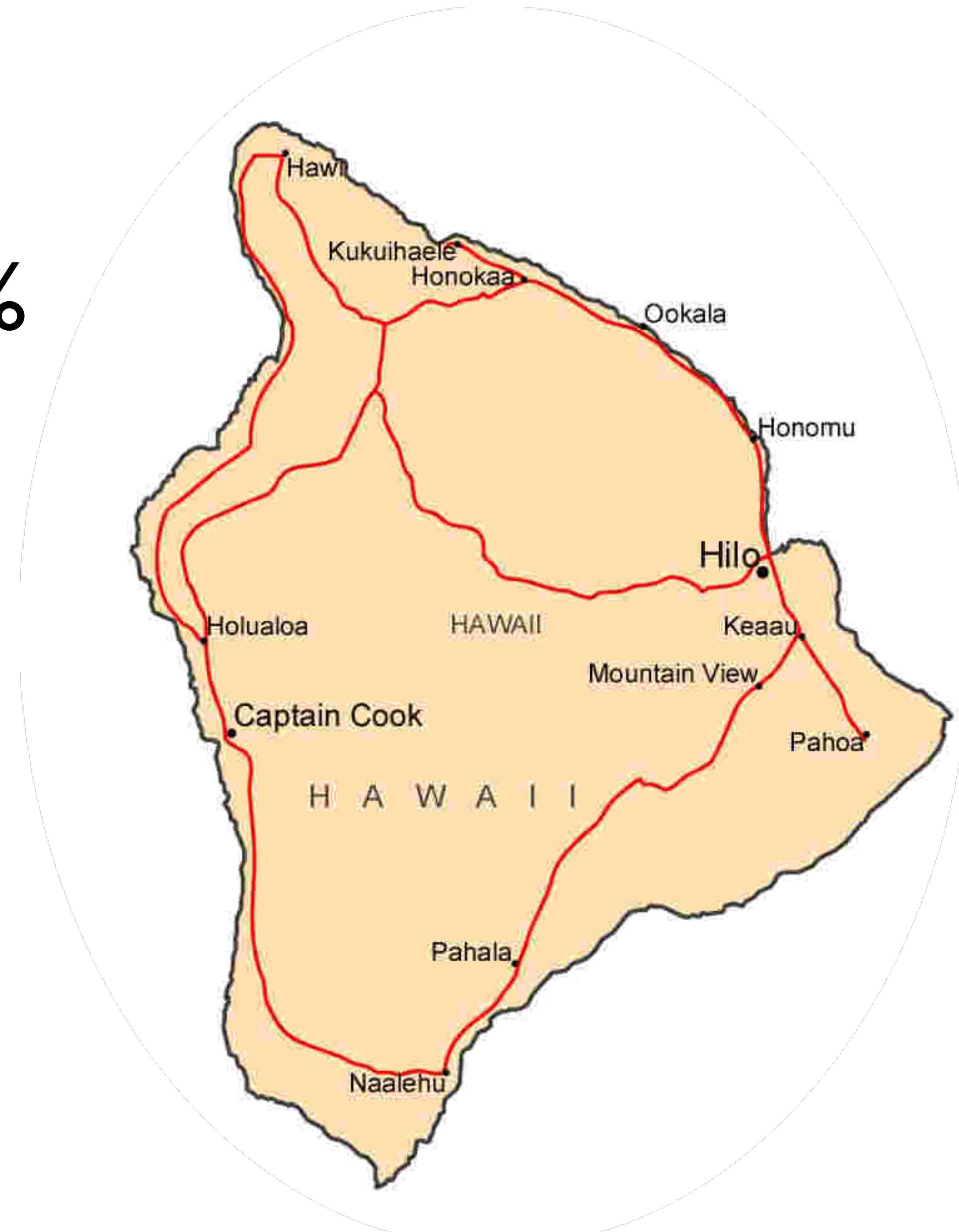
Beyond the Standard Model:
Dark Matter and Supersymmetry

Pearl Sandick
University of Utah

Matter Inventory

"Regular" Matter ~15%

Dark Matter ~ 85%

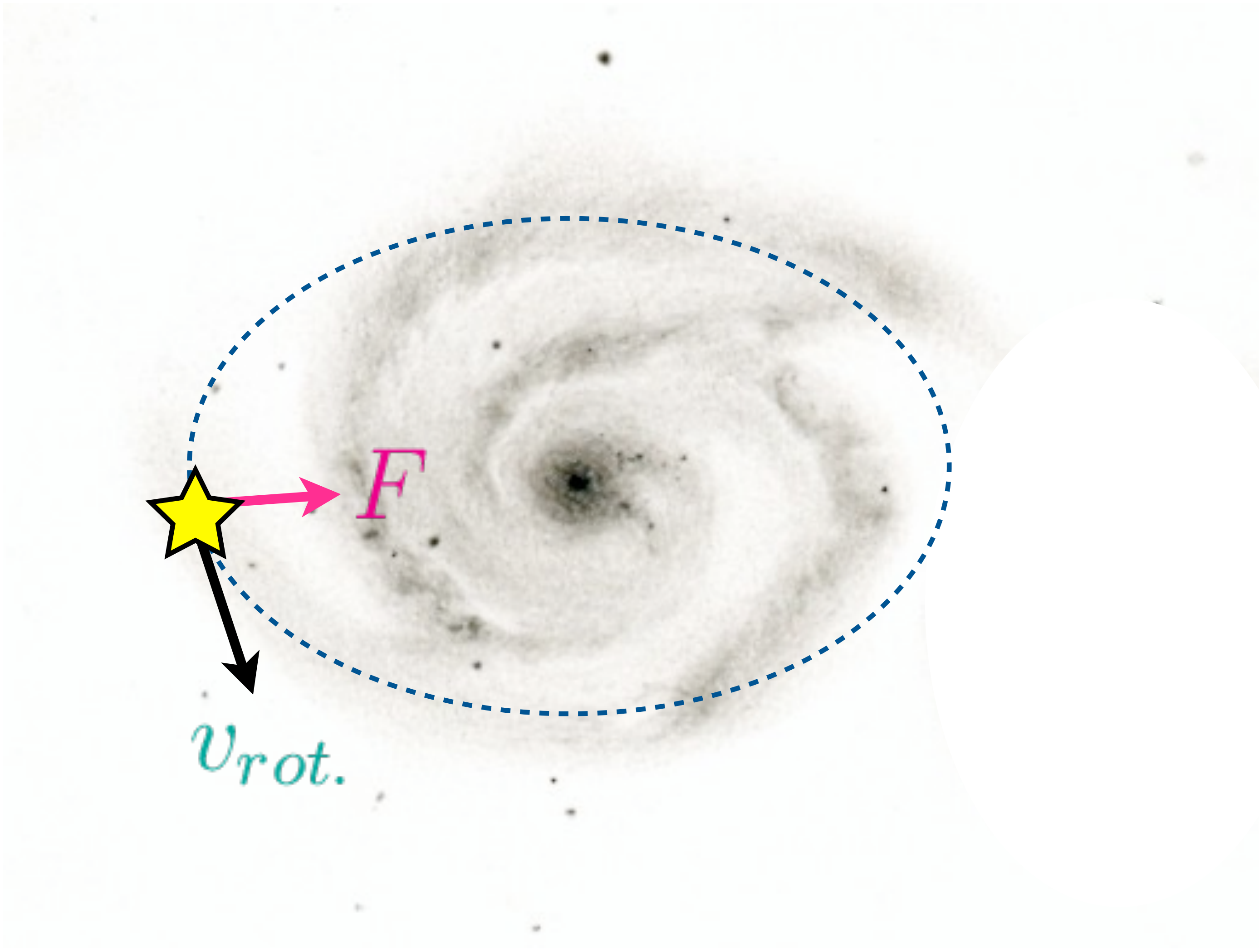


Gravitational Evidence

If you know the
rotational velocity ($v_{rot.}$),
you can compute the
force (F).

$$F = \frac{G\,M(r)\,m}{r^2} = \frac{m v_{rot.}^2}{r}$$

$$v_{rot.} = \sqrt{\frac{G\,M(r)}{r}}$$



Galaxy-Scale Evidence

- Vera Rubin: Galactic Rotation Curves (1960's-70s)

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Far away from the galaxy, $v_{rot.} = \dfrac{\text{const.}}{\sqrt{r}}$

Steele, Mottram, Newsam & the LT Project

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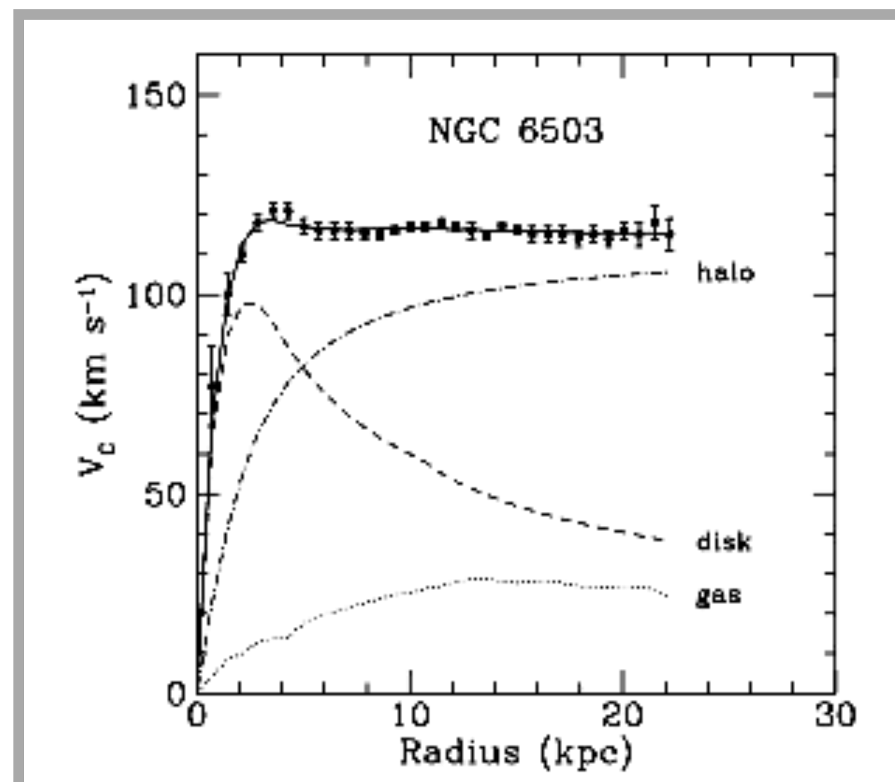
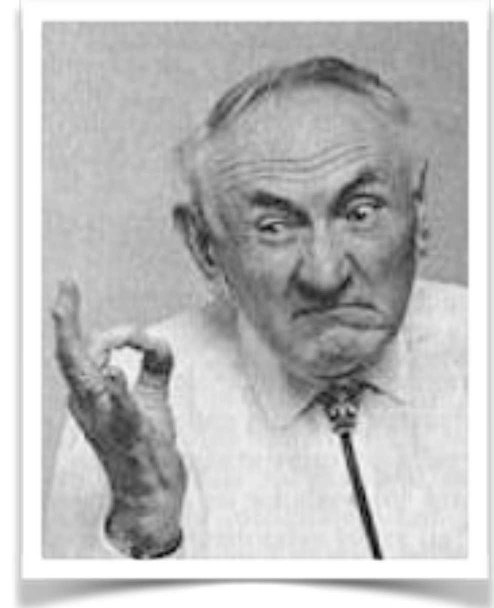
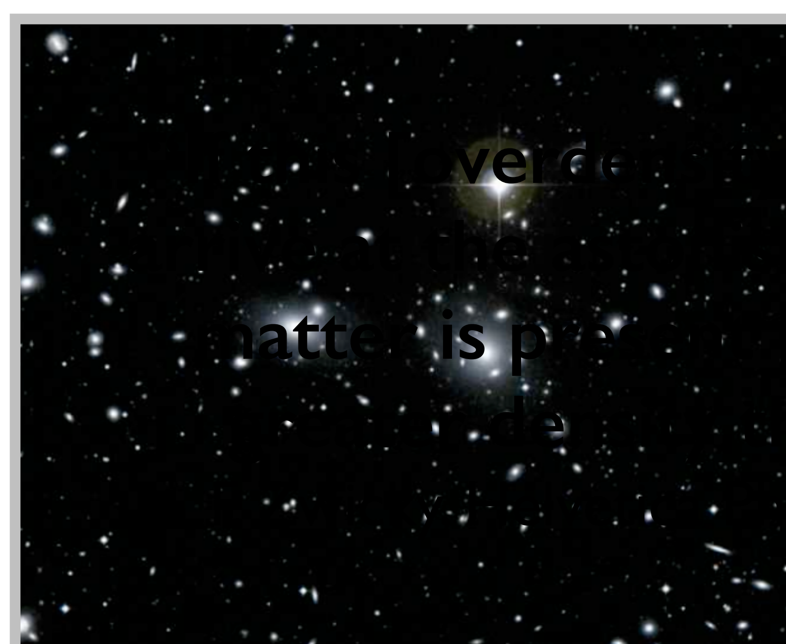


Begeman et al. (1991)

Cluster-Scale Evidence



- Fritz Zwicky: used Doppler shift to measure peculiar velocities of galaxies at the edge of the Coma Cluster
  - Virial Theorem $\langle \mathrm{KE} \rangle = -\frac{1}{2}\langle \mathrm{GPE} \rangle \implies M = \frac{2\langle r \rangle \langle v^2 \rangle}{G}$
  - Velocities implied MUCH more mass than that visible

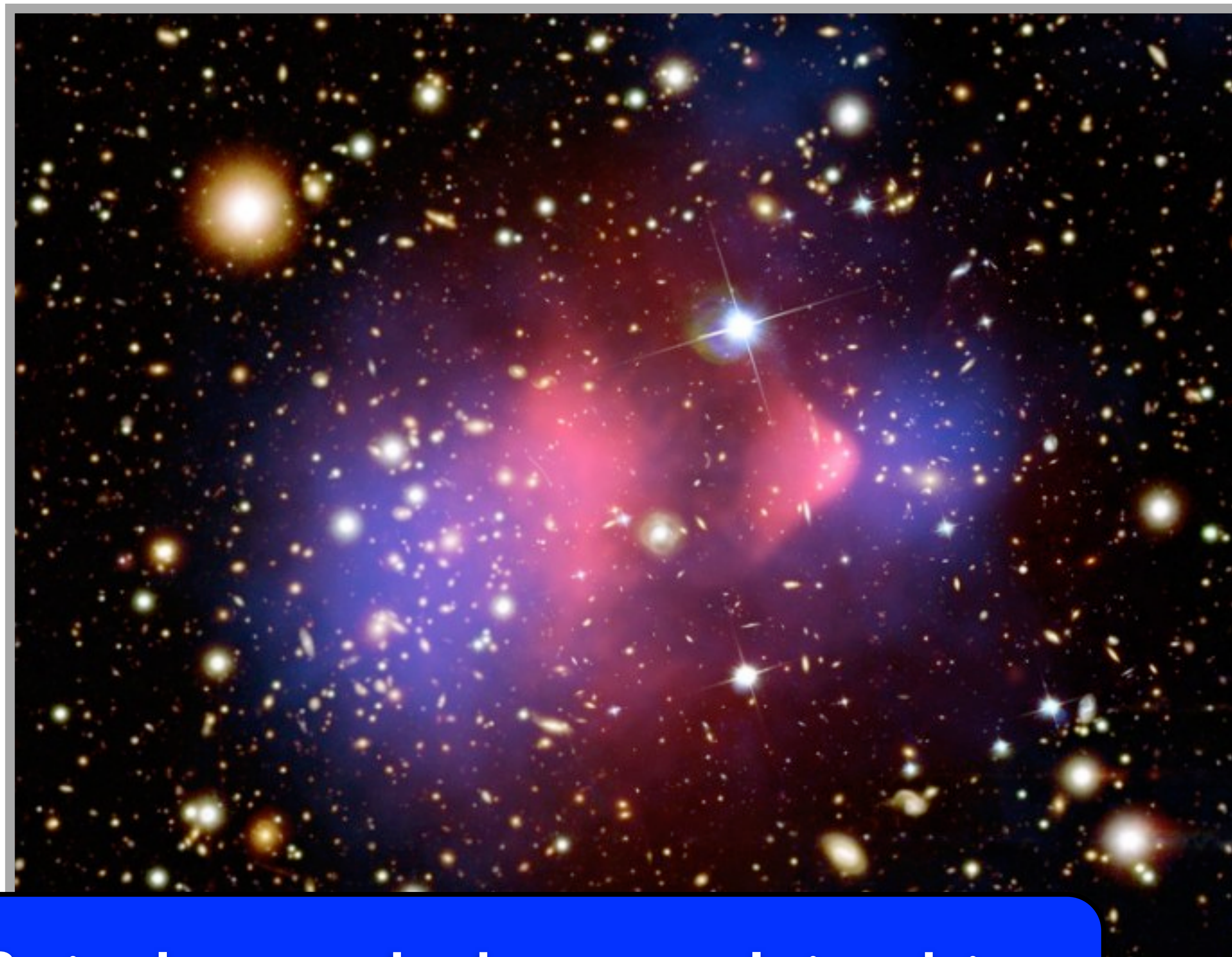


] is confirmed we would
hing conclusion that dark
[in Coma] with a much
han luminous matter."
ysica Acta 6: 110-127 (1933)

The Bullet Cluster

- ✓ Optical (galaxies)
- ✓ X-ray measurements reveal hot gas
- ✓ Weak gravitational lensing shows where the mass is

Clowe et al. (2006)

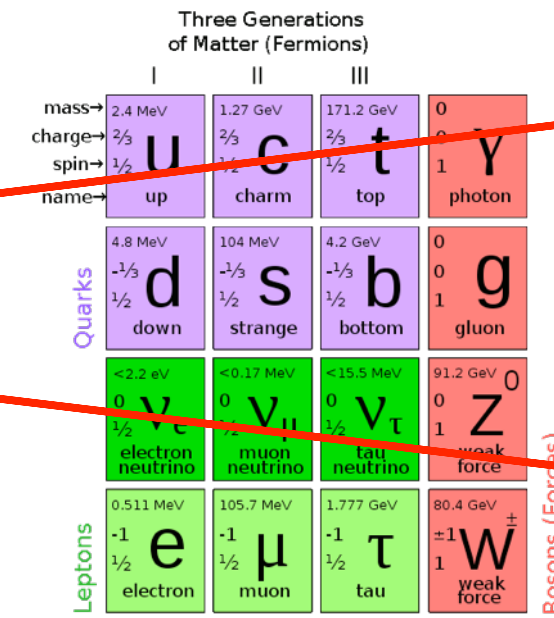


Dark matter is definitely needed to explain this.
Natarajan & Zhao (2008)

What We Know:

- Some explanation is necessary for observed gravitational phenomena.
- It's non-baryonic (Not Normal Matter!).
- We know how much there is: $\Omega_{CDM} = 0.26$
- It's neutral.
- It's stable or very long-lived.
- It's slow-moving/cold (structure formation).

What Could It Be?



- ~~Standard Model Particles~~
- New DM particles just for DM
- New particles from SM extensions that happen to have the right properties to be DM. I find this more compelling, but that doesn't mean it's right.

We have ample theoretical evidence that the SM is incomplete.

Completions involve new physics with mass scale *O*(100) GeV.

