Orsay, 25 October 2023

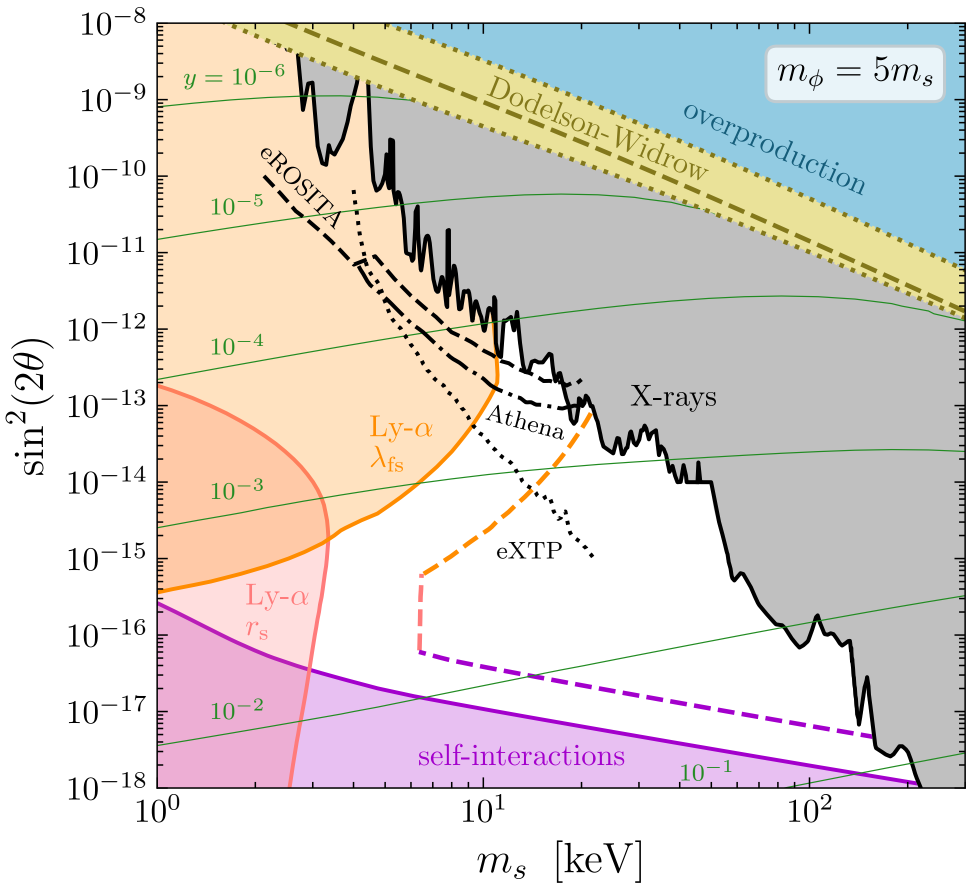
AstroParticle Symposium
Université Paris-Saclay

Minimal sterile neutrino dark matter

Torsten Bringmann

Based on

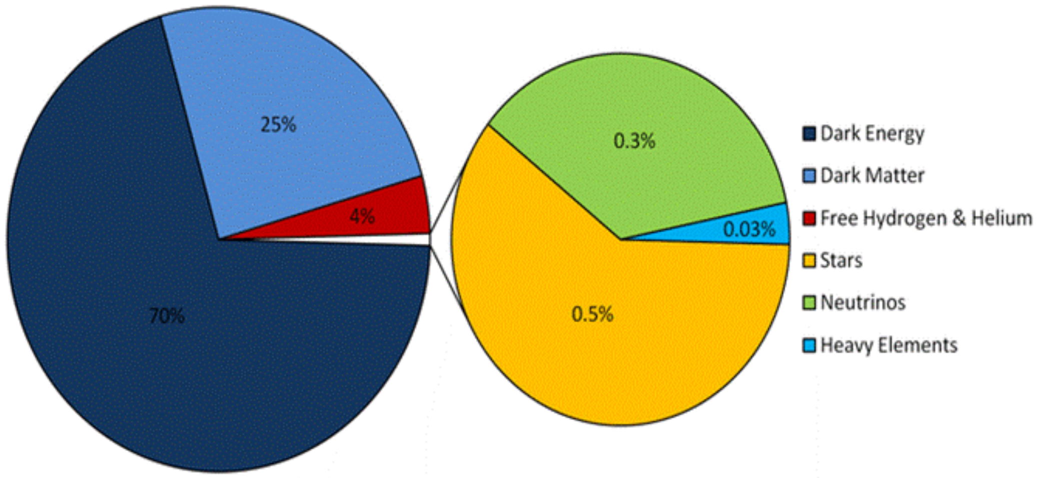
TB, Depta, Hufnagel, Kersten, Ruderman & Schmidt-Hoberg, PRD '23



UiO : University of Oslo

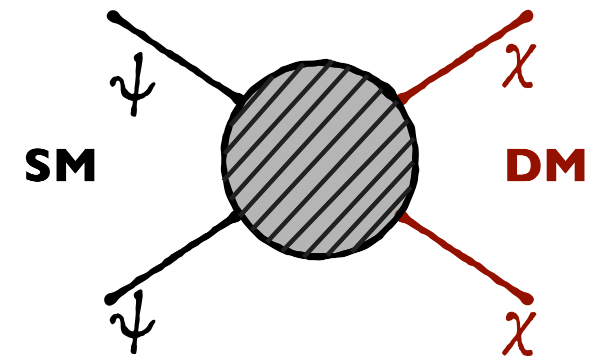
Part I

Dark matter production form the thermal bath



Dark matter production

- 'Generic' interactions with the primordial heat bath:

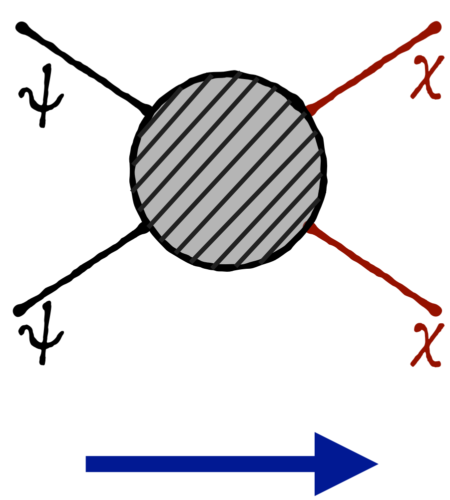


➡ Correct relic abundance in two regimes:

