Magnetogenesis form axion-U(1) preheating

Simple model - rich phenomenology

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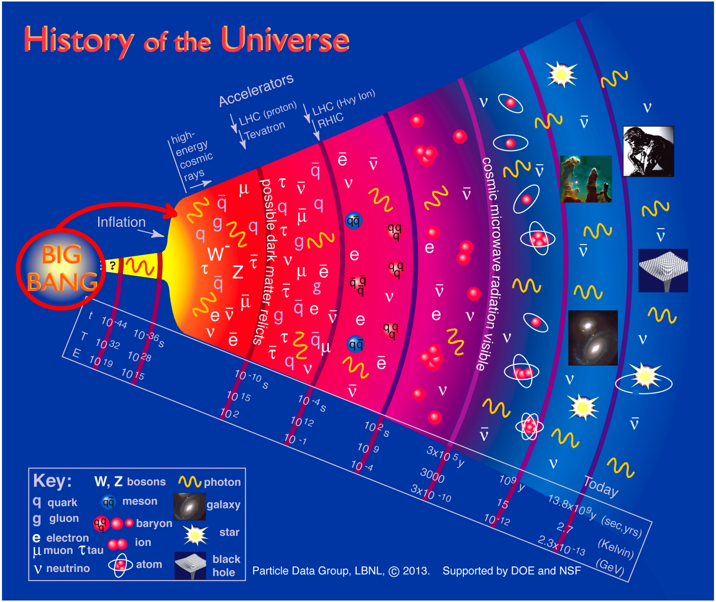
CWRU

May 2, 2024, Bernoulli Workshop

in collaboration with: P. Adshead, K. Freese, T. Giblin, A. Long,
T. Scully, P. Stengel, L. Visinelli

related to the work of: Lorenzo, Dani, Valerie, Kohei, ...

Into slide



Particle Data Group, LBNL, © 2013. Supported by DOE and NSF

Into slide for this crowd

- Inflation is great
- Natural / axion inflation is even greater

Allowed couplings

A field with a shift symmetry can only couple **derivatively**

$$\mathcal{L}_{\mathrm{Int}} \subset \overset{\text{E/M field}}{\boxed{\frac{\alpha}{8f}\phi\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}}} + \overset{\text{electrons, neutrinos, ...}}{\boxed{\frac{C}{f}\partial_\mu\phi\bar{\psi}\gamma_5\gamma^\mu\psi}}$$

$$\updownarrow$$

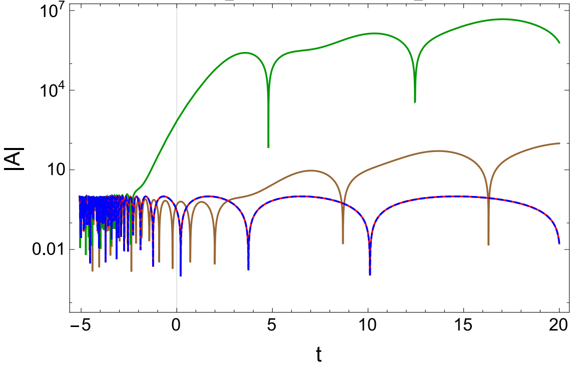
$$\boxed{-\frac{\alpha}{f}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\phi A_\nu\partial_\alpha A_\beta}$$

From a EFT perspective, we expect these terms to be present. (see Valerie's talk)

Gauge field production

We work with an abelian gauge field (e.g. $U(1)_Y$) & decompose in two polarizations $(+,-)$.

$$\ddot{A}_k^{\pm} + H\dot{A}_k^{\pm} + \left[\left(\frac{k}{a}\right)^2 \mp \frac{\alpha}{f}\frac{k}{a}\dot{\phi}\right] A^{\pm} = 0$$



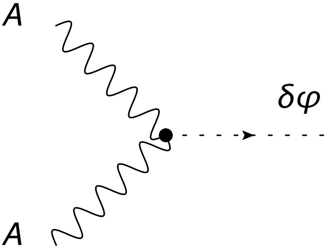
For non-zero coupling each polarization $(+,-)$ exhibit different **exponential enhancement**.

Backreaction

Gauge fields source **density fluctuations** by back-reacting on the inflaton through the usual **axion-photon interaction**

$$\left[\partial_t^2 + 3H\partial_t + \left(\frac{k^2}{a^2} + V_{\phi\phi}\right)\right]\delta\phi = \frac{\alpha}{f}\frac{1}{a^2}\left(\vec{E}\cdot\vec{B} - \langle\vec{E}\cdot\vec{B}\rangle\right)$$

$$\boxed{|A| = e^{\pi\frac{\alpha}{f}\frac{|\dot{\phi}|}{H}}}$$



Constraints on the coupling through:

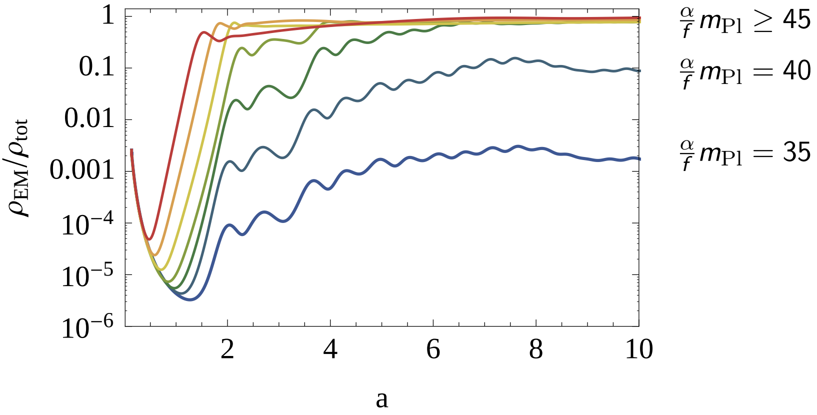
- non-Gaussianity at the CMB
- Primordial Black Hole production

$$\Rightarrow \quad \frac{\alpha}{f} \lesssim 110 m_{\rm Pl}^{-1}$$

$\Longrightarrow$ **Lattice simulations** are needed to compute strong back-reaction effects for large coupling (Dani's talk)

Reheating Efficiency

Coupling the axion to gauge fields can lead to explosive transfer of energy from the inflaton.



