Title: Simplified Models of Co-annihilating Dark Matter

Date: Sep 15, 2015 01:00 PM

URL: http://pirsa.org/15090019

Abstract: The continued lack of definitive signals at direct detection experiments places many models of weakly interacting dark matter into tension. Direct detection is naturally suppressed in models where the dark matter co-annihilates with another particle in the early universe. The cosmology, direct detection, and LHC signals of such models can often be well understood by considering only the most relevant low-energy degrees of freedom. We draw lessons for the Minimal Supersymmetric Standard Model.

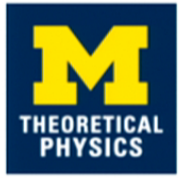
Simplified Models of Co-annihilating Dark Matter

Aaron Pierce
Perimeter Institute, 15 September

based in part on Phys.Rev. D91 (2015) 9, 095018 and upcoming work with N. Shah (MCTP to Pittsburgh), A. Ibarra (Munich), S. Vogl (Stockholm)

Where is the Dark Matter?

- What direct detection cross section should I expect for WIMP dark matter?
- We'll focus on spin-independent cross section, which usually is the most sensitive.



Outline

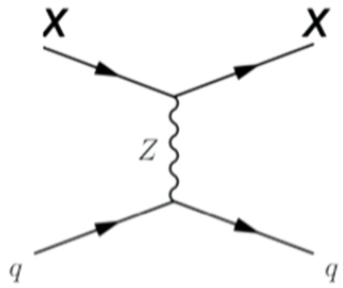
- Where do I expect DM?
- A case where DM is hard...
  - Understanding using "low energy DOF"
  - Lessons for direct detection
  - Lessons for LHC

Spin independent Z-boson mediated

Dirac fermion dark matter:

$$\sigma \approx \frac{G_F^2}{2\pi}\mu_{XN}^2 \frac{1}{A^2}((1-4\sin^2\theta_W)Z-(A-Z))^2 Y_{ave}$$

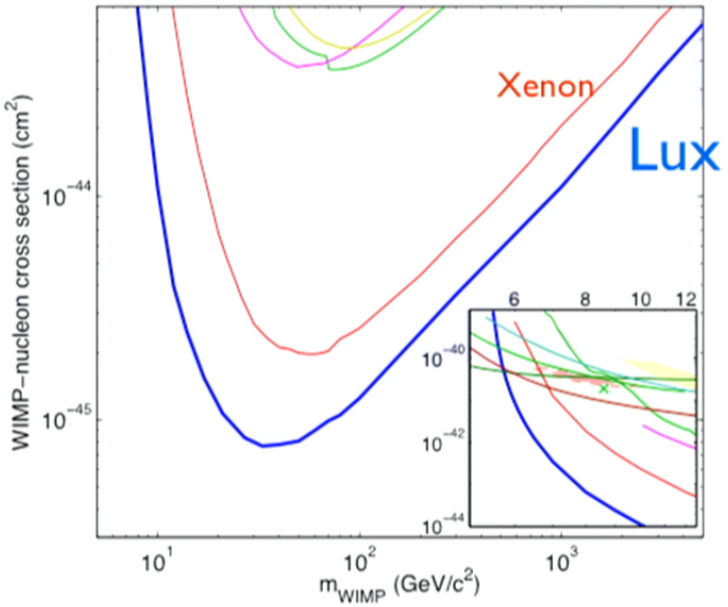
- This is huge ~ 10^{-39} cm^2



$$(\bar{\chi}\gamma_\mu\chi)\ (\bar{q}\gamma^\mu q)$$

THEORETICAL PHYSICS

Z-boson mediated



Excluded by
~a factor of a million!

~~$(\bar{\chi}\gamma_\mu\chi)\,(\bar{q}\gamma^\mu q)$~~

Majorana!

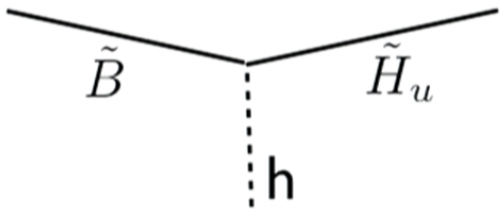
THEORETICAL PHYSICS

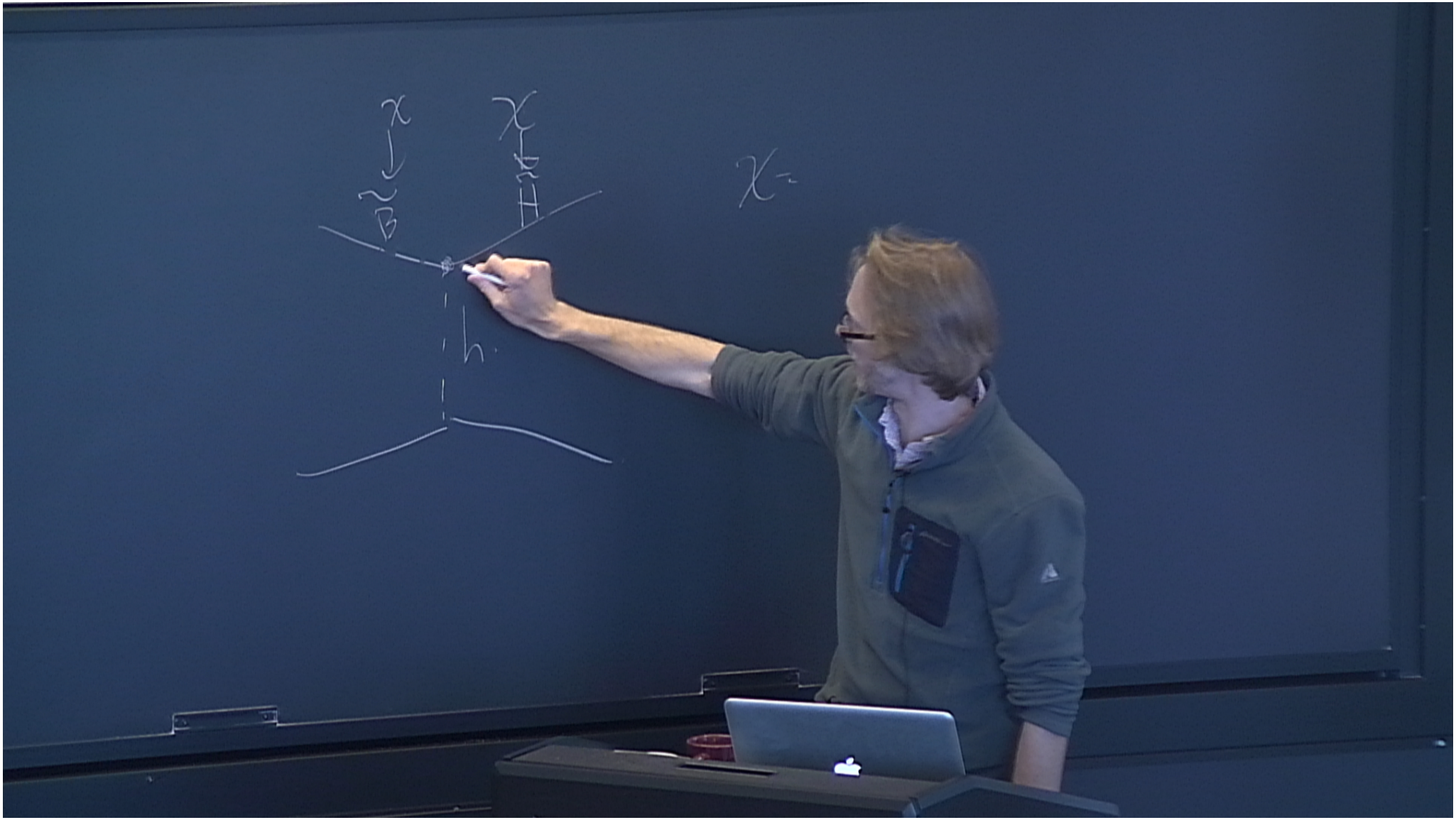
Aside: a tiny amount of such a particle could be first "Dark Matter" signal: J. Halverson, N.Orlofsky, AP. **Phys.Rev. D90 (2014) 1, 015002**

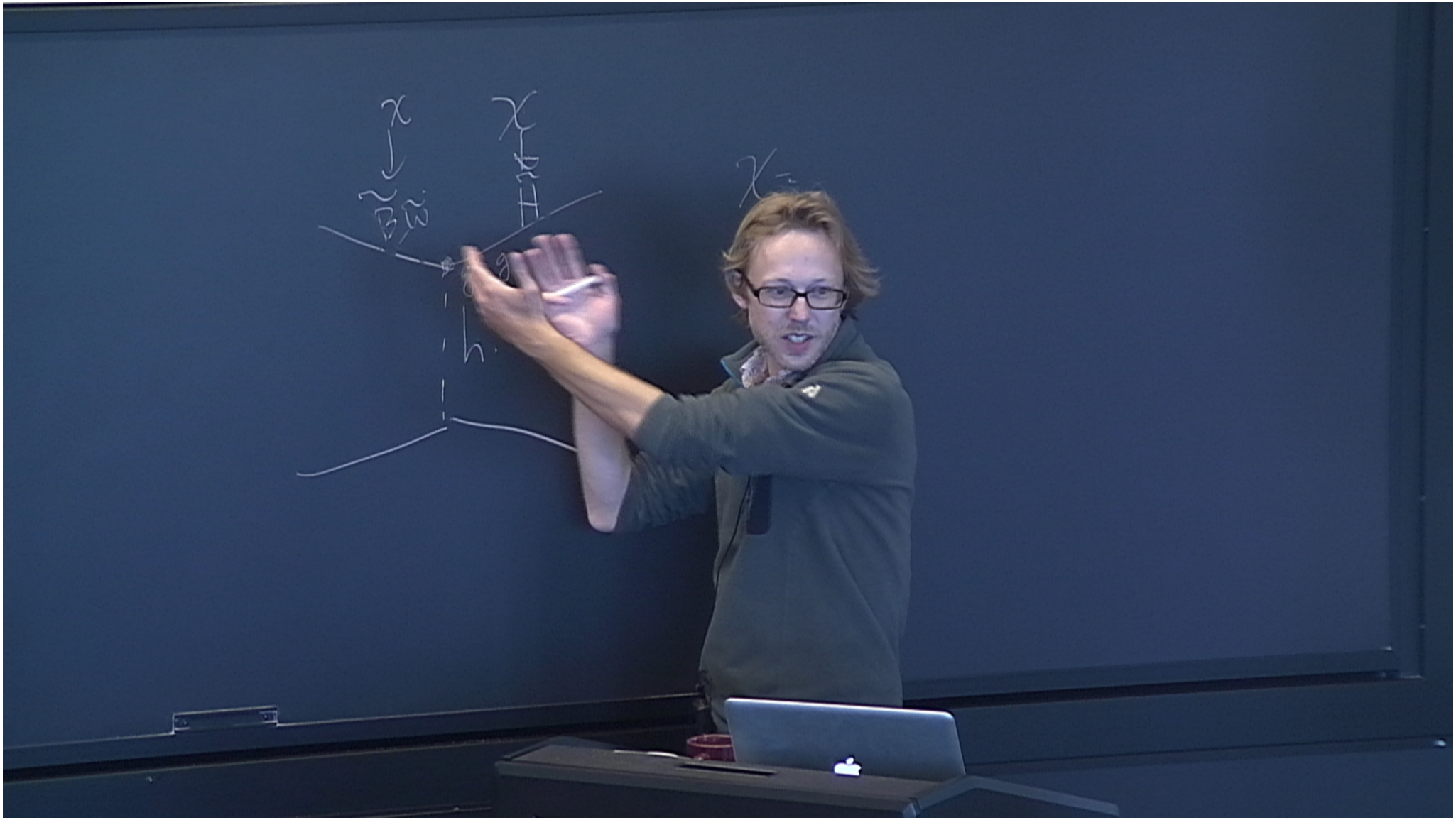
MSSM Reminder

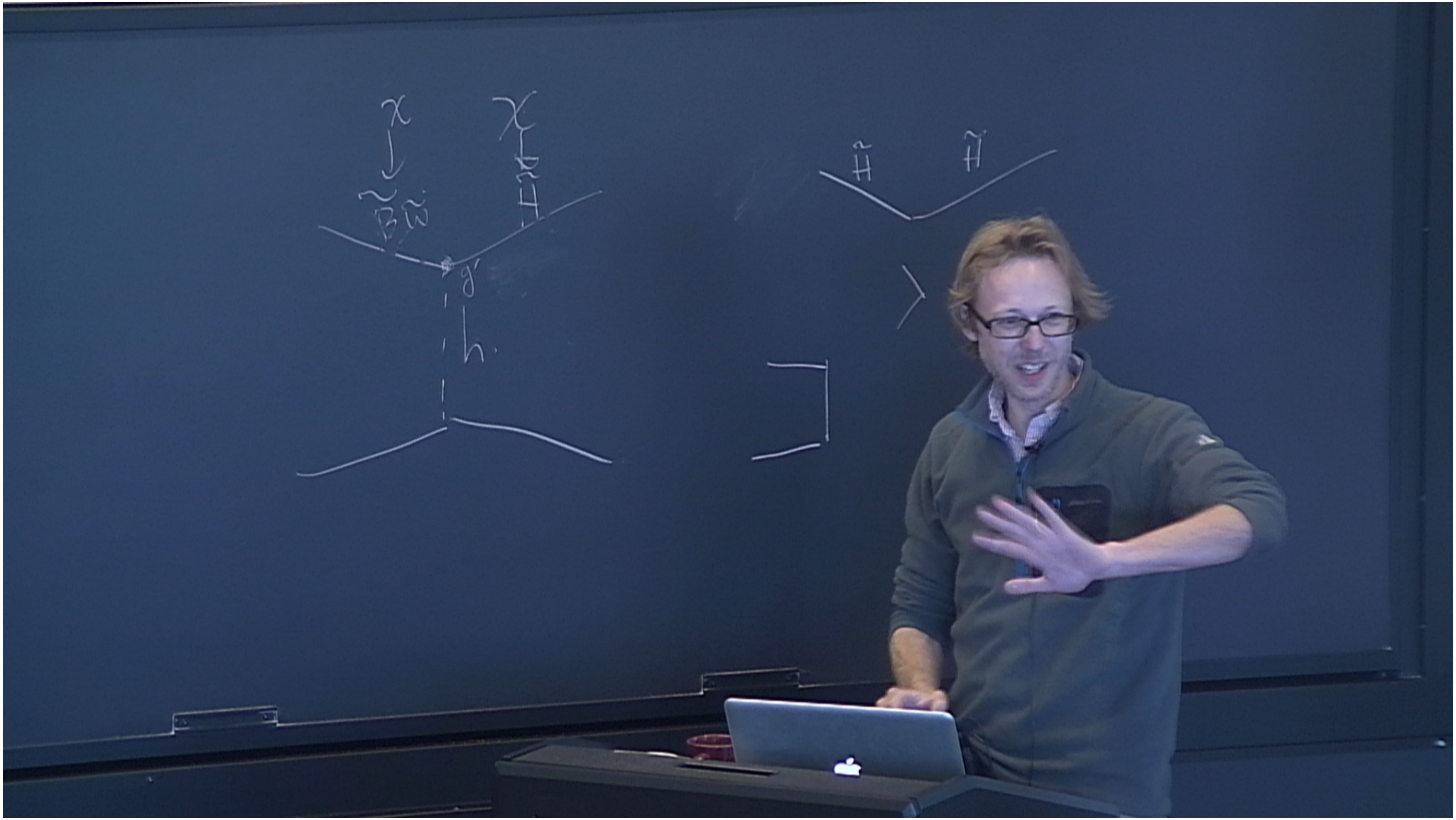
$$\boldsymbol{M}_N = \begin{array}{c} \\ \tilde{B} \\ \tilde{W} \\ \tilde{H}_d \\ \tilde{H}_u \end{array} \begin{array}{c} \begin{array}{cccc} \tilde{B} & \tilde{W} & \tilde{H}_d & \tilde{H}_u \end{array} \\ \begin{bmatrix} M_1 & 0 & -m_Z \sin\theta_W \cos\beta & m_Z \sin\theta_W \sin\beta \\ 0 & M_2 & m_Z \cos\theta_W \cos\beta & -m_Z \cos\theta_W \sin\beta \\ -m_Z \sin\theta_W \cos\beta & m_Z \cos\theta_W \cos\beta & 0 & -\mu \\ m_Z \sin\theta_W \sin\beta & -m_Z \cos\theta_W \sin\beta & -\mu & 0 \end{bmatrix} \end{array}$$

$$\chi_i = N_{1i}\tilde{B} + N_{2i}\tilde{W} + N_{3i}\tilde{H}_d + N_{4i}\tilde{H}_u$$




