Dark Matter: Models

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VSOP22

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Outline of Lectures

- Characteristics of a Dark Matter Candidate Particle
  - Stabilization
  - Relic Density
- WIMPs
  - R-parity: The SUSY WIMP
    - Relic Density
    - Indirect Signals
    - Direct Detection
    - Colliders

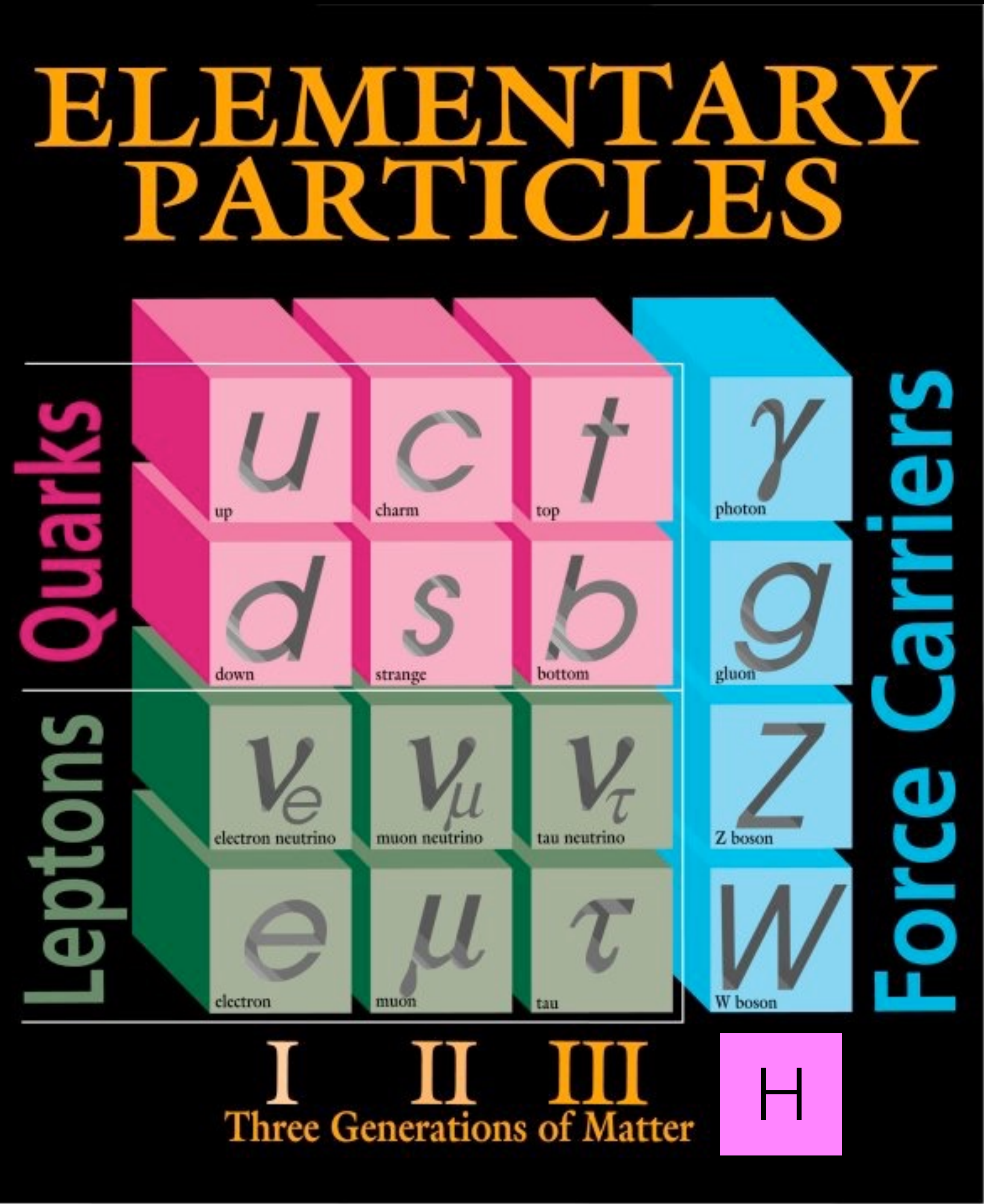
So what is this stuff?

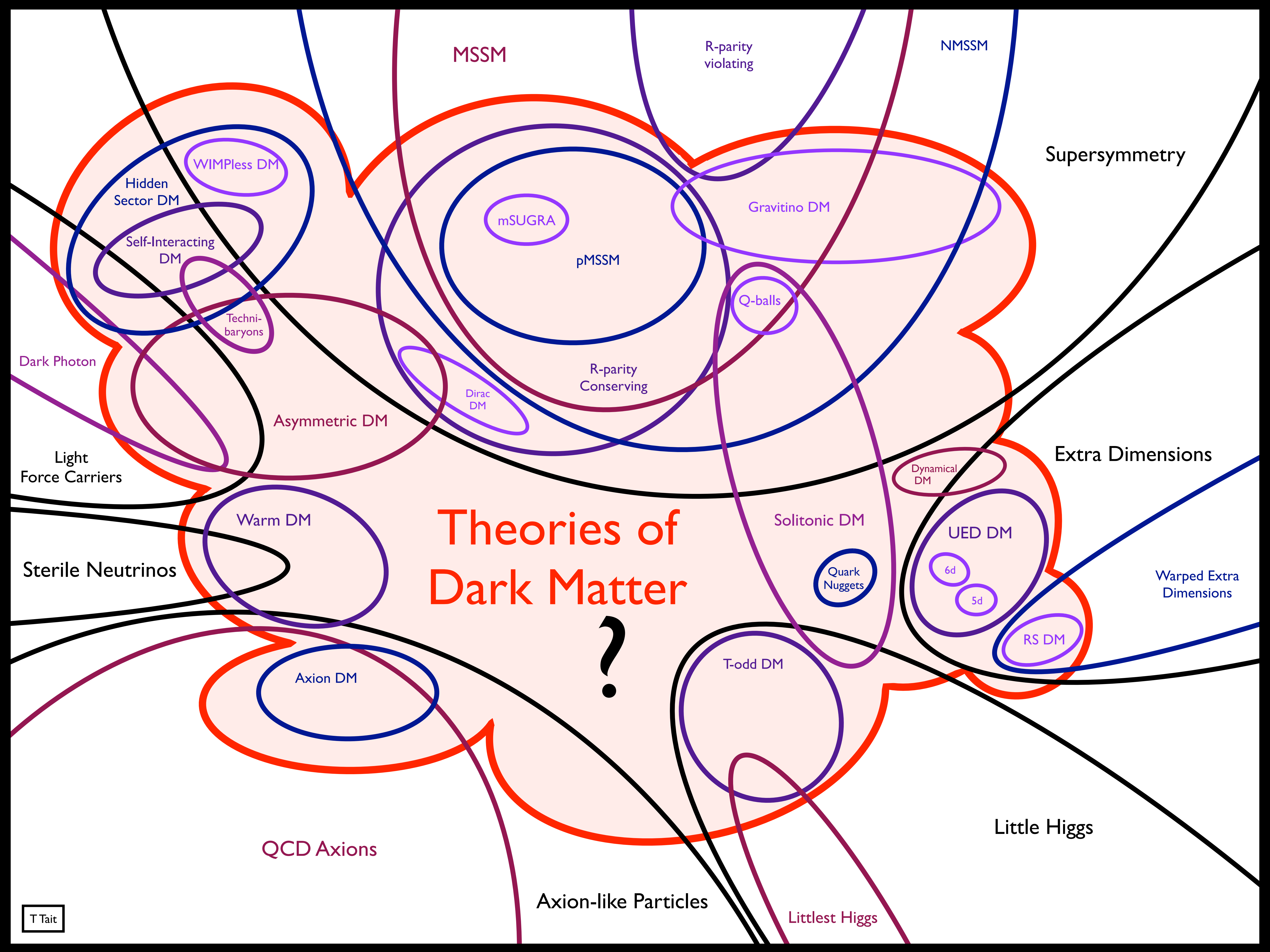

“Cold Dark Matter: An Exploded View” by Cornelia Parker

- As a particle physicist, my job is to explore how dark matter fits into the bigger picture of particles.
- What do we know about dark matter?
  - Dark (neutral)
  - Massive
  - Still around today
  - Stable or with a lifetime of the order of the age of the Universe itself).
- Nothing in the Standard Model of particle physics fits the description.

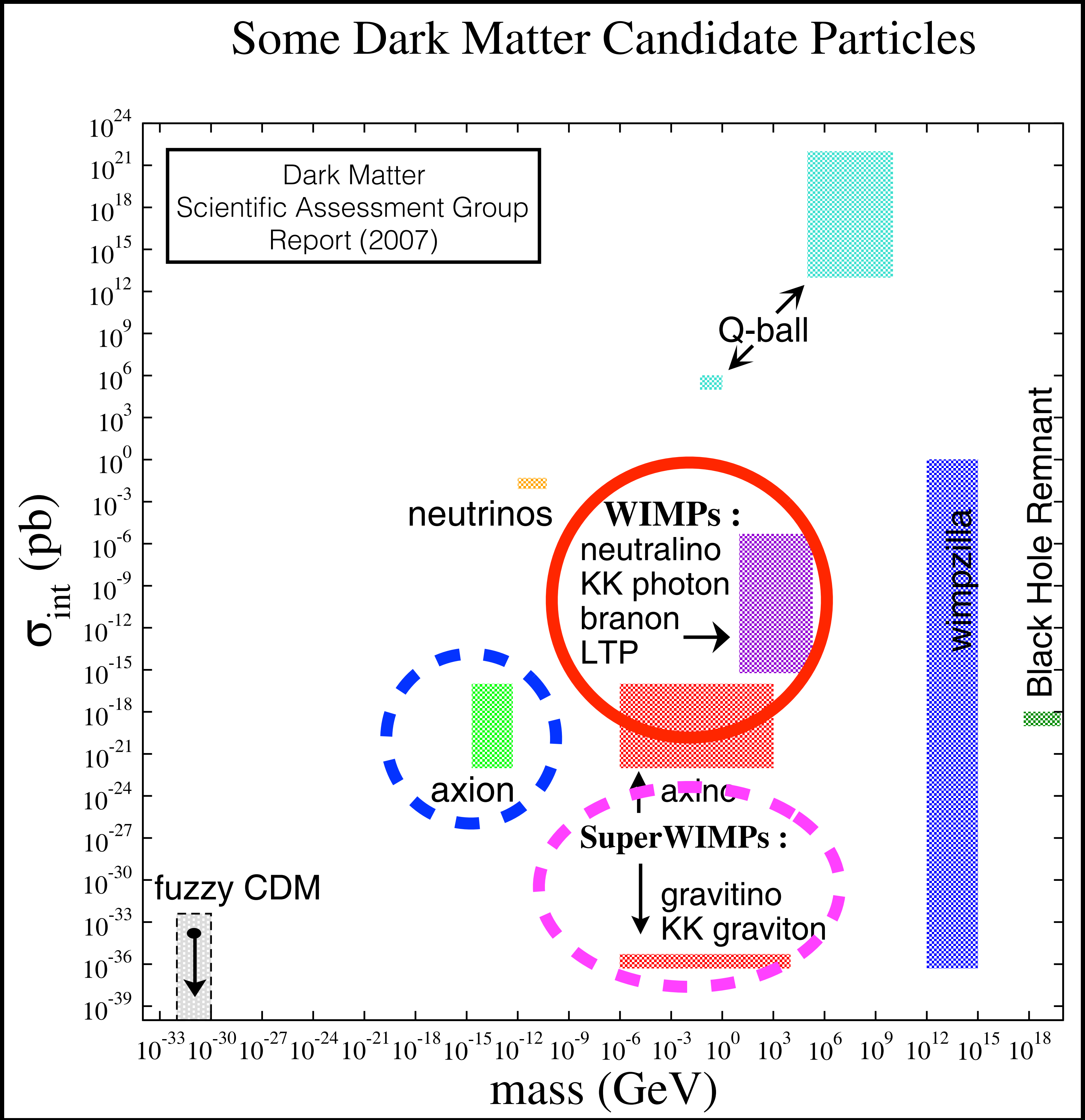
Physics Beyond the SM

- The Standard Model of particle physics has nothing with the right properties to be dark matter:
  - Photons, leptons, hadrons, and W bosons all shine too brightly.
  - Neutrinos are too light.
  - Z and Higgs bosons are too short-lived.
- Dark matter is a manifestation of physics beyond the Standard Model.
- We have **lots** of ideas for what it *could* be…

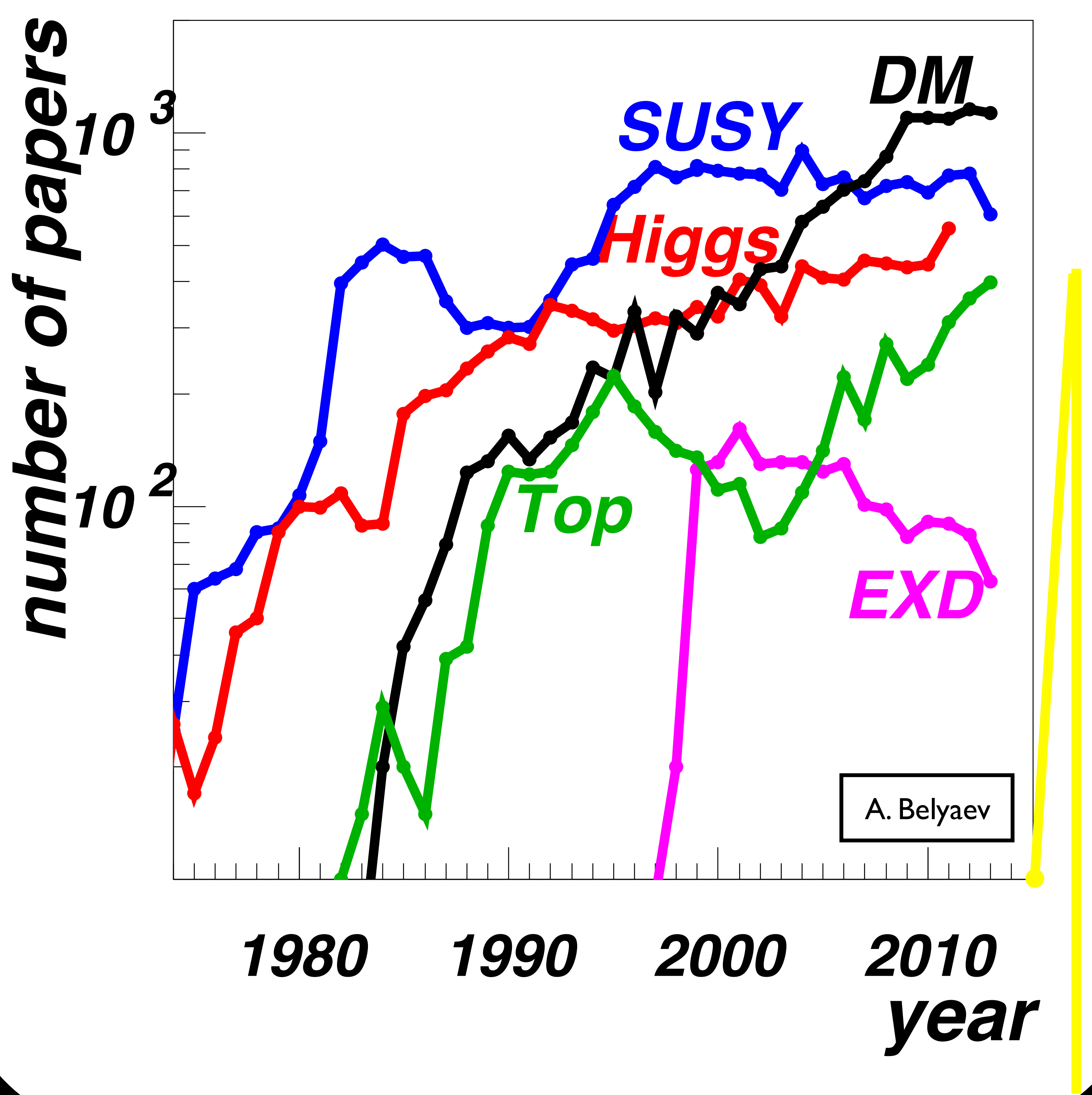



Theories of Dark Matter
?
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
Dark Photon
Dirac DM
R-parity Conserving
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

Wide Ranging Parameters...



Lots of Activity…



The Dark Matter Questionnaire

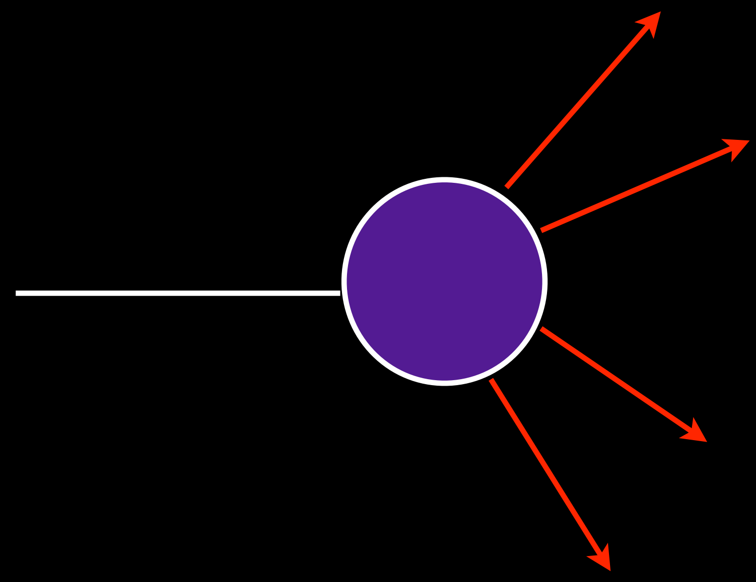
- [ ] Mass
- [ ] Spin
- [ ] Stable?
  - [ ] Yes
  - [ ] No

Couplings:

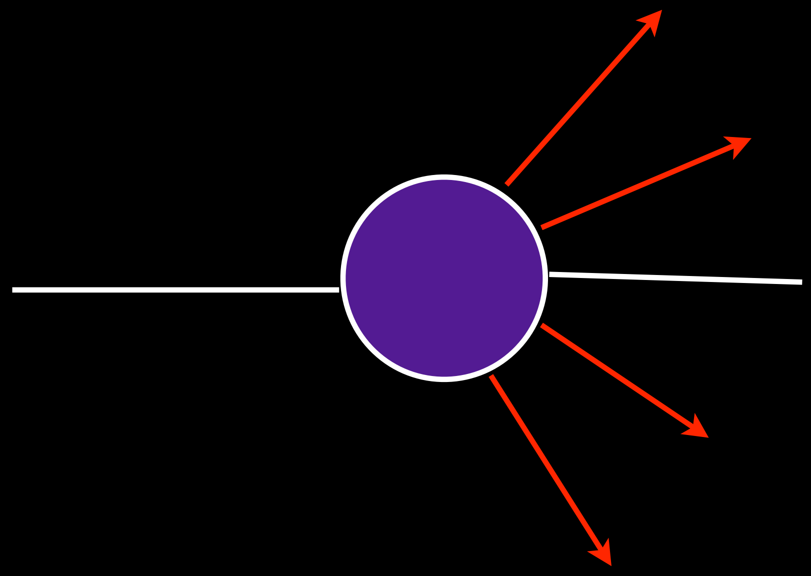
- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [ ] Quarks / Gluons?
- [ ] Leptons?
- [ ] Thermal Relic?
  - [ ] Yes
  - [ ] No

(Quasi) Stable

- One of the mysteries of dark matter is why it is very massive but (at least to very good approximation) stable.
- This is actually telling us something very important about how it can interact with the Standard Model.
  - We need a symmetry (at least approximately) to prevent dark matter particles from decaying.
  - The simplest example is a new kind of parity (a Z_2 discrete symmetry) which forces them to couple in pairs to SM fields.
  - We could explore larger (and continuous) symmetries as well.



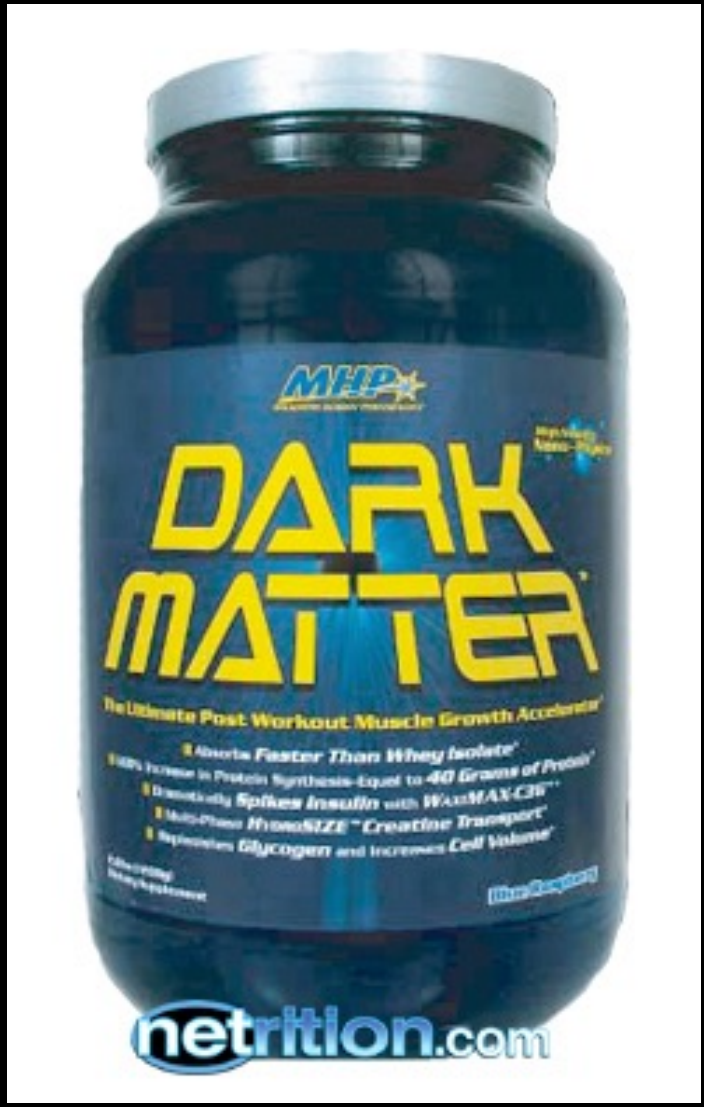
χ decays.



The number of χ's is conserved.

WIMPs

- One of the most attractive proposals for dark matter is that it is a Weakly Interacting Massive Particle.
  - WIMPs naturally can account for the amount of dark matter we observe in the Universe.
  - WIMPs automatically occur in many models of physics beyond the Standard Model, such as i.e. supersymmetric extensions.
- WIMPs are a vision of dark matter for which we can use particle physics experimental techniques to search very effectively.
  - Are we looking under the lamp post?
- We will classify different WIMPs based on which symmetry allows them to be stable.



