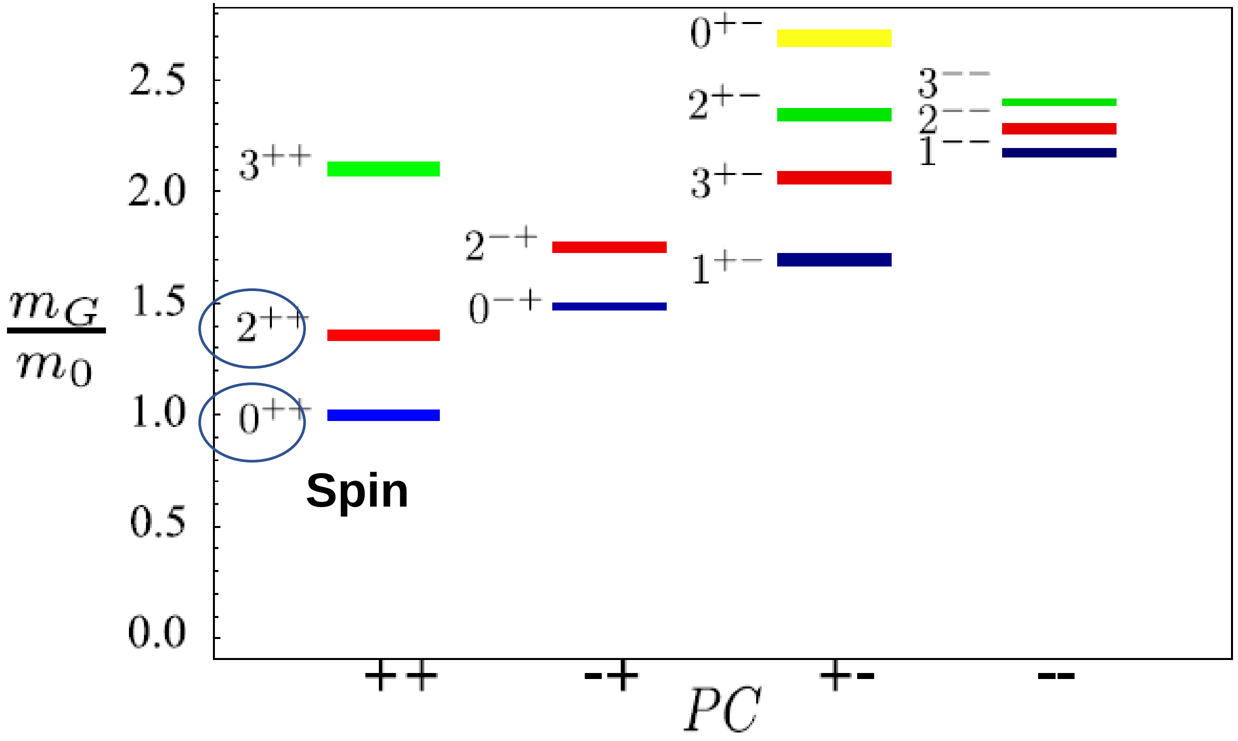

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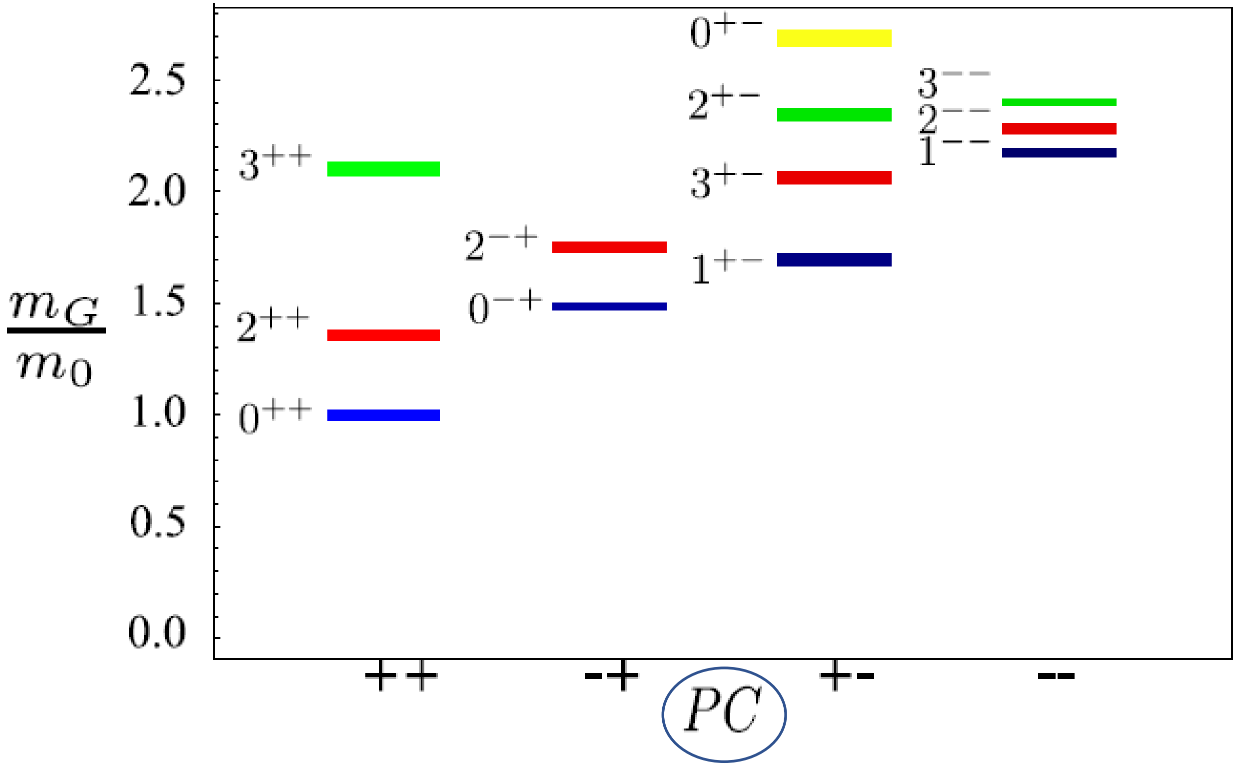

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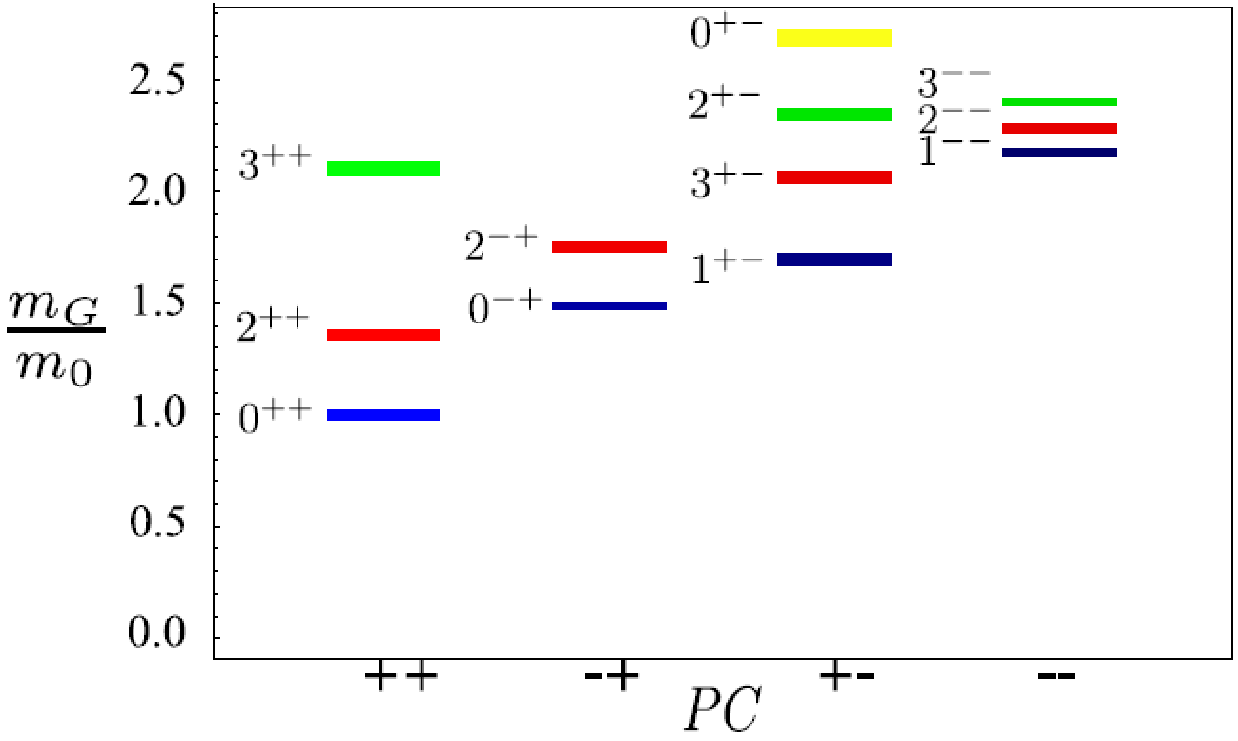
Transformation properties under P and C

Glue-ball bound states

Glue-ball spectrum can be computed on the lattice for simple groups



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How do we build glue-ball states?

Glue-ball bound states

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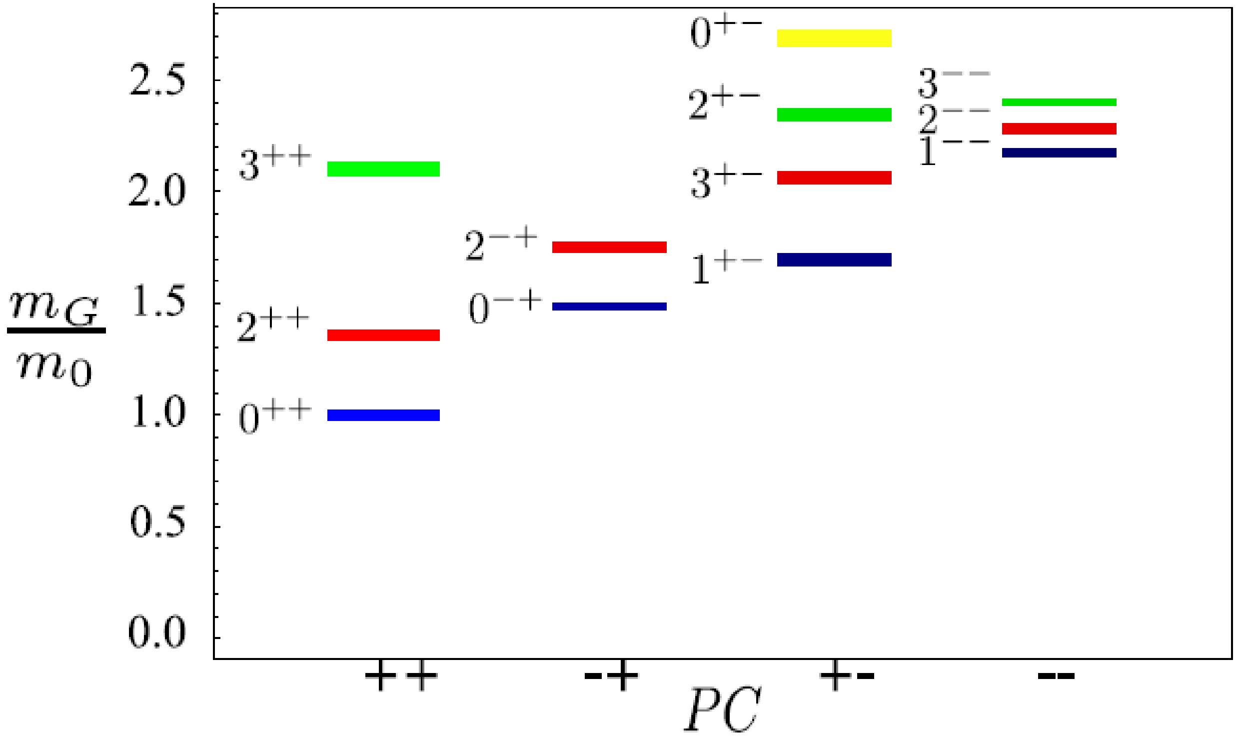

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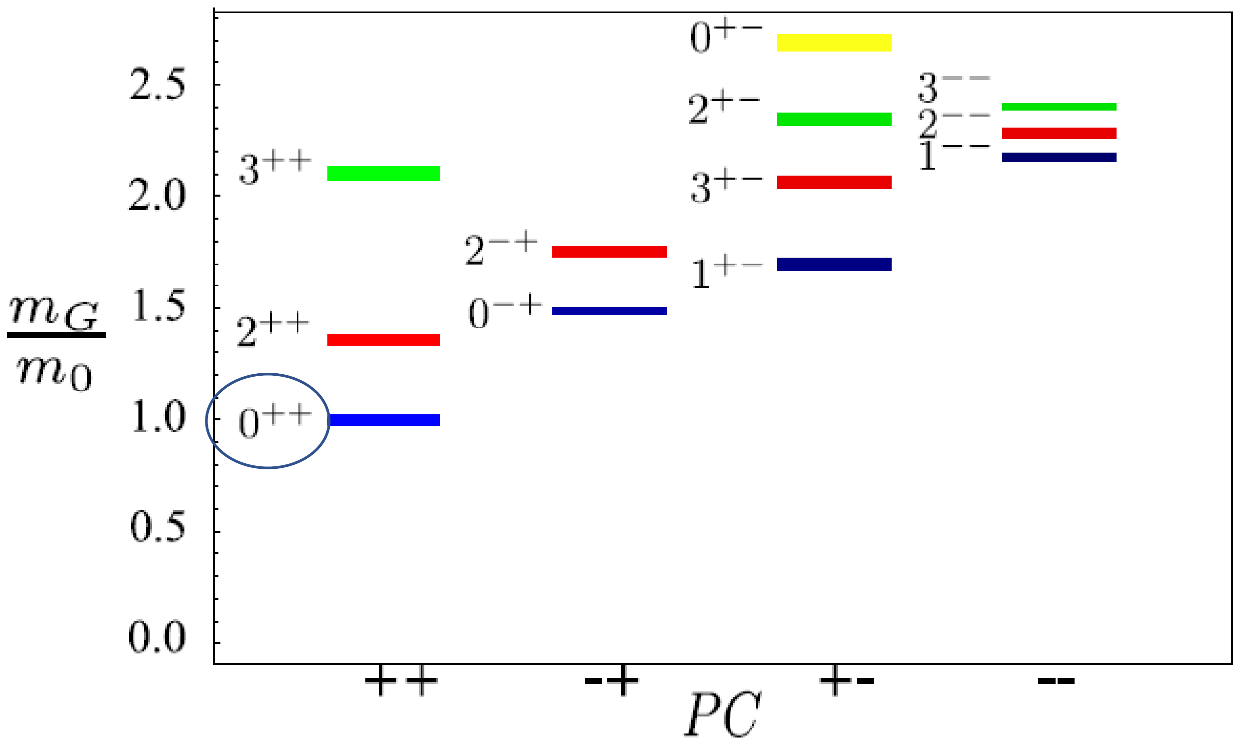
How do we build glue-ball states?

