Importance of Dark Sector Searches

Nima Arkani-Hamed

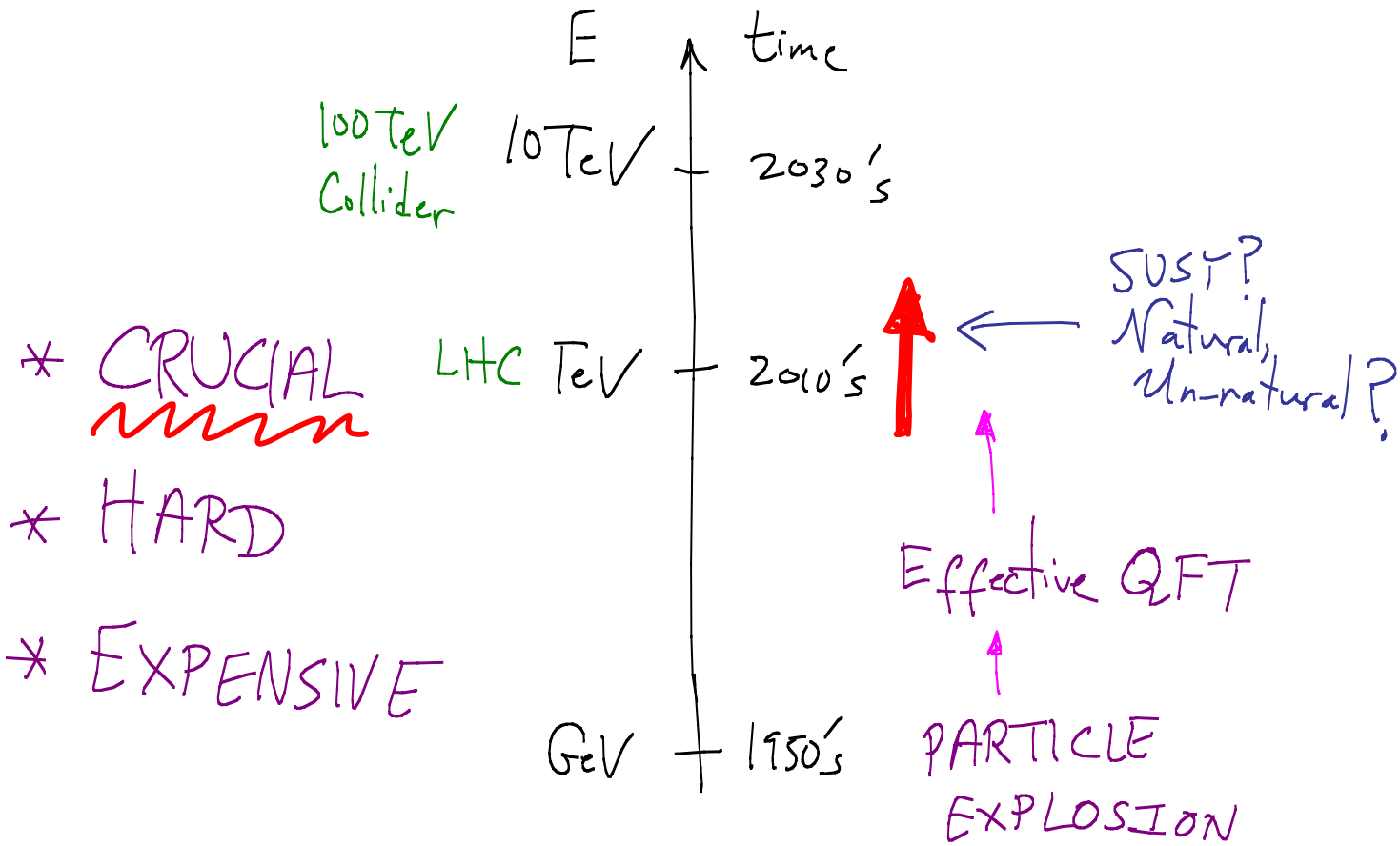
1960's View

NP = New Heavy Particles

More Broadly

NP = New Phenomena

New Principles


E
time
100 TeV Collider
10 TeV
2030's
LHC TeV
2010's
GeV
1950's
SUSY?
Natural,
Un-natural?
Effective QFT
PARTICLE EXPLOSION
* CRUCIAL
* HARD
* EXPENSIVE

* Searches for WIMP Dark Matter complement colliders

[e.g. 1 TeV "Higgsino" directly inaccessible @ LHC; copiously produced @ 100 TeV collider]

