

# 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]

JHEP 1911 (2019) 147 [arXiv:1907.05766 ]

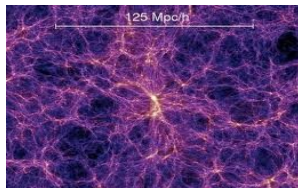
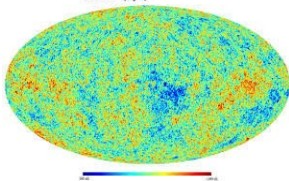
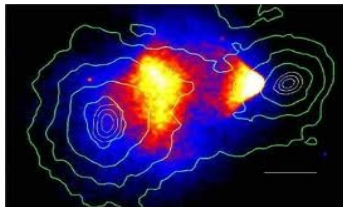
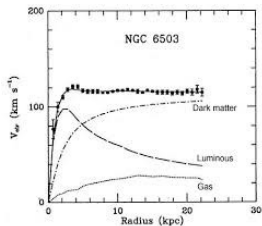
in collaboration with:

S. Biondini, M. Garny, B. Lülfi, J. Heisig



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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

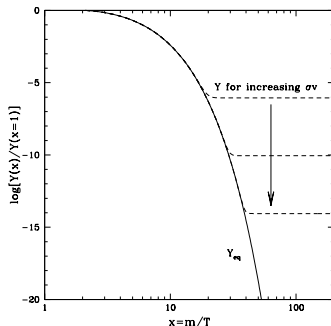
$$dn_{\chi}/dt + 3Hn_{\chi} = C$$

- ▶ 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

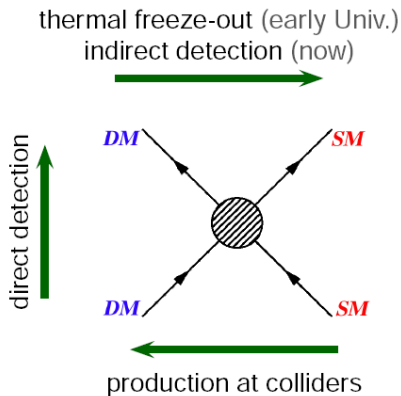
- ▶ universe starts at a high temperature
- ▶ dark matter part of plasma and in thermal equilibrium
- ▶ universe expands and cools
- ▶ once  $m_{DM} \gtrsim T$  interactions rate becomes suppressed  $\rightarrow$  DM drops out of thermal equilibrium



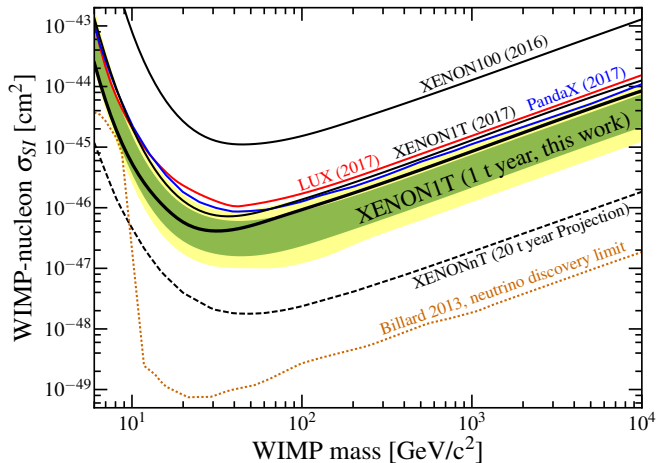
$$\frac{dY_x}{dx} = \frac{1}{3H} \frac{ds}{dx} \left[ \langle \sigma_{xx} v \rangle (Y_x^2 - Y_x^{\text{eq}2}) \right]$$

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

# Thermal dark matter

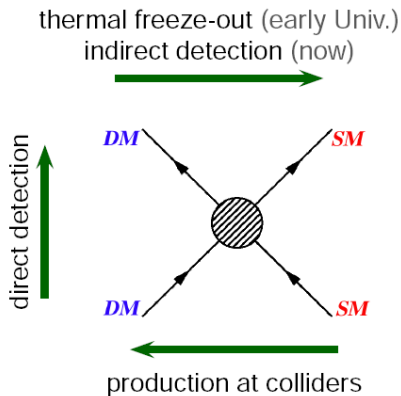


# Direct detection limits



XENON1T 2018

# Thermal dark matter

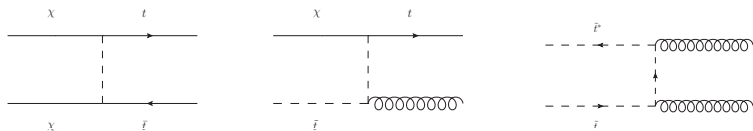


Direct detection limits very stringent. Models with simple crossing symmetry are getting in trouble.

