"GRAVITY'S GIFT: BARYONS FROM THE BIG BANG"

RICE

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@ Cosmo 2026
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based on: 2605.05304 with Tammi Chowdhury, Leah Jenks, Rocky Kolb, and Evan McDonough

What’s the matter with matter?

What's the matter with matter?

Although, we've measured the amount
of ordinary (baryonic) matter ...

CMB anisotropies tells us the cosmological energy fraction in baryons

$$\Omega_b h^2 = 0.0224 \pm 0.0001$$

[Planck (2018)]

for baryogenesis studies, we conventionally use the baryon-to-entropy ratio

$$Y_{\mathrm{B}}^{\mathrm{obs}} = (0.879 \pm 0.004) \times 10^{-10}$$

... we still don't know *why* there's any matter at all.

baryogenesis = an event that we think occurred
in the early universe and gave rise
to the excess of matter over antimatter

simple & testable baryogenesis scenario

gravity creates

a nonthermal population of heavy Majorana neutrinos

their out-of-equilibrium decays create the BAU

gravity creates

primordial grav. waves

their imprint on CMB polarization should be detected with next-generation telescopes

Nonthermal leptogenesis with Type-I seesaw

leptogenesis: Fukugita & Yanagida (1986)
nonthermal LG: Lazarides & Shafi (1991) + tons

The model = Type-I seesaw

$$\mathscr{L} = [\mathrm{SM}] + 3 \text{ heavy Majorana neutrinos } N_i$$

$$M_1 \simeq 10^{13}\ \mathrm{GeV} \ll M_2 < M_3$$ (hierarchical spectrum)

Yukawa interaction

$$\mathscr{L}_{\text{int}} = -y_{ij}\epsilon_{ab}\bar{L}_{a,i}N_j\Phi_b^* + \text{h.c.}$$

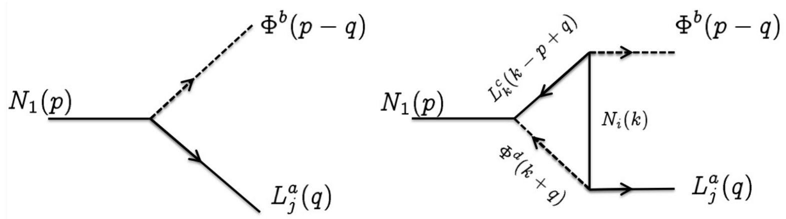
Decay channels

$$N_1 \to \begin{cases} L_{a,i}\Phi_b & \Rightarrow \quad \Delta\mathrm{L} = +1 \\ \bar{L}_{a,i}\bar{\Phi}_b & \Rightarrow \quad \Delta\mathrm{L} = -1 \end{cases}$$

Total decay rate

$$\Gamma = (yy^\dagger)_{11} M_N / 8\pi$$

CP-violation favors decays into leptons



$$\varepsilon \equiv \frac{\Sigma_{ab}\Sigma_i[\mathrm{Br}(N_1 \to L_{a,i}\Phi_b) - \mathrm{Br}(N_1 \to \bar{L}_{a,i}\bar{\Phi}_b)]}{\Sigma_{ab}\Sigma_i[\mathrm{Br}(N_1 \to L_{a,i}\Phi_b) + \mathrm{Br}(N_1 \to \bar{L}_{a,i}\bar{\Phi}_b)]}$$

$$\varepsilon = -\frac{3}{16\pi}\frac{1}{(yy^\dagger)_{11}}\sum_{i=2,3}\mathrm{Im}[(yy^\dagger)_{1i}^2]\frac{M_1}{M_i}$$ (if masses are hierarchical)

If decays occur in R-dom @ temp T_*

$$[a^3 n_{\mathrm{B}}]_{\text{final}} = -\frac{28}{79}\,\varepsilon\,[a^3 n_N]_{\text{init}}$$ (assumes: inv. decays & scattering are out of equilib)

Where does the initial population of N's come from?