χ
B̃
χ
H̃
h

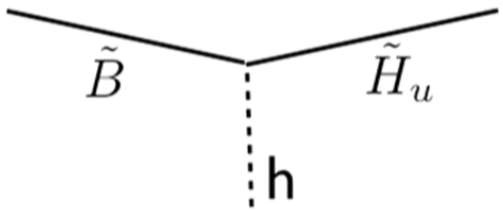



χ
χ
g'
h.

MSSM Reminder

$$\boldsymbol{M}_N = \begin{array}{c} \\ \tilde{B} \\ \tilde{W} \\ \tilde{H}_d \\ \tilde{H}_u \end{array} \begin{array}{c} \begin{array}{cccc} \tilde{B} & \tilde{W} & \tilde{H}_d & \tilde{H}_u \end{array} \\ \begin{bmatrix} M_1 & 0 & -m_Z \sin\theta_W \cos\beta & m_Z \sin\theta_W \sin\beta \\ 0 & M_2 & m_Z \cos\theta_W \cos\beta & -m_Z \cos\theta_W \sin\beta \\ -m_Z \sin\theta_W \cos\beta & m_Z \cos\theta_W \cos\beta & 0 & -\mu \\ m_Z \sin\theta_W \sin\beta & -m_Z \cos\theta_W \sin\beta & -\mu & 0 \end{bmatrix} \end{array}$$

$$\chi_i = N_{1i}\tilde{B} + N_{2i}\tilde{W} + N_{3i}\tilde{H}_d + N_{4i}\tilde{H}_u$$

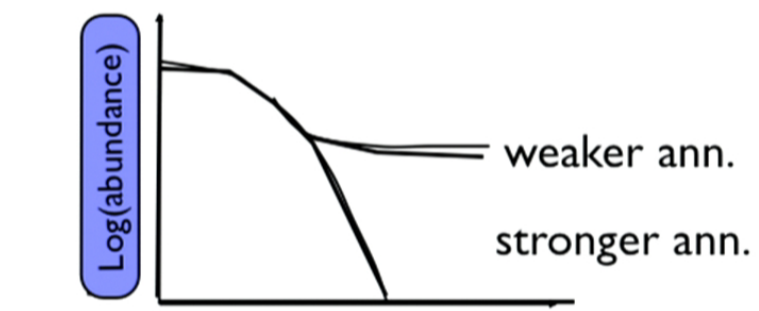


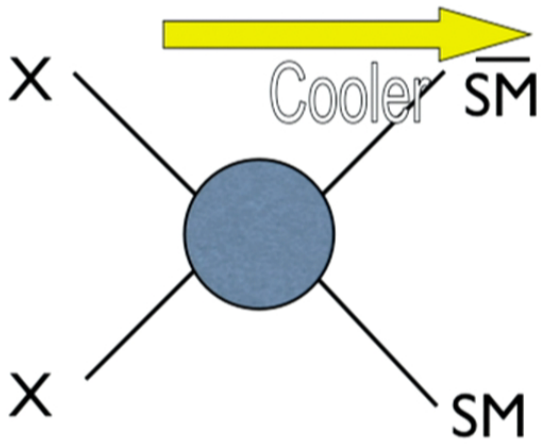
How Much Dark Matter...

Solve the Boltzmann equation in an expanding universe.

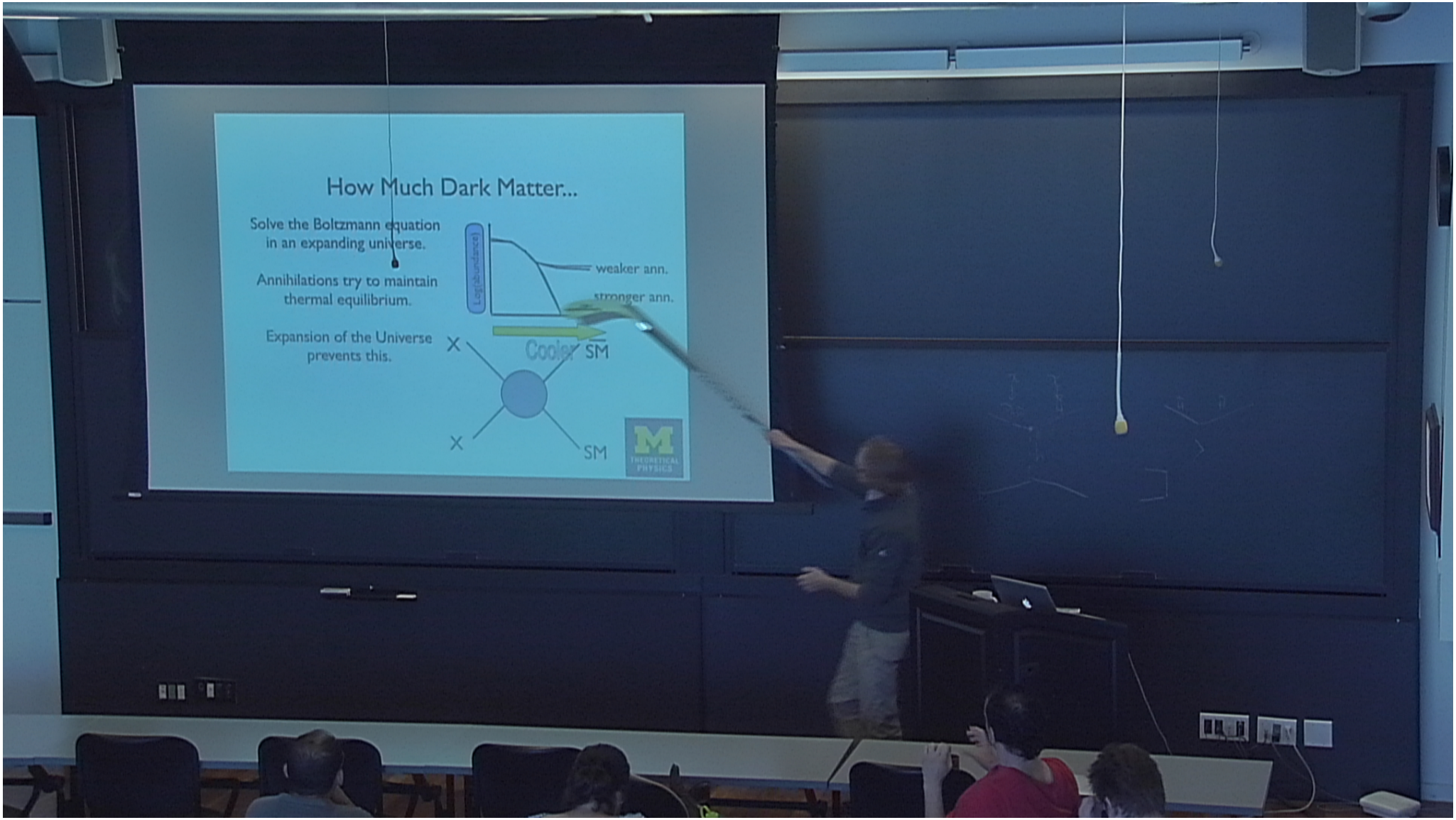
Annihilations try to maintain thermal equilibrium.

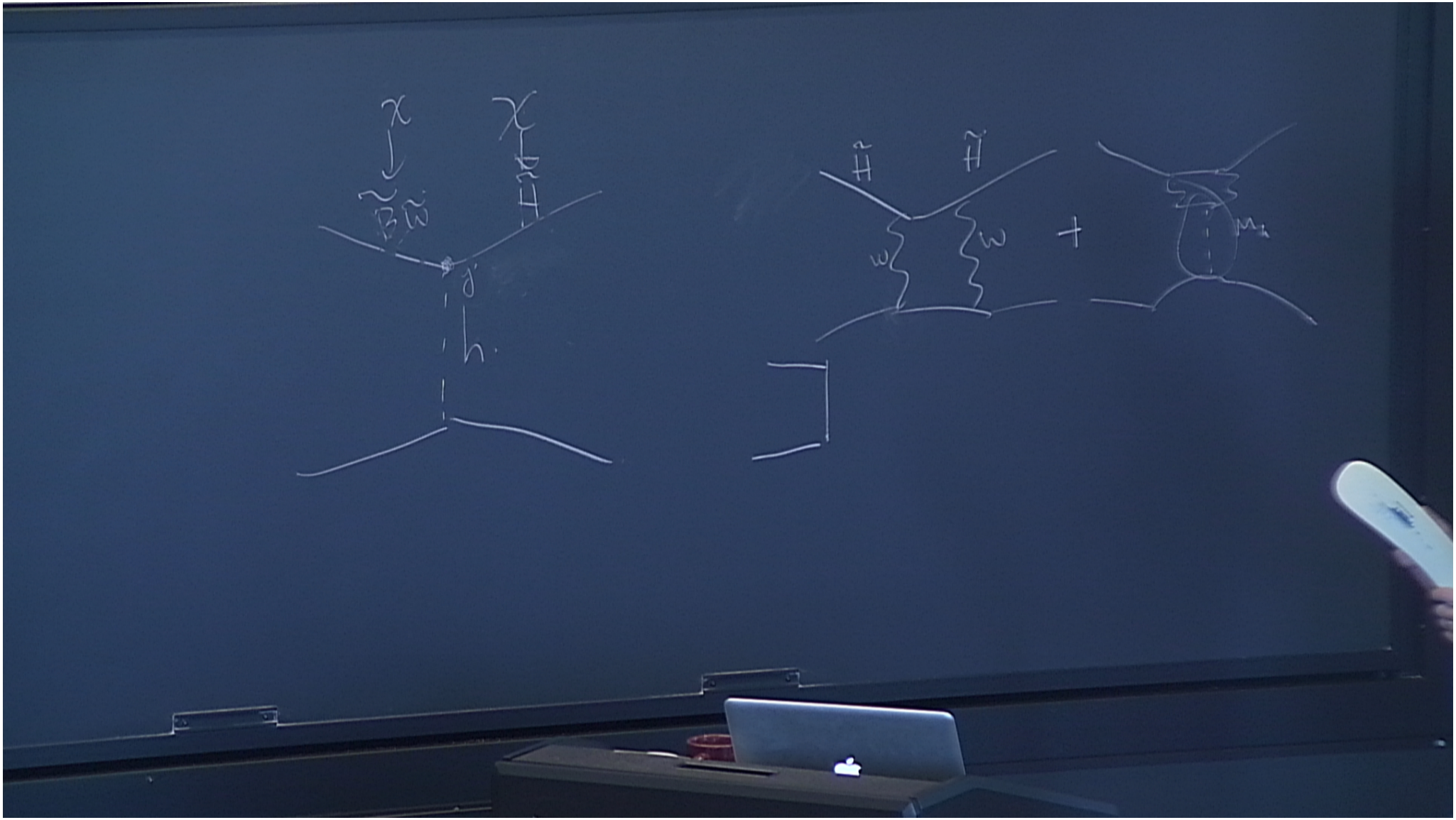
Expansion of the Universe prevents this.

