Towards a post-Inflationary Universe

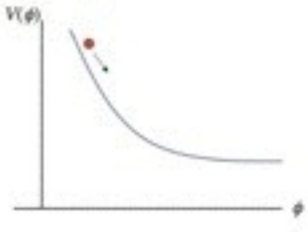
Scott Watson
Syracuse University

Work in Progress with Jiji Fan and Ogan Ozsoy

Supersymmetry, Nonthermal Dark Matter and Precision Cosmology
ArXiv:1307.2453
with R. Easther (Auckland), R. Galvez (Syracuse), and O. Ozsoy (Syracuse)

Constraining SUSY with Heavy Scalars — using the CMB
ArXiv:1312.363
with L. Illiesiu (Princeton), D. Marsh (PI), K. Moodley (KwaZulu Natal U.)

Post Inflation?



m_p

Quantum Gravity

10^{16} GeV

GUTs

Inflation

Baryogenesis

(p)reheating

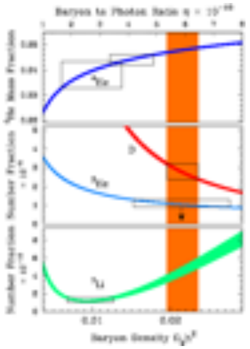
Cosmic Dark Age

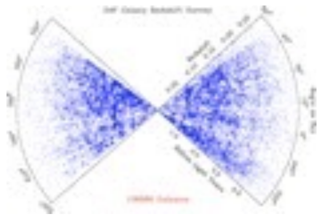
TeV

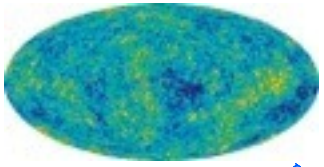
GeV

MeV

Nucleosynthesis







eV

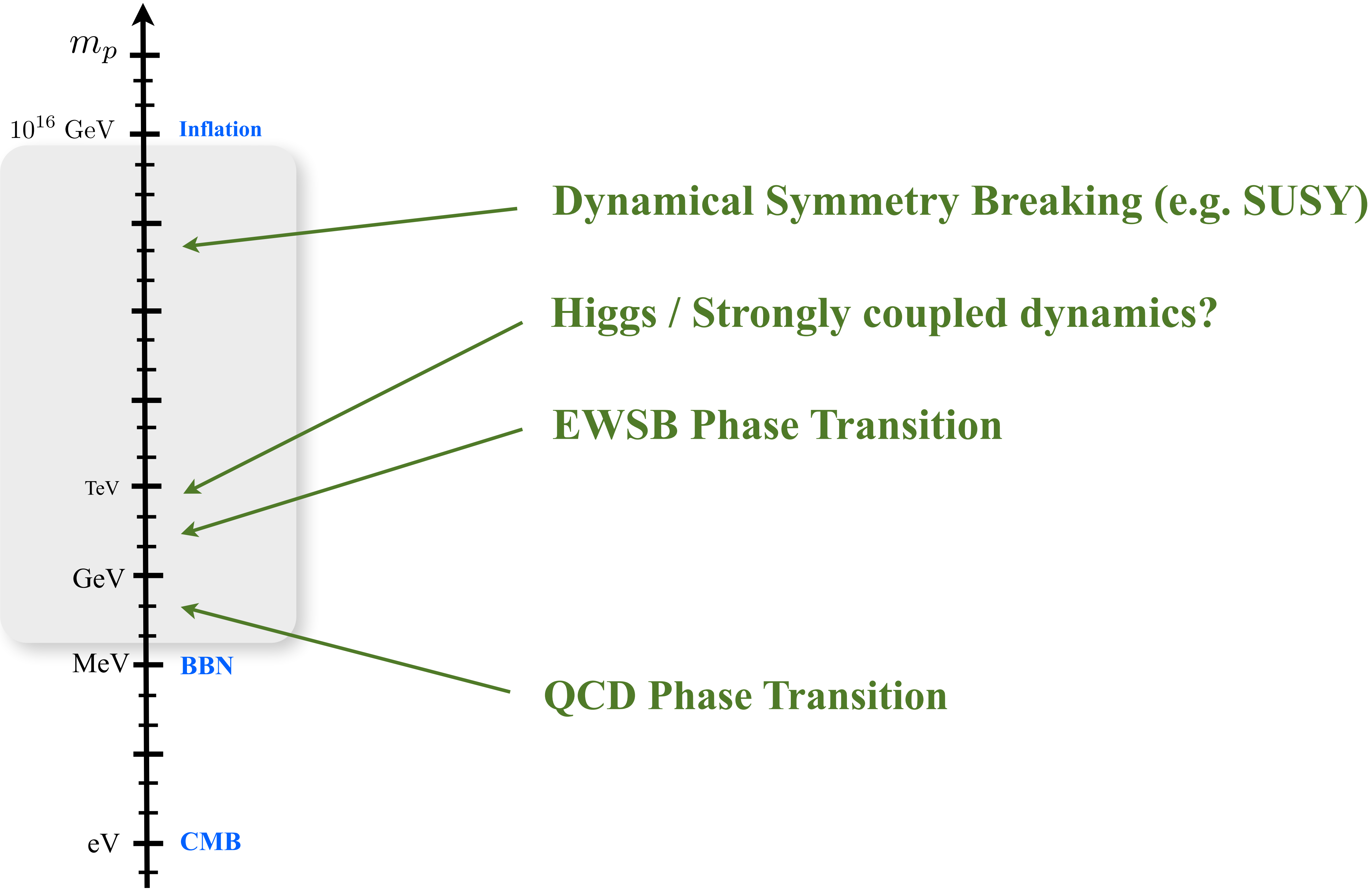
CMB

First Stars

Structure formation

Dark Energy

Cosmic Dark Ages



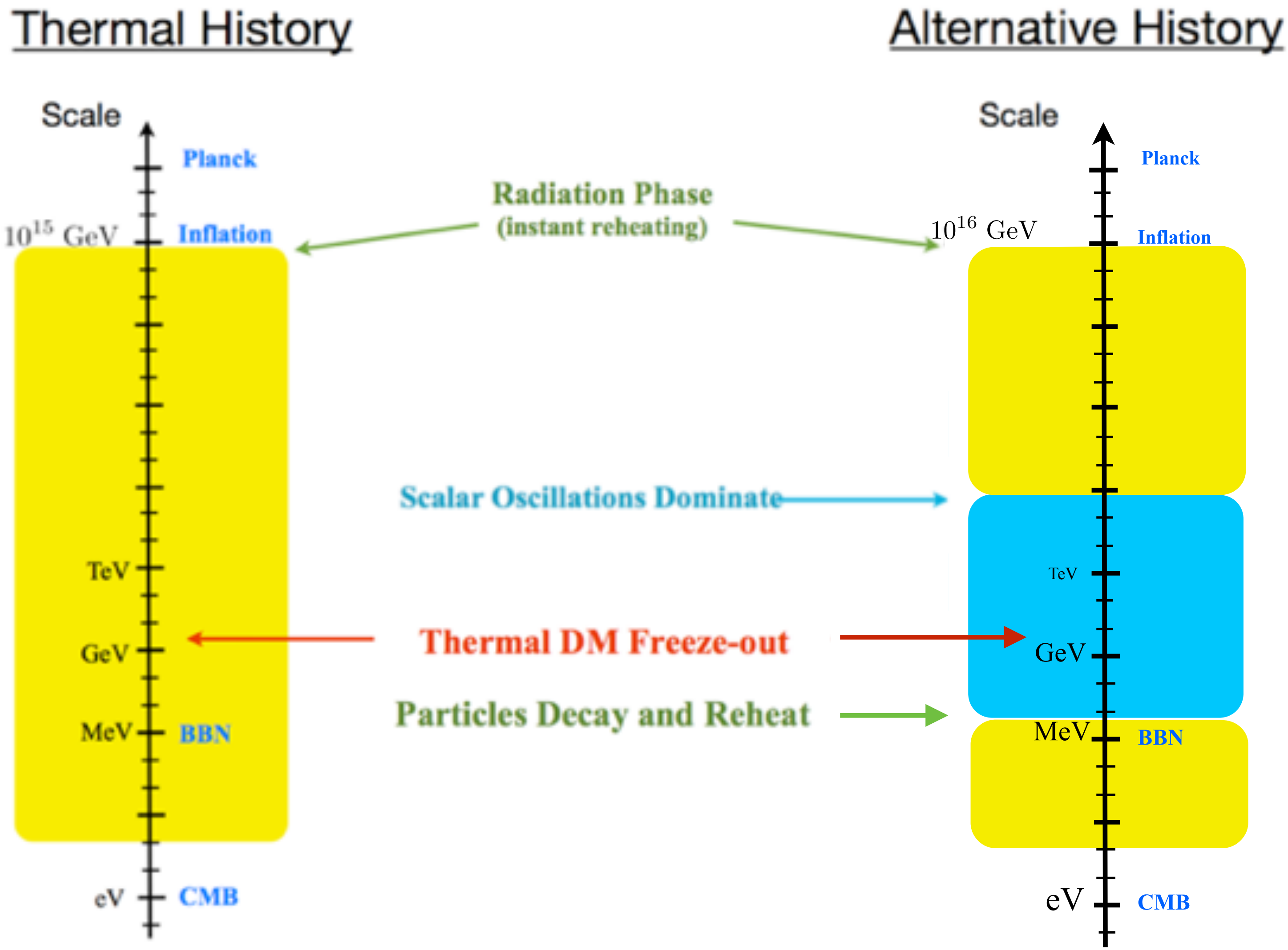
Dynamical Symmetry Breaking (e.g. SUSY)

Higgs / Strongly coupled dynamics?

EWSB Phase Transition

QCD Phase Transition

Can we probe the cosmic Dark Ages?



We've seen a number of reasons to consider a "non-thermal" alternative history.

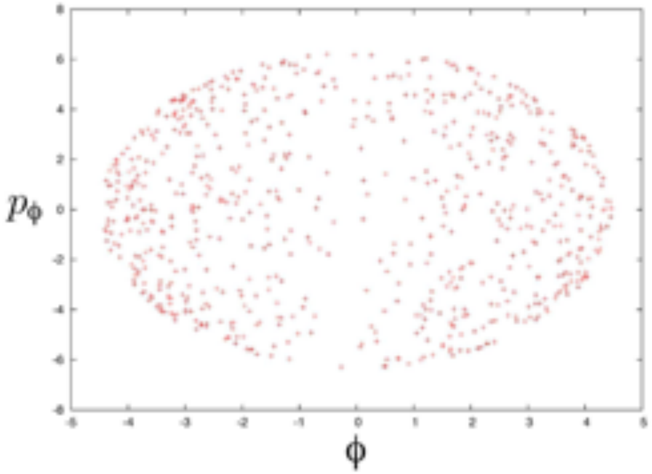
See talks by Allahverdi, Cicoli, and Sinha

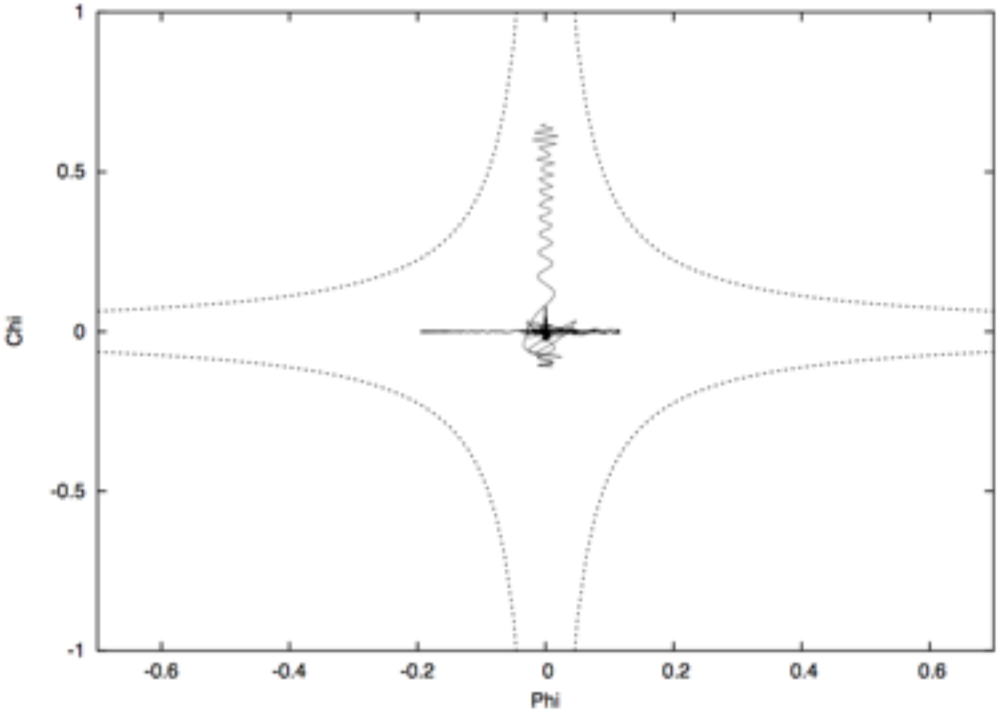
Motivation for non-thermal histories

Motivation from fundamental theory

Banks and Dine
S.W.   hep-th/0404177
with S. Cremonini hep-th/0601082
with B. Green, J. Levin, S. Jude, and A. Weltman (Arxiv: hep-th/0702220)

At least one scalar with shift symmetry expected.
(required for UV to decouple!)





Motivation for non-thermal histories

Motivation from fundamental theory

Banks and Dine (long ago)
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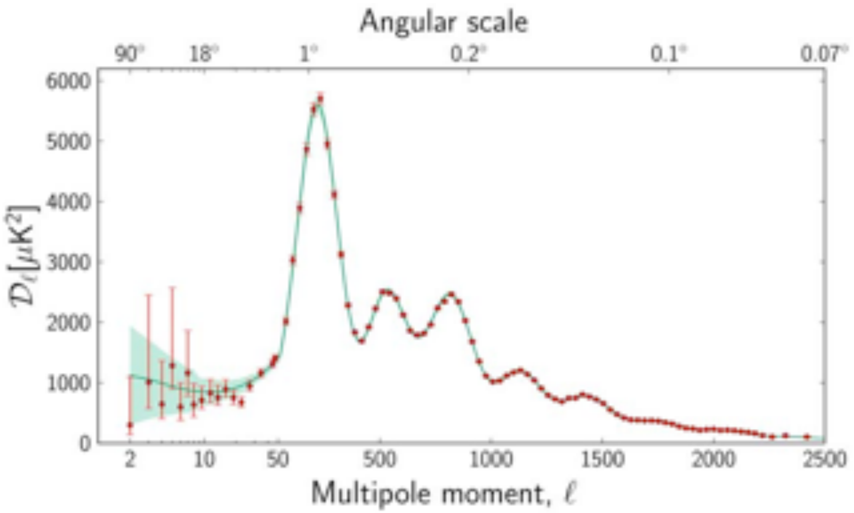
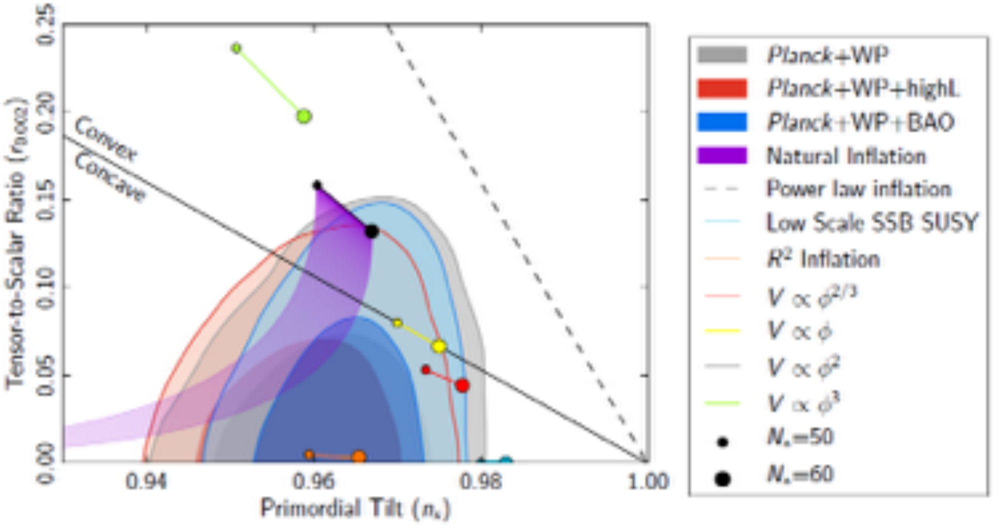
Motivation from model building

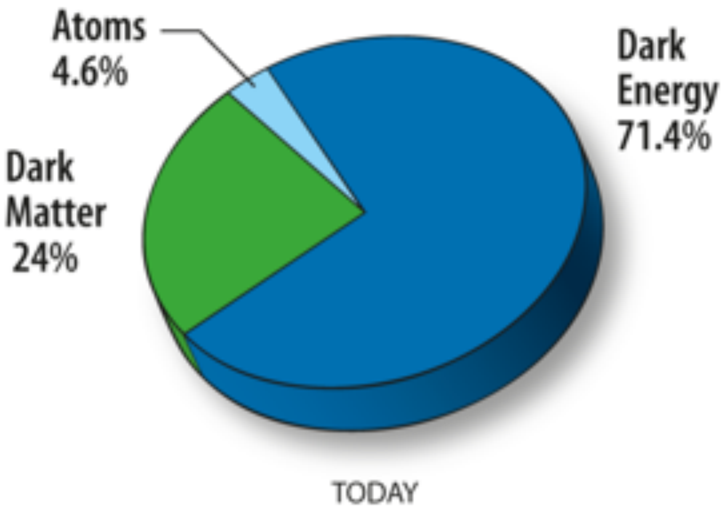
with B. Acharya, G. Kane, P. Kumar (Arxiv:0804.0863)
with G. Kane, A. Pearce, et. al. (Arxiv: 0807.1508)
(see talks by Allahverdi, Cicoli, and Sinha)

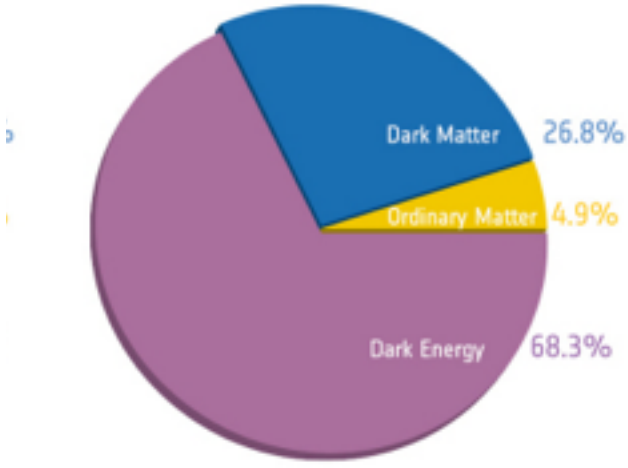
Another Motivation?

We have achieved an impressive level of precision within early and late universe cosmology









After Planck

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.

BICEP: Inflation is UV Sensitive

IF BICEP is confirmed:

Simplest interpretation implies an energy scale of inflation of 10^{16} GeV

Good: **Inflation probes GUT / String Scale Physics**
(also: gravity waves!)

Bad: **Difficult to build self consistent models.**

BICEP: Inflation is UV Sensitive

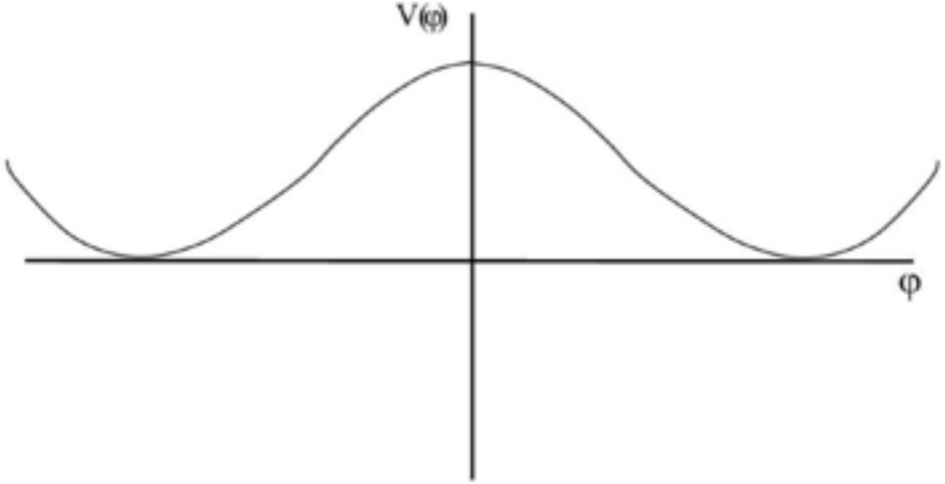
Bad: **Difficult to build self consistent models.**

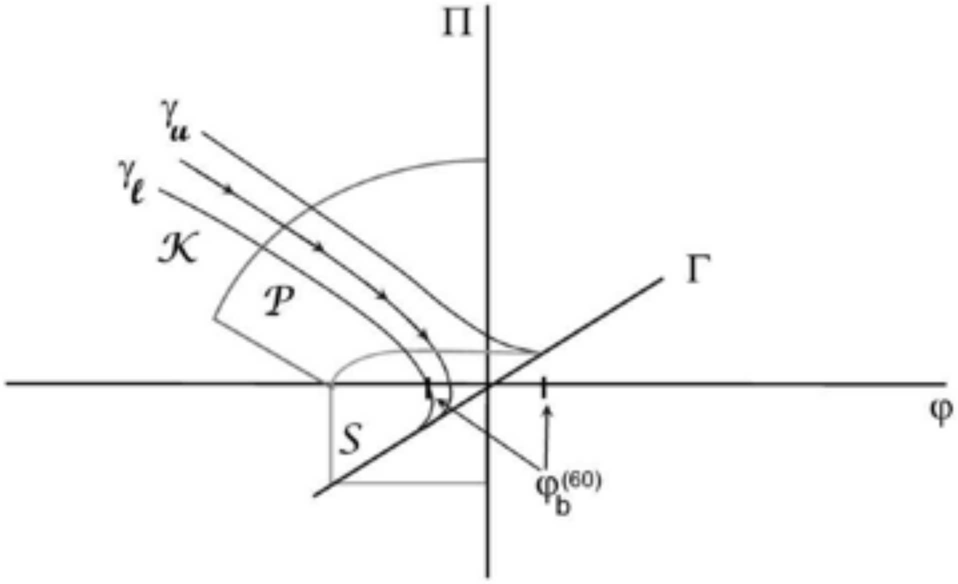
$$\mathcal{L}_{\rm eff}(\phi) = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{4}\lambda\phi^4 - \sum_{p=1}^{\infty}\left[\lambda_p\phi^4 + \nu_p(\partial\phi)^2\right]\left(\frac{g\,\phi}{\Lambda}\right)^{2p} + \dots,$$

Many of these operators can spoil inflation, particularly if r=0.2 (require large field models)

$$\hat{\mathcal{O}}_6 \subset \frac{\phi^6}{\Lambda^2} \to \frac{\langle\phi^4\rangle\phi_2}{\Lambda^2} \sim \frac{V_0}{m_p^2}\phi^2 = H^2\phi^2$$

Even without BICEP, large field models preferred





Small field models require tuning of initial conditions

shown long-ago:
D. S. Goldwirth, Phys. Lett. B 243, 41 (1990)
S.W. with R. Brandenberger, G. Geshnizjani (hep-th/0302222)

Successful Inflation?

$$\mathcal{L}_{\rm eff}(\phi) = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{4}\lambda\phi^4 - \sum_{p=1}^{\infty}\left[\lambda_p\phi^4 + \nu_p(\partial\phi)^2\right]\left(\frac{g\,\phi}{\Lambda}\right)^{2p} + \dots,$$

1. **Accept infinite fine tuning**

OR

2. **Impose shift symmetry**

$$\phi \to \phi + c$$

Even that is not enough, radiative / gravity corrections generically restore problem.

