

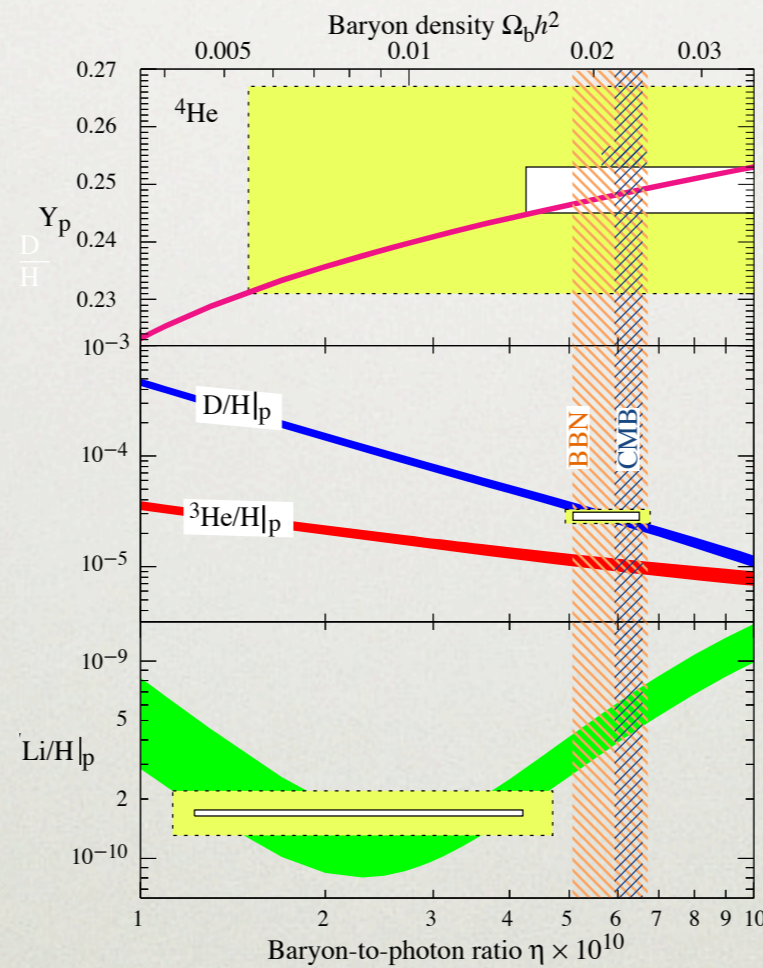
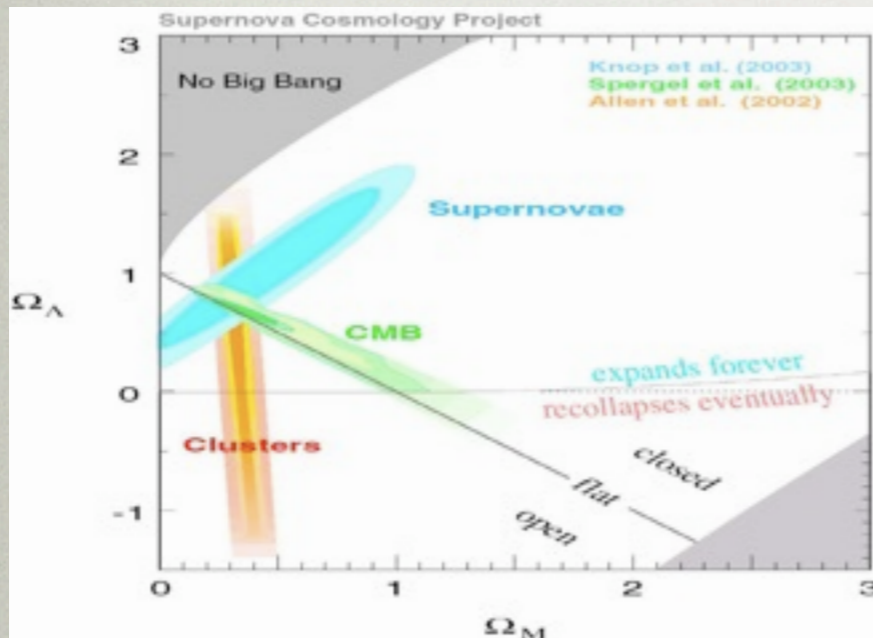
DM RESULTS AND  
THEORY:  
WHERE ARE WE?

KATHRYN M. ZUREK  
UNIVERSITY OF MICHIGAN

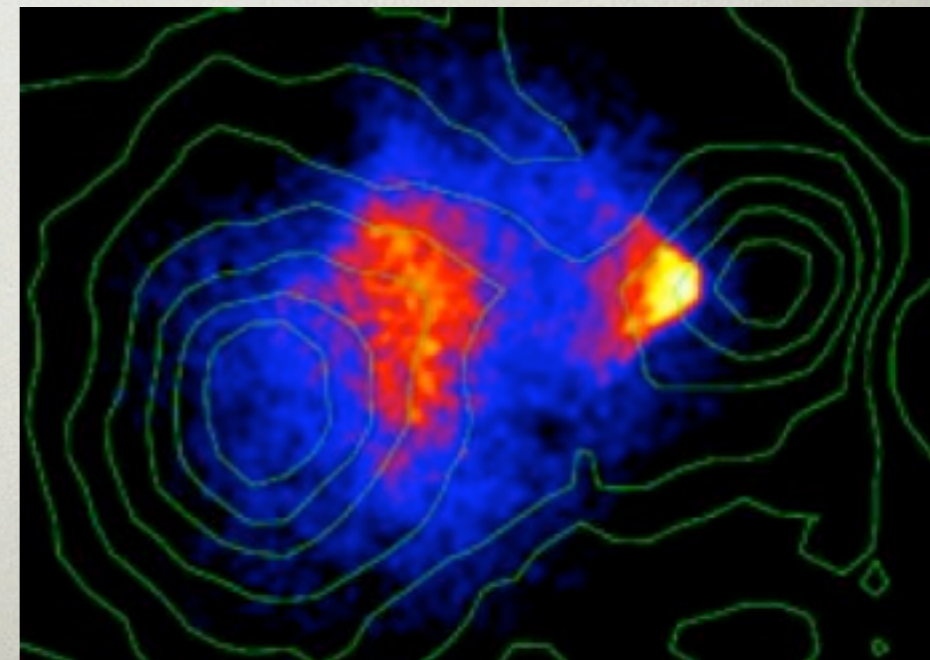
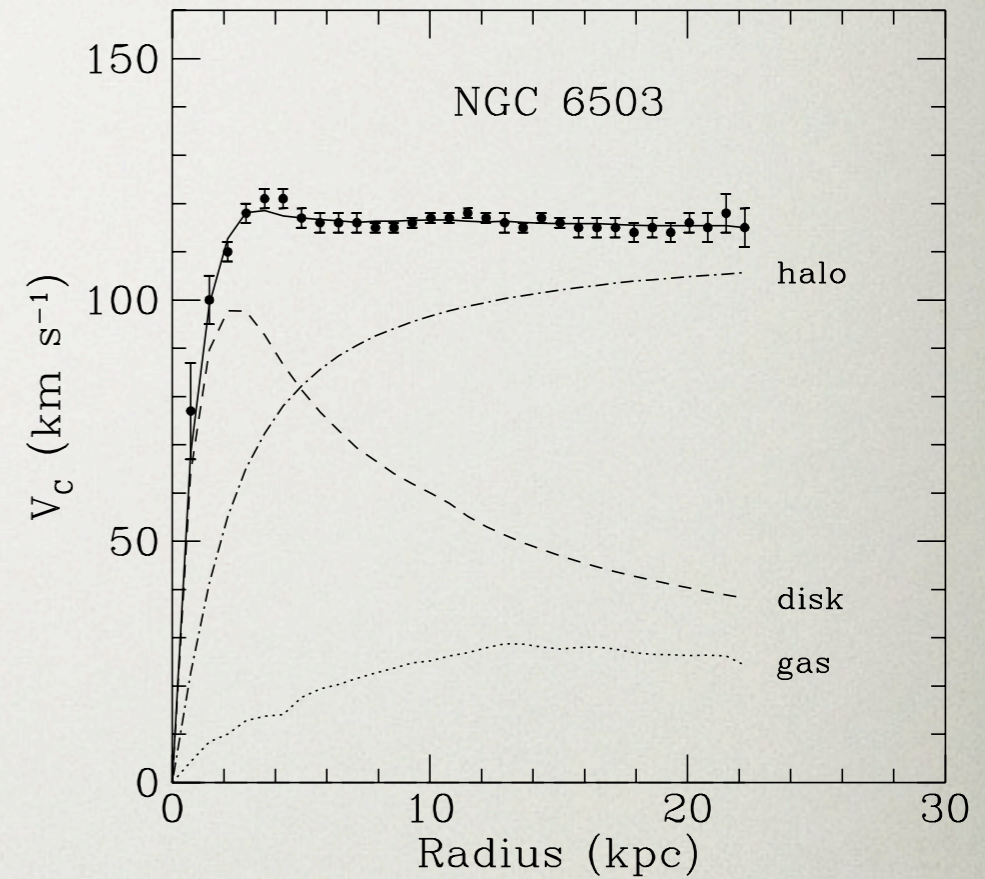


# EVIDENCE FOR DM OVERWHELMING

- Hunt dates to 1933



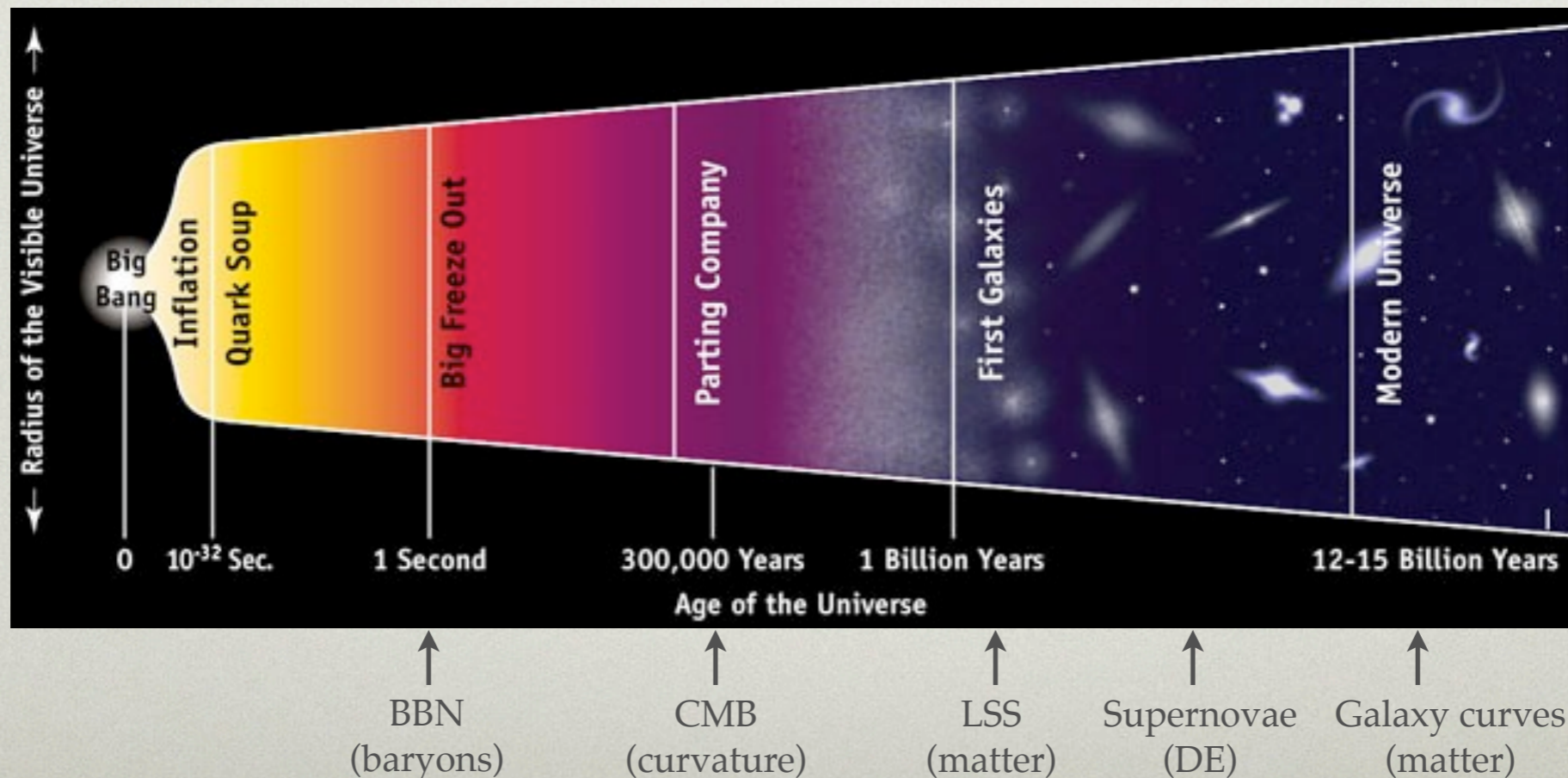
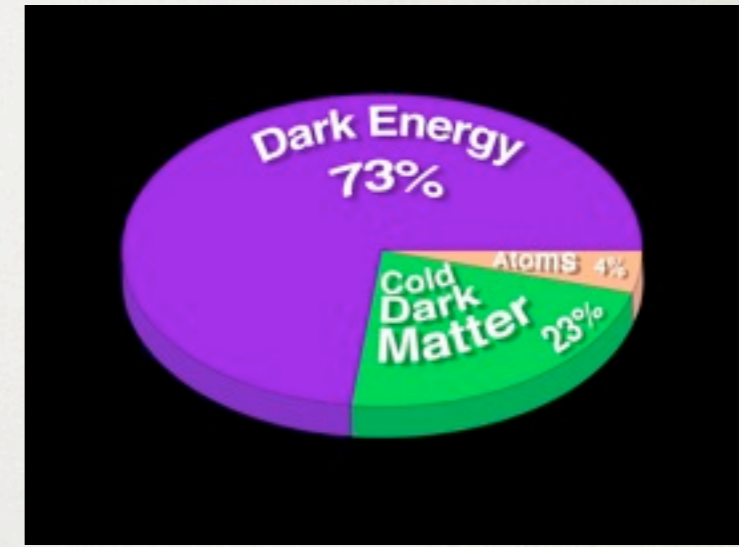
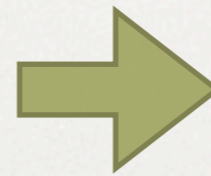
Fields, Sarkar '09





# EVIDENCE FOR DM OVERWHELMING

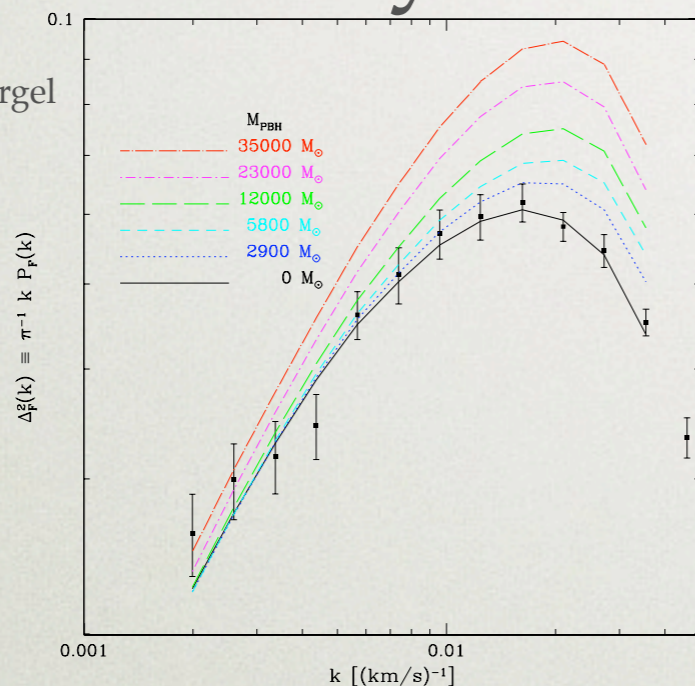
All evidence points  
toward





# WHAT DO WE KNOW ABOUT DM?

- Not baryonic



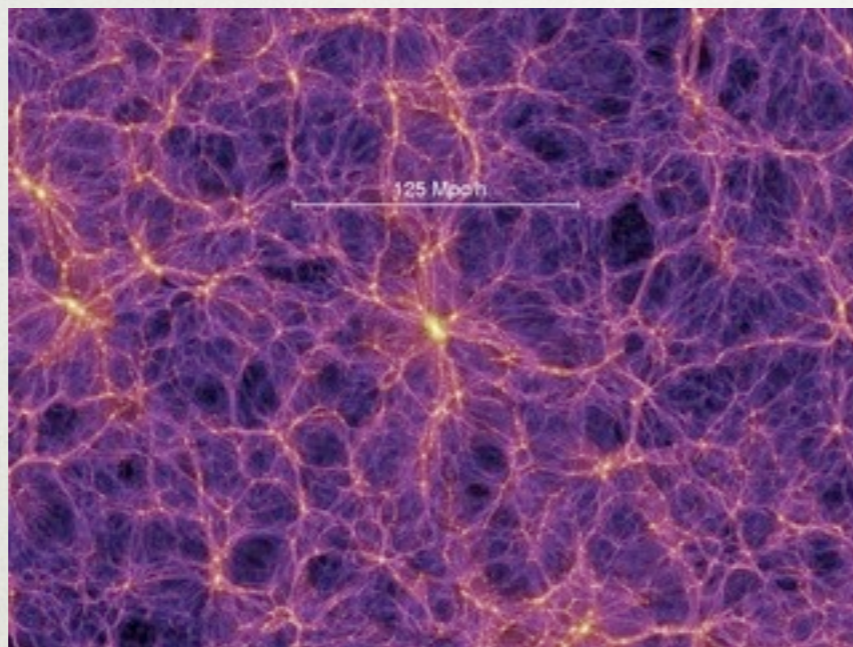
- Not modified gravity

- BBN --> not free baryons
- MACHO searches + Ly $\alpha$  --> not bound baryons
- CMB + LSS + Bullet --> not neutrinos as DM

