Cosmology of keV-scale scalar Dark Matter

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Based on **arXiv:1809.04849** in collaboration with **Saniya Heeba** and **Patrick Stoecker**

Emmy Noether-Programm

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Outline

- A few words on WIMPs and Higgs portal models
- Decaying scalars via the freeze-in mechanism
- Freeze-in production in the Early Universe
- Cosmological evolution and self-interactions
- Phenomenology

Quick recap: Higgs portal models

- Assume that the DM particle is **uncharged** under the SM gauge group
  → Can only couple to other gauge invariant operators

- The invariant operator of lowest dimensional in the SM is $\boldsymbol{H^\dagger H}$

- Models in which DM couples only to this operator are called **Higgs portal models**

- Simplest realisation of Higgs portal: Real scalar with $\boldsymbol{Z_2}$ **symmetry**

$$V_{\mathbb{Z}_2} = \mu_H^2 |H|^2 + \frac{1}{2}\lambda_h |H|^4 + \frac{1}{2}\lambda_{hS} S^2 |H|^2 + \frac{1}{2}\mu_S^2 S^2$$

- Scalars enter into **thermal equilibrium** in the Early Universe and then freeze out
  - **Prototypical WIMP**
  - Many potential signatures, strong experimental constraints

Where are the WIMPs?

by Saniya Heeba

- Higgs portal models are **still viable** in some regions of parameter space

  Athron, FK et al., arXiv:1806.11281

- But the non-observation of WIMPs mounts **substantial pressure** on the idea

- Well-motivated to **question underlying assumptions** and consider alternative production mechanisms

What if there is no stabilising symmetry?

- Assume that the Z_2 symmetry of the scalar singlet is **spontaneously broken**

$$\mathcal{L}_{\text{scalar}} = \frac{1}{2}\partial^\mu s \partial_\mu s - \frac{1}{2}m_s^2\, s^2 - \frac{1}{4}\lambda_s\, s^4 - \lambda_s\, v_s\, s^3 - \frac{1}{2}\lambda_{hs}\, |H|^2 (s^2 + 2\, s\, v_s)$$

- After EW symmetry breaking this becomes

$$\mathcal{L}_{\text{scalar}} = \frac{1}{2}\partial^\mu s \partial_\mu s - \frac{1}{2}m_s^2\, s^2 - \frac{1}{4}\lambda_s\, s^4 - \lambda_s\, v_s\, s^3 - \frac{1}{4}\lambda_{hs}\, (h^2 + 2\, h\, v)(s^2 + 2\, s\, v_s)$$

→ Scalar singlets can mix with SM Higgs bosons:

$$\begin{pmatrix} h_{\text{SM}} \\ h_s \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix} \qquad \tan 2\theta \equiv \frac{\lambda_{hs}\, v\, v_s}{\lambda\, v^2 - \lambda_s\, v_s^2}$$

What if there is no stabilising symmetry?

- Because of this mixing scalar singlets can decay into fermions and gauge bosons
- Higgs portal coupling needs to be tiny (and scalar singlet mass small) to ensure survival of scalar singlets to present day
- Tiny coupling means scalar singlets will no longer enter into thermal equilibrium:

$$\vdots \; \langle \sigma v \rangle \, n^{\mathrm{eq}} < H(T)$$

- Need to consider alternative production mechanisms (**WIMP → FIMP**)

Freeze-in mechanism

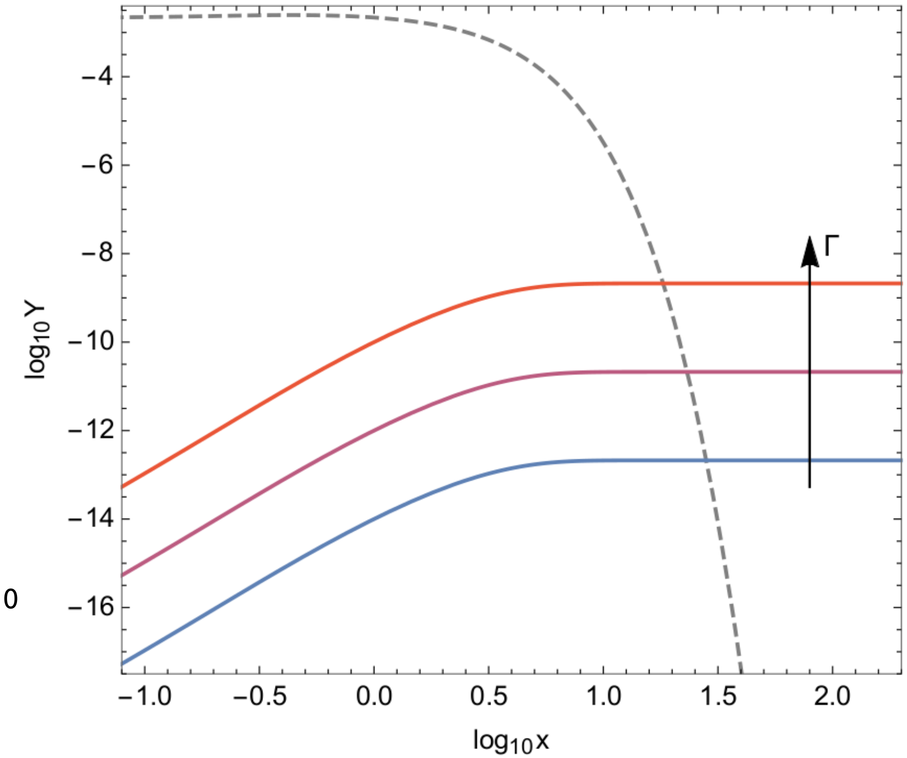
- Assume that only the visible sector is populated after inflation
  → initial abundance of DM particles **negligible**

Hall et al., arXiv:0911.1120
Bernal et al., arXiv:1706.07442

- If the dark sector is not thermalised, particle production proceeds via “energy leakage” from the visible sector

- Simplified Boltzmann equation:

$$\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = \mathcal{C}_{ab}\frac{s}{Hx}\langle\sigma v\rangle Y^2_{\mathrm{eq},SM}$$



