Supersymmetry and Dark Matter

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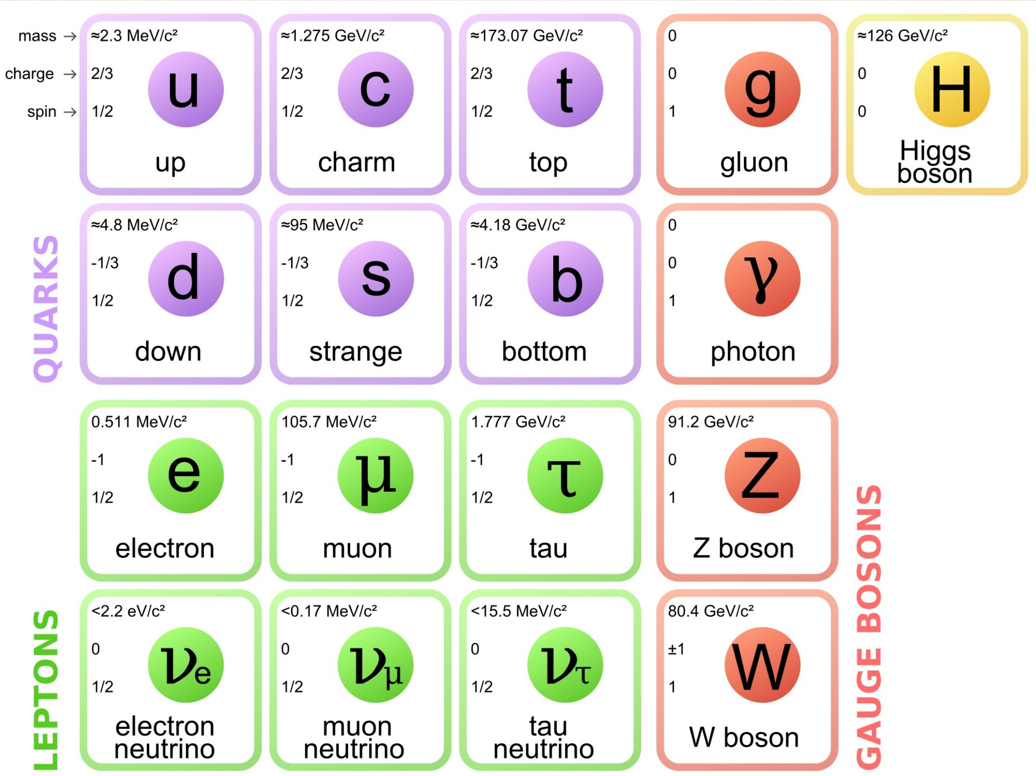
Outline

- Big questions in particle physics
- A brief general introduction of Higgs boson and supersymmetry (SUSY)
- Particle dark matter and the WIMP miracle
- Predictions and experimental tests of SUSY dark matter scenarios

Big Open Questions in Particle Physics

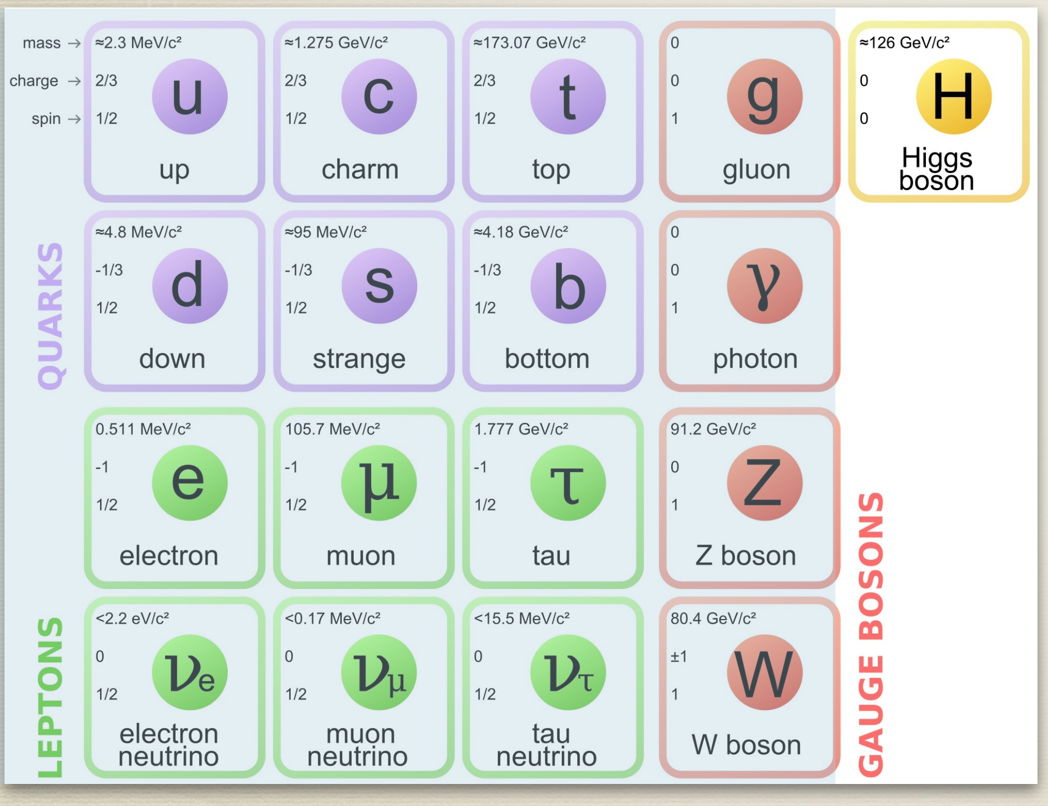
Standard Model of Particle Physics



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson	
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon		
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS	
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson		

Triumph of the 20th century:
discover sub-atomic particles and their interactions;
confirm quantum field theory (quantum mechanics + special relativity)

A long journey to establish this picture: (SM framework 1960's) the latest discovery and milestone is that of the Higgs boson (July 4th, 2012)



Now a fifth force is known: short-range force mediated by the Higgs boson. Very different from other forces: spin zero, very weak

Is this the end of story?

Big Questions on Table

Most of our Universe is dark. 85% of the matter does not come from the Standard Model.
What is dark matter?

The light Higgs boson we observed is puzzling!
What gives the Higgs boson its mass?
Why is it light?

Why is there a mass hierarchy of the SM fermions?

Why is there more matter than antimatter in the Universe?

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Big questions on table

Most of our Universe is dark. 85% of the matter does not come from the Standard Model.
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focus of the school

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Before discussing SUSY and its prediction for dark matter, I want to discuss briefly the Higgs boson, its properties and what is puzzling about it.

The puzzle of the light Higgs boson is one major motivation for low energy SUSY. In addition, Higgs **may** be a portal to the dark sector.

Higgs and Supersymmetry

Higgs Physics in a Nutshell

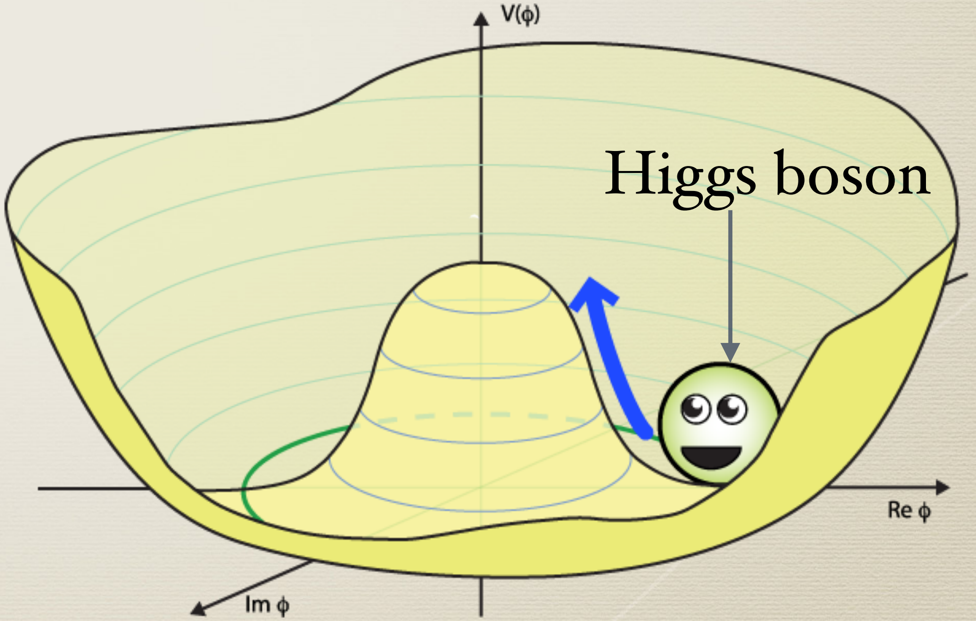
Higgs is a field that permeates the vacuum. It can store energy, depending on the field value in some region. This is just like electrodynamics, where electromagnetic fields carry energy density:

$$\frac{\text{Energy}}{\text{Volume}} = \frac{1}{2}\epsilon_0 E^2 + \frac{1}{2}\frac{1}{\mu_0}B^2$$

The Higgs has a non-zero vacuum "**expectation value**": at the minimum of its potential, the field value is non-zero.

The non-zero expectation value is responsible for electroweak symmetry breaking (EWSB).

Higgs potential energy



The non-zero expectation value of the Higgs field, v = 246 GeV, a constant throughout space and time, gives rise to masses of **all the other particles** in the Standard Model, for example:

gauge coupling

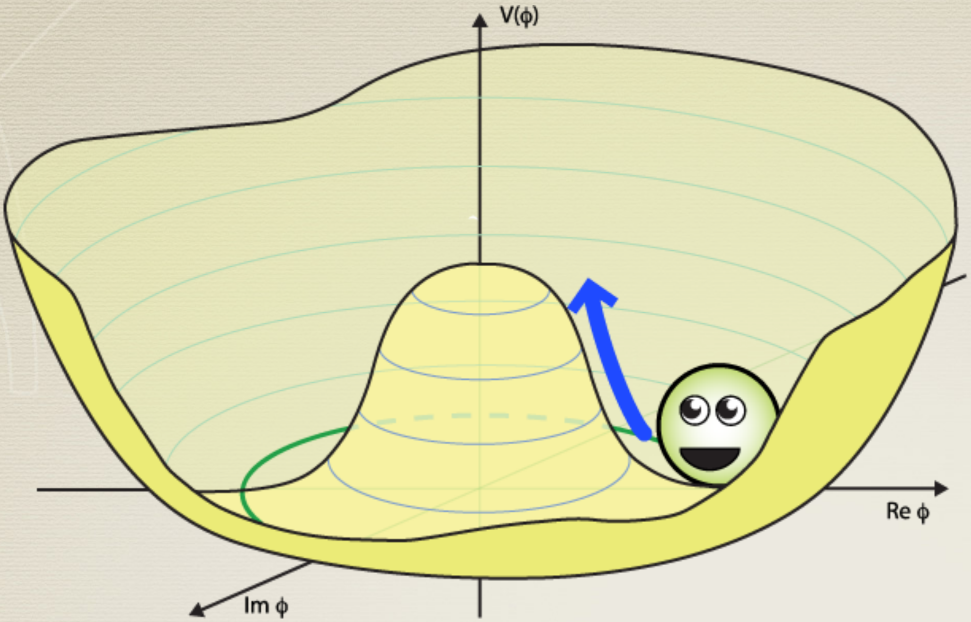
W gauge boson:
mediate weak force

$$m_W = \frac{1}{2} g v = 80.4 \text{ GeV}$$

top quark:
heaviest fermion

$$m_{\text{top}} = y_t v = 173.2 \text{ GeV}$$

Yukawa coupling:
largest coupling to the Higgs



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The standard model *assumes* this potential but doesn't *explain* it.