We build them applying interpolating operators on the vacuum

Glue-ball bound states

The **lightest state** 0^{++}



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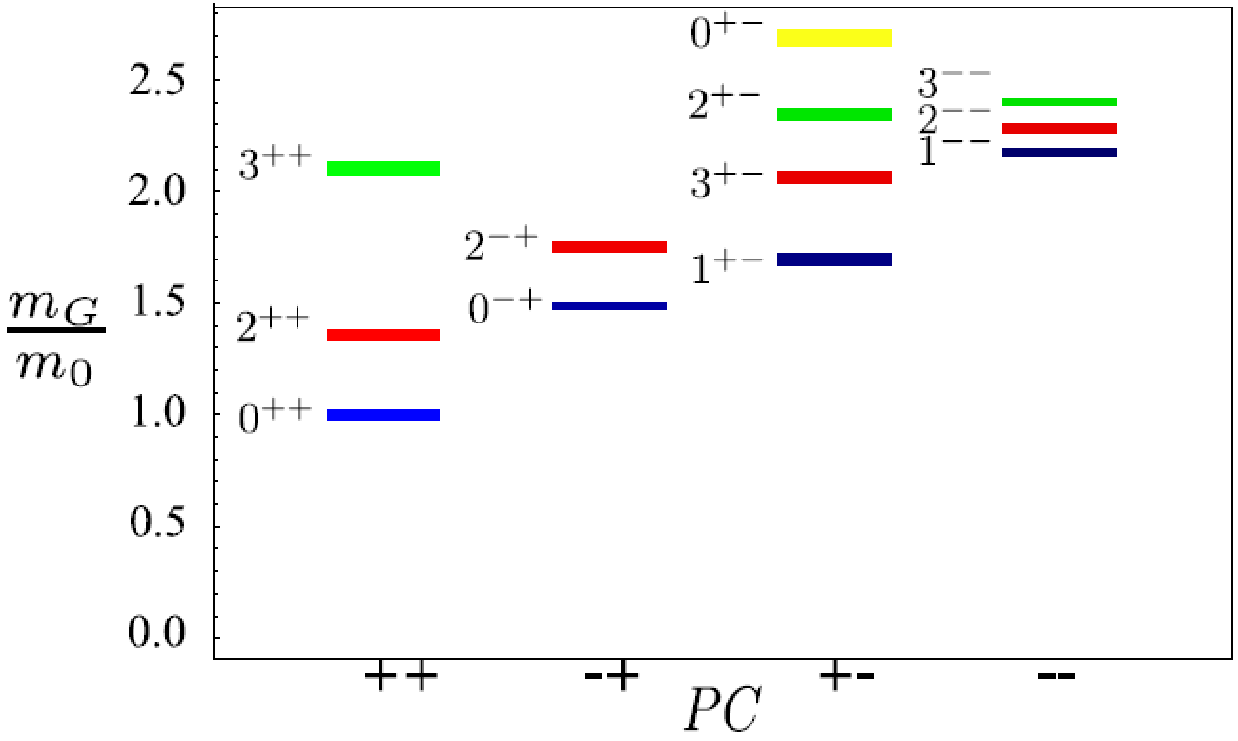
Gauge - invariant

Spin 0

CP even

Glue-ball bound states

The **lightest state** 0^{++}



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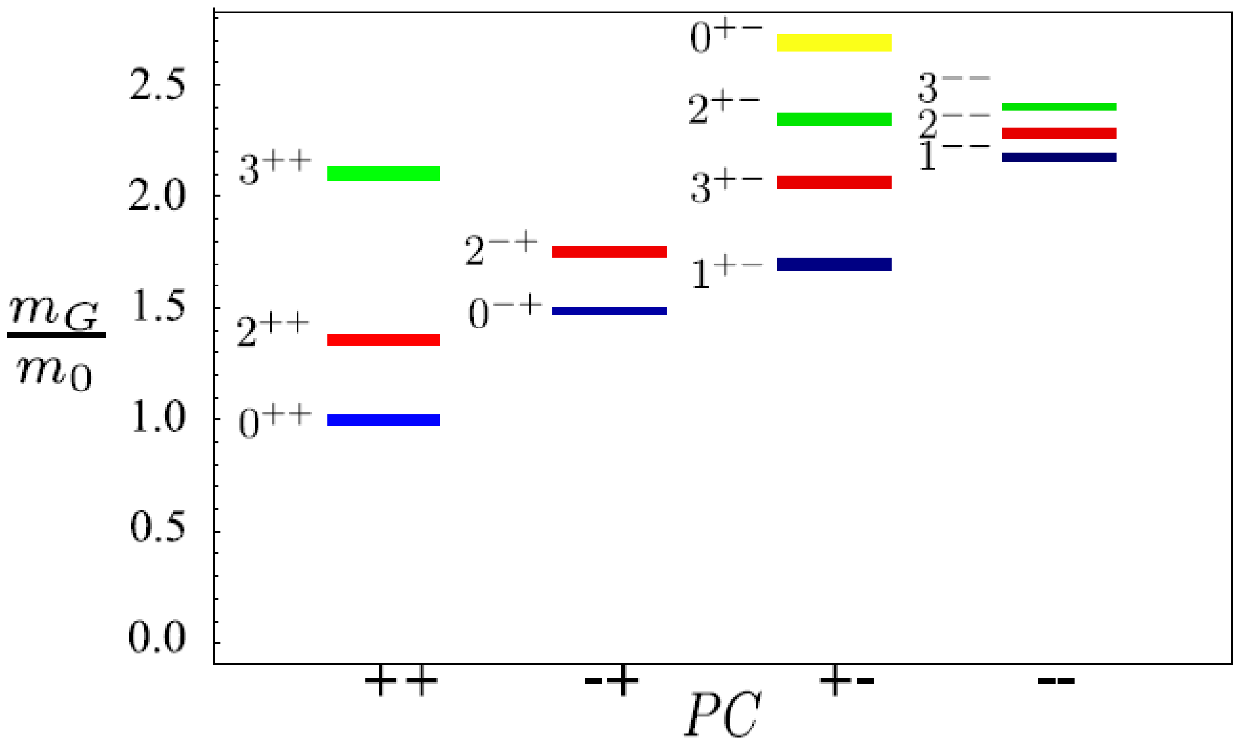
$$\mathcal{S} = Tr[G_{\mu\nu}G^{\mu\nu}] \qquad \langle 0^{++}|\mathcal{S}|\text{vac}\rangle = F_S$$

Glue-ball bound states



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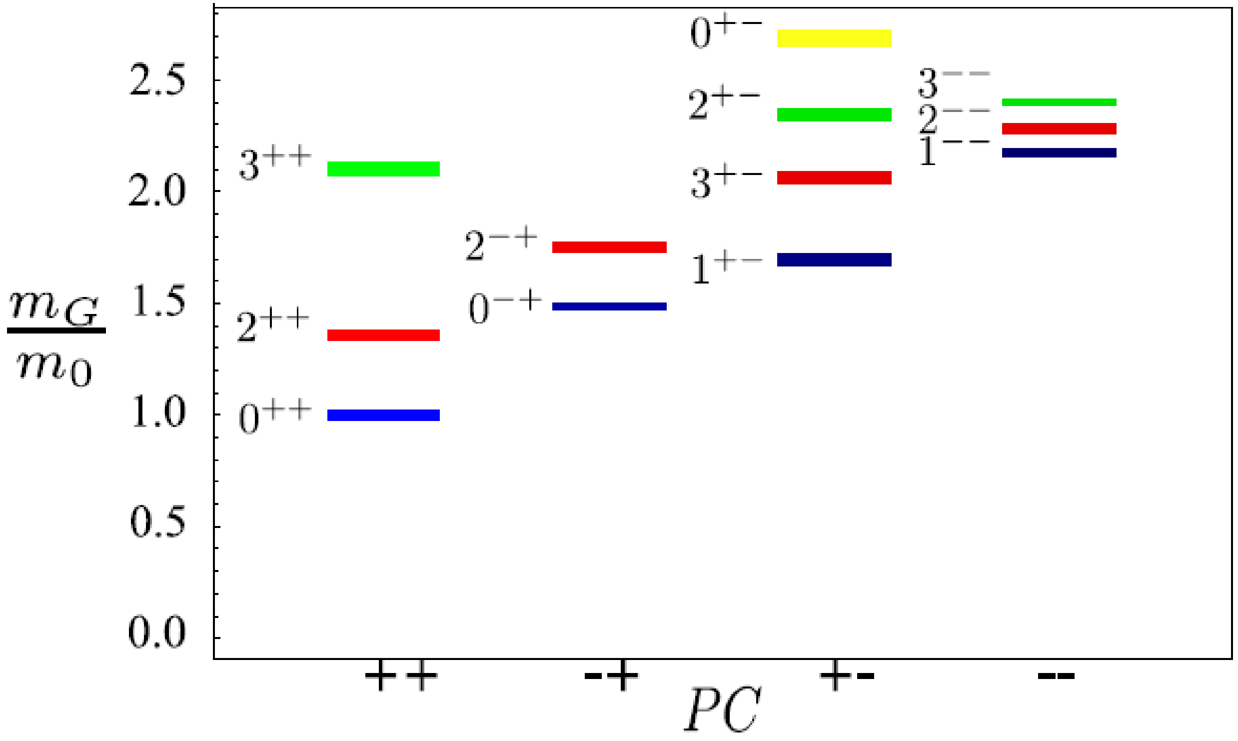
How to extract the mass?

Glue-ball bound states



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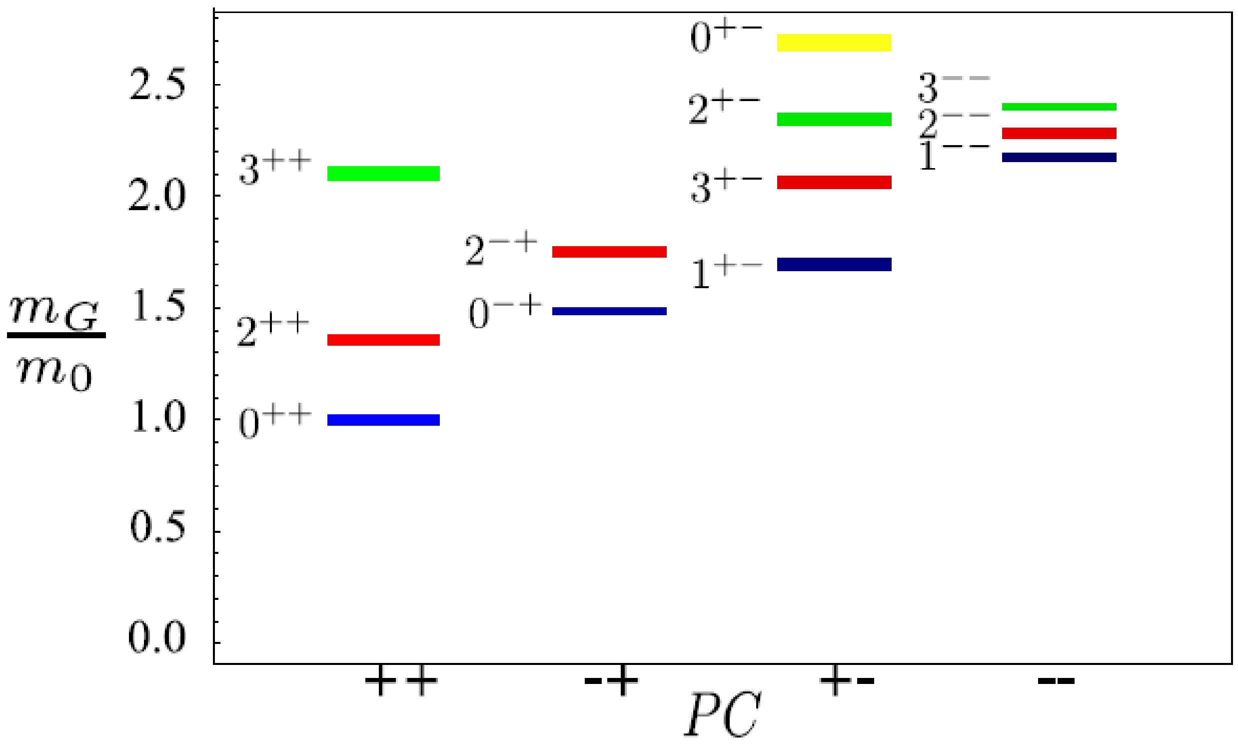
$$C(t) = \langle 0|\mathcal{S}(t)\mathcal{S}(0)|0\rangle \qquad \lim_{t\to\infty} C(t) = Z e^{-m_{0^{++}} t}$$

Glue-ball bound states



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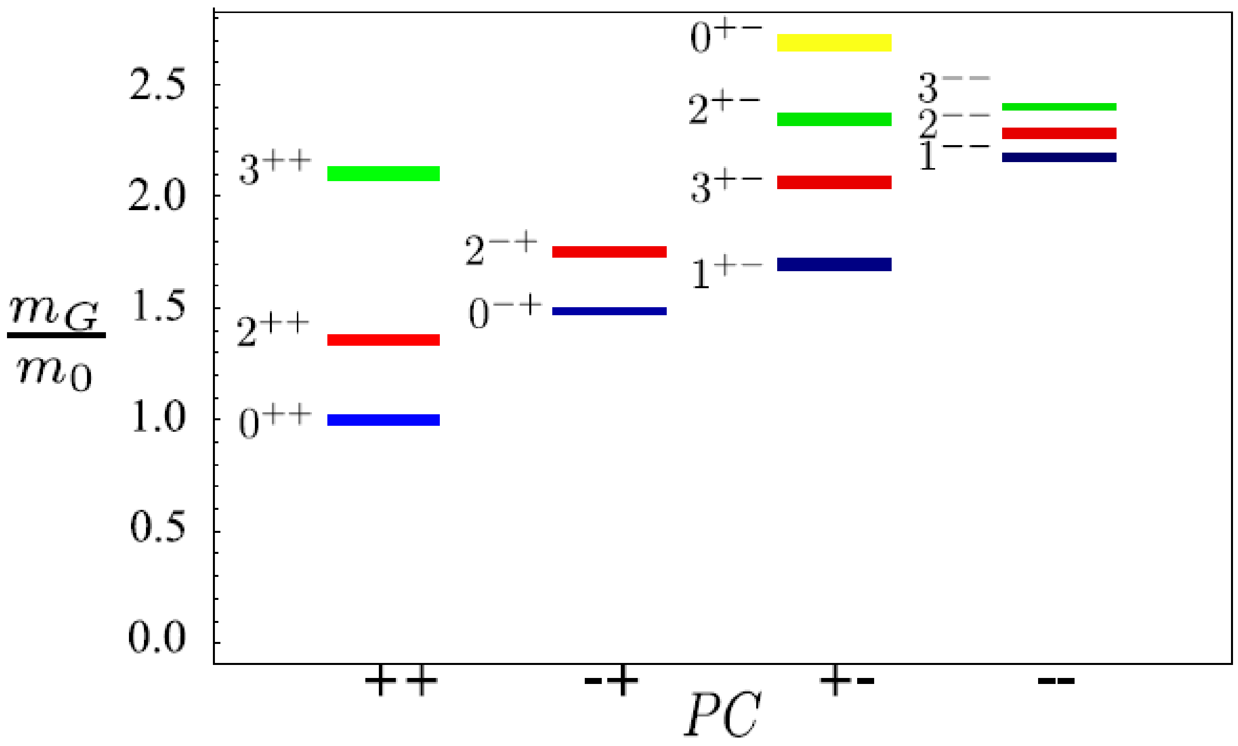
Energy of the lightest state that can be created by $\mathcal{S}$

Glue-ball bound states



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$$C(t) = \langle 0|\mathcal{S}(t)\mathcal{S}(0)|0\rangle$$

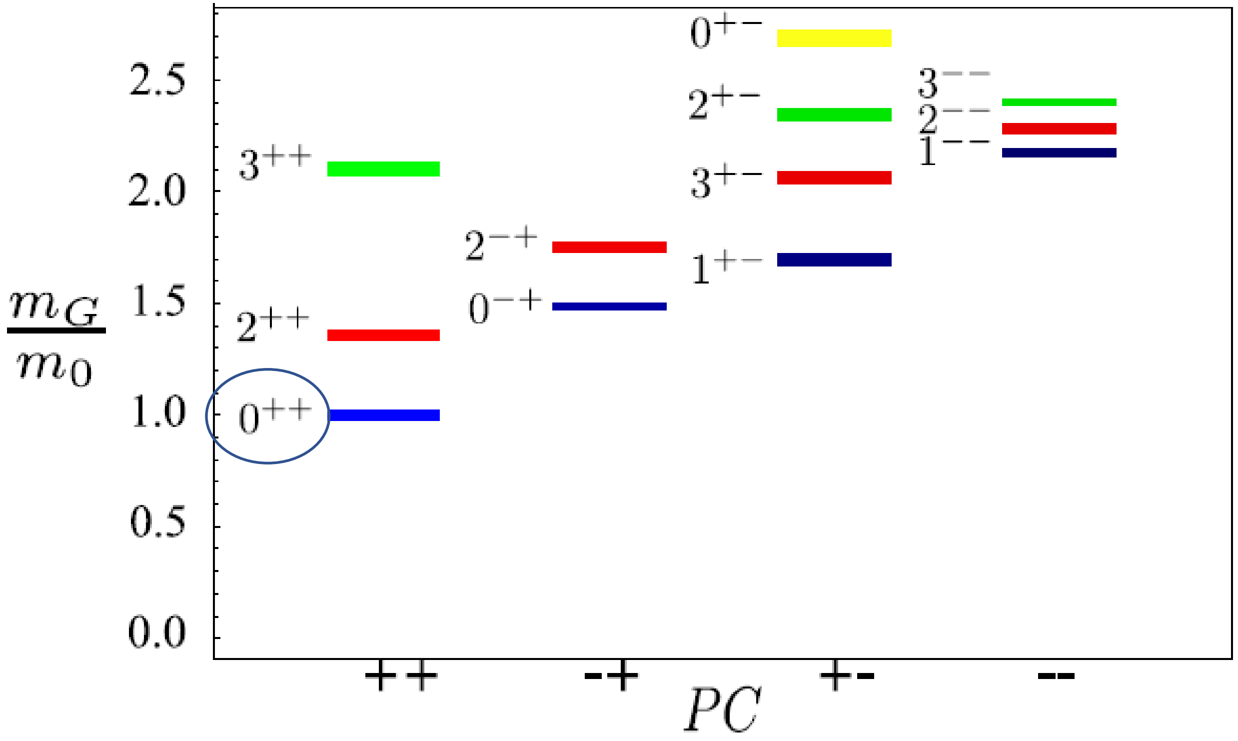
$$\lim_{t\to\infty} C(t) = Ze^{-m_{0^{++}}t}$$

$$m_{0^{++}} = \mathcal{O}(1) \times \Lambda_{\rm DM}$$

Operator $\mathcal{O}_v^\xi$	J^{PC}
$S = \mathrm{tr}\, \mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}$	0^{++}
$P = \mathrm{tr}\, \mathcal{F}_{\mu\nu}\tilde{\mathcal{F}}^{\mu\nu}$	0^{-+}
$T_{\alpha\beta} = \mathrm{tr}\, \mathcal{F}_{\alpha\lambda}\mathcal{F}_{\beta}{}^{\lambda} - \frac{1}{4}\, g_{\alpha\beta} S$	2^{++}, 1^{-+}, 0^{++}
$L_{\mu\nu\alpha\beta} = \mathrm{tr}\, \mathcal{F}_{\mu\nu}\mathcal{F}_{\alpha\beta} - \frac{1}{2}\,(g_{\mu\alpha}T_{\nu\beta} + g_{\nu\beta}T_{\mu\alpha} - g_{\mu\beta}T_{\nu\alpha} - g_{\nu\alpha}T_{\mu\beta})$ $-\frac{1}{12}\,(g_{\mu\alpha}g_{\nu\beta} - g_{\mu\beta}g_{\nu\alpha})S + \frac{1}{12}\,\epsilon_{\mu\nu\alpha\beta}P$	2^{++}, 2^{-+}

