Super-cool Dark Matter

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In collaboration with A. Strumia and D. Teresi, arXiv:1805.01473

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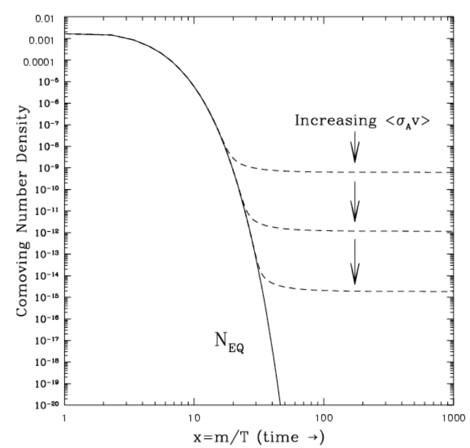
Dark Matter relic density: $\Omega_{DM} \simeq 26\,\%$

requires a suppression of the DM particle number density during the radiation dominated era: $n_{DM}/n_\gamma \sim 10^{-11}$

$m_{DM} \sim 100\,\mathrm{GeV}$

thermal freeze-out scenario: Boltzmann suppression

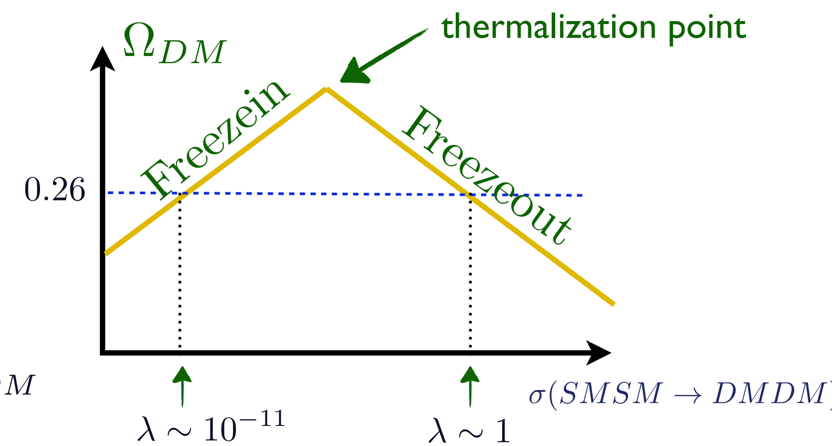
at $T = T_f \sim m_{DM}/22$



freeze-in production: slow out-of-equilibrium DM pair production: needs $n_{DM}/n_\gamma \sim 10^{-11}$

at $T = T_f \sim m_{DM}$

needs tiny couplings: $\lambda \sim 10^{-11}$



Super-cool DM: another possibility of n_{DM}/n_γ *suppression*

applies to 'dimensionless models': no mass term to start with in the $\mathcal{L}$

no μ^2 term(s) for the scalar field(s)

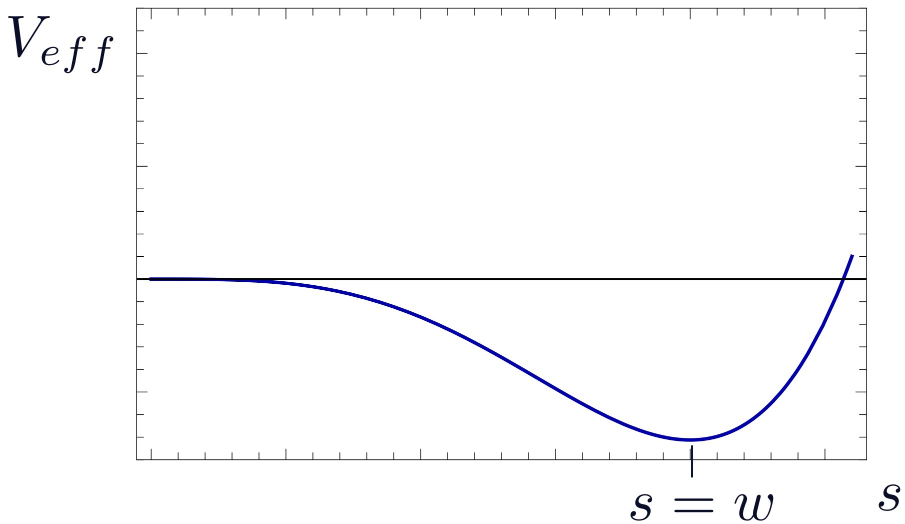
EWSB induced by radiative corrections:
radiative effective potential

Coleman-Weinberg 73'

Super-cool DM: another possibility of n_{DM}/n_γ suppression

sketch of the general mechanism:

⇒ at $T = 0$:

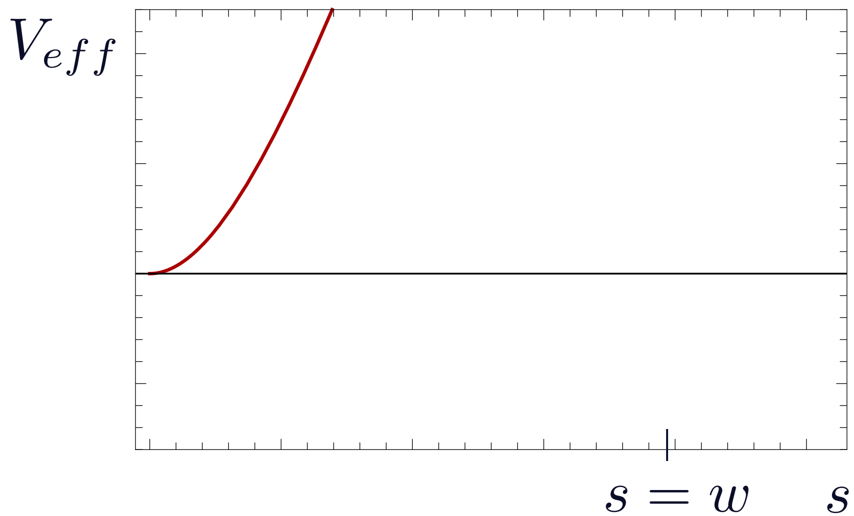


non trivial minimum:
symmetry breaking

Super-cool DM: another possibility of n_{DM}/n_γ suppression

sketch of the general mechanism:

⇒ but at $T >> w$: potential has a minimum at the origin due to finite T contributions

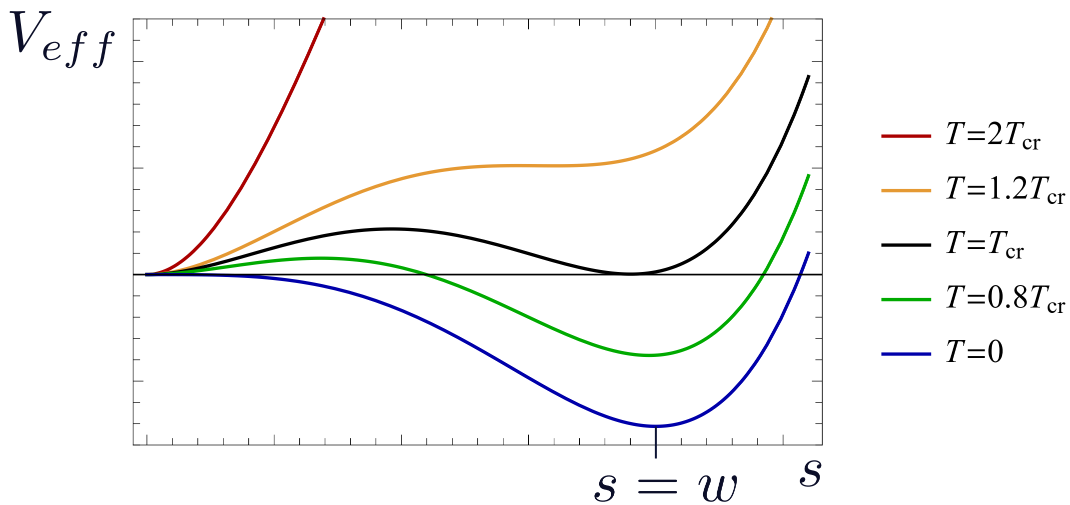


minimum at origin:
no symmetry breaking

Super-cool DM: another possibility of n_{DM}/n_γ suppression

sketch of the general mechanism:

⇒ at intermediate T :



scalar field is trapped in false vacuum at origin: this leads to a period of low scale thermal inflation

Witten, …. ,
TH, Strumia 12', …. ,
Iso, Serpico, Shimada 17'

Super-cool DM: another possibility of n_{DM}/n_γ suppression

sketch of the general mechanism:

→ during inflation DM is still massless at this stage and gets super-cooled (diluted) until end of this inflation period

from bubble nucleation to true vacuum or at the QCD phase transition

$$V \ni -y_q\, h\, \langle q\bar{q}\rangle$$

ends inflation at $T \sim \Lambda_{QCD}$

Witten, ….; Iso, Serpico, Shimada 17'

⇒ after reheating, given the value of Λ_{QCD}, the left diluted DM leads to $\Omega_{DM} = 26\,\%$ if $m_{DM} \sim \mathrm{TeV}$

An explicit example model

Standard Model

a new scalar S charged under a new gauge symmetry

$\downarrow$

radiative breaking occurs for this S scalar due to the gauge boson loops contributing to S effective potential

$\downarrow$

$$\langle S \rangle = \mathrm{w} \neq 0$$

An explicit example model

Standard Model $\longleftrightarrow$ a new scalar S charged under a new gauge symmetry

$$\mathcal{L} \ni -\lambda_{HS} S^\dagger S H^\dagger H$$
$$\ni -\lambda_{HS}\, \mathrm{w}^2\, H^\dagger H$$

$$\Downarrow$$

EWSB

Hempfling 96'

An explicit example model

Standard Model

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$$\ni -\lambda_{HS}\, \mathrm{w}^2\, H^\dagger H$$

$\Downarrow$

EWSB

+ we want a DM candidate: a possibility: stabilized by the new gauge symmetry

An explicit example model

Standard Model

a new scalar S charged under a new gauge symmetry

a new $SU(2)_X$ gauge symmetry with S a scalar doublet of it

$$\Rightarrow S = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ s + w \end{pmatrix}$$

$$M_X = \frac{g_X w}{2}$$

``Hidden vector dark matter''

TH 08', TH, Strumia 13'

the 3 X massive gauge bosons are stable because they form a triplet of remnant $SO(3)_C$ custodial symmetry, whereas all other particles are singlets of it

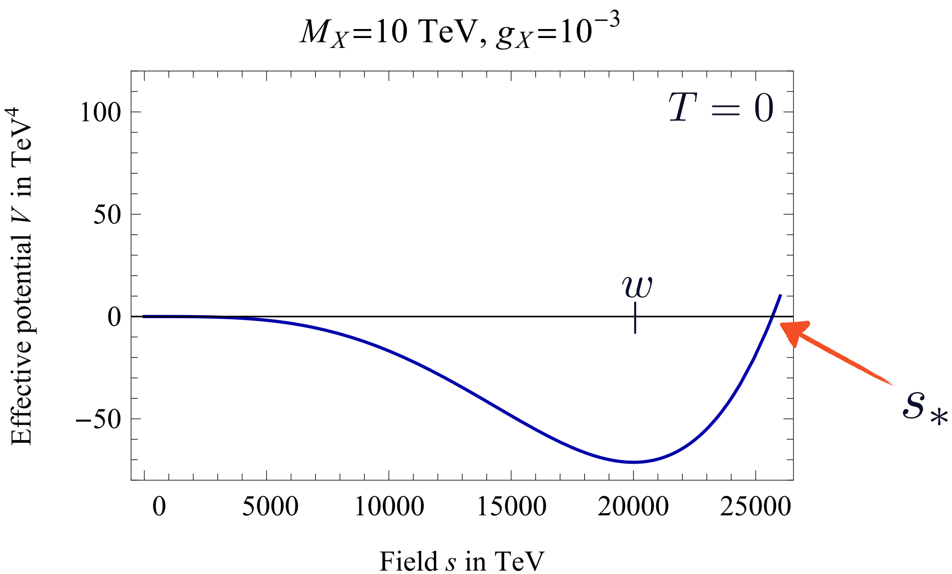
$\Rightarrow$ DM are the 3 massive non-abelian gauge bosons which drive the symmetry breaking: DM = ''Hidden forces''

Potential at zero temperature

$$V_0 = \lambda_H |H|^4 - \lambda_{HS}|HS|^2 + \lambda_S |S|^4$$

$\Rightarrow$ $$\beta_{\lambda_S} \equiv \frac{d\lambda_S}{d\ln\mu} = \frac{1}{(4\pi)^2}\left[\frac{9g_X^4}{8} - 9g_X^2\lambda_S + 2\lambda_{HS}^2 + 24\lambda_S^2\right] \approx \frac{1}{(4\pi)^2}\frac{9\,g_X^4}{8}$$

$\Rightarrow$ λ_S becomes negative at low scale $\Rightarrow$ $V_1(s) \approx \beta_{\lambda_S}\dfrac{s^4}{4}\ln\dfrac{s}{s_*}$



$$\langle s \rangle = w = s_* e^{-1/4}$$

$$v/w = \sqrt{\lambda_{HS}/2\lambda_H}$$

$$M_s = w\sqrt{\beta_{\lambda_S}}$$

after we fix $v = 246\,\mathrm{GeV}$ and $m_h = 125\,\mathrm{GeV}$ the model has only 2 parameters

$g_X,\ M_X = \dfrac{g_X w}{2}$

finally we add a constant to the potential to have ~0 cosmological constant today: $V_\Lambda \approx \beta_{\lambda_S} w^4/16 \approx 9M_X^4/8(4\pi)^2$

