New Dark Matter Models and Implications for the ILC

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Many slides taken from 2 theory/expt workshops:
"Unusual Dark Matter" Eugene Oregon July 6-10
"Dark Forces" SLAC, Sept 24-26

Talk Outline

- Intro: WIMPs
- Quick review of recent anomalies in
  - Indirect detection Dark Matter signals
  - DAMA
- “Unusual” Dark Matter?
- Hidden Sectors and Portals
- possible (still unstudied) ILC signatures

Dark Matter Knowns

- 23% of critical density of Universe
- 84% of non relativistic matter in universe
- gravitationally clumps, necessary for galaxy formation
- DARK (no electromagnetic interactions)
- (nearly) collisionless
- much weaker than weak cross section for direct detection

What is Dark Matter?

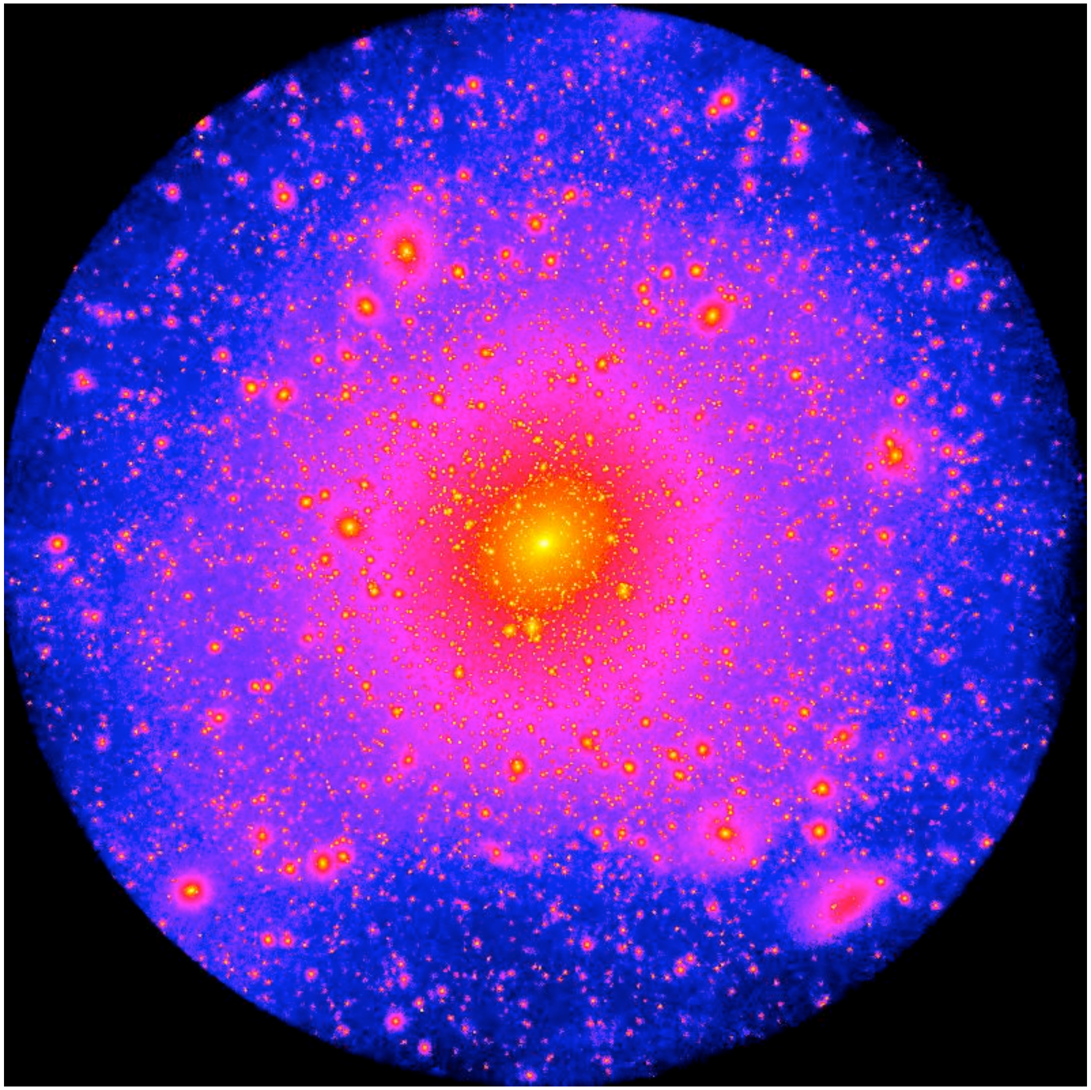
- Weakly Interacting Massive Particle?
  - well motivated (SUSY, natural relic abundance)
  - Large, multifaceted Experimental Search Program: Colliders, Direct Detection, Indirect Detection
- Axion?
  - well motivated (Strong CP, misalignment mechanism)
  - small Experimental Search Program-ADMX
- Something else? (not baryons, neutrinos, MACHOS)

WIMP Miracle

- standard WIMP; for M~100 GeV, correct abundance for $M/T_{freeze} \sim 20$ (varies as log(M))
- $\langle \sigma\, v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$ gives observed relic abundance for standard WIMP
- typical weak cross section for annihilation!

Indirect Detection ?

- Our Dark Galaxy (simulated)
- Very Clumpy, lots of substructure
- annihilation rate/volume~ $n_{\chi}^2 \sigma v$
- Can we see annihilation products?



UW N-body shop

Indirect Signals of Dark Matter Annihilation

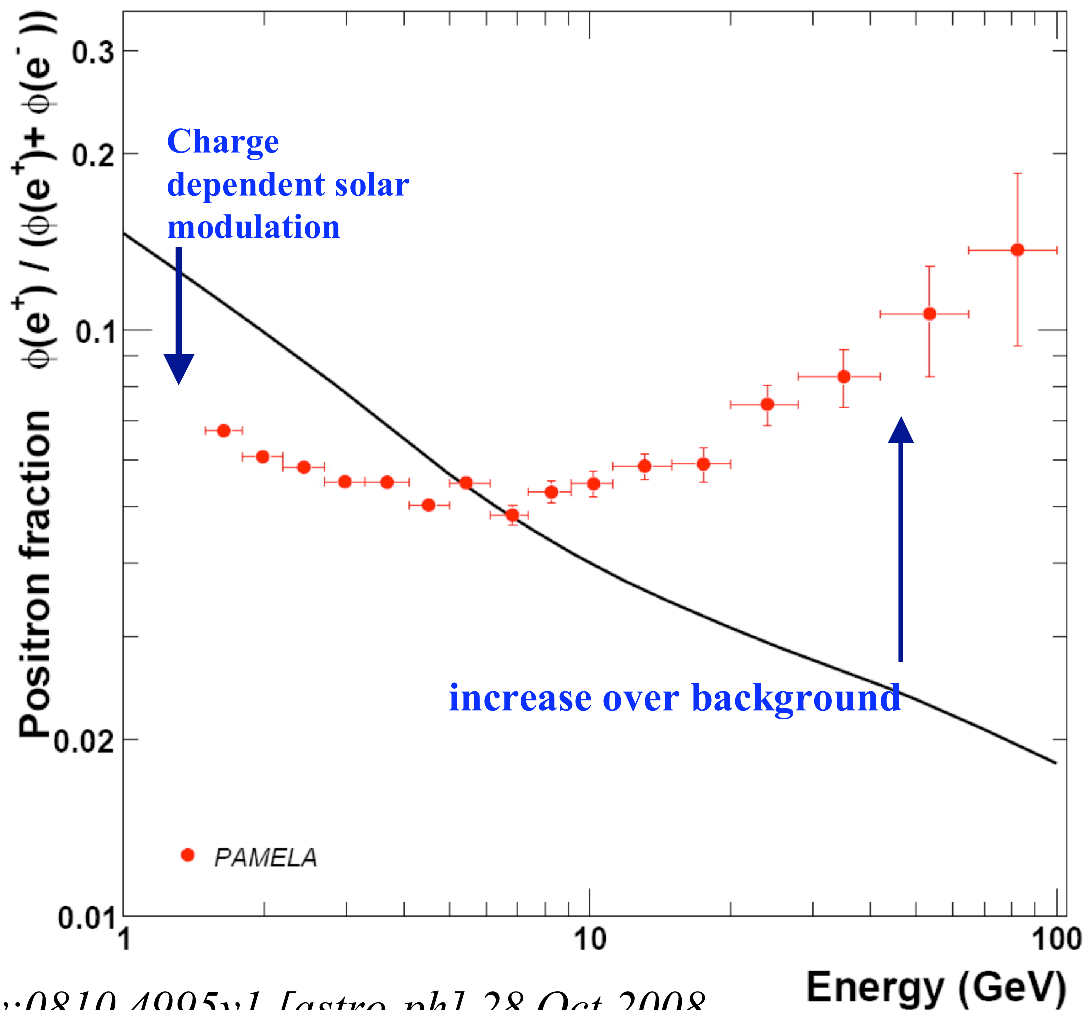
- Photons (Fermi?)
- Neutrinos (particularly from DM captured by Sun)
- charged Cosmic Rays
  - antiprotons (not!)
  - ***positrons (yes?)***
  - **electrons *(high energy excess?)***

