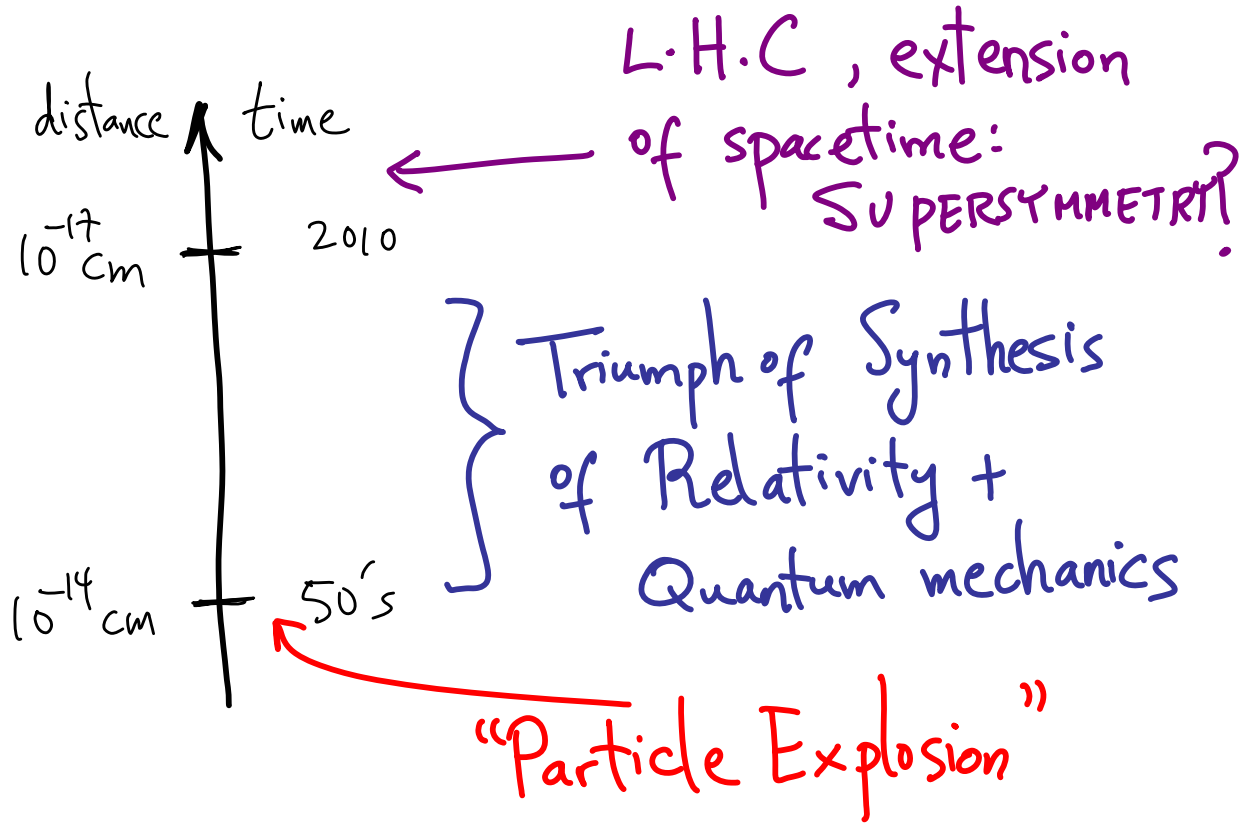
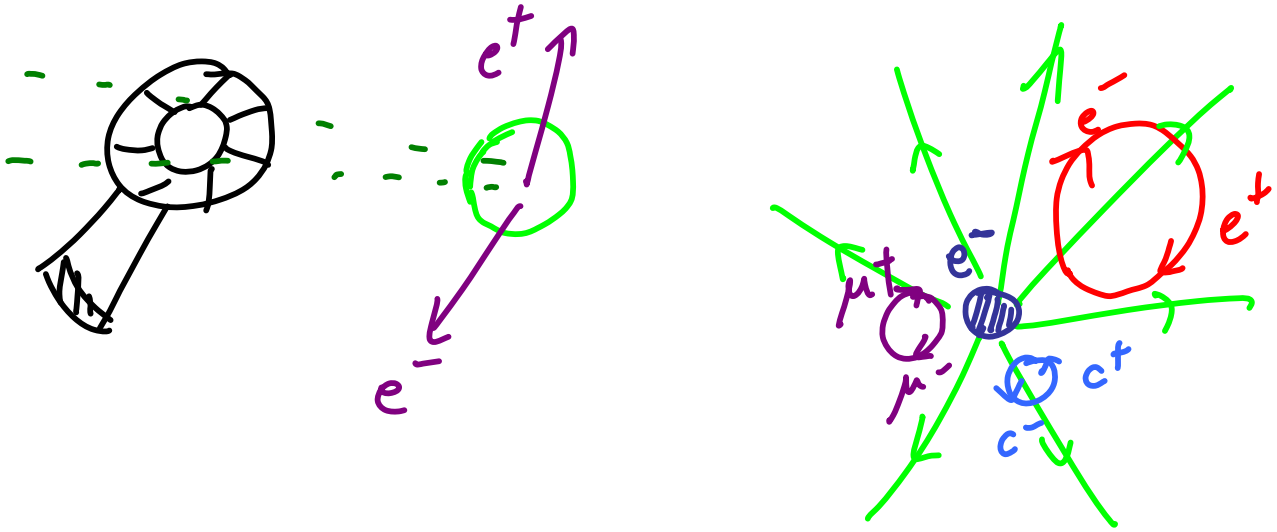
Exploring the Dark Universe

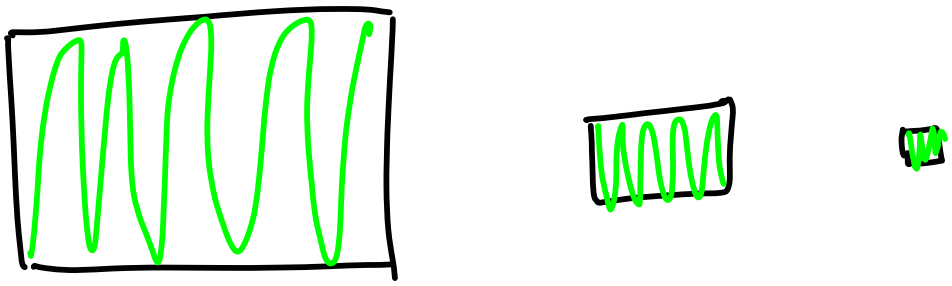
Nima Arkani-Hamed
I.A.S


distance
time
10^{-17} cm
2010
10^{-14} cm
50's
L.H.C, extension of spacetime: SUPERSYMMETRY?
Triumph of Synthesis of Relativity + Quantum mechanics
"Particle Explosion"

"Vacuum" is Exciting!



Too Exciting!!

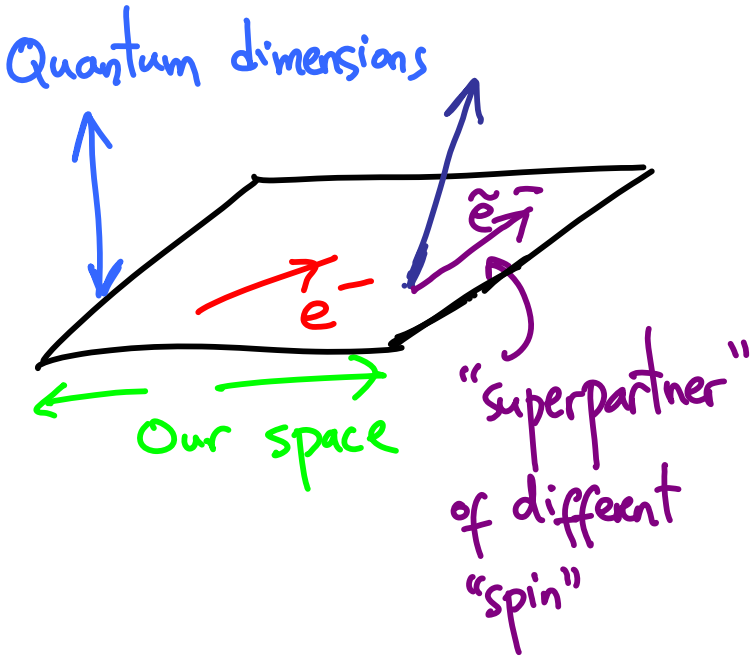


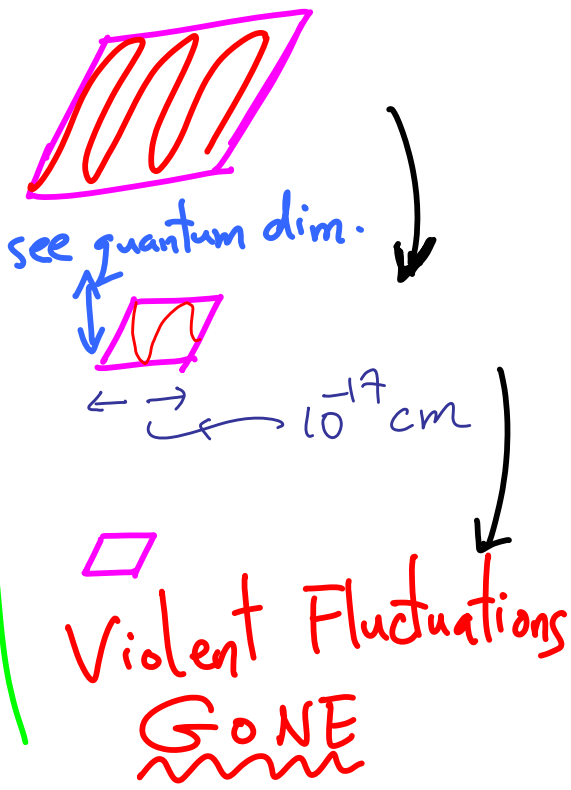
WHAT TAMES VIOLENT QUANTUM FLUCTUATIONS OF VACUUM?

WHY IS THERE A MACROSCOPIC WORLD?