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

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

freeze-in



depends on initial conditions

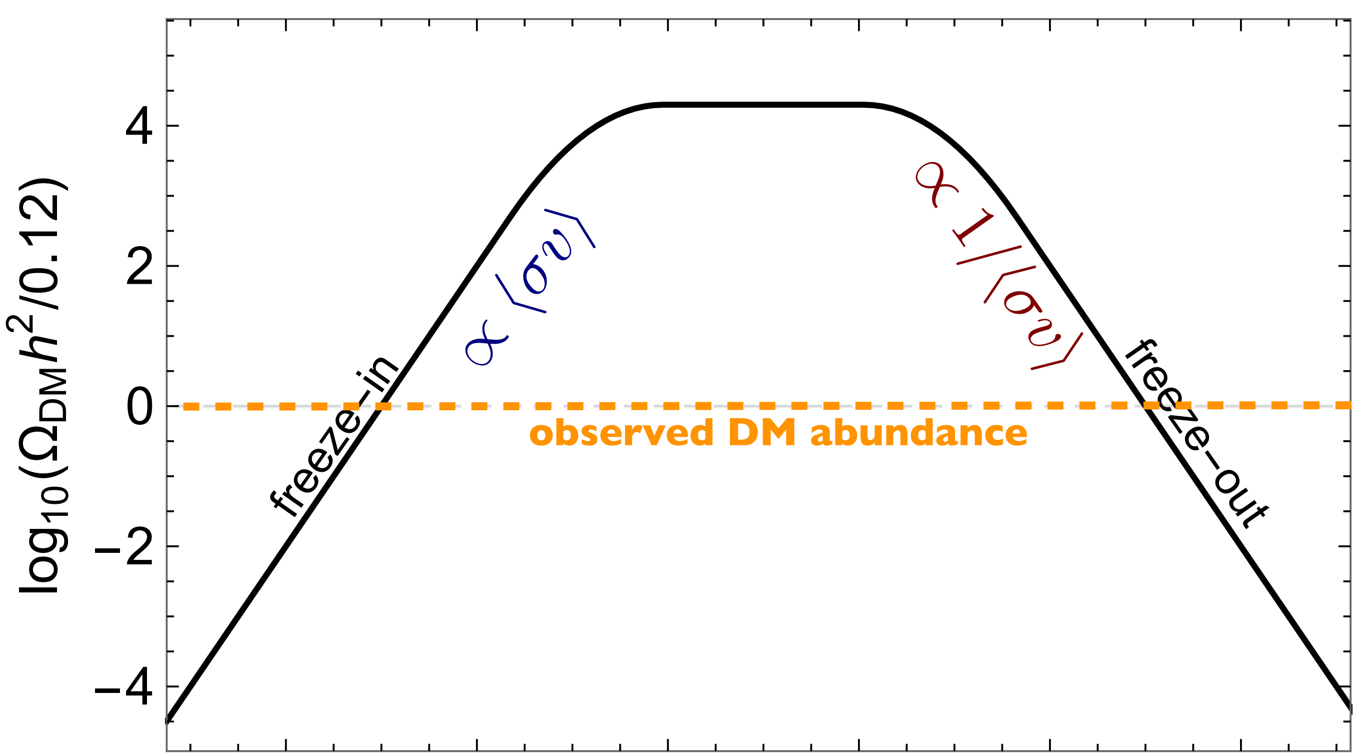
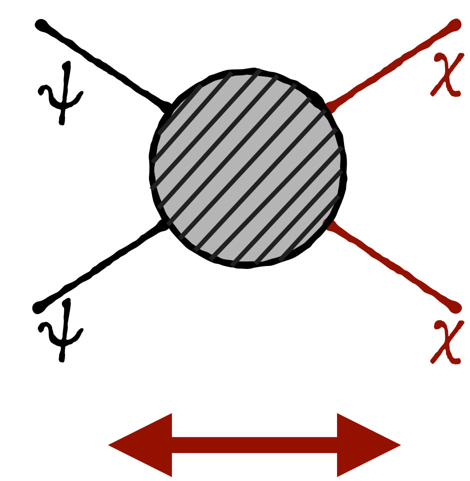


Fig: Bernal+, IJMP '17

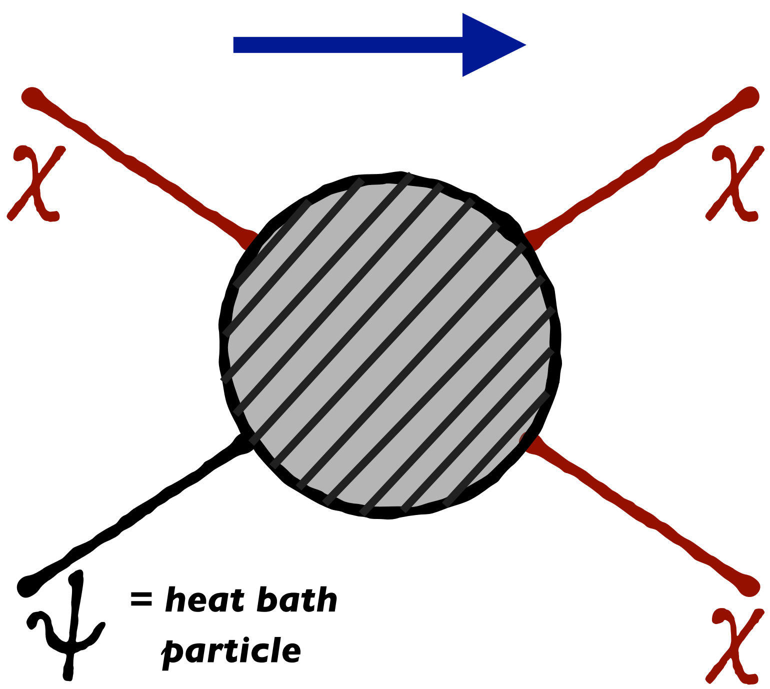
freeze-out



insensitive to initial conditions

New avenues

- **'Pandemic' dark matter**



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

Hryczuk & Laletin, 2104.05684

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

[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 $(R = \mathrm{tot} - S - I)$