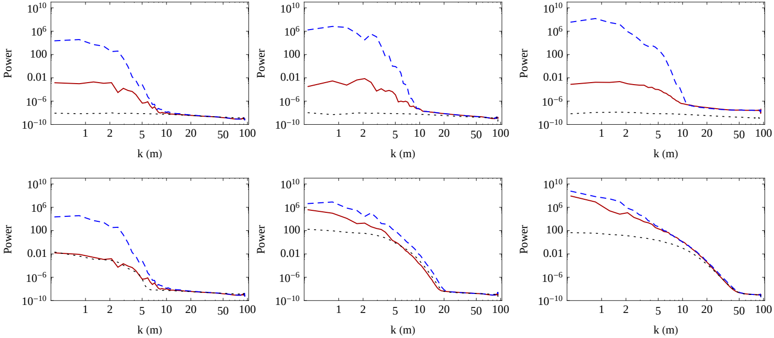
Reheating occurs after a **single axion oscillation** for $\frac{\alpha}{f} m_{\mathrm{Pl}} > 45$.

Re-Scattering and Polarization

$\frac{\alpha}{f} m_{\rm Pl} = 35$ $\frac{\alpha}{f} m_{\rm Pl} = 45$ $\frac{\alpha}{f} m_{\rm Pl} = 60$

NO back-reaction

WITH back-reaction

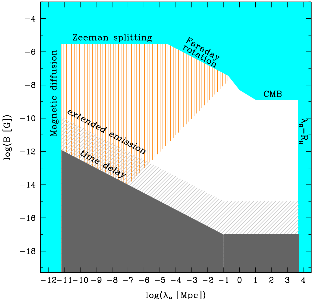


Strong re-scattering **suppresses polarization** on sub-horizon scales for large couplings.

Observables

Magnetic fields are observed at all scales. We focus on large scales

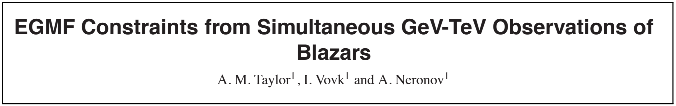
- Galactic magnetic fields at *kpc* scales of $10^{-6}G$
- Intergalactic magnetic fields with correlation length of λ



$$B \gtrsim 10^{-17}G \; (or\ 10^{-15}G) \;\; \text{for } \lambda \geq 1\text{Mpc}$$

$$B \gtrsim \sqrt{\frac{1Mpc}{\lambda}}10^{-17}G \qquad \text{for } \lambda < 1\text{Mpc}$$

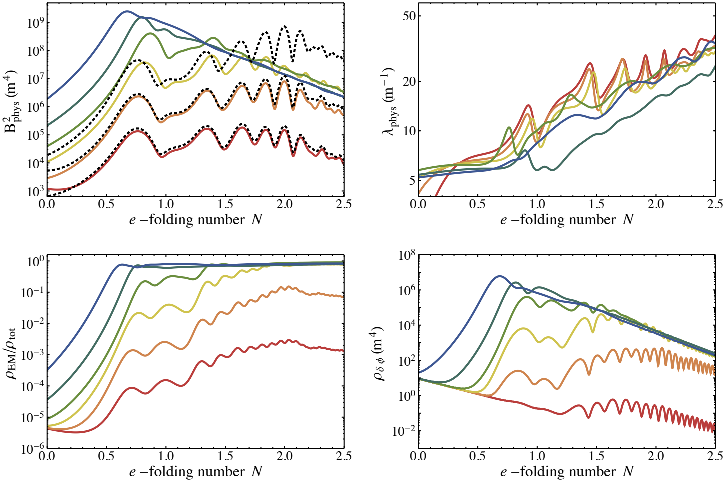
define $B_{\text{eff}} \equiv B\sqrt{\lambda/1Mpc} > 10^{-17}G$



EGMF Constraints from Simultaneous GeV-TeV Observations of Blazars

A. M. Taylor[1], I. Vovk[1] and A. Neronov[1]

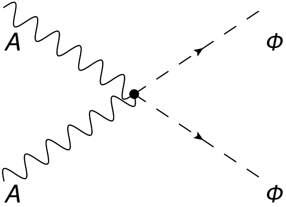
Lattice Results



Photons → Charged Plasma

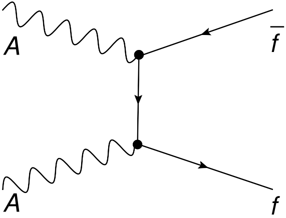
Instantaneous preheating efficiently generates gauge fields, but we are not made of gauge fields...

$\Longrightarrow$ The "missing link" are Standard Model interactions



$$\sigma_{AA\to\Phi\Phi} \sim \frac{\alpha_Y^2}{s}$$

$$\frac{\Gamma}{H} = \frac{n\sigma v}{H} \sim \alpha_Y^2 \left(\frac{m_{\rm Pl}}{m}\right)^2 \gg 1$$



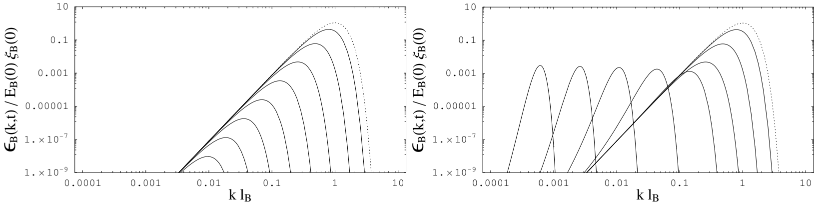
Fast interactions lead to

$$T_{\rm reh} \sim \sqrt{m \times m_{\rm Pl}} \sim 10^{-3}\, m_{\rm Pl}$$

Evolution of Helical Fields

In a turbulent plasma $B-$fields undergo **inverse cascade** :

- **helicity conservation**
- energy transfer from smaller to larger scales.