The standard model doesn't *explain* the Higgs mass itself.

It is only an **effective** description of electroweak symmetry breaking. Yet the microscopic details aren't specified.

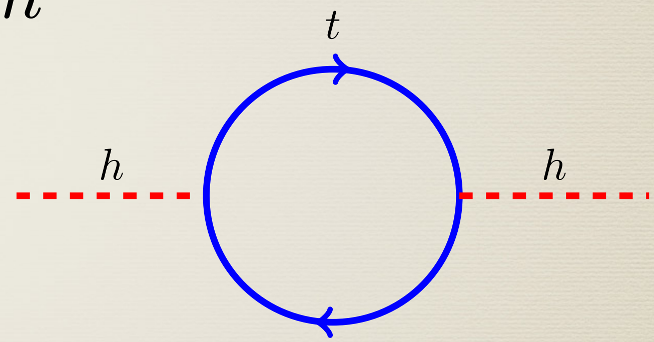
What we really want is a **dynamical** explanation:
what are the interactions driving the preference for a nonzero vacuum expectation value?

Hierarchy Problem of an Elementary Scalar (fine-tuning problem)

Physical mass
125 GeV

$$m_h^2 = m_0^2 + \Delta m_h^2$$

← quantum correction such as



Bare mass,
parameter in the potential term

$$\sim \frac{y_t^2}{16\pi^2}\Lambda^2 \sim \frac{\Lambda^2}{100}$$

Λ: scale up to which SM is valid

In the language of ordinary quantum mechanics, the quantum correction arises in second-order perturbation theory:

$$\Delta E_h = \sum_{t\bar{t}\ \text{states}} \frac{\left|\langle t\bar{t}|\, H_{\text{int}}\, |h\rangle\right|^2}{E_h^{(0)} - E_{t\bar{t}}^{(0)}}$$

Hierarchy Problem of an Elementary Scalar (fine-tuning problem)

Physical mass
125 GeV

$$\longrightarrow m_h^2 = m_0^2 + \Delta m_h^2 \longleftarrow$$

quantum correction

Bare mass,
parameter in the potential term

$$\Delta m_h^2 \sim \frac{y_t^2}{16\pi^2}\Lambda^2 \sim \frac{\Lambda^2}{100}$$

Λ: scale up to which SM is valid

Suppose $\Lambda = 10^{19}$ GeV, and the observed Higgs mass is 125 GeV, we need, say, a huge bare mass to cancel the quantum fluctuations

$m_0^2 = (1{,}500{,}473,\ 789,\ 254,\ 211{,}536\ \text{GeV})^2$;

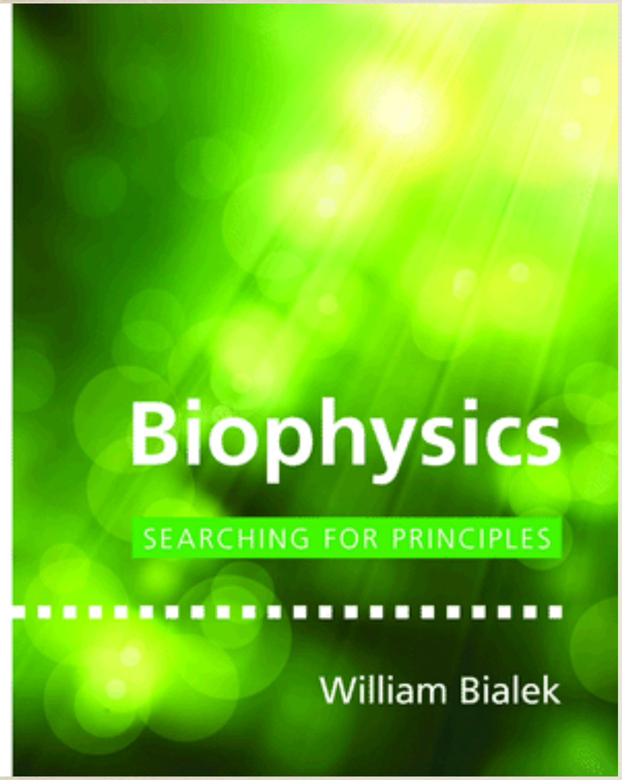
If we miss by 10 GeV, $m_0^2 = (1{,}500{,}473,\ 789,\ 254,\ 211{,}526\ \text{GeV})^2$;

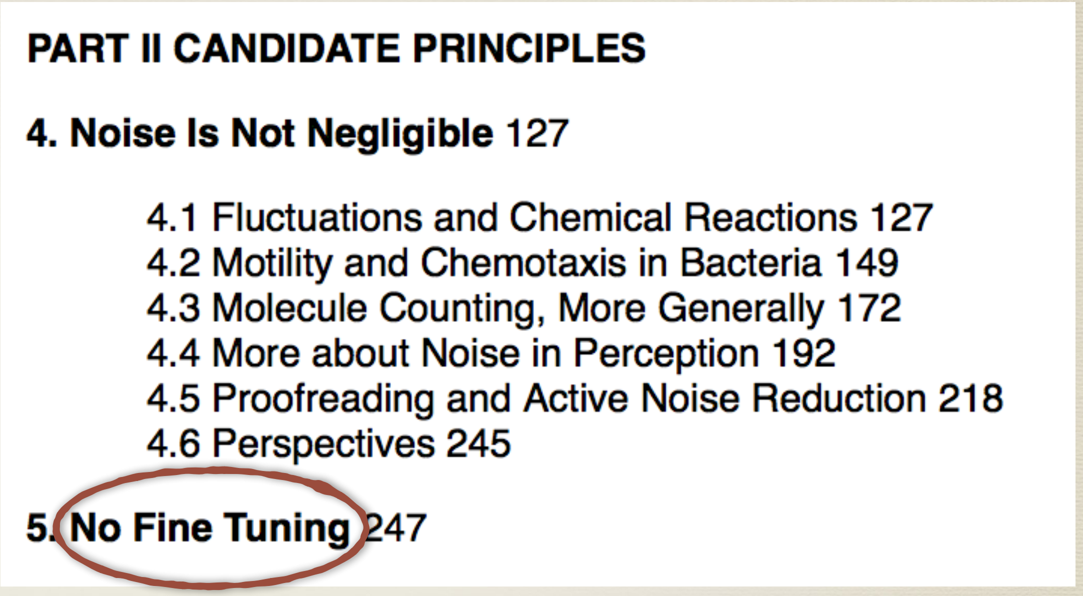
The physical Higgs mass is ~ **10^9** GeV!

If the Standard Model is the effective description up to Planck scale (10^{19} GeV), it will be tuned one part in 10^{32}, way more tuned than a balanced can.

http://xperienceadventures.com/1950/

No fine-tuning is a possible candidate principle not only for particle physics




PART II CANDIDATE PRINCIPLES

Whether we like it or not, it could be tested **experimentally**

A lot of theories have been proposed to explain why we may find a light Higgs boson in nature with the right potential for EWSB:

- Higgs is protected by an extended spacetime symmetry. boson ↔ fermion (“supersymmetry”).
- It is a composite (bound state). We know spin-0 atoms, spin-0 mesons. Pseudo Nambu-Goldstone Higgs (Kaplan, Georgi).
- It is an accident (“anthropic”) or maybe something we could compute from some very high-scale fundamental physics if we were smart enough (“final theory”).
- ……

Supersymmetry

For every standard model particle, introduce a supersymmetric partner (with similar properties except for different **spins**).

Simplest low-energy SUSY model: minimal supersymmetric standard model (MSSM).

In MSSM,

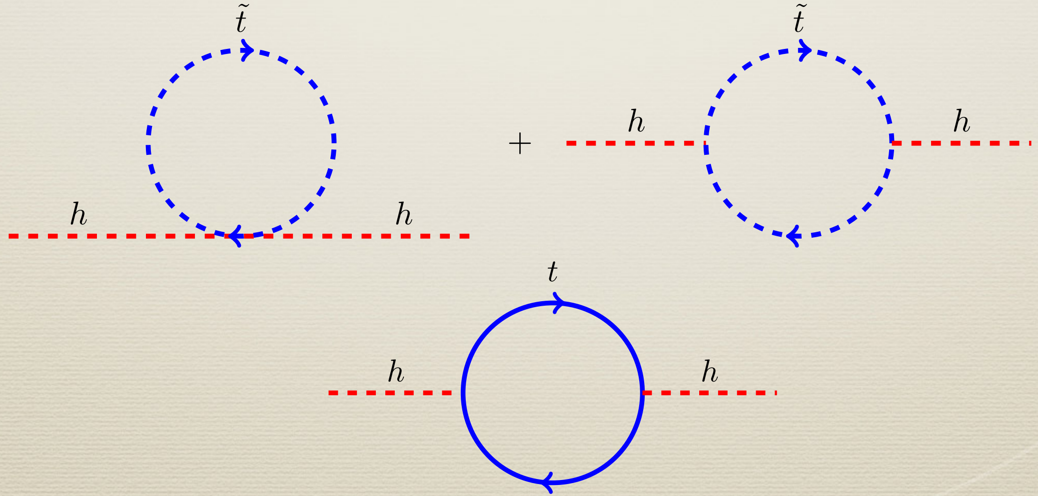
Gauge bosons W, Z, γ's (spin-1)	**Gauginos (spin-1/2)**
Higgs boson (spin-0)	**Higgsino (spin-1/2)**
Leptons and quarks (spin-1/2)	**Sleptons and squarks (spin-0)**

Supersymmetry

For every Standard Model particle, introduce a supersymmetric partner (with similar properties except for different **spins**).

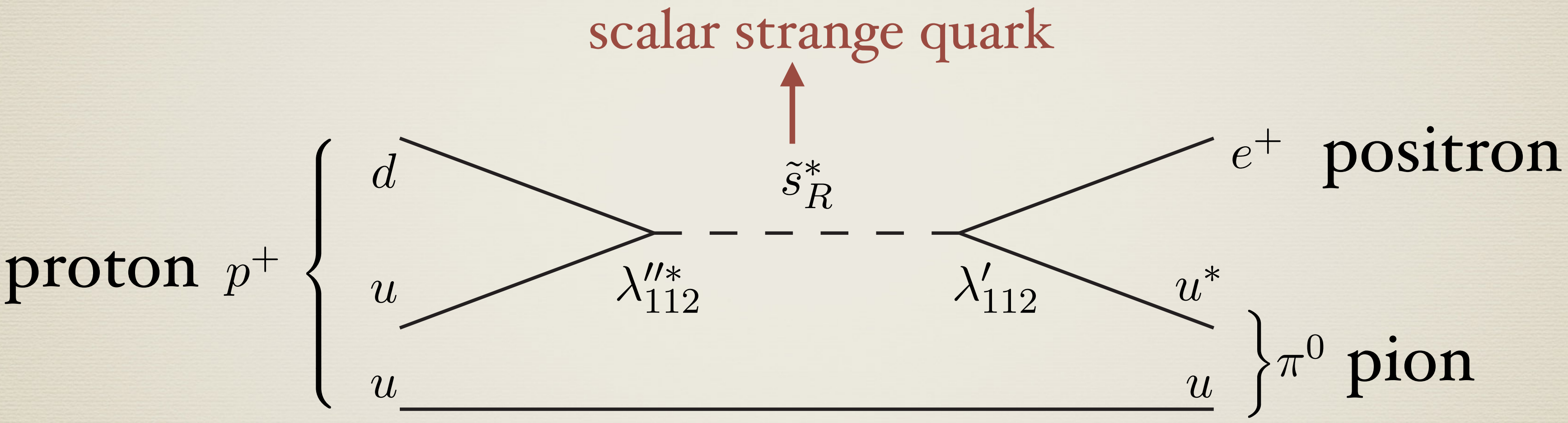
Different-spin pieces combine to cancel large quantum corrections to the Higgs potential and help solve the fine-tuning problem.

