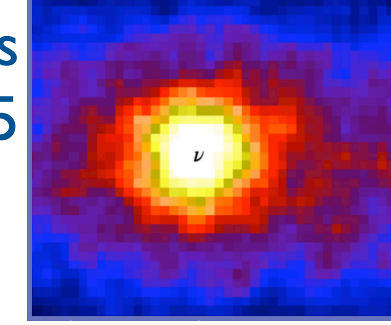
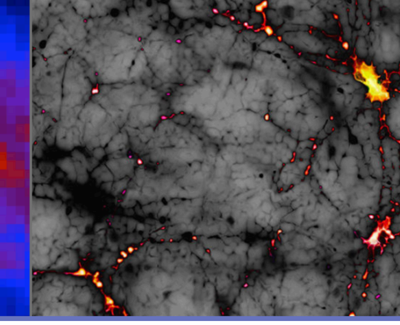
Dark Matter and Neutrinos, Paris
19 May 2025





Minimal sterile neutrino dark matter

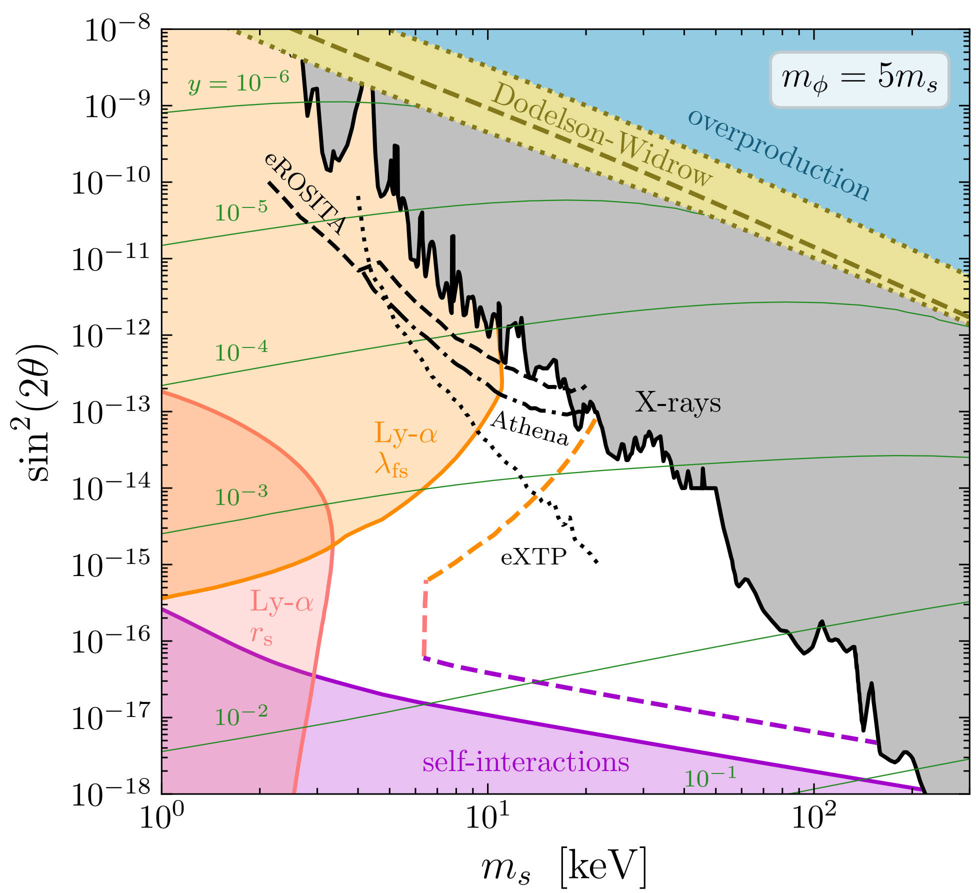
Torsten Bringmann

Mostly based on

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

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

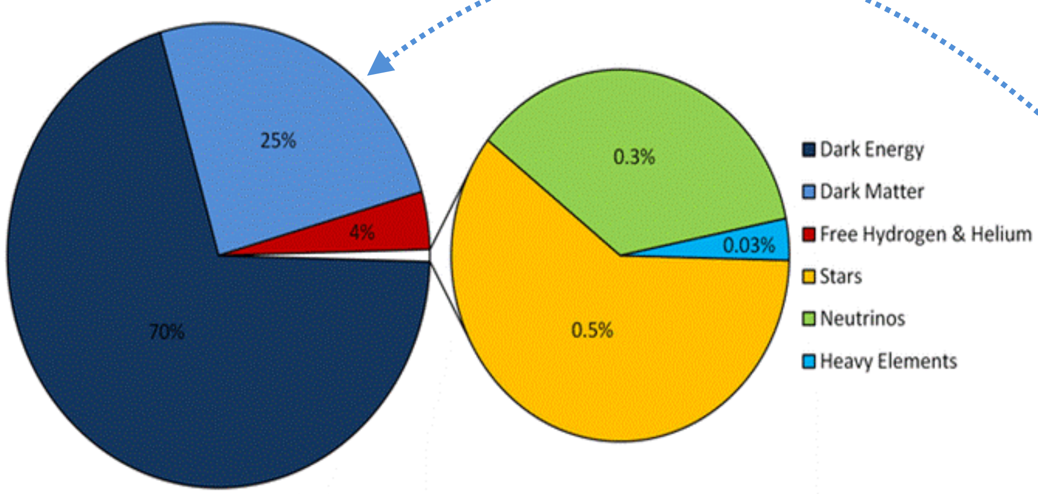
+ *ongoing work w/ A. Brekke*



UiO : University of Oslo

Part I

Dark matter production from the thermal bath

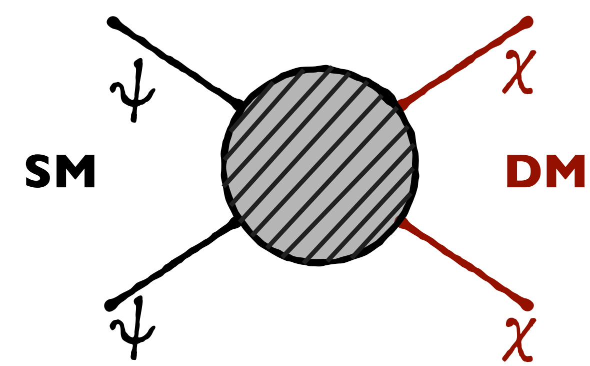


$$\Omega_{\rm CDM} h^2 = 0.1188 \pm 0.0010$$

Ade+ [Planck Coll.], A&A '16

Dark matter production

- ‘Generic’ interactions with the primordial heat bath:

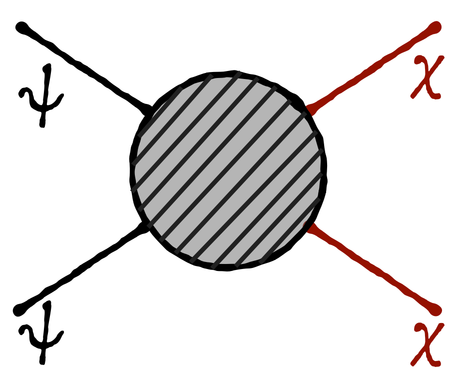


➡ Correct relic abundance in two regimes:

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

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

freeze-in



depends on initial conditions

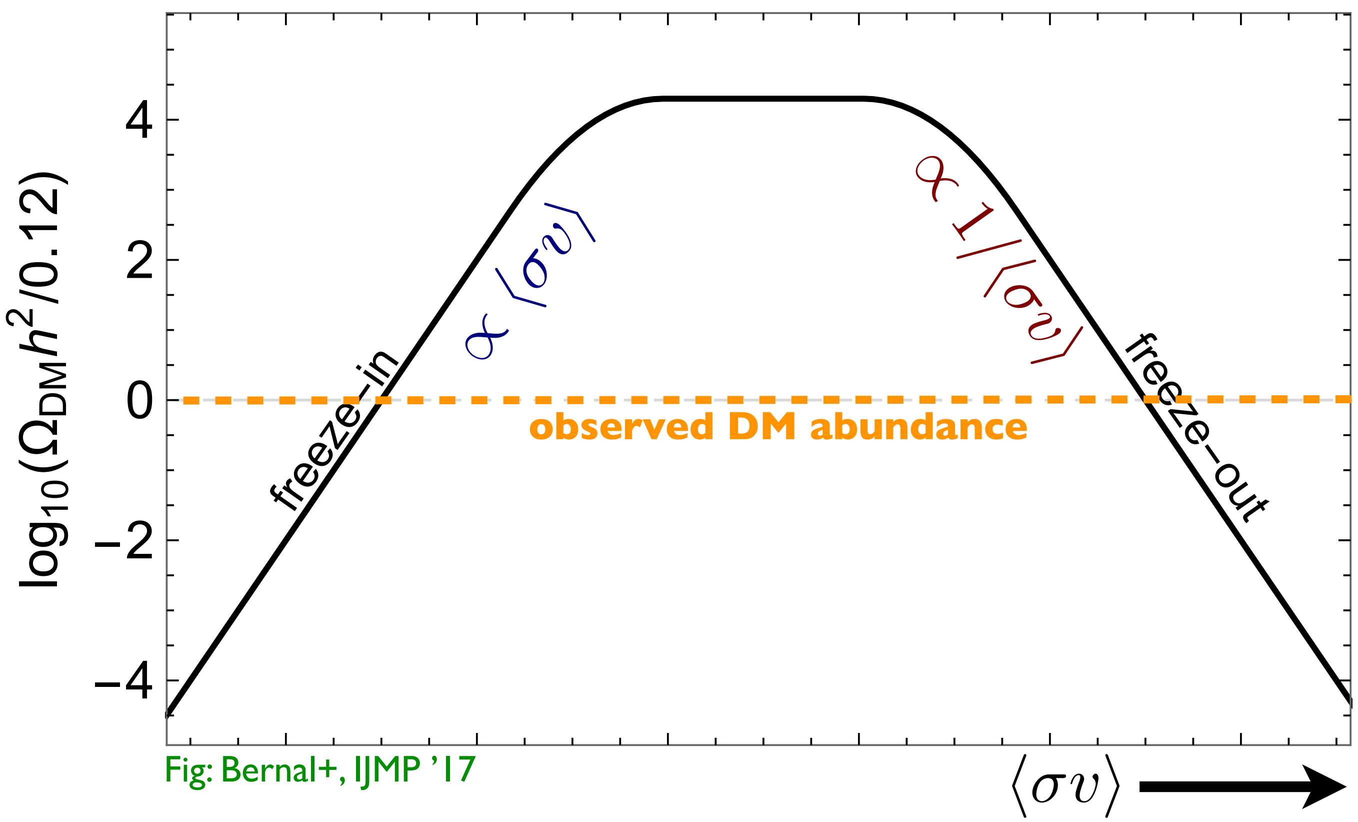
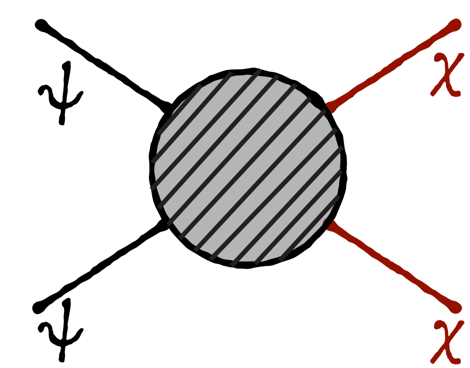