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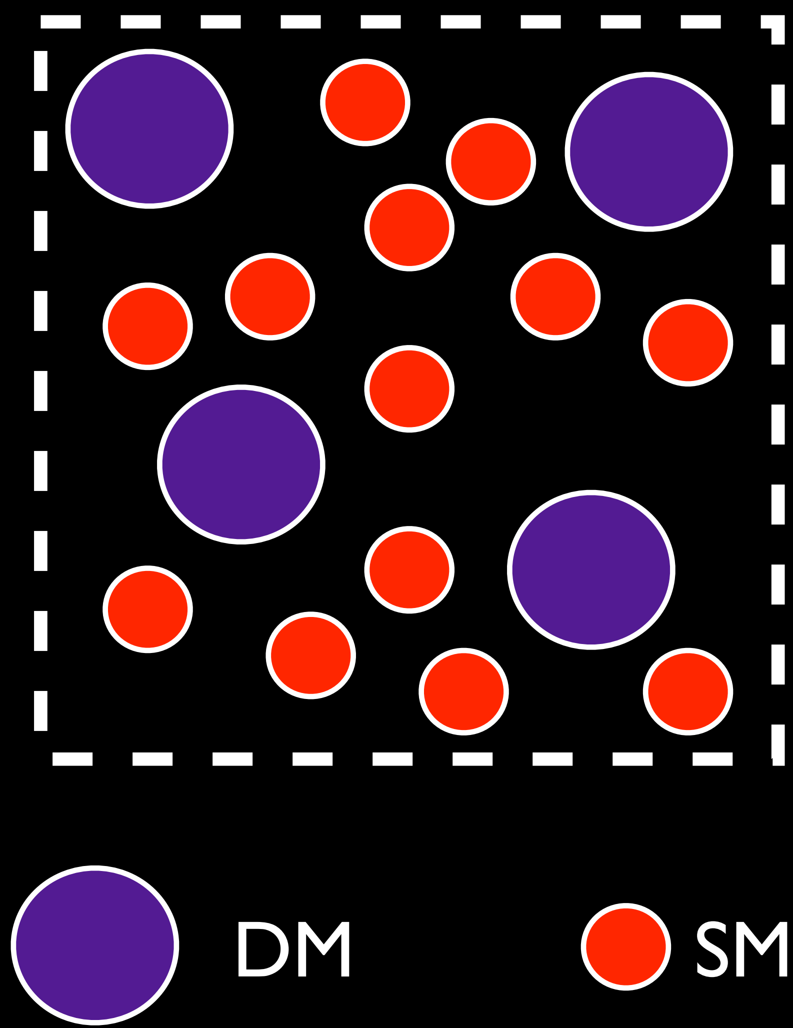
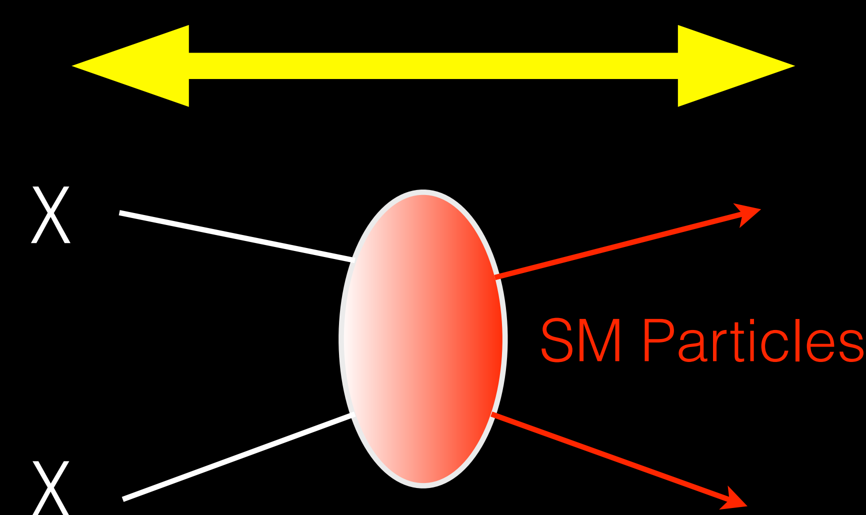
The WIMP Miracle

- One of the primary motivations for WIMPs is the "WIMP miracle", an attractive picture explaining the density of dark matter in the Universe today.
- While not strictly a requirement for a successful theory of dark matter, this picture is very attractive [meaning: we think it is likely that things work this way], and so it is worth understanding the argument.
- The picture starts out with the WIMP in chemical equilibrium with the Standard Model plasma at early times.
- Equilibrium is maintained by scattering of WIMPs into SM particles, $\chi\chi$ -> SM and vice-versa.

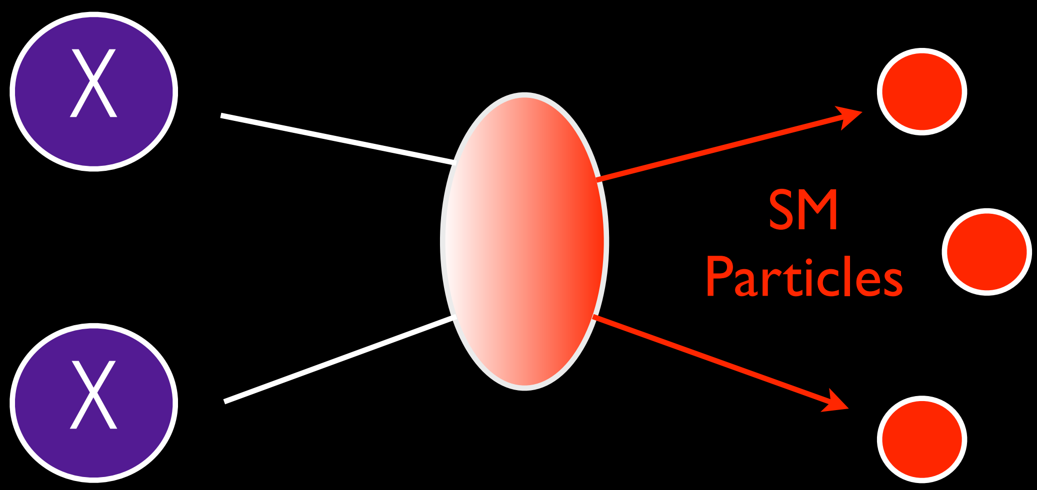




Boltzmann Equation

- The evolution of the dark matter number density (n) is controlled by a Boltzmann equation, which tracks the effect of the expansion of the Universe (H) and the creation and destruction of dark matter.

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left[n^2 - n_{eq}^2 \right]$$



- A Universe where WIMPs stayed in equilibrium would be pretty boring.
  - As the temperature falls, there will be fewer and fewer WIMPs present, since the fraction of the plasma with enough energy to produce them will become smaller and smaller.
  - (Almost) Nothing would be left!

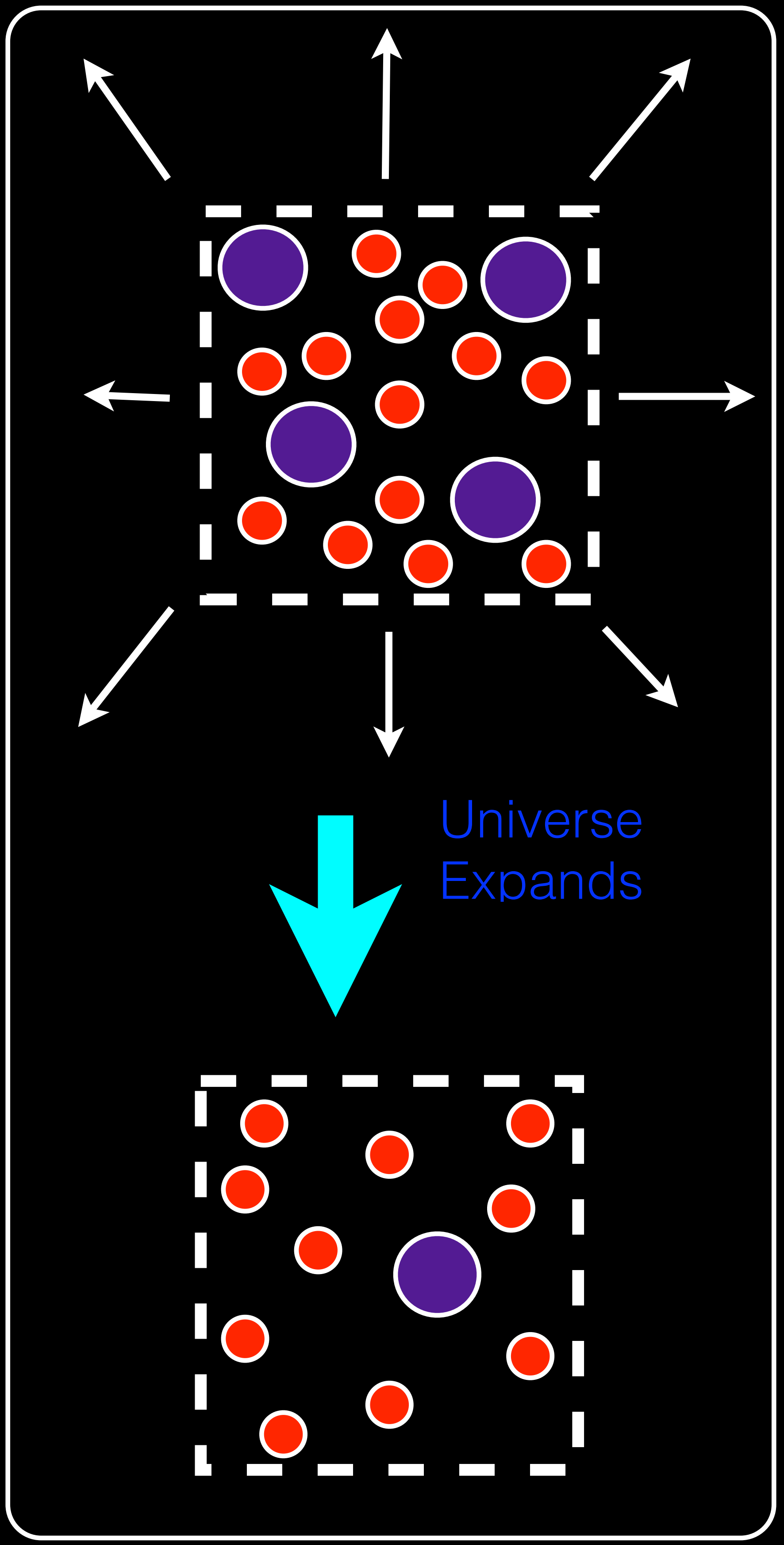
$$n_{eq} = g \left(\frac{mT}{2\pi} \right)^{3/2} \mathrm{Exp}\left[-m/T \right]$$

Freeze-Out

- However, the expansion of the Universe eventually results in a loss of equilibrium.

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left[n^2 - n_{eq}^2 \right]$$

- When (n_{eq} $\langle\sigma v\rangle$) $\ll$ H, the scattering that maintains equilibrium can't keep up with the expansion.
- The WIMPs become sufficiently diluted that they can no longer find each other to annihilate and they cease tracking the Boltzmann distribution.
- Where they "freeze out" obviously depends on how big $\langle\sigma v\rangle$ is.



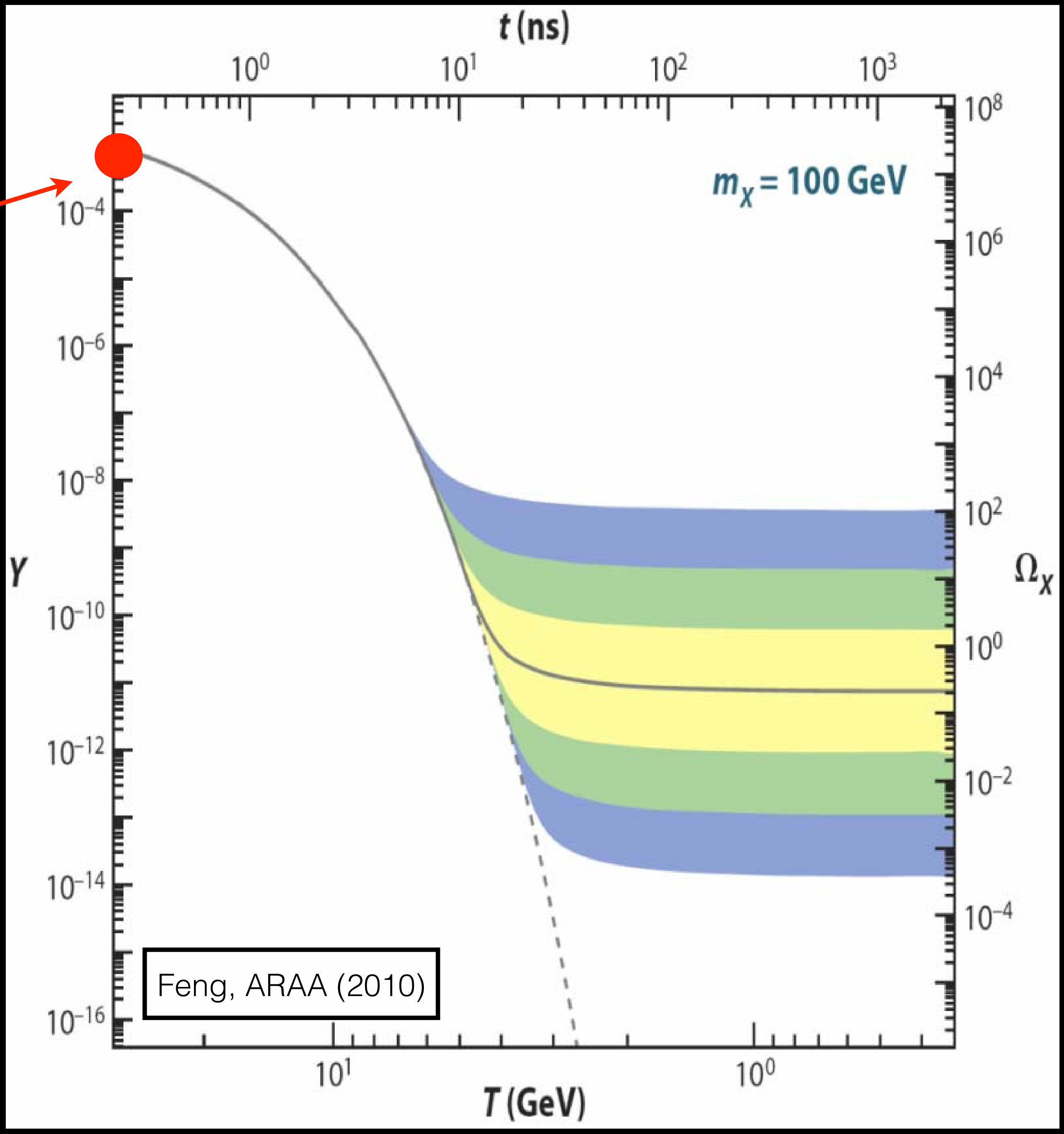
Relic Density

- So the basic picture is:
  - We start out with dark matter in equilibrium with the SM plasma.
  - As the temperature falls, the number of WIMPs does too.
  - We track the equilibrium density until freeze-out:

$$n_{eq}\langle\sigma v\rangle \sim H$$

$$(mT)^{3/2}e^{-m/T} \qquad \frac{g^4}{m^2} \qquad \sim \frac{T^2}{M_{Pl}}$$

$$\frac{m}{T} \sim \log\left[\frac{M_{Pl}}{m}\right] \qquad m \sim 100\ \text{GeV} : \frac{m}{T} \sim 40$$



...and that's how much dark matter we get!

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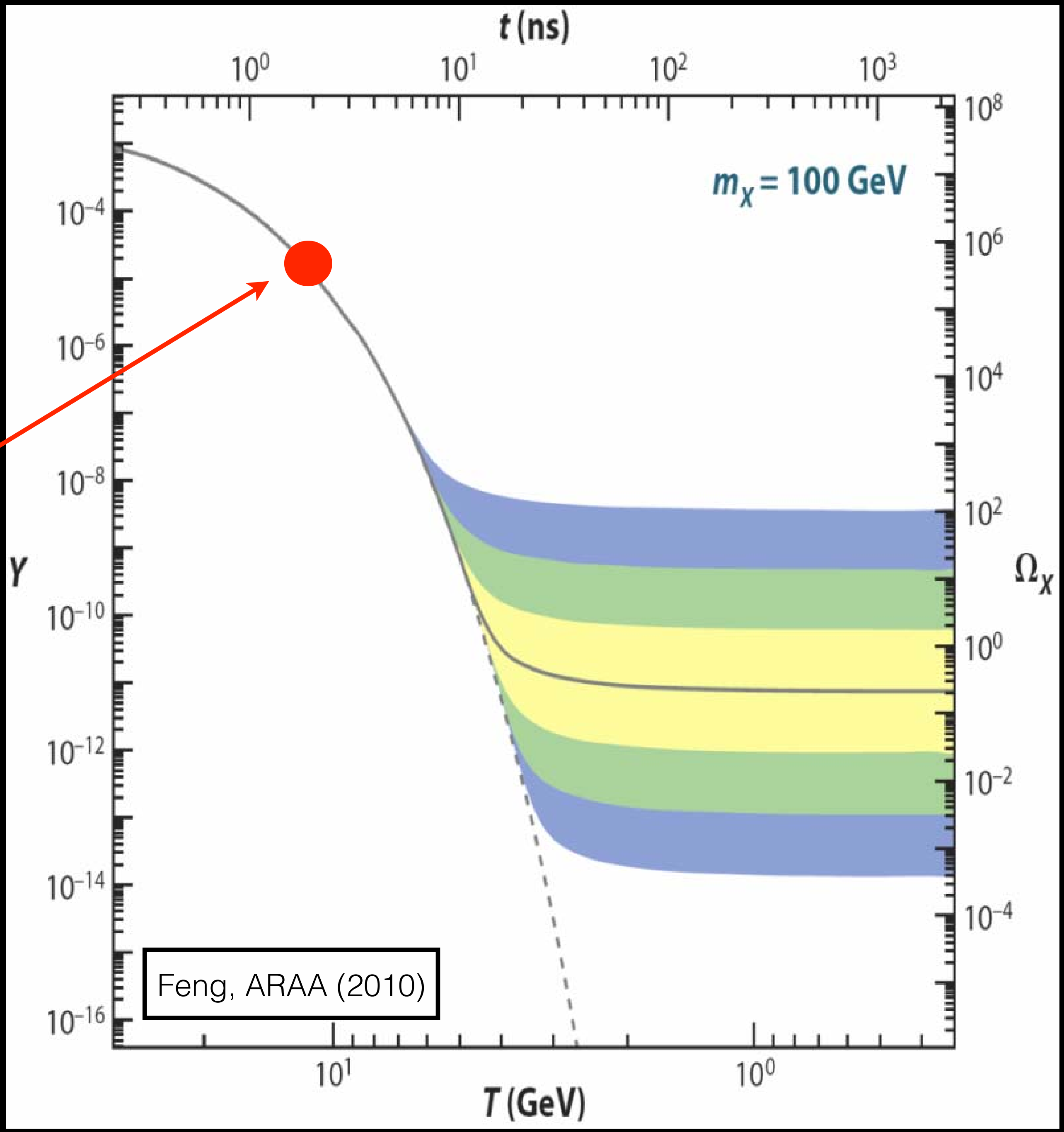

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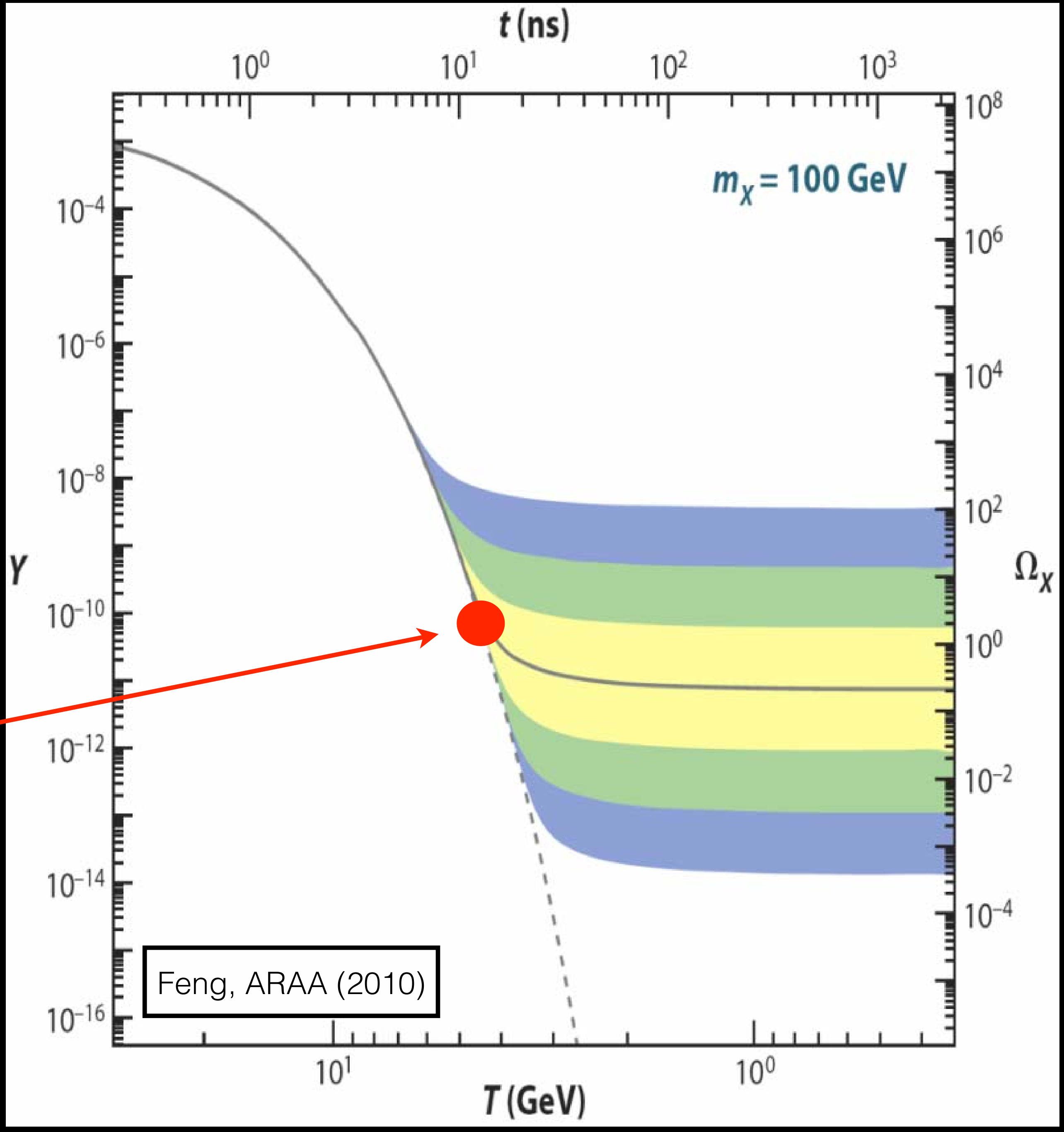

