WIMPS and beyond
Supercool Dark Matter

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

PACTS-Tallinn, 19/06/2018

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

from the model building point of view the way the relic density can be accounted for depends crucially on whether DM has thermalized with Standard Model thermal bath during radiation dominated era

if DM has thermalized: straightforward way to account for the 26%:

expected as soon as:
- Universe thermal bath has known a period with $T \sim m_{DM}$
- SM-DM coupling not tiny

$\lambda \gtrsim 10^{-7}$ for $m_{DM} \sim \text{TeV}$

``thermal freeze out scenario''

(``WIMP scenario'')

Thermal freeze out scenario

at $T \gtrsim m_{DM}$: DM in thermal equilibrium with SM thermal bath from e.g. $DM\,DM \leftrightarrow SM\,SM$

at $T \lesssim m_{DM}$: DM Boltzmann suppressed as long as in thermal equilib.

$n_{DM}^{Eq.} \propto e^{-m_{DM}/T}$

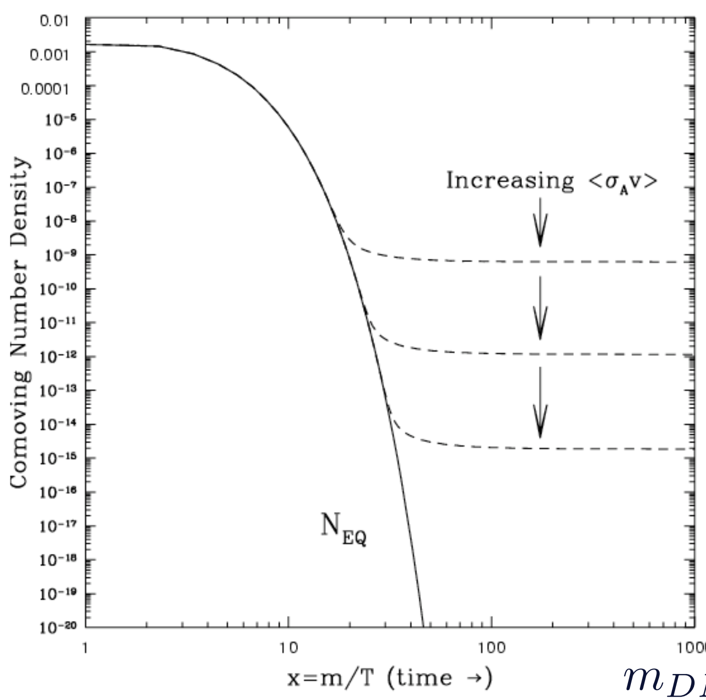
⇓

DM cannot stay for long in thermal equilibrium

once too few DM particles: freezeout of DM particle number

$\Gamma_{annih.} < H$

$\frac{n_{DM}^{Eq}}{s}$



m_{DM}/T

⇒ $\Omega_{DM} \propto 1/\langle\sigma_{annih.} v\rangle$

$\Omega_{DM} \simeq 26\%$ requires $\langle\sigma_{annih.} v\rangle \simeq 10^{-26}\,\mathrm{cm}^3/\mathrm{sec}$

for electroweak couplings or couplings of order unity: $m_{DM} \sim \mathrm{TeV}$

⇒ great perspectives of discovery: direct or indirect detection, or LHC, ...

Should we have seen already the DM particle(s) if thermal????

- it is true that we didn't discover low scale supersymmetry and its neutralino
  - what is maybe surprising is that we didn't discover susy at LHC, but not much the fact that we didn't see the neutralino at DM experiments!
  - even if there is no low scale susy still the DM experimental fact has to be explained!

    it is not because susy is not there that DM is non thermal

    DM experimental fact is there no matter whether it is connected to the hierarchy problem

- it is true that the LHC didn't discover any WIMP
  - but this is not at all a big surprise: most DM WIMP are not easy to see at the LHC

- it is true that so far we didn't discover the DM particle(s) in direct or indirect DM detection experiments

see M. Cirelli talk

Should we have seen already the DM particle(s) in direct detection experiments if thermal????

not necessarily at all:

minimal models where a same interaction governs both the relic density and the direct detection

should have been seen for some of such models

should not have been seen for many other such models

more involved models

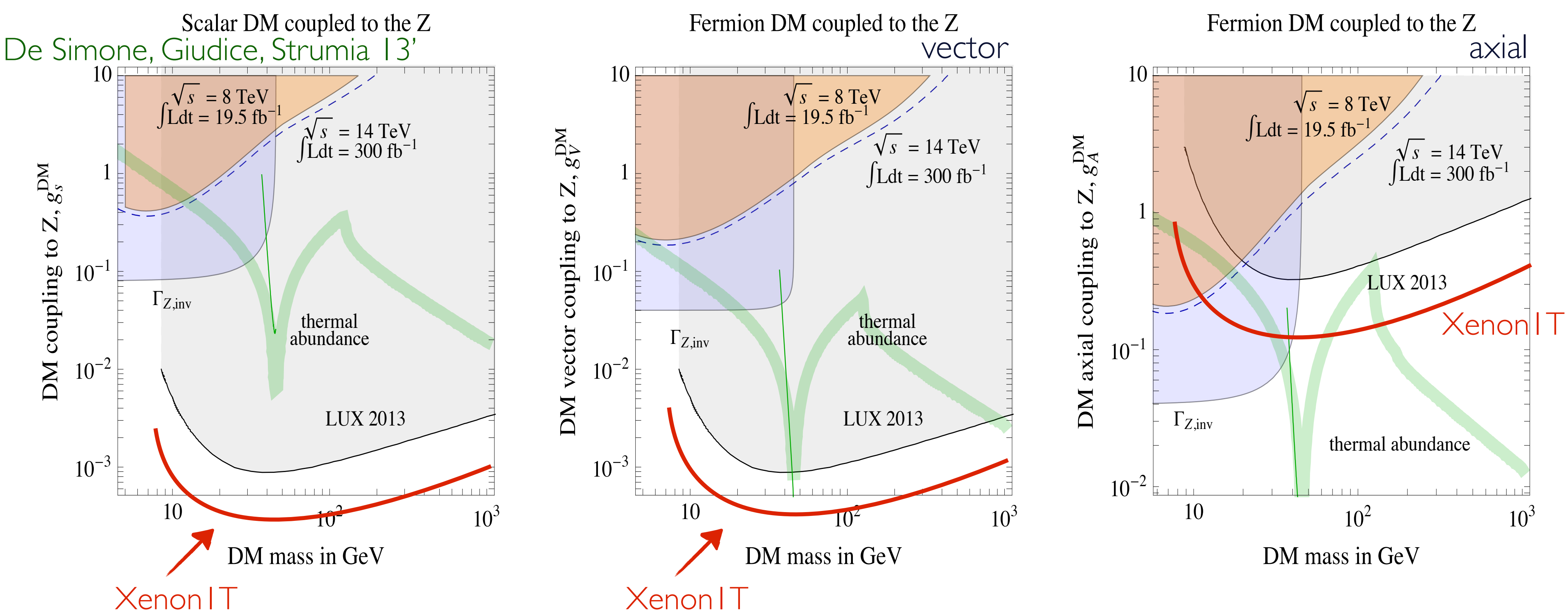
should not have been seen for some of these models

Should we have seen already the DM particle(s) in direct detection experiments if thermal????

example of minimal models already excluded:

DM candidates with hypercharge $Y \neq 0$: direct detection through Z exchange

⇒ lead to far too large direct detection cross section for hypercharge of order unity
still allowed by relic density for high masses for effectively small hypercharge



allowed above $\sim 10\,\text{TeV}$ allowed above $\sim 2\,\text{TeV}$ allowed above $\sim 150\,\text{GeV}$

Should we have seen already the DM particle(s) in direct detection experiments if thermal????

