A Unified Model of Dark Energy, Dark Matter, and Baryogenesis

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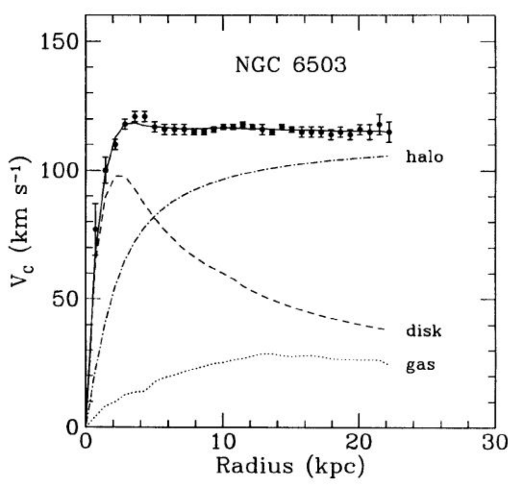
Work in collaboration with J. Fröhlich
`arXiv:2004.10025`

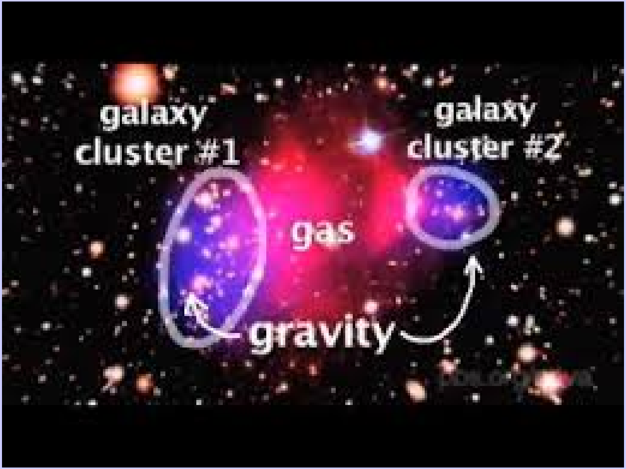
Outline

Plan

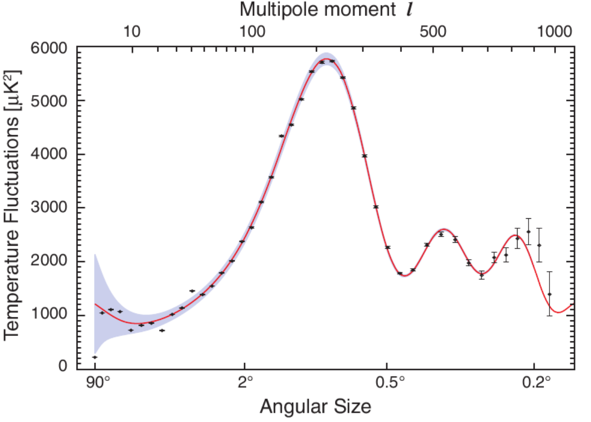
Evidence for Dark Matter: Galaxy Velocity Rotation Curves



Evidence for Dark Matter: Bullet Cluster



Evidence for Dark Matter: Cosmological Structure Formation



Credit: NASA/WMAP Science Team

Evidence for Dark Matter: Cosmological Structure Formation

- Without DM: matter fluctuations on galaxy scales couple to radiation for $t_{eq} < t < t_{rec} \rightarrow$ decay as $a(t)^{-1/2}$.
- If DM dominates over baryonic matter: matter fluctuations grow $\propto a(t)$ for $t_{eq} < t < t_{rec}$.
- Fix the matter power spectrum by observations.
- $\rightarrow$ without DM the matter fluctuations at t_{eq} were larger than in the case of dominant DM by a factor of $(a(t_{rec})/a(t_{eq}))^{3/2}$
- $\rightarrow$ amplitude of the angular power spectrum of CMB anisotropies predicted to be $\sim 10^{-3}$ (R. Sachs and A. Wolfe, Ap. J. 147, 73 (1967)).

