# Exotic Dark Matter Candidates
# SLAC Summer Institute

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CCPP - NYU
Aug 8, 2007

# Lesson One

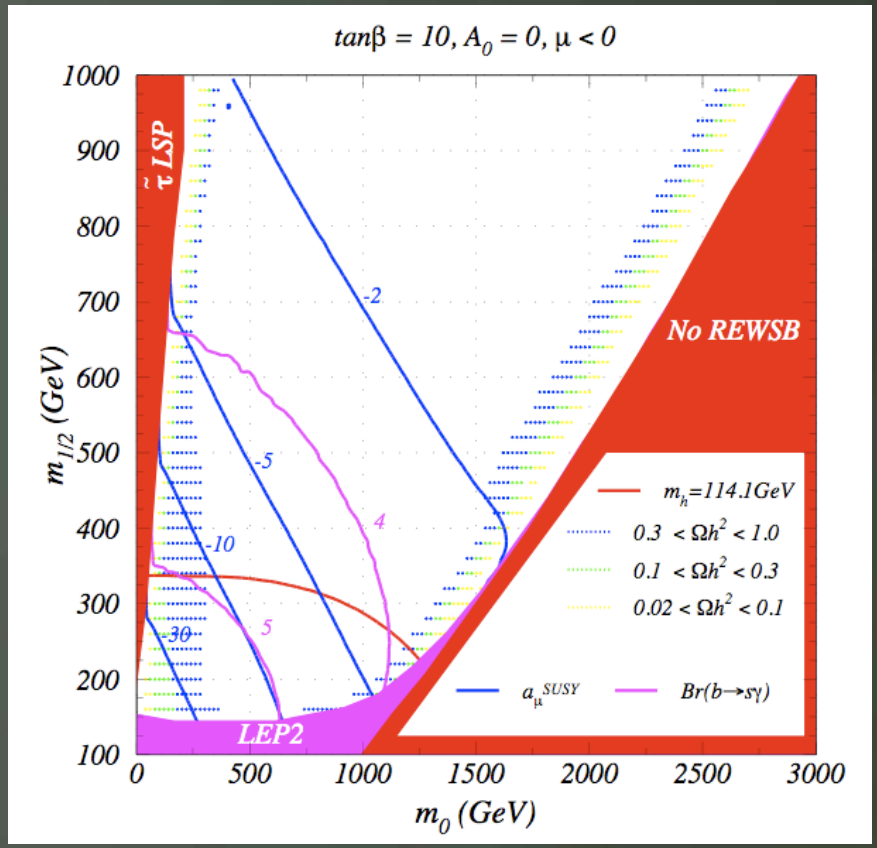
- ALL dark matter candidates are exotic
  - Anyone who tells you differently is selling something

# Why Consider Exotica

- Why consider models of DM at all?
  - Direct Detection Predictions:
    - What size, mass, properties for detectors?
    - Detection strategies (primakoff process)
  - Indirect Detection Predictions:
    - Gamma ray spectrum
    - Microwave emission
    - Cosmic Ray Spectrum
    - Neutrino Spectrum (solar or Earth capture)
  - Cosmological Properties
    - Power spectrum
    - Clustering Properties (e.g. from additional forces)
- DM Models give a sense of what to look for and/or what existing hints may be interesting

# Why not consider exotica

- DM can limit your parameter range in a particular model
- Of course, your model is wrong*




Stolen from Baer, et al

*Except for the one of you that's right, but everyone else's is wrong

# So what's wrong with SUSY

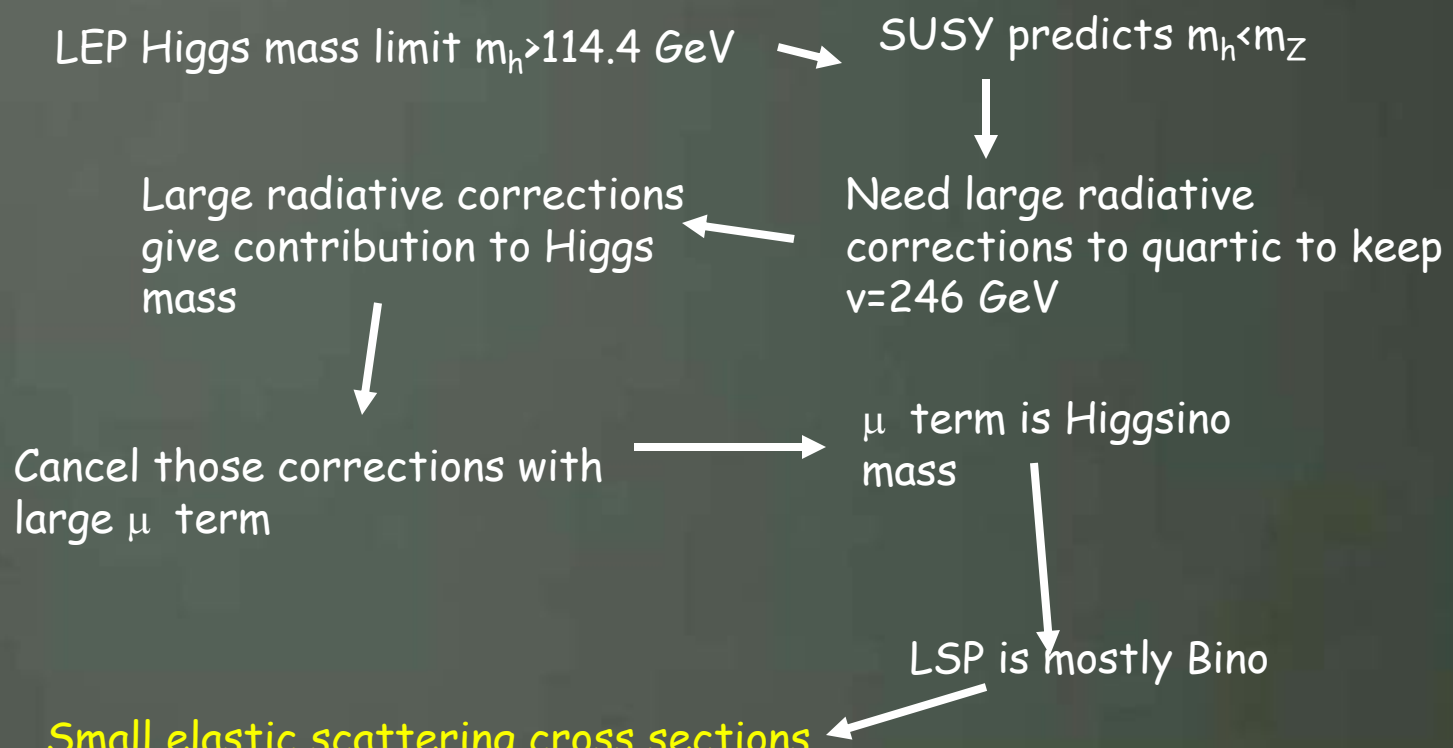
- Jonathan Feng's talk: "Supersymmetry is the best motivated framework for new particle physics"
- Counter argument: Supersymmetry has made a total of zero verified predictions
- Counter-counter argument: What about SUSY grand unification? That predicts $\sin^2\theta$
- $C^3A$: Sure, but that also predicts that protons decay at rates ridiculously higher than observed
- $C^4A$: Wait, wait, no I have a model that evades that!
- $C^5A$: Isn't that still a really tuned model?
- $C^6A$: Well, sure, but do you have a better one?
- $C^7A$: No, but that's not really the point, is it?
- $C^8A$: We need some model to address phenomenology, and this is the best one we have
- $C^9A$: I'm hungry, do you want to get a snack?
- $C^{10}A$: Sure, sounds good!

