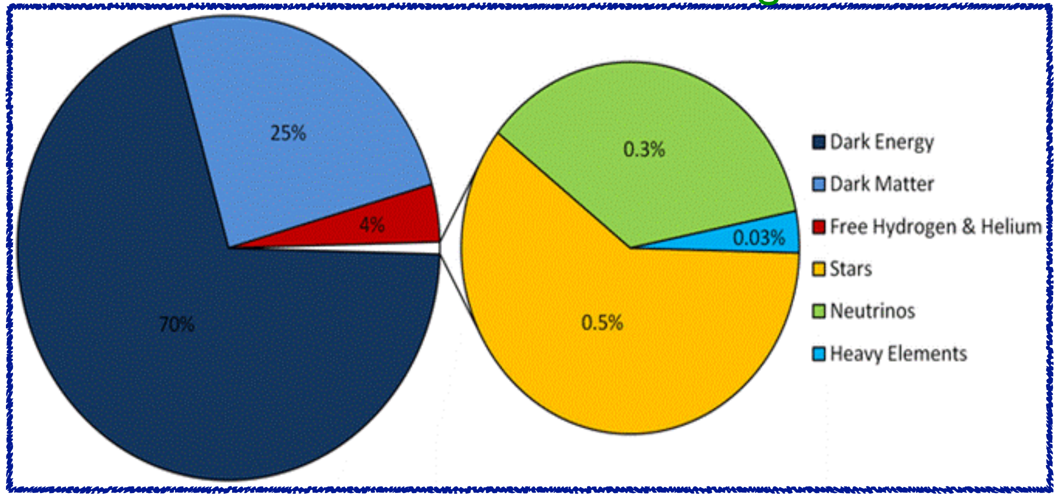
N-PACT meeting, Kristiansand, 4-6 Aug 2020

Thermal decoupling of Dark Matter in hidden sectors

Based on:
TB, Depta, Hufnagel & Schmidt-Hoberg, 2007. 03696

Image credit: KIAS



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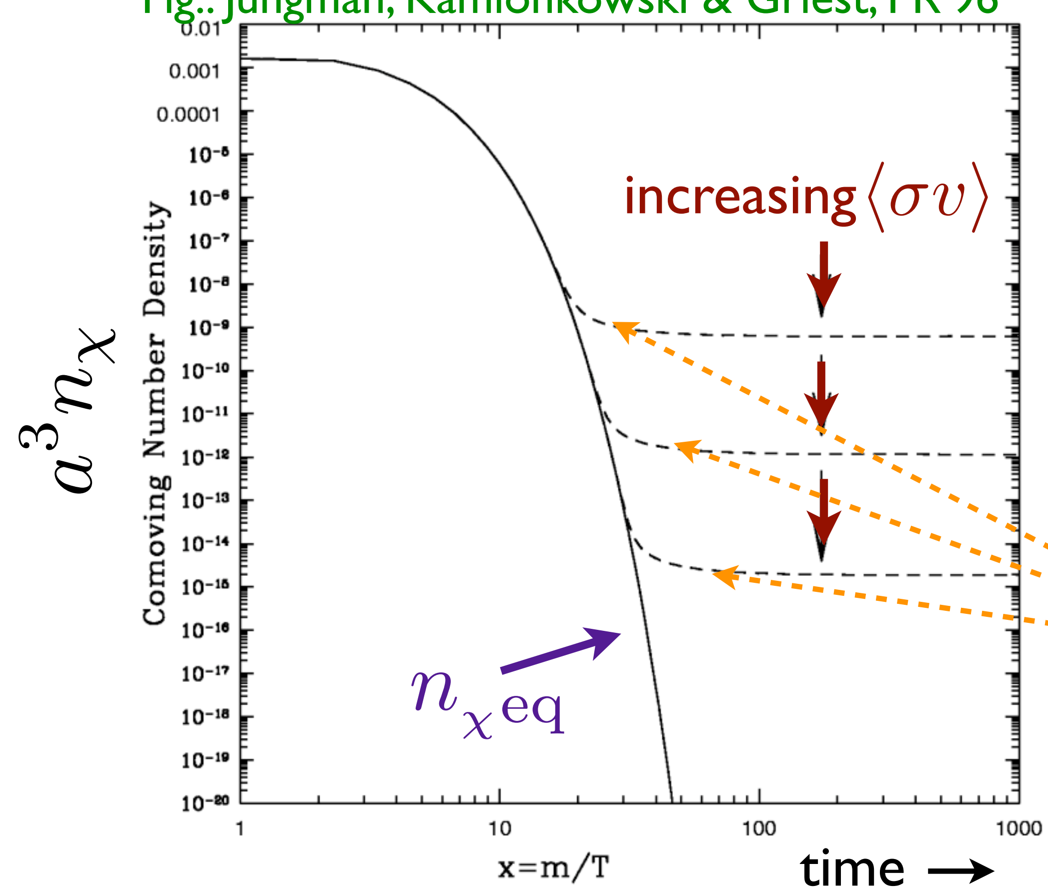
The standard treatment™ (Gelmini & Gondolo, NPB '91)

