

# MeV to GeV Dark Matter

Eric Kuflik

Light Dark Matter @ Accelerators (LDMA)



האוניברסיטה העברית בירושלים  
THE HEBREW UNIVERSITY OF JERUSALEM

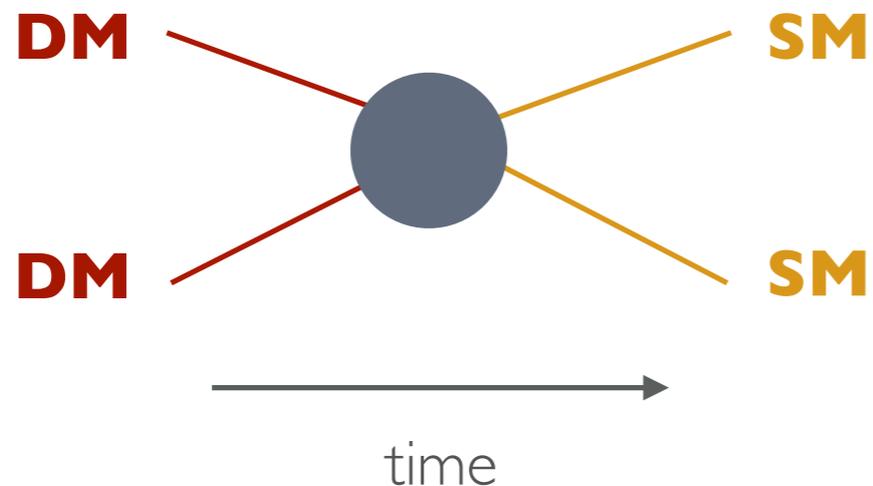
**Why?**

# Past 40 years

**WIMP, glorious WIMP\***

**\*Also axions**

# WIMP



$$\langle \sigma_{\text{ann}} v \rangle = \frac{\alpha^2}{m_{\text{DM}}^2}$$

Correct relic abundance for

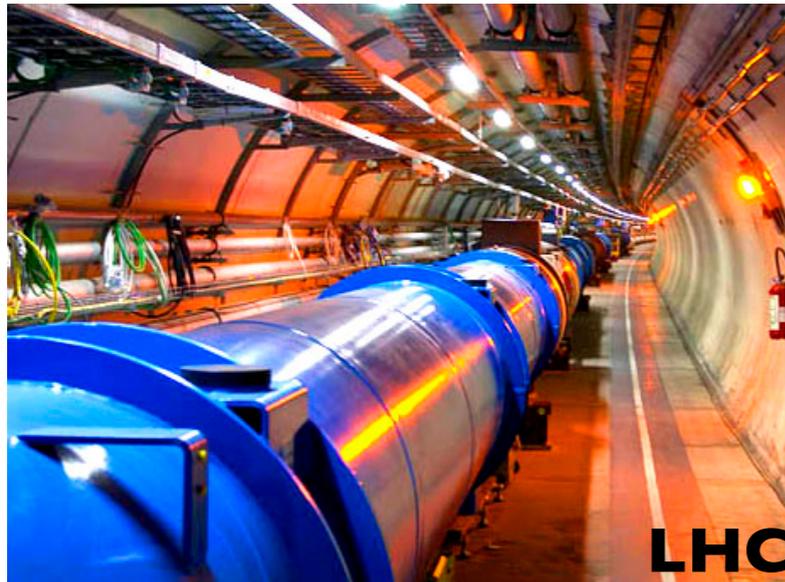
$$m_{\text{DM}} = \alpha \times 30 \text{ TeV}$$

For Weak coupling, Weak scale emerges

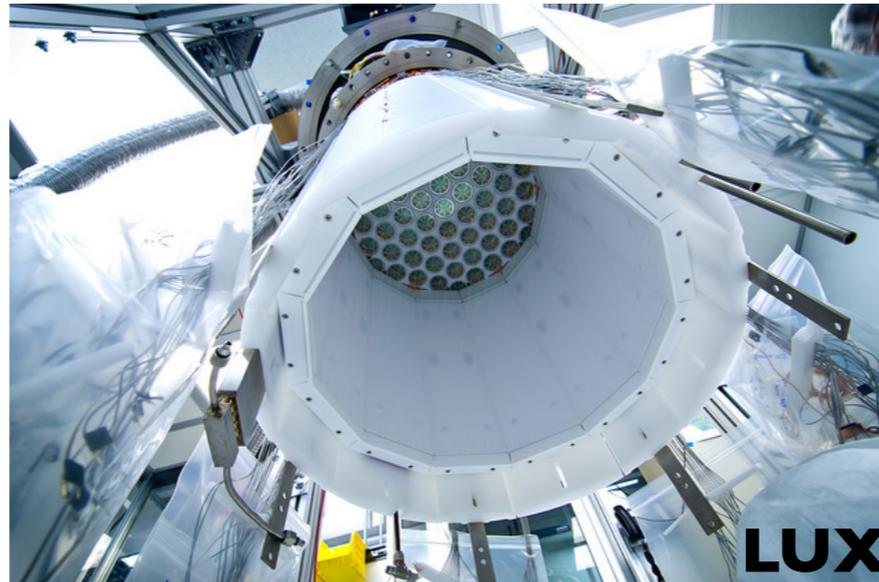
Weakly Interacting Massive Particle (WIMP)

# Searching for WIMPs

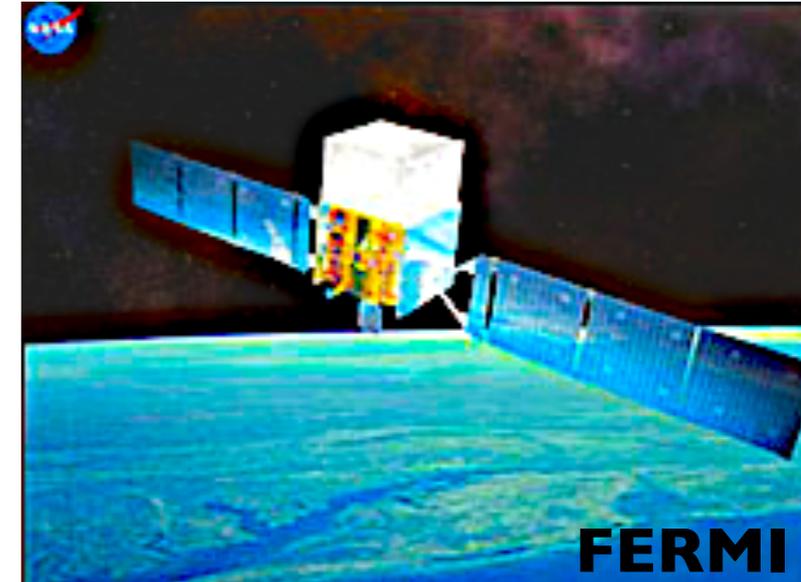
## Direct Production



## Direct Detection



## Indirect Detection



Experiments are getting increasingly sensitive...  
but we still haven't found it

**Dominant paradigm being challenged.**

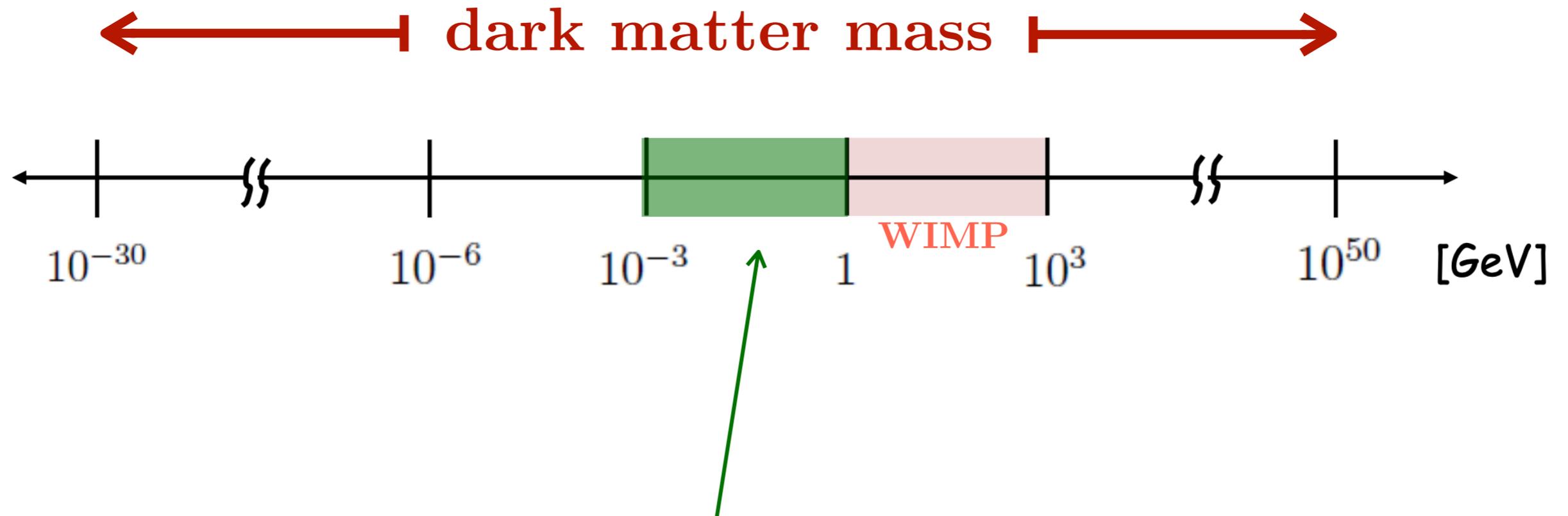
**Great opportunity for new ideas!**

# Beyond the WIMP

← dark matter mass →



# Beyond the WIMP



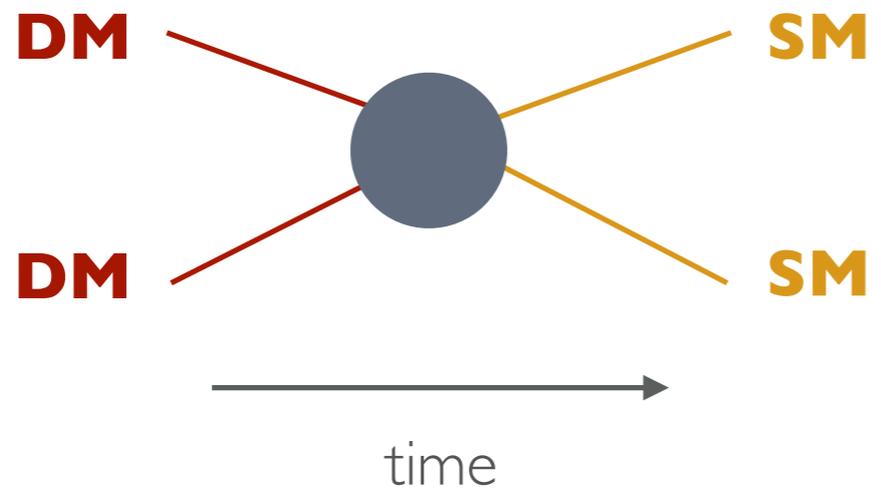
Lots of activity in recent years:  
Theory & Experiment

# New Theory Ideas

- .....
- Weakly coupled WIMPs [Pospelov, Ritz, Voloshin 2007; Feng, Kumar 2008]
- Asymmetric dark matter [Nussinov 1984; Kaplan, Luty, Zurek, 2009]
- Freeze-in dark matter [Hall, Jedamzik, March-Russell, West, 2009]
- SIMPs [Hochberg, EK, Volansky, Wacker, 2014; + Murayama, 2015]
- ELDERs [EK, Perelstein, Rey-Le Lorier, Tsai, 2016 & 2017]
- Forbidden dark matter [Griest, Seckel 1991; D'Agnolo, Ruderman 2015]
- Co-decaying dark matter [Dror, EK, Ng 2016]
- Co-scattering dark matter [D'Agnolo, Pappadopulo, Ruderman 2015]
- .....