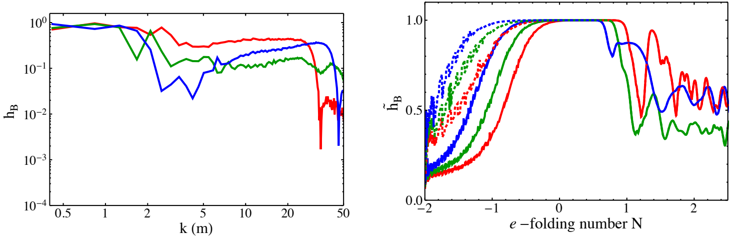
Campanelli, arXiv:0705.2308

also Brandenburg & Kahniashvili

This protects magnetic fields from fast decay

$\Longrightarrow$ **stronger magnetic fields today**.

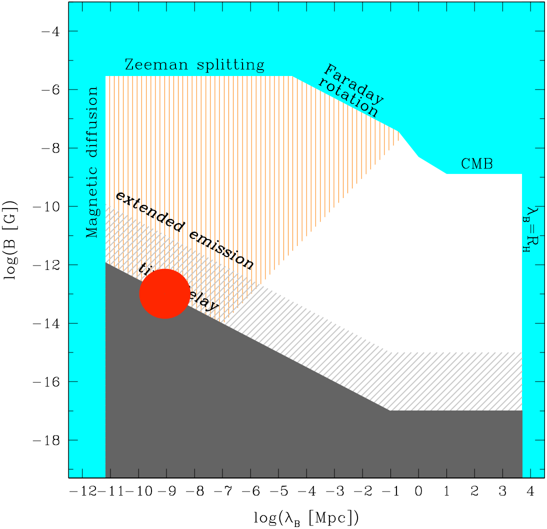
Late Universe Magnetic Field



- Conversion of gauge fields to charged particles $\mathcal{O}(1)$
- Conversion of hypercharge to EM $\cos\theta_W \sim 0.9$
- Inverse cascade starts shortly after inflation

$$\boxed{B_{\rm eff} \gtrsim 10^{-16}\, G} \quad \Leftrightarrow \quad B_{\rm phys} \sim 10^{-13} G \quad \& \quad \lambda_{\rm phys} \sim 10\, pc$$

Connection with observations



Gauge fields and baryons

The chiral anomaly in the Standard model for a fermion species f is

$$\partial_\mu J_f^\mu = C_y^f \frac{\alpha_y}{16\pi} Y_{\mu\nu} \tilde{Y}^{\mu\nu} + C_w^f \frac{\alpha_y}{8\pi} W_{\mu\nu} \tilde{W}^{\mu\nu} + C_s^f \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

Integrating this equation gives

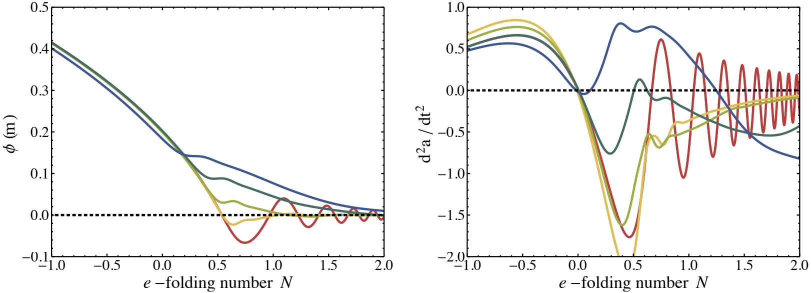
$$\Delta N_f = -C_y^f \frac{\alpha_y}{4\pi} \int d^4x \vec{E} \cdot \vec{B} = C_y^f \frac{\alpha_y}{8\pi} \Delta \mathcal{H}$$

where

- ΔN_f is the change in baryon number
- $\Delta \mathcal{H}$ is the change in helicity

see Kohei's talk

Who ordered that?



- Strong back-reaction from the gauge-field traps the inflaton.
- Inflation ends momentarily.
- Once the gauge fields red-shift enough, inflation re-starts.

see Dani's tak

Diverse Observables from Gauge Fields

Axion inflation naturally has a Chern-Simons coupling to $U(1)$

⇓

Lattice simulations needed for large coupling

⇓

Instantaneous preheating &
efficient scattering to the SM
⟹ **high reheat temperature**