- Abundance of species χ initially in equilibrium with SM:

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): $\Omega_\chi h^2 \sim \frac{3\cdot 10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle} \sim \mathcal{O}(0.1)$

for weak-scale interactions!

= **WIMP 'miracle'**

- WIMP DM is seriously pressured, but not (yet) 'dead' !

Arcadi+, EPJC '18
Athron+, EPJC '19
(+ many more)

Ingredients for numerical evaluation

- Thermal average:

$$\langle \sigma v \rangle \equiv \frac{g_\chi^2}{n_{\chi,\mathrm{eq}}^2} \int \frac{d^3p}{(2\pi)^3} \frac{d^3\tilde{p}}{(2\pi)^3} \sigma v_{\bar{\chi}\chi \to \bar{f}f} f_{\chi,\mathrm{eq}}(\mathbf{p}) f_{\chi,\mathrm{eq}}(\tilde{\mathbf{p}})$$

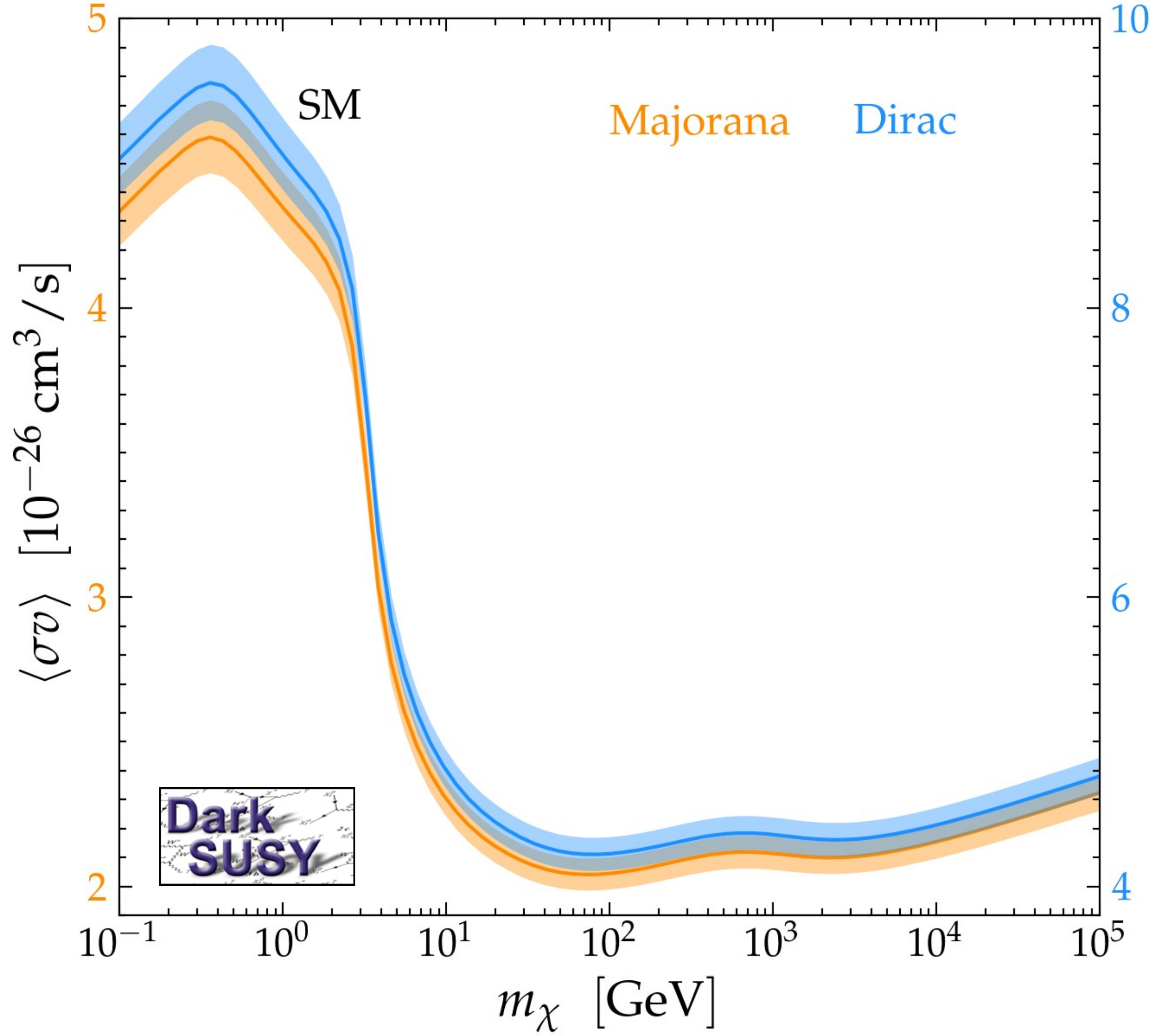
$$= \int_1^\infty d\tilde{s}\, \sigma_{\bar{\chi}\chi \to \bar{f}f} v_{\mathrm{lab}} \frac{2m_\chi \sqrt{\tilde{s}-1}(2\tilde{s}-1) K_1\!\left(\frac{2\sqrt{\tilde{s}} m_\chi}{T}\right)}{T {K_2}^2(m_\chi/T)}$$