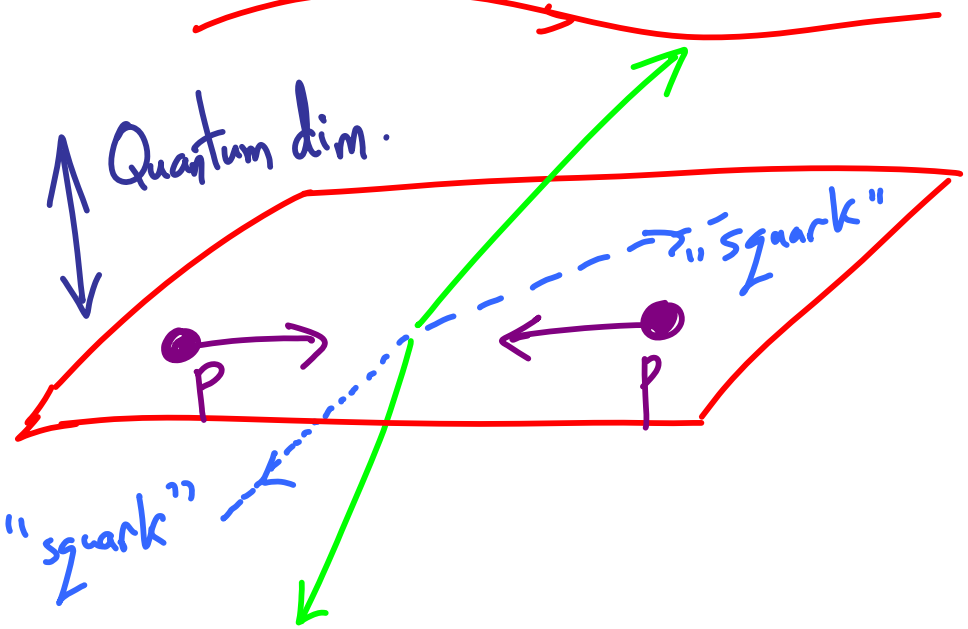
$\Rightarrow$ NEED AN EXTENSION OF OUR USUAL NOTIONS OF SPACETIME. BEST BET:

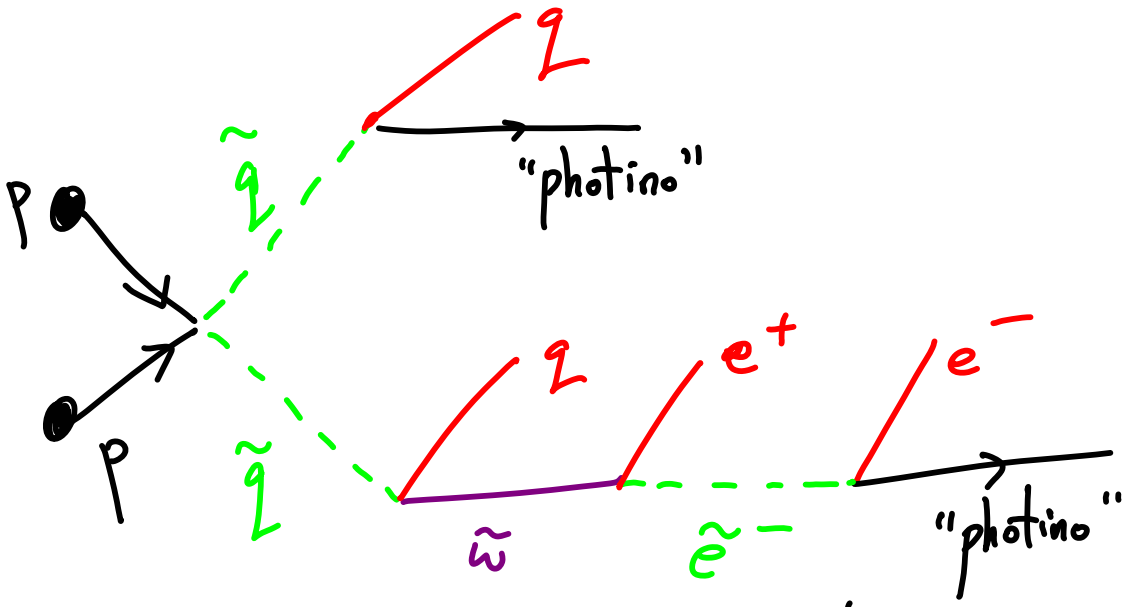
"SUPERSYMMETRY" — new "quantum dimensions".





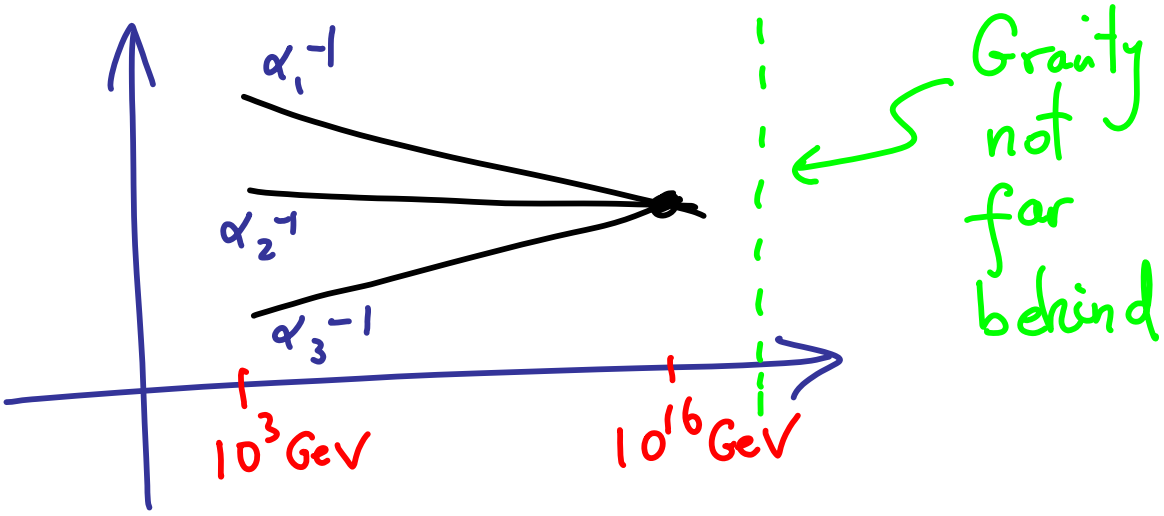
SUSY @ LHC



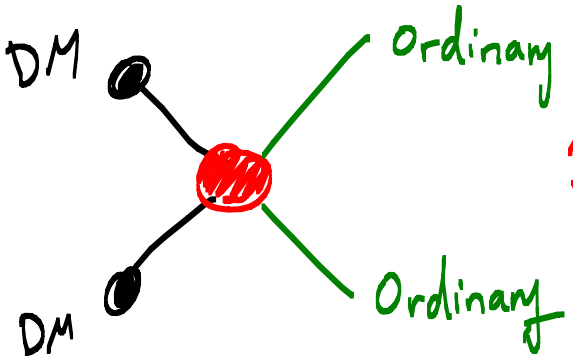


"Photinos" : very feebly interacting, escape detectors!

