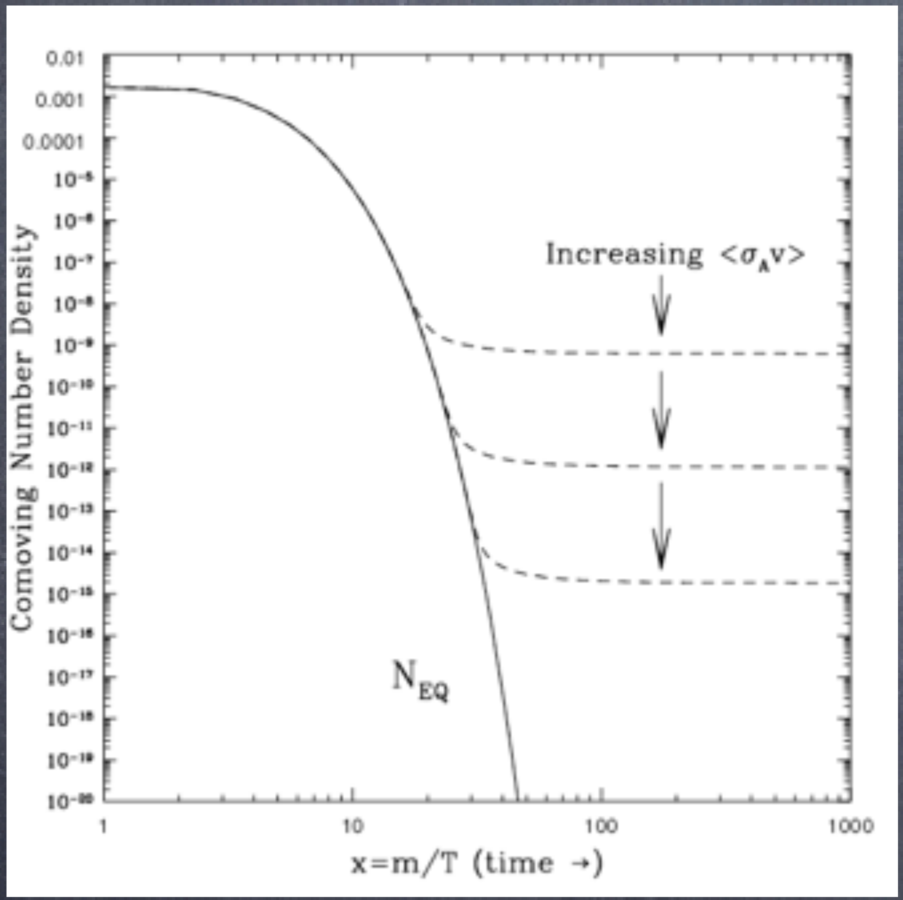
Particle Dark Matter II

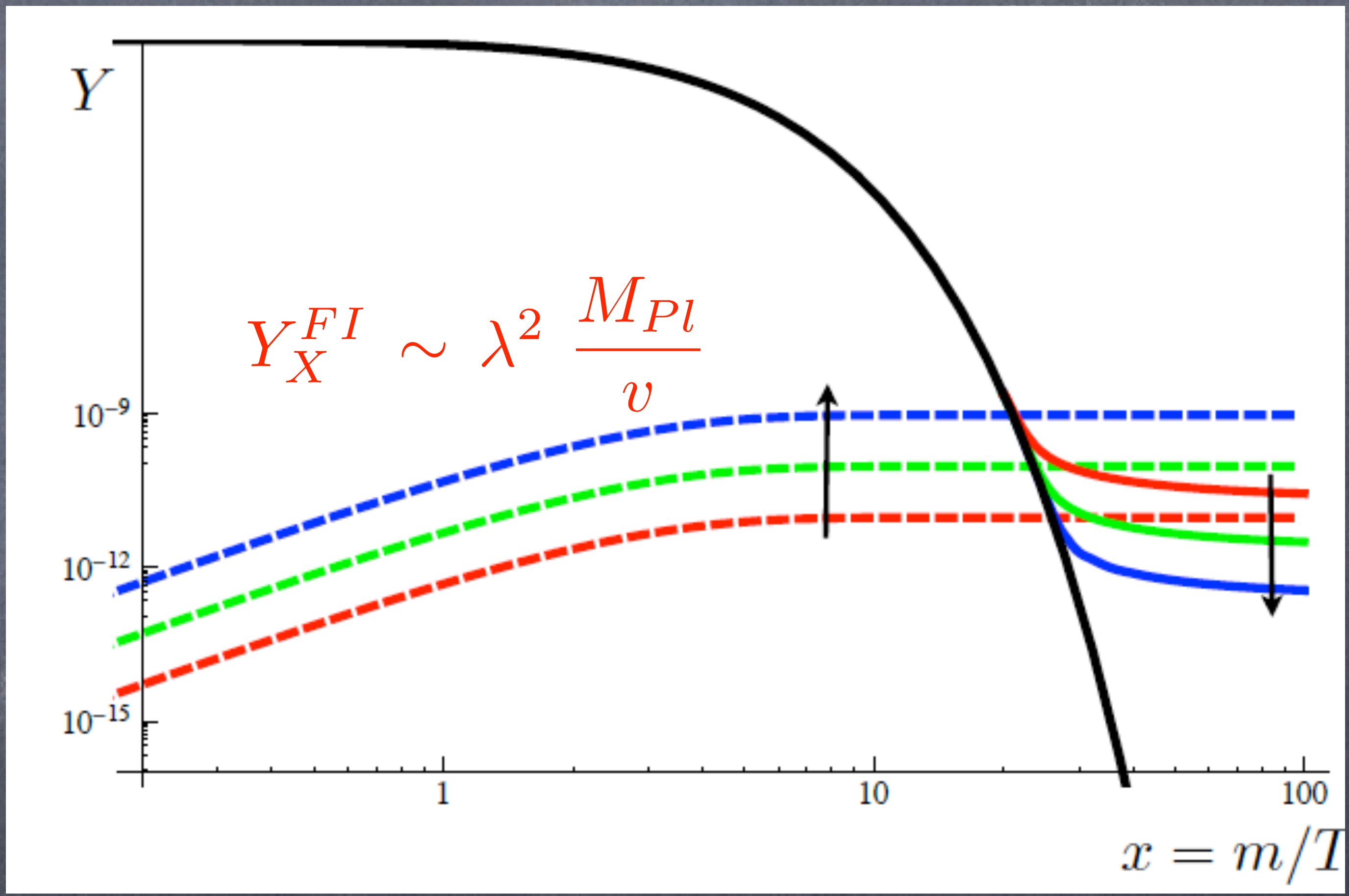
Kathryn M Zurek
LBL Berkeley

Summary: paradigms for DM relic density

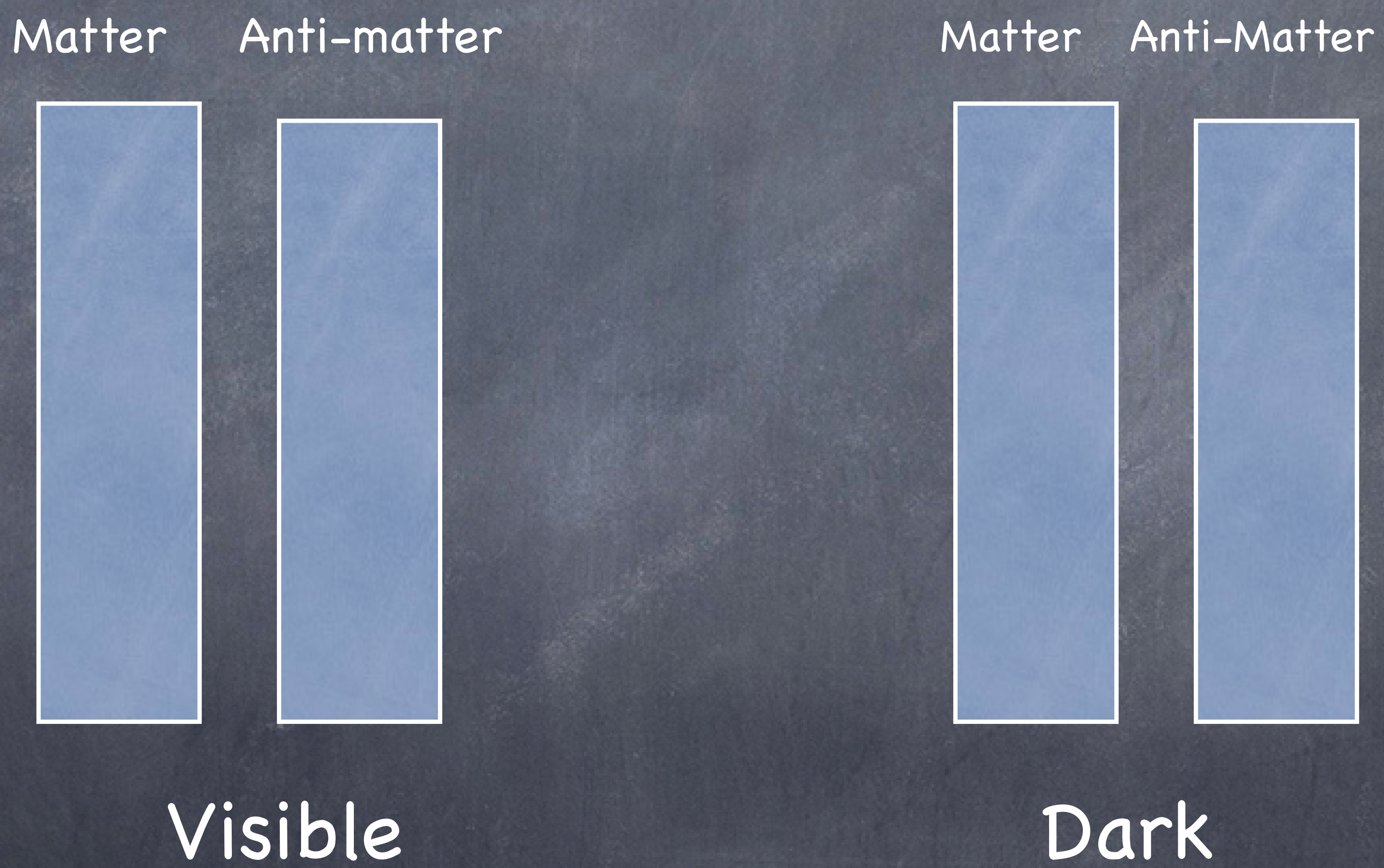
- thermal freeze-out is the most commonly considered paradigm for setting the DM density, but it is not the only way, e.g.
  - chemical potential (ADM)
  - freeze-out and decay
  - freeze-in
  - mis-alignment mechanism (oscillating scalar field)

