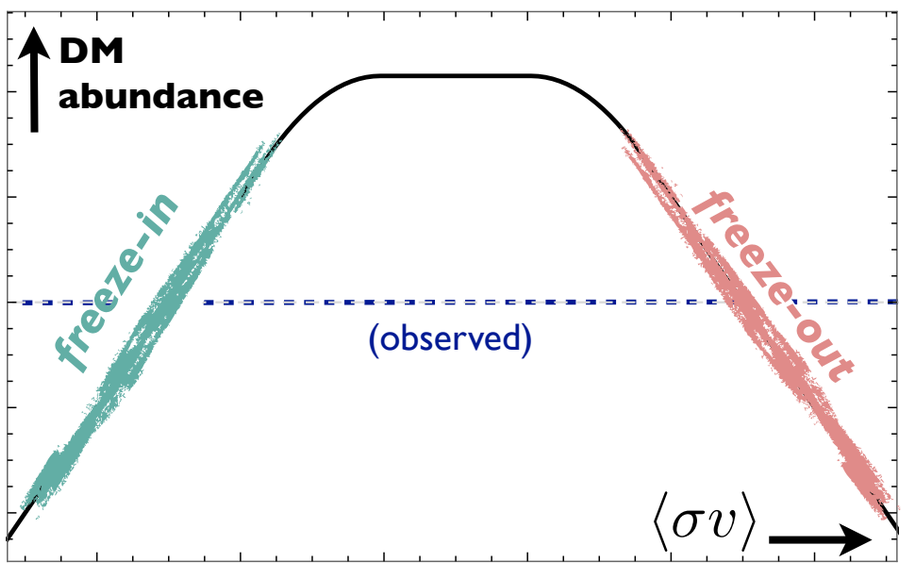
N-PACT meeting 2022, Stavanger

Dark Matter from the Primordial Plasma

From freeze-in to pandemic production

Torsten Bringmann



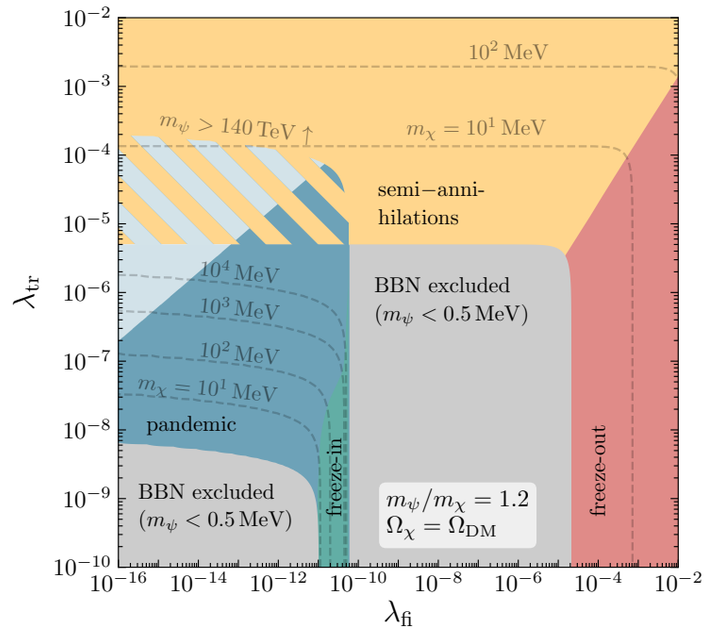
standard production mechanisms

Based on

TB, Heeba, Kahlhoefer & Vangsnes, JHEP '22

TB, Depta, Hufnagel, Ruderman & Schmidt-Hoberg, PRL '21

TB, Depta, Hufnagel, Kersten, Ruderman & Schmidt-Hoberg, arXiv:2206.10630

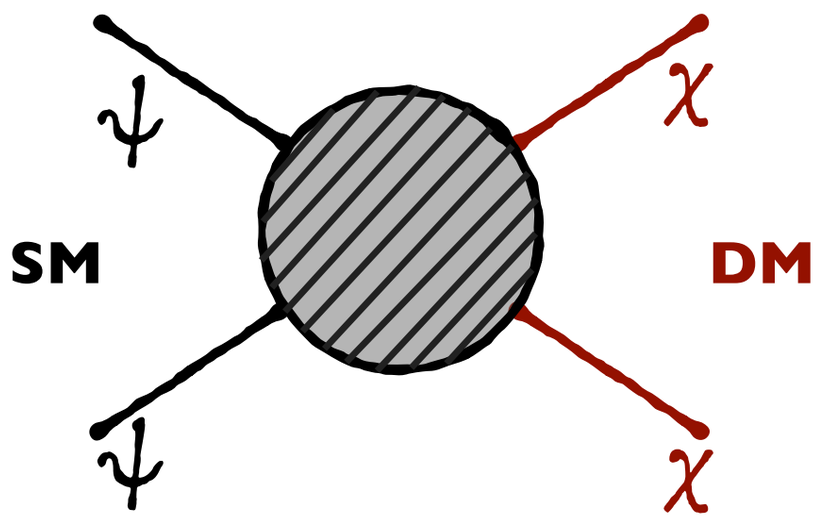


'pandemic' production

UiO : University of Oslo

The origin of dark matter

- Existence of (particle) DM = evidence for BSM physics
- Guiding principle: any convincing model for dark matter must include a production mechanism
- Let's postulate some interaction with the primordial heat bath:
  - [Z_2 symmetry not strictly necessary, but automatically guarantees stability of DM]



Boltzmann equation

- Evolution of DM phase-space density:

$$L[f_\chi] = C[f_\chi]$$

$$\text{“}= \frac{\mathrm{d}f_\chi}{\mathrm{d}t}\text{”} = E\left(\partial_t - H\mathbf{p}\cdot\nabla_\mathbf{p}\right) f_\chi \quad \textbf{for FRW metric}$$

- Collision term:

$$C[f_\chi] = \frac{1}{2g_\chi}\int\frac{d^3\tilde{p}}{(2\pi)^3 2\tilde{E}}\int\frac{d^3k}{(2\pi)^3 2\omega}\int\frac{d^3\tilde{k}}{(2\pi)^3 2\tilde{\omega}}(2\pi)^4\delta^{(4)}(\tilde{p}+p-\tilde{k}-k)$$

$$\times\Big[|\mathcal{M}|^2_{\bar{\chi}\chi\leftarrow\bar{\psi}\psi}\, f_\psi(\omega)f_\psi(\tilde{\omega}) - |\mathcal{M}|^2_{\bar{\chi}\chi\rightarrow\bar{\psi}\psi}\, f_\chi(E)f_\chi(\tilde{E})\{1\pm f_\psi(\omega)\}\{1\pm f_\psi(\tilde{\omega})\}\Big]$$

‘production’ ‘annihilation’

- Detailed balance: ‘production’ = ‘annihilation’ *in equilibrium*

  ⇝ allows to re-write everything in terms of a *would-be* equilibrium population of DM

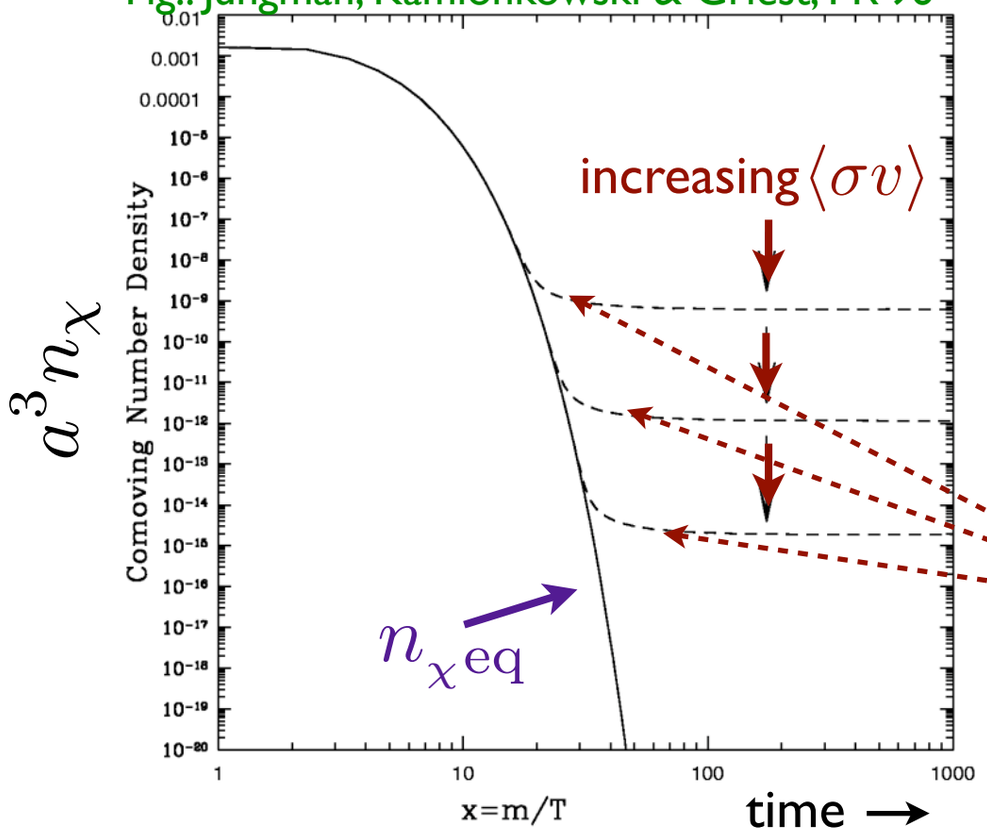
- Pauli suppression / Bose enhancement

  ⇝ not relevant for production of non-relativistic ***DM*** [energy conservation!]

Weakly Interacting Massive Particles

- well-motivated from particle physics [SUSY, EDs, …]
- thermal production in early universe:

Fig.: Jungman, Kamionkowski & Griest, PR'96



$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi\,\mathrm{eq}}^2\right)$$

$\langle\sigma v\rangle$: $\chi\chi \to \mathrm{SM\ SM}$ (thermal average)

"Freeze-out" when annihilation rate falls behind expansion rate

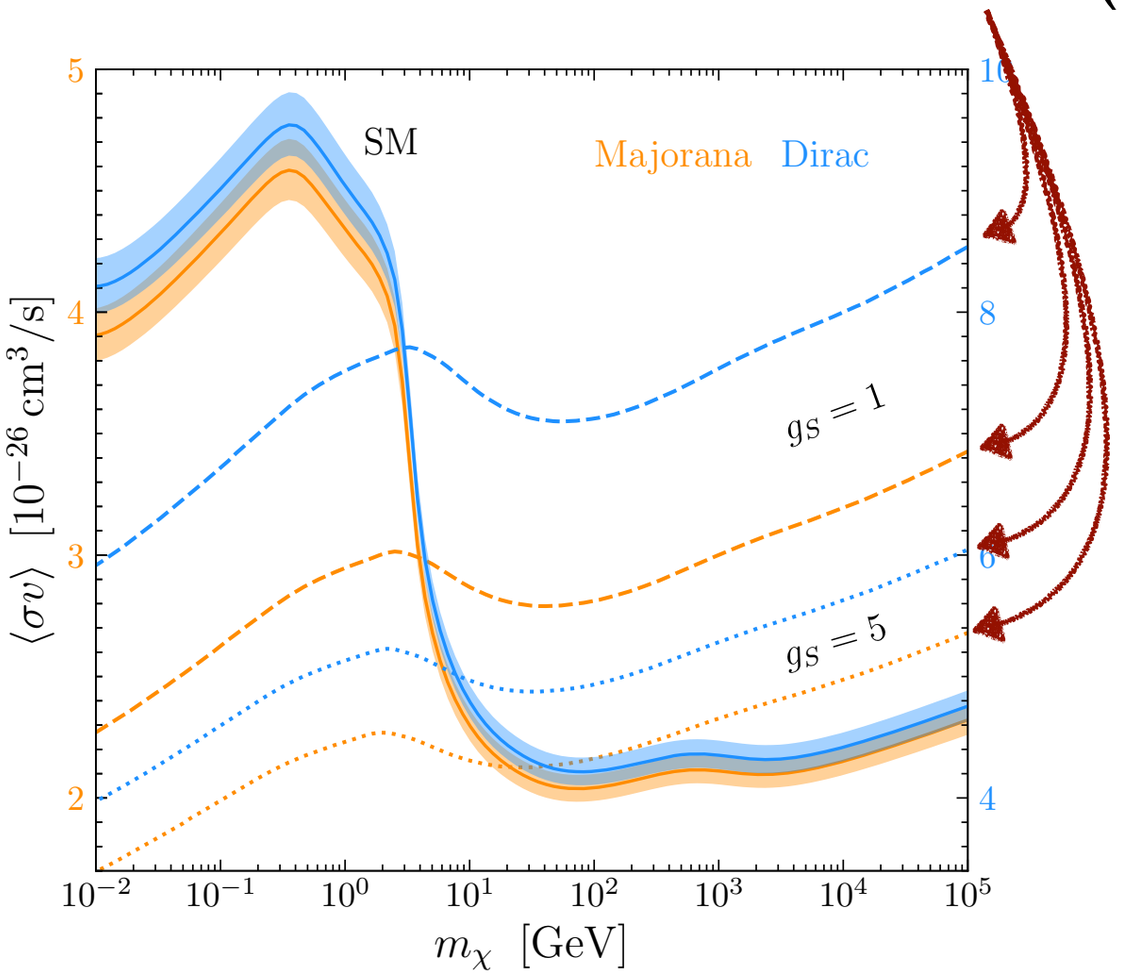
⇒ Relic density (today): $\Omega_\chi h^2 \sim \dfrac{3\cdot 10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle}$

