IT CAME FROM THE SWAMPLAND

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Planck Data Release 2 (February 2015)

Planck 6-param best fit
[arXiv:1502.01589]

$\Omega_b h^2 = 0.02234089$, $\Omega_c h^2 = 0.1176152$

$\tau_{reio} = 0.07789481$, $A_s = 2.1853 \times 10^{-9}$

$n_S = 0.9707712$, $H_0 = 68.26965 \text{ km/s/Mpc}$

(Data: Planck Legacy Archive)
Planck 2015 (Residuals)

Planck 6-param best fit
[arXiv:1502.01589]

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(Data: Planck Legacy Archive)
Inflation /ɪnˈfleɪʃ(ə)n/ (noun)
A period of accelerated cosmological expansion preceding the hot big bang
Inflation: Basic Predictions

- Adiabatic density perturbations ✓
- Superhorizon correlations ✓
- Gaussian statistics ✓

\[ \mathcal{L} = \frac{1}{2} g^{\mu \nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \]

Fully consistent with data.
Cosmological expansion

Analogy: special relativity \( ds^2 = dt^2 - dx^2 \)

Cosmology: Robertson-Walker Metric

\[ ds^2 = dt^2 - a^2(t)dx^2 = a^2(\tau) \left[ d\tau^2 - dx^2 \right] \]

expanding space \hspace{1cm} conformal time

Light cone: \[ ds^2 = g_{\mu\nu}dx^\mu dx^\nu = 0 \]

\[ \Rightarrow dx = d\tau \]
You Are Here

BIG BANG
You Are Here

HORIZON

BIG BANG
Accelerated expansion (a.k.a “inflation”)

Key ingredient: negative pressure

\[ p < -\frac{1}{3}\rho \Rightarrow \frac{\ddot{a}}{a} > 0 \]

Extreme case: de Sitter space (cosmological constant)

\[ H = \frac{\dot{a}}{a} \propto \rho = \text{const.} \quad a(t) \propto e^{Ht} \]
Accelerated expansion (a.k.a “inflation”)

Key ingredient: negative pressure

\[ p < -\frac{1}{3}\rho \Rightarrow \frac{\ddot{a}}{a} > 0 \quad \text{expansion accelerates} \]

Extreme case: de Sitter space (cosmological constant)

\[ H = \frac{\dot{a}}{a} \propto \rho = \text{const.} \quad a(t) \propto e^{Ht} \]

Spacetime expands faster than cosmological horizon!
Evolution of Quantum Modes
Generation of Perturbations

Horizon $\rightarrow$

Mode freezing

$u_k/a$

$(aH/k)$
The Horizon in Inflation

\[ ds^2 = a^2(\tau)(d\tau^2 - d\vec{x}^2) \]
Mode Exit and Reentry

exit

re-entry

classical

quantum

\lambda

\tau
Shorter Wavelength Modes Exit Later
Longer Wavelength Modes Exit Earlier
We See The Last 60 E-folds
Initial Conditions: Inaccessible
Superhorizon Perturbations
Inflation: Basic Predictions
Primordial Perturbations

(Image: ESA and the Planck collaboration)
\[ r = 8 M_P^2 \left( \frac{V'}{V} \right)^2 \]

\[ n_s = 1 - 3 M_P^2 \left( \frac{V'}{V} \right)^2 + 2 M_P^2 \frac{V''}{V} \]
Convex or Concave?
Convex or Concave?
Inflation: Swampland or Landscape?

WHK, Vagnozzi, Visinelli [arXiv:1808.0624]
The String Landscape
The Weak Gravity Conjecture

Diagram illustrating a charged black hole with labeled radii $R_Q$ and $R_M$. The text "charged black hole" is written below the diagram.
The Weak Gravity Conjecture
The Weak Gravity Conjecture
The Weak Gravity Conjecture
The Weak Gravity Conjecture
The Weak Gravity Conjecture
The Weak Gravity Conjecture

THIS IS BAD
The Weak Gravity Conjecture
The Weak Gravity Conjecture

Any UV-complete theory must contain light charged states under all global symmetries.