Fig: Bernal+, IJMP ’17

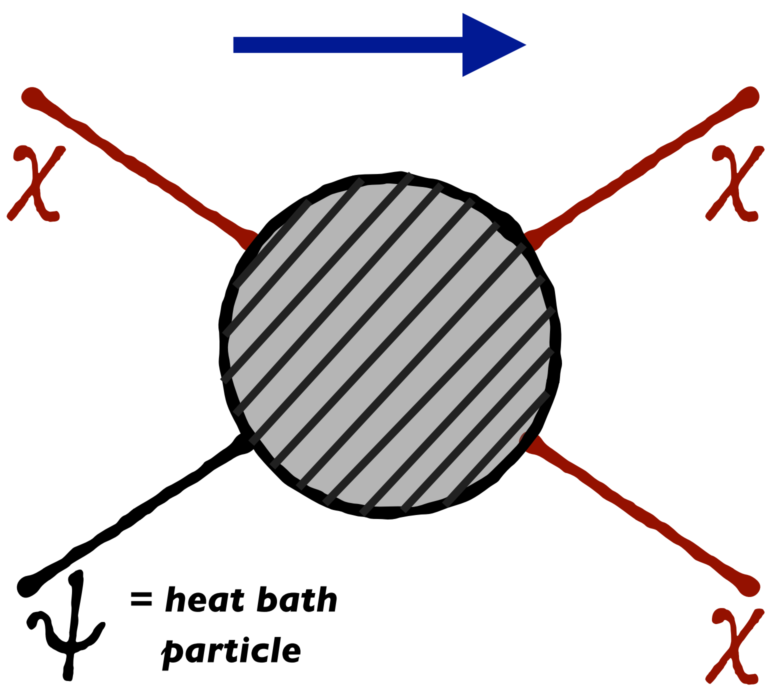
freeze-out



insensitive to initial conditions

New avenues

- 'Pandemic' dark matter



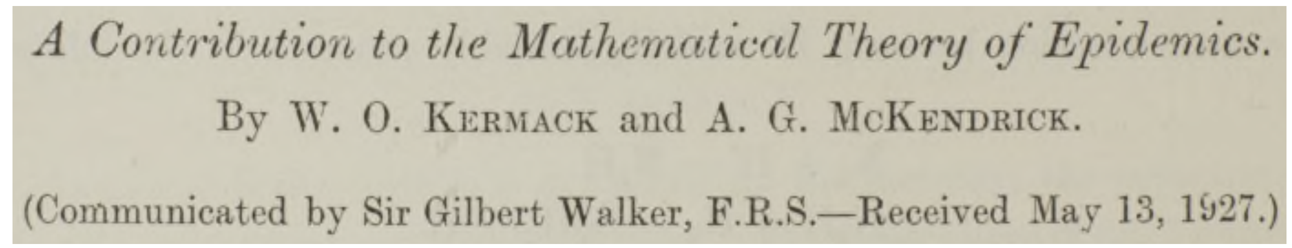
TB, Depta, Hufnagel, Rudermann & Schmidt-Hoberg, PRL '21

Hryczuk & Laletin, JHEP '21

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

[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***

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

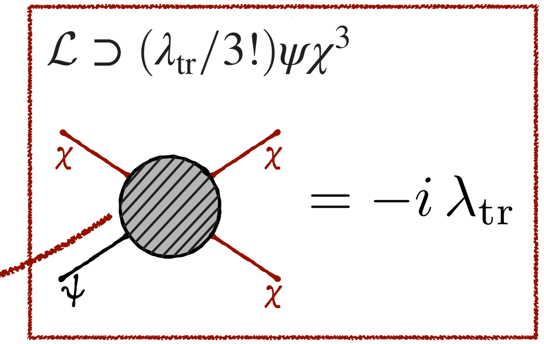
β ***infection rate***

γ ***recovery rate***

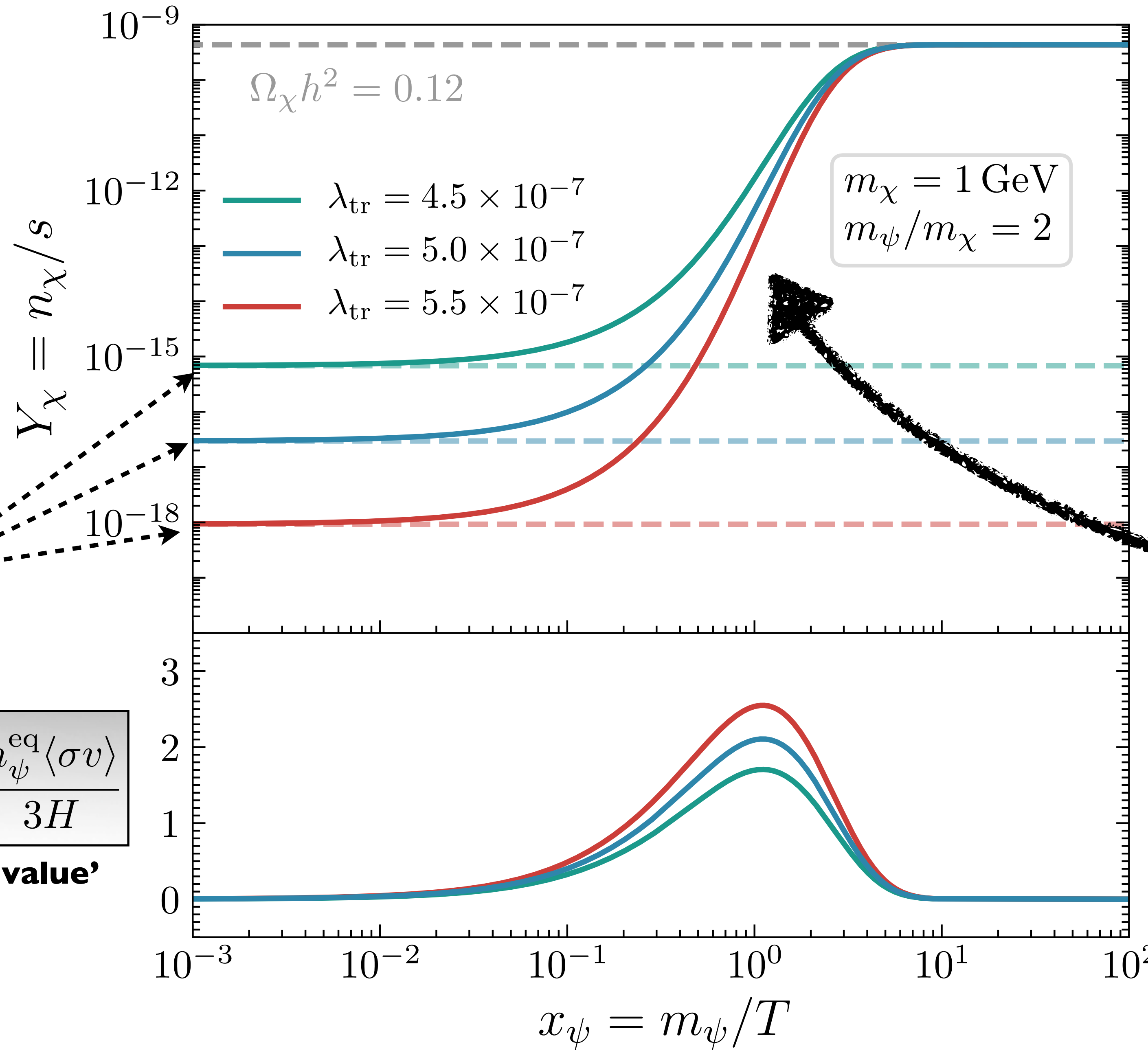
$$\dot{I} = \beta S I - \gamma I$$

Exponential DM production

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



toy model



Tiny initial DM abundance

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

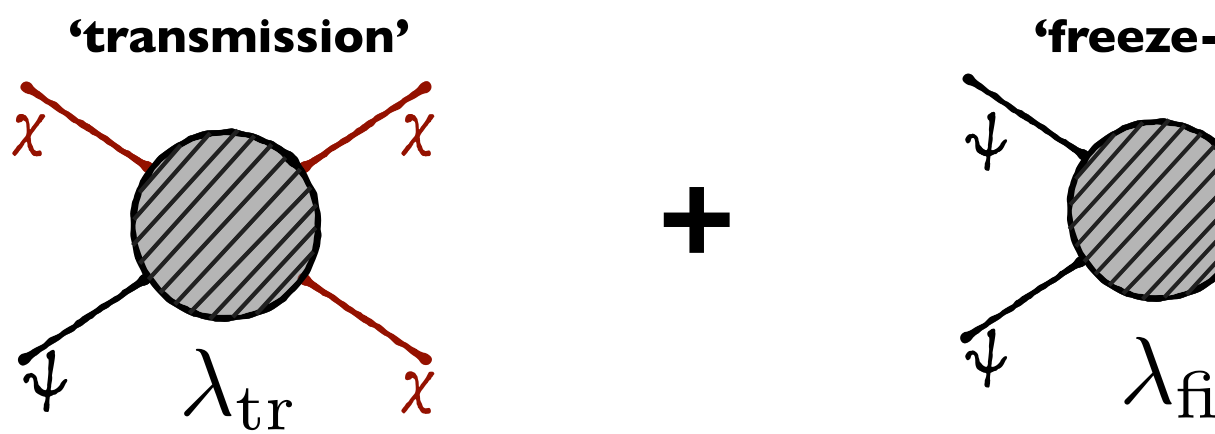
'reproduction value'

