Title: UV Sensitivity of Dark Matter

Date: Apr 17, 2012 11:00 AM

URL: http://pirsa.org/12040057

Abstract: In this talk I will present evidence that accounting for the presence of hierarchies in string compactifications naturally leads to a UV sensitivity of dark matter in contrast to what is usually assumed. In particular, we will see that the existence of cosmological moduli may lead to a non-thermal history for the early universe and modifications in the primordial production of dark matter. If such a history were realized it would not only require probing new regions in dark matter searches, but also imply that a detection of dark matter would provide a direct probe on the early universe and the UV -- contrary to the thermal WIMP case. Regardless of the history of the early universe I will argue that if current string constructions are representative of more general models then all weak-scale dark matter would indeed be UV sensitive and would be a new prediction of string theory - falsifiable by experiment.

What Microscopic Physics is Required?

(1) New symmetries beyond Std. Model

(2) Stable particle charged under the symmetry (i.e. Dark Matter X)

(3) Unstable particle φ which is:

(a) gravitationally coupled $\Gamma = c \frac{m_\varphi^3}{m_p^2}$

(b) Mass generated at Sym e.g. $\varphi \to \varphi + C$

(4) Hierarchies:

$$\frac{m_{3/2}}{m_p} \ll 1 \qquad \frac{\Lambda^4}{M_p^4} \ll 1$$

Condensate decays and reheats universe

$$\Gamma \simeq \frac{m_\varphi^3}{m_p^2} \qquad T_r \simeq \left(\frac{m_\varphi}{10\,\text{TeV}}\right)^{3/2} \text{MeV}$$

φ decays → Std. Model

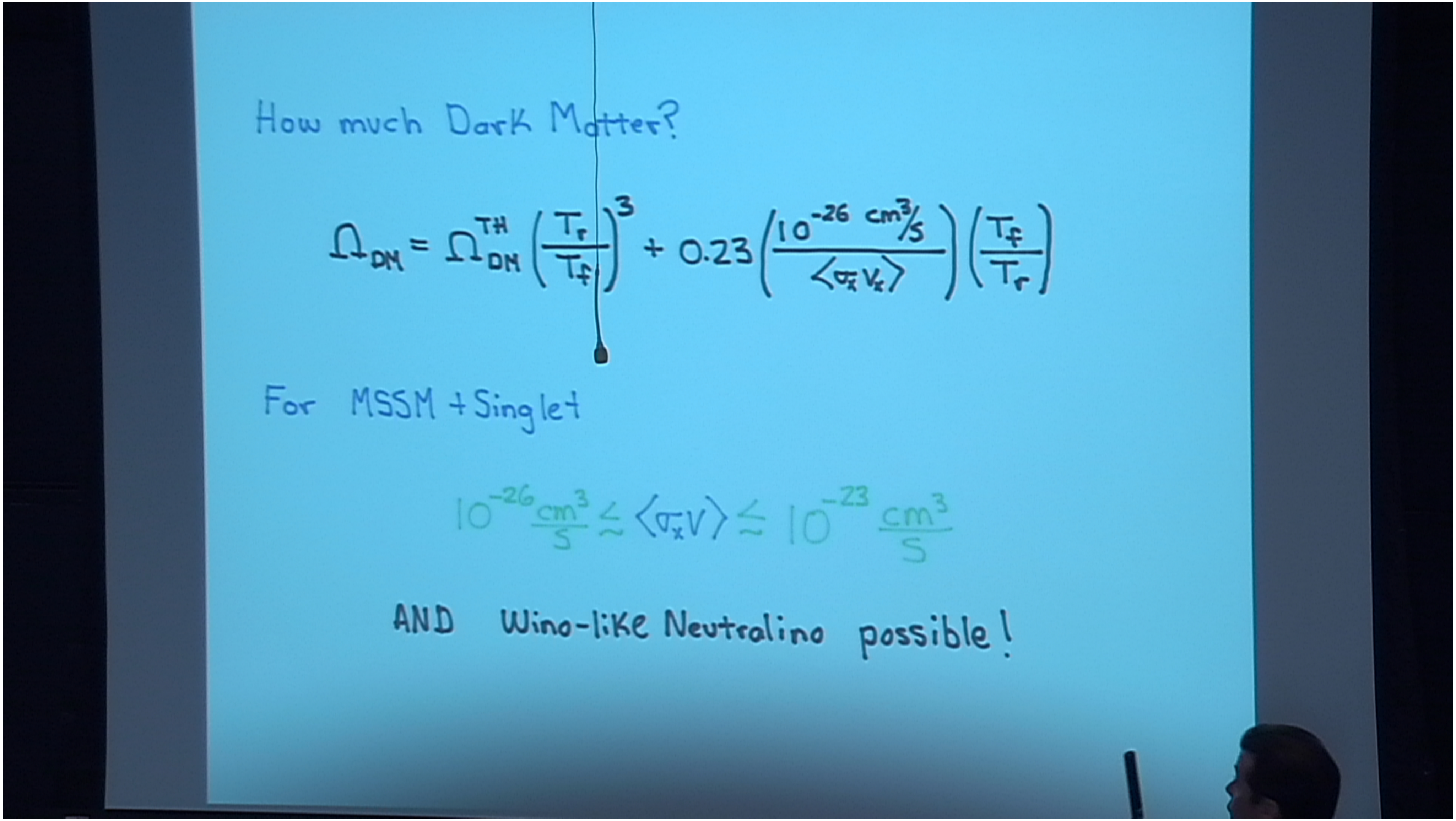
φ decays → SUSY partners → → → LSP (Neutrolino DM)

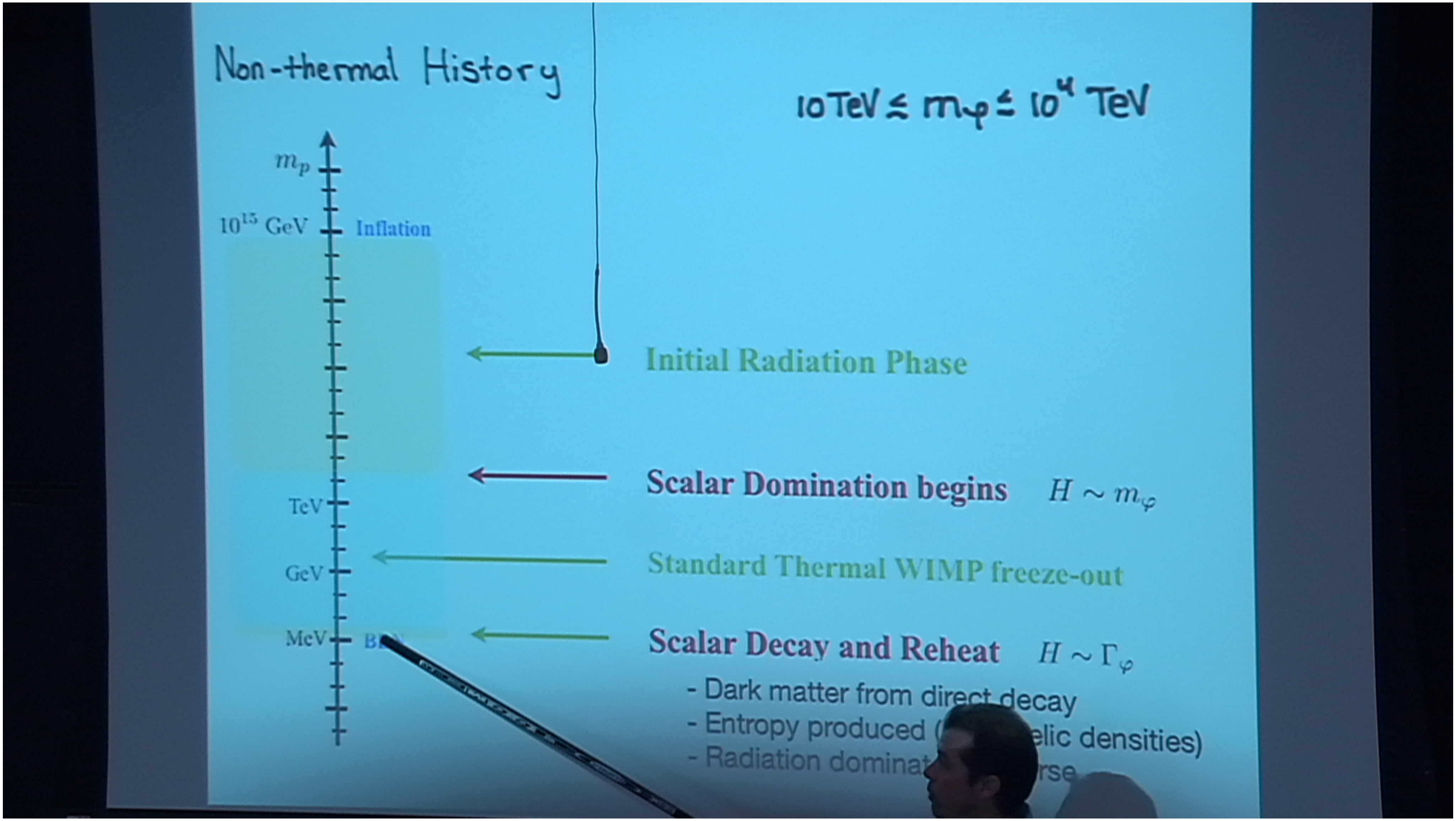
How much Dark Matter?

$$\Omega_{DM} = \Omega_{DM}^{TH}\left(\frac{T_r}{T_f}\right)^3 + 0.23\left(\frac{10^{-26}\ \text{cm}^3/\text{s}}{\langle \sigma_\chi v_\chi \rangle}\right)\left(\frac{T_f}{T_r}\right)$$

<u>Ex</u> $m_\varphi \sim 10\,\text{TeV}$ $\quad T_r \sim \text{MeV}$ $\quad T_f \sim \text{GeV}$

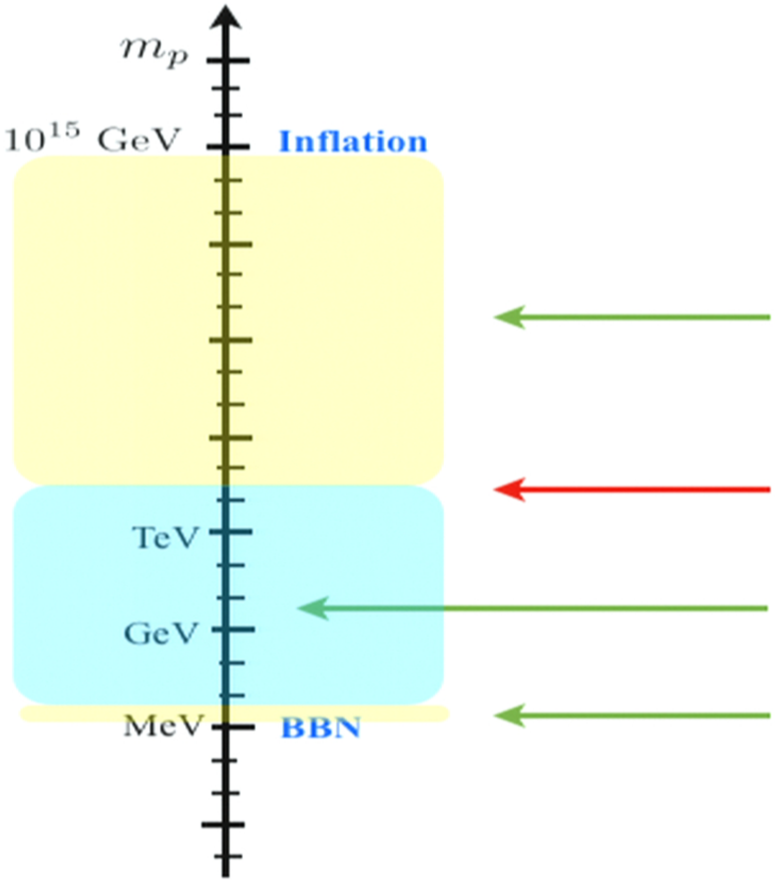
$$\Omega_{DM} = 10^{-9}\,\Omega_{DM}^{Th} + 0.23 \times 10^3 \left(\frac{10^{-26}\ \text{cm}^3/\text{s}}{\langle \sigma_\chi v_\chi \rangle}\right)$$


How much Dark Matter?
$\Omega_{DM} = \Omega_{DM}^{TH}\left(\frac{T_r}{T_f}\right)^3 + 0.23\left(\frac{10^{-26}\ cm^3/s}{\langle\sigma_\chi v_\chi\rangle}\right)\left(\frac{T_f}{T_r}\right)$
For MSSM + Singlet
$10^{-26}\frac{cm^3}{s} \lesssim \langle\sigma_\chi v\rangle \lesssim 10^{-23}\frac{cm^3}{s}$
AND Wino-like Neutralino possible!


