Cosmology and New Physics

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Observations Agree with Theory

- Gaussian
- Adiabatic
- Scale-invariant
- Superhorizon
- Homogeneous
- Flat
- Isotropic

Image courtesy D. Baumann
We know a lot about inflation

\[ r \equiv \frac{\Delta_t^2}{\Delta_s^2} \]

\[ N_s = 50 \]

\[ N_s = 60 \]

\[ r \]

\[ n_s \]

\[ \phi^3 \]

\[ \phi^2 \]

\[ \phi^1 \]

\[ \phi^{2/3} \]

\[ R^2 \]

slow-roll

end of inflation

oscillations & decay

little or no interactions

\[ f_{\text{local}} = -0.9 \pm 5.1 \]

\[ f_{\text{equil}} = -26 \pm 47 \]

\[ f_{\text{ortho}} = -38 \pm 24 \]

planck 2018 (68% cl)
And we will know more…

A detection of gravitational waves would tell us the scale of new physics

\[ \frac{H_I}{m_p} \sim 10^{-5} \left( \frac{r}{0.1} \right)^{1/2} \]
And we will know more…

Projected bounds on new light particles

![Graph showing projected bounds on new light particles with different spin states.](image)
How did inflation end?

Does this require new physics?
How did inflation end?

**Slow-roll inflation**

A scalar field (inflaton) slowly-rolling down to its potential minimum

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1. Inflation at slow-roll era
2. End of Inflation
3. Coherent oscillations
4. Decays to Standard Model particles
5. Reheating $\rightarrow$ Big-Bang Cosmology

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Lecture notes on Cosmology (UT Austin)
The process of reheating can be highly non-linear and NOT instantaneous.

The transition from inflation to “reheating” can be complicated.

**Stages of Reheating:**

1. Non-perturbative (parametric resonance)
2. Non-linear Dynamics and Chaos
3. Turbulence
4. Thermalization
We know a lot about inflation

How long does reheating take?

Weak couplings to other fields during inflation

\[ r \equiv \frac{\Delta^2_t}{\Delta^2_s} \]

Little or no interactions

\[
\begin{align*}
    f_{NL}^{\text{local}} &= -0.9 \pm 5.1 \\
    f_{NL}^{\text{equil}} &= -26 \pm 47 \\
    f_{NL}^{\text{ortho}} &= -38 \pm 24
\end{align*}
\]

Planck 2018 (68% CL)
Prolonged reheating phase can alter the early expansion history implying a departure from a standard thermal history (Observational consequences in a few minutes)
When / how did the universe thermalize?

Observational Implications?

Image courtesy S. Watson
Constraints on Inflation and reheating

Can’t a dimension five or six operator provide reheating to the Standard Model?
Inflation is UV Sensitive (Eta problem)

Gravity is non-renormalizable

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

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

Example: Dimension 6 operators present a challenge for inflation given proximity to the Planck scale

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

Systematically and self consistently calculating these corrections are crucial and require UV theory (e.g. String Theory)

Lesson: You can’t just have an inflaton
The end of Inflation?
Gravitationally coupled hidden sectors are a natural consequence of inflationary model building.

Expect many fields in addition to the inflaton (moduli)

Additional Hidden Sectors are natural expectation

3-cycle size: $U$ (Complex structure moduli)

4-cycle size: $\tau$ (Kahler moduli)

Image courtesy F. Quevedo
The presence of additional fields (e.g. moduli) also alter the early expansion history — “Non-thermal Histories”.

Equation of State?
Non-Thermal Histories Are Well Motivated

with Kuver Sinha and Gordon Kane  [arXiv: 1502.07746]

**Experimental:**

**CMB and Inflation** (Planck)
Many inflationary models favor non-thermal history.

**Lack of thermal WIMP detection**

**Recombination Constraints** (Planck)
Thermal WIMPs in tension

**Non-Standard History —> New Phenomenology**

**Theoretical:**

Many **String Theory** models motivate non-thermal histories.
(Example: Moduli with low-scale masses (near TeV) form condensates.)

**Inflationary Reheating:**
Transfer of energy from inflationary sector to Standard Model and hidden sectors (BSM / dark matter) can lead to prolonged matter domination.
How did inflation end?

