DARK MATTER ④ - GGI '22

[Yonit Hochberg, HUJI]

Outline: - Dark sectors

- Constraints

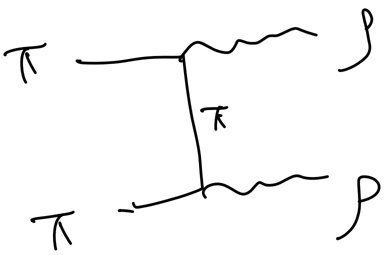
DARK SECTORS - continued:

Inspired by SM - strongly coupled gauge theories

QCD-like theories, Dark mesons

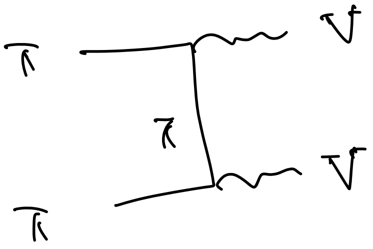
PNGBs = Pions = dark pions = can play the role of DM.

E.g. 2→2:



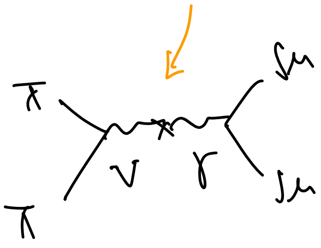
$m_\rho \gtrsim m_\pi$

forbidden



2→2 ann.

(WIMP)



2→2 ann.

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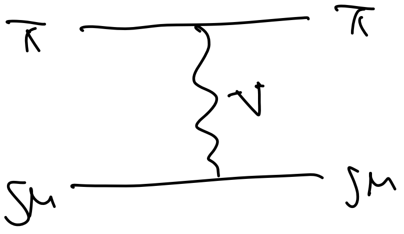
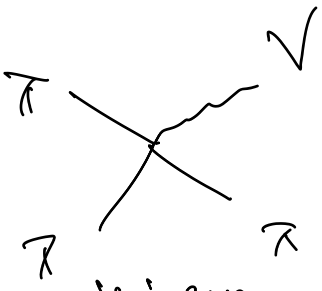


elastic scattering



semi-ann.

· — · ·

(kin. eq. / ELDER)

In each case, can compute from your $\mathcal{L}$ ($\alpha_d, m_\pi, f_\pi, m_V \ldots$)

the xsec you need for DM abundance -

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

$\Rightarrow$ translate the xsec we developed previously into this model to understand what parameters are needed here.

E.g. 3→2 SIMPs:

3→2 <u>might</u> seem more "exotic" than 2→2 processes which are more familiar. But actually have 3→2 in the SM!

Reminder - QCD:

An 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 PNGBs - kaons, pions, etc.

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

Through a topological term in $\mathcal{L}$ = WZW term

[Wess, Zumino 1971

Witten x2, 1983]

If calculate the rate, find - just right to be a

SIMP if m_s ~ 100 MeV !! ☺

→ Inspired by this, QCD-like theory:

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

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

χ_{SB} occurs → SU(N) diagonal = exact!

N_π PNGB = the pions = DM

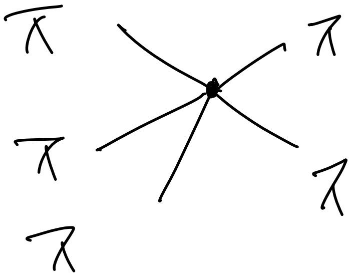
5pt. int' - WZW:

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

5 pions, contracted in a particular way.

