III DARK SECTORS :

[Yonit Hochberg, HUJI]

Developed several mechanisms to understand behavior

(m, α..)

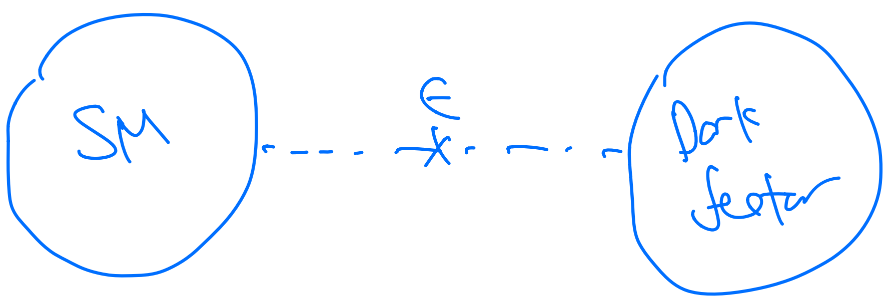
$\Rightarrow$ Models = theories that realize these mechanisms.

(SUSY = poster child for WIMP / co-ann.
Say toy $\mathbb{Z}_3$ for $3 \to 2$ SIMP)

These mechanisms generic in theory land !!

DARK SECTOR

why not in dark sector too?



Zoo of particles
symmetry structure
$SU(3)_c \times SU(2)_w \times U(1)_Y$

New gauge sym?

(?)

Inspired by the SM : $SU(3)_{dark} \times U(1)_{dark}$

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

strongly coupled gauge theories, QCD-like gauge theories

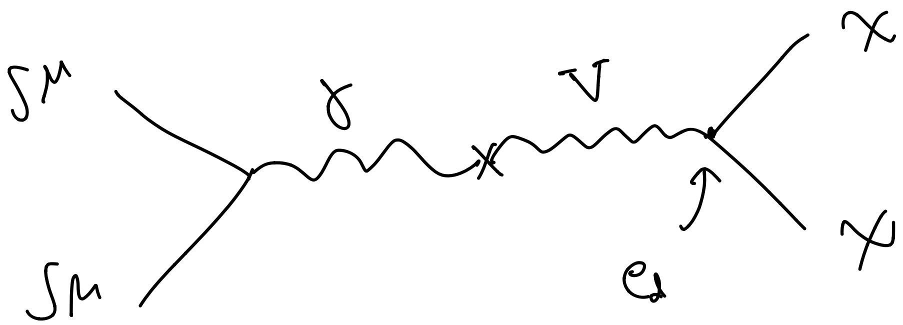
Kinetically-mixed dark photon

$V\ (\gamma_d)$

~ dark ~ QCD ~ QED ...

Could be just dark $U(1)$ - dark QED w/ dark particles charged under it.

$$\mathcal{L} \supset -\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$, dark e_d (α_d)



Kinetic mixing gives us DM-SM way to communicate - Dark sector couples to SM.

Can be more complicated - QCD-like dark sectors.

Rich theories - rich playground for many DM mechanisms & processes to occur.

True in general: for a given model/theory.

Often there multiple process that can occur.

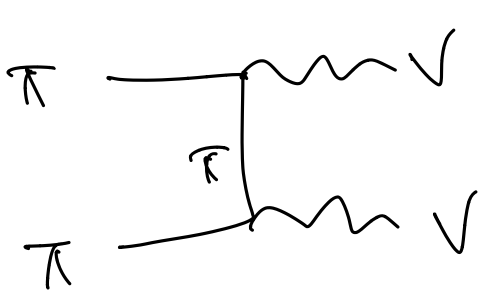
Depending on relative size, different mechanism control the abundance!

"different phases of the theory" - e.g. (WIMP/SIMP/ELDER)

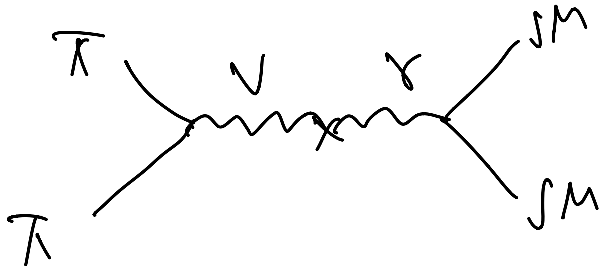
QCD-like theories → have host of mesons ($\pi, \rho, K \ldots$) ← Dark versions

"Pions" = Pseudo Nambu Goldstone bosons (PNGB) of these theories = can play the role of dark matter. π = dark pions.

