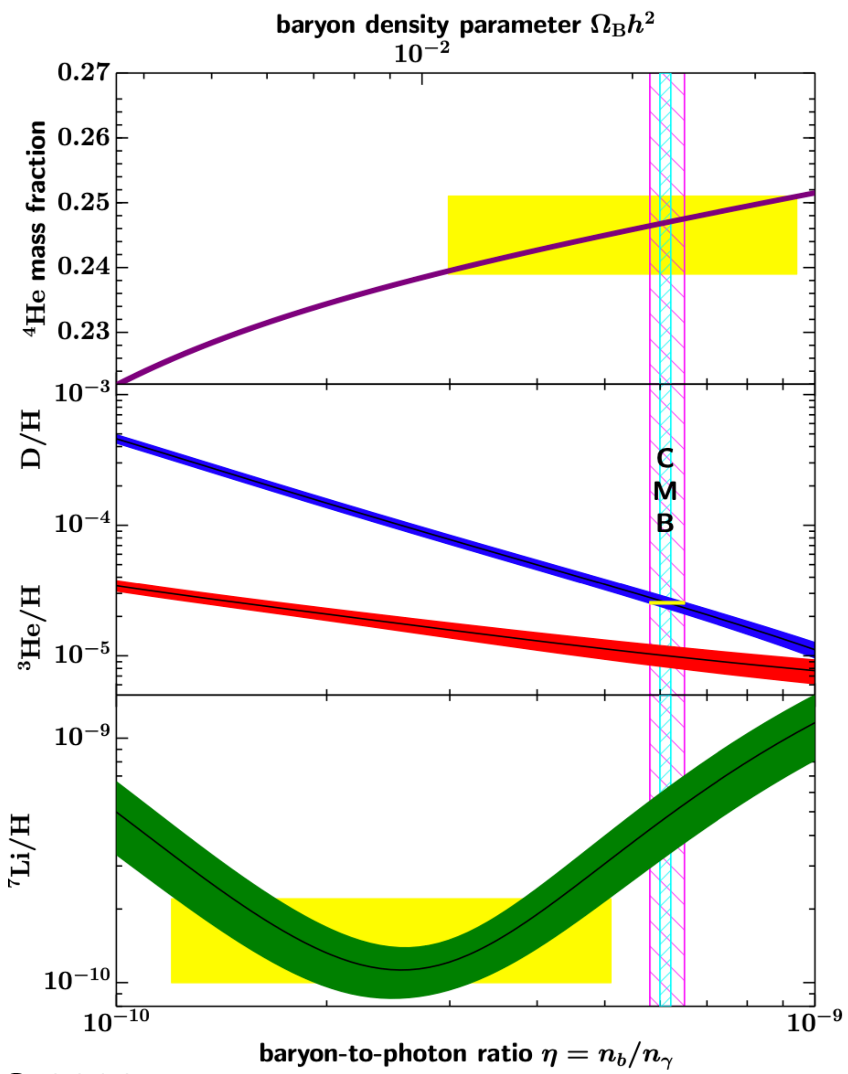
The Loitering Universe: A New Beginning

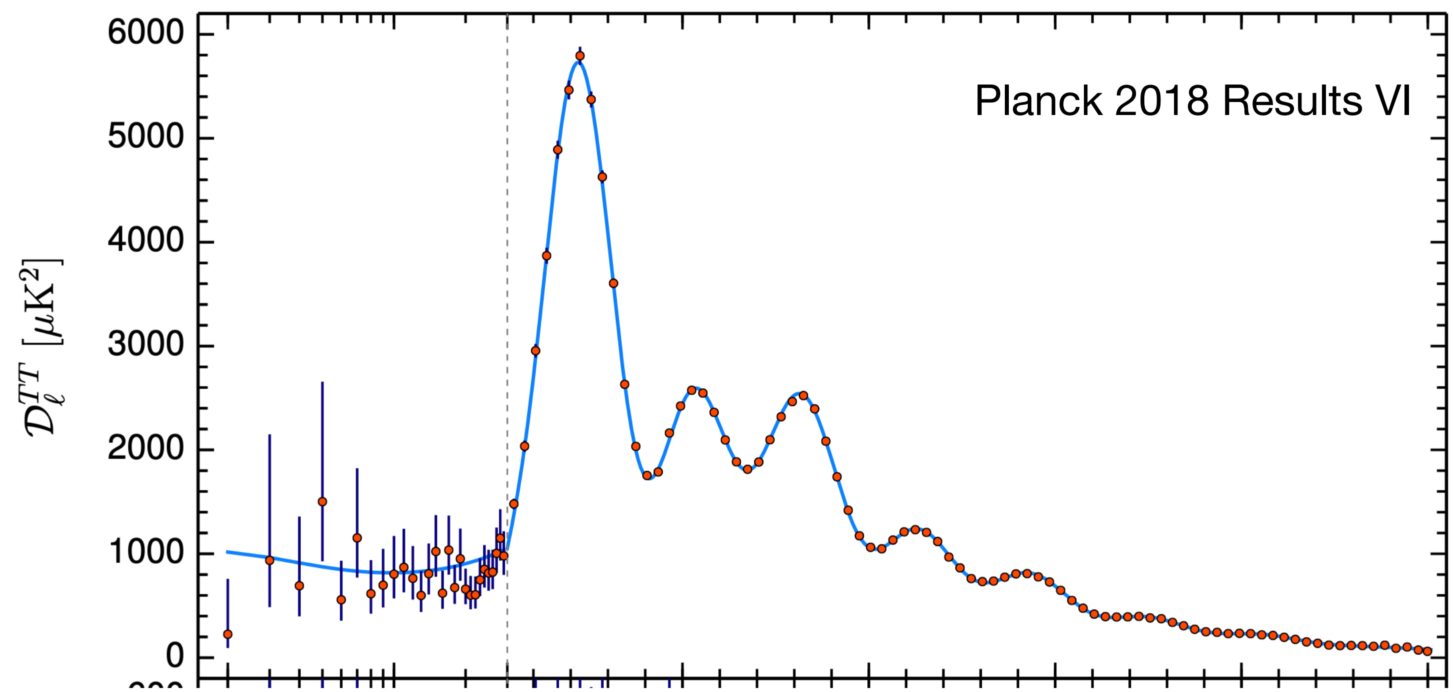
Based on 21XX.XXXXX with Arnab Pradhan and Scott Watson

