Searches for Physics Beyond the Standard Model

A Theoretical Perspective

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SLAC

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The Plan

Motivations for Physics Beyond the Standard Model

New Hints from Dark Matter

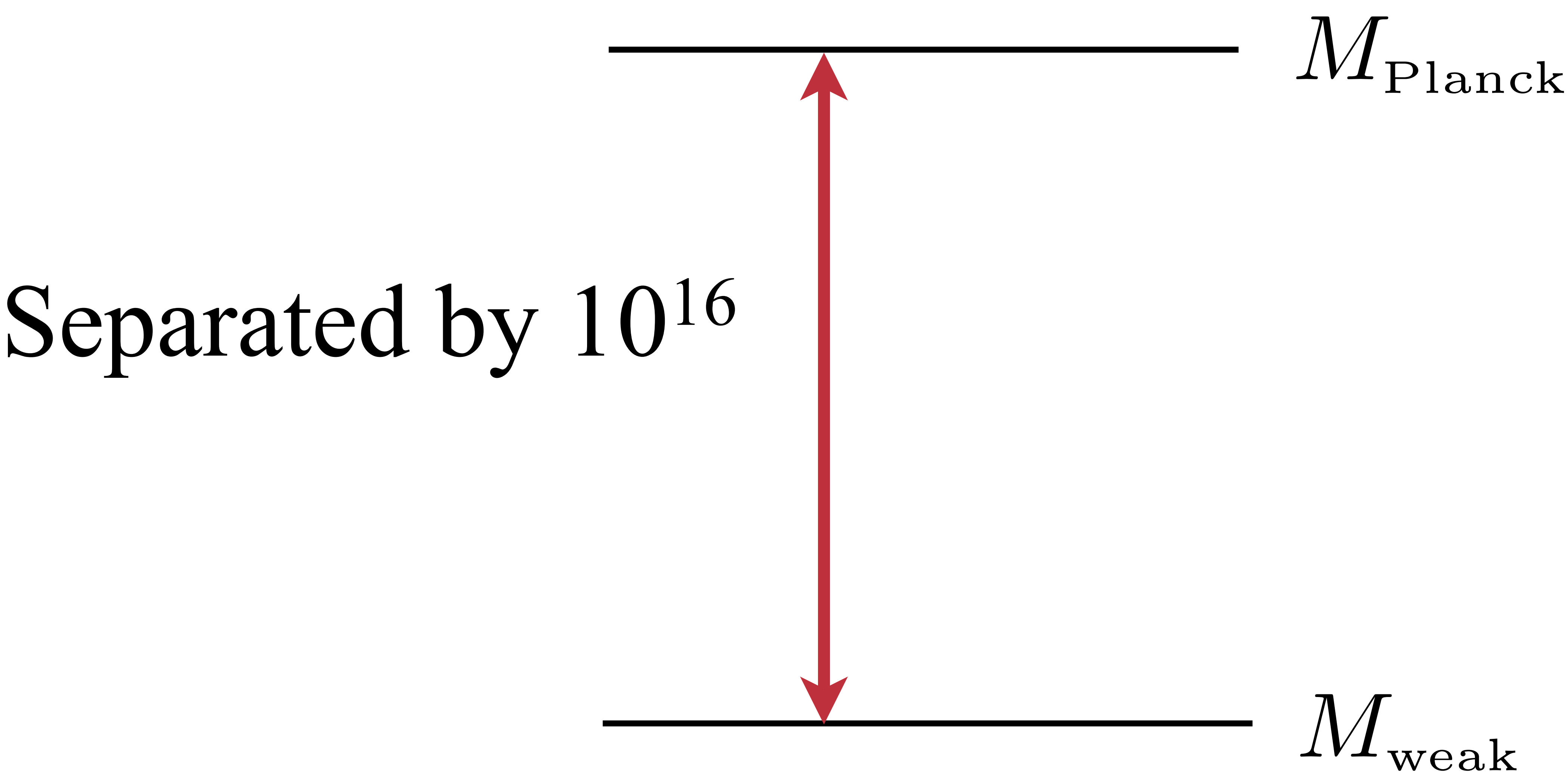
Possible Interpretations

Implications for the LHC

The hierarchy

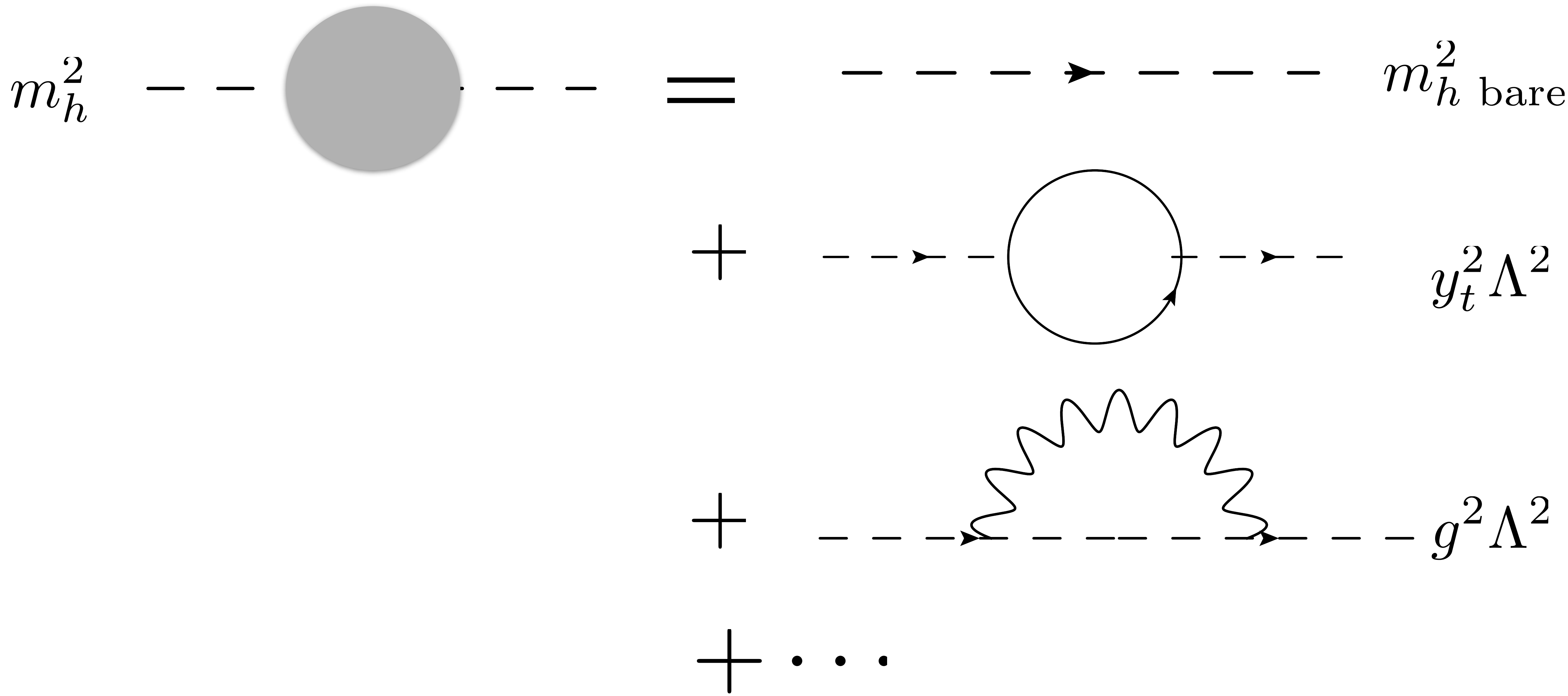
$$G_{\text{Newton}}/G_{\text{Fermi}} = 10^{-32}$$

$$M_{\text{Planck}} = G_{\text{Newton}}^{-\frac{1}{2}} = 10^{19}\ \text{GeV}$$
$$M_{\text{weak}} = G_{\text{Fermi}}^{-\frac{1}{2}} = 10^{3}\ \text{GeV}$$



The Hierarchy Problem

Big numbers adding up to something small

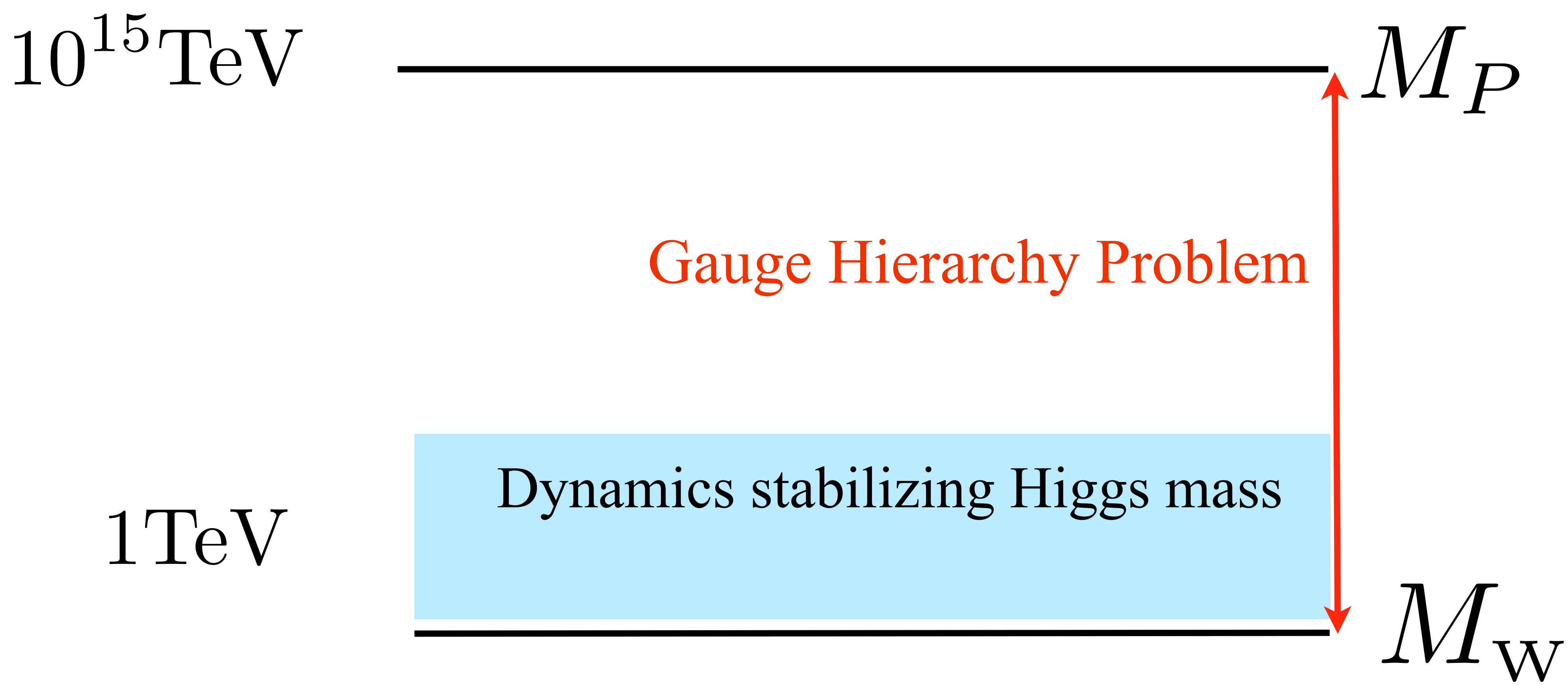


If $\Lambda \gg M_{W^\pm}$: a delicate fine-tuning

Hints that $\Lambda \sim M_{W^\pm}$

Naturalness

Primary motivation for new theories



Dynamics predict new particles & resonances

Tevatron & LHC are directly testing different theories of naturalness

Supersymmetry

Doubles Standard Model particles

$$\text{Fermion} \longleftrightarrow \text{Boson}$$

Quark	$\longrightarrow$	Squark	Gluon	$\longrightarrow$	Gluino
Lepton	$\longrightarrow$	Slepton	Photon	$\longrightarrow$	Neutralino

