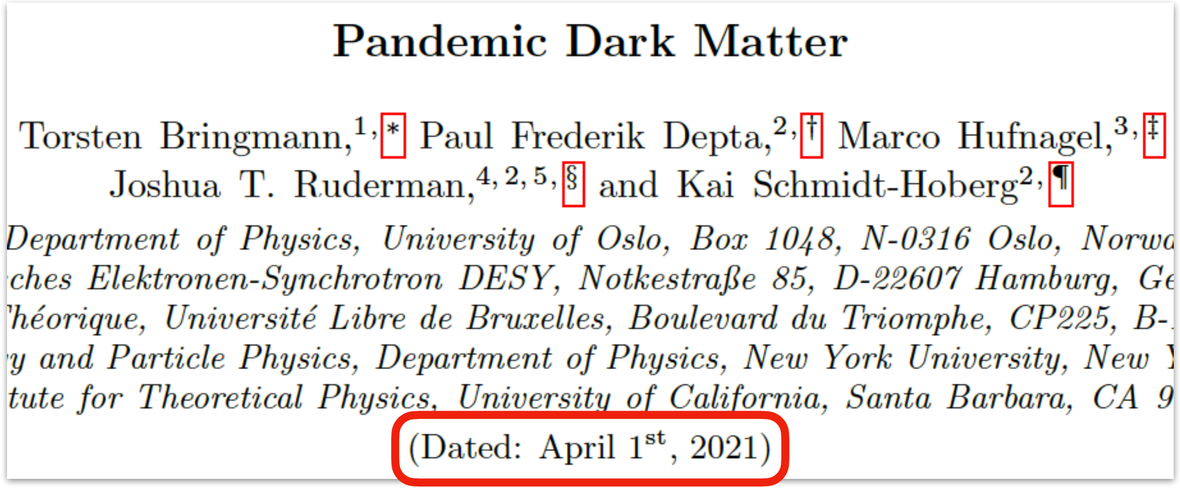
Dark matter from exponential growth

originally proposed as: Pandemic dark matter

Based on **Phys. Rev. Lett. 127 (2021) 191802**
and **2206.10630** with Jörn Kersten



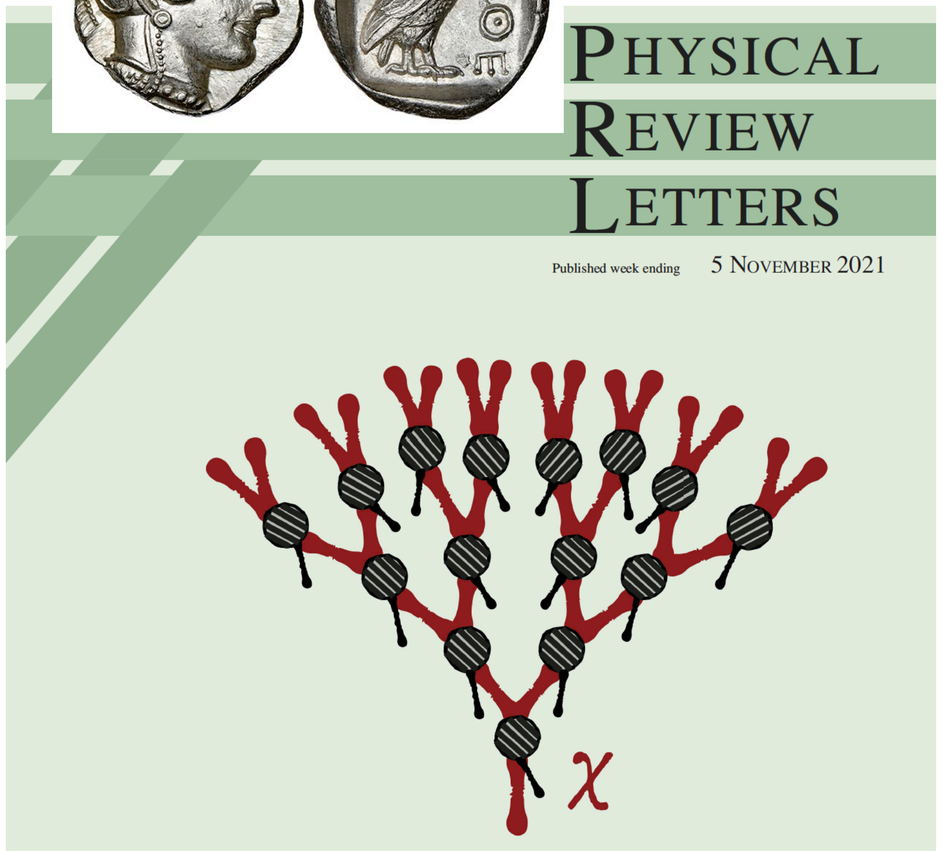
Pandemic Dark Matter

Torsten Bringmann,[1,*] Paul Frederik Depta,[2,†] Marco Hufnagel,[3,‡]
Joshua T. Ruderman,[4,2,5,§] and Kai Schmidt-Hoberg[2,¶]

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ches Elektronen-Synchrotron DESY, Notkestraße 85, D-22607 Hamburg, Ge
Théorique, Université Libre de Bruxelles, Boulevard du Triomphe, CP225, B-
y and Particle Physics, Department of Physics, New York University, New Y
tute for Theoretical Physics, University of California, Santa Barbara, CA 9

(Dated: April 1st, 2021)





Kai Schmidt-Hoberg

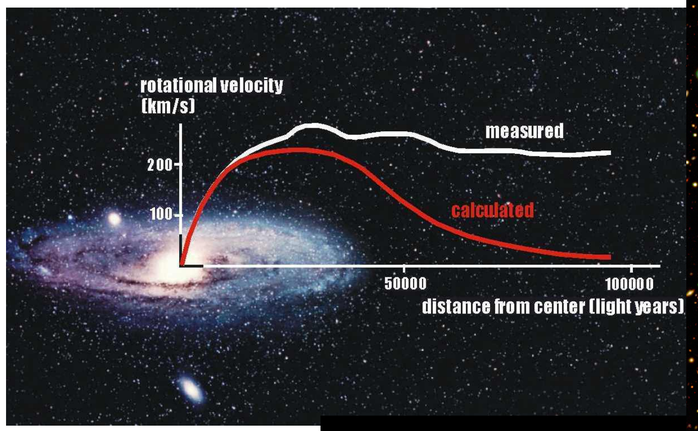
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

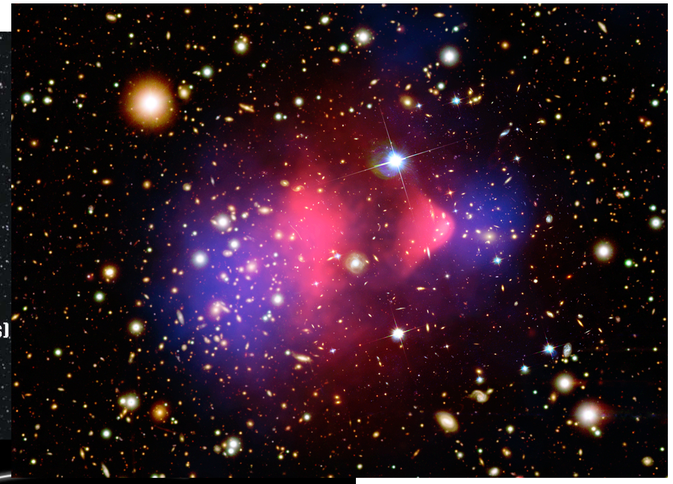
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

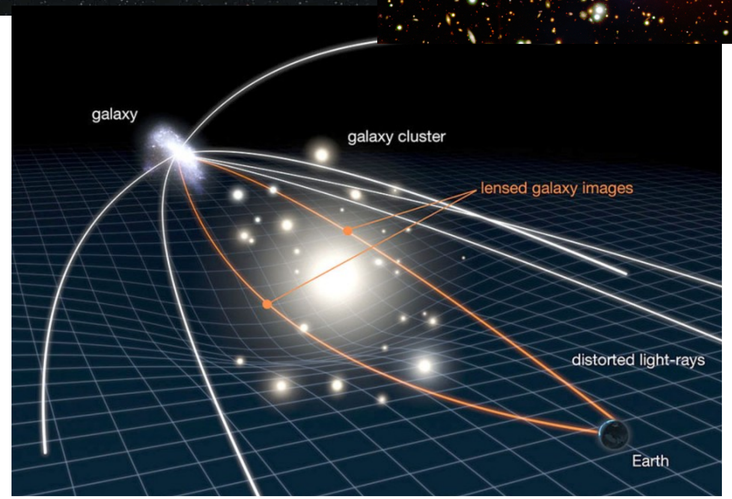
DESY.

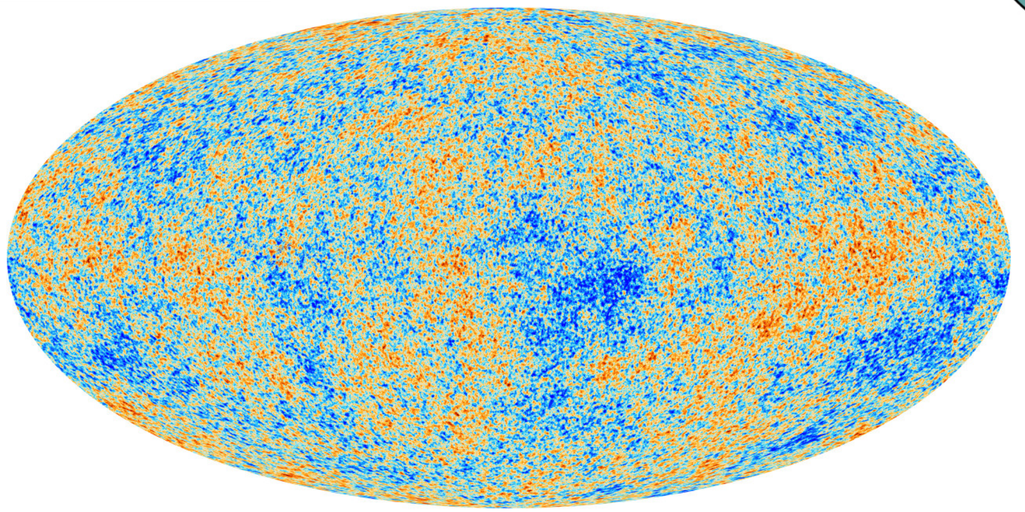
Evidence for dark matter

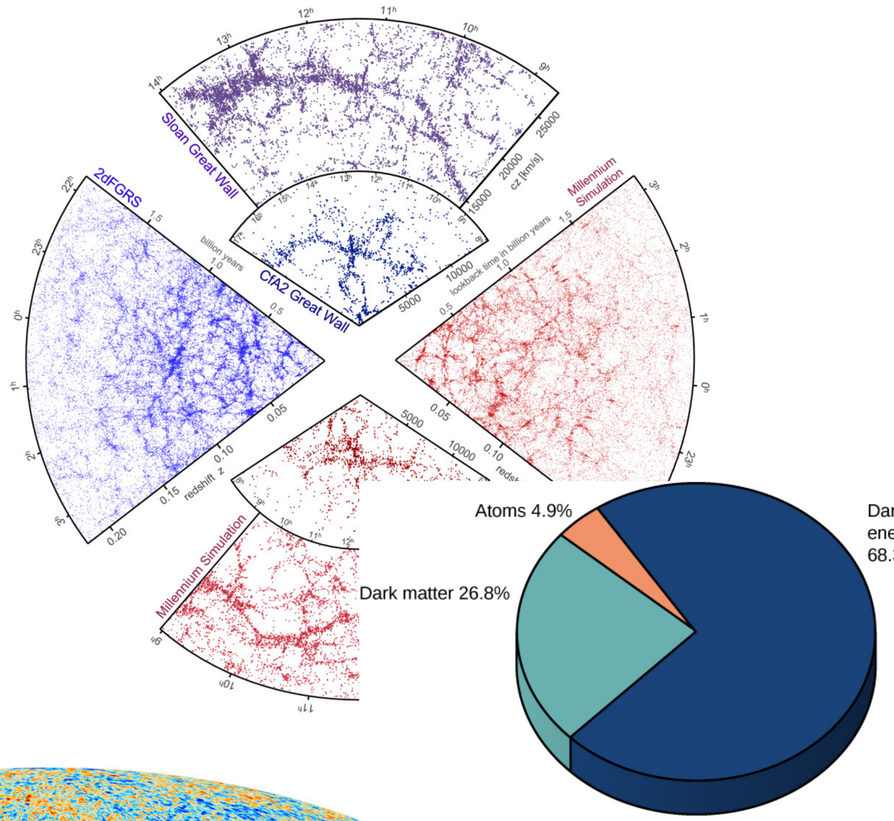
Compelling evidence for dark matter on **all** astrophysical scales





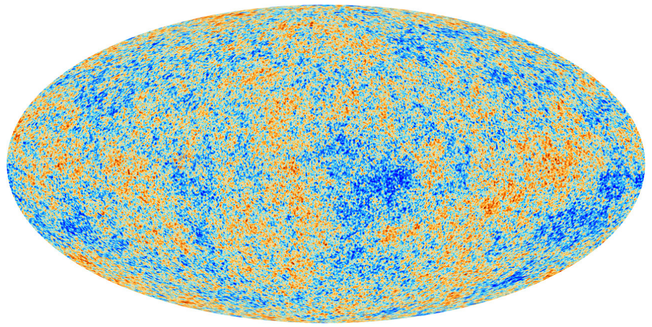


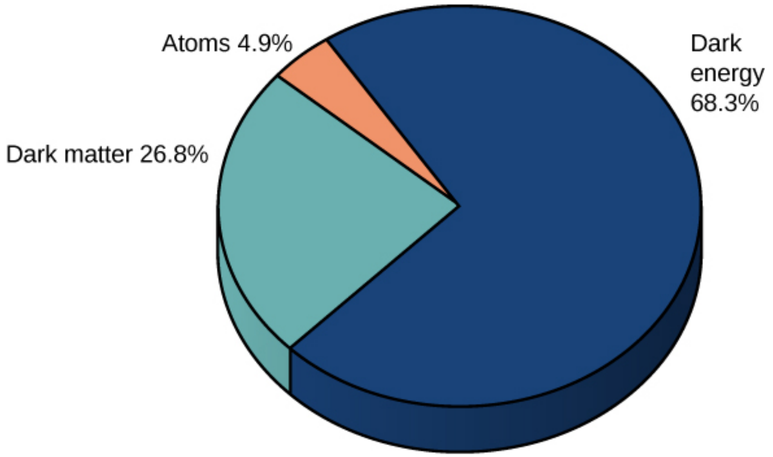




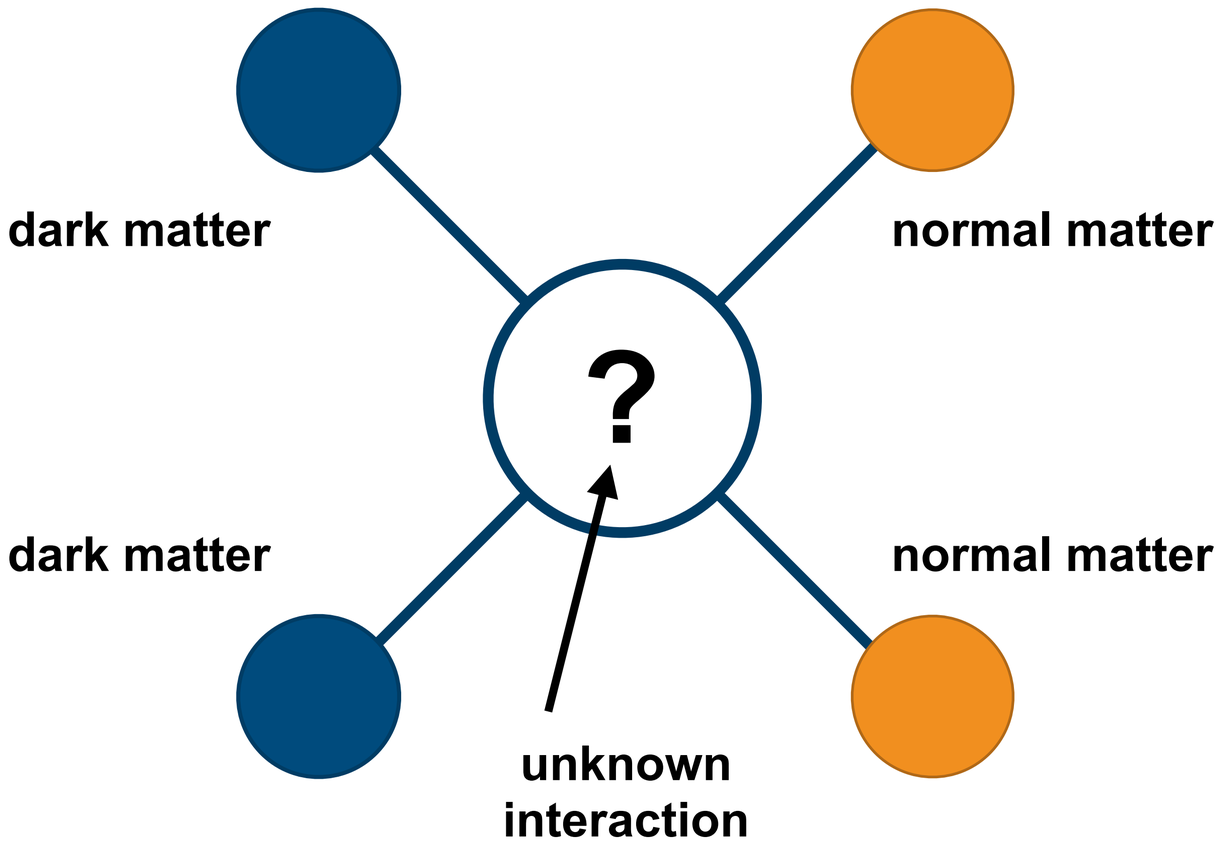
What do we know?

- **How much:** $\Omega \simeq 0.26$
- **Dark**
  - **almost electrically neutral**
  - **probably colour neutral**
- **Stable**
  - **sufficiently long-lived**
- **Cold**
  - **non-relativistic (structure formation)**
- **Non-baryonic**



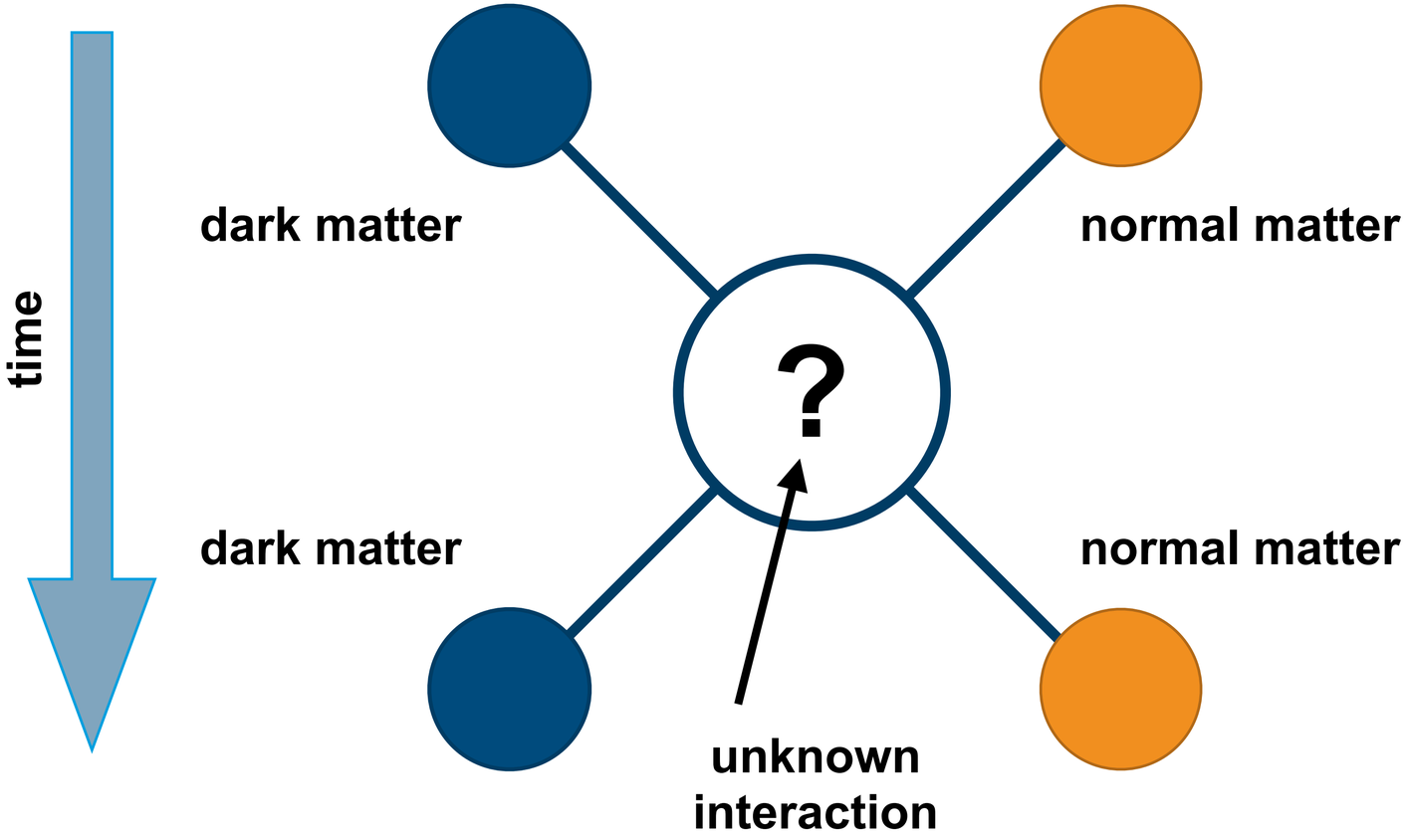


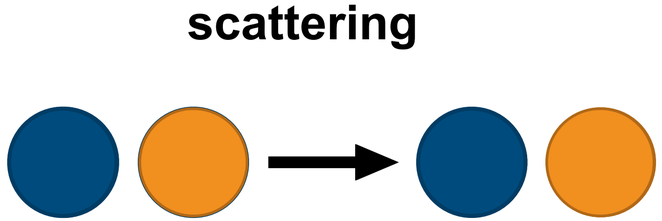
Searches for dark matter



- We observe dark matter only via its gravitational interaction…
- To identify its particle physics nature need additional stronger interactions to have any hope…

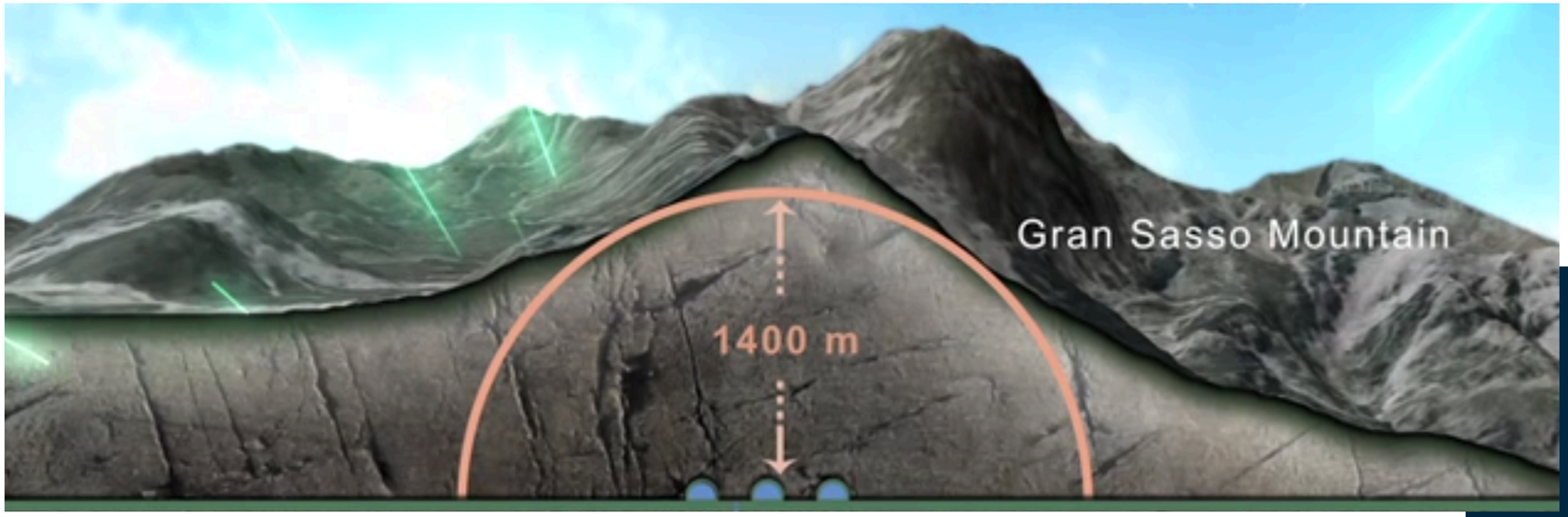
Searches for dark matter



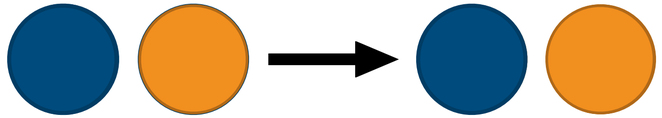




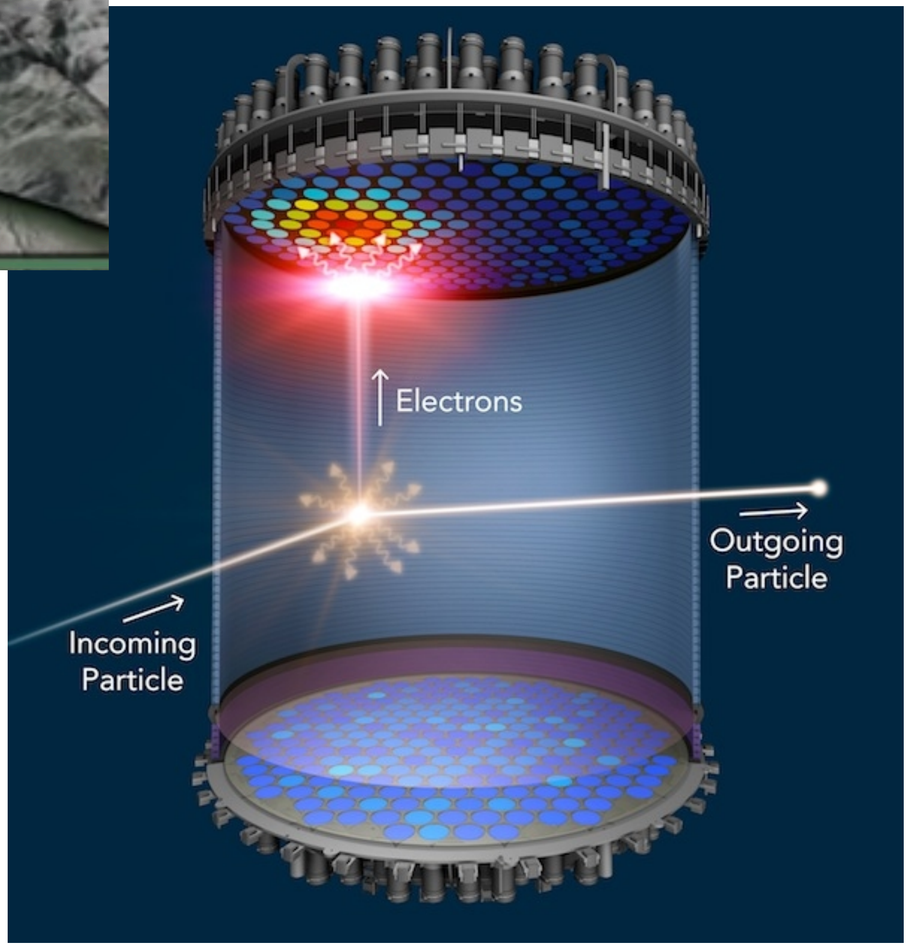
Direct searches



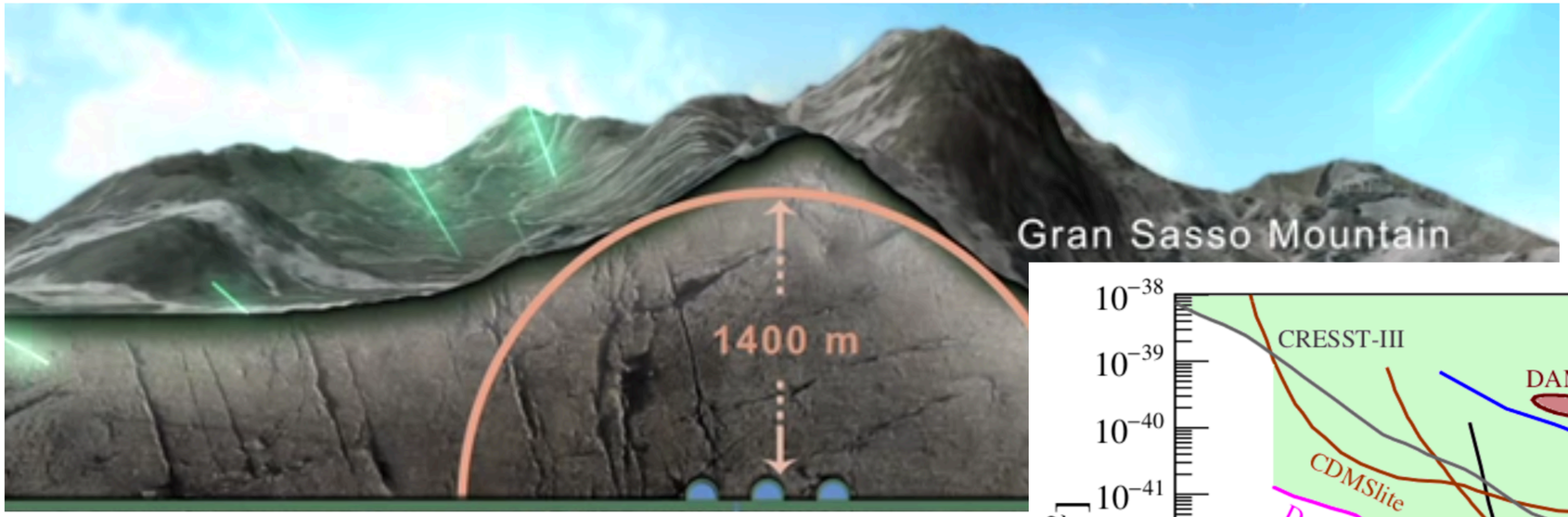
scattering



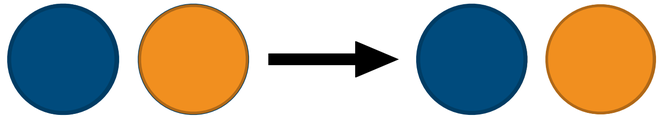
- Searches deep underground to minimise background
- very rare event (~ less than 1 event per kg per year)