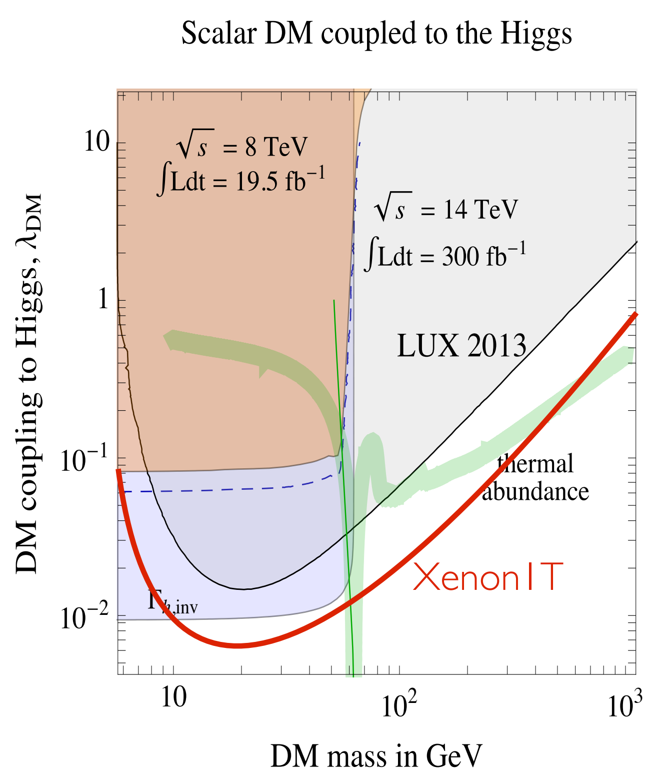
example of minimal models already excluded at low scale but not at high scale:

DM candidates coupling in pairs to h boson: direct detection through h exchange

typically the scalar singlet DM setup: $\mathcal{L} \ni -\lambda_{HS} H^\dagger H S S$

$\Rightarrow$ once this coupling set from relic density constraint: excluded for $m_{DM} \lesssim 500\,\text{GeV}$

(allowed also around $m_{DM} \sim m_h/2$ resonance)



De Simone, Giudice, Strumia 13'

Should we have seen already the DM particle(s) in direct detection experiments if thermal????

example of minimal models not at all excluded by direct detection:

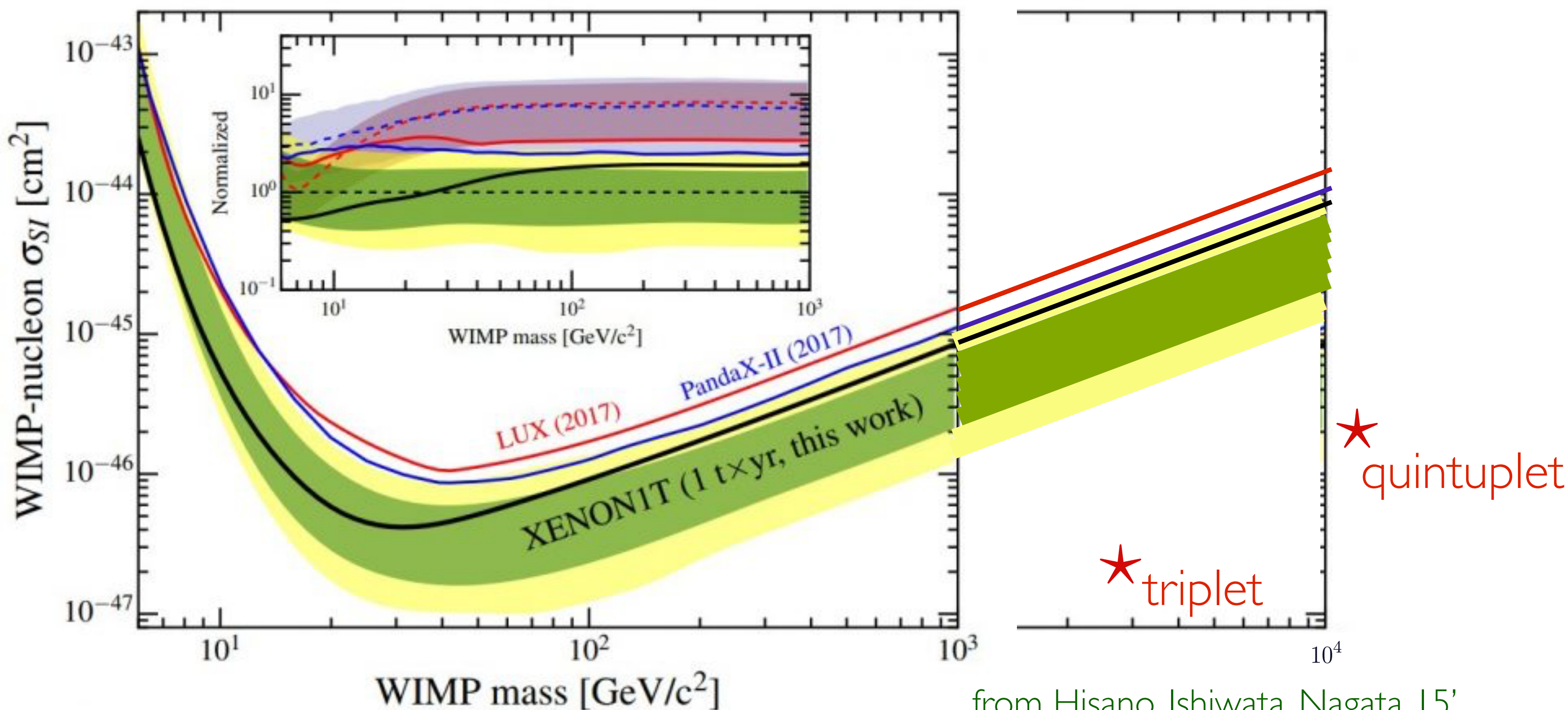
→ if one just adds a $SU(2)_L$ multiplet to the SM

Cirelli, Fornengo, Strumia 05', ...

e.g. a $Y=0$ fermion triplet, quintuplet, ...

``minimal dark matter''

→ relic density determined by SM gauge coupling $\Rightarrow$ m_{DM} fixed



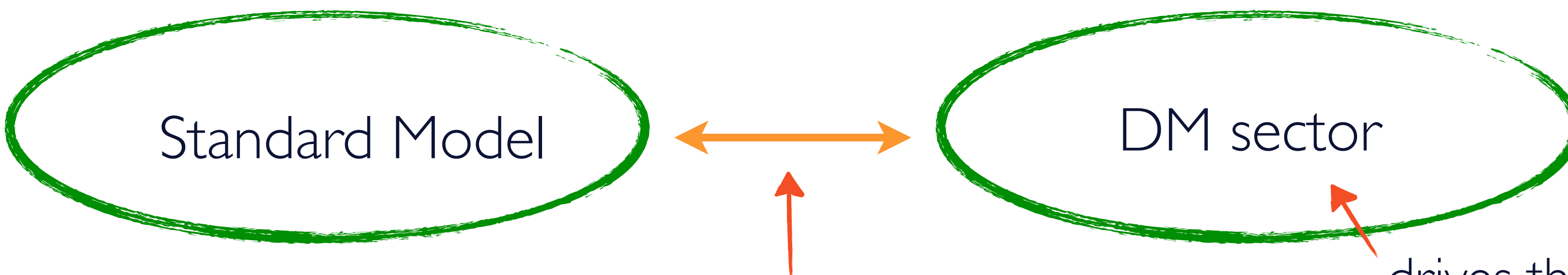
from Hisano, Ishiwata, Nagata 15'
Mitridate, Redi, Smirnov, Strumia 17'
....

see M. Cirelli talk for indirect detection constraints

Should we have seen already the DM particle(s) in direct detection experiments if thermal????

