Particle Theory, Cosmology, and the LHC

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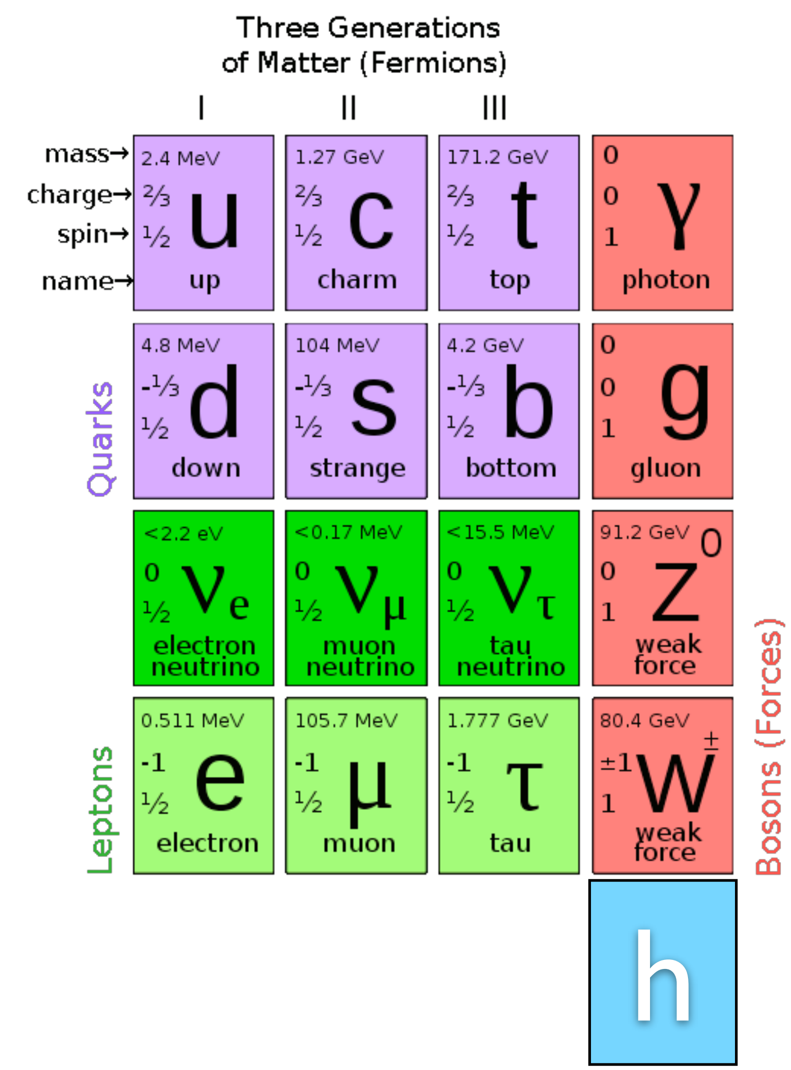
Standard Model

- The Standard Model works.
  - verified by collider experiments
- The Standard Model is not complete.
  - does not include neutrino masses
  - does not include dark matter
  - does not include dark energy
  - does not include gravity
  - cannot explain the matter-antimatter asymmetry
  - *does* include a Hierarchy Problem
  - and more…

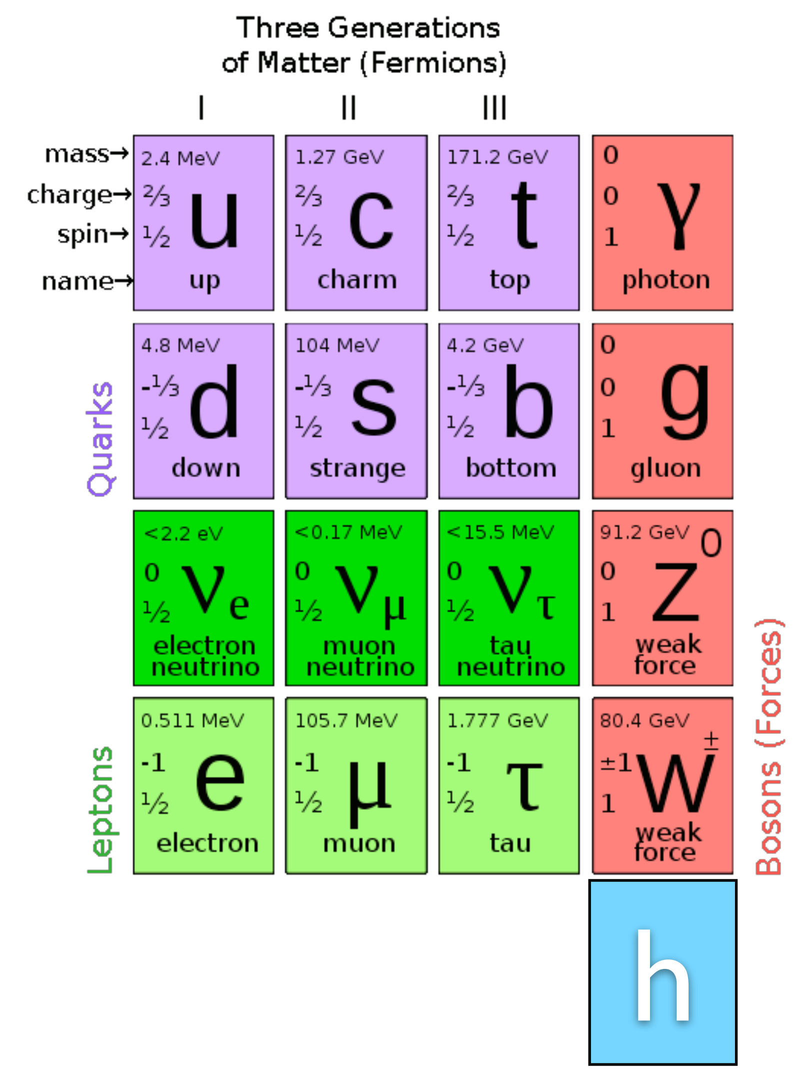


Higgstory

- By 2000, all elementary particles of the SM (except the HIggs) had been discovered, and many of their properties are well-studied.