Brandon Melcher
November 3rd
Brookhaven Forum 2021

What do we know about the very early universe?



PDG 2020



Parameter	Plik best fit	Plik [1]	CamSpec [2]	([2] − [1])/σ_1	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	−0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	−0.2	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	−0.1	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	−0.3	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	+0.2	0.9652 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	−0.3	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}]	67.32	67.36 ± 0.54	67.39 ± 0.54	+0.1	67.37 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	−0.2	0.3147 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	+0.4	13.801 ± 0.024
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	−0.3	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.8331	0.832 ± 0.013	0.828 ± 0.013	−0.3	0.830 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	−0.1	7.64 ± 0.74
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	−0.1	1.04108 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	+0.6	147.18 ± 0.29

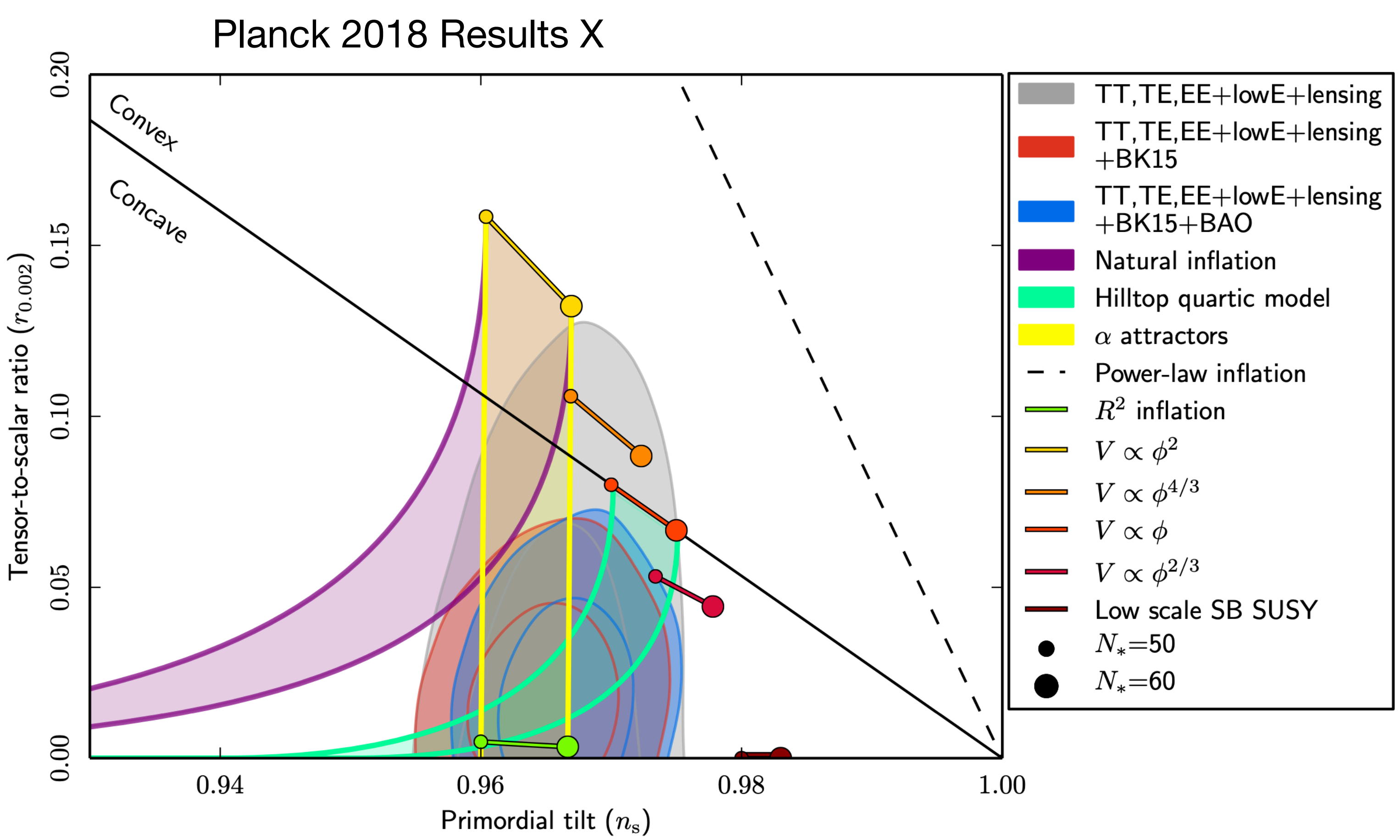
CMB and BBN tell us:

- **Composition of Universe**
- **Two-Point Statistics of Primordial Perturbations**

Inflation to the Rescue?