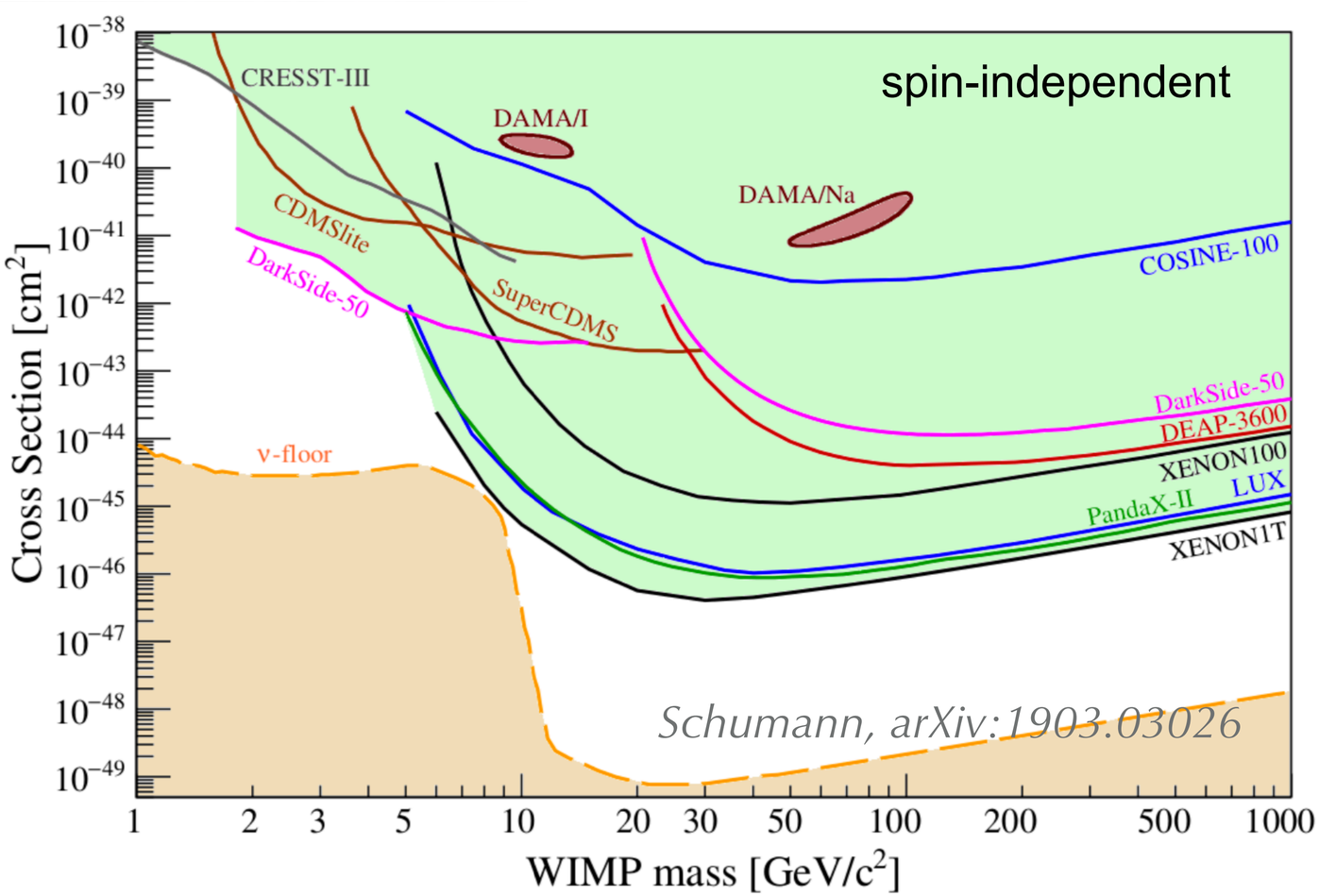
Direct searches



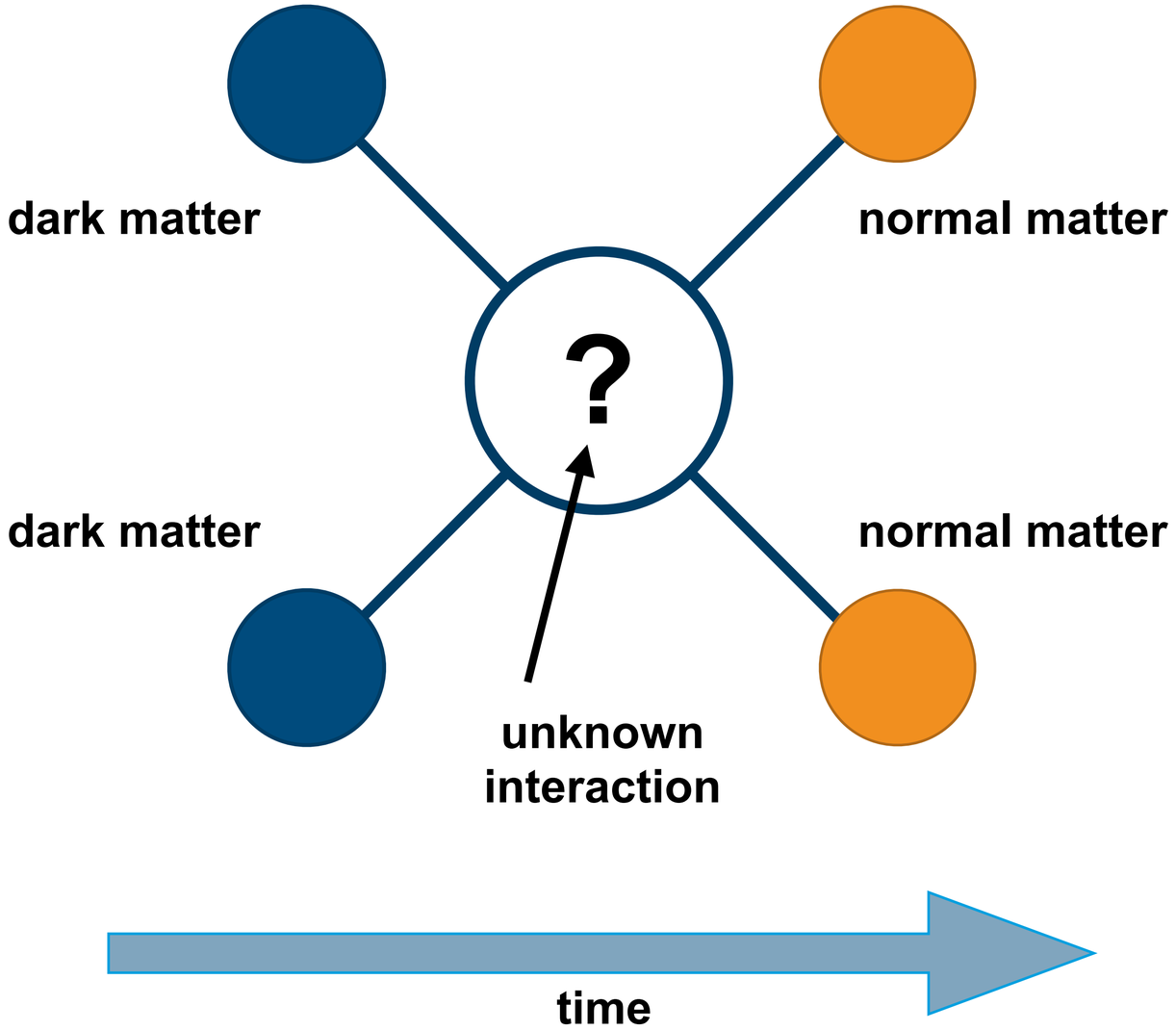
scattering

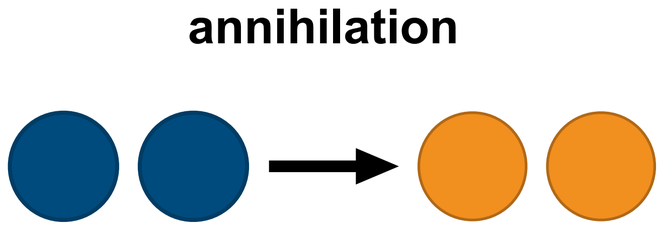


- **Searches deep underground to minimise background**
- **very rare event (~ less than 1 event per kg per year)**
- **no signal…**



Searches for dark matter



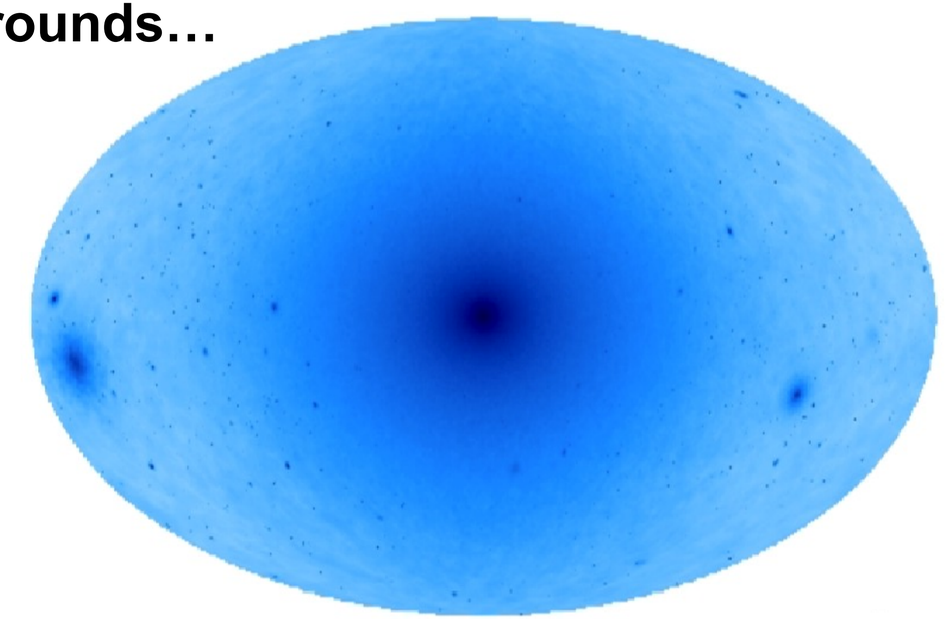




Indirect searches

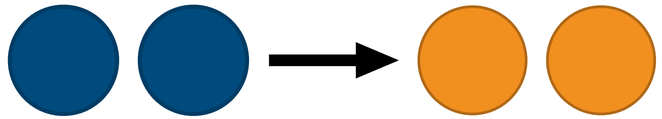
- **Searches with satellites for annihilation signal e.g. from the Galactic centre.**

- **there are some excesses, but hard to discriminate from astrophysical backgrounds…**



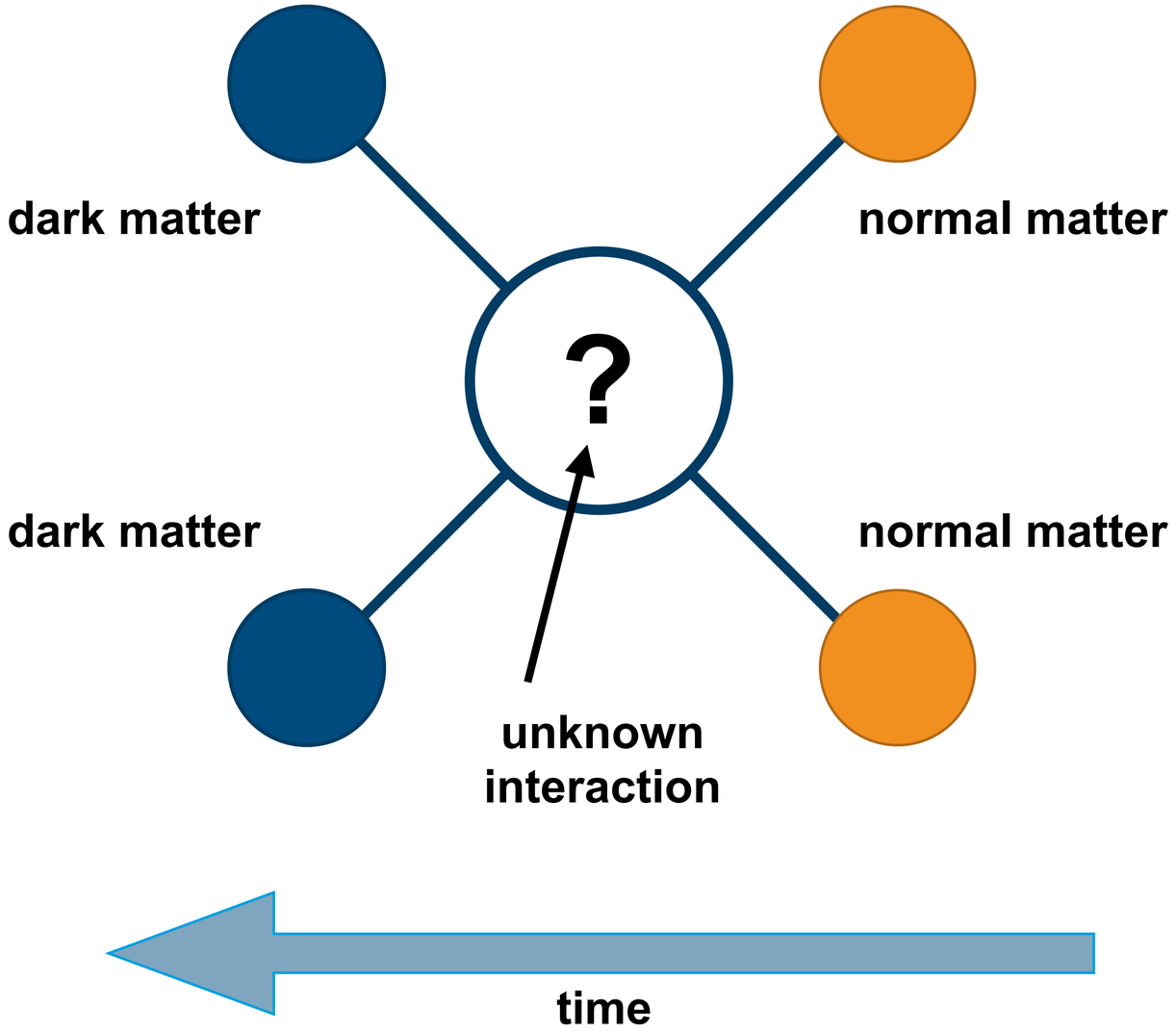
simulated signal

annihilation

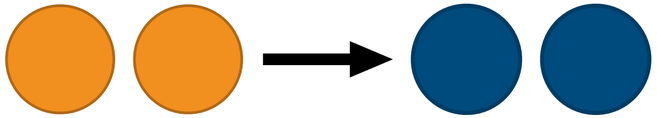


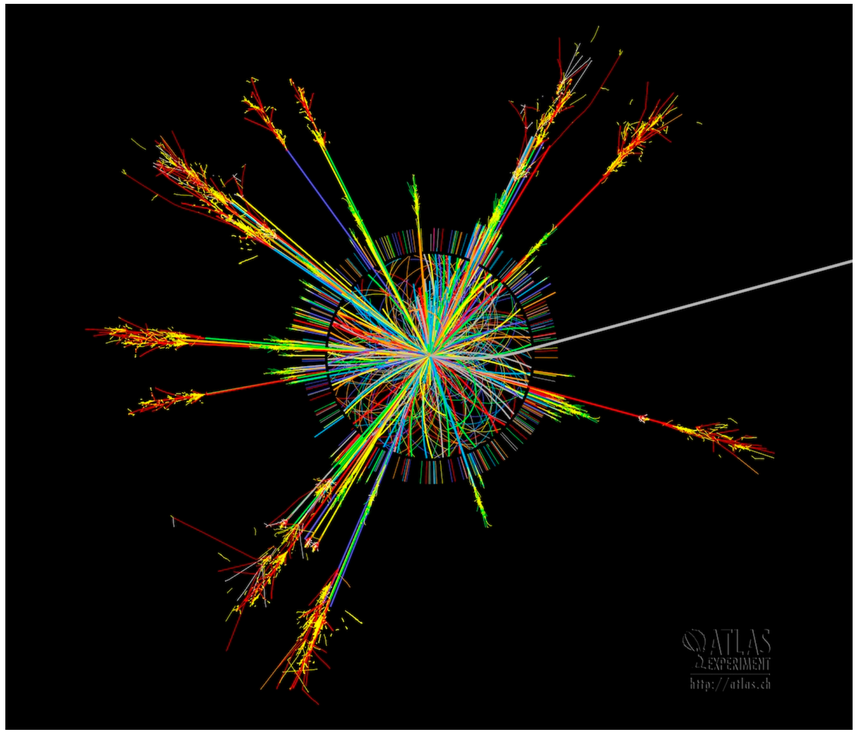


Searches for dark matter



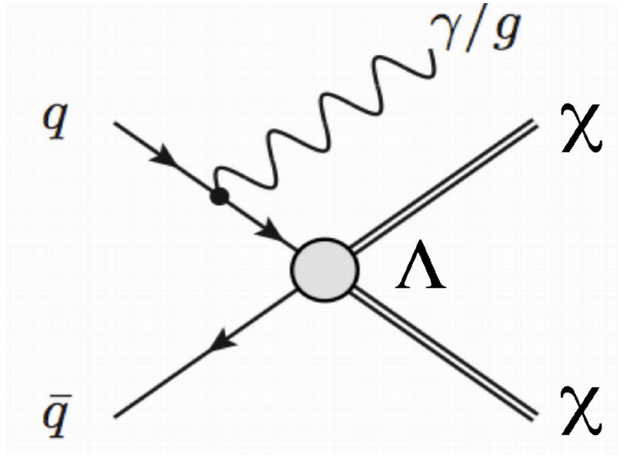
DM production

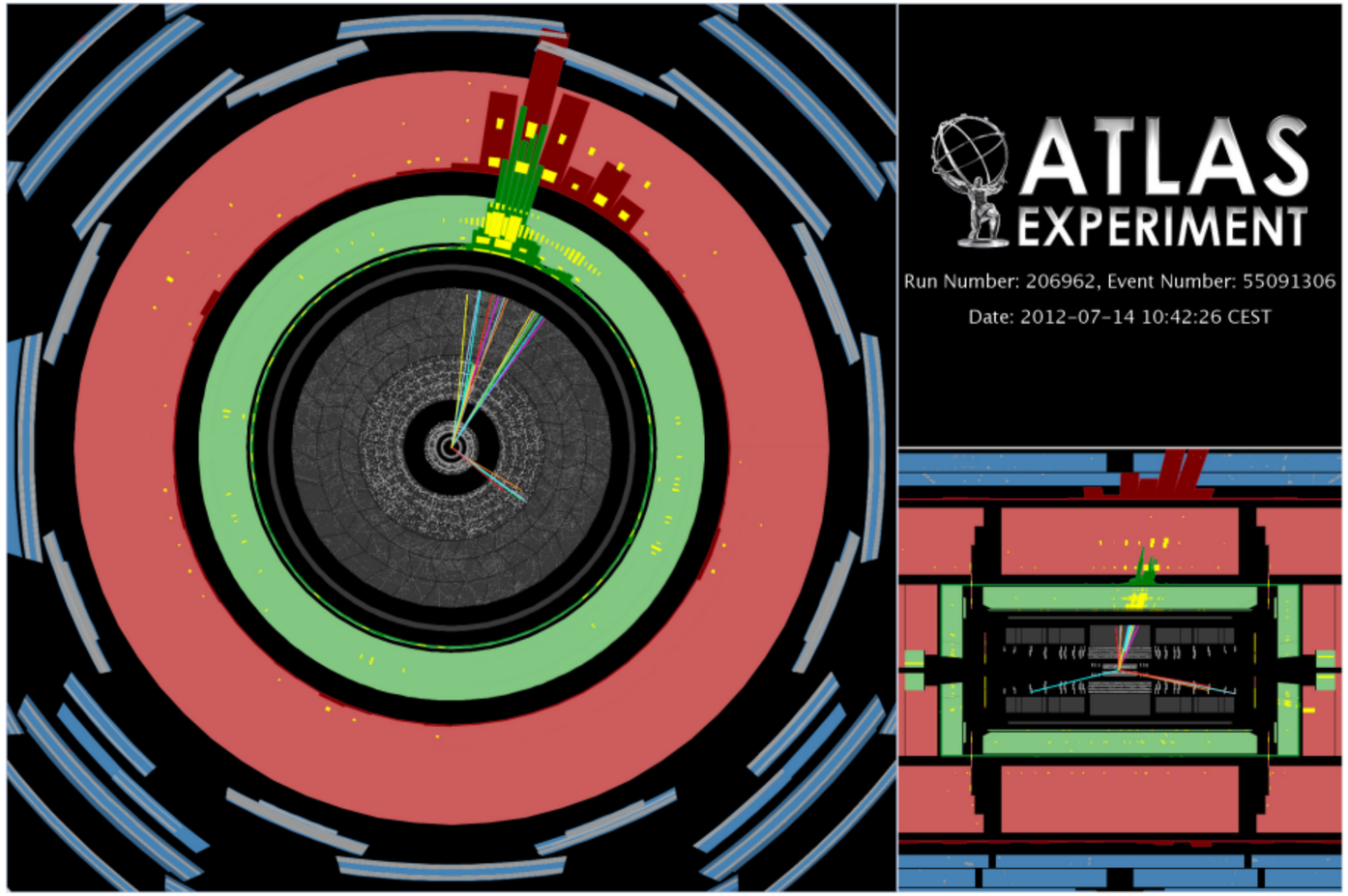




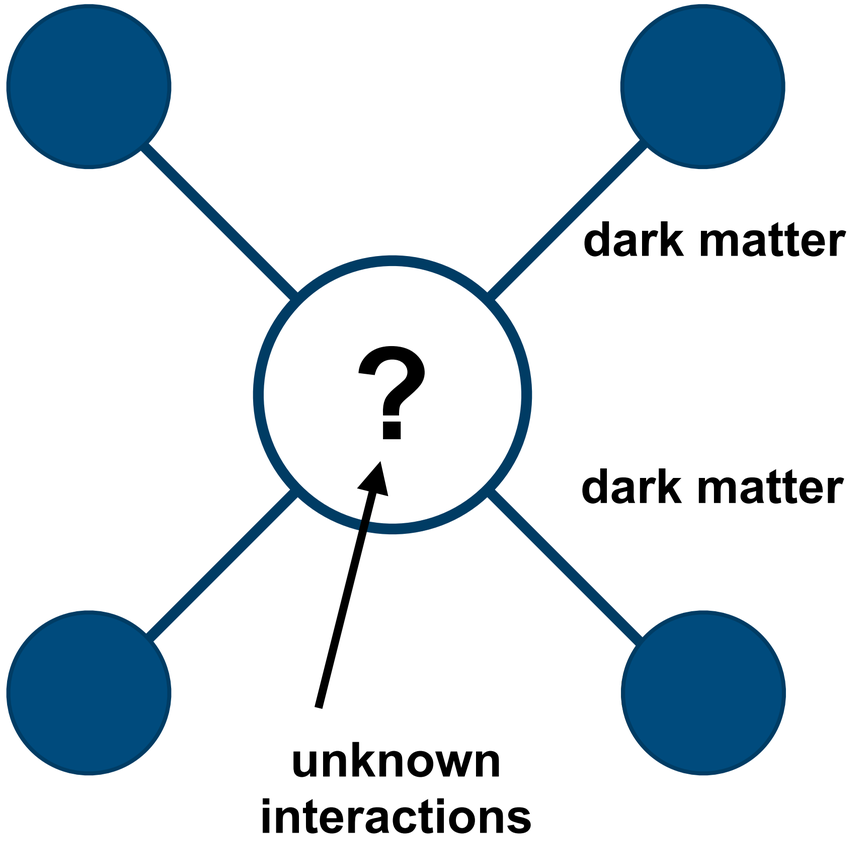
Dark matter at colliders

- **Problem with dark matter: leaves no signal in detector**
- **Trick: use energy/momentum conservation**
- **So far consistent with expected background**

