Theories for Dark Forces

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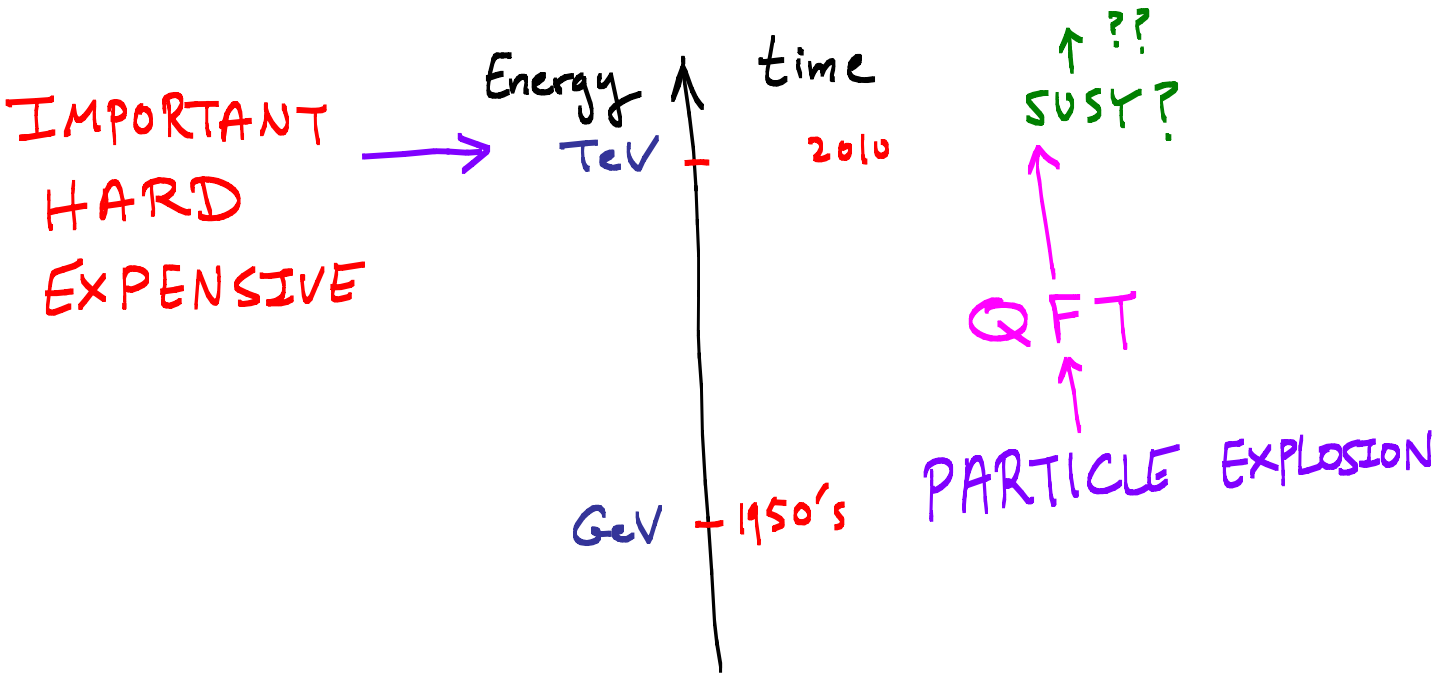
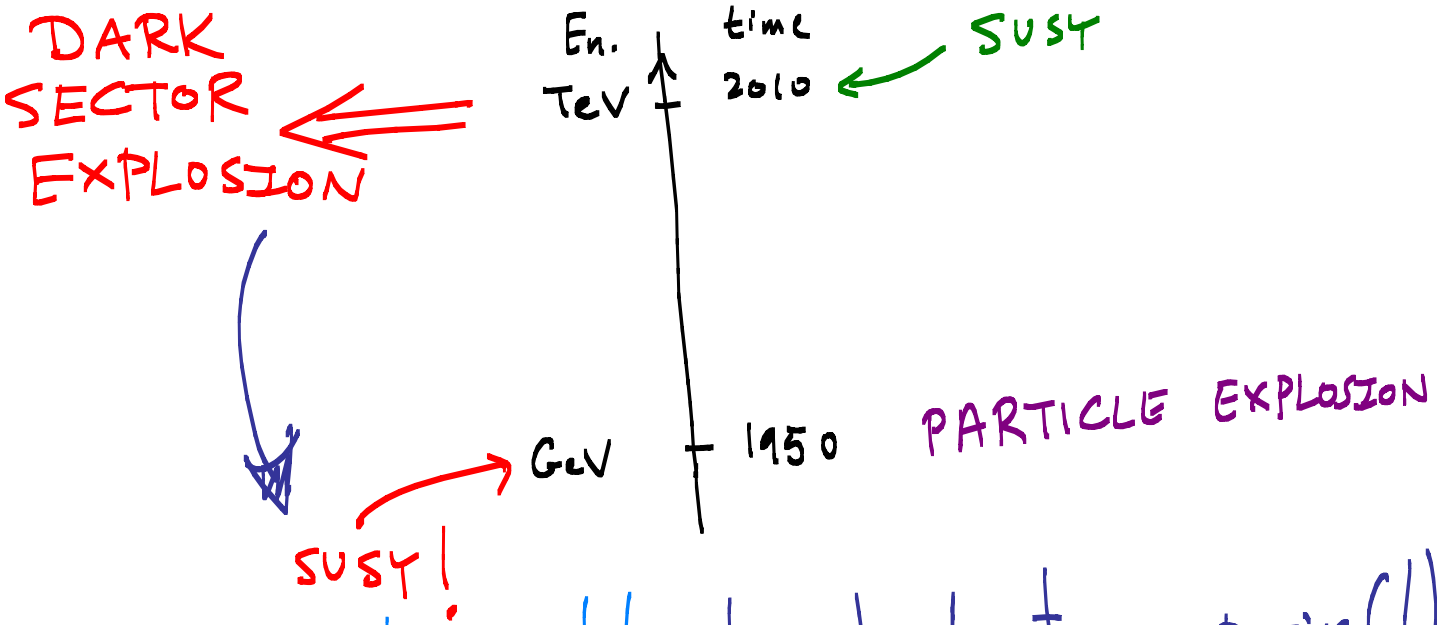