(imply Hubble scale mass)

Need additional symmetry, e.g. SUSY can help.

SUSY and Cosmology

Case One: Field resides within inflaton multiplet

$$X \subset x = \varphi + i\sigma$$

Case Two: Field and inflaton in different multiplets

$$x_1 = \varphi + i\varphi_2$$

$$x_2 = \sigma + i\sigma_2$$

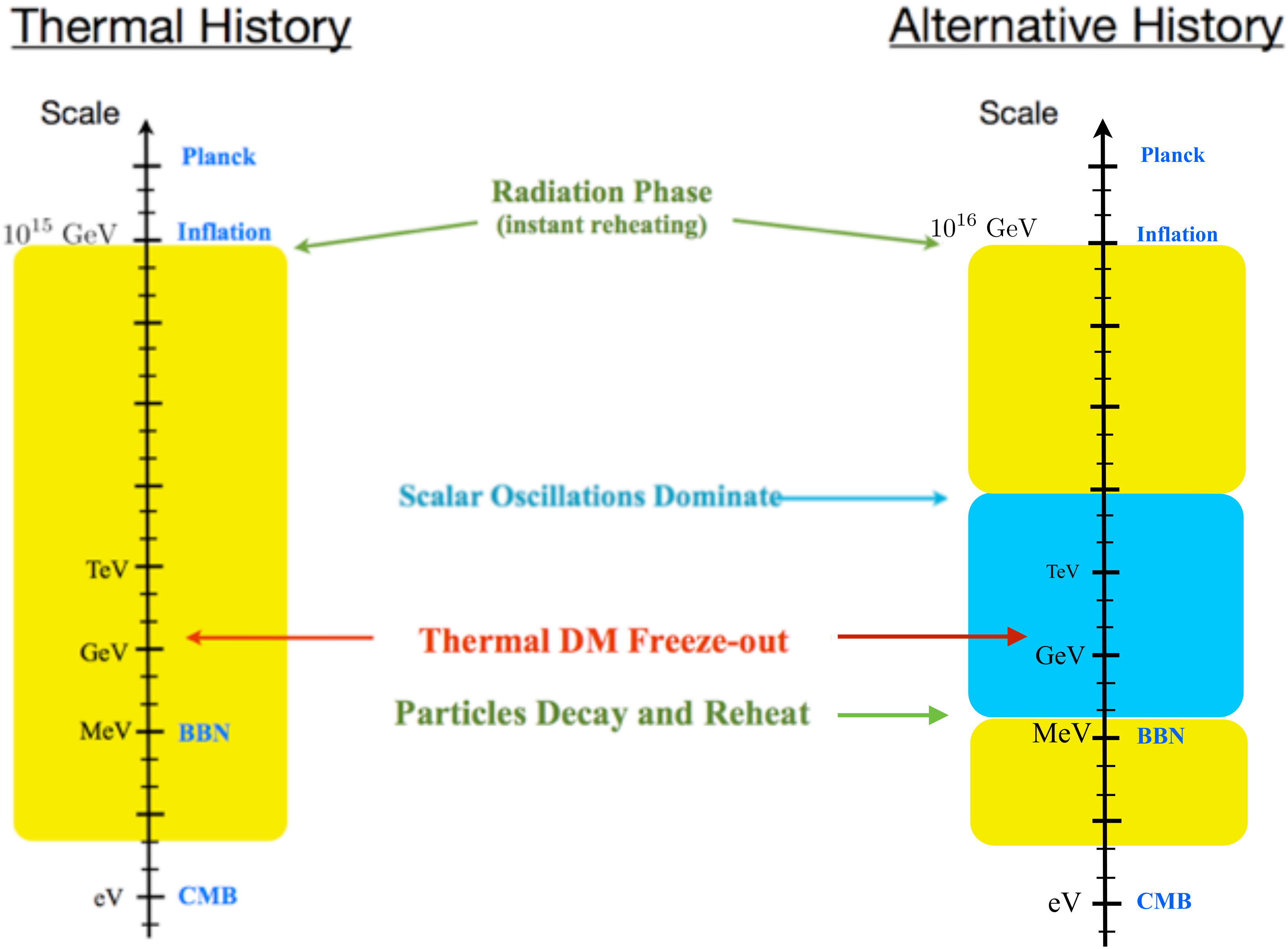
"Split Spectrum" $m_{3/2} \sim H_I$

$m_I < H_I$ **"Higgs"**

$m_\sigma \sim H_I$ **"Squarks"**

Upshot:

Consistent Inflation requires new, shift symmetric scalars with additional symmetry (like SUSY)



Thermal History

Scale

Planck

10^{15} GeV

Inflation

TeV

GeV

MeV

BBN

eV

CMB

Alternative History

Scale

Planck

10^{16} GeV

Inflation

TeV

GeV

MeV

BBN

eV

CMB

Radiation Phase
(instant reheating)

Scalar Oscillations Dominate

Thermal DM Freeze-out

Particles Decay and Reheat

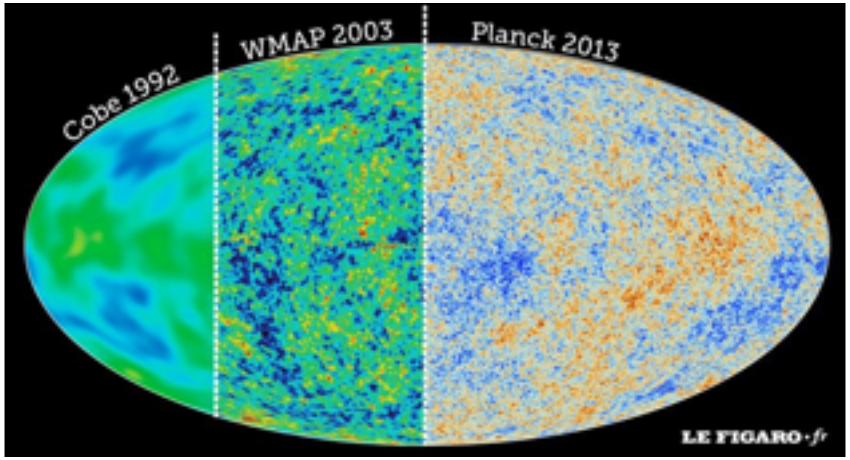
We have seen a number of arguments for alternatives to a thermal history

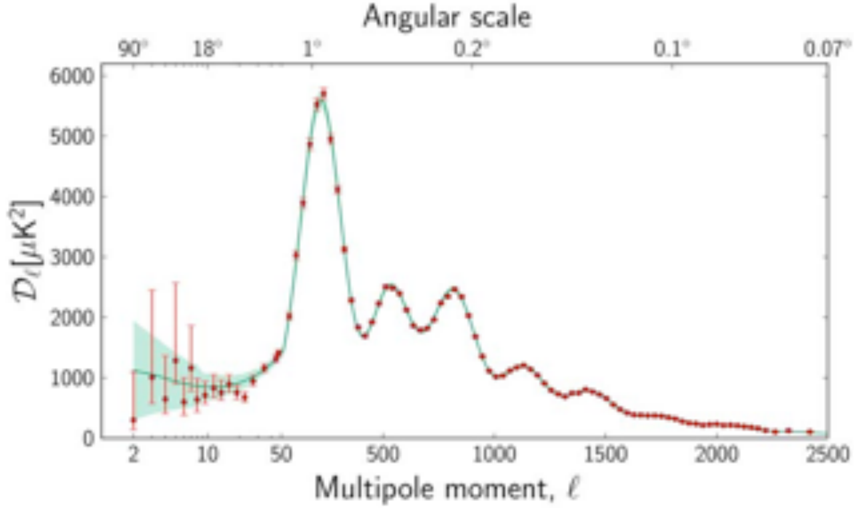
Plan for rest of talk

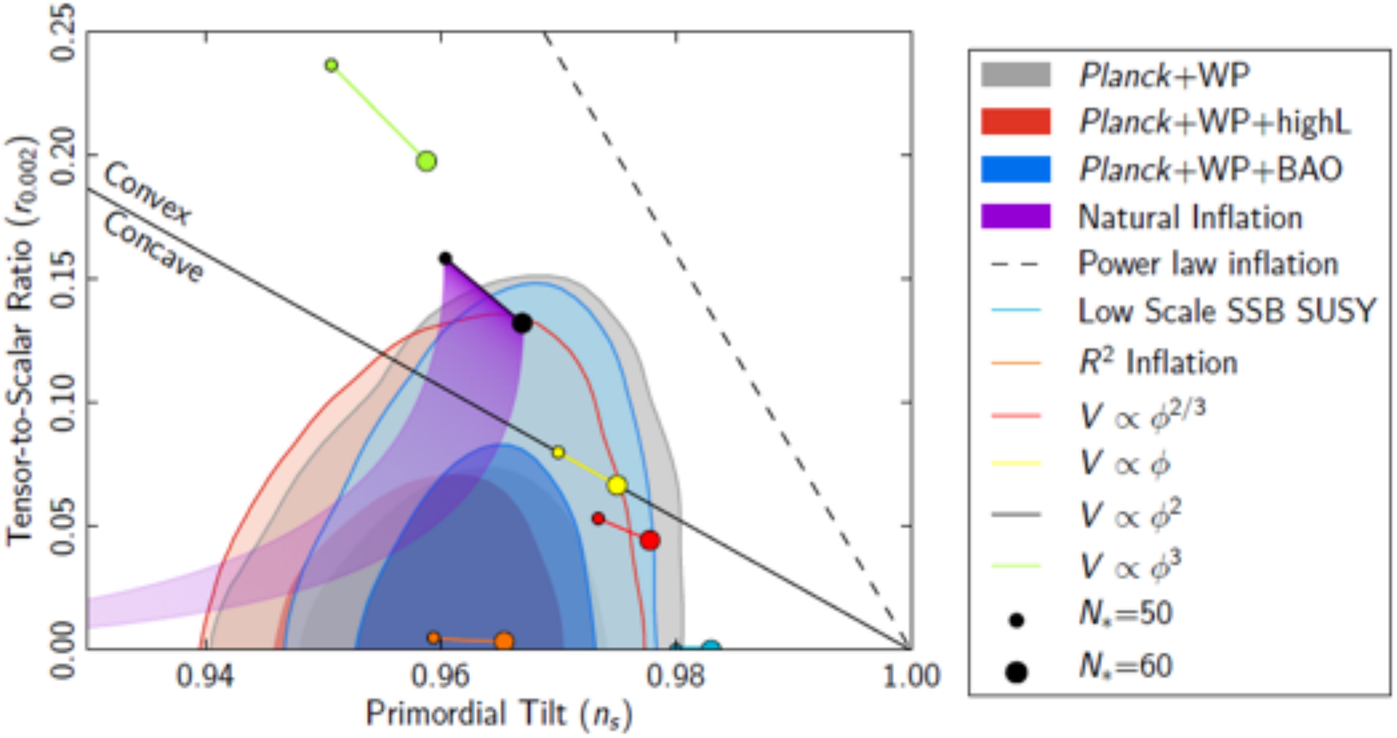
With motivation for an additional matter dominated phase:

- **Can alternative histories be tested?**
  - **Effect on CMB**
  - **Effect on Growth of Structure**
  - Effect on Dark Matter

Planck has constrained models of inflation to an impressive level of accuracy

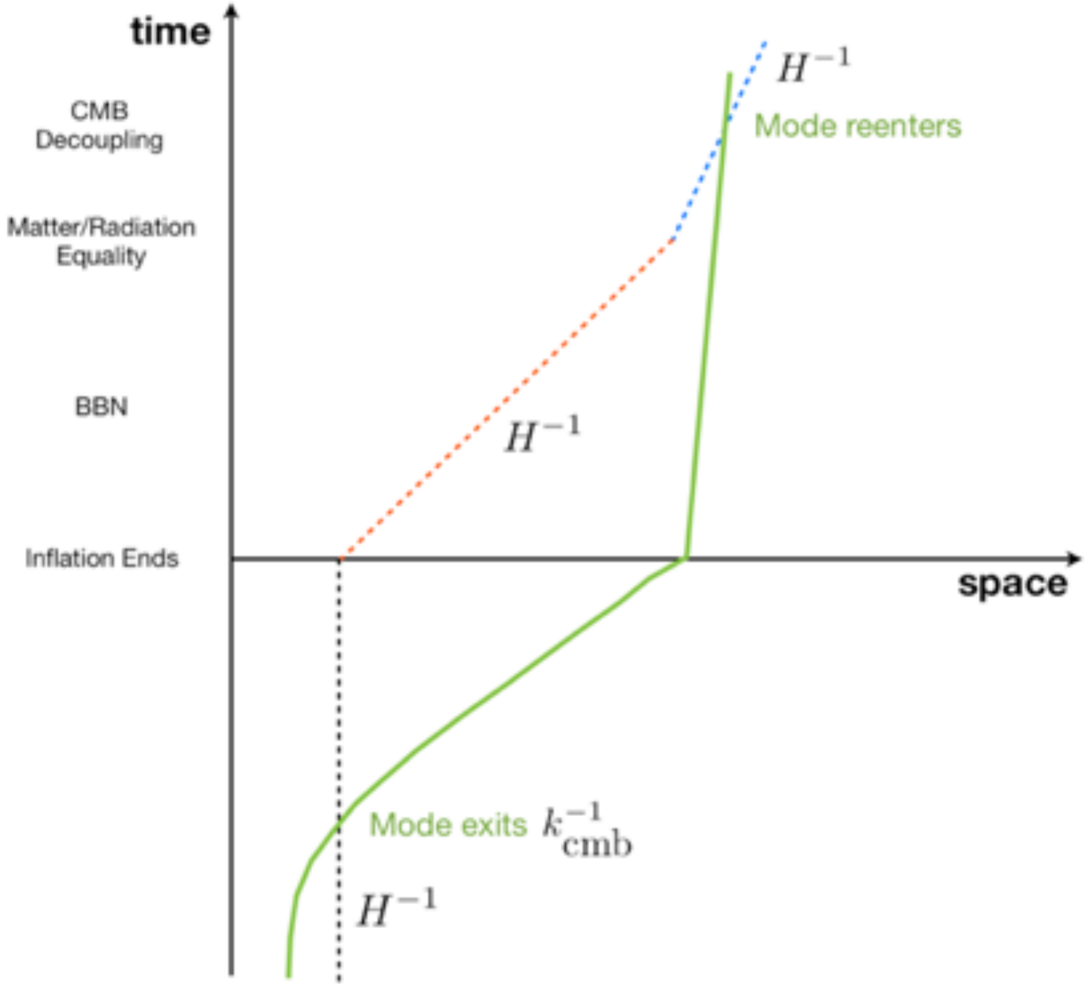






There is an uncertainty in matching observable modes today with a particular inflationary model during inflation

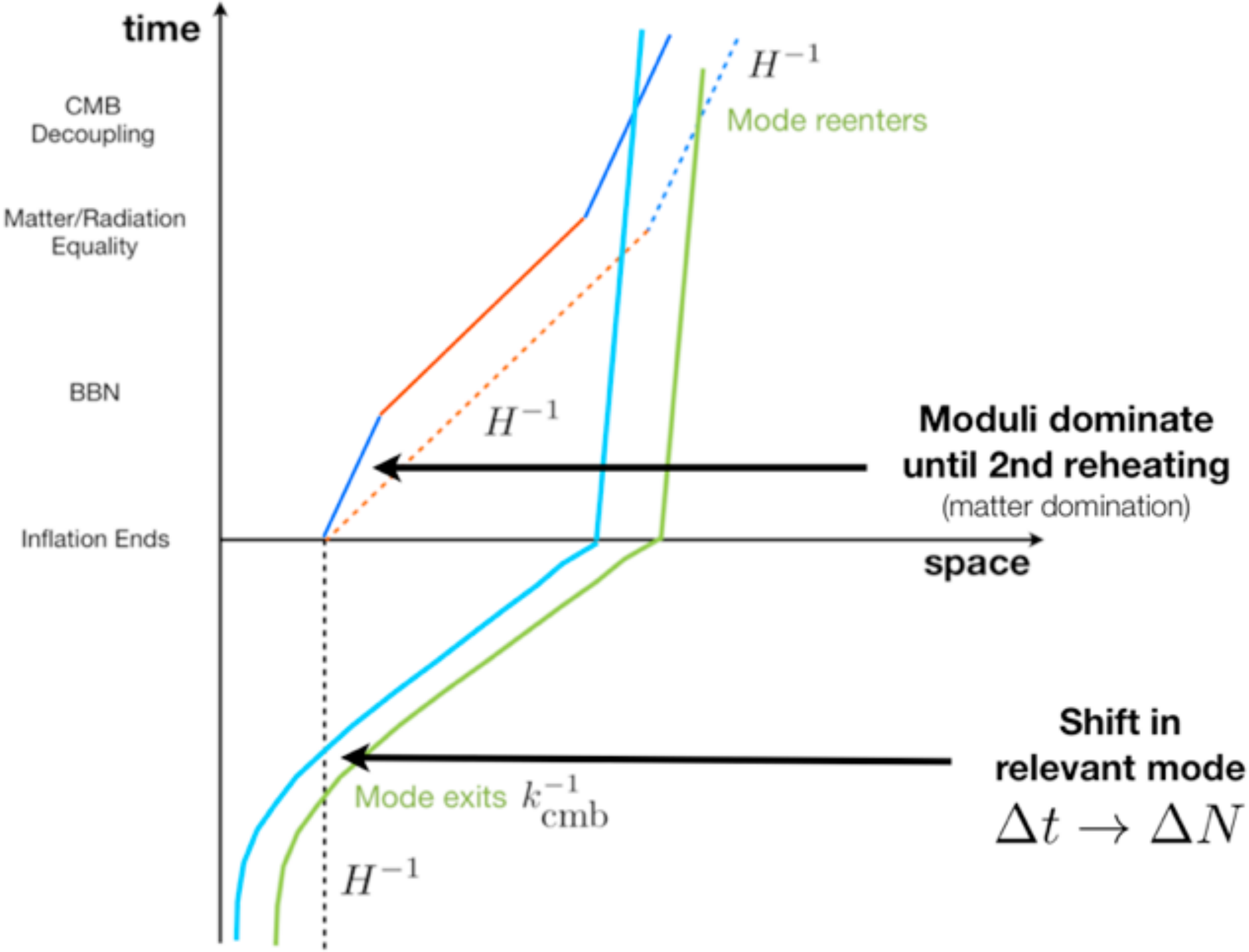
(related to scale of inflation and how it ends)



Matching Equation

$$N(k,w) \simeq 71.21 - \ln\left(\frac{k}{a_0 H_0}\right) + \frac{1}{4}\ln\left(\frac{V_k}{m_p^4}\right) + \frac{1}{4}\ln\left(\frac{V_k}{\rho_{end}}\right)$$

Universe with Non-thermal History



Moduli dominate until 2nd reheating

(matter domination)

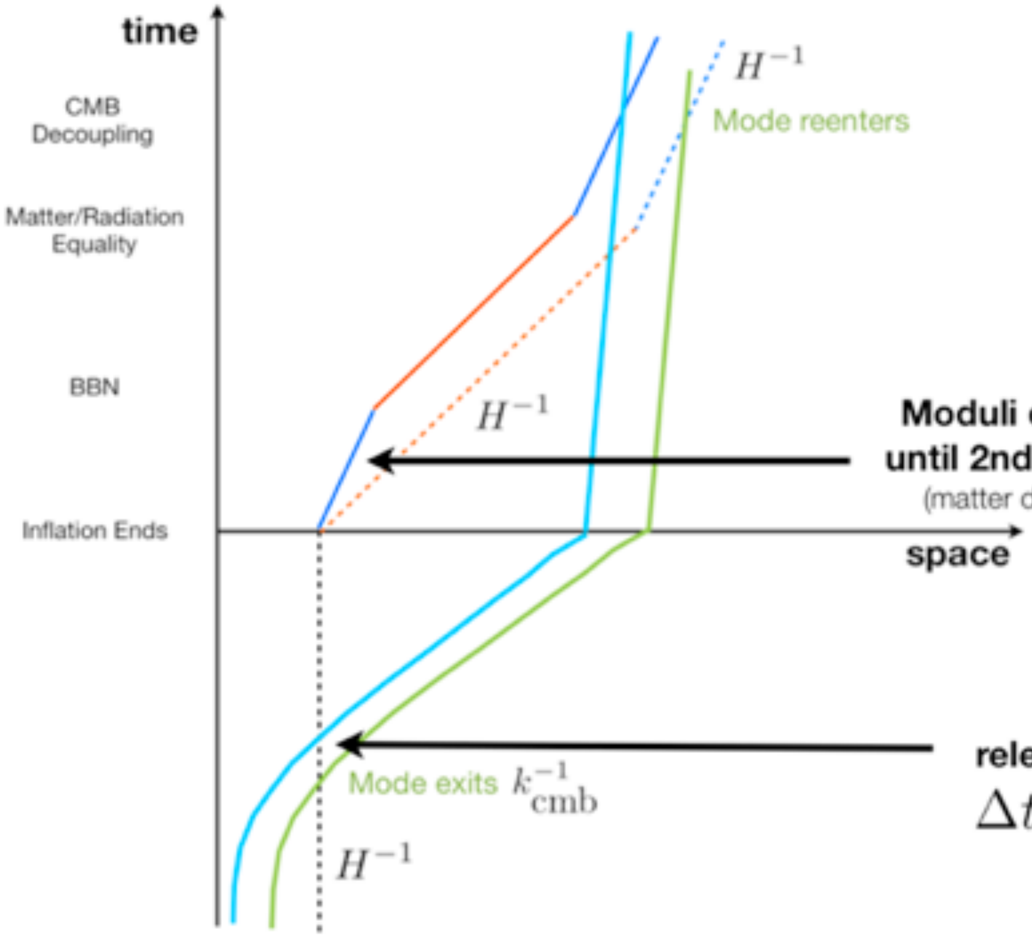
Shift in relevant mode

$\Delta t \to \Delta N$

Universe with Non-thermal History

Additional change from standard case

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



Moduli dominate until 2nd reheating
(matter domination)