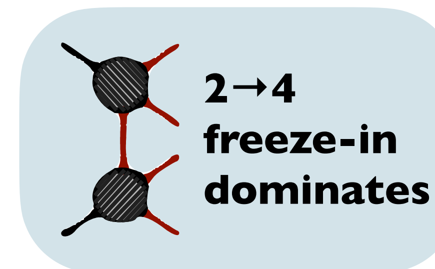
exponential growth $R \gtrsim 1$

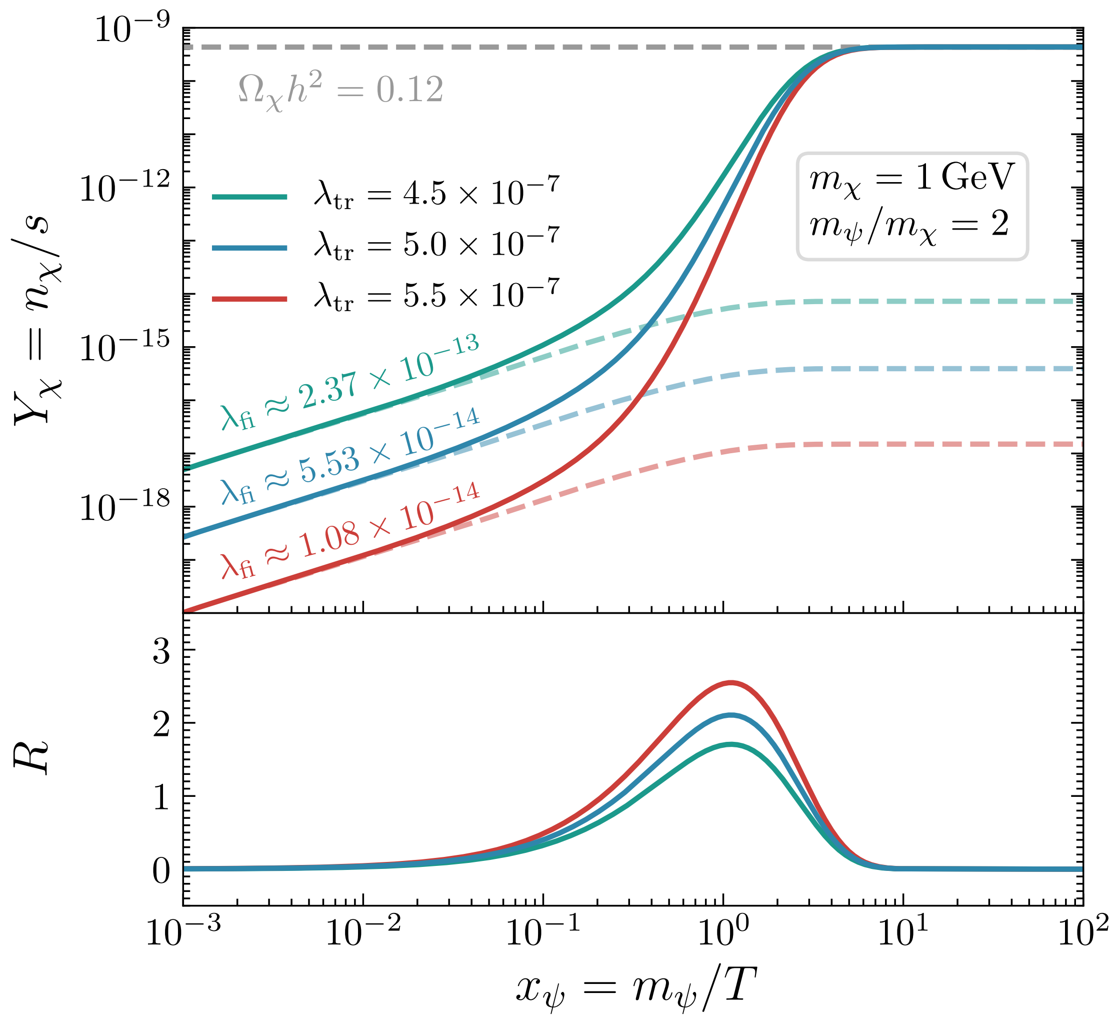
large H

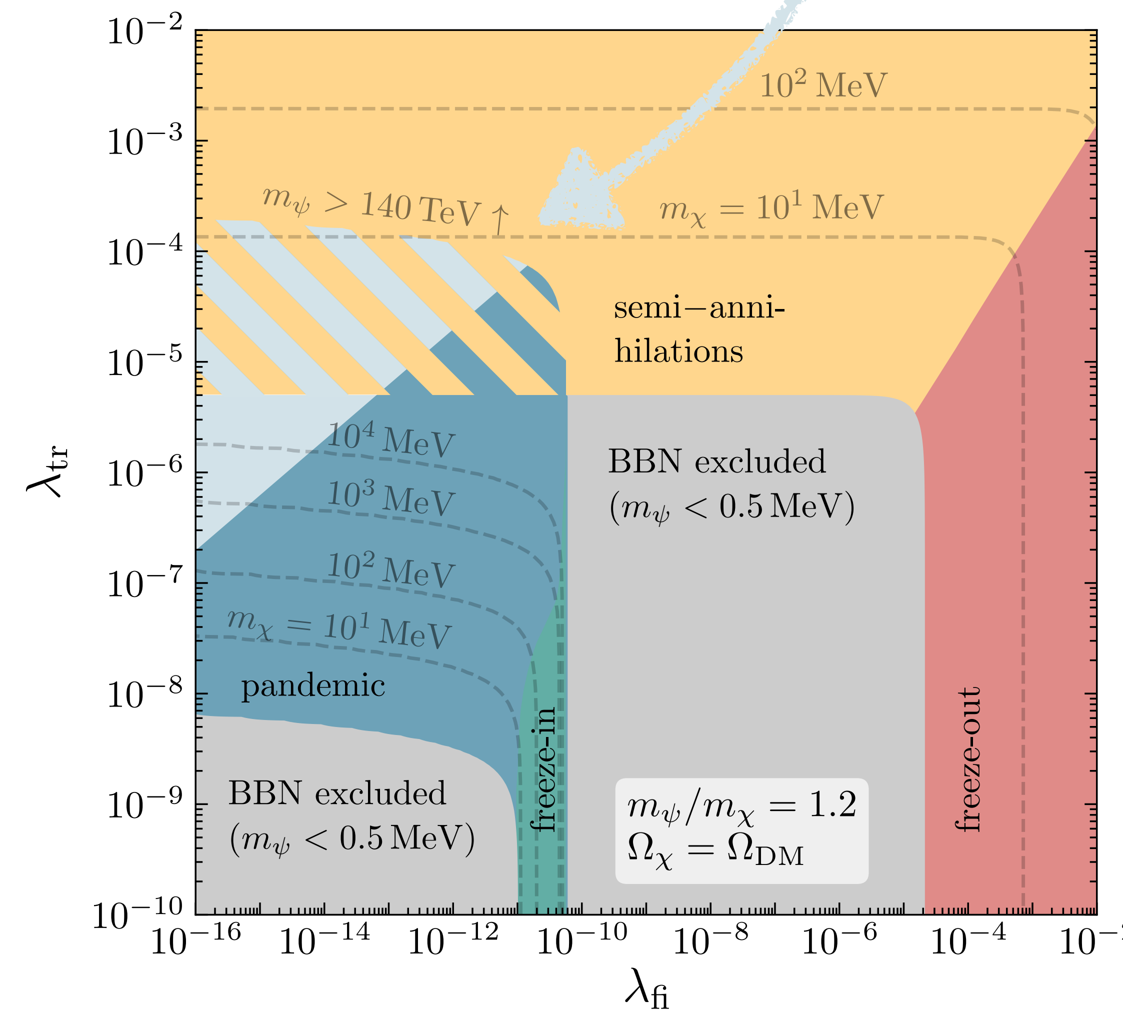
small $n_\psi^{\rm eq}$

Adding freeze-in production









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

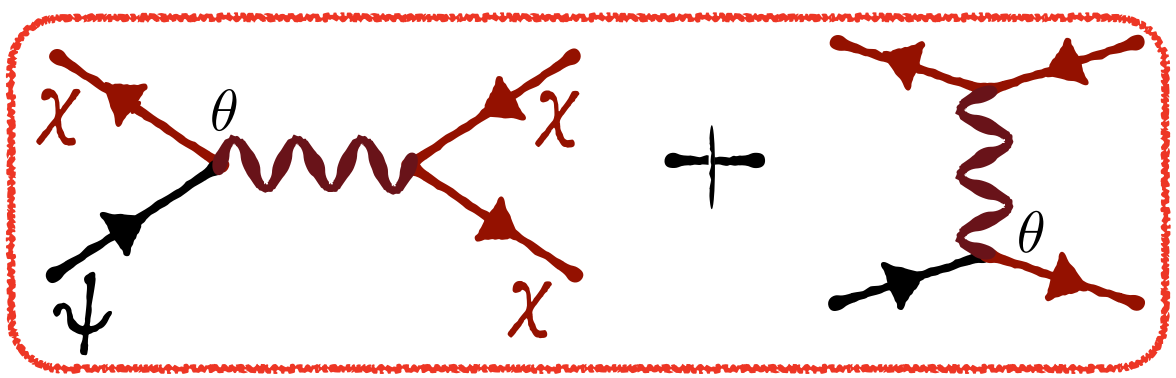
But… how ?

- How to *generically* realize $\langle\sigma v\rangle_{\rm fi} \ll \langle\sigma v\rangle_{\rm tr}$?

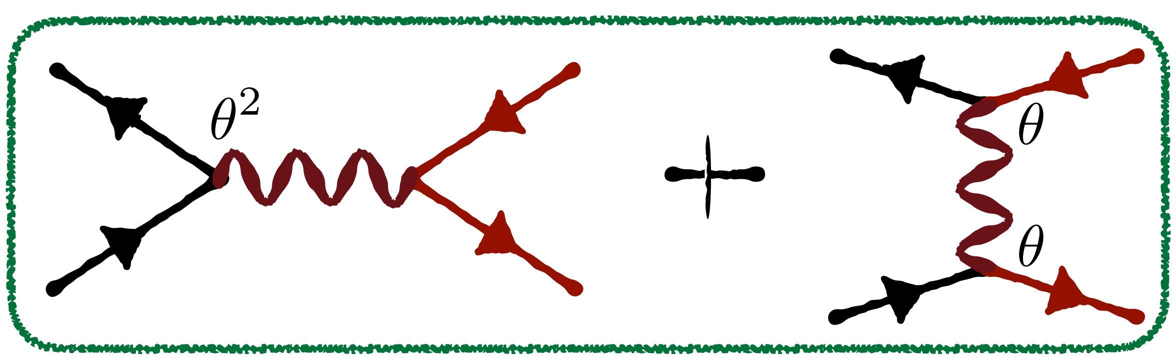
- Most easily by adding a dark sector mediator and mass mixing :

$$\mathcal{L} \supset -\delta m\,(\bar\psi\chi + \bar\chi\psi) - g\bar\chi \not{V}\chi$$