* Scores of experiments indirectly probe collider accessible higher scales:

  * EDM's [10 TeV scale]
  * Q/L flavor [100 TeV scale]

Axions

* Not just sol'n of strong CP....
* More importantly: First confirmation of DYNAMICAL COUPLING "CONSTANTS"
* Crucial feature of Unification [+ reason for ubiquity of axions in string theory]

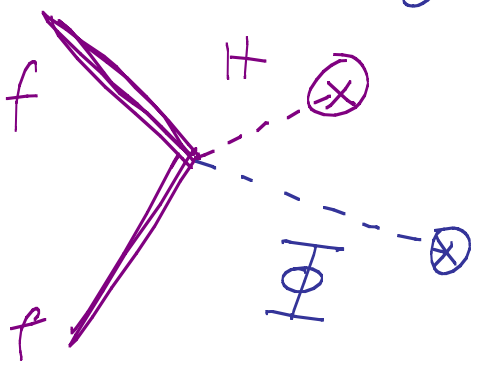
* There are Exciting, New ideas for probing $f_A \sim M_{GUT}$

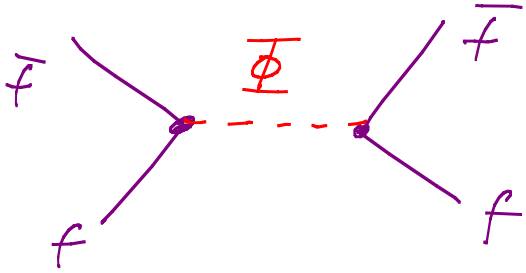
* Superradiance of Rotating BH's — Arvanitaki, Dubovsky ⋮

* Time varying EDM's + NMR — Graham, Rajendran ⋮

MORE LIKE THIS NEEDED!

* Short-range gravity experiments can also probe light "moduli"

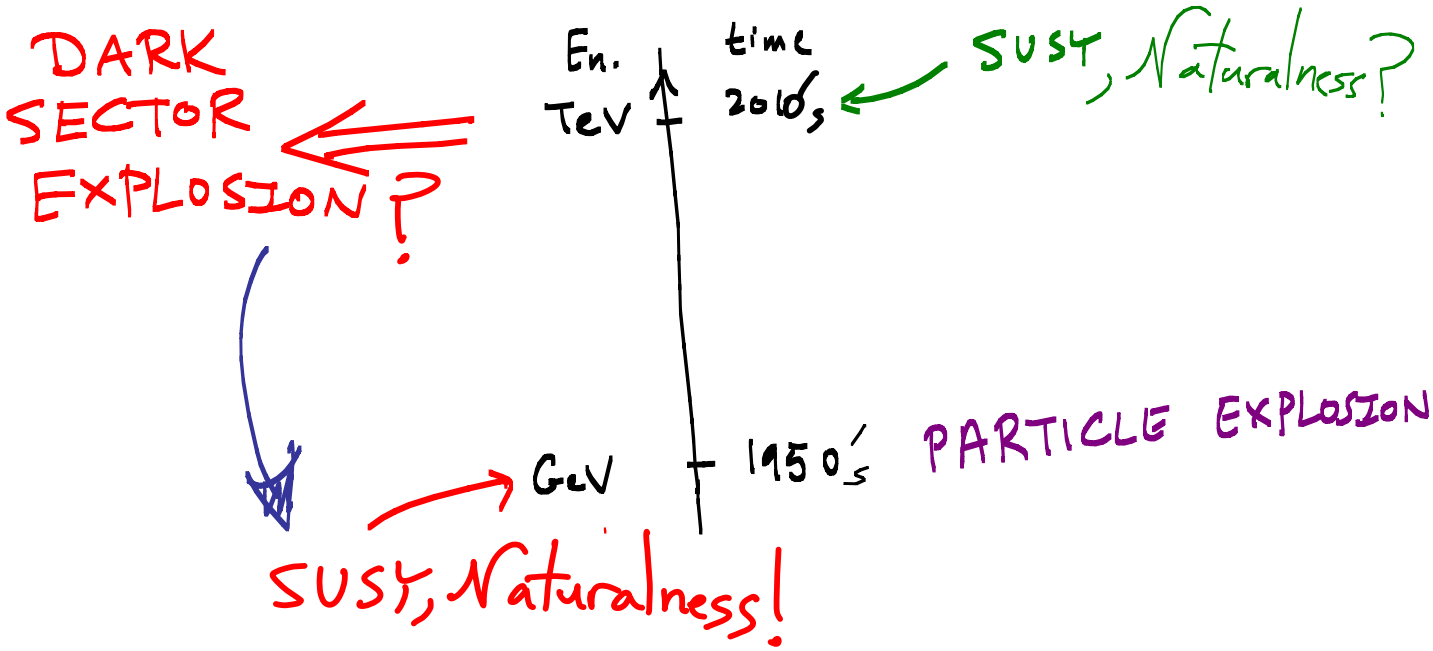




→ Direct indication of DYNAMICAL COUPLING "CONSTANTS"

