Revisiting Dark Matter in the Aftermath of LHC and FERMI

Scott Watson

Syracuse University

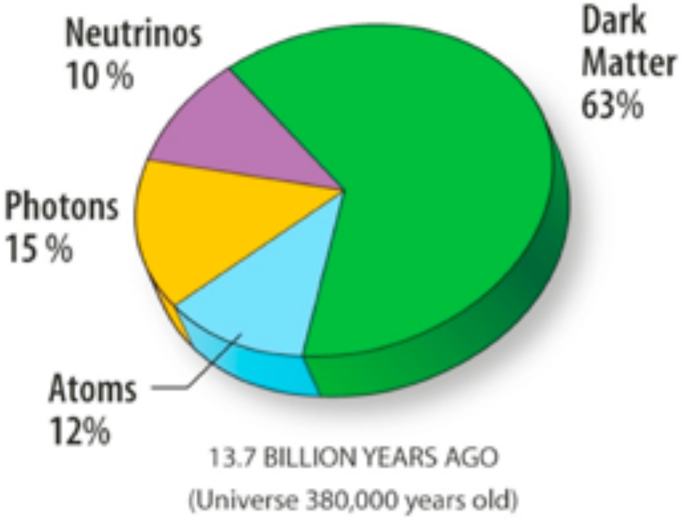
“Cosmological Moduli and the Post-Inflationary Universe: A Critical Review ”

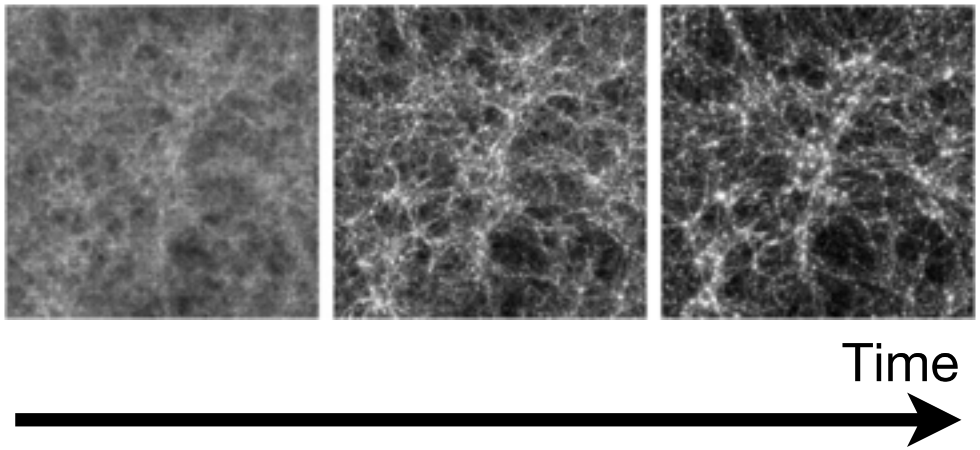
with Kuver Sinha and Gordon Kane [arXiv:1502.07746]

(See also Adrienne’s talk next)

Gravitational Evidence for Dark Matter

- Galaxy collisions (e.g. Bullet Cluster)
- Galactic Rotation Curves
- Gravitational Lensing
- Evolution of Cosmological Perturbations (CMB / LSS)

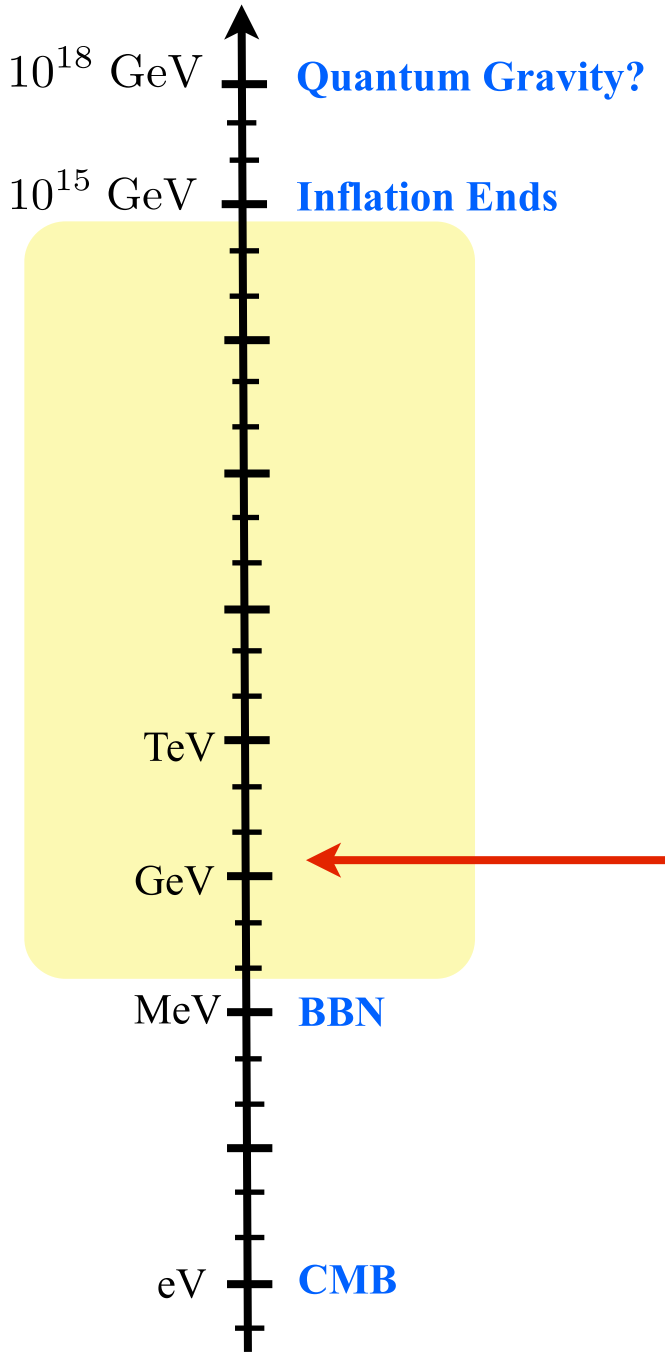




Given the lack of evidence for conventional particle dark matter, perhaps it is time to revisit the “WIMP Miracle”.

In fact, there are cosmological challenges to realizing the “WIMP Miracle”

The “WIMP Miracle” (Thermal History)


10^{18} GeV **Quantum Gravity?**

10^{15} GeV **Inflation Ends**

TeV

GeV

MeV **BBN**

eV **CMB**

Dark Matter Abundance from Thermal Production

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

$$\Omega_{dm}^{\mathrm{Observed}} = 0.23$$

Weak Scale Physics

Dark Matter WIMPs?

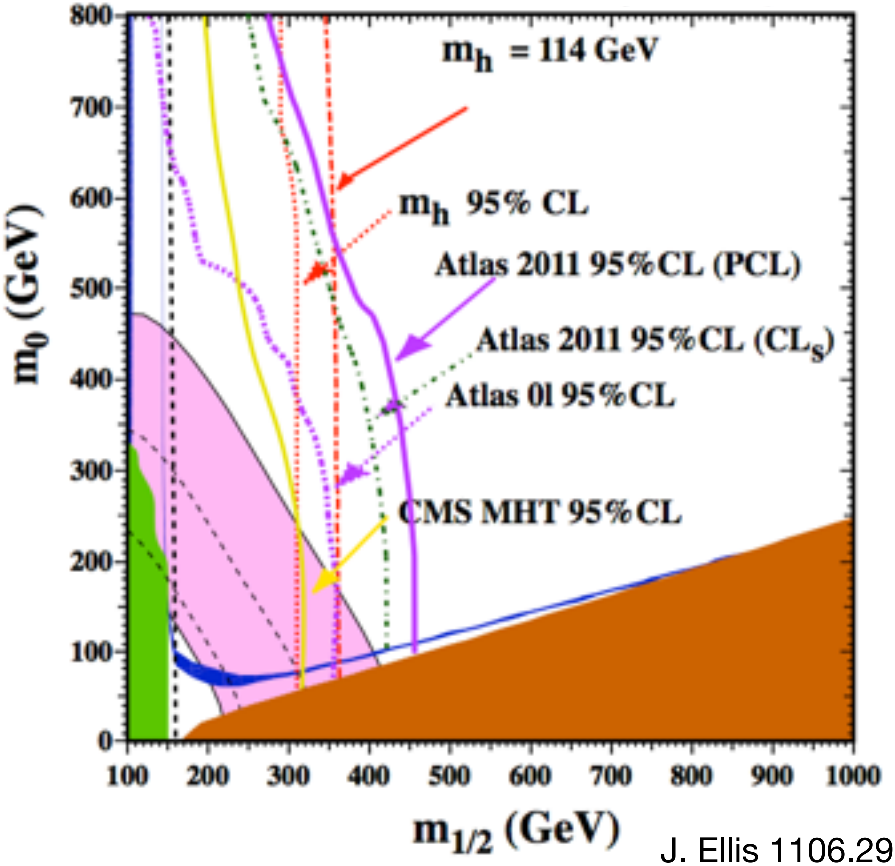
Robust, simple, elegant.

Tension in the *simplest* models

Thermal Relic Density

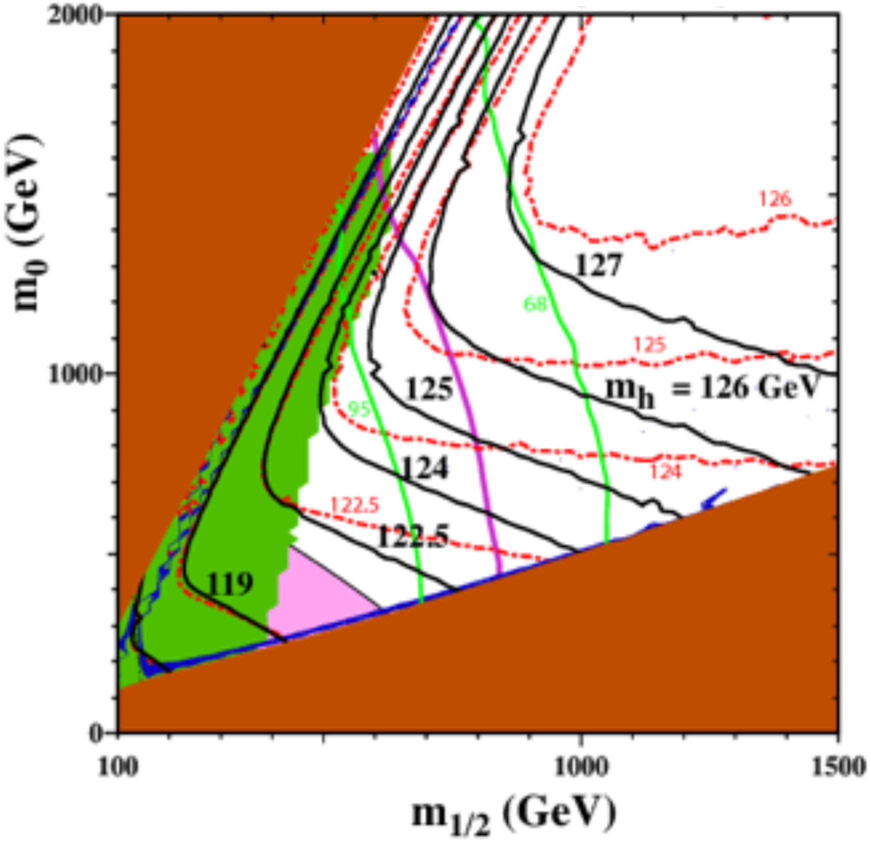
$$\Omega_x = \frac{\rho_x}{\rho_c} = 0.23 \times \left(\frac{10^{-26}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle} \right)$$