E.g. 2→2:



2→2 ann.
(WIMP-like)



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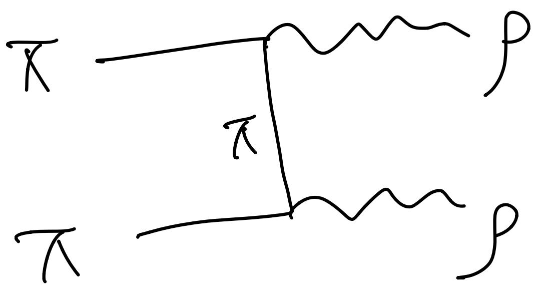
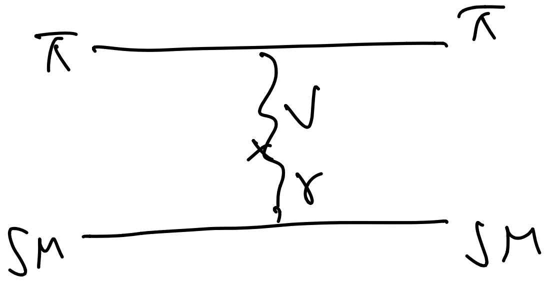


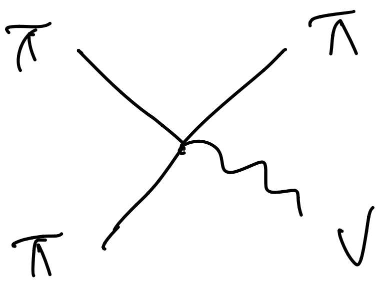
forbidden

($m_\rho \gtrsim m_\pi$)



elastic scattering

(kin. eq. / ELDER)



semi-ann.

In each case, can compute from $\mathcal{L}$ (α_d, m_π, f_π, m_V...) the cross-section you need for relic abundance.

$$\langle \sigma v \rangle = f\,(\text{parameters}).$$

⇒ translate the cross-section we developed previously into this model, to understand what parameters are need in your model.

E.g. 3→2 SIMP:

In a way, 3→2 interactions might seem most exotic — less familiar than 2→2.

But the SM has 3→2 interactions!

Reminder QCD:

SU(3) gauge theory w/ 3 light flavors u, d, s

$SU(3)_L \times SU(3)_R$ global sym.

The theory confines — chiral sym. breaking:

$$SU(3)_L \times SU(3)_R \to SU(3)_{diag}.$$

Has 8 PNGB — kaons, pions, etc.

Has 5 pt interactions! $K^+ K^- \to \pi^+ \pi^- \pi^0$

Through a topological term in $\mathcal{L}$ called Wess-Zumino-Witten (WZW)

[Wess & Zumino 1971
Witten x2 1983]

If calculate the rate, find — just right to be a SIMP if mass ~ 100 MeV!

⇒ Inspired by this – QCD-like theories:

$SU(N)$ gauge theory, w/ N_f flavors degenerate mass

$SU(N)_L \times SU(N)_R$ global sym:

confines → broken to diagonal $SU(N)_{diag}$.

(= exact sym!)

N_π PNGB = the pions = DM.

(massive + stable!)

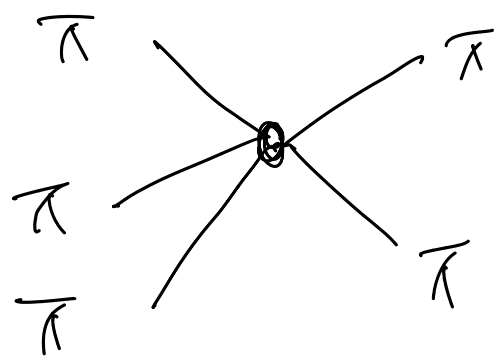
has 5-pt. interacting – WZW:

$$\mathcal{L}_{WZW} = \frac{2N}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} \mathrm{Tr}\left[\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi\right]$$

↑ pion decay constant

5 pions contracted in particular way.