See Juknevich, Melnikov, Strassler JHEP 07 [0903.0883]

Glue-ball bound states



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The lightest glue-ball is stable

Depending on mass and quantum numbers extra states could be stable

Switching on gravity

We expand the metric around flat space-time

$$\int d^4x \sqrt{|\det g|}\mathcal{L}$$

$$g_{\mu\nu}(x) = \eta_{\mu\nu} + 2h_{\mu\nu}(x)/M_{\rm Pl}$$

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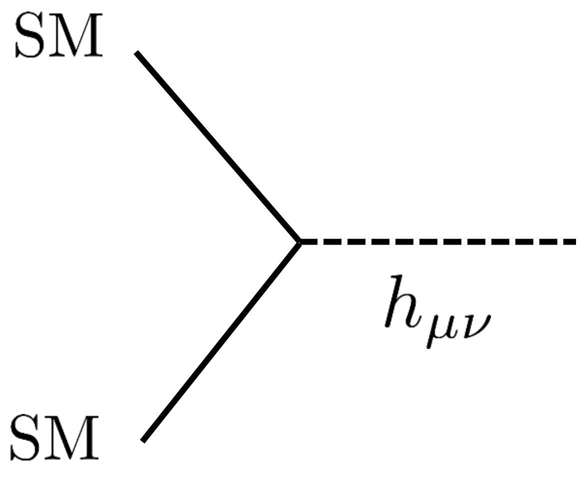
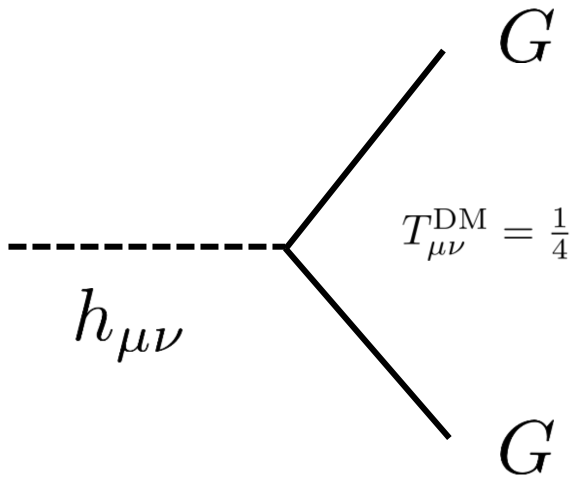
This induces gravitational interactions in the dark sector



$$\frac{h_{\mu\nu}}{M_{\rm Pl}}\left(T^{\mu\nu}_{\rm DM} + T^{\mu\nu}_{\rm SM}\right)$$



$$T^{\rm DM}_{\mu\nu} = \frac{1}{4}G_{\alpha\beta}G^{\alpha\beta}\eta_{\mu\nu} - G^{\alpha}_{\mu}G^{\beta}_{\nu}$$

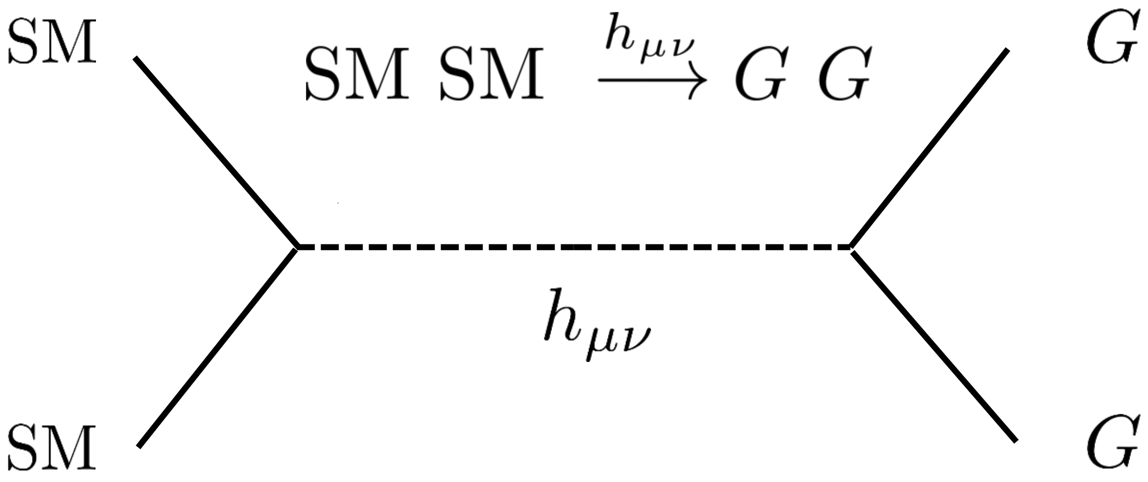
Switching on gravity

We expand the metric around flat space-time

$$\int d^4x \sqrt{|\det g|}\mathcal{L}$$

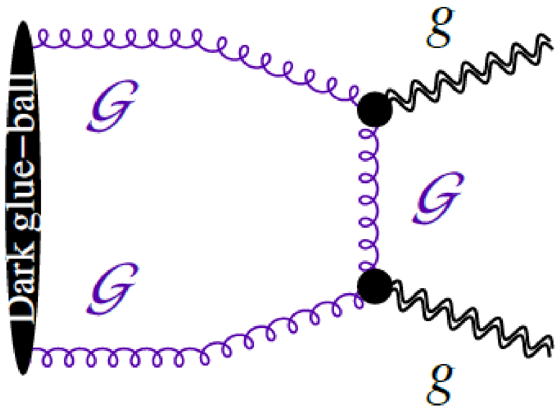
$$g_{\mu\nu}(x) = \eta_{\mu\nu} + 2h_{\mu\nu}(x)/M_{\text{Pl}}$$

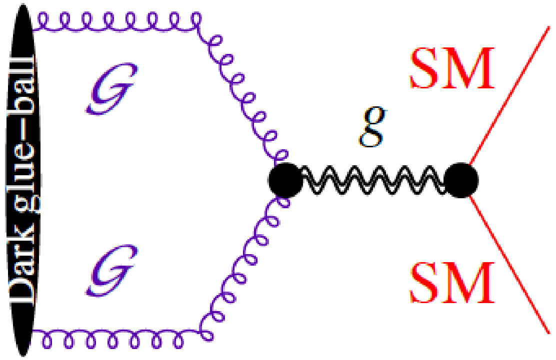
Gravity is a portal between the dark sector and the SM!

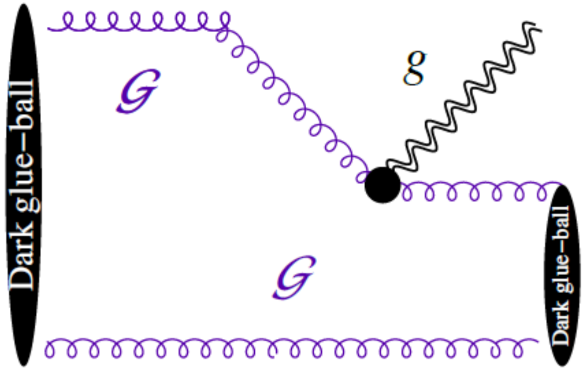


Gravitational decays of the Glue-balls

Glue-balls can decay gravitationally







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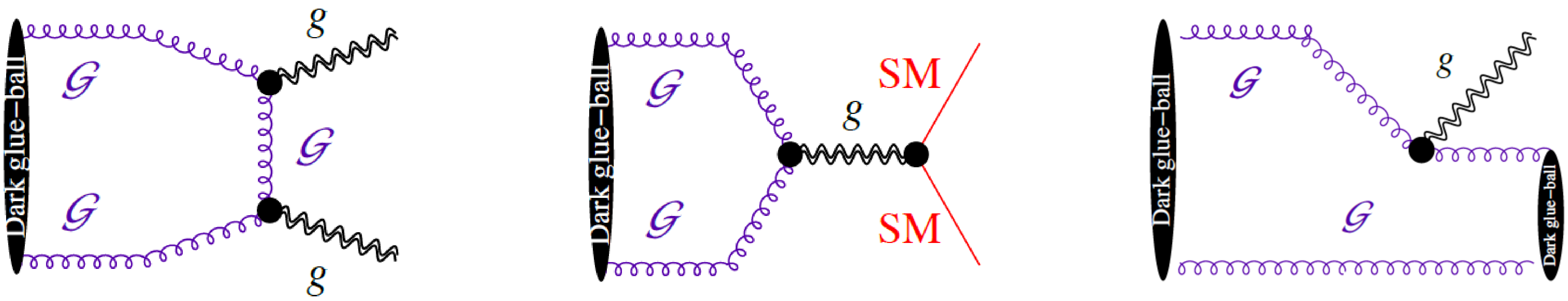

$$\Gamma_{\rm DG} \equiv \tau_{\rm DG}^{-1} \sim M_{\rm DG}^5/M_{\rm Pl}^4 \sim \Lambda_{\rm DM}^5/M_{\rm Pl}^4$$

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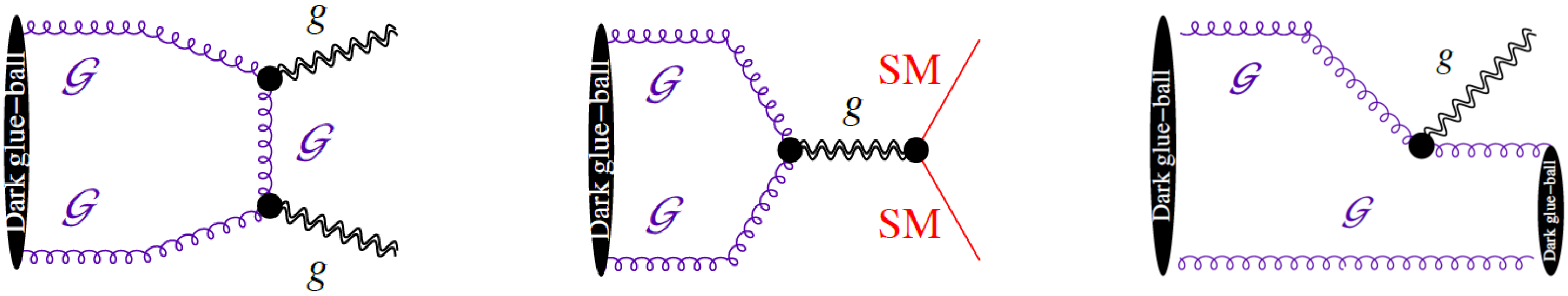

$$\Gamma_{\mathrm{DG}} \equiv \tau_{\mathrm{DG}}^{-1} \sim M_{\mathrm{DG}}^5 / M_{\mathrm{Pl}}^4 \sim \Lambda_{\mathrm{DM}}^5 / M_{\mathrm{Pl}}^4$$

The lightest(s) is (are) cosmologically stable if $M_{\mathrm{DG}} \leq 100 \ \mathrm{TeV}$

→ $\tau \geq 10^{26} \ \mathrm{sec}$

→ Contribute to **Glue-ball DM** in that regime

(Discrete) Accidental Symmetries

Gauge-invariance provides ***accidental*** *global symmetries respected by gravitational interactions!*

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Gauge-invariance provides ***accidental*** *global symmetries respected by gravitational interactions!*

G = SU(N) → dark charge conjugation **C**

$$G = G^a T^a \to -G^*$$

$$T^a = \{T_I, T_R\}$$

$$\begin{cases} G_I \to G_I \\ G_R \to -G_R \end{cases}$$

(Discrete) Accidental Symmetries

Gauge-invariance provides ***accidental*** *global symmetries respected by gravitational interactions!*

G = SU(N) → dark charge conjugation **C**

$$G = G^a T^a \to -G^*$$

$$\begin{cases} G_I \to G_I \\ G_R \to -G_R \end{cases}$$

$$Tr(G\{G,G\}) \equiv Tr G_{\mu\mu'}\{G_{\nu\nu'}, G_{\rho\rho'}\} \propto d^{abc} G^a_{\mu\mu'} G^b_{\nu\nu'} G^c_{\rho\rho'}$$

is C-odd

$$d^{RRR}, d^{RII} \neq 0$$

The lightest C-odd state is gravitationally stable

(Discrete) Accidental Symmetries

Gauge-invariance provides ***accidental*** *global symmetries respected by gravitational interactions!*

G = SO(N) → **group parity O**

$$G_{ij} = G^a T^a_{ij} \to (-1)^{\delta 1i + \delta 1j} G_{ij}$$

Adjoint = Antisymmetric

Reflection in group space along arbitrary direction

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Gauge-invariance provides ***accidental*** *global symmetries respected by gravitational interactions!*

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Adjoint = Antisymmetric

Reflection in group space along arbitrary direction

$$\begin{cases} G_{11} \to G_{11} \\ G_{1j} \to -G_{1j} \\ G_{ij} \to G_{ij} \end{cases}$$

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Gauge-invariance provides ***accidental*** *global symmetries respected by gravitational interactions!*

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We can build glue-ball states odd under O-parity

$$\epsilon_N G^{N/2} = \epsilon_{i_1 \cdots i_N} G_{i_1 i_2} \cdots G_{i_{N-1} i_N}$$

$M_{\rm OB} \underset{\text{guess}}{\sim} N\Lambda_{\rm DM}/2$

The lightest O-odd state (*odd-ball*) is gravitationally stable

(Discrete) Accidental Symmetries

So, given the theory

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + \text{ Gravity } + \text{ SM}$$

The lightest(s) *«ordinary» even* glue-ball(s) is (are) cosmologically stable

if $M_{\rm DG} \leq 100~\text{TeV}$ is satisfied

The C-odd glue-ball(s) of SU(N) or the odd-balls of SO(N) are stable

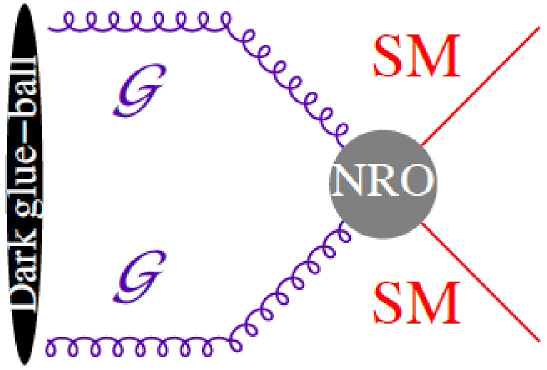
Decays through NRO

Generic (gauge-invariant) Planck-suppressed Non-Renormalizable Operators might be present as a remnant of quantum gravity

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + \text{ Gravity } + \text{SM } + \mathcal{L}_{\rm NRO}$$

$$\mathcal{L}_{\rm NRO} = \frac{\mathcal{O}^{4+n}}{M^n_{\rm Pl}}$$

$$\mathcal{O}_{\rm decay} = \mathcal{O}_{\rm SM} \mathcal{O}_{\rm DM}$$



Decays through NRO

Generic (gauge-invariant) Planck-suppressed Non-Renormalizable Operators might be present as a remnant of quantum gravity

The C-odd states of SU(N) can decay to SM through dim-8 operators

$$Tr(G\{G,G\})|H|^2/M_{\rm Pl}^4, Tr(G\{G,G\})_{\mu\nu}B^{\mu\nu}/M_{\rm Pl}^4$$

$$\Gamma_{\rm C-odd} \sim \Lambda_{\rm DM}^9/M_{\rm Pl}^8$$

Decays through NRO

Generic (gauge-invariant) Planck-suppressed Non-Renormalizable Operators might be present as a remnant of quantum gravity