⇒ 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  $\eta$

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

- ▶ simplified t-channel model with fermionic mediator

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

- ▶ fermionic dark matter with color octet fermion partner

$$\mathcal{L} = \dots$$

- ▶ ...

qualitative features model independent

# Dark sector annihilations

$$\frac{dY_\chi}{dx} = \frac{1}{3H} \frac{ds}{dx} \left[ \langle \sigma_{\chi\chi\nu} \rangle (Y_\chi^2 - Y_\chi^{\text{eq}2}) + \langle \sigma_{\chi\bar{q}\nu} \rangle (Y_\chi Y_{\bar{q}} - Y_\chi^{\text{eq}} Y_{\bar{q}}^{\text{eq}}) \right. \\ \left. + \frac{\Gamma_{\chi \rightarrow \bar{q}}}{s} \left( Y_\chi - Y_{\bar{q}} \frac{Y_\chi^{\text{eq}}}{Y_{\bar{q}}^{\text{eq}}} \right) - \frac{\Gamma_{\bar{q}}}{s} \left( Y_{\bar{q}} - Y_\chi \frac{Y_{\bar{q}}^{\text{eq}}}{Y_\chi^{\text{eq}}} \right) + \langle \sigma_{\chi\chi \rightarrow \bar{q}\bar{q}^\dagger \nu} \rangle \left( Y_\chi^2 - Y_{\bar{q}}^2 \frac{Y_\chi^{\text{eq}2}}{Y_{\bar{q}}^{\text{eq}2}} \right) \right]$$

$$\frac{dY_{\bar{q}}}{dx} = \frac{1}{3H} \frac{ds}{dx} \left[ \frac{1}{2} \langle \sigma_{\bar{q}\bar{q}^\dagger \nu} \rangle (Y_{\bar{q}}^2 - Y_{\bar{q}}^{\text{eq}2}) + \langle \sigma_{\chi\bar{q}\nu} \rangle (Y_\chi Y_{\bar{q}} - Y_\chi^{\text{eq}} Y_{\bar{q}}^{\text{eq}}) \right. \\ \left. - \frac{\Gamma_{\chi \rightarrow \bar{q}}}{s} \left( Y_\chi - Y_{\bar{q}} \frac{Y_\chi^{\text{eq}}}{Y_{\bar{q}}^{\text{eq}}} \right) + \frac{\Gamma_{\bar{q}}}{s} \left( Y_{\bar{q}} - Y_\chi \frac{Y_{\bar{q}}^{\text{eq}}}{Y_\chi^{\text{eq}}} \right) - \langle \sigma_{\chi\chi \rightarrow \bar{q}\bar{q}^\dagger \nu} \rangle \left( Y_\chi^2 - Y_{\bar{q}}^2 \frac{Y_\chi^{\text{eq}2}}{Y_{\bar{q}}^{\text{eq}2}} \right) \right]$$

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

# Effective cross section

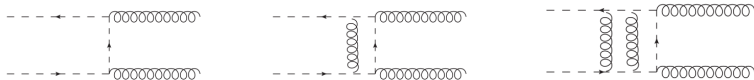
for sufficiently fast conversion rate system simplifies

$$\frac{dY_\chi}{dx} = \frac{1}{3H} \frac{ds}{dx} \left[ \langle \sigma_{\chi\chi} \mathbf{v} \rangle_{eff} (Y_\chi^2 - Y_\chi^{eq2}) \right]$$