(Light) Dark Sectors:

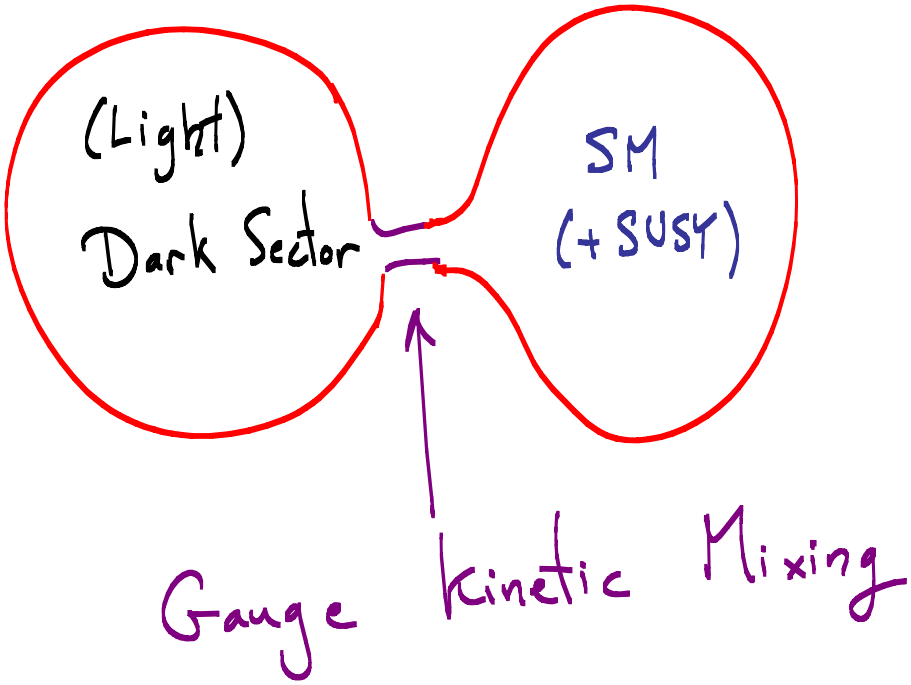
Robust, New Frontier in Fundamental Physics



NO GUARANTEES

BUT, if it's there: FUTURE OF HEP

* NOT HARD * NOT EXPENSIVE


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

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

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

Leading couplings are dimensionless,
[otherwise really tiny]

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

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

$\downarrow$ After EWSB

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

$\uparrow$ Still dimless, dominates @ low E.

Other candidate:

$$\epsilon \, h^* h \, \varphi^*_{dark} \varphi_{dark}$$

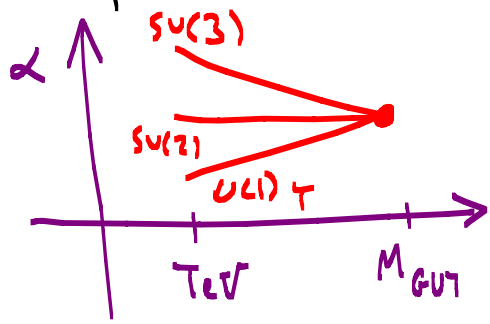
$\downarrow$ After EWSB

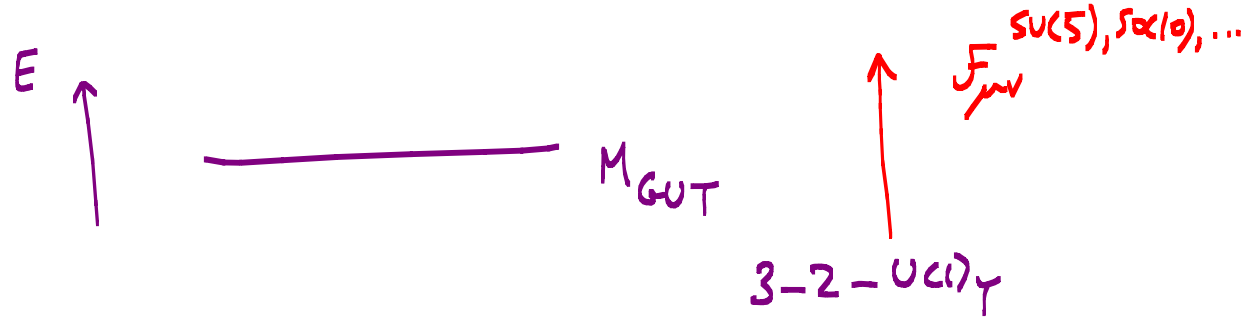
$$\epsilon \, \varphi^*_{dark} \varphi_{dark} \, \frac{\bar{\psi}\psi \, m_\psi}{M_W^2}$$