Susy particles at TeV scale

Proton stability linked to LSP stability

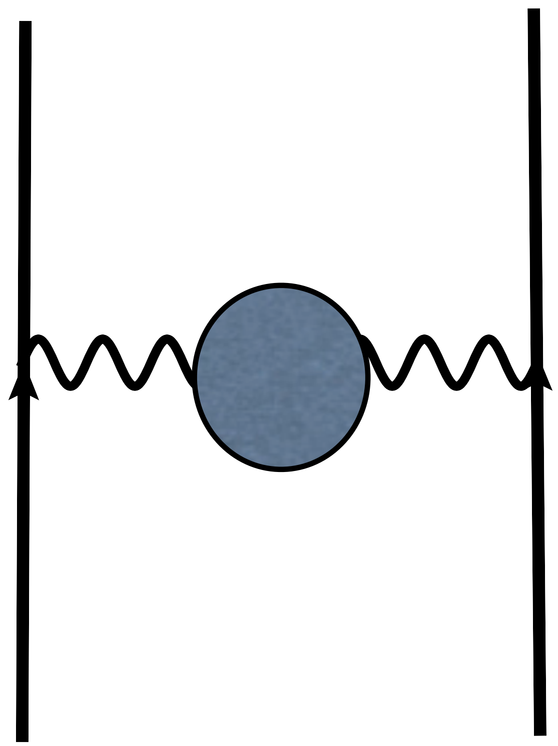
Natural DM candidate

Stabilizes the Higgs vev automatically

Adds 100+ new parameters

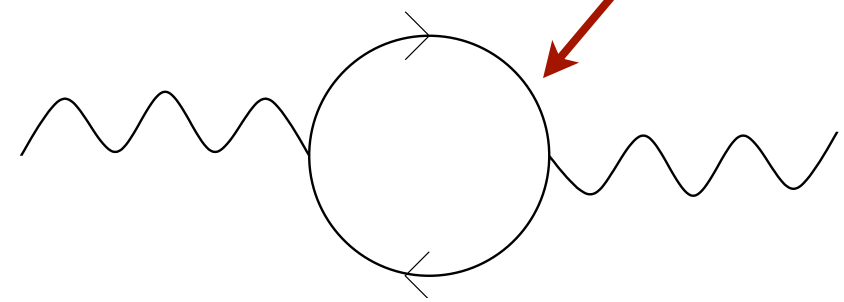
Leads to benchmark based searches

Gauge Coupling Running



$$V(r) = \frac{\alpha(r)}{r}$$

$$\alpha^{-1}(r) \sim \alpha_0^{-1} + \beta \log r$$



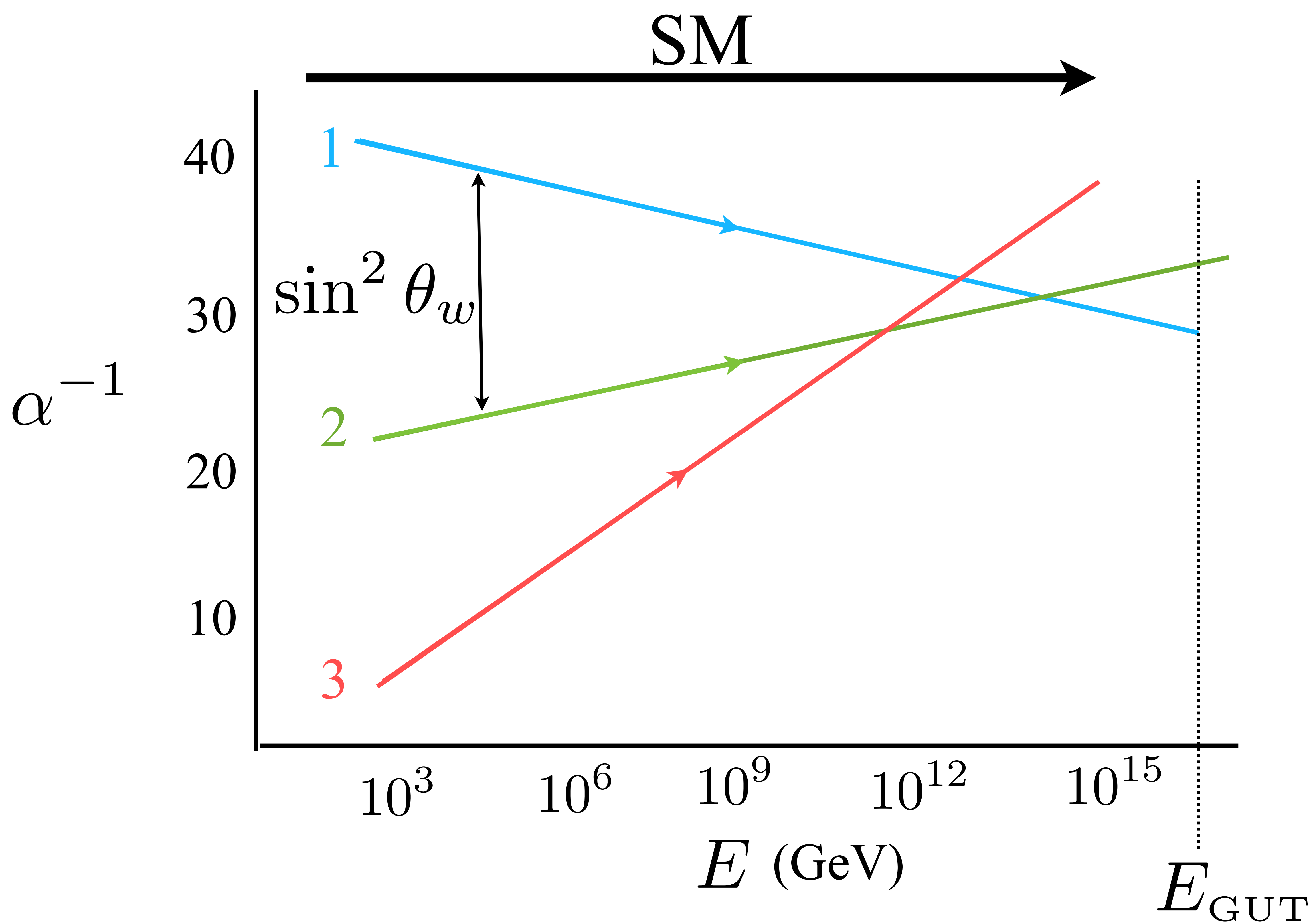
Counts charged particles

All 3 couplings run

If couplings were unified at short distances

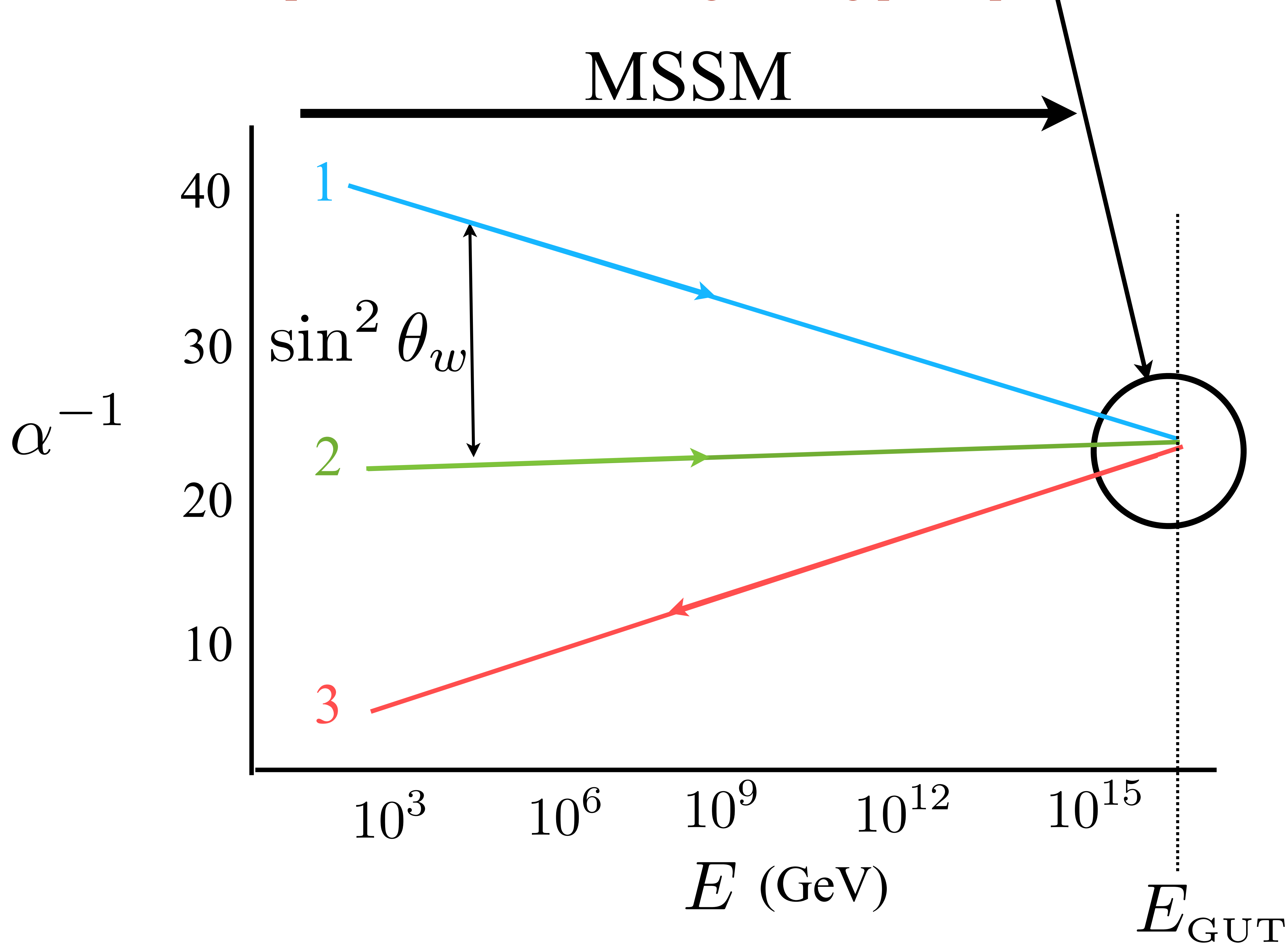
$$\alpha \text{ and } \sin^2\theta_{\mathrm{w}} \Longrightarrow \alpha_s$$