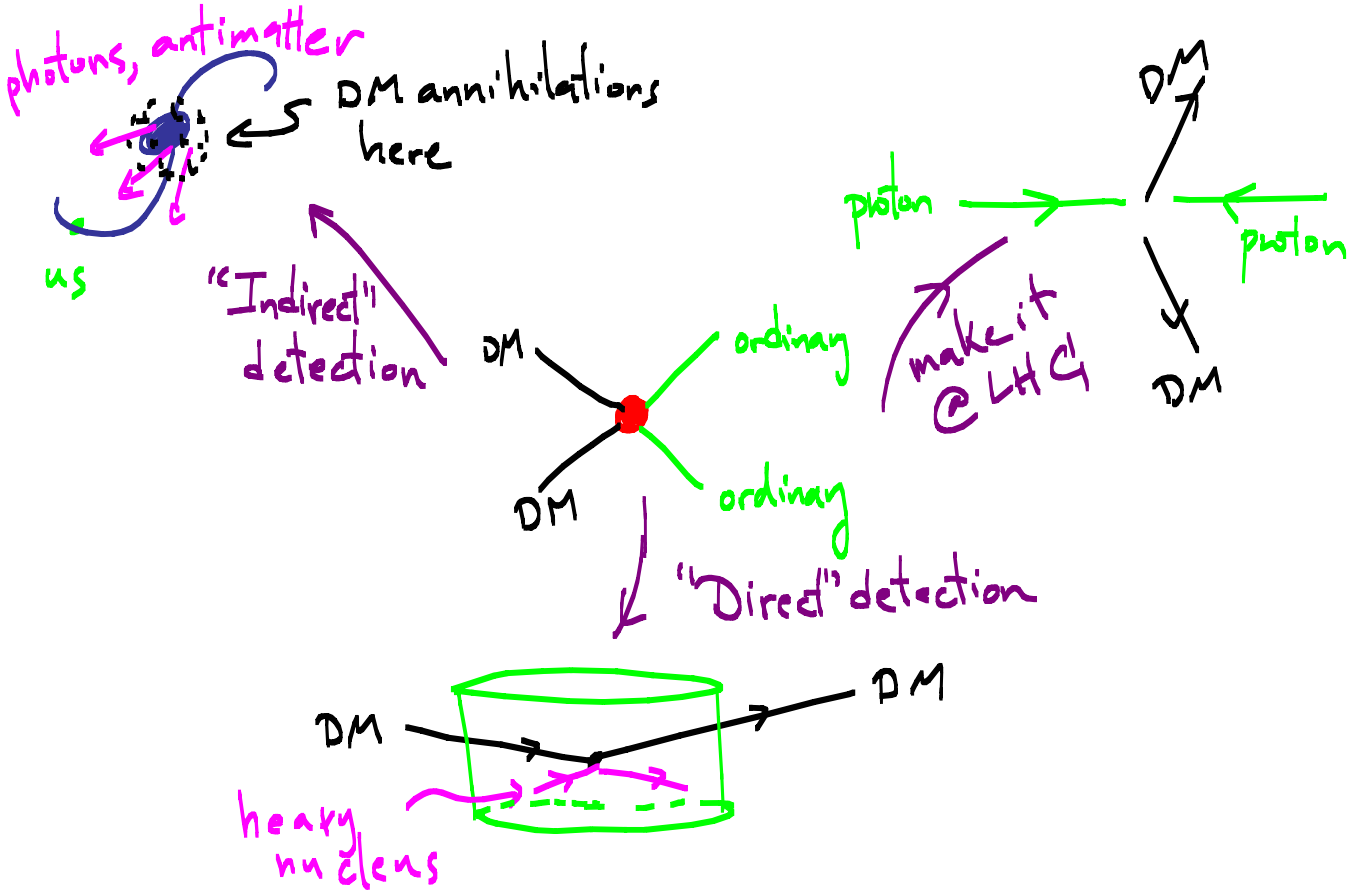
SUSY Unification

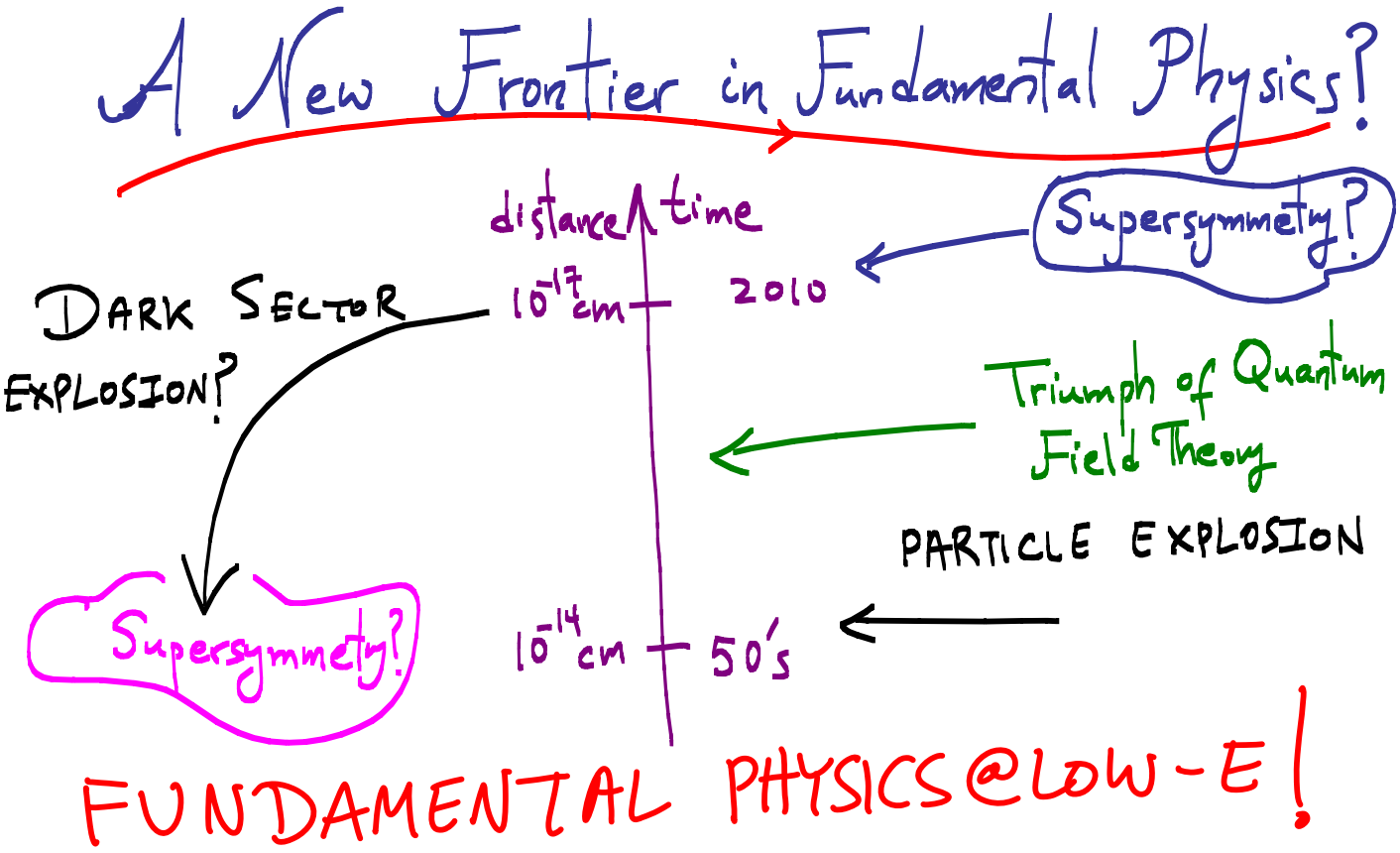


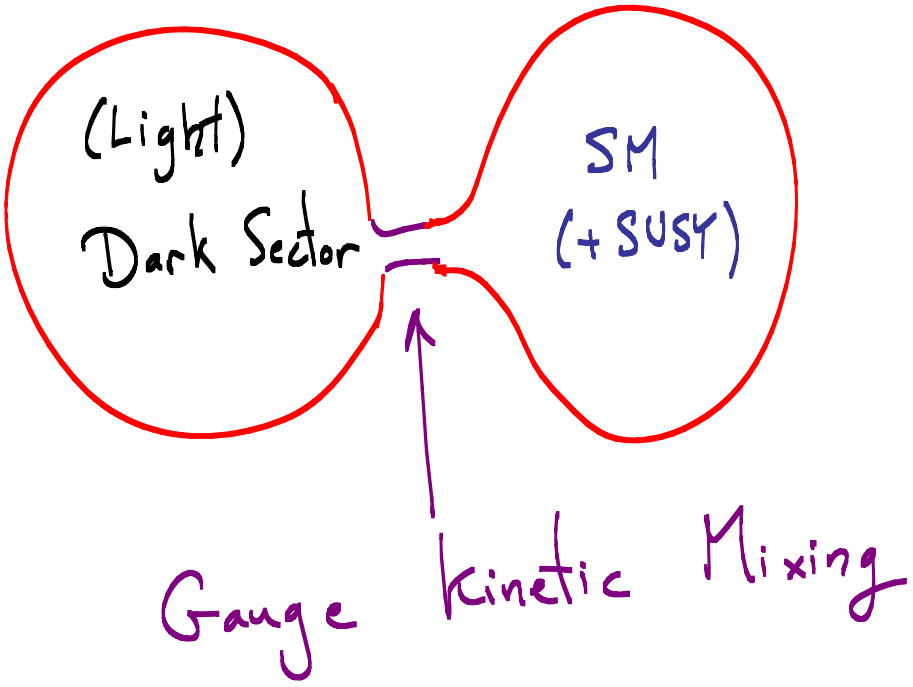
"WIMP Miracle"

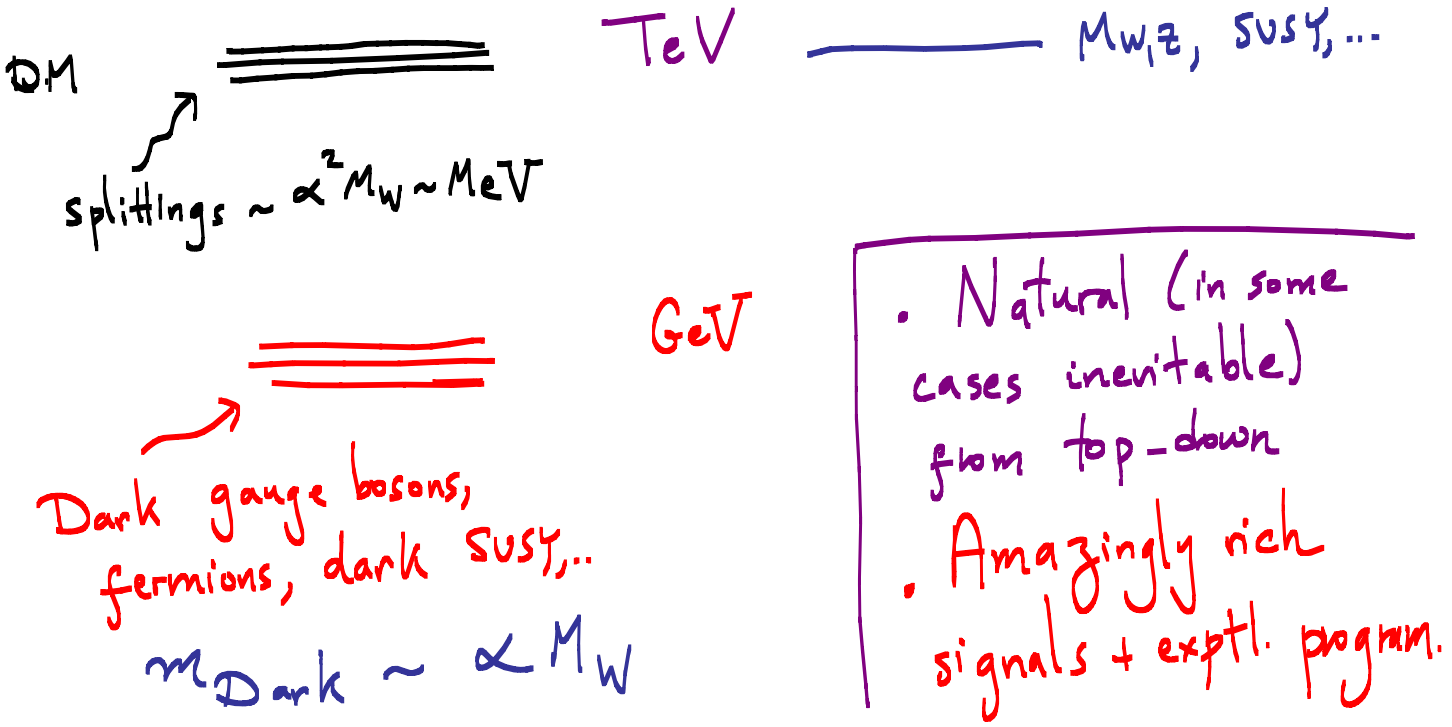


↕ needed range $\sim 10^{-17}$ cm,
exactly what will be
probed @ the L·H·C.!
["Dark Matter Factory"]




A New Frontier in Fundamental Physics!
distance
time
Supersymmetry?
2010
10^{-17} cm
DARK SECTOR EXPLOSION?
Triumph of Quantum Field Theory
PARTICLE EXPLOSION
Supersymmetry?
10^{-14} cm
50's
FUNDAMENTAL PHYSICS @ LOW-E!