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



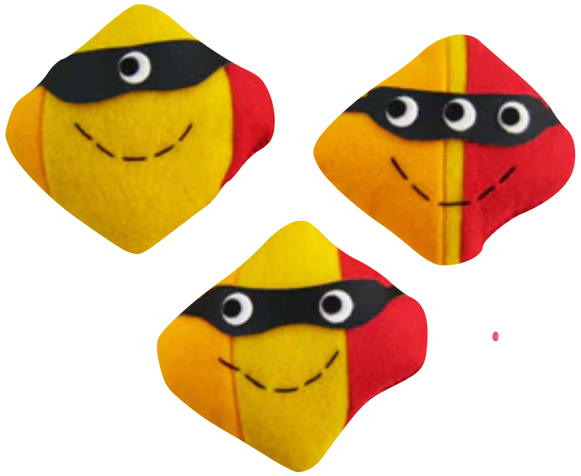
transmission $\propto \theta$



freeze-in $\propto \theta^2$

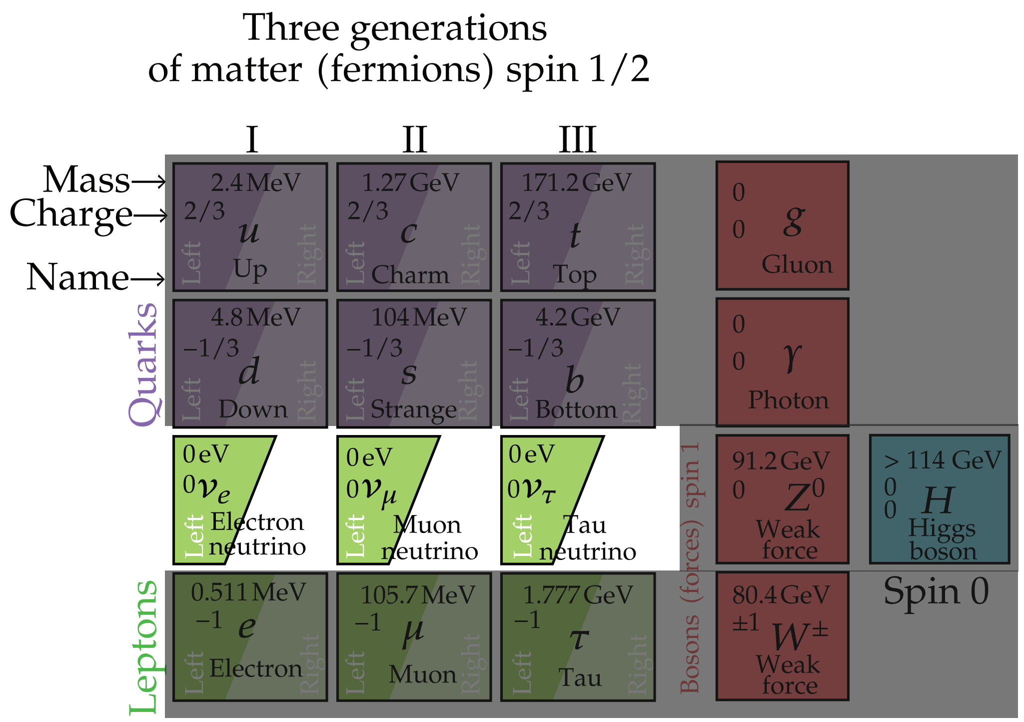
Part II

Sterile neutrinos as dark matter



Recap: DM = BSM

Fig: Gninenko, Gorbunov & Shaposhnikov, Adv. HEP '12



- most particles are 'obviously' ruled out as dark matter…

  strongly interacting

  charged / visible

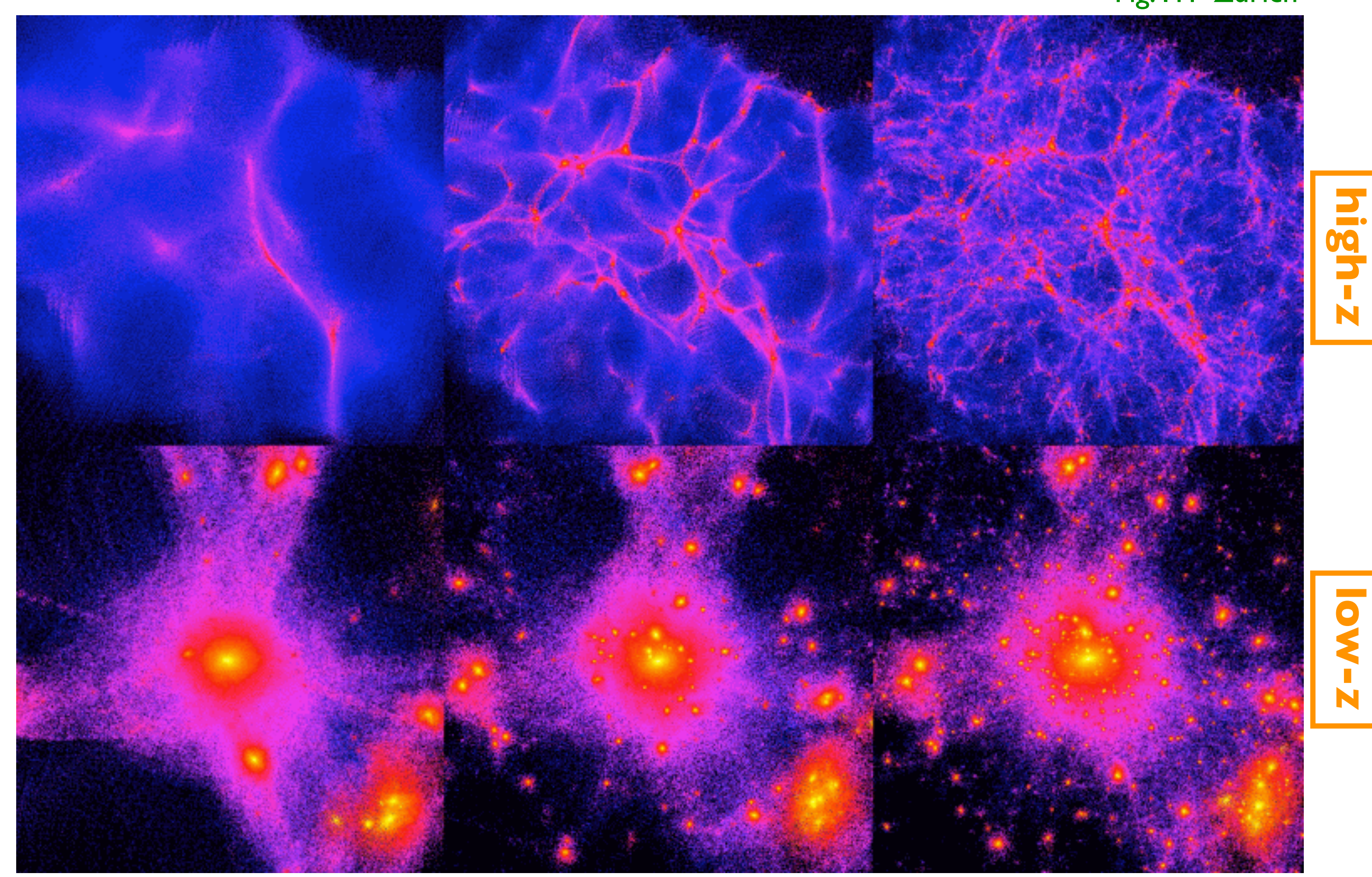
  unstable

- … but neutrinos were for some time considered to be very good candidates

→ *Free streaming out of overdense regions removes too much power on small scales !*

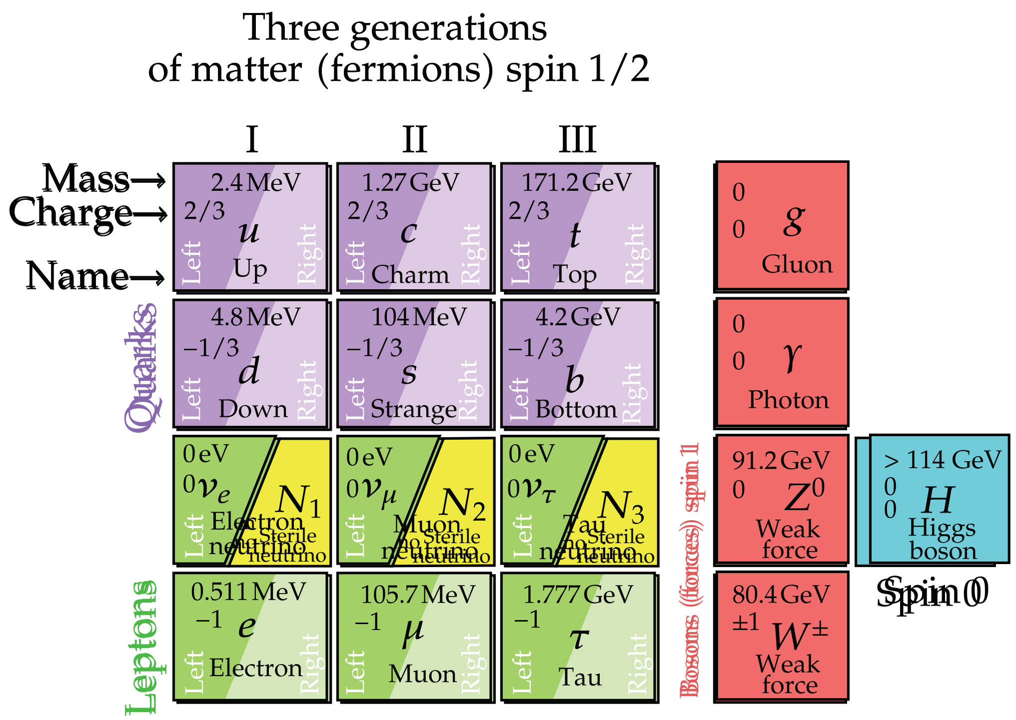
White, Frenk & Davis, ApJ '83

Fig: ITP Zurich



Hot DM	Warm DM	Cold DM
$m_{DM} \lesssim \mathrm{keV}$	$m_{DM} \sim \mathrm{keV}$	$m_{DM} \gtrsim \mathrm{keV}$

Sterile neutrinos



- Right-handed neutrinos would
  - 'complete the picture'
  - be singlets under the SM gauge group
  - but still interact through the neutrino portal

$$\mathcal{L} \supset y\,(i\sigma^2 H^*)LN$$

= *only possible renormalizable coupling between SM particles and (BSM) singlet fermions !*

- Highly motivated from phenomenological point of view:

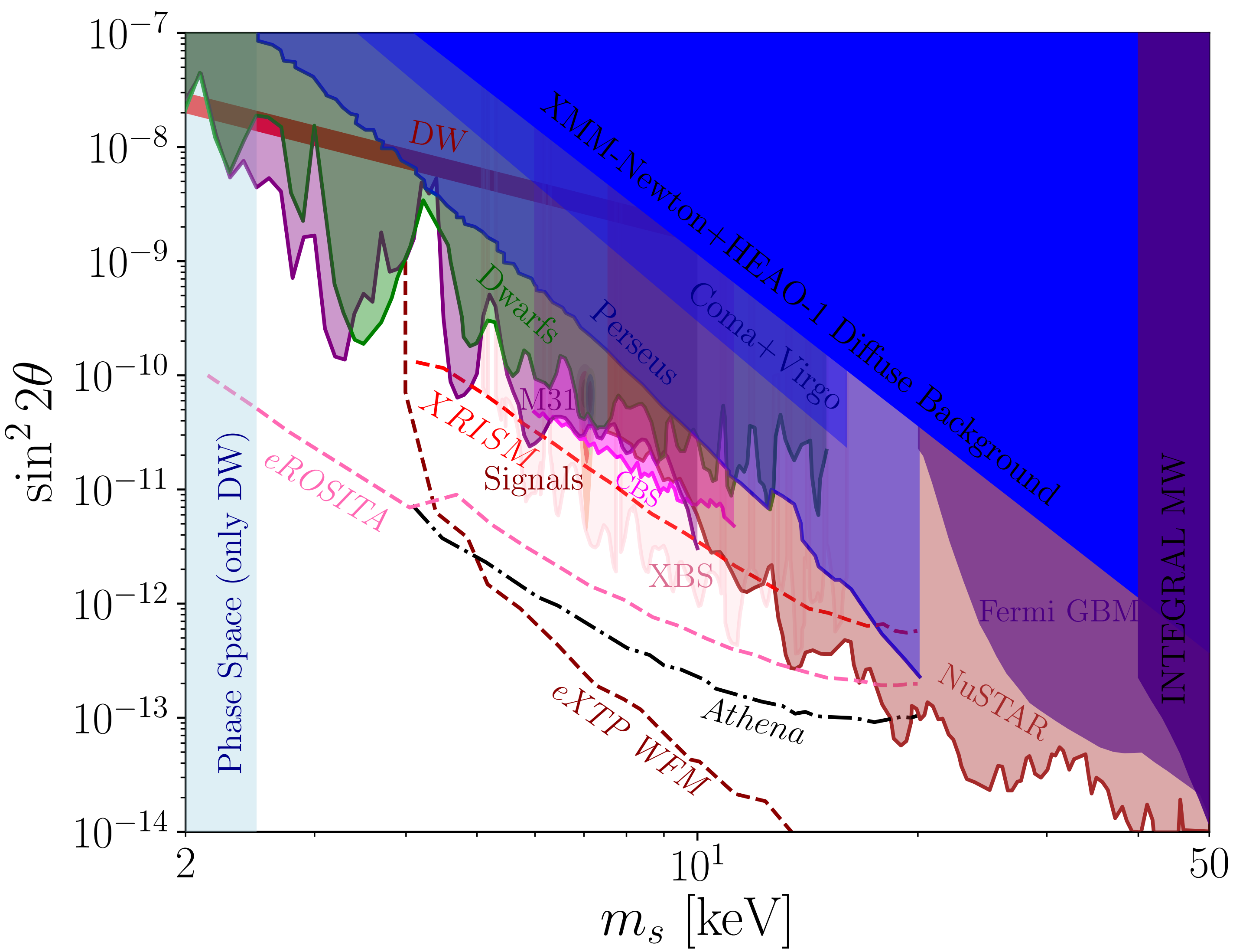
	N mass	ν masses	eV ν anomalies	BAU	DM	M_H stability	Direct search	experiment
GUT seesaw	10–16 10 GeV	Yes	No	Yes	No	No	No	—
EWSB	2-3 10 GeV	Yes	No	Yes	No	Yes	Yes	LHC
ν MSM	keV-GeV	Yes	No	Yes	Yes	Yes	Yes	a'la CHARM
ν scale	eV	Yes	Yes	No	No	Yes	Yes	a'la LSND

Gninenko, Gorbunov & Shaposhnikov, Adv. HEP '12

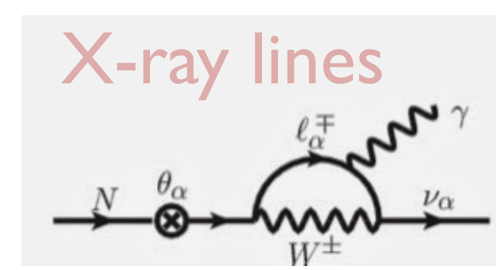
Sterile neutrinos

- 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
    - ⇝ 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

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

- $m_\phi \sim 100\,\mathrm{keV},\ y \lesssim 10^{-8}$ 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
- $m_\phi > 1\,\mathrm{GeV},\ y \sim \mathcal{O}(1)$ Johns & Fuller, PRD '19
  - Induces sharp resonance in V_{eff}
    - ⇒ either no impact or runaway behaviour
- $10\,\mathrm{keV} \gtrsim m_\phi > 2m_s,\ \ y \gtrsim 10^{-6}$ **This talk** TB, Depta, Hufnagel, Kersten, Ruderman & Schmidt-Hoberg, PRD '23

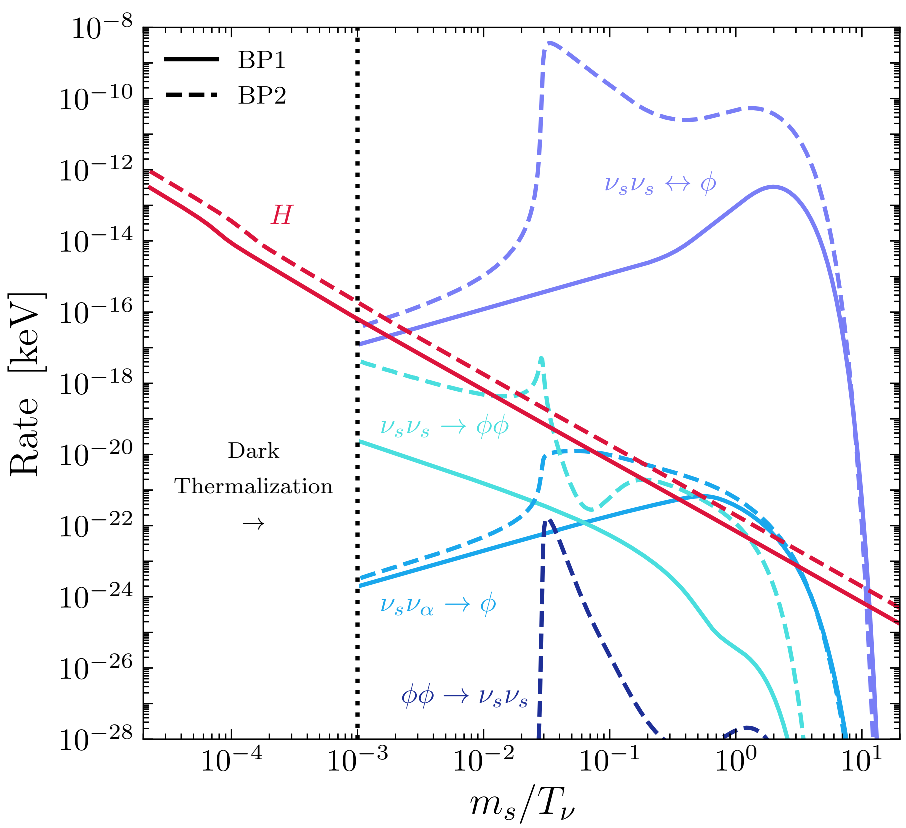
see also Astros & Vogl, JHEP '24 *for discussion of 'entire' scalar mass range*