- **Stronger interactions ↔ larger abundance**

- $\Omega h^2 = 0.12$ typically requires coupling $\lambda < 10^{-10}$

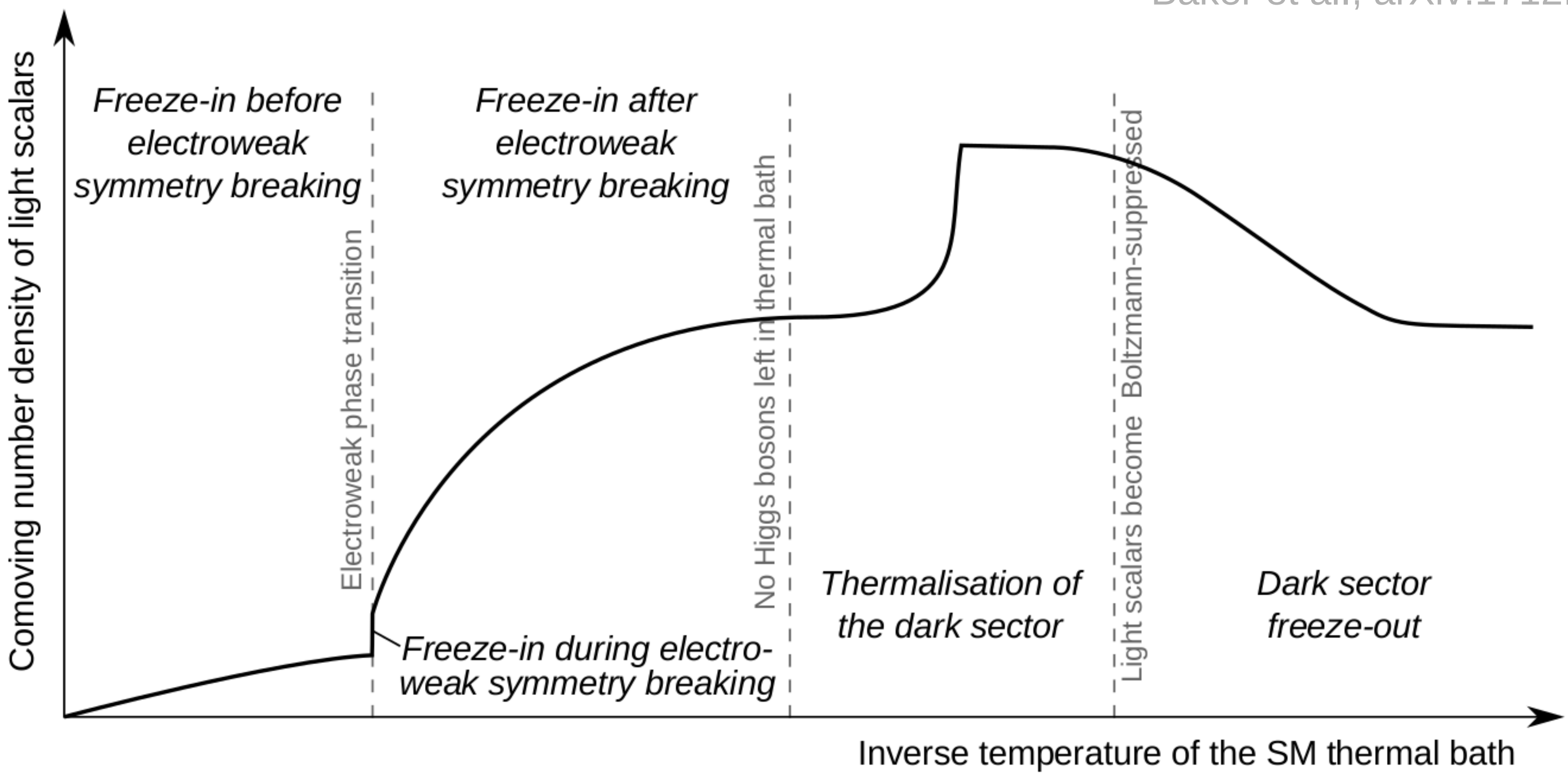
Freeze-in production in five steps

- Freeze-in calculation for scalar FIMPs with Z_2 symmetry well-established

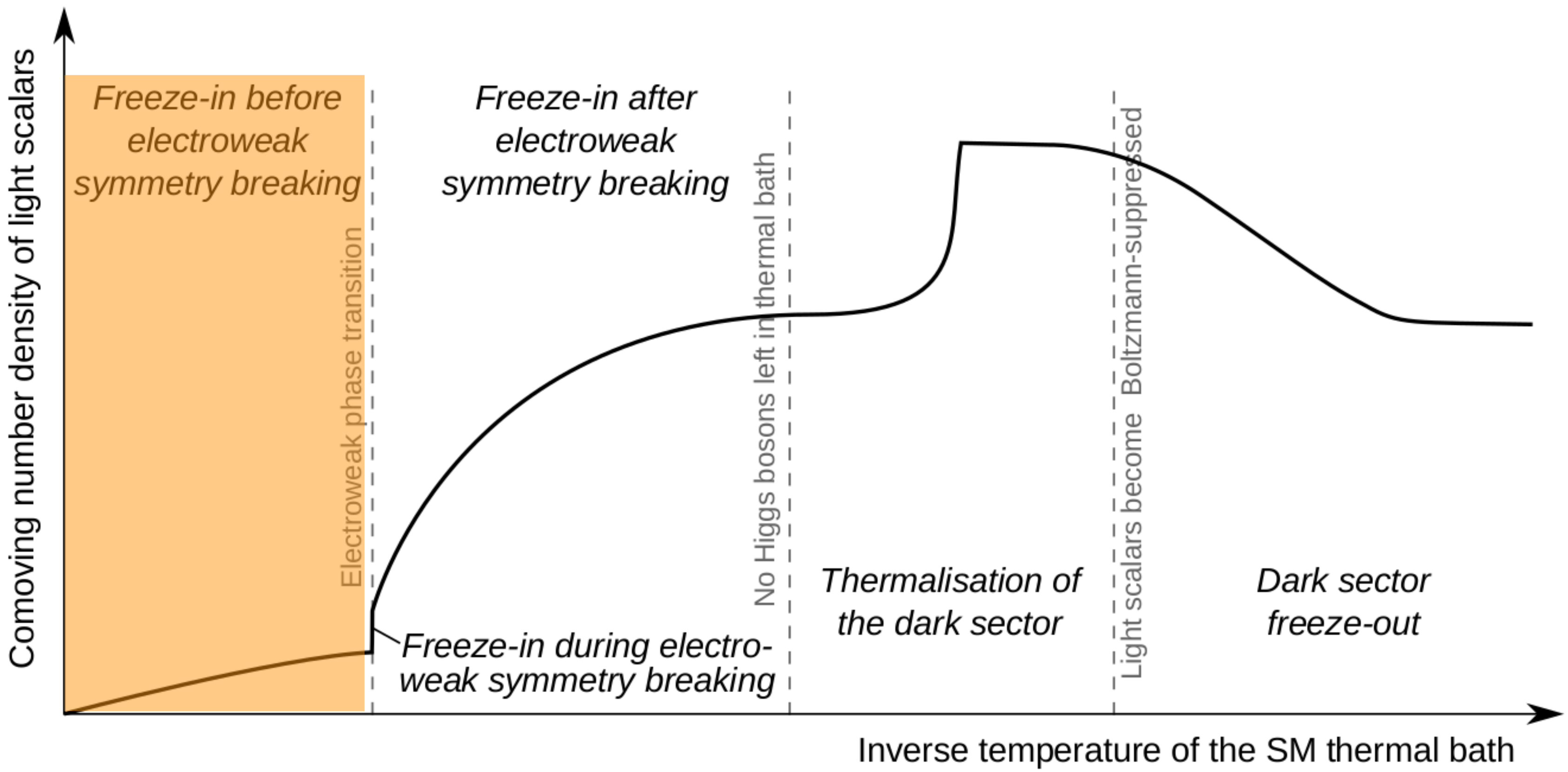
Heikinheimo et al., arXiv:1604.02401

- In the absence of a stabilising symmetry, the story becomes a **lot more complicated**