Before the Higgs Discovery



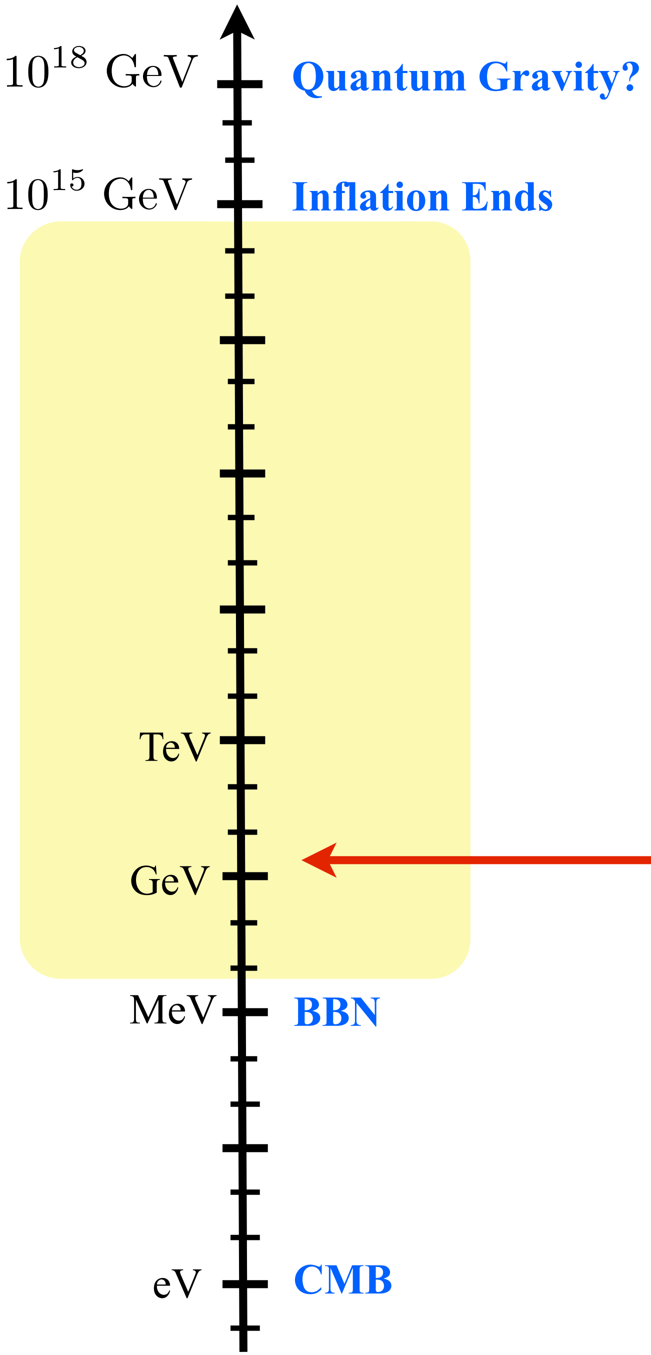
J. Ellis 1106.2923

After the Higgs Discovery



Thermal WIMPs can still exist, but the tension with data is growing rapidly!

Thermal History



Dark Matter Abundance from Thermal Production

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

$$\Omega_{dm}^{\mathrm{Observed}} = 0.23$$

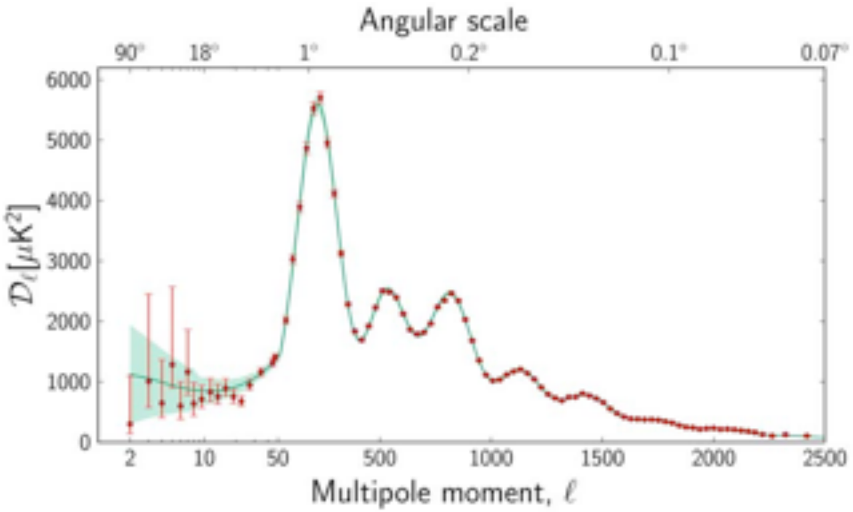
Weak Scale Physics

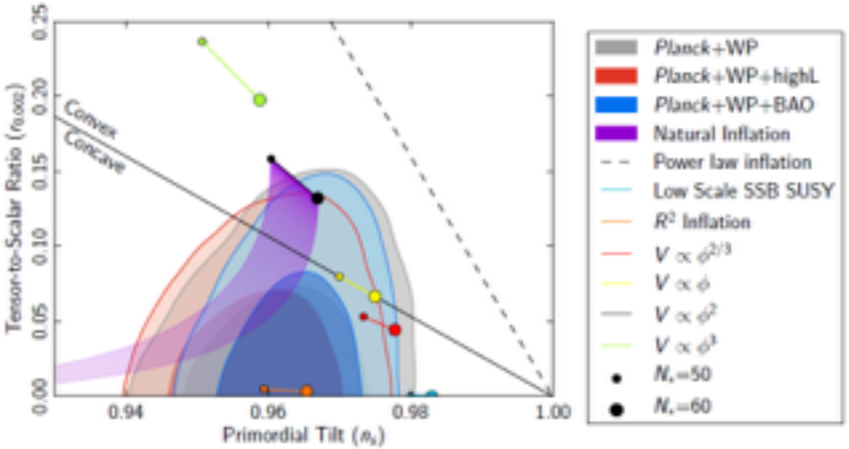
Dark Matter WIMPs?

Robust, simple, elegant.?

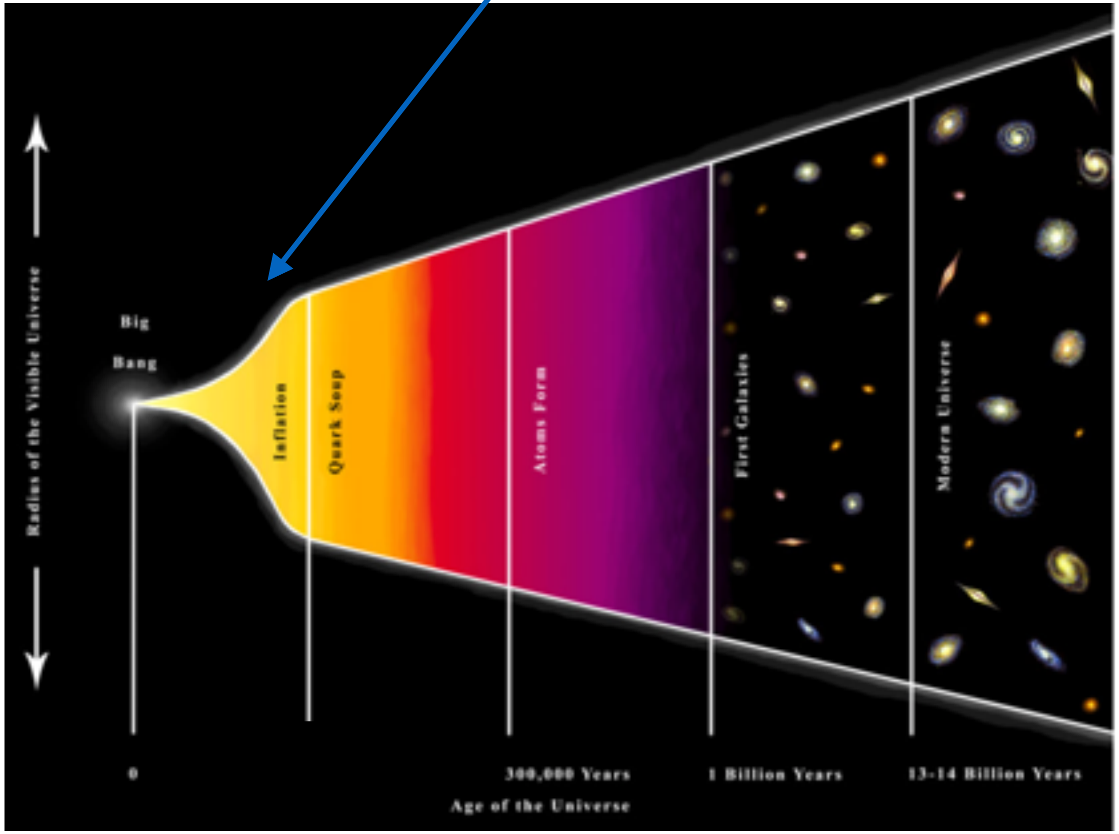
Do we expect the cosmic history to be so simple?

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





Depart from thermal picture (e.g. Inflation)



A strictly thermal history can not account for the data!

When does the universe thermalize?

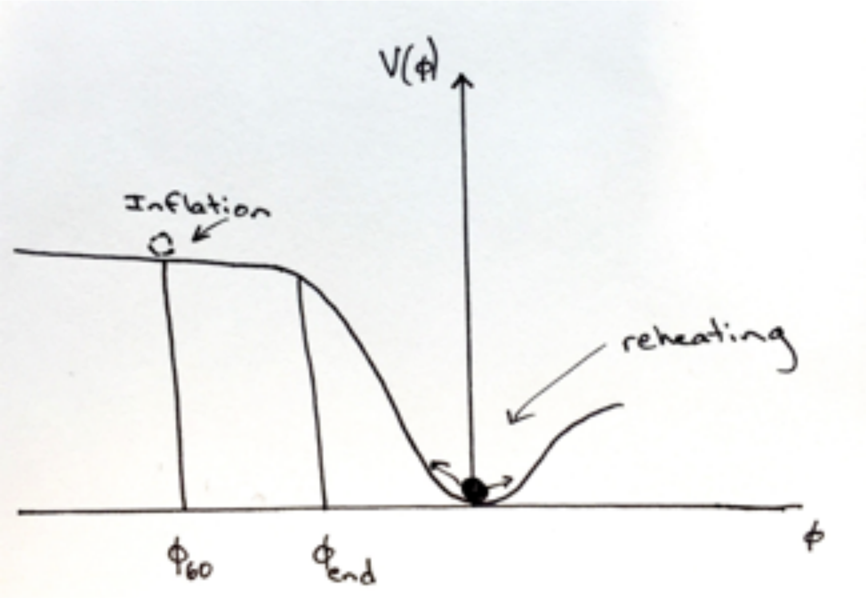
Perturbative Reheating

$$\ddot{\phi} + 3H\dot{\phi} + \Gamma\dot{\phi} + m^2\phi = 0$$

$$\phi(t) = \Phi(t)\cos(mt)$$

$$a(t) \sim t^{2/3}$$

Matter dominated Universe



Reheat temperature

$$\rho = \frac{\pi^2}{30} g_* T^4 = 3M_{\rm pl}^2 H^2$$

$$T_{\rm reh} \sim \left(\frac{90}{g_* \pi^2}\right)^{1/4} \sqrt{M_{\rm pl}\,\Gamma}$$