- Issues with Hot Big Bang: Horizon and Flatness Problems

- Both fixed by accelerated expansion: Inflation, usually posited to be driven by scalar fields…



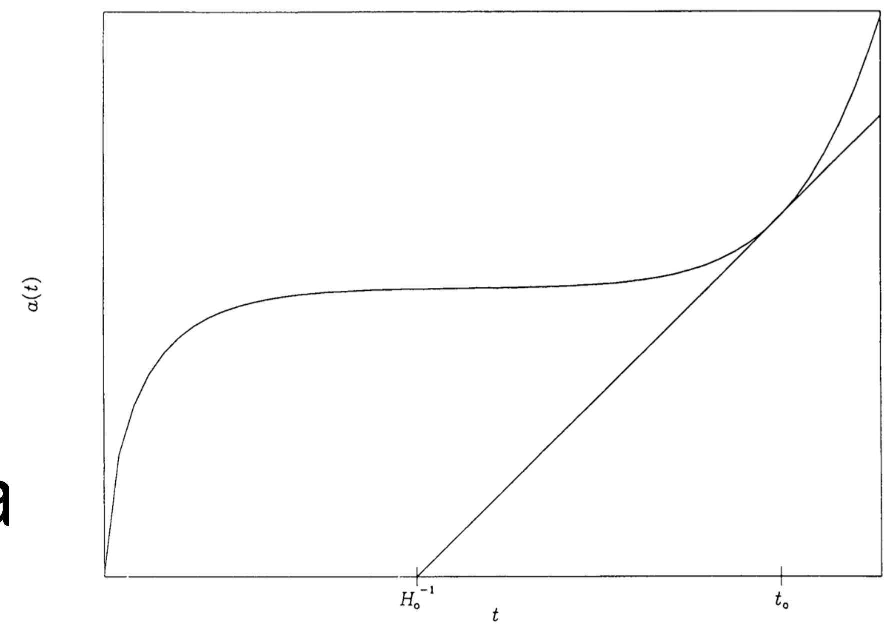
Open Questions:

- **Ending Inflation?**
- **Initial Conditions?**
- **Eternal Inflation?**
- **Initial Singularity?**

History of Static/Stationary Universes

- Einstein’s Greatest Blunder
- Post-Inflationary Loitering
- Superstring Theory/String Gas Cosmology
- Emergent Universe inspired by Ellis and Maartens