‘s-wave’ vs. ‘p-wave’

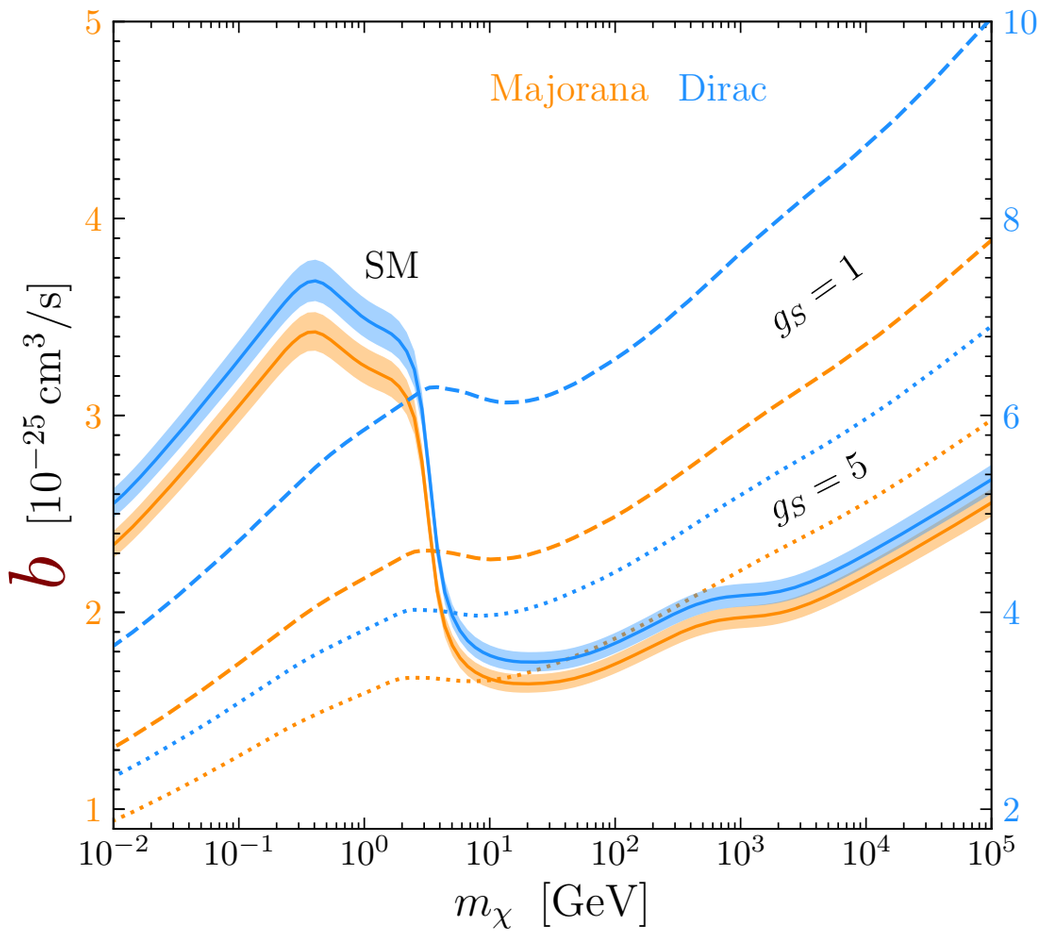
- Precision calculations of ‘thermal cross section’:

  TB, Depta, Hufnagel & Schmidt-Hoberg, PLB ’21

  - works also in secluded dark sectors (with g_S heat bath d.o.f.)



$$\langle \sigma v \rangle = const.$$

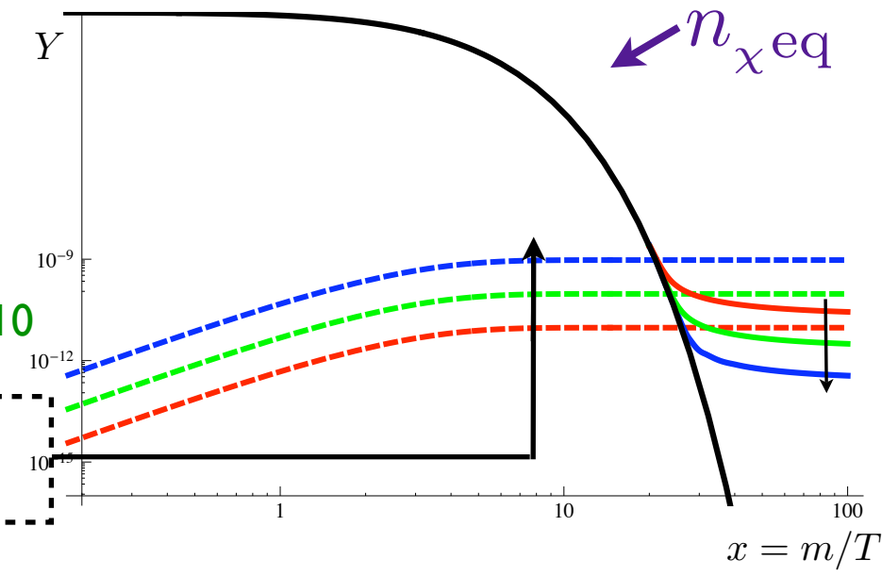


$$\langle \sigma v \rangle = b\, v^2$$

- $v \sim 0.3$ around freeze-out
- $v \sim 10^{-3}$ today

Feably Interacting Massive Particles

- WIMP DM is seriously pressured (but not dead!)
- alternative production from thermal bath with much smaller interactions
  - DM never equilibrates in this case

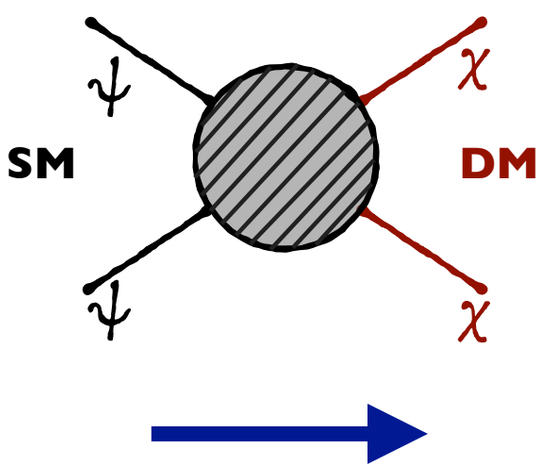


Hall+, JHEP '10

***Increasing* interaction rate for freeze-in**

- Smooth transition between two regimes:

freeze-in



depends on initial conditions

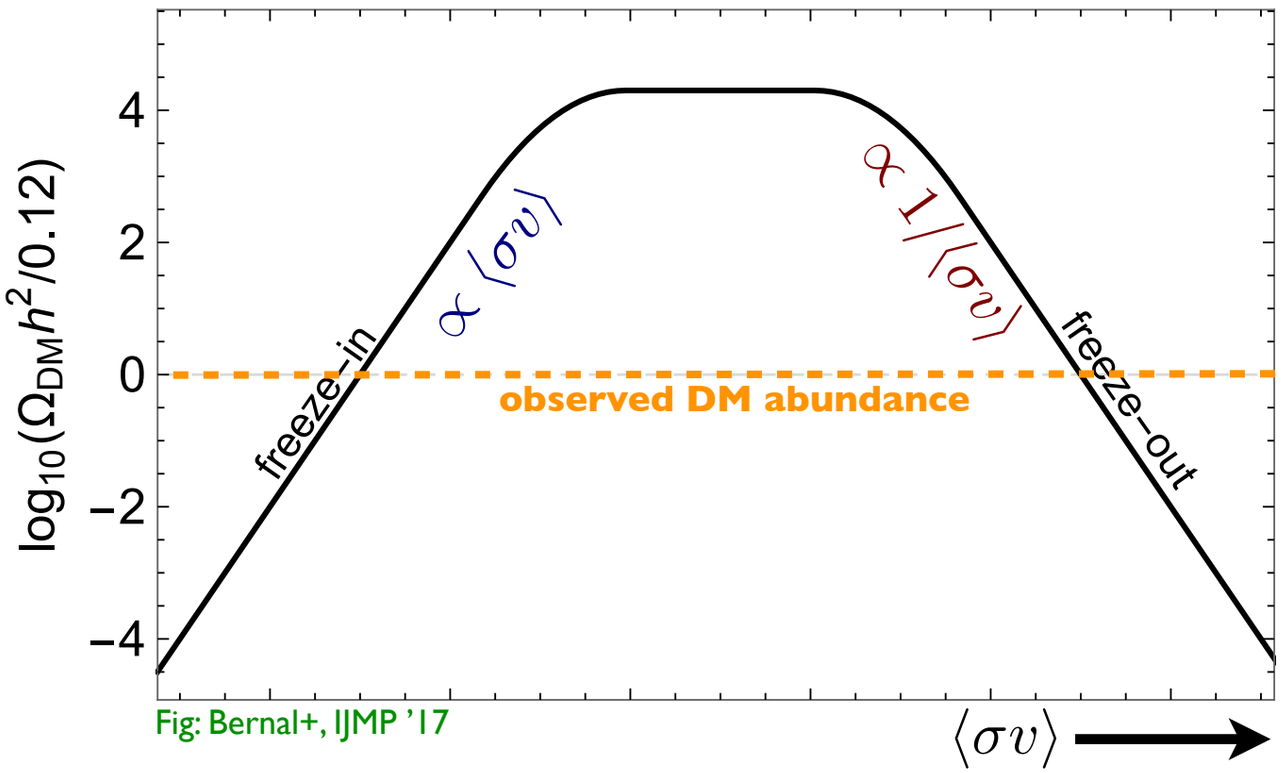
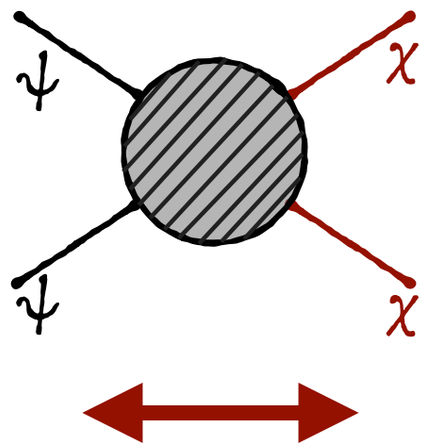


Fig: Bernal+, IJMP '17

freeze-out



insensitive to initial conditions

Collision term for FIMPs

$$C[f_\chi] = \frac{1}{2g_\chi}\int\frac{d^3\tilde{p}}{(2\pi)^3 2\tilde{E}}\int\frac{d^3k}{(2\pi)^3 2\omega}\int\frac{d^3\tilde{k}}{(2\pi)^3 2\tilde{\omega}}(2\pi)^4\delta^{(4)}(\tilde{p}+p-\tilde{k}-k)$$
$$\times\left[|\mathcal{M}|^2_{\bar{\chi}\chi\leftarrow\bar{\psi}\psi}\, f_\psi(\omega) f_\psi(\tilde{\omega}) - |\mathcal{M}|^2_{\bar{\chi}\chi\to\bar{\psi}\psi}\, f_\chi(E) f_{\bar{\chi}}(\tilde{E})\{1\pm f_\psi(\omega)\}\{1\pm f_\psi(\tilde{\omega})\}\right]$$