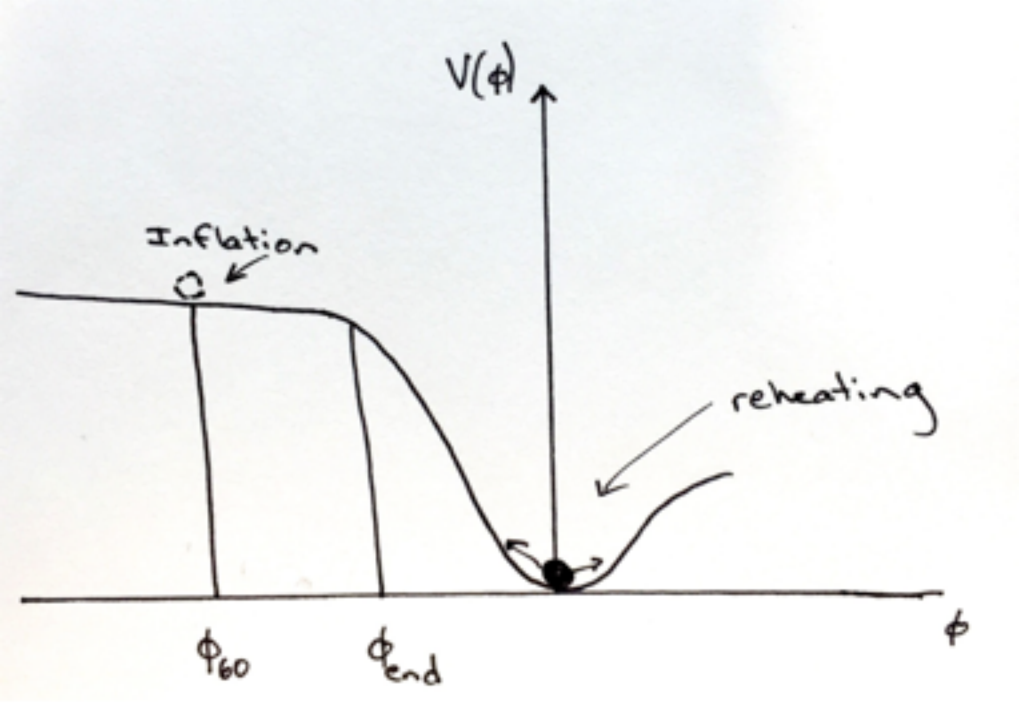
Perturbative Reheating

Challenges:

$$\mathcal{L}_{\text{int}} = g^2\phi^2\chi^2$$

$$\Gamma(\phi\phi \to \chi\chi) \sim \frac{g^4\Phi^2}{8\pi m}$$

$$\Phi^2 \sim \frac{1}{t^2} \qquad H \sim \frac{1}{t}$$



Require

$$H \lesssim \Gamma$$

Complete decay of inflaton challenging.

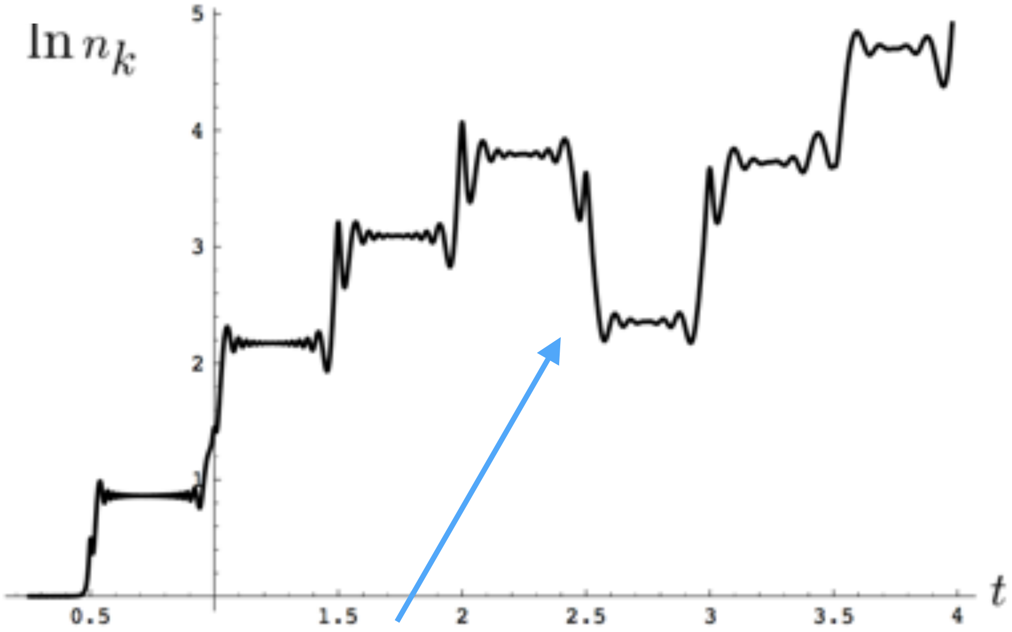
L. Kofman, A. D. Linde and A. A. Starobinsky, *Phys. Rev. Lett.* **73** (1994) 3195

Inflationary (P)reheating

A. Dolgov and D. Kirilova, *Sov. J. Nucl. Phys.* **51** (1990) 172.
J. H. Traschen and R. H. Brandenberger, *Phys. Rev.* **D42** (1990) 2491.
L. Kofman, A. D. Linde and A. A. Starobinsky, *Phys. Rev. Lett.* **73** (1994) 3195

Non-perturbative effects can be crucial

$$\frac{d^2X_k}{dt^2}+\left(\frac{k^2}{a^2}+g^2\Phi^2m^2(t-t_j)^2\right)X_k=0$$



Particle number can decrease
due to stochastic behavior

Inflationary (P)reheating

A. Dolgov and D. Kirilova, *Sov. J. Nucl. Phys.* **51** (1990) 172.
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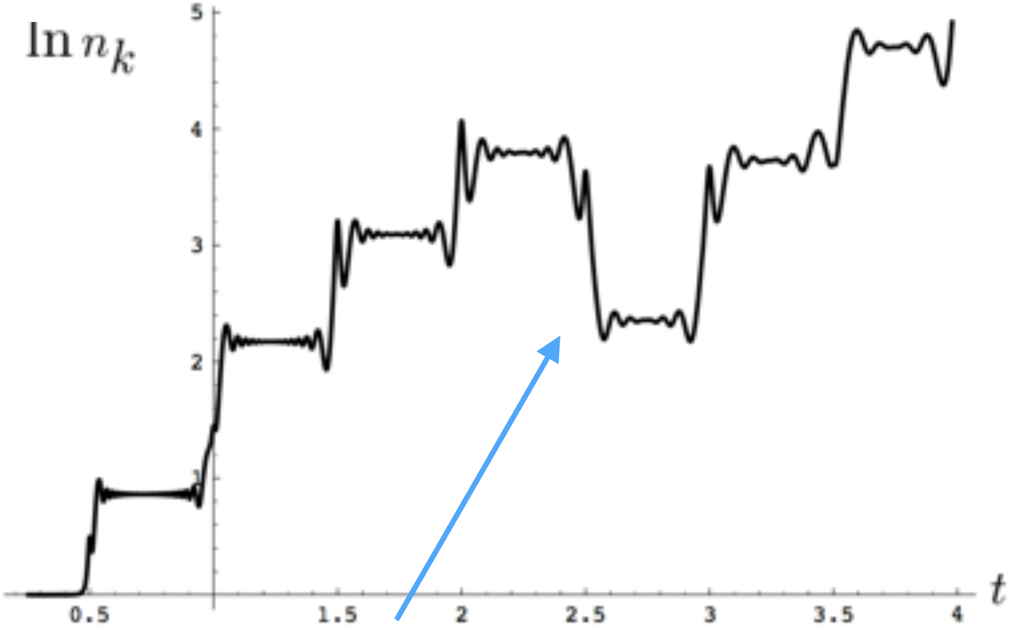
Non-perturbative effects can be crucial

$$\frac{d^2X_k}{dt^2} + \left(\frac{k^2}{a^2} + g^2\Phi^2 m^2 (t-t_j)^2\right) X_k = 0$$

$$n_k^{(0)} = \exp\left[-\pi \underbrace{\left(\frac{k^2+m_\chi^2}{\sqrt{2}gm\Phi_0}\right)}_{\kappa^2}\right]$$



Particle number can decrease due to stochastic behavior

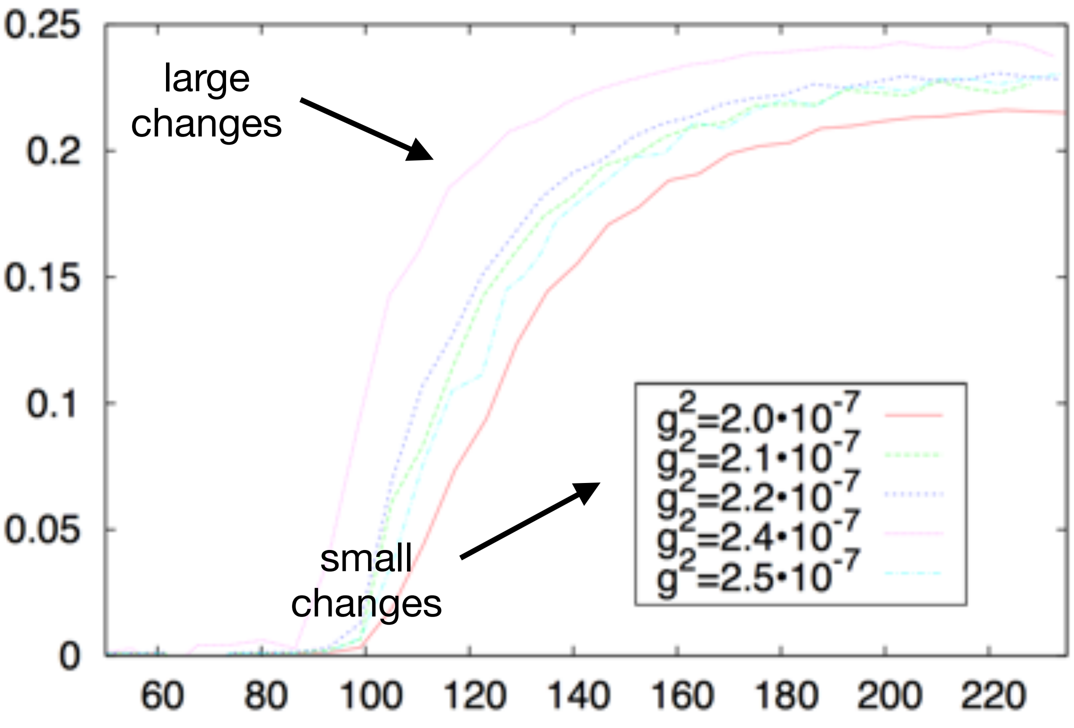
$$n_k^{j+1} \approx \left(1 + 2e^{-\pi\kappa^2} - 2\sin\theta^j_{tot}\, e^{-\frac{\pi}{2}\kappa^2}\, \sqrt{1+e^{-\pi\kappa^2}}\right) n_k^j$$

When does the universe thermalize?

- Inflationary reheating was possibly a complicated, non-thermal, non-equilibrium process.