... are abundant

# Weakly Coupled 2→2



$$\langle \sigma_{\text{ann}} v \rangle = \frac{\alpha^2}{m_{\text{DM}}^2}$$

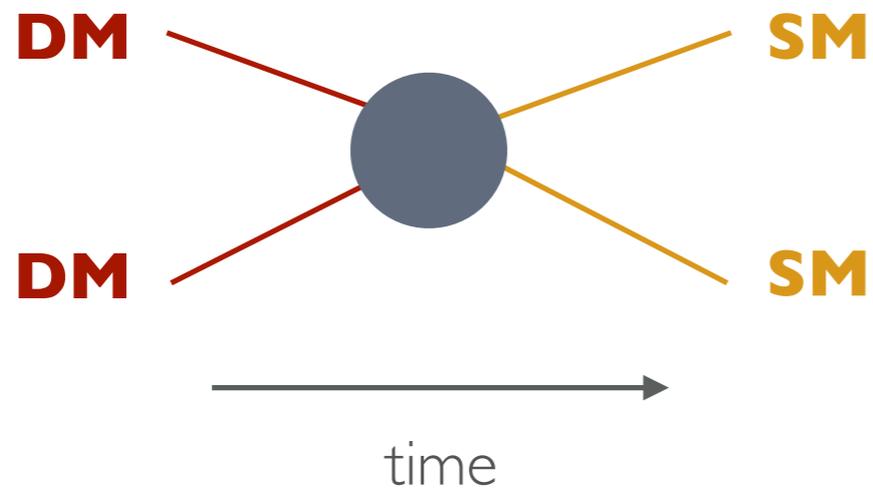
$$m_{\text{DM}} = \alpha \times 30 \text{ TeV}$$

$$\alpha \ll 1$$

[Pospelov, Ritz, Voloshin 2007

Feng, Kumar 2008]

# Forbidden Channels



$$m_{\text{DM}} < m_{\text{SM}}$$

$$\langle \sigma_{\text{ann}} v \rangle = \frac{\alpha^2}{m_{\text{DM}}^2}$$

$$m_{\text{DM}} = \alpha \times 30 \text{ TeV} \times e^{-x_f \Delta}$$

freezeout  
temp

$$x = m/T$$

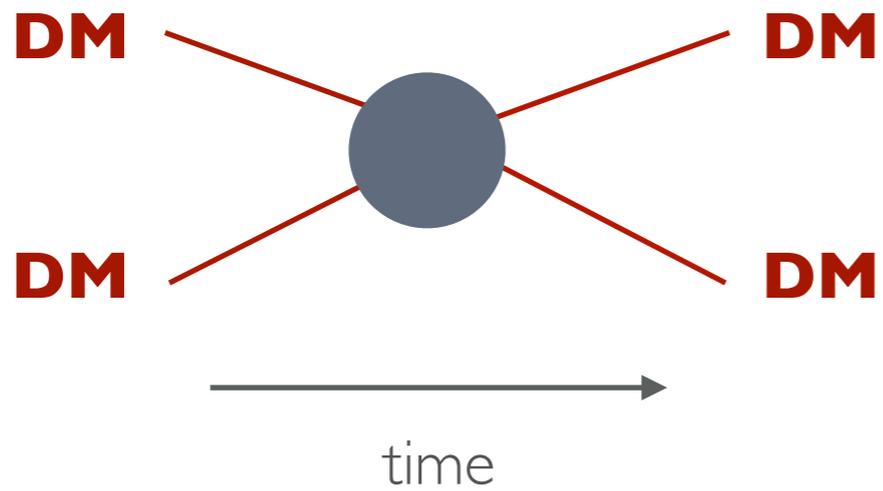
mass  
difference

Forbidden @  $T=0$ ;

Proceeds via Boltzmann tail

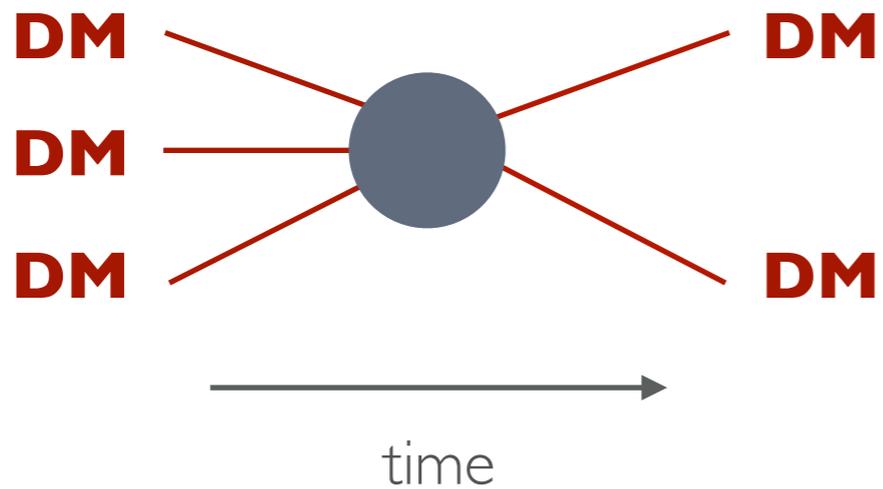
[Griest, Seckel 1991;  
D'Agnolo, Ruderman 2015]

# SIMPs



$2 \rightarrow 2$  annihilations does not  
change number density

# SIMPs

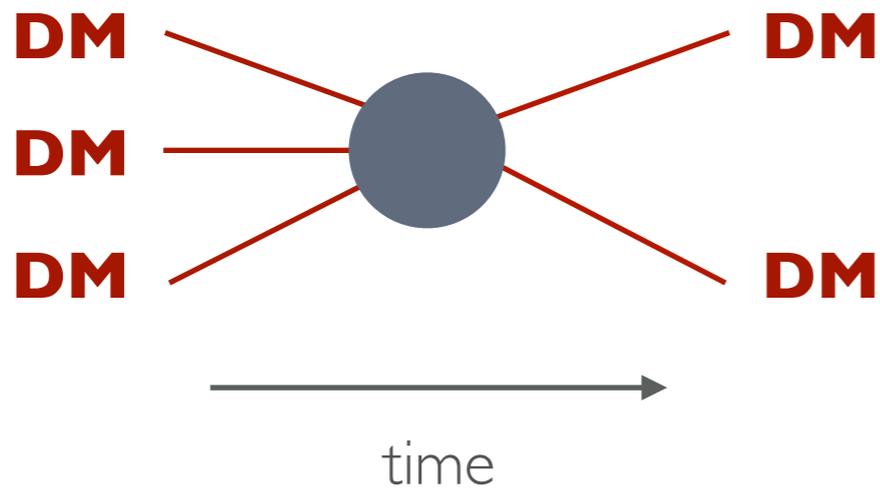


$2 \rightarrow 2$  annihilations does not  
change number density

$3 \rightarrow 2$  annihilations do

[Hochberg, EK, Volansky,  
Wacker, 2014]

# SIMPs



$$\langle \sigma v^2 \rangle_{3 \rightarrow 2} = \frac{\alpha^3}{m_{\text{DM}}^5}$$

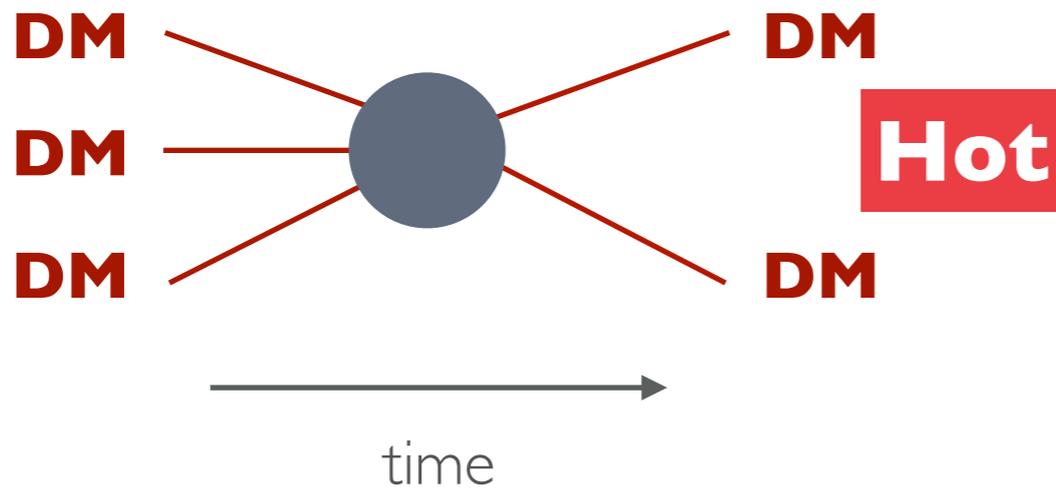
$$m_{\text{DM}} = \alpha \times 100 \text{ MeV}$$