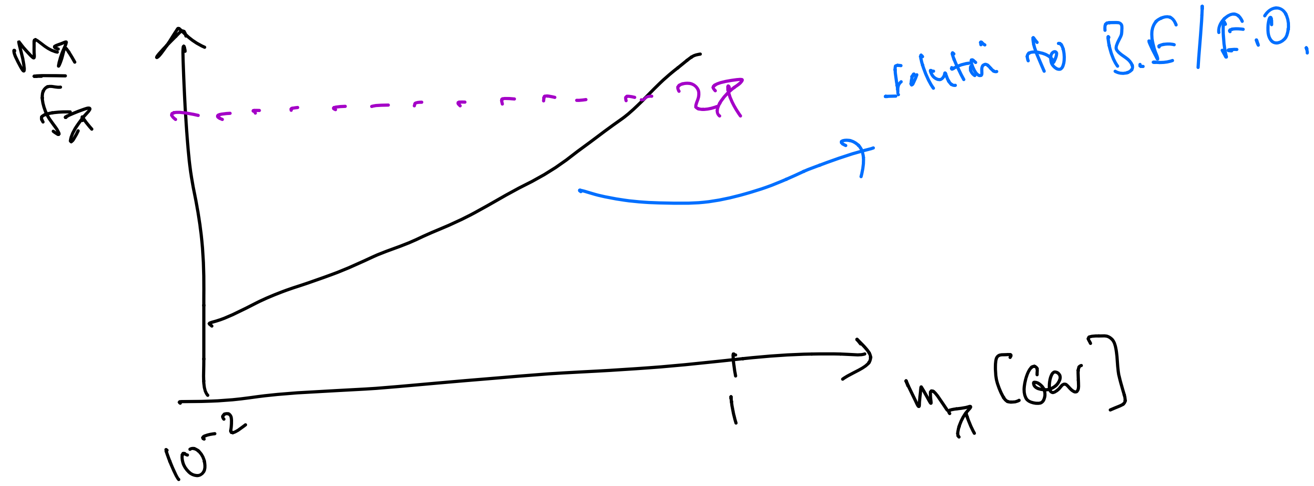
Can do this for any $SU(N)$, $SO(N)$, $Sp(N)$
($N_f \geq 3$, 3, 2)



$$\langle \sigma v^2 \rangle_{3\to 2} = \frac{5\sqrt{5}}{2\pi^5}\,\frac{N^2}{x_F^2}\,\frac{m_\pi^5}{f_\pi^{10}}\left(\frac{t^2}{N_\pi^3}\right) = \frac{\alpha_{eff}^3}{m_\pi^5}$$

(combinatorial factor, depends on group, N_f ...)

$\Rightarrow \quad \alpha_{eff} \sim \# \left(\frac{m_\pi}{f_\pi}\right)^{10/3}$



Generic in QCD-like theories!

mass ~ 100 MeV

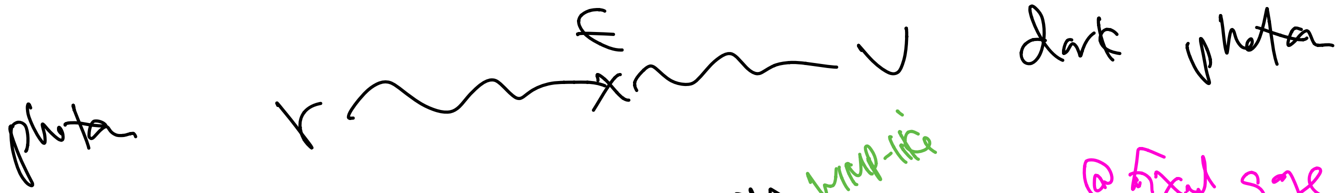
The simplest miracle ← [Hochberg, Kuflik, Murayama, Volansky, Wacker PRL 1411.3727]