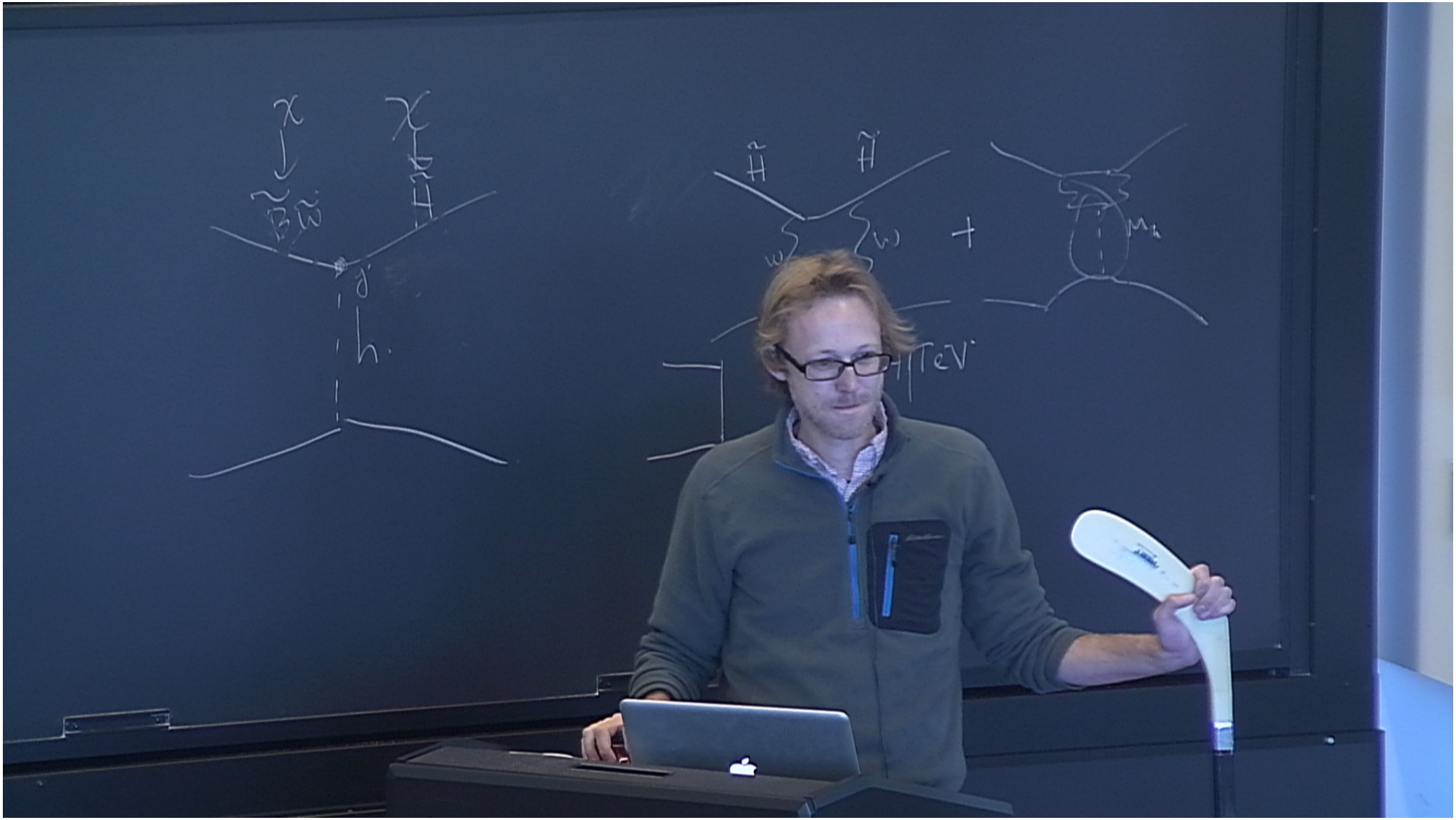


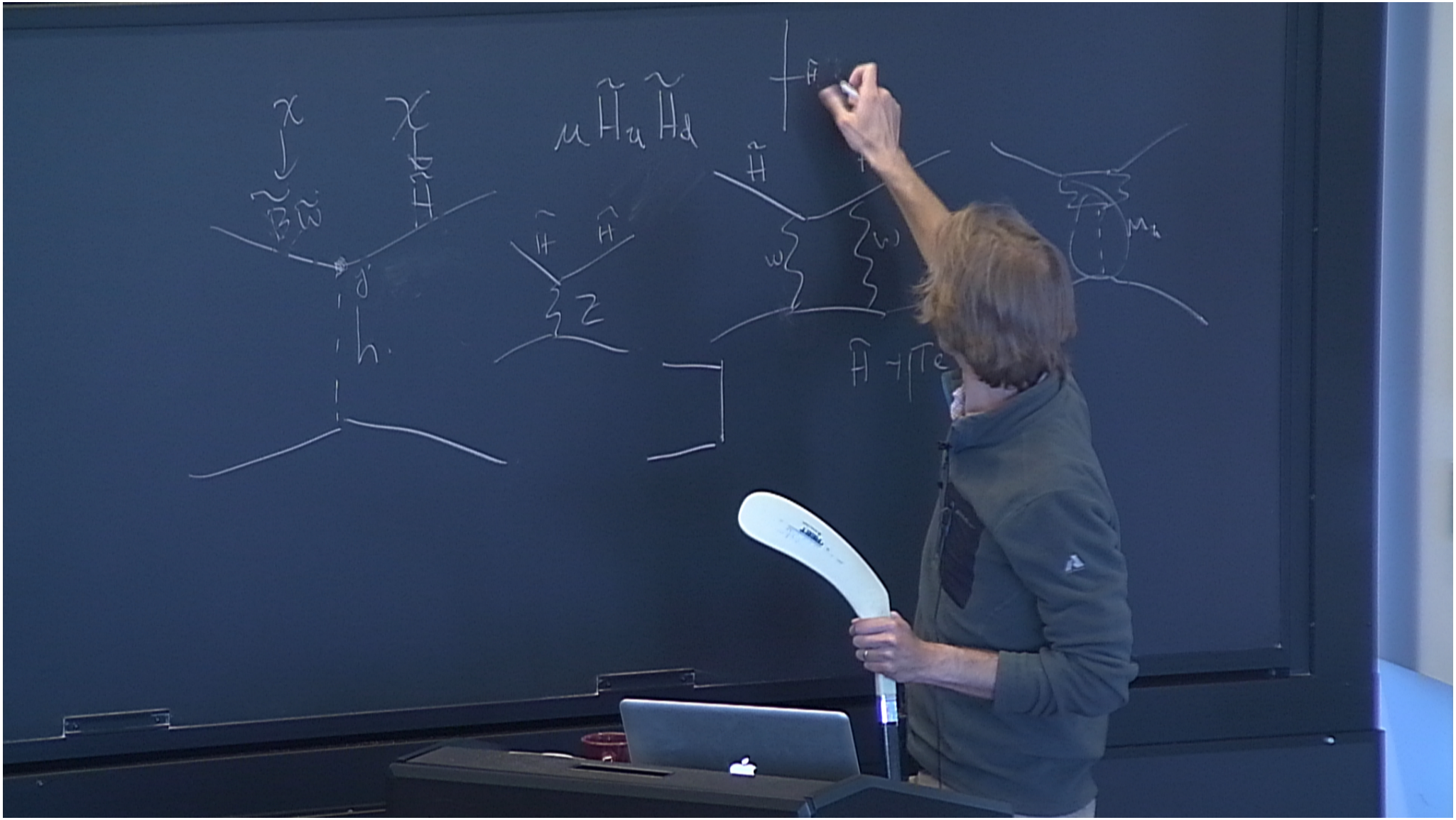


THEORETICAL PHYSICS

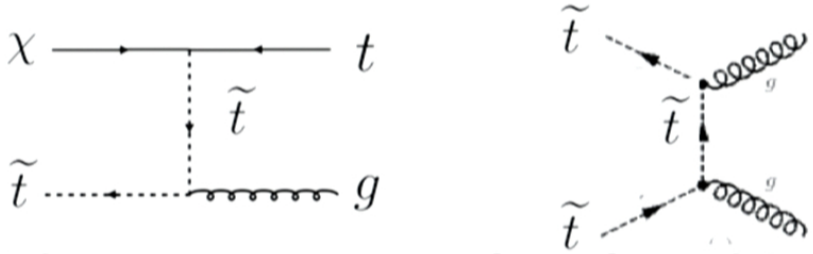

How Much Dark Matter...
Solve the Boltzmann equation in an expanding universe.
Annihilations try to maintain thermal equilibrium.
Expansion of the Universe prevents this.
Log(abundance)
weaker ann.
stronger ann.
Cooler
X
SM
X
SM
THEORETICAL PHYSICS


χ
χ
B̃
W̃
H̃
j
h
H̃
H̃
W
W
+
M_h


χ
χ
h
W
W
+
1 TeV



Stop Co-annihilation and Direct Detection



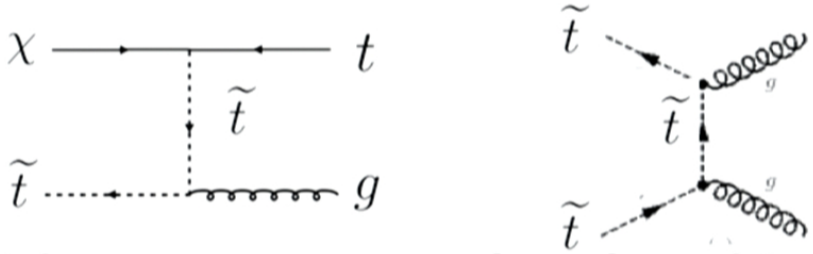
- Light top partners often found in BSM theories.
- Both particles reside in thermal bath.
- Relative abundance suppressed by:

$$e^{-\Delta m/T_{fo}} \longrightarrow \Delta m \sim T_{fo} \sim m/20$$

Griest and Seckel, Phys.Rev. D43 (1991) 3191-3203

THEORETICAL PHYSICS

Stop Co-annihilation and Direct Detection



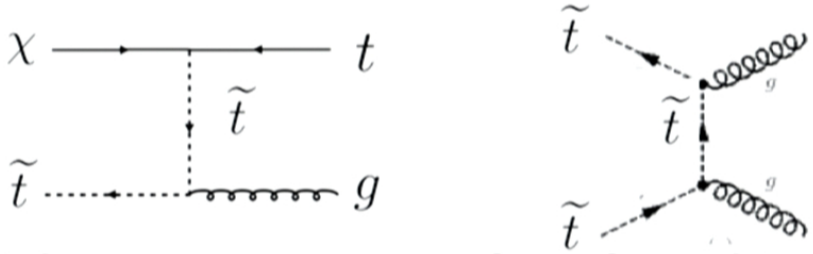
- Light top partners often found in BSM theories.
- Both particles reside in thermal bath.
- Relative abundance suppressed by:

$$e^{-\Delta m/T_{fo}} \longrightarrow \Delta m \sim T_{fo} \sim m/20$$

Griest and Seckel, Phys.Rev. D43 (1991) 3191-3203

THEORETICAL PHYSICS

Stop Co-annihilation and Direct Detection

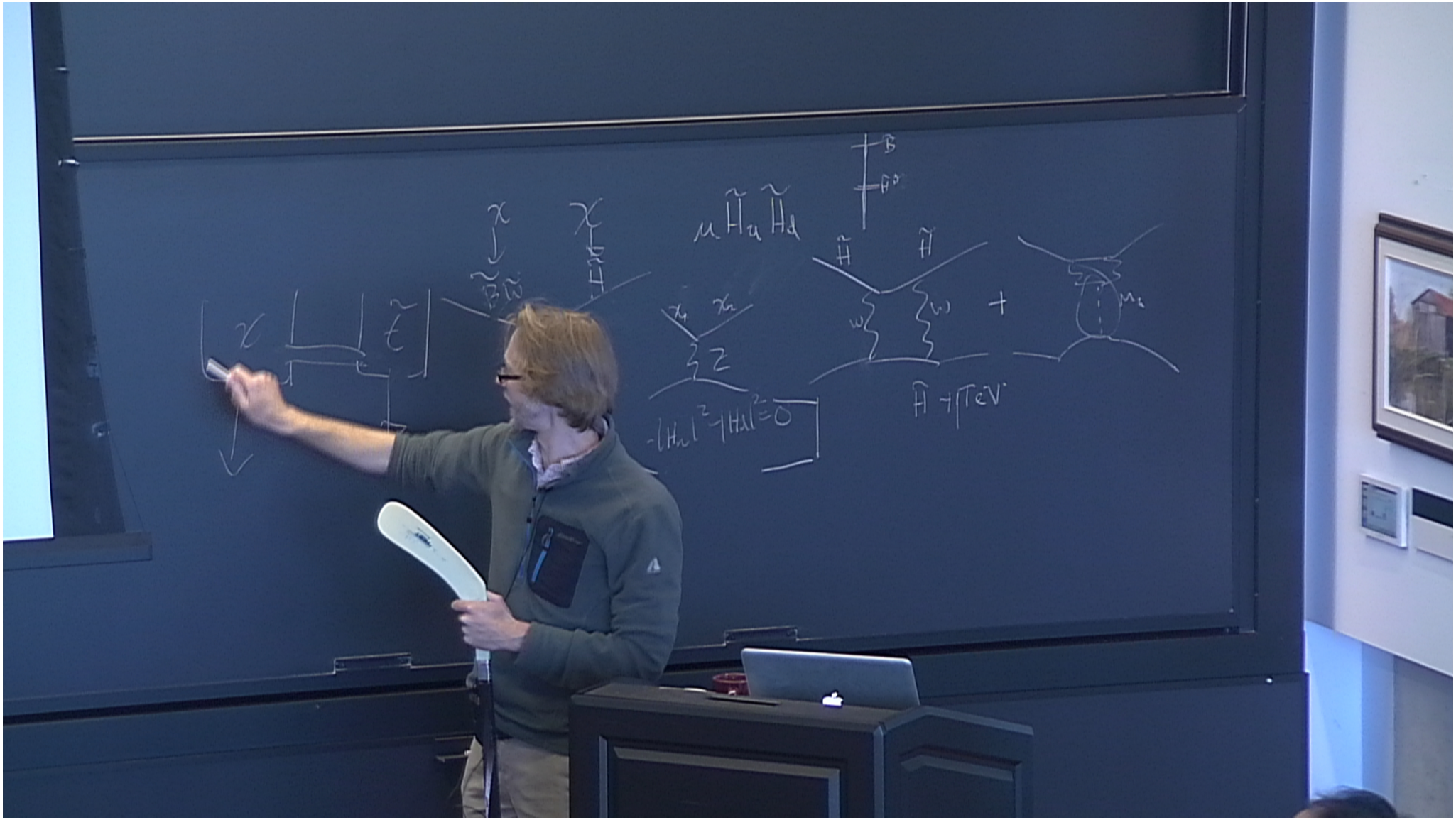


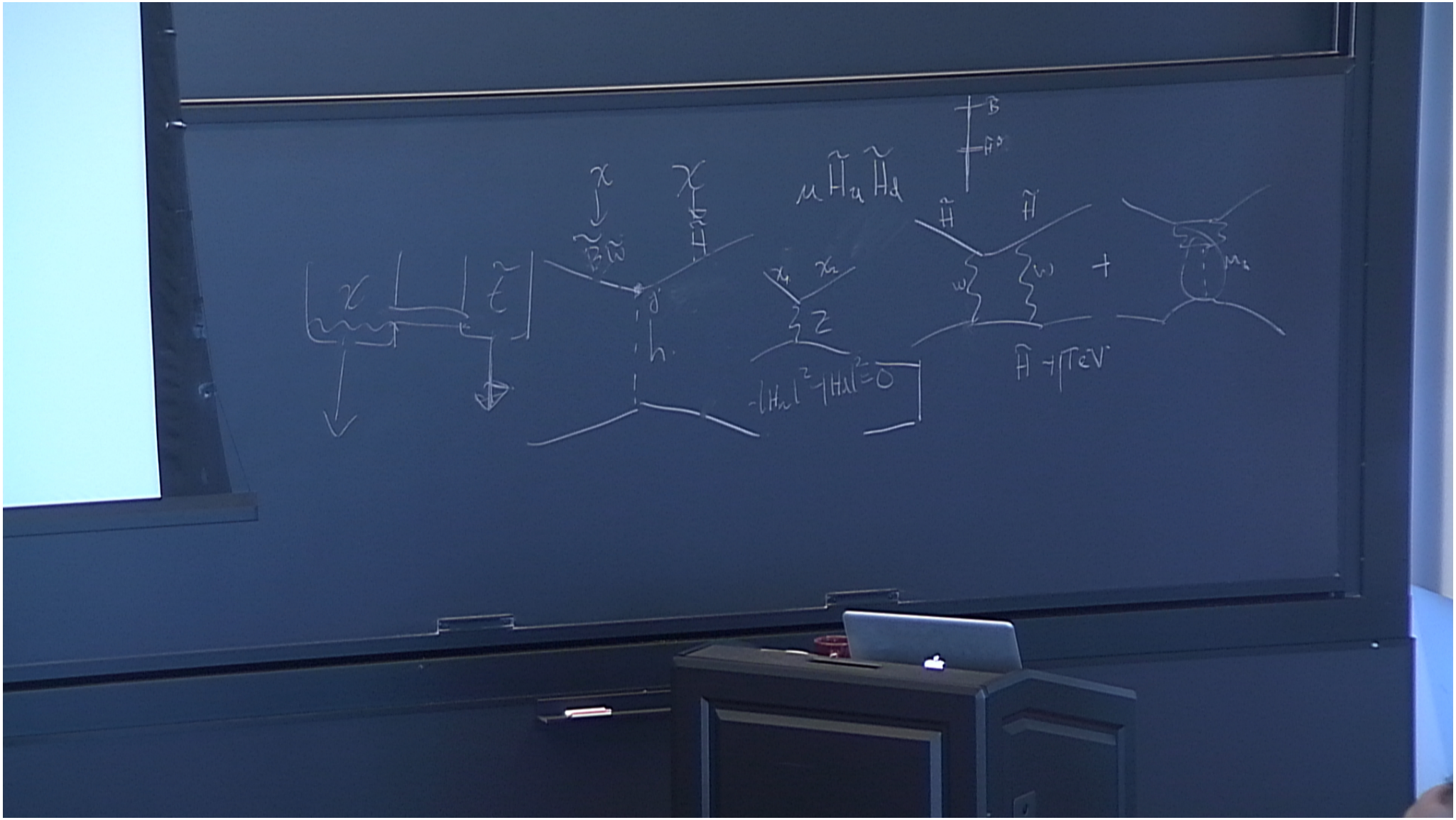
- Light top partners often found in BSM theories.
- Both particles reside in thermal bath.
- Relative abundance suppressed by:

$$e^{-\Delta m/T_{fo}} \longrightarrow \Delta m \sim T_{fo} \sim m/20$$

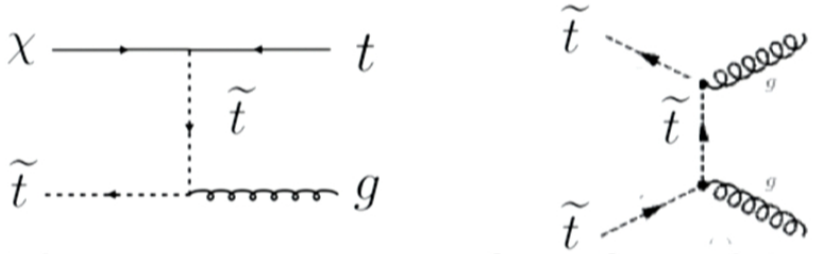
Griest and Seckel, Phys.Rev. D43 (1991) 3191-3203

THEORETICAL PHYSICS


$\mu \tilde{H}_u \tilde{H}_d$
$-|H_u|^2 + |H_d|^2 = 0$
$\tilde{H} \sim$ TeV


$\mu \tilde{H}_u \tilde{H}_d$
$-|H_u|^2 + |H_d|^2 = 0$
$\tilde{H} \sim TeV$

Stop Co-annihilation and Direct Detection



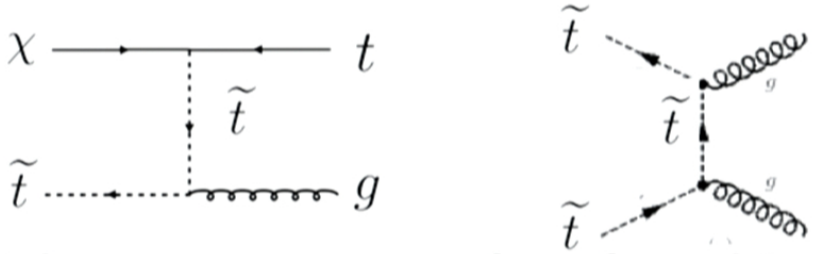
- Light top partners often found in BSM theories.
- Both particles reside in thermal bath.
- Relative abundance suppressed by:

$$e^{-\Delta m/T_{fo}} \longrightarrow \Delta m \sim T_{fo} \sim m/20$$

Griest and Seckel, Phys.Rev. D43 (1991) 3191-3203

THEORETICAL PHYSICS

Stop Co-annihilation and Direct Detection



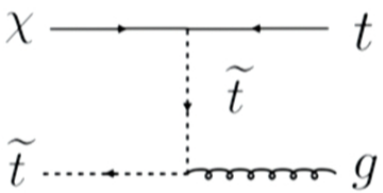
- Light top partners often found in BSM theories.
- Both particles reside in thermal bath.
- Relative abundance suppressed by:

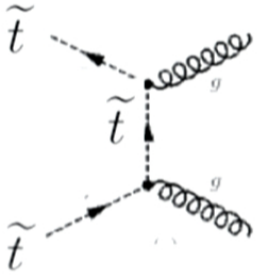
$$e^{-\Delta m/T_{fo}} \longrightarrow \Delta m \sim T_{fo} \sim m/20$$

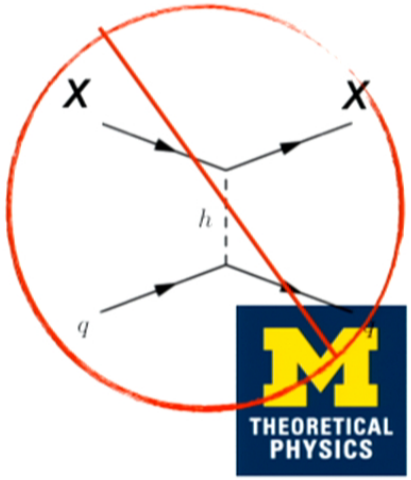
Griest and Seckel, Phys.Rev. D43 (1991) 3191-3203

THEORETICAL PHYSICS

Co-annihilation and Direct Detection

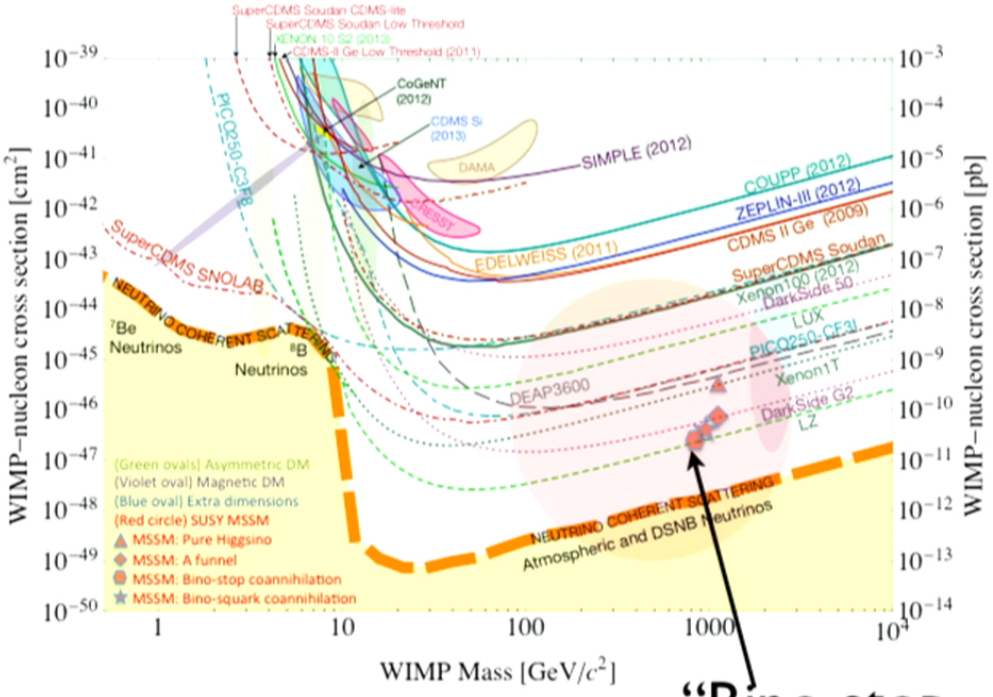






- Neatly explains why Dark matter not yet seen.
- Will it ever be?

Direct Detection



"Bino stop coannihilation"

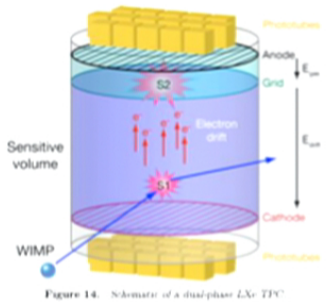
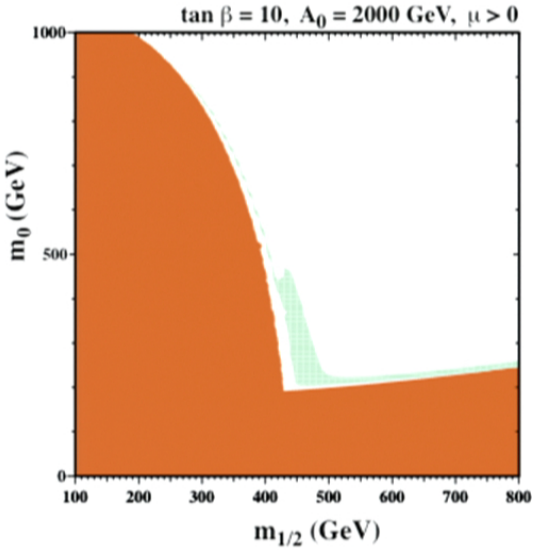


Figure 14. Schematic of a dual-phase LXe TPC

From Snowmass CF1: Direct Detection

THEORETICAL PHYSICS

Also, analyses often done in CMSSM

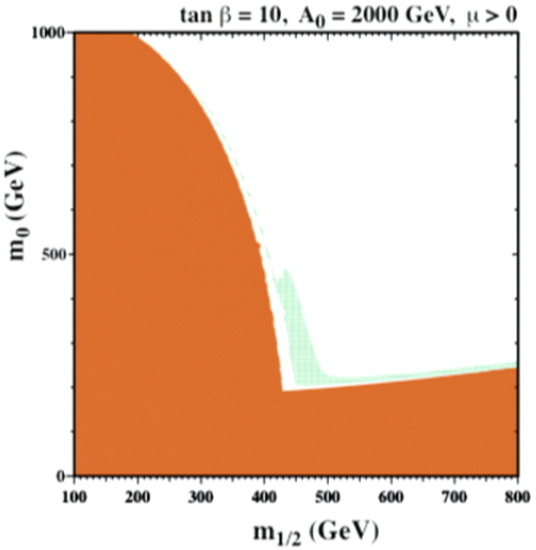


Santoso, hep-ph/0205026

- Advantages:
  - connects to high scale theory
- Disadvantages:
  - (probably) wrong high scale theory? Potentially "unwanted" correlations between parameters.
  - Can obscure low energy physics

THEORETICAL PHYSICS

Also, analyses often done in CMSSM

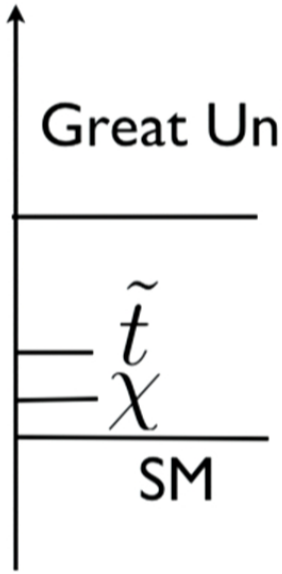


Santoso, hep-ph/0205026

- Advantages:
  - connects to high scale theory
- Disadvantages:
  - (probably) wrong high scale theory? Potentially "unwanted" correlations between parameters.
  - Can obscure low energy physics

THEORETICAL PHYSICS

Simplified Dark Matter Model



$$\mathcal{L}_{\chi}^{int} = y_{\chi} \bar{t}_R \, \chi \, \tilde{t} + \text{h.c.}$$

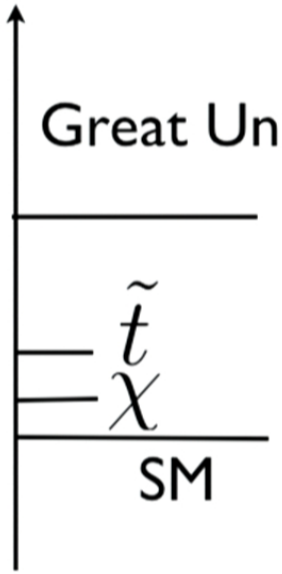
$$\mathcal{L}_{\tilde{t}}^{int} = |D_\mu \tilde{t}|^2 + \lambda_h h^\dagger h \tilde{t}^\dagger \tilde{t}$$

Example: $y_{\chi} \sim \frac{2}{3} g'$

MSSM with $\lambda_h \sim \lambda_t$

THEORETICAL PHYSICS

Simplified Dark Matter Model



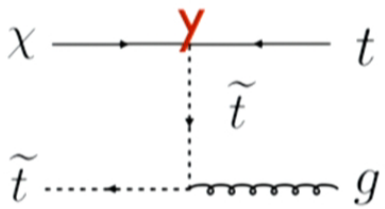
$$\mathcal{L}_{\chi}^{int} = y_{\chi} \bar{t}_R \, \chi \, \tilde{t} + \text{h.c.}$$

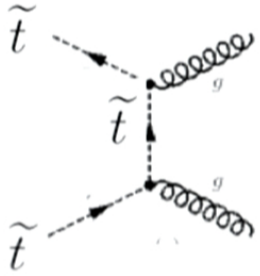
$$\mathcal{L}_{\tilde{t}}^{int} = |D_\mu \tilde{t}|^2 + \lambda_h h^\dagger h \tilde{t}^\dagger \tilde{t}$$