⇓

Largely **helical** magnetic fields &
inverse cascade

⇓

Possible origin of
intergalactic magnetic fields

⇓

Large backreaction effects
⟹ Inflaton **trapping**
can mimic potential feature

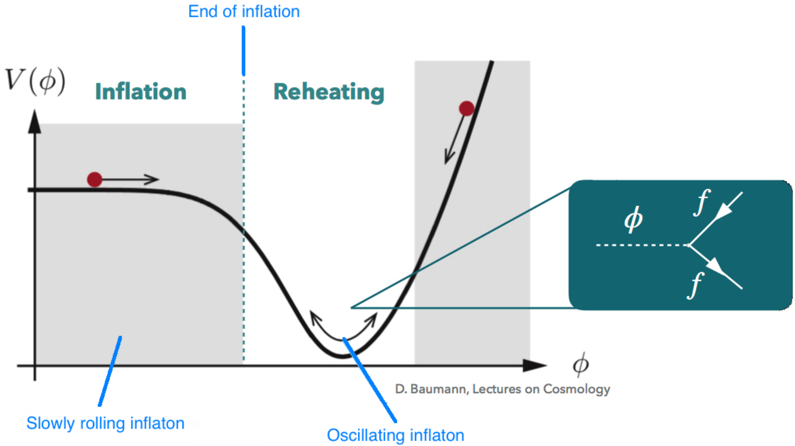
⇓

Possible enhanced **PBH**
production

⇓

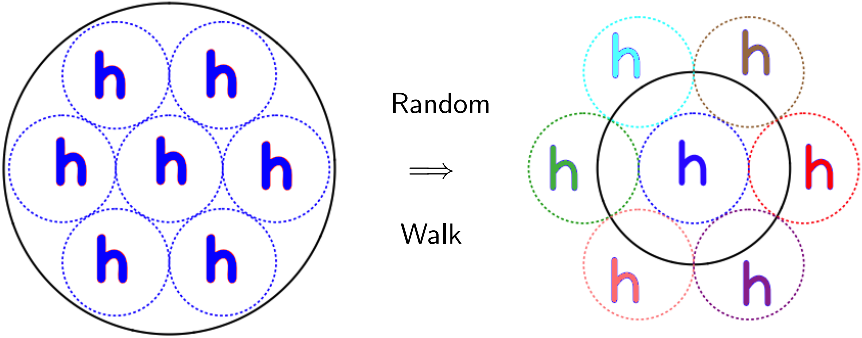
Coupling constraints must be
updated

Anatomy of single field inflation



D. Baumann, Lectures on Cosmology

Hubble patches during inflation

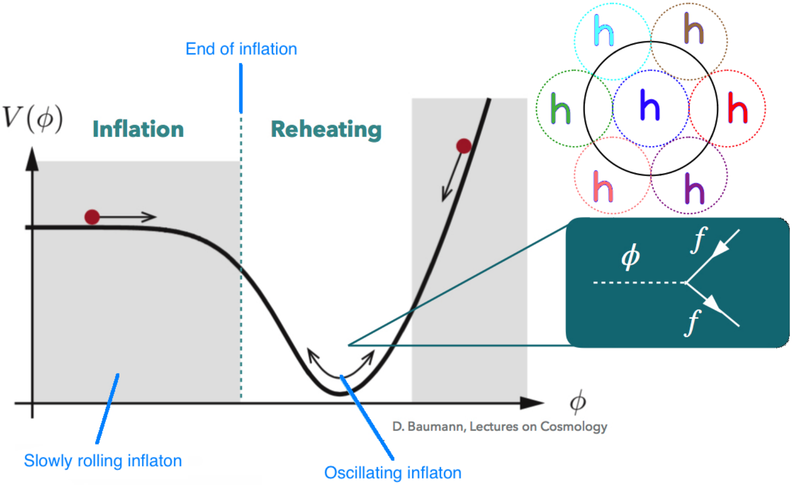


Random $\Longrightarrow$ Walk

During inflation the Higgs field performs
a random walk on super-horizon scales,
acquiring a different value in each Hubble patch.

$$\sqrt{\langle h^2 \rangle} = 0.36 \lambda_I^{-1/4} H_I$$

Single field inflation with a spectator

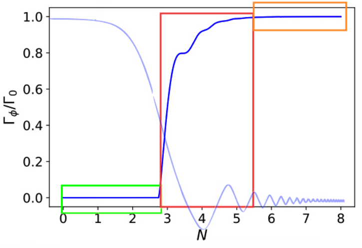


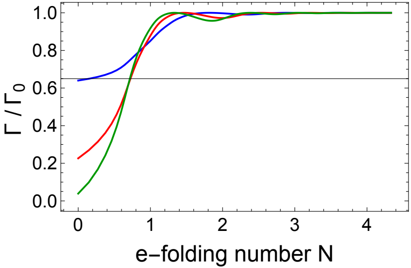
D. Baumann, Lectures on Cosmology

Higgs modulation

Perturbative decays to fermions

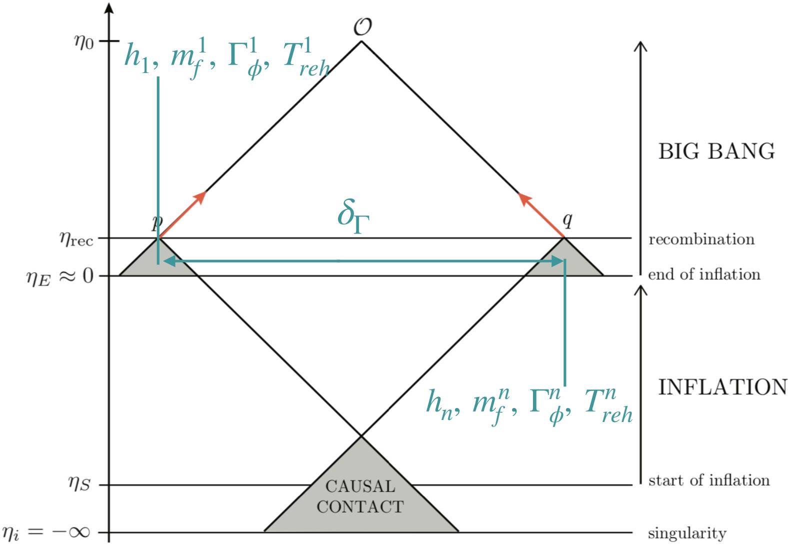
$$\Gamma_\phi = \Gamma_0 \left(1 - \frac{2y^2h^2}{m_\phi^2}\right)^{3/2} \Theta(m_\phi^2 - 2y^2h^2)$$





Even for $m_\phi^2 > 2y^2h^2$, Γ_ϕ still depends on the Higgs field, which is **space-depenent**

Space-dependent reheat temperature



Higgs blocking for gauge bosons 1/2

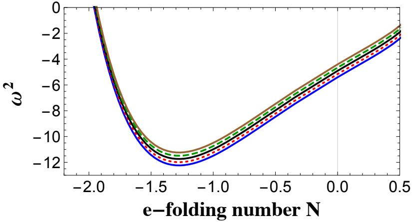
The effective Lagrangian is

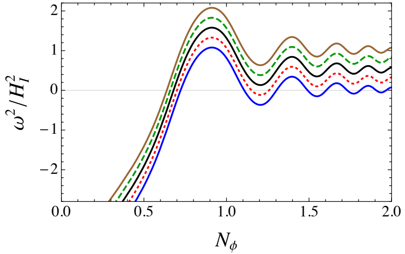
$$\boxed{\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4f}\phi F^{\mu\nu}\tilde{F}_{\mu\nu} + \frac{M^2}{2}A^\mu A_\mu}$$

where $M = g|h|/2$ is the gauge field mass.