Gauge coupling unification



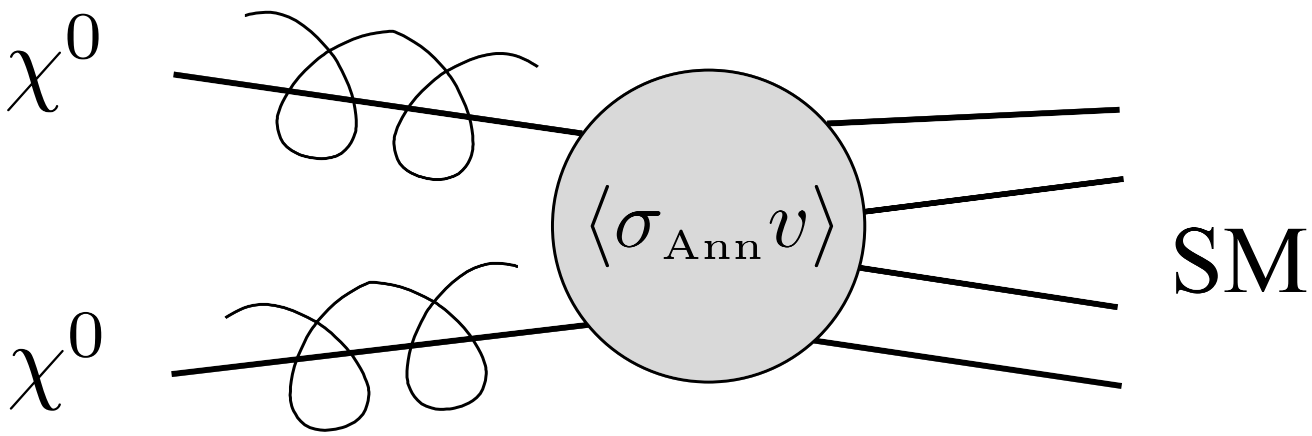
Gauge coupling unification

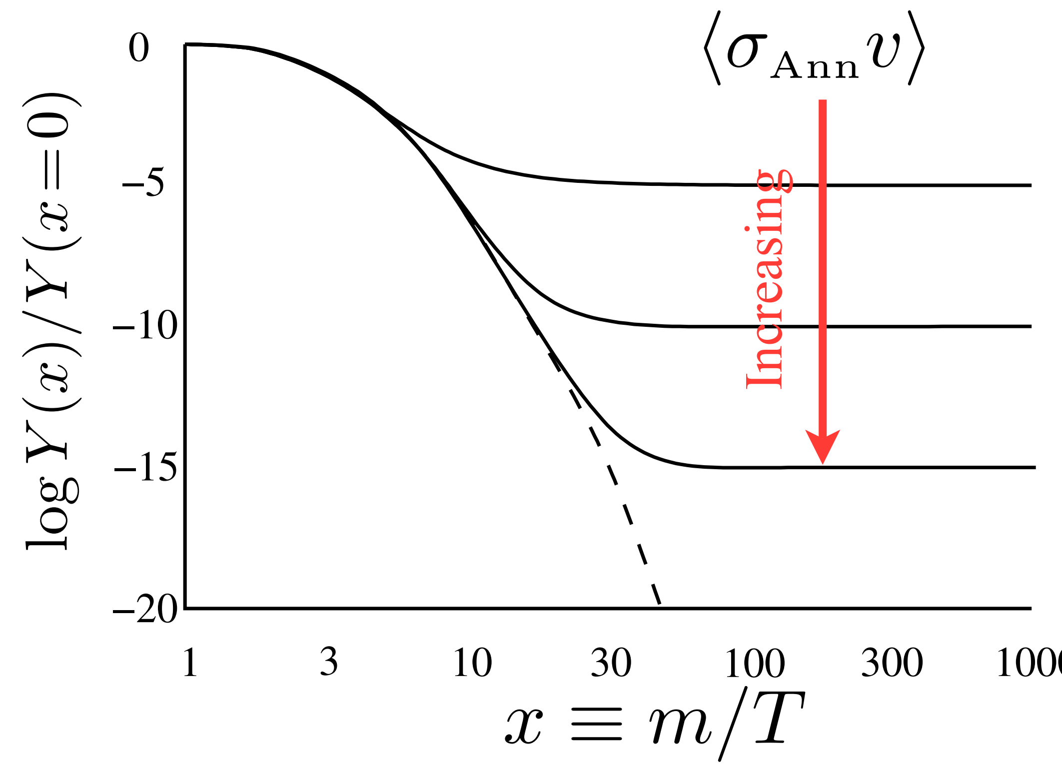
powerful hint at an organizing principle



LSP Dark Matter

Lightest supersymmetric particle stable





Annihilation cross section determines DM abundance

$$\sigma(\chi^0\chi^0 \to \mathrm{SM})v \sim \frac{\alpha^2}{m_\chi^2}$$

SM Gauge Coupling

DM Mass

Fixes DM Mass (w/o hierarchy problem!) $\Longrightarrow m_\chi \sim 100\ \mathrm{GeV}$

WIMP Miracle

LSP: an early Universe relic and could be DM

Motivations for New Physics haven't changed

Hierarchy Problem

Gauge Coupling Unification

Dark Matter

Same story was told in 1991...

I still find it compelling!

Anomalies in Indirect & Direct Detection

DAMA	NaI annual modulation experiment Only non-null direct detection result	
PAMELA	$\phi(e^+)\,/\,\phi(e^-)$	$E \gtrsim 100\ \mathrm{GeV}$
ATIC Fermi/GLAST	$\}\ \phi(e^- + e^+)$	$E \gtrsim 800\ \mathrm{GeV}$
INTEGRAL	$511\ \mathrm{keV\ Photons}$	$E \lesssim 5\ \mathrm{MeV}$
WMAP Haze	Anomalous synchrotron	

All won't be DM signals

If one is, could change expectations for colliders

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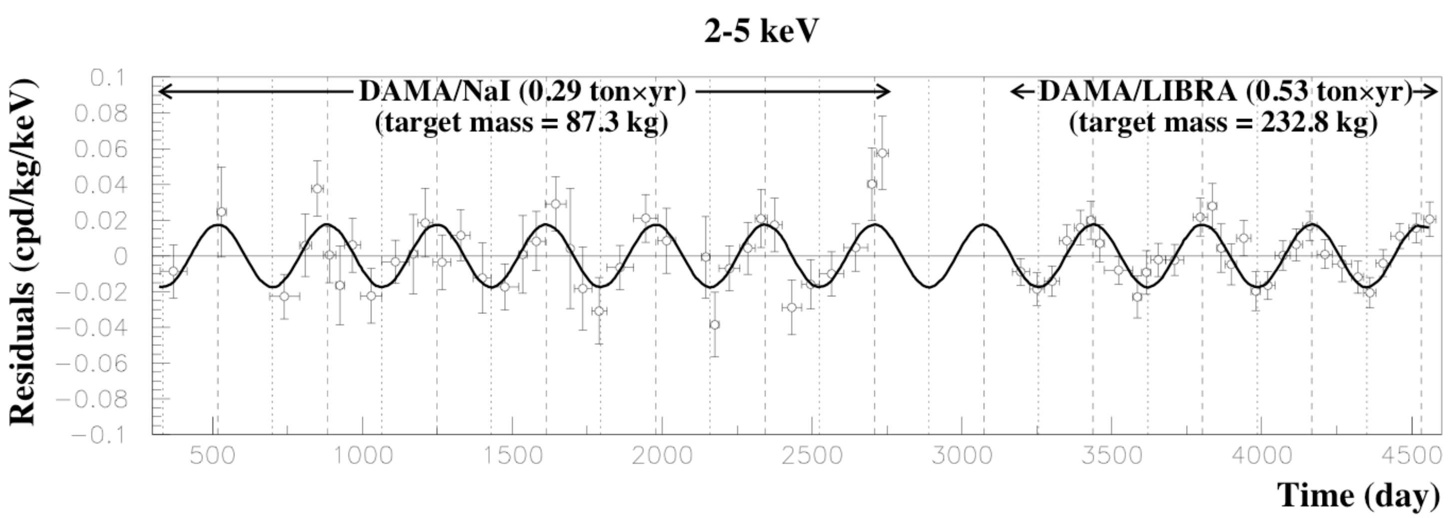
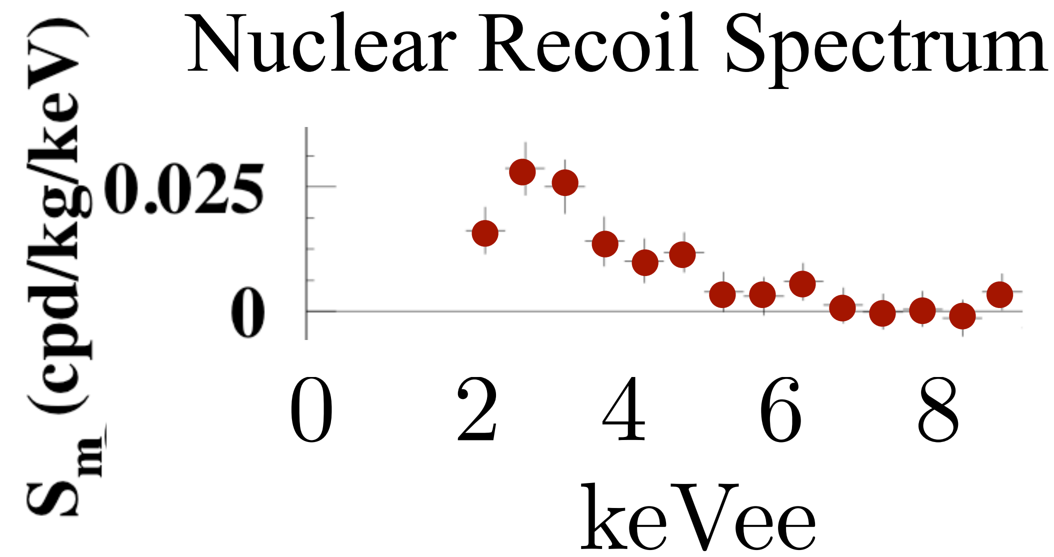
DAMA & Inelastic Dark Matter