“Stop” or “scalar top”: cancels the biggest correction.



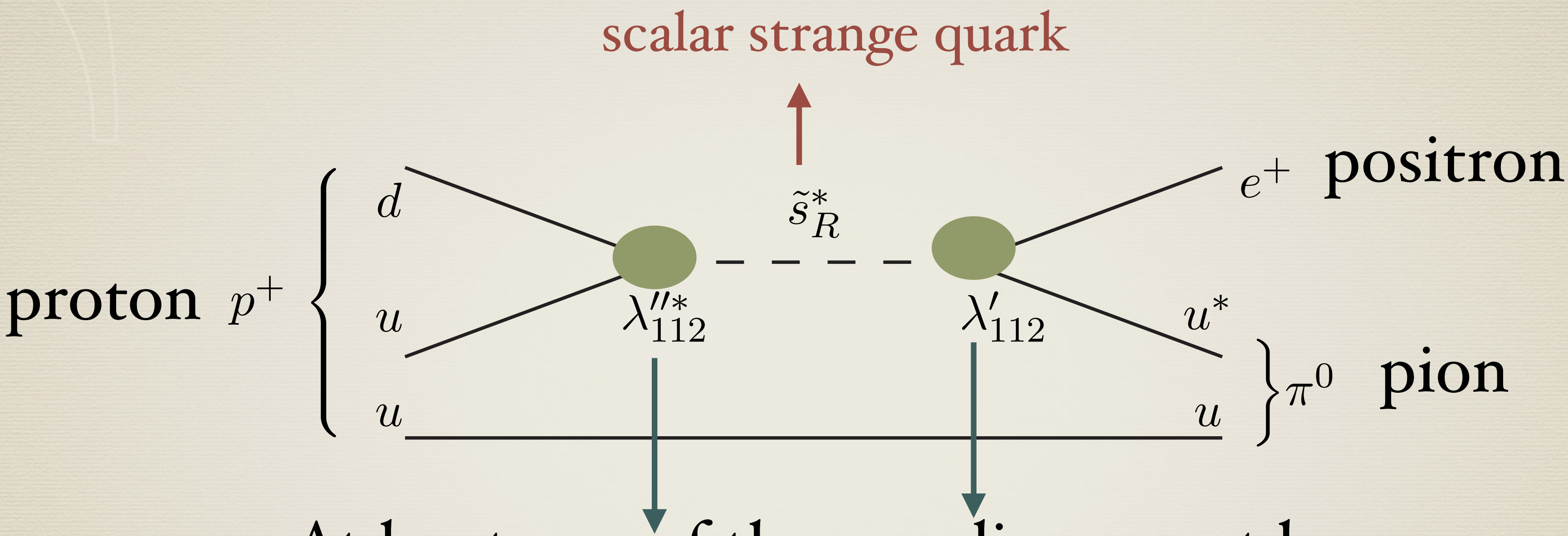
R-parity in MSSM

Without imposing additional symmetry, MSSM allows for baryon and lepton number violating interactions, which could lead to proton decays:



Experimentally, the decay time of proton to positron and pion final states is tested to be in excess of 10^{33} years! (the age of the Universe is 10^{10} years)

How to reconcile MSSM with the constraint ?

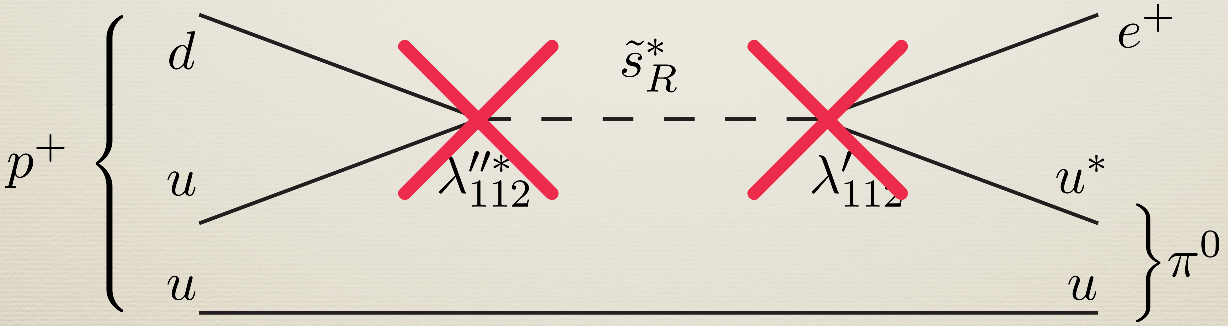


At least one of the couplings must be extremely small

In addition to proton decays, other lepton and baryon number violating processes are also strongly constrained.

A more elegant and simple solution: add to MSSM a new symmetry, which has the effect of eliminating possible baryon and lepton number violating interactions. This new symmetry is “**R-parity**”.

All standard model particles have even R-parity and all supersymmetric partners have odd R-parity. All interactions are invariant under R-parity (equivalently, have even R-parity).



Three important phenomenological consequences of R-parity

- Lightest supersymmetric particle (LSP) must be absolutely stable. If it is **electrically neutral**, it only interacts weakly with ordinary matter, and thus **a cold dark matter candidate**.

- Each supersymmetric particle other than the LSP must eventually decay into a state that contains an odd number of LSPs (usually just one).

- In collider experiments such as the Large Hadron Collider (LHC), supersymmetric particles can only be produced in even numbers (usually two-at-a-time).

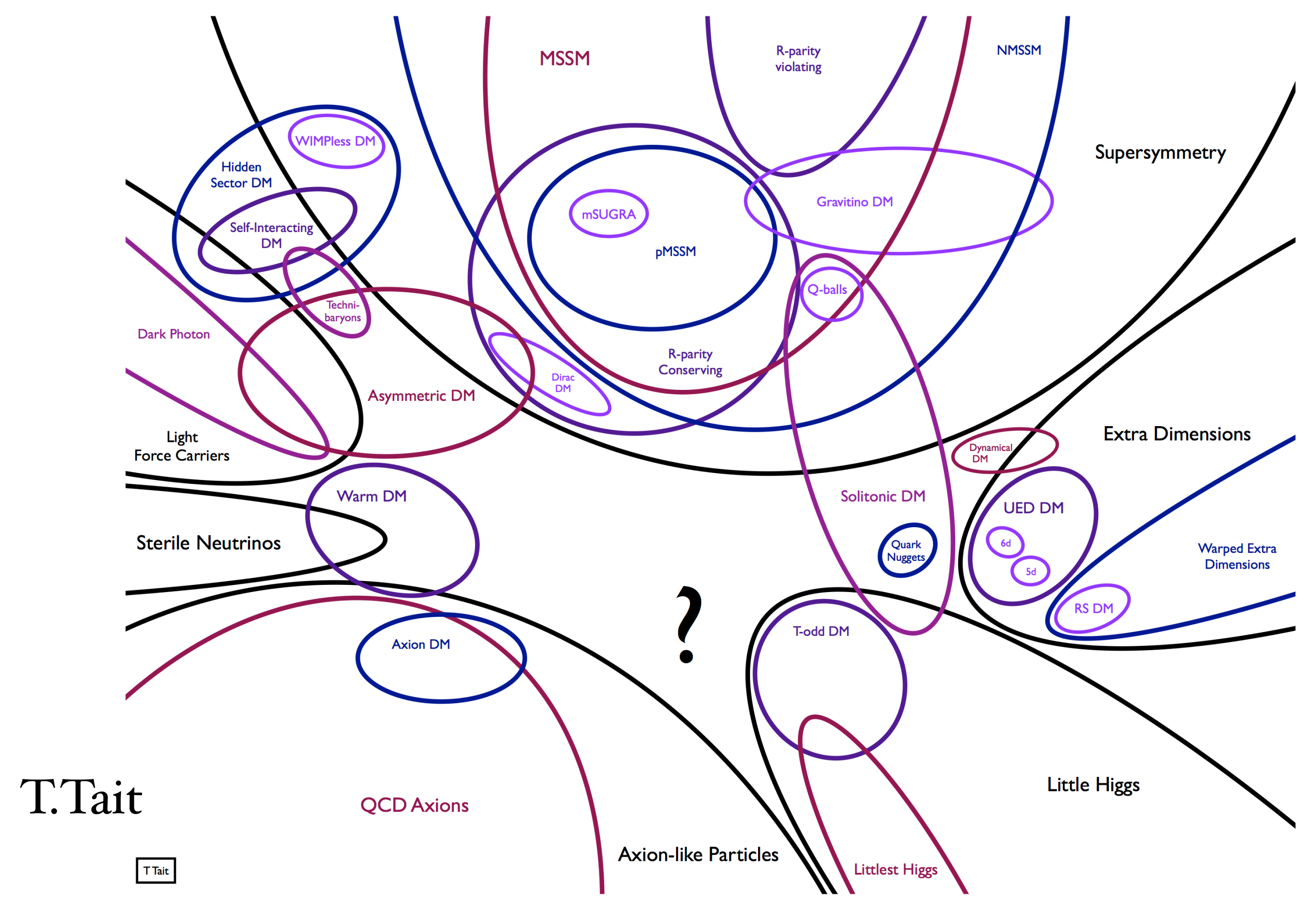
General Particle Dark Matter and WIMP Miracle

Cosmic Origin of DM and WIMP Miracle

In general, dark matter candidates arising from models of particle physics beyond the Standard Model are a dime a dozen.

It’s very easy to find particles that are stable, either because they are the lightest state carrying some charge, or just by accident.

There exists a huge number of theoretical possibilities: A corner of the landscape



MSSM

R-parity violating

NMSSM

Supersymmetry

Hidden Sector DM

WIMPless DM

Self-Interacting DM

Techni-baryons

Dark Photon

Light Force Carriers

Asymmetric DM

mSUGRA

pMSSM

Gravitino DM

Q-balls

Dirac DM

R-parity Conserving

Dynamical DM

Extra Dimensions

UED DM

6d

5d

Warped Extra Dimensions

RS DM

Solitonic DM

Quark Nuggets

Warm DM

Sterile Neutrinos

Axion DM

?

T-odd DM

Little Higgs

Littlest Higgs

QCD Axions

Axion-like Particles

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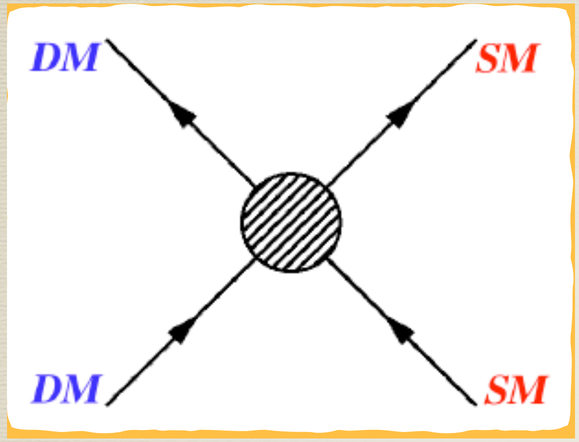
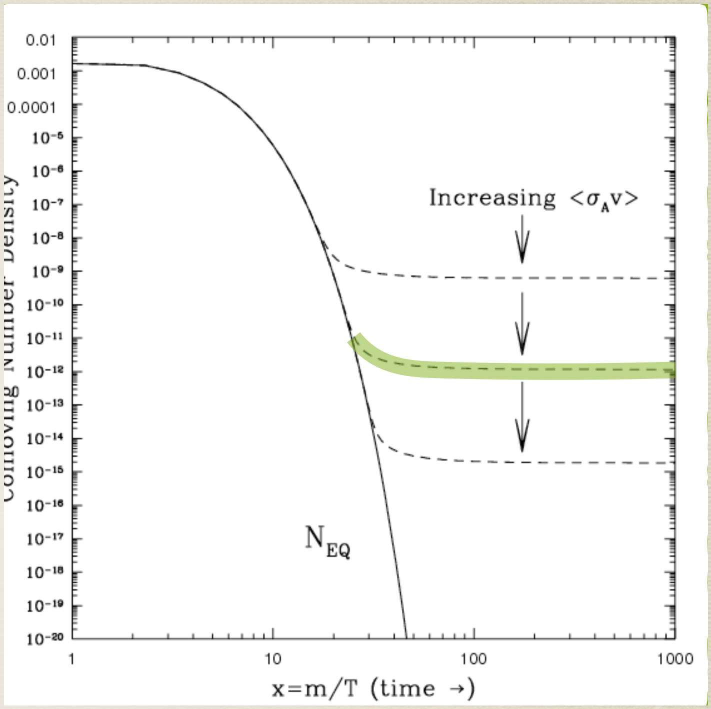
One basic question for all dark matter scenarios:
how to get the right relic abundance?