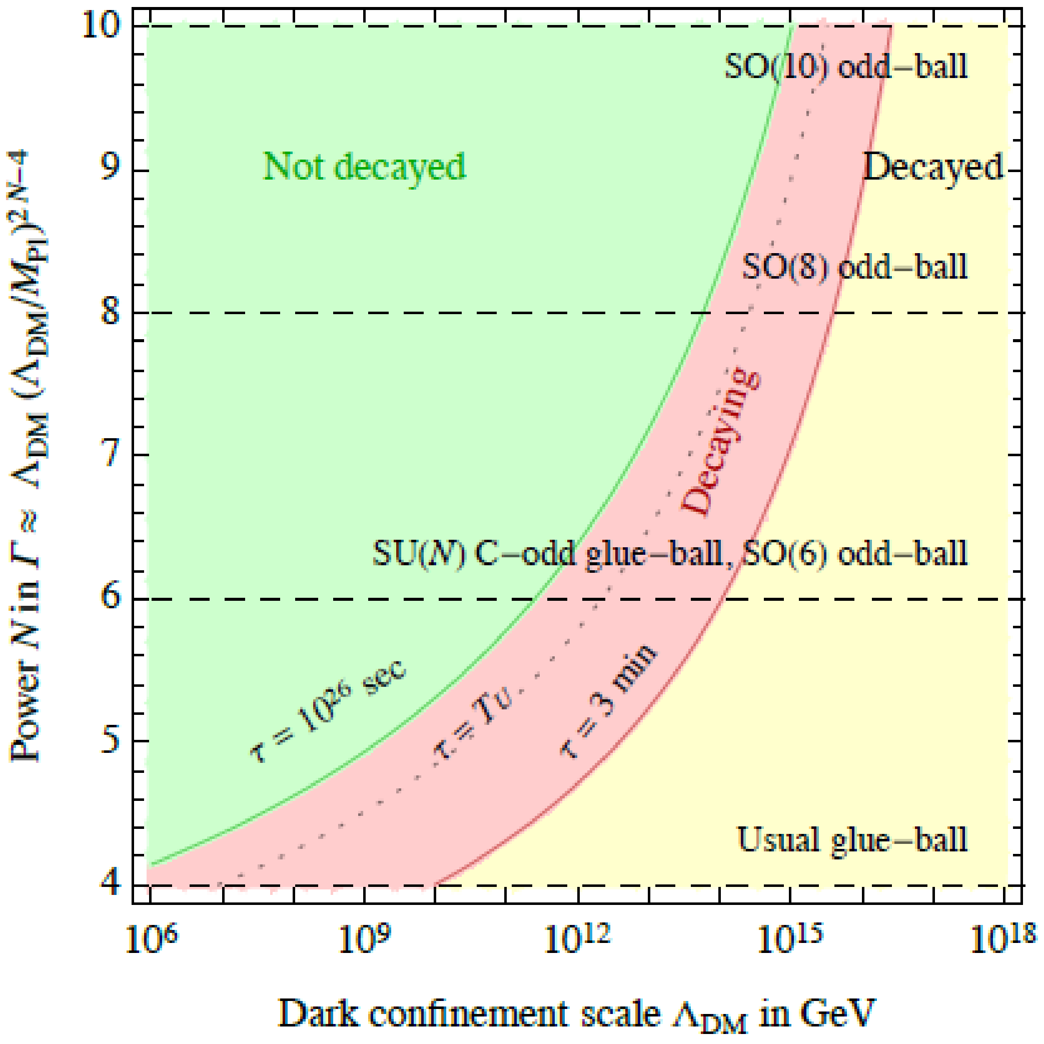
The odd-balls of SO(N) can decay through dim-(N+2) operator

$$\mathcal{O}_{N+2} \sim \epsilon_N G^{N/2} |H|^2 / M_{\rm Pl}^{N-2}$$

$$\Gamma_{OB} \sim M_{\rm OB} (M_{\rm OB}/M_{\rm Pl})^{2N-4}$$

$$M_{\rm OB} \sim N \Lambda_{\rm DM}/2$$

Decays through NRO



(Cosmologically) Stable Glue-balls

«Ordinary» even glueballs **decay gravitationally**

They are cosmologically stable if **mass < 100 TeV**

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SU(N) has **C- odd** glue-balls

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They are cosmologically **stable up to 10^11 GeV** in presence of NRO

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Ordinary «even» glueballs decay gravitationally

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SU(N) has C- odd glue-balls

They are gravitationally stable

They are cosmologically stable up to 10^{11} GeV in presence of NRO

SO(N) has **odd-balls** (odd under O-parity)

They are **gravitationally stable**

They are cosmologically stable **up to very large masses** for large N

Example: SO(10) gauge theory

Ordinary «even» glue-balls are cosmologically stable if

$$\tau_{\rm DG} \sim \left(\frac{M_{\rm DG}^5}{M_{\rm Pl}^4}\right)^{-1} > 10^{26}{\rm sec} \to M_{\rm DG} \sim \underline{\Lambda_{\rm DM} < 100\ {\rm TeV}}$$

Example: SO(10) gauge theory

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Odd-balls are cosmologically stable (in presence of NRO) if

$$\tau_{\rm OB} \sim \left(\frac{M_{\rm OB}^{17}}{M_{\rm Pl}^{16}}\right)^{-1} > 10^{26}\ {\rm sec} \to M_{\rm OB} \sim \underline{5\Lambda_{\rm DM} < 10^{15}\ {\rm GeV}}$$

Example: SO(10) gauge theory

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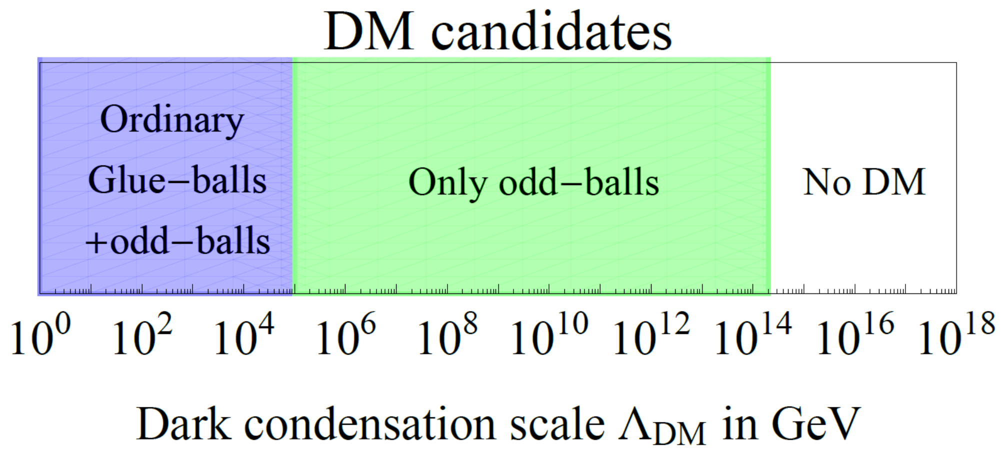


Dark Matter production and evolution

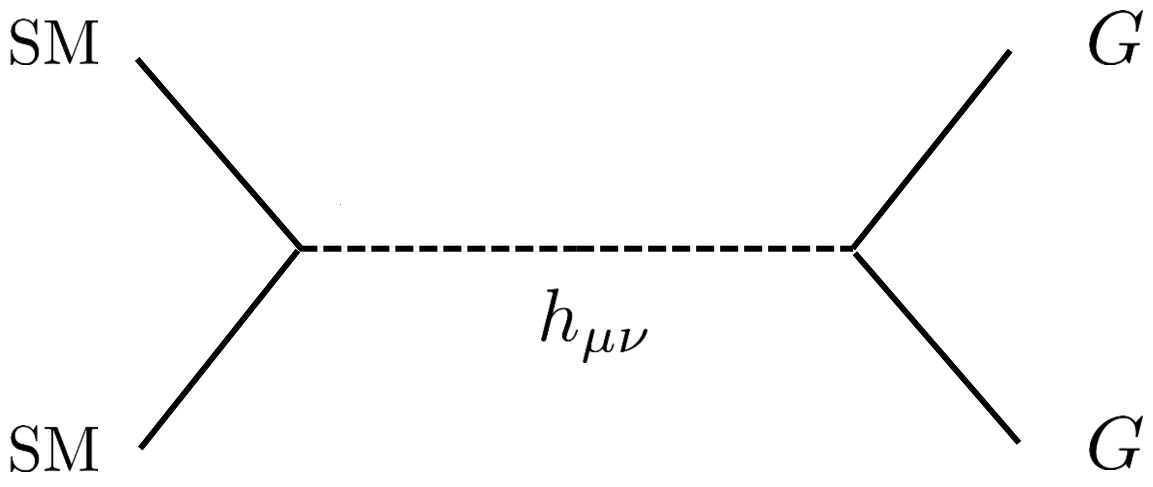
We study gravitational freeze-in within our model

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + \text{ Gravity } + \text{ SM } \; (+\mathcal{L}_{\mathrm{NRO}})$$

Dark Matter production

Gravitational freeze-in production of massless gauge vectors

$$T \simeq T_{\rm RH} \gg \Lambda_{\rm DM}$$



$$Y_G = Y_{\rm FI} \simeq 7.4 \times 10^{-5} d_G \left(\frac{T_{\rm RH}}{M_{\rm Pl}}\right)^3$$

$$d_G = \begin{cases} N^2 - 1 \text{ if } G = SU(N) \\ N(N-1)/2 \text{ if } G = SO(N) \end{cases}$$

Dark Matter cosmological evolution

How do the gauge vectors evolve after production?

$$T < T_{\mathrm{RH}}$$

Depending on Λ_{DM} they can self-thermalize $(\to T_D)$

Dark Matter cosmological evolution

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The gauge group confines when

$T_D < \Lambda_{\rm DM}$ (thermal)

$n_G < \Lambda^3_{\rm DM}$ (not thermal)

$d_G > (1/\Lambda_{\rm DM})$

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→ Massive Glue-balls

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$T_D < \Lambda_{\rm DM}$ (thermal)

$n_G < \Lambda_{\rm DM}^3$ (not thermal)

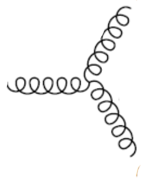
$d_G > (1/\Lambda_{\rm DM})$

→ Massive Glue-balls → **The (cosmologically) stable glue-balls contribute(s) to DM**

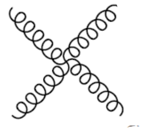
Self-thermalization of vectors

Dark gauge vectors have self-interactions

$(\partial G)GG$



G^4



If self-interactions are fast enough gauge vectors self-thermalize

Hubble expansion rate $H \propto T^2/M_{\rm Pl}$

$$\Gamma_{\rm int} = n_G \; \sigma_{\rm int} > H\big|_{T=T_{\rm therm}}$$

Number-changing processes

$\sigma_{2\to 3} \sim g_{\rm DC}^6/T^2$

Self-thermalization of vectors

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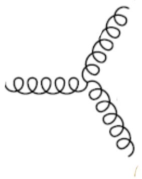
$(\partial G)GG$



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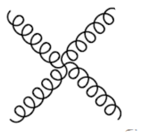

If self-interactions are fast enough gauge vectors self-thermalize

$$\Gamma_{\rm int} = n_G \, \sigma_{\rm int} > H\big|_{T=T_{\rm therm}}$$

Determine this temperature

Self-thermalization of vectors

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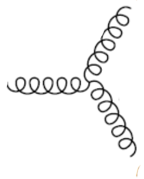

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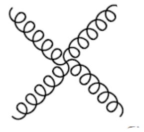


Radiation scaling with the scale factor

$$\rho_D, \rho_{\rm SM} \sim a^{-4}$$

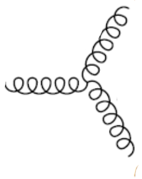
$$\frac{\rho_D}{\rho_{\rm SM}}\Big|_{\rm prod} = \frac{\rho_D}{\rho_{\rm SM}}\Big|_{\rm therm}$$

$$\frac{T_{\rm RH}^4 Y_{\rm FI}}{T_{\rm RH}^4}$$

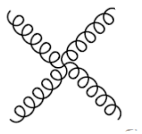
Self-thermalization of vectors

Dark gauge vectors have self-interactions

$(\partial G)GG$



G^4



Radiation scaling with the scale factor

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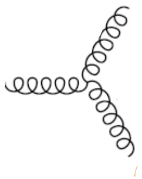
$$\frac{\rho_D}{\rho_{\rm SM}}\Big|_{\rm prod} = \frac{\rho_D}{\rho_{\rm SM}}\Big|_{\rm therm}$$

$$\left(\frac{T_D}{T}\right)^4$$

Self-thermalization of vectors

Dark gauge vectors have self-interactions

$(\partial G)GG$



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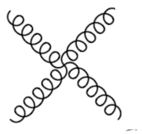

Radiation scaling with the scale factor

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$$\frac{\rho_D}{\rho_{\rm SM}}\Big|_{\rm prod} = \frac{\rho_D}{\rho_{\rm SM}}\Big|_{\rm therm}$$

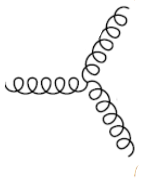
$$\frac{T_D}{T_{\rm SM}} \sim \left(\frac{T_{\rm RH}}{M_{\rm Pl}}\right)^{3/4} \ll 1$$

This is a viable mechanism to produce a (very) *cold dark sector!!*

Self-thermalization of vectors

Dark gauge vectors have self-interactions

$(\partial G)GG$



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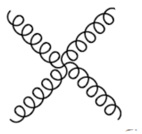

If self-interactions are fast enough gauge vectors self-thermalize

$$\Gamma_{\rm int} = n_G \, \sigma_{\rm int} > H\big|_{T=T_{\rm therm}}$$

Determine this temperature

$$\frac{T_D}{T_{\rm SM}} \sim \left(\frac{T_{\rm RH}}{M_{\rm Pl}}\right)^{3/4}$$

Determine this temperature

$$T_D^{\rm therm}$$

Self-thermalization of vectors

Dark gauge vectors have self-interactions

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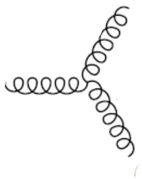

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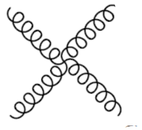

If self-interactions are fast enough gauge vectors self-thermalize

$$\Gamma_{\rm int} = n_G \, \sigma_{\rm int} > H|_{T=T_{\rm therm}}$$

Requiring $T_D^{\rm therm} > \Lambda_{\rm DM}$ → $\Lambda_{\rm DM} < M_{\rm Pl}(T_{\rm RH}/M_{\rm Pl})^{15/4}$

Thermal Glue-ball DM

Dark vectors self-interactions lead to thermal abundance

$$n_{\text{therm}} \propto T_D^3 \quad \longrightarrow \quad Y_{\text{therm}} \sim \left(\frac{T_D}{T_{\text{SM}}}\right)^3 = \left(\frac{T_{\text{RH}}}{M_{\text{Pl}}}\right)^{9/4}$$

Confinement $T_D = \Lambda_{\text{DM}}$

Glue-balls form and preserves the thermal abundance*

$$Y_{\text{DM}} \sim \kappa \left(\frac{T_{\text{RH}}}{M_{\text{Pl}}}\right)^{9/4}$$

κ → energy fraction of vectors which ends up in stable glue-balls

*neglecting logarithmic corrections (cannibal 3to2 interactions)

Self-thermalization of Glue-balls

If $\Lambda_{\rm DC} > M_{\rm Pl}(T_{\rm RH}/M_{\rm Pl})^{15/4}$ → confinement before vector thermalization

↓

$n_G = \Lambda_{\rm DM}^3$ → $T_\Lambda = \Lambda_{\rm DM}(M_{\rm Pl}/T_{\rm RH}) \gg \Lambda_{\rm DM}$

High-energy gluons hadronize and produce a shower of glue-ball jets

Each gluon produces $N_{\rm DG}$ glue-balls with energy which scales as $E_{\rm DG}(T) = T/N_{\rm DG}$

$N_{\rm DG} \sim \exp[\sqrt{\log \frac{T_\Lambda}{\Lambda_{\rm DM}}}]$

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$N_{\rm DG} \sim \exp[\sqrt{\log \frac{T_\Lambda}{\Lambda_{\rm DM}}}]$

Glue-ball interactions $\Gamma_{\rm int} = n_{\rm DG}\sigma_{\rm int} > H|_{T=T_{\rm th}}$

$n_{\rm DG} = N_{\rm DG} n_G$

Relativistic glue-balls: $\sigma_{\rm int} \sim N_{\rm DG}^2/T^2$ → $T_{\rm th}$ → consistent if $E_{\rm DG}(T_{\rm th}) > \Lambda_{\rm DM}$

$\Lambda_{\rm DM} < N_{\rm DG}^2 \left(\frac{T_{\rm RH}^3}{M_{\rm Pl}^2}\right)$ → Thermal Glue-balls

Non-thermal Glue-ball DM

For larger values $\Lambda_{\rm DM} > N_{\rm DG}^2 \left(\frac{T_{\rm RH}^3}{M_{\rm Pl}^2}\right)$

Self-interactions are too weak and the dark vectors/glue-balls do not *self-thermalize*