Freeze-out vs Freeze-in



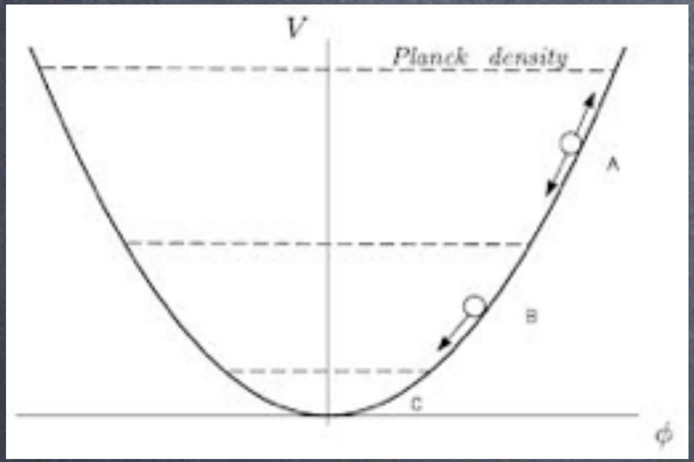


Chemical Potential



Mis-alignment mechanism

- Oscillating field in a quadratic potential behaves like cold DM



$$\rho = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m^2\phi^2 \qquad p = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}m^2\phi^2$$

$$\phi = A\cos(mt)$$

$$\Rightarrow \quad \langle\rho\rangle = \frac{1}{2}m^2A^2 \qquad \langle p\rangle = 0$$

Bose Einstein condensate = CDM! (Ex: axion)

PROGRAM

- Paradigms for DM density
  - freeze-out, freeze-in, asymmetric DM, freeze-out and decay, misalignment, compact object formation
- The classic: Supersymmetric Dark Matter
  - Direct and indirect detection basics

PROGRAM

- Looking beyond the vanilla WIMP
  - motivations, experimental search techniques
- Cosmological constraints on particle DM
  - BBN, CMB, formation of structure, stellar capture, DM self-interactions
- LHC searches for particle DM

Standard SUSY Dark Matter

(let's back up and talk about the most studied case)

Further reading:
Martin, a Supersymmetry primer, hep-ph/9709356
Supersymmetric Dark Matter, Jungman, Kamionkowski, Griest

Models of Dark Matter

- The classic
- SUSY
  - has all the ingredients
  - and they are present for other reasons
  - DM (sort of) free

DM Paradigm: recap

- Usual picture of dark matter is that it is:
  - single
  - stable
  - (sub-?) weakly interacting
  - neutral

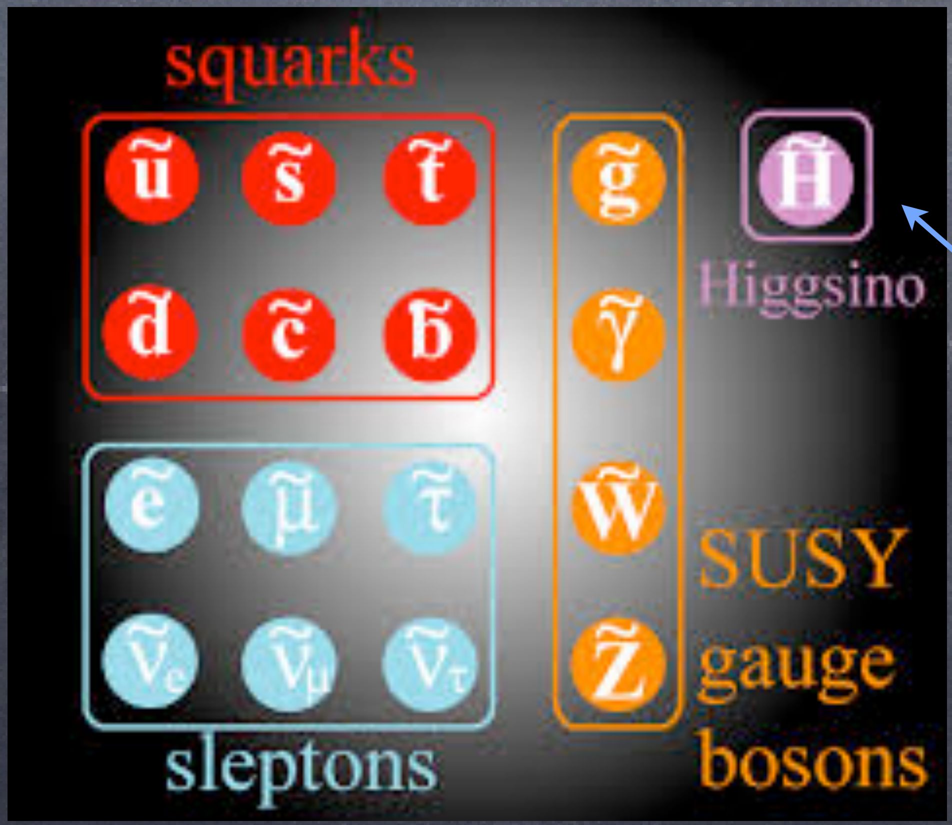
Stability

- To make candidate absolutely stable, need a symmetry in the theory
- In SM:
  - p: stable by baryon number (global symm)
  - e-: electric charge (gauge symm)
  - nu's: lepton number (global symm)

Stability

- SUSY has built in symmetry to stabilize one of the SUSY particles
- Each SM particle has a superpartner that differs in spin by 1/2 from SM particle

scalar superpartners to SM fermions



fermionic superpartners to SM scalar and gauge bosons

(actually, require two Higgses in SUSY)

gauginos

Stability

- Why is one of these states stable? R-parity
- Symmetry which appears in UV completions
- For proton stability; DM stability by-product
- Because, scalars in SUSY allow to write down additional interactions

$$W_{\Delta \mathrm{L}=1} = \frac{1}{2}\lambda^{ijk} L_i L_j \overline{e}_k + \lambda'^{ijk} L_i Q_j \overline{d}_k + \mu'^{i} L_i H_u$$

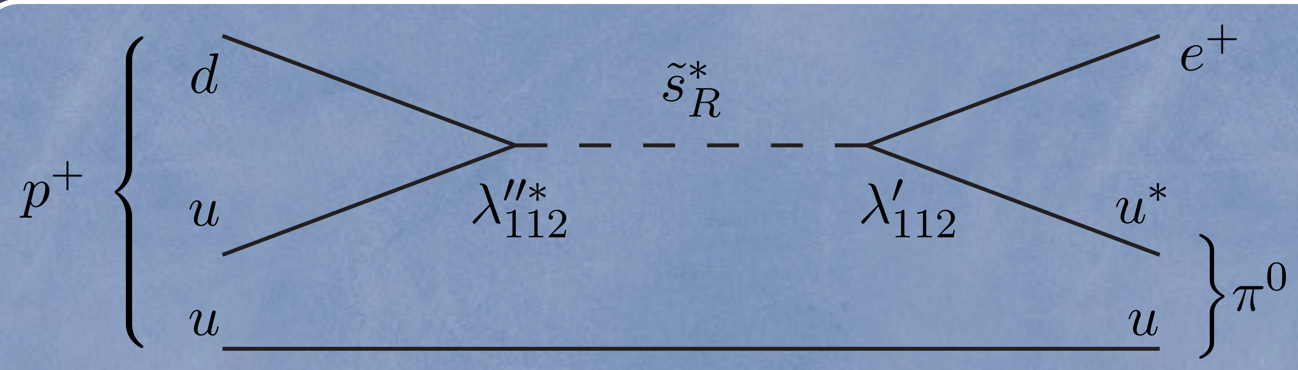
$$W_{\Delta \mathrm{B}=1} = \frac{1}{2}\lambda''^{ijk} \overline{u}_i \overline{d}_j \overline{d}_k$$