- Number density in EQ:

$$n_{\chi,\mathrm{eq}} = g_\chi m_\chi^2 T K_2(m_\chi/T)/(2\pi^2)$$

- Radiation domination:

$$H^2 = \frac{8\pi G}{3}\rho \equiv \frac{8\pi^3 G}{90} g_{\mathrm{eff}} T^4$$



[See also Steigman+, PRD '12]

(Often forgotten) assumptions

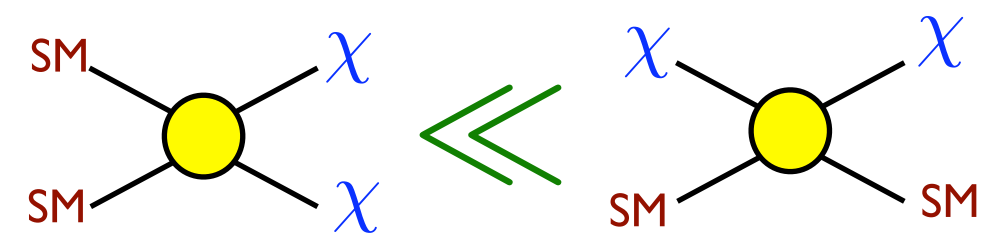
- Boltzmann equation at phase-space level:

[$\int d^3p$ gives Eq for number density n_χ]

$$\boxed{E(\partial_t - H\mathbf{p}\cdot\nabla_{\mathbf{p}})f_\chi = C[f_\chi]}$$

Expansion
(in FRW spacetime)

Interactions with SM:



I) DM becomes non-relativistic while still in (full) EQ:

$$\boxed{f_\chi^{\mathrm{eq}} = e^{-E/T} \ll 1}$$

II) DM remains in kinetic EQ during freeze-out

$$\boxed{f_\chi = e^{-(E-\mu_\chi)/T} = e^{\mu_\chi/T} f_\chi^{\mathrm{eq}}} \qquad \mu_\chi/m_\chi \ll 1$$

III) SM particles never build up significant chemical potentials

$$\boxed{f_{\mathrm{SM}} = e^{-E_{\mathrm{SM}}/T}}$$

(energy conservation: $E_{\mathrm{SM}} = E_\chi$)

Generic dark sector models

$SU(3)_c \times SU(2)_L \times U(1)_Y$

Standard Model

- SM particles

e.g. $\mathcal{L}_{\text{Higgs}} \supset \kappa|\phi|^2|\Theta|^2$

e.g. $U(1)_X \times \ldots$

Dark Sector

- Dark matter
- Dark radiation
  ('sterile neutrinos', 'dark photons', ...)

- A 'portal' typically still ensures thermalisation at high temperatures
  - *Separate entropy conservation after decoupling*
    $\rightsquigarrow T_{\text{photon}} \neq T_{\text{dark}}$

$$\xi(T) \equiv \frac{T_\chi(T)}{T} = \frac{\left[g_*^{\text{SM}}(T)/g_*^{\text{SM}}(T_{\text{dec}})\right]^{\frac{1}{3}}}{\left[g_*^{\text{DS}}(T)/g_*^{\text{DS}}(T_{\text{dec}})\right]^{\frac{1}{3}}}$$