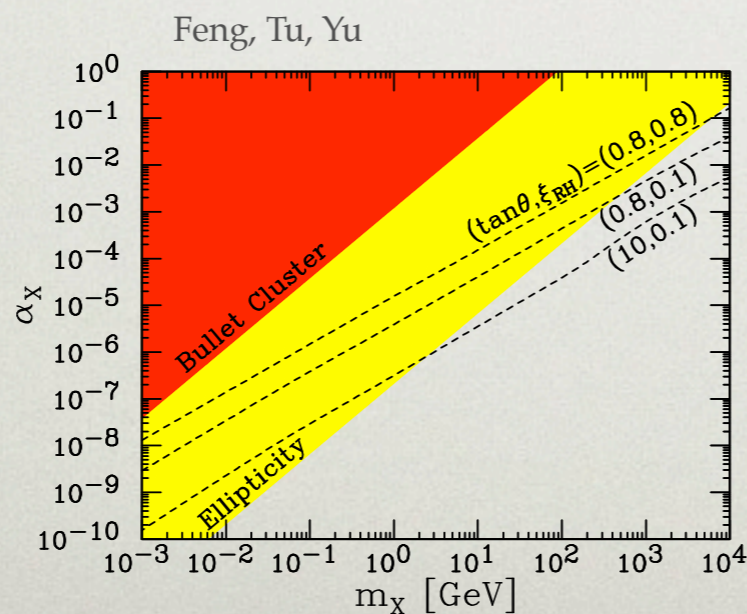


# WHAT DO WE KNOW ABOUT DM?

- Cold



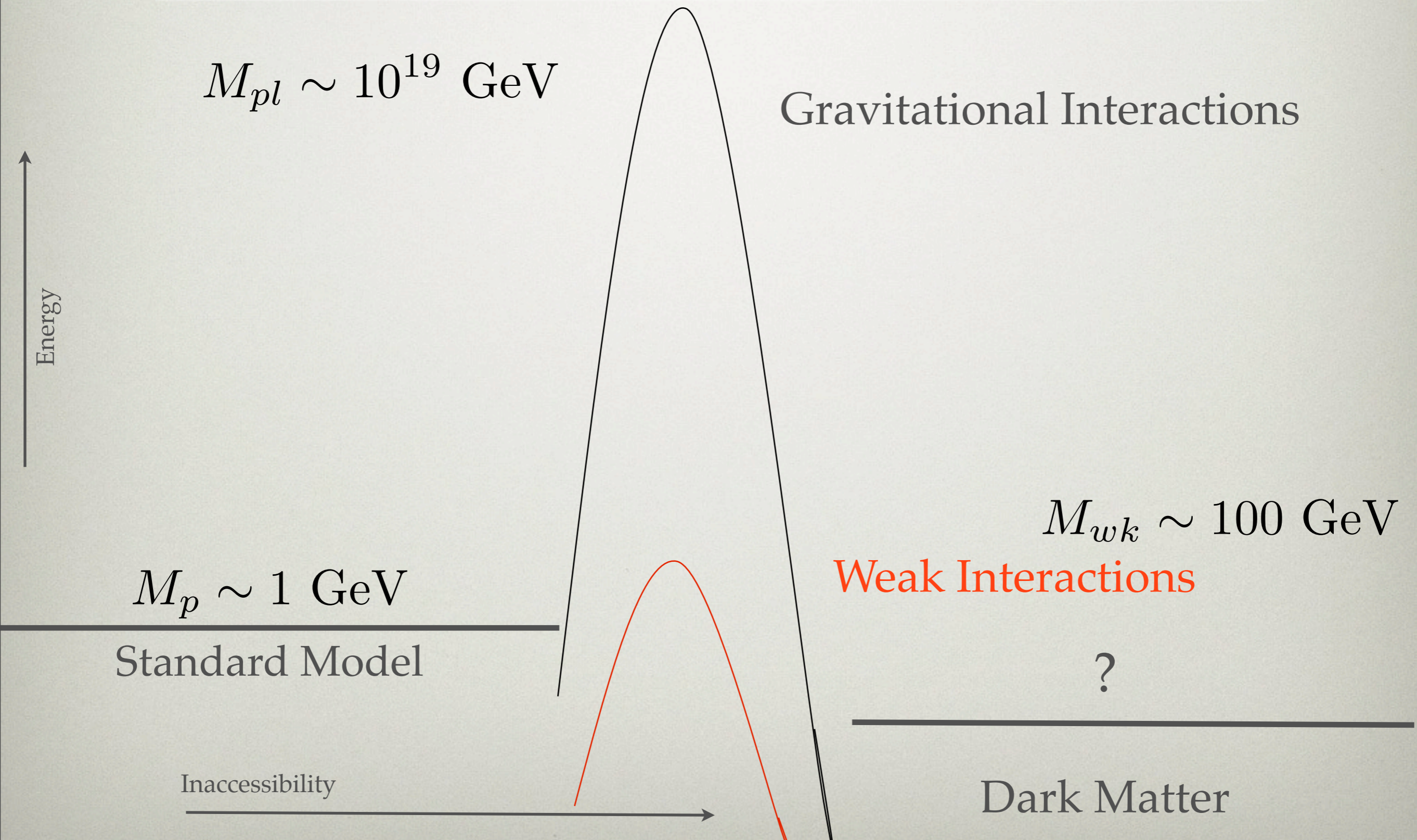
- Weakly interacting



- CMB + LSS -- clustering properties
- With us -- direct detection
- With itself -- halo shape bounds



# NEUTRINOS AND THE WEAK INTERACTIONS

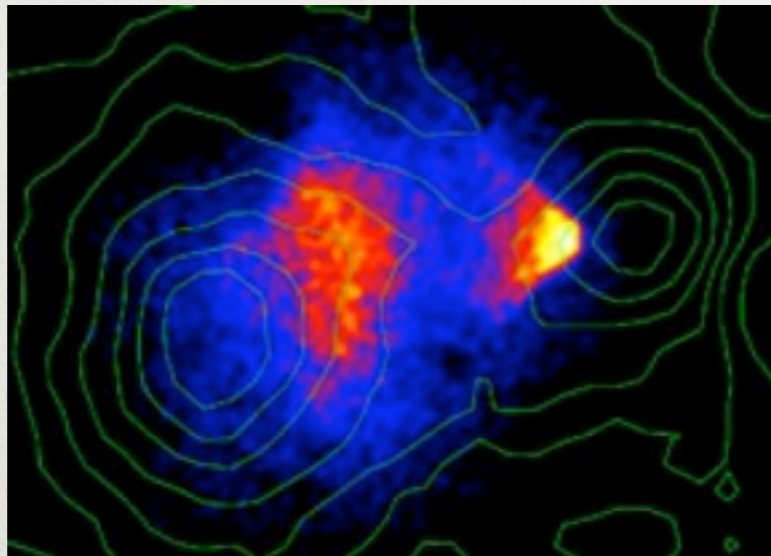




# SUPER-WEAKLY INTERACTING

---

- Gravitational Coherence



Cosmological Scales!

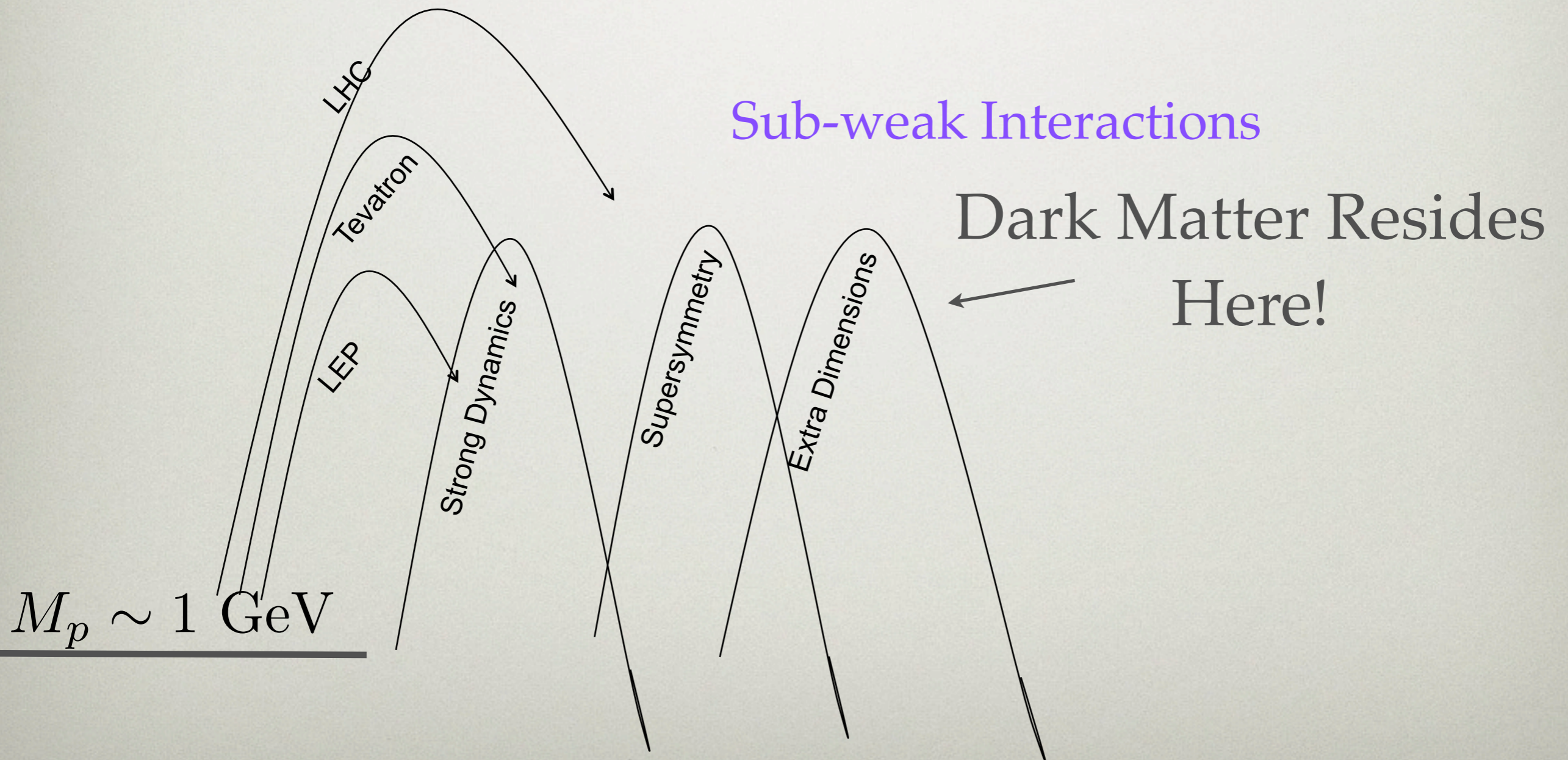
- Helps us learn about aggregate properties of dark matter
- Particle properties much harder



# PARTICLE PHYSICS PROVIDES SOME IDEAS

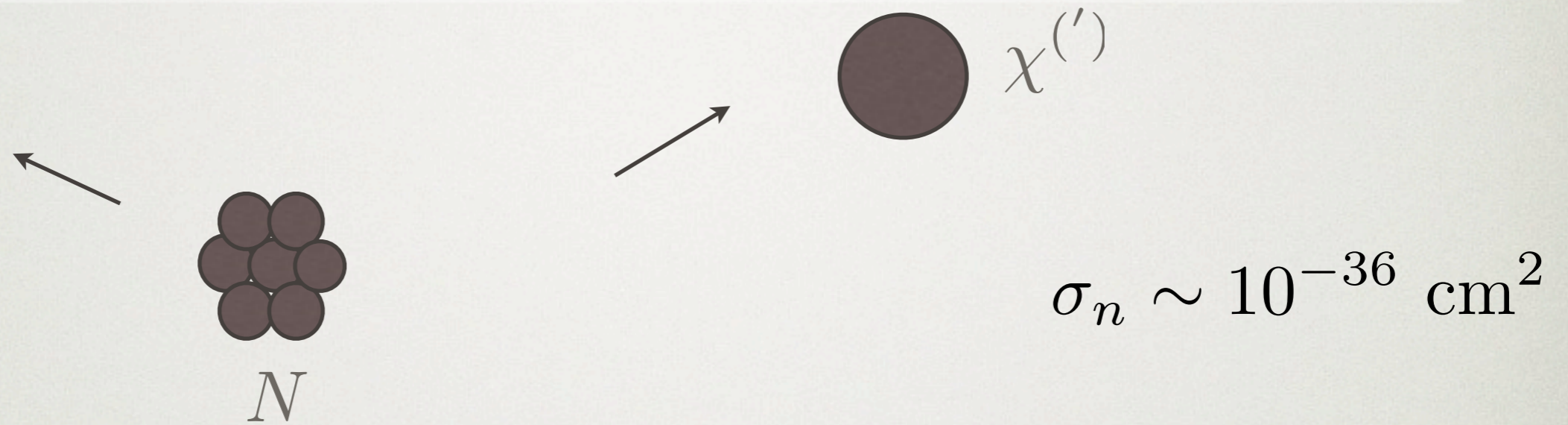
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- Particle Physics Zoo!





# SUB-WEAKLY INTERACTING MASSIVE PARTICLES



Weak interactions  
Z boson

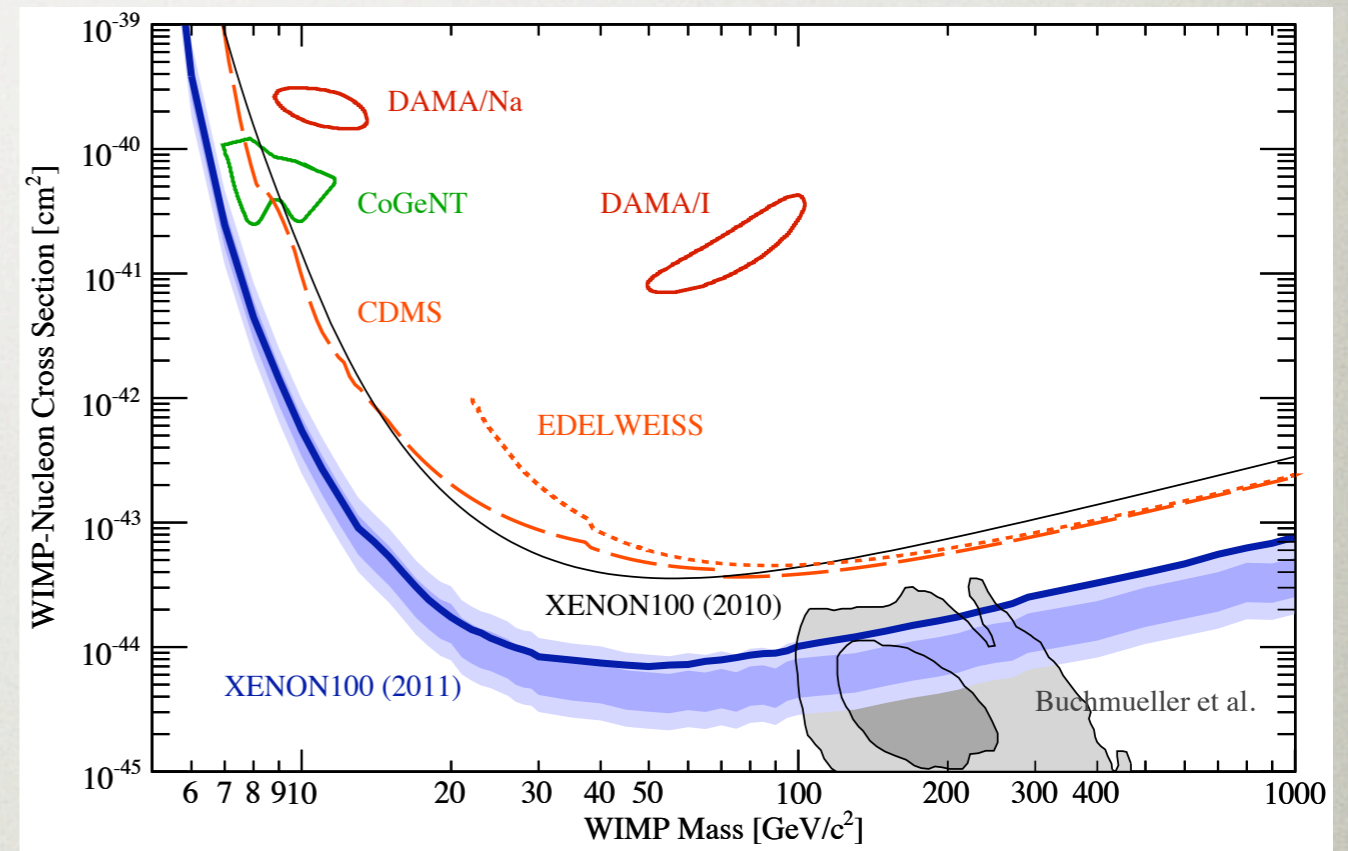
?