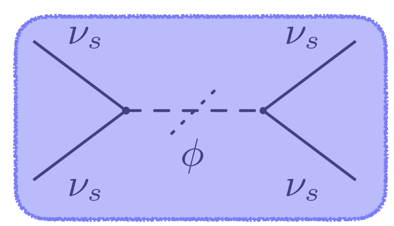
Production — phase 1

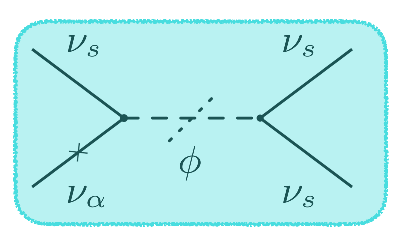
- $\mathcal{L} \supset \frac{y}{2}\overline{\nu_s^c}\phi\nu_s + \text{h.c.}$, $m_\phi > 2m_s$
- Early times (~QCD PT): standard DW production
  - Adopt resulting number & energy density as initial condition

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 $T_d(T), \mu_s(T), \mu_\phi(T)$

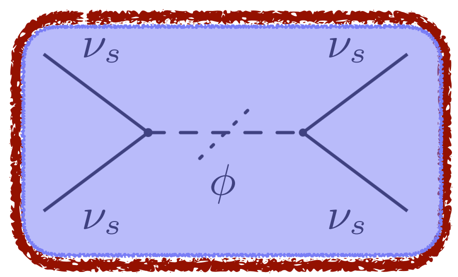
Production — phase II

- $\mathcal{L} \supset \frac{y}{2}\overline{\nu_s^c}\phi\nu_s + \text{h.c.}$, $m_\phi > 2m_s$

- Evolution after DW:

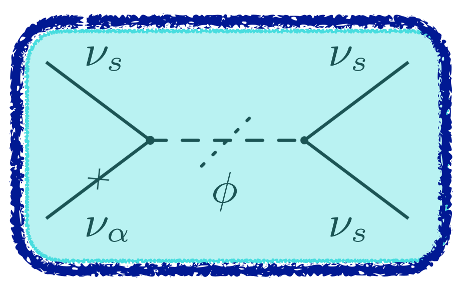
  solid: benchmark point with large θ, small y
  dashed: benchmark point with small θ, large y

  - Thermalization in dark sector

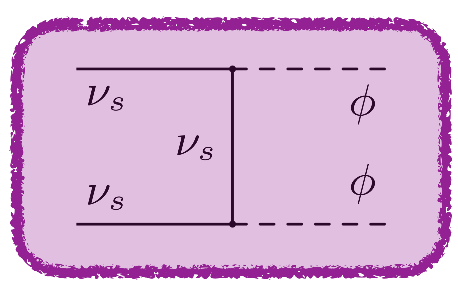


NB: This allows exact solution of Boltzmann equation!

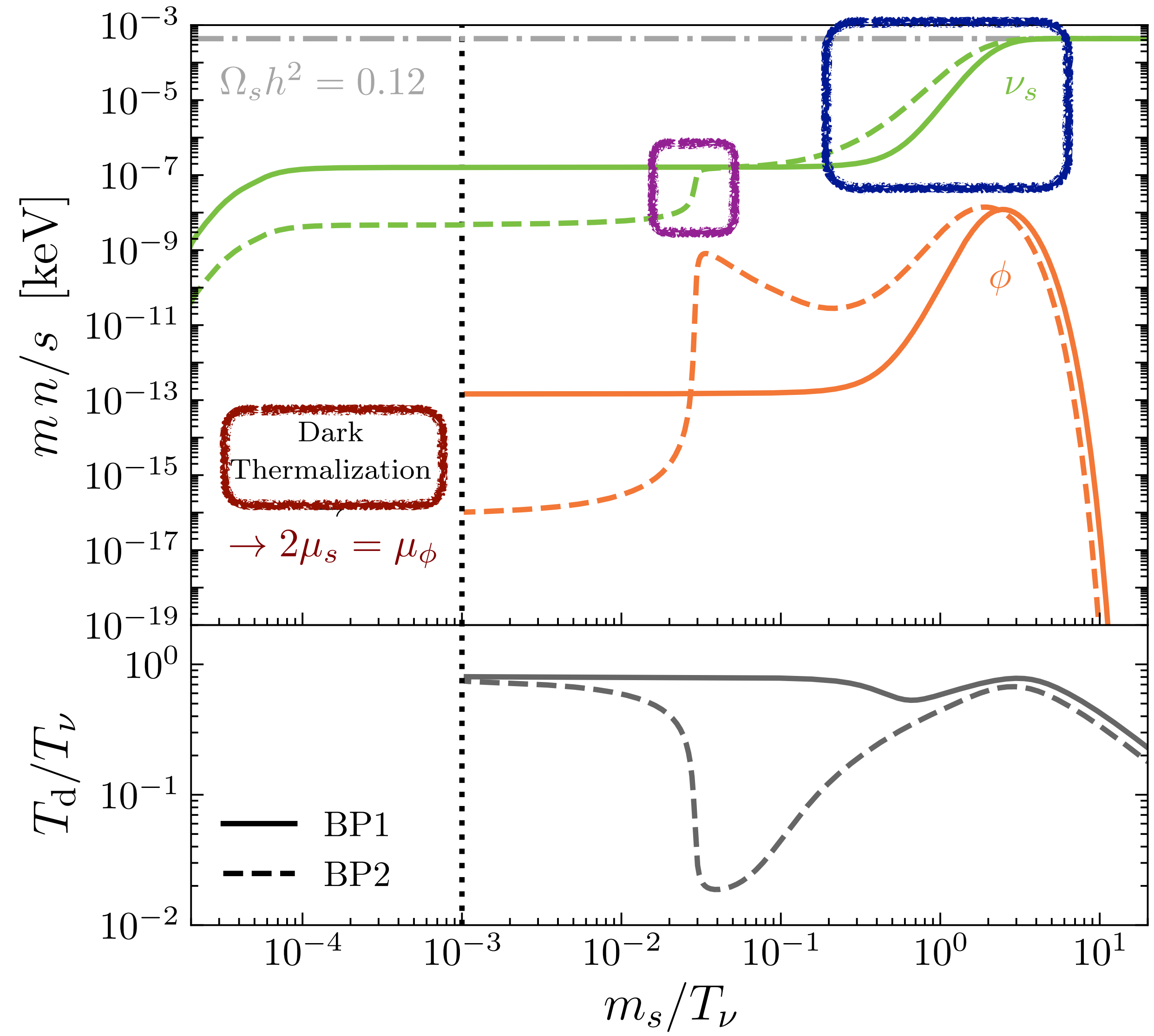
  - Exponential growth



  - Reproductive freeze-in



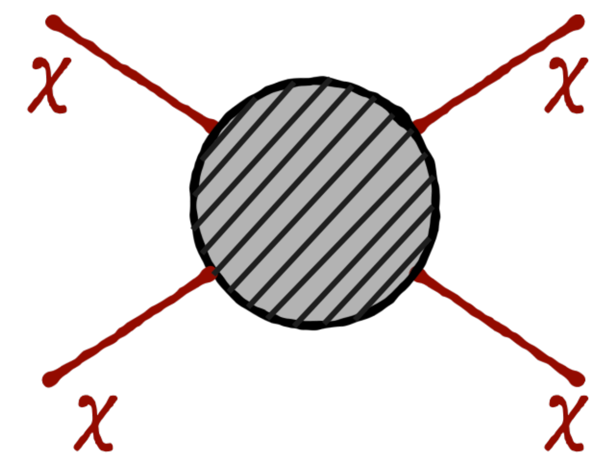
$+ \;\; \phi \to 2\nu_s$

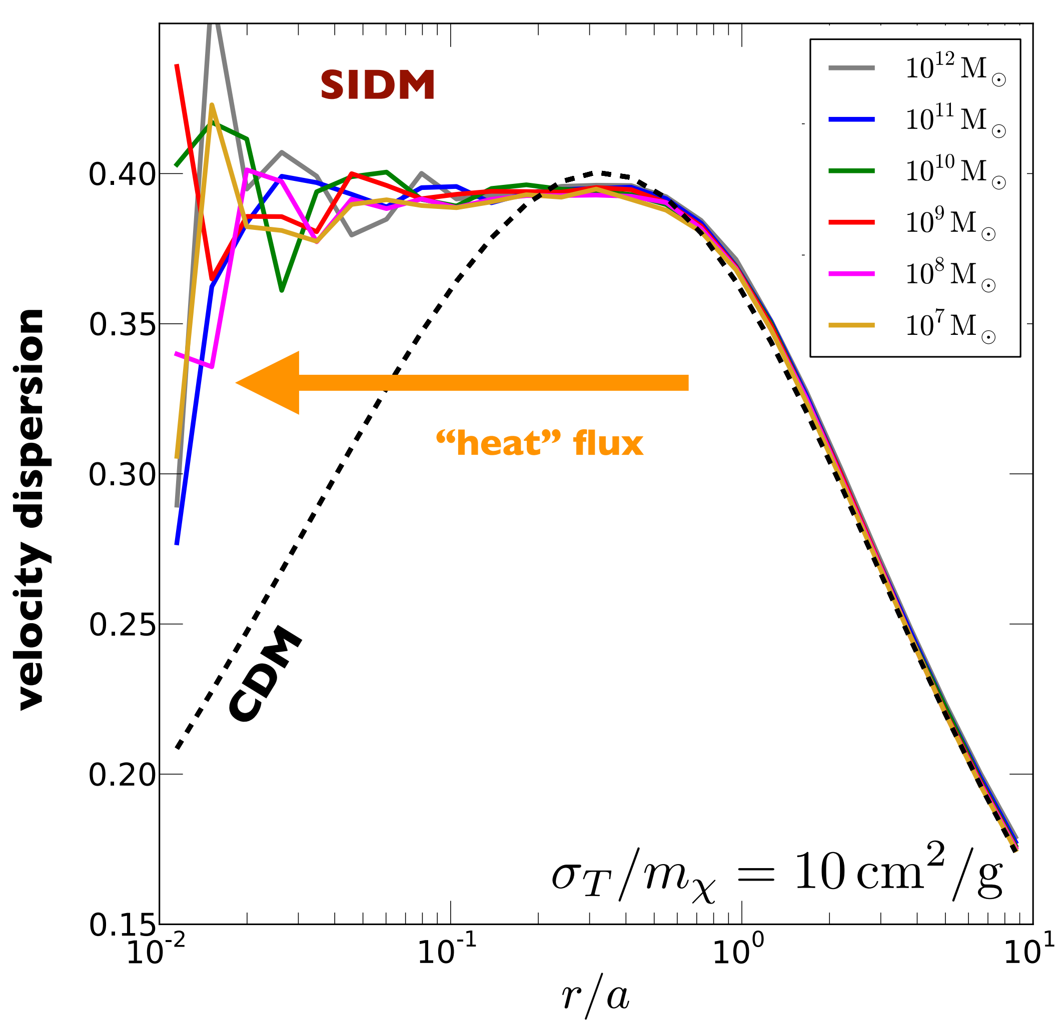


Self-interacting DM (SIDM)