Non-thermal History
10 TeV ≲ m_φ ≲ 10^4 TeV
m_p
10^{15} GeV
Inflation
Initial Radiation Phase
Scalar Domination begins $H \sim m_\varphi$
TeV
Standard Thermal WIMP freeze-out
GeV
MeV
Scalar Decay and Reheat $H \sim \Gamma_\varphi$
- Dark matter from direct decay
- Entropy produced (
elic densities)
- Radiation dominat

Non-thermal History

$10\,\text{TeV} \lesssim m_\varphi \lesssim 10^4\,\text{TeV}$



Initial Radiation Phase

Scalar Domination begins $H \sim m_\varphi$

Standard Thermal WIMP freeze-out

Scalar Decay and Reheat $H \sim \Gamma_\varphi$

- Dark matter from direct decay
- Entropy produced (dilute relic densities)
- Radiation dominated universe

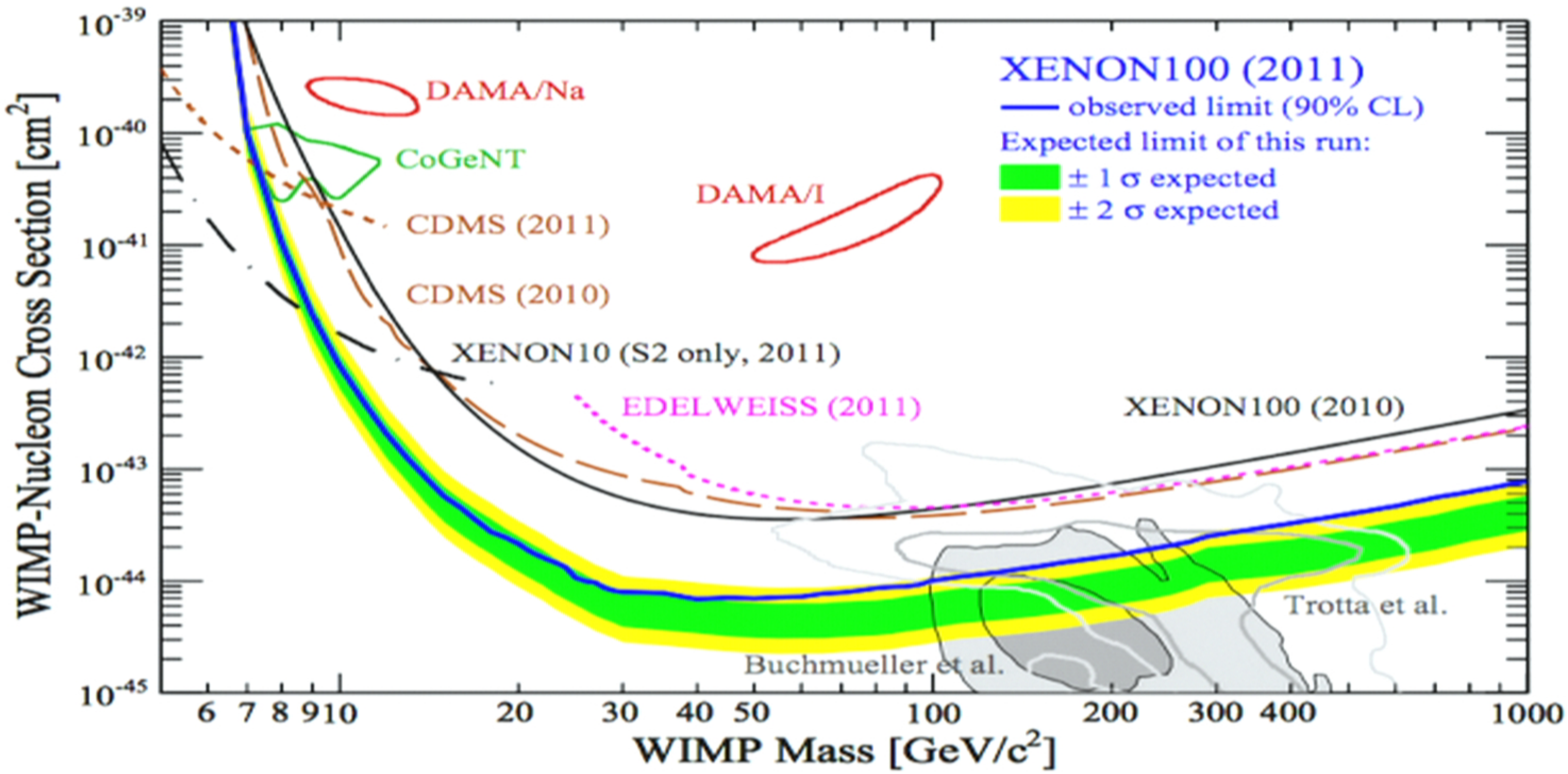
Non-thermal history implies:

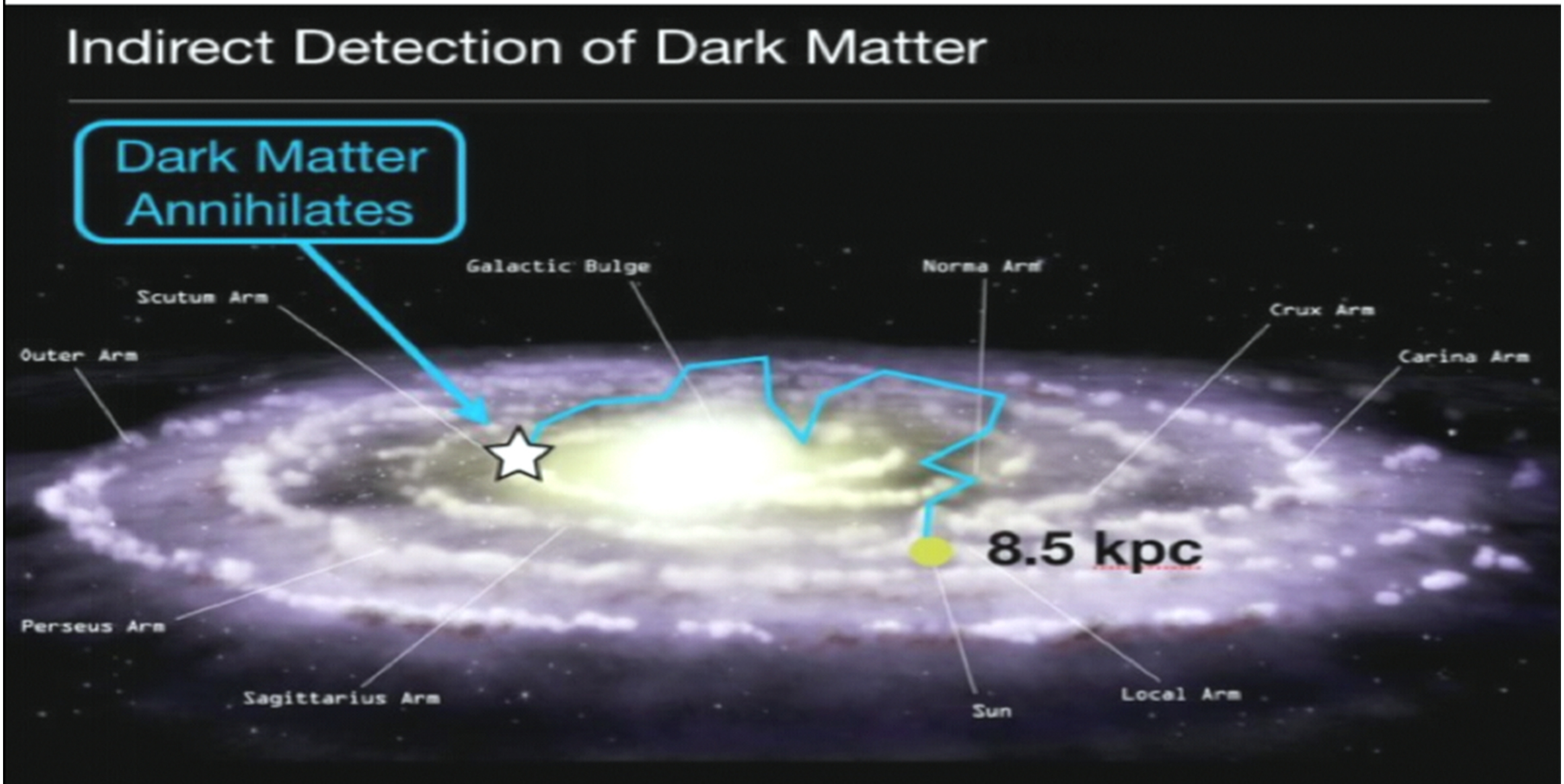
$$10^{-26}\frac{cm^3}{s} \lesssim \langle \sigma_x v \rangle \lesssim 10^{-23}\frac{cm^3}{s}$$

Implications

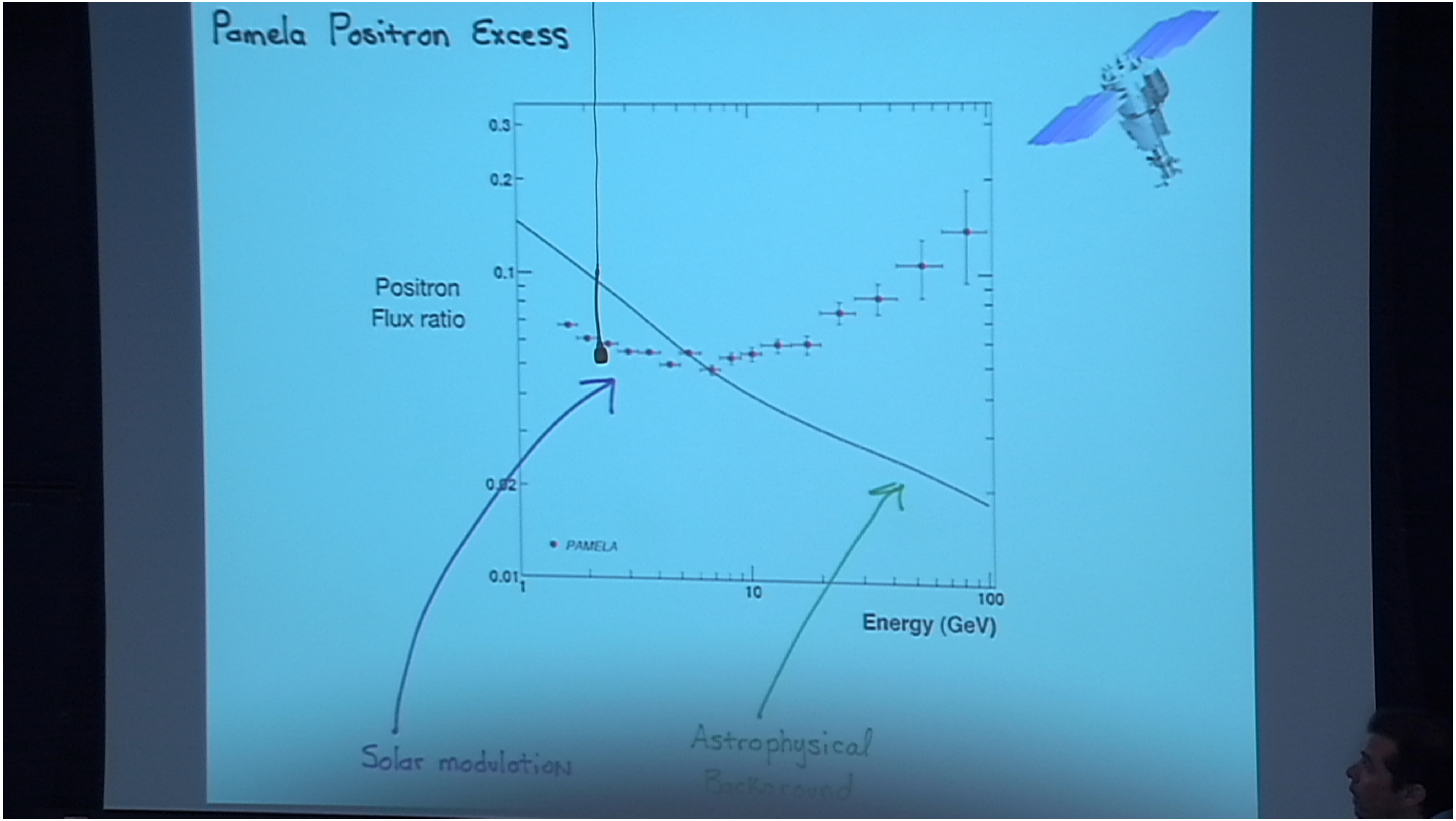
- Direct Detection
- Indirect Detection
- LHC
- CMB / LSS

Direct detection: Pure wino would give NO SIGNAL!



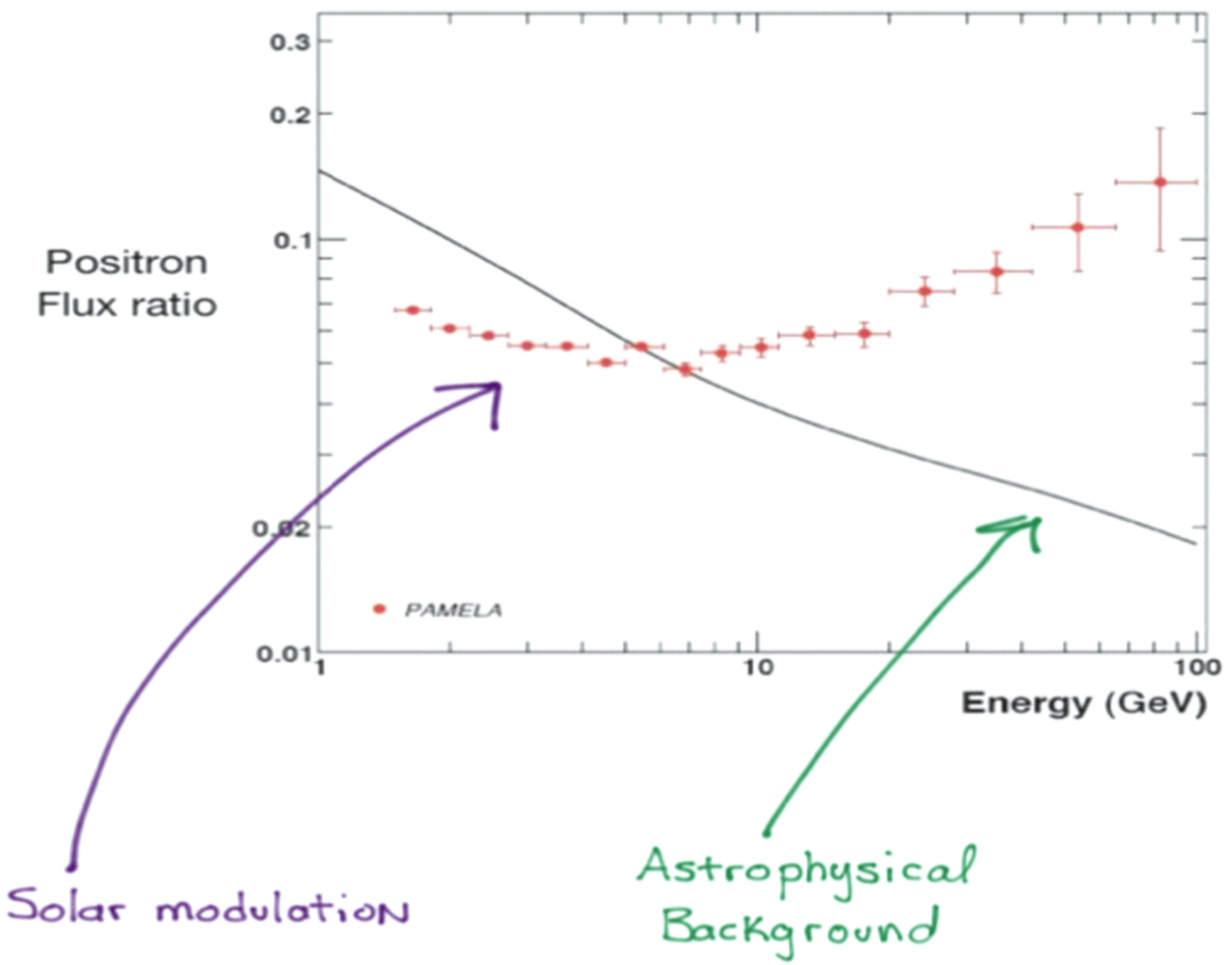


Indirect Detection of Dark Matter
Dark Matter Annihilates
Galactic Bulge
Norma Arm
Scutum Arm
Crux Arm
Outer Arm
Carina Arm
8.5 kpc
Perseus Arm
Sagittarius Arm
Sun
Local Arm