'production' 'annihilation'

$$\Rightarrow \boxed{C[f_\chi] = \langle\sigma v\rangle_{\chi\chi\to\psi\psi}\left(n_\chi^{\rm MB}\right)^2}$$

annihilation of ***would-be*** MB population → ***actual*** (in eq)

- Only 2 integrals after exploiting spherical symmetry:
  [γ : Lorenz boost to CMS; $\tilde{s} = s/(4m_\chi^2)$]

$$\langle\sigma v\rangle_{\chi\chi\to\psi\psi} = \frac{8x^2}{{K_2}^2(x)}\int_1^\infty d\tilde{s}\,\tilde{s}\,(\tilde{s}-1)\int_1^\infty d\gamma\,\sqrt{\gamma^2-1}e^{-2\sqrt{\tilde{s}}x\gamma}\sigma_{\chi\chi\to\psi\psi}(s,\gamma)$$

→ $K_1(2\sqrt{\tilde{s}}x)/(2\sqrt{\tilde{s}}x)$ ✔

TB, Heeba, Kahlhoefer & Vangsnes, JHEP '22
(see also Lebedev & Toma, PLB '19
Arcadi+, JHEP '19)

$$\sigma_{\chi\chi\to\psi\psi}(p,\tilde{p}) = \frac{(2\pi)^4}{4N_\psi E\tilde{E}\,v_{\rm Møl}}\int\frac{d^3k}{(2\pi)^3 2\omega}\int\frac{d^3\tilde{k}}{(2\pi)^3 2\tilde{\omega}}\,\delta^{(4)}(\tilde{p}+p-\tilde{k}-k)\,\left|\overline{\mathcal{M}}\right|^2\{1\pm f_\psi(\omega)\}\{1\pm f_\psi(\tilde{\omega})\}$$

→ 1

- In *this* formulation, direct analogy with WIMP case!
  - Can recycle sophisticated numerical tools for thermal averages
  - Easier to estimate higher-order corrections

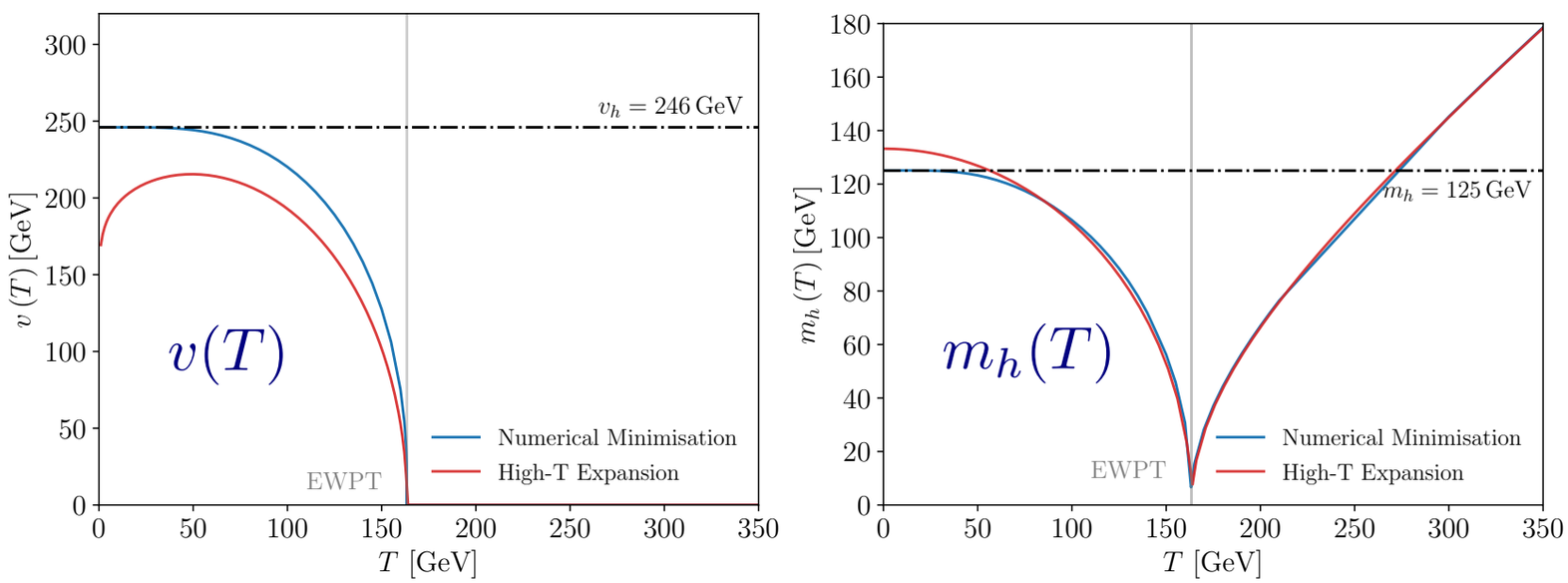
(Further) Finite temperature effects

- FIMPs are dominantly produced at higher temperatures than WIMPs, and over a larger range

➡ Not only quantum statistics matters, but also

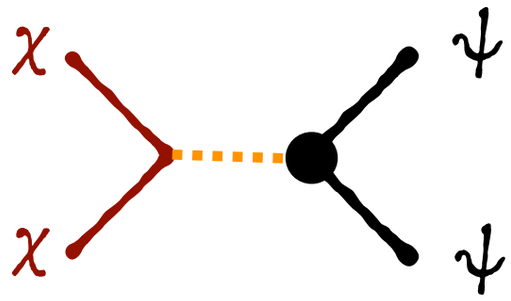
- Thermal masses of heat bath particles $\delta m^2 \sim g^2 T^2$
- Phase transitions:
  - Potentially a*dditional* $m(T)$
  - Spectrum of states changes

- For example the EWPT:



DM from decays

- 2→2 or 1→2 ?
  - Expect difference only at NLO !



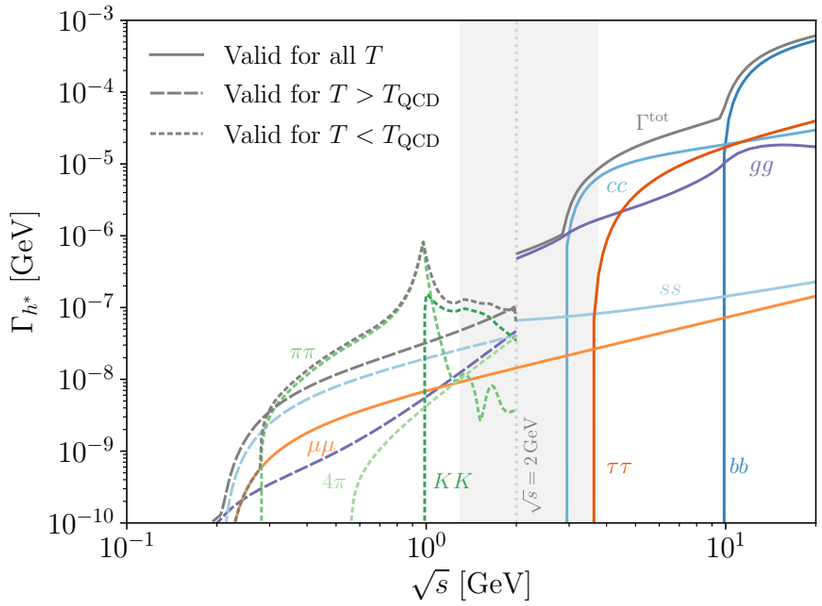
- For a fully thermalized mediator *A*, this requires

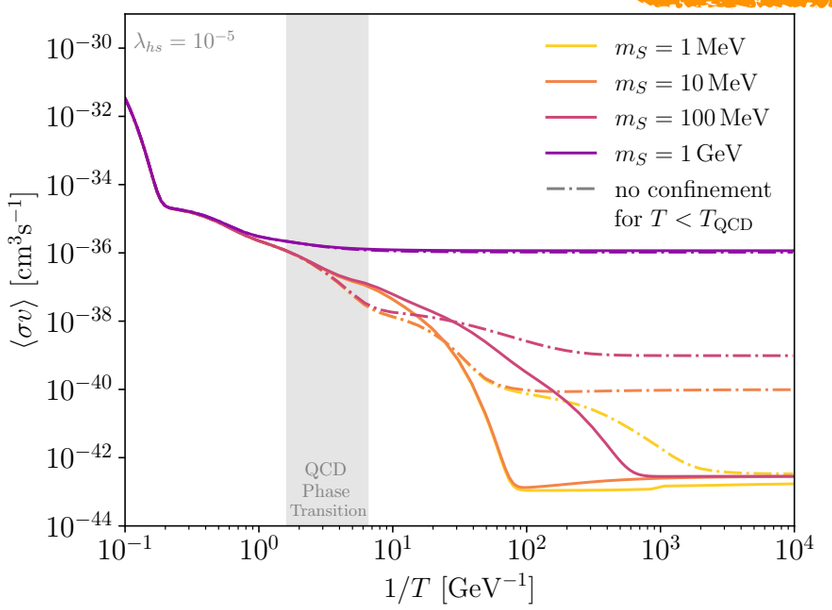
$$\Gamma_{\rm BW} = \frac{1}{1+f_A(\omega')} \sum_{\psi_1\psi_2} \Gamma_{\psi_1\psi_2} \overline{G}_{\psi_1\psi_2}(\gamma, m_A^2)$$

TB, Heeba, Kahlhoefer & Vangsnes, JHEP '22

width in propagator — **width in vacuum** — **final state quantum enhancement/suppression**

- For a SM Higgs mediator, e.g., we can directly use tabulated partial widths, both below and above QCD PT (for "→", but not for "←"!)





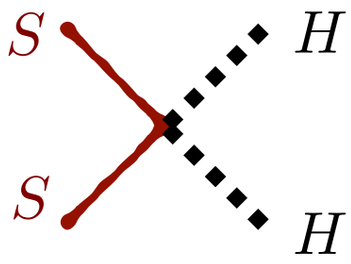
Freeze-in: Case study

- Scalar Singlet DM

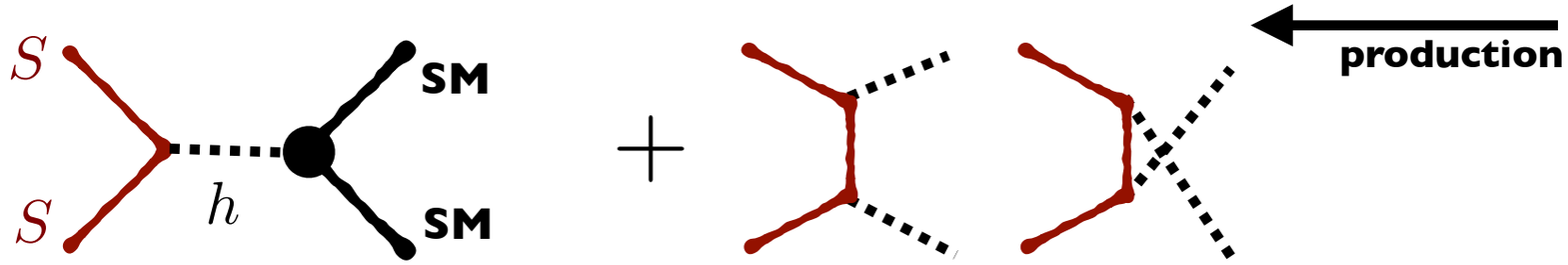
$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hs} S^2 |H|^2 + \frac{1}{4}\lambda_s S^4$$

