Dark matter self-interaction:

the fate of the spike & annihilation-boosted dark matter in the Milky Way galaxy

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Collaboration w/

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(TU Munich)

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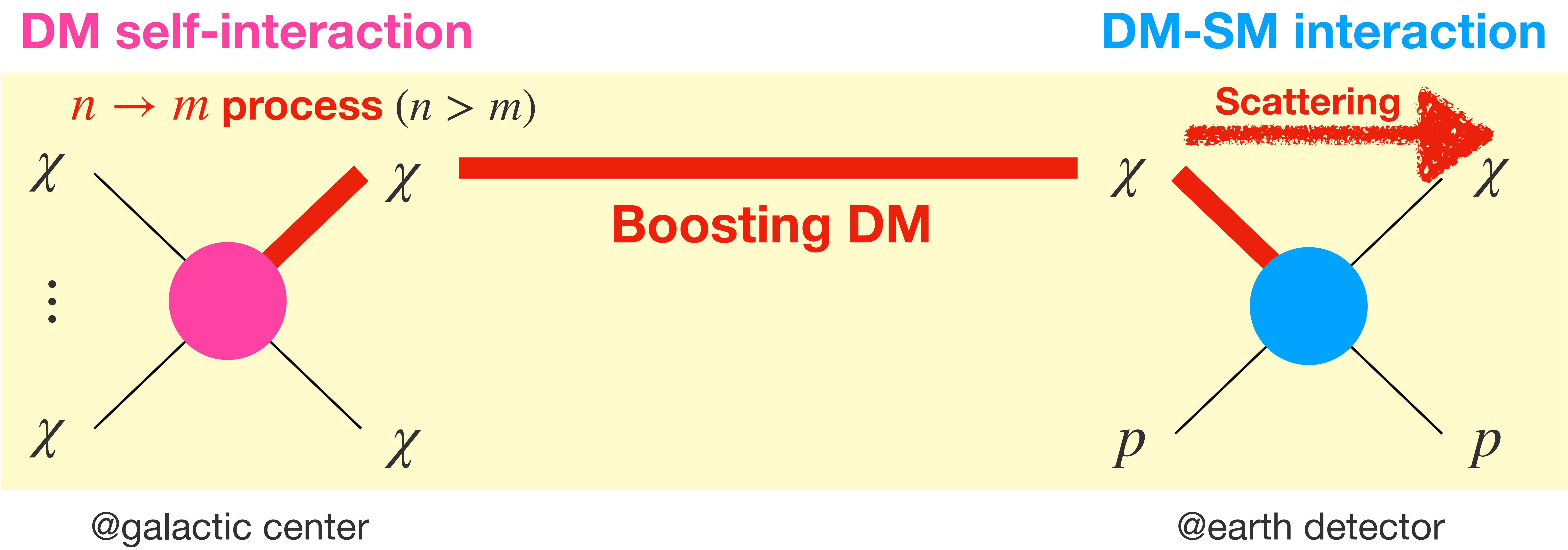
(Kanazawa U.)

Seminar @MITP workshop, Mainz Sept. 3rd, 2024

[Work in progress]

Dark matter self-interaction

Question: **What is the DM search strategy, including self-interaction?**



Answer: **“Annihilation” Boosted DM scatt. w/ $n \to m$ kinematical feature**

Particle Dark Matter

Idea: Dark Matter (DM) $\stackrel{?}{=}$ elementary particle

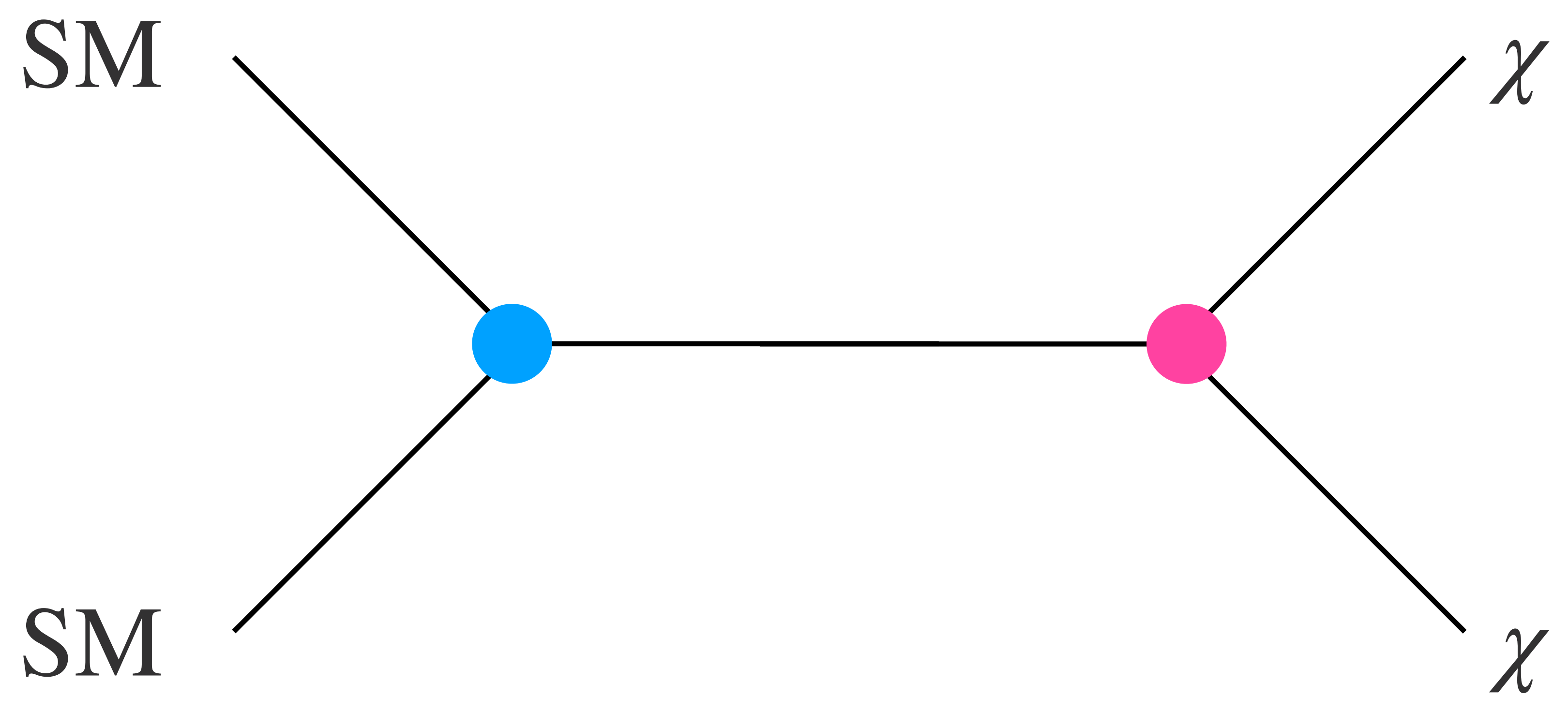
Goal: Elucidate DM interaction theory

$\simeq$ Writing down SM + DM Lagrangian

$$\{\ m_\chi,\ \alpha_{\rm SM},\ \alpha_{\rm self}\ \}$$

DM mass | DM-SM int. | DM self-int.

cf. DM-SM interaction via mediator



Particle Dark Matter

Idea: Dark Matter (DM) $\stackrel{?}{=}$ elementary particle

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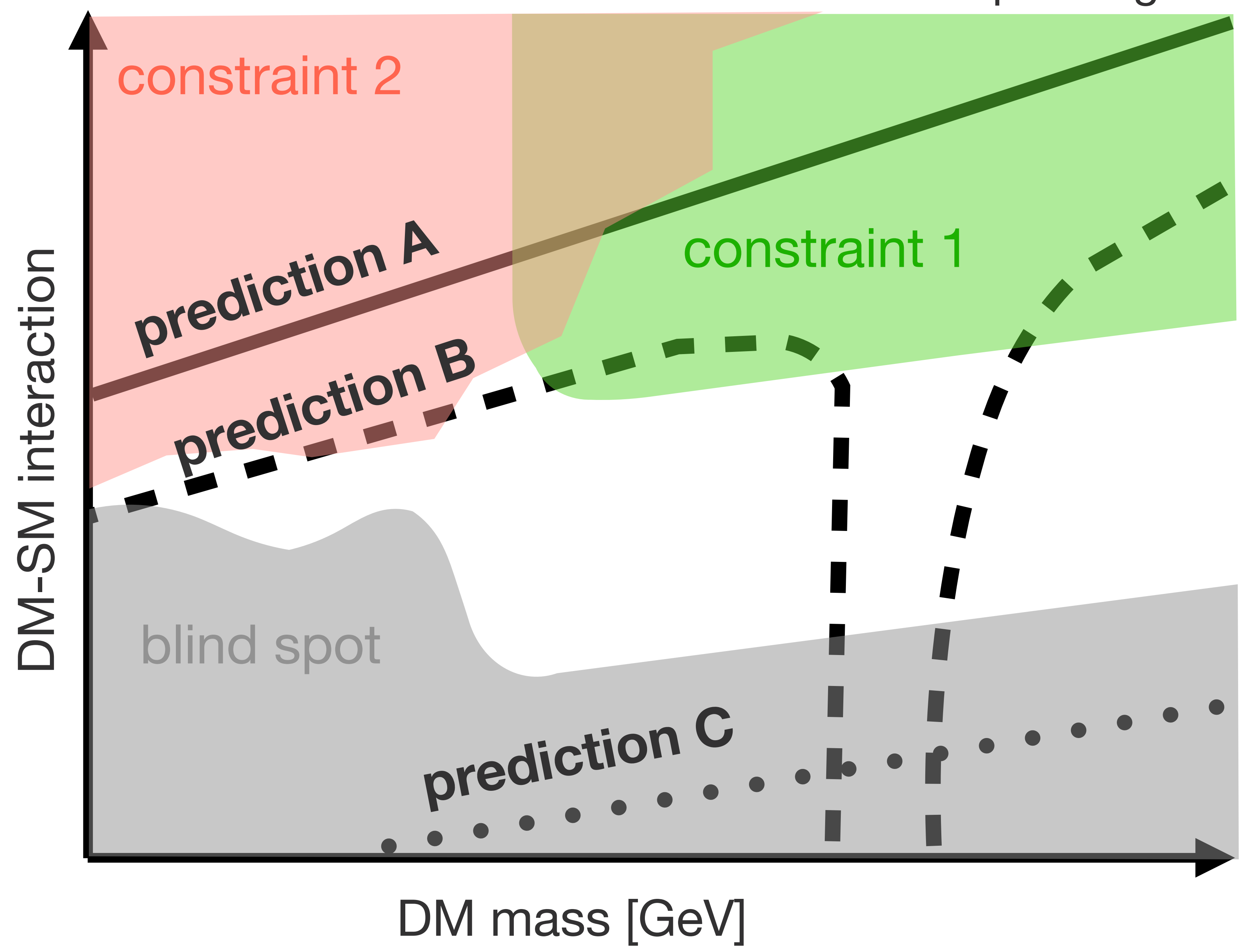
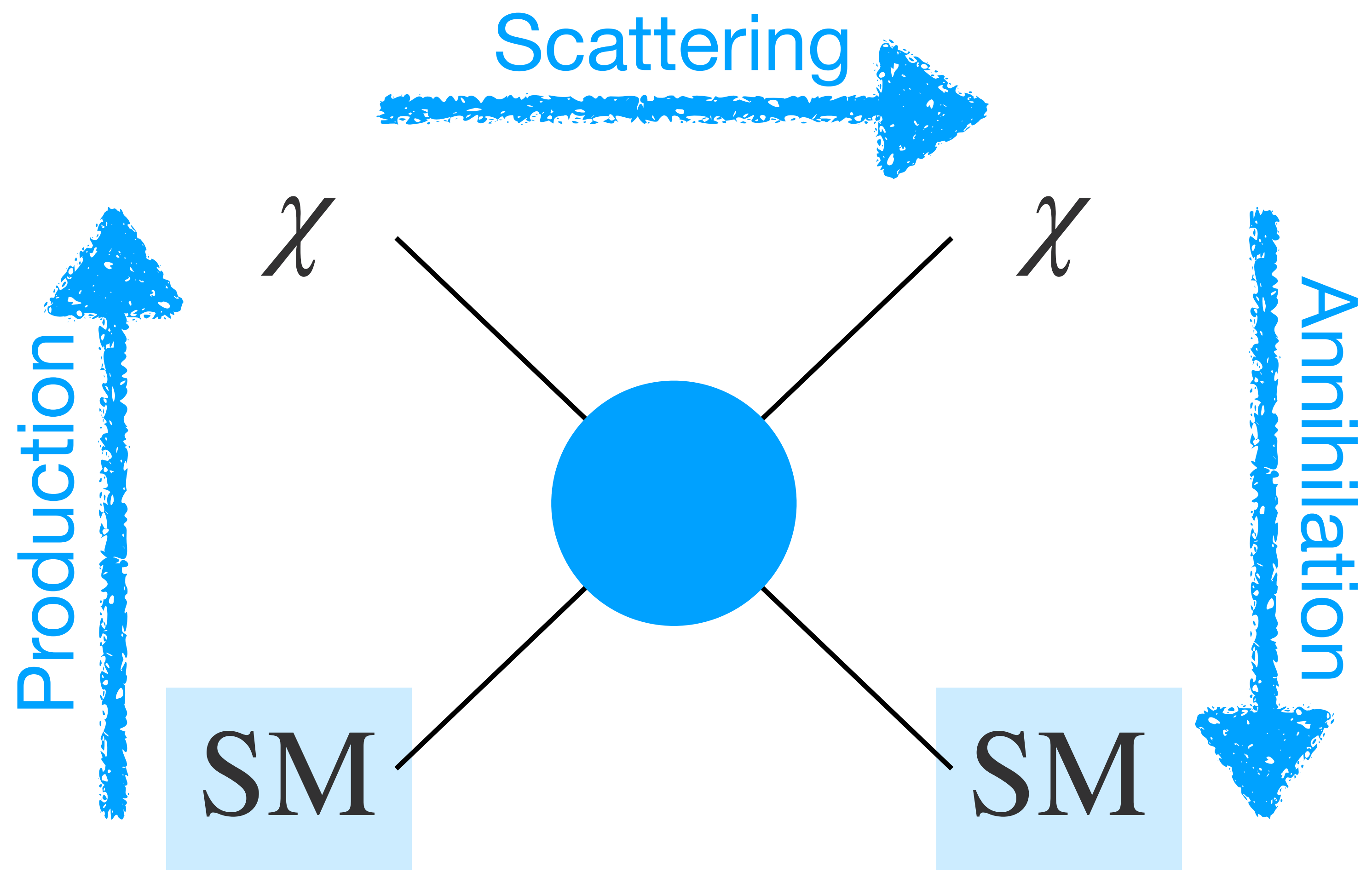
※ conceptual figure



Search strategy?

$$\{ m_\chi,\ \alpha_{SM},\ \alpha_{self} \}$$

cf. WIMP search strategy



DM-SM interaction

- As we have studied broadly so far!
- cf. Discussions last week [(Strongly interacting) DM at collider] [Sub-GeV DM]

Particle Dark Matter

Idea: Dark Matter (DM) $\stackrel{?}{=}$ elementary particle

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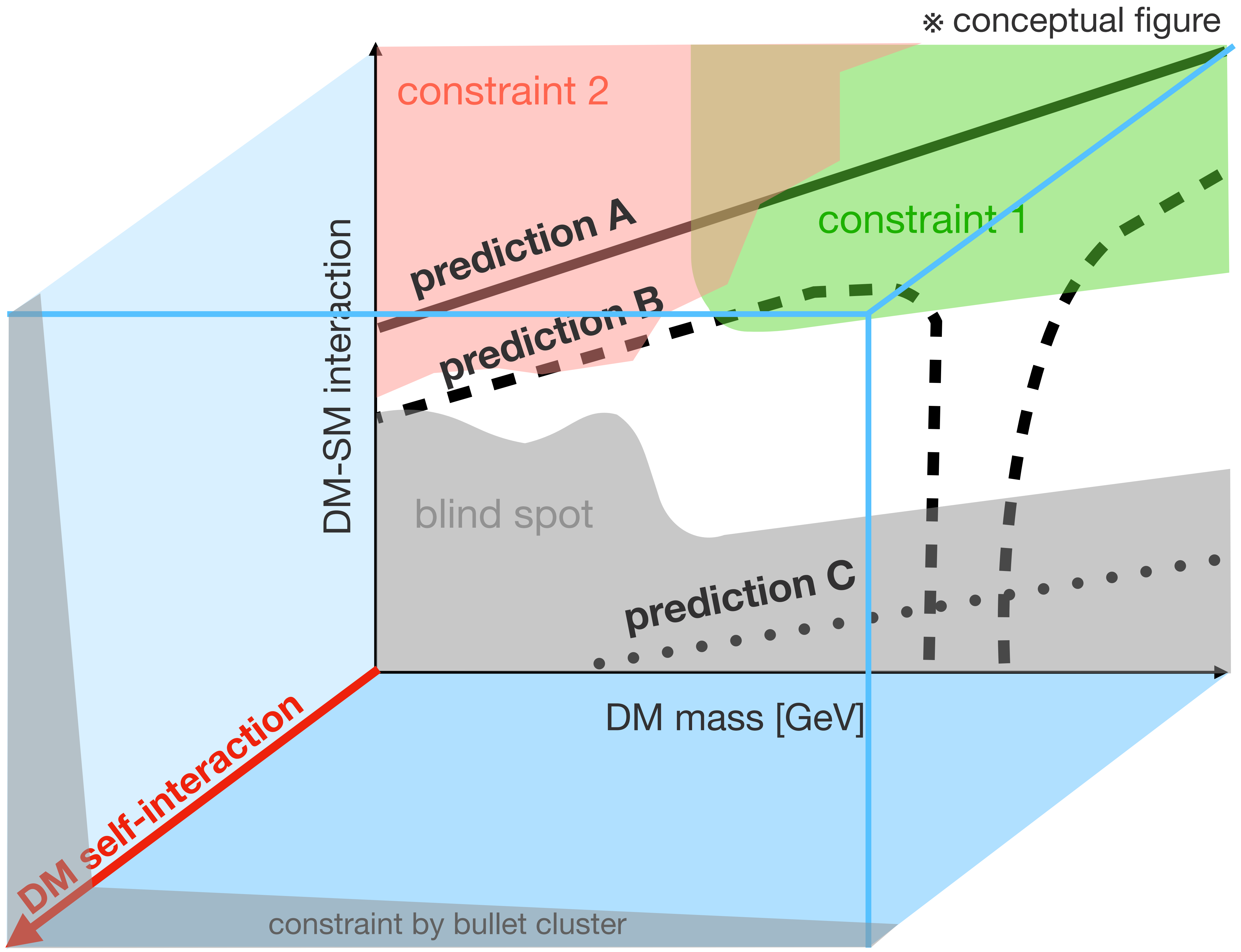
$\simeq$ Writing down SM + DM Lagrangian

Search strategy?

$$\{ m_\chi, \quad \alpha_{\rm SM}, \quad \alpha_{\rm self} \}$$



Question: **What is the DM search strategy, including self-interaction?**

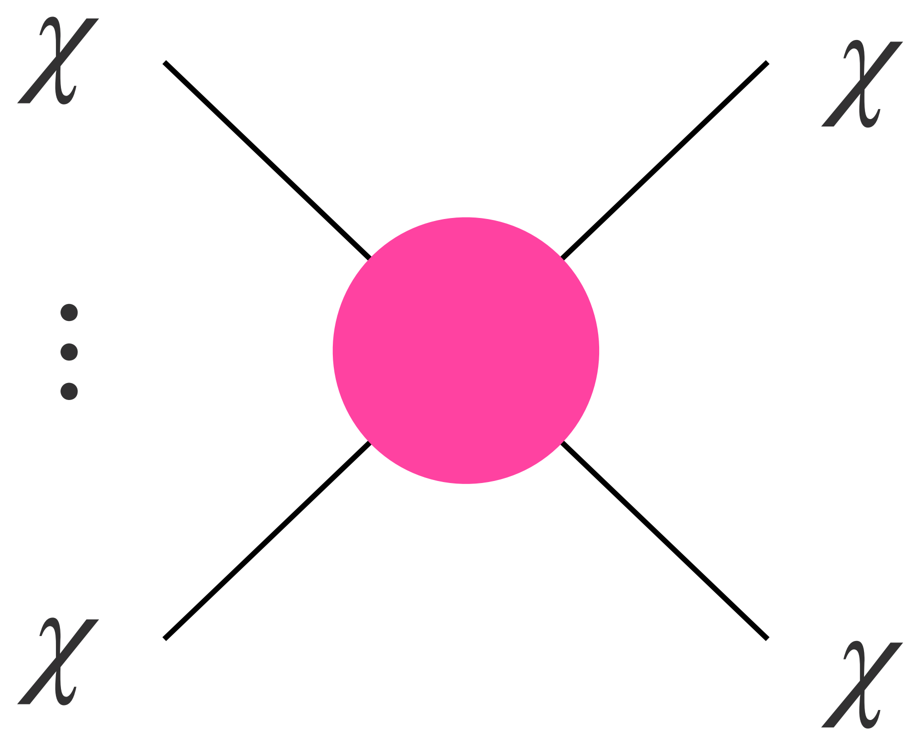
DM self-interaction

- (Could be) the most challenging part for experimental search
- Key to determine DM density distribution around galactic center → "DM circumstance" = Crucial input for astro. studies

cf. Gonzalo's talk

Question: **What is the key prediction of DM self-interaction to determine search strategy?**

DM number changing process ($n \to m$ process)