The **simplest** mechanism to explain abundance of dark matter: thermal freeze out and weakly interacting massive particle (**WIMP**)



universe expands and cools down;



dark matter interacts with the SM to stay in equilibrium

dark matter could not find each other to annihilate: "freeze out" dark matter mass

coupling

DM thermal relic abundance $\sim 1/\sigma_{\text{annihilation}} \sim M^2/g^2$

- Larger cross section, smaller abundance;
- Upper bound on the dark matter mass < O(10) TeV (when pushing to the strong coupling limit);
- for weak interaction, M ~ (100 GeV - TeV), WIMP miracle (connected to explanation of the weak scale and kill two birds with one stone)!
- A benchmark number: dark matter annihilation cross section $3 \times 10^{-26}\ \text{cm}^3/\text{s}$ gives the observed relic abundance 0.1

$$\Omega_{\text{DM}} h^2 \approx 0.1 \left(\frac{3 \times 10^{-26}\ \text{cm}^3/\text{s}}{\langle \sigma v \rangle} \right).$$

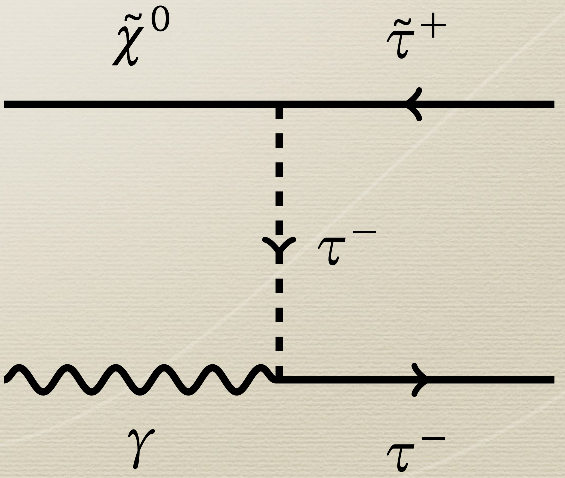
Loopholes

Dark matter can be a **thermal relic** even if its present-day annihilation cross section is not $3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$.

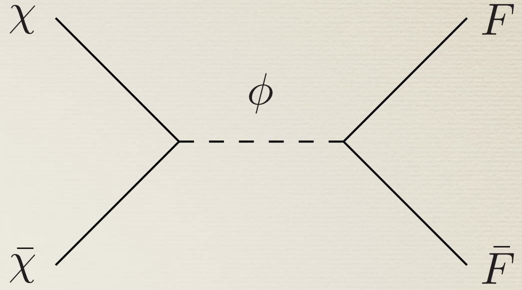
There are a number of loopholes that allow the annihilation rate *today* to be different from what established the DM abundance in the early universe.

1. **Coannihilation**: another particle nearby in mass plays an important role in equilibrating the DM.

Result: **lower-than-expected** cross section in the current universe. Griest, Seckel '91



2. **Annihilation to slightly heavier states**: very similar to coannihilation.



Both require new masses within about 10% of DM mass. Accident, or symmetries.

Griest, Seckel '91

3. **p-wave annihilation in the early universe**. Annihilation cross section is velocity-dependent. Suppressed now because DM is non-relativistic ($v \sim 10^{-3}$ c)

4. **Sommerfeld enhancement** today: cross section in the early universe was lower because velocities were higher.

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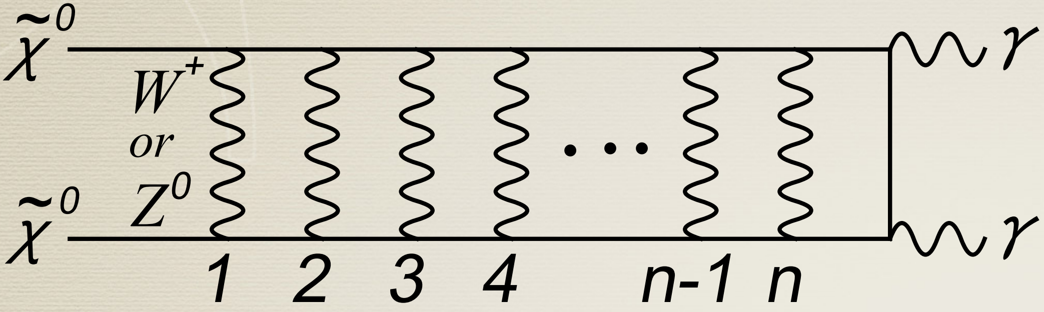


Long-range force distorts the wavefunction of particles in the initial state

At low velocities, a long-range force can significantly enhance annihilation cross sections.

$$\sigma v(\text{today}) \gg \sigma v(\text{early})$$

Relevant for heavy SUSY winos (Hisano, Matsumoto, Nojiri, Saito '04) or possibly with new forces (Arkani-Hamed, Finkbeiner, Slatyer, Weiner '08).

Alternative Cosmic Origins

Don't trust theory bias too much. Thermal relics are one compelling possibility, but not necessarily the whole story. Cautionary (if unconvincing) example:

Late-decaying scalar field populates SM radiation, which can annihilate to DM.
Chung, Kolb, Riotto hep-ph/9809453

$$\Omega_{\rm DM} h^2 \approx M_{\rm DM}^2 \langle \sigma v \rangle \left(\frac{2000 T_{RH}}{M_{\rm DM}} \right)^7$$

Totally inverted $\langle \sigma v \rangle$ dependence!

Predictions and Experimental Probes of SUSY DM

MSSM Dark Matter Candidates

Neutralinos: (spin-1/2 neutral fermions in MSSM)

Two neutral higgsinos ($\widetilde{H}_u^0$ and $\widetilde{H}_d^0$) and two neutral gauginos ($\widetilde{B}$, $\widetilde{W}^0$) combine to form four mass eigenstates.

Higgsinos are SUSY partners of the Higgs fields and gauginos are SUSY partners of neutral gauge bosons (Z and photon). They mix with each other due to electroweak symmetry breaking.

In the gauge-eigenstate basis, $\psi^0 = (\widetilde{B}, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0)$
the neutralino mass matrix is

$$\mathcal{L}_{\text{neutralino mass}} = -\frac{1}{2}(\psi^0)^T \mathbf{M}_{\widetilde{N}} \psi^0 + \text{c.c.},$$

where

$$\mathbf{M}_{\widetilde{N}} = \begin{pmatrix} M_1 & 0 & -g'v_d/\sqrt{2} & g'v_u/\sqrt{2} \\ 0 & M_2 & gv_d/\sqrt{2} & -gv_u/\sqrt{2} \\ -g'v_d/\sqrt{2} & gv_d/\sqrt{2} & 0 & -\mu \\ g'v_u/\sqrt{2} & -gv_u/\sqrt{2} & -\mu & 0 \end{pmatrix}.$$

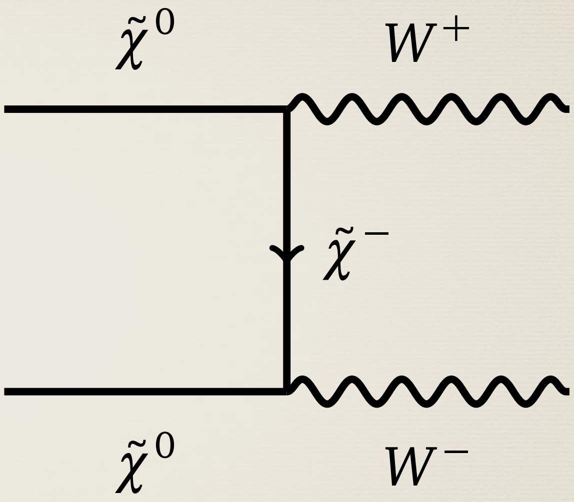
mixing due to electroweak
symmetry breaking

For more details, see “A Supersymmetry Primer” by Stephen Martin (hep-ph/9709356).

Next discuss possible viable MSSM dark matter with right relic abundance.

1. Pure wino dark matter (other neutralinos are much heavier and mixing is negligible): can annihilate a lot.

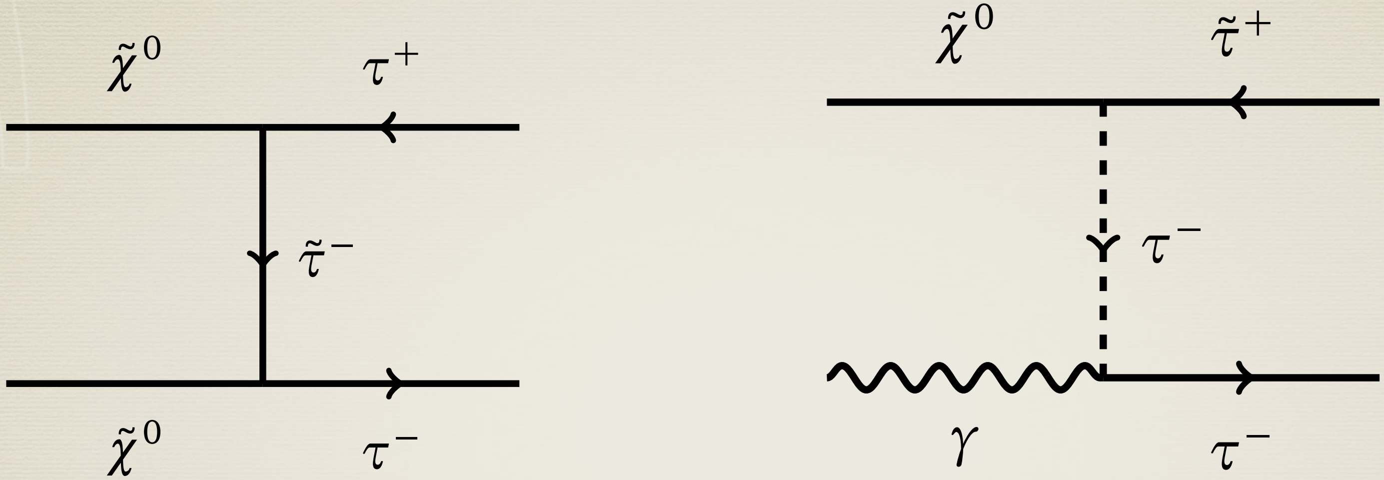
Thermal relic abundance is underpopulated unless it's heavy with mass at ~**2.7 TeV**.



$$\langle \sigma v(\chi\chi \to W^+W^-)\rangle \approx 3 \times 10^{-24}\frac{\mathrm{cm}^3}{\mathrm{s}} \text{ for } m_\chi \approx 140 \text{ GeV}$$

2. Pure higgsino dark matter (other neutralinos are much heavier and mixing is negligible): have the right thermal relic at **1 TeV** .

3. Pure bino (other neutralinos are much heavier and mixing is negligible): overpopulates, unless slepton is very light or degenerate with Bino within *5%* for **coannihilation**.



