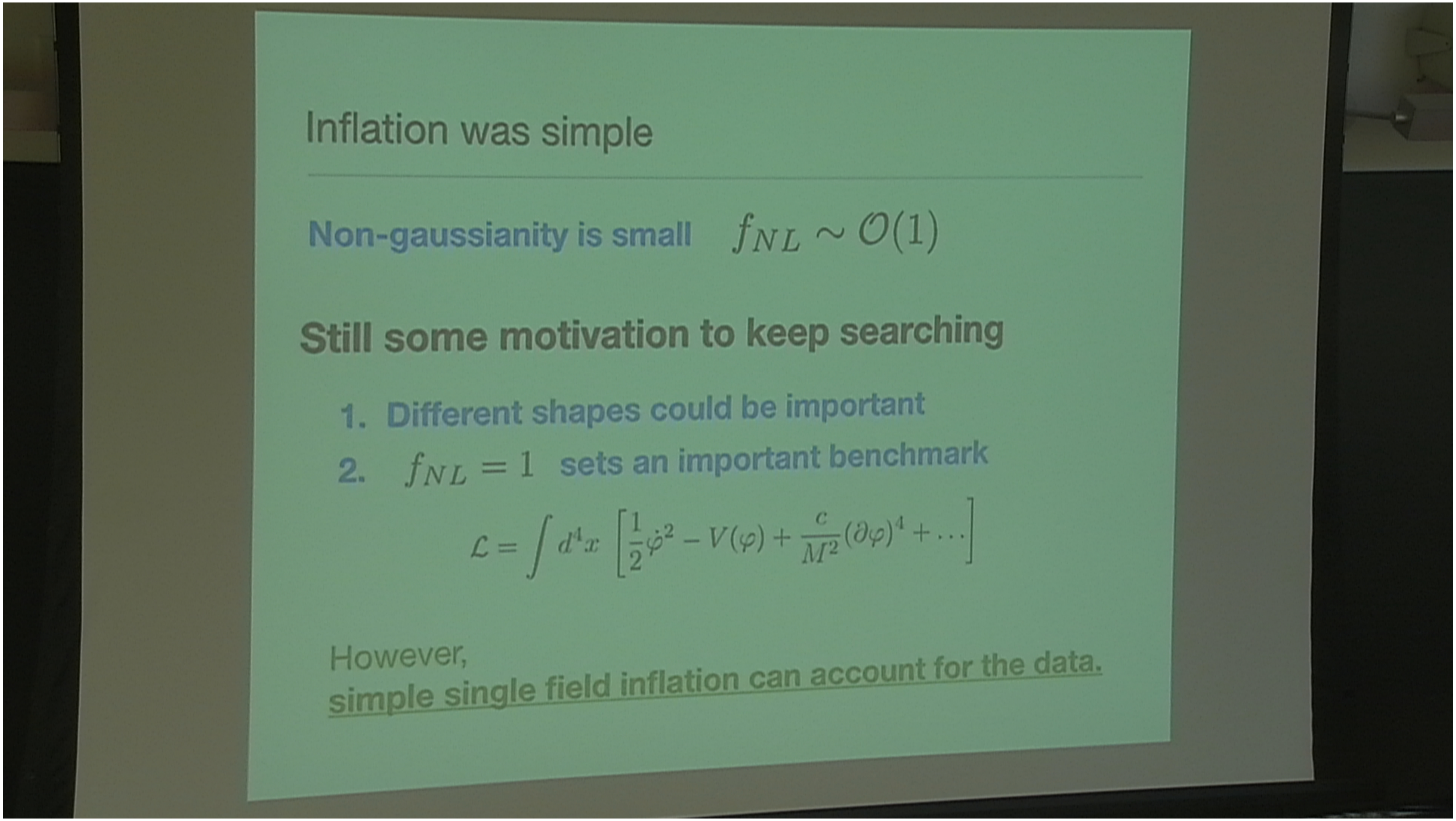
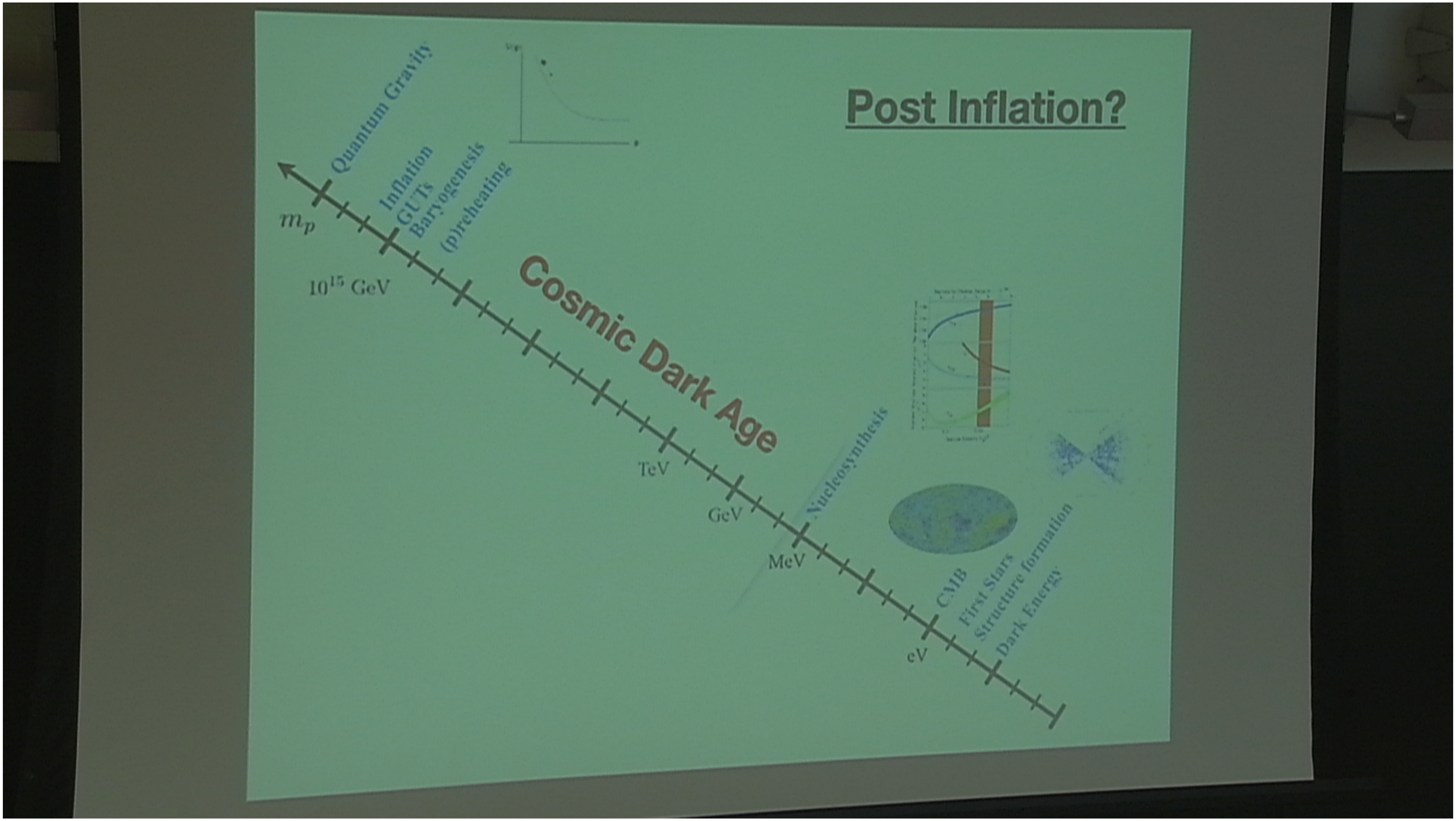
Title: Supersymmetry, Non-thermal Dark Matter and Precision Cosmology

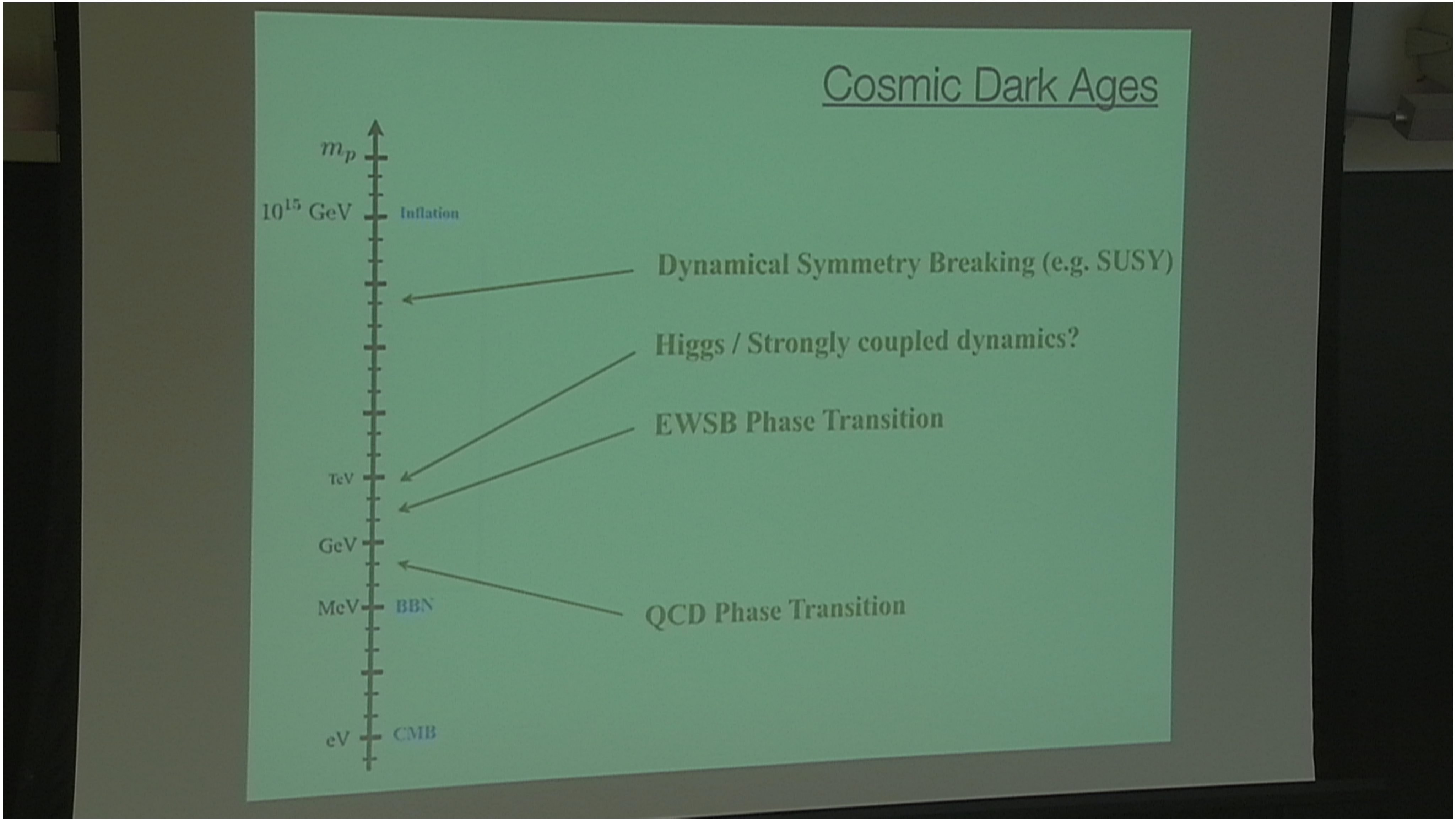
Date: Dec 05, 2013 11:00 AM

URL: http://pirsa.org/13120054

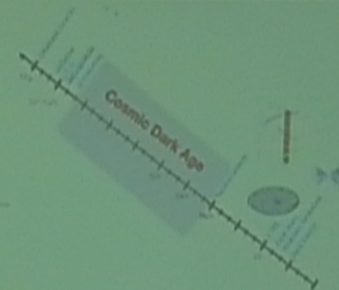
Abstract: Within the Minimal Supersymmetric Standard Model (MSSM), LHC bounds suggest that scalar superpartner masses are far above the electroweak scale. Given a high superpartner mass, nonthermal dark matter is a viable alternative to WIMP dark matter generated via freezeout. In the presence of moduli fields nonthermal dark matter production is associated with a long matter dominated phase, modifying the spectral index and primordial tensor amplitude relative to those in a thermalized primordial universe. Nonthermal dark matter can have a higher self-interaction cross-section than its thermal counterpart, enhancing astrophysical bounds on its annihilation signals. I will review recent progress in this program, and discuss how we can constrain the contributions to the neutralino mass from the bino, wino and higgsino using existing astrophysical bounds and direct detection experiments for models with nonthermal neutralino dark matter. Using these constraints we will then see how expected changes to inflationary observables result from the nonthermal phase.


Inflation was simple
Non-gaussianity is small $f_{NL} \sim \mathcal{O}(1)$
Still some motivation to keep searching
1. Different shapes could be important
2. $f_{NL} = 1$ sets an important benchmark
$\mathcal{L} = \int d^4x \left[\frac{1}{2}\dot{\varphi}^2 - V(\varphi) + \frac{c}{M^2}(\partial\varphi)^4 + \dots\right]$
However,
simple single field inflation can account for the data.


Post Inflation?
Quantum Gravity
Inflation
GUTs
Baryogenesis
(p)reheating
m_p
10^{15} GeV
Cosmic Dark Age
TeV
GeV
MeV
Nucleosynthesis
eV
CMB
First Stars
Structure formation
Dark Energy


Cosmic Dark Ages
m_p
10^{15} GeV
Inflation
Dynamical Symmetry Breaking (e.g. SUSY)
Higgs / Strongly coupled dynamics?
EWSB Phase Transition
TeV
GeV
MeV
BBN
QCD Phase Transition
eV
CMB

Two questions to get us started:

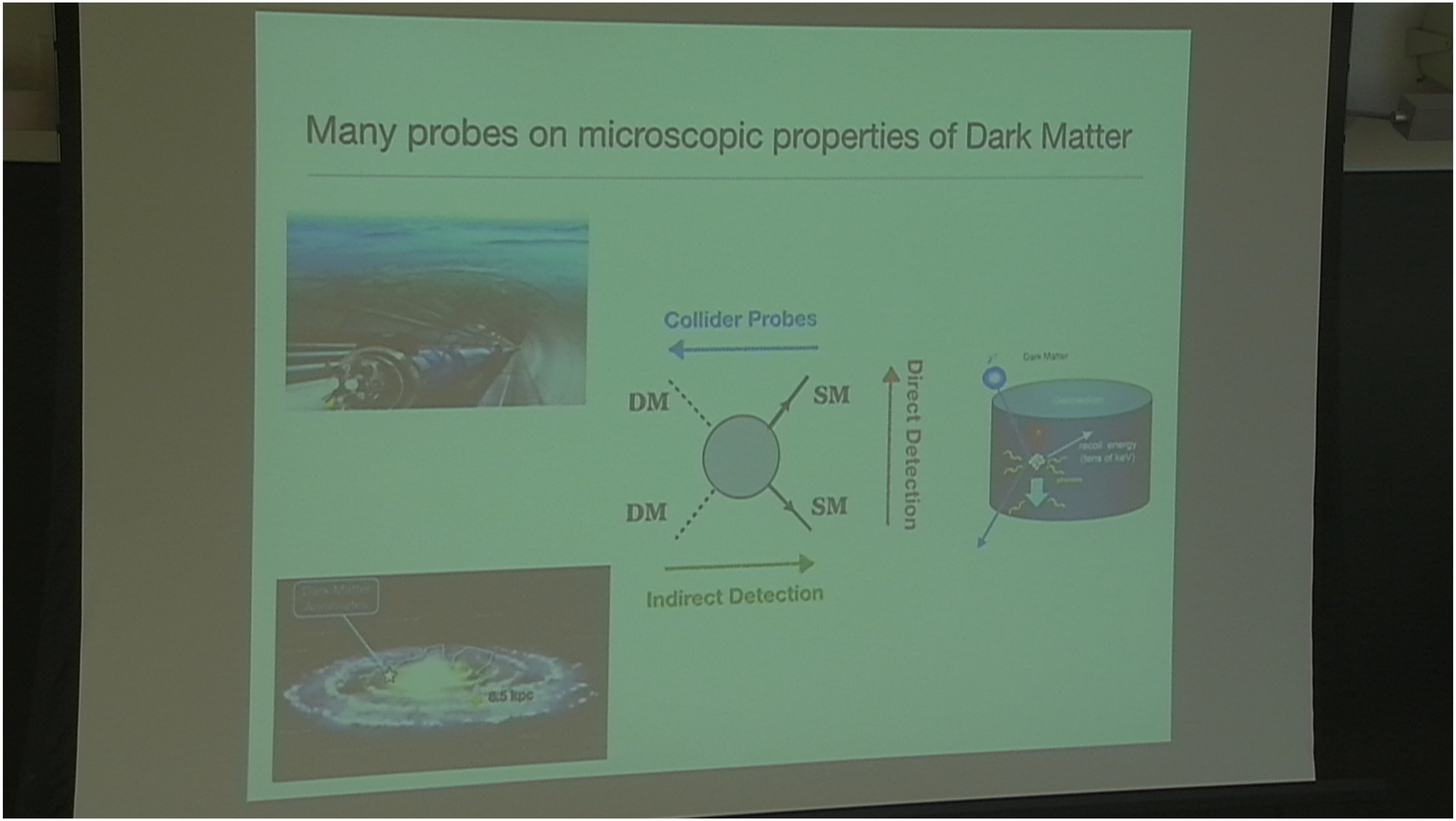


#1

How do changes in the post-inflationary history alter constraints on inflationary model building?

#2

How do changes in the cosmic history effect the expected properties of dark matter?


Many probes on microscopic properties of Dark Matter
Collider Probes
DM
SM
DM
SM
Direct Detection
Indirect Detection
Dark Matter
recoil energy
(tens of keV)
8.5 kpc

For clarity:

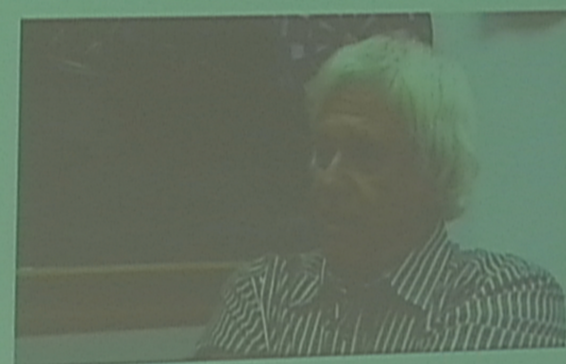
In the rest of the talk I will assume we live in a world with Supersymmetry

However!

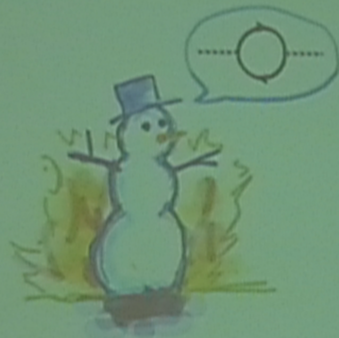
This need not be the case

(The main points will not rely on the existence of SUSY).

(happy to elaborate afterwards)



Friend, collaborator, and
SUSY enthusiast: Gordy Kane

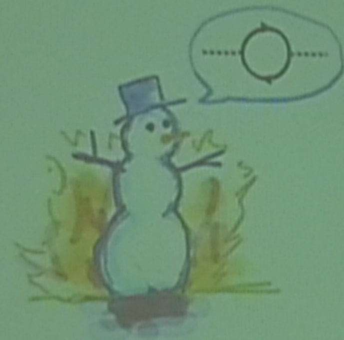


Assumption: Supersymmetry
I.e., we need to address the (big) hierarchy problem, dark mater, gauge coupling unification, Coleman–Mandula, …

Caveat: We may not need physics beyond the Standard Model?

