Dark Matter Theory

Eric Kuflik

ICHEP 2020

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

New Ideas in Dark Matter Theory

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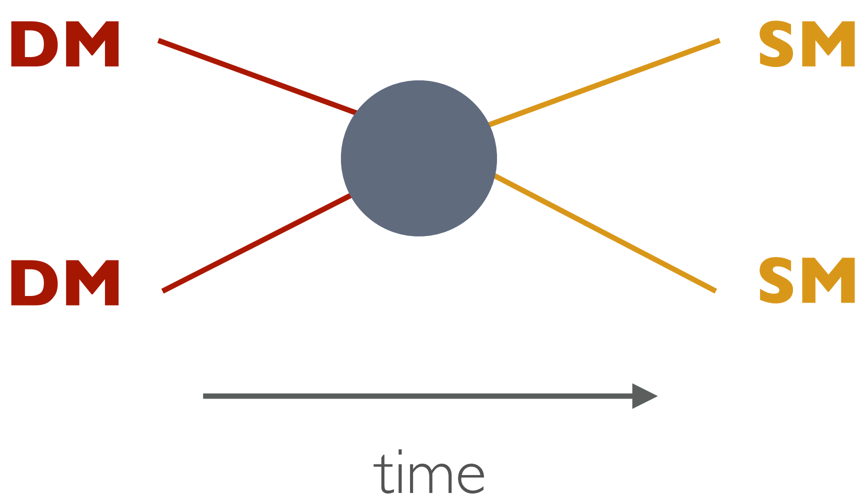
Why?

Past 40 years

WIMP, glorious WIMP*

***Also axions**

WIMP



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

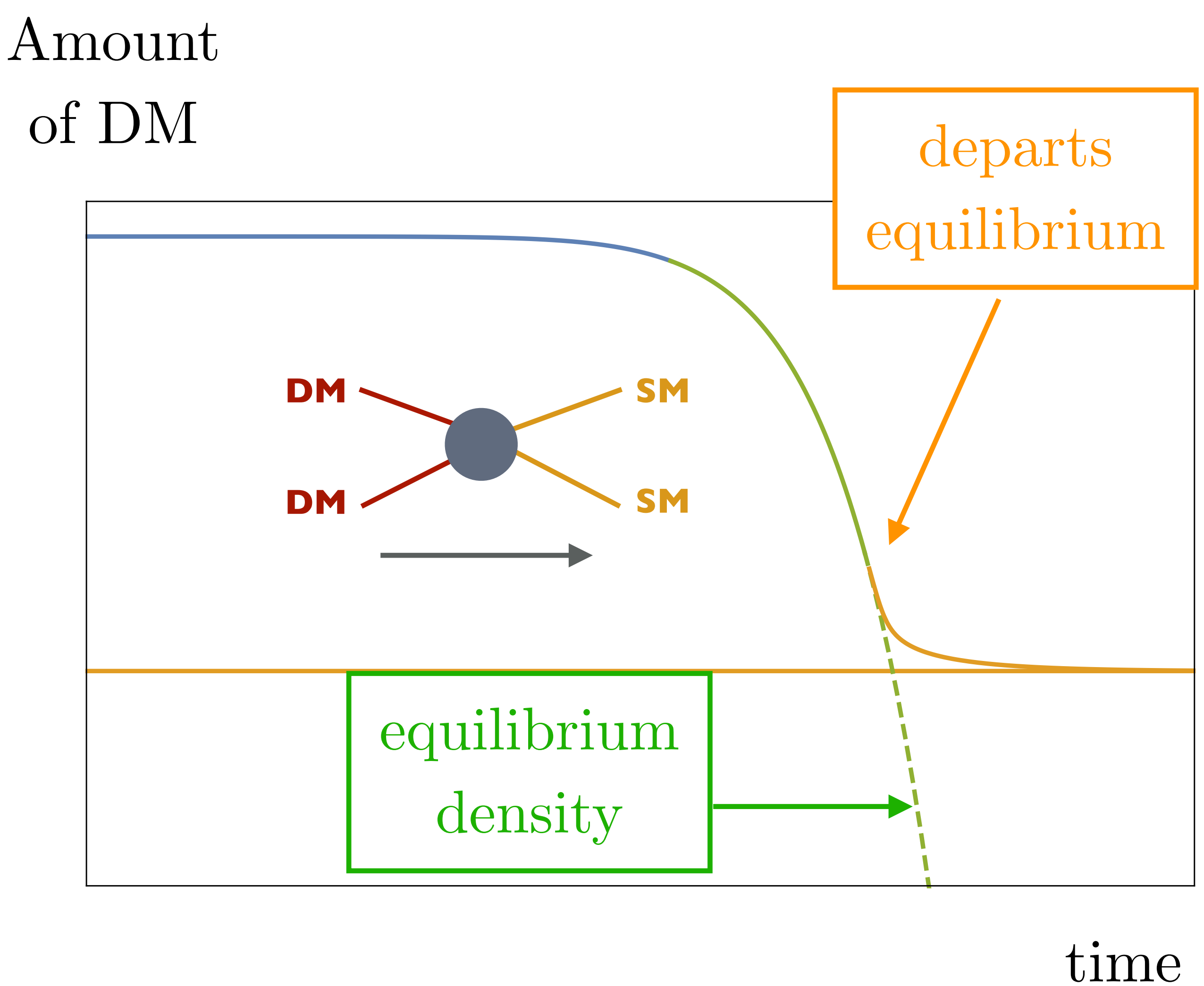
Correct relic abundance for

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

For Weak coupling, Weak scale emerges

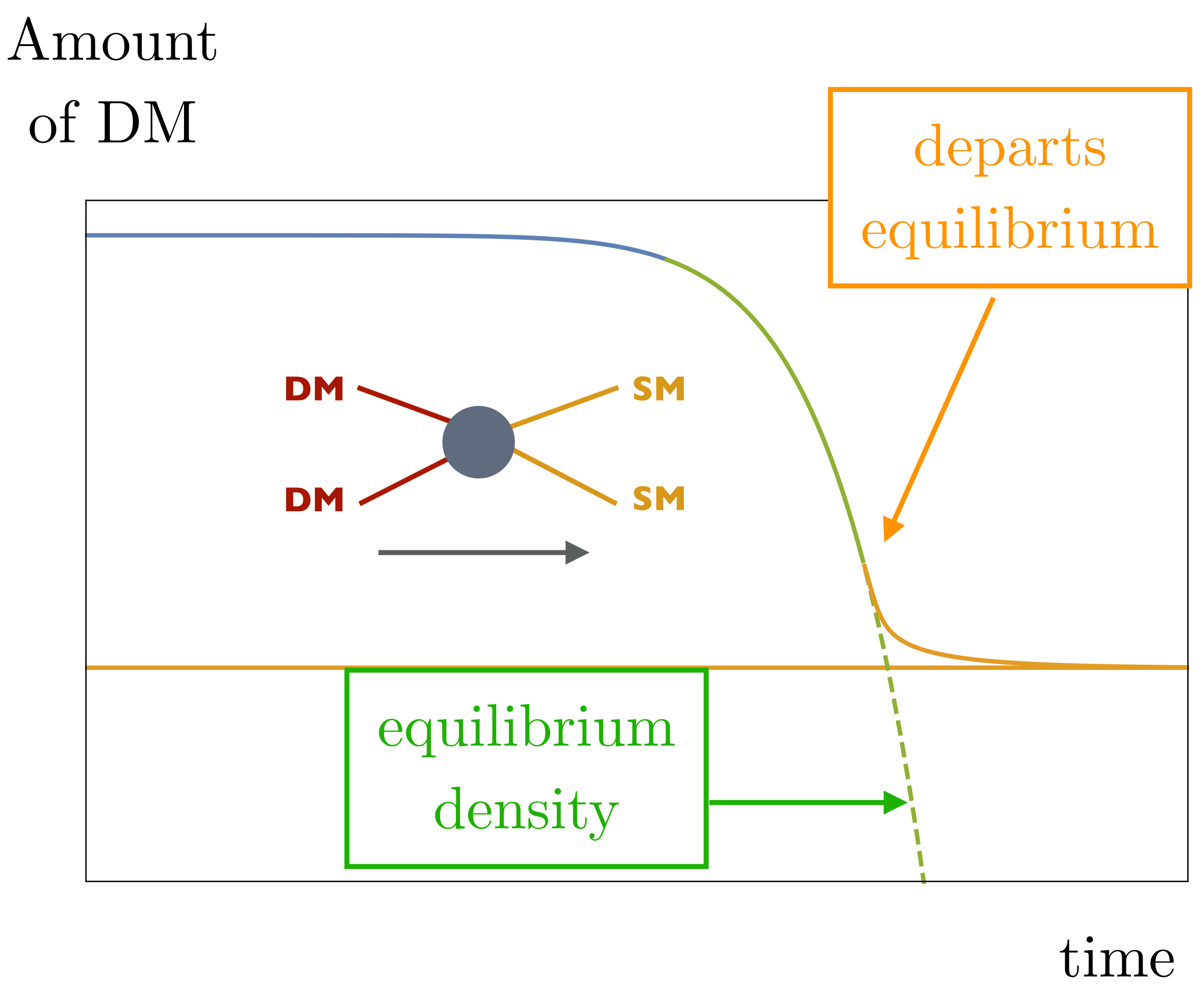
Weakly Interacting Massive Particle (WIMP)

WIMP



Thermal Relic:
Simple and Predictive

WIMP



Thermal Relic:
Simple and Predictive

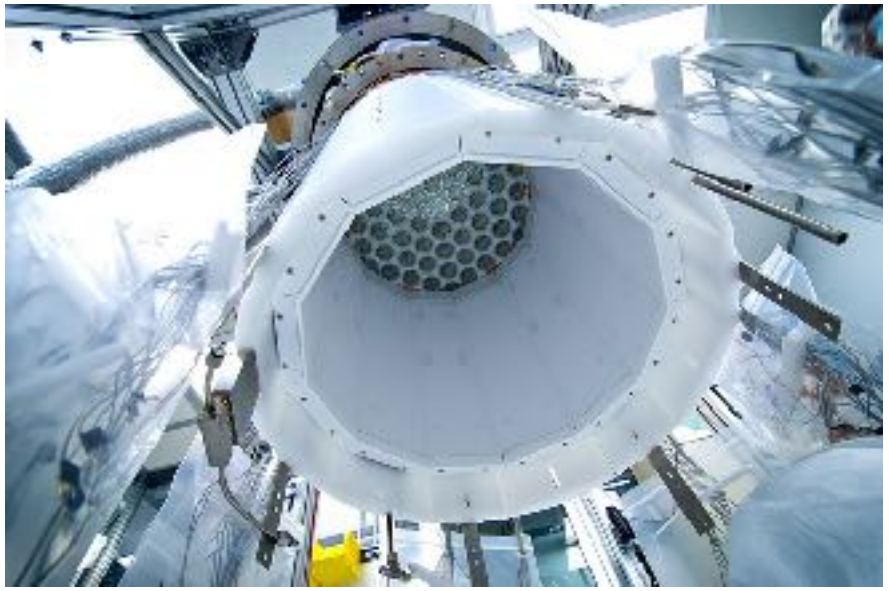
Guiding principle in cosmology

Searching for WIMPs

Direct Production

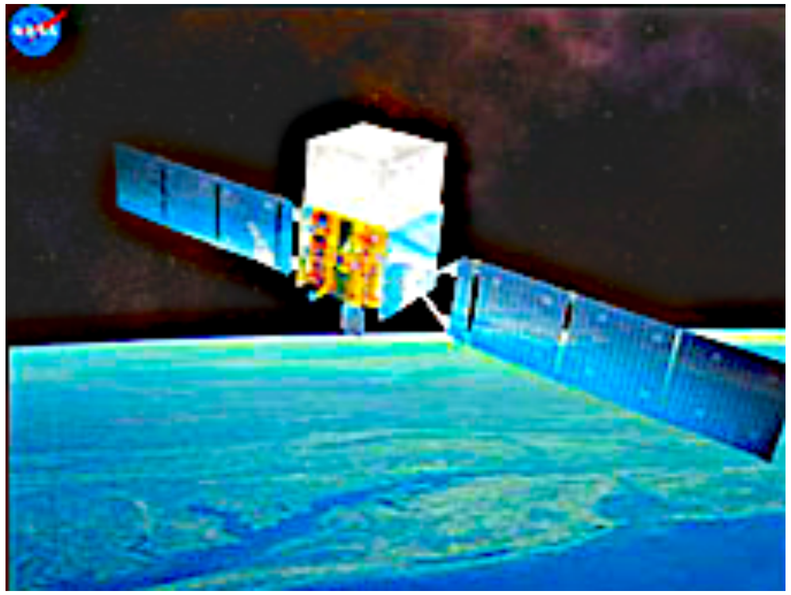
e.g. LHC

Direct Detection



e.g. LUX

Indirect Detection



e.g. FERMI

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

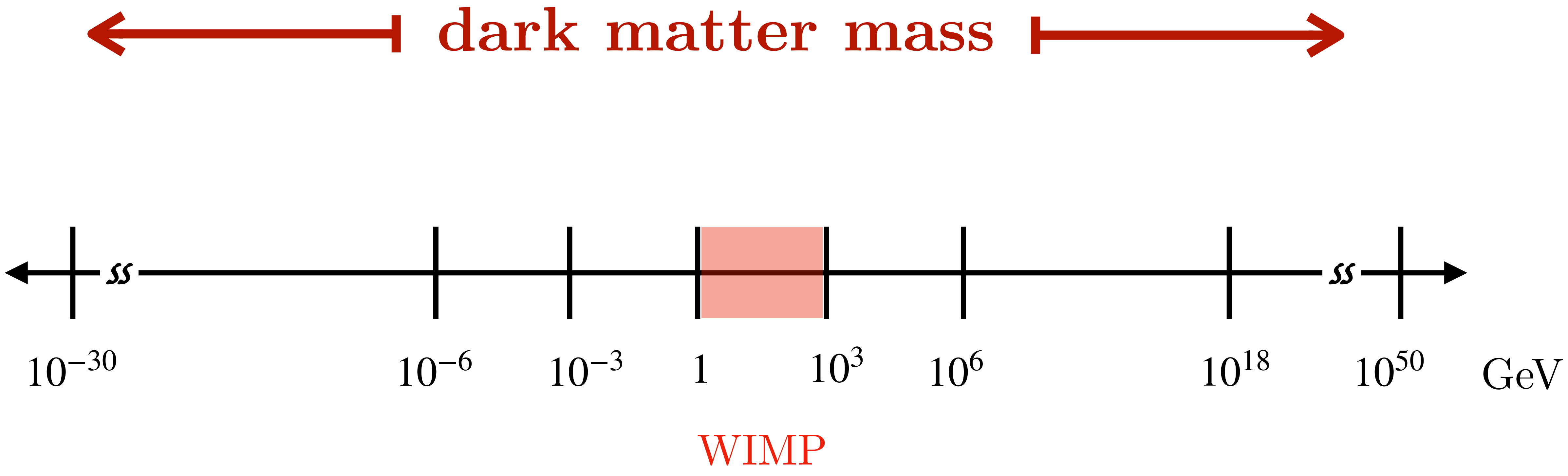
Status in 2019*

Dominant paradigm being challenged.