where

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

# Sommerfeld effect



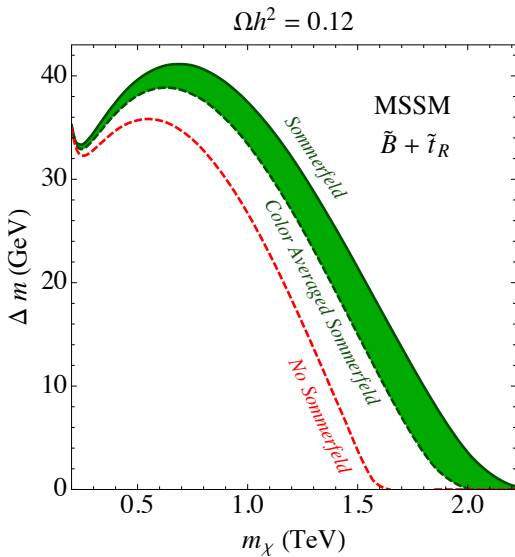
- ▶ exchange of long-range mediator leads to non-perturbative modification of annihilation rates Hisano et al '05
- ▶ intuitive description: distortion of the wave-function due to potential
- ▶ extract wave function from non-relativistic Schrödinger equation with Coulomb potential

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

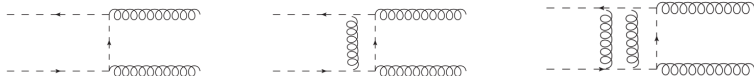
De Simone et al '14, Ibarra, Pierce, Shah, SV '15

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

# Relic density with Sommerfeld



# 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

→ 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 be expressed in terms of spectral functions  $\rho$

Kim, Laine '16, Biondini, Laine '18

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

# NREFT for coannihilations in a nutshell II

## spectral functions

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

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

$$\lim_{\mathbf{r}, \mathbf{r}' \rightarrow \mathbf{0}} \text{Im} G_i(E'; \mathbf{r}, \mathbf{r}') = \rho_i(E'), \quad (2)$$

- ▶ 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

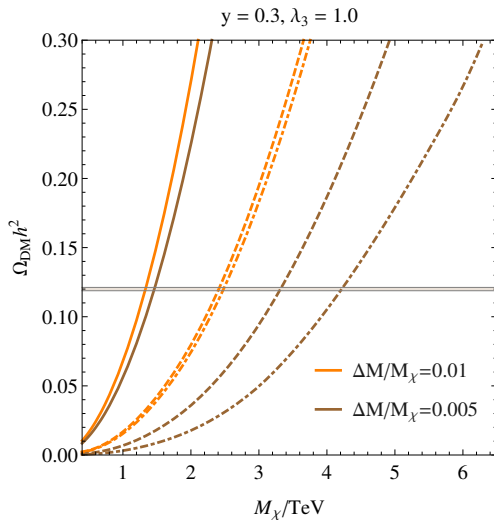
- ▶ effective thermally averaged annihilation cross section

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

- ▶  $c_i$  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

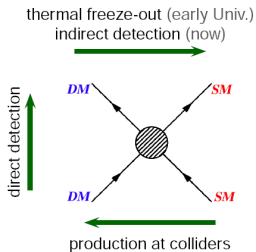


Biondini, SV '18

significant shifts in relic density

# NREFT meets pheno

use precise prediction for thermal production to predict experimental signatures

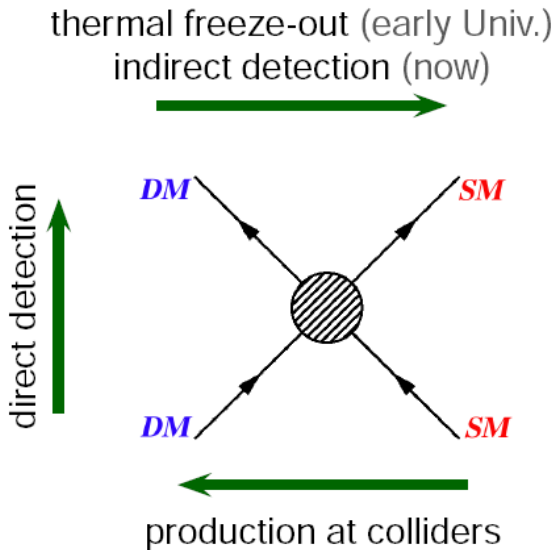


Test it with

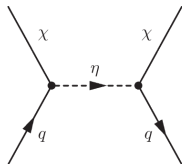
- ▶ ID: suppressed  $\sigma v$  ✗
- ▶ LHC searches: ✗ (✓)
- ▶ DD: guaranteed for colored mediators ✓