Baker et al., arXiv:1712.03962

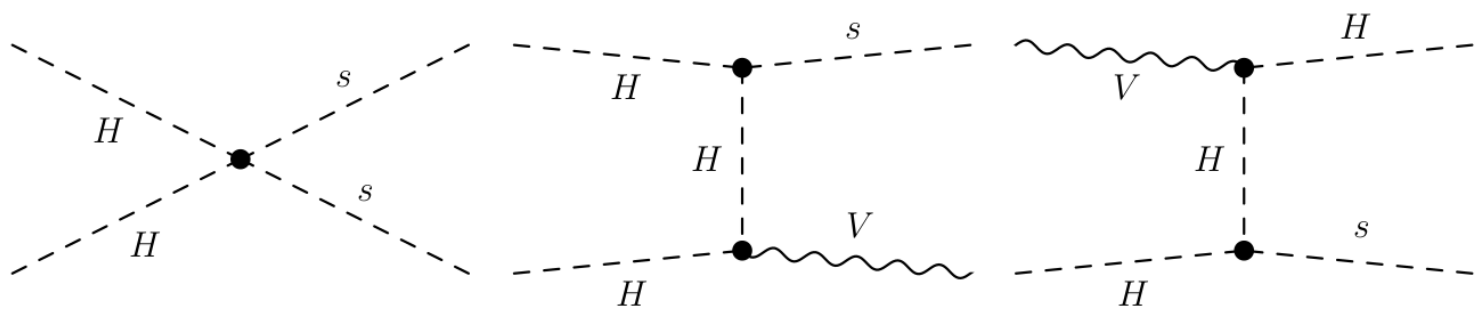


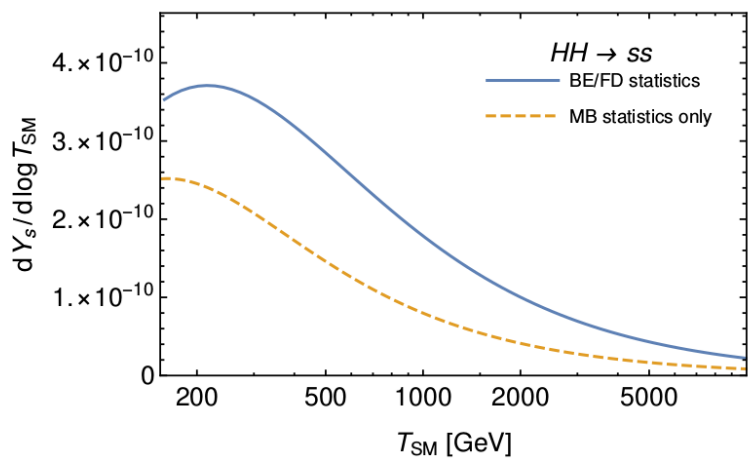
Step 1: Freeze-in before EWSB



Production modes before EWSB

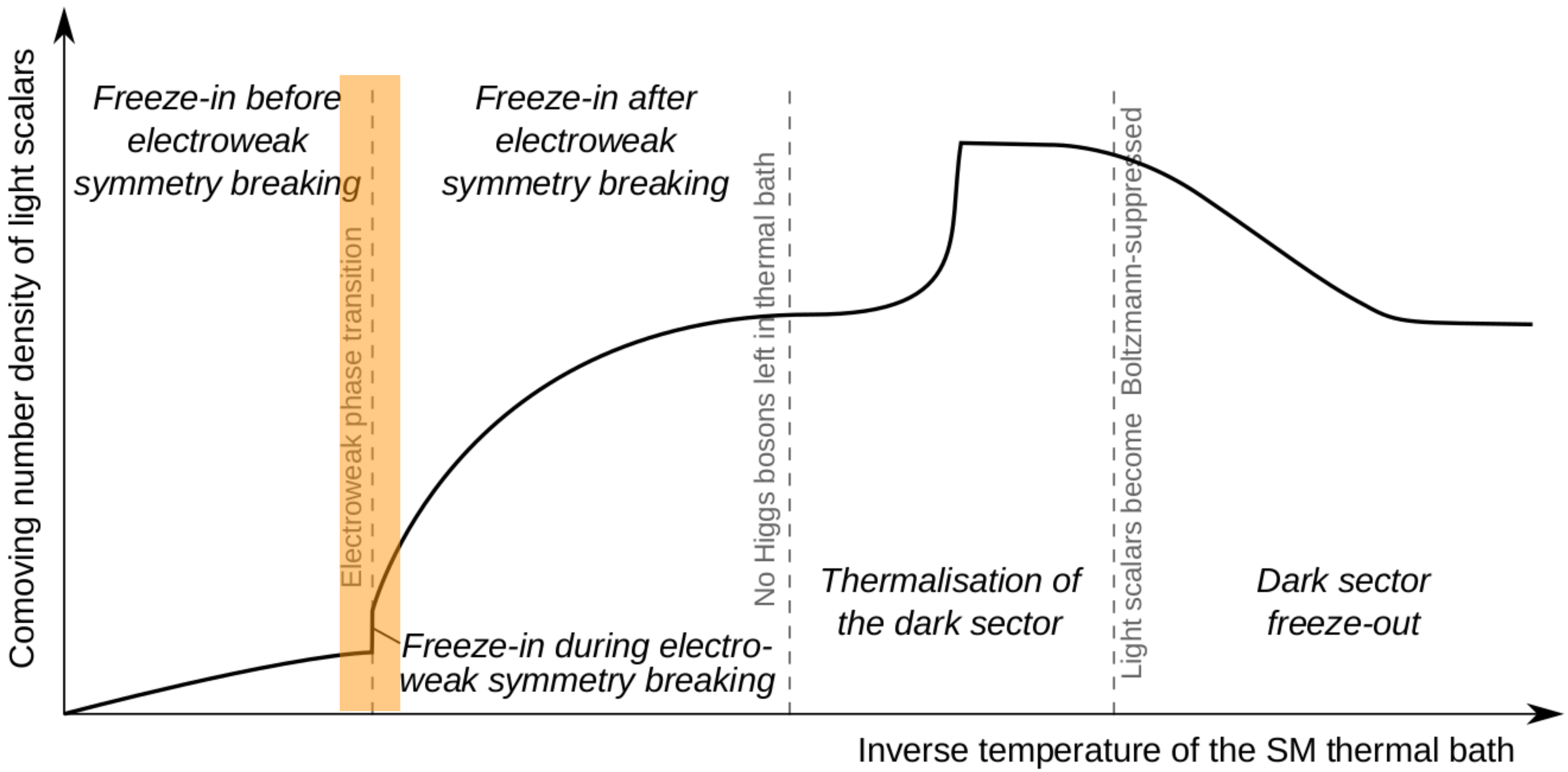
- Unbroken electroweak symmetry: No Higgs vacuum expectation value
  → Higgs and light scalar cannot mix
  → Light scalar does not couple to SM fermions
  → Limited number of production channels





- Technical complications:
  - Temperature-dependent Higgs mass
  - Relativistic Higgs bosons in initial state
    → Need to use Bose-Einstein statistics

Step 2: Freeze-in during EWSB



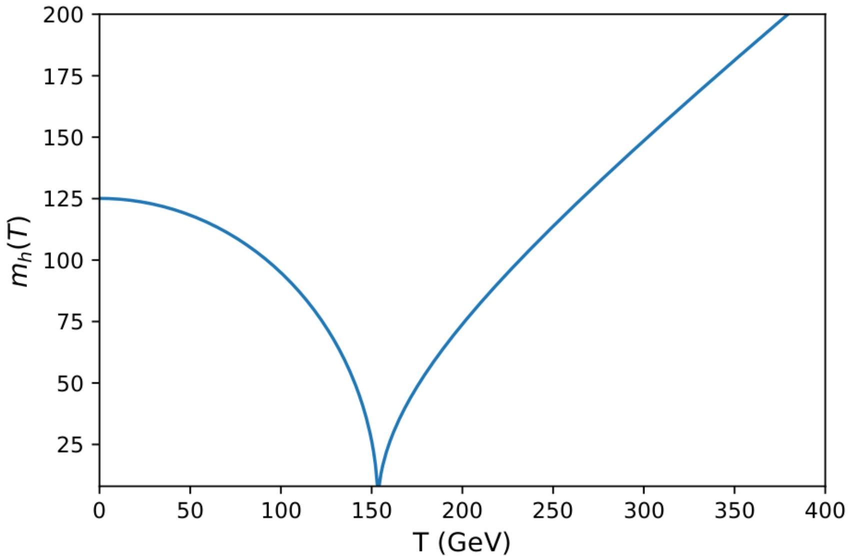
Production through oscillations

- Just after EW phase transition, Higgs has a vev and a very small mass

- Mixing between the two scalars can be large:

$$\theta(T) = \frac{\lambda_{hs}\, v(T)\, v_s}{m_h^2(T) - m_s^2}$$

- Similar to production of dark photons



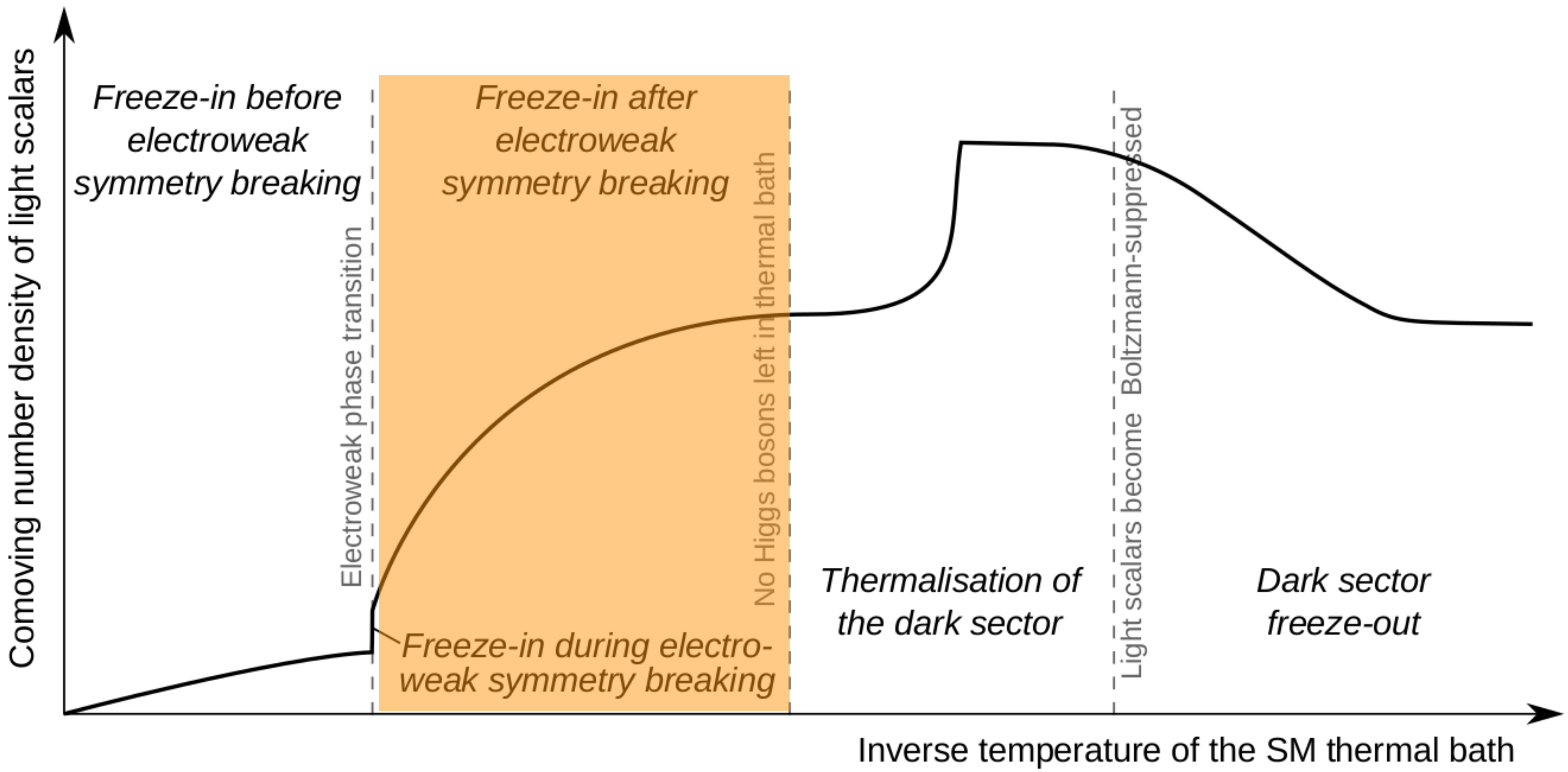
Redondo & Postma, arXiv:0811.0326

- Final abundance depends on how quickly the Higgs mass changes:

$$\Delta Y_{s,2} = \frac{\pi\,\zeta(2)\, Y_h(T_{\rm osc})}{\zeta(3)} \frac{\lambda_{hs}^2\, v(T_{\rm osc})^2\, v_s^2}{H(T_{\rm osc})\, T_{\rm osc}^2} \left| \frac{\mathrm{d}m_h^2}{\mathrm{d}T} \right|^{-1}_{T=T_{\rm osc}}$$