Relic Abundance

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

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

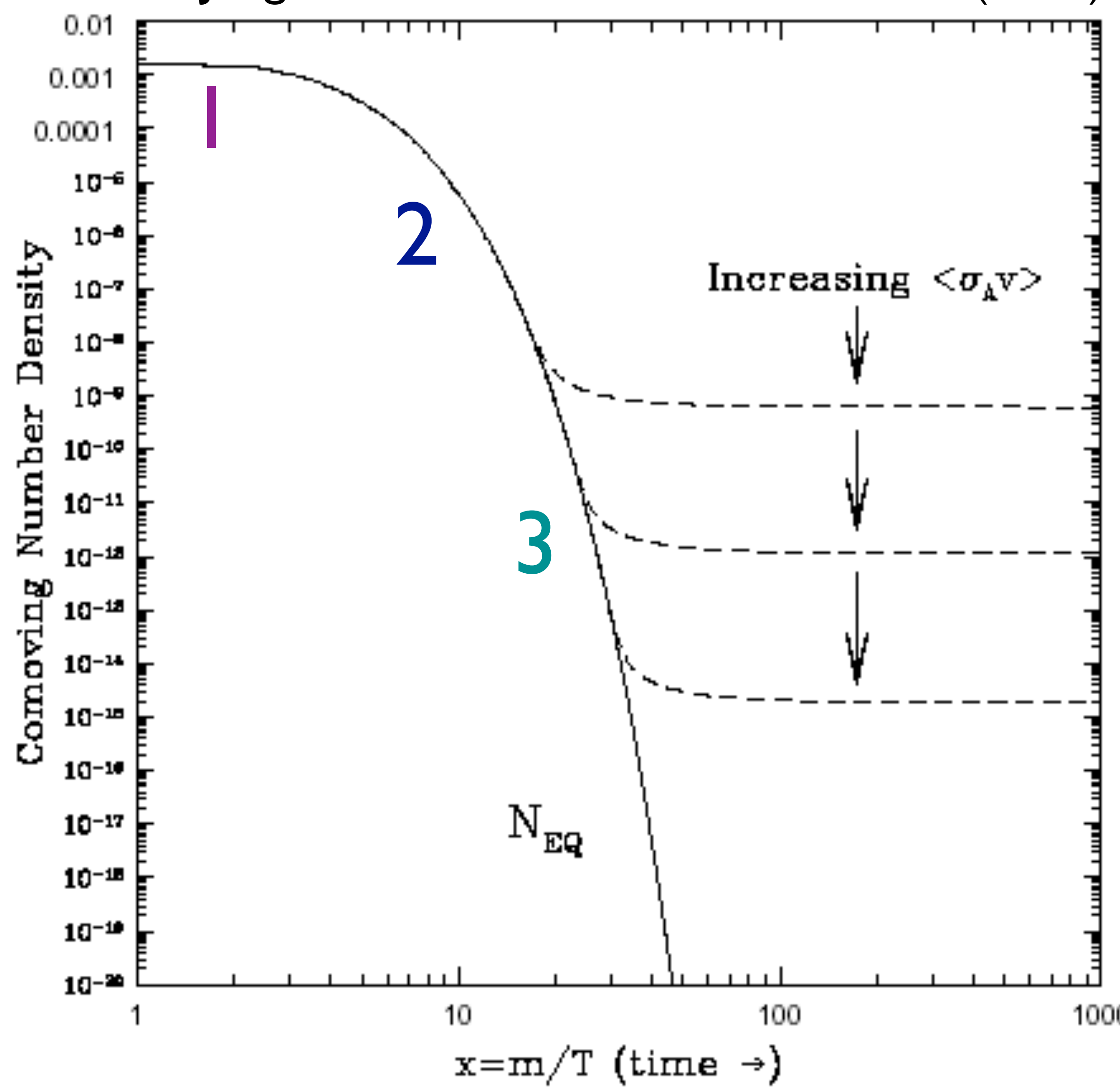
2. Universe expands
   and cools:

$$\chi\chi \,\overset{\rightarrow}{\not\leftarrow}\, f\bar{f}$$

3. χ's "freeze out"

$$\chi\chi \,\not\rightleftarrows\, f\bar{f}$$

Jungman, Kamionkowski & Griest, PR (1996)



Relic Abundance

WIMP "Miracle"

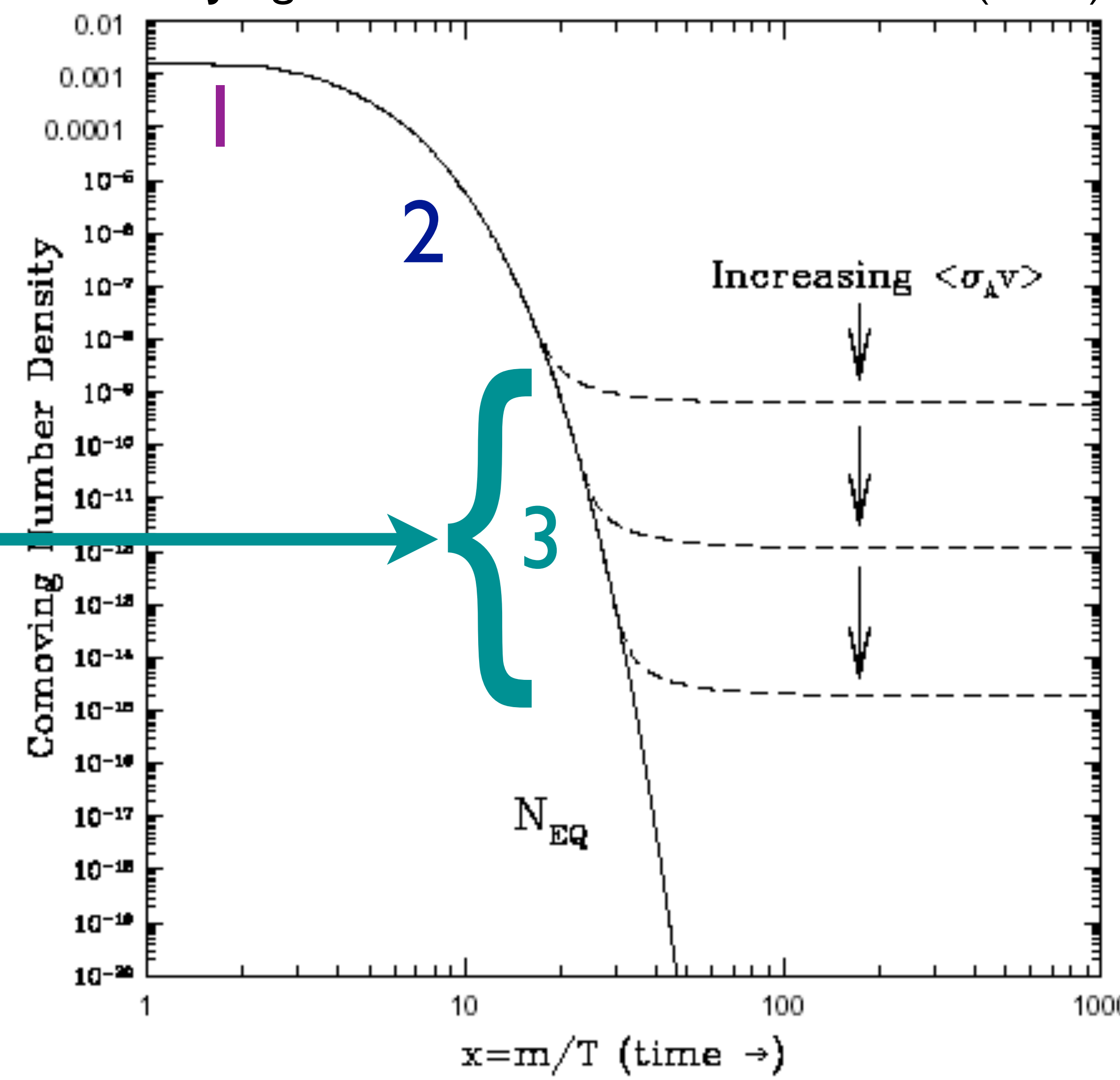
Expansion and annihilation compete to determine the number density:

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

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

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

Jungman, Kamionkowski & Griest, PR (1996)



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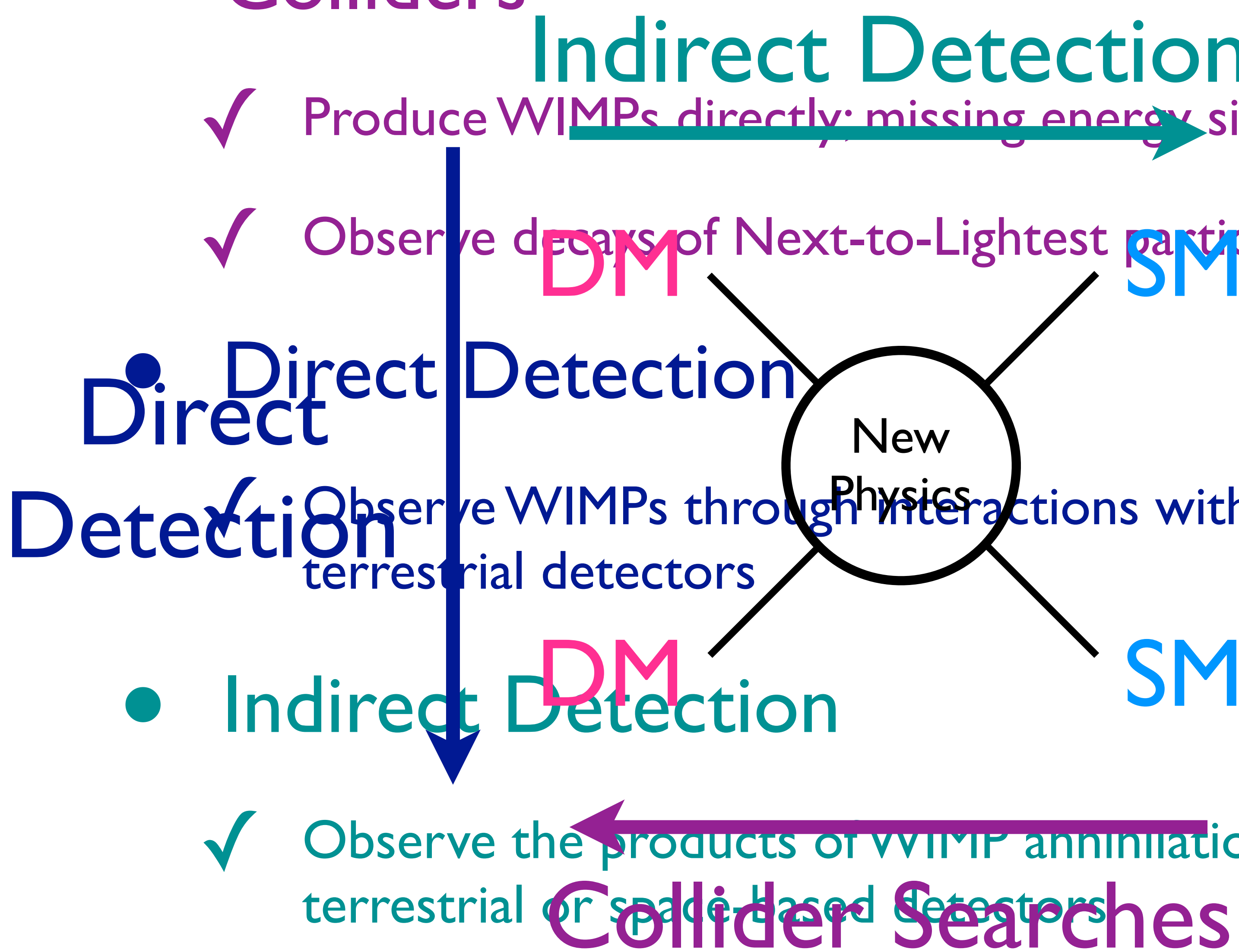
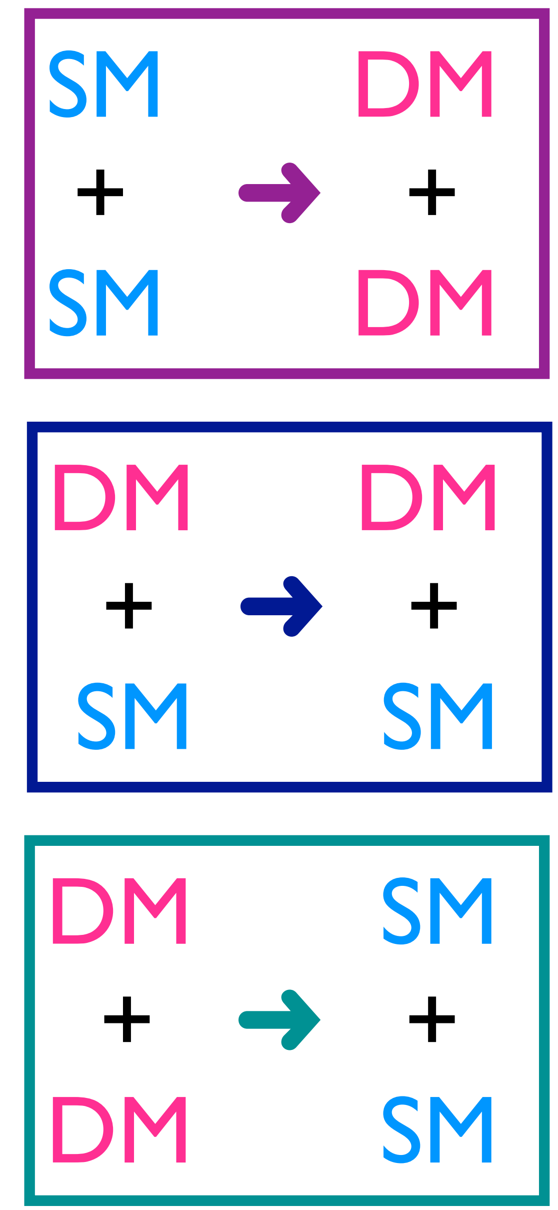
We DO NOT KNOW that dark matter is made of WIMPs.

To Catch a WIMP

- Colliders
  - ✓ Produce WIMPs directly: missing energy signature
  - ✓ Observe decays of Next-to-Lightest particles to DM
- Direct Detection
  - ✓ Observe WIMPs through interactions with nuclei in terrestrial detectors
- Indirect Detection
  - ✓ Observe the products of WIMP annihilation or decay in terrestrial or space-based detectors



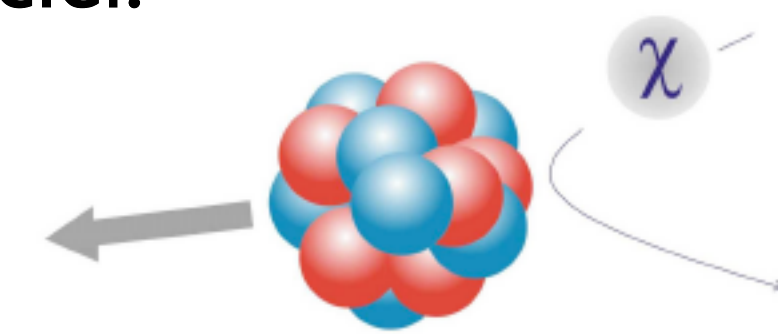


1. Experiment
2. Theory

Direct Detection

- If WIMPs are the dark matter, they are all around us, and will *occasionally* bump into nuclei.

➡ How *occasionally*?



$$\frac{dR}{dE_R}(E_R) = \frac{1}{m_N}\int_{v>v_{min}(E_R)} d^3\vec{v}\,\boxed{\frac{\rho_0 v}{m_\chi}}\,\boxed{f(\vec{v}+\vec{v}_e)}\,\boxed{\frac{d\sigma_{\chi N}(v, E_R)}{dE_R}}$$

Differential Rate
(counts/ton/yr/keV)