Pamela positron fraction

- Till August 30th about 20000 positrons from 200 MeV up to 200 GeV have been analyzed

- More than 15000 positrons over 1 GeV

- Other one year of data to be analyzed



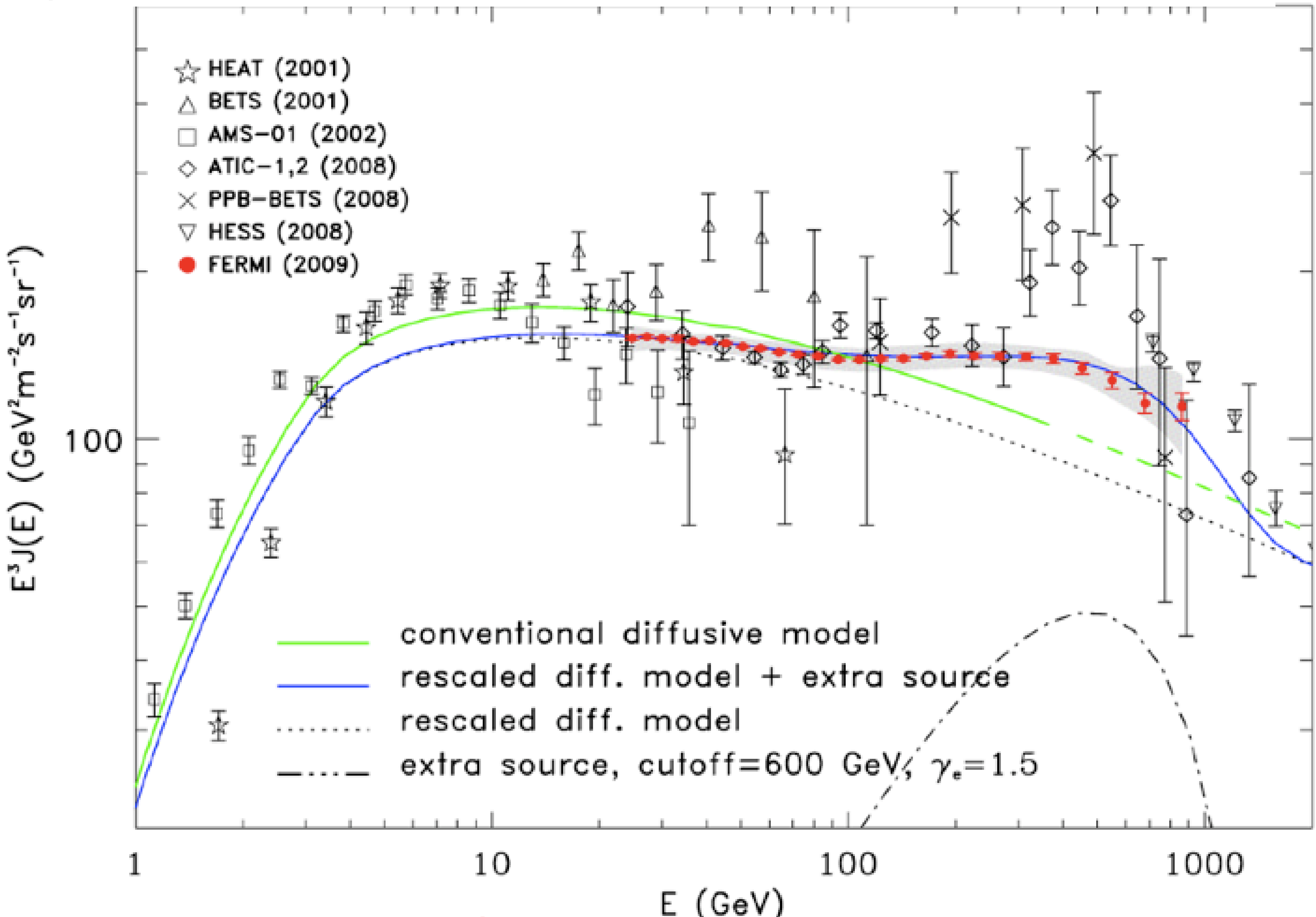
arXiv:0810.4995v1 [astro-ph] 28 Oct 2008

Nature ***458***, *607-609 (2 April 2009)*

M. Casolino, INFN & University Roma Tor Vergata

July talk at Eugene Unusual Dark Matter conference

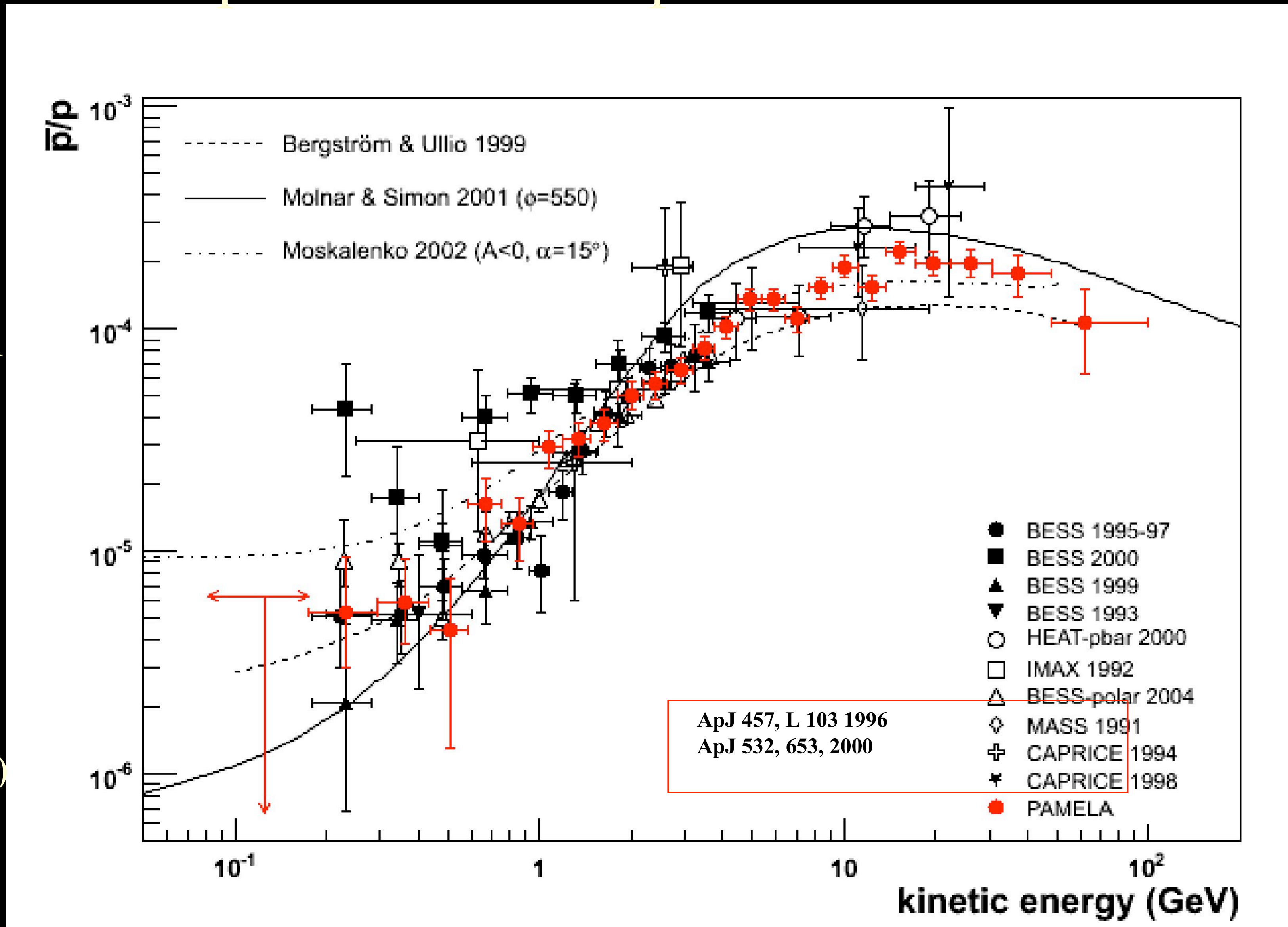
high energy excess in $e^+ + e^-$ spectrum?