↓

The DM abundance is directly fixed by freeze-in

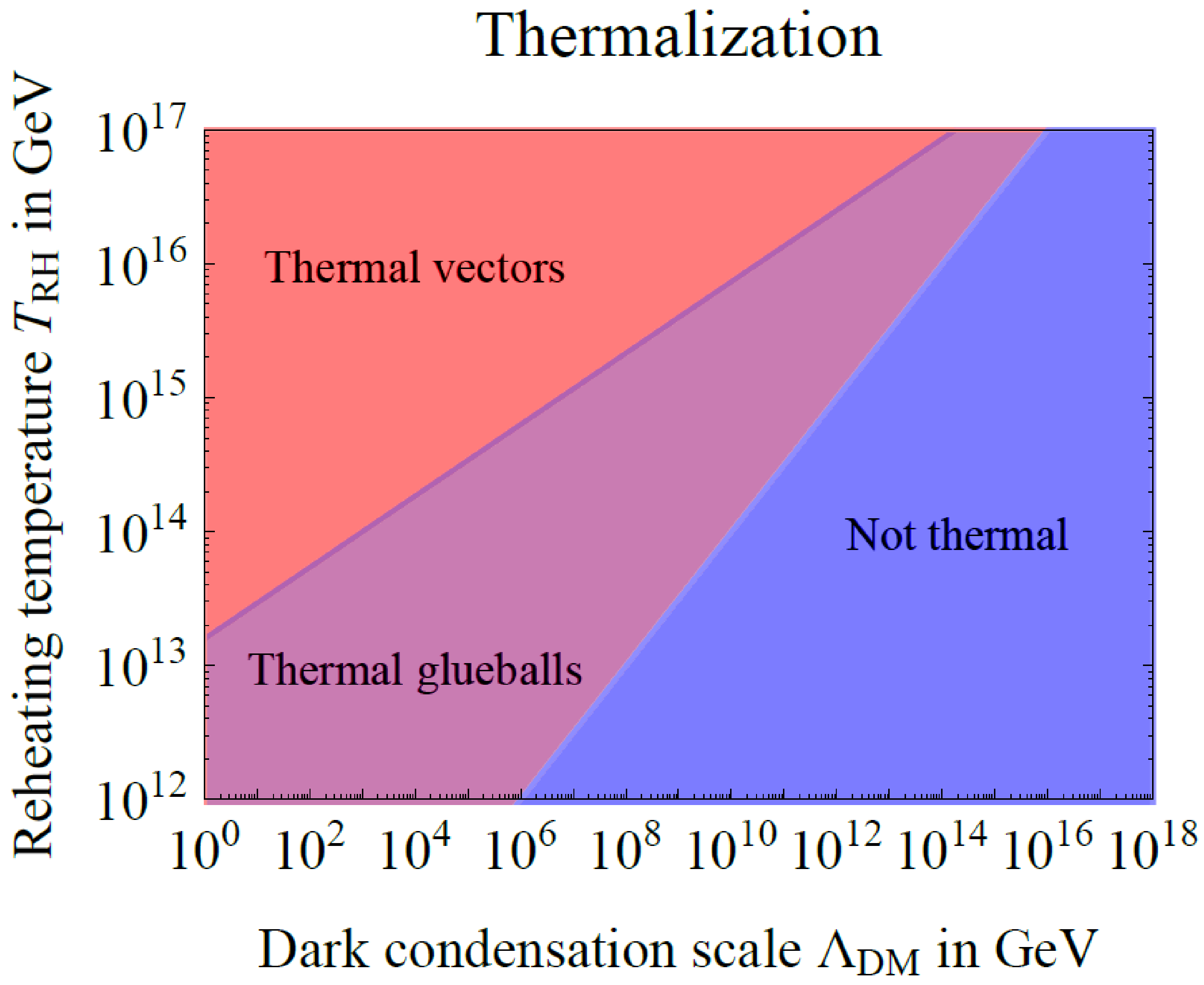
$$Y_{\rm DM} \sim \kappa N_{\rm DG} \left(\frac{T_{\rm RH}}{M_{\rm Pl}}\right)^3$$

- $N_{\rm DG}$ → glue-balls multiplicity
- $\left(\frac{T_{\rm RH}}{M_{\rm Pl}}\right)^3$ → Freeze-in abundance
- κ → energy fraction of vectors which ends up in stable glue-balls

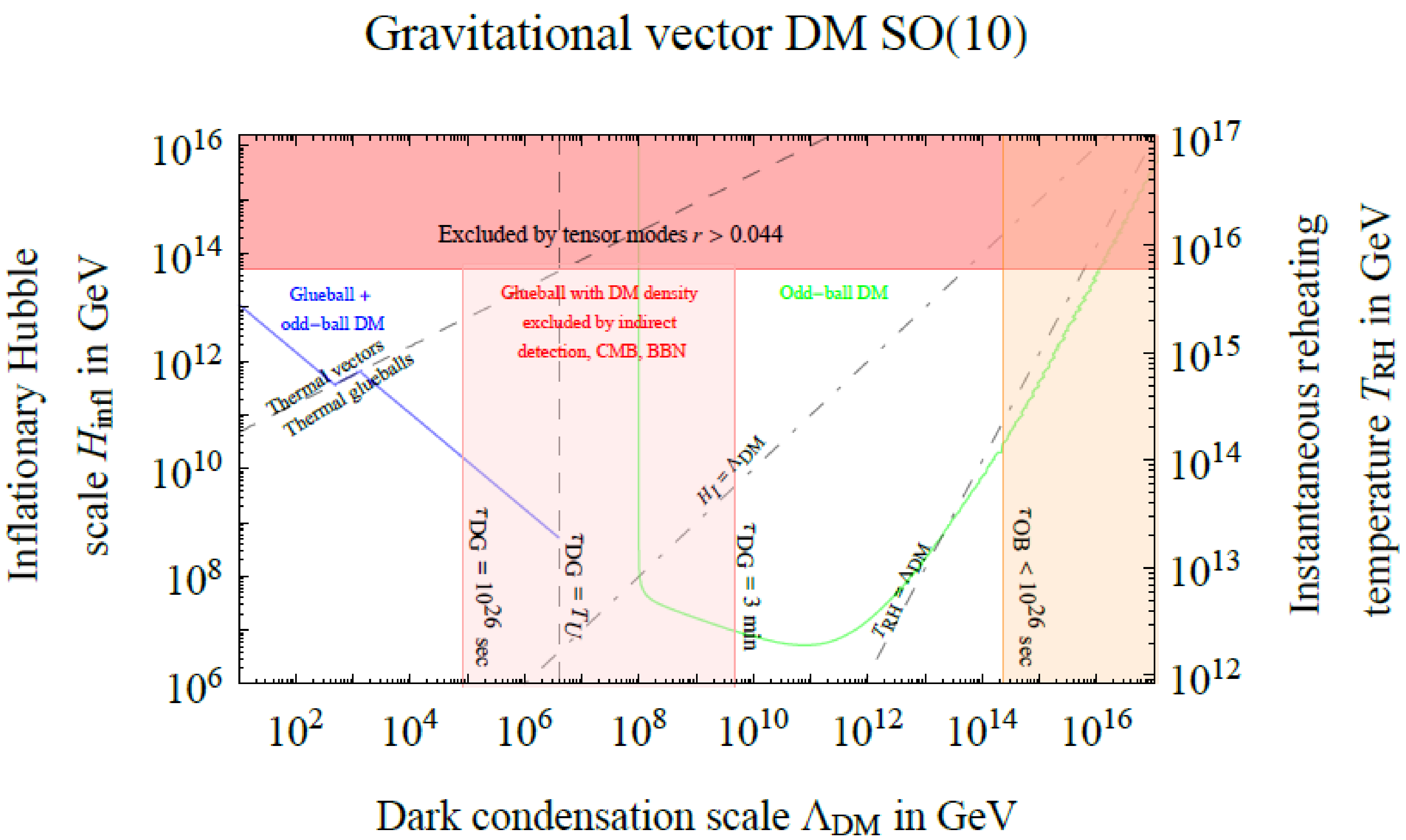
The parameter space is wide: DM can be super-heavy $\sim 10^{15}$ GeV

Example: SO(10) gauge theory

Self-thermalization of the dark sector



Gravitational vector DM



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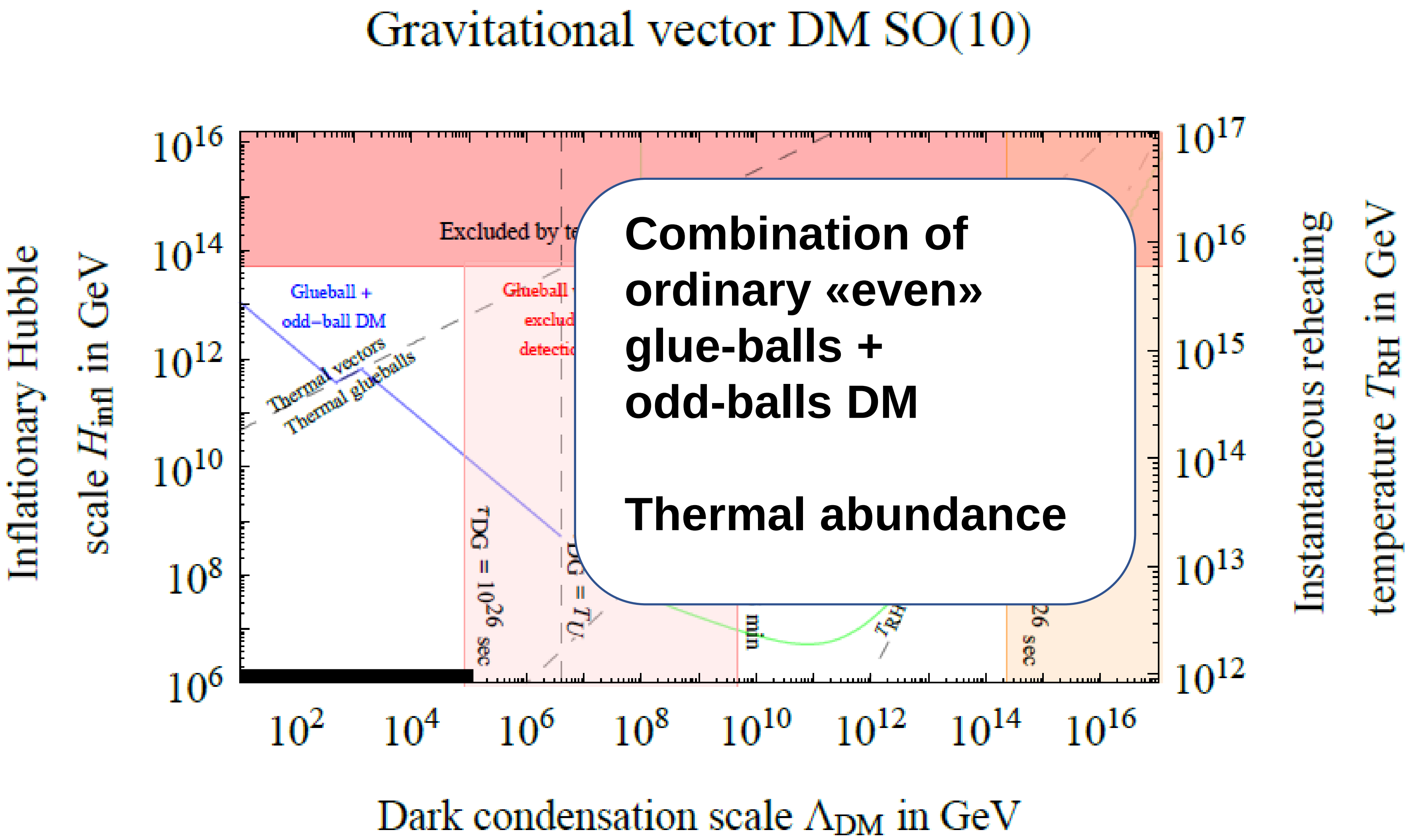
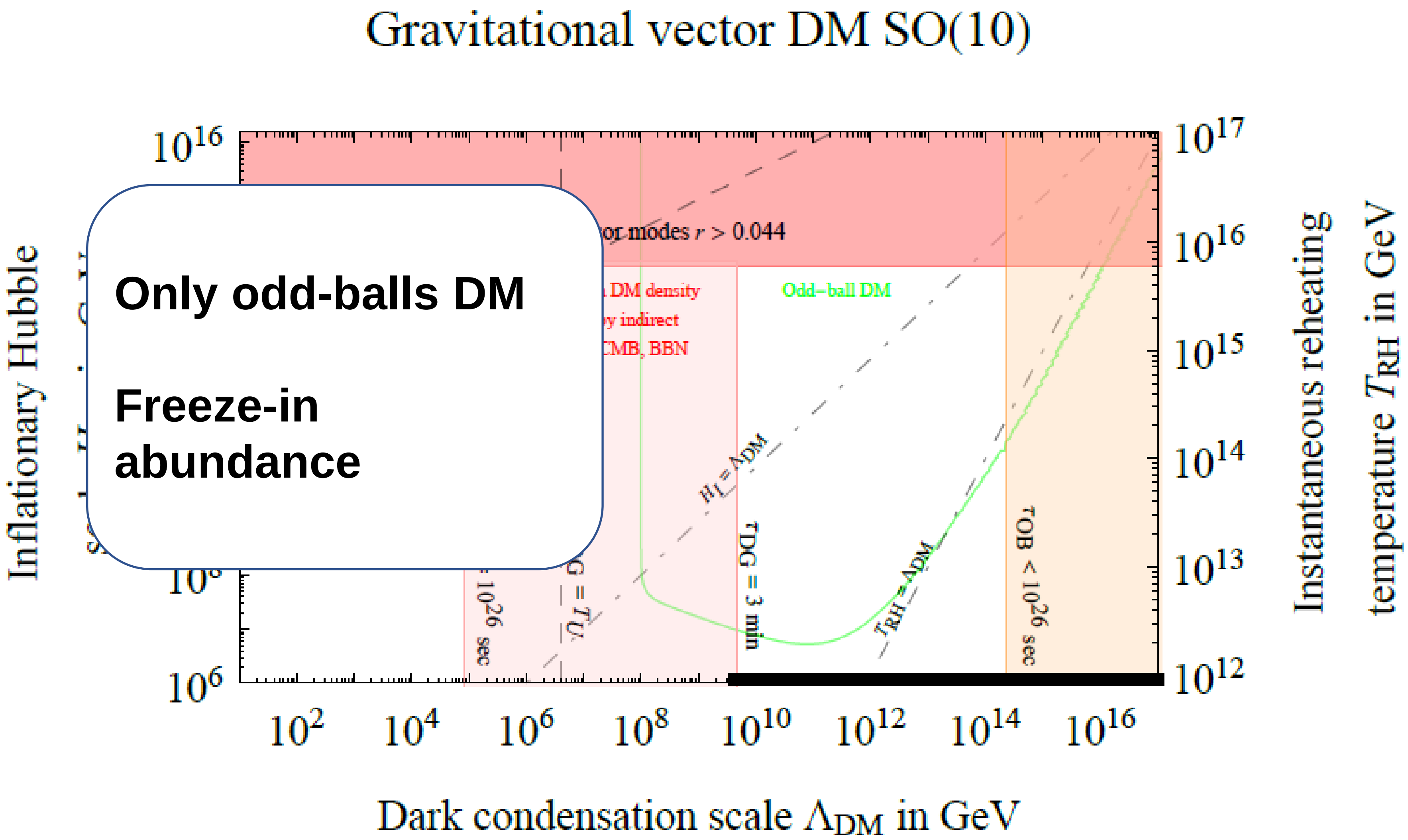