4. The right mixture of bino/higgsino or bino/wino can have a thermal relic abundance. Arkani-Hamed/Delgado/Giudice hep-ph/0601041: "**Well-tempered neutralino**."

5. Non-thermal neutralino scenario.

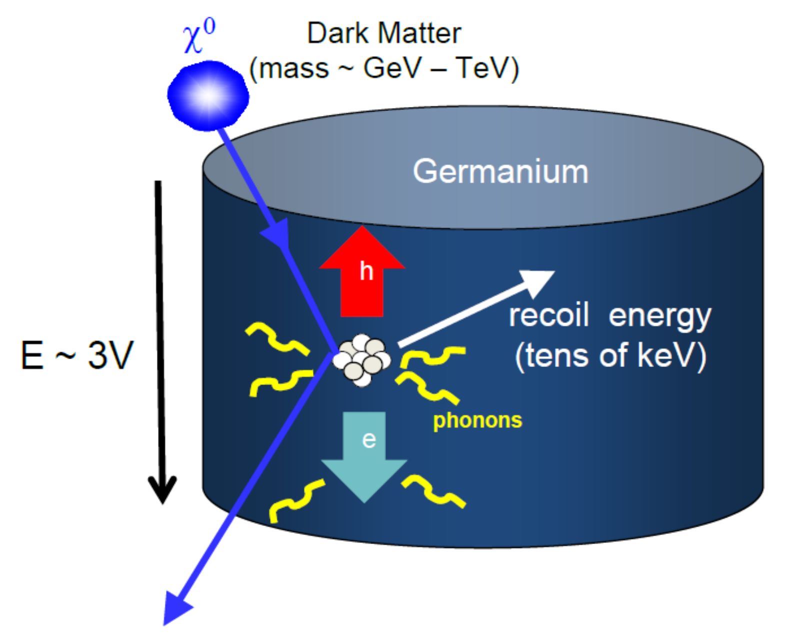
For example, a late decaying scalar with a matter domination era after inflation could modify DM relic abundance.

Non-thermal wino scenario, Moroi, Randall hep-ph/9906527: in this case, light winos with mass ~ O(100) GeV and a small thermal relic abundance could still have a right non-thermal relic abundance.

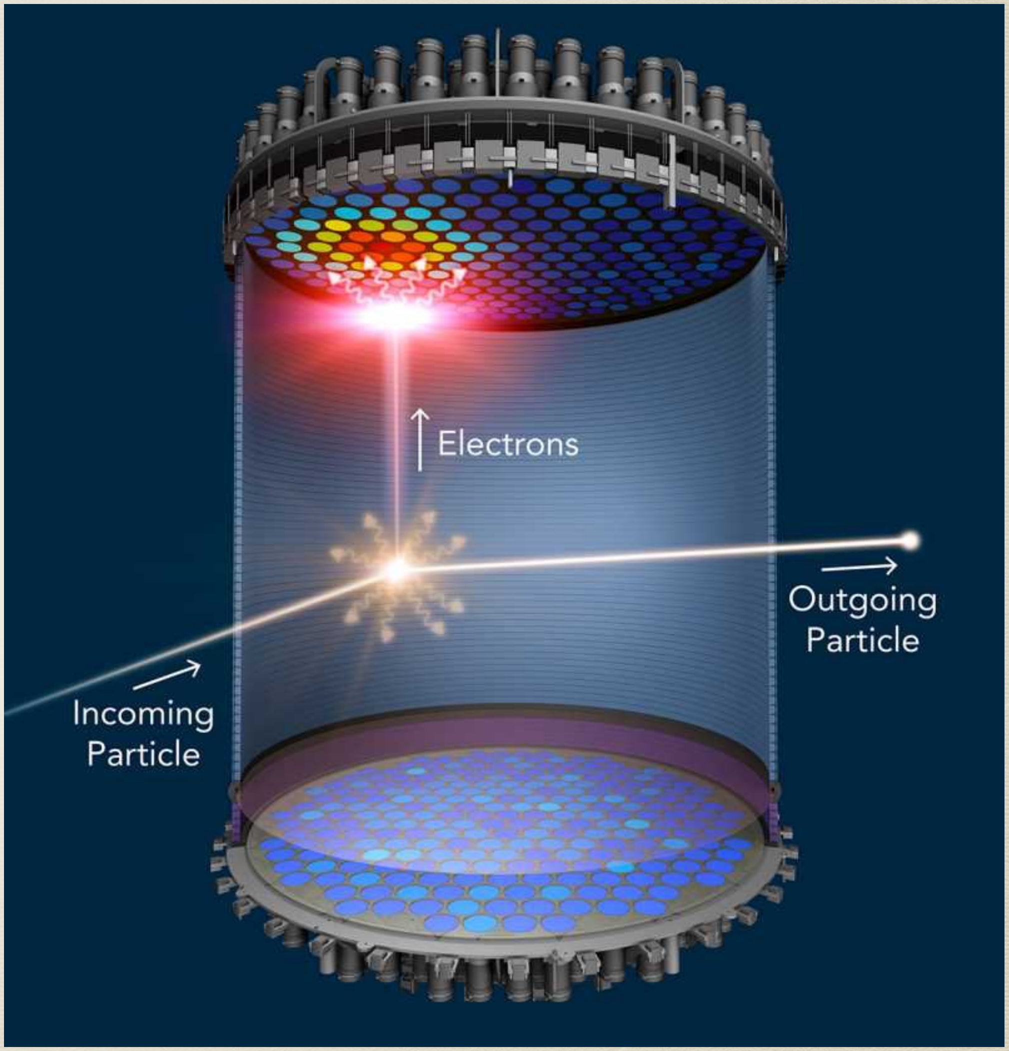
6. Multi-component dark matter scenarios with neutralino as a component.

I'll review some of the most important experimental probes of (MSSM) dark matter.

Direct Detection



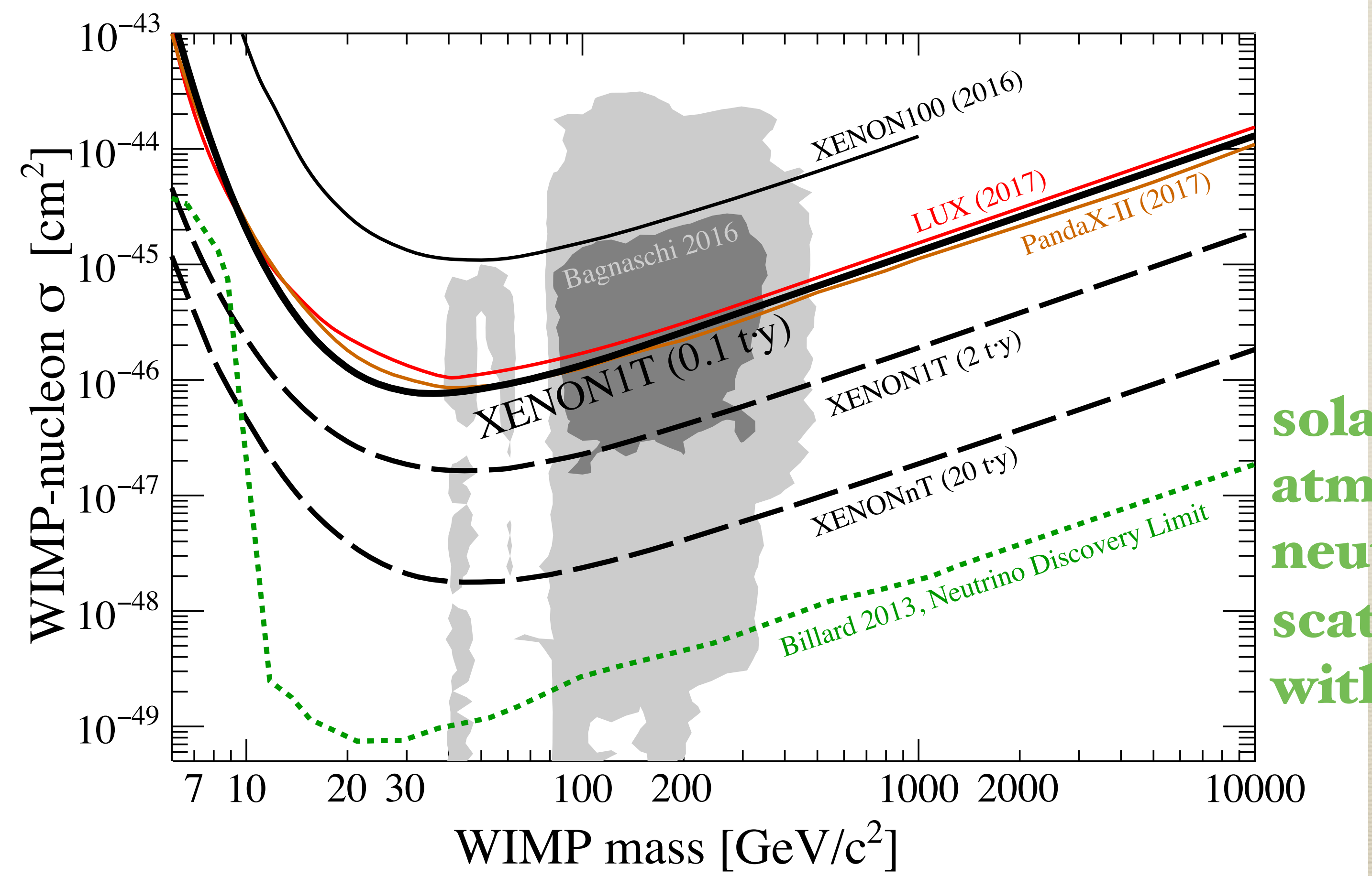
Cryogenic Dark Matter Search (CDMS): silicon and germanium detector



Lux-zeplin (LZ): liquid xenon

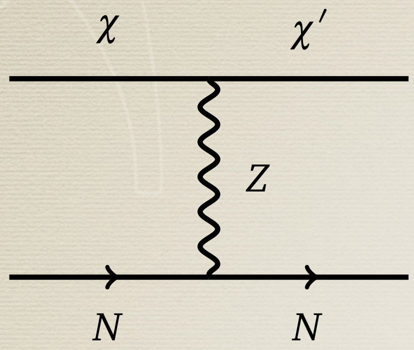
Direct Detection

Current bounds are ruling out WIMP-nucleon elastic scattering with cross sections of around 10^{-45} - 10^{-46} cm^2 for dark matter mass above 10 GeV to about TeV. What does this mean?



solar, atmospheric neutrino scattering with nucleus

Direct Detection Rates



The first theoretical expectation might have been dark matter scattering with nuclei through a Z boson elastically.