**Slow-roll inflation**

A scalar field (inflaton) slowly-rolling down to its potential minimum

1. Inflation at slow-roll end
2. End of Inflation
3. Coherent oscillations
4. **Decays to Standard Model particles**
5. Reheating → Big-Bang Cosmology

Lecture notes on Cosmology (UT Austin)
Cascading Energy from Inflaton to Radiation

End of Inflation

annihilation into closed string loops

Decay into KK + gravitons

Decay into SM brane modes

φ decay

ψ, F, gravitons, long-living KK

1

2

3

4
Very little work on UV complete theories of Inflationary reheating...

Perturbative reheating in Large Volume Inflation
(closed string model)

Reheating and Dark Radiation after Fibre Inflation
Cicoli and Piovano  arXiv:1809.01159

Reheating for Closed String Inflation
Cicoli and Mazumdar  arXiv:1005.5076

**Standard Model on D3 branes**

\[
\frac{\text{Br} (\varphi \to \text{SM})}{\text{Br} (\varphi \to \text{Hidden})} \approx \frac{2}{5} (\alpha_{\text{SM}})^2 \ll 1
\]

**Standard Model on D7 branes** (difficult to avoid hidden sector production)

\[
\Gamma_{\varphi \to a_i a_i} = \frac{5}{96\pi} \left( \frac{m_\phi^3}{m_p^2} \right) \qquad \Gamma_{\varphi \to \text{SM}} = \frac{\gamma^2 N_g}{48\pi} \left( \frac{m_\phi^3}{m_p^2} \right)
\]

Sufficiently isolating the inflaton is problematic for reheating.
Hidden Sectors v.s. Standard Model

New ways to populate Dark Matter
(Hidden Sector)
Co-decay Mechanism

"Co-Decaying Dark Matter" — PRL 117 (arXiv: 1607.03110) by J. Dror (Berkeley), E. Kuflik (Hebrew University), and W. Ng (Cornell)

Dark Sector is not in thermal equilibrium with Standard Model (it decouples completely, very early, and while relativistic).

Dark sector temperature scales differently than Standard Model.

Dark Sector particles in equilibrium until decay. No Boltzmann suppression.
Co-decay Mechanism

$T_{dec}$  $m_D$  $T_\Gamma$  $T_f$

1/T (time)

Comoving Density

$10^{-2}$  $10^{-3}$  $10^{-4}$  $10^{-5}$  $10^{-6}$  $10^{-7}$  $10^{-8}$  $10^{-9}$  $10^{-10}$  $10^{-11}$

$x = m/T$

$T_{dec}$:
- Dark Sector decouples from SM (while relativistic)

$m_D$:
- Dark Matter non-Relativistic

$T_\Gamma$:
- Light particles Decay to SM

$T_f$:
- Dark Matter freezes out

$10^{-1}$  $1$  $10$  $10^2$  $10^3$

Freezeout

Decay

$mY^\text{eq}$

$mY_A$

$mY_B$
Co-decaying Dark Matter: An Explicit Model

Dark SU(2) Gauge theory

\[ D^\mu \Phi_D^\dagger D_\mu \Phi_D - \frac{1}{4} F_{D,\mu\nu}^a F_{D,\mu\nu}^a - \lambda_D \left( \Phi_D^\dagger \Phi_D - \frac{v_D^2}{2} \right)^2 \]

Custodial symmetry implies nearly degenerate masses and stability of gauge bosons

Explicitly broken to U(1)

\[ \mathcal{O}_6 = \left( \Phi_D^\dagger D^\mu \Phi_D \right) \left( \Phi_D^\dagger D^\mu \Phi \right) / \Lambda^2 \]  
(E.g. integrate out heavy fermions charged under both sectors)

Stable Dark Matter ("A" sector)

\[ W^\pm_D = \left( W^1_D \mp W^2_D \right) / \sqrt{2} \]

Decaying particle ("B" sector)

\[ Z_D \equiv W^3_D \]  
Decays to Standard model through mixing

\[ m_D \simeq m_Z^{(D)} \simeq m_W^{(D)} \]
Co-decay leads to interesting consequences for the early cosmic history and the structure of dark matter.

\[
\rho'_A + \rho'_B = -3(\rho_A + \rho_B) - \frac{\Gamma_B}{H} \rho_B,
\]

\[
\rho'_A = -3\rho_A - \frac{\langle \sigma v \rangle}{mH} [\rho_A^2 - \rho_B^2],
\]

\[
\rho'_r = -4\rho_r + \frac{\Gamma_B}{H} \rho_B,
\]

The Dark Sector leads to an early matter dominated phase.
Concentrated Dark Matter

“Concentrated Dark Matter” — PRD 97 (arXiv: 1711.04773) with J. Dror (Berkeley), E. Kuflik (Hebrew University), and B. Melcher

Unlike, Standard SUSY WIMPs, Dark matter decouples from Standard Model early.