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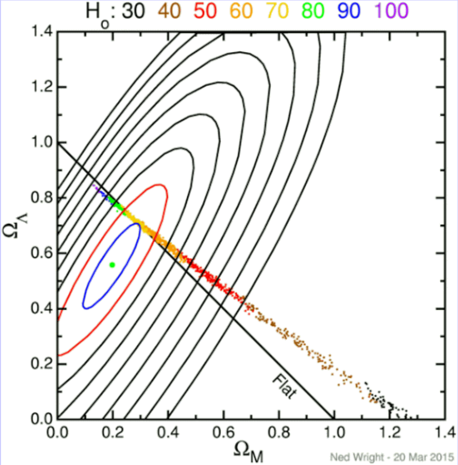
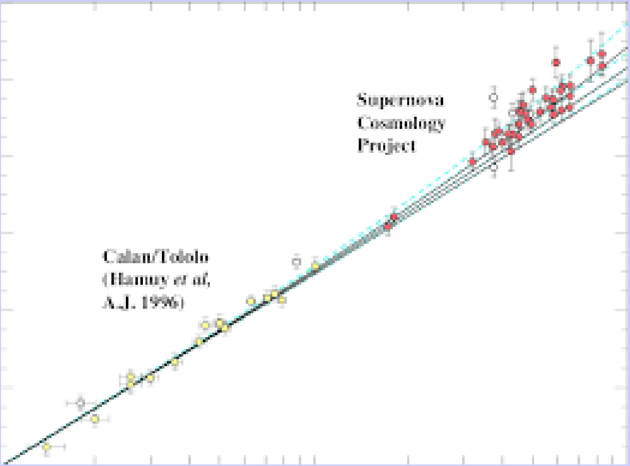
Evidence for Dark Energy: Cosmological Probes



Evidence for Dark Energy: Supernovae

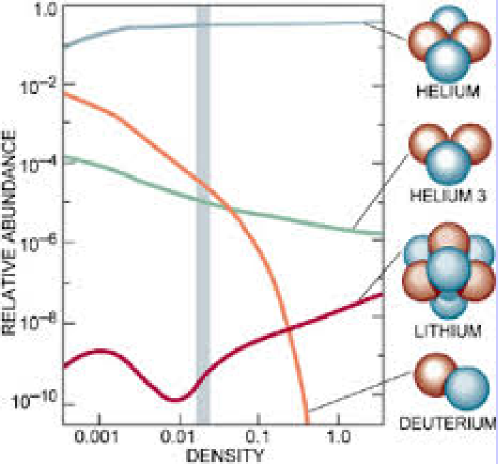


Evidence for Baryogenesis: Cosmic Rays

A. Cohen, A. De Rujula and S. Glashow., *Ap. J. 495, 539 (1998)*

- Assume a patchwork of matter and antimatter regions.
- $\rightarrow$ after recombination annihilations at the regional boundaries.
- $\rightarrow$ cosmic diffuse γ-ray background.
- Excludes $B = 0$ universe with domains smaller than Hubble volume.

Evidence for Baryogenesis: Nucleosynthesis



Standard Paradigm

- Dark Energy is the Cosmological Constant Λ.
- Dark Matter is a WIMP (weakly interacting massive particle).

Standard Paradigm for Dark Energy: LCDM

- Dark Energy is a cosmological constant.
- No new parameters - Λ must arise in the low energy EFT of gravity.
- No conflict with data.
- Cosmological constant problem: why is Λ no small?
- Coincidence problem: why is $\rho_\Lambda \sim \rho_m$ today?

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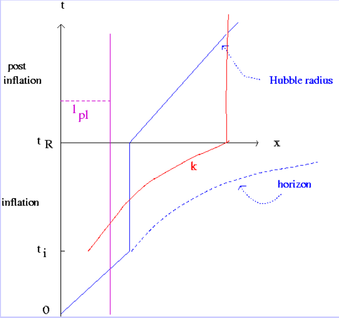
Plan

Trans-Planckian Problem

J. Martin and R.B., *Phys. Rev. D63, 123501 (2002)*



- **Success of inflation**: At early times scales are inside the Hubble radius $\rightarrow$ causal generation mechanism is possible.
- **Problem:** If time period of inflation is more than $70H^{-1}$, then $\lambda_p(t) < l_{pl}$ at the beginning of inflation.
- $\rightarrow$ new physics MUST enter into the calculation of the fluctuations.