History of Static/Stationary Universes



$$H^2 = \frac{8\pi}{3}\left(\rho_T - \frac{k}{a^2}\right)$$

$$\rho_T = \rho_m a^{-3} + \rho_e a^{-3(1+w)}$$

or

$$\rho_T = \rho_m a^{-3} + \frac{1}{2}\dot{\varphi}^2 + V(\varphi)$$

Sahni, Feldman, and Stebbins Astrophys. J. 1992

- Einstein's Grea
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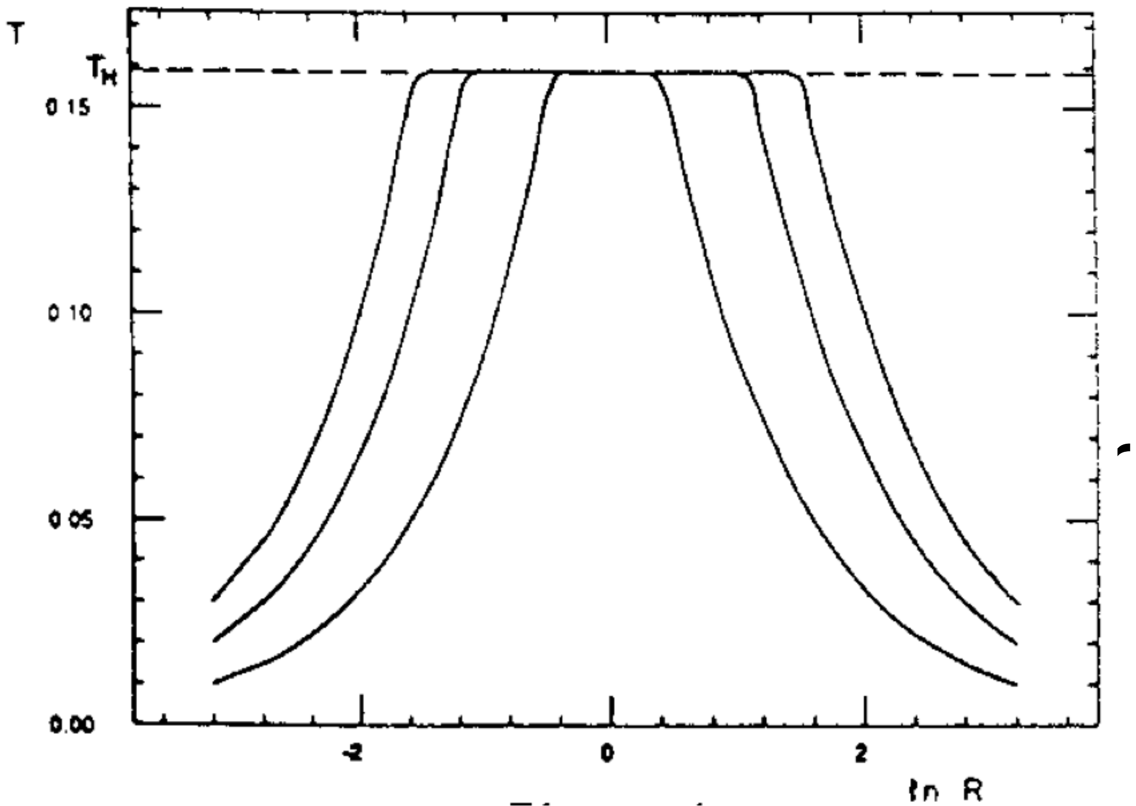
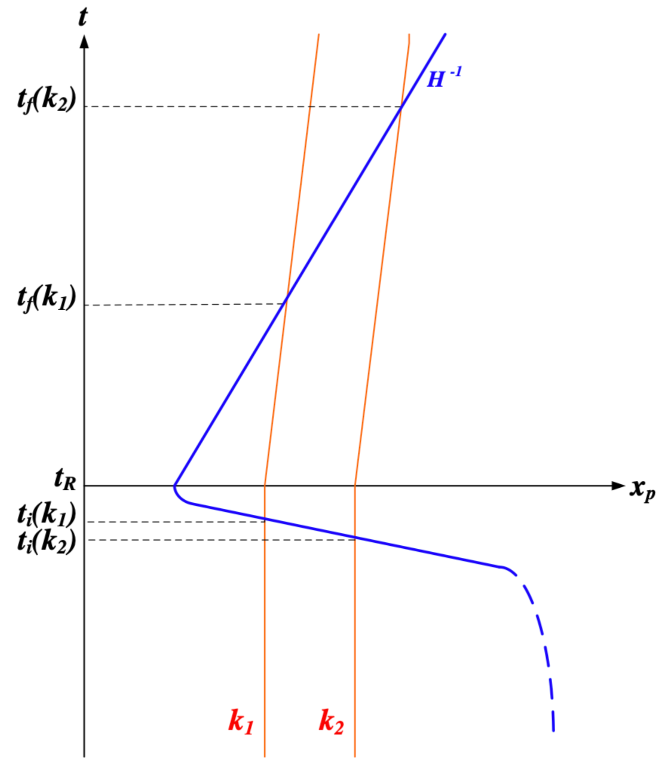
History of Static/Stationary Universes

Brandenberger and Vafa, Nucl. Phys. B, 1989



Nayeri, Brandenberger, and Vafa, PRL, 2006



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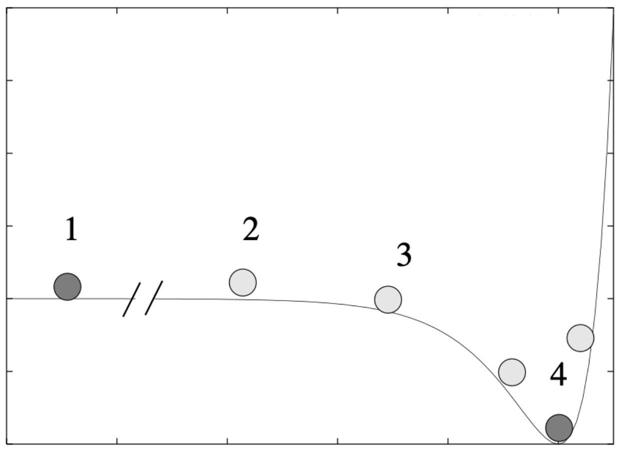

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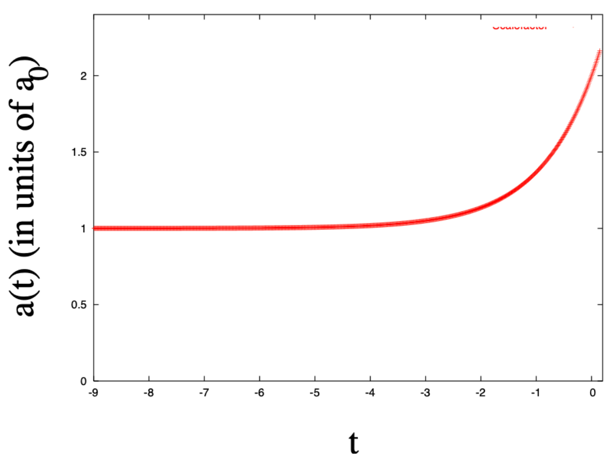