Cosmological Dark matter results from decay of hidden sector particles. Growth of substructure can lead to enhanced signals for indirect detection.

Compare to:
Fan, Ozsoy, and Watson (Phy. Rev. D90)
Erickcek and Sigurdson (Phy. Rev. D84)
Concentrated Dark Matter

“Concentrated Dark Matter” — PRD 97 (arXiv: 1711.04773) with J. Dror (Berkeley), E. Kuflik (Hebrew University), and B. Melcher (Syracuse)

DM decouples from Standard Model early in the universe.

Enhanced DM substructure will not suffer from free streaming and kinetic coupling.

If these structures survive until today, they lead to enhanced indirect detection signals.
Could Black Holes be a significant fraction of the Dark Matter?
Did LIGO see PBH Dark Matter?

Bird, et. al. PRL116 [arXiv: 1603.00464]

“GW150914”

LIGO detected a gravity wave signal consistent with the merger of two \( \sim 30 \, M_\odot \)
Black holes at around a 1.3 billion Lyr away

Dark Matter Interpretation

\[
20 \, M_\odot \lesssim M \lesssim 100 \, M_\odot
\]

Lensing (improved) \hspace{1cm} Disrupt Wide Binaries (perhaps CMB as well)

LIGO observation lies in the window where MACHOs are still viable to be all of the dark matter.

Constraints weaken if PBHs are not all of the dark matter.

1603.08338 Sasaki, et. al.;
Could primordial Black Holes be some of the dark matter?

If structures can form in a matter phase, why can’t black holes?

Mass Fraction in PBHs (Thermal History)

\[ \beta_0(M) \simeq \delta_M(t_H) \exp \left( -\frac{w^2}{2\delta^2_M(t_H)} \right) \]

Equation of State \( (w > 0) \)

\[ \delta_M = \frac{\delta M}{M} \]

Evolution of Density Perturbations

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

Hubble “friction” slows the instability

Pressure prevents collapse

Gravity drives collapse

Unlike PBH formation in a thermal universe
Could primordial Black Holes be some of the dark matter?

with J. Georg  JHEP 1709 (2017)

If structures can form in a matter phase, why can’t black holes?

Mass Fraction in PBHs (Thermal History)

\[ \beta_0(M) \simeq \delta_M(t_H) \exp \left( -\frac{w^2}{2\delta_M^2(t_H)} \right) \]

Equation of State \((w > 0)\)

\[ \delta_M \equiv \frac{\delta M}{M} \]

Mass Fraction in PBHs (Early Matter Phase)

\[ \delta_k(t_H) \sim 10^{-4} \rightarrow \delta_k(t > t_H) \sim O(1) \]  

(Unlike PBH formation in a thermal universe)

Non-linearity does not guarantee PBH formation!

\[ \beta(M) \simeq 2 \times 10^{-2} \delta_M^{13/2} \]  

(Fraction of density in black holes at Mass scale M)
PBH Mass Range from an Early Matter Phase

\[ M_{\text{min}} = 3 \frac{m_p^2}{m_\sigma} \]

\[ M_{\text{max}} \sim \left( \frac{M_{\text{cmb}}}{m_p} \right)^{\frac{n-1}{n+3}} \left( \frac{m_p}{m_\sigma} \right)^{\frac{12}{n+3}} m_p \]

Duration of matter phase determines maximal mass

\[ T_r^2 \sim \frac{m_\sigma^3}{m_p} \]

Mass range depends on two parameters.

