STANDARD WIMPS

Dark Matter

Les Houches Summer School

Jonathan Feng, UC Irvine, 27-28 July 2021

NSF
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CONGRATULATIONS TO THE ORGANIZERS

Marco Cirelli <marco.cirelli@gmail.com> Sun, Sep 30, 2018, 9:30 PM
to me, Babette, Jure

Dear Jonathan,

we are submitting a proposal for a **Les Houches School in the summer of 2021** and we would like to invite you to be one of our **key lecturers**.

…

We really hope that you can accept our invitation!
Please let us know at your earliest convenience.

Best regards,
Marco Cirelli (LPTHE Paris), Babette Döbrich (CERN), Jure Zupan (U Cincinnati) — Organizers

Re: Les Houches school on DM 2021 approved FZINANCE/travel ×

Jonathan Feng <jlf@uci.edu> Dec 20, 2018, 7:51 PM
to Marco, Anne, Josh, Tracy, Philip, Igor, Jodi, Joachim, Annika, Justin, Clare, Bernard, Yonit, Tongyan, Joachim, Ji

Dear Marco, Babette, Jure,

Congratulations, and thanks for letting me know.

For me, this sets the record for how far in advance I have entered a speaking engagement on my calendar. I'm expecting that just a few months before the School, the LHC will have turned on again, FASER will have found dark photons, and the lectures will be really interesting.

Best, Jonathan

STEVEN WEINBERG (1933-2021)

- Four Golden Lessons

Weinberg (2003)

  - No one knows everything, and you don't have to.
  - Head for the messes.
  - Forgive yourself for wasting time [working on the wrong questions].
  - Learn some of the history of your field.

OUTLINE

I. Why WIMPs?

- The Weak Scale
- The WIMP Miracle
- The Discrete WIMP Miracle

II. WIMPs in Supersymmetry

- Supersymmetry
- Stability and LSPs
- Neutralino Freezeout
- Cosmologically-Preferred Supersymmetry

III. WIMP Detection

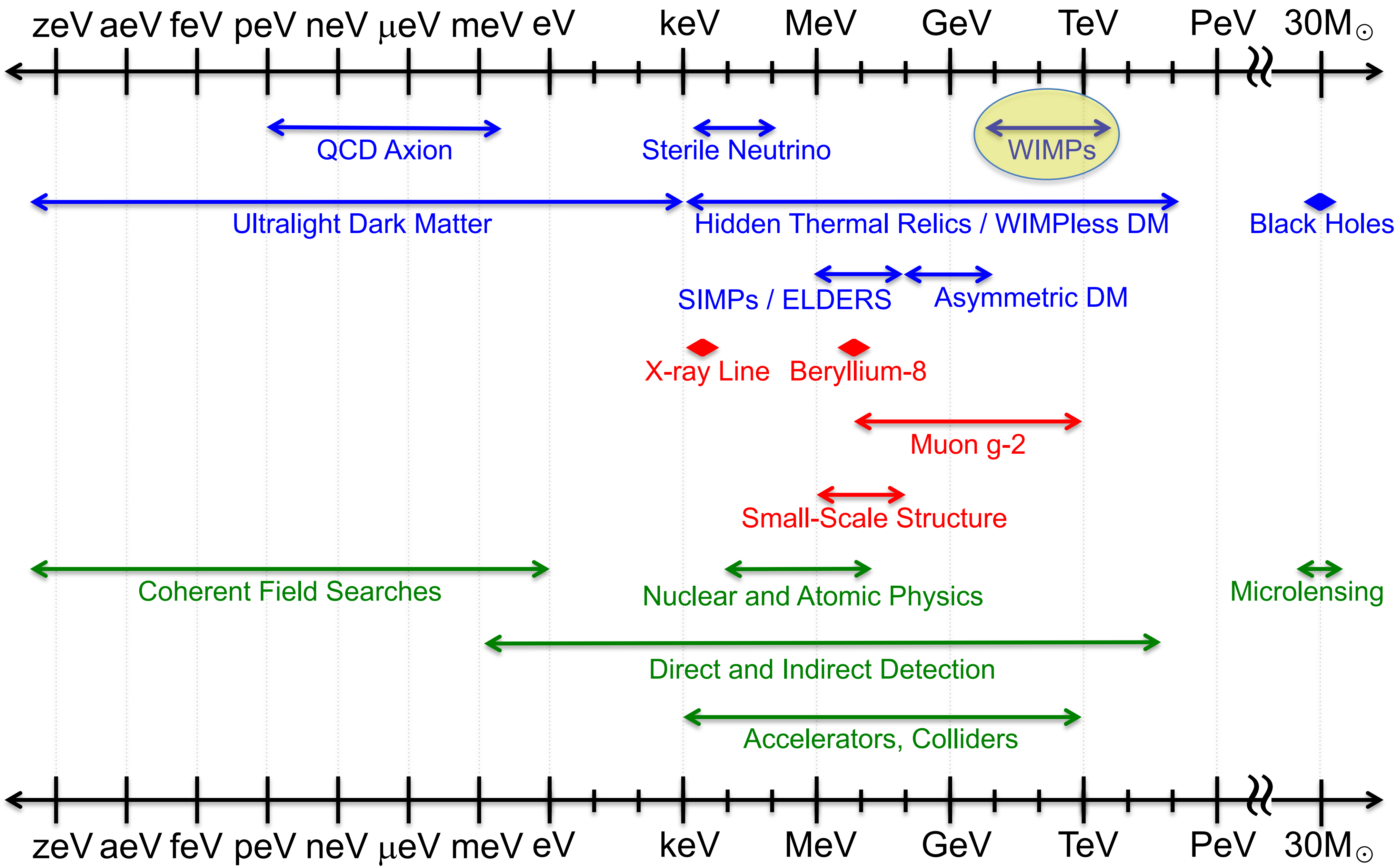
- Direct Detection
- Indirect Detection
- Collider Searches

IV. WIMP Variations

- Inelastic WIMPs
- Isospin-Violating WIMPs
- SuperWIMPs
- WIMPless Dark Matter

I. WHY WIMPS?

WHY WIMPS?