Finite temperature period

$$V_T(s) = \frac{9T^4}{2\pi^2} f(\frac{M_X}{T}) + \frac{T}{4\pi}[M_X^3 - (M_X^2 + \Pi_X)^{3/2}]$$

$$f(r) = \int_0^\infty x^2 \ln(1 - e^{-\sqrt{x^2+r^2}})dx$$

$$\Pi_X = 11 g_X^2 T^2/6$$

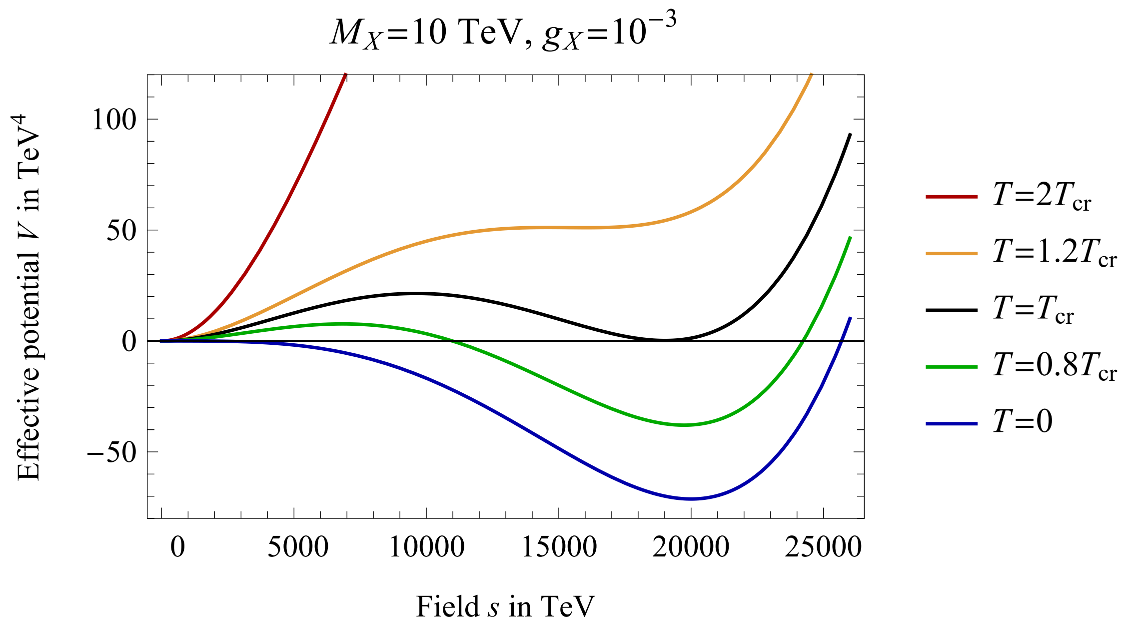
$$M_s^{2T} = \frac{3}{16} g_X^2 T^2$$

$$M_h^{2T} = \left(\frac{3}{16} g_2^2 + \frac{1}{16} g_Y^2 + \frac{1}{4} y_t^2 + \frac{1}{2}\lambda_H\right) T^2$$

Start of supercool period

at $T >> w$: minimum at $s = 0$ due to finite temperature potential

at $T = T_{crit} \sim 0.3\, M_X$: 2 minimum at same level as a result of:
- no $T = 0$ quadratic term
- positive quadratic term from thermal potential
- radiative potential developing a second minimum



$\Rightarrow$ scalar field is trapped in false vacuum at origin: this leads to a period of low scale thermal inflation

Witten, …. ,TH, Strumia 12', …. , Iso, Serpico, Shimada 17'

at $T = T_{infl} < T_{crit}$: inflation starts when $\rho_{rad} = \dfrac{g_* \pi^2 T^4_{infl}}{30} < \rho_\Lambda = V_\Lambda$

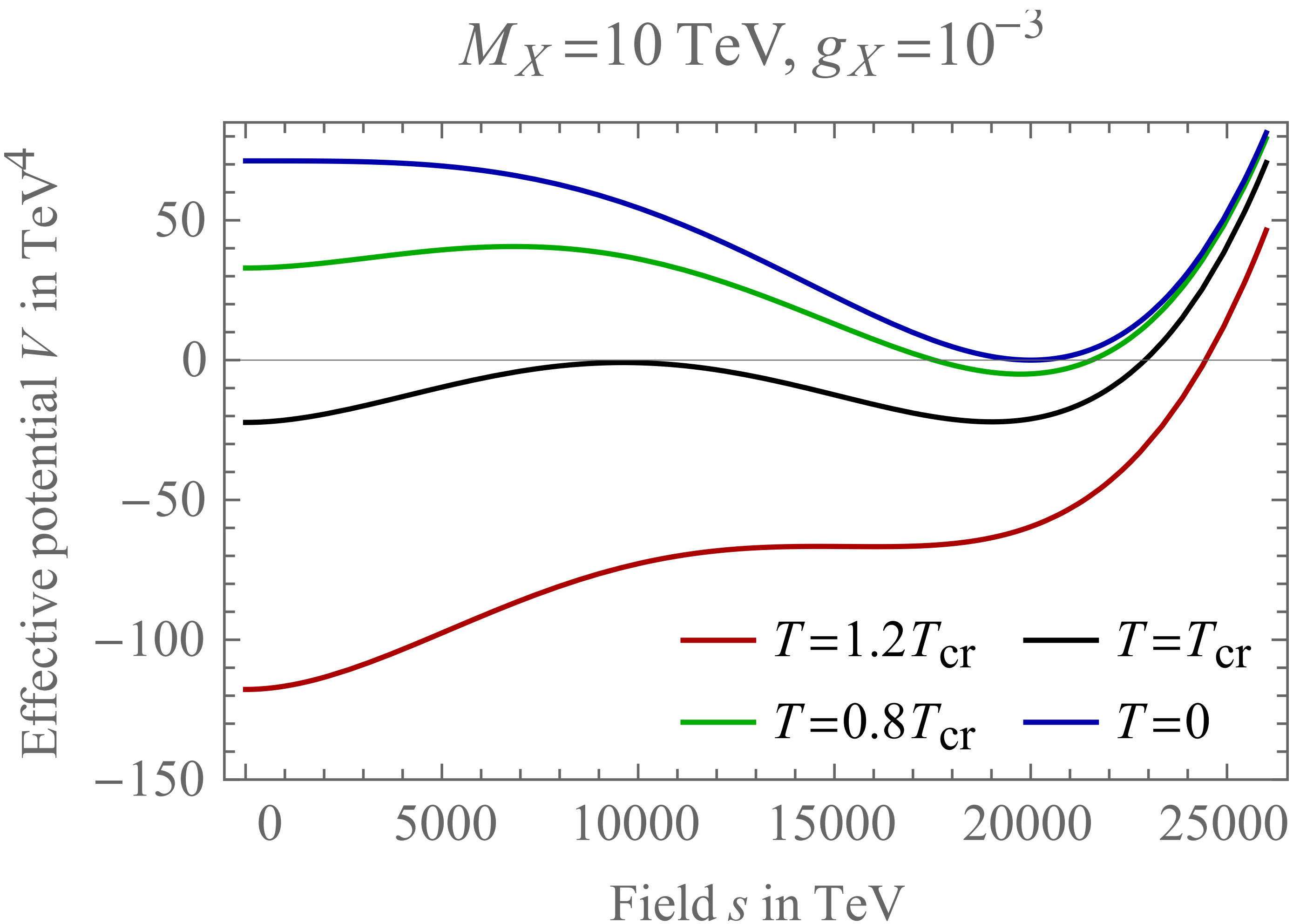
$$\Rightarrow \; T_{\rm infl} = \left(\frac{135}{64 g_*}\right)^{1/4} \frac{M_X}{\pi} \approx \frac{M_X}{8.5} < T_{crit} < w \;\Rightarrow\; a = a_{\rm infl} e^{Ht}$$