includes the dark photon ← Hochberg, Kuflik, Murayama, 1512.07917

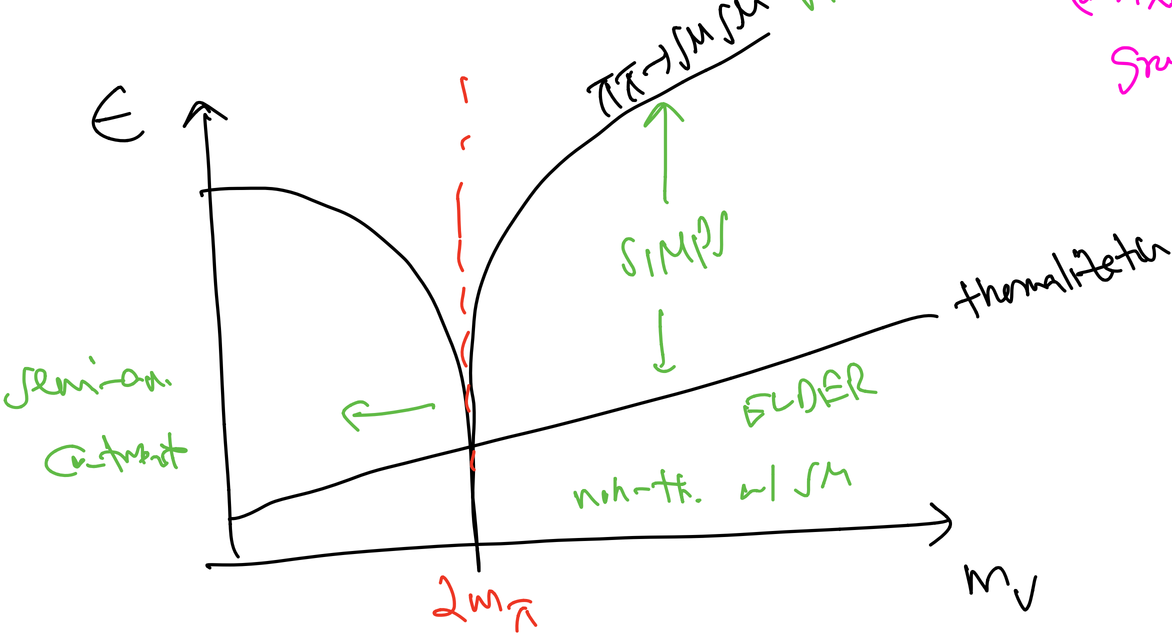
[also 3→2: dark glueballs.
Carlson, Hall, Machacek 1992
Soni, Zhang 2016
Forestell..., 2017]

Also predictive?

QCD-like theory x dark U(1) :



@ fixed gauge coup, m_π, etc..



different region of parameter space give different mechanism for DM.

Constraints on this parameter space -

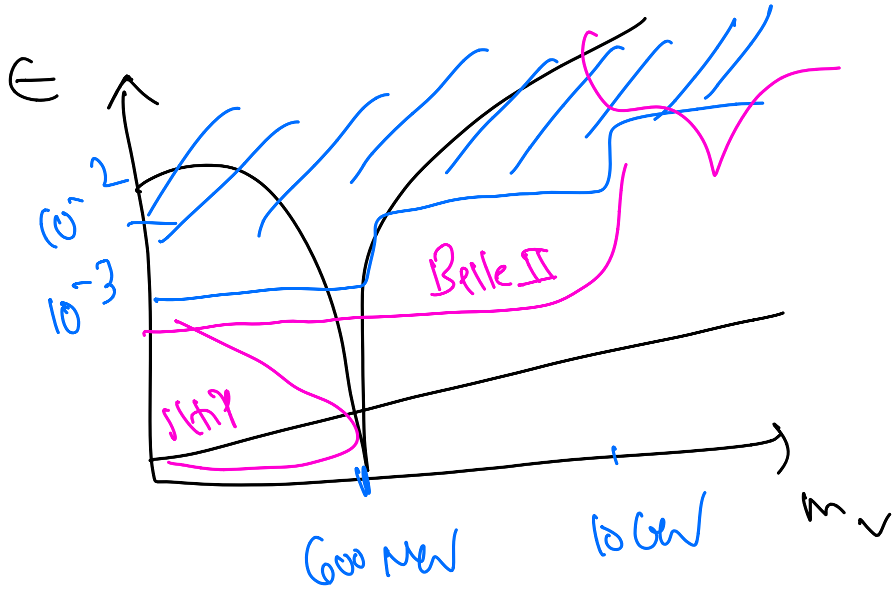
High energy colliders & low-energy colliders

& future probe - High/low energy machines,

beam dump (APEX, SHiP...)

fixed target

Direct detection (SENSEI, SuperCDMS...)



$\epsilon \lesssim 10^{-3} - 10^{-2}$

$f(m_V)$ over broad range of values.

Many future probes.

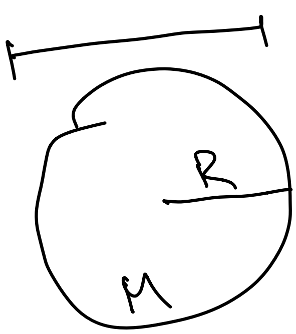
General Constraints:

"Keep in mind when you're designing the next amazing DM mechanism/model"

* minimal mass bound:

- Fuzzy DM bound:

deBroglie wavelength < size of dwarf galaxies



$\Rightarrow m_\chi \gtrsim 10^{-22}$ GeV

(bosons, fermion, not applicable to subcomponent $\lesssim 10\%$)

- Phase space packing: Fermion DM

  ~ "Treimaine-Gunn Bound".