Modified from the Cosmic Visions Report (2017)

GOALS

- WIMPs have dominated the particle dark matter landscape for decades.
- It would be inconceivable to lecture about
  - DM production (Ruderman) without talking about WIMP freeze out.
  - DM direct detection (Cooley) without talking about WIMP direct detection.
  - DM indirect detection (Slatyer) without talking about WIMP indirect detection.
  - DM at accelerators (Harris) without talking about WIMPs at colliders.
- So there will be a lot of overlap with other lectures. The goal here is to
  - explain why WIMPs have been a dominant paradigm for so long,
  - gather together some of their basic features,
  - highlight the example of WIMPs in supersymmetry,
  - and present some of the variations on the WIMP theme that have by now suffused the literature and illustrate the richness of this circle of ideas.
- These lectures are targeted to graduate students starting DM research, but I hope there will be something of interest to others as well.

THE WEAK SCALE

- Fermi's constant G_F was introduced in the 1930s to describe nuclear beta decay

$$n \to p\, e^- \bar{\nu} \,.$$

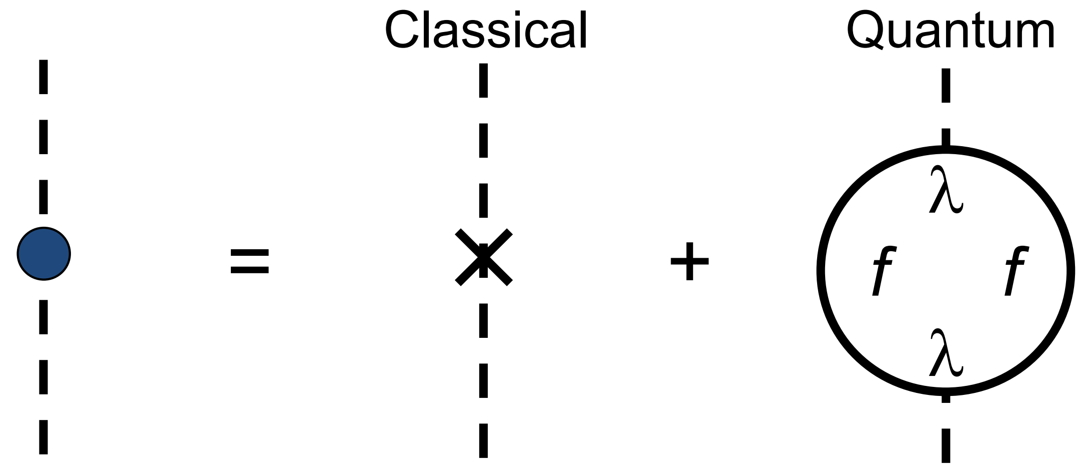
- The measured value, $G_F \sim 10^{-5}\ \mathrm{GeV}^{-2}$, introduces a new mass scale in nature, the weak scale:

$$m_{weak} \sim 100 \text{ GeV} \,.$$

- We still don't understand the origin of this mass scale, but every reasonable attempt so far introduces new particles at the weak scale.

NATURALNESS

- We have now discovered a particle that looks like a fundamental scalar with a mass $m_h \simeq 125$ GeV: the Higgs boson. Scalars are different:

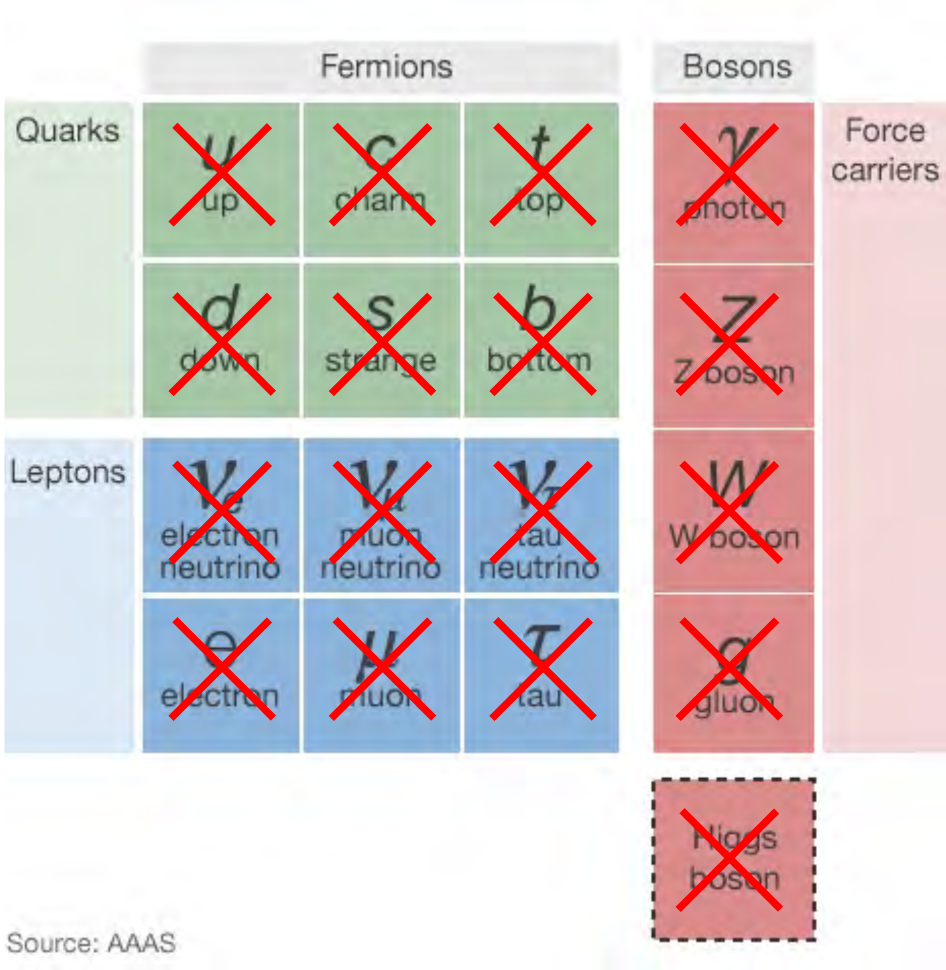


$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

- For $\Lambda \sim m_{Planck} \sim 10^{19}$ GeV, and f = top ($\lambda \sim 1$), the classical and quantum contributions must cancel to 1 part in 10^{32} to yield the physical Higgs mass.

- This is the naturalness, fine-tuning, or gauge hierarchy problem of the Standard Model. Its resolution likely requires new particles at the weak scale that introduce new quantum contributions to cancel the existing ones.

DARK MATTER



Known DM properties

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

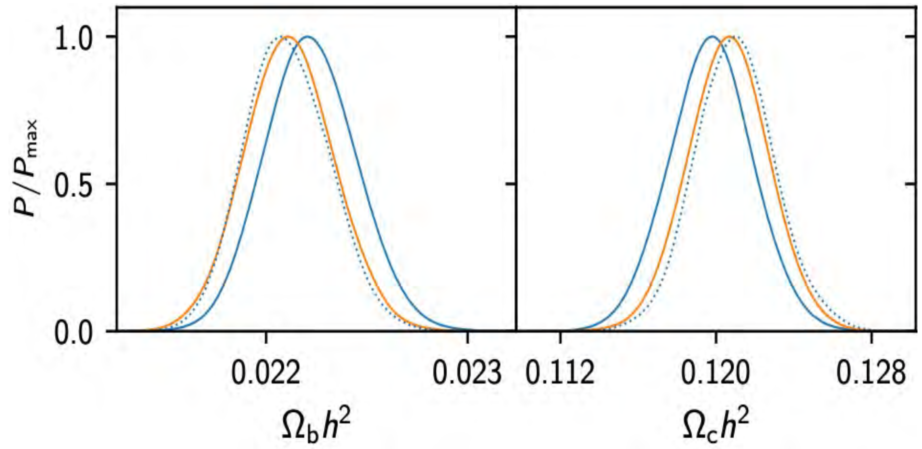
None of the known particles can be cold DM.

RELIC DENSITY

- We know little about dark matter. We know more about what it isn't than what it is.

- The one thing we do know *precisely* is the dark matter's relic density: $\Omega_{\mathrm{DM}}h^2 = 0.1200 \pm 0.0012.$

Planck Collaboration (2018)



- What can we learn from this about dark matter's particle properties?
  - Generically: nothing.
  - But if the dark matter now is a surviving relic of the hot Big Bang through thermal freeze out: a lot.

THERMAL FREEZE OUT

(1) Assume a new heavy particle X is initially in thermal equilibrium:

$$XX \leftrightarrow f\bar{f}$$

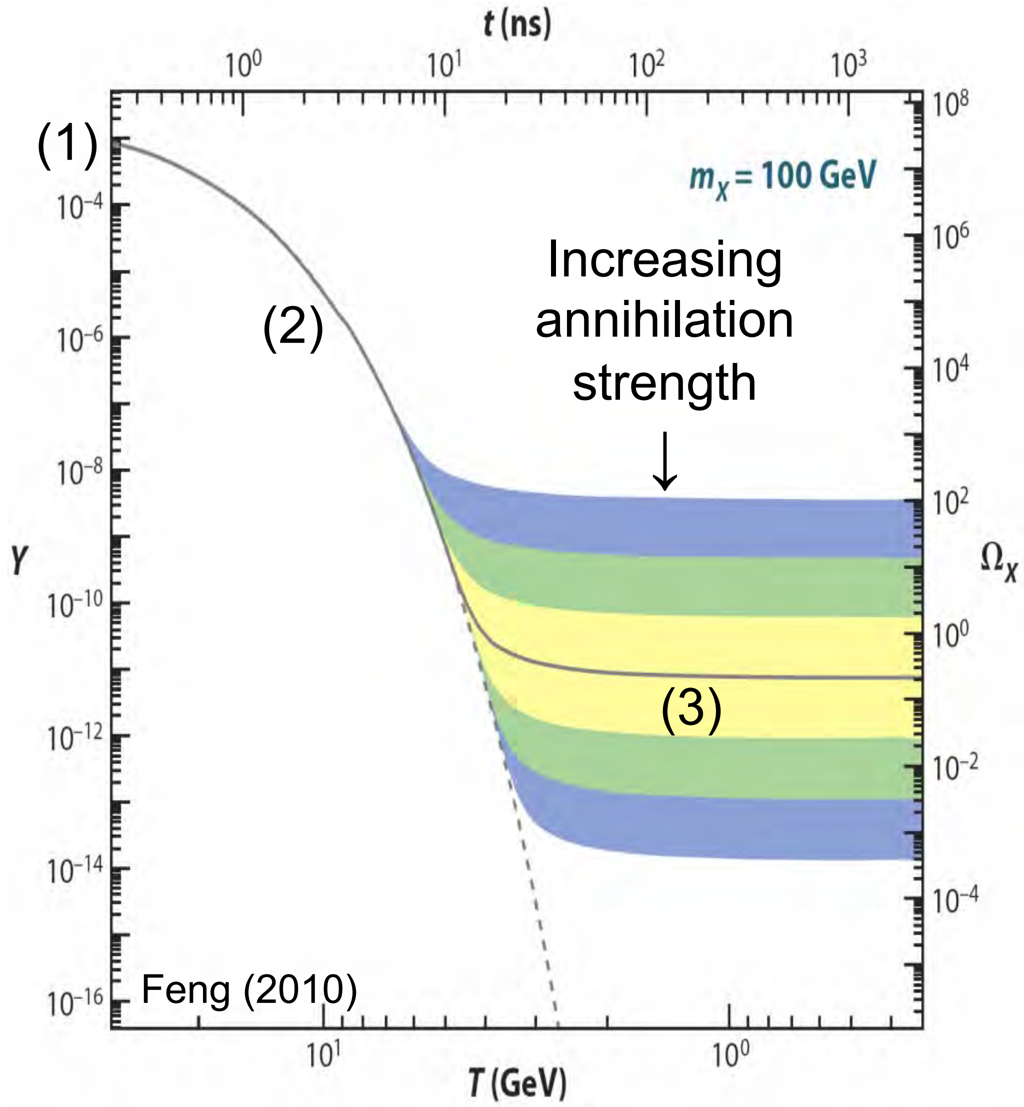
(2) Universe cools:

$$XX \underset{\not\leftarrow}{\rightarrow} f\bar{f}$$

(3) Universe expands:

$$XX \underset{\not\leftarrow}{\not\rightarrow} f\bar{f}$$

Zeldovich et al. (1960s)



THERMAL FREEZE OUT

- The Boltzmann equation:

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

Dilution from expansion

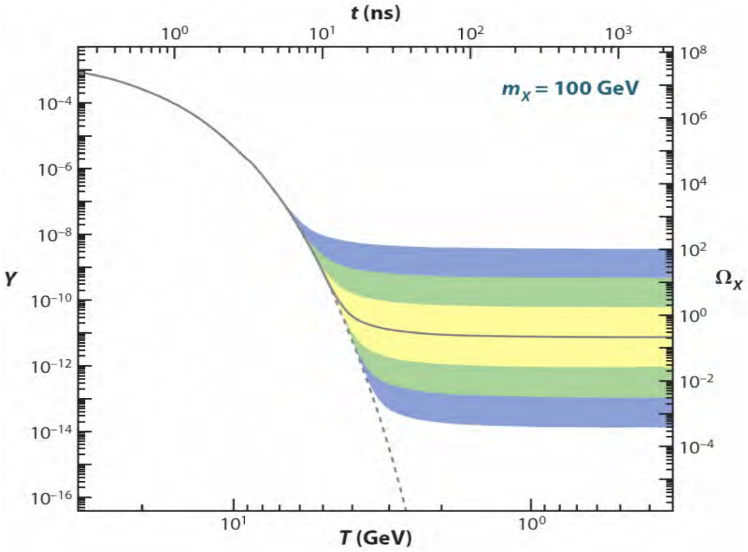
$\chi\chi \to f\bar{f}$

$f\bar{f} \to \chi\chi$

- $n \approx n_{eq}$ until interaction rate drops below expansion rate:

$$n_{\rm eq} \langle \sigma_A v \rangle \sim H$$

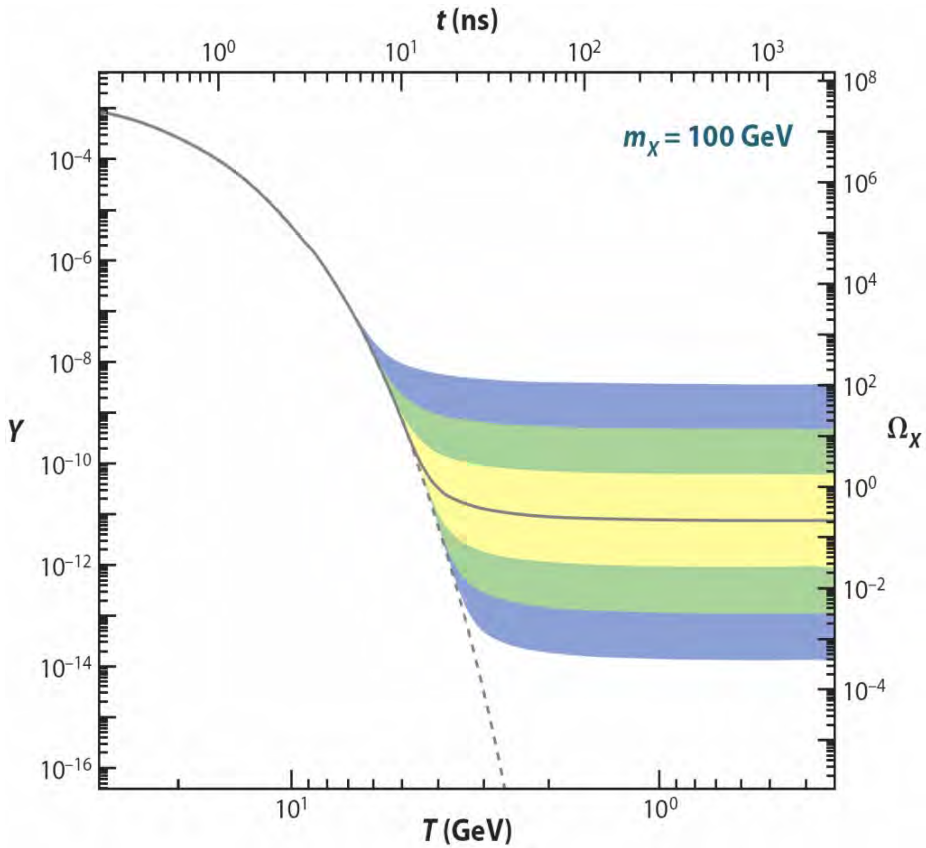
$$(mT)^{3/2} e^{-m/T} \qquad \frac{\alpha^2}{m^2} \qquad \frac{T^2}{M_{\rm Pl}}$$