For strong coupling, strong scale emerges

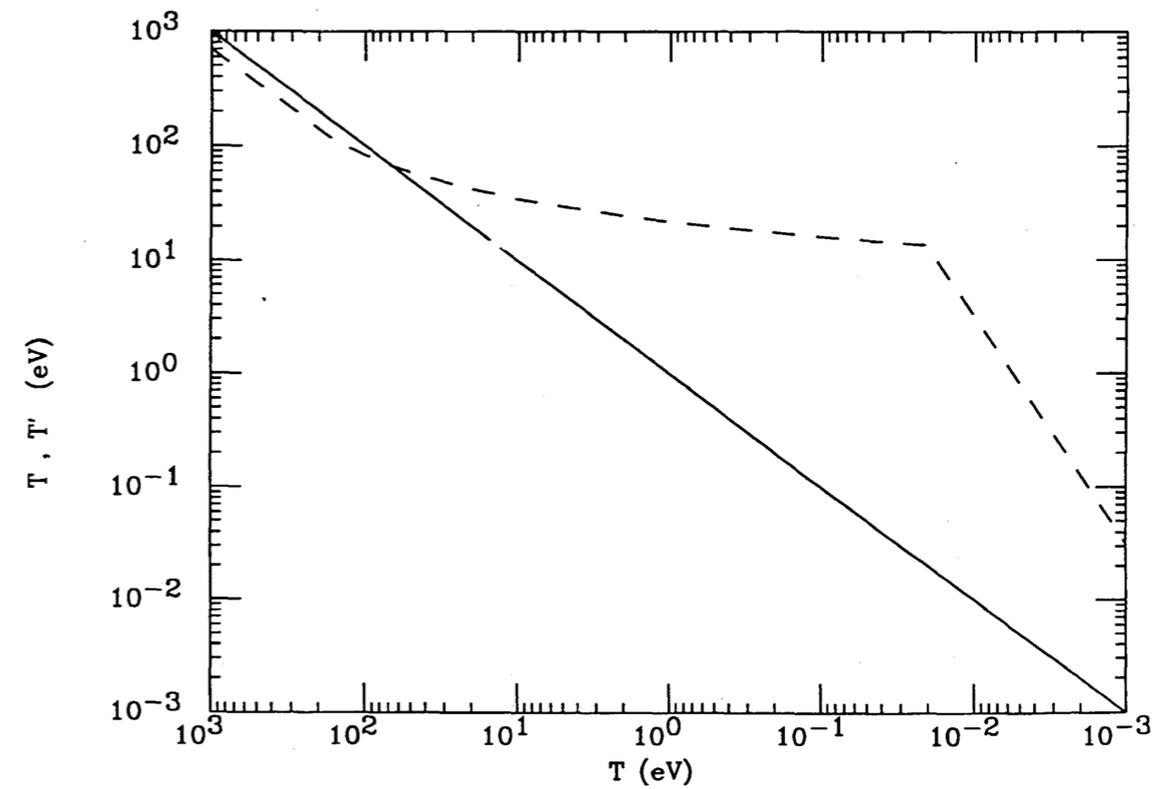
Strongly Interacting Massive Particle (SIMP)

# Beware: cannibals

Cold



Carlson, Hall and Machacek (1992)

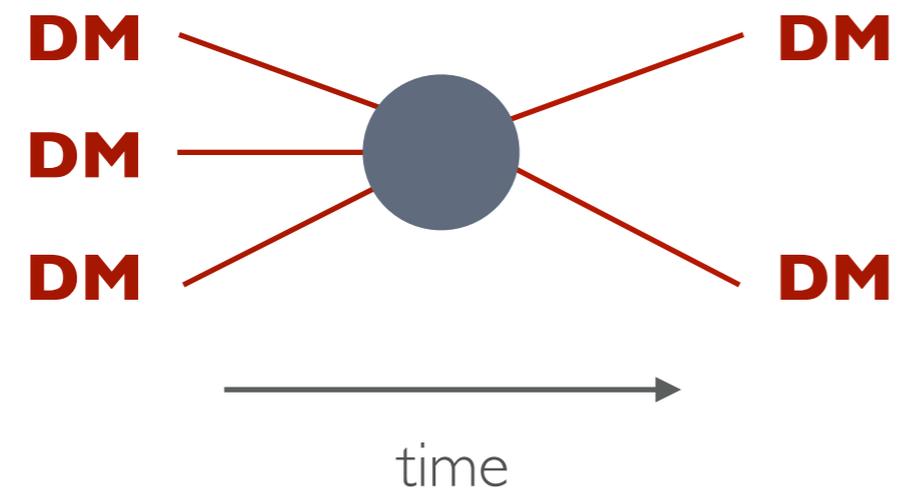


**Excluded:  
Hot Dark Matter**

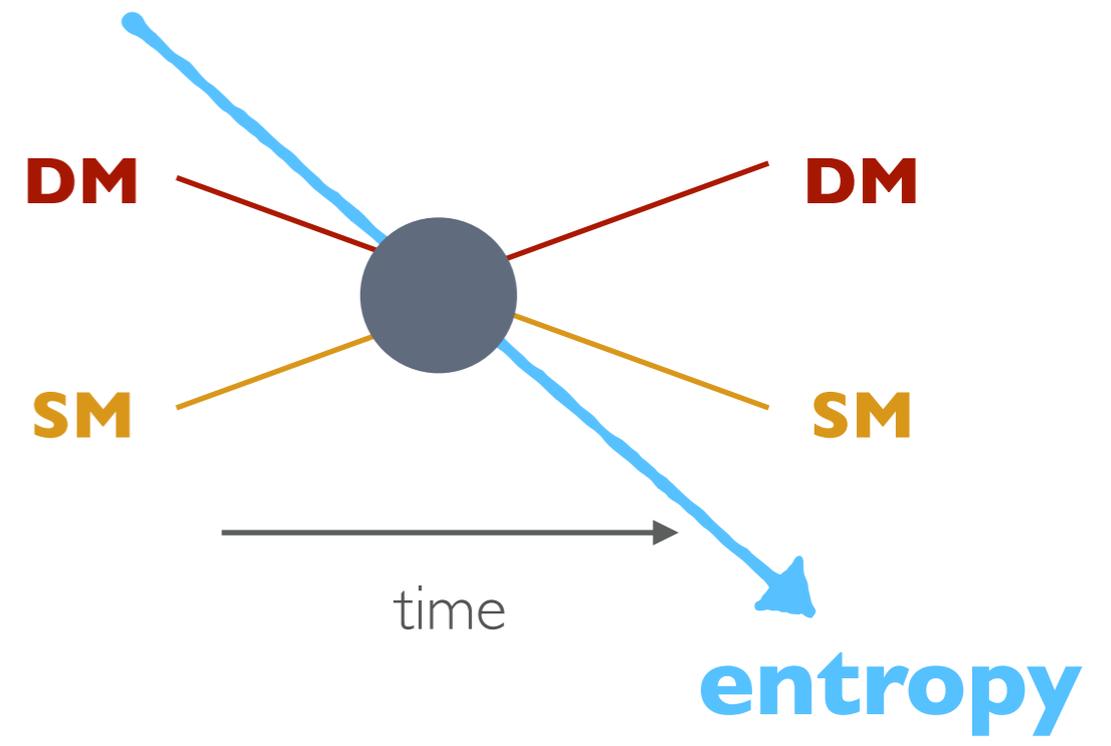
[Hochberg, EK, Volansky,  
Wacker, 2014]