Silveira & Zee, PLB '85

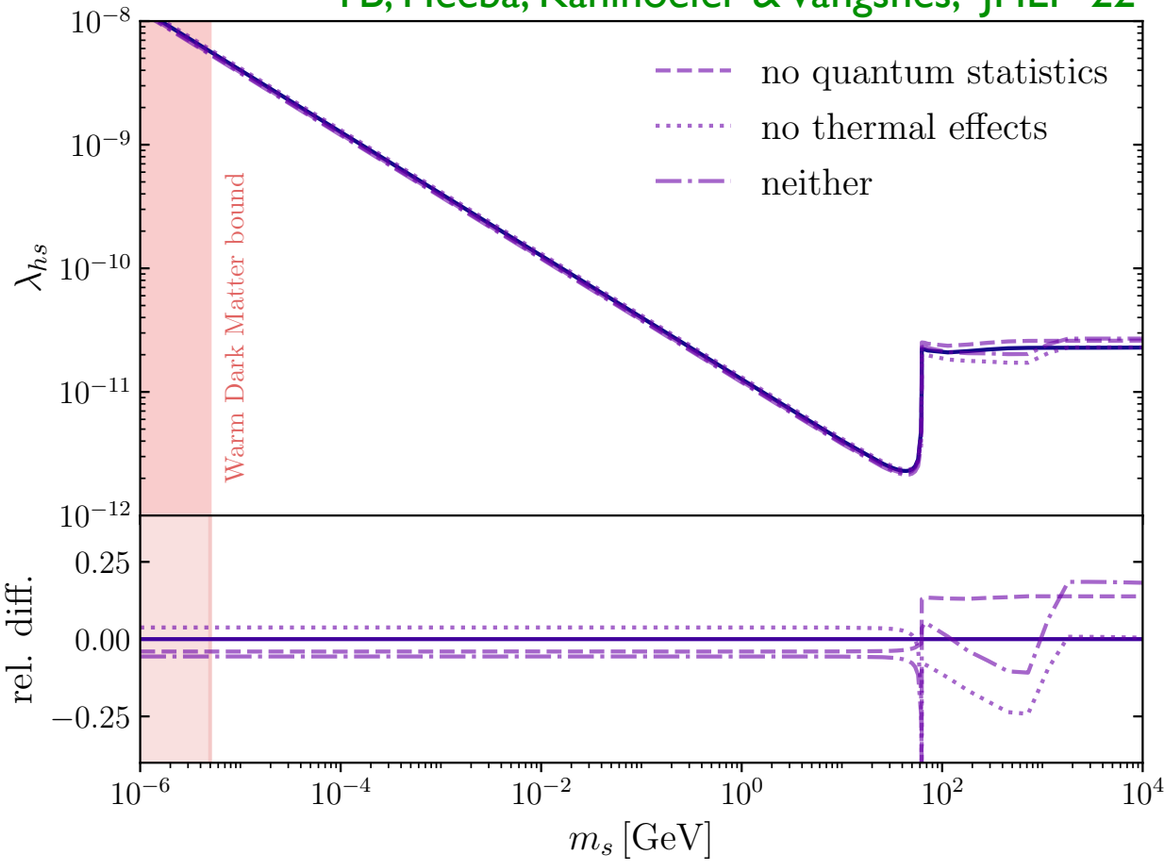
- before EWSB:



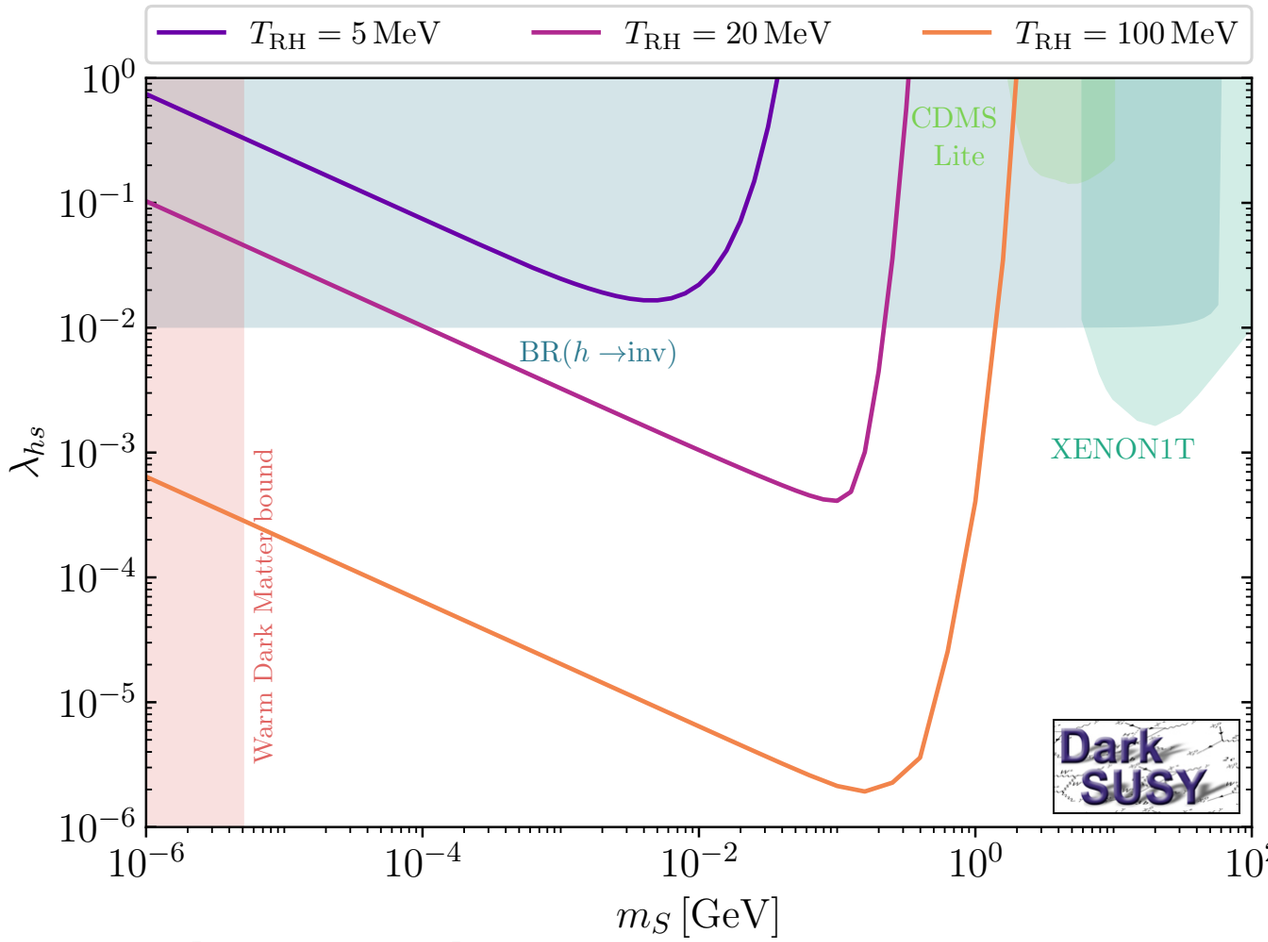
- after EWSB:



TB, Heeba, Kahlhoefer & Vangsnes, JHEP '22



- High reheating temperature



- Low reheating temperature

A new production mechanism

- In the past, many variants of freeze-out scenario have been explored:

ELDER DARK MATTER

HIDDEN SECTOR FREEZE-OUT

KINDER DARK MATTER

CANNIBAL DARK MATTER

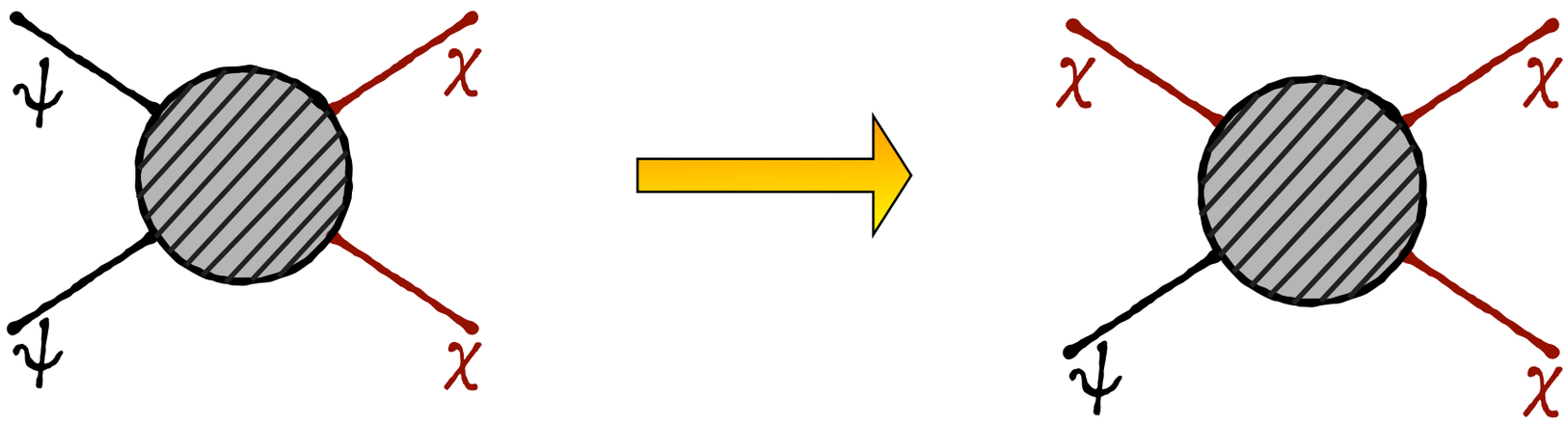
FORBIDDEN DARK MATTER

ZOMBIE DARK MATTER

SIMP DARK MATTER

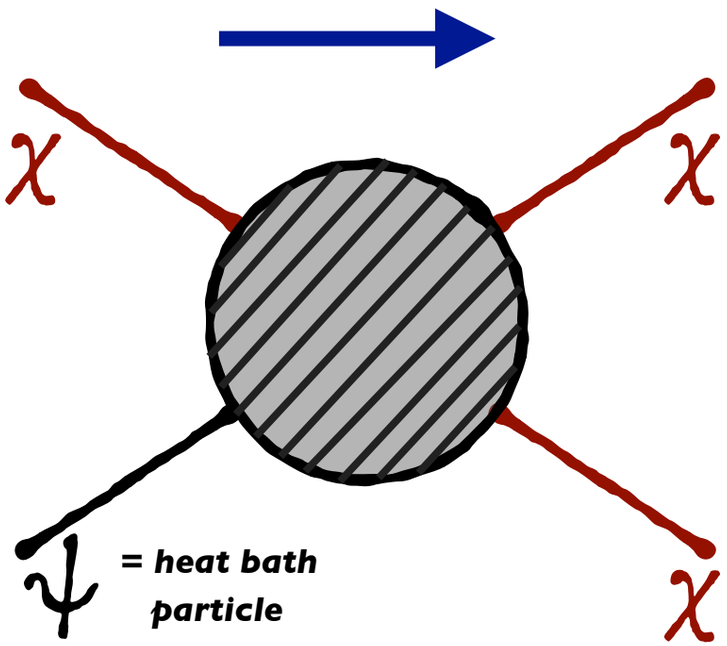
...

- Can we get a qualitatively different freeze-in scenario?



A new production mechanism

- 'Pandemic' dark matter



TB, Depta, Hufnagel, Rudermann & Schmidt-Hoberg, 2103.16572

Hryczuk & Laletin, 2104.05684

$$\dot{n_\chi} + 3Hn_\chi = n_\chi n_\psi^{\rm eq} \langle\sigma v\rangle$$

[for $n_\chi \ll n_\psi^{\rm eq}$]

- The 'SIR' compartmental model

A Contribution to the Mathematical Theory of Epidemics.

By W. O. Kermack and A. G. McKendrick.

(Communicated by Sir Gilbert Walker, F.R.S.—Received May 13, 1927.)

S ***# susceptible individuals***

I ***# infected individuals***

 # recovered $(R = \text{tot} - S - I)$

β ***infection rate***

γ ***recovery rate***

$$\dot{I} = \beta S I - \gamma I$$

➡ *reproduction number, or 'R-value':* $R \equiv \frac{\beta S}{\gamma} = \frac{n_\psi^{\rm eq}\langle\sigma v\rangle}{3H}$

A new production mechanism

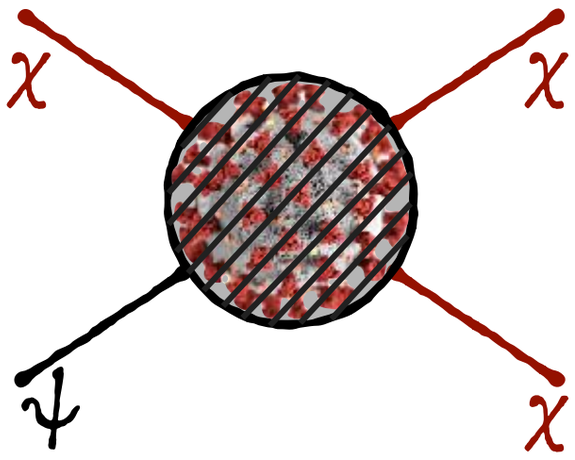


FIG. 1. The transformation process leading to exponential production of DM (χ) from the heat bath (ψ).