Example: $y_\chi \sim \frac{2}{3} g'$

MSSM with $\lambda_h \sim \lambda_t$

THEORETICAL PHYSICS



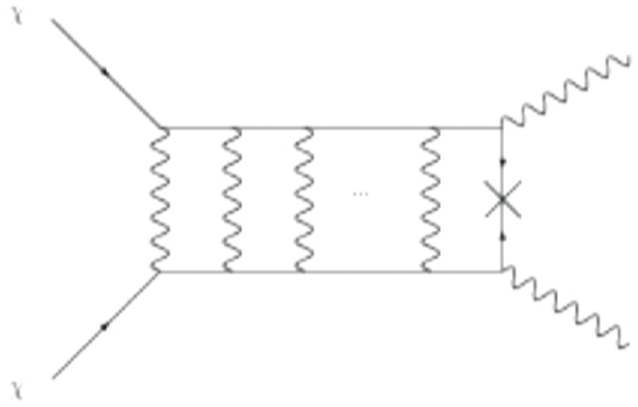


$$\sigma \mathrm{v}(\chi\tilde{\mathrm{t}} \to \mathrm{tg}) = \frac{g_s^2 y_\chi^2}{24\,\pi\, r(r+1)\, m_\chi^2}\left[1 - \frac{m_t^2}{m_\chi^2\,(r+1)^2}\right] \qquad \sigma \mathrm{v}(\tilde{t}\tilde{t}^* \to gg) = \frac{7 g_s^4}{216\,\pi\, m_{\tilde{t}}^2}$$

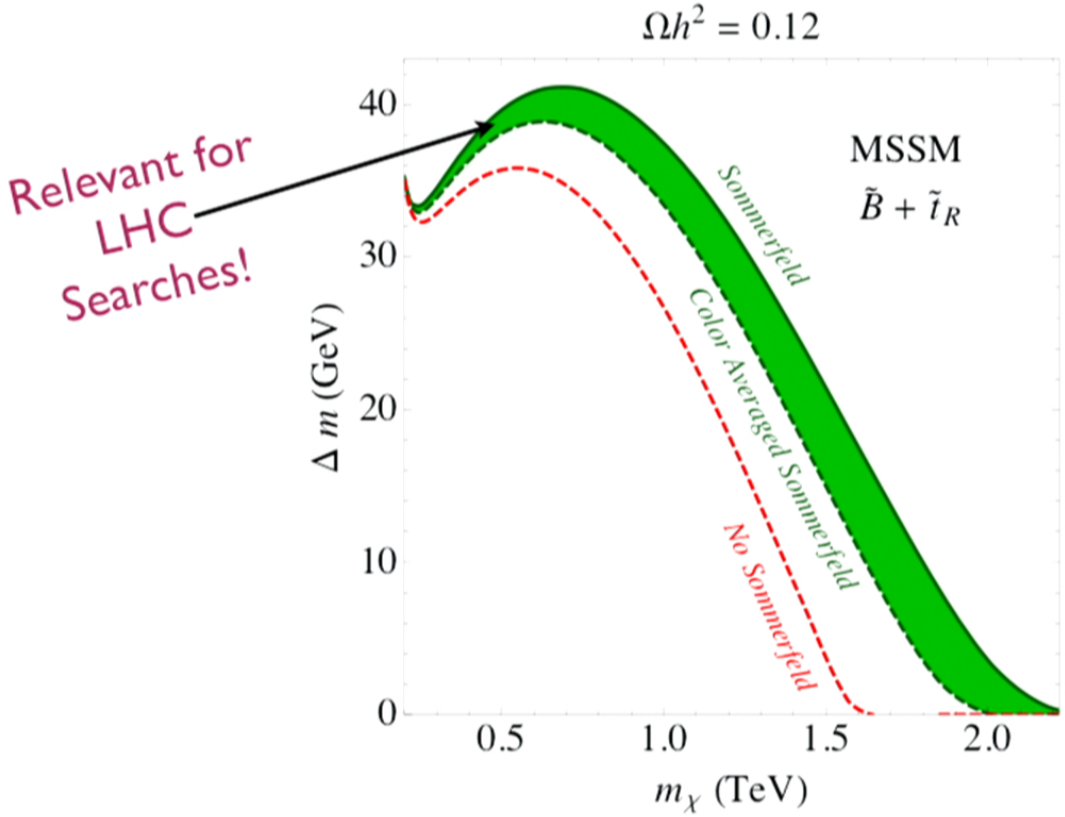
Sommerfeld

$$S_0 = \frac{-\pi\alpha/\beta}{1 - e^{\pi\alpha/\beta}}$$

$$S_{l>0} = S_0 \times \prod_{n=1}^{l} \left(1 + \frac{\alpha^2}{4\beta^2 n^2}\right)$$



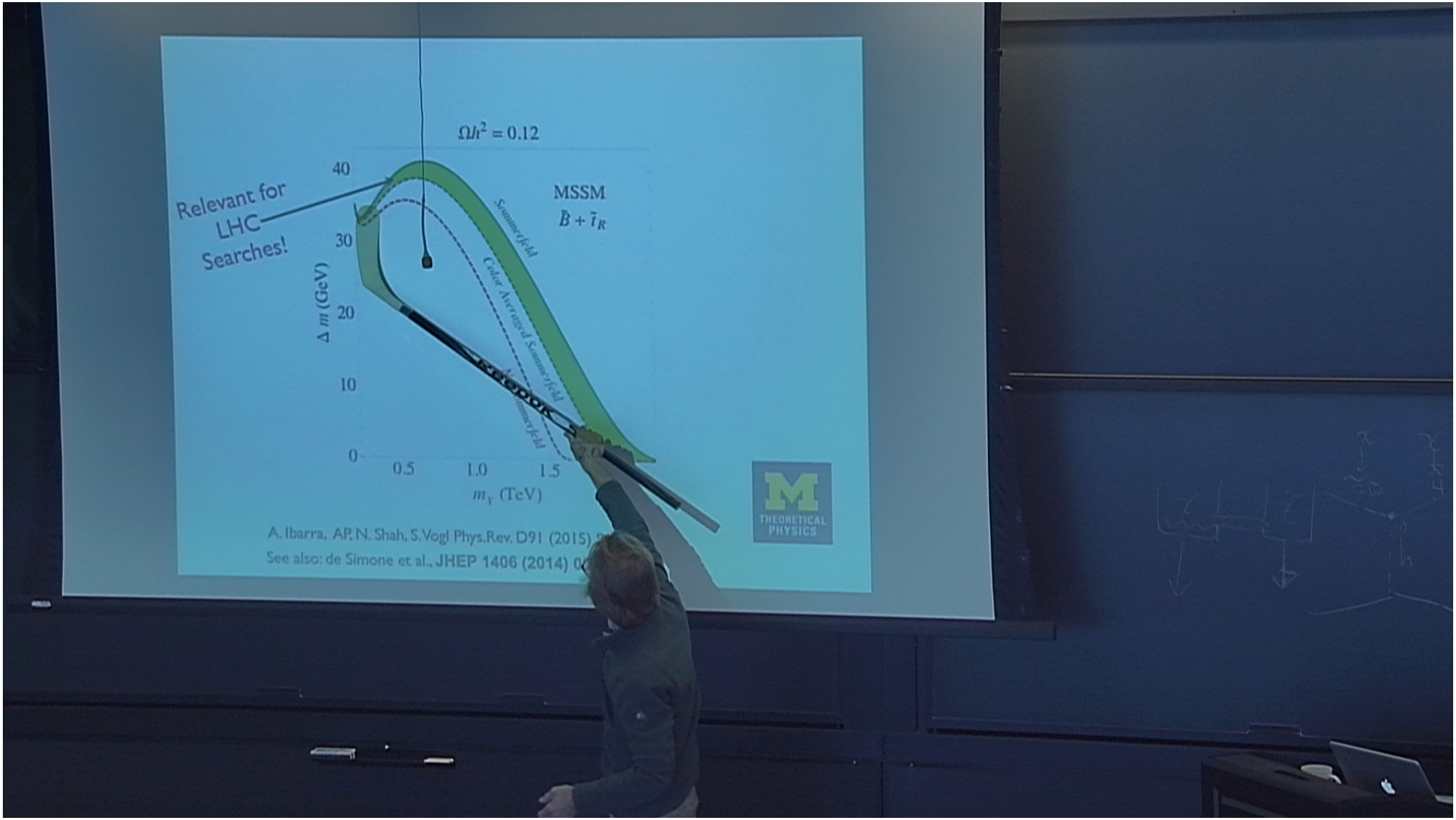
Also relevant for stops with gluon ladder!

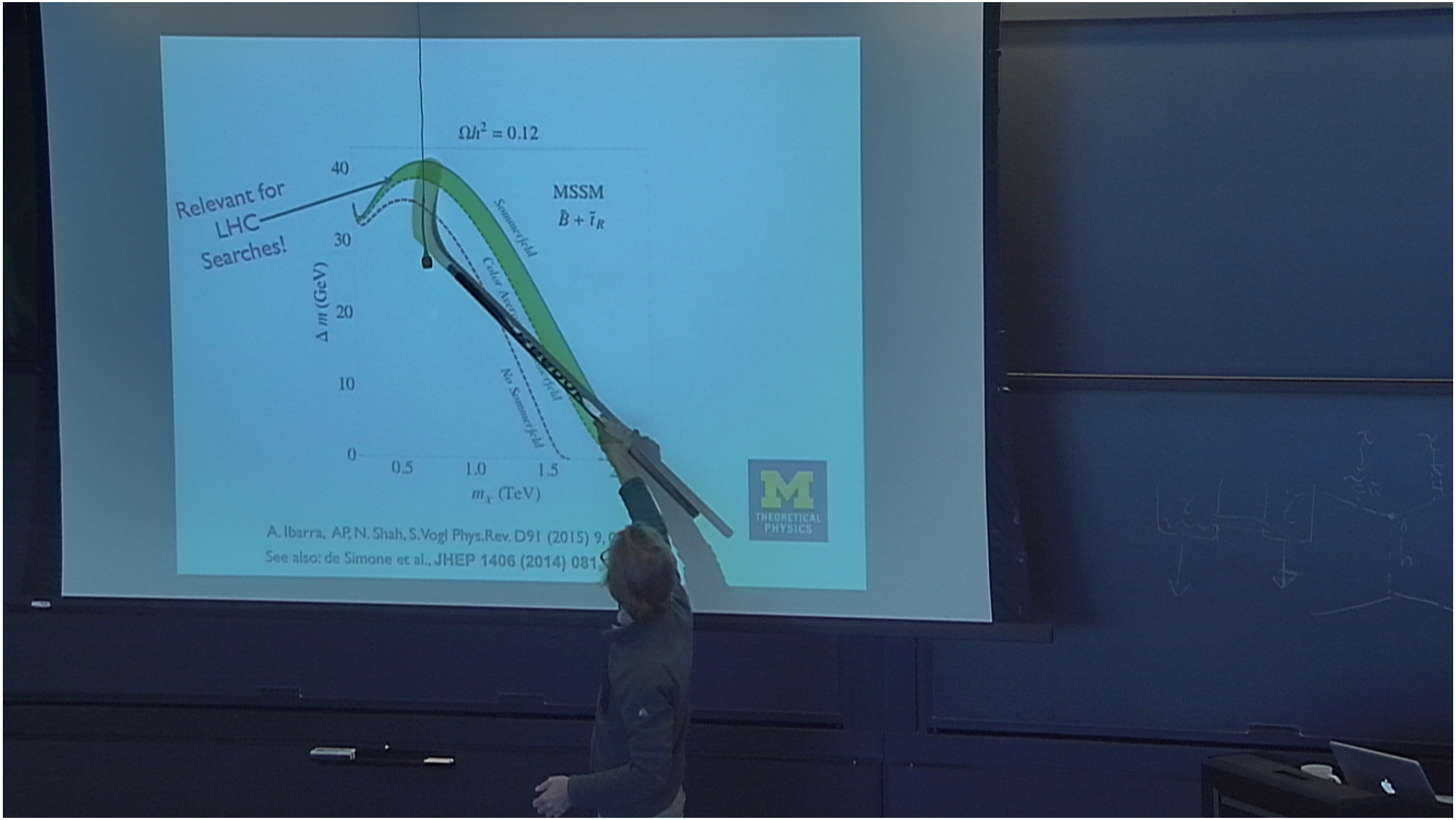


A. Ibarra, AP, N. Shah, S.Vogl Phys.Rev. D91 (2015) 9, 095018

See also: de Simone et al., **JHEP 1406 (2014) 081**

THEORETICAL PHYSICS


$\Omega h^2 = 0.12$
Relevant for LHC Searches!
MSSM
$\tilde{B} + \tilde{t}_R$
Sommerfeld
Coulomb Averaged Sommerfeld
Resonant Sommerfeld
Δm (GeV)
40
30
20
10
0
0.5
1.0
1.5
m_χ (TeV)
THEORETICAL PHYSICS
A. Ibarra, A.P. N. Shah, S.Vogl Phys.Rev. D91 (2015)
See also: de Simone et al., JHEP 1406 (2014)


$\Omega h^2 = 0.12$
Relevant for LHC Searches!
MSSM
$\tilde{B} + \tilde{t}_R$
Sommerfeld
Color Averaged Sommerfeld
No Sommerfeld
Δm (GeV)
40
30
20
10
0
0.5
1.0
1.5
m_χ (TeV)
THEORETICAL PHYSICS
A. Ibarra, A.P. N. Shah, S.Vogl Phys.Rev. D91 (2015) 9,
See also: de Simone et al., JHEP 1406 (2014) 081