- The reheating phase may have lasted for a long time and this would imply **departures from a strictly thermal history** for the early universe.

$$w = \frac{p}{\rho}$$

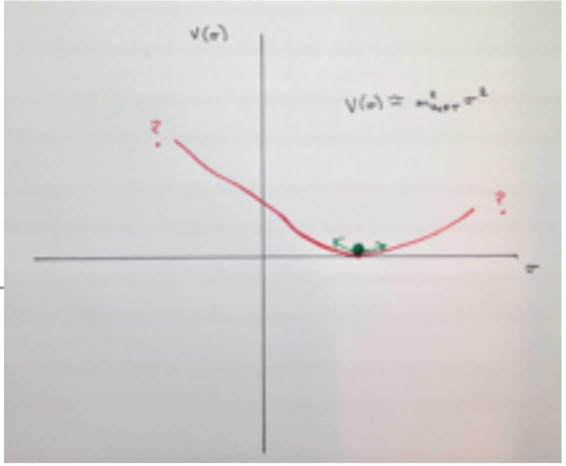


Podolsky, et. al. hep-ph/0507096

Standard Thermal History

$$w = \frac{1}{3}$$

The Cosmological Moduli “Problem”



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

Moduli couple gravitationally

$$\Gamma_\sigma \sim \frac{m_\sigma^3}{m_p^2}$$

Universe reheated (again)

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

Dark Matter Abundance diluted

$$\Omega_i \to \Omega_i^{(0)} \left(\frac{T_r}{T_f}\right)^3$$

Ex:

$m_\phi \sim 10 \text{TeV} \longrightarrow T_r \sim \text{MeV}$ $T_f \sim \text{GeV}$

$$\Omega_{DM} = 10^{-9} \Omega_\chi^{(0)}$$

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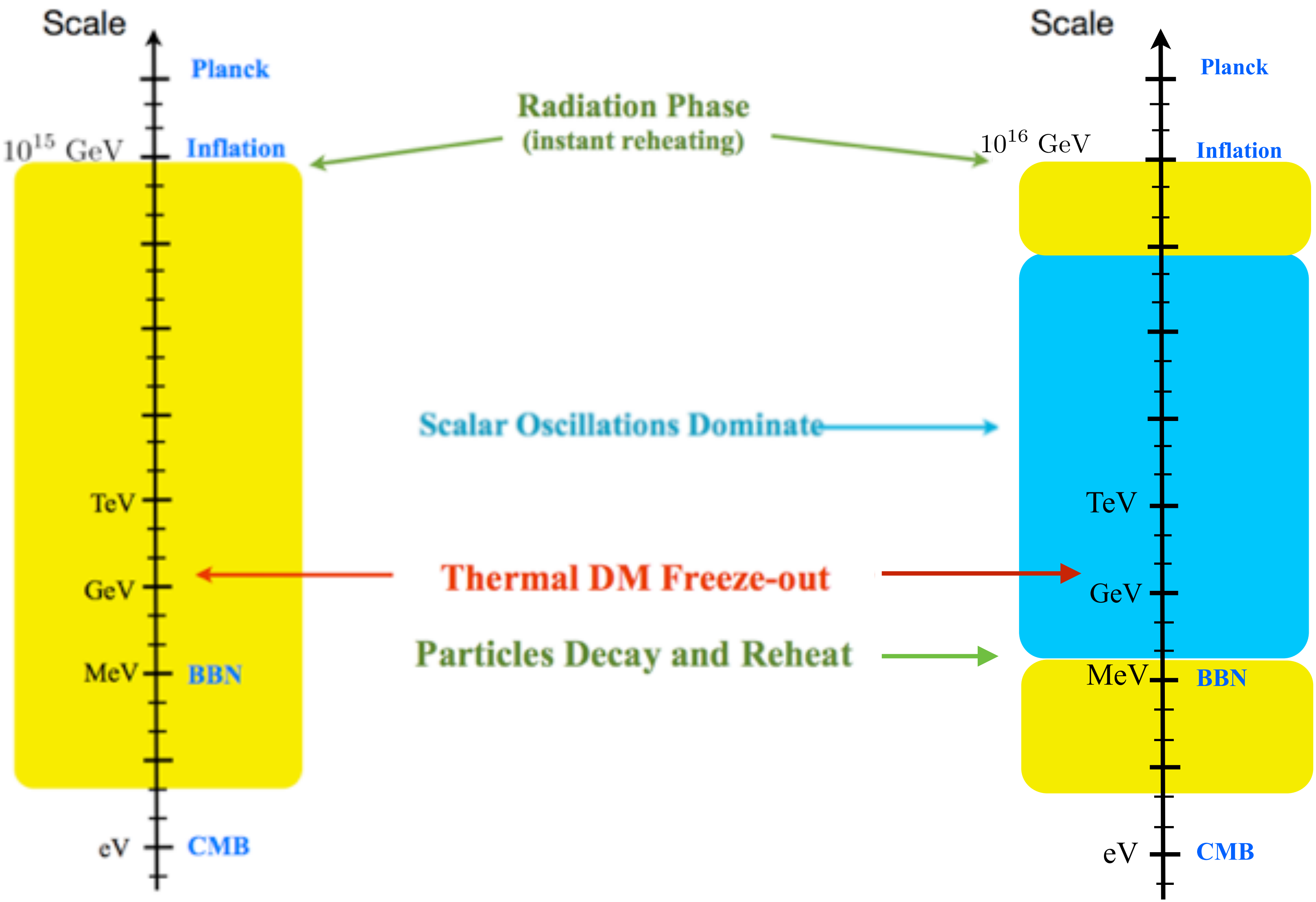
When does the universe thermalize?



Thermal History

Alternative History

Radiation Phase
(instant reheating)

Scalar Oscillations Dominate

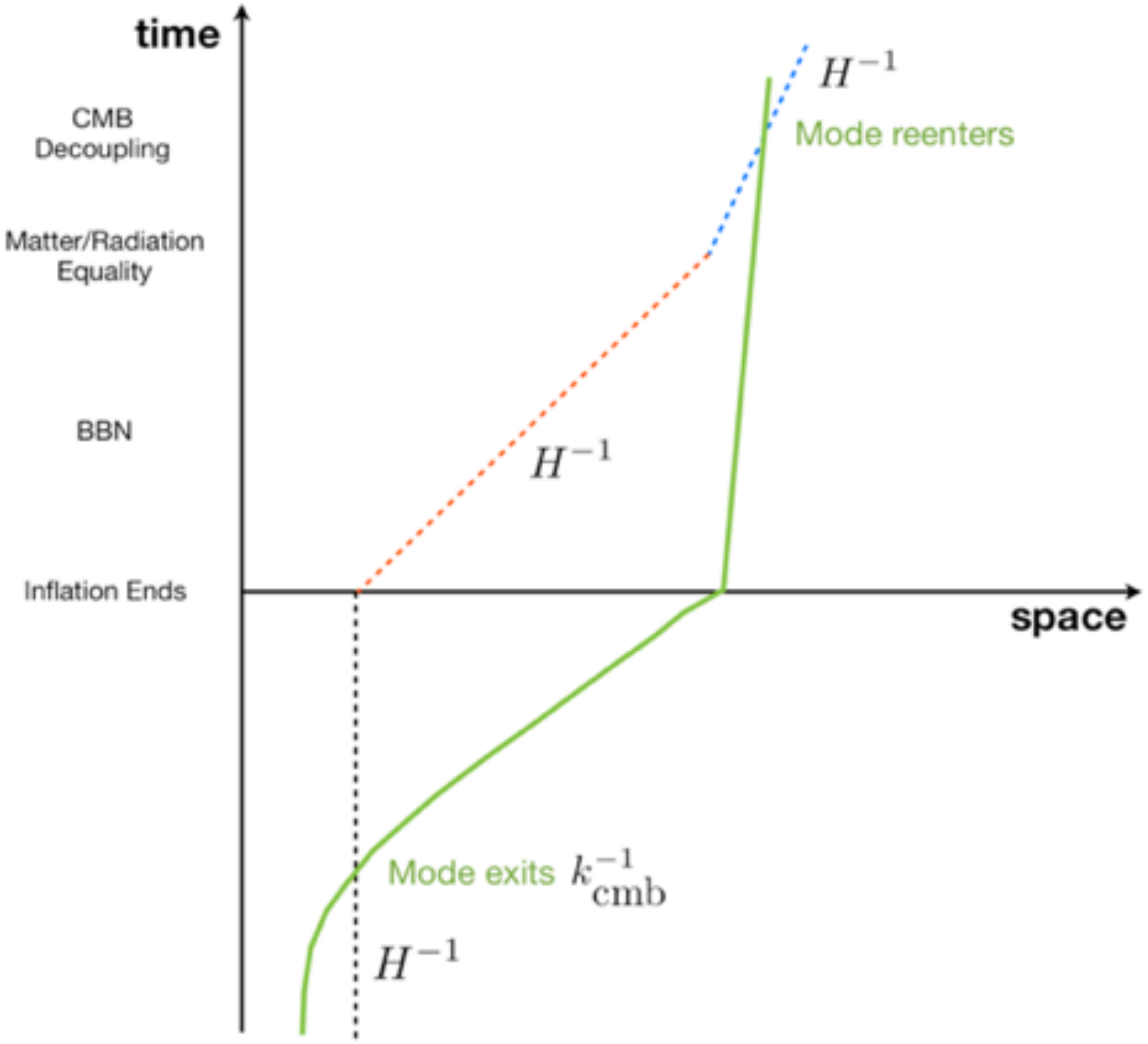
Thermal DM Freeze-out

Particles Decay and Reheat

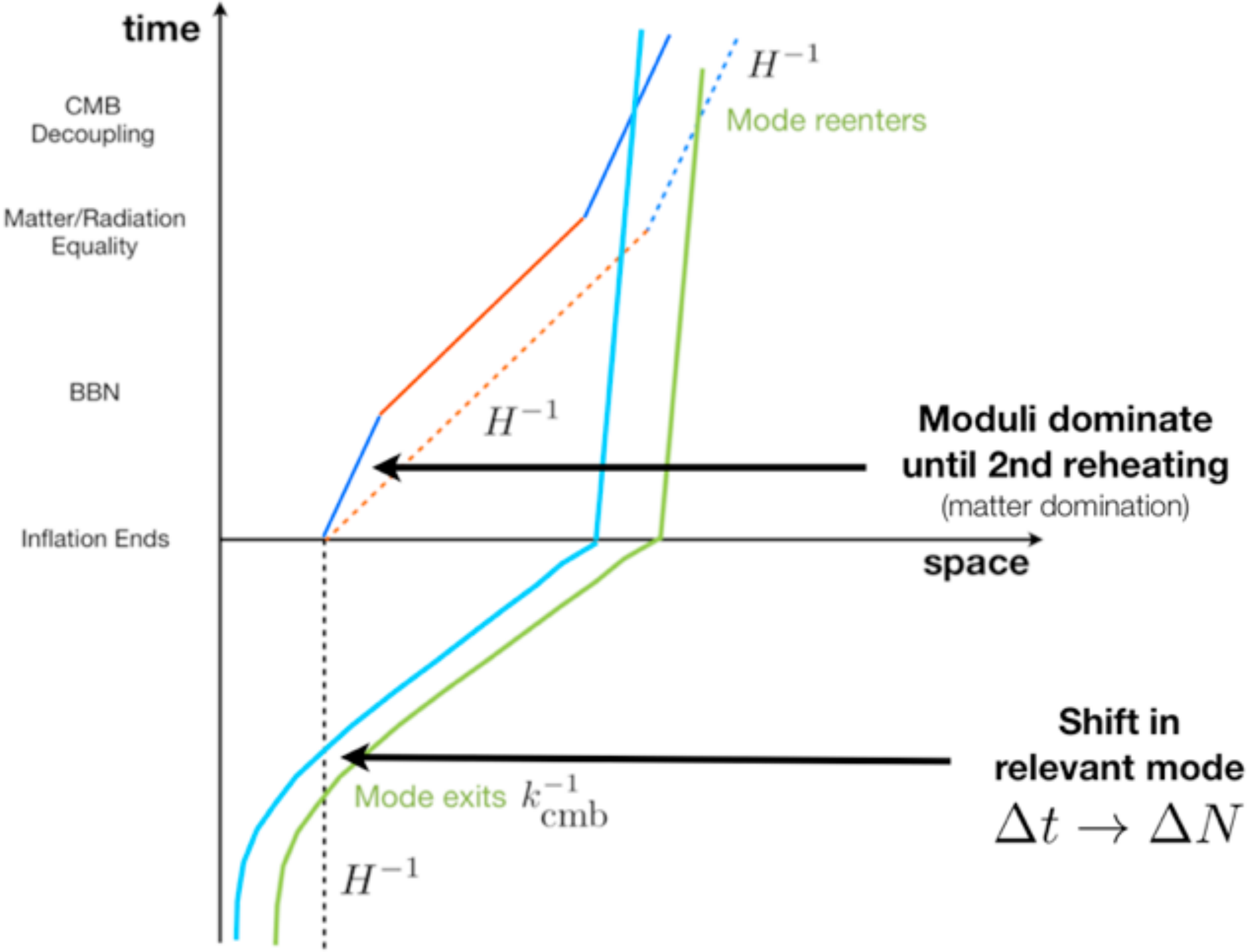
Both reheating and the CMP help motivate alternative histories.

Observational Implications?