$$\sigma \gtrsim 5 \times 10^{-40} \mathrm{cm}^2$$

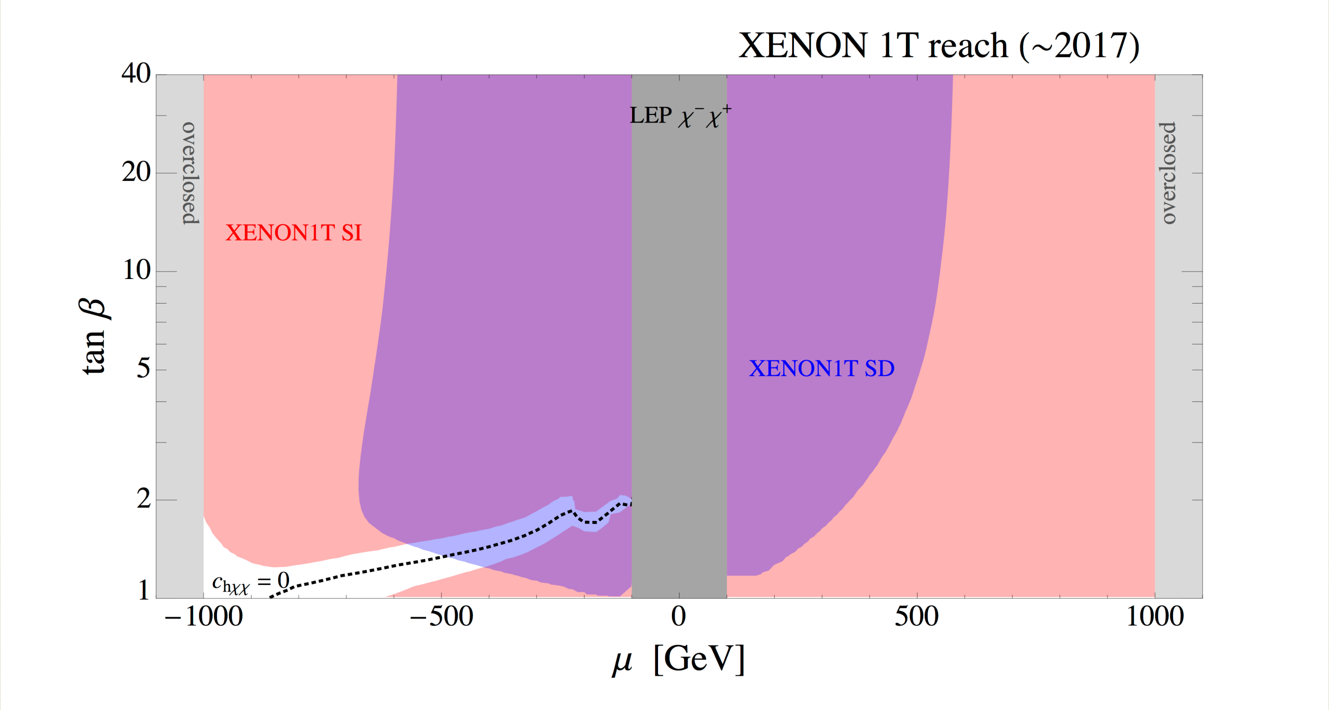
This was ruled out long ago. But only really applies to matter with purely chiral masses, like fourth generation neutrinos.

Generally, X, X' have at least *slightly* different masses; shut off this channel (or "inelastic dark matter").

The next expectation is that DM can scatter with nuclei through a *Higgs boson*. Happens if DM gets part of its mass from the Higgs.

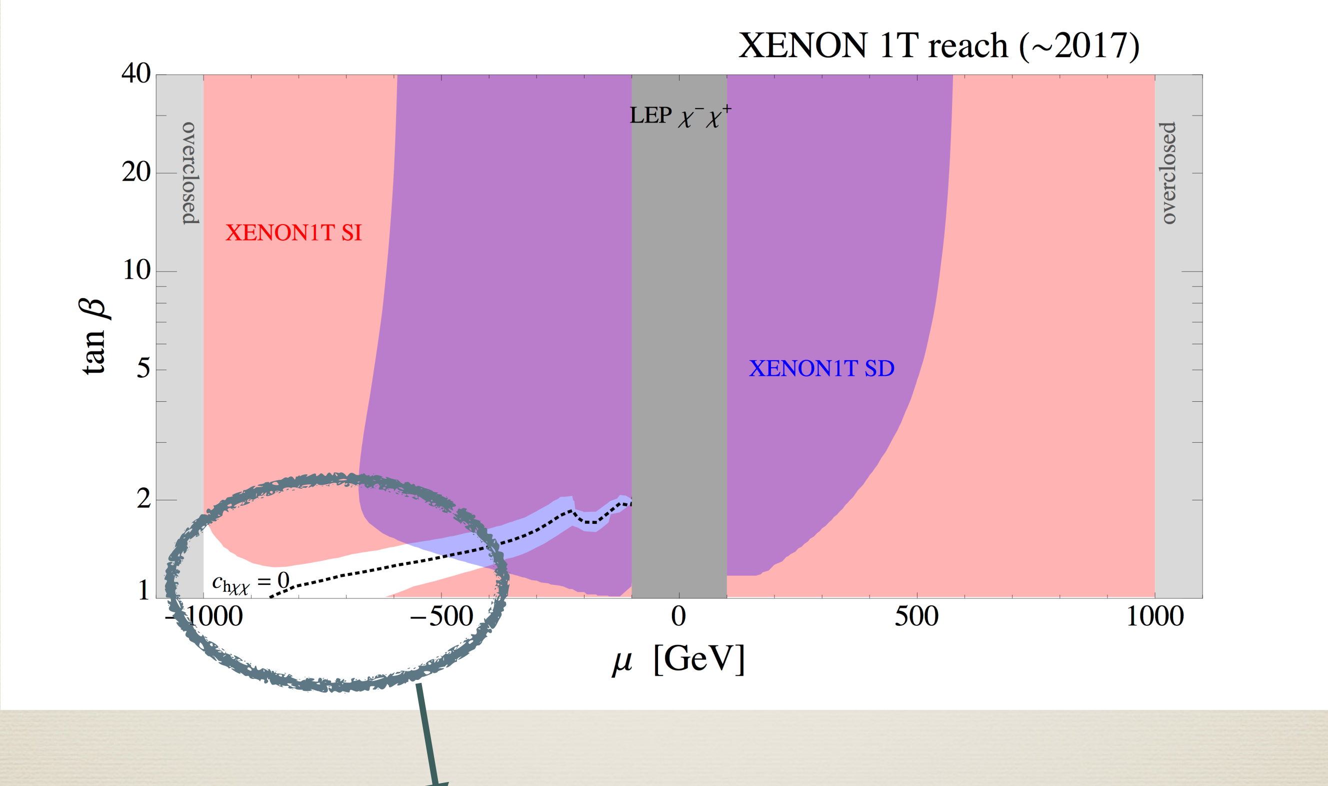
Higgs exchange is what experiments are strongly constraining now.

In MSSM, well-tempered neutralino (mixed bino/higgsino or bino/wino) could scatter off nucleus through Higgs exchange and thus are strongly constrained by direct detection.



bino/higgsino well-tempered scenario fixing M1 (bino soft mass) at every point to have the right thermal relic abundance. Cheung, Hall, Ruderman, Pinner 1211.4873.

In MSSM, well-tempered neutralino (mixed bino/higgsino or bino/wino) could scatter off nucleus through Higgs exchange and thus are strongly constrained by direct detection.

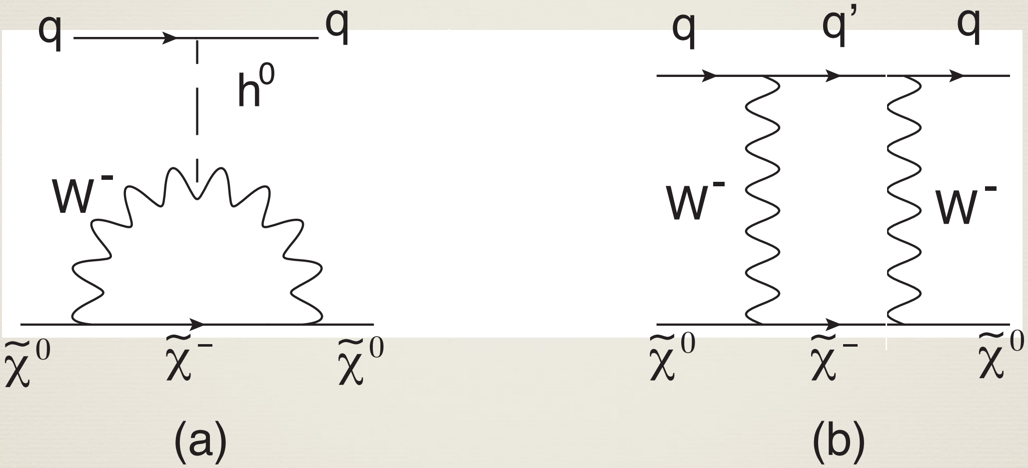


Blind spot with neutralino dark matter coupling to Higgs **vanishes** at tree level (due to accidental cancelation)!

Other blind spots for well-tempered neutralino dark matter: Huang and Wagner 1404.0392

There can be weakly-interacting particles with neither *Z*- nor Higgs-mediated interactions, but with ***W* loops**.

E.g. pure wino dark matter (with other neutralinos much heavier and thus decoupled):

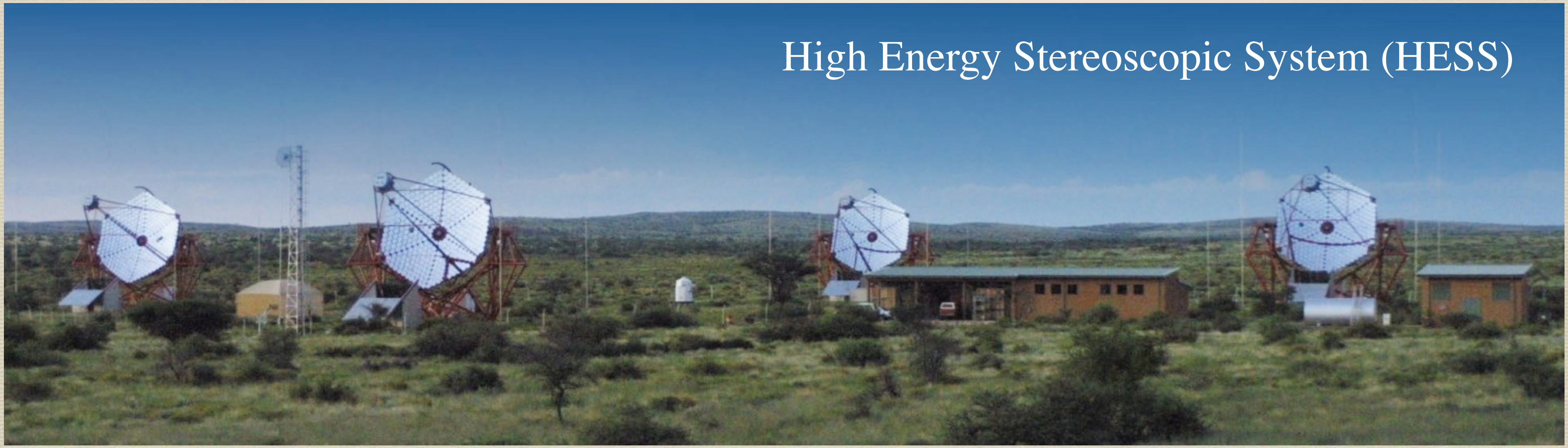


Hisano et al. 1004.4090 $\sigma \lesssim 10^{-47}\ \mathrm{cm}^2$

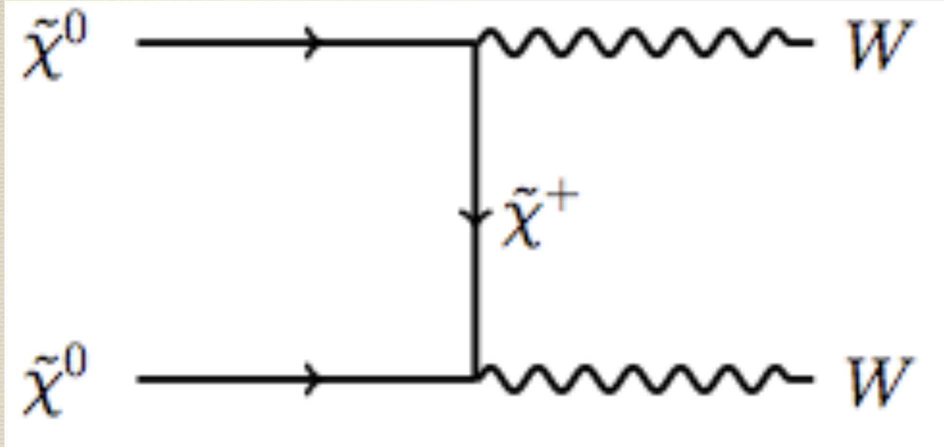
Down close to the neutrino background. Even "WIMPs" may not show up at direct detection!

