Non-standard annihilations of dark matter

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From the Cosmos to the Lab:
Novel Links and Strategies @ Mainz,
12th September 2025

Based on Phys. Lett. B **864** 139425 (2025)
In collaboration with B. Betancourt Kamenetskaia, M. Fujiwara, A. Ibarra

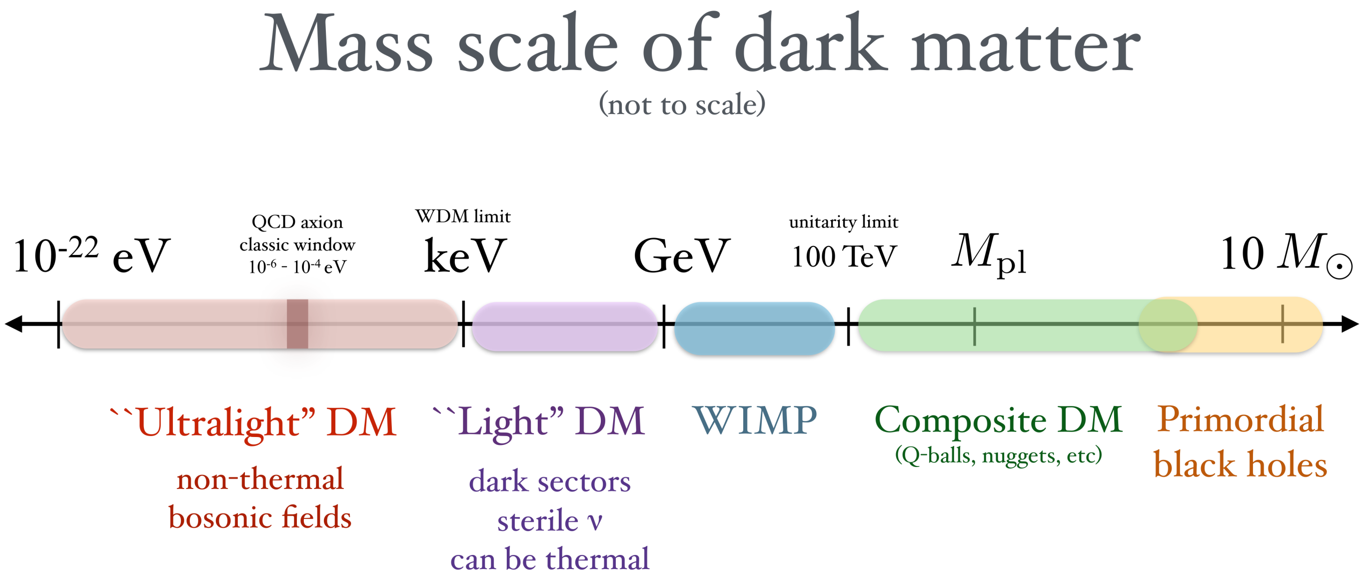
Outline

1. Thermal dark matter (WIMPs) and experimental status
2. Non-standard annihilations (semi-anns and $n \to 2$)
3. Boosted dark matter from semi-annihilations
4. Summary

Nature of DM

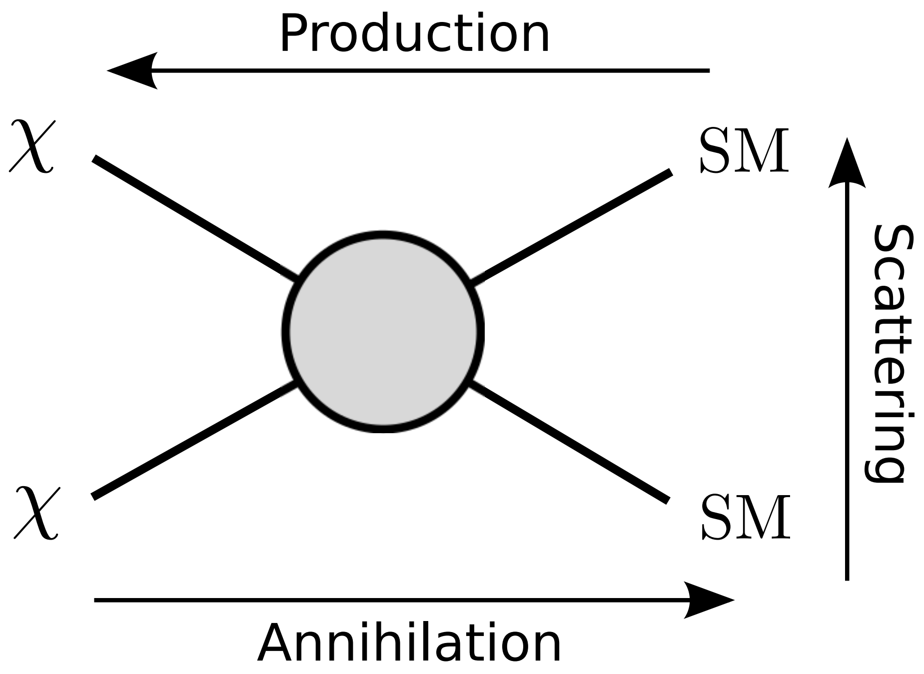
- Stable (at least longer than age of universe)
- Electrically neutral (may have very small charge)
- Occupy 27% of energy density of the universe
- Gravitational interaction
- Non-relativistic (cold)

Strong candidates:
WIMP (thermal DM),
axion, FIMP, SIMP,
sterile neutrino,
Fuzzy DM,
primordial black holes
etc