No hierarchy problem if no new mass scale.

And SUSY doesn’t seem to help with Cosmological Constant.



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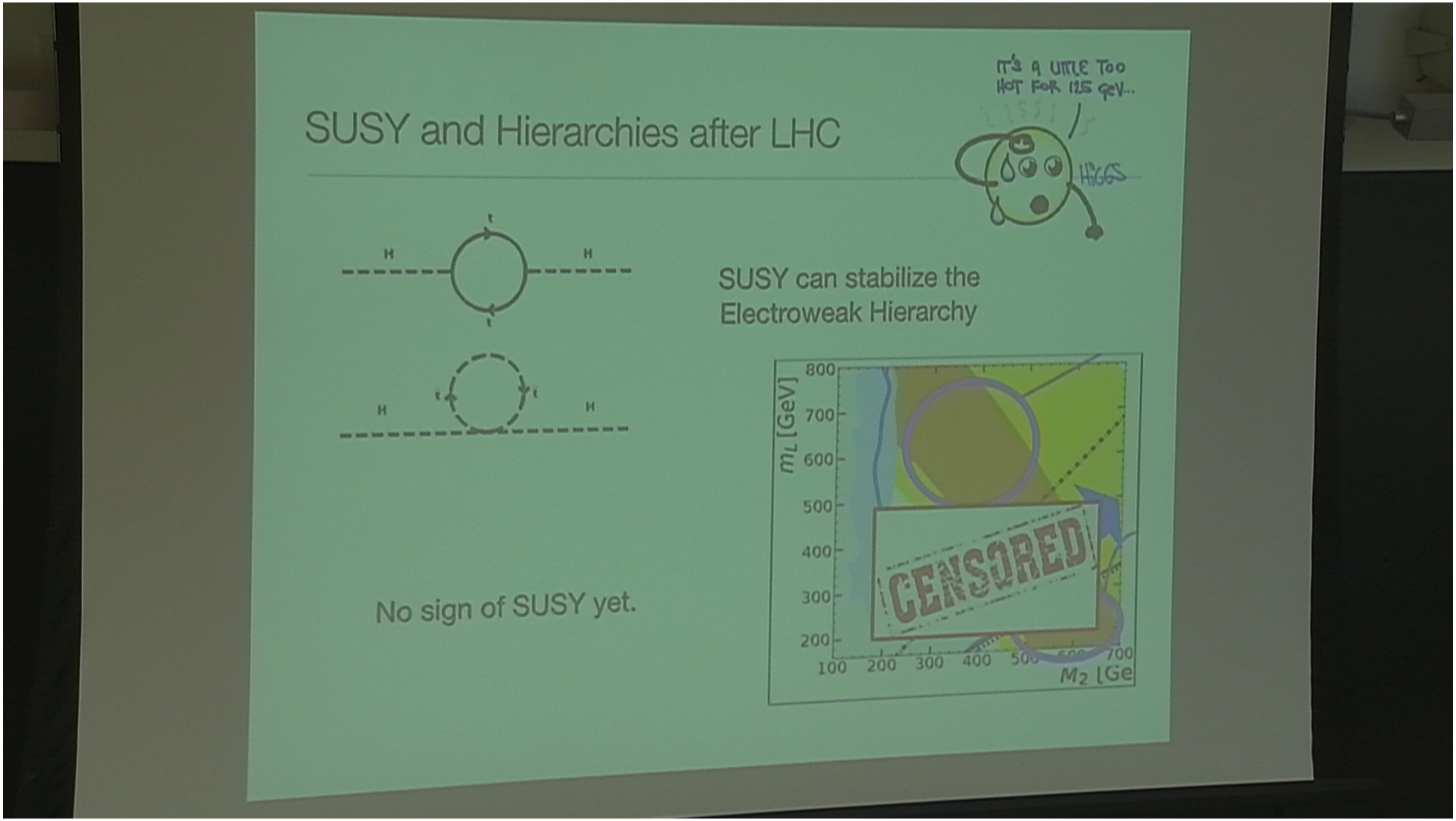
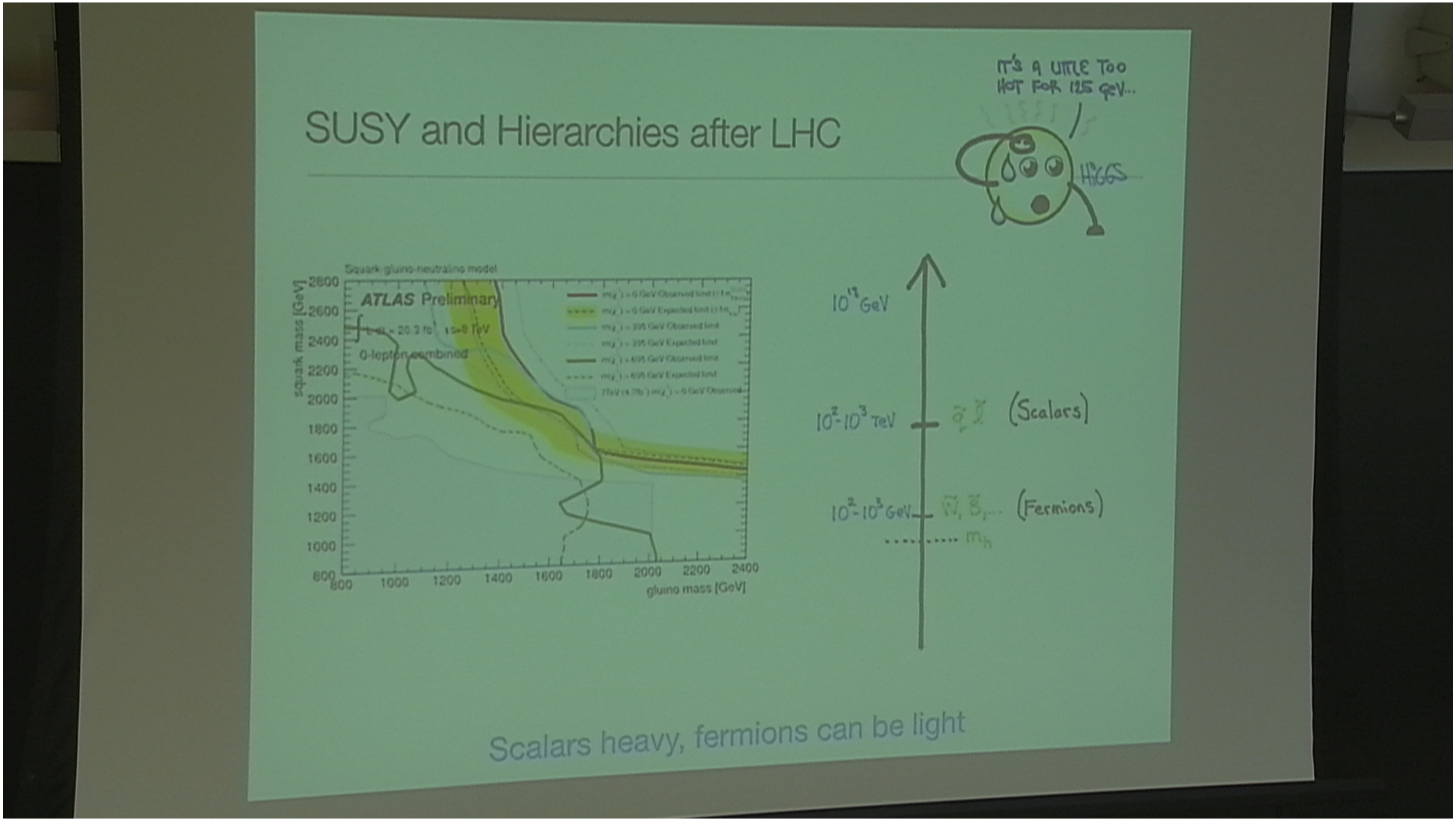
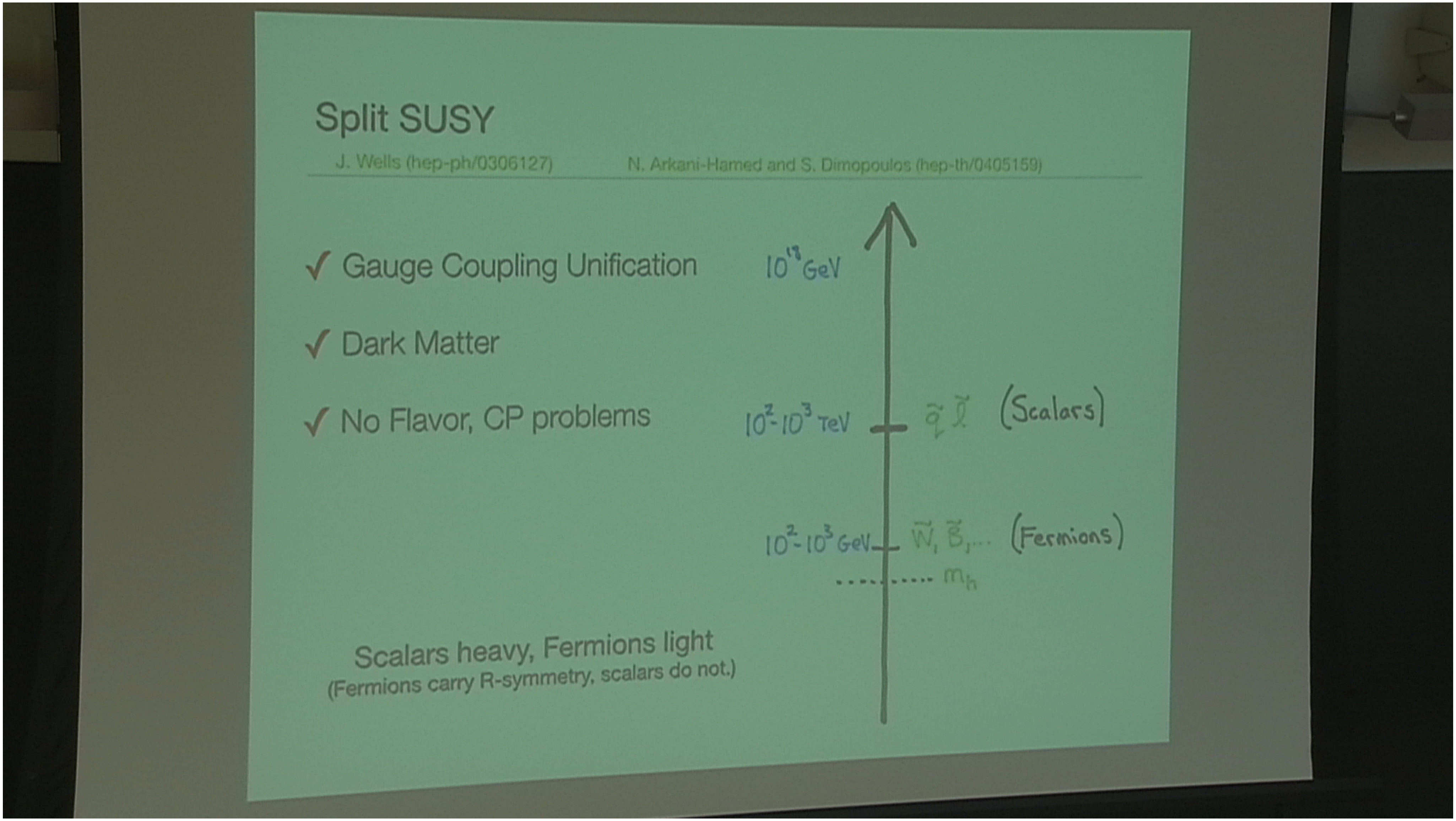

SUSY and Hierarchies after LHC
IT'S A LITTLE TOO HOT FOR 125 GeV...
HIGGS
H
t
SUSY can stabilize the Electroweak Hierarchy
No sign of SUSY yet.
m_L [GeV]
800
700
600
500
400
300
200
100
200
300
400
500
700
CENSORED


SUSY and Hierarchies after LHC
IT'S A LITTLE TOO HOT FOR 125 GeV...
HIGGS
Squark-gluino-neutralino model
ATLAS Preliminary
0-lepton combined
squark mass [GeV]
gluino mass [GeV]
10^17 GeV
10^2-10^3 TeV
(Scalars)
10^2-10^3 GeV
(Fermions)
Scalars heavy, fermions can be light


Split SUSY
J. Wells (hep-ph/0306127)
N. Arkani-Hamed and S. Dimopoulos (hep-th/0405159)
✓ Gauge Coupling Unification
✓ Dark Matter
✓ No Flavor, CP problems
10^{18} GeV
10^2-10^3 TeV
$\tilde{q}$ $\tilde{l}$
(Scalars)
10^2-10^3 GeV
$\tilde{W}$, $\tilde{B}$,...
(Fermions)
m_h
Scalars heavy, Fermions light
(Fermions carry R-symmetry, scalars do not.)

Another possibility

Perhaps nature allows for some tuning (1/1000)?

Advantage: Addresses a potential cosmological problem

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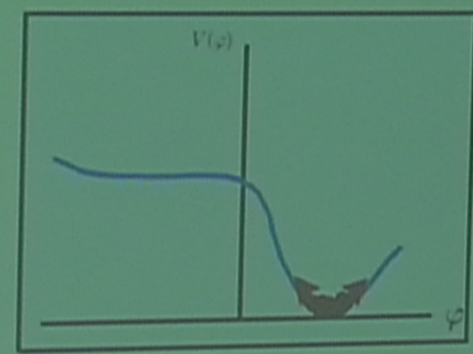
The Cosmological Moduli Problem



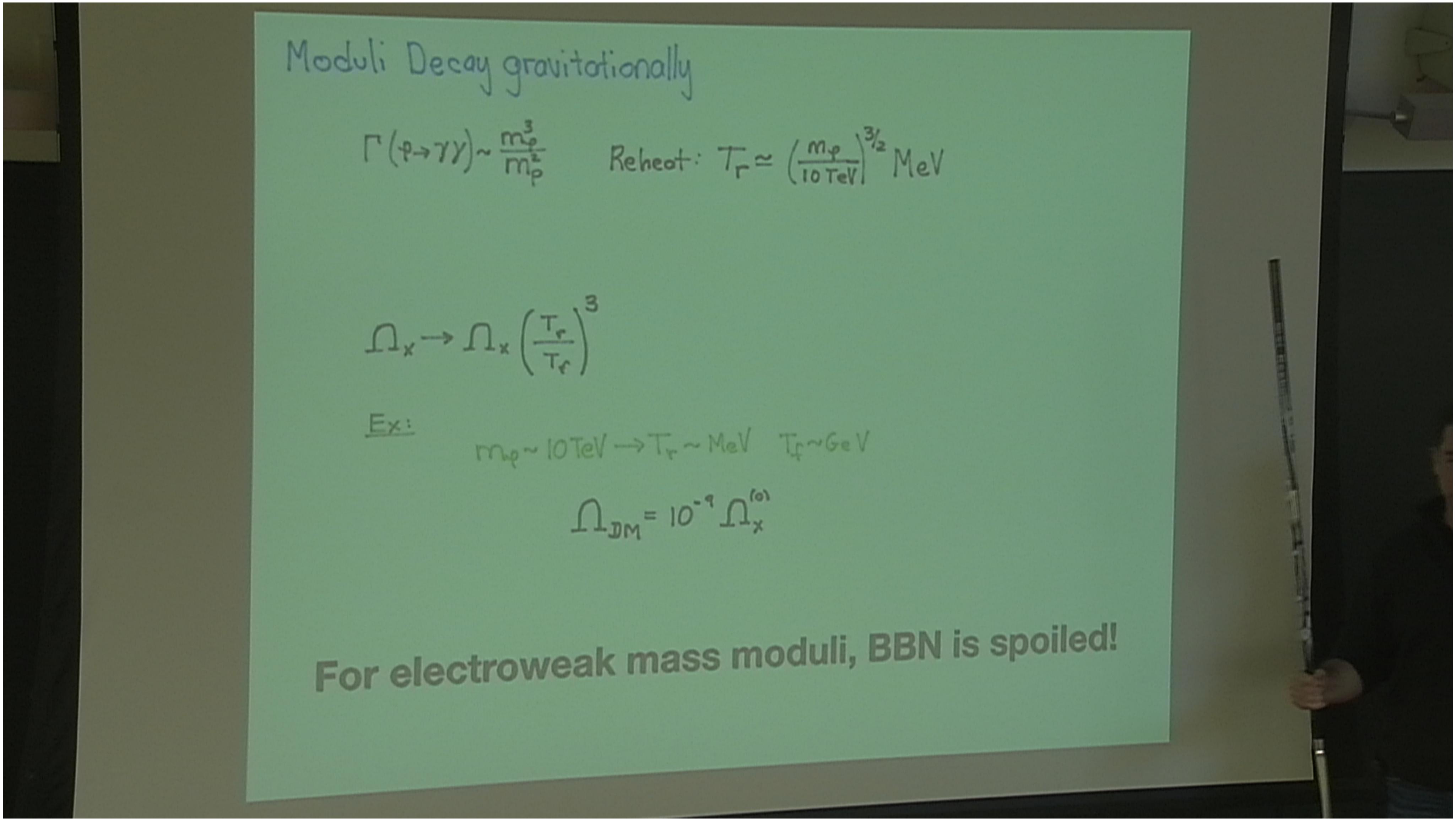
Moduli generically displaced.

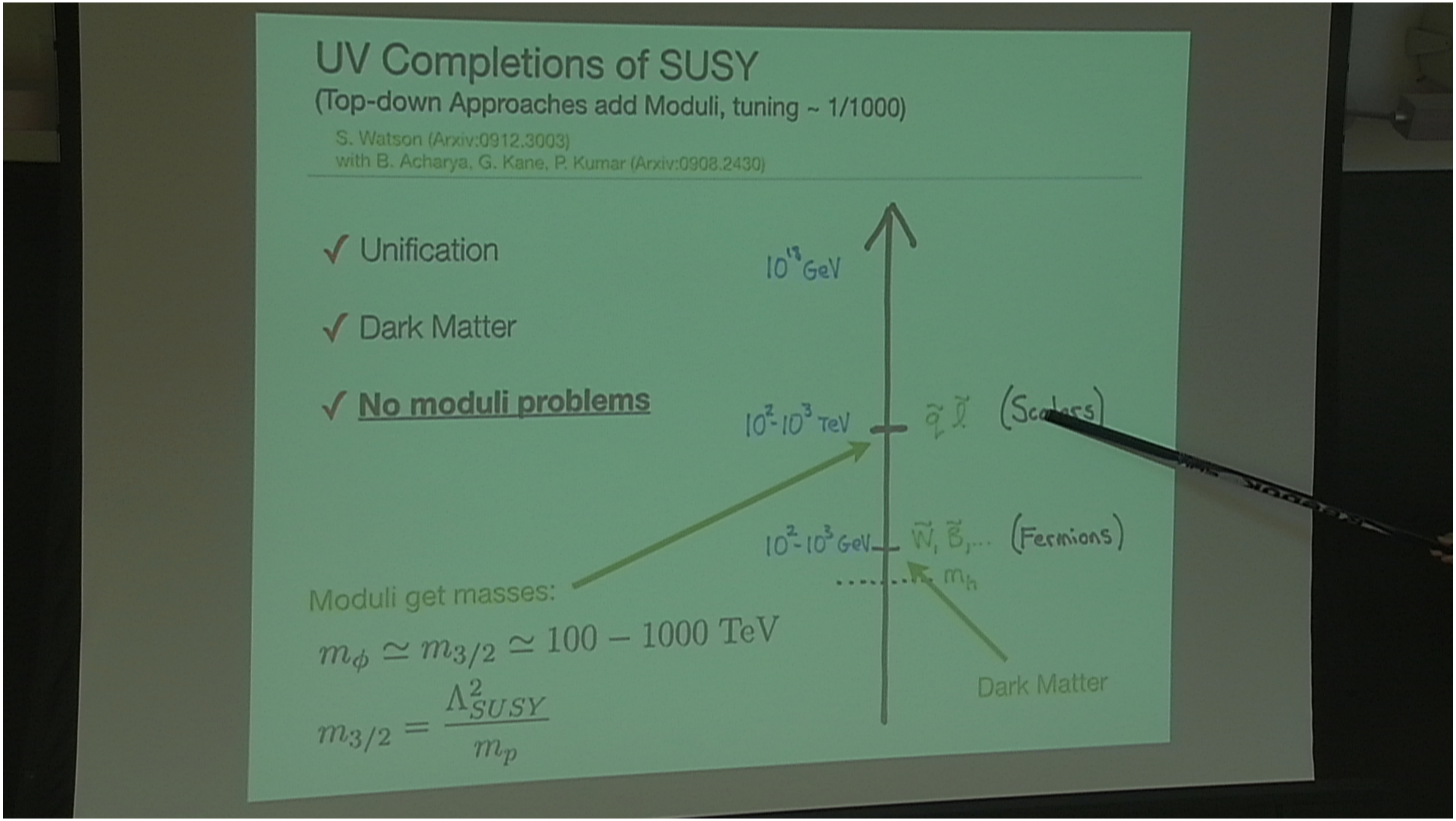
Energy stored in condensate.

