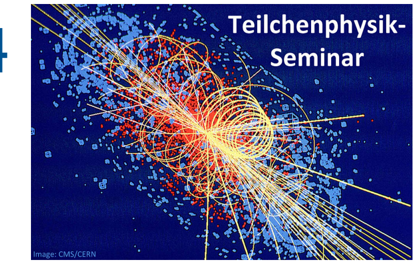
Vienna, 07 June 2024



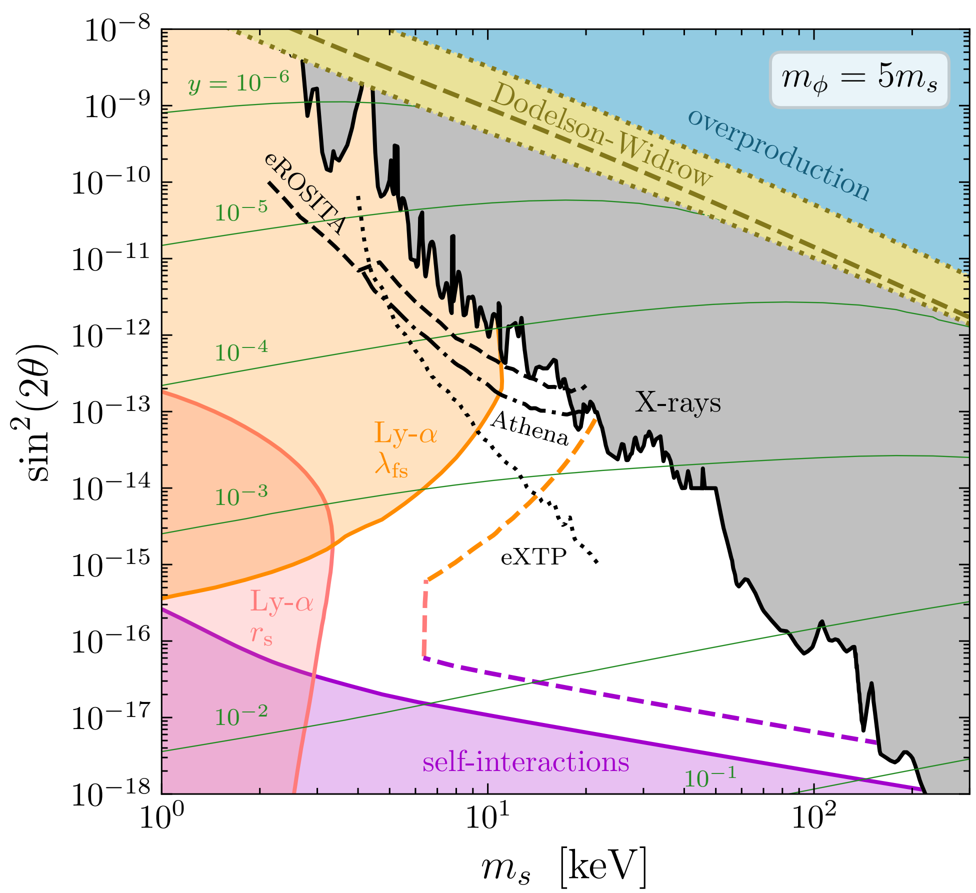
Minimal sterile neutrino dark matter

Torsten Bringmann

Based on

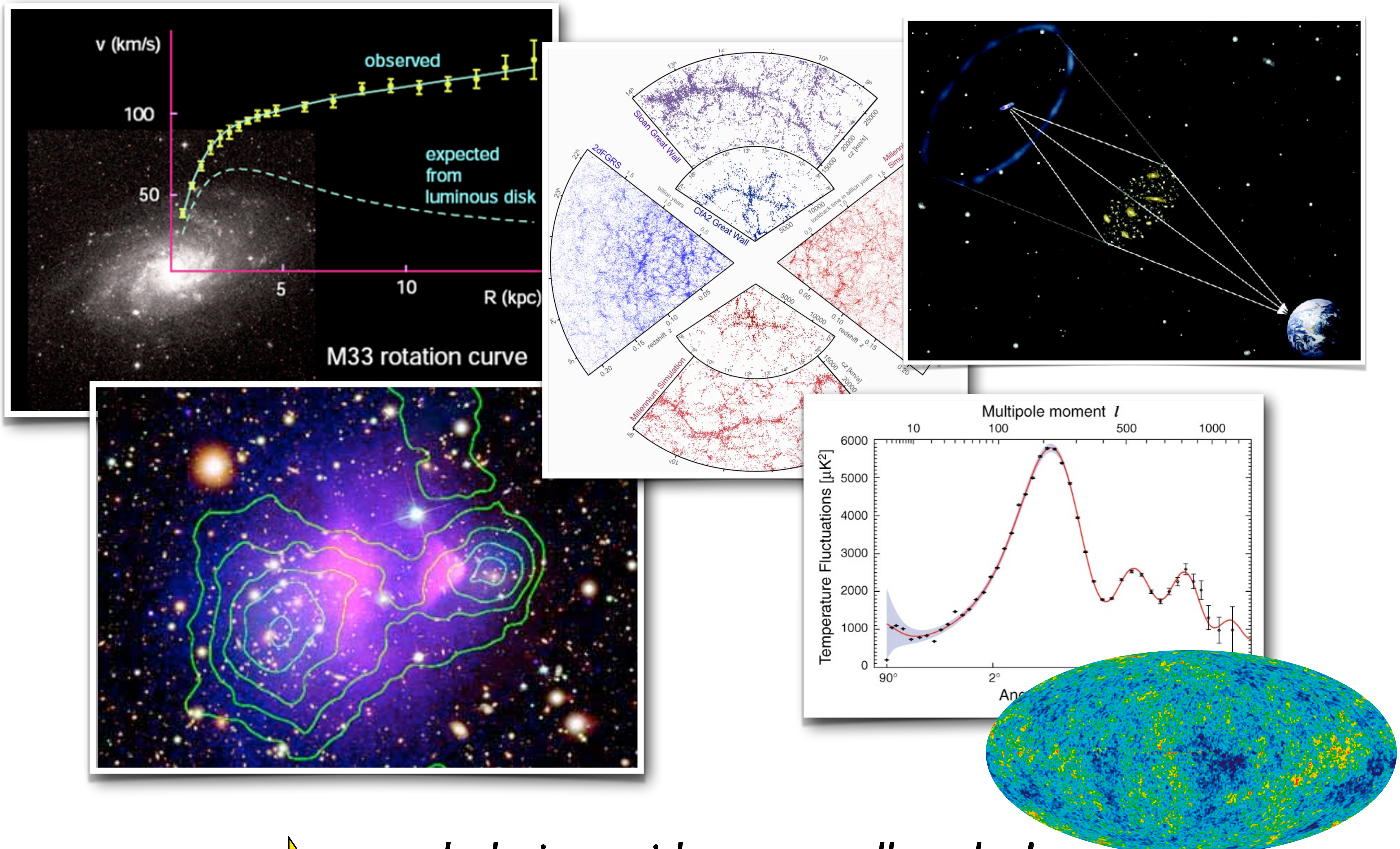
TB, Depta, Hufnagel,
Ruderman & Schmidt-Hoberg, PRL '21

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



UiO : University of Oslo

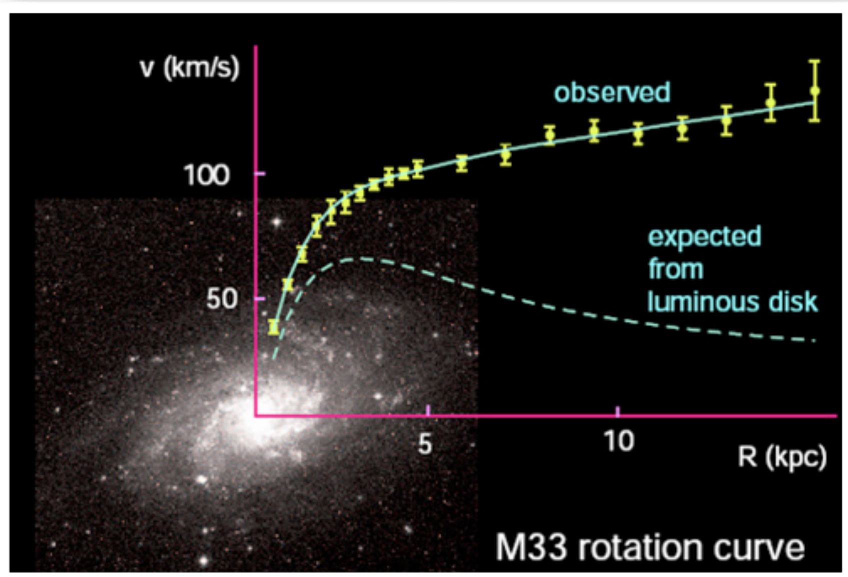
Dark matter all around



→ *overwhelming evidence on <u>all</u> scales!*

Evidence from all scales

- Galactic scales →



'missing' mass

Newton:

$$G_N m_\odot \frac{M(r<R)}{R^2} = m_\odot \frac{v^2}{R}$$

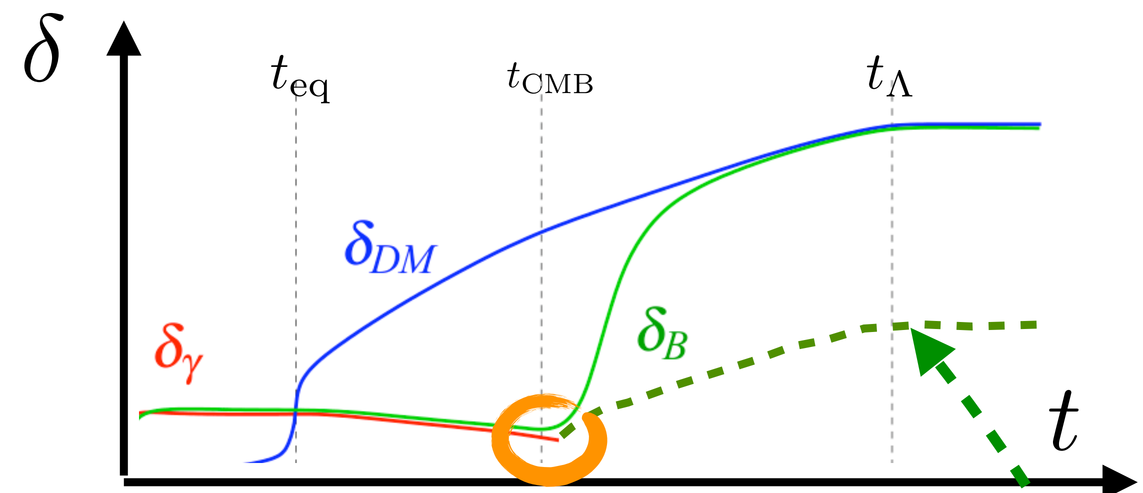
No longer main argument for *existence* of dark matter!

- observed rotation curves quite diverse
- other potential explanations *for this particular discrepancy*

- Cosmological scales

Linear gravity:

$$\rho(t,\mathbf{x}) = \bar{\rho}(t)[1+\delta(t,\mathbf{x})]$$



- Observation

$$\Delta T/T_{\rm CMB} \sim \delta \equiv |\rho - \bar{\rho}|/\bar{\rho} \sim 10^{-5}$$

- Assuming no dark matter

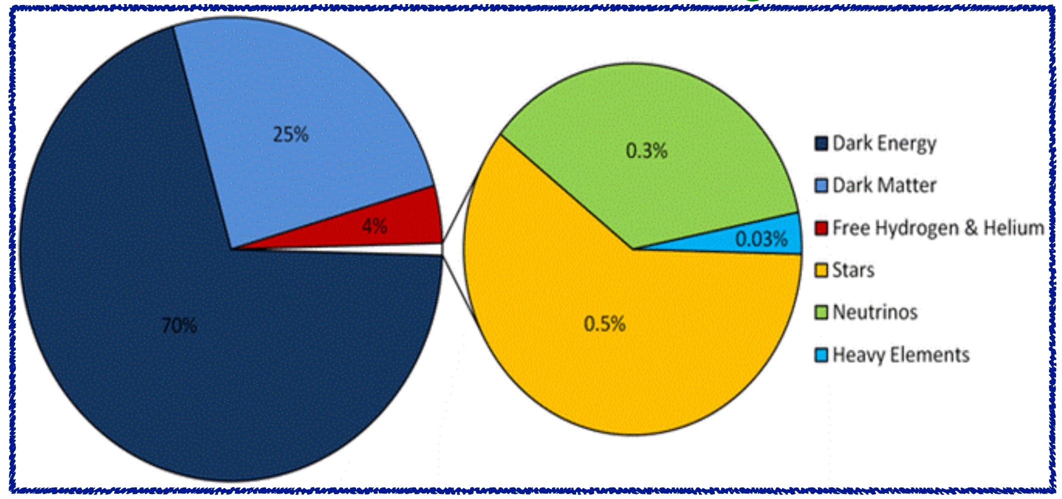
$$\delta_b^{\rm today} \simeq \delta_\gamma^{\rm CMB}\left(1+z^{\rm CMB}\right) \sim 10^{-2}$$

→ Without DM, we'd still be in the *linear* regime: no galaxies, stars, planets, …!