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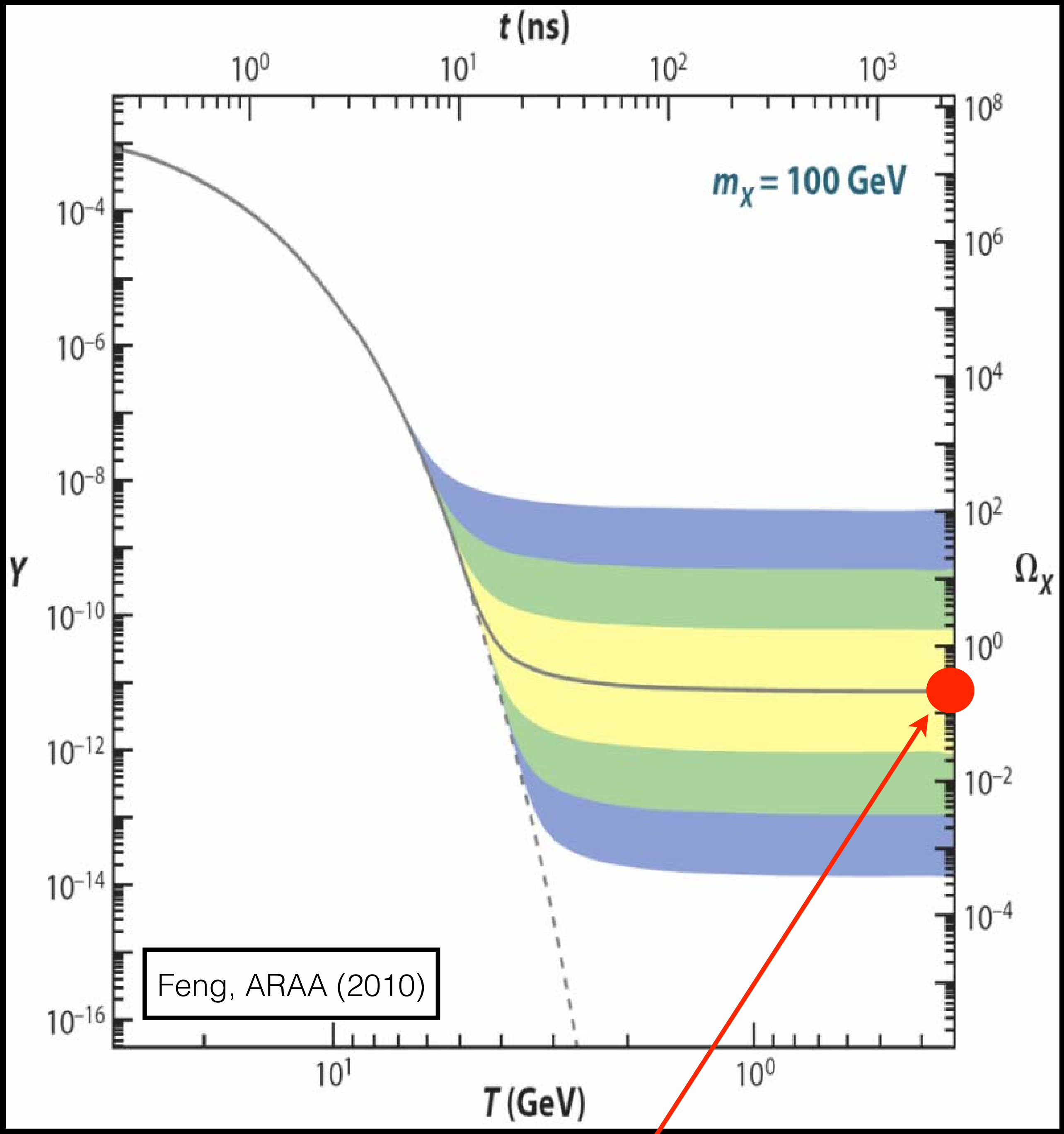

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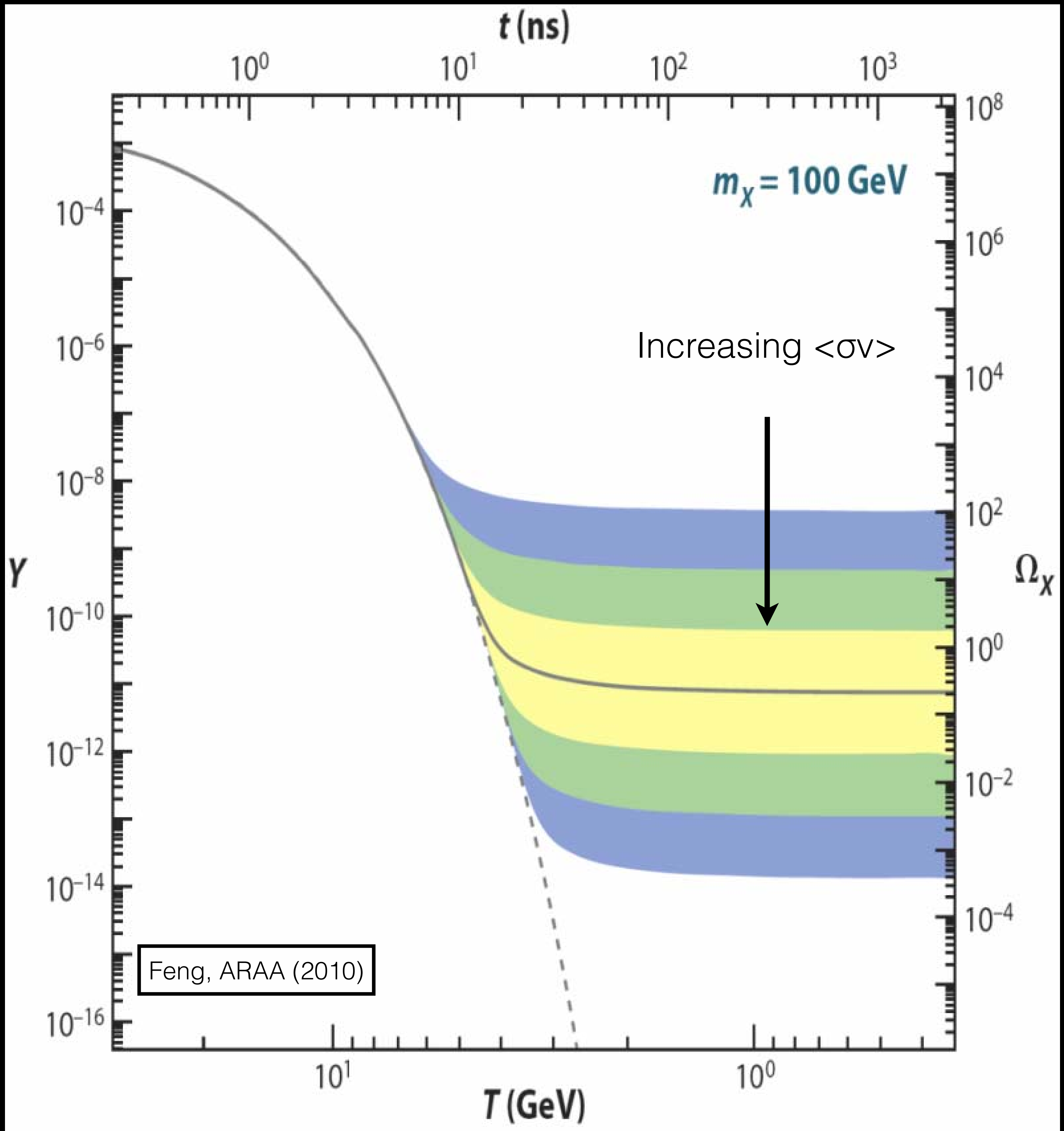
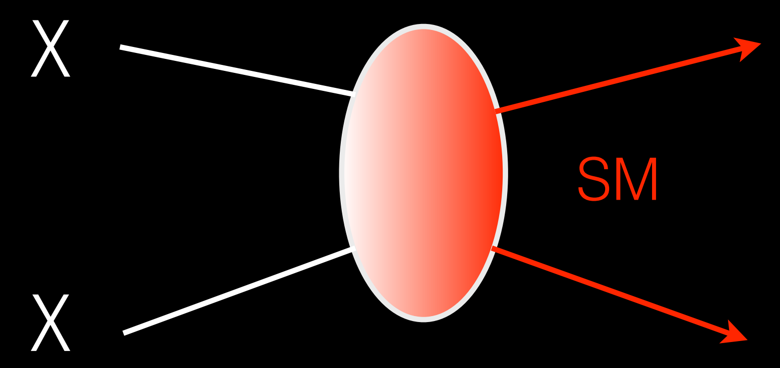
Relic Density



- For a WIMP, once we know its mass and cross section into SM particles, we can predict its relic density.
- I find it remarkable that one simple, reasonable assumption (DM is in equilibrium with the SM at early times) is enough to predict the dark matter density today in terms of the particle physics properties of DM.

WIMP Interactions

- Ideally, we would like to measure WIMP interactions with the Standard Model, allowing us to compute $\sigma(\chi\chi \rightarrow \text{SM particles})$ and check the relic density.



  - If our predictions "check out" we have indirect evidence that our extrapolation backward to higher temperatures is working.
  - If not, we will look for signs of new physics to make up the difference.

- The first step is to actually rediscover dark matter by seeing it interact through some force other than gravitational.
- That tells us which SM particles it likes to talk to and in some cases something about its spin, mass, etc.

Thermal Relic?

We all love the WIMP miracle.
We have to admit that this is
really why we love WIMPs.

But what do we *know* about the
history of the Universe?

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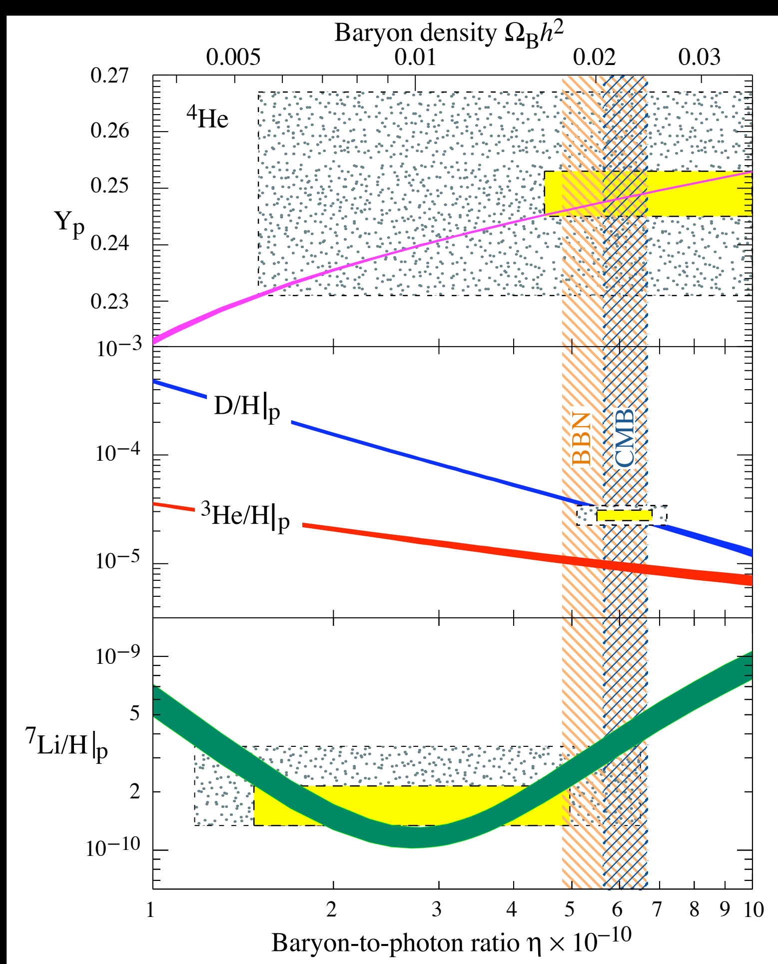
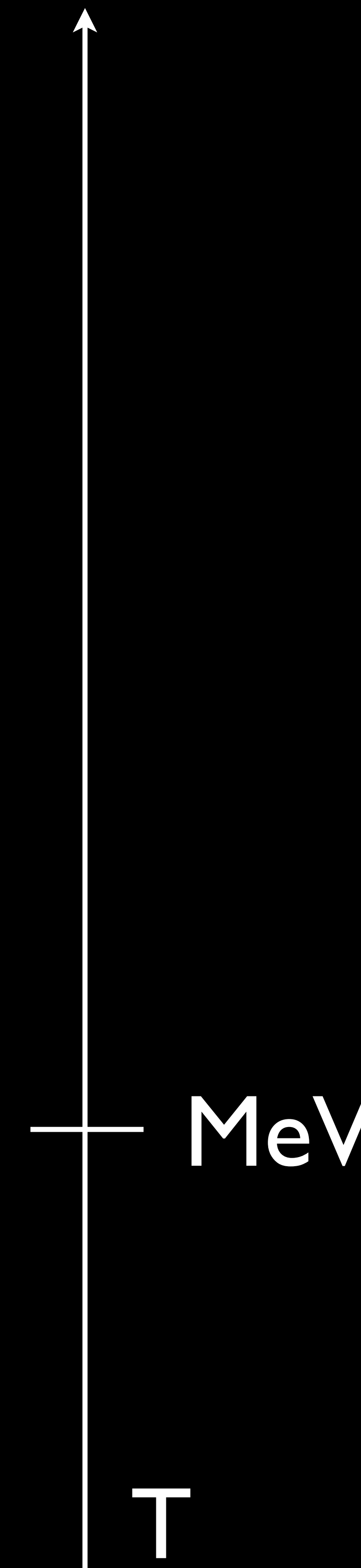


We understand the Universe back to the time of Nucleosynthesis



Thermal Relic?

What does that mean for DM?

A typical WIMP had already frozen out through annihilation

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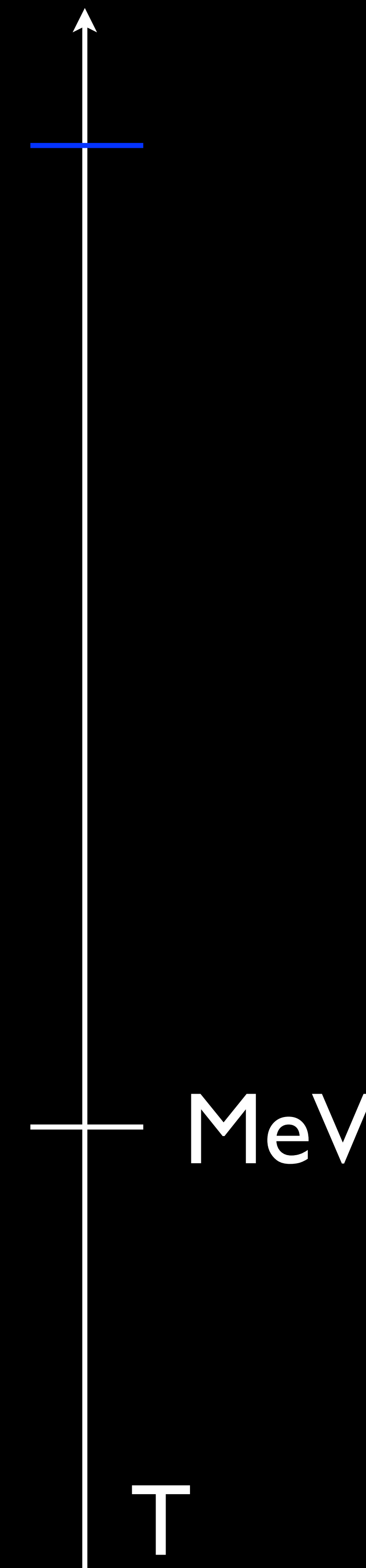
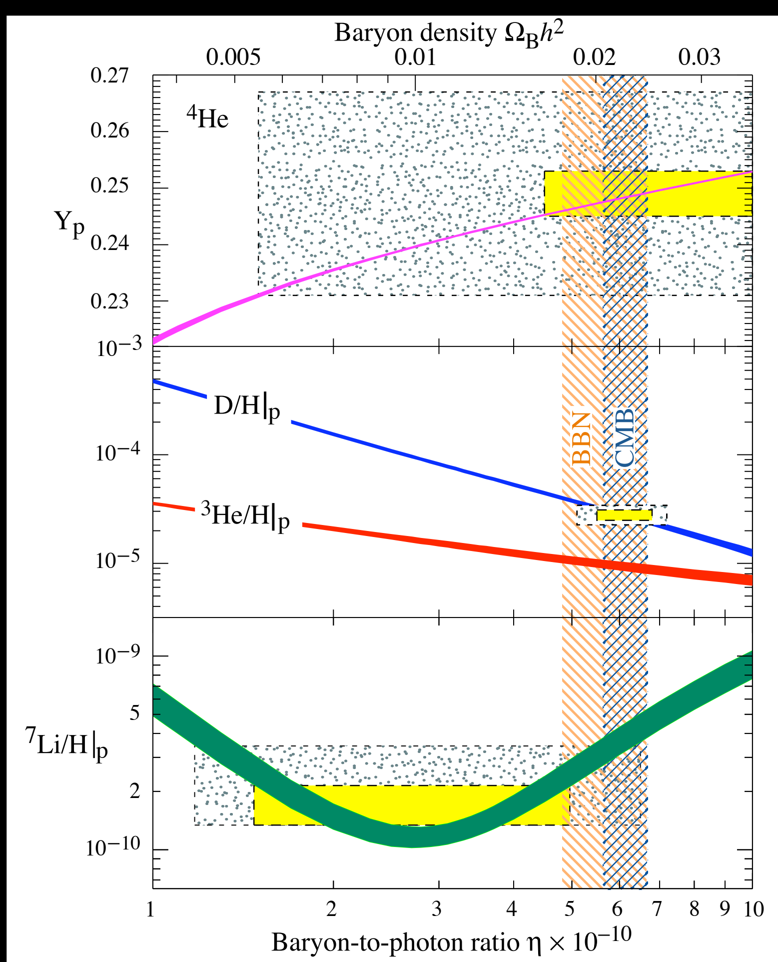
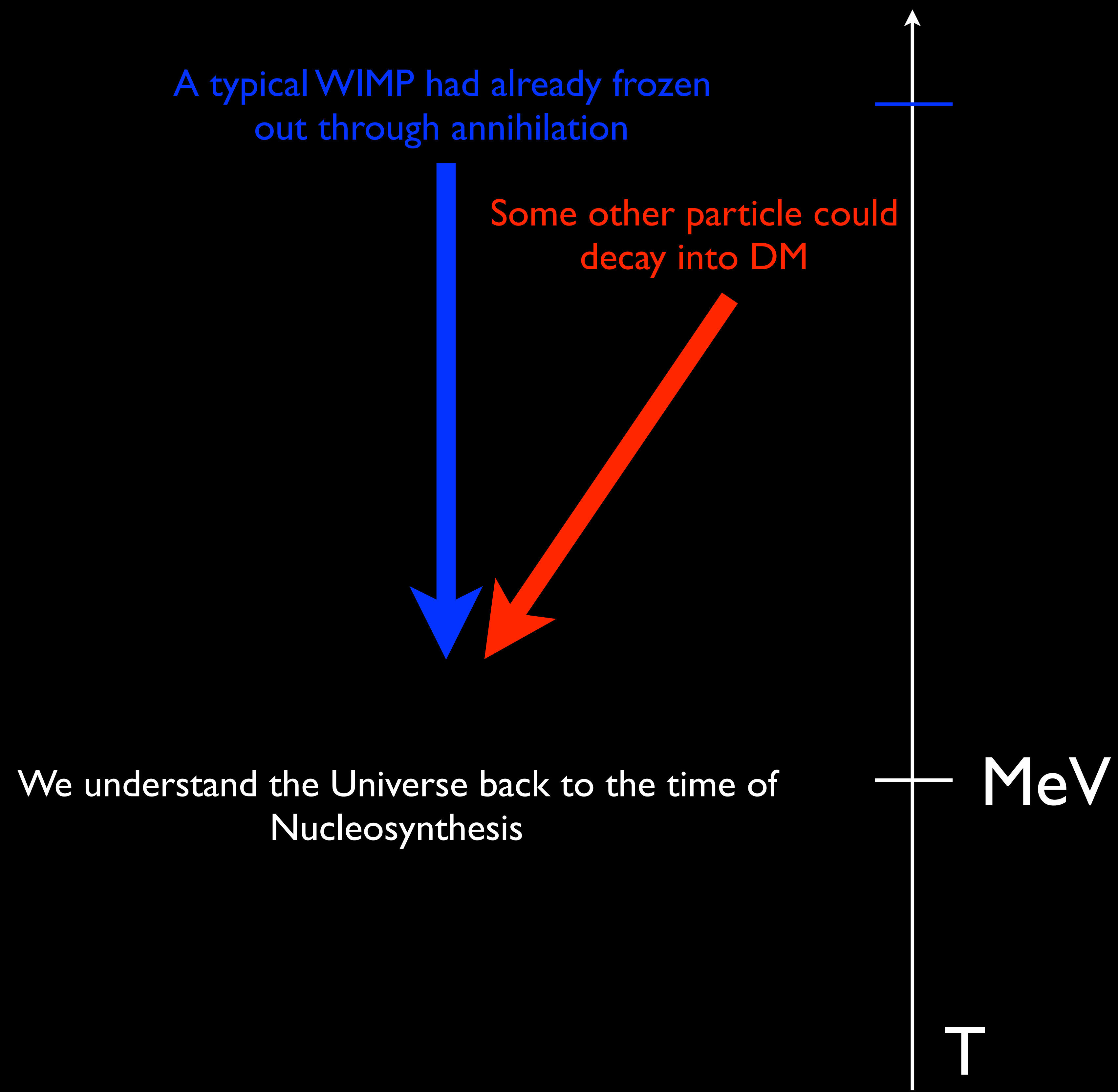




Lots Could Happen



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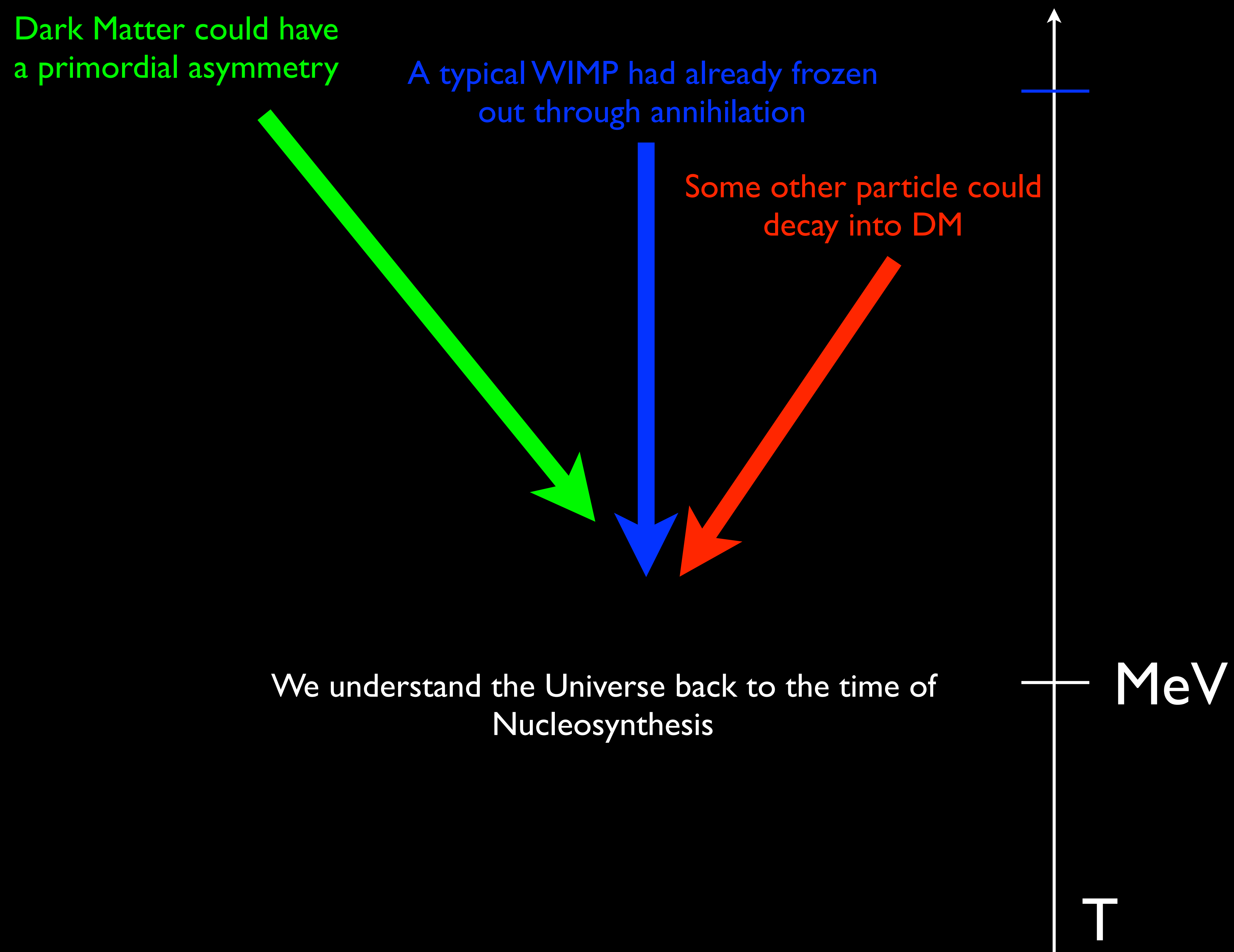