- Let's study a simple set-up for concreteness:
  - *only fermionic DM (χ) and a scalar (S) in dark sector (with $m_S < m_\chi$)*
  - *decoupling at high temperatures:* $T_{\text{dec}} \gg m_t, m_\chi$
  - *(directly) afterwards EQ in DS through* $\bar{\chi}\chi \leftrightarrow SS$

Case I: massless DS 'heat bath'

- Vanishing chemical potential for S
  - *e.g. because of* $\bar{\chi}\chi \to \bar{\chi}\chi S$
  - ➡ identical assumptions to standard case possible, after replacing $T \to T_\chi$

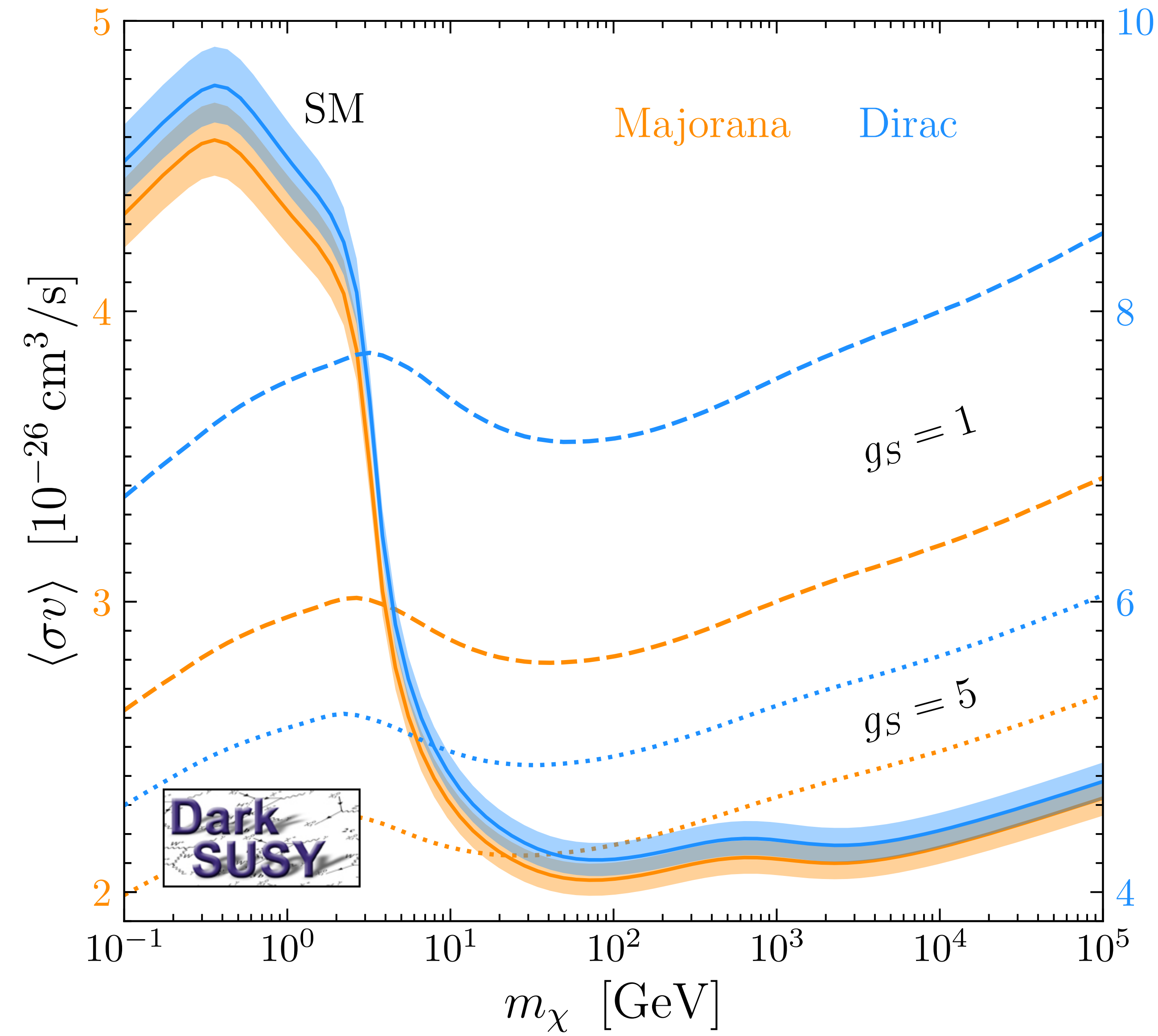
➡ Can use *same* Boltzmann equation for n_χ, after changing

