# New effects in dark matter production
## Sommerfeld, bound states, conversion and all that

Stefan Vogl

based on:
Phys.Rev. D96 (2017) no.10, 103521 [arxiv:1705.09292]
JHEP 1902 (2019) 016 [arxiv:1811.02581]
and work in progress

in collaboration with:
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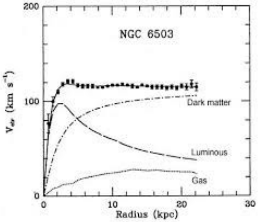
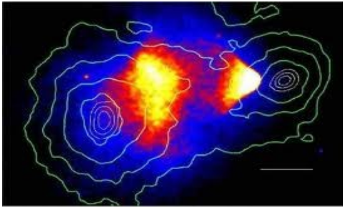
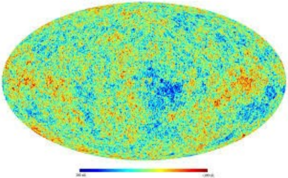
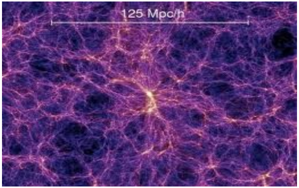
# What we know








gravitational evidence for dark matter on all scales: rotation curves, clusters, large scale structure, CMB

$$\Omega h^2 \approx 0.12$$

# What we don’t know

- gravitational signatures do not provide any information about the nature of dark matter as a particle
- interactions with SM are highly uncertain
- will need different experiments and observations to determine properties of dark matter

Where should we look?

- your favorite BSM model
- under the lamp post
- ...

# Taking a hint from cosmology

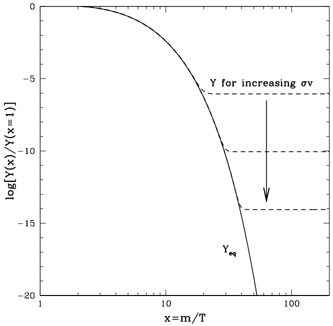
$$\mathrm{d}n_\chi/\mathrm{d}t + 3Hn_\chi = C$$

- ingredients:
  - interactions of dark matter
  - evolution of the universe
  - initial conditions
- the production mechanism sets key aspects of DM phenomenology

here: focus on interactions

# Thermal freeze-out

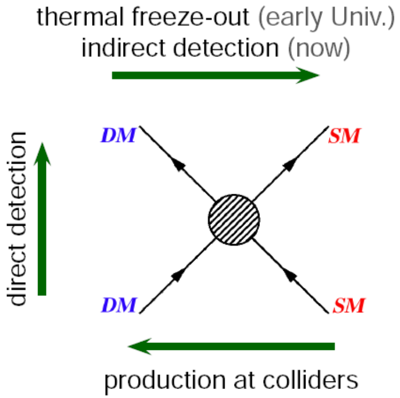
- universe starts at a high temperature
- dark matter part of plasma and in thermal equilibrium
- universe expands and cools
- once $m_{DM} \gtrsim T$ interactions rate becomes suppressed $\rightarrow$ DM drops out of thermal equilibrium



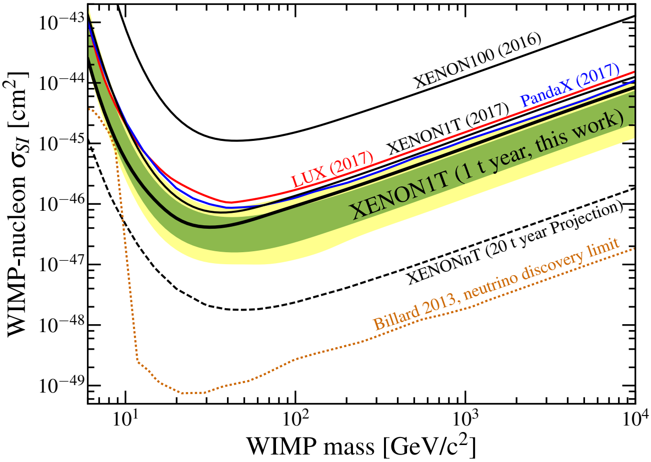

$$\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\langle\sigma_{\chi\chi}v\rangle\left(Y_\chi^2 - Y_\chi^{\mathrm{eq}\,2}\right)\right]$$