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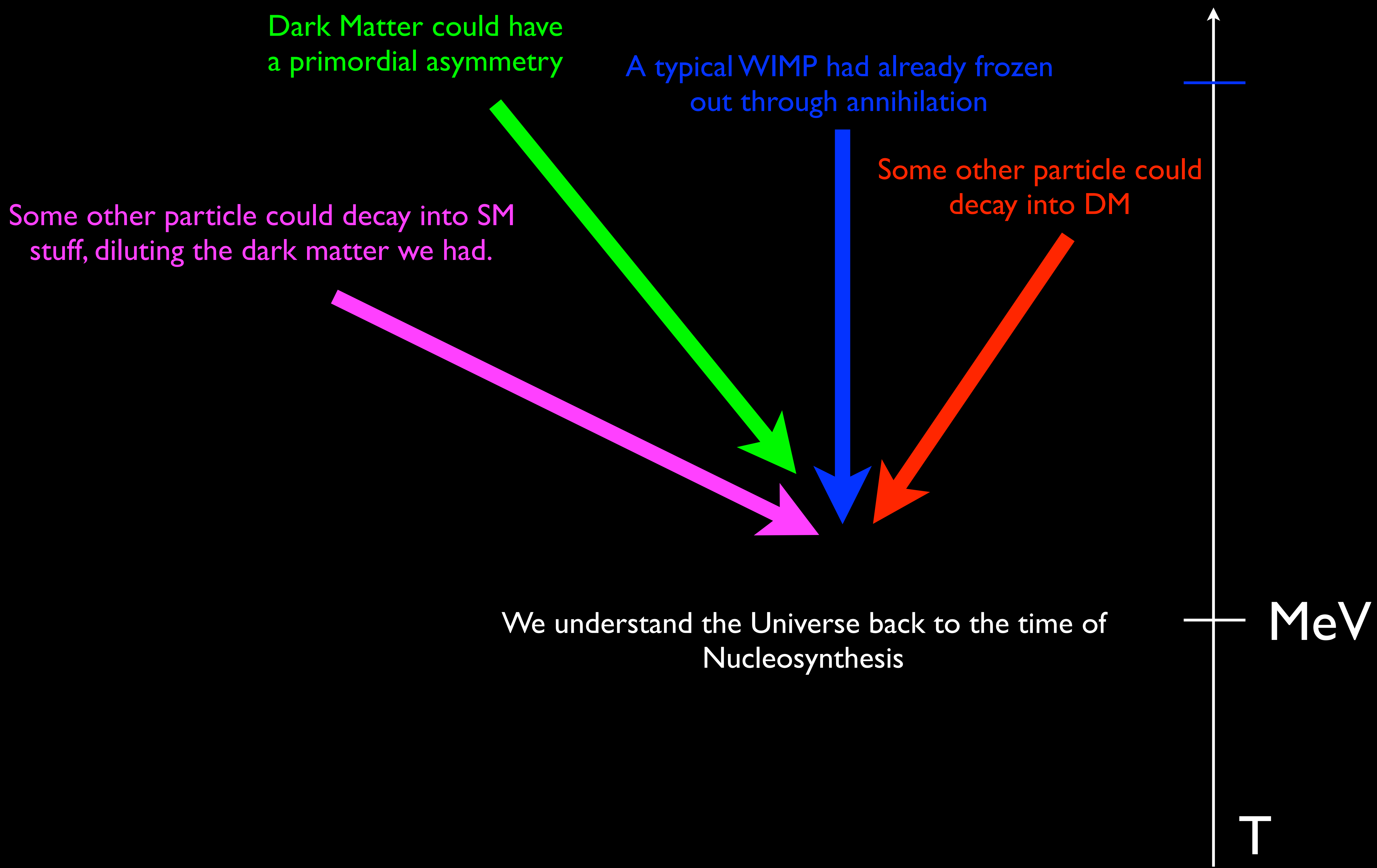


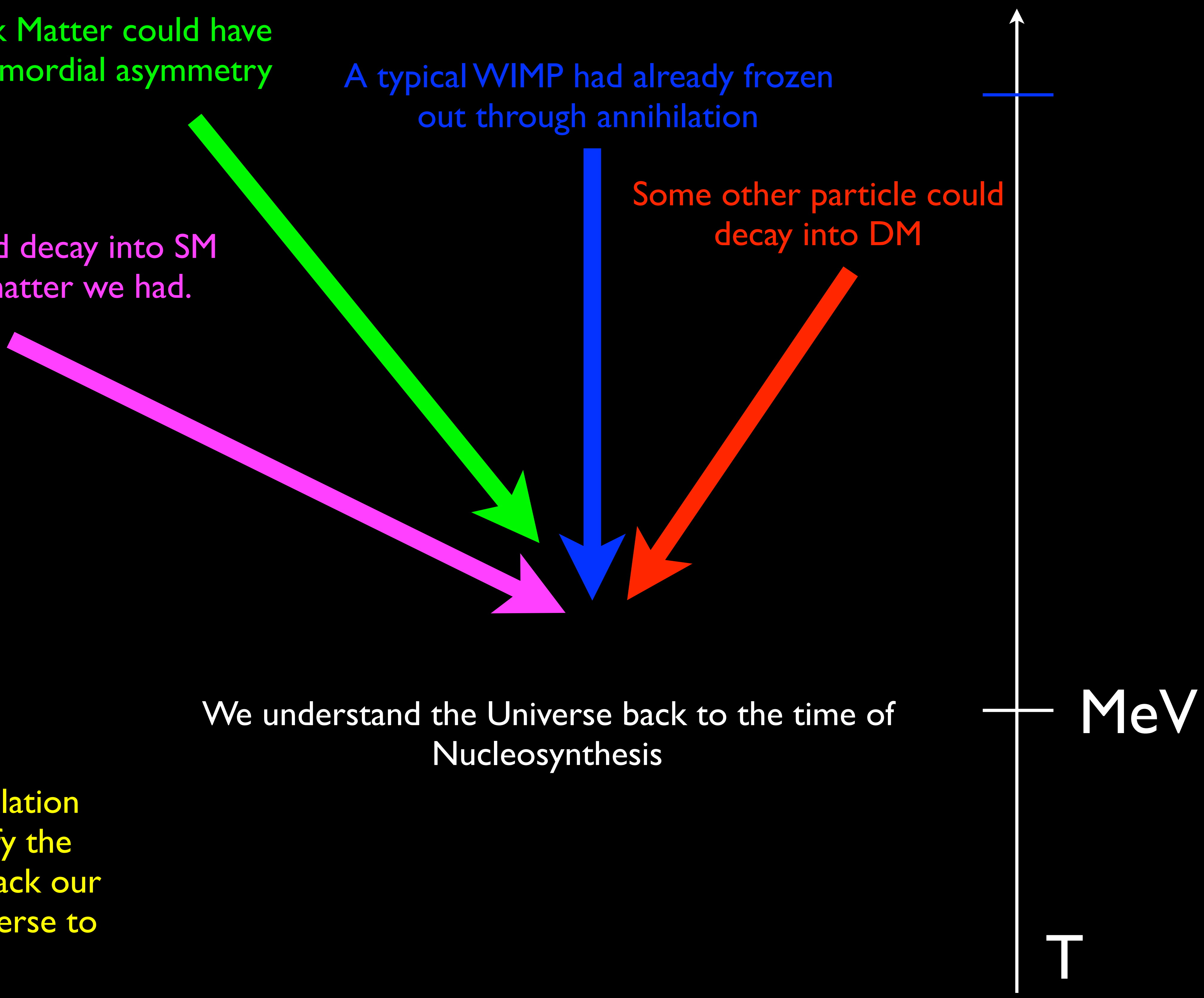
Lots Could Happen

Dark Matter could have a primordial asymmetry

A typical WIMP had already frozen out through annihilation

Some other particle could decay into DM

Some other particle could decay into SM stuff, diluting the dark matter we had.



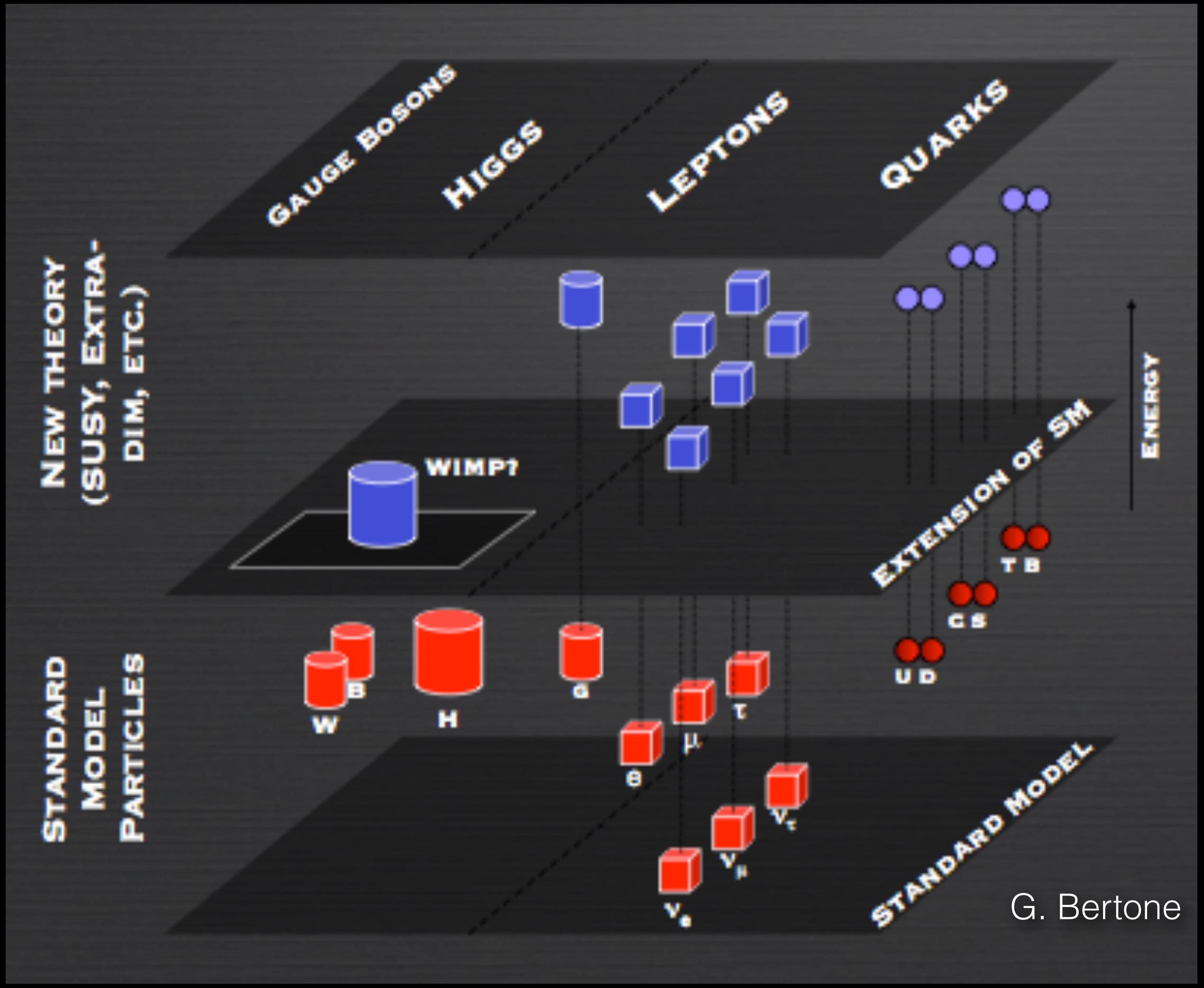
We understand the Universe back to the time of Nucleosynthesis

This is a feature!

Understanding the annihilation cross section could verify the WIMP miracle and push back our understanding of the Universe to earlier times.

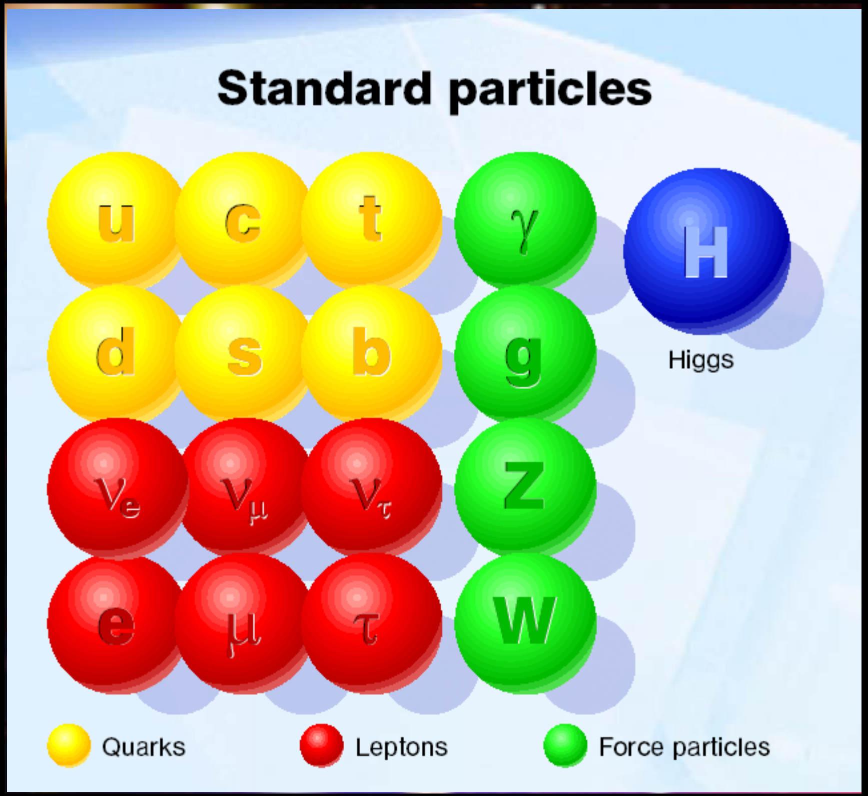
Catalogue of Candidates

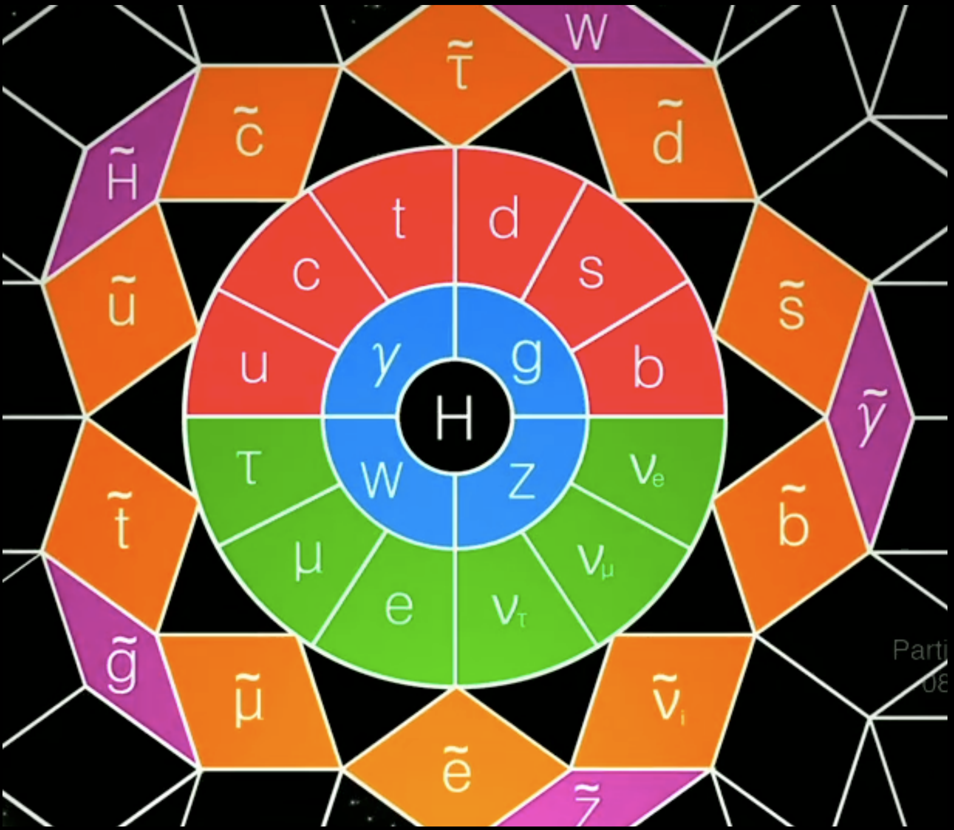
- So here is how we'll catalogue WIMPs:
  - Stability Mechanism
  - How they interact with the SM:
    - Relic density
    - Detection prospects
      - Direct
      - Indirect
      - Collider
- The picture that emerges will be that there are a lot of interesting ideas for DM -- and we can test them!



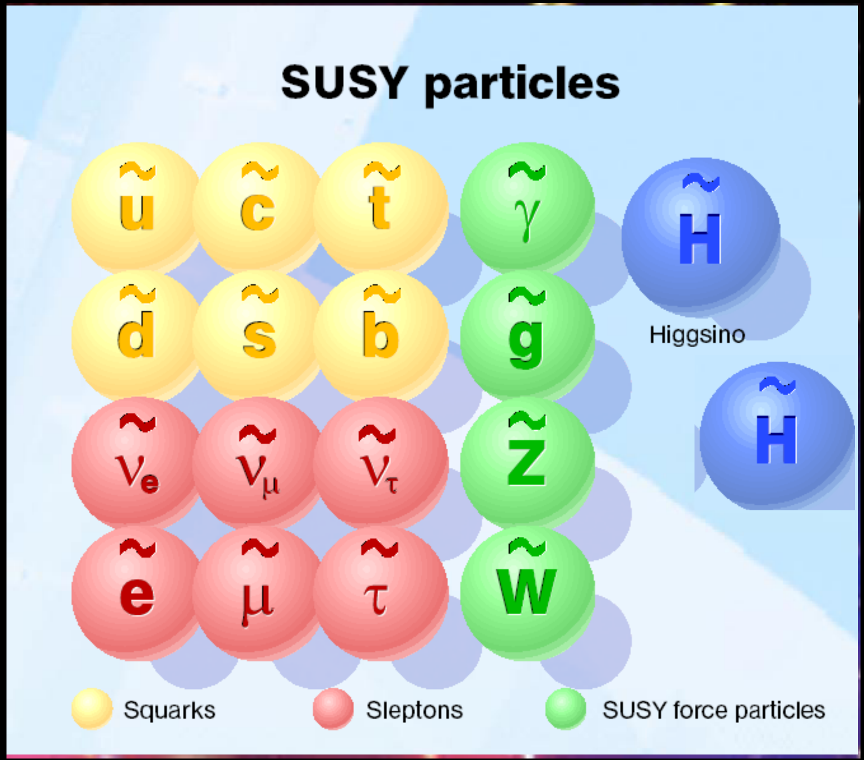
Supersymmetry (SUSY)

- The most famous candidate for dark matter is a supersymmetric particle.
- Supersymmetry famously doubles the number of fields by postulating a symmetry that rotates bosons into fermions (and vice versa).
- I'll focus on how to pick out the features of a supersymmetric theory such as the MSSM that are important to understand how it describes dark matter.