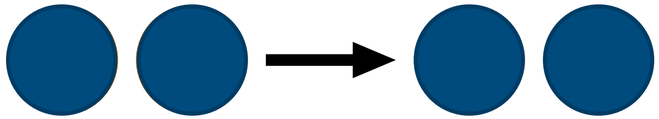


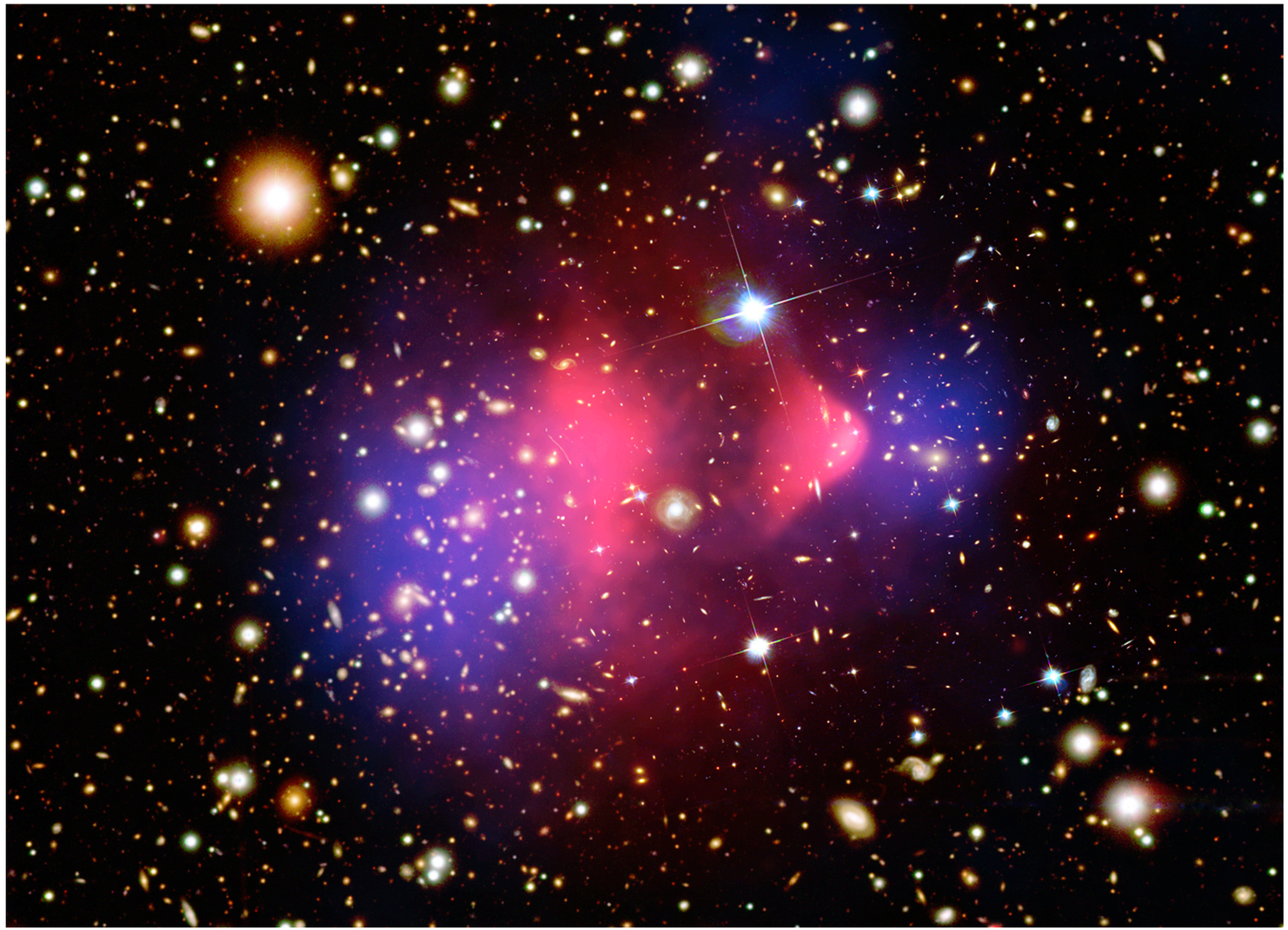


DM self-interactions

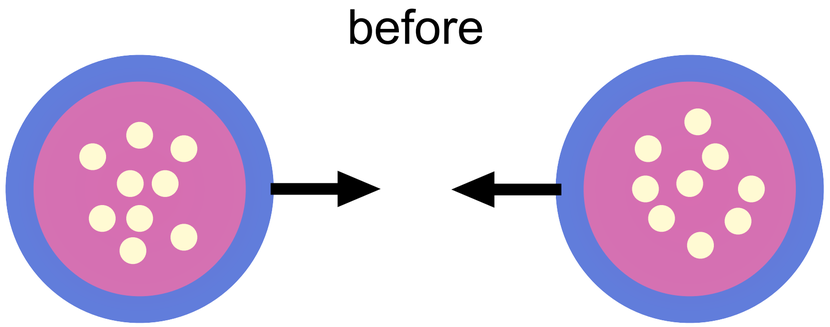


DM scattering

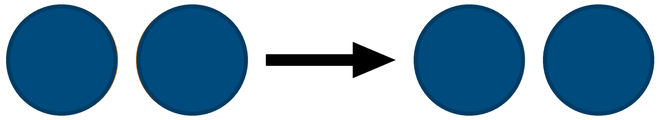


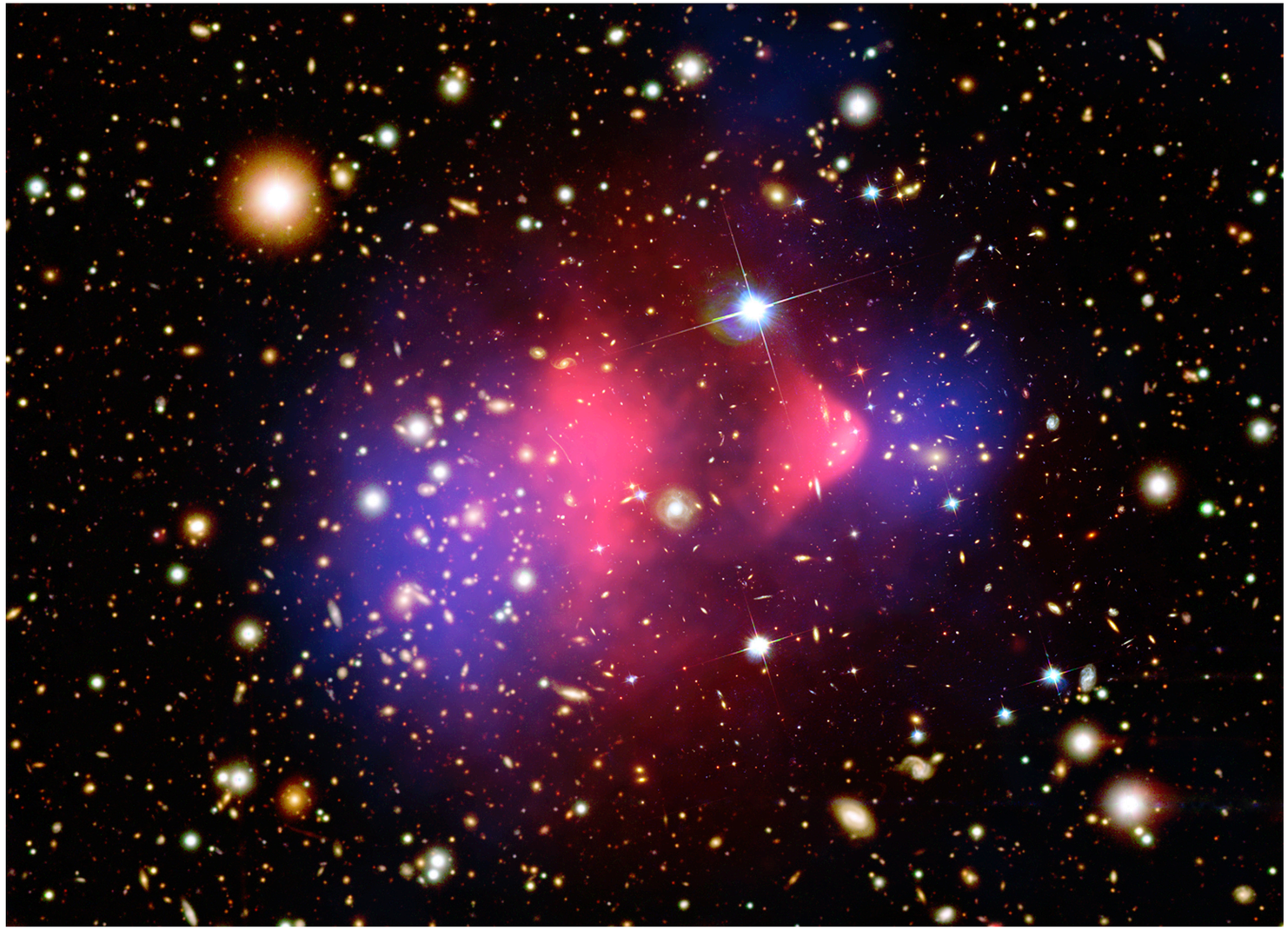


DM self-interactions



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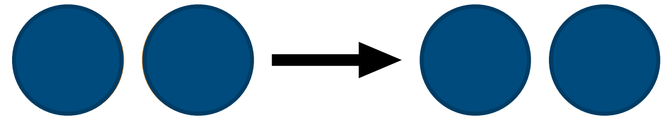


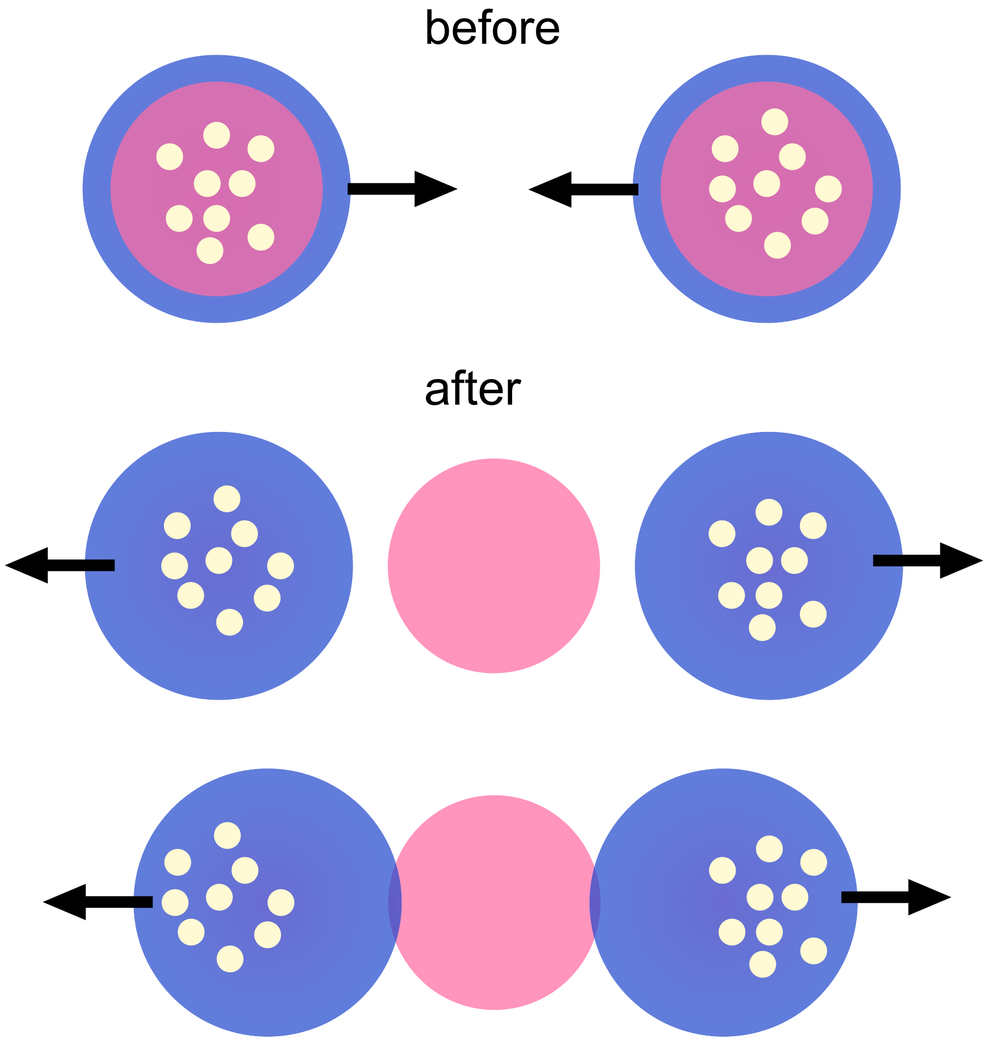


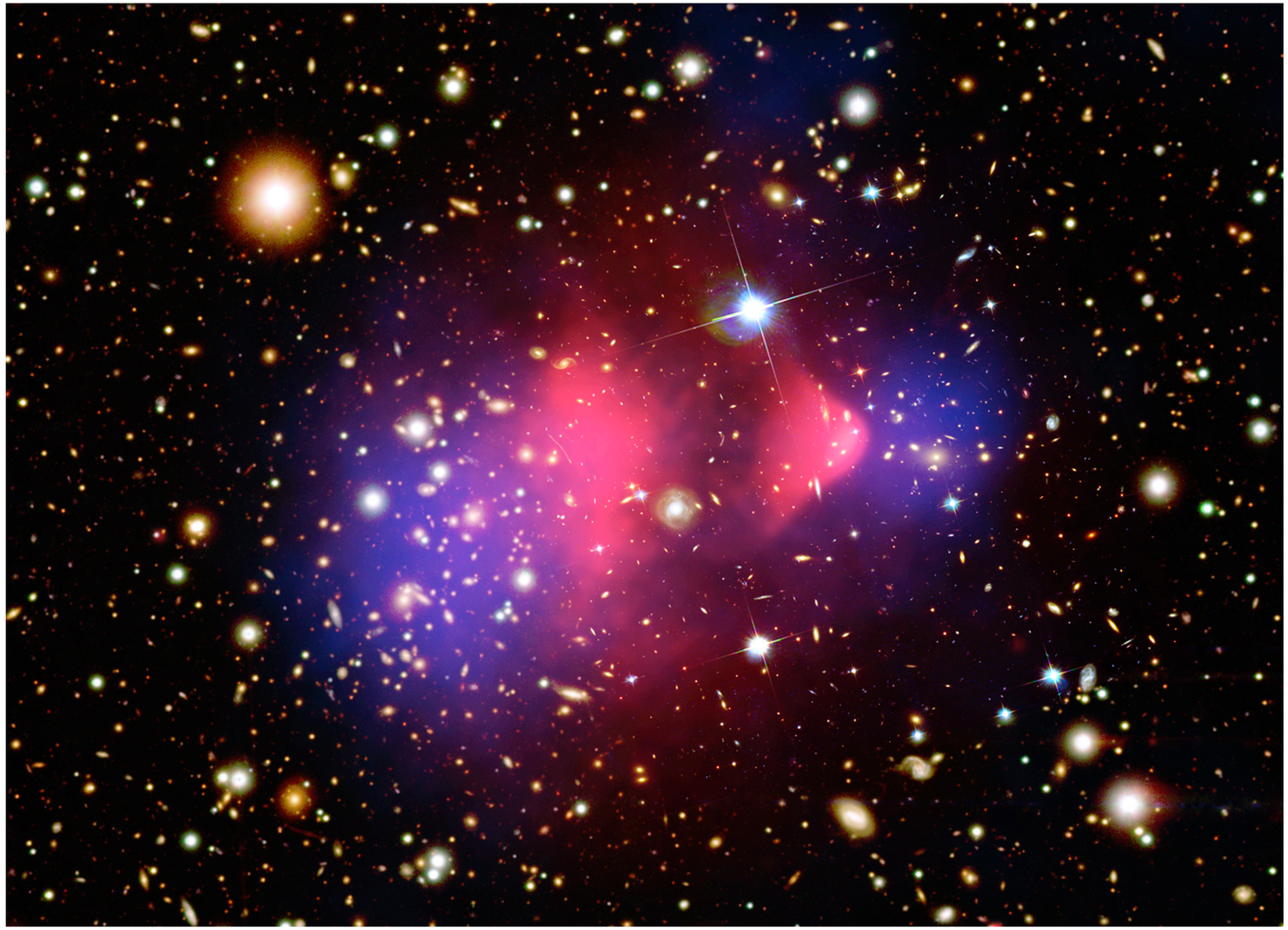
DM self-interactions

$\sigma_T/m_{DM} \lesssim 1\text{barn/GeV}$

DM scattering



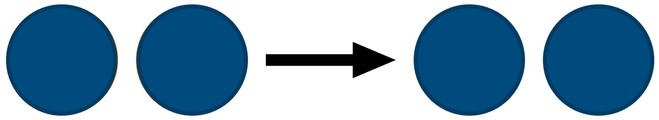


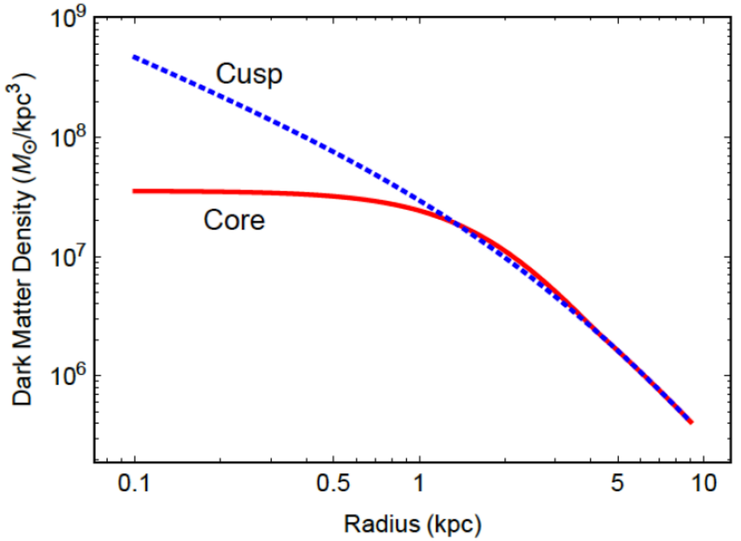


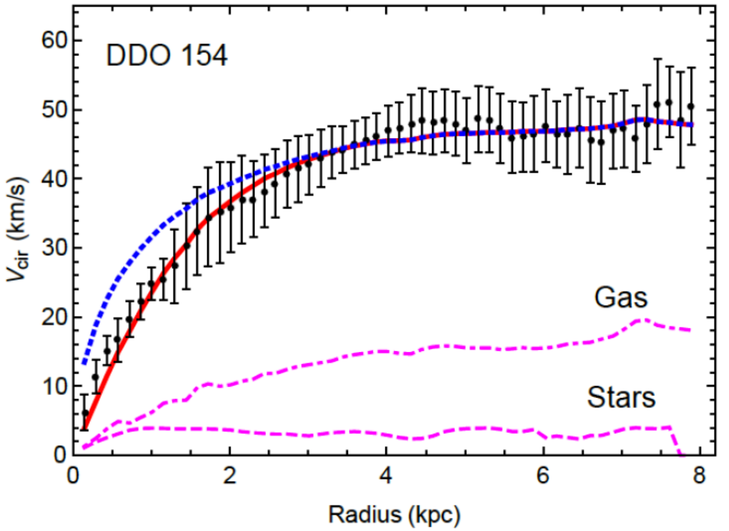
DM self-interactions interesting

- The collisionless cold dark matter paradigm fits perfectly at large scales
- There are however various discrepancies between N-body simulations of collisionless cold DM and astrophysical observations on galactic scales
  - cusp- vs. core problem

DM scattering







Tulin, Yu: 1705.02358

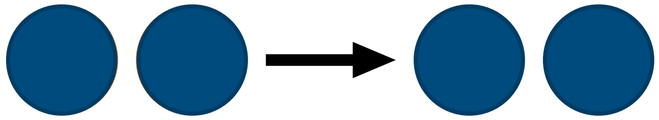
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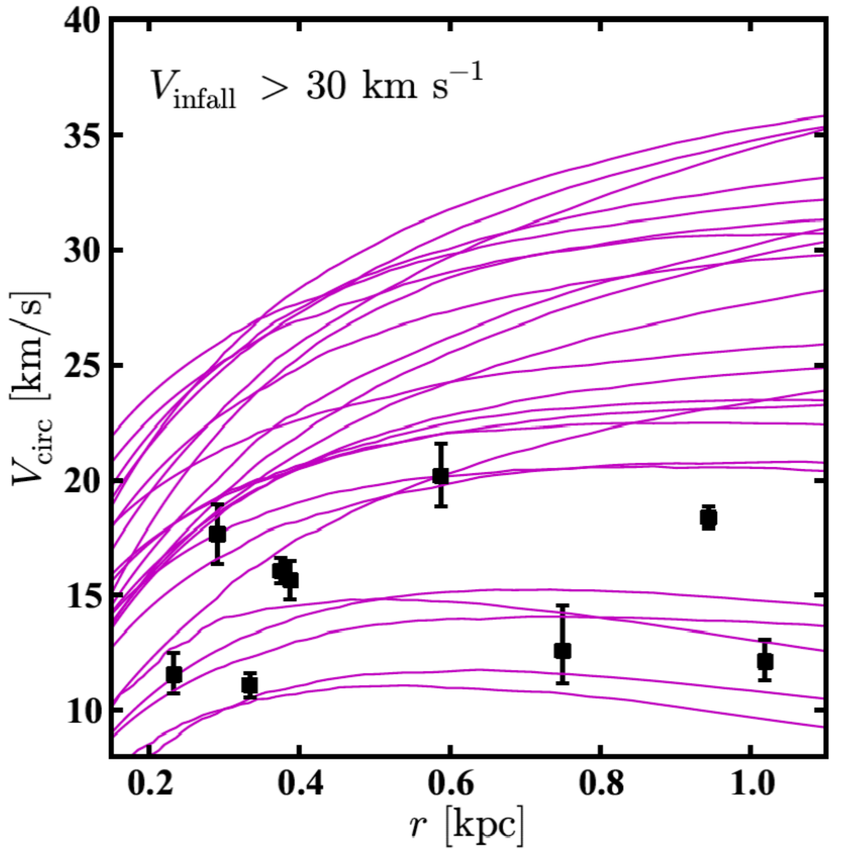
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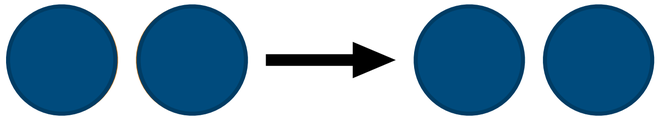
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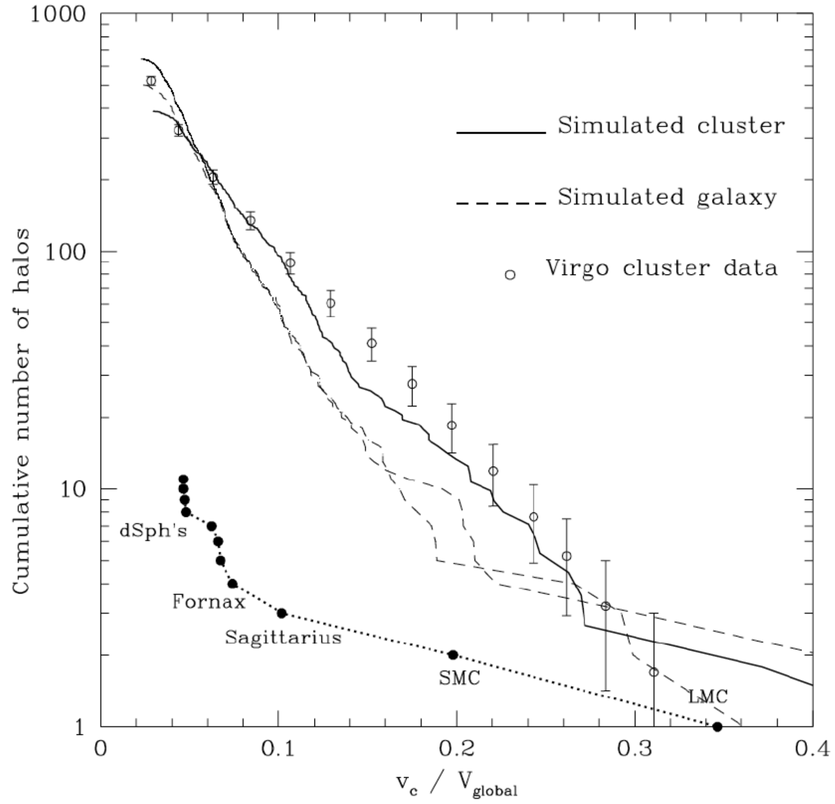
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  - missing satellite problem → no longer a problem…

DM scattering

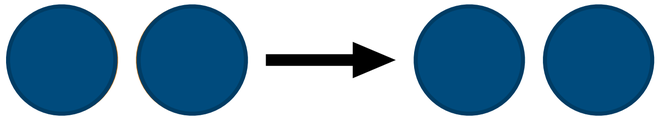




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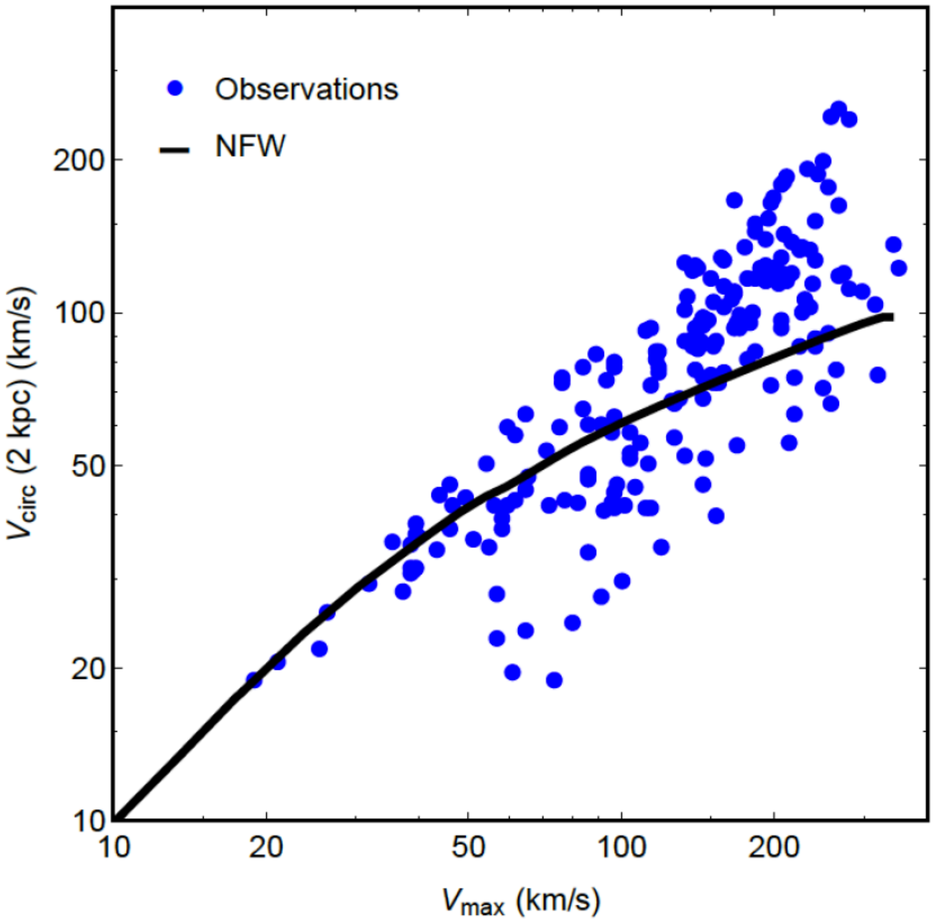
DM scattering



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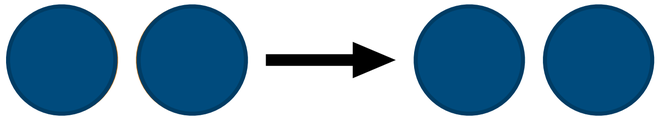
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DM scattering



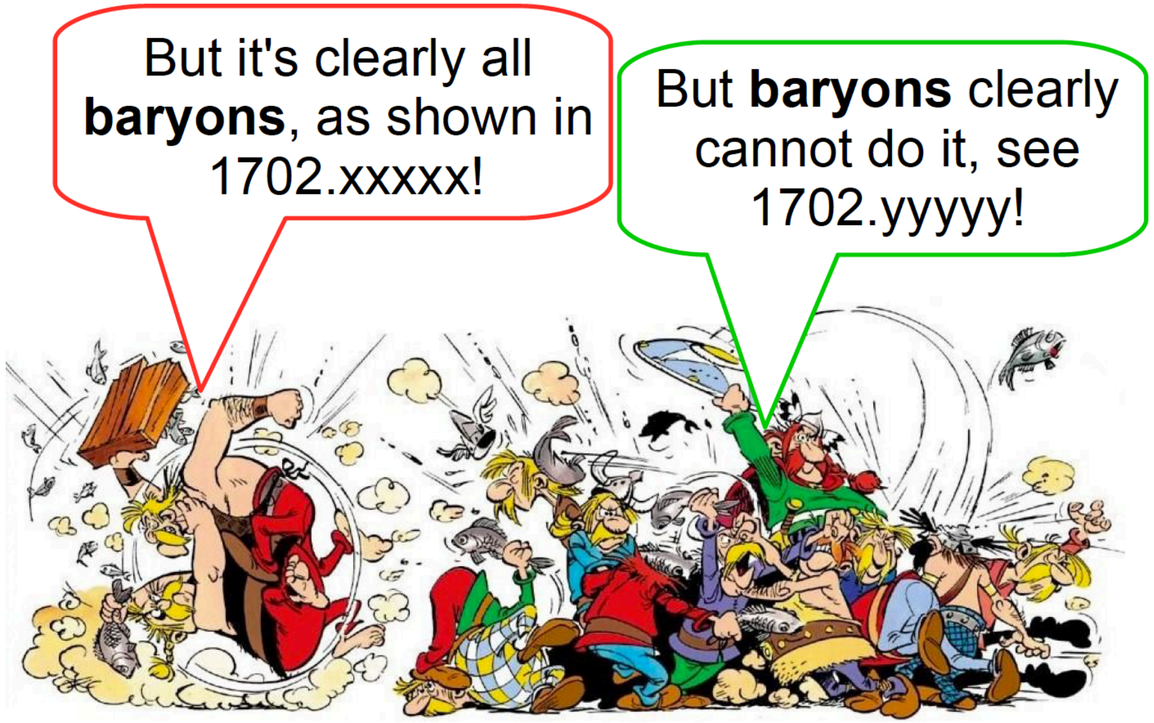
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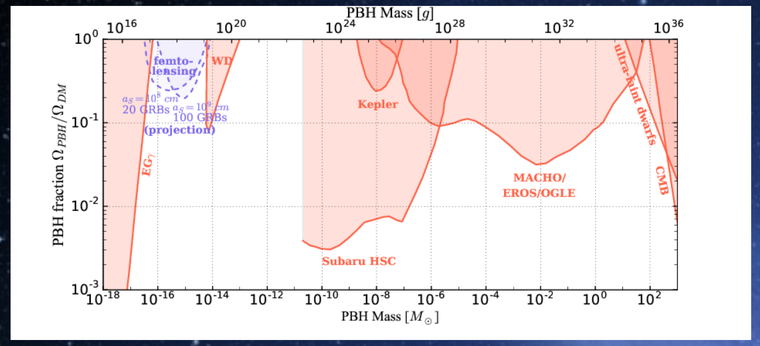
  - cusp- vs. core problem
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- Self-interactions may solve these problems

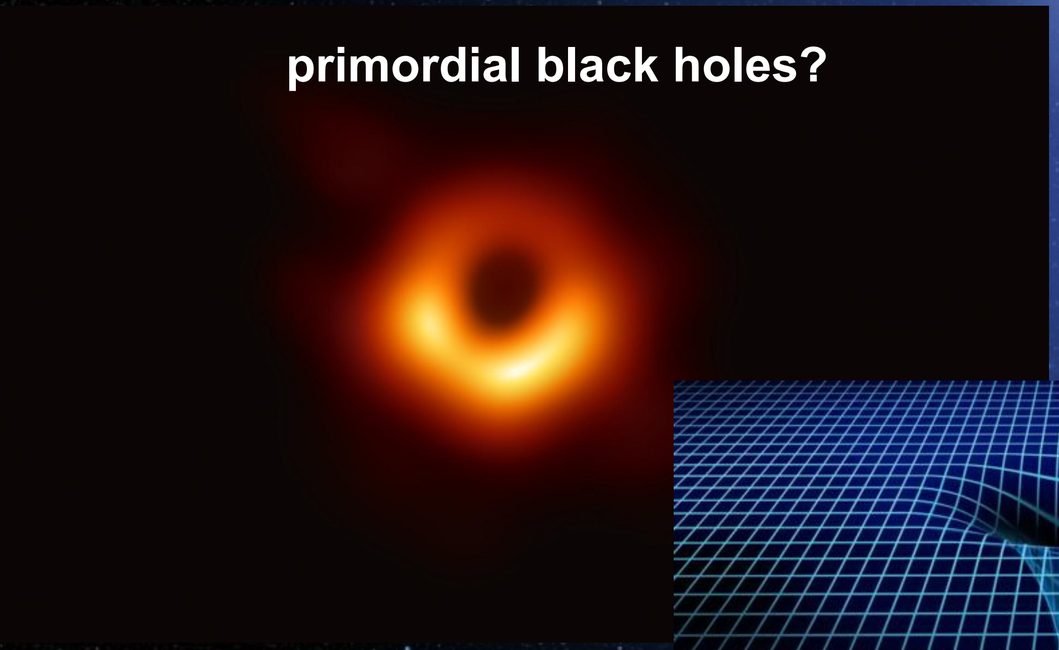
- Here: only take the upper bound…

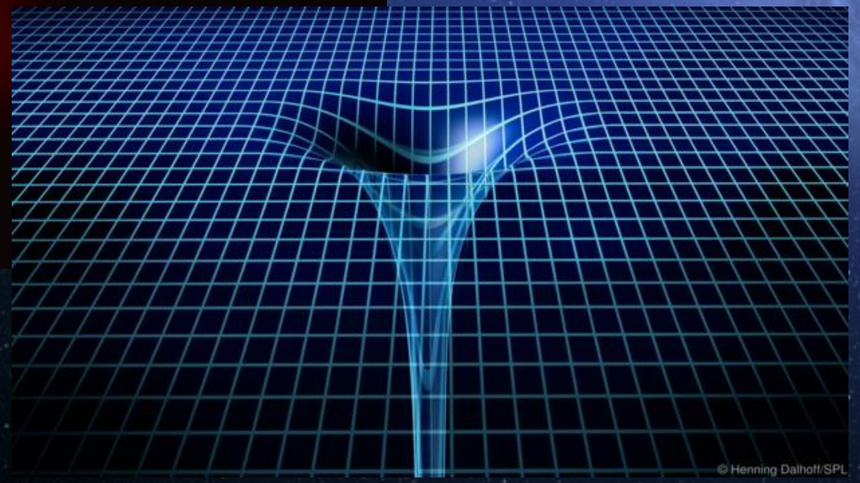


…so what is dark matter made of?



primordial black holes?