Suppressed @ low-E

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

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

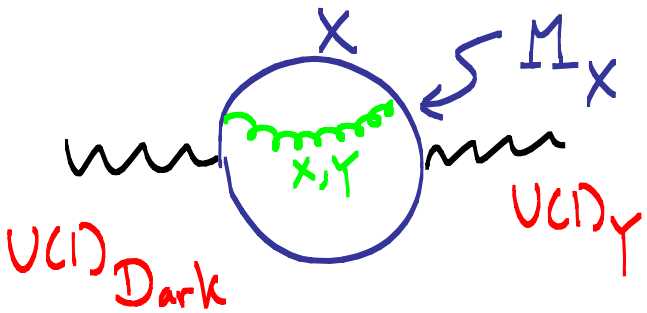




Above GUT scale, can't have mixing

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

But mixing generated radiatively after GUT is broken!



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

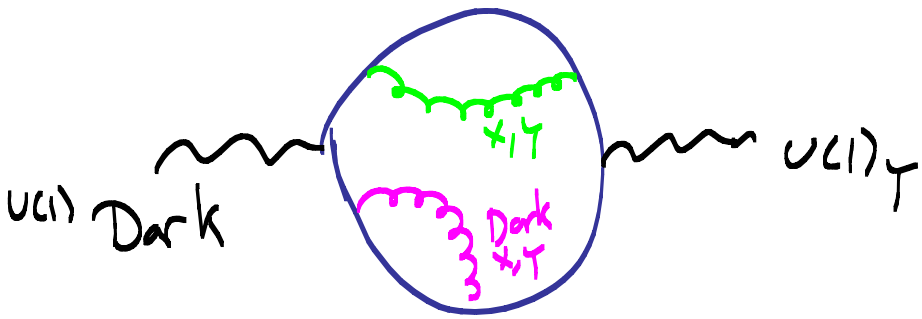
$$\sim 10^{-5} \rightarrow 10^{-3} \text{ naturally}$$

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

Low energies

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

[Could even have dark GUT:



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

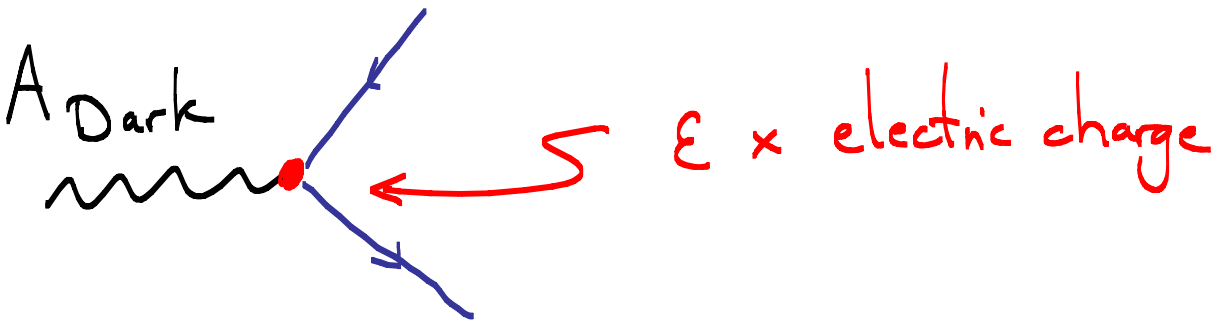
$\sim$ as small as 10^{-7} perhaps]

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

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

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

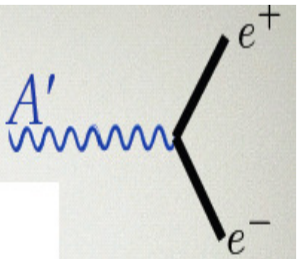
$$\Longrightarrow \quad j_{\text{EM}}^\mu \left[A_\mu^{\text{EM}} + \varepsilon A_\mu^{\text{Dark}} \right]$$

