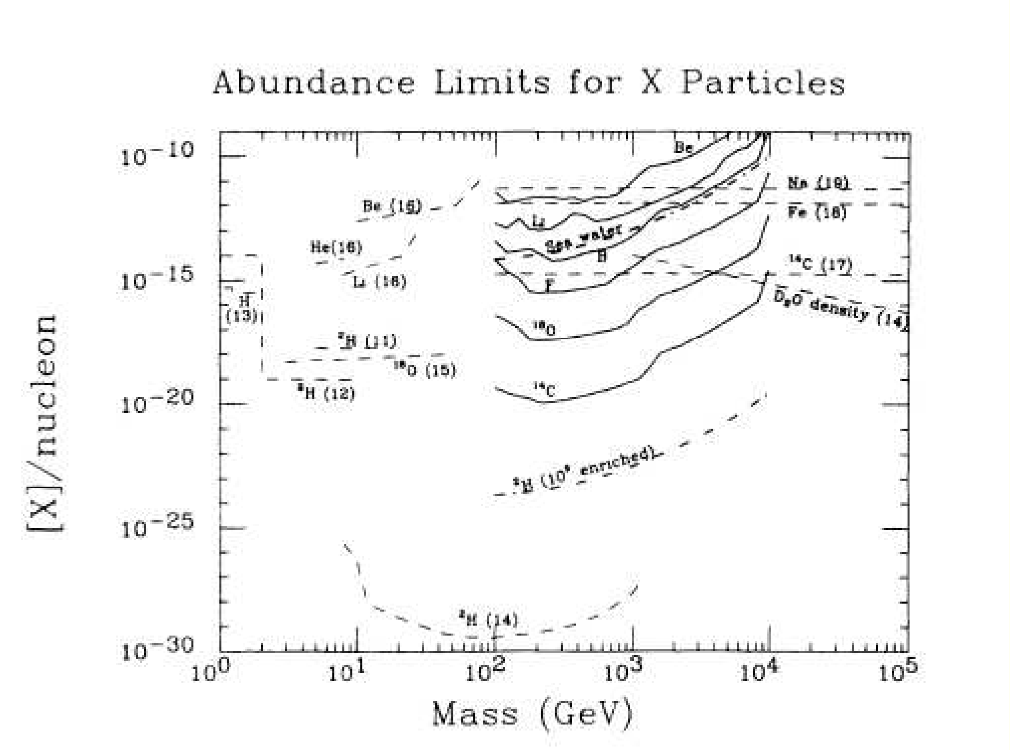
# Dark Matter Properties

- ⋆ Stable, or at least very long-lived.
- ⋆ The DM is not strongly interacting.



Expected isotope abundance for 100-1000 GeV particles formed in the Big Bang is $10^{-6} - 10^{-10}$ (Wofram), way above these experimental limits.

## Dark matter Properties (contd)

- ⋆ Of course, DM is not electrically charged
- ⋆ The Milky Way rotation curves suggest a DM density of about 0.3 GeV/cm$^3$.
- ⋆ The DM is non-relativistic as suggested by simulations of large scale structure formation. DM that is relativistic tends to freestream out, and does not seed structure. (WARM DM?)

THE STANDARD MODEL HAS NO PARTICLES THAT SATISFY THESE PROPERTIES.

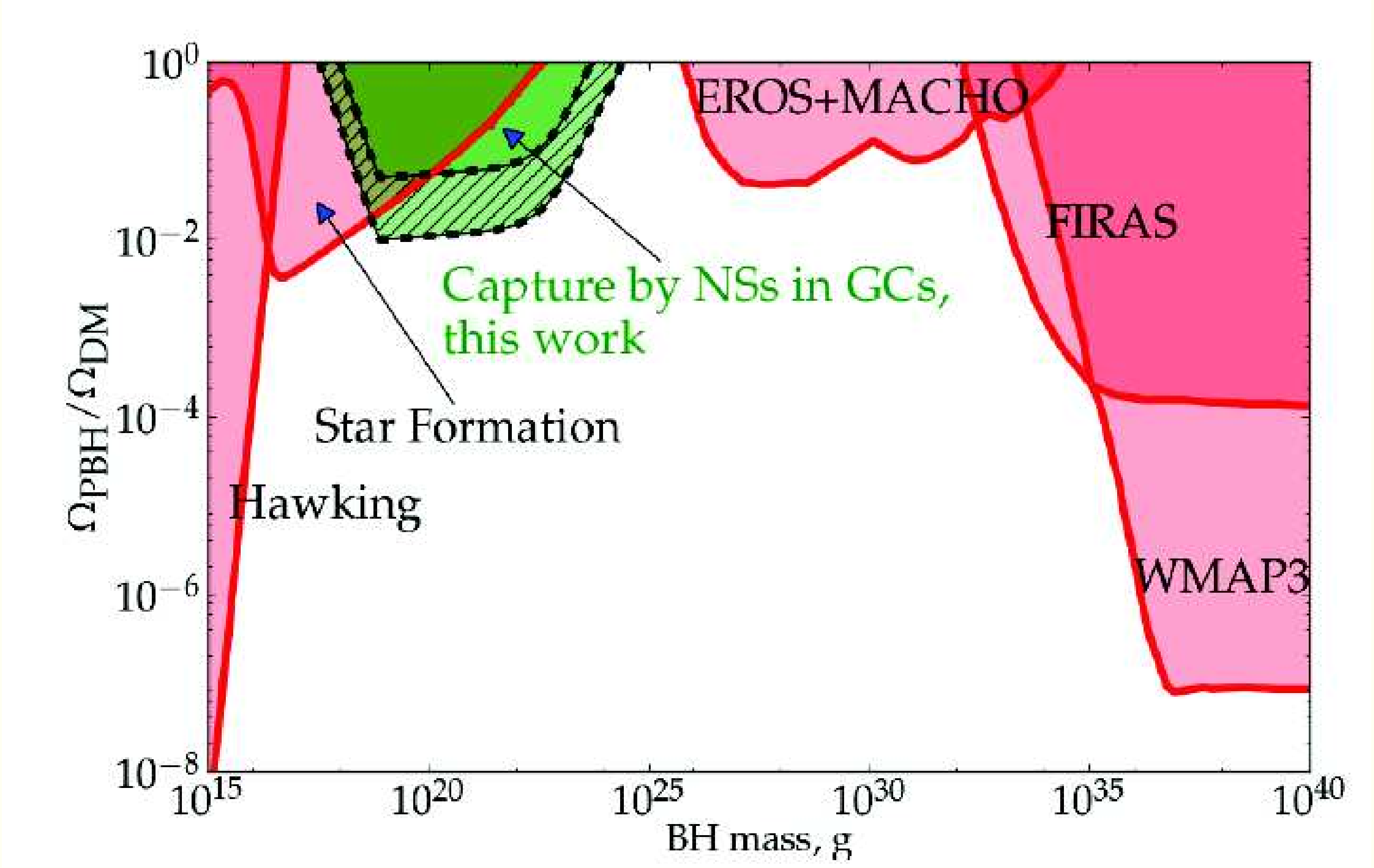
- ★ The only electrically neutral, non-strongly coupled particles are the active neutrinos, and stretching things, perhaps the graviton.