Fermi degenerate pressure set a minimal halo mass.

Limit on how many fermions can pack into a halo.

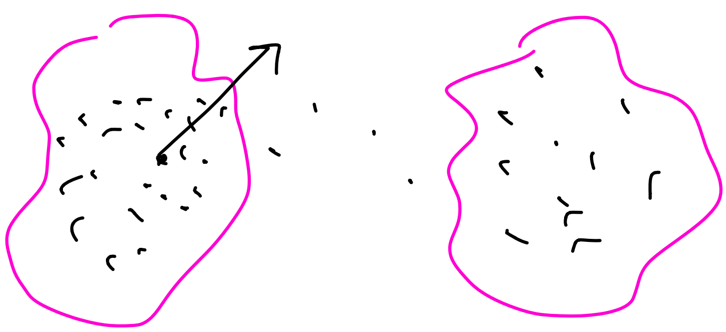
$\Rightarrow m_\chi \gtrsim$ KeV (or 0.1 keV)

[1311.0282 - recent details]

"DM is not active neutrinos".

(fermions, does not apply to subcomponent $\lesssim 10\%$)

- Warm DM:



structure forms from DM overdensities.

free streaming washes out structure.

structure will be suppressed on scales < free streaming length.

$\Rightarrow$ $m_\chi \gtrsim$ keV [astro-ph/0501562]

(doesn't apply to bosons that are produced @ rest in early universe - axions.

& not apply to subcomponent $\lesssim 10\%$)

N_{eff} : constraints on new relativistic dof beyond the SM - constrained by:

- BBN $T \sim 1$ MeV
- CMB $T \sim$ eV

conversion - count dof relative to ν's:

$$\delta N_{eff} = \frac{\rho_d}{\rho_\nu} = \frac{4}{7} g_*^d \left(\frac{T_d}{T_\nu}\right)^4$$

Bounds:
- BBN $\delta N_{eff} < 0.4$ 1912.01132
- CMB $\delta N_{eff} < 0.6$ 1807.06209

(CMB-stage 4 - improve $\mathcal{O}(10)$ improvement)

Dark sector w/ $m_i <$ MeV :

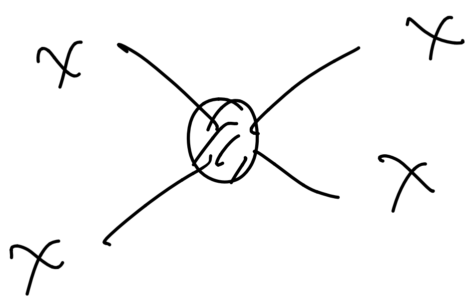
must have $T_d < T_\gamma$

⇒ must be kinetically decoupled @ MeV!

⟺ If kinetically coupled @ MeV temperature, mass ≳ MeV!

⇒ sets SIMP bound (thermal): $m \gtrsim$ MeV.

* **self-scattering** : distort dynamics in DM halos.



(Bullet cluster + halo shapes)

$$\frac{\sigma_{\text{self-scatt}}}{m_\chi} \lesssim 1 \frac{\text{cm}^2}{g}$$

4

(0.1 - 10 depending on v')

longstanding puzzles in structure formation!

Core vs. cusp ⨍ too big to fail

possible that could be addressed by astrophysics?