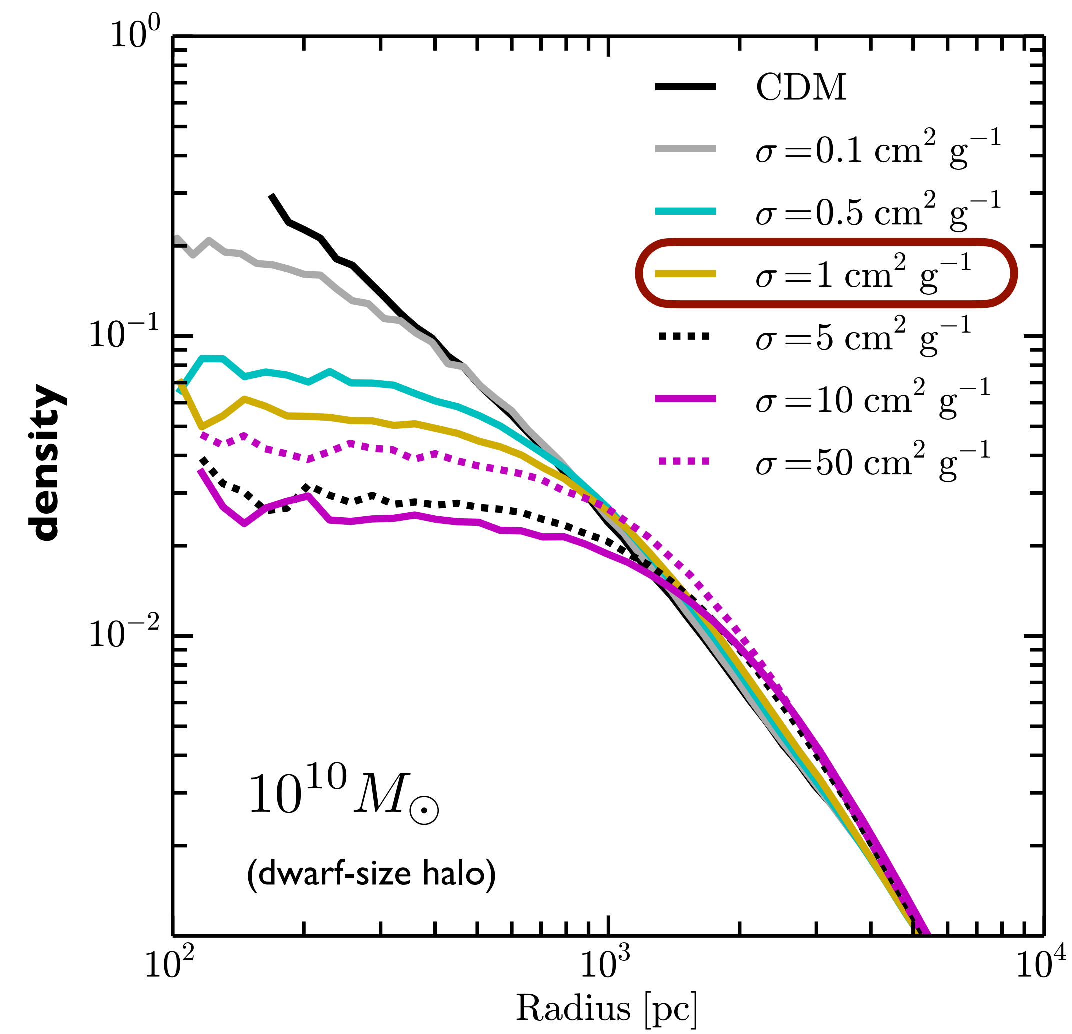
- DM-DM scatterings Spergel & Steinhardt, PRL '99
  - do not affect linear perturbations (number densities too small)
  - but isotropise DM distribution in inner parts of halo

➡ core formation once $\mathcal{O}(1)$ scatters per dynamical time





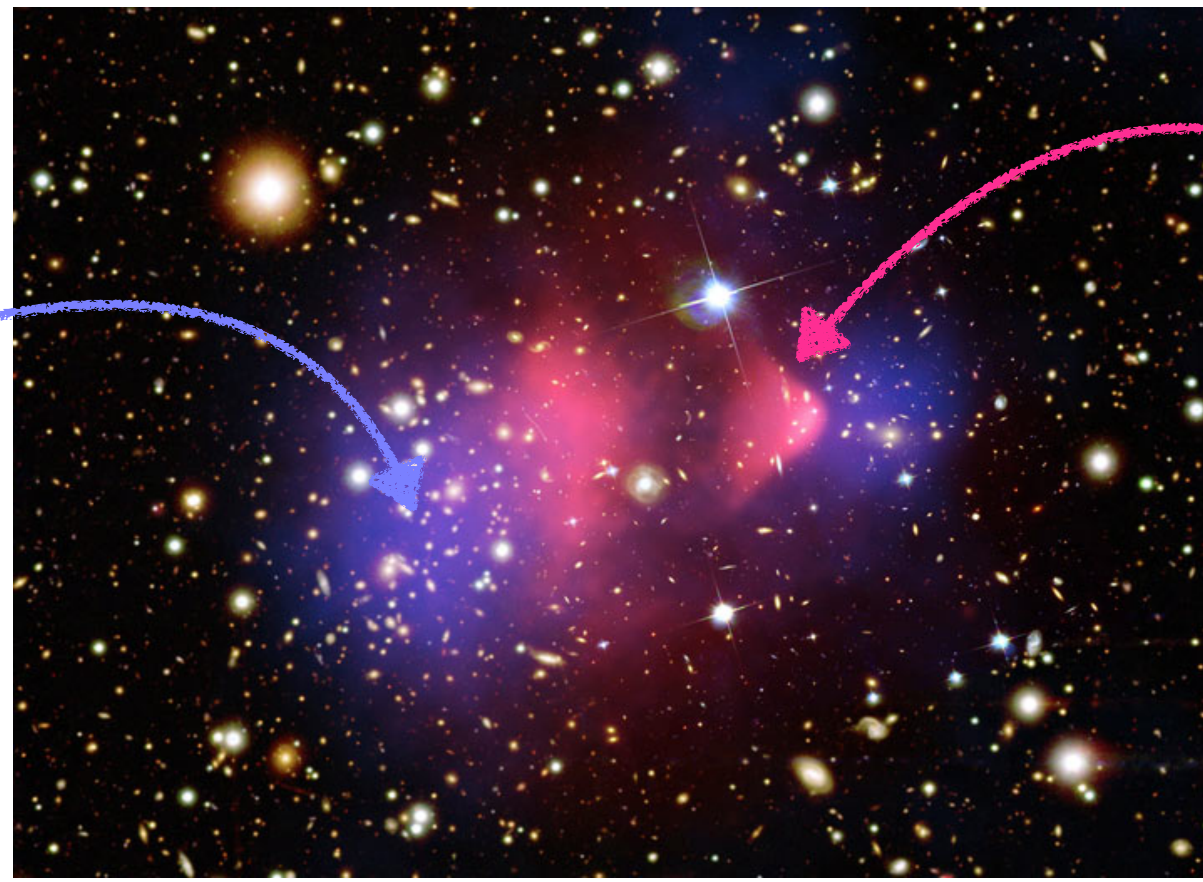
Vogelsberger, Zavala & Loeb, MNRAS '12



Elbert+, MNRAS '15

Self-interacting DM (SIDM)

- Observed DM density profiles constrain $\sigma_{\rm SIDM}$ at galactic scales
- Larger scales: e.g. colliding galaxy clusters



Clowe+, ApJ '06

- Various individual constraints. Largely agreed-upon value:

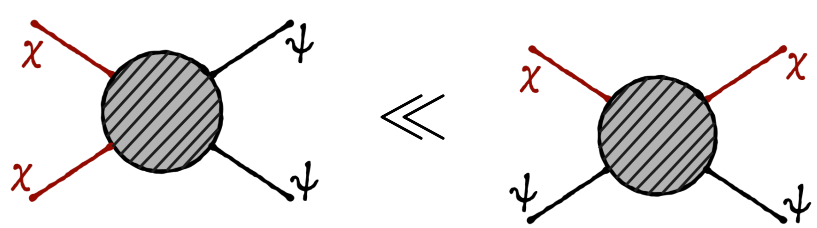
review: Tulin & Yu, PR '18

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

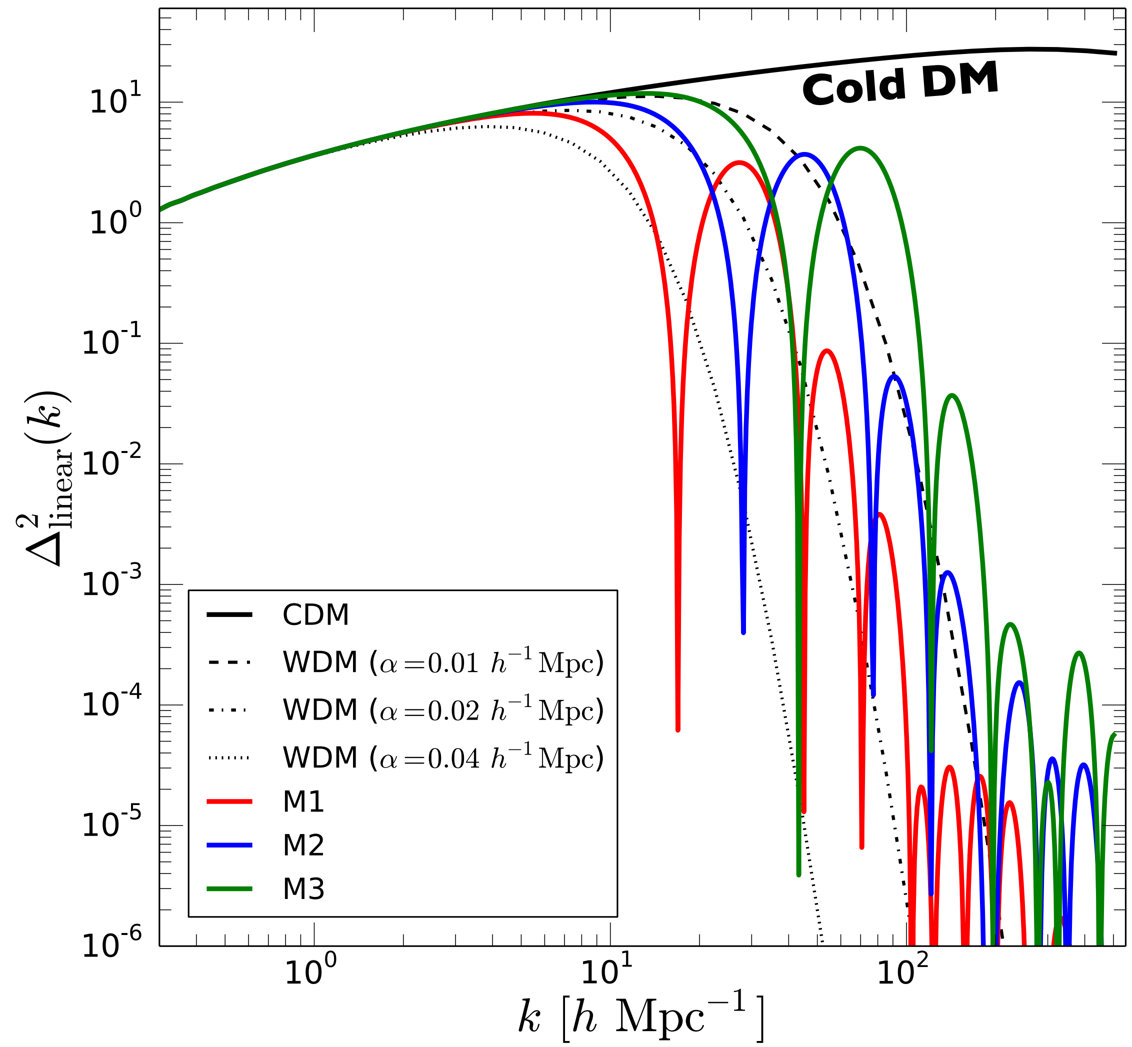
Suppressing power at small scales

- The (linear) CDM spectrum of matter density perturbations can be suppressed by
  - free-streaming of warm DM **[dashed]**
  - (late) kinetic decoupling of cold DM **[solid]**

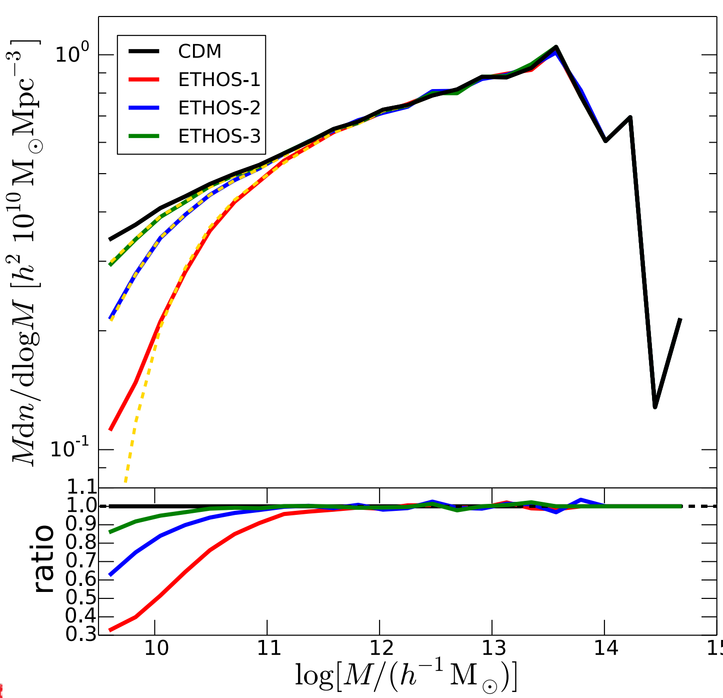
review: TB, NJP '09



(annihilation) (scattering)