From evidence to precision

- DM is a crucial ingredient of the cosmological SM!
  - constant co-moving energy density
  - only gravitational interactions
  - cold + dissipation-less

Image credit: KIAS



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

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

Percent-level measurements of a single parameter!

- DM conversion into (in)visible energy?
  - E.g. decays, late-time annihilation, coalescing PBHs, …

➡ Ω_{CDM} decrease of up to 10% possible during matter domination!

(*model-independent*; NB: much more allowed during RD)

TB, Kahlhoefer, Schmidt-Hoberg & Walia, PRD '18

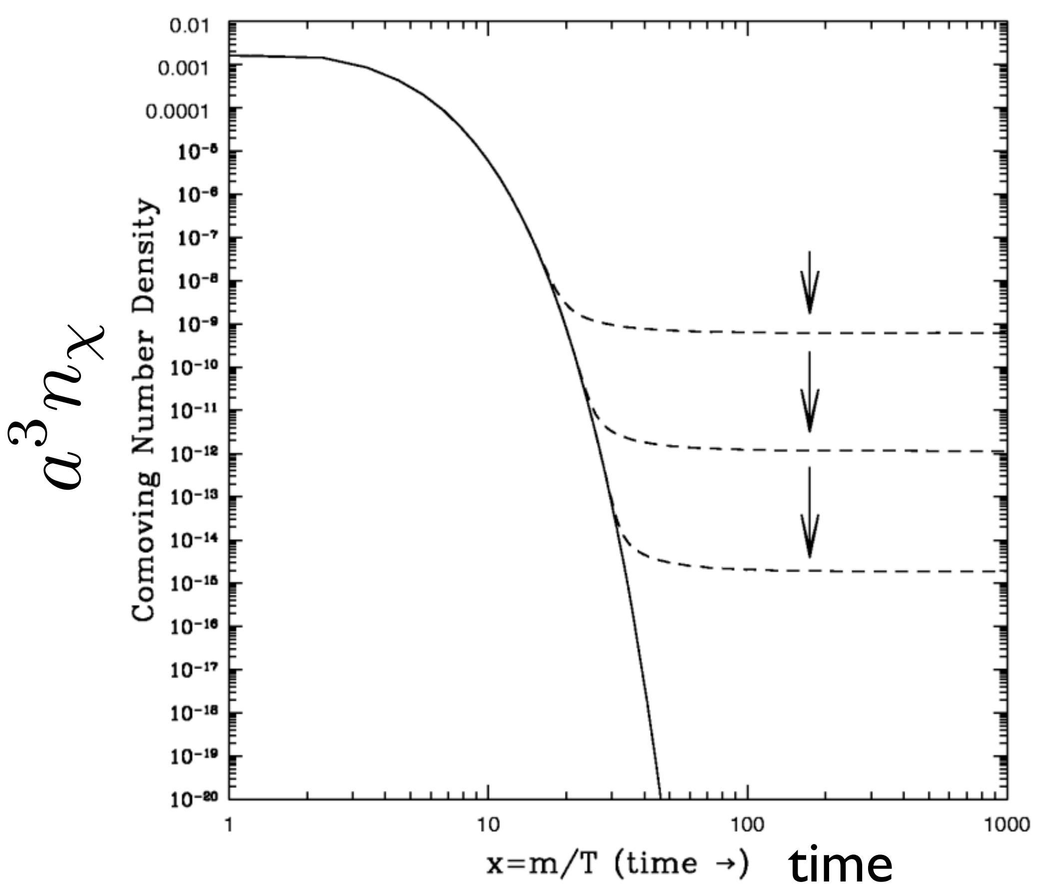
- Q: Can't we explain *all* this also by modified gravity?
  - A: **No!** [though definitely yes for *selected* observations]

The nature of dark matter

- Existence of (particle) DM = evidence for BSM physics

?

- ~ 10 - 20 years ago:

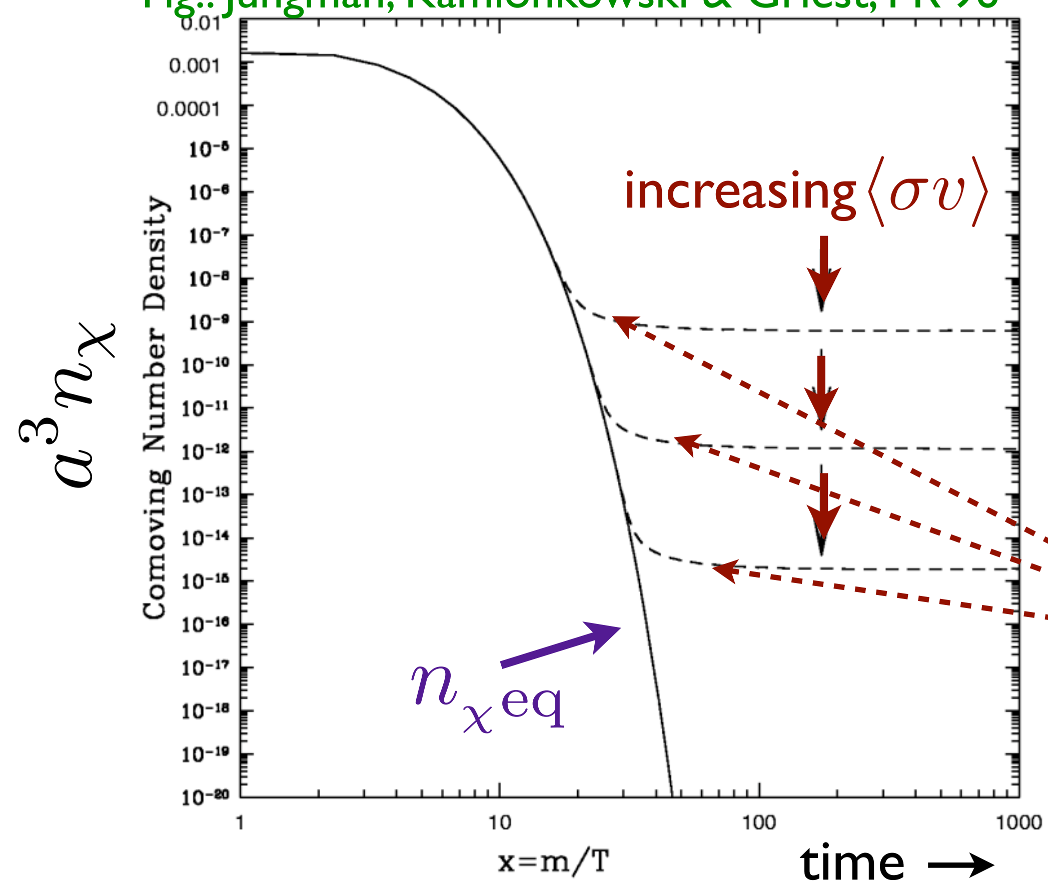


'It's a (SUSY) WIMP !'

Weakly Interacting Massive

- extremely 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

for weak-scale interactions!

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

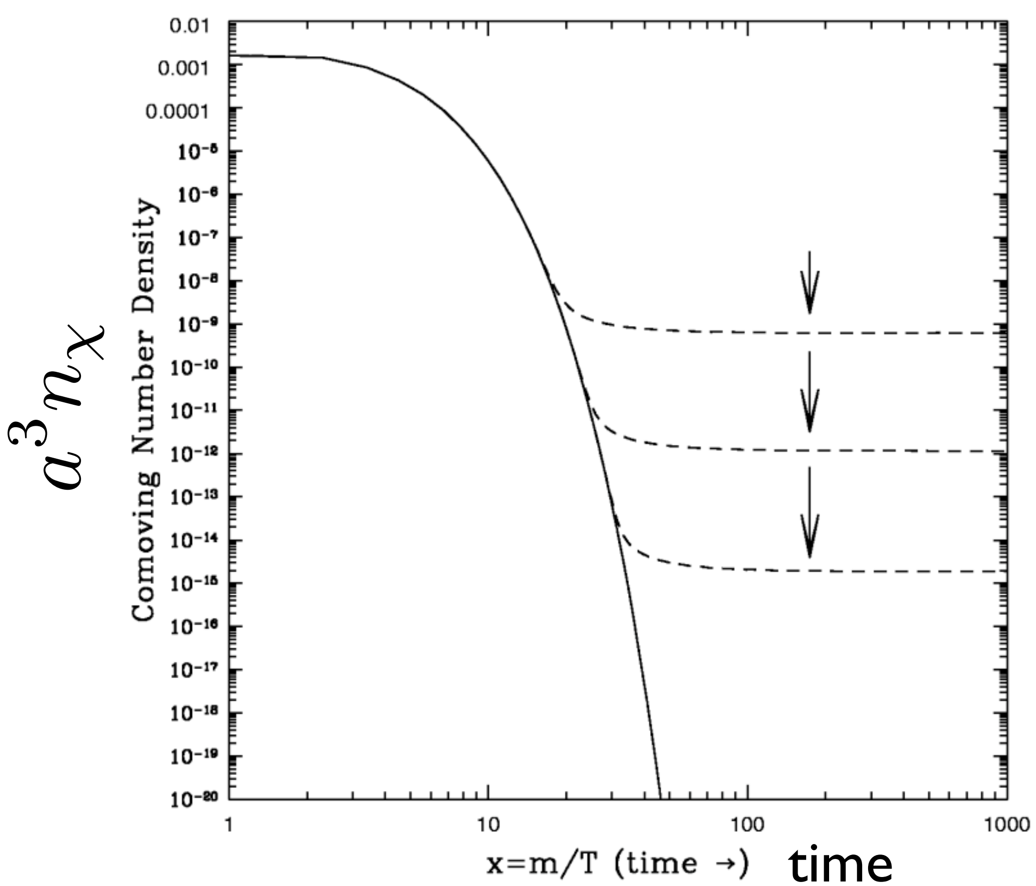
= a 'miracle' ?

The nature of dark matter

- Existence of (particle) DM = evidence for BSM physics

?

- ~ 10 - 20 years ago:



'It's a (SUSY) WIMP !'

- today:

Bertone & Tait, Nature '18

'We have (almost) no clue…'

Where next?

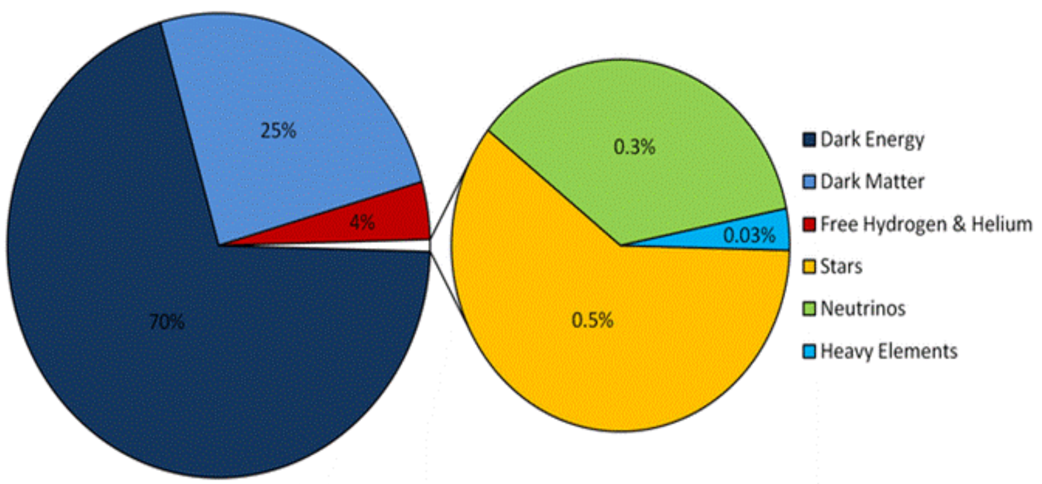
- Can we *somehow* link DM to one of the other big open questions in HEP ?
  - Hierarchy problem → WIMPs
  - Baryon asymmetry
  - Neutrino masses
  - Strong CP problem
  - Inflation
  - Flavour puzzle

- Or should we abandon theoretical guiding principles, leaving 'no stone unturned'?
  Bertone & Tait, Nature '18
  - Problem: there might be quite a few of them (not even counting those that cannot be unturned)…

Any convincing model must include a production mechanism that can explain the observed dark matter abundance!