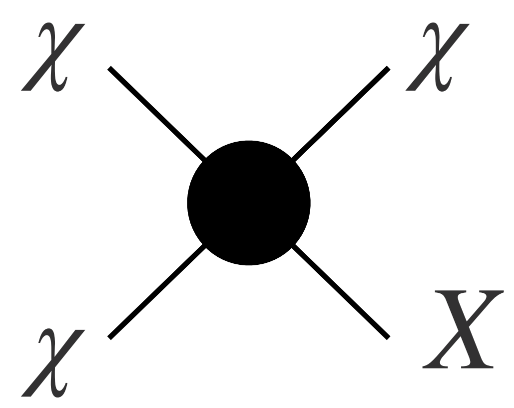


Initial: n DM

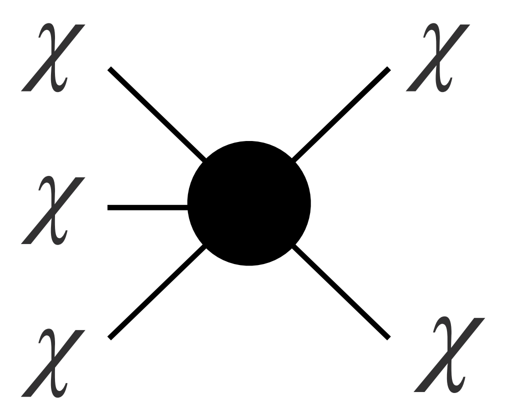
Final: m DM

$(n > m)$

- $n = 2:$ $\chi\chi \to \chi X$



- $n = 3:$ $\chi\chi\chi \to \chi\chi$



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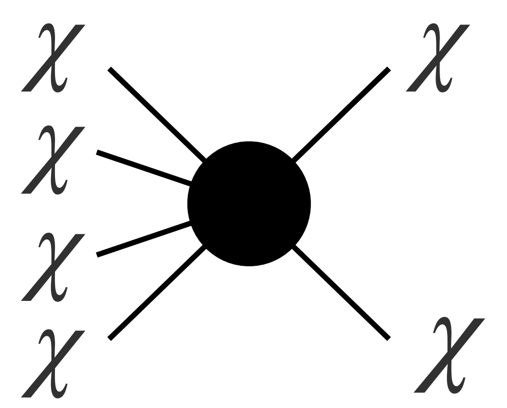
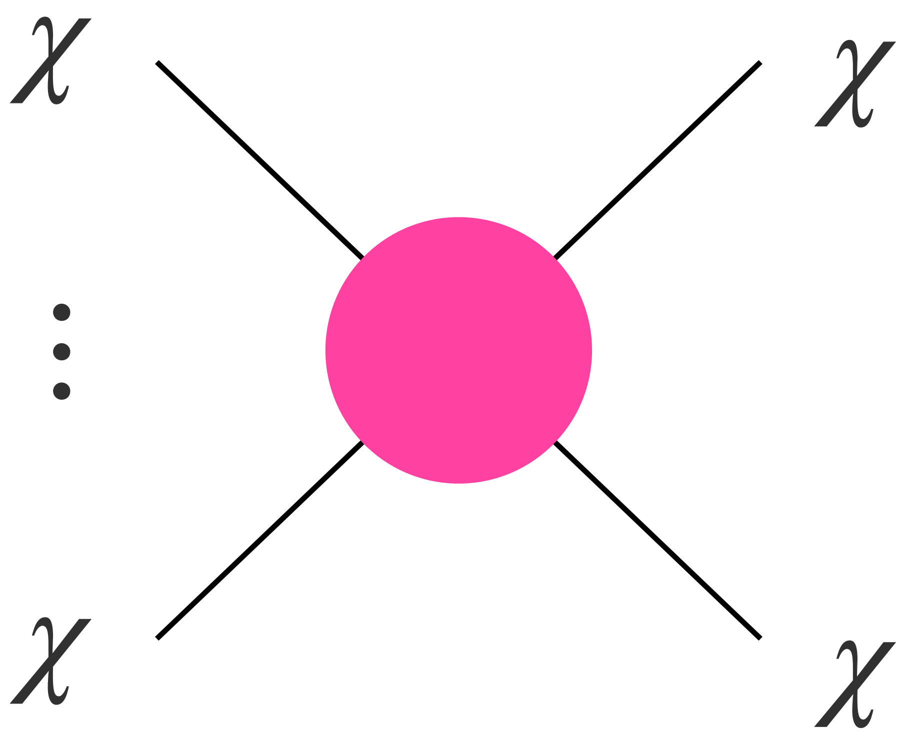


⋮

DM number changing process ($n \to m$ process)



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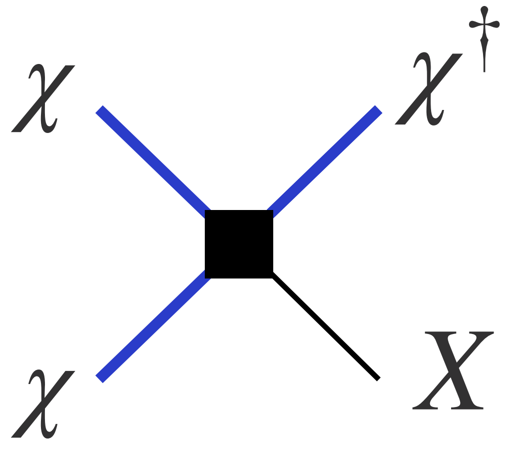
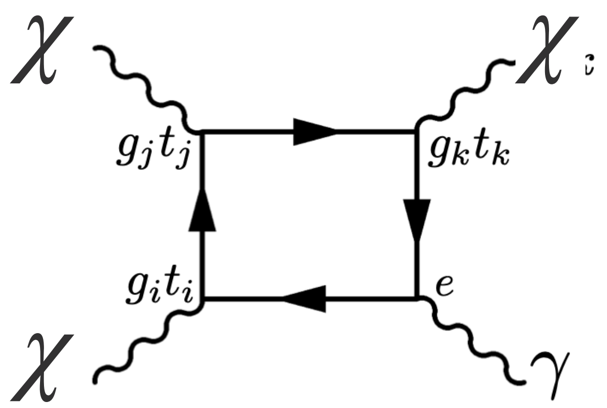


[F. D'Eramo, J. Thaler (2010)]



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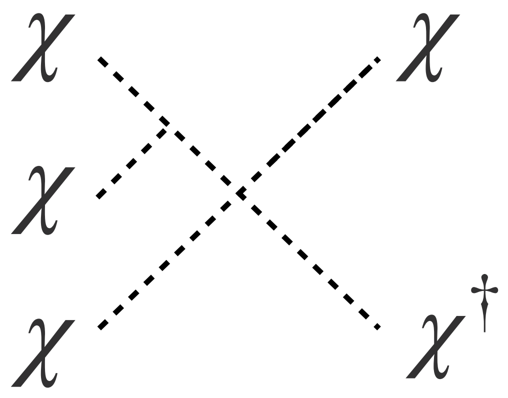

e.g. [Y. Hochberg, et al. (2014)]

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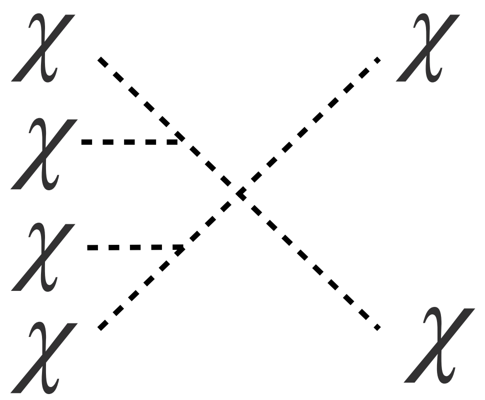


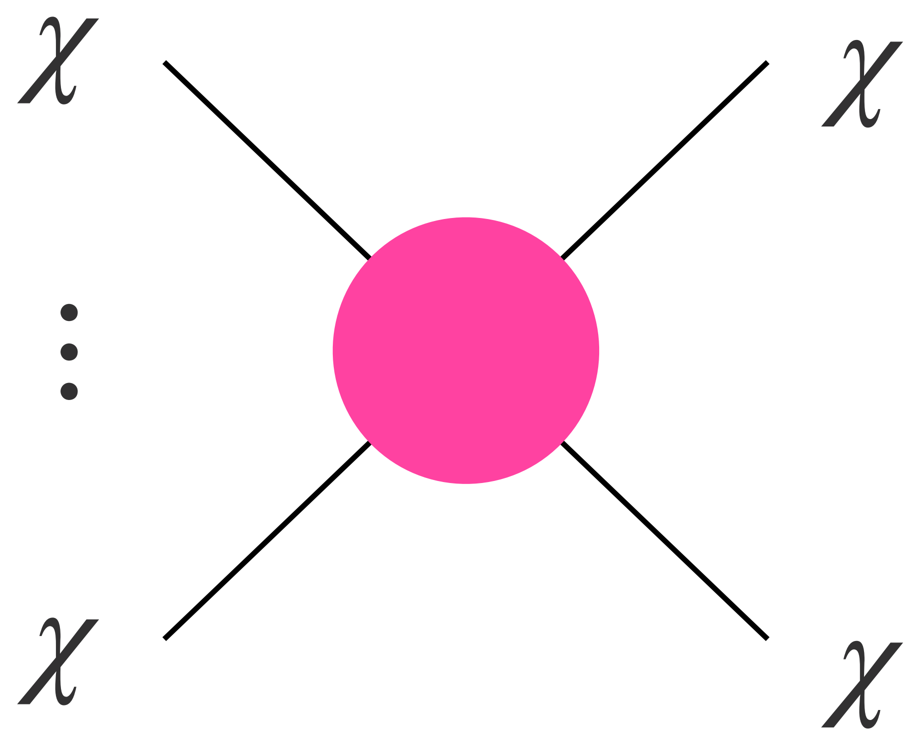
e.g. [J. Herms, et al. (2018)]

⋮

DM number changing process ($n \to m$ process)

Several functions

- Associated by DM self-interaction (cf. DM self-scattering) → Break correlation btw DM-SM interaction & self-interaction
- Affect DM density profile → The effect may be inherited in DM signature at local galaxy
- Accelerate DM particle by $n \to m$ kinematics → New functions in DM search?



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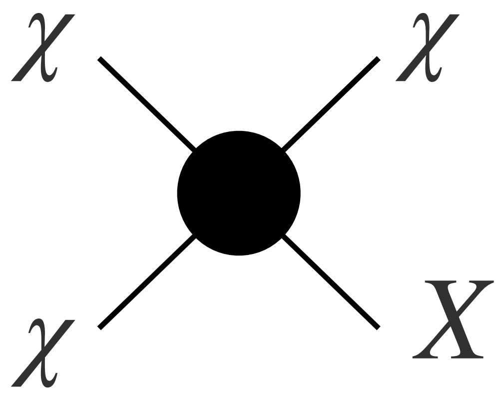
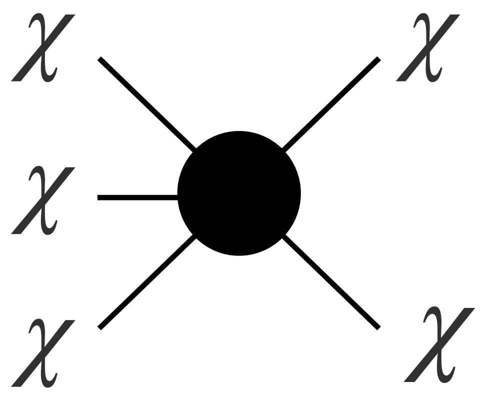


(∵ momentum cons.)

- $n = 3$: $\chi\chi\chi \to \chi\chi$



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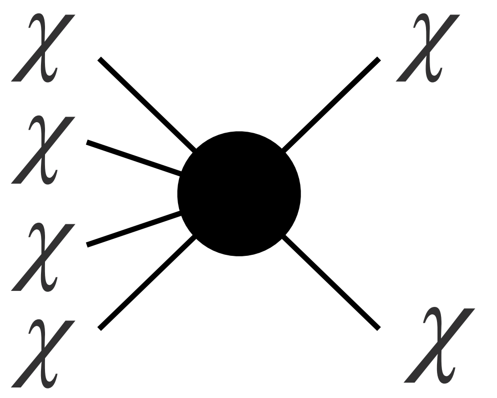


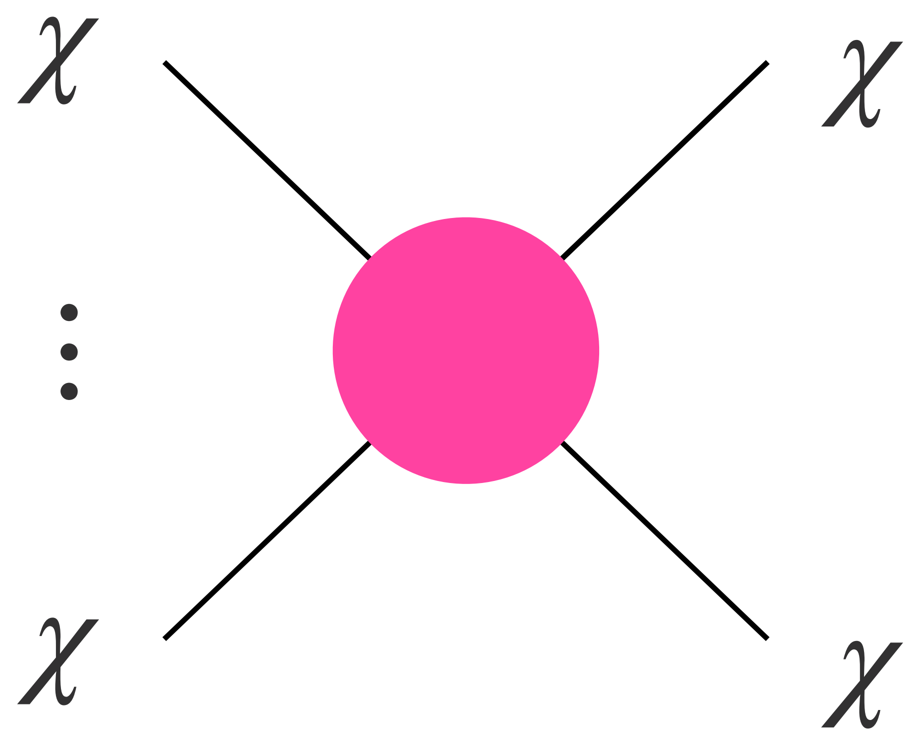
⋮

Strategy

New approach to probe DM self-interaction

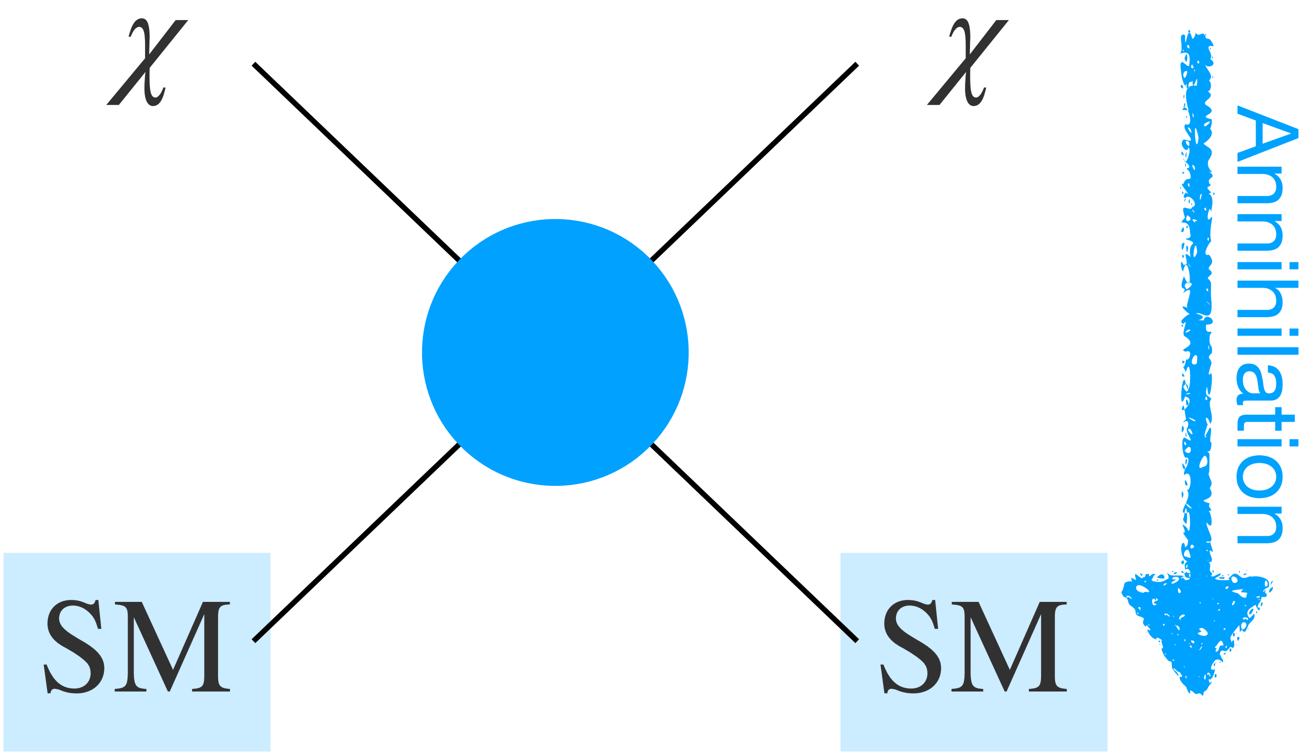
- Challenging to probe DM-only process?
- Absence of smoking gun signature?
- Suppressed rate by number density?

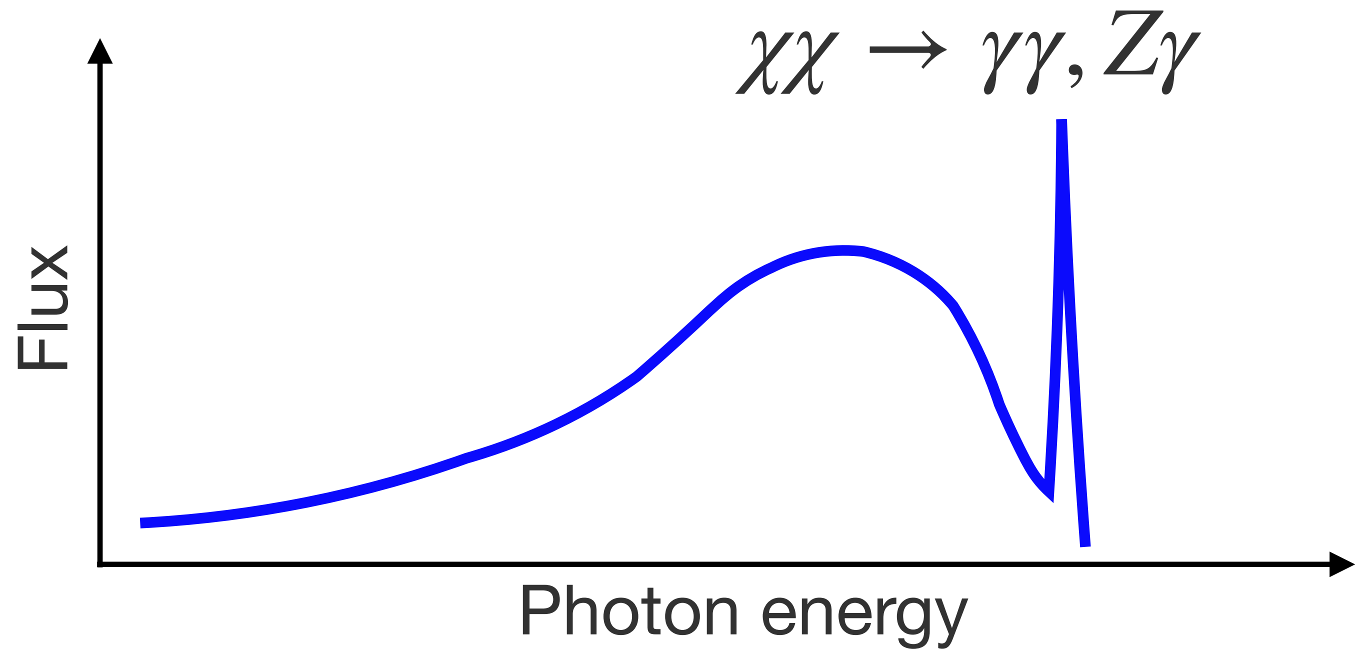
$n \to m$ **process**



$$\Gamma = \# \left(\frac{\rho_\chi}{m_\chi} \right)^n \langle \sigma_{n \to m} v^{n-1} \rangle$$

cf. WIMP search strategy





Strategy

New approach to probe DM self-interaction

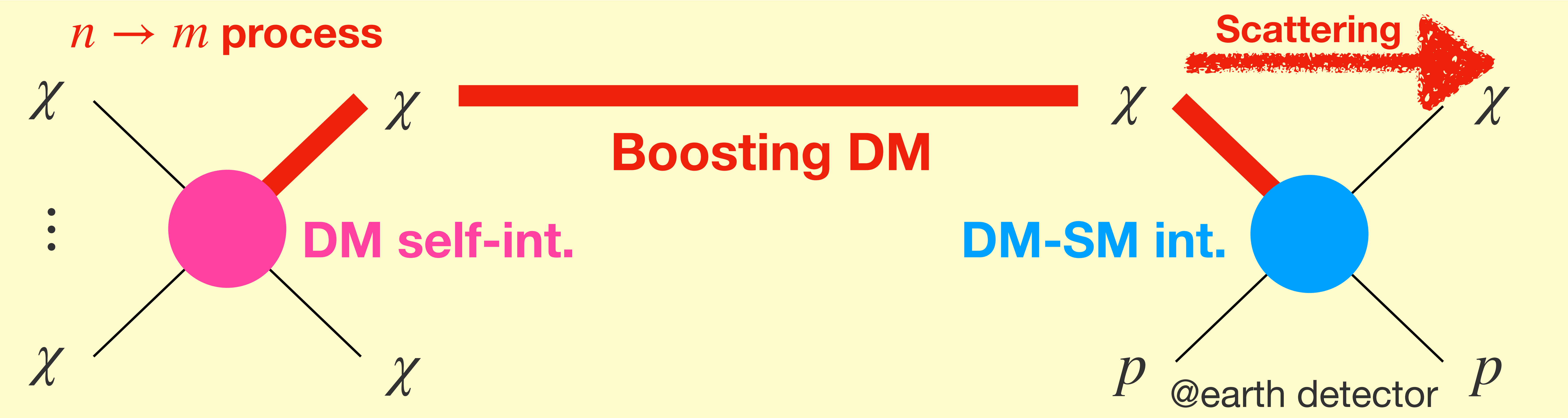
- Challenging to probe DM-only process? → **Clear policy that we MUST combine w/ DM-SM interaction**
- Absence of smoking gun signature?
- Suppressed rate by number density?

$$\Gamma = \# \left(\frac{\rho_\chi}{m_\chi} \right)^n \langle \sigma_{n \to m} v^{n-1} \rangle$$

Strategy

New approach to probe DM self-interaction

- Challenging to probe DM-only process? → Clear policy that we MUST combine w/ DM-SM interaction
- Absence of smoking gun signature? → **Search for Boosted DM Signature** ($E_\chi \simeq \mathcal{O}(m_\chi)$) cf. Shao-Feng's talk
- Suppressed rate by number density?