# Wrong SUSY Part 2: SUSY is not a good model for SUSY

- Most popular formulation of SUSY is mSUGRA
  - 5 parameters: $m_{1/2}$, $m_0$, $A$, $m$, $\tan\beta$
  - A reasonable starting point!
  - But there are built in correlations, and these can cause problems

# The CMSSM/mSUGRA neutralino is not your friend

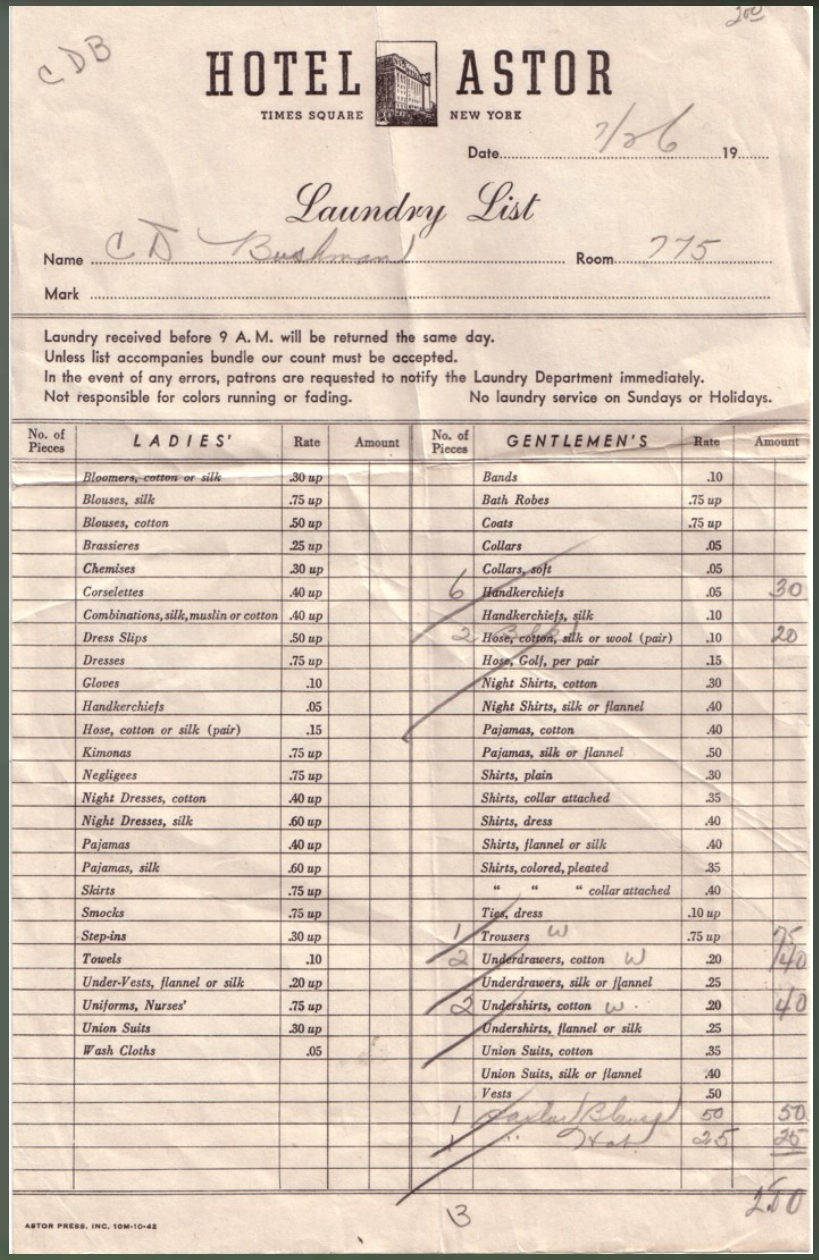
- Common logical path in mSUGRA*




* No, not every point in mSUGRA, this is just an example

# Beyond mSUGRA

- Many parameter searches can give broader phenomenology (see e.g., Baltz, Battaglia, Peskin and Wizansky)
- Sometimes new models may capture phenomenology not found in SUSY parameter scans



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## Laundry List

Name C D Bushman Room 775

Mark

Laundry received before 9 A. M. will be returned the same day.
Unless list accompanies bundle our count must be accepted.
In the event of any errors, patrons are requested to notify the Laundry Department immediately.
Not responsible for colors running or fading. No laundry service on Sundays or Holidays.

| No. of Pieces | LADIES' | Rate | Amount |
|---|---|---|---|
| | Bloomers, cotton or silk | .30 up | |
| | Blouses, silk | .75 up | |
| | Blouses, cotton | .50 up | |
| | Brassieres | .25 up | |
| | Chemises | .30 up | |
| | Corselettes | .40 up | |
| | Combinations, silk, muslin or cotton | .40 up | |
| | Dress Slips | .50 up | |
| | Dresses | .75 up | |
| | Gloves | .10 | |
| | Handkerchiefs | .05 | |
| | Hose, cotton or silk (pair) | .15 | |
| | Kimonas | .75 up | |
| | Negligees | .75 up | |
| | Night Dresses, cotton | .40 up | |
| | Night Dresses, silk | .60 up | |
| | Pajamas | .40 up | |
| | Pajamas, silk | .60 up | |
| | Skirts | .75 up | |
| | Smocks | .75 up | |
| | Step-ins | .30 up | |
| | Towels | .10 | |
| | Under-Vests, flannel or silk | .20 up | |
| | Uniforms, Nurses' | .75 up | |
| | Union Suits | .30 up | |
| | Wash Cloths | .05 | |

| No. of Pieces | GENTLEMEN'S | Rate | Amount |
|---|---|---|---|
| | Bands | .10 | |
| | Bath Robes | .75 up | |
| | Coats | .75 up | |
| | Collars | .05 | |
| | Collars, soft | .05 | |
| 6 | Handkerchiefs | .05 | 30 |
| | Handkerchiefs, silk | .10 | |
| 2 | Hose, cotton, silk or wool (pair) | .10 | 20 |
| | Hose, Golf, per pair | .15 | |
| | Night Shirts, cotton | .30 | |
| | Night Shirts, silk or flannel | .40 | |
| | Pajamas, cotton | .40 | |
| | Pajamas, silk or flannel | .50 | |
| | Shirts, plain | .30 | |
| | Shirts, collar attached | .35 | |
| | Shirts, dress | .40 | |
| | Shirts, flannel or silk | .40 | |
| | Shirts, colored, pleated | .35 | |
| | " " " collar attached | .40 | |
| | Ties, dress | .10 up | |
| 1 | Trousers W | .75 up | 75 |
| 2 | Underdrawers, cotton W | .20 | 40 |
| | Underdrawers, silk or flannel | .25 | |
| 2 | Undershirts, cotton W | .20 | 40 |
| | Undershirts, flannel or silk | .25 | |
| | Union Suits, cotton | .35 | |
| | Union Suits, silk or flannel | .40 | |
| | Vests | .50 | |
| 1 | Sweater (Blue) | 50 | 50 |
| 1 | " Hat | 25 | 25 |
| | | | |
| | | | |
| 13 | | | 2.50 |

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8/29/2007

N. Weiner CCPP

# Dark Matter Candidates: Motivated by Theory Issues

- SUSY: neutralino, gravitino, axino, "mixed"/non-standard sneutrino, singlino (really neutralino) (motivated by hierarchy problem)
- Axion (motivated by strong CP problem)
- Lightest T-Odd Particle (LTOP - little Higgs models, generic BSM, motivated by HP+precision electroweak)
- ED: Lightest KK Particle (LKP - motivated by hierarchy problem… sometimes)
- Qballs (motivated by presence of new symmetry groups in BSM theories)
- Fourth generation neutrino (motivated by first three generations)

# Dark Matter: Motivated by "Observation"

- Galaxy Structure: strongly interacting DM (not really a theory), warm dark matter (keV sterile neutrino), late forming DM
- INTEGRAL Excess: MeV DM, Decaying DM, "Exciting" DM (XDM)
- DAMA: Light DM, inelastic DM, mirror DM

There is also your, your friend's and/or your advisor's favorite model which I have neglected to mention, for which I apologize