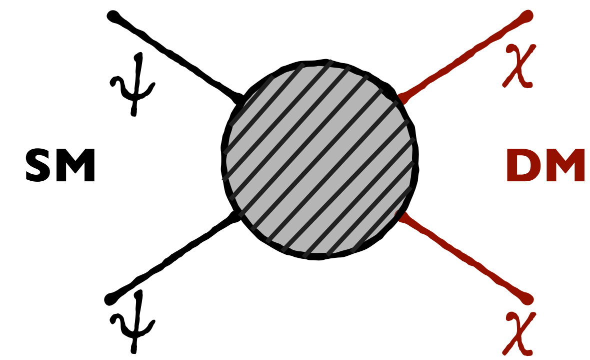
Part I

Dark matter production form the thermal bath



Dark matter production

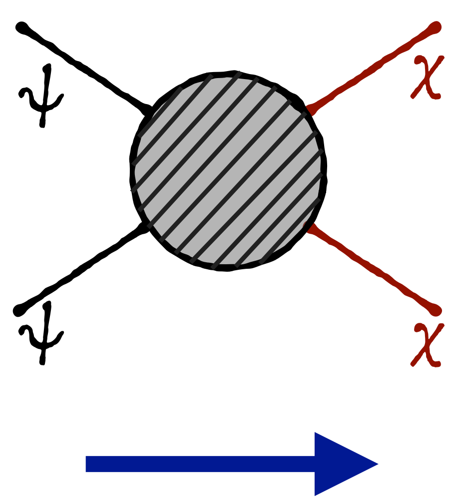
- 'Generic' interactions with the primordial heat bath:



➡ Correct relic abundance in two regimes:

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

freeze-in



depends on initial conditions

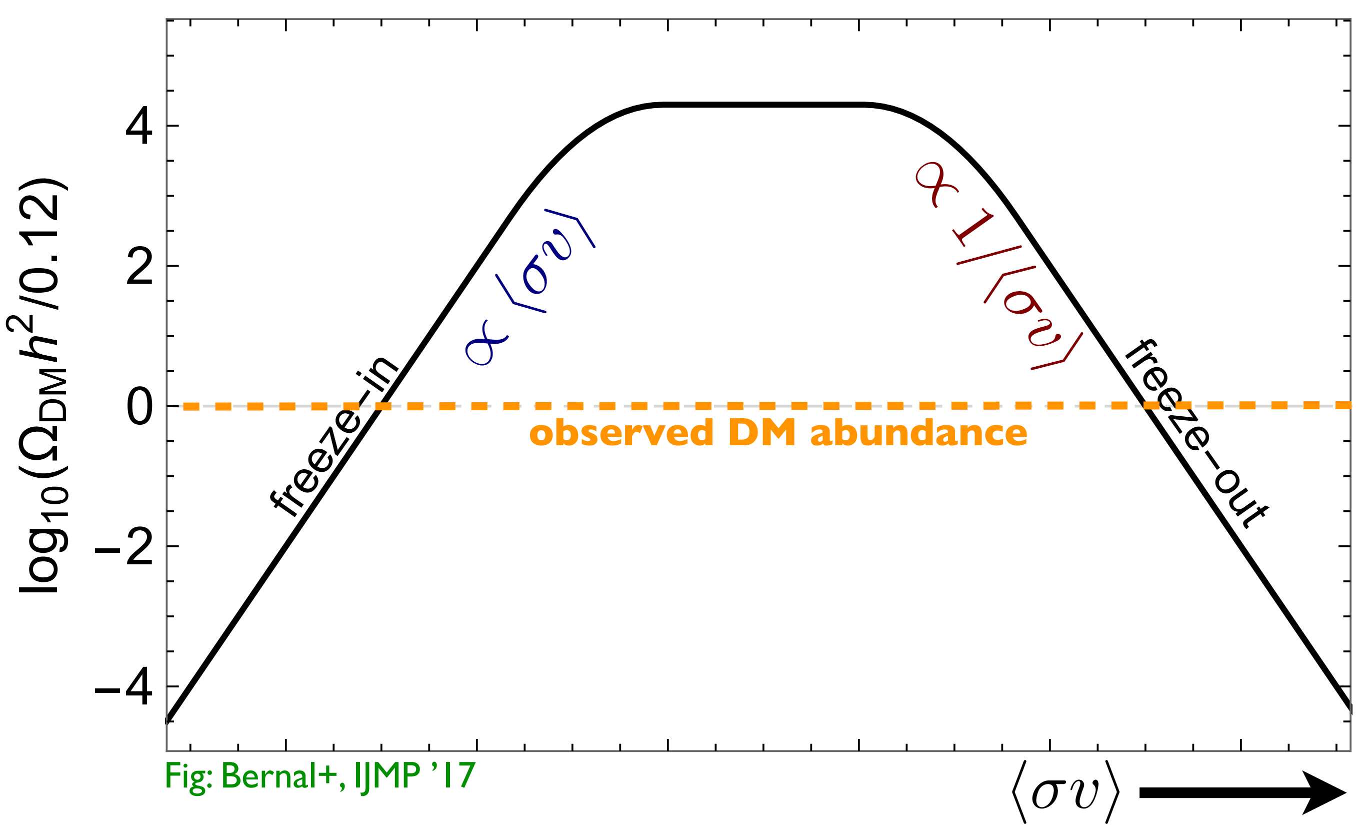
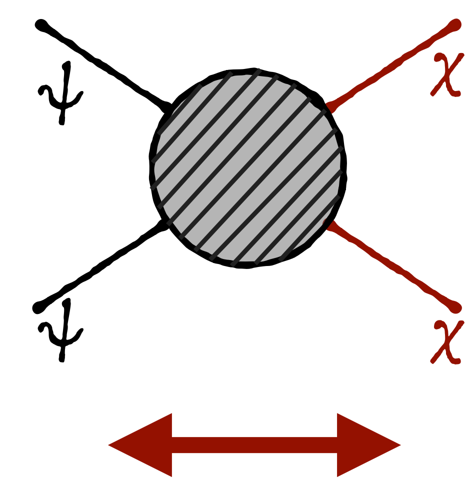


Fig: Bernal+, IJMP '17

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

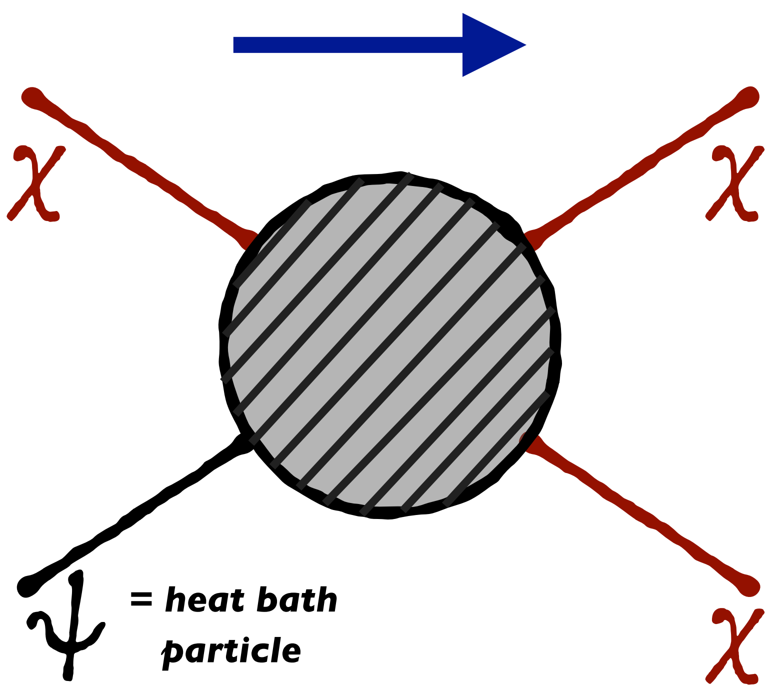
freeze-out



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***

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

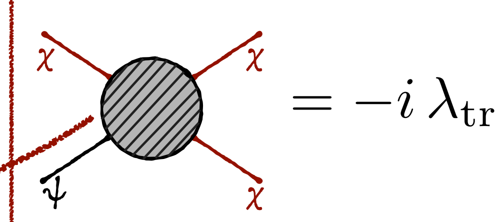
β ***infection rate***

γ ***recovery rate***

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

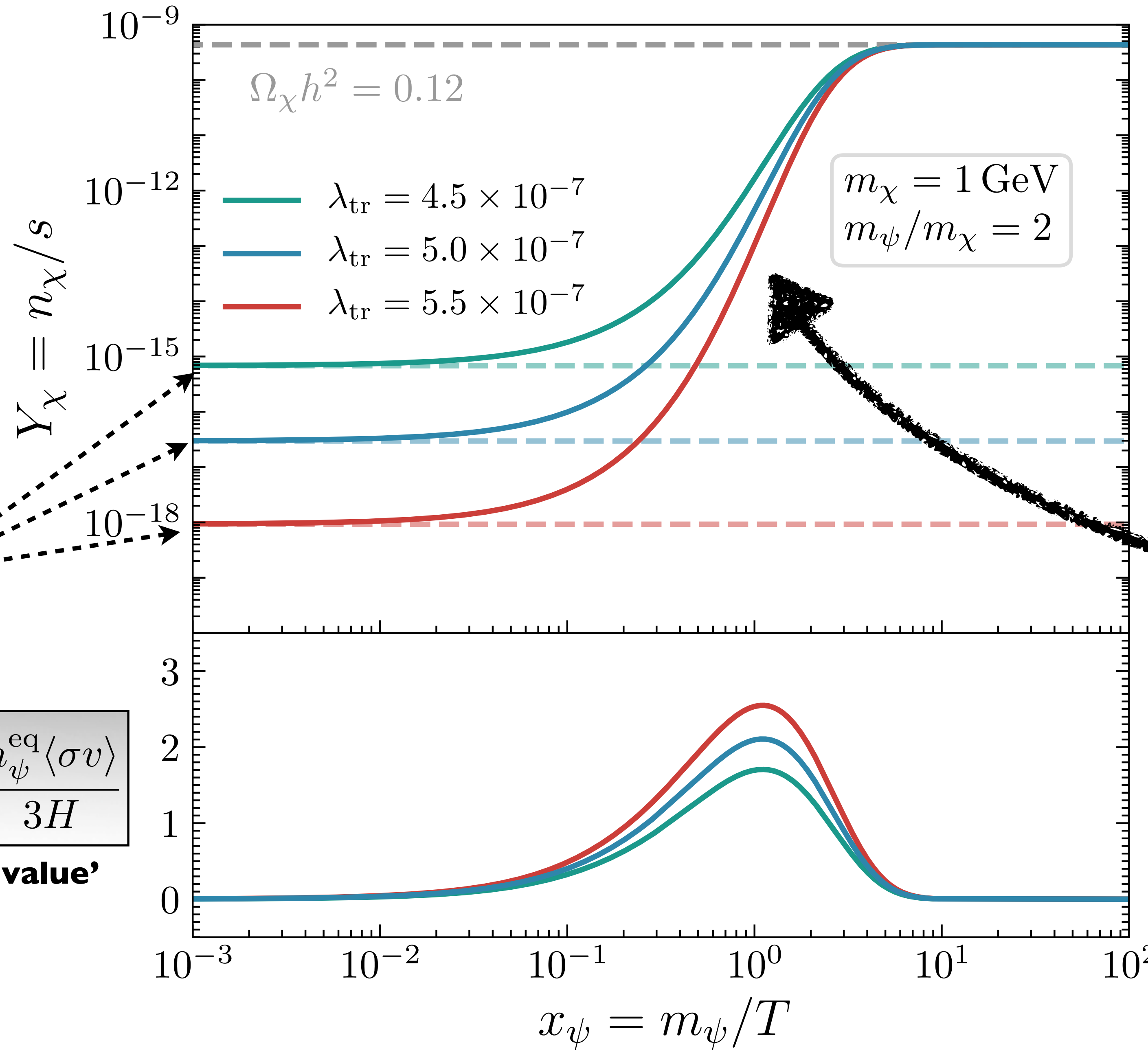
Exponential DM production

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



toy model

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



Tiny initial DM abundance

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

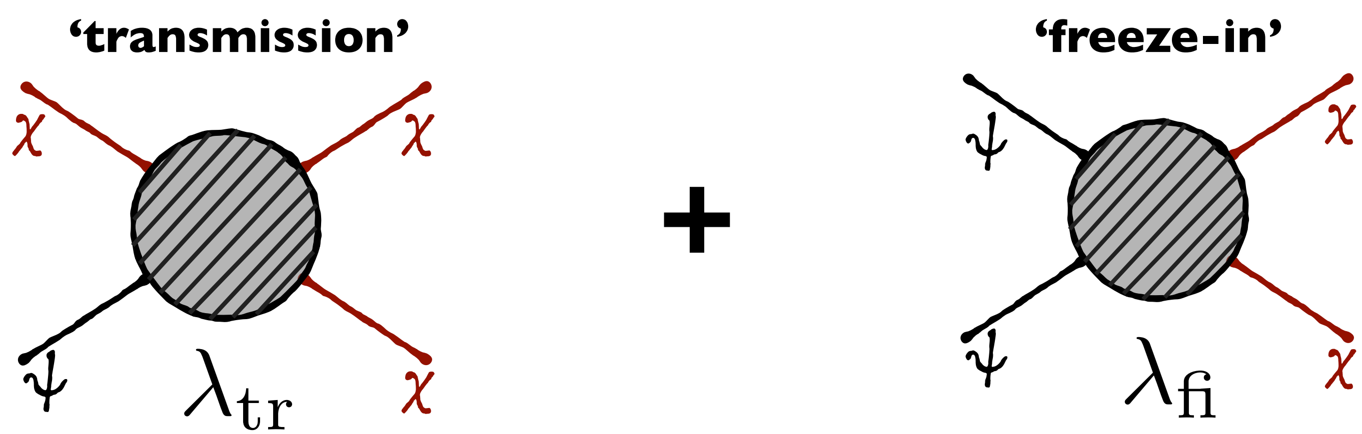
'reproduction value'