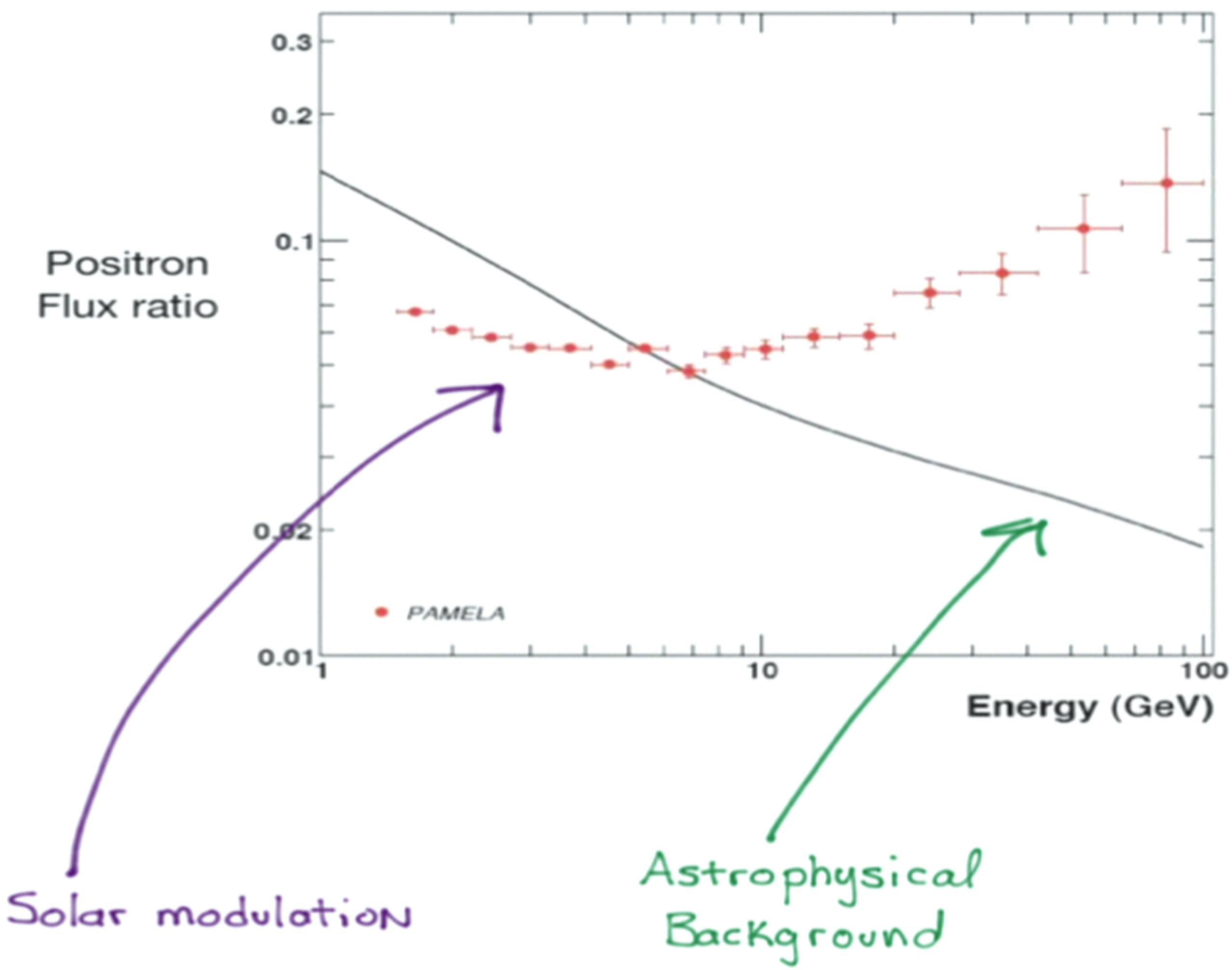


Pamela Positron Excess
Positron Flux ratio
0.3
0.2
0.1
0.02
0.01
1
10
100
Energy (GeV)
PAMELA
Solar modulation
Astrophysical

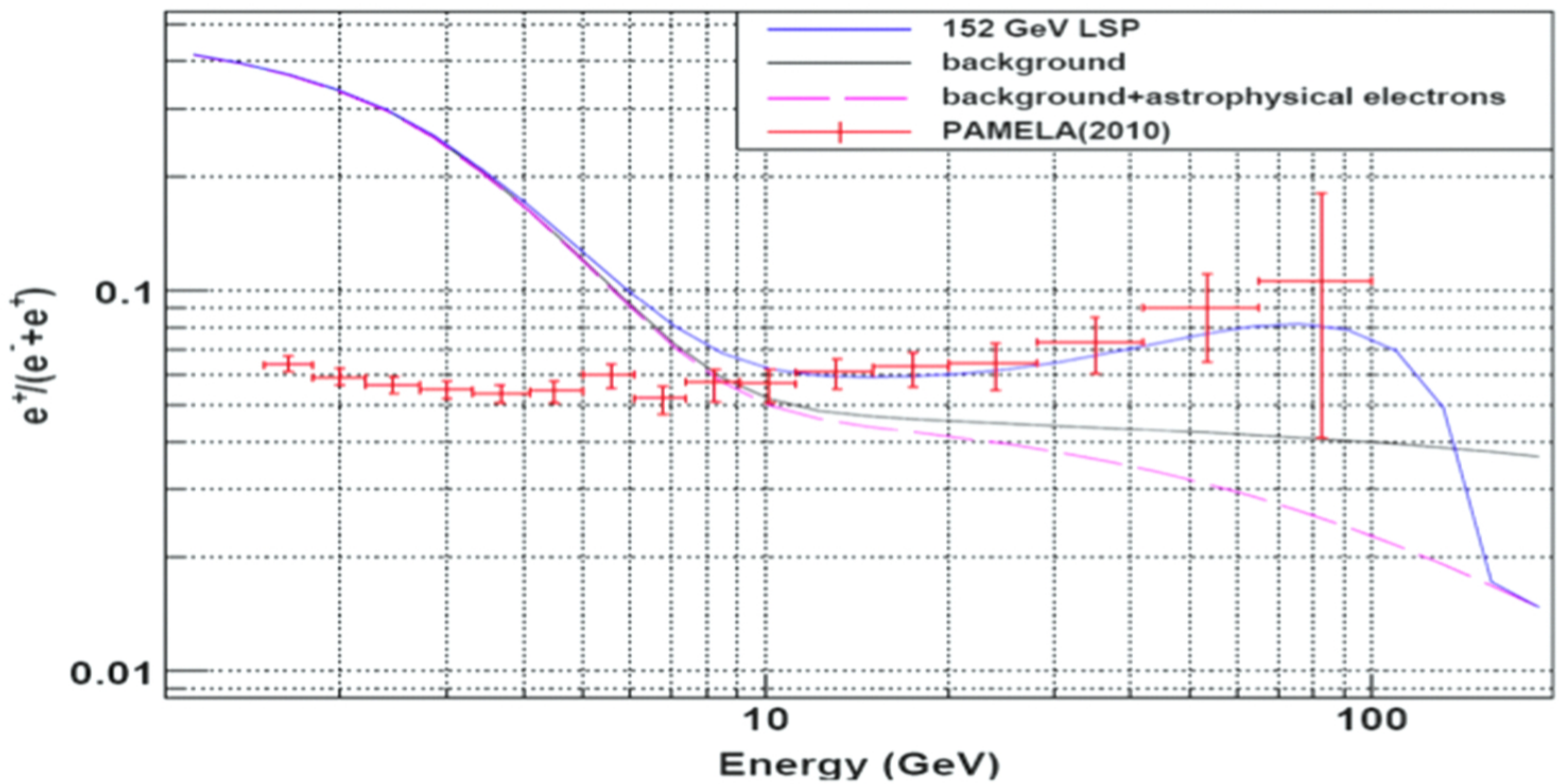
Pamela Positron Excess



Pamela Positron Excess

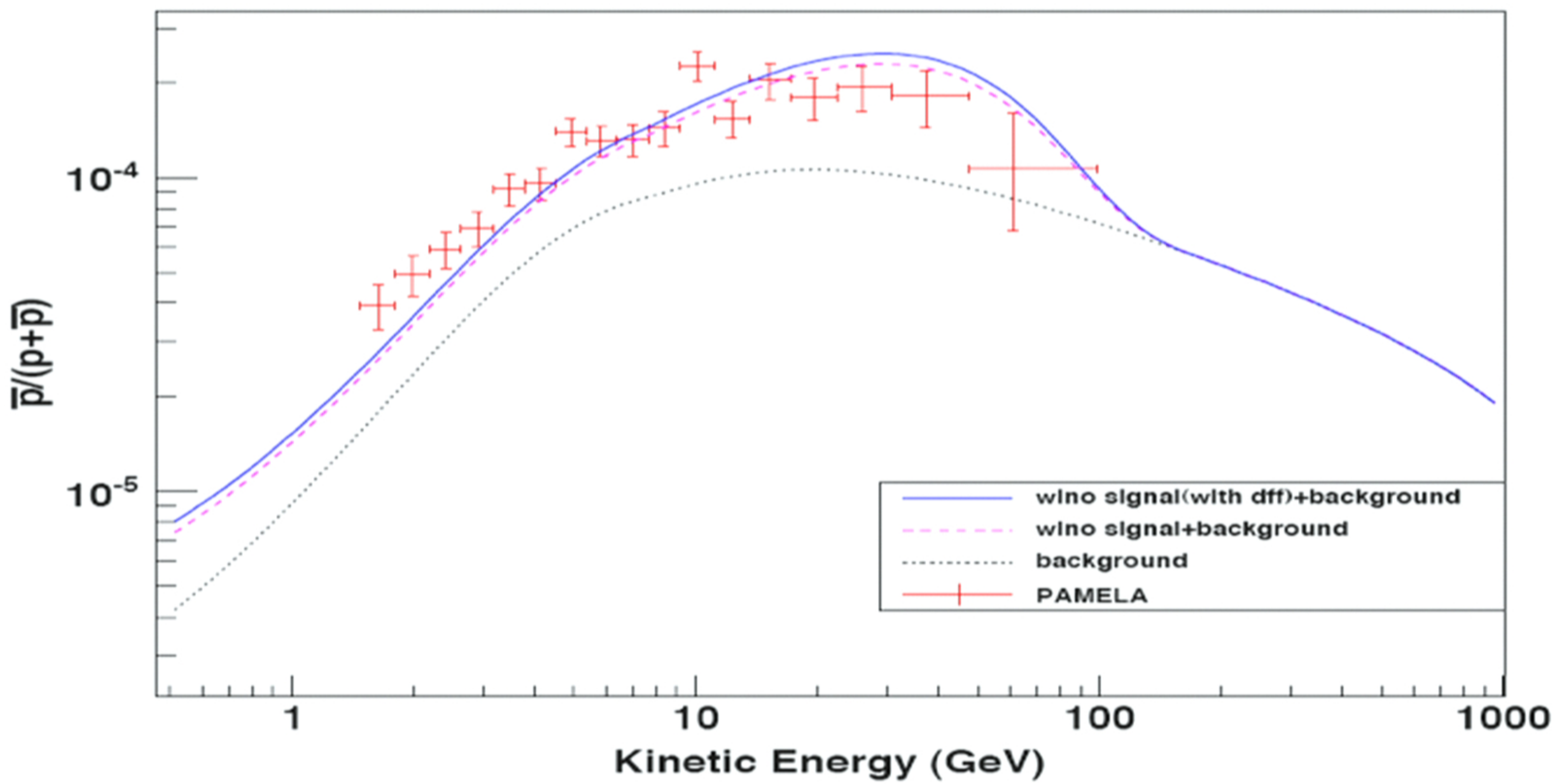


Larger cross-section can address PAMELA excess



with G. Kane and Ran Lu (Michigan)

Pamela anti-protons



with G. Kane and Ran Lu (Michigan)

Given non-thermal history:
Can the SUSY Neutralino account for the Pamela data?

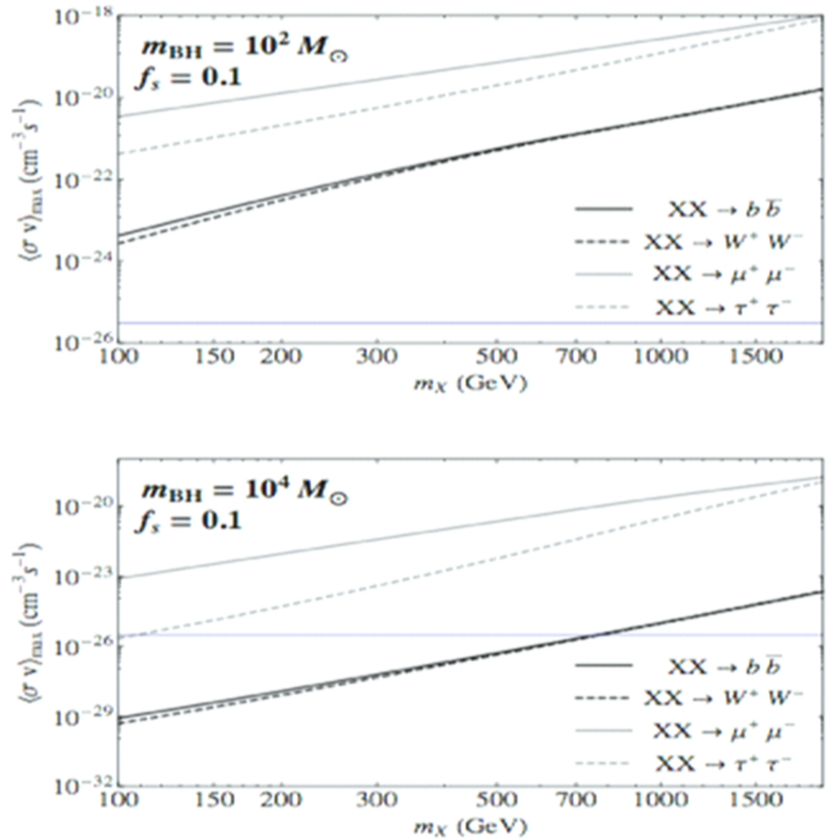
✓ Yes, but there is a tension with the data.

with G. Kane and R. Lu. arXiv:0906.4765
with P. Grajek, G. Kane, D. Phalen, A. Pierce. arXiv:0812.4555
with P. Grajek, G. Kane, D. Phalen, A. Pierce, arXiv:0807.1508