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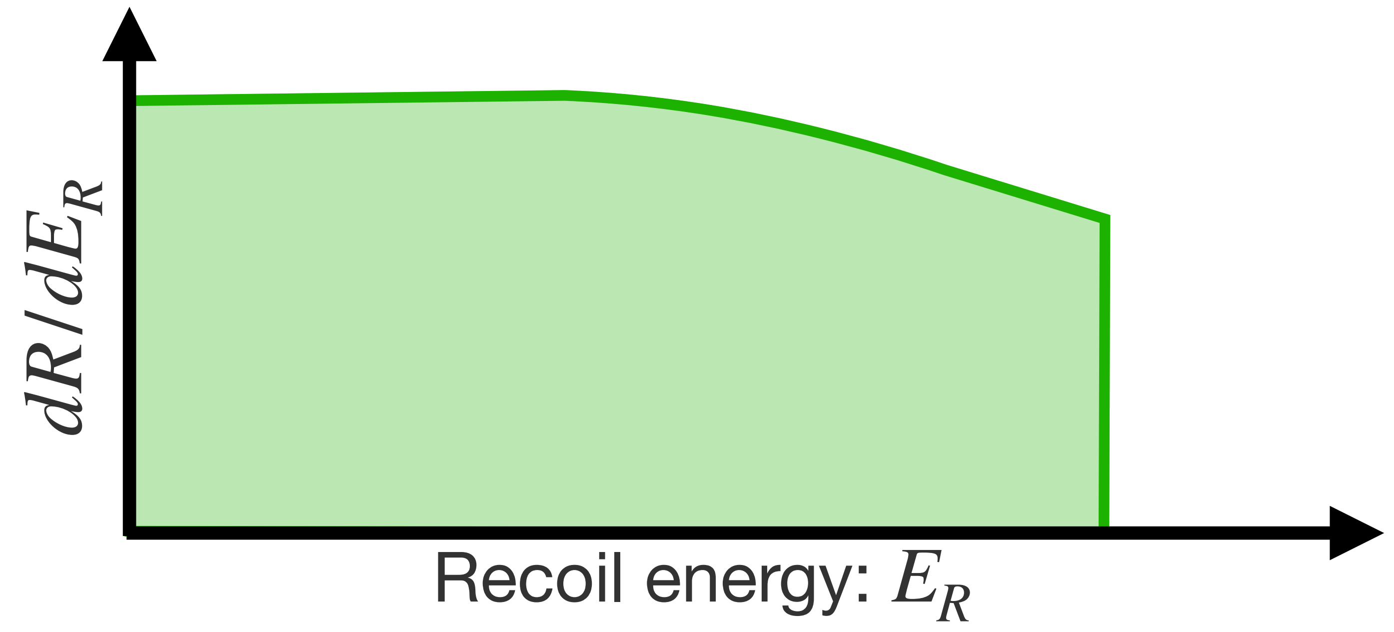
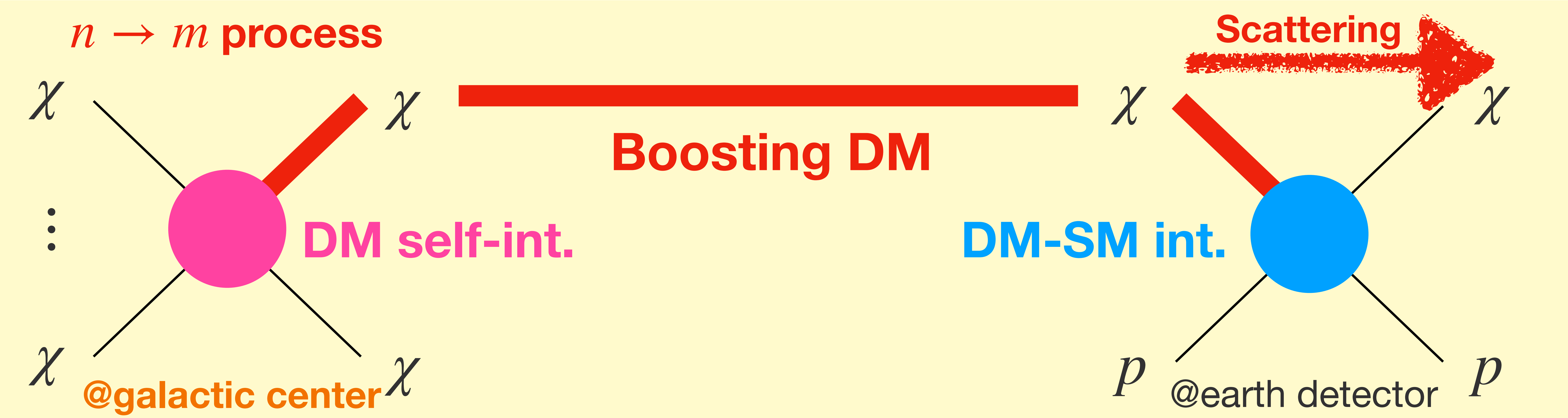


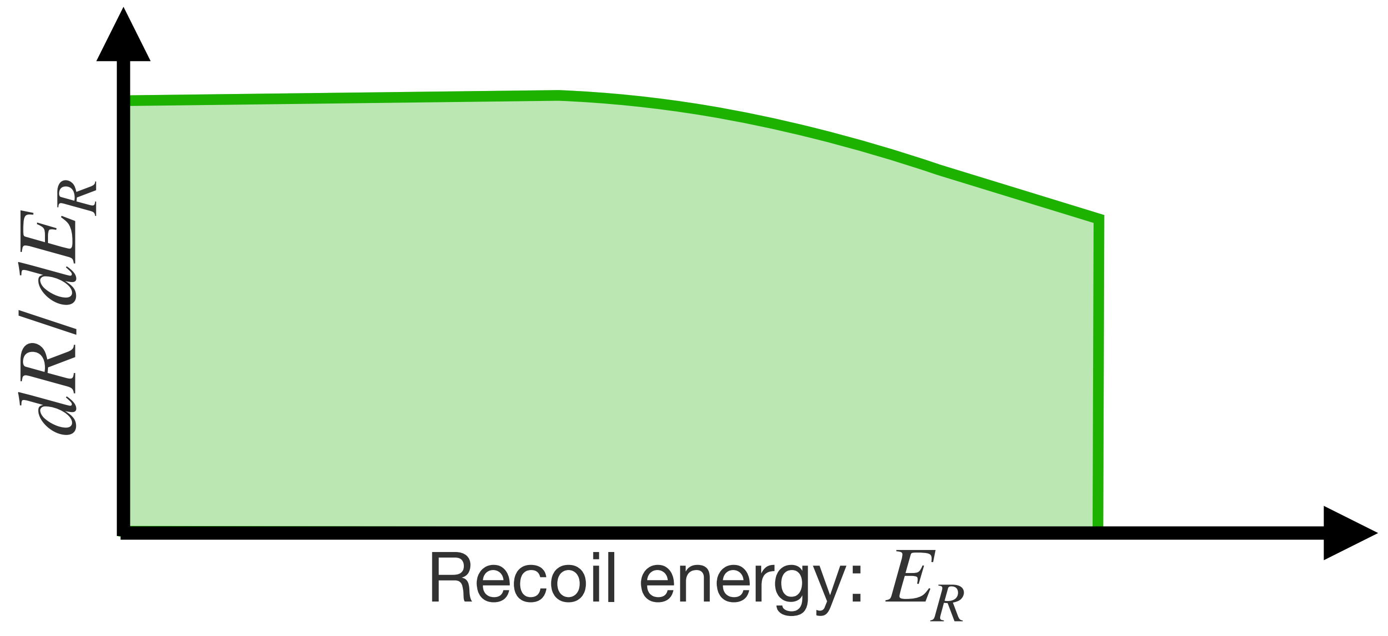
Strategy

New approach to probe DM self-interaction

- Challenging to probe DM-only process? → Clear policy that we MUST combine w/ DM-SM interaction
- Absence of smoking gun signature? → Search for Boosted DM Signature ($E_\chi \simeq \mathcal{O}(m_\chi)$)
- Suppressed rate by number density? → **DM dense circumstance may enhance boosted DM source**



$$\Gamma = \#\left(\frac{\rho_\chi}{m_\chi}\right)^n \langle \sigma_{n\to m} v^{n-1} \rangle$$



Strategy

New approach to probe DM self-interaction

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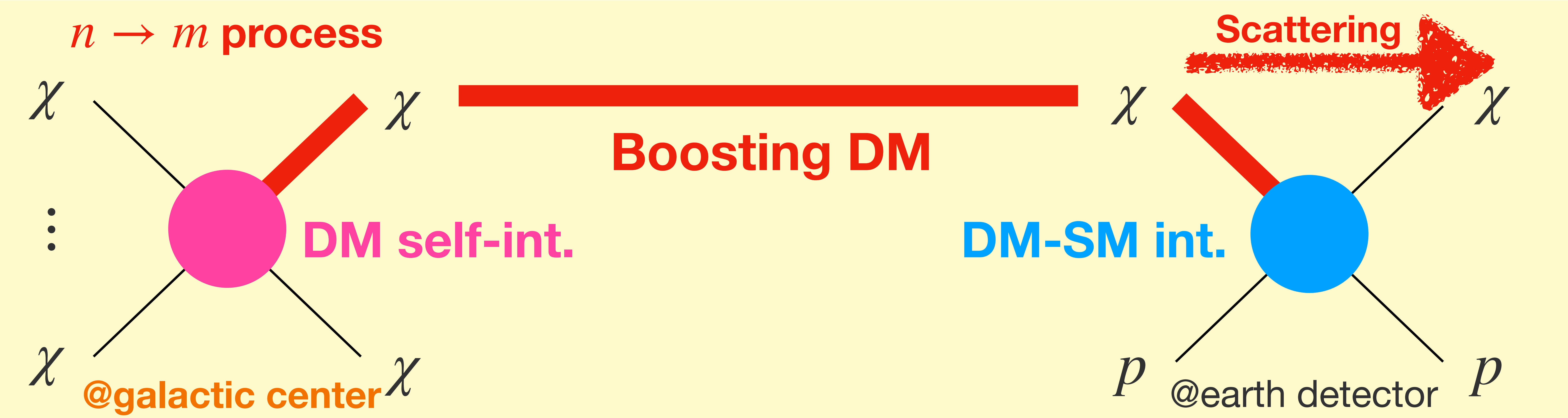


See also [K. Agashe, et al. (2014)] [D. McKeen, N. Raj (2019)] [T. Toma (2022)] [M. Aoki, T. Toma (2023)]

Our question: **What is the consequence of $n \to m$ processes?**

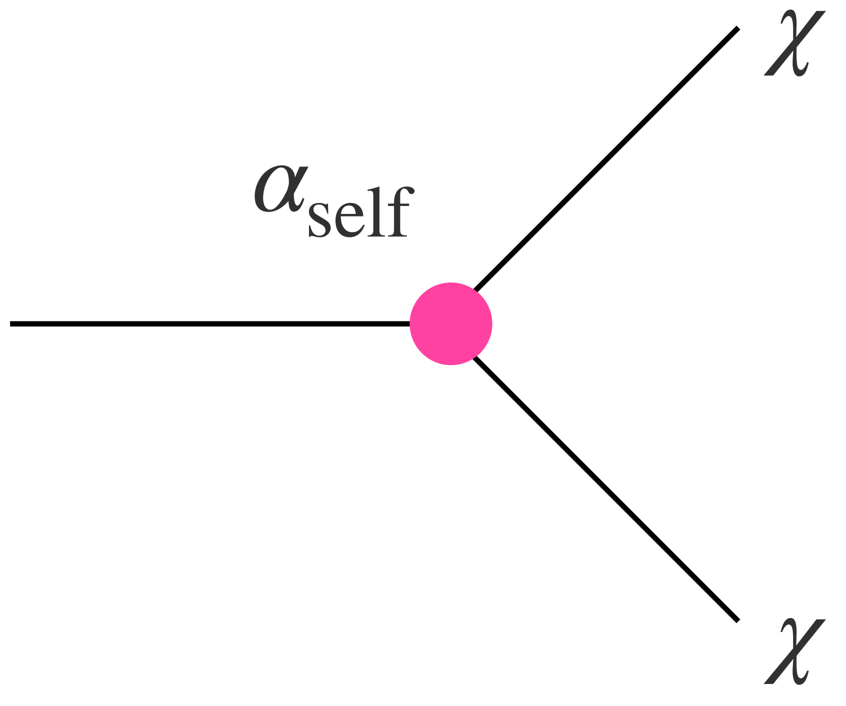
How can we probe parameters of DM interaction theory?

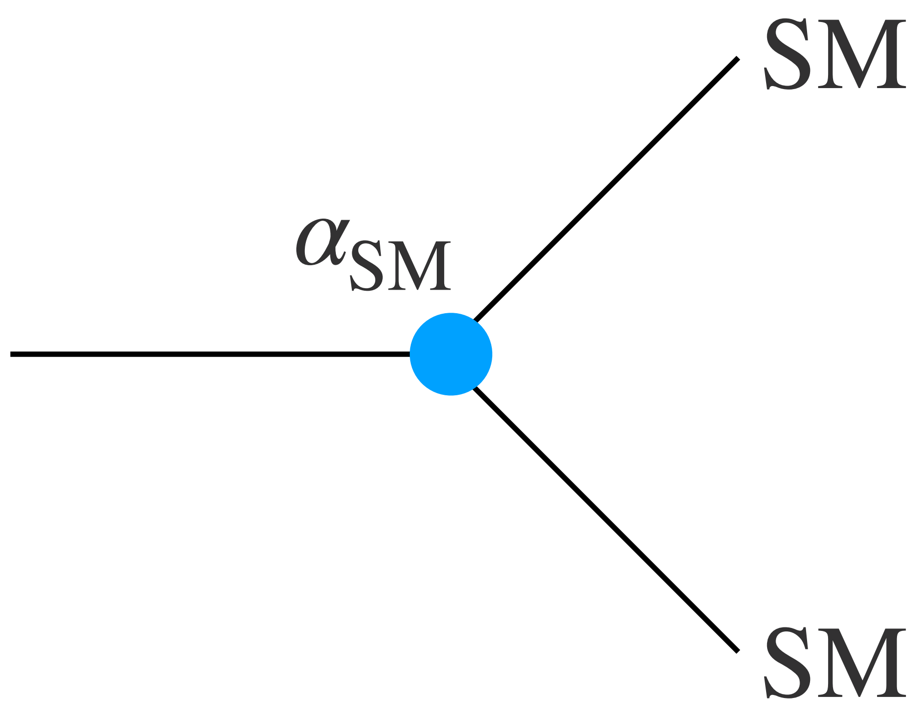
Contents

Setup

Model-independent parametrization

Boosted DM flux from GC: $\Phi_{\mathrm{BDM}} = \frac{1}{n!}\frac{r_\odot}{4\pi}\left(\frac{\rho_\odot}{m_\chi}\right)^n \times \langle \sigma_{n\to m} v^{n-1}\rangle \times \left[2\pi \int d\theta \sin\theta \int_{\mathrm{l.o.s}} \frac{ds}{r_\odot}\left(\frac{\rho_\chi(r(s,\theta))}{\rho_\odot}\right)^n\right]$

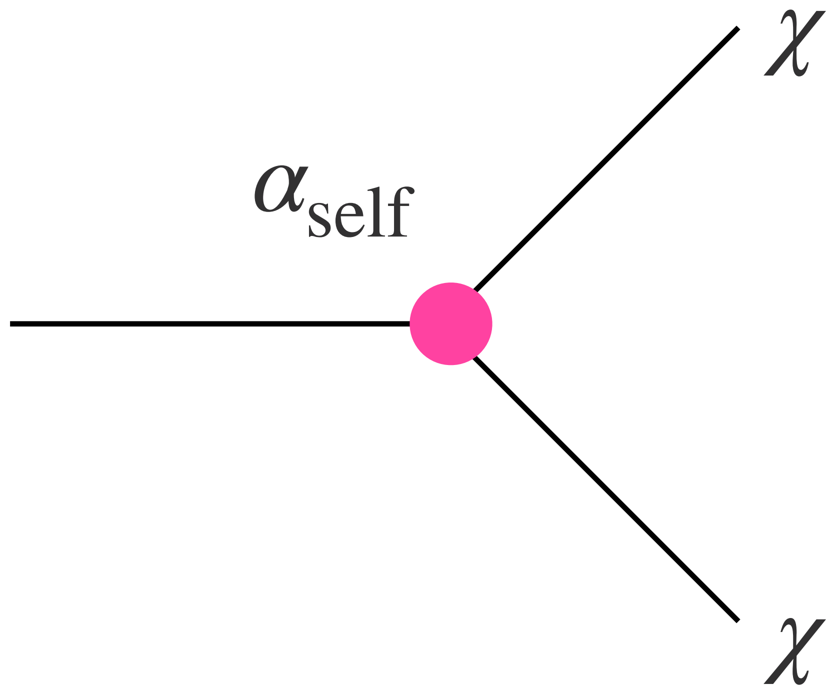


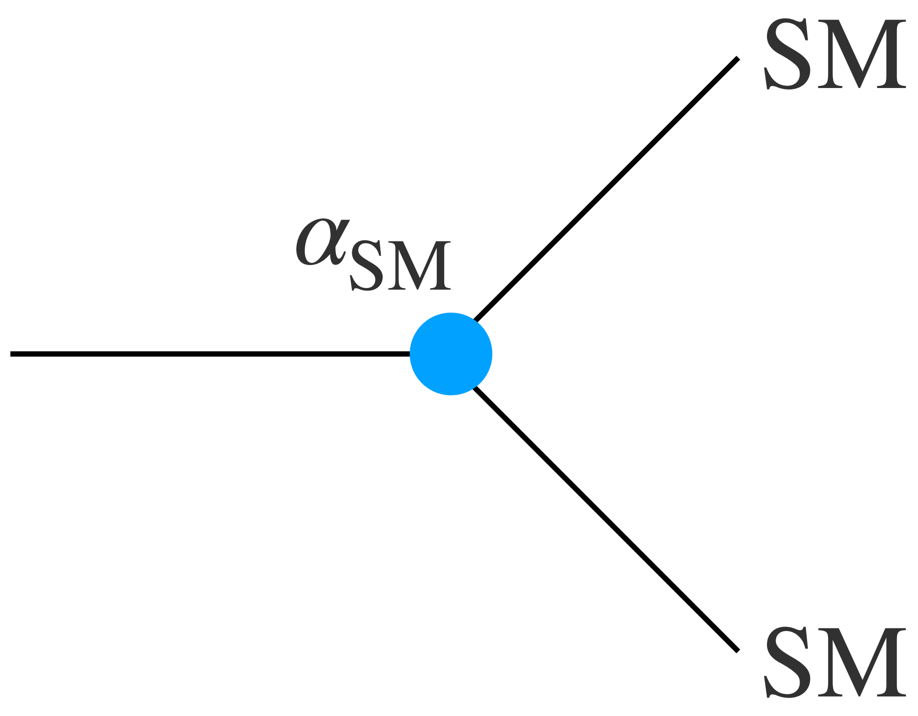


Cross section	Boost DM	Determine ρ_χ
$\langle \sigma_{n\to m} v^{n-1}\rangle = \frac{\alpha_{\mathrm{self}}^n}{m_\chi^{3n-4}}$	✔	
$\sigma_{2\to 2} = \frac{\alpha_{2\to 2}^2}{m_\chi^2} \equiv a^2 \frac{\alpha_{\mathrm{self}}^2}{m_\chi^2}$	$a \sim 1$	
$\langle \sigma_{\mathrm{ann}} v\rangle = \frac{\alpha_{2\to 0}^2}{m_\chi^2} \equiv b^2 \frac{\alpha_{\mathrm{self}}^2}{m_\chi^2}$	$b \sim \left(\frac{\alpha_{\mathrm{SM}}}{\alpha_{\mathrm{self}}}\right)^{\frac{1}{2}}$	

Model-independent parametrization

Boosted DM flux from GC: $\Phi_{\rm BDM} = \frac{1}{n!}\frac{r_\odot}{4\pi}\left(\frac{\rho_\odot}{m_\chi}\right)^n \times \langle \sigma_{n\to m} v^{n-1}\rangle \times \left[2\pi \int d\theta \sin\theta \int_{\rm l.o.s} \frac{ds}{r_\odot}\left(\frac{\rho_\chi(r(s,\theta))}{\rho_\odot}\right)^n\right]$

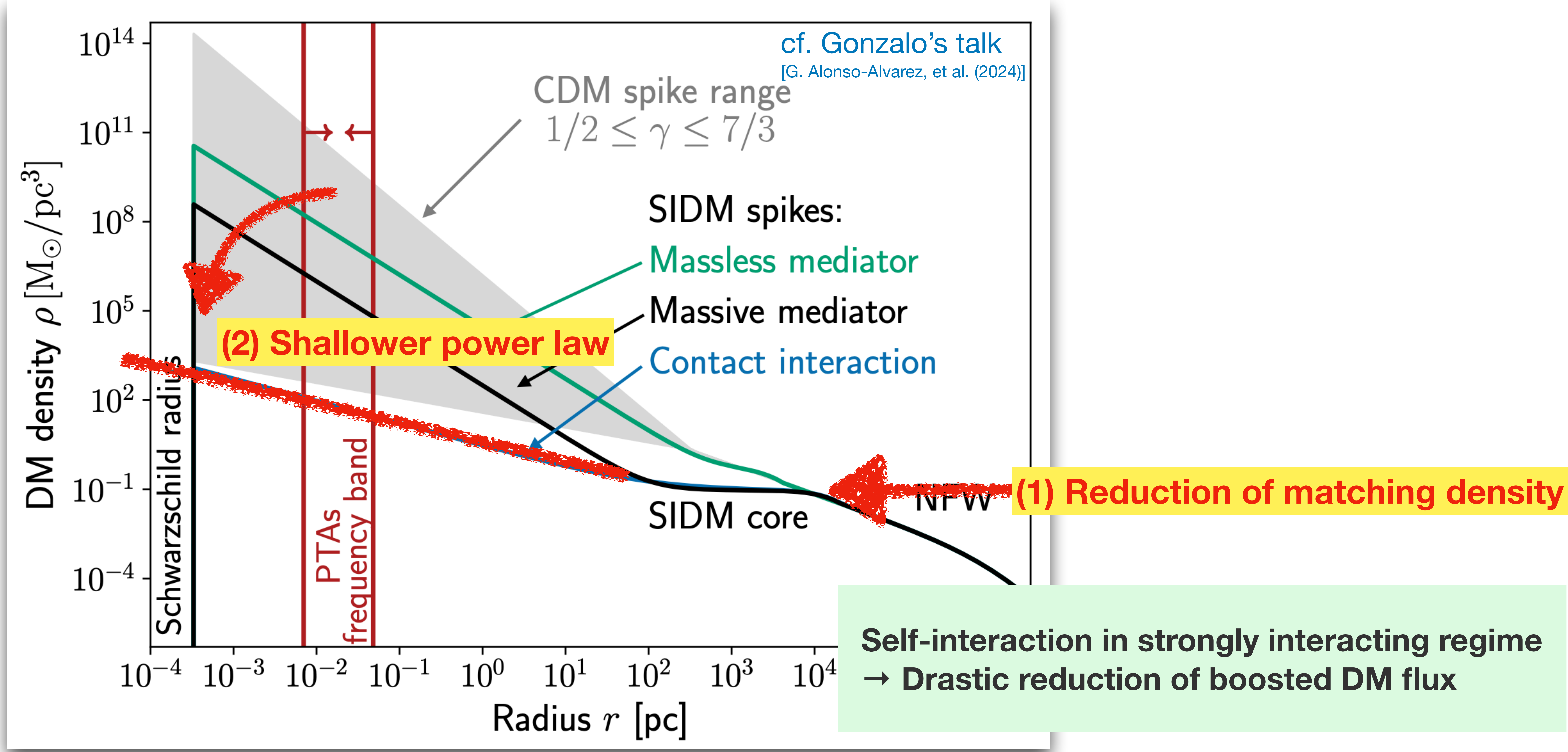




Cross section	**Boost DM**	**Determine ρ_χ**
$\langle \sigma_{n\to m} v^{n-1}\rangle = \frac{\alpha_{\rm self}^n}{m_\chi^{3n-4}}$	✔	✔ Self-heating Dissolving via $n \to m$
$\sigma_{2\to 2} = \frac{\alpha_{2\to 2}^2}{m_\chi^2} \equiv a^2 \frac{\alpha_{\rm self}^2}{m_\chi^2}$	$a \sim 1$	✔ Self-scattering
$\langle \sigma_{\rm ann} v\rangle = \frac{\alpha_{2\to 0}^2}{m_\chi^2} \equiv b^2 \frac{\alpha_{\rm self}^2}{m_\chi^2}$	$b \sim \left(\frac{\alpha_{\rm SM}}{\alpha_{\rm self}}\right)^{\frac{1}{2}}$	✔ Dissolving via $2 \to 0$