# SIMPs

## Sets the abundance



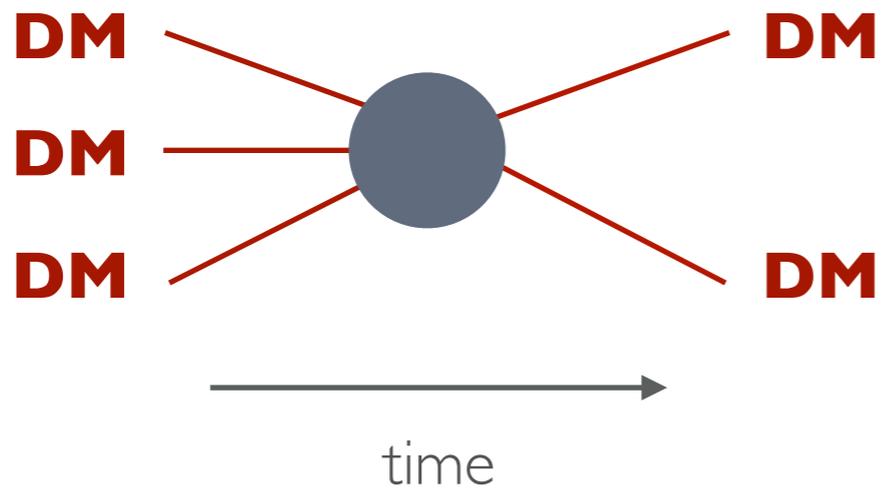
## Shed the heat



Interactions much smaller than WIMPs

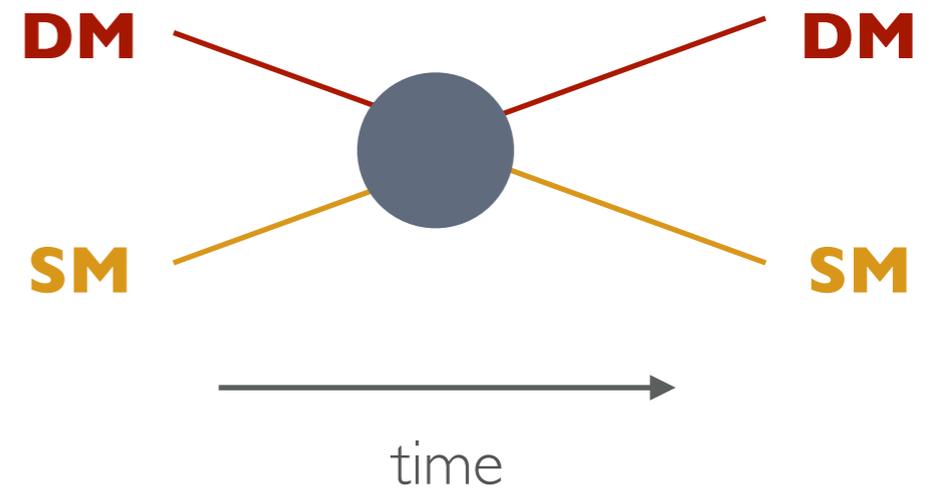
# SIMPs

**Sets the abundance**



Decouples **1st**

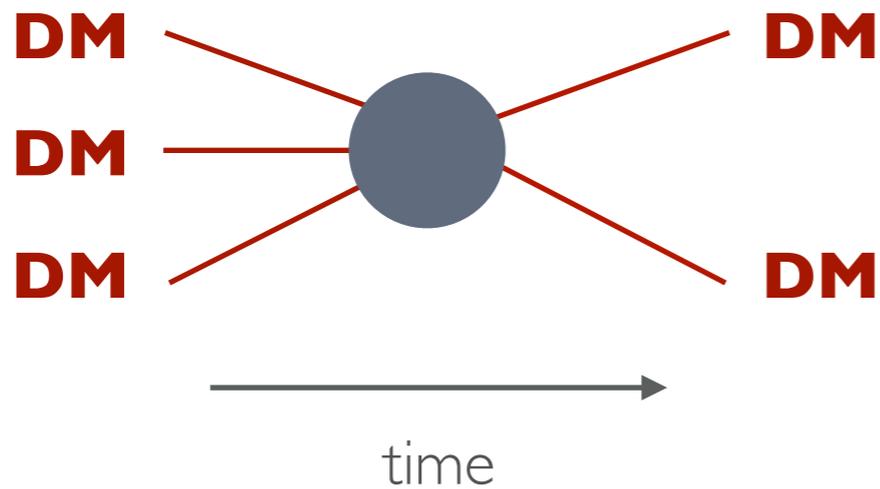
**Shed the heat**



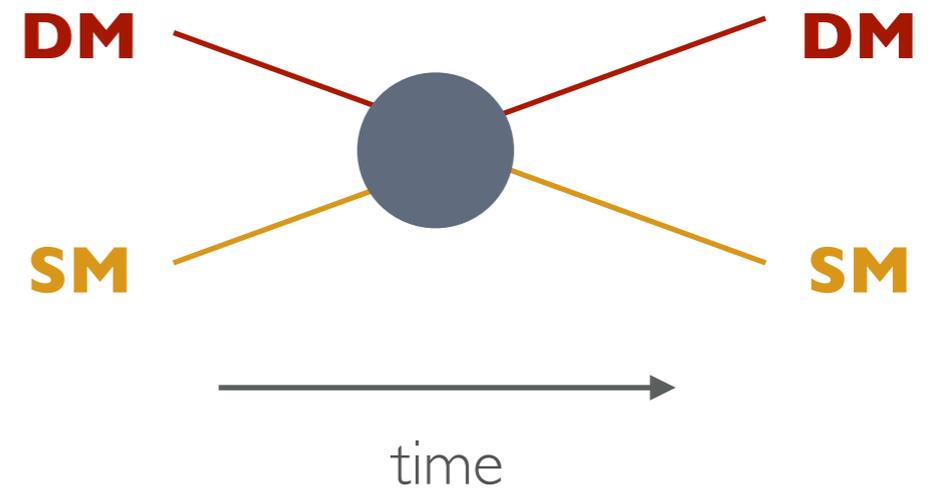
Decouples **2nd**

# ELDER: ELastically DEcoupling Relic

**Sets the abundance**



Decouples **2nd**



Decouples **1st**

$$\Omega_{\text{DM}} \propto e^{-\langle \sigma v \rangle_{\text{el}} \#}$$

# Cannibalization

Temp

2 → 2 ann  
2 → 2 el

At early times the DM and SM sector decouple

- After decoupling total entropy is separately conserved in each sector. In terms of entropy density:

$$\frac{s'}{s} = \frac{s'_{\text{dec}}}{s_{\text{dec}}} = \text{constant}$$

primes denote  
dark matter

$m_{\text{DM}}$

3 → 2

- Number density when 3 → 2 freezeout:

$$n'_f = \frac{\rho'_f}{m_{\text{DM}}} = \frac{s'_f T'_f}{m_{\text{DM}}} = \frac{s_f}{m_{\text{DM}}/T'_f} \frac{s'_d}{s_d}$$

# Cannibalization

Temp

2 → 2 ann  
2 → 2 el

At early times the dark sector and SM sector decouple

- The abundance today

$$\Omega = 0.6 \frac{m_{\text{DM}}/\text{eV}}{x'_f} \left( \frac{s'_{\text{dec}}}{s_{\text{dec}}} \right)$$

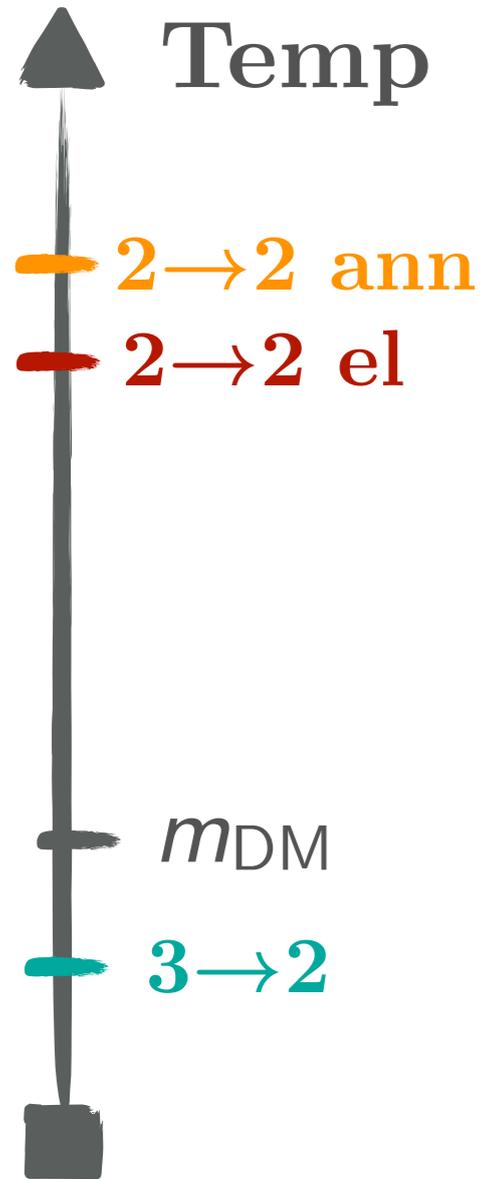
$$x' \equiv m_{\text{DM}}/T'$$

$m_{\text{DM}}$   
3 → 2

- Hot dark matter, unless...

$$\left( \frac{s'_{\text{dec}}}{s_{\text{dec}}} \right) \ll 1$$

# Cannibalization

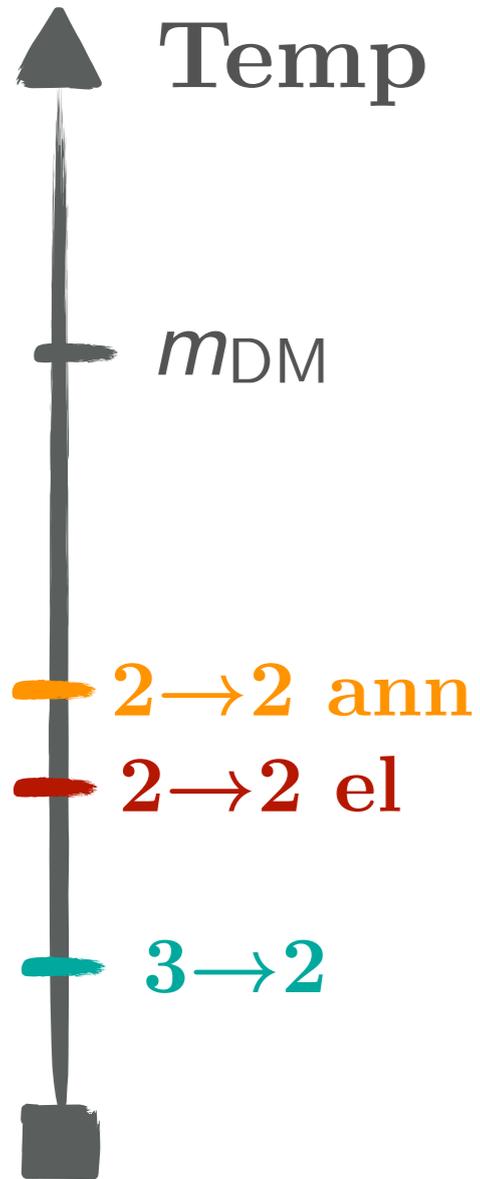


$$\Omega = 0.6 \frac{m_{\text{DM}}/\text{eV}}{x'_f} \left( \frac{s'_{\text{dec}}}{s_{\text{dec}}} \right)$$

- Decoupling in the early universe (while dark matter relativistic):

$$\left( \frac{s'_{\text{dec}}}{s_{\text{dec}}} \right) = \frac{g_{\text{dark}}}{g_{\text{SM}}}$$

# ELDER



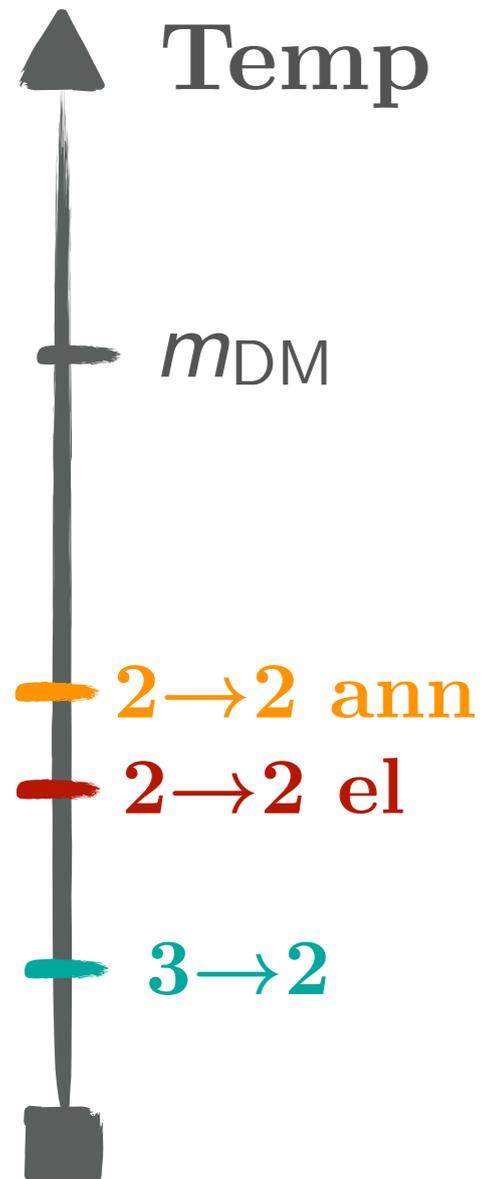
$$\Omega = 0.6 \frac{m_{\text{DM}}/\text{eV}}{x'_f} \left( \frac{s'_{\text{dec}}}{s_{\text{dec}}} \right)$$

- Decoupling while dark matter is non-relativistic:

$$\left( \frac{s'_{\text{dec}}}{s_{\text{dec}}} \right) \sim e^{-x'_{\text{dec}}} \ll 1$$