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


DM
TeV
$M_{W,Z}$, susy, ...
splittings ~ $\alpha^2 M_W \sim$ MeV
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.

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

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

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:

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

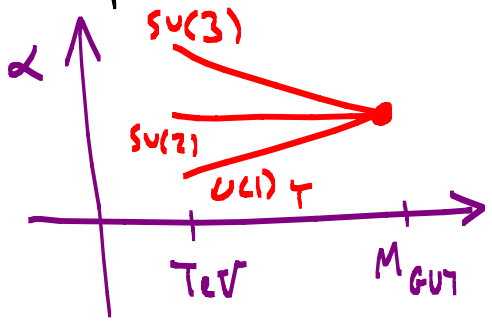
↓ After EWSB

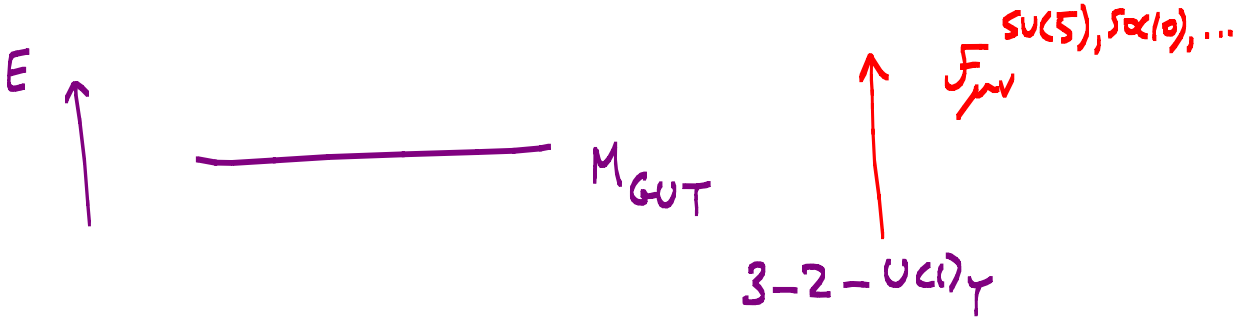
$\epsilon \; \varphi^{*}_{dark} \varphi_{dark} \; \frac{\bar{\psi}\psi \, m_{\psi}}{M_W^2}$

↑ Suppressed @ low-E

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

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

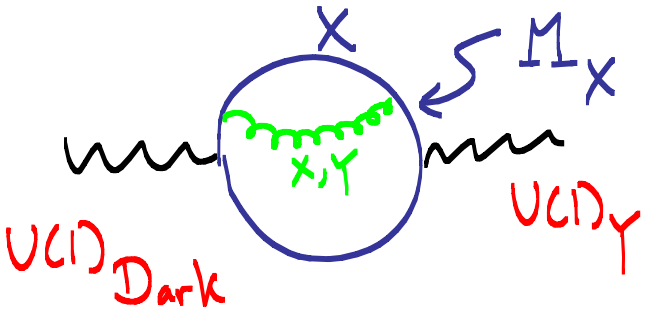




Above GUT scale, can't have mixing

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

But mixing generated radiatively after GUT is broken!



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

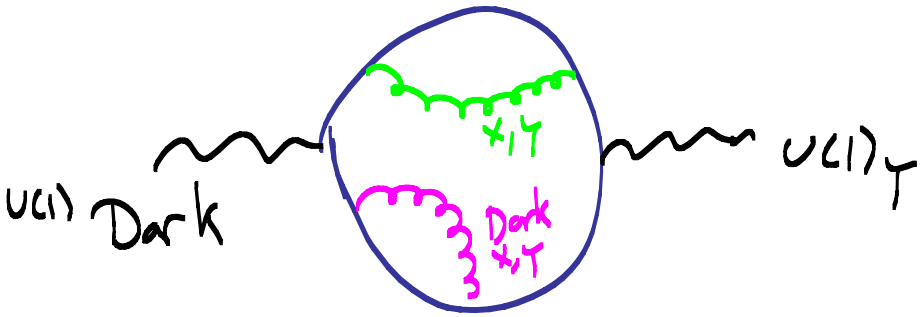
$$\sim 10^{-5} \rightarrow 10^{-3} \text{ naturally}$$

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

Low energies

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

[Could even have dark GUT:



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

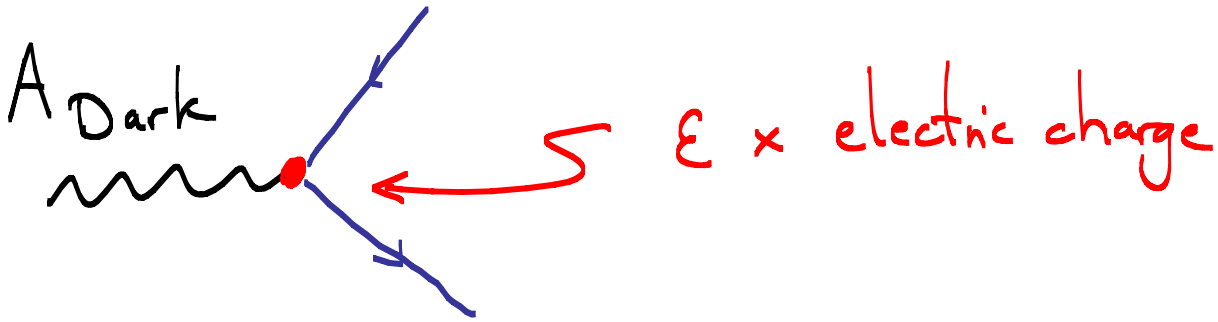
$\sim$ as small as 10^{-7} perhaps]

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

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

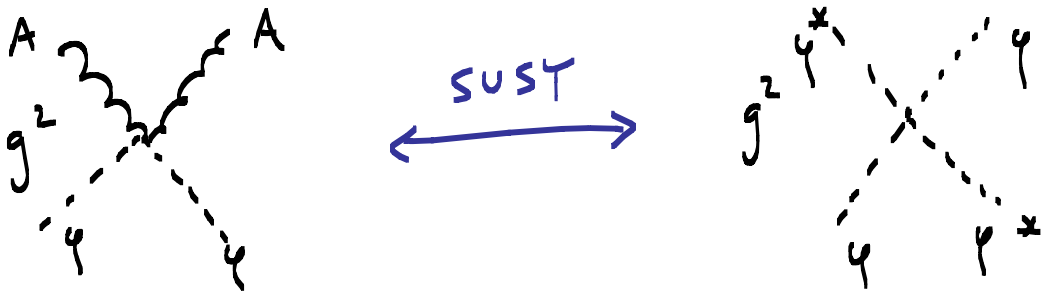
$A_\mu^{EM} \longrightarrow A_\mu^{EM} + \varepsilon A_\mu^{\text{Dark}}$ eliminates mixing.

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

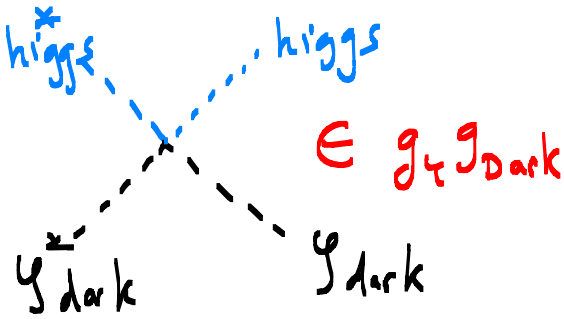


Amazing that $\varepsilon \sim 10^{-3}$, $m_{Dark} \sim 100$'s MeV not ruled out!