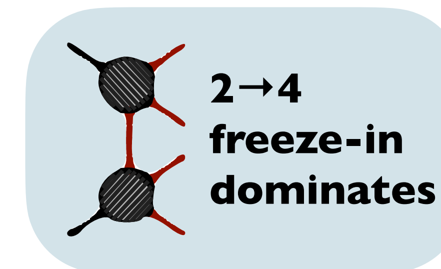
exponential growth $R \gtrsim 1$

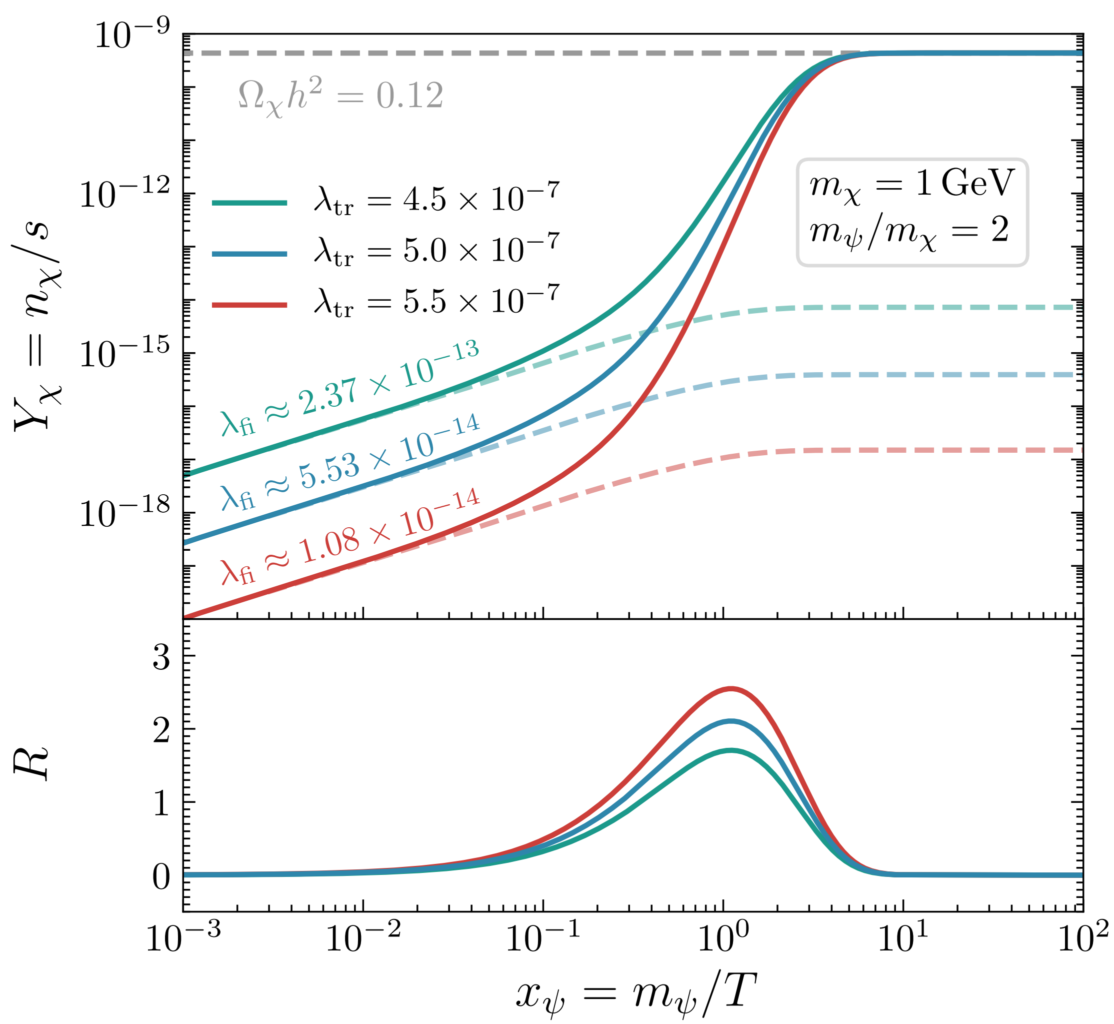
large H

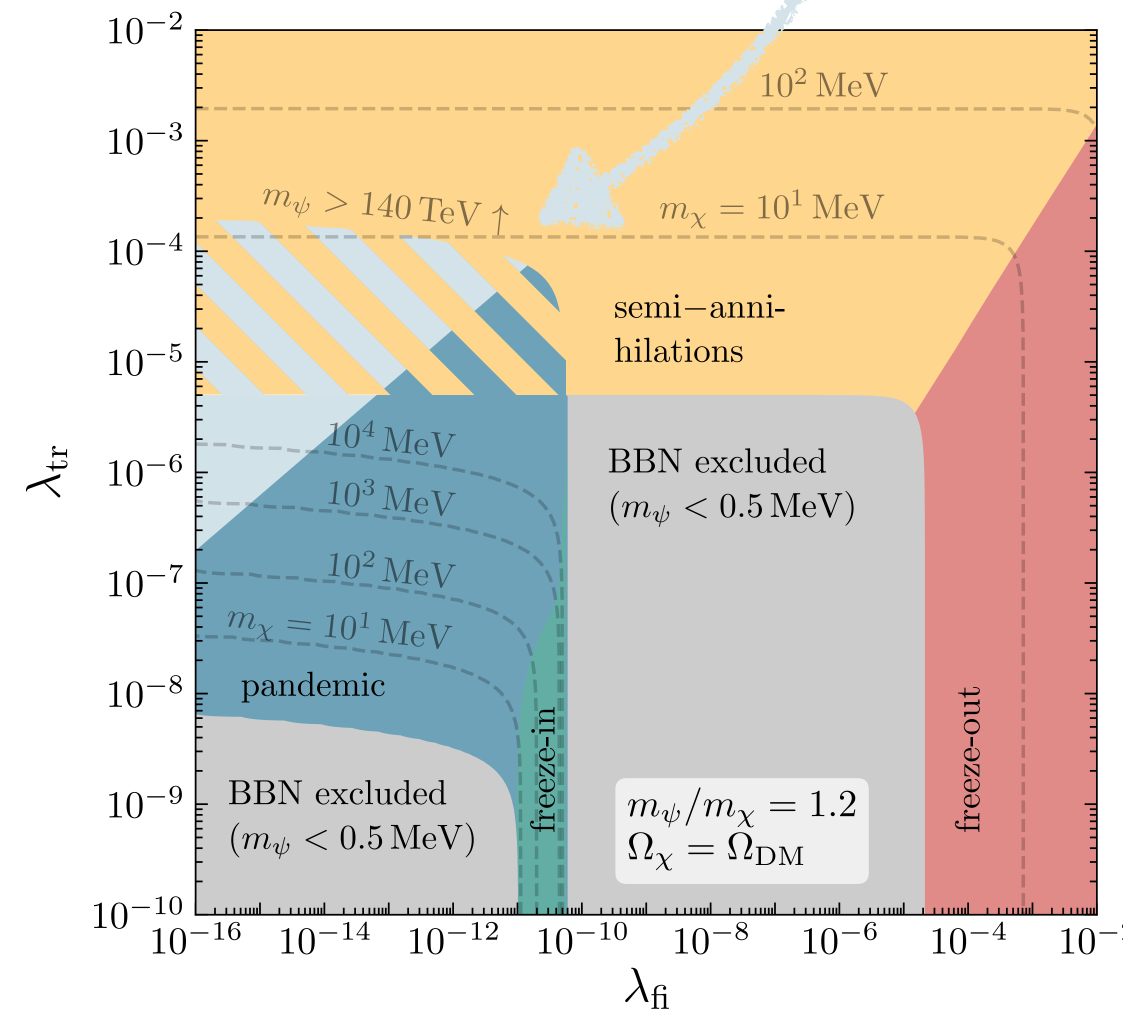
small n_ψ^{eq}

Adding freeze-in production









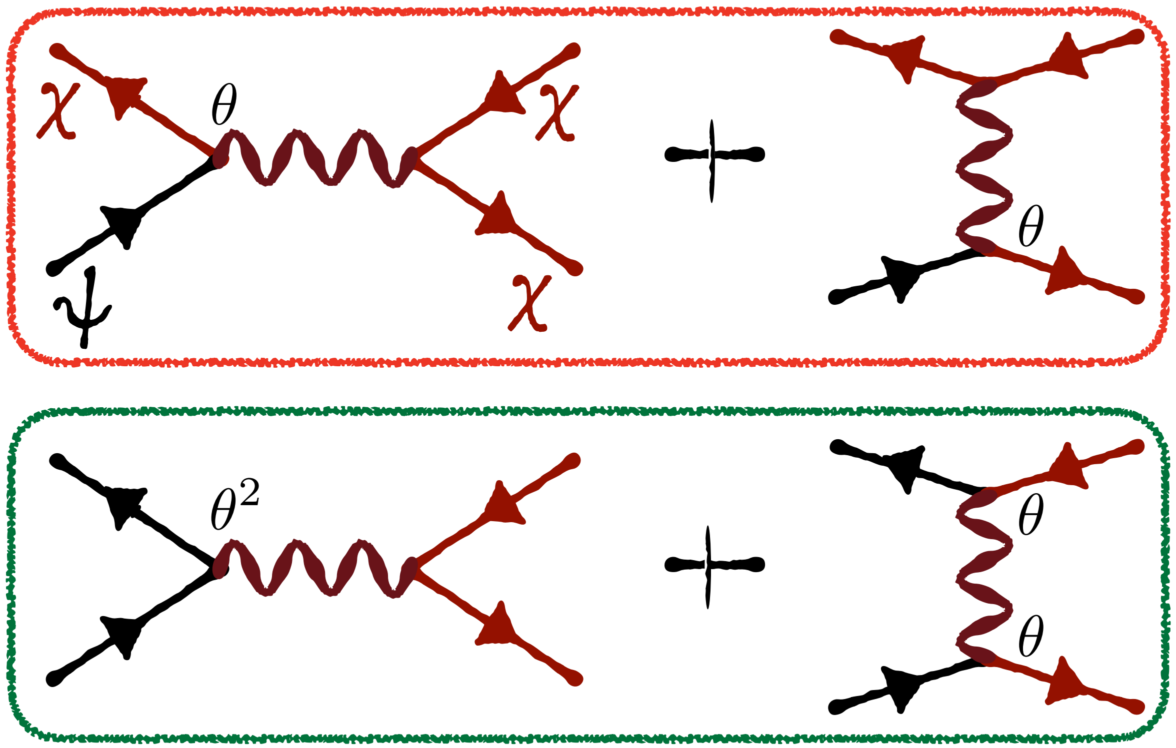
➡ *‘Pandemic’ production turns out to be a rather generic mechanism for the genesis of DM!*

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 :