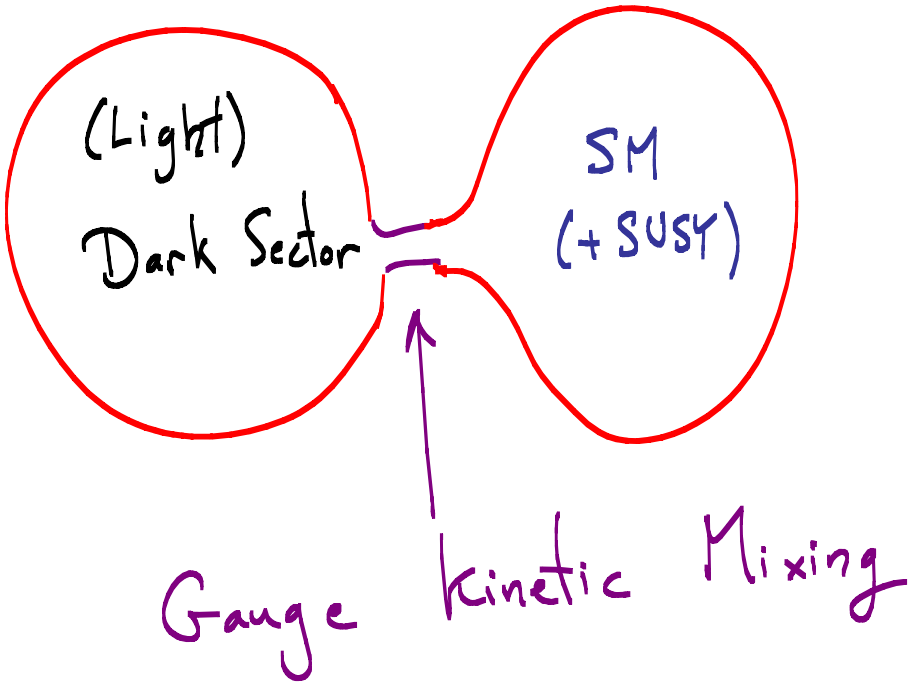
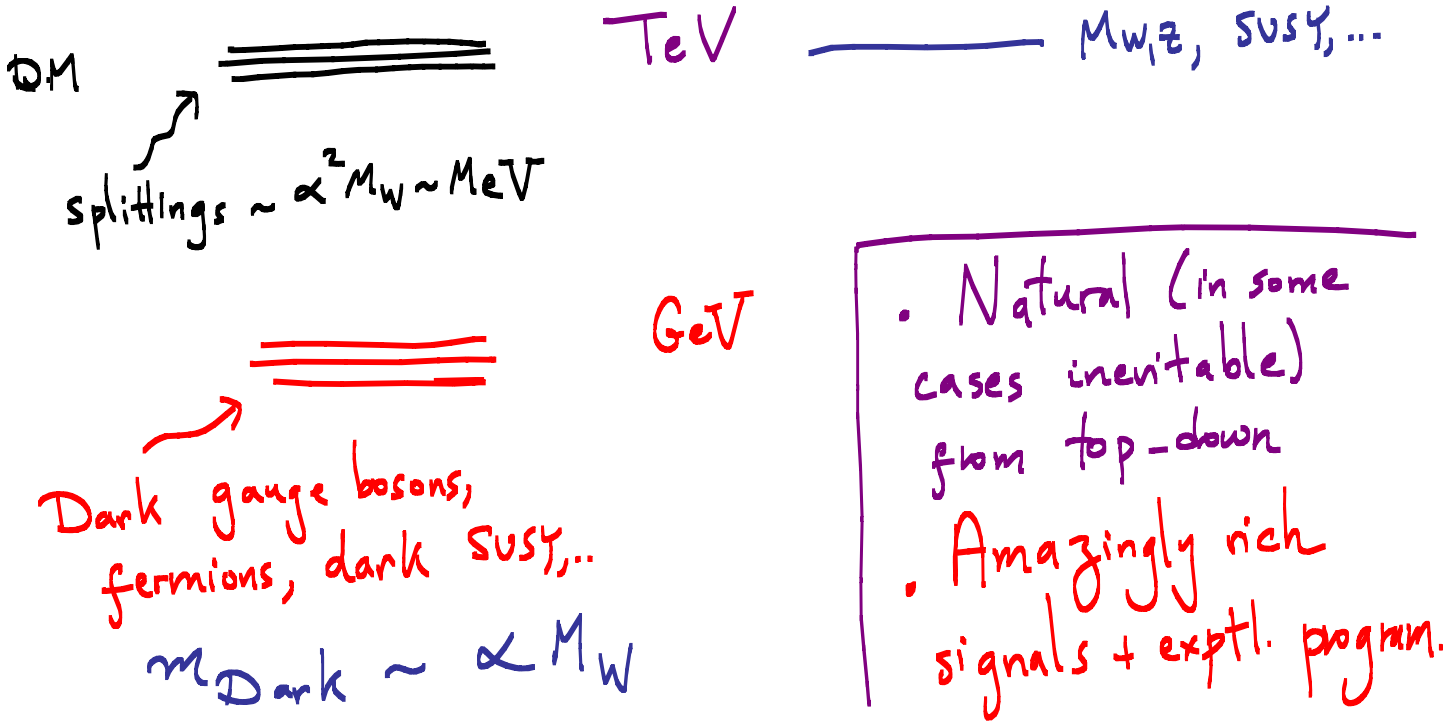