→ as soon as we allow for a looser connection between direct detection and relic density many thermal models could perfectly not have be seen so far

→ e.g. models based on DM sector coupling to the SM sector through a portal



drives the relic detection

portal interaction:

drives the direct detection and thermalization with SM

possible even if portal interaction is large

Super-cool DM

→ *another possibility to get the relic density for a thermal candidate*

→ *another way of n_{DM}/n_γ suppression*

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

Super-cool DM: structure of the models

applies to "dimensionless models":

no mass term to start with in the $\mathcal{L}$

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

↓

spontaneous symmetry breaking induced by radiative corrections: effective potential

Coleman-Weinberg 73'

See also M. Lindner and M. Shaposhnikov talks

Super-cool DM: structure of the models

Standard Model ⟷ a new scalar S charged under a new gauge symmetry

↓

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

↓

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

Super-cool DM: structure of the models

Standard Model ⟷ 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

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

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

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

→ DM are the 3 massive non-abelian gauge bosons

TH 08'
TH, Strumia, 12'

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

→ for example: a $U(1)_{B-L}$ with S a scalar charged under it

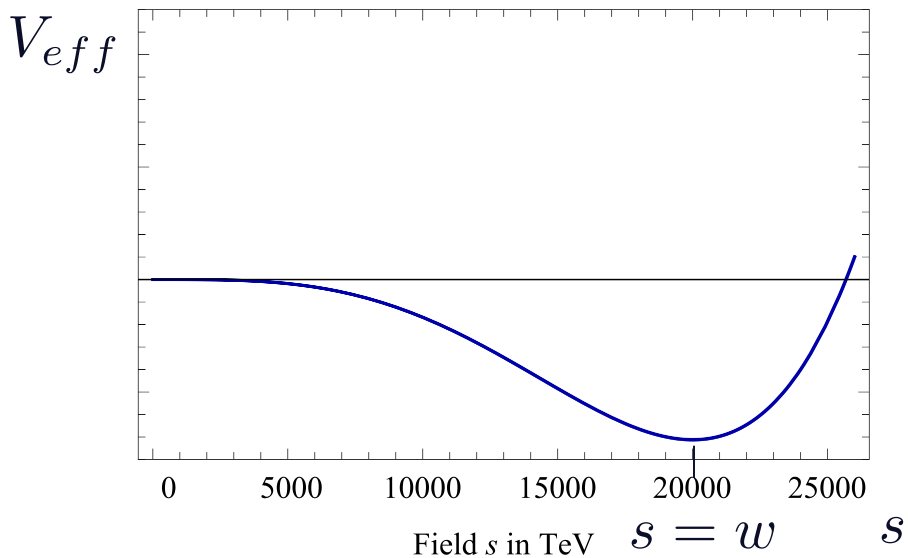
(of charge 2, so that it can also gives neutrino masses and leptogenesis)

→ with DM a scalar ϕ_{DM}

(of charge unity for example so that it is stable)

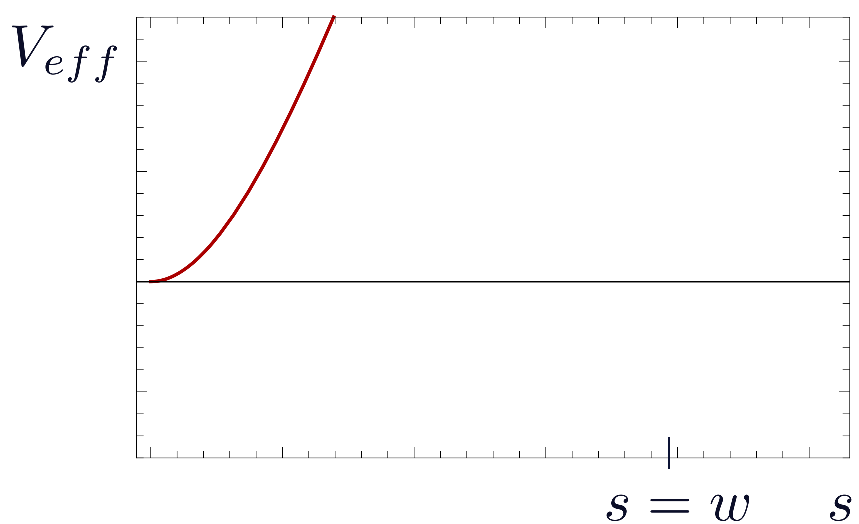
Super-cool DM: thermal evolution of the system

⇒ at $T = 0$:



non trivial minimum:
symmetry breaking

⇒ but at $T >> w$:

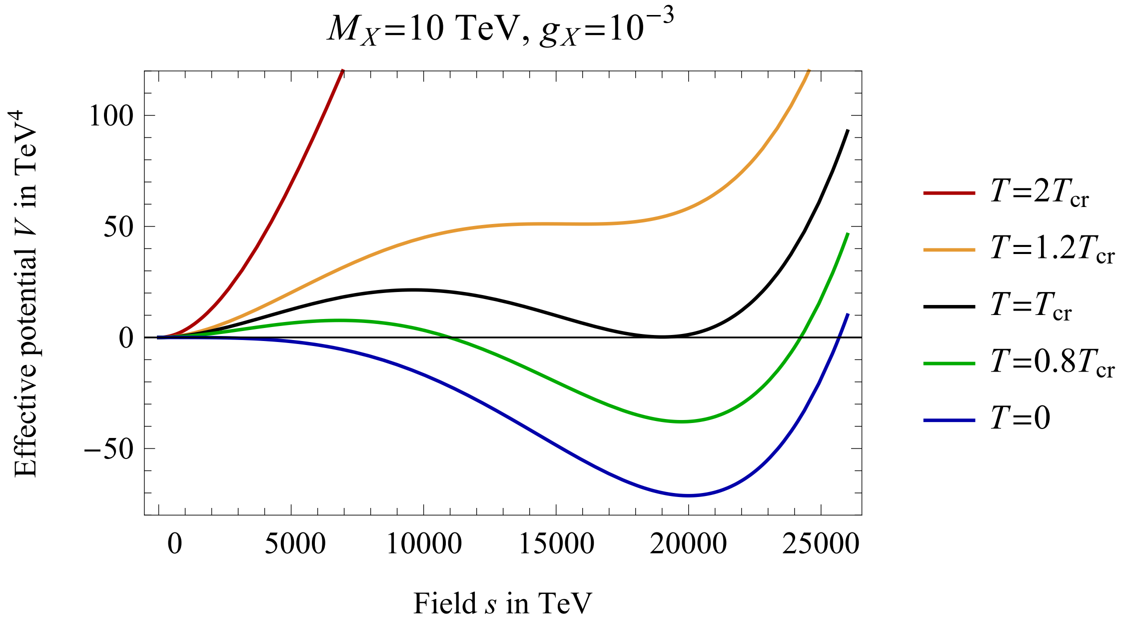


minimum at origin:
no symmetry breaking

Super-cool DM: thermal evolution of the system

⇒ at intermediate T:

at $T = T_{crit}$: 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



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'

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

⇒ $T_{infl} \simeq \dfrac{m_{DM}}{8.5} < T_{crit} < w$

Super-cool DM: thermal evolution of the system

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

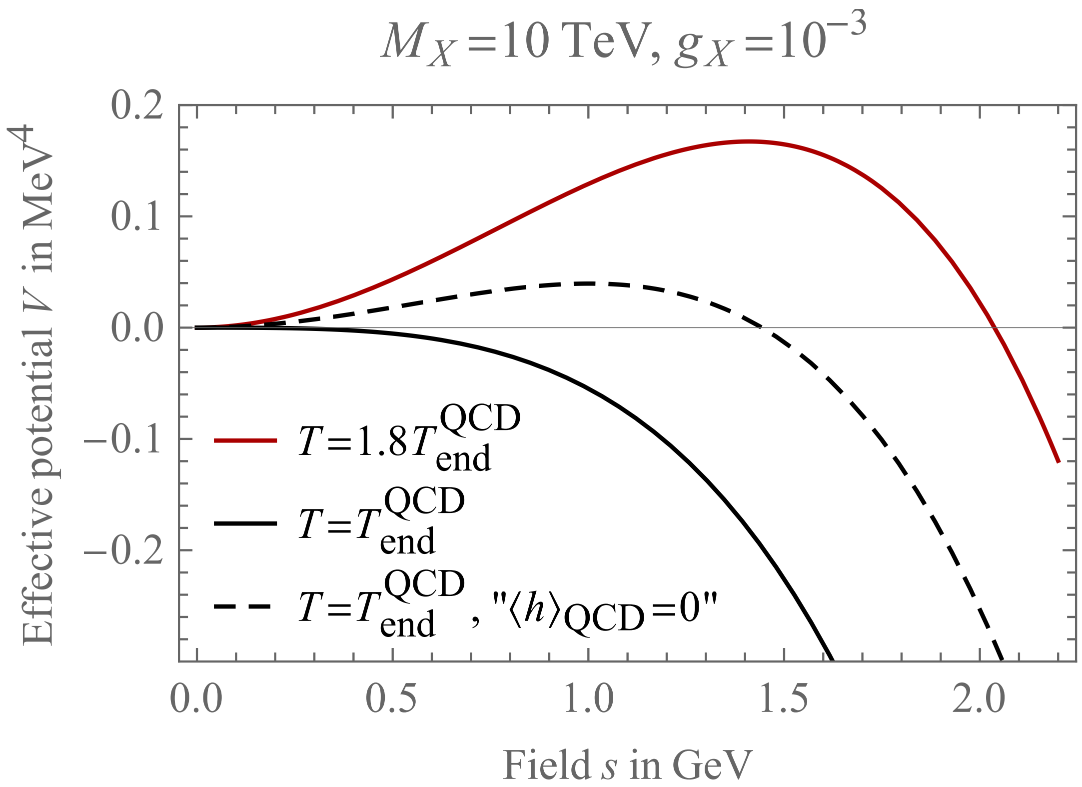
$$V \ni -y_q\, h\, \langle q\bar{q} \rangle$$