Standard Model

Dark Matter

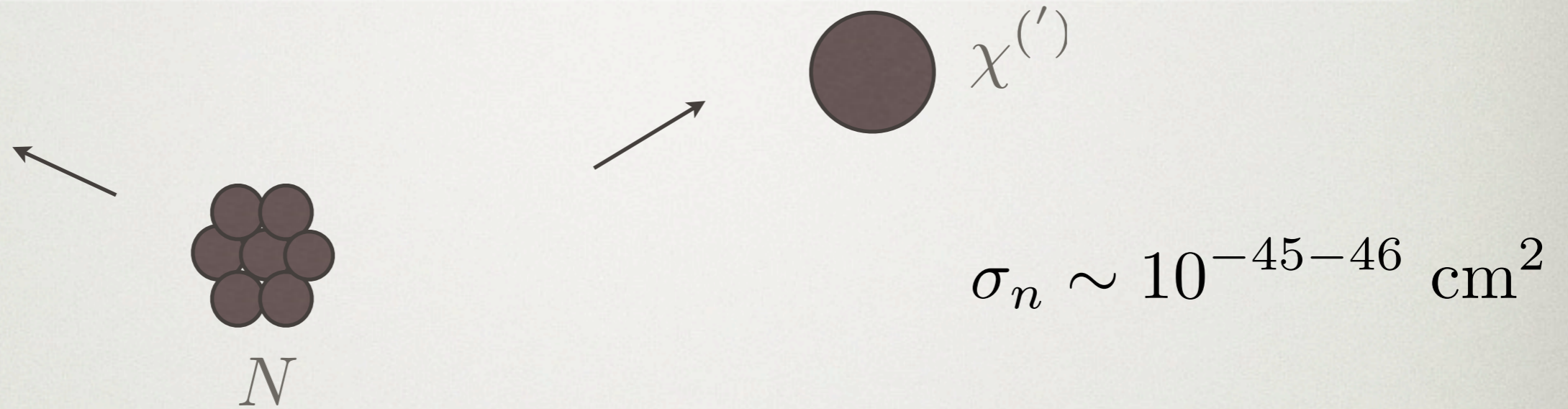


# SUB-WEAKLY INTERACTING MASSIVE PARTICLES





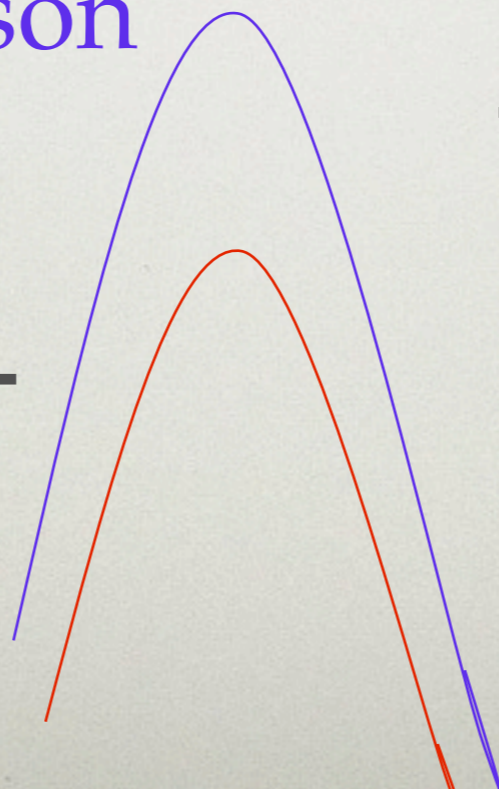
# SUB-WEAKLY INTERACTING MASSIVE PARTICLES



Higgs boson

$M_p \sim 1 \text{ GeV}$

Standard Model



?

Dark Matter



# WHY THE WEAK SCALE IS COMPELLING

---

- New scale, 100's GeV set by SM
- Abundance of new stable states set by interaction rates

Measured by WMAP + LSS

$$\Gamma = n \overset{\downarrow}{\sigma} v = H \quad \implies \sigma \sim \frac{1}{(100\text{GeV})^2}$$
$$\sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$$



# VIEW OF DM FROM THE WEAK SCALE

---

DM is:

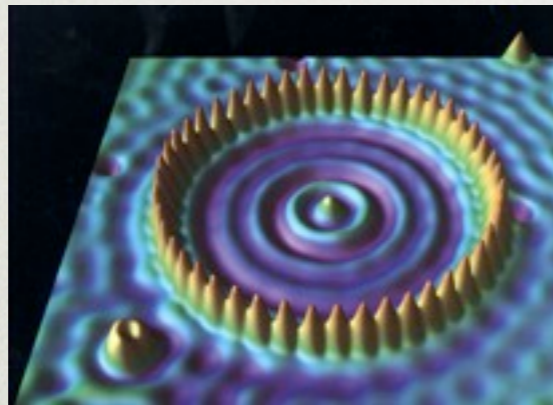
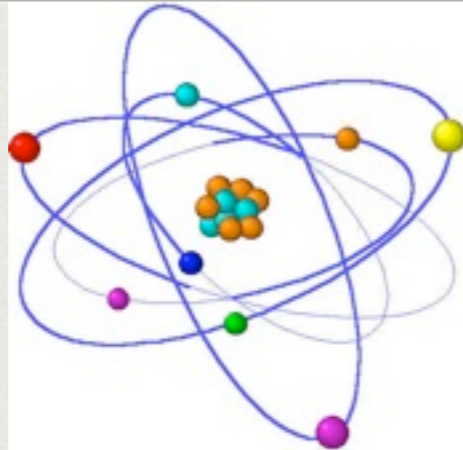
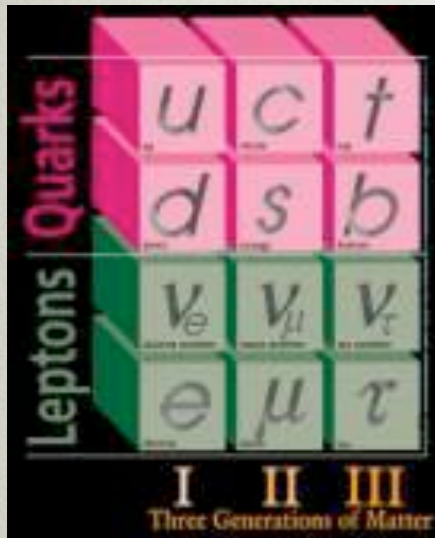
- Single
- Stable
- Weakly Interacting
- Massive Particle with Weak Scale Mass

Successes:

- Neutral, stable particle appears naturally
- Reproduces correct relic abundance



# CHALLENGES



$$M_p \sim 1 \text{ GeV}$$

Standard Model

- Why are the DM and baryon densities so close to each other?
- Are the dynamics of the two sectors really so different?

Dark Matter



# LOOKING BEYOND WIMP DM

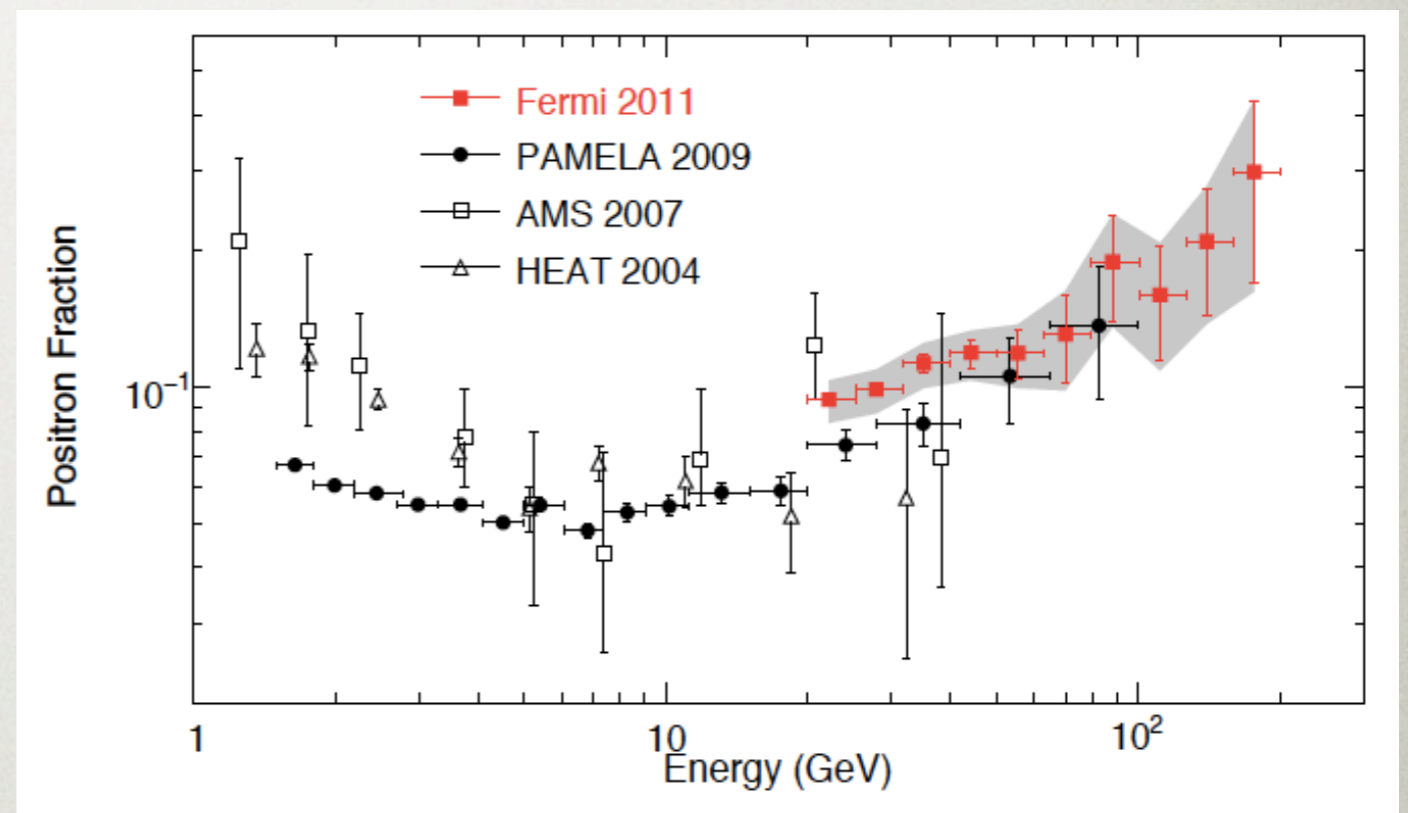
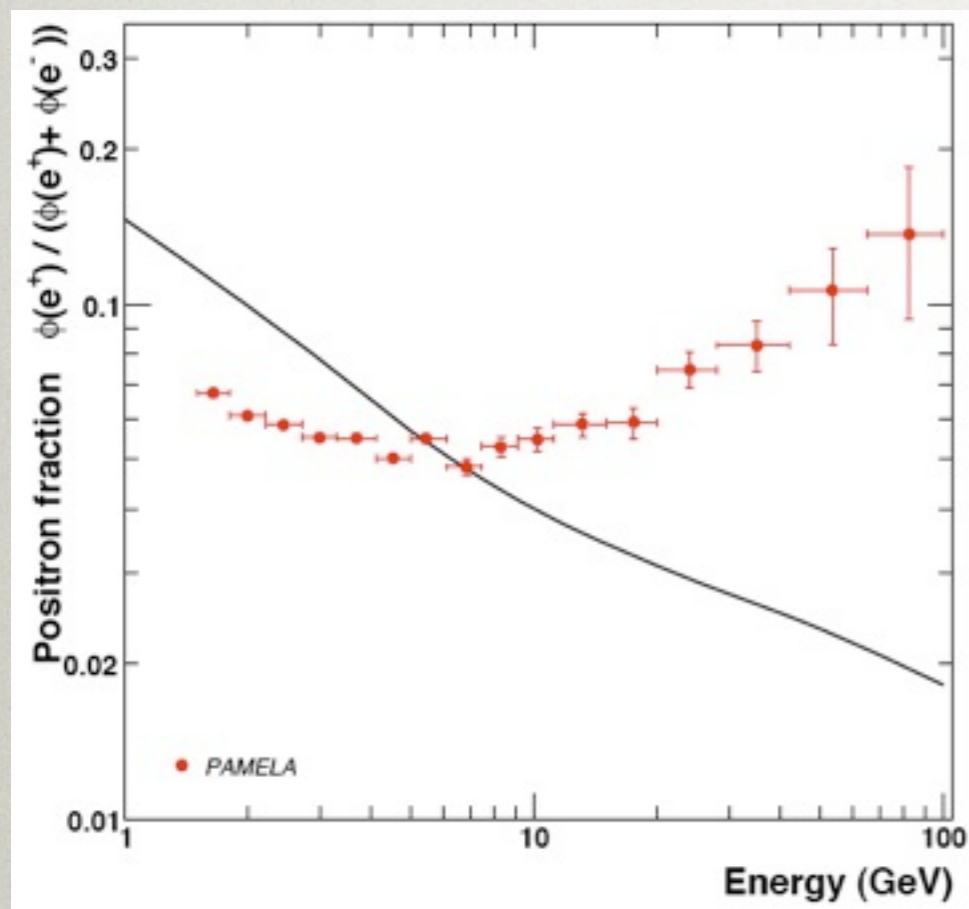
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- Experimental: A look at Recent anomalies
- The Lamppost problem: Beyond the WIMP freeze-out paradigm



# EVOLUTION OF ANOMALIES

Indirect



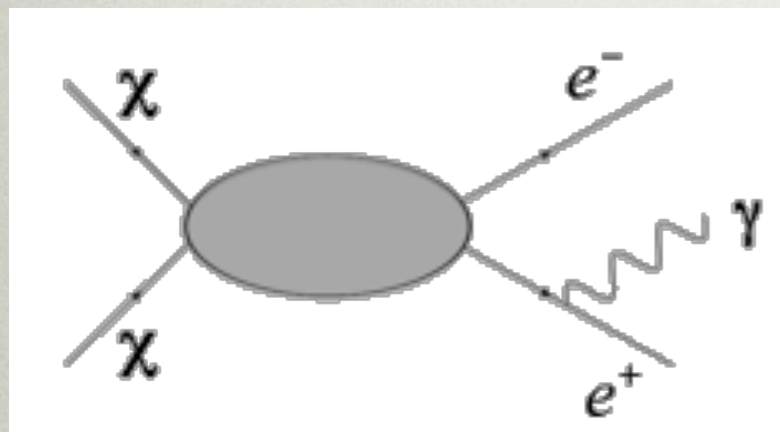
PAMELA, then Fermi added to the mix



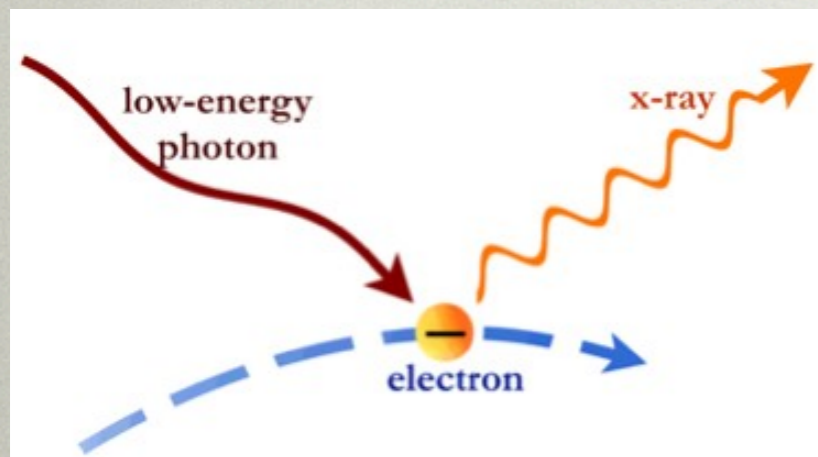
# COULD IT BE DUE TO DM ANNIHILATION?