$$e^N = \frac{T_{\rm infl}}{T_{\rm end}}$$

$$T = T_{\rm infl}\, a_{\rm infl}/a$$

Start of supercool period

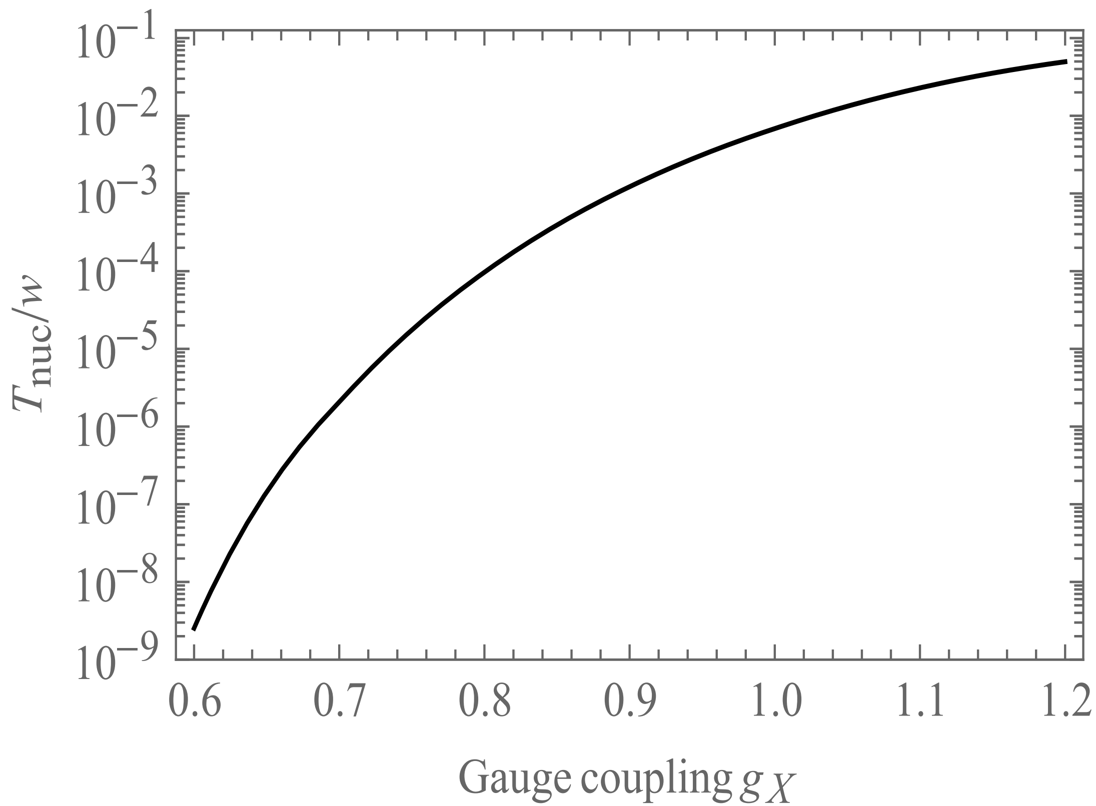
true potential (not shifting it to have $V = 0$ in $s = 0$):



End of super-cool period

could anyway end through bubble nucleation at $T = T_{nuc}$

but T_{nuc} is very low as soon as gauge coupling below unity



End of super-cool period

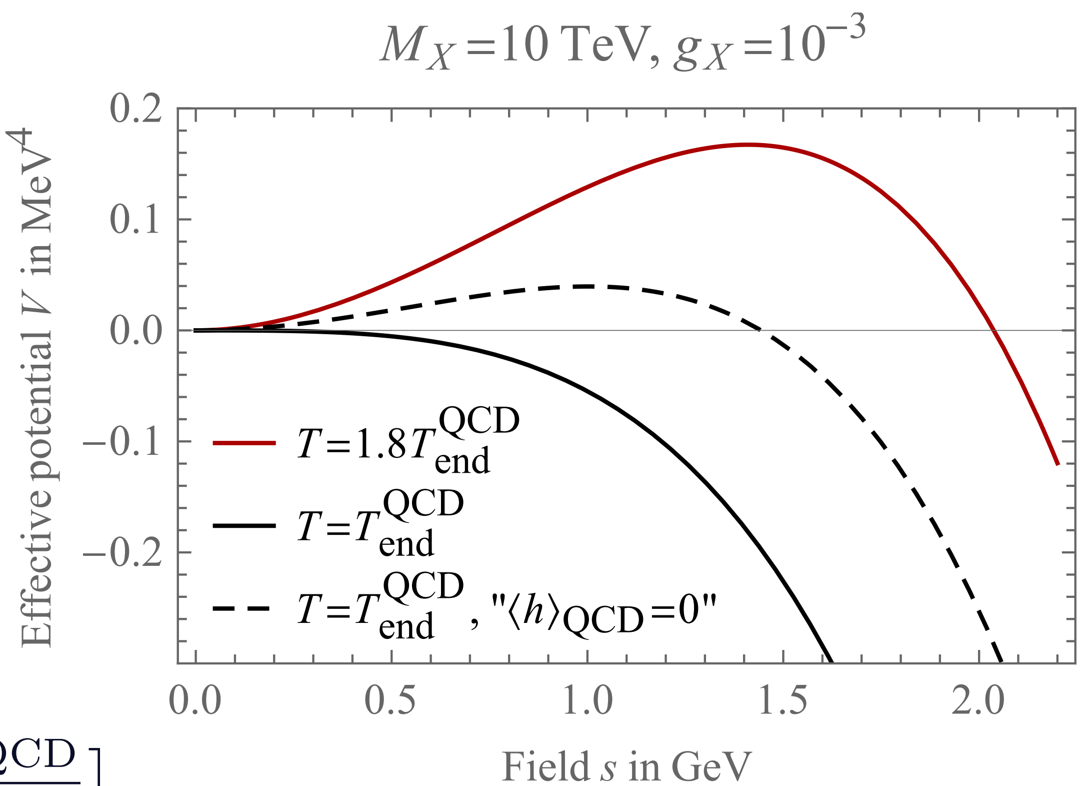
⇒ unless gauge coupling very close to unity, the super cool period does not end at T_{nuc} but earlier at the QCD phase transition: $T_{cr}^{QCD} \sim 85\,\mathrm{MeV}$ ← massless quarks

$$V \ni -y_q\, h\, \langle q\bar{q}\rangle$$

$$\langle h\rangle_{QCD} \sim 100\,\mathrm{MeV}$$

Witten, ….; Iso, Serpico, Shimada 17'