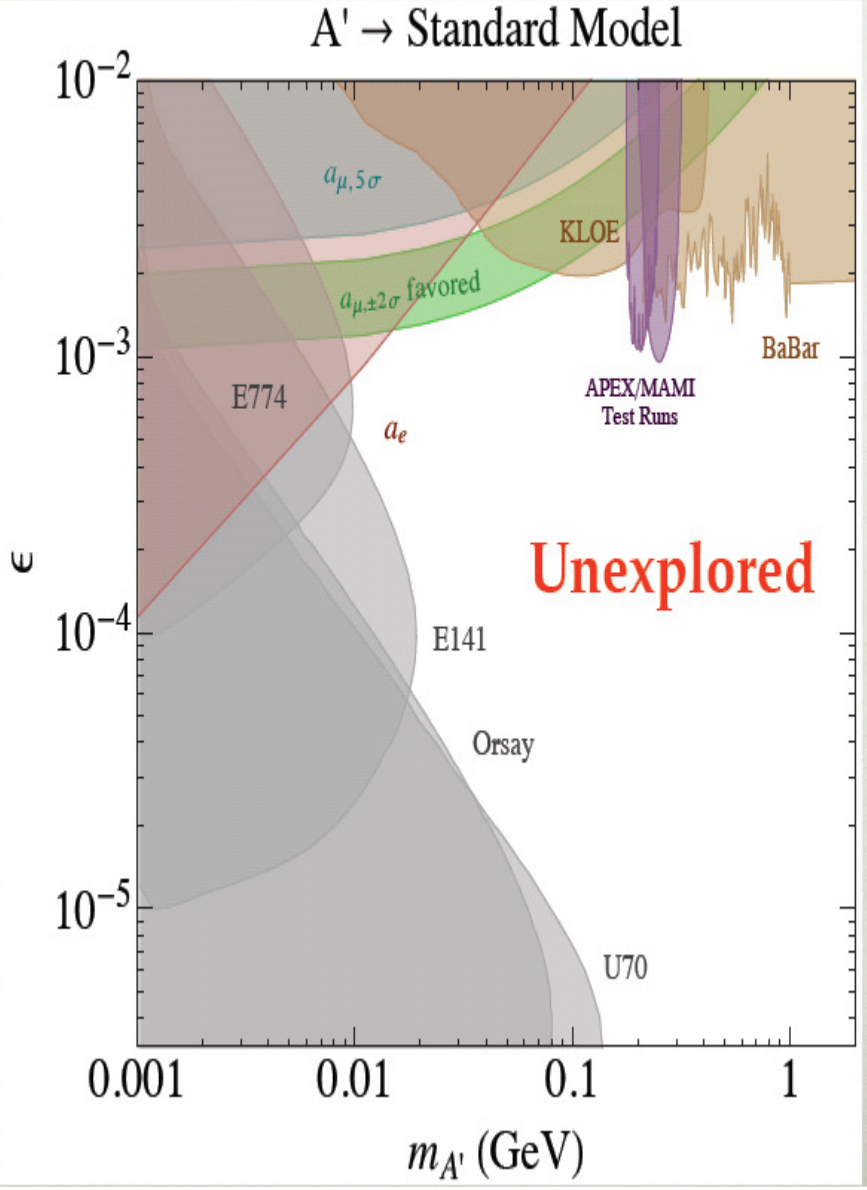


Amazing that $\varepsilon \sim 10^{-3}$, $m_{Dark} \sim$ GeV is not ruled out!

The Territory

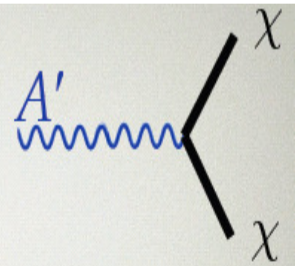
(A′ Electron/Muon Decays)