Vogelsberger+, MNRAS'16



- Both effects turn out to produce almost identical shapes in non-linear spectrum (halo mass function)

➡ straight-forward to recast standard WDM limits

The Lyman-α forest

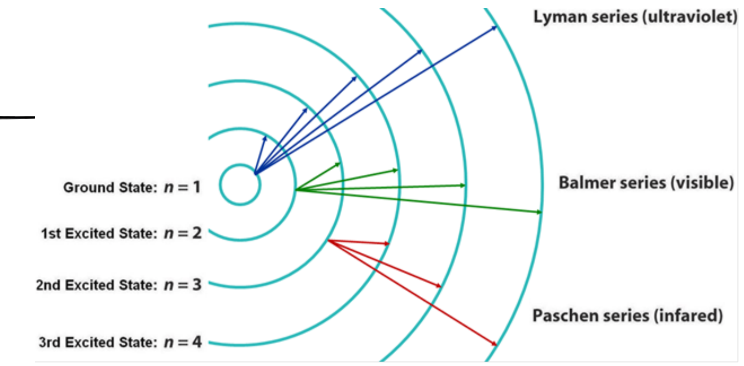
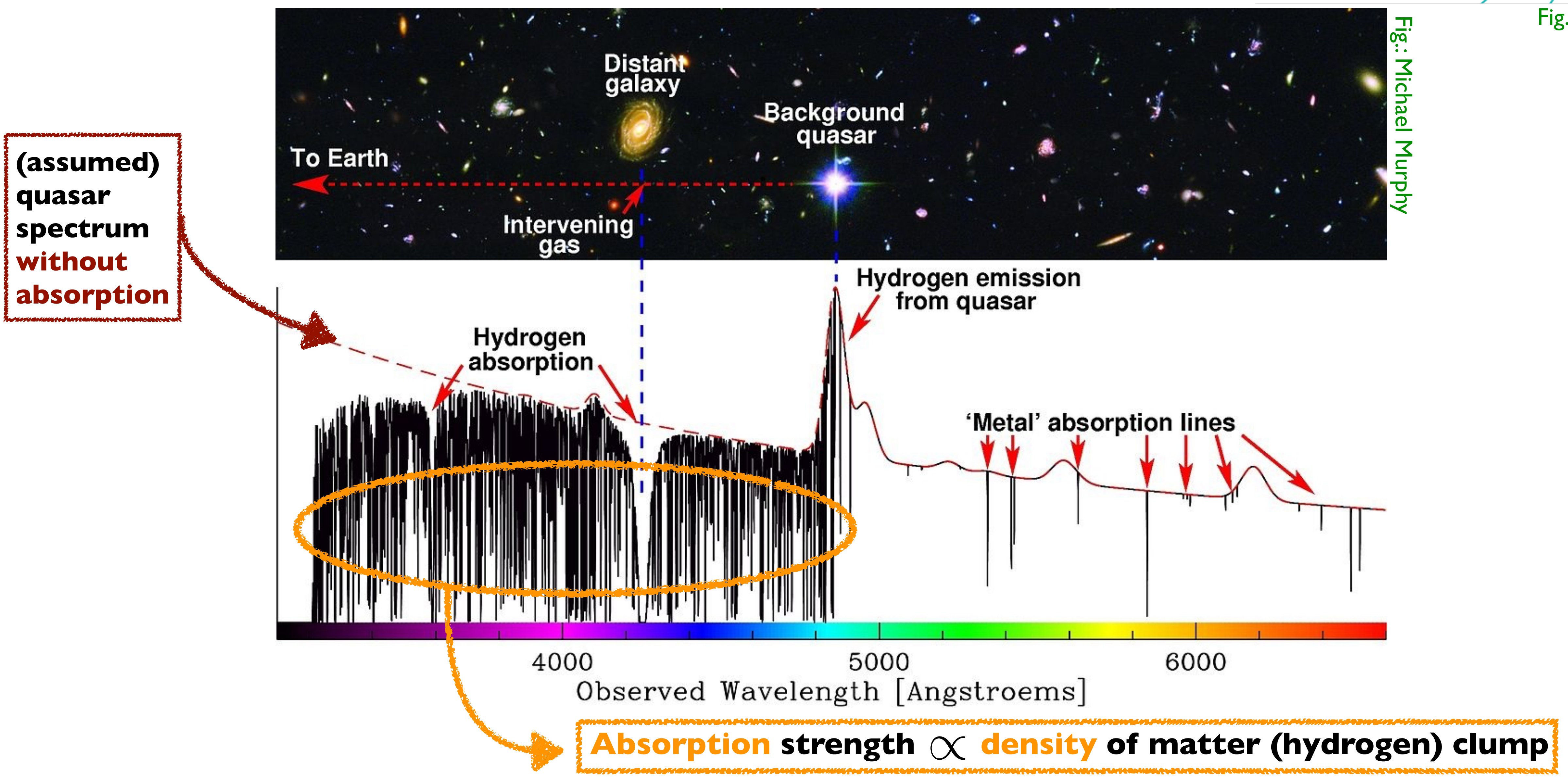


Fig.: Daniel Reichart

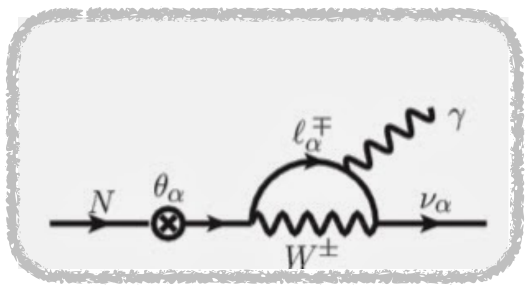


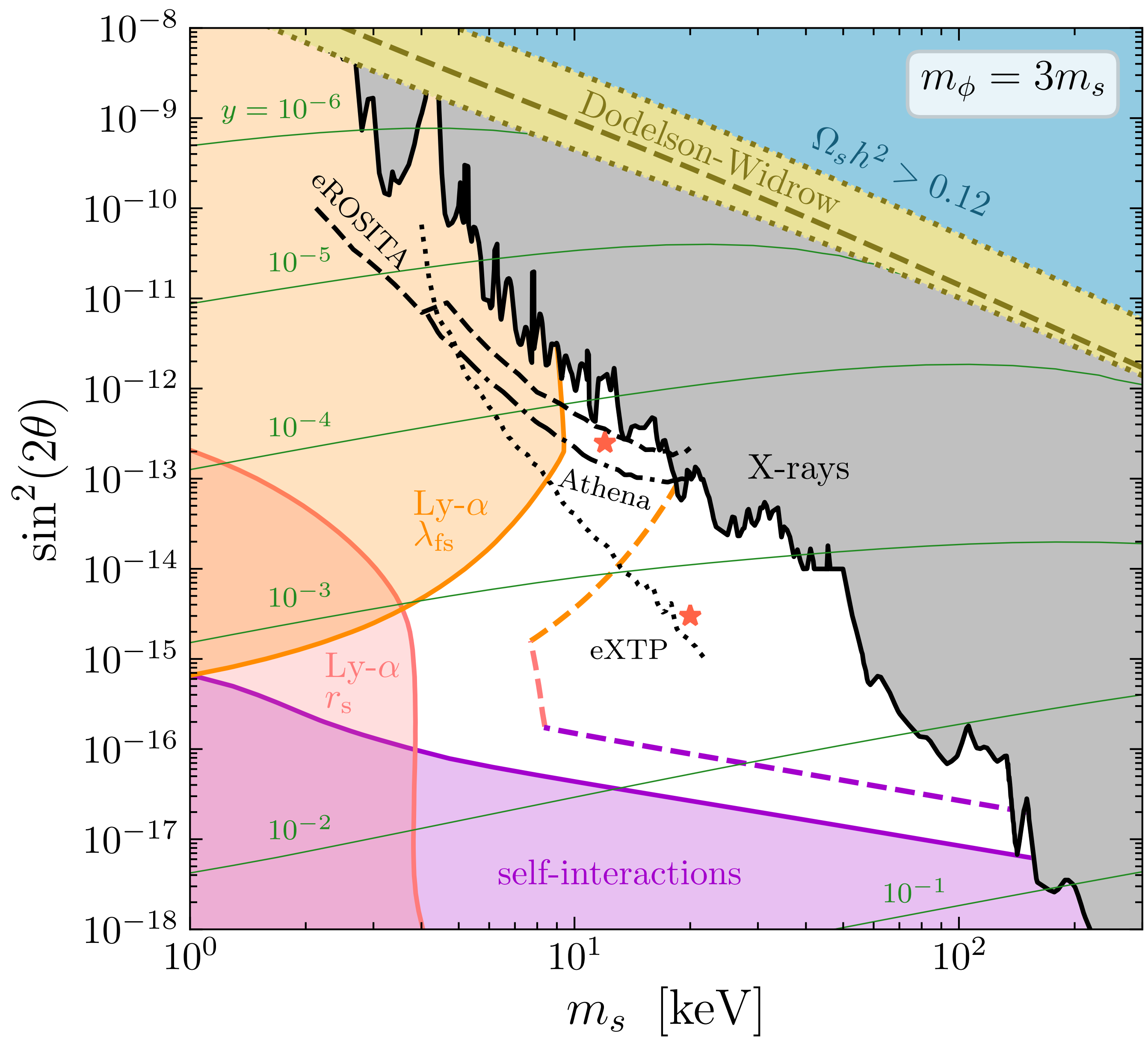
➡ *This gives the currently strongest limit on a possible small-scale cutoff of the spectrum of matter density perturbations*

Sterile neutrinos… revived !

- Correct relic density possible for much smaller mixing angles
  - $\Omega_{\nu_s} h^2 = 0.12$ by choosing Yukawa coupling

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

Garzilli+, MNRAS '21

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

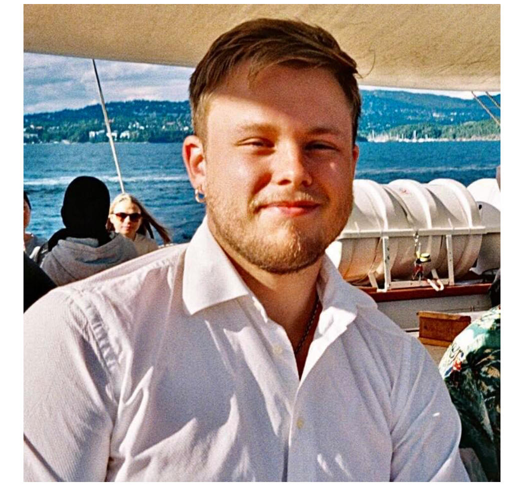
$r_{\rm s} < 0.36\,\mathrm{Mpc}$

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

Palanque-Delabrouille+, JCAP '20

Vector mediator

ongoing work with Anton Brekke



- Maybe more appealing option: charge ν_s under dark *U(1)'*

$$\mathcal{L} \supset \frac{y}{2}\overline{\nu_s^c}\phi\nu_s + \mathrm{h.c.} \quad \Longrightarrow \quad \mathcal{L} \supset g_X X_\mu \bar{\nu}_s \gamma^\mu \nu_s$$

  - anomaly cancellation requires another ν_s with opposite charge (can be heavy $\rightsquigarrow$ decouples)
  - NB: this is 'really' an axial vector coupling of the Majorana field