Oscillations when $H \simeq m_{SOFT}$ with amplitude $\Delta\varphi$

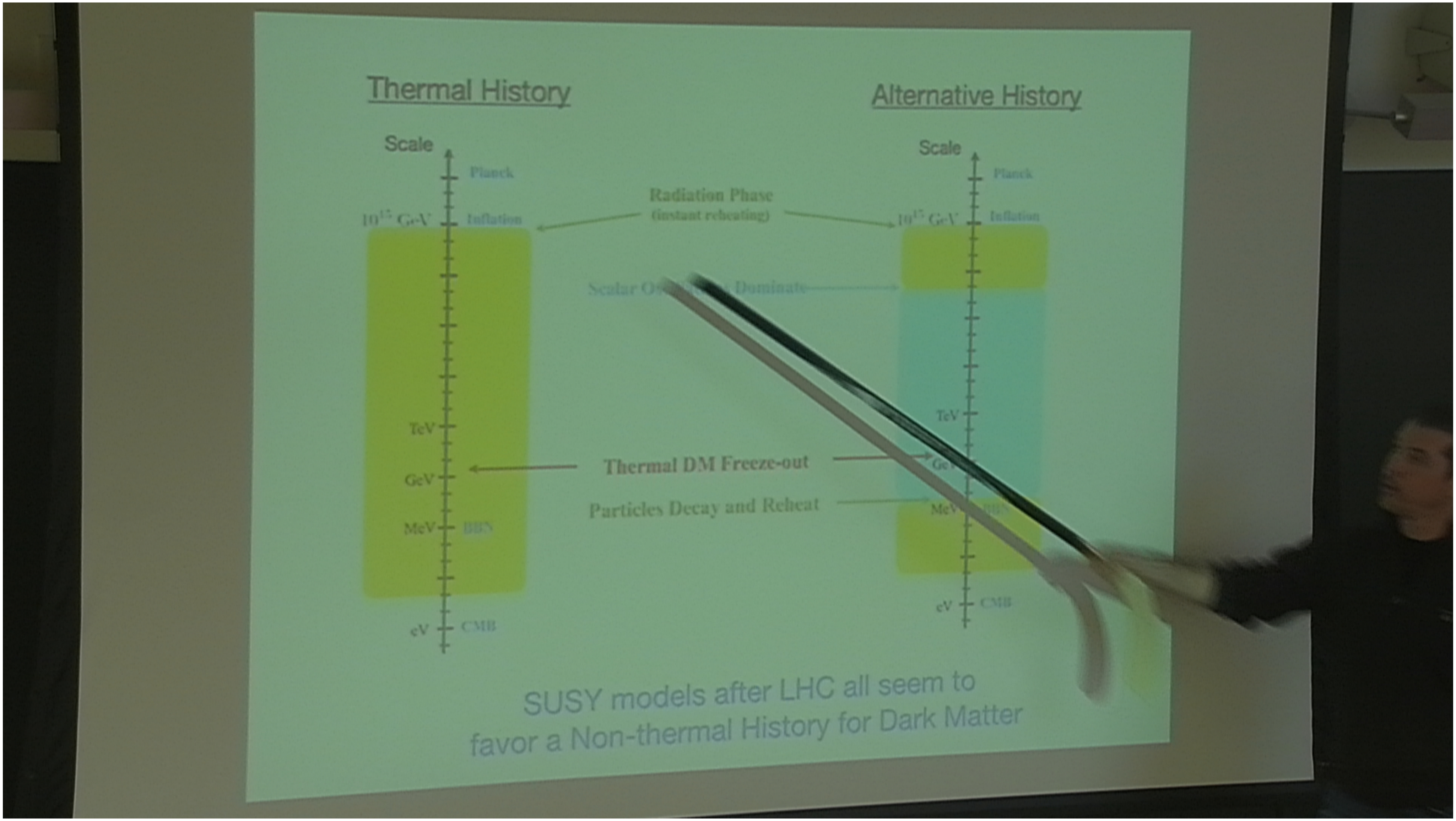
Scalar condensate $\rho_\varphi = \frac{1}{a^3}$ $P_\varphi = 0$

$\rho_\varphi / \rho_r \sim a(t)$ Danger for BBN


Moduli Decay gravitationally
$\Gamma(\varphi \to \gamma\gamma) \sim \frac{m_\varphi^3}{m_p^2}$
Reheat: $T_r \simeq \left(\frac{m_\varphi}{10\,\mathrm{TeV}}\right)^{3/2}$ MeV
$\Omega_x \to \Omega_x \left(\frac{T_r}{T_f}\right)^3$
Ex:
$m_\varphi \sim 10$ TeV $\to T_r \sim$ MeV $T_f \sim$ GeV
$\Omega_{DM} = 10^{-9}\,\Omega_x^{(0)}$
For electroweak mass moduli, BBN is spoiled!


UV Completions of SUSY
(Top-down Approaches add Moduli, tuning ~ 1/1000)
S. Watson (Arxiv:0912.3003)
with B. Acharya, G. Kane, P. Kumar (Arxiv:0908.2430)
✓ Unification
✓ Dark Matter
✓ No moduli problems
Moduli get masses:
$m_\phi \simeq m_{3/2} \simeq 100 - 1000 \text{ TeV}$
$m_{3/2} = \frac{\Lambda^2_{SUSY}}{m_p}$
10^{18} GeV
10^2-10^3 TeV
$\tilde{q}$ $\tilde{l}$
(Scalars)
10^2-10^3 GeV
$\tilde{W}$, $\tilde{B}$,...
(Fermions)
m_h
Dark Matter

SUSY after LHC data suggests spectrum with
heavy scalars and **light dark matter**


Thermal History
Alternative History
Scale
Planck
10^{15} GeV
Inflation
Radiation Phase
(instant reheating)
TeV
GeV
MeV
BBN
eV
CMB
Thermal DM Freeze-out
Particles Decay and Reheat
SUSY models after LHC all seem to
favor a Non-thermal History for Dark Matter

Planck Bayesian Analysis for post-inflation model selection

Model	Instant Reheating		History 1		History 2	
	$\ln[\mathcal{E}/\mathcal{E}_0]$	$\Delta\chi^2_{\rm eff}$	$\ln[\mathcal{E}/\mathcal{E}_0]$	$\Delta\chi^2_{\rm eff}$	$\ln[\mathcal{E}/\mathcal{E}_0]$	$\Delta\chi^2_{\rm eff}$
$n = 4$	−14.9	25.9	−18.8	27.2	−13.2	17.4
$n = 2$	−4.7	5.4	−7.3	6.3	−6.2	5.0
$n = 1$	−4.1	3.3	−5.4	2.8	−4.9	2.1
$n = 2/3$	−4.7	5.1	−5.2	3.1	−5.2	2.3
Natural	−6.6	5.2	−8.9	5.5	−8.2	5.0
Hilltop	−7.1	6.1	−9.1	7.1	−6.6	2.4
ΛCDM	−4940.7	9808.4	...	...	...	...

History 1 (Blue)

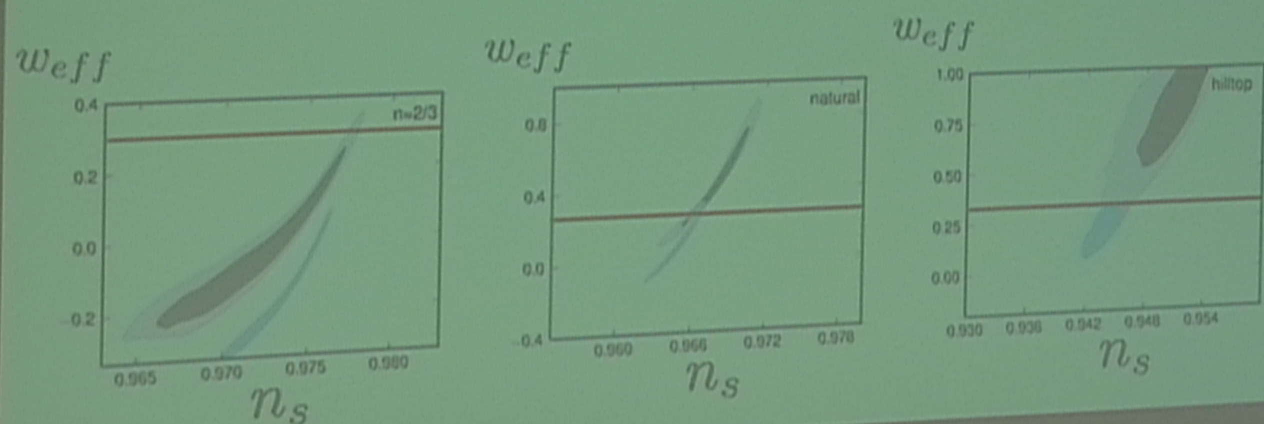
$$T_r = 10^8 \text{ GeV}$$

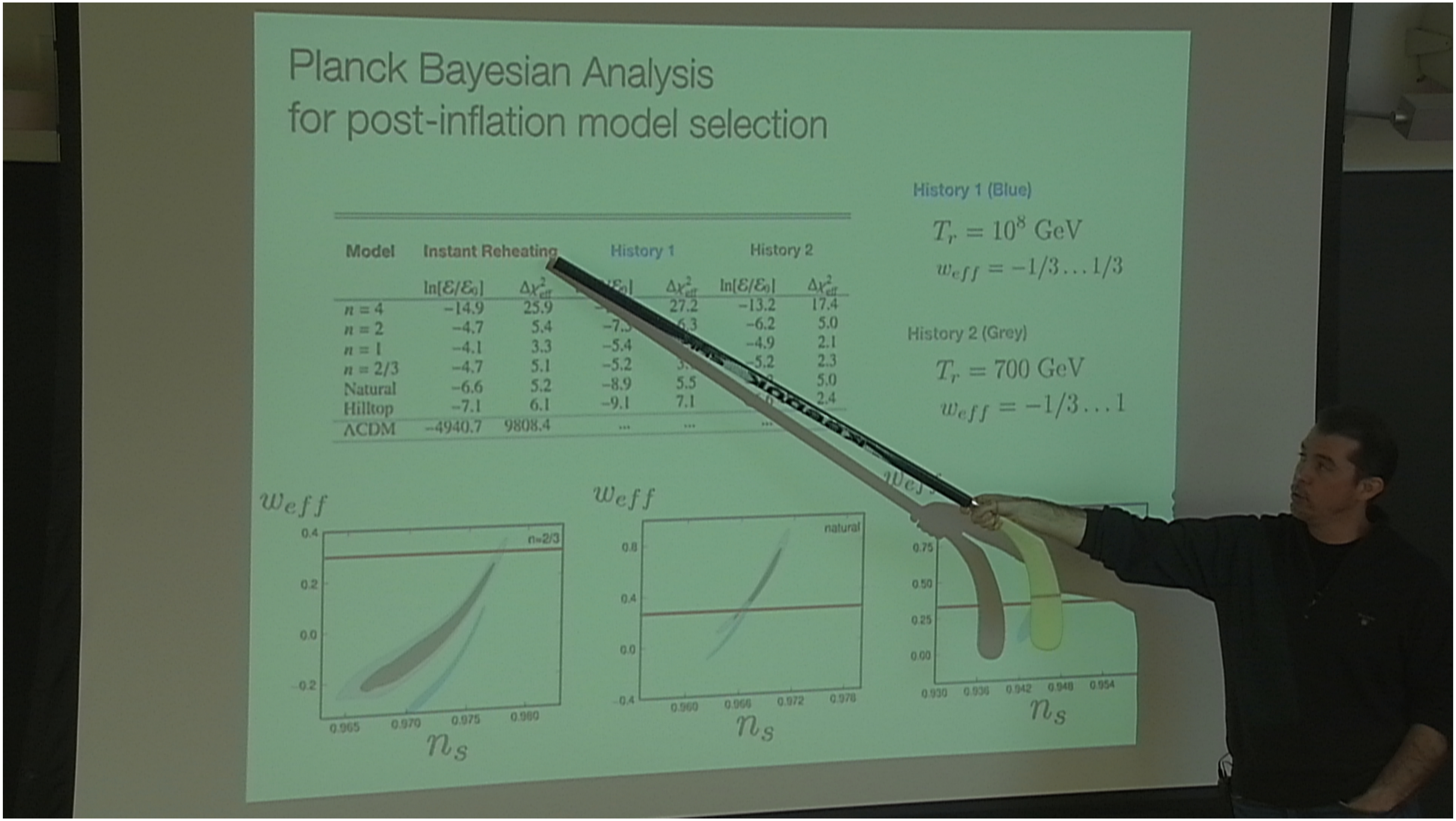
$$w_{eff} = -1/3 \ldots 1/3$$

History 2 (Grey)

$$T_r = 700 \text{ GeV}$$

$$w_{eff} = -1/3 \ldots 1$$




Planck Bayesian Analysis
for post-inflation model selection
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Model
Instant Reheating
History 1
History 2
$\ln[\mathcal{E}/\mathcal{E}_0]$
$\Delta\chi^2_{eff}$
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$n = 2$ −4.7 5.4 −6.2 5.0
$n = 1$ −4.1 3.3 −5.4 −4.9 2.1
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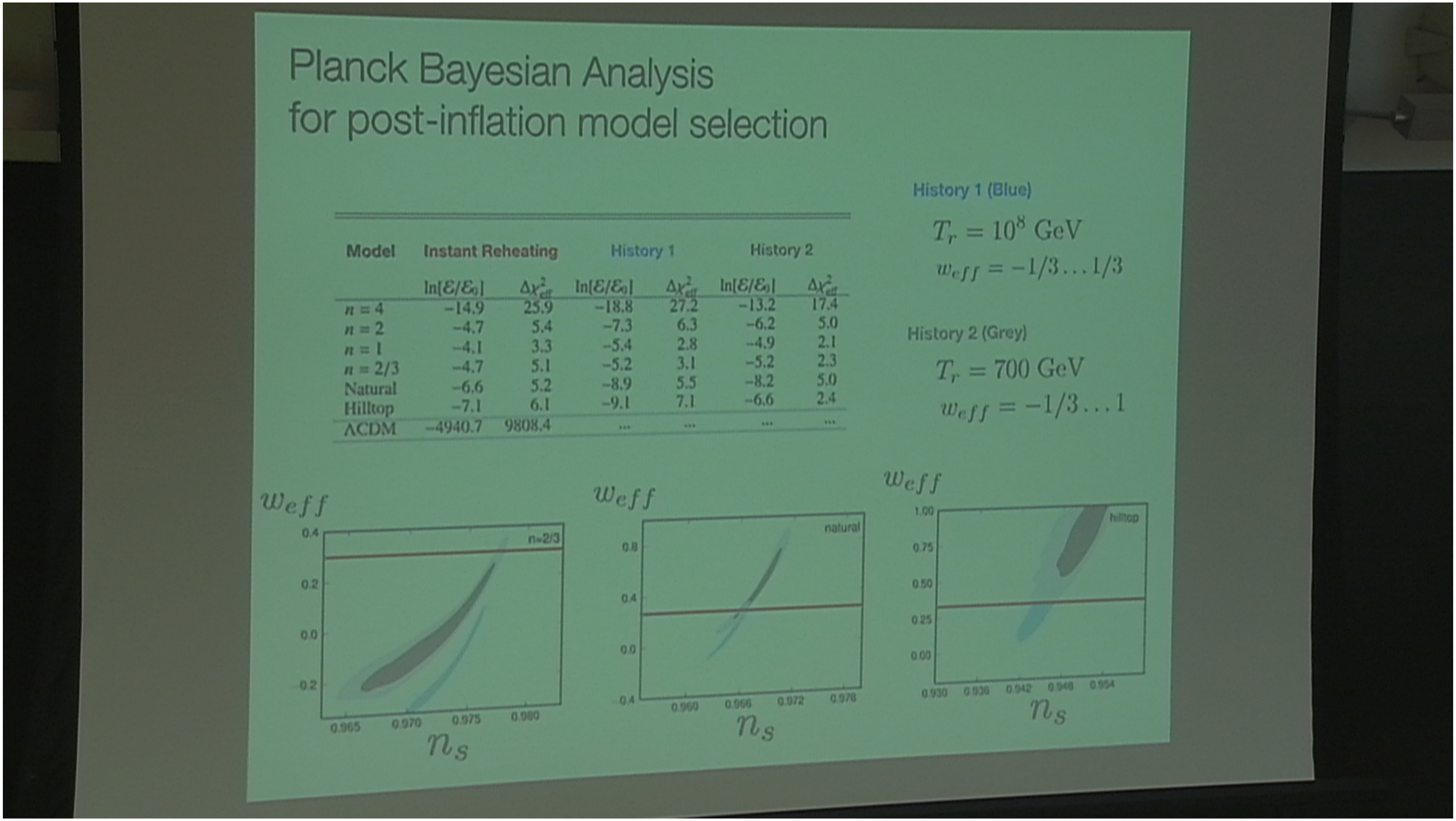
Natural −6.6 5.2 −8.9 5.5 5.0
Hilltop −7.1 6.1 −9.1 7.1 2.4
ΛCDM −4940.7 9808.4 ... ...
w_{eff}
n_s
n=2/3
natural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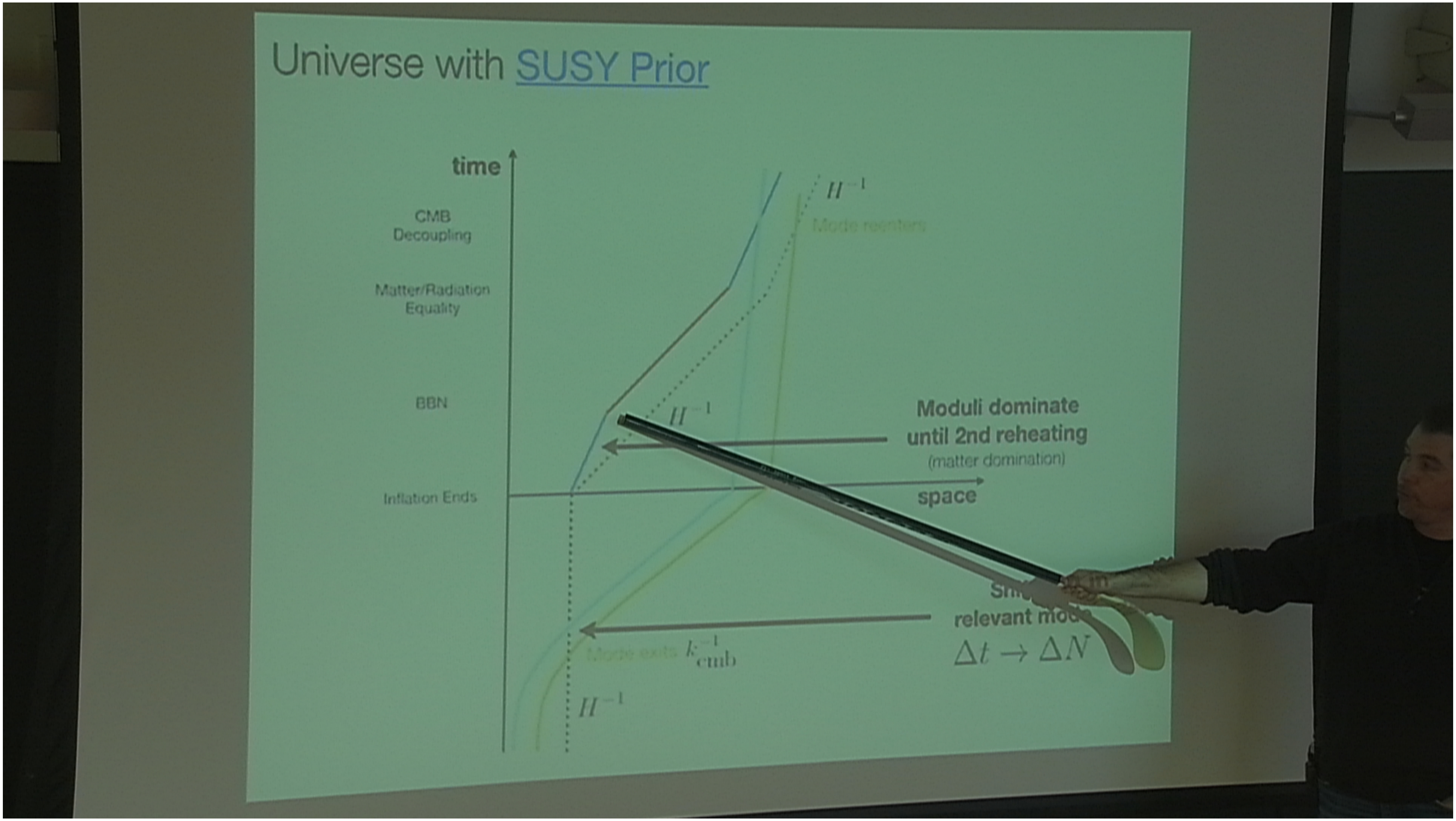
w_{eff}
n=2/3
n_s
w_{eff}
natural
n_s
w_{eff}
hilltop
n_s