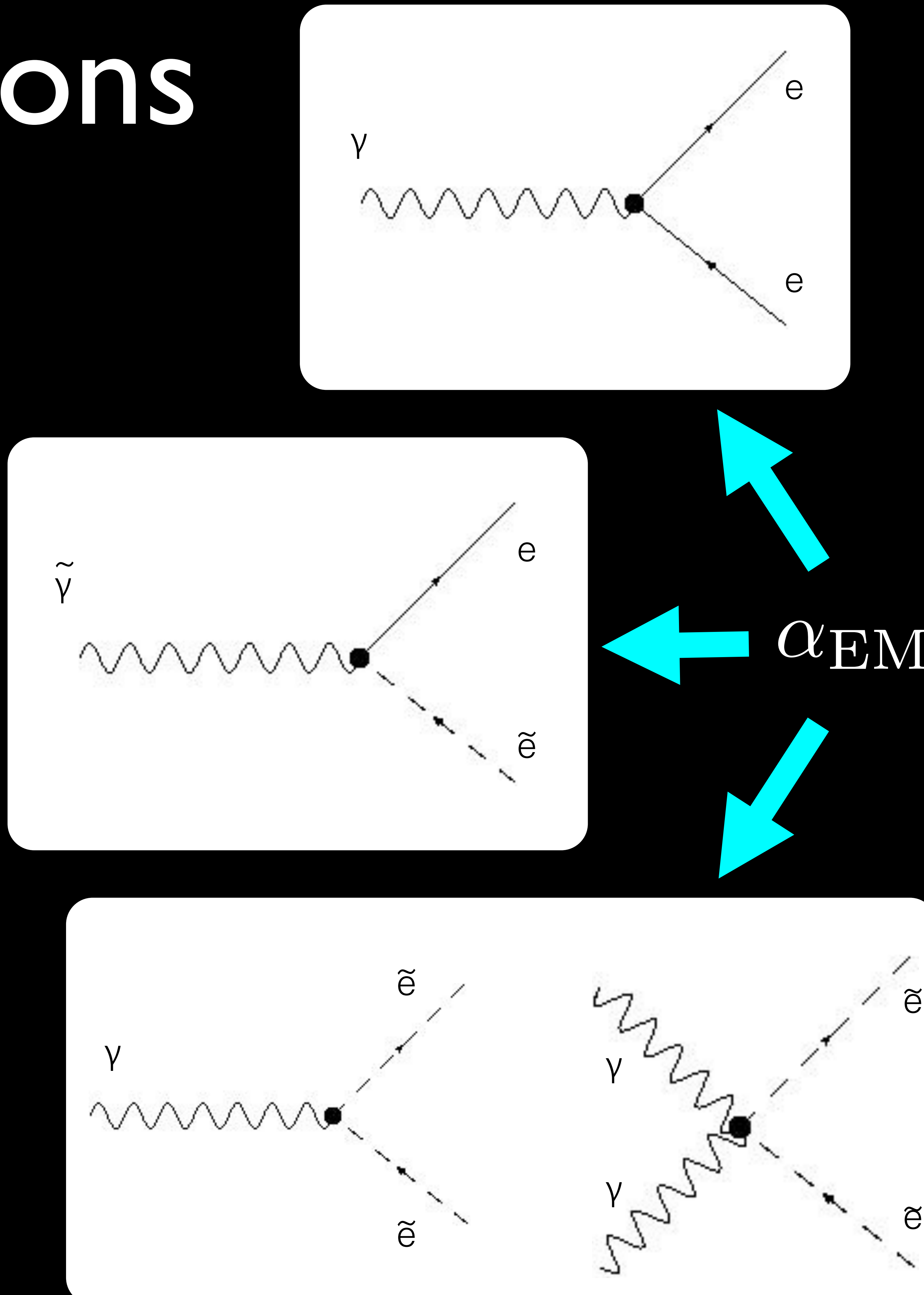


Particle Fever
D.E. Kaplan



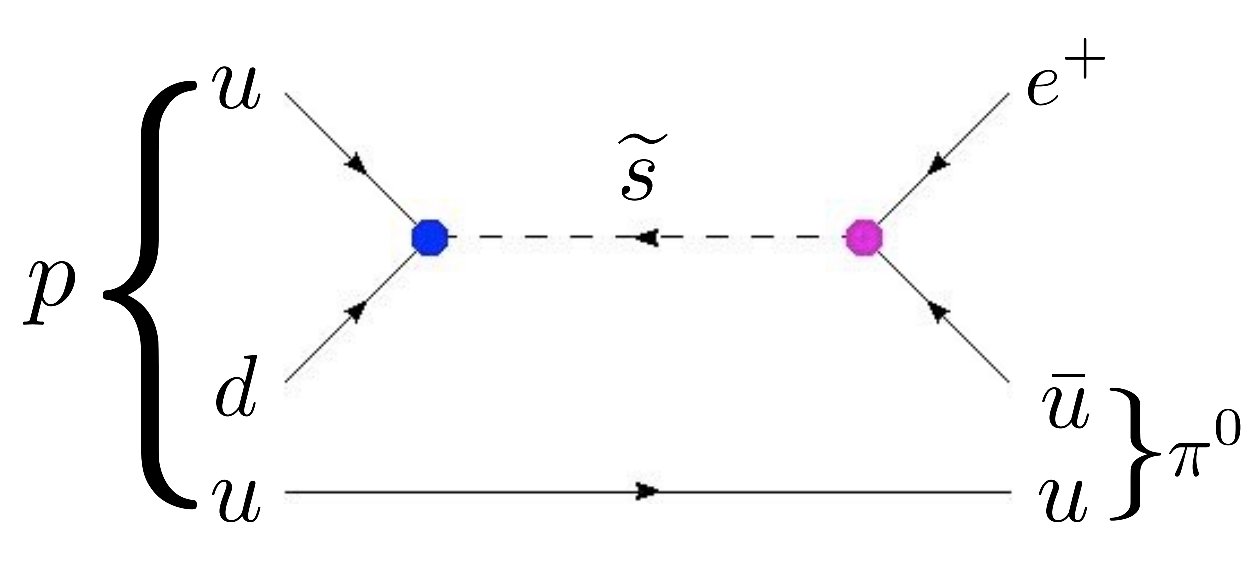
SUSY Interactions

- If we break supersymmetry “softly”, the masses of the super-partners will separate, but the interactions remain fixed by supersymmetry.
- Despite having many, many new parameters, SUSY theories inherit a huge structure from the SM.
- This implies that many things can be calculated in supersymmetric theories in terms of the masses of the superpartners.
- See: Martin, hep-ph/9709356 for a more complete introduction to SUSY.



R-Parity

- By itself, supersymmetry does not imply a stable massive particle.
- It has interactions which would naively violate baryon and lepton number, and do scary things like make protons decay.
- The usual take on this is to simply forbid all of these interactions by invoking a symmetry: R-parity.
- R-parity insures that the superpartners only couple in pairs to the SM.
  - It produces a stable particle!

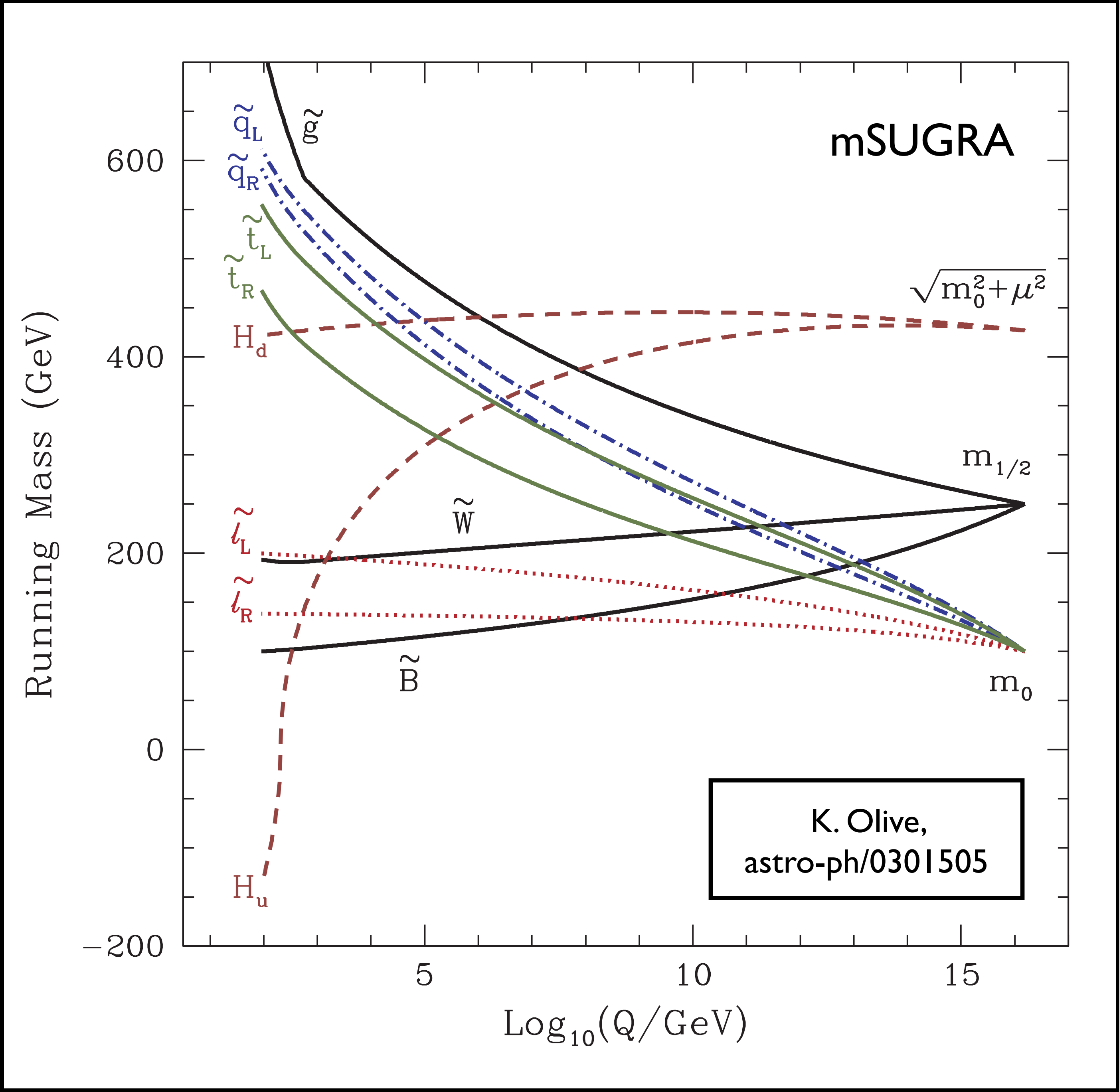


$$R_P \equiv (-1)^{3(B-L)+2S}$$

SM particles: +1
Superpartners: -1

Identity of the LSP

- If the Lightest Supersymmetric Particle is stable, any superpartners present in the early universe will eventually decay into them.
- The LSP had better turn out to be neutral if we would like it to play the role of dark matter.
- For a given model of SUSY breaking, we can calculate the spectrum and determine which particle is the lightest.
- In fact, there are some generic trends that come about from the renormalization group.



Neutralino Dark Matter

- In the MSSM, the 4 neutralinos are Majorana fermions which are mixtures of the superpartners of W_3, B, and the two neutral Higgses.

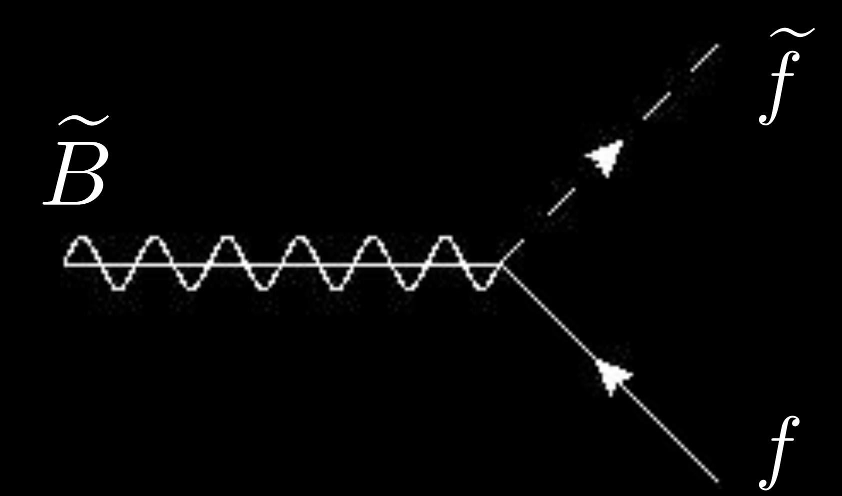
$$\widetilde{\chi}_1^0 = N_{11}\widetilde{B} + N_{12}\widetilde{W}_3 + N_{13}\widetilde{H}_1^0 + N_{14}\widetilde{H}_2^0$$

- As a result, their interactions are a little complicated: it depends on what admixture of each state is present.

- The RGEs typically result in an LSP which is mostly Bino, with a small amount of Higgsino and W3ino.

- Specific models of SUSY breaking may upset these expectations.
    - AMSB: W_3ino WIMP

Bino: Couples to g_1 Y (interactions with the SM involve the sfermions)



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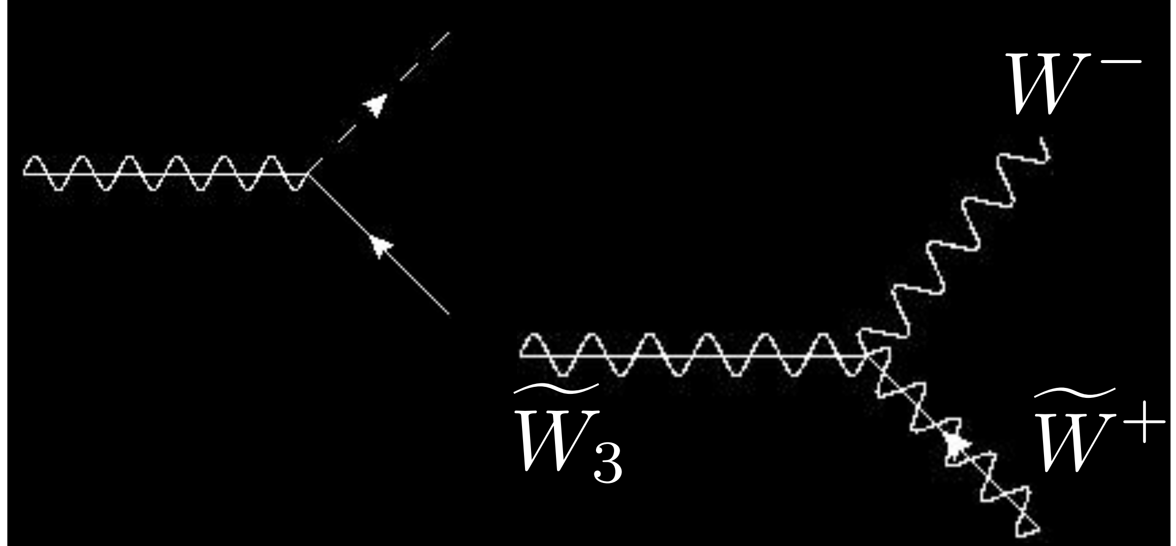
W3ino: Couples to g2 T3 (interactions with sfermions and W -- not Z! -- bosons)



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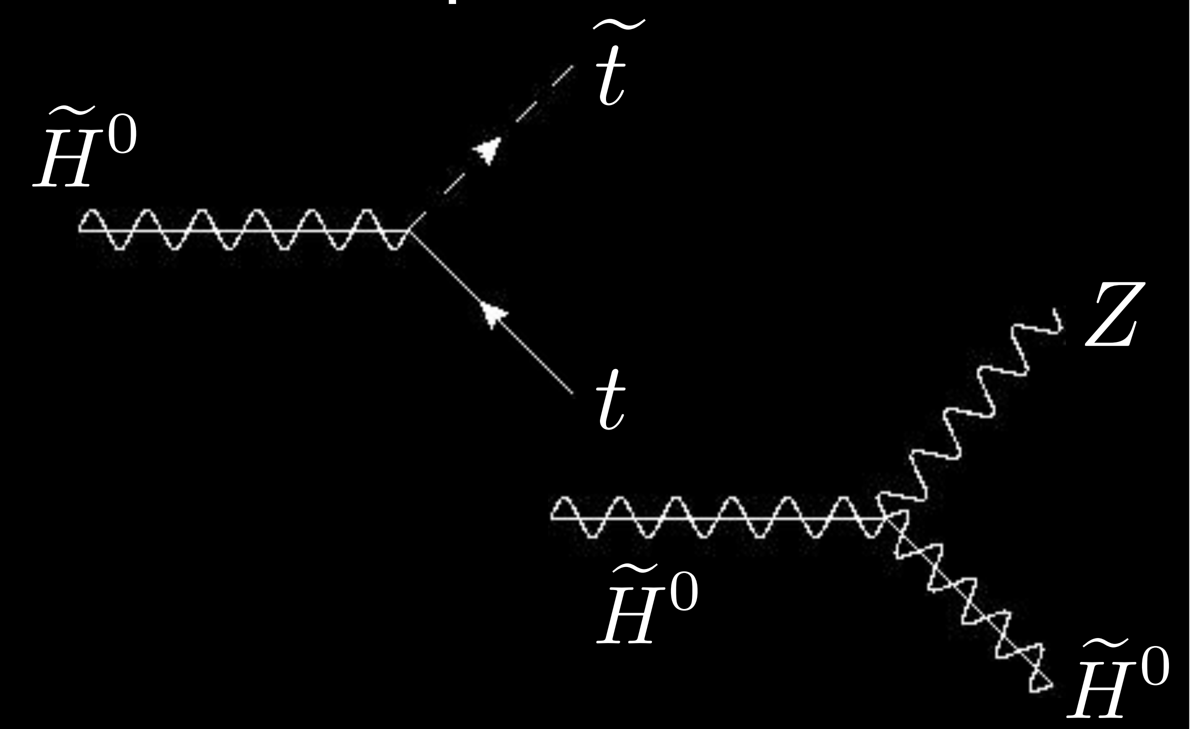
Higgsino: Couples to massive particles



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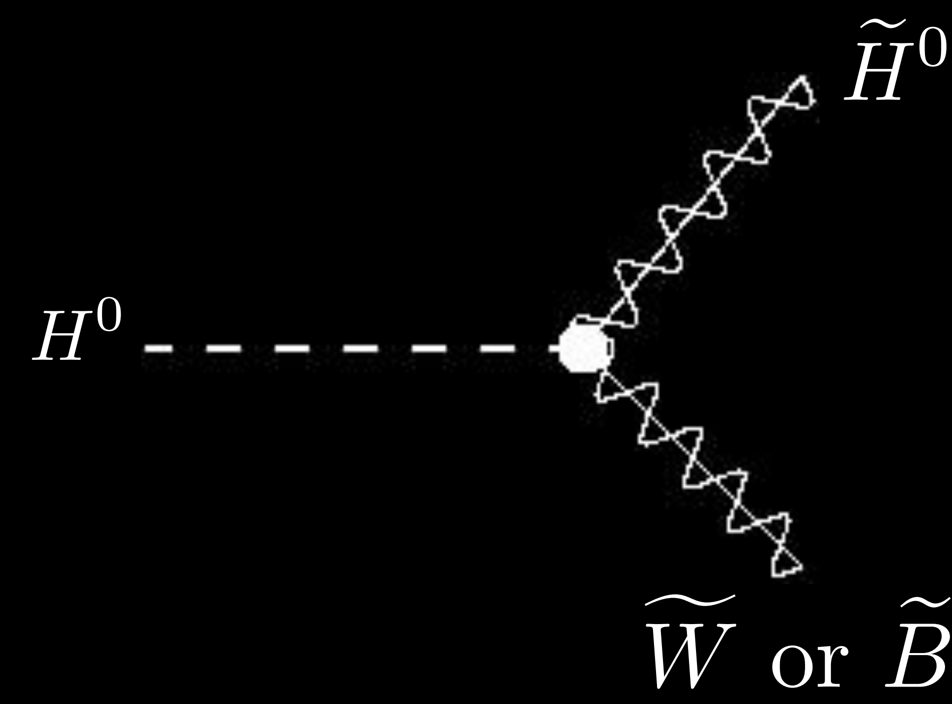
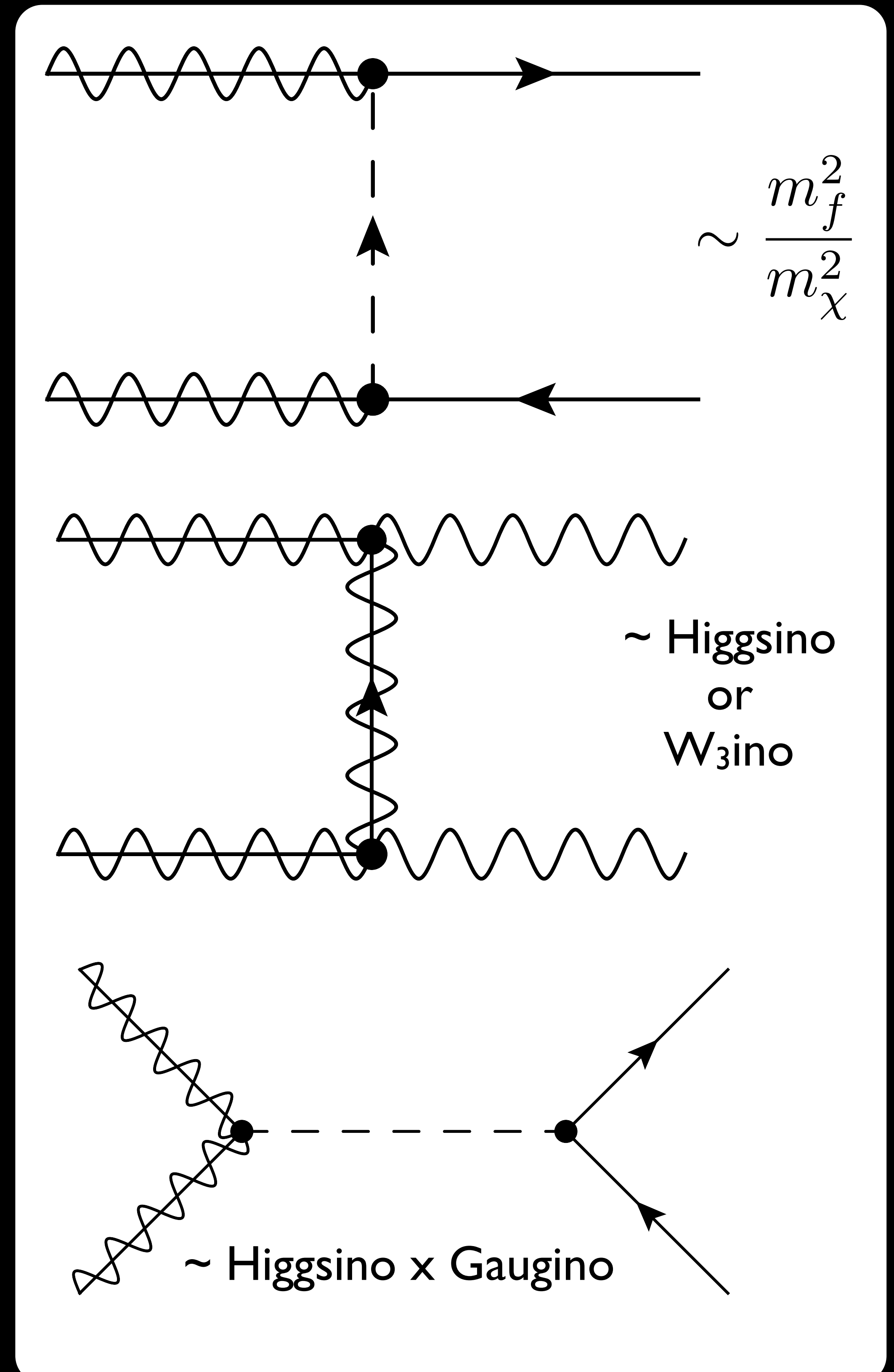
Higgs interactions are hybrids...