[S. L. Shapiro, et al. (2014)] [S. L. Shapiro (2018)]

1. Spike from self-scattering core



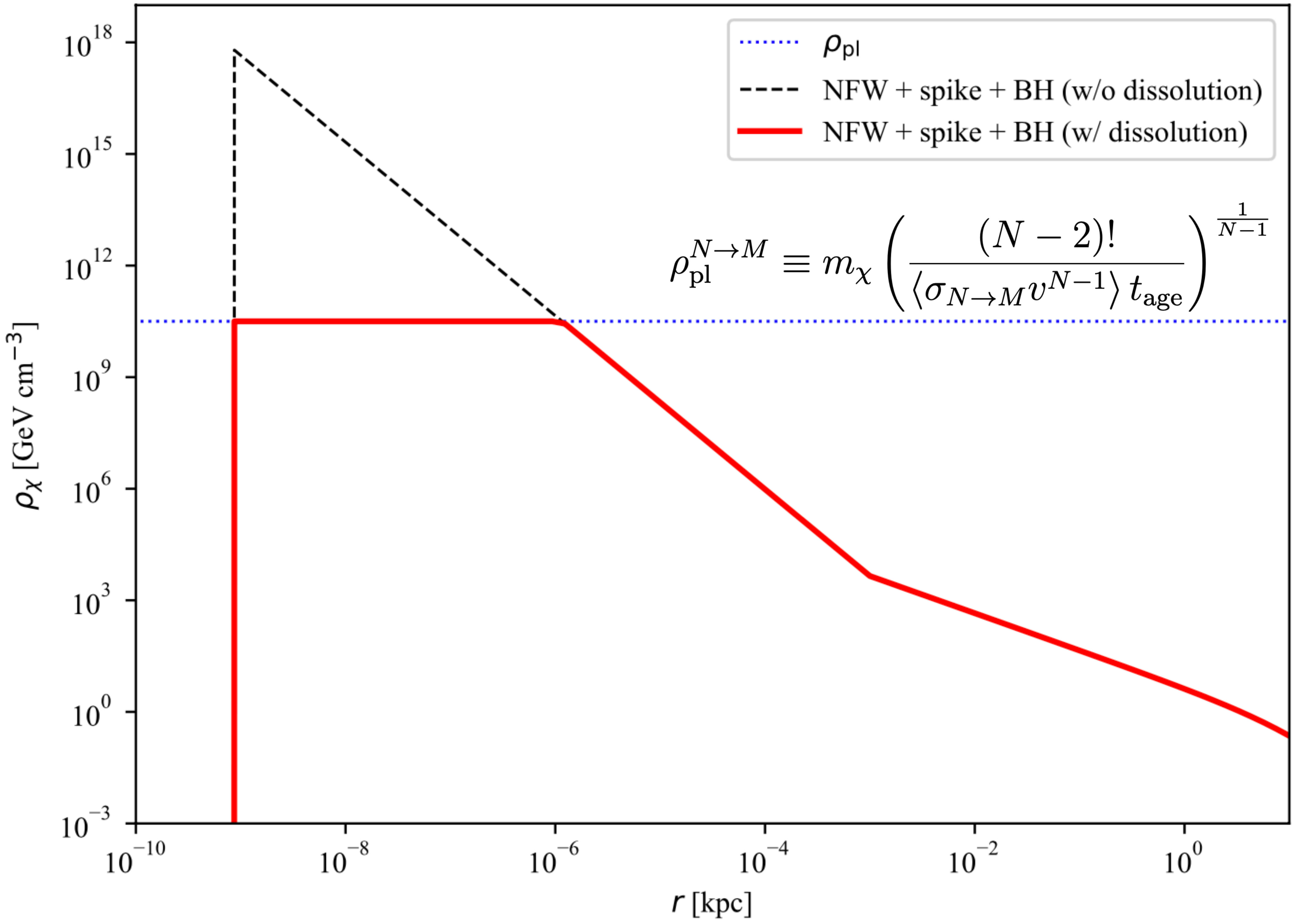
Self-interaction in strongly interacting regime
→ Drastic reduction of boosted DM flux

2. Dissolution via # changing: $2 \to 0$ (Annihilation) & $n \to m$

DM # evolution @fixed orbit

$2 \to 0$ process | $n \to m$ process

$$\dot{n}_\chi(r,t) = -\langle \sigma_{\rm ann} v \rangle (n_\chi(r,t))^2 - \frac{n}{n!} \left\langle \sigma_{n\to m} v^{n-1} \right\rangle (n_\chi(r,t))^n$$



- One process ($N \to M$) dominance → analytical solution

$$\rho_\chi(r,t) = \frac{\rho_{\rm pl}^{N\to M} \rho_\chi(r, t_{\rm ini})}{\left[(\rho_{\rm pl}^{N\to M})^{N-1} + \rho_\chi(r,t_{\rm ini})^{N-1} \right]^{\frac{1}{N-1}}}$$

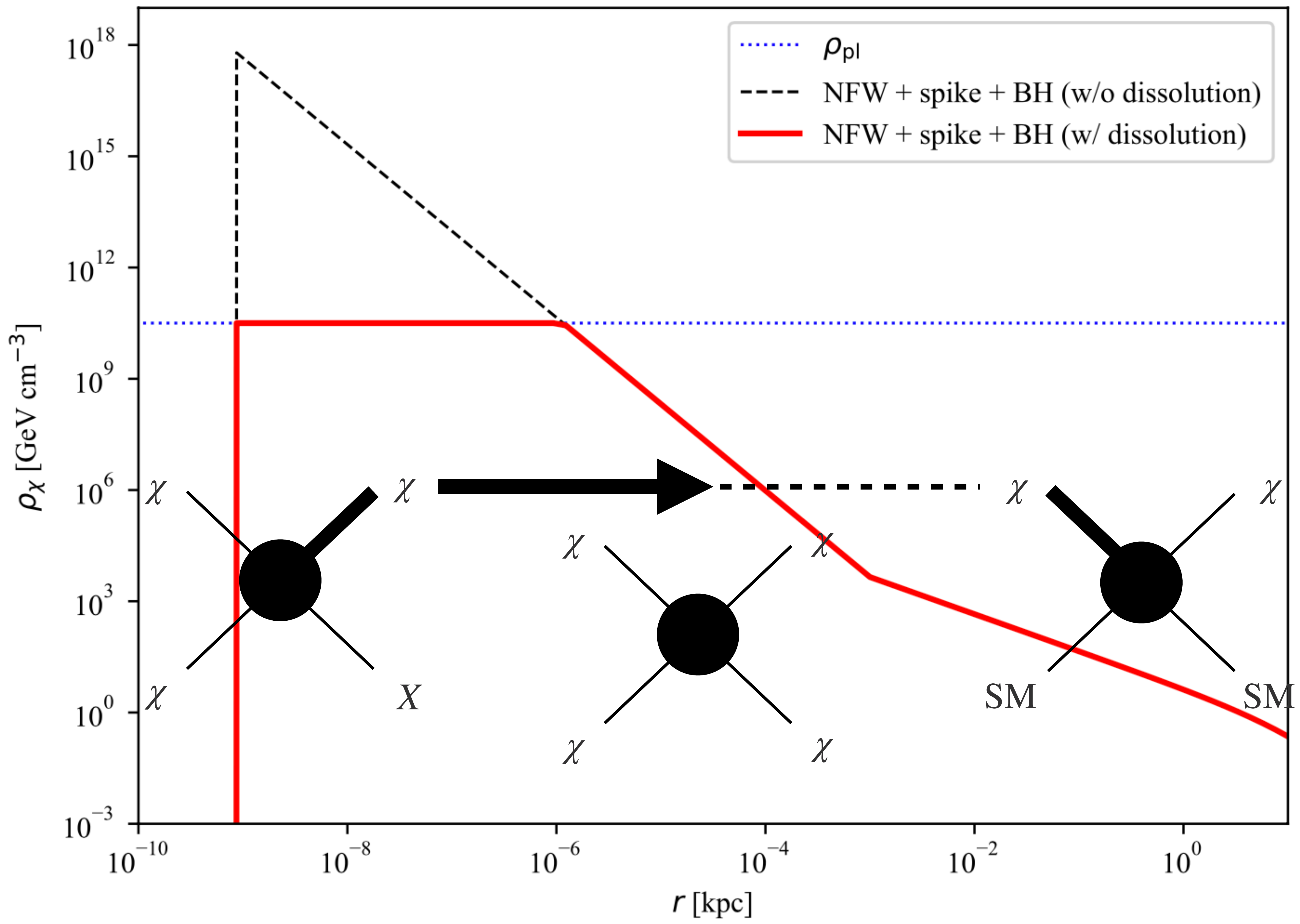
- More than one process → numerical solution

DM # changing processes
→ plateau density around the central region

[X. Chu, C. Garcia-Cely (2018)] [A. Kamada, H. J. Kim (2020)]

3. Self-heating: $n \to m$

- If boosted DM is captured on the way to the earth…
  - Energy will be deposited into DM halo → escalating core formation
  - We will lose boosted DM flux @ earth position



Capture factor: $\xi(r) = r \times \frac{\rho_\chi(r)\ \sigma_{2\to2}}{m_\chi}\ (<1)$

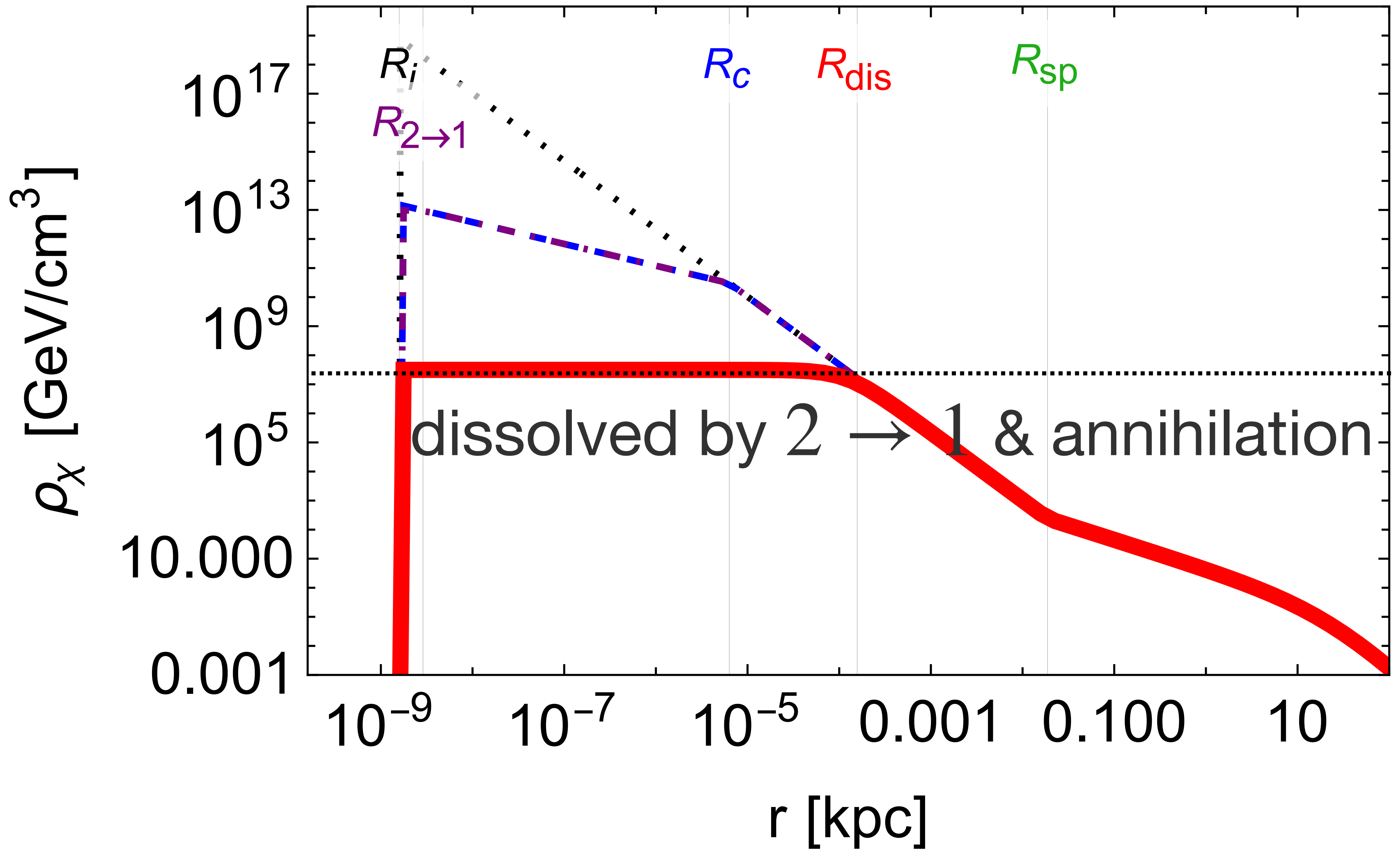
$n \to m$ **process** $(n > m)$
→ **DM capture & core formation**

DM density profile ~fate of DM spike~

$2 \to 1$

- DM-SM interaction & DM self-interaction are both in weak regime
- Core formation effect ($2 \to 2$) is irrelevant
- Dissolution effect ($2 \to 1$ & annihilation) crucially determine ρ_χ

→ **High-density region may survive & realize boosted DM flux**

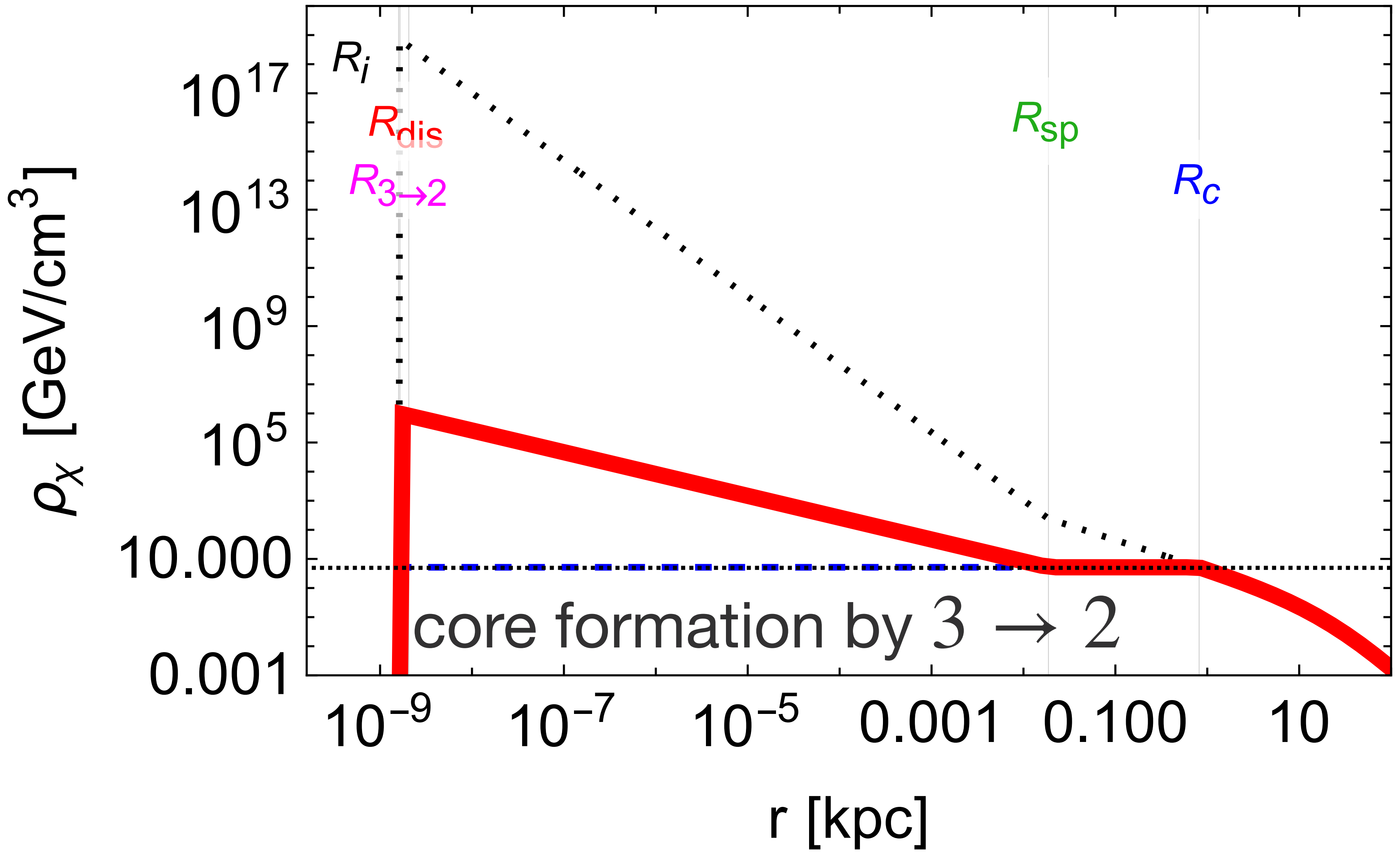


$3 \to 2$

- DM-SM interaction: weak & DM self-interaction: strong
- Core formation ($2 \to 2$) reduces high-density region [Y. Hochberg, et al. (2014)]
- Modified power law for spike from isothermal core [S. L. Shapiro, et al. (2014)]

→ **Boosted DM flux is totally irrelevant**

- Same conclusion for $n \to m$ $(n \geq 3)$



[T. Toma (2022)] [M. Aoki, T. Toma (2023)]

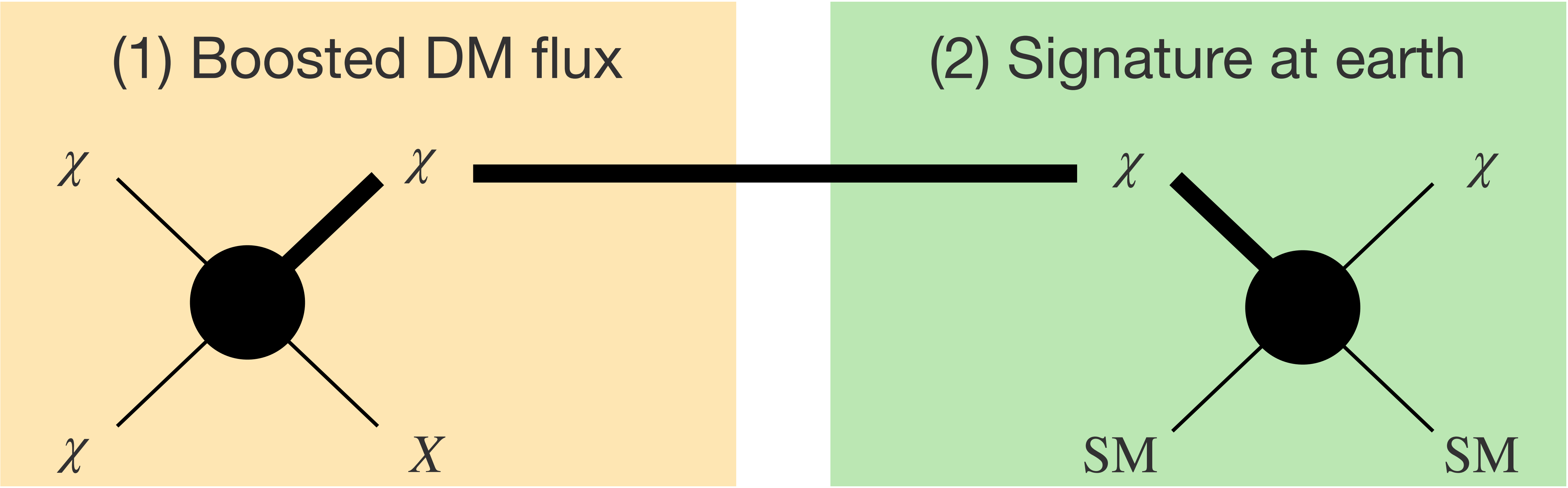
Annihilation Boosted DM via $2 \to 1$ (= semi-annihilation)

Cross section	Boost DM	Determine ρ_χ
$\langle \sigma_{2\to1} v \rangle = \frac{\alpha_{\rm eff}^2}{m_\chi^2}$	✔ $E_\chi = m_\chi/4$	Self-heating Dissolving via $2 \to 1$ ⇒ Crucial
$\sigma_{2\to2} = \frac{\alpha_{2\to2}^2}{m_\chi^2} \equiv a^2 \frac{\alpha_{\rm eff}^2}{m_\chi^2}$	$a \sim 1$	Self-scattering ⇒ Irrelevant
$\langle \sigma_{\rm ann} v \rangle = \frac{\alpha_{2\to0}^2}{m_\chi^2} \equiv b^2 \frac{\alpha_{\rm eff}^2}{m_\chi^2}$	$b \sim \left(\frac{\alpha_{\rm SM}}{\alpha_{\rm self}}\right)^{\frac{1}{2}}$	Dissolving via $2 \to 0$ ⇒ Crucial

Sensitivity at current experiment?

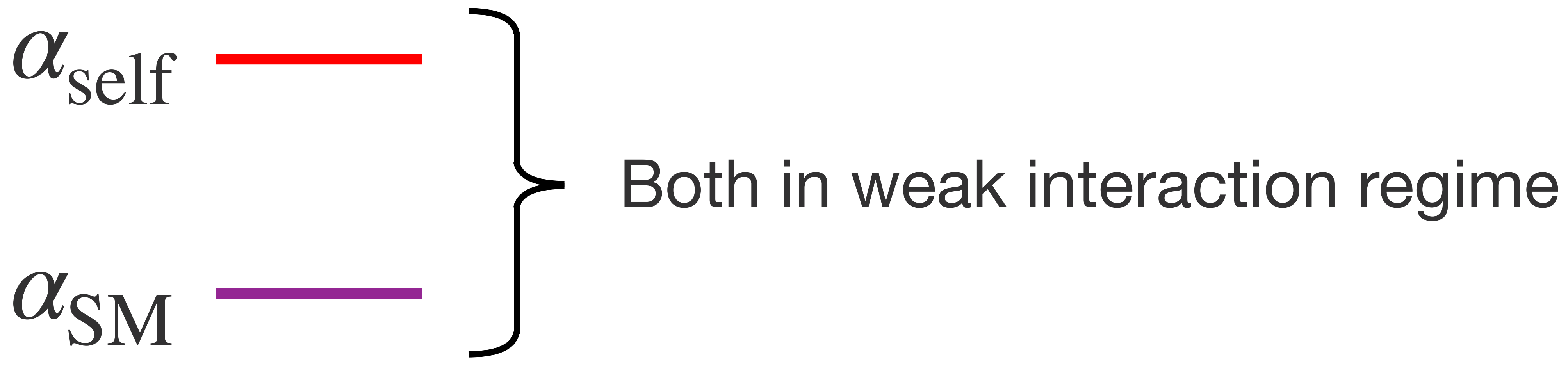
Smoking gun signature?