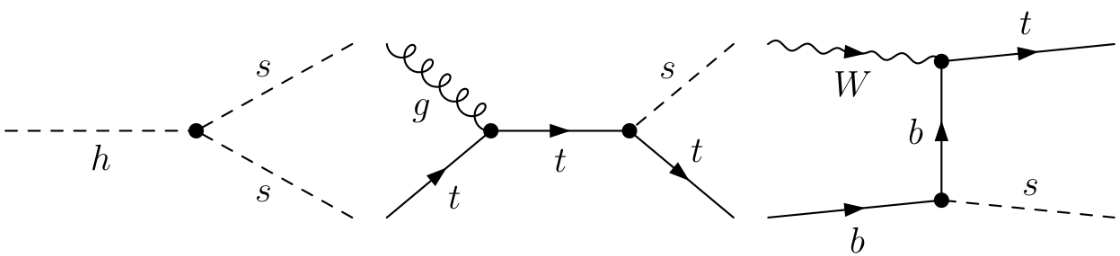
Effect turns out to be negligible for sub-GeV scalars

Step 3: Freeze-in after EWSB



New production modes

- Mixing remains non-zero also at lower temperatures
  → Higgs bosons can decay into pairs of light scalars
  → Light scalars obtain couplings to fermions



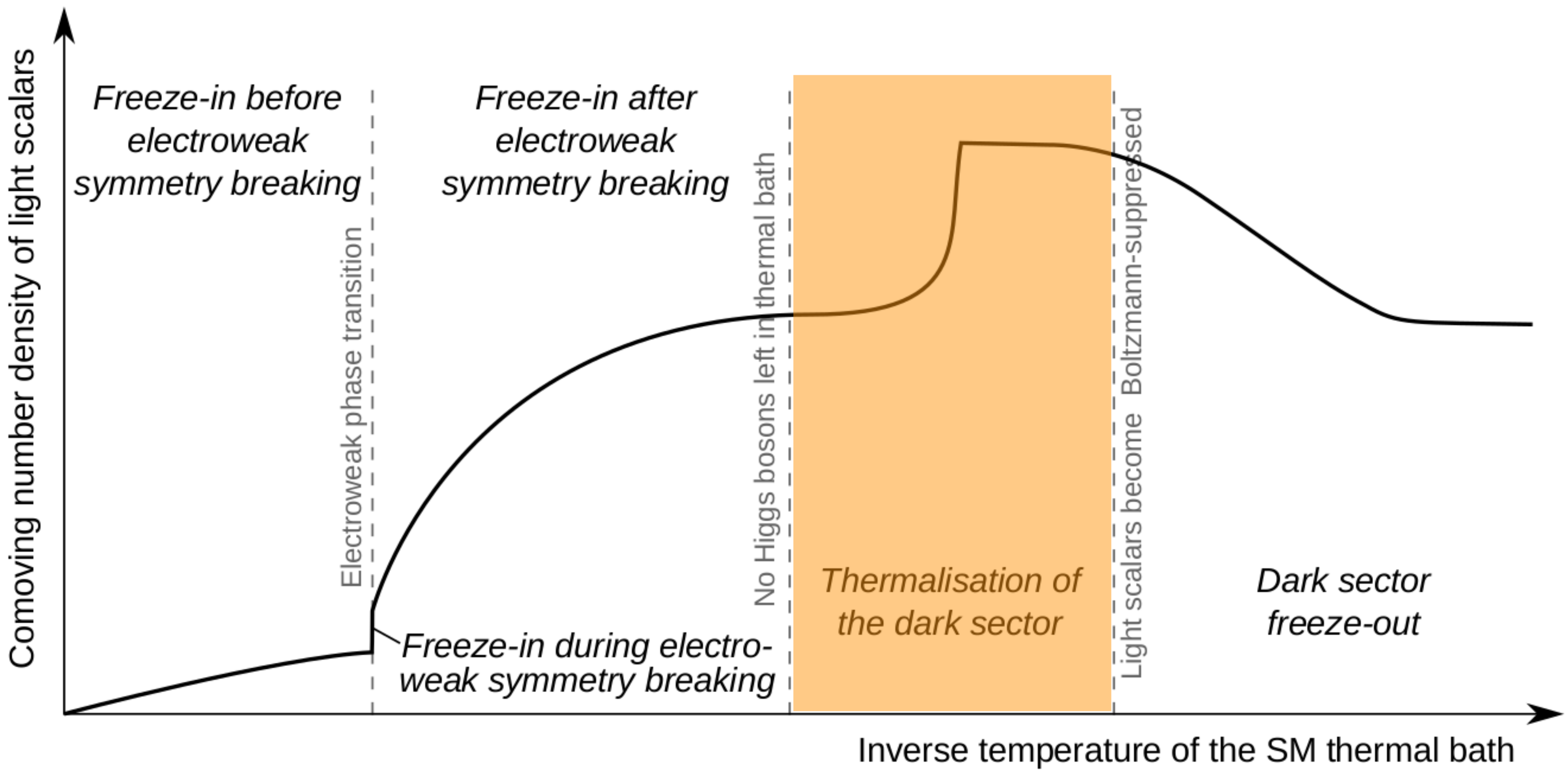
- Tons of production modes → need micrOmegas!

Belanger et al., arXiv:1801.03509

- Not all processes are well-behaved at high energies
  → Essential to cut off production at EWPT

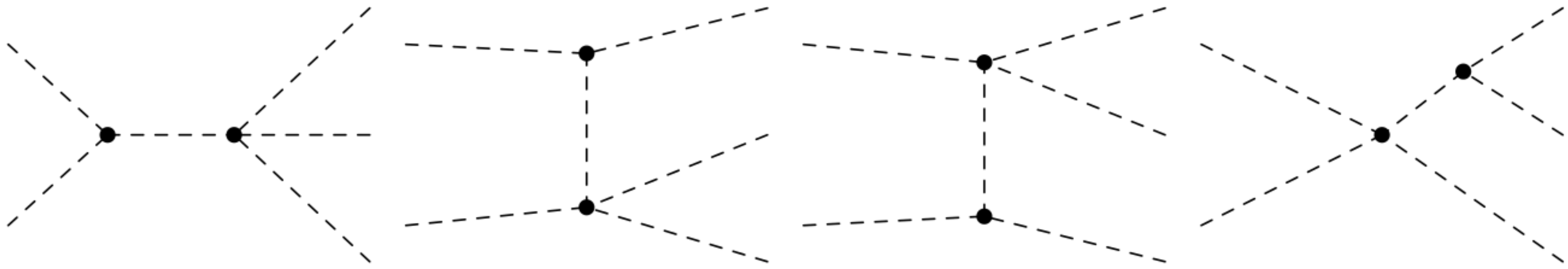
$W^+, b \to t, \rho$	$\tau^+, \tau^- \to \gamma, \rho$	$W^-, W^+ \to h, \rho$	$W^+, e^- \to \nu_e, \rho$
$Z, W^+ \to W^+, \rho$	$\bar{c}, c \to \gamma, \rho$	$\bar{\nu}_e, \nu_e \to Z, \rho$	$W^-, \nu_e \to e^-, \rho$
$g, t \to t, \rho$	$\gamma, b \to b, \rho$	$\bar{\nu}_m, \nu_m \to Z, \rho$	$W^-, \nu_m \to \mu^-, \rho$
$W^-, t \to b, \rho$	$\bar{b}, b \to \gamma, \rho$	$\bar{\nu}_t, \nu_t \to Z, \rho$	$W^-, \nu_t \to \tau^-, \rho$
$W^-, c \to s, \rho$	$\gamma, \mu^- \to \mu^-, \rho$	$Z, \tau^- \to \tau^-, \rho$	$Z, t \to t, \rho$
$W^-, u \to d, \rho$	$W^-, W^+ \to \rho, \rho$	$Z, e^- \to e^-, \rho$	$g, b \to b, \rho$
$W^+, d \to u, \rho$	$\mu^+, \mu^- \to \gamma, \rho$	$Z, \mu^- \to \mu^-, \rho$	$W^-, W^+ \to \gamma, \rho$
$W^+, s \to c, \rho$	$\bar{c}, c \to h, \rho$	$\bar{d}, d \to g, \rho$	$\bar{b}, b \to \rho, \rho$
$W^-, W^+ \to Z, \rho$	$\gamma, s \to s, \rho$	$\bar{t}, t \to h, \rho$	$\bar{\nu}_e, e^- \to W^-, \rho$
$\bar{u}, d \to W^-, \rho$	$Z, Z \to \rho, \rho$	$Z, h \to Z, \rho$	$\bar{\nu}_m, \mu^- \to W^-, \rho$
$\bar{c}, s \to W^-, \rho$	$h, h \to \rho, \rho$	$Z, Z \to h, \rho$	$\bar{\nu}_t, \tau^- \to W^-, \rho$
$\bar{t}, t \to g, \rho$	$\bar{s}, s \to \gamma, \rho$	$g, u \to u, \rho$	$\bar{t}, b \to W^-, \rho$
$Z, b \to b, \rho$	$\bar{s}, s \to \rho, \rho$	$\bar{u}, u \to g, \rho$	$g, s \to s, \rho$
$Z, d \to d, \rho$	$\tau^+, \tau^- \to h, \rho$	$e^+, e^- \to Z, \rho$	$\bar{b}, b \to g, \rho$
$Z, s \to s, \rho$	$b, h \to b, \rho$	$\mu^+, \mu^- \to Z, \rho$	$\gamma, W^+ \to W^+, \rho$
$Z, c \to c, \rho$	$\bar{u}, u \to \gamma, \rho$	$\tau^+, \tau^- \to Z, \rho$	$\bar{d}, d \to Z, \rho$
$Z, u \to u, \rho$	$\gamma, u \to u, \rho$	$W^-, c \to d, \rho$	$\bar{s}, s \to Z, \rho$
$W^+, \tau^- \to \nu_t, \rho$	$\mu^+, \mu^- \to \rho, \rho$	$W^+, s \to u, \rho$	$\bar{b}, b \to Z, \rho$
$W^+, \mu^- \to \nu_m, \rho$	$\gamma, d \to d, \rho$	$W^-, u \to s, \rho$	$Z, \nu_e \to \nu_e, \rho$
$\mu^-, h \to \mu^-, \rho$	$\bar{d}, d \to \gamma, \rho$	$W^+, d \to c, \rho$	$Z, \nu_m \to \nu_m, \rho$
$\bar{d}, d \to h, \rho$	$\bar{t}, t \to \rho, \rho$	$\bar{u}, s \to W^-, \rho$	$Z, \nu_t \to \nu_t, \rho$
$e^+, e^- \to \rho, \rho$	$e^+, e^- \to \gamma, \rho$	$\bar{c}, d \to W^-, \rho$	$\bar{u}, u \to Z, \rho$
$\bar{u}, u \to h, \rho$	$c, h \to c, \rho$	$\gamma, t \to t, \rho$	$\bar{c}, c \to Z, \rho$
$d, h \to d, \rho$	$\gamma, e^- \to e^-, \rho$	$\bar{c}, c \to \rho, \rho$	$\bar{s}, s \to g, \rho$
$u, h \to u, \rho$	$\tau^-, h \to \tau^-, \rho$	$\bar{t}, t \to \gamma, \rho$	$W^+, h \to W^+, \rho$
$e^+, e^- \to h, \rho$	$\bar{s}, s \to h, \rho$	$\tau^+, \tau^- \to \rho, \rho$	$t, h \to t, \rho$
$e^-, h \to e^-, \rho$	$\mu^+, \mu^- \to h, \rho$	$h, h \to h, \rho$	$g, c \to c, \rho$
	$\bar{d}, d \to \rho, \rho$	$\bar{b}, b \to h, \rho$	$\bar{t}, t \to Z, \rho$
	$\bar{u}, u \to \rho, \rho$	$\gamma, c \to c, \rho$	$\bar{c}, c \to g, \rho$
	$s, h \to s, \rho$	$\gamma, \tau^- \to \tau^-, \rho$	$g, d \to d, \rho$