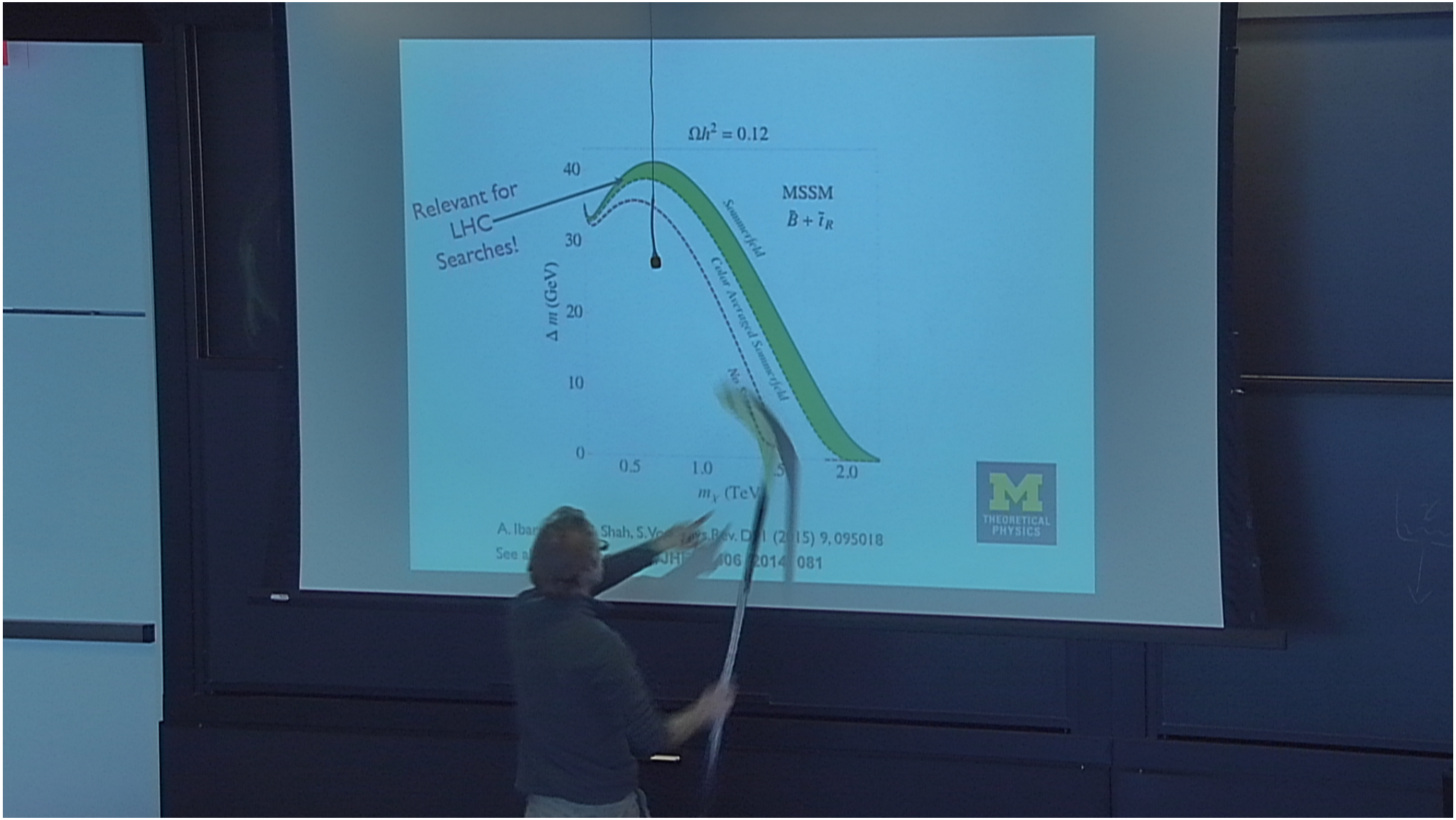
LHC Comments

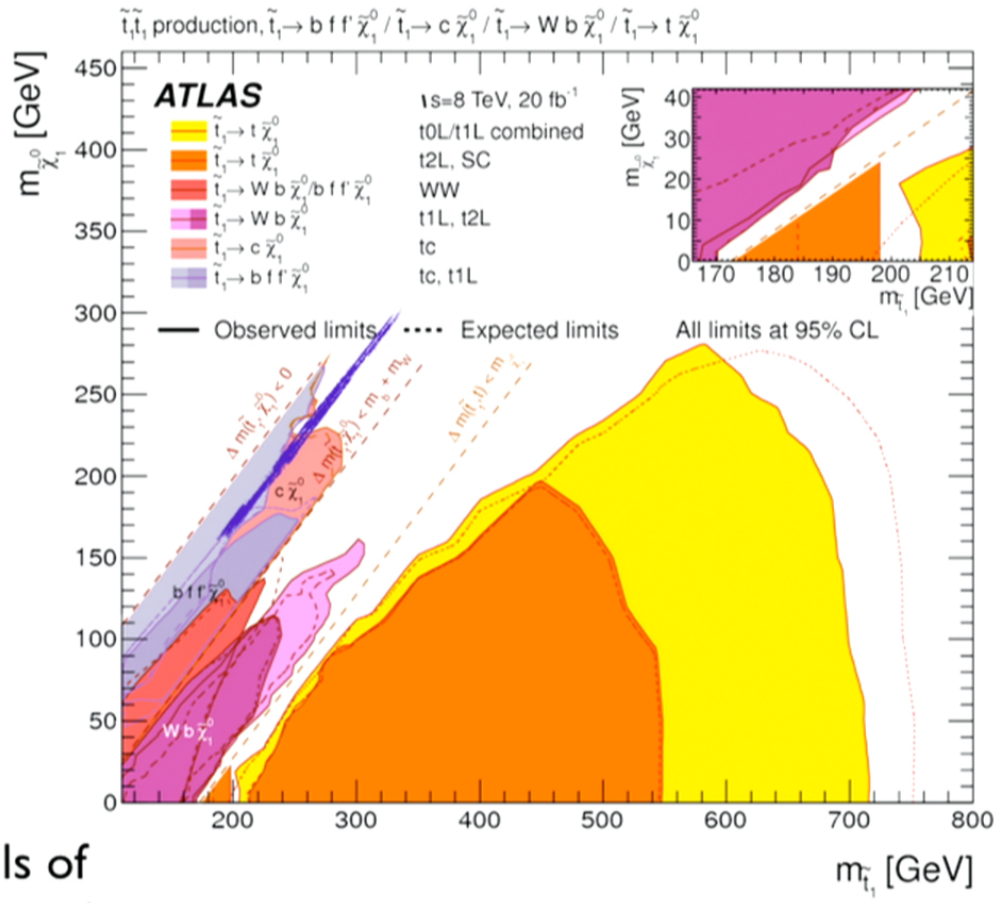
- In this mass regime, "stop" decays as

$\tilde{t} \to c\chi^0$ OR $\tilde{t} \to \chi b f \bar{f}$

e.g. Blanke et al. 1302.7232

Can even compete, which can modify limits: Grober, et al: 1408.4662


$\Omega h^2 = 0.12$
Relevant for LHC Searches!
MSSM
$\tilde{B} + \tilde{t}_R$
Sommerfeld
Color Averaged Sommerfeld
Δm (GeV)
40
30
20
10
0
0.5
1.0
2.0
m_χ (TeV)
THEORETICAL PHYSICS

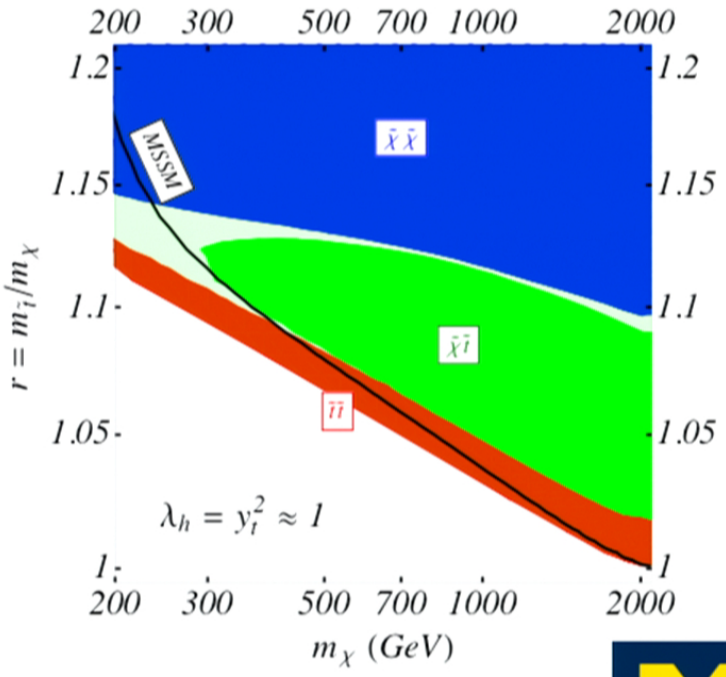


Details of implementation of jet vetos very relevant

THEORETICAL PHYSICS

At each point, adjust the Yukawa coupling to get right relic density.

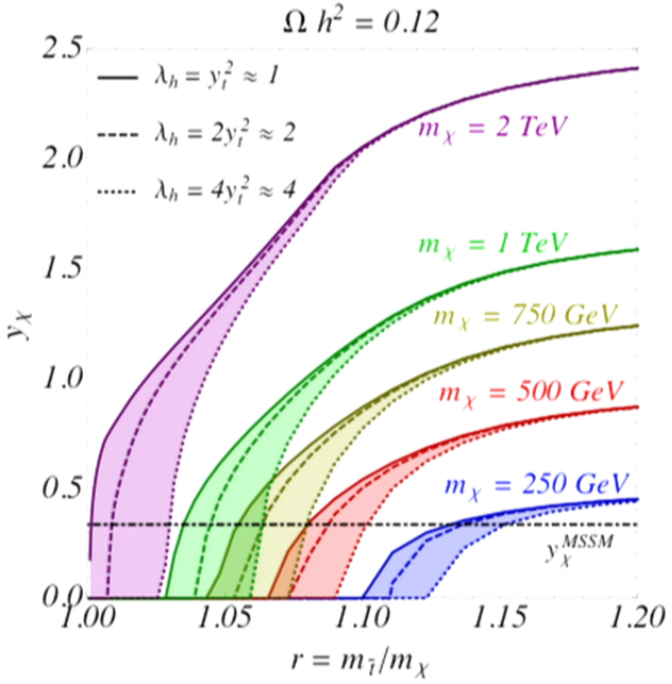
$$\mathcal{L}_{\chi}^{int} = y_{\chi} \bar{t}_R \, \chi \, \tilde{t} + \text{h.c.}$$



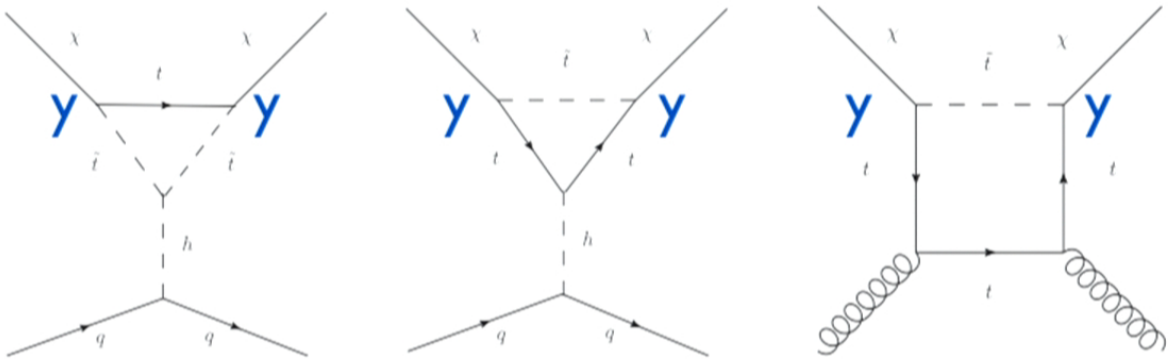
THEORETICAL PHYSICS

A. Ibarra, AP, N. Shah, S. Vogl Phys.Rev. D91 (2015) 9, 095018

Modifying the coupling to the Higgs



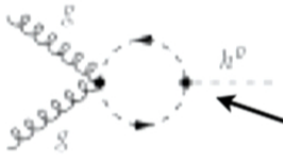
Direct Detection



$$\frac{\chi\chi H^\dagger H}{\Lambda} \qquad \frac{\chi\chi G^{\mu\nu} G_{\mu\nu}}{\Lambda^3}$$

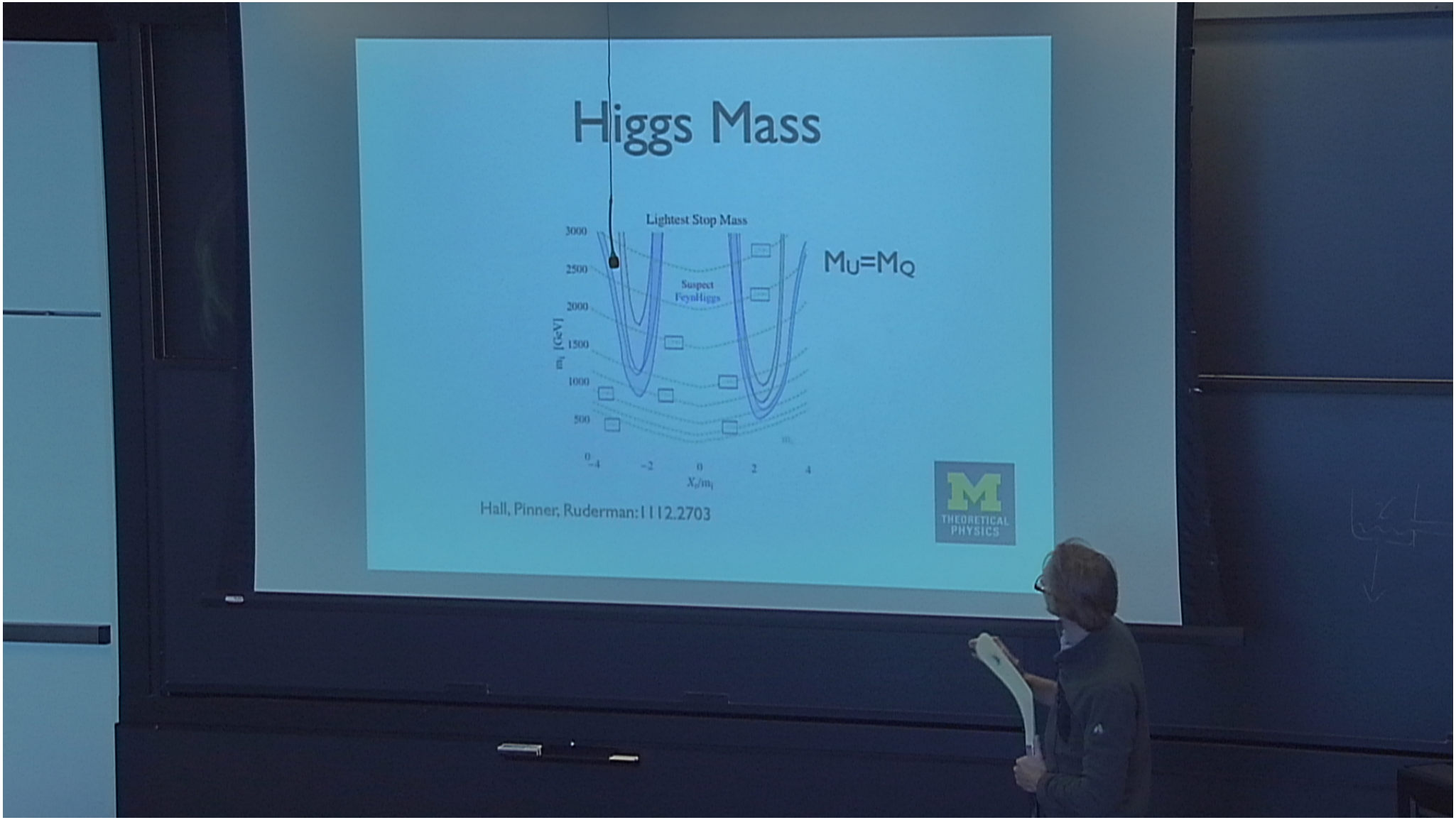
THEORETICAL PHYSICS

Caveat:

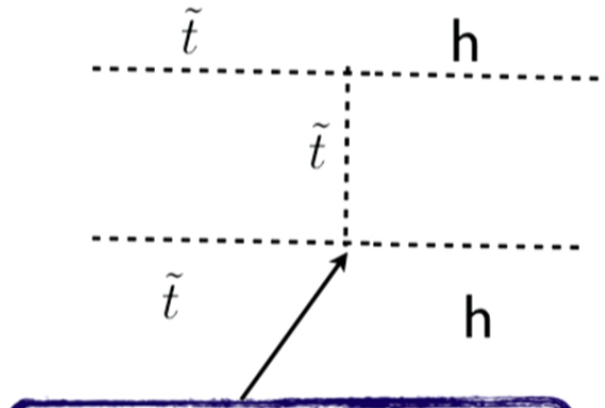


Gluon Fusion is important constraint

$$\mathcal{A}_{hgg} \simeq \mathcal{A}_{hgg}^{\mathrm{SM}} + \frac{\lambda_h v^2}{2m_{\tilde{t}}^2}$$


Higgs Mass
Lightest Stop Mass
3000
2500
2000
1500
1000
500
0
m_t [GeV]
Suspect
FeynHiggs
−4
−2
0
2
4
X_t/m_t
$M_U=M_Q$
Hall, Pinner, Ruderman: 1112.2703
THEORETICAL PHYSICS

Importance of Higgs Annihilations



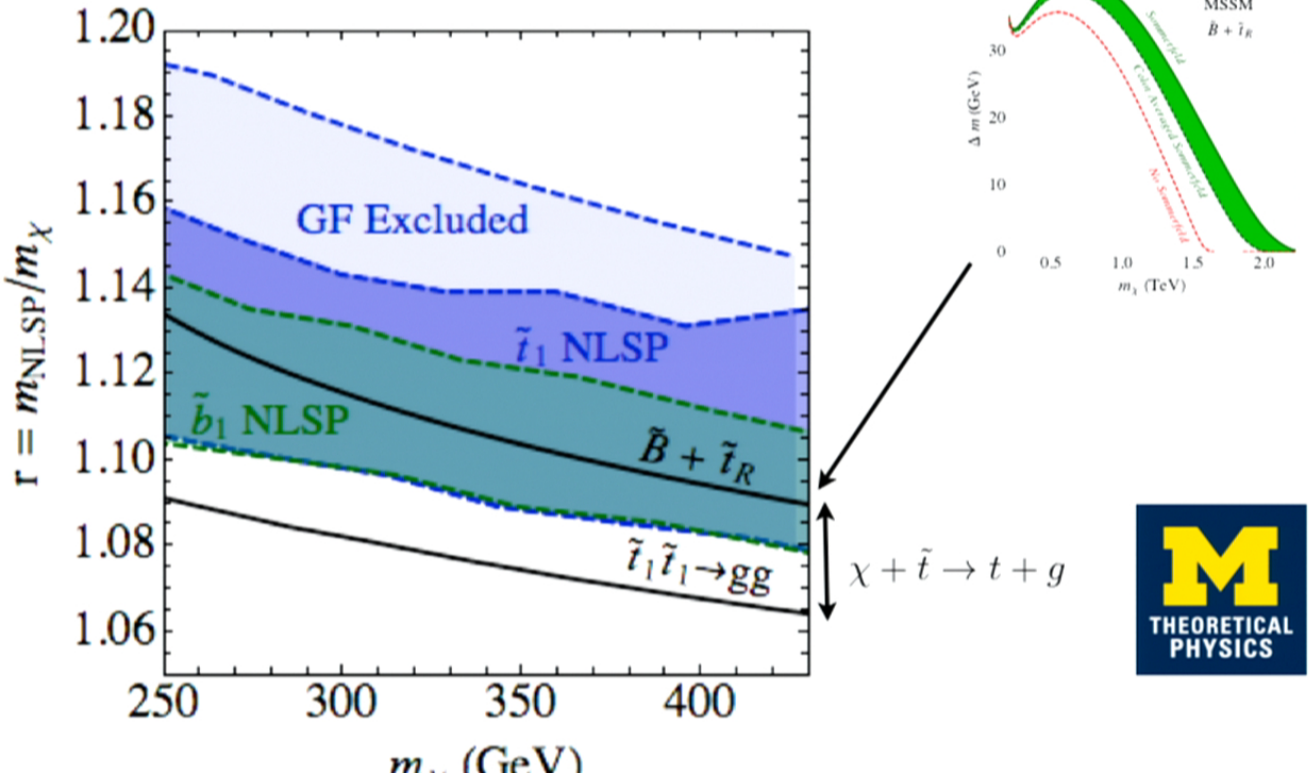
Large A-terms can motivate large value here

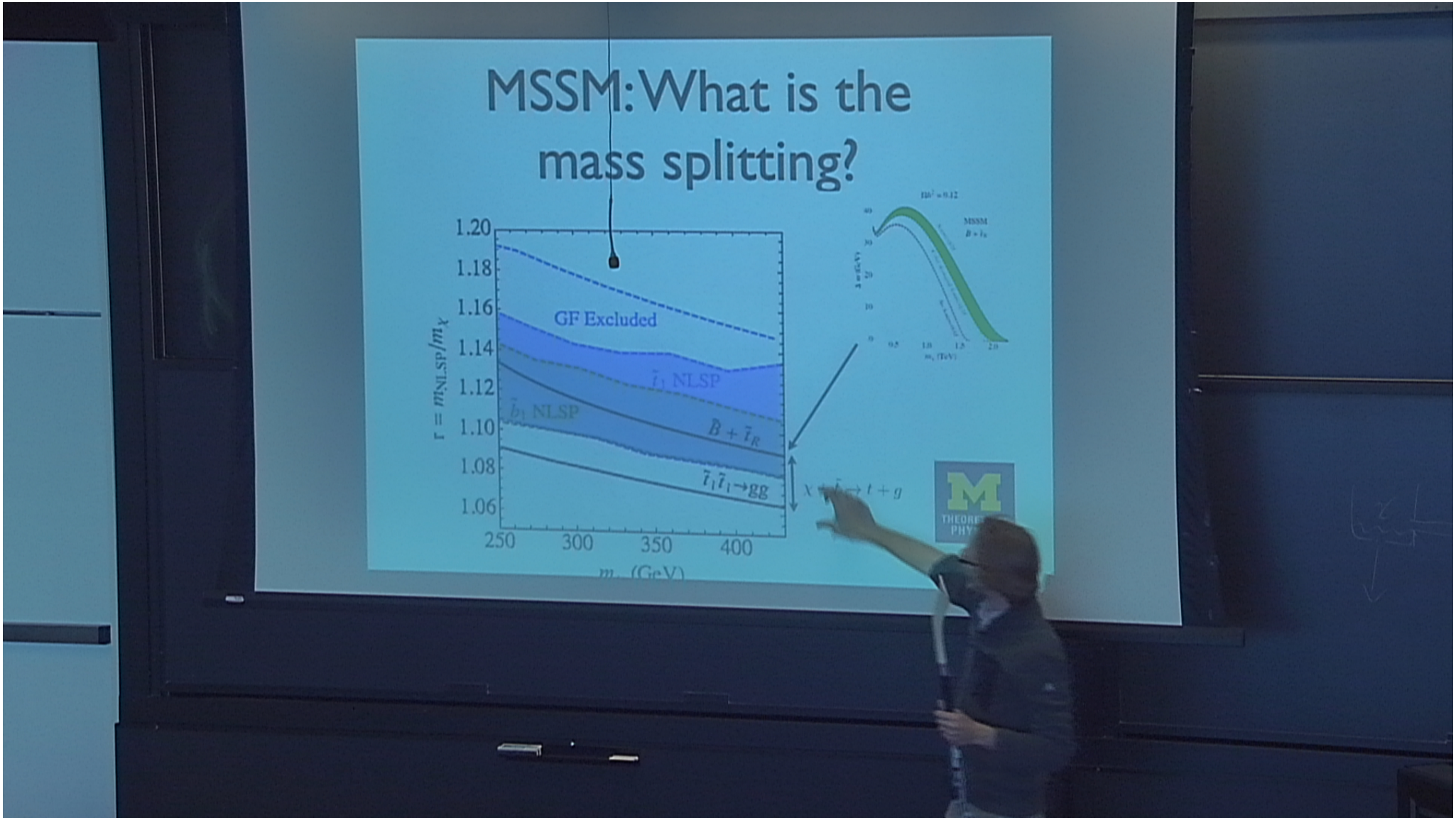
Also: $\delta\rho$

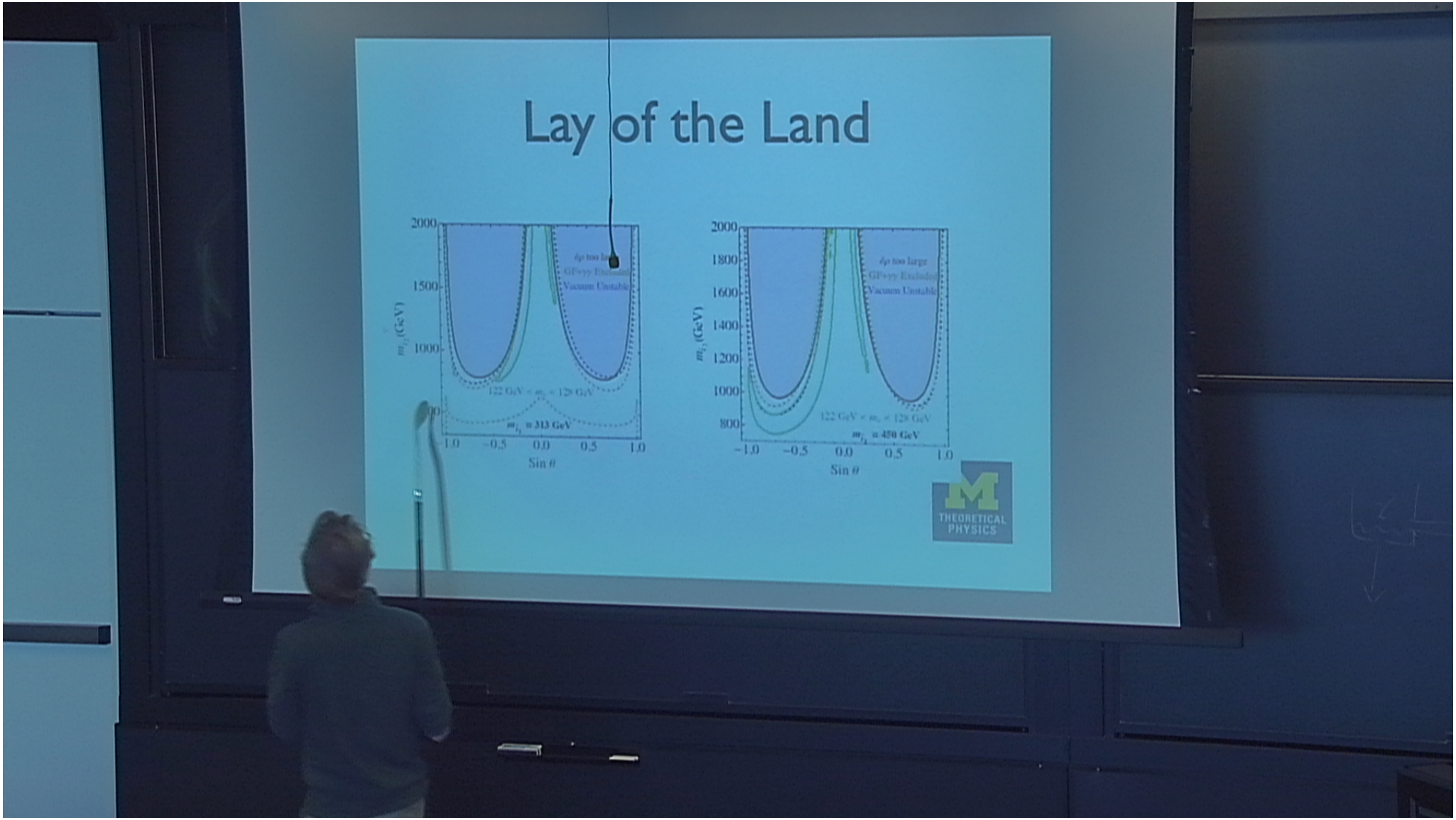
Vacuum Stability

THEORETICAL PHYSICS

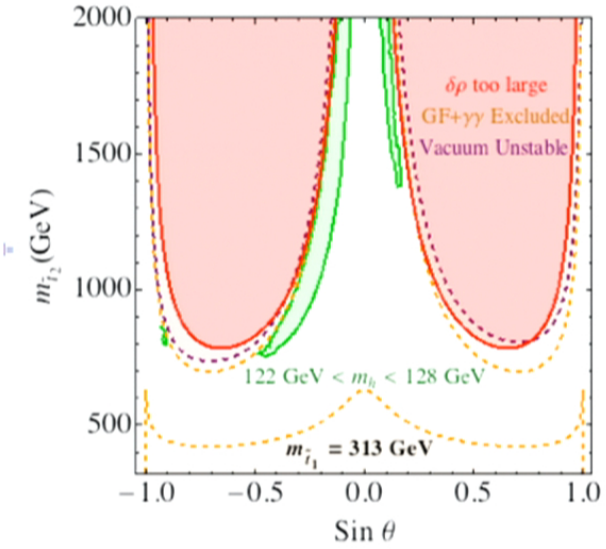
MSSM: What is the mass splitting?