Neutrinos are relativistic at decoupling, and the graviton is not matter.

- ★ Primordial blackholes remain a logical possibility. MACHO survey (microlensing) excludes masses between $10^{-7} M_{\rm Sun}$ to (30-40) $M_{\rm Sun}$ from making majority of galactic halo DM No one knows how these might have been produced. Yet heavier BHs excluded by WMAP because X-rays emitted by gas accretion in the recombination era would have produced measureable effects. (arXiv:0709.0524) Blackholes smaller than $10^{-19} M_{\rm Sun}$ thought to evaporate by Hawking radiation w/in the lifetime of the Universe.
- ★ Planck Mass blackhole remnants of tiny blackholes created in the Big Bang have also been suggested as a possibility.

We are forced to regard DM as evidence for physics beyond the Standard Model.

# Blackholes as DM?



from arXiv: 1301.4984

Assuming that the DM is a new particle, it presumably was produced during the Big Bang, after the inflationary era along with everything else.

We will assume that it interacts sufficiently to have come into equilibrium with the rest of the cosmic soup.

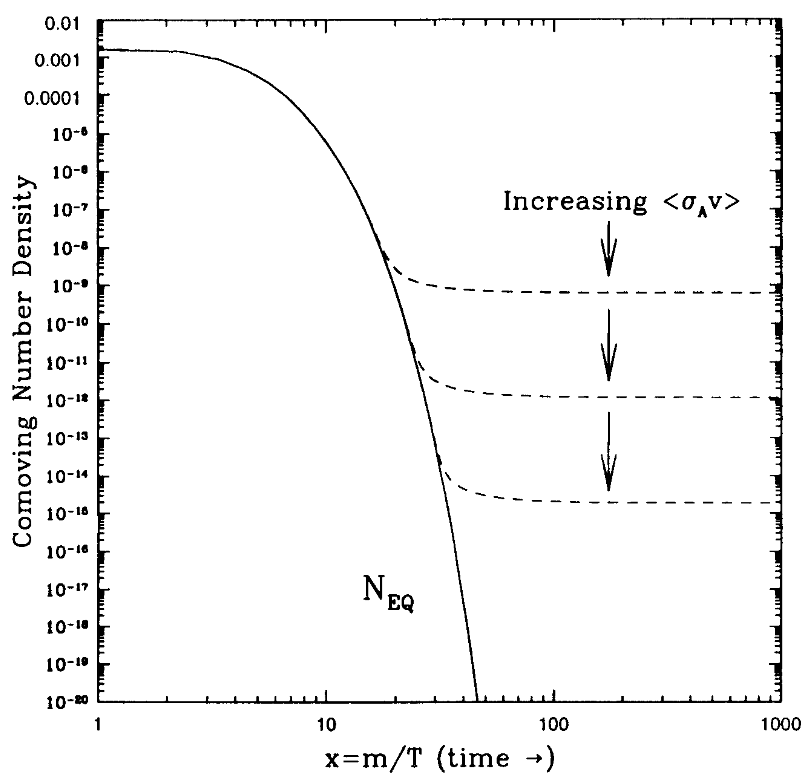
The number density is governed by Boltzmann equation for FRW universe,

$dn/dt = -3Hn - \langle \sigma v_{rel} \rangle (n^2 - n_{\rm eq}^2)$

The red term dominates at early time, and drives $n$ to its equilibrium value $\propto e^{-m/T)}$.

As the temperature falls below the DM particle mass, the number density of neutralinos becomes exponentially suppressed, and the green term takes over. In this regime, $n \propto R^{-3}$, much larger than expected from thermal equilibrium.

The freeze-out temperature $T_F \sim m/20$.



$$\Omega_{\rm DM} = mn(T_0) = Constant T_0^3 \int_0^{x_F} \langle v\sigma \rangle dx$$

Putting in numbers, $\Omega_{\rm DM} h^2 \simeq 0.1 \Longrightarrow \langle v\sigma \rangle \sim$ few pb.

# The WIMP Miracle

A typical cross section is $\frac{\pi\alpha^2}{8m^2} \sim 1$ pb for $m \sim 100$ GeV!

For masses and couplings of the weak scale, the thermal cross section is just about what cosmological data seem to require!

This is such a coincidence that it has come to be known as the WIMP Miracle.