## DM explanation constrained

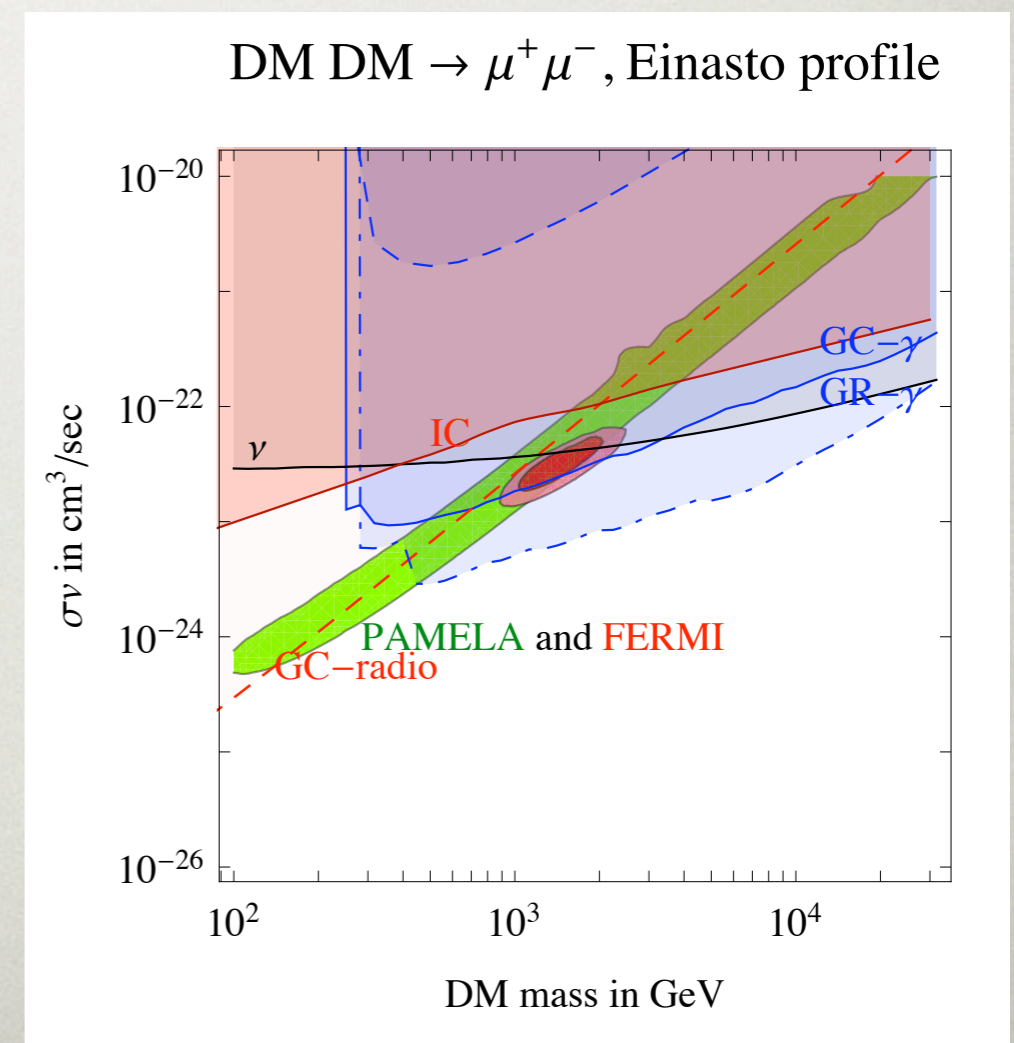
Meade, Papucci, Strumia, Volansky



Final State Radiation



Inverse Compton





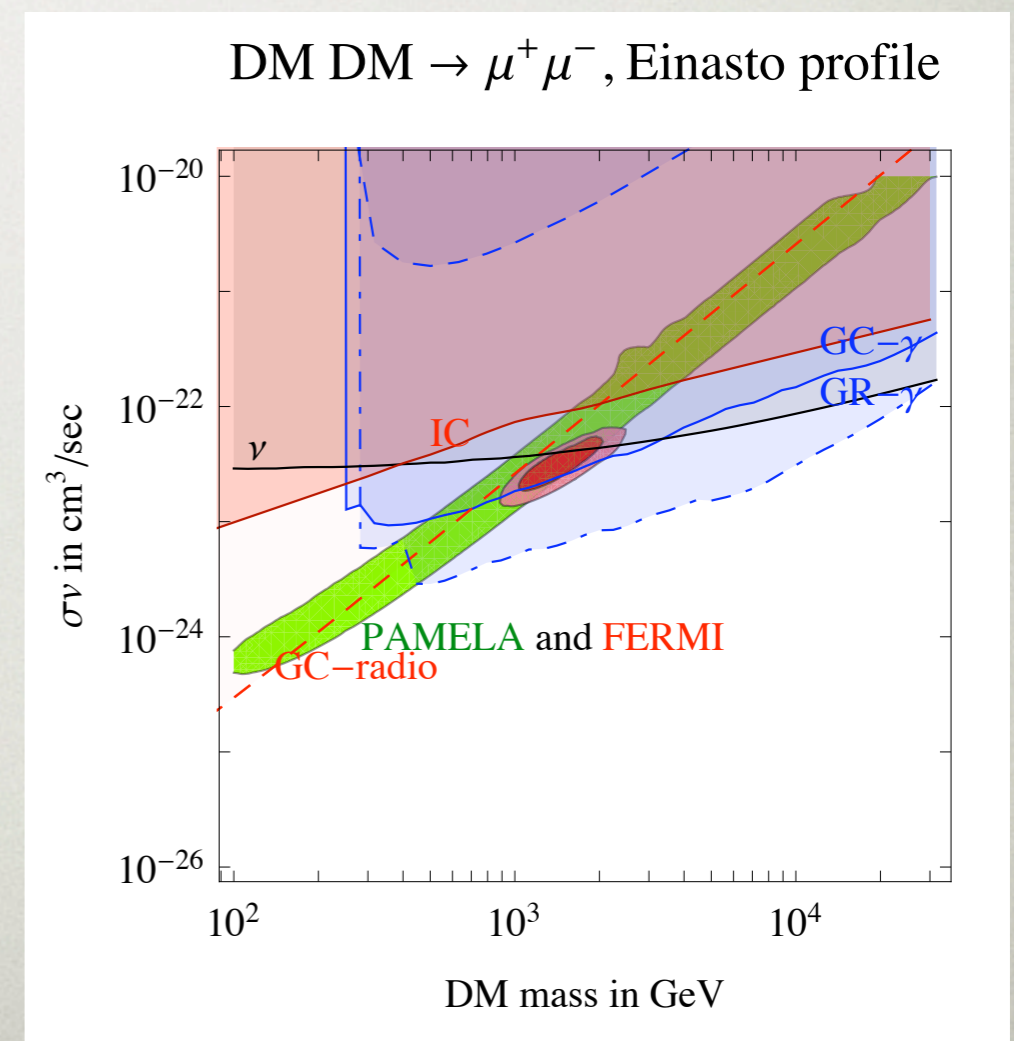
# COULD IT BE DUE TO DM ANNIHILATION?

DM explanation constrained

Meade, Papucci, Strumia, Volansky

Notice non-standard  
features:

1. LARGE annihilation  
cross-section
2. Annihilation to leptons



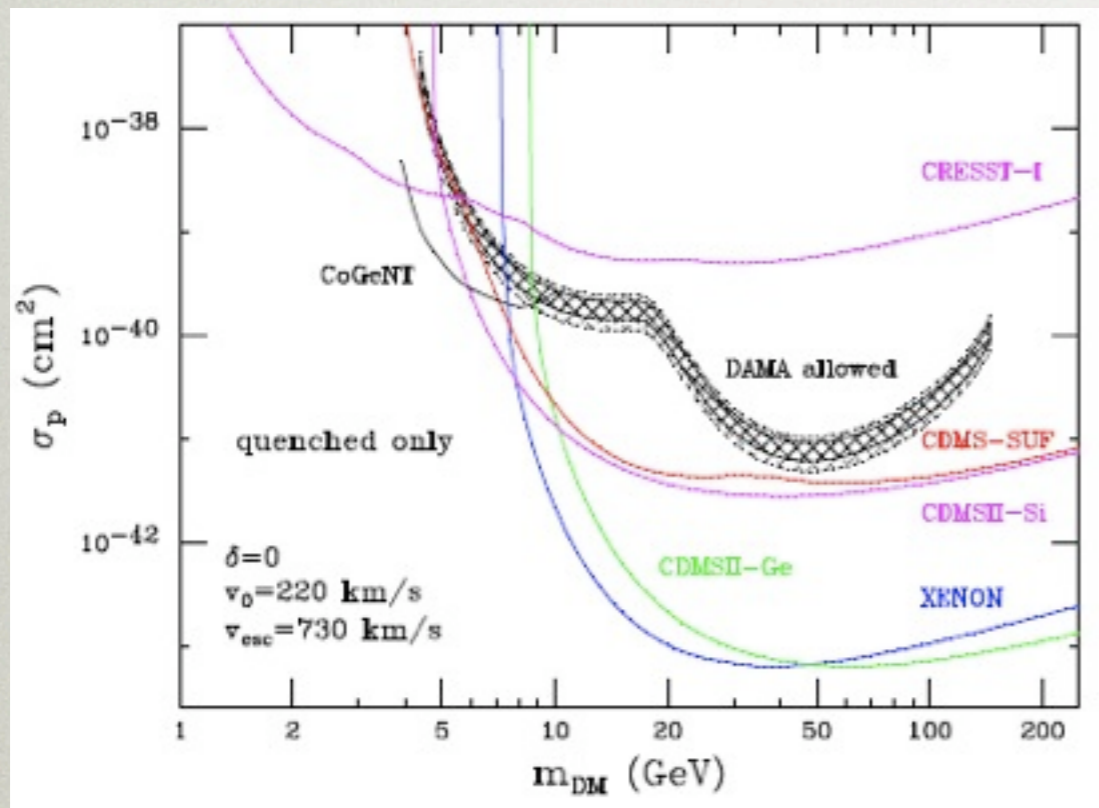


# EVOLUTION OF ANOMALIES

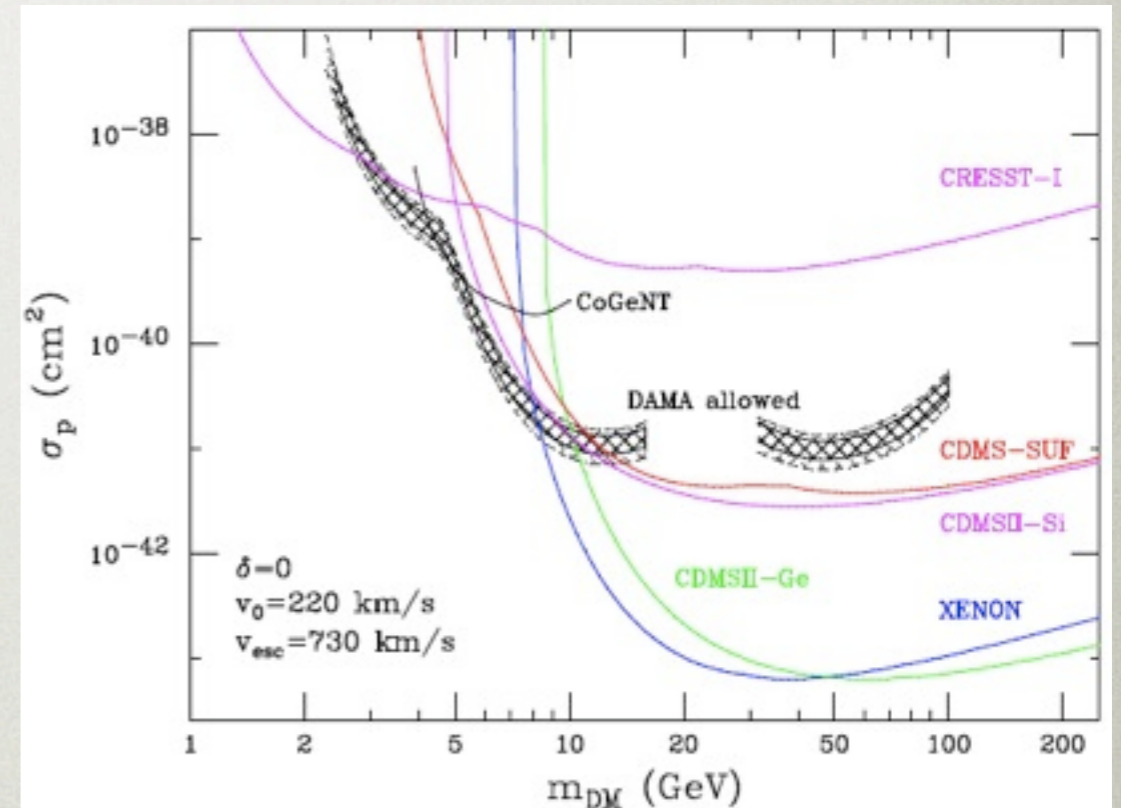
## Direct

Experiment is sensitive to lower mass WIMPs than thought before

Petriello, KZ '08



$$E_{thresh} = 7 \text{ keV (Na), } 22 \text{ keV (I)}$$

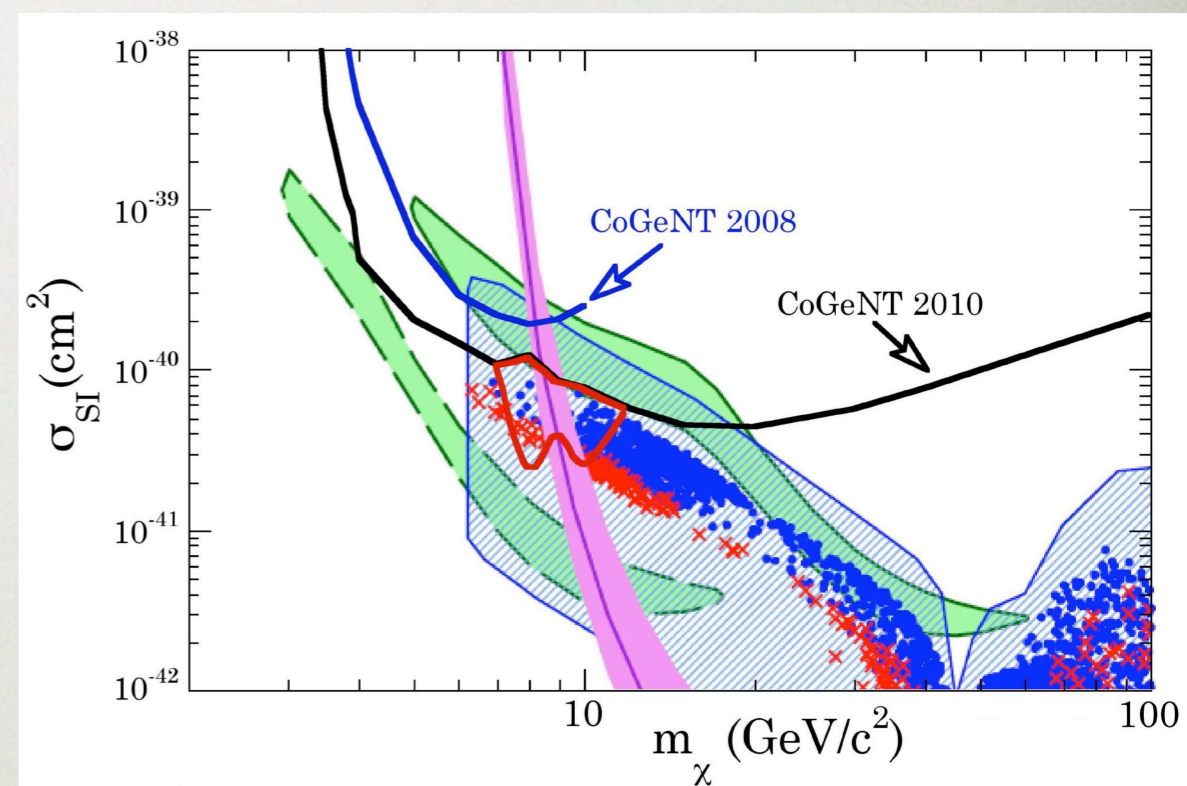
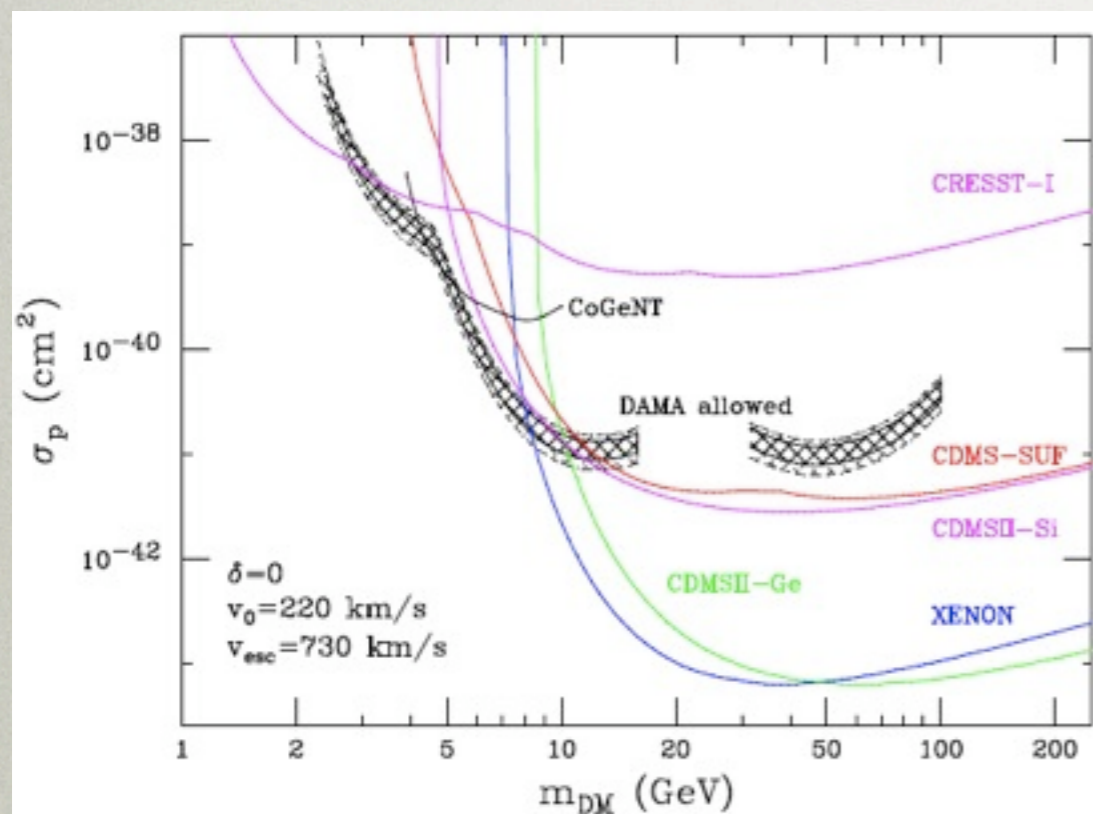


$$E_{thresh} = 2 \text{ keV}$$



# EVOLUTION OF ANOMALIES

Direct

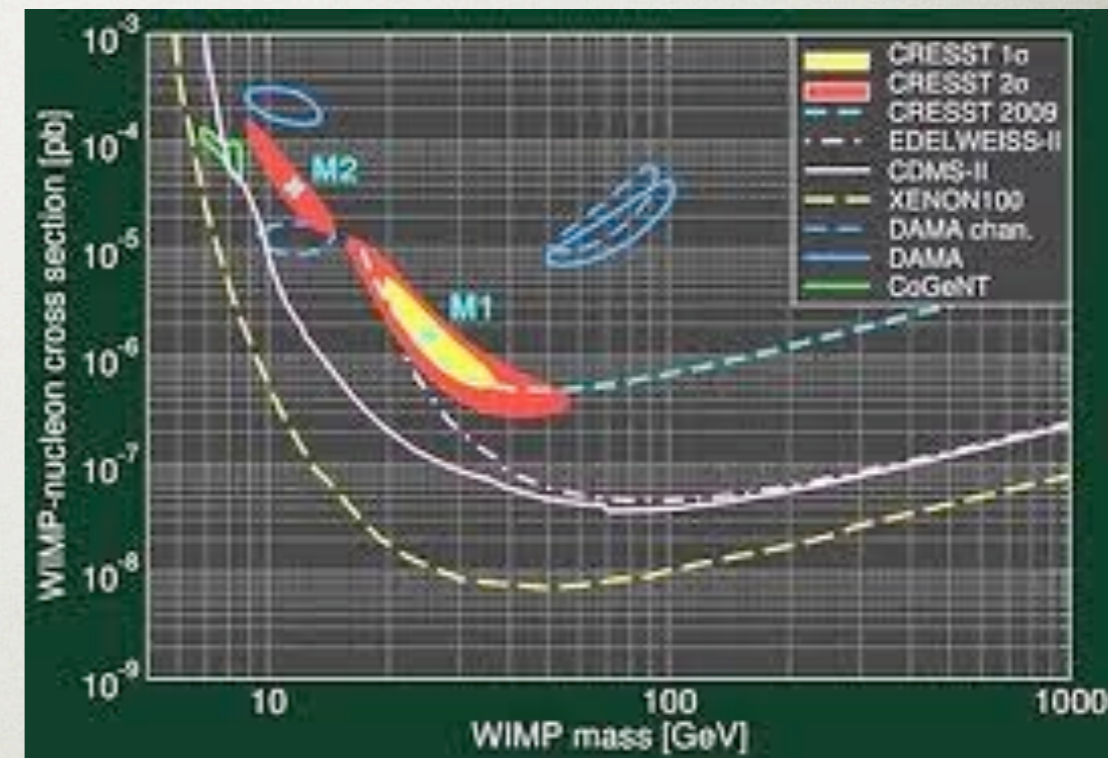
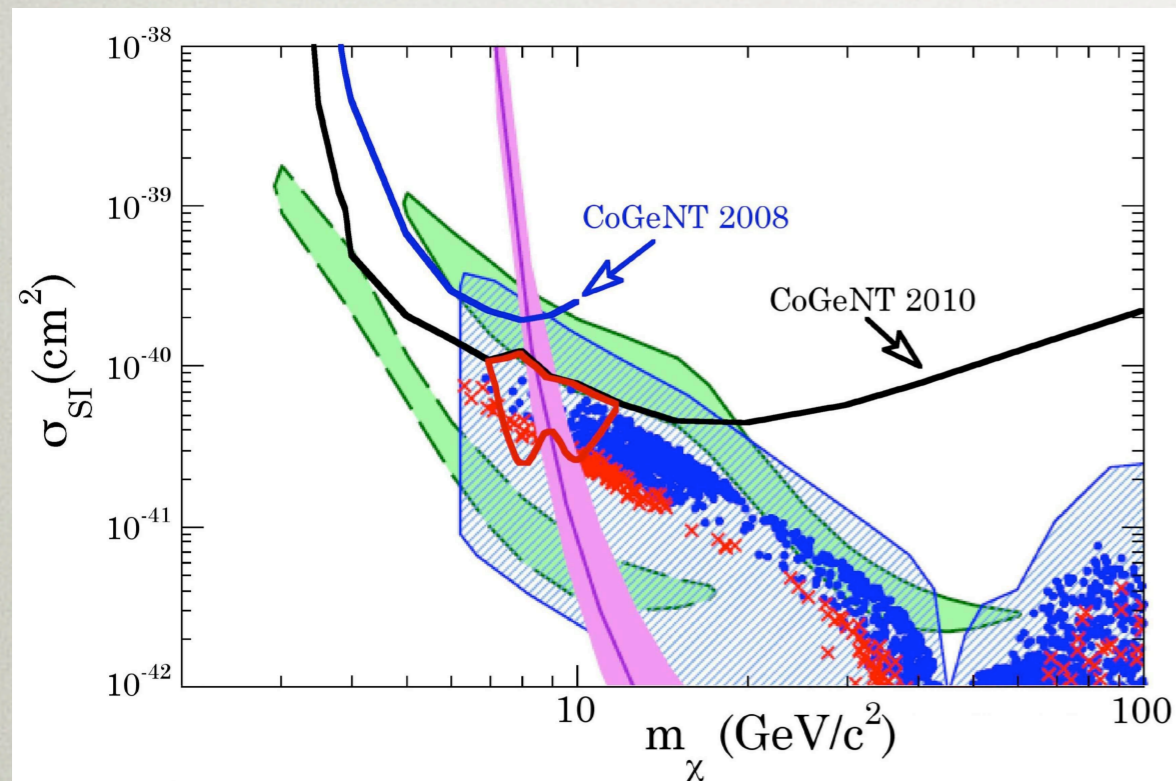


CoGeNT added to the mix



# EVOLUTION OF ANOMALIES

Direct



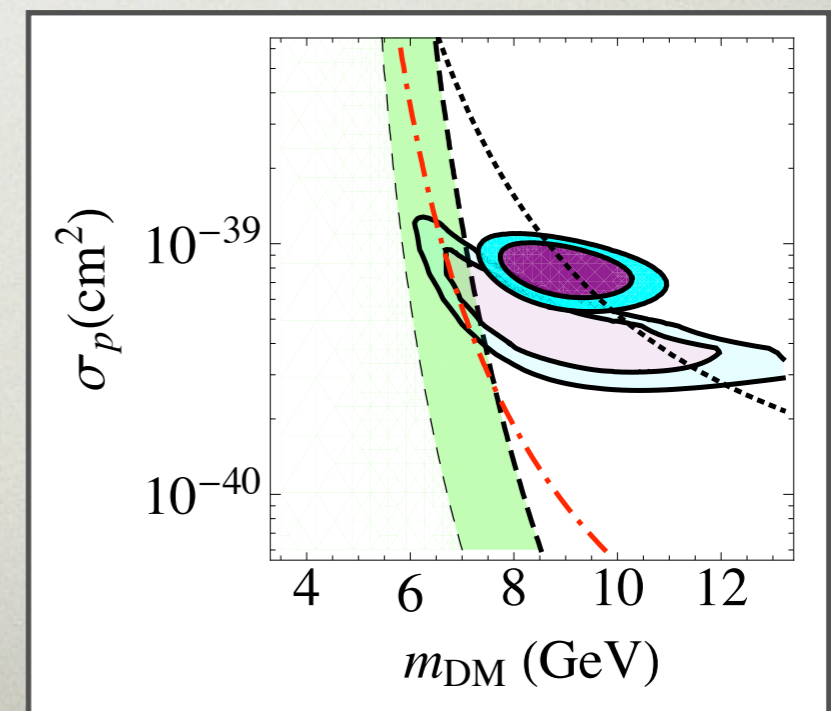
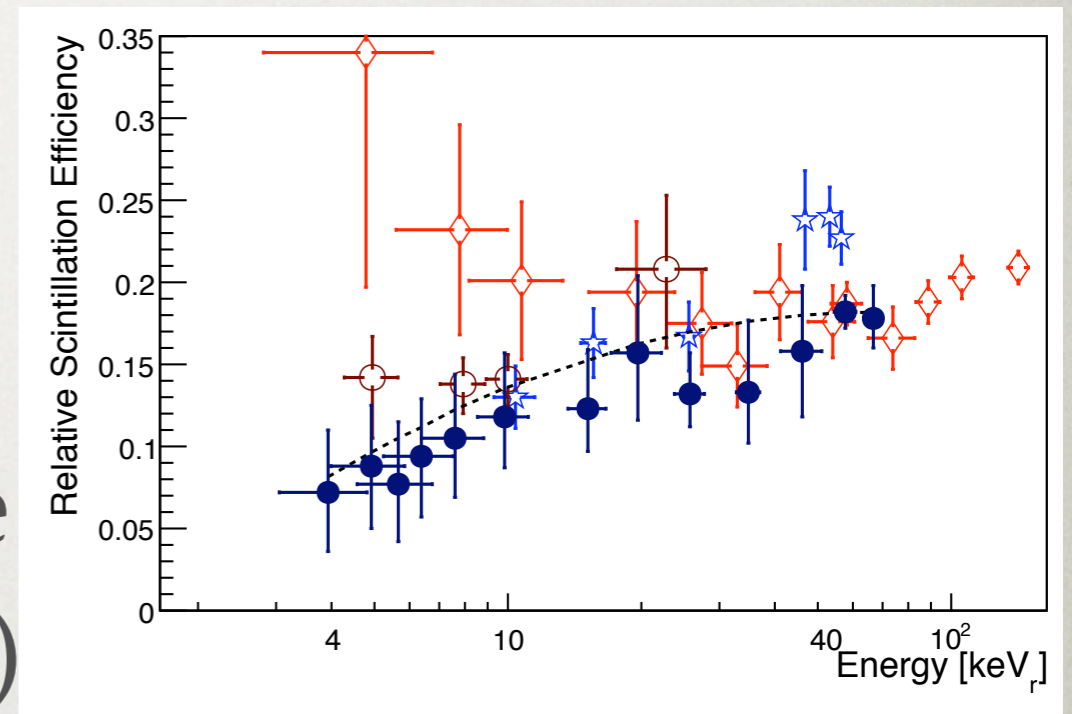
Then CRESST ...



# ALL COMPLICATED BY UNCERTAINTIES ...

- ... of the experimental kind
- How do you calibrate energy? (What is  $L_{\text{eff}}$ ?)
- $L_{\text{eff}}$  measurements seem to be converging

Manzur et al



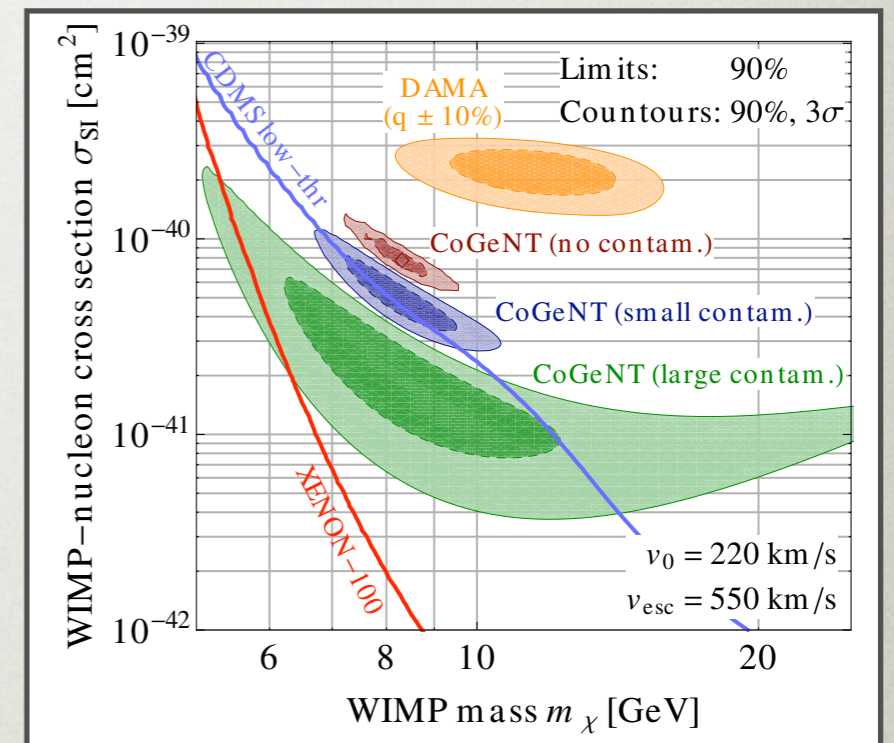
Fitzpatrick, KZ



# ALL COMPLICATED BY UNCERTAINTIES ...

- ... of the experimental kind
- How much of CoGeNT's signal is actually background?
- CoGeNT now says 60-70%