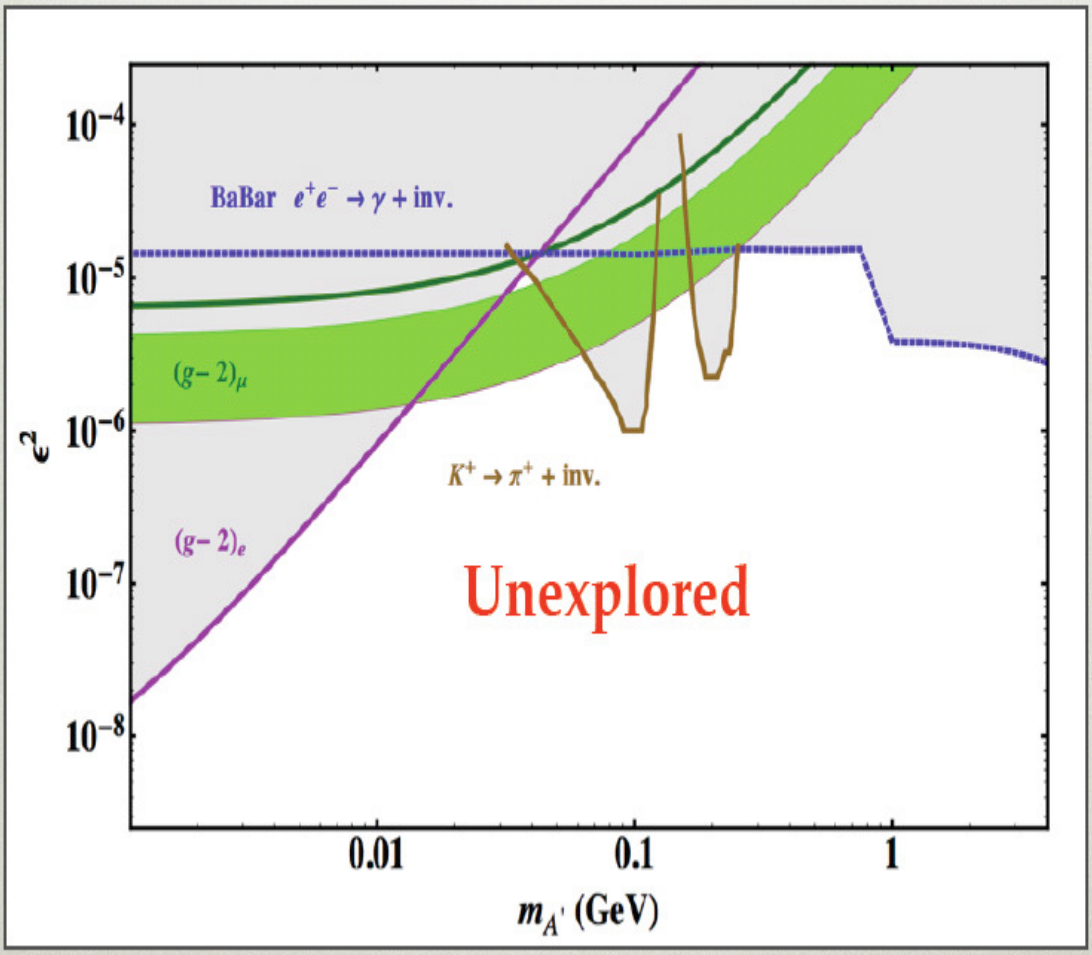




The Territory

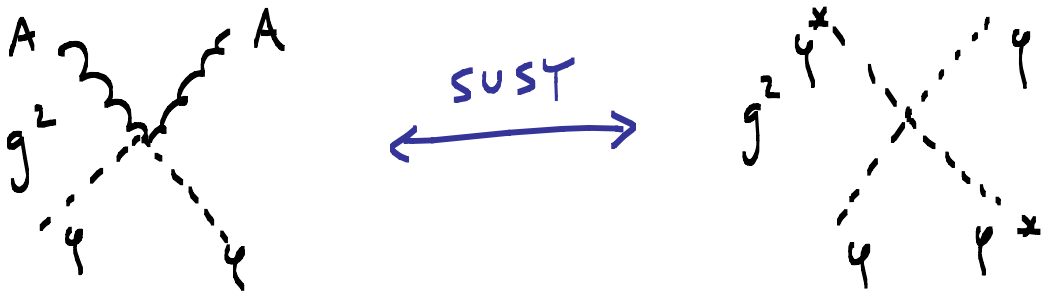
(A′ invisible "dark matter" Decays)