Flux of WIMPs

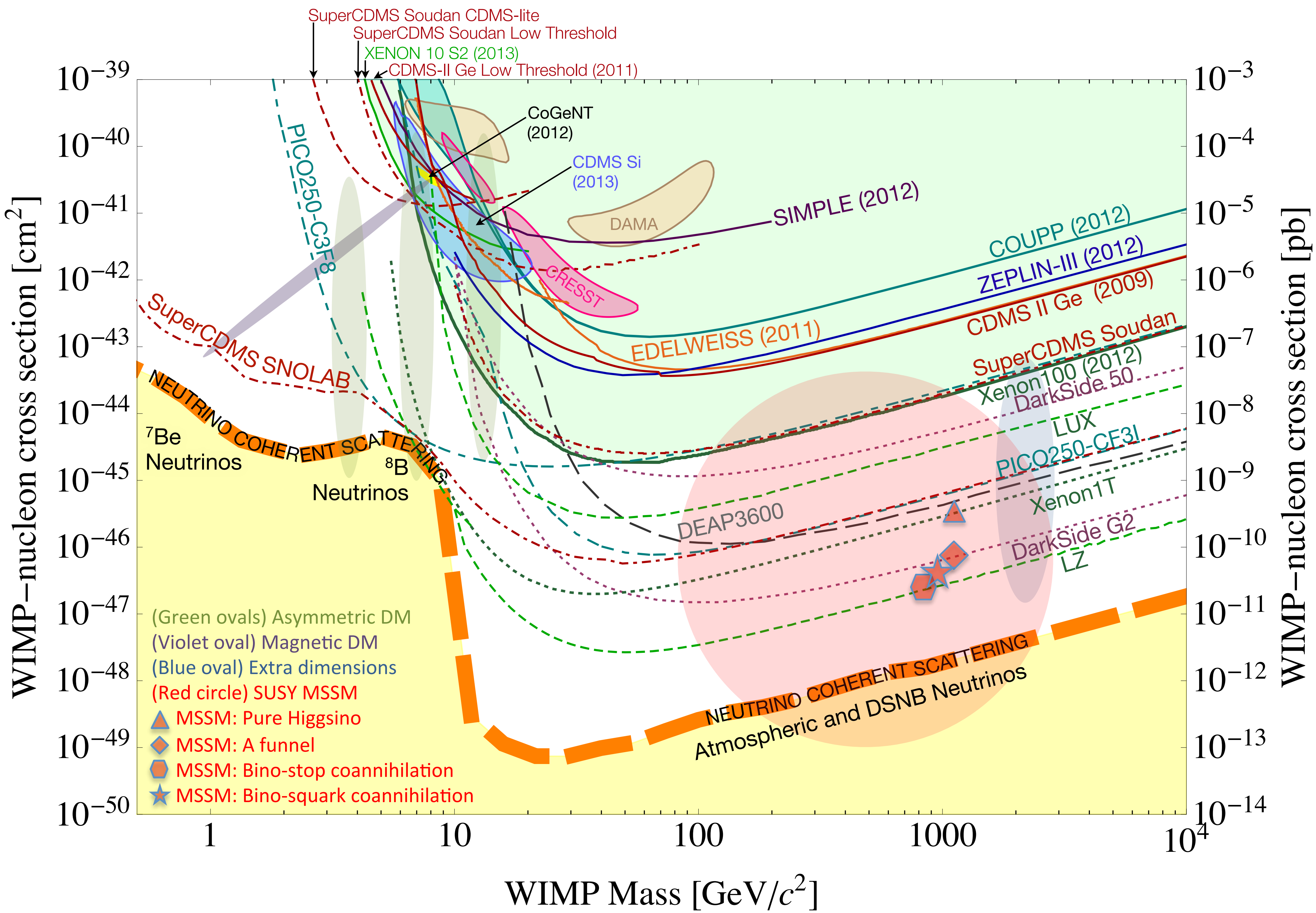
Velocity
Distribution

Probability of Interaction
w/ Target Nucleus

Direct Detection

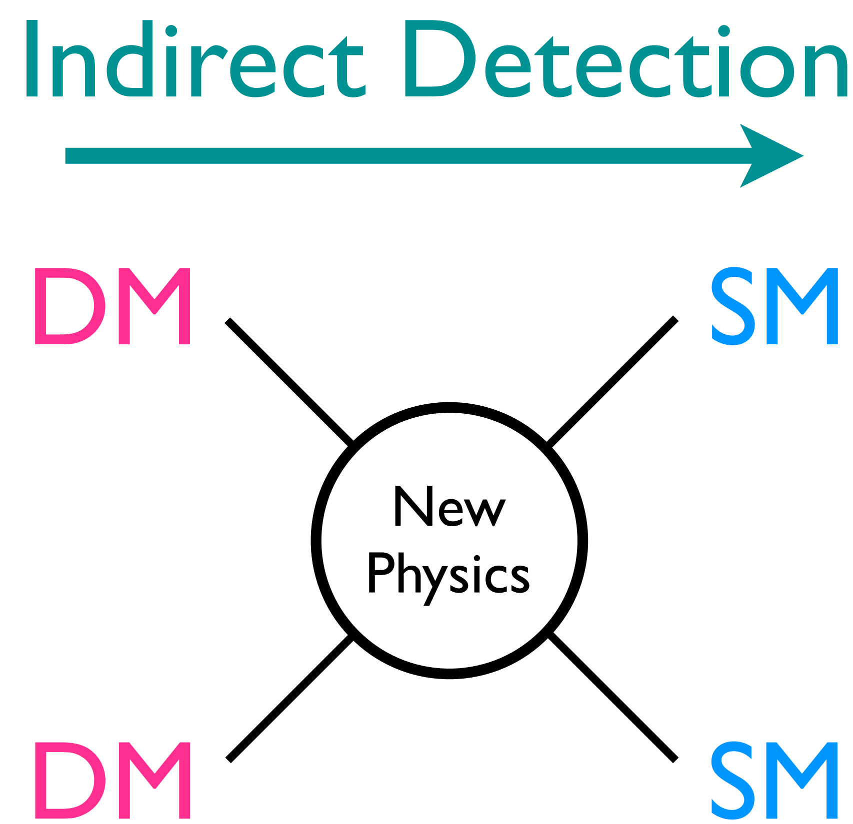
slide by Laura Baudis

Direct Detection



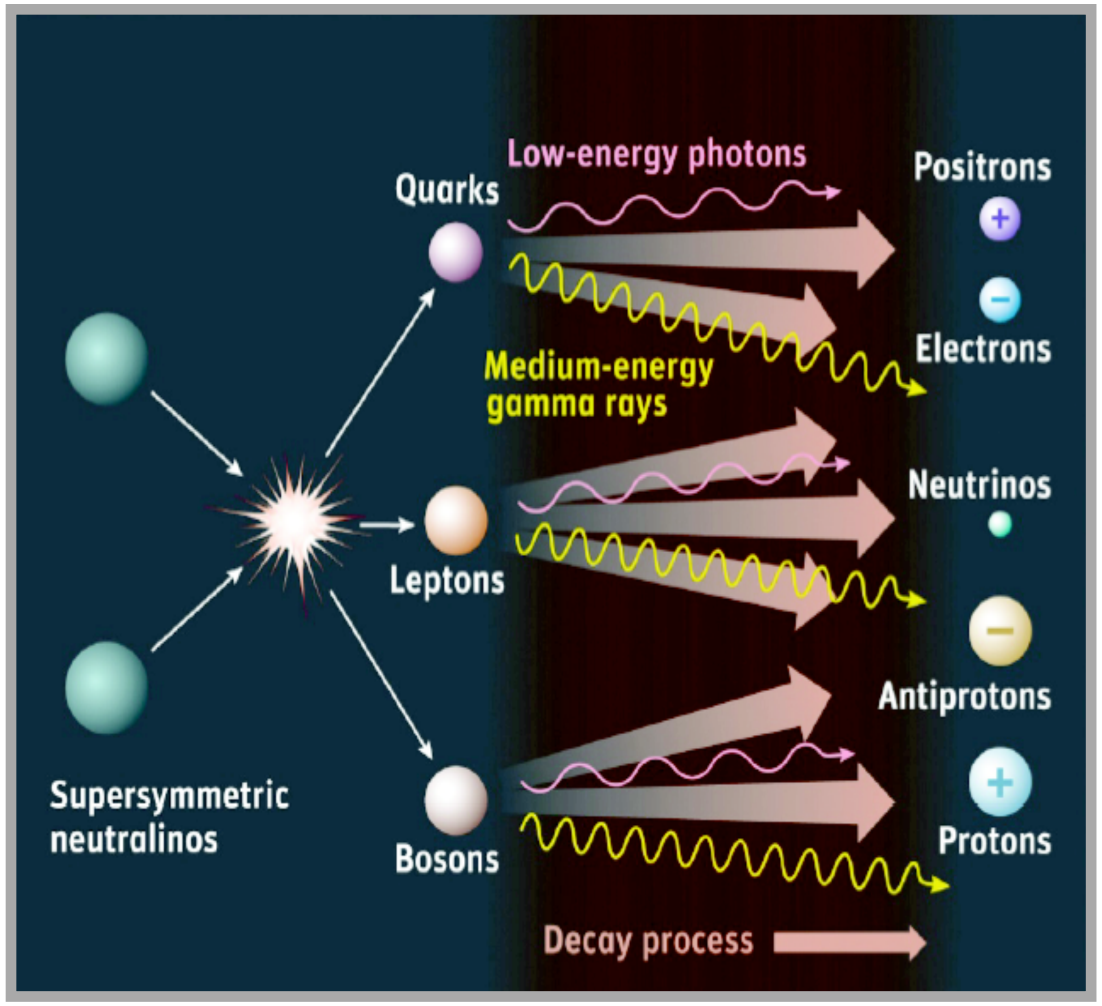
Indirect Detection

- Look for end-products of WIMP annihilation (decay?)
- If WIMPs annihilated in the early universe, this process should still be occurring today.
- Downside: Astrophysics is complicated.
- Up-side: Many places to look, many experiments looking(ed)



Indirect Detection

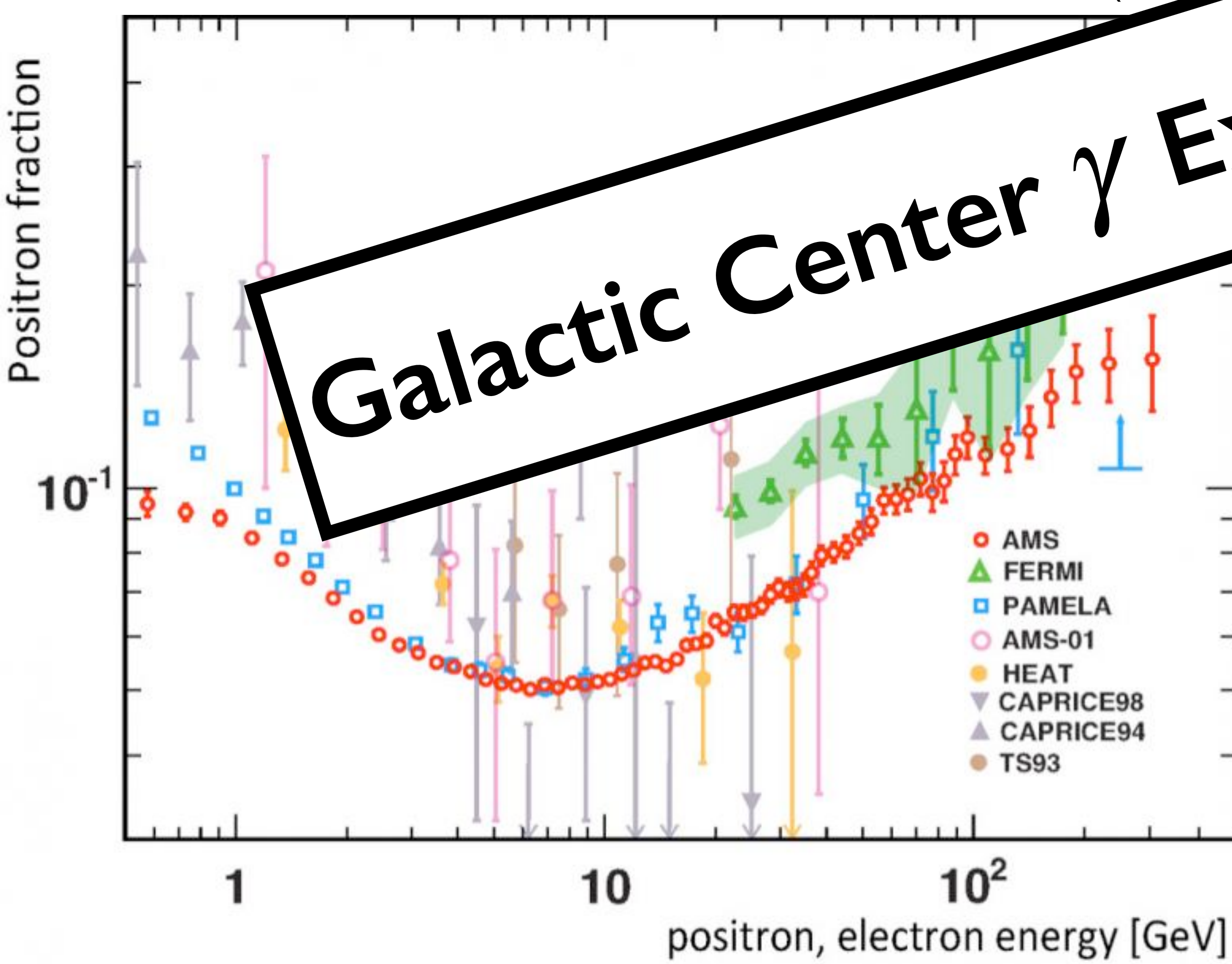
- WIMP annihilation (or decay)
- Need a LOT of dark matter:
  - In the Milky Way halo
    Ellis, Freese et al. 1987; Feldman & Sandick, 2013; Kumar & Sandick, 2013
  - Near the Milky Way GC
    Gondolo and Silk, 2000
  - In the Sun or the Earth
    Silk et al. 1985; Kraus et al. 1986; Freese 1986
  - In nearby dwarf galaxies
    Evans, Ferrer & Sarkar 2004; Sandick et al. 2009; Feldman & Sandick, 2013
  - In Milky Way substructure
    Evans, Ferrer & Sarkar 2004, Sandick et al. 2010, 2011a,b



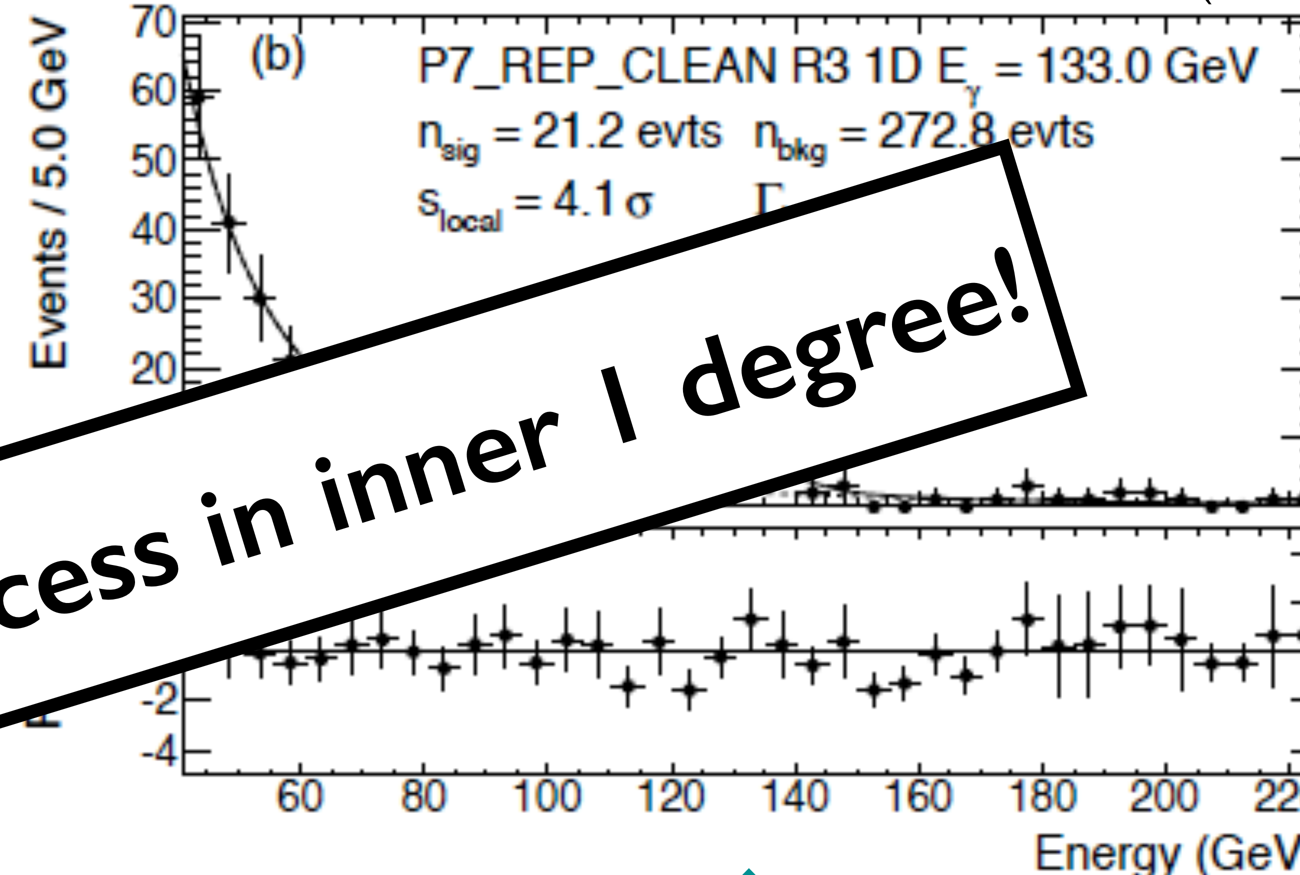
Interesting (positive) Results...

Rising positron fraction?

AMS Collaboration, PRL (2013)



Fermi LAT Collaboration (2013)



Galactic Center γ Excess in inner 1 degree!

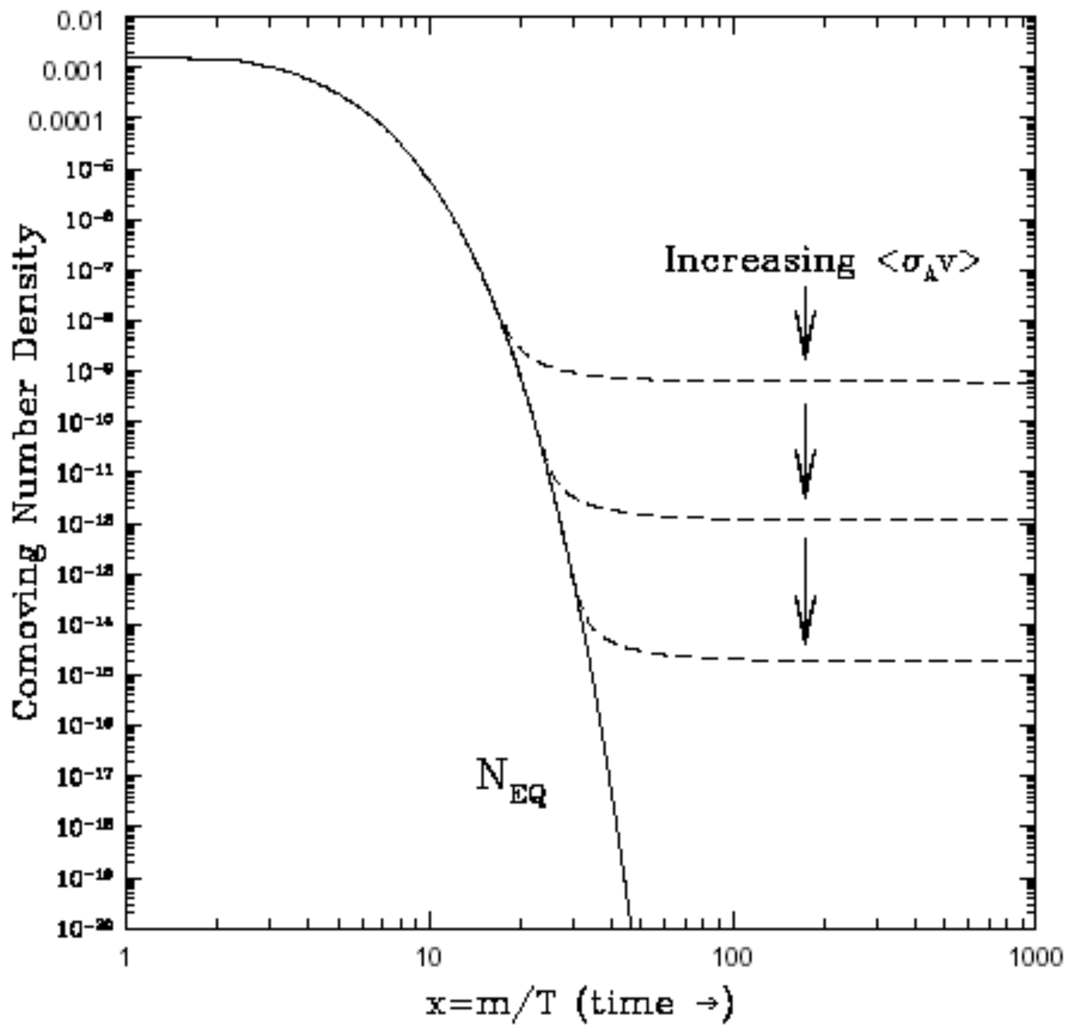
Gamma-ray line?

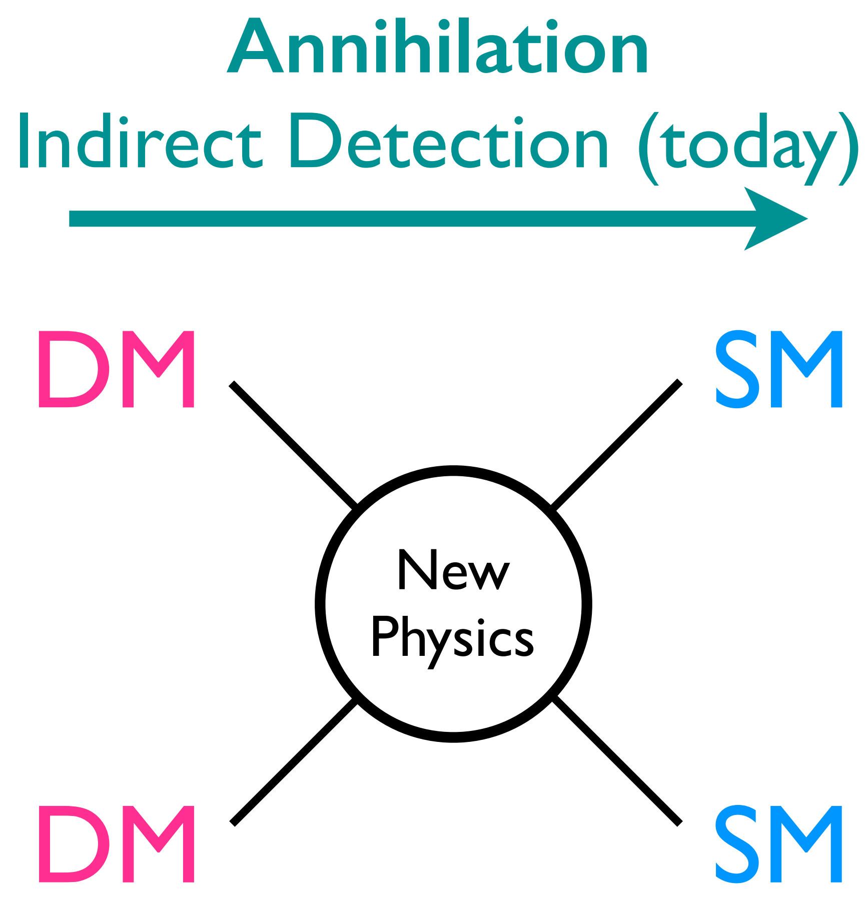
(In a generic MSSM model, how large can a line signal be relative to the continuum gamma-ray flux?