Can do this for any $SU(N)$, $SO(N)$, $Sp(N)$

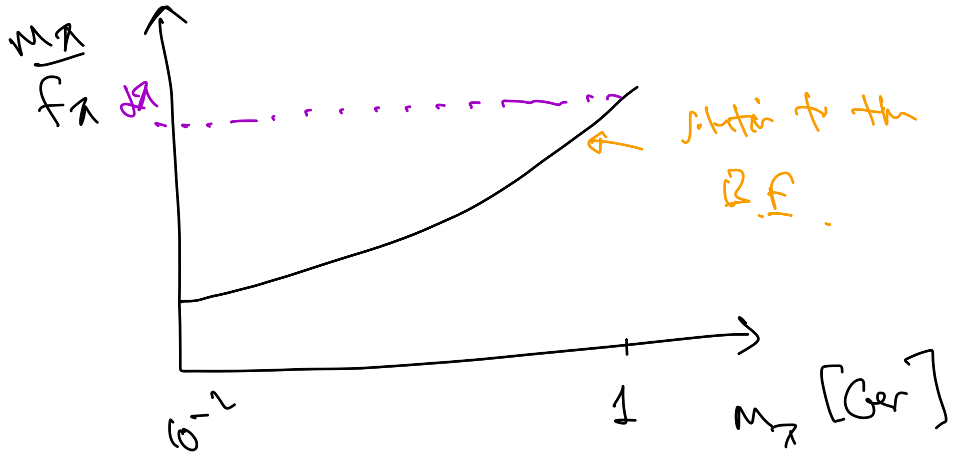
$(N_f \geq 3)$ $(N_f \geq 3)$ $(N_f \geq 2)$



generic in QCD-like dark sectors!

$O(100\ \text{MeV})$

$$\langle \sigma v^2 \rangle_{3\to 2} = \frac{5\sqrt{5}}{2\pi^5} \frac{N^2}{x_f^2} \frac{m_\pi^5}{f_\pi^{10}} \underbrace{\left(\frac{t^2}{N_\pi^3}\right)}_{\text{combinatorial factor - depends on group + } N_f}$$



solution to the B.E.

[YH, Kuflik, Murayama, Wacker, Volansky PRL 1411.3727]

– the SIMPlest Miracle

[YH, Kuflik, Murayama, 1512.07917] → includes dark photon.

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

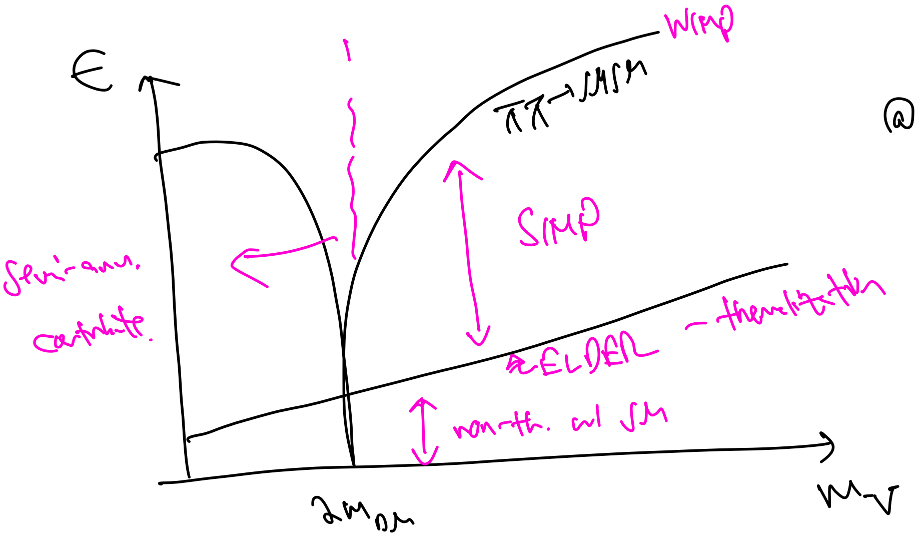
[Y.H., Kuflik ... 1806.10139 – axion portal]

Also predictive :