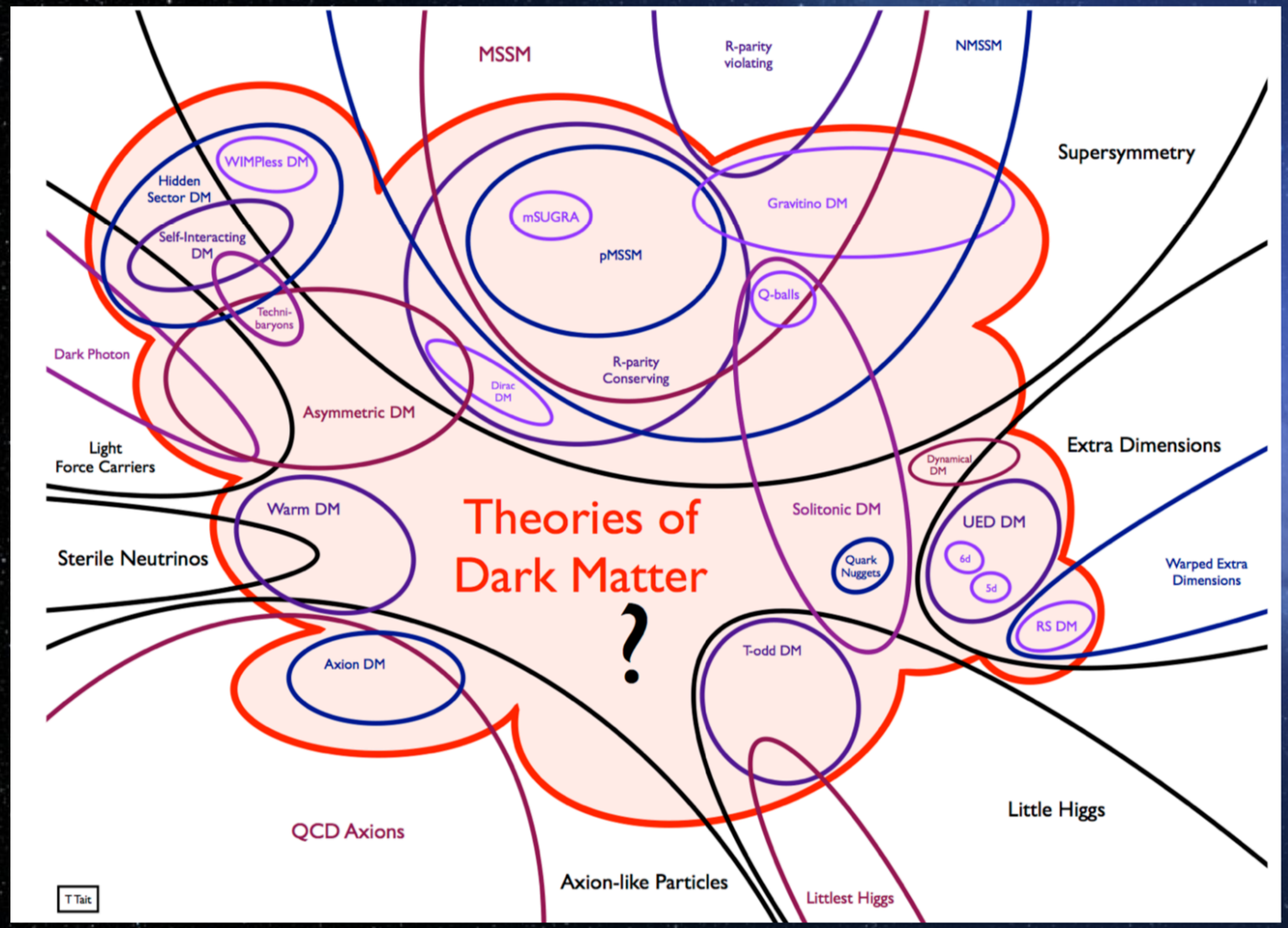
unknown elementary particle?



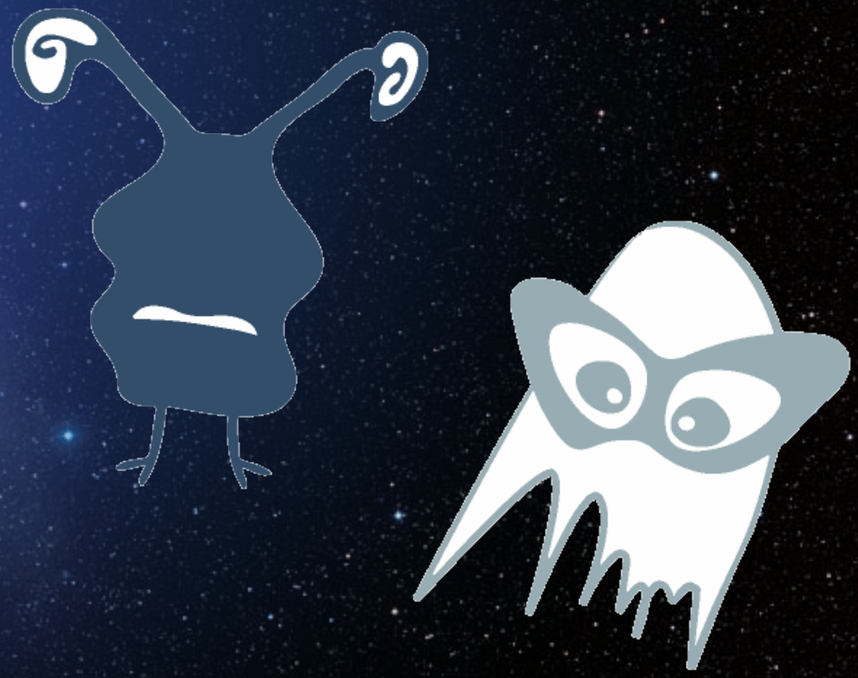


…so what is dark matter made of?

huge model space

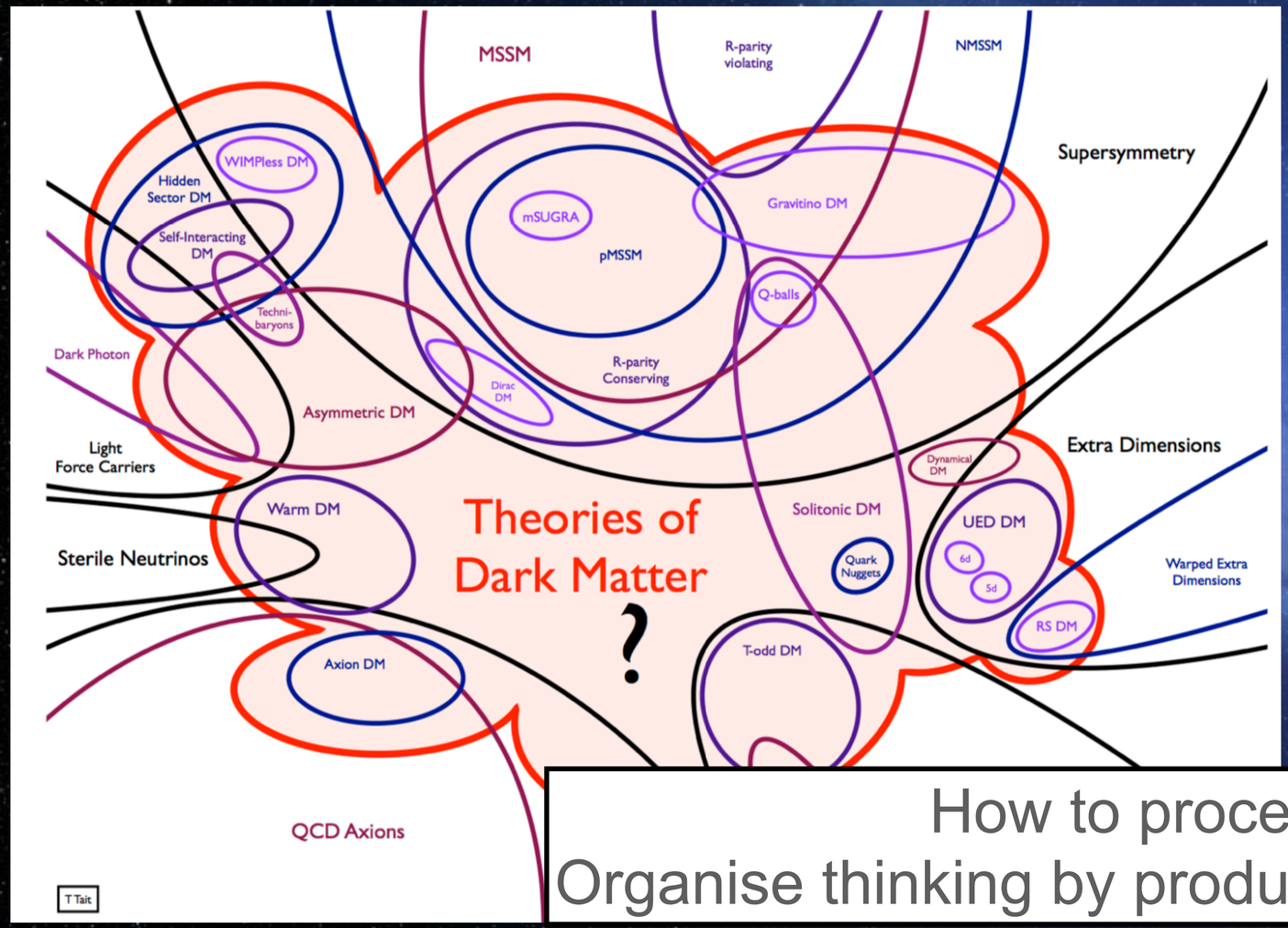


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…so what is dark matter made of?

huge model space



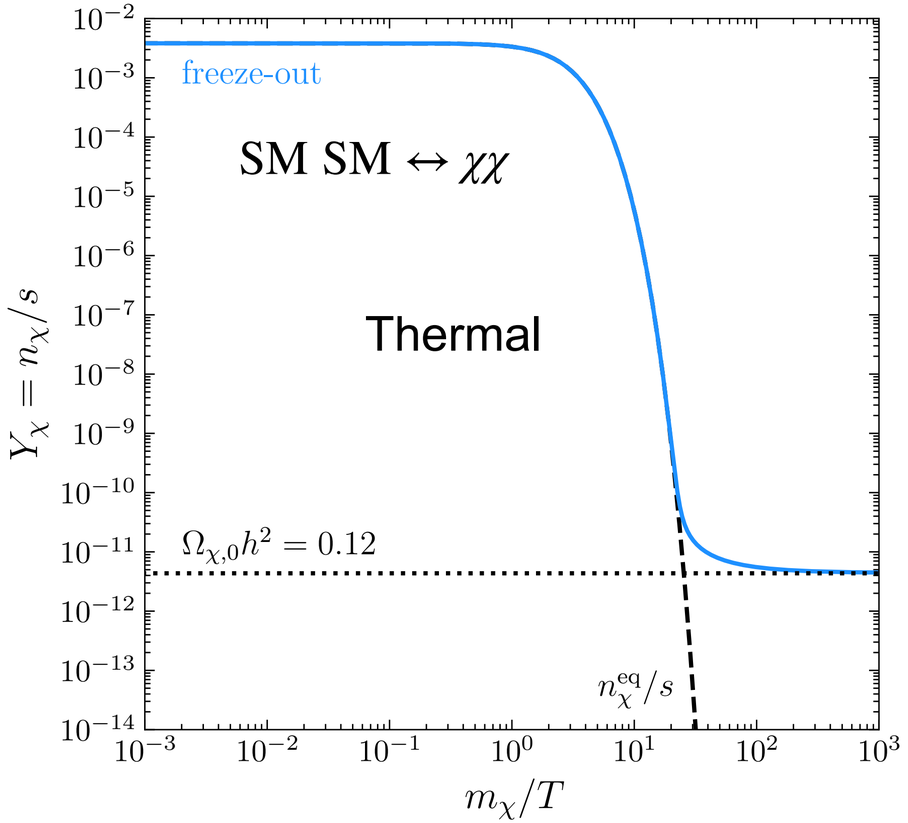
unknown elementary particle?





How to proceed?
Organise thinking by production mechanism!

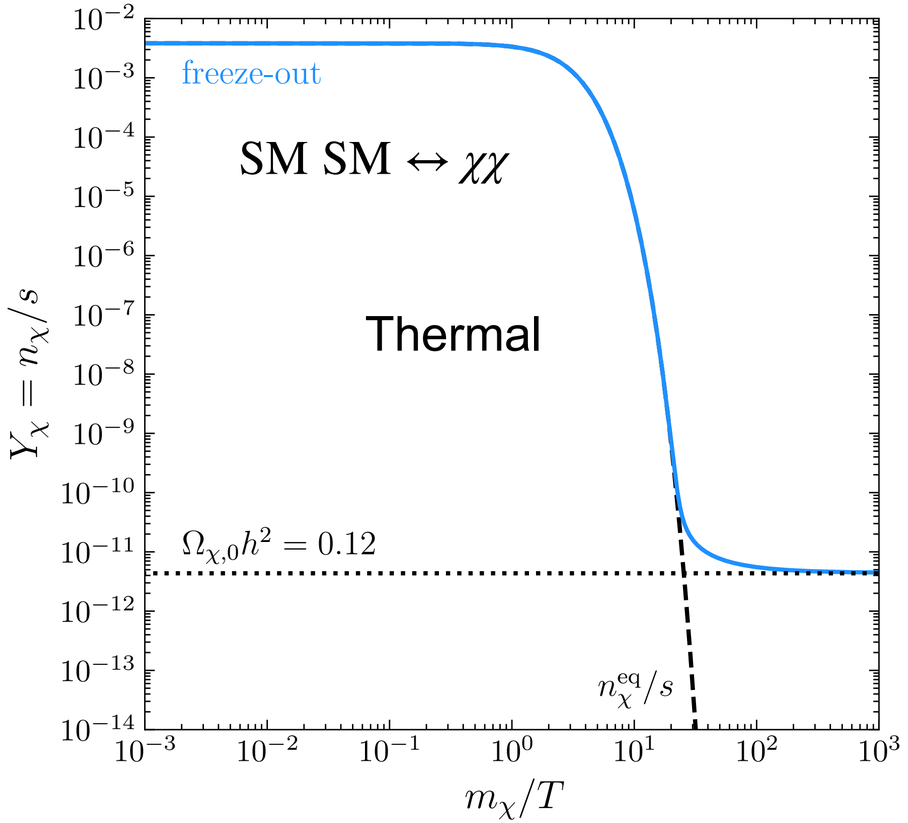
DM Production

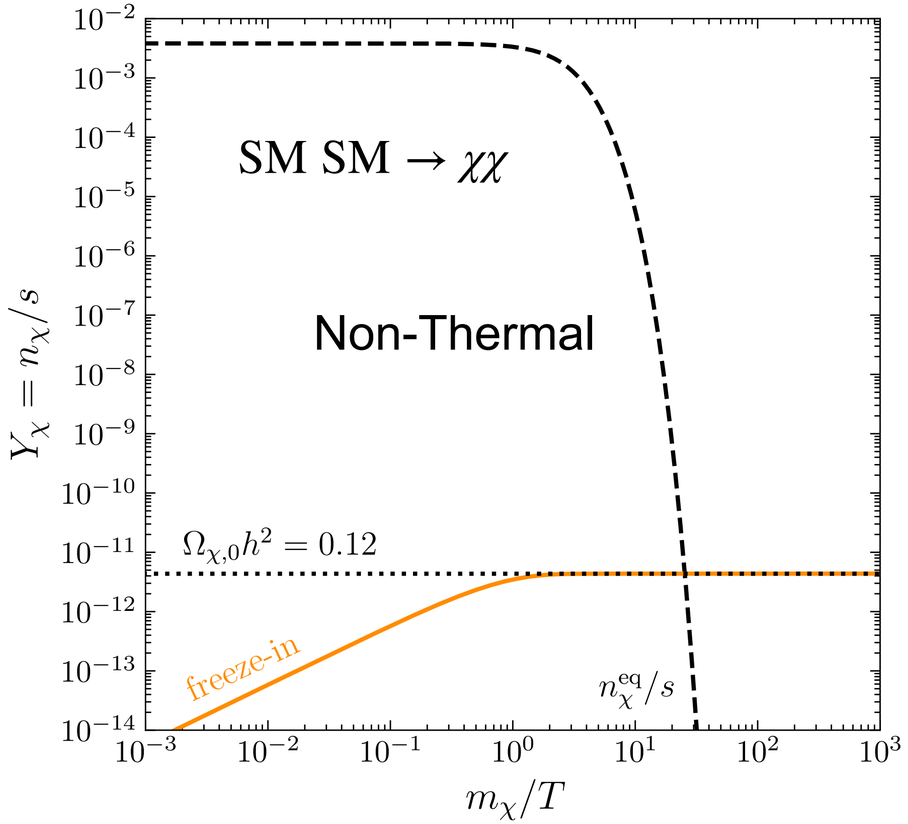


$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle\,(n_\chi^2 - n_{\chi,\rm eq}^2)$$

- vanilla case: thermal freeze out
  1. assume dark matter χ in thermal equilibrium $\chi\chi \leftrightarrows SM\ SM$
  2. Universe cools $\chi\chi \rightarrow SM\ SM$
  3. Universe expands $\chi\chi \not\rightarrow SM\ SM$

DM Production

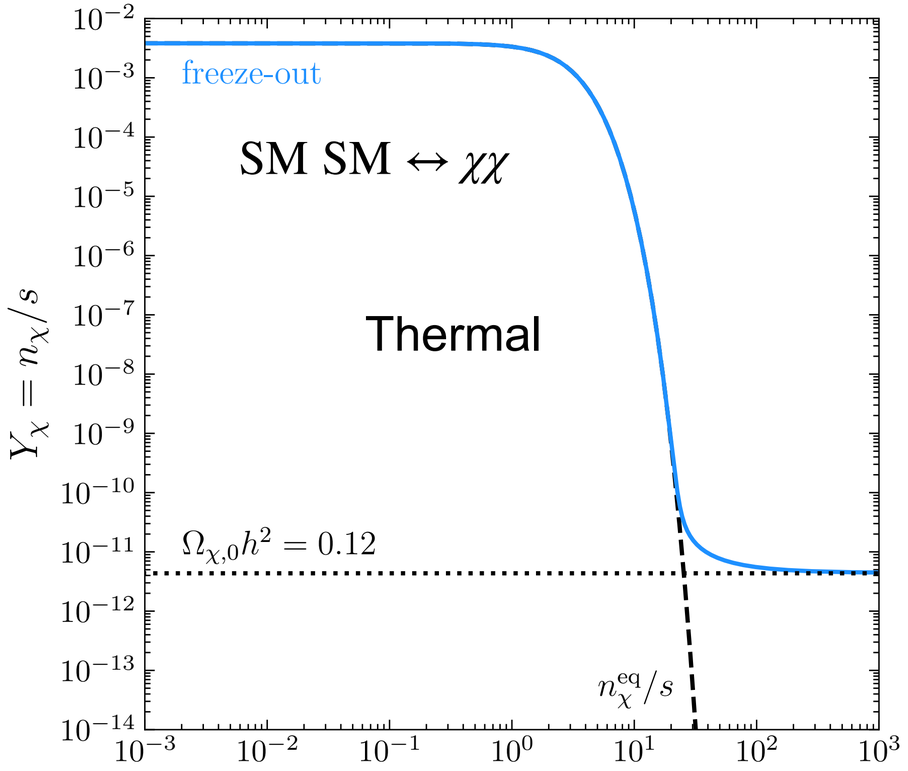




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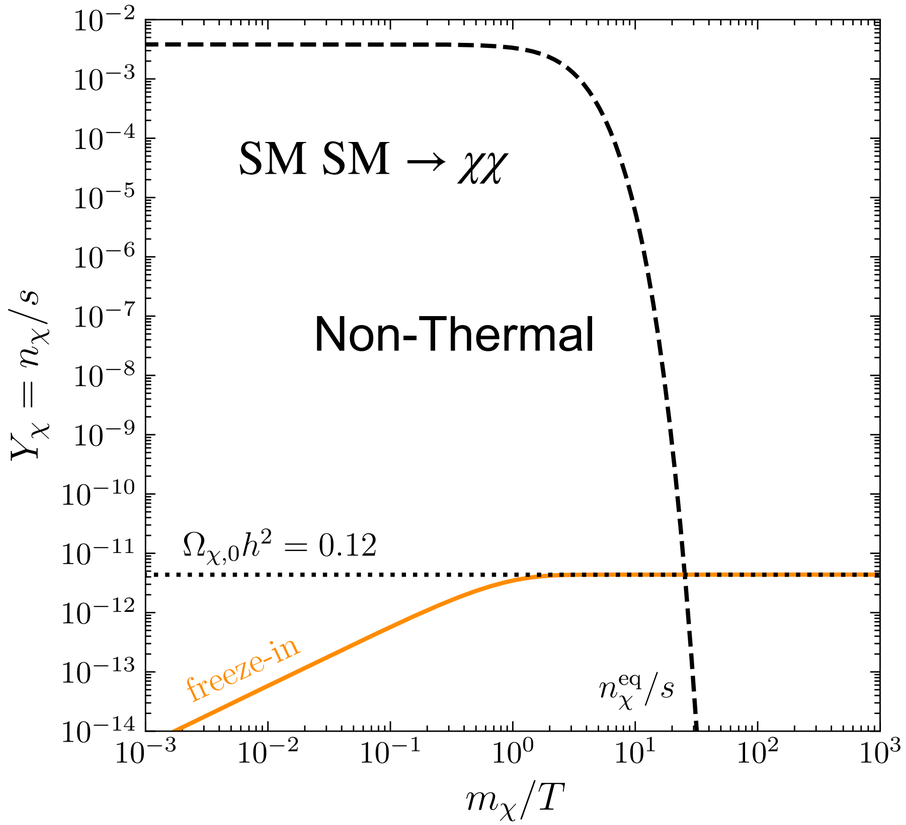
$$\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle\, n_{\psi,\rm eq}^2$$

DM Production



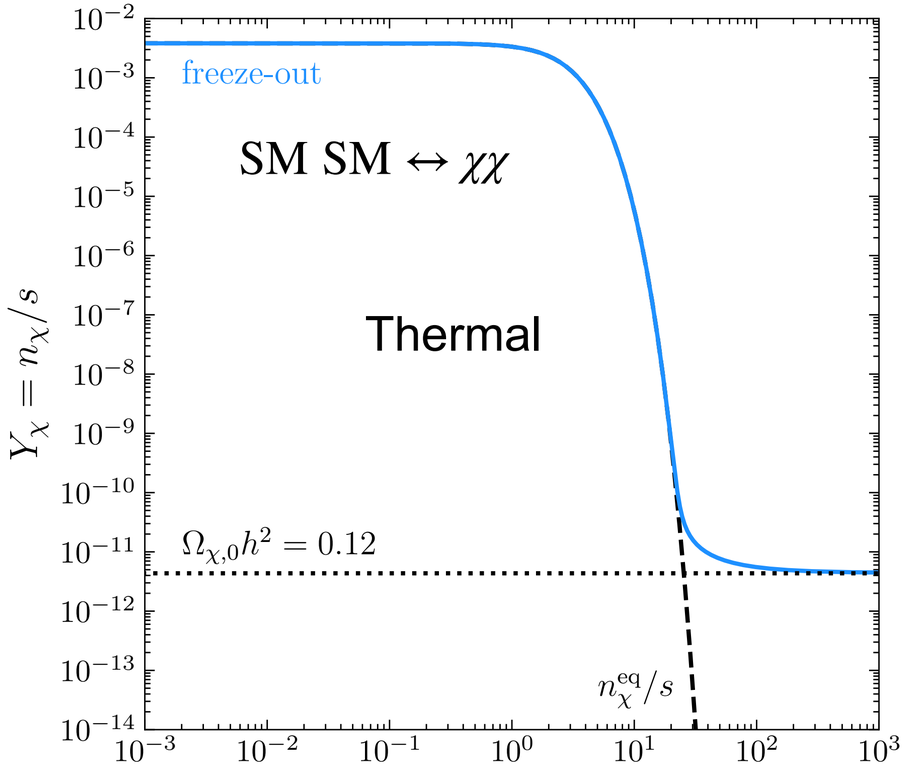
Many variants of freeze-out:

- Hidden sector FO
- Cannibal DM
- Forbidden DM
- Zombie DM
- Elder DM
- Kinder DM
- SIMP DM
- …



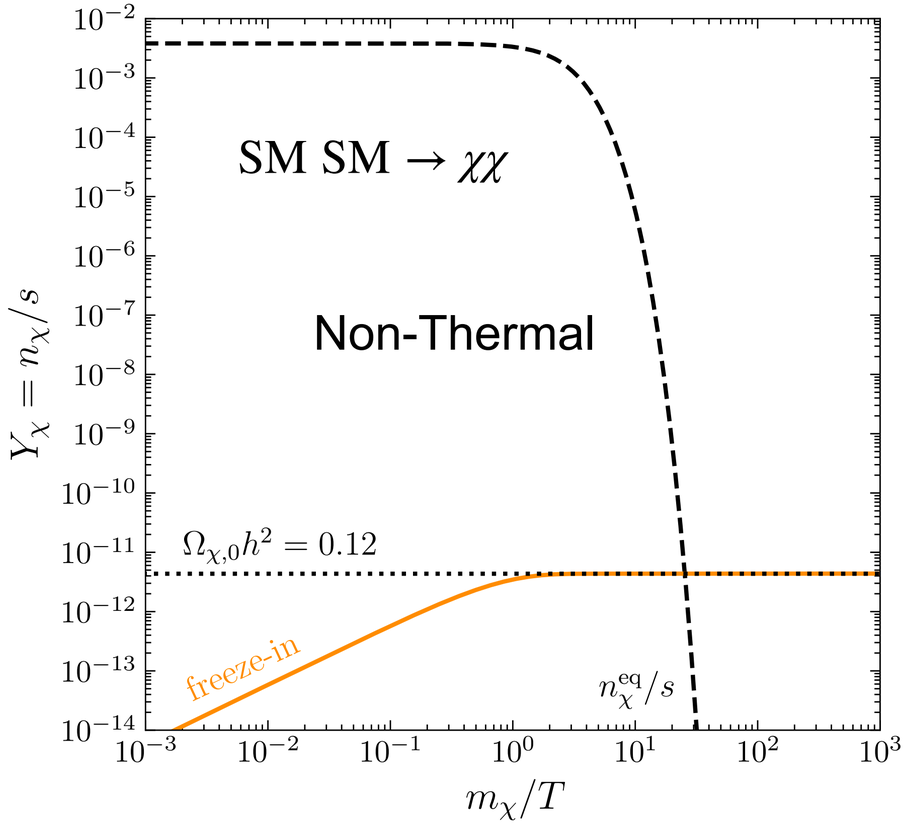
Less variants for freeze-in

DM Production



Many variants of freeze-out:

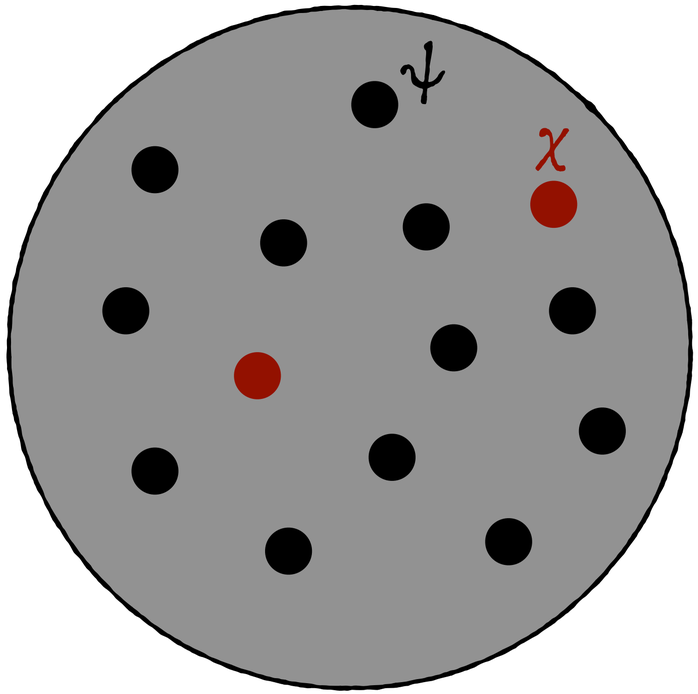
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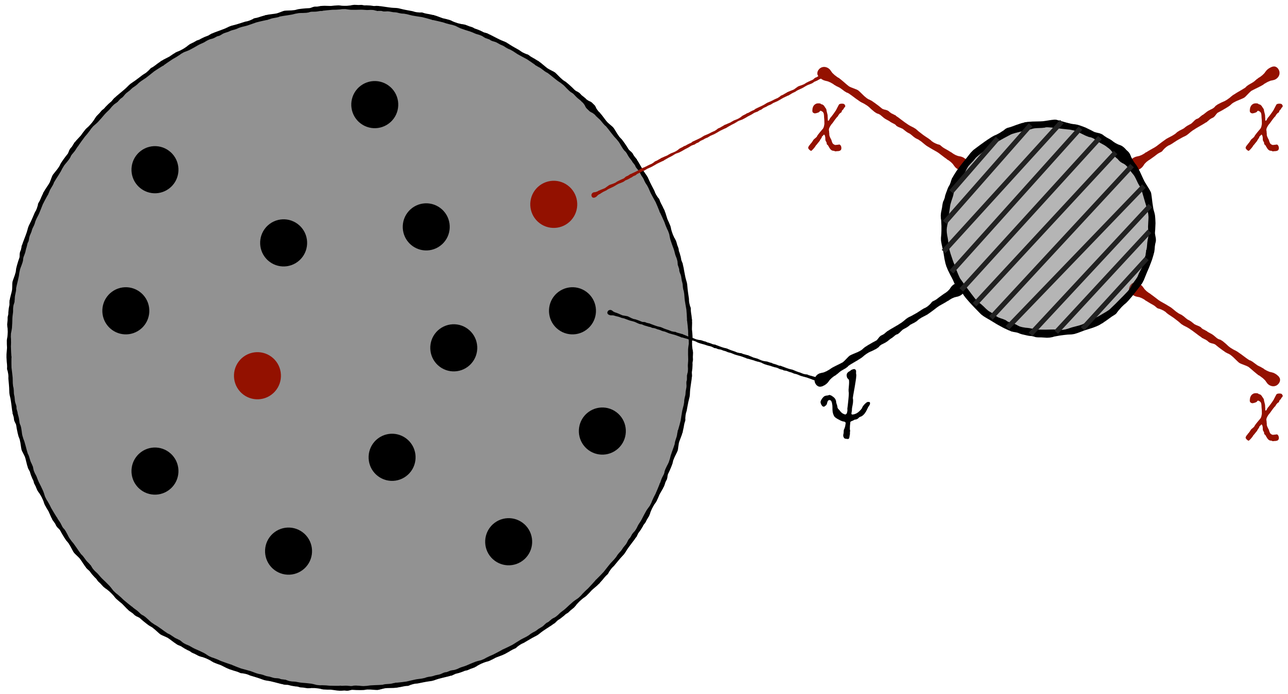
Less variants for freeze-in

Today:
Dark Matter from Exponential Growth

Production by transformation

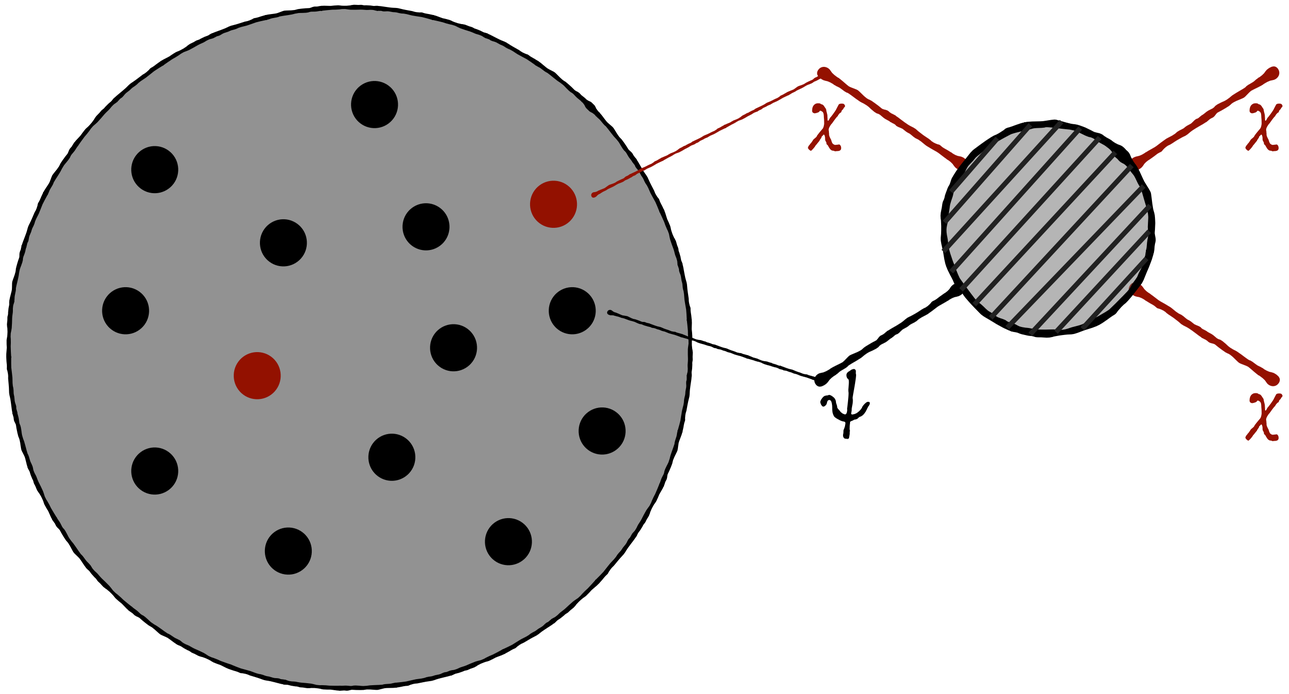


Production by transformation



Production by transformation

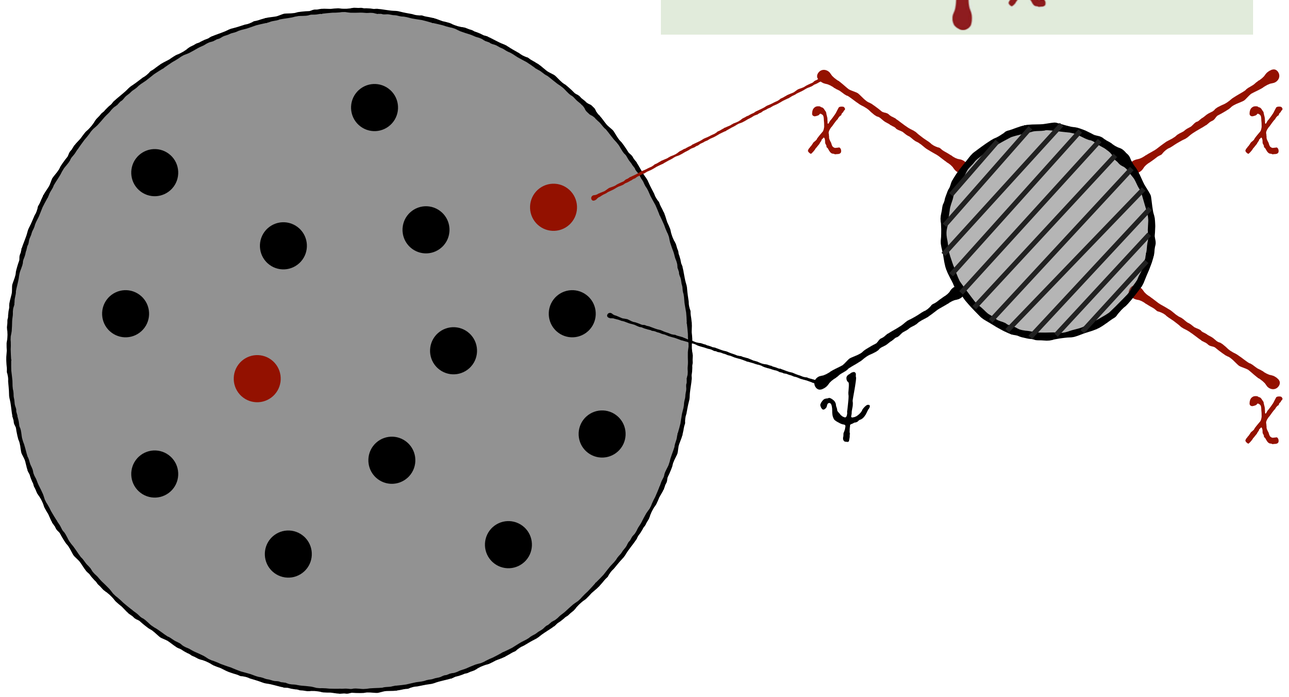
- $\dot{n}_\chi + 3Hn_\chi = \langle \sigma v \rangle_{\mathrm{tr}} n_\psi^{\mathrm{eq}} n_\chi$



Production by transformation



- $\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{\rm tr}\, n_\psi^{\rm eq} n_\chi$
- $Y_\chi(x_\psi) \equiv n_\chi/s \simeq Y_\chi^0 \exp\left(3\int_{x_\psi^0}^{x_\psi} \frac{{\rm d}x}{x} R(x)\right)$
- $R(x) = \frac{n_\psi^{\rm eq}\langle\sigma v\rangle_{\rm tr}}{3H}$: # of transformations of DM particle per Hubble time
- $\rightarrow$ Phase of exponential production
- Shutoff by kinematical or Boltzmann suppression



V-duality to the SIR model

A Contribution to the Mathematical Theory of Epidemics.

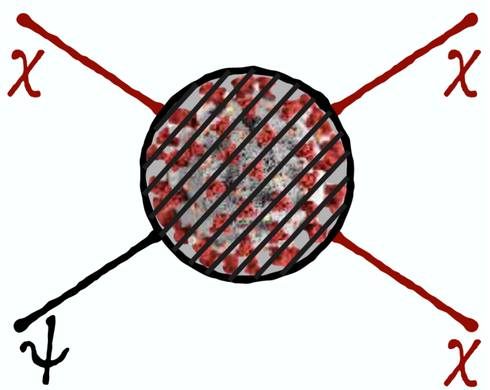
By W. O. Kermack and A. G. McKendrick.

(Communicated by Sir Gilbert Walker, F.R.S.—Received May 13, 1927.)

- $\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{\rm tr}\, n_\psi^{\rm eq} n_\chi$
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- $R(x) = \frac{n_\psi^{\rm eq}\langle\sigma v\rangle_{\rm tr}}{3H}$: # of transformations of DM particle per Hubble time
- $\rightarrow$ Phase of exponential production
- Shutoff by kinematical or Boltzmann suppression

- $\dot{I} = \beta SI - \gamma I$
  - I: # of infected
  - S: # of susceptible
  - β: infection rate
  - γ recovery rates

Pandemic DM



$$I \leftrightarrow n_\chi \quad S \leftrightarrow n_\psi^{\rm eq} \quad \beta \leftrightarrow \langle\sigma v\rangle_{\rm tr} \quad \gamma \leftrightarrow 3H$$

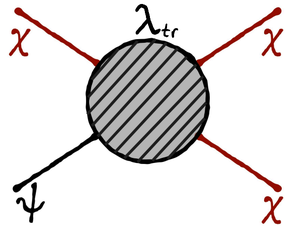
$$R \equiv \frac{\beta S}{\gamma}$$

…how many people will one infected person infect on average

Evolution of DM abundance

Fixed initial abundance

$$Y_\chi(x_\psi \ll 1) = \underbrace{Y_\chi^0 = \text{const.}}_{\text{Initial condition}}$$

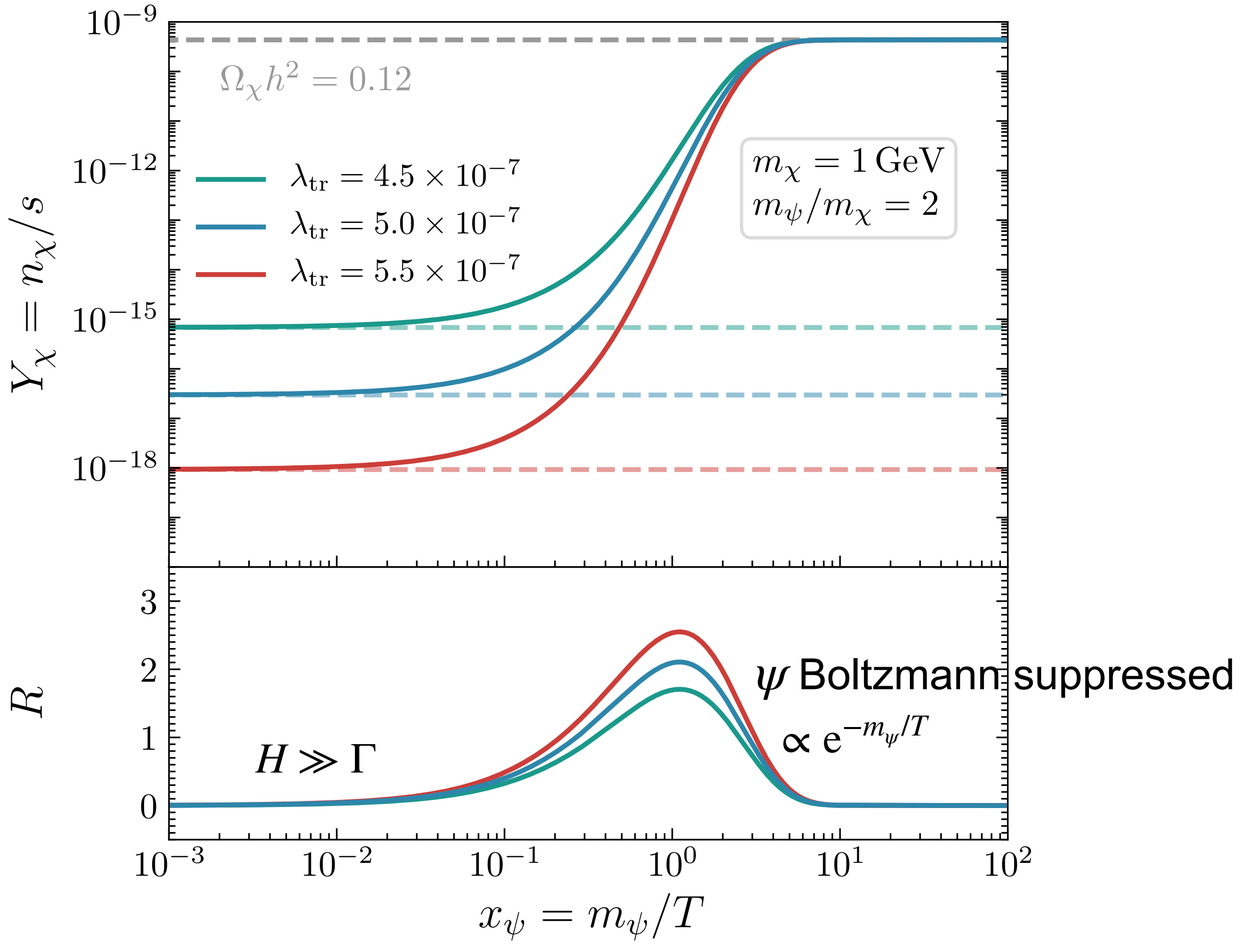


$$\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{\rm tr}\, n_\psi^{\rm eq} n_\chi$$

- Constant matrix element for simplicity

$$\mathscr{L} \supset (\lambda_{\rm tr}/3!)\,\psi\chi^3 \qquad |\mathscr{M}_{\rm tr}|^2 = \lambda_{\rm tr}^2$$

4 free parameters: m_χ m_ψ $\lambda_{\rm tr}$ Y_χ^0

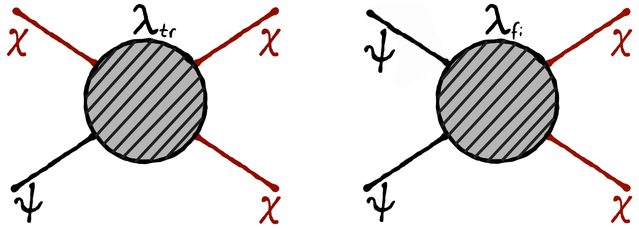


Evolution of DM abundance

Freeze-in

4 free parameters: m_χ m_ψ $\lambda_{\rm tr}$ $\lambda_{\rm fi}$

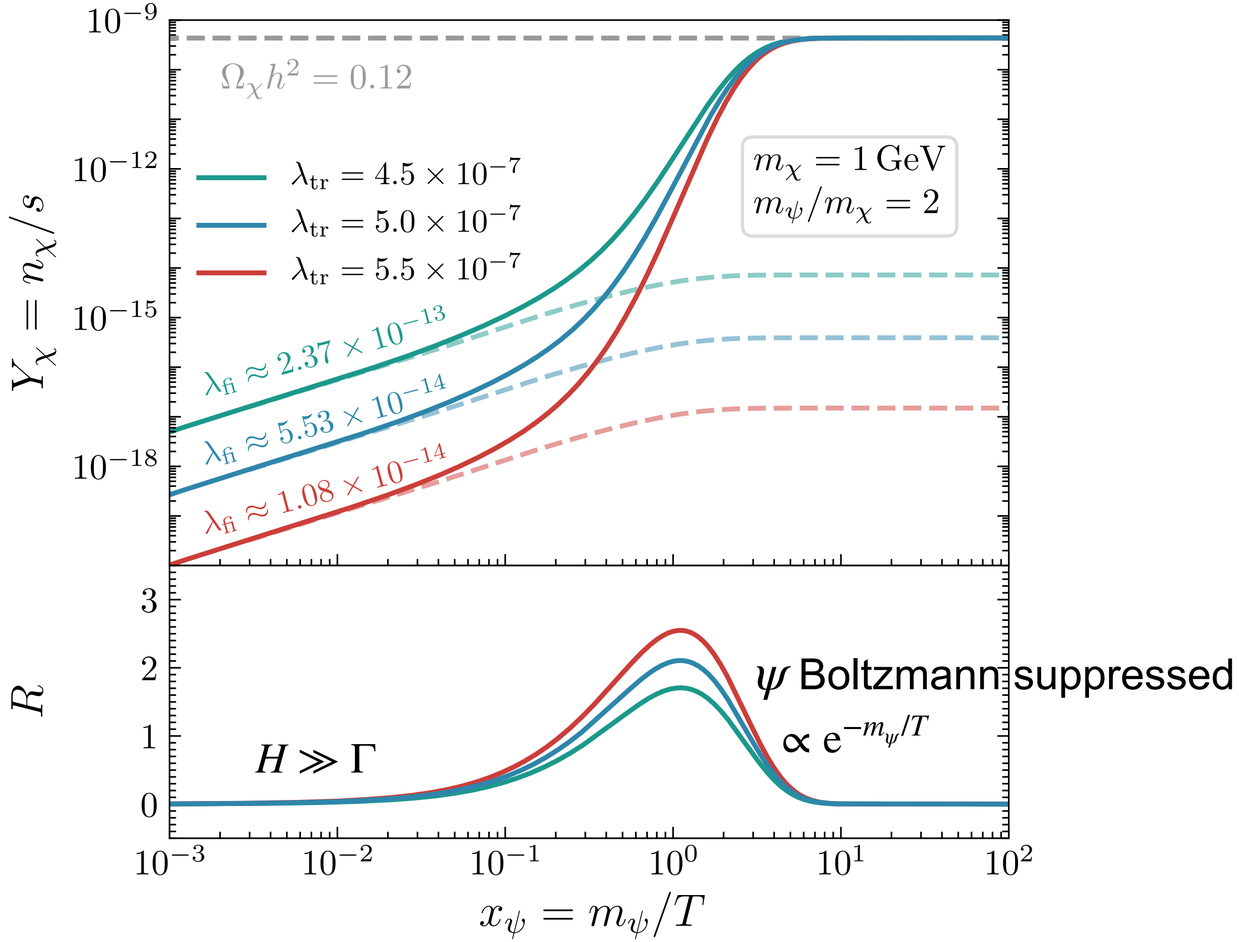
Need $\lambda_{\rm fi} \ll \lambda_{\rm tr}$



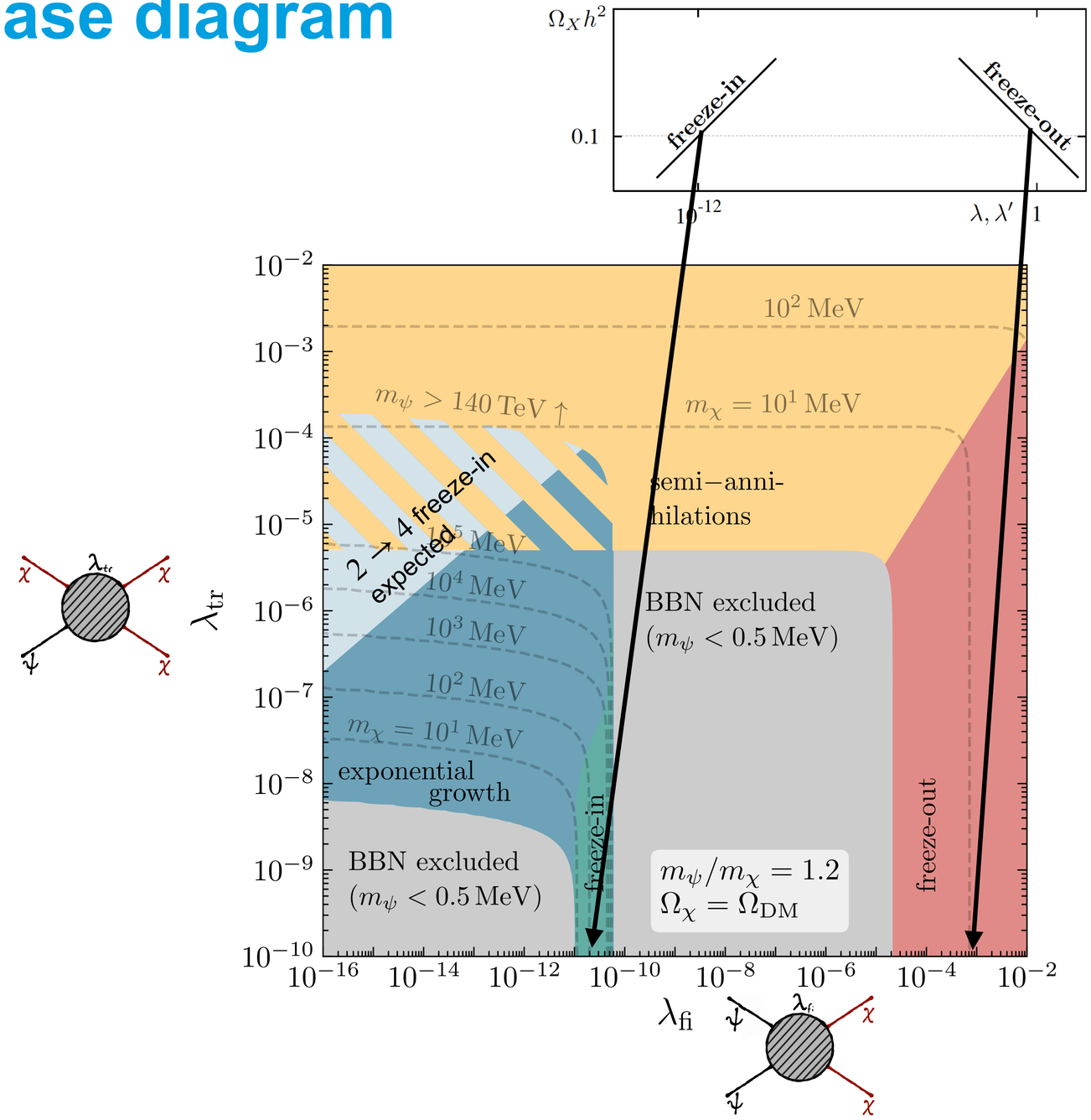
$$\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{\rm tr}\, n_\psi^{\rm eq} n_\chi + \langle\sigma v\rangle_{\rm fi}\, (n_\psi^{\rm eq})^2$$

- Constant matrix element for simplicity

$$\mathscr{L} \supset (\lambda_{\rm tr}/3!)\,\psi\chi^3 \qquad |\mathscr{M}_{\rm tr}|^2 = \lambda_{\rm tr}^2$$



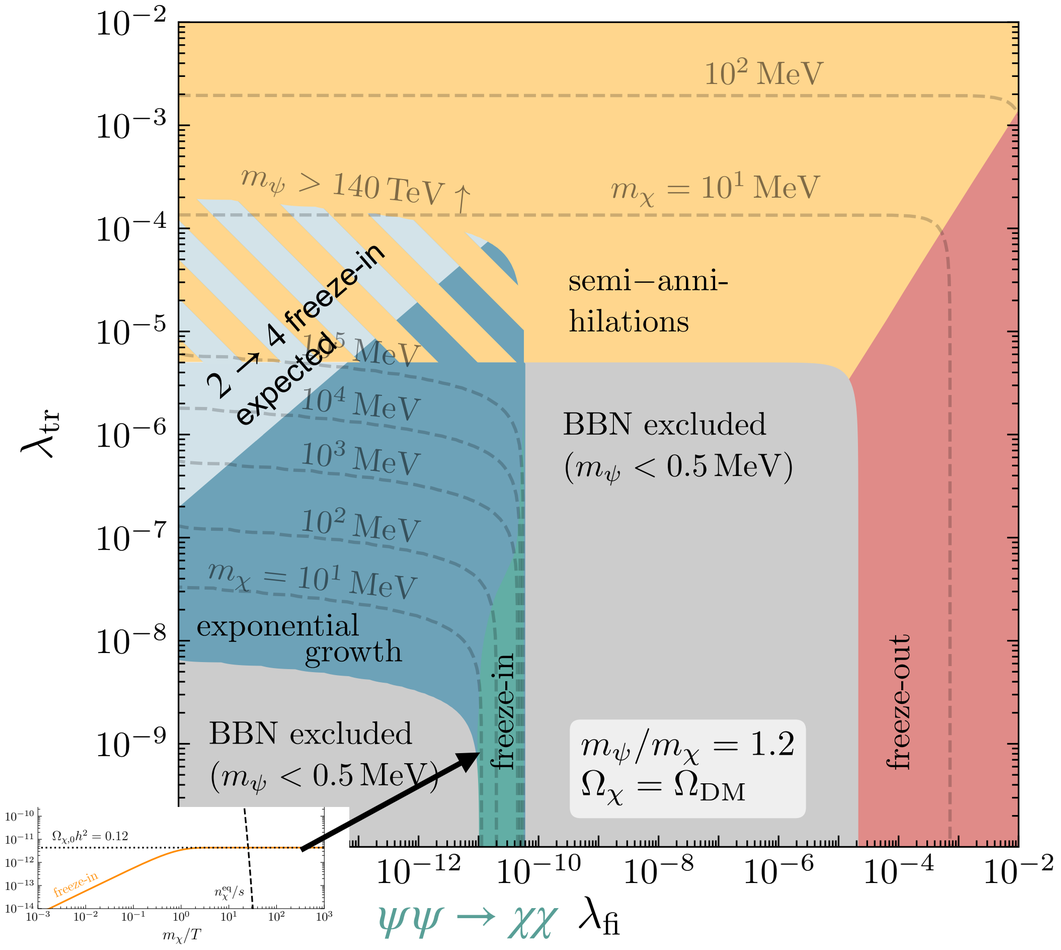
Example Phase diagram



2 solutions!