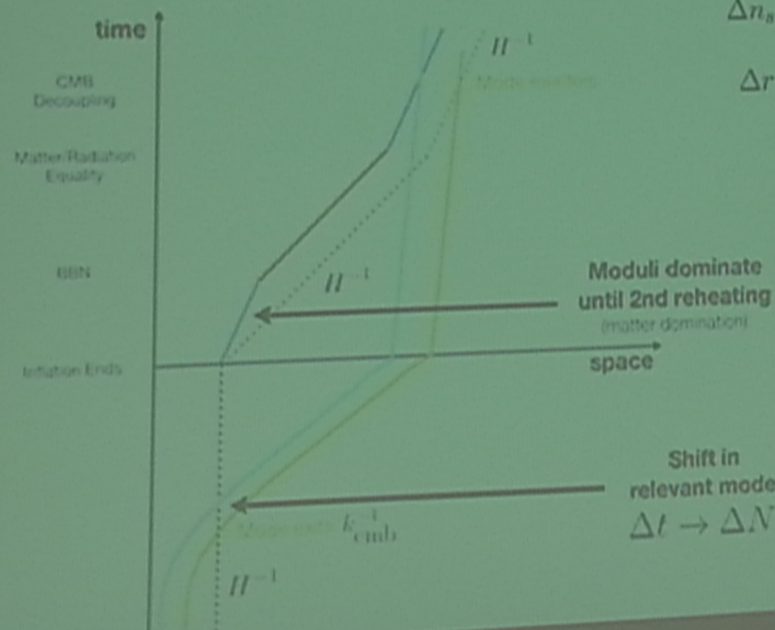

Universe with SUSY Prior
time
CMB
Decoupling
Matter/Radiation
Equality
BBN
Inflation Ends
H^{-1}
Mode reenters
H^{-1}
Moduli dominate
until 2nd reheating
(matter domination)
space
relevant mode
$\Delta t \to \Delta N$
Mode exits $k_{\rm cmb}^{-1}$
H^{-1}

Universe with SUSY Prior

Additional change from standard case

$$\Delta N = -10.68 + \frac{1}{18}\ln\left[\left(\frac{g_*(T_r^\sigma)}{10.75}\right)\left(\frac{T_r}{3\text{ MeV}}\right)^4\left(\frac{m_p}{\Delta\sigma}\right)^3\right]$$

$$\begin{aligned}\Delta n_s &= (n_s-1)\left[-\frac{5}{16}r-\frac{3}{64}\frac{r^2}{n_s-1}\right]\Delta N,\\ \Delta r &= r\left[(n_s-1)+\frac{r}{8}\right]\Delta N.\end{aligned}$$

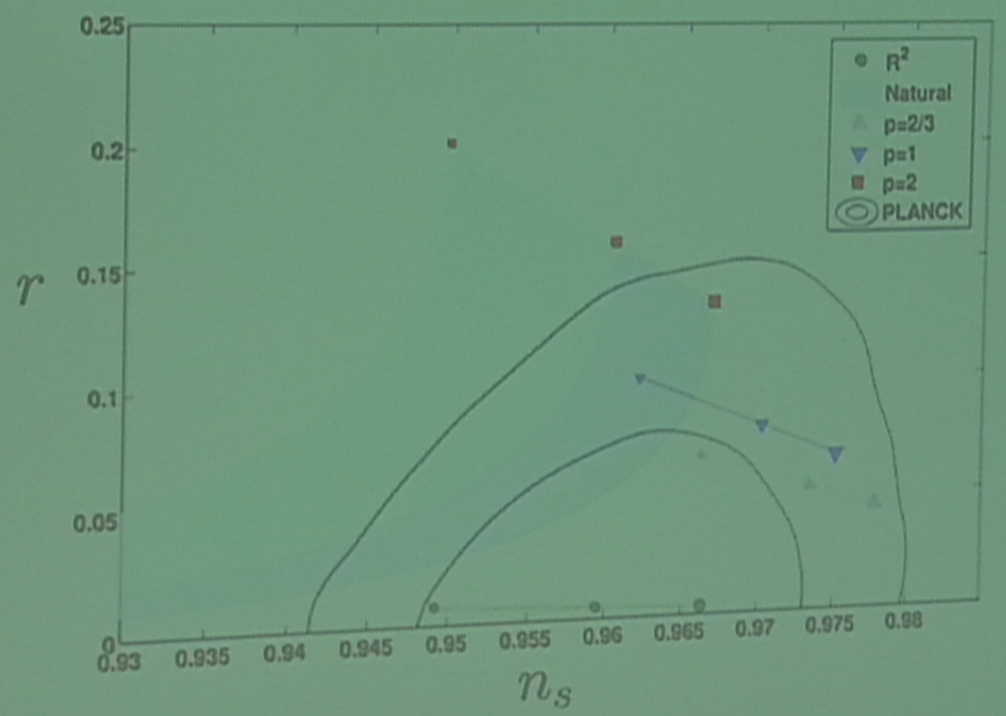


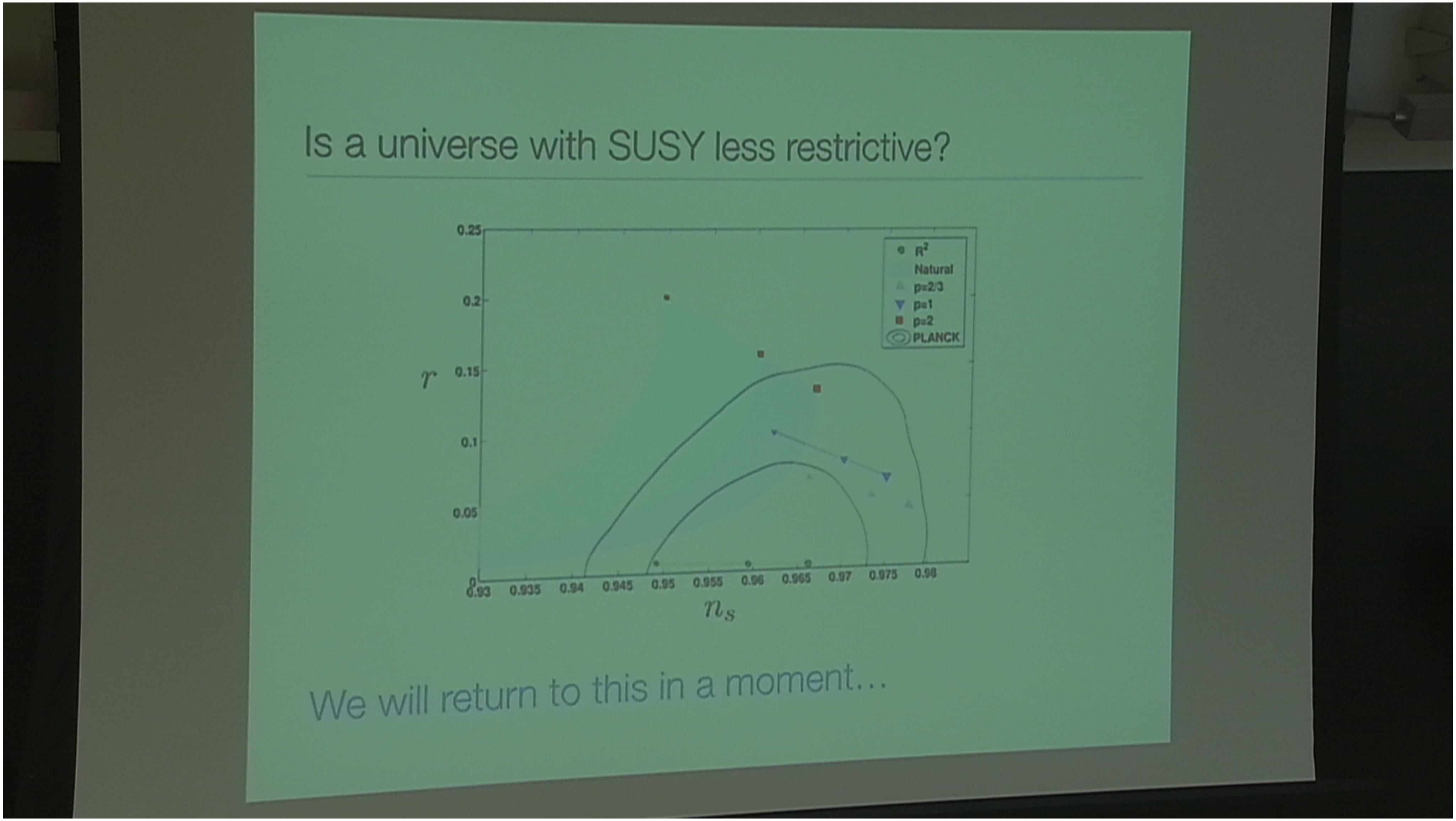
$$\boxed{\Delta N_{\rm total} \simeq 20}$$

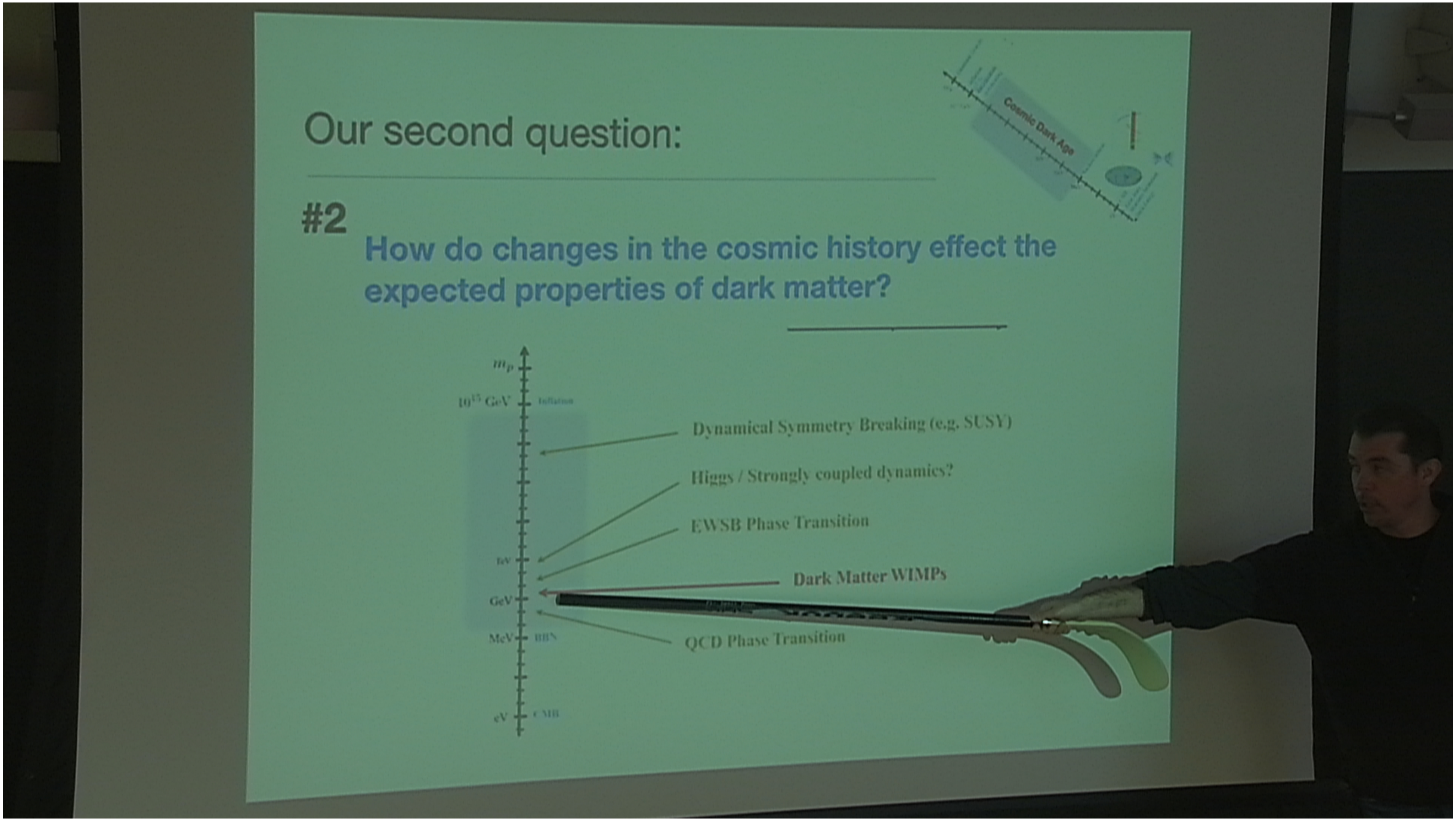
More freedom for inflationary constraints with SUSY

ArXiv:1307.2453

with R. Easther (Auckland), R. Galvez, and O. Ozsoy (Syracuse)



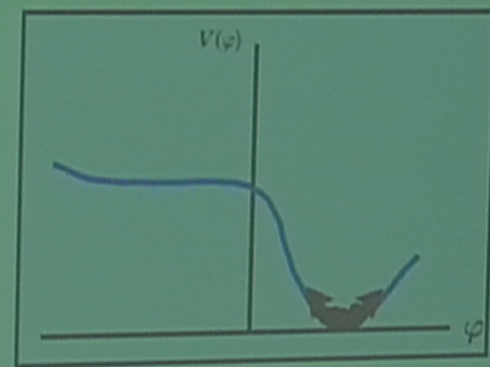

Is a universe with SUSY less restrictive?
0.25
0.2
0.15
0.1
0.05
0
r
0.93 0.935 0.94 0.945 0.95 0.955 0.96 0.965 0.97 0.975 0.98
n_s
R^2
Natural
p=2/3
p=1
p=2
PLANCK
We will return to this in a moment…


Our second question:
#2
How do changes in the cosmic history effect the expected properties of dark matter?
Cosmic Dark Age
m_p
10^{15} GeV
Inflation
Dynamical Symmetry Breaking (e.g. SUSY)
Higgs / Strongly coupled dynamics?
EWSB Phase Transition
TeV
Dark Matter WIMPs
GeV
MeV
BBN
QCD Phase Transition
eV
CMB

The Cosmological Moduli Problem

Moduli generically displaced.

Energy stored in condensate.



Example:

$$V(\varphi) = 0 + m_{SOFT}^2 \varphi^2 - H^2 \varphi^2 + \frac{1}{M^{2n}} \varphi^{4+2n}$$

High Energy: $H \gg m_{3/2} = \text{TeV}$ $\quad \langle \varphi \rangle \simeq M \left(\frac{H}{M}\right)^{\frac{1}{n+1}}$

Low Energy: $H \ll M$ $\quad \langle \varphi \rangle \simeq 0$

Condensate decays and reheats universe

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

$$\varphi \text{ decays} \begin{cases} \to \text{Std. Model} \\ \to \text{SUSY partners} \to \to \to \text{LSP} \left(\begin{array}{c}\text{Neutrolino}\\ \text{DM}\end{array}\right) \end{cases}$$

How much Dark Matter?

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

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

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

Dark matter will be of non-thermal origin:

$$\Omega^{NT}_{dm}h^2 \simeq 0.10\left(\frac{m_X}{100\ \mathrm{GeV}}\right)\left(\frac{10.75}{g_*}\right)^{1/2}\left(\frac{3\times10^{-23}\,\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle}\right)\left(\frac{10\ \mathrm{MeV}}{T_r}\right)$$

$$\Omega_{\mathrm{obs}}h^2 \simeq 0.12$$

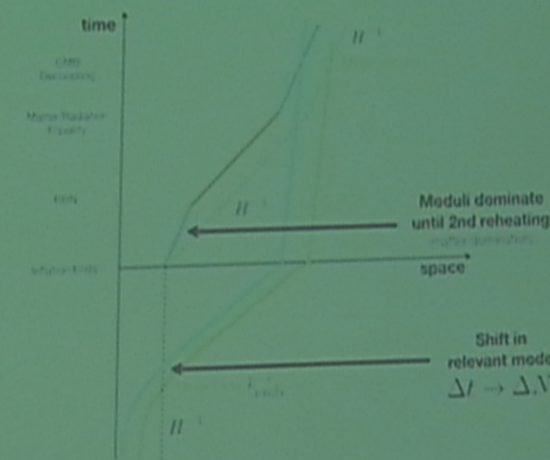
Restrict Mass and Cross-section by dark matter experiments!