Kumar & **Sandick**, PRD 2013)

Indirect Detection

Link to annihilation in the early universe?



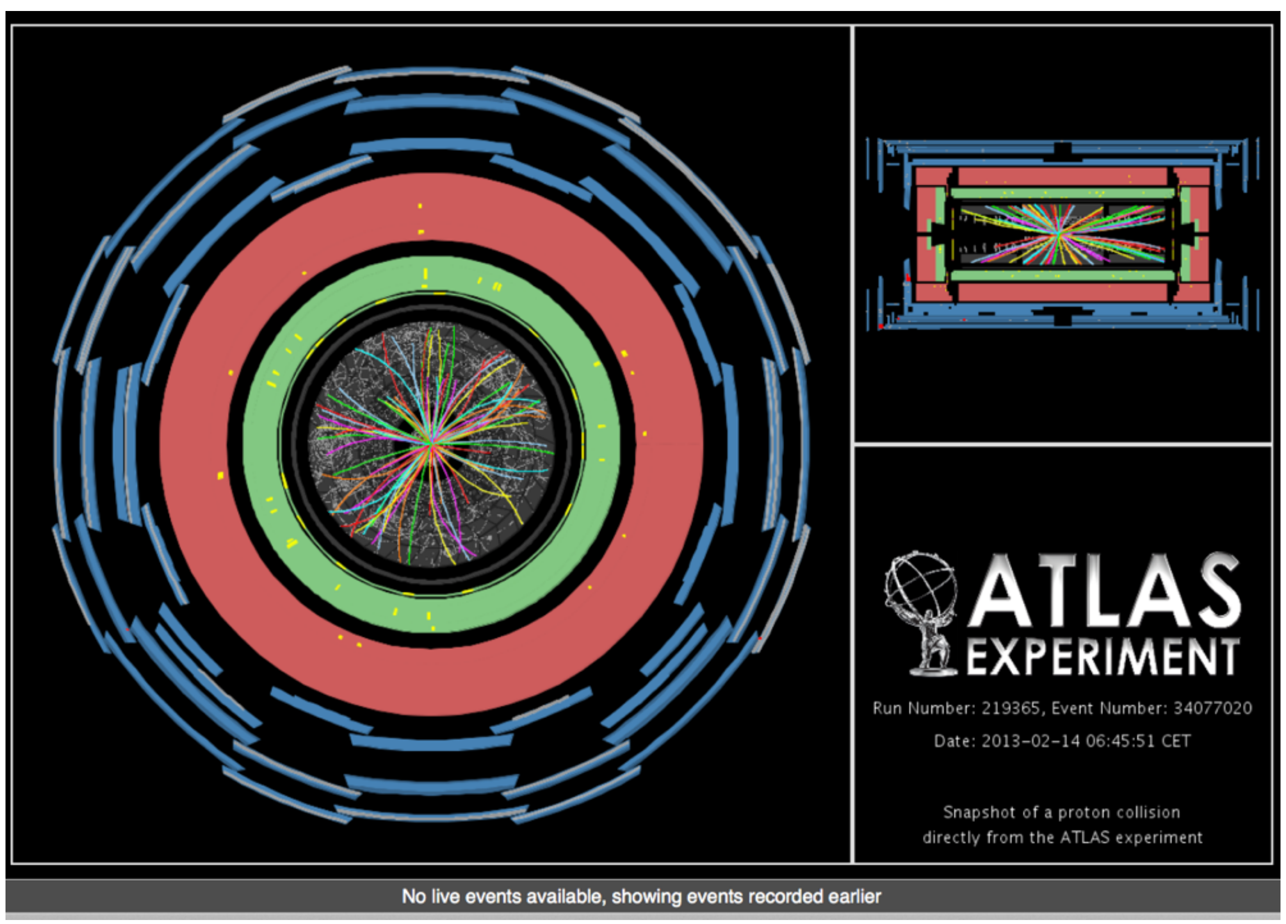


The Large Hadron Collider

Large Hadron Collider

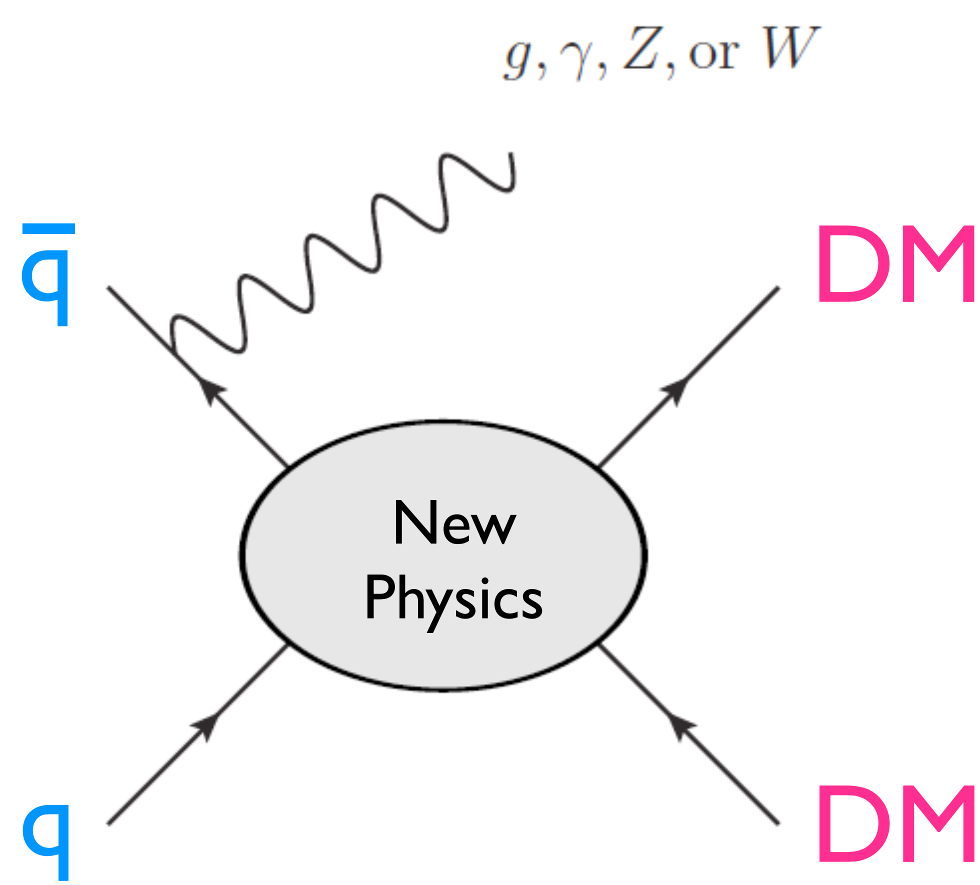
- Missing Energy Searches
- New Physics Searches

http://atlas-live.cern.ch



- Mono-Anything Searches
- Can relate to WIMP-quark elastic scattering if you know what the New Physics is, or if you use an effective operator method

e.g. Zhou, Berge, & Whiteson (2013)



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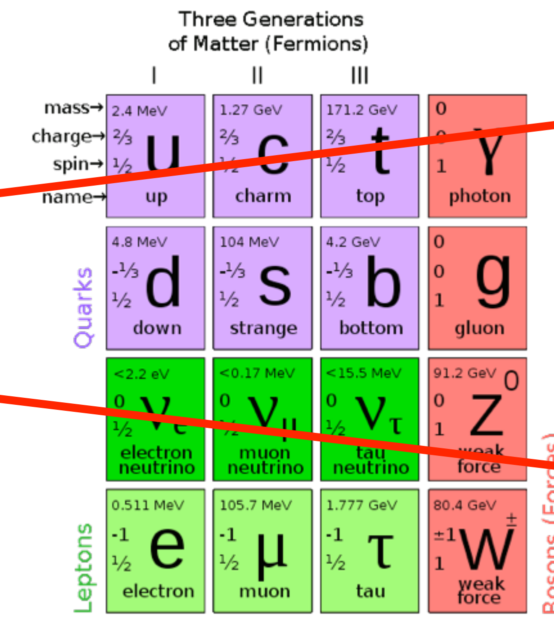

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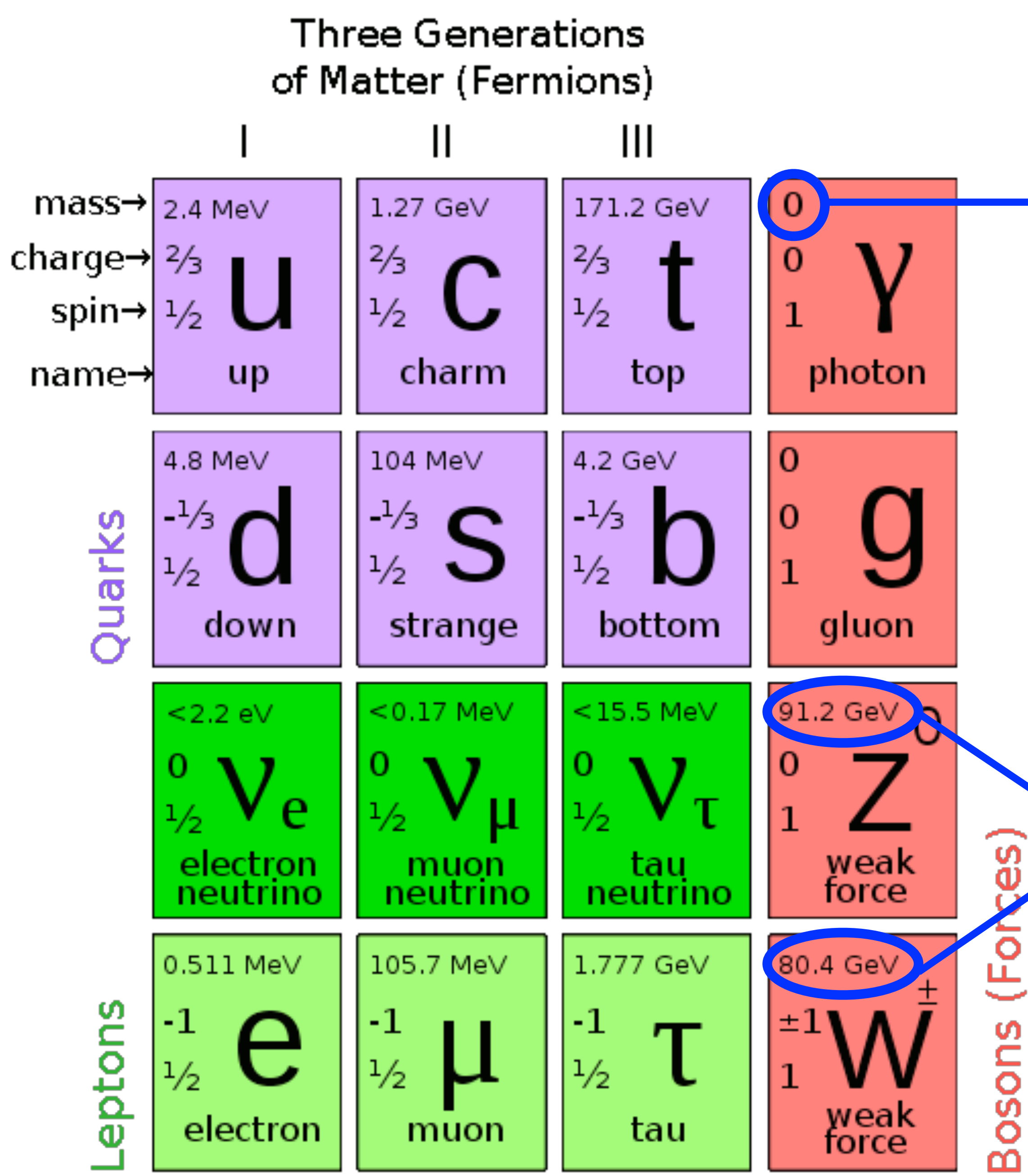
Completions involve new physics with mass scale $O(100)$ GeV.

Standard Model (pre-2012)



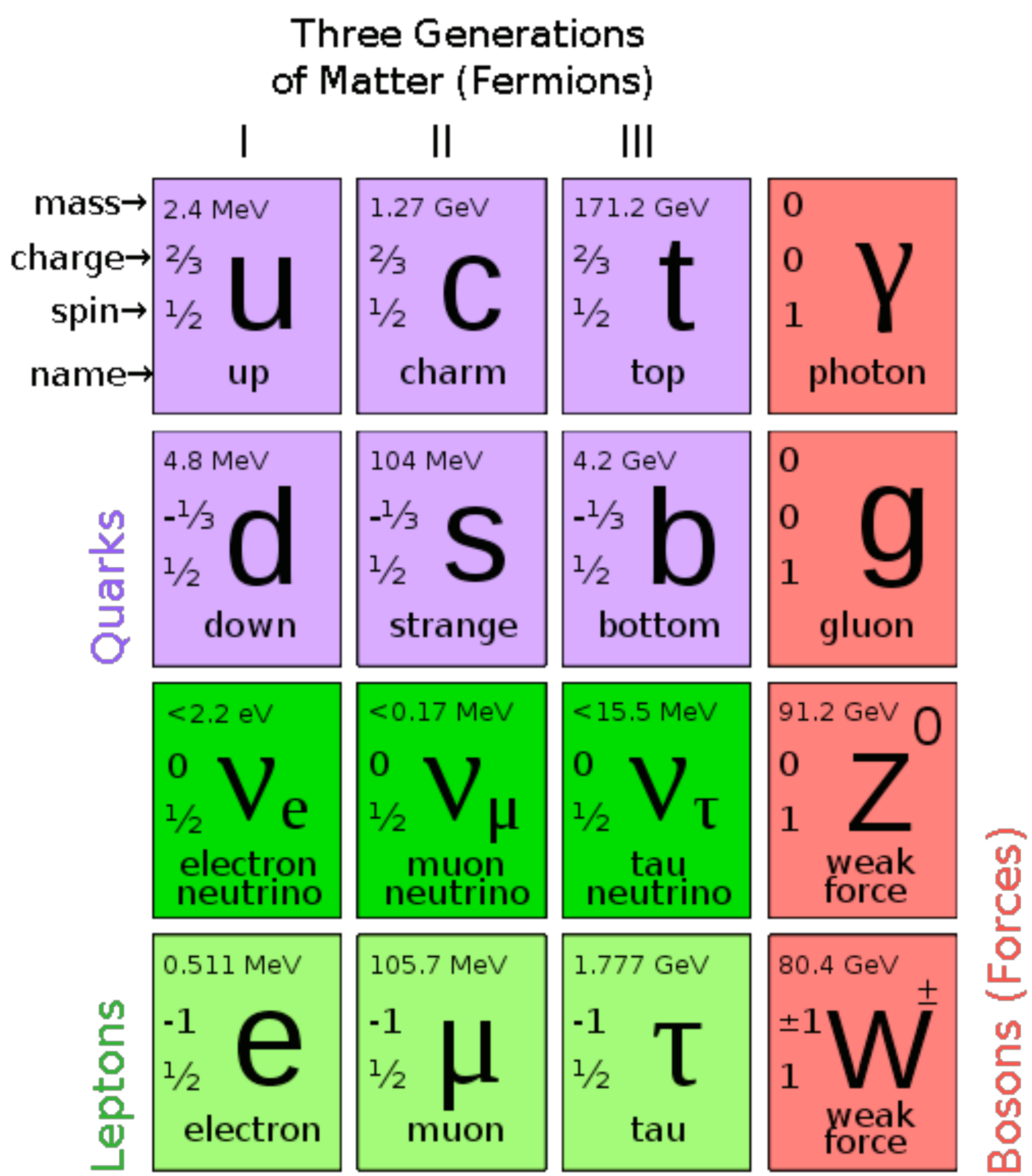
massless

Electroweak Symmetry Breaking (EWSB)

(1)

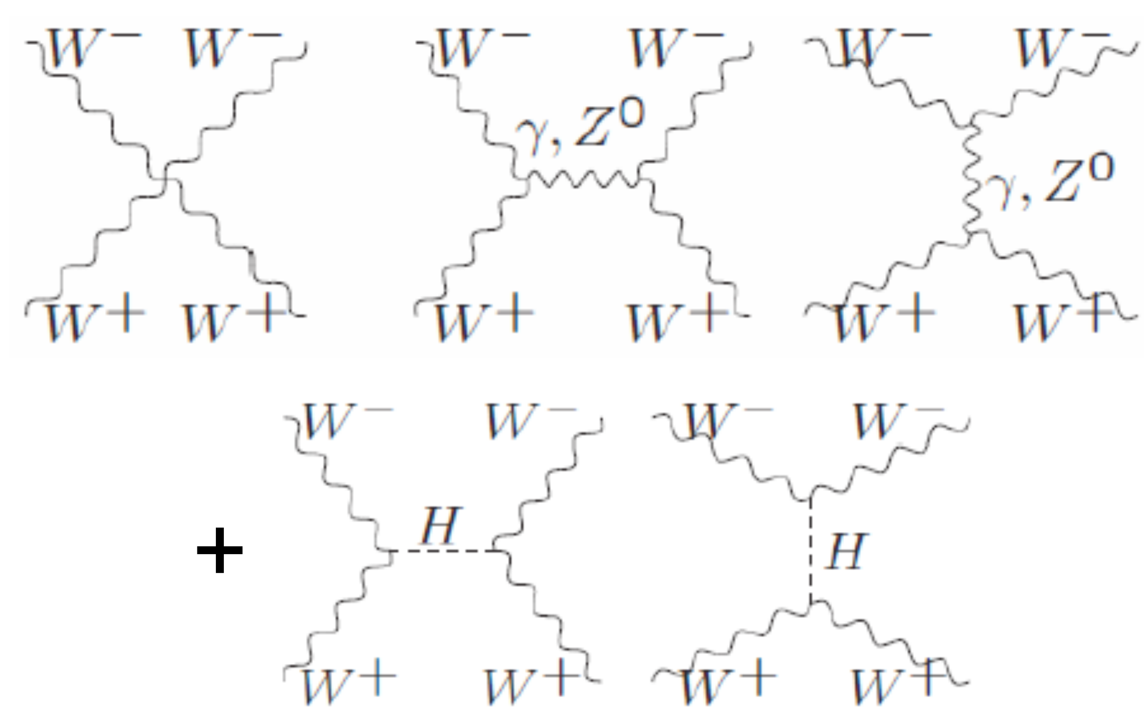
"weak-scale" masses

Standard Model (pre-2012)