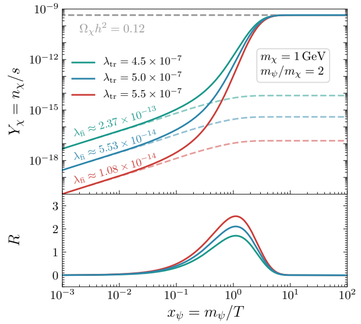
Example Phase diagram

$$\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{\rm fi}\,[(n_\psi^{\rm eq})^2 \quad]$$

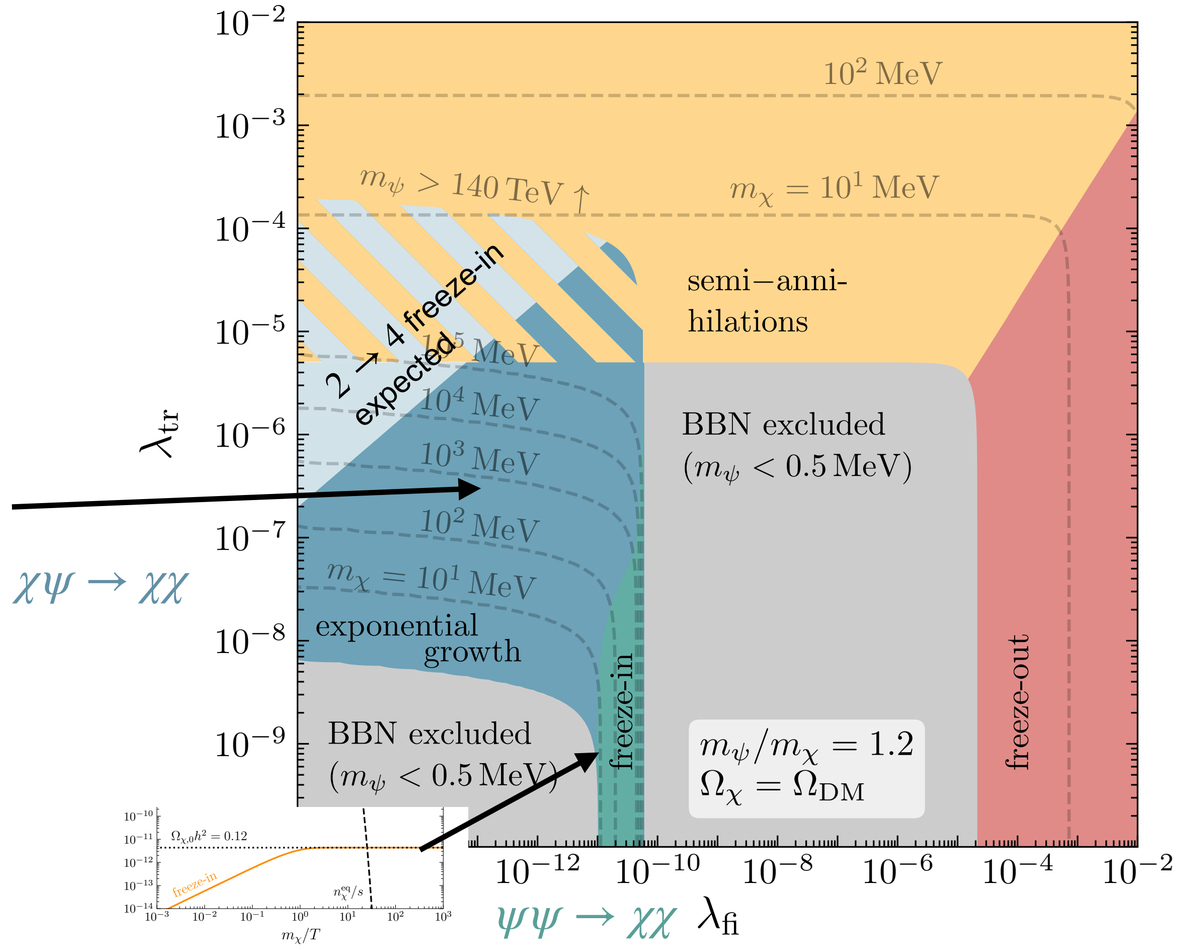


Example Phase diagram

$$\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{\rm tr}\,[n_\psi^{\rm eq} n_\chi \qquad\qquad] + \langle\sigma v\rangle_{\rm fi}\,[(n_\psi^{\rm eq})^2 \qquad\qquad]$$

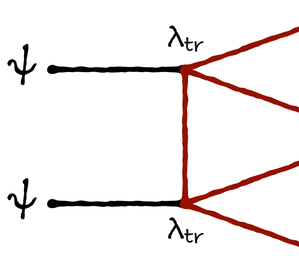


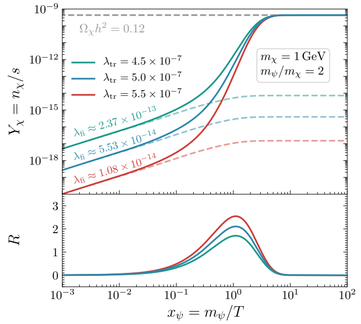
$\chi\psi \to \chi\chi$



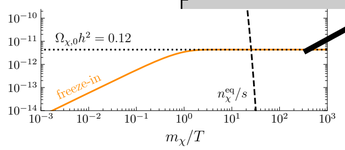
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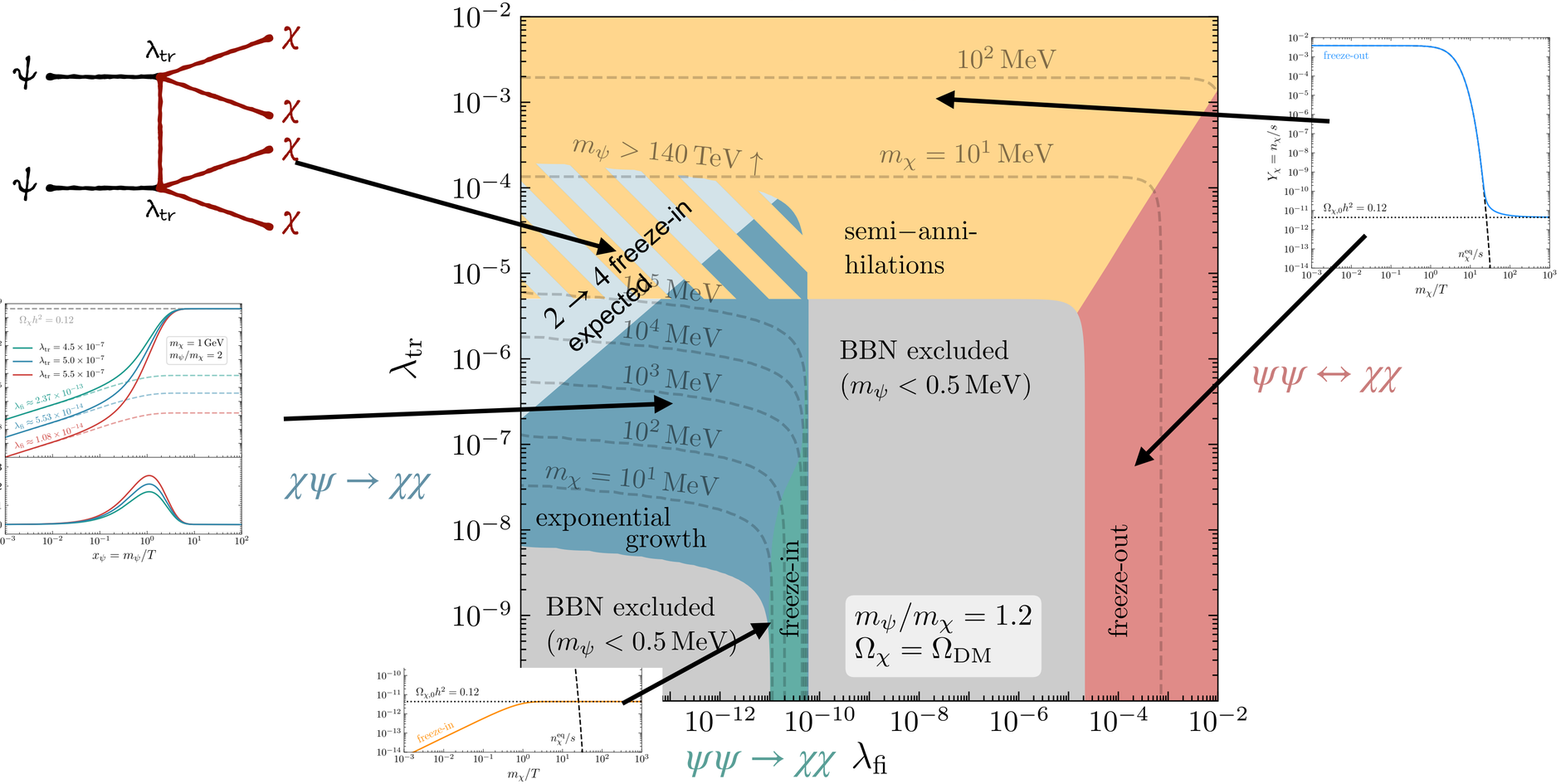


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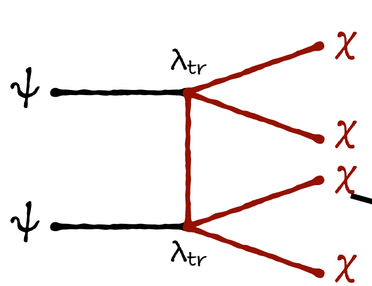
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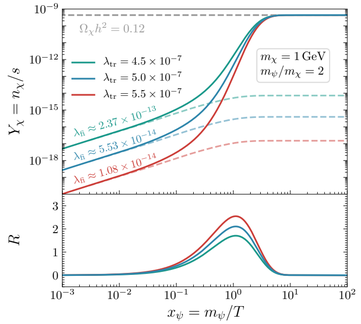
$$\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{\rm tr}\,[n_\psi^{\rm eq} n_\chi - n_\chi^2 n_\psi^{\rm eq}/n_\chi^{\rm eq}] + \langle\sigma v\rangle_{\rm fi}\,[(n_\psi^{\rm eq})^2 - (n_\chi n_\psi^{\rm eq}/n_\chi^{\rm eq})^2]$$



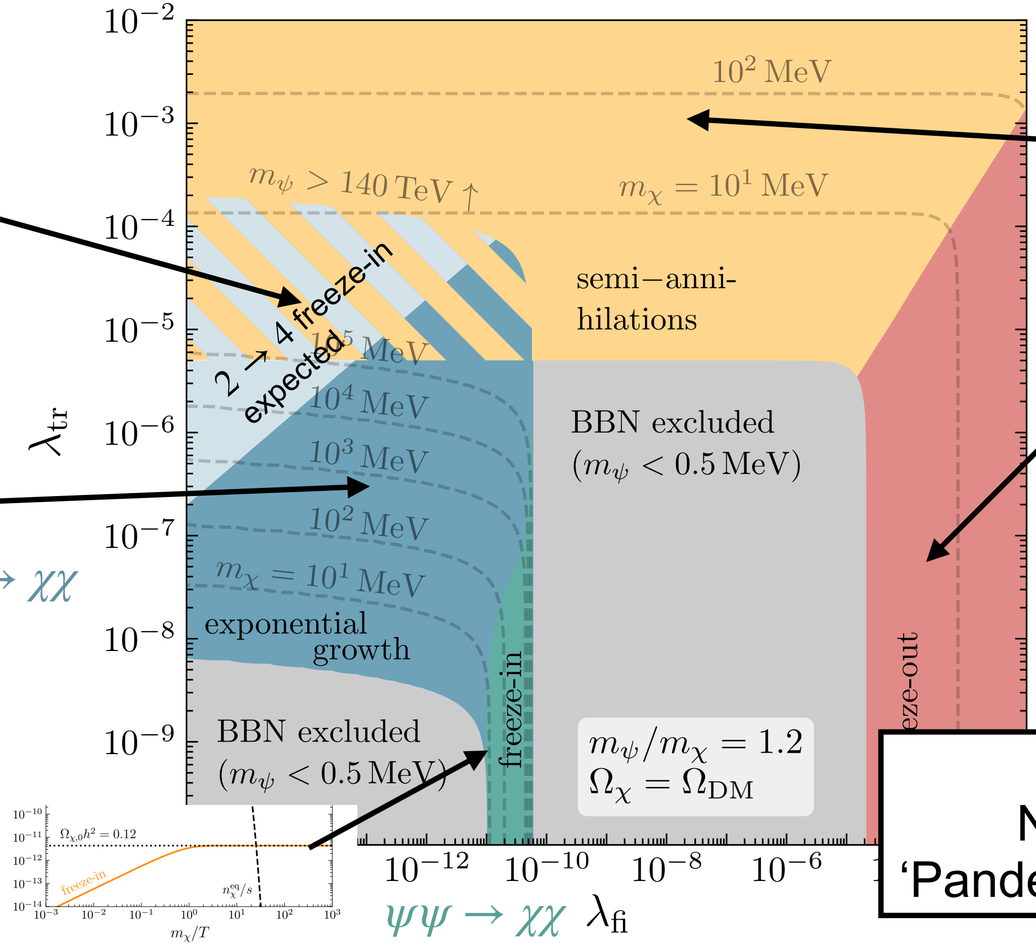
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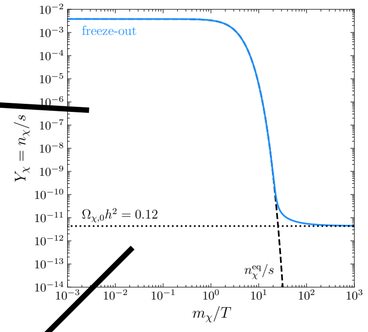
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$\chi\psi \to \chi\chi$



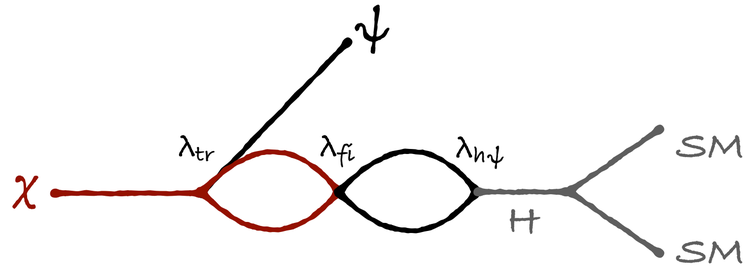


$\psi\psi \leftrightarrow \chi\chi$

Signals?
Necessarily model dependent!
‘Pandemic’ DM a framework like ‘WIMPs’

The Higgs portal as a toy model

$\lambda_{h\psi} |H|^2 \psi^2/2$ with ψ stable

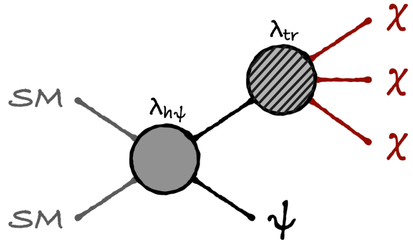


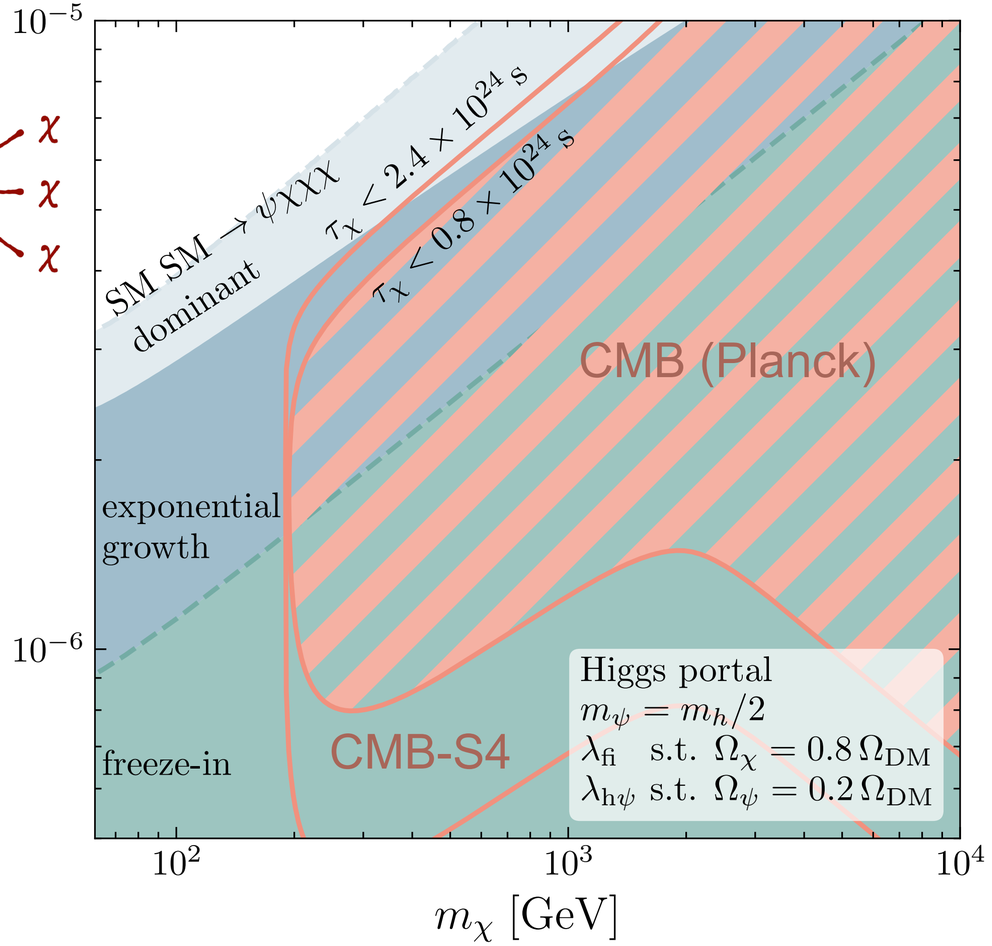
- ψ: abundance set as in singlet scalar DM
- two-component DM!

- want ψ to be sub-dominant
- want $\lambda_{h\psi}$ small not to be dominated by $\mathrm{SM\,SM} \to \psi\chi\chi\chi \to$ resonance ;-/

- χ slowly decays via 2-loop (or higher) decays
- sizeable region already covered by Planck
- For $m_\chi < m_\psi + m_h$ decays suppressed

Are there more natural models?





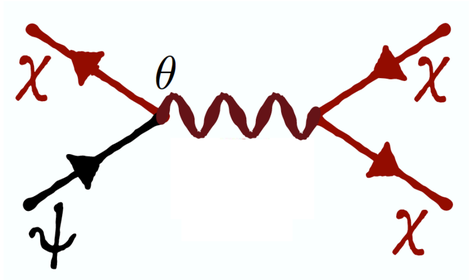
Towards more natural setups

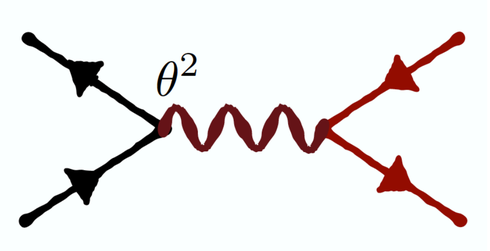
- Natural way to realise $\langle \sigma v \rangle_{\rm fi} \ll \langle \sigma v \rangle_{\rm tr}$?
- Yes! add **dark force** ϕ and **mass mixing**

$$\mathscr{L} \supset -\delta m(\bar{\psi}\chi + \bar{\chi}\psi) - g\bar{\chi}\phi\chi$$

$$\downarrow \text{ mass eigenstates}$$

$$\mathscr{L} \supset -g[\bar{\chi}\phi\chi + \theta(\bar{\psi}\phi\chi + \bar{\chi}\phi\psi) + \theta^2\bar{\psi}\phi\psi]$$





$$\langle \sigma v \rangle_{\rm tr} \gg \langle \sigma v \rangle_{\rm fi}$$

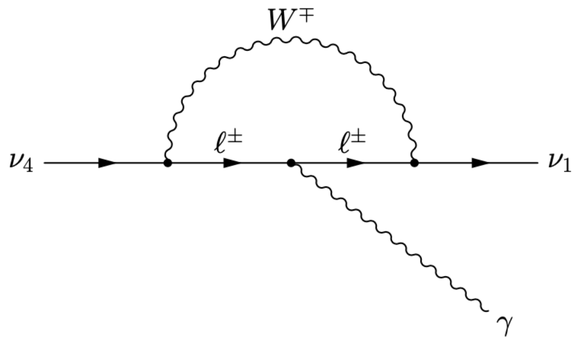
- Could ψ even be a SM particle?

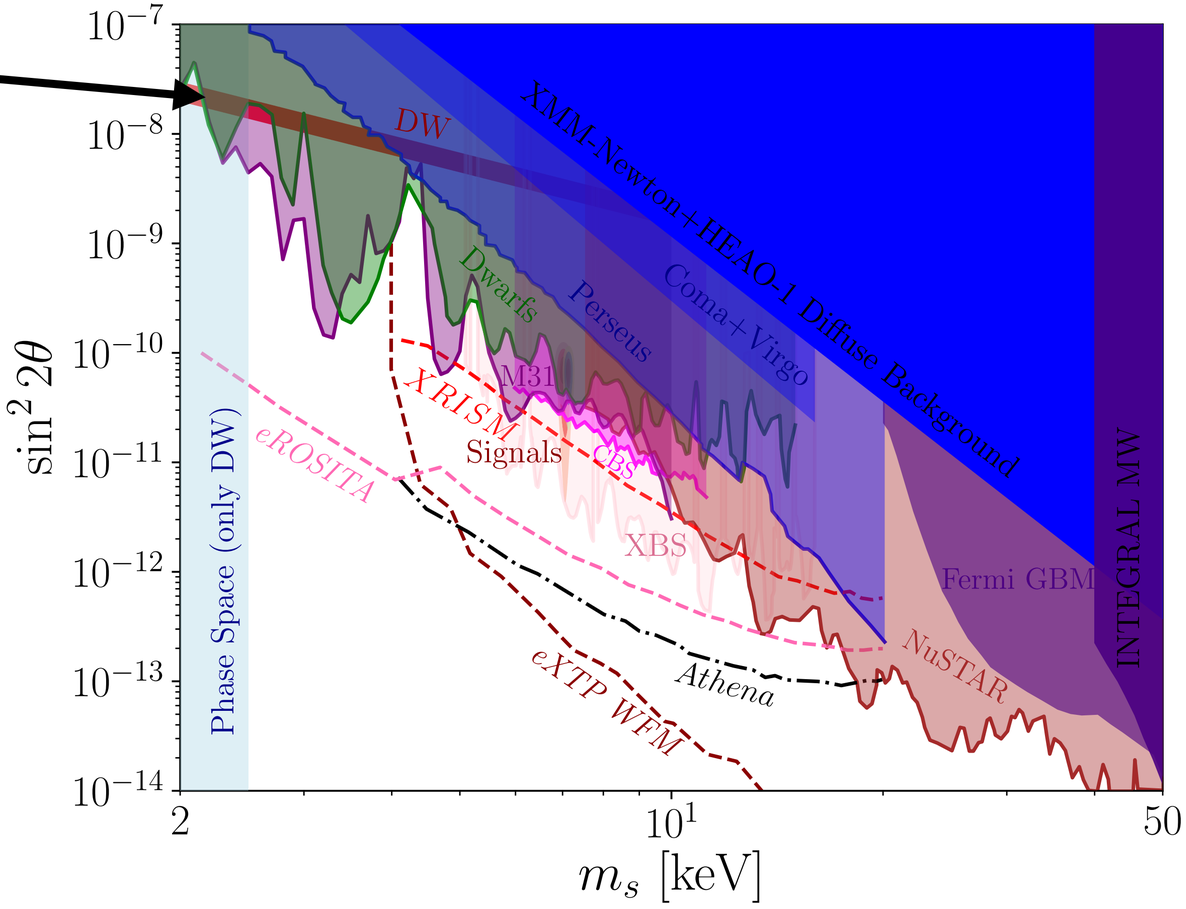
Sterile neutrinos

- Sterile neutrinos are a compelling DM candidate!
- naturally produced via active-sterile oscillations (Dodelson-Widrow mechanism)
- but…

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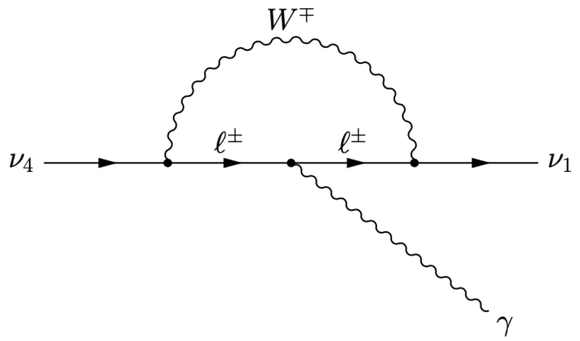


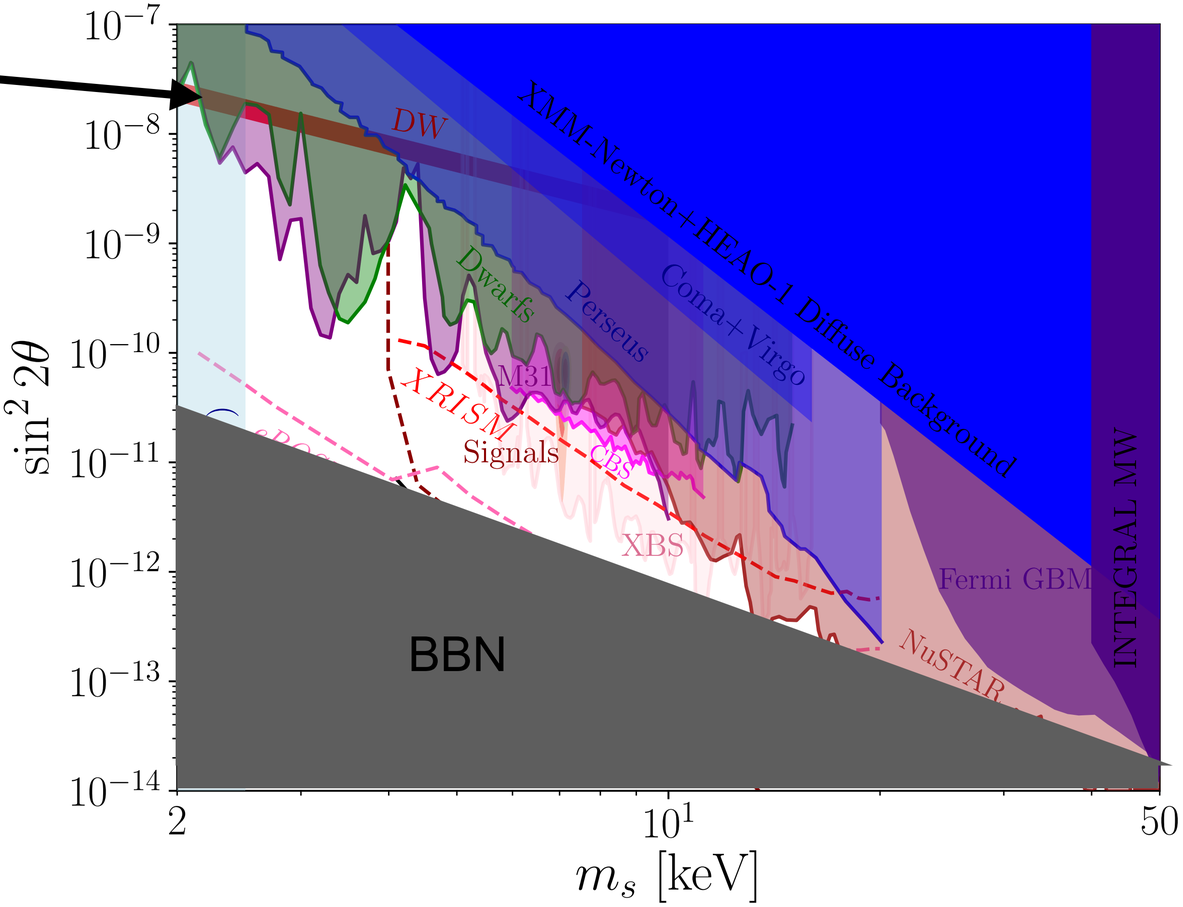
Abazajian al. 2203.07377

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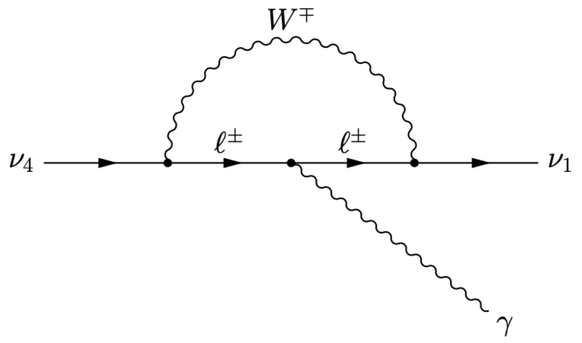
- Possible way out: Fuller-Shi mechanism (resonant production with huge lepton asymmetry)
- Extra new physics hidden in the lepton asymmetry
- also relevant bounds from BBN!