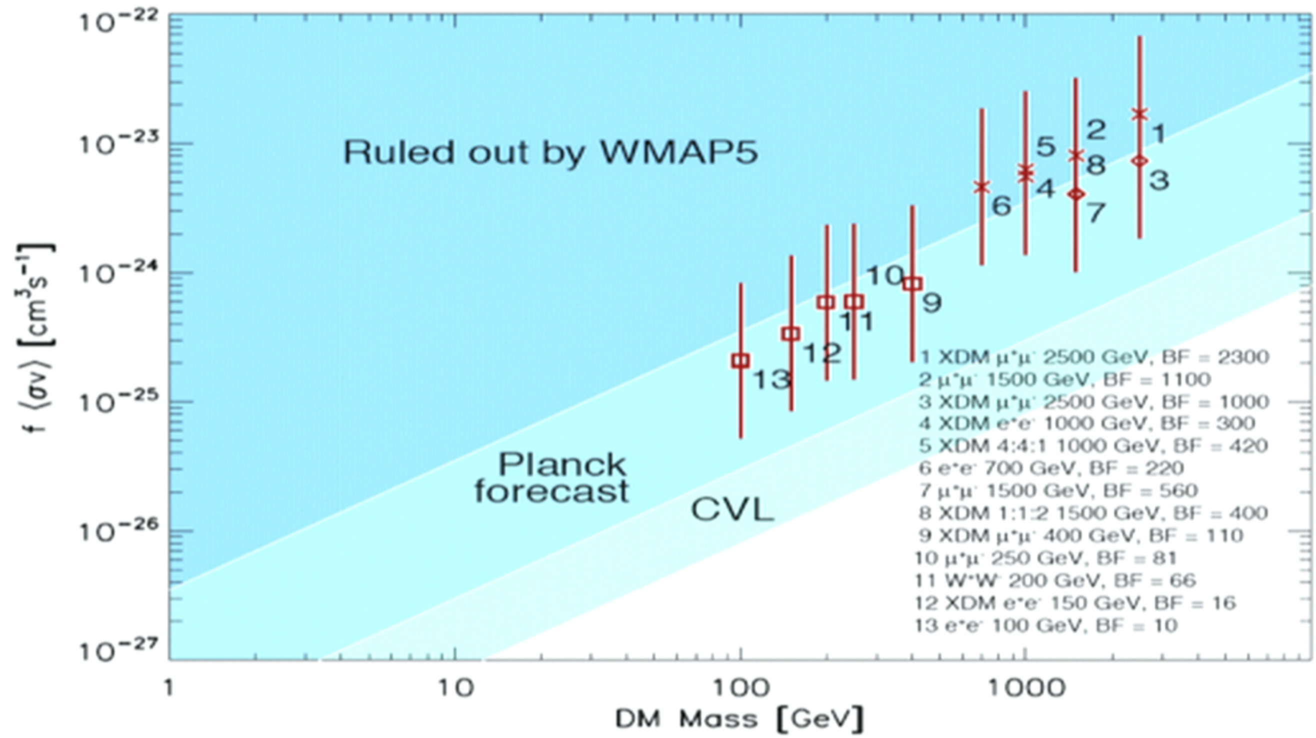
FERMI Constraints and Dark Matter Spikes

with P. Sandick 1102.2897

More realistic density profiles (accounting for substructure) lead to stronger constraints

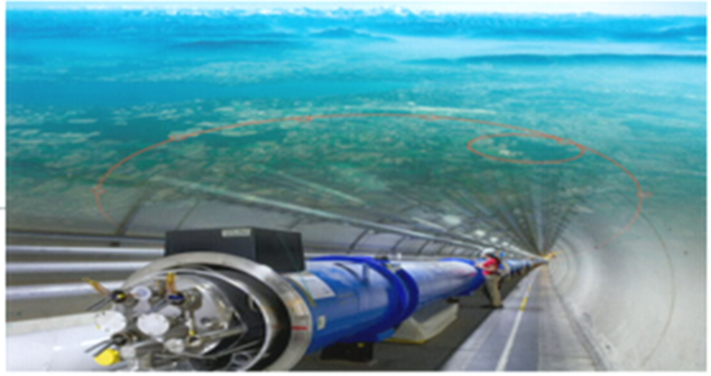


CMB: Last Scattering Surface and a Non-thermal History



Slatyer, Padmanabhan and Finkbeiner 0906.1197

Collider Implications



Assume a thermal history

$$\Omega_{DM} = \frac{\rho_\chi}{\rho_c} = 0.23 \left(\frac{10^{-26}\,cm^3/s}{\langle \sigma_\chi v_\chi \rangle} \right)$$

$$LHC \longrightarrow \sigma_\chi \qquad \Omega_{DM}^{TH} = 0.23 \left(\frac{10^{-26}\,cm^3/s}{10^{-23}\,cm^3/s} \right) \ll \Omega_{DM}^{WMAP}$$

Non-thermal history

$$\Omega_{DM} = \Omega_{DM}^{TH} \left(\frac{T_r}{T_f} \right)^3 + 0.23 \left(\frac{10^{-26}\,cm^3/s}{\langle \sigma_\chi v_\chi \rangle} \right) \left(\frac{T_f}{T_r} \right)$$

"Where is the missing Dark Matter?"

Non-thermal History

Enhanced interaction strength

$$10^{-26}\frac{cm^3}{s} \lesssim \langle \sigma_x v \rangle \lesssim 10^{-23}\frac{cm^3}{s}$$

Phenomenological Implications
(Wino from MSSM + Singlet was a first example):

Direct and Indirect Detection:

with P. Sandick (arXiv:1102.2897, published in PRD)
with G. Kane and L. Ran (arXiv:0906.4765, published in PLB)
with G. Kane, A. Pierce, et. al. (arXiv:0807.1508, arXiv: 0812.4555, published in PRD)

Collider implications:

with G. Kane (arXiv:0807.2244, invited review for MPL)

Baryogenesis:

with G. Kane, J. Shao, and H. Yu (arXiv:1108.5178, published in JCAP)

Lithium abundance (BBN):

(in progress)

- w/ G. Kane, J. Shao, H. Yu 1108.5178

Baryogenesis?

$$\Omega_b \longrightarrow \Omega_b \left(\frac{T_f}{T_r}\right)^3$$

AD Baryogenesis is typically too effective

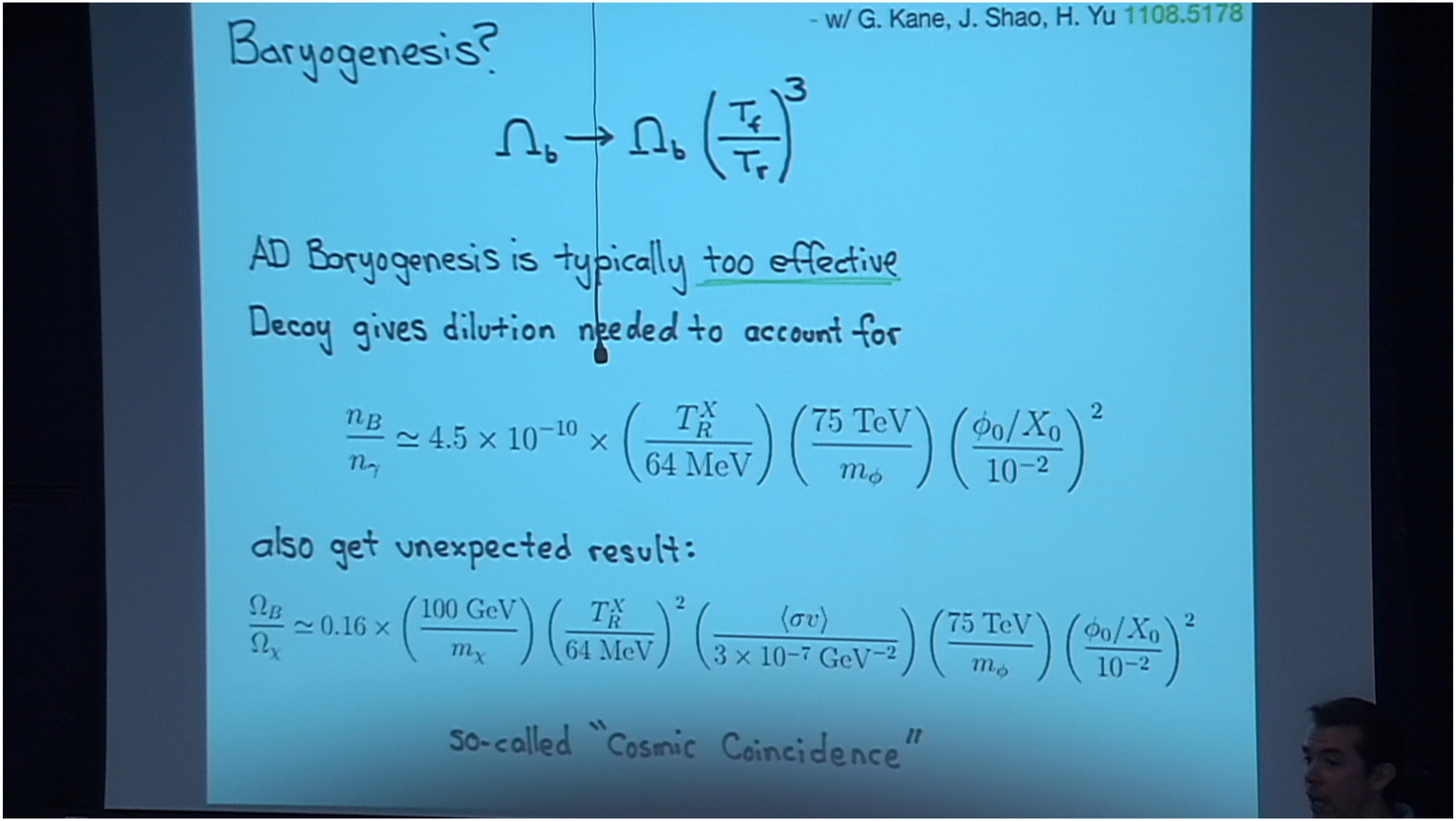
Decay gives dilution needed to account for

$$\frac{n_B}{n_\gamma} \simeq 4.5 \times 10^{-10} \times \left(\frac{T_R^X}{64\ \mathrm{MeV}}\right) \left(\frac{75\ \mathrm{TeV}}{m_\phi}\right) \left(\frac{\phi_0/X_0}{10^{-2}}\right)^2$$

also get unexpected result:

$$\frac{\Omega_B}{\Omega_\chi} \simeq 0.16 \times \left(\frac{100\ \mathrm{GeV}}{m_\chi}\right) \left(\frac{T_R^X}{64\ \mathrm{MeV}}\right)^2 \left(\frac{\langle \sigma v\rangle}{3\times 10^{-7}\ \mathrm{GeV}^{-2}}\right) \left(\frac{75\ \mathrm{TeV}}{m_\phi}\right) \left(\frac{\phi_0/X_0}{10^{-2}}\right)^2$$

so-called "Cosmic Coincidence"


- w/ G. Kane, J. Shao, H. Yu 1108.5178
Baryogenesis?
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so-called "Cosmic Coincidence"

Other cosmic histories are possible.

(non-thermal history is an example)

How is dark matter produced?

↕

What are its microscopic properties?

What Microscopic Physics is Required?

(1) New symmetries beyond Std. Model

(2) Stable particle charged under the symmetry (i.e. Dark Matter X)

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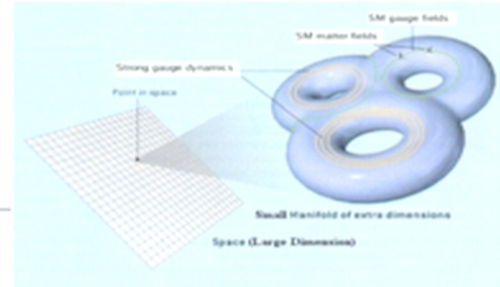
Guidance from Fundamental Theory



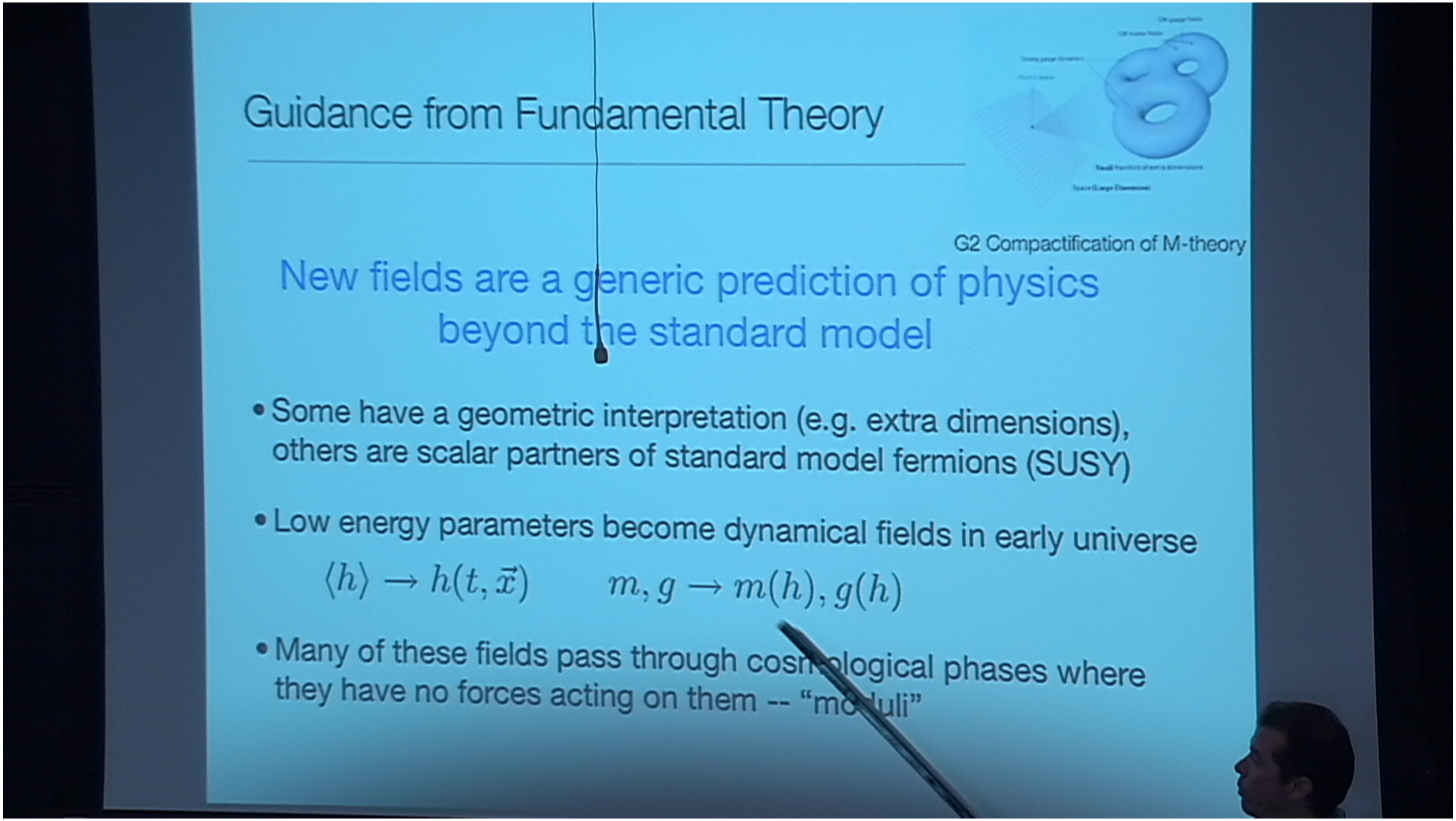
G2 Compactification of M-theory

New fields are a generic prediction of physics beyond the standard model

- Some have a geometric interpretation (e.g. extra dimensions), others are scalar partners of standard model fermions (SUSY)
- Low energy parameters become dynamical fields in early universe

$$\langle h \rangle \longrightarrow h(t, \vec{x}) \qquad m, g \longrightarrow m(h), g(h)$$