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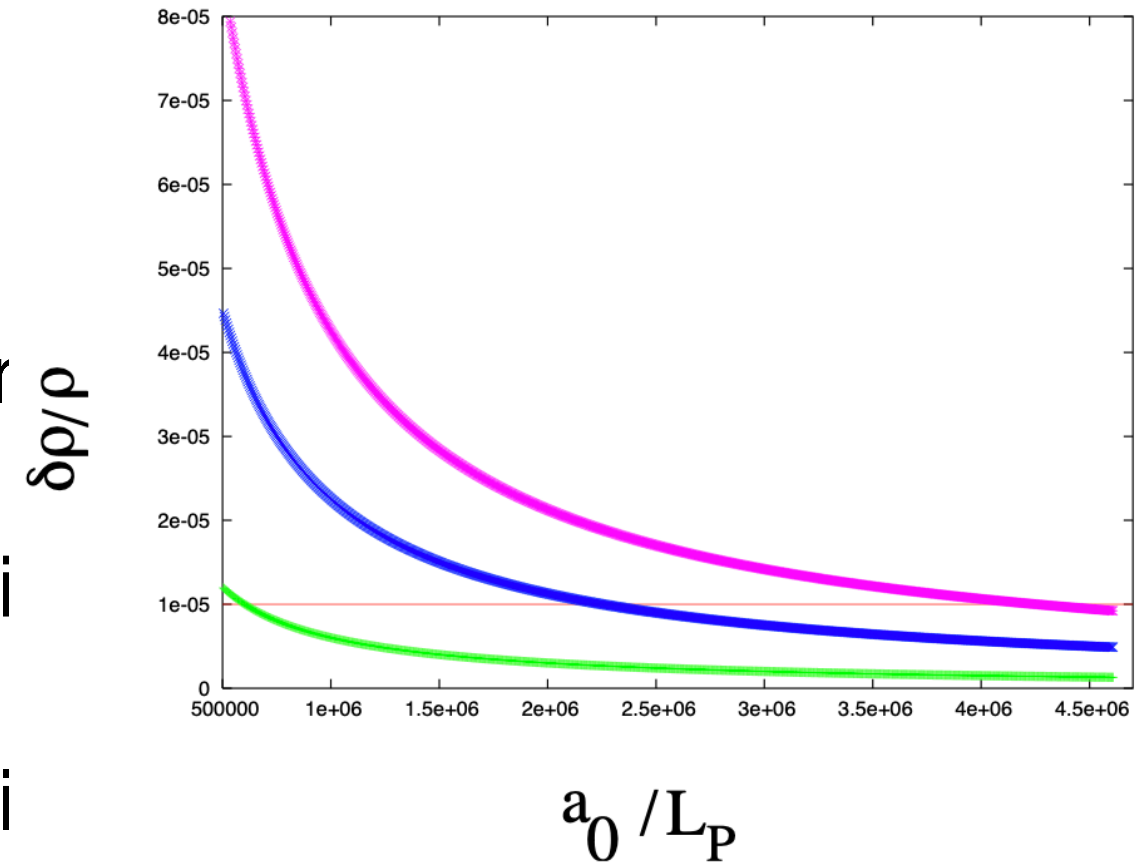


- Emergent Universe inspired by Ellis and Maartens

Ellis and Maartens, Class. Quant. Grav., 2004

Ellis, Murugan, Tsagas, Class. Quant. Grav., 2004

Our Take on Loitering

$$\mathscr{H}^2 = \frac{\kappa^2}{3} a^2 \rho_T - K$$

$$\mathscr{H}' + \frac{\mathscr{H}^2}{2} = -\frac{1}{2}\left(\kappa^2 a^2 p_T + K\right)$$

$$\rho_T = \bar{\rho}_s a^{-m} + \bar{\rho}_e a^{-n}$$

$$p_T = \left(\frac{m}{3} - 1\right)\bar{\rho}_s a^{-m} + \left(\frac{n}{3} - 1\right)\bar{\rho}_e a^{-n}$$

How much "stuff" do we need to loiter at scale factor a_*?

$$\mathscr{H} = \mathscr{H}' = 0$$

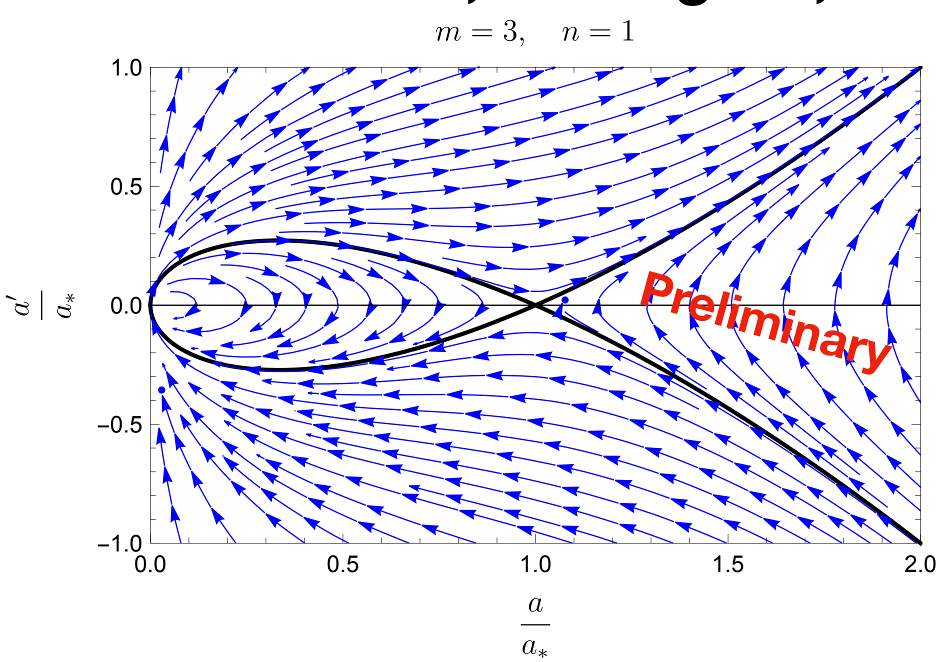
$$\bar{\rho}_s^* = \frac{n-2}{m-n}\frac{3K}{\kappa^2} a_*^{m-2}$$