Consistency with other experiments narrows possibilities

(CDMS & XENON10)

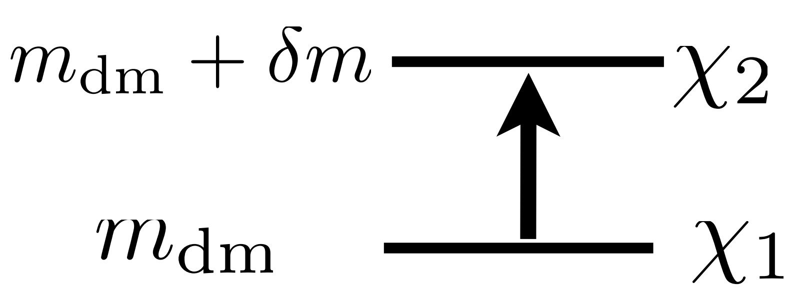
Tucker-Smith, Weiner (2001)
Chang, Kribs, Tucker-Smith, Weiner (2008)

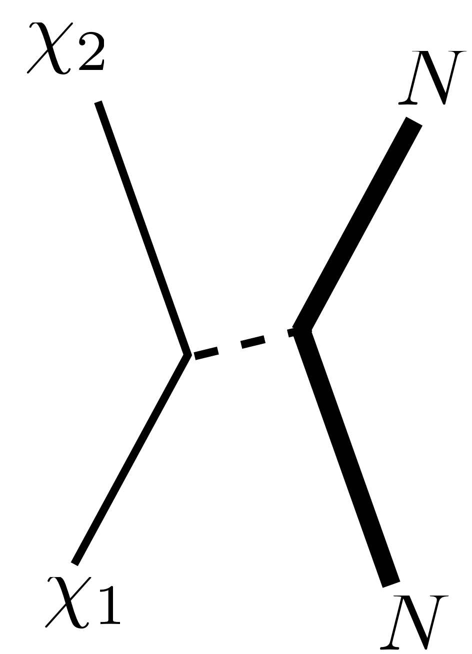




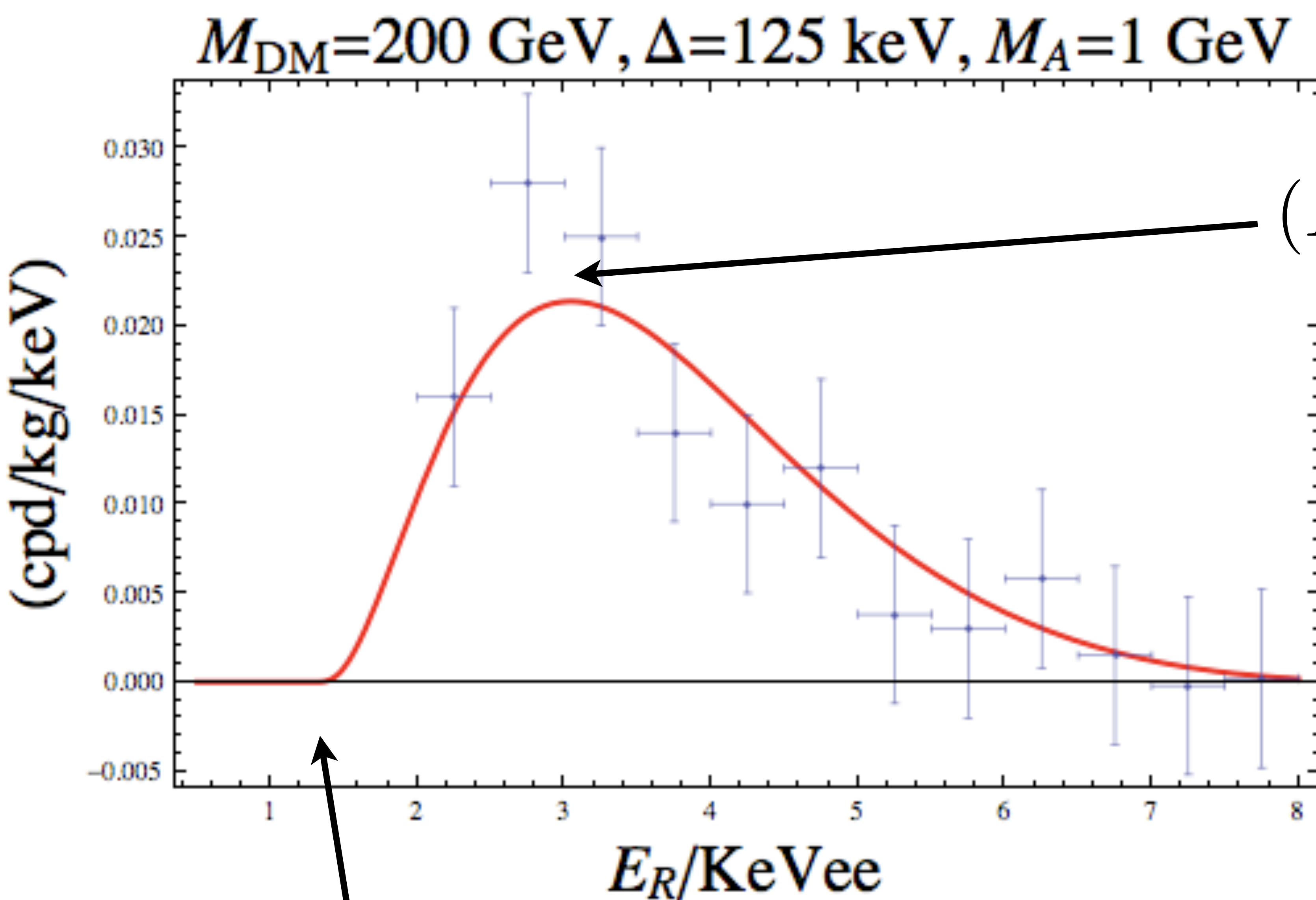
Multiple, near-degenerate states

$$\delta m \sim 100 \text{ keV}$$





Distinctive Recoil Spectrum



$$(E_R)_{peak} \approx \frac{\mu(\Delta m)}{m}$$

$$v_{min}(E_R) \approx \frac{1}{\sqrt{2mE_R}}\left(\frac{mE_R}{\mu} + \Delta\right)$$

Low recoil energies are suppressed

Chang, Pierce, Weiner (2008)

A New Vector Boson

Explanation to DAMA requires
inelastic transitions dominating elastic ones

Scalars couple to everything

Vectors change labels

$$h\phi^\dagger\phi \longrightarrow h\left(\phi_1^2+\phi_2^2\right)$$

$$A_\mu\ \phi^\dagger i\overleftrightarrow{\partial}^\mu\phi \longrightarrow A_\mu\ \phi_1\overleftrightarrow{\partial}^\mu\phi_2$$

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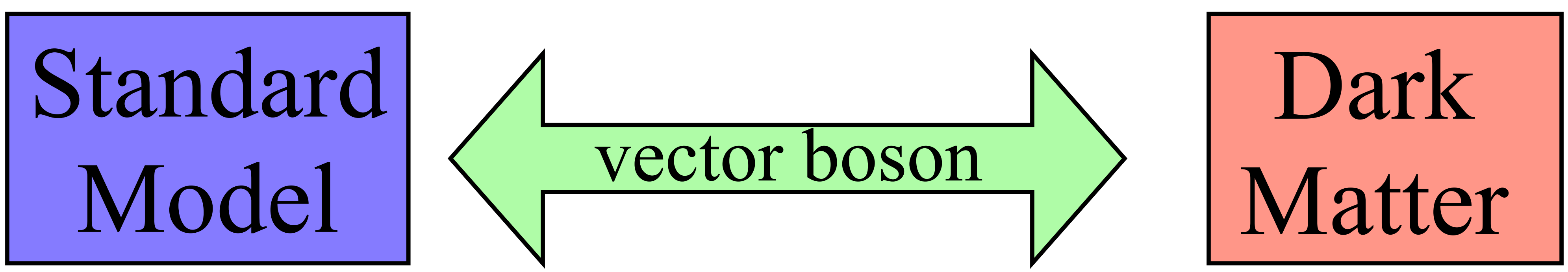
Choices for how to couple



DM has weak charge

SM has new gauge charge

Photon and Dark Photon Mix

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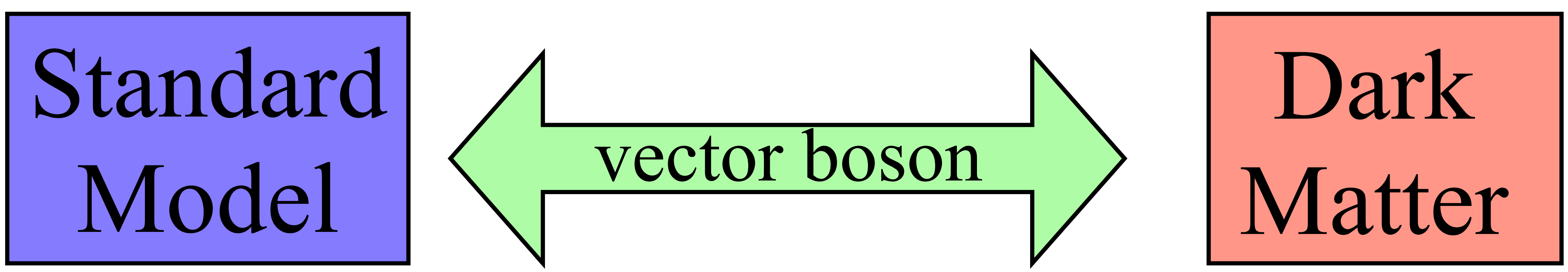

