Heidelberg, Feb 2009

Dark Matter and LHC

(a work in progress)

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Thanks to Heidelberg University!
(what's up Terascale alliance?)

Dark Matter

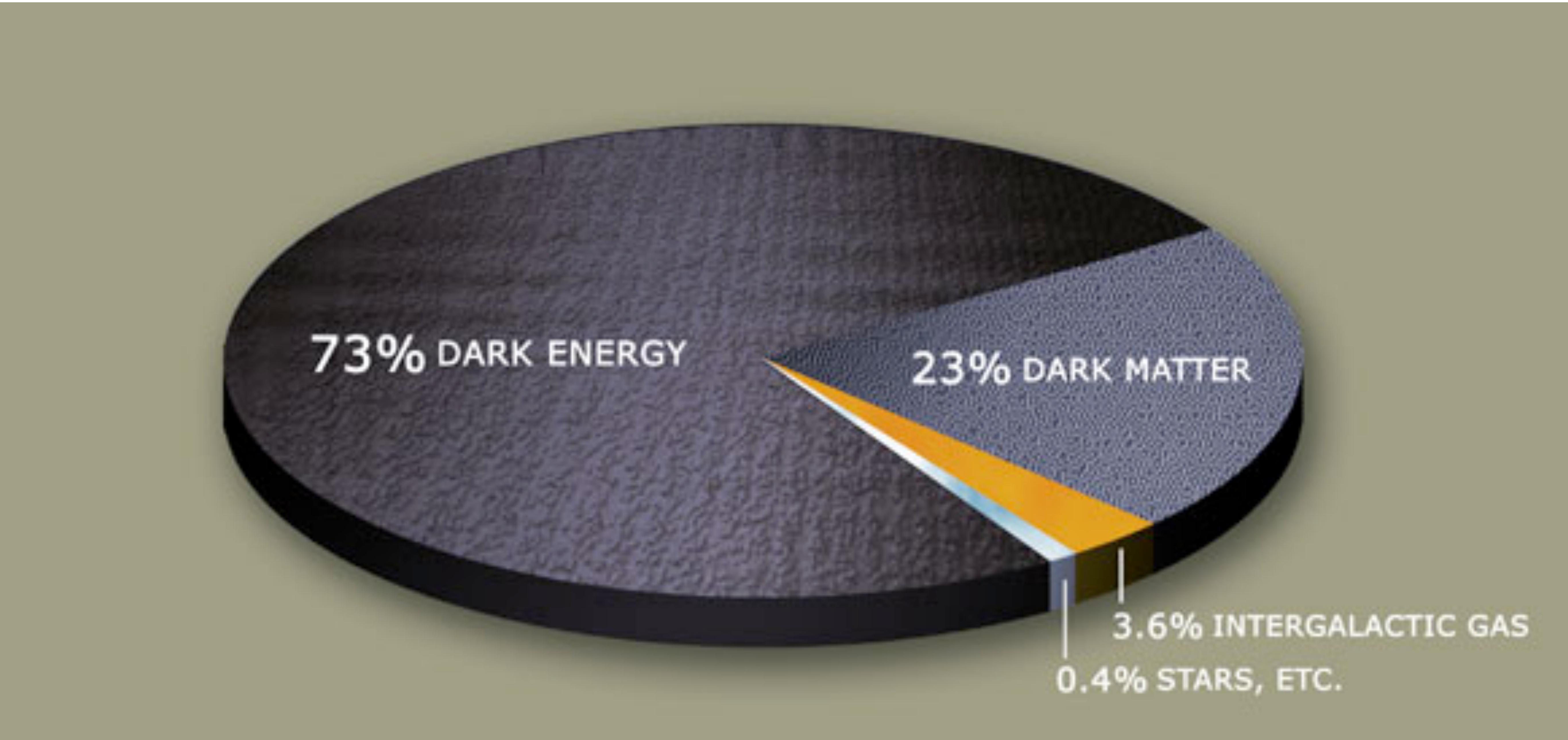
Of all the puzzles in particle physics...

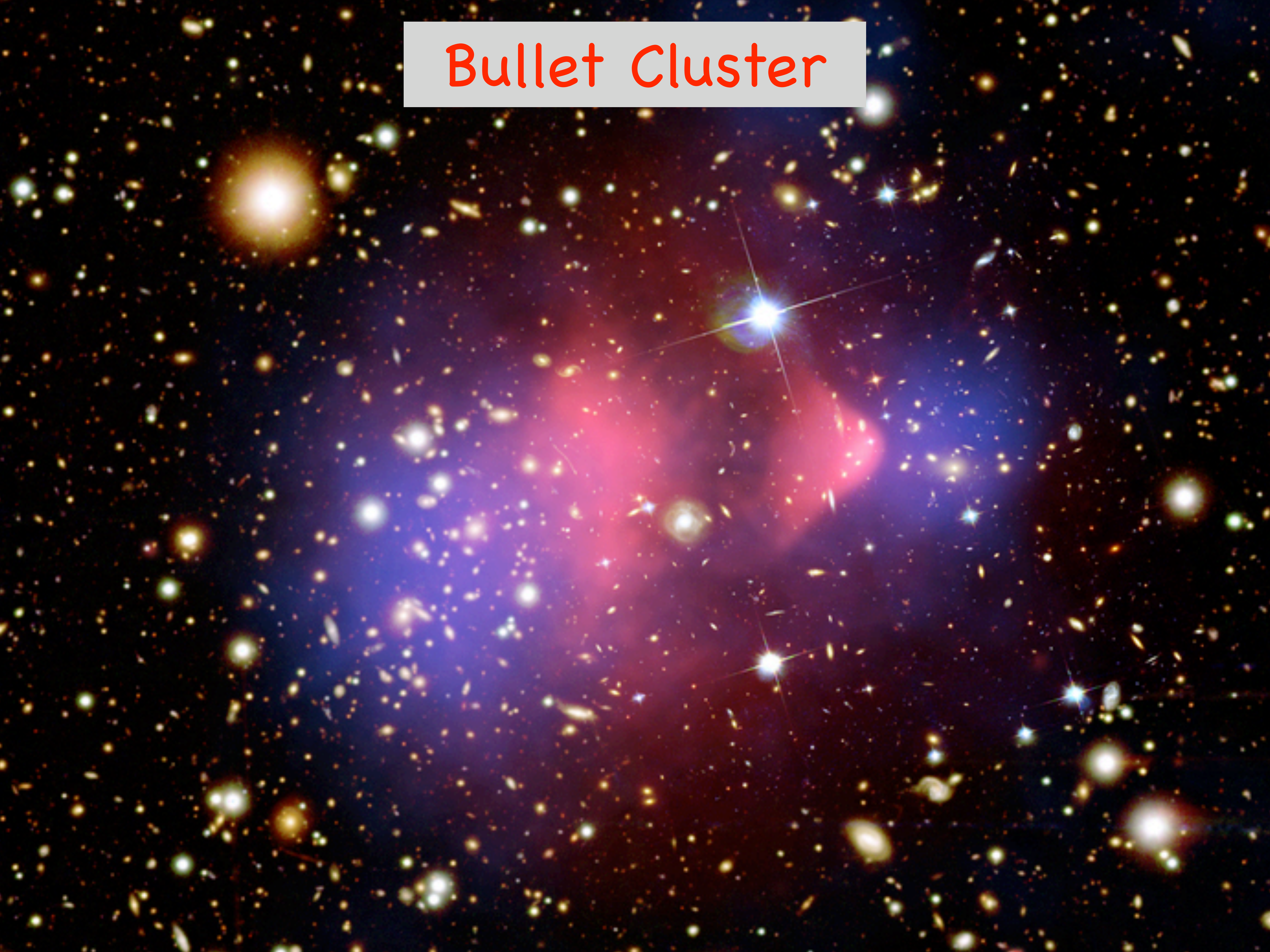
- EWSB: $m^2_H \approx \Lambda^2$
- Cosmological constant: $CC \approx \Lambda^4$
- # generations
- quasi-random quantum numbers
- ...

The existence of dark matter is real BSM that is not about aesthetics, fine-tuning, beauty...