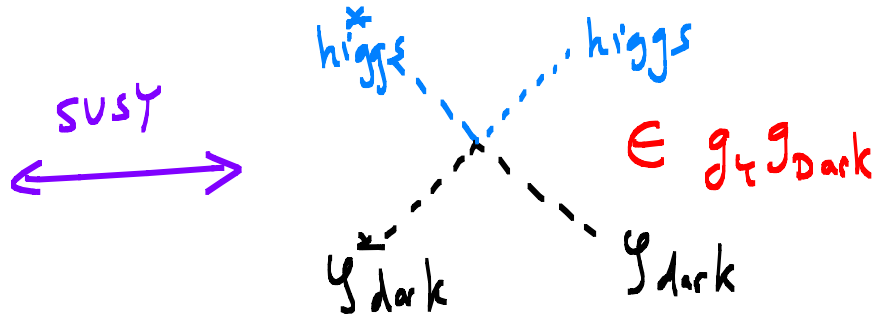


(Izaguirre, Krnjaic, PS, Toro)

Radiative Origin of Dark Scale

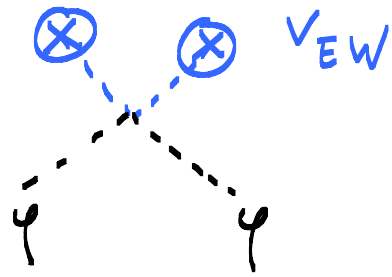


$\epsilon \, F^{Dark}_{\mu\nu} F^{\mu\nu}_{Y}$



$\epsilon \, g_Y g_{Dark}$

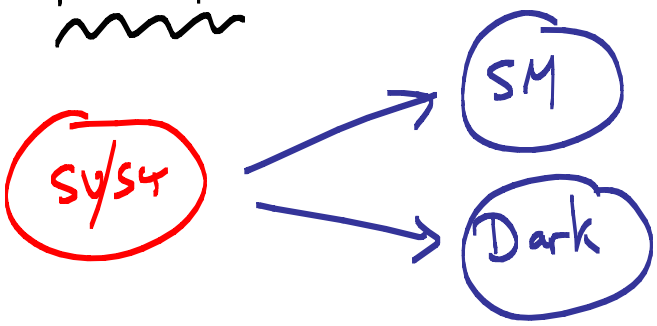
$\Longrightarrow$ a minimal contribution to dark scalar masses



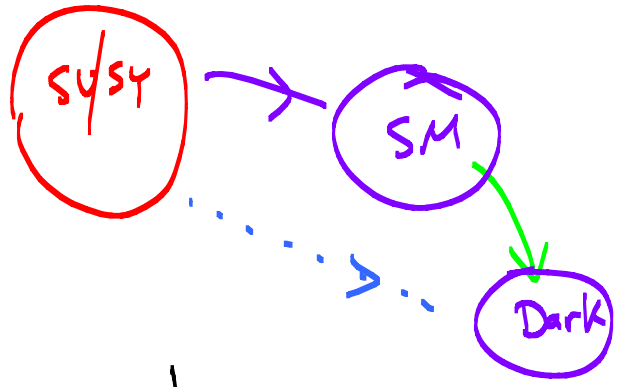
$m_\varphi^2 \sim \epsilon\, m_W^2$; $\epsilon \sim \alpha^2$ most naturally,

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

NOT



Essentially anything else: e.g.



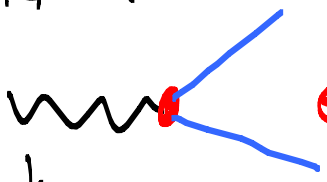
[Familiar from Gauge Mediated SUSY]

★ Note: all that is needed is for

$$G_{Dark} = \underbrace{G_{Non\text{-}Ab.}}_{\text{Could be present}} \times U(1)'s$$

kin. mix with $U(1)_Y$

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



$\epsilon^a \times$ electric charge

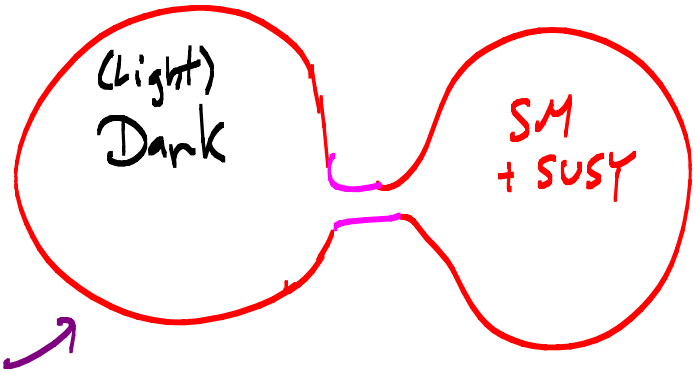
Robustness

* Mixing can come from <u>any</u> <u>scale</u>

* Dark sector can be simple or complicated → so long as it has U(1)'s.