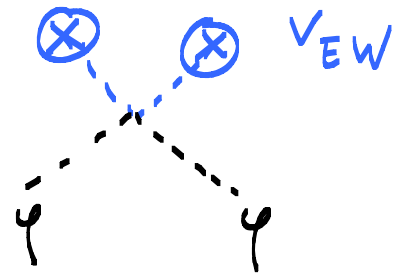
Radiative Origin of Dark Scale



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

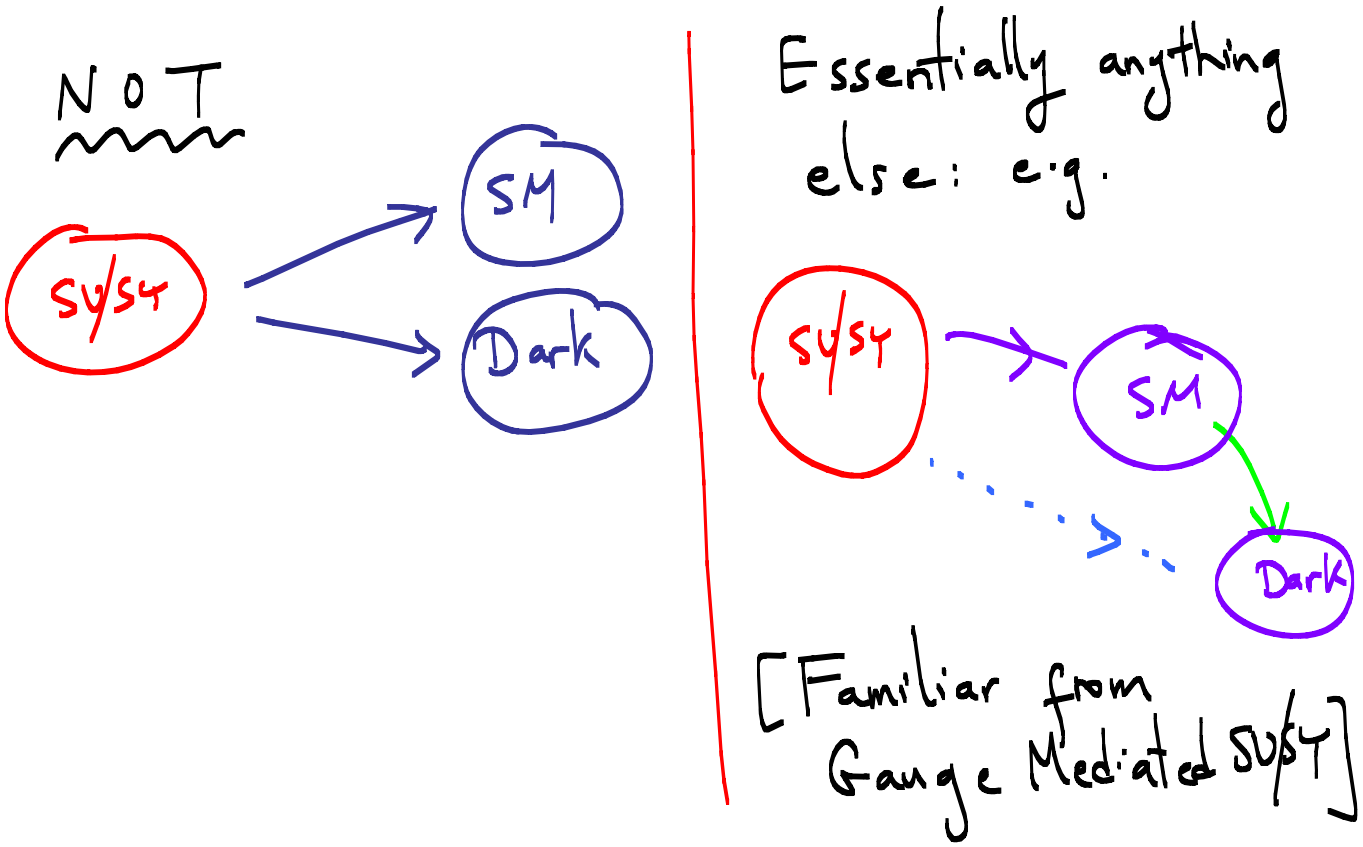


$\Longrightarrow$ a minimal contribution to dark scalar masses



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

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


NOT
SUSY
SM
Dark
Essentially anything else: e.g.
SUSY
SM
Dark
[Familiar from Gauge Mediated SUSY]

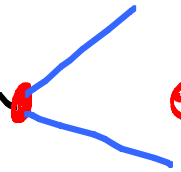
★ Note: all that is needed is for

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

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

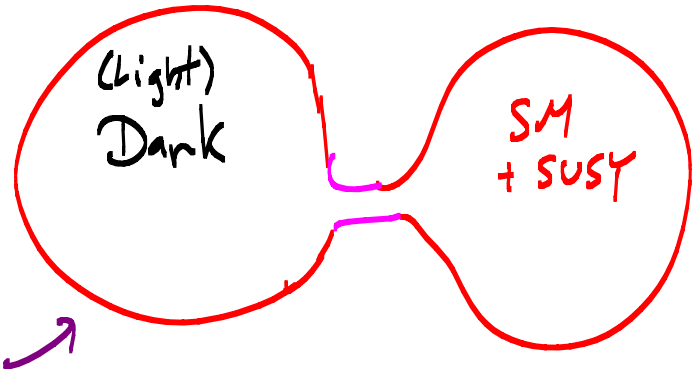
$U(1)'s$: kin. mix with $U(1)_Y$

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



$\epsilon^a \times$ electric charge

Dark Forces + Dark Matter



The LSP is here!

Usual LSP is unstable!

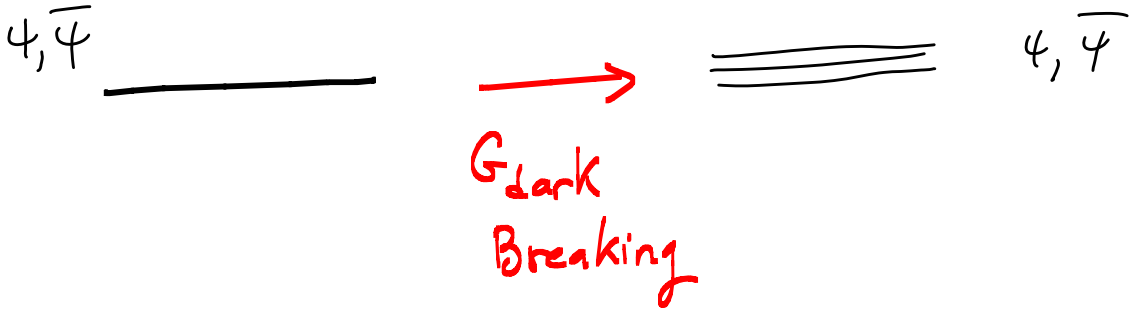
$\epsilon \gtrsim 10^{-4}$: Dark Sector + U_S thermalized at Dark scale $\Rightarrow$ tiny the LSP abundance

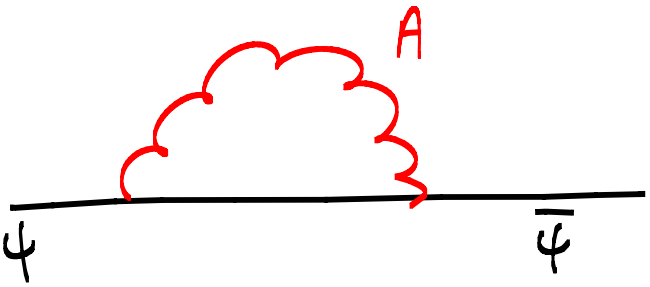
New vector-like states w/ common origin of mass [e.g. PQ breaking]

U_s

Dark

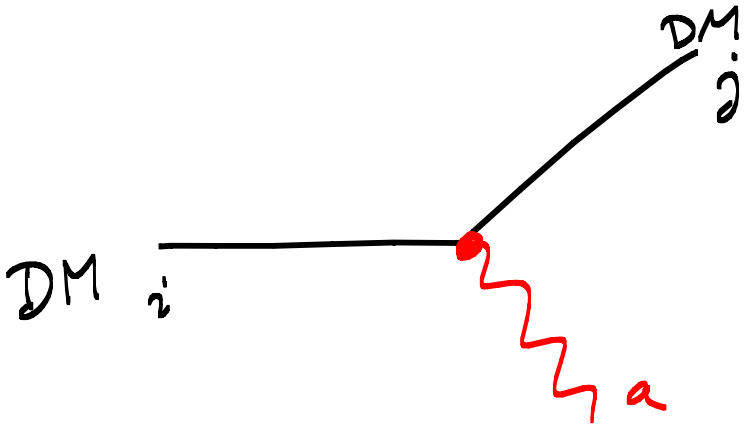
Usual "WIMP Miracle" holds





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

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



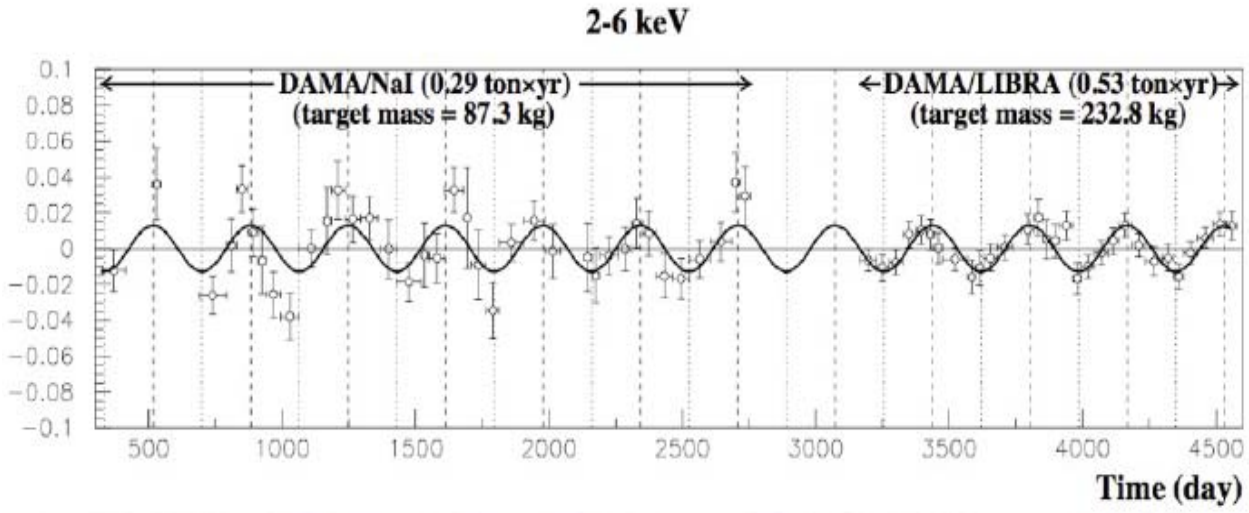
N states

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

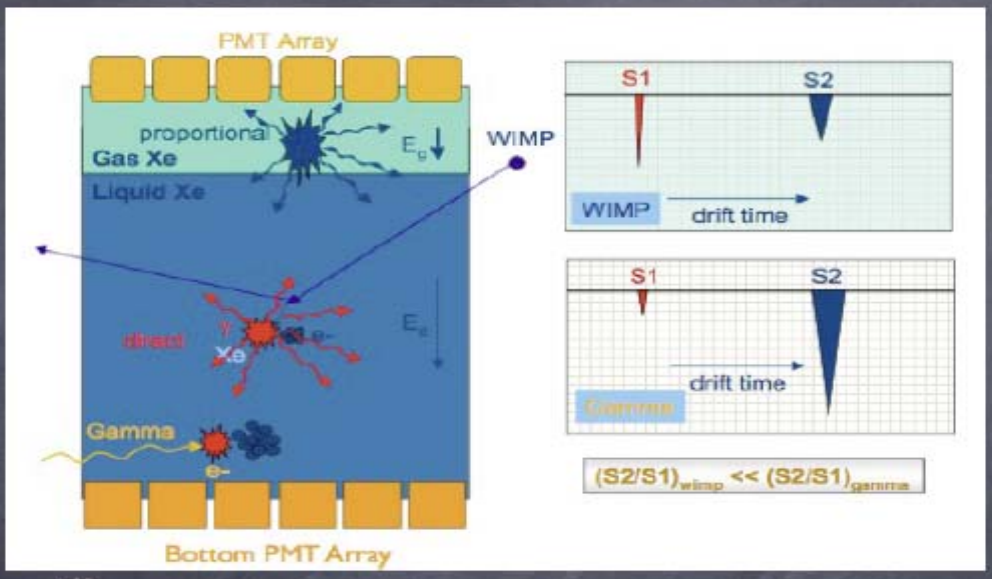
$T^a_{ij} \subset [T^{a\ SO(N)}]_{ij}$ non-vanishing only for $i \neq j$

THE STORY BEGINS IN A DEEP UNDERGROUND CAVERN IN ITALY....