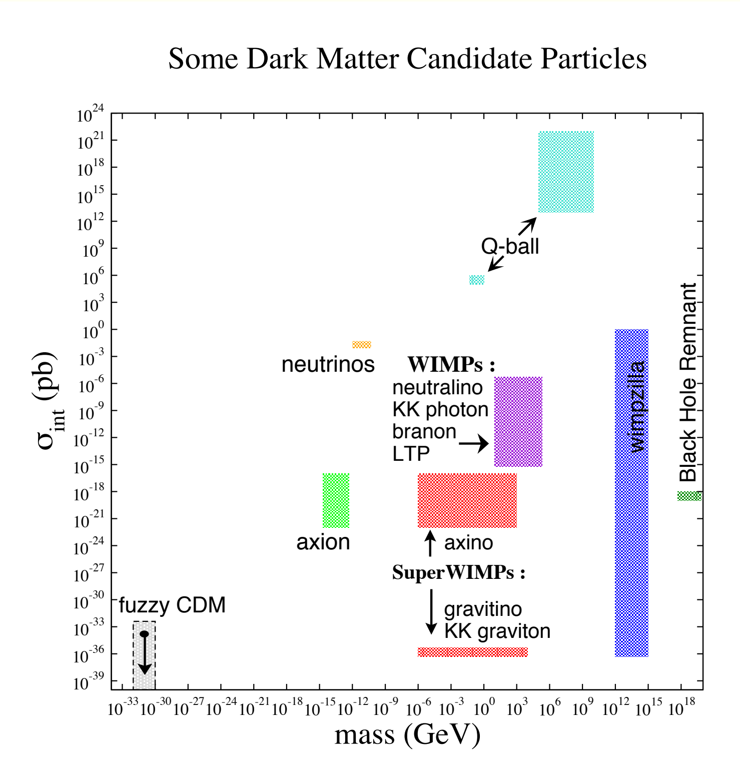
WIMP=Weakly Interacting Massive Particle

Does this suggest a connection between the weak scale with typical gauge couplings?

THIS PRETTY CONNECTION IS ORIGIN OF MUCH SPECULATION IN RECENT TIMES.

WARNING!!!! Really speaking the cross section fixes just $\alpha/m$, not $\alpha$ and $m$ separately. We will return to this later.

# The Dark Matter need not be a WIMP



In my view, from a particle physics perspective, WIMP dark matter and the axion are the best motivated candidates.

Axions are spin-zero particles that occur when we seek a dynamical reason for the strong $CP$ problem (Sourav Roy's lectures)

# WHY WIMPS?

We saw that in the Standard Model with elementary Higgs scalar fields unless we allowed for large unexplained cancellations, there must be new degrees of freedom not terribly far above the weak scale.

## What are the possibilities for the new degrees of freedom?

- ⋆ Eliminate elementary scalars, Higgs appears as a bound state of new fermions bound by a new "technicolour" interaction. Extended TC also needed. (Walking TC dynamics). Announcement of new resonance at LHC perhaps dampens this.
- ⋆ Strong gravity at the "weak scale". Gravity appears weak scale because flux is "lost" in extra spatial dimensions. Compactified dimensions ⟹ KK excitations. Warped dimensions.

- ⋆ Postpone the problem. Arrange things so $\Lambda^2$ term appears only at the multiloop level –Additional factors of $16\pi^2 \Longrightarrow$ higher $\Lambda$ OK. "The Little Higgs" idea. Need complete theory.
- ⋆ Introduce a symmetry that controls corrections to $m_H^2$ in the same way that chiral/gauge symmetries control corrections to the electron/photon mass in QED . Supersymmetry

We note that in each case there is an entire sector of new particles that needs to be introduced. Moreover, these new particles, since they couple to the Higgs sector of the Standard Model, have electroweak interactions. OUR HOPE IS WE WILL BE ABLE TO ACCESS SOME OF THESE PARTICLES AT THE LHC.

Introducing a multitude of new particles (particularly spin zero particles) with unfettered interactions can be very dangerous. This is because the existence of new particles allows new effects that are conflict with observation.

The situation is much better if we introduce a parity-like symmetry under which some particles are even while others are odd. $R$-parity for supersymmetry; $T$-parity for Little Higgs models; $KK$-parity for extra-dimensional models.

AN IMMEDIATE IMPLICATION OF THIS IS THAT THE LIGHTEST OF THE ODD PARITY PARTICLES MUST BE STABLE.

Such a stable particle cannot have strong or electromagnetic interactions; else it would form stable heavy isotopes that do not seem to exist.

MANY PARTICLE PHYSICS MODELS THAT CONTROL THE FINE-TUNING OF THE HIGGS SECTOR NATURALLY INCLUDE WIMP CANDIDATES.

I have made a number of comments that I will illustrate using supersymmetry to exemplify the ideas that we have introduced.

We have no time to discuss how SUSY models are constructed, or what we know of them experimentally. (Sudhir Vempati)