- Many of these fields pass through cosmological phases where they have no forces acting on them -- “moduli”



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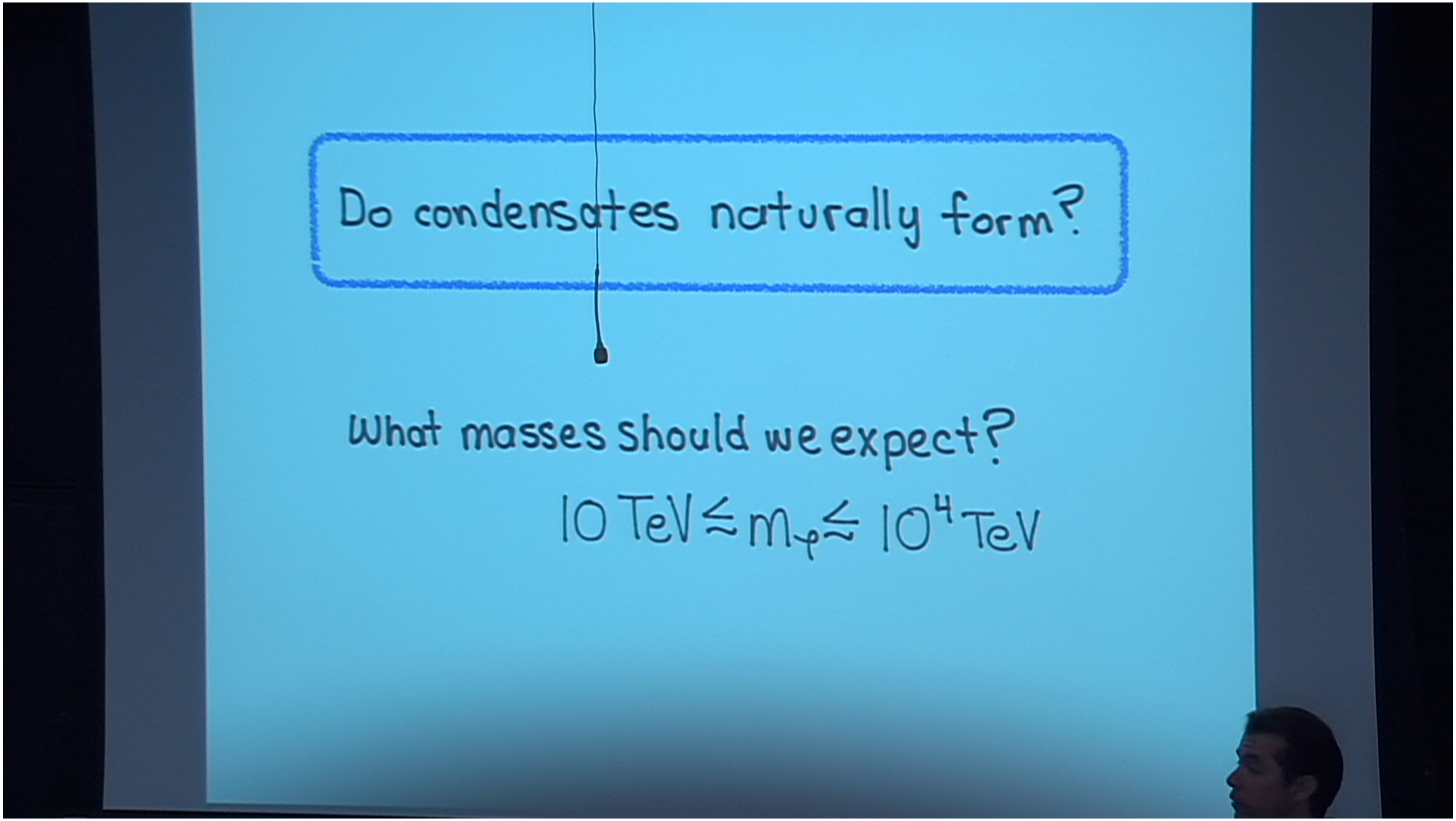

Do condensates naturally form?
What masses should we expect?
$10\ \text{TeV} \lesssim m_\varphi \lesssim 10^4\ \text{TeV}$

Summary of Progress:

Including all degrees of freedom generates stabilizing potentials for many scalars

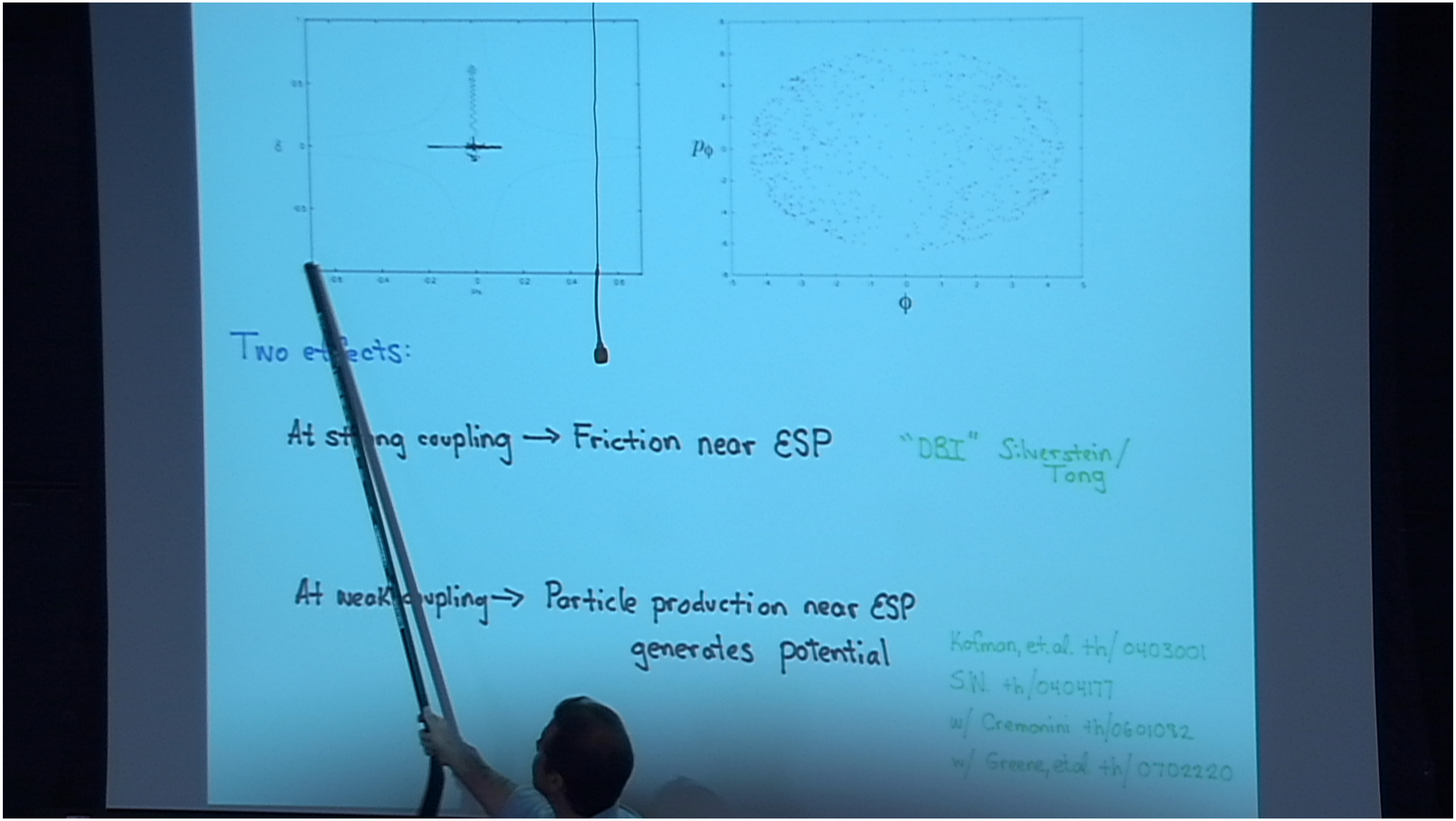
$\longrightarrow M \simeq M_S \simeq M_P$ (Decouple)

Scalars located near points of enhanced symmetry $\rightarrow$ cosmologically stable. Dine, Randall, Thomas

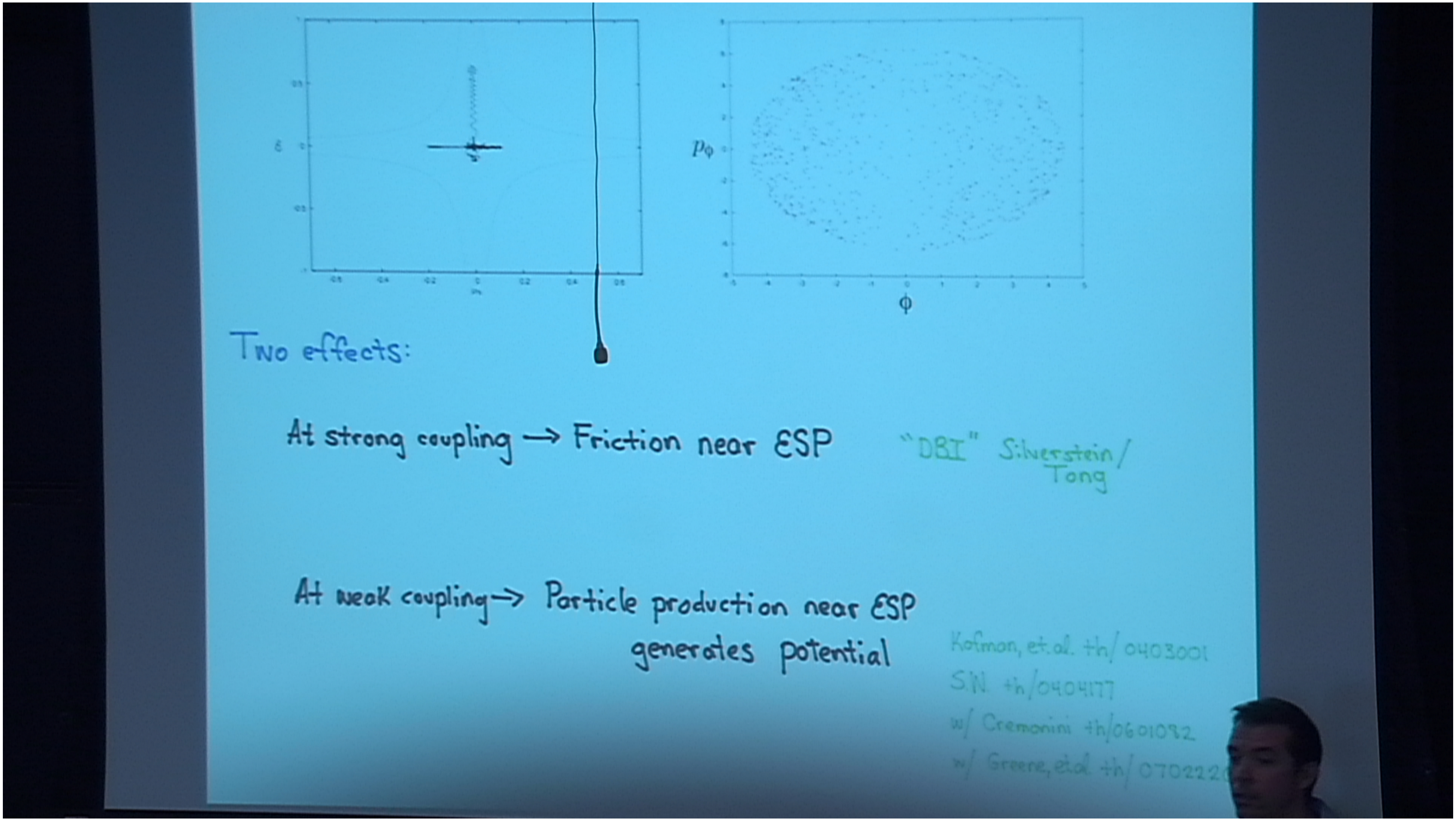
(No condensates form)

These points are cosmological attractors

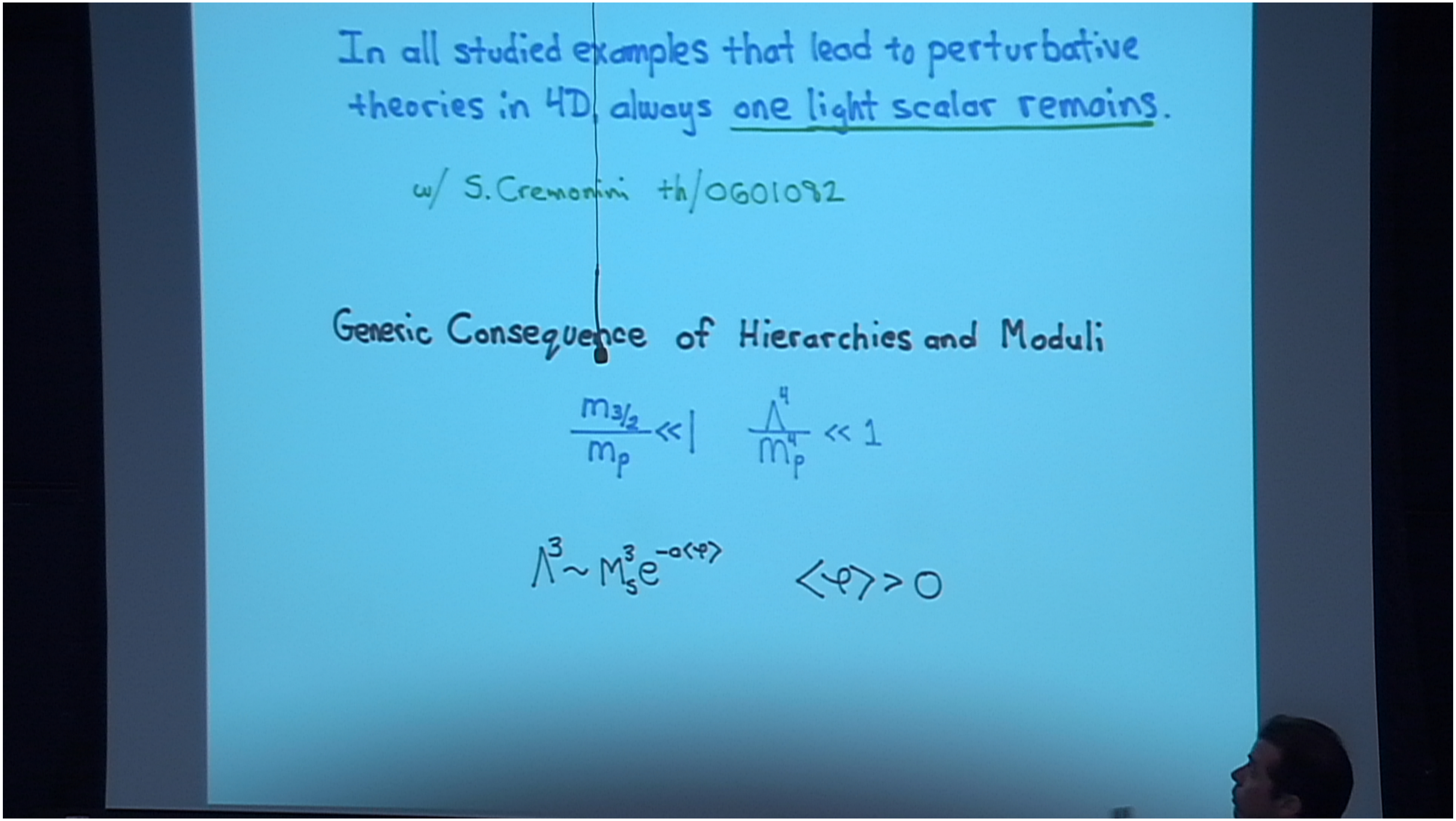
Kofman, et. al. th/0403001
S.W. th/0404177
w/ Cremonini th/0601082
w/ Greene, et.al. th/0702220



p_ϕ
ϕ
Two e ects:
At st ng coupling → Friction near ESP
"DBI" Silverstein/ Tong
At weak upling → Particle production near ESP
generates potential
Kofman, et.al. th/0403001
S.W. th/0404177
w/ Cremonini th/0601082
w/ Greene, et.al. th/0702220



p_φ
φ
Two effects:
At strong coupling → Friction near ESP
"DBI" Silverstein/Tong
At weak coupling → Particle production near ESP generates potential
Kofman, et.al. th/0403001
S.W. th/0404177
w/ Cremonini th/0601092
w/ Greene, et.al. th/070222