QCD-like theory × dark EM

$\gamma \overset{\epsilon}{\sim\sim\times\sim\sim} V$
dark photon

@ fixed gauge group.
& fixed m_{DM}



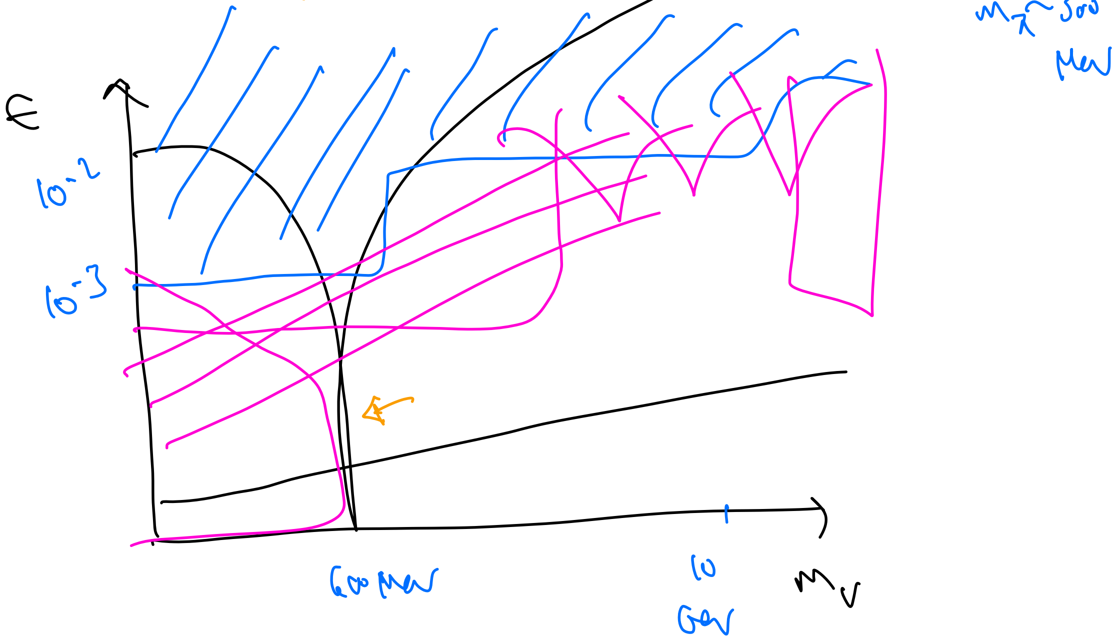
Constraints on parameter space - high energy & low energy colliders.

& future probes - high & low energy colliders. (LHC, ILC, Belle II ...)

beam dump & fixed target exp (APEX, SHiP....)

Direct detection – (electron recoils – SENSEI, SuperCDMS ...)

[recent compilation of bounds & projections: 2008.08608]



roughly $\epsilon \lesssim 10^{-3} - 10^{-2}$ broad range of m_V

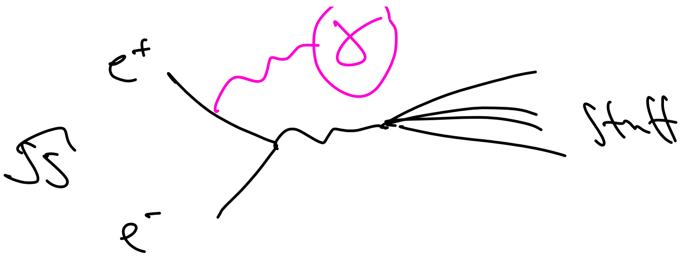
many future probes.

Can go even further – Spectroscopy of dark sector?

[YH, Kuflik, Murayama 1512.07917, 1706.05008]

Draw analogy from QCD: How do we know the beautiful resonance structure of QCD?

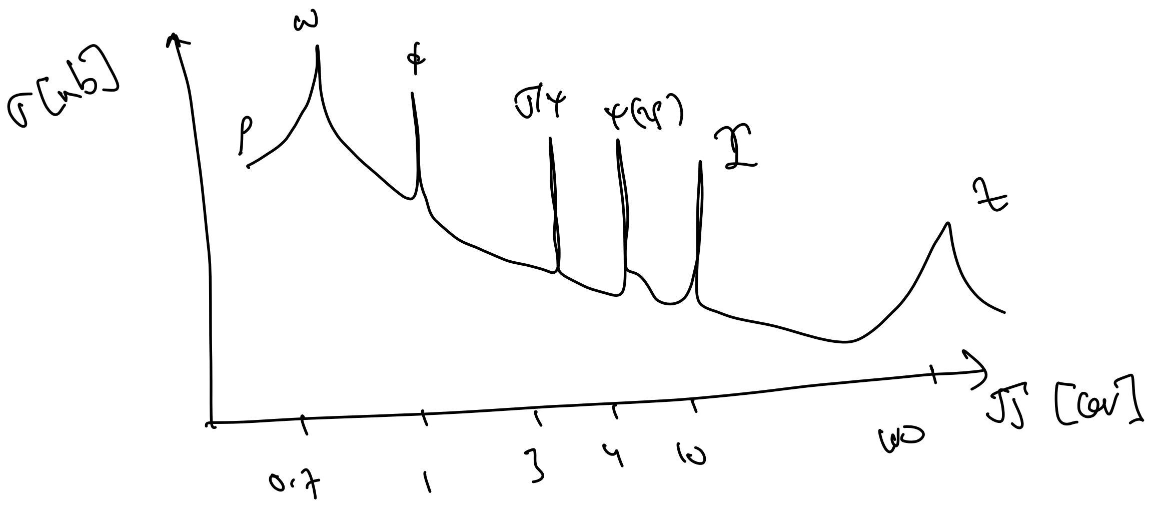
Smash $e^+e^- \longrightarrow$ stuff $\rightarrow$ hadrons :