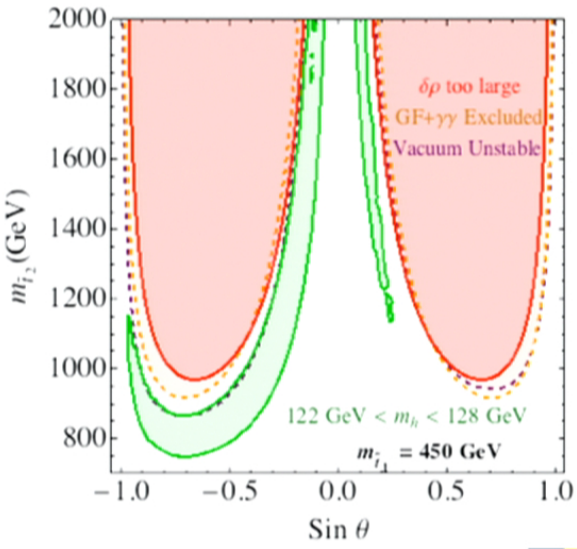



MSSM: What is the mass splitting?
1.20
1.18
1.16
1.14
1.12
1.10
1.08
1.06
$r = m_{\mathrm{NLSP}}/m_\chi$
GF Excluded
$\tilde{t}_1$ NLSP
$\tilde{b}_1$ NLSP
$B + \tilde{t}_R$
$\tilde{t}_1\tilde{t}_1 \to gg$
250
300
350
400
m_χ (GeV)
MSSM


Lay of the Land
2000
1500
1000
500
$m_{\chi_2^0}$ (GeV)
$\delta\rho$ too large
GF+yy Excluded
Vacuum Unstable
122 GeV < m_h < 128 GeV
$m_{\chi_1^0}$ = 313 GeV
−1.0
−0.5
0.0
0.5
1.0
Sin θ
2000
1800
1600
1400
1200
1000
800
$m_{\chi_2^0}$ (GeV)
$\delta\rho$ too large
GF+yy Excluded
Vacuum Unstable
122 GeV < m_h < 128 GeV
$m_{\chi_1^0}$ = 450 GeV
−1.0
−0.5
0.0
0.5
1.0
Sin θ
THEORETICAL PHYSICS

Lay of the Land





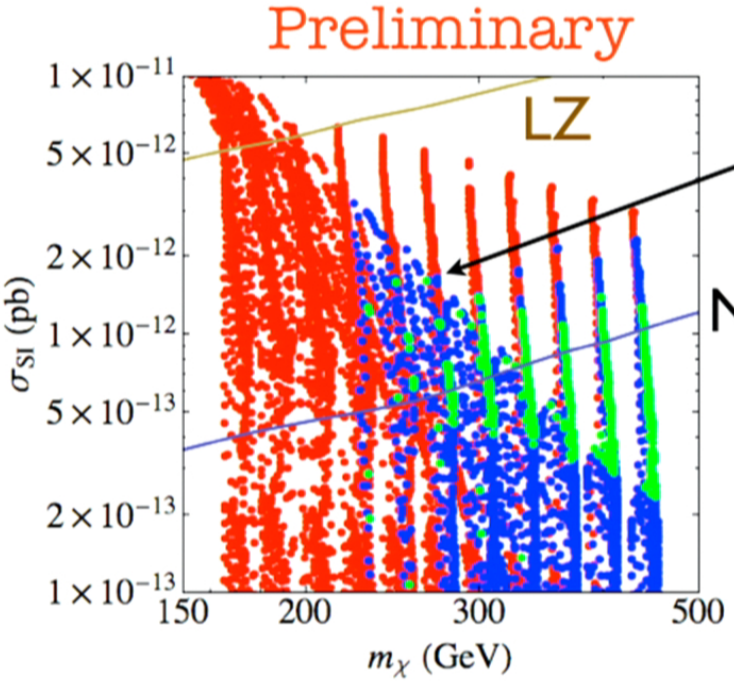
THEORETICAL PHYSICS

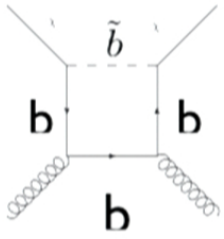
MSSM direct detection challenges

Red = Right relic density

Blue= Impose gluon fusion and direct searches

Green= Correct Higgs boson mass



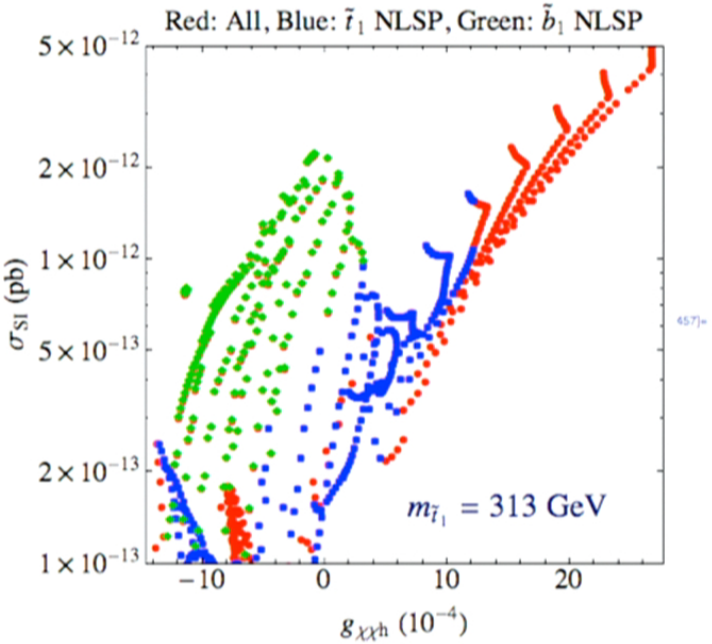


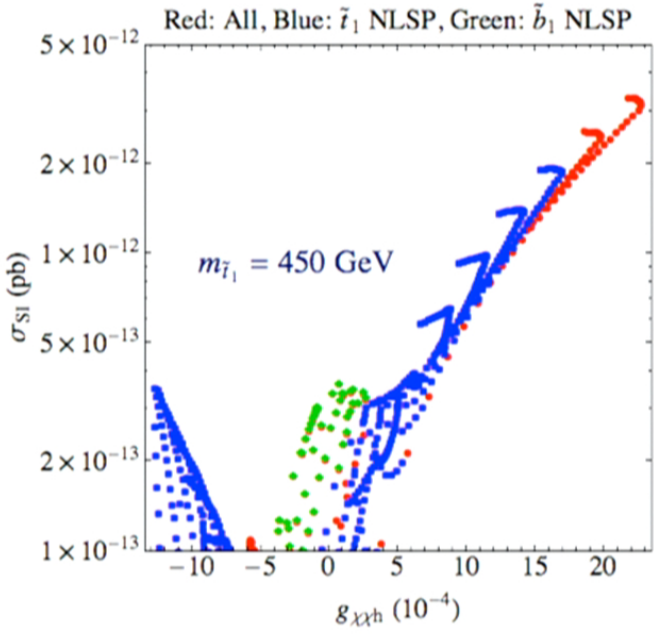
Neutrino Bound

$m_{\tilde{t}_2} < 3\,\mathrm{TeV}$

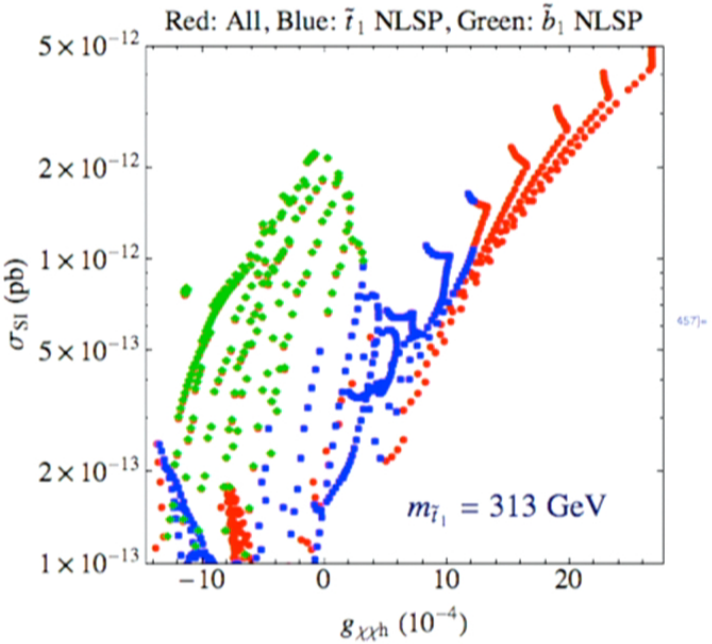
A. Ibarra, AP, N. Shah, S. Vogl in preparation

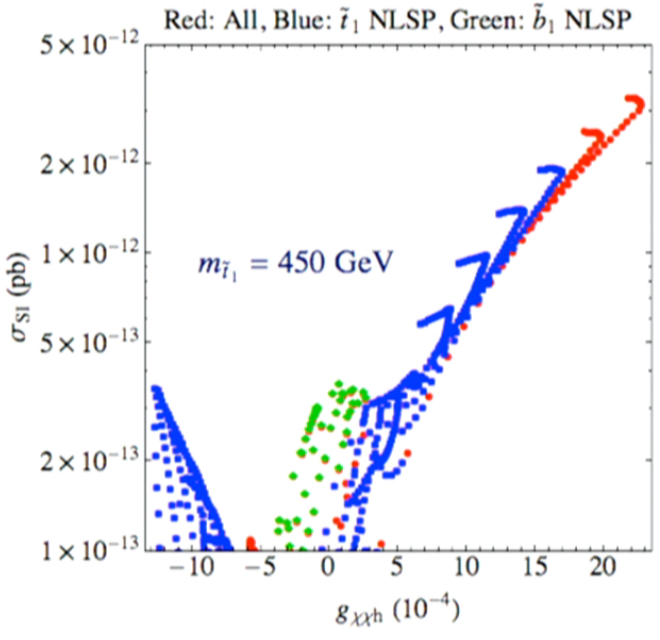
Where DD cross sections are coming from...

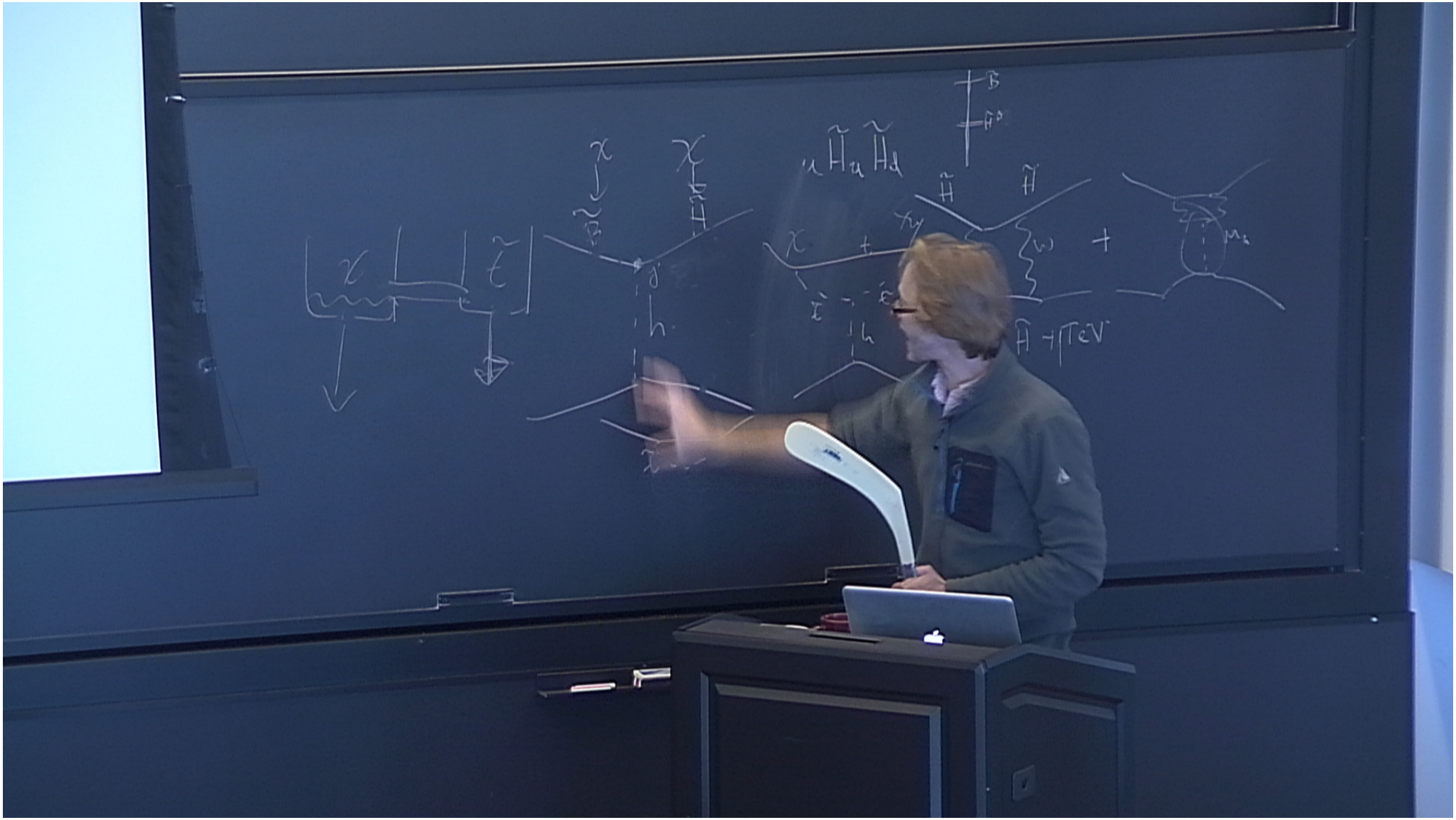




Where DD cross sections are coming from...







Conclusions

- Stop co-annihilation is a well-motivated cosmology.
- Direct detection within MSSM has a very limited window where direct detection is a "sure thing" -- though a serendipitously small μ could help.
- LHC Searches for stops at "small mass splitting" a priority, and should cover up to ~ 600 GeV.
  - Large Higgs mass potentially indicates slightly larger mass splitting due to importance of $\tilde{t}\tilde{t} \to hh$ which impacts LHC searches.

Conclusions

- Stop co-annihilation is a well-motivated cosmology.
- Direct detection within MSSM has a very limited window where direct detection is a "sure thing" -- though a serendipitously small μ could help.
- LHC Searches for stops at "small mass splitting" a priority, and should cover up to ~ 600 GeV.
  - Large Higgs mass potentially indicates slightly larger mass splitting due to importance of $\tilde{t}\tilde{t} \to hh$ which impacts LHC searches.