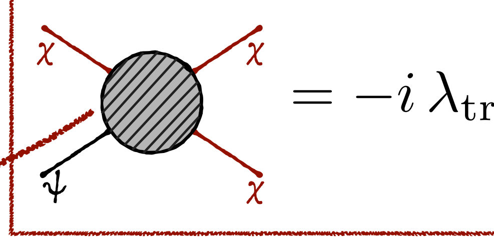
β ***infection rate***

γ ***recovery rate***

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

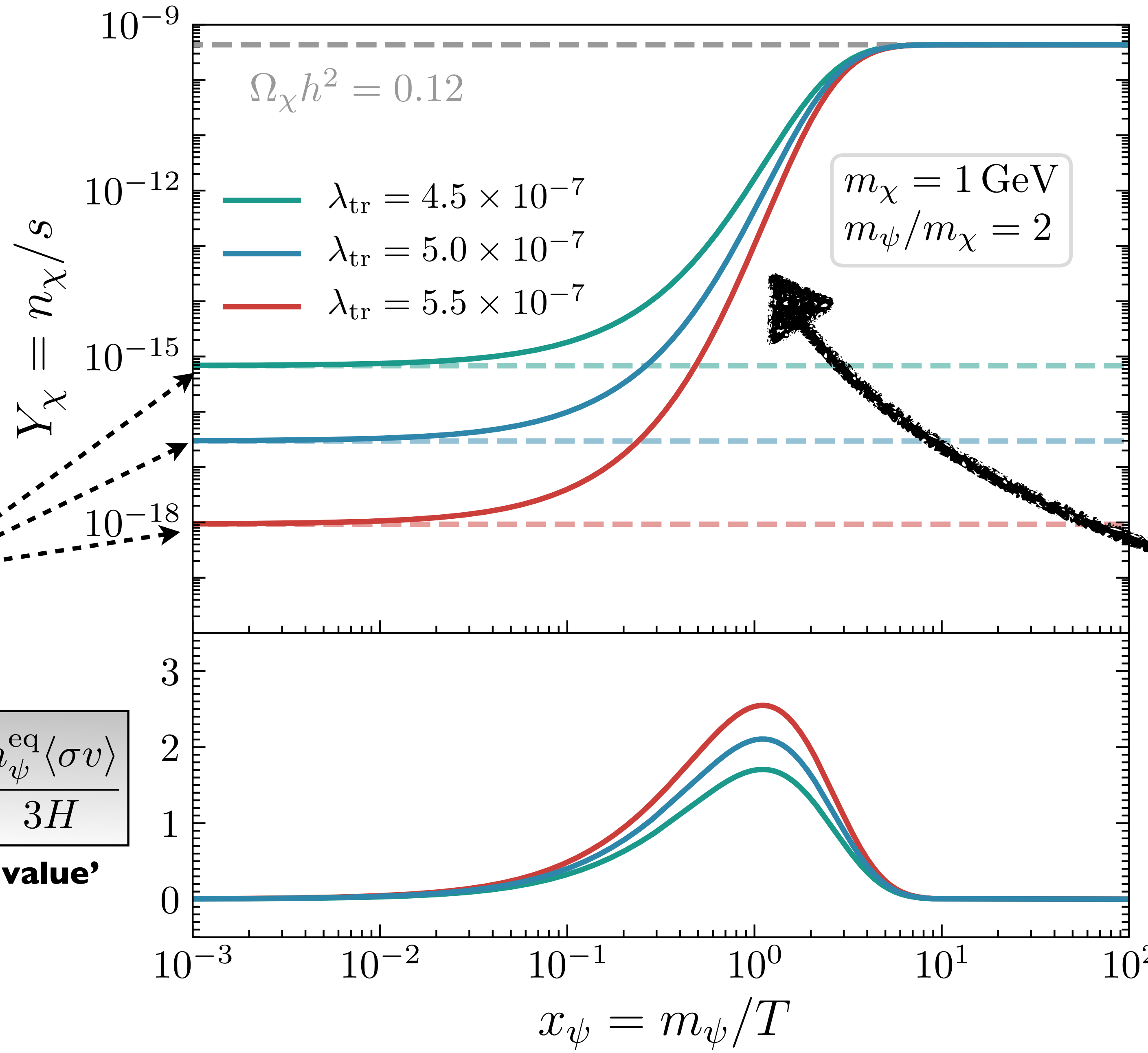
Exponential DM production

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



toy model

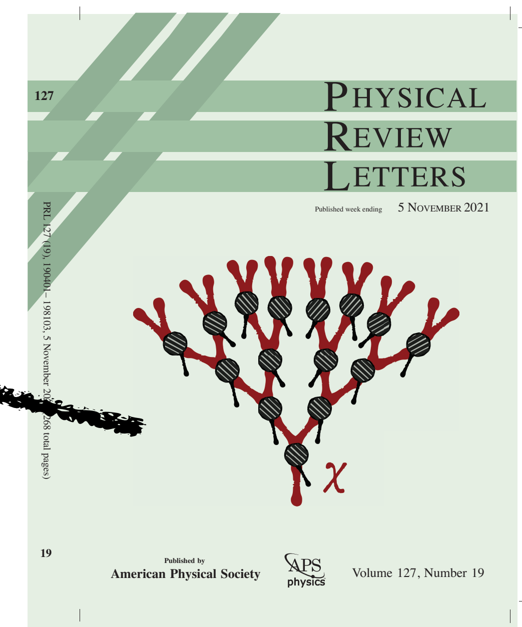
$$\dot{n_\chi} + 3Hn_\chi = n_\chi n_\psi^{\rm eq}\langle\sigma v\rangle$$



Tiny initial DM abundance

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

'reproduction value'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American Physical Society
APS physics
Volume 127, Number 19

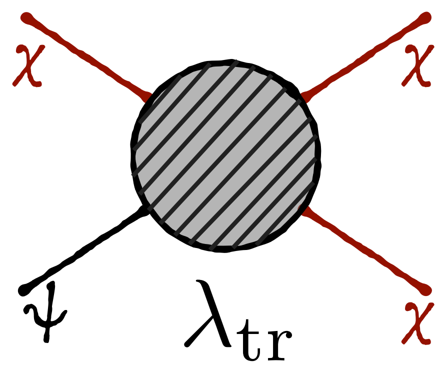
exponential growth $R \gtrsim 1$

large H

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

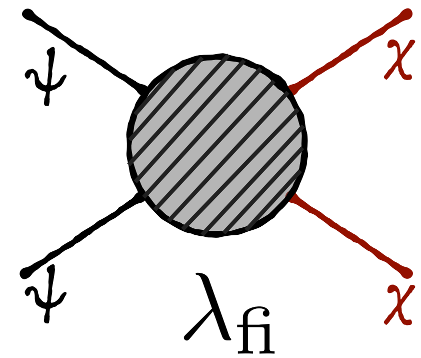
Adding freeze-in production

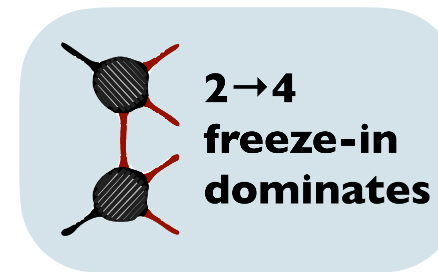
'transmission'