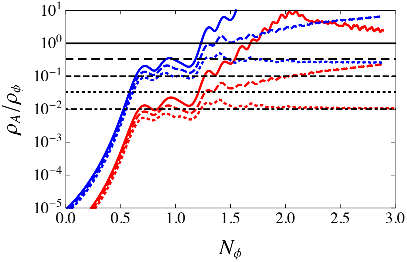
The **linearized** equations of motion for $A_k^\pm$ are

$$\ddot{A}_k^\pm + H\dot{A}_k^\pm + \left(\frac{k^2}{a^2} \mp \frac{k}{a}\frac{\dot{\phi}}{H} + M^2\right)A_k^\pm = 0$$

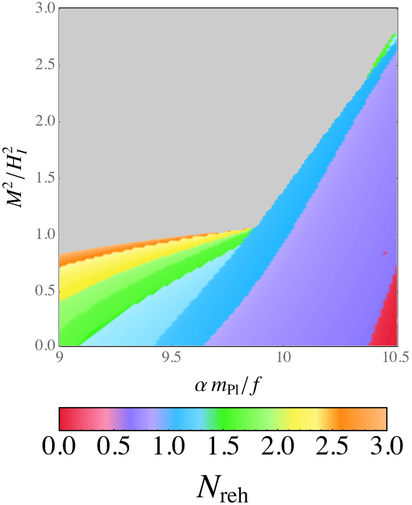




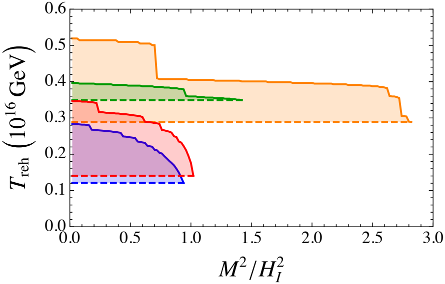
Higgs blocking for gauge bosons 2/2

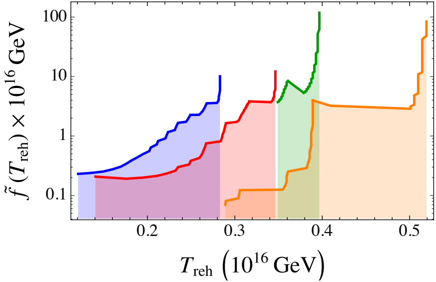


Increasing the gauge boson mass suppressed parametric resonance, delaying preheating or even making it impossible



- The Higgs & the gauge mass are **stochastic variables**.
- The reheat temperature depends on the Higgs RMS value.

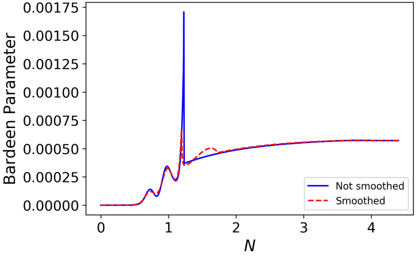




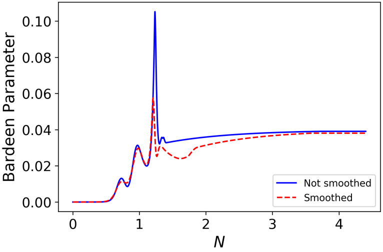
- The universe reheats into **patches** of different temperatures.
- For incomplete preheating, the PDF has a δ-function-like component at the perturbative decay temperature.

Results

$$\boxed{g = 0.1 \Rightarrow \frac{\Delta T}{T} \simeq 10^{-4}}$$



$$\boxed{g = 0.8 \Rightarrow \frac{\Delta T}{T} \simeq 8 \times 10^{-3}}$$



Preheating solely to massive gauge bosons is observationally ruled out

Diverse observables from the Higgs condensate

The reheat temperature depends
on the Higgs behavior during / after inflation.

- Temperature fluctuations from reheating must be bound with respect to the CMB (Dvali, Gruzinov & Zaldarriaga, 2004)
- Leptogenesis & Baryogenesis models must be computed using the Higgs rms effects
  $\Rightarrow$ variable washout $\Rightarrow$ baryon abundance $\Rightarrow$ CIB fluct.

$\Downarrow$

Reheating effects can help us
probe the Higgs potential during inflation!

Fermion Fields

$$\mathcal{L}_{\rm Int} \supset \quad \tfrac{\alpha}{8f}\phi\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta} \quad + \quad \boxed{\frac{C}{f}\partial_\mu\phi\bar{\psi}\gamma_5\gamma^\mu\psi}$$

$$\updownarrow$$

$$-\tfrac{\alpha}{f}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\phi A_\nu\partial_\alpha A_\beta$$

A detailed analysis can be found in:

- P. Adshead and EIS, Phys. Rev. Lett. **116**, no. 9, 091301 (2016) [arXiv:1508.00881 [hep-ph]]
- P. Adshead and EIS, JCAP **1511**, no. 11, 021 (2015) [arXiv:1508.00891 [hep-ph]].

Fermion Summary – due to time constraints

- Coupling to fermions leads to the asymmetric production of helicity states.
    - One helicity state is produced during inflation.
    - The other helicity state, which is produced only after inflation, is produced for a smaller range of wavenumbers.
    - The difference in the range of produced wavenumbers can lead to an asymmetric production
- The peak asymmetry has a very simple expression $\Delta n \sim \left(\frac{C}{f}\right)^3$, with a model-dependent $\mathcal{O}(1)$ factor.
- Helicity asymmetry in SM neutrinos can be converted to an observable baryon asymmetry through the sphaleron process.