→  $\Omega \propto e^{-x'_{\text{dec}}}$

# ELDER



## Decoupling

$$n_{\text{sm}} \langle \sigma v \rangle_{\text{el}} \sim H$$

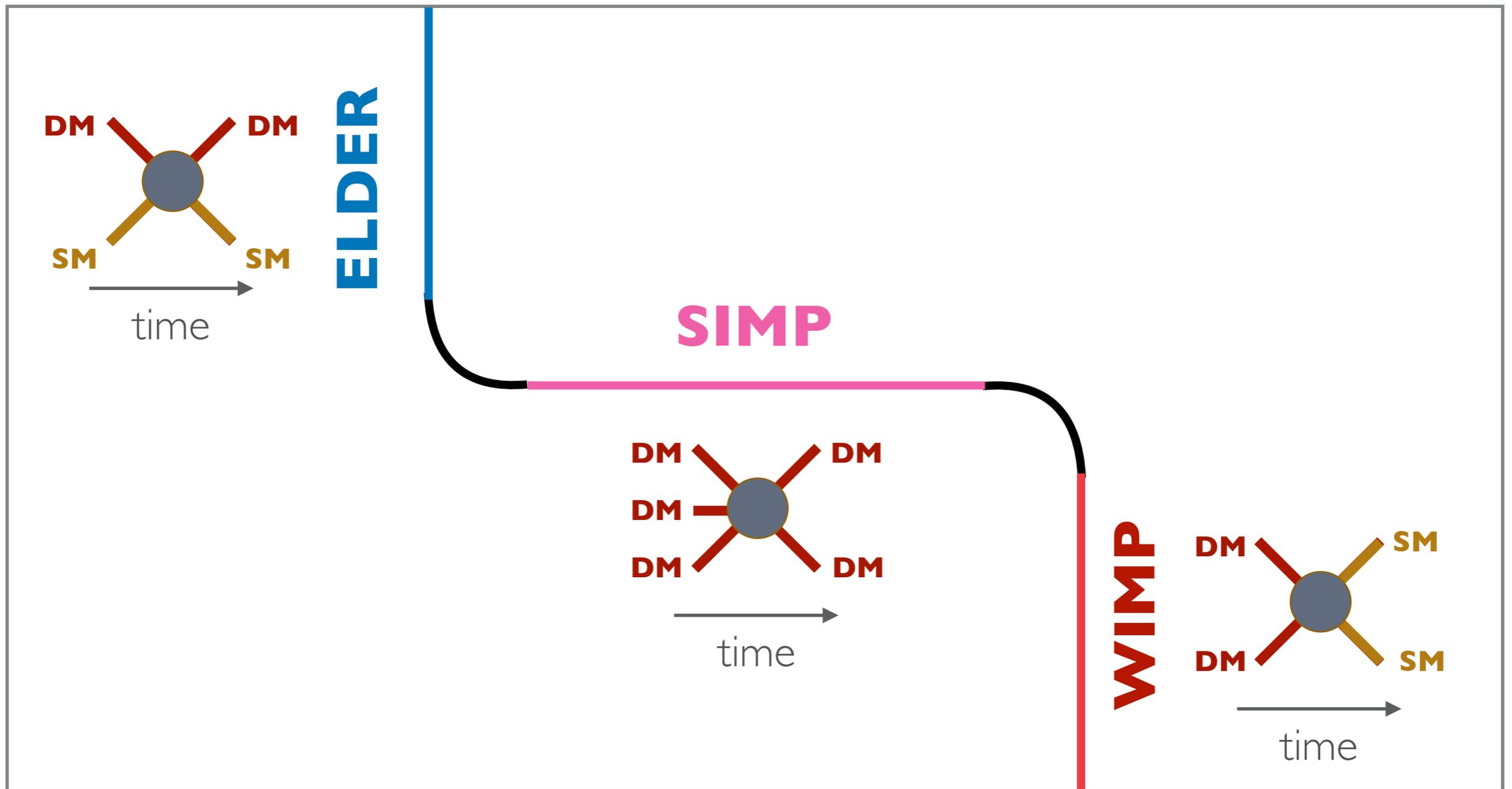
$$x_{\text{dec}}^{-3} \langle \sigma v \rangle_{\text{el}} \sim x_{\text{dec}}^{-2}$$

$$x_{\text{dec}} \sim \langle \sigma v \rangle_{\text{el}}$$

→  $\Omega \propto e^{-x'_{\text{dec}}} \propto e^{-\langle \sigma v \rangle_{\text{el}}}$

# ELDER / SIMP / WIMP

3 → 2 rate



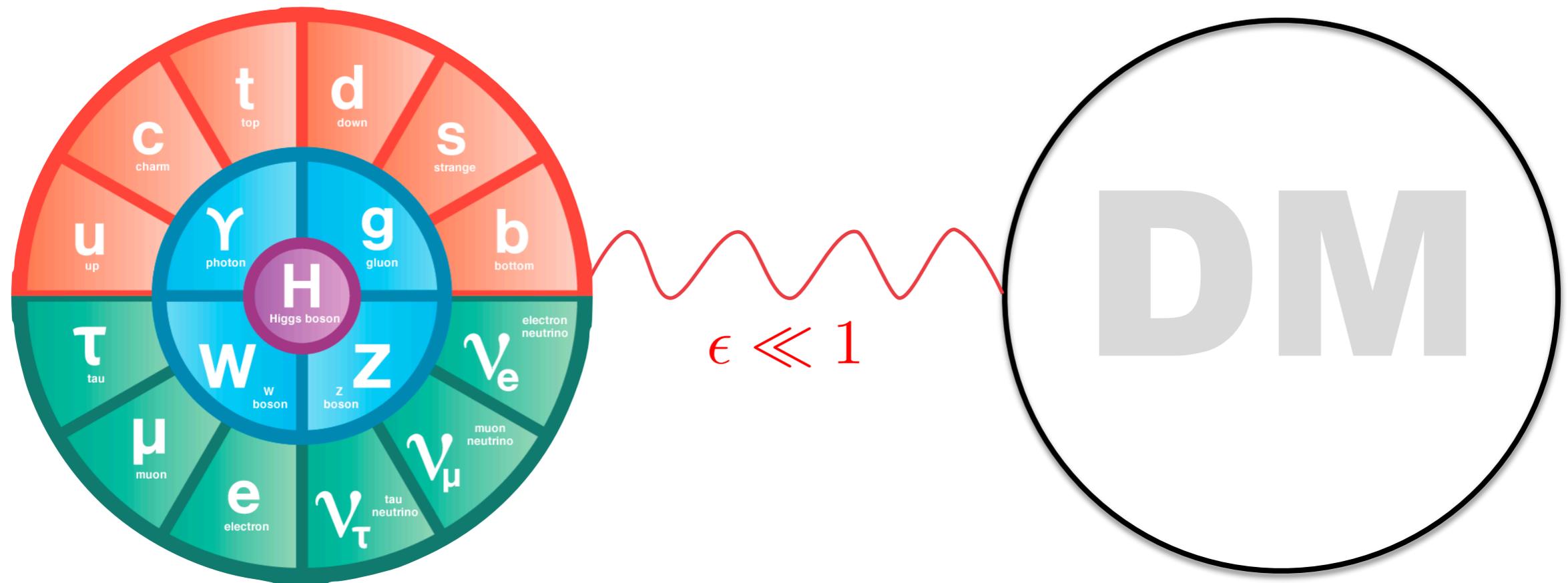
2 → 2 coupling

**Generic.**

# Dark Sectors

Visible sector

Dark sector



SM is a  
particle zoo.

Why not in the  
dark sector too?

# QCD-like sector

Think Standard Model!

Dark matter from strongly coupled gauge theories

*e.g.*  $SU(3)_{\text{dark}} \times U(1)_{\text{dark}}$

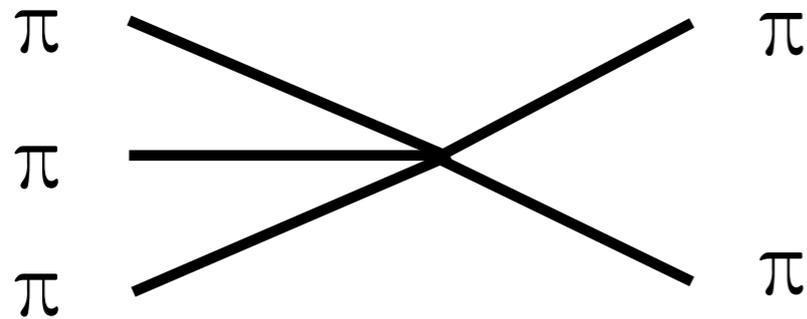
$Sp(N_c), SU(N_c), SO(N_c)$

kinetically mixed  
hidden photon (V)

QCD-like theories, pions = dark matter.

Many processes, many dark matter mechanisms.

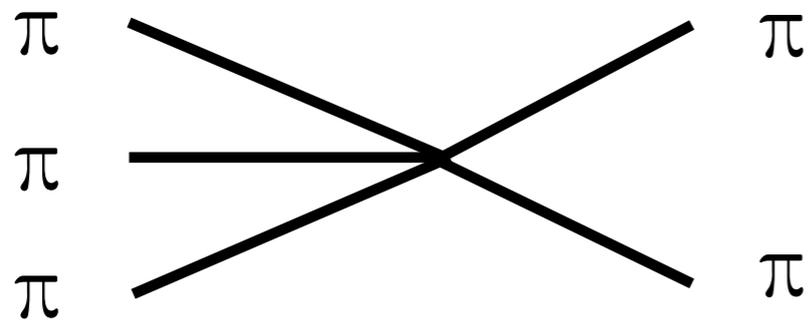
# Processes



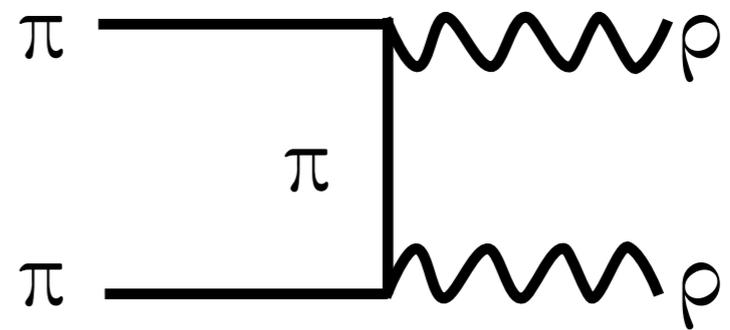
$3 \rightarrow 2$  processes

(From the Wess-Zumino-Witten term. In QCD describes  $K \rightarrow \pi \pi \pi$ )