T. Burnett talk at Eugene Unusual Dark Matter conference

Antiproton ratio measured with Pamela: Comparison with experimental data

- Highest energy up to now
- Coherent with secondary production
- Uncertainties of Galactic Propagation
- Would favour Moskalenko 2002 (except highest energy)



M. Casolino, INFN & University Roma Tor Vergata

arXiv:0810.4994v1 [astro-ph] 28 Oct 2008 PRL

Casolino talk at Eugene Unusual Dark Matter conference

Indirect evidence for Dark Matter annihilation seen at Pamela, ATIC, Fermi, Hess, Integral, WMAP?

Beyond vanilla WIMPS: A new ‘sector’?

Hundreds of new models proposed!

indirect detection of WIMP annihilation in the galaxy?

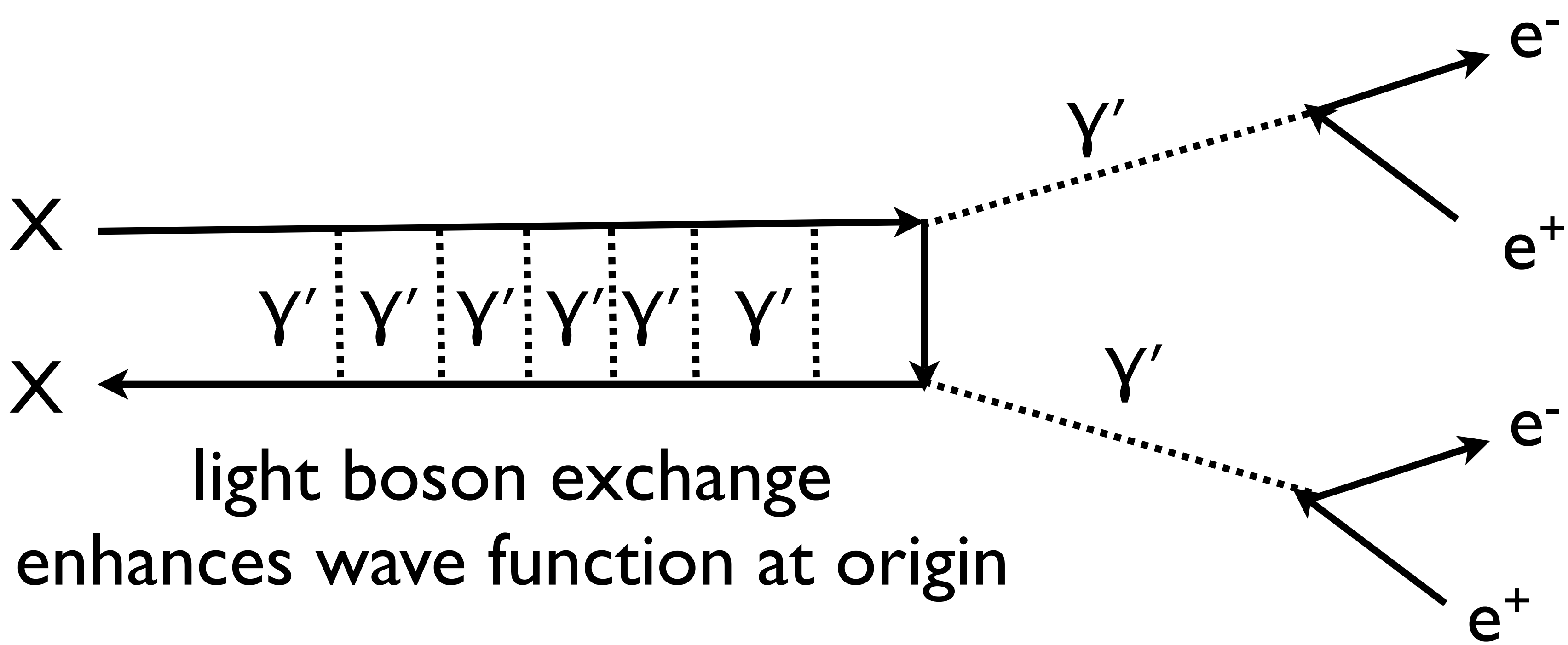
- usual annihilation into weak bosons/higgses would give too many anti protons
- Pamela, Atic, Fermi, Hess signals imply 100-1000X larger rate than the $\langle \sigma v \rangle$ which gives observed relic abundance for standard WIMP
  - not dark matter? (maybe nearby pulsar?)
  - non thermal dark matter production
  - astrophysical boost factor from clumpiness
- **Most popular: Sommerfeld enhancement via "dark force"**

Sommerfeld enhancement

(nonperturbative enhancement of annihilation at low velocity)

Hisano et al, Pospelov & Ritz, Arkani Hamed et al.

requires long range force/light boson (< few GeV)



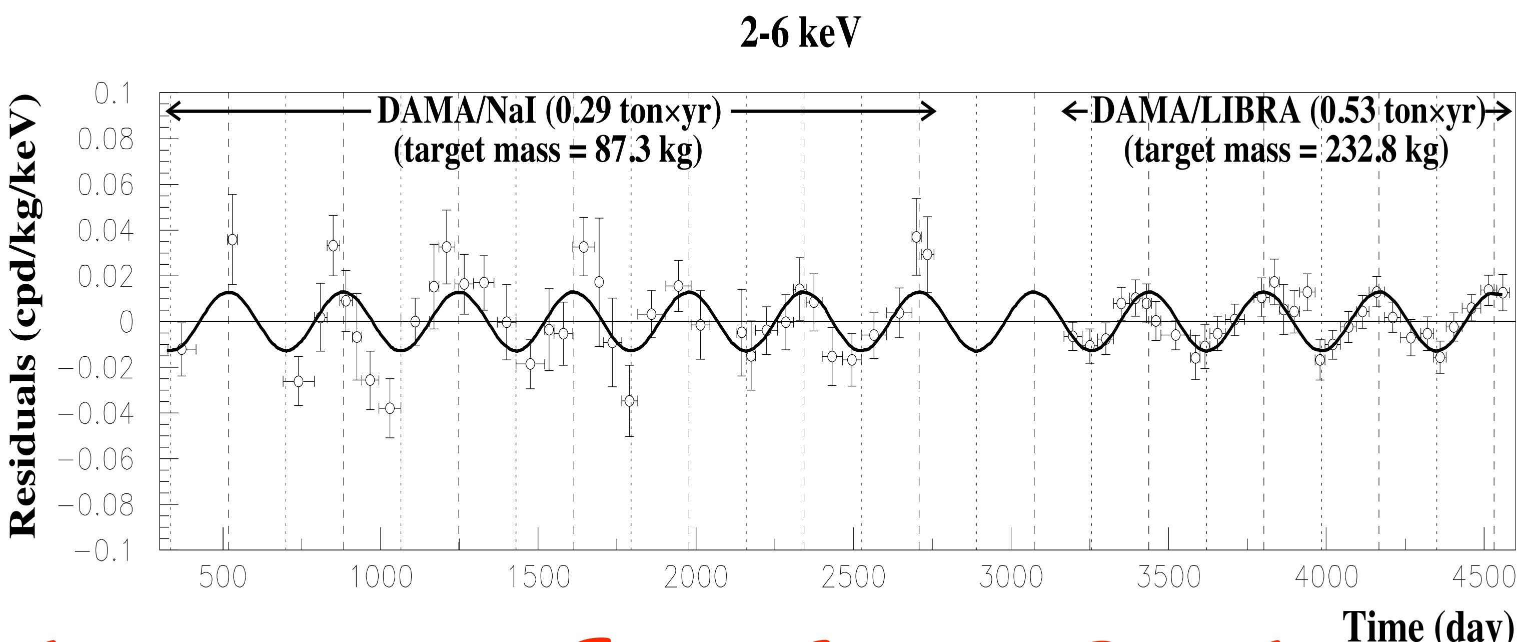
light boson exchange
enhances wave function at origin

Dark Force?