TASI lecture, arXiv:1904.07915

Thermal dark matter



Production

χ

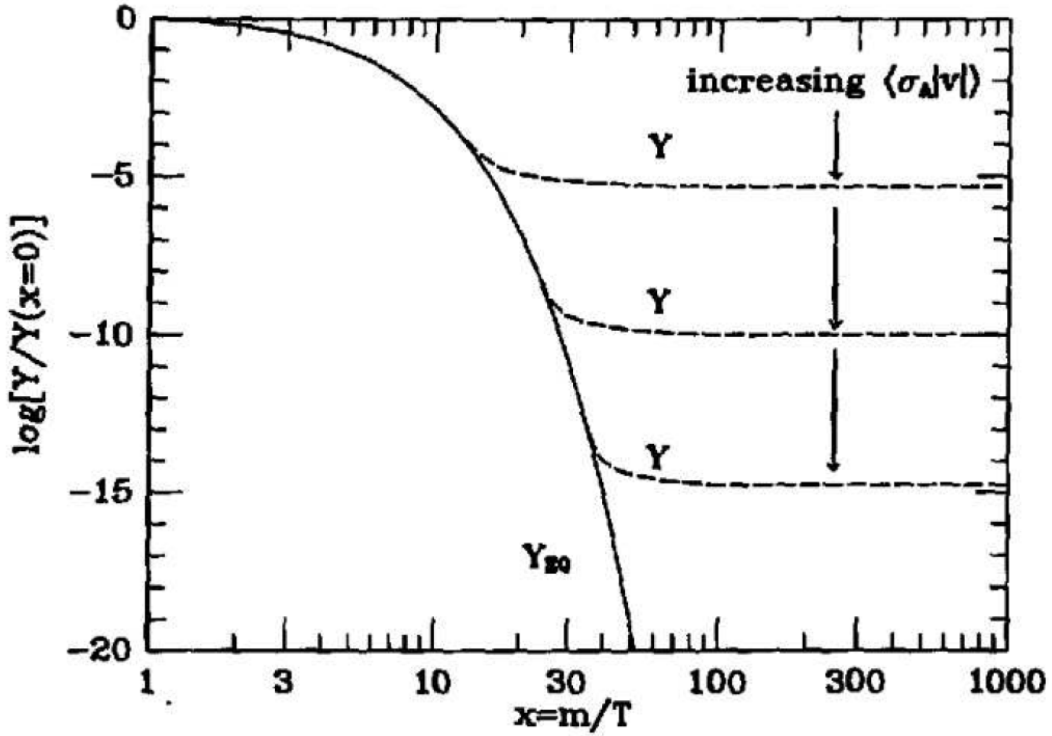
χ

SM

SM

Scattering

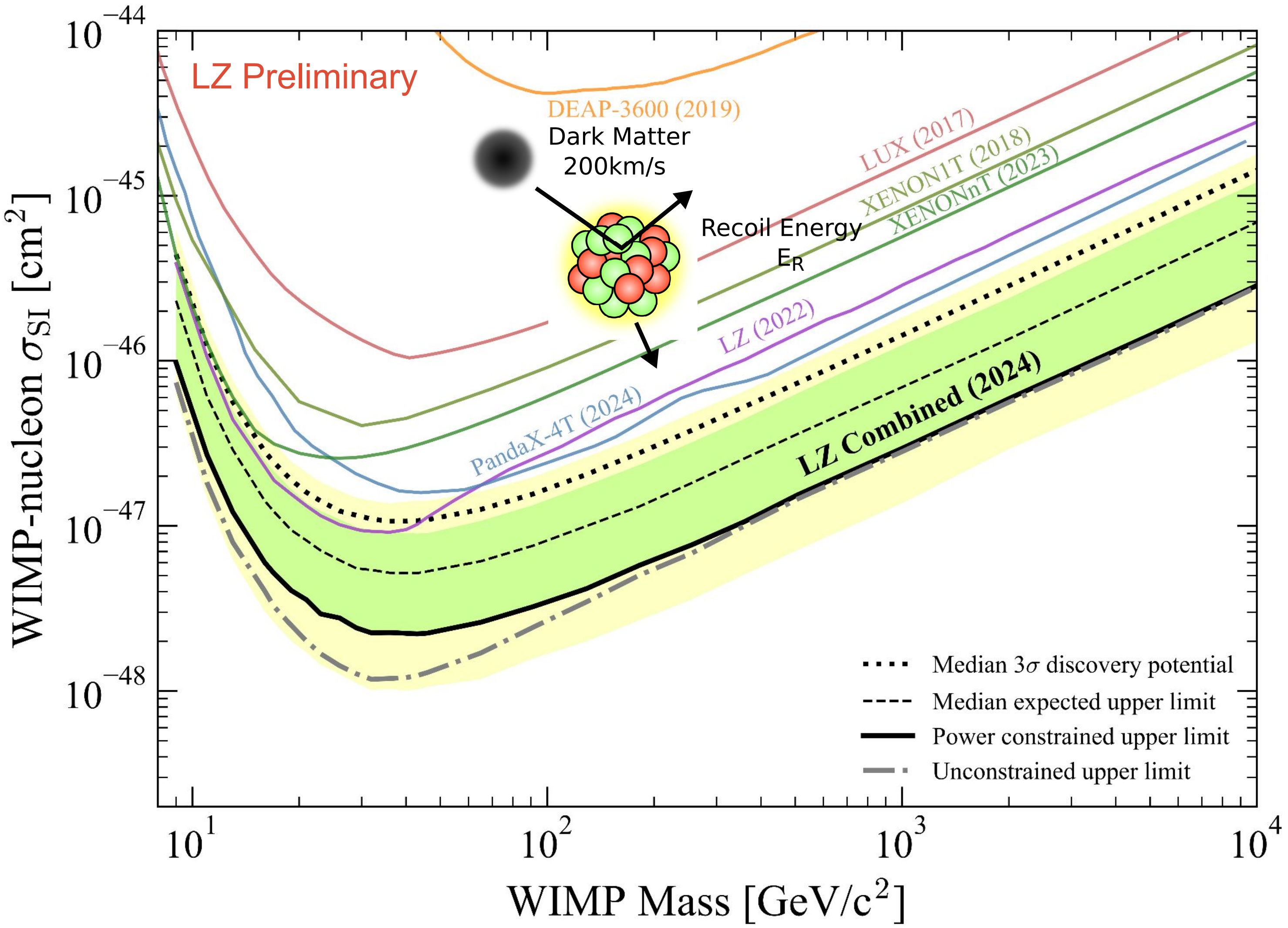
Annihilation

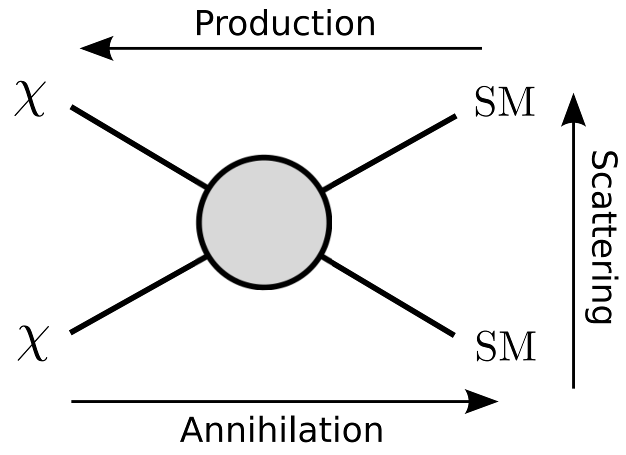


$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_\chi^{\mathrm{eq}2} \right)$$

- Thermalized with SM particles in early universe.
- To get $\Omega_\chi h^2 = 0.12$, roughly $\sigma \sim$ 1pb $\sim 10^{-26}\mathrm{cm}^3/\mathrm{s} \sim 10^{-36}\mathrm{cm}^2$ (only log dependent on DM mass)
- Mass range: 10 MeV – 100 TeV

Status of direct detection experiments





- $\Omega h^2 = 0.12$
  $\Leftrightarrow \sigma_{\mathrm{el}} \sim 10^{-36}$ cm^2
  ($\sigma_{\mathrm{el}} \lesssim 10^{-45}$ cm^2)
  (loop)

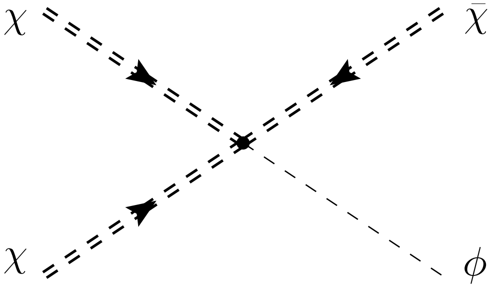
LZ talk @ TeVPA2024

- LZ gives the strongest bound 2.2×10^{-48} cm^2 at 43 GeV.
- Low sensitivity at low DM mass due to experimental threshold

Non-standard annihilations

Semi-annihilations

- $\chi_i\chi_j \to \chi_k\phi$ T. Hambye JHEP (2008), F. D'Eramo and J. Thaler JHEP (2010)
  χ_i: DM particles, ϕ: SM or new unstable particle
  One DM particle is in final state.



- Simplest case: $\chi\chi \to \bar{\chi}\phi$
  χ: DM, ϕ: SM particle or new unstable particle
- Simple $\mathbb{Z}_2$ parity does not work to stabilize DM.
  $\Rightarrow$ DM is a non-self-conjugate particle if it is assumed to be stable.
- Boltzmann equation

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

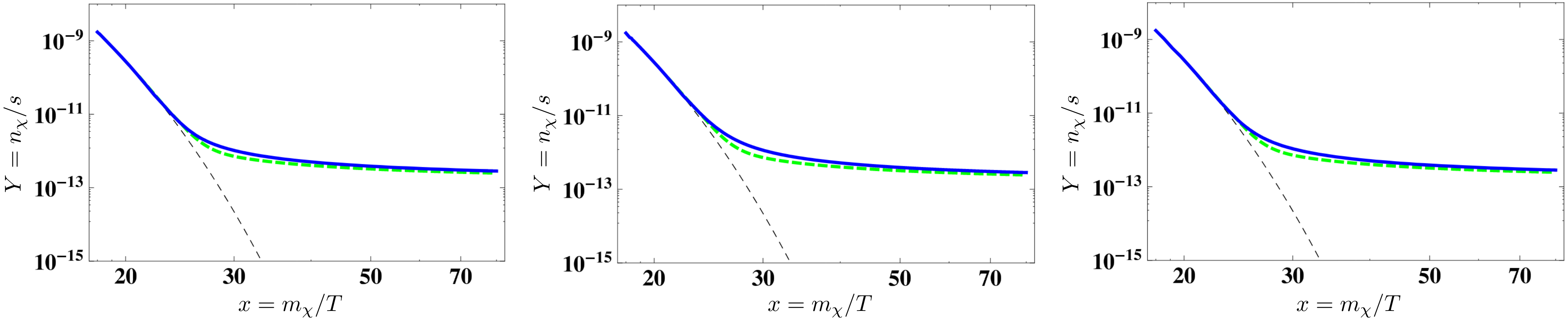
1st term: normal ann. 2nd term: semi-ann.
Note: normal annihilations always exist.

Relic abundance with semi-ann.