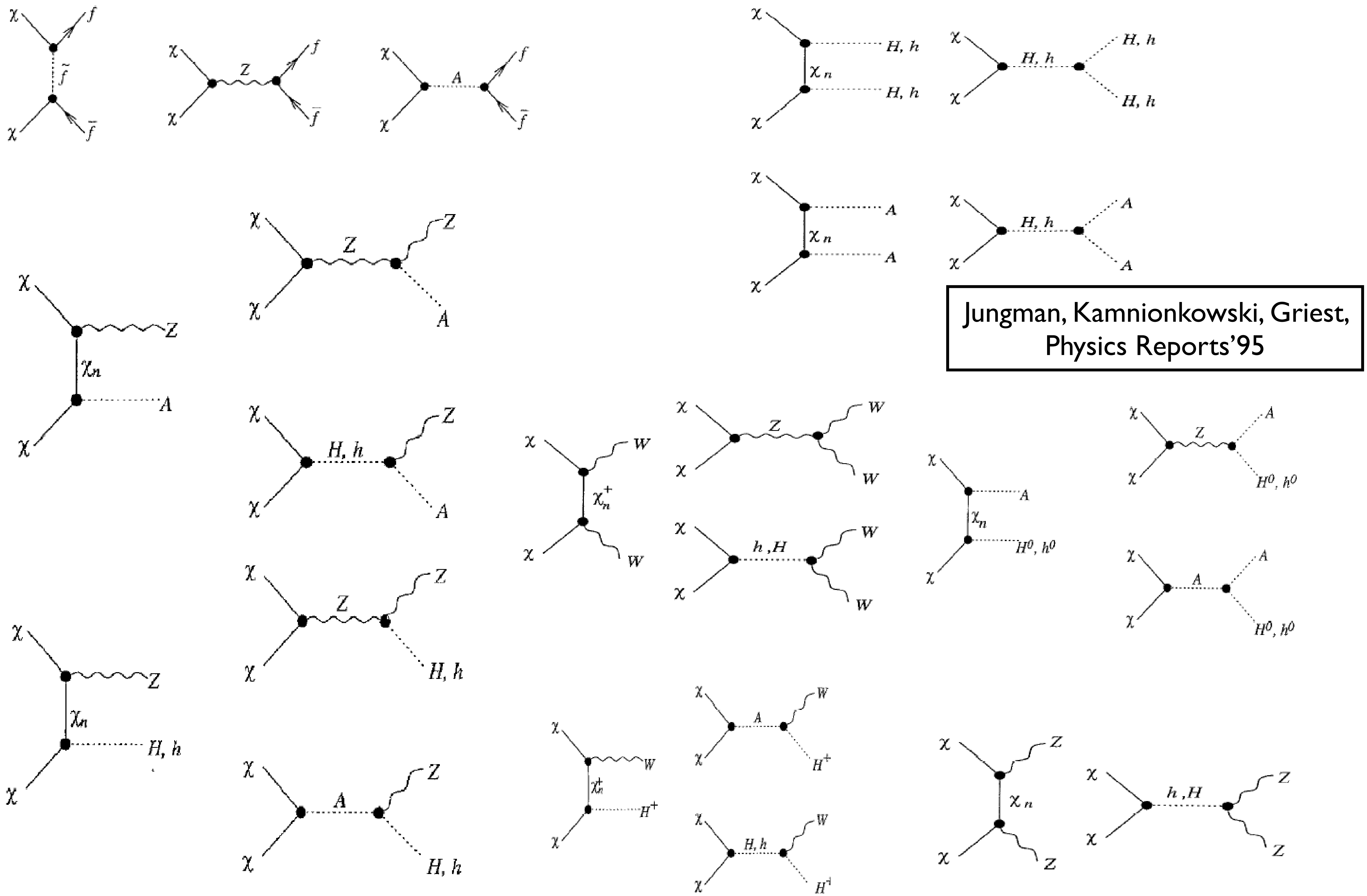
Annihilation

- Now we have everything we need to look at neutralino annihilations. This is a complicated process... but we can understand some general features.
- Neutralinos are Majorana fermions.
  - In the non-relativistic limit, they are Pauli-blocked from an initial S=1 state.
  - No annihilation through an s-channel vector particle.
  - Sfermion exchange likes to produce SM fermions of like-chirality, (S=1) and is suppressed by m_f for an S=0 initial state.



Bottom Line: Suppressed <σ v> leads generically to too many Binos.

A Plethora of Processes



Jungman, Kamnionkowski, Griest, Physics Reports'95

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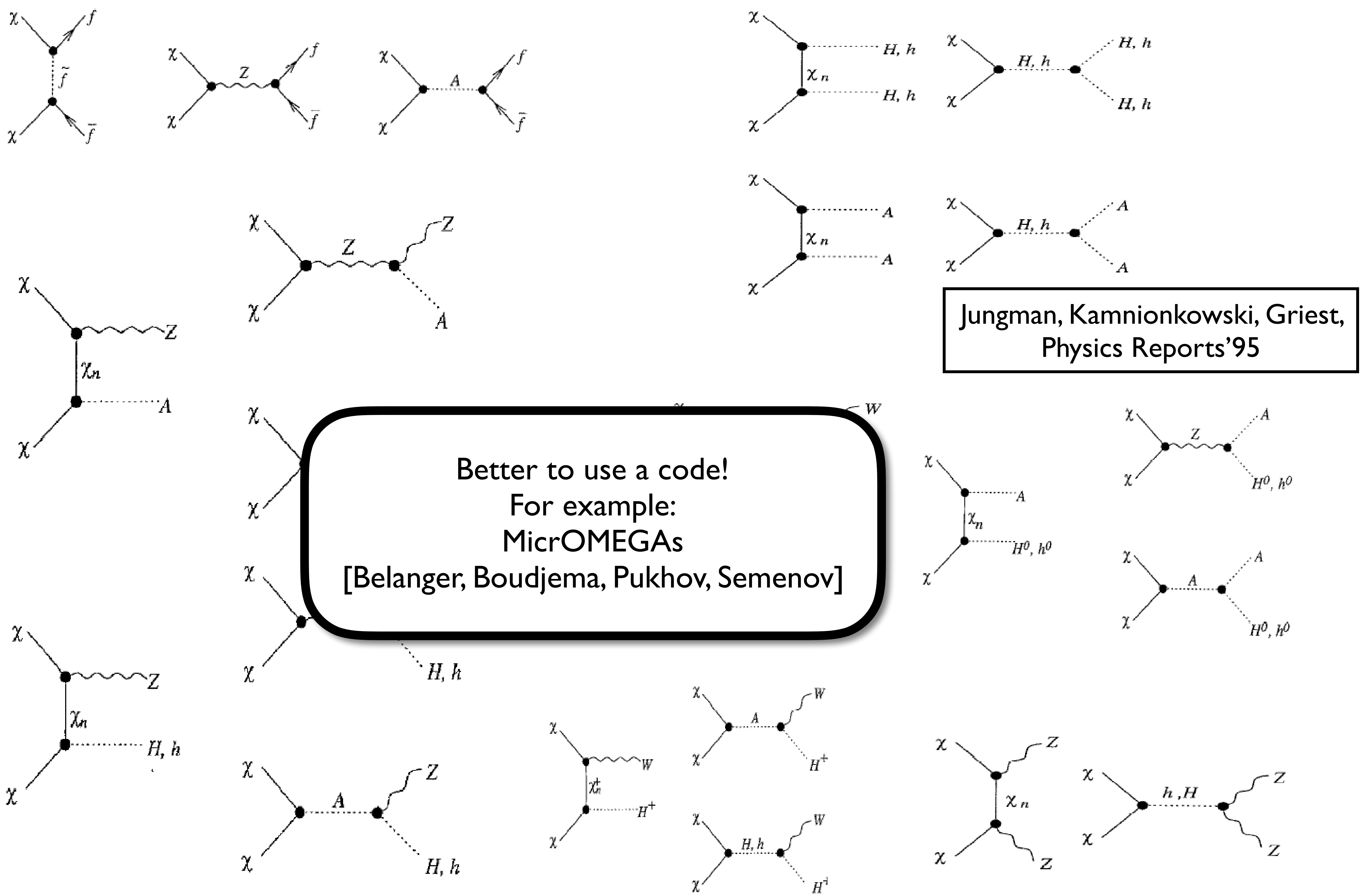
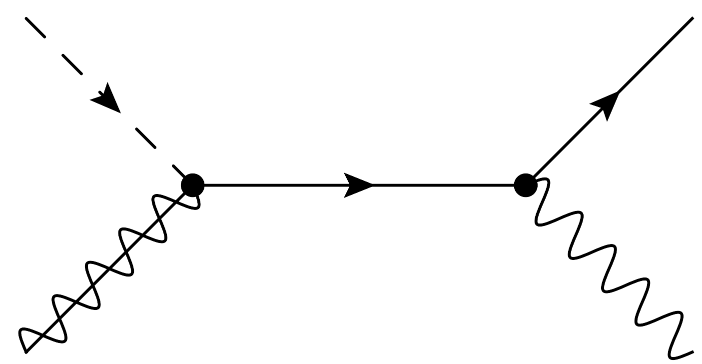


Jungman, Kamnionkowski, Griest, Physics Reports'95

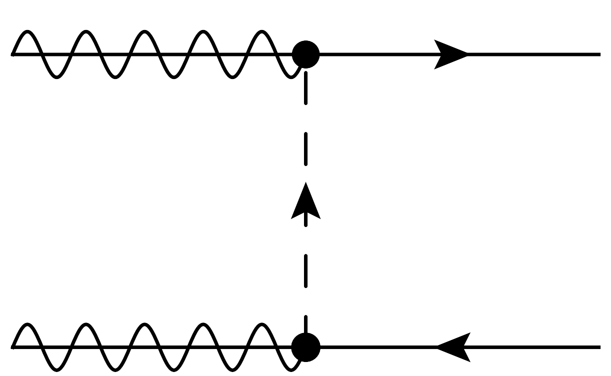
Better to use a code!
For example:
MicrOMEGAs
[Belanger, Boudjema, Pukhov, Semenov]

Relic Density: Small Tan β

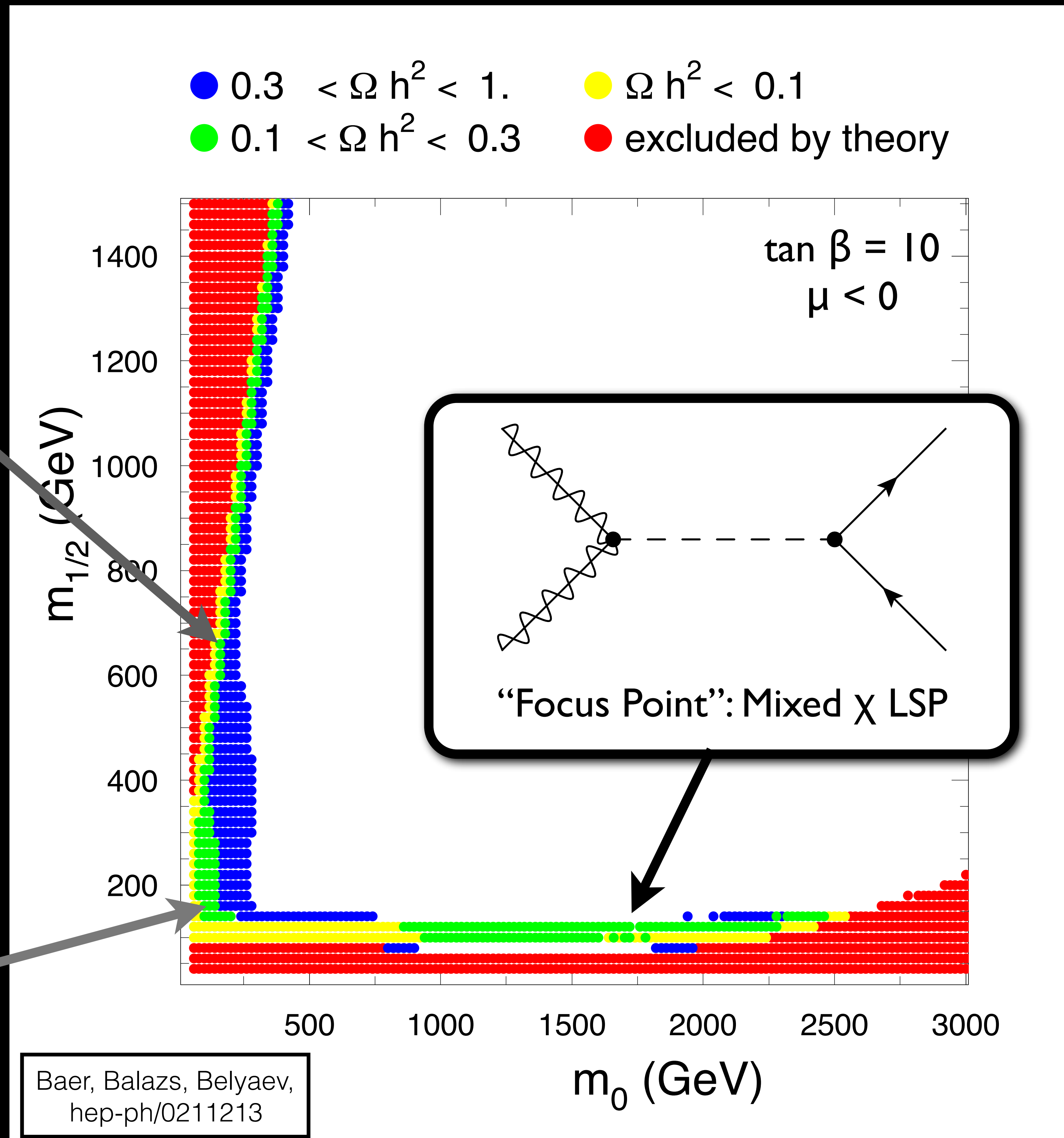
mSUGRA



"Coannihilation Region": Degenerate stau active during freeze-out

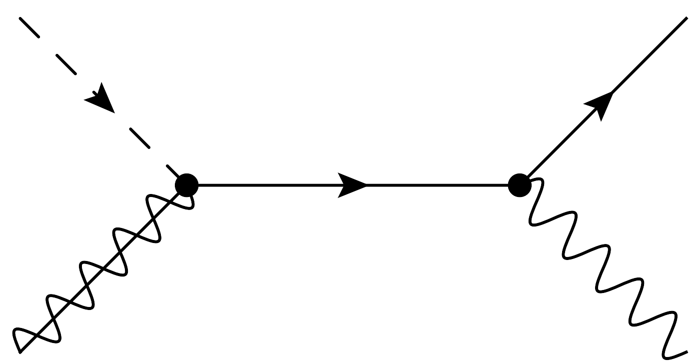


"Bulk Region": Light sfermions (~excluded by LHC)



Large Tan β

mSUGRA



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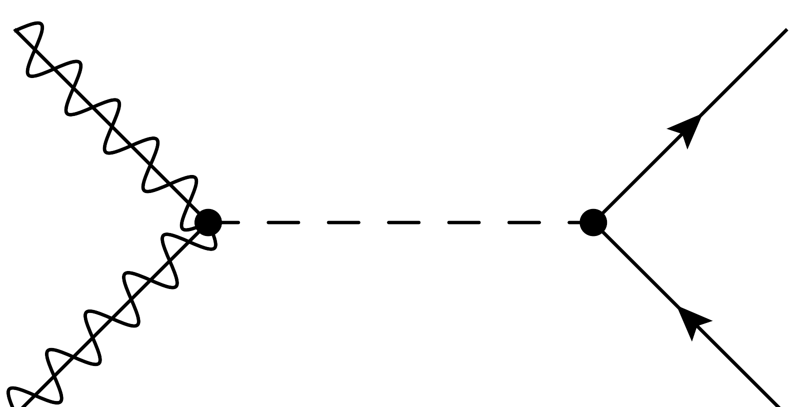
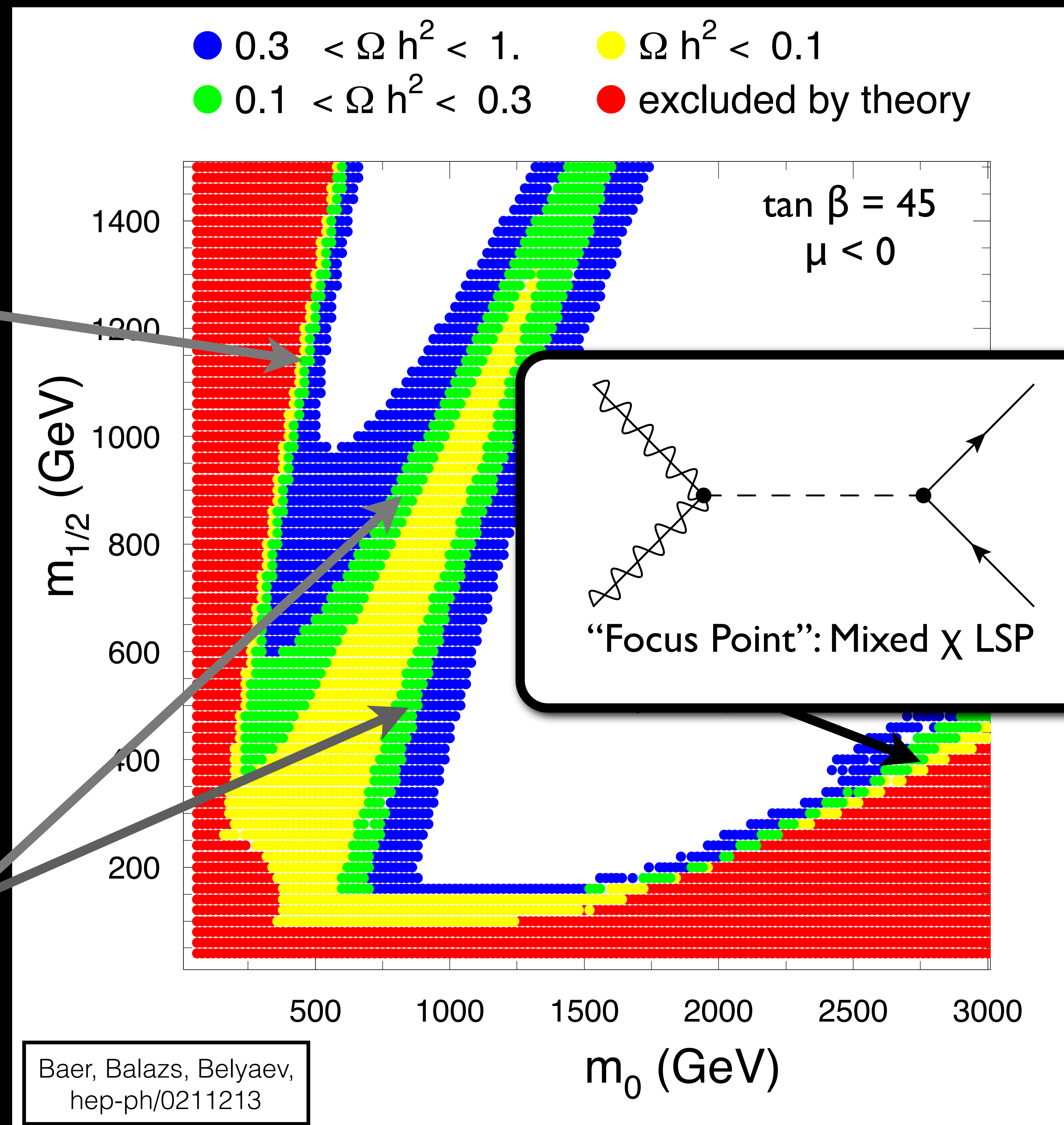


"Funnel Region": Higgs close to on-shell in decay

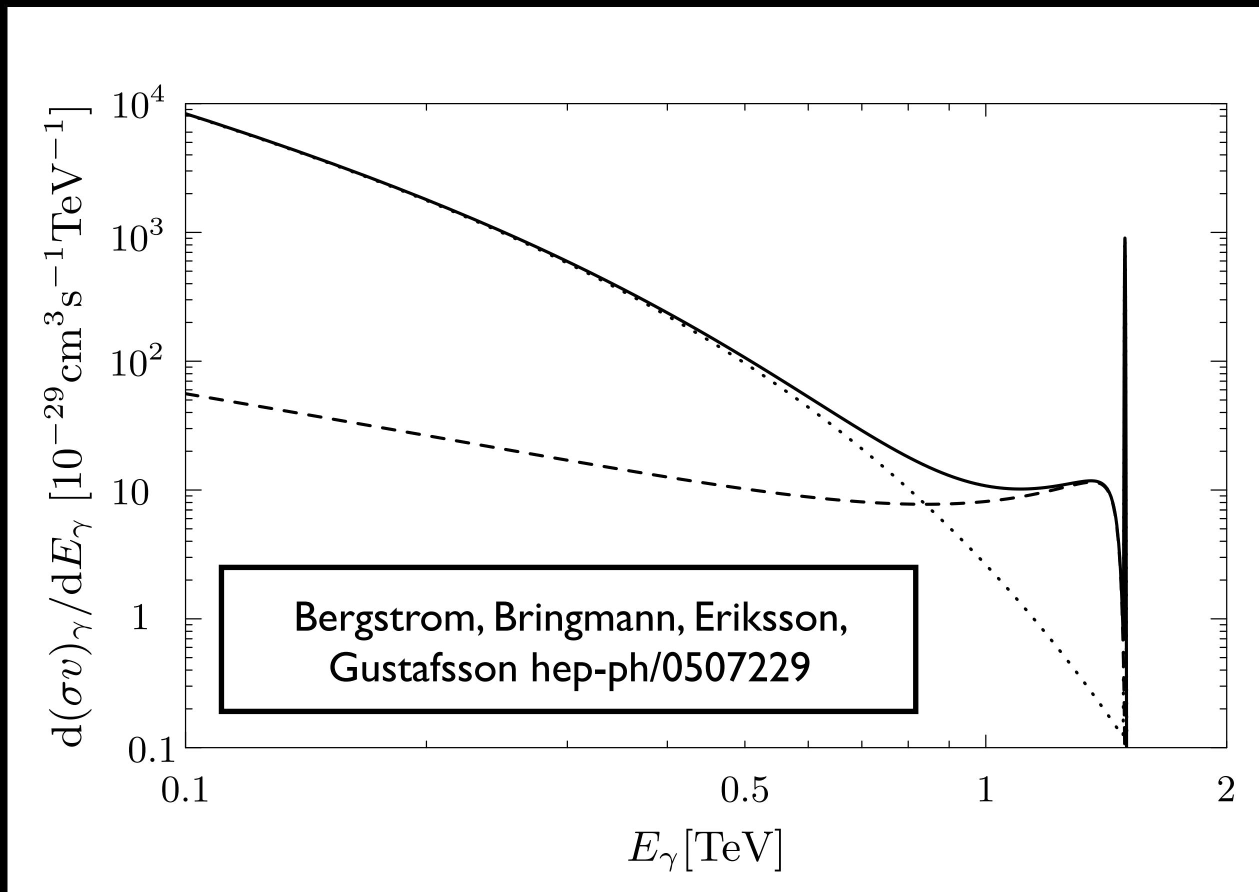


"Focus Point": Mixed χ LSP

Cosmic Neutralino Signals

- We've already learned a fair amount about how neutralinos annihilate by studying the relic density.
- The same physics controls the search for them annihilating in the halo.
  - As Majorana particles, they tend to annihilate into heavier fermions and/ or W bosons.
    - Fermi searches for bb spectra are motivated by this observation...
  - Loops of charged particles allow them to annihilate into γγ or γZ.
    - A "smoking gun" signal!