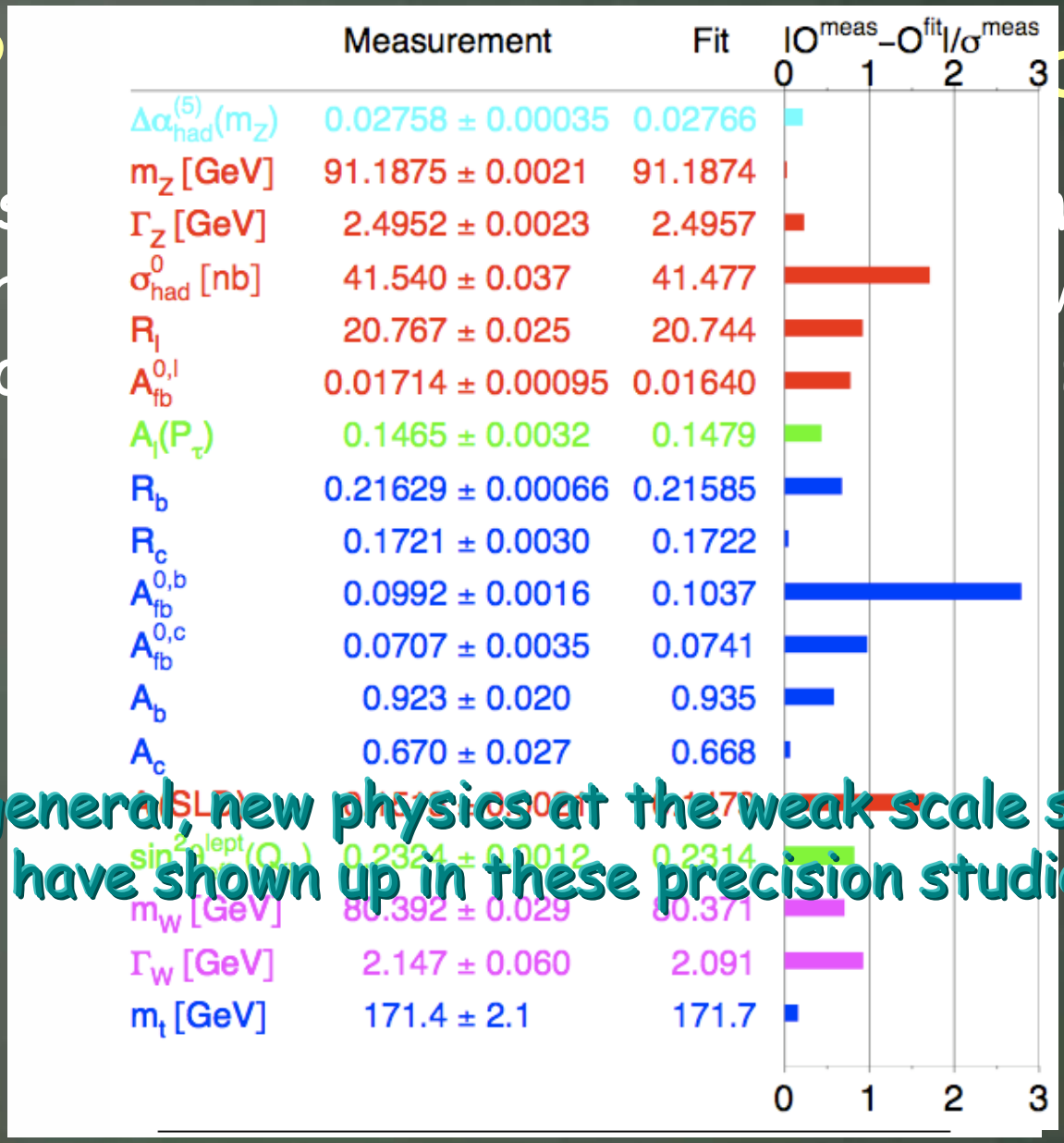
# Is DM generic in BSM theories

- What do you need to have DM?
  - An annihilation cross section

    $\langle \sigma v \rangle \sim 2 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$
  - It should be stable
- Almost all particles at the weak scale will have cross section in the roughly appropriate range ($\sigma \sim \alpha^2/M^2$)
- So what about stability?

# P dies

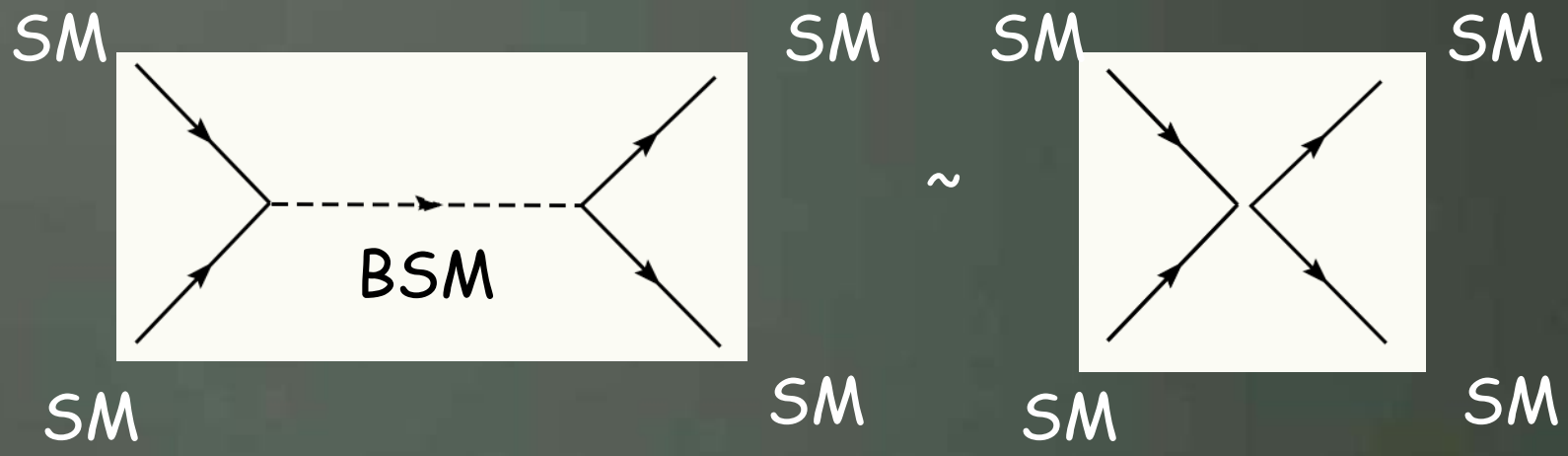
- Jus ew par w much abo model




In general, new physics at the weak scale should have shown up in these precision studies

# T-Parity (Cheng and Low)

- The problem arises from diagrams like




Need to forbid these diagrams somehow

# T-parity, cont

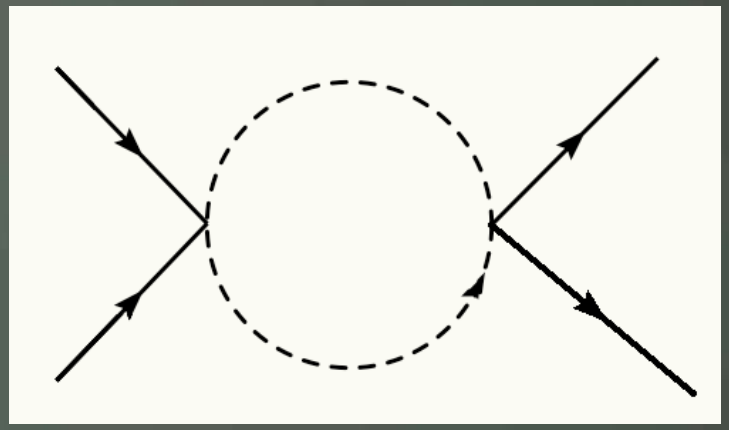
- Vertex comes from Lagrangian term

$$\mathcal{L} \supset SM_1 SM_2 BSM$$

- I.e., problem is presence of single BSM field
  - If only even numbers of BSM fields were allowed, this term is forbidden!