Pandemic Dark Matter

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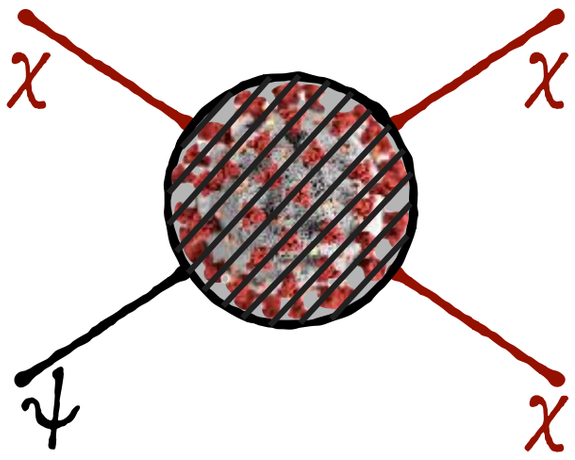
(Date: April 1st, 2021)

arXiv: 2103.16572

PRL wasn't very happy… 🤷

Exponential DM production



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Editors' Suggestion | Featured in Physics

Dark Matter from Exponential Growth

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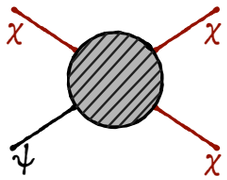
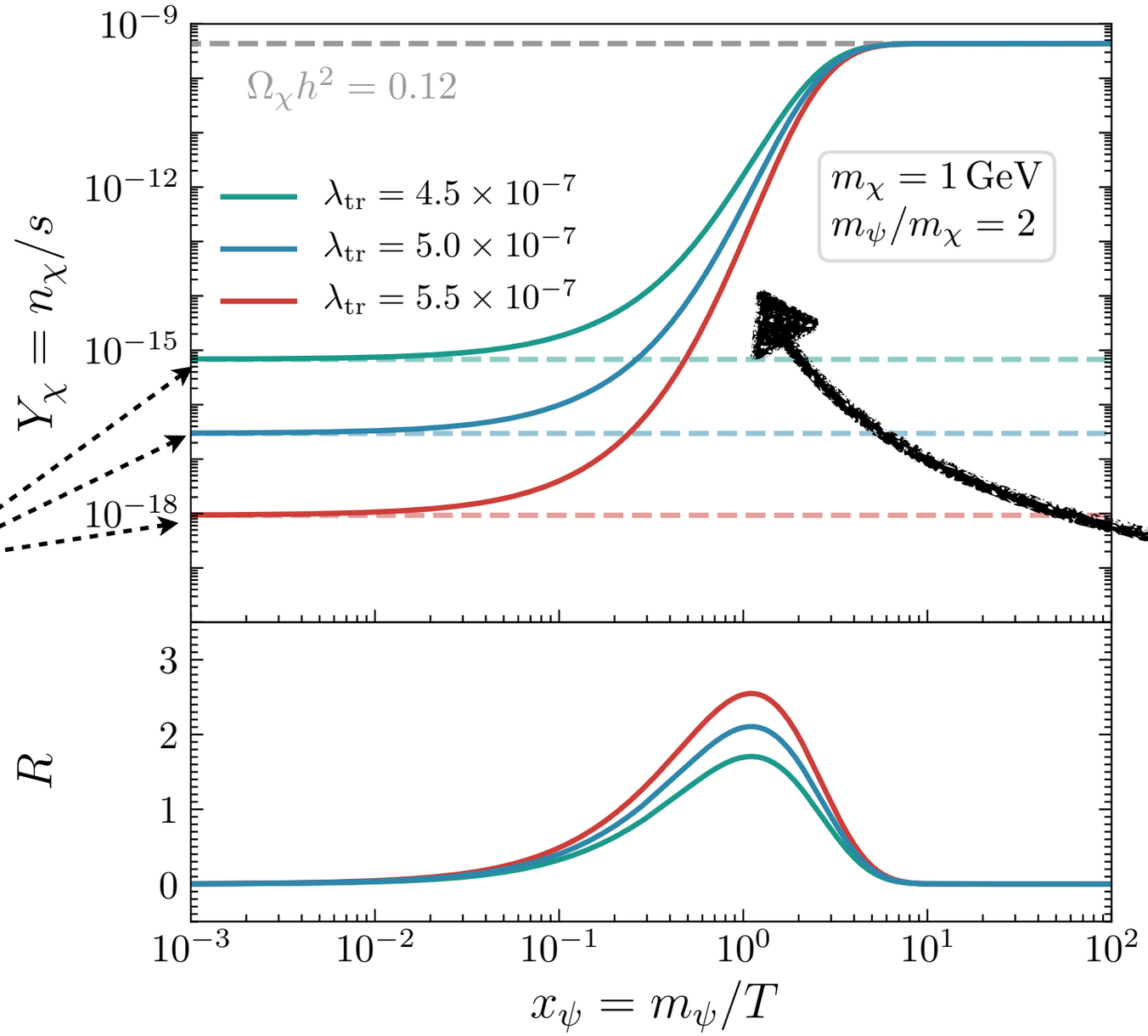
Exponential DM production

$\mathcal{L} \supset (\lambda_{\rm tr}/3!)\psi\chi^3$



$= -i\,\lambda_{\rm tr}$

toy model



Tiny initial DM abundance

exponential growth

$R \gtrsim 1$

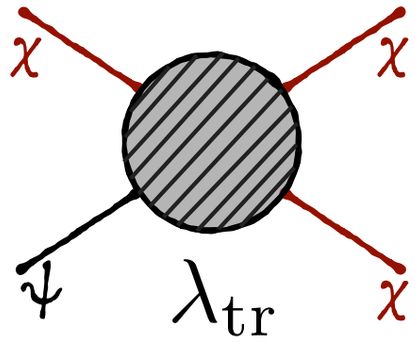
large H

small $n_\psi^{\rm eq}$

$$R \equiv \frac{\beta S}{\gamma} = \frac{n_\psi^{\rm eq}\langle\sigma v\rangle}{3H}$$

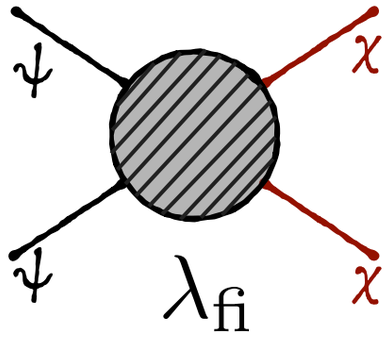
Adding freeze-in production

‘transmission’

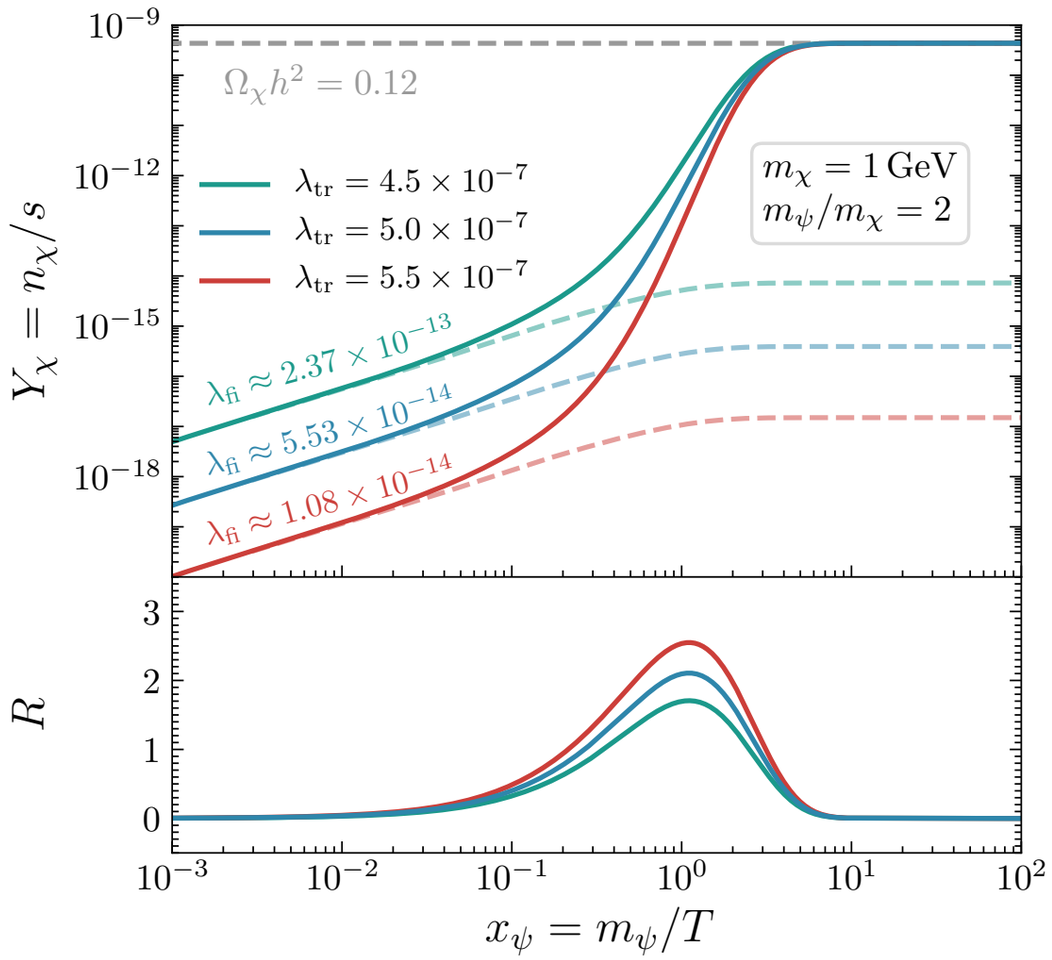


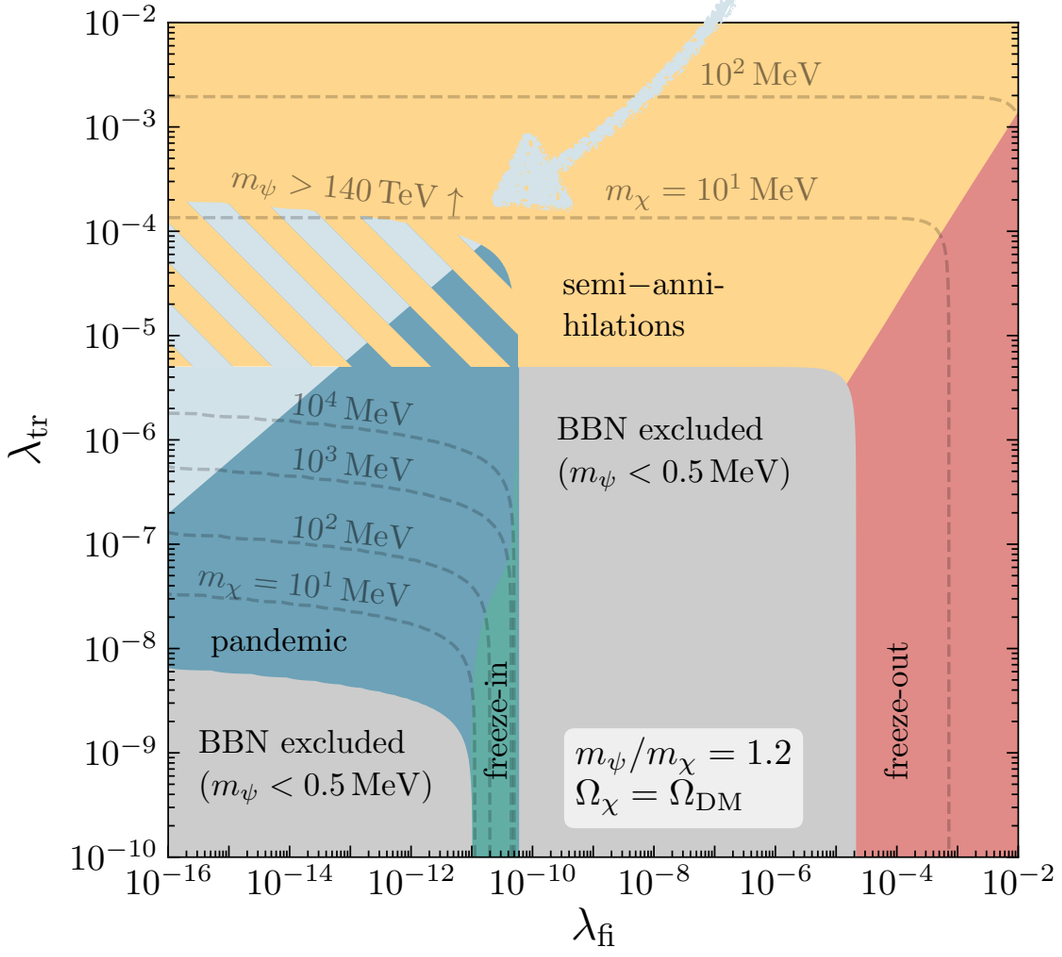
+

‘freeze-in’



2→4 freeze-in dominates





➡ *‘Pandemic’ production turns out to be a rather generic mechanism for the genesis of DM!*

Signals ?