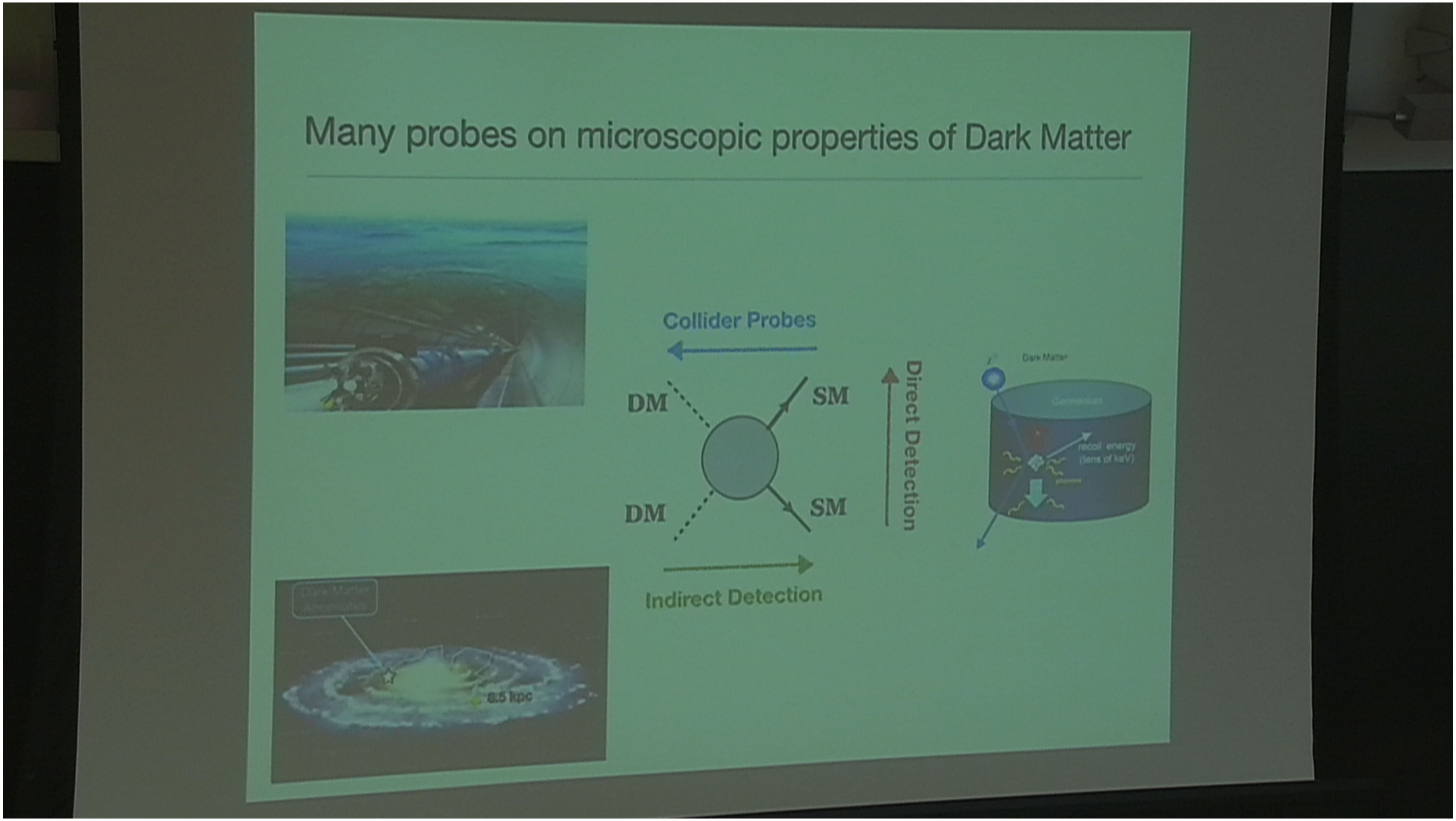
↓

Restrict Reheat temperature

↓

Reduce freedom for Planck constraints




Many probes on microscopic properties of Dark Matter
Collider Probes
DM
SM
DM
SM
Direct Detection
Indirect Detection
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recoil energy
(tens of keV)
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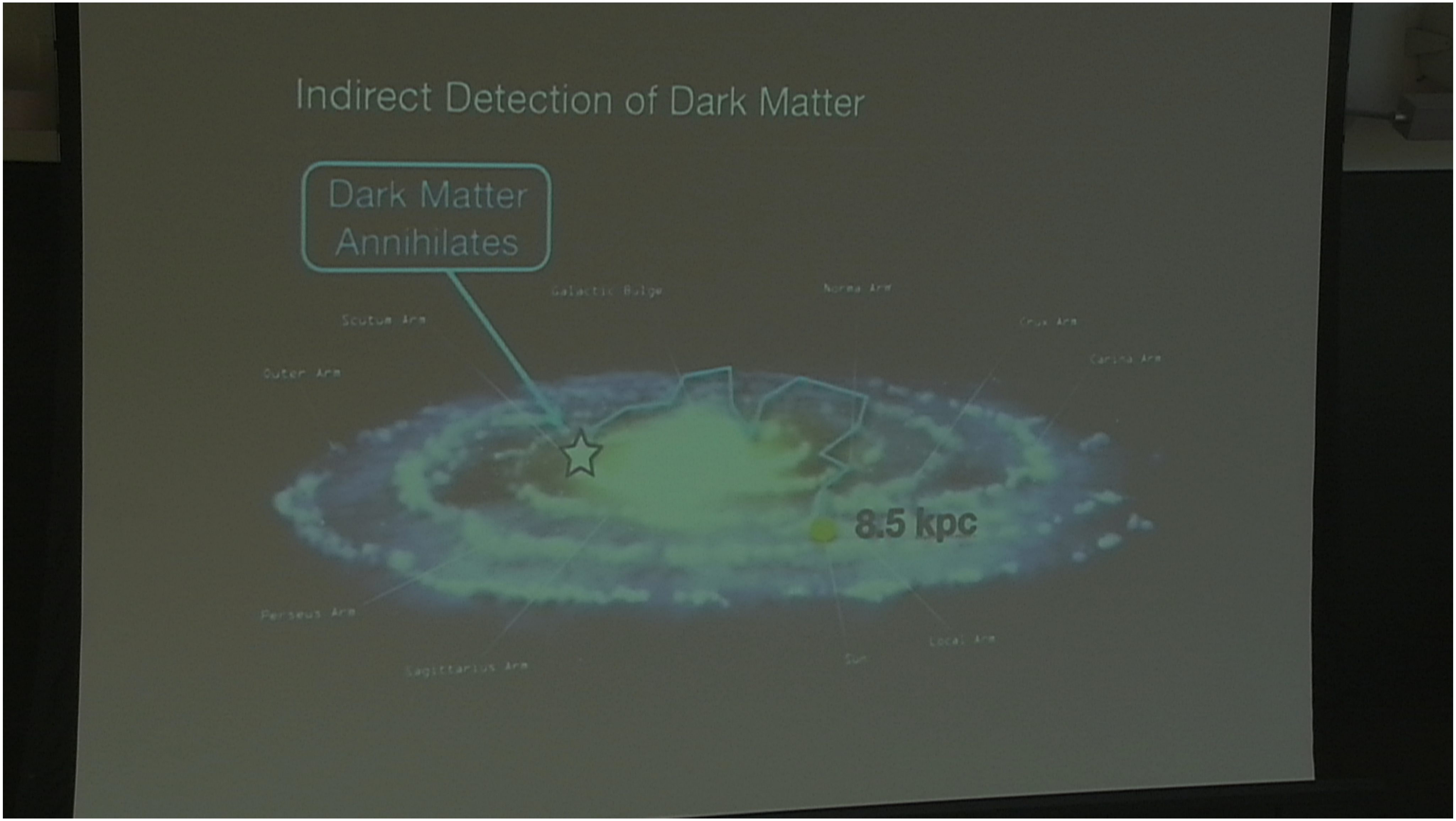
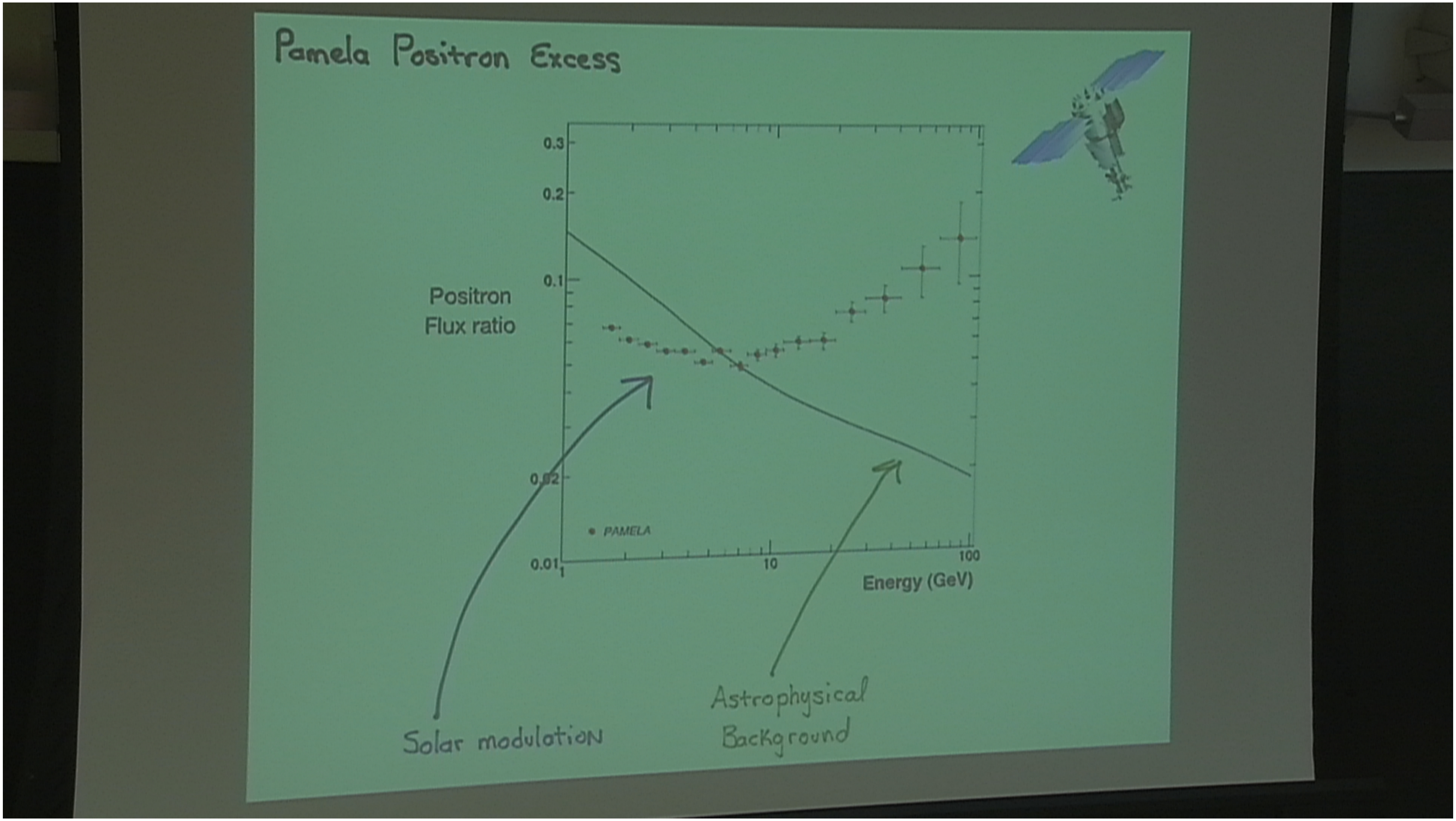
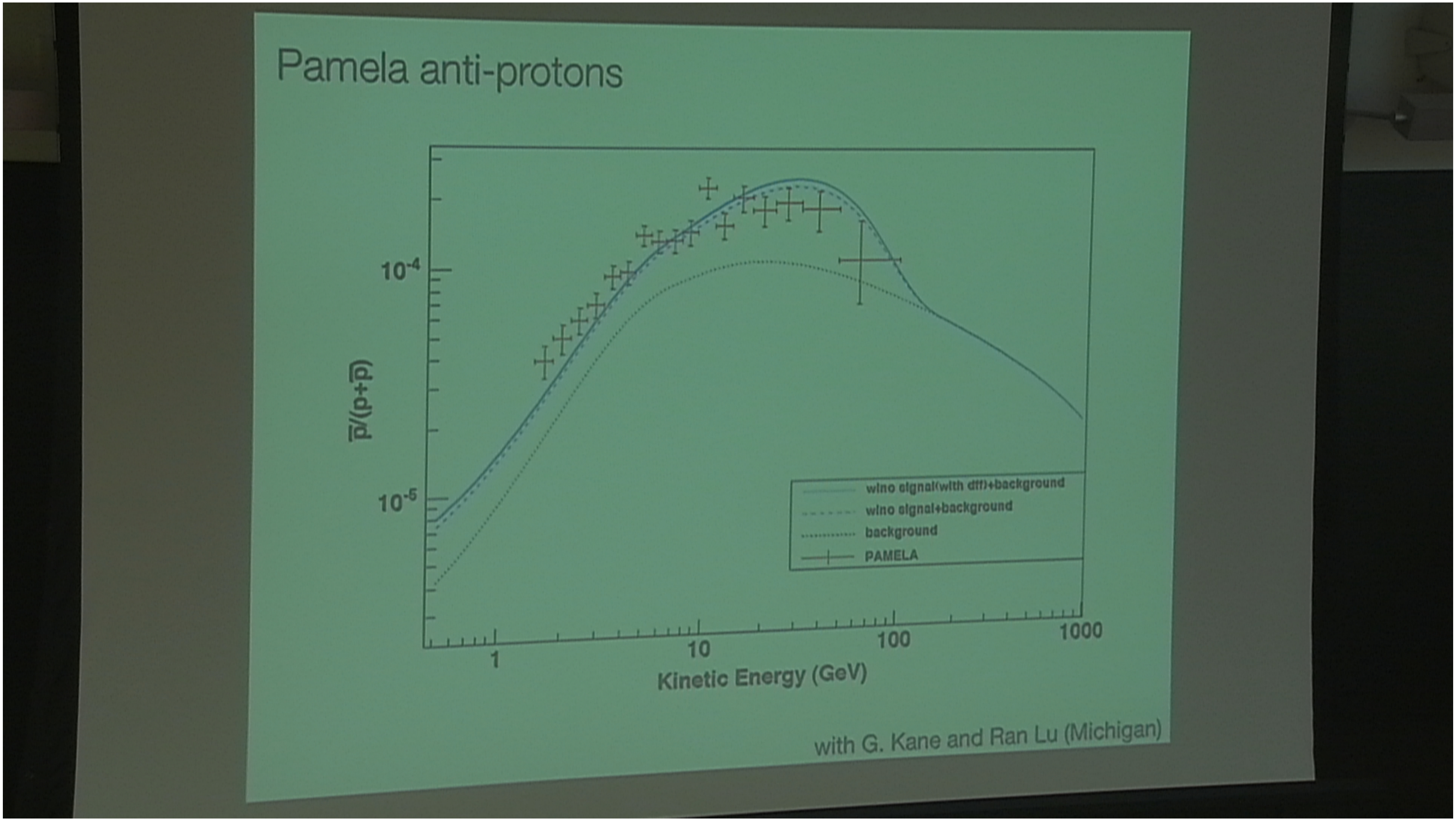

Indirect Detection of Dark Matter
Dark Matter Annihilates
Galactic Bulge
Norma Arm
Scutum Arm
Crux Arm
Carina Arm
Outer Arm
8.5 kpc
Perseus Arm
Sagittarius Arm
Local Arm
Sun



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



Pamela anti-protons
10^{-4}
10^{-5}
$\bar{p}/(p+\bar{p})$
1
10
100
1000
Kinetic Energy (GeV)
wino signal(with diff)+background
wino signal+background
background
PAMELA
with G. Kane and Ran Lu (Michigan)

Cosmic Ray (astro)Physics is Messy

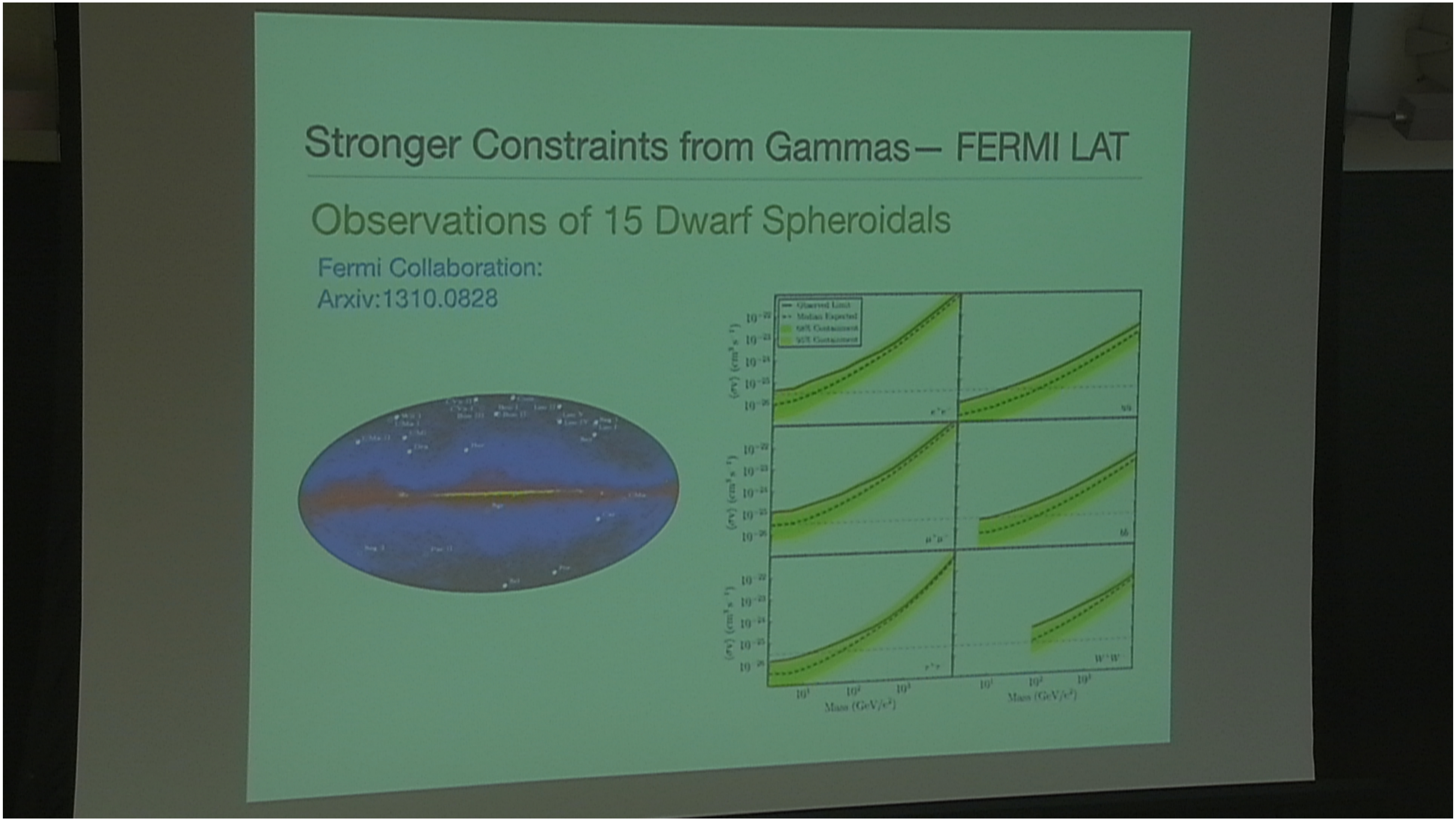
Expected Positron Flux

$$\Phi \sim \boxed{\frac{\langle \sigma v \rangle}{m_X^2}} \times \boxed{\rho^2(r)}$$