Evidence is Overwhelming

Nucleosynethesis | Weak Lensing
Rotation Curves | CMB
Structure Formation | BAO




Bullet Cluster

We don't know:

Mass of Dark Matter

Composition of Dark Matter

Interactions of Dark Matter

We do know:

1) Dark matter is (rather) dark

2) $\rho_{DM} \approx 5\ \rho_{matter}$ (averaging over Universe)

3) DM is cold

4) IF thermal freezeout, $\Omega h^2 \approx 0.1 \frac{1\ \mathrm{pb}}{\langle \sigma v \rangle}$

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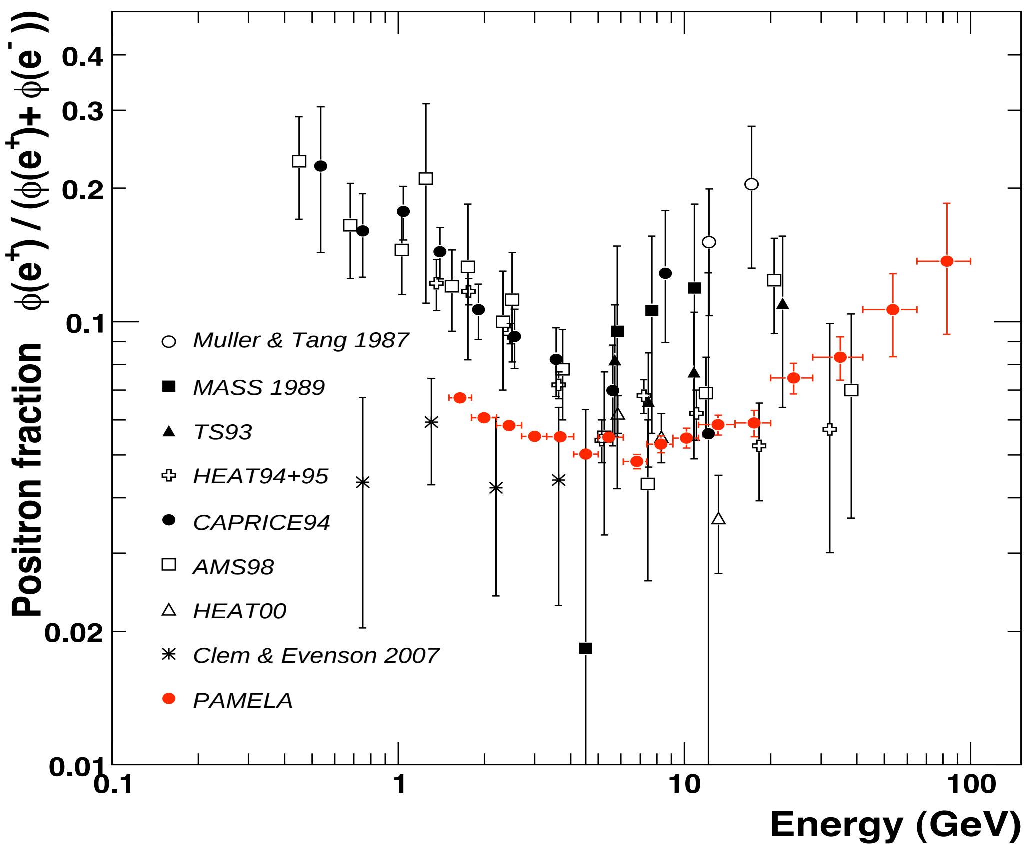
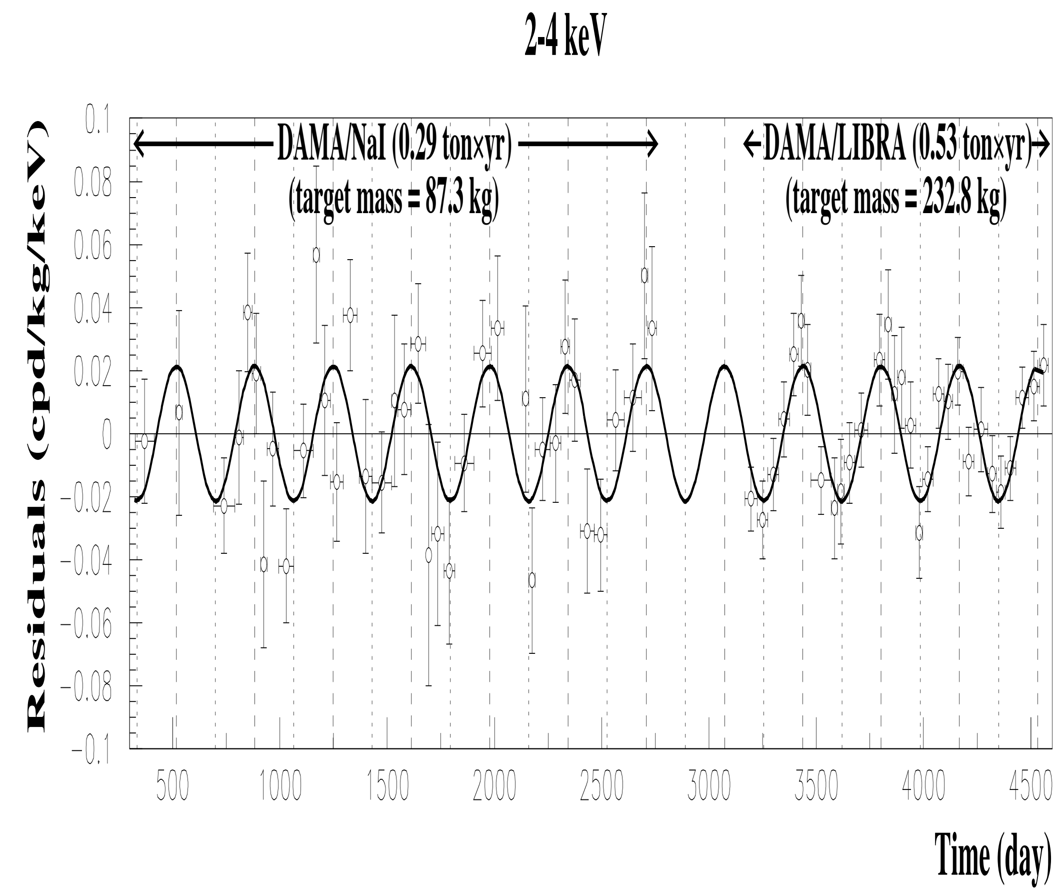
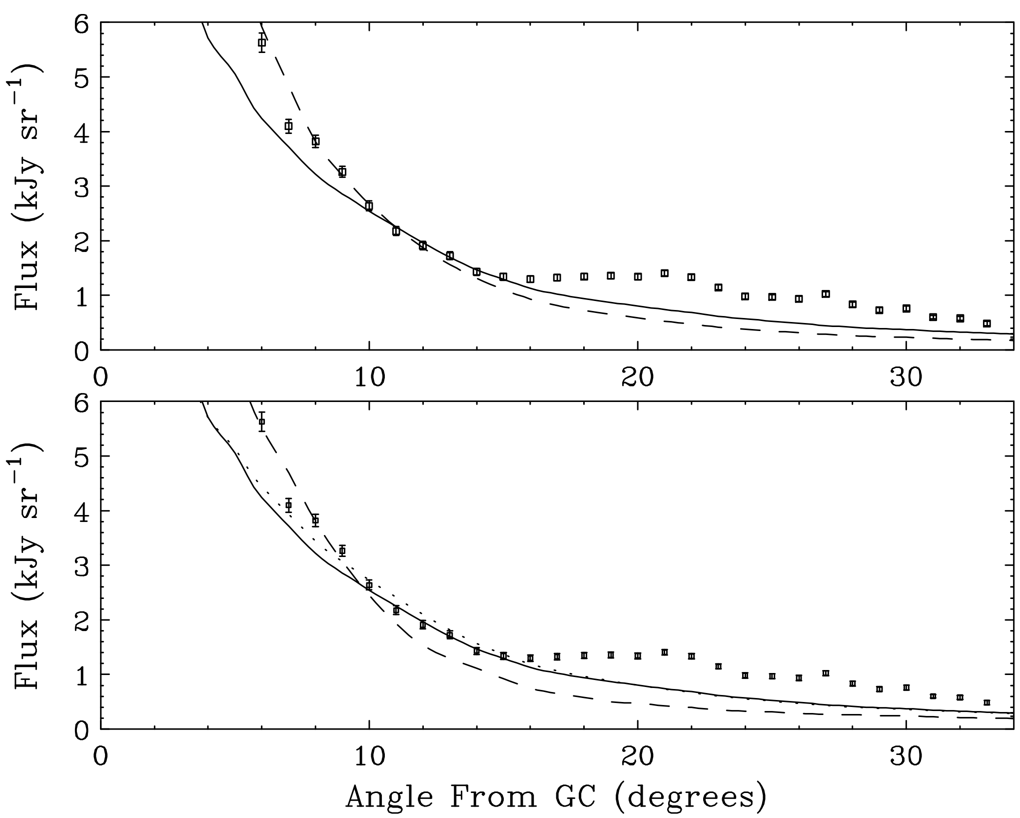
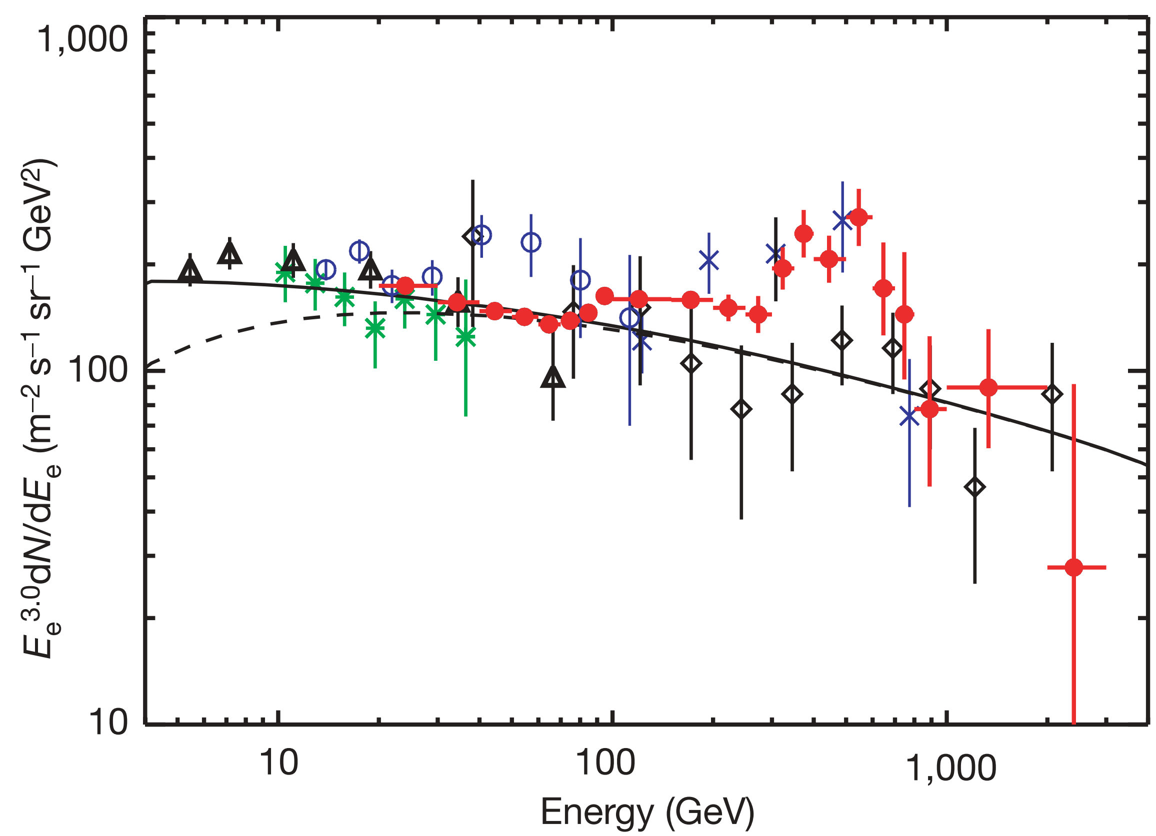
1 pb scale motivates "WIMPs"