Testing inflationary models



Universe with Non-thermal History



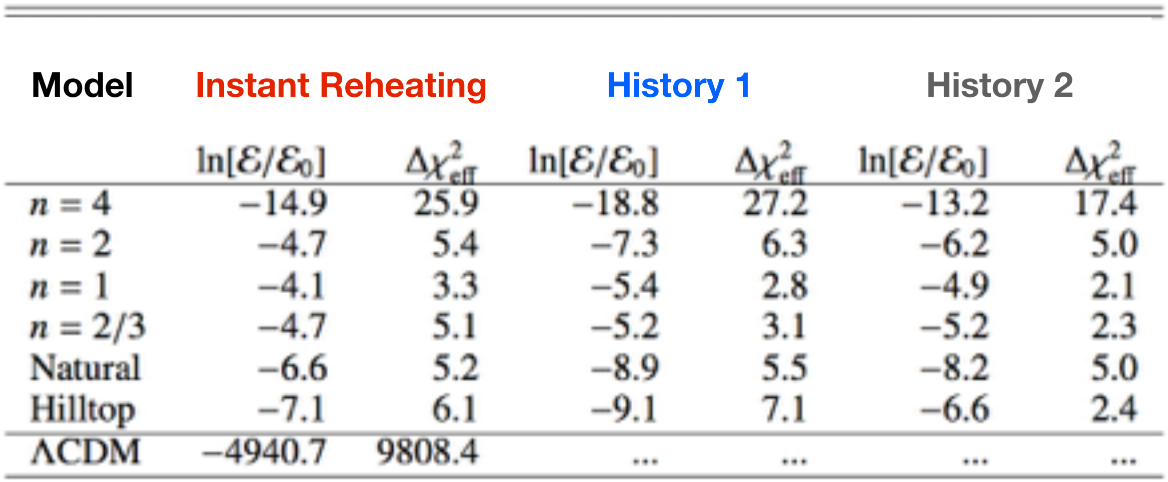
Moduli dominate until 2nd reheating

(matter domination)

Shift in relevant mode

$\Delta t \rightarrow \Delta N$

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)

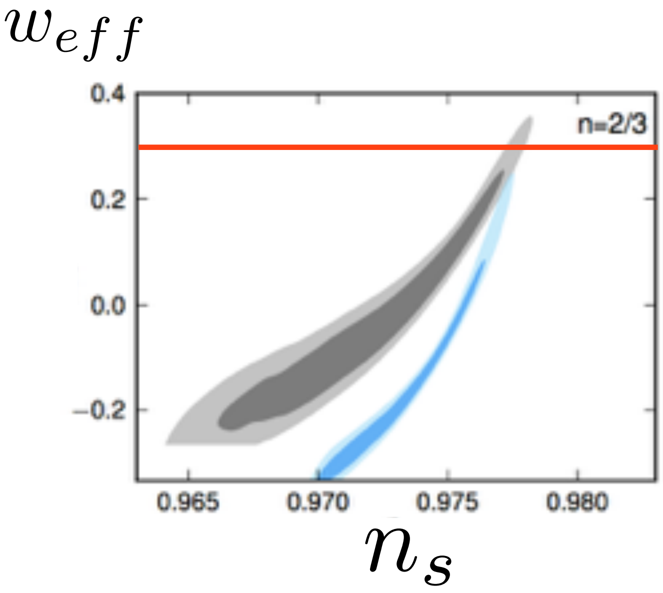
$$T_r = 10^8 \text{ GeV}$$

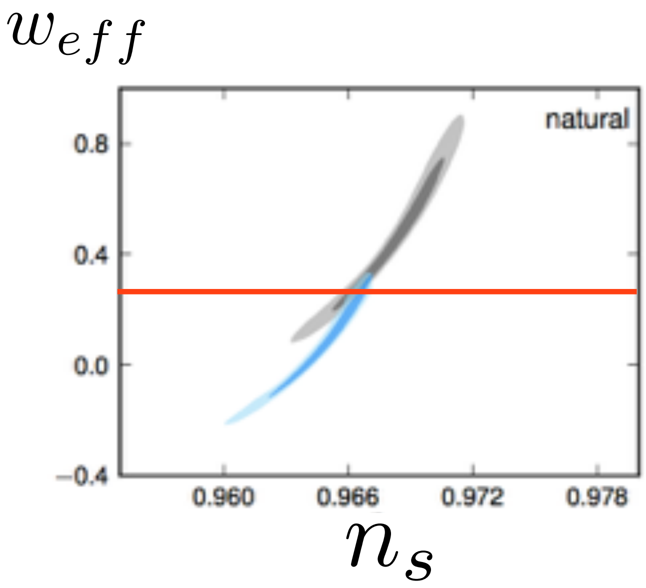
$$w_{eff} = -1/3 \ldots 1/3$$

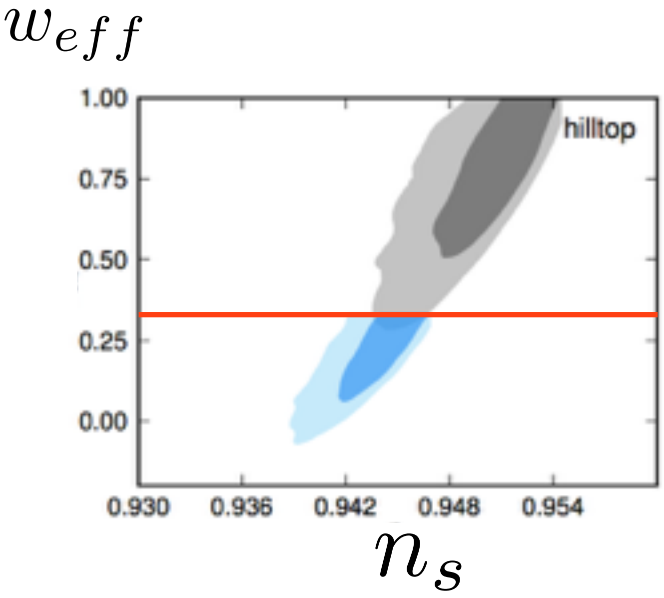
History 2 (Grey)

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

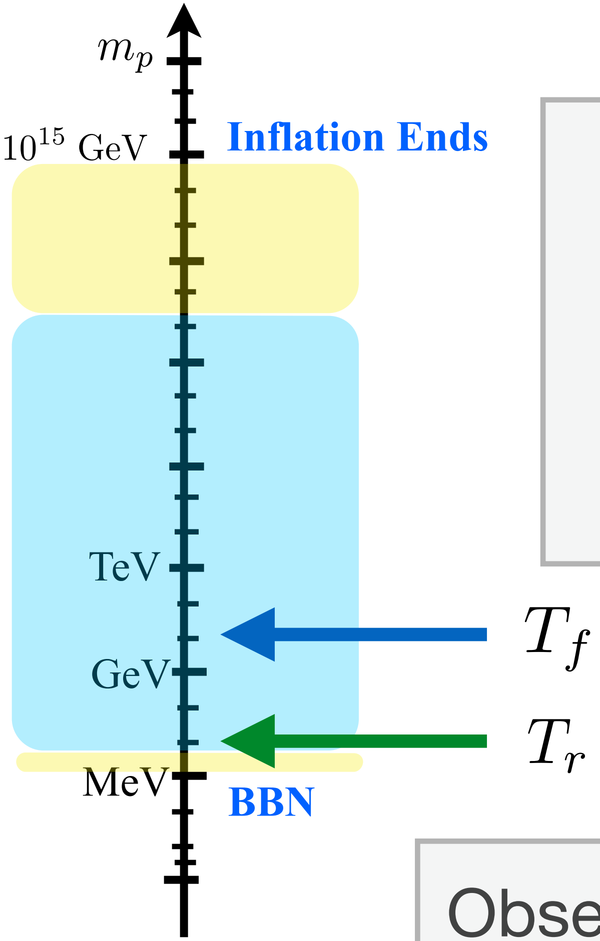
$$w_{eff} = -1/3 \ldots 1$$







New expectations for Dark Matter



Dark Matter Abundance from **Non-Thermal Production**

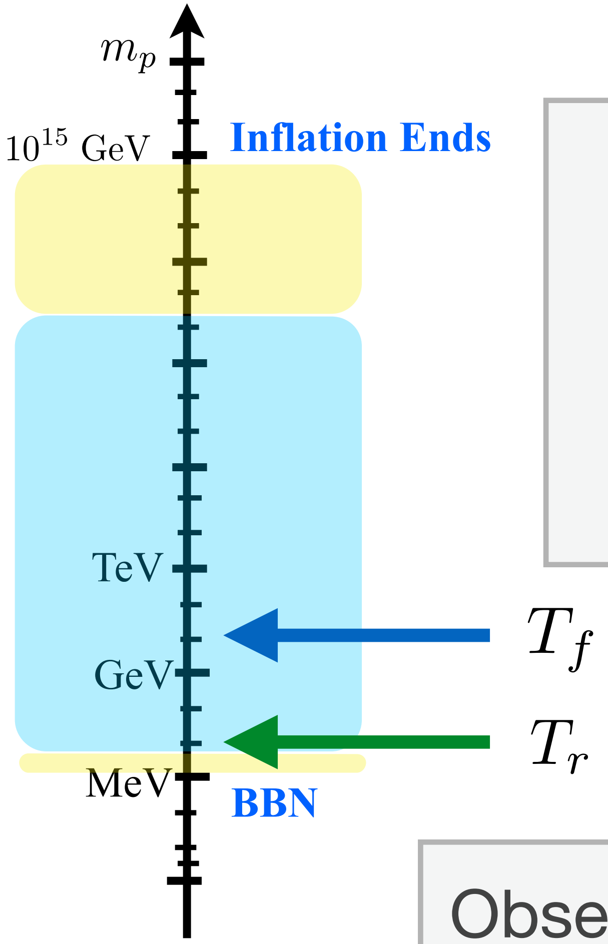
$$\Omega_{dm} \equiv \frac{\rho_{dm}}{\rho_c} = 0.23 \times \left(\frac{10^{-26}\ \mathrm{cm}^3 \cdot \mathrm{s}^{-1}}{\langle \sigma v \rangle} \right) \left(\frac{T_f}{T_r} \right)$$

Observations allow for a range of cross-sections

$$\Omega_{dm}^{\mathrm{Observed}} = 0.23$$

$$\longrightarrow \quad 10^{-26}\ \frac{\mathrm{cm}^3}{\mathrm{s}} \leq \langle \sigma v \rangle \leq 10^{-23}\ \frac{\mathrm{cm}^3}{\mathrm{s}}$$

New expectations for Dark Matter



Dark Matter Abundance from
Non-Thermal Production

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

New parameter

Observations allow

$$\Omega_{dm}^{\mathrm{Observed}} = 0.23$$

$$\longrightarrow \quad 10^{-26}\ \frac{\mathrm{cm}^3}{\mathrm{s}} \leq \langle \sigma v \rangle \leq 10^{-23}\ \frac{\mathrm{cm}^3}{\mathrm{s}}$$