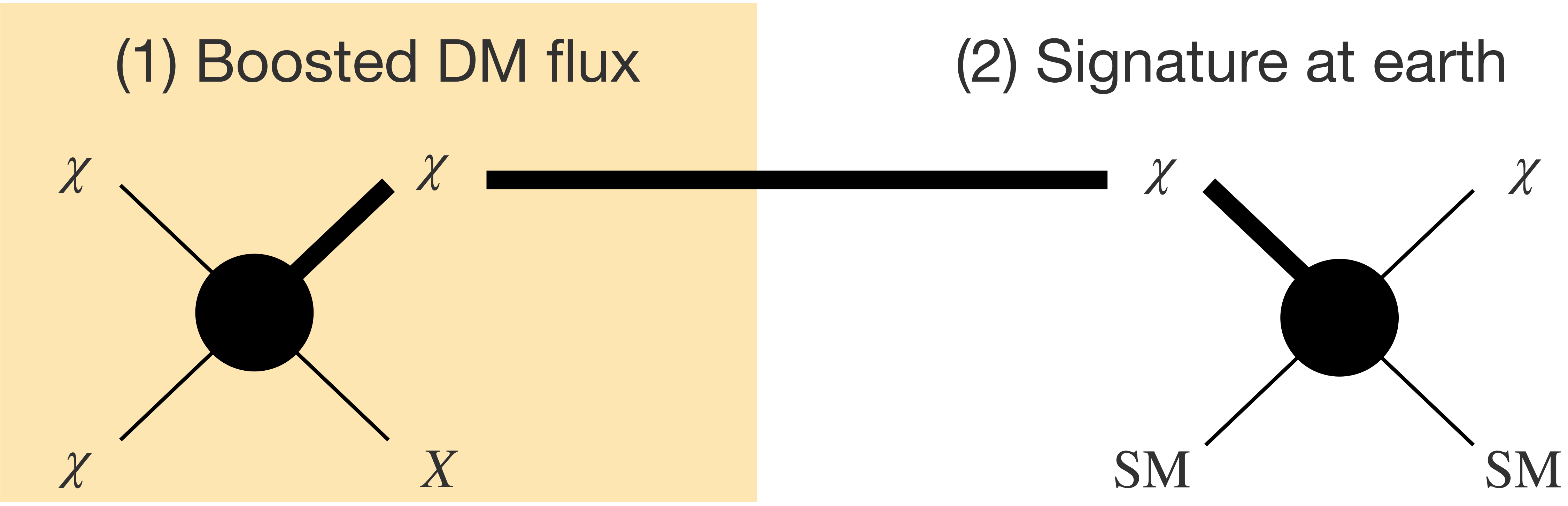
Results

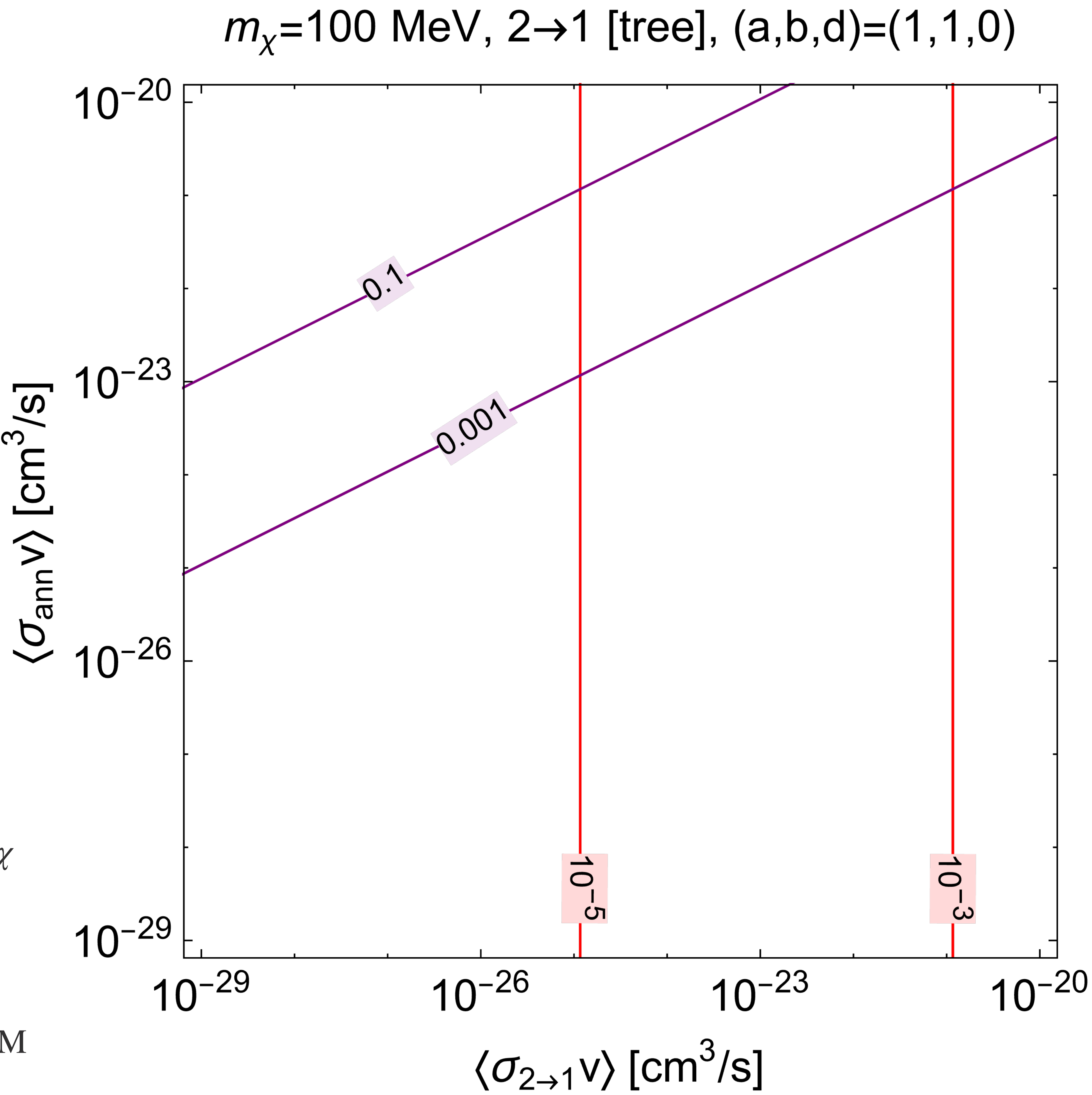

(1) Boosted DM flux
χ
χ
χ
X
(2) Signature at earth
χ
χ
SM
SM

Boosted DM flux

Contours of interactions







[B. B. Kamenetskaia, MF, A. Ibarra, T. Toma (work in progress)]

Boosted DM flux

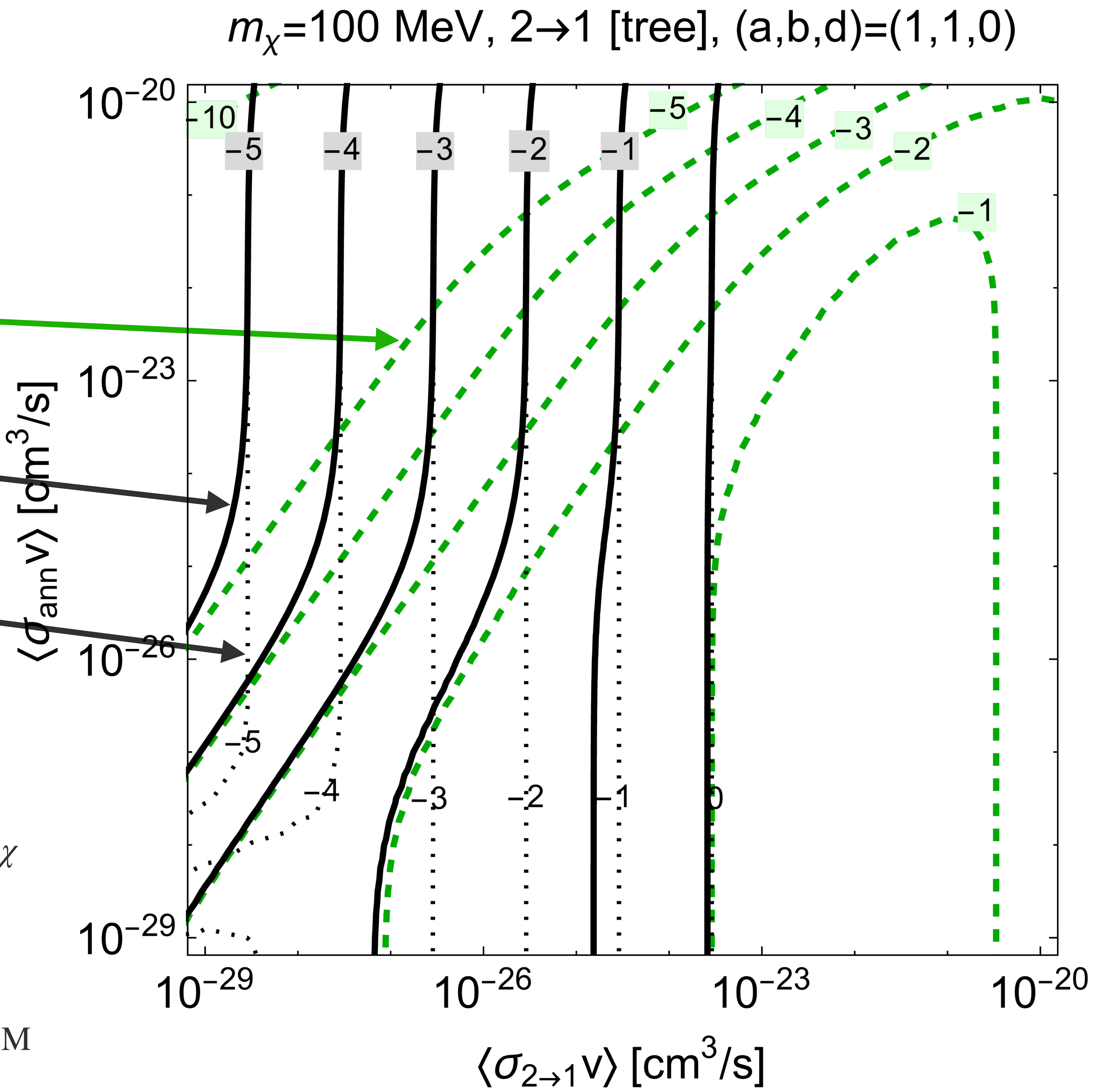
Contours in $\log_{10}\Phi_{\mathrm{BDM}}\ [\mathrm{cm}^{-2}\mathrm{s}^{-1}]$

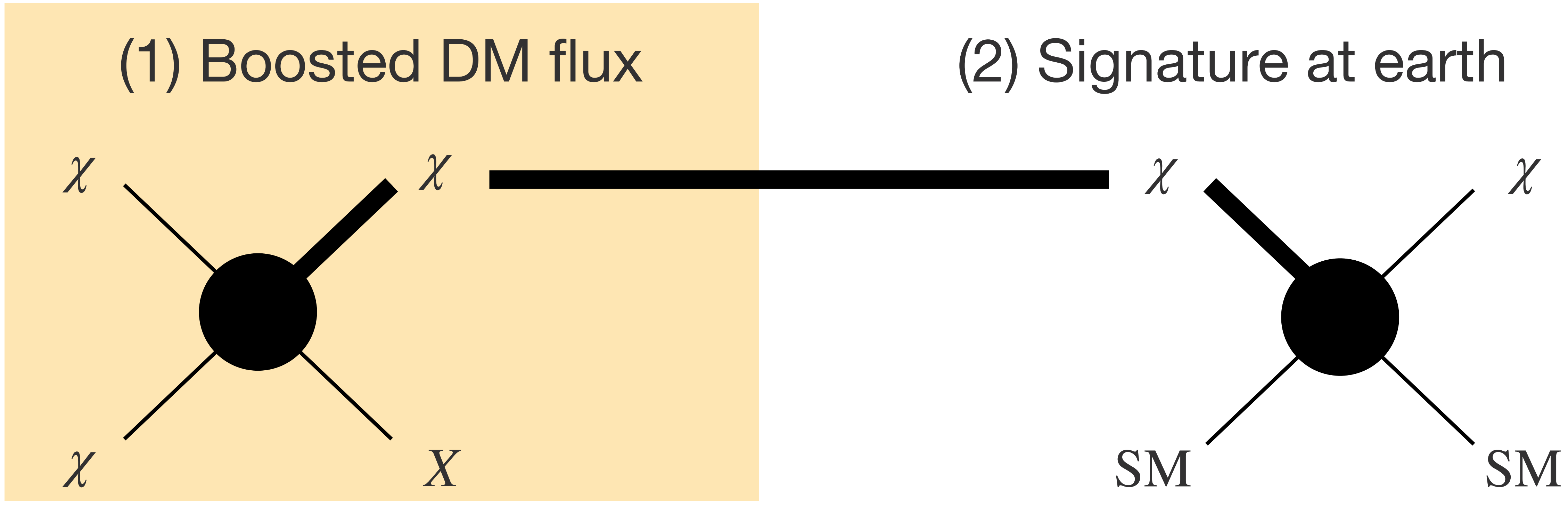
Flux from spike region - - - - -

Total flux (w/ spike) ———

Total flux (w/o spike) · · · · · ·

※ extrapolating NFW profile to spike region



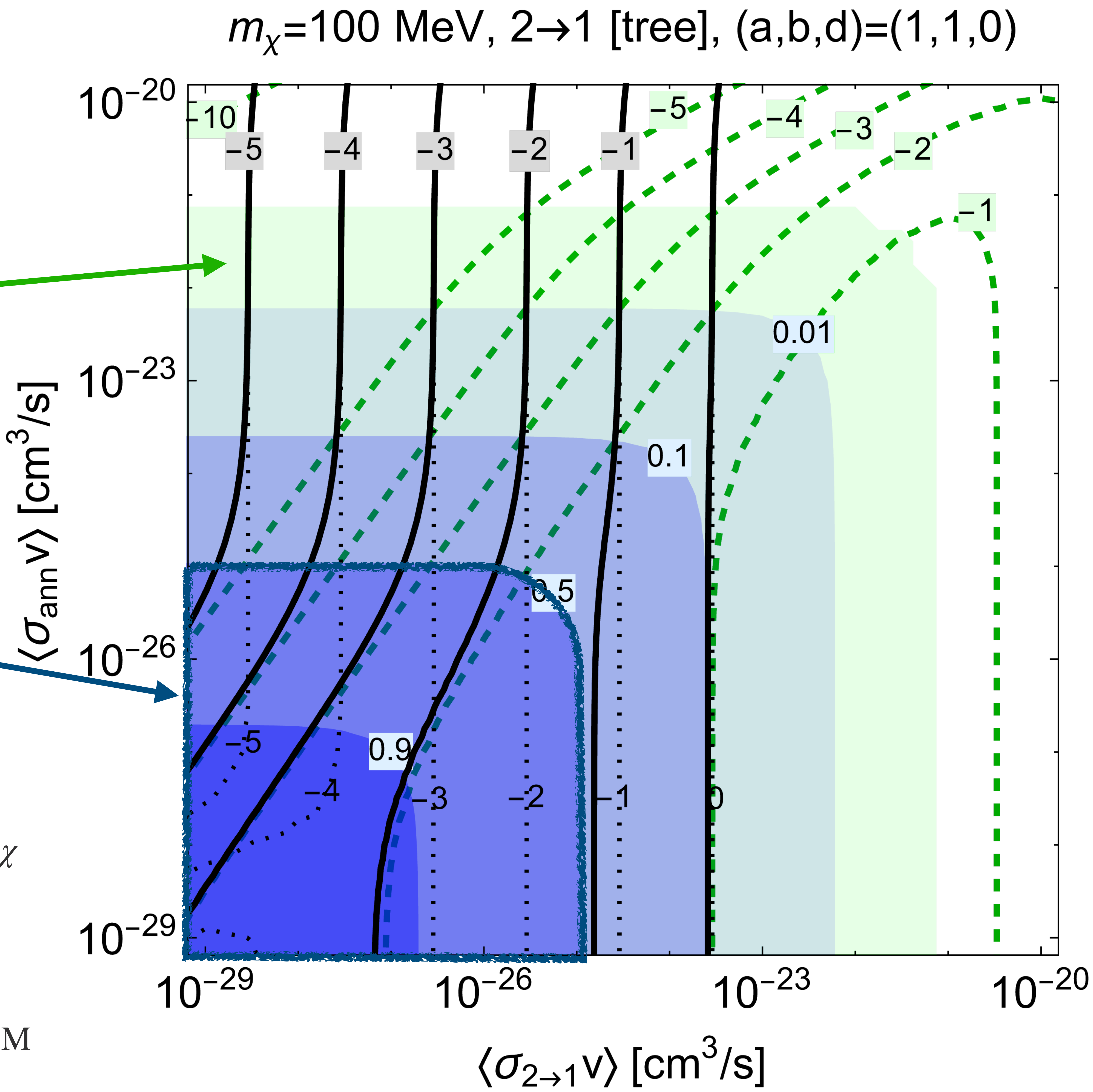


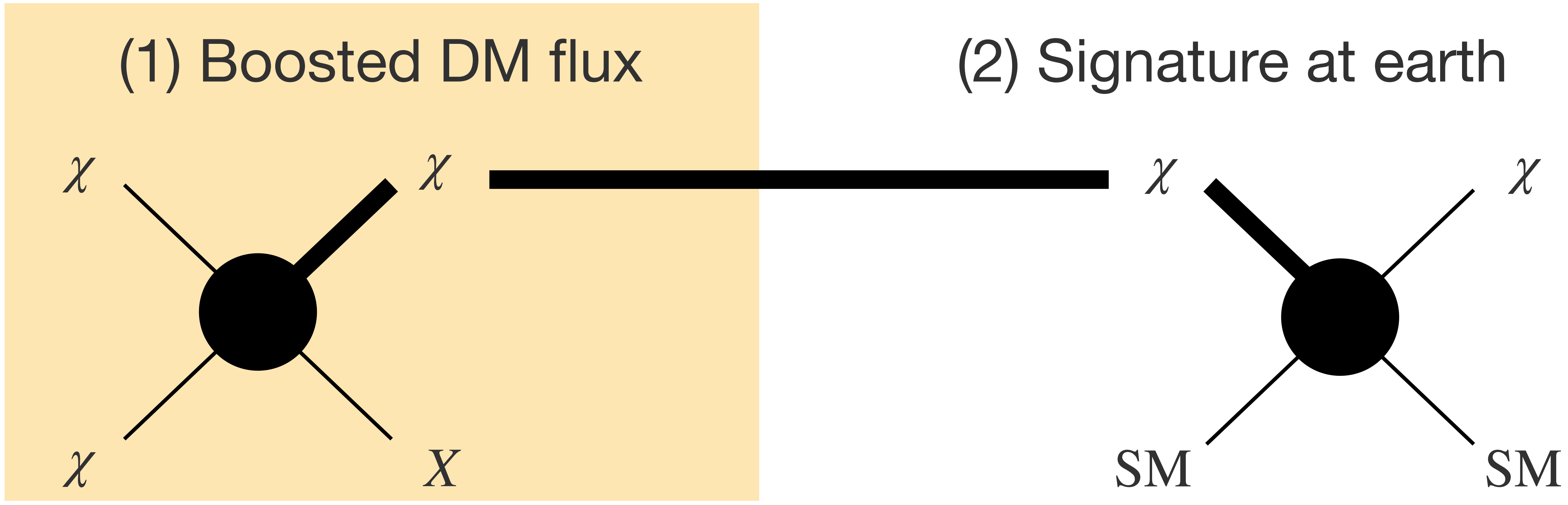
Boosted DM flux

Contours in $\log_{10}\Phi_{\mathrm{BDM}}\ [\mathrm{cm}^{-2}\mathrm{s}^{-1}]$

Spike power law remain in current universe

Spike dominance (>50%)