- Might expect freeze out shortly after T drops below m, when n_{eq} becomes exponentially (Boltzmann) suppressed. But M_{Pl} is large, and the universe expands *slowly*! First guess is pretty good:

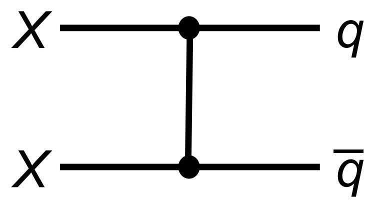
$$\frac{m}{T} \sim \ln\left(\frac{\alpha^2 M_{\rm Pl}}{\sqrt{mT}}\right) \quad \overset{m \sim m_{\rm weak}}{\Longrightarrow} \quad \frac{m}{T} \sim 25$$

THE WIMP MIRACLE



- It turns out that the relation between Ω_X and annihilation strength is wonderfully simple:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



where we've assumed that the annihilation is characterized by a single mass scale.

- Keeping track of the constants, we find $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$.

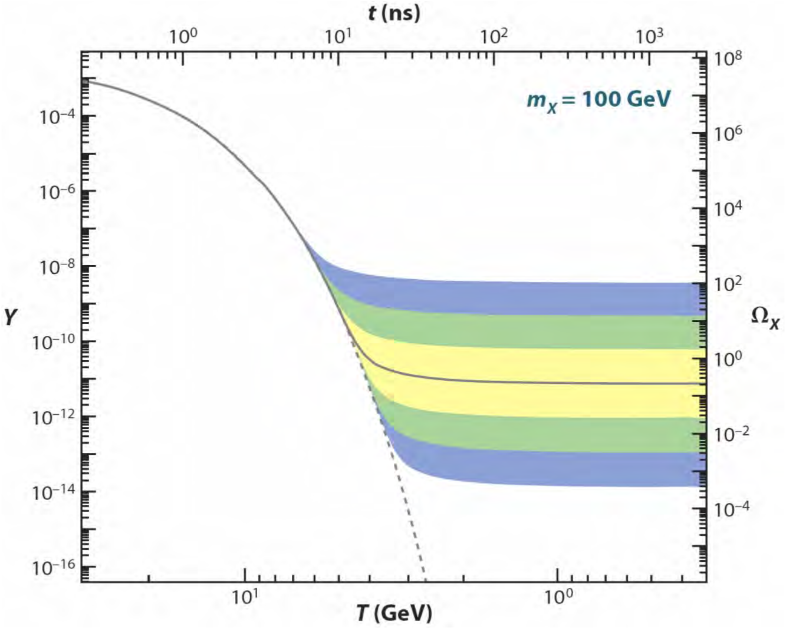
- A remarkable coincidence: particles with the right thermal relic density are now at the energy frontier! The LHC is a big DM search experiment.

THE WIMP MIRACLE

- In more detail, at freeze out, $\frac{m}{T}$ ~ 20, so

  K.E. = $\frac{3}{2} kT \rightarrow T \sim \frac{1}{3} m v^2 \sim \frac{1}{20}\ m \rightarrow v \sim \frac{1}{3}$.

- At freezeout, dark matter was neither ultra-relativistic, nor non-relativistic. But it was far more relativistic then than it is now in our neighborhood, where $v \sim 10^{-3}$. This is a key difference to keep in mind!



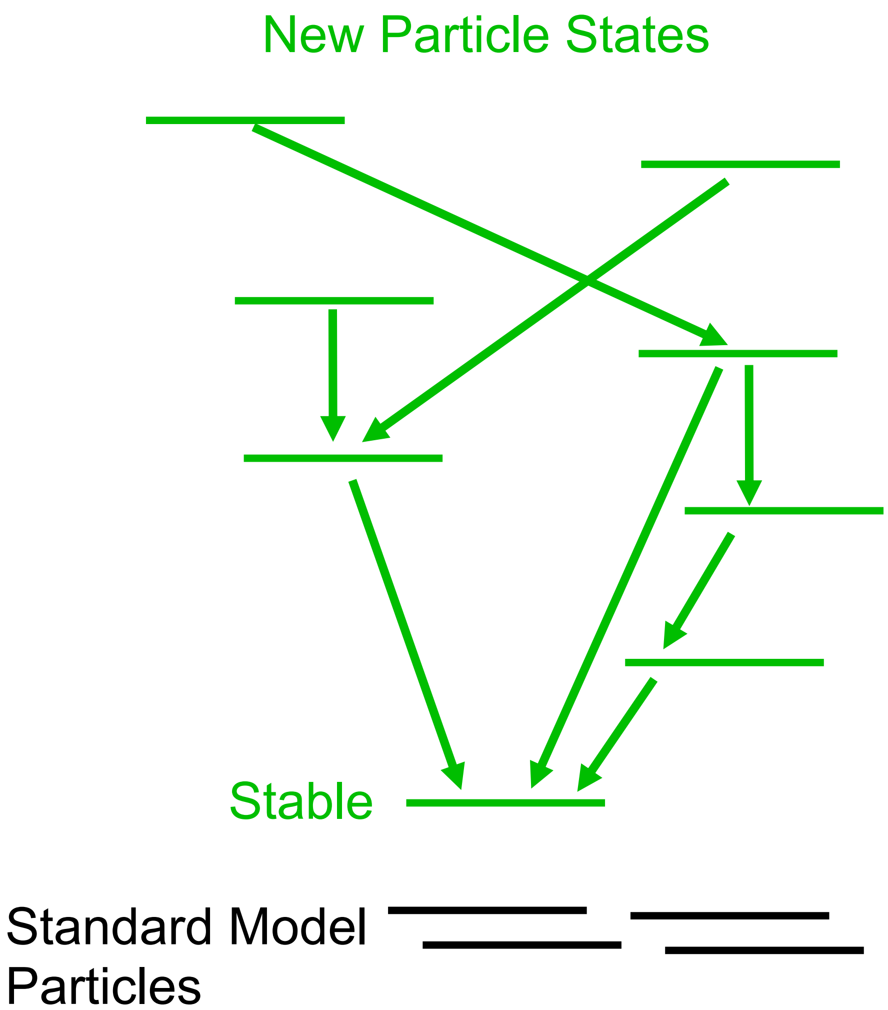
- Freeze out is at T ~ 5 GeV and t ~ ns, not at T ~ 100 GeV and t ~ ps.