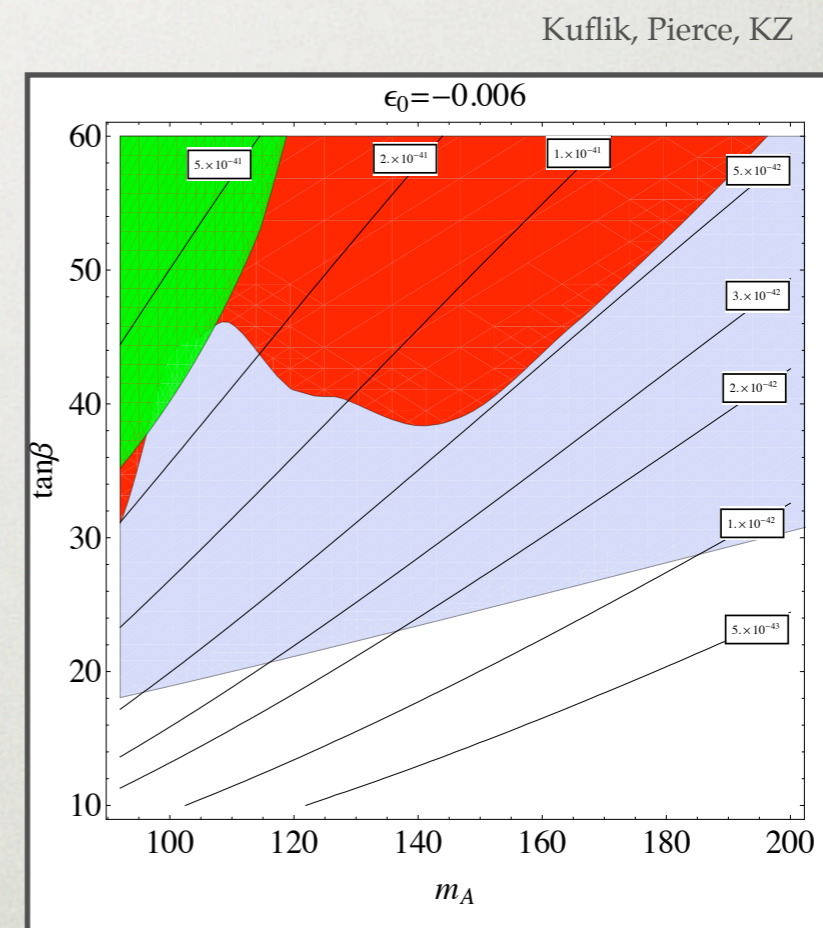
Kopp, Schwetz, Zupan





# LIGHT DM CANDIDATES ARE NOT “STANDARD”

- MSSM: out as a possibility
- Higgsino fraction limited by Z invisible width
- Large tan beta, light pseudo scalar Higgs
- Region constrained by B physics measurements
- Don't obtain large enough cross-section from neutralino



NMSSM changes the story

Belikov, Gunion, Hooper



# WHAT DO WE LEARN?

---

- A DM candidate that could generate such signals is not “standard”



# THE LAMPPOST PROBLEM

---

Is our vision simply too limited?





# NEW AND RESUSCITATED IDEAS

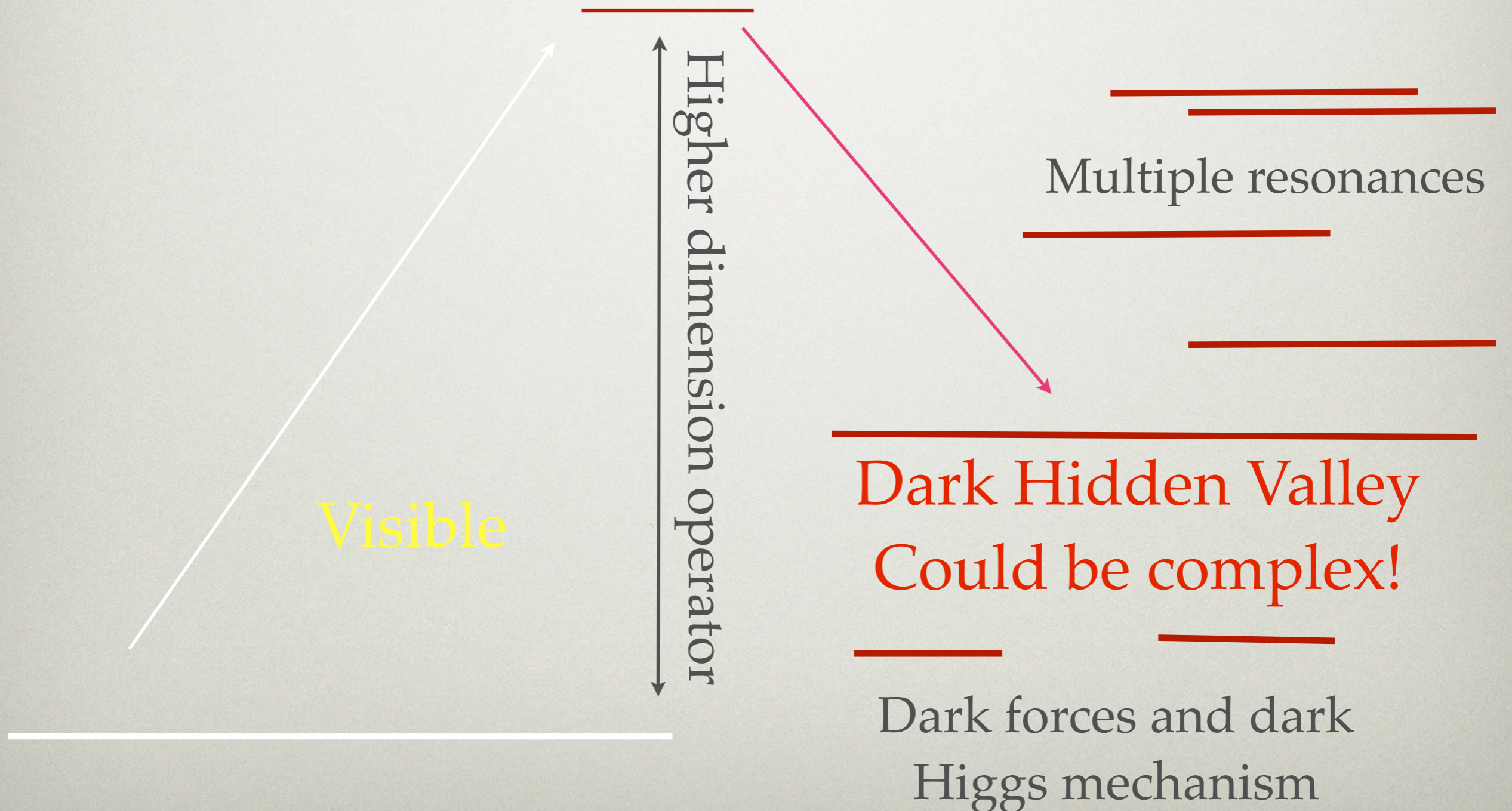
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- iDM for DAMA
- Asymmetric DM
- Dark Forces
- Light DM



# GATEWAY TO A HIDDEN WORLD

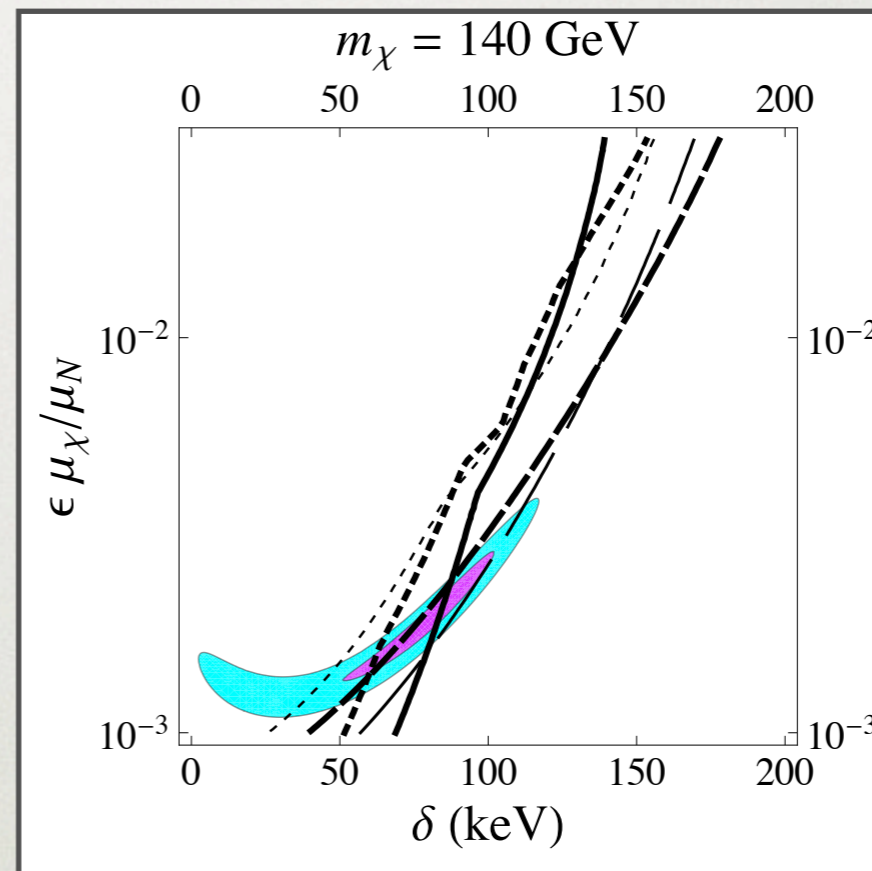
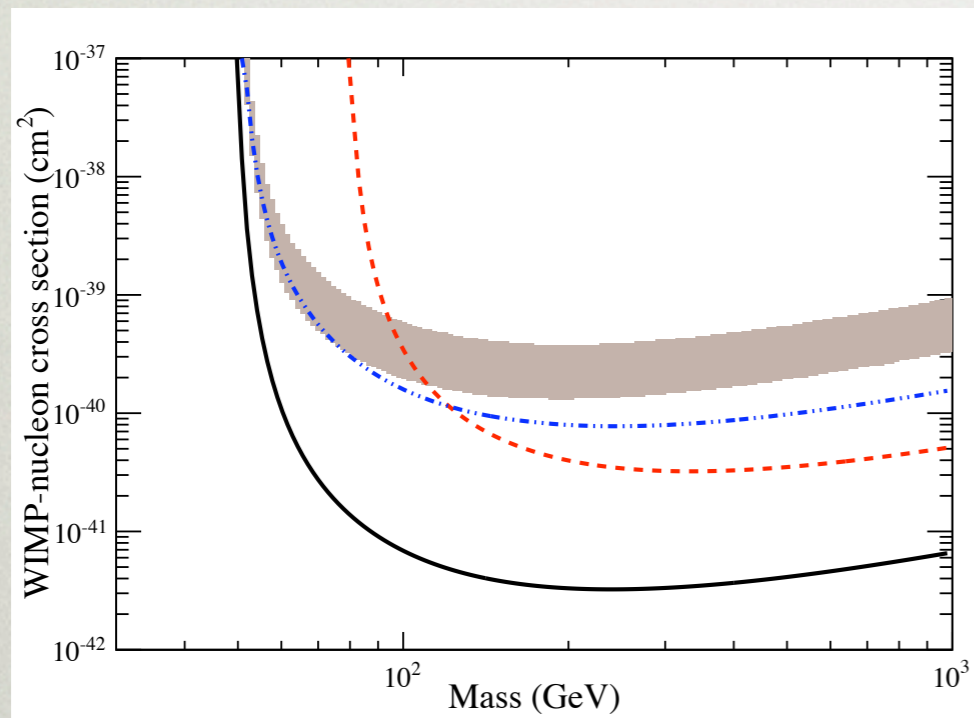
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# IDM FOR DAMA

- Strongly constrained by XENON100 results



Chang, Weiner, Yavin

- But inelastic is a theoretical idea here to stay



# INTERNAL DM STRUCTURE

- Composite inelastic

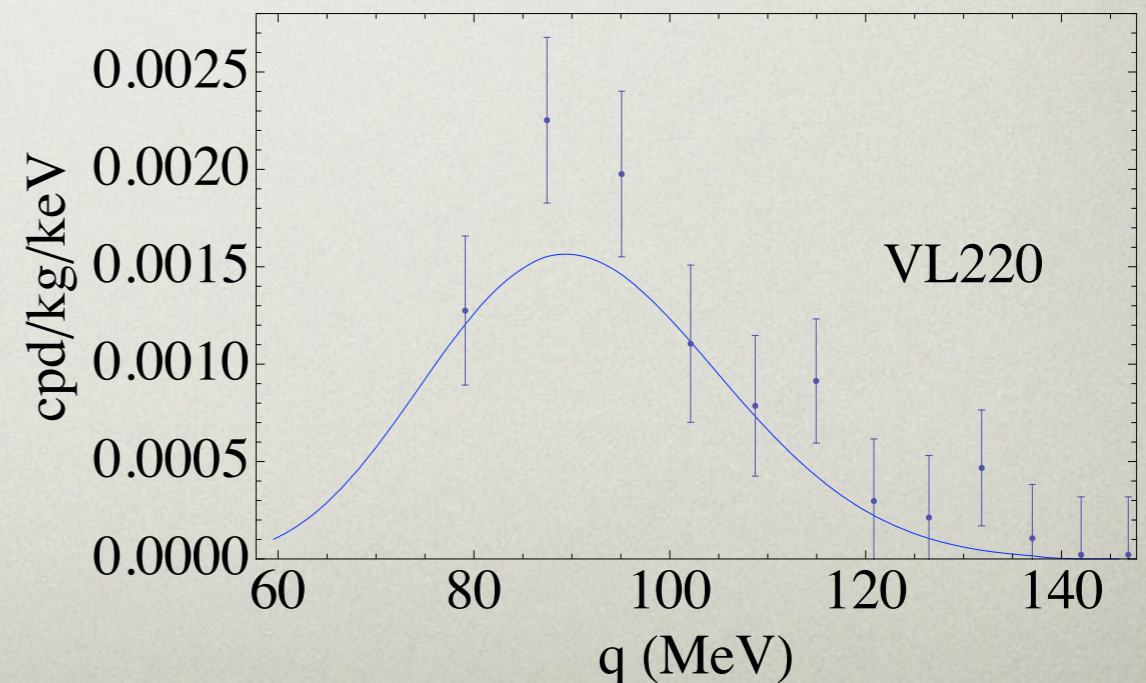
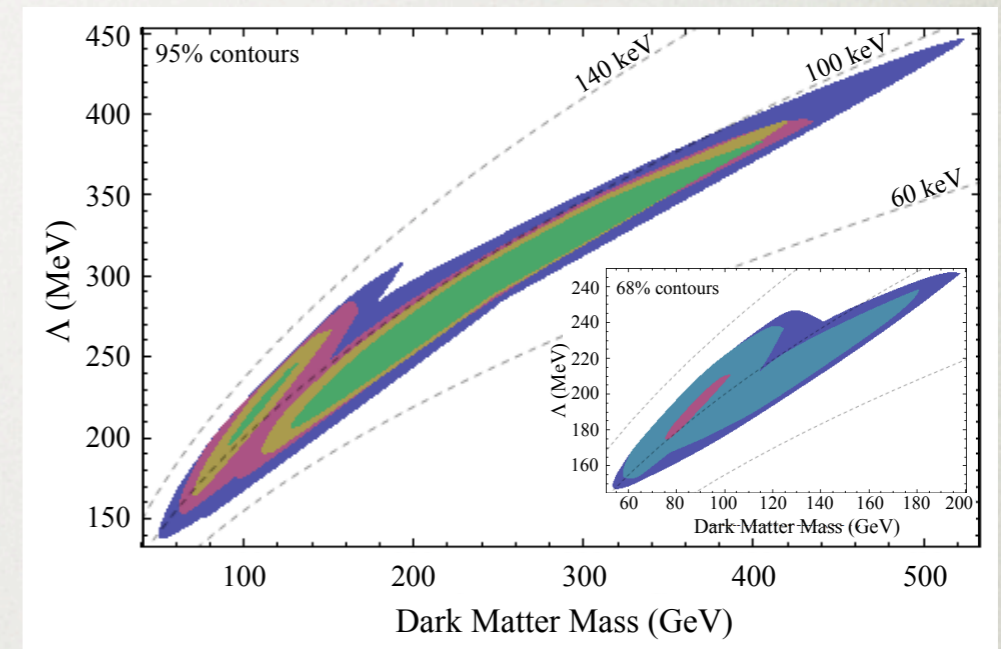
Lisanti, Wacker

- Form Factor DM

Feldstein, Fitzpatrick, Katz

- Atomic DM

Kaplan, Krnjaic, Rehermann, Wells





# ASYMMETRIC DM

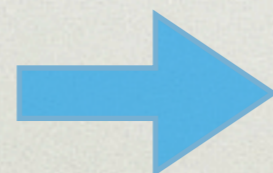
---

- In standard picture, DM abundance set by thermal freeze-out

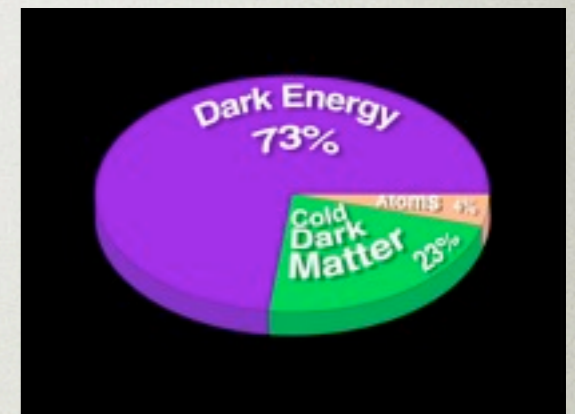
What if instead set by baryon density?