# T-parity, cont

- Then process occurs via loop



loops smaller by ~ $1/16\pi^2$

enough to solve problem

# T-parity, cont

- Only even numbers of BSM fields => parity in the theory*

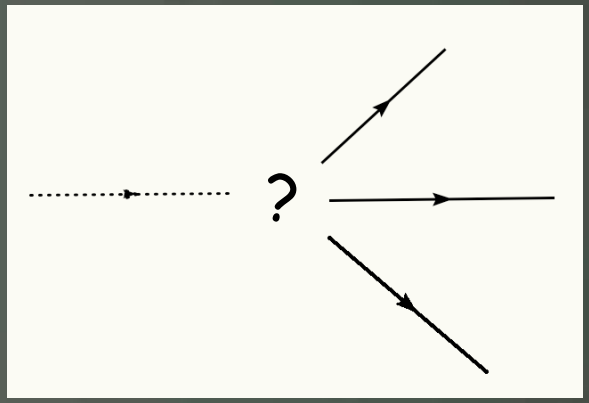
$$\bar{f} f \phi \rightarrow \bar{f} f (-\phi)$$ Not invariant

$$\bar{f} f \phi^2 \rightarrow \bar{f} f (-\phi)^2$$ invariant

*Not all BSM fields must change sign under this parity, but as long as some do, the relevance for DM is unchanged

# Key point

- Consider the lightest T-odd particle, any process like




Such a process cannot occur because there is one LTOP on the left and none on the right, hence the total number is odd, hence forbidden

=> LTOP is stable

# Intermediate Summary

- New states at the weak scale generically have the appropriate cross sections to yield the observed DM density by thermal freezeout
- Precision electroweak studies strongly motivate presence of parity in theory, which implies lightest T-odd particle is stable
- Dark matter is a generic prediction of solutions to the hierarchy problem (I.e., new physics at 1 TeV)

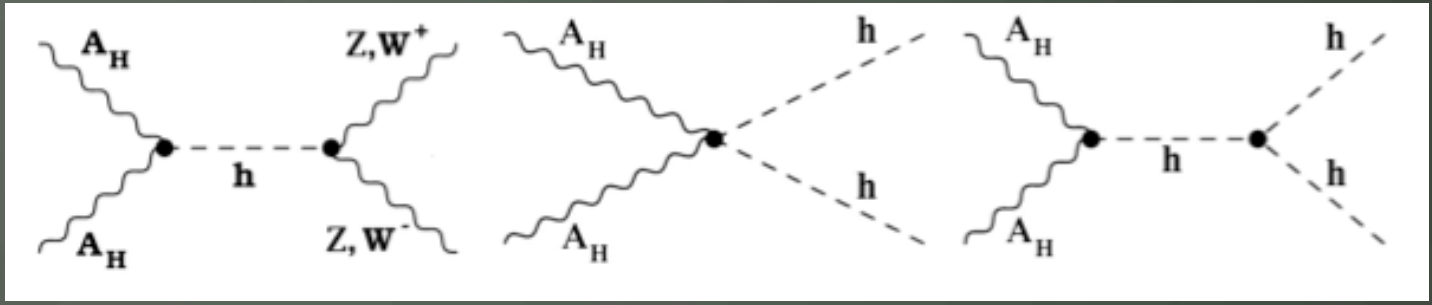
# Models

- Consider:
  - SUSY
  - Extra dimensions
  - Little Higgs
- How can we distinguish?
  - Direct Detection cross sections
  - Masses
  - Indirect Detections

# Little Higgs

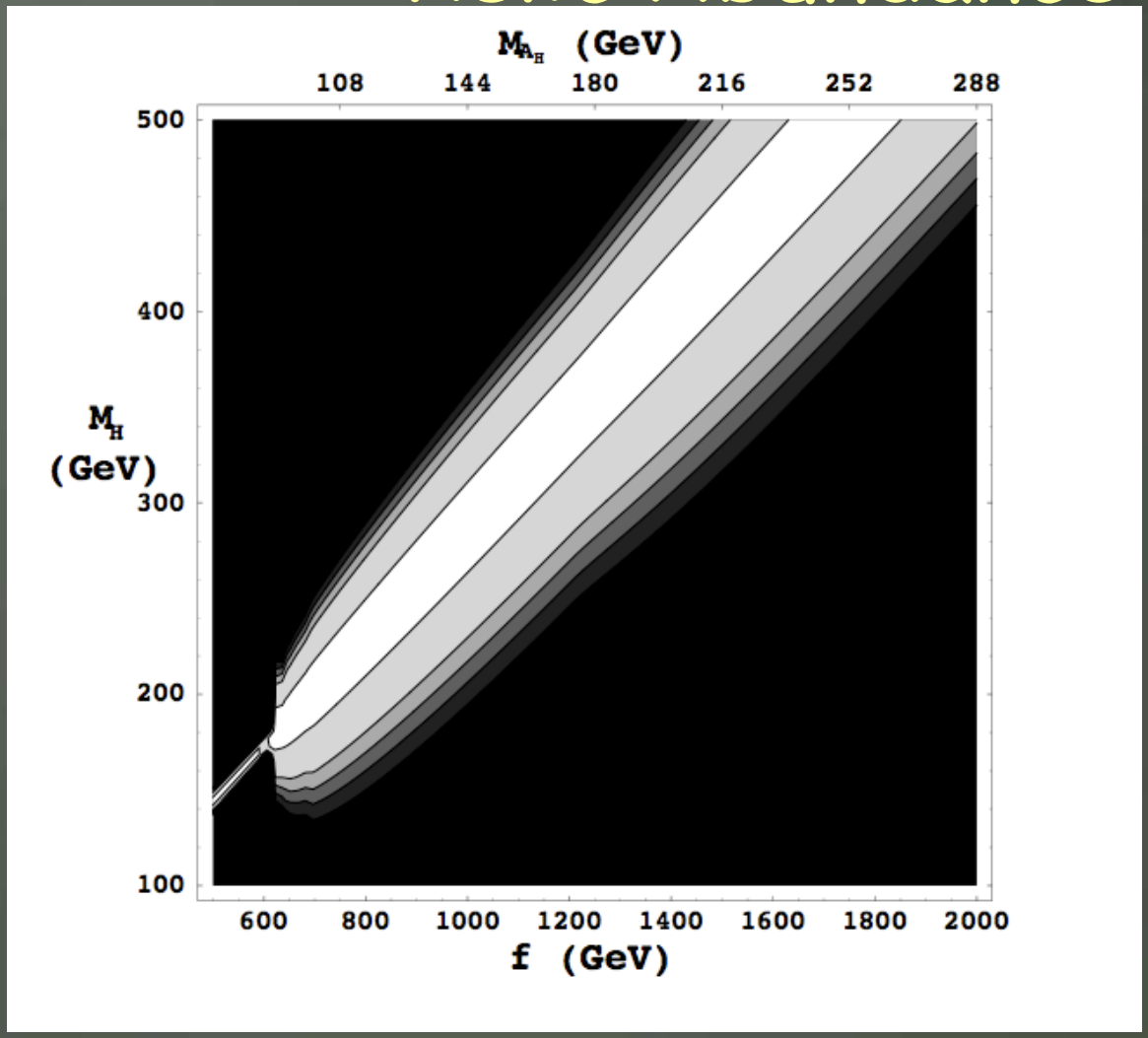
- The Little Higgs Theory (Arkani-Hamed, Cohen, Georgi; Arkani-Hamed, Cohen, Katz, Nelson)
  - Involves embedding the SM gauge group into a larger group
  - Higgs is pseudo-Goldstone boson of the broken larger group
- Dark Matter Candidate is "heavy photon" (Hubisz & Meade; A. Birkedal, A. Noble, M. Perelstein and A. Spray; Asano, Matsumoto,Okada & Okada; Perelstein & Spray)
  - Partner of real photon, but doesn't couple to electric charge

Annihilates typically into Z/W/h states




Not unlike some SUSY models…

# Relic Abundance




Hubisz & Meade

# Lightest Kaluza Klein Particle

(Appelquist, Cheng, Dobrescu; Servant, Tait; also Agashe, Servant; Kakizaki, Matsumoto, Sato, Senami)