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

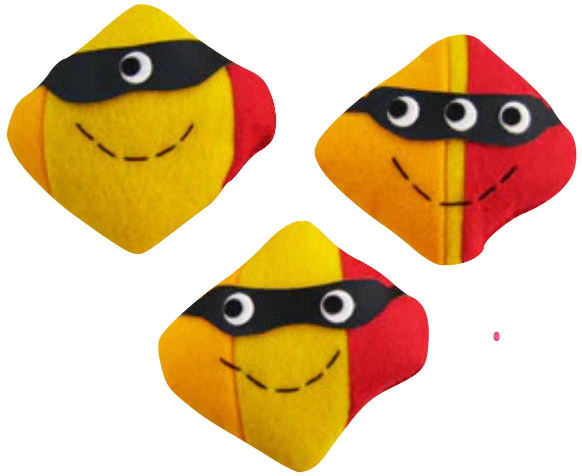


transmission $\propto \theta$

freeze-in $\propto \theta^2$

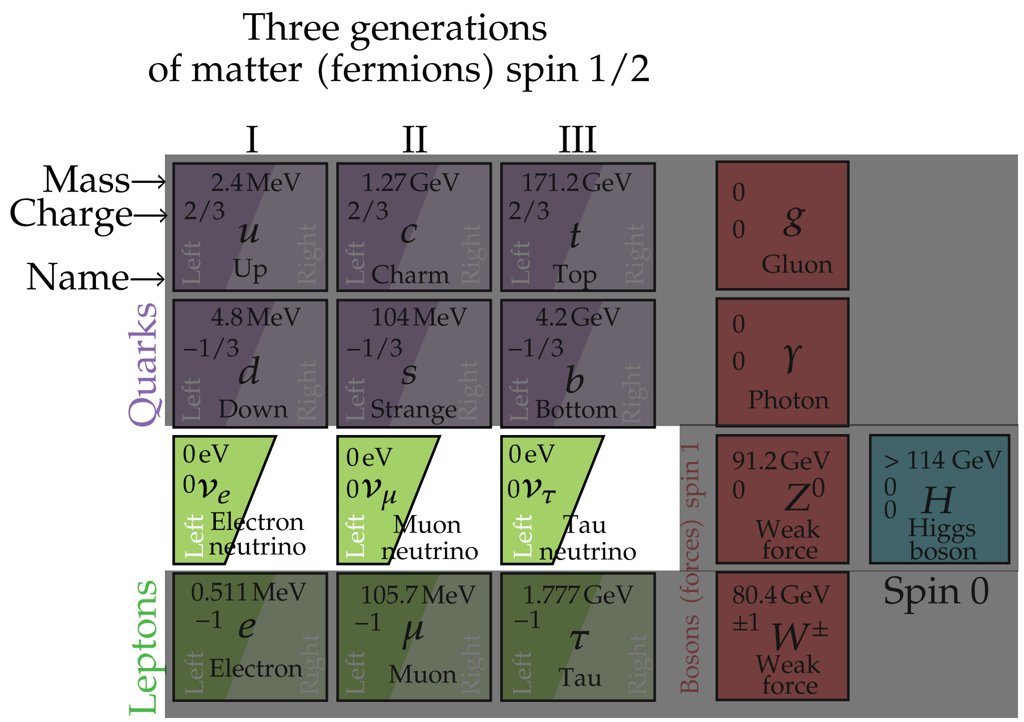
Part II

Sterile neutrinos as dark matter



Recap: DM = BSM

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



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

strongly interacting

charged / visible

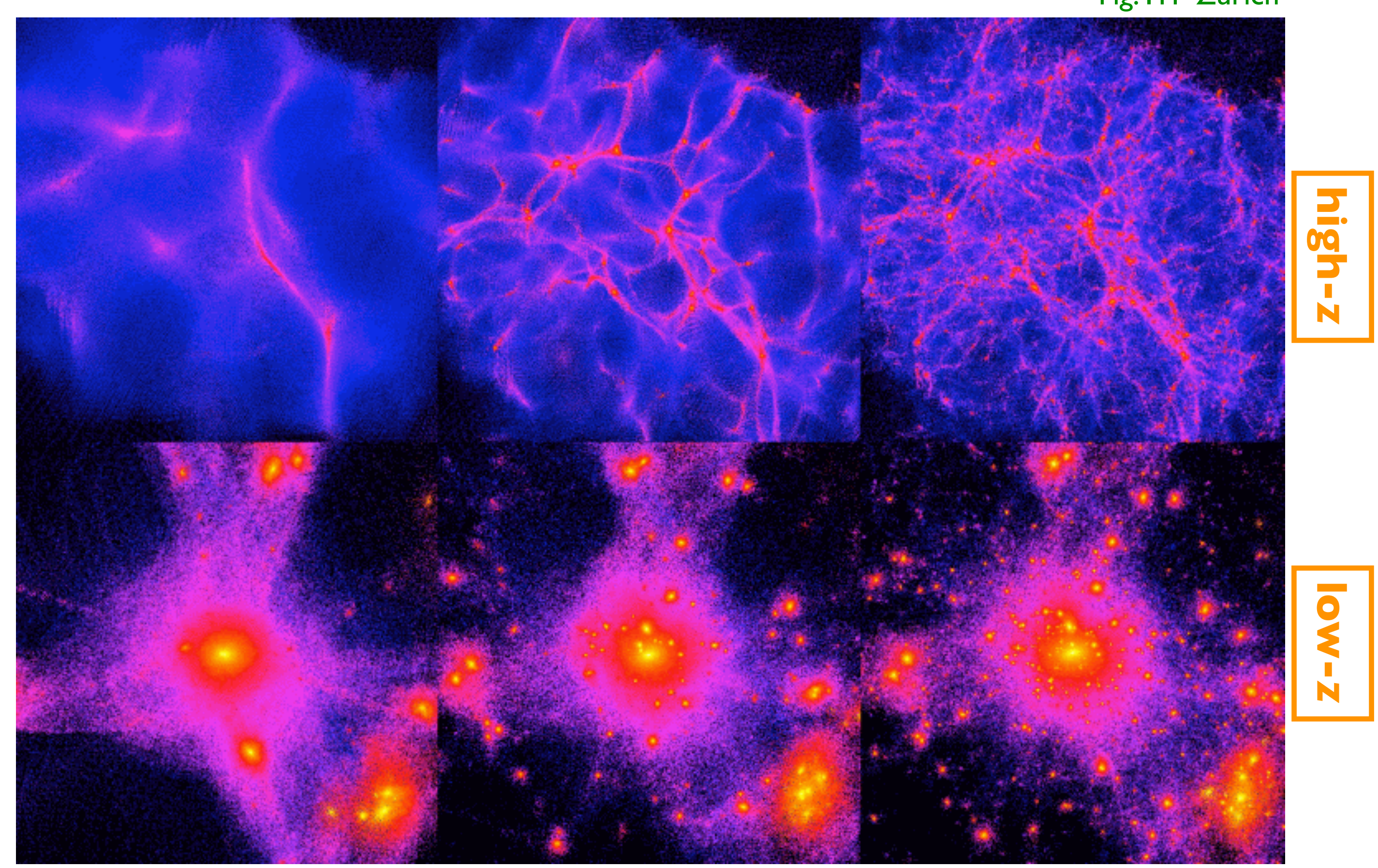
unstable

- … 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 !*

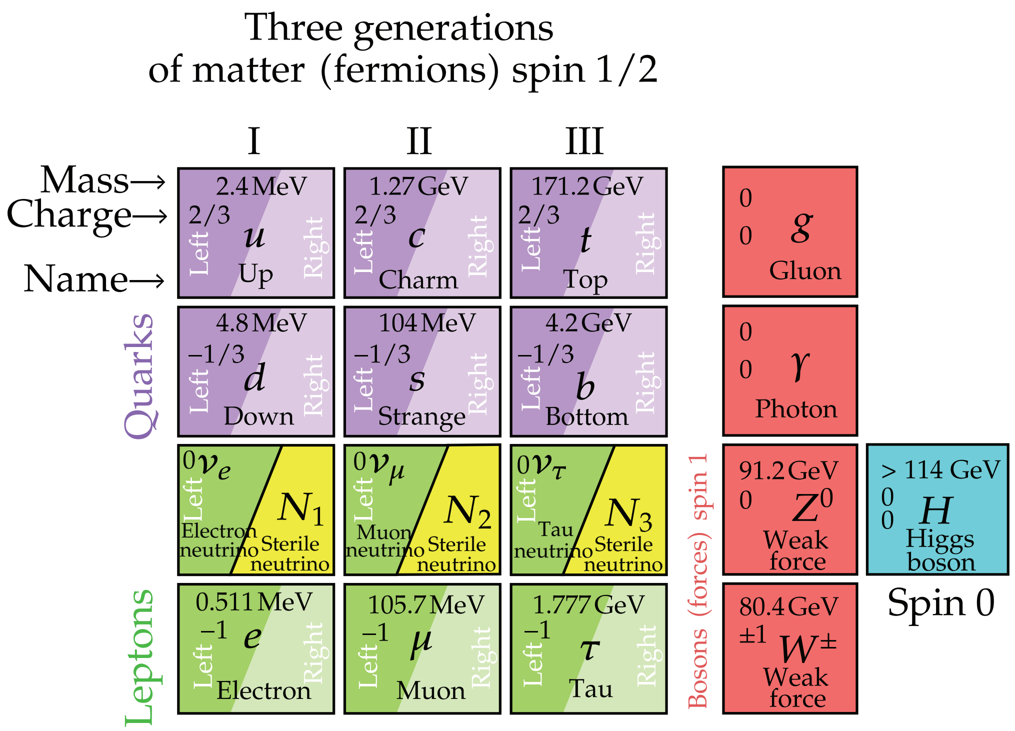
White, Frenk & Davis, ApJ '83

Fig: ITP Zurich



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

Sterile neutrinos



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

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

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

- Highly motivated from phenomenological point of view:

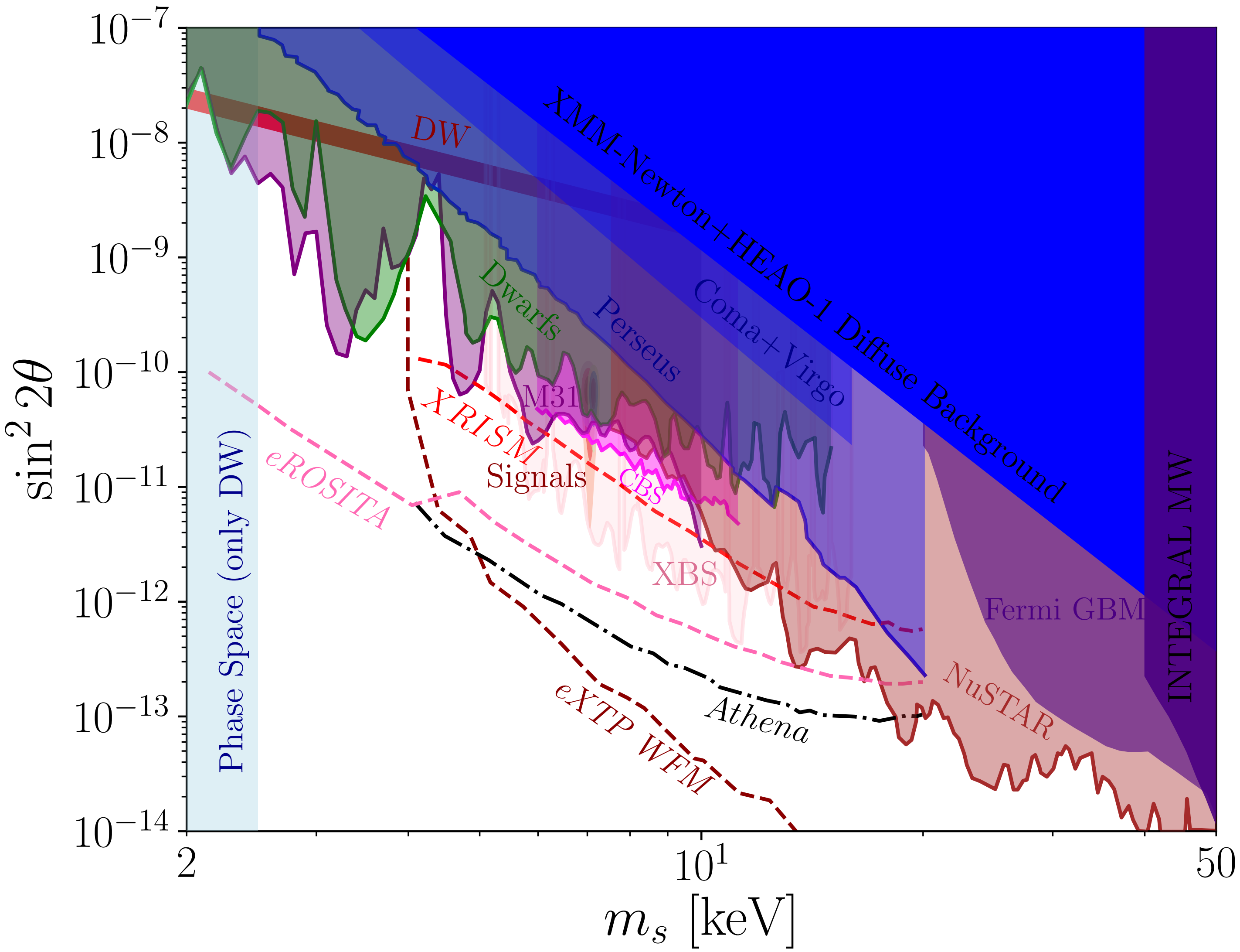
	N mass	ν masses	eV ν anomalies	BAU	DM	M_H stability	Direct search	experiment
GUT seesaw	10–16 10 GeV	Yes	No	Yes	No	No	No	—
EWSB	2-3 10 GeV	Yes	No	Yes	No	Yes	Yes	LHC
ν MSM	keV-GeV	Yes	No	Yes	Yes	Yes	Yes	a'la CHARM
ν scale	eV	Yes	Yes	No	No	Yes	Yes	a'la LSND

Gninenko, Gorbunov & Shaposhnikov, Adv. HEP '12

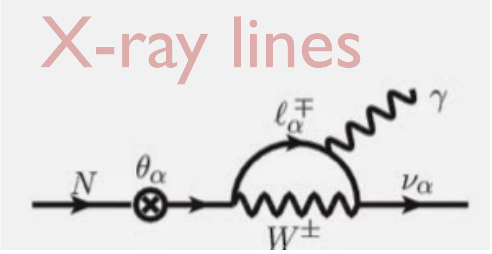
Sterile neutrinos

- 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
- $100\,\mathrm{keV} \gtrsim m_\phi > 2m_s,\ \ y \gtrsim 10^{-6}$ **This talk** TB, Depta, Hufnagel, Kersten, Ruderman & Schmidt-Hoberg, PRD '23