Experimentally,  $\Omega_{DM} \approx 5\Omega_b$

Find mechanism  $n_{DM} \approx n_b$



$$m_{DM} \approx 5m_p$$



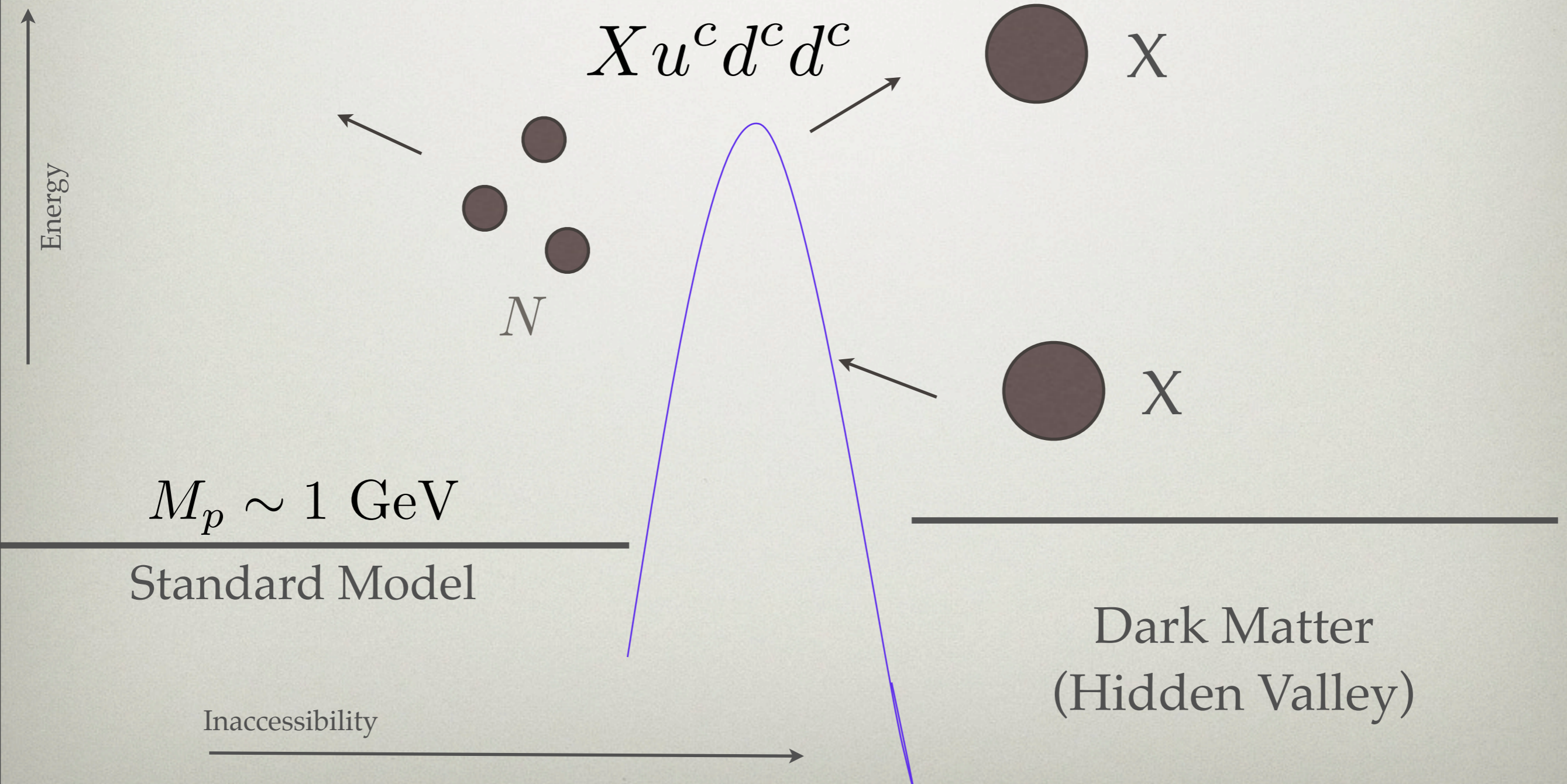
Gelmini, Hall, Lin, Barr, Kaplan,  
Kitano, Low, Farrar, Zaharijas,  
Fujii, Yanagida



# ASYMMETRIC DM

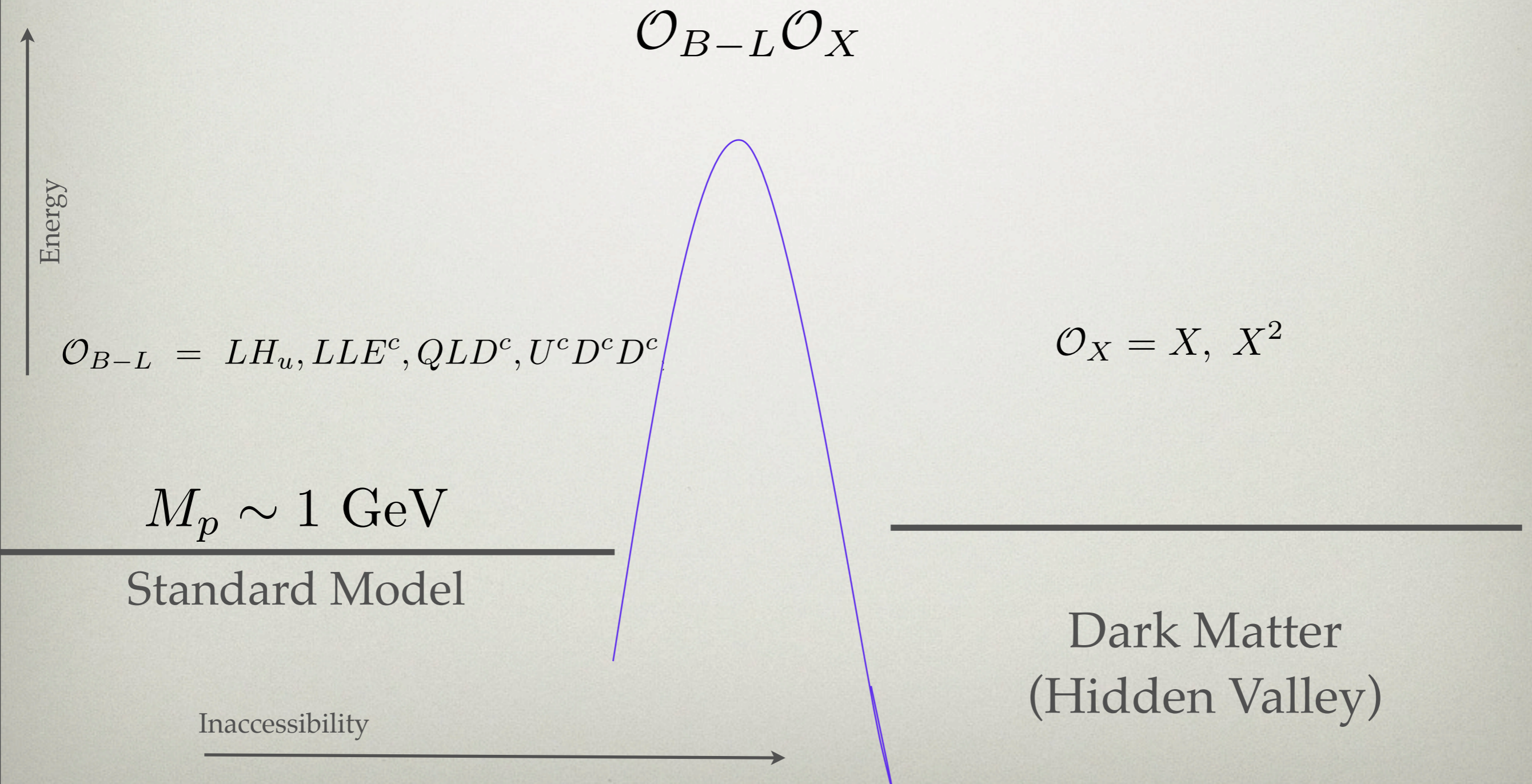
Integrate out heavy state  
Effective operators:

Luty, Kaplan, KZ '09





# ASYMMETRIC DM





# ASYMMETRIC DM

---

1. Transfer lepton or baryon asymmetry to DM through higher dimension operator
2. Have asymmetry transferring operator decouple before DM becomes non-relativistic (Otherwise allows DM asymmetry to wash-out)
3. Annihilate away symmetric abundance of DM

$$n_X - n_{\bar{X}} \approx 10^{-10} n_X$$

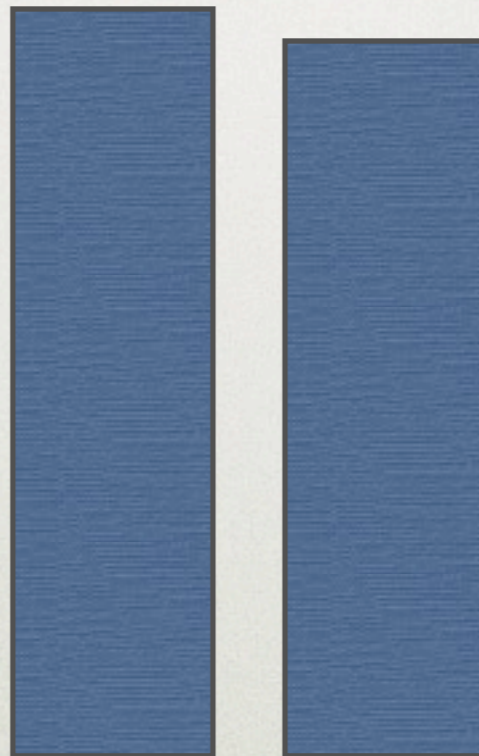


# ANNIHILATING THERMAL ABUNDANCE

---

$$n_{DM} \sim T^3 \rightarrow 10^{-10} T^3$$

Matter Anti-Matter



Dark

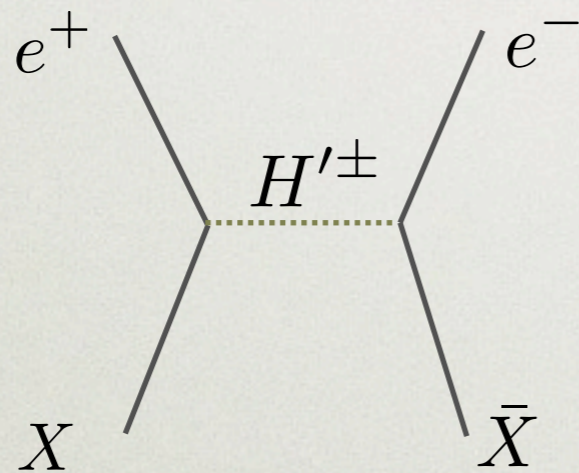


# ANNIHILATING THERMAL ABUNDANCE

---

$$n_{DM} \sim T^3 \rightarrow 10^{-10} T^3$$

- Through heavy mediators



$$m_{H'} / y' \lesssim 200 \text{ GeV}$$

- Tight constraints!



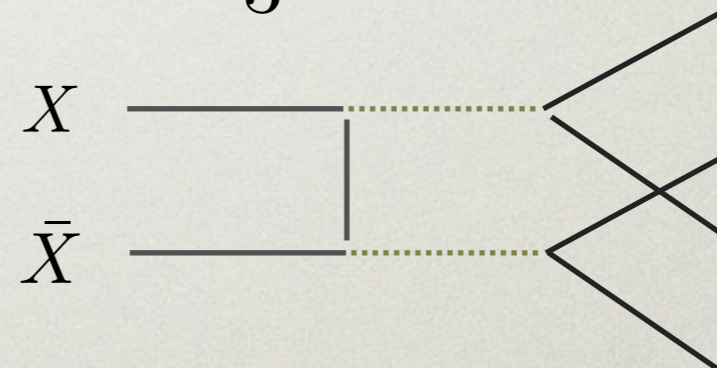
# ANNIHILATING THERMAL ABUNDANCE

---

- Alternative: light states that the DM can annihilate to that rapidly decay
- Much more robust!

$$\Delta W = \lambda_X S X \bar{X} + \lambda_H S H_u H_d + \frac{\kappa}{3} S^3.$$

$$\Delta \mathcal{L}_{\text{eff}} = m_X \bar{X} X e^{ia/s} + \text{h.c.},$$

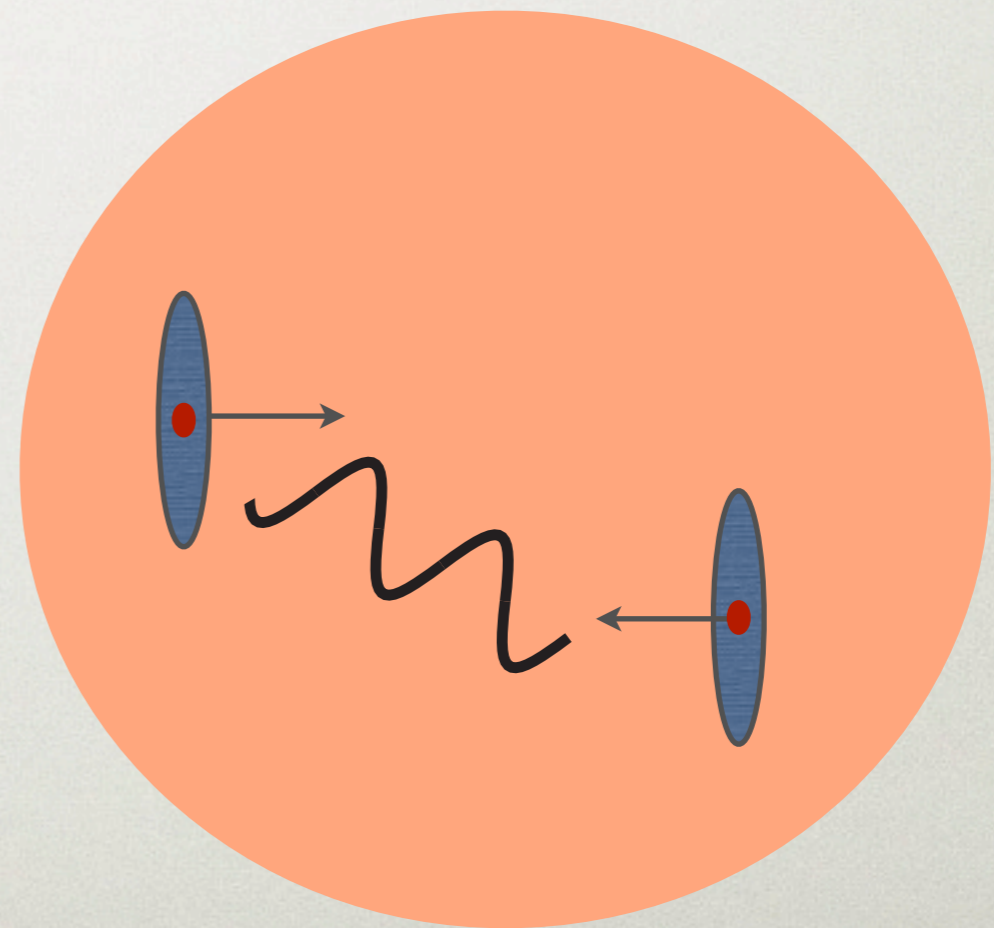
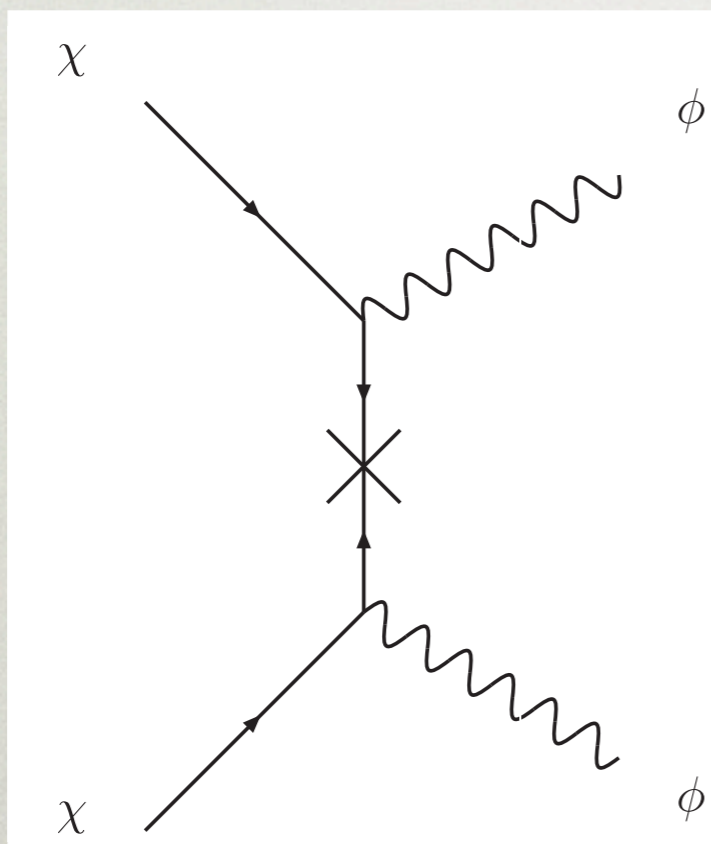