- γ' couples to dark matter charge, O(1)coupling constant
- γ' is lighter than few GeV
- γ' couples to ordinary matter, coupling < 10^{-3}
- Elegant mechanism: kinetic γ' γ mixing
- renormalizable, gauge invariant term in Lagrangian $\varepsilon F_{\mu\nu} F'^{\mu\nu}$ gives γ' $O(\varepsilon)$ coupling to usual electric charge

DAMA/LIBRA DIRECT DETECTION

Sees annual modulation, correct phase

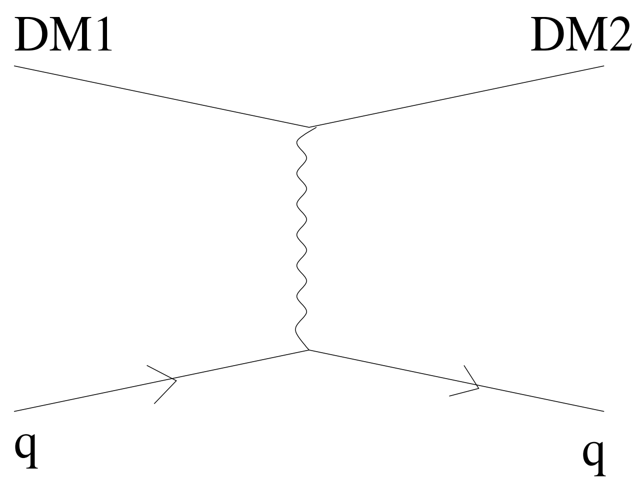


David Morrisey talk at Eugene Unusual Dark Matter conference

- Explanations using *ordinary* DM are in conflict with bounds from CDMS and XENON.

- Inelastic dark matter (iDM) can resolve this.

  Assumption: DM scatters coherently off nuclei preferentially into a slightly heavier state. [Tucker-Smith+Weiner '01]



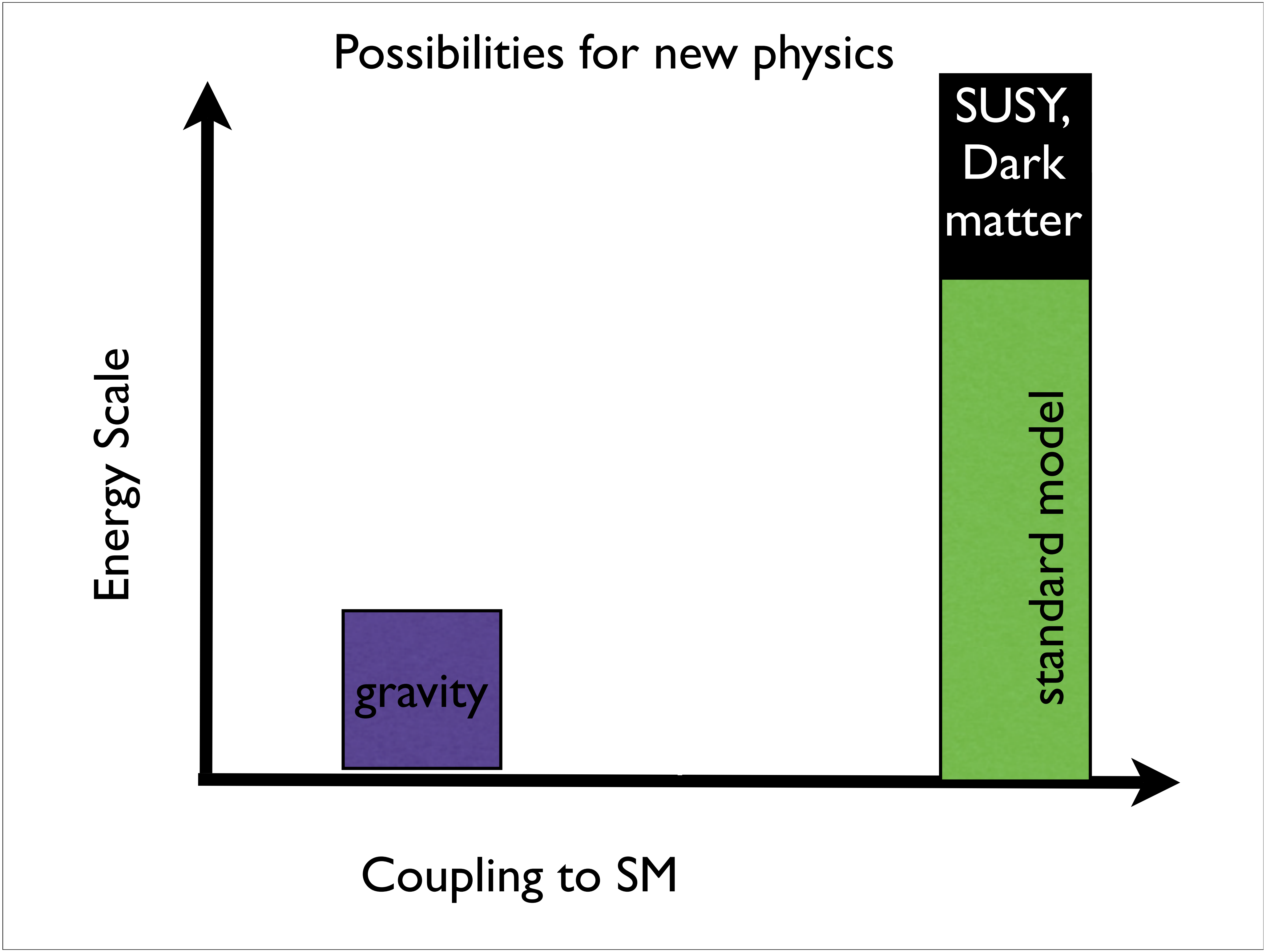
$$M_{DM1} \sim 100\,\text{GeV}, \qquad M_{DM2} - M_{DM1} = \delta \sim 100\,\text{keV}$$

- The inelastic splitting can be generated by a GeV sector.