IMPORTANT
HARD
EXPENSIVE
Energy
time
TeV
2010
GeV
1950's
??
SUSY?
QFT
PARTICLE EXPLOSION



- (Could be) just as important, not as hard, not as expensive (!)


(Light)
Dark Sector
SM
(+ SUSY)
Gauge Kinetic Mixing


DM
splittings ~ $\alpha^2 M_W \sim$ MeV
TeV
$M_{W,Z}$, susy, ...
GeV
Dark gauge bosons, fermions, dark susy, ..
$m_{Dark} \sim \alpha M_W$
• Natural (in some cases inevitable) from top-down
• Amazingly rich signals + exptl. program.

$$\mathcal{L} = \mathcal{L}_{us} + \mathcal{L}_{Dark} + \mathcal{L}_{mix}$$

$$\mathcal{L}_{mix} = \sum_{ij}' K_{ij}\, \mathcal{O}_{us}^{i}\, \mathcal{O}_{dark}^{j}$$

Leading couplings are dimensionless,
[otherwise really tiny]

Most obvious candidates with $U(1)_{Dark}$:

$\epsilon \; F^{Dark}_{\mu\nu} F^{\mu\nu}_{Y}$

↓ After EWSB

$\epsilon \; F^{Dark}_{\mu\nu} F^{\mu\nu}_{EM}$

↑ Still dimless, dominates @ low E.

Other candidate:

$\epsilon \; h^{\dagger} h \; \varphi^{\dagger}_{dark} \varphi_{dark}$

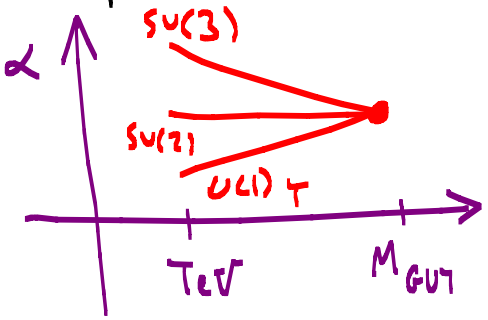
↓ After EWSB

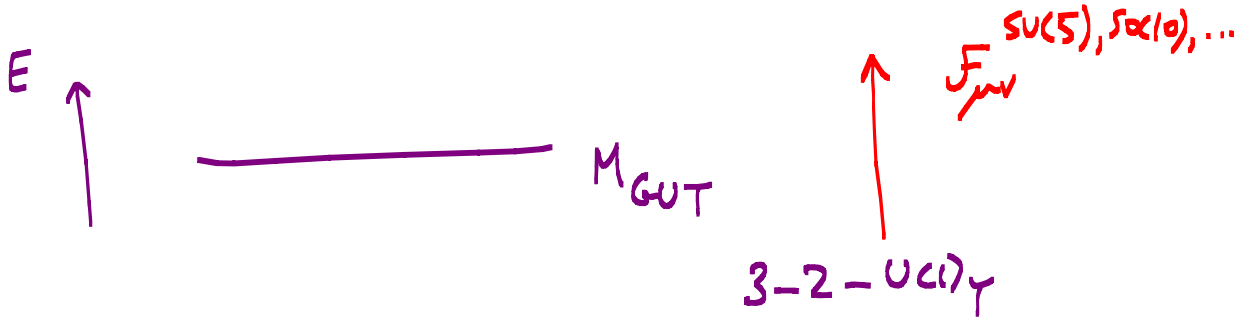
$\epsilon \; \varphi^{*}_{dark} \varphi_{dark} \; \bar{\psi}_f \psi_f \frac{m_f}{M_W^2}$

↑ Suppressed @ low-E

$$\varepsilon \, F^{\mu\nu}_{\text{Dark}} \, F_{\mu\nu}$$

Unification $\Longrightarrow$ $\varepsilon \ll 1$!

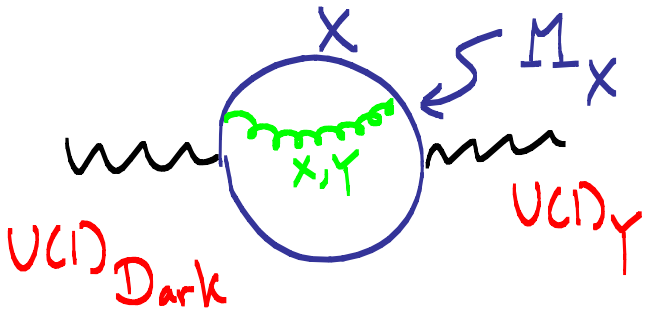




Above GUT scale, can't have mixing

$F^{Dark}_{\mu\nu}$ $\quad$ $tr\, F^{\mu\nu}_{GUT} = 0$

But mixing generated radiatively after GUT is broken!



$$\varepsilon \sim \frac{g_{Dark}\, g_Y}{16\pi^2} \frac{g^2}{16\pi^2} \log \frac{M_{GUT}}{M_X}$$