- Necessarily model-dependent
  - 'Pandemic DM' describes a class of models, just like 'WIMP' does

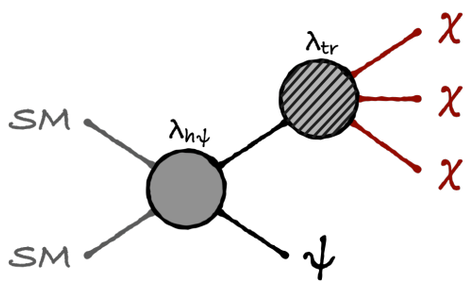
- Example: Higgs portal coupling

  ψ is itself a thermal relic (freeze-out!)

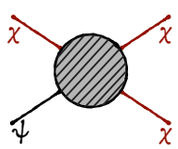
  = subdominant DM component

$$\mathcal{L} \supset \frac{1}{2}\lambda_{h\psi}\,|H|^2\,\psi^2$$

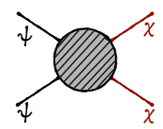
- $2 \to 4$ freeze-in production dominates:

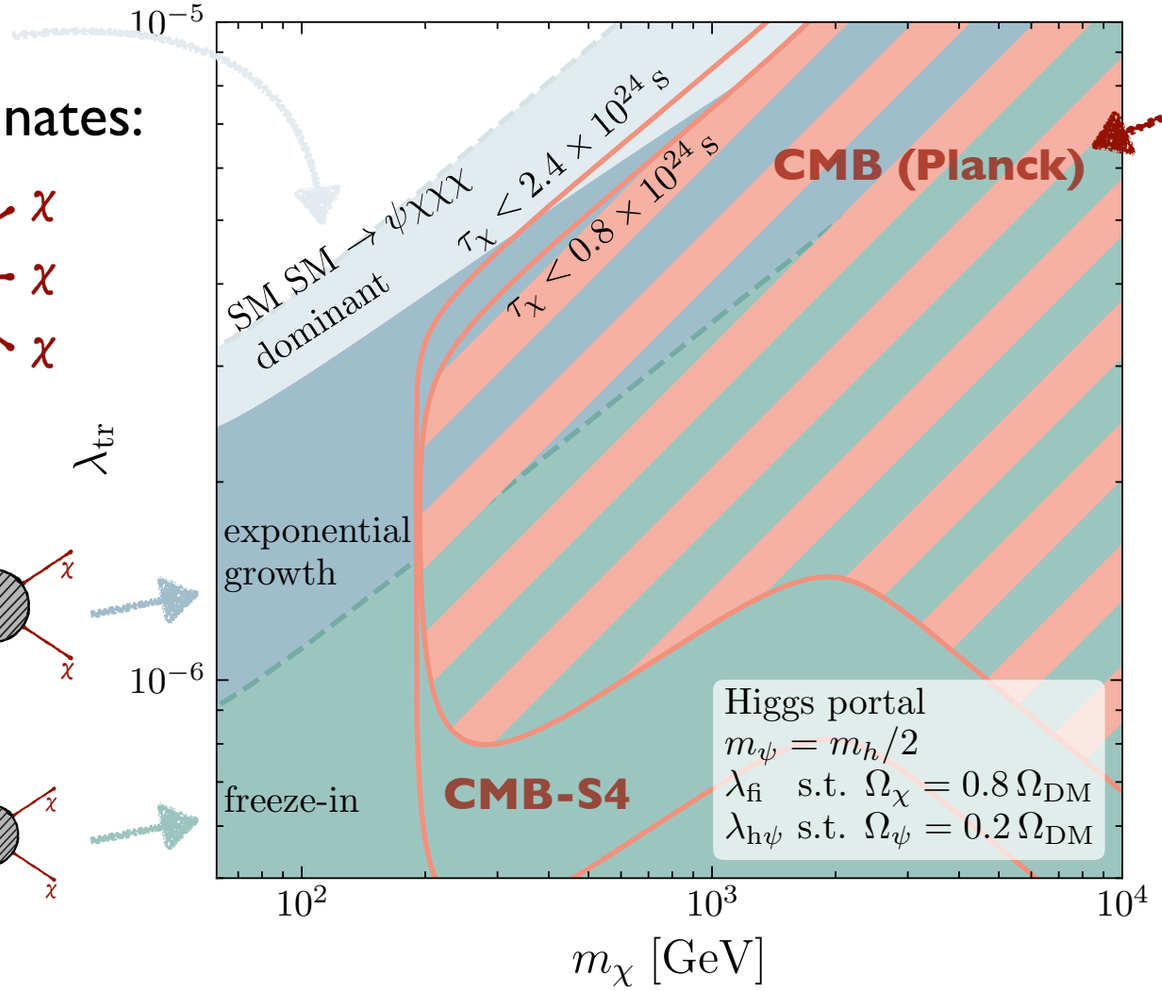


- exponential production

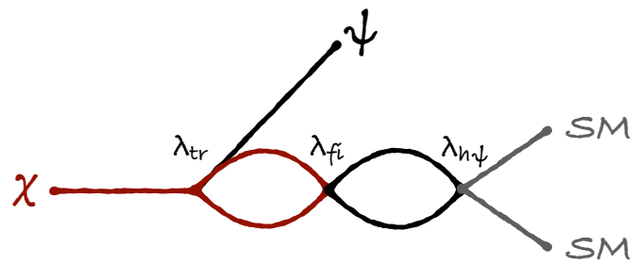


- Freeze-in production





- indirect detection signals from DM decay:

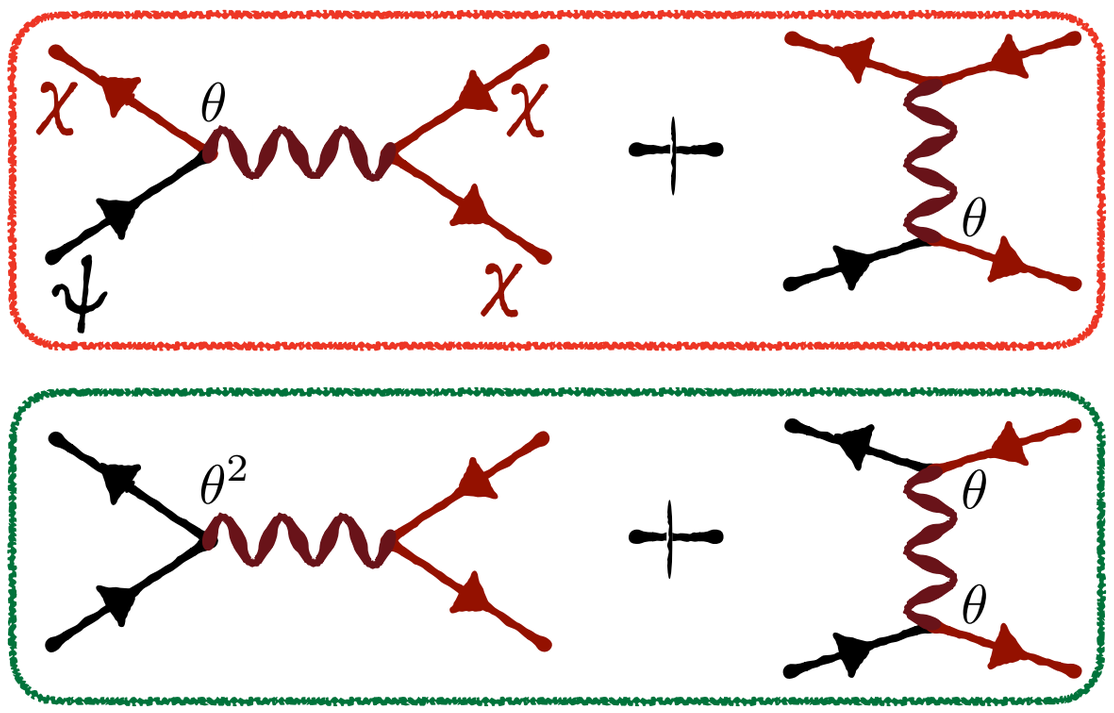


Further model building

- Q: Is there a *generic* way to realize $\langle \sigma v \rangle_{\rm fi} \ll \langle \sigma v \rangle_{\rm tr}$?

- A: yes — just add a dark sector mediator and mass mixing!

$$\mathcal{L} \supset -\delta m \left(\bar{\psi}\chi + \bar{\chi}\psi\right) - g\bar{\chi}\not{V}\chi \quad \Rightarrow \quad \mathcal{L} \supset -g\left[\bar{\chi}\not{V}\chi + \theta\left(\bar{\psi}\not{V}\chi + \bar{\chi}\not{V}\psi\right) + \theta^2\bar{\psi}\not{V}\psi\right]$$



transmission $\propto \theta$

freeze-in $\propto \theta^2$

Sterile neutrinos

- An excellent, well-motivated dark matter candidate
- Production by SM processes: oscillations with active neutrinos, combined with CC and NC scatterings

Dodelson & Widrow, PRL '94

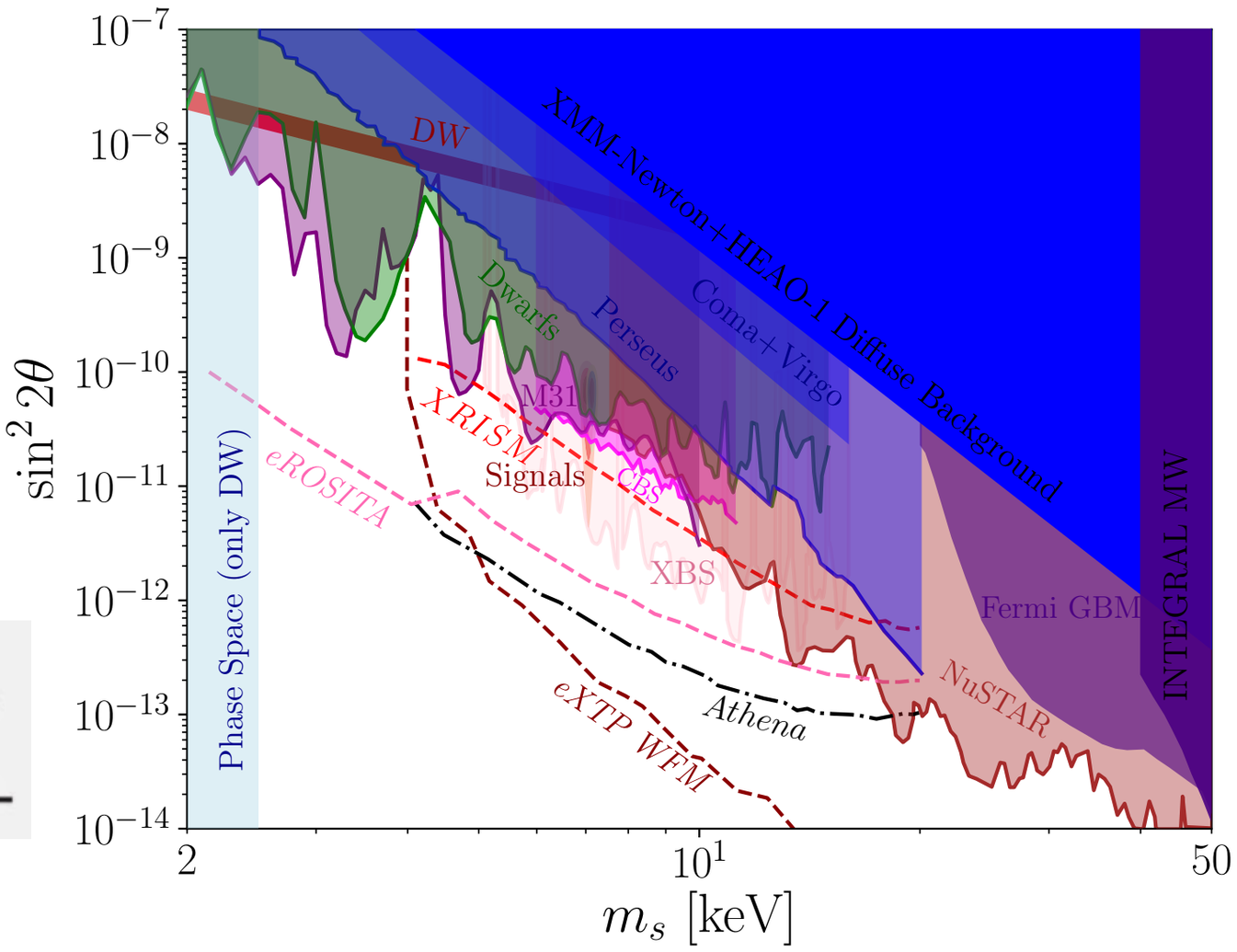
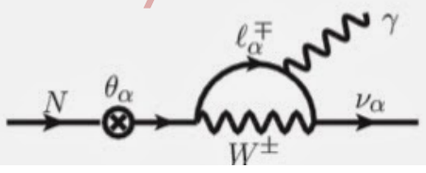