Shift in relevant mode
$\Delta t \rightarrow \Delta N$

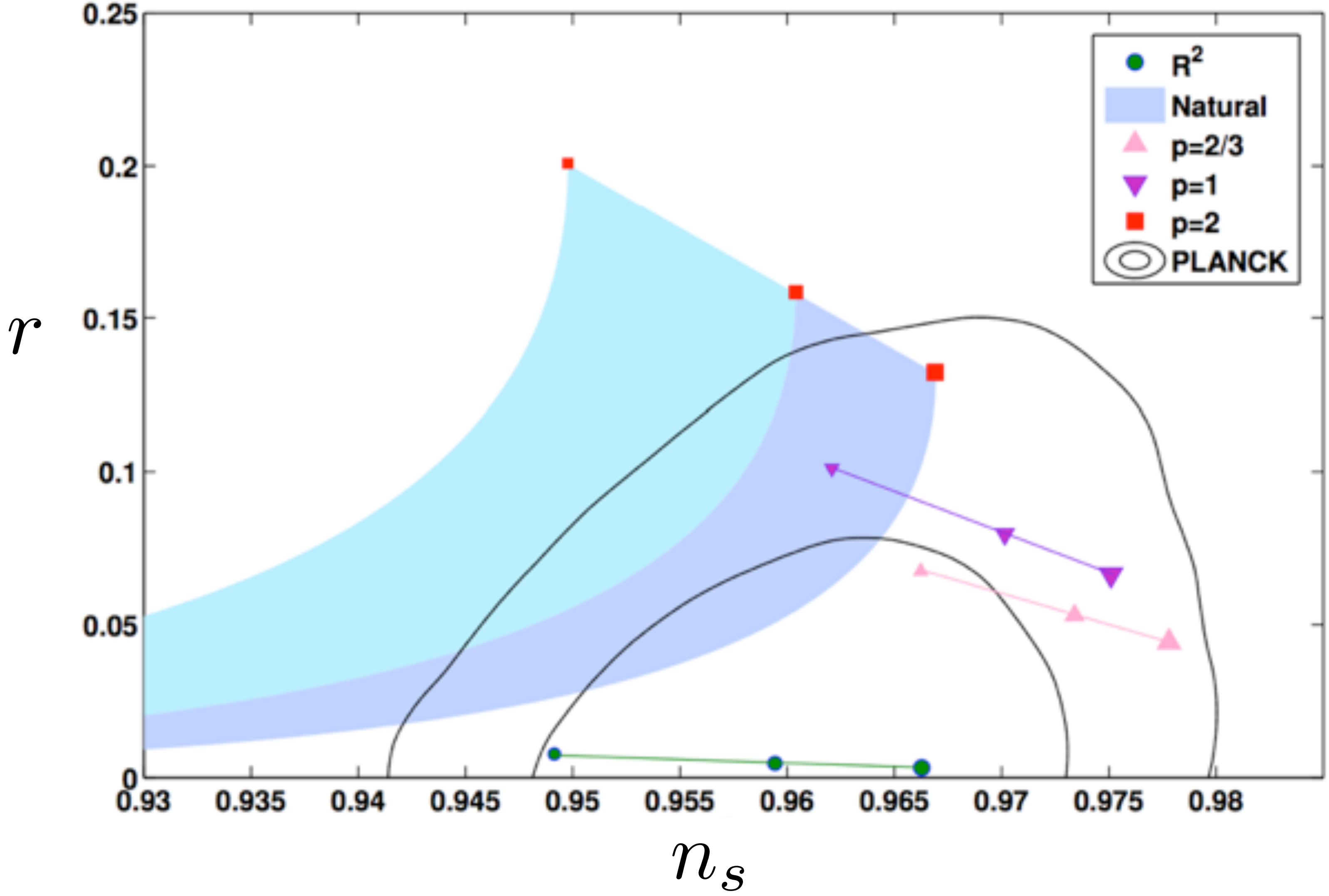
$$\Delta n_s = (n_s - 1)\left[-\frac{5}{16}r - \frac{3}{64}\frac{r^2}{n_s - 1}\right]\Bigg|\,\Delta N,$$

$$\Delta r = r\left[(n_s - 1) + \frac{r}{8}\right]\Bigg|\,\Delta N.$$

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

More freedom for inflationary constraints with SUSY

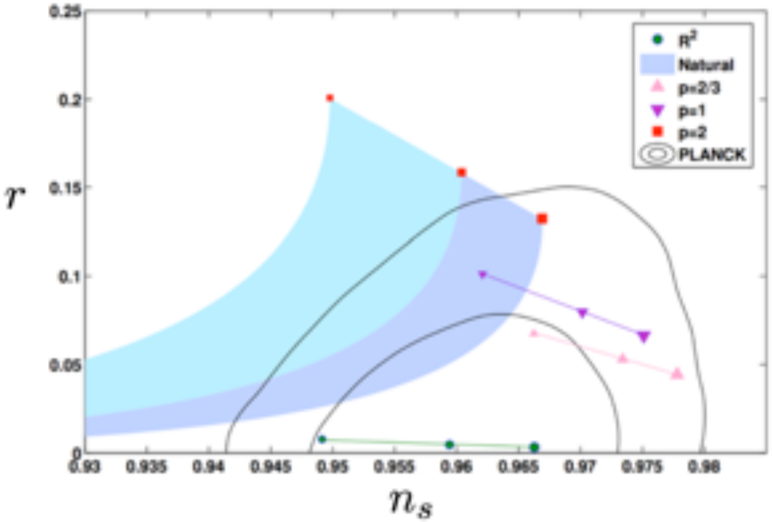
ArXiv:1307.2453
with R. Easther (Auckland), R. Galvez, and O. Ozsoy (Syracuse)



Uncertainty due to reheat temperature

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

$$\Delta N = -10.68 + \underbrace{\frac{1}{18}\ln\left[\left(\frac{g_*(T_r^\sigma)}{10.75}\right)\left(\frac{T_r}{3\ \mathrm{MeV}}\right)^4\left(\frac{m_p}{\Delta\sigma}\right)^3\right]}_{\textbf{Maximum of} \sim \textbf{10}}$$

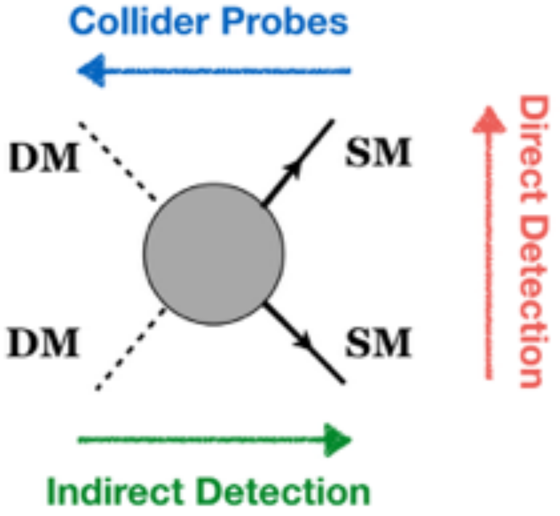


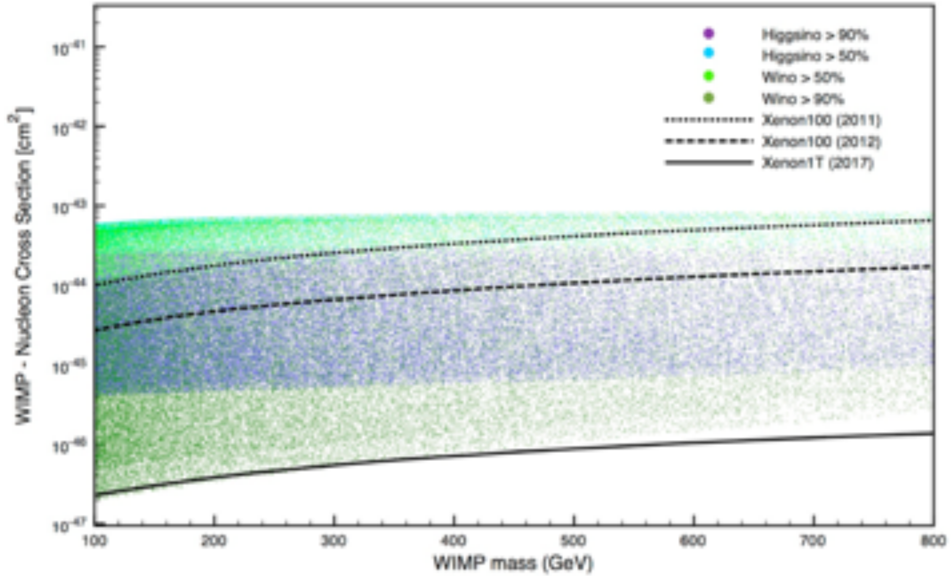
Establish bounds on reheat temperature?

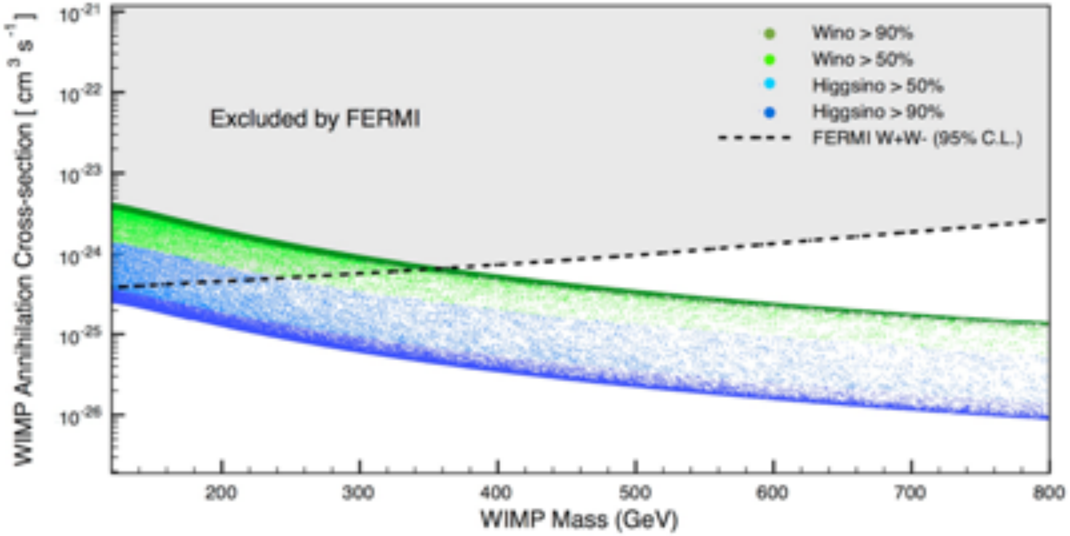
→ Restrict Inflation Models

Reheat temperature and Non-thermal Dark Matter

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







The Plan: $\Omega_{DM} = 0.23 \left(\frac{10^{-26}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_i v_i \rangle}\right)\left(\frac{T_f}{T_r}\right)$

1. $\Omega_{\rm dm}^{\rm Planck} = 0.23$
2. $\langle \sigma_x v_x \rangle^{\rm obs}$
3. Find constraint on reheat temperature

Reheat temperature and Non-thermal Dark Matter

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

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

<u>The Plan:</u> $\Omega_{DM} = 0.23\left(\frac{10^{-26}\ \mathrm{cm}^3/\mathrm{s}}{\langle\sigma_x v_x\rangle}\right)\left(\frac{T_f}{T_r}\right)$

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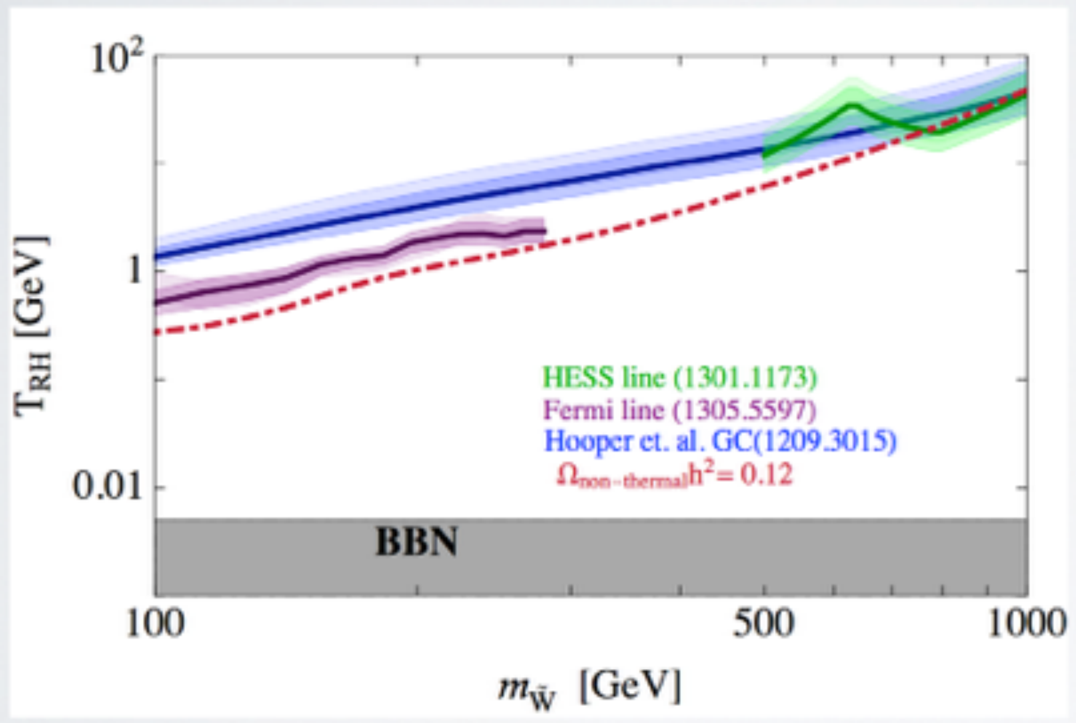


Fan and Reece 1307.4400

Wino in trouble,
Bounds on general neutralinos (Higgsino) will improve with Xenon1T

Not-so Non-thermal Universe and the CMB

Constraining SUSY with Heavy Scalars — using the CMB ArXiv:1312.363

with L. Illiesiu (Princeton), D. Marsh (PI), K. Moodley (KwaZulu Natal U.)

Initial displacement could be sub-Planckian

$$\Delta\sigma \sim M < m_p$$

Operator lifting flat direction is important (model dependent)

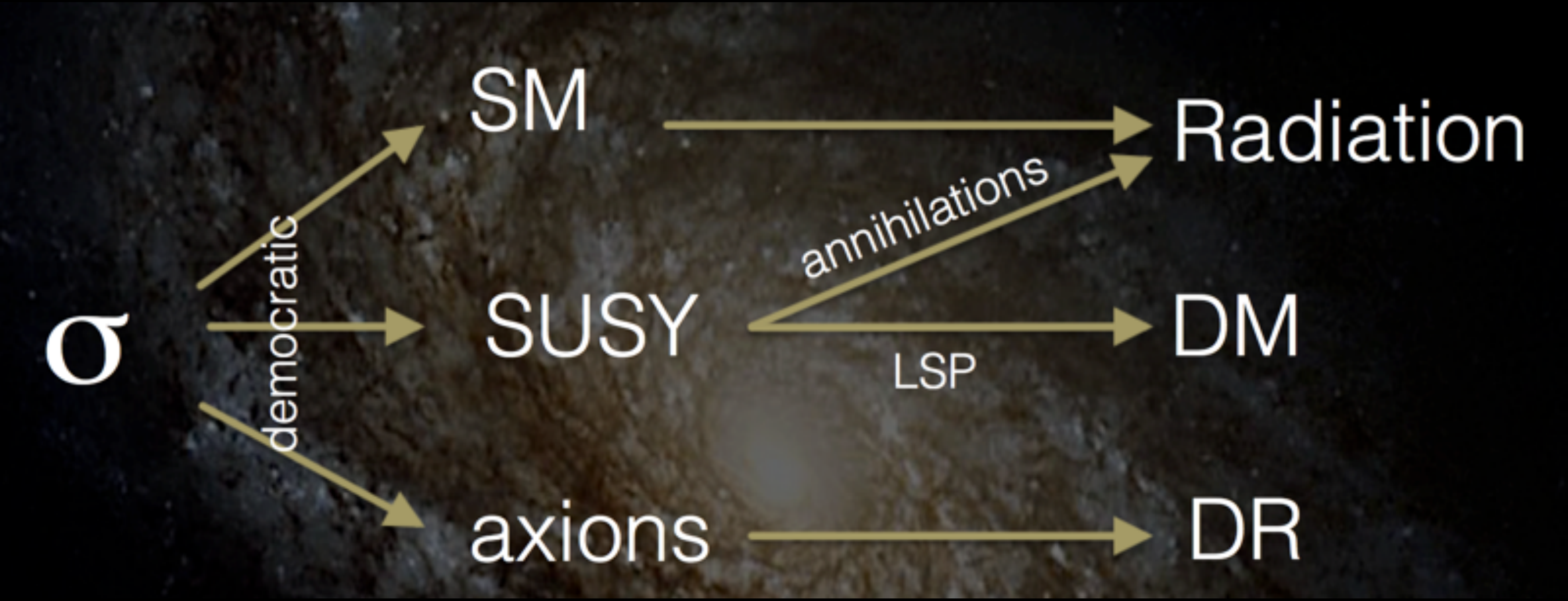
$$V(\sigma) = 0 + m_{\rm soft}^2\sigma^2 - H_I^2\sigma^2 + \frac{1}{M^{2n}}\sigma^{4+2n}$$

$$\langle\sigma\rangle \simeq M\left(\frac{H_I}{M}\right)^{\frac{1}{n+1}}$$

Isocurvature and Dark Radiation constraints?

(sub-dominant case)

In addition to inflaton we have:



Isocurvature and Dark Radiation constraints?

(sub-dominant case)

In addition to inflaton we have:

σ

democratic

SM

SUSY

axions

Radiation

annihilations

DM

LSP

DR

Isocurvature and Dark Radiation Constraints

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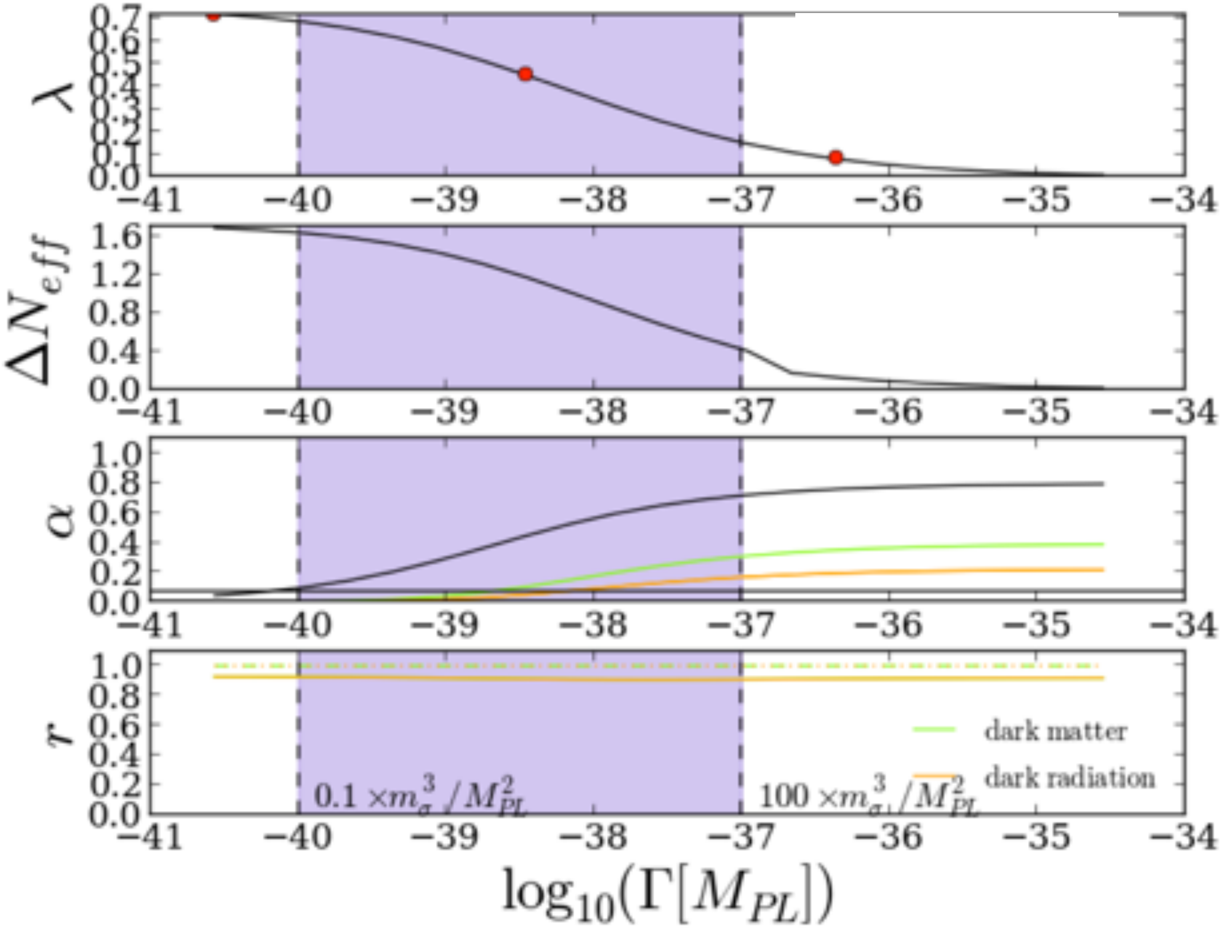
Relative contribution of modulus to curvature perturbation

Amount of Dark Radiation

Isocurvature contribution

Correlation between modes (single source = correlated)