Combination of ordinary «even» glue-balls + odd-balls DM

Thermal abundance

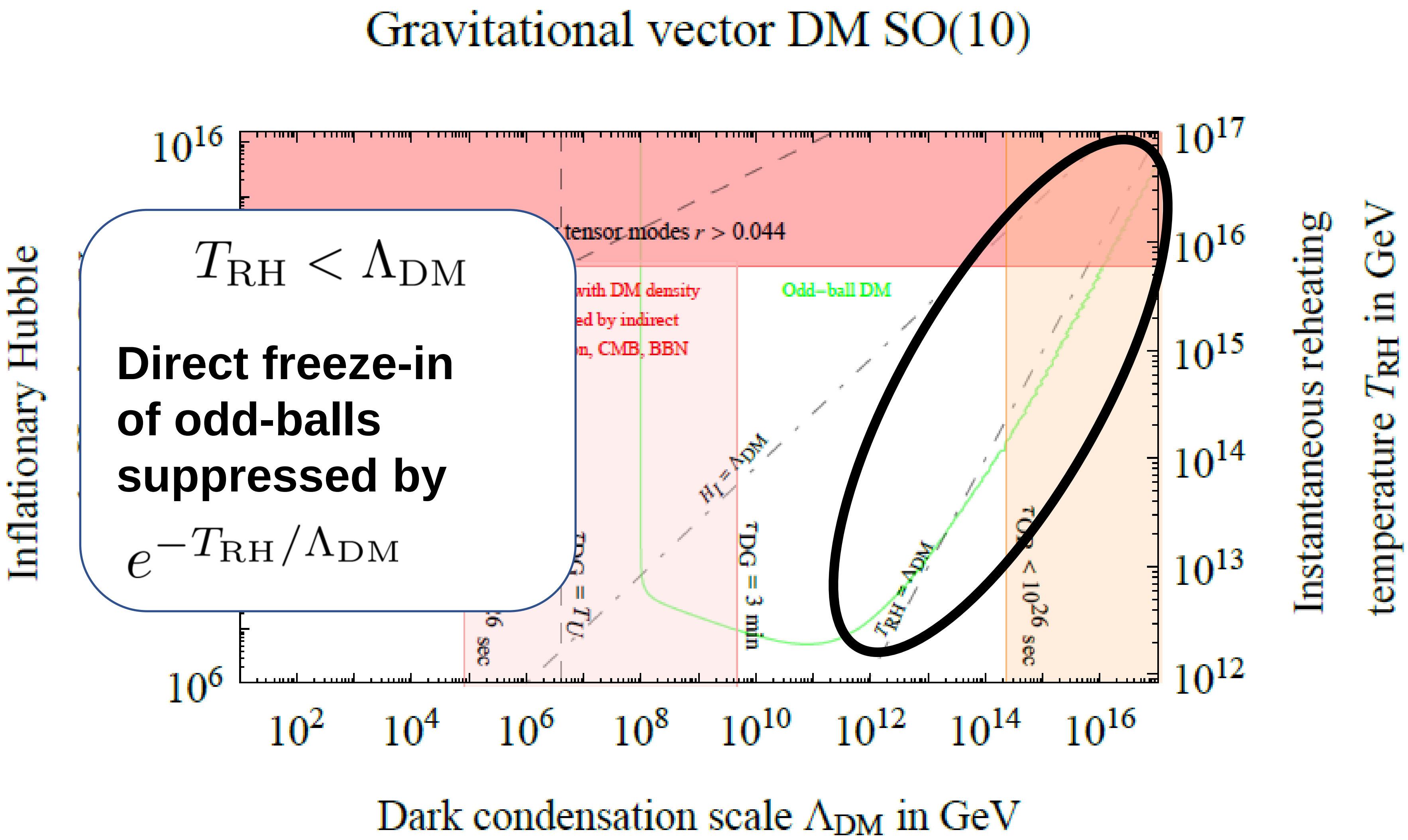
Gravitational vector DM



Only odd-balls DM

Freeze-in abundance

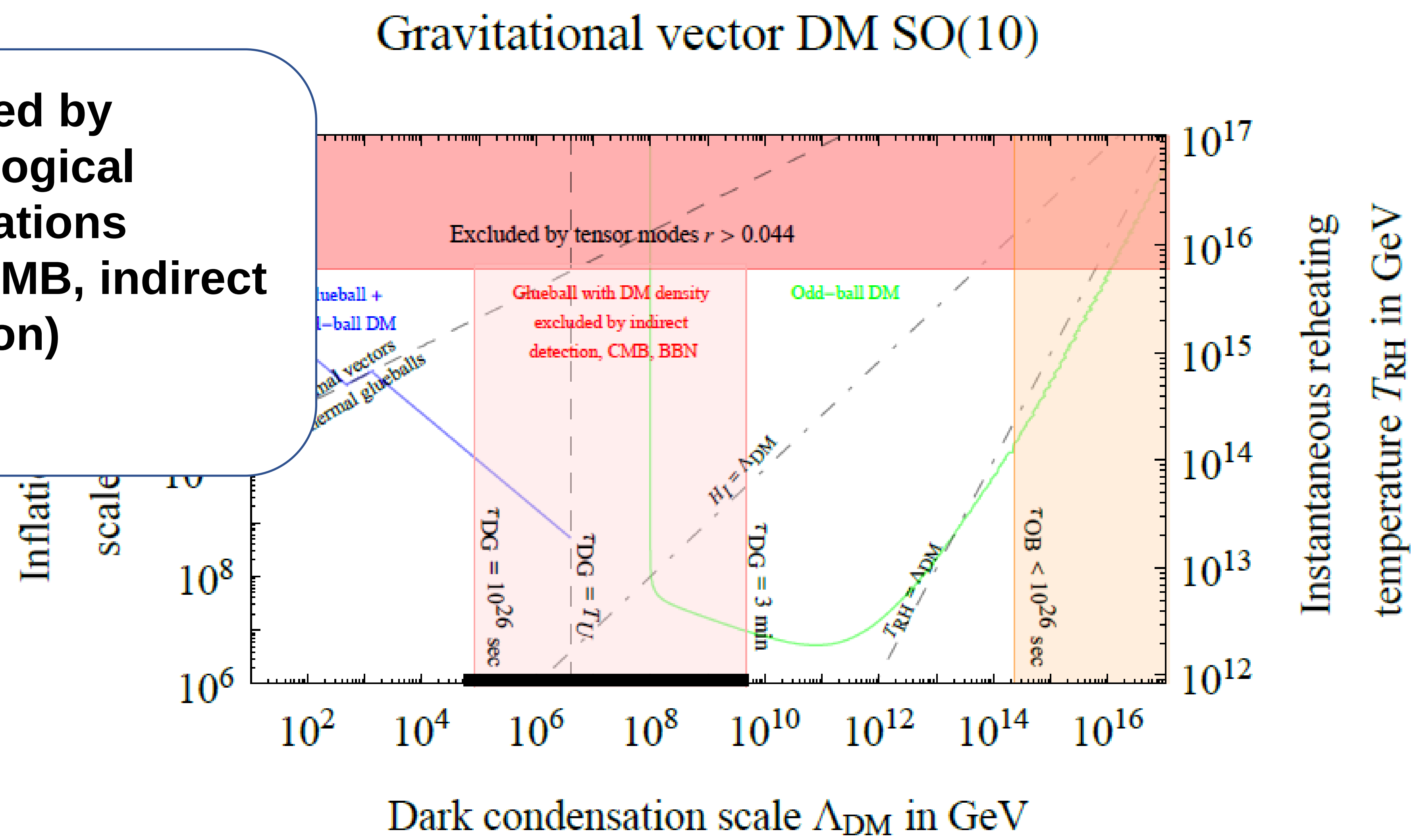
Gravitational vector DM



$T_{\rm RH} < \Lambda_{\rm DM}$

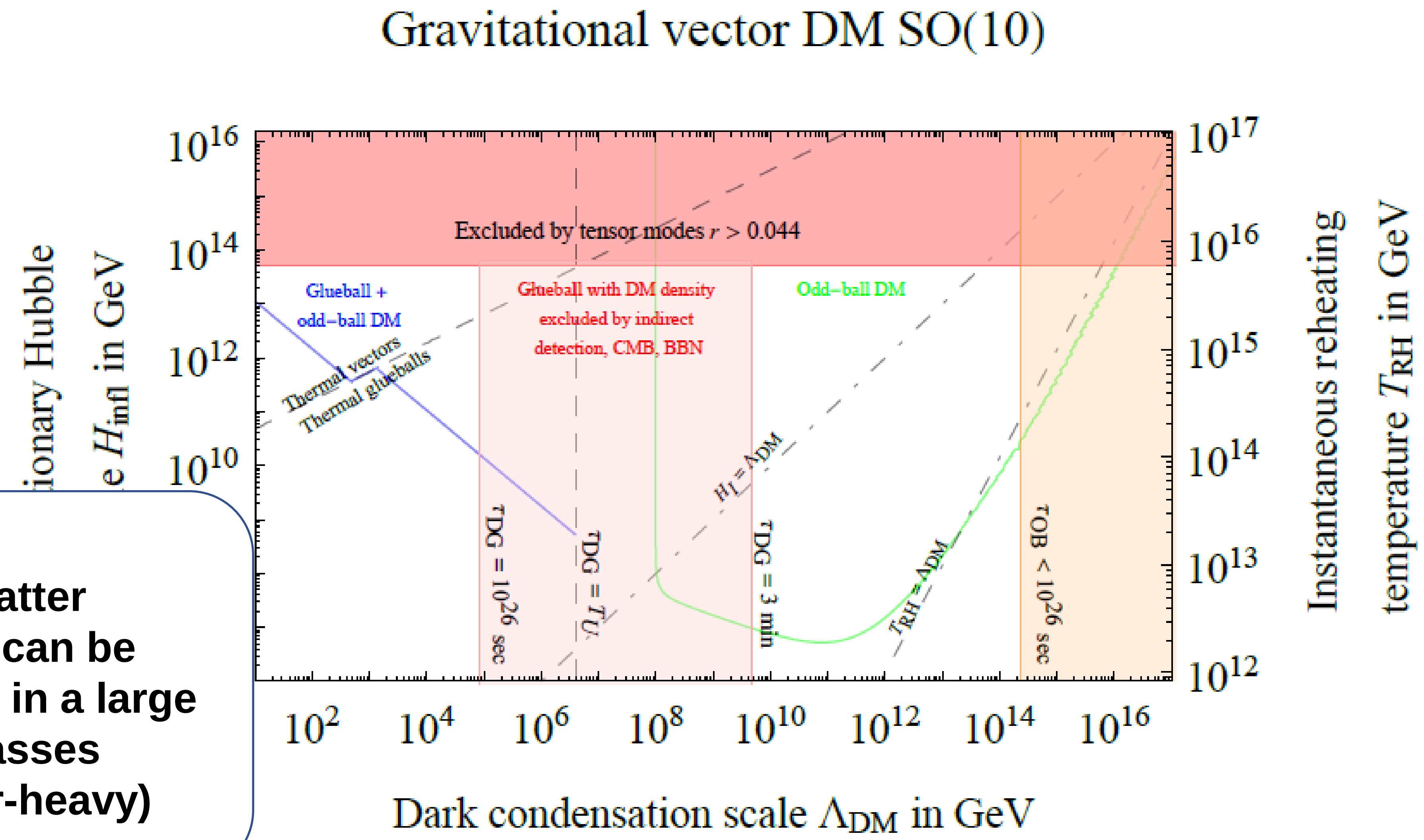
Direct freeze-in of odd-balls suppressed by $e^{-T_{\rm RH}/\Lambda_{\rm DM}}$

Gravitational vector DM



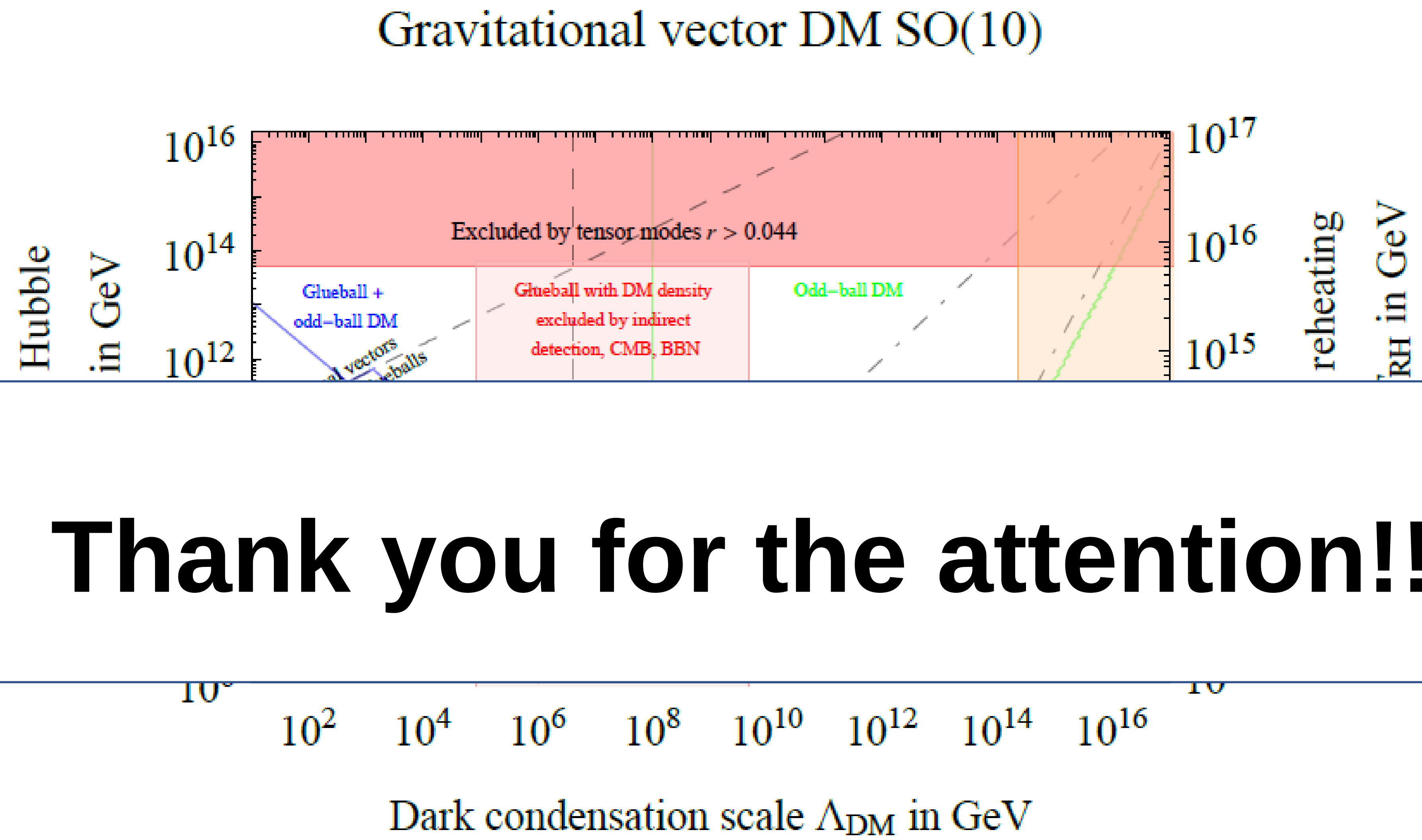
Excluded by cosmological observations (BBN,CMB, indirect detection)

Gravitational vector DM



The Dark Matter abundance can be reproduced in a large range of masses (even super-heavy)

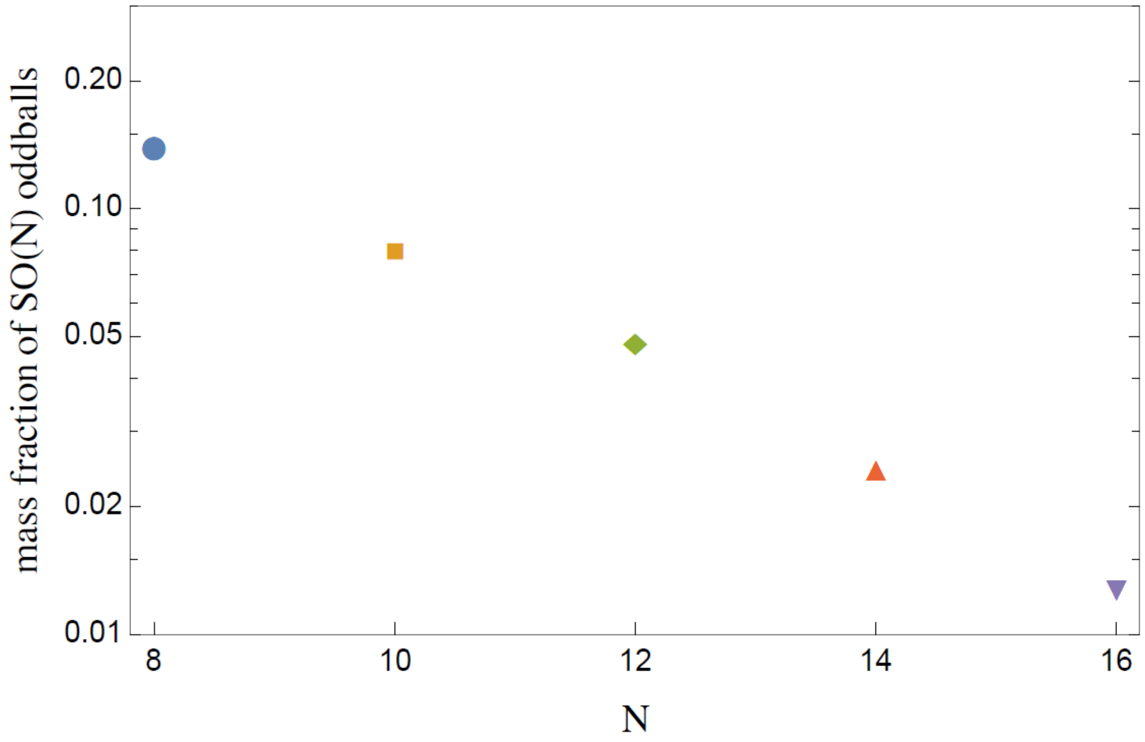
Gravitational vector DM



Thank you for the attention!!