# 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

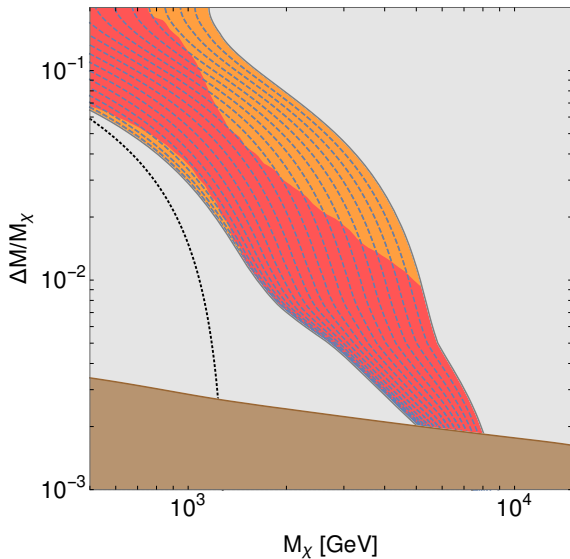
Drees, Nojiri 93

- ▶ resonant enhancement of interactions for small mass difference

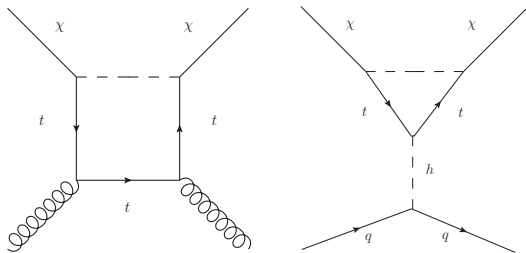
Hisano, Ishiwata, Nagata 2011

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

# Impact on parameter space: up-quark

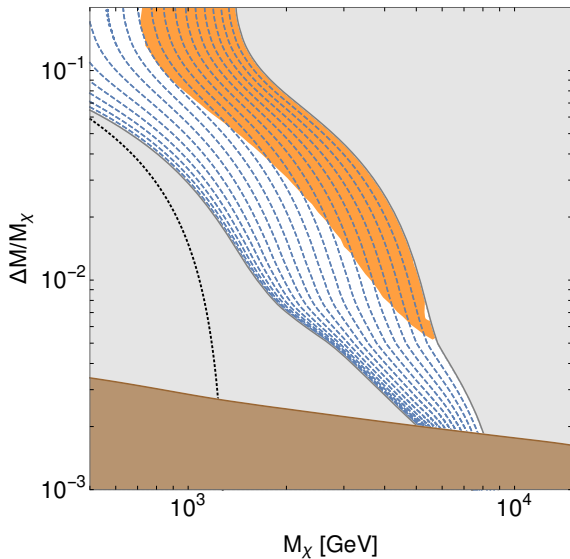


# Scattering of DM off nucleons: heavy flavor



- ▶ 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



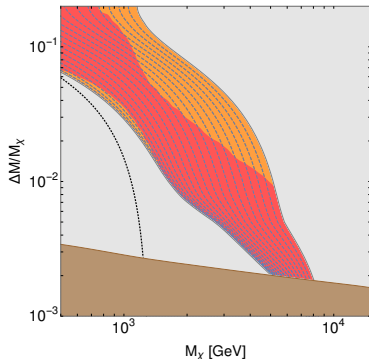
# Current limitation

- ▶ 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 states

Binder, Covi, Mukaída '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

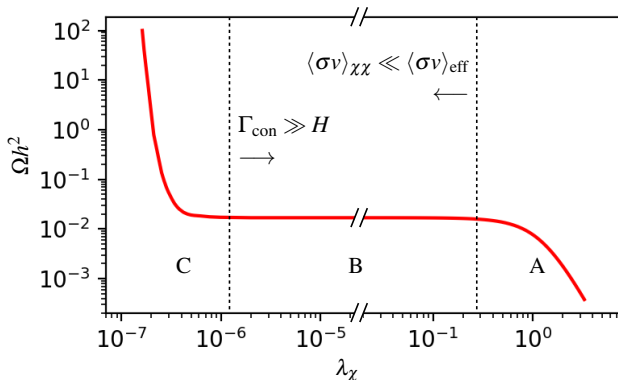
- ▶ revisit coupled Boltzmann equations

$$\frac{dY_\eta}{dx} = \frac{1}{3H} \frac{ds}{dx} \left[ \frac{1}{2} \langle \sigma_{\eta\eta^\dagger} v \rangle (Y_\eta^2 - Y_\eta^{\text{eq}2}) - \frac{\Gamma_{\chi \rightarrow \eta}}{s} \left( Y_\chi - Y_\eta \frac{Y_\chi^{\text{eq}}}{Y_\eta^{\text{eq}}} \right) + \frac{\Gamma_\eta}{s} \left( Y_\eta - Y_\chi \frac{Y_\eta^{\text{eq}}}{Y_\chi^{\text{eq}}} \right) \right]$$