1.5 TeV (Mostly) Higgsino LSP



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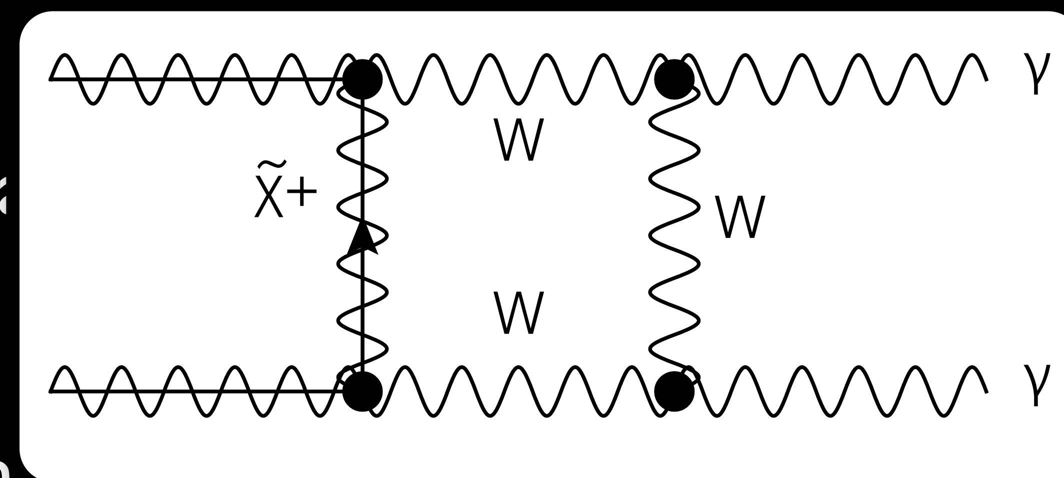

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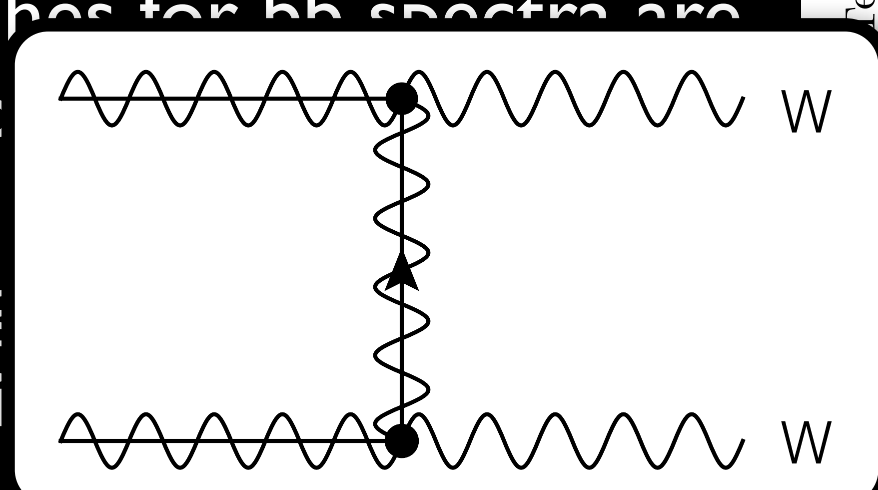
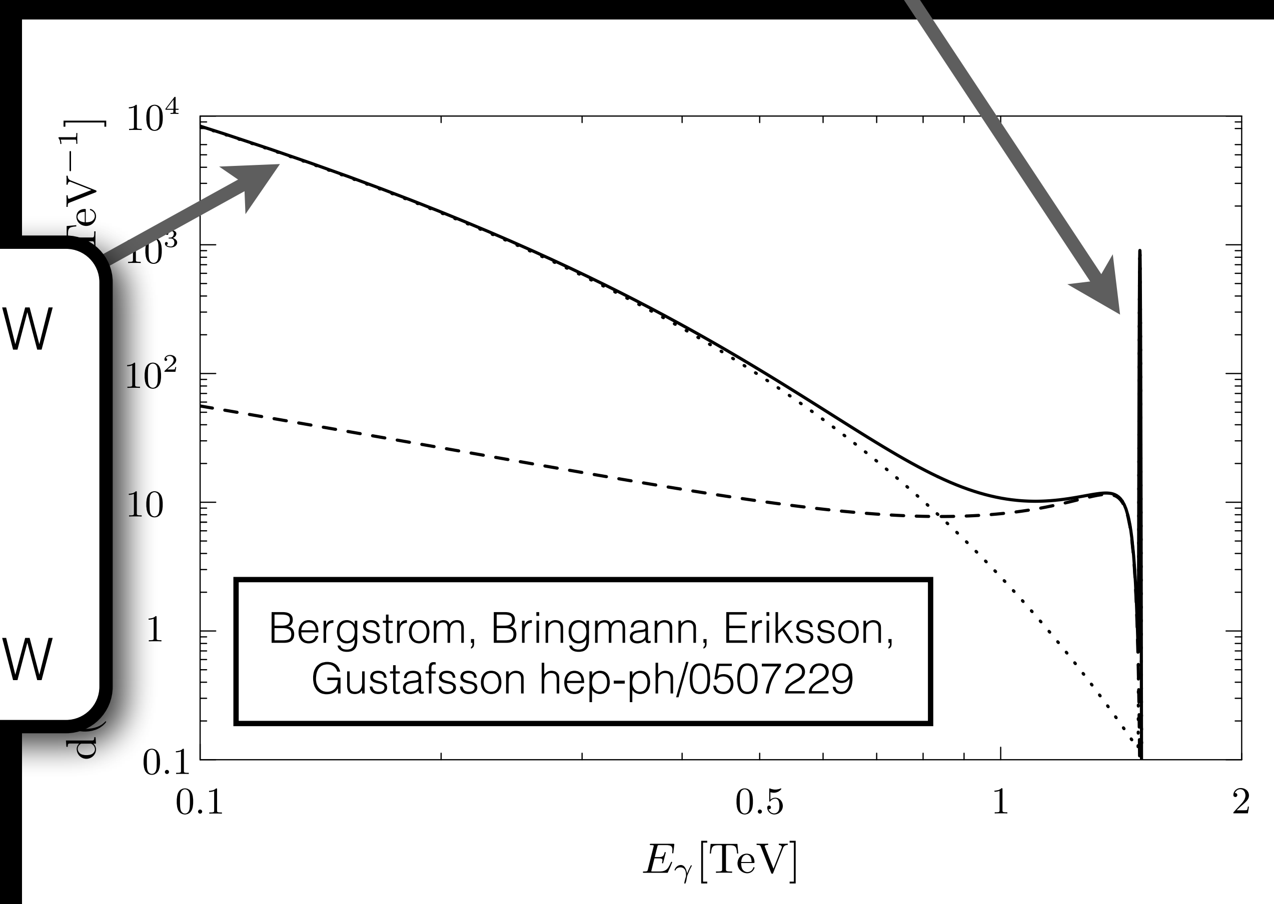
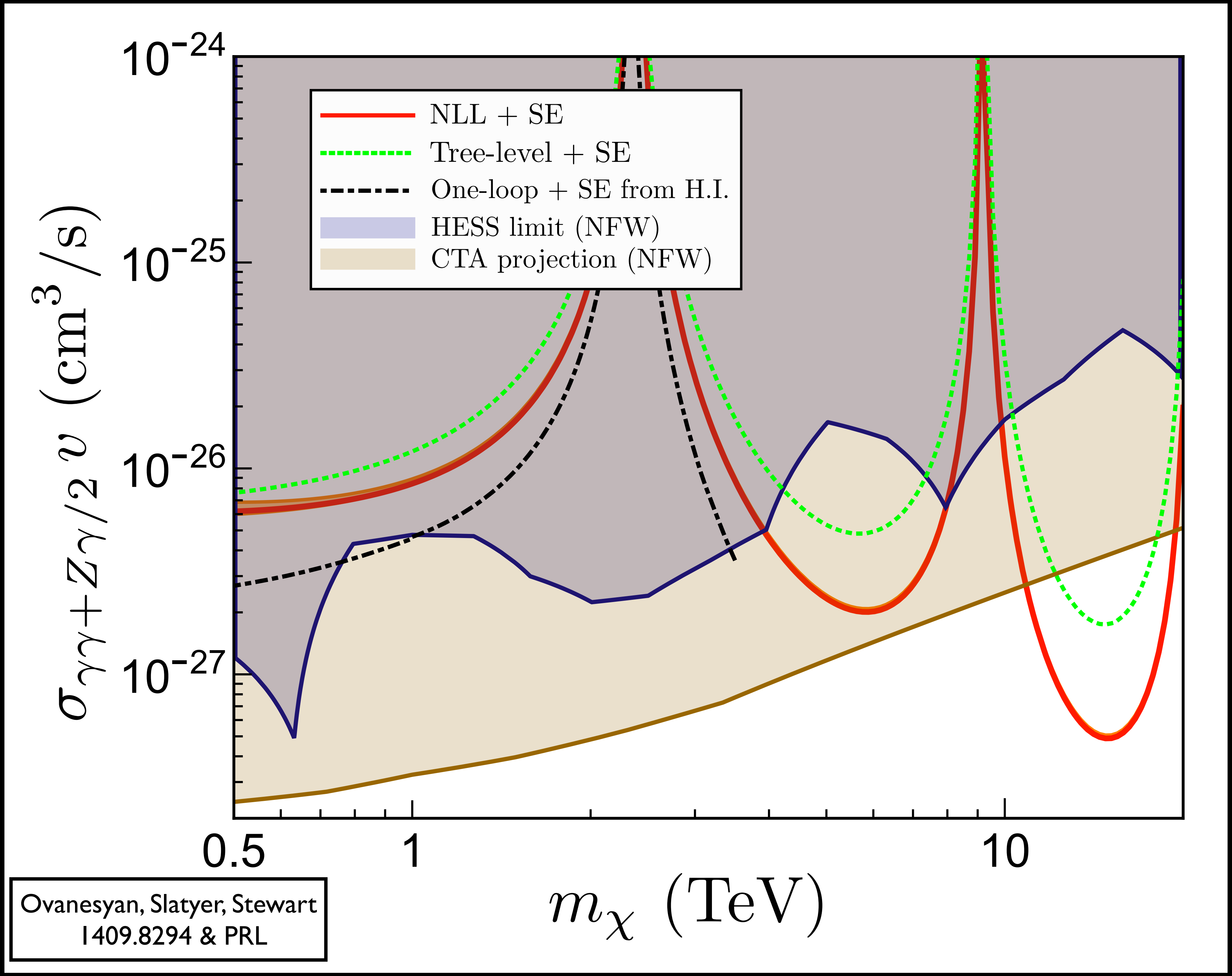




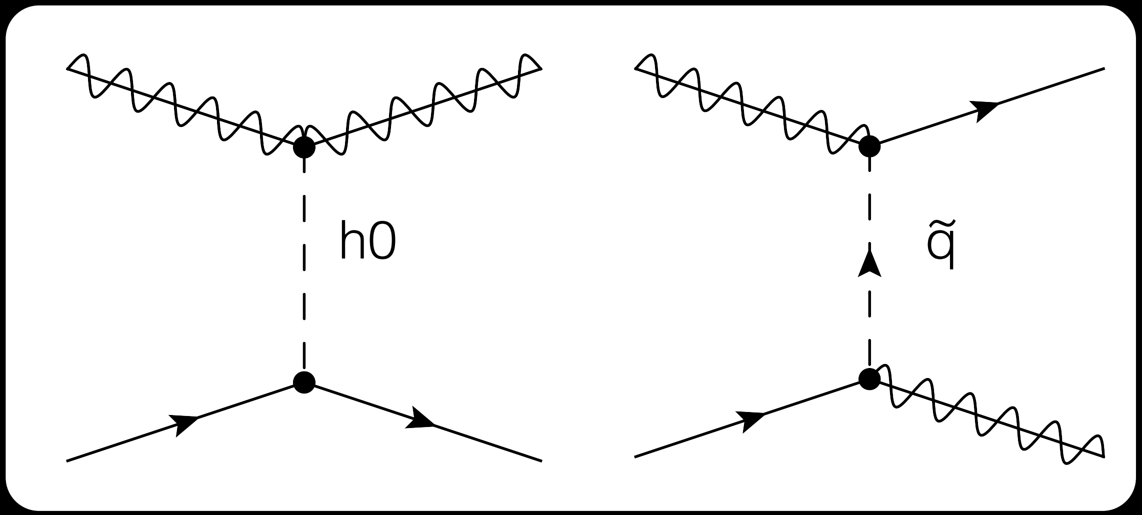
A Window to Winos!

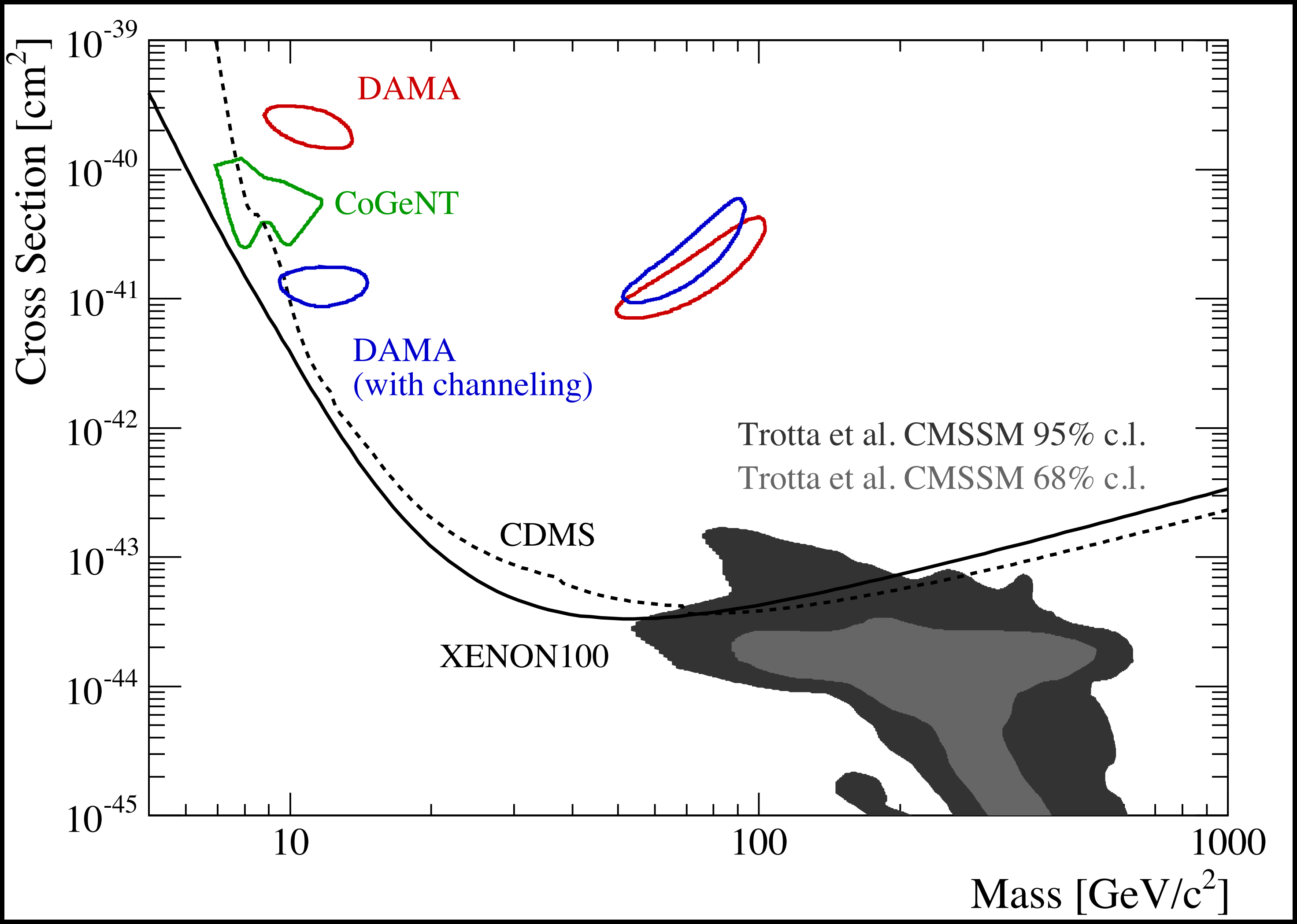


H.E.S.S. limits on the line signal already largely exclude wino dark matter.

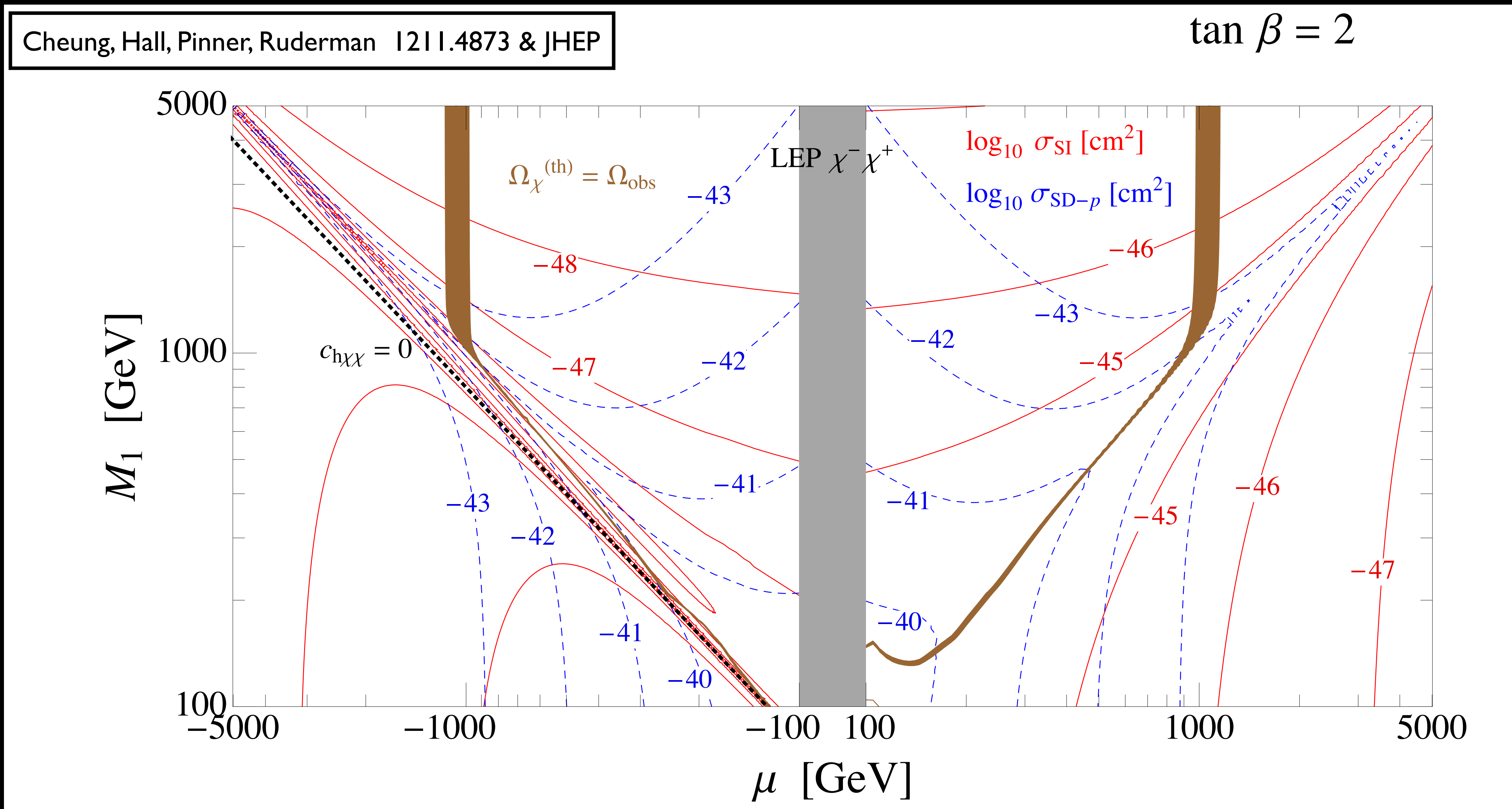
Direct Detection of Neutralinos

- The Majorana character also has important consequences for direct detection.
  - No vector currents imply the Z exchange can only mediate spin-dependent interactions.
  - The Higgs exchange requires both gaugino and higgsino admixture: the rate is very sensitive to the neutralino mixing angles.
  - Direct detection is sensitive to MSSM parameter space!

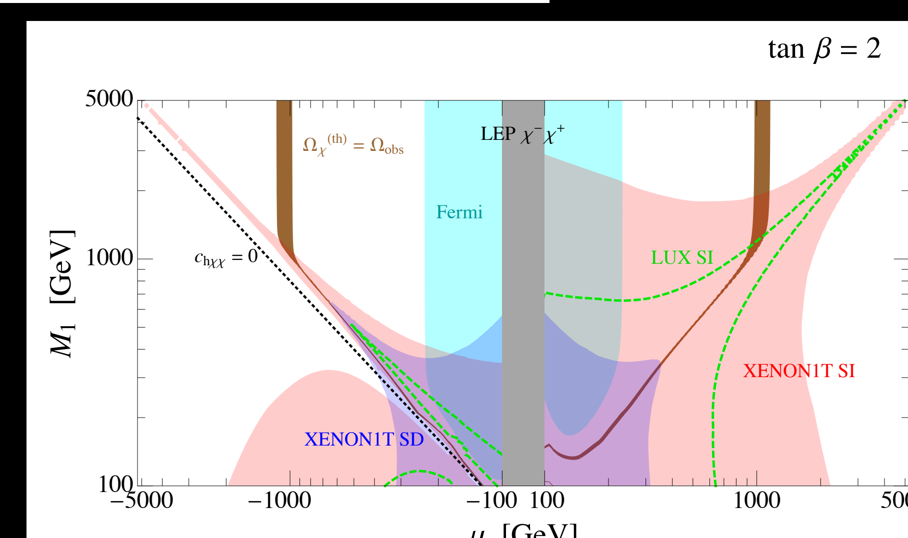




Neutralino Composition

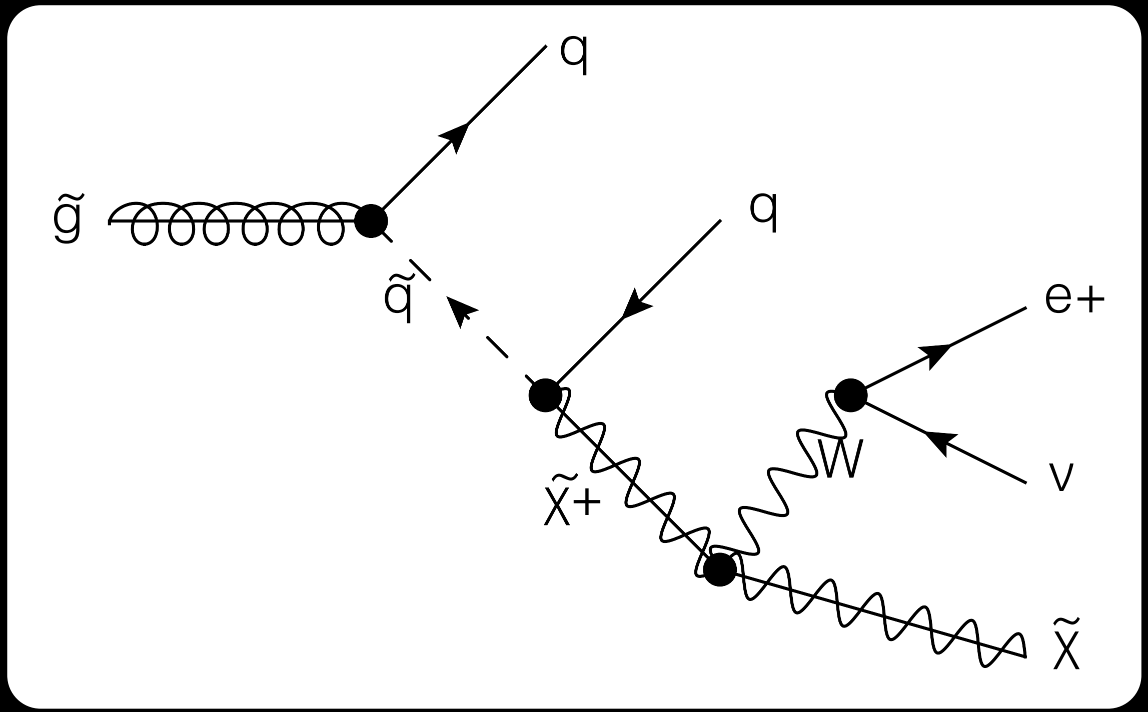


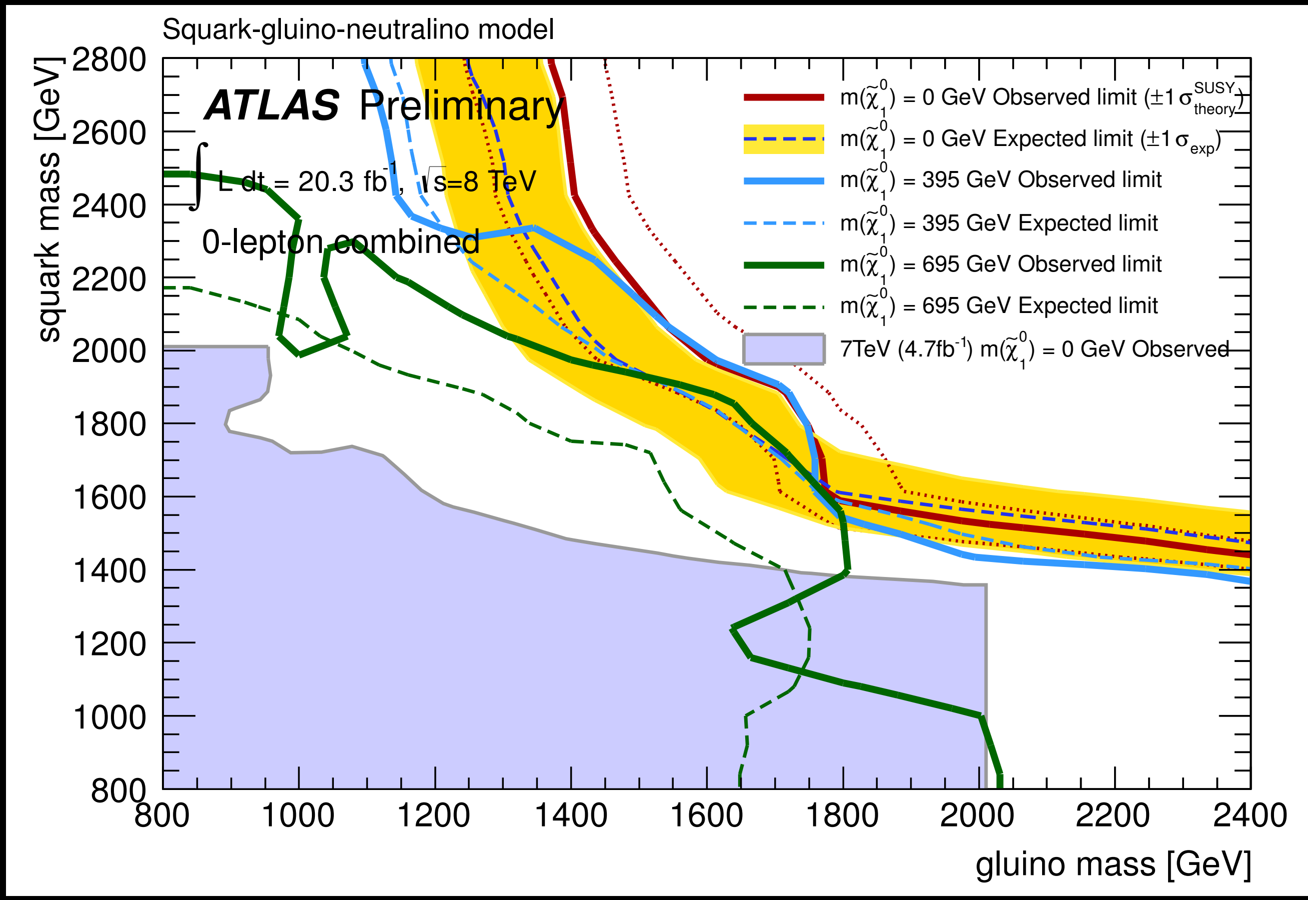
Because of the importance of the coupling to the Higgs, the contours of the SI cross section are highly dependent on the neutralino admixture. A "blind spot" where the neutralino becomes entirely Higgsino occurs for $M_1 + \mu \sin 2\beta = 0$.