Backup slides

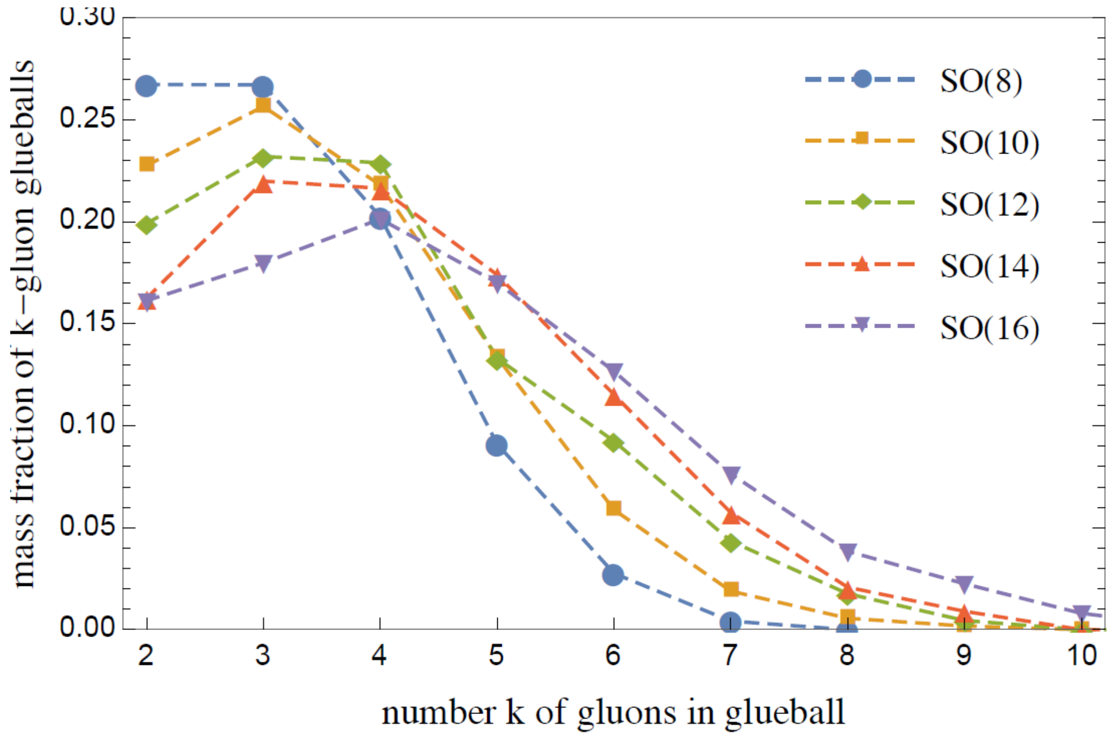
SO(N) Glue-ball distribution: odd-balls



Fraction of vector energy that ends up in SO(N) odd-balls

$$\kappa(N) = 1.2 \times 0.76^N$$

SO(N) Glue-ball distribution: ordinary



Fraction of vector energy that ends up in k-guons glue-ball

$$\epsilon(k) \approx e^{-\mu}\mu^{k-1}/(k-1)! \qquad \mu = (N+4)/6$$

Cannibal Glue-balls

Non-relativistic Glue-balls undergo cannibalistic processes $3 \to 2$

$$Y_{\rm DG} = \frac{T_D^*}{M_{\rm DG}} R \quad \longrightarrow \quad R = \frac{s_D}{s} = \left(\frac{T_D}{T}\right)^3 \sim \left(\frac{T_{\rm RH}}{M_{\rm Pl}}\right)^{9/4}$$

$$\downarrow$$

$$n_{\rm DG}^2(T_D)\sigma_{32}v^2 = H \qquad \sigma_{32}v^2 \approx \alpha_{\rm DC}^3/M_{\rm DG}^5$$

$$\frac{T_D^*}{M_{\rm DG}} \simeq \frac{1}{3\log Q} \qquad Q \approx 0.08(\alpha_{\rm DC}/0.1)^{3/4}(M_{\rm Pl}/M_{\rm DG})^{1/4}(T_{\rm RH}/M_{\rm Pl})^{3/8}$$

$$Y_{\rm DG} \sim \underbrace{\frac{1}{3\log Q}}_{\text{O(1-10) correction}} \underbrace{\left(\frac{T_{\rm RH}}{M_{\rm Pl}}\right)^{9/4}}_{\text{DG thermal abundance}}$$

O(1-10) correction DG thermal abundance

Glue-balls in an extended model

If we enlarge the dark sector with extra states typically:

1) extra-interactions allow the dark sector to thermalize with the SM (Higgs portal,Yukawa,...)

2) the glue-balls can decay to the SM through some portal → $\tau_{\rm DG} < 1 \text{ sec}$

→ glue-balls are not DM

3) some extra state (which interacts with the dark gauge vectors) is the Dark Matter candidate

However, glue-balls can play an important role in the evolution of Dark Matter!

Glue-balls in an extended model

Typically the dynamics of the dark sector is the following:

1) the DM particle decouples from the thermal bath at $M_{\rm DM} > \Lambda_{\rm DC}$

2) the theory confines and the glue-balls decouple keeping the (relativistic) vector abundance $n_{\rm DG} \propto T^3$

3) glue-balls dominate the energy density of the Universe before they decay → **Early matter domination era**

$$\rho_{\rm DG} \sim \Lambda_{\rm DC} T^3 > \rho_{\rm rad} \sim T^4$$

$$H^2 = \frac{\rho_{\rm DG}}{M_{\rm Pl}^2}$$

4) when glue-balls decay, they inject entropy in to the SM bath, heating it

↓

Huge **Dilution** of the Dark Matter abundance

Extended Dark Sector: an example

We enlarge the dark sector with a scalar singlet in the fundamental of SU(N)

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + |D_\mu S|^2 - V(S)$$

$$V(S) \subset \lambda_{HS} |S|^2 |H|^2$$

Portal to the SM

The dark sector is in equilibrium with the SM thermal bath (same T)

The dark vectors are now thermal (with temperature T)

Glue-balls decay and DM dilution

Glue-balls decay to SM states (= radiation) and release entropy into the thermal bath

$$\Gamma_{\rm DG}^2 = H_D^2 = \frac{\rho_{\rm DG}(T_D)}{M_{\rm Pl}^2} \simeq \frac{\Lambda_{\rm DC} T_D^3}{M_{\rm Pl}^2}$$

The energy of the glue-balls is transferred to the radiation bath, which gets hotter

$$\rho_{\rm rad} \sim T_{\rm RH}^4 = \rho_{\rm DG}(T_D)$$

The decays inject entropy into the thermal bath

$$D^{-1} = (T_{\rm RH}/T_D)^3$$

Glue-balls decay and DM dilution

Glue-balls decay to SM states (= radiation) and release entropy into the thermal bath

$$\Gamma^2_{\rm DG} = H^2_D = \frac{\rho_{\rm DG}(T_D)}{M^2_{\rm Pl}} \simeq \frac{\Lambda_{\rm DC} T^3_D}{M^2_{\rm Pl}}$$

The energy of the glue-balls is transferred to the radiation bath, which gets hotter

$$\rho_{\rm rad} \sim T^4_{\rm RH} = \rho_{\rm DG}(T_D)$$

Dilution of the pre-existing Dark Matter relic abundance

$$Y^{\rm after}_{\rm DM} \equiv \frac{n_{\rm DM}}{T^3_{\rm RH}} = \frac{n_{\rm DM}}{T^3_D} D \equiv Y^{\rm before}_{\rm DM} \times D$$

Glue-balls decay and DM dilution

Dilution of the pre-existing Dark Matter relic abundance

$$Y_{\rm DM}^{\rm after} = Y_{\rm DM}^{\rm before} \times D \ll Y_{\rm DM}^{\rm before}$$

$$D^{-1} = \left[1 + \frac{g_{\rm DG}}{g_{\rm SM}^{2/3}} \left(\frac{\Lambda_{\rm DC}^2}{\Gamma_{\rm DG} M_{\rm Pl}}\right)^{2/3}\right]^{3/4} \sim \frac{\Lambda_{\rm DC}}{\sqrt{\Gamma_{\rm DG} M_{\rm Pl}}}$$

$$\frac{\Omega_{\rm DM}}{0.12} = \frac{m_{\rm DM} Y_{\rm DM}}{T_{\rm eq}}$$

→ The dilution opens the DM parameter space to larger DM masses!

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$$V(S) \subset \lambda_{HS} |S|^2 |H|^2$$

Portal to the SM

The scalar singlet gets a vev w and breaks the gauge group SU(N) $\longrightarrow$ SU(N-1)

A **global** U(1) is preserved

Extended Dark Sector: an example

We enlarge the dark sector with a scalar singlet in the fundamental of SU(N)

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + |D_\mu S|^2 - V(S)$$

$$V(S) \subset \lambda_{HS} |S|^2 |H|^2$$

Portal to the SM

The scalar singlet gets a vev w and breaks the gauge group SU(N) $\longrightarrow$ SU(N-1)

A **global** U(1) is preserved

$$\{G_\mu, S\} = \{\mathcal{W}_\mu, \mathcal{Z}_\mu, \mathcal{A}_\mu, s\}$$

Fundamental of SU(N-1), massive, charged under U(1)

Extended Dark Sector: an example

We enlarge the dark sector with a scalar singlet in the fundamental of SU(N)

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + |D_\mu S|^2 - V(S)$$

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SU(N-1) singlets, massive

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Adjoint of SU(N-1), massless

Extended Dark Sector: an example

The SU(N-1) gauge group confines when $T < \Lambda_{\mathrm{DC}} < w$

The degrees of freedom combine into gauge-invariant bound states

Dark Matter

$$\mathcal{B} \sim \epsilon_{N-1} W^{N-1}$$

Charged under U(1)

Stable

The DM relic abundance is computed combining perturbative computations and non-perturbative estimates

Extended Dark Sector: an example

The SU(N-1) gauge group confines when $T < \Lambda_{\rm DC} < w$

The degrees of freedom combine into gauge-invariant bound states

Glue-balls

$Tr[\mathcal{A}_{\mu\nu}\mathcal{A}^{\mu\nu}]$ + heavier states → Unstable

↓

Decay to SM states through the Higgs portal

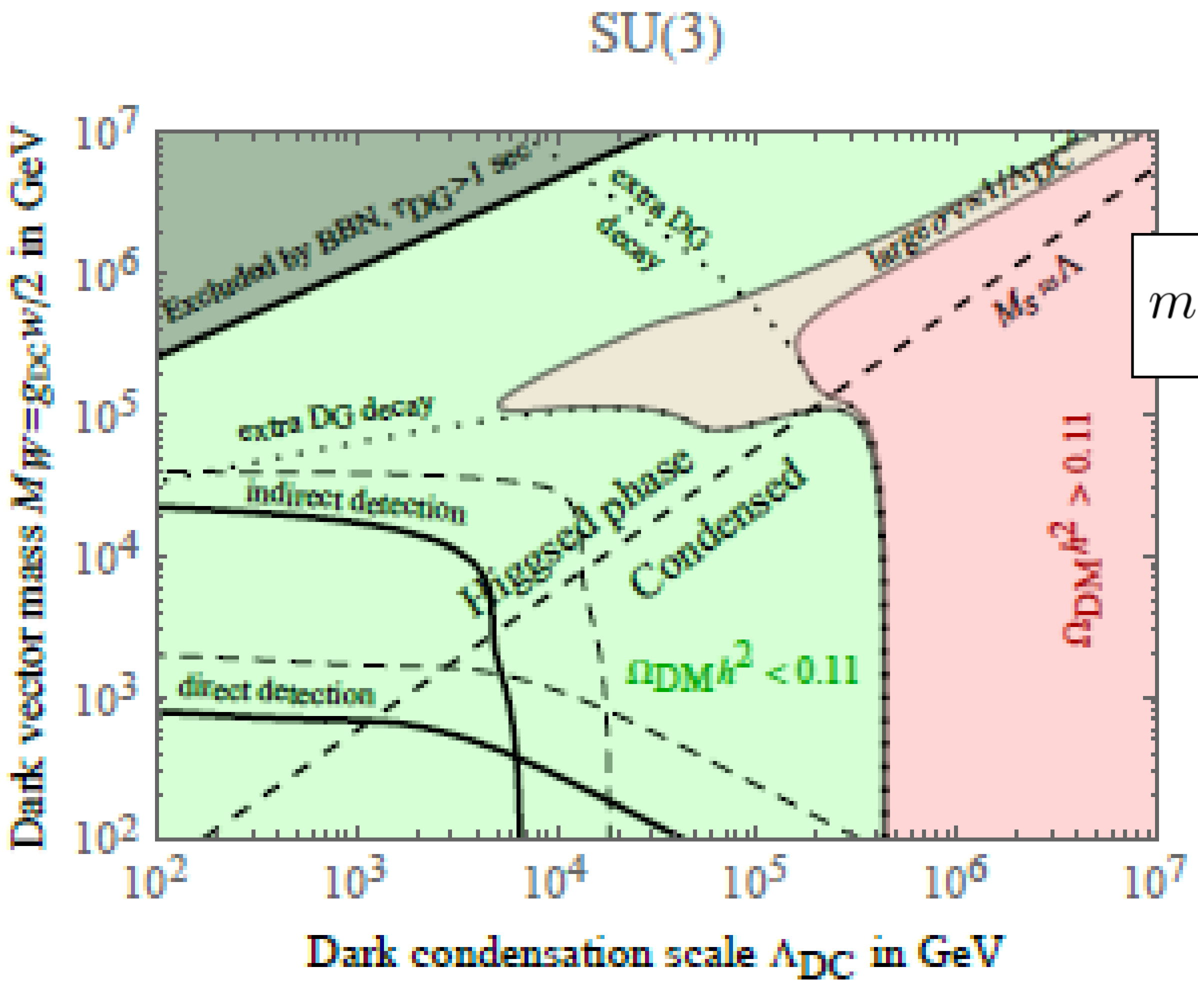
Glue-balls decay

The SU(N-1) glue-balls decay through the Higgs portal

$$\mathcal{L}_{\rm eff}^{H\mathcal{A}\mathcal{A}} = -\frac{7\alpha_{\rm DC}\lambda_{HS}}{16\pi M_s^2}(H^\dagger H)(\mathcal{A}^a_{\mu\nu})^2$$

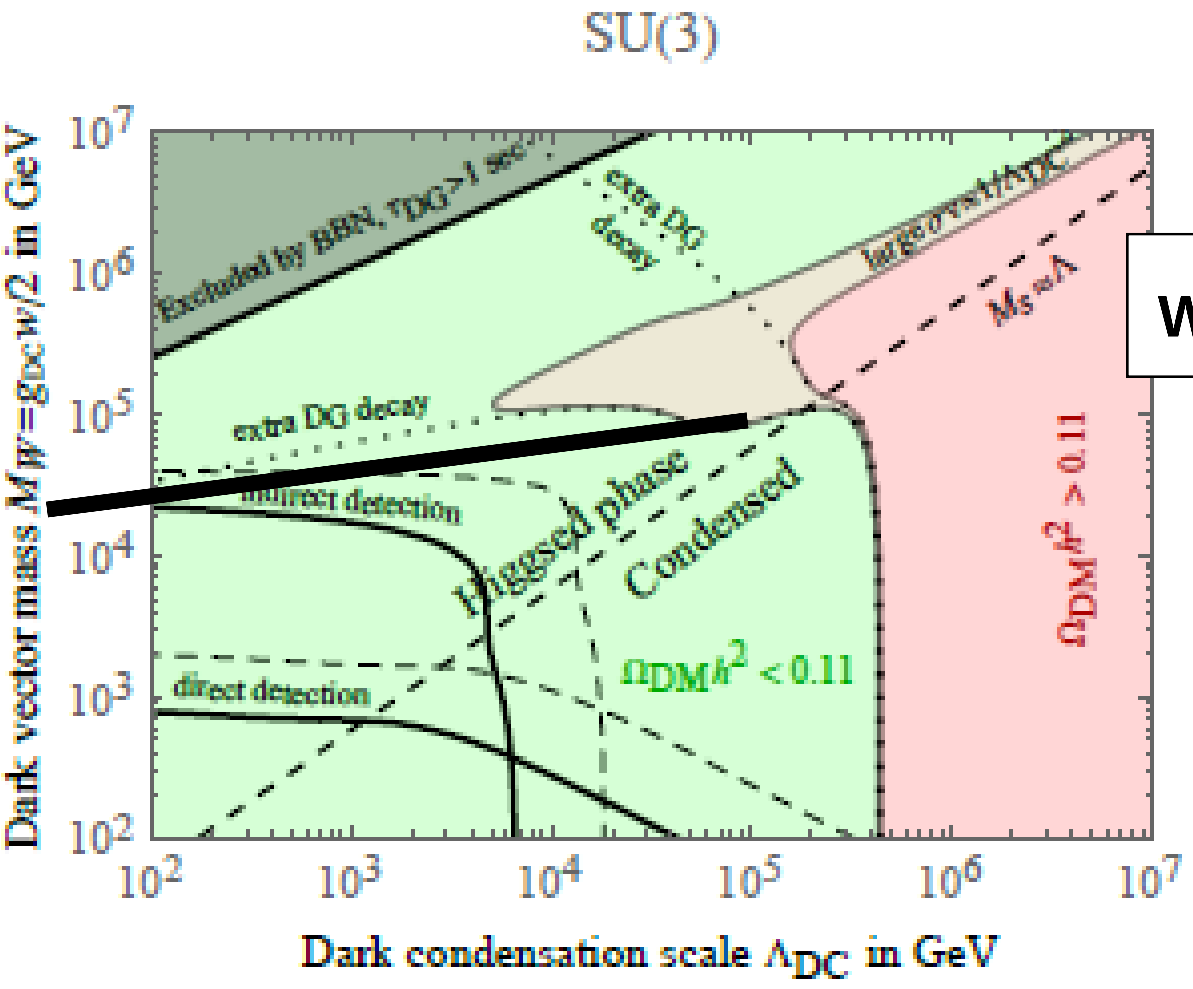
$$\Gamma({\rm DG}\to s\to H^\dagger H = hh + ZZ + WW) = \frac{49 f_{\rm DG}^2\alpha_{\rm DC}^2\lambda_{HS}^2}{2048\pi^3 M_{\rm DG}M_s^4}\sqrt{1-\frac{4M_{h,W,Z}^2}{M_{\rm DG}^2}}$$