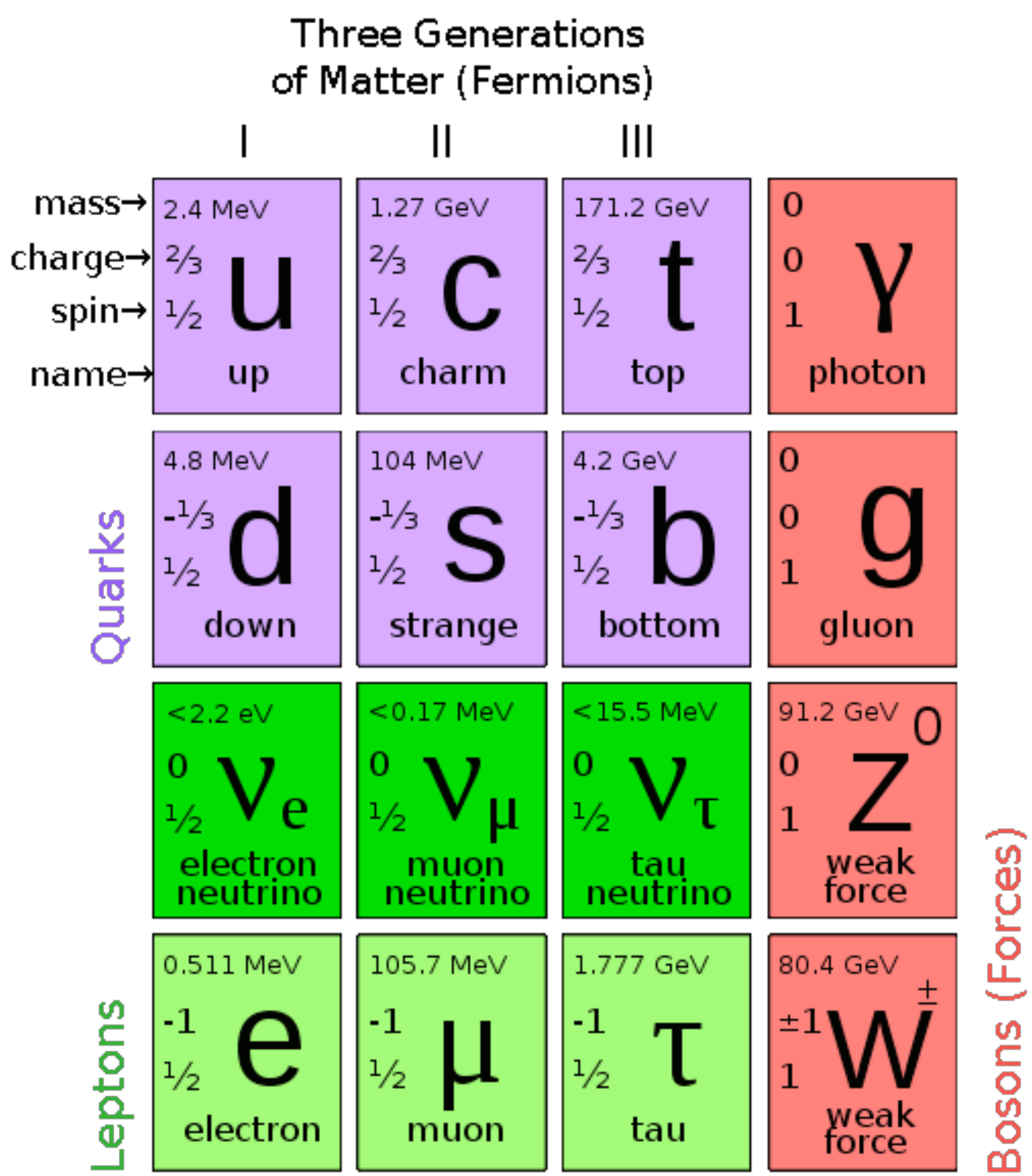


(2) Unitarity

- Prob. of WW scattering increases with energy.
- Prob. > 1 for high energy W's,
- SM-like Higgs prevents this if $m_h \lesssim 800$ GeV, or something else new at or below that scale.



Standard Model (2012)



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New Physics at the Weak Scale?

✓ • Electroweak Symmetry Breaking (EWSB)

✓ • Probability of WW scattering increases with energy

- Gauge Hierarchy Problem
- Dark Matter

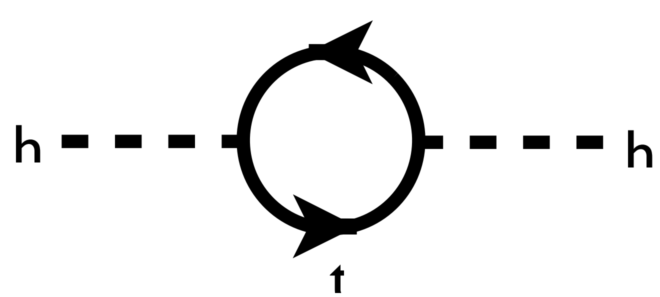
} New Physics *Still* Needed (more than just the Higgs)

New Physics at the Weak Scale?

✓ • Electroweak Symmetry Breaking (EWSB)

✓ • Probability of WW scattering increases with energy

- Gauge Hierarchy Problem
    - Experimentally, $m_h^2 \approx \mathcal{O}(100\ GeV)^2$
    - Quantum corrections:

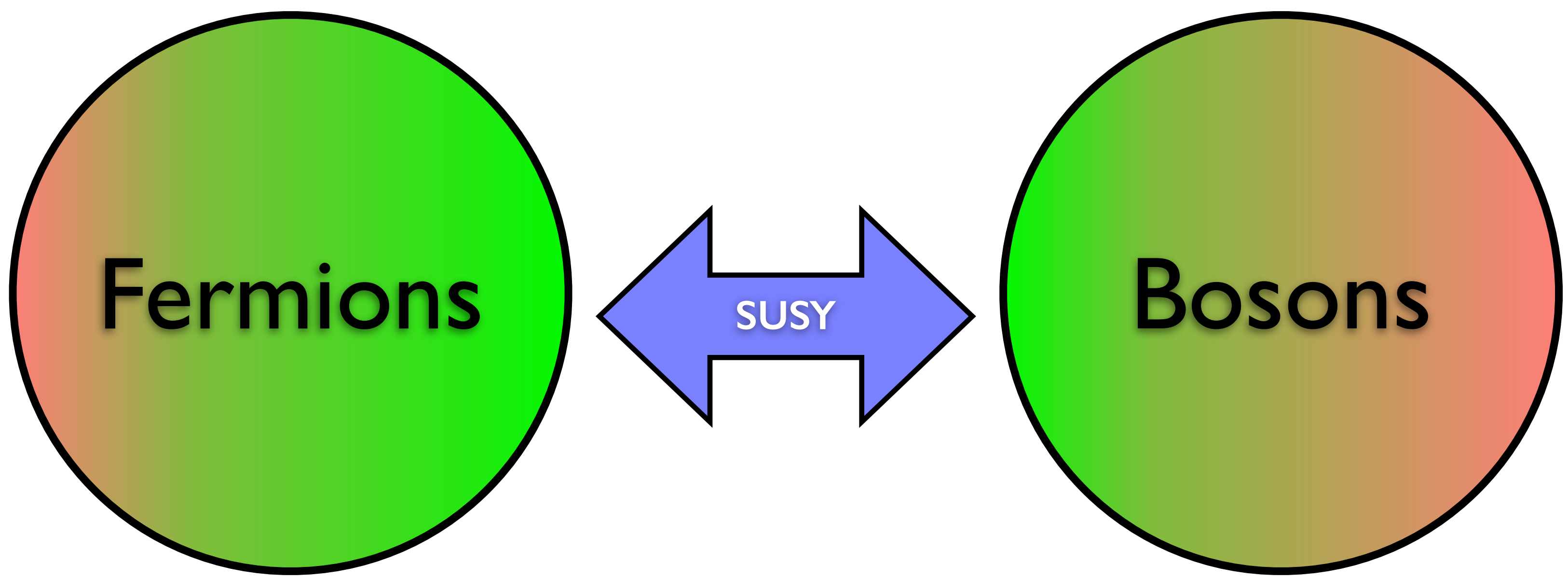


$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + ...$$

New Physics at the Weak Scale?

- ✓ Electroweak Symmetry Breaking (EWSB)
- ✓ Probability of WW scattering increases with energy
- Gauge Hierarchy Problem
- Dark Matter????
  - At least some explanation is needed, since it's not SM particles.
    - Supersymmetric particles: neutralino, sneutrino, gravitino, axino
    - Kaluza-Klein states
    - Little Higgs heavy photons or scalars
    - Lots of other ideas
      - may or may not be related to the weak scale
      - may or may not address particle physics needs

Supersymmetry

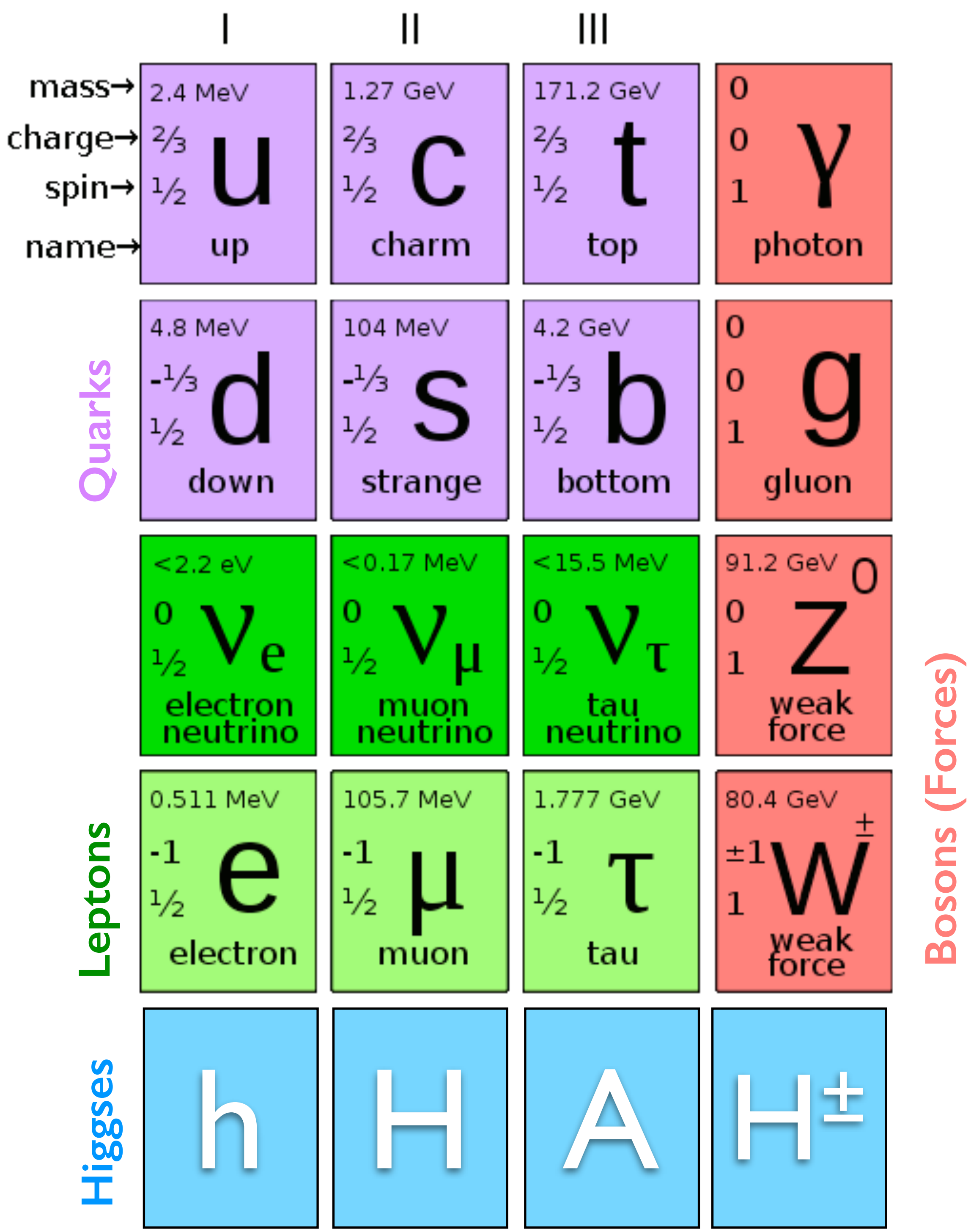


Supersymmetry is the only possible extension of the Poincare algebra in a consistent 4d quantum field theory. Haag, Lopuszanski, & Sohnius (1975)

Each Standard Model particle gets a Supersymmetric partner!

Minimal Supersymmetric Standard Model

Three Generations
of Matter (**Fermions**)



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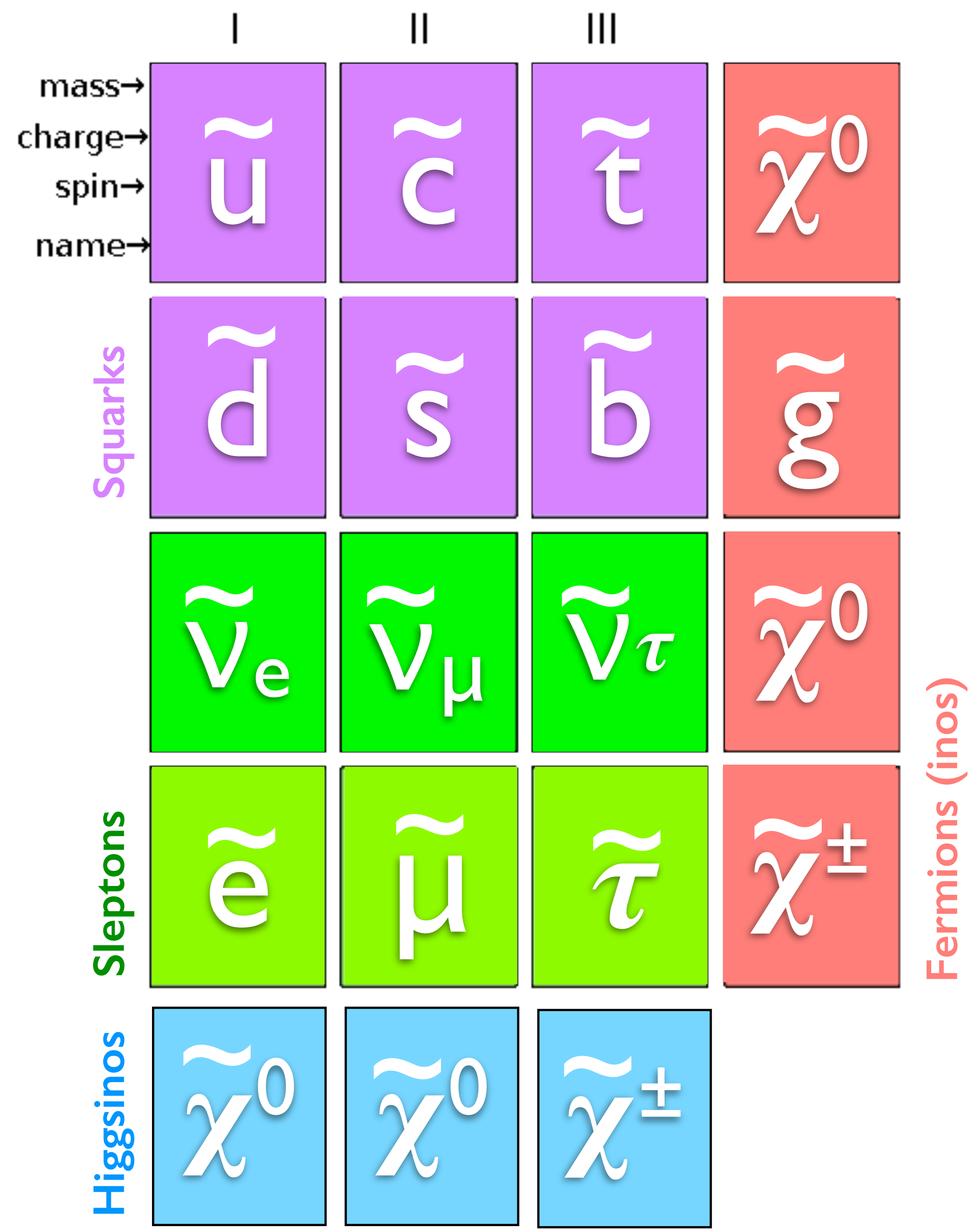

Virtues of Supersymmetry

- Elegance (!)
- Gauge Coupling Unification
- Hierarchy Problem Addressed
- Light Higgs Boson
- Dark Matter

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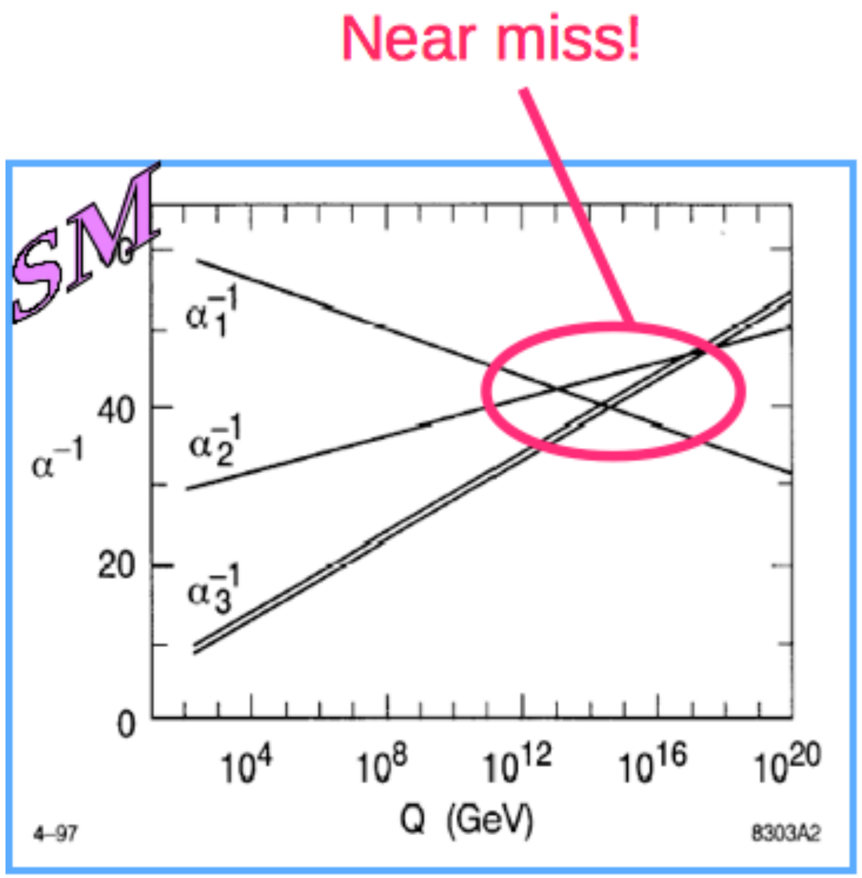