# Processes



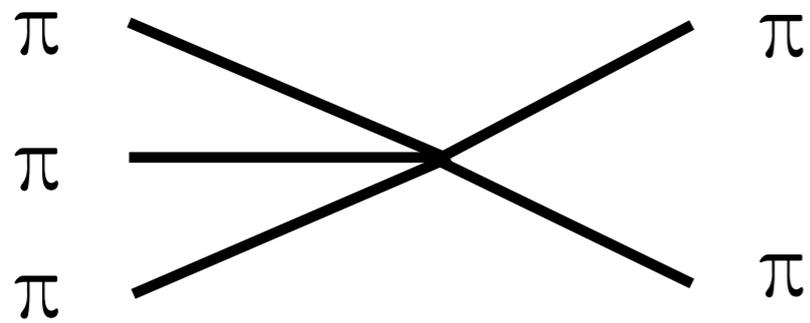
3  $\rightarrow$  2 processes



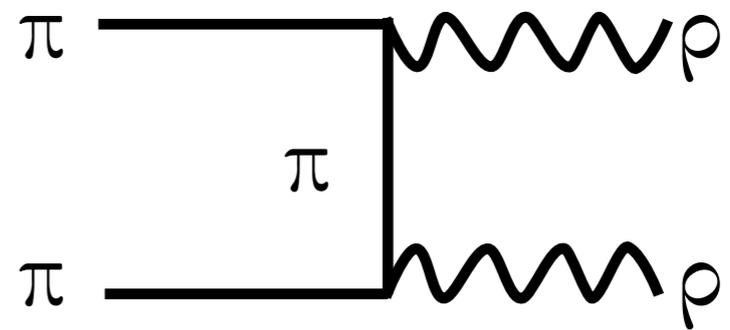
forbidden

$$m_\rho \gtrsim m_\pi$$

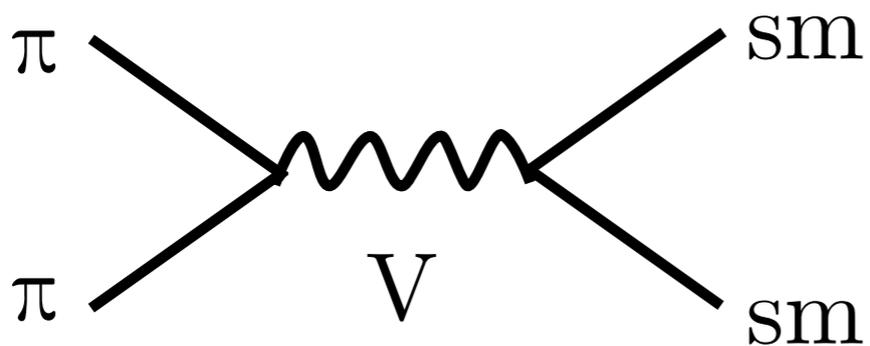
# Processes



3→2 processes

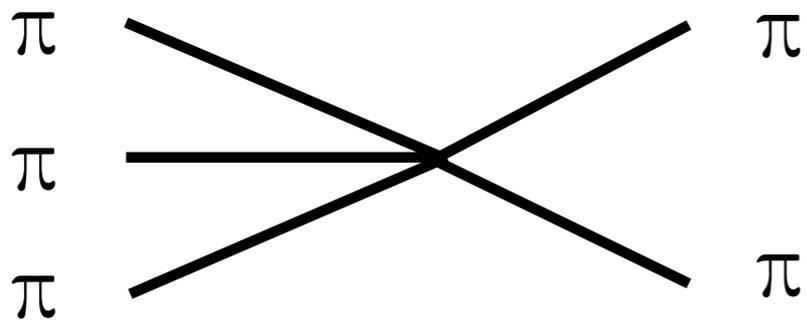


forbidden

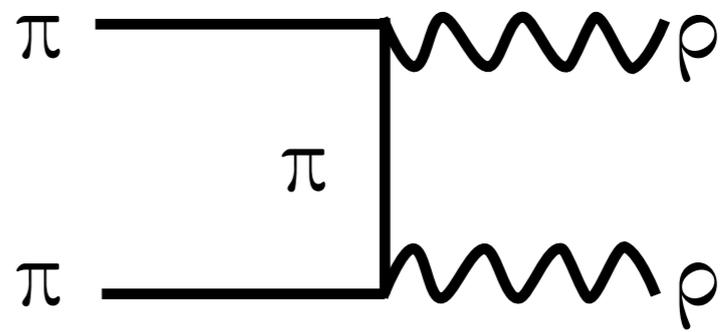


2→2 annihilations

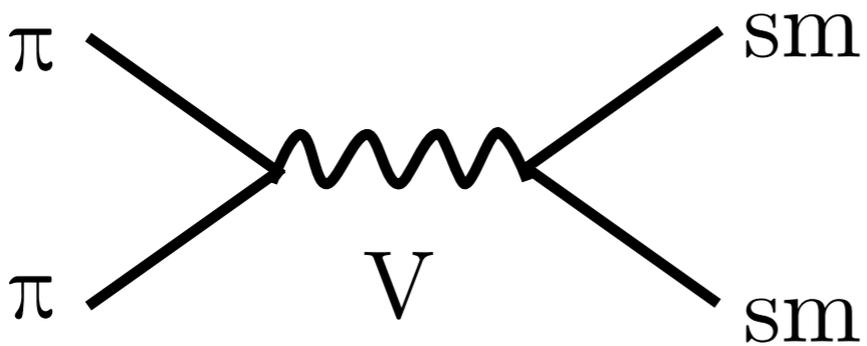
# Processes



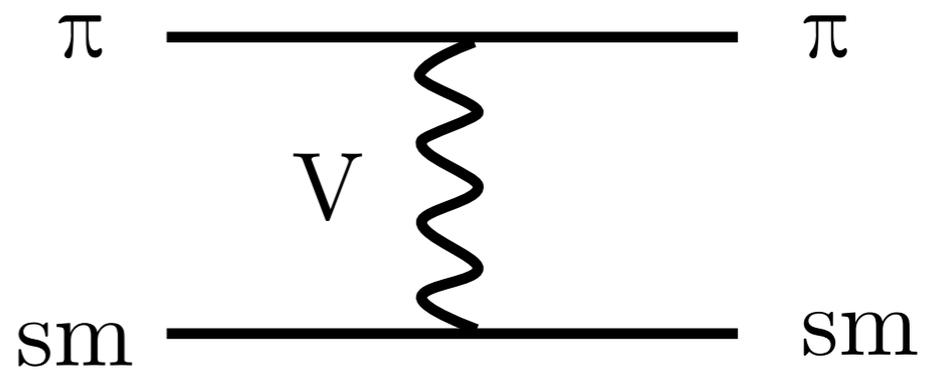
3 → 2 processes



forbidden