Step 4: Thermalisation of the dark sector



Number-changing processes

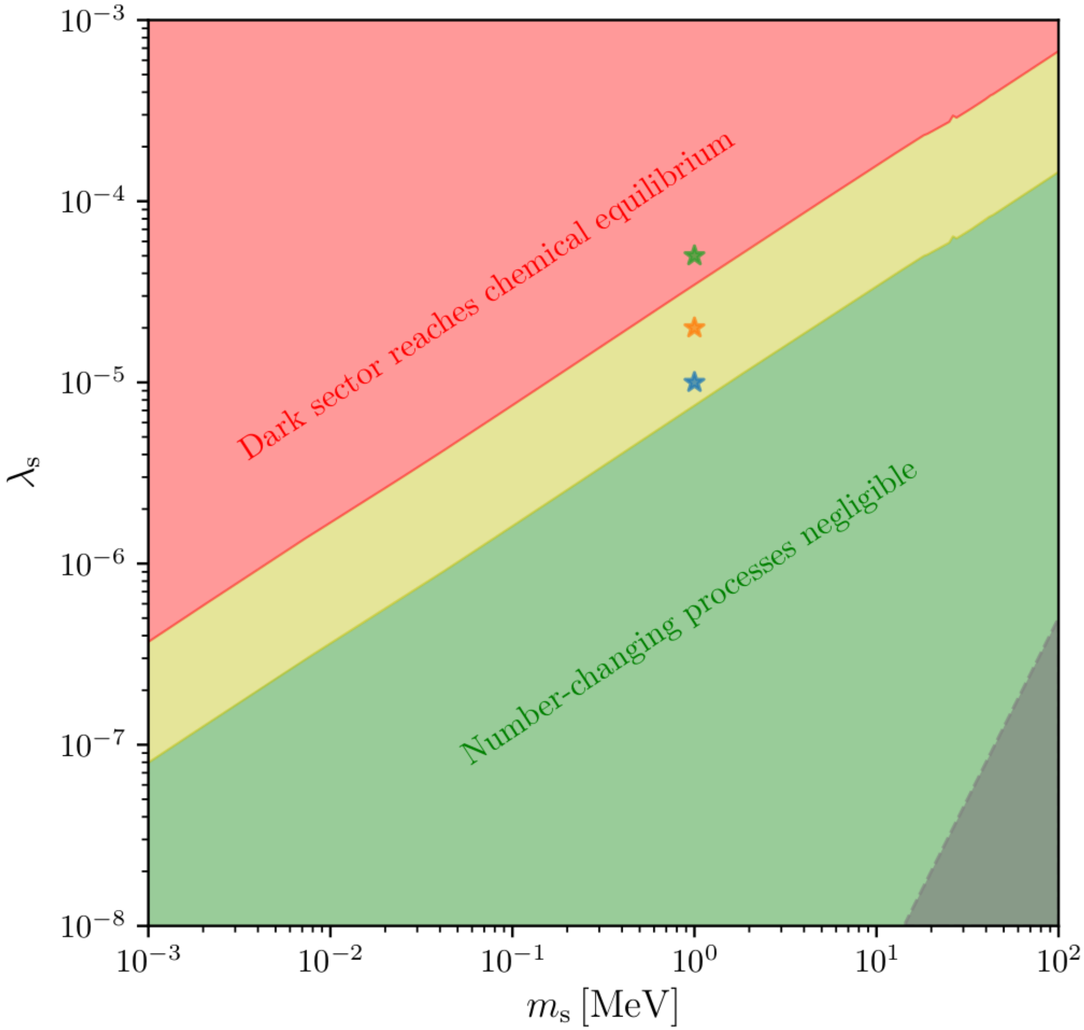
- After freeze-in dark sector is populated with few but highly-energetic particles
  → Non-vanishing chemical potential
  → Need to consider number-changing processes



Broken Z_2-symmetry: 2→3 processes allowed

- Entropy is conserved separately in the two sectors
  → Increase in number density leads to decrease in dark sector temperature T_{dark}