$$\frac{dY_\chi}{dx} = \frac{1}{3H} \frac{ds}{dx} \left[ -\frac{\Gamma_\eta}{s} \left( Y_\eta - Y_\chi \frac{Y_\eta^{\text{eq}}}{Y_\chi^{\text{eq}}} \right) + \frac{\Gamma_{\chi \rightarrow \eta}}{s} \left( Y_\chi - Y_\eta \frac{Y_\chi^{\text{eq}}}{Y_\eta^{\text{eq}}} \right) \right]$$

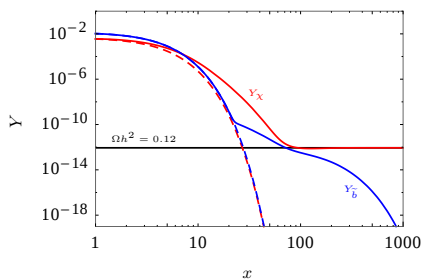
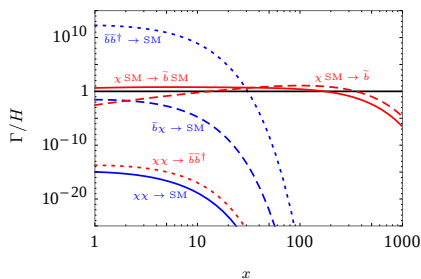
- ▶  $\eta\eta$  annihilations, conversion from scattering and conversion for decay important
- ▶ interesting things will happen for  $\Gamma_{\chi \rightarrow \eta} + \Gamma_\eta \approx H$

# Relic density



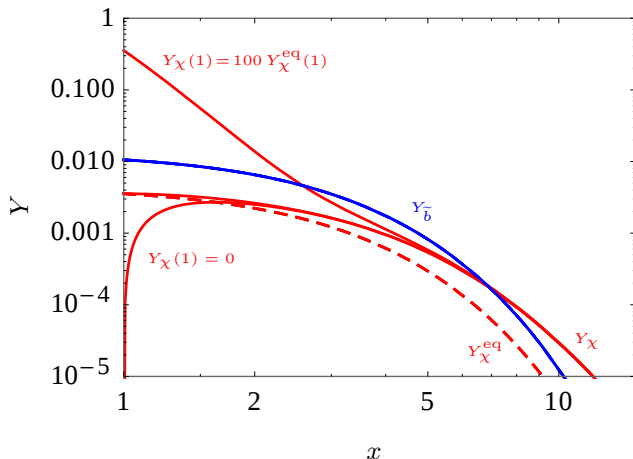
representative parameter point:  $m_\chi = 500$  GeV and  $m_\eta = 510$  GeV

# 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

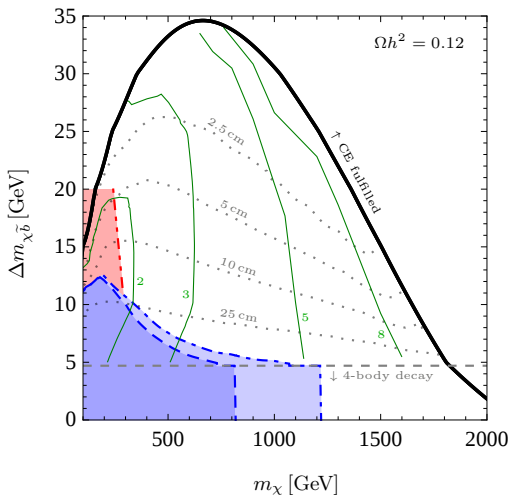
$$\Gamma_\eta \approx H$$

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

$$y \approx 20 \sqrt{\frac{T_{max}^2}{m_\eta M_{Pl}}} \approx 10^{-8} \frac{m_\eta}{100 \text{ GeV}}$$
$$c_T \approx \frac{1}{H} \approx \frac{M_{Pl}}{\sqrt{g_*} m_\eta^2} \approx 100 \left( \frac{\text{GeV}^2}{m_\eta^2} \right) \text{ m}$$

- ▶ 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