Abazajian al. 2203.07377

Sterile neutrinos



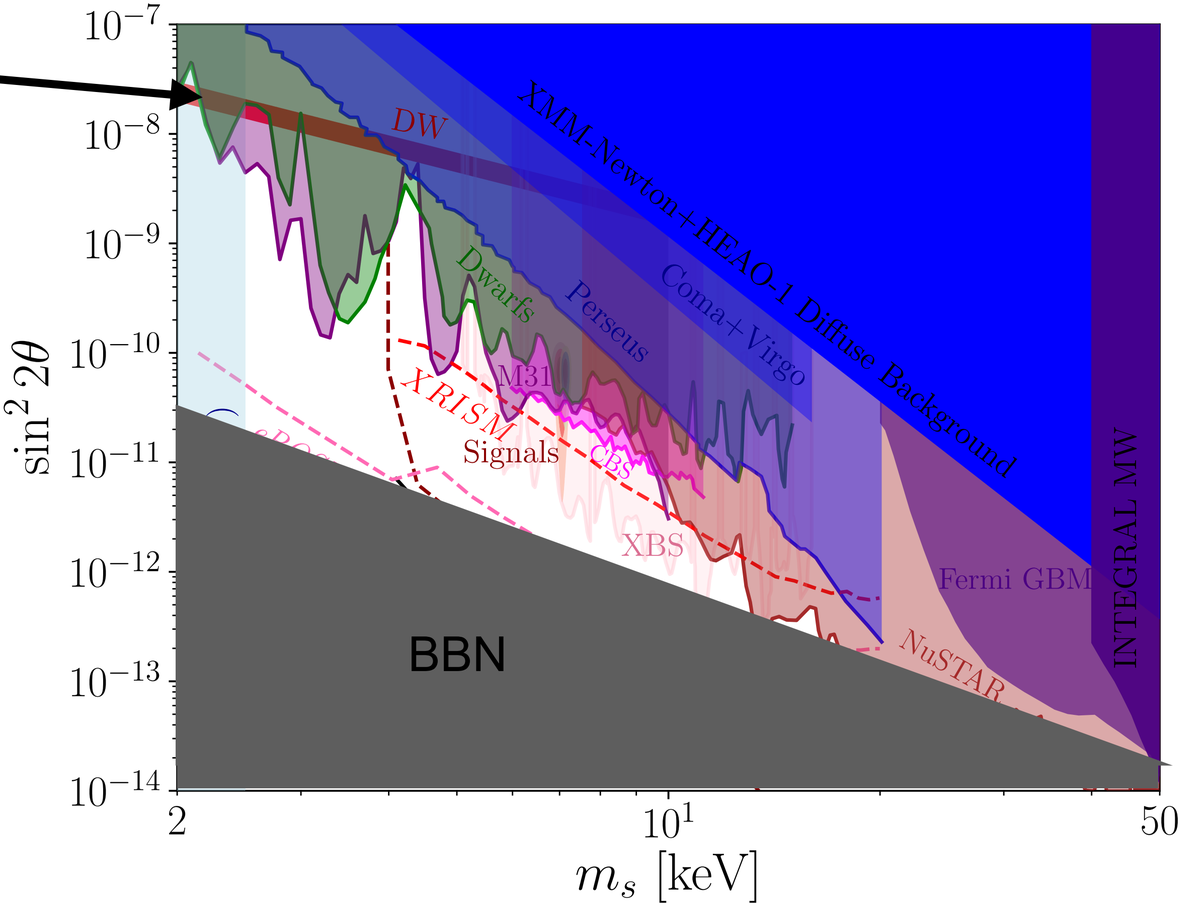
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- Possible way out: Fuller-Shi mechanism (resonant production with huge lepton asymmetry)
- Extra new physics hidden in the lepton asymmetry
- also relevant bounds from BBN!

- nicer: add secret interactions!

$$\mathscr{L} \supset \frac{y}{2}\phi\bar{\nu}_s\nu_s$$

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



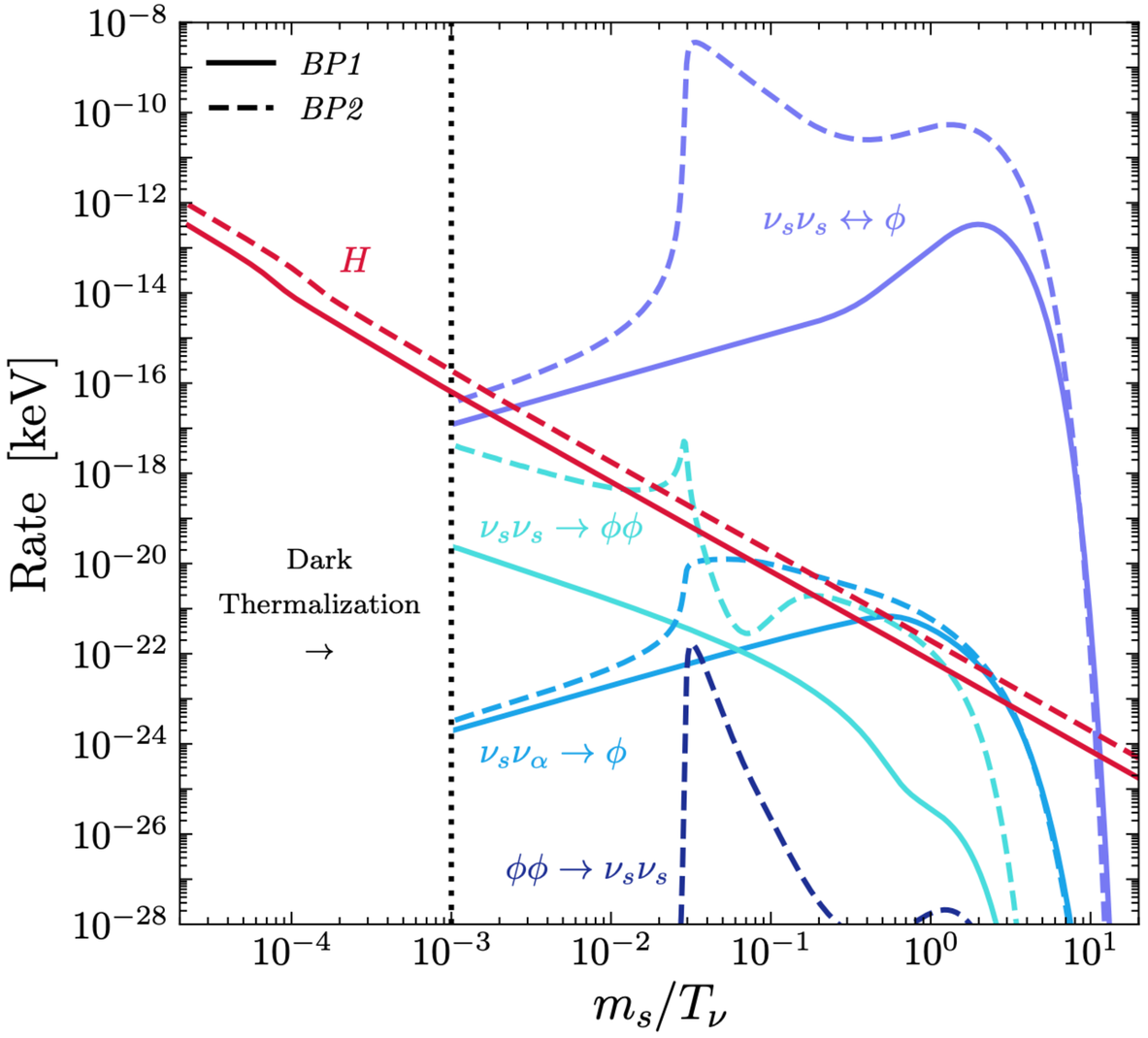
Abazajian al. 2203.07377

Cosmological evolution

- Standard DW production at $T \sim 100\,\mathrm{MeV}$
- rapid dark sector thermalisation via $\phi \to \nu_s\nu_s$ and $\nu_s\nu_s \to \phi$

$$f_s = \frac{1}{e^{(E-\mu_s)/T_d} + 1} \qquad f_\phi = \frac{1}{e^{(E-\mu_\phi)/T_d} - 1}$$

	m_s	m_ϕ	$\sin^2(2\theta)$	y
BP1	12 keV	36 keV	2.5×10^{-13}	1.905×10^{-4}
BP2	20 keV	60 keV	3.0×10^{-15}	1.602×10^{-3}



Cosmological evolution

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$\phi \to \nu_s\nu_s$ and $\nu_s\nu_s \to \phi$

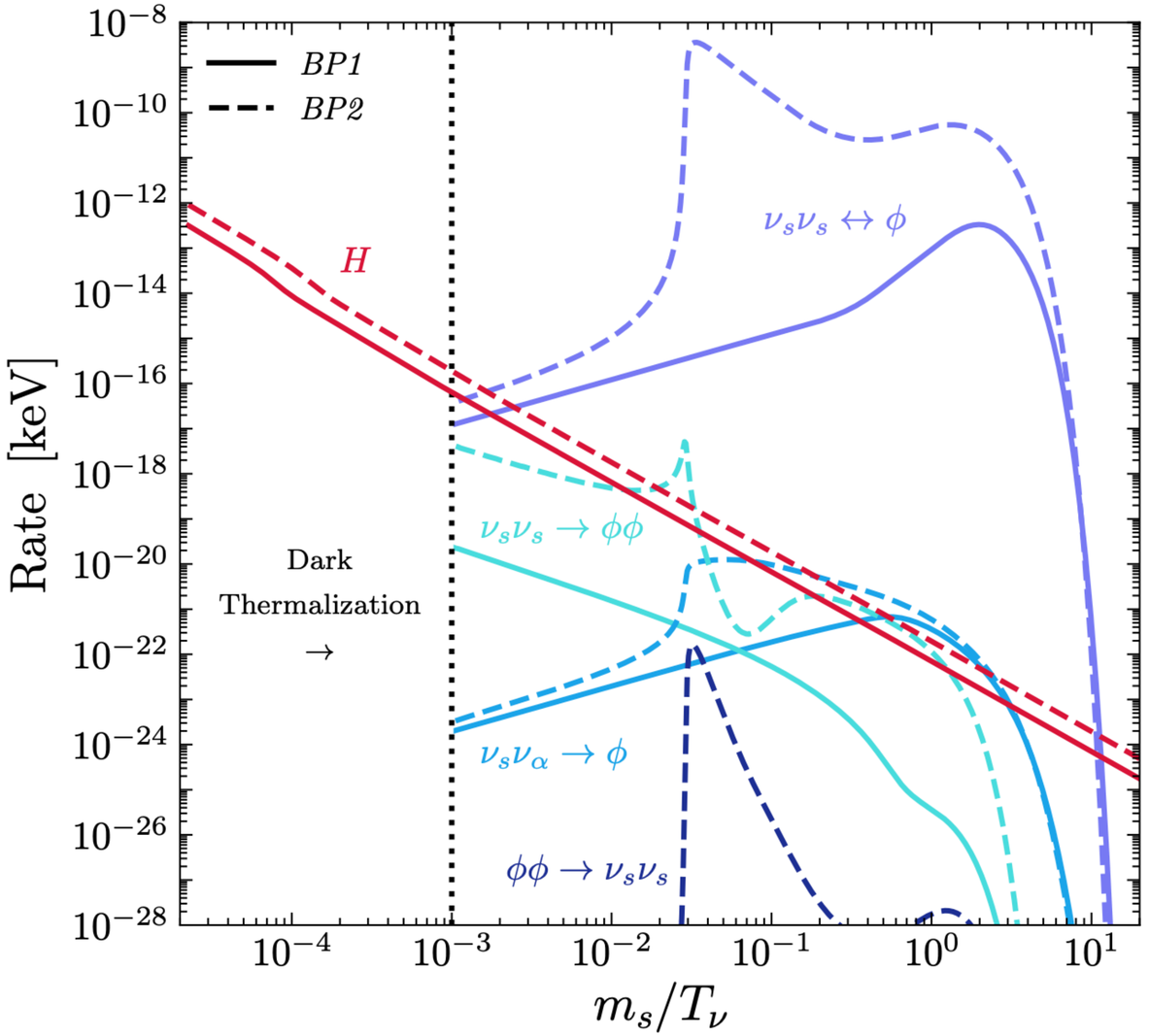
$$f_s = \frac{1}{e^{(E-\mu_s)/T_d}+1} \qquad f_\phi = \frac{1}{e^{(E-\mu_\phi)/T_d}-1}$$

Boltzmann equations

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

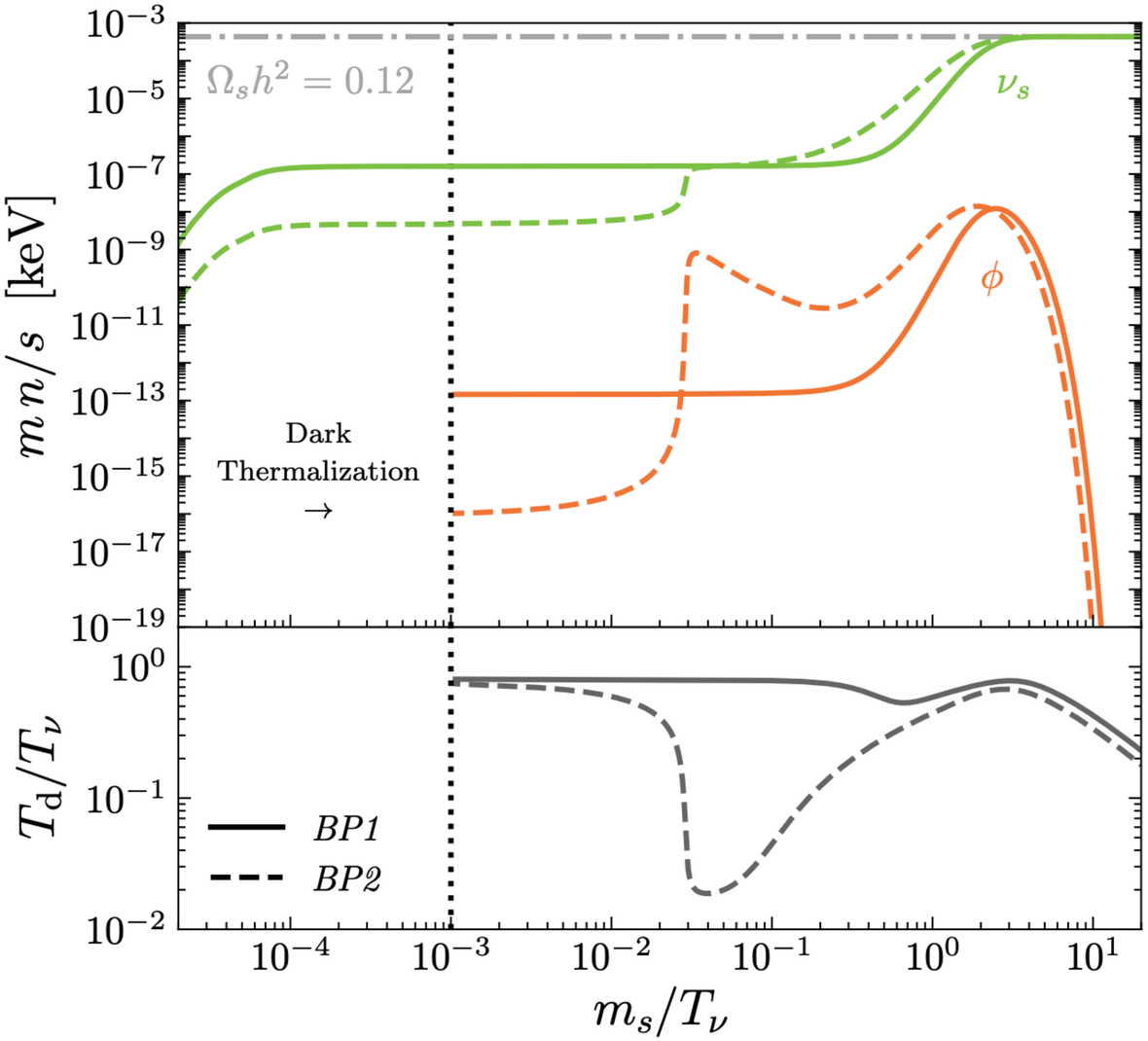
chemical equilibrium: $2\mu_s = \mu_\phi$

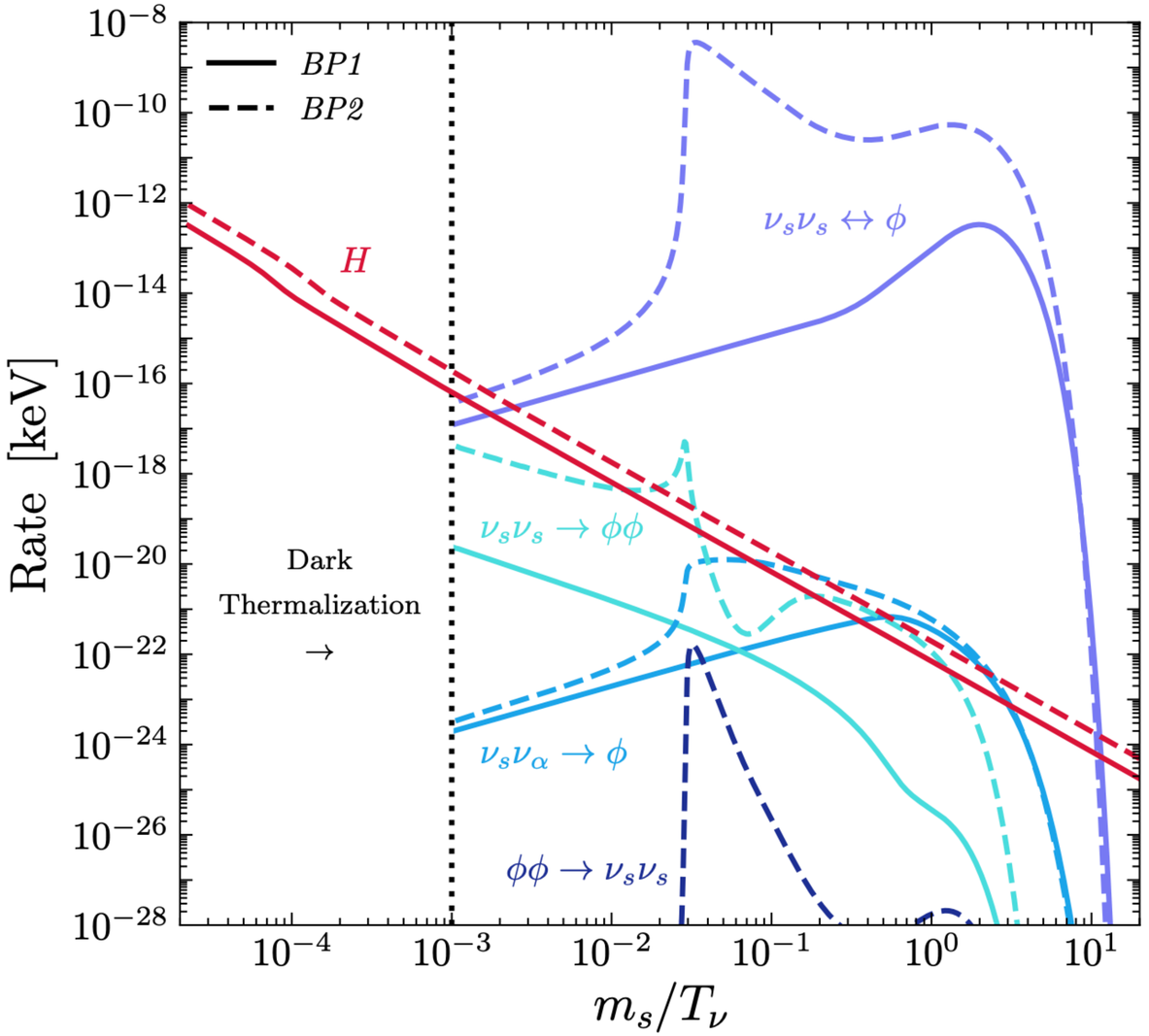
	m_s	m_ϕ	$\sin^2(2\theta)$	y
BP1	12 keV	36 keV	2.5×10^{-13}	1.905×10^{-4}
BP2	20 keV	60 keV	3.0×10^{-15}	1.602×10^{-3}



Cosmological evolution

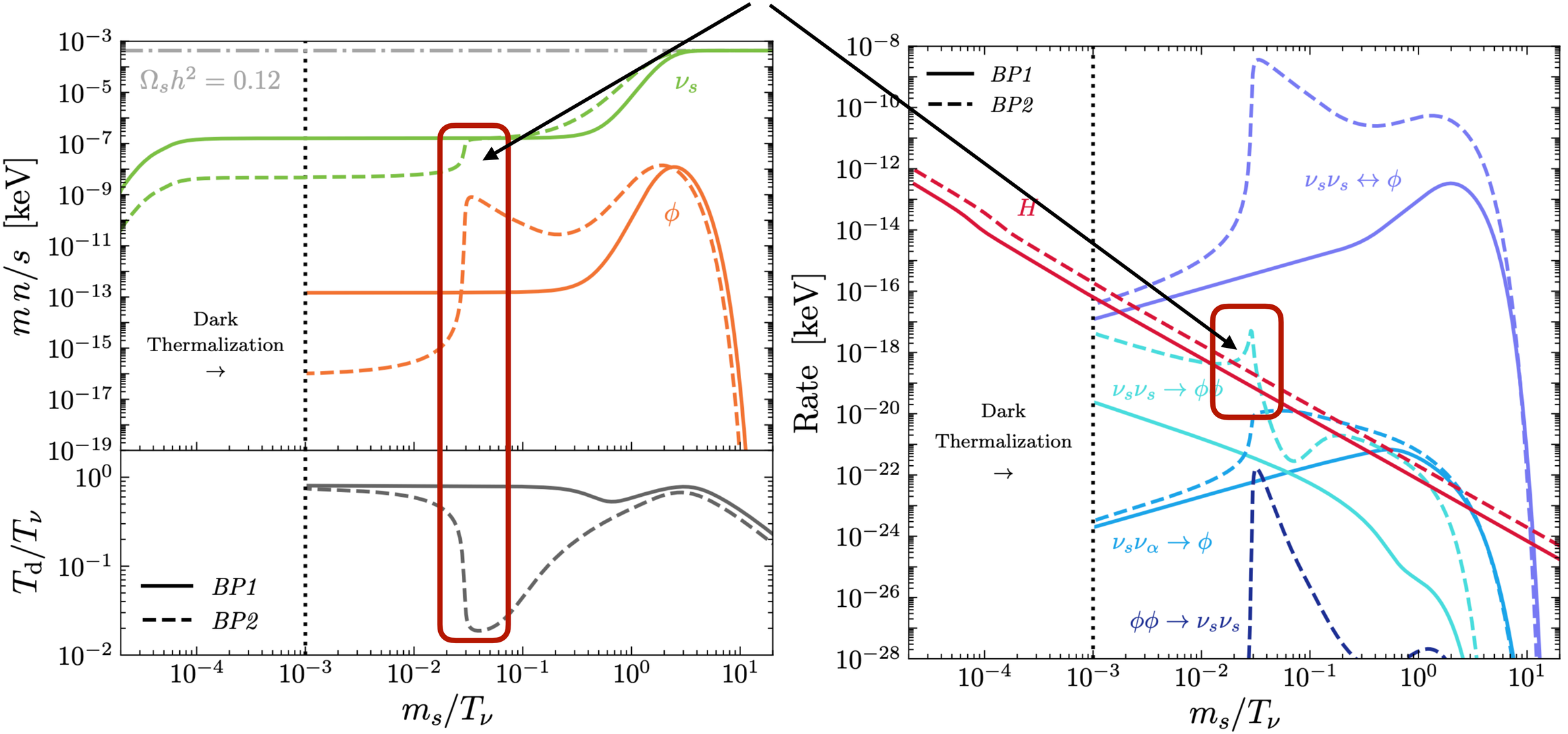
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Cosmological evolution

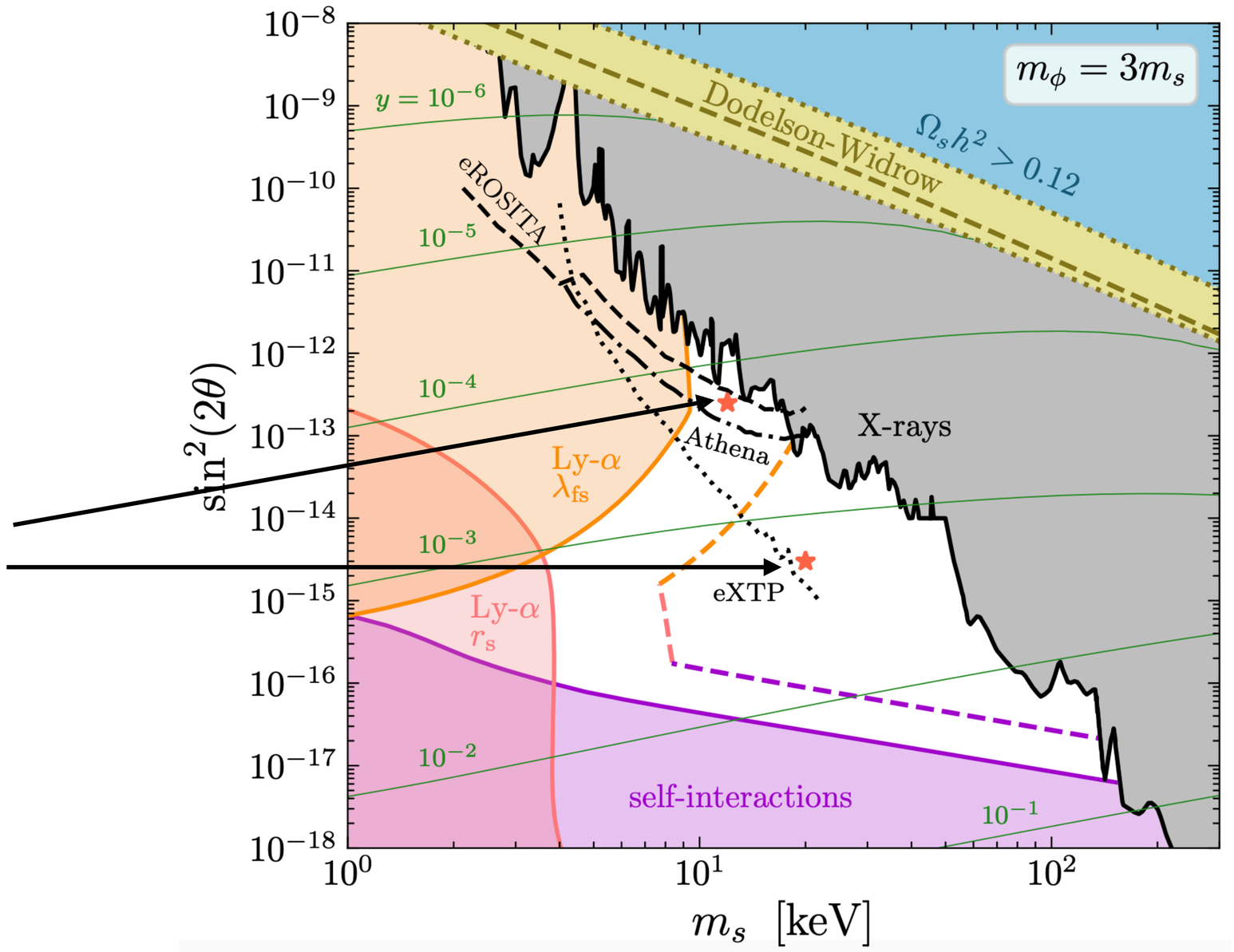
'reproductive freeze-in'
2007.14688, JMR, H Tillim, S West



Parameter space

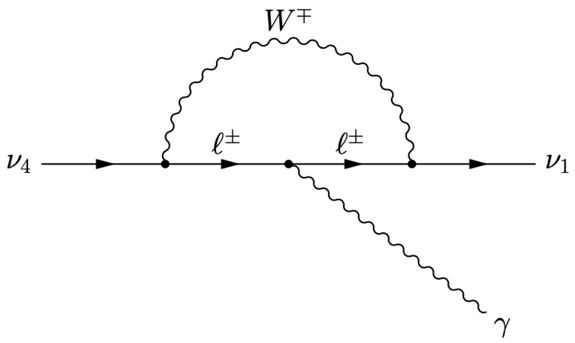
Yukawa y fixed such that $\Omega_s = \Omega_{\rm DM}$

	m_s	m_ϕ	$\sin^2(2\theta)$	y
BP1	12 keV	36 keV	2.5×10^{-13}	1.905×10^{-4}
BP2	20 keV	60 keV	3.0×10^{-15}	1.602×10^{-3}