Isocurvature and Dark Radiation Constraints

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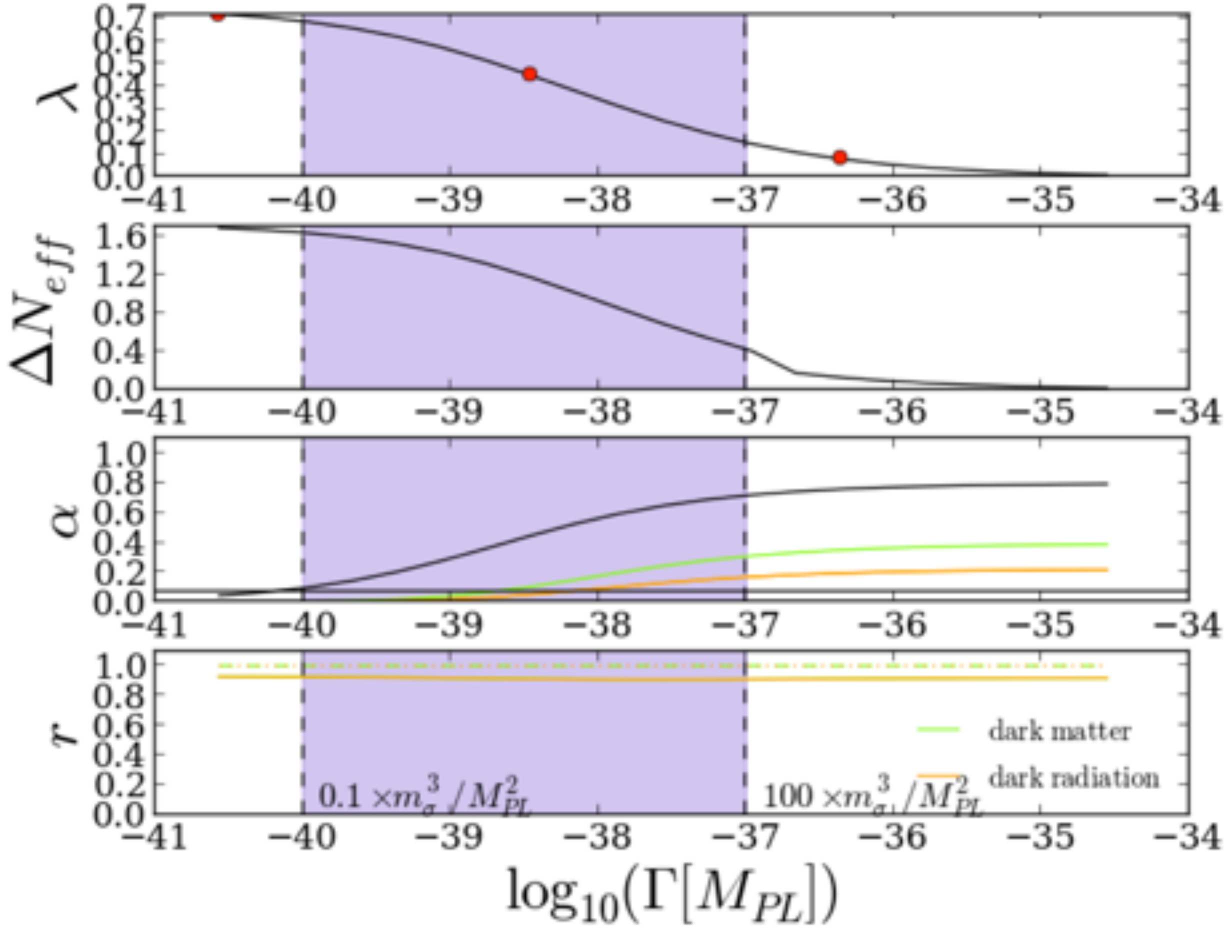


$$t_d \sim H_d^{-1} \sim \Gamma_\sigma^{-1}$$

The longer the moduli live, the larger their contribution to the energy density

$$\rho_\sigma \sim a(t)\rho_r$$

Thus, more dark radiation (Neff), less isocurvature

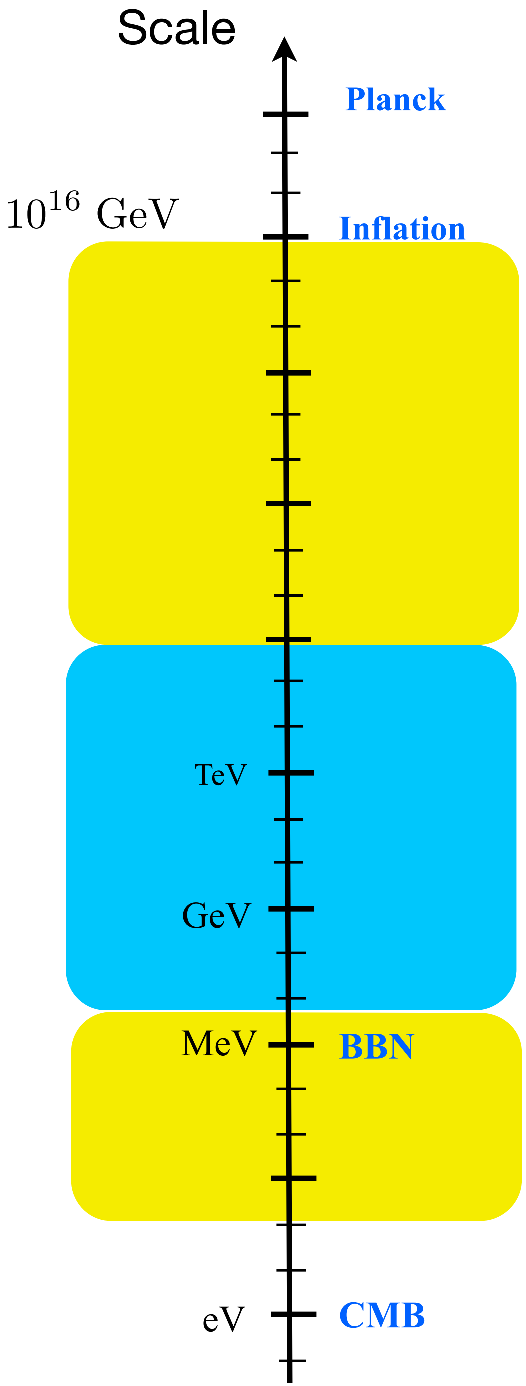
Plan for rest of talk

With motivation for an additional matter dominated phase:

- **Can alternative histories be tested?**
    - **Effect on CMB**
    - **Effect on Growth of Structure**
    - Effect on Dark Matter

Enhancement of Small Scale structure?

To appear with JiJi Fan and Ogan Ozsoy



Radiation Phase
(instant reheating)

Scalar Oscillations Dominate

$$H \sim m_\varphi$$

DM Freeze-out

Scalar Decay $H \sim \Gamma_\varphi$

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

Post Inflationary Evolution

To appear with JiJi Fan and Ogan Ozsoy

Consider the dominant case (with matter domination):

$$\Delta\sigma \sim m_p \qquad m_\sigma \sim 100\,\mathrm{TeV}$$

After coherent oscillations begin $t_{\rm osc} \sim H_{\rm osc}^{-1} \sim m_\sigma^{-1}$

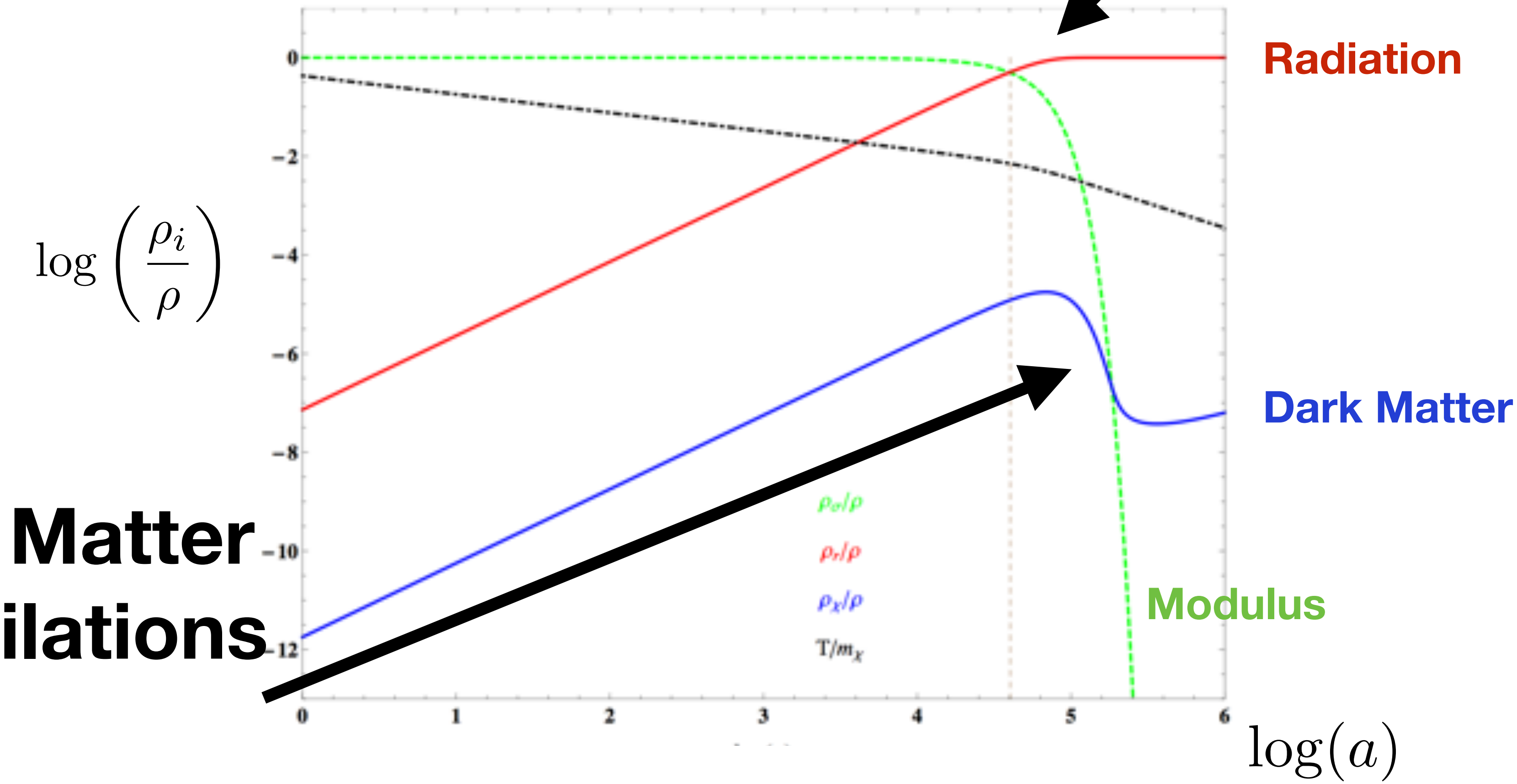
$$\begin{aligned}
\dot{\rho}_\sigma &= -3H\rho_\sigma - \Gamma_\sigma\rho_\sigma, \\
\dot{\rho}_r &= -4H\rho_r + (1-B_\chi)\Gamma_\sigma\rho_\sigma + \frac{\langle\sigma v\rangle}{m_\chi}\left[\rho_\chi^2 - \rho_{\chi,eq}^2\right], \\
\dot{\rho}_\chi &= -3H\rho_\chi + B_\chi\Gamma_\sigma\rho_\sigma -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

Post Inflationary Evolution

To appear with JiJi Fan and Ogan Ozsoy

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

“Reheating”



Radiation

Dark Matter

Modulus

Dark Matter annihilations

Non-thermal Histories and the Matter Power Spectrum

To appear with JiJi Fan and Ogan Ozsoy

$$ds^2 = -(1+2\Phi)dt^2 + a^2(t)(1-2\Phi)d\vec{x}^2$$

$$\left(\frac{k^2}{3a^2H^2}+1\right)\Phi + \Phi' = -\frac{1}{6H^2m_p^2}\sum_\alpha \delta\rho_{(\alpha)},$$

$$\Phi' + \Phi = -\frac{1}{2Hm_p^2}\sum_\alpha \left(\rho_{(\alpha)} + p_{(\alpha)}\right) u_{(\alpha)}$$

$$N = \ln a$$

Non-thermal Histories and the Matter Power Spectrum

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$$N = \ln a$$

$$\begin{aligned}
\delta'_\sigma + \frac{\theta_\sigma}{aH} - 3\Phi' &= \\
\delta'_\chi + \frac{\theta_\chi}{aH} - 3\Phi' &= \\
\delta'_r + \frac{4}{3}\frac{\theta_r}{aH} - 4\Phi' &= \\
\theta'_\sigma + \theta_\sigma - \frac{k^2}{aH}\Phi &= \\
\theta'_\chi + \theta_\chi - \frac{k^2}{aH}\Phi &= \\
\theta'_r - \frac{k^2}{aH}\left(\frac{\delta_r}{4} + \Phi\right) &=
\end{aligned}$$

Non-thermal Histories and the Matter Power Spectrum

To appear with JiJi Fan and Ogan Ozsoy

$$ds^2 = -(1+2\Phi)dt^2 + a^2(t)(1-2\Phi)d\vec{x}^2$$

$$\left(\frac{k^2}{3a^2H^2}+1\right)\Phi + \Phi' = -\frac{1}{6H^2m_p^2}\sum_\alpha \delta\rho_{(\alpha)},$$

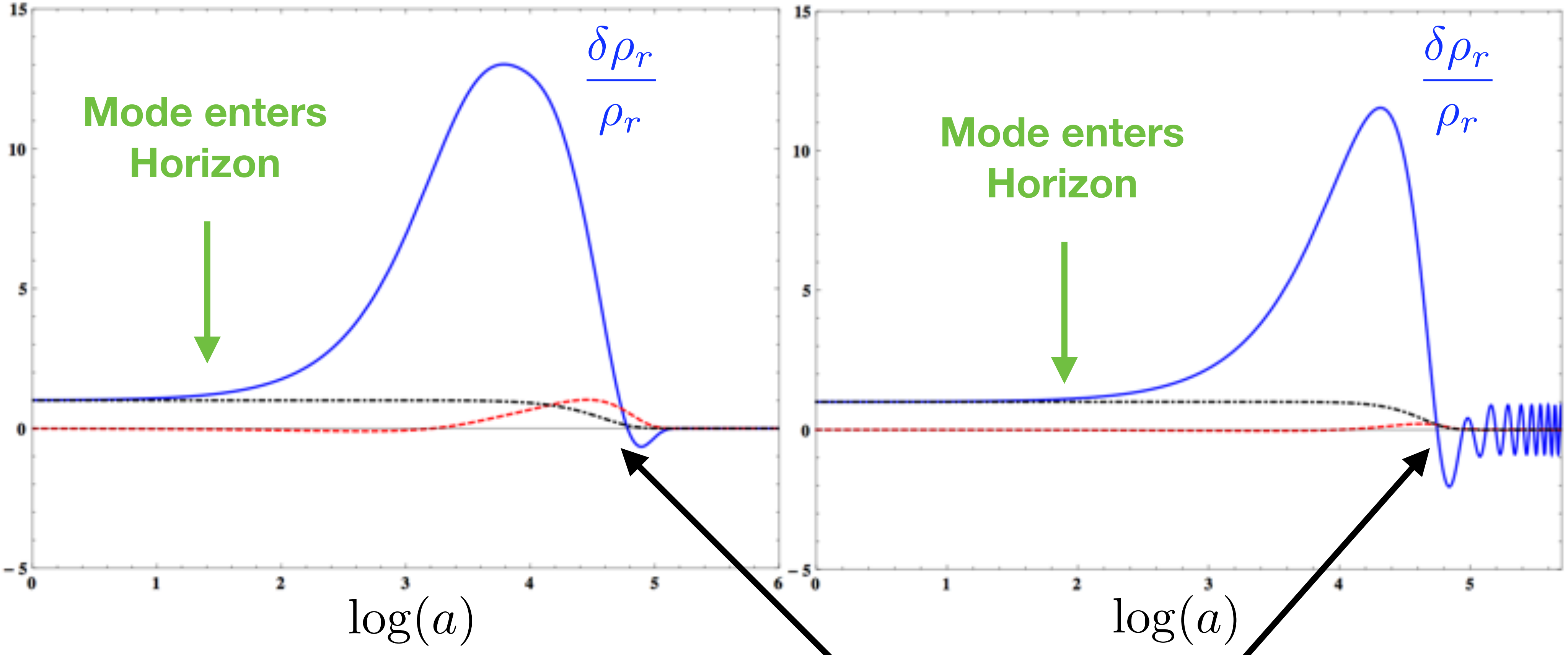
$$\Phi' + \Phi = -\frac{1}{2Hm_p^2}\sum_\alpha \left(\rho_{(\alpha)} + p_{(\alpha)}\right) u_{(\alpha)}$$

$$N = \ln a$$

$$\begin{aligned}
\delta'_\sigma + \frac{\theta_\sigma}{aH} - 3\Phi' &= -\frac{\Gamma_\sigma}{H}\Phi, \\
\delta'_\chi + \frac{\theta_\chi}{aH} - 3\Phi' &= B_\chi \frac{\Gamma_\sigma}{H}\left(\frac{\rho_\sigma}{\rho_\chi}\right)[\delta_\sigma - \delta_\chi + \Phi] - \frac{\langle\sigma v\rangle}{m_\chi H}\rho_\chi[\delta_\chi + \Phi], \\
\delta'_r + \frac{4}{3}\frac{\theta_r}{aH} - 4\Phi' &= (1-B_\chi)\frac{\Gamma_\sigma}{H}\left(\frac{\rho_\sigma}{\rho_r}\right)[\delta_\sigma - \delta_r + \Phi] + \frac{\langle\sigma v\rangle}{m_\chi H}\left(\frac{\rho_\chi}{\rho_r}\right)\rho_\chi[2\delta_\chi - \delta_r + \Phi], \\
\theta'_\sigma + \theta_\sigma - \frac{k^2}{aH}\Phi &= 0, \\
\theta'_\chi + \theta_\chi - \frac{k^2}{aH}\Phi &= B_\chi \frac{\Gamma_\sigma}{H}\left(\frac{\rho_\sigma}{\rho_\chi}\right)[\theta_\sigma - \theta_\chi], \\
\theta'_r - \frac{k^2}{aH}\left(\frac{\delta_r}{4} + \Phi\right) &= (1-B_\chi)\frac{\Gamma_\sigma}{H}\left(\frac{\rho_\sigma}{\rho_r}\right)\left[\frac{3}{4}\theta_\sigma - \theta_r\right] + \frac{\langle\sigma v\rangle}{m_\chi H}\left(\frac{\rho_\chi}{\rho_r}\right)\rho_\chi\left[\frac{3}{4}\theta_\chi - \theta_r\right],
\end{aligned}$$