In all studied examples that lead to perturbative theories in 4D, always one light scalar remains.
w/ S. Cremonini th/0601082
Generic Consequence of Hierarchies and Moduli
$\frac{m_{3/2}}{m_p} \ll 1$
$\frac{\Lambda^4}{M_p^4} \ll 1$
$\Lambda^3 \sim M_s^3 e^{-a\langle\varphi\rangle}$
$\langle\varphi\rangle > 0$

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w/ S. Cremonini th/0601082

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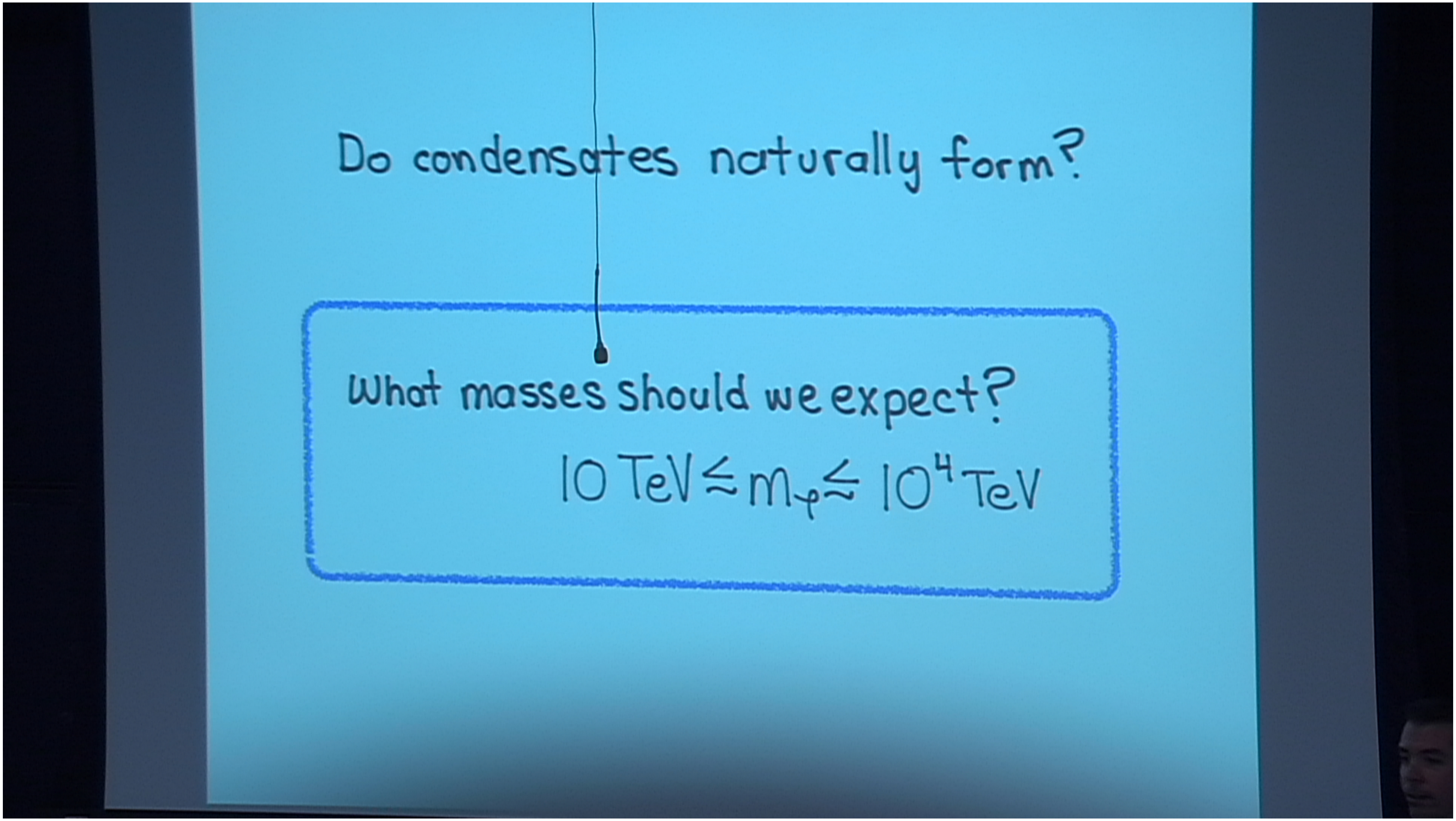

Do condensates naturally form?
What masses should we expect?
$10\ \text{TeV} \lesssim m_\varphi \lesssim 10^4\ \text{TeV}$

Natural when φ participates in ~~SUSY~~ $\langle F_\varphi \rangle \neq 0$

$$V = e^{K/m_p^2} |DW|^2 - 3 m_{3/2}^2 m_p^2$$

Shift Sym

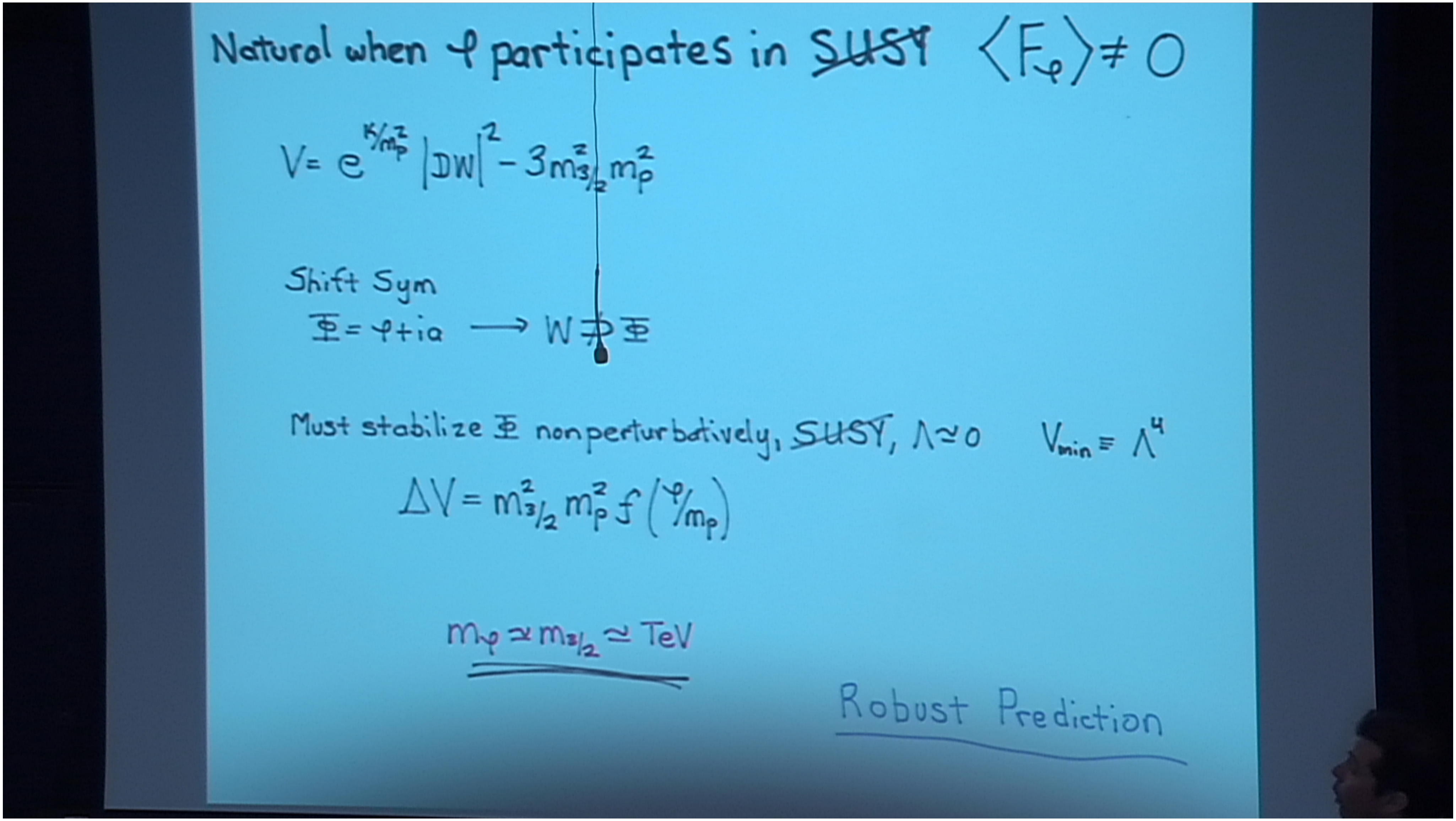
$\Phi = \varphi + ia \longrightarrow W \not\supset \Phi$

Must stabilize Φ nonperturbatively, ~~SUSY~~, $\Lambda \simeq 0$ $\quad V_{min} \equiv \Lambda^4$

$$\Delta V = m_{3/2}^2 m_p^2 f\left(\varphi / m_p\right)$$

$m_\varphi \simeq m_{3/2} \simeq \text{TeV}$

Robust Prediction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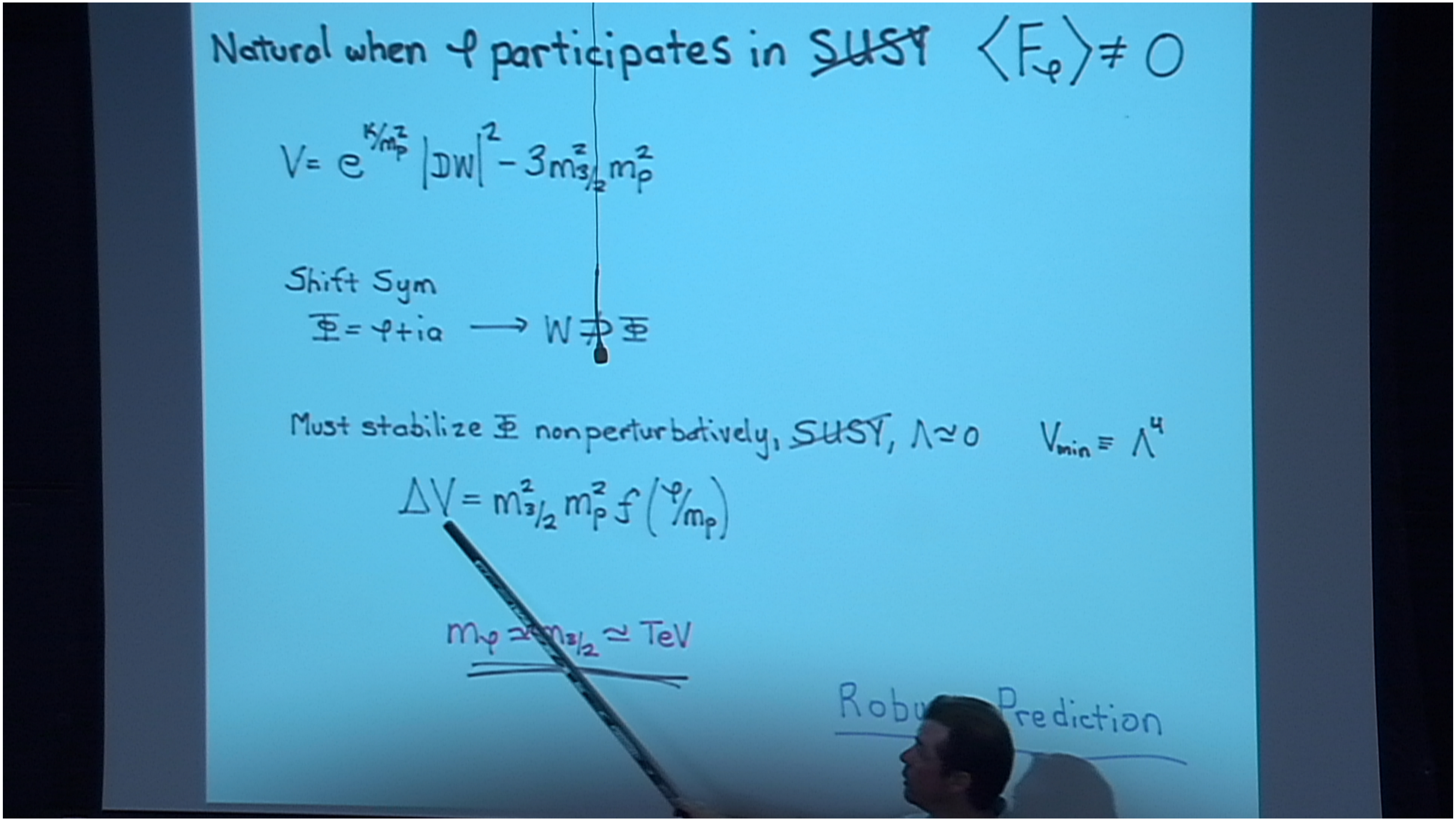
$\Delta V = m_{3/2}^2 m_p^2 f(\varphi/m_p)$
$m_\varphi \simeq m_{3/2} \simeq$ TeV
Robust Prediction


Natural when φ participates in SUSY ⟨F_φ⟩ ≠ 0
V = e^{K/m_p^2} |DW|^2 − 3 m_{3/2}^2 m_p^2
Shift Sym
Φ = φ + ia ⟶ W ∌ Φ
Must stabilize Φ nonperturbatively, SUSY, Λ ≃ 0
V_min ≡ Λ^4
ΔV = m_{3/2}^2 m_p^2 f(φ/m_p)
m_φ ≃ m_{3/2} ≃ TeV
Prediction

More general result:

Even if φ doesn't participate in SUSY

$$\frac{\Lambda^4}{M_p^4} \simeq 10^{-120} \text{ forces relationship}$$

given $M_W \ll M_p$ present.