# DARK FORCES

---

- Introduce new light forces, which are constrained by halo shapes

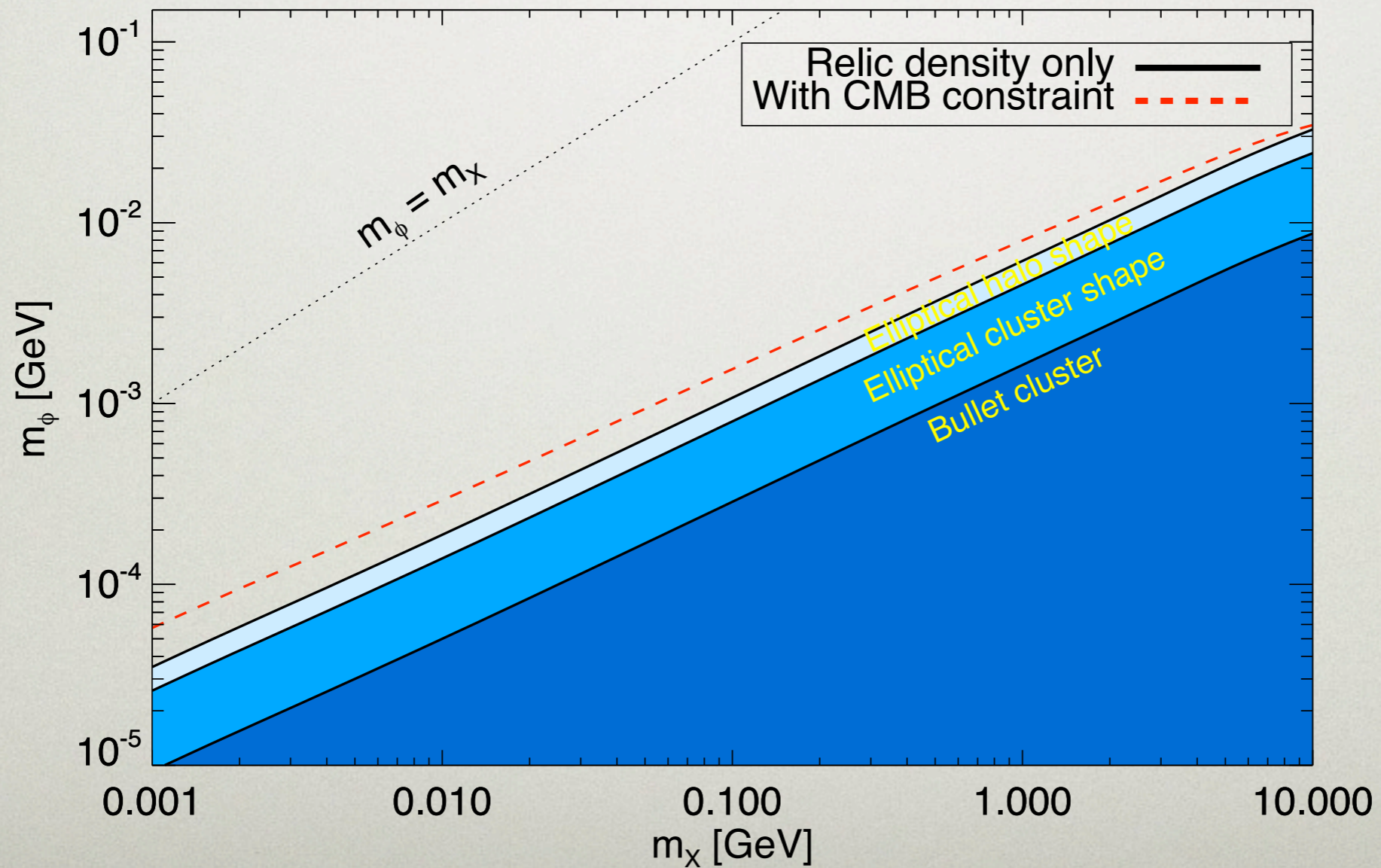




# HALO SHAPES

Eliminates massless force mediators

Lin, Yu, KZ



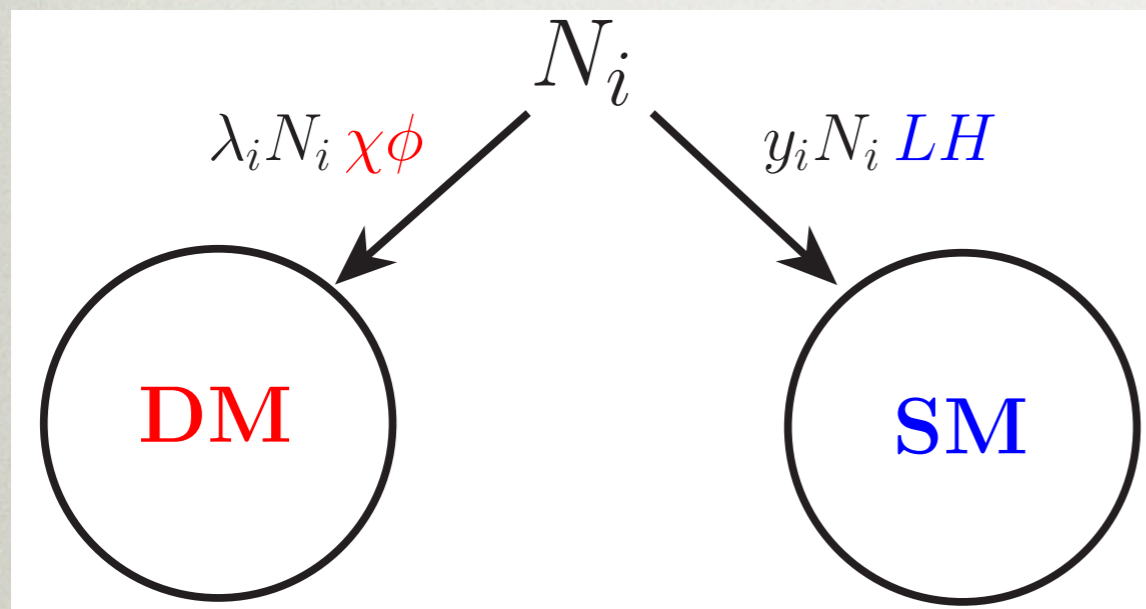


# NATURAL SCALE FOR ADM IS FEW GEV ...

---

- But mechanisms exist to dial the mass scale down, e.g. leptogenesis

Falkowski, Ruderman, Volansky '11



$$\frac{\epsilon_l}{\epsilon_\chi} \simeq \frac{2r \sin(2\phi_l) + \sin(\phi_l + \phi_\chi)}{2r^{-1} \sin(2\phi_\chi) + \sin(\phi_l + \phi_\chi)}$$

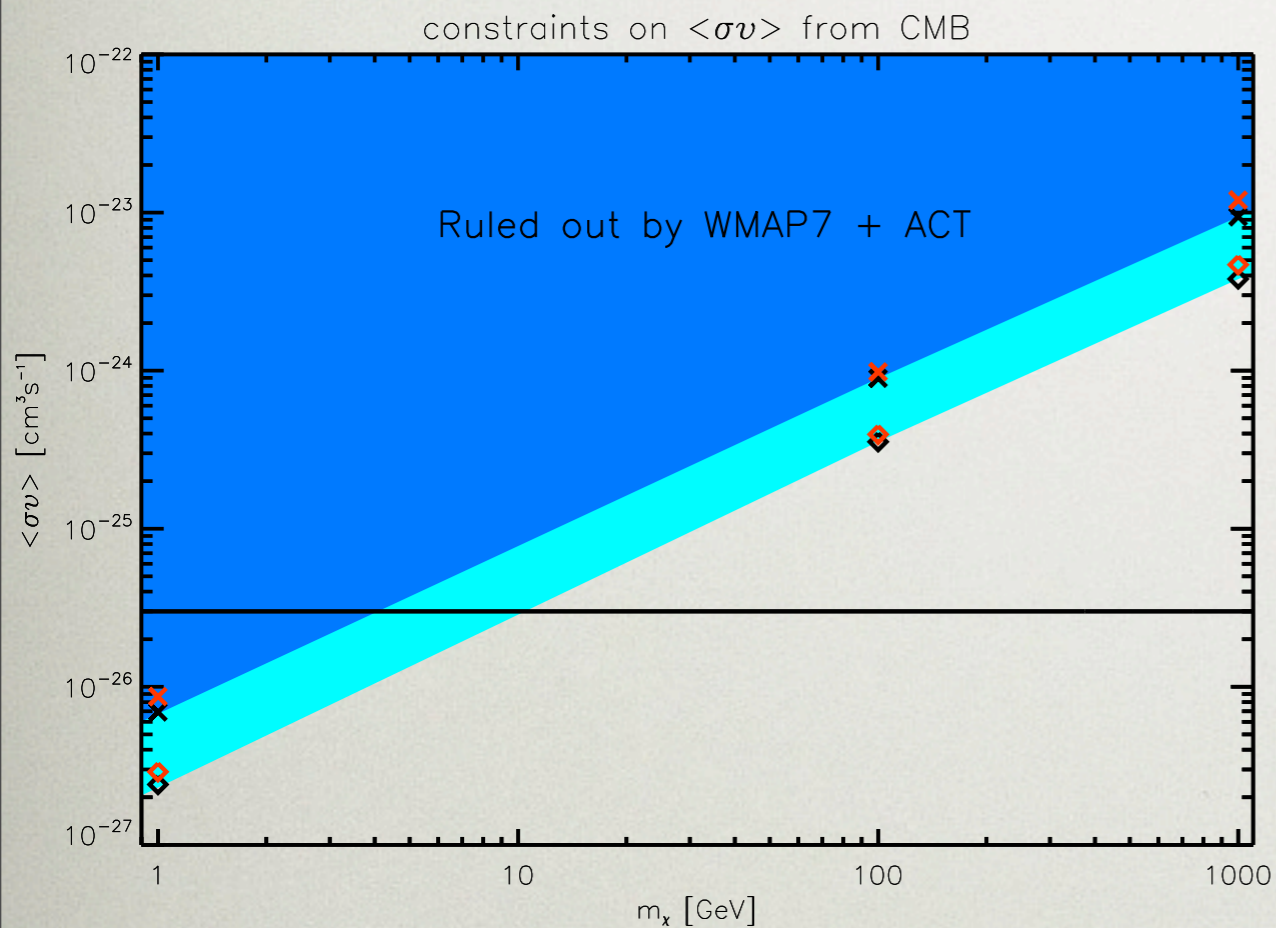
$$m_{DM} \sim \frac{\Omega_{DM}}{\Omega_b} \frac{\epsilon_\chi}{\epsilon_l} m_p$$



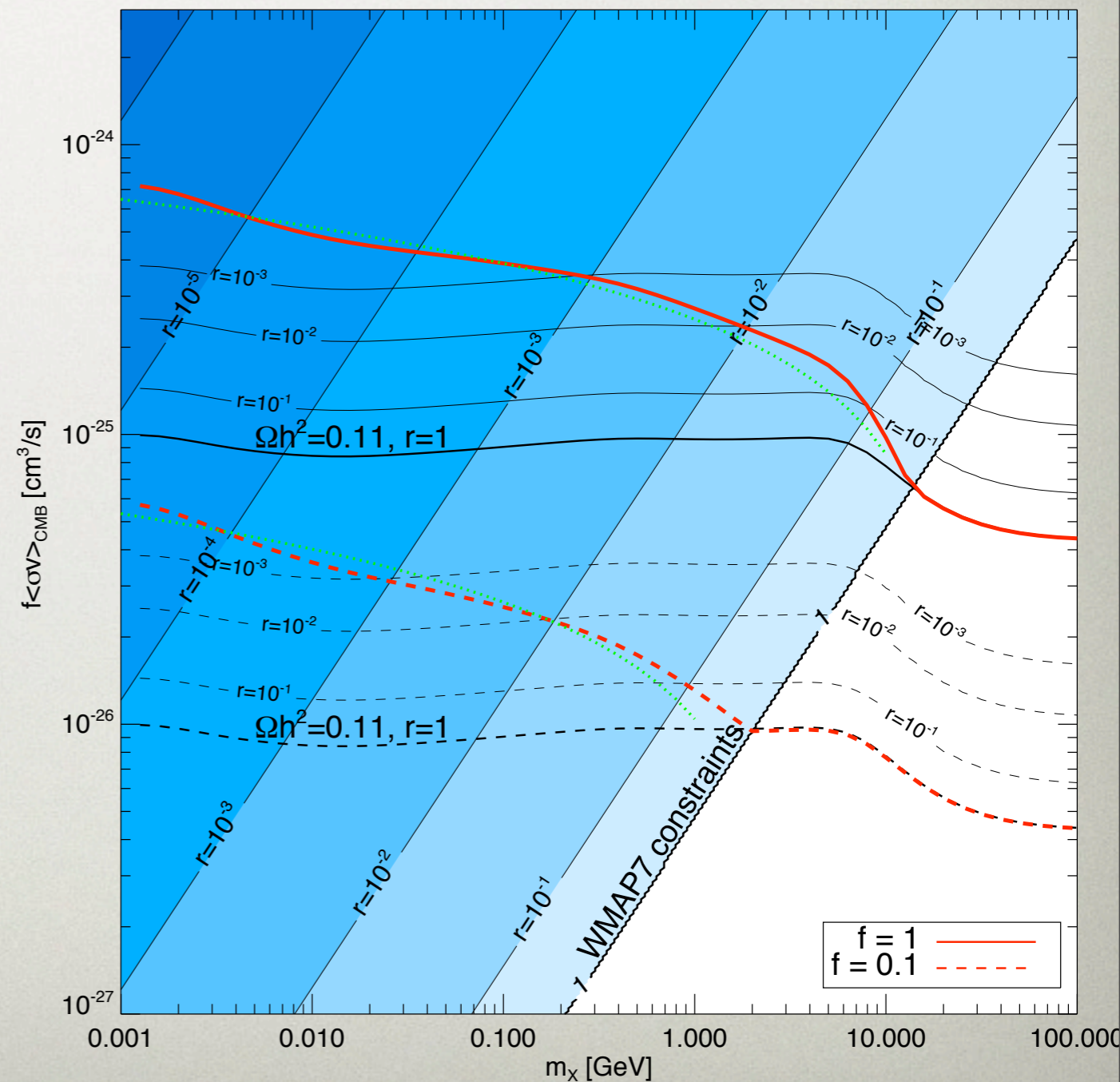
# LIGHT DARK MATTER ...

Must be asymmetric or p-wave suppressed

Lin, Yu, KZ



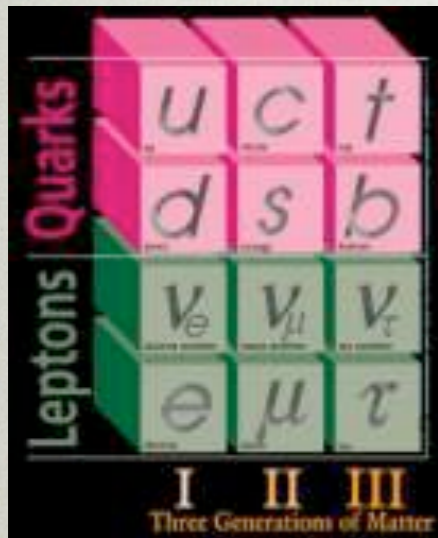
Bertone, Galli, Iocco, Melchiorri





# SUMMARY

While the single, stable, weakly interacting, massive particle paradigm is compelling ...



The dark side may be Complex

$$M_p \sim 1 \text{ GeV}$$

Standard Model