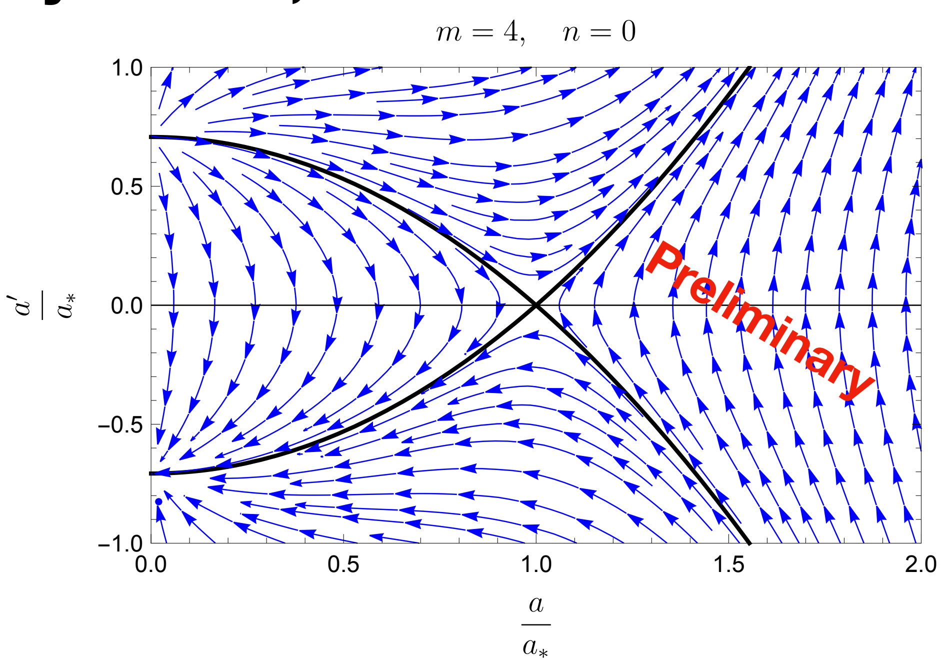
$$n \leq 2$$

$$\bar{\rho}_e^* = \frac{m-2}{m-n}\frac{3K}{\kappa^2} a_*^{n-2}$$

$$m \geq 3$$

Thanks to Einstein, Eddington, and many others, we know this is unstable:





Exiting Loitering

Homogeneous and Isotropic Perturbations: $a \to a_*(1+\Delta(\eta))$ $\bar{\rho}_i \to \bar{\rho}_i^*(1+\Delta_i)$

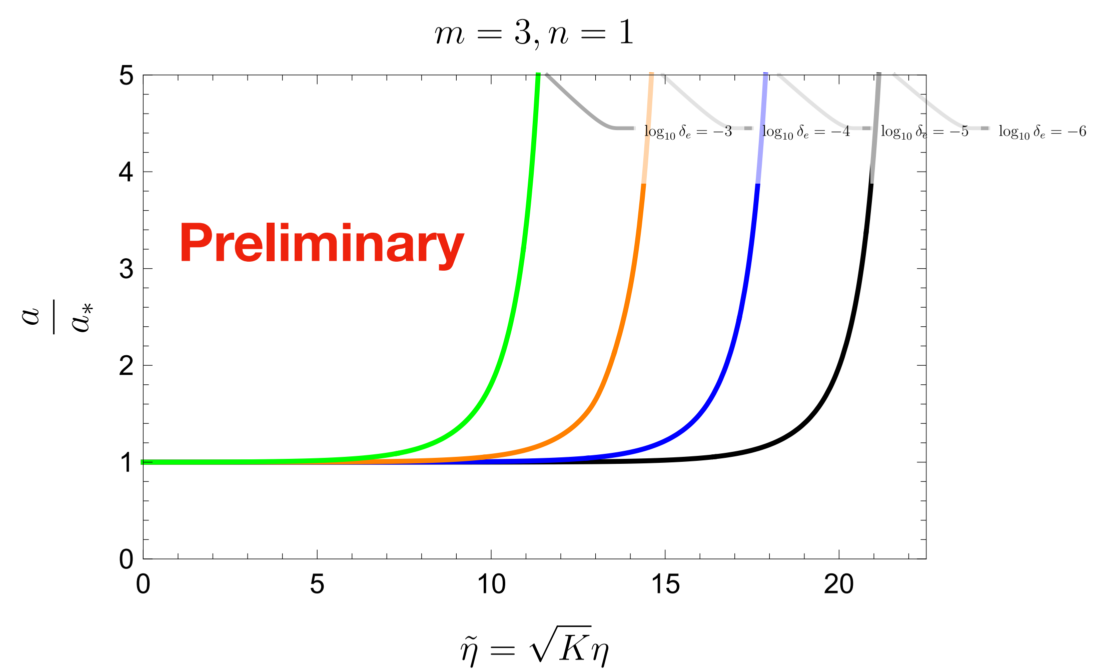
Hubble Equation to $\mathcal{O}(\Delta)$: $\Delta_s = \dfrac{m-2}{2-n}\Delta_e$