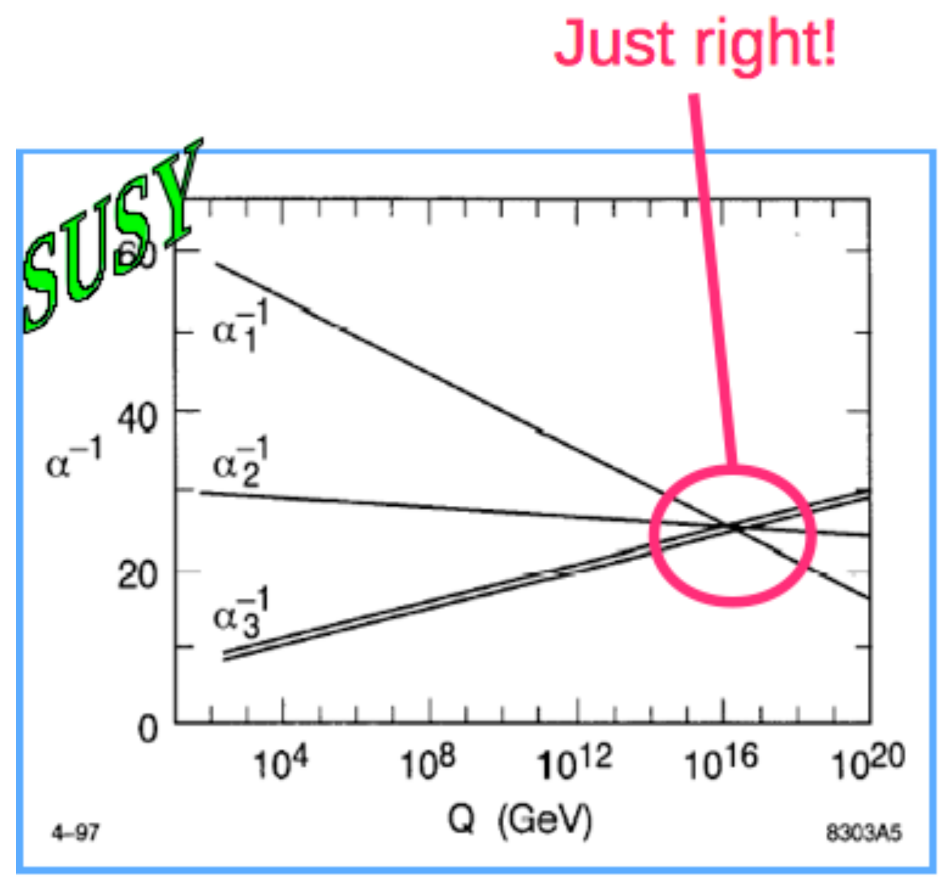

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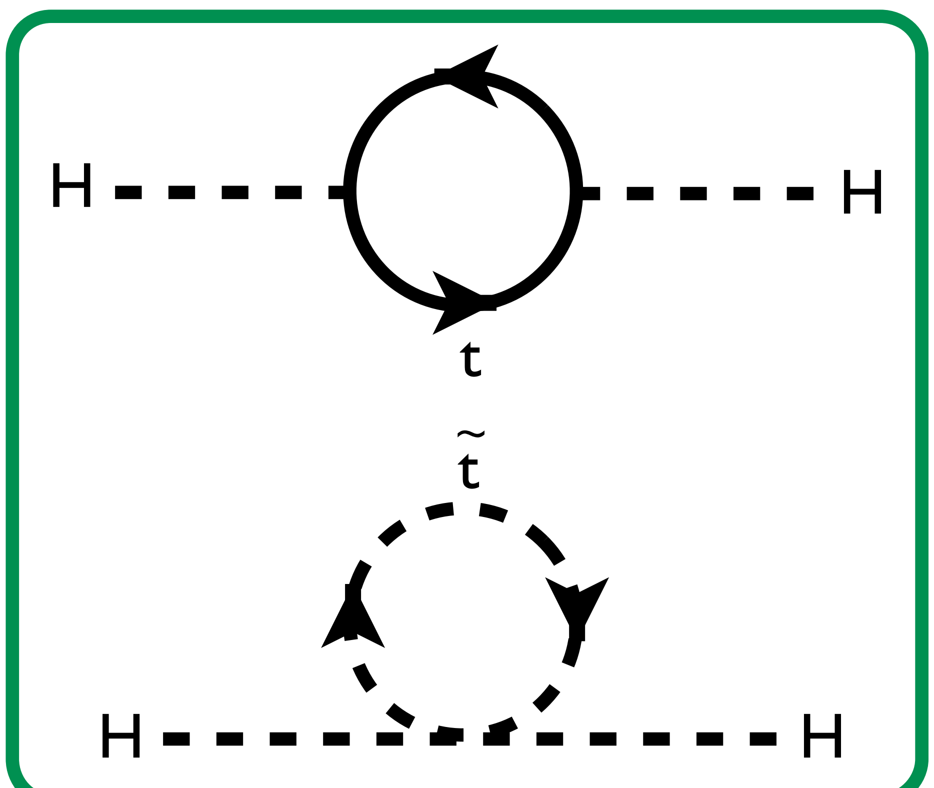
SUSY maintains the hierarchy of mass scales.

SM:

SUSY:



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

$$m_h^2 = (m_h^2)_0 \cancel{- \tfrac{1}{16\pi^2}\lambda^2\Lambda^2 + \tfrac{1}{16\pi^2}\lambda^2\Lambda^2} + \tfrac{1}{16\pi^2}\left(m_{\tilde{f}}^2 - m_f^2\right)\ln\left(\Lambda/m_{\tilde{f}}\right) + \ldots$$

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- Elegance (!)
- Gauge Coupling UnificationClowe et al. (2006)
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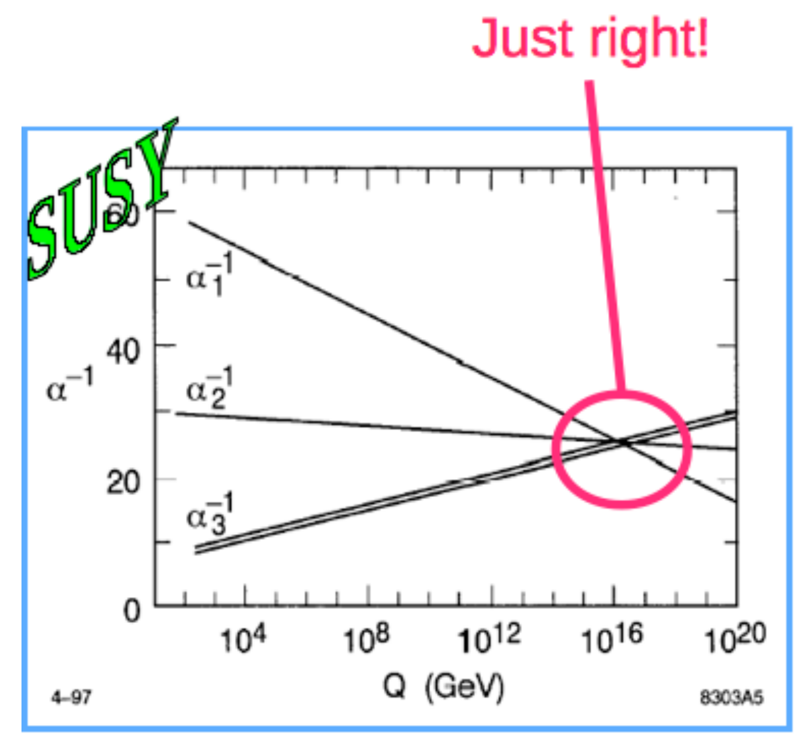
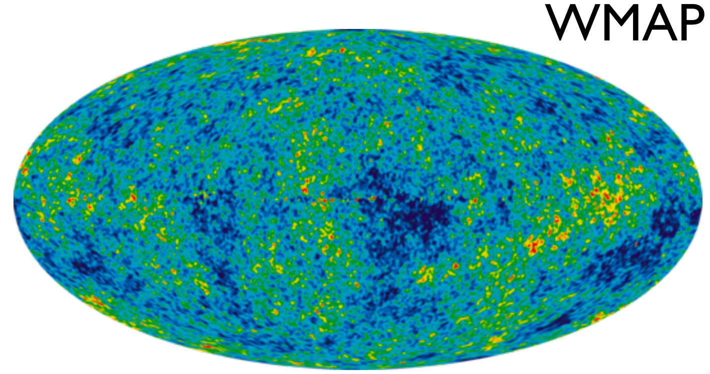
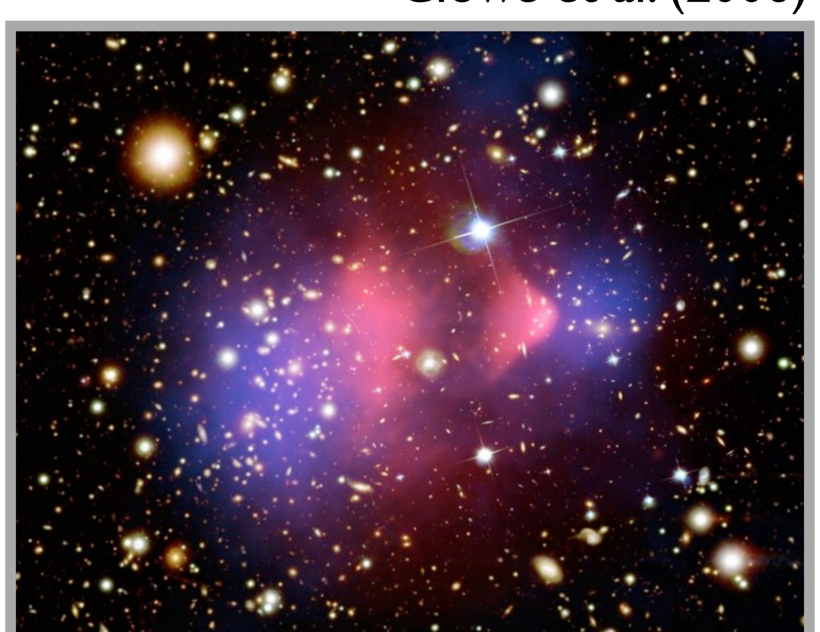


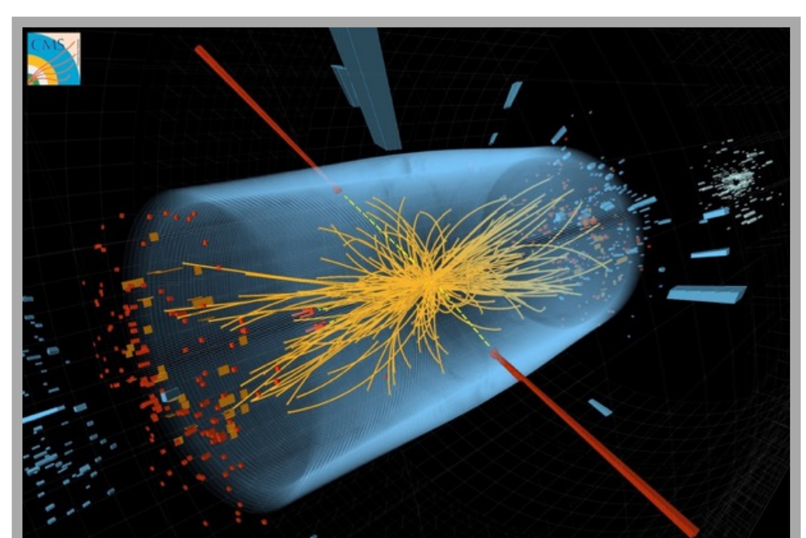
WMAP

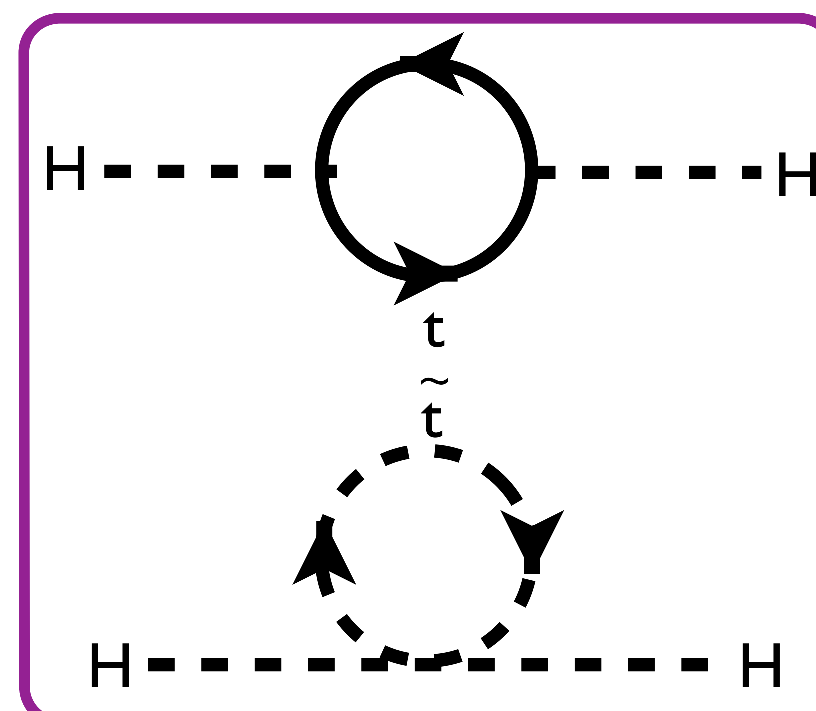


Clowe et al. (2006)



CMS-PHO-EVENTS-2011-010

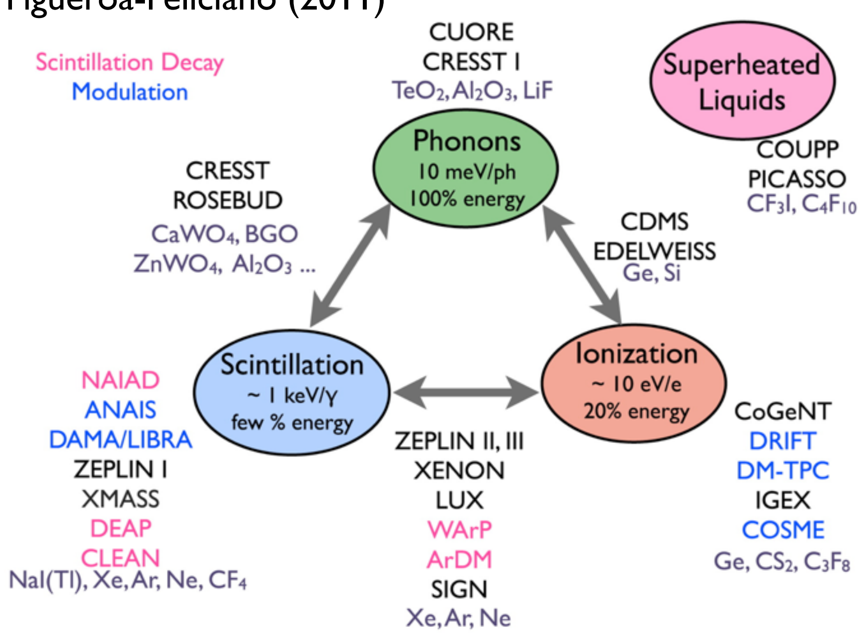


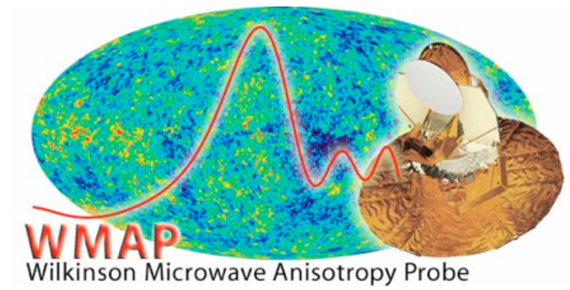


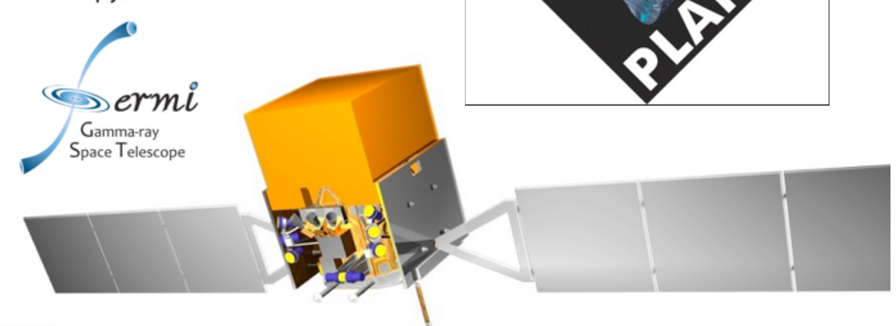
Current Situation

- Abundance of experimental data!

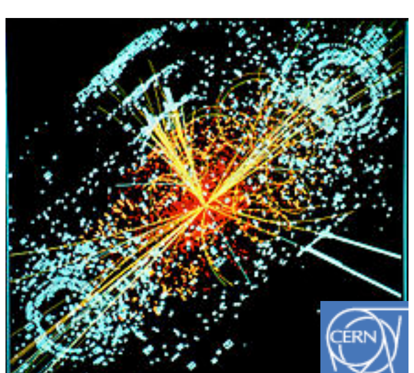
Figueroa-Feliciano (2011)







PAMeLA



Current Situation

- Abundance of experimental data!
  - Dark matter is being explored with unprecedented and growing precision.
- Theoretical approaches:

Totally Data-Driven

$\updownarrow$

Hybrid / Simplified Models

$\updownarrow$

Totally Theory-Driven

From Theory to Predictions

Supersymmetry

MSSM

Non-Minimal Model

Gravity Mediation

Gauge Mediation

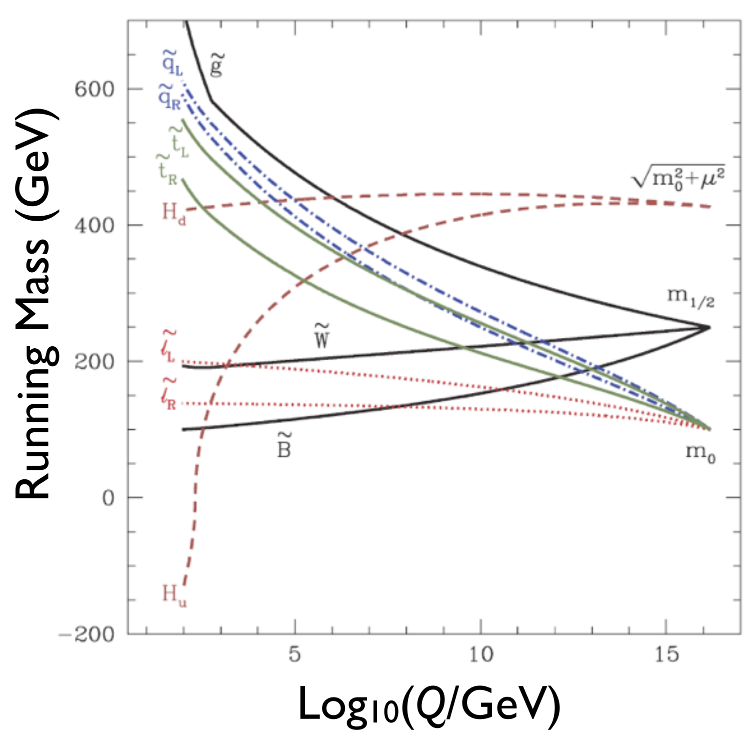
...

EW-Scale Inputs

mSUGRA

CMSSM

NUHM



pMSSM

MSSMn (n=7,9,etc.)