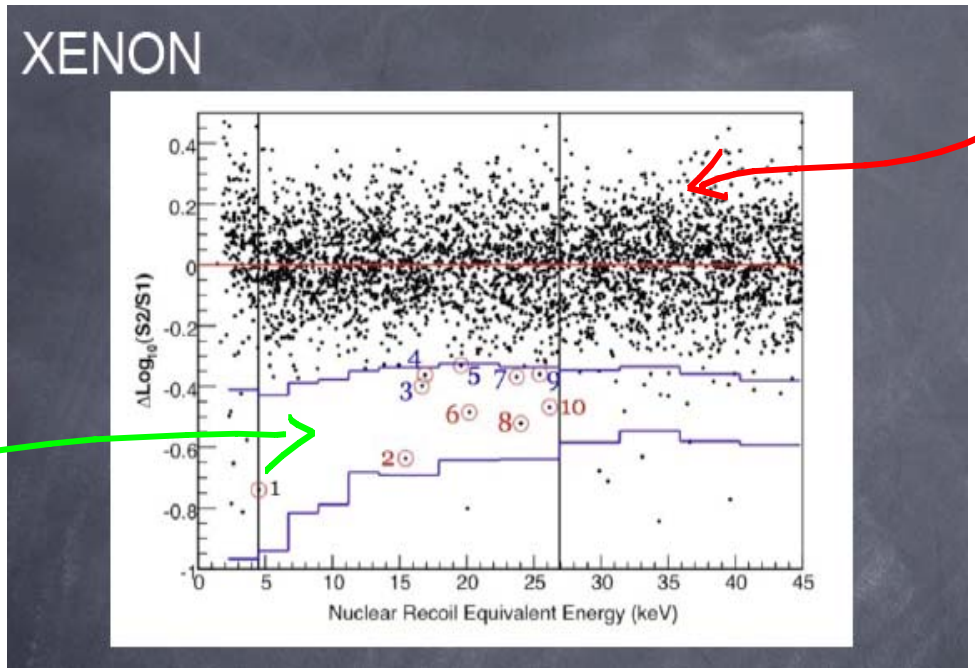
DAMA experiment



XENON

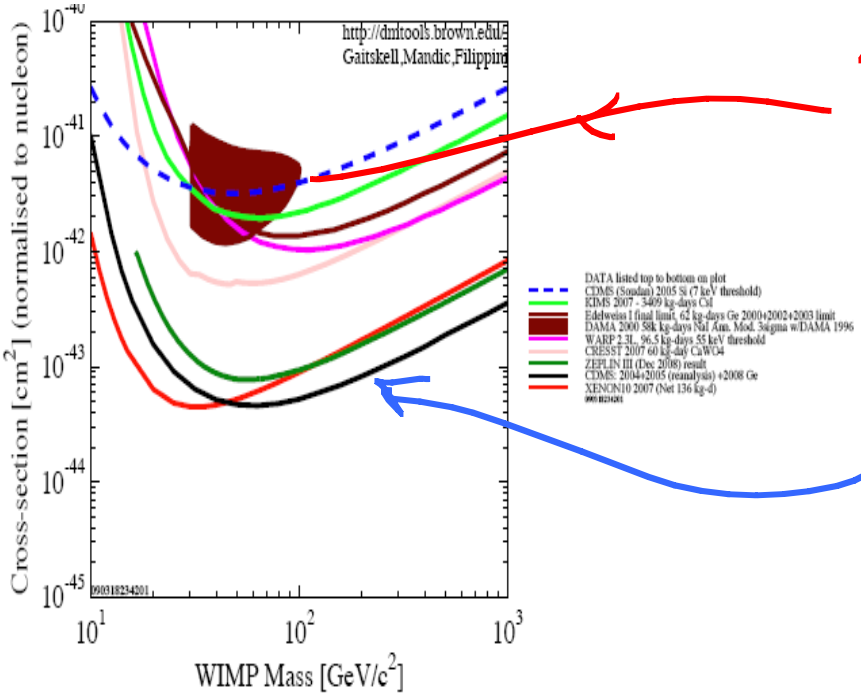


Distinguish events by ratio of scintillation light compared with ionization



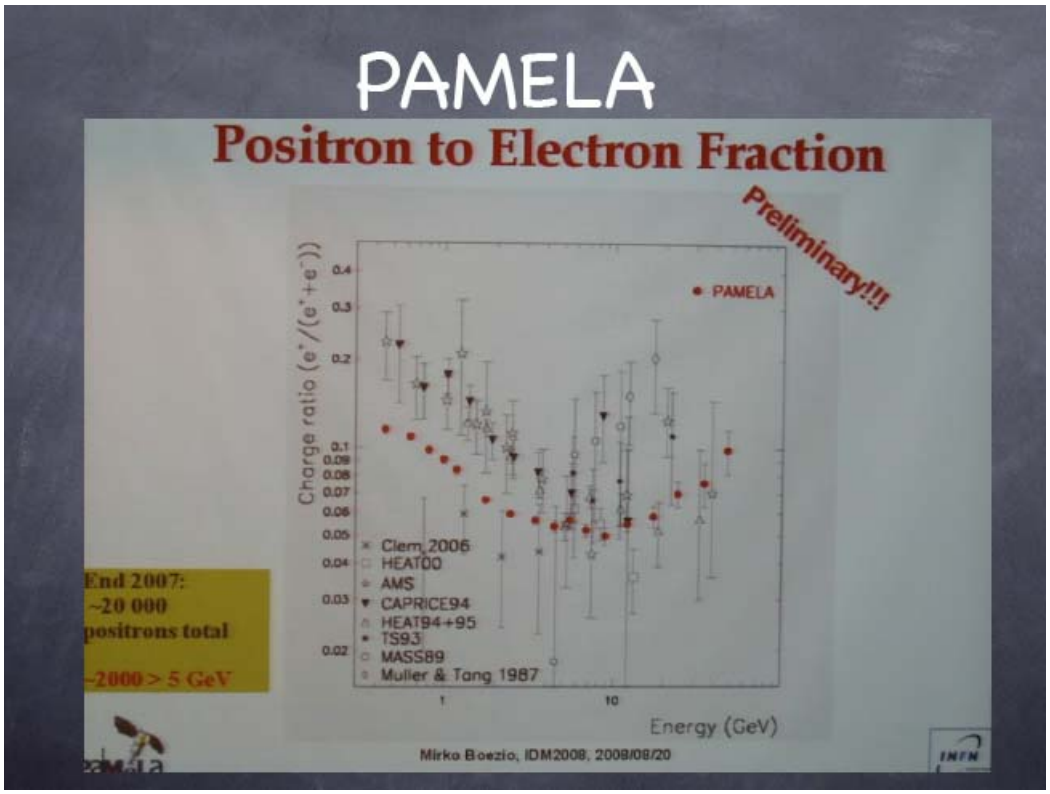
Background

Signal region

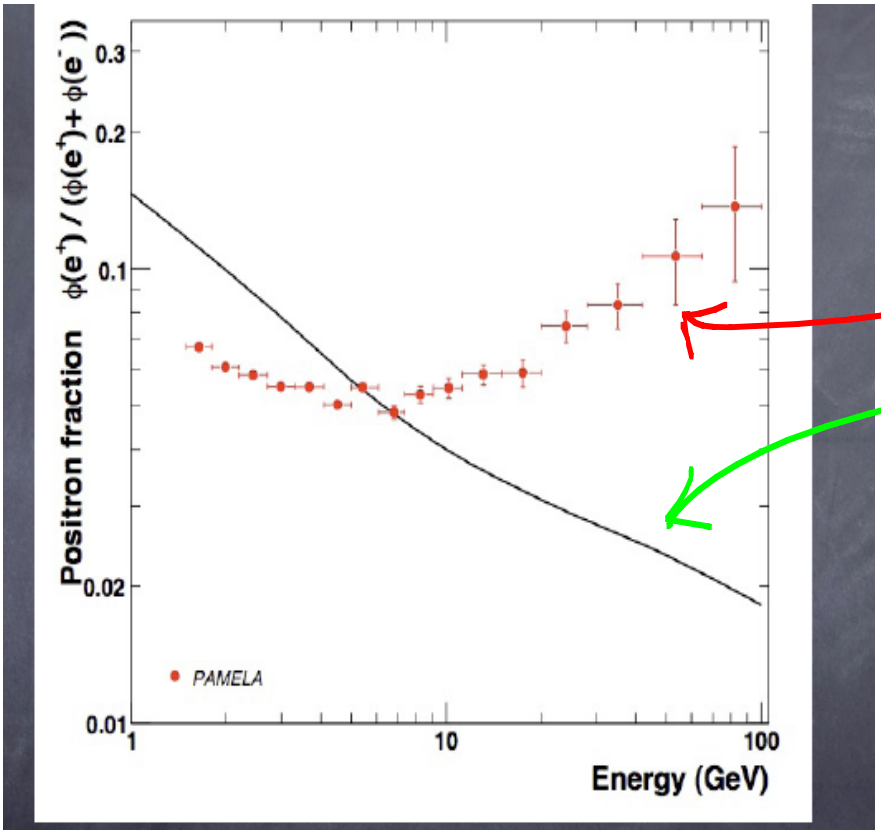


Region for DAMA

excluded by 2–3 orders of magnitude from many other experiments!