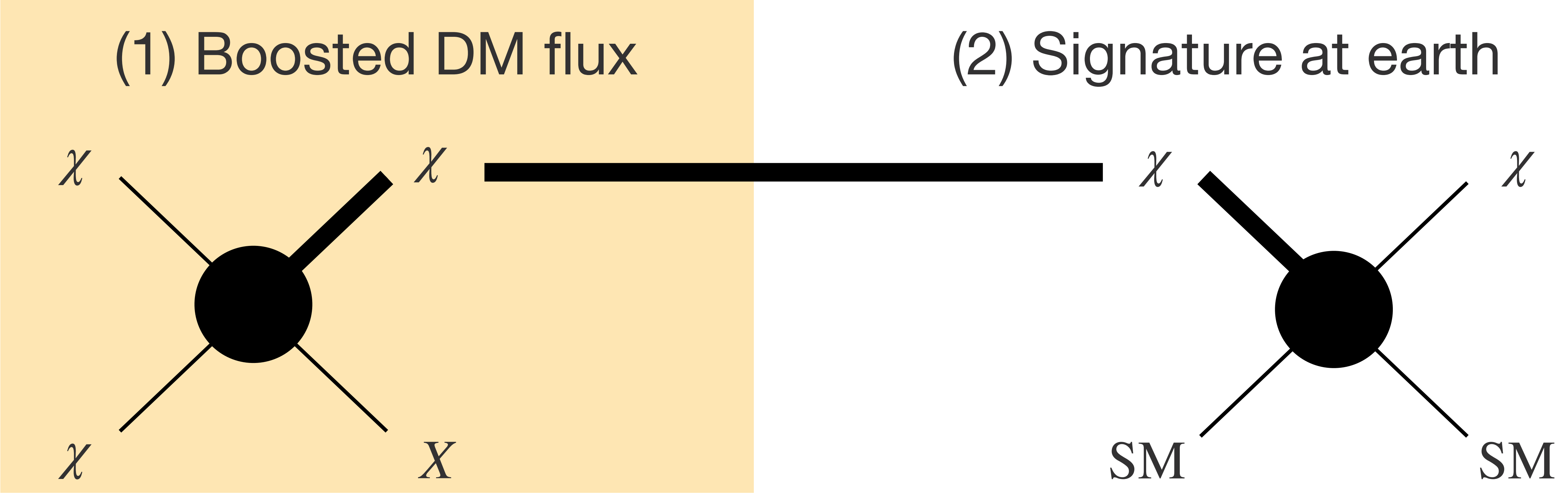
Boosted DM flux

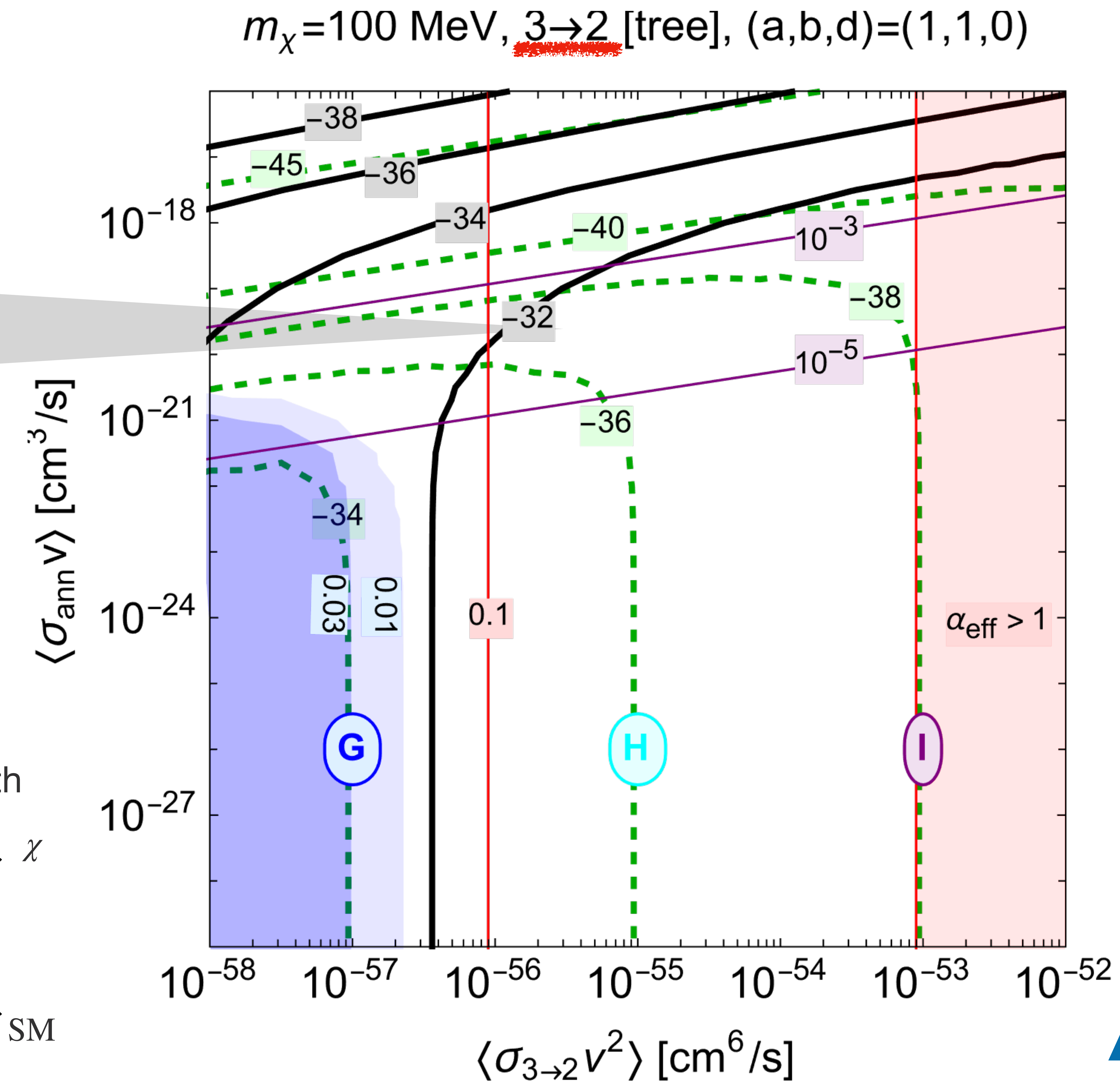
Contours in $\log_{10}\Phi_{\rm BDM}\ [{\rm cm}^{-2}{\rm s}^{-1}]$

For $3 \to 2$ process?

$$\Phi_{\rm BDM}^{3\to2} \lesssim 10^{-32}\ {\rm cm}^{-2}{\rm s}^{-1}$$

→ Hopeless to have boosted DM signature for $n \geq 3$ ...





[B. B. Kamenetskaia, MF, A. Ibarra, T. Toma (work in progress)]

Constraint: σ_p vs. m_χ

Sensitivity @direct detection

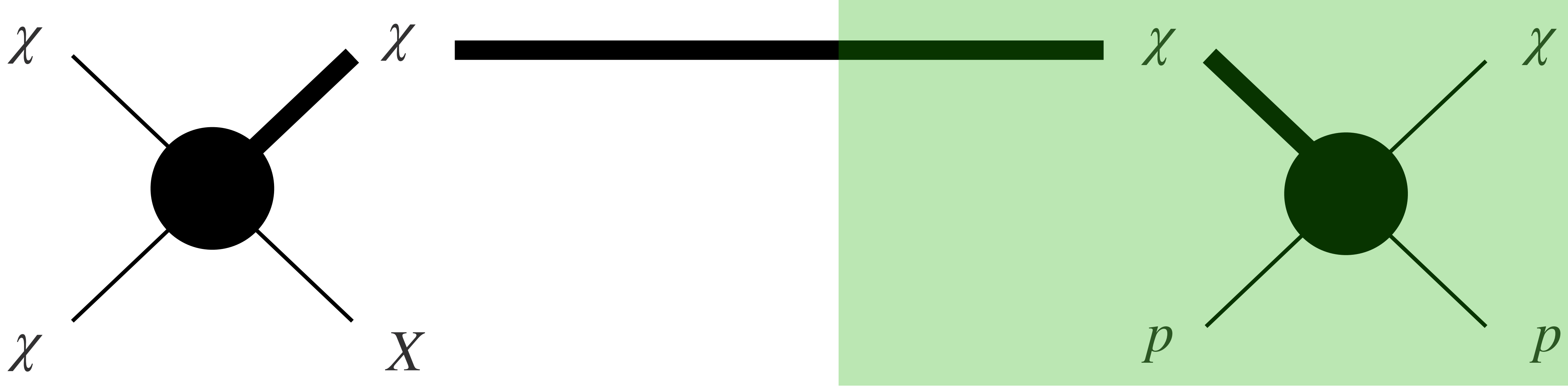
- Projected sensitivity of ordinary DM-proton scattering

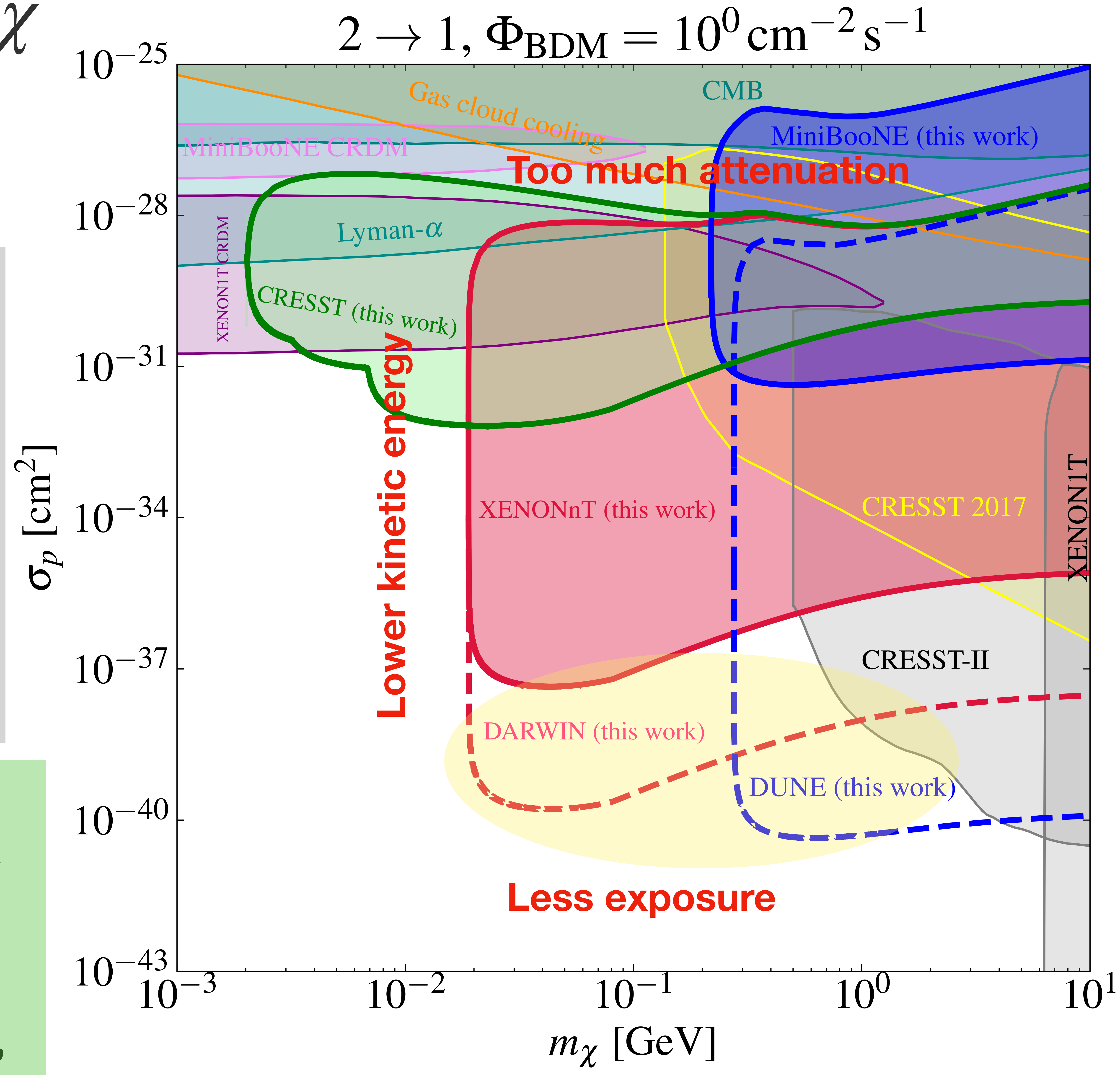
Other constraints:

- CMB : power suppression & acoustic peak shift [W. L. Xu, et al. (2018)]
- Lyman-α : collisional damp of structure growth by σ_p [K. K. Rogers, et al. (2022)]
- Cloud cooling: gas cloud heating via $\chi - p$ scatt. [A. Bhoonah, at al. (2018)]
- CRDM: boosted DM via CR up-scattering [T. Bringmann, M. Pospelov (2018)]

(1) Boosted DM flux

(2) Signature at earth

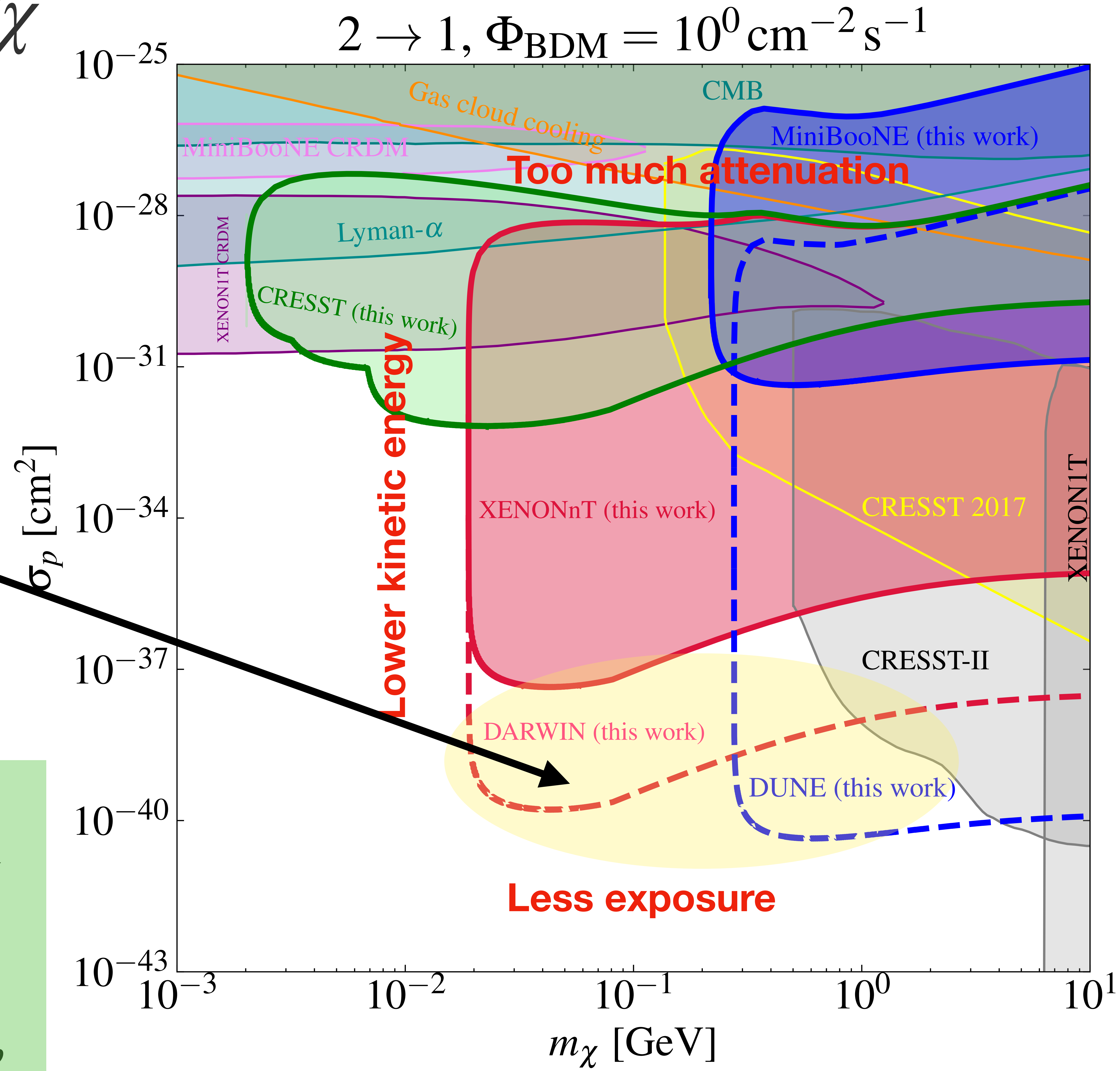


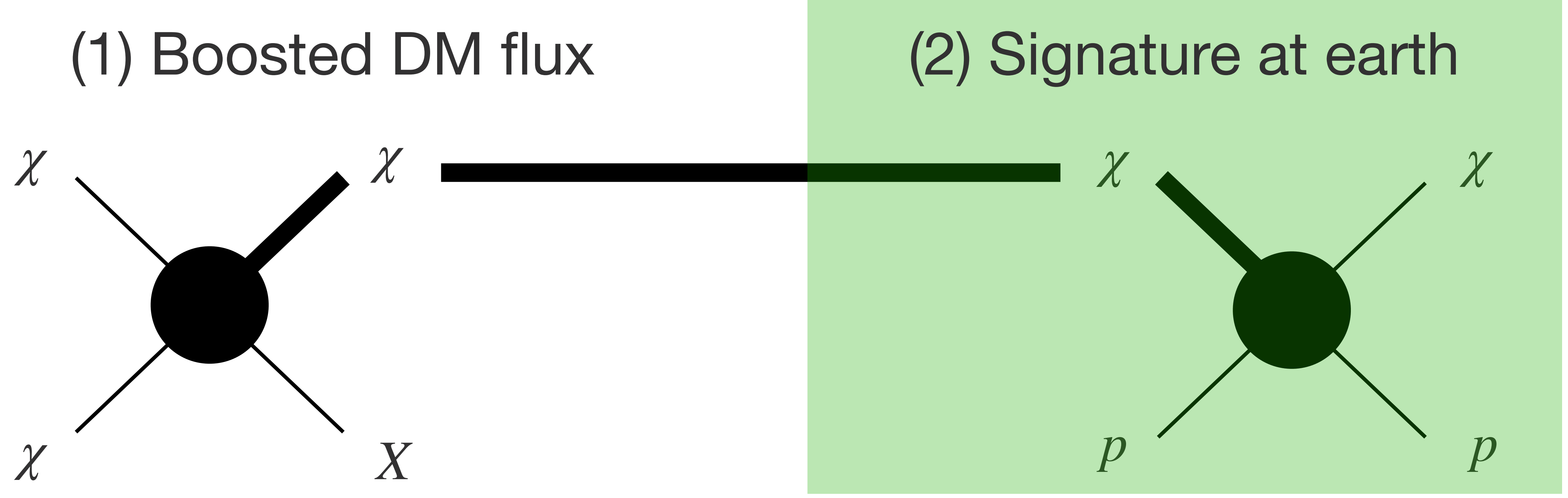


Constraint: σ_p vs. m_χ

Sensitivity @direct detection

- Projected sensitivity of ordinary DM-proton scattering
- High initial E_χ → Better sensitivity for low DM mass
  - Current bound : CRESST, XENON, MiniBooNE
  - Prospect : DARWIN, DUNE
    (up to 10^{-40} cm^2 for $m_\chi \sim 0.1 - 1$ GeV)





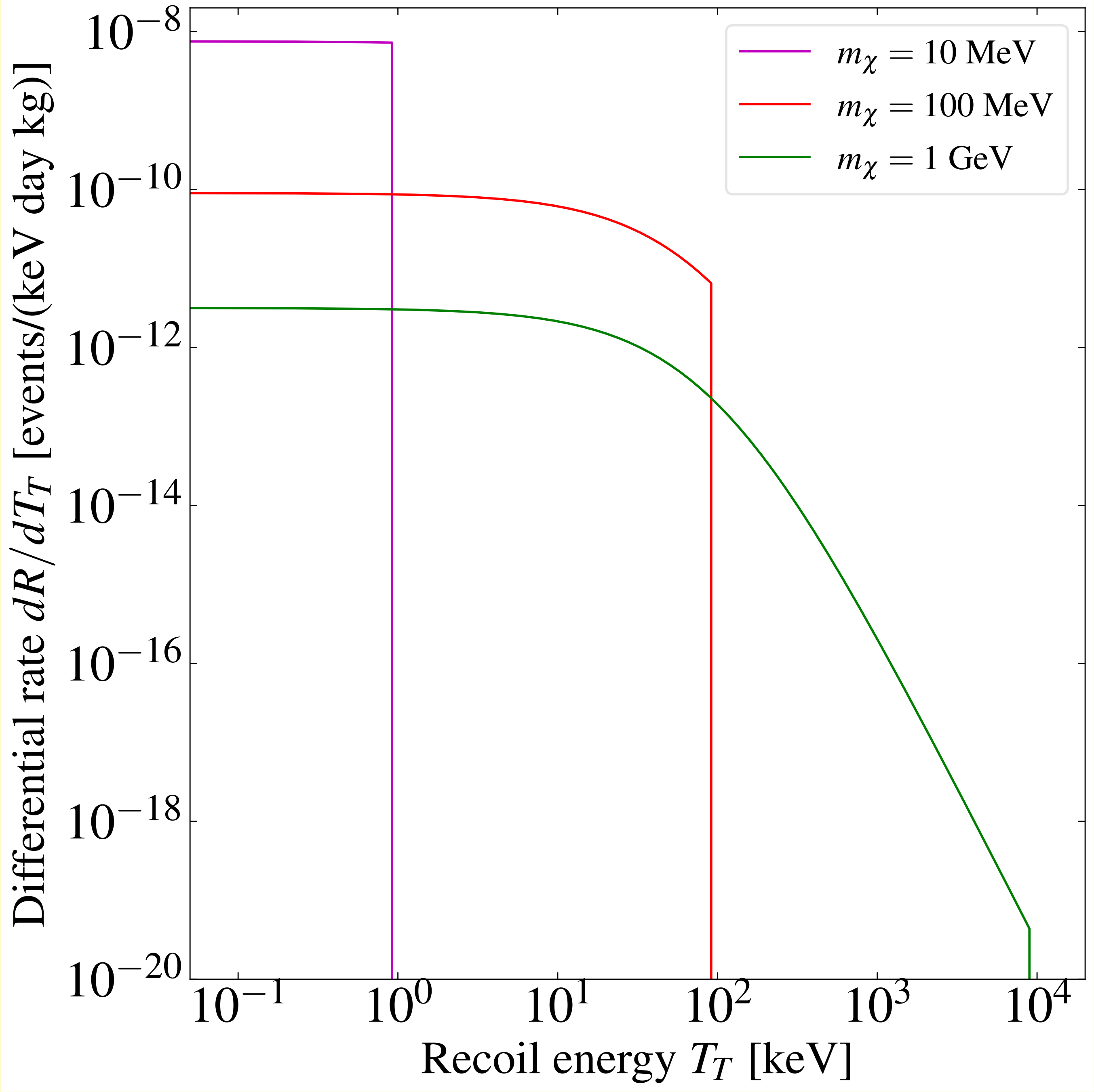
[B. B. Kamenetskaia, MF, A. Ibarra, T. Toma (work in progress)]

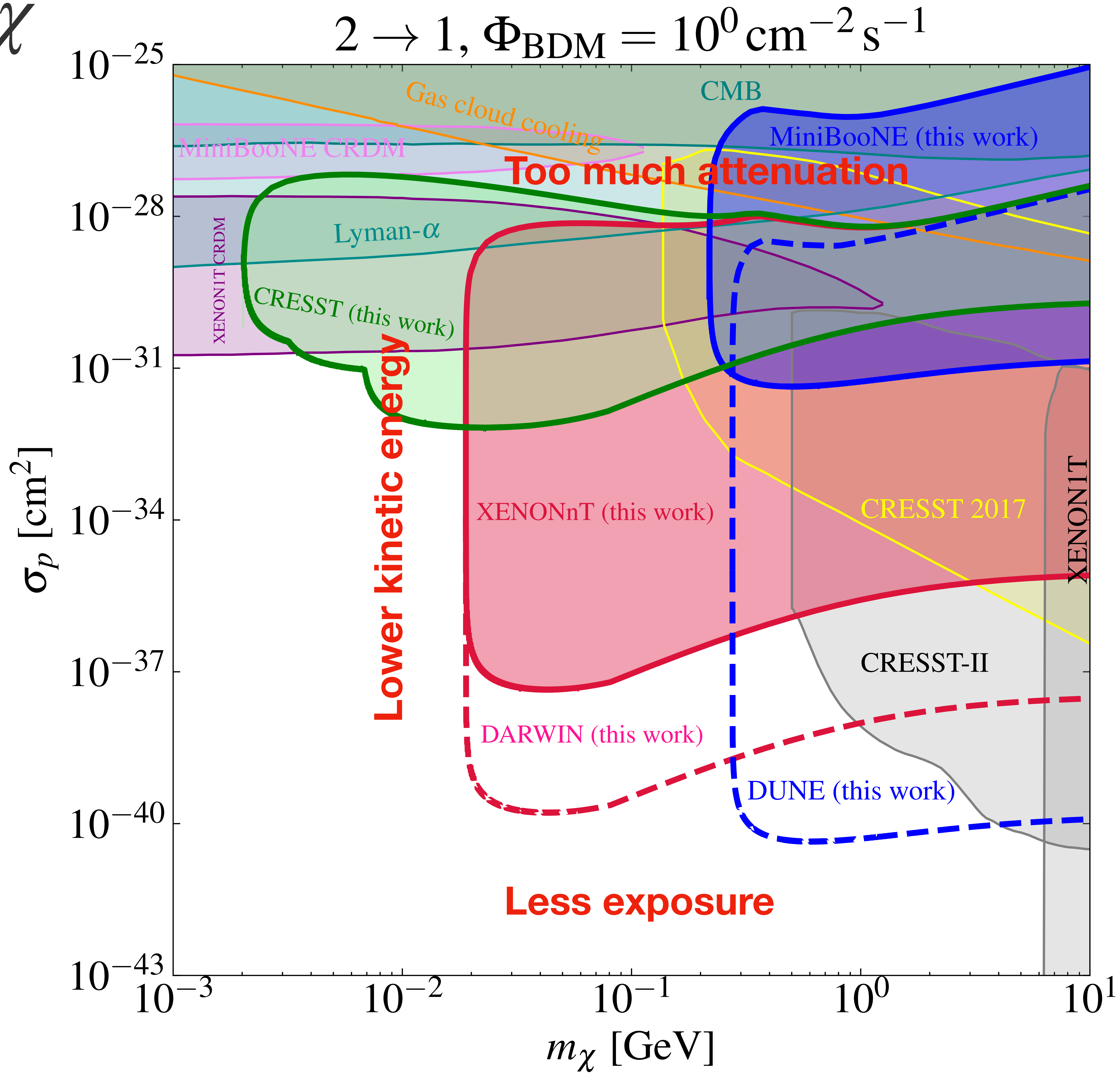
Constraint: σ_p vs. m_χ

Sensitivity @direct detection

- Projected sensitivity of ordinary DM-proton scattering
- High initial E_χ → Better sensitivity for low DM mass
- Recoil energy has a sharp cutoff (@$E_\chi = m_\chi/4$)