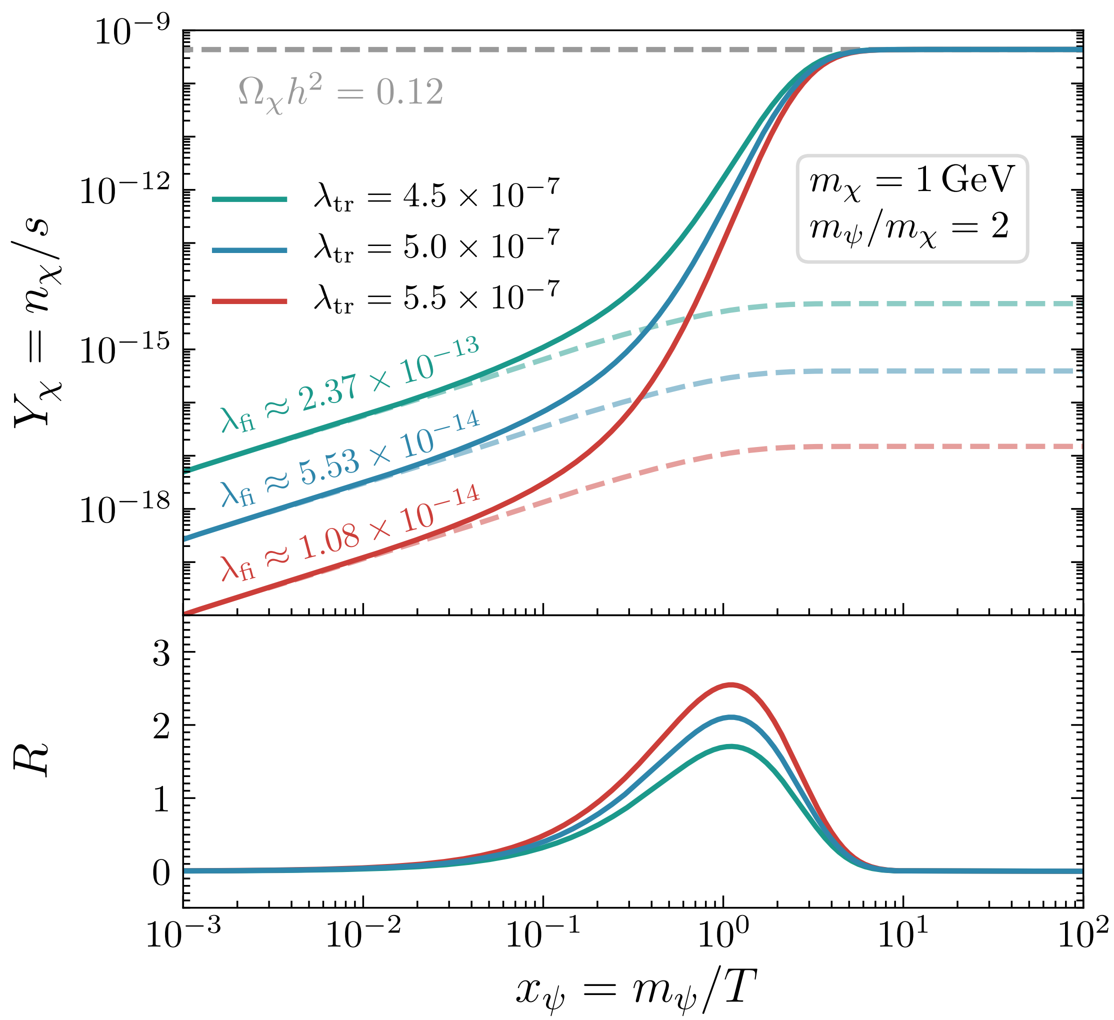


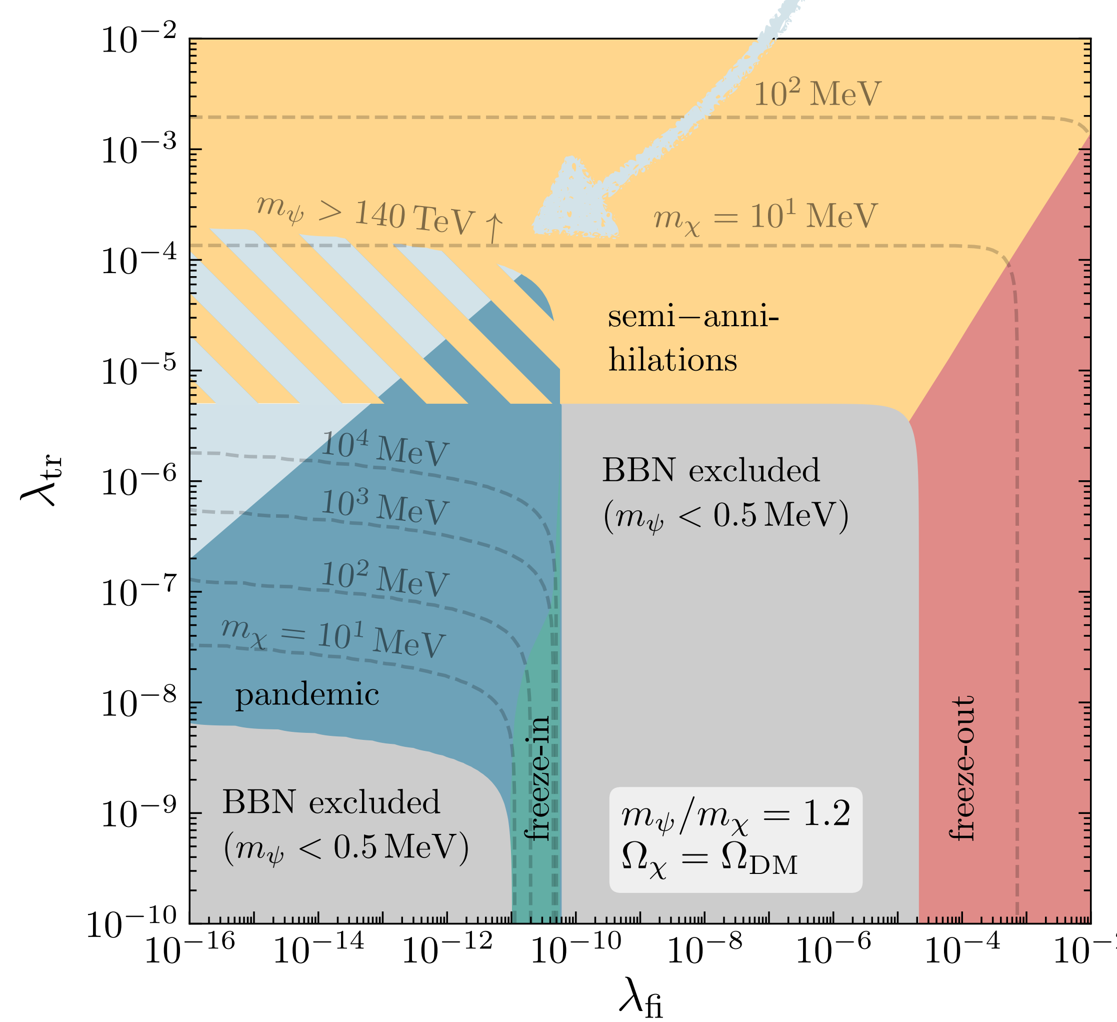
+

'freeze-in'







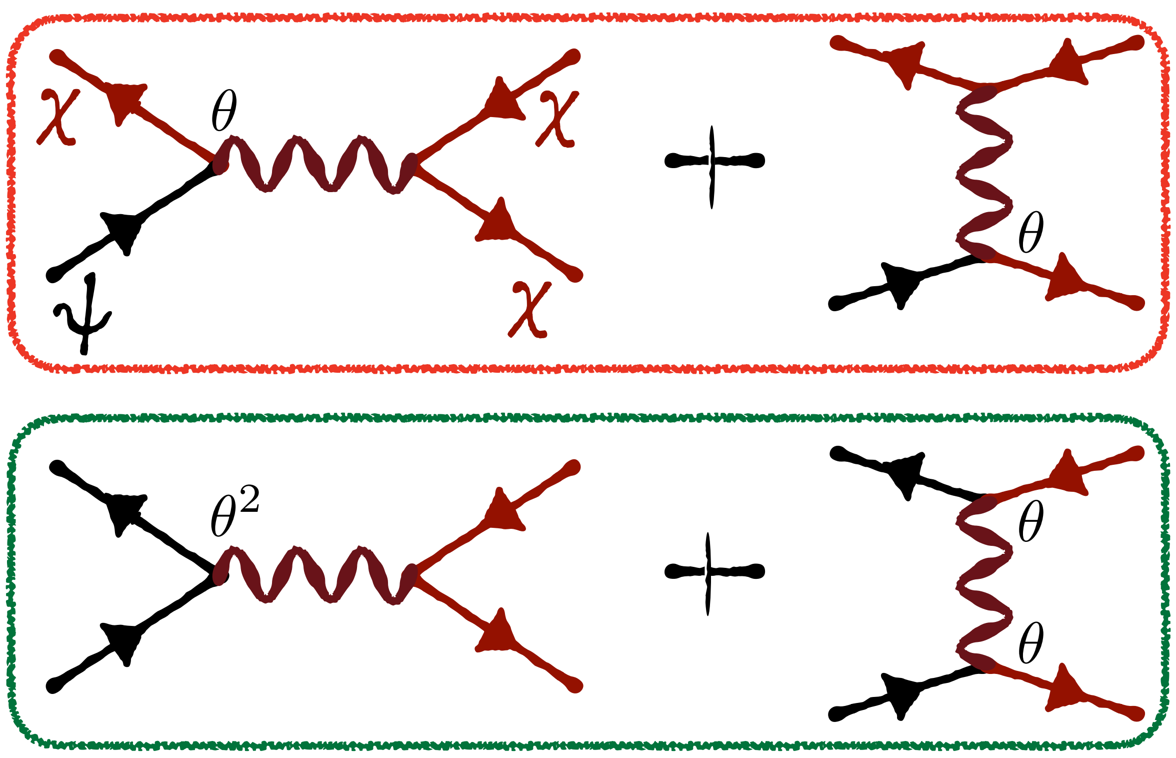


➡ ***'Pandemic' production turns out to be a rather generic mechanism for the genesis of DM!***

But… how ?

- How to *generically* realize $\langle\sigma v\rangle_{\rm fi} \ll \langle\sigma v\rangle_{\rm tr}$?
- Simply 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 $\propto \theta^2$