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Photon & Dark Photon Mixing

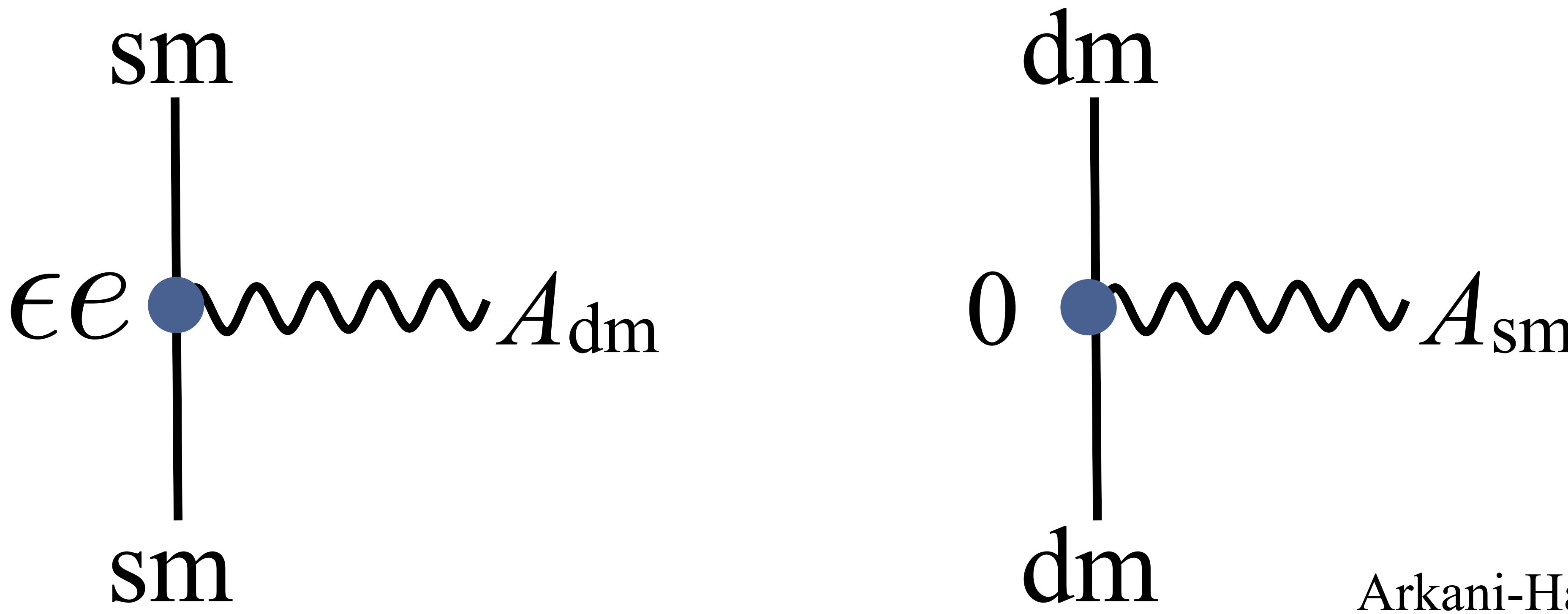
$$\mathcal{L} = (F^{\mu\nu}_{\rm sm})^2 + (F^{\mu\nu}_{\rm dm})^2 + \epsilon F^{\mu\nu}_{\rm dm} F^{\mu\nu}_{\rm sm} + M^2 A^2_{\rm dm}$$

EM Field strength in gauge invariant

Nothing forbids *kinetic* mixing

Holdom (1986)

SM charged under new DM force
DM neutral under SM forces



Arkani-Hamed, Finkbeiner, Slayter, Weiner (2008)

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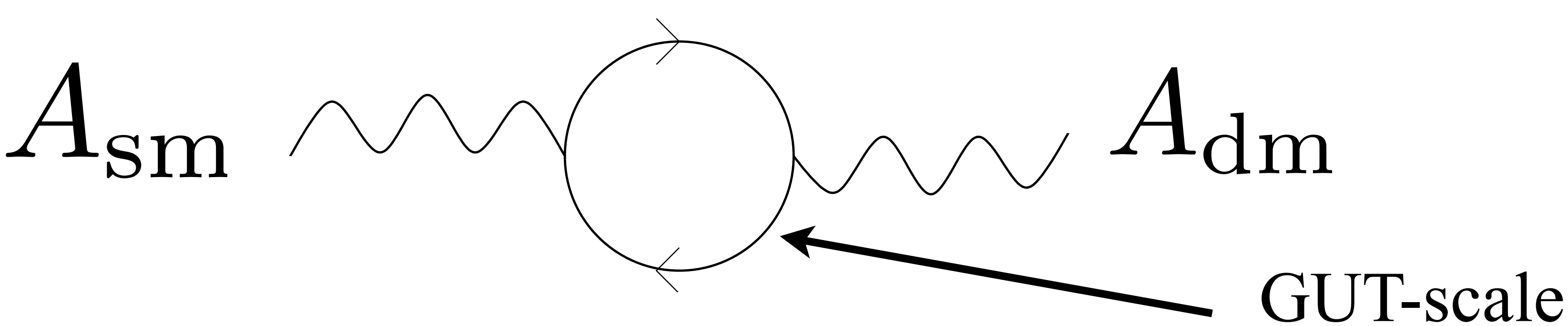
Loop effects generate



$$\epsilon \sim 10^{-3}$$

Arkani-Hamed, Finkbeiner, Slayter, Weiner (2008)

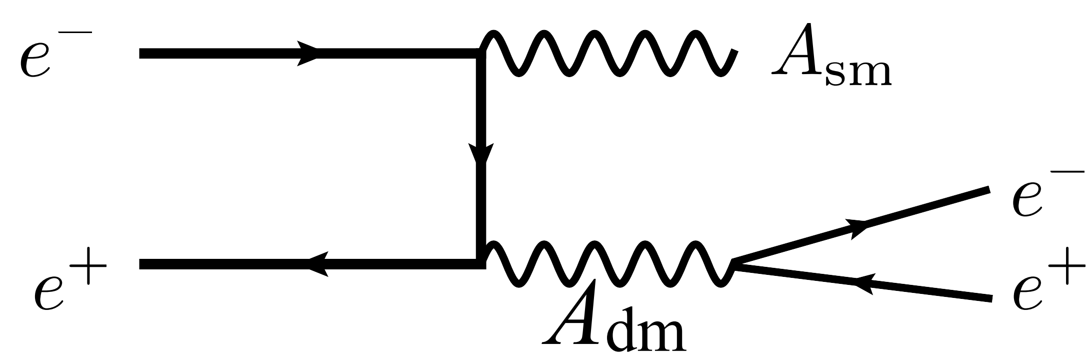
DAMA is a Weak Scale Cross section

$$\sigma \sim \frac{\epsilon^2 \alpha_{\rm dm} \alpha_{\rm sm}}{M_{A_{\rm dm}}^4} \simeq \frac{\alpha_{\rm sm}^2}{M_{W^\pm}^4}$$

$$M_{A_{\rm dm}} \simeq \epsilon^{\frac{1}{2}} M_{W^\pm} \sim \mathcal{O}(1\ \text{GeV})$$

Very light state!

Can directly produce Dark Photon

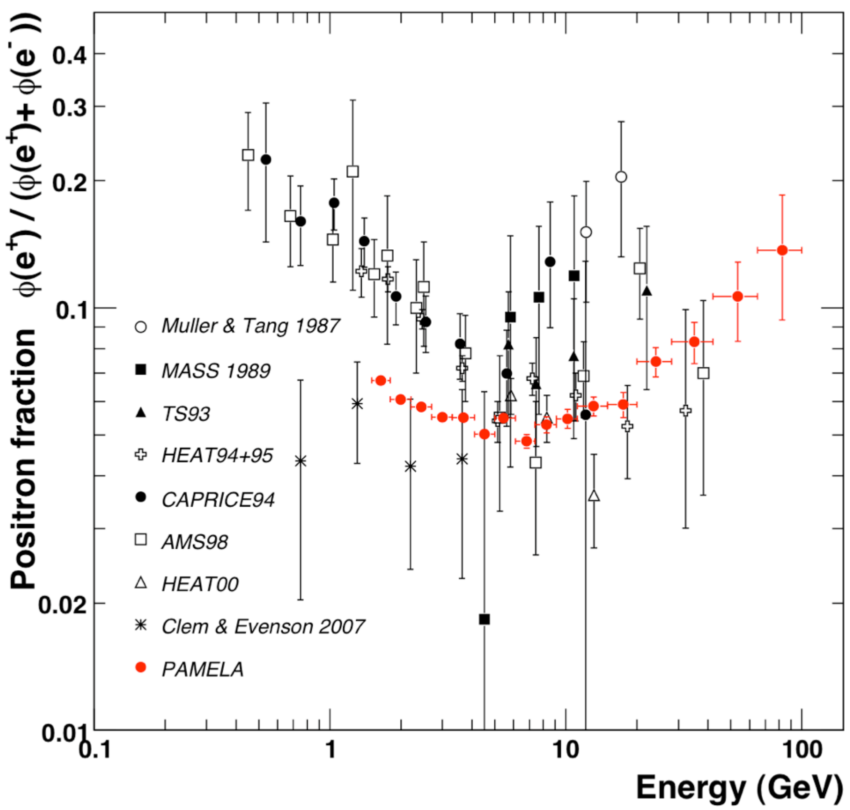


Best Machines are High Intensity, Low Energy

BaBar, Belle, KLOE, CLEO-c, BESIII

Essig, Schuster, Toro (2009)

PAMELA



An excess in $r_{e^+e^-} = \frac{\phi(e^+)}{\phi(e^-)}$

Rising towards 100 GeV

Could be DM annihilation

$\sigma_{\text{Pamela}} v \gg \sigma_{\text{Freeze out}} v$

DM already annihilated!

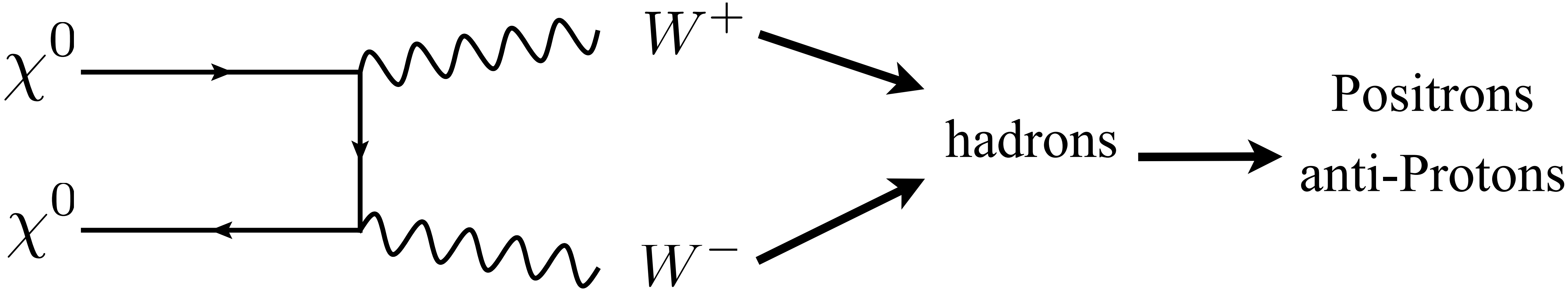
Need an enhancement in annihilation rate