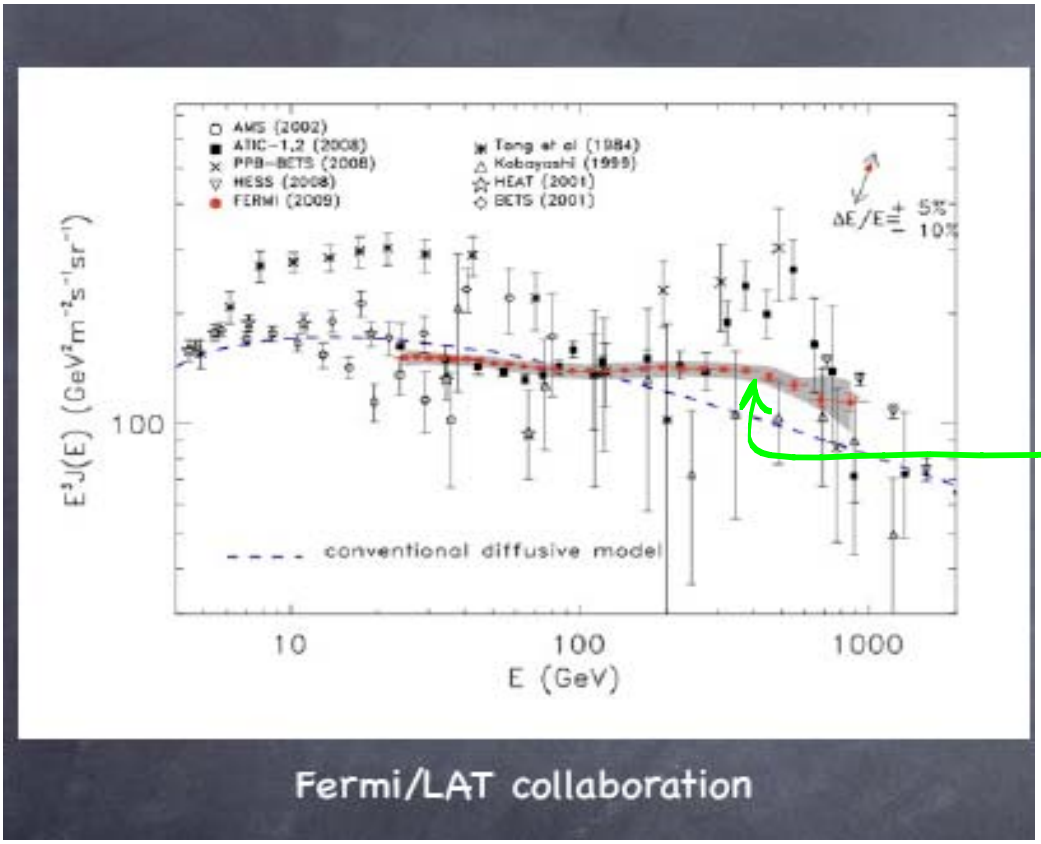


August '08:
Italian
Satellite
reports
puzzling
excess
of positrons.



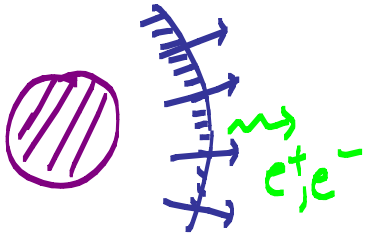
Observation

Expectation

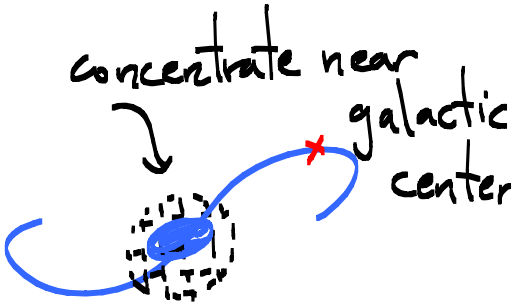


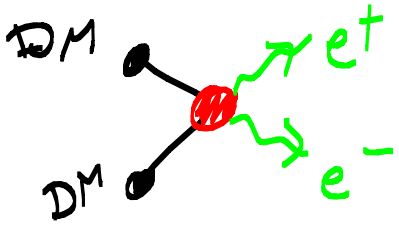
May '09: Fermi Satt. sees a hint of an excess in $e^- + e^+$: consistent with PAMELA excess in e^+

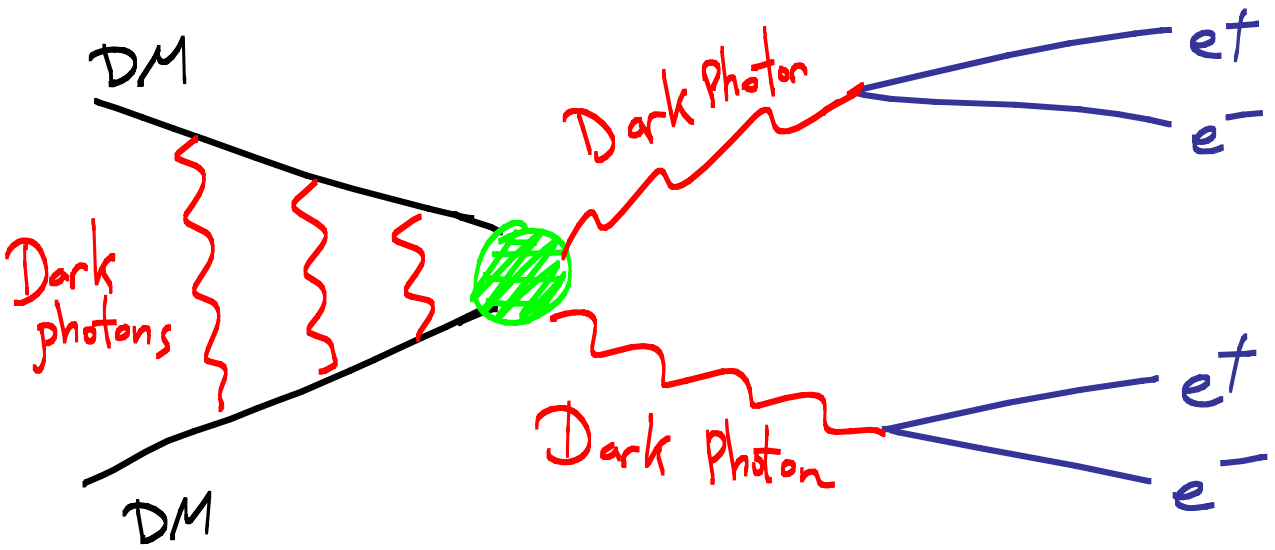
Astrophysics? or Dark Matter?



Pulsars

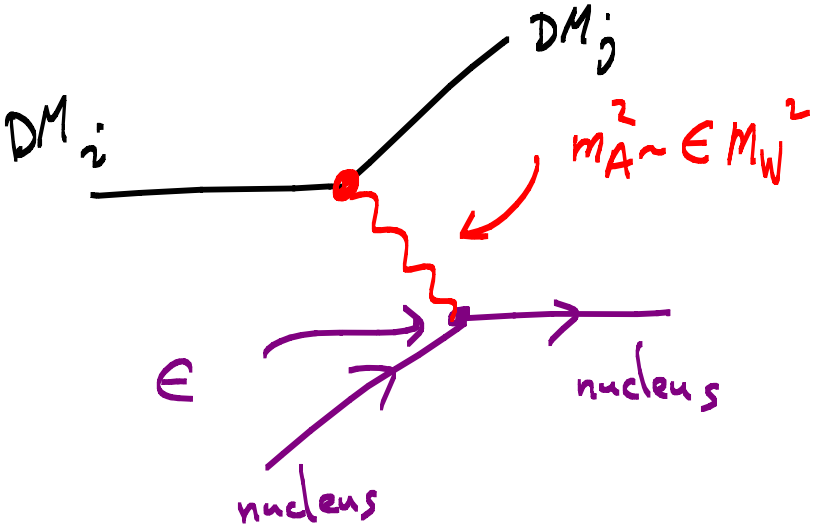






Can Qualitatively + Quantitavely explain anomalies

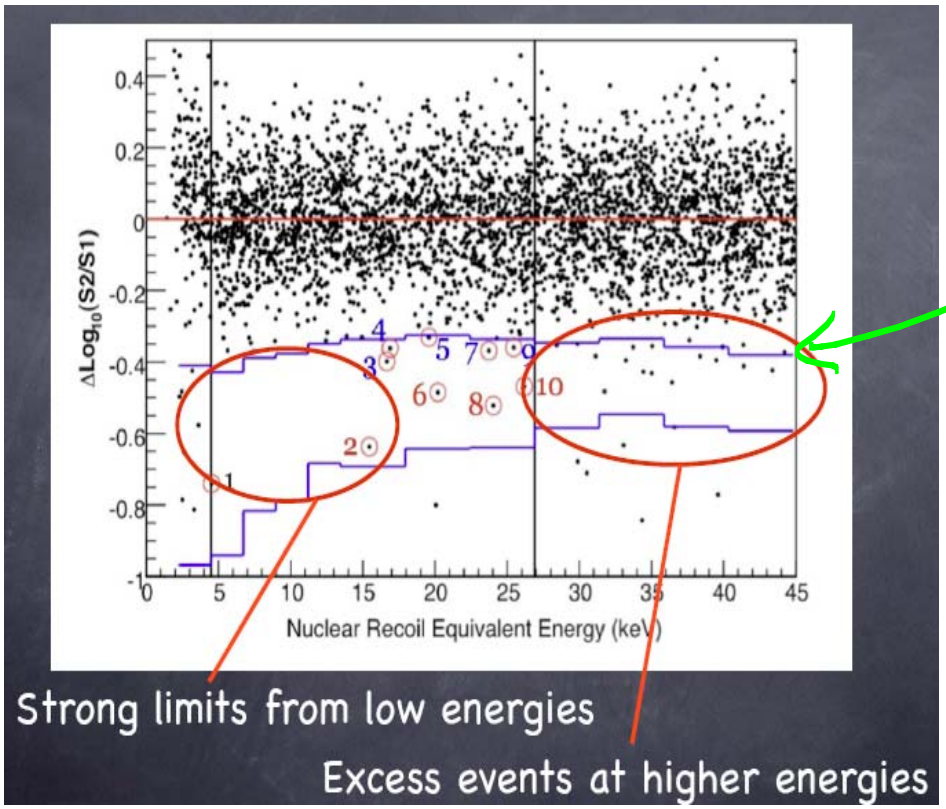
Direct Detection



- Scattering NECESSARILY INELASTIC
- Amp

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

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



Expected pattern from Dark Force Scattering....