Surprises from Type IIB Flux Compactifications

φ doesn't necessarily contribute $\langle F_\varphi \rangle = 0$

Step One

Turning on flux creates stabilizing potential for complex structure and dilaton.

String scale masses

$$m_z \simeq M_s = 10^{17} \text{ GeV}$$

Low Energy 4D

$W = W_0$ SUSY Broken!

Surprises from Type IIB Flux Compactifications

φ doesn't necessarily contribute $\langle F_\varphi \rangle = 0$

Step Two

Stabilize Kähler moduli

Non-perturbative effects (Gaugino condensation / Instantons)

$$W = W_0 + A e^{ia\rho}$$

Restores SUSY!

Surprises from Type IIB Flux Compactifications

ρ doesn't necessarily contribute $\langle F_\rho \rangle = 0$

Tune:

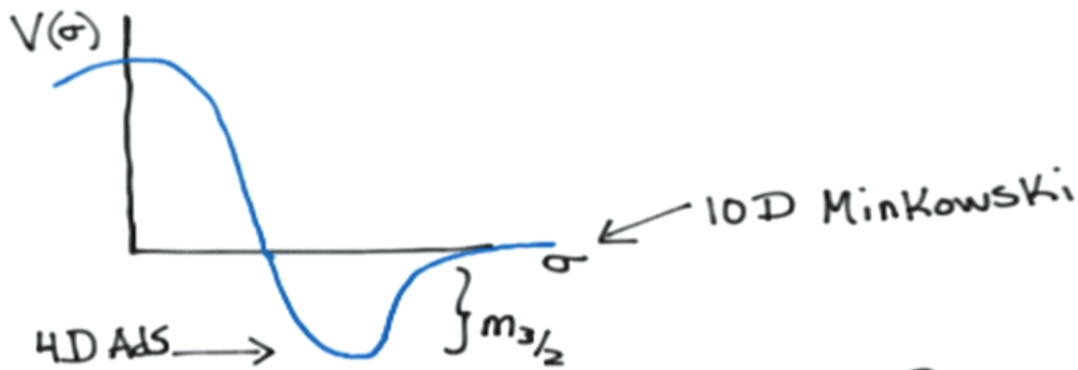
$$m_{3/2} = \frac{|W_0|}{m_P^2 V_6}$$

← $W_0 \ll 1$ KKLT

← $V_6 \gg 1$ Conlon Quevedo $V_6 \simeq 10^{14}$

$$\frac{m_{3/2}}{m_P} \ll 1$$

D=4 N=1 AdS



$\mathrm{Re}\,\rho \equiv \sigma$

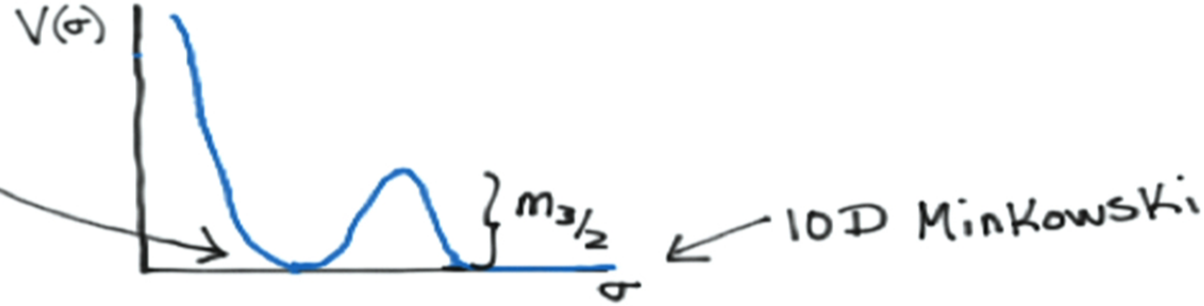
Surprises from Type IIB Flux Compactifications

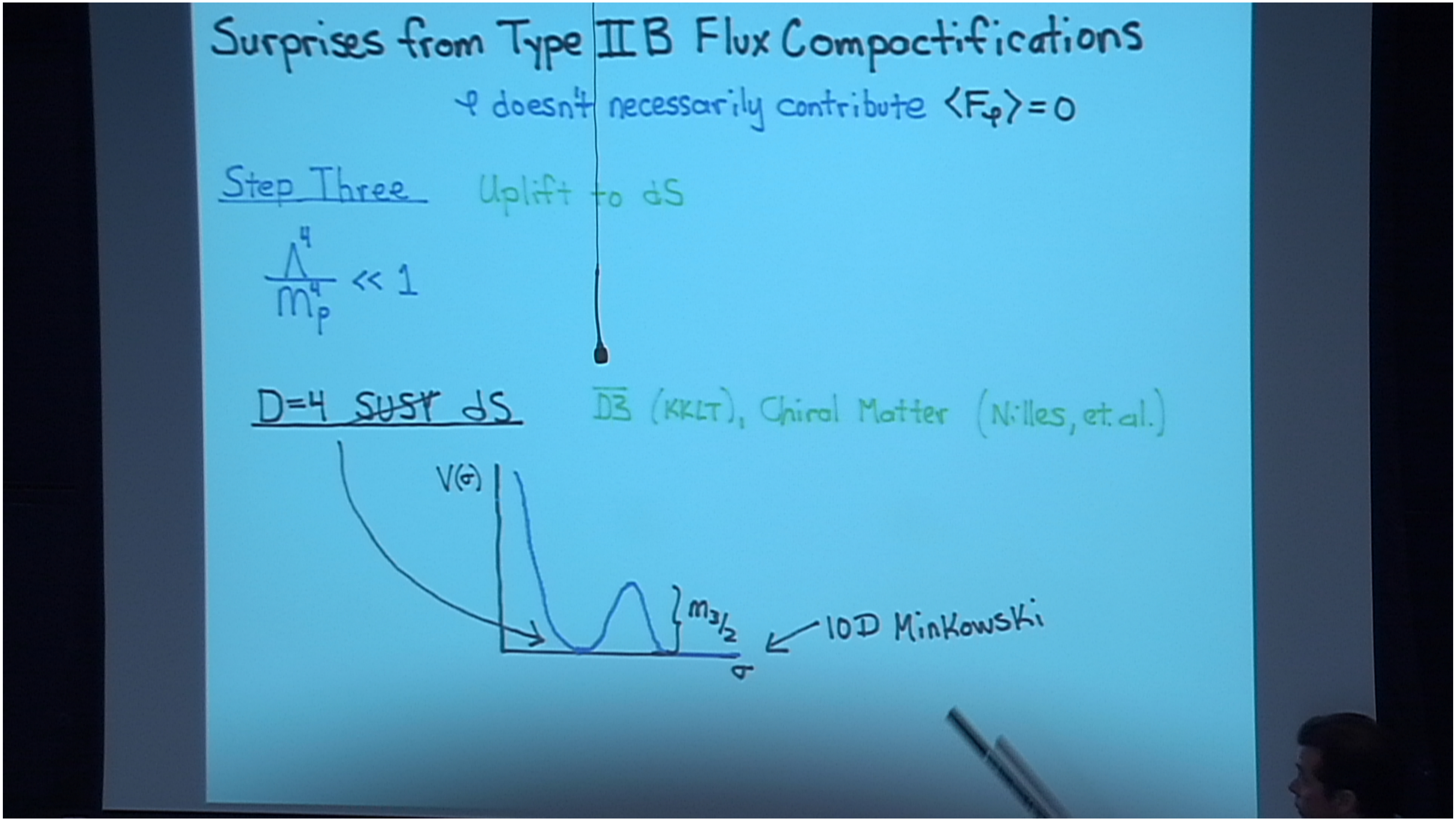
φ doesn't necessarily contribute $\langle F_\varphi \rangle = 0$

Step Three   Uplift to dS

$$\frac{\Lambda^4}{M_p^4} \ll 1$$

D=4 ~~SUSY~~ dS $\overline{D3}$ (KKLT), Chiral Matter (Nilles, et. al.)




Surprises from Type IIB Flux Compactifications
φ doesn't necessarily contribute ⟨F_φ⟩ = 0
Step Three
Uplift to dS
Λ^4 / M_p^4 << 1
D=4 SUSY dS
D3 (KKLT), Chiral Matter (Nilles, et. al.)
V(σ)
m_3/2
10D Minkowski
σ

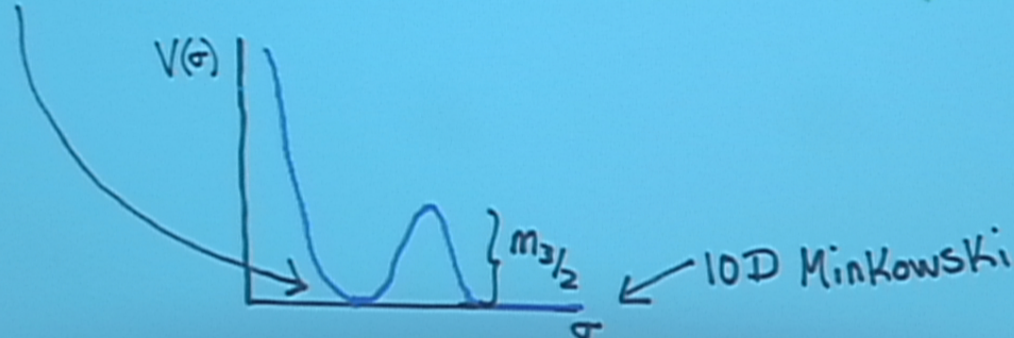
Surprises from Type IIB Flux Compactifications

φ doesn't necessarily contribute $\langle F_\varphi \rangle = 0$

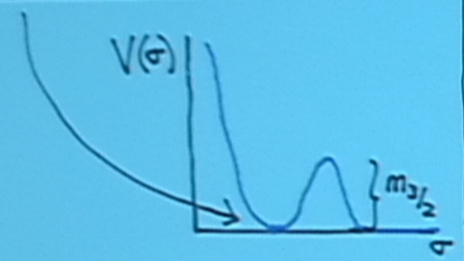
Step Three Uplift to dS

$$\frac{\Lambda^4}{M_p^4} \ll 1$$

D=4 ~~SUSY~~ dS $\overline{D3}$ (KKLT), Chiral Matter (Nilles, et. al.)



D=4 SUSY dS

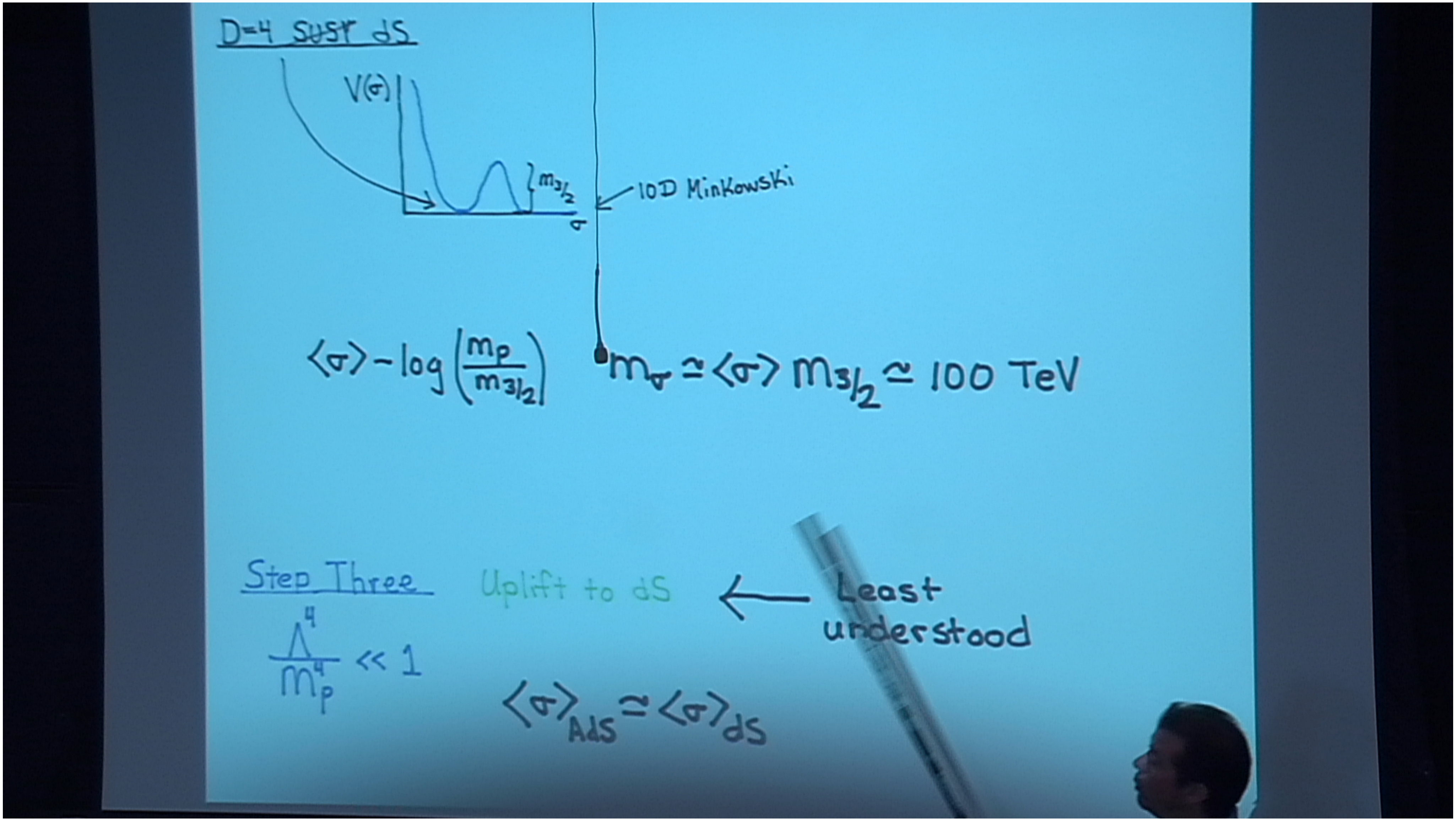


$\langle\sigma\rangle \sim \log\left(\frac{m_p}{m_{3/2}}\right)$ $m_\sigma \simeq \langle\sigma\rangle\, m_{3/2} \simeq 100$ TeV