$$M_s^2 = -\frac{1}{2}\lambda_{HS}\langle h\rangle_{QCD}^2$$

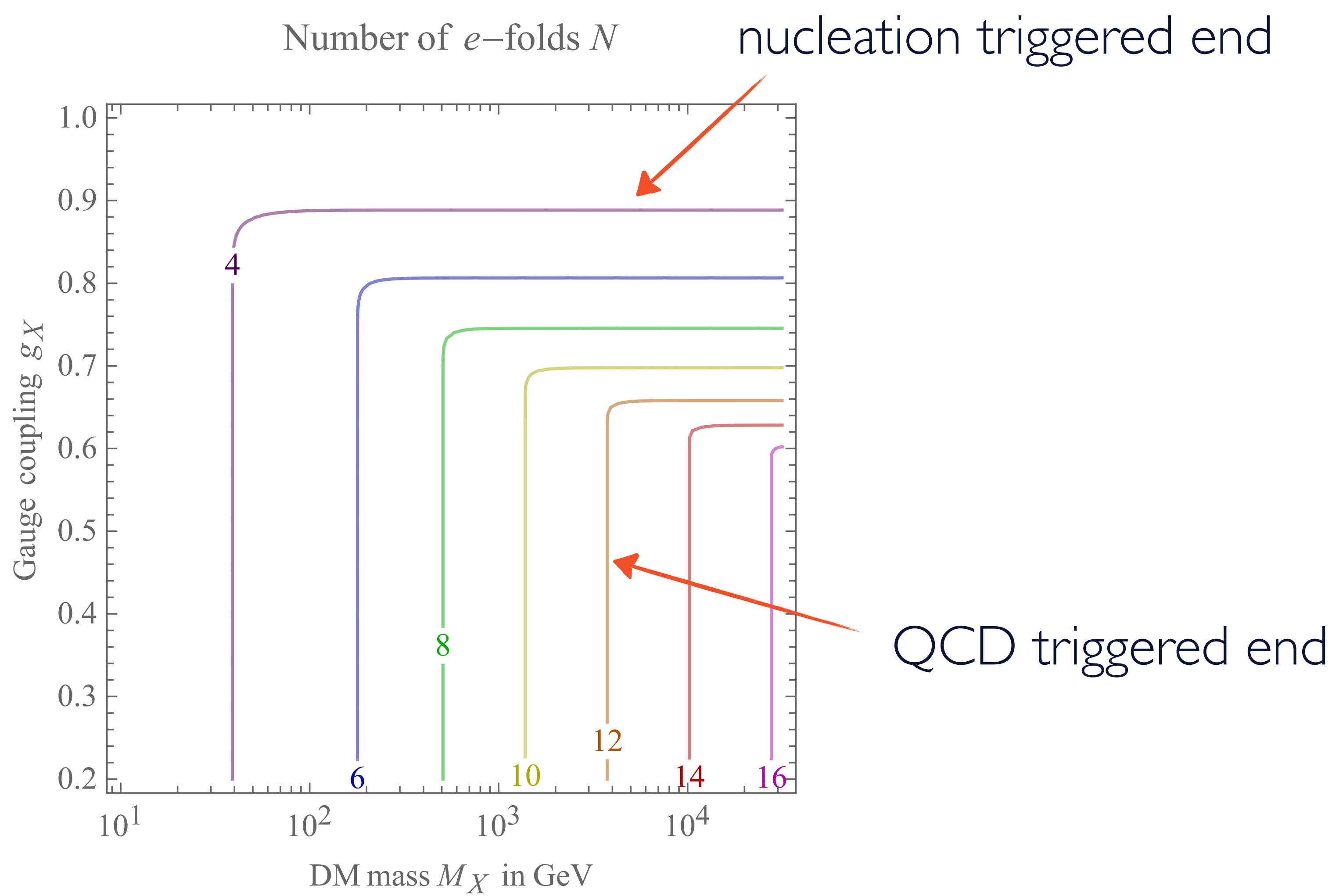


⇒ $$T_{\rm end} = \mathrm{Min}\left[T_{\rm cr}^{\rm QCD}, \frac{0.1\,\langle h\rangle_{\rm QCD}}{M_X/\mathrm{TeV}}\right]$$

if s field destabilized as soon as $\langle q\bar{q}\rangle$ form

if s field destabilized later when thermal mass $\propto T^2$ smaller than QCD induced mass

End of super-cool period



Oscillation of s field around $s = w$ and reheating

reheating with 2 scalar fields which mix

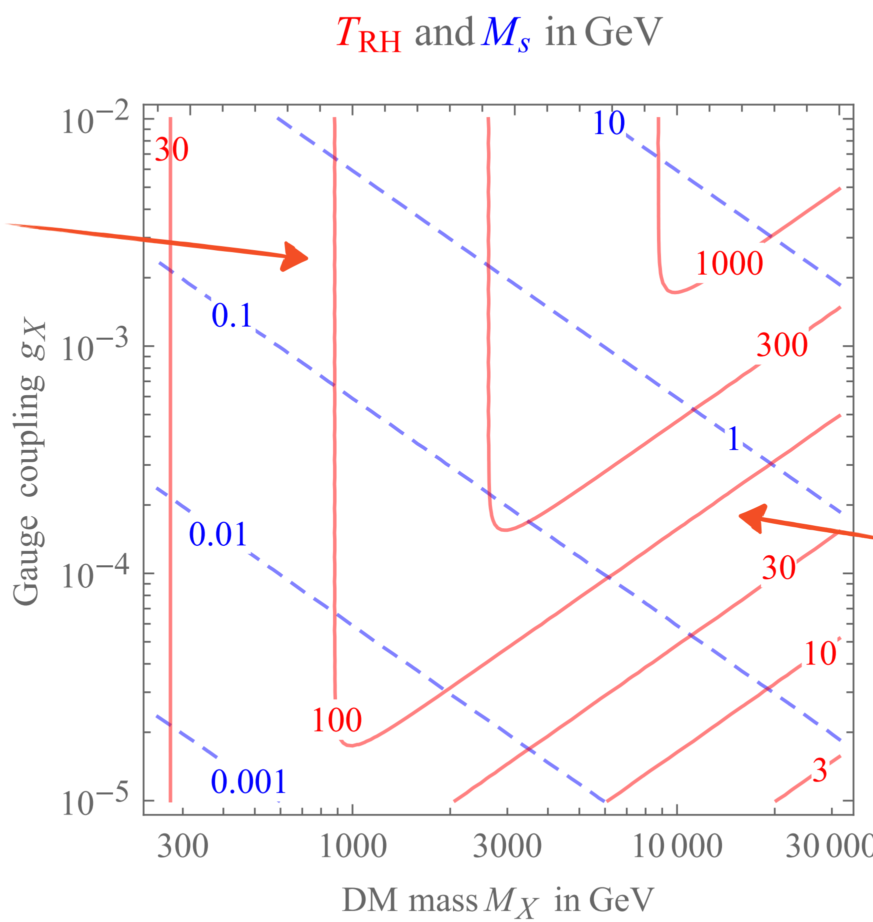
$s \to SM\,SM$

$h \to SMSM$

$s - h$ mixing

instantaneous reheating

$T_{RH} \sim T_{\rm infl} \sim M_X/8.5$



non-instantaneous reheating

smaller T_{RH}

DM relic density: standard freezeout case

if $g_X \sim 1$ and $T_{RH} \gtrsim m_{DM}/22$: DM can thermalize again

$\Downarrow$

DM standard freezeout

$\Downarrow$

$m_{DM} \sim v_{EW}$

TH, Strumia 13'

leads to WIMP miracle

DM relic density: the super cool thing!

if $g_X \sim 1$ and $T_{RH} \gtrsim m_{DM}/22$: DM can thermalize again

$\Downarrow$

DM standard freezeout

$\Downarrow$

$m_{DM} \sim v_{EW}$

TH, Strumia 13'

leads to WIMP miracle

the 'cool miracle' !

(not super-cool, just cool)

but as soon as g_X is sizably smaller than unity, DM doesn't thermalize after supercooling because $T_{RH} < m_{DM}/8.5$ anyway

DM can be created only from tail of distribution of thermal bath particles

$$\Rightarrow \quad Y_{\rm DM} \approx Y_{\rm DM}|_{\rm super-cool} + Y_{\rm DM}|_{\rm sub-thermal}$$

with $Y_{\rm DM}|_{\rm sub-thermal} << Y_{\rm DM}^{EQ}$

DM relic density: the super cool DM population!