Intriguing hints...









LHC:

What kind of WIMPs?

Supersymmetry

Typical rationale:

"SUSY naturally has R-parity"

"SUSY naturally has the right relic abundance"

"SUSY naturally solves the hierarhcy problem"

PDG 2008: "The currently best motivated candidate is the LSP in SUSY models with R-parity"

"SUSY naturally has R-parity"

Actually, SUSY has a disasterous proton decay problem that was swept under the rug by imposing R-parity.

(And there remains a dim-5 proton decay problem.)

Lesson: Any BSM model can have a stable particle, by imposing a parity that may or may not solve some self-created problem.

“SUSY naturally has the right relic abundance”

If sneutrino, ruled out* by direct searches.

If bino, need light slepton otherwise $\Omega h^2 \geq 0.1$
(coannihilation region, etc.)

If Higgsino or neutral Wino; “natural” mass scale
is 1–2 TeV to get Ωh^2 up to 0.1

Lesson: SUSY possible, but getting squeezed.
Need some degree of tuning or TeV scales
or “non-thermal” (abandon 1 pb scale).

"SUSY solves the hierarhcy problem"

Yes, so long as the supersymmetry mass
$\mu \approx$ weak scale.

LEPII taught us $\mu \geq 100$ GeV, while
indirect constraints ($H^{\pm}$ contribution to $b \to s\gamma$)
suggest even larger values, leading to
little hierarchies, and thus more fine-tuning

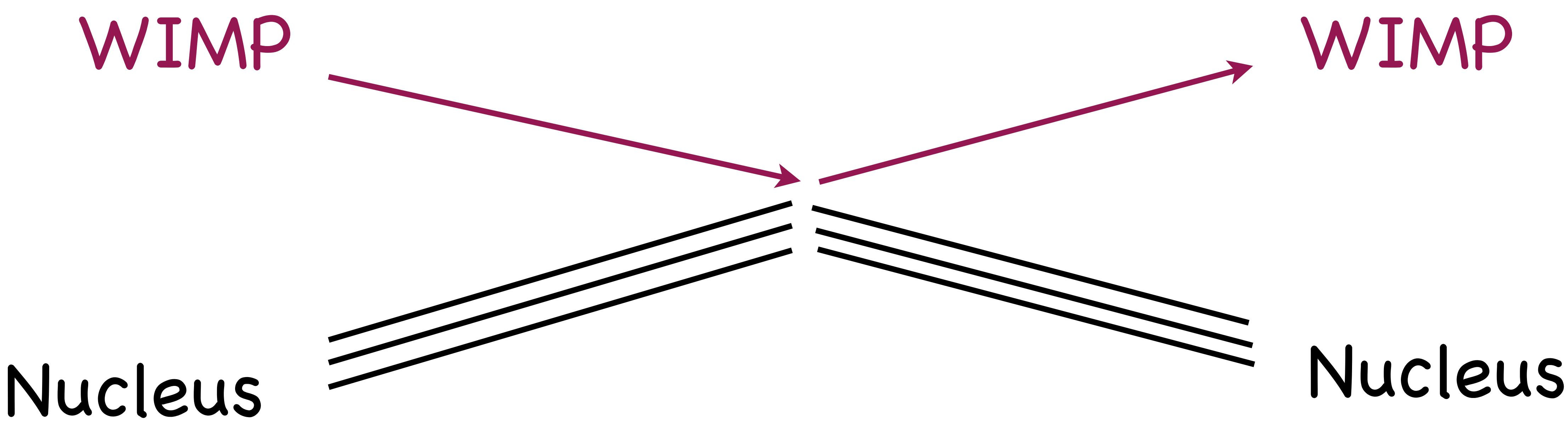
Lesson: Hierarchy problem solved only with SUSY
and solution to "μ problem"

Ready for New Ideas?

Ready for New Ideas?

(experimentally driven)

One of the most striking constraints on WIMPs is direct detection:

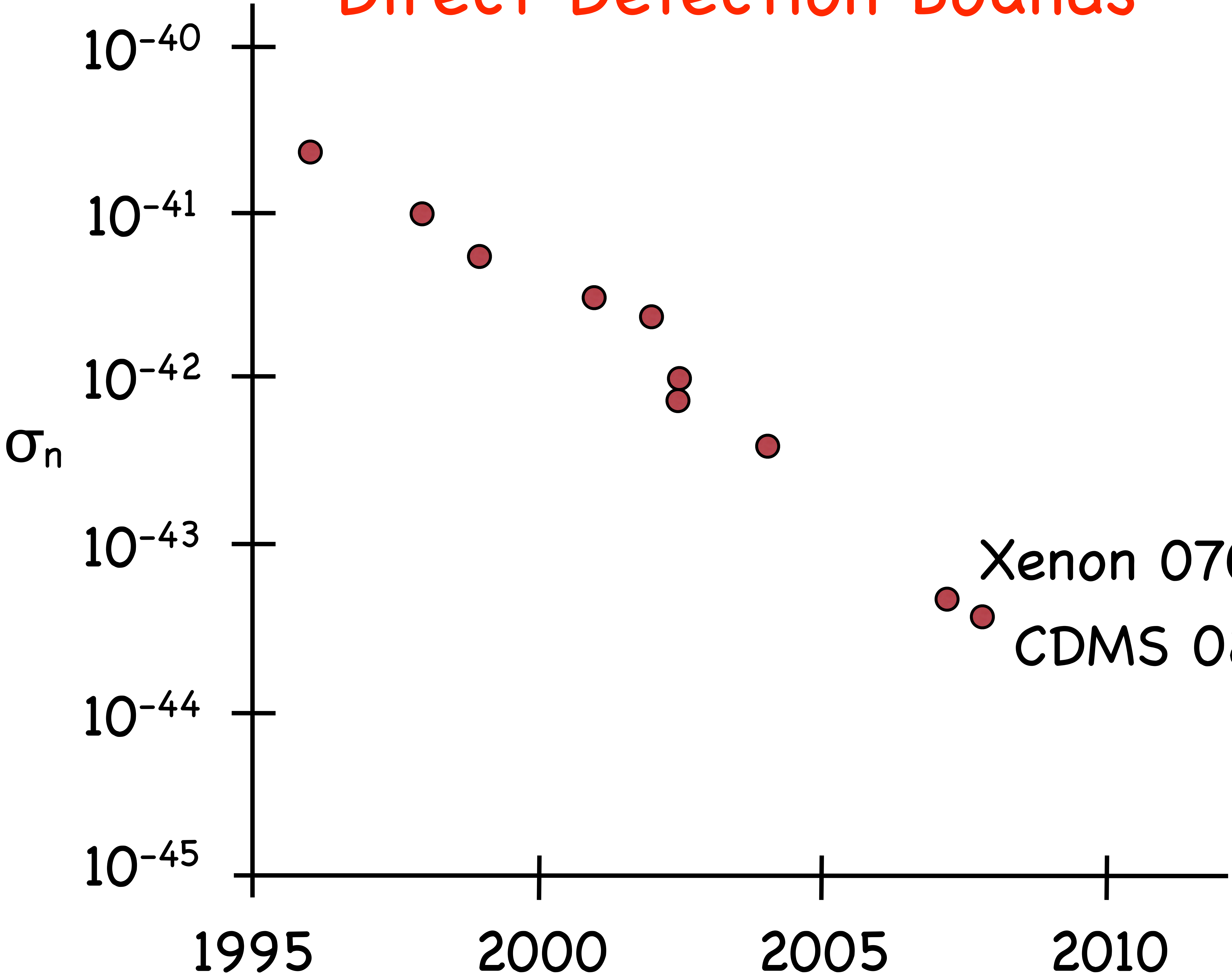


If the WIMP-nucleon coupling is coherent w.r.t. mass

Effective nucleon cross section [for M ≥ m(Nuc)]:

$$\sigma_n \approx \frac{\mu^2(n,D)\ I(n)}{\mu^2(N,D)\ I(N)} \approx \frac{\sigma(N)}{A^4}$$

Direct Detection Bounds



(adapted from Gaitskell 2004)

Original (1980s) hope for WIMPs

Acquire

- mass from EWSB
- coupling to SM through EW interactions

e.g. fourth geneneration neutrino that acquires Dirac mass with ν_{4R}

Such WIMPs have true Weak Interactions:

Vector interactions to SM with G_F strength:

$$\frac{\bar{\nu}_4 \, \gamma^\mu \, \bar{\nu}_4 \, q \, \gamma_\mu \, q}{v^2_{246}}$$

Leads to WIMP-nucleon scattering cross section

$\sigma_n \approx 0.1$ pb! (for $\approx$ 100 GeV WIMP)

This is ruled out by 6 orders of magnitude!!

Direct Detection Suggests:

Either:

- WIMPs couple to all SM fermions with sub-weak interaction strength (vector "g" $\lesssim$ 0.01; or Higgs exchange; or ...)

- WIMPs couple to leptons, not quarks (or gluons) Evades all direct detection constraints.

- Not thermal freezeout (forget about 1 pb scale)

- ...

WIMPs Couple to Leptons?

(a few comments to inspire discussion)

New Dirac Fermion: D

(Harnik, GK)

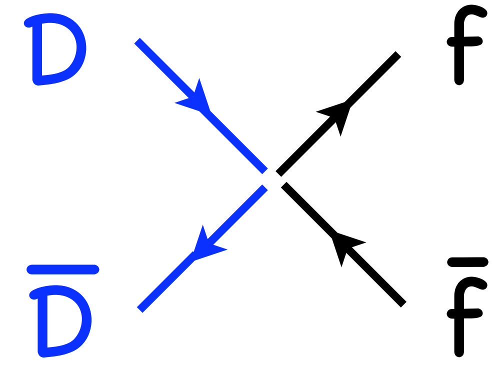
- New Dirac fermion D neutral under SM gauge group

- Global $U(1)_D$ conserved

- Interactions with SM through higher dimensional operators -- effective theory!

Higher Dimensional Operators

$$\frac{\bar{D}D\bar{f}f}{\Lambda^2} \longrightarrow$$



$1/\Lambda^2$

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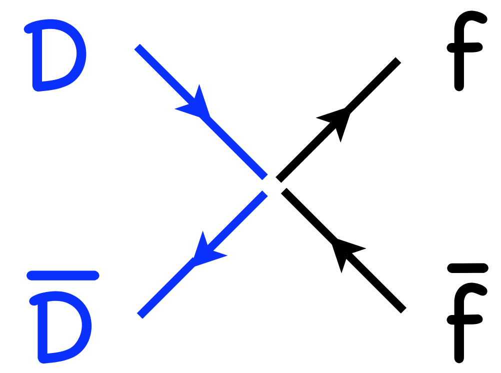

$1/\Lambda^2$

(focus on f = lepton, f ≠ quark; perfectly fine for EFT)

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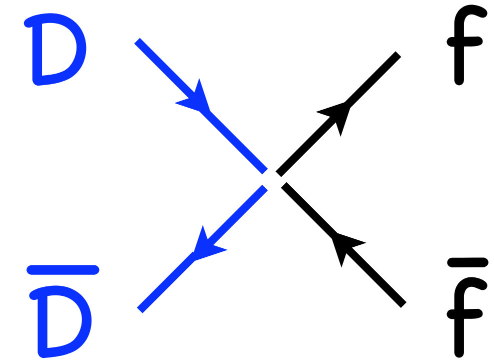
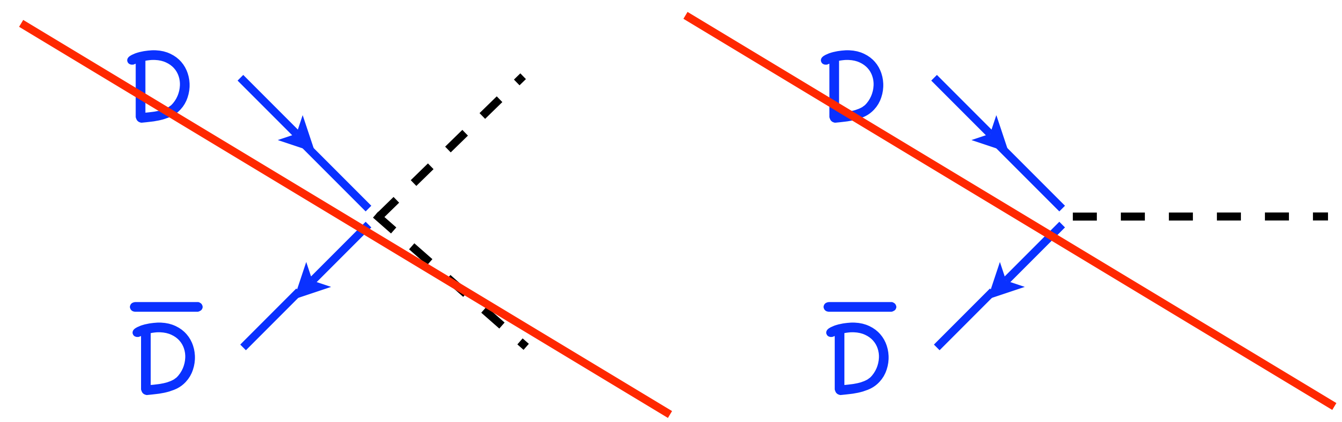