Inflationary Leptogenesis & Neutrinos

The observed baryon number can be connected to inflation through generating a lepton helicity asymmetry

- **Direct coupling during axion inflation:**
  The lepton number depends on the coupling constant and inflaton velocity
- **Gravitational leptogenesis:**

$$\partial_\mu \left(\sqrt{-g}\, J^\mu_{B-L}\right) = -\frac{N_{L-R}}{24}\frac{1}{16\pi^2} R\tilde{R}$$

where the lepton number density is

$$\mathcal{N}_{B-L} \propto \left(\frac{H_e}{M_{\rm Pl}}\right)^2 \mathcal{H}^{GW}_{R-L}$$

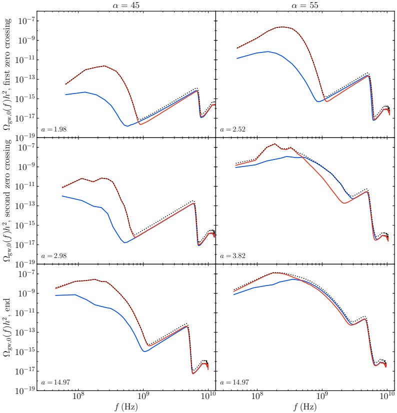
while we parametrize the GW power asymmetry with

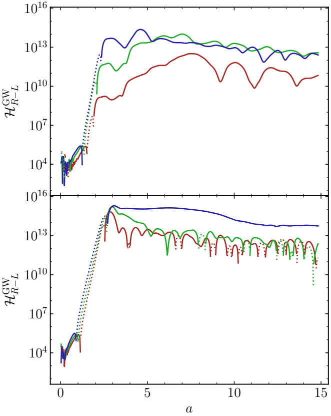
$$\mathcal{H}^{GW}_{R-L} \equiv \int d\ln k \left[\frac{k^3}{H_e^3}\frac{(\Delta_R^2 - \Delta_L^2)}{H_e^2/M_{\rm Pl}^2} - \frac{k}{H_e}\frac{(\Delta_R'^2 - \Delta_L'^2)}{H_e^4/M_{\rm Pl}^4}\right]$$

Origin of helical GW's

$U(1)$ gauge fields can effectively source GW's through

$$h_{ij}'' - \nabla^2 h_{ij} + 2\mathcal{H} h_{ij}' = 16\pi S_{ij}^{TT}$$

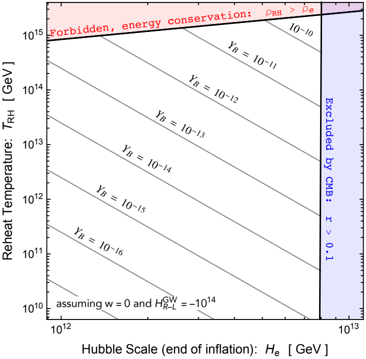


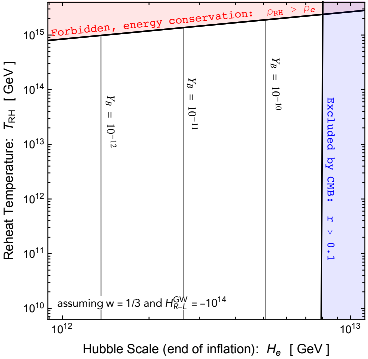


as shown through lattice simulations by Adshead, Giblin & Weiner

Reheating and Asymmetry

$$\frac{Y_B}{4\times 10^{-10}} \propto \left(\frac{H_e}{10^{13}\,\mathrm{GeV}}\right)^{\frac{3+5w}{1+w}} \left(\frac{T_{RH}}{10^{15}\,\mathrm{GeV}}\right)^{\frac{1-3w}{1+w}} \left(\frac{\mathcal{H}^{GW}_{R-L}}{-10^{14}}\right)$$



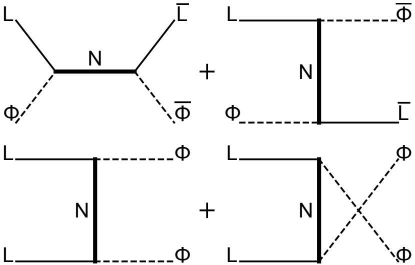


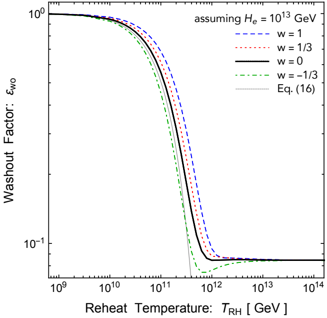
- P. Adshead, A. J. Long and EIS, “Gravitational Leptogenesis, Reheating, and Models of Neutrino Mass,” Phys. Rev. D **97**, no. 4, 043511 (2018) [arXiv:1711.04800 [hep-ph]].

Reheating and Washout

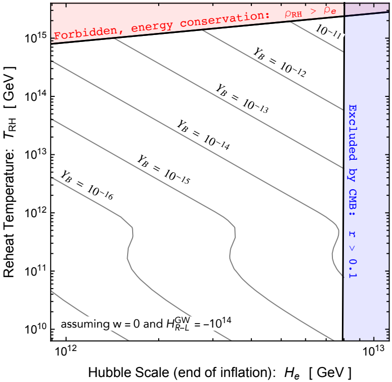
- Massive Dirac neutrinos: No net lepton number arises, BUT the lepton number of right-handed neutrinos is sequestered from the SM ⇒ effective (axial) SM lepton number with no washout.

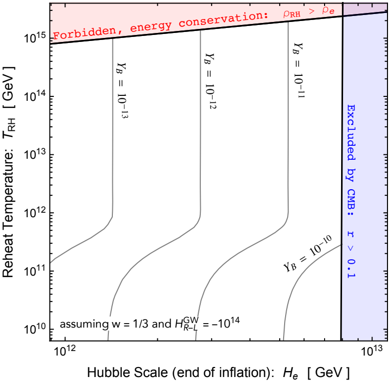
- Massive Majorana neutrinos:





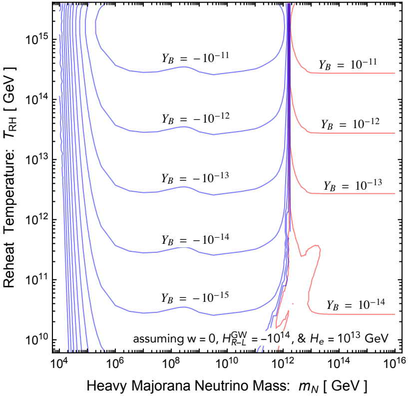
Reheating and equation of state





- Matter-dominated reheating suppresses the asymmetry
- For radiation-dominated reheating, suppresses can be avoided