Microphysics Astrophysics

Important Considerations

- Astrophysical uncertainties: Halo profile, propagation, backgrounds
- Unknown astrophysical sources, e.g. Pulsars
- Proton contamination (10,000/1)


Stronger Constraints from Gammas— FERMI LAT
Observations of 15 Dwarf Spheroidals
Fermi Collaboration:
Arxiv:1310.0828
Observed Limit
Median Expected
68% Containment
95% Containment
Mass (GeV/c²)
Mass (GeV/c²)

Stronger Constraints from Gammas— FERMI LAT

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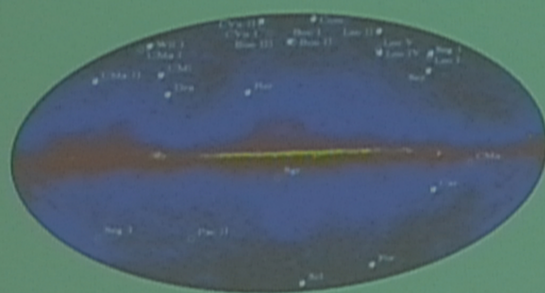
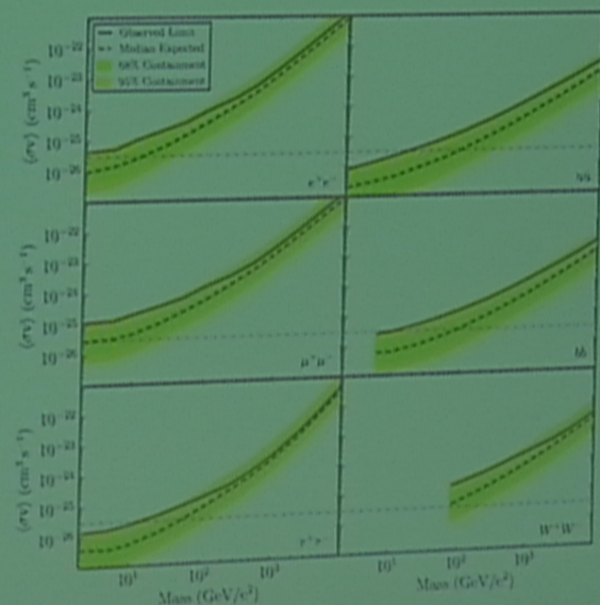
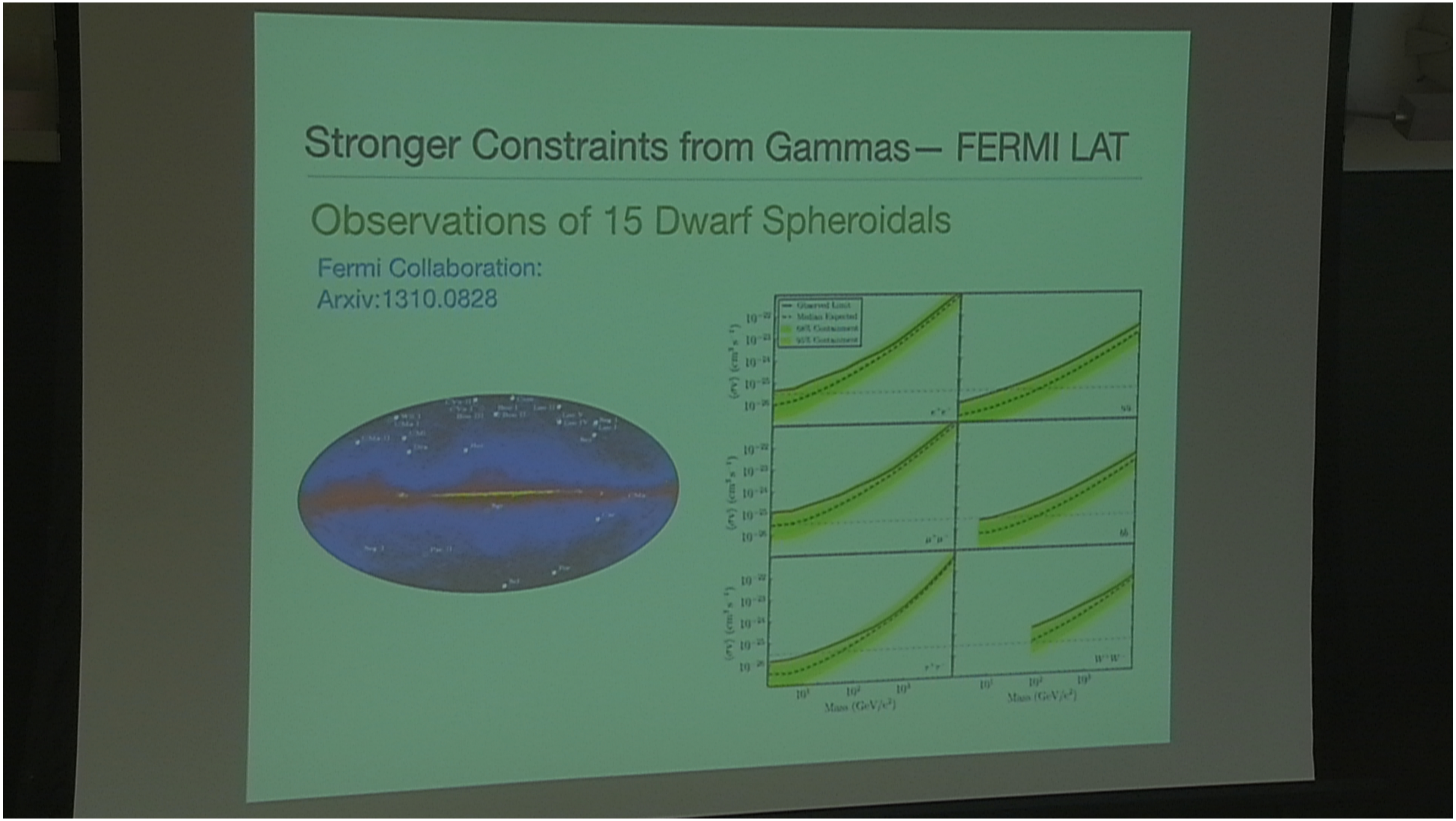
Arxiv:1310.0828

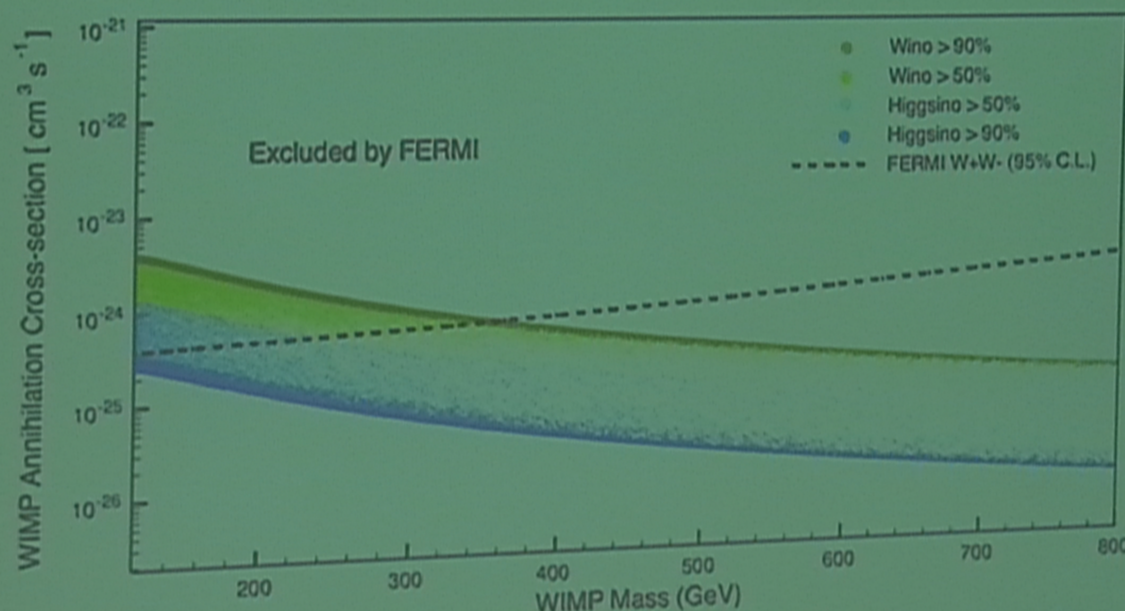


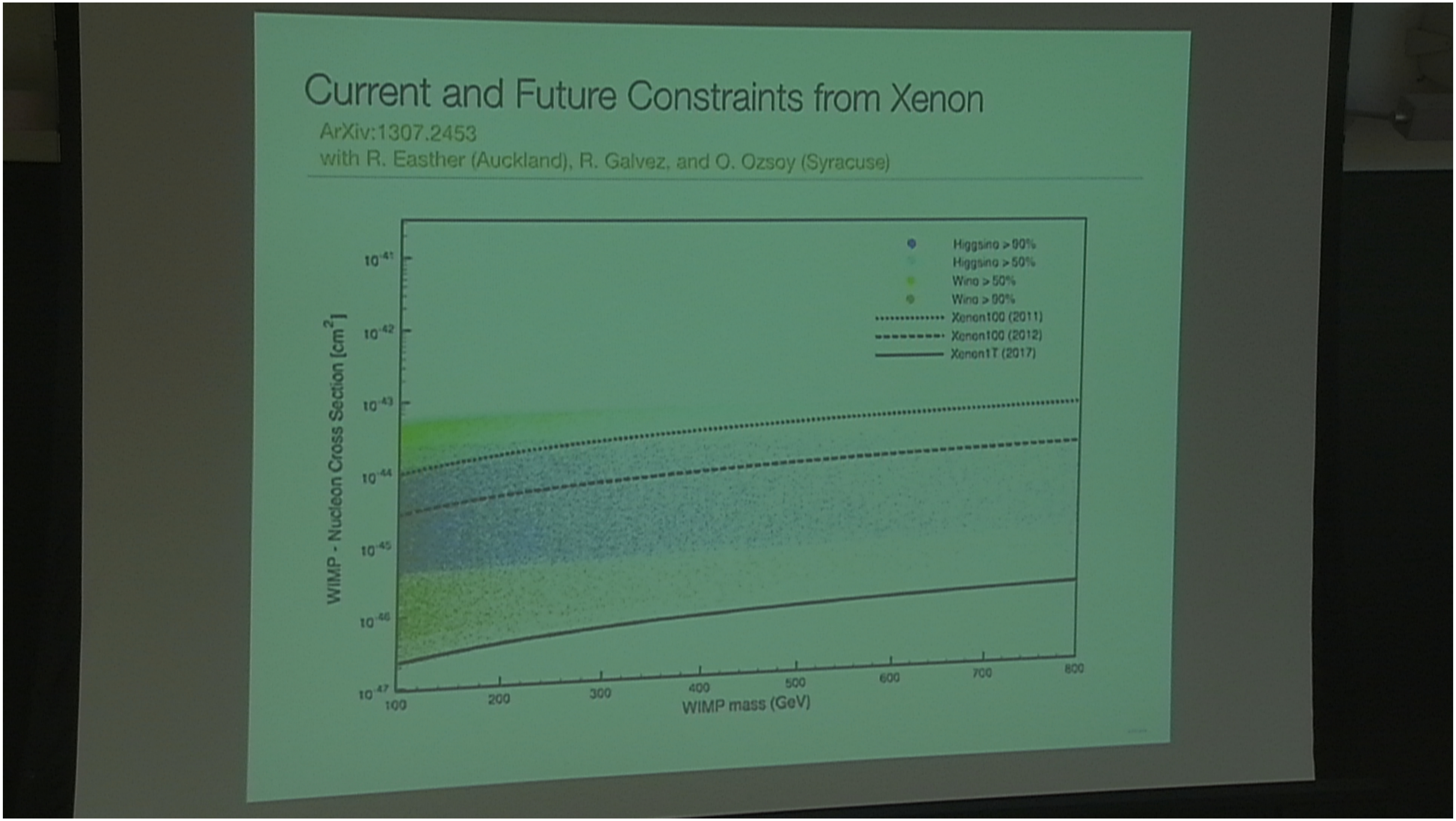



Stronger Constraints from Gammas— FERMI LAT
Observations of 15 Dwarf Spheroidals
Fermi Collaboration:
Arxiv:1310.0828
Observed Limit
Median Expected
Mass (GeV/c²)
Mass (GeV/c²)

Indirect Detection Constraints from FERMI

ArXiv:1307.2453
with R. Easther (Auckland), R. Galvez, and O. Ozsoy (Syracuse)




Current and Future Constraints from Xenon
ArXiv:1307.2453
with R. Easther (Auckland), R. Galvez, and O. Ozsoy (Syracuse)
Higgsino > 90%
Higgsino > 50%
Wino > 50%
Wino > 90%
Xenon100 (2011)
Xenon100 (2012)
Xenon1T (2017)
WIMP - Nucleon Cross Section [cm^2]
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
100
200
300
400
500
600
700
800
WIMP mass (GeV)

Summary of our Results

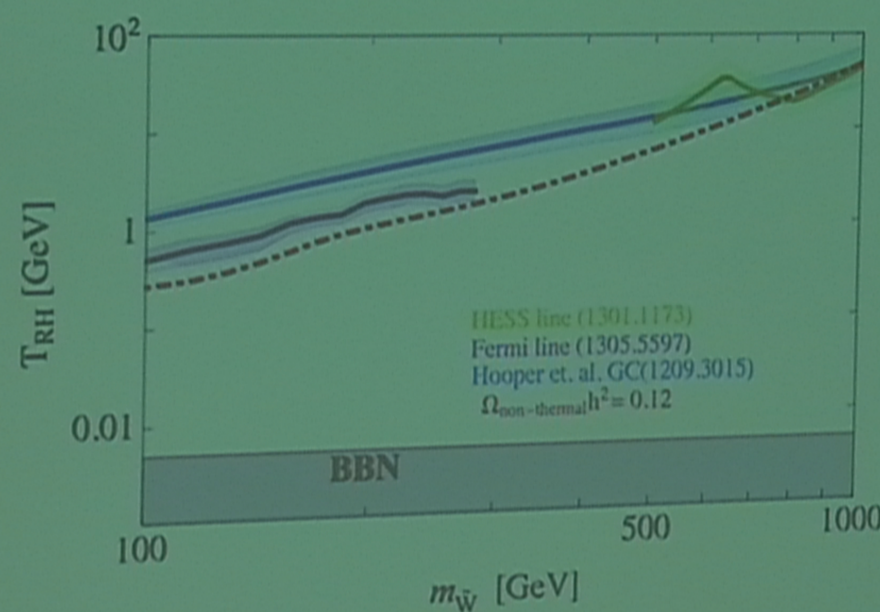
ArXiv:1307.2453
with R. Easther (Auckland), R. Galvez, and O. Ozsoy (Syracuse)

- For pure wino SUSY Dark Matter we find a **lower bound on the reheat temperature of around 700 MeV**, substantially reducing the theoretical prior.
- General SUSY WIMPs are also constrained, but a little more model dependence must be considered (e.g. tan beta, etc..)
- **Lesson learned:** Theory Priors (e.g. world with SUSY) + Cosmological constraints (Planck) + Dark Matter Detection (microscopic), allow us to begin to probe the "Dark Ages".
- Additional data improves these bounds

Recent results of Fan and Reece

Fan and Reece 1307.4400

See also: Cohen, Lisanti, Pierce, and Slatyer 1307.4082



Reheat temperature must be above 1 GeV for wino

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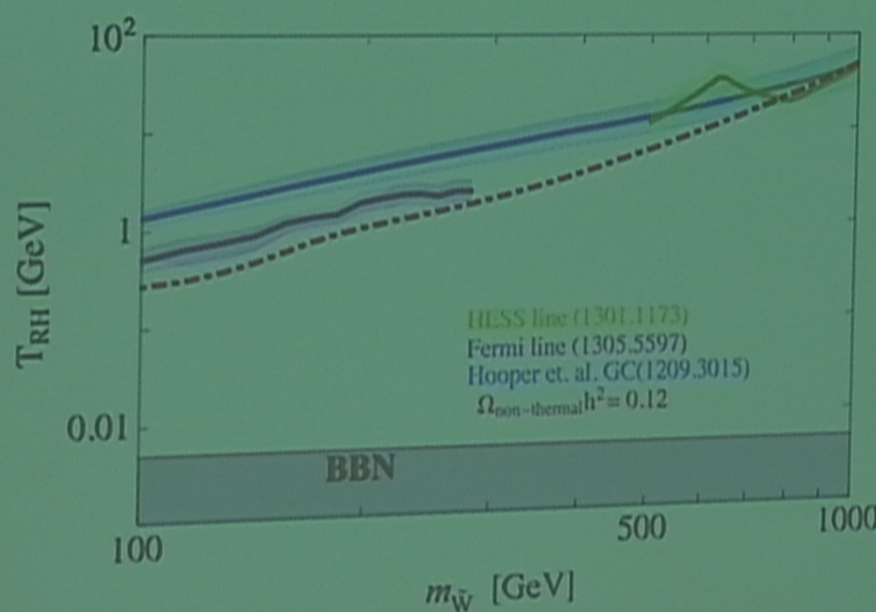

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Partial list of many things I did not mention

- Gravitino Problem (model dependent -- difficult issue)
  For an explicit example that works see: Arxiv:0908.2430 with B. Acharya, G. Kane, P. Kumar
- Baryogenesis?
  Affleck-Dine + moduli decay can address this more work should be done:
  e.g. Arxiv:1108.5178 with Kane, Shao, and Yu
- Isocurvature Constraints and Dark Radiation
  (To appear very soon with L. Iliesiu, Doddy Marsh, K. Moodley)
- Gravity Waves / Preheating? (work in progress with T. Giblin)
- Effect on CMB last scattering and reionization (work in progress with Cora Dvorkin)
- In some models moduli can be lighter
  e.g. Large Volume Stabilization in Type IIB (work in progress with K Sinha and M. Cicoli)
- Behavior of moduli during inflation — are they displaced?
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- **Consequences for Matter Power Spectrum**
  (To appear with O. Ozsoy and J. Neelakanta — with grads at SU)