- In theories of extra dimensions, there are "Kaluza Klein" states

$$\psi(t, \vec{x}_3, u) = \sum \psi_n(t, \vec{x}_3) e^{inu/R}$$

- Momentum in fifth dimension is quantized
- Energy couples to gravity universally, so 5D momentum looks like mass - mass 1/R

# KK Parity

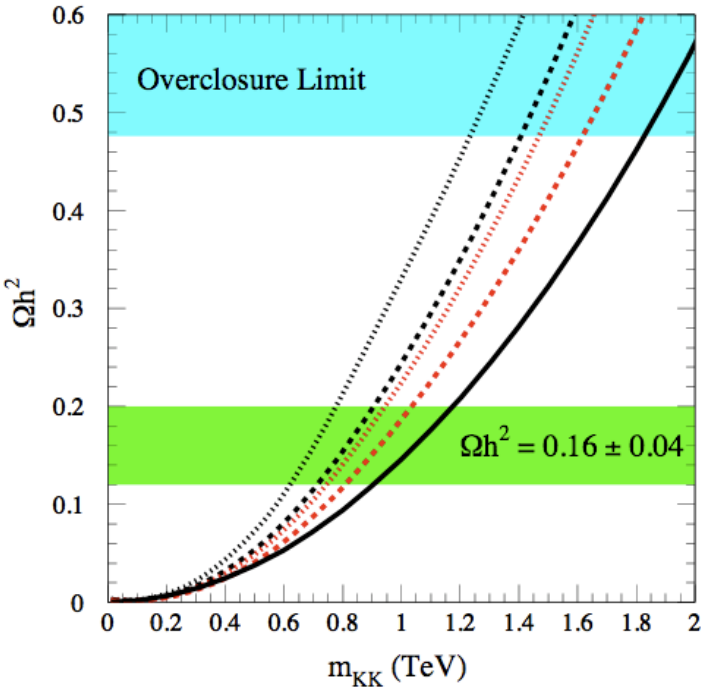
- In extra dimensions, "KK number" is conserved - momentum in fifth dimension
- For viability, u->-u must be imposed, leaves a residual parity in the theory ("KK Parity")
- If no violations of that parity exist, LKP stable
  - Candidates: KK B, KK neutrino

# Coannihilation important

- KK states are close together


Presence of multiple states can influence relic abundance calculation ("coannihilation")

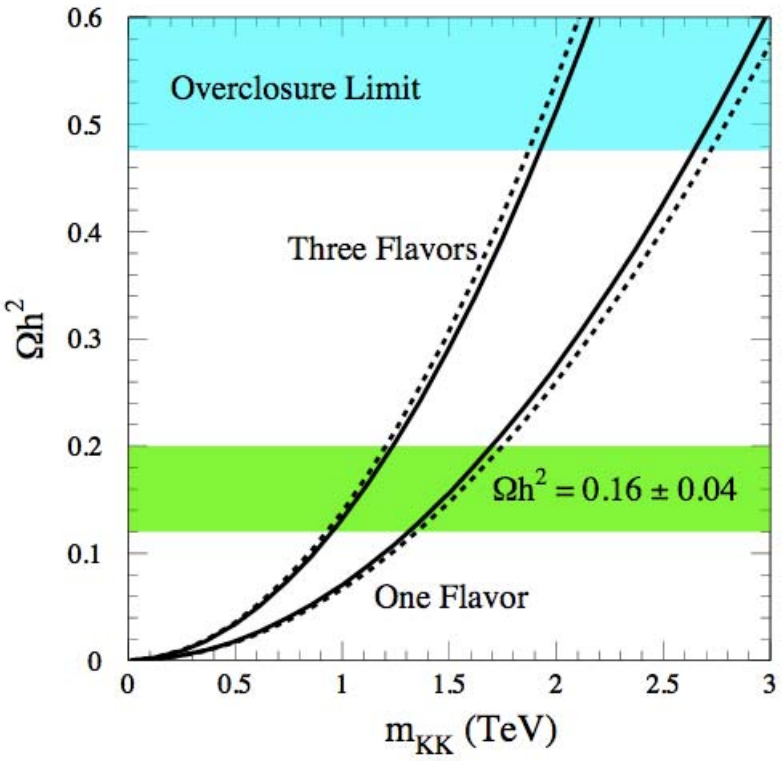
# KK "Photon"




Servant & Tait

Figure 3: Prediction for $\Omega_{B^{(1)}}h^2$ as in Figure 1. The solid line is the case for $B^{(1)}$ alone, and the dashed and dotted lines correspond to the case in which there are one (three) flavors of nearly degenerate $e_R^{(1)}$. For each case, the black curves (upper of each pair) denote the case $\Delta = 0.01$ and the red curves (lower of each pair) $\Delta = 0.05$.