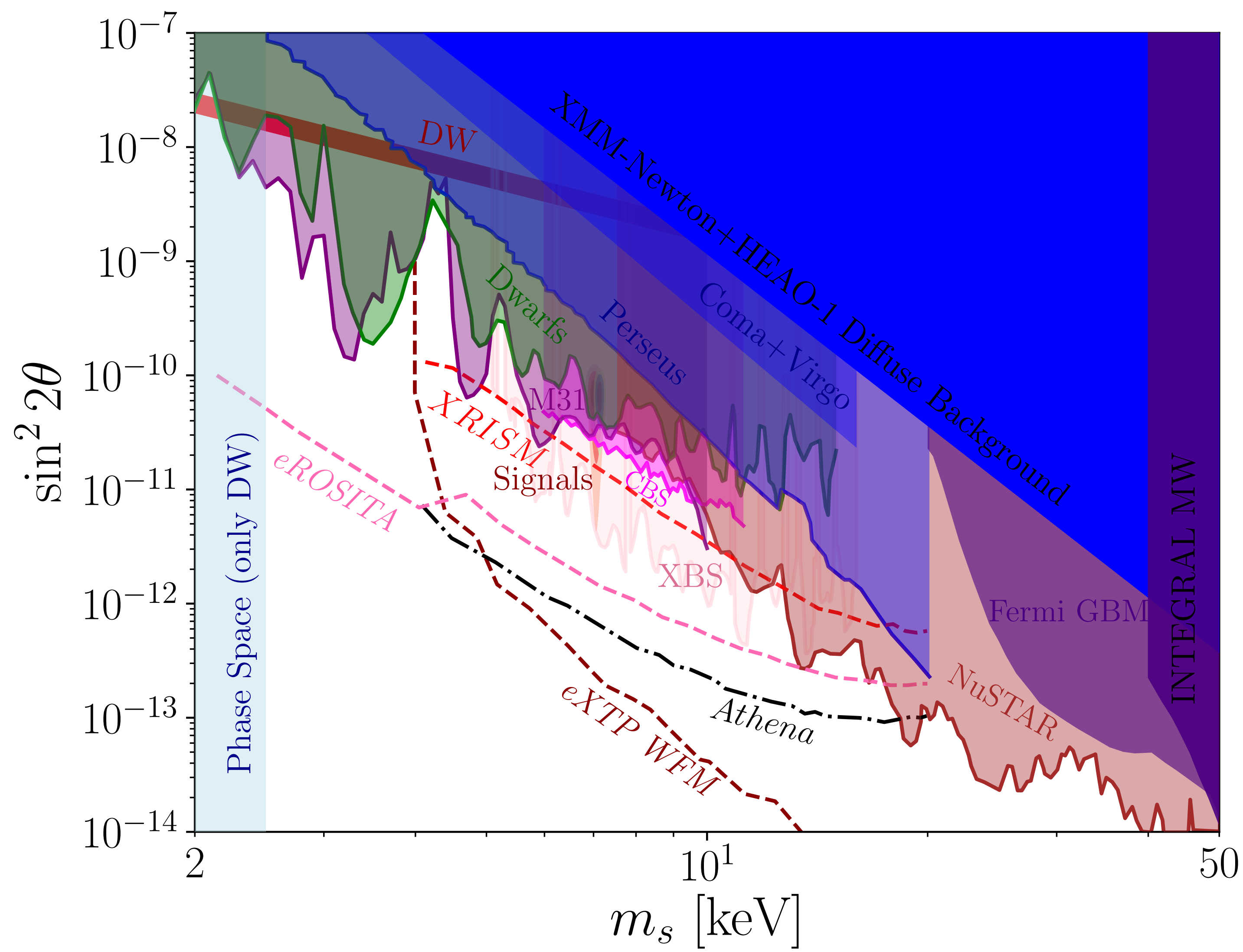
Part II

Sterile neutrinos as dark matter

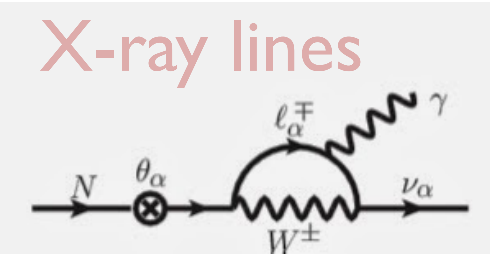
Sterile neutrinos

- 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



Abazajian+, 2203.7377



- Unfortunately, this scenario is ruled out by observations…

Alternative production mechanisms

- An excellent, well-motivated dark matter candidate
  - warrants looking for alternative scenarios !
- Shi-Fuller mechanism Shi & Fuller, PRL '99
  - Introduce large lepton asymmetry ⇦
    - origin ?
    - bounds from BBN
      $\rightsquigarrow$ X-ray & Lyman-α limits still quite close
  - resonant oscillation leads to enhanced production
- Decay of some scalar Shaposhnikov & Tkachev, PLB '06
  Kusenko, PRL '06
  Petraki & Kusenko, PRD '08
  ...
- Extended gauge sector Bezrukov, Hettmansperger & Lindner, PRD '10
  Kusenko, Takashashi & Yanagida, PLB '10
  ...
- New (active) neutrino interactions De Gouvêa+, PRL '20
  Kelly+, PRD '20
  ...

Many options, but maybe not really 'minimal'...

Interacting sterile neutrinos

- What about sterile neutrino self-interactions ?
  - expect ~similar phenomenology for scalar and vector mediator…
- Let's add a scalar ϕ that only couples to the sterile neutrinos

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

- $m_\phi \sim 100\,\mathrm{keV}, y \lesssim 10^{-8}$ Hansen & Vogl, PRL '17
  - Growth in sterile neutrino density due to thermalization of dark sector
  - viable for *a)* small window around 4 keV, or *b)* further lepton asymmetry
- $m_\phi > 1\,\mathrm{GeV}$ Johns & Fuller, PRD '19
  - Induces sharp resonance in V_{eff}

    ⇨ either no impact or runaway behaviour
- $100\,\mathrm{keV} \gtrsim m_\phi > 2m_s, \quad y \gtrsim 10^{-6}$ **This talk** TB+, PRD '23

see also Astros & Vogl, 2308.14594 *for discussion of 'entire' scalar mass range*

Interacting sterile neutrinos

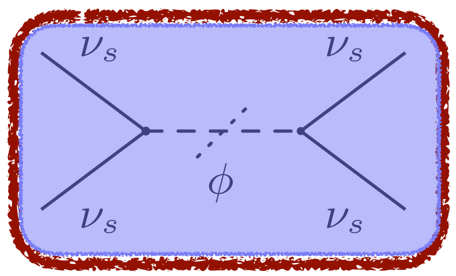
TB, Depta, Hufnagel, Kersten, Ruderman & Schmidt-Hoberg, PRD '23

- $\mathscr{L} \supset \frac{y}{2}\phi\bar{\nu}_s\nu_s$, $m_\phi > 2m_s$
- Early times (~QCD PT): standard DW production
- Evolution afterwards:

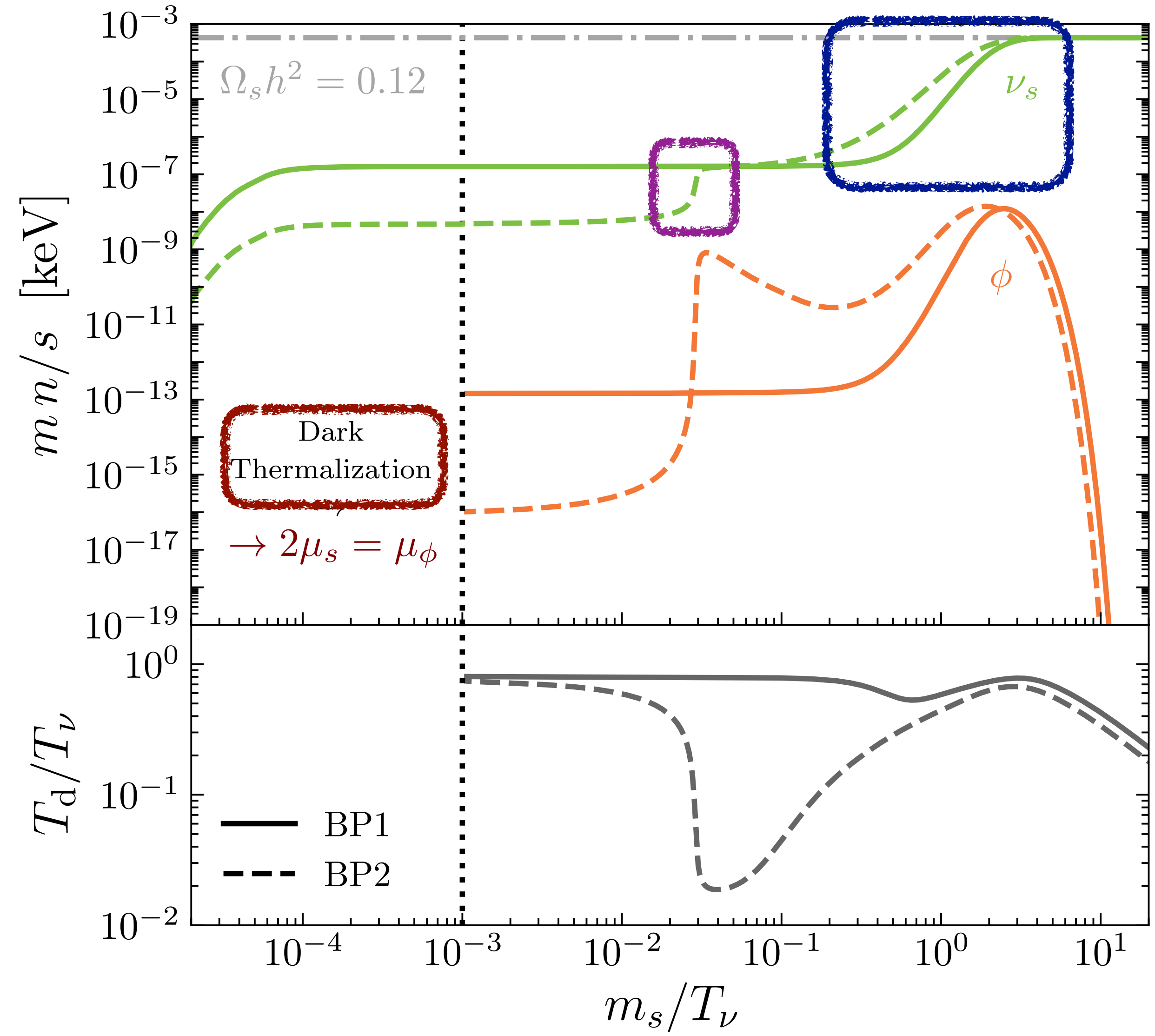
solid: benchmark point with large θ, small y

dashed: benchmark point with small θ, large y

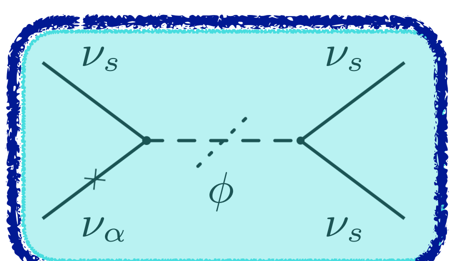
  - Thermalization in dark sector



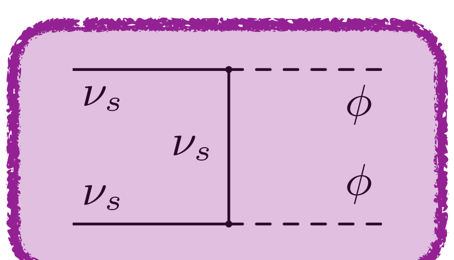
NB: This allows exact solution of Boltzmann equation!



  - Exponential growth



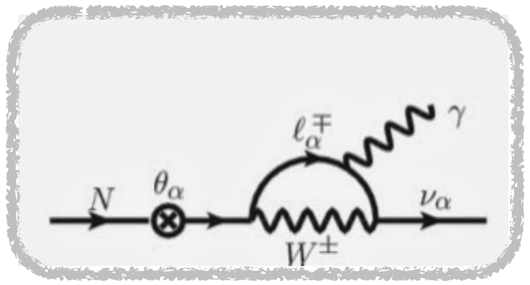
  - Reproductive freeze-in



$+ \ \phi \rightarrow 2\nu_s$

Sterile neutrinos… revived !