- $\chi\chi \to \bar{\chi}\phi$

$$\Omega h^2 \sim 2\frac{10^{-10}}{\langle \sigma_{\chi\bar{\chi}} v\rangle + \langle \sigma_{\chi\chi} v\rangle}, \quad \text{cf} \;\; \Omega h^2 \sim \frac{10^{-10}}{\langle \sigma_{\chi\bar{\chi}} v\rangle} \;\; \text{for normal ann.}$$

- does not change much compared to normal annihilation.
- A bit longer time is needed to reach the freeze-out value Ωh^2.



only $\langle \sigma_{\chi\bar{\chi}} v\rangle$ only $\langle \sigma_{\chi\chi} v\rangle$ mixed

Blue lines: Numerical Green lines: semi-analytic

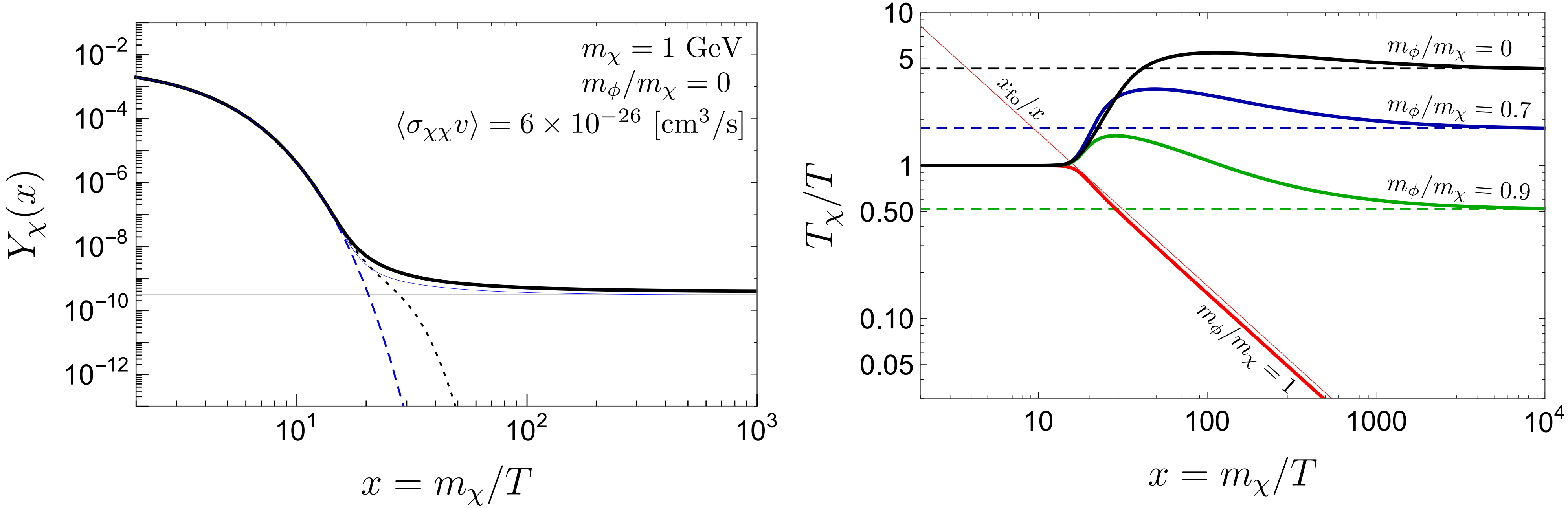
F. D'Eramo and J. Thaler, JHEP (2010) [arXiv:1003.5912]

Self-heating via semi-annihilations

A. Kamada et al.,
PRL (2018) [arXiv:1707.09238]

(implication of semi-ann.)

- Assumption: elastic scattering $\chi\phi \to \chi\phi$ is inefficient.
  $\Rightarrow T_\chi \neq T$

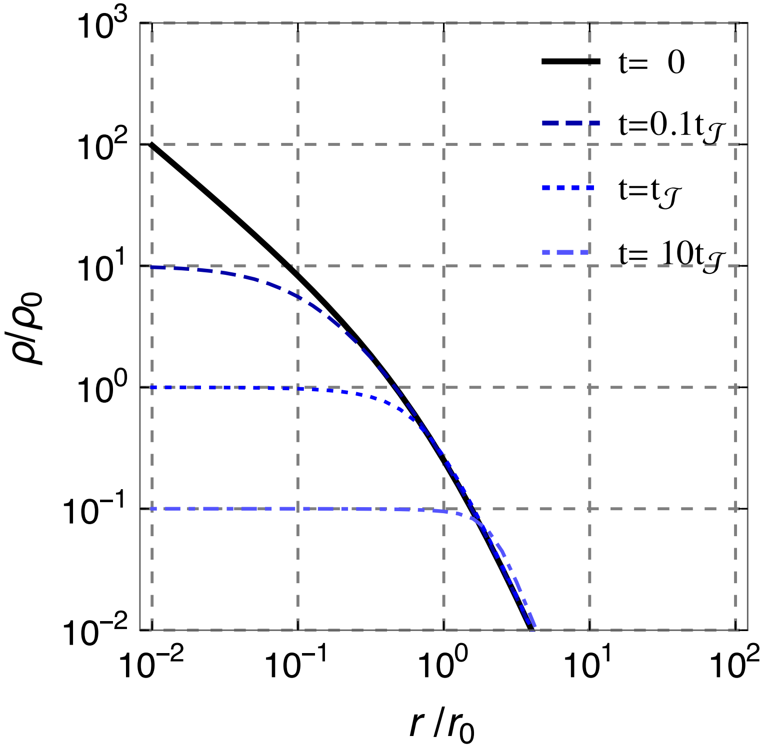


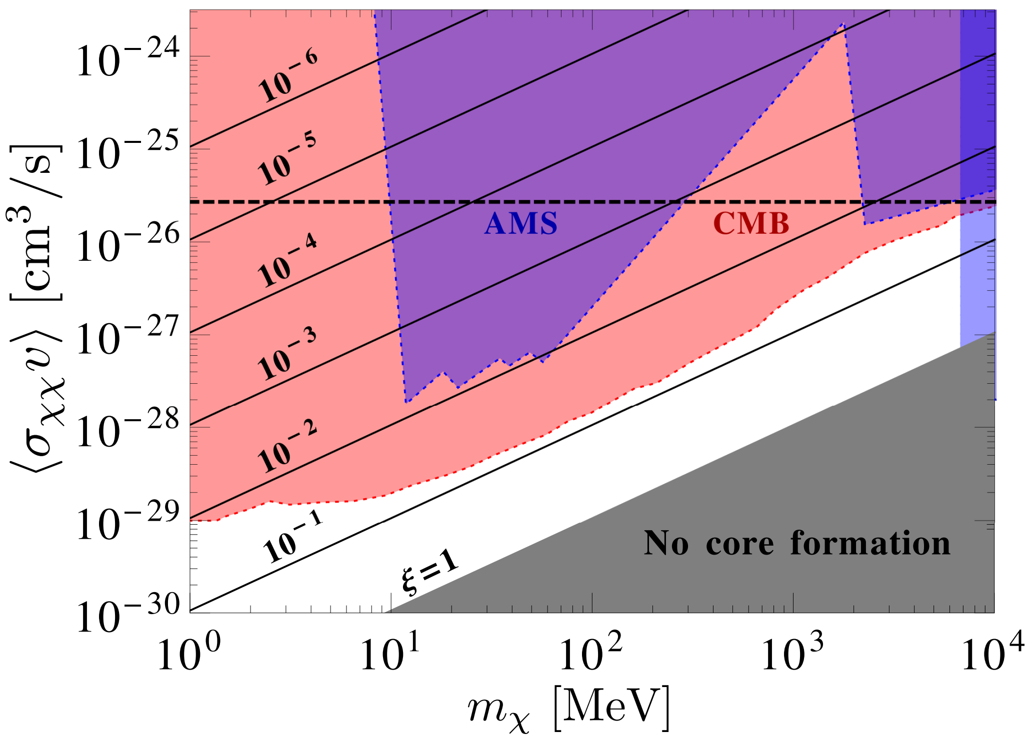
- $T_\chi \propto a^{-1}$ after freeze-out (similar to radiation)
- ∼30% effect on relic abundance calculation

Core formation via self-heating (implication of semi-ann. 2)

- Collisionless WIMP $\Rightarrow$ core vs cusp problem
- semi-ann. $\chi\chi \to \bar{\chi}\phi$ gives a momentum to $\bar{\chi}$ ($E_{\bar{\chi}} \sim 5m_\chi/4$).
  $\Rightarrow$ pressure outward in centre of DM profile
  $\Rightarrow$ DM core is formed. X. Chu and C. Garcia-Cely, JCAP (2018) [arXiv:1803.09762]