$$\langle \sigma v \rangle = \int_1^\infty d\tilde{s}\, \sigma_{\bar{\chi}\chi\to\bar{f}f} v_{\rm lab} \frac{2m_\chi\sqrt{\tilde{s}-1}(2\tilde{s}-1)K_1\left(\frac{2\sqrt{\tilde{s}}m_\chi}{\boxed{T}}\right)}{\boxed{T}K_2{}^2(m_\chi/\boxed{T})}$$

$$n_{\chi,\rm eq} = g_\chi m_\chi^2 \boxed{T} K_2(m_\chi/\boxed{T})/(2\pi^2)$$

$$H^2 = \frac{8\pi G}{3}\rho \equiv \frac{8\pi^3 G}{90} g_{\rm eff} T^4$$

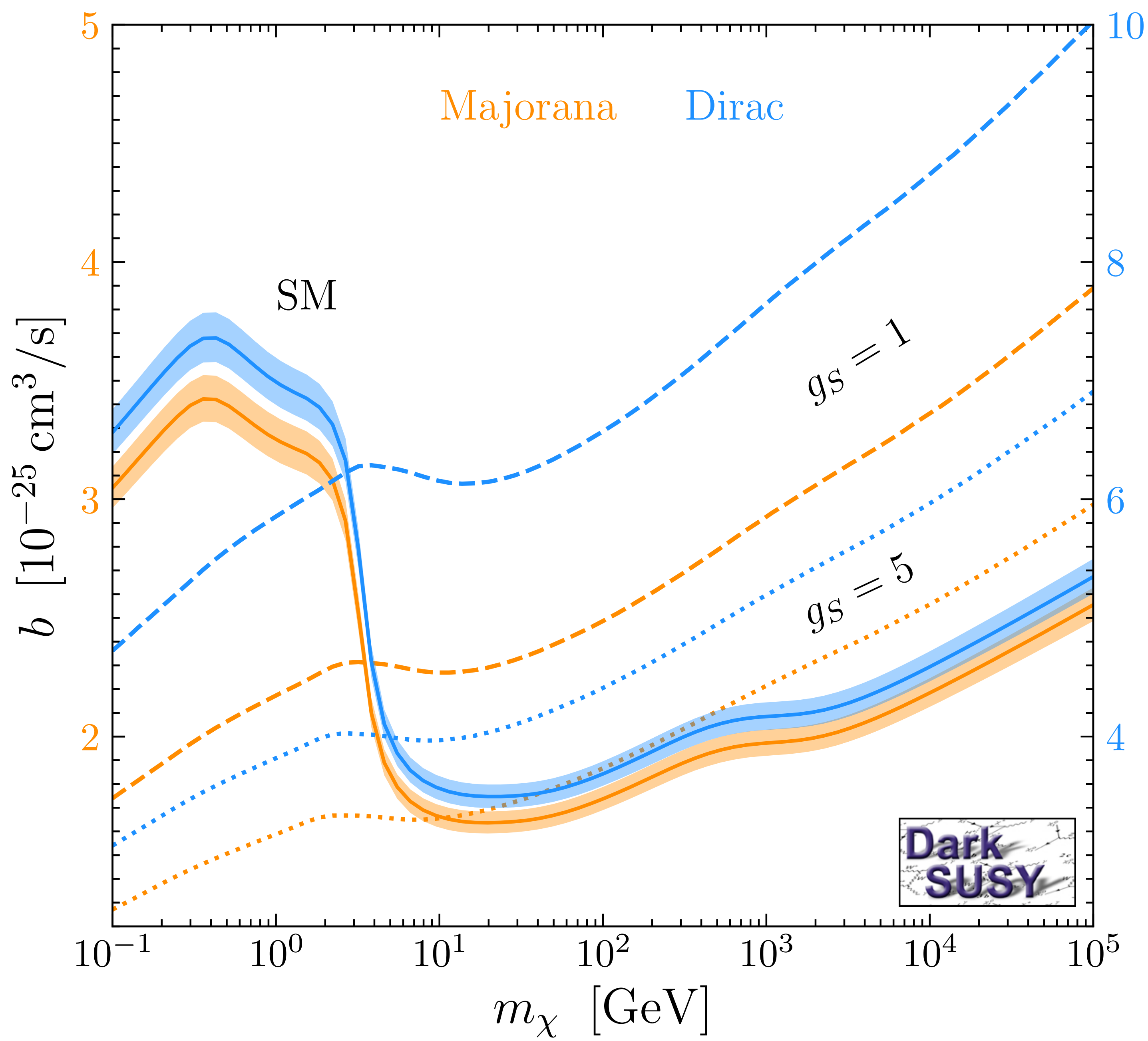
$$= g_{\rm eff}^{\rm SM} + g_{\rm eff}^{\rm DS}$$



p-wave annihilation

[In case you ever wondered how the 'Steigman plot' looks like for non-constant cross sections…]

$$\sigma v_{\rm lab} = b\, v_{\rm lab}^2$$



Case II: massive annihilation products

- In general, nothing prevents S to build up chemical potentials
  - *unless adding new physics, e.g. massless states* N *with* $\Gamma_{\bar{N}N\leftrightarrow SS} \gg \Gamma_{\bar{\chi}\chi\leftrightarrow SS}$