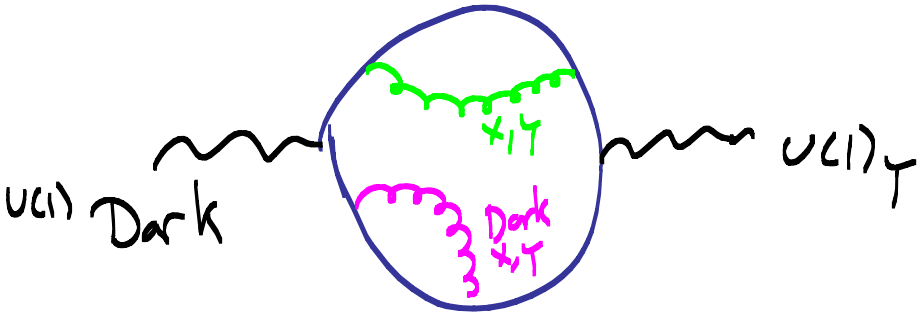
$$\sim 10^{-5} \rightarrow 10^{-3} \text{ naturally}$$

$$\varepsilon F^{Dark}_{\mu\nu} F^{\mu\nu}_{Y}$$

Low energies

$$\varepsilon F^{Dark}_{\mu\nu} F^{\mu\nu}_{E.M.}$$

[Could even have dark GUT:



$$\epsilon \sim \frac{g_{Dark}\, g_Y}{16\pi^2} \left(\frac{g^2}{16\pi^2}\log\frac{M_G}{M_X}\right)\left(\frac{g^2}{16\pi^2}\log\frac{M_G}{M_X}\right)$$

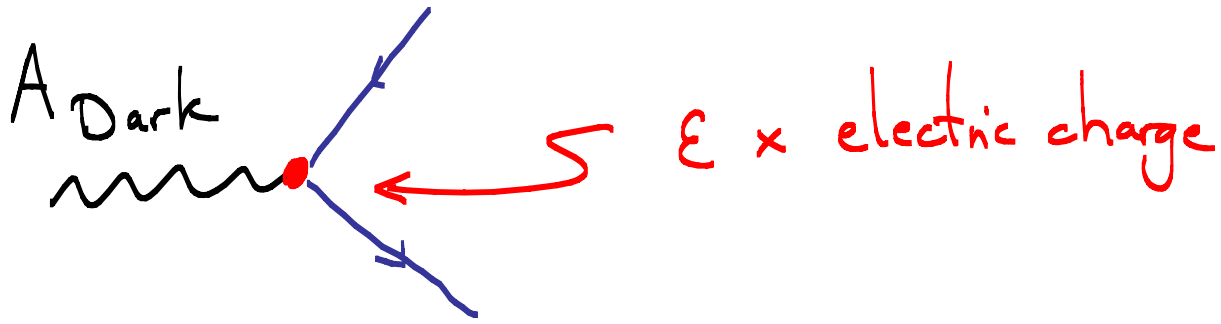
$\sim$ as small as 10^{-7} perhaps]

$$-\frac{1}{4}\left(F_{\mu\nu}^{\text{Dark}}\right)^2 - \frac{1}{4}\left(F_{\mu\nu}^{\text{EM}}\right)^2 + \varepsilon F_{\mu\nu}^{\text{DM}} F^{\mu\nu\,\text{EM}}$$

$$+ \quad m_{\text{Dark}}^2 \left(A_\mu^{\text{Dark}}\right)^2 \quad + j_{\text{EM}}^\mu A_\mu^{\text{EM}}$$