$1/\Lambda^2$

(focus on f = lepton, f ≠ quark; perfectly fine for EFT)

$$\frac{\bar{D}DH^{\dagger}H}{\Lambda} \longrightarrow$$



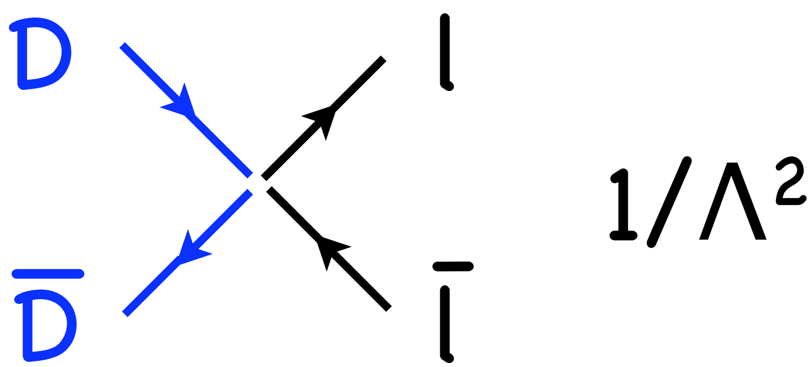
ignore -- Higgs mass dependent
and leads to coupling to quarks, again
(hard to realize in UV completion)

Thermally averaged cross section

$$\langle\sigma v\rangle = \sigma_0 + \sigma_2 v^2 + \ldots$$

Dirac fermion:

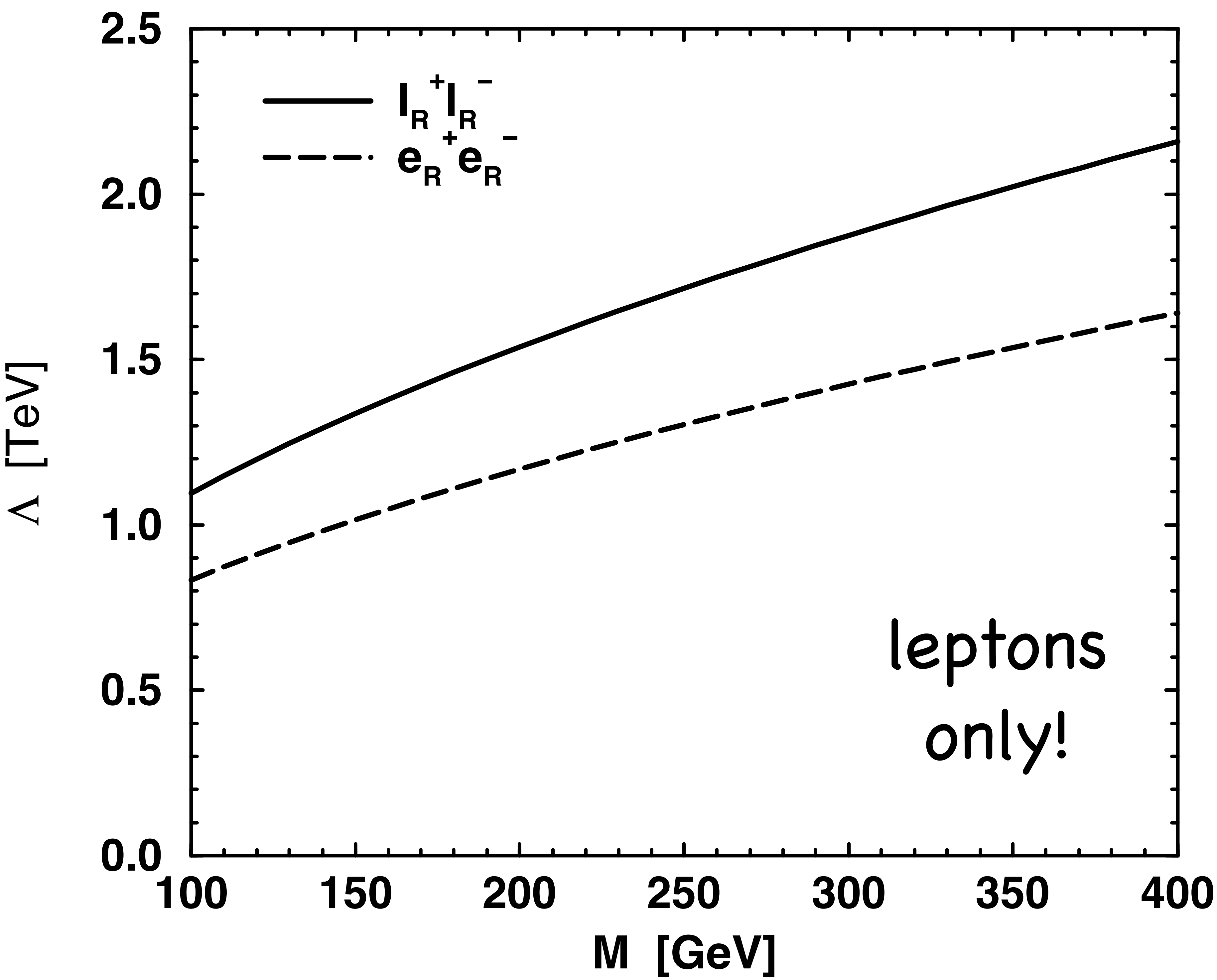
$$\langle\sigma v\rangle \sim M^2/\Lambda^4$$

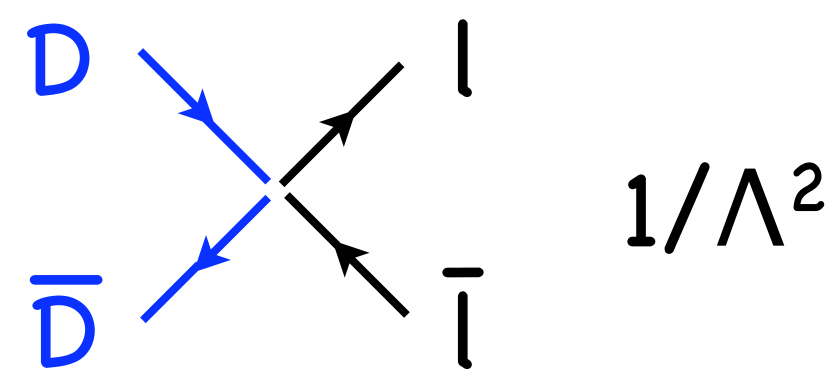


(not velocity suppressed!)

Matching <σv> with thermal relic abundance:

$$\Omega h^2 \approx 0.1 \, (1 \text{ pb}/\langle \sigma v \rangle)$$





Harnik, GK

This candidate obviously has indirect detection implications…

To make indirect DM annihilation predictions...

Astrophysics

Propagation:
- diffusion
- energy loss

Backgrounds:
- secondary production
- pulsars (neglected)

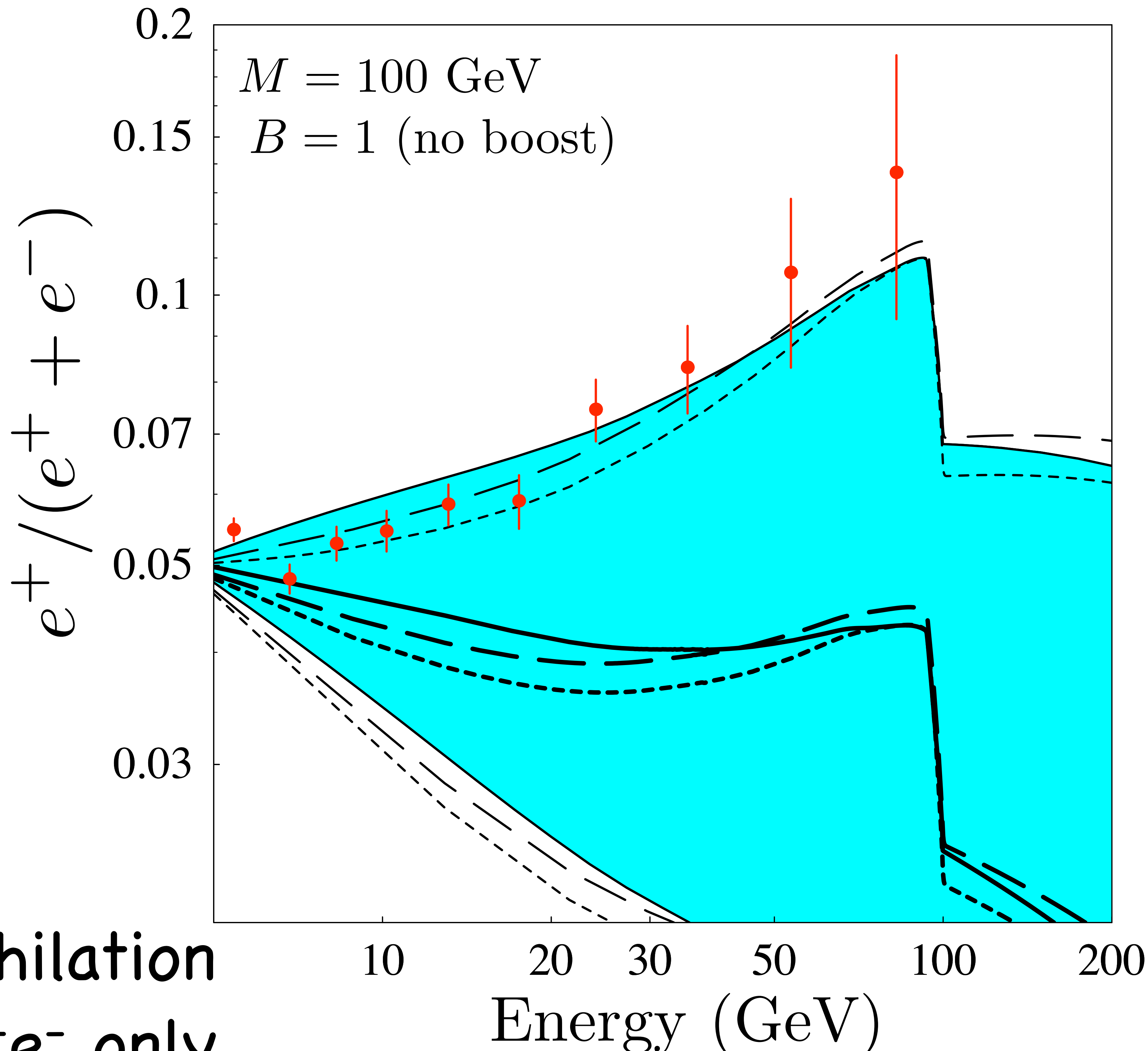
Abundance
- average density
- local clumpiness
  "BOOST factor"