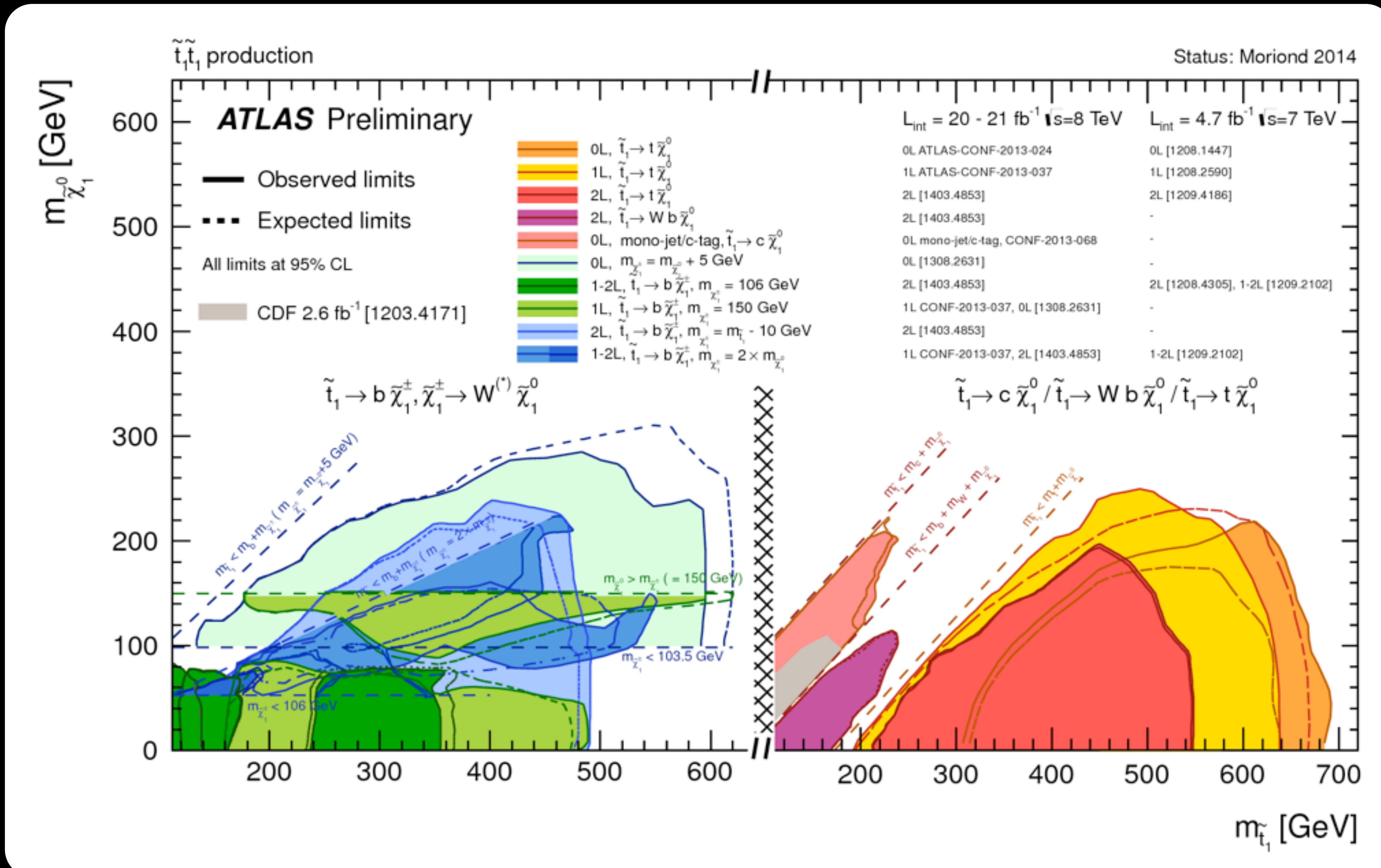
Collider Signals

- At hadron colliders like the LHC, the largest signals tend to come from producing the colored superpartners.
  - There can be "Cascade" decays down to the LSP.
  - The LSP passes through the detector, leading to missing momentum.
  - Hard jets are also present.
  - Depending on the decay chain, there may be hard leptons as well.
  - Often pairs of leptons will have the same charge, a signal with small expected SM backgrounds.





3rd Generation Squarks

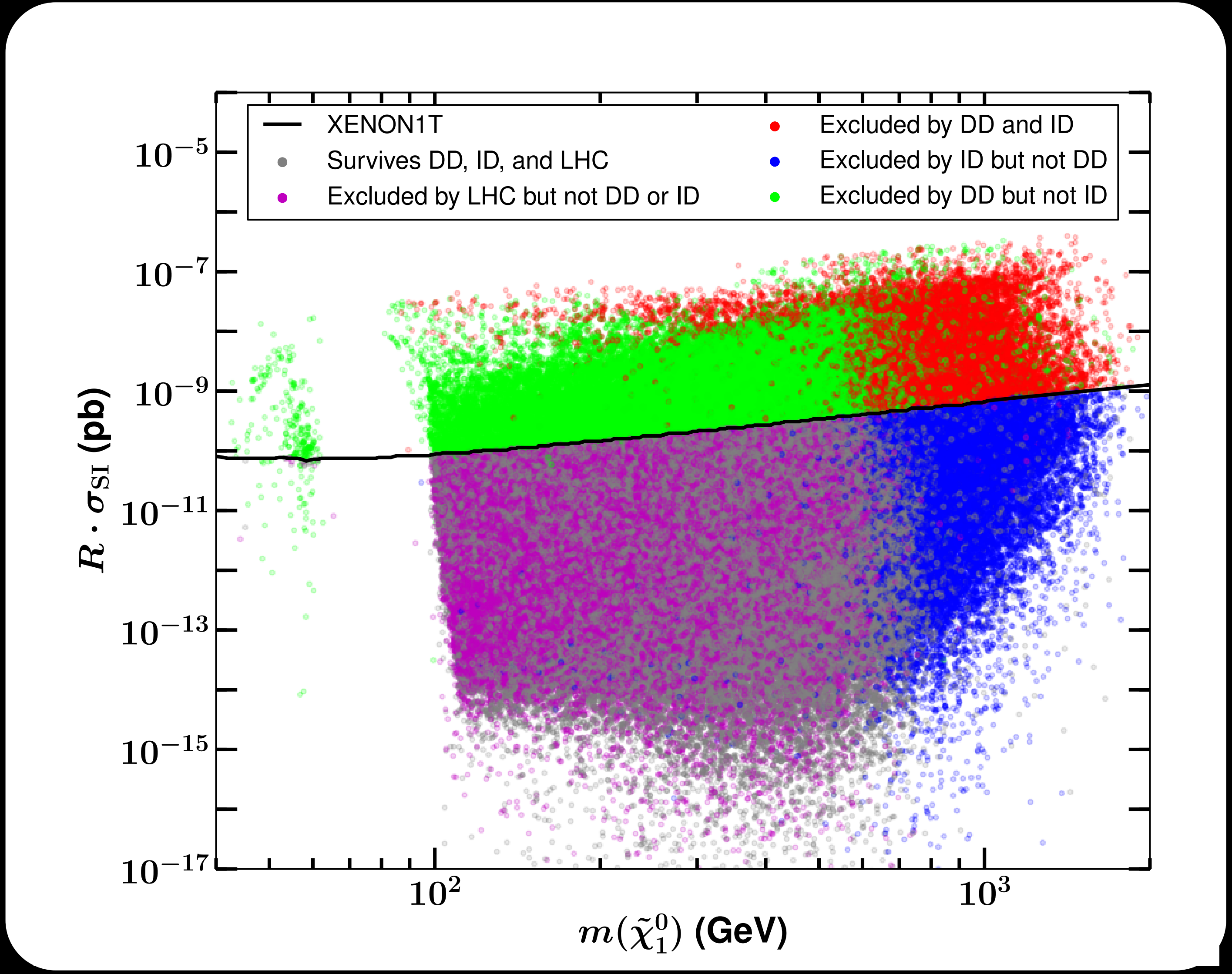


We're also starting to see searches for electroweak superpartners from the LHC.

- Naturalness requires SUSY to have light(ish) stops. This should be balanced by the fact that in the MSSM, the Higgs mass is calculable, suggesting the stops aren't *too* light.
- Searches for stops are starting to reach 600-700 GeV, and carving out the natural regions of supersymmetry!

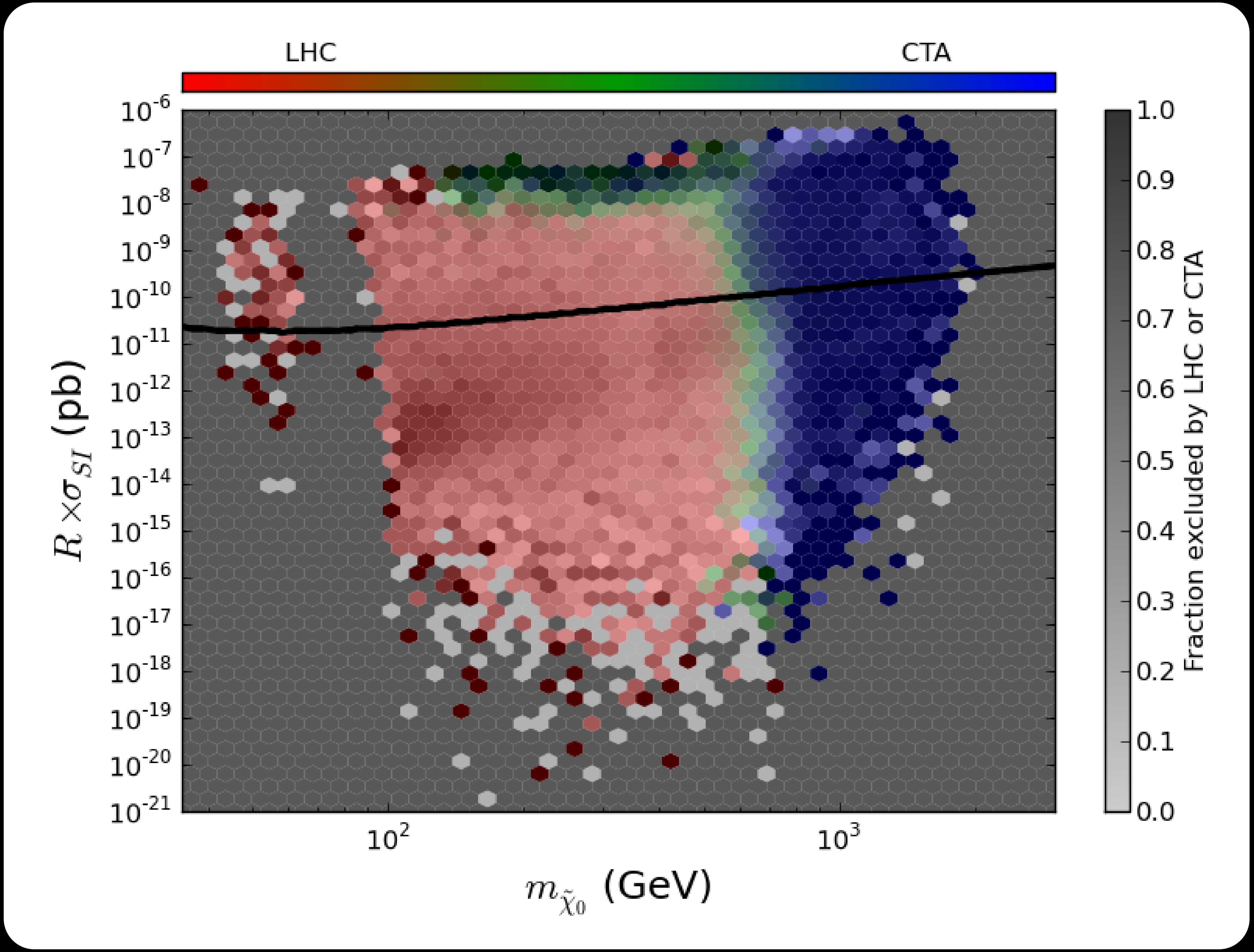
Reconstructing the MSSM

- While we can hope to eventually have many, many signals to measure, the parameter space is also very large.
  - Even simplified versions like the "pMSSM" have ~20 parameters!
  - Mapping from signal to parameter space is very complicated and not generally one to one: there is a complicated inverse problem.
  - The connection to dark matter specifically is often not very clear, leading to statistical approaches based on simulating many (many) model points in the parameter space.



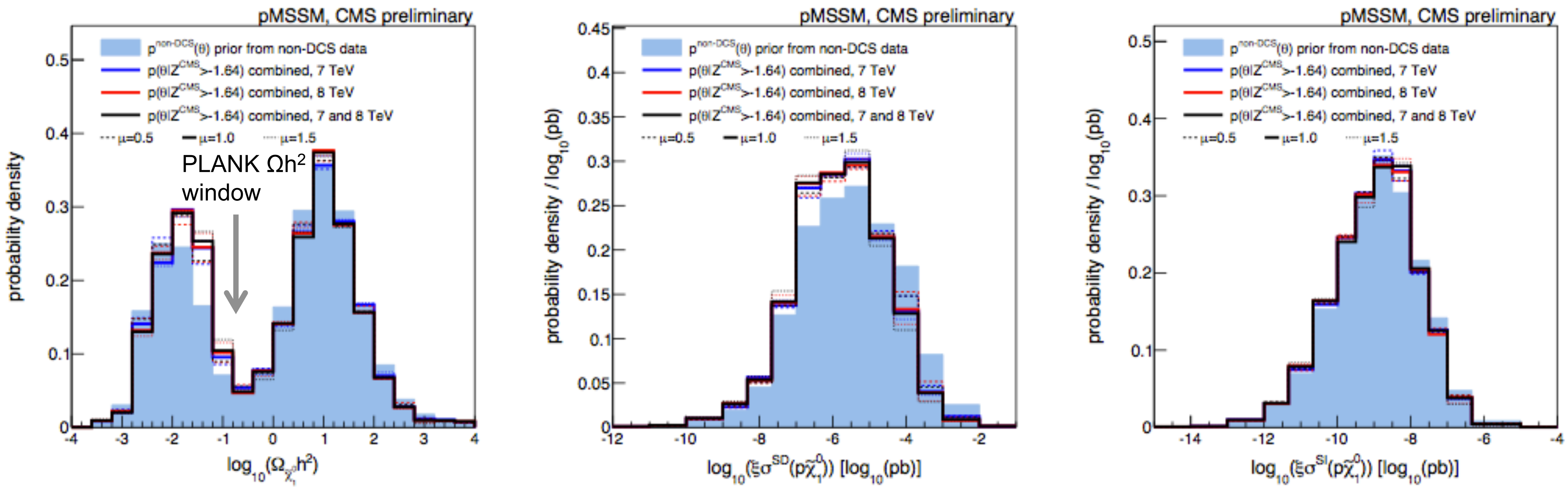
Cahill-Rowley et al, 1305.6921

Coverage Distribution



Cahill-Rowley et al, 1305.6921

pMSSM at the LHC



Neutralino relic density

Spin-dependent direct DM detection cross-section

Spin-independent direct DM cross-section

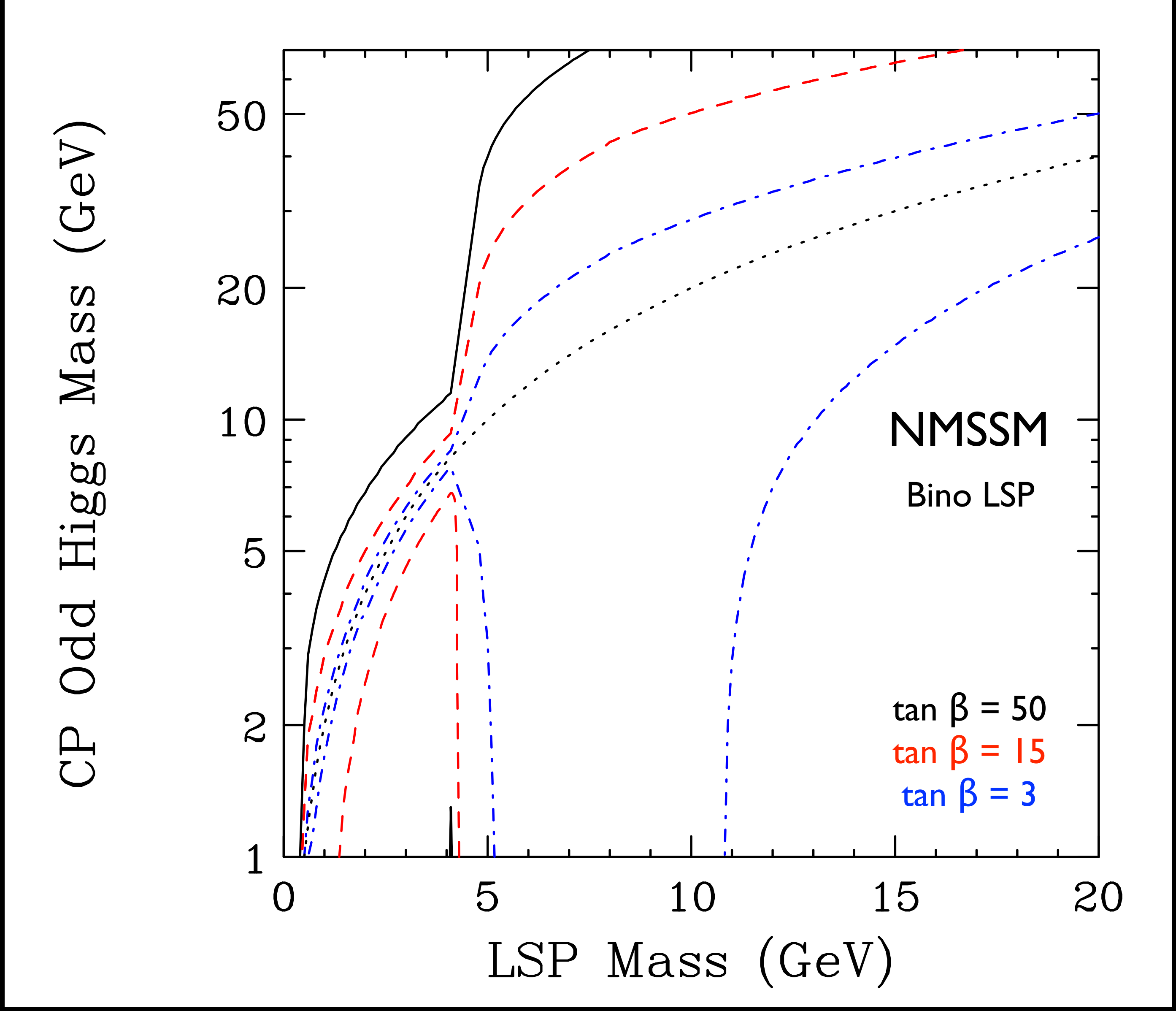
Posterior probabilities give an indication for how dense the coverage is of a given observable.

Note that this depends intimately on the model!

Beyond the MSSM

- As we have seen, the minimal model already contains a lot of interesting physics.
  - But nothing tells us Nature has chosen something minimal!
- Simple extensions such as adding a gauge singlet (i.e. the NMSSM) can have a big impact on the picture of dark matter.
  - New neutralinos
  - New Higgs bosons
  - New couplings
  - New relations between parameters.

Curves of constant $\Omega h^2 = 0.1$



Gunion, Hooper, McElrath, hep-ph/0509024

Recap: DM, WIMPs, SUSY

- There are many ideas for what dark matter could be.
  - Dark, Neutral, and Stable [Symmetry!].
  - WIMPs are a particularly attractive class of dark matter.
    - Their relic density explains the ballpark dark matter abundance.
    - Large interactions give us handles to search for them.
- Supersymmetry is an attractive, representative theory of WIMP dark matter.
  - We can explore the features of a Majorana fermion WIMP.
    - Interesting regions with the correct relic density.
    - Distinctive signals of direct, indirect, and collider searches.
    - We'll see contrasting features when we discuss other visions for WIMP DM, including Universal Extra Dimensions.