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

Witten, ….; Iso, Serpico, Shimada 17'

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

⇒ $T_{end} \sim T_{QCD}^{crit}$



DM relic density: the supercool population

⇒ the DM population which was thermal before thermal inflation remains massless during the thermal inflation period ⇒ no Boltzmann suppression of it, just dilution! ,

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

← $T_{RH} < m_{DM}$

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

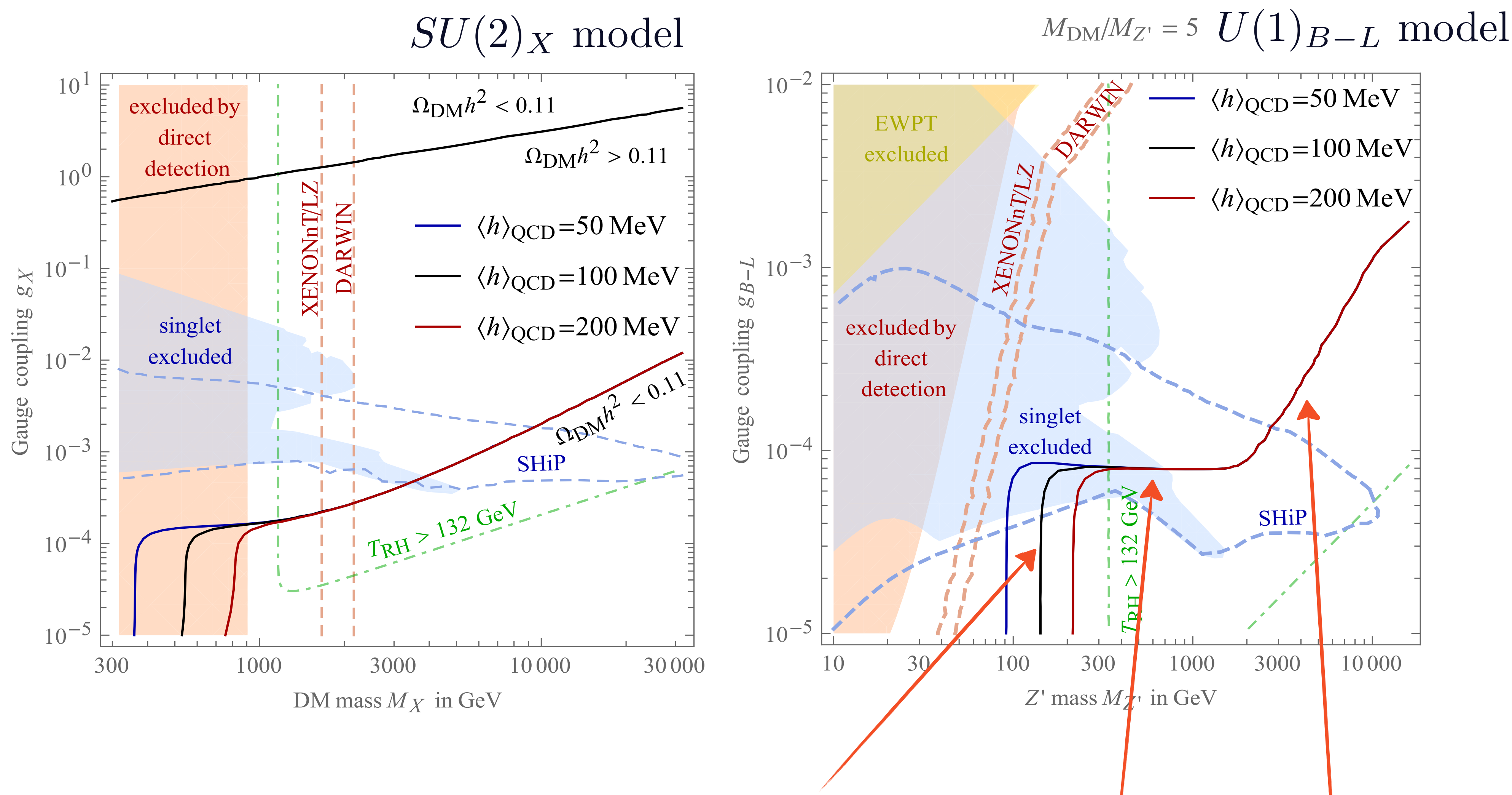
↘ $n_{DM}/n_\gamma \sim 10^{-11}$ $\sim 10\,\text{e-folds}$

DM after reheating doesn't thermalize back because reheating temperature smaller than m_{DM}

↘ still a slow DM pair production in some cases but not too large

⇒ Λ_{QCD} determines end of thermal inflation, which together with $\Omega_{DM} = 26\%$ tell that T_{infl} and so m_{DM} must be few orders of magnitude above which also fits perfectly with the value of the related electroweak scale

DM relic density: final results



super-cool DM population

sub-thermal DM population with instantaneous reheating

sub-thermal DM population with non-instantaneous reheating

Summary

No WIMP discovery so far? Don't worry, be happy…. not much of a surprise so far

↪ clear discovery possibilities for the next years

No WIMP discovery in 10 years from now? still DM could perfectly be thermal but more probably in a way where most likely relic density and direct detection are largely decoupled

Super-cool DM:

another way of suppressing the DM relic density to the right amount

↪ based on the assumption of scale invariance

↪ based on a very minimal set of parameters everything works impressively well:
- chronologically through the many steps
- numerically

Backup: more details from another talk

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 $m_{DM} \sim \mathrm{TeV}$

⇒ more generally a new population of DM particles can be created from thermal bath after end of inflation/reheating, which is also naturally suppres-sed because the reheating temperature obtained is below the DM mass

An explicit example model

Standard Model

a new scalar S charged under a new gauge symmetry

↓

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

↓

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

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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

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

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

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

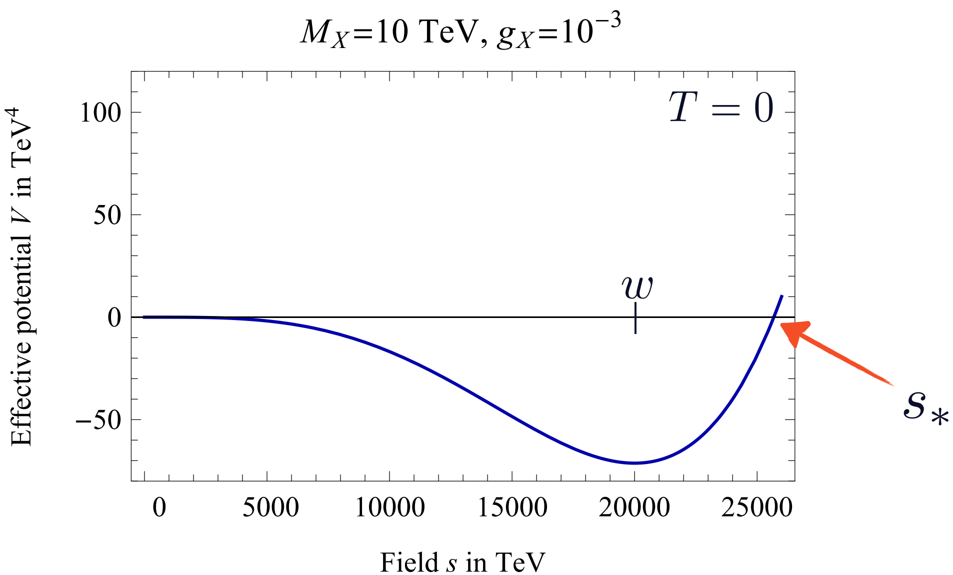
⇒ DM are the 3 massive non-abelian gauge bosons which drive the symmetry breaking