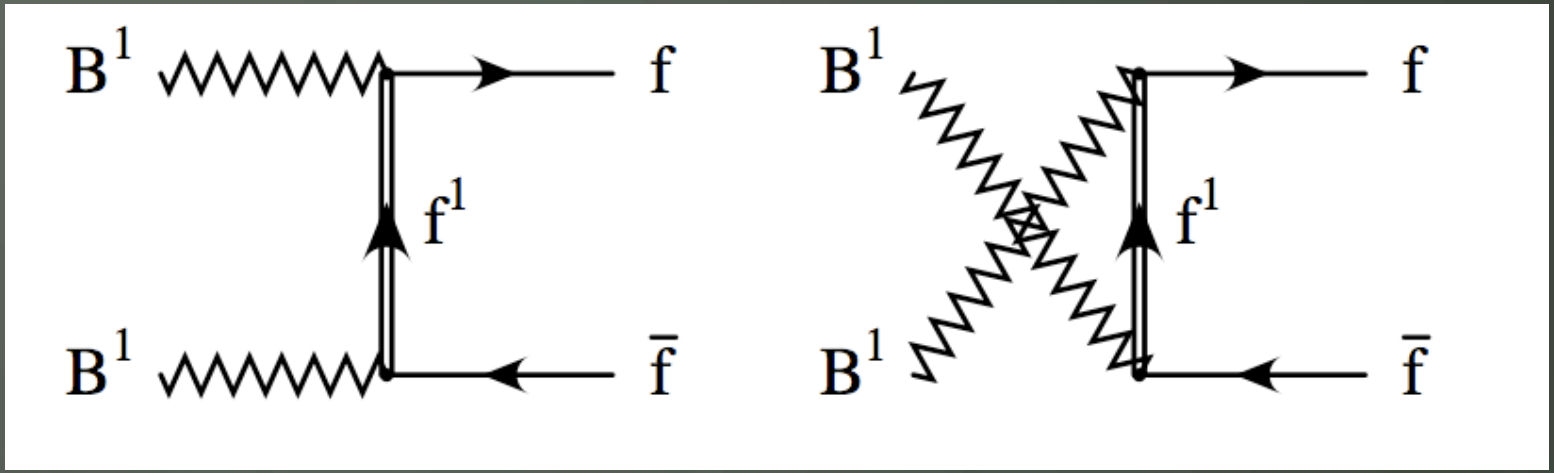
# KK neutrino




Servant & Tait

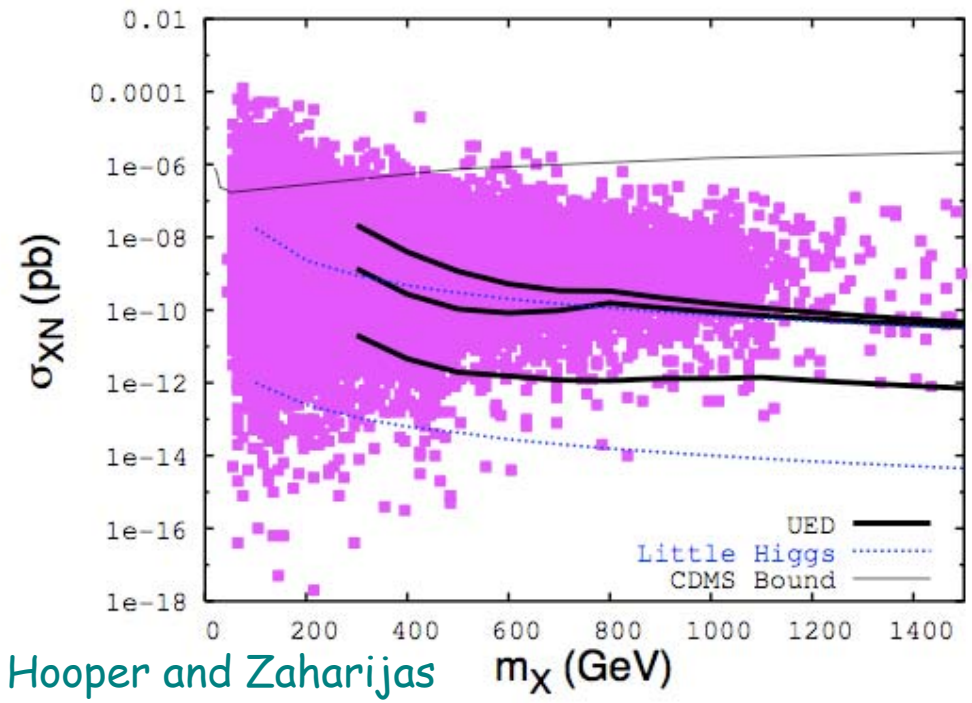
Figure 2: Prediction for $\Omega_{\nu^{(1)}} h^2$ as a function of the KK mass. The solid lines are for $\nu^{(1)}$ alone (in the one and three family cases) and the dotted ones correspond to the cases where coannihilation with degenerate $e_L^{(1)}$ is included.

# LKP can annihilate to "hard" leptons



# Distinguishing Scenarios (see Hooper and Zaharijas)

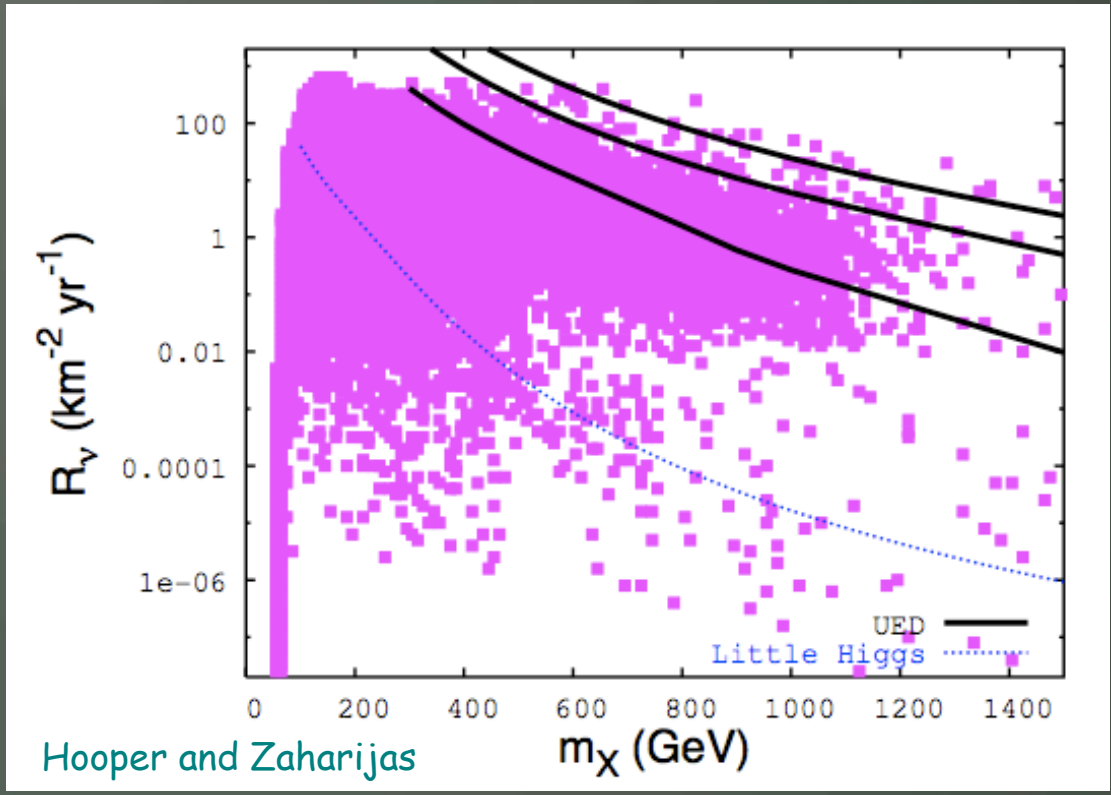
- Direct Detection




Hooper and Zaharijas

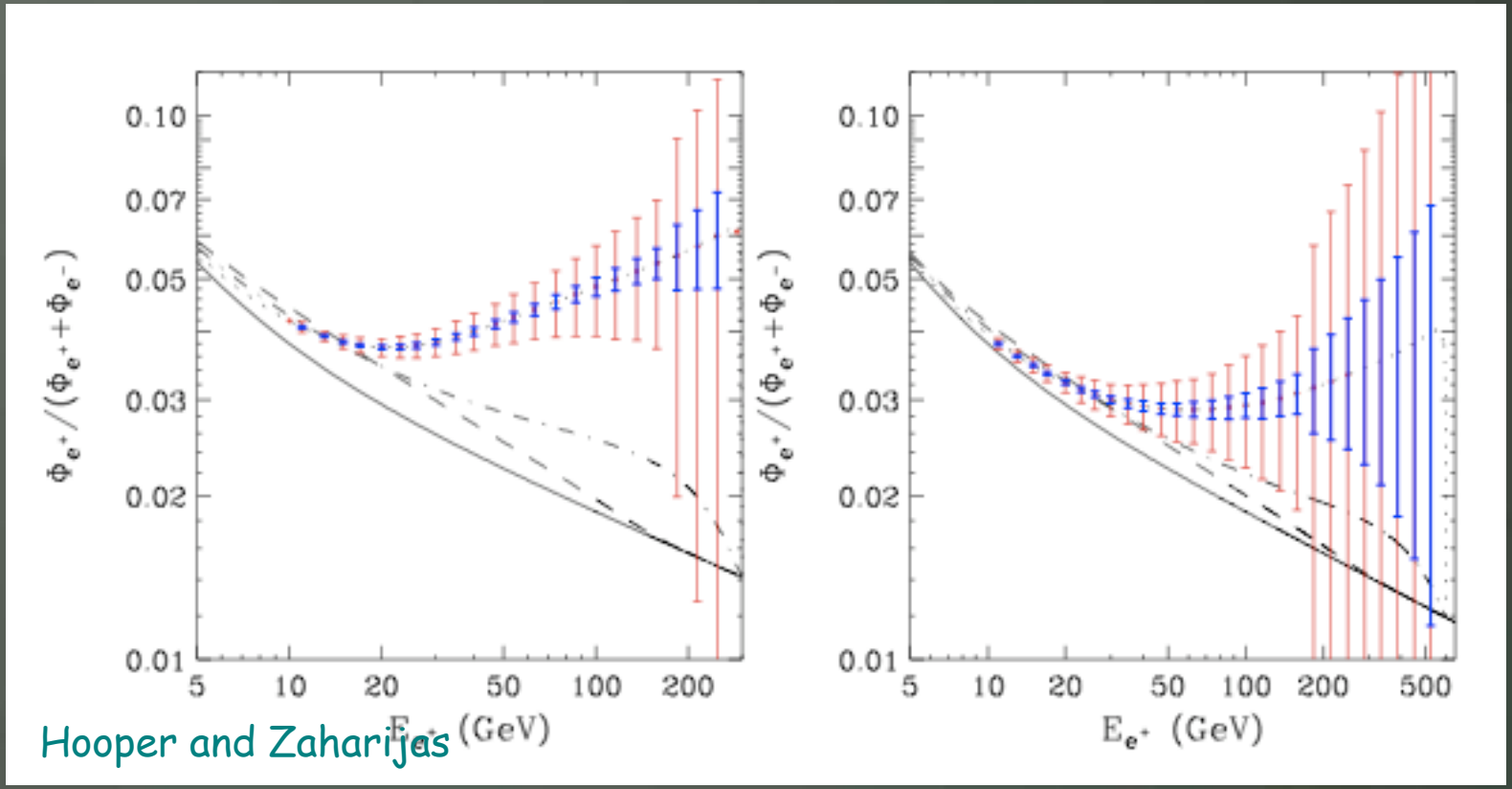
Fairly similar,
But ranges
Somewhat different