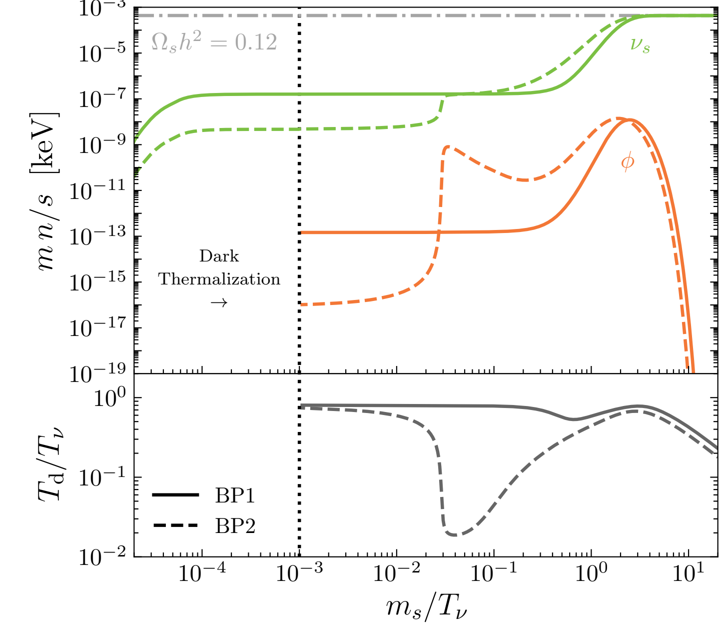
$$\nu_M \equiv \nu_s + \nu_s^c = \nu_M^c \quad \Longrightarrow \quad X_\mu \bar{\nu}_s \gamma^\mu \nu_s = \frac{1}{2} X_\mu \bar{\nu}_M \gamma^\mu \gamma^5 \nu_M$$

- Dark photon acquires a mass through SSB

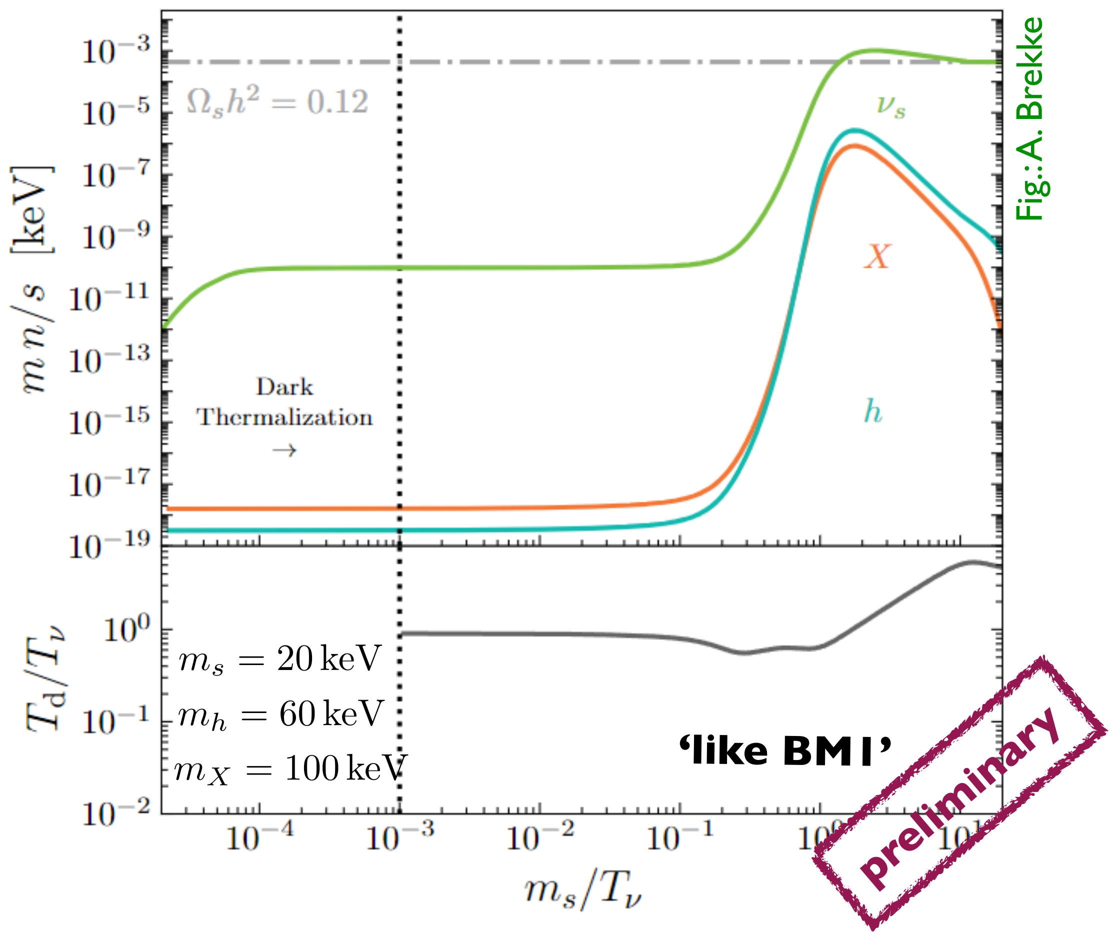
$$\mathcal{L} \supset |D\Phi|^2 - V(|\Phi|) \quad \xrightarrow{|\langle\Phi\rangle| = v/\sqrt{2}} \quad \mathcal{L} \supset \frac{1}{2} g_X^2 {Q'_\Phi}^2 v^2 X_\mu X^\mu$$

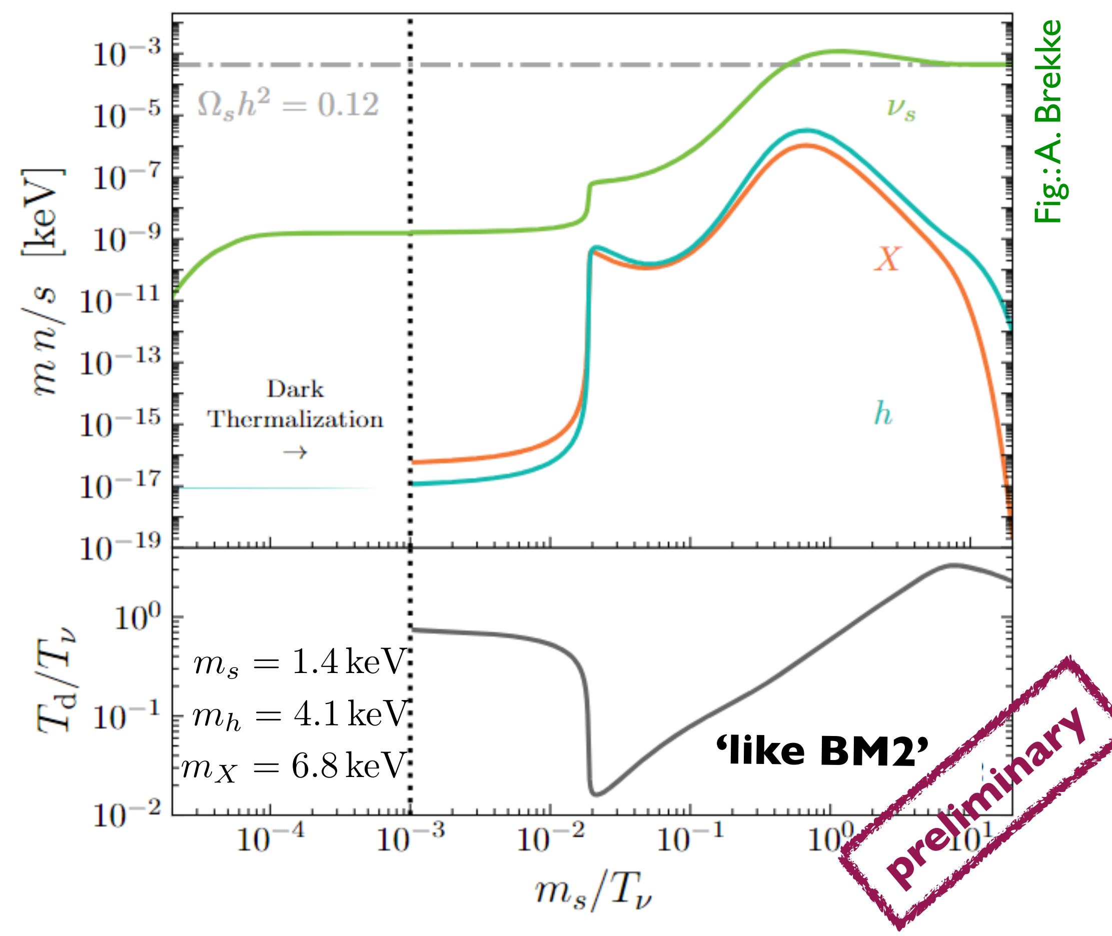
  - NB: mass through Stueckelberg mechanism leads to unitarity violation for $\bar{\nu}_s \nu_s \to X_L X_L$
  - *Must* also include dark higgs *h* in analysis…

Abundance evolution



- More dark sector states imply more phenomenological options
  - Significant proliferation of processes (+ diagrams)

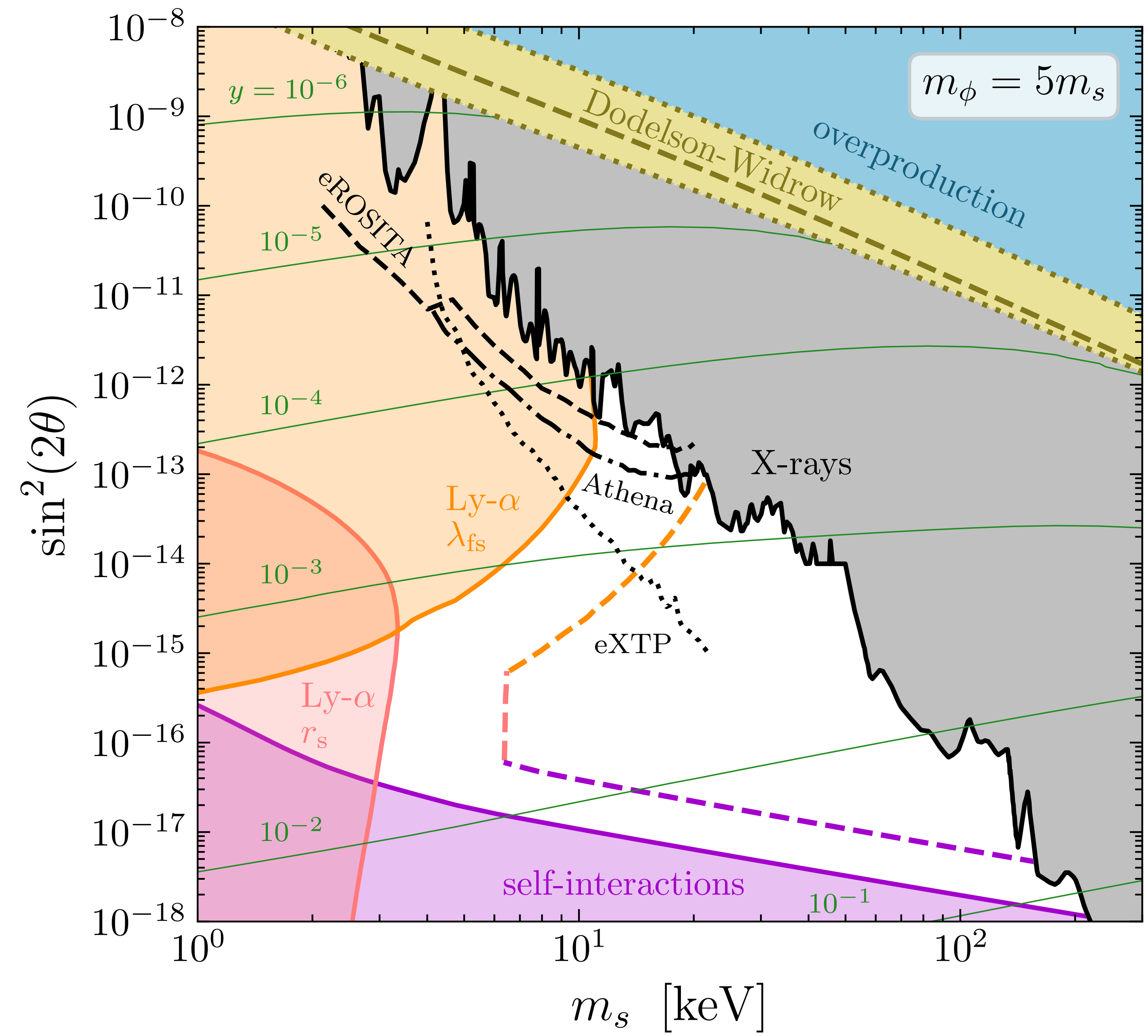




- Most striking difference at late times
  - $\bar{\nu}_s \nu_s \to hh, XX$ at $T_\nu \sim m_\nu$ can noticeably reduce the ν_s abundance
  - Subsequent annihilation of h, X raise the dark sector temperature to $T_\nu > T$

Conclusions

- Sterile neutrino DM **excluded** in simplest form
  - 'despite' excellent theory motivation
- 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
- Alternative model
  - dark photon mediator
  - new phenomenological avenues
  - work in progress…



Thanks for your attention!