I will use these as a framework that includes WIMP dark matter, focussing on the

**The Minimal Supersymmetric Standard Model (MSSM)**

# The MSSM particle content

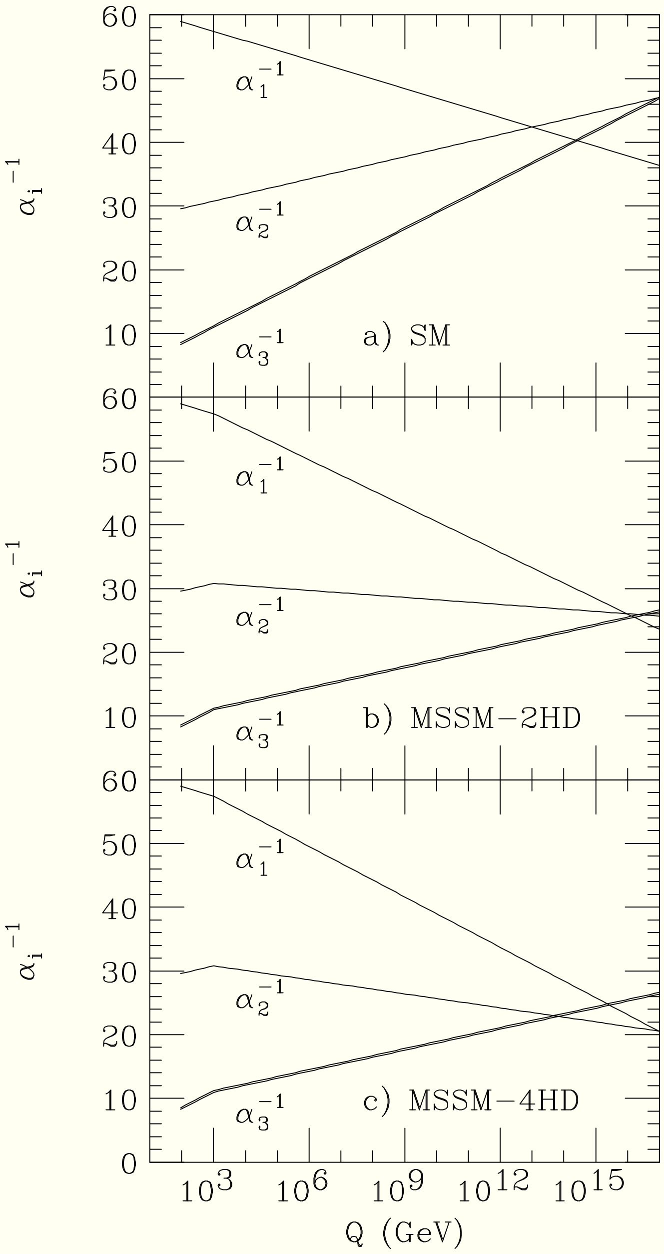
| | |
|---|---|
| spin-$\frac{1}{2}$ $(\nu_L, e_L); e_R$ | spin-0 $(\tilde{\nu}_L, \tilde{e}_L); \tilde{e}_R$ × generations |
| spin-$\frac{1}{2}$ $(u_L, d_L); d_R$ | spin-0 $(\tilde{u}_L, \tilde{d}_L); \tilde{d}_R$ × generations |
| spin-1 $(g,\gamma,W^{\pm},Z)$ | spin-$\frac{1}{2}(\tilde{g}, \tilde{\gamma}, \widetilde{W}^{\pm}, \widetilde{Z})$ |
| spin-0 Higgs bosons $(H_u^+, H_u^0)$, $(H_d^-, H_d^0)$ | spin-$\frac{1}{2}$ higgsinos $(\tilde{H}_u^+, \tilde{H}_u^0)$, $(\tilde{H}_d^-, \tilde{H}_d^0)$ |

Physical particles $(h^0,H^0,A^0,H^{\pm})$

The spin $\frac{1}{2}$ $\tilde{\gamma}$, $\widetilde{Z}$,$\tilde{H}_u^0$, $\tilde{H}_d^0$ mix to form neutral Majorana neutralinos $\widetilde{Z}_1, \widetilde{Z}_2, \widetilde{Z}_3, \widetilde{Z}_4$.

Similarly, there are two Dirac spin-$\frac{1}{2}$ charginos, $\widetilde{W}_1, \widetilde{W}_2$.

INVENTION OF NEW PARTICLES TO COMPLETE SYMMETRY MULTIPLETS HAS WELL-KNOWN PRECEDENTS (Positron, $\Omega^-$)



No unification in SM; “Miracle” in the MSSM; 4 Higgs doublets too many!

# A Confession

In the so-called superpotential, we could have included:

$$\hat{f} = \sum_{i,j,k}\left[\lambda_{ijk}\epsilon_{ab}\hat{L}_i^a\hat{L}_j^b\hat{E}_k^c + \lambda'_{ijk}\epsilon_{ab}\hat{L}_i^a\hat{Q}_j^b\hat{D}_k^c\right] + \sum_i \mu'_i\epsilon_{ab}\hat{L}_i^a\hat{H}_u^b + \sum_{i,j,k}\lambda''_{ijk}\hat{U}_i^c\hat{D}_j^c\hat{D}_k^c$$

Gauge-invariant, renormalizable – so we have no excuse.

$\lambda$, $\lambda'$ and $\mu'$violate lepton number conservation;[a] $\lambda''$violates baryon number conservation.

SUSY $\Longrightarrow$ These will not be generated radiatively if these are absent to start with.

BUT THAT WE CAN WRITE SUCH COUPLINGS IS A STEP BACK FROM THE SM IN WHICH THE CONSERVATION OF $B$ AND $L$ IS AUTOMATIC FOR RENORMALIZABLE OPERATORS. If all such terms are present protons will decay in a jiffy, and we would not be here.

---

[a] Can rotate $\mu'$ term away from the superpotential but not simultaneously the corresponding term in the SSB sector.

If we want to exclude these potentially undesirable terms, we have to manufacture an excuse. Define "Matter Parity" as
+1 for gauge and Higgs superfields
-1 for quark and lepton superfields.

Matter parity conservation forbids unwanted terms.

Equivalent to the conservation of $R = (-1)^{3(B-L)+2S}$

SM particles are $R$-even, SUSY particles are A $R$-odd.

Although $R$-parity conservation is not compulsory, we will assume it holds from now on because it leads to interesting consequences.

EMPHASIZE THAT VIABLE $R$-PARITY MODELS ARE PERFECTLY POSSIBLE. (No time to discuss these in detail here, but please ask me later.)