Neutrino mass and helicity sign



$$m_N \ll H_e$$

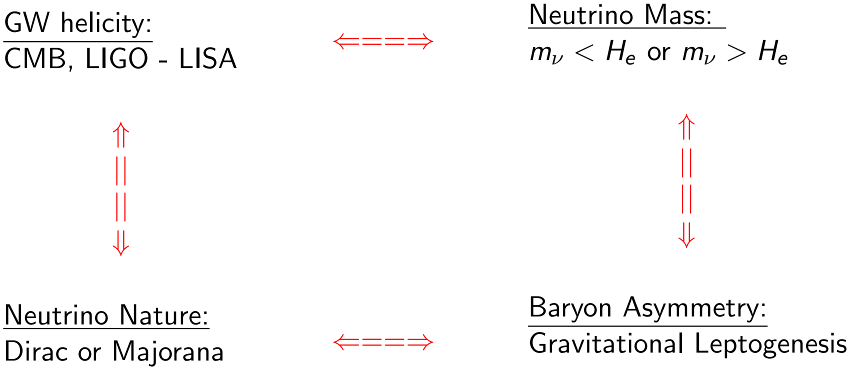
$$\Downarrow$$

lepton asymmetry carried by the left-chiral leptons is efficiently washed out,

$$\Downarrow$$

lepton asymmetry carried by the e_R^i is eventually redistributed when the corresponding Yukawa interaction comes into equilibrium.

Diverse observables



GW helicity:
CMB, LIGO - LISA

Neutrino Mass:
$m_\nu < H_e$ or $m_\nu > H_e$

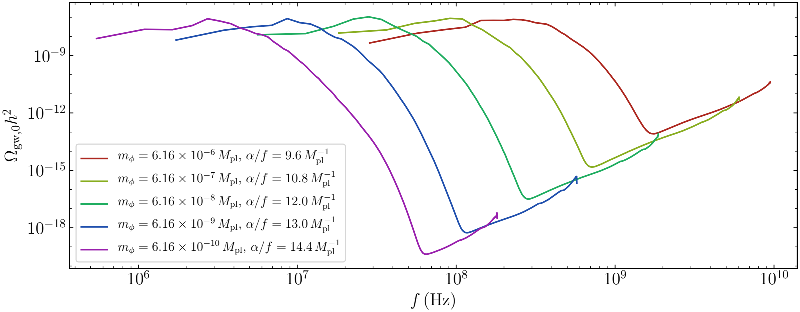
Neutrino Nature:
Dirac or Majorana

Baryon Asymmetry:
Gravitational Leptogenesis

- Right-chiral GW's require Majorana neutrinos with $10^6 < m_N < 10^{12}$ GeV.
- Left-chiral GW's require Dirac neutrinos, or Majorana neutrinos with $m_N \gtrsim 10^{12}$ GeV.

From U(1) to GW's

Gauge field production leads to the **helical GW's**.



Adshead et al, 2020

However, the large frequency makes them **unobservable at interferometers**.

Hybrid Inflation

Multiple fields

⇓

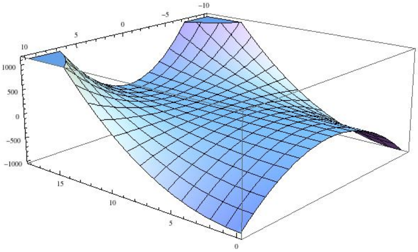
qualitatively different behavior

Hybrid Inflation (Linde, 1994):

a slow rolling field triggers a phase transition

⇒ destabilizes a second field

⇒ Inflation ends



1. (light) real timer scalar field
2. (heavy) complex waterfall scalar field

$$V(\phi,\psi) = V_0 + m_\psi^2\psi^2 - m_0^2\left[1-\left(\frac{\psi}{\psi_c}\right)^r\right]|\phi|^2$$

Result: **Large Spike at Small Scales!!**

(e.g. Guth & EIS, 2012, Garcia-Belido & Clesse, 2015)

Timer field

$$\ddot{\psi} + 3H\dot{\psi} - e^{-2Ht}\nabla^2\psi = -m_\psi^2\psi$$

- Spatially homogenous
- purely classical
- No back-reaction

Trivial solution for quadratic potential

$$\psi(t) = \psi_c e^{pt}$$

where $p = -H\left(\frac{3}{2} - \sqrt{\frac{9}{4} - \frac{m_\psi^2}{H^2}}\right) \approx -\frac{m_\psi^2}{3H}$

Non-Dimensionalize: $N = Ht$, $\mu_\psi = \frac{m_\psi}{H}$, $\mu_\phi = \frac{m_0}{H}$, $\tilde{\mu}_\psi^2 \approx -\frac{rm_\psi^2}{3H}$

Waterfall fields

We expand the waterfall fields in **non-interacting Fourier modes**

$$\phi_i(\vec{x}, t) = \int \frac{d^3k}{(2\pi)^3} \left[c_{k,i} e^{ik\cdot x} u_k(t) + h.c.\right]$$

where at early times $u_k(t) \to \frac{e^{-ikt/a}}{a\sqrt{2k}}$

The power spectrum is $P_\phi(k) = |u_k|^2$ and $\phi^2_{\rm rms} = \int \frac{d^3k}{(2\pi)^3} P_\phi(k)$.