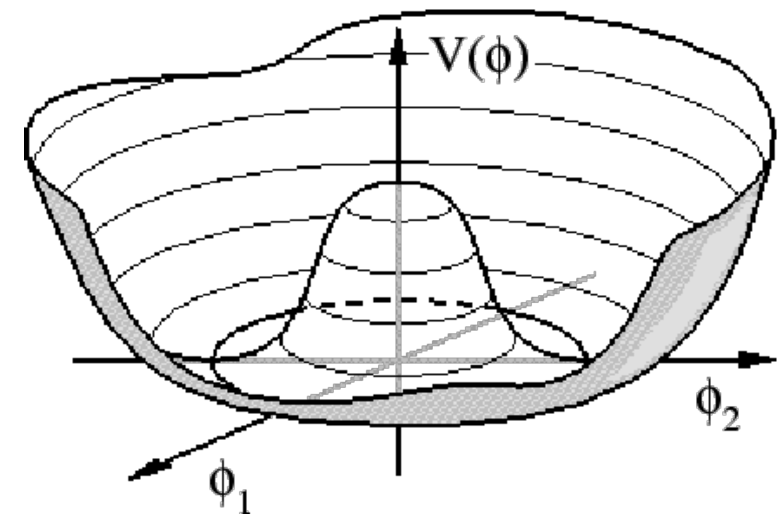
- This picture alone predicted **massless gauge bosons**, in contradiction with observations.

  - Solution: spontaneous symmetry breaking (Higgs mechanism) is incorporated into the SM to generate masses for the *W* and *Z* bosons, fermion mass terms come from coupling to Higgs field



- July 2012 - particle consistent with **Higgs boson discovered at LHC**

How the Higgs has changed the Picture



- First elementary scalar particle discovered!
- Simplest case:

$$V = \mu^2 \left|\phi\right|^2 + \lambda \left|\phi\right|^4$$

- Vacuum state of Higgs field is shifted to a non-zero value when $\mu^2 < 0$

$\boxed{\text{Why is } \mu^2 < 0 \text{ ???}}$

- To understand why any Standard Model particles have mass, ***we must understand the mechanism*** (that leads to the Higgs field acquiring a non-zero vacuum expectation value).

Guidance from Naturalness

$$V = \mu^2 |\phi|^2 + \lambda |\phi|^4$$

- We know the vacuum expectation value, $v = 246\ \mathrm{GeV}$, and expect

$$-\mu^2 = 2\lambda v^2 \approx (100\ \mathrm{GeV})^2$$

- To first order, corrections from ***t***, ***W***, ***Z***, and ***H*** yield

$$\delta\mu^2 = \frac{3\Lambda^2}{32\pi^2 v^2}\left(-4m_t^2 + 2m_W^2 + m_Z^2 + m_h^2\right)$$

  - If $\Lambda \gg m_W$, then precise cancellations are necessary to preserve the weak scale.

  - Fine-tuning of 10% (1%) implies new physics below 2 TeV (9 TeV).

Kolda & Murayama (2000)

$\boxed{\rightarrow \text{TeV scale}}$

Guidance from Cosmology

Observations

- Galactic Rotation Curves
- Cluster Dynamics (incl. collisions)
- Velocity dispersions of galaxies - dark matter extends beyond the visible matter
- Weak Gravitational Lensing (distribution of dark matter)
- CMB (+ Type 1A SNe, plus BAO) all agree on LambdaCDM
- Structure Formation

Summary

- Some explanation is necessary for observed gravitational phenomena.
- It's largely non-relativistic (cold).
- Its abundance is $\Omega_{DM} \approx 0.26$.
- It's stable or very long-lived.
- It's non-baryonic (BBN+CMB, structure).
- It's neutral (heavy isotope abundances).