A large rate to electrons

A small rate to hadrons

Annihilating to a new light vector

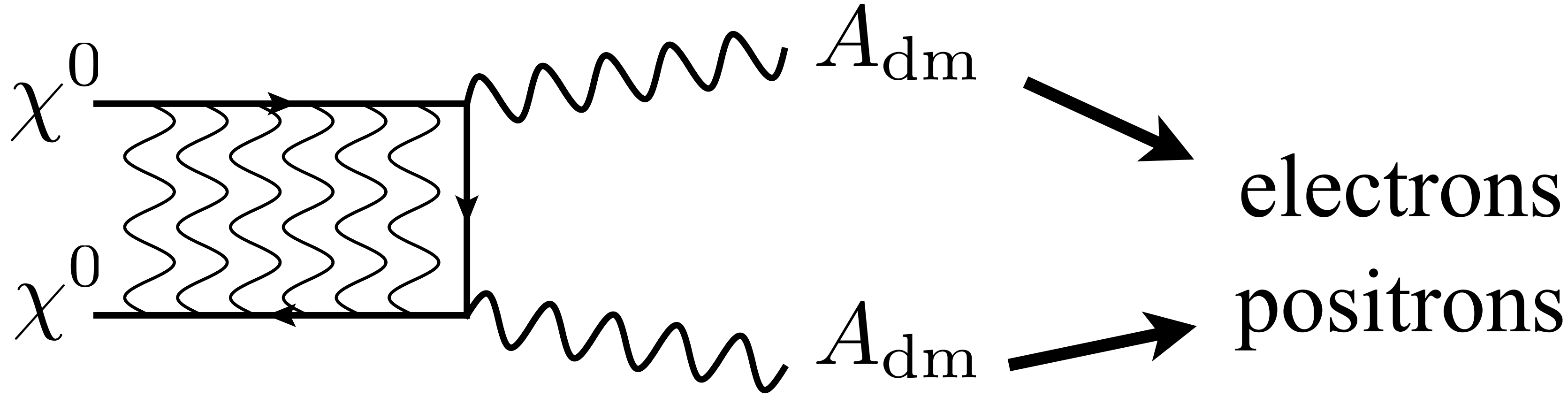
Constraints on usual annihilations



Dark Photon acts as new long range force

$$\sigma_{\text{Pamela}} v \propto \frac{1}{v}$$

Increases cross section when DM is cold!



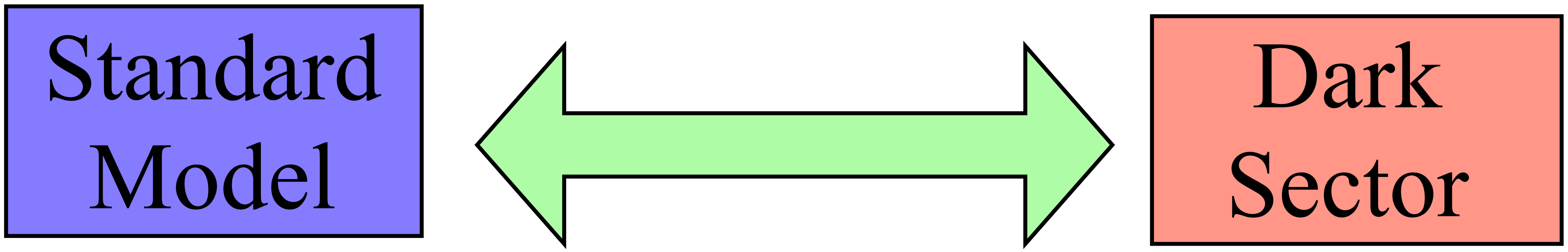
Arkani-Hamed, Finkbeiner, Slayter, Weiner (2008)

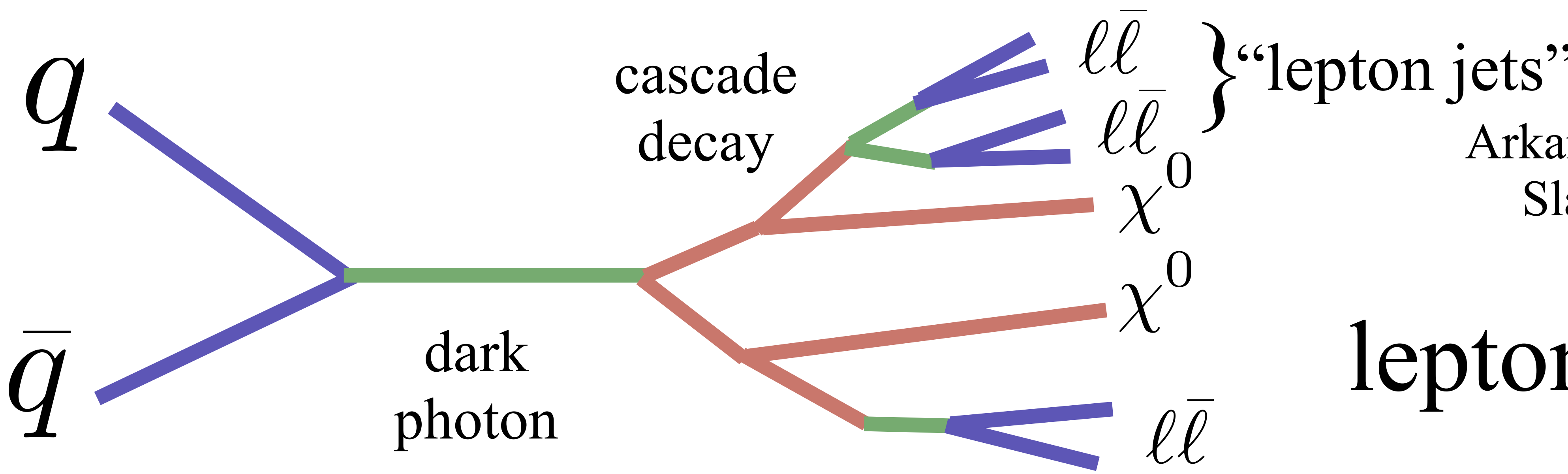
Hints that there might be a Dark Sector

Must give mass to dark photon

Must generate $\delta m_{\rm dm}/m_{\rm dm} \sim 10^{-6}$

Alves, Behbahani, Schuster, JW (2009)





Arkani-Hamed, Finkbeiner, Slayter, Weiner (2008)

leptons + MET

Light particles in cascade: boosted final states

"Hidden Valley"-like

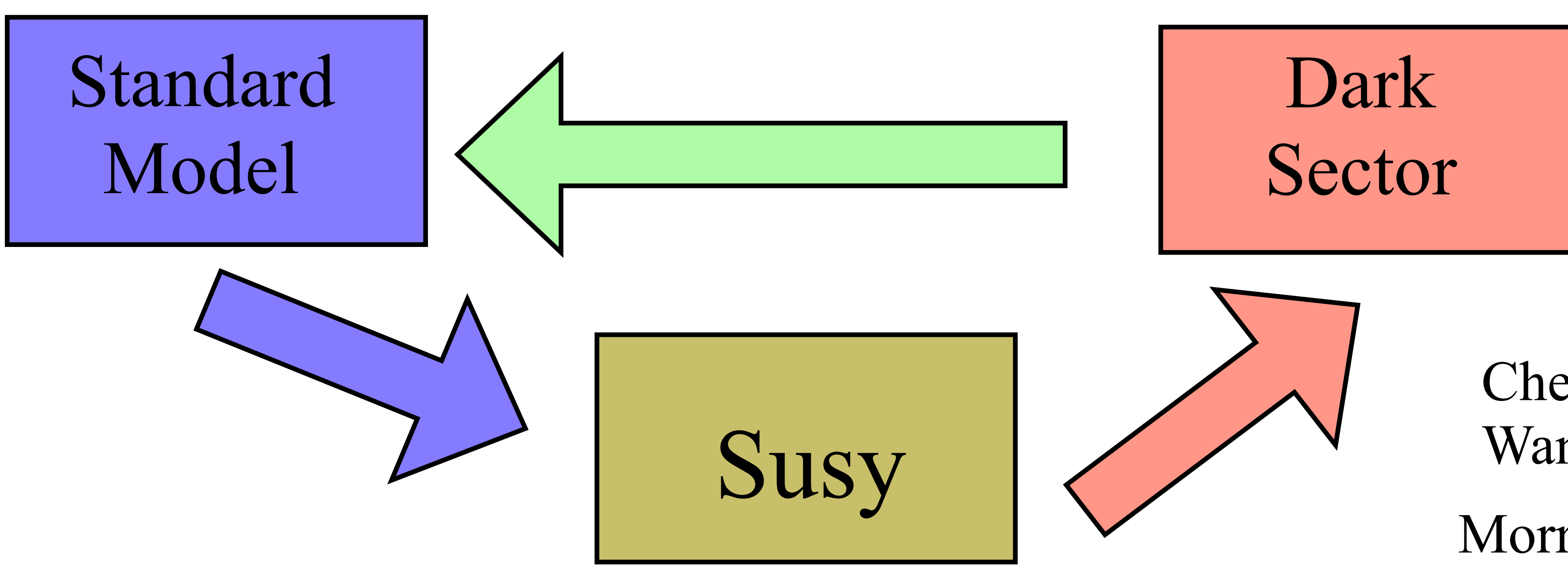
Strassler, Zurek (2006)

Hints at Dark Matter are not MSSM-like

Supersymmetric Standard Model could still be there

(now have SM & DM hierarchy problem!)

Dark Matter Production could look like



Cheung, Ruderman, Wang, Yavin (2009)

Morrissey, Zurek (2009)

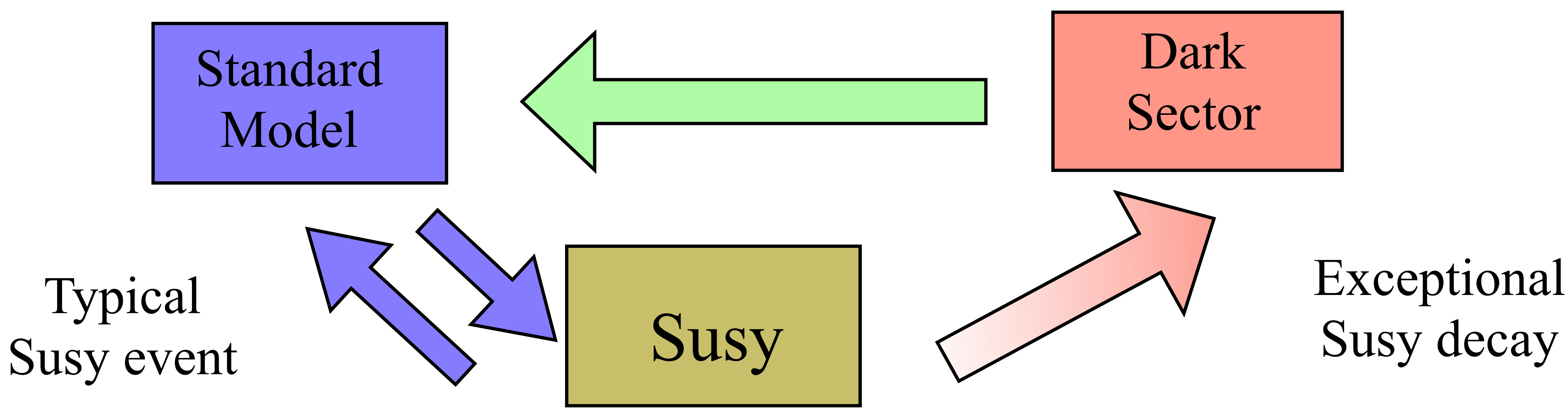
Bottom of susy spectra matters for searches

Neutralino may not be stable

Lightest SSM particle could be charged or colored

R-parity violation -- Lots of Jets & no MET

If LSP is stable, MET could be rare



How robust are the searches to small perturbations?