Relevant Parameters Only
for Specific Signature

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):

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

SUSY Dark Matter

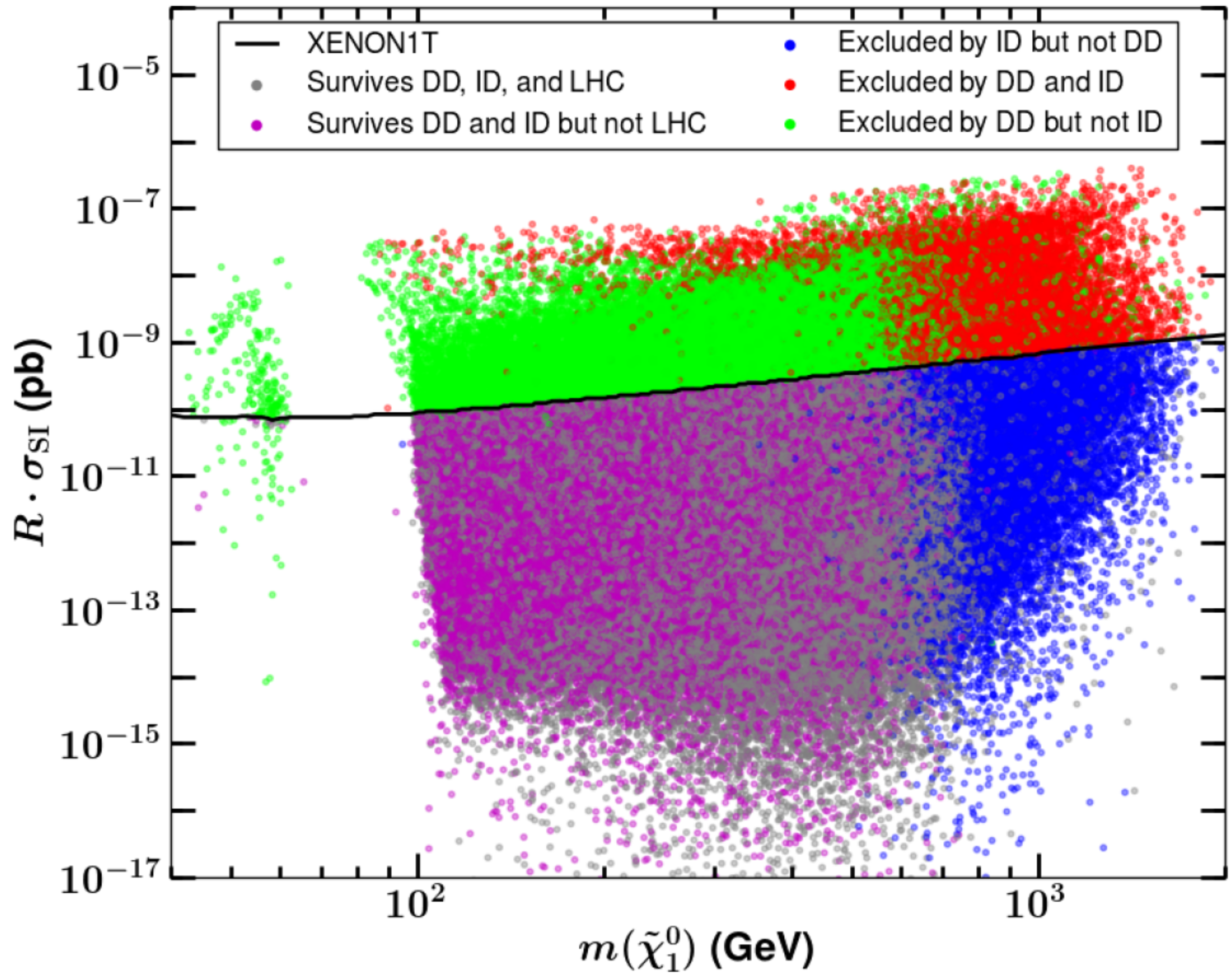
1. What is predicted within the SUSY framework?
   - specific realization or more general possibilities
2. What are the data really telling us?
   - Priors on model
   - Connection to predictions

   } → different interpretations
3. When will we know for sure?

★ **Direct Dark Matter Searches**

pMSSM (19 parameters)

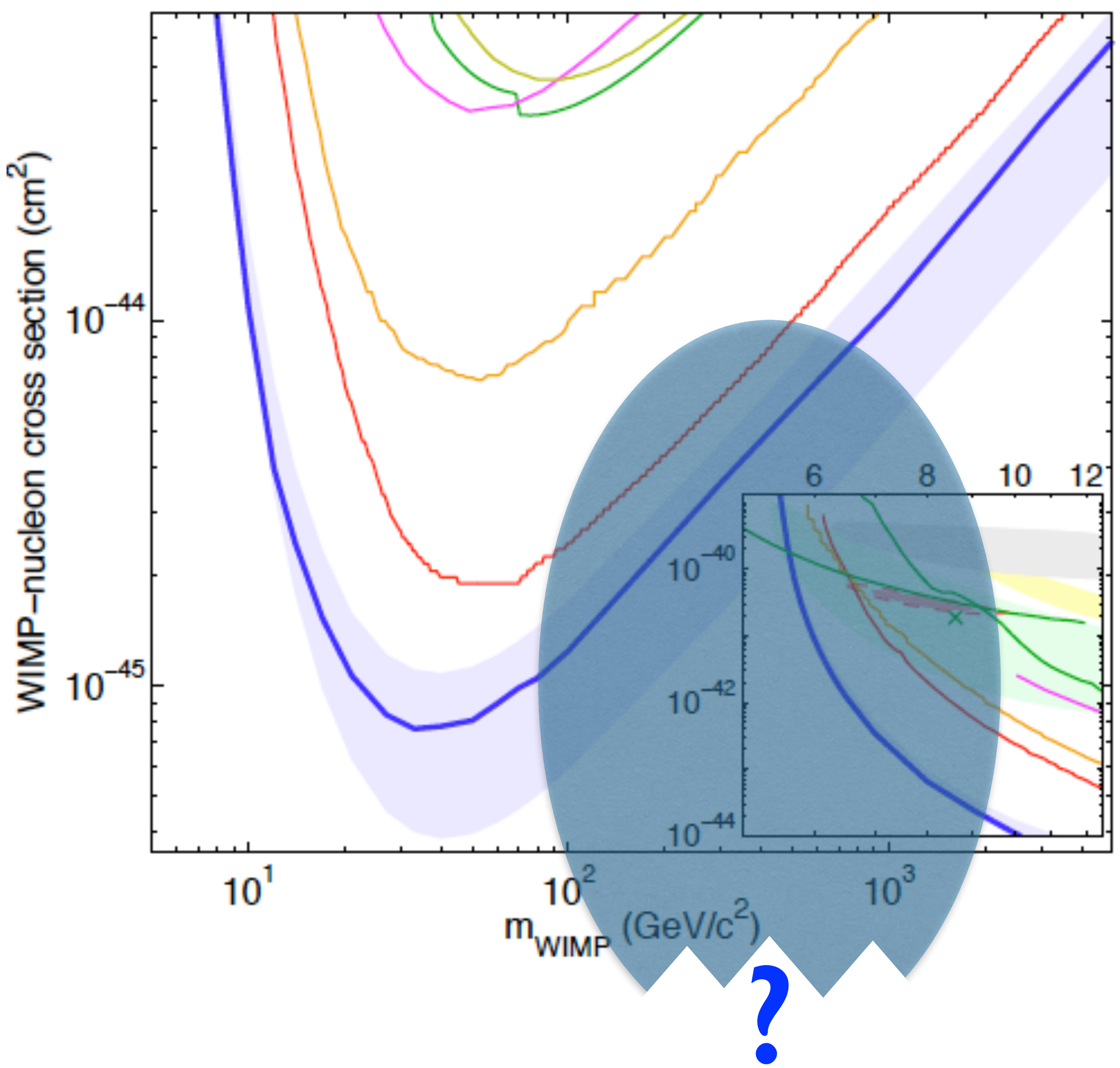
Cahill-Rowley et al. (2013)



Future Prospects

- Timeline for discovery/exclusion?

Akerib *et al.* (LUX Collaboration), 2013



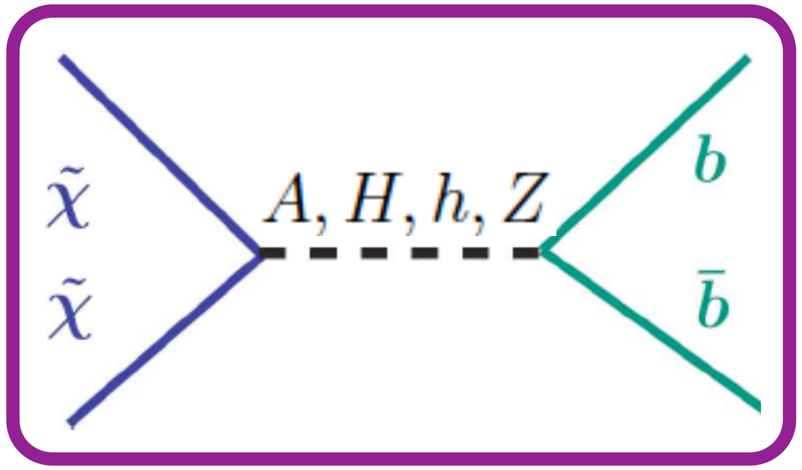
Could answer within a low-dimensional model (not general), or within the MSSM (not conclusive).

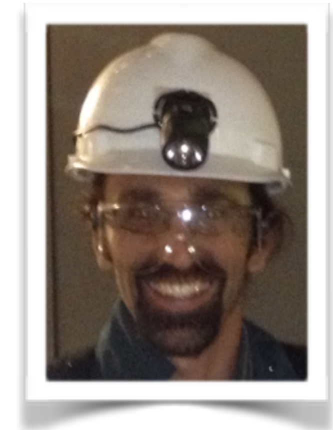
Simplified models can help you construct a definite, model-independent answer.

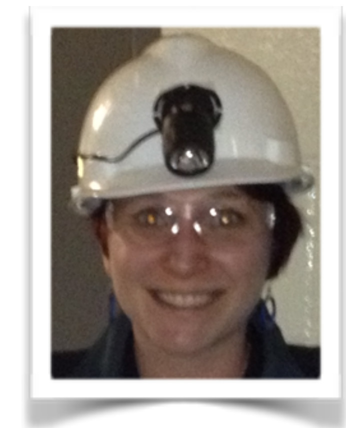
If DM abundance is achieved through a resonance, how small could σ_{SI} possibly be?

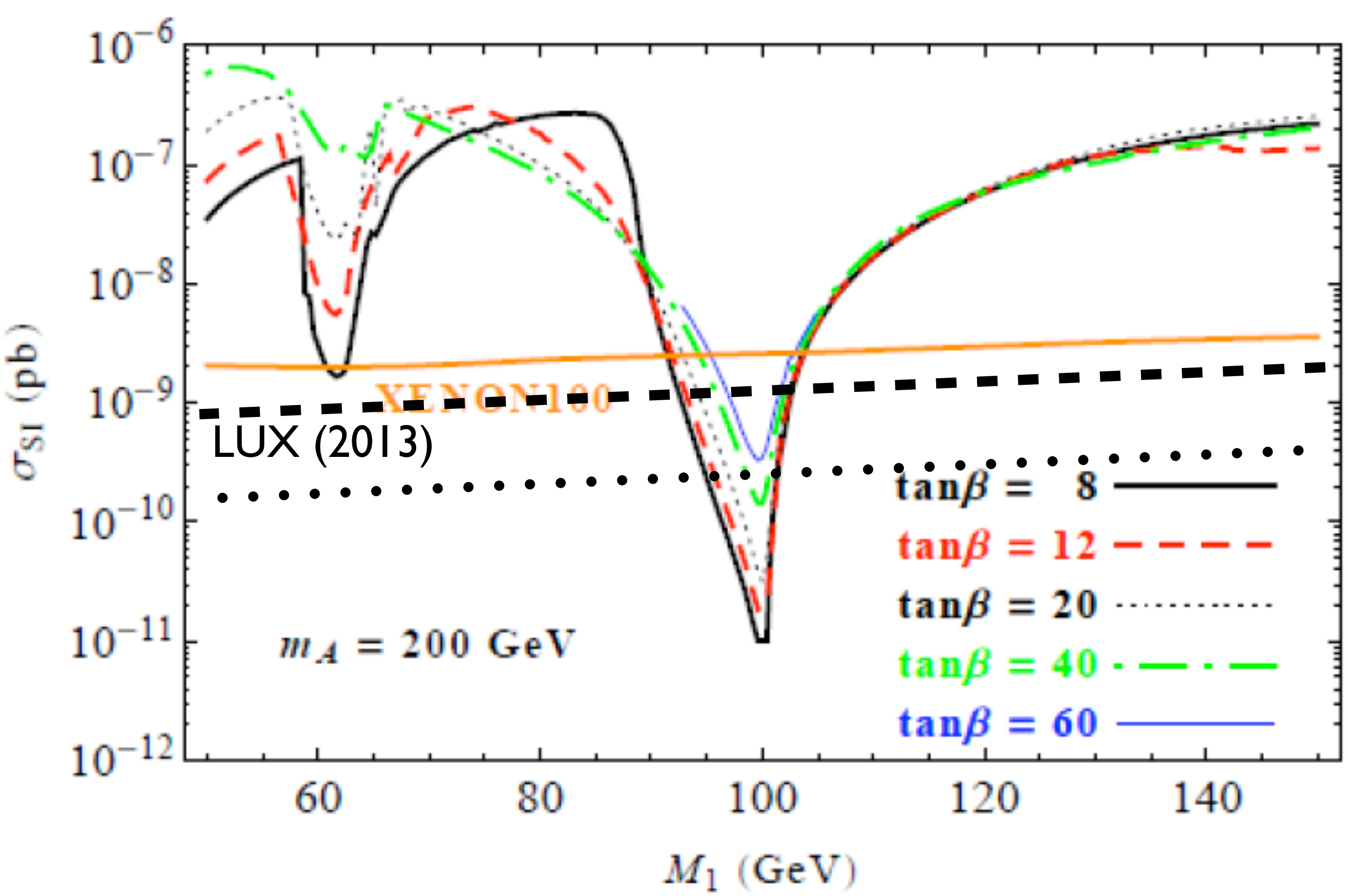
Hooper, **Kelso, Sandick,** & Xue, PRD 2013

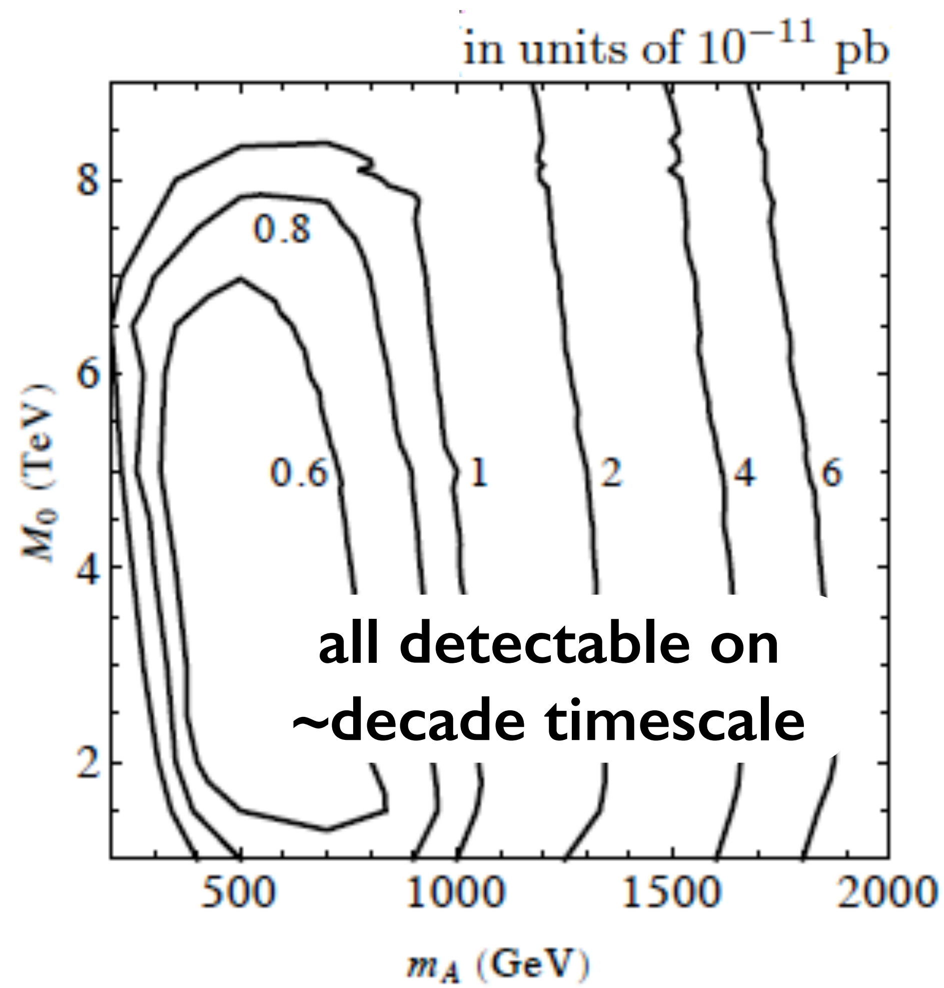
- Relic Abundance: μ
- Higgs mass: A_0
- Free parameters: (m_0, M_1, m_A, tanβ)