- This is also called chemical freeze out (no number changing), which is distinct from kinetic freeze out (no energy exchange through $fX \rightarrow fX$).

- The WIMP miracle is not a precise coincidence. But it is tantalizing, and it is our strongest quantitative hint that our attempts to understand the universe on the largest and smallest scales may be related.

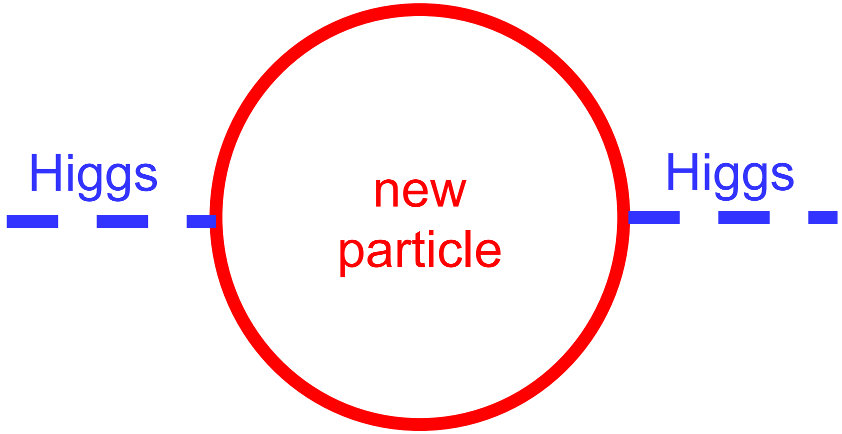
WIMP STABILITY

- The WIMP miracle is well appreciated. But its success relies on another less well-advertised "miracle."
- DM must be stable.
- How natural is this? *A priori*, not very: the only stable particles we know about are very light.
- But there are reasons, based on experimental data, to think that at least one weak scale particle might be stable.

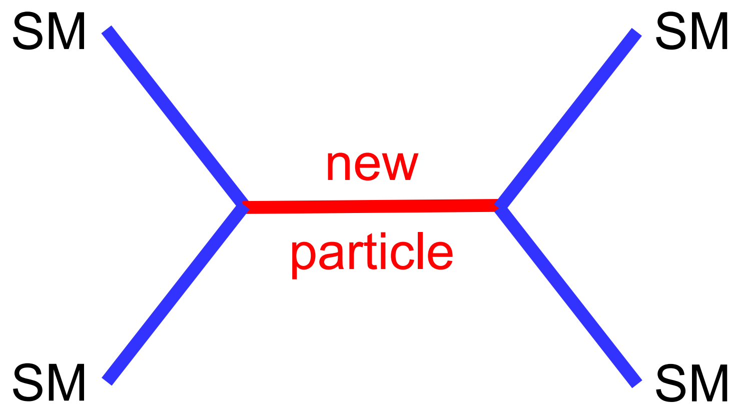


THE DISCRETE WIMP MIRACLE

Gauge Hierarchy requires



Precision EW constrains



- The 4-point SM interactions are highly constrained by many experiments, notably those at LEP through precision electroweak data.

- Simple solution: impose a discrete parity, so all interactions require *pairs* of new particles. This also makes the lightest new particle stable: Discrete Symmetry ↔ Stability.

Cheng, Low (2003); Wudka (2003)

- Remarkable coincidence: particle physics independently motivates particles that are stable enough to be dark matter.

II. WIMPS IN SUPERSYMMETRY

WIMPS IN BSM MODELS

- For the reasons mentioned above, WIMPs appear generically in many BSM theories
  - Propose some new weak scale particles.
  - They help some things, but strain electroweak fits.
  - Impose a discrete symmetry to improve fits.
  - An ideal DM candidate emerges!