  → DM mass reconstruction





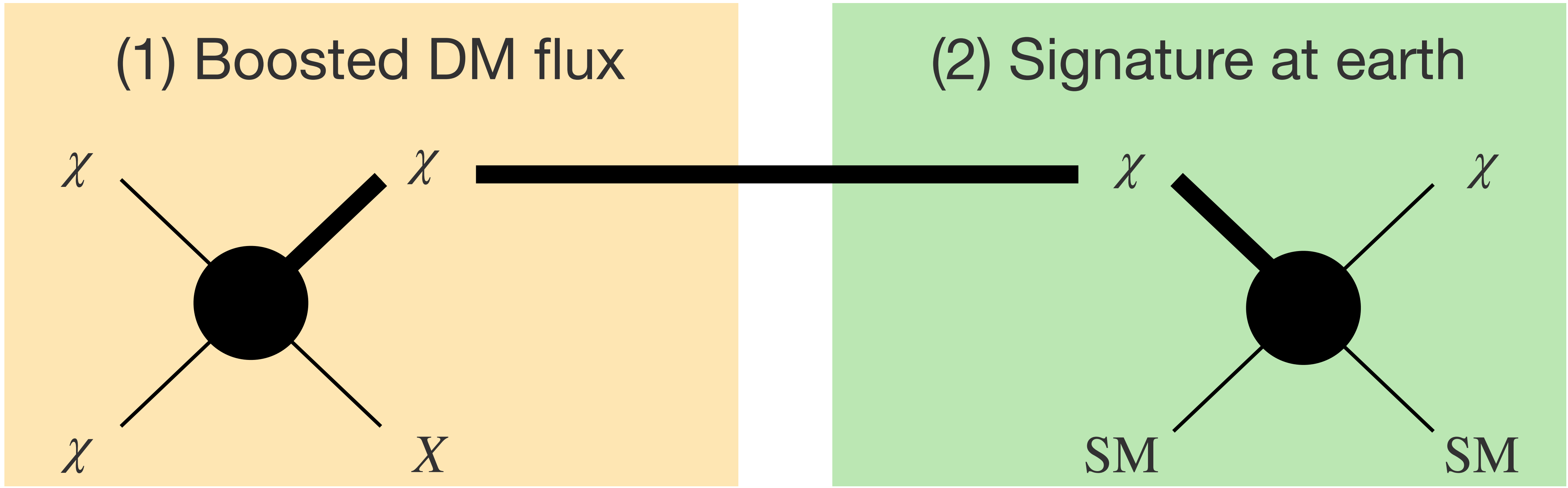
Constraint: $\langle \sigma_{2\to1} v \rangle$ vs. m_χ

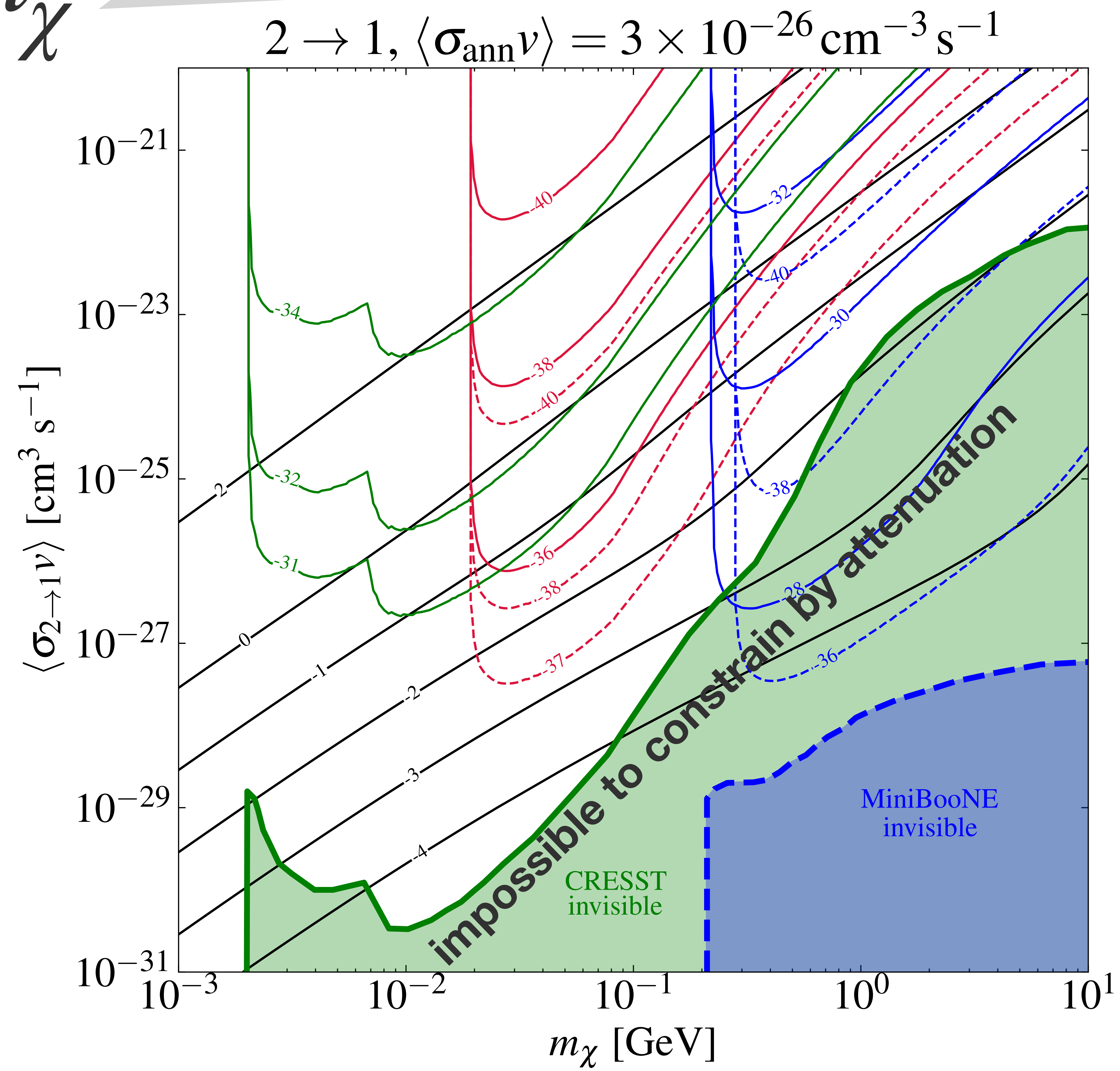
Time to combine everything!

Cross section dependence

- Sensitivity of σ_p is parametrized by $\langle \sigma_{2\to1} v \rangle$ via $\Phi_{\rm BDM}$
- Larger $\langle \sigma_{2\to1} v \rangle$: Sensitive for smaller σ_p
- Smaller $\langle \sigma_{2\to1} v \rangle$: Attenuation reduces DM energy (blind spot)

$$\Phi_{\rm BDM} = \frac{1}{2!}\frac{r_\odot}{4\pi}\left(\frac{\rho_\odot}{m_\chi}\right)^2 \langle \sigma_{2\to1} v \rangle \left[2\pi \int d\theta \sin\theta \int_{\rm l.o.s} \frac{ds}{r_\odot}\left(\frac{\rho_\chi(r(s,\theta))}{\rho_\odot}\right)^2\right]$$





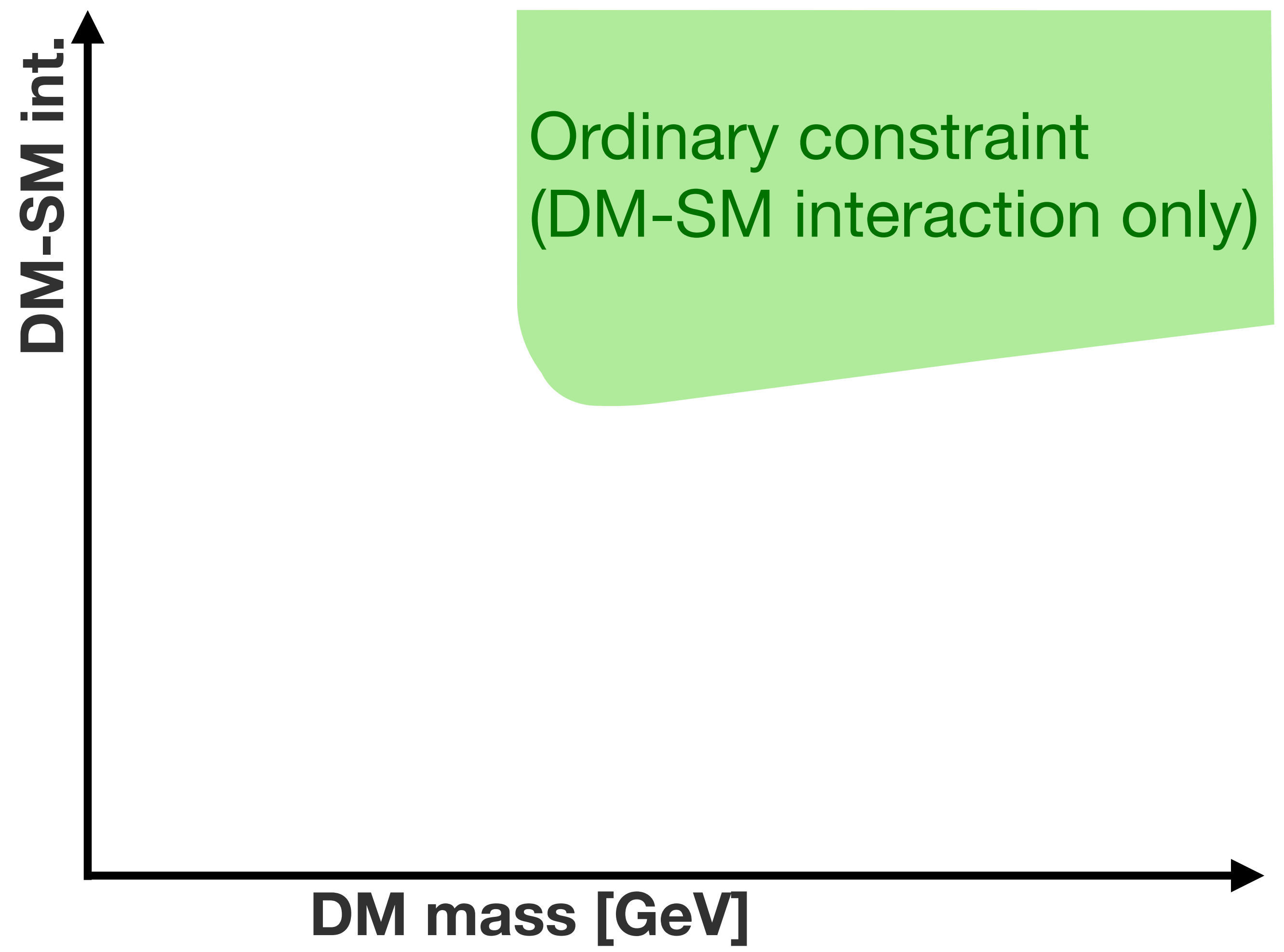
[B. B. Kamenetskaia, MF, A. Ibarra, T. Toma (work in progress)]

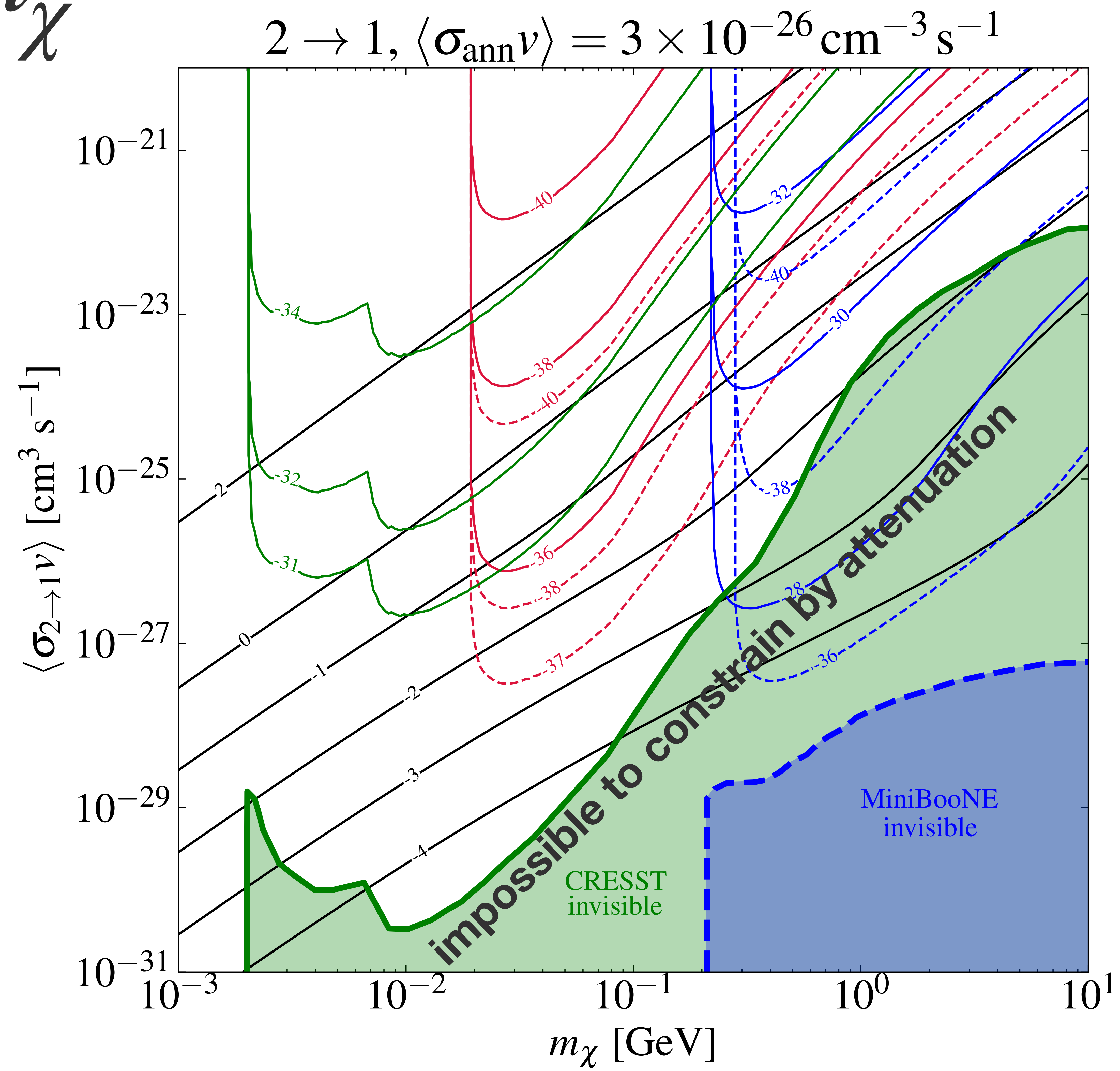
Constraint: $\langle \sigma_{2\to 1} v \rangle$ vs. m_χ

Cross section dependence

- Sensitivity of σ_p is parametrized by $\langle \sigma_{2\to 1} v \rangle$ via Φ_{BDM}
- Larger $\langle \sigma_{2\to 1} v \rangle$: Sensitive for smaller σ_p
- Smaller $\langle \sigma_{2\to 1} v \rangle$: Attenuation reduces DM energy (blind spot)

※ conceptual picture





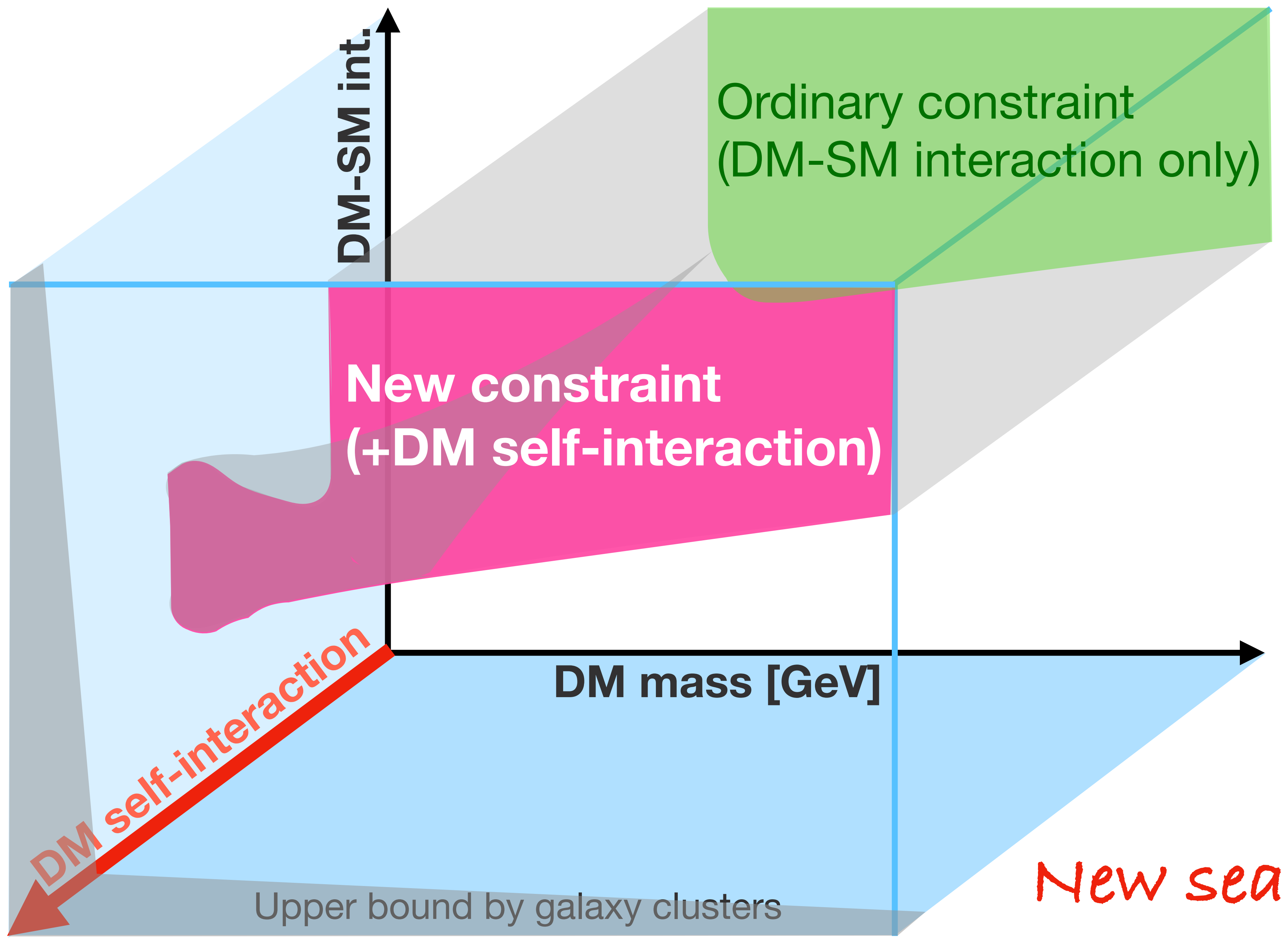
+ DM self-interaction...?