Radiation Perturbation during Non-thermal Phase

To appear with JiJi Fan and Ogan Ozsoy



Reheating

Longer moduli phase, lower reheat temperature = more suppression

Matter Perturbation During Moduli Phase

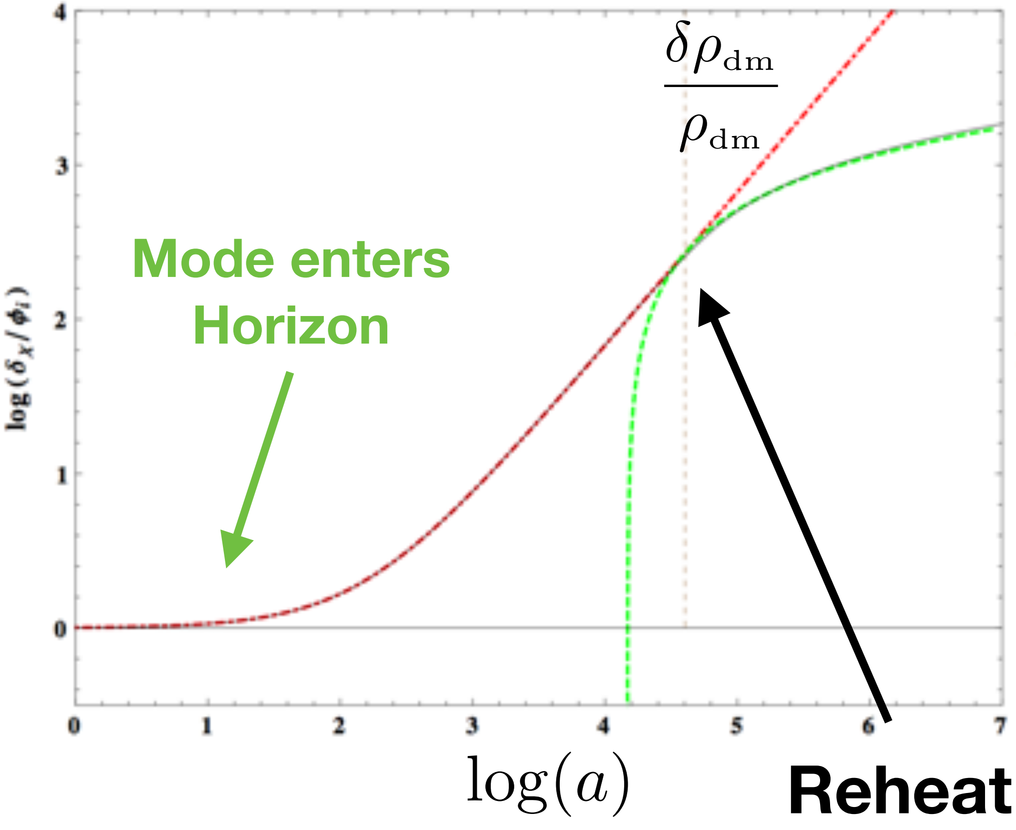
To appear with JiJi Fan and Ogan Ozsoy

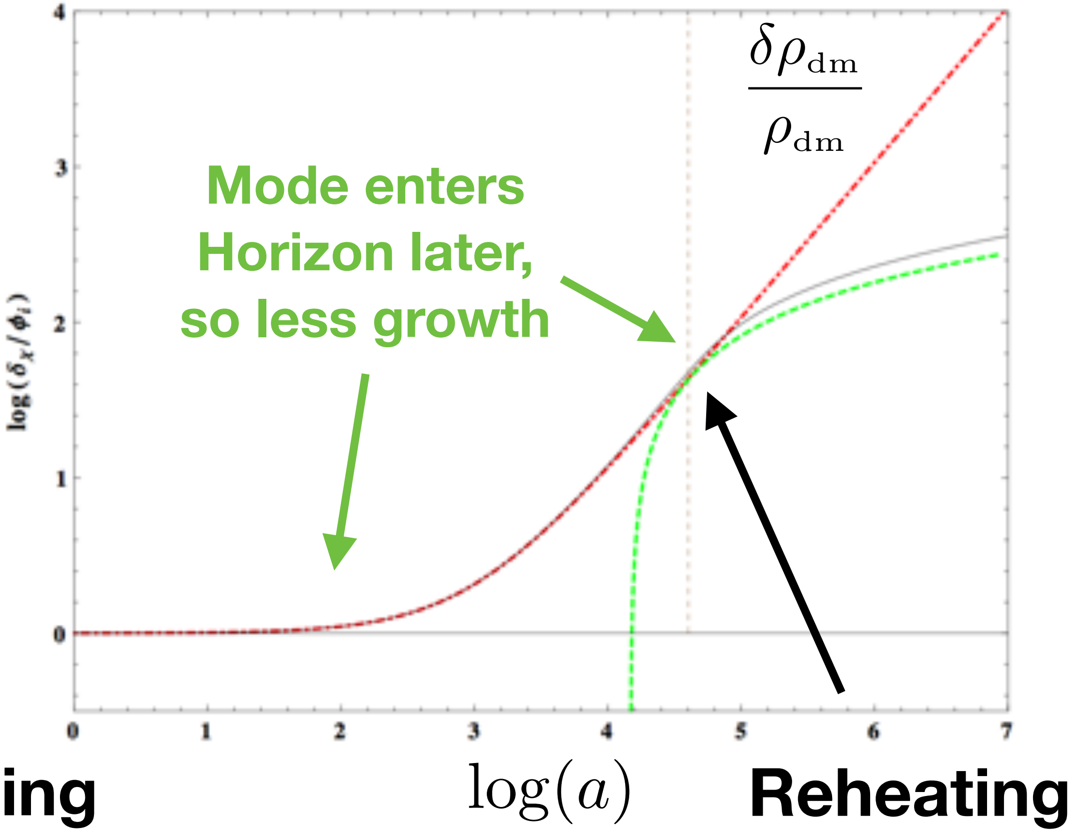
Scalar domination

$$\frac{\delta\rho_{\rm dm}}{\rho_{\rm dm}} \sim a(t)$$

Radiation domination

$$\frac{\delta\rho_{\rm dm}}{\rho_{\rm dm}} \sim \log a(t)$$

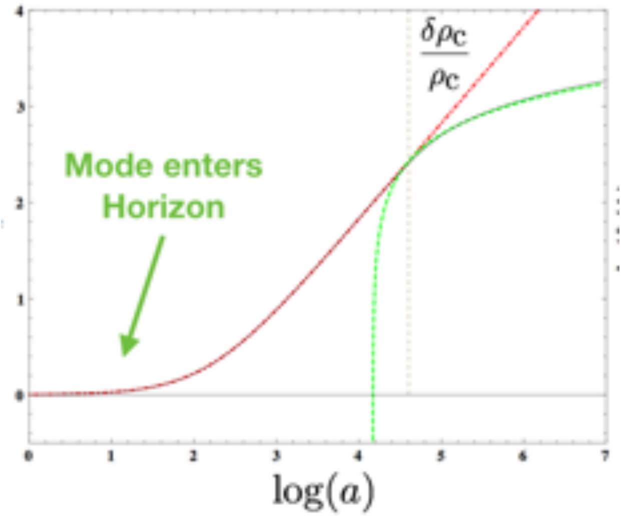




Non-thermal Histories and the Matter Power Spectrum

To appear with JiJi Fan and Ogan Ozsoy

Compare to: Arxiv:1106.0536 Erickcek and Sigurdson

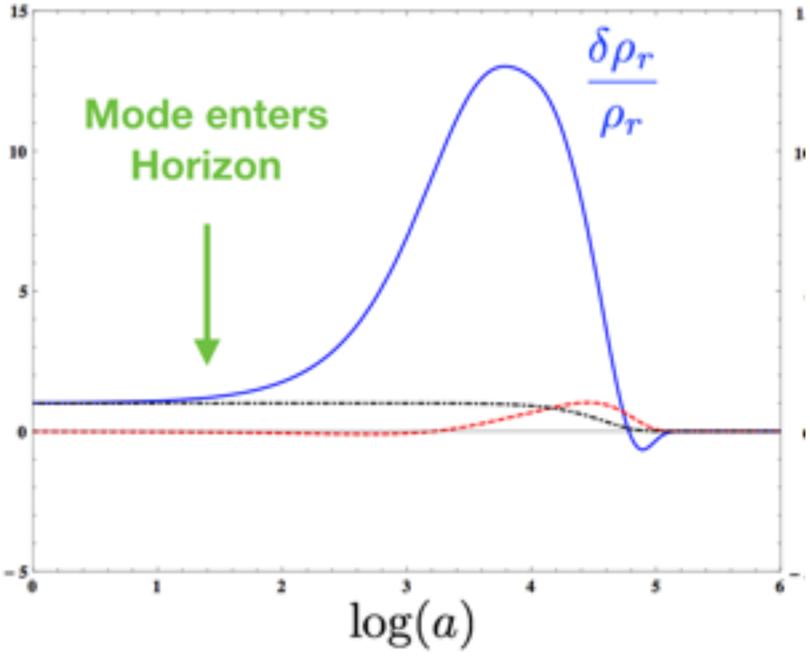


IF: A lot of the dark matter is produced before completed decay

THEN: Enhanced growth of structure on small scales possible.

IF: Most of the dark matter produced from thermal bath after reheating

Then: New suppression scale to determine smallest primordial structures.



Non-thermal Histories and the Matter Power Spectrum

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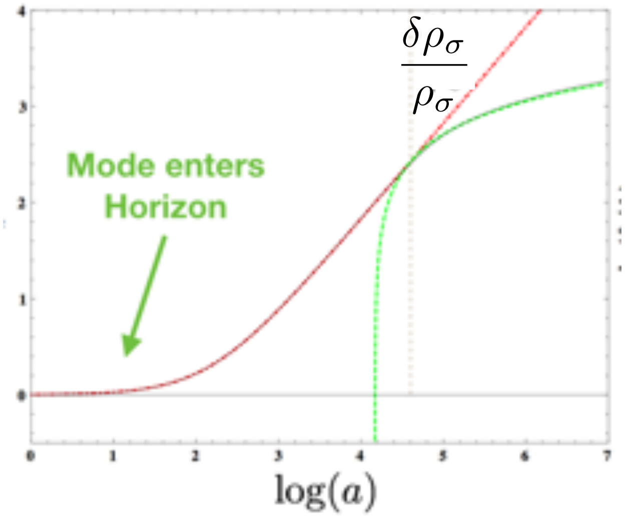


Dominant Effect: Sub-Horizon scalar perturbations also grow! And they are converted to dark matter perturbations (enhanced structure possible)

All three possibilities lead to a new cutoff to consider for the matter power spectrum

$$\boxed{\lambda \sim k_r^{-1} \sim H_r^{-1}}$$

Non-thermal Histories and the Matter Power Spectrum

To appear with JiJi Fan and Ogan Ozsoy

Scales to determine smallest structures (linear regime):

Free-streaming Scale

After kinetic decoupling, dark matter can free-stream erasing structure

$$\lambda_{\mathrm{fsh}}(t) = \int_{t_{\mathrm{RH}}}^{t} \frac{\langle v \rangle}{a}\, \mathrm{d}t,$$

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

Non-thermal Histories and the Matter Power Spectrum

To appear with JiJi Fan and Ogan Ozsoy

It is difficult for the reheating effects to survive

Free-streaming Scale

At scalar decay, dark matter can free-stream erasing structure

$$\lambda_{\rm fsh}(t) = \int_{t_{\rm RH}}^{t} \frac{\langle v\rangle}{a}\,{\rm d}t,$$

$$\frac{\lambda_{fsh}}{\lambda_r} \approx \begin{cases} 2\langle v_{rh}\rangle \left(\sinh^{-1}\sqrt{\frac{\sqrt{2}k_{rh}}{k_{eq}}} - \sinh^{-1}\sqrt{a_{eq}}\right), & \langle p_{rh}\rangle \ll m_\chi \\ \frac{a_{nr}}{a_{rh}} - 1 \approx \frac{\langle p_{rh}\rangle}{m_\chi}, & \langle p_{rh}\rangle \gg m_\chi. \end{cases}$$

$$\langle p_{rh}\rangle = \sqrt{\left(\frac{m_\sigma}{2}\right)^2 - m_\chi^2}.$$

$$\boxed{\lambda_{fsh} \gg \lambda_r}$$

$m_\sigma \sim 100\ \mathrm{TeV}$ $\quad$ $m_\chi \sim 100\ \mathrm{GeV}$

Compare to: Arxiv:1106.0536 Erickcek and Sigurdson

Non-thermal Histories and the Matter Power Spectrum

To appear with JiJi Fan and Ogan Ozsoy

Summary of our study:

Free-streaming Scale

At scalar decay, dark matter can free-stream erasing structure

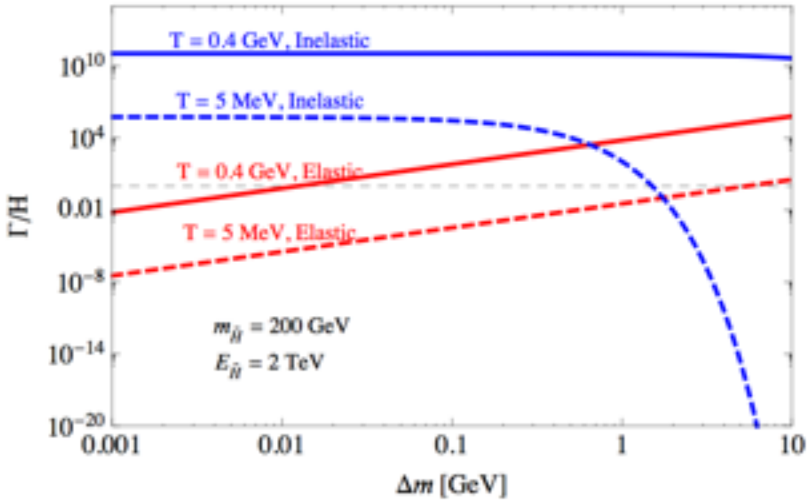
$$\lambda_{\rm fsh}(t) = \int_{t_{\rm RH}}^{t} \frac{\langle v \rangle}{a}\, {\rm d}t,$$

$$\boxed{\lambda_{fsh} \gg \lambda_r}$$

Kinetic Decoupling and Acoustic Oscillations

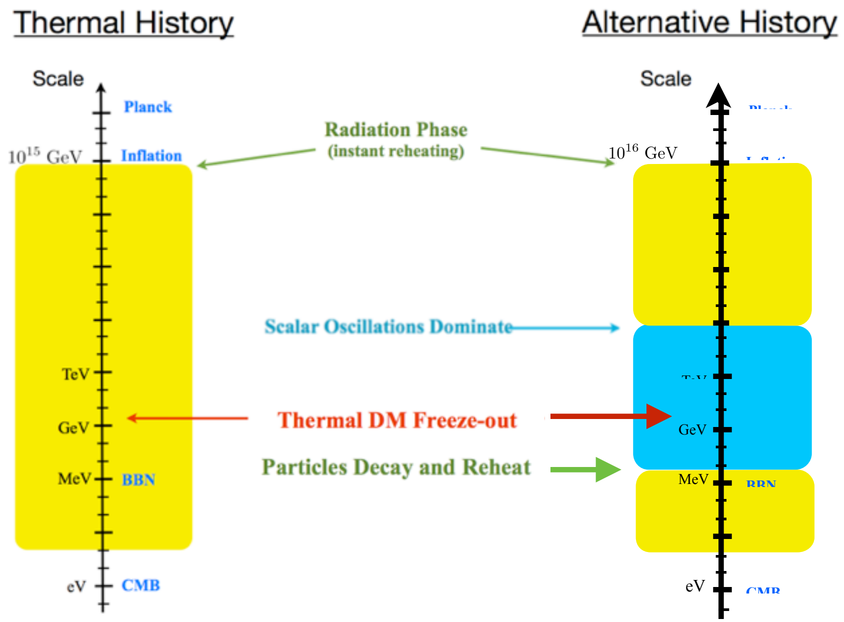
For Non-thermal SUSY Neutralinos

$$\boxed{\lambda_{kd} \gg \lambda_r}$$



Need moduli mass and dark matter nearly same, and still seems difficult to realize.

Concluding remarks



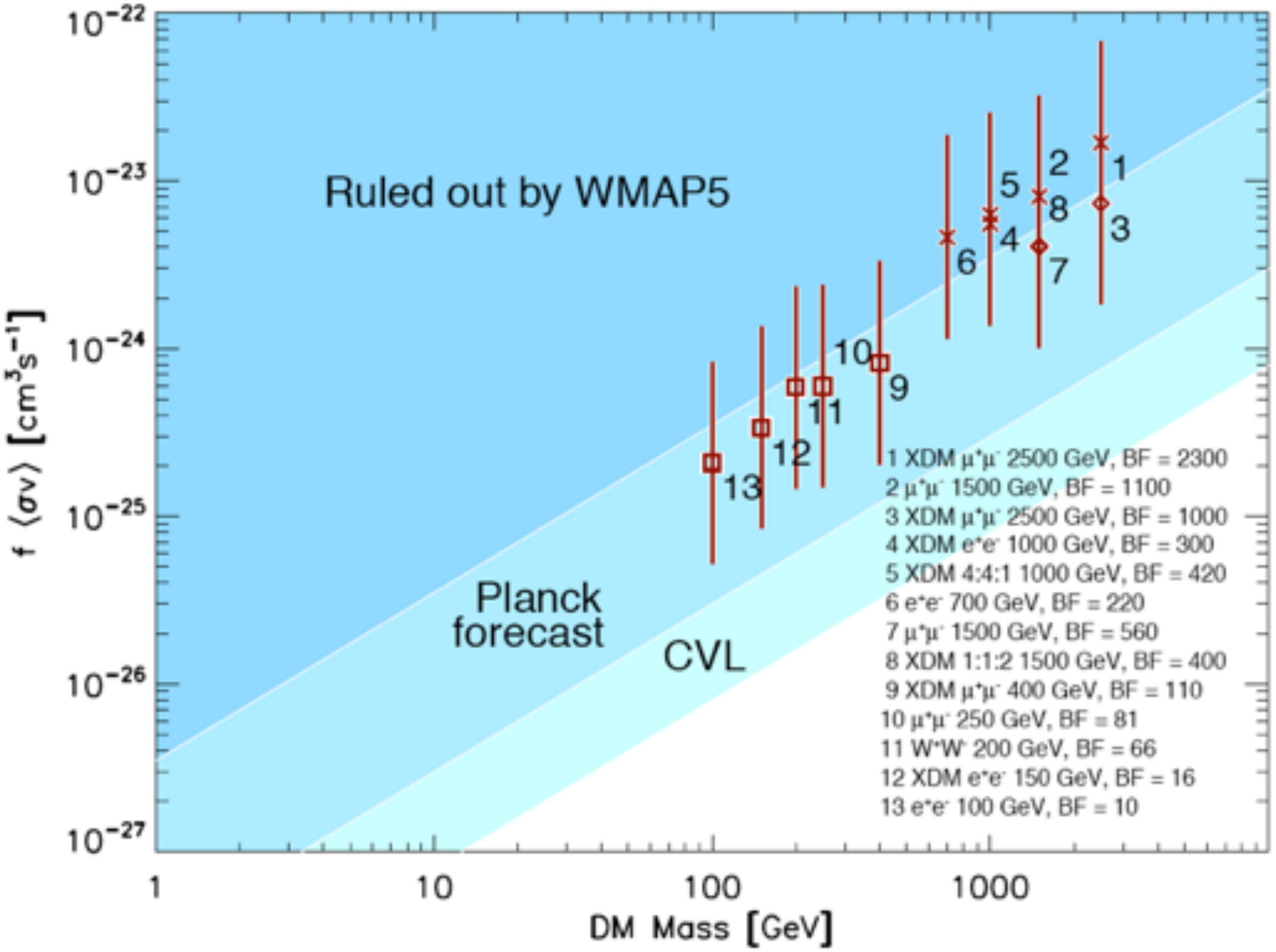
Alternatives to a strictly thermal post inflationary history are viable and well motivated by both inflationary model building and physics beyond the standard model.

It seems feasible to probe the cosmic “dark ages”, but it requires a complete approach — combining theory with dark matter, baryogenesis, and the CMB — into a complete picture of the early universe.

SUSY does not seem essential to anything that I discussed today, only symmetry breaking both in the early and late universe.

Backups

CMB: Last Scattering Surface and a Non-thermal History



Slatyer, Padmanabhan and Finkbeiner 0906.1197

SUSY Fine-Tuning after LHC

$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^4 \left(\log\left(\frac{\overline{m}_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{\overline{m}_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12\overline{m}_{\tilde{t}}^2}\right)\right)$$

Squark Mass

EWSB

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2 .$$

$$\delta m_{H_u}^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right) \log\left(\frac{\Lambda}{\text{TeV}}\right)$$

Back

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

Baryogenesis?

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

AD Baryogenesis is typically too effective

Decay gives dilution needed to account for

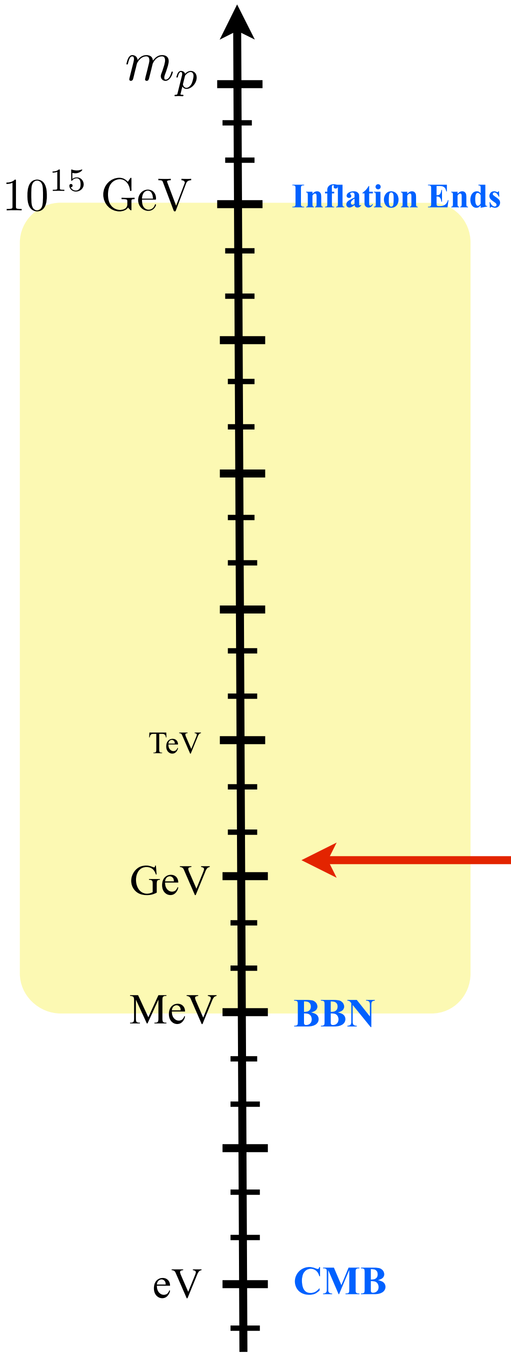
$$\frac{n_B}{n_\gamma} \simeq 4.5 \times 10^{-10} \times \left(\frac{T_R^X}{64\ \mathrm{MeV}}\right) \left(\frac{75\ \mathrm{TeV}}{m_\phi}\right) \left(\frac{\phi_0/X_0}{10^{-2}}\right)^2$$

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"

Thermal History



Dark Matter Abundance from Thermal Production

$$\Omega_{dm} \equiv \frac{\rho_{dm}}{\rho_c} = 0.23 \times \left(\frac{10^{-26}\mathrm{cm}^3 \cdot s^{-1}}{\langle \sigma v \rangle}\right)$$

Cosmological Measurement

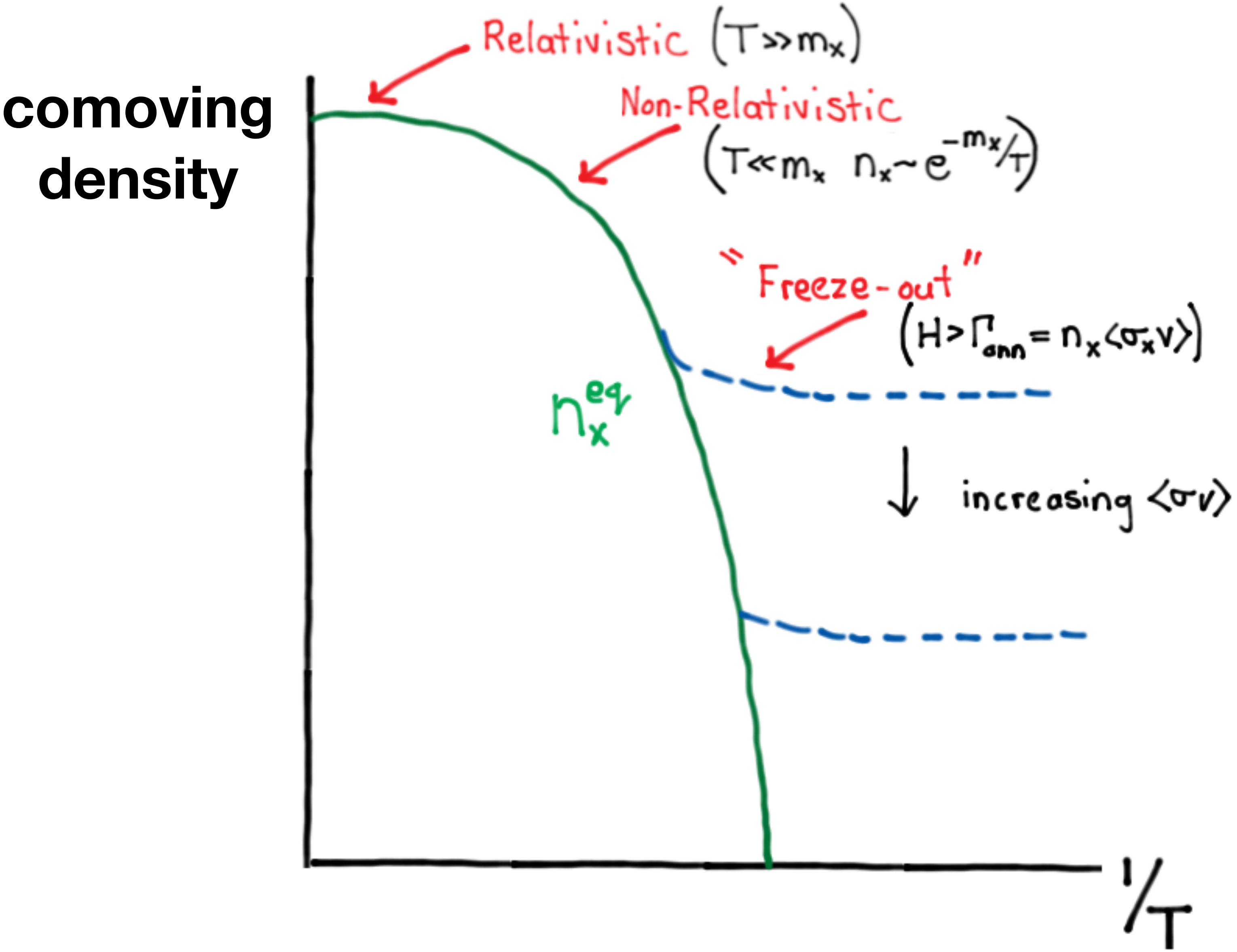
Weak Scale Physics

Dark Matter WIMPs?