- Many examples
  - Neutralinos in supersymmetry

    Goldberg (1983); Elllis et al. (1983)
  - KK B1 (“KK photons”) in universal extra dimensions

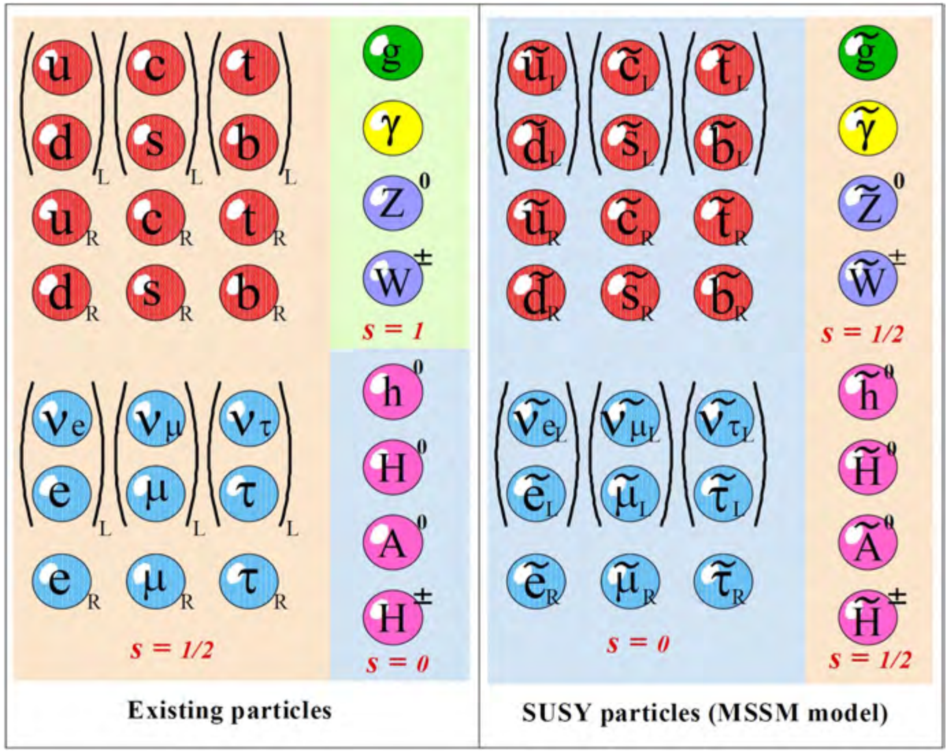
    Servant, Tait (2004); Cheng, Feng, Matchev (2004)
  - Lightest T-odd particle in little Higgs theories

    Cheng, Low (2004)

- Here focus on supersymmetry as an interesting example.

SUPERSYMMETRY

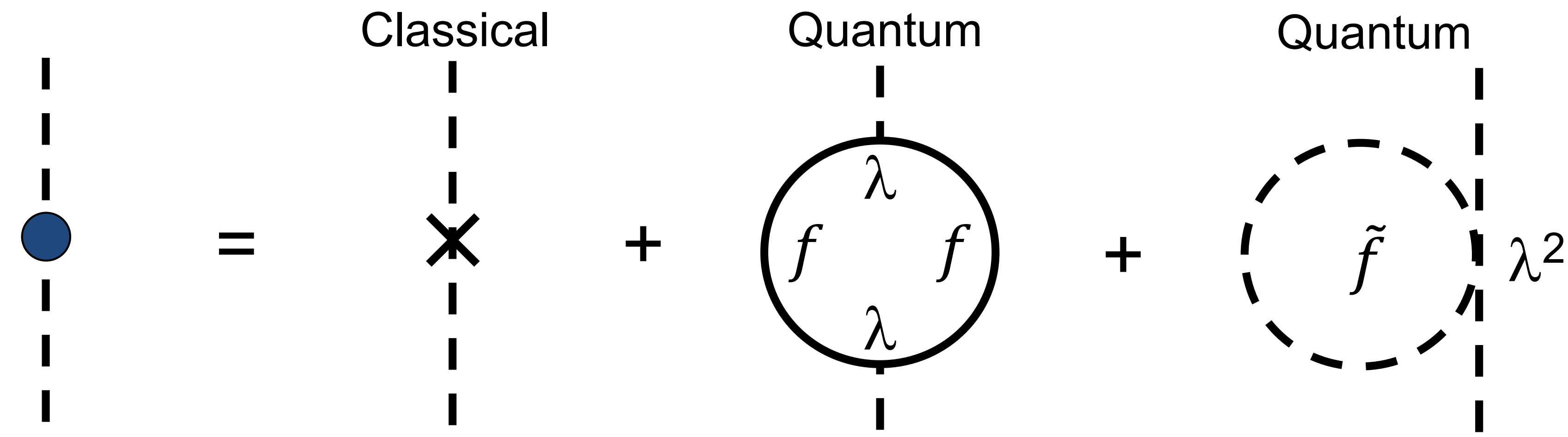
- Supersymmetry predicts a partner particle for every known particle: Spin 0 $\leftrightarrow$ Spin $\frac{1}{2}$, Spin $\frac{1}{2}$ $\leftrightarrow$ Spin 1.



- New particles
  - Spin 0 squarks
  - Spin 0 sleptons
  - Spin $\frac{1}{2}$ gauginos: Bino, Winos, gluinos
  - Spin $\frac{1}{2}$ Higgsinos

- The Higgsino partner of the SM Higgs boson is a new fermion that introduces anomalies. In the Minimal Supersymmetric Standard Model (MSSM), we must add an additional Higgs boson and Higgsino to cancel these anomalies, but no more.