Thermalisation and entropy conservation



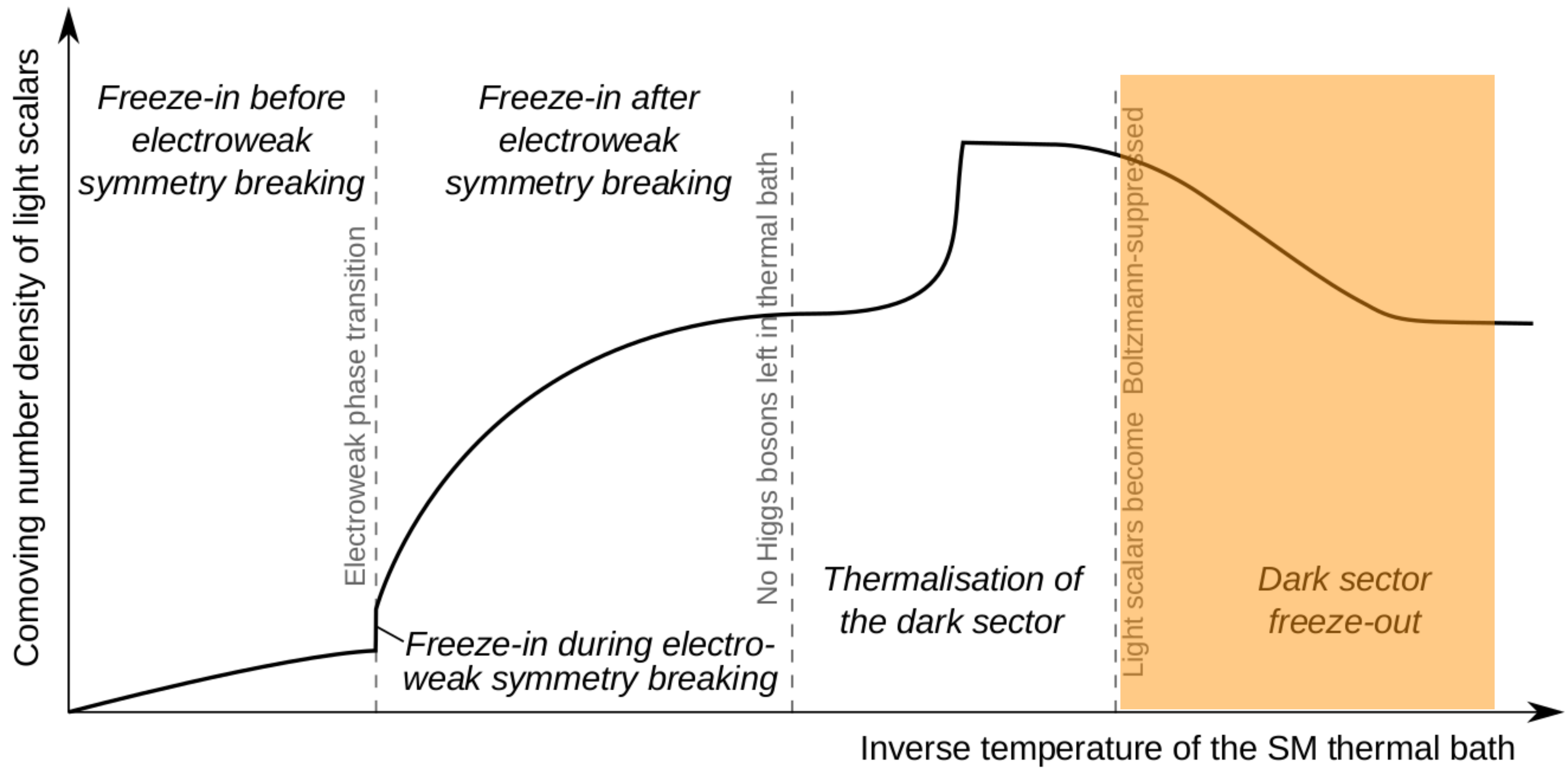
- If rate of 2→3 processes exceeds Hubble rate, dark sector reaches chemical equilibrium
- Number density given by equilibrium distribution ($\mu_{\text{dark}} = 0$):

$$n_s^{\text{eq}} = \frac{1}{2\pi^2} \int \frac{k^2 \, \mathrm{d}k}{\exp\left(E/T_{\text{dark}}\right) - 1}$$

Note: Plot assumes freeze-in dominantly via Higgs decays

→ not valid in gray shaded region

Step 5: Dark sector freeze-out



Cannibalism in the dark sector

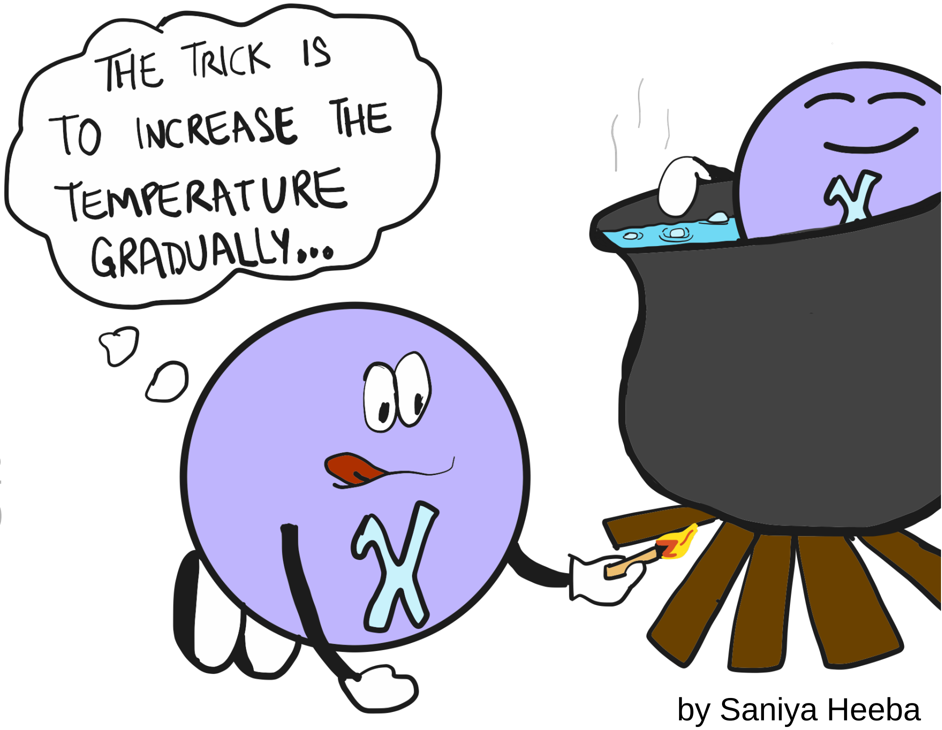
- With decreasing temperature fewer scalar particles have sufficient energy to produce new particles, so 2→3 processes become inefficient
- 3→2 processes stay efficient and deplete the dark sector, leading to an increase of the dark sector temperature

Cannibalistic dark matter

(“*eating each other to stay warm*”)

- At some point chemical equilibrium can no longer be maintained and the number-changing interactions freeze out

Carlson et al., Astrophys.J. 398 (1992) 43-52
Pappadopulo et al., arXiv:1602.04219
Farina et al., arXiv:1607.03108



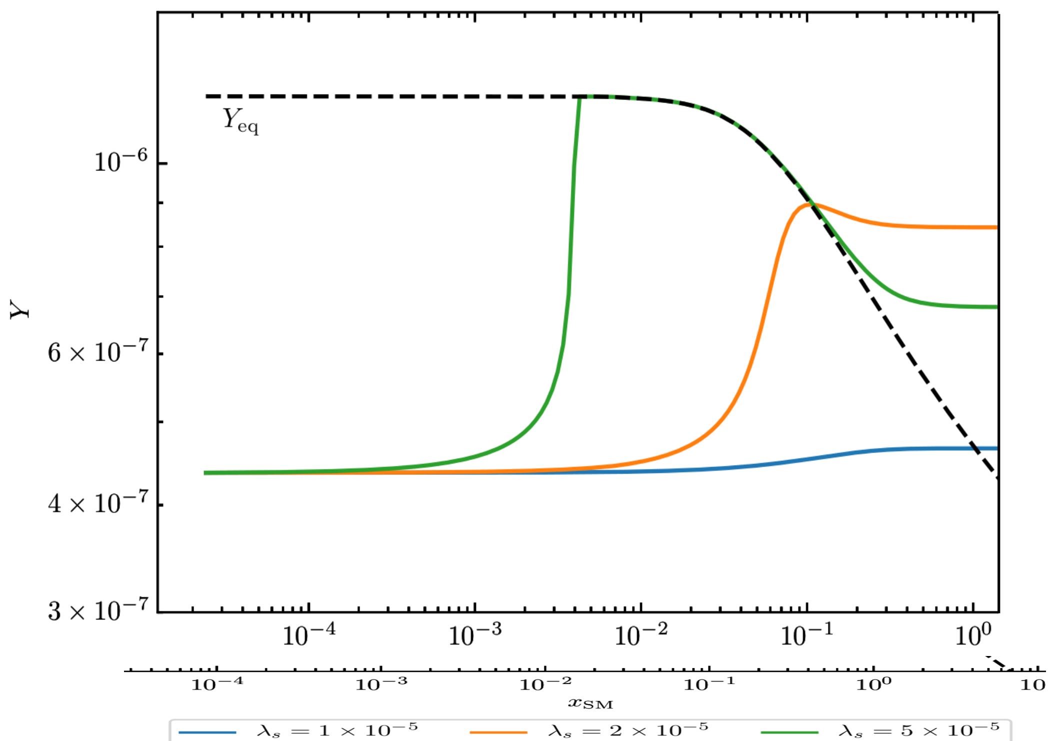
by Saniya Heeba

Solving the Boltzmann equation

- Evolution of comoving number density governed by modified Boltzmann equation

$$\frac{\mathrm{d}Y_s}{\mathrm{d}x_{\mathrm{SM}}} = \frac{s_{\mathrm{SM}}}{H\,x_{\mathrm{SM}}} \langle \sigma v \rangle_{2\to 3} Y_s^2 \left[1 - \frac{Y_s}{Y_s^{\mathrm{eq}}}\right]$$