# Implications of $R$-parity conservation

- ★ Ensures proton stability from disastrous weak rate decays. (Exercise)
- ★ Non-observable $n$-$\bar{n}$ oscillations
- ★ Forbids mixing between leptons and charginos/neutralinos.
- ★ Superpartners can only be produced in pairs at accelarators that collide only SM particles.
- ★ Superparticles cannot decay into only ordinary particles $\Longrightarrow$ Lightest Supersymmetric Particle (LSP) must be stable.
- ★ Decays of superparticles terminates in the LSP.

Stable LSPs would have been in thermal equilibrium with everything else early in the history of the Universe
Freeze out of thermal equilibrium at $T \sim M_{LSP}/20$.
Can compute their abundance now – stringent constraints.

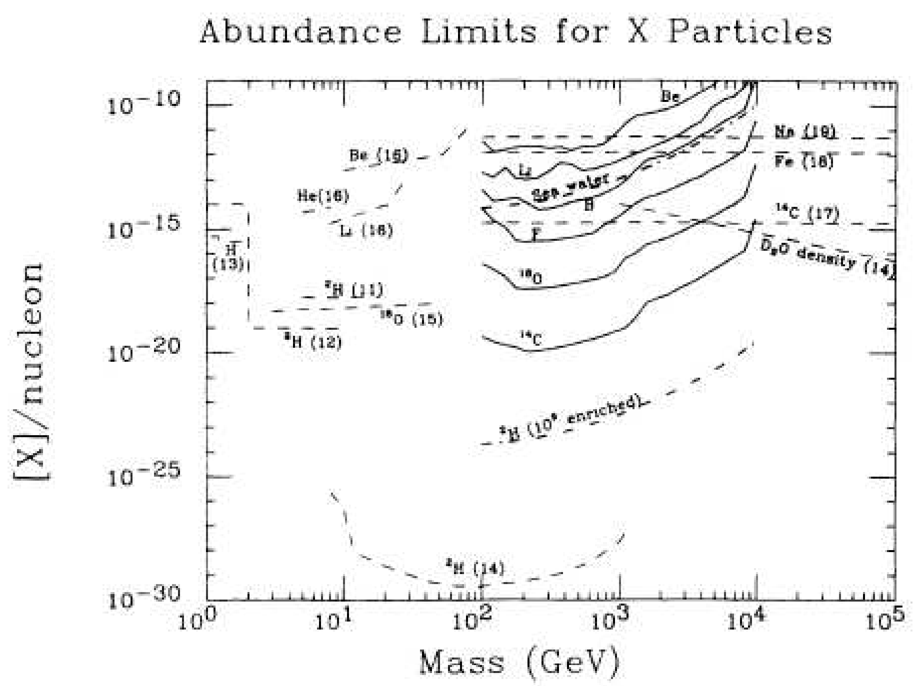
If LSP is electrically charged or coloured, we expect it will bind with ordinary particles to make exotic isotopes. For $M_{LSP} \lesssim \mathcal{O}$(TeV), expected abundance of heavy atoms/nuclei $\sim \mathcal{O}(10^{-10} - 10^{-6})$.

Empirical limits on heavy anomalous, heavy isotopes range from $10^{-12} - 10^{-28}$ (B, F, O, C, D, H, Fe) Lighter charged LSP's excluded by accelerator searches.

LSP generally believed to be neutral.

Measured CDM density imposes stringent constraints on <u>thermally produced</u> LSPs <u>assuming standard Big Bang cosmology</u>

Recall that we had already seen the limits on exotic isotopes.



Expected isotope abundance for 100-1000 GeV particles formed in the Big Bang is $10^{-6} - 10^{-10}$ (Wofram), way above these experimental limits.

Within the MSSM LSP candidates are $\tilde{\nu}$, $\widetilde{Z}_1$.

If we assume that the LSP makes up our galactic DM halo, the active $\tilde{\nu}$ is strongly disfavoured because it has “heavy neutrino-like” cross sections for scattering off nuclei and would have been detected unless its mass $\gtrsim$2 TeV (can evade if clever.)

The neutralino is a viable DM candidate as you must have heard already.

In local SUSY, the gravitino may also be a credible candidate, and in extended models, yet other objects: $\tilde{\nu}_R$, axinos.

Absolutely no reason for all the observed dark matter to consist of just one type of particle though many authors focus upon this simplest possibility.

Newly developed framework dubbed Dynamical Dark Matter takes the diametrically opposite view. (Dienes and Thomas)

Since sparticle decays always terminate in the LSP, every SUSY event has 2 LSPs in it.

If the LSP has no strong or EM interactions, it will be like a neutrino and escape detection in the experimental apparatus.

At colliders, this will manifest itself as apparent momentum/energy imbalance..

At hadron colliders, really in the transverse plane only as the longitudinal momentum of the initial state is not known.

$E_T^{\rm miss}$ events are quite generic in $R$-parity conserving SUSY models.

Let us return to dark matter considerations, and ask what it means when we say that the neutralino (or any other DM candidate) works.

The WMAP 9 data tell is that

- ⋆ $\Omega_\Lambda = 0.721 \pm 0.025$
- ⋆ $\Omega_{\rm Baryon} = 0.0463 \pm 0.0024$
- ⋆ $\Omega_{\rm CDM} = 0.233 \pm 0.023$

We are in an era where cosmology is definitely a respectable science!

Often the results are expressed as:

- ⋆ $\Omega_{\rm CDM}h^2 = 0.1153 \pm 0.0019$

Since dark matter may be multi-component, this last result is most sensibly viewed as yielding an upper limit on the density of any long-lived neutral particle that may be present in any theory.

Asking that this particle provide all the dark matter is a stronger requirement, and really makes sense only if you have reason to believe that you "know it all"!