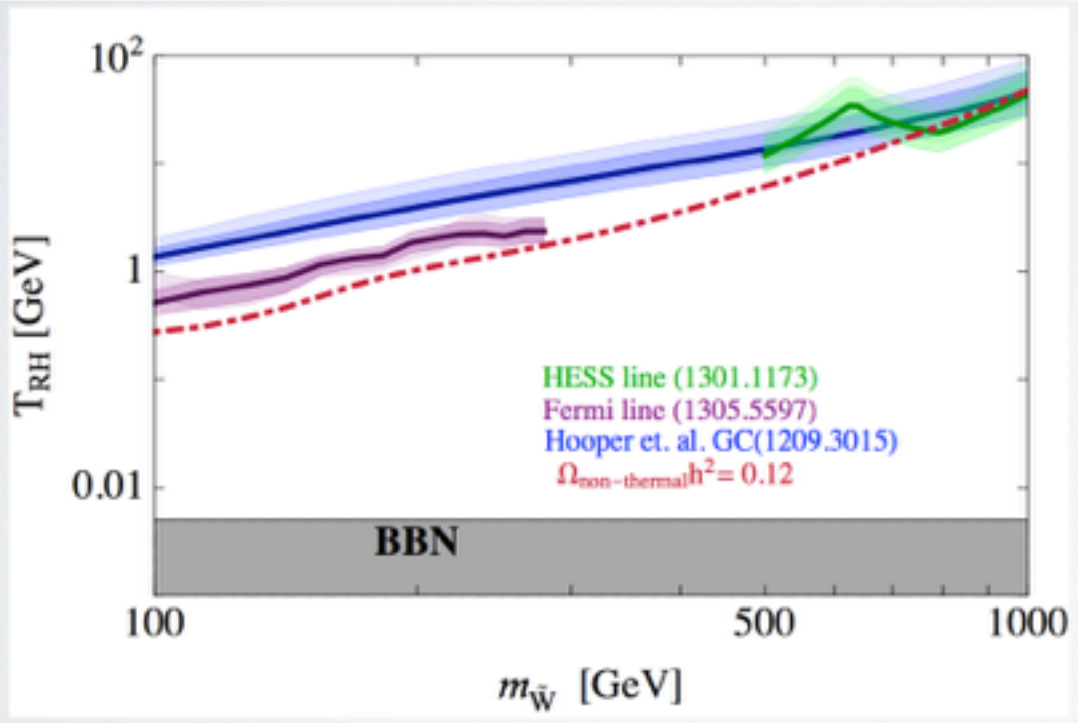
Non-thermal SUSY WIMPs

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

Fan and Reece 1307.4400

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

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



Fan and Reece 1307.4400

Non-thermal SUSY WIMPs are incompatible with low reheat temperatures

Other consequences of a Non-thermal History

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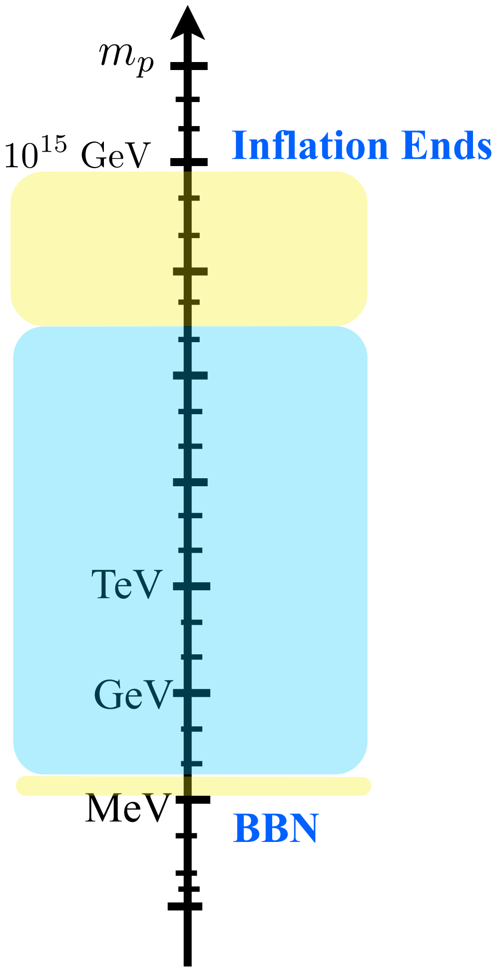

CMB Physics

Extra matter phase changes the way CMB observations are used to constrain inflationary models.

R. Easther, R. Galvez, O. Ozsoy, S.W. [Phys.Rev. D89 (2014)]

Additional relativistic energy from enhanced annihilations of dark matter changes physics of recombination.

Slatyer, Padmanabhan and Finkbeiner [Phys.Rev. D80]

Bounds on isocurvature contribution to CMB anisotropies lead to constraints.

L. Iliesiu, D. Marsh, K. Moodley, S.W. [Phys.Rev. D89]

Dark Radiation

Decays to non-Standard Model (hidden sector) radiation can lead to constraints from bounds on new light species (N_{eff}).

L. Iliesiu, D. Marsh, K. Moodley, S.W. [Phys.Rev. D89]

Enhanced Structure on Small Scales

Extra matter phase leads to additional growth of perturbations on small scales, sometimes enhancing dark matter structure

A. Erickcek and K Sigurdson [Phys. Rev. D84 (2011)]

J. Fan, O. Özsoy, S.W. [Phys. Rev. D90 (2014)]

A. Erickcek arXiv:1504.03335

Other consequences of a Non-thermal History

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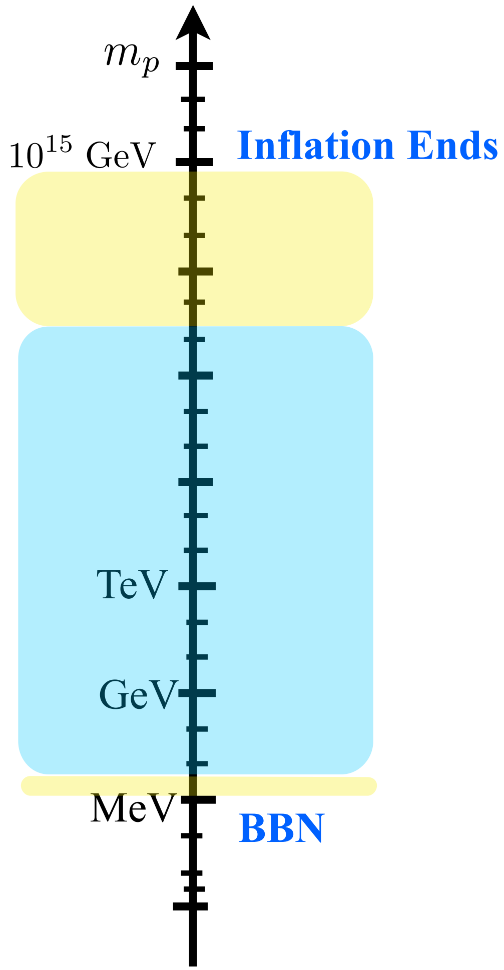

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Rest of this talk

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Dark Matter Perturbations During Non-thermal Phase

1405.7373 w/ JiJi Fan and Ogan Ozsoy
1106.0536 A. Erickcek and K Sigurdson

Scalar domination

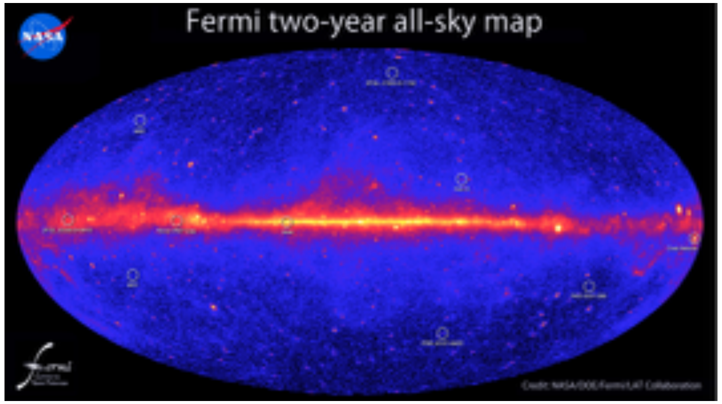
$$\frac{\delta\rho_{\rm dm}}{\rho_{\rm dm}} \sim a(t)$$

For reheat temperatures around 5 MeV, this could lead to Earth size ultra-compact-mini-halos

Horizon Size at Reheating (non-thermal history)

Moduli domination can lead to growth

$$\lambda_r \sim H^{-1}\big|_{T=T_r}$$



Non-thermal Phase and Structure Growth

1405.7373 w/ JiJi Fan and Ogan Ozsoy
1106.0536 A. Erickcek and K Sigurdson

Evolution of Density Perturbations

$$\delta_k \equiv \frac{\delta\rho_k}{\rho_0}$$

$$\ddot{\delta}_k + 2H\dot{\delta}_k + \left(c_s^2 k_p^2 - \frac{3}{2}H^2\right)\delta_k = 0$$

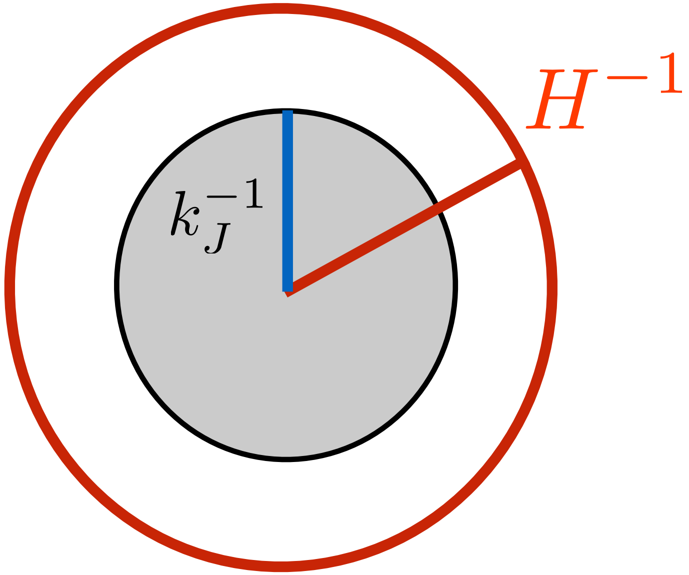
Hubble "friction" slows the instability

Pressure prevents collapse

Gravity drives collapse

$$k_J^2 = \frac{3H^2}{2c_s^2}$$

Jean's scale sets the growth scale

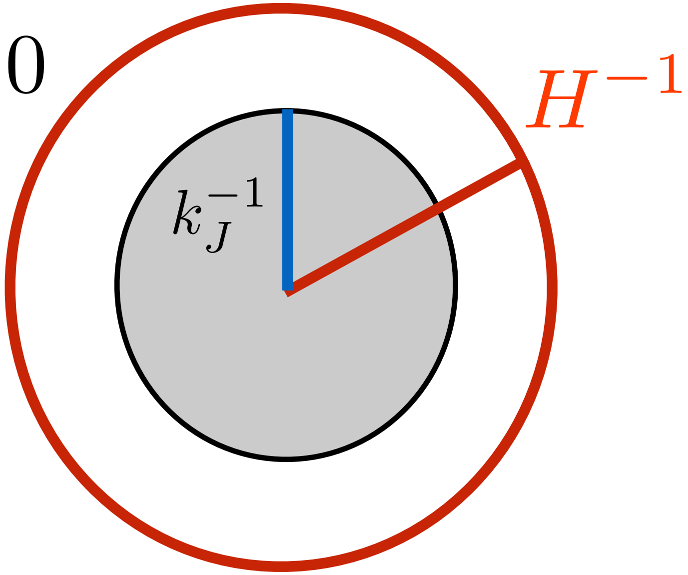


Non-thermal Phase and Structure Growth

1405.7373 w/ JiJi Fan and Ogan Ozsoy
1106.0536 A. Erickcek and K Sigurdson

Evolution of Density Perturbations

$$\ddot{\delta}_k + 2H\dot{\delta}_k + \left(c_s^2 k_p^2 - \frac{3}{2}H^2\right)\delta_k = 0$$