Stability

$$W_{\Delta \mathrm{L}=1} = \frac{1}{2}\lambda^{ijk} L_i L_j \bar{e}_k + \lambda'^{ijk} L_i Q_j \bar{d}_k + \mu'^i L_i H_u$$

$$W_{\Delta \mathrm{B}=1} = \frac{1}{2}\lambda''^{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$$

- Preserve gauge symmetries of Standard Model
- Violate baryon and lepton number; induce proton decay



Stability

- Introduce new symmetry (= R-parity) to forbid those interactions

$$P_R = (-1)^{3(\mathrm{B}-\mathrm{L})+2s}$$

- All SM particles carry R-parity +1

lepton: s=1/2, L=1
quark: s=1/2, B=1/3
gauge boson, s=1, B=L=0

- All super-partners carry R-parity -1

slepton: s=0, L=1
squark: s=0, B=1/3
gaugino, s=1,/2 B=L=0

⇒ Lightest super-partner is stable

Neutral

- Gauge bosons mix

$$\begin{pmatrix} \gamma \\ Z \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B \\ W^0 \end{pmatrix}$$

- Their superpartners the gauginos also mix
  - neutral and charged states -- neutralinos and charginos
  - diagonalize mass matrix to obtain mass eigenstates

Neutral

- Mass matrix:

$$\begin{array}{cccc} \tilde{B} & \tilde{W} & \tilde{H}_u & \tilde{H}_d \end{array}$$

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -M_Z\cos\beta\sin\theta_W & M_Z\sin\beta\sin\theta_W \\ 0 & M_2 & M_Z\cos\beta\cos\theta_W & -M_Z\sin\beta\cos\theta_W \\ -M_Z\cos\beta\sin\theta_W & M_Z\cos\beta\cos\theta_W & 0 & -\mu \\ M_Z\sin\beta\sin\theta_W & -M_Z\sin\beta\cos\theta_W & -\mu & 0 \end{pmatrix}$$

- Soft parameters, M_1 and M_2. Free in SUSY.
- In SM, one Higgs works b/c can write field and conjugate $\mathcal{L}_{SM} = \bar{u}y_u Q\phi - \bar{d}y_d Q\phi^* - \bar{e}y_e L\phi^*$
- Not so in SUSY: $W_{MSSM} = \bar{u}y_u QH_u - \bar{d}y_d QH_d - \bar{e}y_e LH_d$

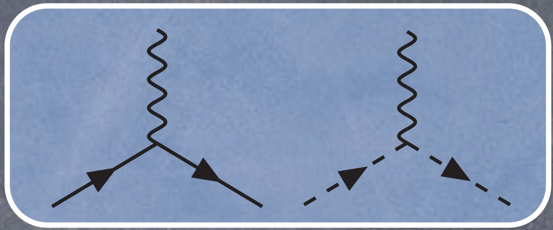
$$\tan\beta = \frac{v_u}{v_d} \qquad v_u^2 + v_d^2 = v^2 = (246\ \text{GeV})^2$$

Weakly-interacting

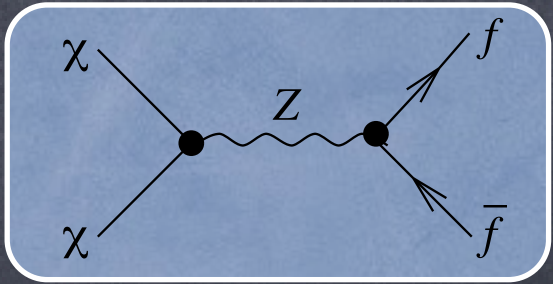
- Sneutrino, also being neutral, is a good DM candidate.... except for direct detection(!)

$Q|\mathrm{neutrino}\rangle = |\mathrm{sneutrino}\rangle$

Gauge interaction:

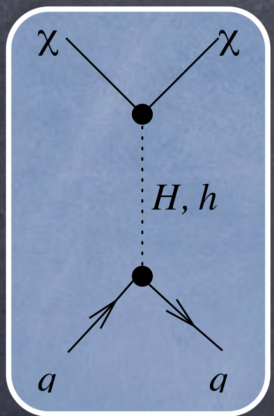


- Its couplings are fixed by gauge interactions
- Scatters off nucleons through Z boson
- Let's compute the rate



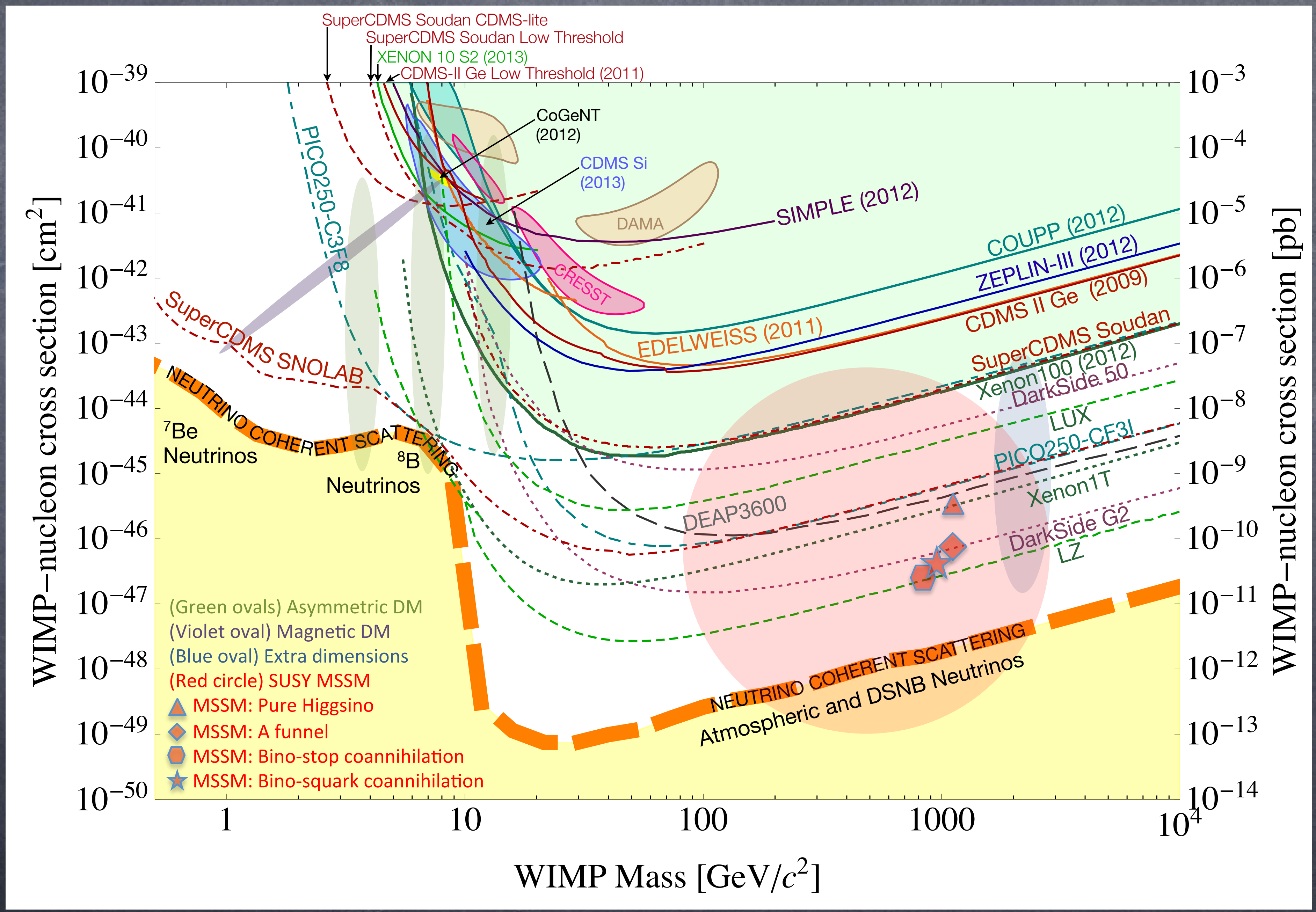
Direct detection basics

- Two types of interactions: spin-dependent, spin-independent
- Spin-independent couples to charge of nucleus --> coherent interactions
- Examples of spin-independent interaction: Higgs