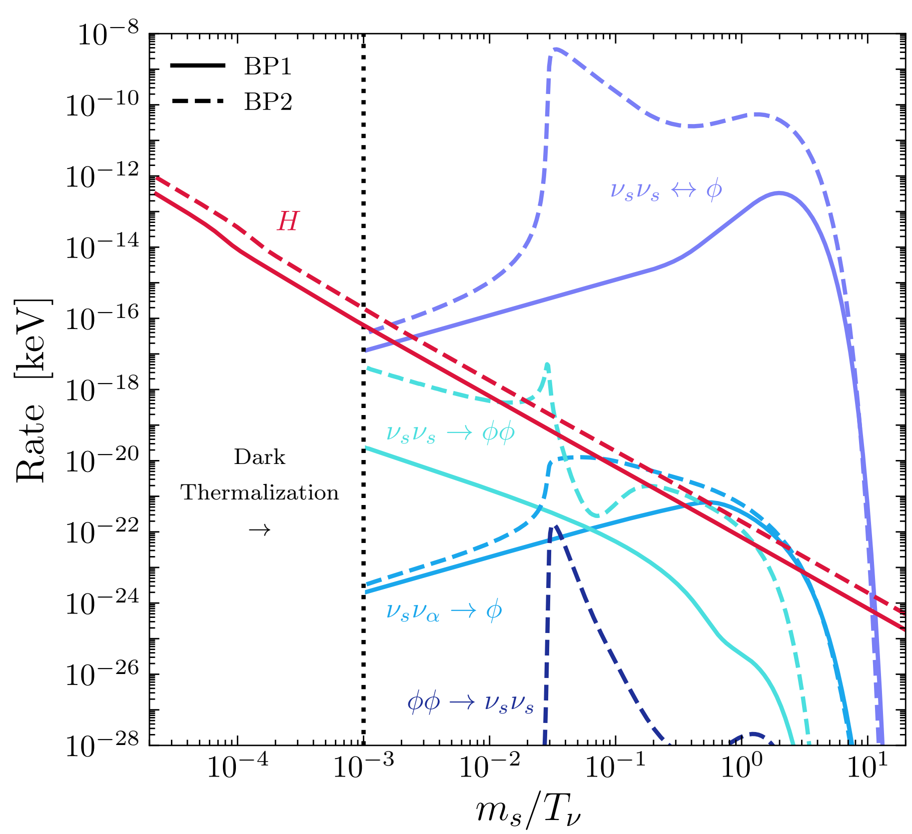
see also Astros & Vogl, JHEP '24 *for discussion of 'entire' scalar mass range*

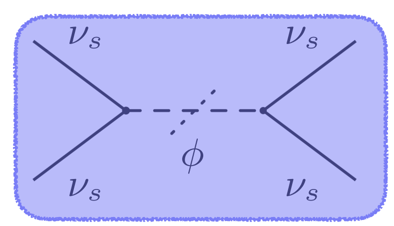
Production — phase 1

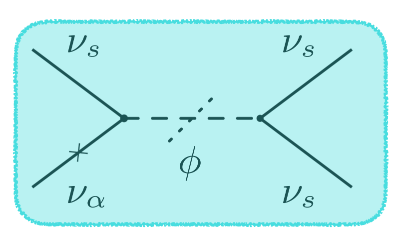
- $\mathscr{L} \supset \frac{y}{2}\phi\bar{\nu}_s\nu_s\,,\; m_\phi > 2m_s$
- Early times (~QCD PT): standard DW production
  - Adopt resulting number & energy density as initial condition

from Asaka, Laine & Shaposhnikov, JHEP '15

- Soon afterwards: efficient dark sector thermalization
  - $\nu_s\,,\,\phi$ follow FD/BE distributions with *large* (negative) chemical potentials







➡ Use Boltzmann equations

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

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

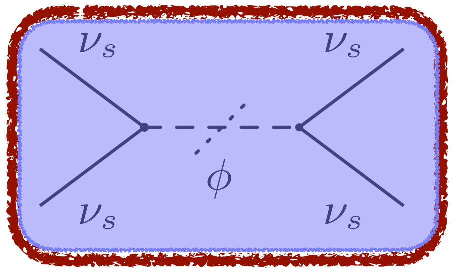
Production — phase II

- $\mathcal{L} \supset \frac{y}{2}\phi\bar{\nu}_s\nu_s$, $m_\phi > 2m_s$

- Evolution after DW:

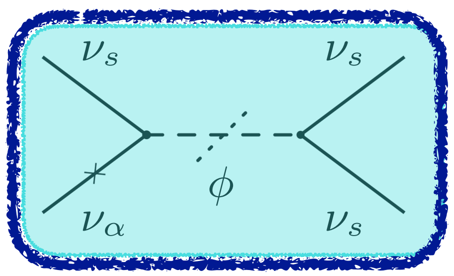
  solid: benchmark point with large θ, small y
  dashed: benchmark point with small θ, large y

  - Thermalization in dark sector

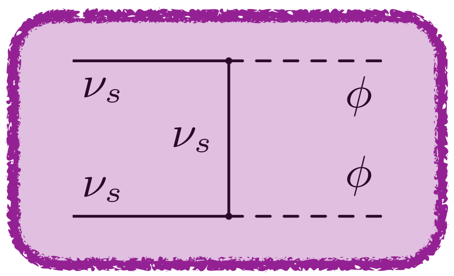


NB: This allows exact solution of Boltzmann equation!

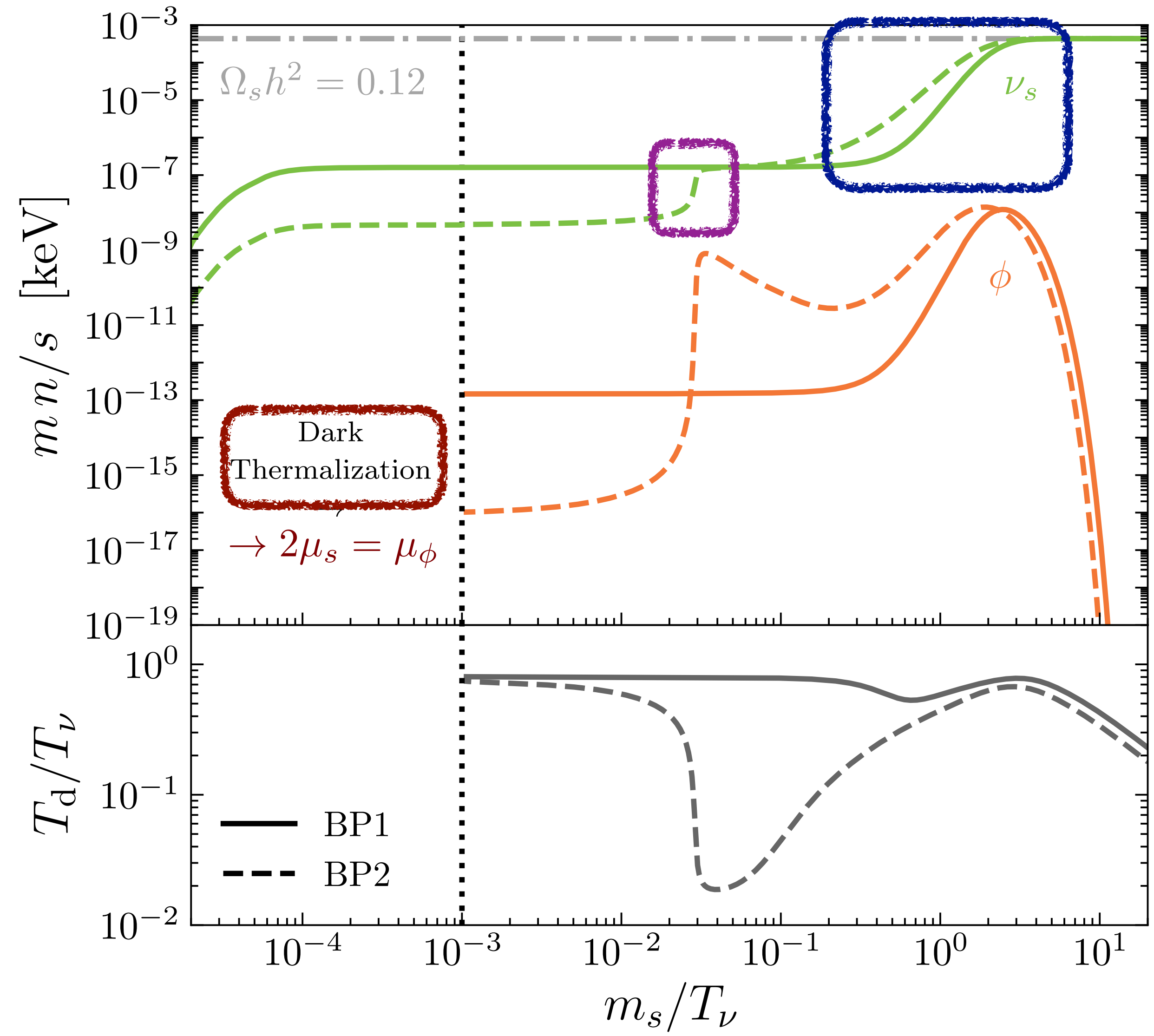
  - Exponential growth



  - Reproductive freeze-in



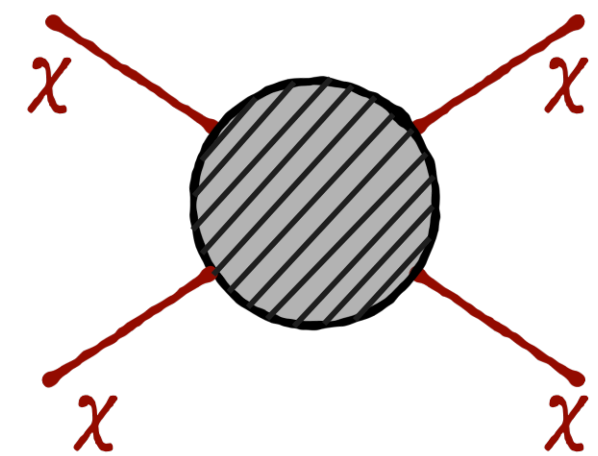
$+ \ \phi \to 2\nu_s$

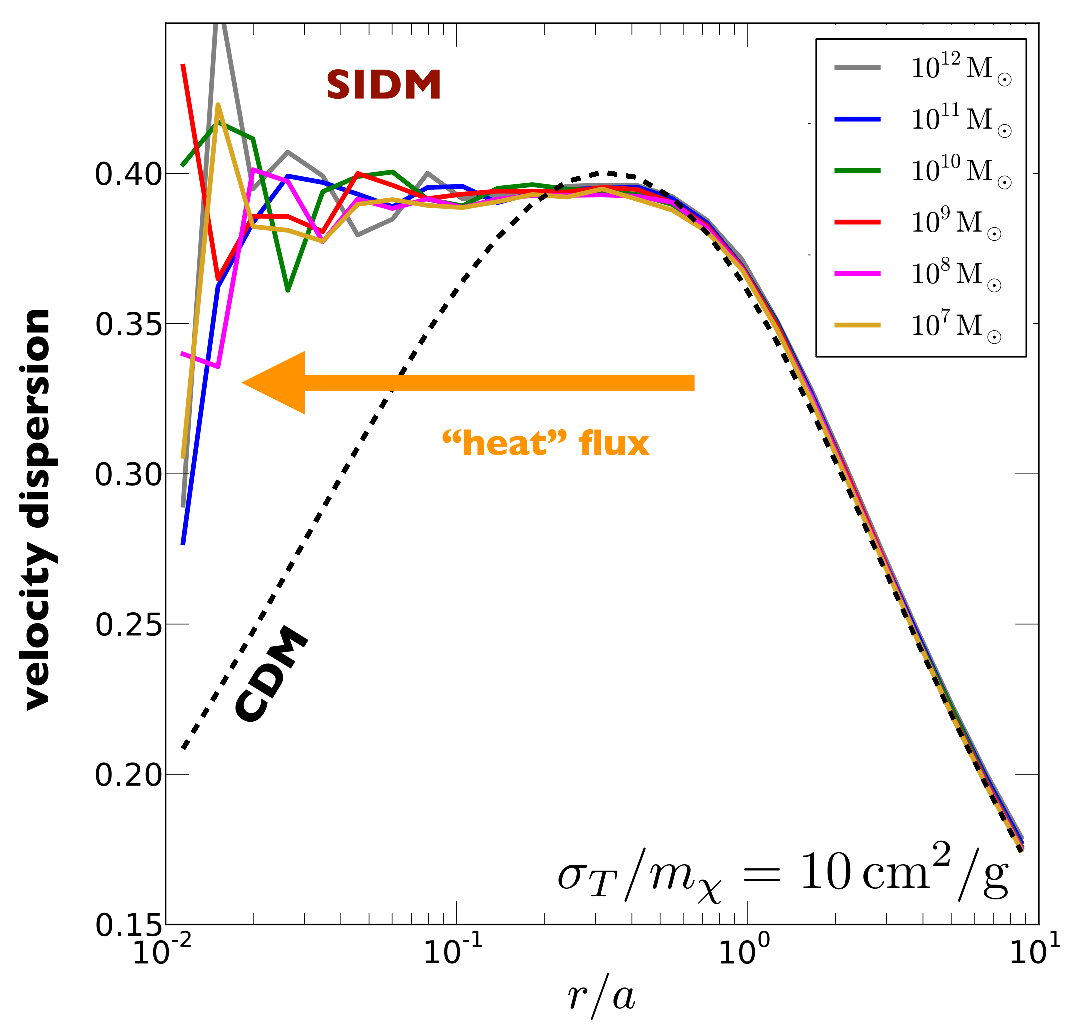


Self-interacting DM (SIDM)