Trans-Planckian Censorship Conjecture (TCC)

A. Bedroya and C. Vafa., arXiv:1909.11063

No trans-Planckian modes ever exit the Hubble horizon.

$$ds^2 = dt^2 - a(t)^2 d\mathbf{x}^2$$

$$H(t) \equiv \frac{\dot{a}}{a}(t)$$

$$\frac{a(t_R)}{a(t_i)} l_{pl} < H(t_R)^{-1}$$

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Implications for Dark Energy

Dark Energy cannot be a Cosmological Constant

- If DE is Λ, then H^{-1} constant to the future.
- $\rightarrow$ Planck scale today eventually becomes larger than H^{-1}.

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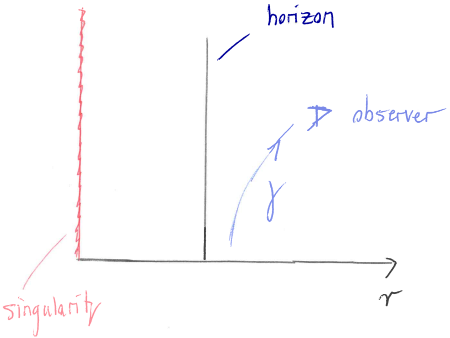
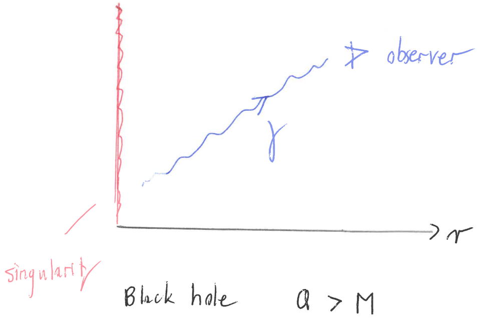
Sub-Extremal Black Hole



Black hole $Q < M$

Super-Extremal Black Hole



Penrose's Cosmic Censorship Hypothesis

R. Penrose, *Riv. Nuovo Cim. 1, 252 (1969)*

Time-like singularities are hidden by horizons.

- Singularity hidden from external observer.
- Non-unitarity and acausality hidden from external observer.

Note: **Effective field theory** of GR allows for naked singularities, but **UV complete theory** does not.

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Non-Unitarity of Effective Field Theory (EFT) in an Expanding Background

N. Weiss, *Phys. Rev. D. 32, 3228 (1985)*

- Hilbert space of EFT: $\mathcal{H} = \prod_{\mathrm{k}} \mathcal{H}_{\mathrm{k}}$
- where $\mathcal{H}_{\mathrm{k}}$ is the Hilbert space of the k'th **comoving** mode.
- UV cutoff required in physical coordinates
- Corresponding comoving UV cutoff is time-dependent
- $k_{UV}(t) \sim a(t)$
- $\rightarrow$ non-unitarity.

Generalizing Penrose's Cosmic Censorship Hypothesis

- Singularity $\rightarrow$ trans-Planckian region.
- Black hole horizon $\rightarrow$ Hubble horizon.

Demand: The external observer is shielded from non-unitarity associated with the trans-Planckian region by the Hubble horizon.

Note:

- EFT of cosmology allows for violations of TCC.
- Conjecture: UV physics prohibits violations of TCC.