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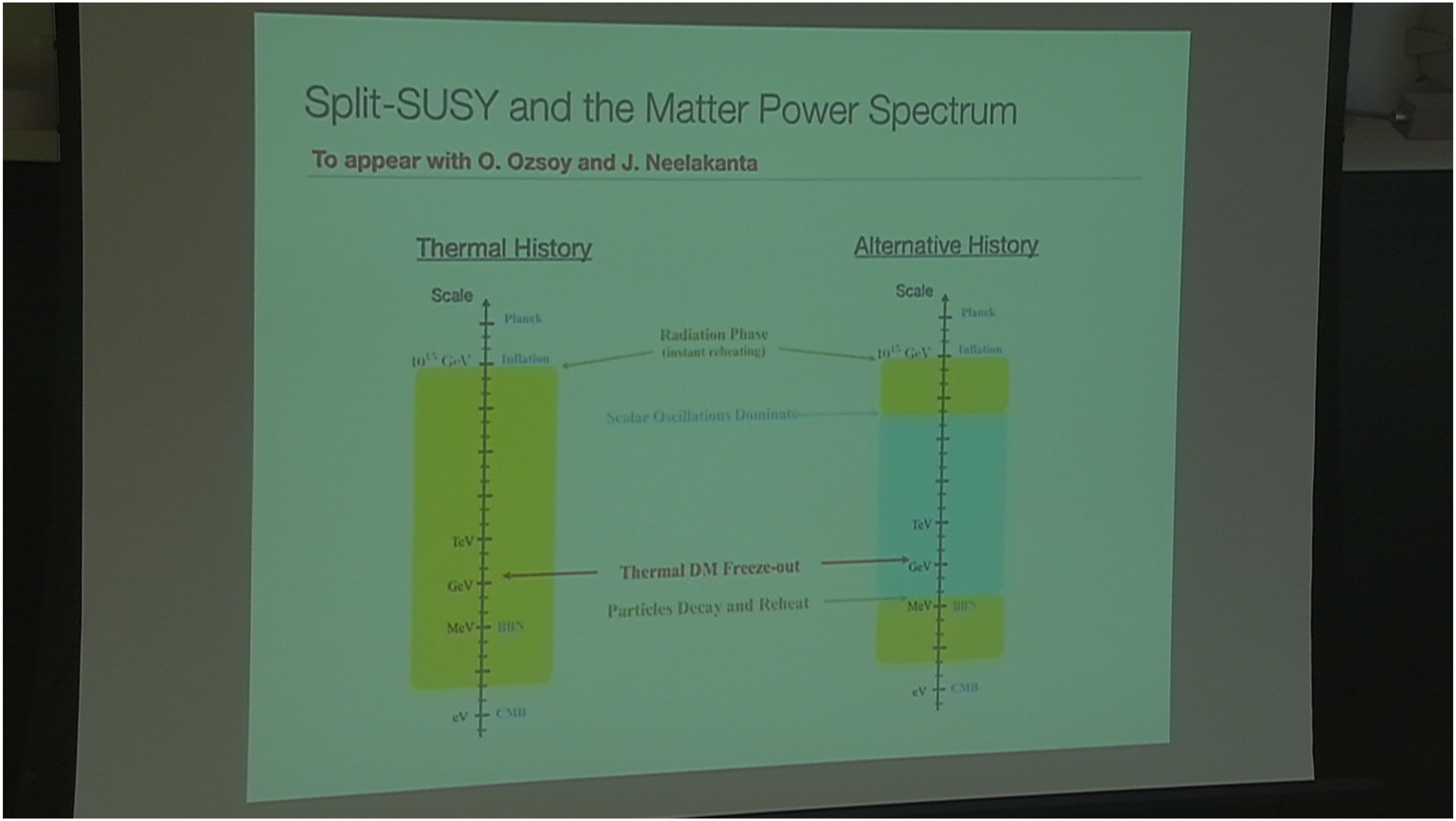
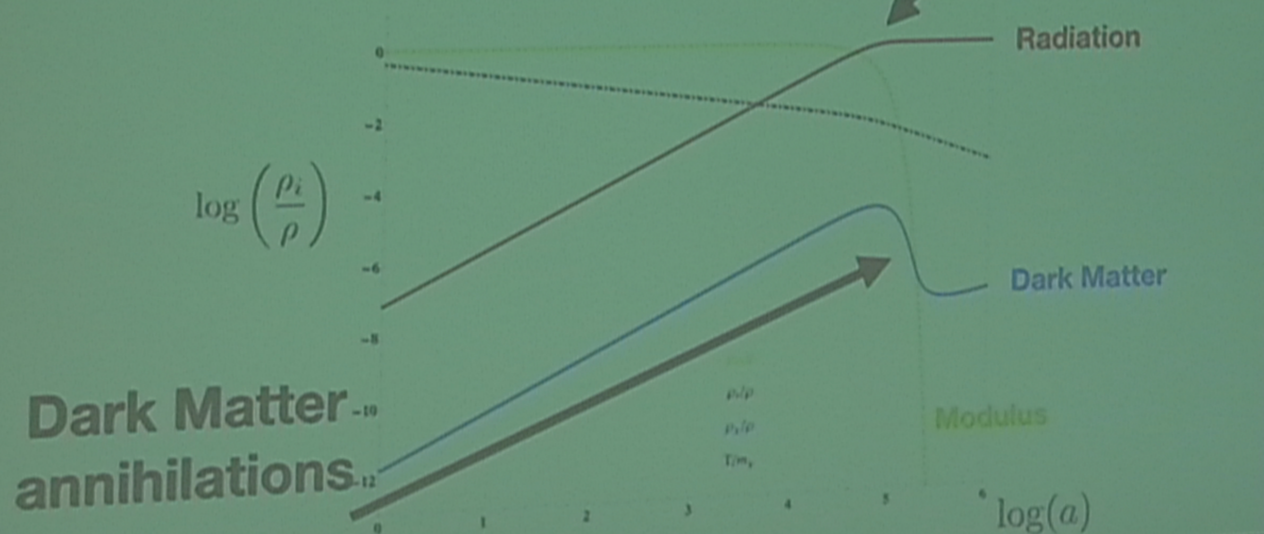

Split-SUSY and the Matter Power Spectrum
To appear with O. Ozsoy and J. Neelakanta
Thermal History
Alternative History
Scale
Planck
10^{15} GeV
Inflation
Radiation Phase
(instant reheating)
Scalar Oscillations Dominate
TeV
GeV
MeV
BBN
eV
CMB
Thermal DM Freeze-out
Particles Decay and Reheat

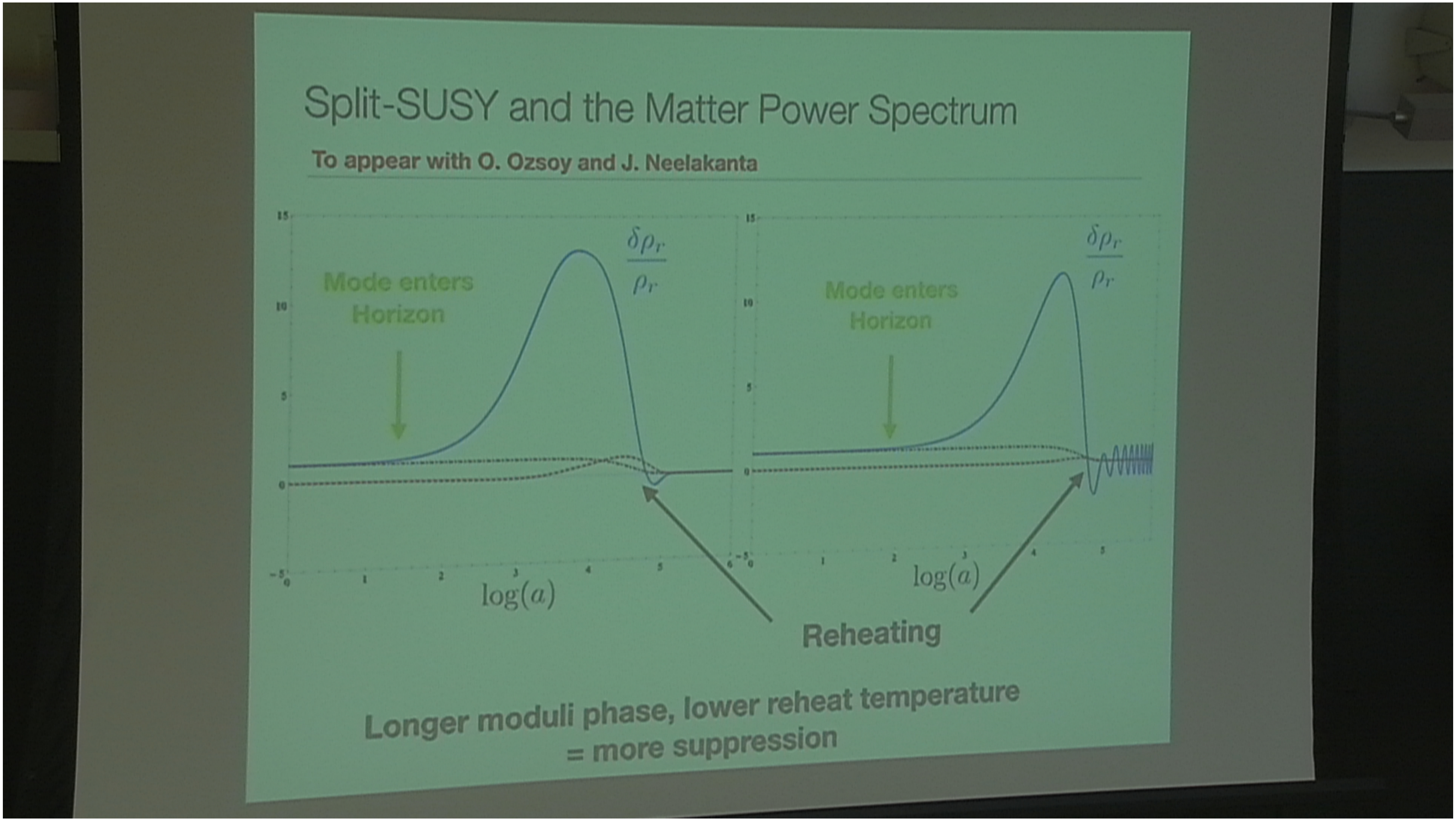
Split-SUSY and the Matter Power Spectrum

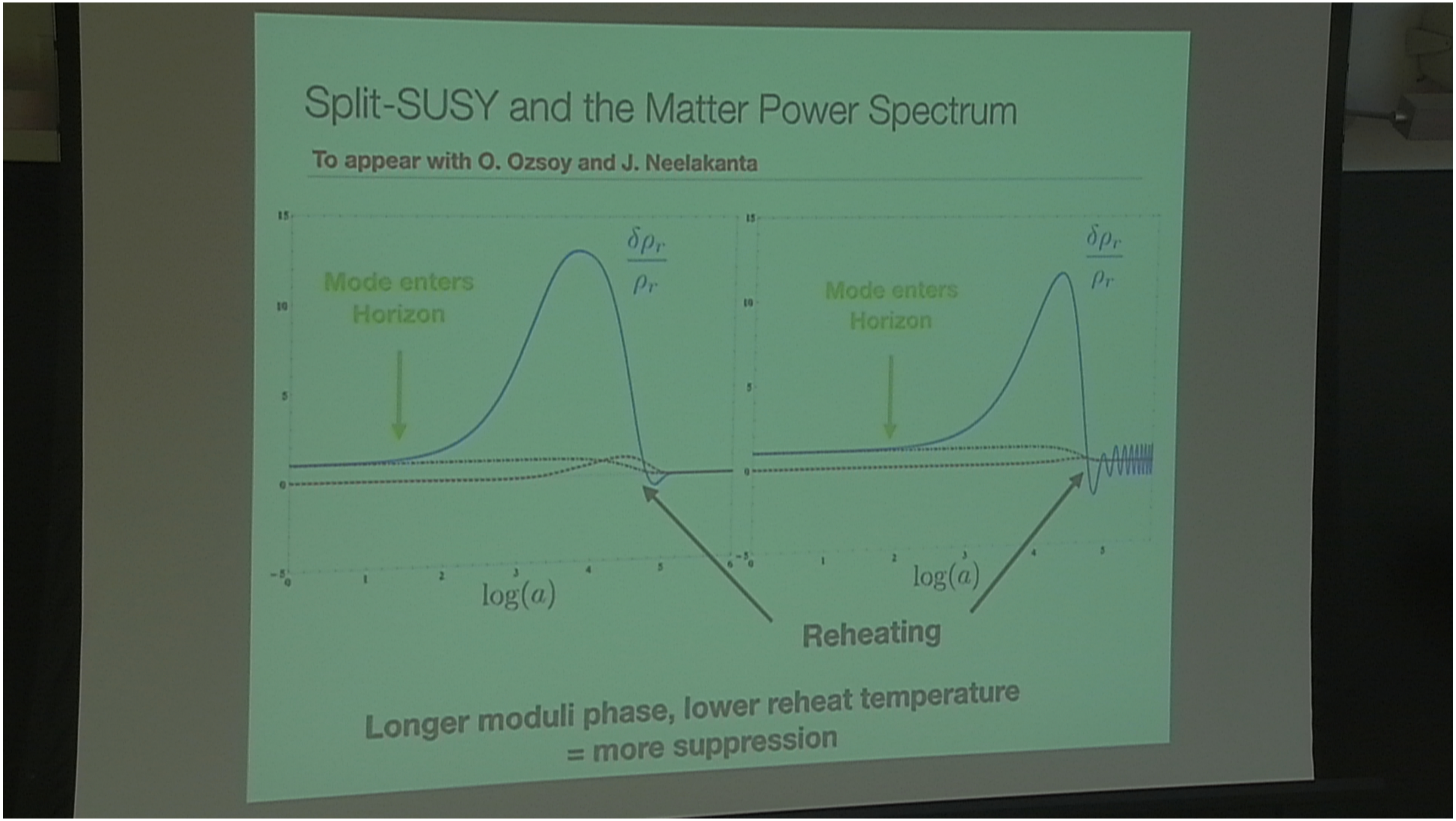
To appear with O. Ozsoy and J. Neelakanta

$$
\begin{aligned}
\dot{\rho}_\sigma &= -3H\rho_\sigma - \Gamma_\sigma \rho_\sigma, \\
\dot{\rho}_r &= -4H\rho_r + (1-B_\chi)\Gamma_\sigma\rho_\sigma + \frac{\langle \sigma v\rangle}{m_\chi}\left[\rho_\chi^2 - \rho_{\chi,eq}^2\right], \\
\dot{\rho}_\chi &= -3H\rho_\chi + B_\chi\Gamma_\sigma\rho_\sigma - \frac{\langle \sigma v\rangle}{m_\chi}\left[\rho_\chi^2 - \rho_{\chi,eq}^2\right],
\end{aligned}
$$

“Instant Reheating”




Split-SUSY and the Matter Power Spectrum
To appear with O. Ozsoy and J. Neelakanta
Mode enters Horizon
$\frac{\delta\rho_r}{\rho_r}$
$\log(a)$
Mode enters Horizon
$\frac{\delta\rho_r}{\rho_r}$
$\log(a)$
Reheating
Longer moduli phase, lower reheat temperature
= more suppression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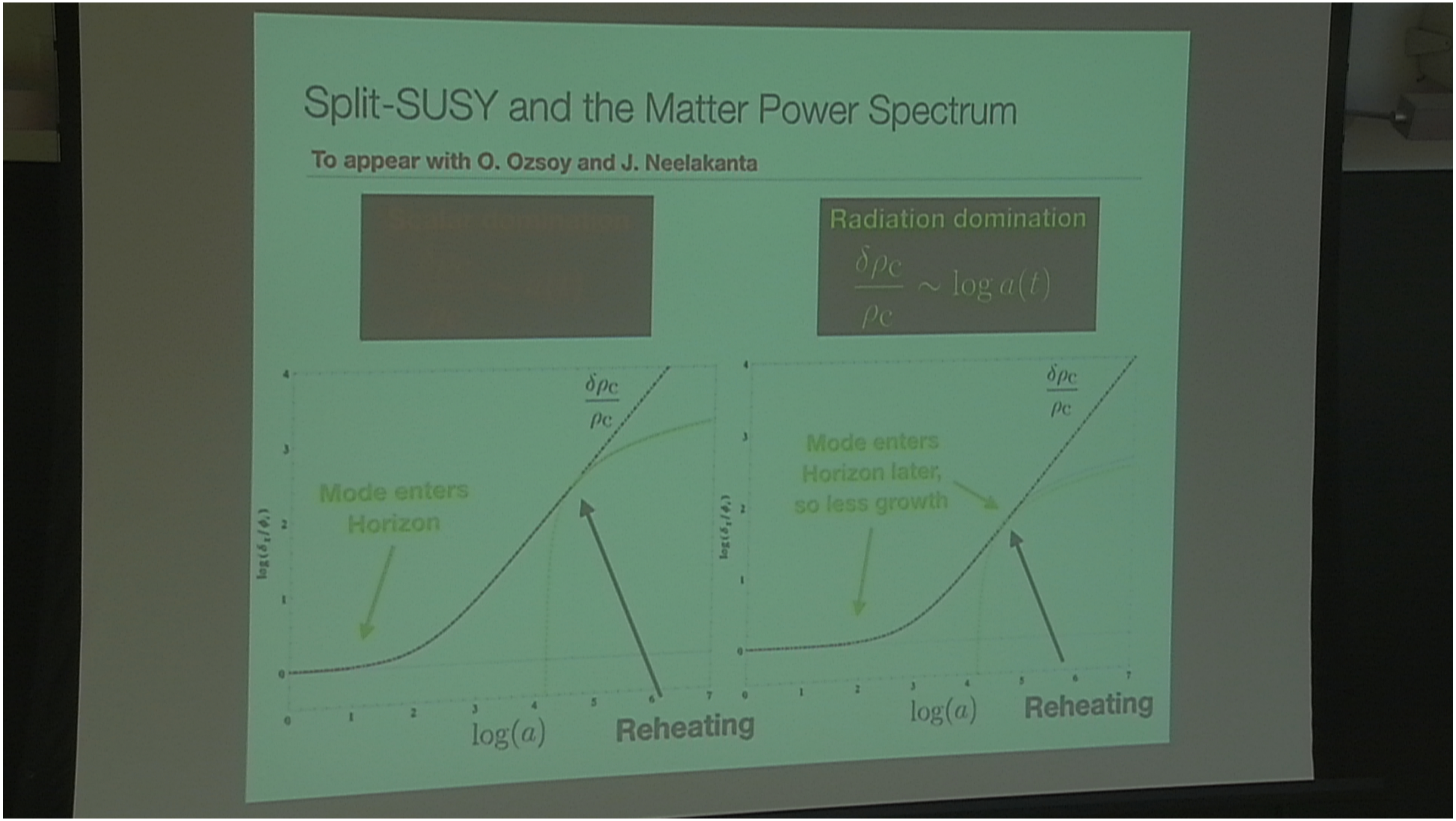
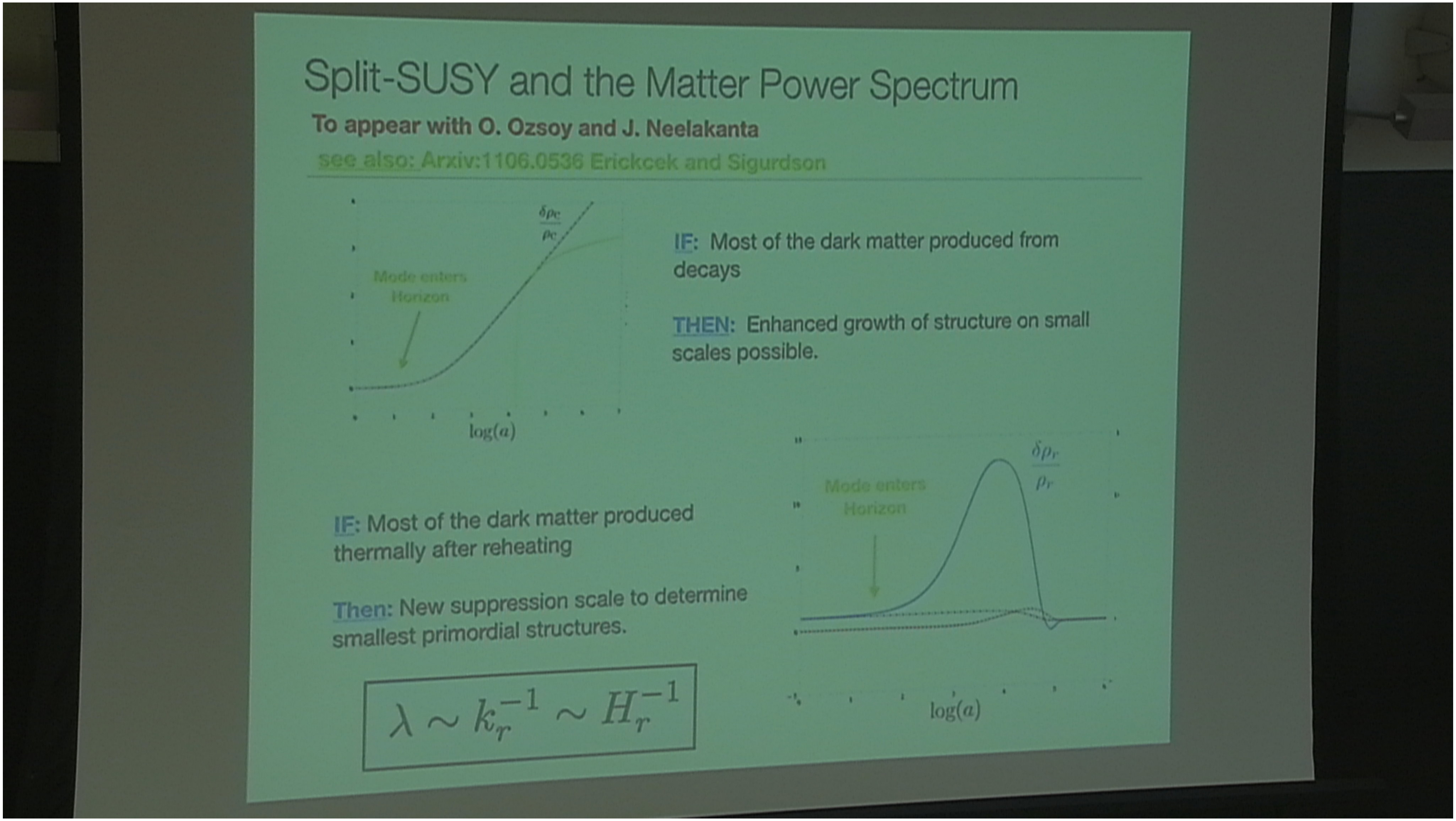
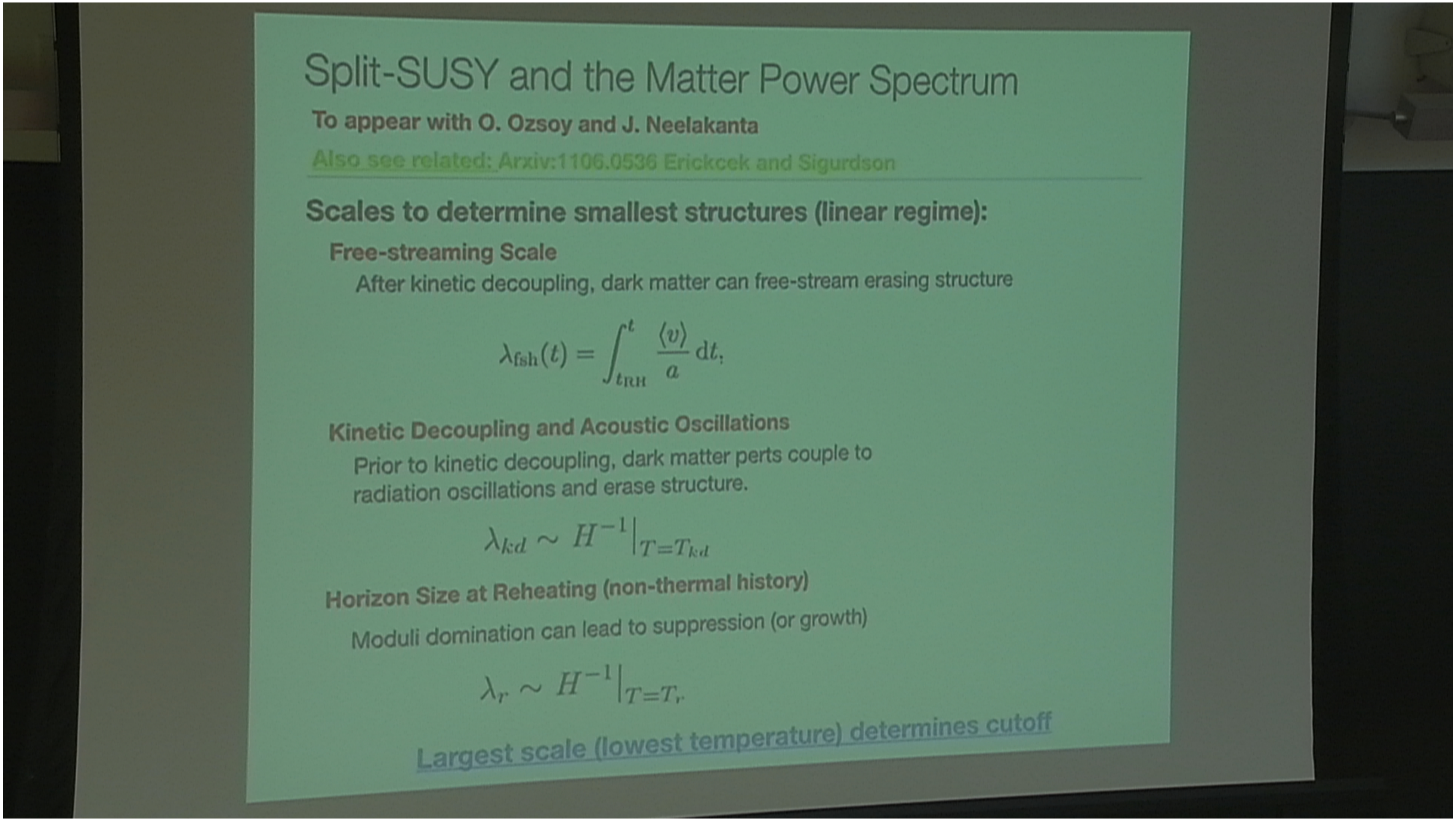