Careful: Both Y^{eq} and <σv> depend on T_{dark}, which in turn depends on Y_s



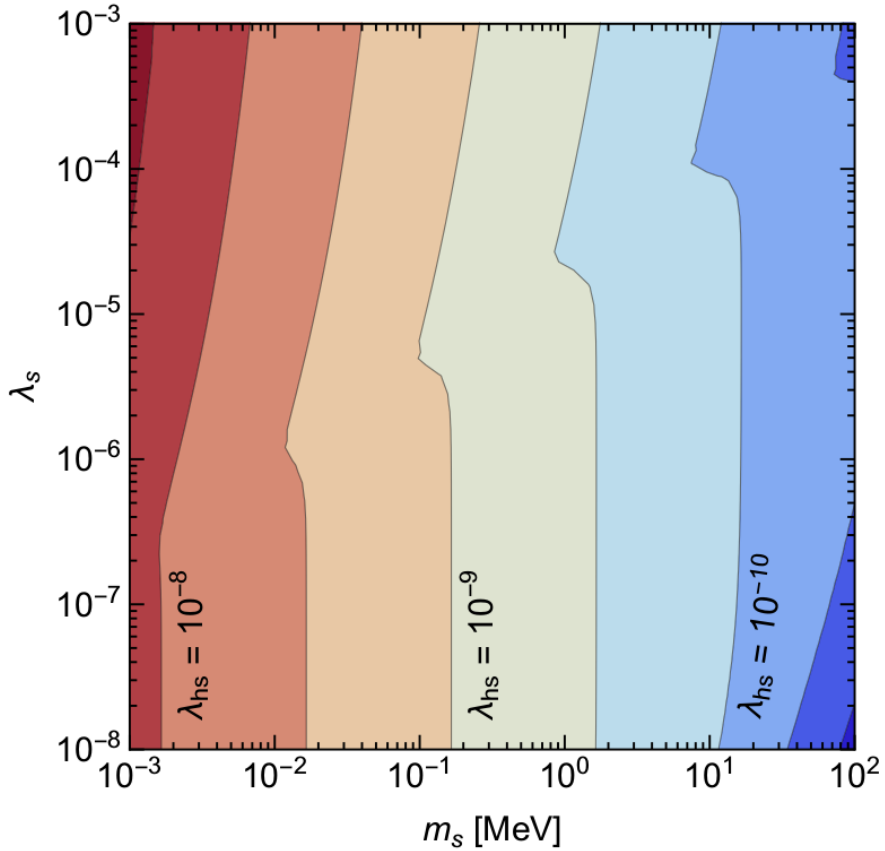
- Approximate solution:
  Y_s depends logarithmically on cross section

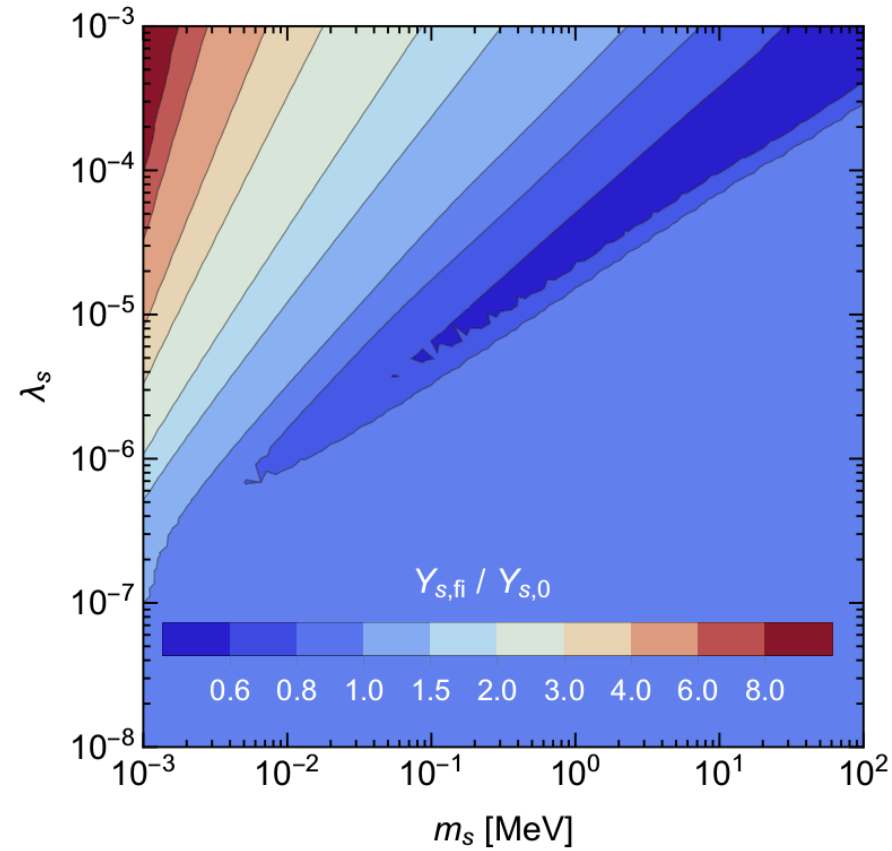
$$Y_s = \frac{4}{3\,\xi \left[\log\left(\frac{M_{\mathrm{P}}\,\lambda_s^3}{m_s\,\xi^{2/3}}\right) - a\right]}$$

→ very different from ordinary freeze-out

Relic abundance of light scalars

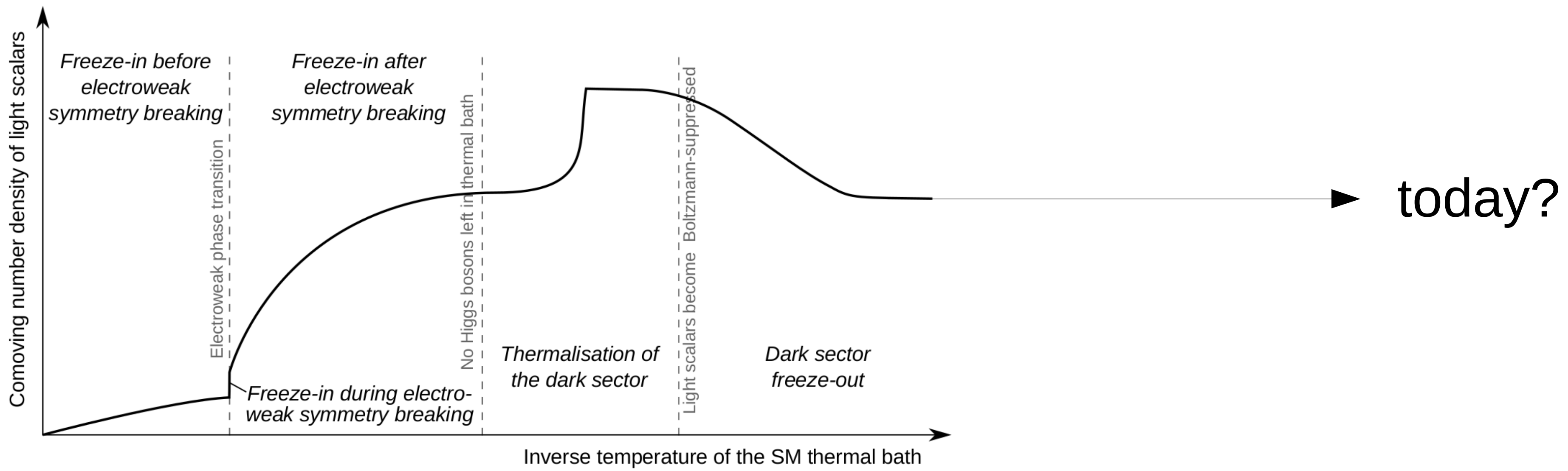
- We can finally determine the value of λ_{hs} that reproduces the observed abundance





Impact of dark sector freeze-out

Phenomenology



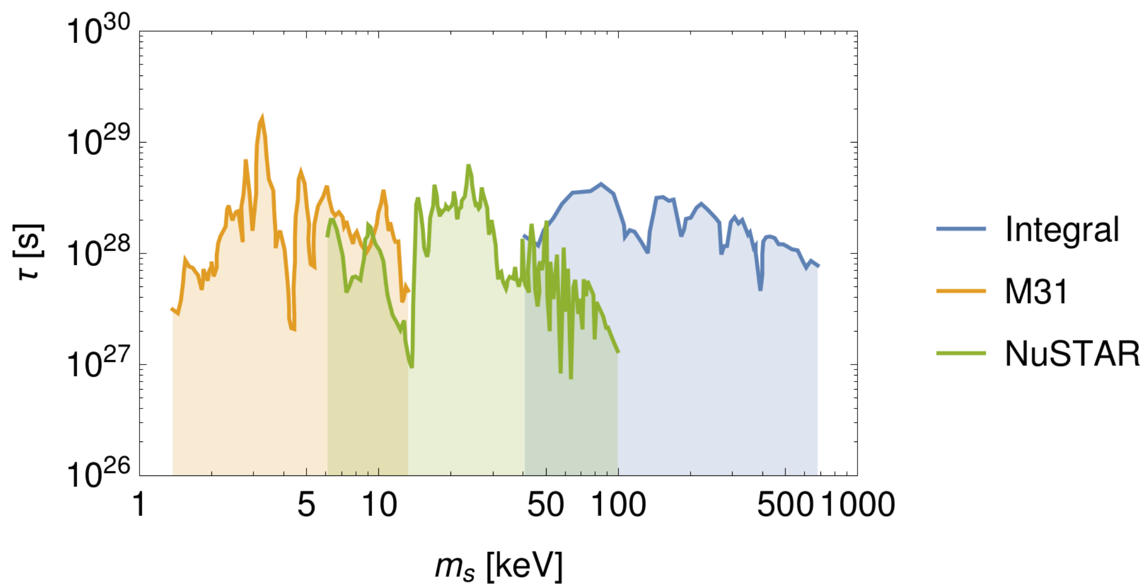
Scalar lifetime

- For m_s < 1 MeV the only allowed decay mode are photon pairs

$$\Gamma(s \to \gamma\gamma) = \sin^2\theta \, \frac{\alpha^2 \, m_s^3}{256\pi^3 \, v^2} \left| f(z_e) + \frac{7}{3} \right|^2$$