$\Rightarrow$ super-cool DM population:

$$Y_{\rm DM}|_{\rm super-cool} = Y^{\rm eq}_{\rm DM}\frac{T_{\rm RH}}{T_{\rm infl}}\left(\frac{T_{\rm end}}{T_{\rm infl}}\right)^3$$

DM particles are massless during super-cooling: even if $T_{RH} < m_{DM}$, no Boltzmann suppression! only dilution!

$\Rightarrow$ given the value of $T_{cr}^{QCD} \sim 100\,\mathrm{MeV}$ one gets the right amount of dilution to get $\Omega_{DM} \simeq 26\,\%$ for: $m_{DM} \sim \mathrm{TeV}$

$\sim 10\,\text{e-folds}$

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the 'super-cool miracle' !

one-to-one relation between Ω_{DM} and m_{DM}

for $\langle h \rangle_{QCD} \simeq 100\,\mathrm{MeV}$ one gets $m_{DM} = 520\,\mathrm{GeV}$

DM relic density: the sub-thermal DM population

$\Rightarrow$ possible additional sub-thermal population

$\hookrightarrow$ DM pair production from thermal bath if g_X not too small

suppressed because created from tail of distribution of thermal bath particles

$T_{RH} < m_{DM}$

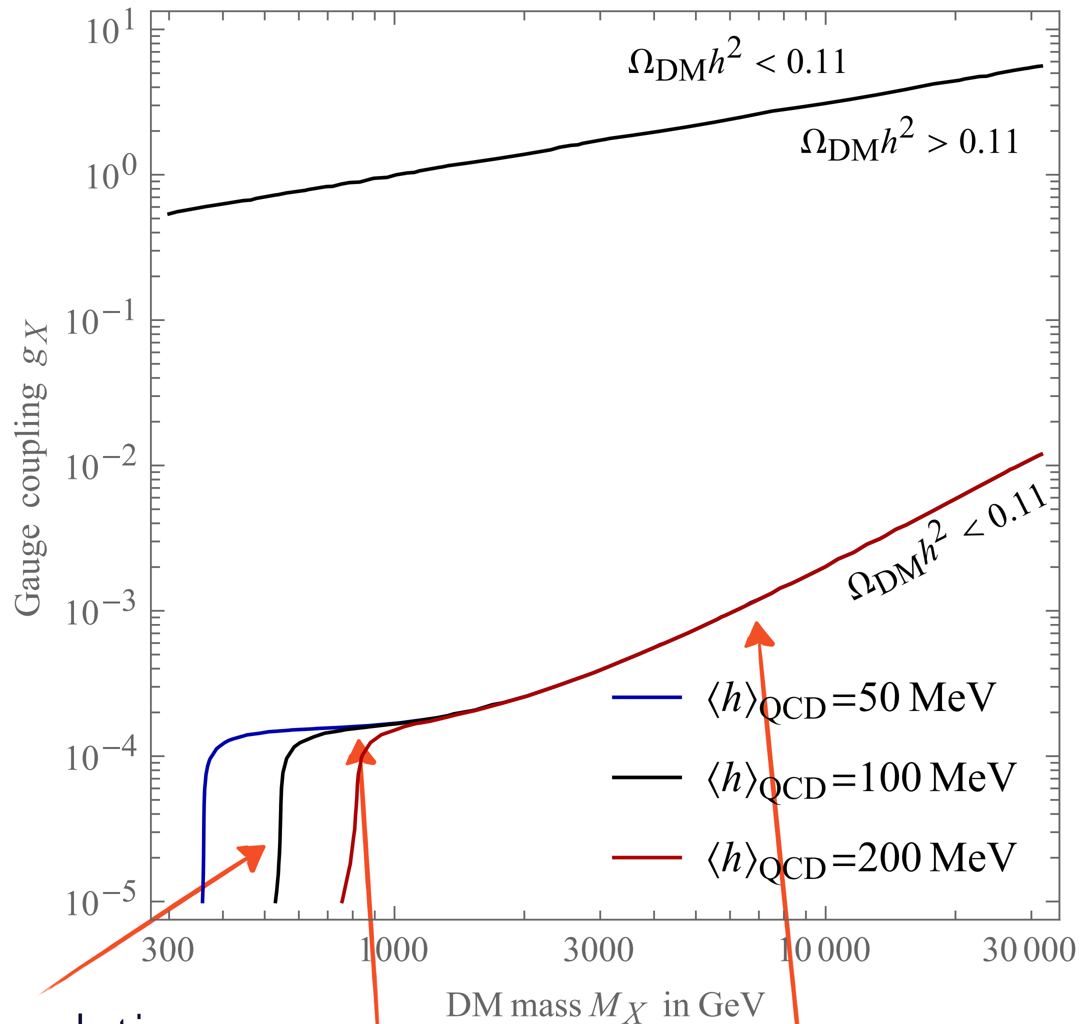
$\Rightarrow$ solving:

$$\dot{n}_{\rm DM} = -3Hn_{\rm DM} + \langle\sigma v\rangle_{\rm ann}(n_{\rm DM}^{\rm eq2} - n_{\rm DM}^2) + \langle\sigma v\rangle_{\rm semi} n_{\rm DM}(n_{\rm DM}^{\rm eq} - n_{\rm DM})$$