Look inside existing susy searches and vary assumptions

Most BSM searches based on Susy

Susy carries a lot of baggage from 28 years of study

SOFTLY BROKEN SUPERSYMMETRY AND SU(5)

Savas DIMOPOULOS[1,2]

Institute of Theoretical Physics, Stanford University,
Institute of Theoretical Physics, University of California, Santa Barbara
and
University of Michigan, Ann Arbor, USA

Howard GEORGI[3]

Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

Received 2 June 1981

Here we explore a simpler alternative possibility – that the supersymmetry is broken explicitly, but softly, by terms of dimension less than four in the lagrangian. We add to the lagrangian (not to v) the following SU(5) invariant mass terms, all of the order of a TeV:

(1) a positive mass squared term for the matter bosons;

(2) a mass for the Higgs fermions (and their SU(5) partners);

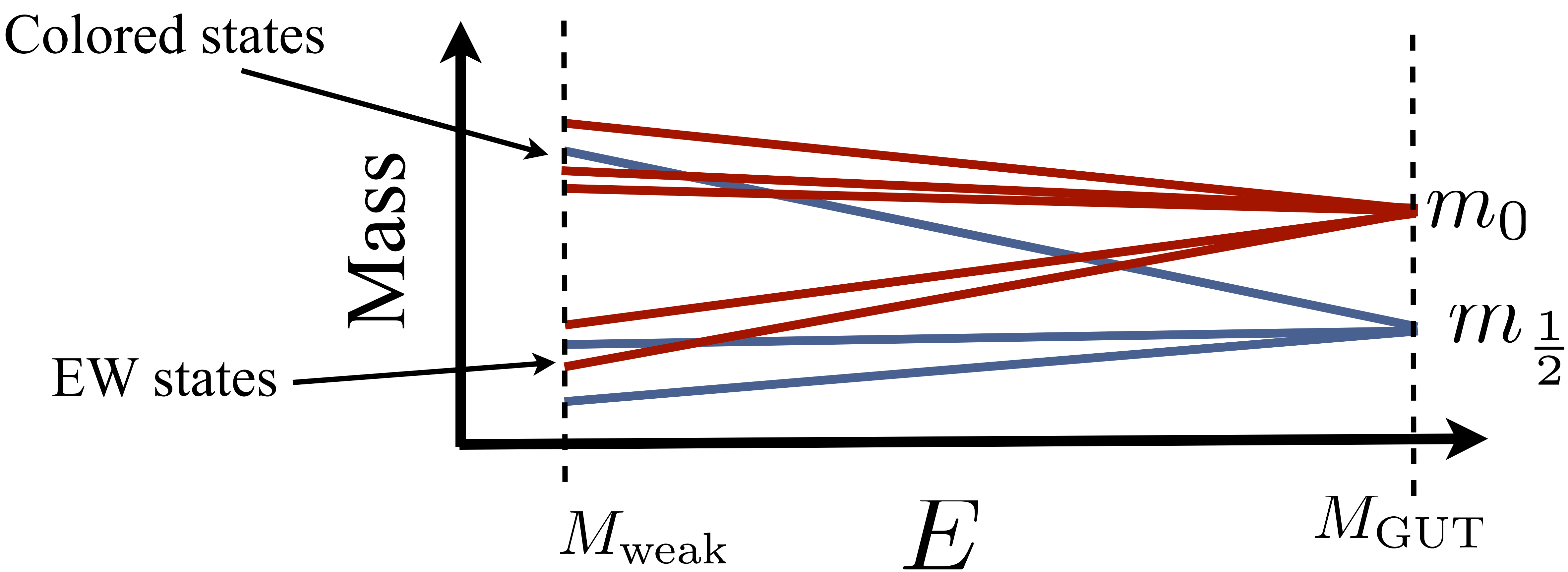
(3) a Majorana mass for the gauge fermions;

(4) a negative mass squared term for the boson fields in the Σ supermultiplet;

(5) a mixed (with positive and negative eigenvalues) mass squared matrix for the Higgs bosons.

mSugra has 5 parameters

Only 2 are relevant for collider searches



Many relations between masses

Driven by an ansätz, not consistency

Tuning searches to mSugra,
limits applicability to other models

mSugra Caveats

Gaugino mass running is multiplicative:

$$m_{\tilde{B}} : m_{\tilde{W}} : m_{\tilde{g}} \qquad 1 : 2 : 7$$

$$\tilde{g} \rightarrow \tilde{B} + q\,\bar{q}$$

Always have very hard jets

What if $m_{\tilde{B}} : m_{\tilde{g}} \sim 1 : 1.5$?

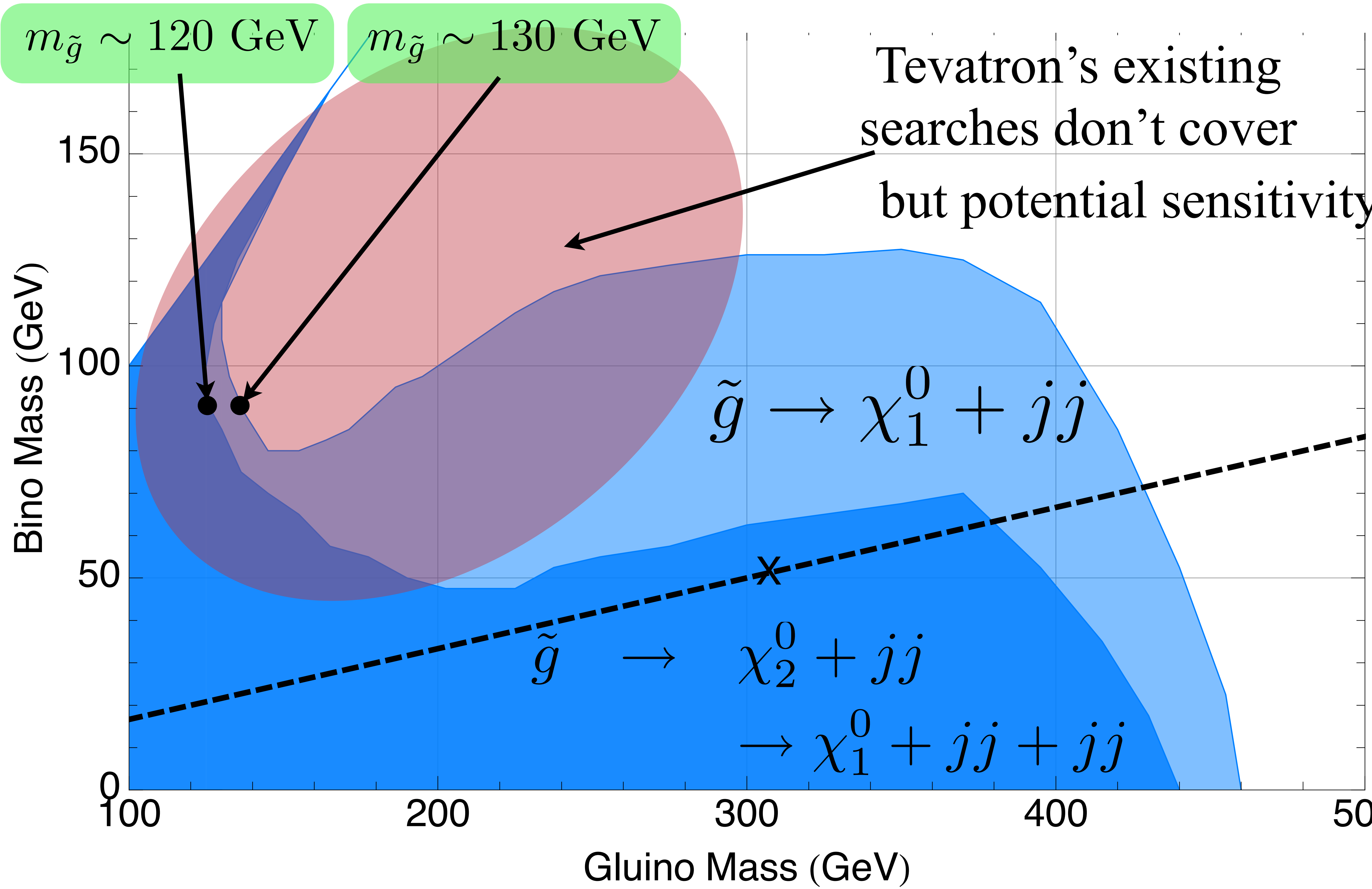
Jets become softer

Challenge to increase S/B, but possible!

In non-Susy theories, mass splittings may be different

$$m_{\tilde{B}} \simeq m_{\tilde{W}} \simeq m_{\tilde{g}} = m_{\frac{1}{2}} + \Delta_i m$$

Tevatron Sensitivity Plot



Alwall, Le, Lisanti, JW (2008)

Results from DM experiments change LHC expectations

If DM is not the LSP:
search philosophy for BSM may be ineffective

Should scrub searches of irrelevant theoretical assumptions

Is the full mSugra framework needed
to search for Jets + MET?