NATURALNESS IN SUPERSYMMETRY



$$m_h^2 = (m_h^2)_0 - \underbrace{\frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2}$$

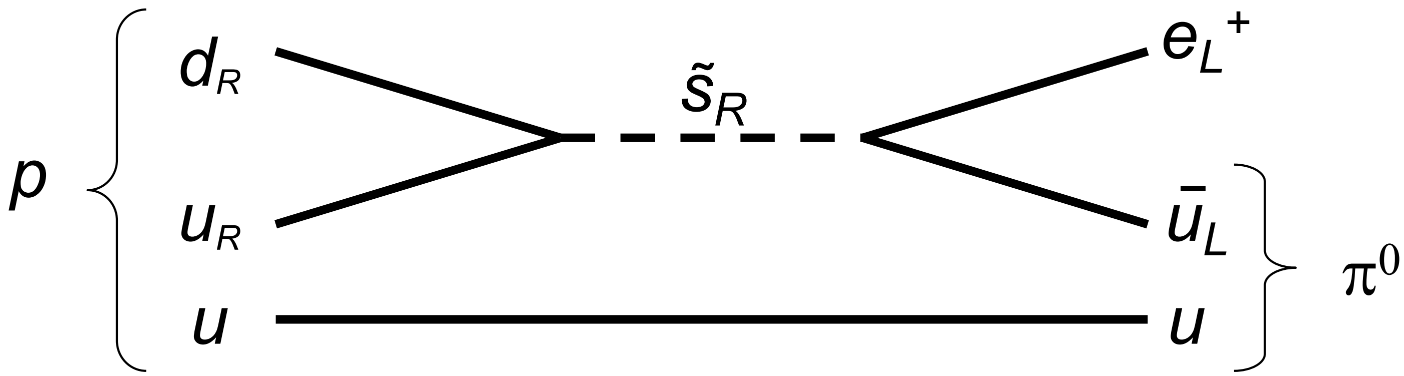
$$+ \frac{1}{16\pi^2}\lambda^2(m_{\tilde{f}}^2 - m_f^2)\ \ln(\Lambda/m_h)$$

- For $\Lambda \sim m_{Pl}$ (m_W), and f = top, 1% fine-tuning → $m_{\tilde{t}} < 1$ (3) TeV
- Also, bounds on other sfermions are much weaker: $m_{\tilde{f}} < 10$ (30) TeV

Drees (1986); Dimopoulos, Giudice (1995); Pomoral, Tomasini (1996)

R-PARITY AND STABLE LSPS

- One immediate problem: supersymmetric particles mediate proton decay $p \to \pi^0 e^+$ and similar decay modes.



- Forbid this with R-parity conservation: $R_p = (-1)^{3(B-L)+2S}$
  - SM particles have $R_p = 1$, SUSY particles have $R_p = -1$.
  - Require $\Pi\ R_p = 1$ at all vertices.

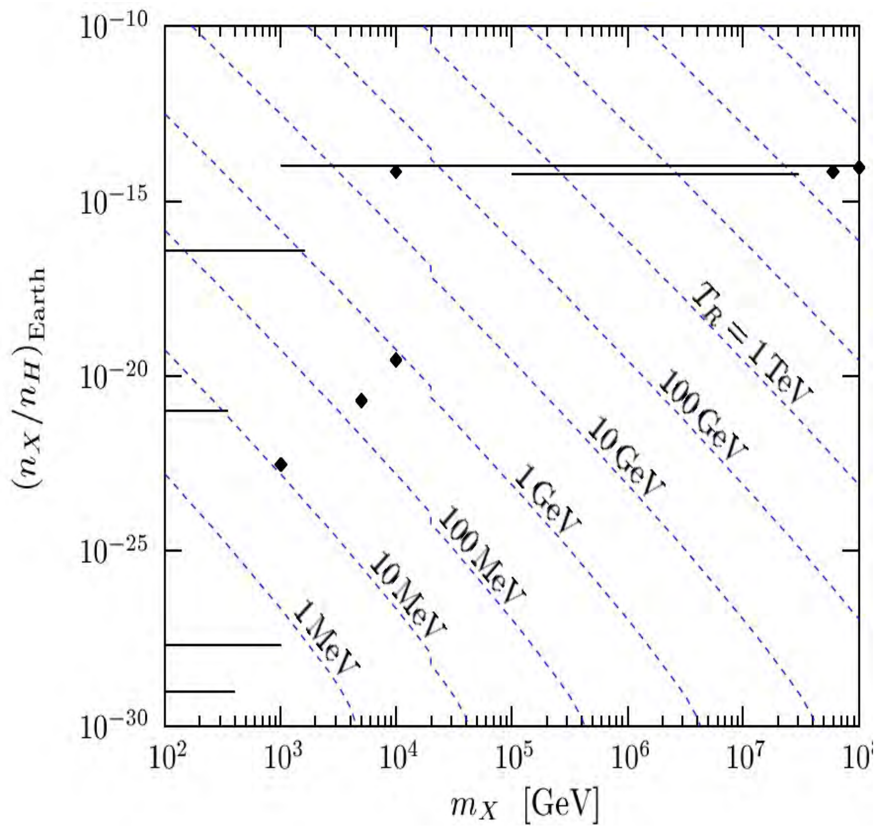
Farrar, Fayet (1978)

- Consequences
  - This eliminates proton decay and also many troubling 4-point interactions of SM particles.
  - The lightest SUSY particle (LSP) is stable and a potential DM candidate.

WHAT IS THE LSP?

- Should be neutral. Yes, but why? The story is more nuanced and interesting than is commonly appreciated.

- A colored LSP (say, a gluino) will bind with quarks to form a color-neutral state.
  - Yes, but there are severe bounds on exotic nuclei from sea water searches (solid lines and dots in figure), where the constraint is strengthened by testing deep sea water.



Kudo, Yamaguchi (2001)

- But inflation can dilute this away.
  - Yes, but they are regenerated by reheating. Masses < TeV are excluded by T_{RH} > 1 MeV, but masses > TeV are allowed.

- Bottom line: for m < TeV, the LSP should be color and electrically neutral.