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 $v = 246\,\text{GeV}$ and $m_h = 125\,\text{GeV}$ the model has only 2 parameters

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

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

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

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

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

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

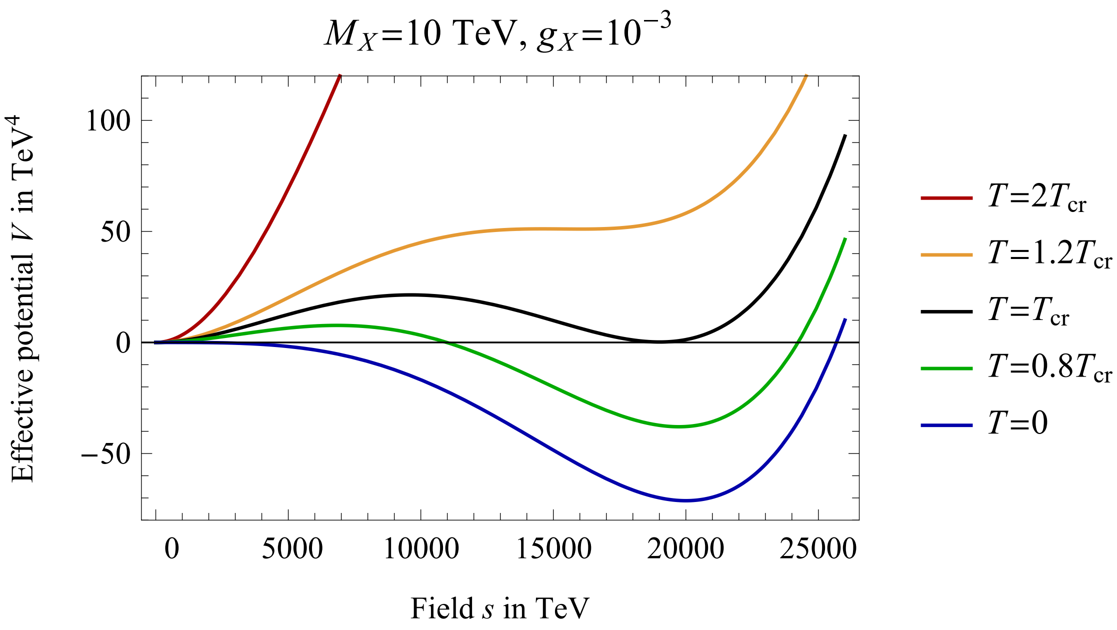
$$M_h^{2T} = \left(\frac{3}{16} g_2^2 + \frac{1}{16} g_Y^2 + \frac{1}{4} y_t^2 + \frac{1}{2}\lambda_H\right) T^2$$

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



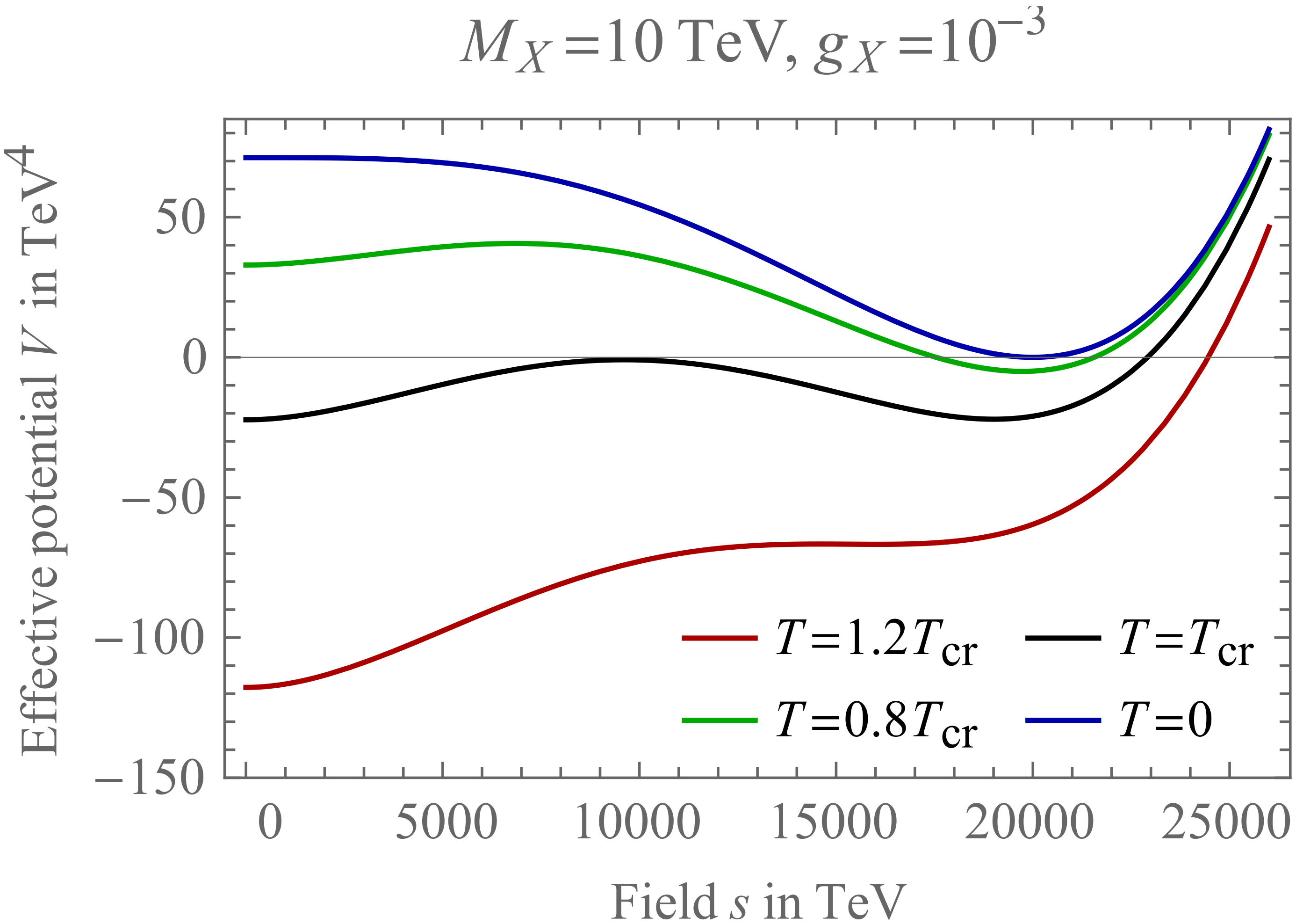
at $T = T_{infl} < T_{crit}$: inflation starts when $\rho_{rad} = \dfrac{g_* \pi^2 T_{infl}^4}{30} < \rho_\Lambda = V_\Lambda$