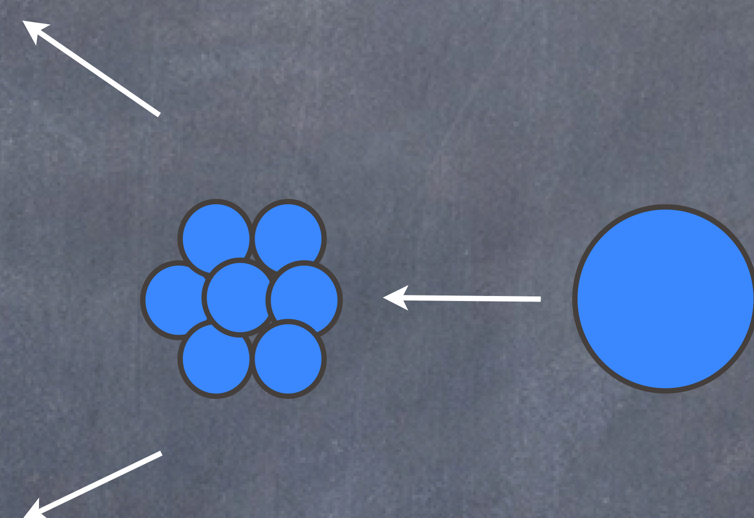
Direct Detection Reach

CF1 Snowmass report, 1310.8327



Kinematics of scattering

$$p_X^i = \begin{pmatrix} m_N \\ 0 \end{pmatrix}$$



$$p_X^i = \begin{pmatrix} \frac{1}{2} m_X v^2 + m_X \\ m_X \vec{v} \end{pmatrix}$$

$$p_X^f = \begin{pmatrix} \frac{p_f^{N\,2}}{2m_N} + m_N \\ \vec{p}_f^N \end{pmatrix}$$

$$p_X^f = \begin{pmatrix} \frac{p_f^{X\,2}}{2m_X} + m_X \\ \vec{p}_f^X \end{pmatrix}$$

$$E_i = E_f \qquad \vec{p}_i = \vec{p}_f$$

$$\implies 2\mu_N v = |\vec{p}_F^N| = \sqrt{2 m_N E_R} \qquad \mu_N \equiv \frac{m_N m_X}{m_X + m_N}$$

$v \sim 300\ \mathrm{km/s} \sim 10^{-3} c \implies E_R \sim 100\ \mathrm{keV}$ for 50 GeV target

Apply to scattering through Z boson

$$\sigma_N = \frac{m_{DM}^2 m_N^2}{4\pi(m_{DM}+m_N)^2}\frac{(Zf_p+(A-Z)f_n)^2}{m_Z^4}$$

$$\sigma_N = \sigma_p \frac{\mu_N^2}{\mu_n^2}\frac{(Zf_p+(A-Z)f_n)^2}{f_p^2}F^2(E_R)$$

$$\frac{dR}{dE_R} = N_T\frac{\rho_\chi}{m_\chi}\int_{|\vec{v}|>v_{min}} d^3v\, v f(\vec{v},\vec{v}_e)\frac{d\sigma}{dE_R}$$

Maxwell-Boltzmann distribution:

$$f \sim \frac{1}{(\pi v_0)^{3/2}} e^{-v^2/v_0^2}$$

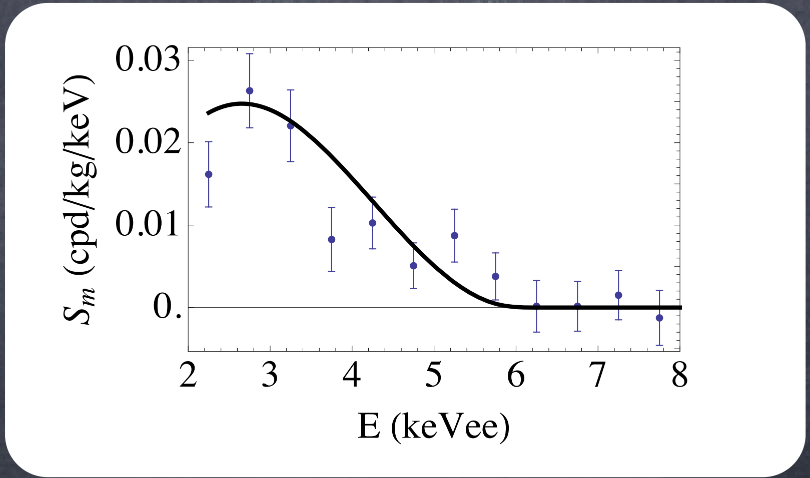
$$\frac{d\sigma}{dE_R} = \frac{m_N\sigma_N}{2\mu_N^2 v^2}$$

Apply to scattering through Z boson

$$\sigma_N = \frac{m_{DM}^2 m_N^2}{4\pi(m_{DM}+m_N)^2} \frac{(Zf_p + (A-Z)f_n)^2}{m_Z^4}$$

$$\sigma_N = \sigma_p \frac{\mu_N^2}{\mu_n^2} \frac{(Zf_p + (A-Z)f_n)^2}{f_p^2} F^2(E_R)$$

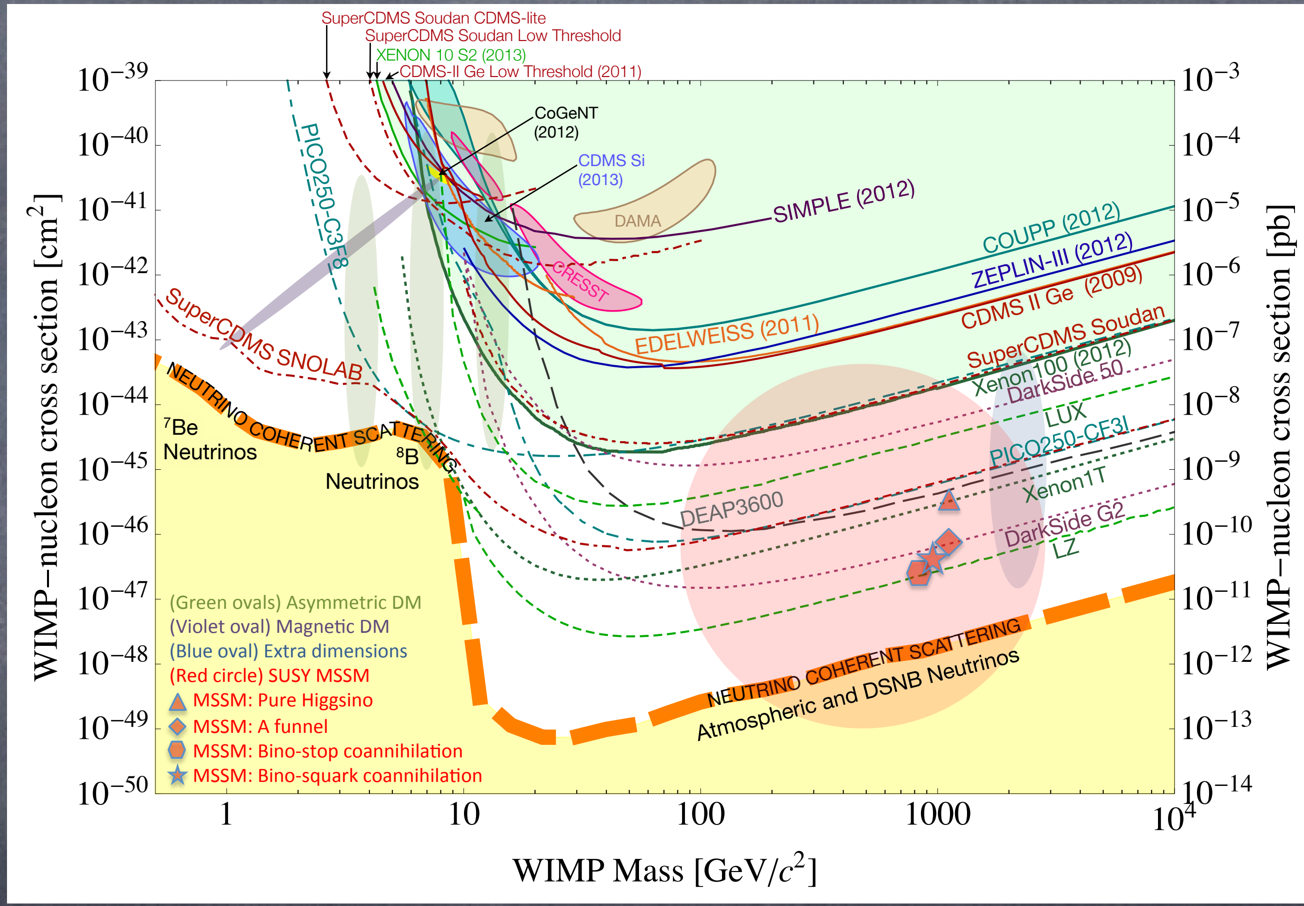
$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{|\vec{v}|>v_{min}} d^3v v f(\vec{v}, \vec{v}_e) \frac{d\sigma}{dE_R}$$



Apply to scattering through Z boson

- plug in and compare

$$\sigma \approx \frac{g^4 \mu_n^2}{4\pi m_Z^4} \approx 10^{-39}\ \mathrm{cm}^2$$



- Active $\tilde{\nu}$ DM excluded by direct detection

Can evade constraint by mixing in sterile $\tilde{\nu}$,$\tilde{N}$. This state does not couple to Z. But is not present in minimal model

What about neutralino?