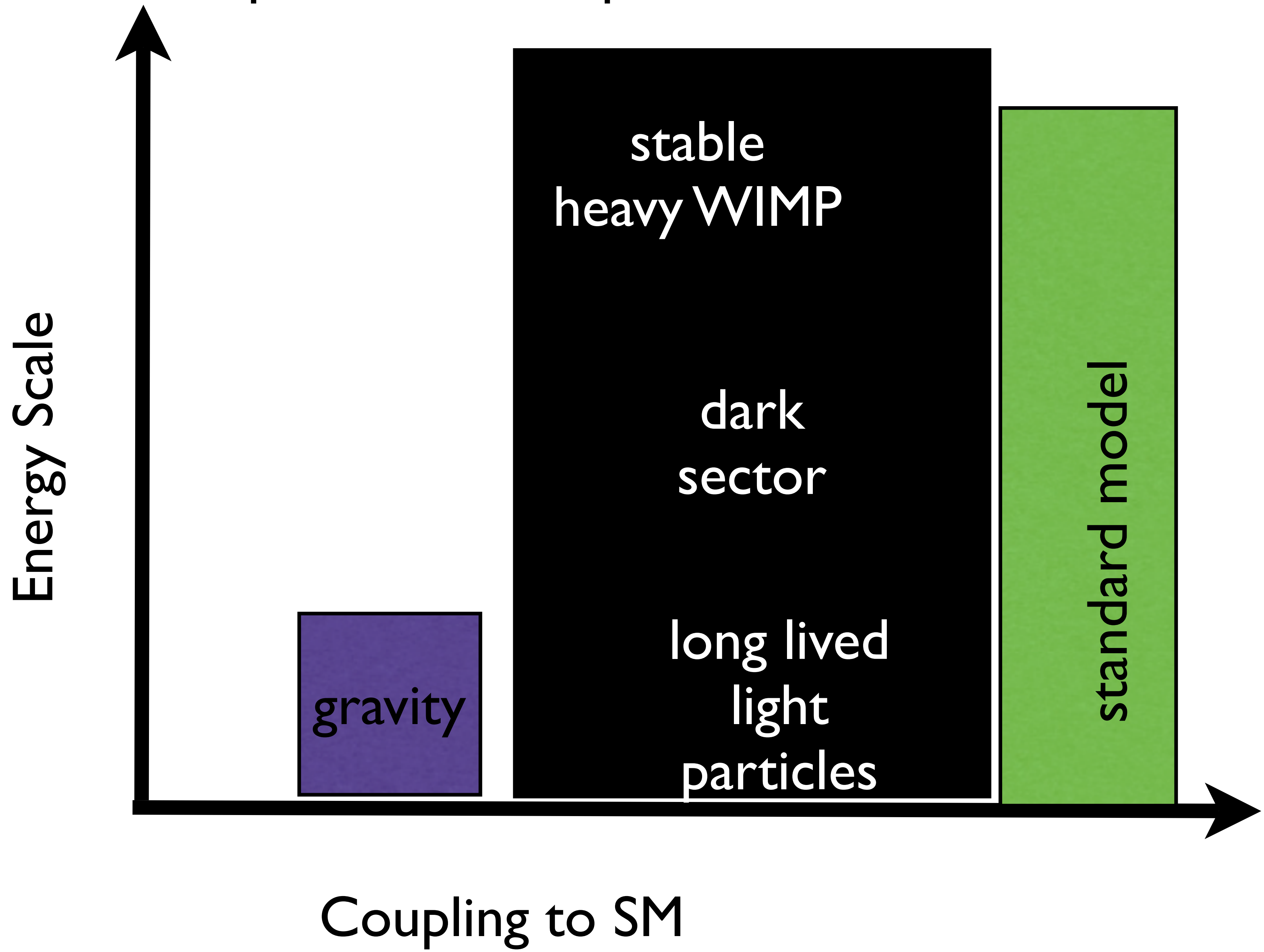
David Morrisey talk at Eugene Unusual Dark Matter conference

Summary of experimental situation

- PAMELA, Fermi and other cosmic ray expts may have provided first clues to identity of dark matter
- or found high energy charged particles created by a pulsar or other astrophysical source
- if dark matter, must explain large annihilation cross section, lack of antiprotons
- a light mediator particle can explain both
- small splitting in dark matter spectrum can reconcile DAMA, CDMS
- A new sector? (particles with O(1) couplings to each other, weak couplings to us)


Possibilities for new physics
Energy Scale
gravity
SUSY, Dark matter
standard model
Coupling to SM

Expanded landscape of Dark Matter



ILC and dark sector

- We’ve designed LHC, ILC to explore the high energy frontier. What if dark matter is in a weakly coupled sector?

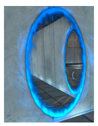
"Portals" into exotic sectors: gauge invariant low dimension operators

Leading low energy visible-hidden couplings:

- Scalar: $H^{\dagger}H\ \varphi$
  - ⇒Higgs mixing with hidden light scalars
  - ⇒Higgs decay to hidden sector
- Vector: $B_{\mu\nu}\ X_{\mu\nu}$
  - ⇒photon mixing with hidden light vector
  - ⇒Z decay to hidden sector

"Portals" into exotic sectors: gauge invariant low dimension operators cont

low energy visible-hidden couplings:

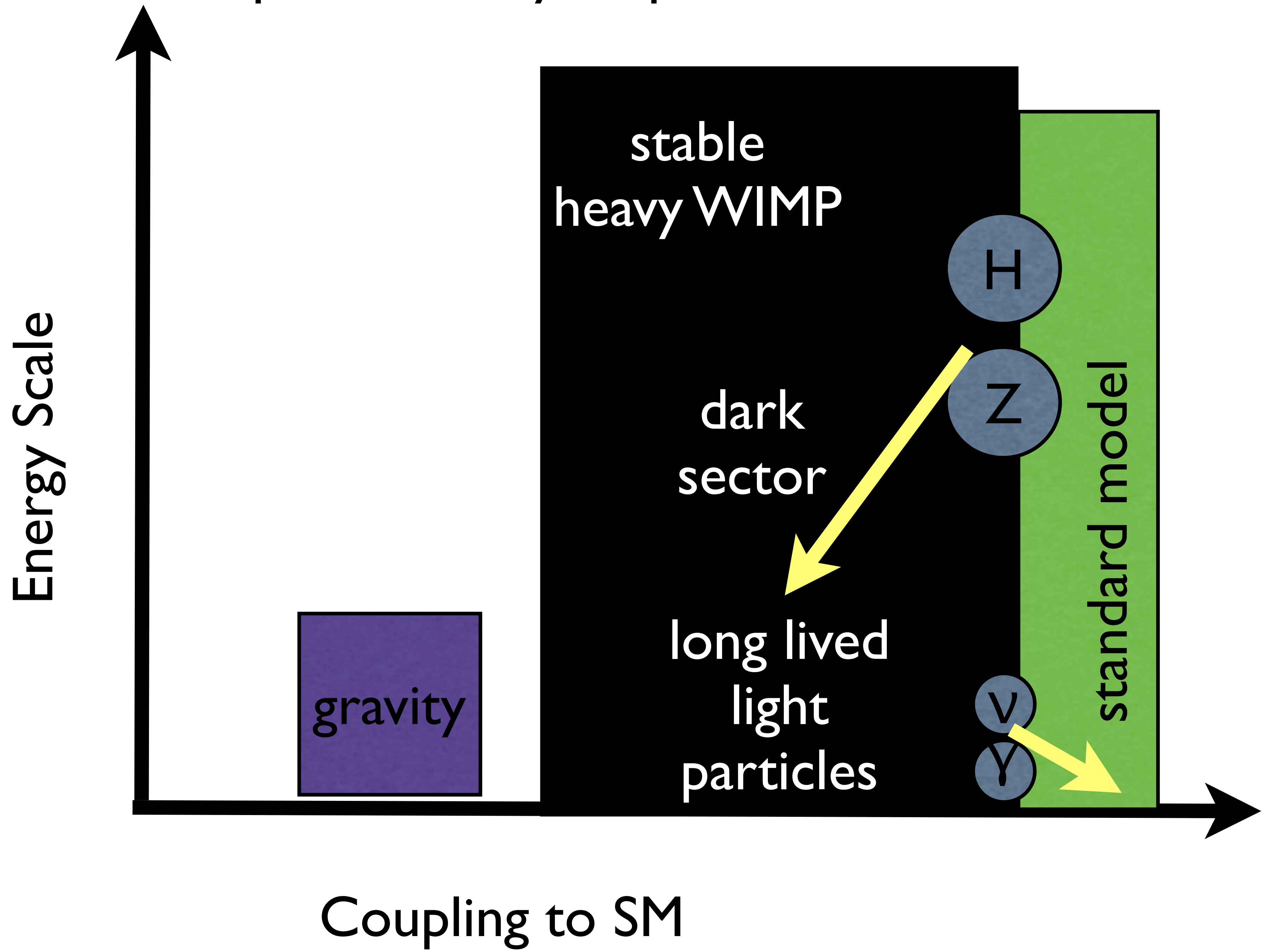
Spin 1/2: $H\ell\mathcal{N}$

⇒neutrino mixing with hidden light fermions

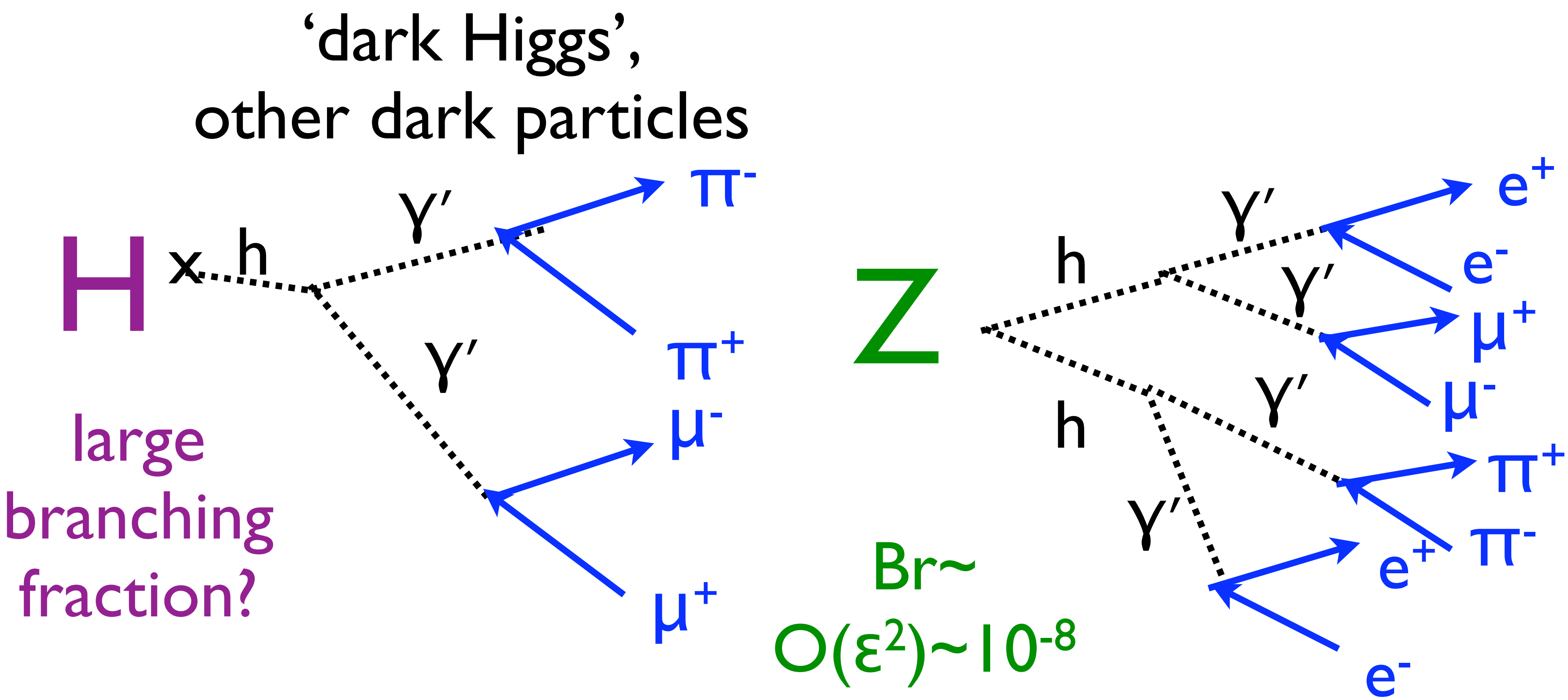
⇒FCNC Dark fermion decay into neutrinos

⇒CC Dark fermion decay, e.g. $e^+ e^- \nu$, $\mu^+ e^- \nu$, $\mu^+ \pi^- \nu$ ....

Neutral particles may be portals to dark sector



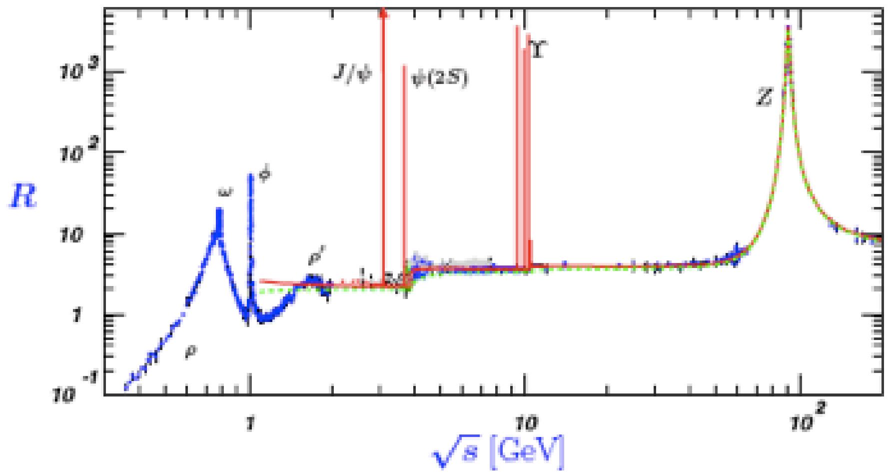
Usual Z, Higgs production, Unusual decays



low mass charged particle pairs, displaced vertices

Dark Photon decay branching ratios:

- Decay form factor has been measured, known as R.



$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons},\ s)}{\sigma(e^+e^- \to \mu^+\mu^-,\ s)} = \frac{BR(b_\mu \to \text{hadrons})}{BR(b_\mu \to \mu^+\mu^-(\text{or } e^+e^-))}\ (m_b = s)$$

$$\sim \frac{BR(b_\mu \to \pi^+\pi^-)}{BR(b_\mu \to \mu^+\mu^-(\text{or } e^+e^-))},\ \text{for } m_b \leq \text{GeV}$$

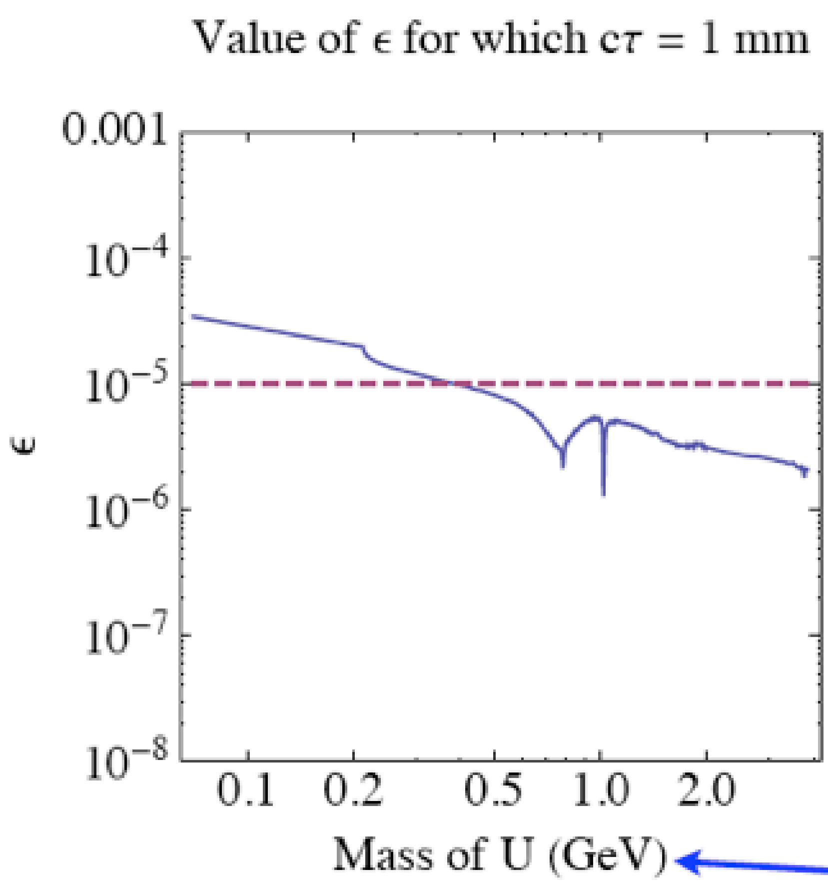
For example: $\pi^+\pi^- : \mu^+\mu^- : e^+e^- \simeq 1 : 1 : 1$ for $m_b \simeq 600$ MeV.

I will focus mainly on leptons here.
But, the hadronic final states can be interesting as well.

Lian Tao Wang talk at SLAC Dark Forces workshop

Life time of dark photon

- Prompt, except for tiny couplings, or very large boost.