$\sigma v \approx 2 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}$ weak scale cross section

# Thermal dark matter

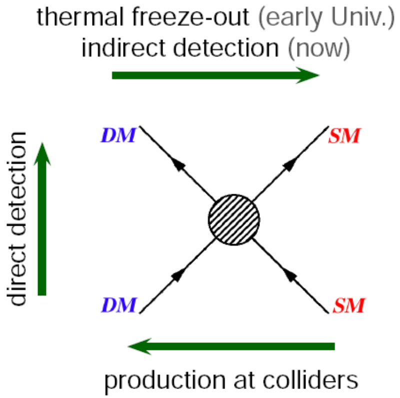


# Direct detection limits




XENON1T 2018

# Thermal dark matter

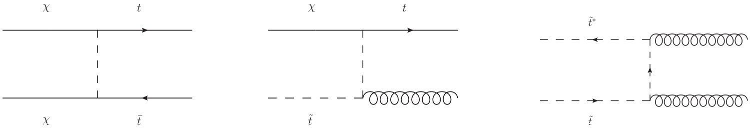



Direct detection limits very stringent. Models with simple crossing symmetry are getting in trouble.

$\Rightarrow$ simple crossing symmetry too simple?

# Coannihilations

For light mediators ($\Delta m_{med} \leq 1.2 m_{DM}$) coannihilation matters during freeze-out




Griest Seckel 1991

- want big cross sections for coannihilation partners $\rightarrow$ colour charge them

# Models for coloured coannihilations

- Majorana fermion dark matter $\chi$ and scalar quark partner $\eta$

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\text{SM}} + \frac{1}{2}\,\bar{\chi}\left(i\not{\partial} - M_\chi\right)\chi + (D_\mu\eta)^\dagger D^\mu\eta - M_\eta^2\,\eta^\dagger\eta - \lambda_2(\eta^\dagger\eta)^2 \\ &- \lambda_3\,\eta^\dagger\eta\,H^\dagger H - y\,\eta^\dagger\bar{\chi}P_R q - y^*\bar{q}P_L\chi\,\eta\,,\end{aligned}$$

- simplified t-channel model with fermionic mediator

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\text{SM}} + \frac{1}{2}\partial_\mu S\partial^\mu S - \frac{M_S^2}{2}\,S^2 - \frac{\lambda_2}{4!}S^4 - \frac{\lambda_3}{2}\,S^2\,H^\dagger H \\ &+ \bar{F}\left(i\not{D} - M_\chi\right)F - y\,S\bar{F}P_R q - y^* S\bar{q}P_L F\quad,\end{aligned}$$

- fermionic dark matter with color octet fermion partner

$$\mathcal{L} = ...$$

- ...