Constraint: $\langle \sigma_{2\to 1} v \rangle$ vs. m_χ

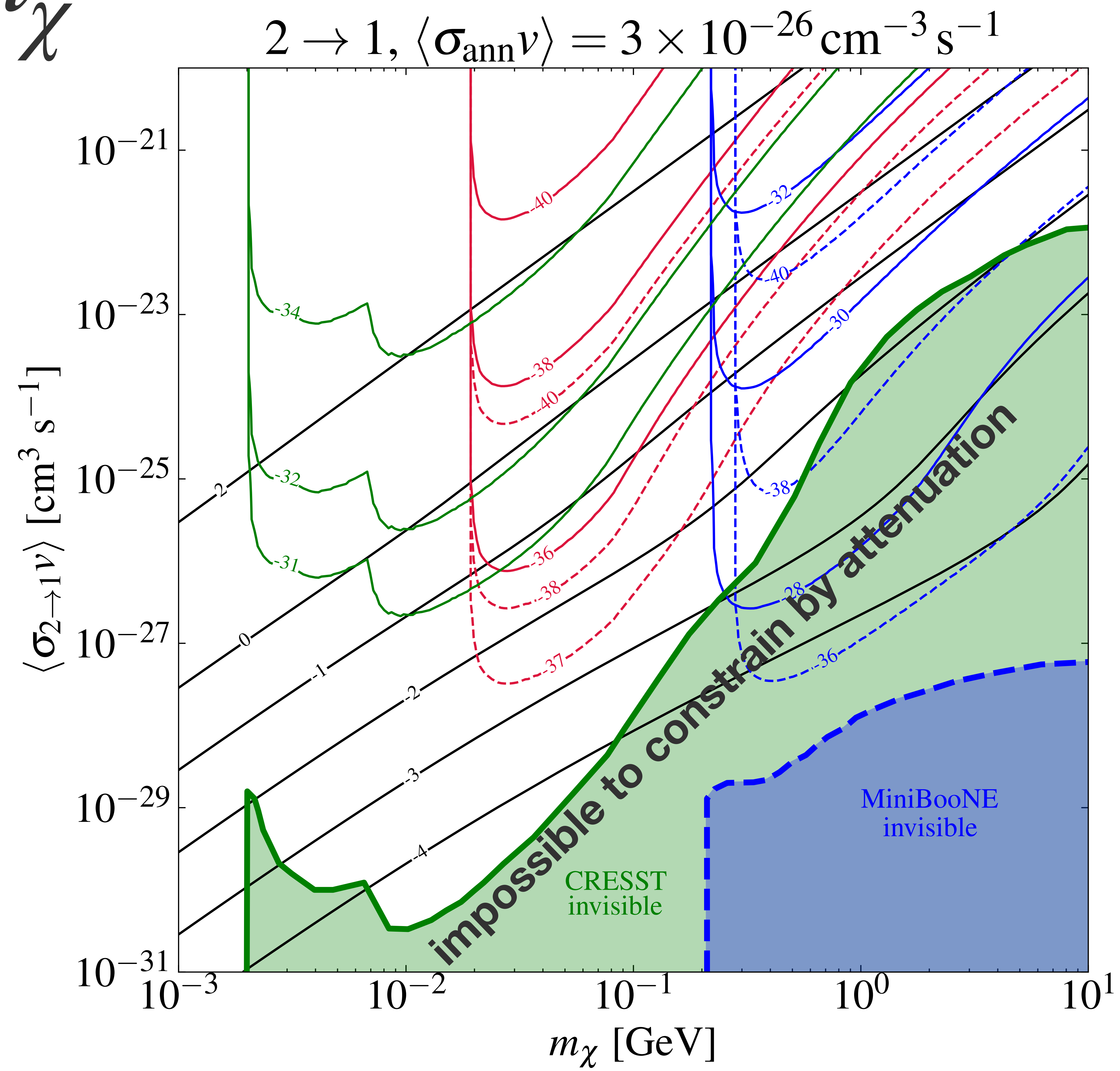
Cross section dependence

- Sensitivity of σ_p is parametrized by $\langle \sigma_{2\to 1} v \rangle$ via $\Phi_{\rm BDM}$
- Larger $\langle \sigma_{2\to 1} v \rangle$: Sensitive for smaller σ_p
- Smaller $\langle \sigma_{2\to 1} v \rangle$: Attenuation reduces DM energy (blind spot)

※ conceptual picture



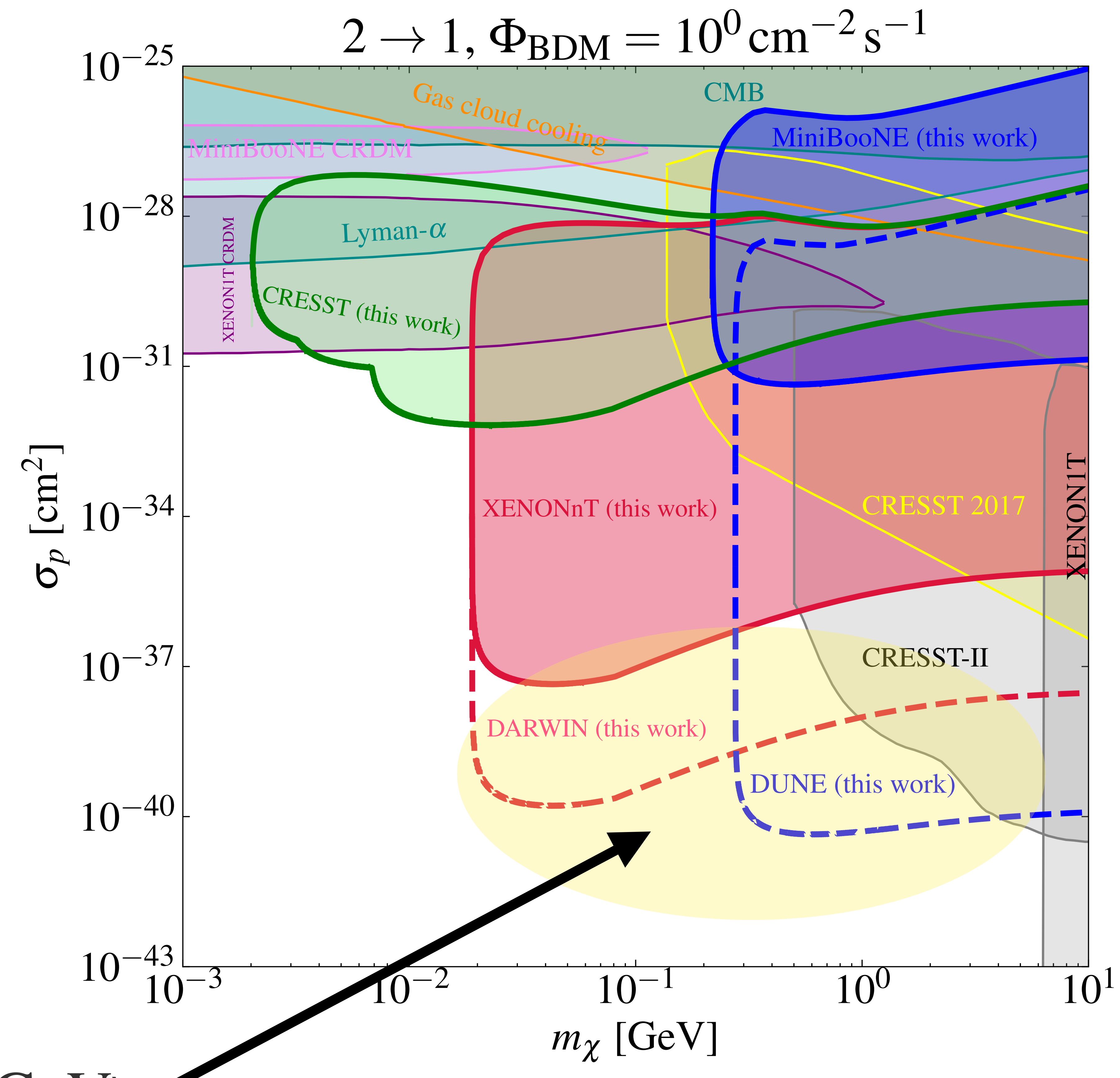
New search strategy!



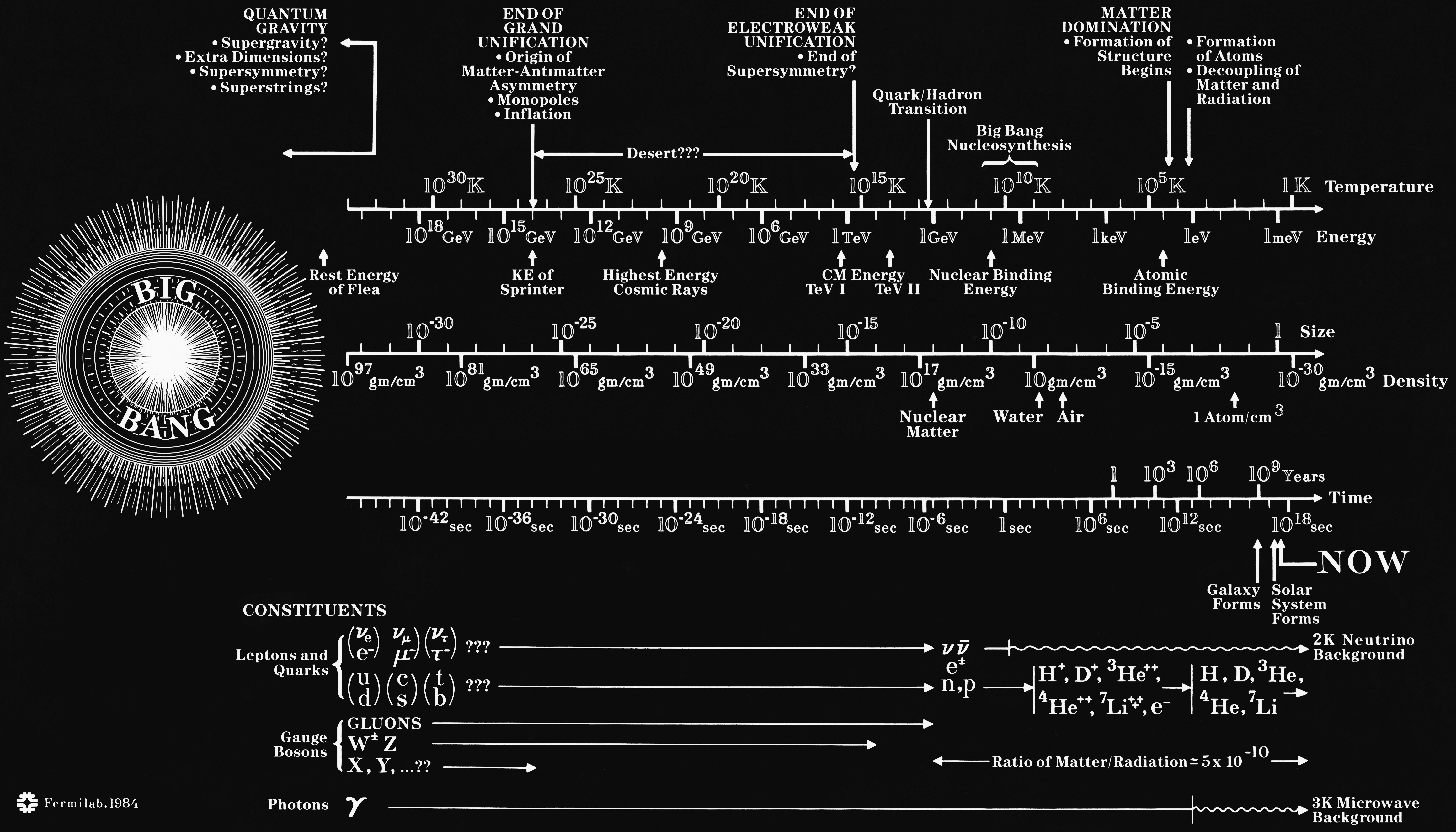
Summary

We systematically studied the conscience of $n \to m$ process at local galaxy

- Key functions of $n \to m$ process:
  - Modifying DM density at the central region
    → Deplete DM high-density region for $n \geq 3$
  - Accelerate DM for $n > m$
    → Realize sizable boosted DM flux for $2 \to 1$
- (Boosted DM flux) × (DM-proton scattering) = (**Boosted DM signature**)
- Energy threshold is determined by $n \to m$ kinematics
  → DM mass reconstruction could be possible for $2 \to 1$ scenario
- Experimental sensitivities:
  - current bound : CRESST, XENON, MiniBooNE
  - prospect : DARWIN, DUNE (up to 10^{-40} cm^2 for $m_\chi \sim 0.1 - 1$ GeV)



Backup

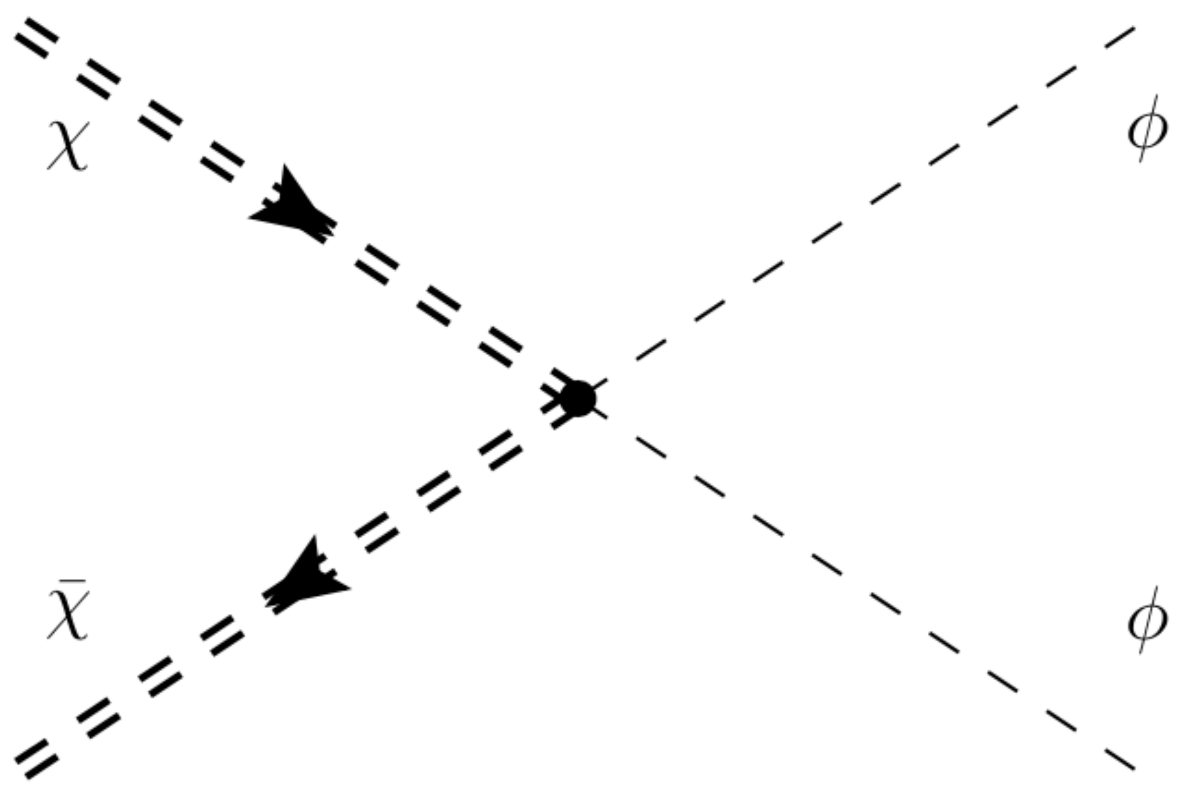

QUANTUM GRAVITY
• Supergravity?
• Extra Dimensions?
• Supersymmetry?
• Superstrings?
END OF GRAND UNIFICATION
• Origin of Matter-Antimatter Asymmetry
• Monopoles
• Inflation
END OF ELECTROWEAK UNIFICATION
• End of Supersymmetry?
Quark/Hadron Transition
Big Bang Nucleosynthesis
MATTER DOMINATION
• Formation of Structure Begins
• Formation of Atoms
• Decoupling of Matter and Radiation
Desert???
10^30 K
10^25 K
10^20 K
10^15 K
10^10 K
10^5 K
1 K
Temperature
10^18 GeV
10^15 GeV
10^12 GeV
10^9 GeV
10^6 GeV
1 TeV
1 GeV
1 MeV
1 keV
1 eV
1 meV
Energy
Rest Energy of Flea
KE of Sprinter
Highest Energy Cosmic Rays
CM Energy
TeV I
TeV II
Nuclear Binding Energy
Atomic Binding Energy
BIG BANG
10^-30
10^-25
10^-20
10^-15
10^-10
10^-5
1
Size
10^97 gm/cm^3
10^81 gm/cm^3
10^65 gm/cm^3
10^49 gm/cm^3
10^33 gm/cm^3
10^17 gm/cm^3
10 gm/cm^3
10^-15 gm/cm^3
10^-30 gm/cm^3
Density
Nuclear Matter
Water
Air
1 Atom/cm^3
1
10^3
10^6
10^9 Years
Time
10^-42 sec
10^-36 sec
10^-30 sec
10^-24 sec
10^-18 sec
10^-12 sec
10^-6 sec
1 sec
10^6 sec
10^12 sec
10^18 sec
NOW
Galaxy Forms
Solar System Forms
CONSTITUENTS
Leptons and Quarks
???
???
2K Neutrino Background
e±
n, p
H+, D+, 3He++, 4He++, 7Li+++, e−
H, D, 3He, 4He, 7Li
Gauge Bosons
GLUONS
W± Z
X, Y, ...??
Ratio of Matter/Radiation ≈ 5 x 10^-10
Photons γ
3K Microwave Background
Fermilab, 1984

Concrete model: semi-annihilation (1/2)

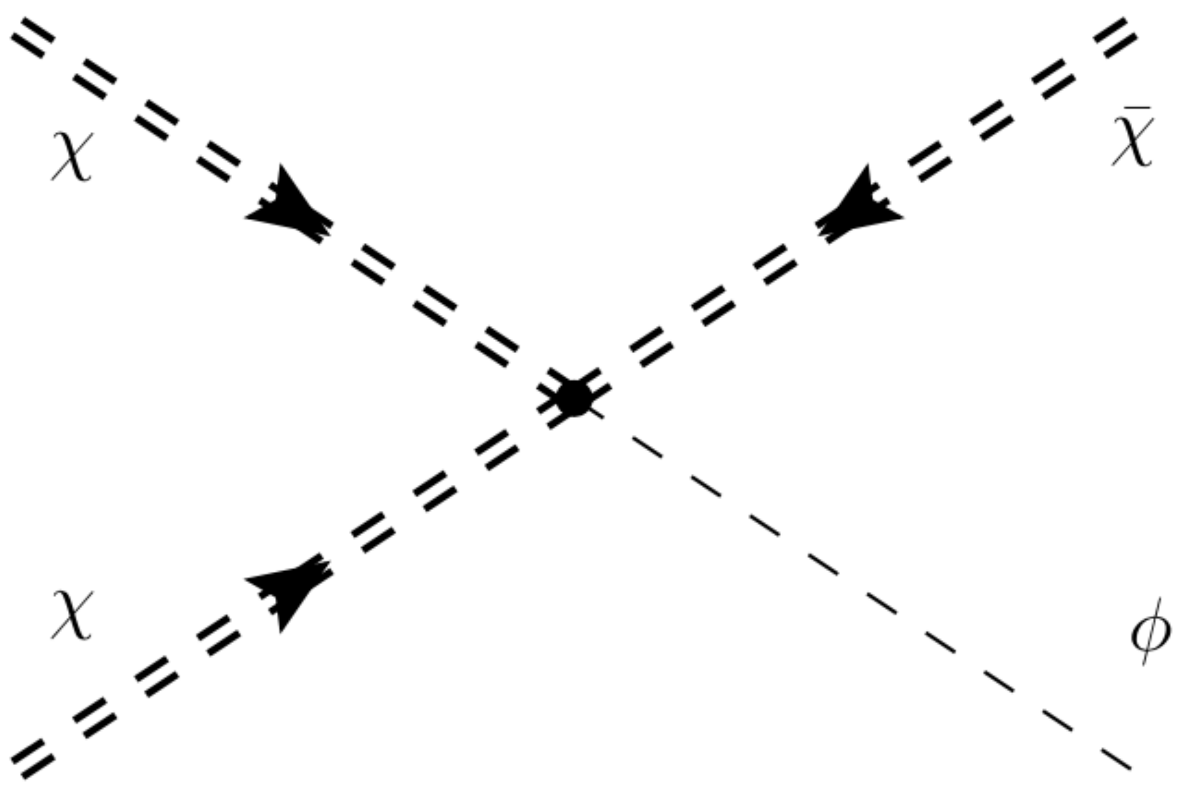
Tree-level scenario w/ Z_3 symmetry

	spin	Z_3
χ	complex scalar	$(-1)^{1/3}$
ϕ	real scalar	0

Table 2: Field content and symmetries of the model with a Z_3 symmetry.



Annihilation

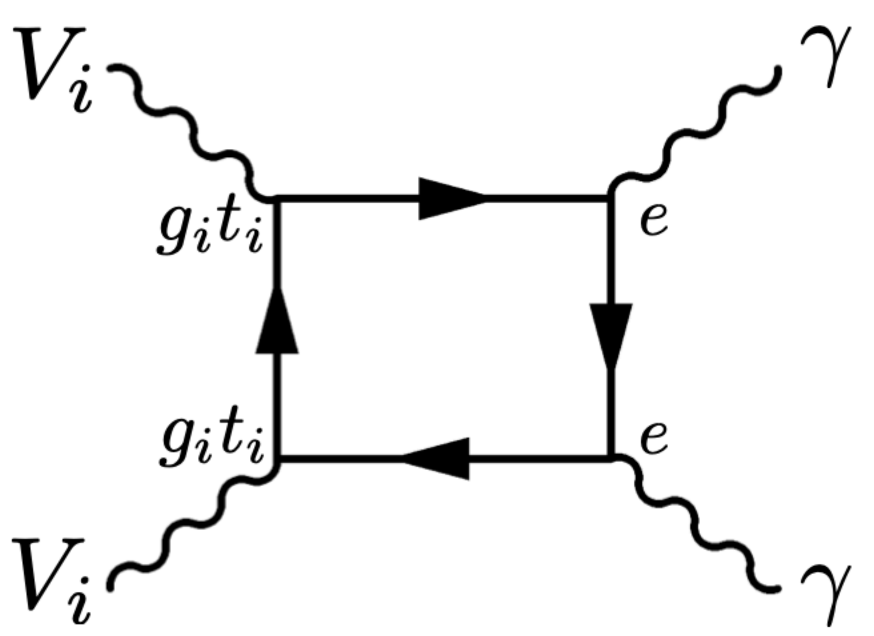


Semi-annihilation

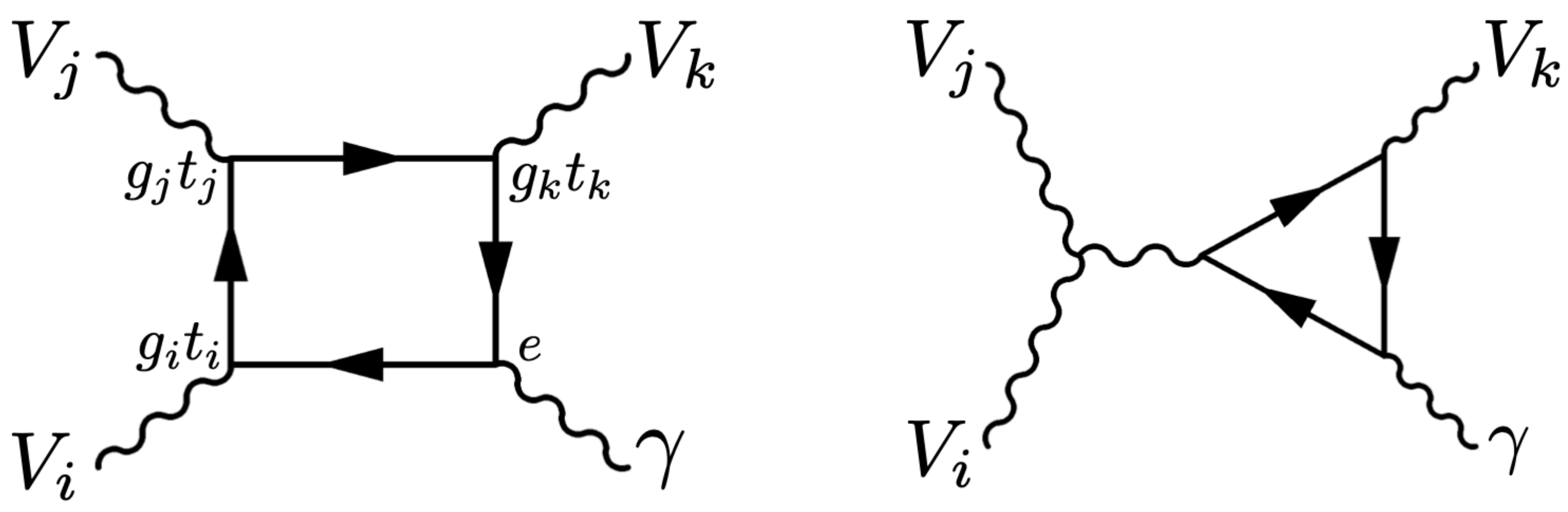
[F. D'Eramo, M. McCullough, J. Thaler (2012)]

Concrete model: semi-annihilation (2/2)

Loop-induced scenario



Annihilation



Semi-annihilation