- 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

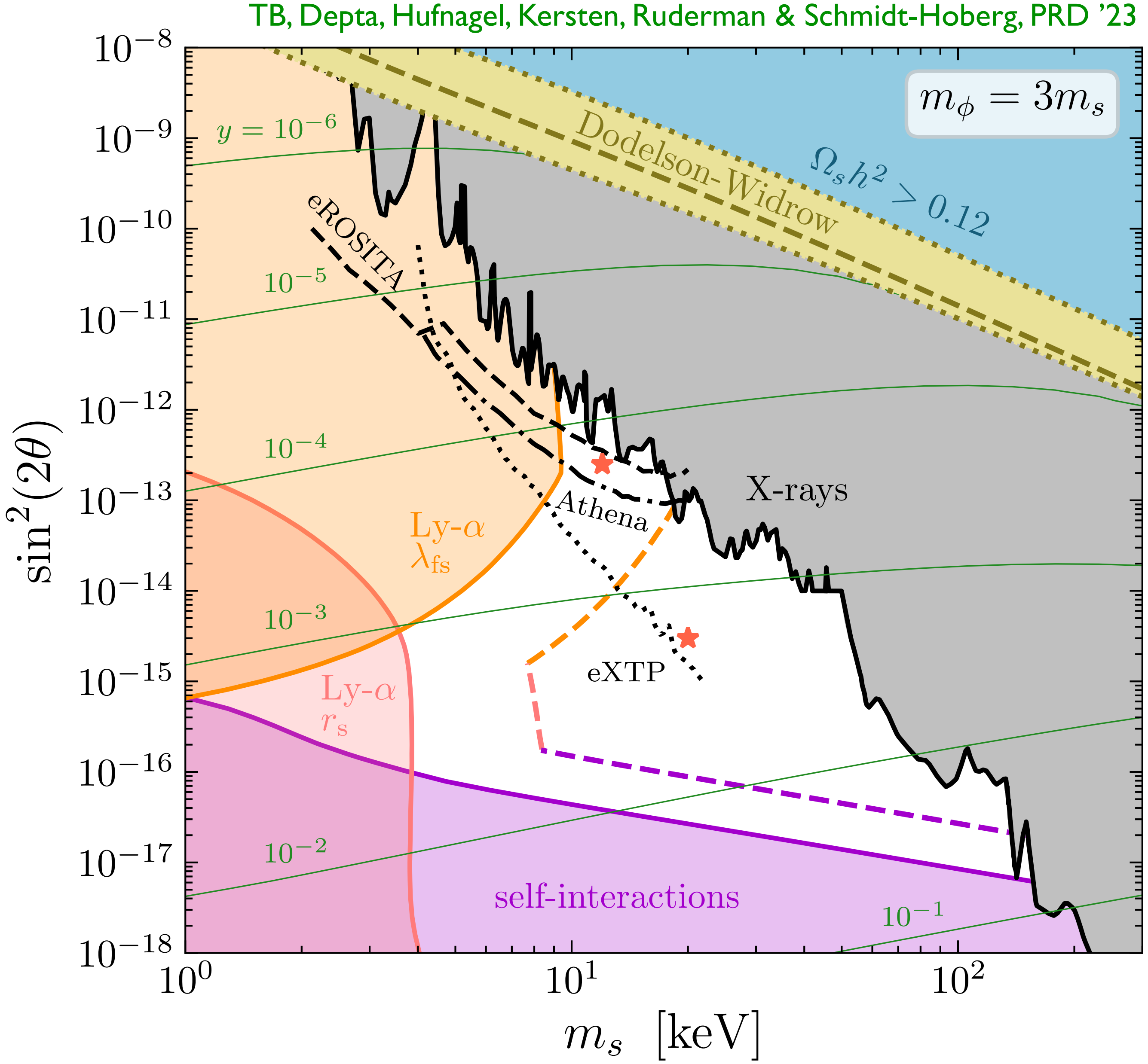
$\lambda_{\mathrm{FS}} < 0.24\,\mathrm{Mpc}$

$r_{\mathrm{s}} < 0.36\,\mathrm{Mpc}$

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

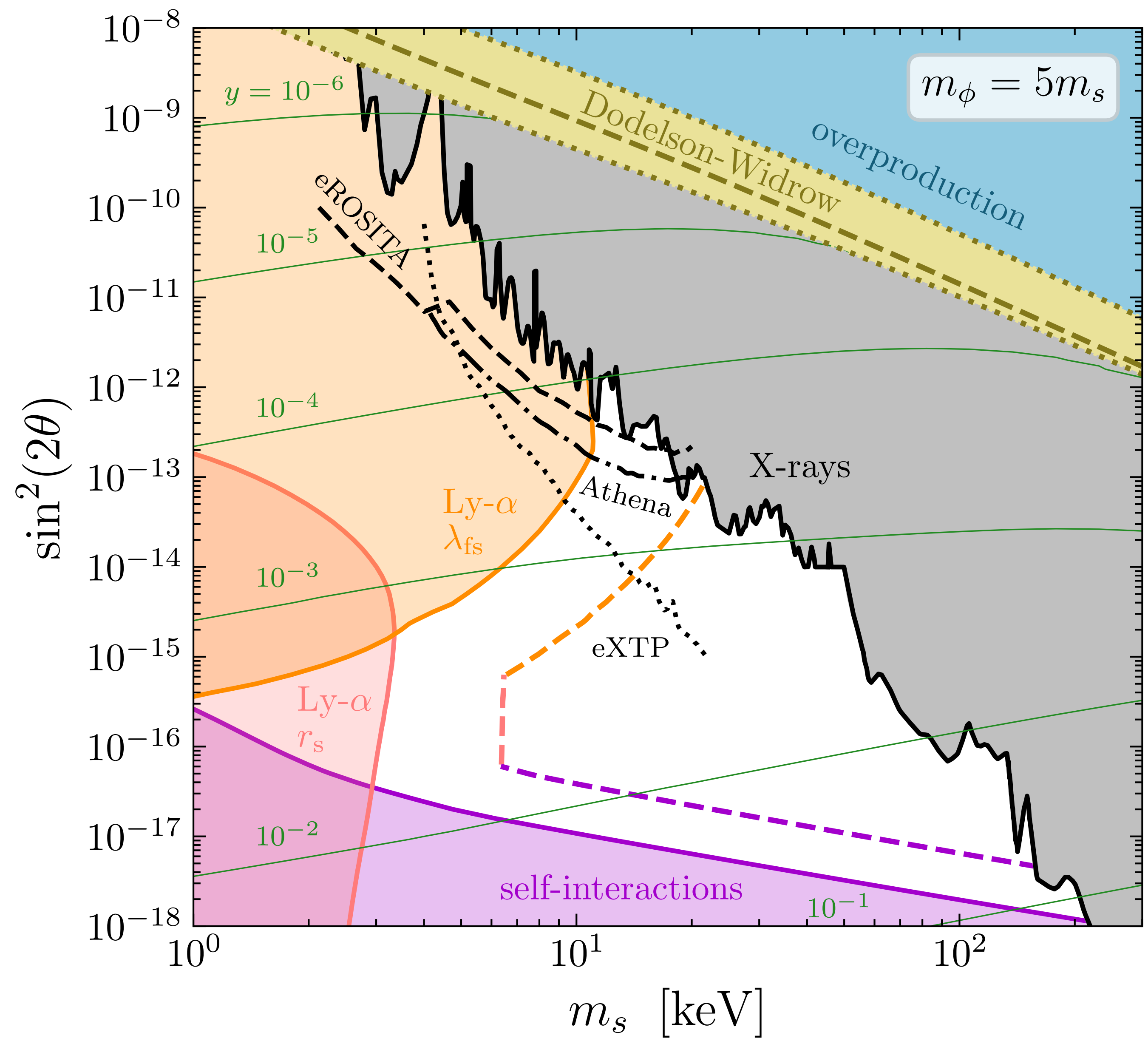
Palanque-Delabrouille+, JCAP '20

TB, Depta, Hufnagel, Kersten, Ruderman & Schmidt-Hoberg, PRD '23



Conclusions

- Sterile neutrino DM **excluded** in simplest form
- A new *minimal* scenario revives this idea
  - Adding only one scalar d.o.f. with $m_\phi \gtrsim 2m_s$
  - Significant new parameter space
  - Bounded from above *and* below
  - Much of it in observational reach



Thanks for your attention!