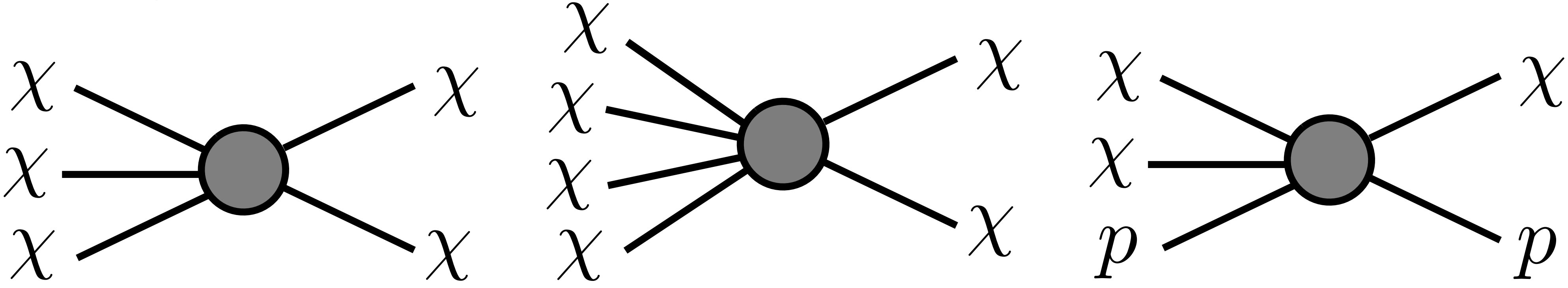
Energy absorption efficiency: $\xi \sim \dfrac{r_s}{\lambda} \sim 10^{-3}\left(\dfrac{r_s}{5\ \mathrm{kpc}}\right)\left(\dfrac{\rho_\chi}{M_\odot/\mathrm{pc}^3}\right)\left(\dfrac{\sigma_{\mathrm{self}}/m_\chi}{10^{-3}\ \mathrm{cm}^2/\mathrm{g}}\right)$





SIMPs (Strongly Interacting Massive Particles)

- SIMPs, Co-SIMPs



Hochberg, Kuflik, Volansky, PRL (2014), Smirnov, Beacom, PRL (2020)

- Boltzmann eq. for $n \to 2$ annihilation

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v^{n-1} \rangle \left(n_\chi^n - n_\chi^{n-1} n_\chi^{\mathrm{eq}} \right)$$

$\langle \sigma v \rangle \sim 10^{-9}\ [\mathrm{GeV}^{-2}]$ for 2→2

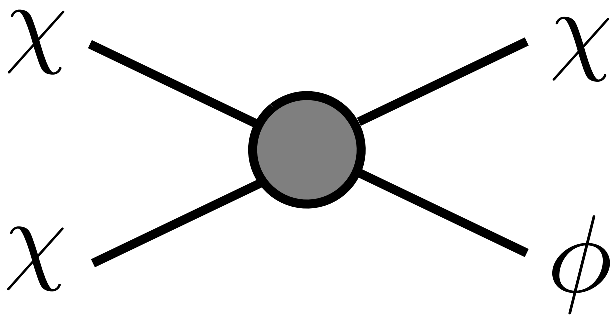
$$\langle \sigma v^2 \rangle \sim 1.6 \times 10^4 \left(\frac{40\ \mathrm{MeV}}{m_\chi} \right)^2\ [\mathrm{GeV}^{-5}] \text{ for } 3\to 2$$

$$\langle \sigma v^3 \rangle \sim 2.6 \times 10^{28} \left(\frac{100\ \mathrm{keV}}{m_\chi} \right)^4\ [\mathrm{GeV}^{-8}] \text{ for } 4\to 2$$

Boosted dark matter

Non-minimal dark sector

$\mathbb{Z}_3$ symmetric DM ⇒ cubic coupling $\mathcal{L} \supset \chi^3$



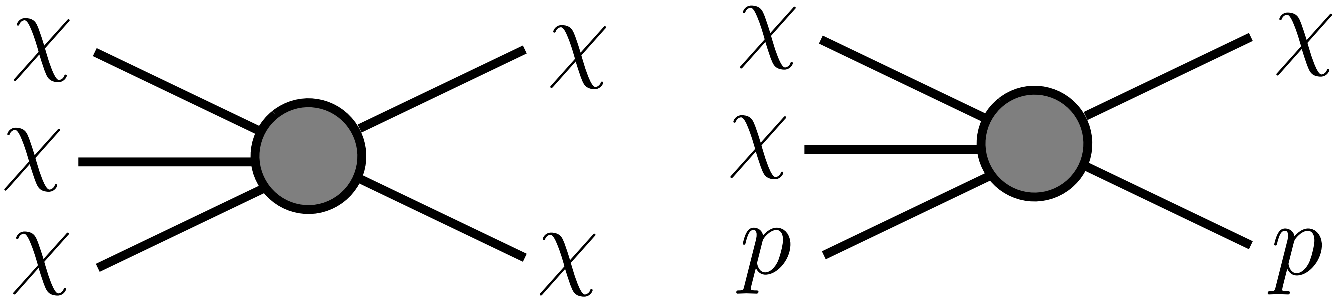
- Semi-annihilations

  Hambye, JHEP (2009), D'Ermao,. Thaler, JHEP (2010)

  $\chi\chi \to \overline{\chi}\phi \; (v_\chi = \mathcal{O}(0.1 - 1))$

- SIMP, Co-SIMP Hochberg, Kuflik, Volansky, PRL (2014), Smirnov, Beacom, PRL (2020)

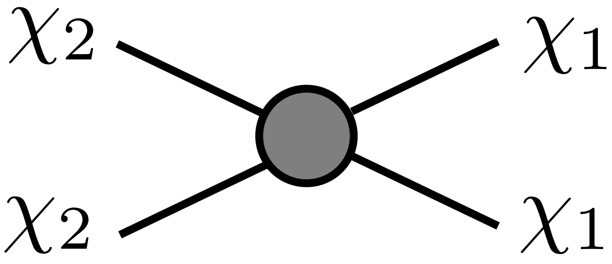
  $\chi\chi\chi \to \chi\overline{\chi}$, $\chi\chi p \to \chi p$



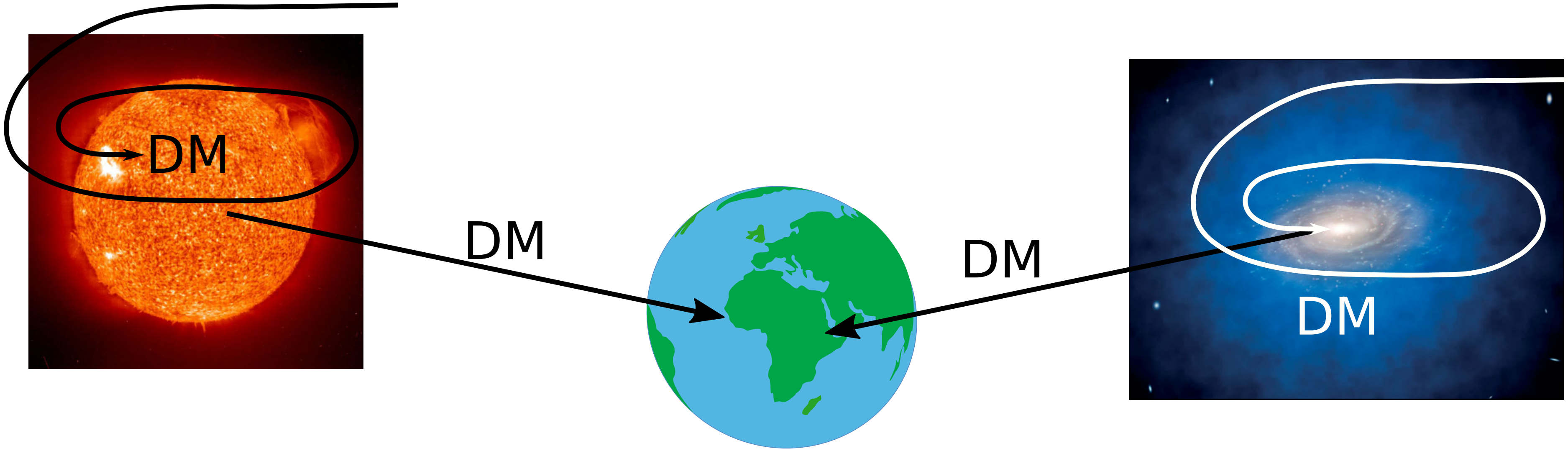
- Multi-component DM

  $\chi_2\chi_2 \to \chi_1\chi_1$

  Nagao, Naka, Nomura, JCAP (2025)