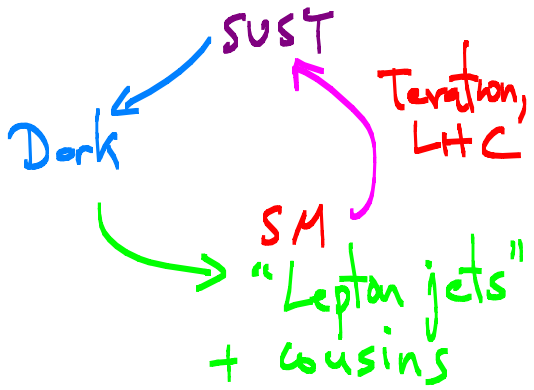
Awaiting more news from XENON 100 – soon!

Looking for the Dark Sector

Don't pay ϵ

★ Direct Detection

★

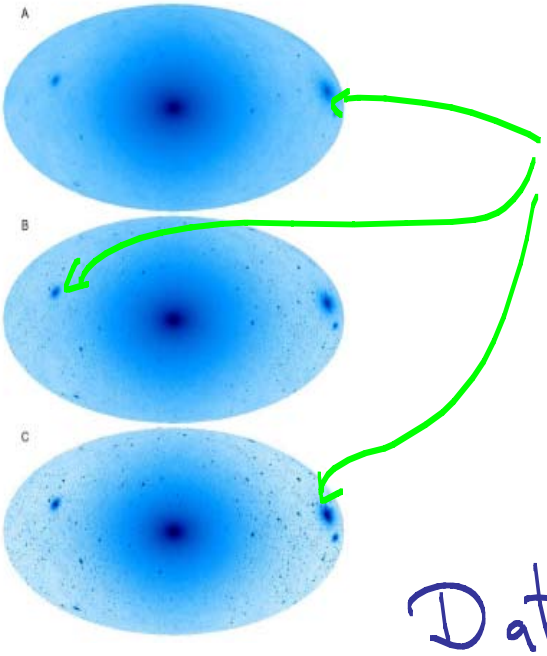


Pay ϵ

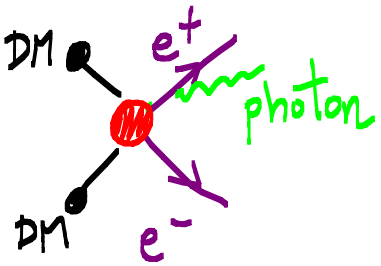
★ But use high-luminosity, low-E e^+e^- data (existing from B-factories!)

★ Lay a Coulomb into it [fixed target expts]

Galactic Photons Smoking Gun

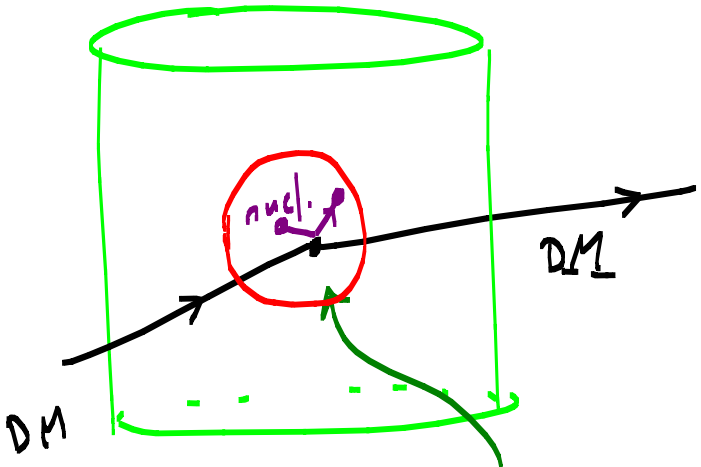


"Subhalos" should light up – away from galactic center!



Data within ~ few years

Direct Detection Smoking Gun

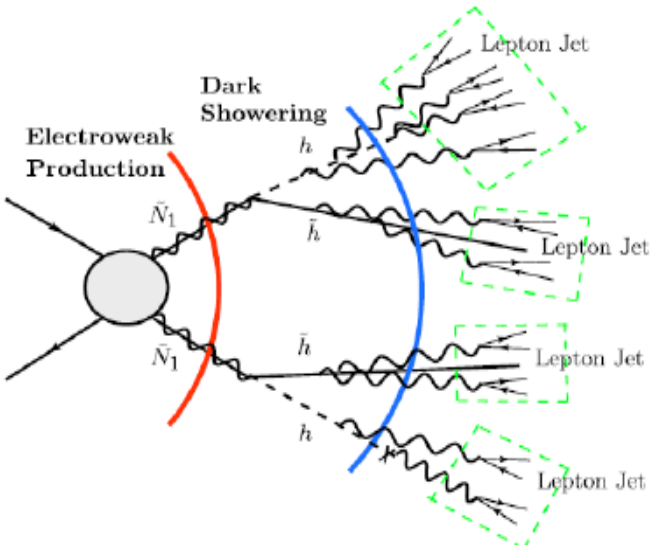


XENON 100 ZERO background

If explanation of DAMA is correct, 100's of events in ~ few months.

NEWS SOON!

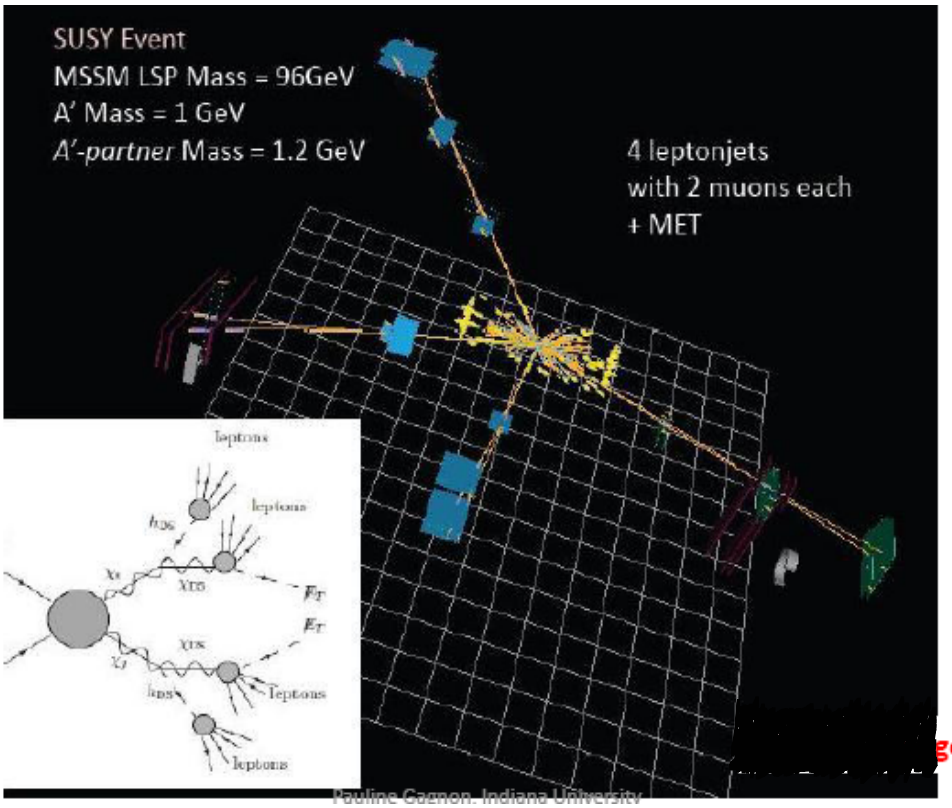
L·H·C. Smoking Gun



Into the Dark Sector

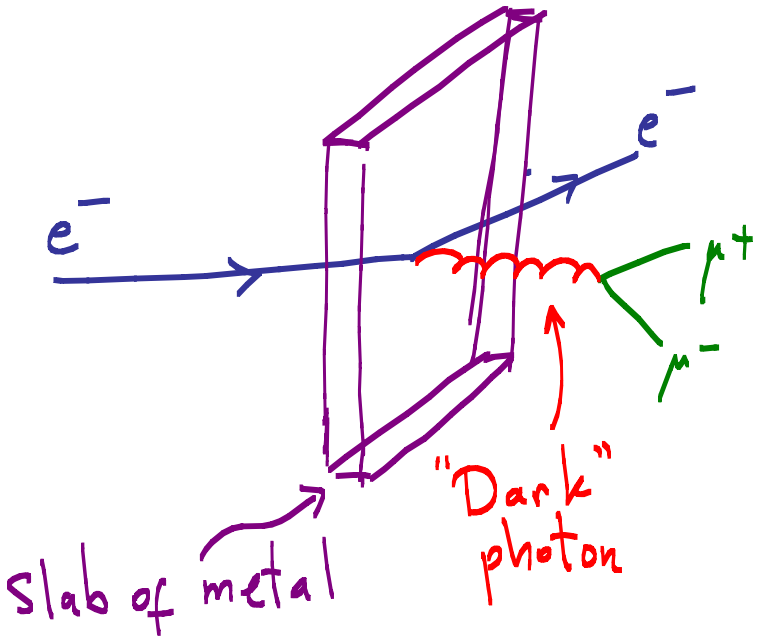
+

Back, as "Jets" of electrons + positrons ...



BIG increase on LHC reach for susy!

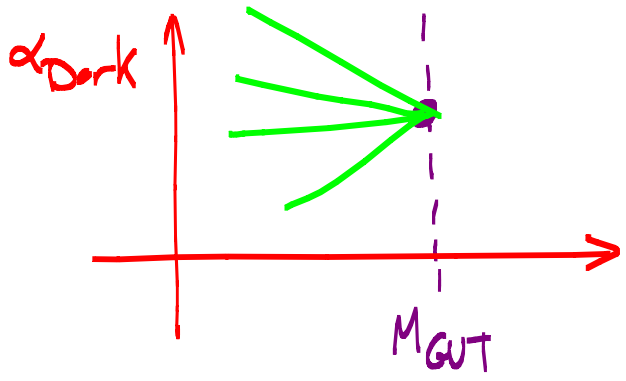
"Low"-Energy Smoking Guns



ENORMOUSLY exciting that APEX experiment will do this physics @ JLAB, this summer! $m \sim 100$'s MeV, $\epsilon \sim 10^{-3}$.

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 ...]

STAY TUNED

Developments on Many Fronts expected in next ~ 5 yrs.