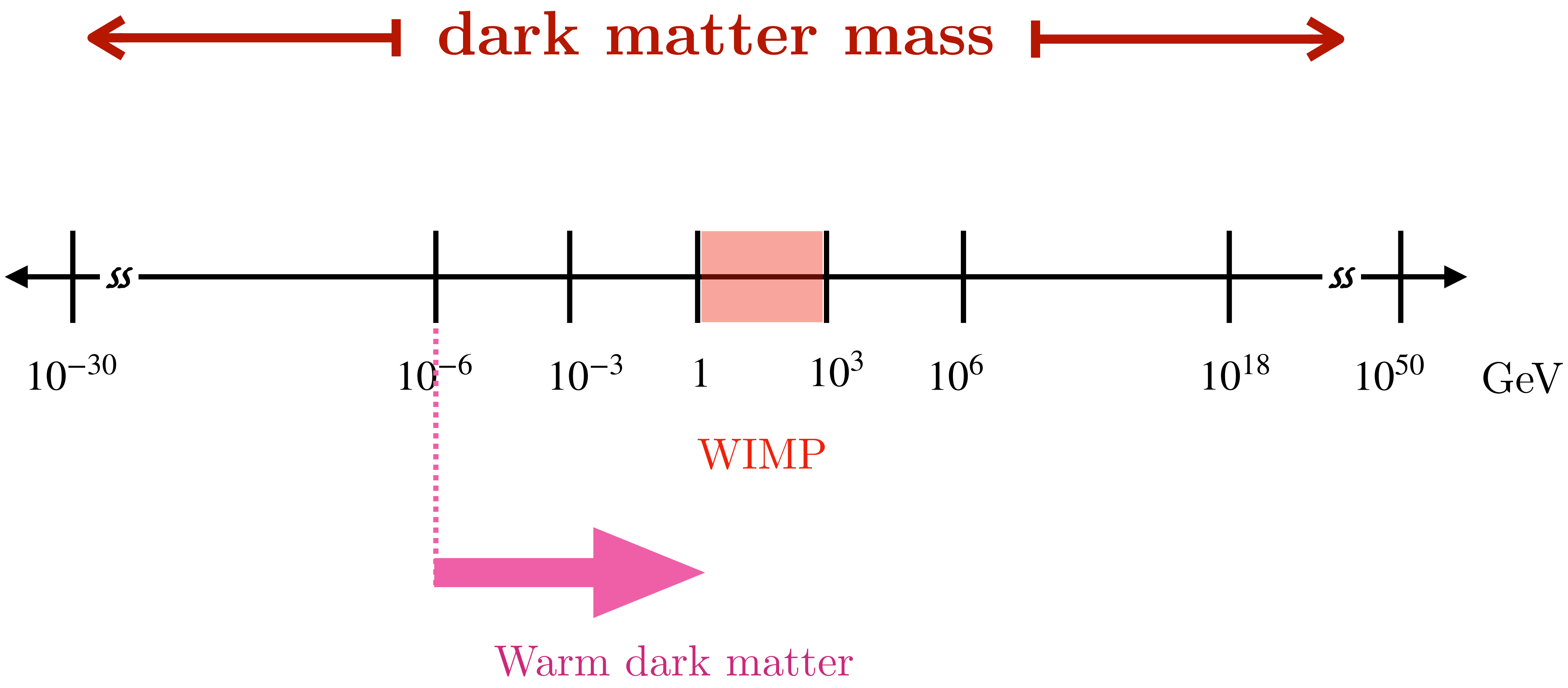
Great opportunity for new ideas!