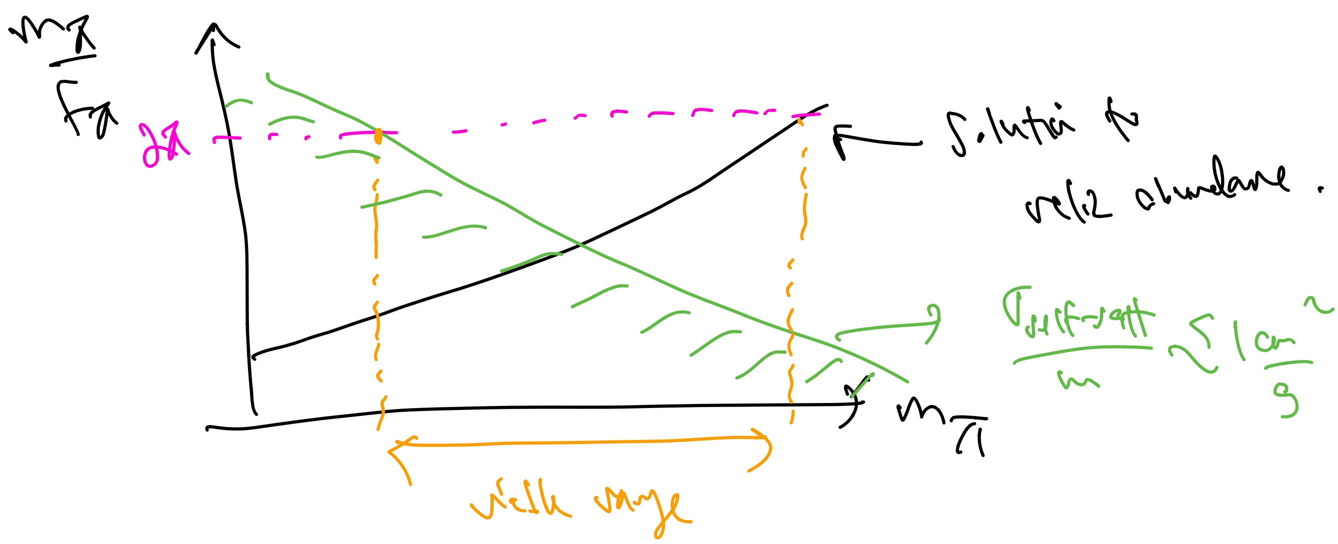
But also self-int @ $\frac{1\,cm^2}{g} \sim \frac{100\,barn}{MeV} \sim$ could assist

~ strong scale int.

[Tulin, Yu 1705.02358 review]

⇒ SIMP: expect that strong 3→2 also generally get strong 2→2 self scattering.

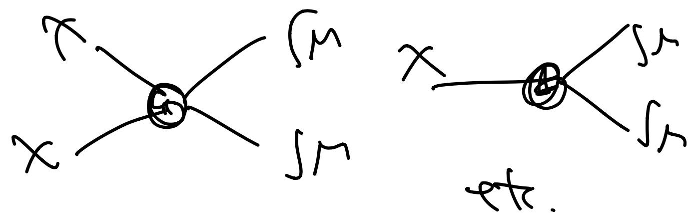
Constraints + possible signal = assist in puzzles.



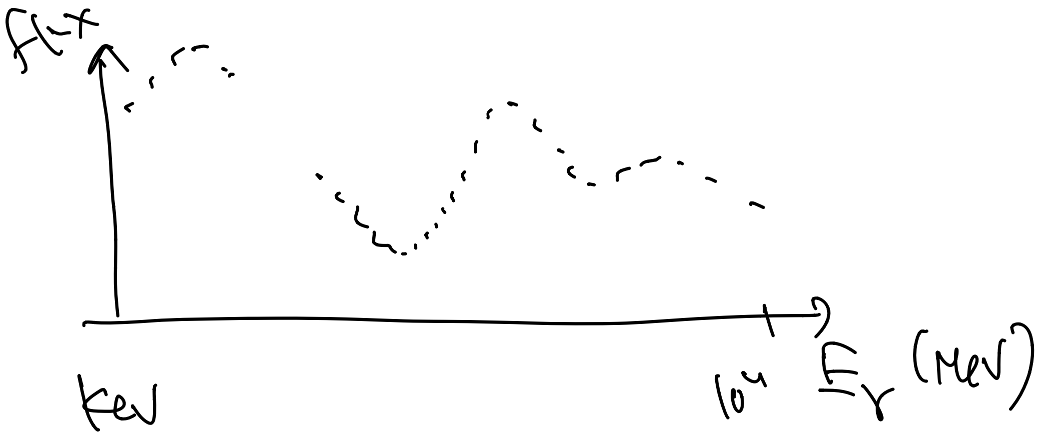
$m_\pi \sim$ few 100's MeV.

(also get large self-scattering w/ forbidden DM).

* Indirect Detection:



look to the sky & hope to see anni/decay products (γ, $e^+ e^-$, ...) of DM interactions.



Energy injection to the CMB. [TASI NOTES, Slatyer 1710.05137]

decays: $\left(\tau \gtrsim 10^{24-28} \text{ sec}\right)$

$$\tau \sim 10^{+27} \text{ sec}$$

$$\left(\tau_{\text{universe}} \sim 4 \cdot 10^{17} \text{ sec}\right)$$

*** Direct Detection — Friday IV**

In the lab