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

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

Start of supercool period

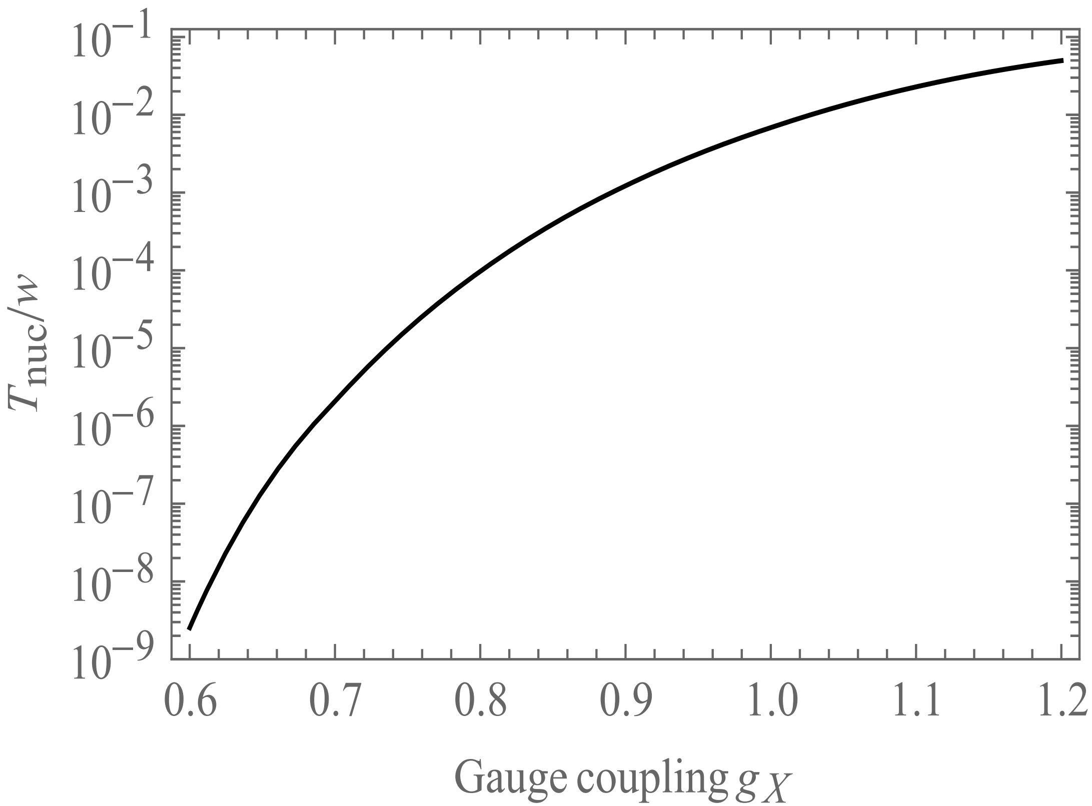
true potential (not shifting it to have $V = 0$ in $s = 0$):



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

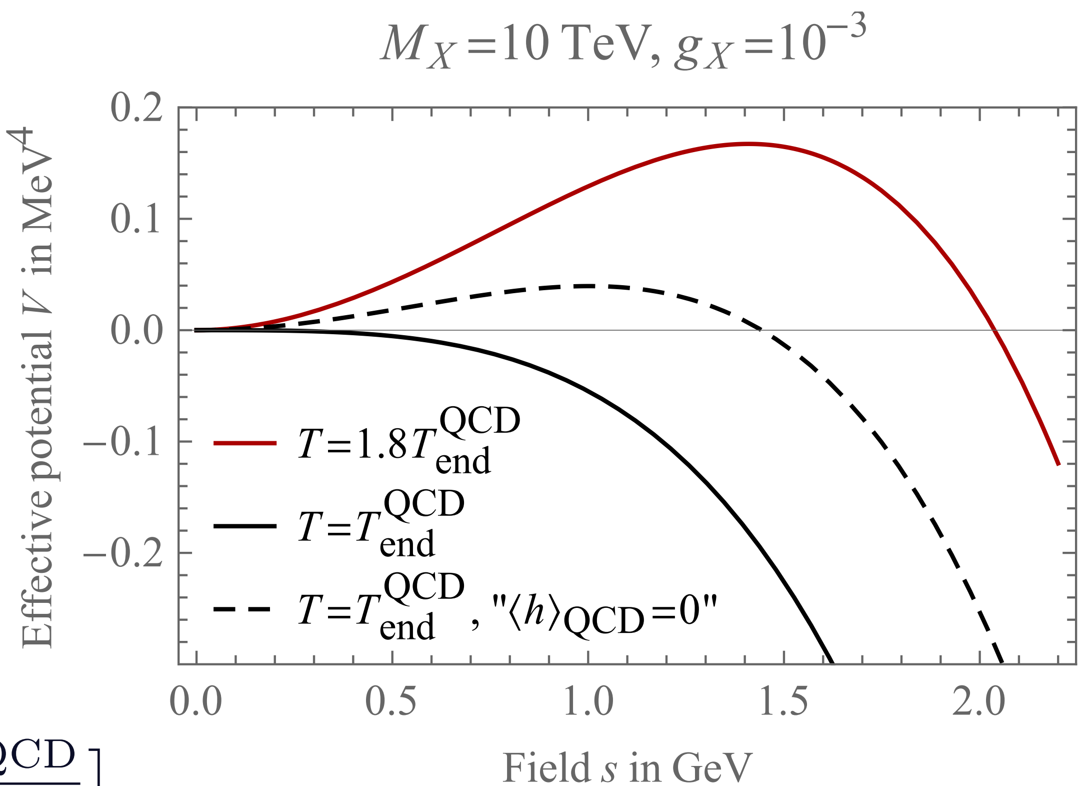
⇒ unless gauge coupling very close to unity, the super cool period does not end at T_{nuc} but earlier at the QCD phase transition: $T_{cr}^{QCD} \sim 85\,\mathrm{MeV}$ ← massless quarks

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

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

Witten, ...; Iso, Serpico, Shimada 17'

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

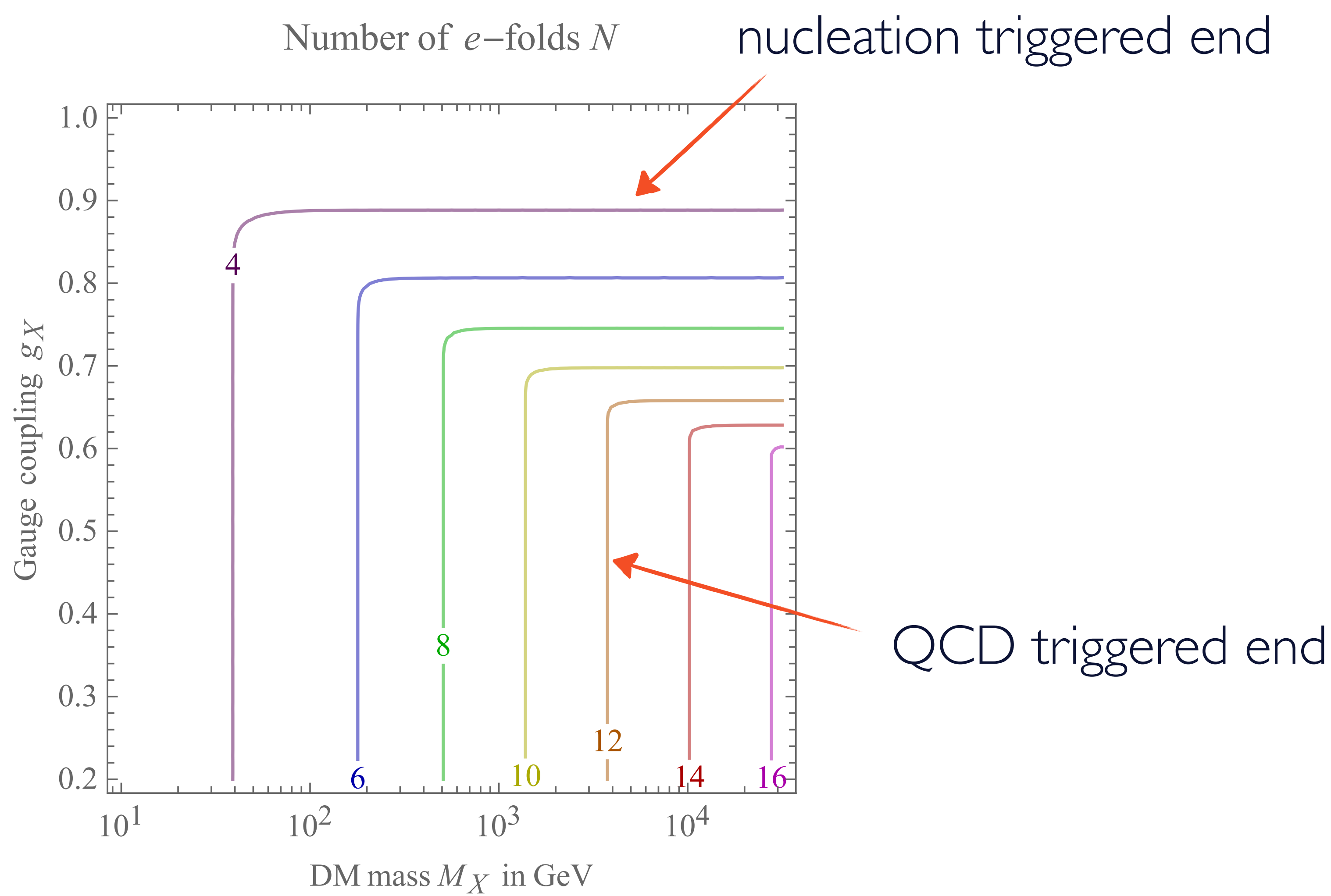


$$\Rightarrow T_{\rm end} = \mathrm{Min}\left[T_{\rm cr}^{\rm QCD}, \frac{0.1\,\langle h\rangle_{\rm QCD}}{M_X/\mathrm{TeV}}\right]$$