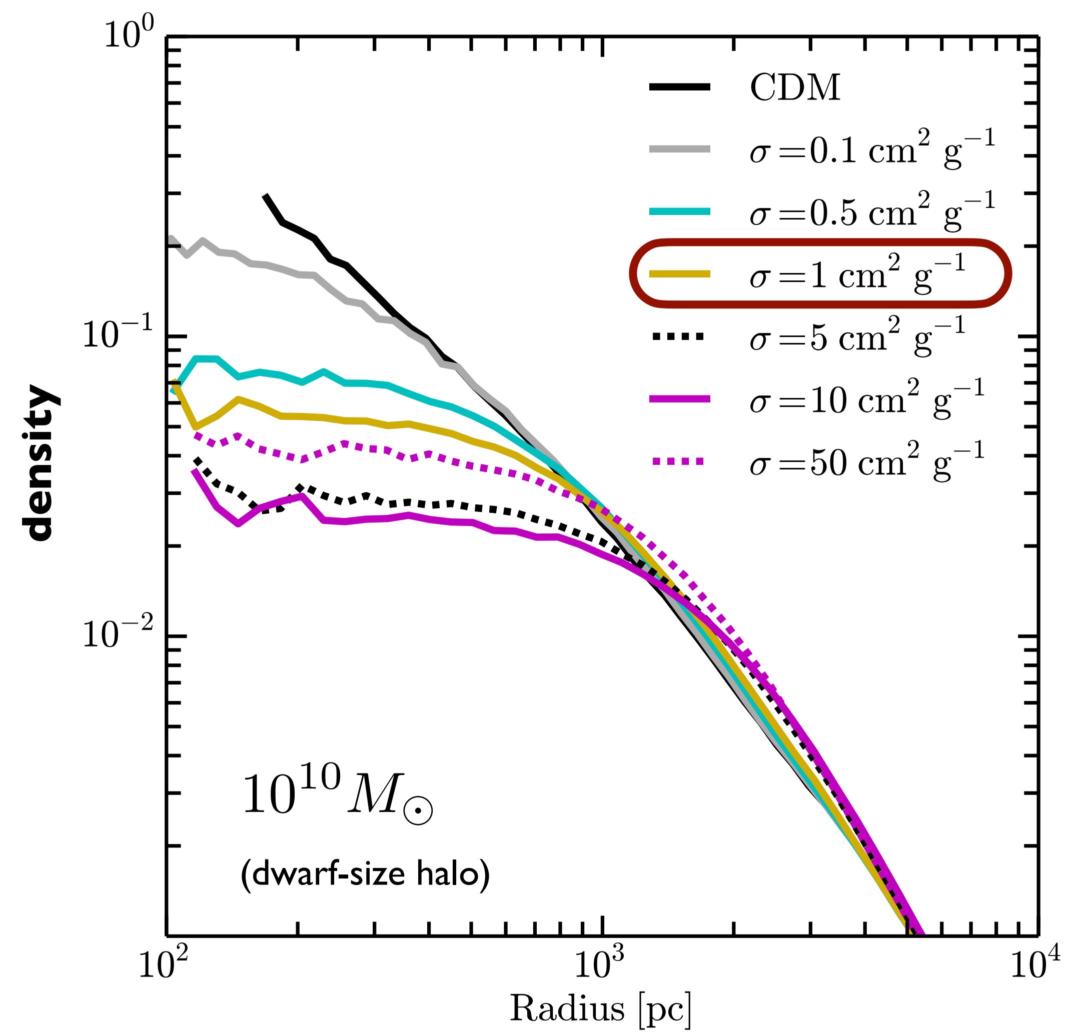
- DM-DM scatterings Spergel & Steinhardt, PRL '99
  - do not affect linear perturbations (number densities too small)
  - but isotropise DM distribution in inner parts of halo

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





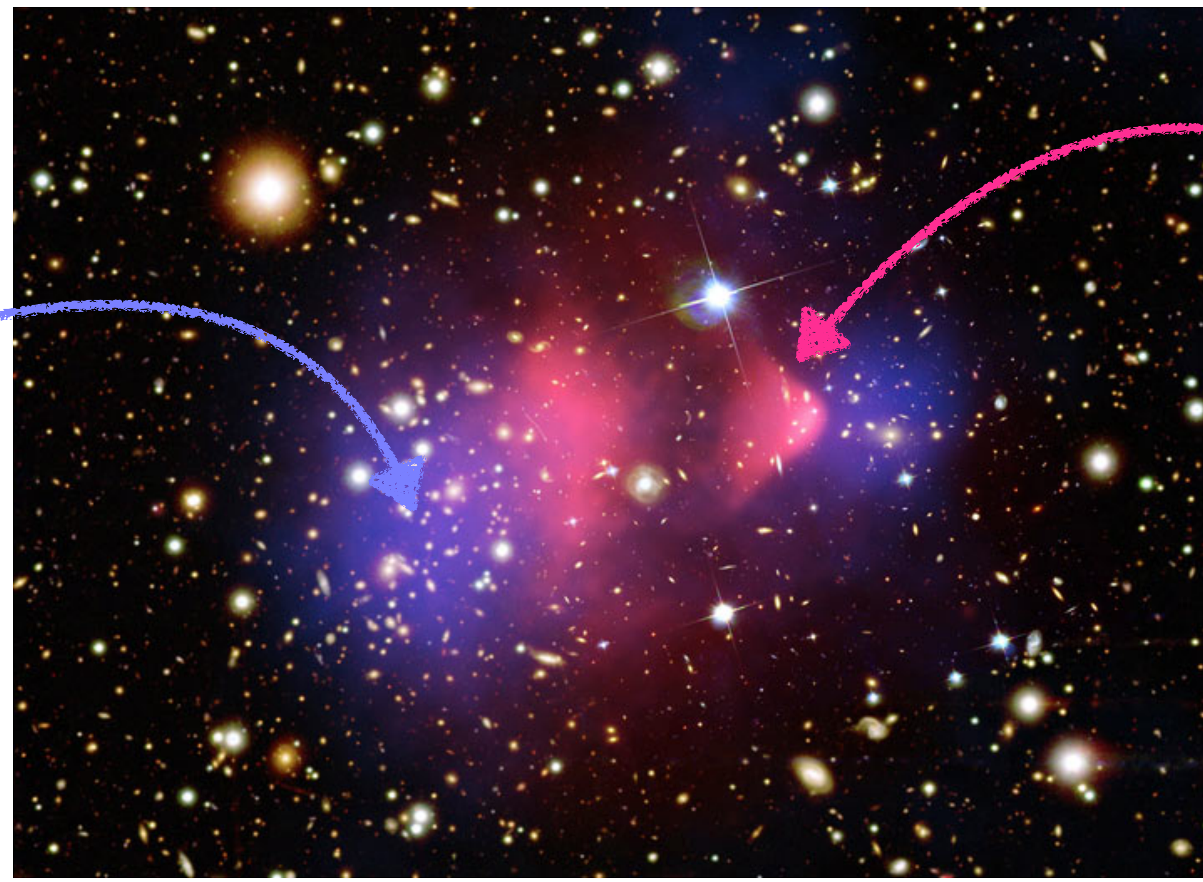
Vogelsberger, Zavala & Loeb, MNRAS '12



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:

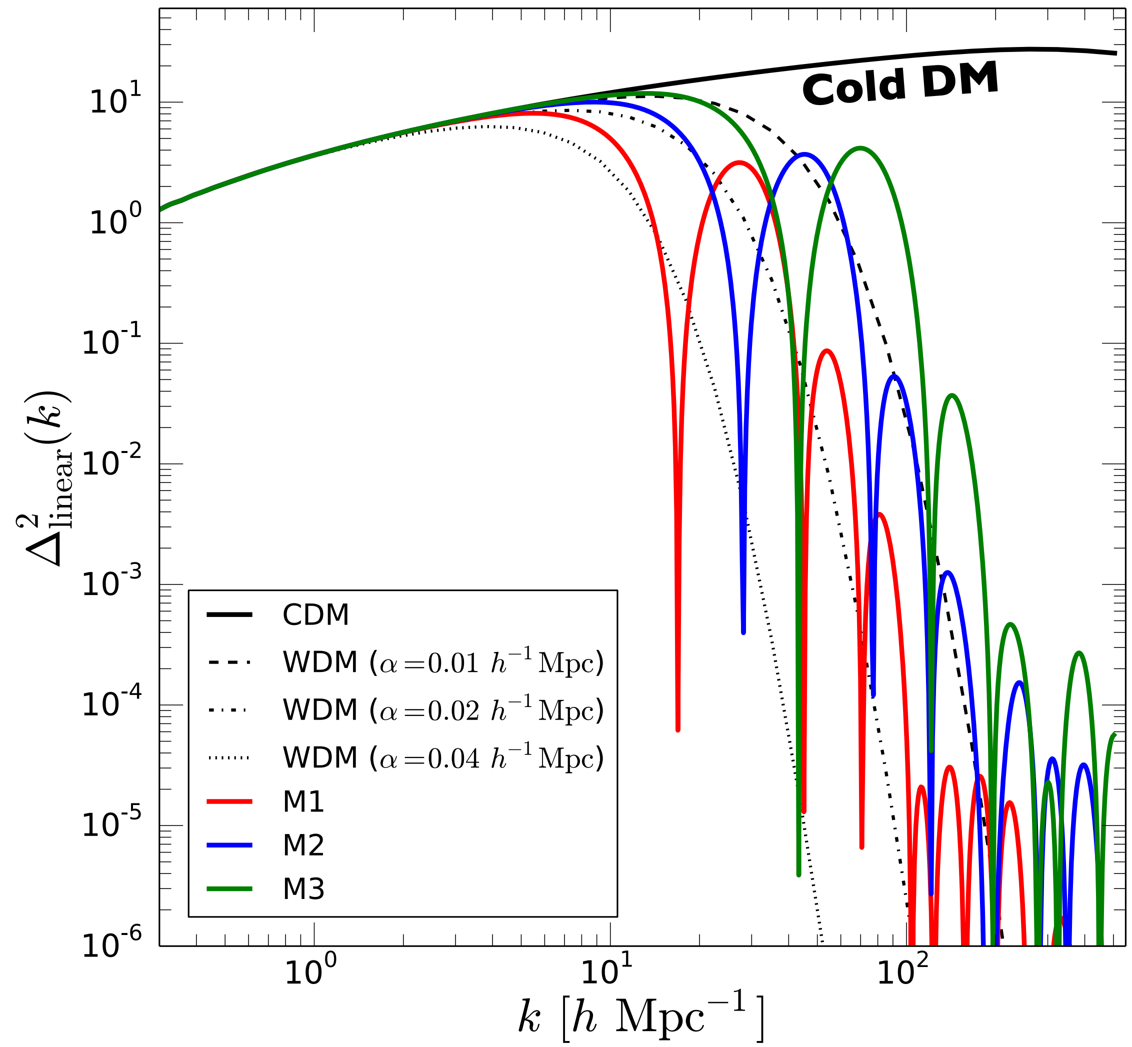
review: Tulin & Yu, PR '18

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

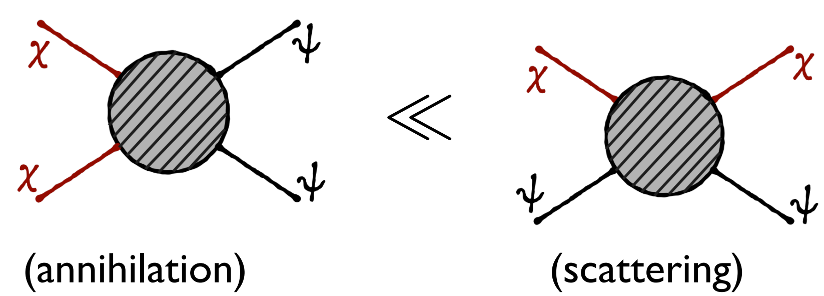
Suppressing power at small scales

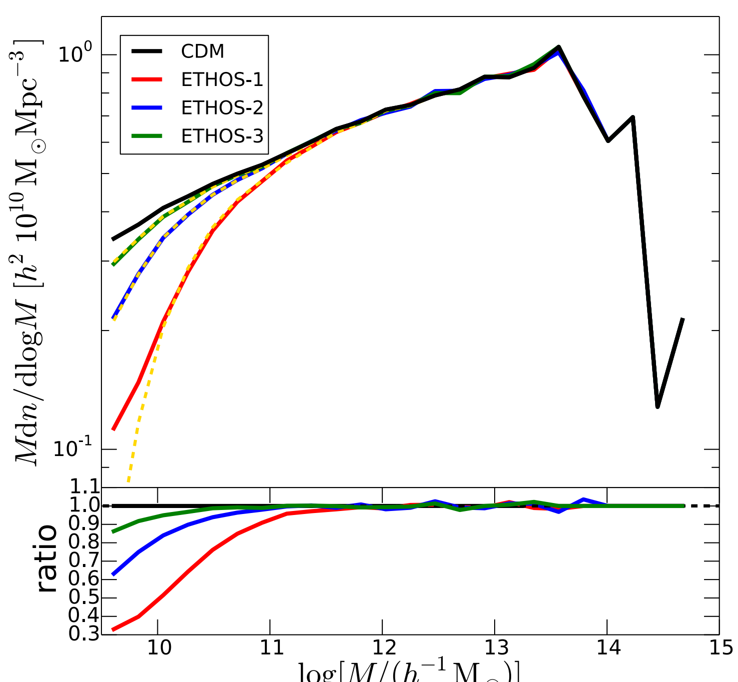
- The (linear) CDM spectrum of matter density perturbations can be suppressed by
  - free-streaming of warm DM **[dashed]**
  - (late) kinetic decoupling of cold DM **[solid]**