Guidance from Cosmology

1. New (heavy) particle χ in thermal equilibrium:

$$\chi\chi \rightleftarrows f\bar{f}$$

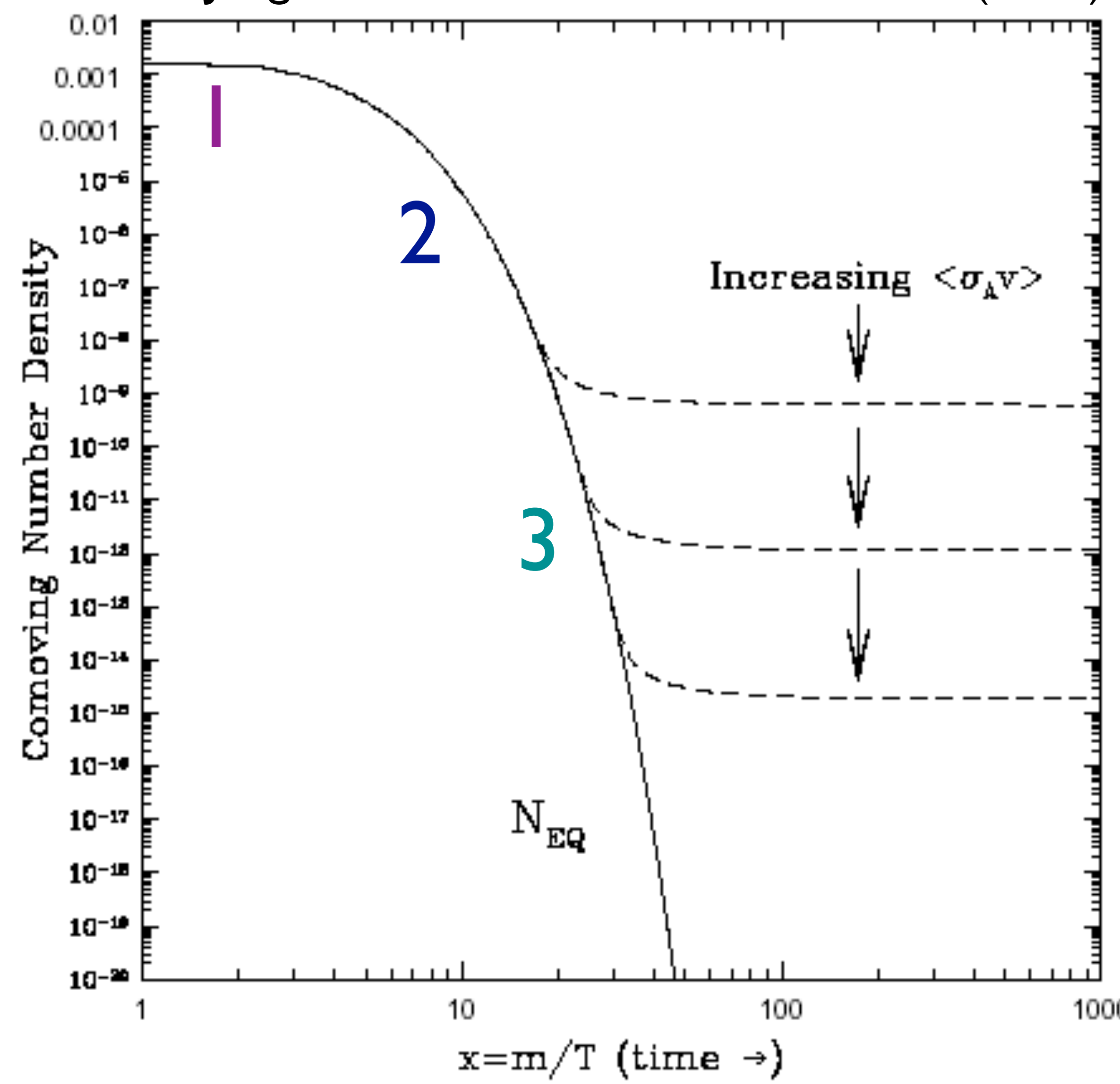
2. Universe expands and cools:

$$\chi\chi \;\underset{\not\leftarrow}{\rightarrow}\; f\bar{f}$$

3. χ's “freeze out”

$$\chi\chi \;\underset{\not\leftarrow}{\not\rightarrow}\; f\bar{f}$$

Jungman, Kamionkowski & Griest, PR (1996)



Guidance from Cosmology

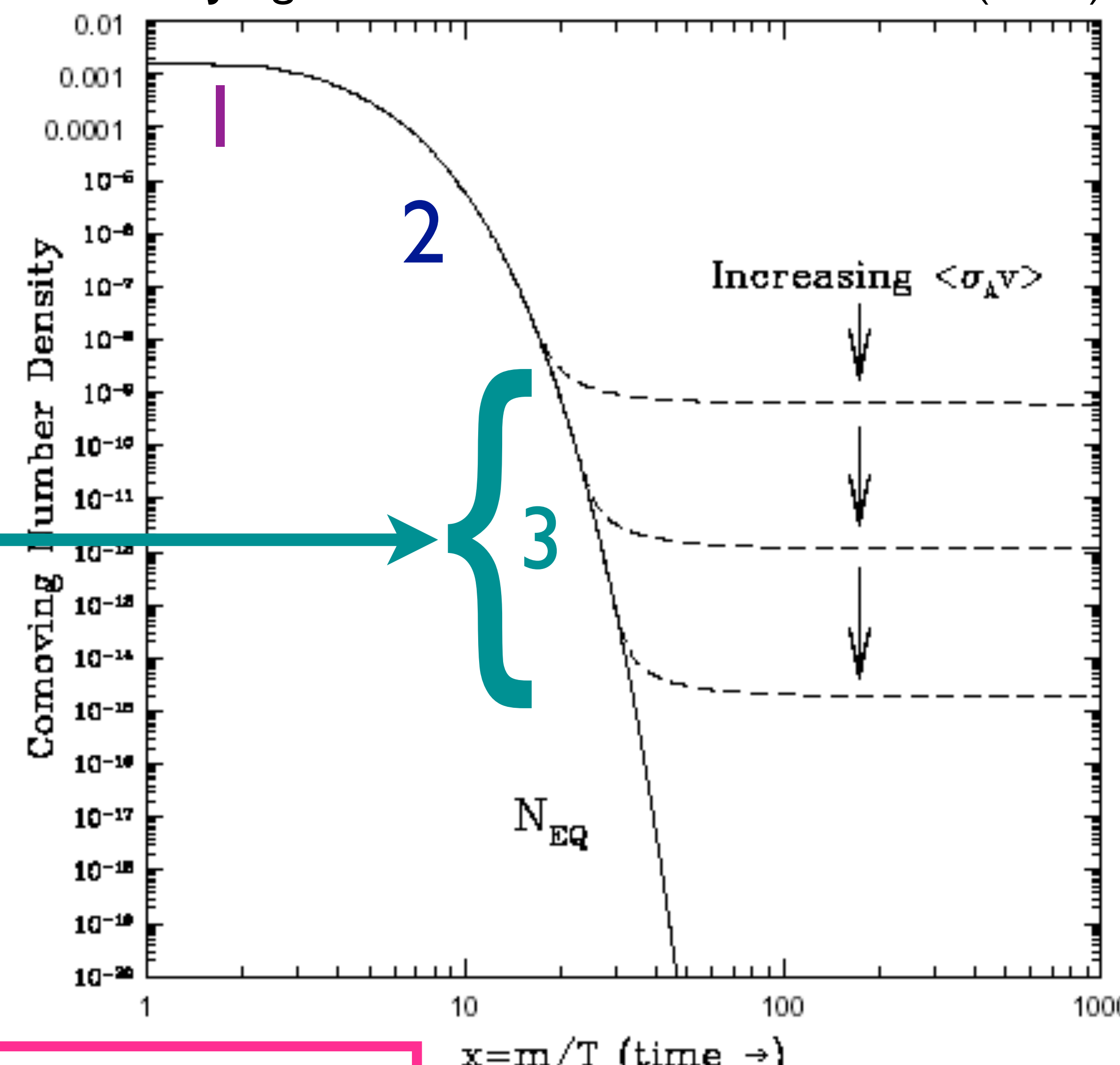
Weakly **I**nteracting **M**assive **P**articles