***2020 never happened**

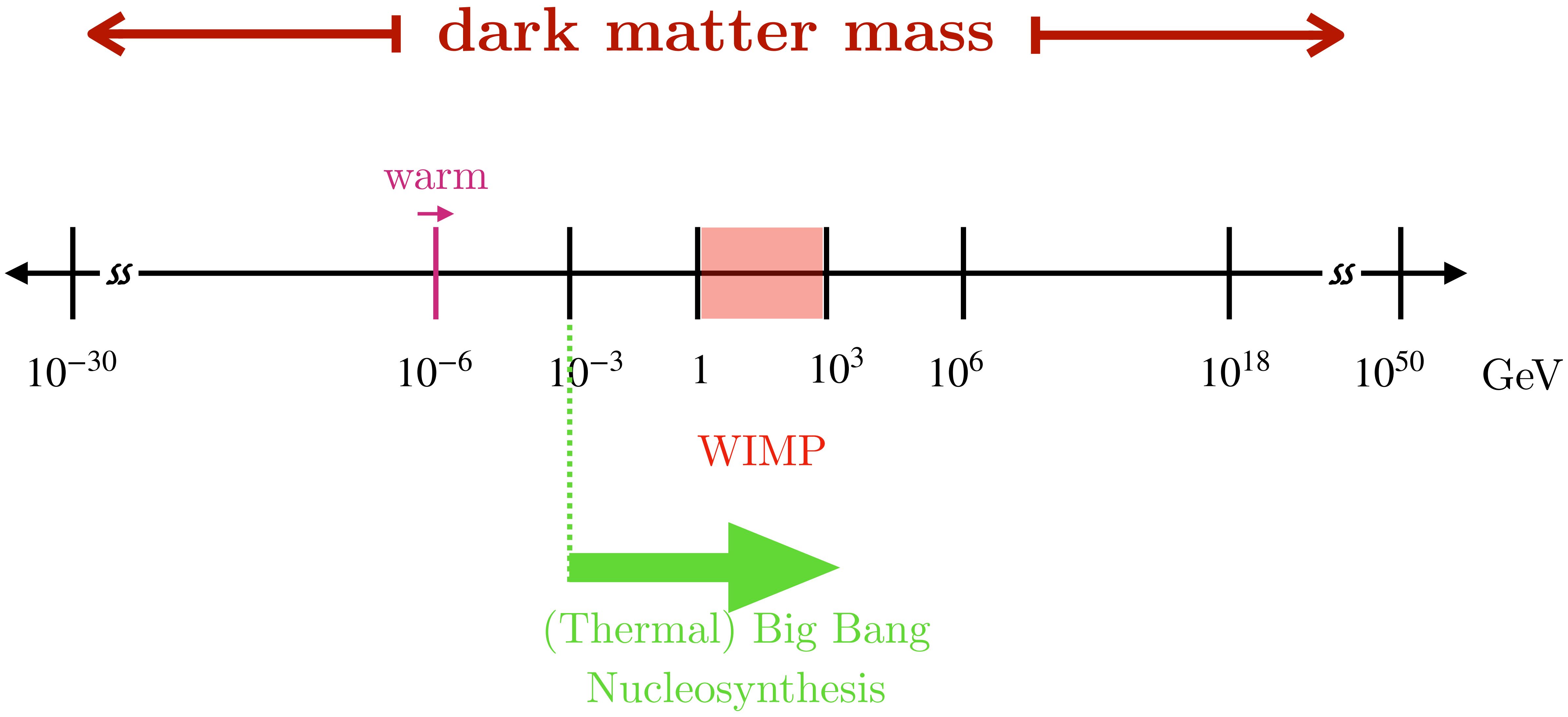
Beyond the WIMP



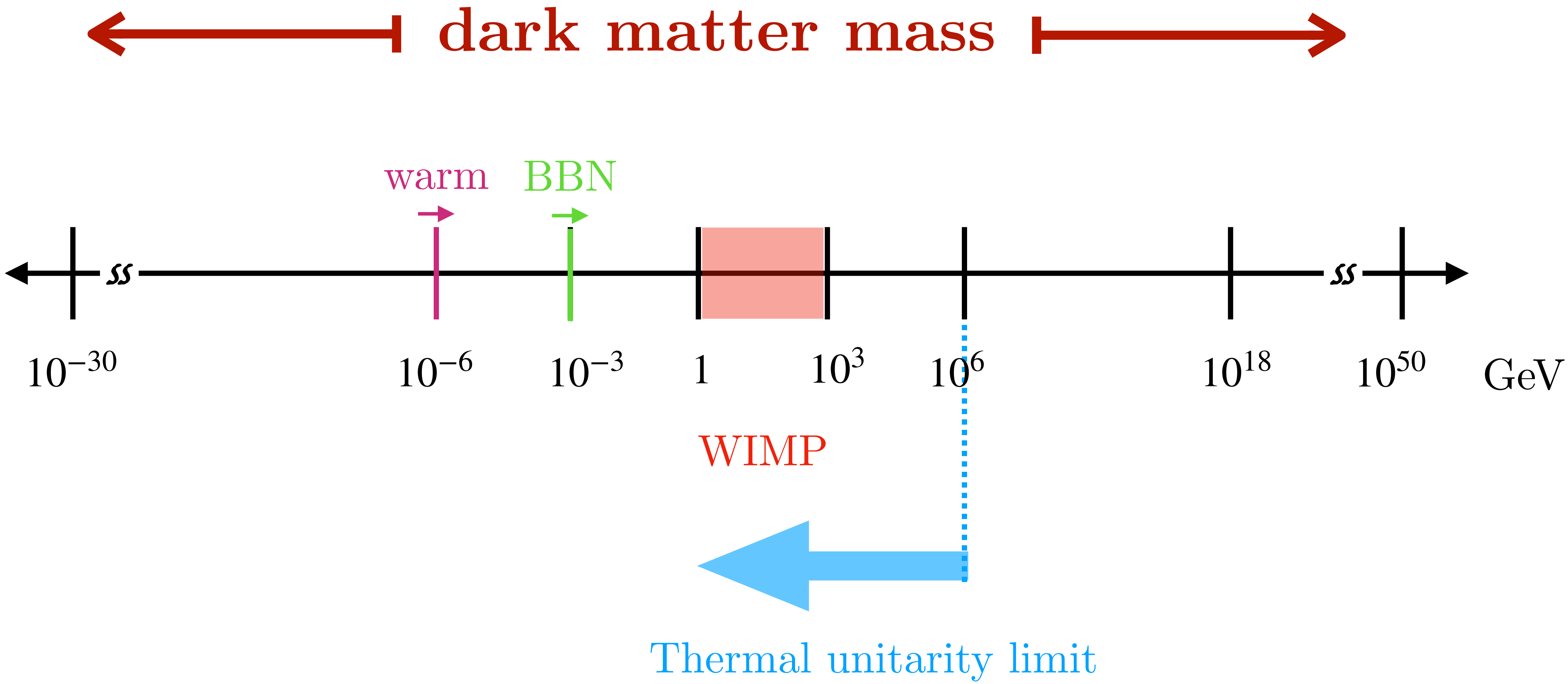
Beyond the WIMP



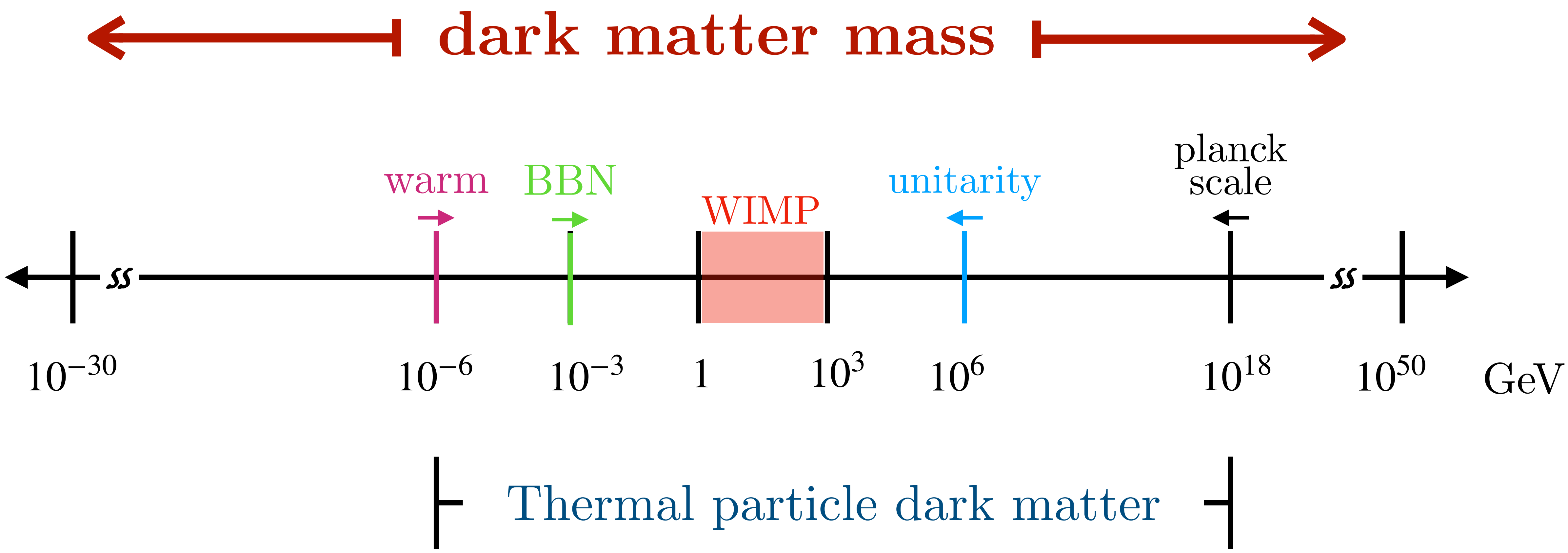
Beyond the WIMP



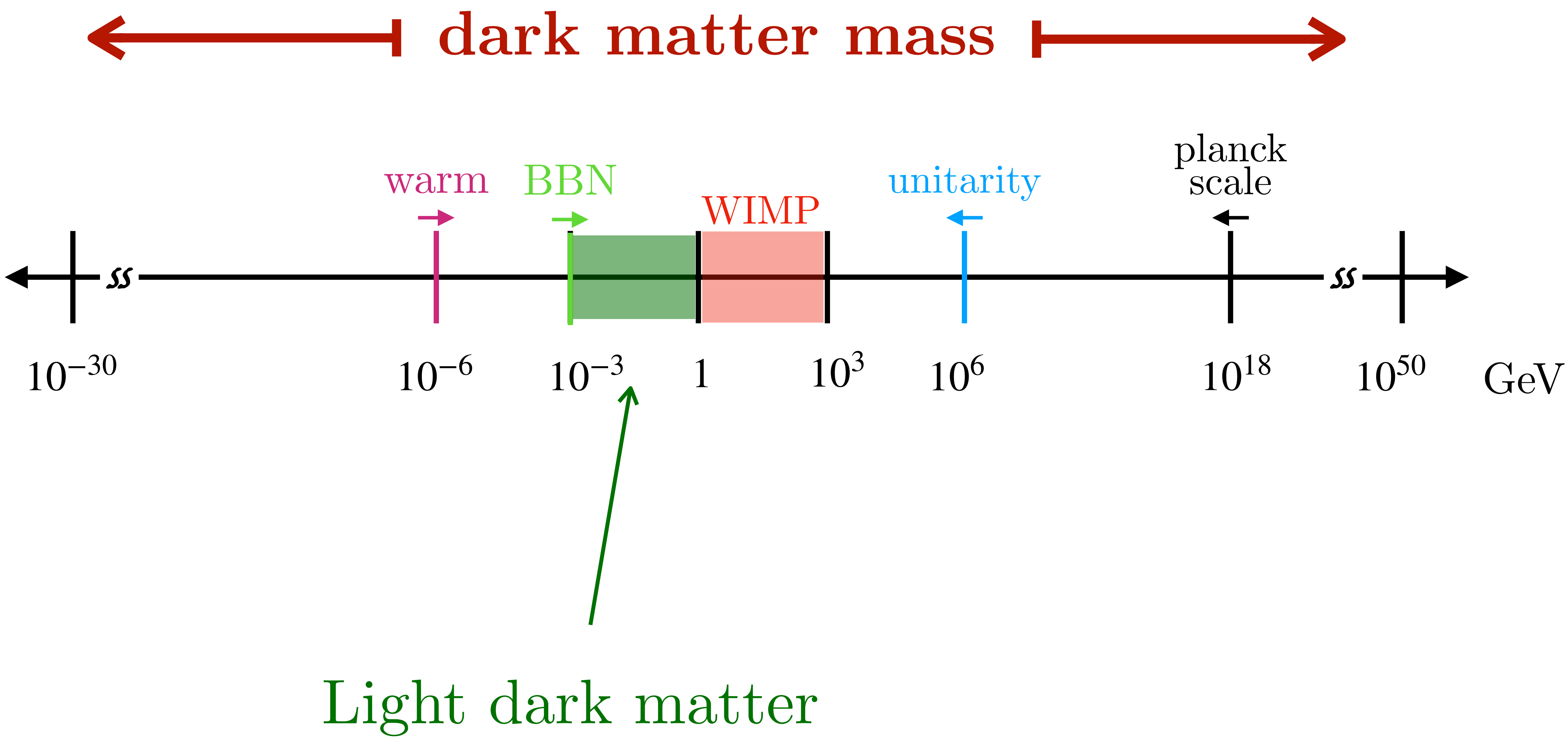
Beyond the WIMP



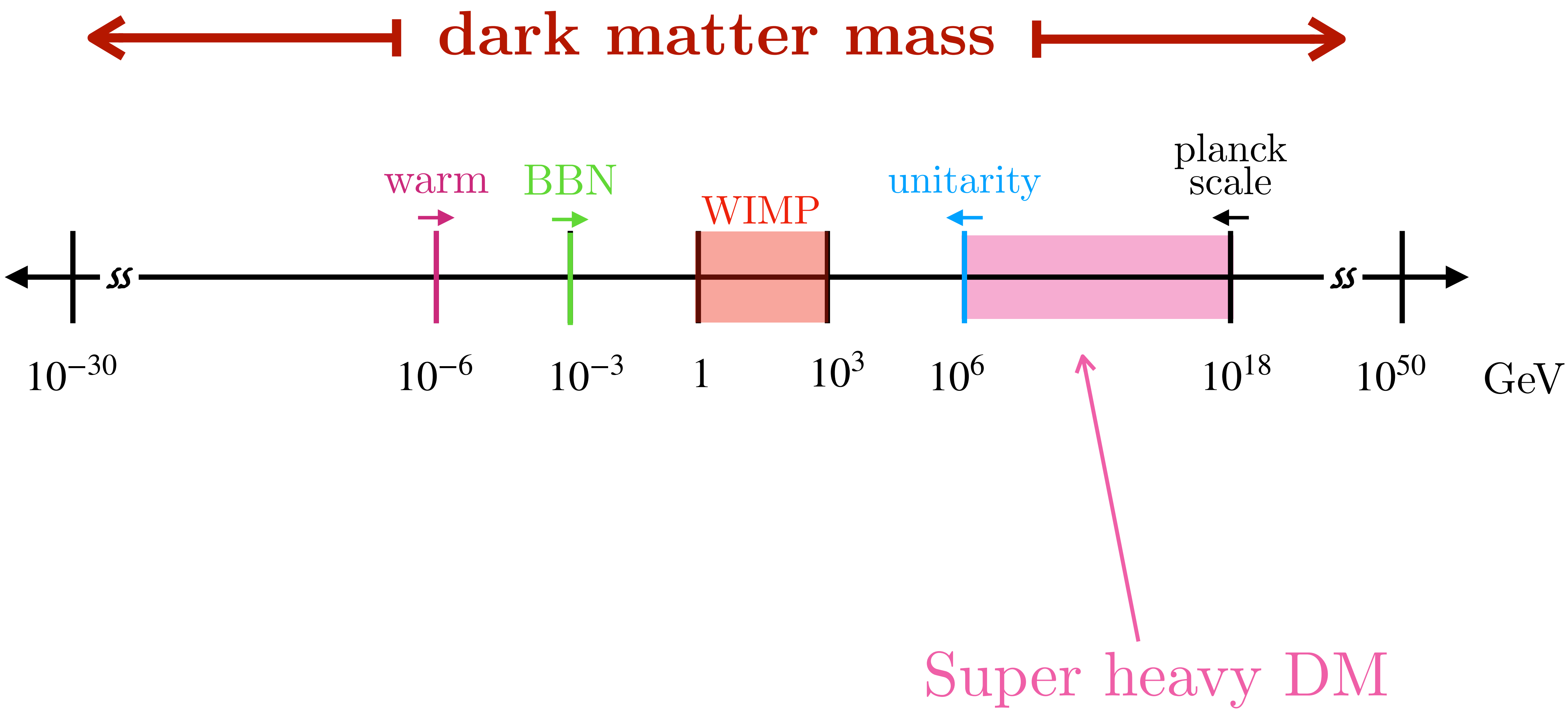
Beyond the WIMP



Beyond the WIMP



Beyond the WIMP

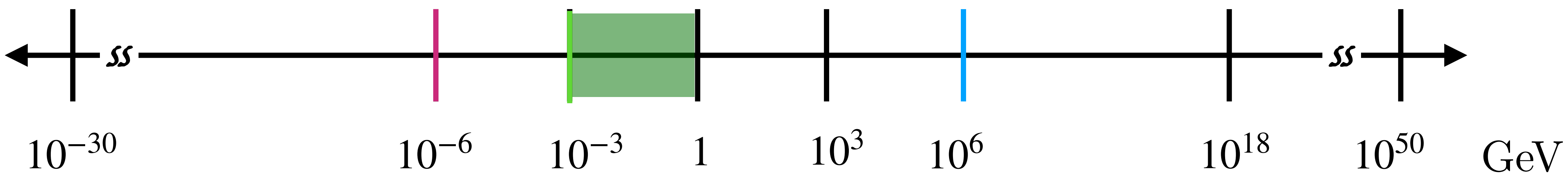


New Theory Ideas

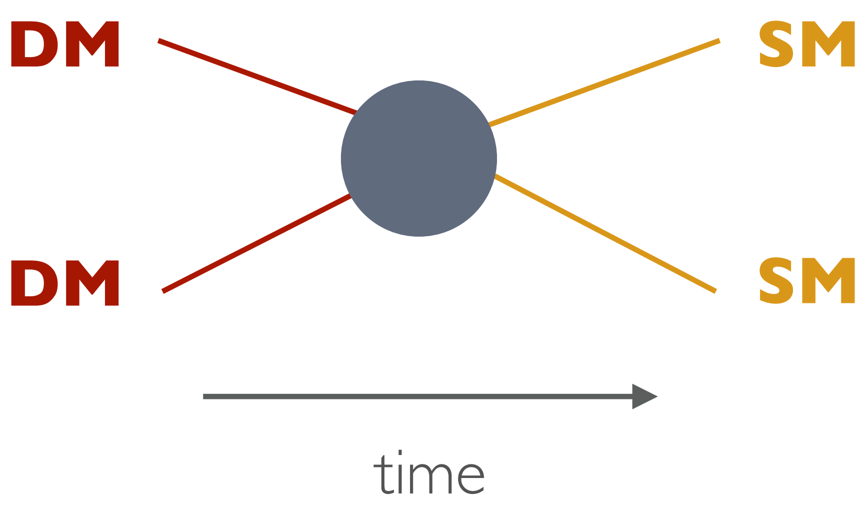
- ....
- Weakly coupled WIMPs [Pospelov, Ritz, Voloshin 2007; Feng, Kumar 2008]
- SIMPs [Hochberg, **EK**, Volansky, Wacker, 2014; + Murayama, 2015]
- ELDERs [**EK**, Perelstein, Rey-Le Lorier, Tsai, 2016]
- Forbidden dark matter [Griest, Seckel 1991; D'Agnolo, Ruderman, 2015]
- Co-scattering dark matter [D'Agnolo, Pappadopulo, Ruderman, 2017]
- Sub-MeV thermal dark matter [Berlin, Blinov 2017]
- Super heavy thermal dark matter [Kim, **EK** 2019]
- Zombies [Kramer, **EK**, Levi, Outmezguine, Ruderman, 2020]

... are abundant

Light dark matter



Ex. 1: Weakly Coupled 2→2



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

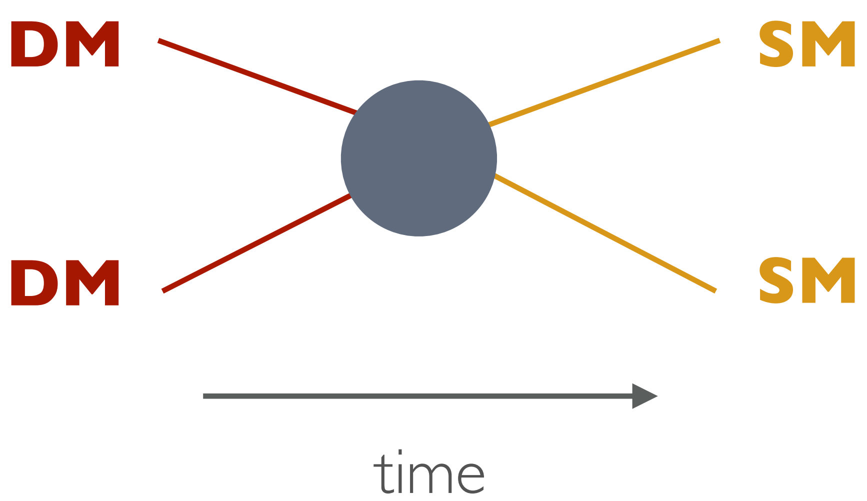
$$m_{\rm DM} = \alpha \times 30 \ {\rm TeV}$$

$$\alpha \ll 1$$

[Pospelov, Ritz, Voloshin 2007

Feng, Kumar 2008]

Ex. 2: Forbidden Channels



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

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

freezeout temp

$x = m/T$

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

mass difference

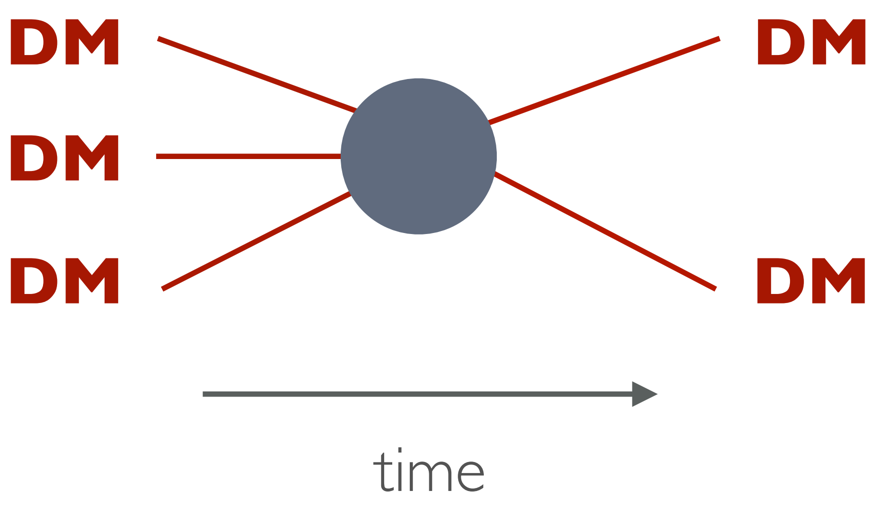
Forbidden @ T=0;

Proceeds via Boltzmann tail

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

[Hochberg, **EK**, Wacker, Volansky, 2014]

Ex. 3: SIMPs



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

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

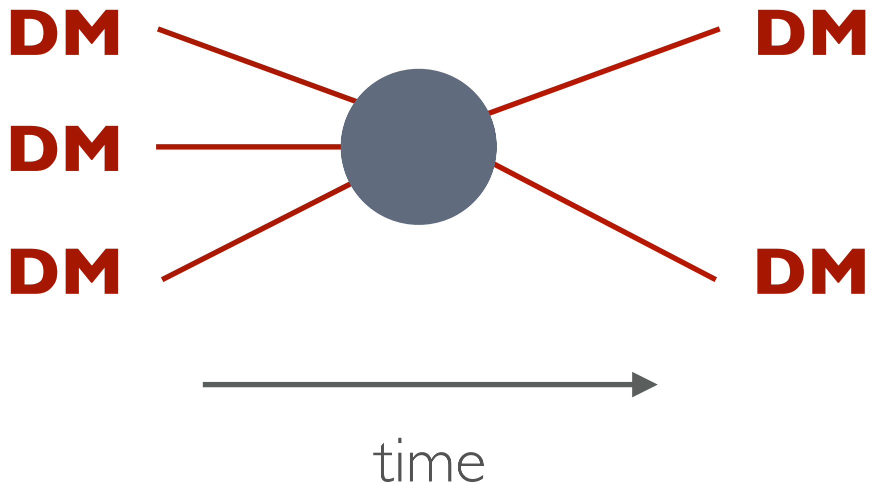
For strong coupling, strong scale emerges

Strongly Interacting Massive Particle (SIMP)

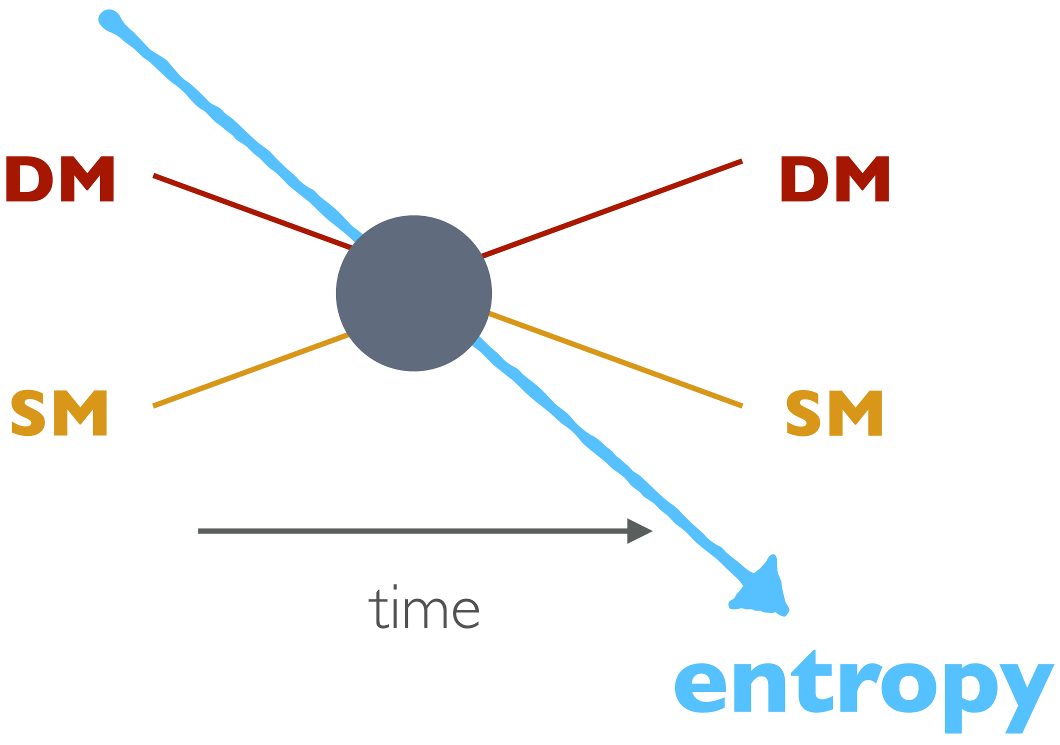
[Hochberg, **EK**,
Wacker, Volansky, 2014]