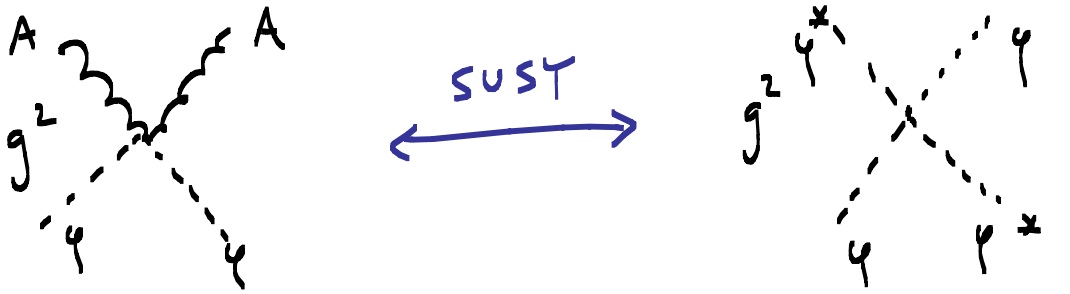
$A_\mu^{\text{EM}} \longrightarrow A_\mu^{\text{EM}} + \varepsilon A_\mu^{\text{Dark}}$ eliminates mixing.

$$\Longrightarrow \quad j_{\text{EM}}^\mu \left[A_\mu^{\text{EM}} + \varepsilon A_\mu^{\text{Dark}} \right]$$

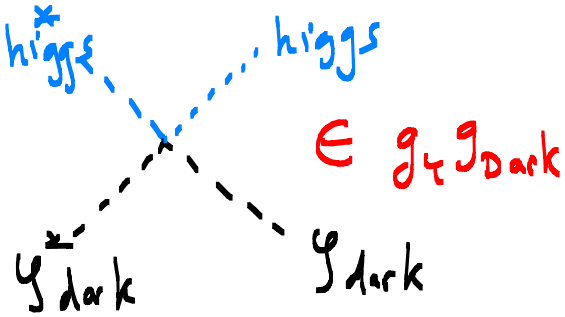


Amazing that $\varepsilon \sim 10^{-3}$, $m_{Dark} \sim$ GeV is not ruled out!

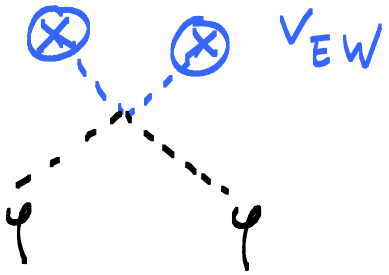
Radiative Origin of Dark Scale



$\epsilon \, F_{\mu\nu}^{Dark} F^{\mu\nu}_{\gamma}$ SUSY



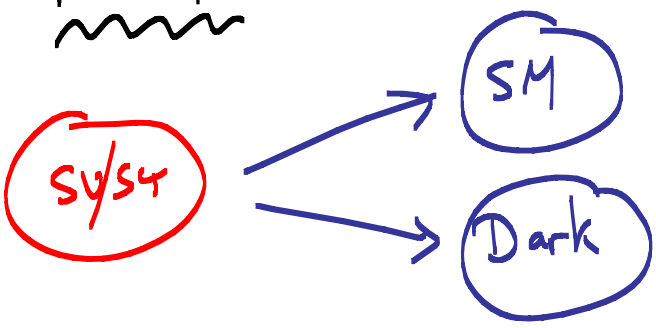
$\Longrightarrow$ a minimal contribution to dark scalar masses



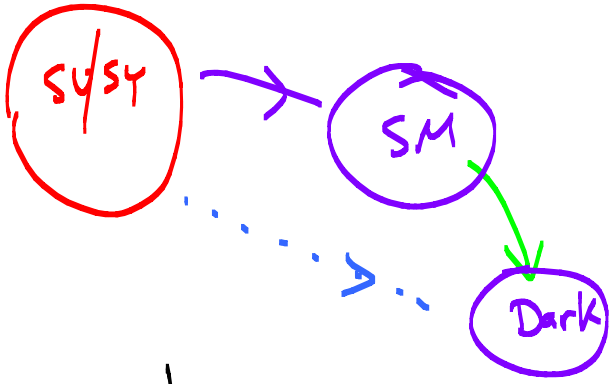
$m_\varphi^2 \sim \epsilon\, m_W^2$; $\epsilon \sim \alpha^2$ most naturally,

$m_\varphi \sim \alpha\, m_W \sim$ GeV !

NOT



Essentially anything else: e.g.