Maintains balance between curvature and energy densities

Raychaudhuri Equation to $\mathcal{O}(\Delta)$: $\Delta'' + \dfrac{1}{2}(m-2)(n-2)\Delta = (m-2)\Delta_e$

$$\Delta = \frac{\Delta_e}{2-n}\left(\cosh\left(\sqrt{\frac{1}{2}(m-2)(2-n)}\eta\right) - 1\right)$$

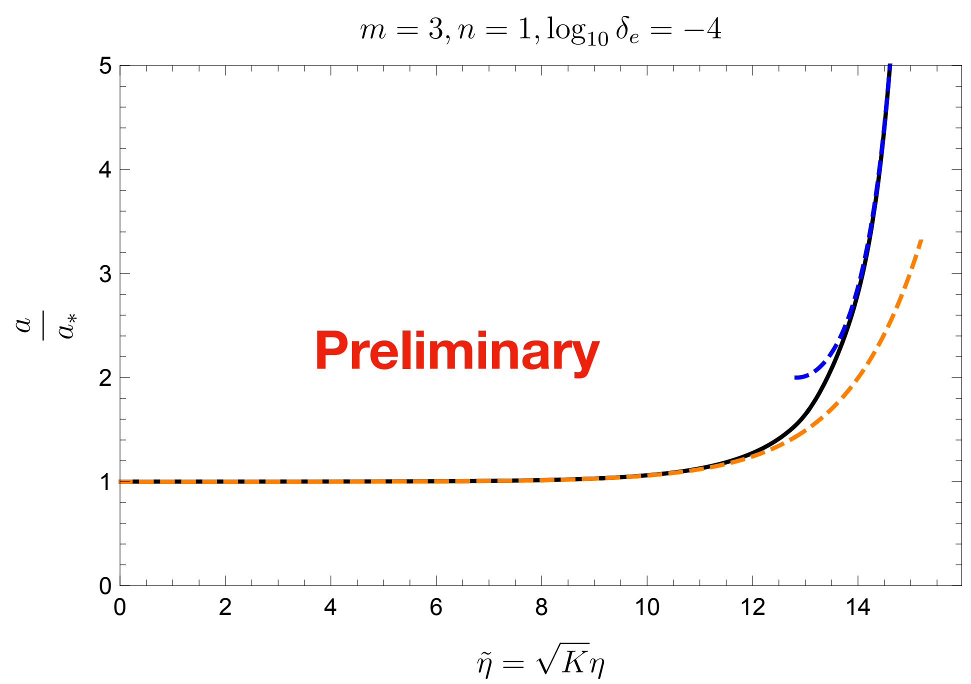
sign(a') = sign(Δ_e)

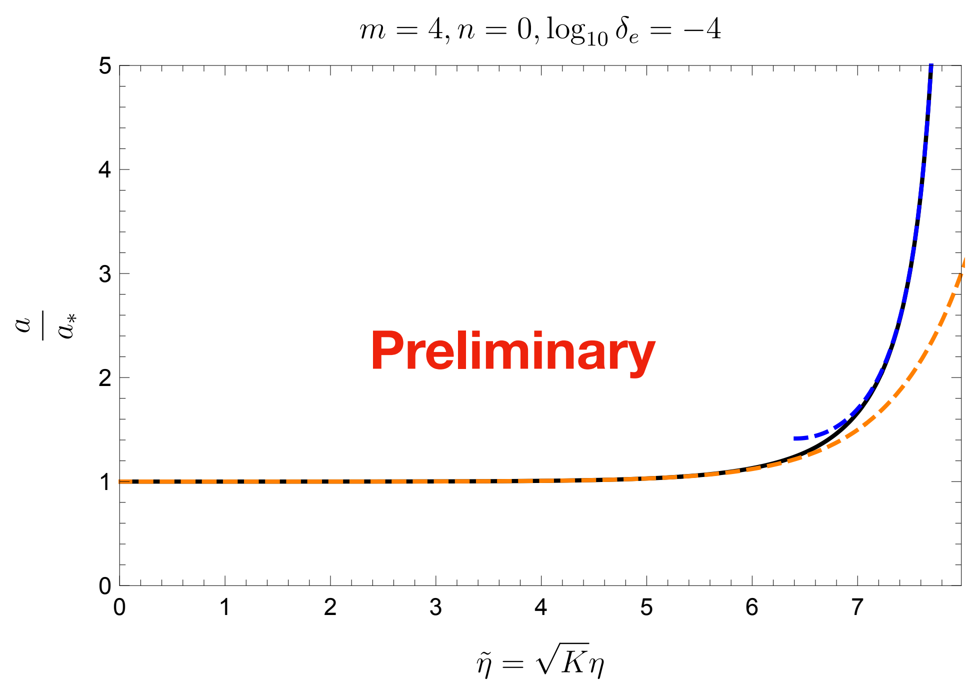


Post-Loitering Behavior

Ignore ρ_s component: $\mathscr{H}^2 = \frac{\kappa^2}{3}\bar{\rho}_e a^{-n} - K$ $\qquad a'' + a = -\frac{\kappa^2}{6}(4-n)\bar{\rho}_e a^{3-n}$

$$\Rightarrow \qquad a = \left(-\frac{m-2}{n-m}\frac{1+\Delta_e}{a_*^{2-n}}\right)^{1/(n-2)} \sin\left(\frac{n-2}{2}\Delta\eta + \eta_0\right)^{2/(n-2)}$$





We have a loitering phase followed by an accelerated expansion phase sourced only by two fluids; note for $n \leq 2$, $1 + 3w_e \leq 0$

Perturbations?