$$M < Q M_P \ \forall U(1)$$

The deSitter Swampland Conjecture

\[ \Delta \phi \leq M_p \]
The de Sitter Swampland Conjecture
The de Sitter Swampland Conjecture

\[ V(\phi) \]

\[ \Delta \phi \sim \mu \leq M_p \]

\[ M_p \frac{\Delta V}{V} \sim c \geq O(1) \]
Single-Field Inflation and the Swampland

Planck 2015 TT/TE/EE+lowTEB + BK14

\( c = 0.10 \)

\( c = 0.08 \)

\( c = 0.06 \)

\( V'' > 0 \)

\( V'' < 0 \)

\( 95\% \text{ CL} \)

\( 68\% \text{ CL} \)

\( (1 - e^{\phi/\mu})^2 \)

\( \Lambda^3 \phi \)

\( m^2 \phi^2 \)

\( N = 46 \)

\( N = 60 \)

WHK, Vagnozzi, Visinelli [arXiv:1808.0624]
What about symmetry breaking?
What about symmetry breaking?
The Refined Swampland Conjecture

\[ M_P^2 \left( \frac{V'}{V} \right)^2 \geq c^2 \]

OR

\[ M_P^2 \frac{V''}{V} \leq -c' \]

Ooguri, Palti, Shiu, Vafa [arXiv:1810.05506]
The Refined Swampland Conjecture

\[ \left| \frac{V''}{V} \right| \geq M_p^2 \]

\[ \frac{V'}{V} = 0 \]

Ooguri, Palti, Shiu, Vafa [arXiv:1810.05506]
The *Refined Swampland Conjecture*

\[ \left| \frac{V''}{V} \right| \geq M_p^2 \]

\[ \frac{V'}{V} = 0 \]

\[ m^2 \sim V'' < Q \]

Ooguri, Palti, Shiu, Vafa [arXiv:1810.05506]
Single-Field Inflation and the Swampland

Planck 2015 TT/TE/EE+lowTEB + BK14

$c = 0.10$
$c = 0.08$
$c = 0.06$

$M_{Pl}^2 V'' = -0.01V$

$(1 - e^{\phi/\mu})^2$

$N = 46$
$N = 60$

$\Lambda^3\phi$

WHK, Vagnozzi, Visinelli [arXiv:1808.0624]
Trans-Planckian Censorship

Bedroya and Vafa [arXiv:1909.11063]
Trans-Planckian Censorship
Trans-Planckian Censorship
Trans-Planckian Censorship

Diagram showing the relationship between $\log(\lambda)$ and $\log(a)$ with a marked area indicating no TCC (Trans-Planckian Censorship).
Trans-Planckian Censorship
DBI Inflation: Non-Canonical Lagrangians

Lagrangian with arbitrary kinetic term:

\[ \mathcal{L} = F(X, \phi) - V(\phi) \]

\[ X \equiv \frac{1}{2} g^{\mu \nu} \partial_\mu \phi \partial_\nu \phi \]

(Figure: Meerburg, et al., arXiv:0910.4986)
Lagrangian with arbitrary kinetic term:

\[ \mathcal{L} = F (X, \phi) - V (\phi) \quad X \equiv \frac{1}{2} g^{\mu \nu} \partial_\mu \phi \partial_\nu \phi \]

\[ = \frac{1}{2} G^{\mu \nu} \partial_\mu \phi \partial_\nu \phi - V (\phi) \]

Acoustic metric

Light cone: \[ g^{\mu \nu} dx_\mu dx_\nu = 0 \]

Acoustic cone: \[ G^{\mu \nu} dx_\mu dx_\nu = 0 \]
Inflation from non-Canonical Lagrangians

Acoustic Horizon

Hubble Horizon

$\tau$
Generalized Trans-Planckian Censorship

Lin, WHK [arXiv:1911.03736]
So, should we take these conjectures ... seriously?
Conjecture, Smonjecture...

So, should we take these conjectures ... seriously?

Probably not.
Flat $w_{\text{CDM}}$:

$$w = -0.978 \pm 0.059$$

Flat $w_0/w_a$ CDM:

$$w_0 = -0.885 \pm 0.114$$
$$w_a = -0.387 \pm 0.430$$

So, should we take these conjectures ... seriously?

Probably not.

If string theory doesn't support de Sitter solutions, so what?

Danielsson & Van Riet, [arXiv:1804.01120]