$$k_J^2 = \frac{3H^2}{2c_s^2}$$

Radiation Dominated Universe

$$H^{-1} > \lambda > k_J^{-1} \qquad c_s^2 = \frac{1}{3}$$

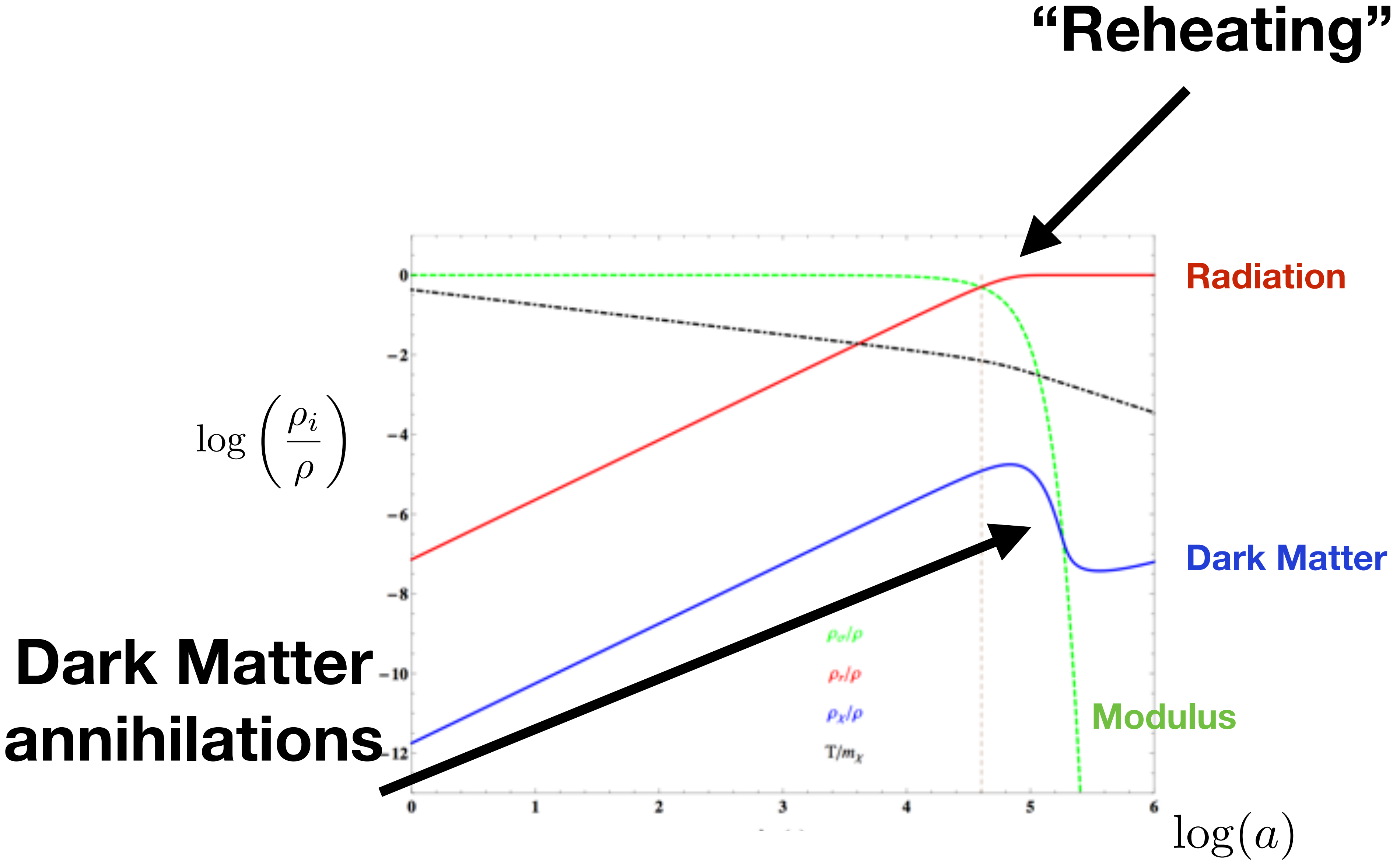
Matter Dominated Universe

$$k_J^{-1} = 0 \qquad c_s^2 = 0$$

Structures grow in a Matter Dominated Universe

Post Inflationary Evolution

1405.7373 w/ JiJi Fan and Ogan Ozsoy
1106.0536 A. Erickcek and K Sigurdson



“Reheating”

Radiation

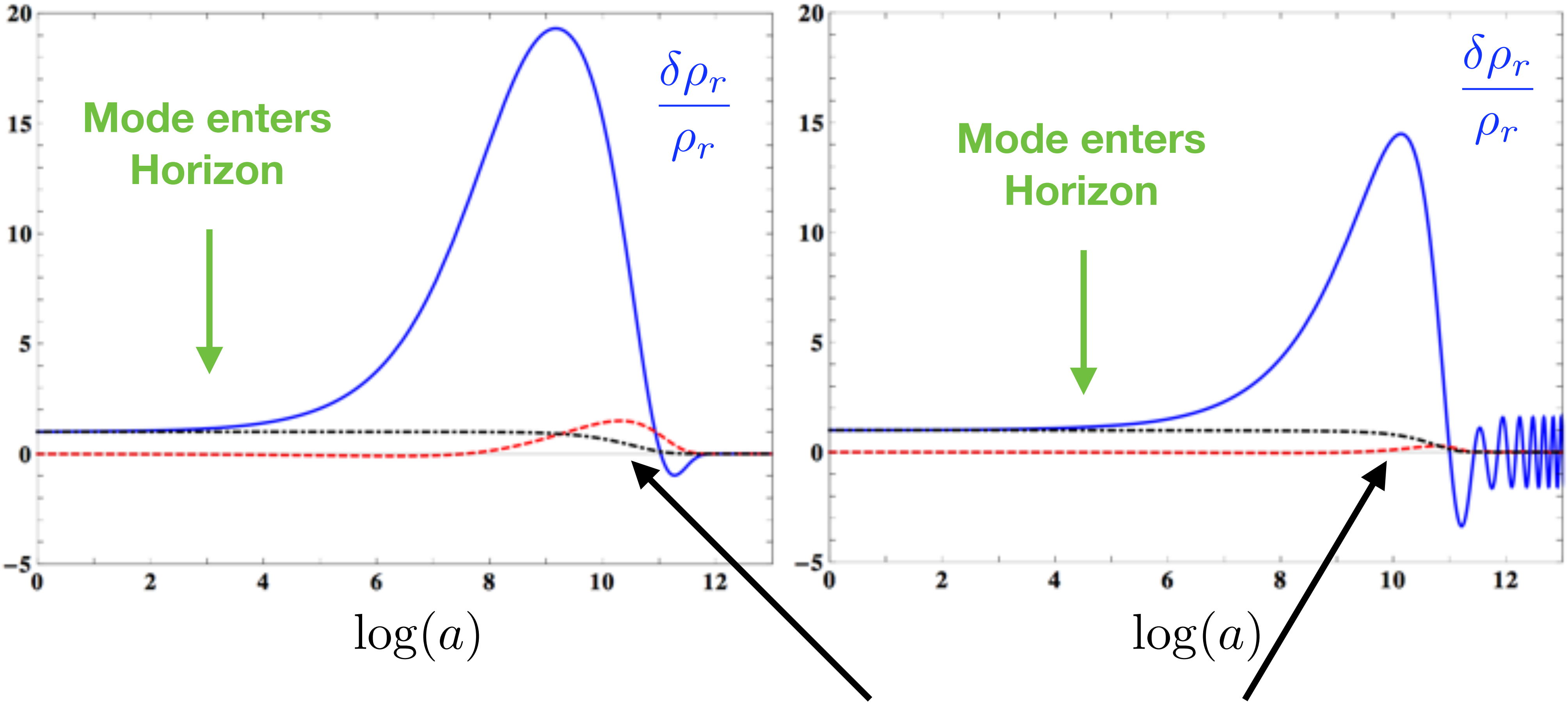
Dark Matter

Modulus

Dark Matter annihilations

Radiation Perturbation During Non-thermal Phase

1405.7373 w/ JiJi Fan and Ogan Ozsoy
1106.0536 A. Erickcek and K Sigurdson



Reheating

Longer moduli phase, lower reheat temperature
= more suppression

Matter Perturbation During Non-thermal Phase

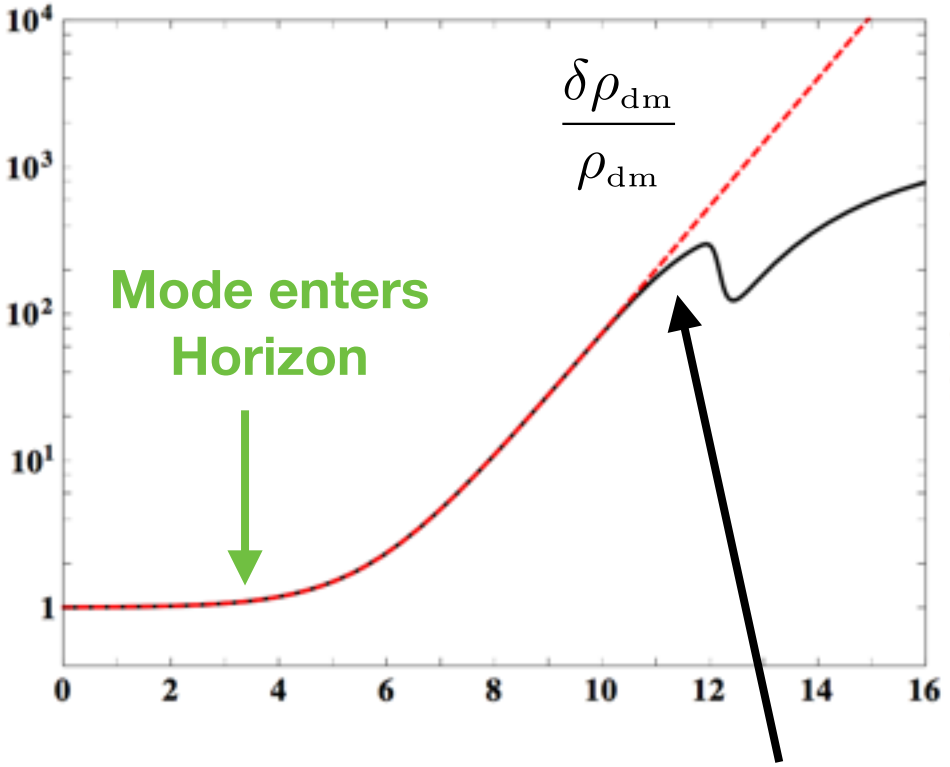
1405.7373 w/ JiJi Fan and Ogan Ozsoy
1106.0536 A. Erickcek and K Sigurdson