Ex. 3: SIMPs

Pumps heat



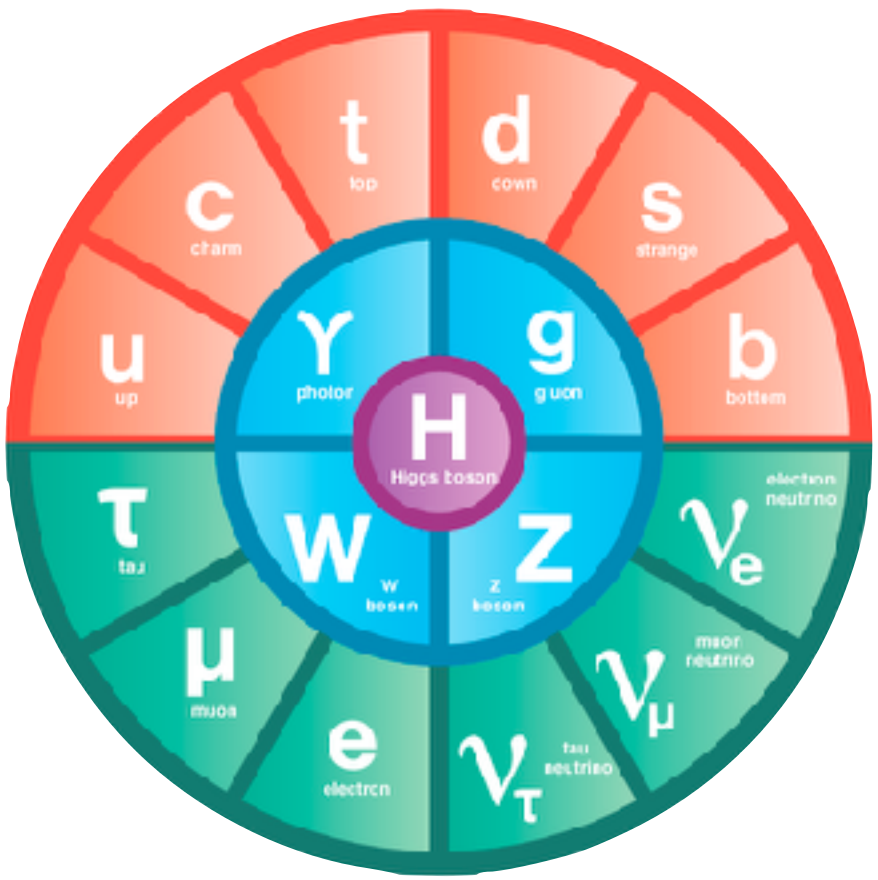
Shed the heat



Generic.

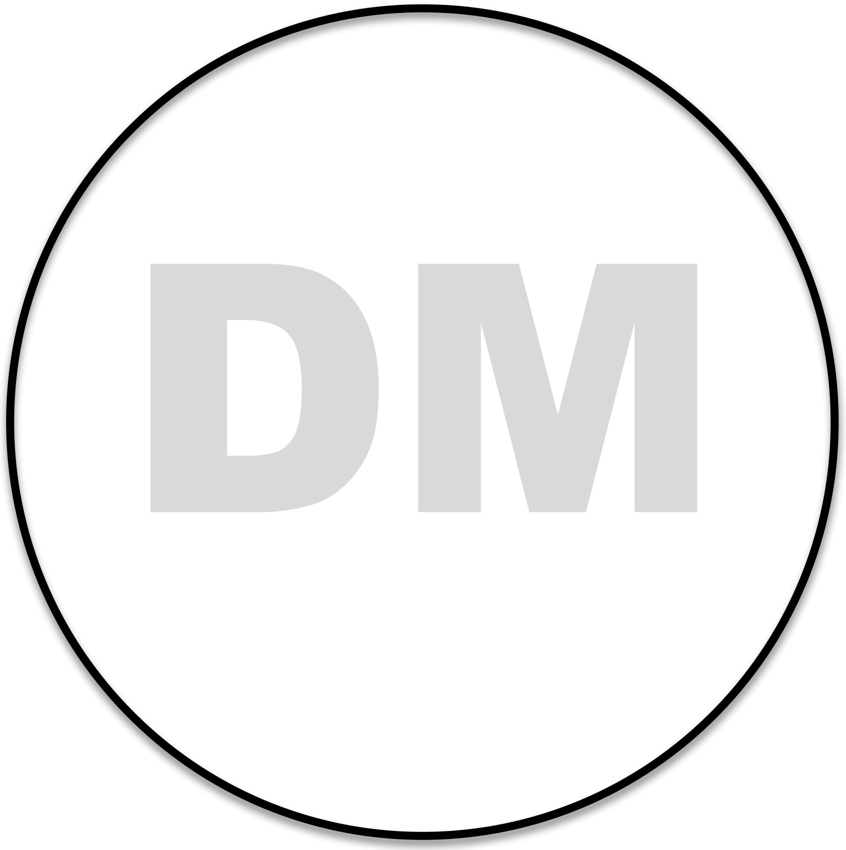
Dark Sectors

Visible sector



SM is a particle zoo.

Dark sector



Why not in the dark sector too?

[Hochberg, **EK**, Murayama, Volansky, Wacker, 2015]

QCD-like sector

Think Standard Model!

Dark matter from strongly coupled gauge theories

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

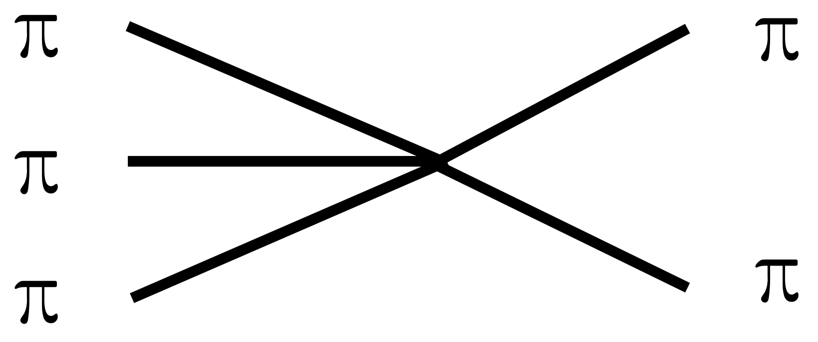
$\mathrm{Sp}(N_c)$, $\mathrm{SU}(N_c)$, $\mathrm{SO}(N_c)$

kinetically mixed hidden photon (V)

QCD-like theories, pions = dark matter.

Many processes, many dark matter mechanisms.