Fig.: Abazajian+, 2203.7377

X-ray lines



- Unfortunately, this scenario is ruled out by observations…

Sterile neutrinos — a new life ?

TB, Depta, Hufnagel, Kersten, Ruderman & Schmidt-Hoberg, arXiv:2206.10630

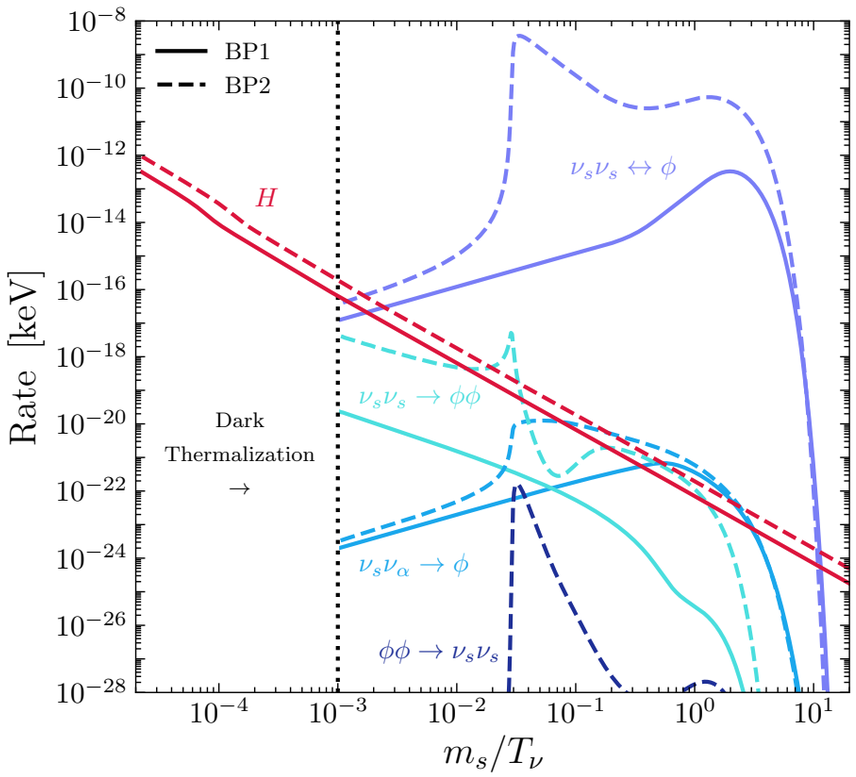
- Simply add a scalar ϕ that only couples to the sterile neutrinos

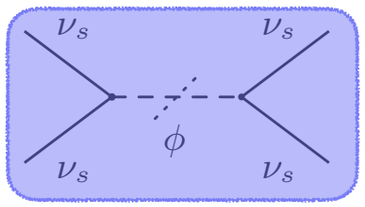
$$\mathscr{L} \supset \frac{y}{2}\phi\bar{\nu}_s\nu_s \Rightarrow \frac{y}{2}\phi[\sin^2\theta\bar{\nu}_\alpha\nu_\alpha - \sin\theta\cos\theta(\bar{\nu}_\alpha\nu_s + \bar{\nu}_s\nu_\alpha) + \cos^2\theta\bar{\nu}_s\nu_s] \qquad m_\phi > 2m_s$$

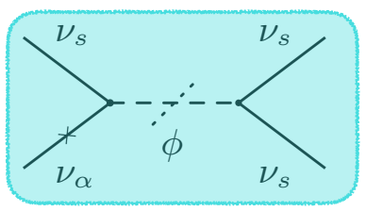
- Early times (~QCD PT): standard DW production
  - Adopt resulting number & energy density as initial condition

from Asaka, Laine & Shaposhnikov, JHEP '15

- Soon afterwards: efficient dark sector thermalization
  - ν_s, ϕ follow FD/BE distributions with *large* (negative) chemical potentials







⇒ Use Boltzmann equations

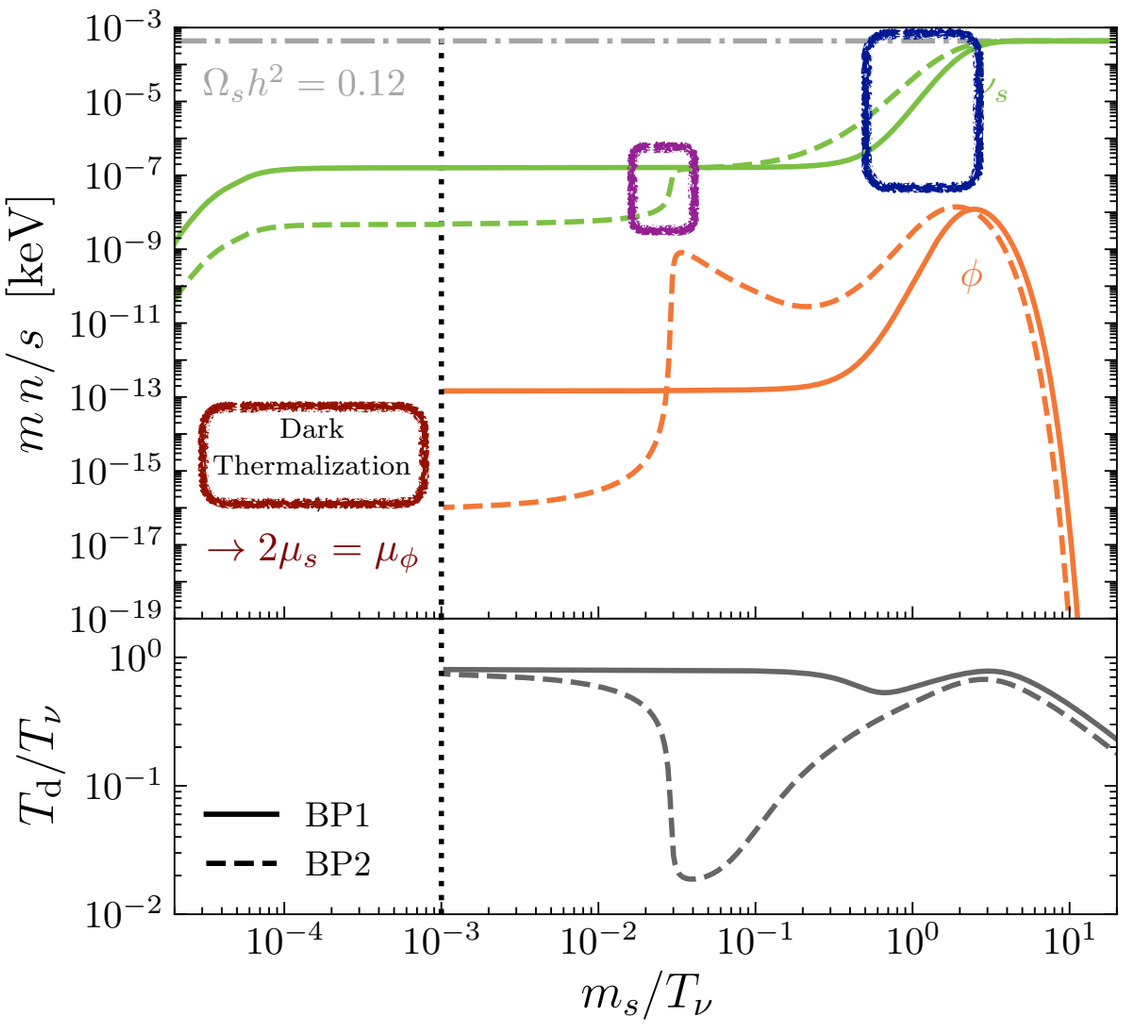
$$\dot{n}_s + 3Hn_s = C_{n_s}$$
$$\dot{n}_\phi + 3Hn_\phi = C_{n_\phi}$$
$$\dot{\rho} + 3H(\rho + P) = C_\rho\,,$$

to solve for $T_d(T), \mu_s(T), \mu_\phi(T)$

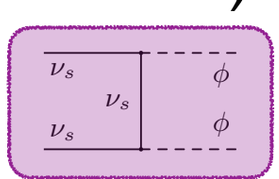
Evolution and constraints

TB, Depta, Hufnagel, Kersten, Ruderman & Schmidt-Hoberg, arXiv:2206.10630

- Two benchmark points
  - Solid: 'large' θ, small y
  - Dashed: smaller θ, larger y

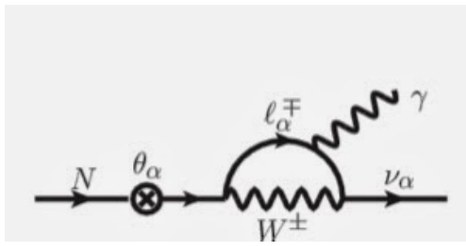


- 3 phases (after DW): dark thermalization
  exponential growth
  reproductive freeze-in



March-Russell+, PRD '20 ; Mondino+, PRD '21

- Observational constraints
  - (Standard) X-ray lines



  - ν_s self-interactions

$$\sigma_T/m_s \lesssim 1\,\mathrm{cm}^2/\mathrm{g}$$

cf. Tulin & Yu, PR '18

maybe 0.1 possible… (?)