=**WIMP**

Expansion and annihilation compete to determine the number density:

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma v_{rel} \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

Jungman, Kamionkowski & Griest, PR (1996)



Stable matter with GeV-TeV mass and weak-scale annihilation cross section yields

$\Omega_\chi h^2 \approx 0.1$

$\boxed{\rightarrow \text{GeV-TeV scale}}$

The TeV Scale

- **The Higgs potential and dark matter could both be addressed by new particles at the TeV scale.**
  - New sources of CP violation could generate the matter-antimatter asymmetry.
  - New particles would affect the running of the SM gauge couplings, potentially leading to unification of the SM gauge interactions at high energies.
  - Any higher energy phenomena should be addressed within the context of the theory that includes new TeV-scale physics: neutrino masses, flavor-mixing among quarks and leptons, gravity

The LHC

- **Run 1:** March 30, 2010 - February 14, 2013
    - 6 fb^{-1} at 7 TeV (peak luminosity of 3.7×10^{33} $cm^{-2}s^{-1}$)
    - 23 fb^{-1} at 8 TeV (peak luminosity of 7.7×10^{33} $cm^{-2}s^{-1}$)
- **Long Shutdown (LS) 1:** February 14, 2013 - early 2015
- **Run 2:** May 21, 2015
    - 13-14 TeV, peak luminosity of 1.7×10^{34} $cm^{-2}s^{-1}$
    - 10 fb^{-1} by end of 2015
    - current gluino sensitivity in ~few months
- **LS2:** July 2018 - December 2019
- **Run 3:** 14 TeV, peak luminosity of 2×10^{34} $cm^{-2}s^{-1}$

Collider Searches for Dark Matter

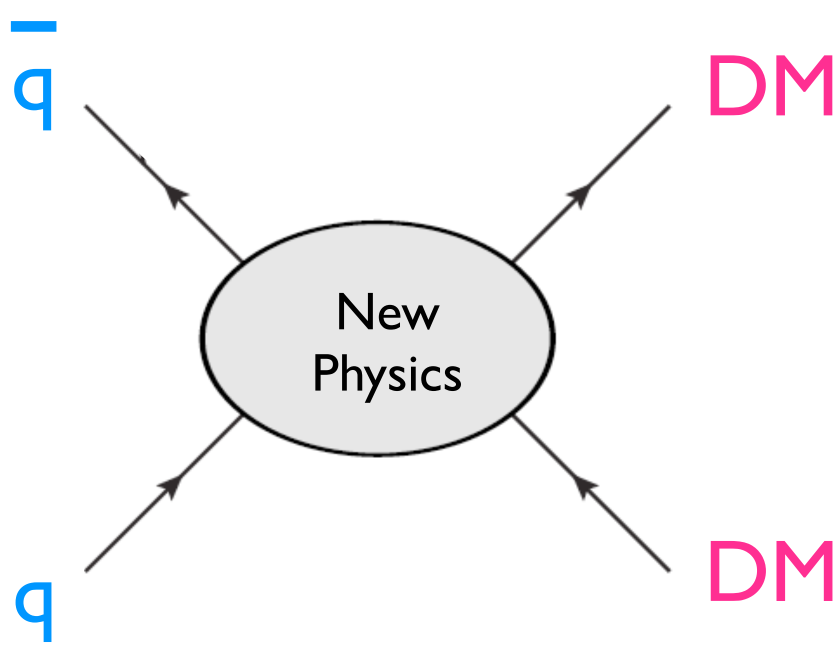
- Direct Production (and mono-anything)

  $\chi\chi + \mathrm{SM}$
- Associated Production with New Particle(s)

  $\chi + \mathrm{NP}, \ \mathrm{then\ NP} \to \chi + \mathrm{SM}$
- Production of heavier NPs, then decay to DM

  $\mathrm{NP} + \mathrm{NP}, \ \mathrm{then\,each\ NP} \to \chi + \mathrm{SM}$
- SM decays to DM

  $h \to \chi\chi$



Upside:

- Independent of astrophysics
- Can measure mass and couplings of new particles.

Of Note:

- Limits on the properties of new particles are often model-dependent (fine print).

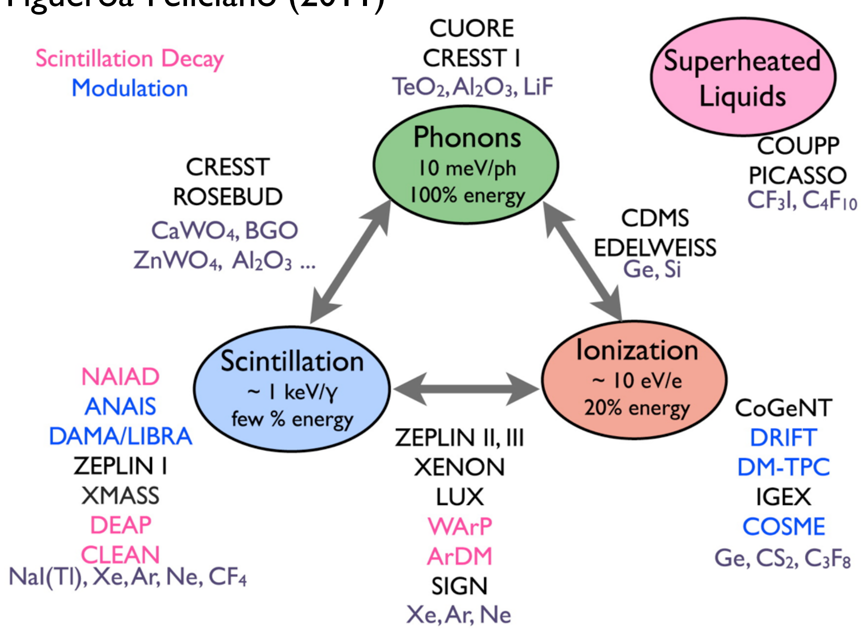
Downside:

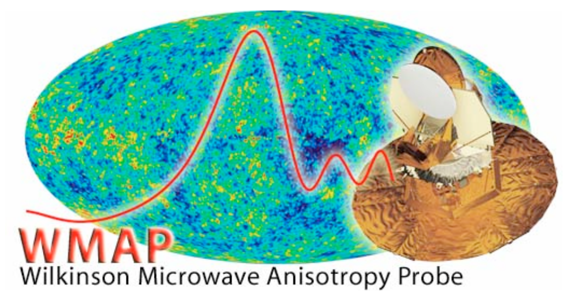
- Can't confirm that a new particle is dark matter (stability) → need some astrophysical measurement.

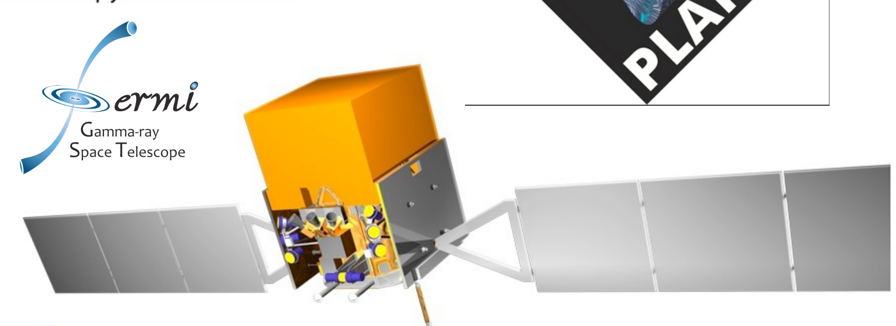
Current Situation

- Abundance of experimental data!

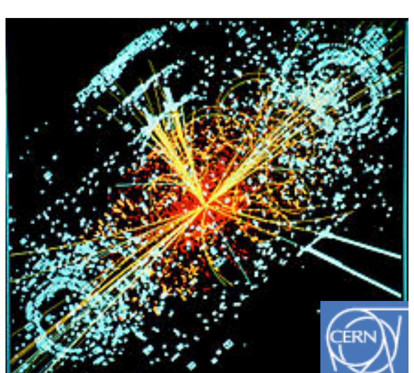
Figueroa-Feliciano (2011)

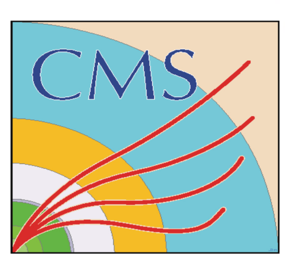






PAMeLA





Current Situation

- Abundance of experimental data!
  - New physics scenarios are being explored with unprecedented and growing precision.
- Theoretical approaches:

Totally Theory-Driven

↕

Hybrid / Simplified Models

↕

Totally Phenomenology-Driven

From Theory to Predictions

Supersymmetry

MSSM

Non-Minimal Model

The MSSM

	particle	sparticle	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
quarks and squarks	$\begin{pmatrix} u \\ d \end{pmatrix}_i$	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_i$	3	2	$\frac{1}{6}$
	u_i^c	$\tilde{u}_i^c$	$\bar{3}$	1	$-\frac{2}{3}$
	d_i^c	$\tilde{d}_i^c$	$\bar{3}$	1	$\frac{1}{3}$
leptons and sleptons	$\begin{pmatrix} \nu \\ e \end{pmatrix}_i$	$\begin{pmatrix} \tilde{\nu} \\ \tilde{e} \end{pmatrix}_i$	1	2	$-\frac{1}{2}$
	e_i^c	$\tilde{e}_i^c$	1	1	1
W boson and wino	W	$\tilde{W}$	1	3	0
gluon and gluino	g	$\tilde{g}$	8	1	0
B boson and bino	B	$\tilde{B}$	1	1	0
Higgs bosons and higgsinos	$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$	1	2	$\frac{1}{2}$
	$\begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$	1	2	$-\frac{1}{2}$