Acceleration of DM



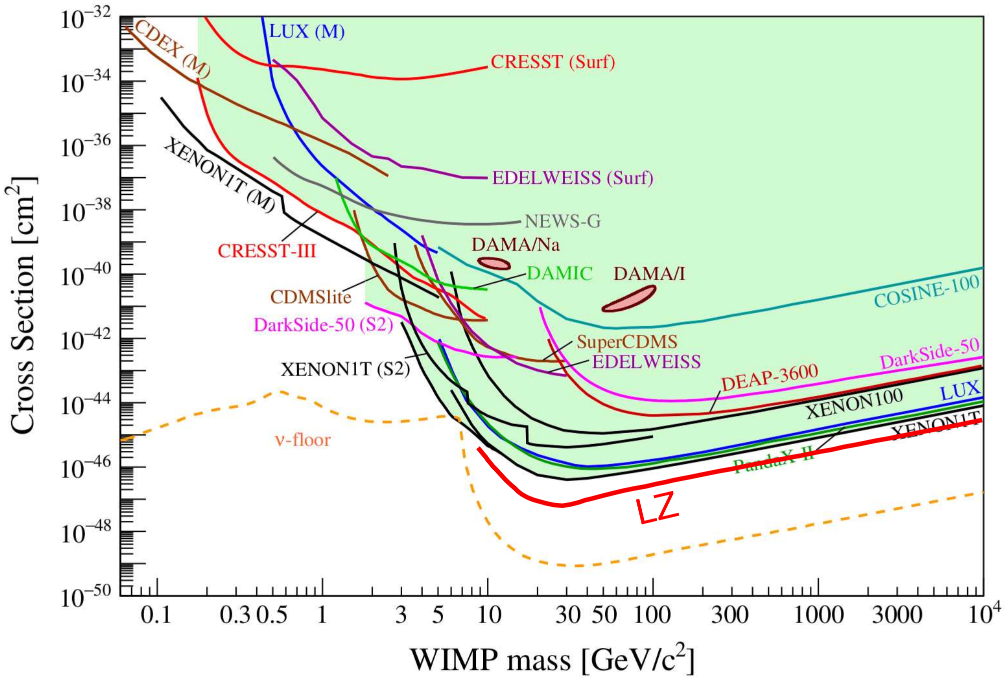
Other acceleration mechanisms and models

- Scattering with high energy cosmic-rays Bringmann and Pospelov, PRL (2019) Ema, Sala, Sato, PRL (2019)
- Scattering with Blazar Wang, Granelli, Ullio, PRL (2022)
- Solar reflection Emken, PRD (2022)
- Vacuum decay Cline, Puel, Toma, Wang, PRD (2023), Cline, Puel, Toma, PLB (2024)

Boosted DM from semi-ann.

- We focus on $\chi\chi \to \overline{\chi}\nu \Rightarrow$ Dirac DM
  ($\chi\chi \to \overline{\chi}\phi \to \overline{\chi}f\overline{f} \Rightarrow$ indirect detection)
- DM energy in the final state: $E_\chi = \frac{5}{4}m_\chi$ (monochromatic)
  $\Rightarrow$ Moderate boost factor $\gamma_\chi \equiv \frac{E_\chi}{m_\chi} = \frac{5}{4} = 1.25 \; (v_\chi = 0.6)$
- $\gamma_\chi < \gamma_{\text{Cherenkov}}^{\text{th}} \approx 1.5$
- No deep inelastic scattering
  $\Rightarrow$ simple calculation
- Sub-GeV DM mass range can be target for semi-annihilations.

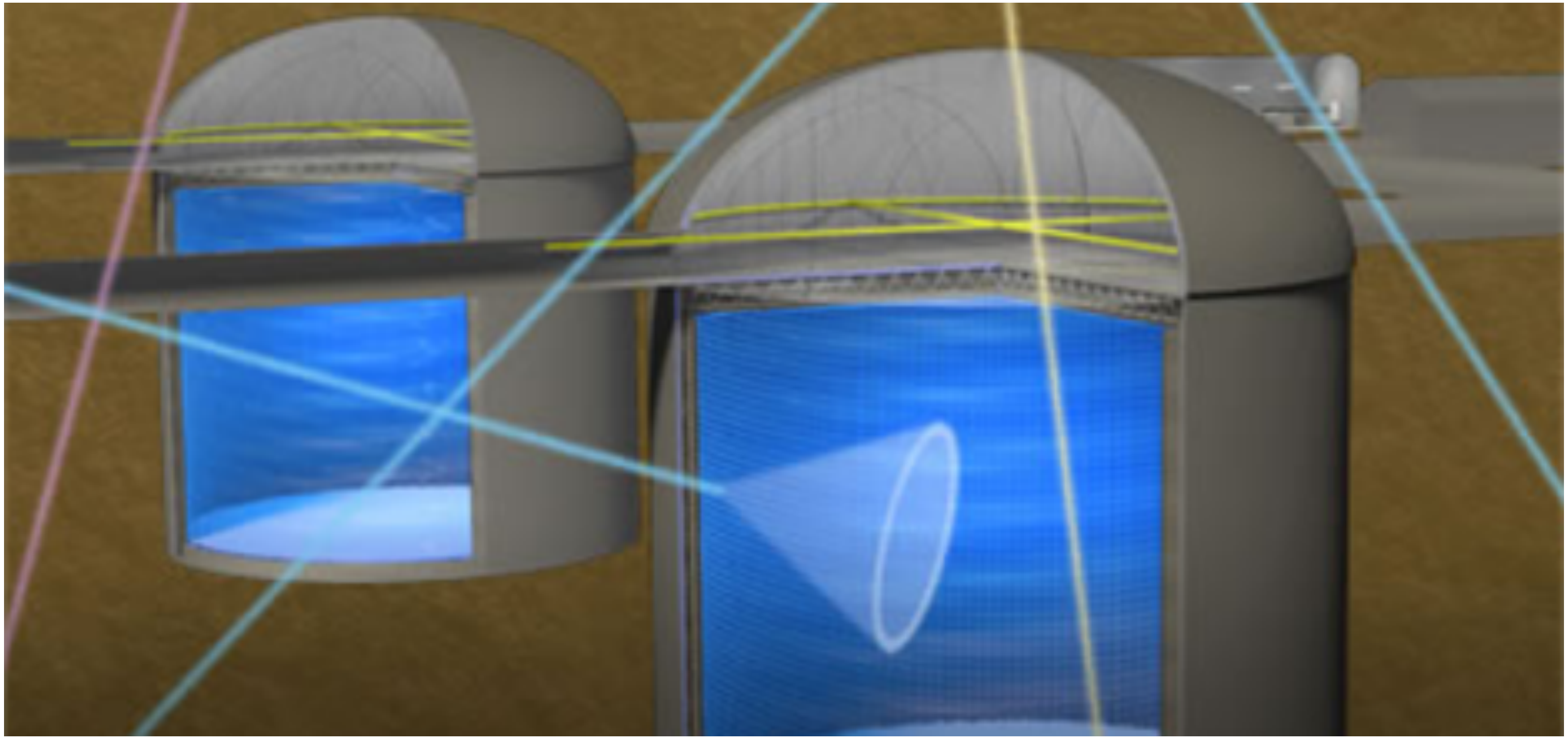
J. Billard et al., Rept.Prog.Phys. 85 (2022) 5, 056201



Detection of boosted DM

- Boosted DM ($v_\chi = 0.6$) is difficult to produce Cherenkov radiation.