➡ Underlying assumptions for standard Boltzmann equation not satisfied anymore, even when assuming kinetic EQ:

$$f_S \cancel{=} e^{-E_S/T_\chi}$$

$$f_\chi^{\mathrm{eq}} \cancel{=} e^{-E/T_\chi} \cancel{\ll} 1$$

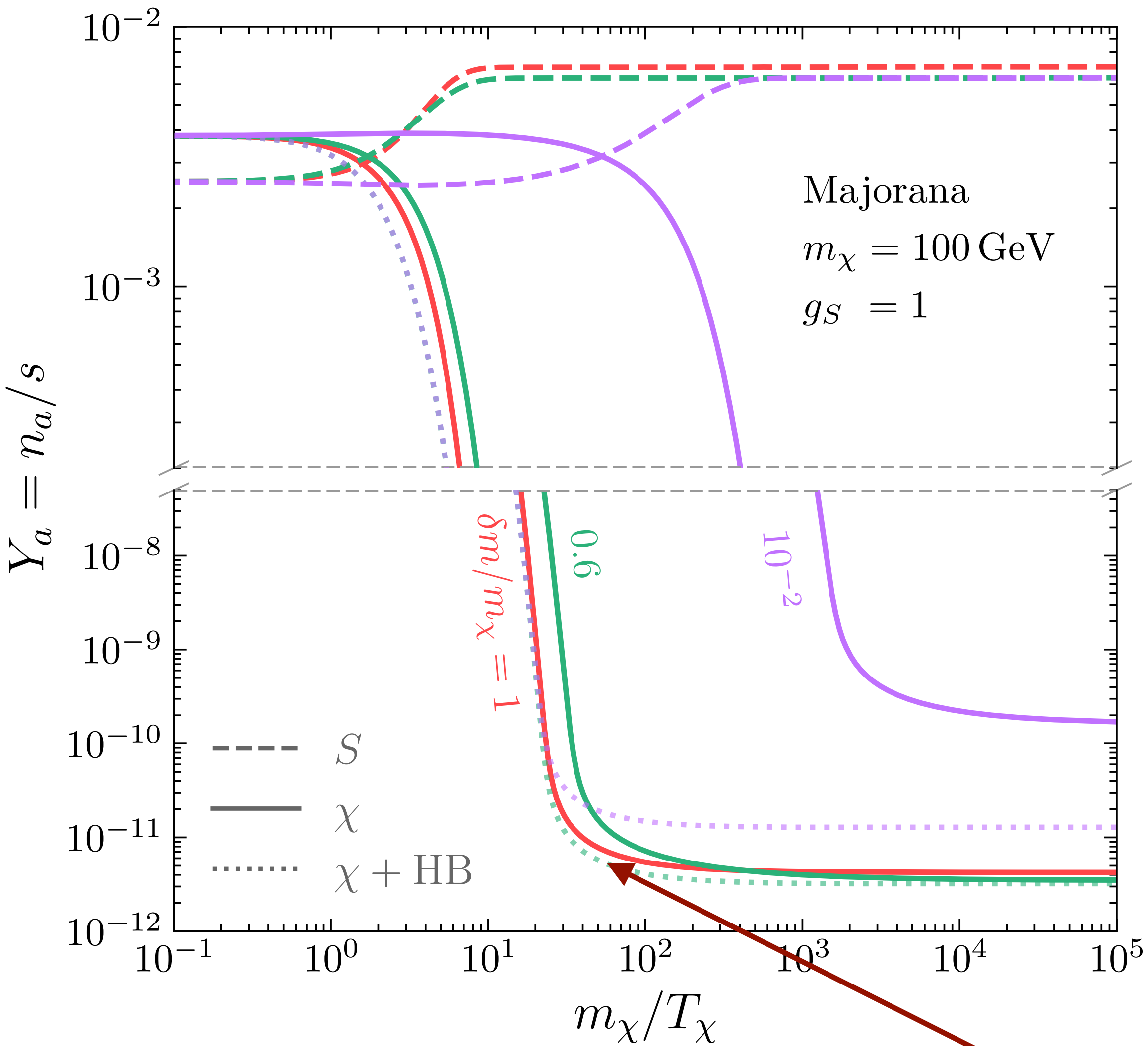
$$f_\chi \cancel{=} e^{-(E-\mu_\chi)/T_\chi} \cancel{=} e^{\mu_\chi/T_\chi} f_\chi^{\mathrm{eq}}$$