Possible to cut away a visible signal
(e.g. additive vs multiplicative renormalization)

Excess baggage usually avoidable
Search for simplified models

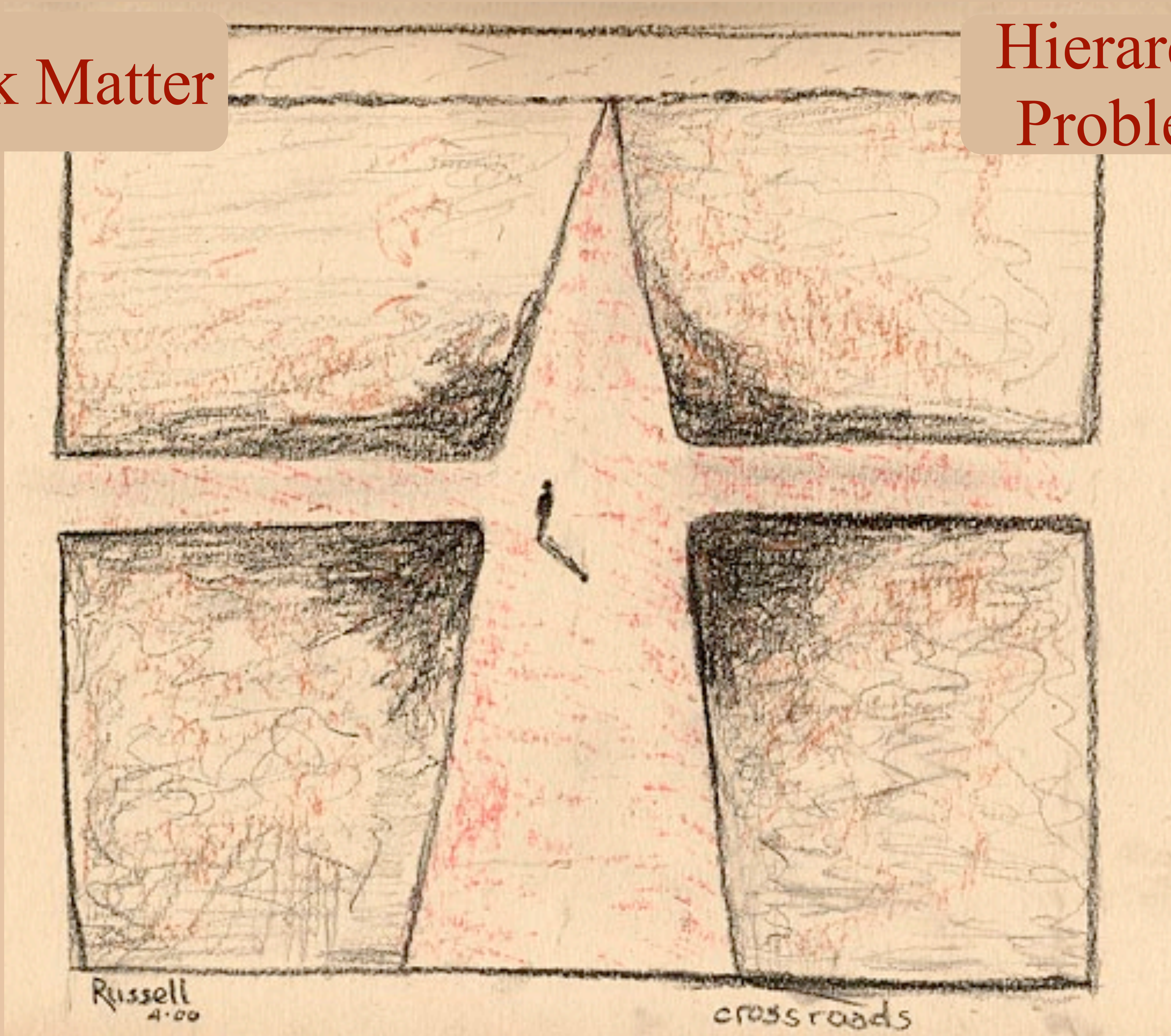
More robust against small changes in spectra

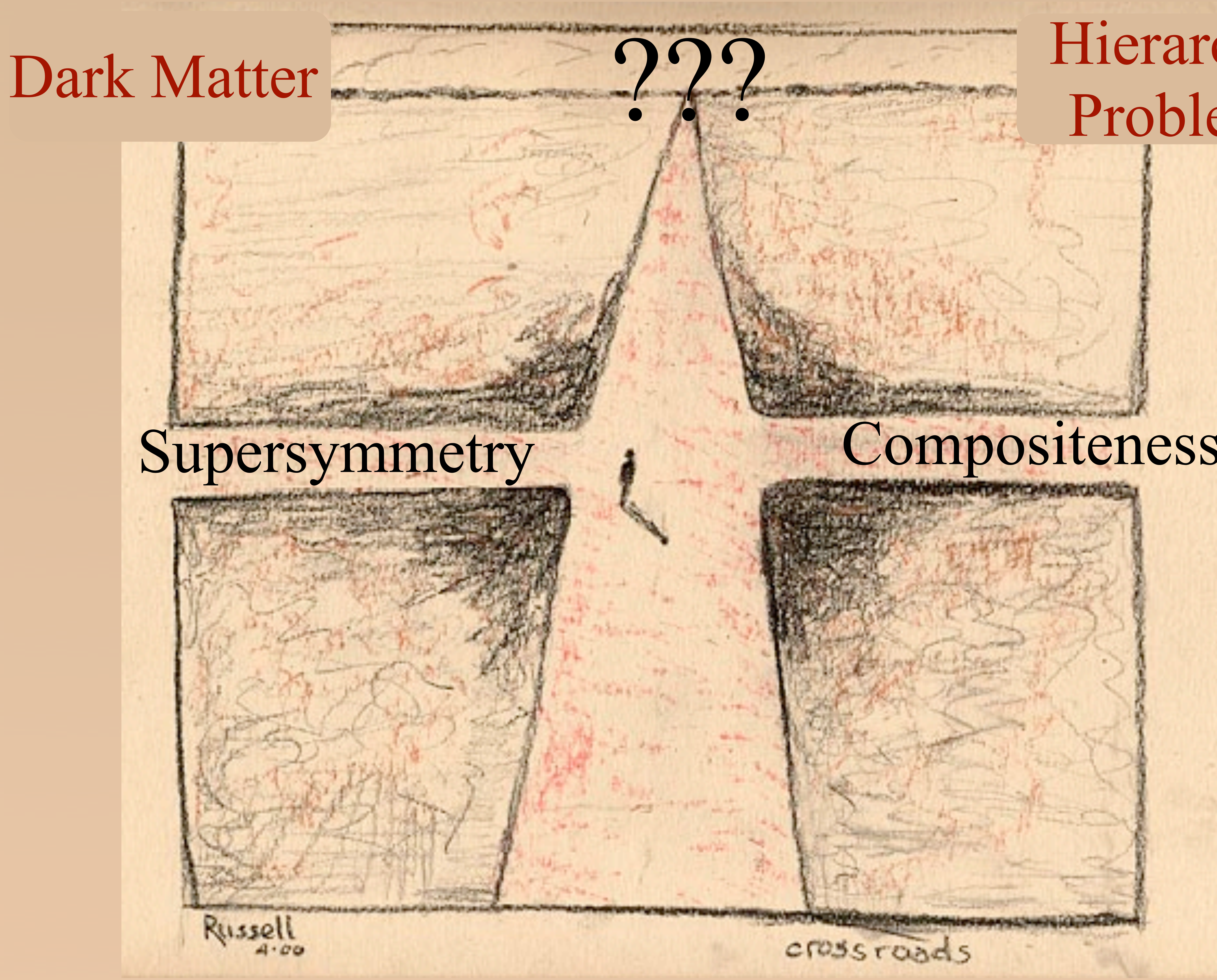
Alwall, Schuster, Toro (2008)

Dark matter may be pointing to novel final states!

Dark Matter

Hierarchy Problem




Dark Matter
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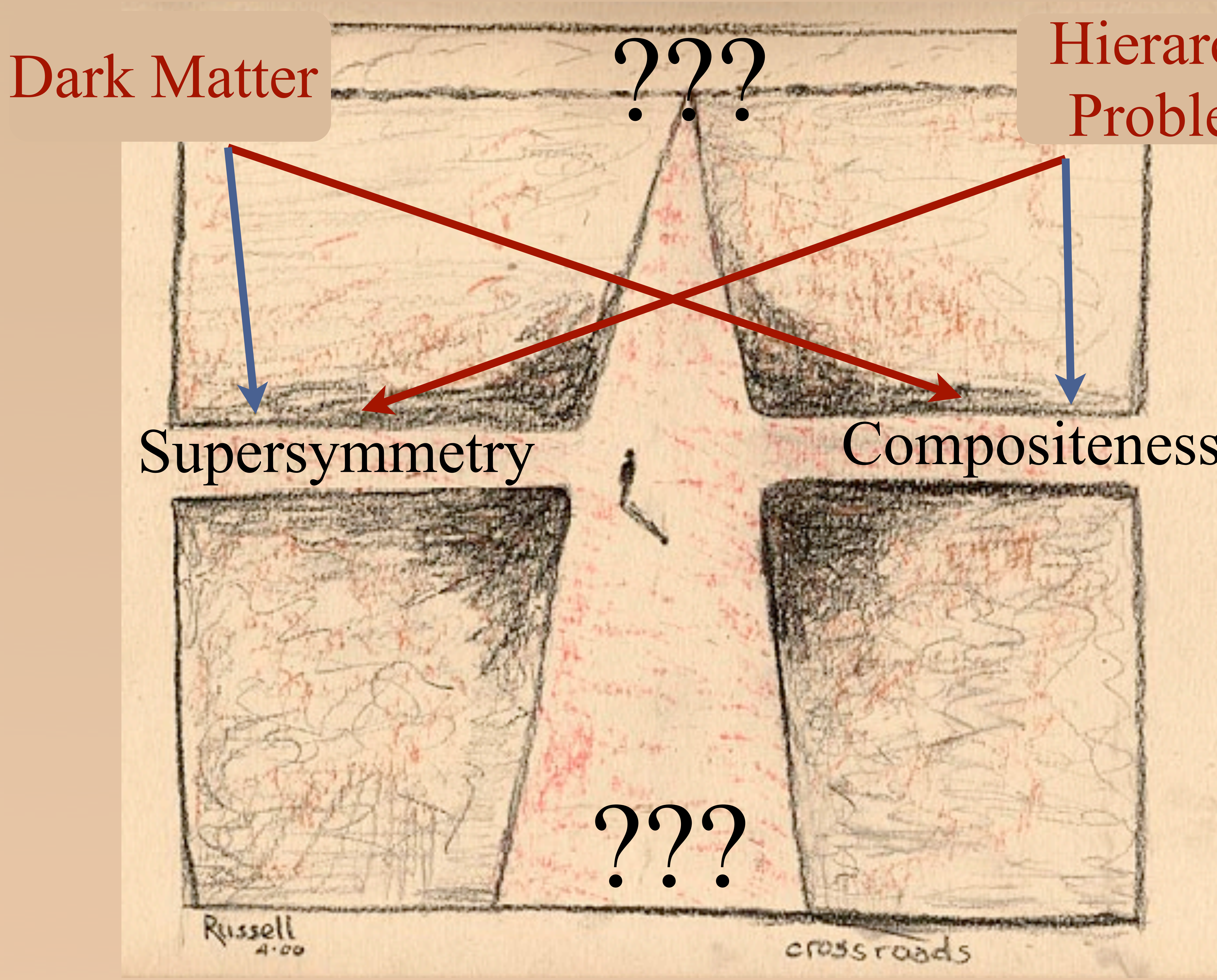
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