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

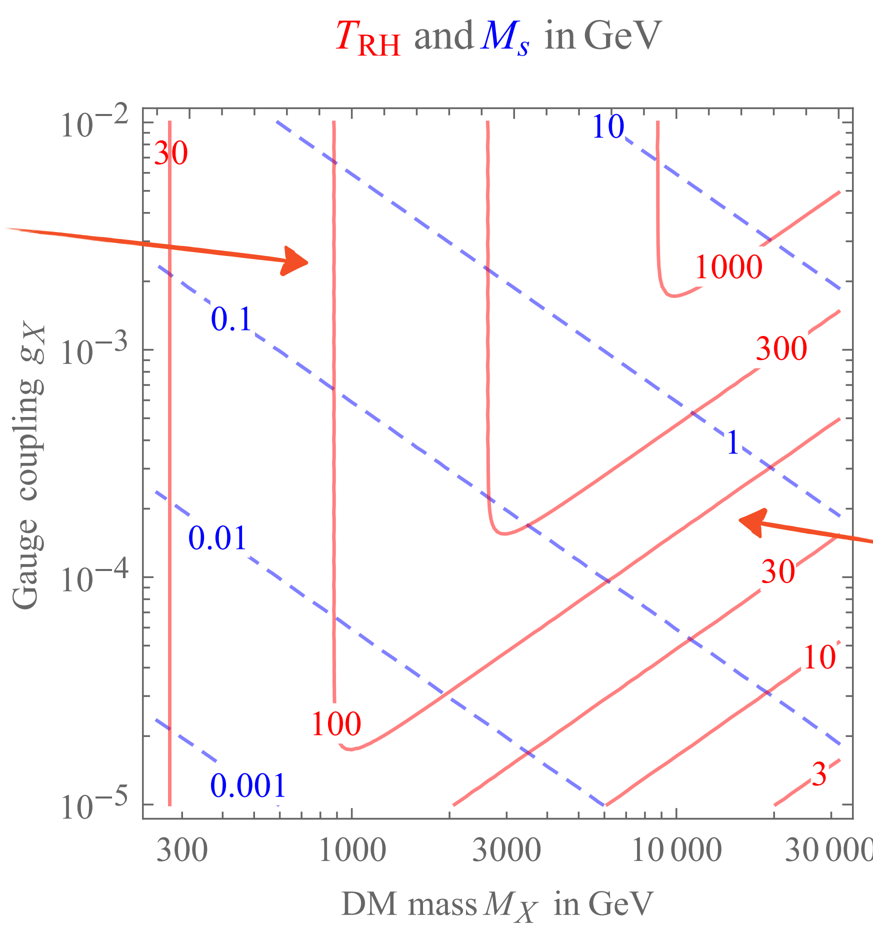
$s \to SM\,SM$

$h \to SMSM$

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

⇓

DM standard freezeout

⇓

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

TH, Strumia 13'

↪ leads to WIMP miracle

DM relic density: standard freezeout case

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$\Downarrow$

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$\Downarrow$

TH, Strumia 13'

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the 'cool miracle' !

(not super-cool, just cool)

DM relic density: the super cool thing!

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

$\Downarrow$

DM standard freezeout

$\Downarrow$

TH, Strumia 13'

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

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 $T_{RH} < m_{DM}$ 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!

⇒ super-cool DM population:

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

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

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

↑ $\sim 10\,$e-folds

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$\sim 10\,$e-folds

the 'super-cool miracle' !

(not only just cool !)

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

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

DM relic density: the sub-thermal DM population

⇒ possible additional sub-thermal population

↪ DM pair production from thermal bath if g_X not too small

↑ suppressed because created from tail of distribution of thermal bath particles

$T_{RH} < m_{DM}$

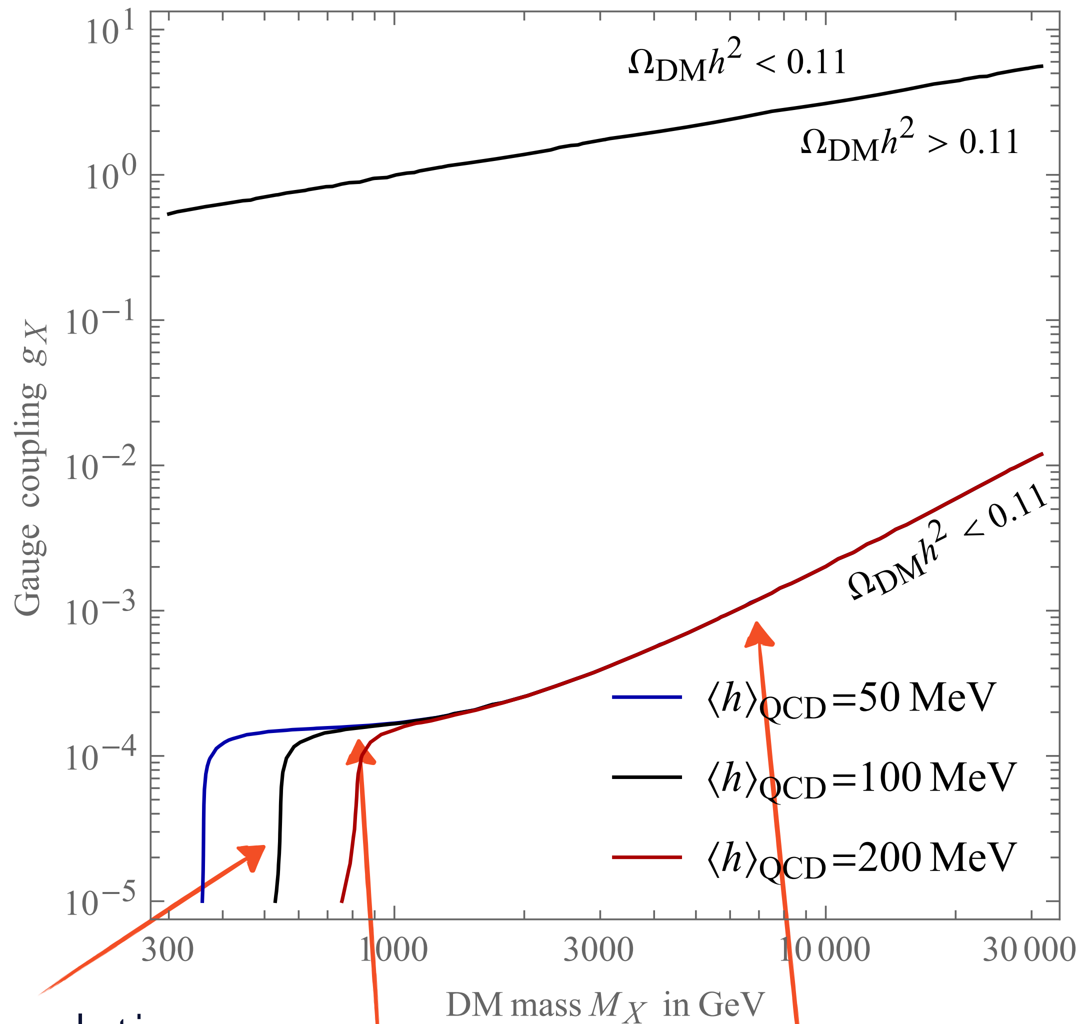
⇒ solving:

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

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

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

DM relic density: final results

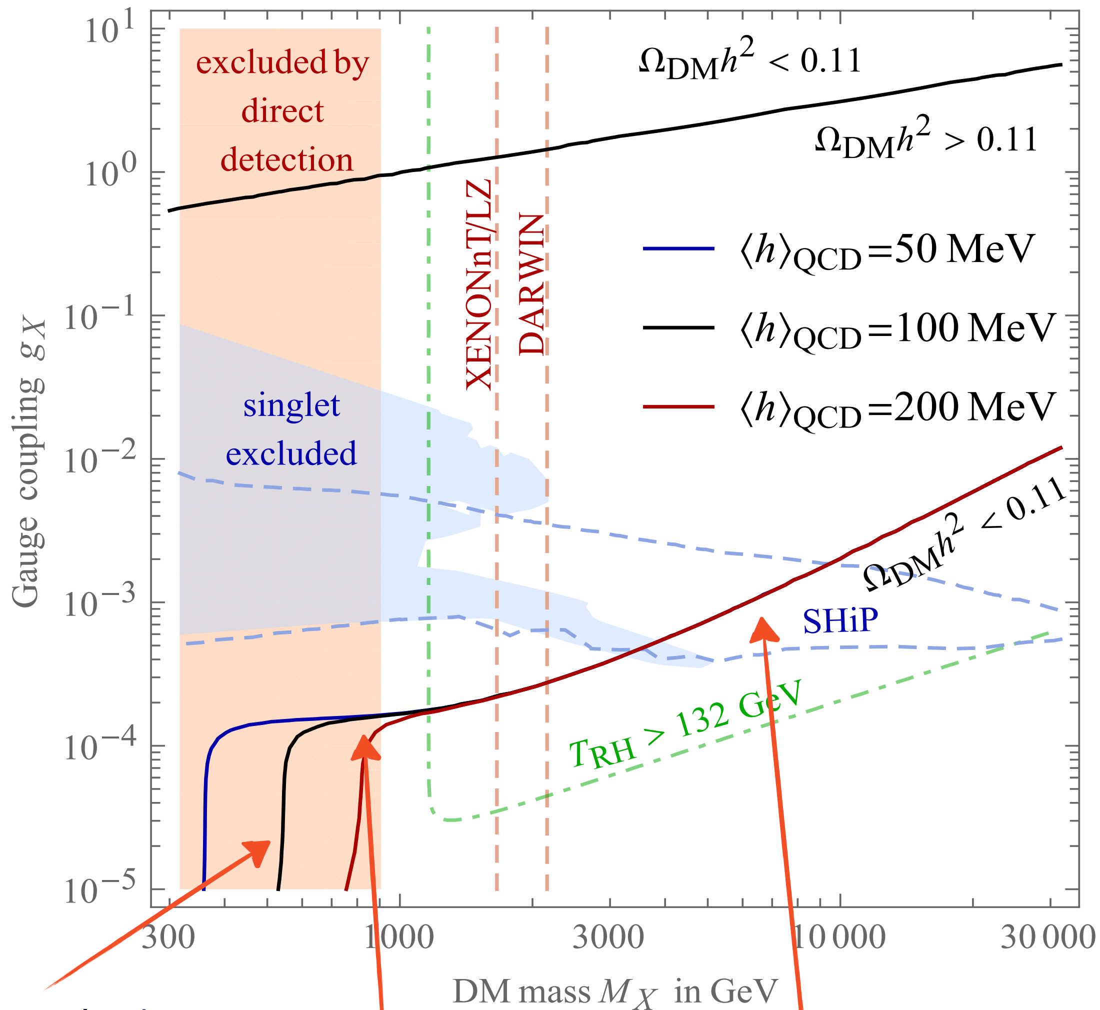


super-cool DM population

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

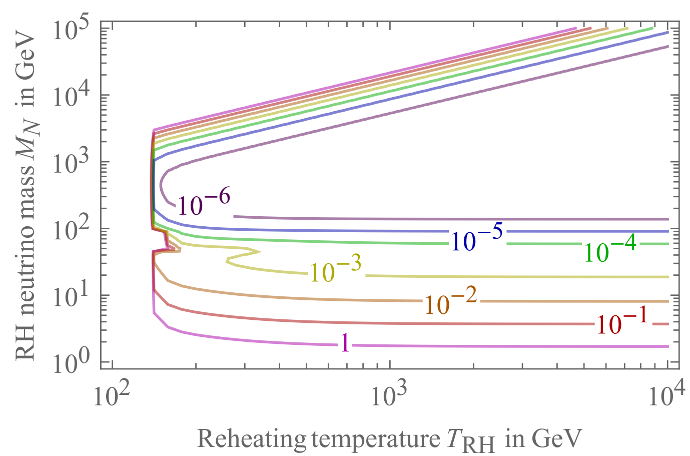
⇒ leptogenesis: possible because $T_{RH} > T_{sphaler.} \sim 132\,\mathrm{GeV}$ is possible

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'



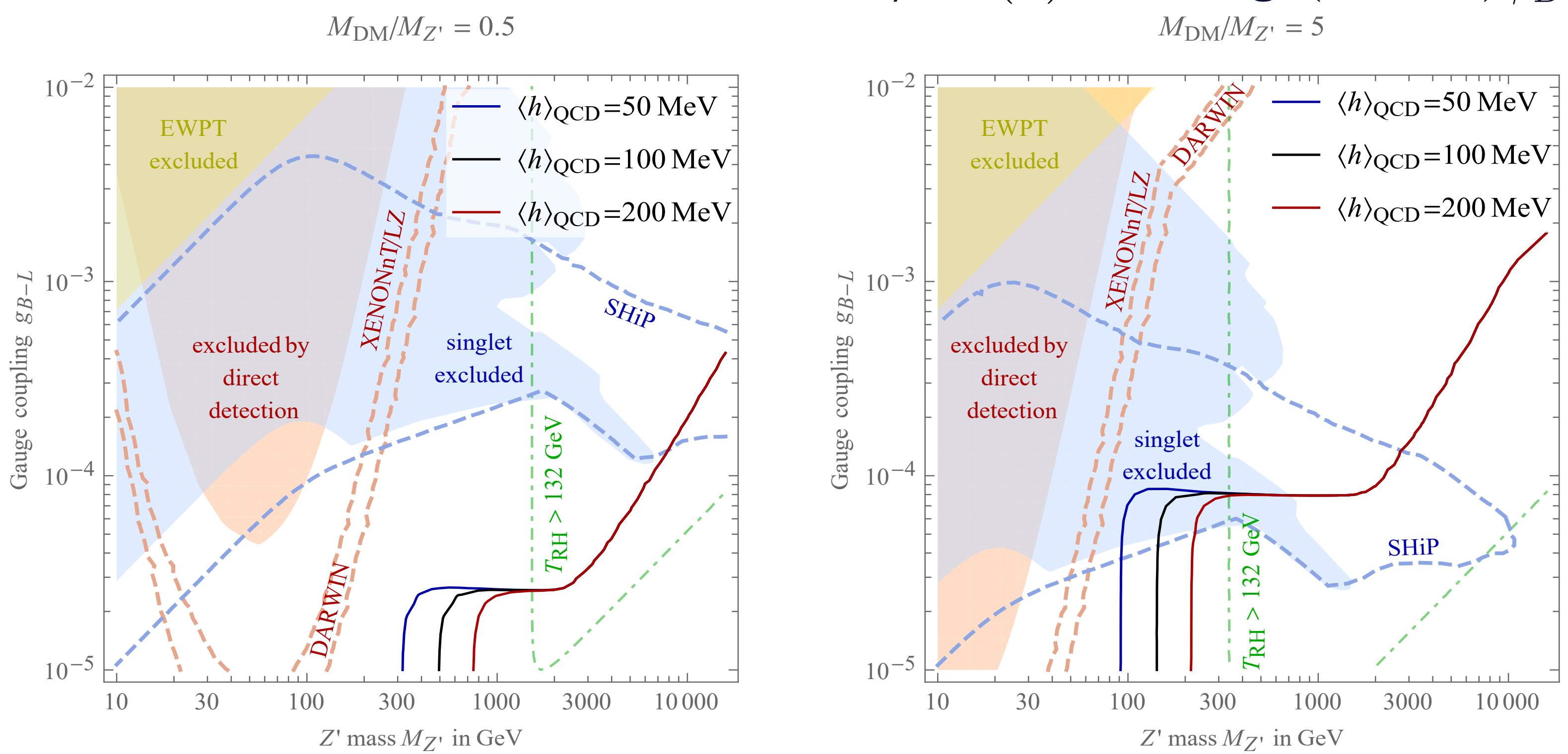
Another example of simple model

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