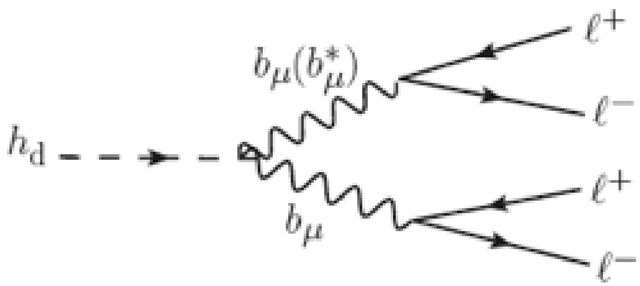


$$c\tau \sim \alpha\epsilon^2 m_{b_\mu}$$
$$= 3\times 10^{-6}\text{cm}\left(\frac{\text{GeV}}{m_{b_\mu}}\right)\left(\frac{10^{-3}}{\epsilon}\right)$$

$m_{\rm U} = m_{b_\mu}$, dark photon mass

Lian Tao Wang talk at SLAC Dark Forces workshop

Decay of dark higgs



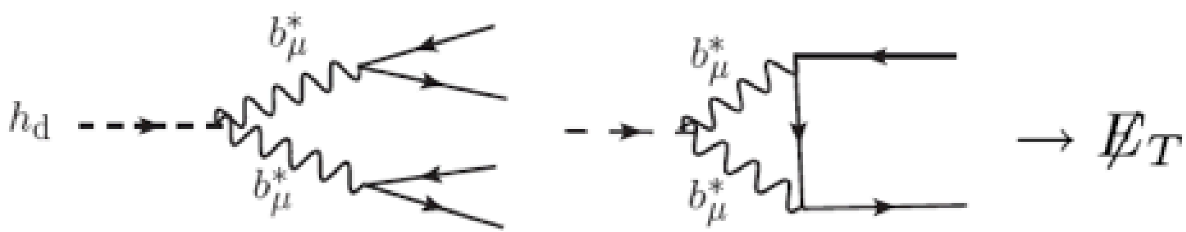
$m_{h_d} > m_b \;\rightarrow\; 4\ell$ final state

Can have displaced vertex if $m_{h_d} < 2m_b$

For example:

$\epsilon = 10^{-3}, \;\; m_{h_d} = 1.2 \text{ GeV}, \;\; m_{b_\mu} = 1 \text{ GeV}$

$c\tau \sim 10(\text{s})$ cm



For $m_{h_d} < m_{b_\mu}$

Very long lived: $c\tau \sim 10\text{s m} - 10^2$ km.

Lian Tao Wang talk at SLAC Dark Forces workshop

Exotic Portals into exotic sectors

- New heavy particle with interactions in both sectors

  ⇒ SM production of charged, colored particles with new gauge interaction

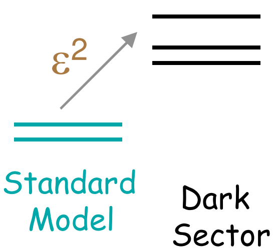
  ⇒ Z′ decaying into both visible, hidden sectors

- Metastable heavy particle with shared quantum number

  ⇒ SUSY LSP with R parity

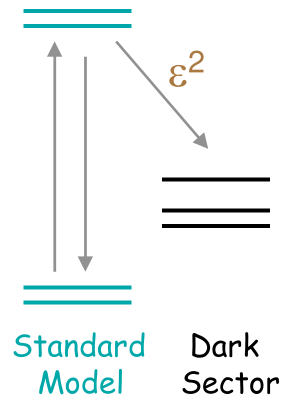
Dark Sector Production at High Energy Colliders