2 → 2 annihilations

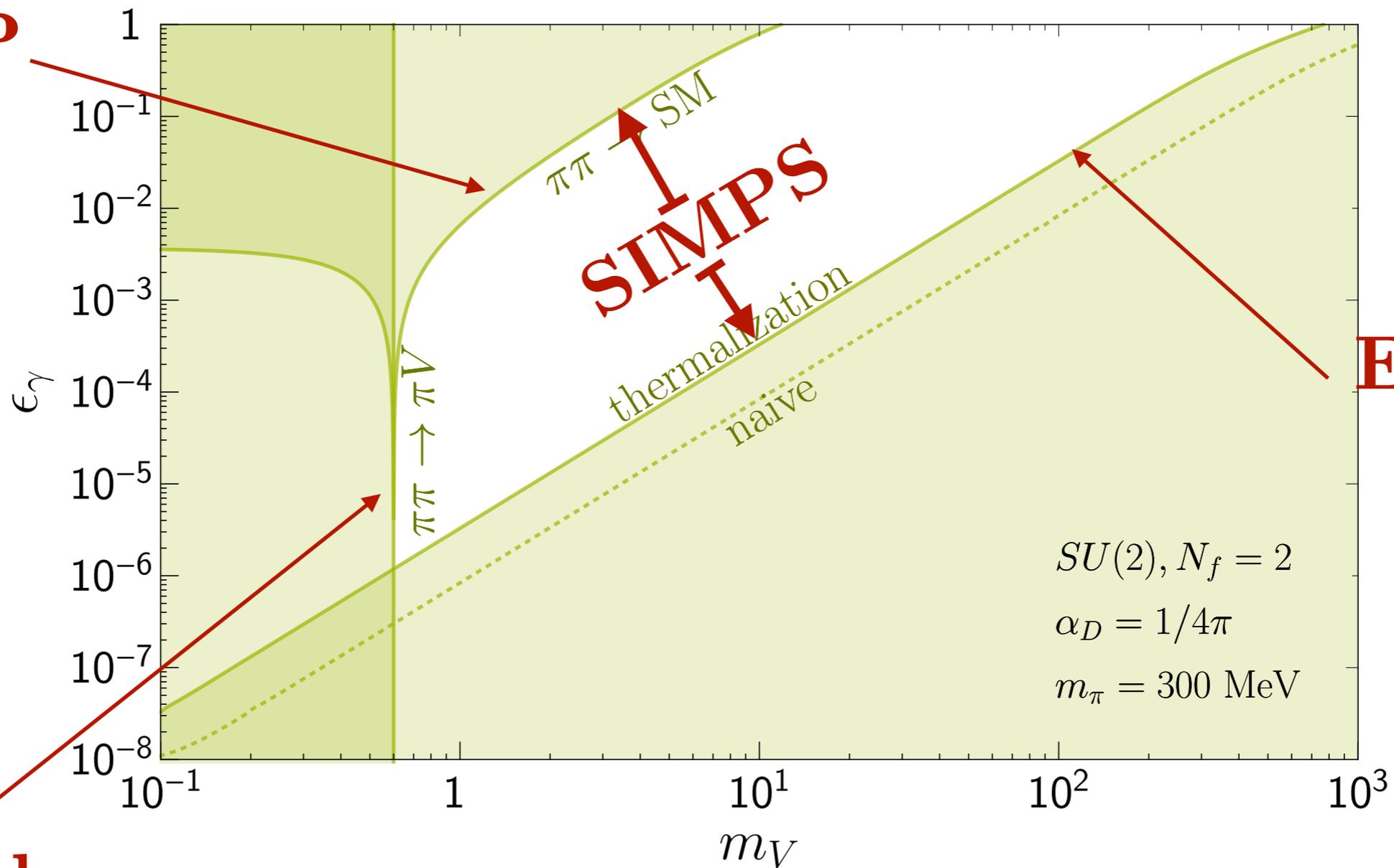


elastic scattering

# Predictive

## Kinetically mixed U(1)

**WIMP**

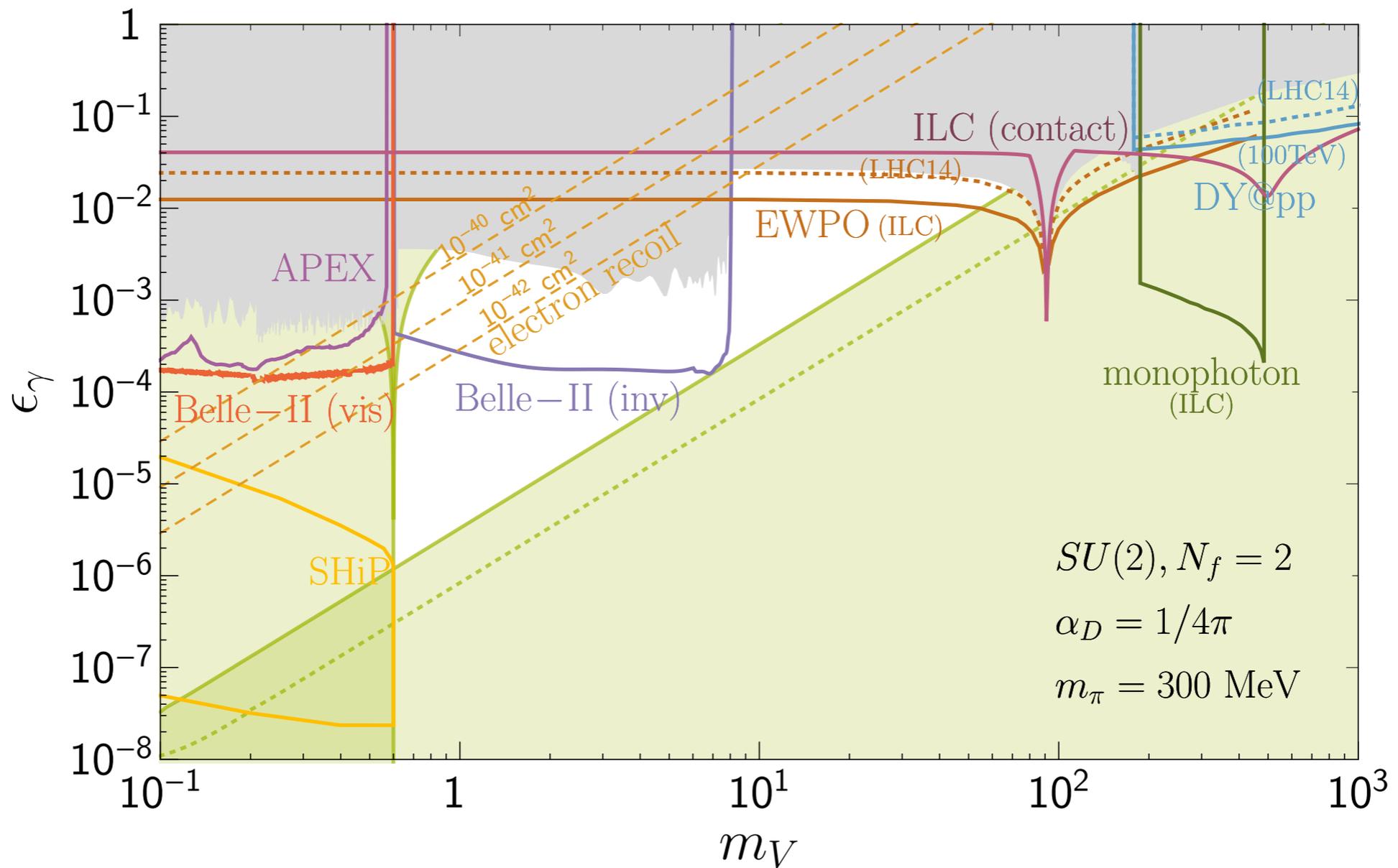


**ELDER**

**Forbidden**

# Predictive

## Kinetically mixed U(1)

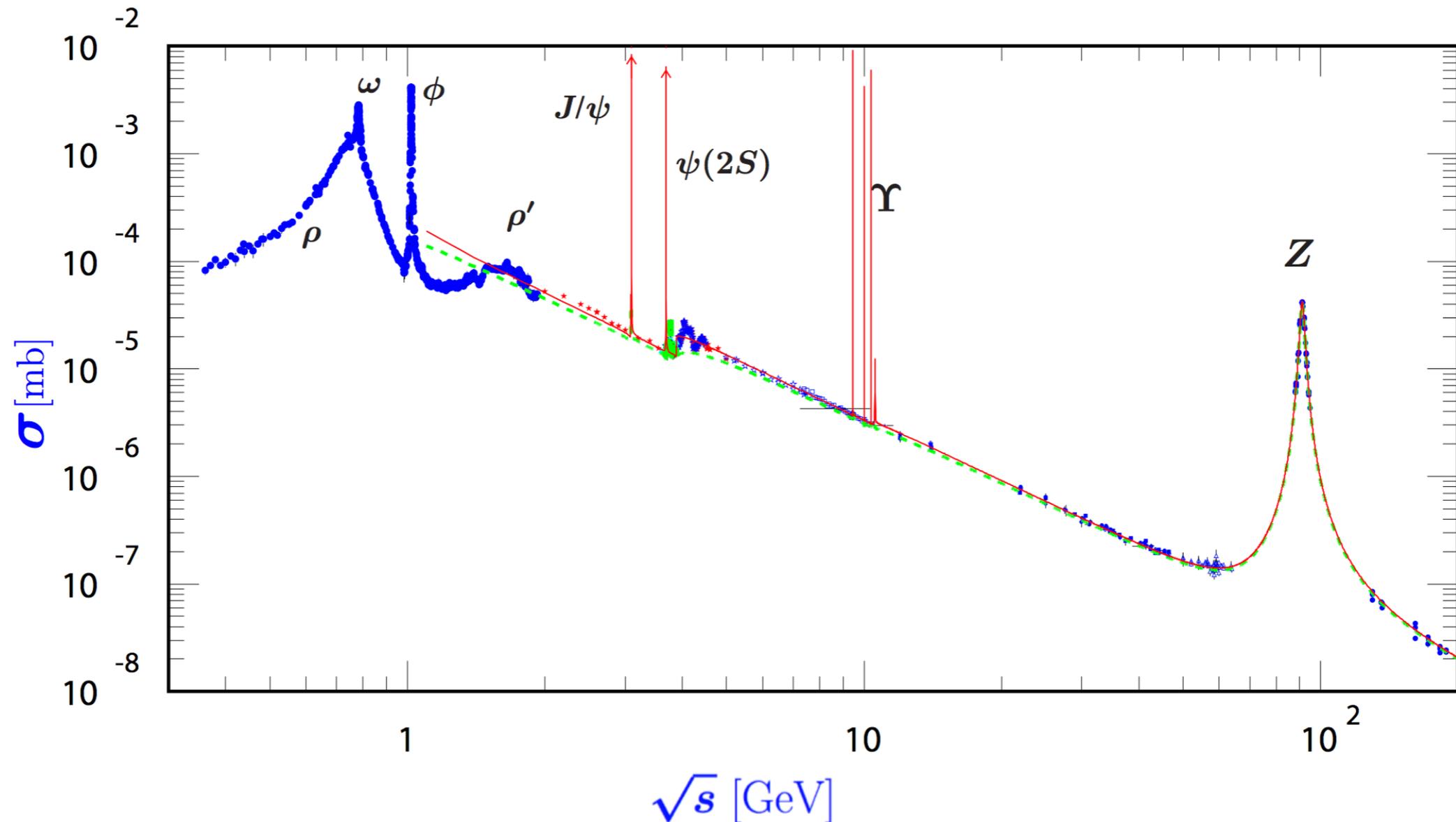


**Future probes**

# Dark Spectroscopy

$$e^+e^- \rightarrow \text{resonances}$$

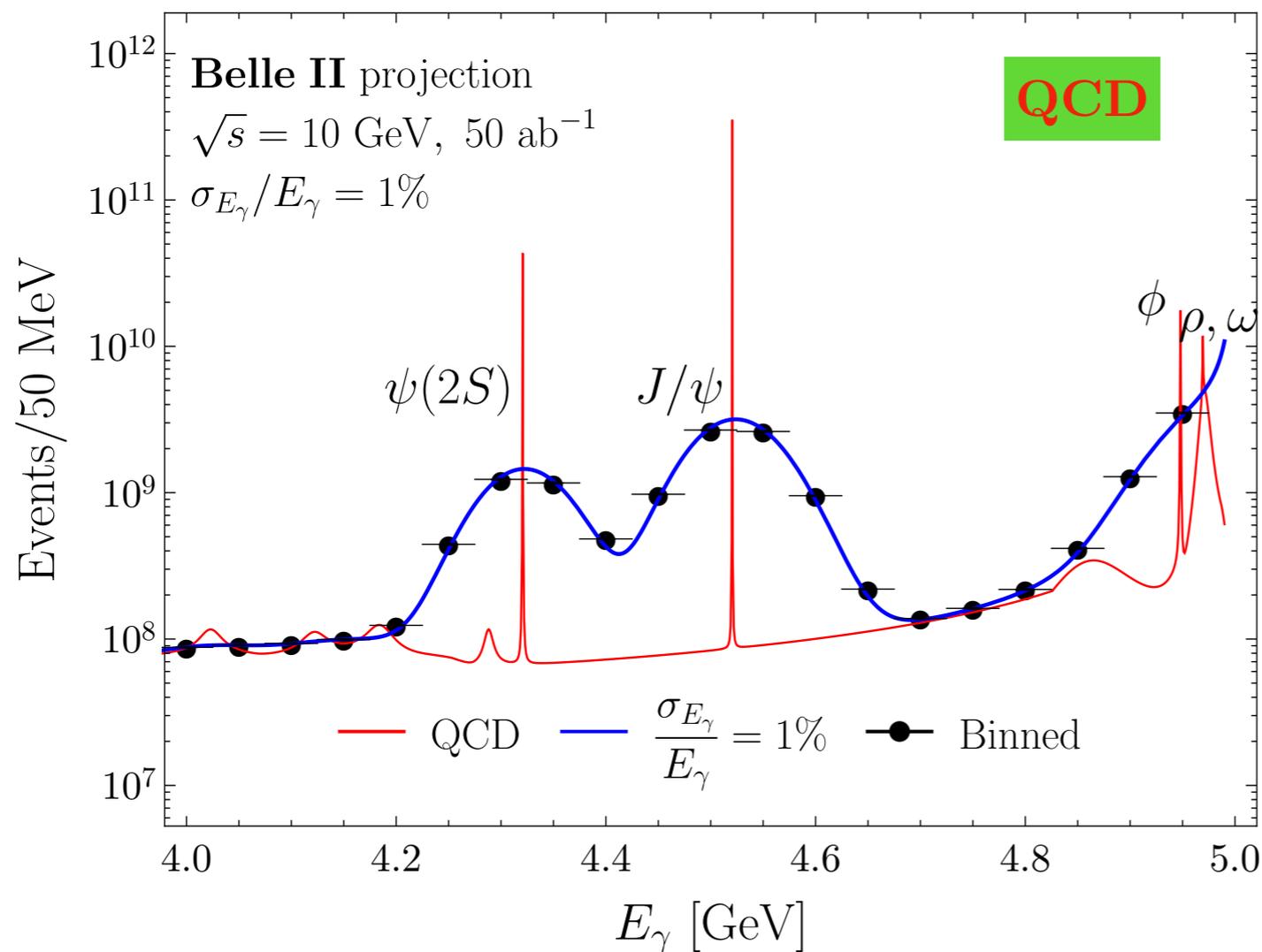
center of mass energy traces the **QCD** resonance structure