# Indirect Detection: Neutrinos




Hooper and Zaharijas

# Distinguishing Via Positrons



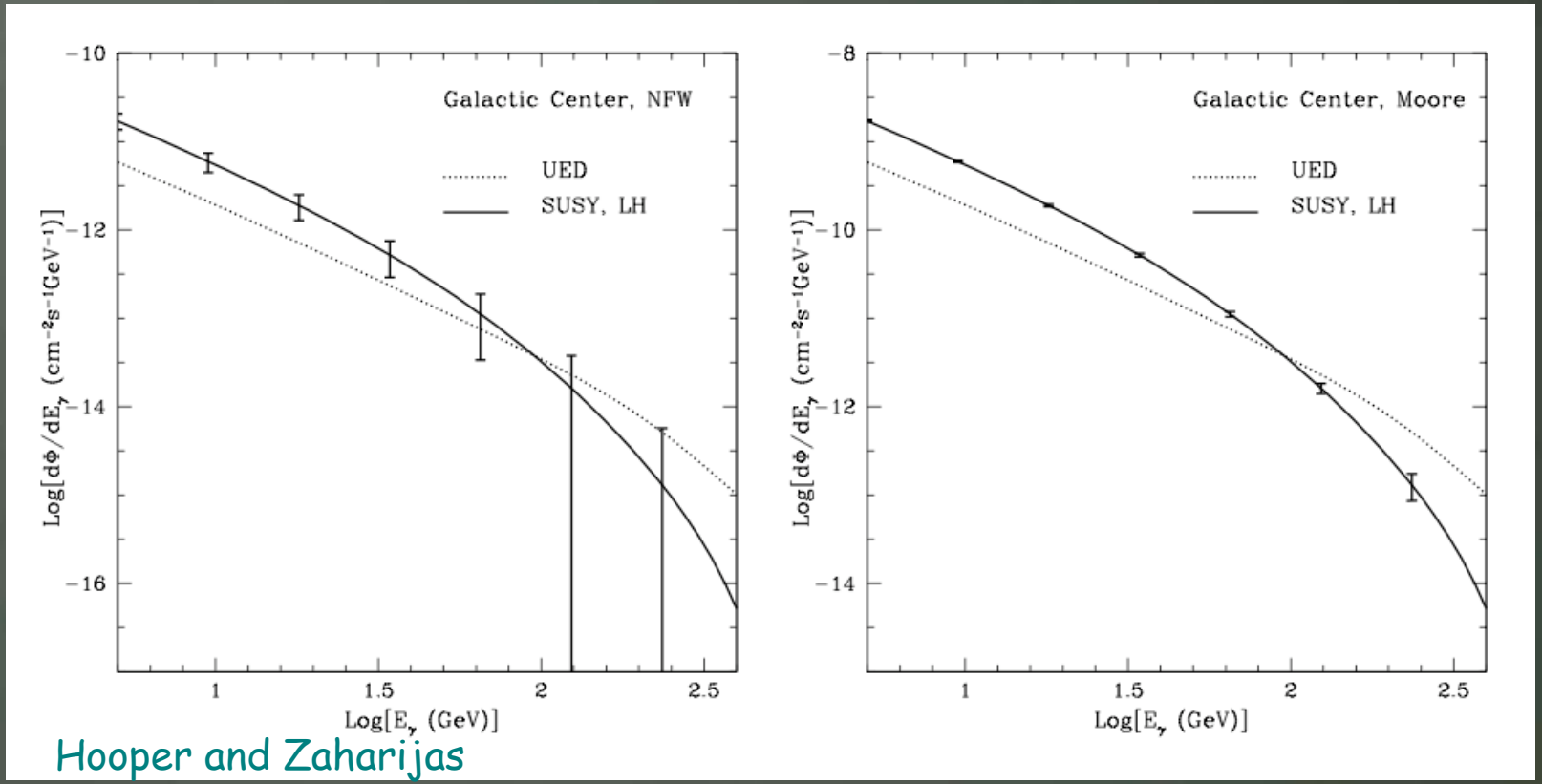

Hooper and Zaharijas

300

600

Requires boost of 30

# Gamma Rays




Hooper and Zaharijas

# Intermediate Summary #2: Distinguishing DM Models

- Direct Detection hard to distinguish, but can specify mass ranges (high/low)
- Indirect can be useful:
  - Strong Neutrino Signal
  - Hard Positron spectrum
- Strong interplay with colliders

# Motivating Exotica: The INTEGRAL Excess

- Are there things we simply cannot do in the MSSM?
- Yes!