THIS MEANS THAT DARK MATTER PARTICLES PRODUCED IN THE BIG BANG MUST ANNIHILATE FAST ENOUGH....ELSE, TOO MANY WOULD BE LEFT OVER TODAY, AND THE UNIVERSE WOULD NOT HAVE BEEN AS LONG-LIVED AS WE KNOW IT IS.

Although SUSY DM serves as a good illustrative example, the Majorana nature of the neutralino LSP causes some special features

Remember the DM is non-relativisitic when it decouples, which means its velocity is not very large. Scattering in higher partial waves suppressed.

For identical fermions, antisymmetry of the 2 particle wave function tells is that either:

- ⋆ $L = 0$ and $S = 0$ (for S-wave annihilation), or
- ⋆ $L = 1$ and $S = 1$ (for P-wave annihilation, suppressed by $\beta^2$).

For S-wave annihilation to SM fermions, $J = 0$.

Since $L_z = 0$, $S_z = 0 \Longrightarrow$ Fermions have same helicities.

Thus the amplitude is $\propto m_f$ (or Yukawa coupling), and will vanish if $m_f = 0$, and annihilation will occur in P-wave.

Not so for DM particles with other spins, or for Dirac DM particles

No P-wave suppression for annihilation to $WW$ or $ZZ$ final states.

# How SUSY gives the right DM Density

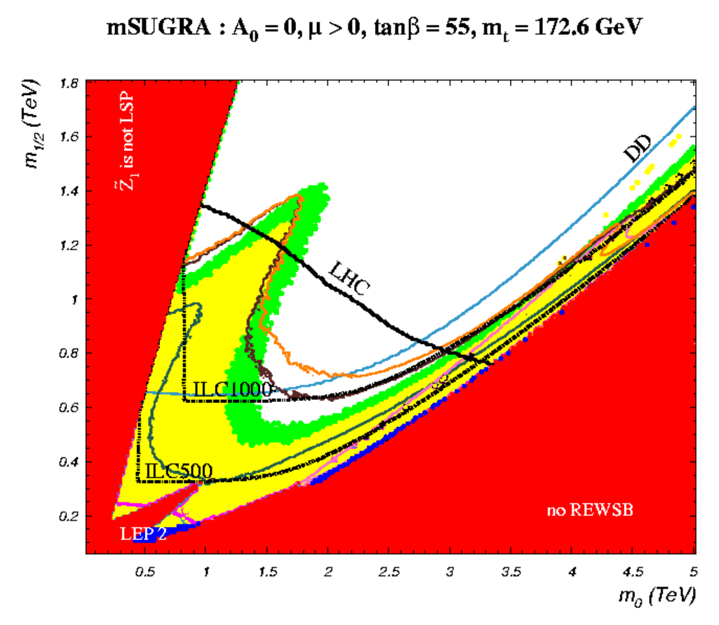
We saw that the thermal density depends on $g^2/M$, and that we expect to obtain $\Omega h^2 \sim 0.1$ with $M = 100$ GeV and typical electroweak couplings.

In SUSY, we naturally have the latter, but the 100 GeV mass scale is in tension with the data (Sudhir Vempati).

We need to find ways of increasing the DM annihilation cross section. (This discussion will also teach us how DM annihilates.)

I will use the familiar mSUGRA framework to illustrate the ideas, disregarding the recent LHC data that have excluded much of the parameter space that I will show.

Relic-density-allowed regions in the mSUGRA model (Green and Yellow)



$b$-tagging increases HB/FP reach where LSP has higgsino admixture

Notice DM detection reach in this MHDM region .

# Jacking up the annihilation cross section

- ⋆ If the mass scale of sparticles is 100 GeV, we automatically get the right DM density, and the "WIMP miracle" really works.

- ⋆ Co-annihilation with a charged or coloured sparticle in thermal equilibrium with $\widetilde{Z}_1$ (usually $\tilde{\tau}_1$ or $\tilde{t}_1$)

  If $M_1 \simeq -M_2$, $m_{\widetilde{Z}_1} \simeq m_{\widetilde{W}_1} \simeq m_{\widetilde{Z}_2}$ but mixing is tiny, and a bino-like neutralino can co-annihilate with a chargino-wino (BWCA). But not in models with gaugino mass unification.

- ⋆ Resonance enhancement if $2m_{\widetilde{Z}_1} \simeq m_\phi$, where $\phi = A, H$ or even $h$ or $Z$. Not as fine-tuned as it seems because resonances can be wide, and because LSP has thermal motion. (Higgs funnel)

- ⋆ Increase higgsino content of LSP since higgsinos couple to $W/Z$ bosons (small $\mu$ hyperbolic branch/focus point region) Resurgence in so-called natural SUSY models!

- ⋆ <u>“Pseudo-bulk”</u> region in models with non-universality. (one specie of light sfermions)
- ⋆ Increase wino content of LSP because winos have big couplings to $Z$ and $W$ (need non-universal gaugino masses at GUT scale.)

There are numerous ways to get the dark matter density at the correct value in WIMP models, but we may have to do some work to get it right.

# Light Dark Matter

We will see later that some experiments have reported possible signals from few GeV Dark Matter.

Can we accommodate such particles, or do we need to rethink from scratch?

Think about how gauge mediation works: $m \propto g^2 \left(\frac{F}{M}\right)$, where $M$ is the messenger mass, $F$ is the SUSY breaking scale and $g$ a typical SM gauge coupling.

In a hidden sector with its own gauge coupling that also feels SUSY breaking, we'd have $m_{\rm hid} \propto g_{\rm hid}^2 \left(\frac{F}{M}\right)$.

This automatically gives $\frac{m}{g^2} = \frac{m_{\rm hid}}{g_{\rm hid}^2}$.