Step Three Uplift to dS ⟵ Least understood

$\frac{\Lambda^4}{M_p^4} \ll 1$

$\langle\sigma\rangle_{AdS} \simeq \langle\sigma\rangle_{dS}$


D=4 SUSY dS
V(σ)
m3/2
10D Minkowski
σ
⟨σ⟩ ~ log (mp / m3/2)
mσ ≃ ⟨σ⟩ m3/2 ≃ 100 TeV
Step Three
Uplift to dS
Least understood
Λ^4 / Mp^4 << 1
⟨σ⟩AdS ≃ ⟨σ⟩dS

Note: We lost the nice result:

$$\Lambda^3 \simeq m_p^3 e^{-aX}$$

G2 manifolds → Geometric moduli stabilized w/out flux

$$W = 0 + m_p^3 \left(c_1 \phi^{-2/p} e^{ib_1 f} + c_2 e^{ib_2 f} \right)$$

Result: $m_X \simeq m_{3/2} \simeq 100\,\text{TeV}$

Note: We lost the nice result:

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Result: $m_X \simeq m_{3/2} \simeq 100$ TeV

Many more examples where hierarchies $\Longrightarrow \frac{m}{m_p} \ll 1$

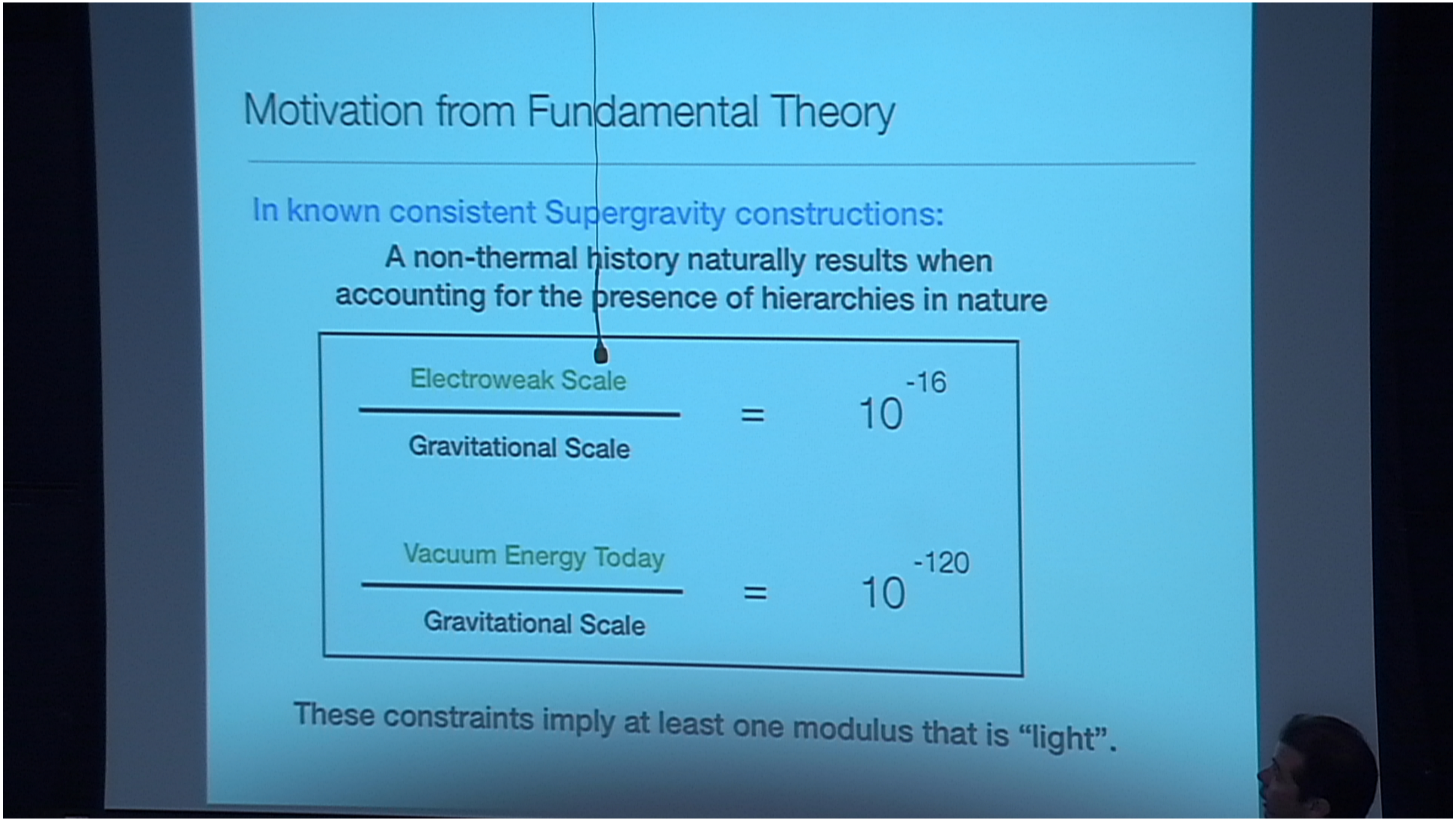
F-theory (Heckman, et.al. 0812.3155)

Warped Compactifications in general

Kachru, et.al. th/0601111

Adams, et.al. 1104.3155

$m \simeq |W_0| \simeq m_{3/2}$


Motivation from Fundamental Theory
In known consistent Supergravity constructions:
A non-thermal history naturally results when accounting for the presence of hierarchies in nature
Electroweak Scale
Gravitational Scale
= 10^-16
Vacuum Energy Today
Gravitational Scale
= 10^-120
These constraints imply at least one modulus that is "light".

Non-thermal History from Microscopic Theory

(1) New symmetries beyond Std. Model

(2) Stable particle charged under the symmetry (i.e. Dark Matter X)

(3) Unstable particle φ which is:

- (a) gravitationally coupled $\Gamma = c \frac{m_\varphi^3}{m_p^2}$
- (b) Mass generated at Sym $m_\varphi = c_2 m_{3/2}$

(4) Hierarchies:

$$\frac{m_{3/2}}{m_p} \ll 1 \qquad \frac{\Lambda^4}{m_p^4} \ll 1$$

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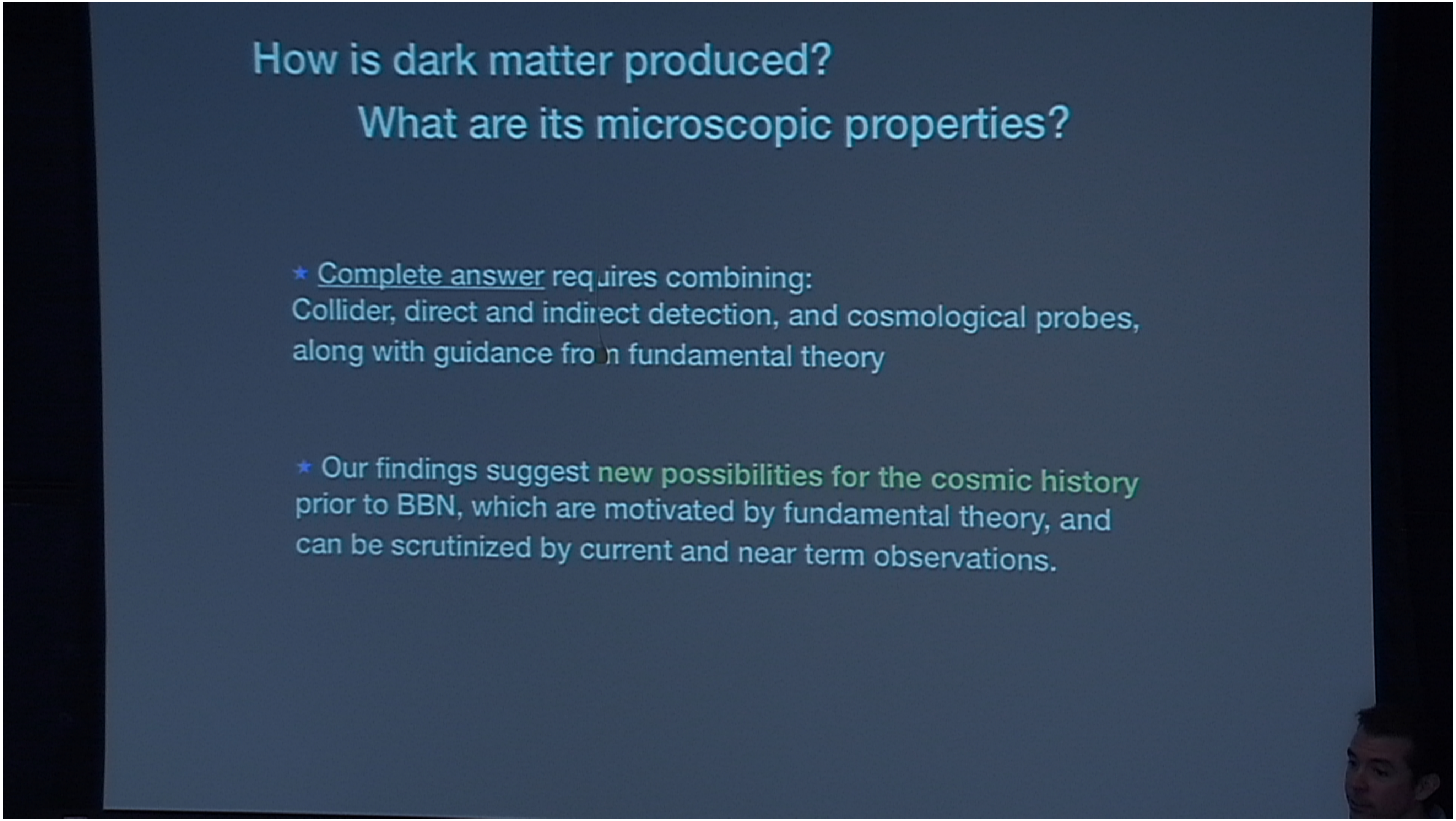
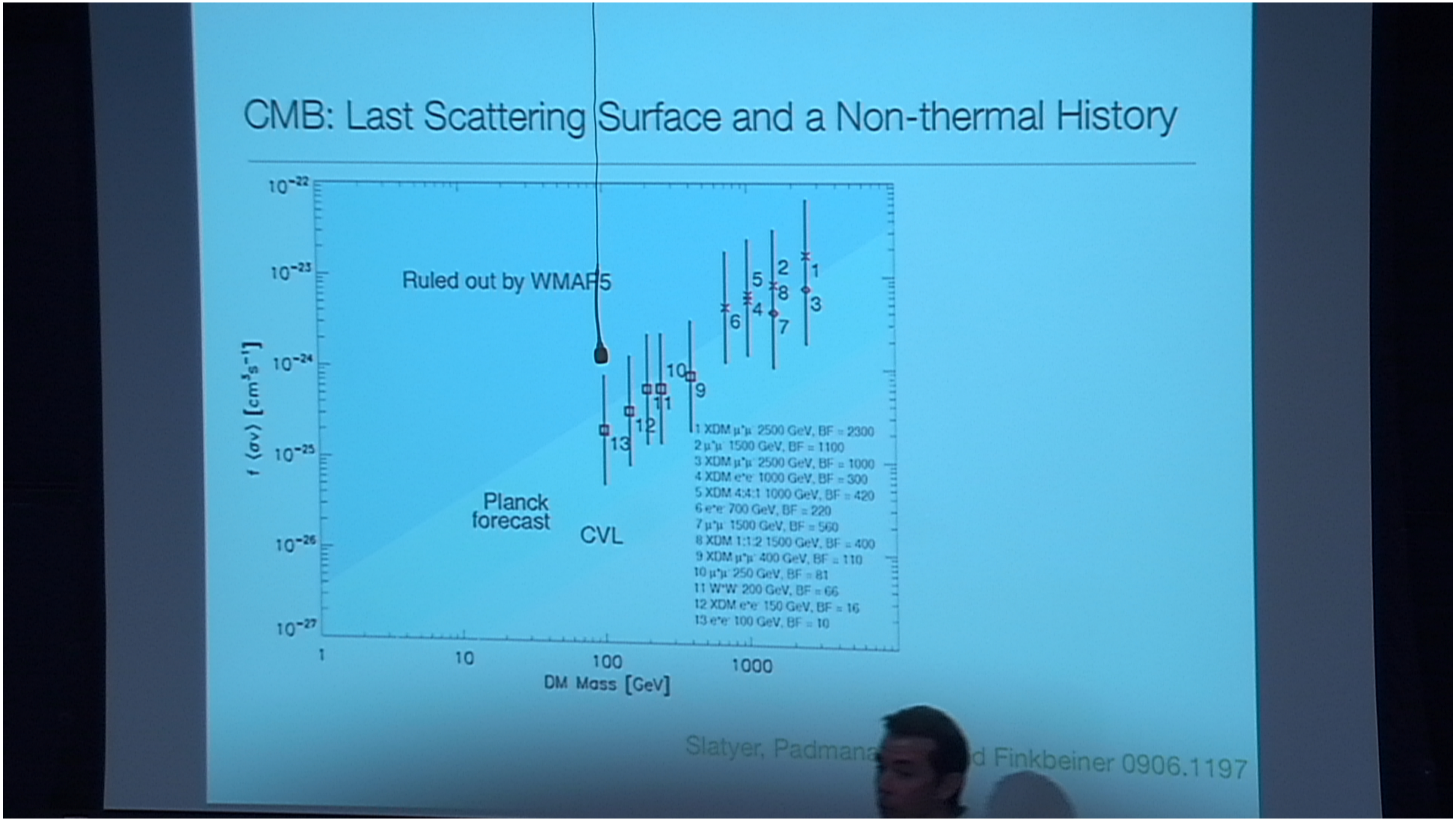

How is dark matter produced?
What are its microscopic properties?
★ Complete answer requires combining:
Collider, direct and indirect detection, and cosmological probes,
along with guidance from fundamental theory
★ Our findings suggest new possibilities for the cosmic history
prior to BBN, which are motivated by fundamental theory, and
can be scrutinized by current and near term observations.


CMB: Last Scattering Surface and a Non-thermal History
Ruled out by WMAP5
Planck forecast
CVL
f ⟨σv⟩ [cm³s⁻¹]
DM Mass [GeV]
1 XDM μ⁺μ⁻ 2500 GeV, BF = 2300
2 μ⁺μ⁻ 1500 GeV, BF = 1100
3 XDM μ⁺μ⁻ 2500 GeV, BF = 1000
4 XDM e⁺e⁻ 1000 GeV, BF = 300
5 XDM 4:4:1 1000 GeV, BF = 420
6 e⁺e⁻ 700 GeV, BF = 220
7 μ⁺μ⁻ 1500 GeV, BF = 560
8 XDM 1:1:2 1500 GeV, BF = 400
9 XDM μ⁺μ⁻ 400 GeV, BF = 110
10 μ⁺μ⁻ 250 GeV, BF = 81
11 W⁺W⁻ 200 GeV, BF = 66
12 XDM e⁺e⁻ 150 GeV, BF = 16
13 e⁺e⁻ 100 GeV, BF = 10
Finkbeiner 0906.1197