neutralinos

From Theory to Predictions

Supersymmetry

MSSM

Non-Minimal Model

Gravity Mediation

Gauge Mediation

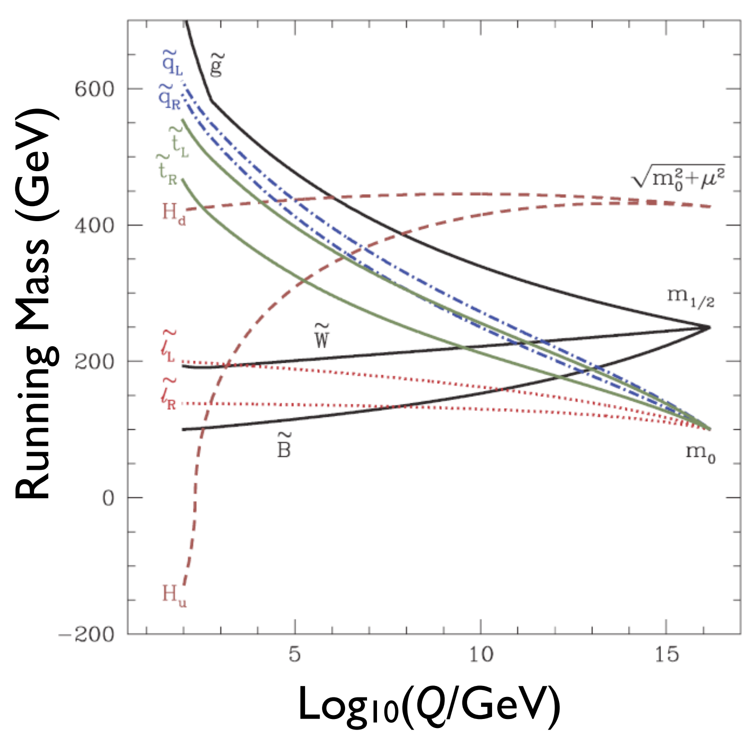
...

EW-Scale Inputs

mSUGRA

CMSSM

NUHM



pMSSM

MSSMn (n=7,9,etc.)

Relevant Parameters Only
for Specific Interaction

Constraints

- Higgs mass
- Sparticle mass limits from collider searches
- Flavor constraints
- Lepton dipole moments, etc.
- DM abundance
- Indirect and Direct dark matter searches

Lightest Supersymmetric Particle (LSP):

$$\tilde{\chi}_i^0 = \alpha_i \underbrace{\tilde{B}}_{\text{(bino)}} + \beta_i \underbrace{\tilde{W}^3}_{\text{(wino)}} + \underbrace{\gamma_i \tilde{H}_1^0 + \delta_i \tilde{H}_2^0}_{\text{(higgsino)}}$$

Example

- **Higgs boson mass**

$$m_h^2 \approx m_Z^2 \cos^2(2\beta) + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left\{\log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right\}$$

$$\begin{aligned} m_{\tilde{t}} &= \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \\ \tan\beta &= v_u/v_d \\ v_u^2 + v_d^2 &= v^2 = 2m_Z^2/(g^2 + g'^2)^2 \\ X_t &= A_t - \mu/\tan\beta \end{aligned}$$

Example

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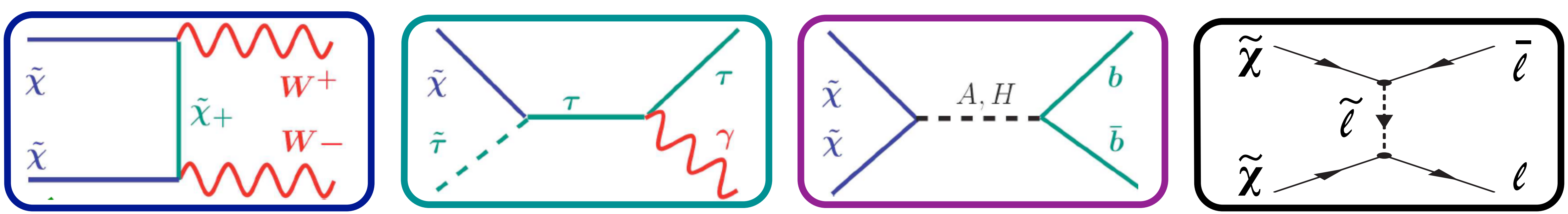
$$m_{\tilde{t}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$
$$\tan\beta = v_u/v_d$$
$$v_u^2 + v_d^2 = v^2 = 2m_Z^2/(g^2 + g'^2)^2$$
$$X_t = A_t - \mu/\tan\beta$$

- **Dark matter abundance**
  - Bino-higgsino or bino-wino (“well-tempered”) LSP
  - Coannihilations with sleptons or squarks (nearly degenerate masses)
  - Coannihilations with neutralinos or charginos (nearly degenerate masses, wino- or higgsino-like neutralino LSP)
  - Resonant annihilations
  - t-channel slepton exchange (light sleptons w/ L-R mixing)



$m_{\tilde{\chi}_1^0} \approx m_{\tilde{\tau}_1, \tilde{t}_1, \tilde{\chi}_1^\pm}$

$2m_{\tilde{\chi}_1^0} \approx m_{h,A}$

Example

- **Higgs boson mass (and other collider constraints)**

Heavy sector: μ, heavy squark masses, top trilinear coupling,
plus decouple wino, gluino …

- **Dark matter abundance**
  - t-channel slepton exchange (light sleptons w/ L-R mixing)

Relic density sector: bino mass, slepton masses, mixing angle(s)
(CP-violating phase free)