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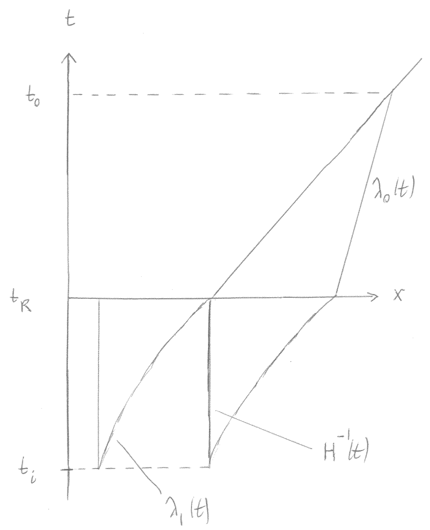
Application to Inflation

A. Bedroya, R.B., M. Loverde and C. Vafa., arXiv:1909.11106



Application to Inflation

A. Bedroya, R.B., M. Loverde and C. Vafa., arXiv:1909.11106

TCC implies:

$$\frac{a(t_R)}{a(t_*)} l_{pl} < H(t_R)^{-1}$$

Demanding that inflation yields a causal mechanism for generating CMB anisotropies implies:

$$H_0^{-1} \frac{a(t_0)}{a(t_R)} \frac{a(t_R)}{a(t_*)} < H^{-1}(t_*)$$

Implications for Inflation

Upper bound on the **energy scale of inflation**:

$$V^{1/4} < 3 \times 10^9 \mathrm{GeV}$$

$\rightarrow$ upper bound on the **primary tensor to scalar ratio** r:

$$r < 10^{-30}$$

Note: Secondary gravitational waves are generated from scalar fluctuations.

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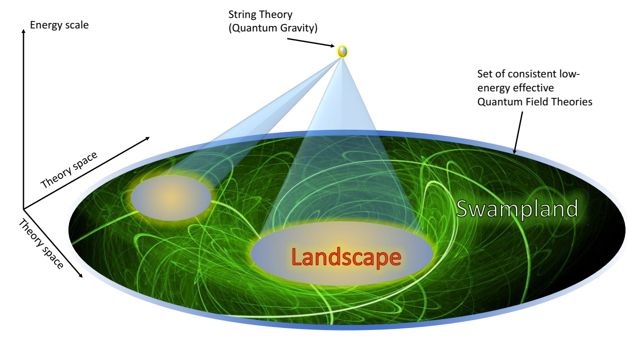
Swampland

- There is a vast landscape of **effective field theories.**
- Any space-time dimension, and number of fields, any shape of the potential, any field range, and value of Λ.
- Superstring theory is very **constraining.**
- Only a **small subset** of all EFTs is consistent with string theory.
- The rest lie in the swampland.


Energy scale
String Theory
(Quantum Gravity)
Set of consistent low-energy effective Quantum Field Theories
Theory space
Theory space
Swampland
Landscape

Swampland Conjectures

H. Ooguri and C. Vafa, hep-th/0605264; G. Obied, H. Ooguri, L. Spodyneiko and C. Vafa, arXiv:1806.08362; H. Ooguri, E. Palti, G. Shiu and C. Vafa, arXiv:1810.05506.

What are conditions for habitable islands sticking out from the swamp?

- Bare $\Lambda \leq 0$.
- The effective field theory is only valid for $\Delta\varphi < dm_{pl}$ (field range condition).
- The potential of φ obeys (de Sitter conjecture)

$$
\begin{aligned}
|\frac{V'}{V}| m_{pl} &\geq c_1 \quad \text{or} \\
\frac{V''}{V} m_{pl}^2 &\leq -c_2
\end{aligned}
$$

Note: d, c_1, c_2 constants of order 1.

Lesson

Dark Energy cannot be Λ.

Reasoning

- φ is a string theory modulus field.
- **Field range condition**: move $\delta\varphi \sim m_{pl} \rightarrow$ tower of string states becomes massless and must be included in low energy EFT.
- **De Sitter conjecture**: moduli stabization $\rightarrow$ steep potential.
- Example: S. Laliberte and R.B., arXiv:1911.00199:

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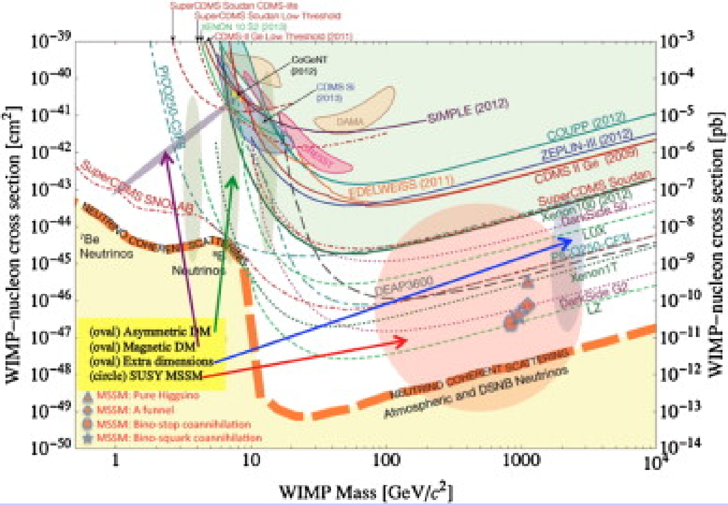
Current Limits on WIMPs



Alternatives to WIMP DM Exist

Alternatives to WIMP DM exist:

- Axions Well motivated, arising in the solution of the Strong CP Problem.
- Superfluid Dark Matter (see e.g. E. Ferreira arXiv:2005.03254 for a review)
- Ultralight Dark Matter
- .....

Plan

Motivation

R.B. and J. Fröhlich, arXiv:2004.10025

- Can a single (complex) scalar field describe both dark matter and dark energy?
- Can one obtain baryogenesis as an added bonus?

See also R.B., J.F. and R. Namba, *Unified Dark Matter, Dark Energy and baryogenesis via a cosmological wetting transition* JCAP **1909**, 069 (2019) [arXiv:1907.06353] .

See also S. Alexander, R.B. and J.F. *Tracking Dark Energy from Axion-Gauge Field Couplings*,, arXiv:1601.00057 [hep-th].

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Model

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Consider a complex scalar field ζ

$$\zeta \equiv e^{-(\varphi+i\theta)/f}$$

whose angular variable θ is an axion.

Action:

$$S = \int d^4x\sqrt{-g}\left\{\frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi + \frac{1}{2}\partial_\mu\theta\partial^\mu\theta - \right.$$
$$\left. - \Lambda e^{-2\varphi/f} - V(\varphi,\theta) + \ldots\right\},$$

Potential energy function:

$$V(\varphi,\theta) = \frac{1}{2}\mu^4\sin^2(\theta/f)e^{-2\varphi/f}$$

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Equations of Motion

Variational equations in an expanding cosmological background:

$$\ddot{\varphi} + 3H\dot{\varphi} = [\frac{2}{f}\Lambda + \frac{\mu^4}{f}\sin^2\frac{\theta}{f}]e^{-2\varphi/f},$$

$$\ddot{\theta} + 3H\dot{\theta} = -\frac{\mu^4}{f}\sin(\frac{\theta}{f})\cos(\frac{\theta}{f})e^{-2\varphi/f},$$

Roles of the fields:

- Dark matter: θ oscillates about $\theta = 0$.
- Dark energy: φ rolls at late times towards ∞.

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Dark Energy Phase

After sufficient relaxation of θ:

$$\frac{1}{2}\mu^4 \sin^2(\theta/f) \ll \Lambda$$

$\rightarrow \varphi$ evolves as a standard quintessence field:

$$\varphi(t) \, = \, f \ln(\beta t) \, ,$$

$$\beta^2 \, \simeq \, \frac{4}{3}\frac{\Lambda}{f^2}\left(\frac{m_{pl}}{f}\right)^2 \, ,$$

Leads to an equation of state $w \equiv p/\rho$ with

$$w \, \simeq \, -1 + \frac{4}{3}\left(\frac{m_{pl}}{f}\right)^2 \, .$$

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While

$$\frac{1}{2}\mu^4 \sin^2(\theta/f) > \Lambda$$

- The axion dominates the energy-momentum tensor
- The axion undergoes dampled oscillations with amplitude $\mathcal{A}(t)$

$$\mathcal{A}(t) \sim a(t)^{-3/2} \sim T(t)^{3/2} .$$

- The axion dominates the source term in the equation of motion for φ
- Resulting evolution of φ:

$$\varphi(t) = \alpha \ln\left(\frac{t}{t_{eq}}\right) + \varphi(t_{eq}) .$$

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Early Phase

Assume an early confining force which traps θ at $\theta = -\pi f/2$.