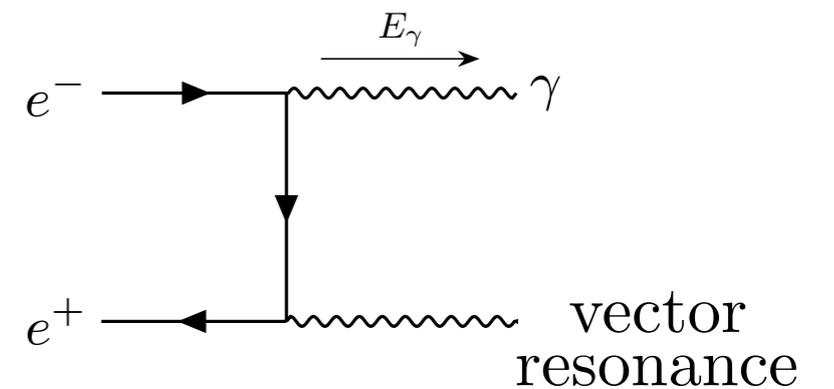
# Dark Spectroscopy

$$e^+e^- \rightarrow \gamma + \text{resonances}$$

mono-photon energy also traces the resonance structure



$$E_\gamma = \frac{\sqrt{s}}{2} \left( 1 - \frac{M_{\text{res}}^2}{s} \right)$$



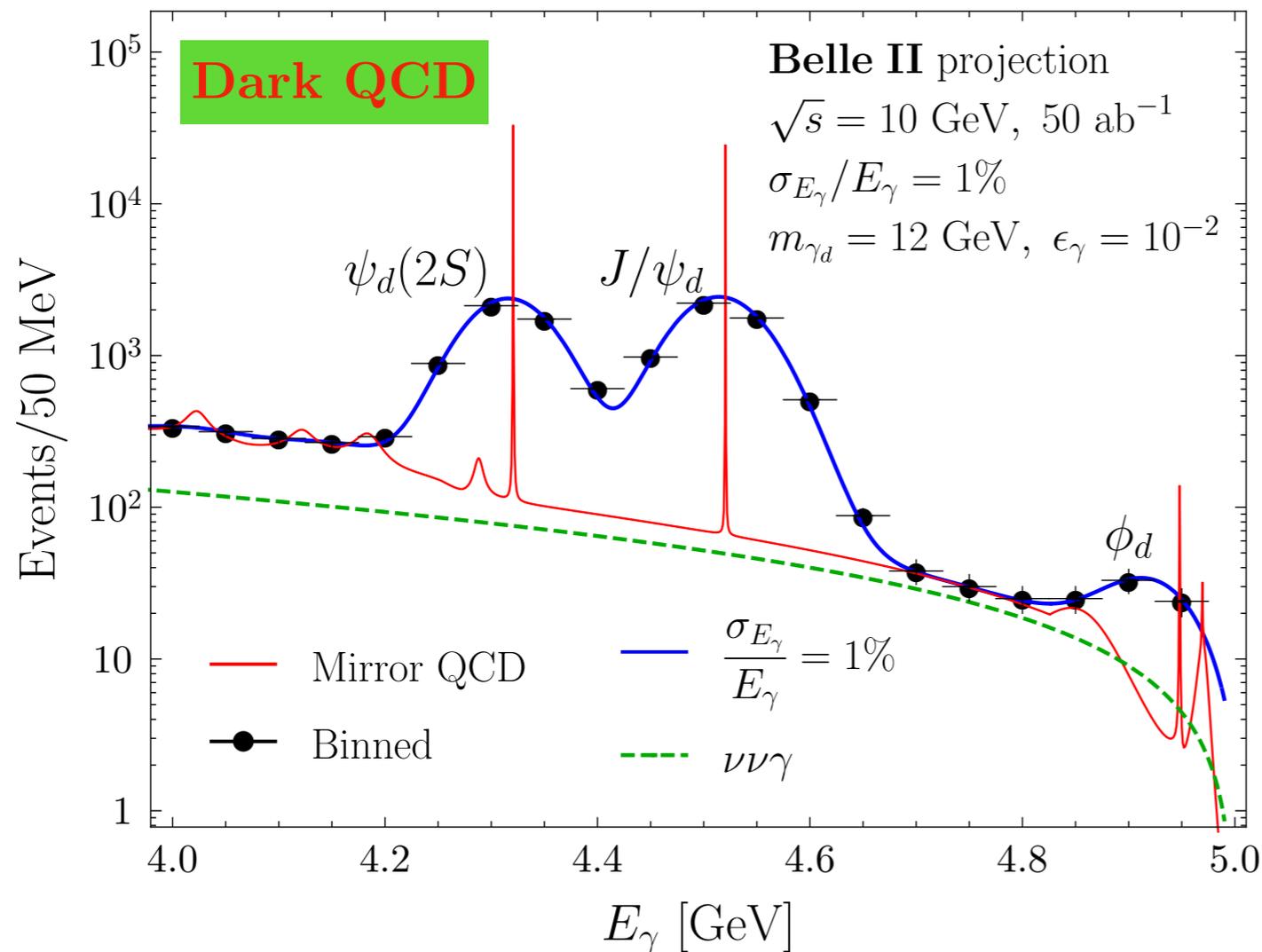
( $\phi, \rho, \omega, J/\psi, \psi(2S), \text{etc...}$ )

[Hochberg, EK, Murayama, 2016, 2017]

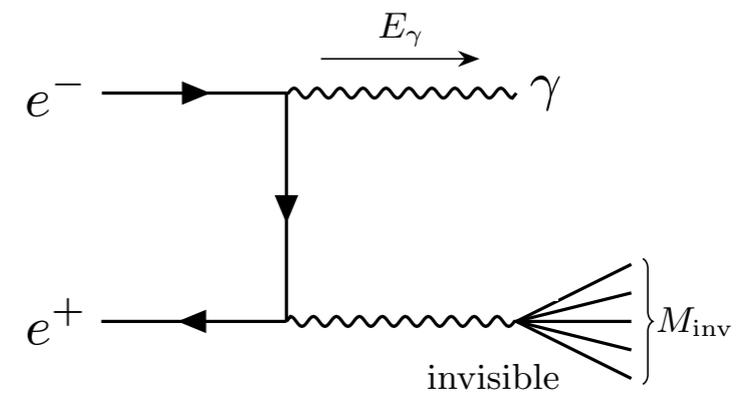
# Dark Spectroscopy

$$e^+e^- \rightarrow \gamma + \text{invisible resonances}$$

mono-photon energy also traces the resonance structure



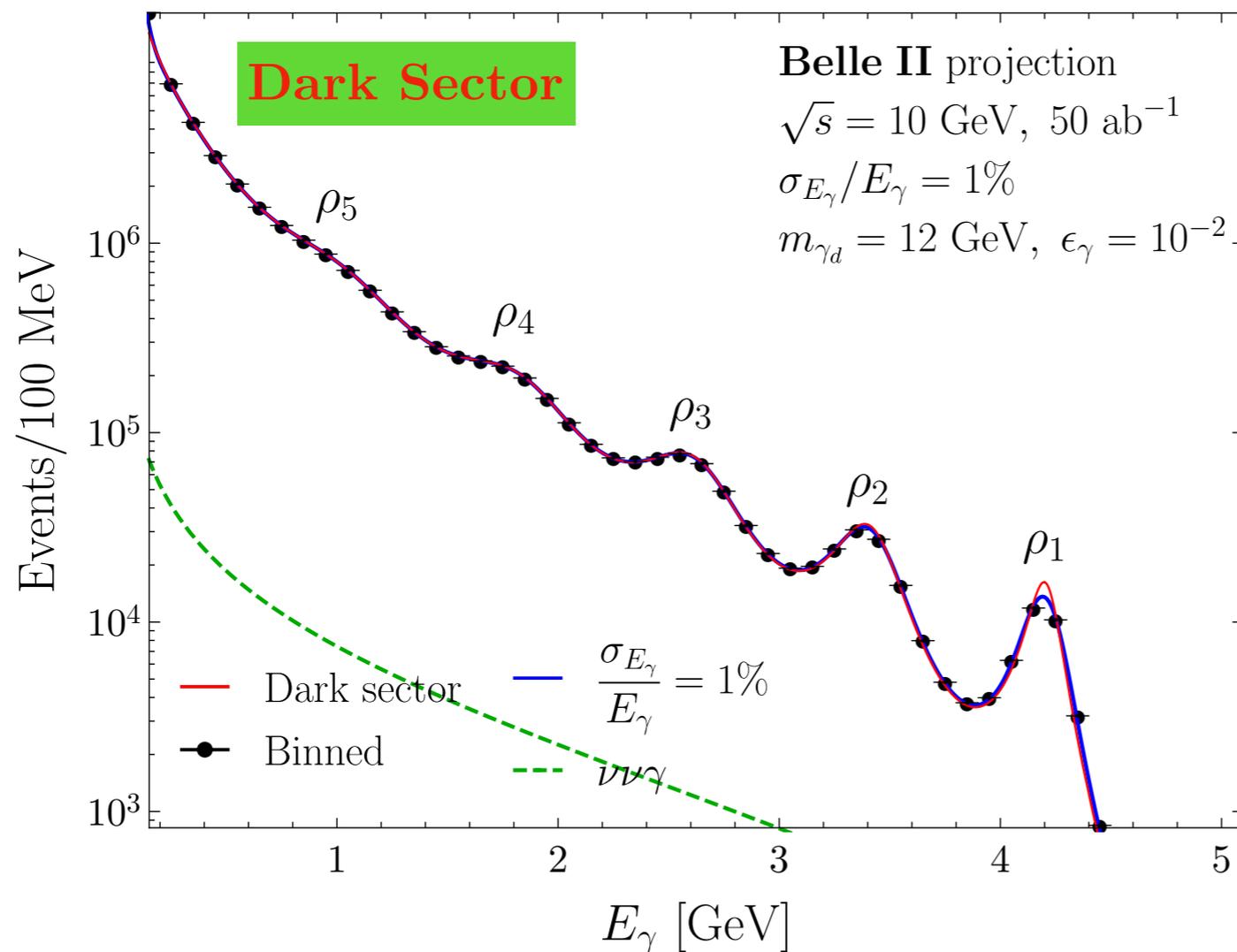
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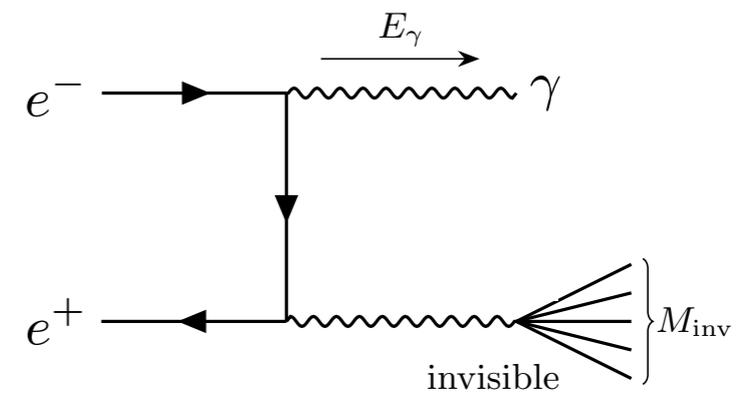
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$$E_\gamma = \frac{\sqrt{s}}{2} \left( 1 - \frac{M_{\text{res}}^2}{s} \right)$$



# Summary

- Lots of activity for light dark matter.
- Many different interactions, processes, and their relative importance throughout the cosmological history.
- Novel dark matter frameworks.
- Generic.
- Lots of discovery potential.

**Thank you!**