Particle Physics

- annihilation rate
- annihilation channels

Effective theory allows:
- annihilation into e^+e^-,
- no other collider constraints ($M > 100$ GeV)!

M=100 GeV Dirac Dark Matter



Annihilation to e^+e^- only

Harnik, GK

Dirac Dark Matter:

$$\text{BOOST} \propto M^2$$

BOOST = 1 for

$M = 100$ GeV

$\Phi_{e-} \approx E^{-3.5}$;

$\rho_{local} = 0.3\ \text{GeV/cm}^3$

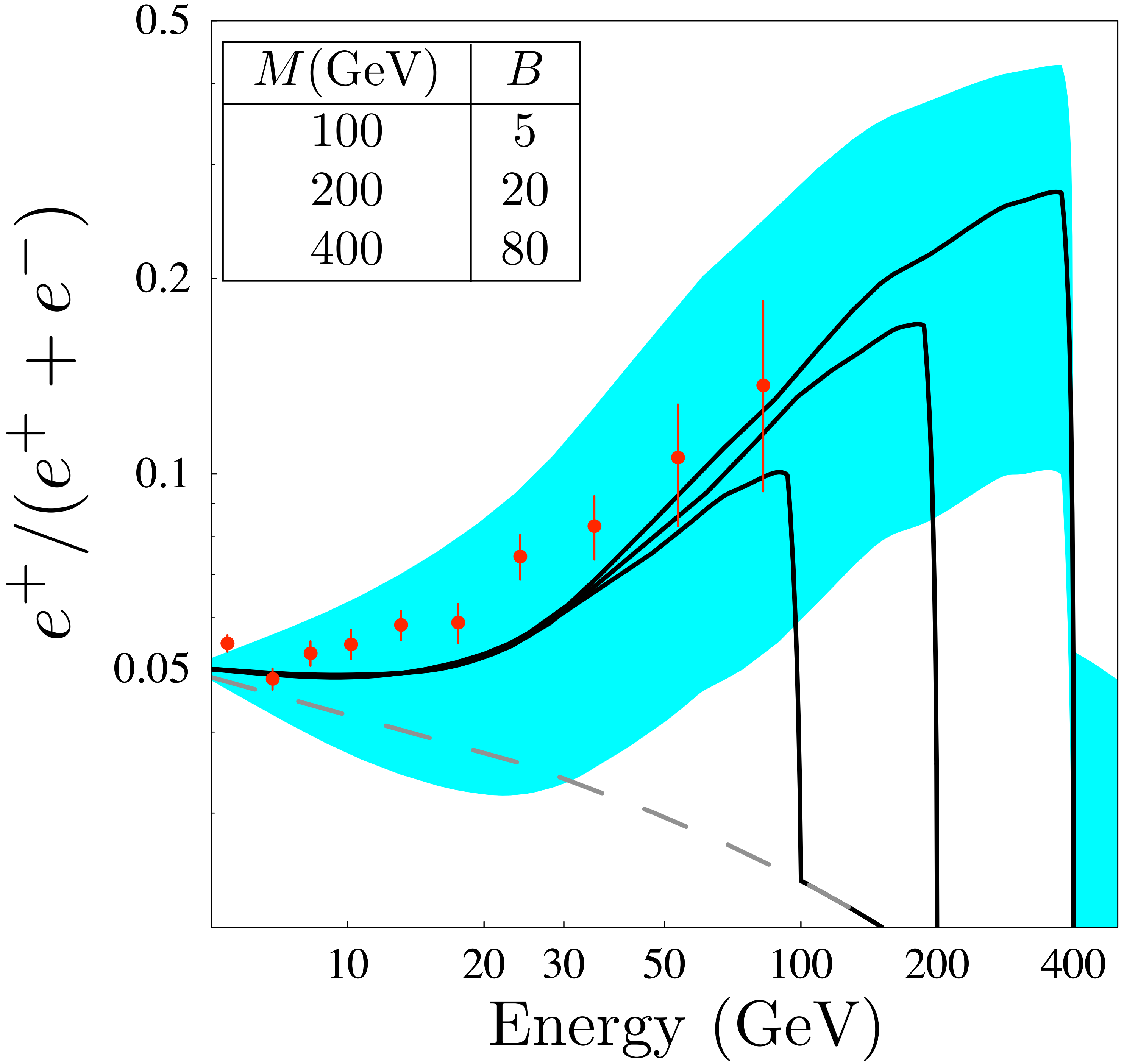
BOOST = 5 for

$M = 100$ GeV

$\Phi_{e-} \approx E^{-3.15}$;