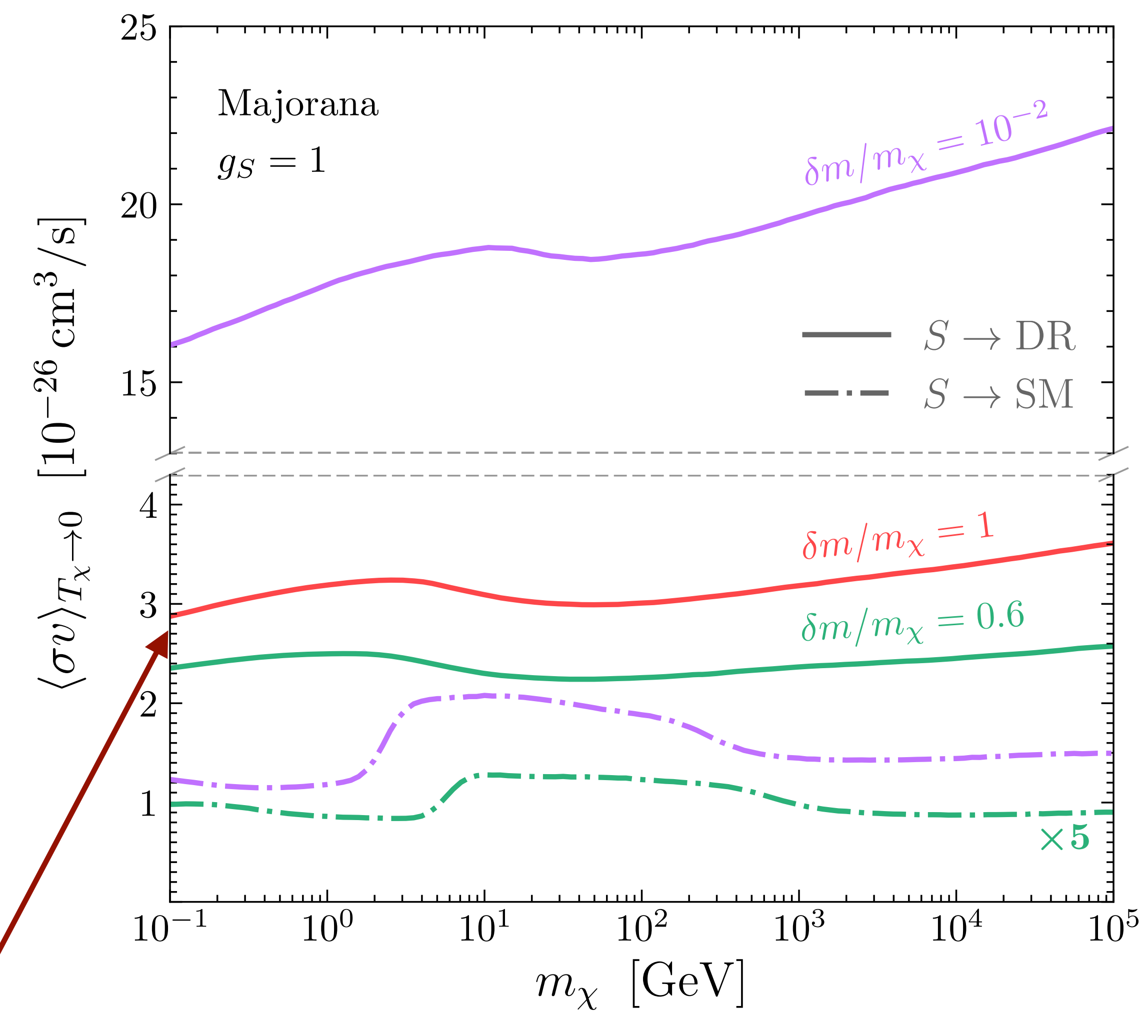
- In kinetic EQ, particles will still follow BE / FD distributions

  ➡ Need to independently solve for T_χ, μ_χ and μ_S, with full spin-statistics!