Glue-balls decay and DM dilution



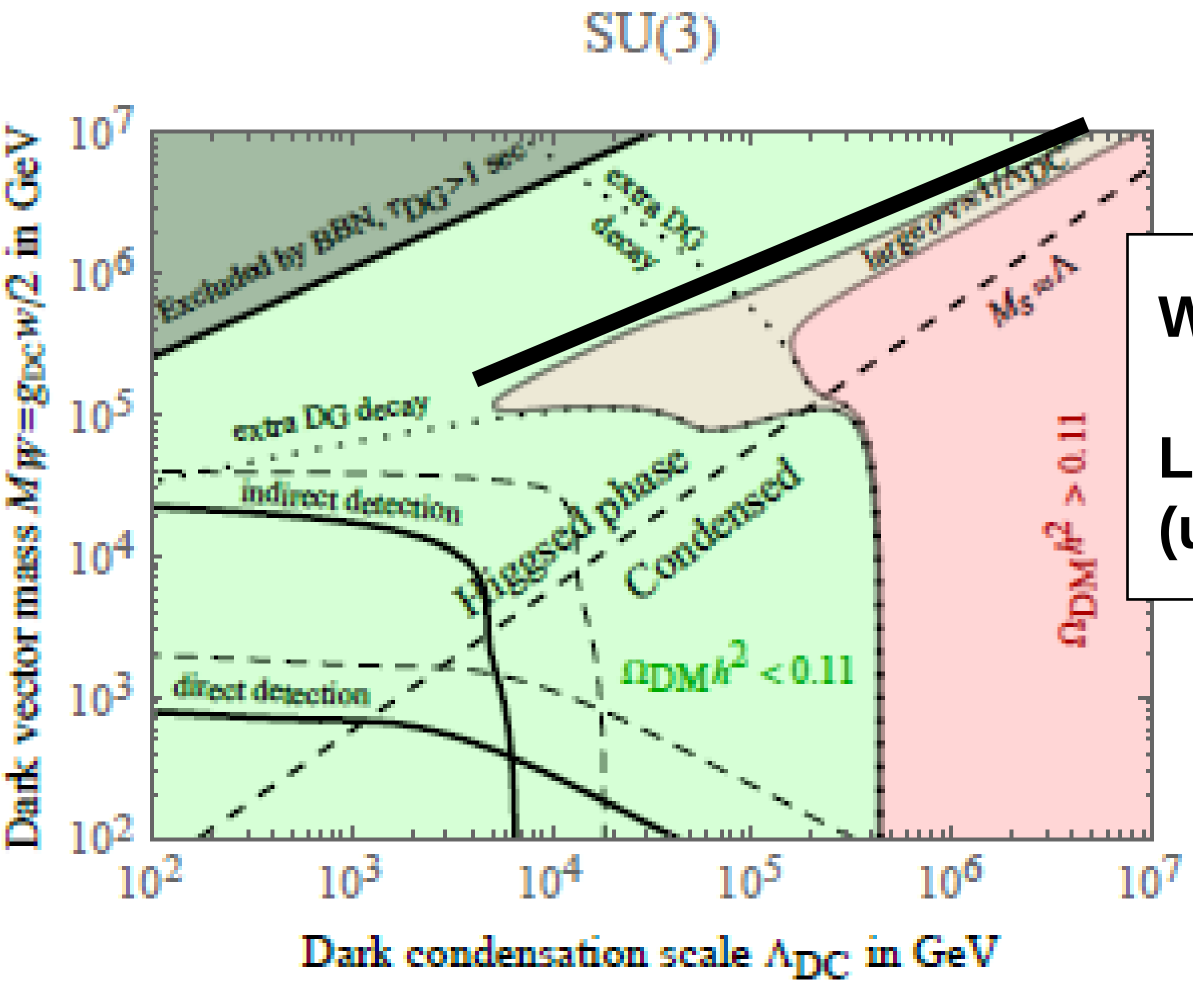
$$m_{\rm DM} \approx \max\{M_W, \Lambda_{\rm DC}\}$$

Glue-balls decay and DM dilution



Without the dilution

Glue-balls decay and DM dilution



With the dilution

Larger DM masses (up to a factor 10^3)

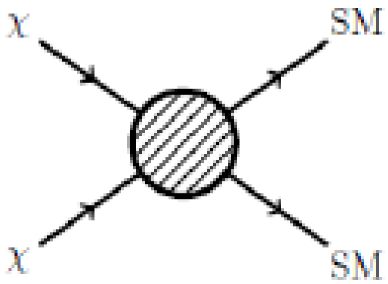
Dark Matter production

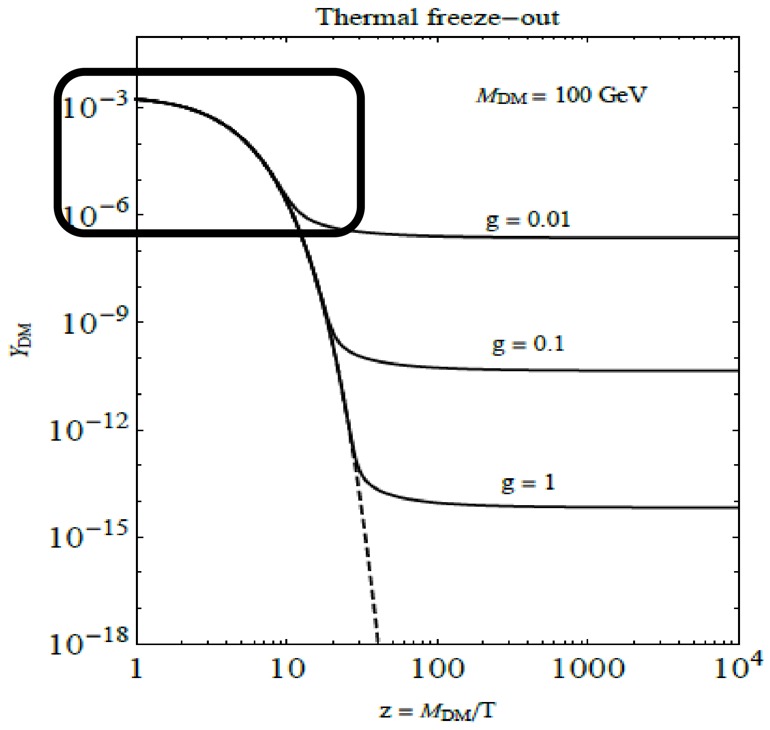
Freeze-out

DM is in thermal equilibrium with the SM bath

$$\Gamma_{\rm int} = n_{\rm DM}\sigma v_{\rm ann} > H$$

$$H \propto T^2/M_{\rm Pl}$$



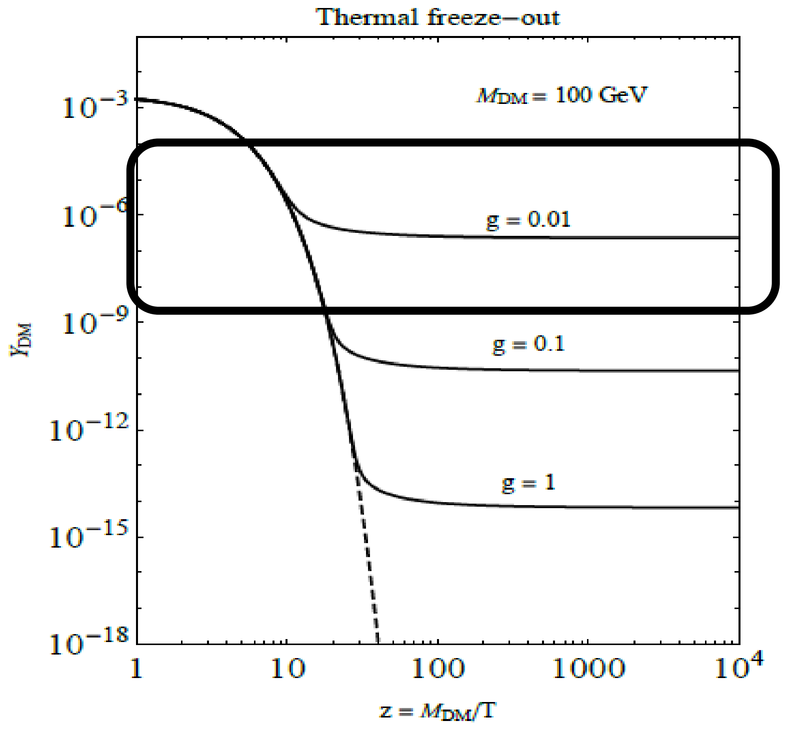


Dark Matter production

Freeze-out

DM decouples from the thermal bath

$$\Gamma_{\rm int} < H$$



Dark Matter production

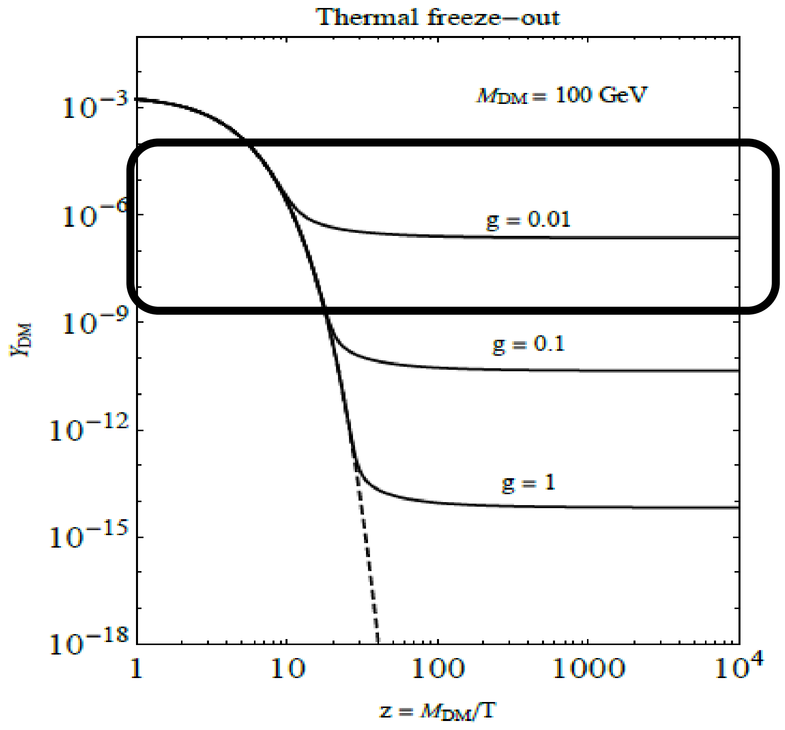
Freeze-out

DM decouples from the thermal bath

$$\Gamma_{\text{int}} < H$$

The DM abundance is conserved

$$Y_{\text{DM}} \equiv \frac{n_{\text{DM}}}{s}$$



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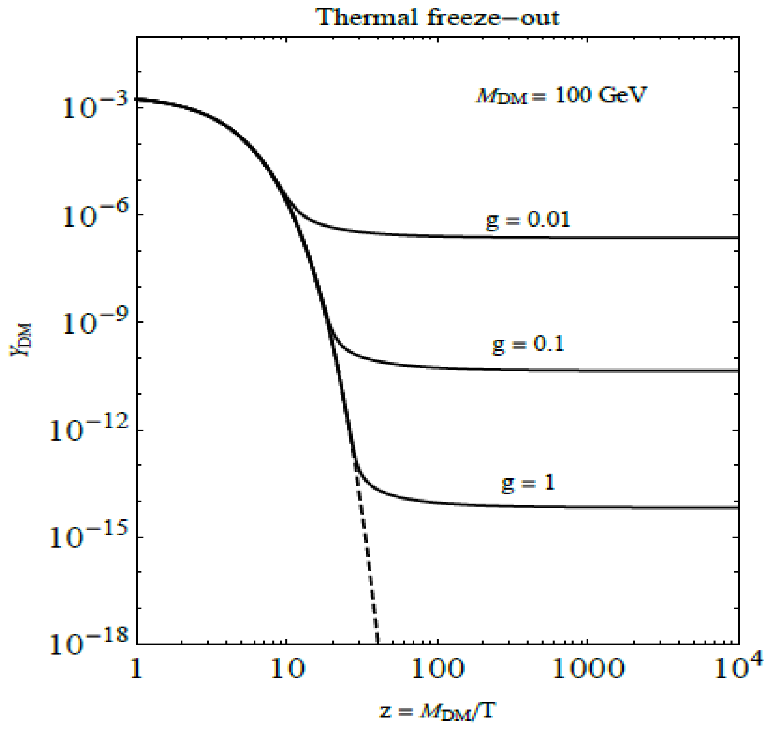
DM relic abundance

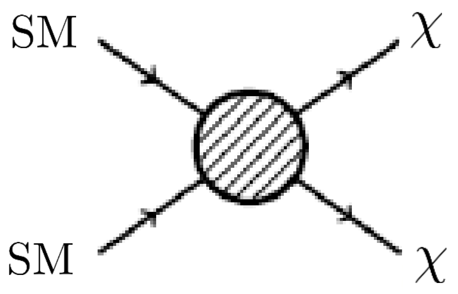
$$\frac{\Omega_{\rm DM}}{0.12} = \frac{m_{\rm DM} Y_{\rm DM}}{T_{\rm eq}}$$



Freeze-in

DM is never in thermal equilibrium with the SM bath

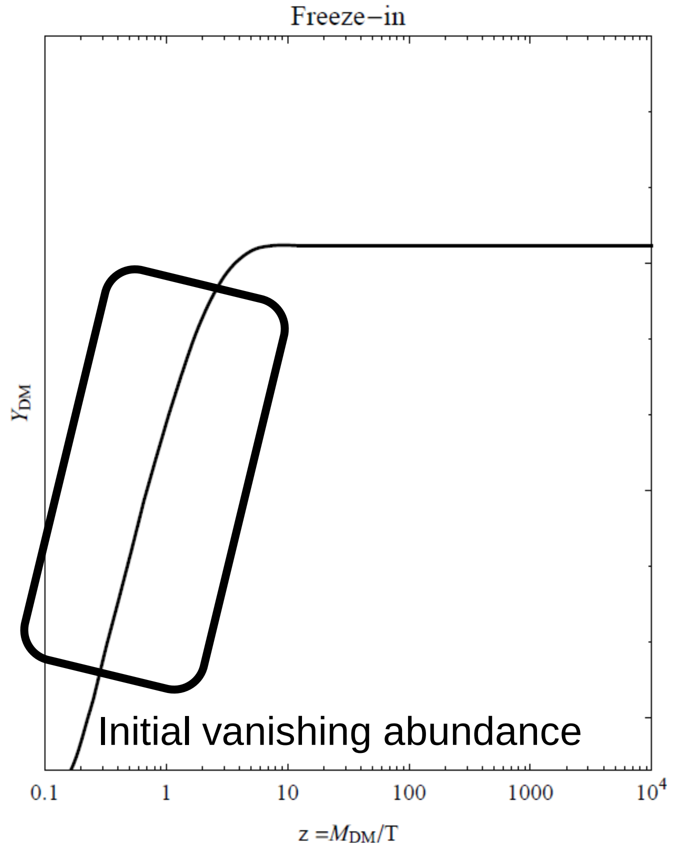
DM production from bath particles



$$\Gamma_{\rm int} < H$$

$$H \propto T^2/M_{\rm Pl}$$

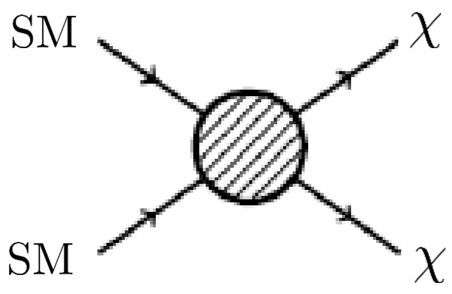
Small couplings needed



Freeze-in

DM is never in thermal equilibrium with the SM bath

The production is peaked around some T



$$\Gamma_{\rm int} < H$$

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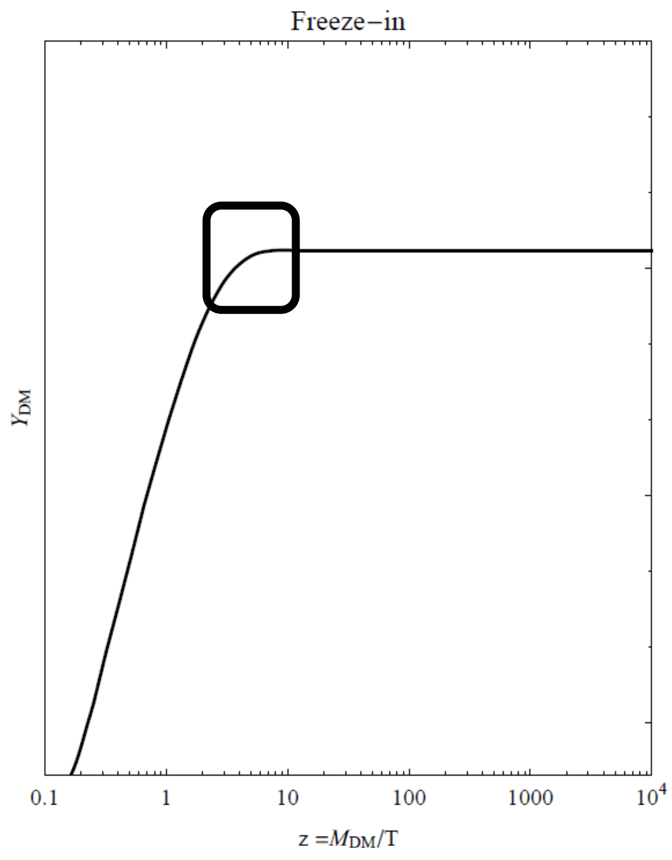
Small couplings needed



Freeze-in

DM is never in thermal equilibrium with the SM bath

The number of DM particles is conserved

$$Y_{\rm DM} \equiv \frac{n_{\rm DM}}{s}$$

DM relic abundance $$\frac{\Omega_{\rm DM}}{0.12} = \frac{m_{\rm DM} Y_{\rm DM}}{T_{\rm eq}}$$