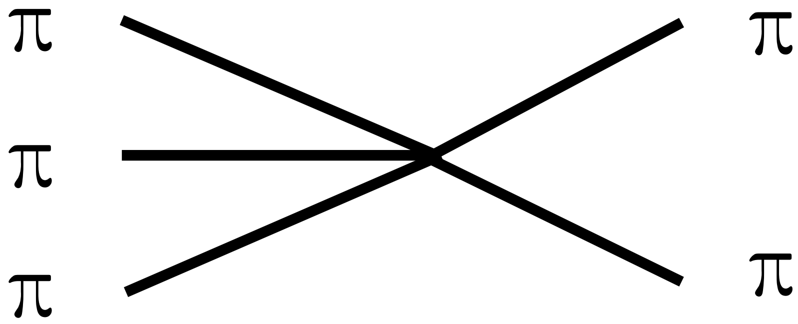
Processes



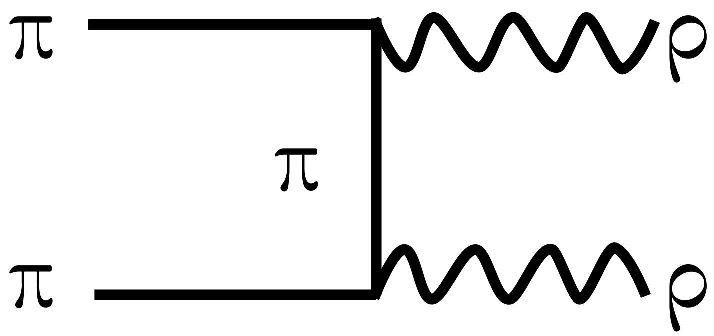
3→2 processes

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

Processes



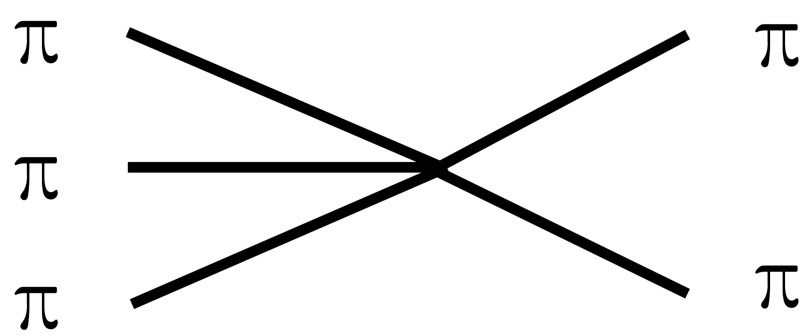
$3 \to 2$ processes



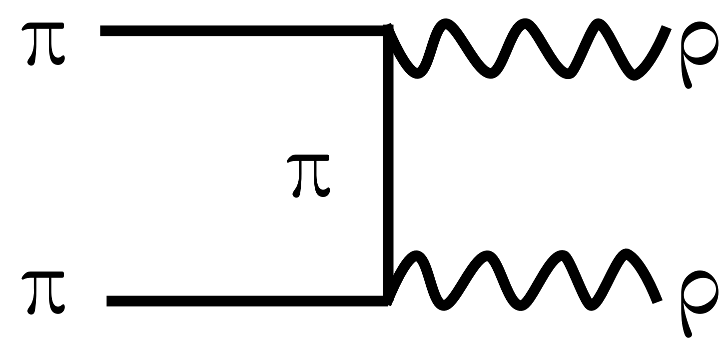
forbidden

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

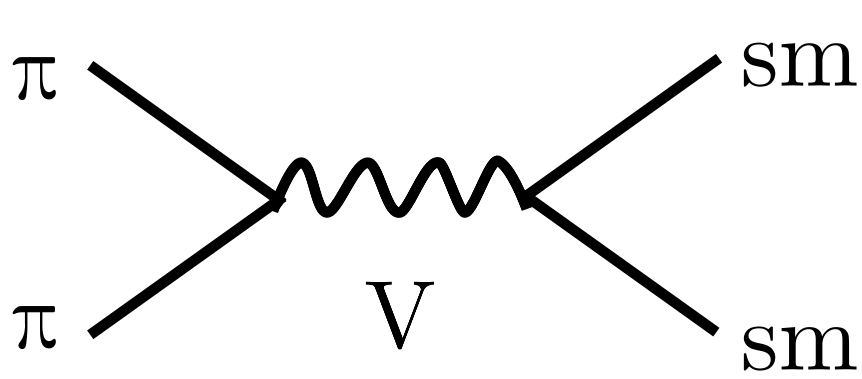
Processes



3→2 processes

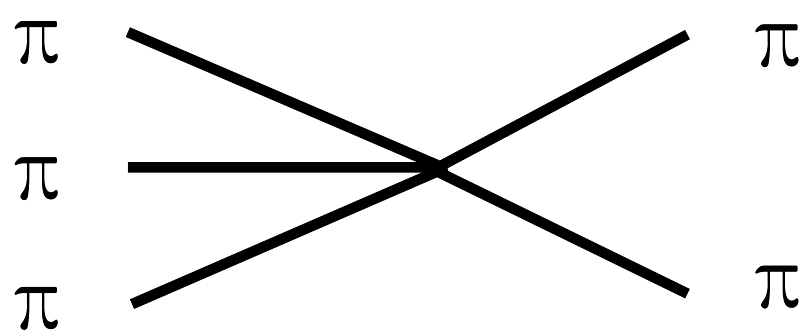


forbidden

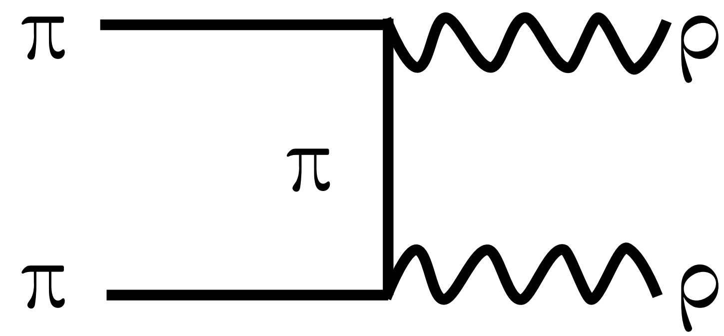


2→2 annihilations

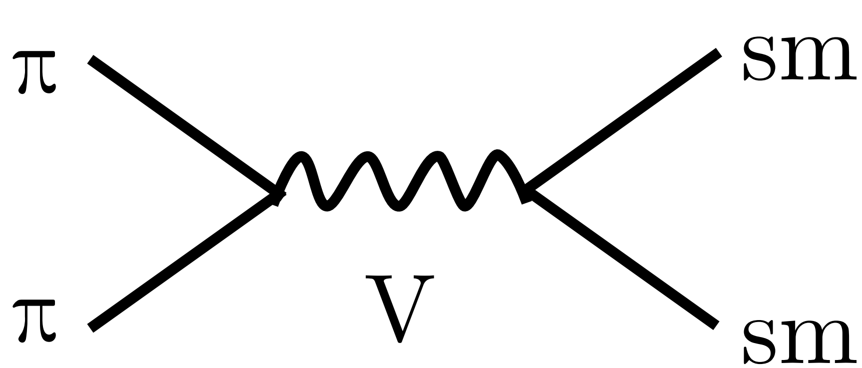
Processes



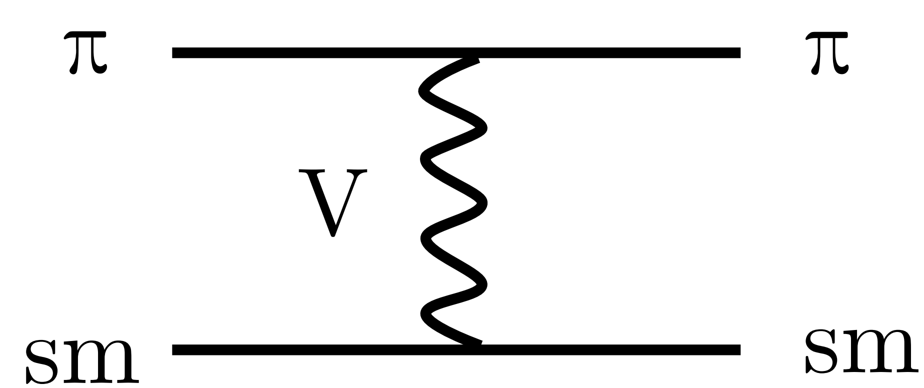
3→2 processes



forbidden



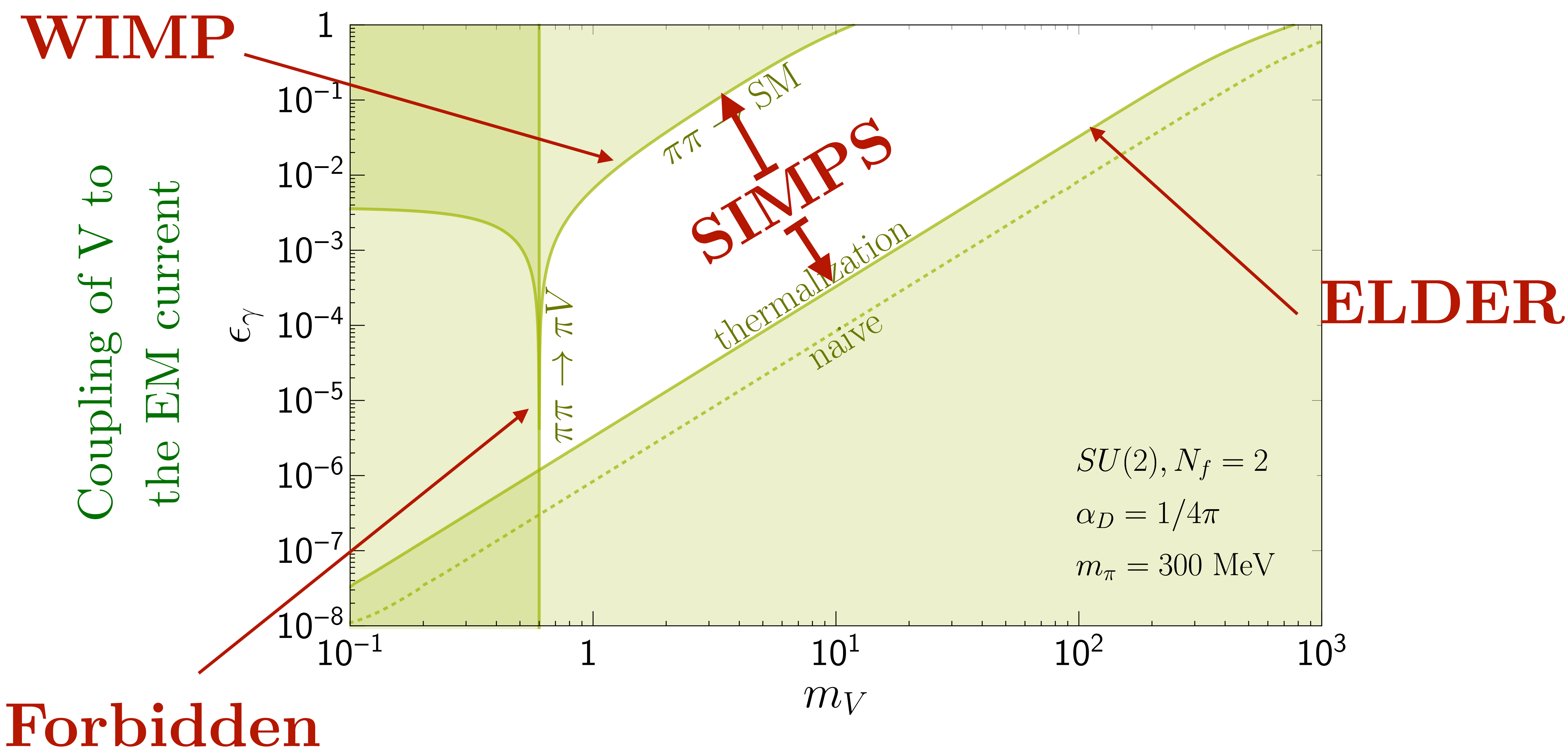
2→2 annihilations



elastic scattering

Predictive

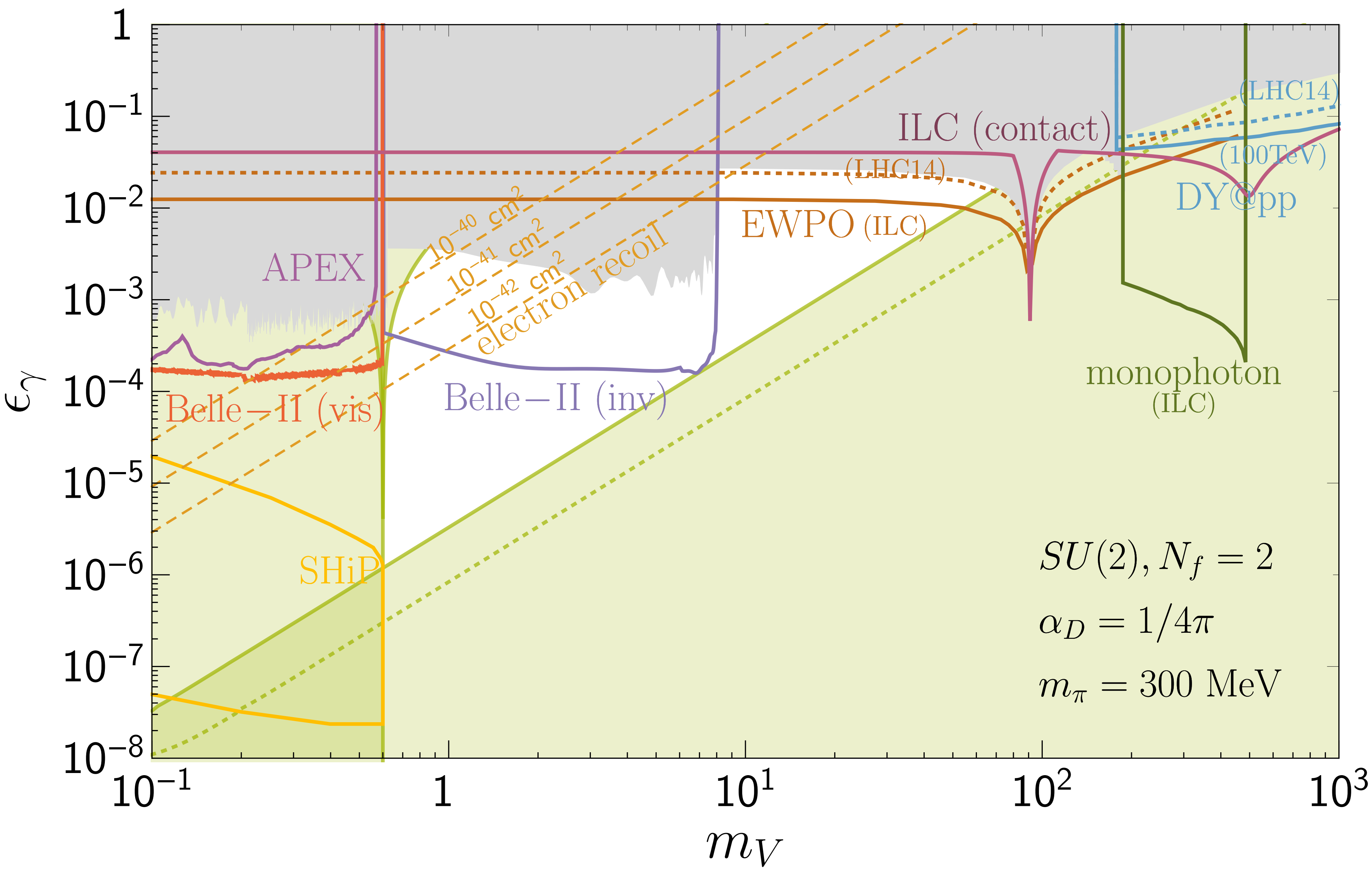
Kinetically mixed U(1) mediator



Predictive

Kinetically mixed U(1) mediator

Coupling of V to the EM current



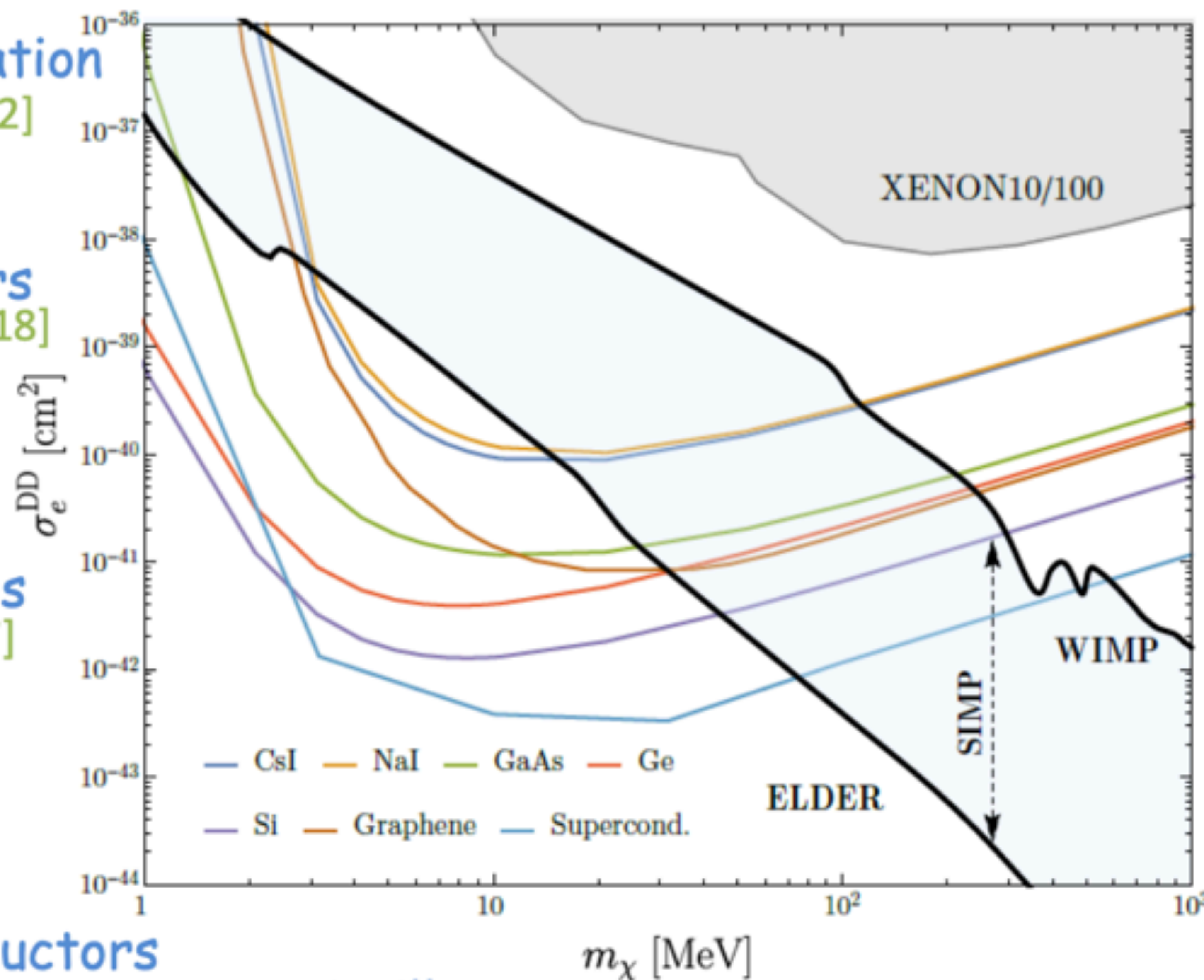
Future probes

Direct Detection

atomic ionization
[Essig et al, 2012]

color centers
[Budnik et al, 2018]

semi-metals
[YH et al, 2017]



SuperCDMS
[2020]

SENSEI
[2020]

Polar materials
[**Griffin** et al, 2018]

semiconductors
[Essig et al, 2012;
SuperCDMS & SENSEI 2018;
Kurinsky et al, 2019]

superfluid helium
[Schutz, Zurek, 2016;
Hertel et al 2018;
Acanfora et al 2019]

superconductors
[**YH** et al, 2015 x 2, 2019]

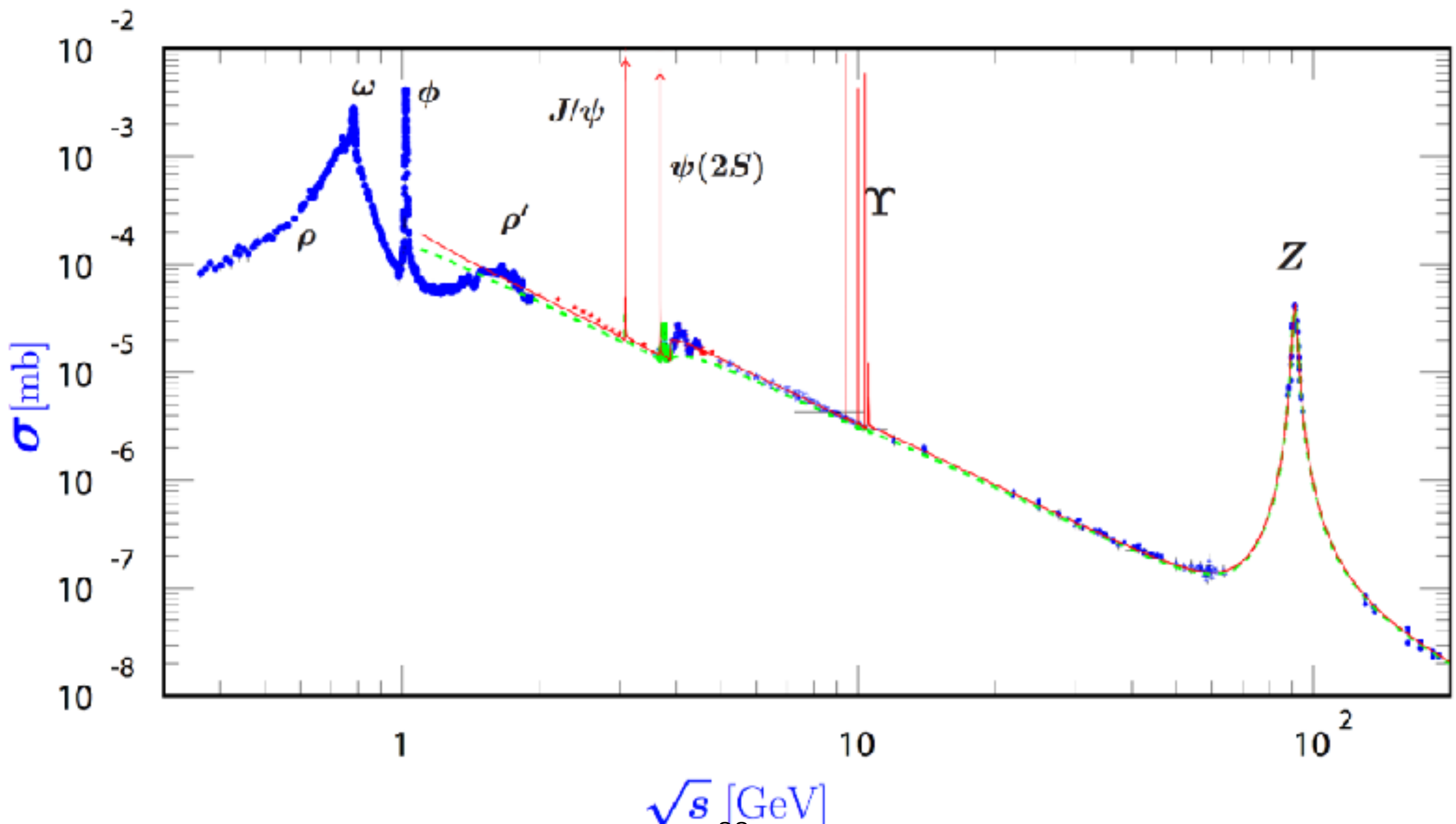
scintillators
[Derenzo et al, 2016]