- 2 component fermion χ Majorana fermion
- Possible operators, four Fermi, V-A structure:

$$\mathcal{O}_{SI} = (\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q) = 0$$

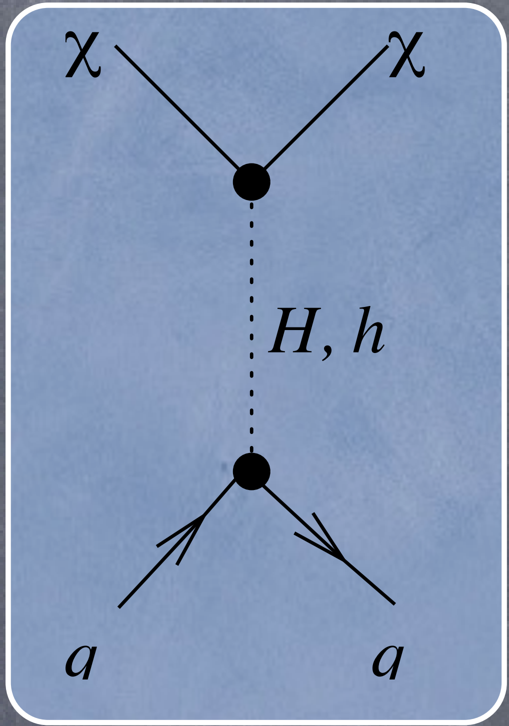
$$\mathcal{O}_{SD} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)$$

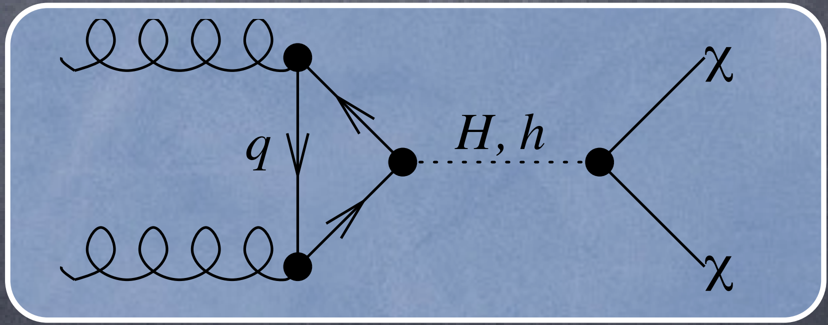
$$\mathcal{O}_{\text{vel dep.}} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu q)$$

- SI vanishes identically; others are SD or velocity suppressed

Higgs Scattering

- So neutralino is safe from Z-pole scattering
- It scatters predominantly through Higgs boson
- Higgs boson coupling to nucleon comes predominantly through a loop



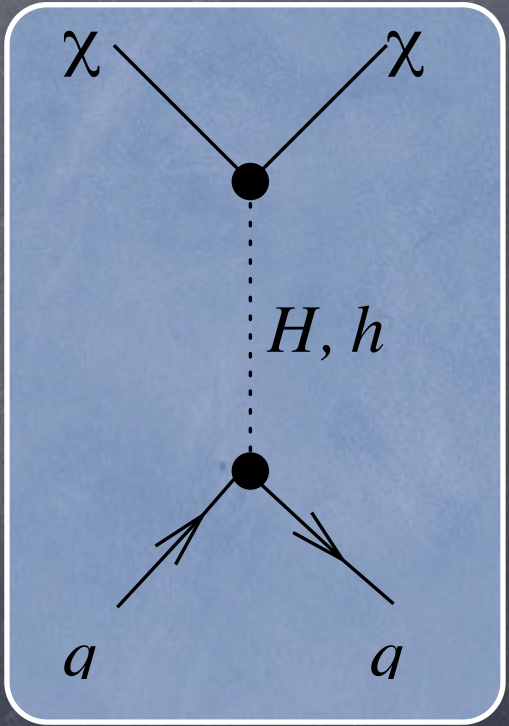


$$\frac{f_{p,n}}{m_{p,n}} = \sum_{q=u,d,s} f_{Tq}^{p,n} \frac{y_q}{m_q} + \frac{2}{27} f_{TG}^{p,n} \sum_{q=c,b,t} \frac{y_q}{m_q}$$

Shifman, Vainshtein, Zakharov,
Phys.Lett. B78 (1978) 443

Higgs Scattering

- Scattering cross-section depends on DM coupling to Higgs; structure of Higgs boson sector.



- MSSM has two Higgses, H_u and H_d
- Ratio of vevs $\tan\beta = \frac{v_u}{v_d}$

$$m_{u,c,t} = y_{u,c,t} v_u \qquad m_{d,s,b} = y_{d,s,b} v_d$$

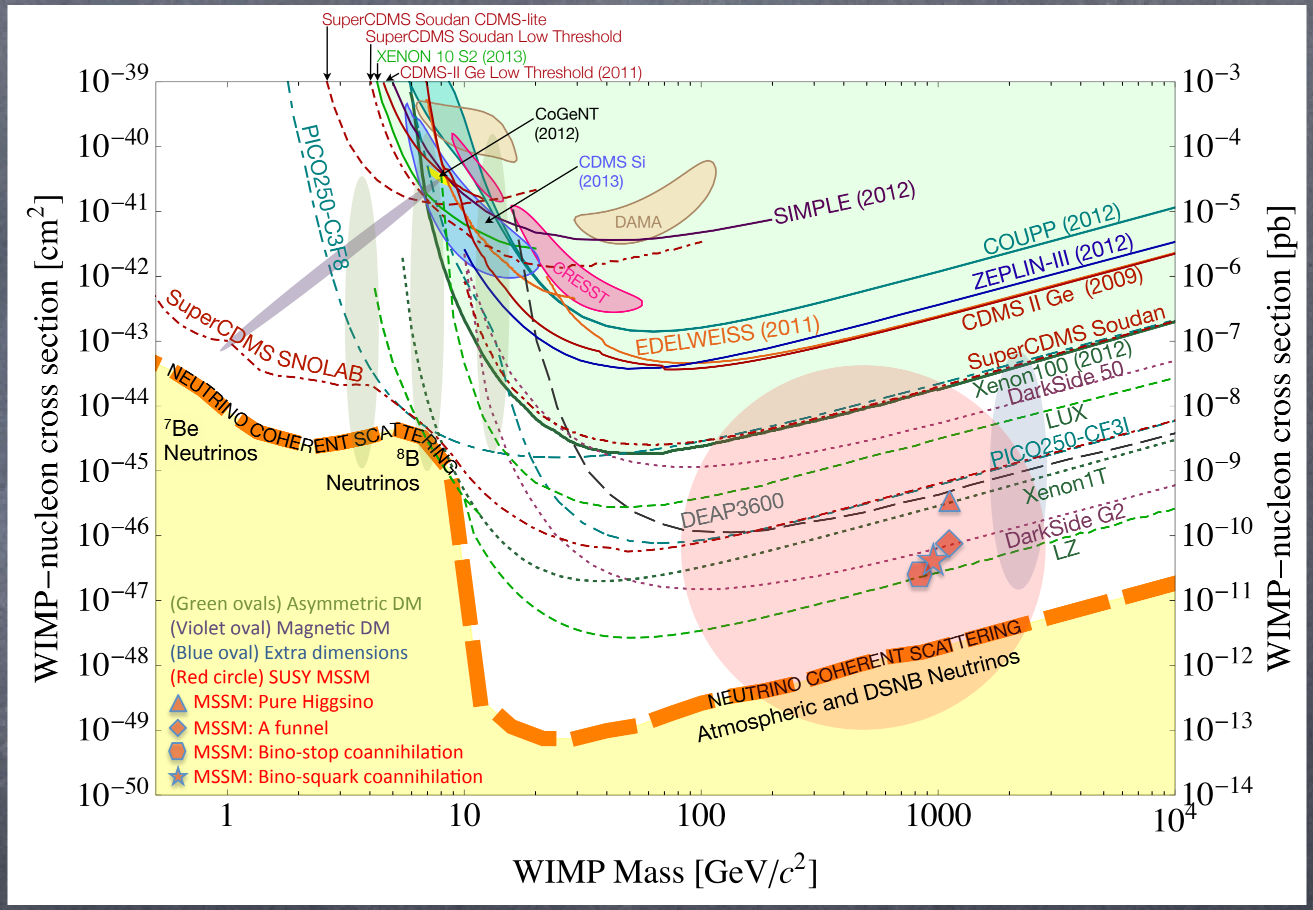
$$v_u^2 + v_d^2 = v^2 = (246 \text{ GeV})^2$$

- Cross-section:

$$\sigma_n \approx 8.3 \times 10^{-42} \text{ cm}^2 \left(\frac{Z_d}{0.4}\right)^2 \left(\frac{\tan\beta}{30}\right)^2 \left(\frac{100 \text{ GeV}}{m_H}\right)^4$$

Higgs scattering cross-section

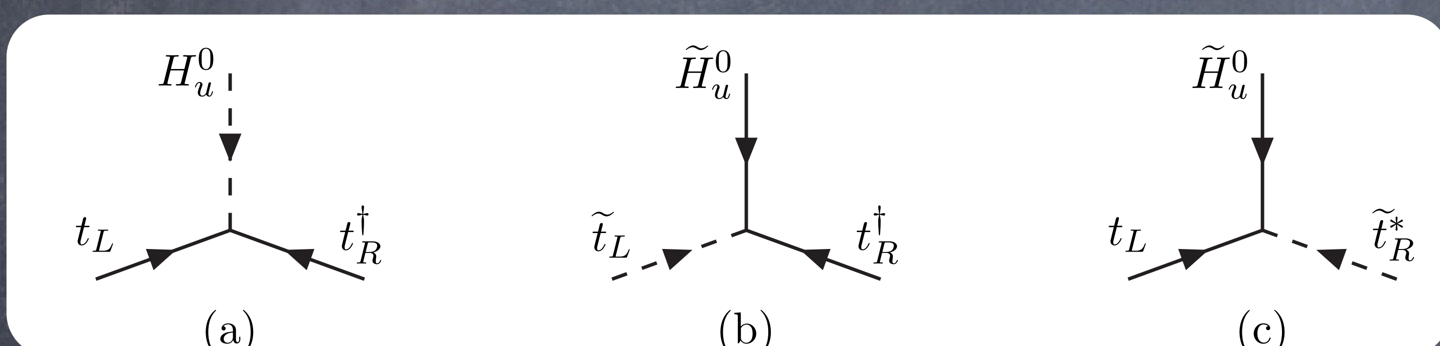
$$\sigma_n \approx 8.3 \times 10^{-42}\ \mathrm{cm}^2 \left(\frac{Z_d}{0.4}\right)^2 \left(\frac{\tan\beta}{30}\right)^2 \left(\frac{100\ \mathrm{GeV}}{m_H}\right)^4$$



Are there ways around?