But this is exactly what fixes the annihilation cross section, so the lightest hidden sector particle will end up with the right magnitude of the relic density. If $g_X$ is small, $m_X$ will also be small, and we can get the WIMP miracle without a WIMP. (Feng and Kumar)

# Searching for WIMP Dark Matter

- ⋆ Direct Detection
- ⋆ Indirect Detection
- ⋆ Collider Searches (In my view, these are not DM searches, but are searches for quasi-stable weakly interactng particles.)

# Direct Detection

If the WIMP is the DM in our galactic halo, we know its density which, as we have said is about 0.3 GeV/cm$^3$.

As the earth moves through this WIMP halo, the neutralino wind with $\beta \sim 10^{-3}$ hits it, and everything on it.

In particular, if the neutralino collides with a nucleus, it will cause it to recoil. If the surrounding volume is sufficiently instrumented, experiments can detect this nuclear recoil and say they have found a DM wind signal.

Recoil energy is very small, $\lesssim \frac{4m_X m_N}{(m_X+m_N)^2} E_i \leq E_i$

Note that for a 100 GeV DM particle, $E_i \sim 100$ GeV $\times 10^{-6} \sim 100$ keV. Hard to see without specialized detectors.

More importantly, the maximum momentum transfer is less than $\sqrt{\frac{4m_X m_N}{(m_X+m_N)^2}} m_X v$. This is typically smaller than tens of MeV!

COHERENT SCATTERING OF THE ENTIRE NUCLEUS!

## WHAT DOES COHERENT SCATTERING MEAN?

Classically the scattering rate would be proportional to $R_p Z + R_n(A - Z)$.

The same would also be true quantum mechanically if we could tell (at least in principle) which nucleon the neuttralino scattered from.

In our case, the wavelength of the probe is too large for the different nucleons to be resolved, and the scattering rate is proportional to $[f_p Z + f_n(A - Z)]^2$, where $f_p$ and $f_n$ are amplitudes to scatter off a proton and neutron, respectively.

If neutralino interactions are isospin-independent, then $A_p = A_n$ and the scattering rate is proportional to $A^2$. USING LARGE NUCLEI IS AN ADVANTAGE FOR THESE SPIN-INDEPENDENT CROSS SECTIONS.

DM interactions mediated by $Z$ exchange (via axial vector coupling), however lead to a coupling between the nucleon and WIMP spin.

The $Z$ boson mediated interactions of DIRAC fermions can result in spin-independent as well as spin-dependent cross sections.

If the cross section is dominated by spin-dependent interactions, scalar candidates for DM will obviously be excluded.

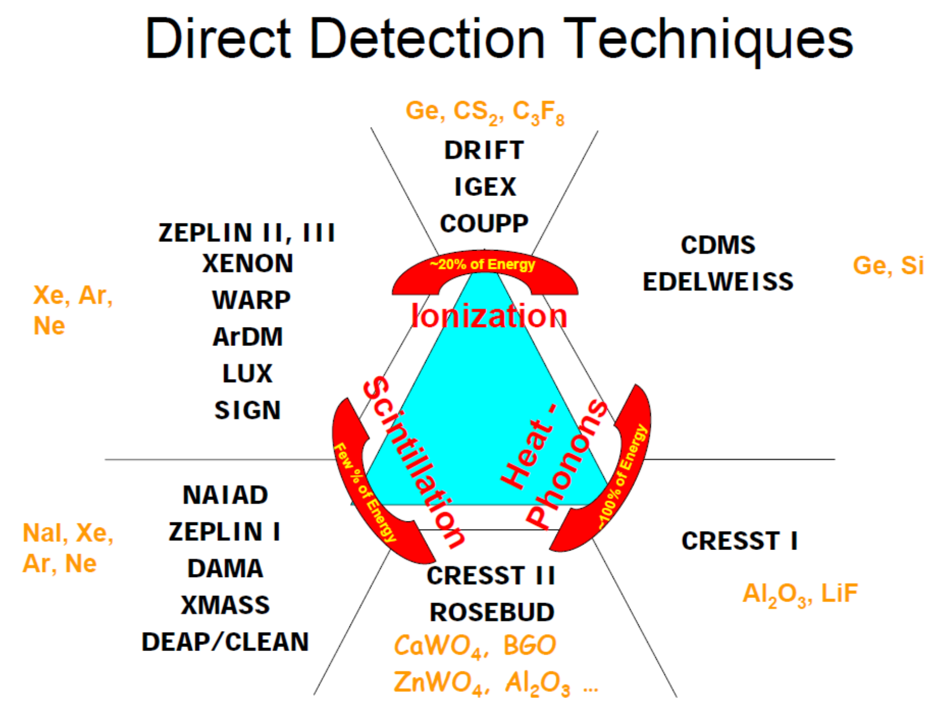
How big can these DM scattering cross sections be? Illustrate this for the neutralino of the MSSM.

# Direct Detection of WIMPS

Collisions with stray neutrons can cause nuclear recoils

Need to distinguish between nuclear and electron recoils.

Many searches using different techniques to detect/discriminate the recoils.



## SOME COMMENTS

- ⋆ All detectors have a lower recoil energy threshold below which backgrounds are too large.
- ⋆ The recoil energy needs to be inferred from the observed signal.
- ⋆ There are uncetainties from nuclear form factors.
- ⋆ The maximum momentum transfer depends on the reduced mass of the WIMP-nucleon system. Hence, maximum sensitivity to WIMP mass when these masses roughly match.
- ⋆ If the form factor becomes too small at the maximum momentum transfer, we will not be able to probe $q_{\rm max}$.
- ⋆ The WIMP velocity distribution needs to be modelled.

There are a number of experiments at various stages.