- WORK IN PROGRESS

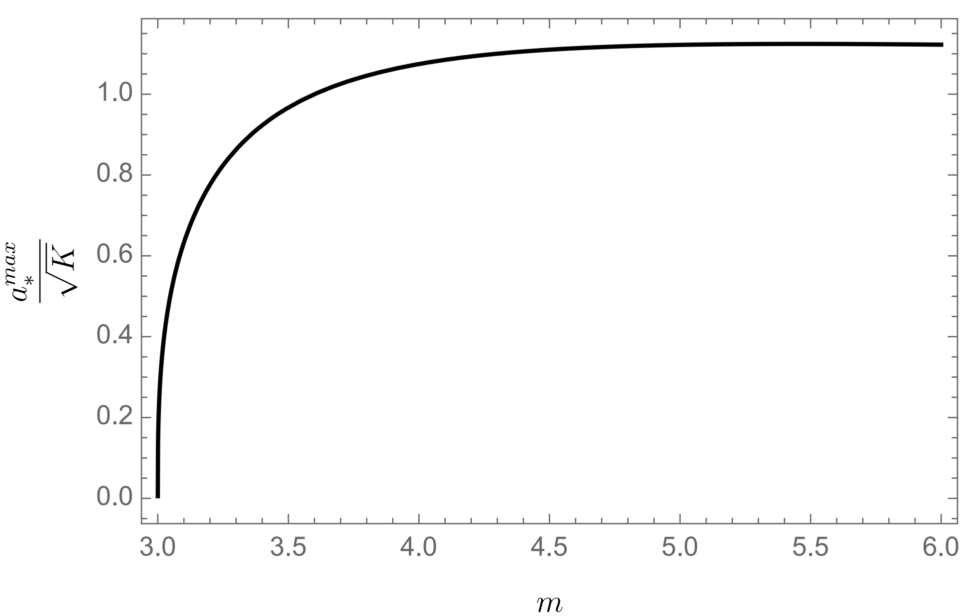
- Stability in "perfect" loitering:

$$\delta_s'' + A(a_*, m, n, k, c_{s,s}^2)\delta_s = B(a_*, m, n, c_{s,e}^2)\delta_e$$

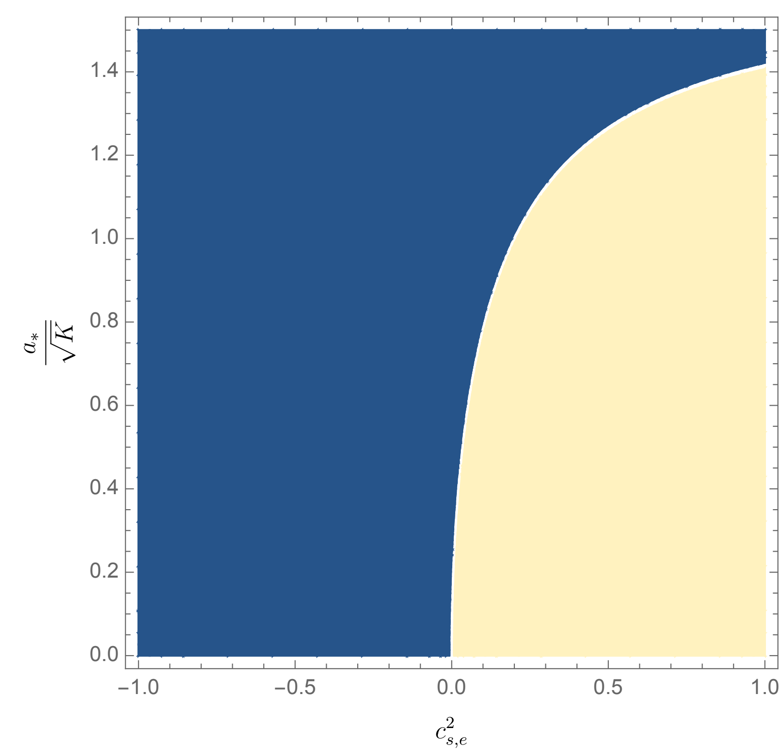
$> 0 \Rightarrow \delta_s, \delta_e$ **bounded**

$$\delta_e'' + C(a_*, m, n, k, c_{s,e}^2)\delta_e = D(a_*, m, n, c_{s,s}^2)\delta_s$$

$A > 0$:



$C > 0$:



Open Questions/Conclusions

- Correct Power Spectrum? See Ellis and Maartens, Class. Quant. Grav., 2004; Ellis, Murugan, Tsagas, Class. Quant. Grav., 2004
- Matter source with negative w but positive c_s^2? See Bucher and Spergel, PRD 1999
- Tensor Modes?
- Ending accelerated expansion?
- Viable start to inflation?

Thank You!