[Familiar from Gauge Mediated SUSY]

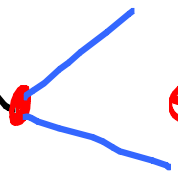
★ Note: all that is needed is for

$$G_{Dark} = G_{Non\text{-}Ab.} \times U(1)'s$$

$G_{Non\text{-}Ab.}$: could be present

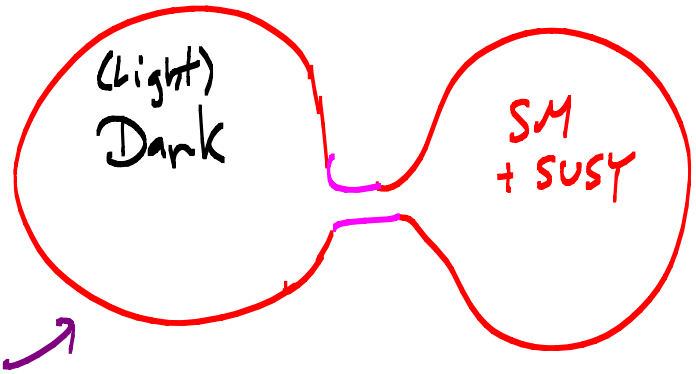
$U(1)'s$: kin. mix with $U(1)_Y$

After G_{Dark} is broken, abelian + non-abelian pieces get all mixed up $\Longrightarrow$ A^a_{Dark}



ϵ^a x electric charge

Dark Forces + Dark Matter



Usual LSP is unstable!

The LSP is here!

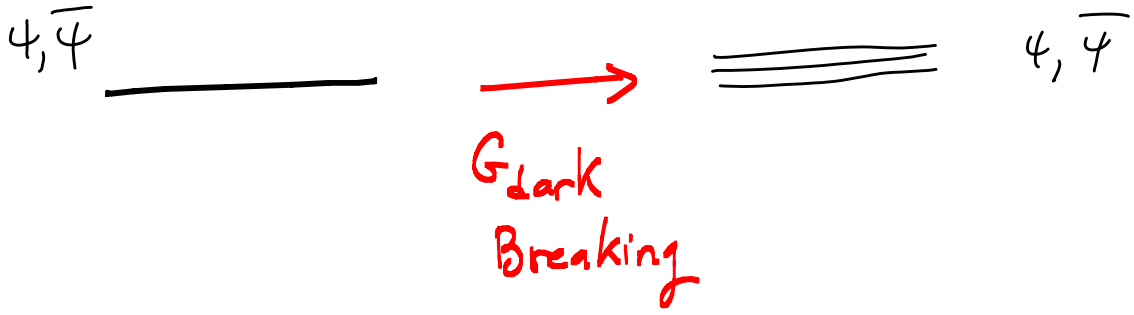
$\epsilon \gtrsim 10^{-4}$: Dark Sector +Us thermalized at Dark scale $\Rightarrow$ tiny tme LSP abundance

New vector-like states w/ common origin of mass [e.g. PQ breaking]