review: TB, NJP '09



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

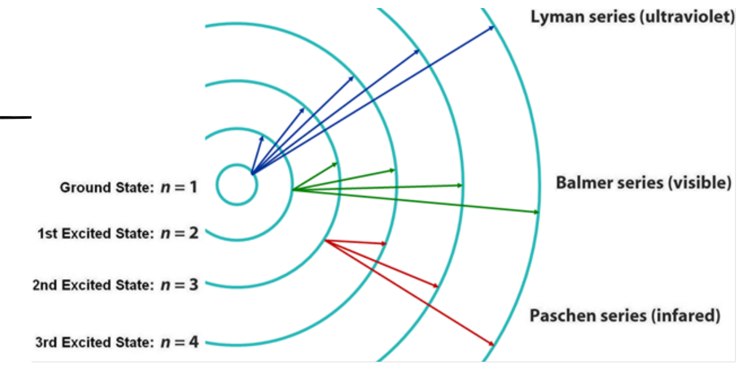


Fig.: Daniel Reichart

(assumed) quasar spectrum **without absorption**

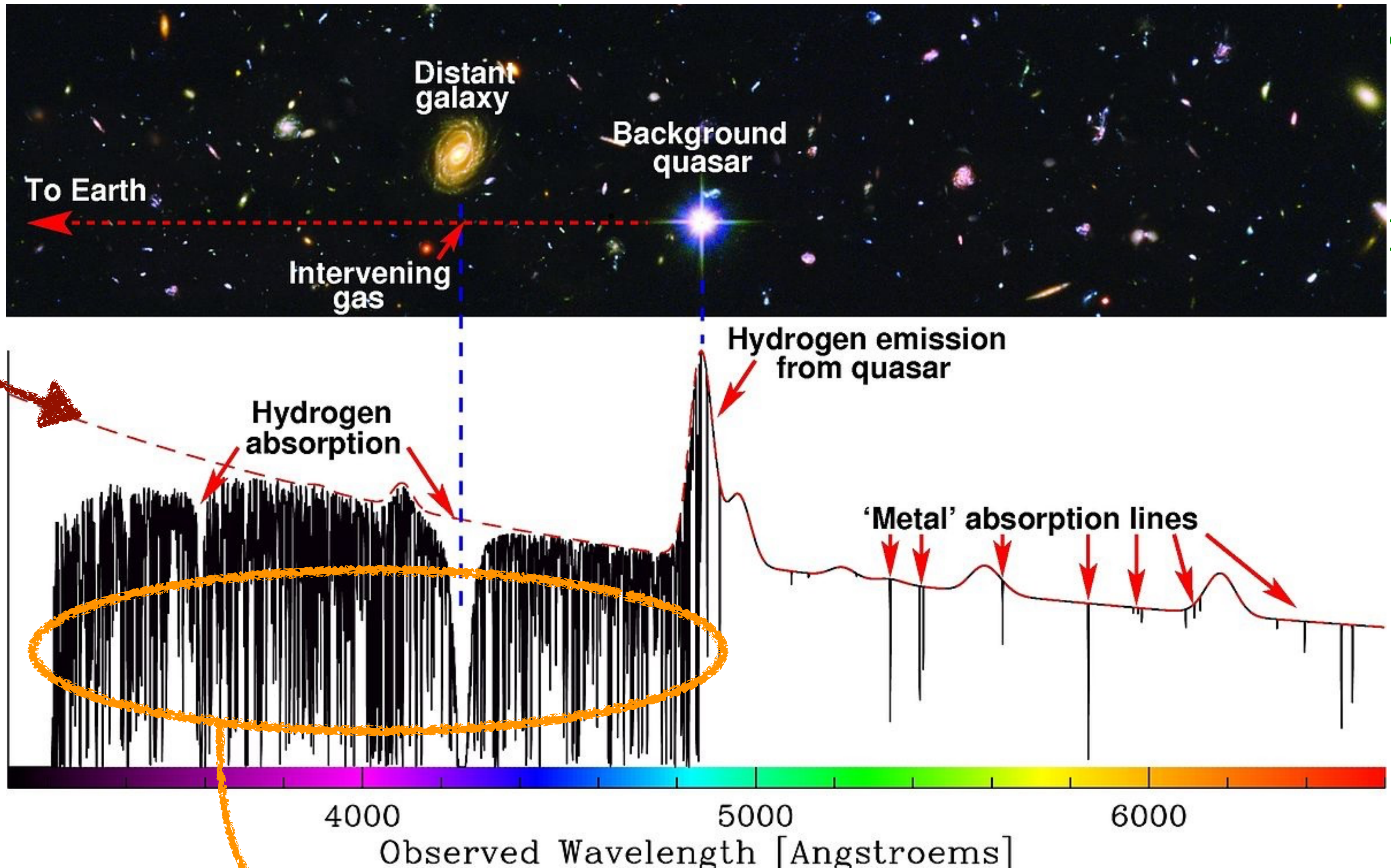


Fig.: Michael Murphy

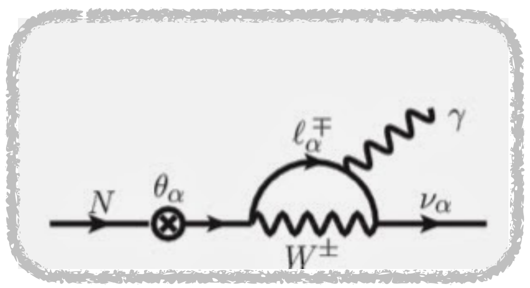
Absorption strength $\propto$ density of matter (hydrogen) clump

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

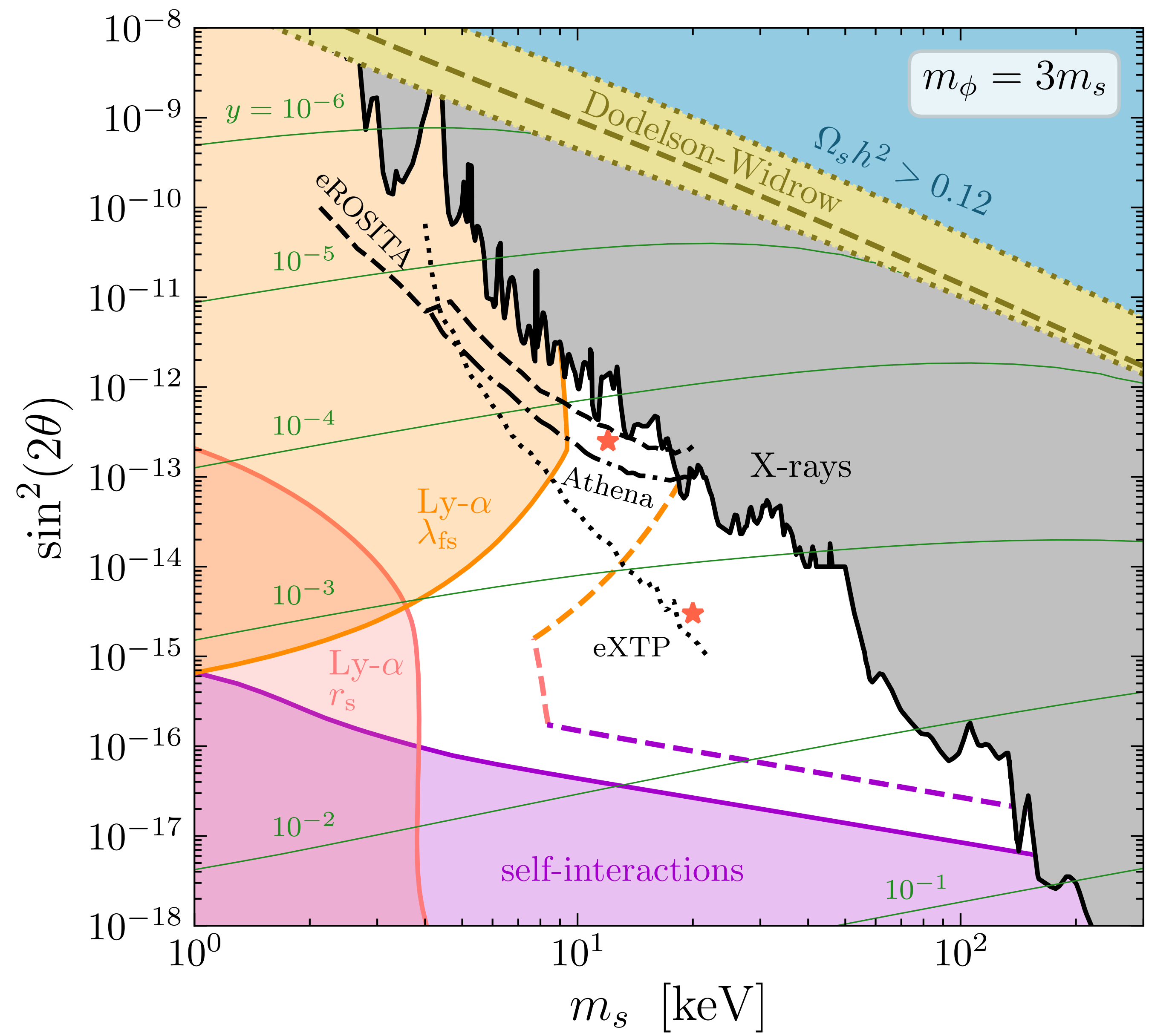
recast $m_{\mathrm{WDM}} > 1.9\,\mathrm{keV}$ to Garzilli+, MNRAS '21

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

$r_s < 0.36\,\mathrm{Mpc}$

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

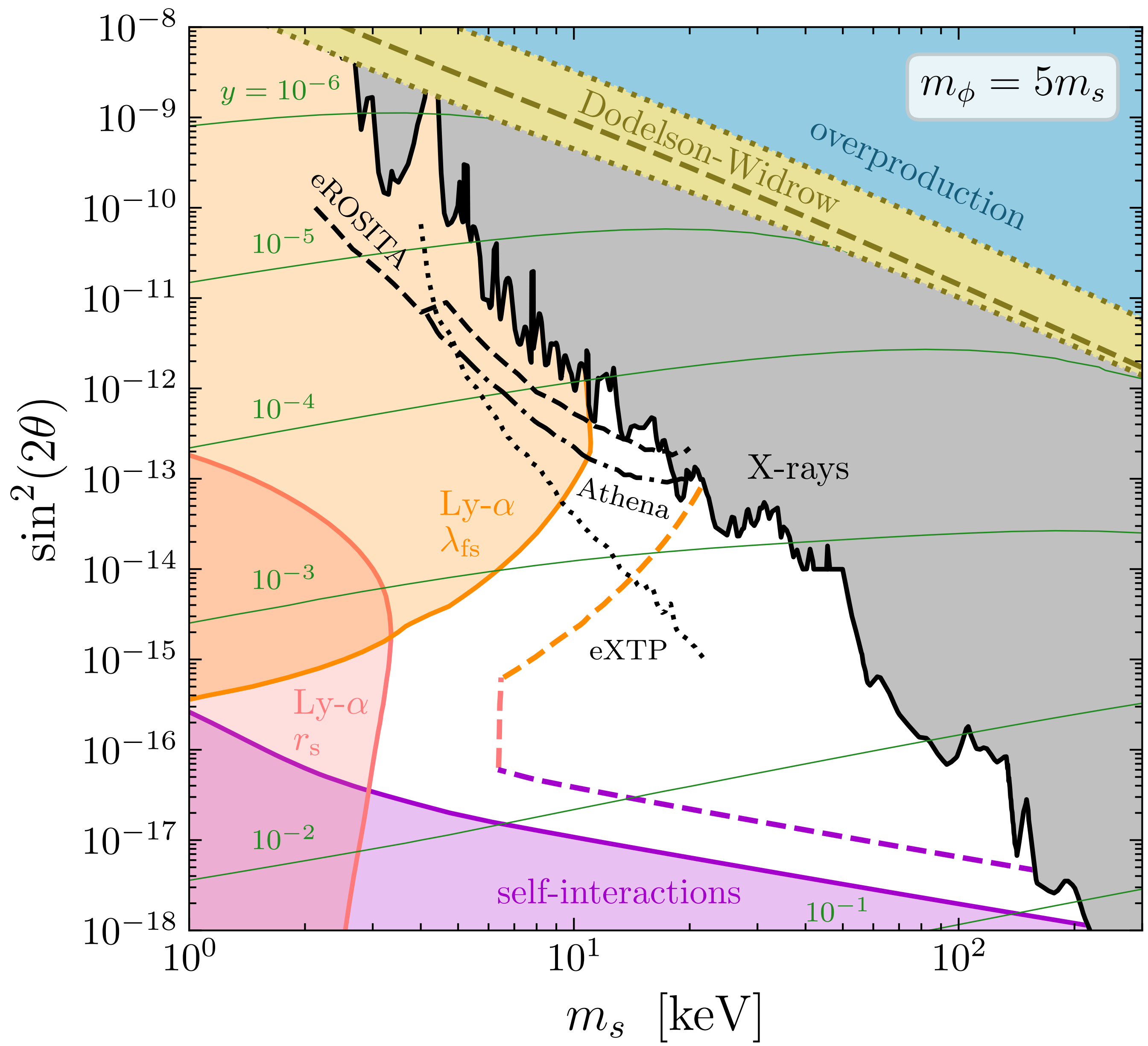
Palanque-Delabrouille+, JCAP '20



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

Conclusions

- Sterile neutrino DM **excluded** in simplest form
  - ‘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



Thanks for your attention!