2D targets (graphene)
[**YH** et al, 2016; Cavoto et al, 2018]

Dark Spectroscopy

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

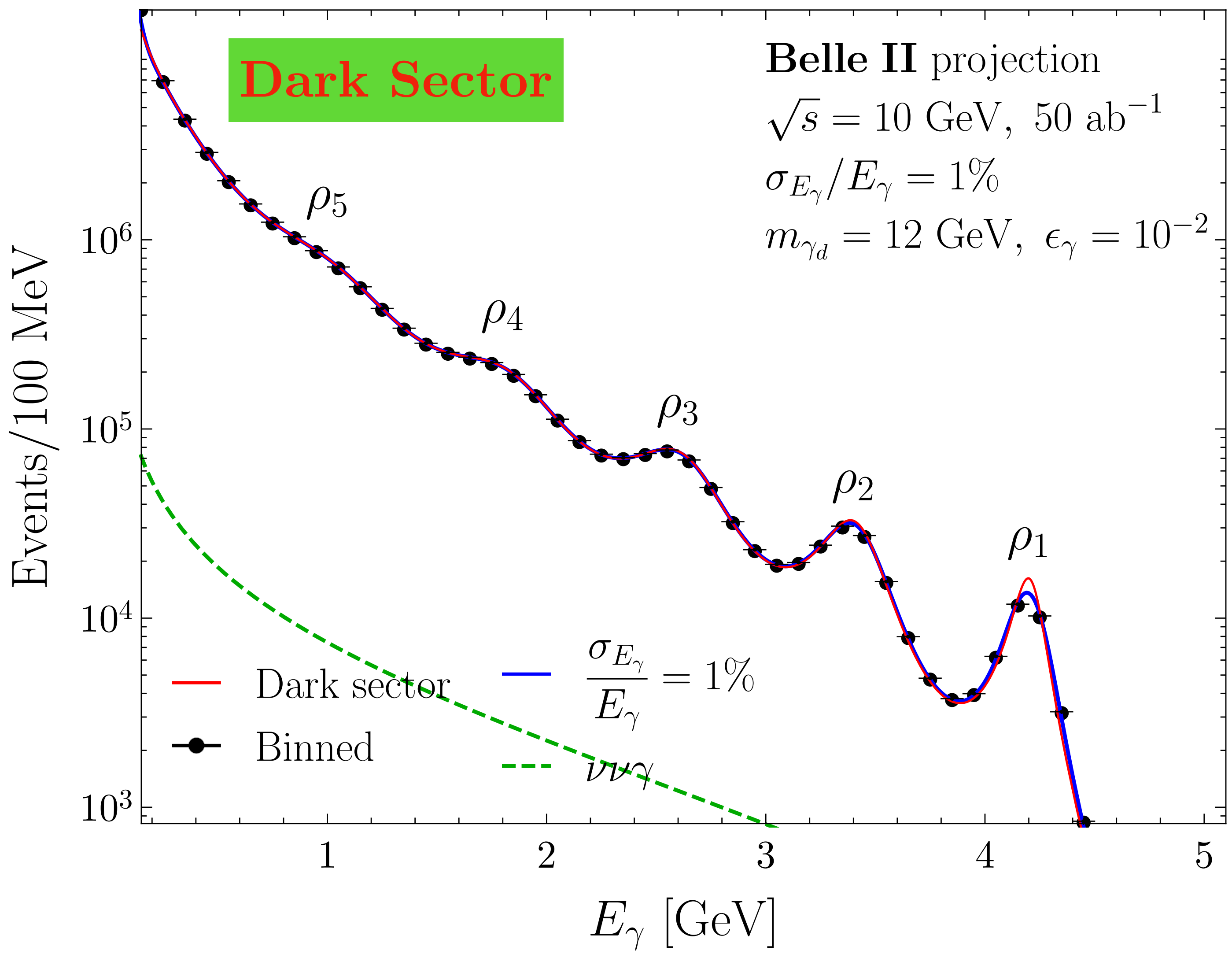
center of mass energy traces the **QCD** resonance structure



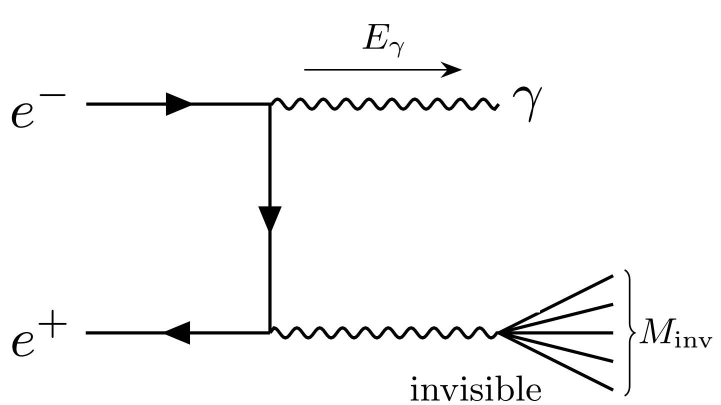
Dark Spectroscopy

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

mono-photon energy also traces the resonance structure

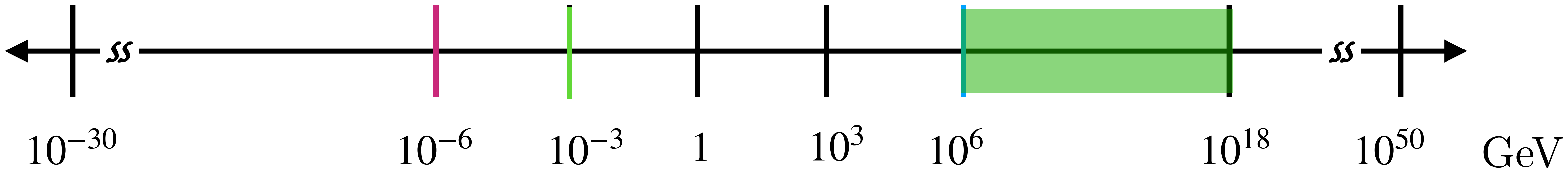


$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\text{res}}^2}{s}\right)$$

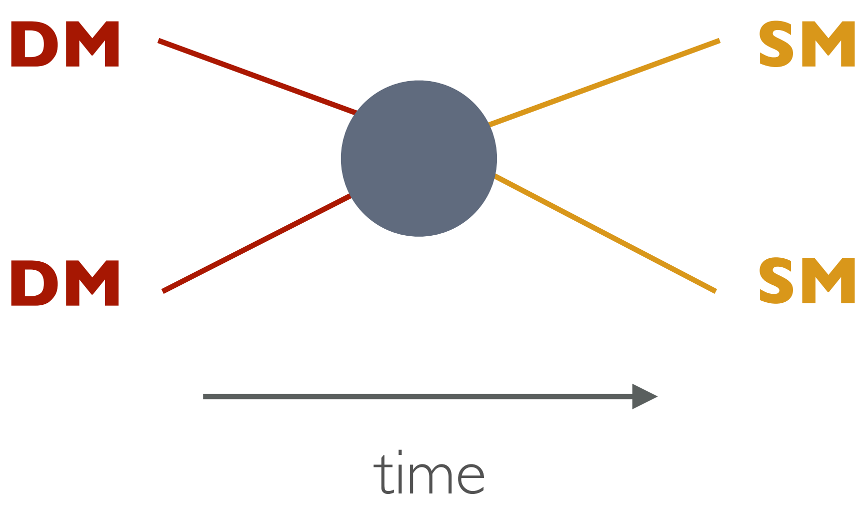


[Hochberg, EK, Murayama, 2016, 2017]

Super heavy dark matter



Unitarity Bound



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

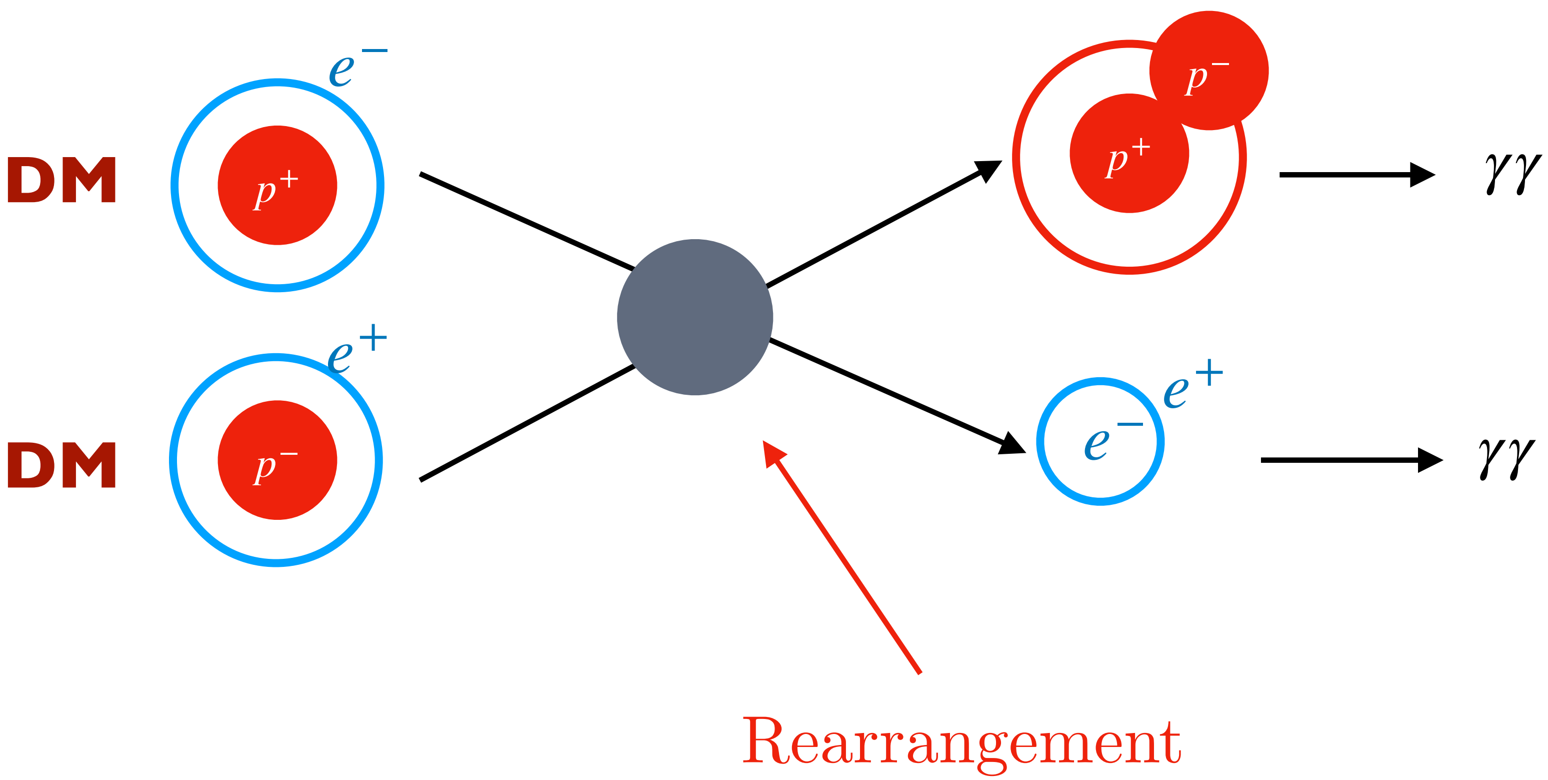
Correct relic abundance for $m_{\rm DM} = \alpha \times 30 \text{ TeV}$

For perturbative couplings $\alpha < 4\pi$

$$m_{\rm DM} \lesssim 300 \text{ TeV}$$

Ex. 1: Composite Interactions

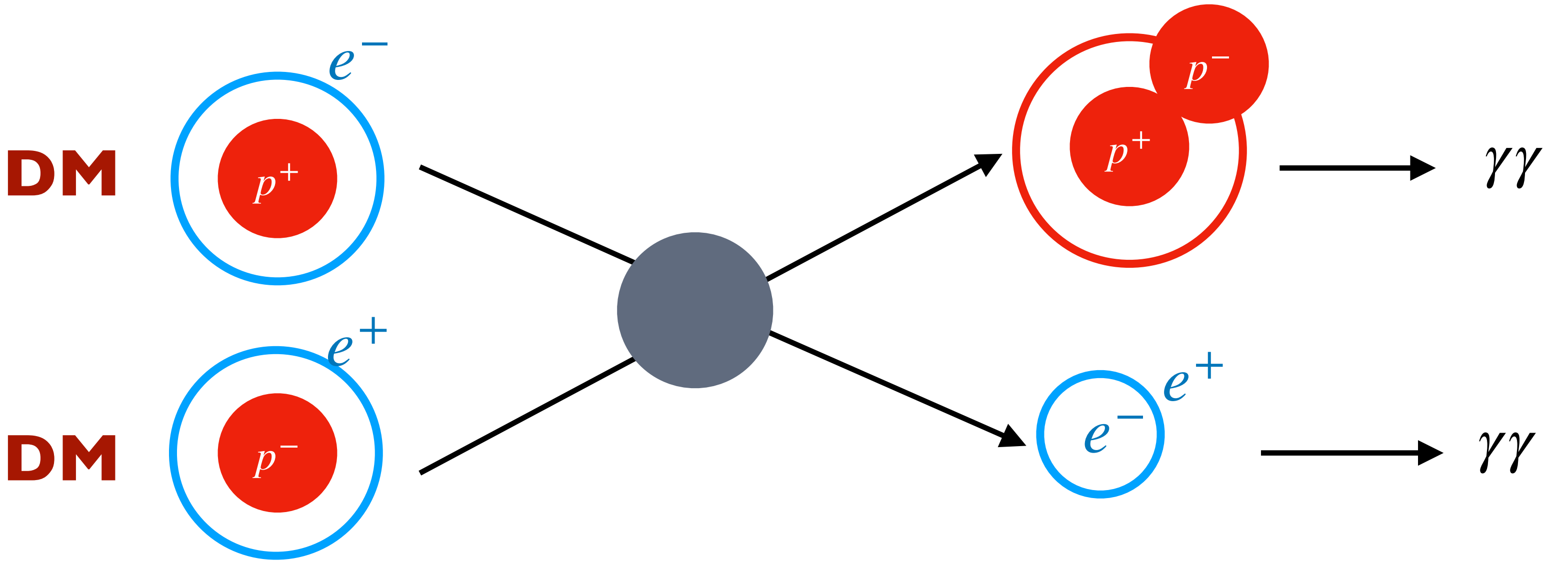
dark hydrogen anti-hydrogen annihilation