Scan $\sqrt{s}$

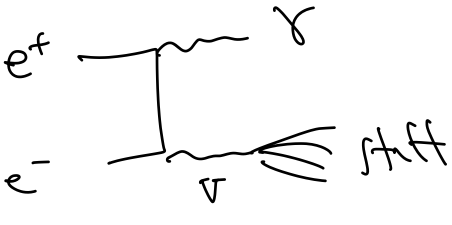
→ scan "stuff".

⇒ beautiful picture we are all familiar with:



ask yourself: How could we see this @ fixed energy machine?

Monophoton events! add photon - tracer for the system it recoils against.

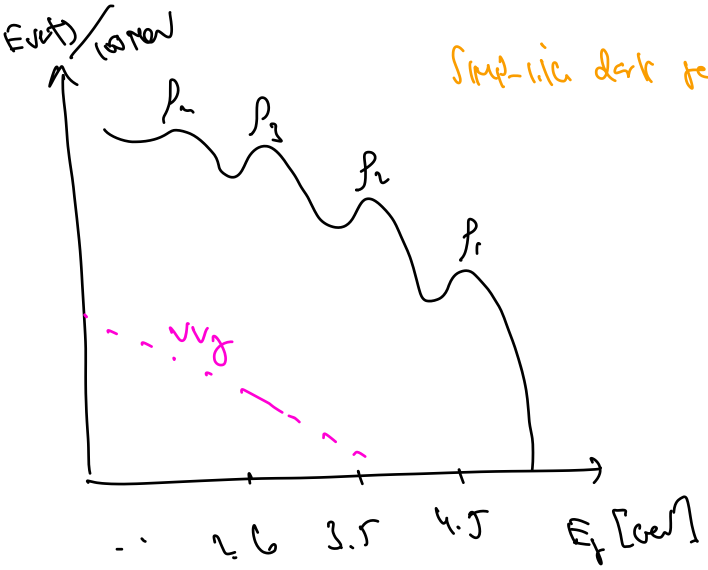


$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{inv}^2}{s}\right)$$

can do this for dark "stuff" too!

E.g @ Belle-II

$\sqrt{s} = 10$ GeV



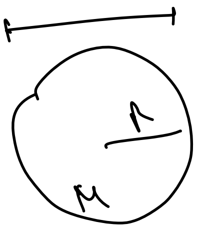
Simplistic dark sector

General Constraints :

"Keep in mind when you write down new mechanism/model / work through details for your case".

* minimal mass bound :

- Fuzzy DM bound - de Broglie wavelength < size of dwarf galaxies



DM can fit.

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

(bosons, fermions, not for subcomponent of $\lesssim 10\%$)

- phase space packing : Fermion DM "Tremaine Gunn Bound".

Limit on how many fermions can pack into a halo.

⇒ $m_\chi \gtrsim$ keV (more recent: 0.1 keV)

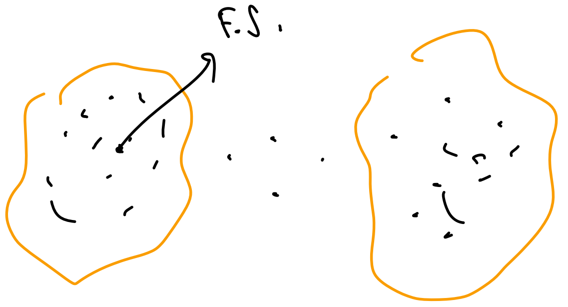
↑

1311.0282 for recent details.