qualitative features model independent

# Dark sector annihilations

$$\begin{aligned}
\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} &= \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\Bigg[\langle\sigma_{\chi\chi}v\rangle\left(Y_\chi^2 - Y_\chi^{\mathrm{eq}\,2}\right) + \langle\sigma_{\chi\tilde{q}}v\rangle\left(Y_\chi Y_{\tilde{q}} - Y_\chi^{\mathrm{eq}}Y_{\tilde{q}}^{\mathrm{eq}}\right) \\
&\quad + \frac{\Gamma_{\chi\to\tilde{q}}}{s}\left(Y_\chi - Y_{\tilde{q}}\frac{Y_\chi^{\mathrm{eq}}}{Y_{\tilde{q}}^{\mathrm{eq}}}\right) - \frac{\Gamma_{\tilde{q}}}{s}\left(Y_{\tilde{q}} - Y_\chi\frac{Y_{\tilde{q}}^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right) + \langle\sigma_{\chi\chi\to\tilde{q}\tilde{q}^\dagger}v\rangle\left(Y_\chi^2 - Y_{\tilde{q}}^2\frac{Y_\chi^{\mathrm{eq}\,2}}{Y_{\tilde{q}}^{\mathrm{eq}\,2}}\right)\Bigg] \\
\frac{\mathrm{d}Y_{\tilde{q}}}{\mathrm{d}x} &= \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\Bigg[\frac{1}{2}\langle\sigma_{\tilde{q}\tilde{q}^\dagger}v\rangle\left(Y_{\tilde{q}}^2 - Y_{\tilde{q}}^{\mathrm{eq}\,2}\right) + \langle\sigma_{\chi\tilde{q}}v\rangle\left(Y_\chi Y_{\tilde{q}} - Y_\chi^{\mathrm{eq}}Y_{\tilde{q}}^{\mathrm{eq}}\right) \\
&\quad - \frac{\Gamma_{\chi\to\tilde{q}}}{s}\left(Y_\chi - Y_{\tilde{q}}\frac{Y_\chi^{\mathrm{eq}}}{Y_{\tilde{q}}^{\mathrm{eq}}}\right) + \frac{\Gamma_{\tilde{q}}}{s}\left(Y_{\tilde{q}} - Y_\chi\frac{Y_{\tilde{q}}^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right) - \langle\sigma_{\chi\chi\to\tilde{q}\tilde{q}^\dagger}v\rangle\left(Y_\chi^2 - Y_{\tilde{q}}^2\frac{Y_\chi^{\mathrm{eq}\,2}}{Y_{\tilde{q}}^{\mathrm{eq}\,2}}\right)\Bigg]
\end{aligned}$$

coupled Boltzmann equations with annihilation, co-annihilation and conversion terms

# Effective cross section

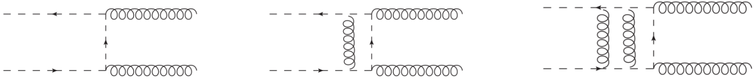
for sufficiently fast conversion rate system simplifies

$$\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\langle\sigma_{\chi\chi}v\rangle_{eff}\left(Y_\chi^2 - Y_\chi^{\mathrm{eq}\,2}\right)\right]$$

where

$$\sigma v_{eff} \approx \sigma_{\chi\chi}v + \sigma_{\chi\eta}v\, e^{-\Delta m/T} + \sigma_{\eta\eta}v\, e^{-2\Delta m/T}$$

# Sommerfeld effect



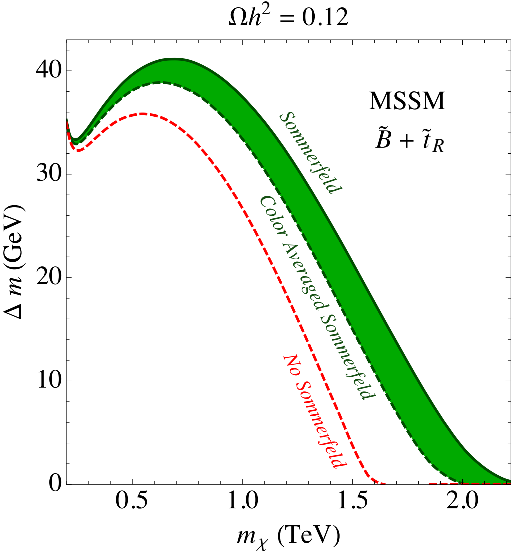
- exchange of long-range mediator leads to non-perturbative modification of annihilation rates Hisano at al '05
- intuitive description: distortion of the wave-function due to potential
- extract wave function from non-relativistic Schrödinger equation with Coulomb potential

$$V(r) = \frac{\alpha}{r} \quad \Rightarrow \quad S = \frac{-\pi\alpha/\beta}{1 - \exp^{\pi\alpha/\beta}} \quad \text{with} \quad \beta = v/2$$

De Simone et al '14, Ibarra, Pierce, Shah, SV '15

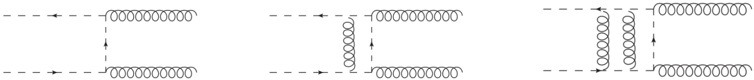
- effect large for large $\alpha$ and small $\beta$ (i.e. long time)

# Relic density with Sommerfeld




Ibarra, Pierce, Shah, SV '15

# more non-perturbative effects



need to treat long range interactions in thermal background

- Sommerfeld enhancement Hisano et al '05
- bound state formation von Harling, Petraki '14
- thermal background

complicated problem but similarities with heavy quarkonium in medium

$\rightarrow$ re-purpose tools for quarkonium at finite temperature
use non-relativistic effective field theories (NREFT)