Look For Same Signatures

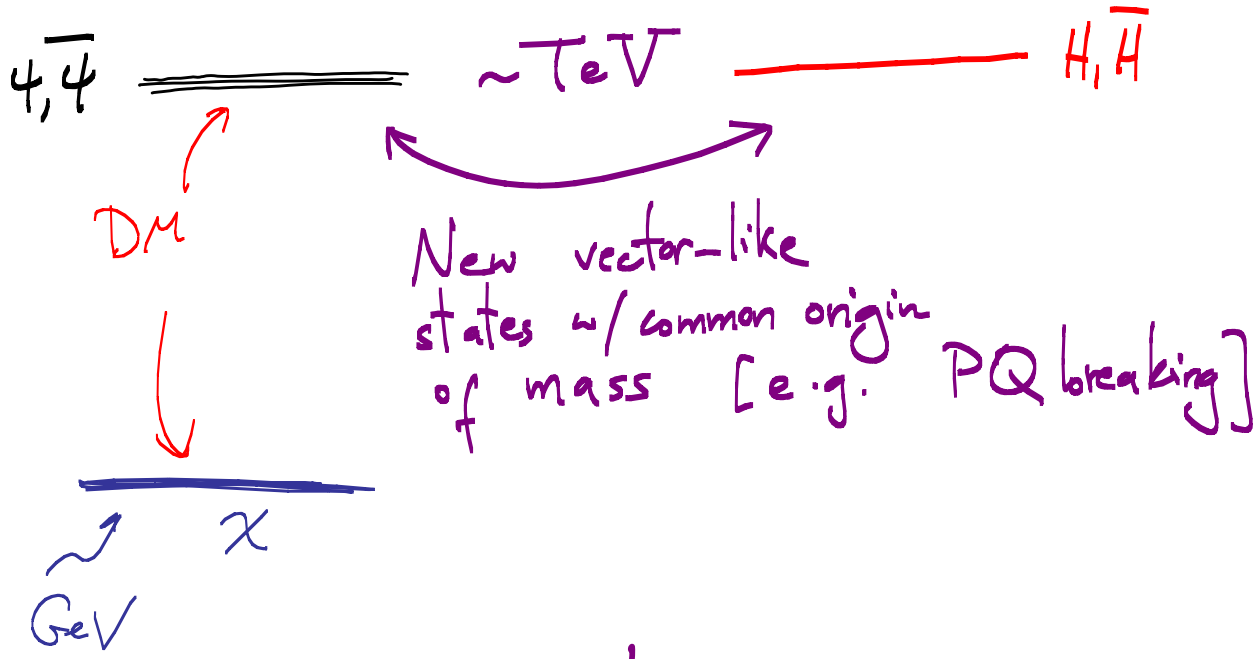
Dark Forces + Dark Matter



Usual LSP is unstable!

True LSP is here!

$\epsilon \gtrsim 10^{-7}$: Dark Sector + U_s thermalized at Dark scale $\Longrightarrow$ tiny true LSP abundance



* Dark photons can decay back to SM
* They can decay to ~ GeV DM in Dark Sector

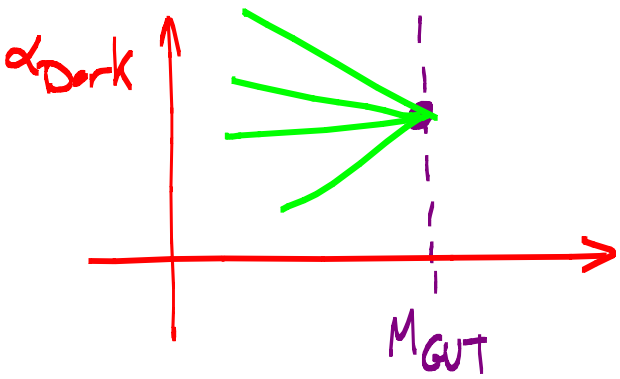
* Early motivation for studying dark forces came from certain models for DM.

* Those models aren't especially relevant to discussion now — they merely shone a light on this important new experimental frontier.

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

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

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



Dark Unification @ same M_{GUT}!

Naturalness

* There may be some degree of EWSB tuning, for anthropic reasons
* No such anthropic reason in Dark Sector!
* Better be perfectly natural — window into physics free of "environmental pressure"

Finding Dark Sectors would be analogous to Galileo's discovery of a new "solar system" in the moons of Jupiter

Possibility Of

HUGE PAYOFF

on

SMALL INVESTMENT

IT'S THE AMERICAN WAY!