U_S

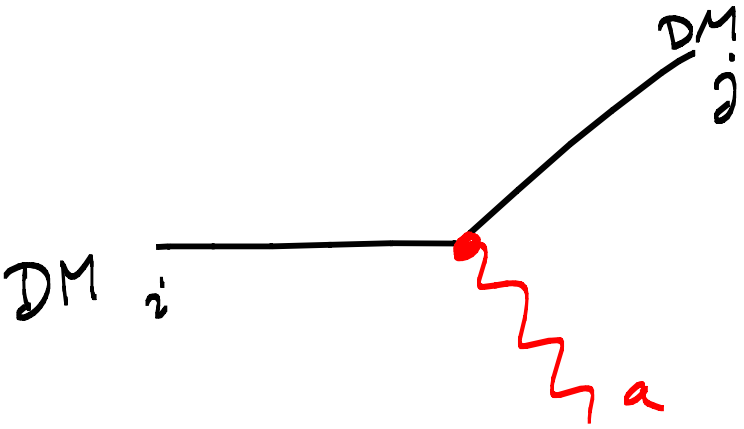
Dark

Usual "WIMP Miracle" holds



$$\delta m \sim \alpha_{Dark}\, m^{A}_{Dark}$$

$$\sim \alpha^2 m_Z \sim \text{MeV}!$$

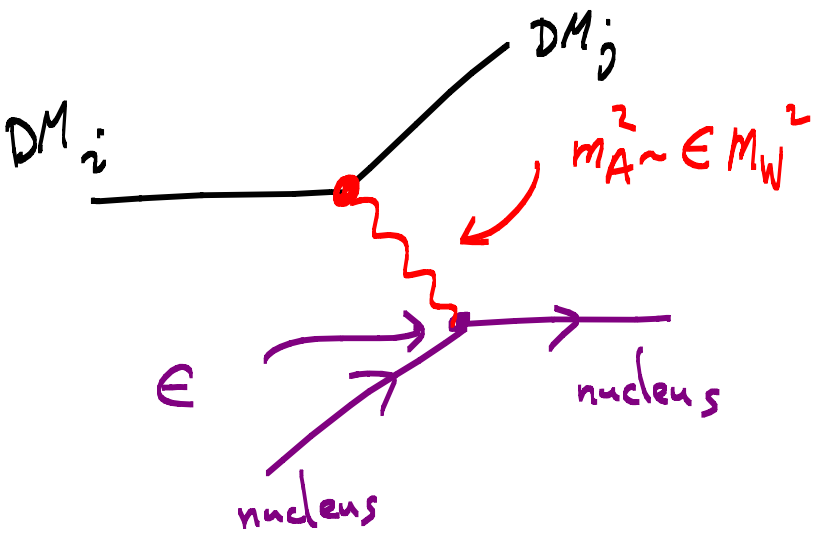


N states

$G_{gauge} \subset SO(N)$

$T^a_{ij} \subset [T^{a\ SO(N)}]_{ij}$ non-vanishing only for $i \neq j$

Direct Detection



- Scattering NECESSARILY INELASTIC
- Amp

$$\sim \epsilon \times \frac{1}{(70\,\text{MeV})^2} \rightsquigarrow \frac{1}{Q^2 + \epsilon M_W^2}$$

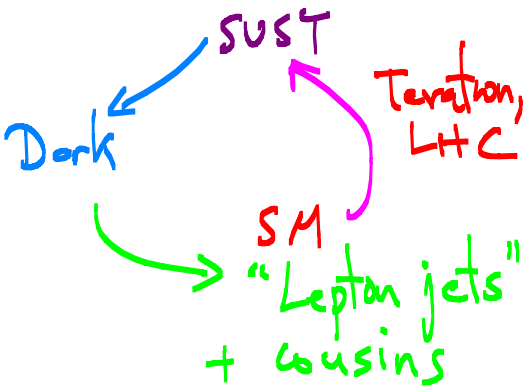
$$\sim \frac{1}{M_W^2} \quad \text{for } \epsilon \gtrsim 10^{-6}!$$

Looking for the Dark Sector

Don't pay ϵ

★ Direct Detection

★



Pay ϵ

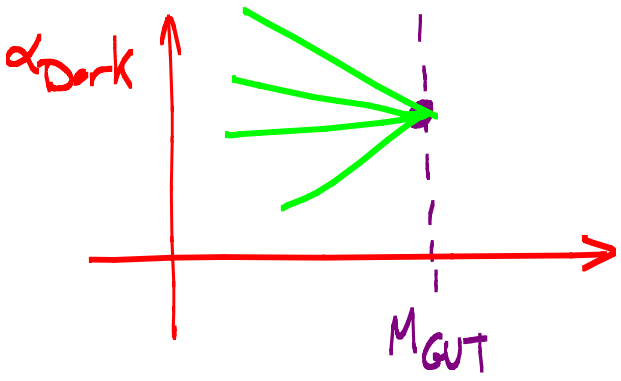
★ But use high-luminosity, low-E e^+e^- data (existing from B-factories!)

★ Lay a Coulomb into it [fixed target expts]

IF such a sector exists + we find it, not merely "very cool".

It could revolutionize fundamental physics by allowing us to study the core concepts we care about @ low-E!

e.g. probe SUSY + SUSY in the Dark Sector! Also suppose we find



Dark Unification @ same M_{GUT}!

[Analogy: Galileos discovery of "solar-system" of Jupiter + moons ...]

THIS SHOULD BE AN EXCITING MEETING!