# NREFT for coannihilations in a nutshell I

non-relativistic EFT

- factorize hard process from initial state effects (non-relativistic EFT, essentially $1/M_\eta$ expansion)
- $\sigma v = \sum_i c_i \langle \mathcal{O}_i \rangle_T$ (thermal expectation value of NREFT operators)
- $\langle \mathcal{O}_i \rangle_T$ can expressed in terms of spectral functions $\rho$

Kim, Laine '16, Biondini, Laine '18

$$\langle \mathcal{O}_i \rangle_T = e^{-2M_\chi/T} \left( \frac{M_\chi T}{\pi} \right)^{\frac{3}{2}} \int_{-\Lambda}^{\infty} \frac{dE'}{\pi} e^{-E'/T} \rho_i(E')$$

# NREFT for coannihilations in a nutshell II

spectral functions

- spectral function can be extracted from solution of plasma modified Schrödinger equation

$$\left[H_T - i\Gamma_T(r) - E'\right] G_i(E'; \boldsymbol{r}, \boldsymbol{r}') = N_i\, \delta^{(3)}(\boldsymbol{r} - \boldsymbol{r}')\,, \qquad (1)$$

$$\lim_{\boldsymbol{r},\boldsymbol{r}' \to \boldsymbol{0}} \mathrm{Im} G_i(E'; \boldsymbol{r}, \boldsymbol{r}') = \rho_i(E')\,, \qquad (2)$$

- thermal potentials $V_T$ for static charges and interaction rates with plasma constituents $\Gamma_T$
- derive potentials in pNREFT (i.e. EFT with degrees of freedom $M_\eta v$ integrated out)
- most relevant effects: Debye screening (thermal gluon mass), Landau damping and gluo-dissociation

# After the dust settles

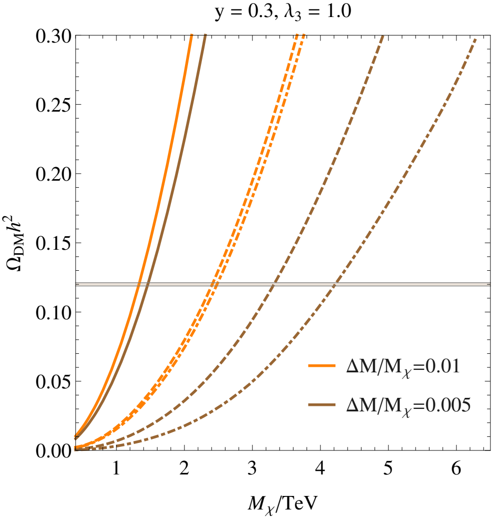
- effective thermally averaged annihilation cross section

$$\langle \sigma_{\rm eff} v \rangle = \frac{2c_1 + 4c_2 N_c e^{-\Delta M_T/T} + N_c \left[ c_3 \bar{S}_3 + c_4 \bar{S}_4 C_F + 2c_5 \bar{S}_5 (N_c + 1) \right] e^{-2\Delta M_T/T}}{(1 + N_c e^{-\Delta M_T/T})^2}$$

- $c_i$ are coefficients of NREFT
- generalized Sommerfeld factors

$$\bar{S}_i = \left( \frac{4\pi}{M_\chi T} \right)^{\frac{3}{2}} e^{\frac{2\Delta M_T}{T}} \int_{-\Lambda}^{\infty} \frac{dE'}{\pi} e^{-E'/T} \frac{\rho_i}{N_i} \, .$$