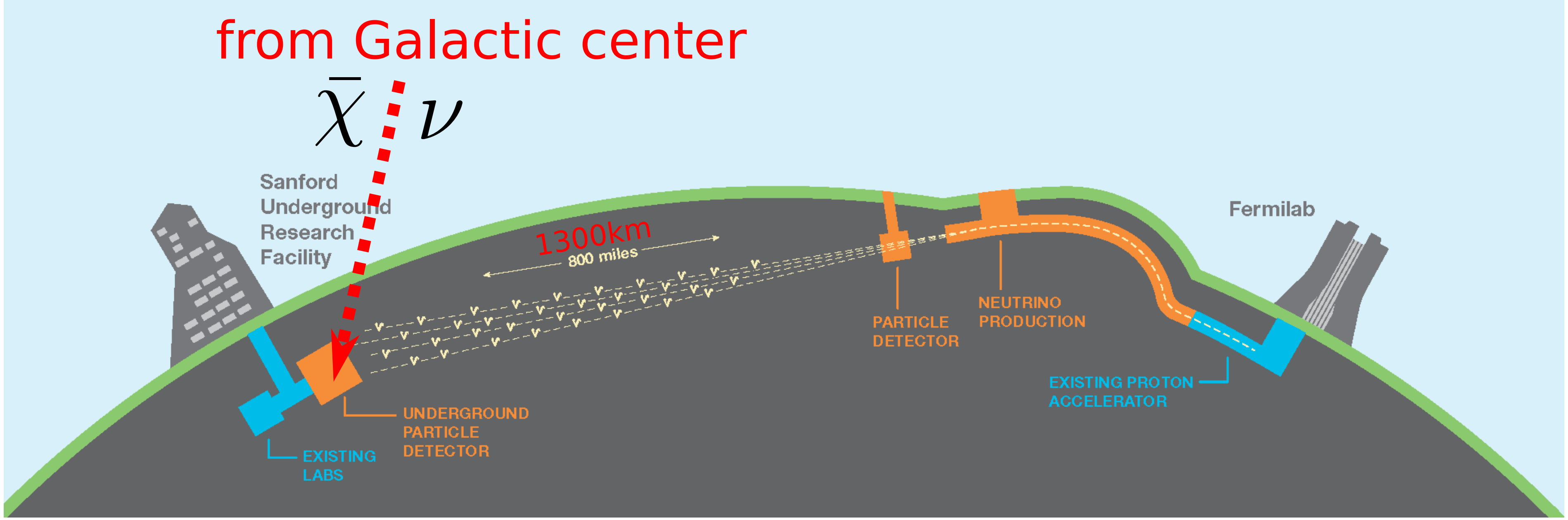
  $v_p > 0.75$ is required to produce Cherenkov radiation.



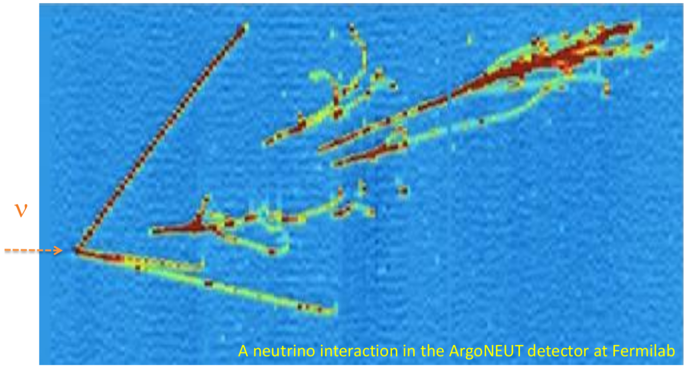
Hyper-Kamiokande Collaboration

⇒ We focus on DUNE and DM direct detection experiments.

DUNE (Deep Underground Neutrino Experiment)



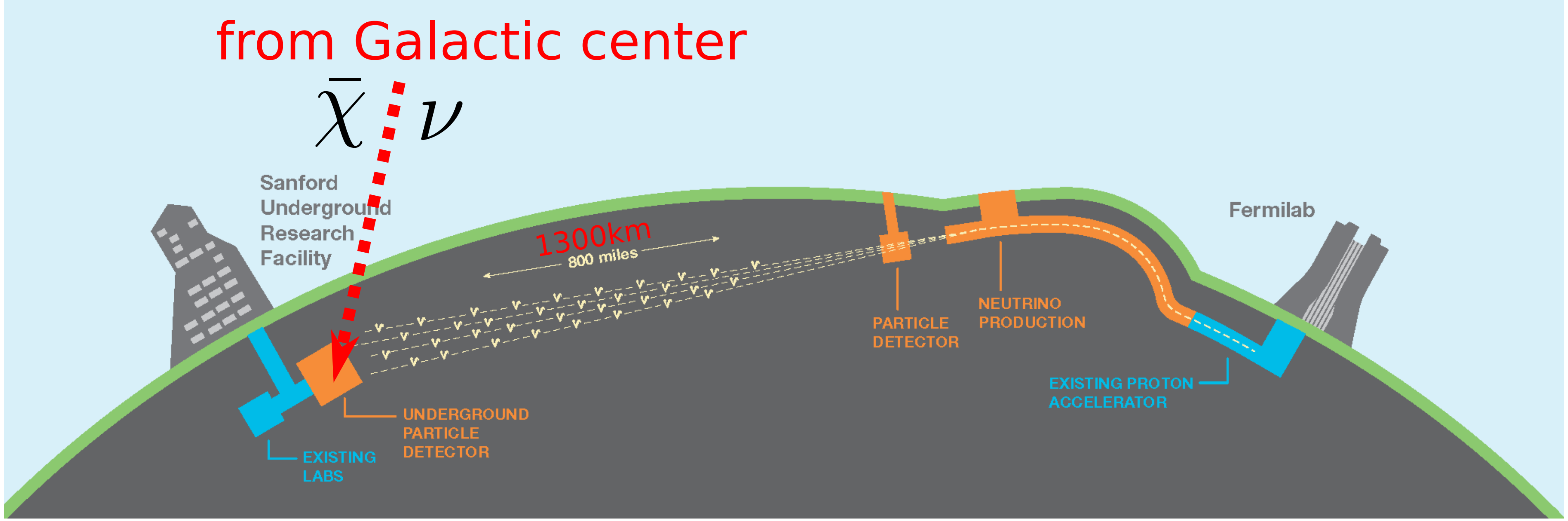
- Two detectors: near and far detectors.
- Massive liquid argon (fiducial volume: 40kt)
- Precise reconstruction of particle trajectories with LArTPC



A neutrino interaction in the ArgoNEUT detector at Fermilab

DUNE Coll., [arXiv:2002.03005]

DUNE (Deep Underground Neutrino Experiment)



DUNE Coll., [arXiv:2002.03005]

Timeline of far detector modules ⇒ Delayed

More cost is needed than initially expected. (2 billion ⇒ 3 billion dollars)

- 2029: slimmed version of DUNE will run
- 2035: DUNE full spec (40kt) ⇔ 2028: Hyper-K data taking

  ⇒ HK (2028) has advantage for ν mass ordering, CP violation etc.

Boosted DM is detectable at DUNE, but not at HK.

Scattering with nuclei

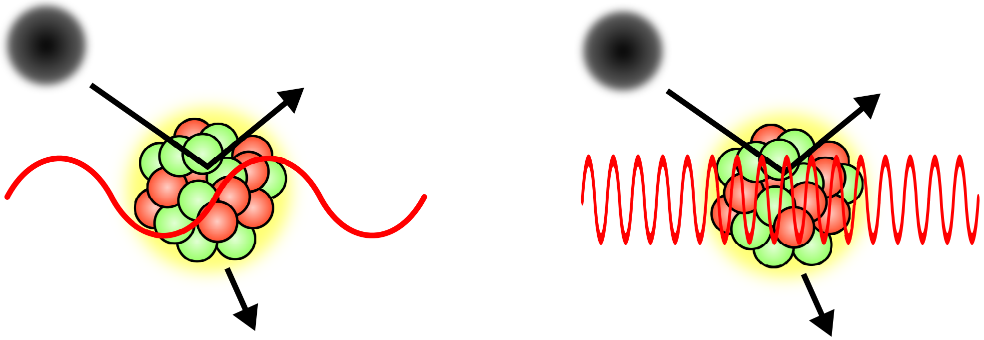
- Coherent enhancement for non-relativistic DM may be lost.
- Parametrization of incoherent scattering

$$\frac{d\sigma_{\chi N}}{dT_N} = \underbrace{\left(\frac{d\sigma_{\chi N}}{dT_N}\right)_{\text{coh}}}_{\color{red}{qR \ll 1}} + \underbrace{\left(\frac{d\sigma_{\chi N}}{dT_N}\right)_{\text{inc}}}_{\color{red}{qR \gg 1}} = \frac{\sigma_{\text{SI}}^{\text{coh}}}{T_N^{\text{max}}} F_{\text{SI}}^2(q^2) + \frac{\sigma_{\text{SI}}^{\text{inc}}}{T_N^{\text{max}}}\left[1 - F_{\text{SI}}^2(q^2)\right]$$

where $\sigma_{\text{SI}}^{\text{coh}} = \sigma_p \left(\frac{\mu_N}{\mu_p}\right)^2 \left[Z_N f_p + (A_N - Z_N) f_n\right]^2$

$$\sigma_{\text{SI}}^{\text{inc}} = Z_N \sigma_p + (A_N - Z_N)\sigma_n, \qquad F_{\text{SI}}(q^2) = \left(1 + q^2/\Lambda_N^2\right)^{-1}$$