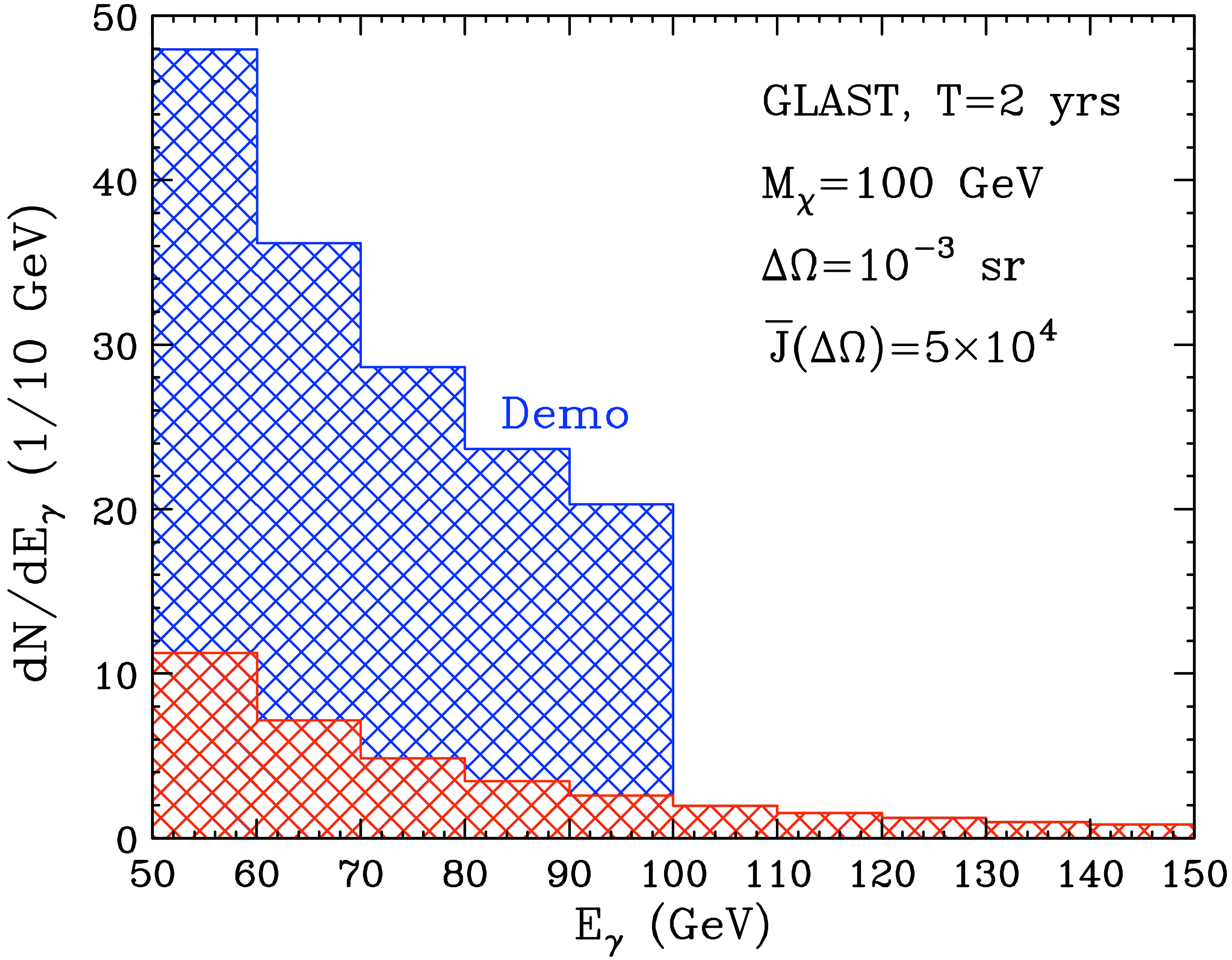
$\rho_{local} = 0.3\ \text{GeV/cm}^3$

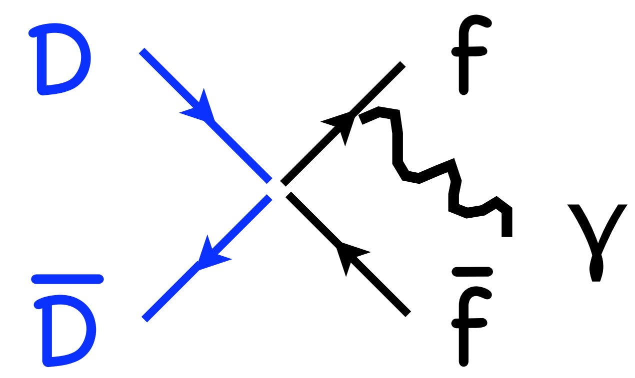
M=100,200,400 GeV Dirac Dark Matter



Lesson: Need <σv> enhancement for "heavy" DM (M » 100 GeV) not "light" DM (M ≈ 100 GeV)

Fermi/GLAST feature: FSR radiation





Size of signal *dependent* on DM density profile of galactic center

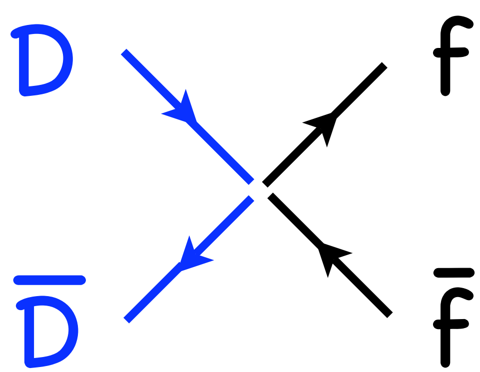
Birkedal, Mathev, Perelstein, Spray, hep-ph/0507194

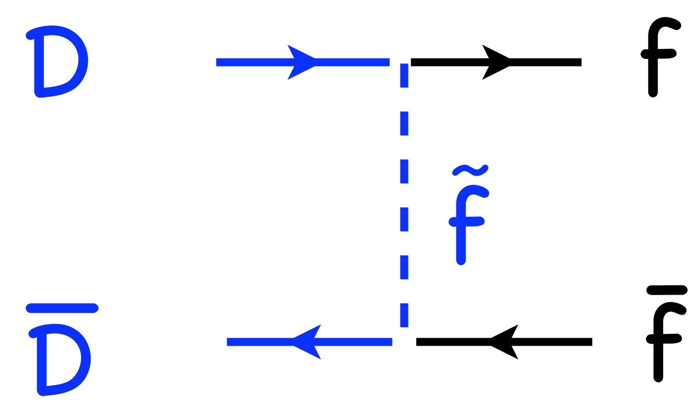
Dirac Bino as Dirac Dark Matter

(towards LHC)

Interpretation of D as a (pure) Dirac Bino

Resolve the 4-fermion vertex as

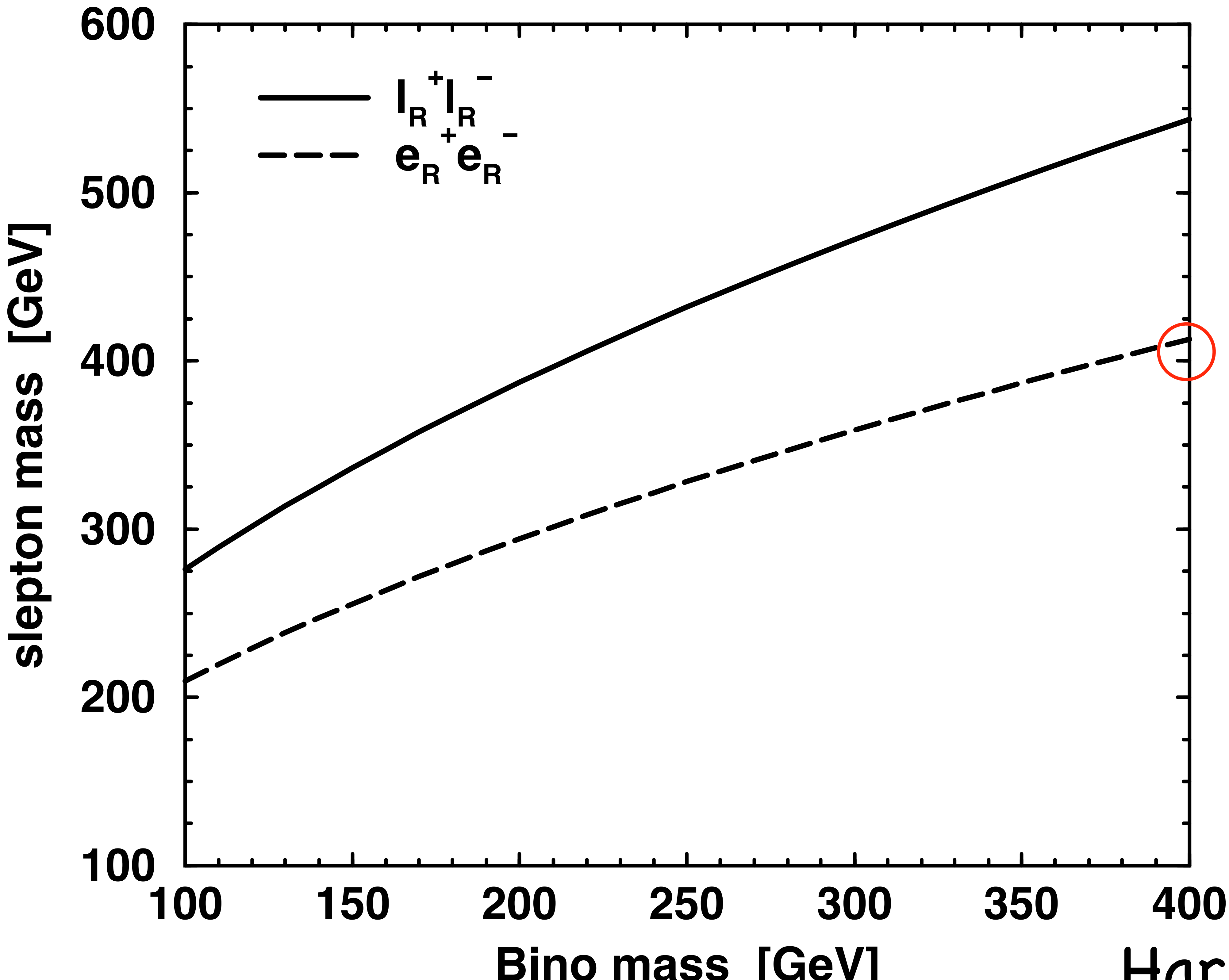




The dominance of leptonic annihilation results automatically given $Y_{eR}=1$ and some mild hierarchy, $m_{\tilde{l}} < m_{\tilde{q}}$