- Corresponding lifetime greater than 10^{25} s

- Relevant constraints from x-ray observations



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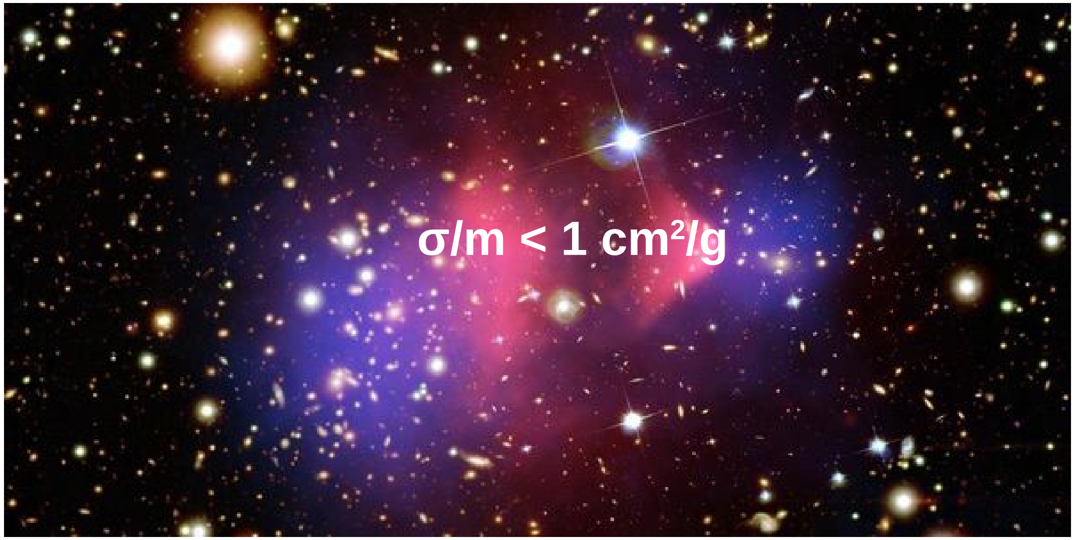
Scalar self-interactions

- Scalar self-coupling fixed by assumed pattern of symmetry breaking
  → prediction for self-interaction cross section:

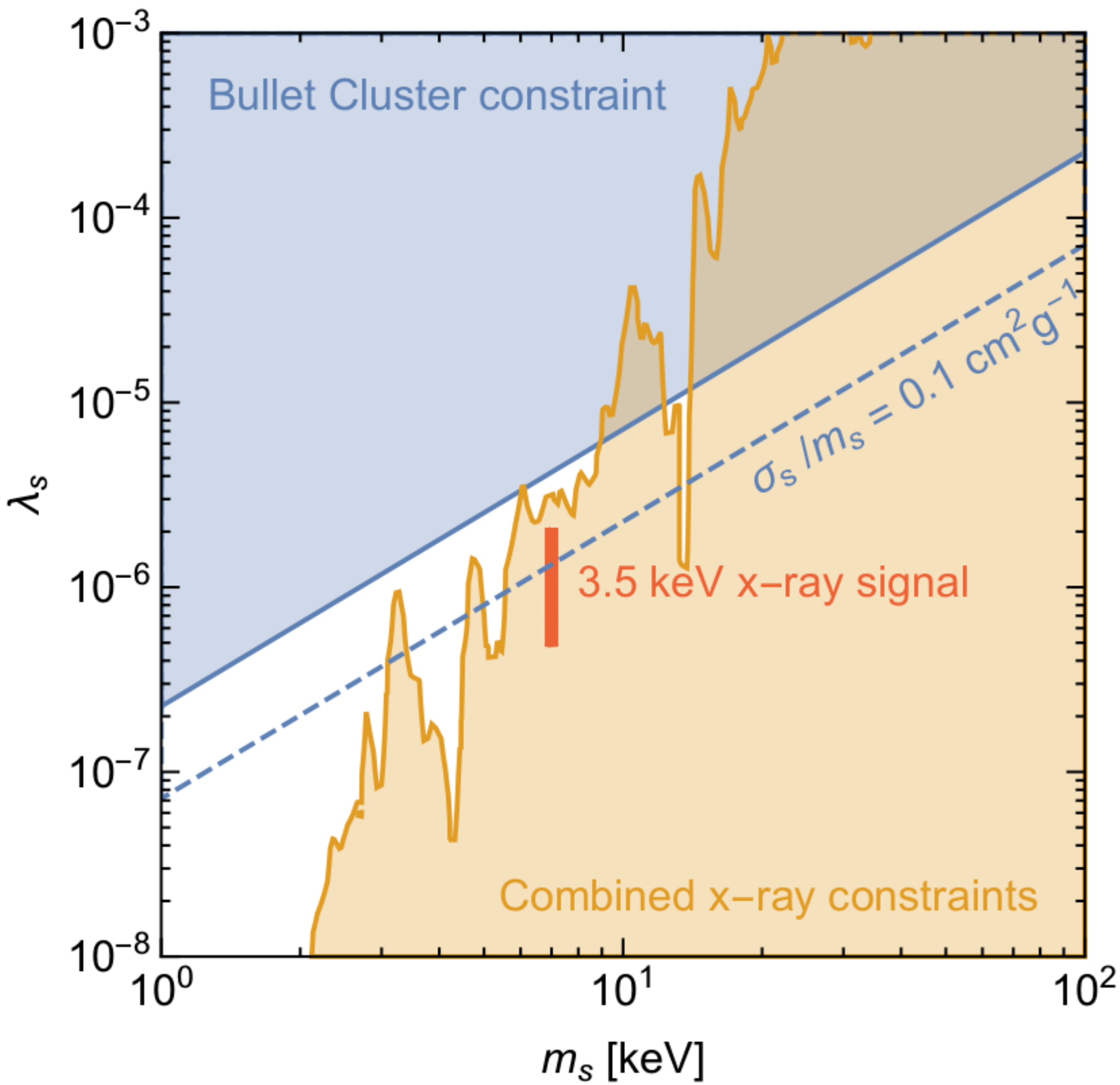
$$\frac{\sigma_s}{m_s} = \frac{9\,\lambda_s^2}{32\pi\, m_s^3}$$

- Strong enhancement for small scalar mass
  → observable effects possible even for small λ_s

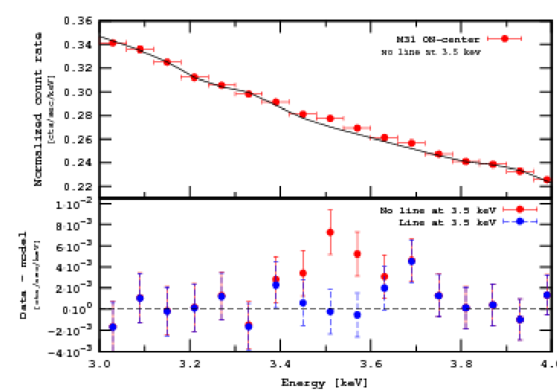
- No velocity dependence,
  so strong constraints from
  Bullet Cluster



Results



- Upper bound on λ_s from self-interactions
- Upper bound on Higgs mixing from indirect detection ↔ lower bound on λ_s
- Possible hint for an x-ray signal at 3.5 keV can be explained



- Corresponding self-interactions may be observable in the future

Effect on structure formation

- Potential constraint on light dark matter from free-streaming
  → Suppression of small-scale structure

An et al., arXiv:1812.05699

- Strong self-interactions prevent free-streaming
  → Structures can only be erased by diffusion

$$l_s^2 = \int_0^{t_{\rm dec}} \frac{{\rm d}t \, \langle v_s \rangle^2}{a^2 \, n_s \, \langle \sigma_s v_s \rangle}$$

- Diffusion length small enough to evade Ly-α constraints even for keV-scale DM

- Potential problem: Dark acoustic oscillations
  → Light scalars can support pressure waves
  → Need self-interactions to become inefficient (well) before recombination

→ Work in progress

Conclusions

- WIMPs produced through the Higgs portal are strongly constrained (although still viable), so we should think about alternative production mechanisms

- Attractive idea: Light scalars with mixing
  → Small portal coupling ensures cosmological stability
  → Production via freeze-in mechanism (and dark sector freeze-out)

- Most interesting parameter range: m_s ~ 1-10 keV
  → Potential explanation of anomalous x-ray emission at 3.5 keV
  → Interesting implications for self-interacting DM and structure formation