Scalar domination

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

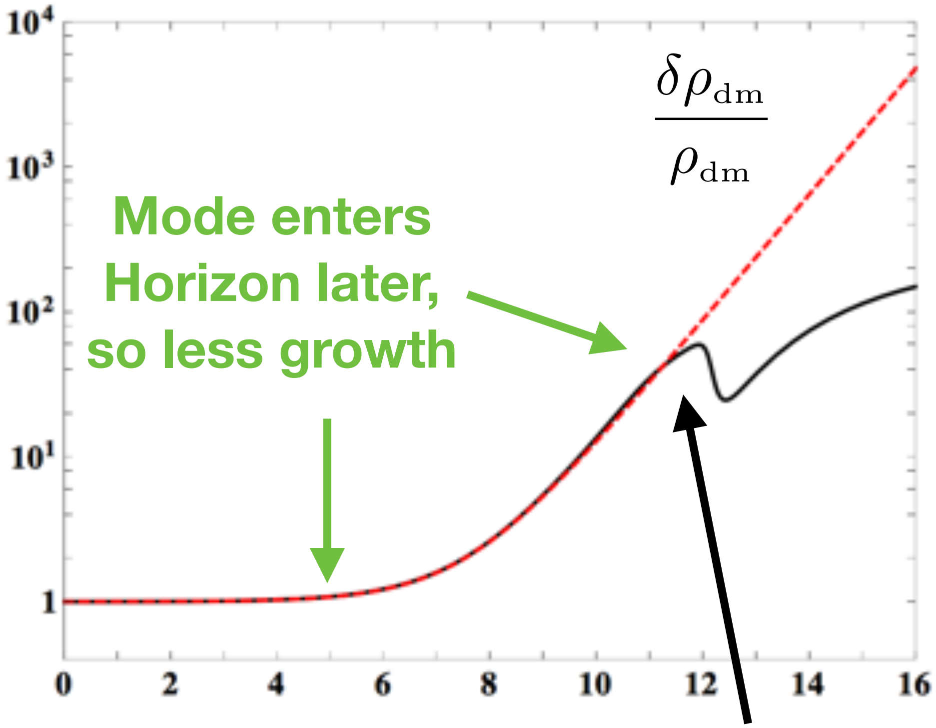
Radiation domination

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



Mode enters Horizon

$\log(a)$ **Reheating**

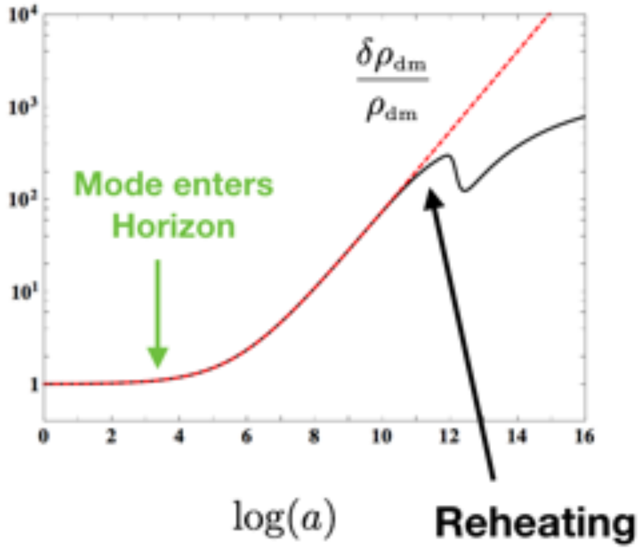


Mode enters Horizon later, so less growth

$\log(a)$ **Reheating**

Non-thermal Histories and the Matter Power Spectrum

1405.7373 w/ JiJi Fan and Ogan Ozsoy

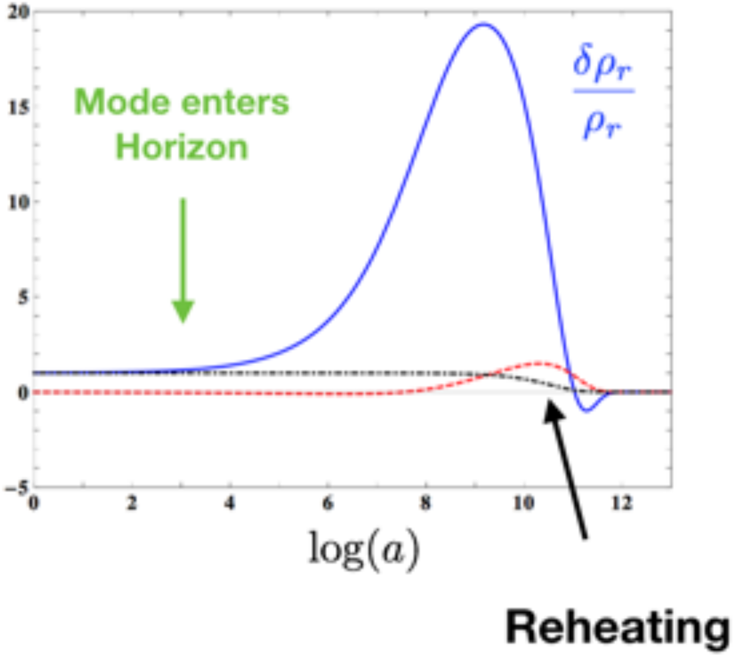


IF: A lot of the dark matter is produced before completed decay

THEN: Enhanced growth of structure on small scales possible.

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

Then: Kinetically coupled dark matter will be more suppressed than usual.



Non-thermal Histories and the Matter Power Spectrum

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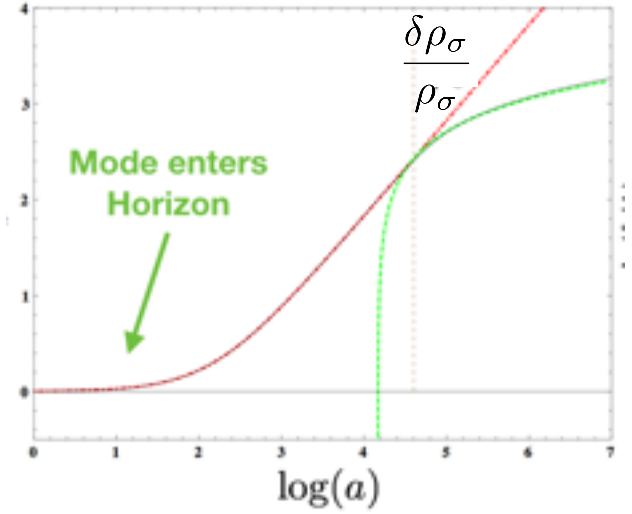

Dominant Effect: Sub-Horizon scalar perturbations also grow! And they are converted to dark matter perturbations (enhanced structure possible)

$$\frac{\delta\rho_\sigma}{\rho_\sigma} \longrightarrow \frac{\delta\rho_{\mathrm{DM}}}{\rho_{\mathrm{DM}}}$$

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

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

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Scales to determine smallest structures (linear regime):

Free-streaming Scale

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

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

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

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Summary of our study (Non-thermal SUSY WIMPs):

Free-streaming Scale

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

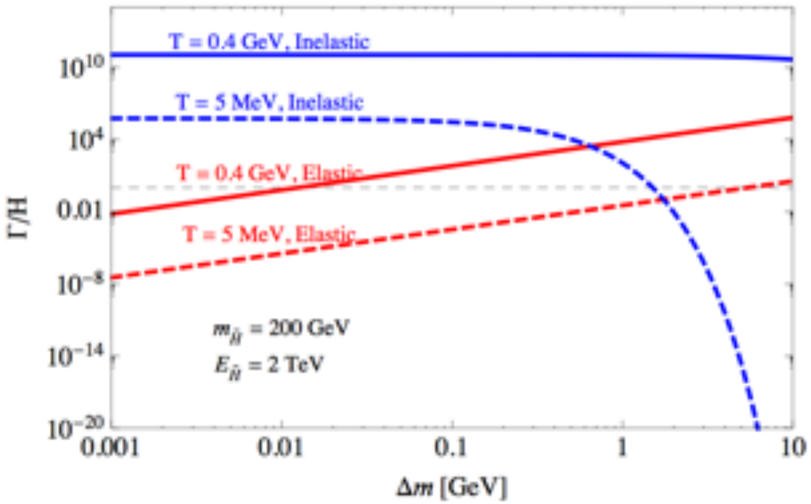
$$\lambda_{\rm fsh}(t) = \int_{t_{\rm RH}}^{t} \frac{\langle v \rangle}{a}\, {\rm d}t,$$

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

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.

Conclusions

- **Inflationary model building, reheating and BSM scalars (moduli) all imply an early matter dominated phase prior to BBN — a strictly thermal history for the early universe does not agree with existing data.**

- **The non-thermal phase leads to new expectations for the microscopic properties of dark matter, as well as important implications for the CMB and LSS.**

- **In both thermal and non-thermal histories, SUSY WIMPs as the only source of dark matter is in increasing tension with the data.**

- **Although non-thermal histories can lead to interesting phenomenology very little has been done to explore them outside of a SUSY framework.**

Backup Slides

Non-thermal Histories and the Matter Power Spectrum

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It is difficult for the reheating effects to survive for SUSY WIMPs

Free-streaming Scale

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

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

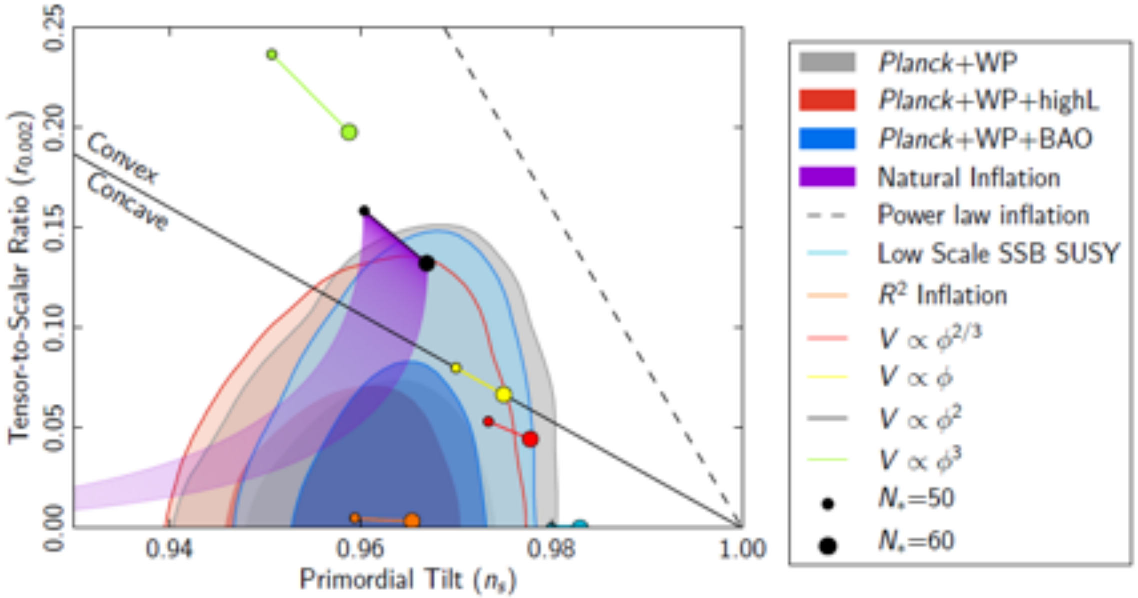
$$\frac{\lambda_{fsh}}{\lambda_r} \approx \begin{cases} 2\langle v_{rh}\rangle \left(\sinh^{-1}\sqrt{\frac{\sqrt{2}k_{rh}}{k_{eq}}} - \sinh^{-1}\sqrt{a_{eq}}\right), & \langle p_{rh}\rangle \ll m_\chi \\ \frac{a_{nr}}{a_{rh}} - 1 \approx \frac{\langle p_{rh}\rangle}{m_\chi}, & \langle p_{rh}\rangle \gg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

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

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

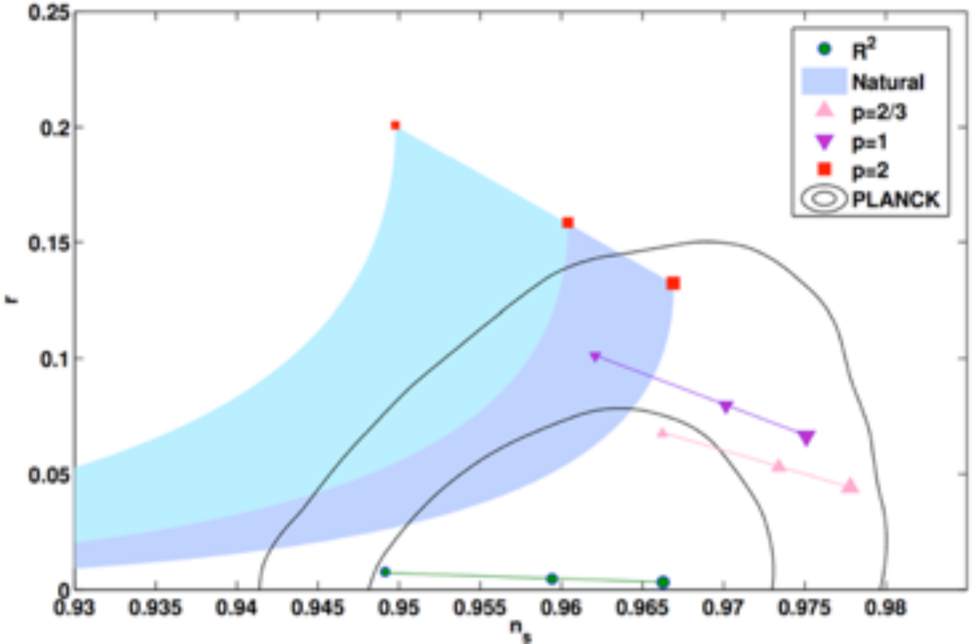
$$m_\sigma \sim 100\ {\rm TeV} \qquad m_\chi \sim 100\ {\rm GeV}$$

Changes in history imply changes in constraints



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

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



Dimension 5 and Dimension 6 Operators

Gravity is non-renormalizable

Graviton scattering is non-unitary near Planck scale, new degrees of freedom expected.

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

Dimension 5 operators can be forbidden by a discrete $\mathbb{Z}_2$ But dimension 6 operators remain a challenge

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

Quantum gravity is expected to break (global) shift symmetries.
Quantum corrections will then make this problem worse.

Shift symmetry alone is not enough.