Example

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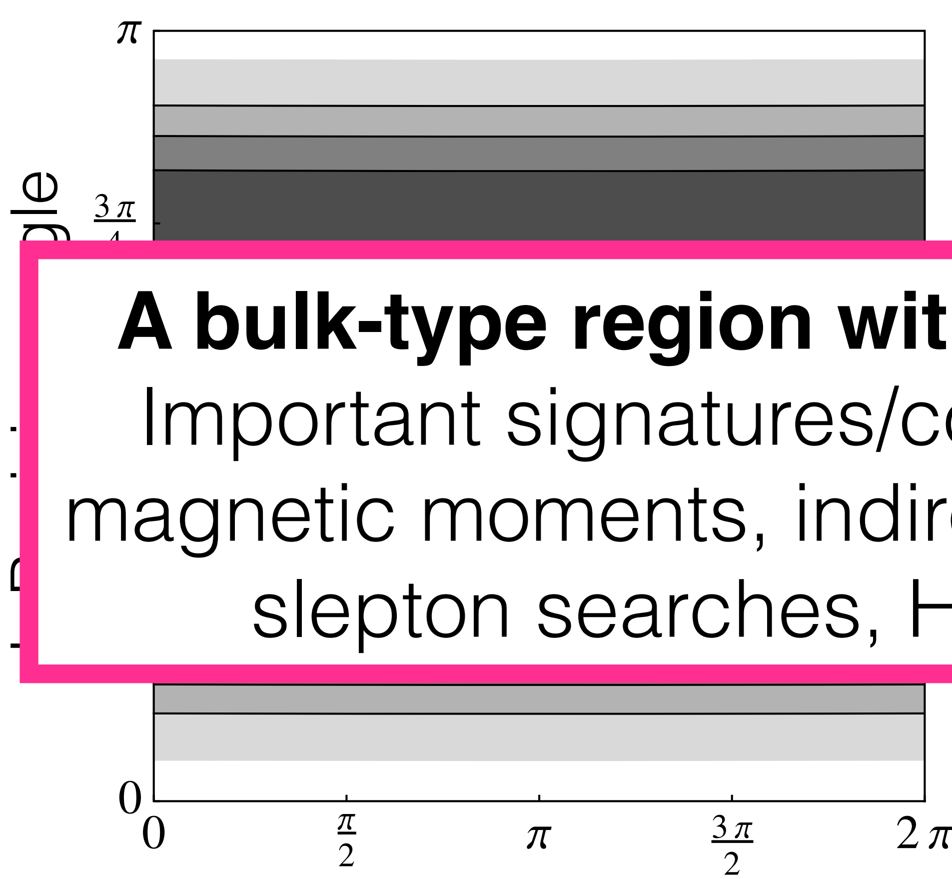
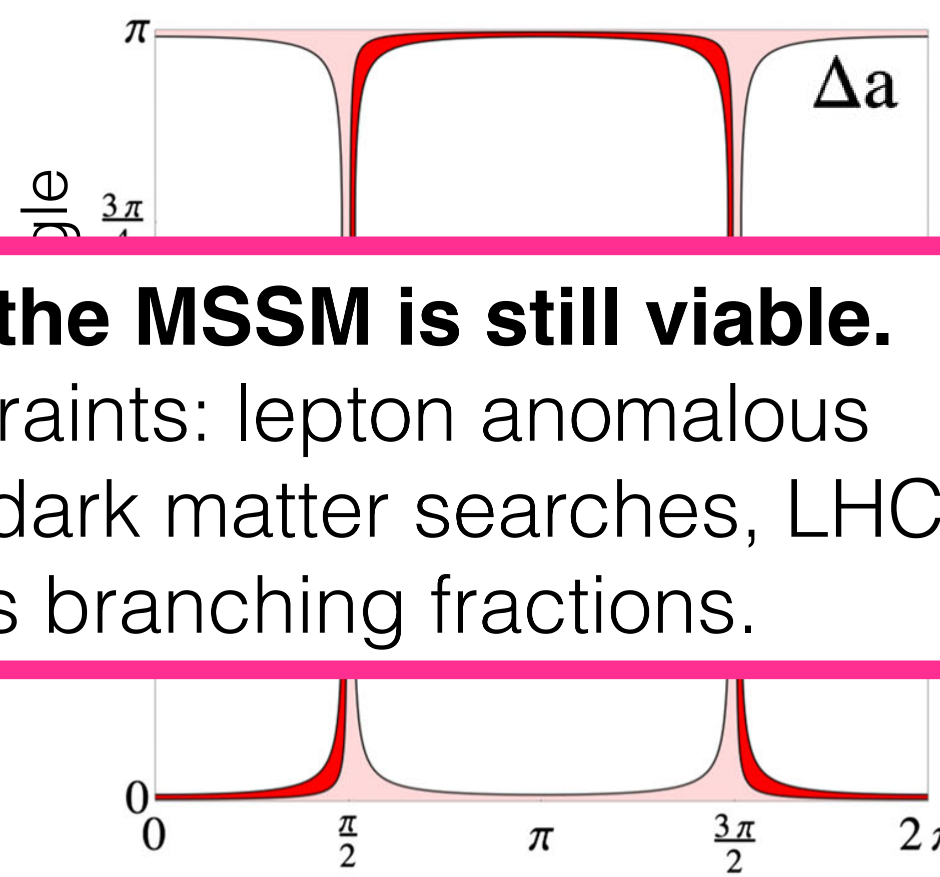




A bulk-type region within the MSSM is still viable.
Important signatures/constraints: lepton anomalous magnetic moments, indirect dark matter searches, LHC slepton searches, Higgs branching fractions.

Fukushima, Kelso, Kumar, Sandick, & Yamamoto, (2014)

see also Pierce, Shah, & Freese, (2013).

Example

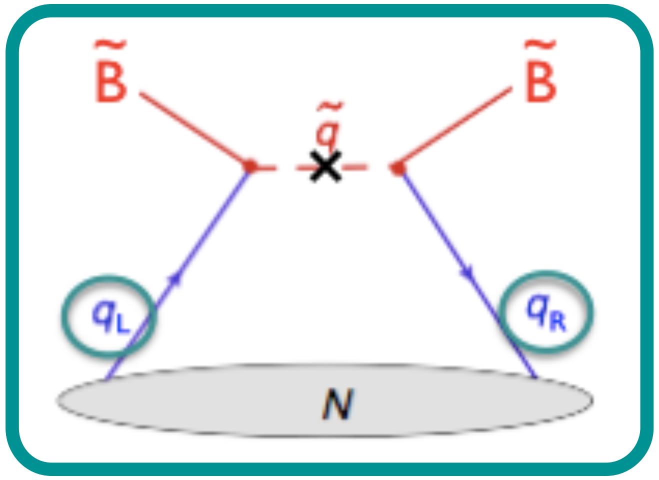
- **Higgs boson mass (and other collider constraints)**

Heavy sector: μ, heavy squark masses, top trilinear coupling,
plus decouple wino, gluino …