  - *number conservation* $\dot{n}_i + 3Hn_i = \mathfrak{C}/N_\chi, \quad \dot{n}_S + 3Hn_S = -\mathfrak{C}$
  - *energy conservation* $\nabla_\mu T^{0\mu}_{\mathrm{DS}} = 0$
  - *transform all time derivatives as* $\dot{Q} = \frac{\partial Q}{\partial T_\chi}\dot{T}_\chi + \frac{\partial Q}{\partial \mu_\chi}\dot{\mu}_\chi + \frac{\partial Q}{\partial \mu_S}\dot{\mu}_S$

Case II: results





$m_S = 0$ **(case I)**

Conclusions

- Increasing interest in dark sector models
  to explain dark matter

- Thermal freeze-out works equally well in this case…
  … but must be treated correctly for consistent interpretation of experimental searches and pheno studies!

- Difference to 'vanilla' approach can be orders of magnitude
  [*c.f. percent* accuracy in total *observed* DM abundance]

- Even DarkSUSY can't do everything [yet] ;)

Thanks for your attention!

DarkSUSY

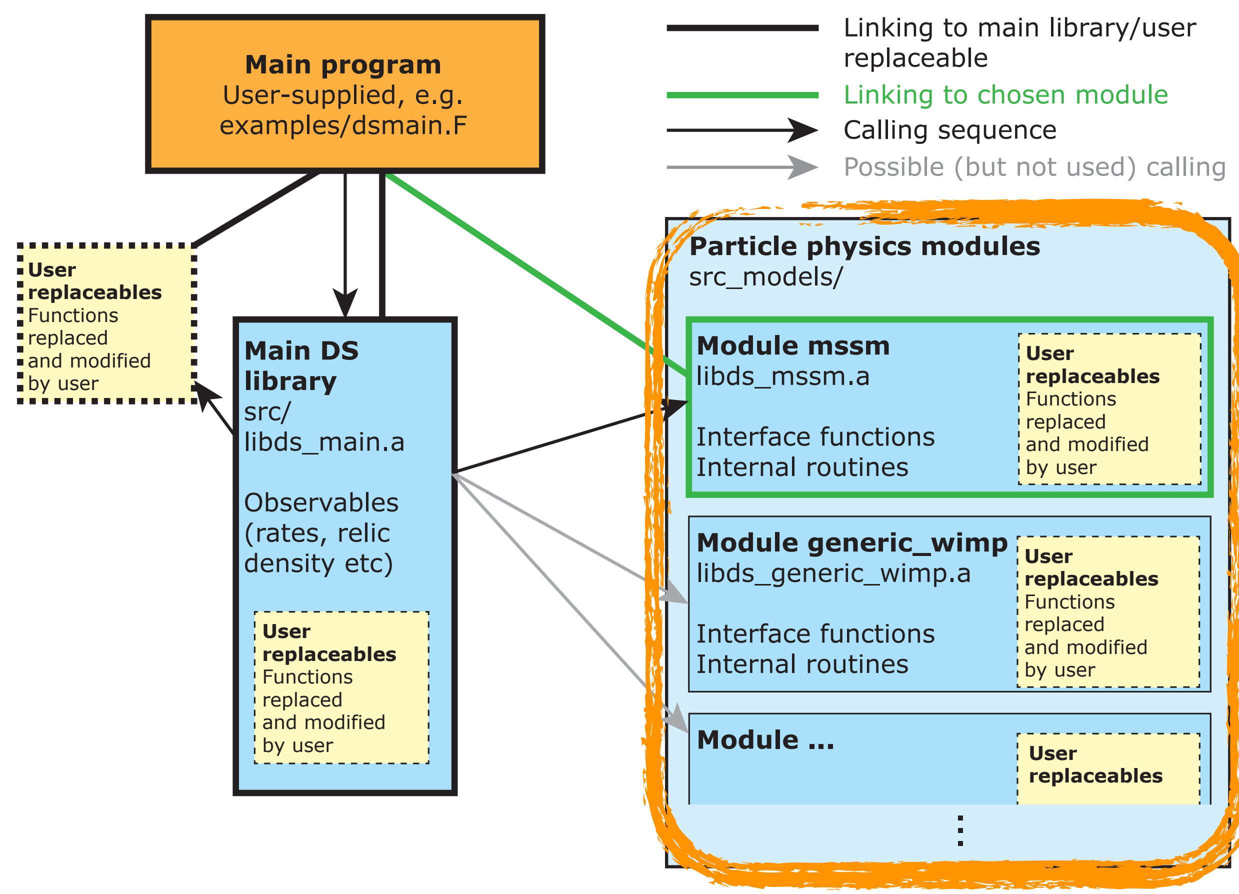
FREE DOWNLOAD ;)

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 (see later)