Split-SUSY and the Matter Power Spectrum
To appear with O. Ozsoy and J. Neelakanta
Radiation domination
$\frac{\delta\rho_c}{\rho_c} \sim \log a(t)$
$\frac{\delta\rho_c}{\rho_c}$
Mode enters Horizon
$\log(a)$
Reheating
$\frac{\delta\rho_c}{\rho_c}$
Mode enters Horizon later, so less growth
$\log(a)$
Reheating


Split-SUSY and the Matter Power Spectrum
To appear with O. Ozsoy and J. Neelakanta
see also: Arxiv:1106.0536 Erickcek and Sigurdson
$\frac{\delta\rho_c}{\rho_c}$
Mode enters Horizon
$\log(a)$
IF: Most of the dark matter produced from decays
THEN: Enhanced growth of structure on small scales possible.
$\frac{\delta\rho_r}{\rho_r}$
Mode enters Horizon
$\log(a)$
IF: Most of the dark matter produced thermally after reheating
Then: New suppression scale to determine smallest primordial structures.
$\lambda \sim k_r^{-1} \sim H_r^{-1}$


Split-SUSY and the Matter Power Spectrum
To appear with O. Ozsoy and J. Neelakanta
Also see related: Arxiv:1106.0536 Erickcek and Sigurdson
Scales to determine smallest structures (linear regime):
Free-streaming Scale
After kinetic decoupling, dark matter can free-stream erasing structure
$\lambda_{\rm fsh}(t) = \int_{t_{\rm RH}}^{t} \frac{\langle v \rangle}{a}\, dt,$
Kinetic Decoupling and Acoustic Oscillations
Prior to kinetic decoupling, dark matter perts couple to radiation oscillations and erase structure.
$\lambda_{kd} \sim H^{-1}\big|_{T=T_{kd}}$
Horizon Size at Reheating (non-thermal history)
Moduli domination can lead to suppression (or growth)
$\lambda_r \sim H^{-1}\big|_{T=T_r}$
Largest scale (lowest temperature) determines cutoff

Split-SUSY and the Matter Power Spectrum

To appear with O. Ozsoy and J. Neelakanta

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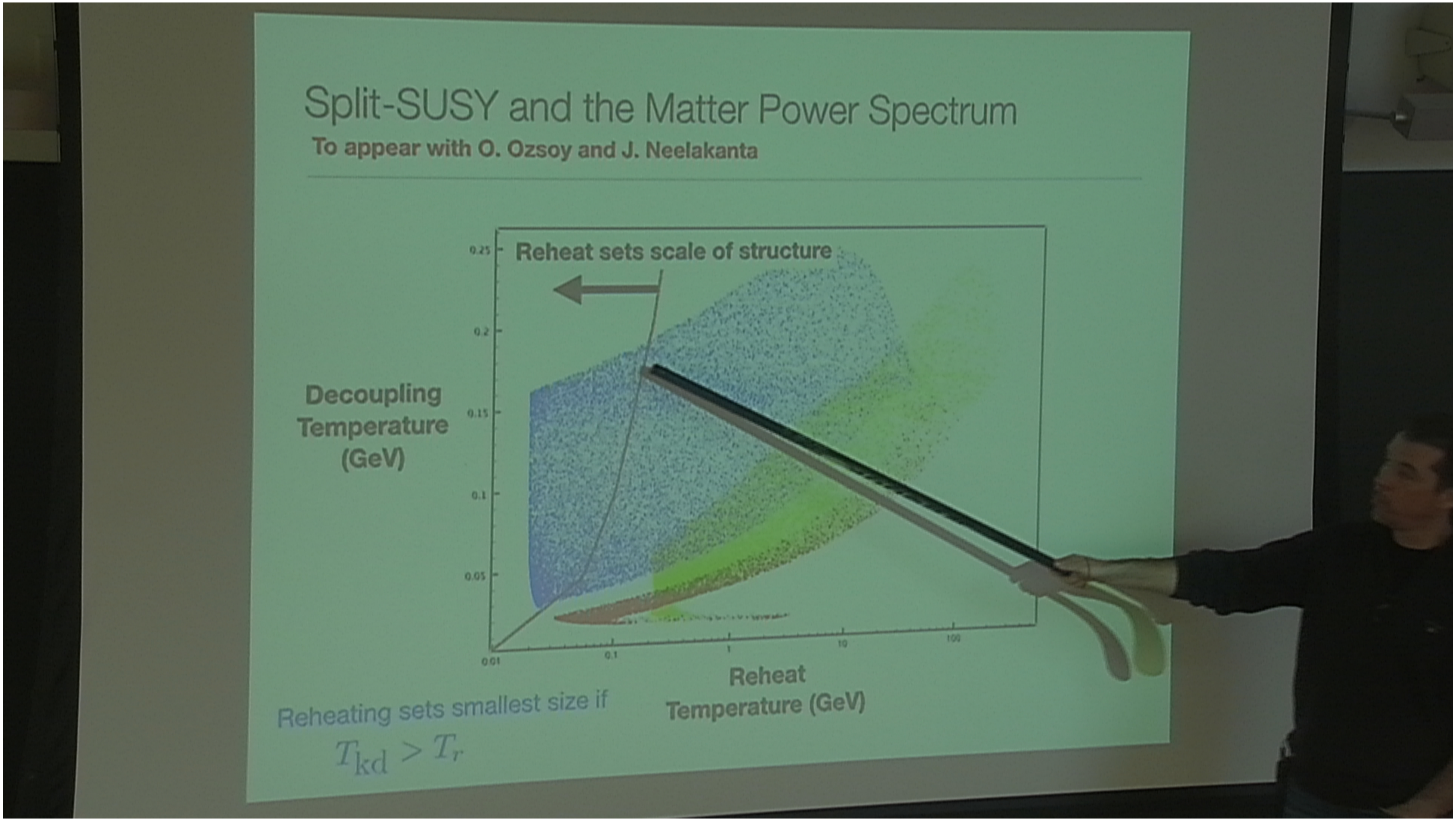
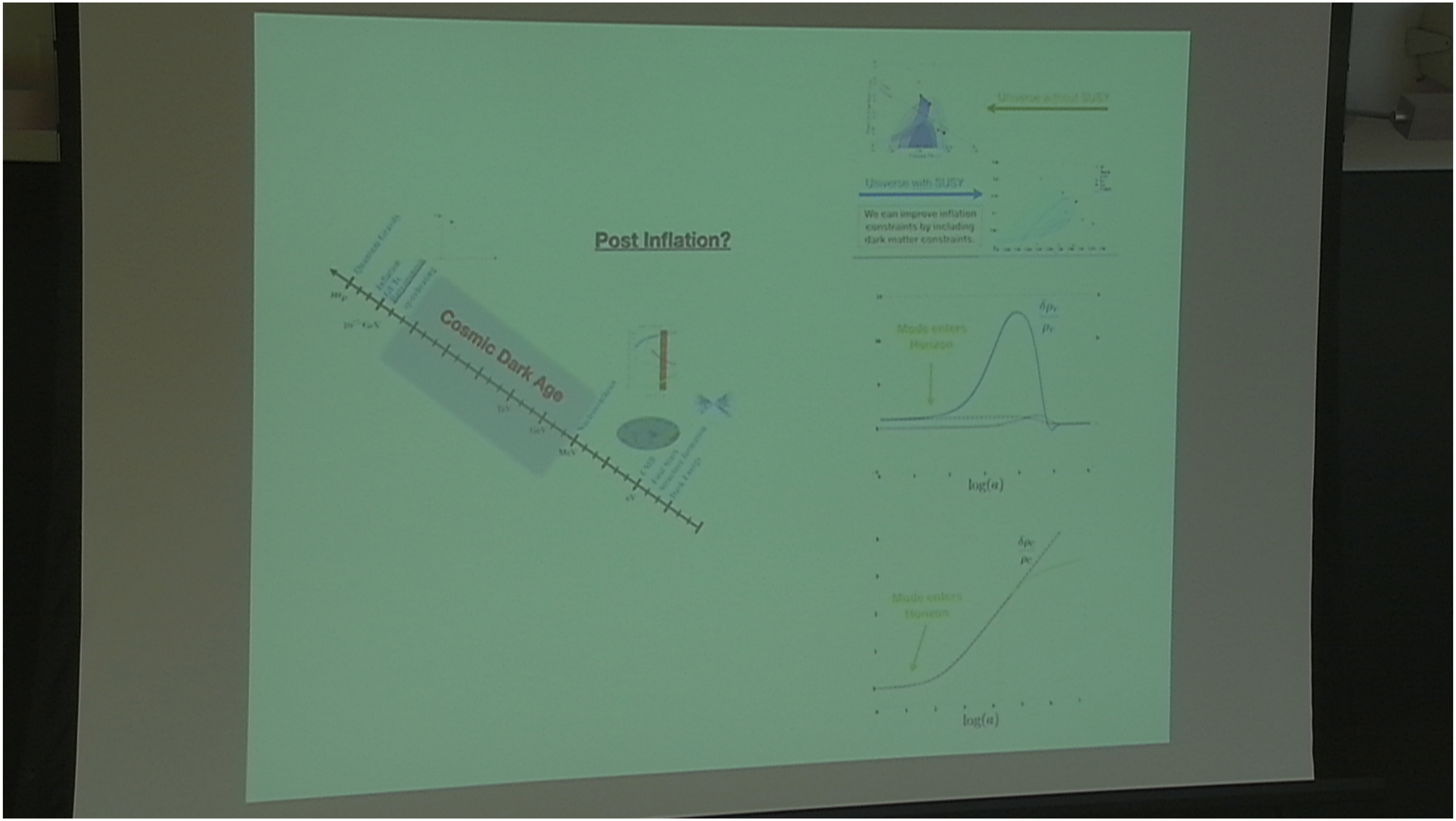
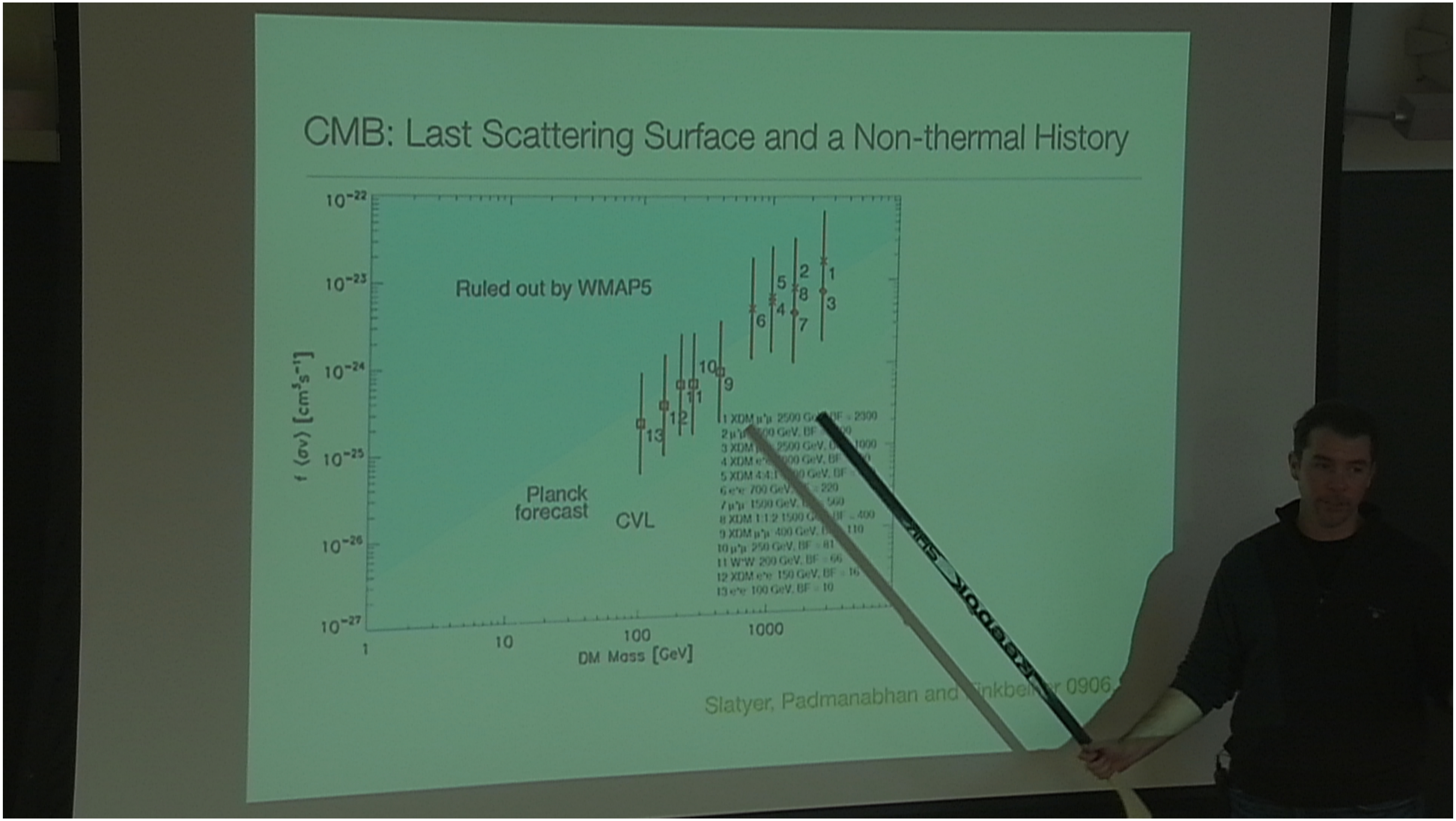


Split-SUSY and the Matter Power Spectrum
To appear with O. Ozsoy and J. Neelakanta
Reheat sets scale of structure
Decoupling Temperature (GeV)
Reheat Temperature (GeV)
Reheating sets smallest size if
$T_{\rm kd} > T_r$


Post Inflation?
Cosmic Dark Age
Universe without SUSY
Universe with SUSY
We can improve inflation constraints by including dark matter constraints.
Mode enters Horizon
log(a)
Mode enters Horizon
log(a)



CMB: Last Scattering Surface and a Non-thermal History
Ruled out by WMAP5
Planck forecast
CVL
$f\ \langle\sigma v\rangle$ [cm^{3}s^{-1}]
DM Mass [GeV]
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
Slatyer, Padmanabhan and