# Relic density

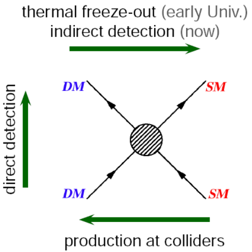



Biondini, SV '18

significant shifts in relic density

# NREFT meets pheno

use precise prediction for thermal production to predict experimental signatures

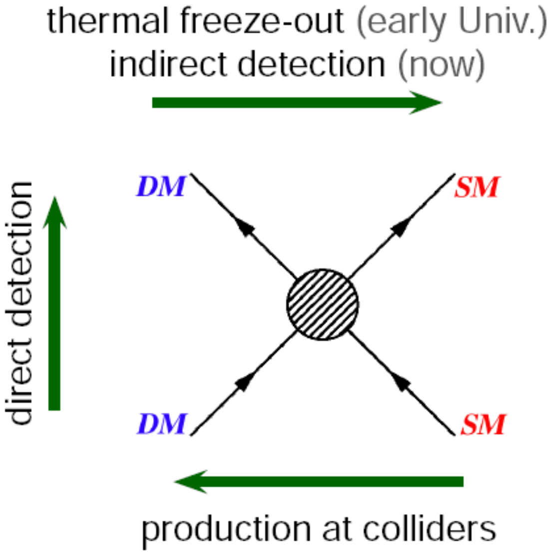



Test it with

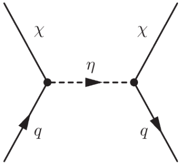
- ID: suppressed $\sigma v$ ✗
- LHC searches: ✗ (✓)
- DD: guaranteed for colored mediators ✓

# NREFT meets pheno

use precise prediction for thermal production to predict experimental signatures



# Scattering of DM off nucleons: light flavor



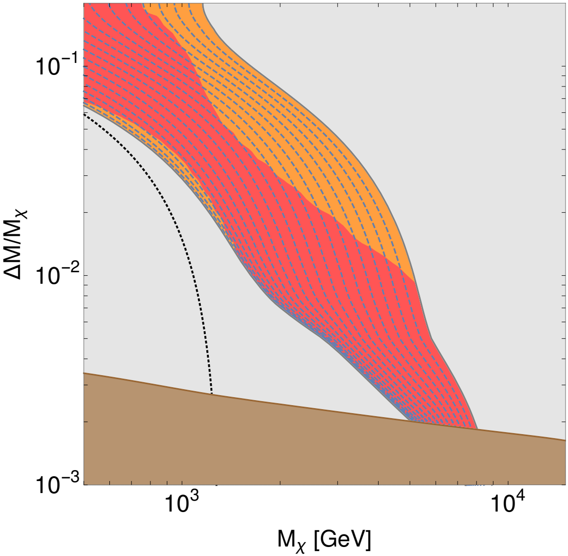

- tree-level interactions with light quarks
- SD scattering at lowest order
- contribution to SI scattering cancels at lowest order for Majorana DM with chiral interaction; expansion to higher order necessary

  Drees, Nojiri 93
- resonant enhancement of interactions for small mass difference

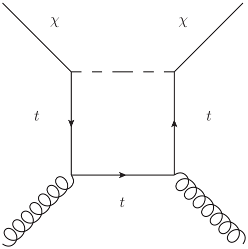
  Hisano, Ishiwata, Nagata 2011

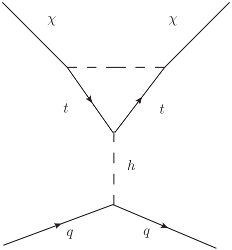
$$\sigma_{SD(SI)} \sim \left[\frac{1}{m_\eta^2 - (m_\chi + m_q)^2}\right]^{2(4)}$$

# Impact on parameter space: up-quark



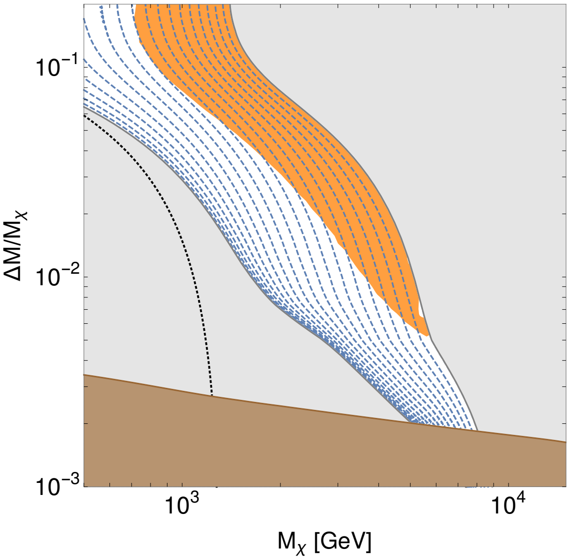
# Scattering of DM off nucleons: heavy flavor