$\Rightarrow$ smooth transition between coh and inc



- Simple assumption: $f_p = f_n = 1$ and $\sigma_p = \sigma_n$

Recoil energy spectra

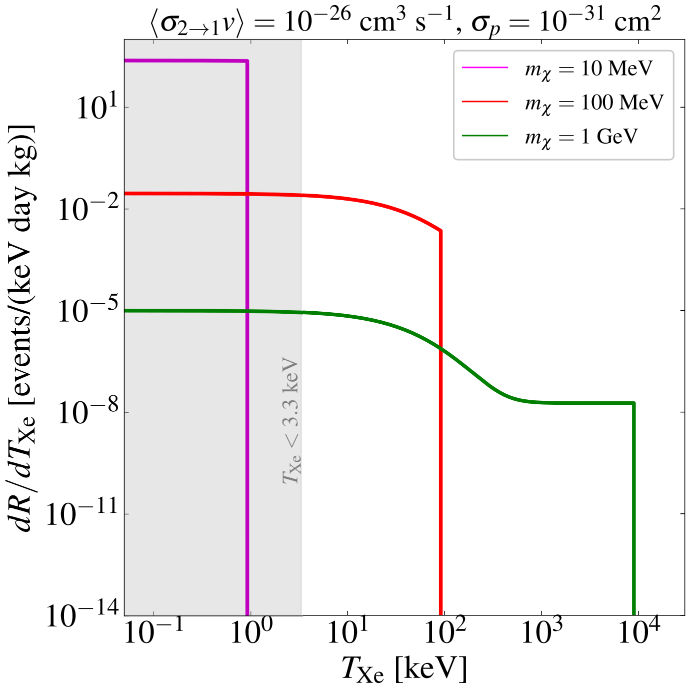
- $\frac{dR_N}{dT_N} = \frac{1}{m_N}\int_{T_\chi^{\min}}^{\infty} \frac{d\sigma_{\chi N}}{dT_N}\frac{d\Phi_\chi}{dT_\chi}dT_\chi$ where $\frac{d\Phi_\chi}{dT_\chi} = \Phi_{\mathrm{BDM}}\delta\left(T_\chi - \frac{m_\chi}{4}\right)$

  $$\Phi_{\mathrm{BDM}} \approx 3.2\times 10^{-3}\ [\mathrm{cm}^{-2}\mathrm{s}^{-1}]\left(\frac{m_\chi}{100\ \mathrm{MeV}}\right)^{-2}\left(\frac{\langle\sigma_{2\to1}v\rangle}{10^{-26}\ \mathrm{cm}^3/\mathrm{s}}\right)$$

- Mass threshold: $m_\chi^{\min} = \frac{5}{4}m_N\left(\frac{9m_N}{8T^{\mathrm{th}}} - 1\right)^{-1}\left(1 + \frac{3}{5}\sqrt{1 + \frac{2m_N}{T^{\mathrm{th}}}}\right)$

- For XENONnT, $T_{\mathrm{Xe}} =$ 3.3keV $\Rightarrow m_\chi^{\min} =$19 MeV

- $R = \sum_N \int \frac{dR_N}{dT_N}dT_N$ (events/kg/yr)

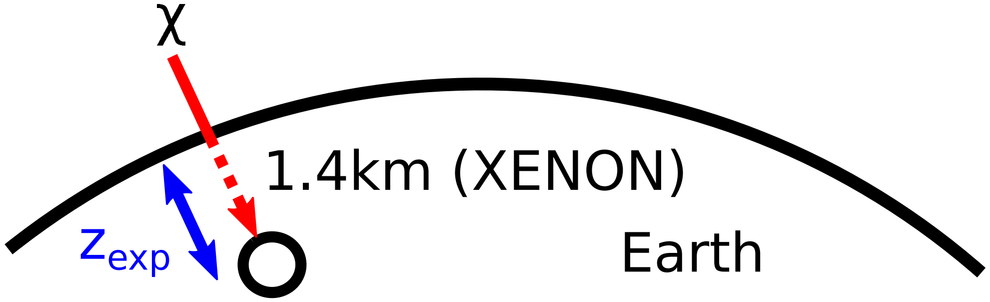


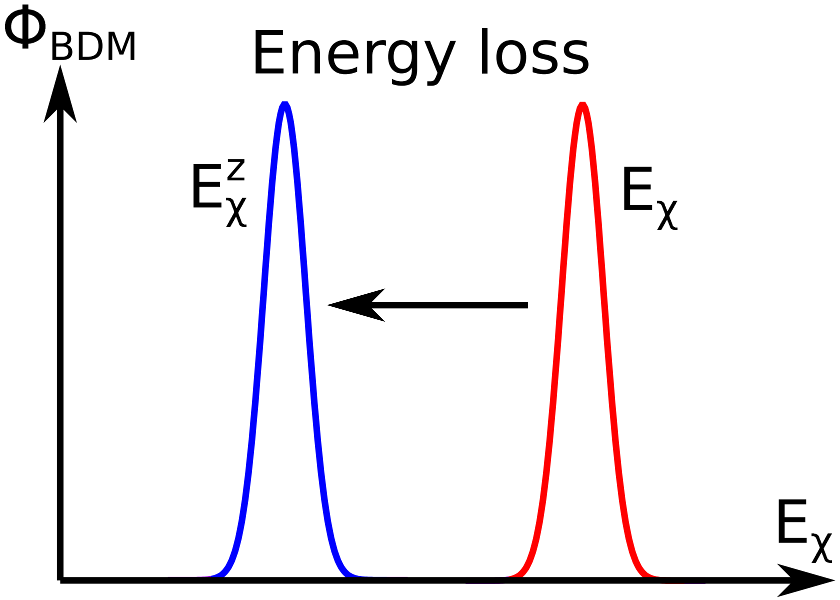
Attenuation due to overburden

Bringmann and Pospelov, PRL (2019)

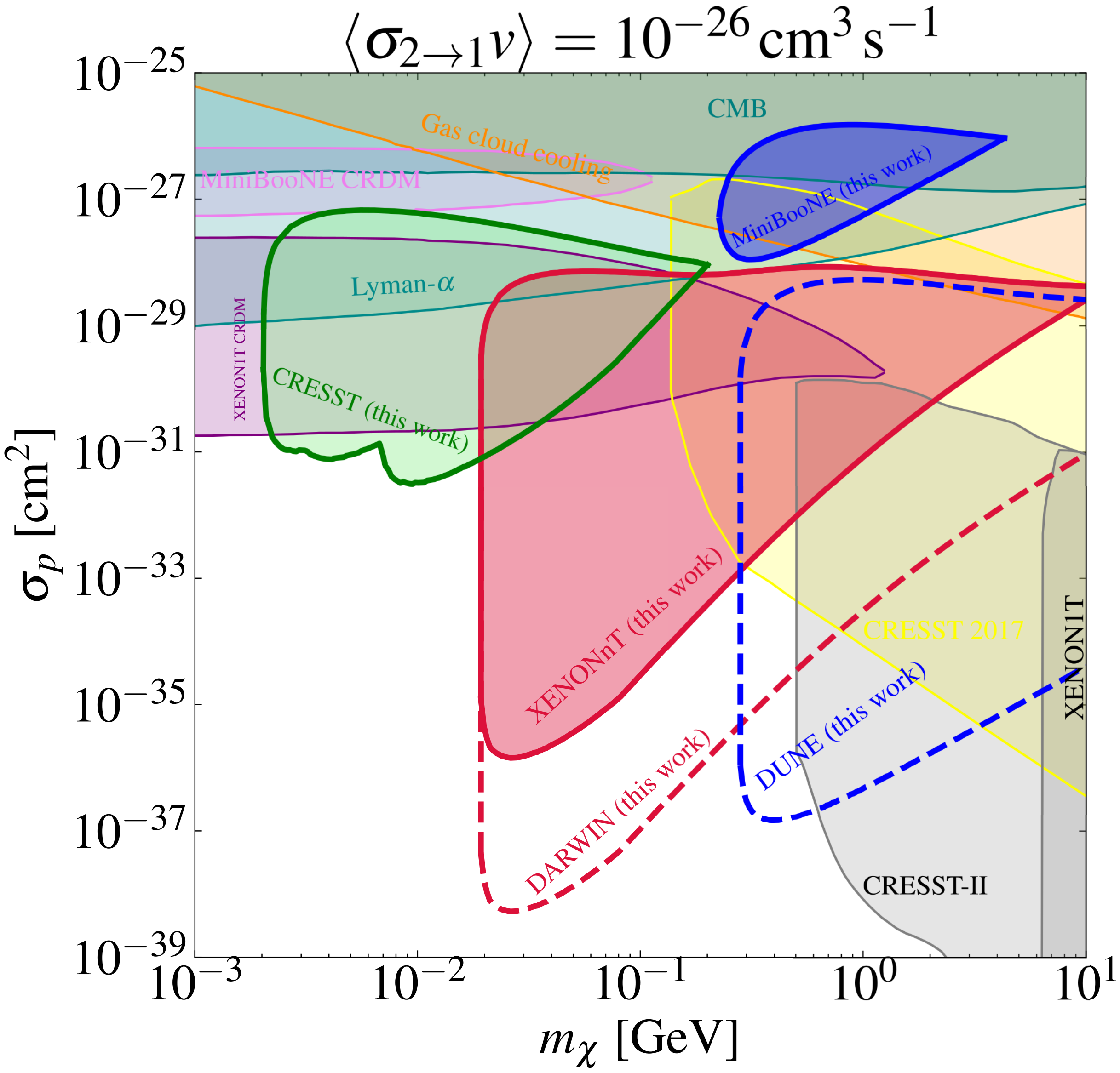
- Energy loss: $\dfrac{dT_\chi^z}{dz} = -\sum_N n_N \int_0^{T_\chi^{\max}} T_\chi \dfrac{d\sigma_{\chi N}}{dT_\chi} dT_\chi$
- If $m_\chi \ll m_N$, $T_\chi(z) \approx T_\chi(0) e^{-z/\ell}$