A bit more about neutralino couplings

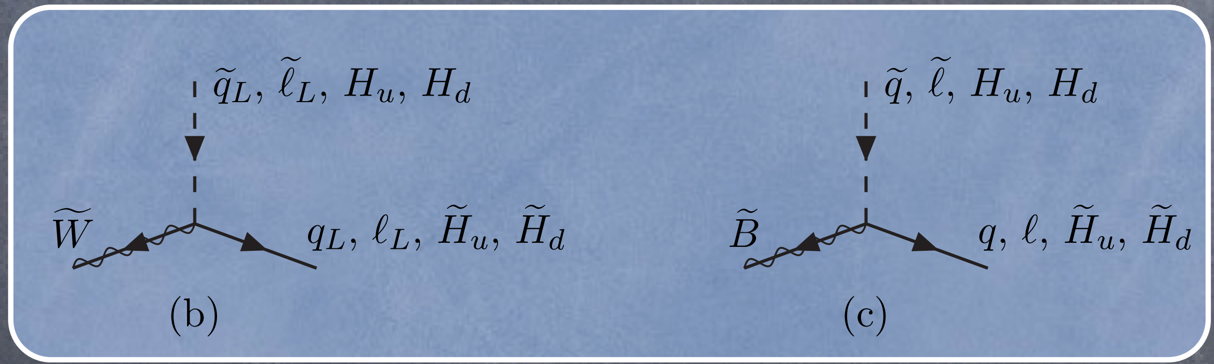
- Supersymmetry relates SM couplings to SUSY particle couplings



- This fixes the interactions that can occur ....

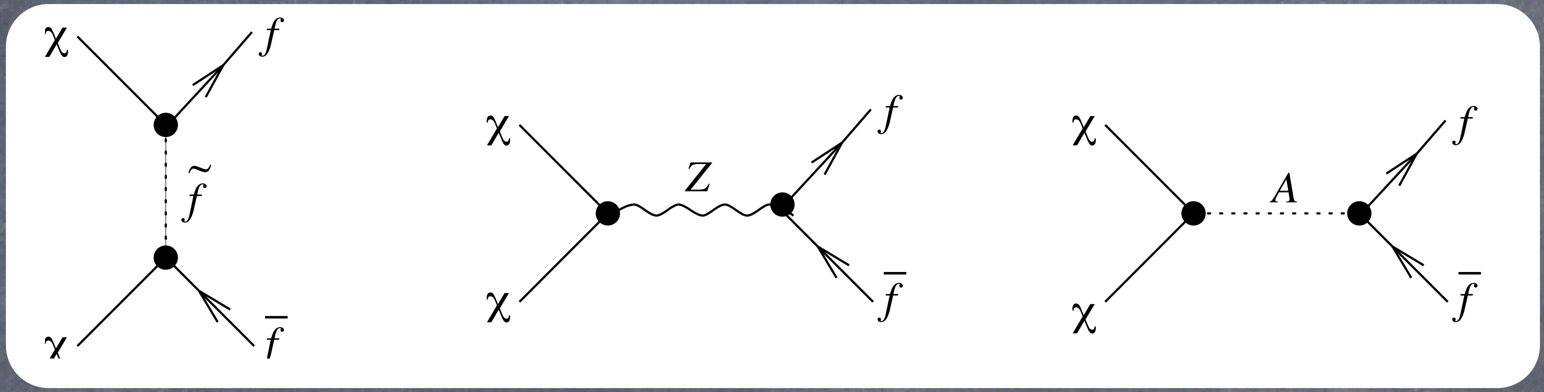
A bit about neutralino couplings

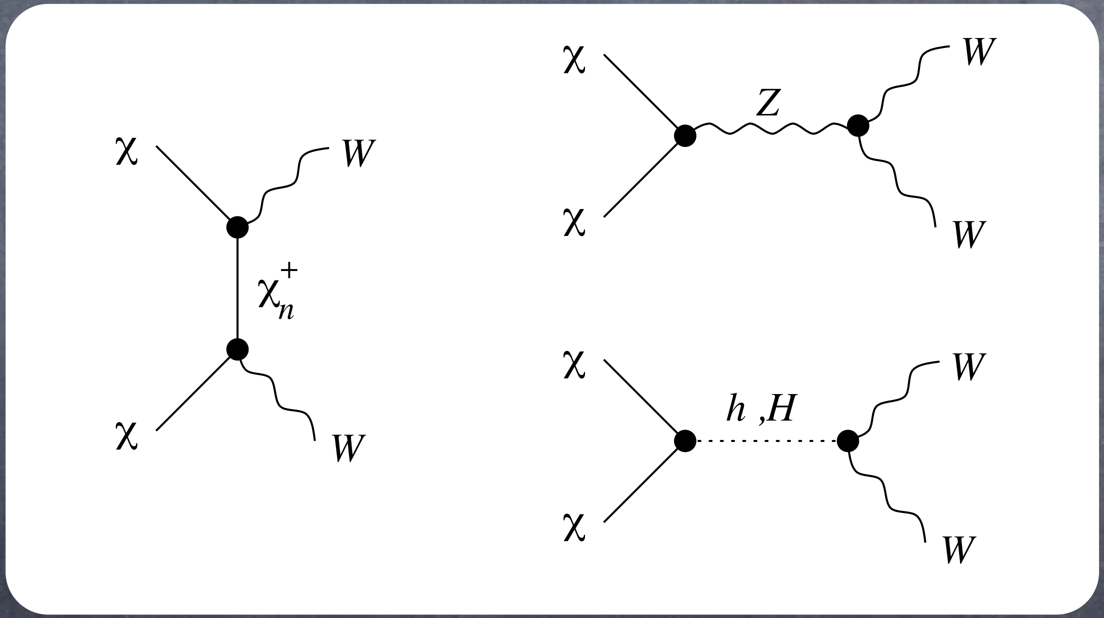
- .... and what interactions cannot occur
- Higgs does not interact with a "pure" state