- no top-quarks in the nucleus $\rightarrow$ no tree level coupling
- loop induced dark matter nucleus coupling
  - gluon box Drees, Nojiri 93
  - Higgs triangle Ibarra, Pierce, Shah, SV '15
- Higgs typically dominates
- Gluons lead to cancellation close to top mass

# Impact on parameter space: top-quark



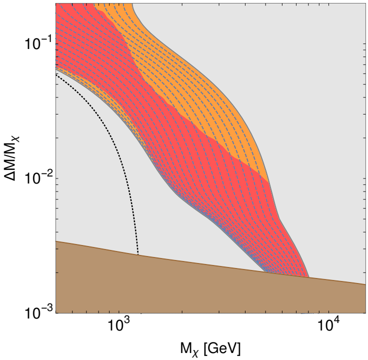
# Current limitation

- long decoupling time $\rightarrow$ potential become unreliable for low masses (lattice?)
- generalized thermal potentials (different hierarchy of scales)
- systems without mass gap need improvements $\rightarrow$ formalism assumes equilibrium between bound states and ionized stated

  Binder, Covi, Mukaida '18

# What happens in the lower left corner?

# Inaccessible region?




- for smaller $y$ smaller $\Delta M$ needed
- $\sigma v_{\chi\chi} \propto y^4$ and $\sigma v_{\chi\eta} \propto y^2$
- $\sigma v_{\eta\eta} \propto \alpha_S$
- eventually $\sigma v_{eff} = \sigma v_{\eta\eta}$

make $y$ arbitrarily small?

# Conversion driven freeze-out

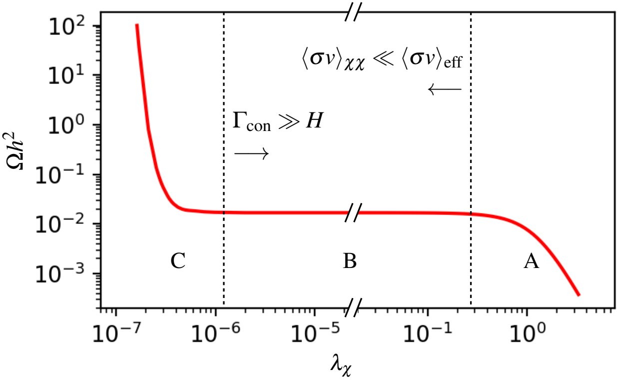
- revisit coupled Boltzmann equations

$$\frac{\mathrm{d}Y_\eta}{\mathrm{d}x} = \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\Bigg[\frac{1}{2}\langle\sigma_{\eta\eta^\dagger} v\rangle\left(Y_\eta^2 - Y_\eta^{\mathrm{eq}\,2}\right) - \frac{\Gamma_{\chi\to\eta}}{s}\left(Y_\chi - Y_\eta\frac{Y_\chi^{\mathrm{eq}}}{Y_\eta^{\mathrm{eq}}}\right) + \frac{\Gamma_\eta}{s}\left(Y_\eta - Y_\chi\frac{Y_\eta^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right)\Bigg]$$

$$\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\Bigg[-\frac{\Gamma_\eta}{s}\left(Y_\eta - Y_\chi\frac{Y_\eta^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right) + \frac{\Gamma_{\chi\to\eta}}{s}\left(Y_\chi - Y_\eta\frac{Y_\chi^{\mathrm{eq}}}{Y_\eta^{\mathrm{eq}}}\right)\Bigg]$$

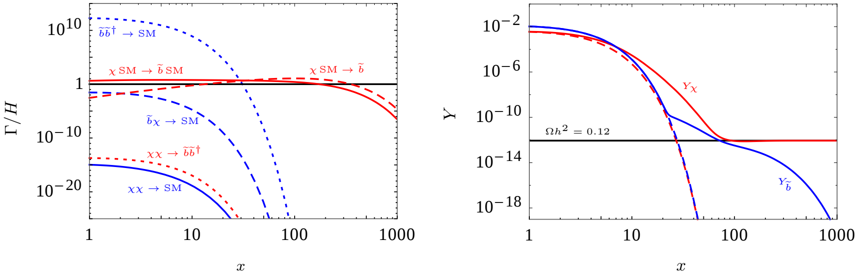
- $\eta\eta$ annihilations, conversion from scattering and conversion for decay important
- interesting things will happen for $\Gamma_{\chi\to\eta} + \Gamma_\eta \approx H$