A hybrid^2 model

An attempt to combine **hybrid** and **natural** inflation

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \sum_i \frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_i - \frac{1}{2}\partial_\mu\psi\partial^\mu\psi \right.$$
$$\left. -V(\psi,\phi_i) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4f}\sum_i \frac{\phi_i}{\Lambda_i}F_{\mu\nu}\tilde{F}^{\mu\nu}\right]$$

where

$$V(\psi,\phi_i) = V_0 + V_1(\psi) - \frac{m_0^2(\phi_i)^2}{2}\left(1-\frac{\psi^2}{\psi_0^2}\right) + \frac{g}{4}(\phi_i)^4$$

Waterfall Field Dynamics

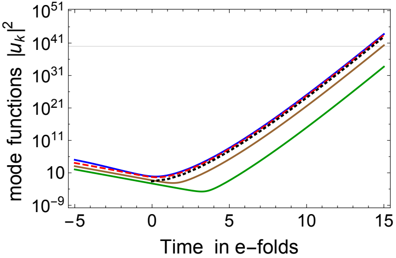
$$\ddot{\psi} + 3H\dot{\psi} + m_\psi^2\psi = 0$$

$$\ddot{\phi}_i + 3H\dot{\phi}_i + \left[\frac{k^2}{a^2} + m_\phi^2(t)\right]\phi_i = 0$$

where

$$m_\phi^2(t) = -m_0^2\left(1 - \frac{\psi^2}{\psi_0^2}\right)$$

Waterfall field modes grow exponentially

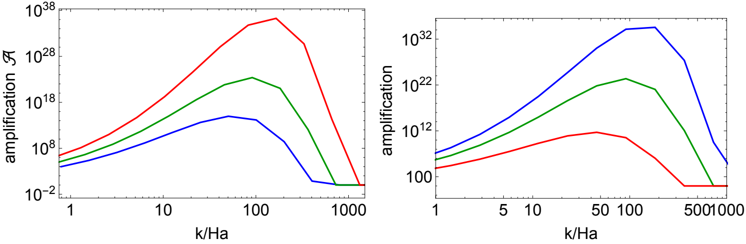


$$\boxed{\phi_i(\vec{x}, t) = \phi_i(\vec{x}, t_c)e^{\int_{t_c}^{t} dt'\lambda(t')}}$$

where $\frac{\lambda(t)}{H} \simeq -\frac{3}{2} + \sqrt{\frac{9}{4} + \frac{m_0^2}{H^2}\left(1 - e^{-2\frac{m_\psi^2}{3H^2}t}\right)}$

Gauge field Dynamics

Peaked spectrum with $\frac{k_{\rm peak}}{aH} \sim \frac{\lambda}{10H}\frac{H}{\Lambda_{i,\rm min}}\frac{M_{\rm Pl}}{H}$.



Gauge field energy density $\rho_A \sim \mathcal{A}^2 k_{\rm peak}^4/a^4$, where $\mathcal{A}$ is the amplification factor.

Complete preheating requires $\rho_{\rm infl} \simeq \rho_A$, leading to

$$\mathcal{A} \sim \left(\frac{M_{\rm Pl}}{H}\right)\left(\frac{k_{\rm peak}}{aH}\right)^2.$$

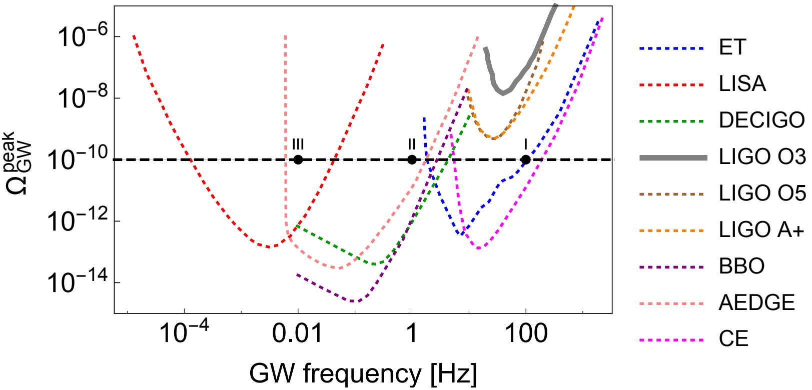
GW signals

A simple way to estimate GW production (Giblin & Thrace, 2014)

$$\begin{aligned} \nu_{GW}^{\rm peak} &= 2.7 \times 10^{10} \frac{k_*}{\sqrt{M_{\rm Pl}\, H}}\, {\rm Hz}\,, \\ \Omega_{\rm GW}^{\rm peak} &= 2.3 \times 10^{-4}\, \alpha^2\, \beta\, w \left(\frac{k_*}{\sigma}\right) \left(\frac{H_*}{k_*}\right)^2 . \end{aligned}$$

- α: fraction of the energy in the GW source relative to the Universe's total energy density
- β:encodes the anisotropy of the source
- w: EOS of the universe
- k_*: peak wavenumber of the source spectrum
- σ: width of the source spectrum

Signals and experiments



Primordial Black Holes & Parameter Dependence

The density perturbations spike leads to the formation of PBH's with $\boxed{M = (M_{\rm Pl}^2/H_*)e^{2N_*}}$ and probability

$$\boxed{\beta_{\rm BH}(M) = erfc\left(\frac{\zeta_c}{\sqrt{2}\sigma}\right) \simeq \frac{\sqrt{2}\sigma}{\sqrt{\pi}\zeta_c}e^{-\zeta_c^2/(2\sigma^2)}}$$

$H/M_{\rm Pl}$	m_0	Λ/H	$N_{\rm wf}$	$\nu_{\rm GW}^{\rm peak}$	$\Omega_{\rm GW}^{\rm peak}$	$M_{\rm BH}$
10^{-20}	$6\,H$	10^{18}	14.2	$100\,\rm Hz$	10^{-10}	$10^{-5}M_\odot$
10^{-20}	$15\,H$	10^{18}	6.2	$100\,\rm Hz$	10^{-10}	$10^{-13}M_\odot$
10^{-24}	$7\,H$	10^{22}	14	$1\,\rm Hz$	10^{-10}	$0.1M_\odot$
10^{-30}	$8\,H$	10^{27}	14.5	$10^{-3}\,\rm Hz$	10^{-10}	$10^5M_\odot$
10^{-30}	$12\,H$	10^{27}	10	$10^{-3}\,\rm Hz$	10^{-10}	$10M_\odot$

Summary

A rare way to **probe low-scale inflation**

- A simple model leading to **detectable GW signals from preheating**, using axions and dark photons in a hybrid inflation setup
- **Helical GW's** provide a distinguishing feature
- Associated **PBH production** provides more correlated observables

Summary

A simple model of inflation leads to rich phenomenology

- Magnetic fields
- GWs
- Large over-densities and PBHs (?)
- Baryogenesis and **neutrino physics**
- CIB fluctutations and **Higgs physics**
- oscillons
- ...

Thank you!