- Must have bino-Higgsino or Higgsino-wino mix

WIMP annihilation processes

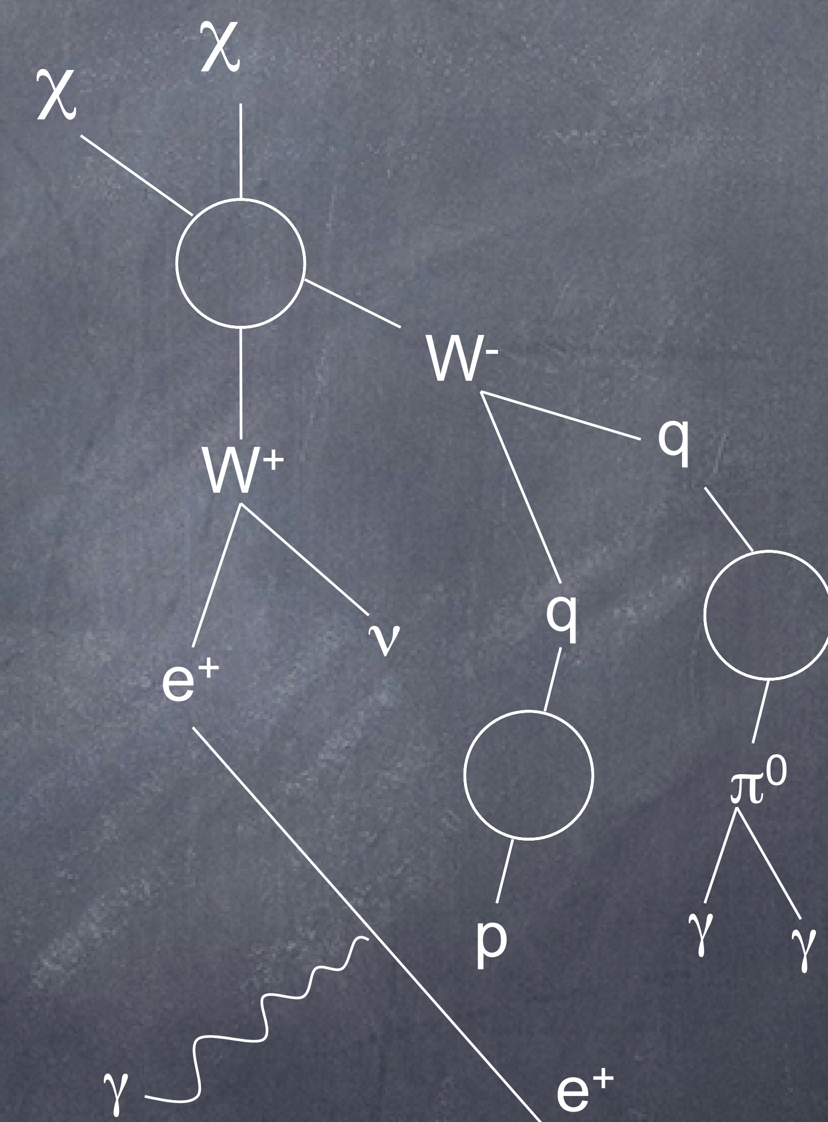




- Bottom diagrams often dominate if DM is largely wino or largely Higgsino

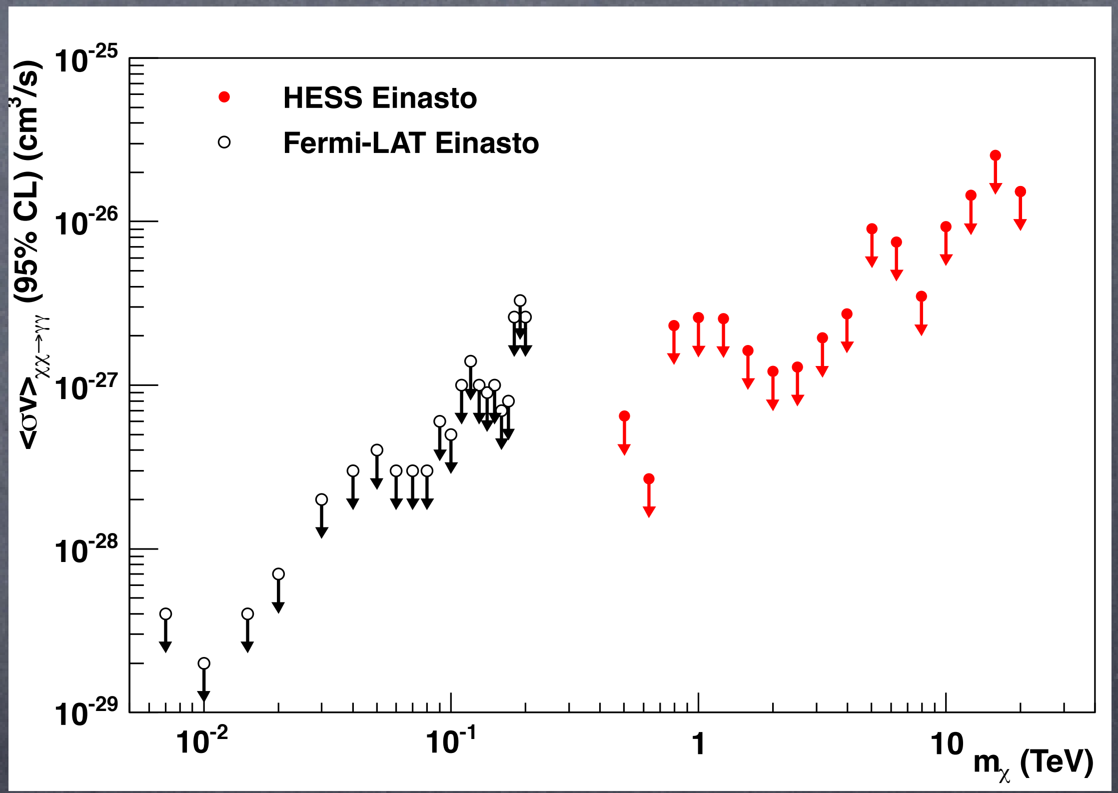
Escaping direct detection constraints

- So even if direct detection constraints are escaped by making neutralino pure ....
- there may be strong indirect detection constraints
- Photons from annihilation in galaxy today constrain pure wino or Higgsino DM



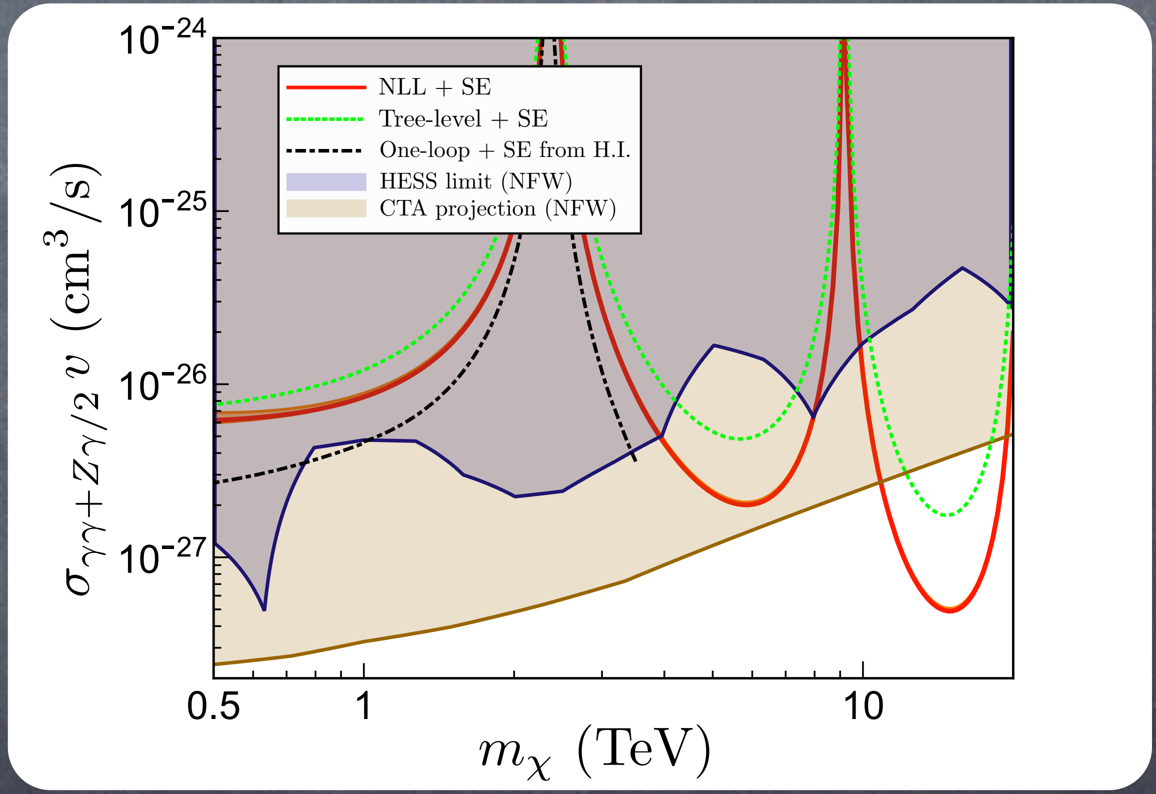
Escaping direct detection constraints

- Make neutralino a pure state -- wino, Higgsino, or bino
- Wino and Higgsino: strong indirect detection constraints
- Photons from annihilation in galaxy today constrain pure wino or Higgsino DM



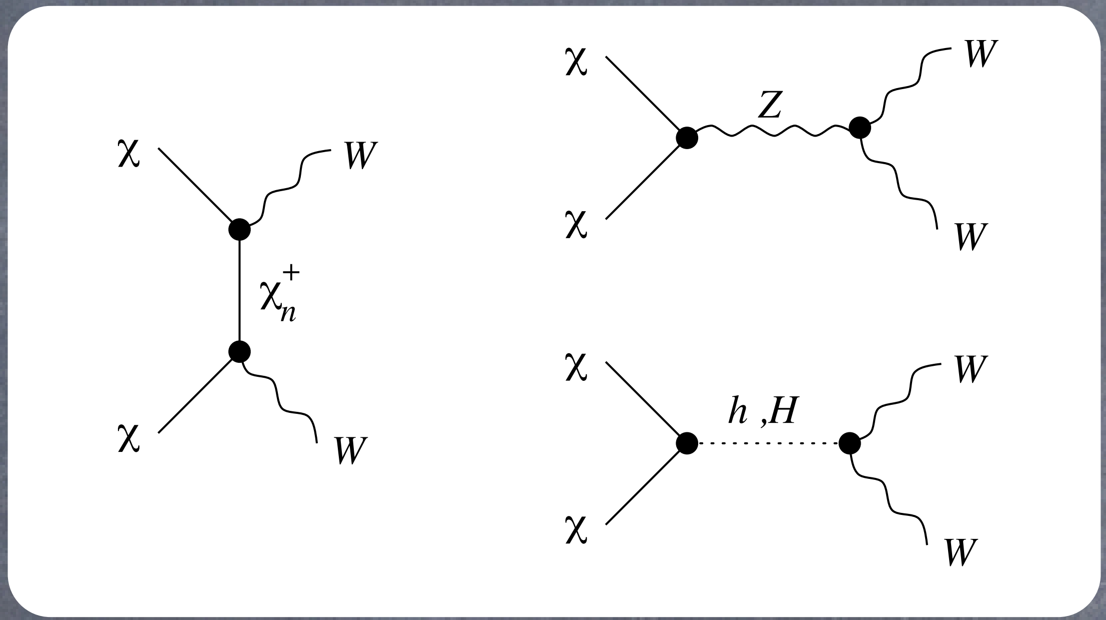
Escaping direct detection constraints

- Make neutralino a pure state -- wino, Higgsino, or bino
- Wino and Higgsino: strong indirect detection constraints
- Photons from annihilation in galaxy today constrain pure wino or Higgsino DM



Ovanesyan, Stewart, Slatyer

Relic density of wino or Higgsino



$$3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s} \simeq \frac{g_{wk}^4}{(2\ \mathrm{TeV})^2} \sim \frac{g_{wk}^4}{\pi m_X^2}$$

Thermal wino or Higgsino DM is heavy!