Indirect Detection

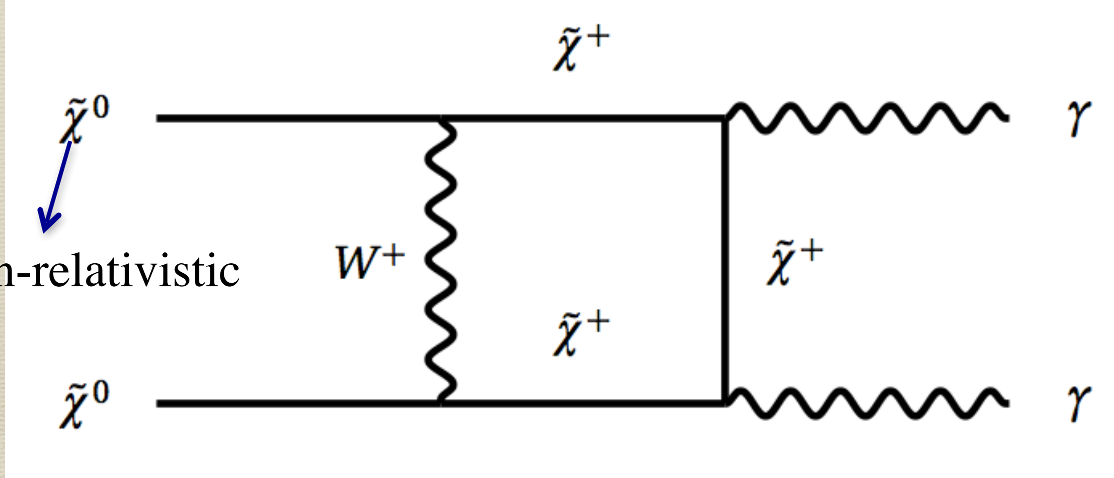
search for excesses in the photon continuum spectrum or a line-like feature in a dark matter dense region, e.g., galactic center.



It is a powerful probe for pure wino dark matter, which has a large annihilation cross section.



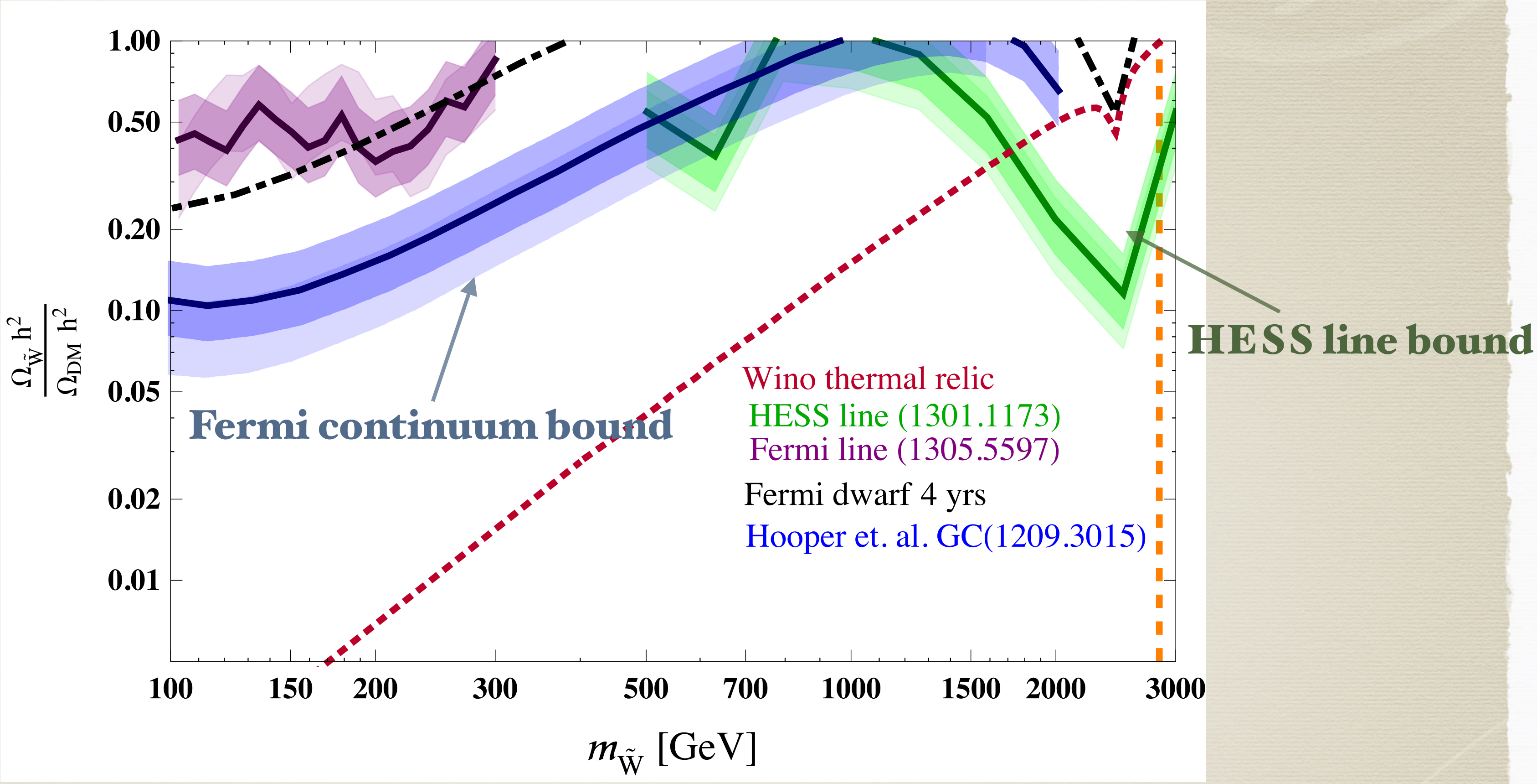
W decays produce photons
with continuos energy: continuum
photon spectrum



Non-relativistic

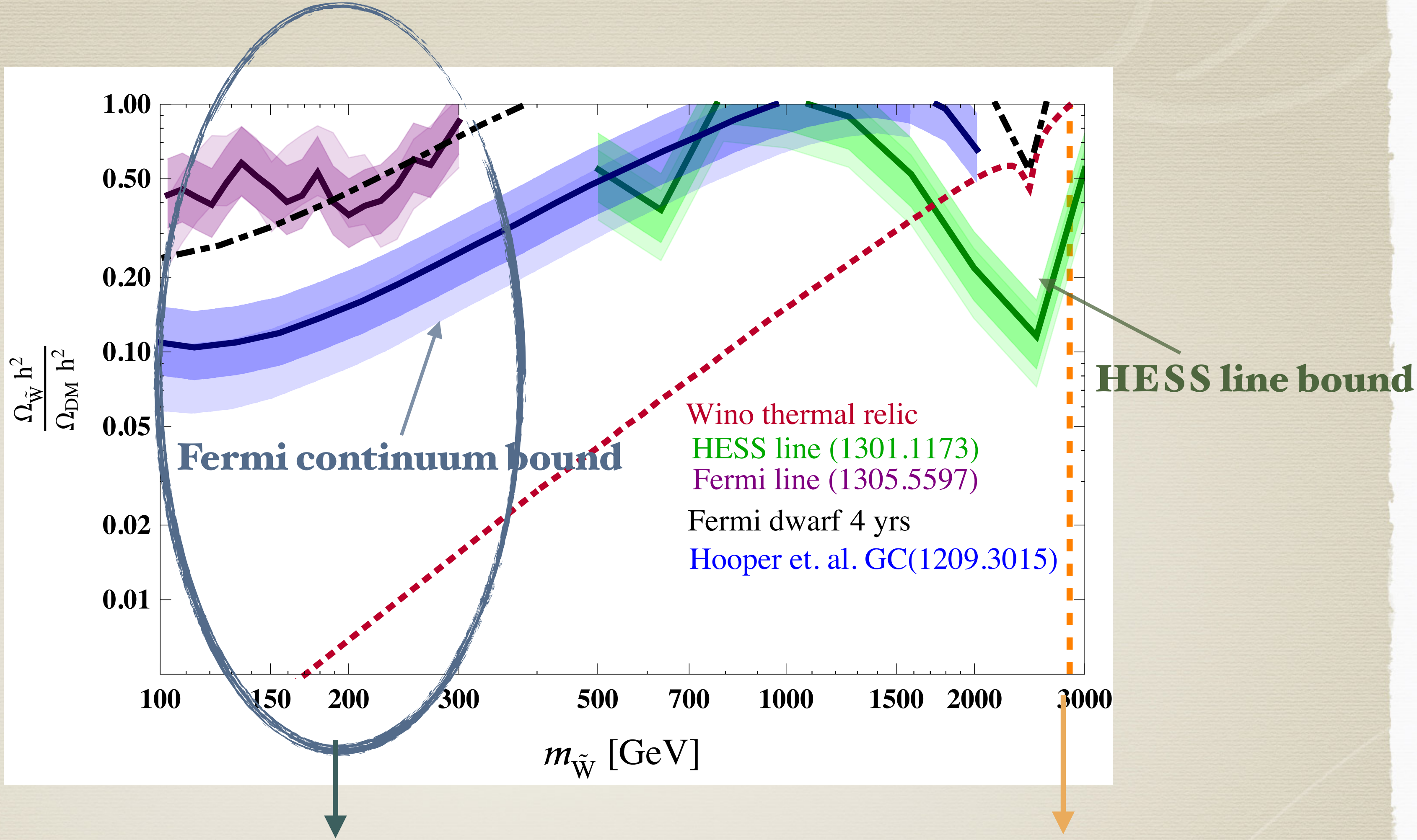
Monochromatic photon:
a photon line

$$E_\gamma = m_{\tilde{\chi}_0}$$



Pure wino dark matter in the whole range from 100 GeV to 3 TeV (with the possible exception of a range between 700 GeV and 1.4 TeV) is ruled out for both DM NFW and Einasto profiles, allowing astrophysical parameters to vary in the 2σ range.

Fan, Reece, 1307.4400

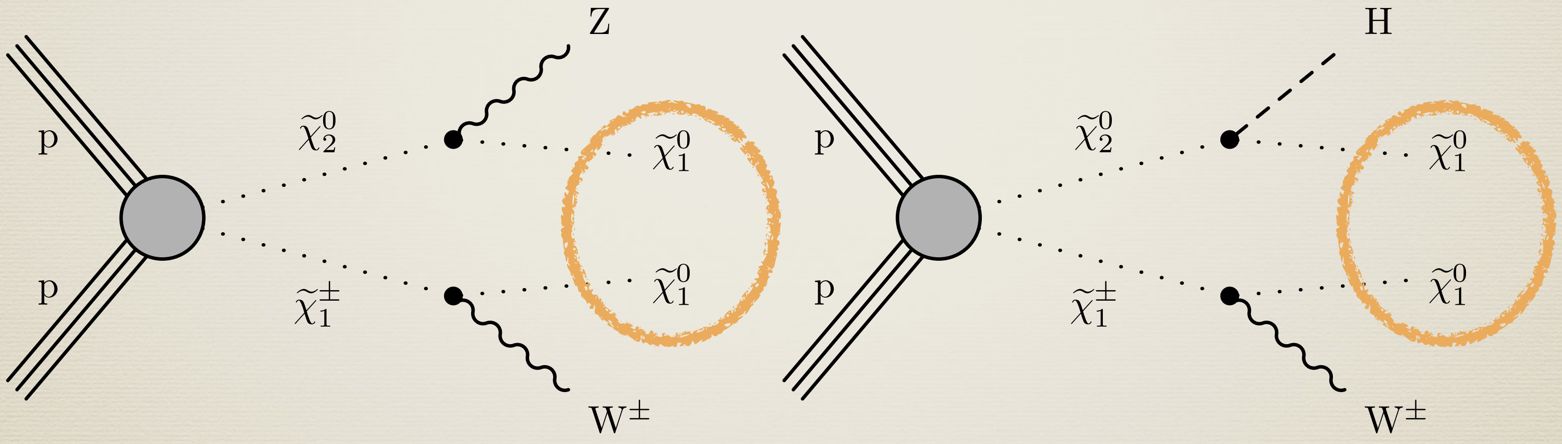


Non-thermal light wino scenario (Moroi, Randall hep-ph/9906527)

Thermal heavy wino (updated constraint: Baumgart et.al 1712.07656)

Collider Searches

SUSY particles could be produced in pairs at the Large Hadron Collider, leading to events with a large amount of missing energy (carried away by the invisible LSP) as well as a lot of standard model particles.