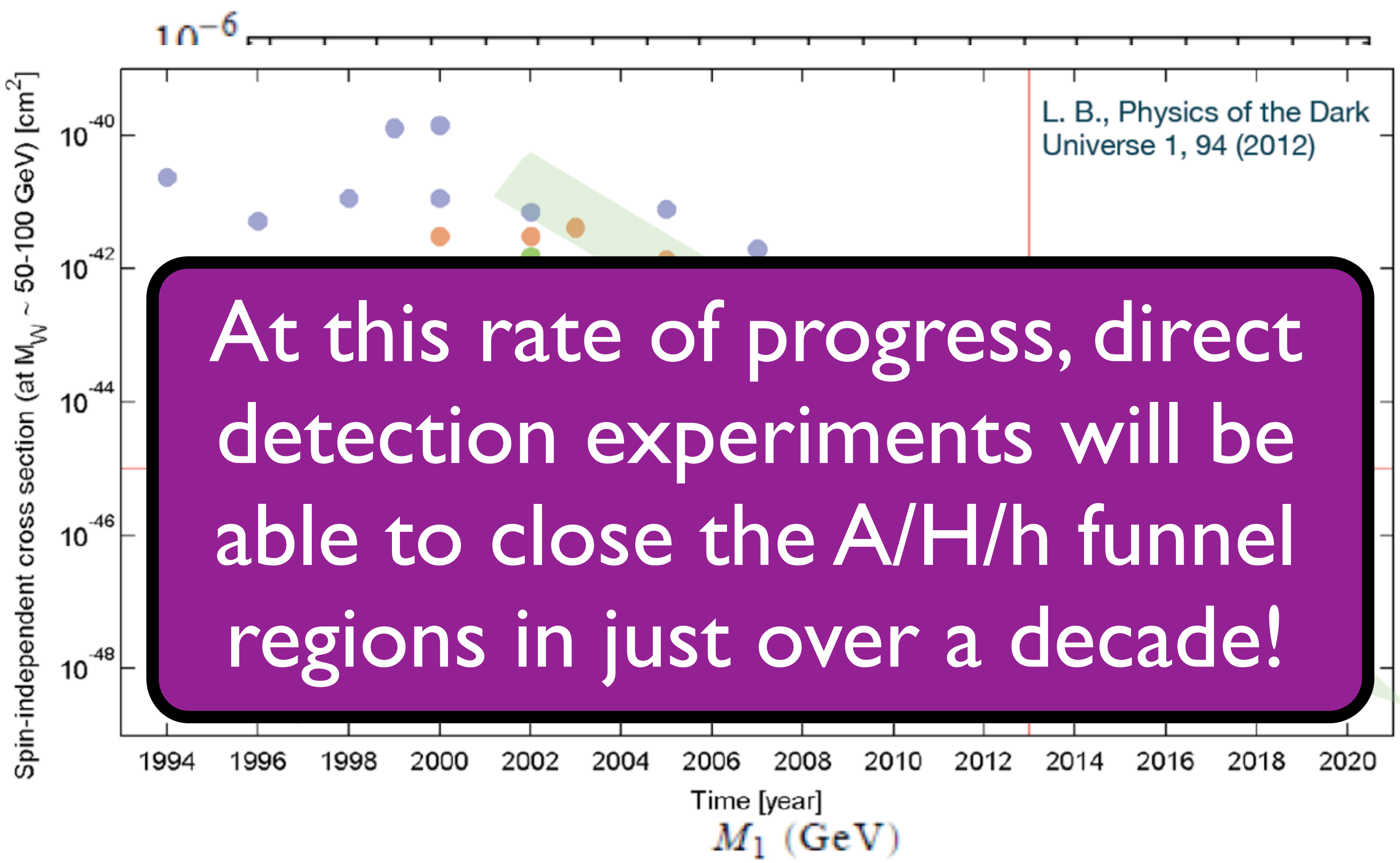


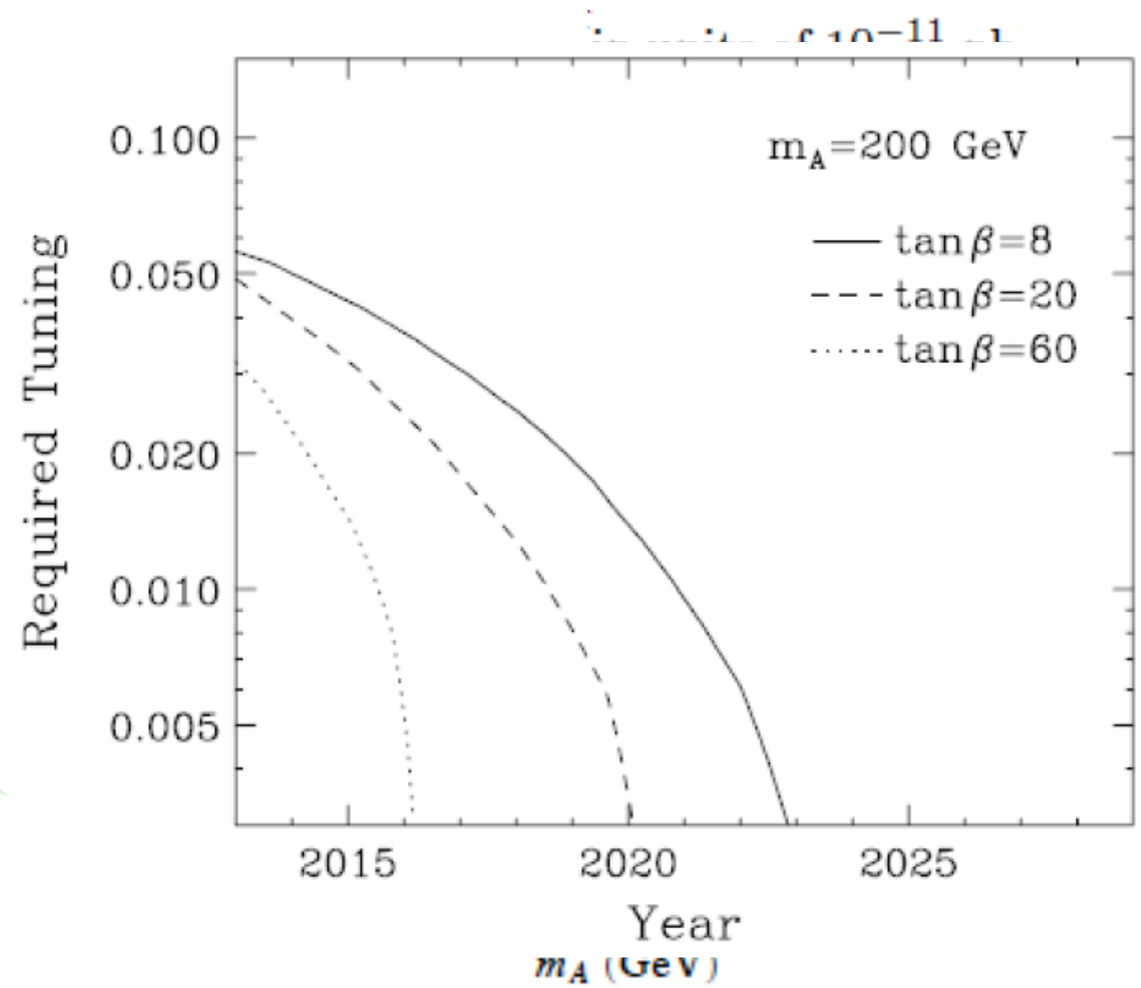
If DM abundance is achieved through a resonance, how small could σ_{SI} possibly be?

Hooper, **Kelso, Sandick,** & Xue, PRD 2013

- Relic Abundance: μ
- Higgs mass: A_0
- Free parameters: (m_0, M_1, m_A, $\tan\beta$)

If Nature is MSSM-like, and neutralino dark matter at a resonance makes up all the dark matter in the Universe, then direct detection experiments are pushing the resonance to be more and more exact.





SUSY Dark Matter

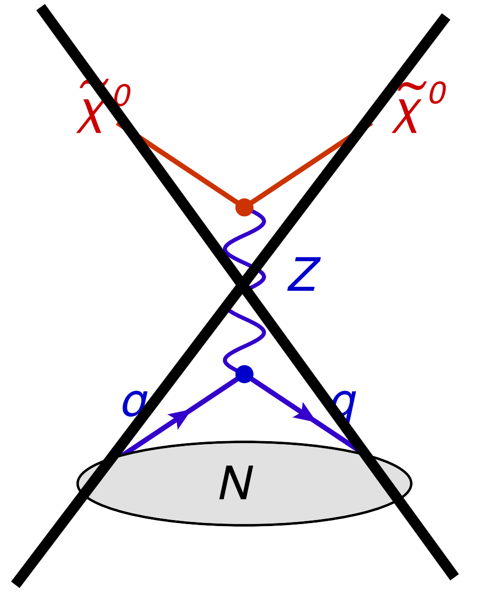
1. What is predicted within the SUSY framework?
   - specific realization or more general possibilities
2. What are the data really telling us?
   - Priors on model
   - Connection to predictions

   } ➔ different interpretations
3. When will we know for sure?

★ **Direct Dark Matter Searches**

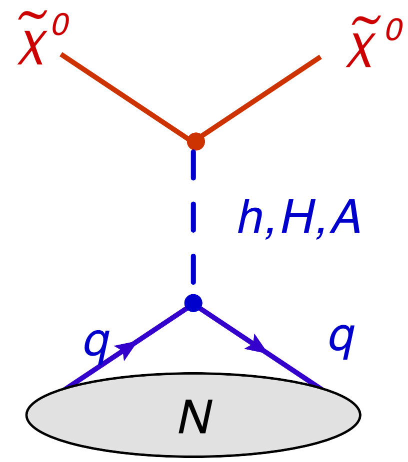
Spin-Independent Scattering with Nuclei

Figure from Gladyshev & Kazakov (2012)

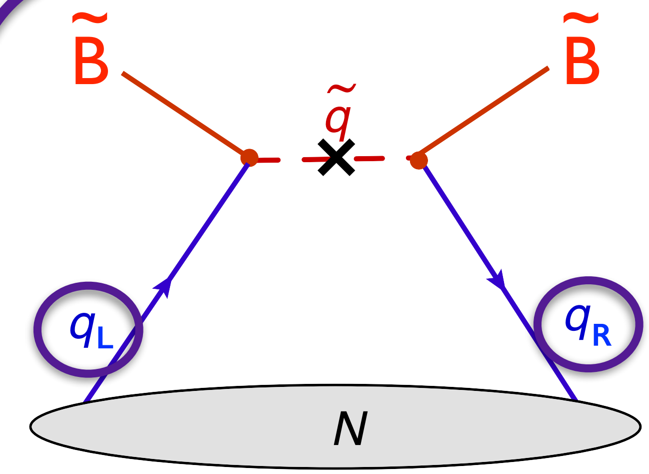


velocity-suppressed

$\left(\frac{v}{c}\right)^2 \approx \mathcal{O}(10^{-6})$



$\tilde{H}$-$\tilde{B}$-Higgs coupling



$\tilde{B}$-$\tilde{q}$-q coupling

Need L-R squark mixing!

$$\tilde{q}_L = \tilde{q}_1 \cos\phi_q + \tilde{q}_2 \sin\phi_q$$
$$\tilde{q}_R = -\tilde{q}_1 \sin\phi_q + \tilde{q}_2 \cos\phi_q$$

Pure bino dark matter:

$$\mathcal{O} = \frac{1}{4} g'^2 \sin(2\phi_q) Y_L Y_R \left[\frac{1}{m^2_{\tilde{q}_1} - m^2_X} - \frac{1}{m^2_{\tilde{q}_2} - m^2_X}\right] (\bar{X}X)(\bar{q}q) \equiv \alpha_q (\bar{X}X)(\bar{q}q)$$

Lightest Supersymmetric Particle (LSP):

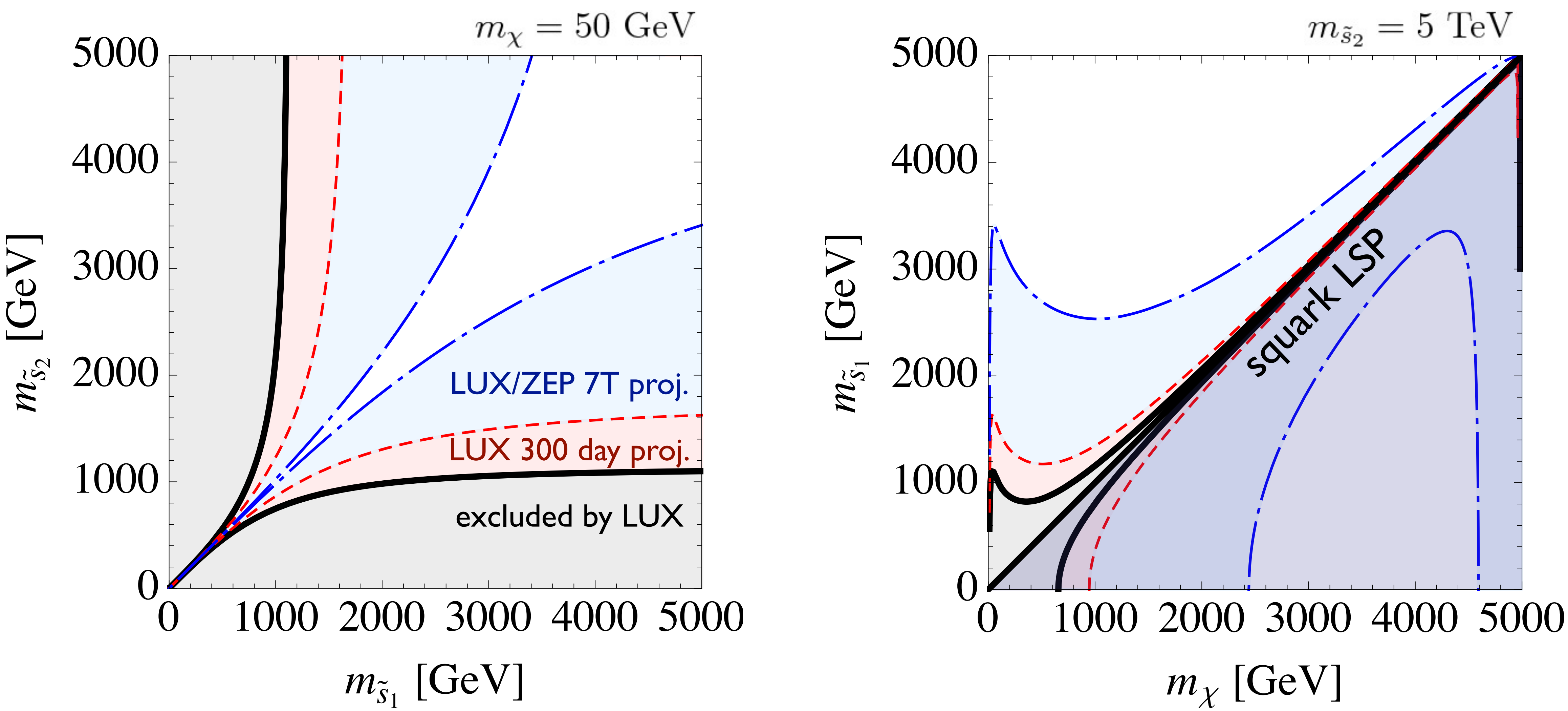
$$\tilde{\chi}^0_i = \alpha_i \tilde{B} + \beta_i \tilde{W}^3 + \gamma_i \tilde{H}^0_1 + \delta_i \tilde{H}^0_2$$

(bino) (wino) (higgsino)

$$\sigma^N_{\rm SI} = \frac{\mu^2}{4\pi} g'^4 Y_L^2 \left\{ \sum_q \sin(2\phi_q) Y_{Rq} \left[\frac{1}{m^2_{\tilde{q}_1} - m^2_X} - \frac{1}{m^2_{\tilde{q}_2} - m^2_X}\right] (B^N_q) \right\}^2$$

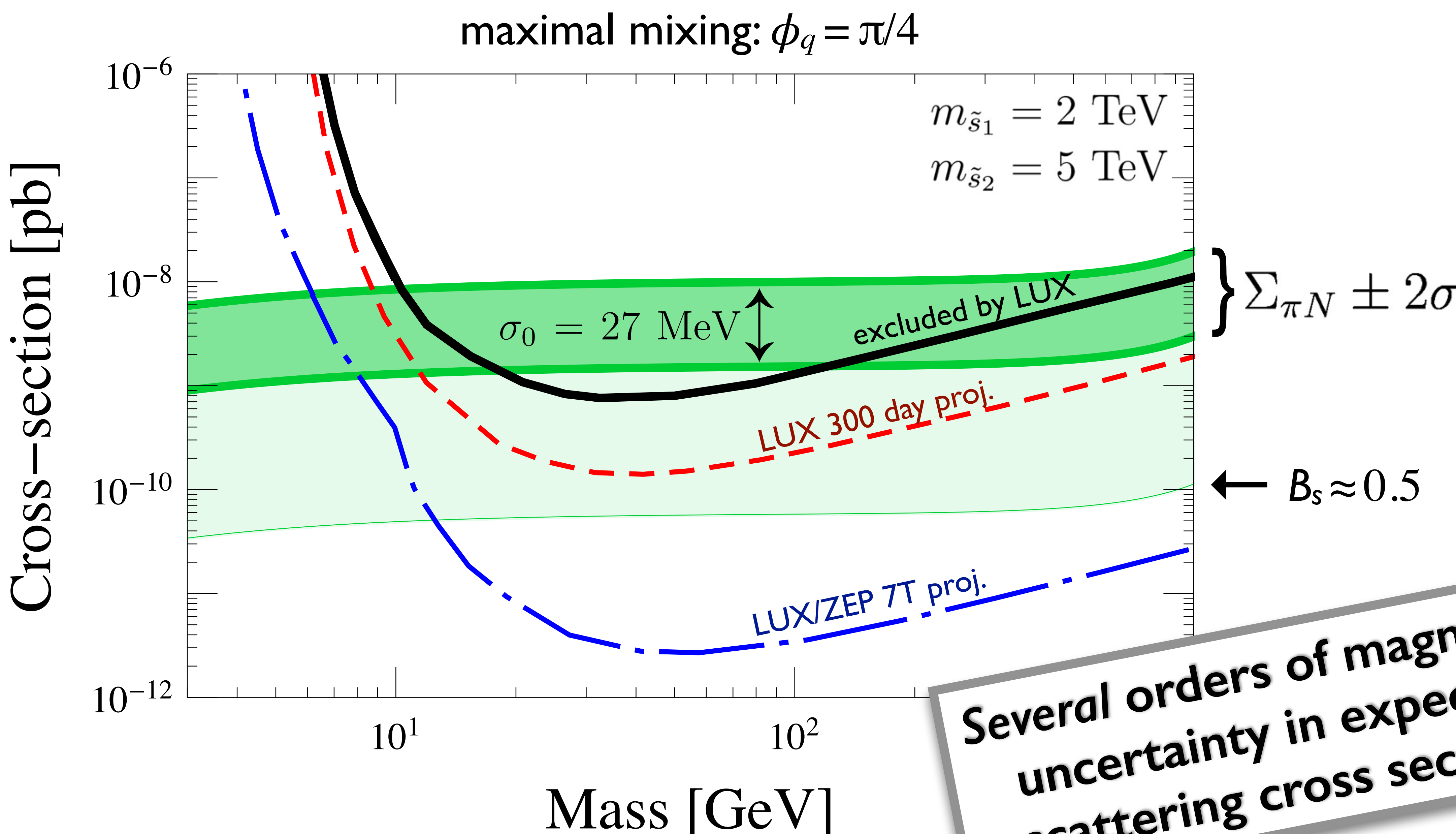
Strange Squark Mass Reach

Benchmark: $\begin{cases} \text{small strangeness: } B_s \approx 0.5 \\ \text{maximal mixing: } \phi_q = \pi/4 \end{cases}$



Kelso, Kumar, Sandick, & Stengel (*in prep.*)

Direct Detection Reach



Several orders of magnitude uncertainty in expected scattering cross section!

Kelso, Kumar, Sandick, & Stengel (*in prep.*)

What does it mean?

- We considered light bino-like dark matter that scatters with nuclei via squark exchange (all other sparticles heavy/irrelevant).
- Direct detection experiments are sensitive to a broad range of models, *which may defy the common MSSM presumption of isospin invariance.*
- Uncertainties in predictions for SI scattering of WIMPs with nuclei **can span several orders of magnitude** if scattering occurs mainly through squark exchange. *Uncertainties in the strange quark content of the nucleon may be **devastating** to our ability to draw conclusions from direct dark matter searches!*
- **The lack of knowledge of the quark content of the nucleon is seriously impacting our ability to interpret sensitivities of direct dark matter searches for WIMPs.**

Looking Forward

- Direct dark matter searches - towards the neutrino background! and directional searches!
- Indirect dark matter searches - AMS-02, Fermi, CTA…
- LHC - SUSY/DM discovery potential at 14 TeV.
- Linear Collider - 500 GeV linear collider will study Higgs properties in detail! CLIC at 3TeV?

- What is left in SUSY, and when will we know we've covered it?
  - Minimal models still viable (and still desirable)? Non-neutralino dark matter (axinos, gravitinos, axions, primordial black holes)?
- How to analyze compatibility with experimental constraints..? "With great data, comes great responsibility!"