  - Lyman-α

recast $m_\mathrm{WDM} > 1.9\,\mathrm{keV}$ to

Garzilli+, MNRAS '21

$$\lambda_\mathrm{FS} < 0.24\,\mathrm{Mpc}$$
$$r_\mathrm{s} < 0.36\,\mathrm{Mpc}$$

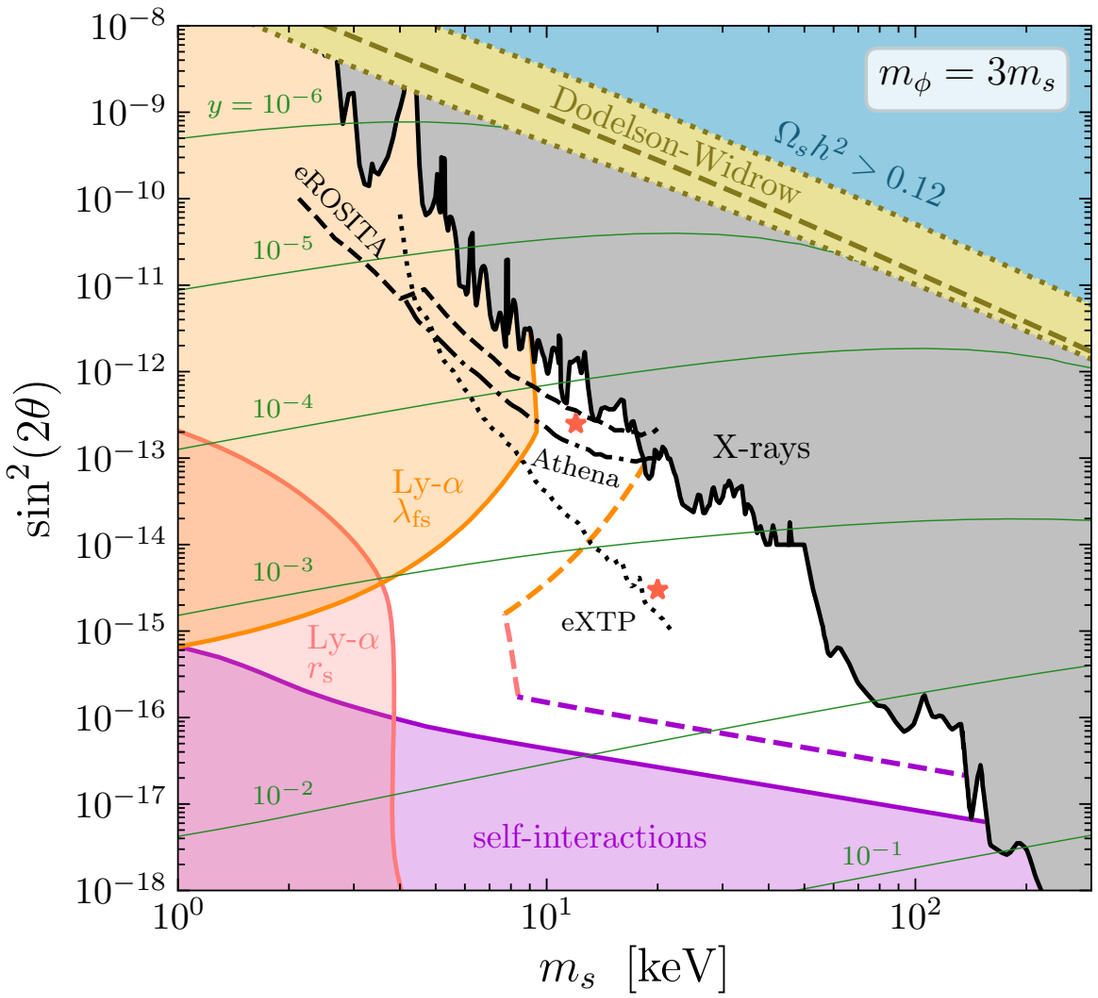
maybe $m_\mathrm{WDM} > 5.3\,\mathrm{keV}$ possible… (?)

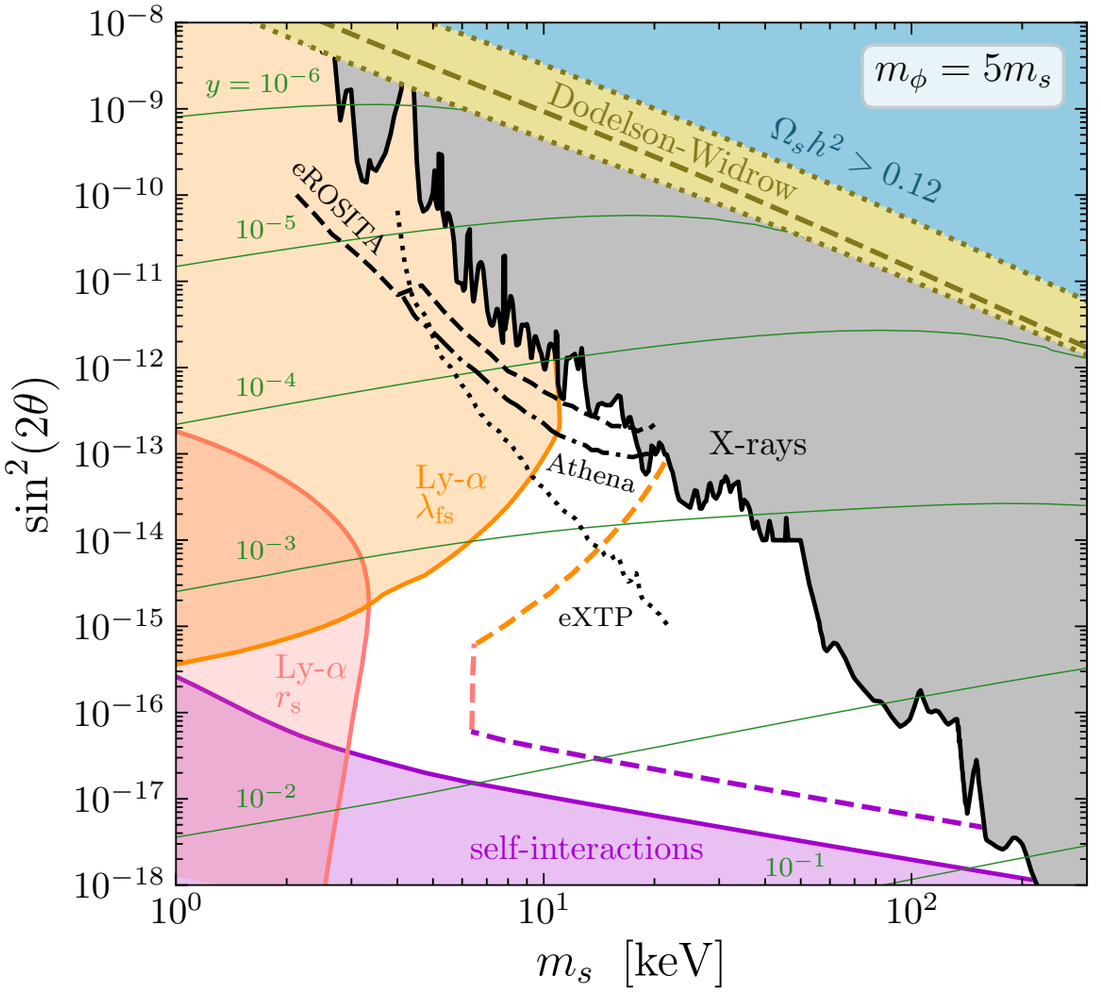
Palanque-Delabrouille+, JCAP '20

Sterile neutrinos — a new life !

TB, Depta, Hufnagel, Kersten, Ruderman & Schmidt-Hoberg, arXiv:2206.10630

- New parameter space below DW line
  - Bounded from above *and* below
  - Significant parts are (or will be) in observational reach

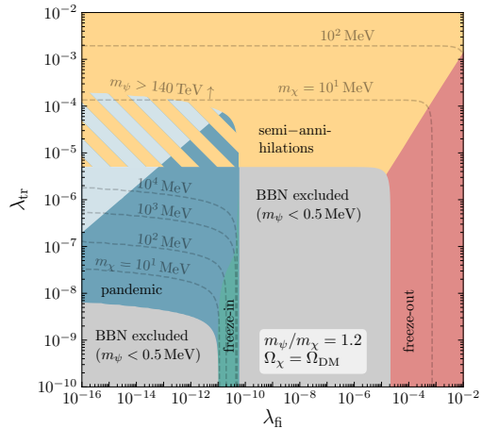




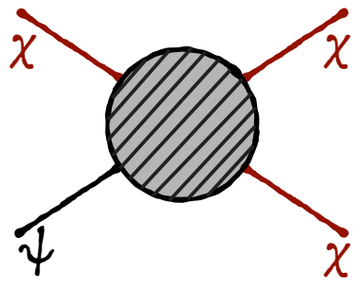
- Larger mediator masses widen possible window for sterile neutrino dark matter

Conclusions

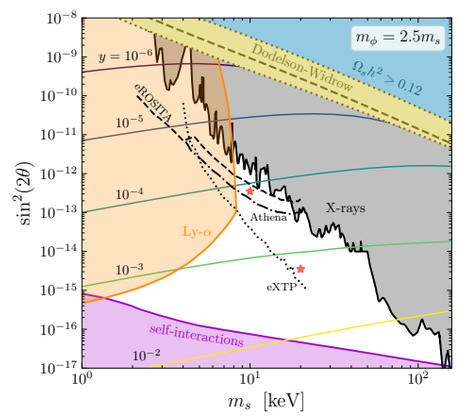
- There are a handful of generic ways of DM genesis from the primordial heat bath



- Pandemic dark matter is a novel such mechanism.
  Mathematical analogy to spread of diseases works almost scarily well



- Maybe this even brings new life to sterile neutrino DM ?!



Thanks for your attention!

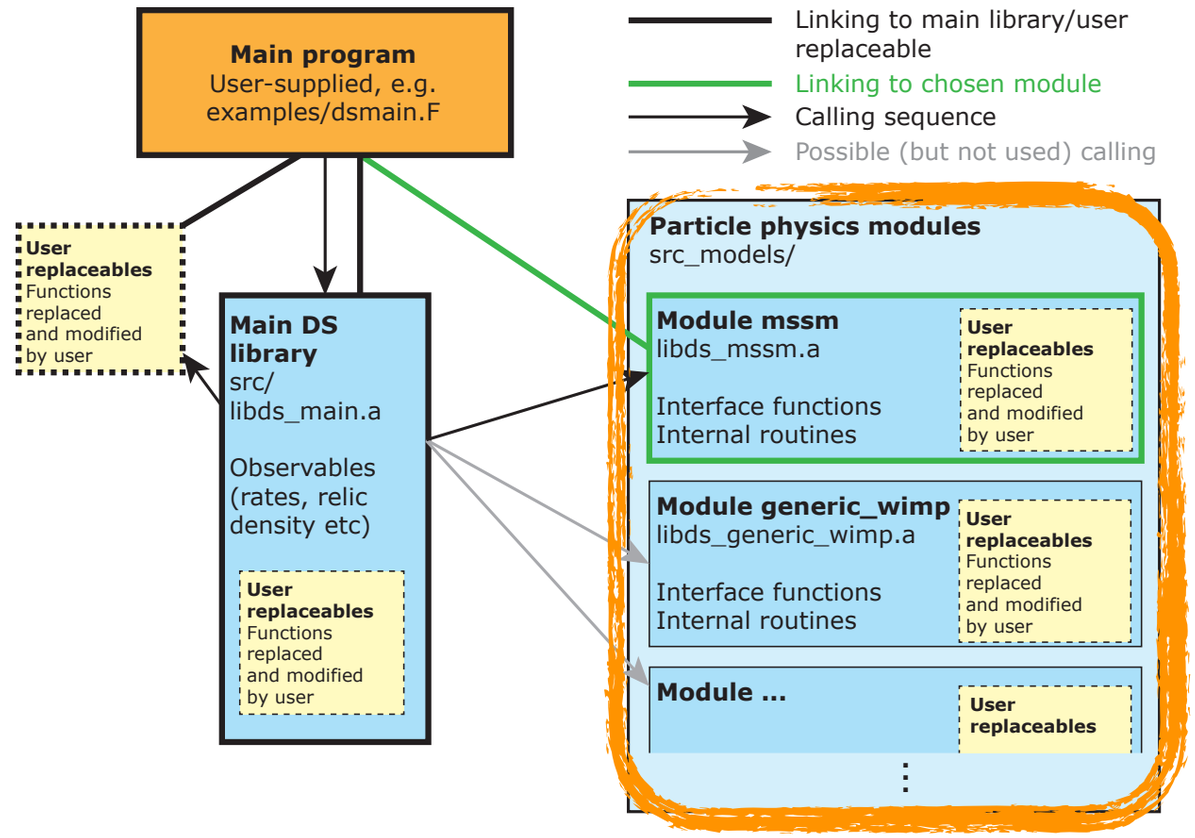
DarkSUSY

TB, Edsjö, Gondolo, Ullio & Bergström, JCAP '18

http://darksusy.hepforge.org

Since version 6: no longer restricted to supersymmetric DM !

- Numerical package to calculate 'all' DM related quantities:
  - *relic density + kinetic decoupling* **(also for $T_{\rm dark} \neq T_{\rm photon}$)**
  - *generic SUSY models + laboratory constraints implemented*
  - *cosmic ray propagation*
  - particle yields for generic DM annihilation or decay
  - *indirect detection rates: gammas, positrons, antiprotons, neutrinos*
  - *direct detection rates*
  - …



since 6.1: DM self-interactions

since 6.2: 'reverse' direct detection
(incl. full Q^2 -dependent scattering!)

since 6.3: freeze-in