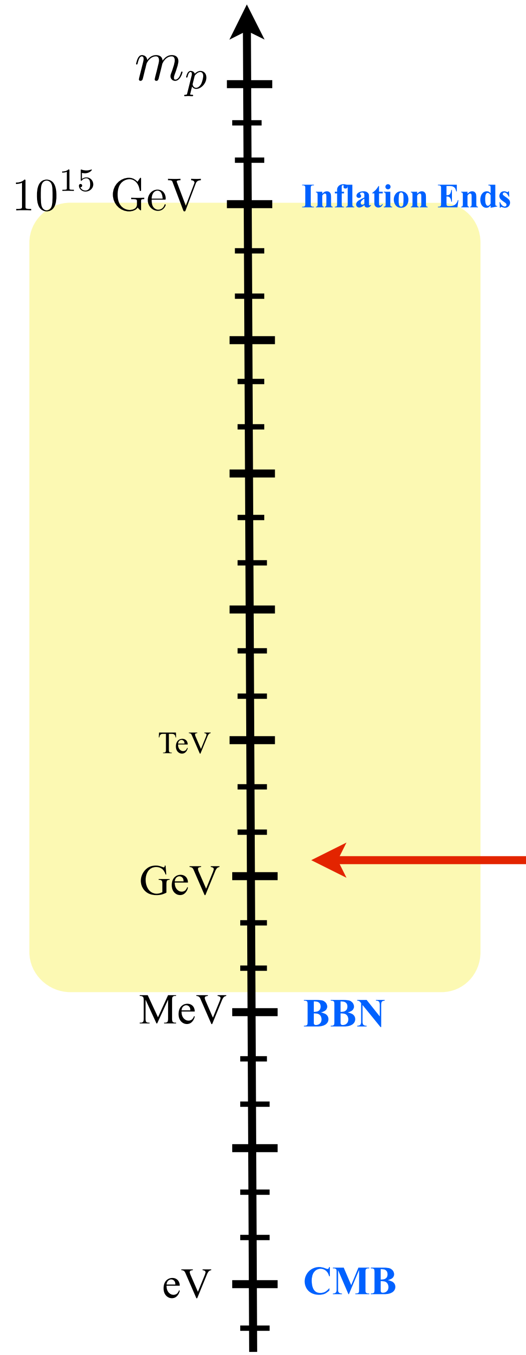
Thermal Relic Density

$$\Omega_\chi = \frac{\rho_\chi}{\rho_c} = 0.23 \times \left(\frac{10^{-26}\,\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle}\right)$$

$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{eq}^2\right)$$



Thermal History



Dark Matter Abundance from Thermal Production

$$\Omega_{dm} \equiv \frac{\rho_{dm}}{\rho_c} = 0.23 \times \left(\frac{10^{-26}\mathrm{cm}^3 \cdot s^{-1}}{\langle \sigma v \rangle} \right)$$

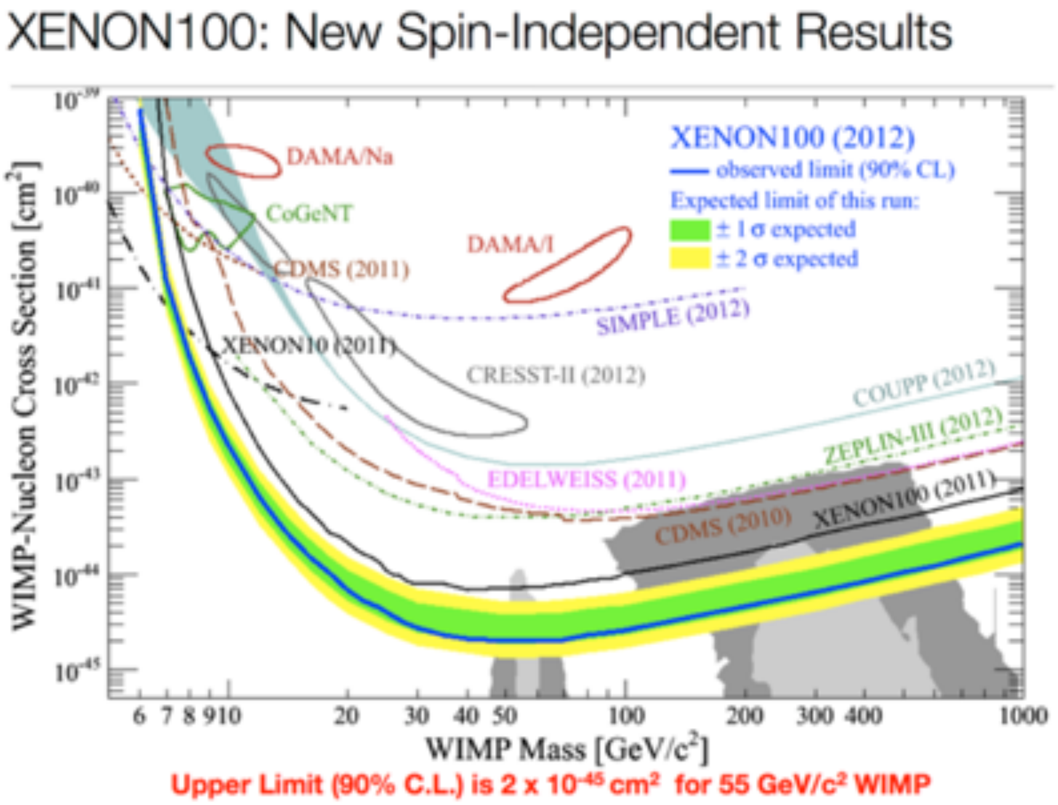
Cosmological Measurement

Weak Scale Physics

Dark Matter WIMPs?

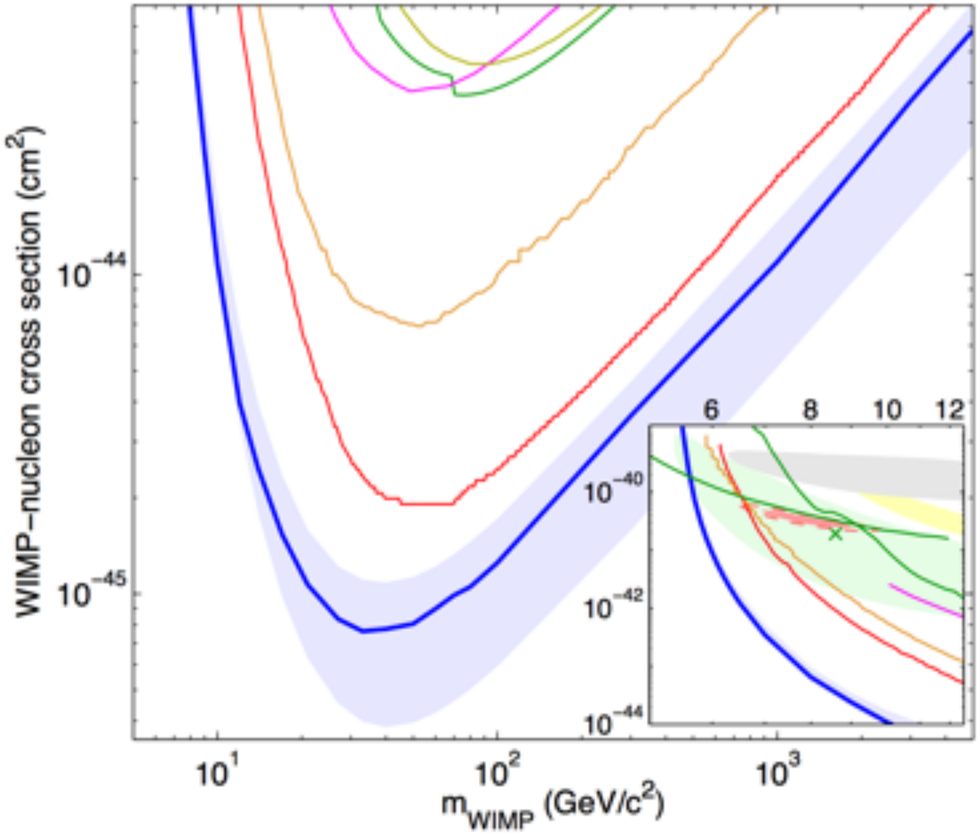
Robust, simple, elegant.

New Lux Result



XENON100: New Spin-Independent Results

Upper Limit (90% C.L.) is 2 x 10^{-45} cm^2 for 55 GeV/c^2 WIMP



return

Approximate Moduli

Moduli Potential

$$V_\varphi(T, H, \varphi) = 0$$

Approximate Moduli

Moduli Potential

$$V_{\varphi}(T, H, \varphi) = 0 + V_{soft}$$

Approximate Moduli

Moduli Potential

$$V_\varphi(T,H,\varphi) = 0 + V_{soft} + \frac{1}{M^{2n}}\varphi^{4+2n}$$

Approximate Moduli

Moduli Potential

$$V_\varphi(T,H,\varphi) = 0 + V_{soft} + \frac{1}{M^{2n}}\varphi^{4+2n} + V_{SUGRA}$$

Approximate Moduli

Moduli Potential

$$V_\varphi(T,H,\varphi) = 0 + V_{soft} + \frac{1}{M^{2n}}\varphi^{4+2n} + V_{SUGRA} + V_{np}\,.$$

Approximate Moduli

Moduli Potential

$$V_\varphi(T,H,\varphi) = 0 + V_{soft} + \frac{1}{M^{2n}}\varphi^{4+2n} + V_{SUGRA} + V_{np} + V_{thermal}$$

Approximate Moduli

Moduli Potential

$$V_\varphi(T,H,\varphi) = 0 + V_{soft} + \frac{1}{M^{2n}}\varphi^{4+2n} + V_{SUGRA} + V_{np} + V_{thermal}$$

Example:

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

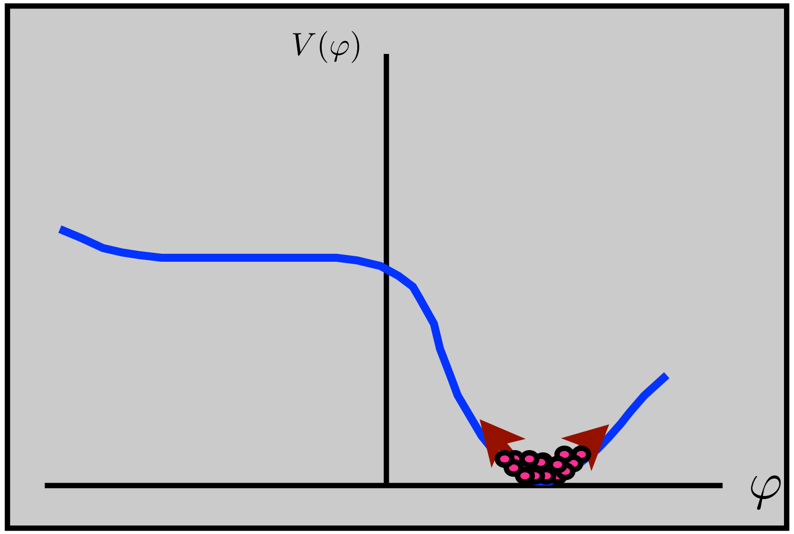
$$\langle\varphi\rangle \sim M\left(\frac{H}{M}\right)^{\frac{1}{n+1}} \qquad H \gg m_{3/2} \sim \mathrm{TeV}$$

$$\langle\varphi\rangle \approx 0 \qquad H \ll M$$

$\Delta\Phi \to \Delta E$ ⟶ Scalar Condensate

Effect of Decaying Scalars

Dark Matter from Scalar Decay:



- Moduli generically displaced in early universe
- Energy stored in scalar condensate

$$\Delta\Phi \to \Delta E$$

- Typically decays through gravitational coupling

$$T_r \simeq \left(\frac{m_\phi}{10\ \mathrm{TeV}}\right)^{3/2} \ \mathrm{MeV}$$

- Large entropy production dilutes existing dark matter of thermal origin

$$\Omega_{cdm} \to \Omega_{cdm}\left(\frac{T_r}{T_f}\right)^3$$

Thermal abundances diluted

Non-thermal Dark Matter from Light Scalars

$\Phi \to X$ Additional source of Dark Matter (after freeze-out)

Critical yield $$n_c = \left.\frac{3H}{\langle \sigma v \rangle}\right|_{T_r}$$

Two possibilities:

Sub-critical

$n_X < n_c$ No annihilations take place (yield preserved)

Super-critical

$n_X > n_c$ Rapid annihilation down to fixed point

Additional Source of Dark Matter from Scalar Decay

Super-critical case (attractor)

Given $T_r < T_f$ then dark matter populated non-thermally

$$\Omega_{cdm} \sim \frac{m_x}{T}\left(\frac{H}{T^2\langle\sigma v\rangle}\right)\Bigg|_{\cancel{T=T_f}\;T=T_r}$$

$$\Omega_{cdm}^{NT} = 0.23 \times \left(\frac{10^{-26}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle}\right)\left(\frac{T_f}{T_r}\right)$$

← Freeze-out temp

← Reheat temp

$$T_f \sim \mathrm{GeV} \qquad T_r \sim MeV$$

Can vary over 3 orders of magnitude -- Allowed values still imply weak-scale physics “WIMP Miracle” survives

The Cosmological Moduli Problem

Coughlan, Fischler, Kolb, Raby, and Ross -- Phys. Lett. B131, 1983
Banks, Kaplan, and Nelson -- Phys. Rev. D49, 1994

“ Model Independent properties and cosmological implications of the dilaton and moduli sectors of 4-d strings ”

Carlos, Casas, and Quevedo -- Phys. Lett. B318, 1993

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

Shift symmetry

$$\Phi = \phi + ia \longrightarrow W \neq W(\Phi)$$

Zero vacuum energy, stabilize scalar, break SUSY (spontaneously)

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

$$\boxed{m_\phi \sim m_{3/2} \sim \text{TeV}}$$

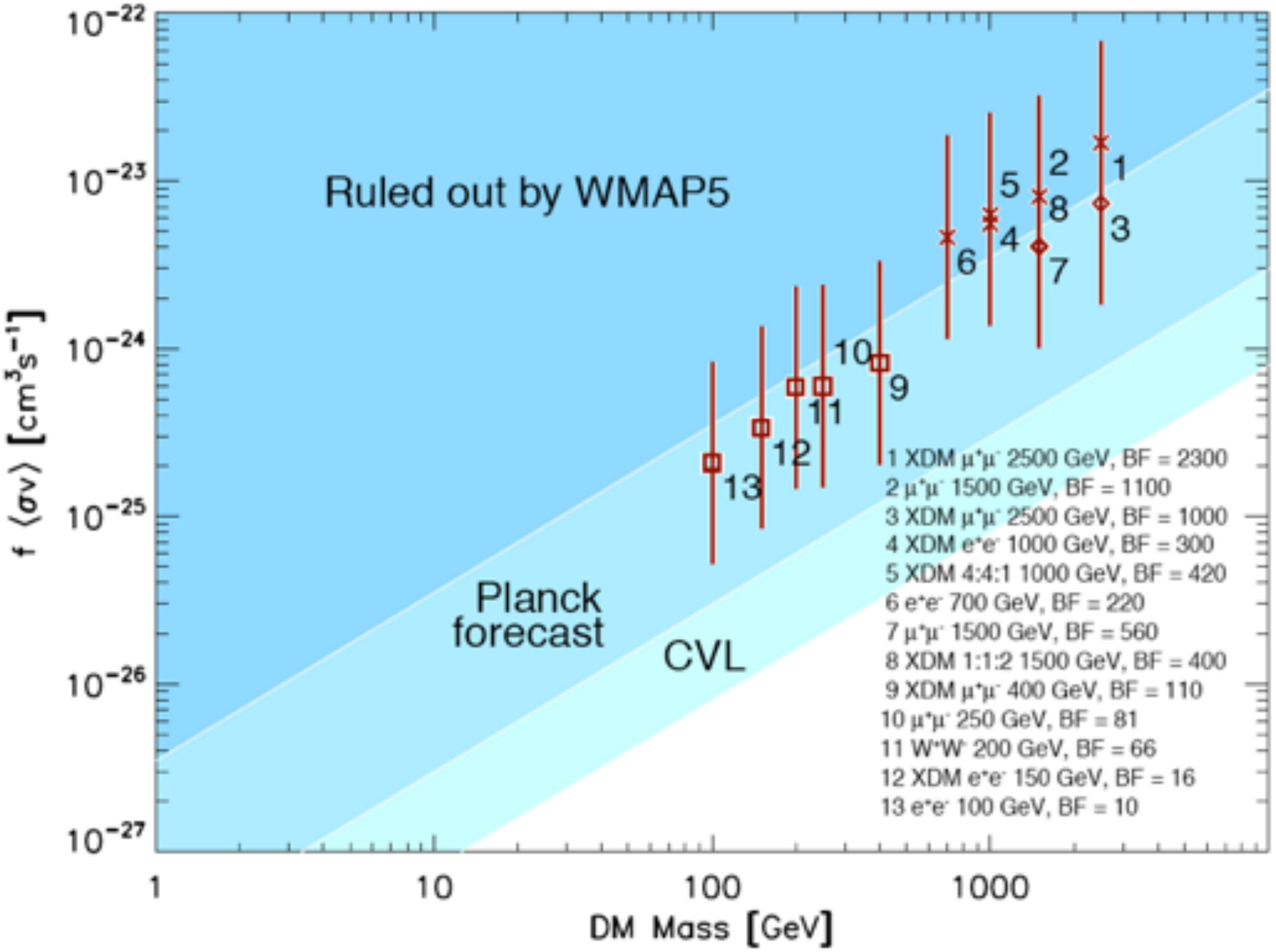
Slow-roll Inflation

$$P_s(k) = \frac{1}{24\pi^2 M_{\rm pl}^4} \frac{V}{\epsilon}\bigg|_{k=aH}, \qquad n_s - 1 = 2\eta - 6\epsilon\,,$$

$$P_t(k) = \frac{2}{3\pi^2} \frac{V}{M_{\rm pl}^4}\bigg|_{k=aH}, \qquad n_t = -2\epsilon\,, \qquad r = 16\epsilon\,.$$

$$r = 16\epsilon = \frac{8}{M_{\rm pl}^2}\left(\frac{\dot\phi}{H}\right)^2. \qquad r = -8n_t\,.$$

CMB: Last Scattering Surface and a Non-thermal History



Slatyer, Padmanabhan and Finkbeiner 0906.1197

SUSY Fine-Tuning after LHC

$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^4 \left(\log\left(\frac{\overline{m}_{\tilde{t}}^2}{m_t^2} \right) + \frac{X_t^2}{\overline{m}_{\tilde{t}}^2} \left(1 - \frac{X_t^2}{12\overline{m}_{\tilde{t}}^2} \right) \right)$$