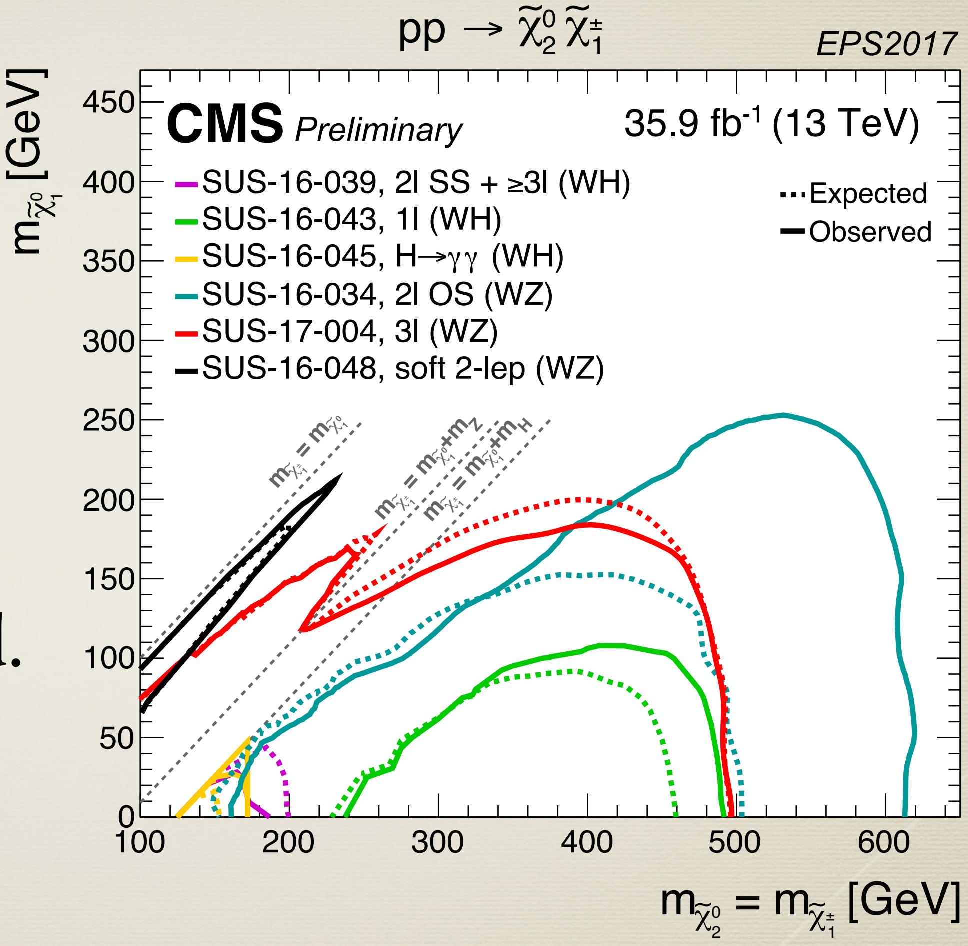


invisible LSP

Collider Searches

So far no signal found yet; strong constraints are set.

Yet be aware that the constraints depend on the final states and still big parameter space uncovered.



You might have heard dire comments about the state of supersymmetry in light of the LHC. Basically, there are two worries:

- Might have expected collider signals of ***colored*** SUSY particles with strong interactions but didn't see any (e.g: gluinos, stops) so far. Bounds are set to be around 1 - 2 TeV depending on the decays of the particles.
- The Higgs mass is 125 GeV, which suggests that MSSM is somewhat tuned and scalar tops could be heavy.

What the LHC current results suggest is that there is certainly tension between data and the idea of using (simplest) low-energy SUSY models to entirely solve the fine-tuning problem.

Yet it doesn't mean that SUSY is ruled out: maybe fine-tuning problem is solved in a more subtle and non-minimal way; maybe our world is a bit fine-tuned with a little hierarchy between weak scale and say 100 TeV (10^5 GeV) while we still need mechanisms such as SUSY to stabilize the big hierarchy between 100 TeV and the Planck scale (10^{19} GeV).

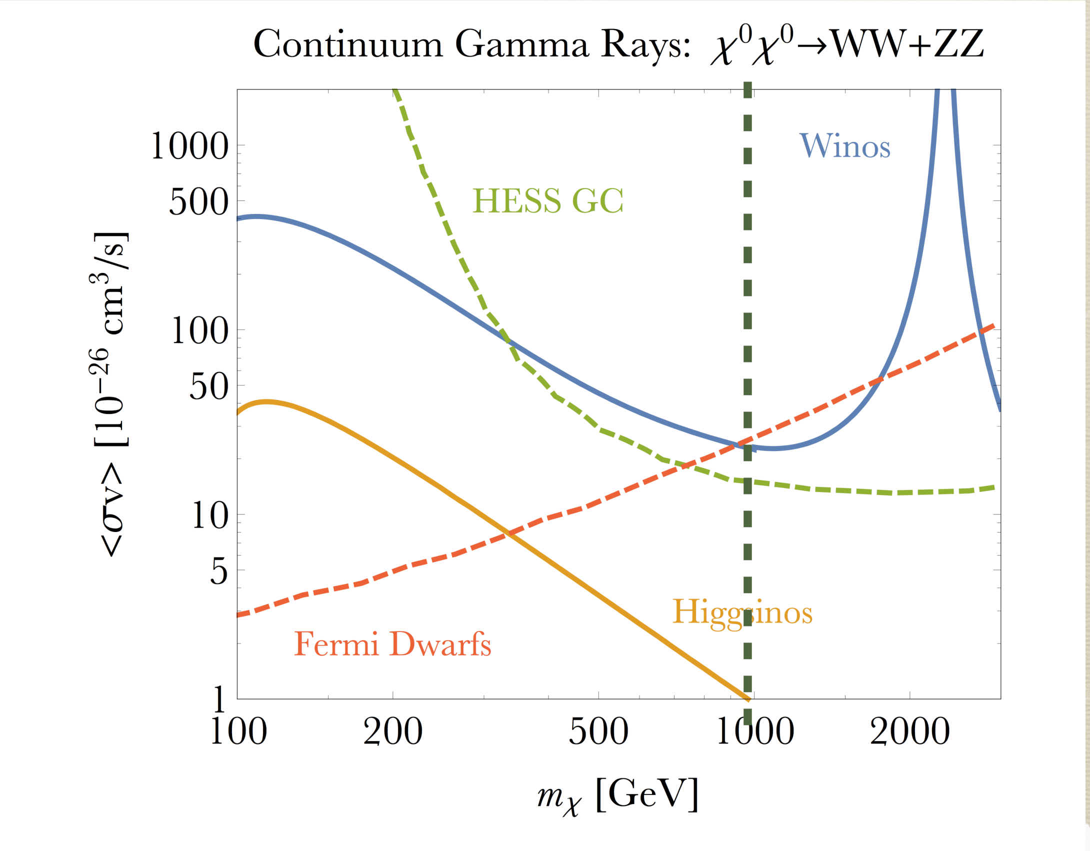
SUSY dark matter (electroweakinos) is still very much a possibility and a benchmark to be covered experimentally.

Pure thermal higgsino with mass at ~ 1 TeV :

This is a benchmark which not only evades the current experimental constraints but may be difficult to probe in the next generation of experiments!

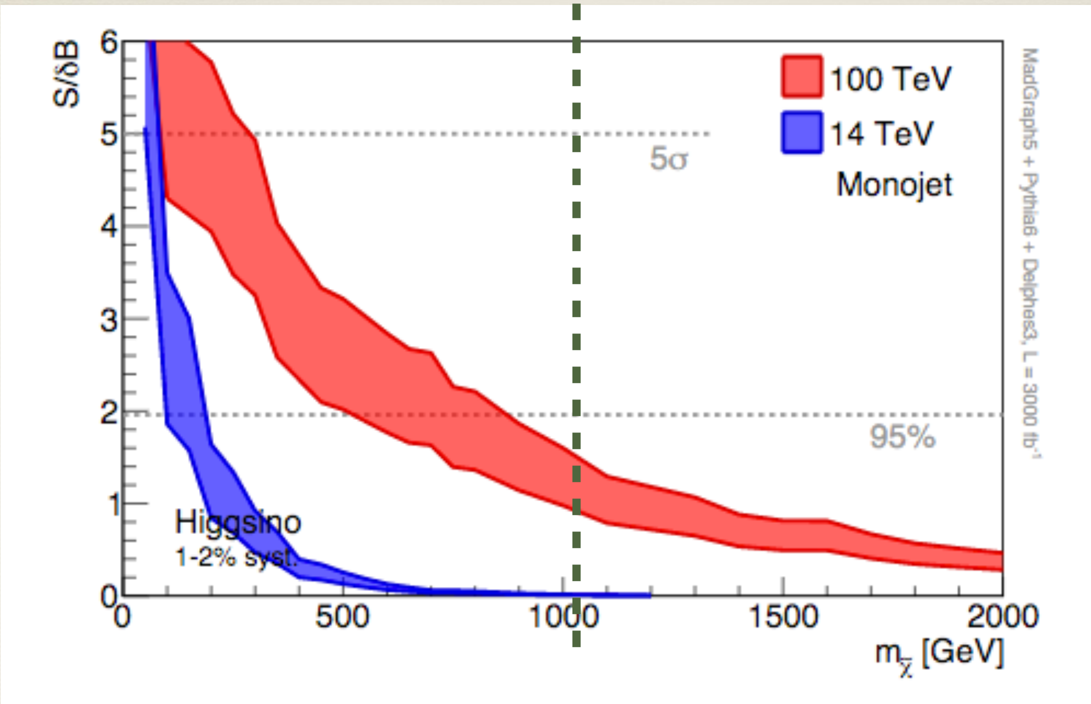
Direct detection: scattering with nucleus happens at one loop level with a cross section <~ neutrino floor;

Indirect detection:
about a factor of 50 below the current Fermi sensitivity.
Future indirect detection?



Krall, Reece 1705.04843

Collider: search for pair production of higgsinos using monojet plus missing energy



Thermal higgsino benchmark

Low, Wang: 1404.0682

Summary of MSSM dark matter status

Pure thermal or non-thermal wino dark matter is ruled out (strongly constrained) by indirect detection (there are large astrophysical uncertainties though).

Pure (thermal) higgsino dark matter is still at large and could remain like this for a while!

Well-tempered neutralino dark matter (mixing of bino/higgsino or bino/wino) is strongly constrained by direct detection. Yet there are still blind spots left.

Pure bino dark matter (with sleptons around to co-annihilate) are constrained by direct and collider searches but with parameter space left that could be relatively easily covered by future experiments. Baker and Thamm 1806.07896

If we allow neutralino to be just a component of dark matter, more parameter space opens up.

SUSY WIMP is not ruled out and still serves as a benchmark to be probed experimentally! We need different kinds of complementary probes and new ideas as always.

Thank you and questions?