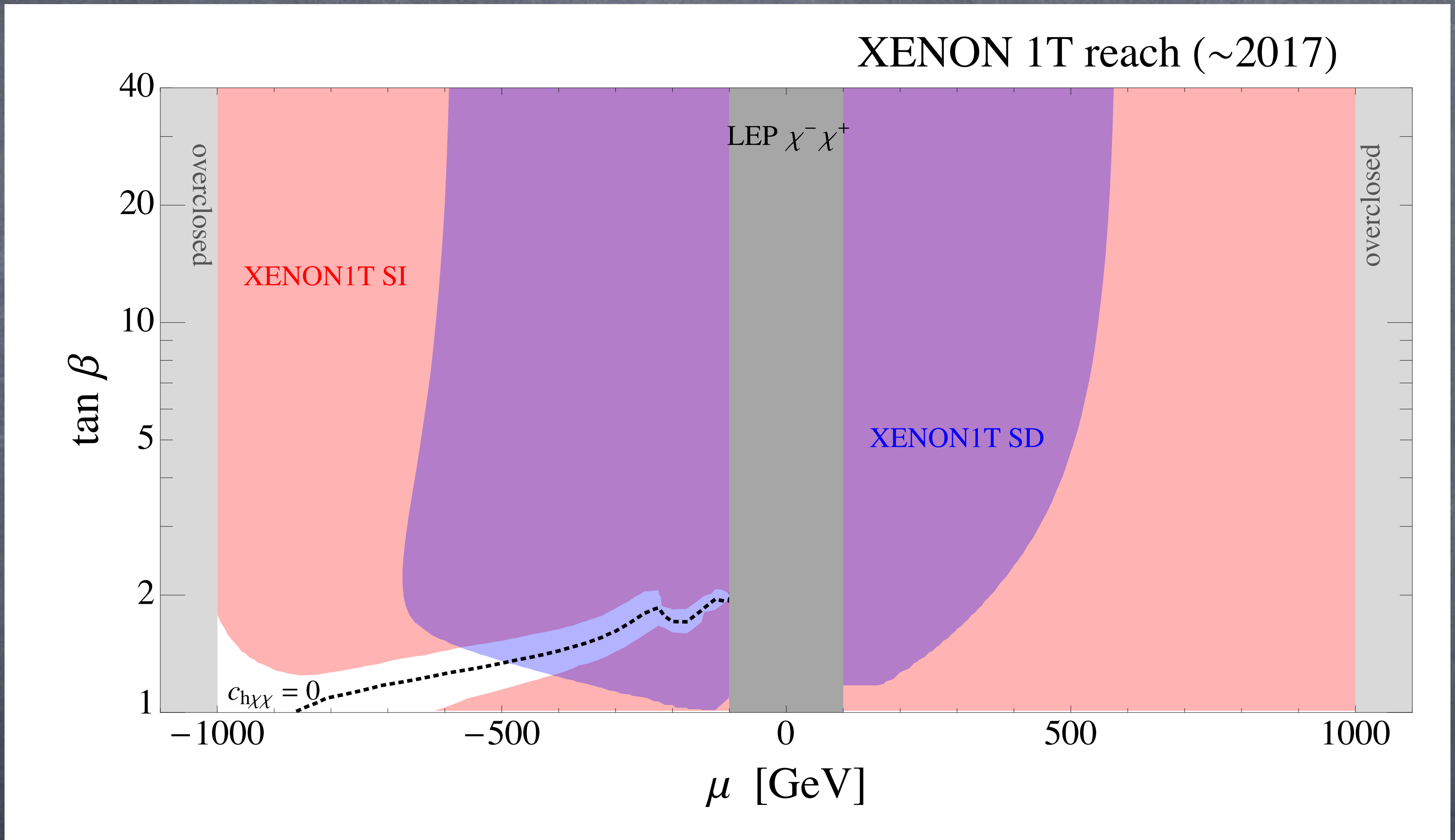
Pure bino DM escapes

- While wino and Higgsino may be constrained by indirect detection, bino escapes
- But, even bino has Higgsino component set by μ
- Require $\mu \gg M_1 \sim m_{wk}$ to get rid of Higgsino component
- Same parameter enters into Z boson mass

$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2$$

⇒ Must tune parameters

How much param space escapes?



Cheung, Hall, Pinner, Ruderman

When Should We Start Looking Elsewhere?

- Cannot kill neutralino DM via direct detection, but paradigm does become increasingly tuned
- Somewhat below Higgs pole -- Neutrino background?
- Well-motivated candidates that are much less costly to probe
- We will talk about **alternative** models later

SUSY is not the only model

- SUSY is nice because it is highly predictive and still consistent with current constraints in certain regions of parameter space
- Related models = DM mass still at weak scale; freeze-out sets abundance
- Only need symmetry to stabilize DM AND some interactions to set abundance

Two good examples

- Extra dimensions: Kaluza Klein symmetry

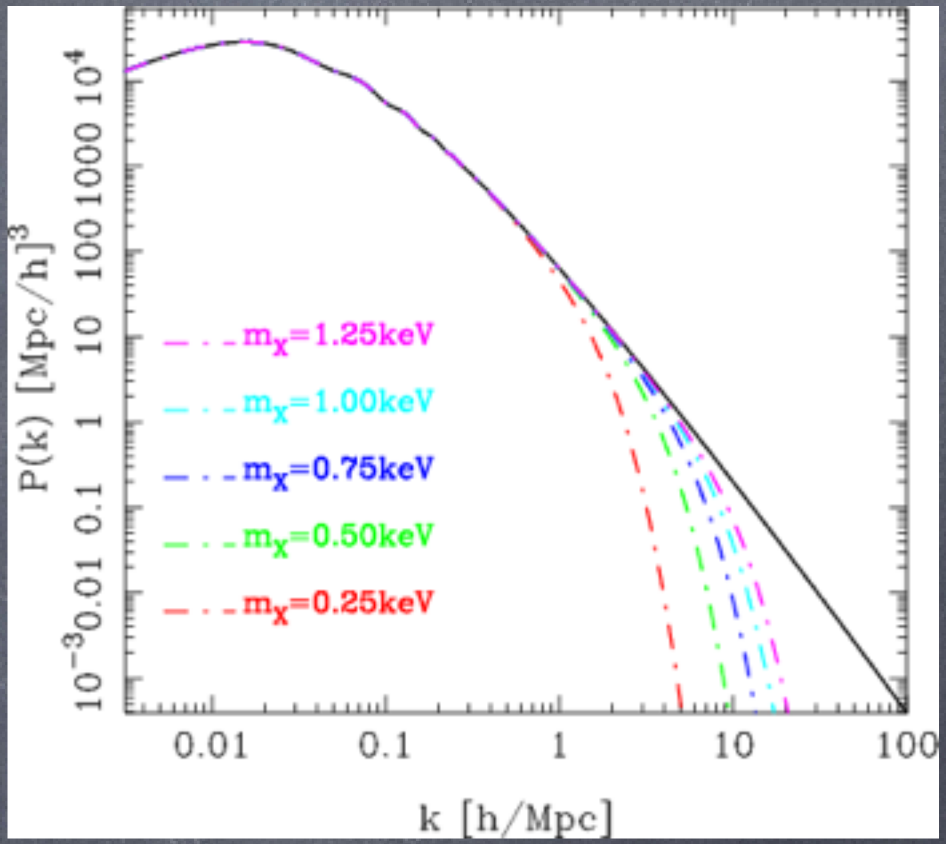
- Sterile neutrinos $\mathcal{L} = y\chi\phi LH$

$$C(\chi)_{Z_2} = C(\phi)_{Z_2} = -1$$

- Invent your own; check cosmology; look for LHC signatures

“Massive” Dark Matter

- Typically means heavier than a keV
- Relativistic and non-relativistic matter form structure differently
- Relativistic matter free-streams out of gravitational wells (hard to trap) -- allows us to constrain neutrinos
- Dark matter needs to clump



Smith and Markovic 1103.2134