- \( m_\sigma \): Moduli mass
- \( n \): Tilt of primordial power spectrum

\( m_\sigma \sim m_{3/2} \sim 10 - 100 \text{ TeV} \)

Not a free parameter: Connected to underlying theory
Allowed fraction of DM in PBHs Produced from Co-Decay

“Primordial Blackholes and Co-decaying Dark matter”
with J. Georg (RPI) and B. Melcher (Syracuse) — arXiv: 1902.04082

\[ n_s = 1.8, m_A = 10^4 \text{ GeV}, \Gamma_B = 10^{-16} \text{GeV} \]
\[ n_s = 2, m_A = 100 \text{ GeV}, \Gamma_B = 10^{-20} \text{GeV} \]
\[ n_s = 2.2, m_A = 1 \text{ GeV}, \Gamma_B = 10^{-24} \text{GeV} \]

(dashed lines are 10 times the decay rate)

See talk by Stefano

Data set courtesy of B. V. Lehmann, S. Profumo, and J. Yant
Conclusions

Cosmology and New Physics

A positive B-mode detection would establish the scale of new physics associated with inflation.

These observations will also put constraints on the presence of new light particles.

Dark matter can be represented by many sources (WIMPs, axions, PBHs, etc...)

Uncertainties in the expansion history prior to BBN can have interesting and impactful implications.

Reheating to the Standard Model, compared to other sectors, could present a substantial challenge for complete models of inflation.
Backup Slides
Early Matter Domination and Structure Growth

**Evolution of Density Perturbations**

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

- Hubble "friction" slows the instability
- Pressure prevents collapse
- Gravity drives collapse

Jean’s scale sets the growth scale

\[ k_J^2 = \frac{3H^2}{2c_s^2} \]
Co-decaying Dark Matter: An Explicit Model

**Self annihilation**

\[ \sigma \sim \frac{\alpha_D^2}{m_D^2} \]

**Decay Rate**

\[ \Gamma_B \sim \frac{m_D^5}{\alpha_D^2 \Lambda^4} |g|^2 \]

**Example:**

\[ \Lambda \simeq 10 \text{ TeV} \]
\[ m_D \simeq \text{GeV} \]

No direct detection, no collider signal, but meaningful constraints from indirect detection.
Co-decaying Dark Matter: An Explicit Model

Self annihilation

\[ \sigma \sim \frac{\alpha^2_D}{m_D^2} \]

Decay Rate

\[ \Gamma_B \sim \frac{m_D^5}{\alpha^2_D \Lambda^4} |g|^2 \]

Example:

\[ \Lambda \simeq 10 \text{ TeV} \]
\[ m_D \simeq \text{GeV} \]

\[ f_A \equiv \frac{\Omega_A}{\Omega_{DM}} = \left( \frac{1 \text{ pb}}{\sigma} \right) \left( \frac{m_A}{1 \text{ GeV}} \right)^2 \left( \frac{10^{-18} \text{ GeV}}{\Gamma_B} \right) \]
Did LIGO see PBH Dark Matter?

Bird, et. al.  PRL116  [arXiv: 1603.00464]

**Dark Matter Interpretation**

\[ 20 \, M_\odot \lesssim M \lesssim 100 \, M_\odot \]

**LIGO Merger rate:**

\[ 0.5 - 12 \, \text{Gpc}^{-3} \, \text{yr}^{-1} \]

Majority reside in low mass halos
5 years of advanced LIGO data  (No PBH DM)
(Kovetz et al., arXiv:1611.01157)
5 years of advanced LIGO data (with PBH DM)
(Kovetz et al., arXiv:1611.01157)
PBH Mass Range from an Early Matter Phase

Low Mass Region

Matter phase begins at $H_{osc} \simeq m_{\sigma}$

No sub-horizon growth yet, only possibility is collapse of entire Hubble patch into a PBH.

$$3H_{osc}^2m_p^2 = \rho_{PBH} = M_{PBH}H_{osc}^{-3}$$

$$M_{min} = 3\frac{m_p^2}{m_{\sigma}}$$

Overly conservative!
PBH Mass Range from an Early Matter Phase

High Mass Region

Sub-horizon growth is important.

$$\delta_M(t_r) = \delta_{cmb} \left( \frac{M_{max}}{M_{cmb}} \right)^{\frac{1-n}{6}} \left( \frac{t_r}{t_H} \right)^{2/3} \simeq O(1)$$

Tilt of Primordial spectrum

Normalize to CMB scales

Sub-horizon growth

Solve this equation implicitly for mass

$$M_{max} \sim \left( \frac{M_{cmb}}{m_p} \right)^{\frac{n-1}{n+3}} \left( \frac{m_p}{m_\sigma} \right)^{\frac{12}{n+3}} m_p$$

Duration of matter phase determines maximal mass

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