# Relic density



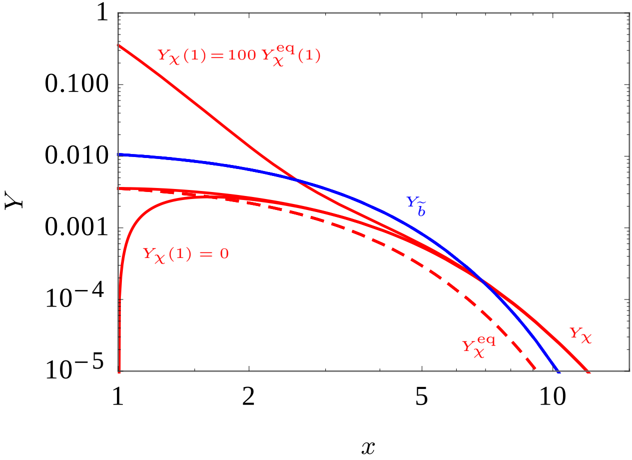

representative parameter point: $m_\chi = 500$ GeV and $m_\eta = 510$ GeV

# Quantitative analysis




- point with correct relic density:: $m\chi = 500$ GeV, $m_\eta = 510$ GeV and $y = 2.6 \times 10^{-7}$
- conversion driven freeze-out effective for $\Gamma \approx H$

# Conversion driven equilibration




- $\Gamma \approx H$ is sufficient to allow equilibration
- no dependence on initial condition

# Pheno estimates

small coupling of $\mathcal{O}(10^{-7})$

- ID: suppressed $\sigma v$ ✗
- DD: suppressed $\sigma v$ ✗

but: interaction rate has to be about the Hubble rate

$$\Gamma_\eta \approx H$$

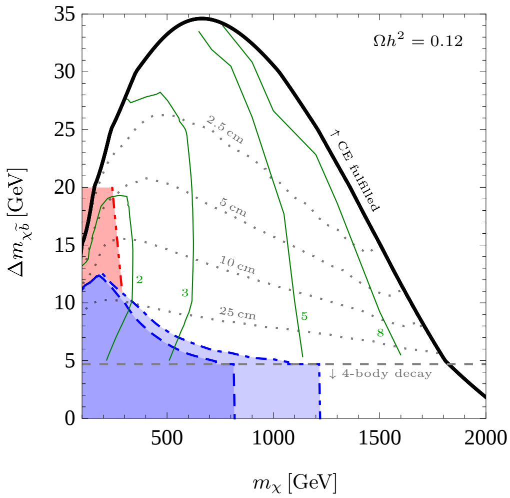
this is the decay rate of a heavy particle $\phi$ in a plasma

$$y \approx 20\sqrt{\frac{T_{max}^2}{m_\eta M_{Pl}}} \approx 10^{-8}\frac{m_\eta}{100\text{ GeV}}$$

$$c\tau \approx \frac{1}{H} \approx \frac{M_{Pl}}{\sqrt{g_*}m_\eta^2} \approx 100\left(\frac{\text{GeV}^2}{m_\eta^2}\right)\text{m}$$

- non-thermal dark matter indicates long-lived particles ✓
- LHC production controlled by gauge interactions of $\eta$ ✓

# Parameter space




- monojet search ATLAS 1604.07773
- search for detector stable R-hadrons CMS 1305.0491 and CMS-PAS-EXO-16-036

# Conclusion

- dark matter production is excellent guide to dark matter phenomenology
- need to explore full range of possibilities
- new effects can have profound impact on dark matter production, for example
  - bound state formation
  - conversion-driven freeze-out
  - dark sector self-thermalization
- new effects in production $\Rightarrow$ new effects in phenomenology