  where $\ell \equiv \sigma_p \sum_A 2 n_N A_N^2 \left(\dfrac{m_\chi}{m_N}\right)\left(1+\dfrac{m_\chi}{m_p}\right)^2\left(1+\dfrac{m_\chi}{m_N}\right)^{-4}$
- Soil component:
  O: 48%, Ca: 30%,
  C: 12%, Mg: 5.6%
  Density: $\rho = 2.71\ \mathrm{g/cm^3}$





Bound for SI cross section



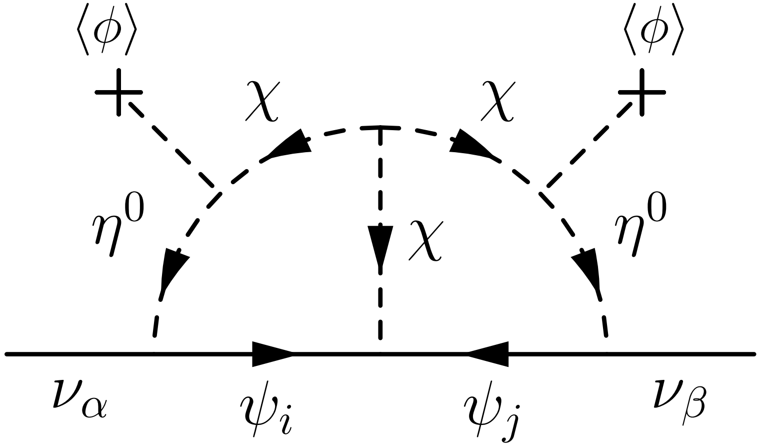
- Large σ_p region is not excluded due to strong attenuation.
- The excluded region is sharply cut at a small DM mass due to experimental threshold.
- XENONnT excluded $\sigma_p \sim 10^{-35}$ [cm^2] around $m_\chi \sim$ 30 MeV DARWIN: $\sigma_p \sim 10^{-38}$ [cm^2]
- Coherent enhancement is lost for larger DM mass.

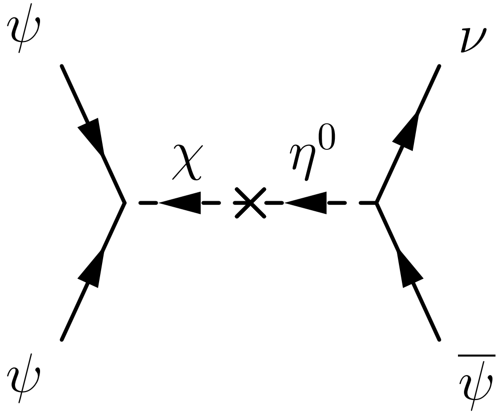
Concrete model

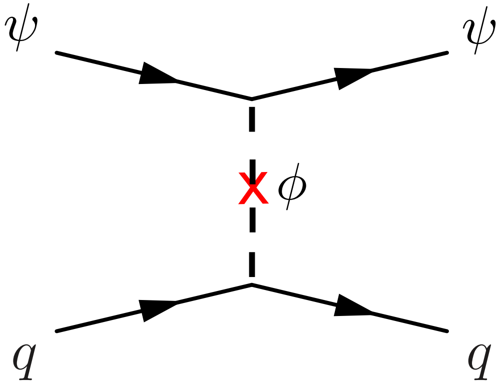
- $\mathbb{Z}_3$ symmetric neutrino mass model with a light scalar ϕ

  Ma, PLB 662 (2008), Aoki, TT, JCAP 09 016 (2014)

	SU(2)$_L$	U(1)$_Y$	$\mathbb{Z}_3$	spin
ψ_i	$\mathbf{1}$	0	1	1/2
χ	$\mathbf{1}$	0	1	0
η	$\mathbf{2}$	1/2	1	0
ϕ	$\mathbf{1}$	0	0	0







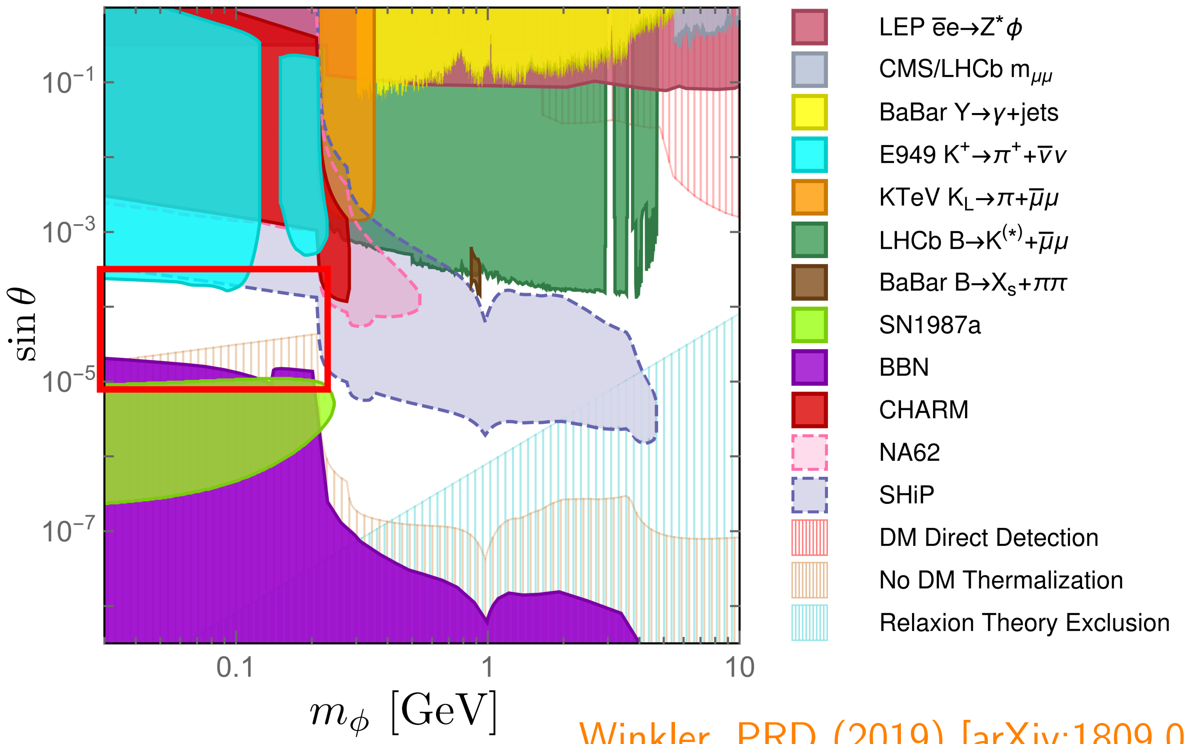
$\psi\overline{\psi} \to q\bar{q}$: p-wave

Concrete model

- $\mathbb{Z}_3$ symmetric neutrino mass model with a light scalar ϕ

  Ma, PLB 662 (2008), Aoki, TT, JCAP 09 016 (2014)

  - Scattering with nuclei through light scalar ϕ
  - Check other constraints (ν masses and mixings, LFV, EWPT etc)



Winkler, PRD (2019) [arXiv:1809.01876]

Summary

1. Conventional thermal DM scenarios are strongly constrained.
2. Direct detection experiments have low sensitivity in sub-GeV scale.
3. Semi-annihilations accelerate DM coming from Galactic Center.
4. We found high sensitivity for BDM in sub-GeV mass range through XENON and DUNE.

Future work

- Explore a concrete DM model