Harigaya, Ibe, Kaneta, Nakano, Suzuki (2016); J. Smirnov, J. F. Beacom, (2019); Contino, Mitridate, Podo, Redi, (2019); Gross, Mitridate, Redi, Smirnov, Strumia (2019); Geller, Iwamoto, Lee, Shadmi, Telem (2018)

Ex. 1: Composite Interactions

dark hydrogen anti-hydrogen annihilation



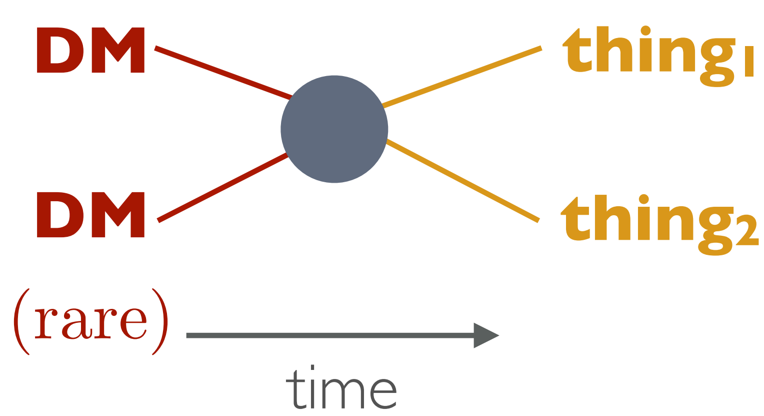
$$\sigma_{\text{ann}} \simeq 4\pi a_0^2$$

Bohr Radius

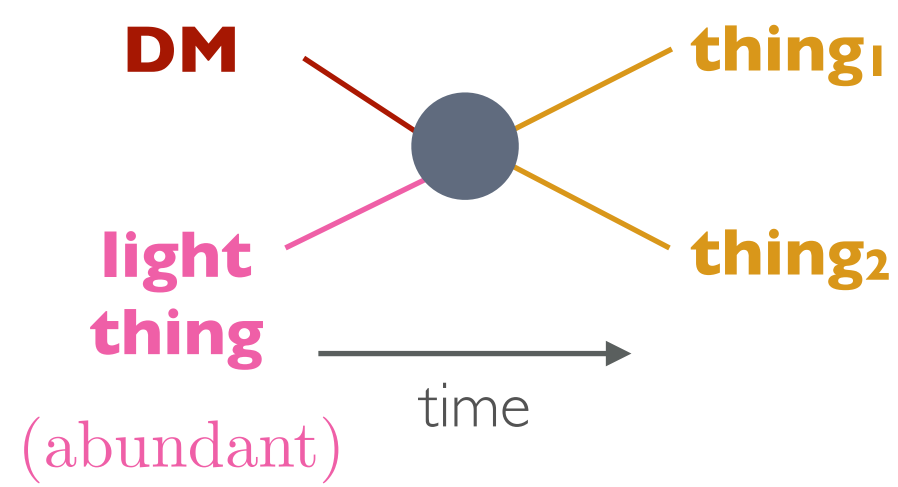
$$a_0 \simeq \frac{1}{\alpha m_e}$$

Predicts much heavier DM

Compare Processes



vs.



$$\Gamma_{\rm ann} = n_{\rm DM} \left\langle \sigma_{\rm ann} v \right\rangle \propto e^{-m_{\rm DM}/T}$$

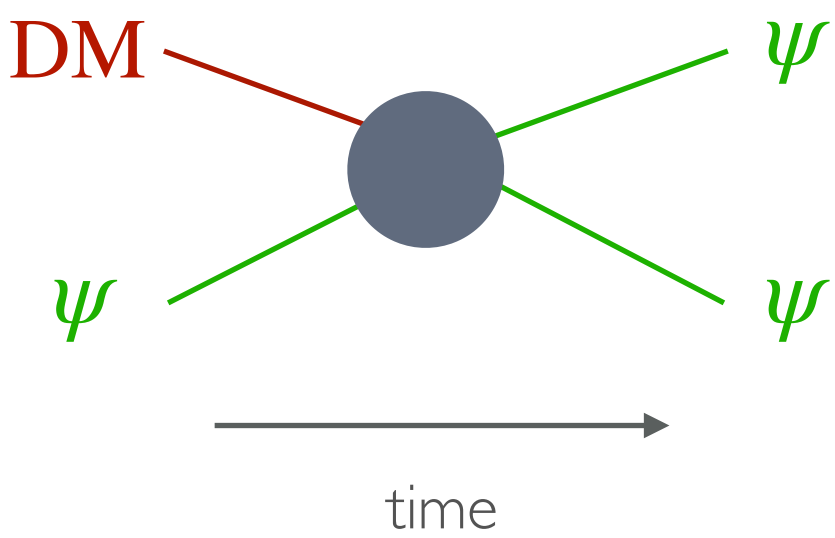
$$\Gamma_{\rm ann} = n_{\rm light} \left\langle \sigma_{\rm ann} v \right\rangle$$

Less efficient

Much more efficient!

[Kramer, **EK**, Levi, Outmezguine, Ruderman, 2020]

Ex. 2: Zombies



$$m_{\rm DM} > m_{\psi}$$

[Kramer, **EK**, Levi, Outmezguine, Ruderman, 2020]

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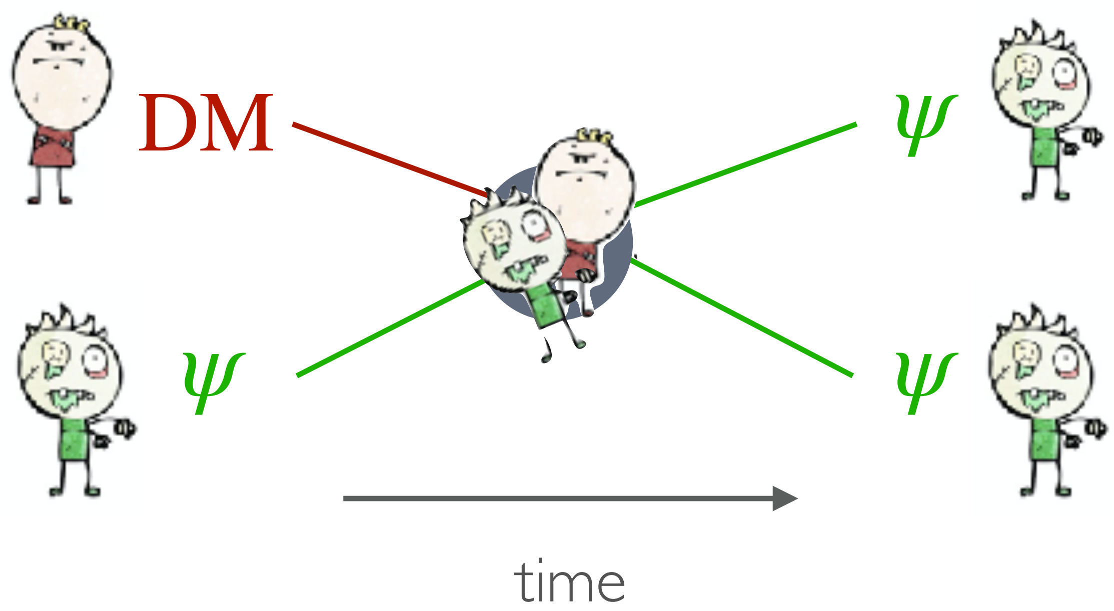
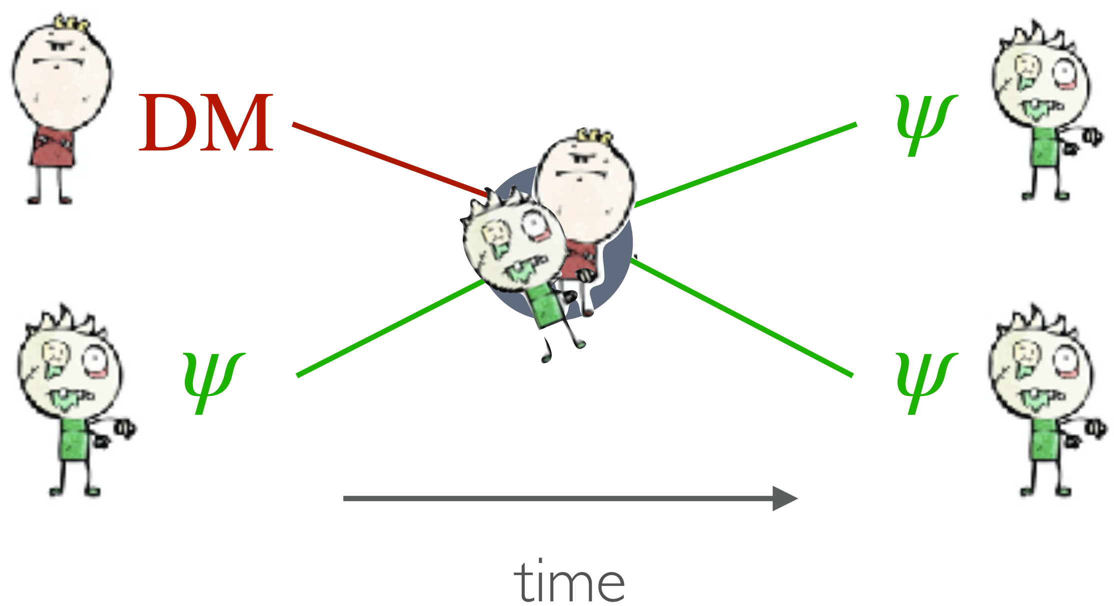


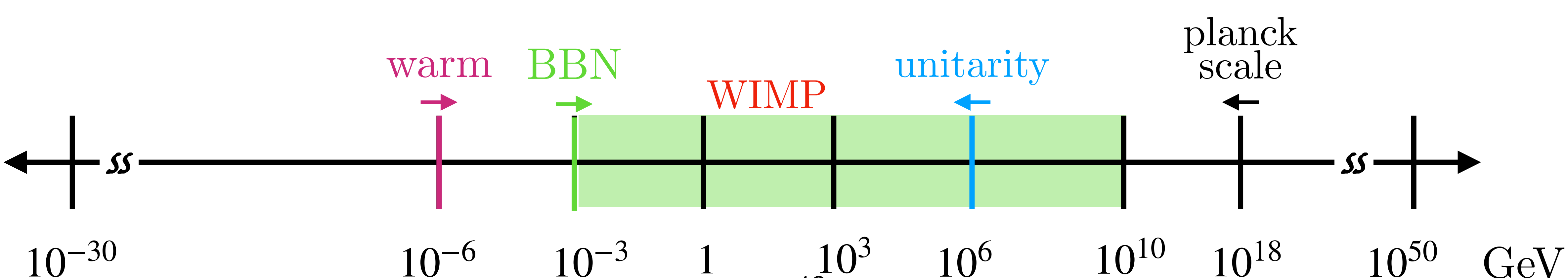
$$m_{\rm DM} > m_\psi$$

Ex. 2: Zombies



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

$$m_{\text{DM}} = \alpha^{2/3} \times 10^6 \text{ TeV} \qquad (\text{m}_{\text{DM}} = 2\text{m}_{\psi})$$



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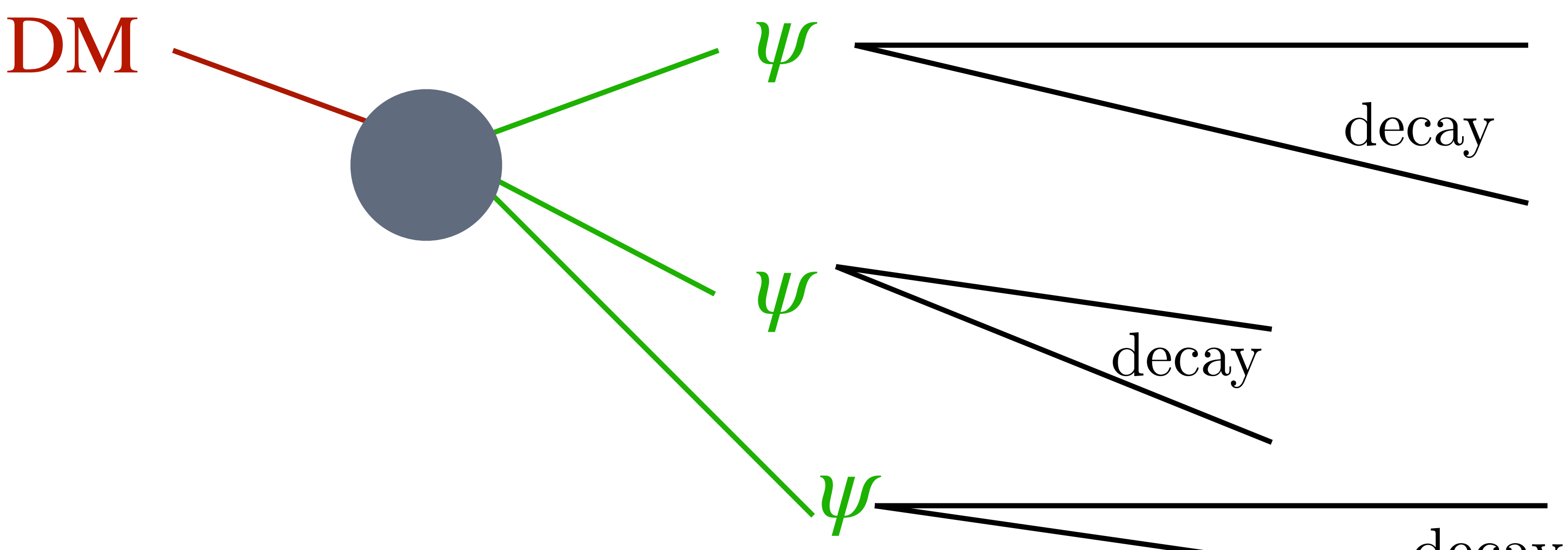
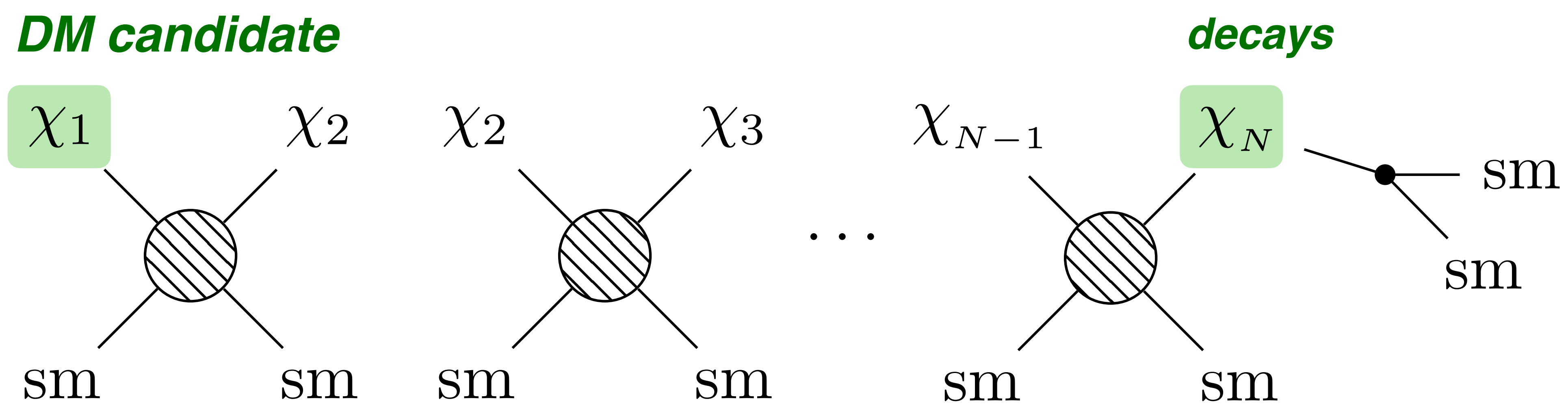