- ⋆ Experiments using noble elements: XENON***; LUX, PANDA-X, XMASS use xenon. Darkside, DEAP/CLEAN class and others use argon. Relatively cheap and large size may be possible. This allows for dramatic background reduction because we can look only at inner fiducial region! Use of depleted argon may allow us to see modulated WIMP signal in DEAP.
- ⋆ Germanium crystal experiments: CDMS, superCDMS, Edelweiss, CoGeNT,Majorana...
- ⋆ Salt crystals (NaI, CsI):DAMA/LIBRA, KIMS, DM-ICE
- ⋆ Superheated liquid: COUPP, PICASSO, SIMPLE
- ⋆ Gas TPC: D$^3$, DMTPC,DRIFT, NEWAGE

## HOW BIG A SIGNAL DO WE EXPECT?

It depends on what the WIMP is and how it couples.

Things like superpartners of active sneutrinos that have gauge strength couplings to the $Z$ have huge cross sections and have long since been excluded.

Majorana neutralinos of SUSY (long thought to be a superb WIMP candidate) will have much smaller spin-independent cross sections. We will illustrate results for these neutralinos.

# CHARGINOS AND NEUTRALINOS IN THE MSSM

Combinations of gauginos and higgsinos that mix upon EWSB

$$\mathcal{M}_{\rm neutral} = \begin{pmatrix} 0 & \mu & -\frac{gv_u}{\sqrt{2}} & \frac{g'v_u}{\sqrt{2}} \\ \mu & 0 & \frac{gv_d}{\sqrt{2}} & -\frac{g'v_d}{\sqrt{2}} \\ -\frac{gv_u}{\sqrt{2}} & \frac{gv_d}{\sqrt{2}} & M_2 & 0 \\ \frac{g'v_u}{\sqrt{2}} & -\frac{g'v_d}{\sqrt{2}} & 0 & M_1 \end{pmatrix}$$

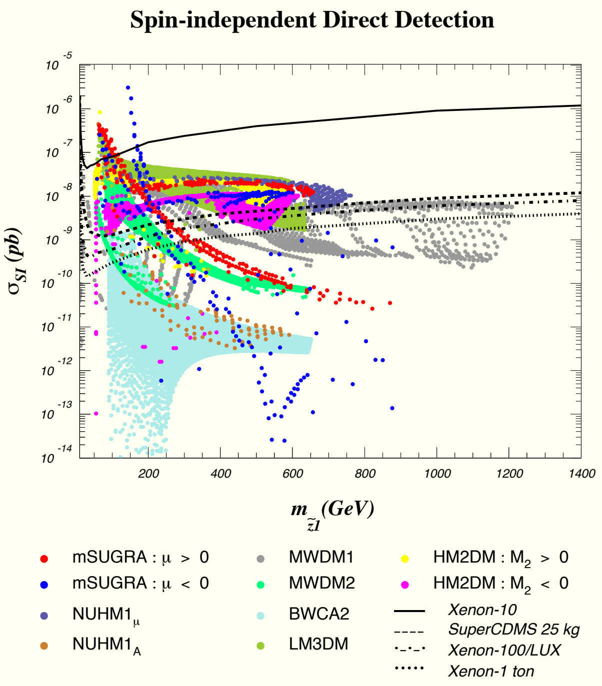
4 Majorana neutralinos that are combinations of $\tilde{h}_u^0, \tilde{h}_d^0, \widetilde{W}_3, \tilde{B}$

$\mathcal{M}_{\rm charge} = \begin{pmatrix} M_2 & -gv_d \\ -gv_u & -\mu \end{pmatrix}$ 2 Dirac charginos that are comb. of $\widetilde{W}^{\pm},\ \tilde{h}^{\pm}$

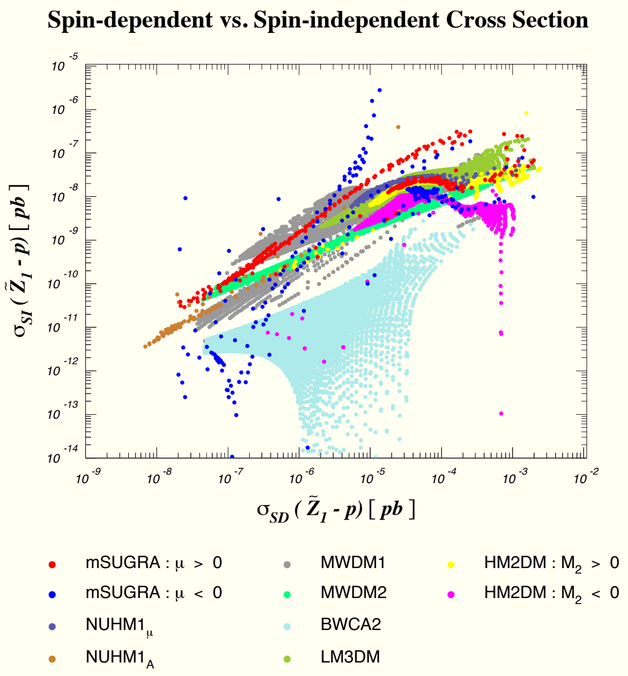
If $M_1,\ M_2 \gg |\mu|$, $\widetilde{Z}_3 \sim \tilde{B}, \widetilde{Z}_4 \sim \widetilde{W}$, $\widetilde{W}_1 \sim \tilde{h}^-$.

If $M_1,\ M_2 \ll |\mu|$, $\widetilde{Z}_1 \sim \tilde{B}, \widetilde{Z}_2 \sim \widetilde{W}$, $\widetilde{W}_1 \sim \widetilde{W}^-$.

# $p\widetilde{Z}_1$ CROSS SECTIONS: RELIC-DENSITY-CONSISTENT MODELS



Spin-independent Direct Detection



Spin-dependent vs. Spin-independent Cross Section

Notice that there are two branches for the spin-independent cross section.