"DM is not active neutrino".

(fermions, doesn't apply to bosons, doesn't apply to subcomponents $\lesssim 10\%$)

- warm DM : freestreaming washes out structure.



Structure is suppressed on scales < free streaming.

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

(doesn't apply to bosons produced @ rest - axion, etc,

subcomponent $\lesssim 10\%$)

– **Neff** : constraints on new relativistic dof beyond the SM, constrained by:

$$\begin{cases} \text{BBN} & T_\gamma \sim \text{MeV} \\ \text{CMB} & T_\gamma \sim \text{eV} \end{cases}$$

Convention: count dof relative to ν's:

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

fields...

Bounds

$$\begin{cases} \text{BBN:} & \delta N_{eff} < 0.4 \\ \text{CMB:} & \delta N_{eff} < 0.6 \end{cases}$$

[1912.01132]

[1802.06209]

Planck

(CMB stage 4 - claim $\delta N_{eff} \lesssim 0.05$

$O(10)$ improvement!)

$\Longrightarrow$ Dark sector w/ $m_i <$ MeV must have $T_d < T_\gamma$

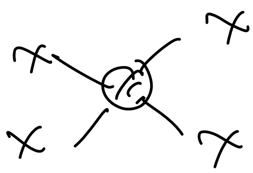
$\Longrightarrow$ must be kin. decoupled @ MeV.

$\Longleftrightarrow$ if kinetically coupled @ MeV temp., mass $\gtrsim$ MeV.

Sets SIMP bound (others) $\gtrsim$ MeV in general.

[more: Josh Ruderman, IIAS winter school 2019, lecture 4]

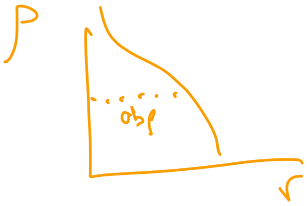
- **self-scattering**: distort dynamics in DM halos.



$$\frac{\sigma_{\text{self-scatter}}}{m_\chi} \underset{\uparrow}{\overset{}{\lesssim}} 1 \,\frac{\text{cm}^2}{\text{g}} \quad \left(\begin{array}{l}\text{bullet cluster} \\ \text{halo shapes}\end{array}\right)$$

(0.1 - 10) v' dependent of system.

puzzles - core vs. cusp, $\underbrace{\text{too big to fail.}}_{}$



mismatch between
MW brightest sats &
Biggest satellites.

Can be altered by astrophysics (e.g. baryonic effects)

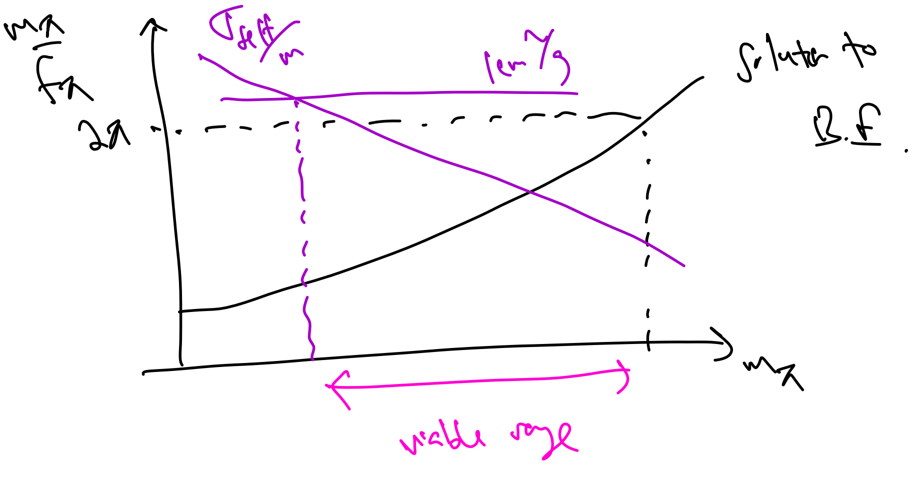
But also self-int @ $1 \frac{\text{cm}^2}{\text{g}}$ $\left(\sim \frac{1 \text{ barn}}{\text{MeV}} \sim \text{strong scale int} \right)$

[Tulin, Yu 1705.02358 review]

⟹ SIMPs: expect that strong 3→2 also generically have strong 2→2 self-scattering.