Direct Production



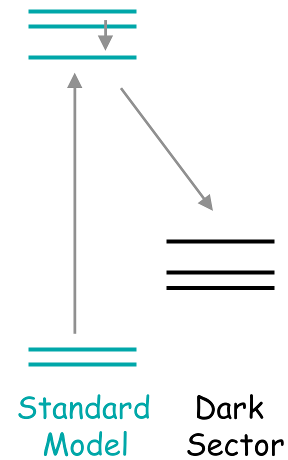
σ » $O(\varepsilon^2)$

Indirect Production



Br » $O(\varepsilon^2)$

Indirect Production with Shared Conserved Quantum Number



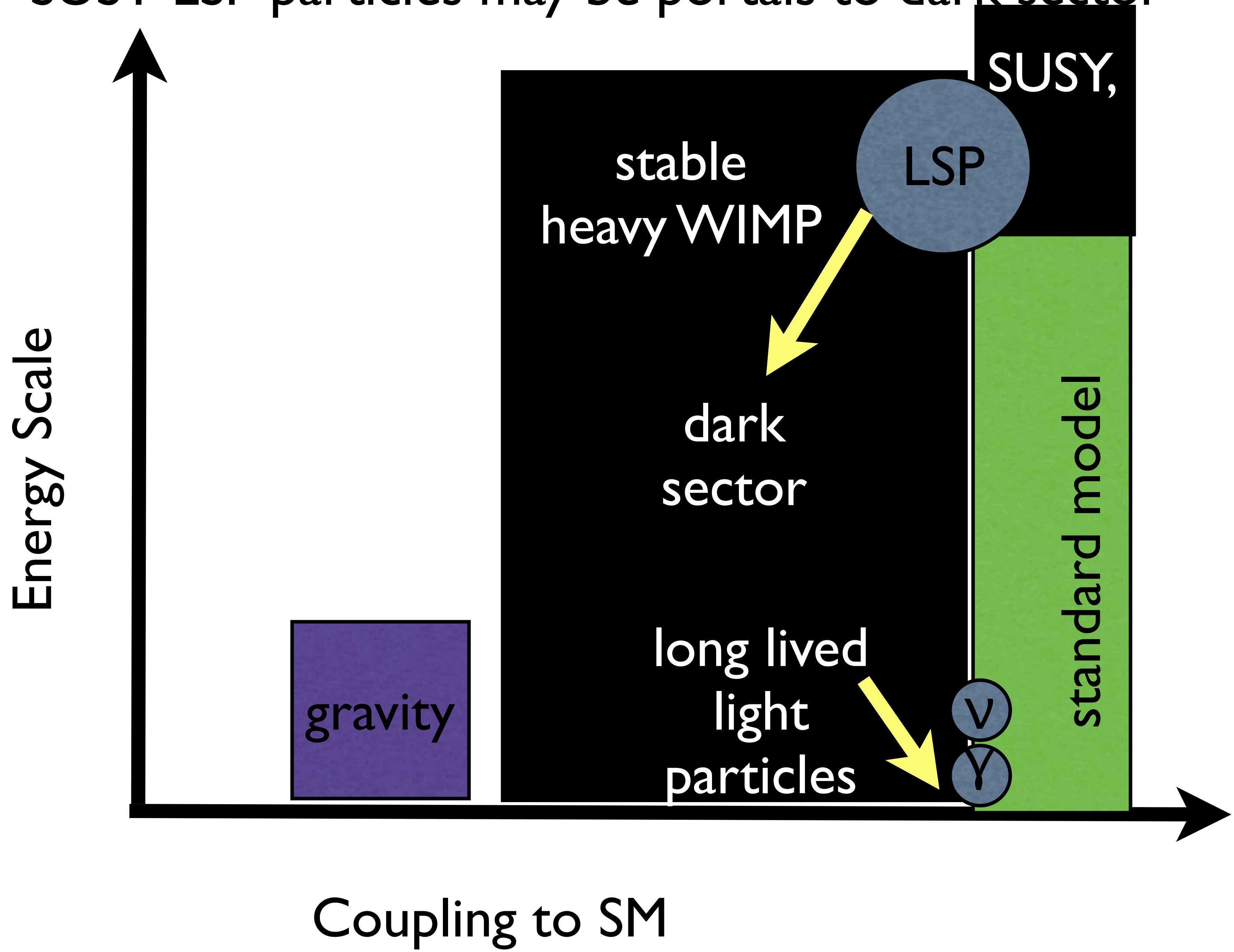
σ ¢ Br » $O(\varepsilon^0)$

Which Dark Sector States Populated –
Depends on Production Portals

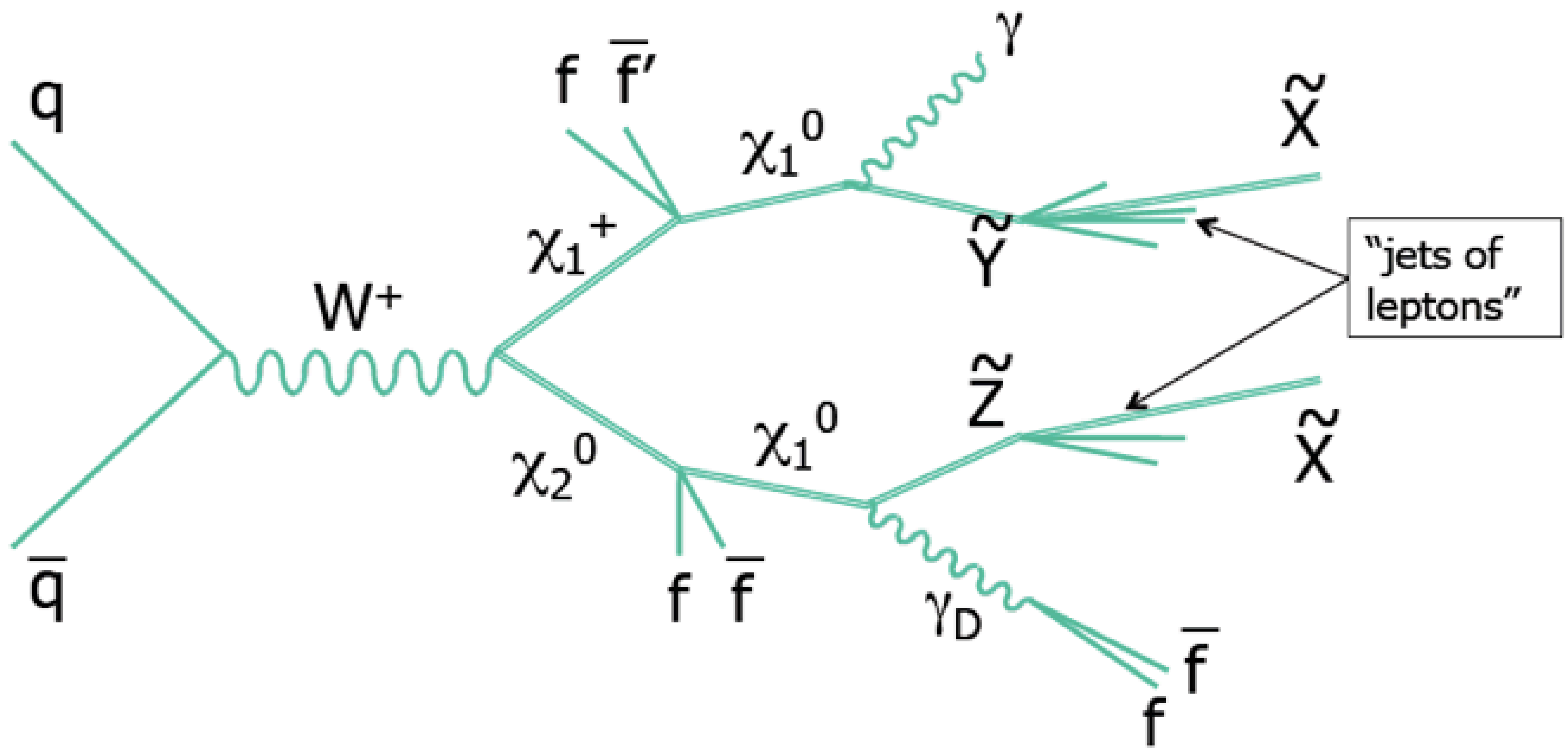
Portal » ε

Scott Thomas talk at SLAC Dark Forces workshop

SUSY LSP particles may be portals to dark sector



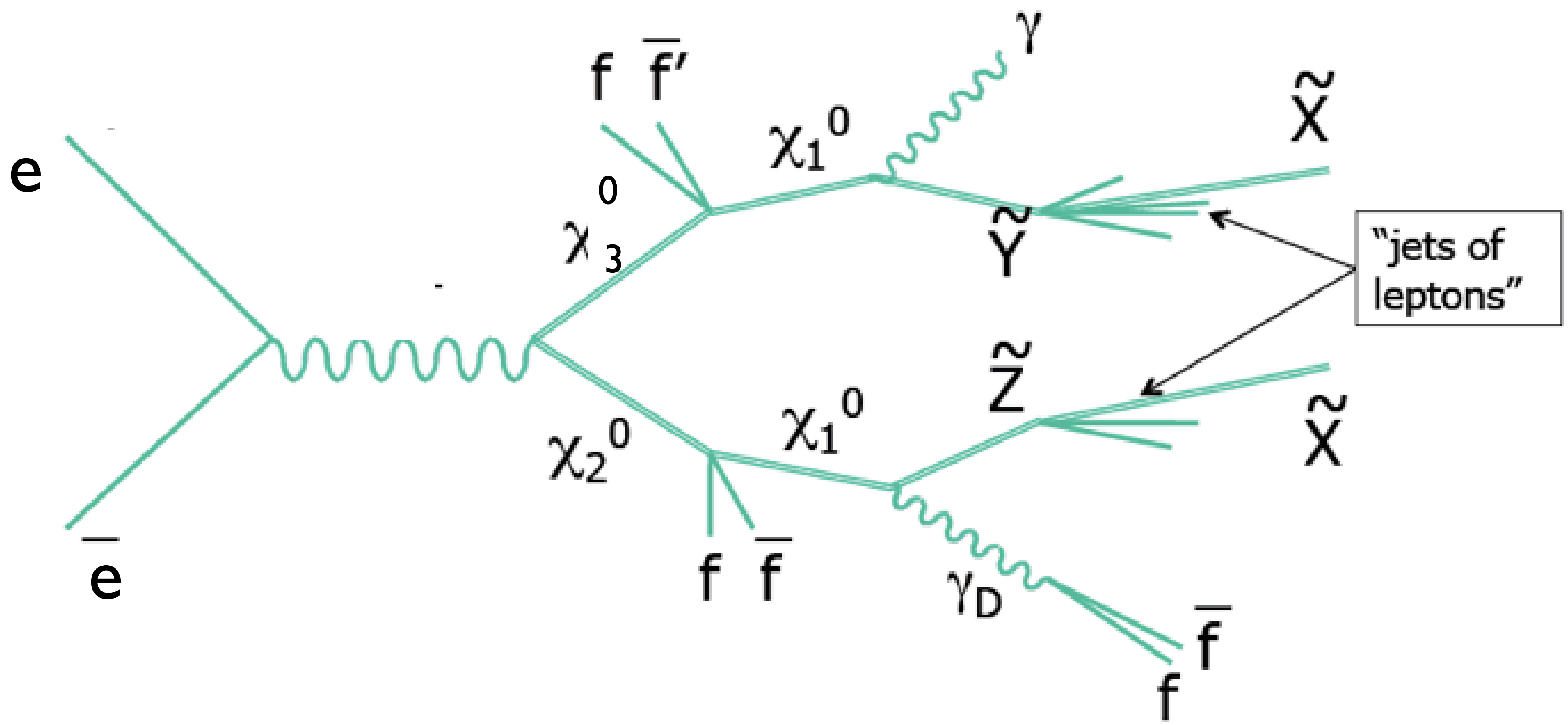
SUSY with a Hidden Valley



smaller MET, but not by much:
splitting between dark states ~O(MeV), leptons/hadrons from transition are relatively soft (and may be delayed). Have not tried to simulate

Y. Gershtein talk at SLAC Dark forces conference

Lepton jets at the ILC?



Summary

- Era of exploration of dark matter is well underway
- Just as for Electroweak symmetry breaking, consider wide variety of models (not just SUSY/UED WIMP!)
- "non minimal hidden sector" models for recent anomalies, with unusual implications for
  - direct detection
  - indirect detection
  - collider production
- a few possible ILC signatures:
  - displaced vertices
  - GigaZ: unusual rare Z decays
  - lepton jets