$\rightarrow$ early slow-rolling phase of θ:

$$\theta \; = \; -\frac{\pi f}{2} + \Delta\theta \, .$$

$$(\Delta\theta)^{\cdot\cdot} + \frac{3}{2t}(\Delta\theta)^{\cdot} \; \simeq \; \frac{\mu^4}{f^2} e^{-2\varphi/f} \Delta\theta \, .$$

$$\Delta\theta(t) \; \sim \; \frac{t^{1/2}}{t_c^{1/2}} \Delta\theta(t_c) \, ,$$

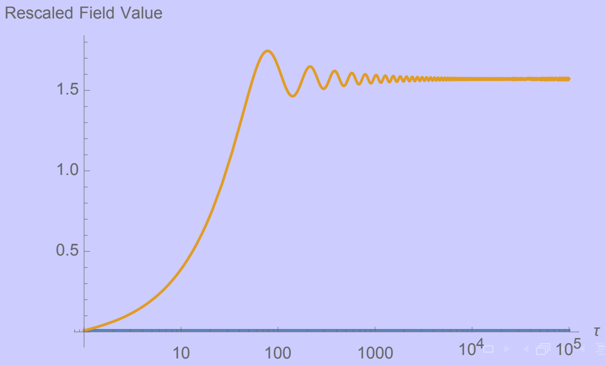
Early Phase II

Slow rolling of φ during the early phase:

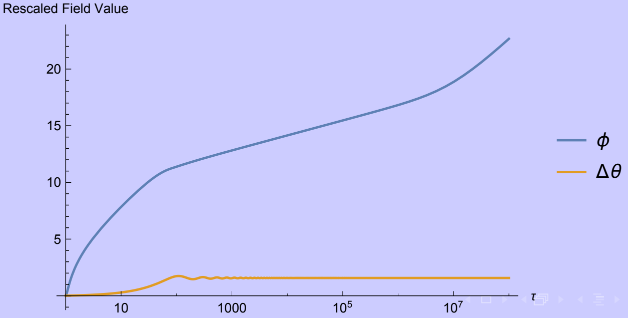
$$e^{-2\varphi/f} = \frac{f^2}{2\mu^4}\frac{1}{t^2}.$$

Numerical Evolution: θ field

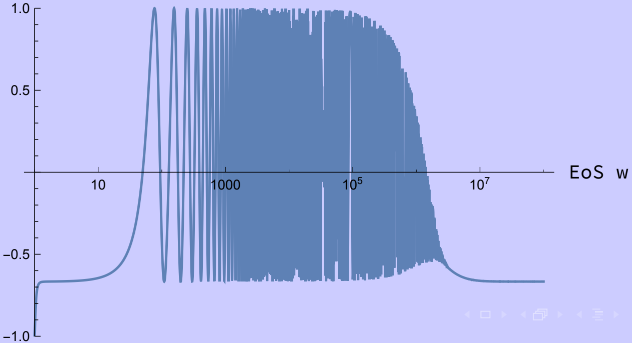
Thanks to Z. Wang for the numerical work