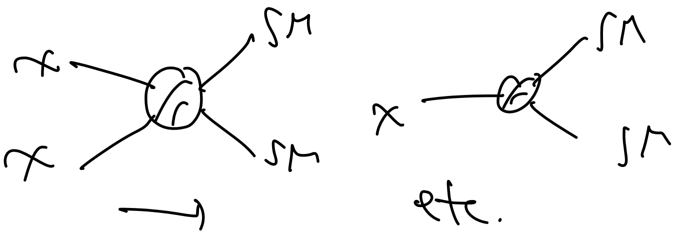
$$\mathcal{L} \supset \text{tr}\,\pi^4 - \pi\partial\pi\partial\pi\pi \ldots$$

$$\Rightarrow \quad \sigma_{\text{self-scatter}} = \frac{m_\pi^2}{32\pi^2 f_\pi^4} \underbrace{\left(\frac{a^2}{N_\pi^2}\right)}_{\text{combinatorics}}$$



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

- Indirect detection:

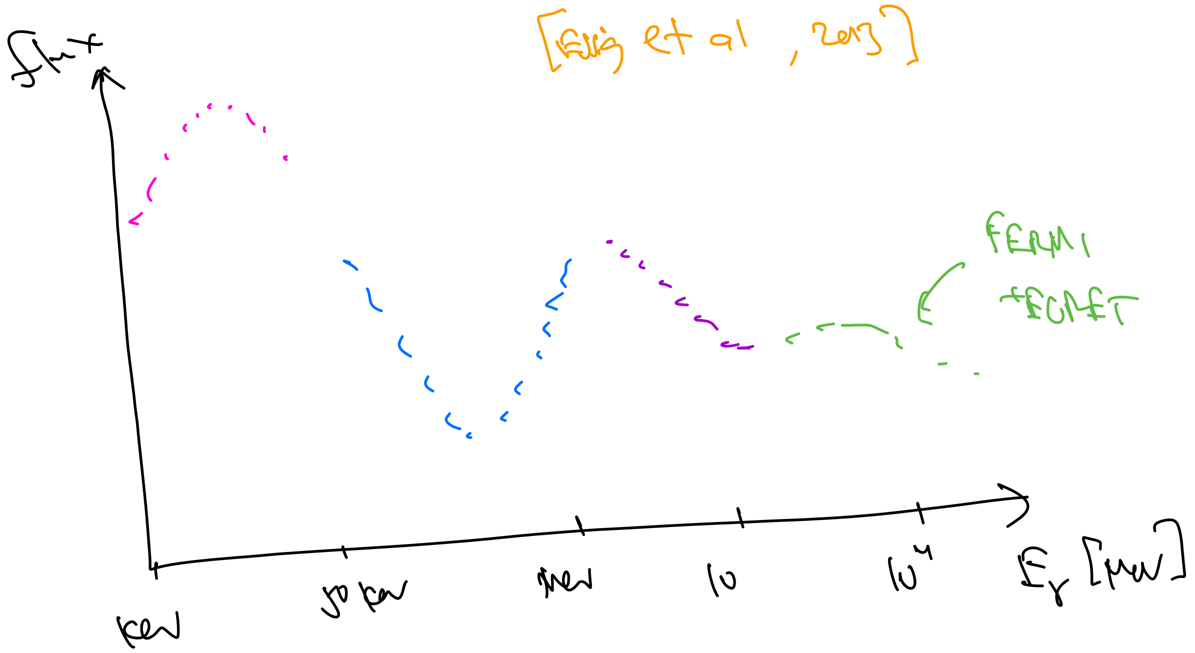


look to the sky - & hope to see anni/decay products of DM 'out'

↑

(γ's, e^+, e^- ...)

flux sets limits - measurements over broad range of energies:



[Essig et al , 2013]

Sets bounds on late time ann/decays of DM.

Energy injection into CMB [TASI notes, Tracy Slatyer 1710.05137]

decay : $\tau \gtrsim 10^{24} - 10^{28}$ sec

$\uparrow$

depends on m_{DM} + final states.

rule of thumb ballpark : $\tau \gtrsim 10^{27}$ sec.

- Direct Detection - tomorrow