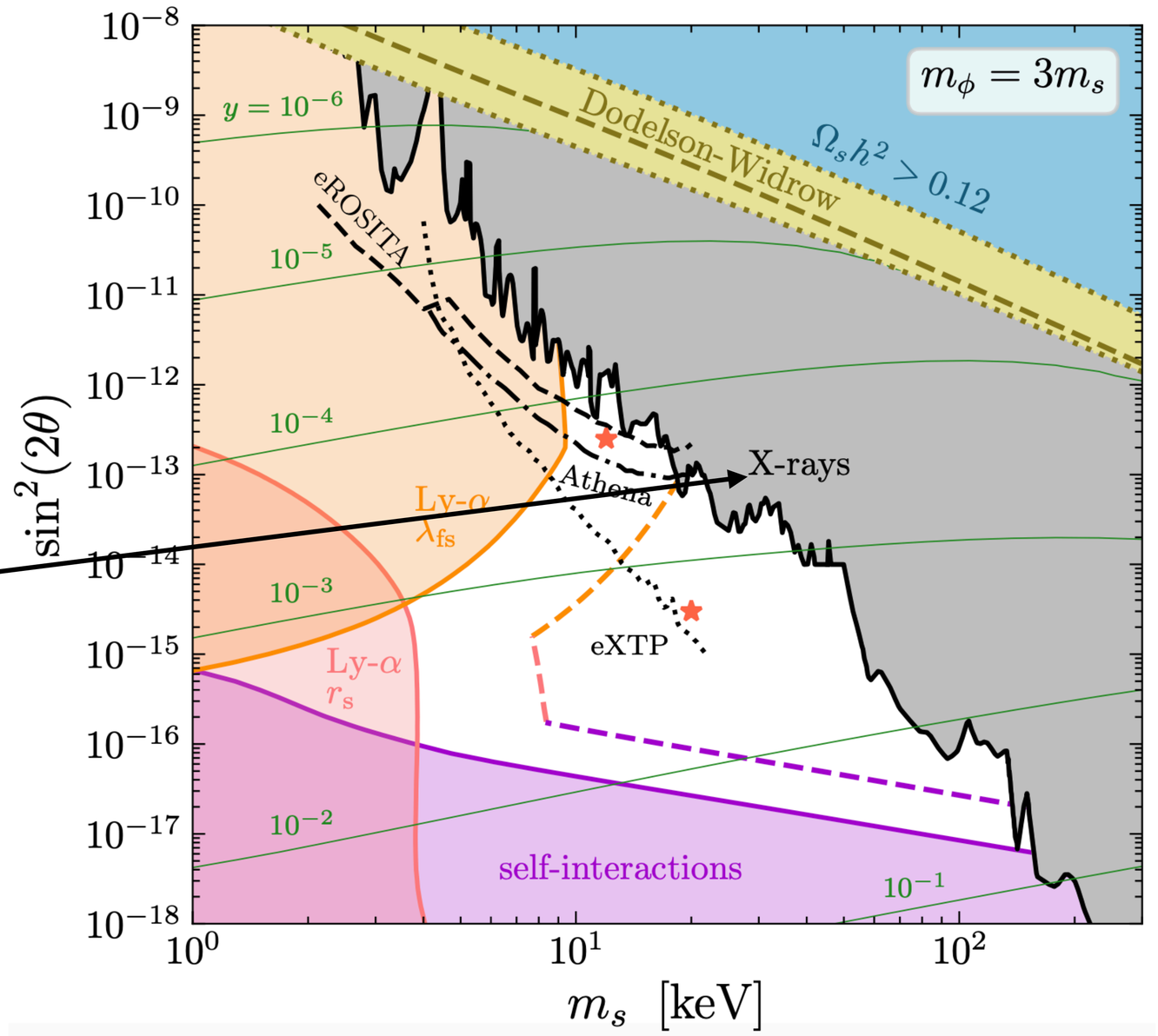


Parameter space

For $m_\phi > m_s$ decays of ν_s unchanged



→ Standard X-ray limits apply



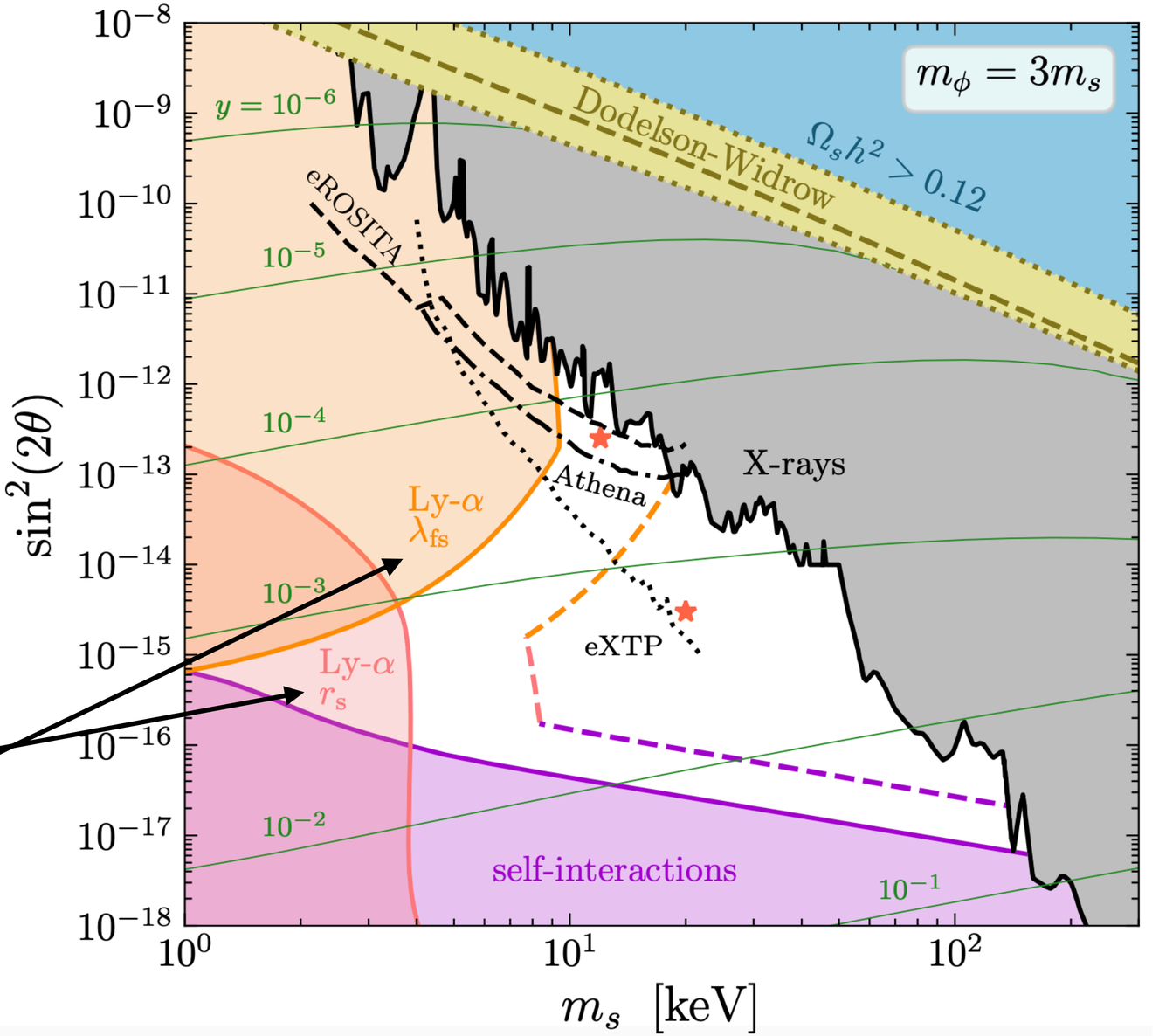
Parameter space

Constraints from small scale structure



Full analysis requires hydrodynamical N-body simulations. Here:

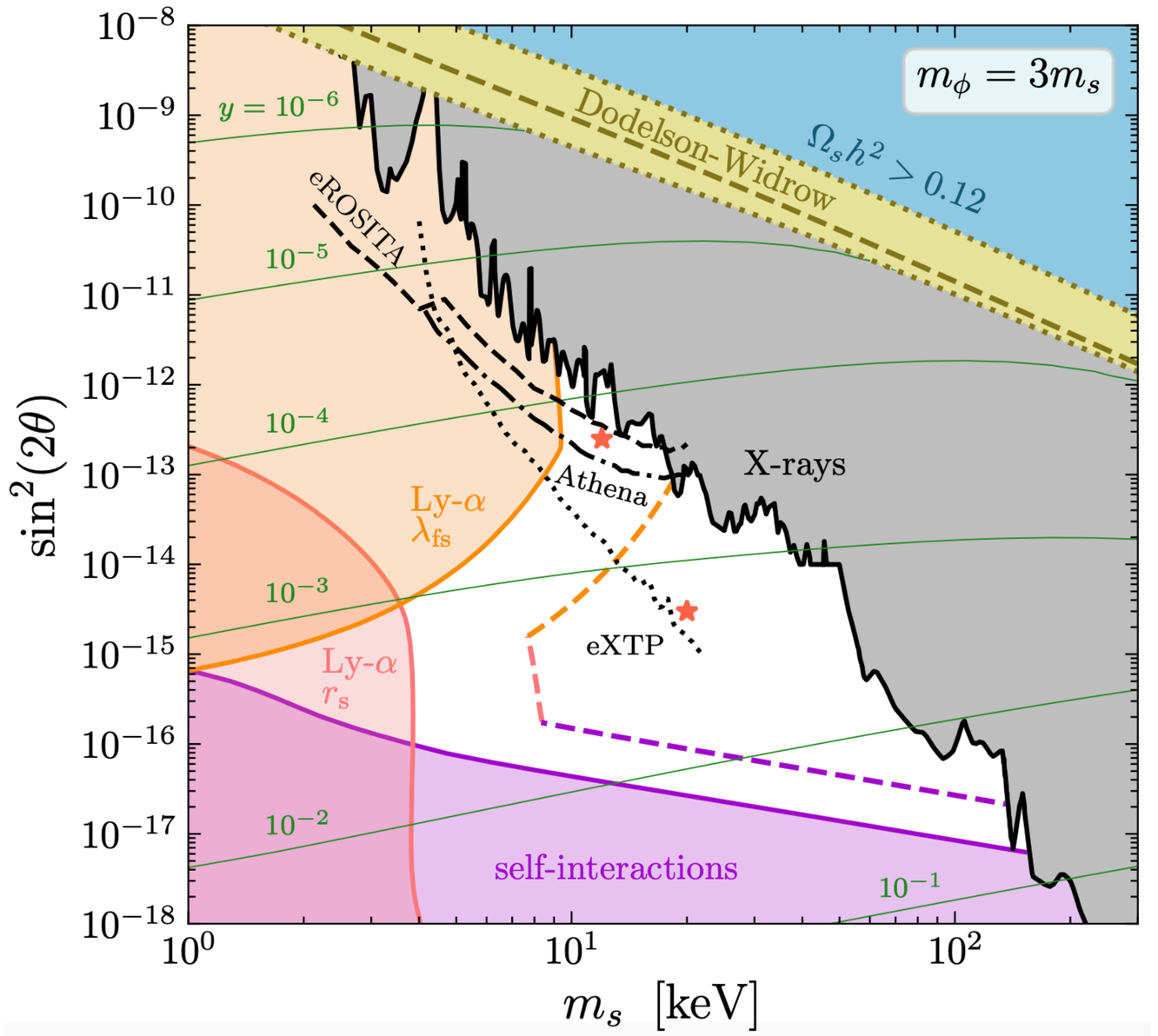
- pressure (until kinetic decoupling)
- free-streaming length of DM (after kinetic decoupling)



$$\lambda_{\rm fs} = \int_{t_{\rm kd}}^{t_{\rm nl}} {\rm d}t \frac{\langle v \rangle}{a(t)} \lesssim 0.24 \text{ Mpc} \qquad r_s = \int_0^{t_{\rm kd}} dt \, \frac{c_s}{a(t)} < 0.34 \text{ Mpc}$$

Parameter space

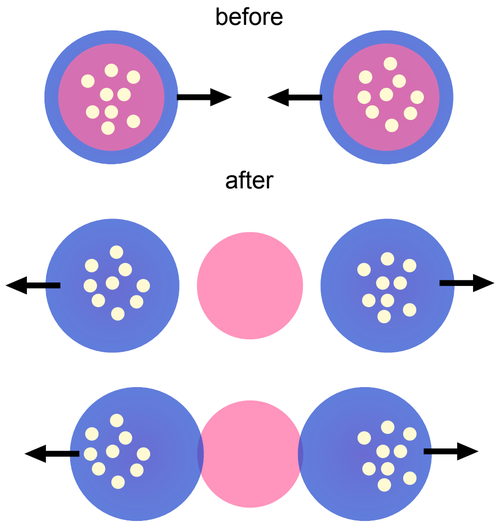
DM self-interactions constrained by astrophysical observations (but also interesting!)

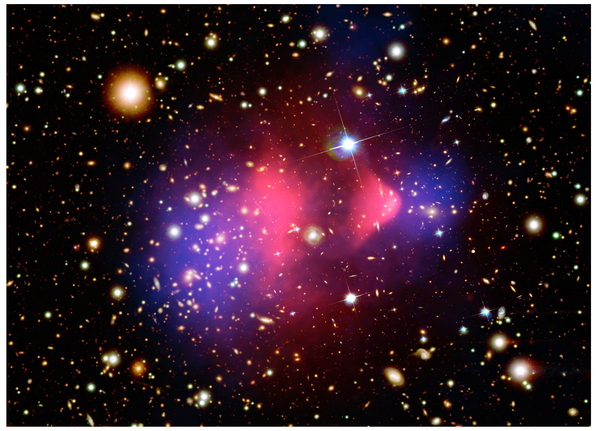


Parameter space

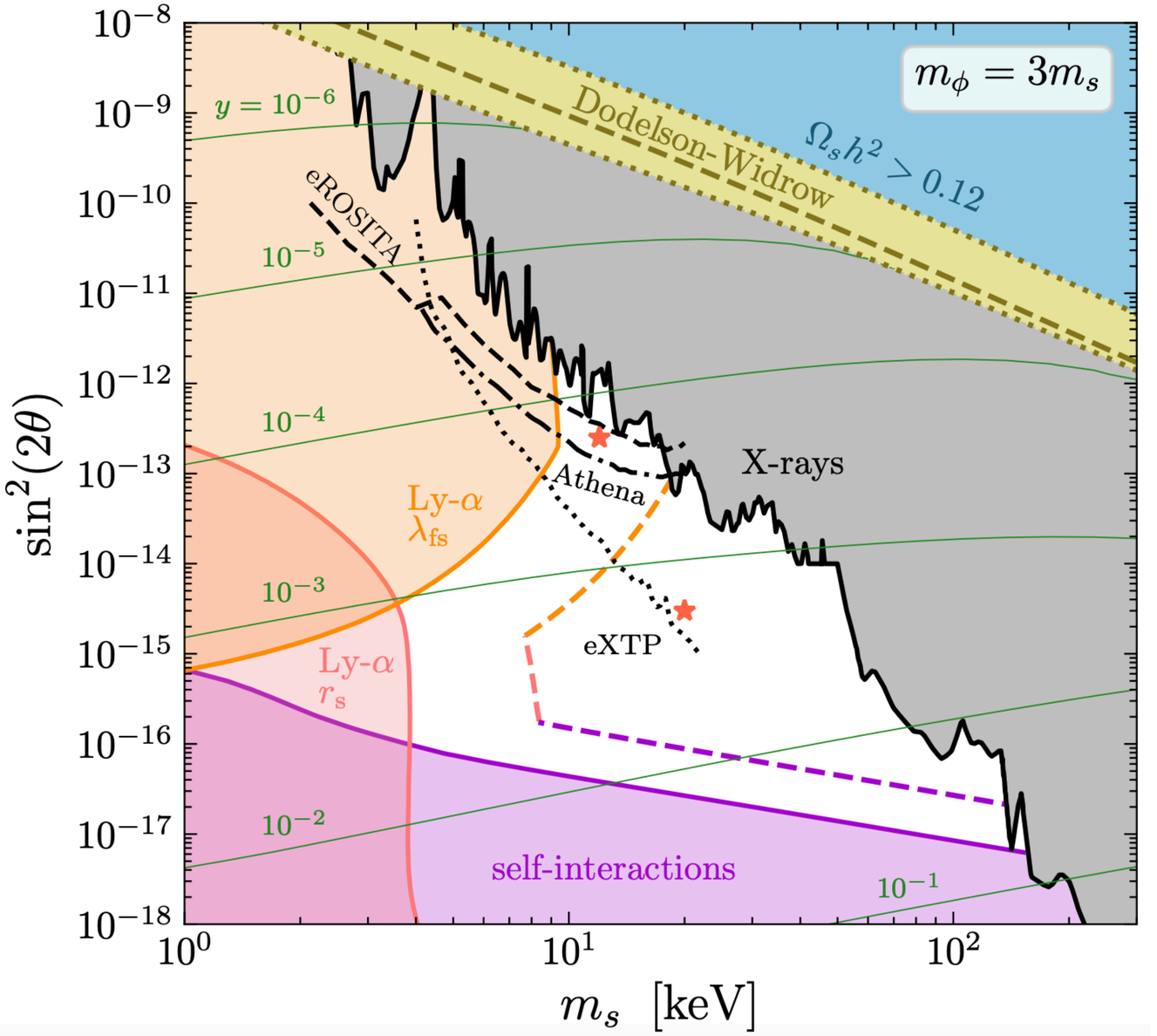
DM self-interactions constrained by astrophysical observations (but also interesting!)

- Phenomenology largely determined by σ_T
- $m_\phi > m_s \rightarrow$ velocity-independent scatterings





- Take $\sigma_T/m_s < 1\,\mathrm{cm}^2/\mathrm{g}$

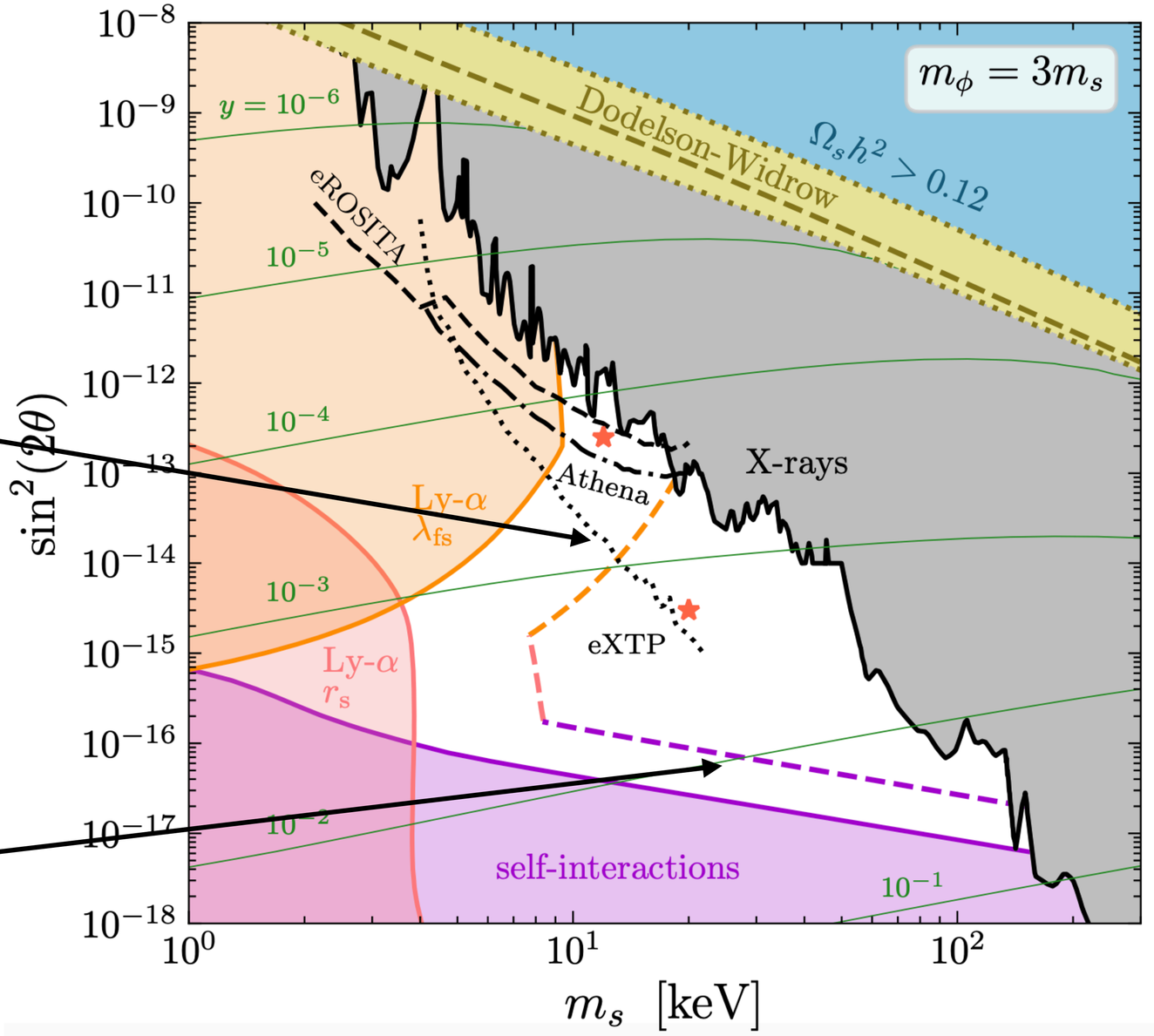


Parameter space

Sizeable fraction of parameter space will be tested in the upcoming years…

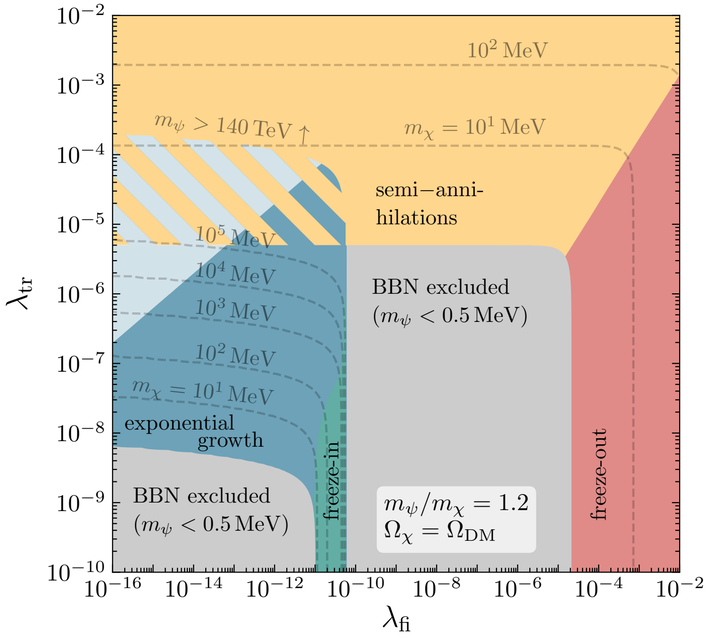
future X-ray searches

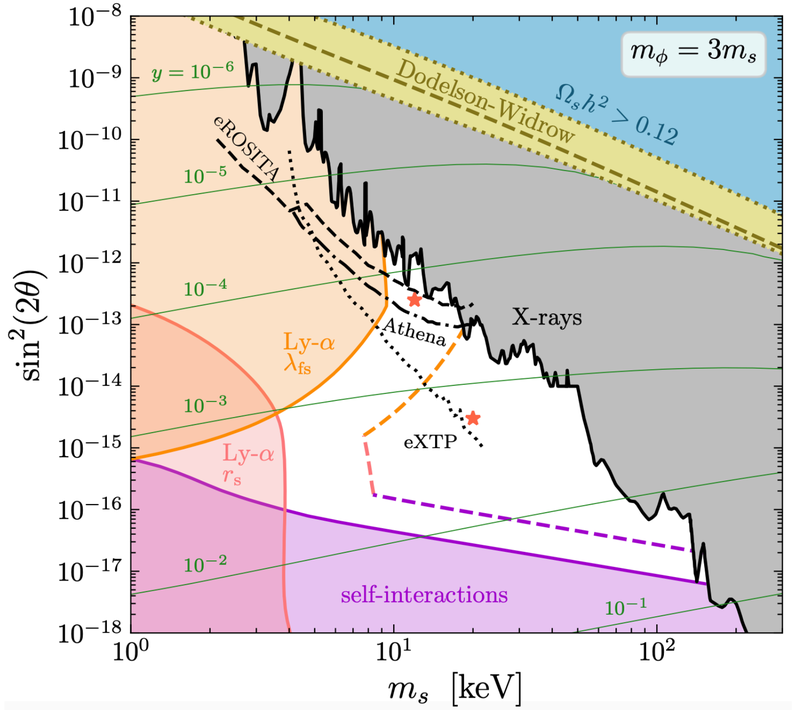
$\sigma_T/m_s < 0.1\,\mathrm{cm}^2/\mathrm{g}$



Conclusions

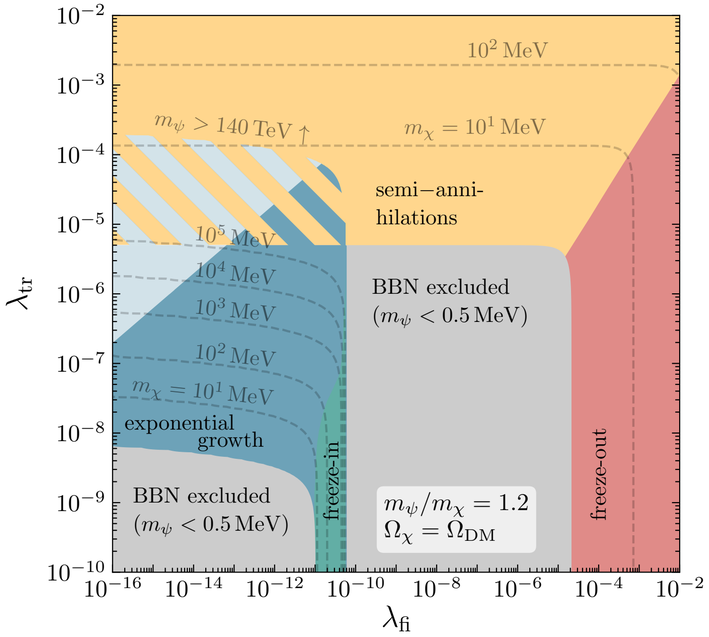
- Generic new DM production mechanism involving exponential growth
- Complements freeze-in and freeze-out scenarios
- Interesting phenomenological consequences
- Specific model realisations:
  - Higgs portal as simple (toy) example
  - **A new (simple!) life for sterile neutrinos!**
  - other applications?

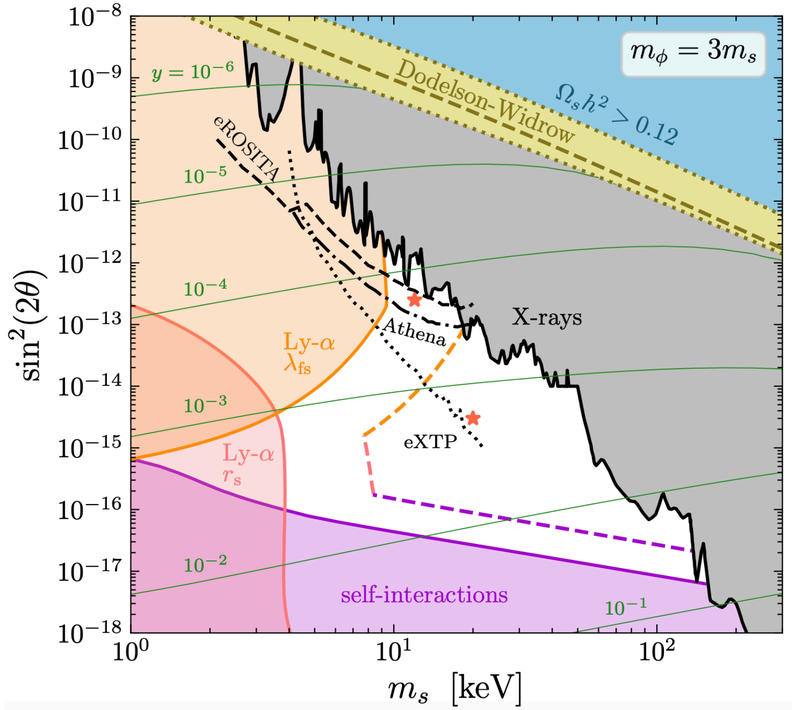




Conclusions

- Generic new DM production mechanism involving exponential growth
- Complements freeze-in and freeze-out scenarios
- Interesting phenomenological consequences
- Specific model realisations:
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Thank you!