Numerical Evolution - Field Values



Numerical Evolution - Equation of State



Parameter Requirements

Parameters: Λ, μ, T_c, f

- f determines the equation of state in the DE phase: $f \sim m_{pl}$.
- Λ has the right value to yield DE today.
- Note: no solution of the coincidence problem!
- μ and T_c chosen such that we get the observed matter energy density today.
- Note: dark matter mass set by μ

$$m_{DM} \sim \frac{\mu^2}{f}$$

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Parameter Choices

$$m_{DM} \equiv m_a 1\mathrm{eV},$$

$$\mu \sim m_a^{1/2} 10^5 \mathrm{GeV}$$
$$T_c \sim m_a 10^{14} \mathrm{GeV}.$$

Plan

Coupling to the Baryon Current

Assume a coupling between ζ and the baryon current:

$$\delta\mathcal{L} = \tilde{\alpha}\partial_\mu \Im\zeta \, j_B^\mu \,,$$

Can be generated by the chiral anomaly for the baryon current:

$$\partial_\mu j_B^\mu \sim \frac{g^2}{16\pi^2} F \wedge F \,,$$

Spontaneous Baryogenesis

A. Cohen and D. Kaplan, Phys. Lett. 199B, 251 (1987)

During the early phase when both φ and θ are uniformly rolling a chemical potential for baryon number is induced:

$$\mu_B = \tilde{\alpha}(\Im\zeta)^{\cdot} = \frac{\tilde{\alpha}}{f}\left[\dot{\theta} - \frac{\dot{\varphi}}{f}\theta\right]e^{-\varphi/f}.$$

Evaluation:

$$\mu_B \sim \tilde{\alpha}\frac{T^4}{\mu^2 m_{pl}},$$

Induced baryon number density:

$$n_B \sim \mu_B T^2,$$

Evaluation:

$$\frac{n_B}{s} \sim \tilde{\alpha}\left(\frac{T}{\mu}\right)^2\frac{T}{m_{pl}},$$

Baryogenesis from Hypermagnetic Helicity

Baryon current anomaly $\rightarrow$

$$\Delta N_B = C_y \frac{\alpha_y}{8\pi} \Delta \mathcal{H} \,,$$

Helicity density:

$$\dot{h} = -2 < E \cdot B > \,,$$

Magnetohydrodynamics $\rightarrow$

$$E \cdot B = \frac{1}{\sigma} B \cdot (\nabla \wedge B) \,,$$

$\sigma \sim T$: conductivity

$$< B \cdot (\nabla \wedge B) > = \int_k \frac{d^3k}{(2\pi)^3} |k|^3 \left(|A_{k,+}|^2 - |A_{k,-}|^2 \right) ,$$

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Growth of Helicity

Assume the coupling

$$\delta\mathcal{L}_2 = \alpha\frac{\Im\zeta}{4}\widetilde{Y}_{\mu\nu}Y^{\mu\nu},$$

Equation of motion for the gauge field becomes:

$$\ddot{A}_{k,\pm} + \left(k^2 \pm \alpha k(\Im\zeta)^{\cdot}\right)A_{k,\pm} = 0,$$

$$\ddot{A}_k + (k^2 \pm \alpha k e^{-\varphi/f}\frac{\dot{\theta}}{f})A_k = 0.$$

Exponential growth for $k < k_c$:

$$k_c = \alpha\tau^{-1}(\frac{T_c}{\mu})^2.$$

Resulting Baryon to Entropy Ratio

Duration of the instability is set by back-reaction: density in the produced gauge particles must remain smaller than the pre-existing radiation density.

Resulting baryon to entropy ratio:

$$\frac{\Delta n_B}{s} \sim C_y \frac{\alpha_y}{8\pi} \alpha^{-1/2} .$$

Plan

Embedding of the Model in a UV Theory

- Example: ζ is the axion-dilaton field of string theory:

$$\zeta = e^{-\Phi} + iC_0$$

- Φ: dilaton; C_0: Ramond-Ramond zero form axion.
- Classical level: potential flat in angular direction.
- Quantum level: instantons break the symmetry and generate a potential.
- Example: ζ is a complex scalar field whose real part describes the size of the compact space.
- Negative curvature of the internal manifold $\rightarrow$ positive exponential potential for the real part.

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Conclusions

- Unified model of dark energy and dark matter
- Complex scalar field ζ
- **Radial component** yields dark energy.
- **Angular component** yields an axion acting as dark matter.
- Early evolution: uniform motion of $\zeta \rightarrow$ spontaneous breaking of CPT symmetry $\rightarrow$ spontaneous baryogenesis.