starting from super-cool population at $T = T_{RH}$

$\Rightarrow$ can also give easily $\Omega_{DM} \simeq 26\,\%$

DM relic density: final results

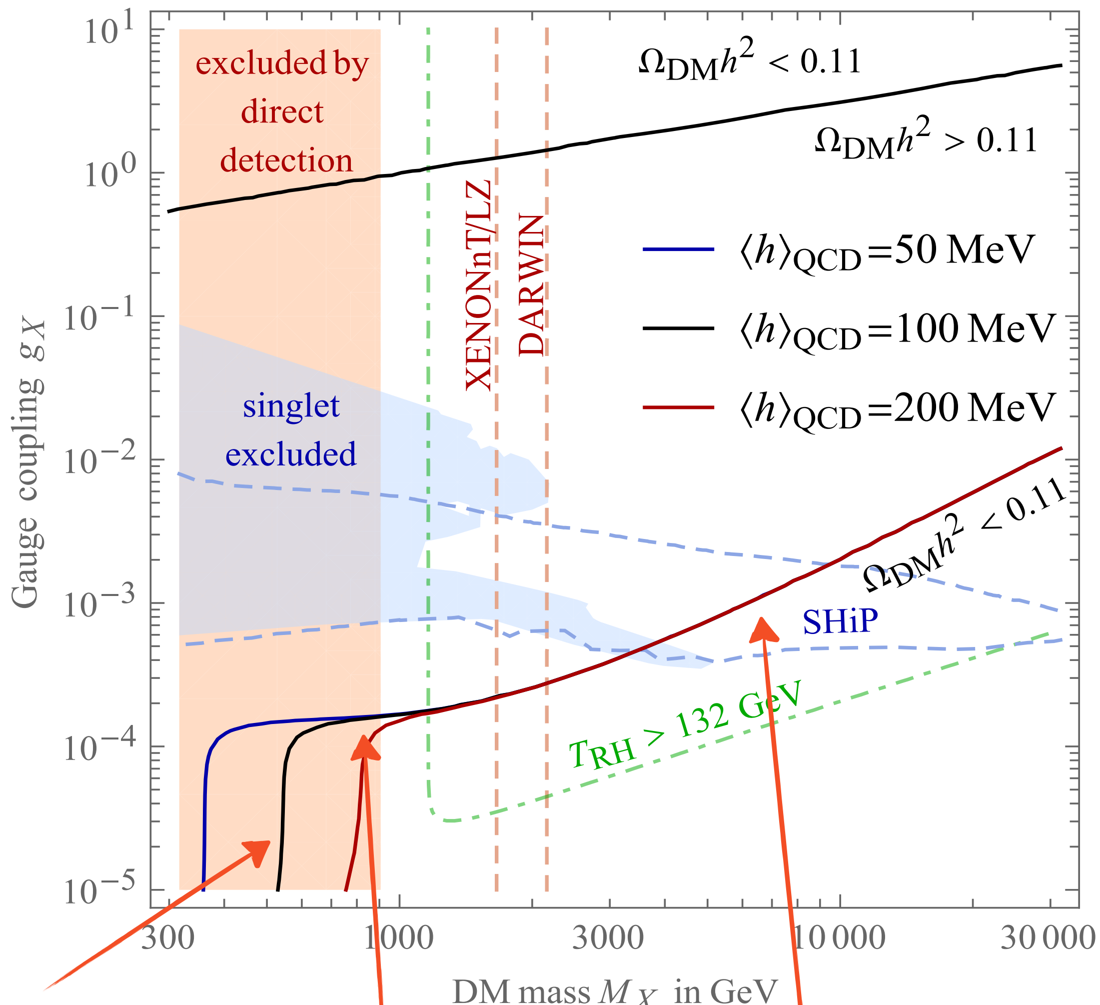


super-cool DM population

sub-thermal DM population with instantaneous reheating

sub-thermal DM population with non-instantaneous reheating

DM relic density: final results



super-cool DM population

sub-thermal DM population with instantaneous reheating

sub-thermal DM population with non-instantaneous reheating

Neutrino masses, baryogenesis?

baryogenesis must be created after super-cool period because supercool period basically dilutes any preexisting B-asymmetry

cold baryogenesis? ← to be seen   Servant et al

leptogenesis: add e.g. right-handed neutrinos N_i and extra scalar to give masses to them once it gets a vev from s scalar vev

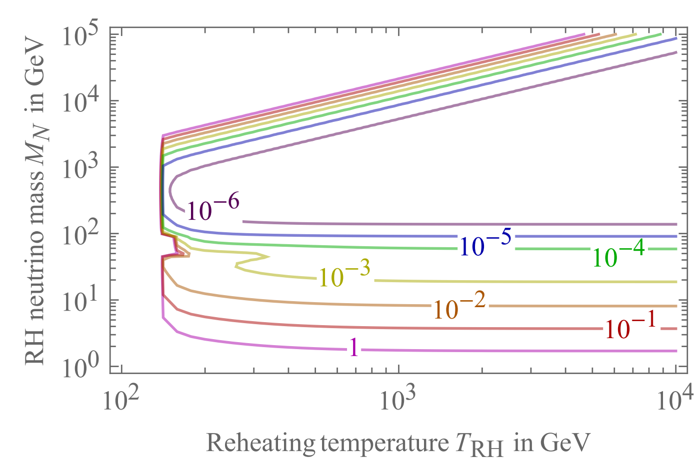
⇒ leptogenesis: possible because $T_{RH} > T_{sphaler.} \sim 132\,\mathrm{GeV}$ is possible

Akhmedov, Rubakov, Smirnov; Asaka, Shaposhnikov, ….

from total lepton number conserving ARS N_i oscillation setup: not easy because generically requires $T_{RH} >>> v_{EW}$

from total lepton number violating Higgs decay setup: fine: infrared production just above $T_{sphaler.}$

TH, Teresi 16', 17'



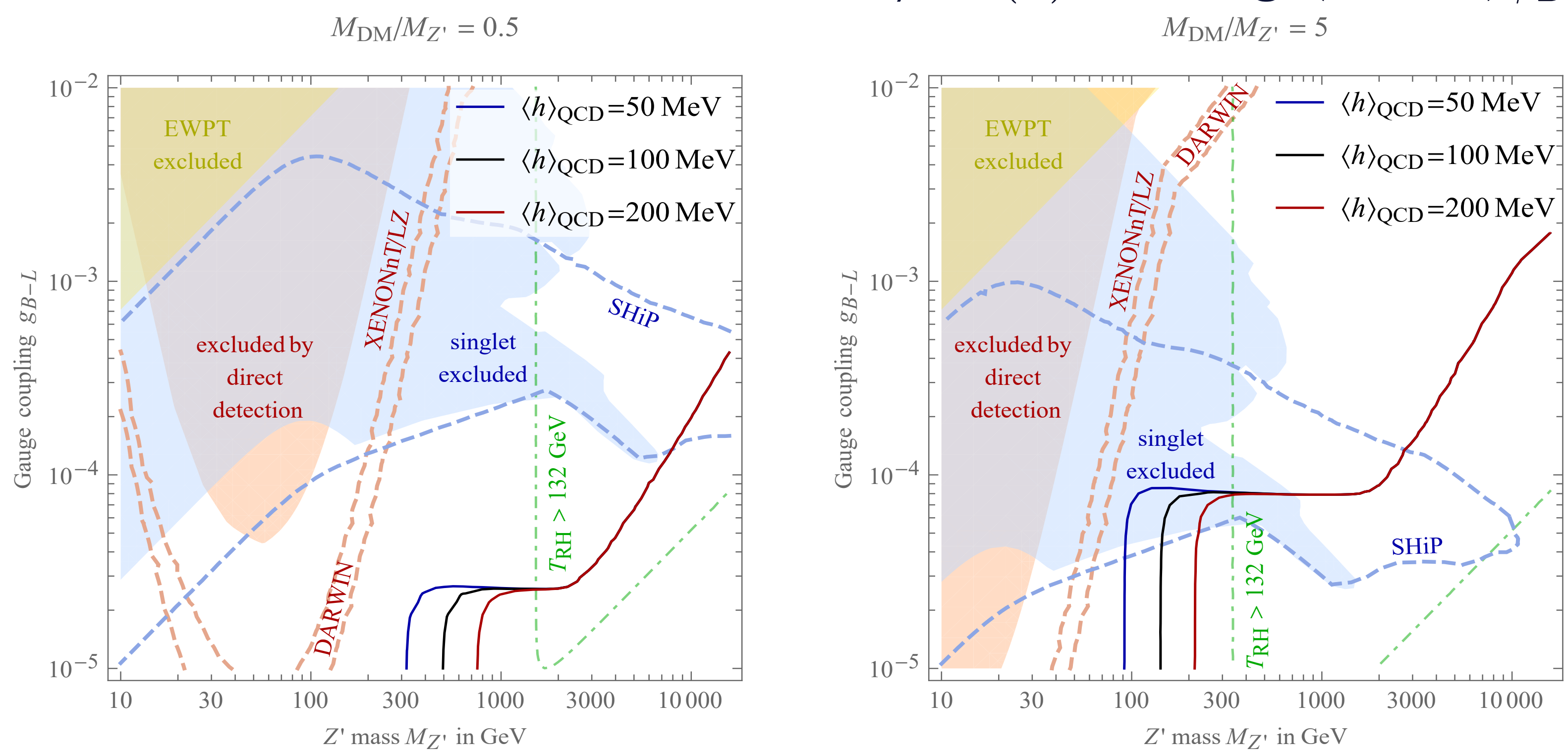
Another example of simple model

simply assume:

- $U(1)_{B-L}$ instead of $SU(2)_X$
- a scalar S charged under $U(1)_{B-L}$ instead of the $SU(2)_X$ doublet

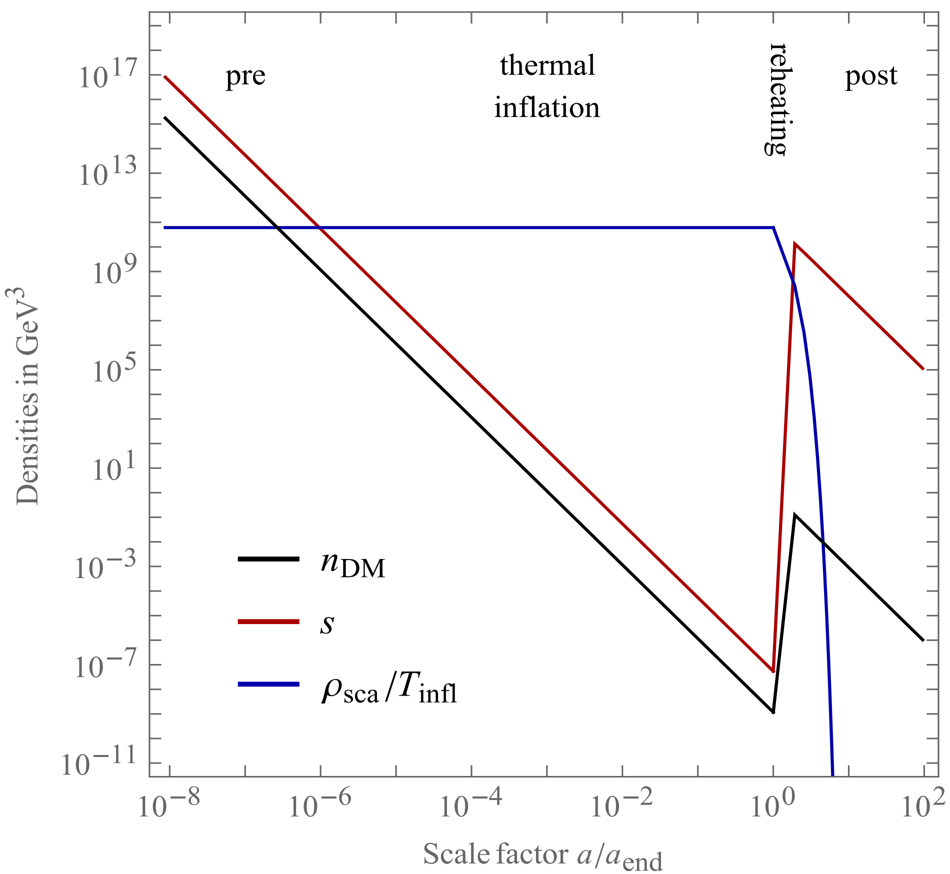
  inducing sym. breaking radiatively and
  neutrino masses/leptogenesis through $\mathcal{L} \ni -Y_N\, S\, \overline{N^c} N + h.c.$

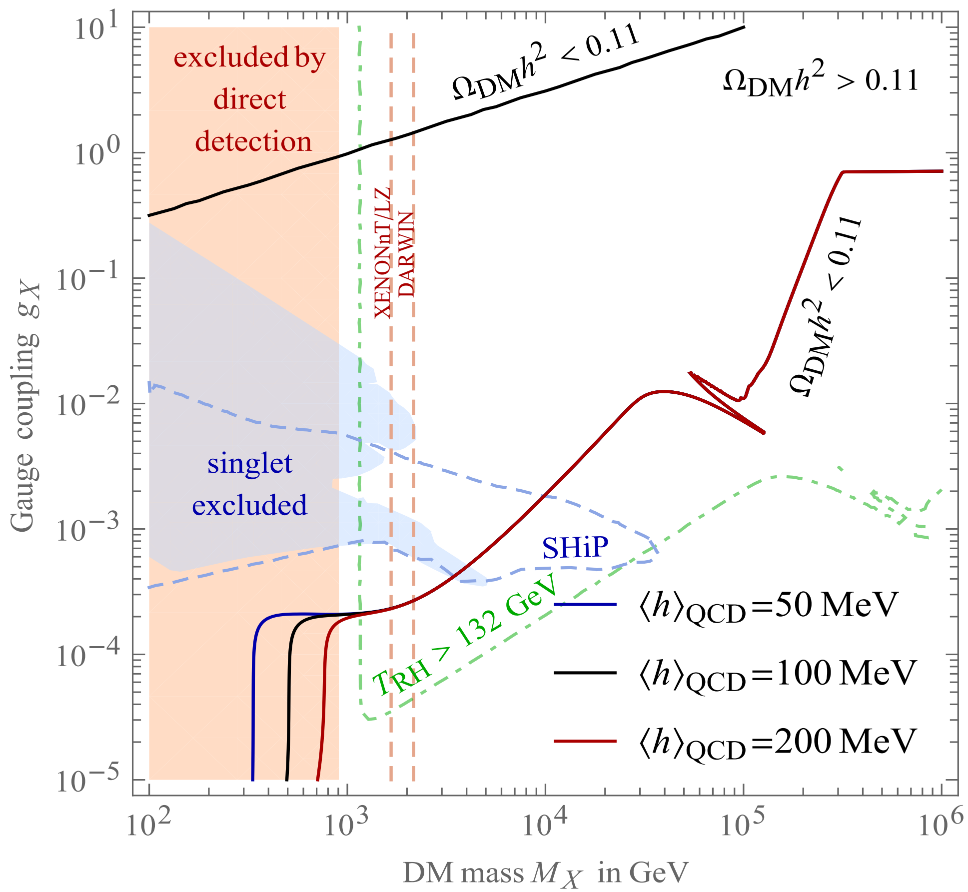
- an extra scalar ϕ_{DM} stabilized by $U(1)_{B-L}$: e.g. $(B-L)_{\phi_{DM}} = 1$



not ruled out by DM direct detection as usual B-L models

Thank you


pre
thermal inflation
reheating
post
10^{17}
10^{13}
10^{9}
10^{5}
10^{1}
10^{-3}
10^{-7}
10^{-11}
Densities in GeV^3
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
Scale factor $a/a_{\rm end}$
$n_{\rm DM}$
s
$\rho_{\rm sca}/T_{\rm infl}$



excluded by direct detection
singlet excluded
SHiP
XENONnT/LZ
DARWIN
$\Omega_{\rm DM}h^2 < 0.11$
$\Omega_{\rm DM}h^2 > 0.11$
$\Omega_{\rm DM}h^2 < 0.11$
TRH > 132 GeV
$\langle h\rangle_{\rm QCD}$=50 MeV
$\langle h\rangle_{\rm QCD}$=100 MeV
$\langle h\rangle_{\rm QCD}$=200 MeV
Gauge coupling g_X
DM mass M_X in GeV