- **Dark matter abundance**
  - t-channel slepton exchange (light sleptons w/ L-R mixing)

Relic density sector: bino mass, slepton masses and mixing angle(s)
(CP-violating phase free)

- **Dark matter-nucleon spin-independent scattering cross section**
  - Pure bino → squark exchange
    - no L-R mixing in squark sector - spin-dependent or velocity-suppressed
    - w/L-R mixing - velocity-independent SI scattering, depends only on bino mass, squark masses and mixing angles

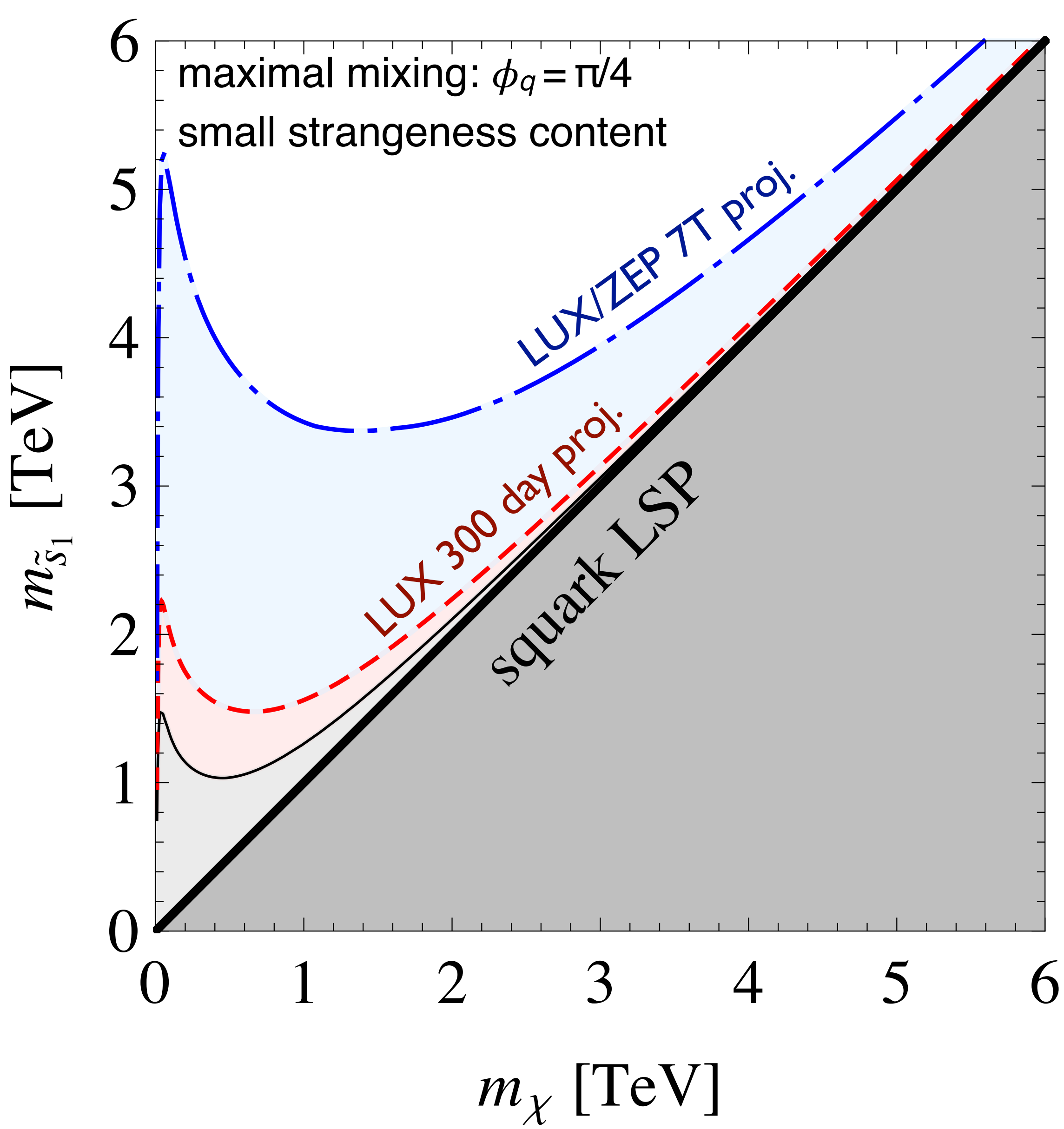


Direct detection sector: light squark masses and mixing angle(s)

Example

- **Dark matter-nucleon spin-independent scattering cross section**

Direct detection sector: light squark masses and mixing angle(s)



If heavy QCD-charged particles couple to dark matter,

first evidence might come from direct dark matter searches!

Kelso, Kumar, Sandick, & Stengel (2015)

Example

- **Higgs boson mass (and other collider constraints)**

Heavy sector: μ, heavy squark masses, top trilinear coupling,
plus decouple wino, gluino …

- **Dark matter abundance**
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Relic density sector: bino mass, slepton masses and mixing angle(s)
(CP-violating phase free)

- **Dark matter-nucleon spin-independent scattering cross section**

Direct detection sector: light squark masses and mixing angle(s)

Two simplified models shed light on corners of MSSM parameter space.
(singlet DM coupled to SM fermions via charged scalars)

Closing Thoughts

- **Theoretical particle physics is at an interesting juncture: the SM is verified, we have a fairly successful understanding of the details of the SM, now we continue with enthusiasm on the questions of *why the SM is the way it is* and *what is the more complete theory*.**

- Experimental searches for new physics continue to improve.

  - We are learning more about the true nature of the Universe!

  - We must use extreme care in interpreting constraints (read the fine print) and/or hints (be skeptical).

- Theoretical analyses are responding in a variety of ways.

- **Neutralino dark matter in the MSSM remains a viable option, but other possibilities should not be neglected.**

- **We have a lot to look forward to…**