Squark Mass

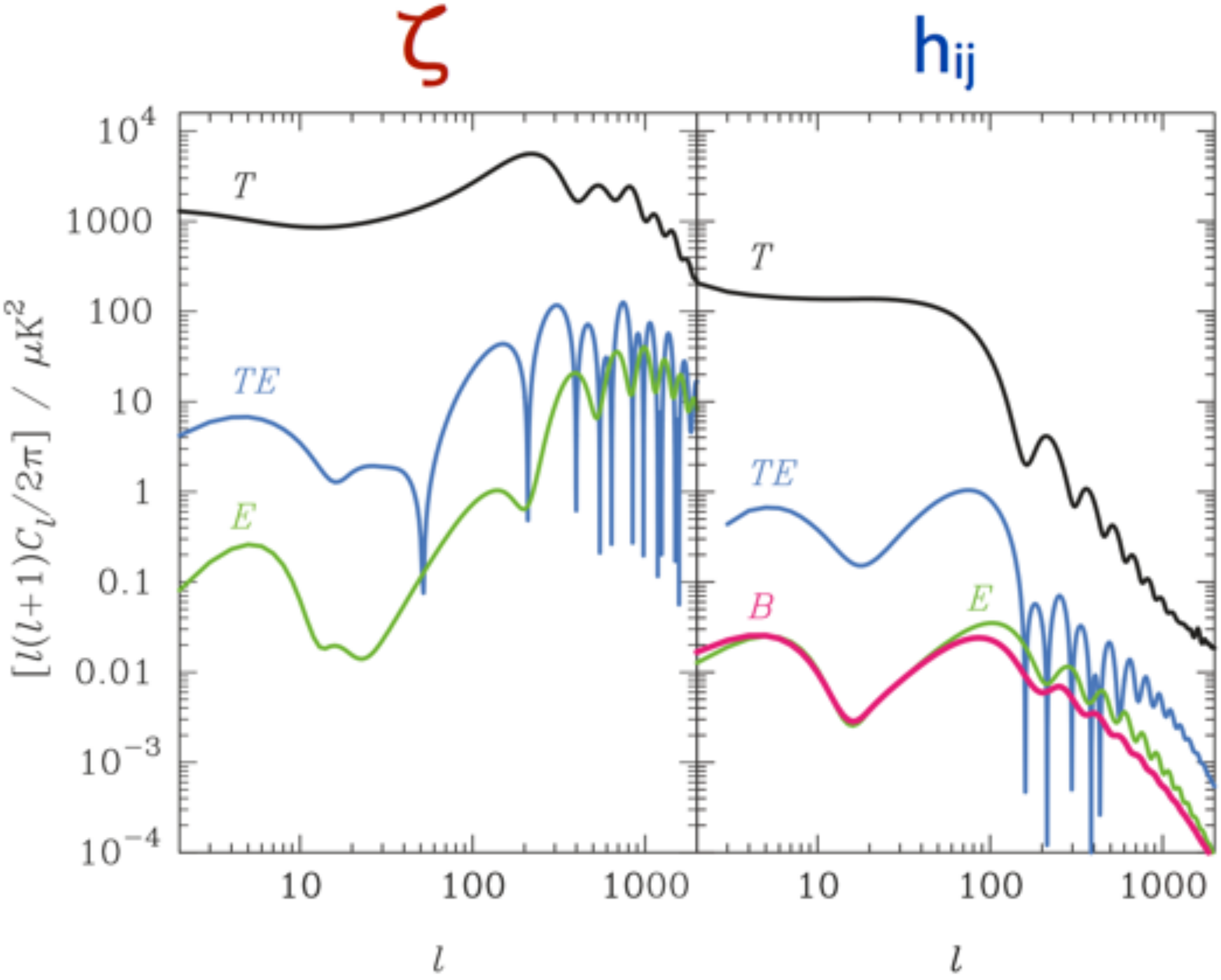
EWSB

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2 .$$

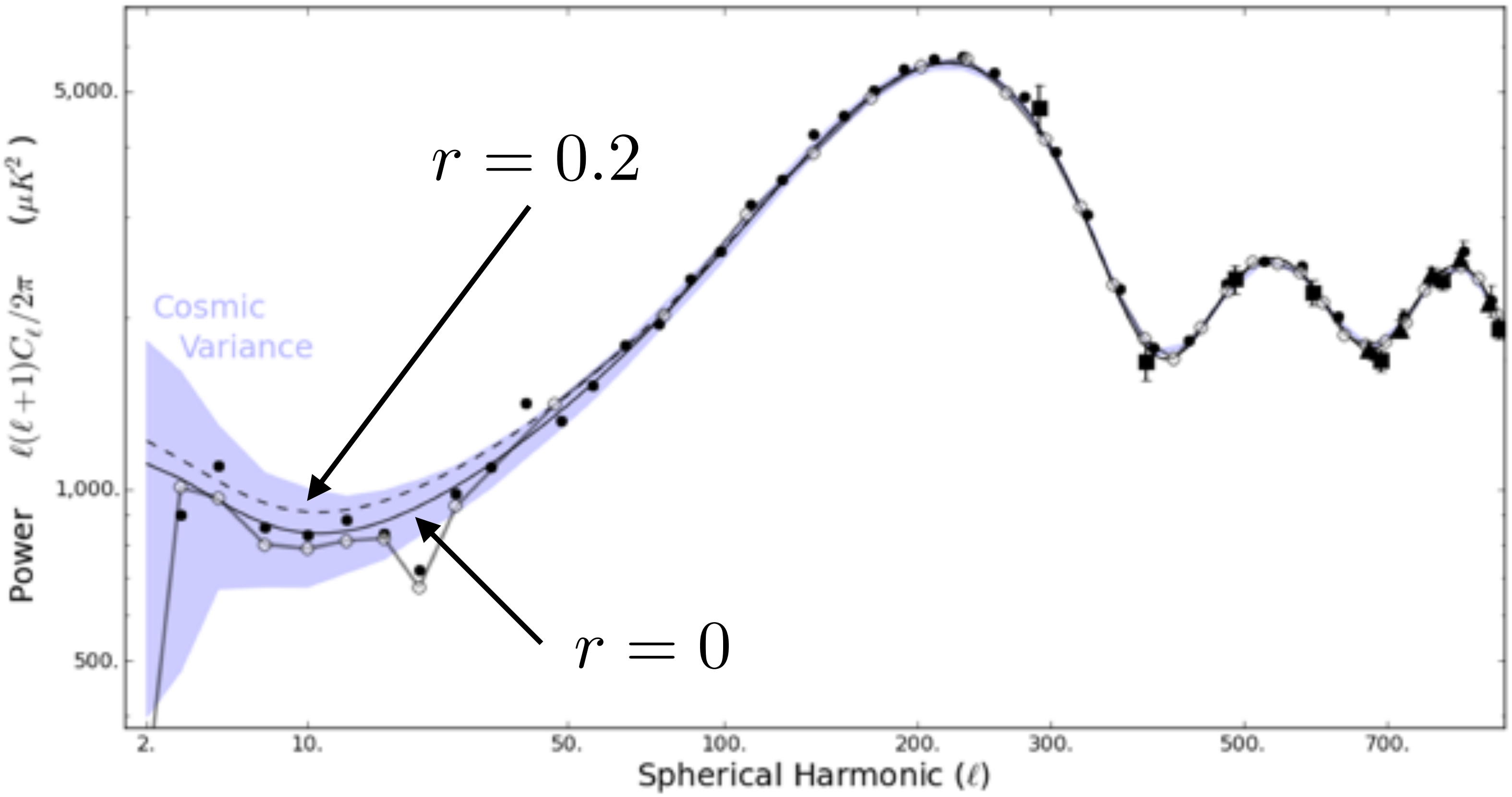
$$\delta m_{H_u}^2 |_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2 \right) \log\left(\frac{\Lambda}{\mathrm{TeV}} \right)$$

Back

Scalar and tensor spectrum



BICEP increases low-power tension

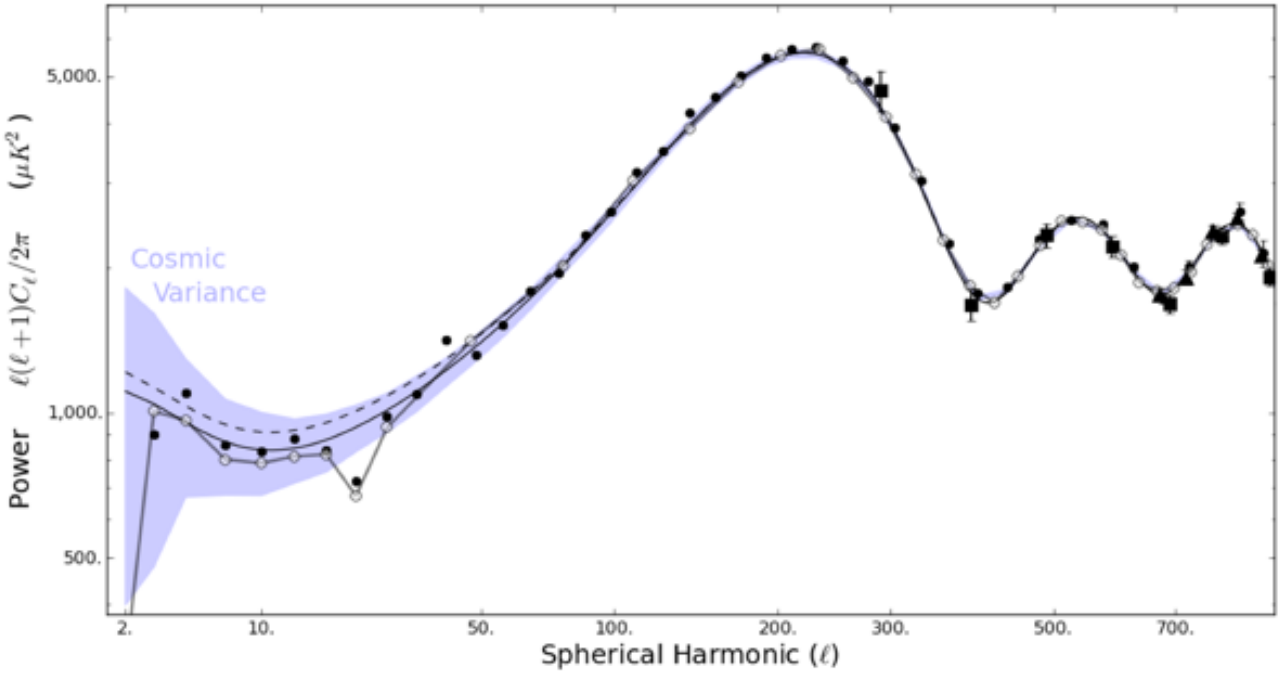


$r = 0.2$

$r = 0$

BICEP increases low-power tension

See e.g., ArXiv: 1404.0373 Smith, et. al.

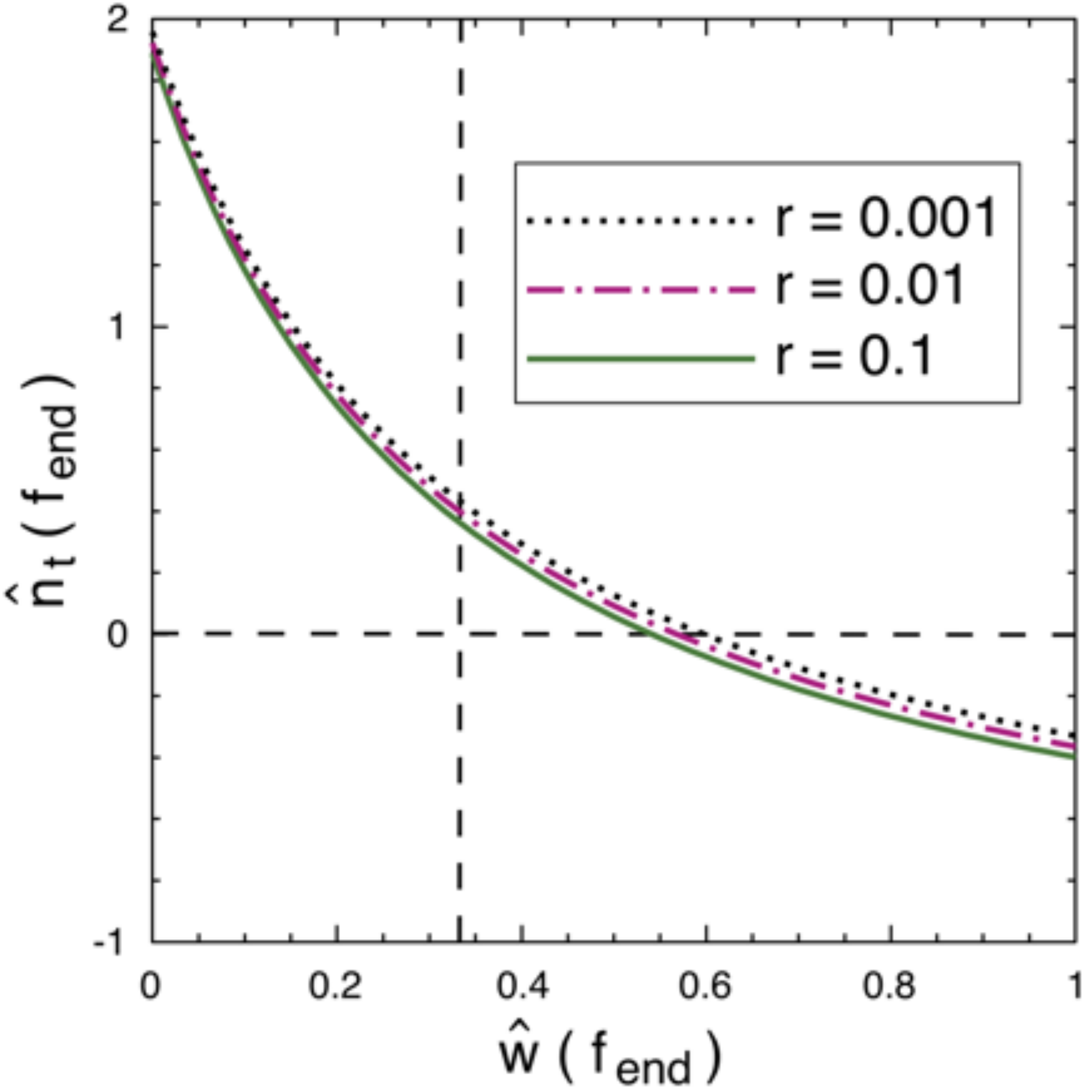


Possible Explanations:

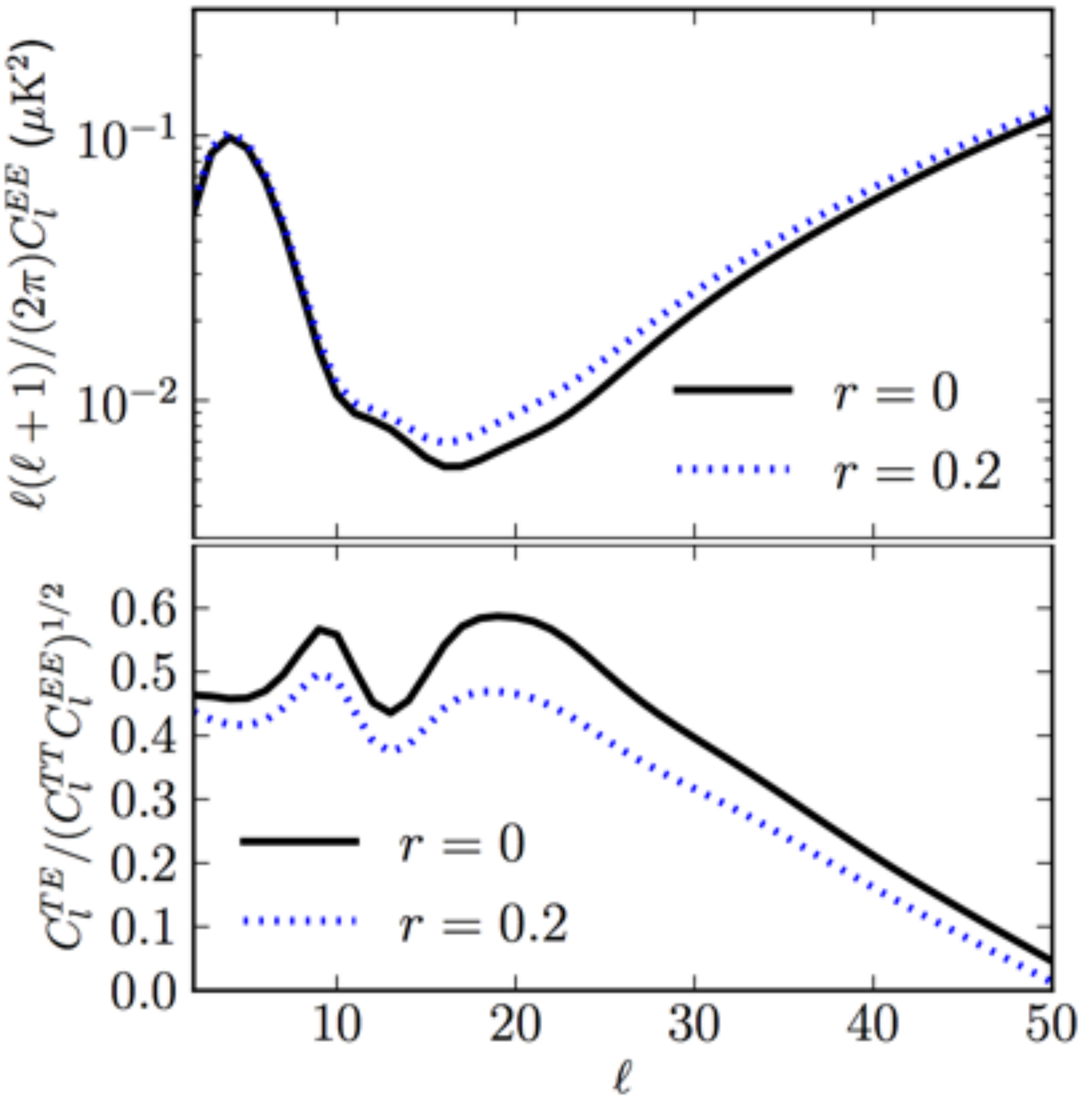
1. **Systematics?**
2. **Accept 0.1% statistical fluke?**
3. **Introduce new parameter: running, tensor tilt, N_{eff}**

Non-zero Tensor tilt favors **matter dominated phase** for post-inflation

ArXiv:0708.2279
L. Boyle and A. Buonanno



E-mode Polarization Measurement can distinguish possible solutions

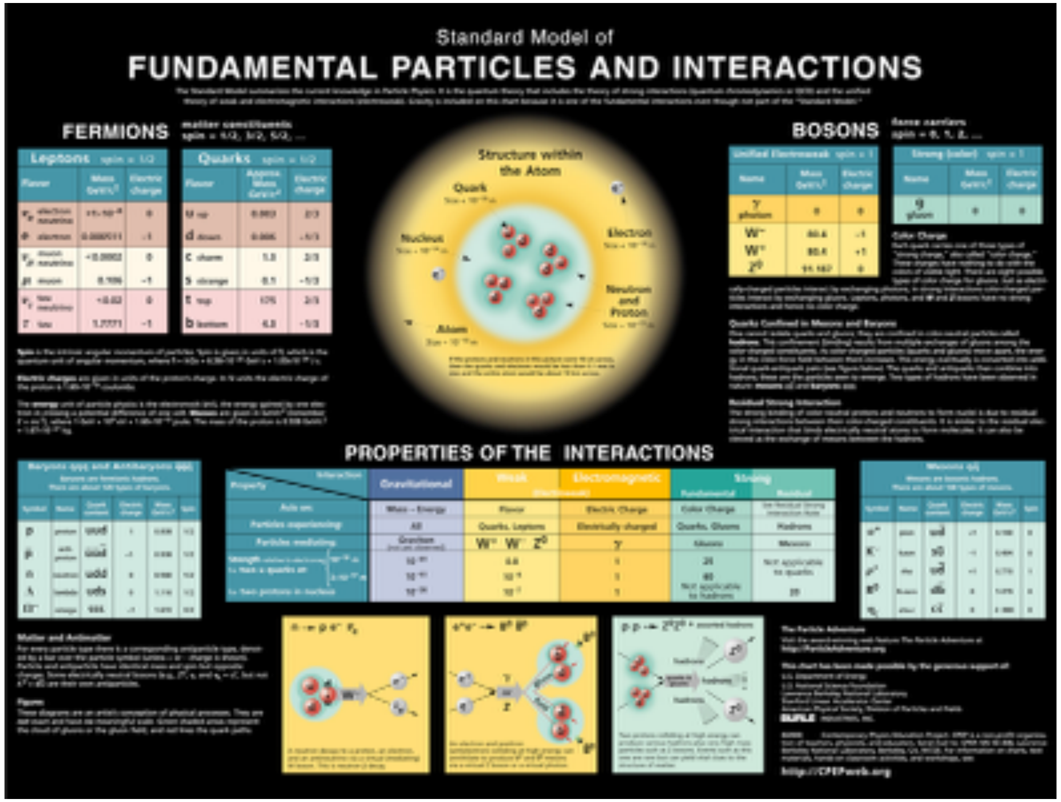


If truly low power
on large scales

(not a statistical fluke)