Metastable DM with strong indirect detection signal

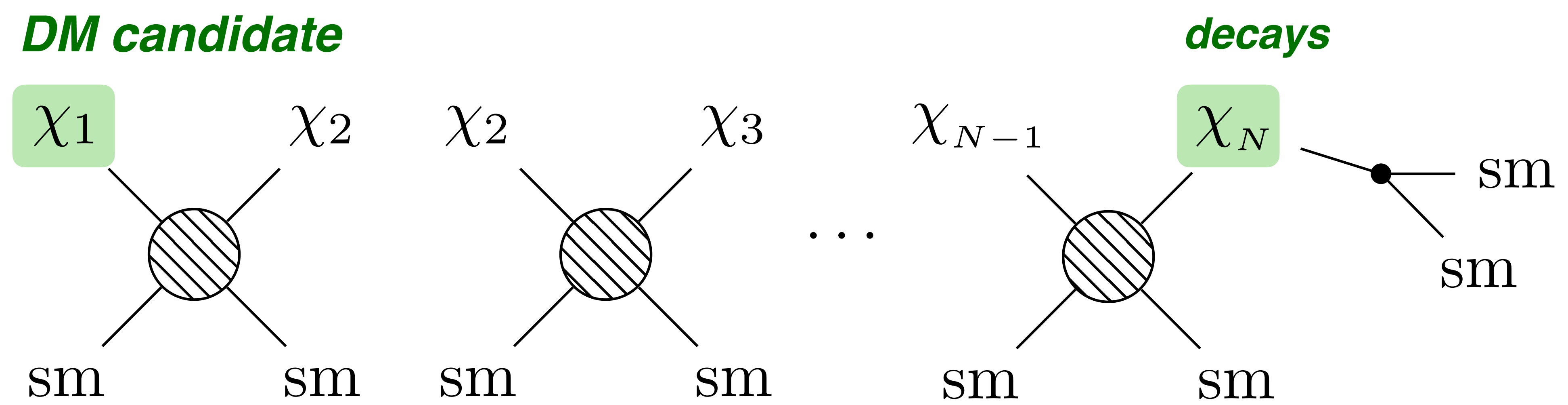
Ex. 3: Chain DM

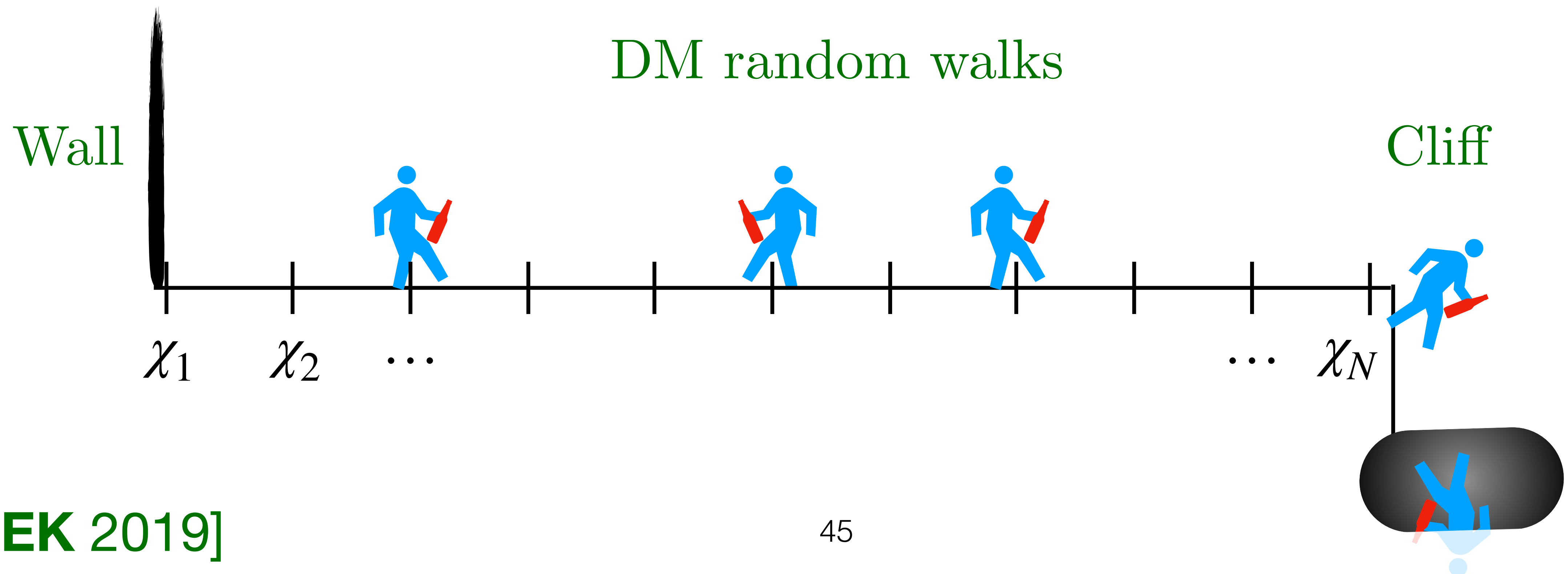


Very efficient because the SM particles are abundant

[Kim, **EK** 2019]

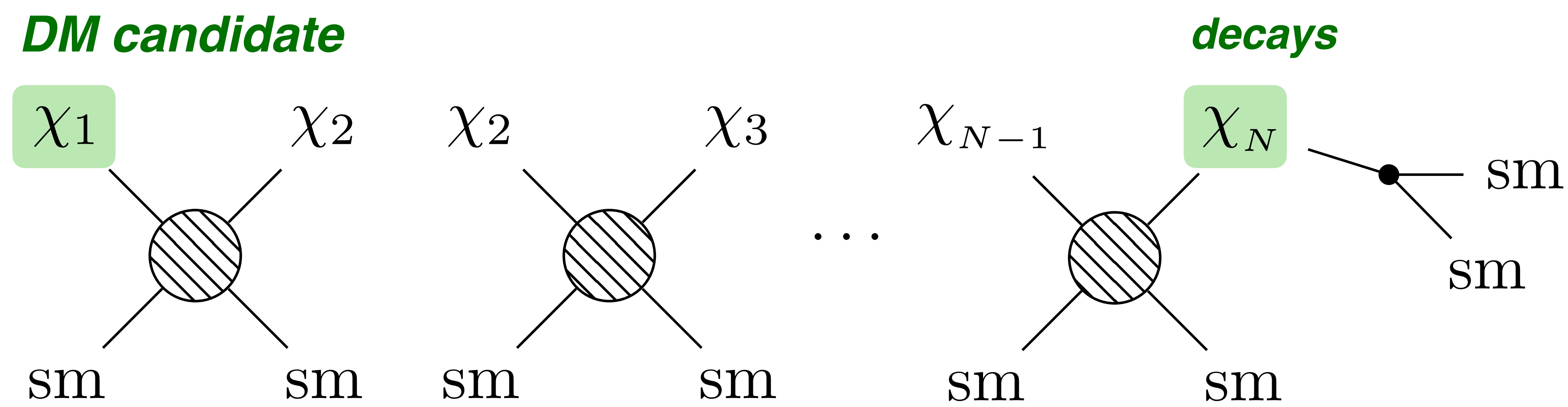
Ex. 3: Chain DM

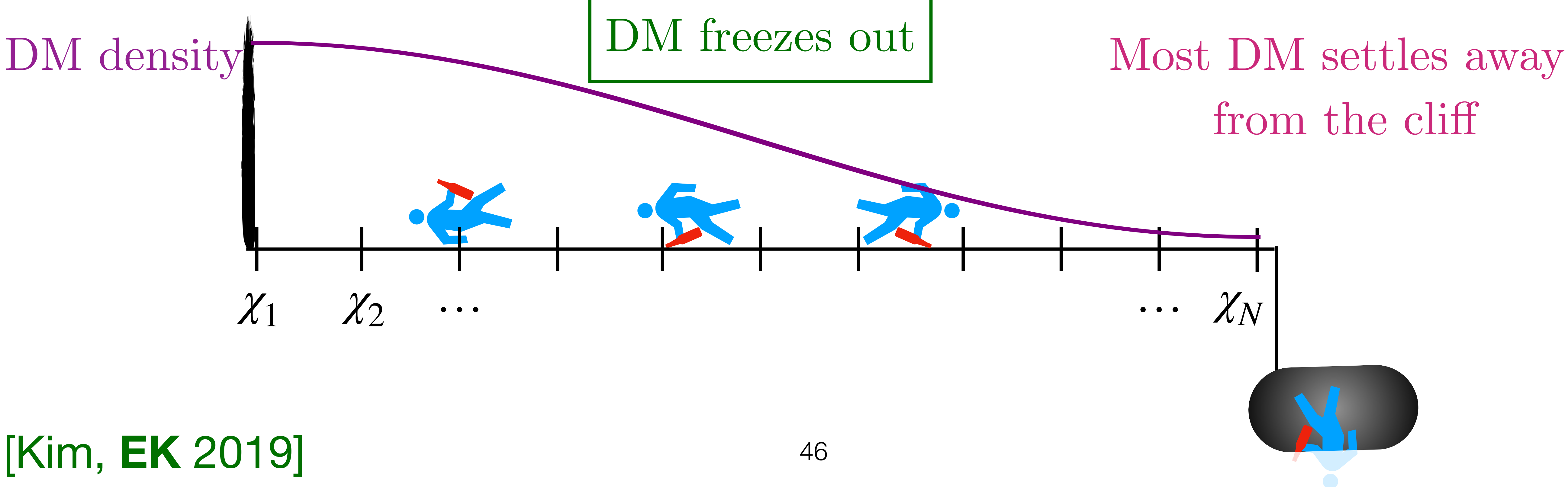




[Kim, **EK** 2019]

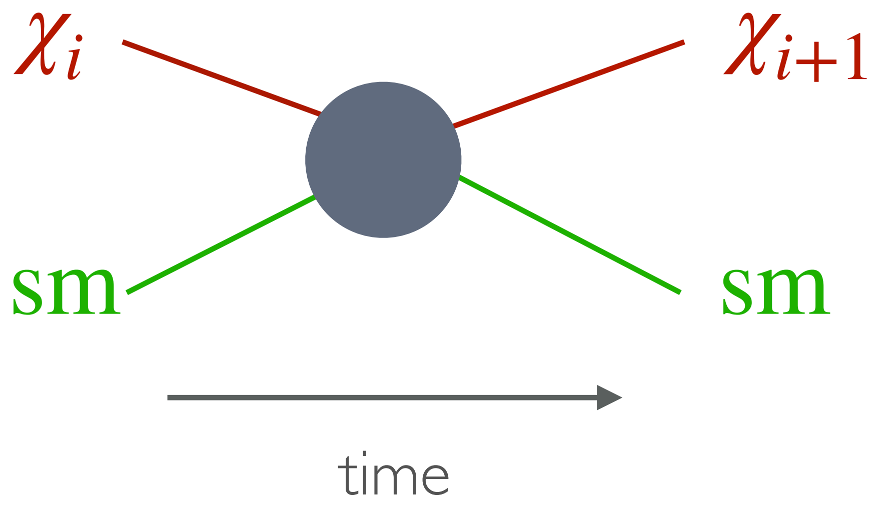
Ex. 3: Chain DM





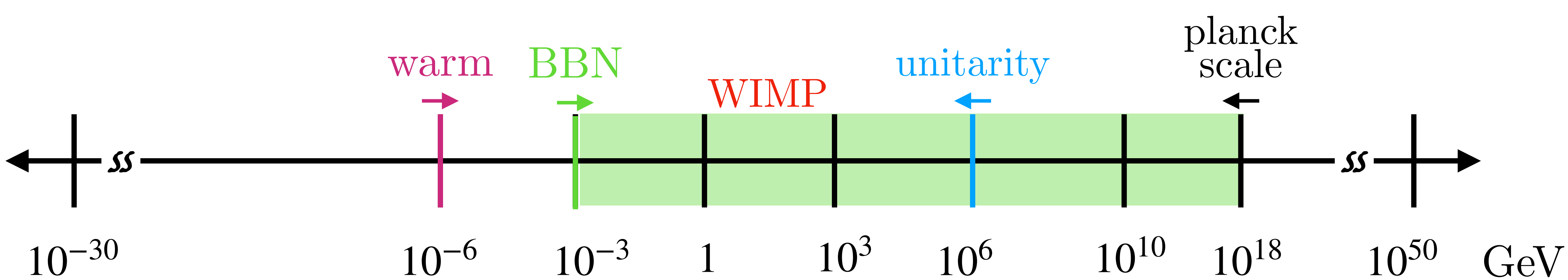
[Kim, **EK** 2019]

Ex. 3: Chain DM



$$\langle \sigma_{\rm chain} v \rangle = \frac{\alpha^2}{m_{\rm DM}^2}$$

$$m_{\rm DM} \simeq \alpha^2 \times 10^{16}\ {\rm GeV}$$



[Kim, **EK** 2019]

Outlook

- Lots of activity for thermal dark matter.
- Many different interactions, processes, and their relative importance throughout the cosmological history.
- Novel dark matter frameworks.
- Generic.
- Lots of discovery potential for experiments.
- Much more to do.

Thank you!