(and, dim-5 Higgs operator is absent)

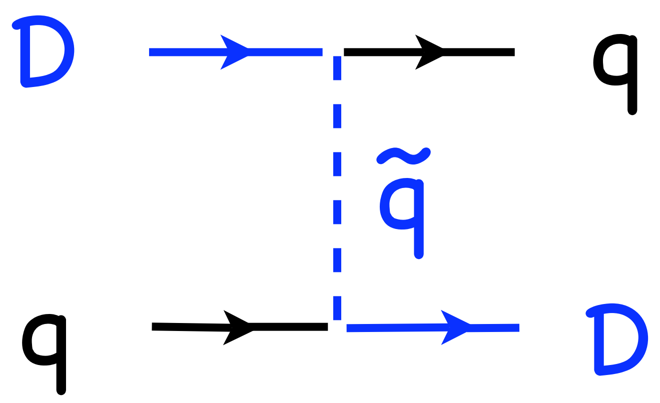
Matching thermal relic abundance, $\langle \sigma v \rangle$ = 1 pb



Harnik, GK

Absence of Direct Detection (and no Antiproton Annihilation signal)

Implies



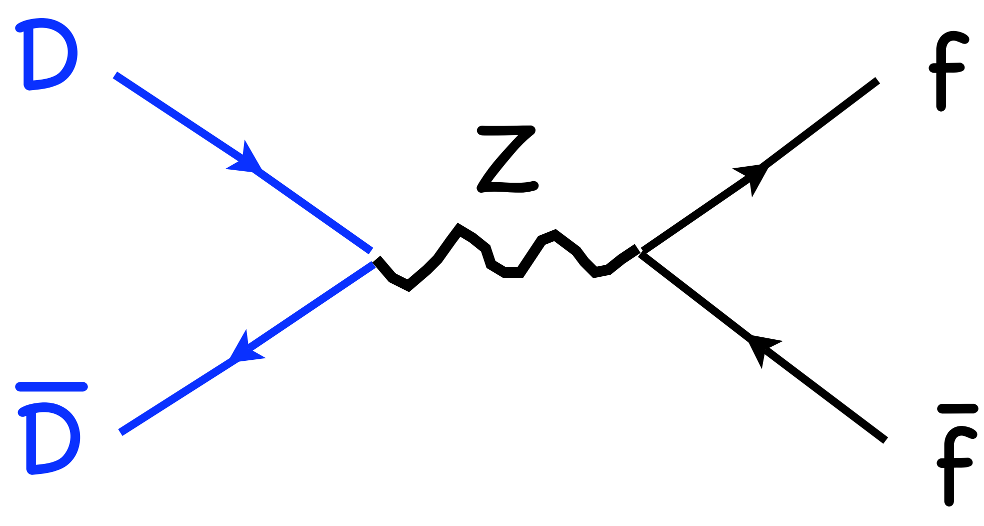
cannot be large.

Rough estimates of direct detection bounds suggest

$$m_{\tilde{q}} > 1.5 \text{ TeV}$$

for first generation, right-handed squarks.

Also constraint on Higgsino content of LSP from direct detection



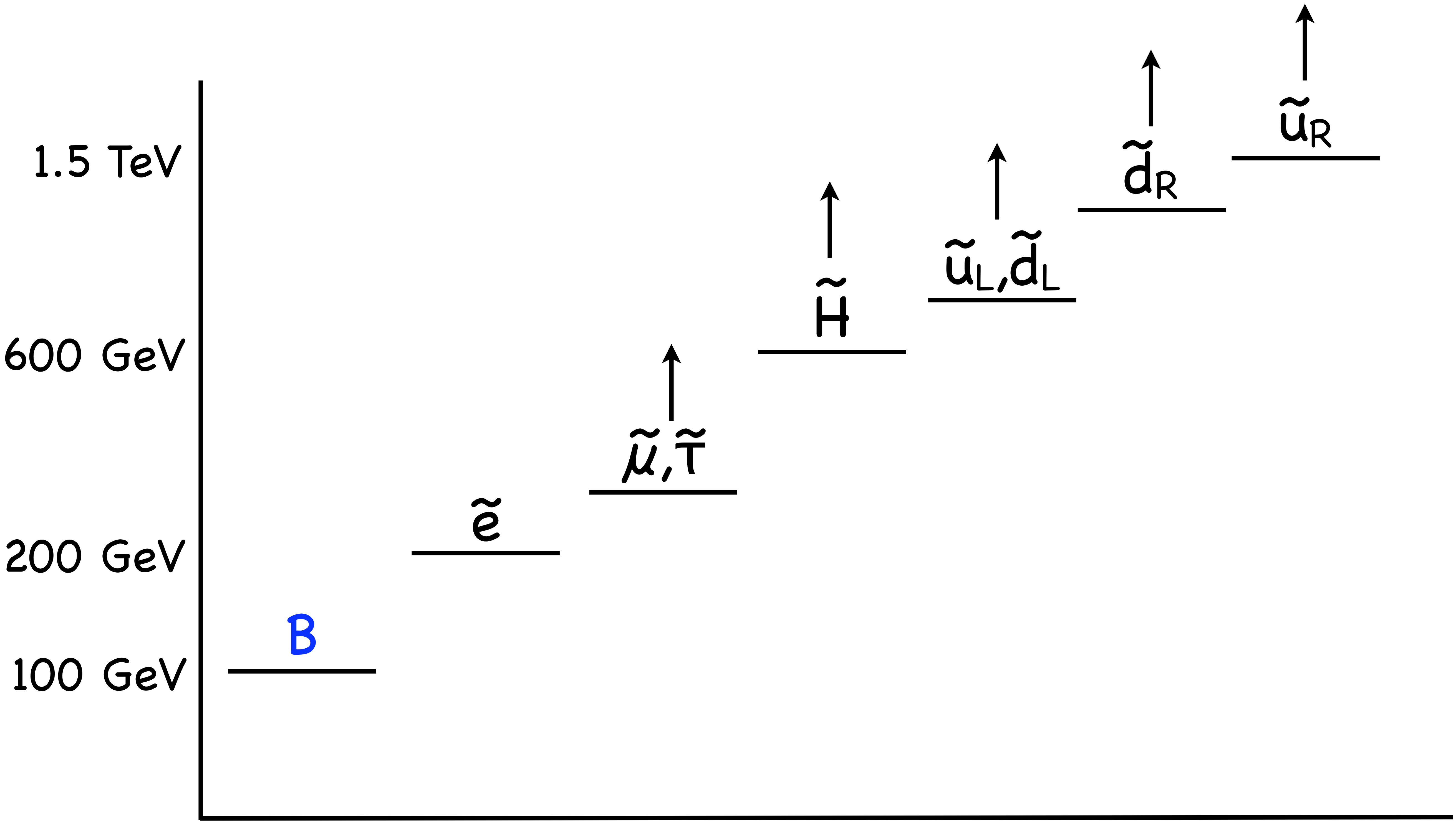
Our estimate, from $(g'v)^2/\mu^2 < 0.01$,

$\mu > 600$ GeV

Implications for LHC

(just a few comments...)

Spectrum to explain “just” PAMELA...



R Symmetry

Dirac gauginos are intriging prediction of R-symmetric supersymmetric models (Poppitz, Weiner, GK)

These models have very interesting flavor properties; Bino lighter than selectron, different from smuon/stau suggests observable LFV (work in progress)

Understanding how supergravity could exactly conserve a visible sector R-symmetry remains a puzzle...

Summary: Dark Matter

- Remarkable dark matter detection experiments underway; already strong constraints and hints towards the particle nature of DM

- One DM-DM-l-l operator can:
  - thermally produce $\Omega h^2 \approx 0.1$ relic abundance
  - automatically avoid direct detection
  - explain PAMELA ratio with minimal boost factor

- Collider implications of "unusual" dark matter candidates is ripe for exploitation

Darkness in Heidelberg...

John Terning: Ask him about composite dark matter
Tim Tait: Ask him about WIMPonium
Matt Strassler: Ask him about hidden valley sector dark matter
Patrick Meade: Ask him about light U(1)s, Sommerfeld, and ATIC/HESS tension
David Morrissey: Ask him about iDM/DAMA and about early phase transitions
Mihoko Nojiri: Ask her about SUSY and/or decaying DM
Frank Petriello: Ask him about DAMA, channeling and light dark matter
Michael Schmitt: Ask him about MeV DM and rare decays
Koichi Hamaguchi: Ask him about decaying dark matter
Maria Spiropulu: Ask her about missing energy look-alikes

(and more...just what I could fit on one slide!)