then we expect a difference in E-modes by 30%

The Standard Model of Particle Physics is also well tested



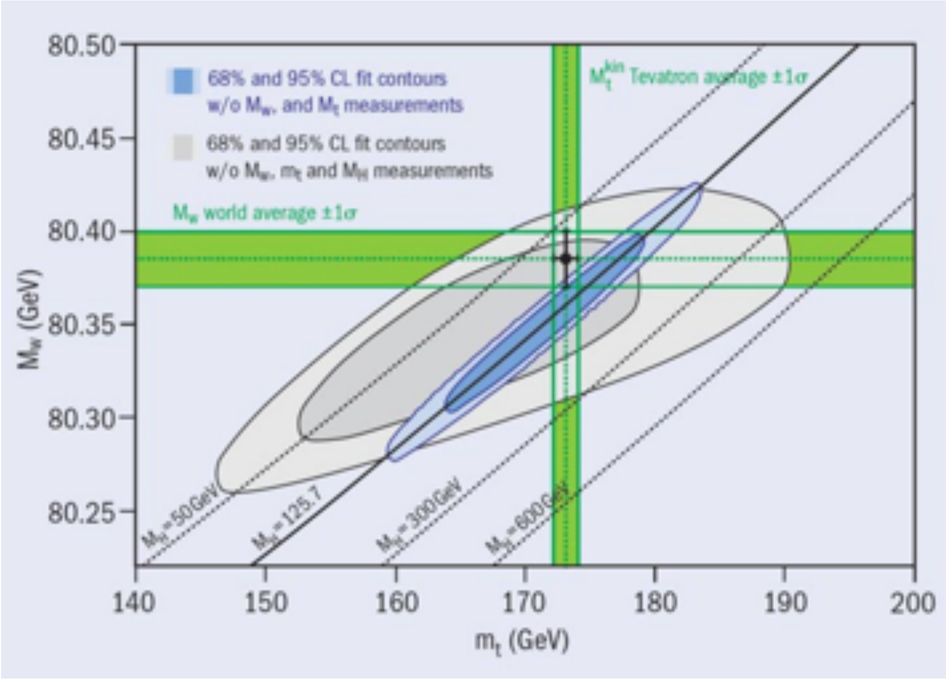
Standard Model of

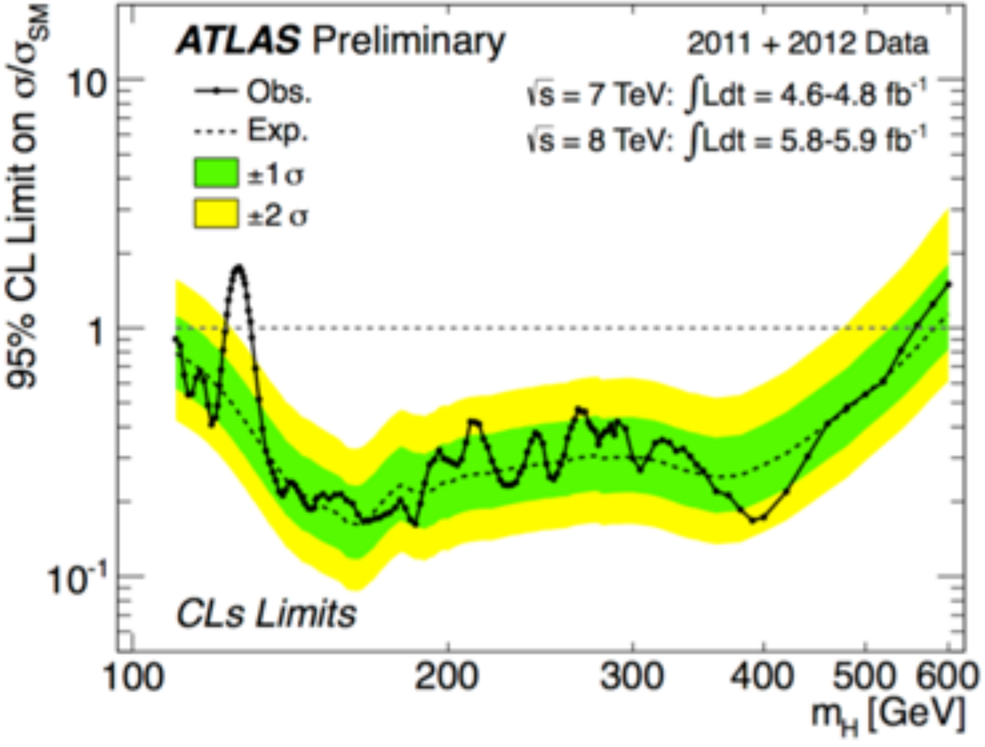
FUNDAMENTAL PARTICLES AND INTERACTIONS

FERMIONS

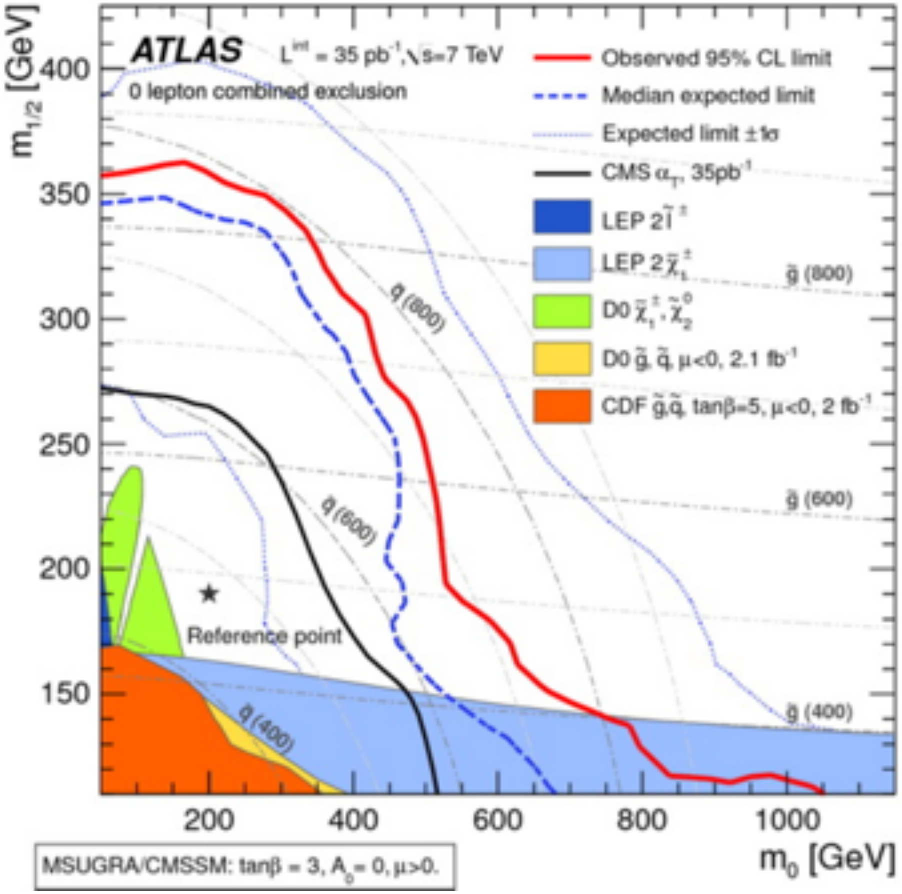
BOSONS

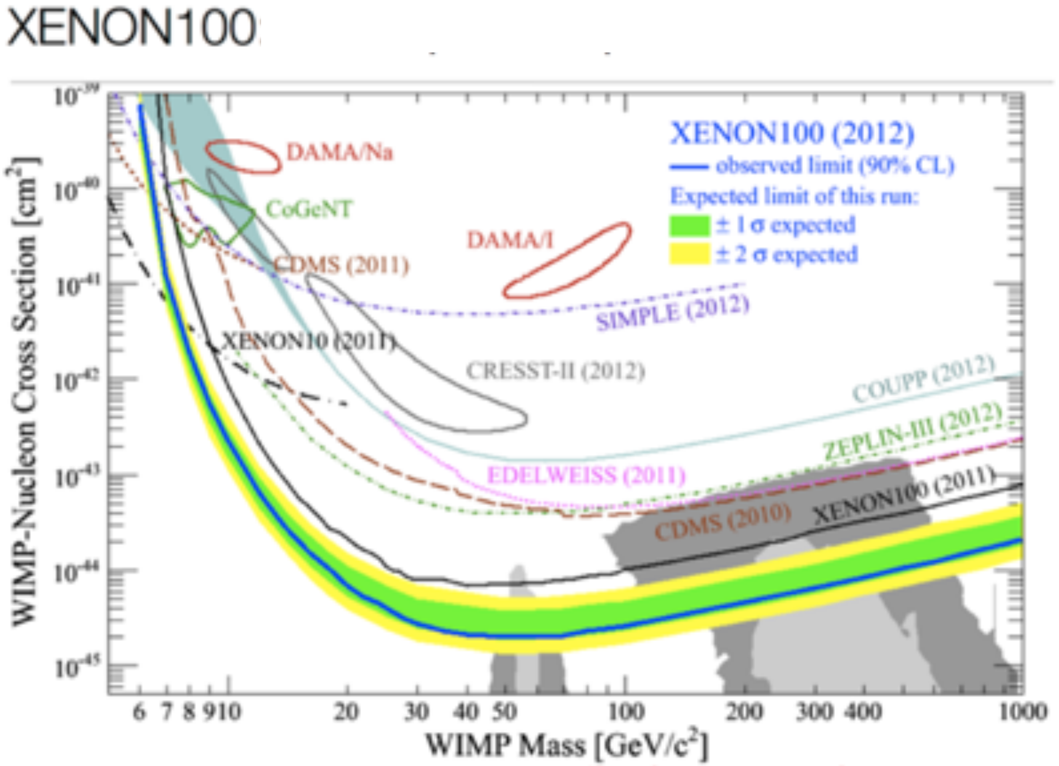
PROPERTIES OF THE INTERACTIONS





Simplest models of thermal dark matter are increasingly in tension with experiment



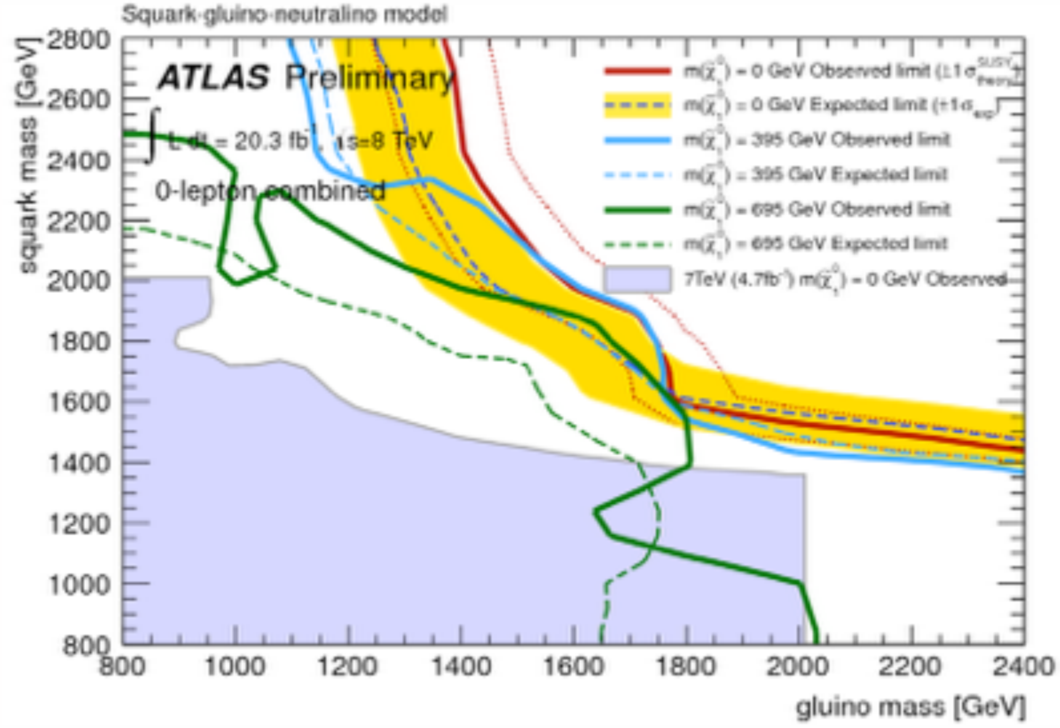


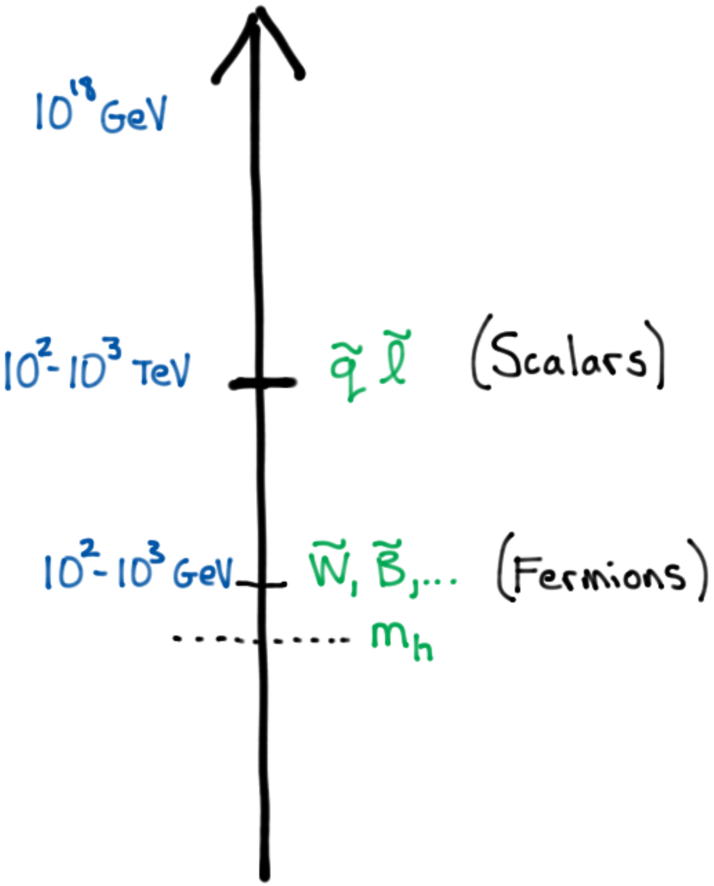
Upper Limit (90% C.L.) is 2 x 10^{-45} cm² for 55 GeV/c² WIMP

SUSY and Hierarchies after LHC

SUSY can still stabilize the Electroweak Hierarchy and be “natural”

(At cost of complex model building)





Scalars heavy, fermions can be light

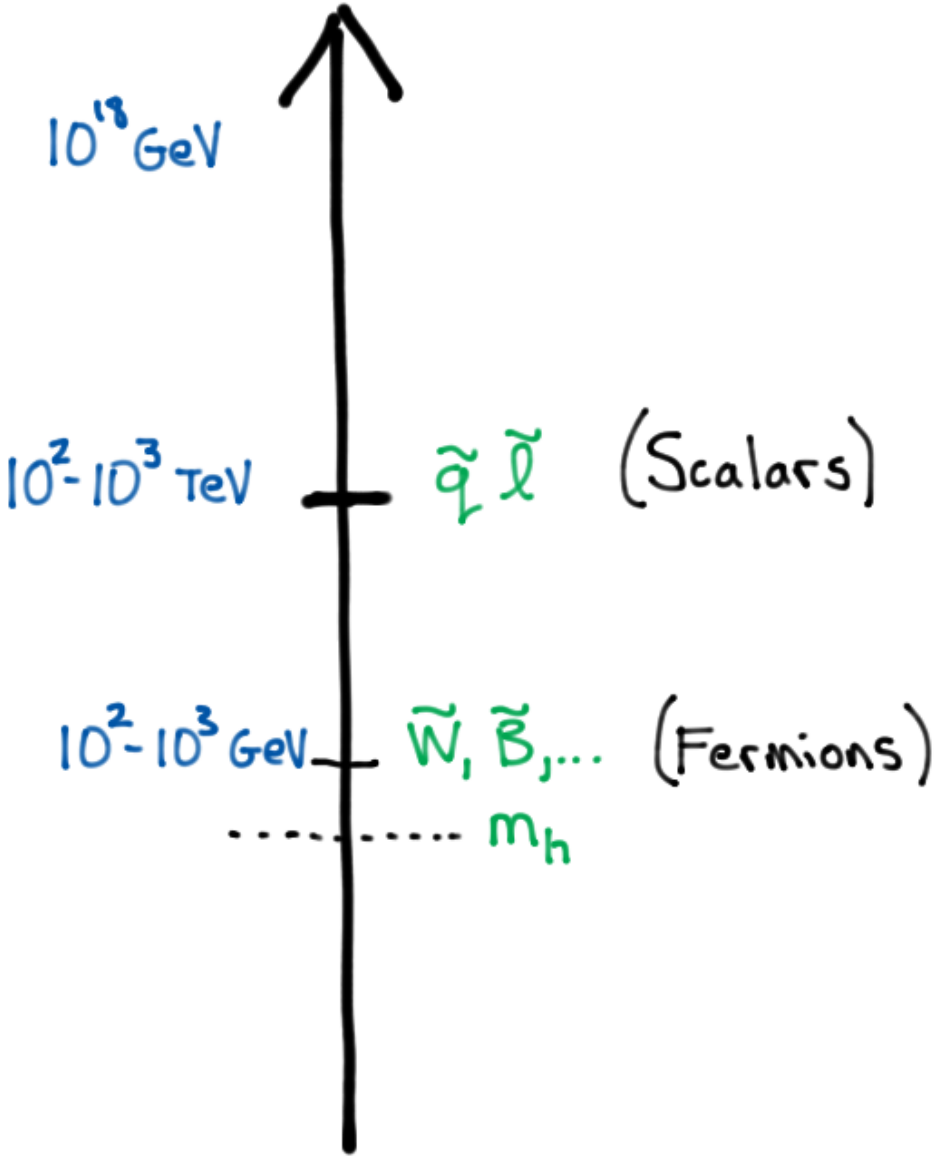
Split SUSY

J. Wells (hep-ph/0306127) N. Arkani-Hamed and S. Dimopoulos (hep-th/0405159)

✓ Gauge Coupling Unification

✓ Dark Matter

✓ No Flavor, CP problems



Scalars heavy, Fermions light

(Fermions carry R-symmetry, scalars do not.)

Possibility #3

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

$$10^{-3} \approx \frac{2\pi}{3(4\pi)^3}$$

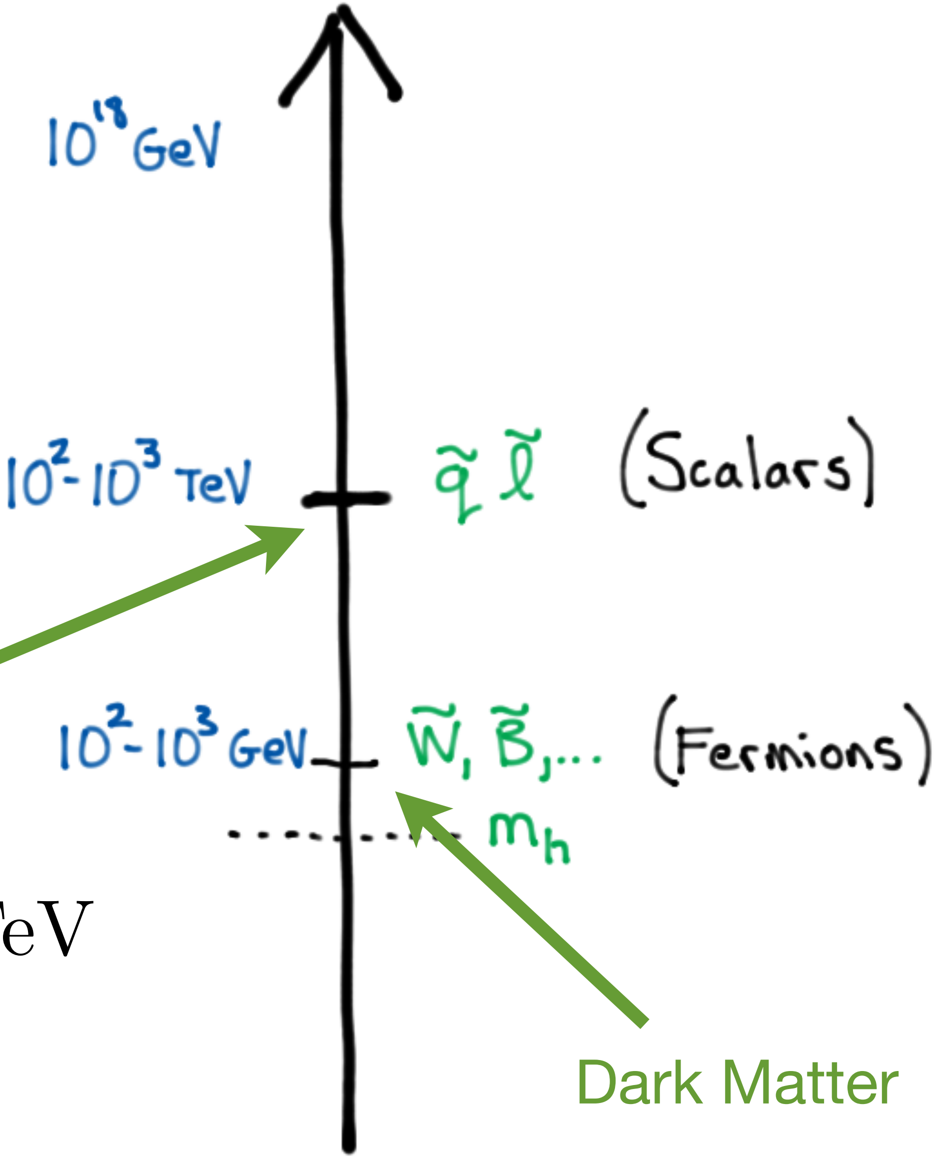
Advantage: Addresses the cosmological moduli problem

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 Flavor, CP problems
- ✓ **No moduli problems**



Moduli get masses:

Dark Matter

$$m_\phi \simeq m_{3/2} \simeq 100 - 1000 \text{ TeV}$$

$$m_{3/2} = \frac{\Lambda^2_{SUSY}}{m_p}$$

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

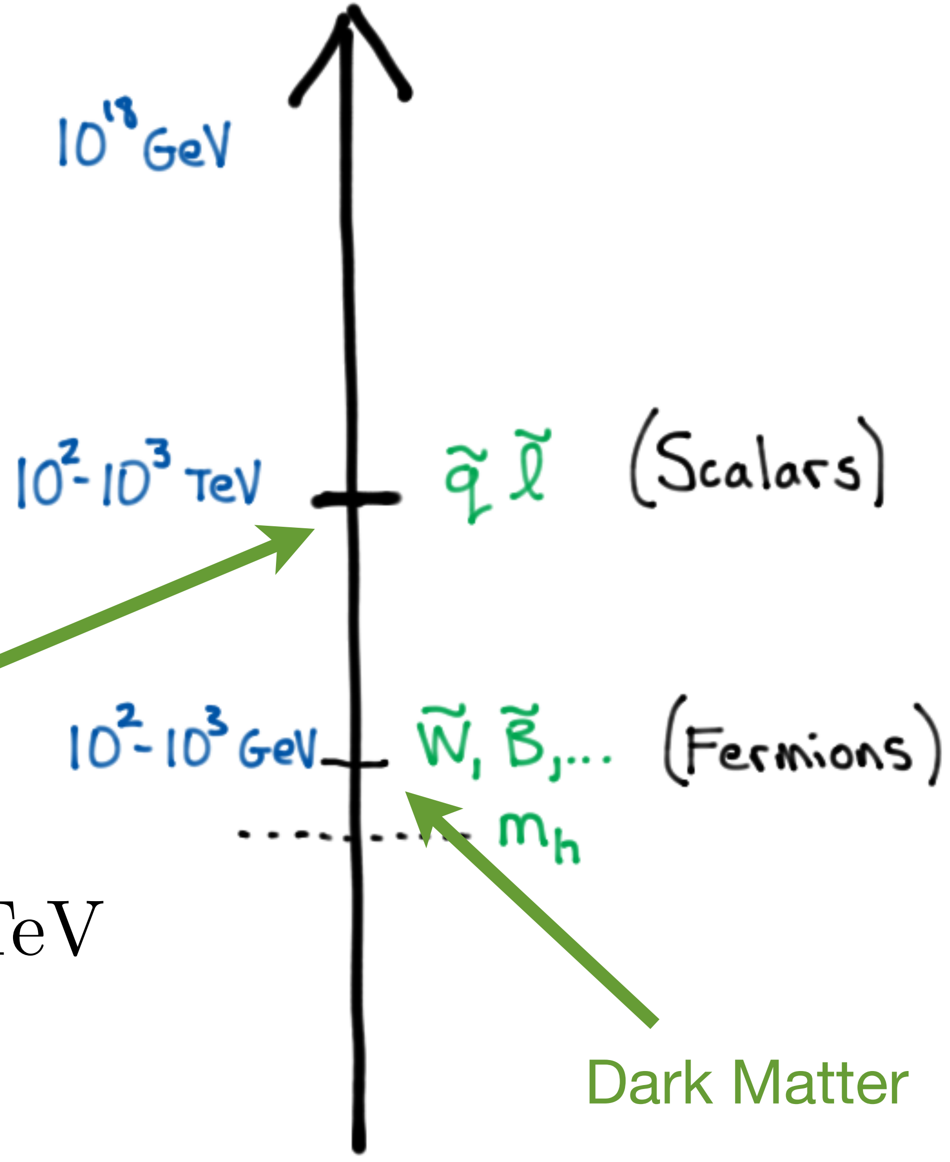
Reheat: $T_r \simeq \left(\frac{m_\varphi}{10\ \mathrm{TeV}}\right)^{3/2}$ MeV

✓ **No moduli problems**

Moduli get masses:

$$m_\phi \simeq m_{3/2} \simeq 100 - 1000\ \mathrm{TeV}$$

$$m_{3/2} = \frac{\Lambda^2_{SUSY}}{m_p}$$



Dark Matter

Familiar from Curvatons

$$m_\sigma < H_I$$

$$\begin{tikzcd}
 & \zeta_{\mathrm{r}} \\
\zeta_\varphi \arrow[ur] \arrow[dr] & \\
 & \zeta_{\mathrm{dm}}
\end{tikzcd}$$

$$\delta\sigma \sim \frac{H_I}{2\pi} \qquad \zeta_\sigma \neq \zeta_\varphi$$

$$\begin{tikzcd}
 & \zeta_{\mathrm{r}}^{(2)} \\
\zeta_\sigma \arrow[ur] \arrow[dr] & \\
 & \zeta_{\mathrm{dm}}^{(2)}
\end{tikzcd}$$

$$S_{\sigma\varphi} = 3\left(\zeta_\sigma - \zeta_\varphi\right)$$

With multicomponent isocurvature,
the level of constraint depends on priors
(not a simple "less than 7% of spectrum" statement)

Bucher, Moodley, Turok
astro-ph/0012141

N_{eff} and Dark Radiation

Another constraint is provided by bounds on relativistic degrees of freedom after neutrino decoupling

(both CMB and BBN are sensitive)

Planck Constraint

$$N_{\text{eff}} \leq 3.57$$

$$\Delta N_{\text{eff}} = \frac{8}{14}\Delta g_* \left(\frac{T^h_{rec}}{T_\nu}\right)^4 \leq 0.42$$

$$\left(\frac{11}{4}\right)^{4/3}$$

(If same temperature as standard model radiation)