# INTEGRAL Line

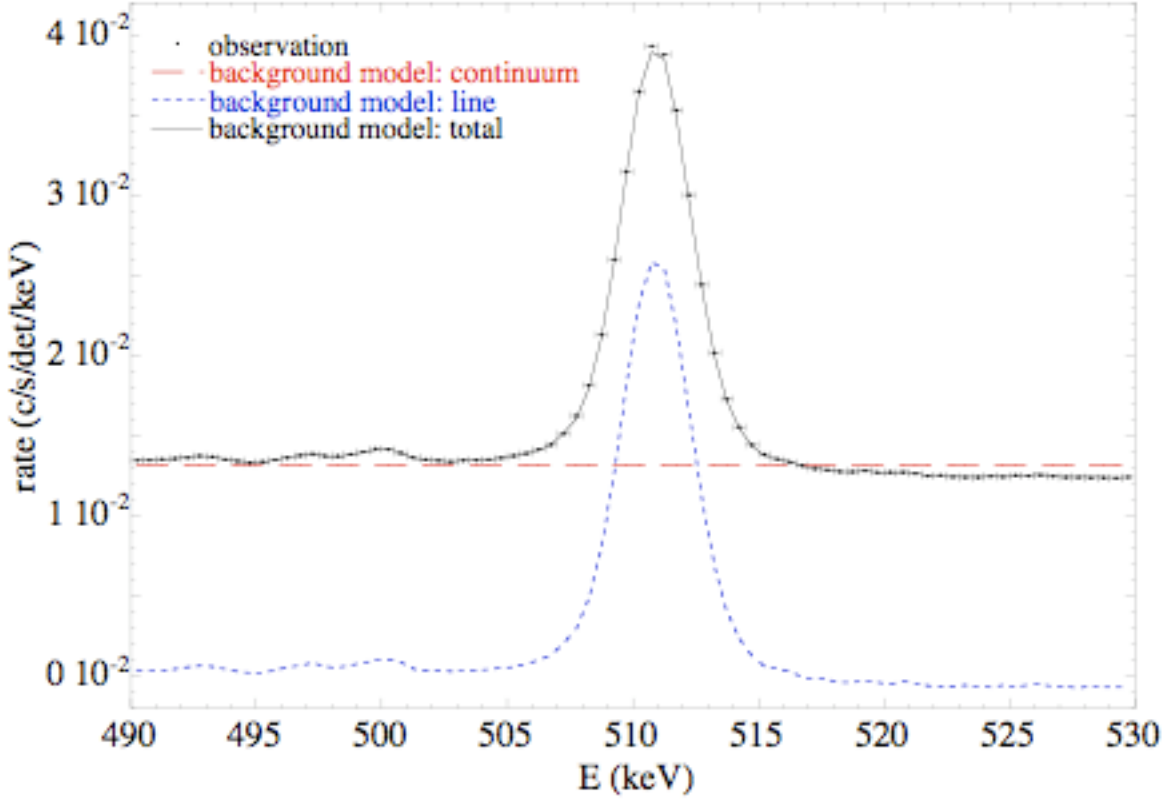
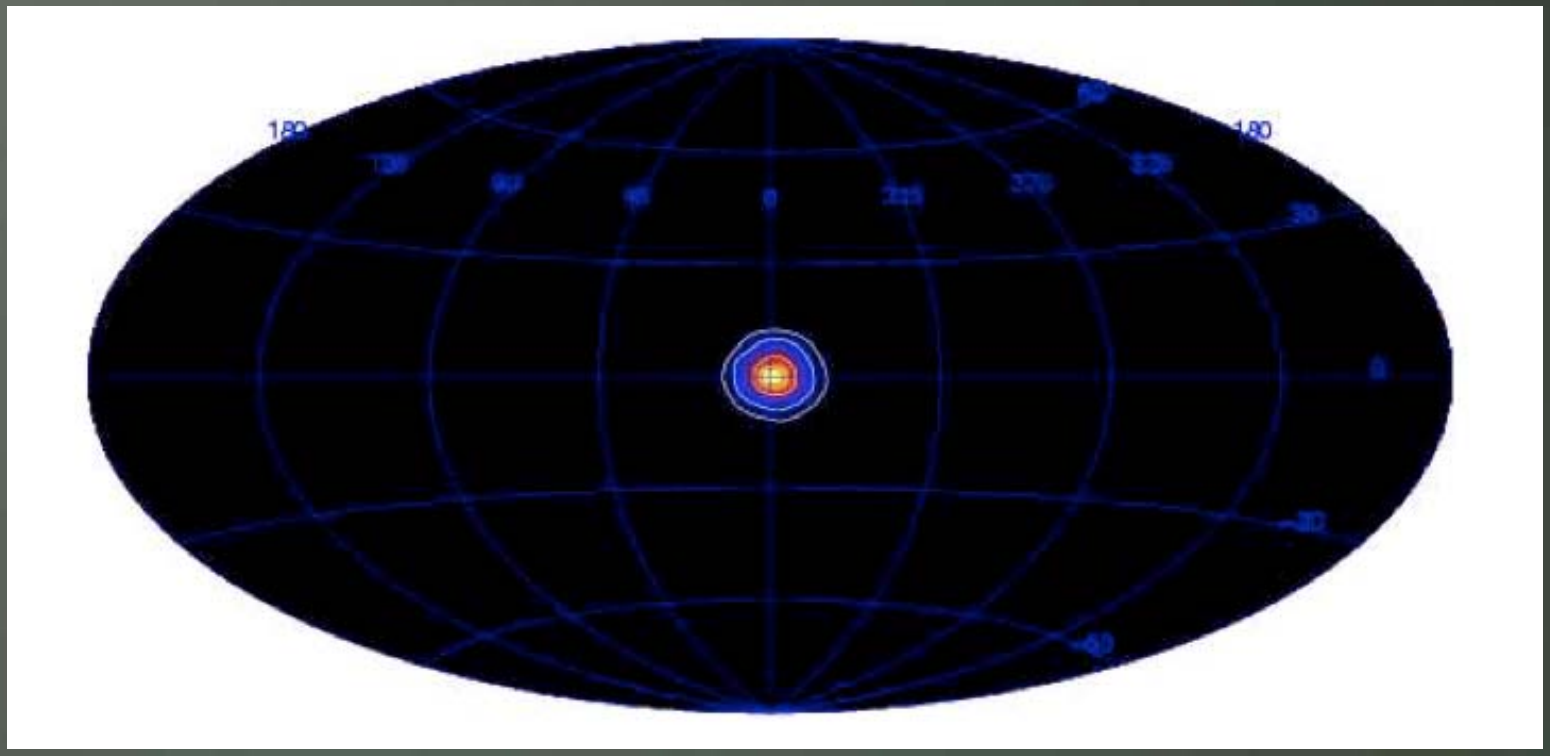


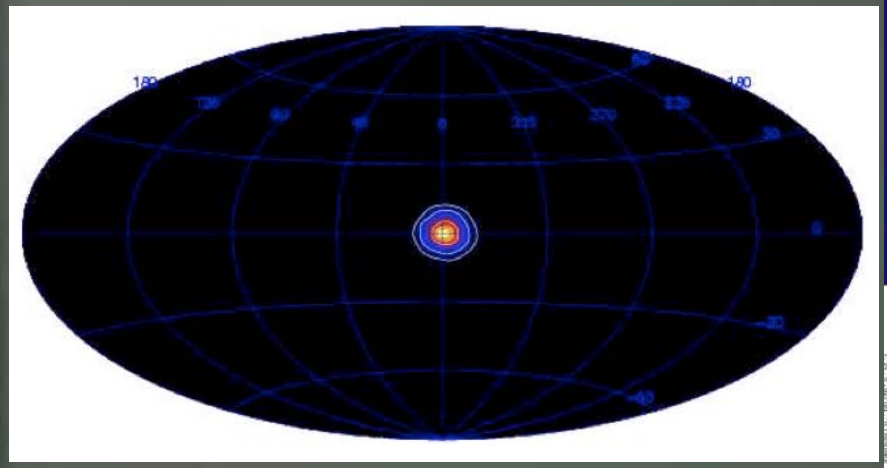

**Fig. 1.** Raw spectrum and background model components.

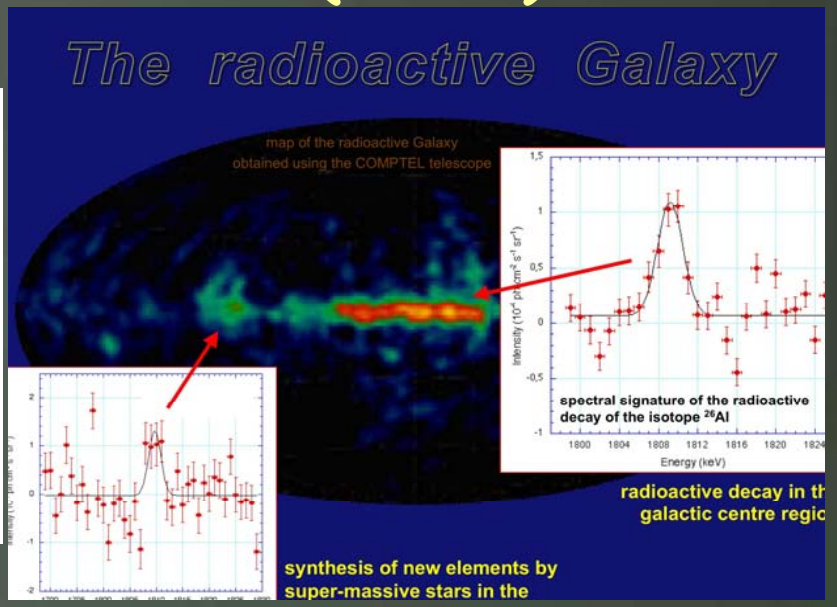
# INTEGRAL source



- Not consistent with point source
  - (needed 7 in 1yr data)

# 511keV vs 1800keV ($^{26}Al$)






Doesn't (by eye) appear to correlate with supernovae

# What the INTEGRAL signal is NOT

- It is NOT a standard WIMP annihilating into positrons
  - Need cross section ~ 1 mbn
  - Spectrum of line implies positrons produced with at most few MeV energy

# What might it be?

- MeV dark matter (LDM - Boehm and Fayet)
  - Dark Matter Annihilates into Positrons
- "Exciting" Dark Matter (XDM - Finkbeiner, NW)
  - Dark matter has an nearby excited state which is excited by collisions in the halo
- Decaying DM? (Hooper and Wang; Pospelov and Ritz)

Not the MSSM for sure!

# Real Summary

- SUSY is a popular model, but there's no evidence for it
  - Many models miss important phenomenology
- BSM theories *generically* have DM in the same way that SUSY does
- Astrophysical Studies may distinguish these *if* we get enough positive signals
  - More likely need interplay between collider and astro
- Possible Astrophysical Signals point away from any scenario we've considered so far!

# Can we ignore exotic DM?

- After all, we'll do these tests anyway, right?
- Except: Light DM (MeV, 1-10 GeV), should be considered
- Keep an open mind - we don't know as much as we think we do!