cosmological gravitational particle production (CGPP)

$$a(t) \rightarrow \hat{H}(t) \rightarrow \langle \hat{N}_{\vec{k}} \rangle$$

cosmological expansion → time-dependent Hamiltonian → particles produced

CGPP for Majorana fermions

a homogeneous & isotropic spacetime

$$(\mathrm{d}s)^2 = (\mathrm{d}t)^2 - a(t)^2 |\mathrm{d}\boldsymbol{x}|^2$$

expansion is driven by inflaton field

$$\frac{\dot a}{a} = \sqrt{\frac{\frac{1}{2}\dot\phi^2 + V(\phi)}{3M_{\mathrm{Pl}}^2}}$$

$$\ddot\phi + 3H\dot\phi + V'(\phi) = 0$$

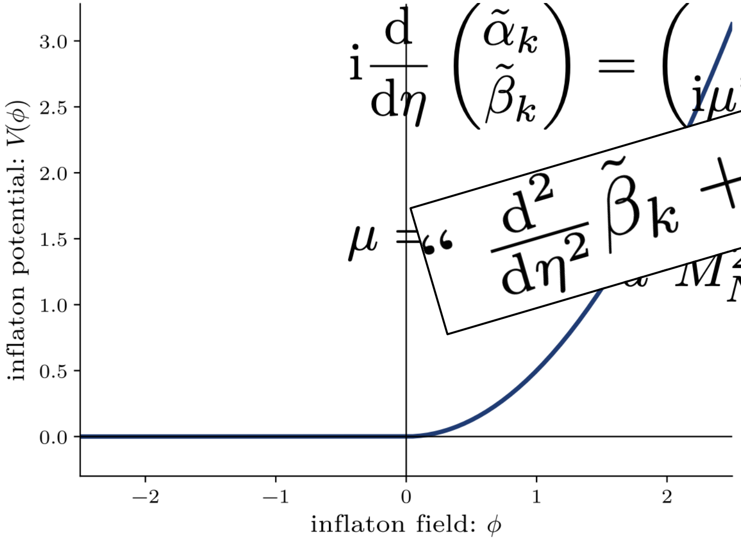
inflaton rolls down a potential

$$\begin{aligned} V(\phi) &= \tfrac{1}{2} m_\phi^2 \phi^2 \quad &\text{for } \phi > 0 \\ &= 0 &\text{for } \phi < 0 \end{aligned}$$

$\phi_i = 10 M_{\mathrm{Pl}}$

$m_\phi \approx 2\times 10^{13}\ \mathrm{GeV}$

$H_e \approx 1\times 10^{13}\ \mathrm{GeV}$



QFT of Majorana spinor in curved spacetime

$$S[\Psi(x), e^a_\mu(x)] = \int \mathrm{d}^4x\, e \left[\tfrac{\mathrm{i}}{4}\bar\Psi\gamma^\mu\nabla_\mu\Psi - \tfrac{\mathrm{i}}{4}\bar\Psi\overleftarrow{\nabla}_\mu\gamma^\mu\Psi - \tfrac{1}{2}M_N\bar\Psi\Psi \right]$$

Dirac equation on FRW background

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}\eta}\begin{pmatrix} u_{A,k} \\ u_{B,k} \end{pmatrix} = \begin{pmatrix} aM_N & k \\ k & -aM_N \end{pmatrix}\begin{pmatrix} u_{A,k} \\ u_{B,k} \end{pmatrix}$$

After a change of variables

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}\eta}\begin{pmatrix} \tilde\alpha_k \\ \tilde\beta_k \end{pmatrix} = \begin{pmatrix} 0 & -\mathrm{i}\ldots \\ \mathrm{i}\mu^* e^{-2\mathrm{i}\ldots} & \ldots \end{pmatrix}\ldots$$

$$\text{“}\ \frac{\mathrm{d}^2}{\mathrm{d}\eta^2}\tilde\beta_k + |\mu(\eta)|^2\tilde\beta_k = 0\ \text{”}$$

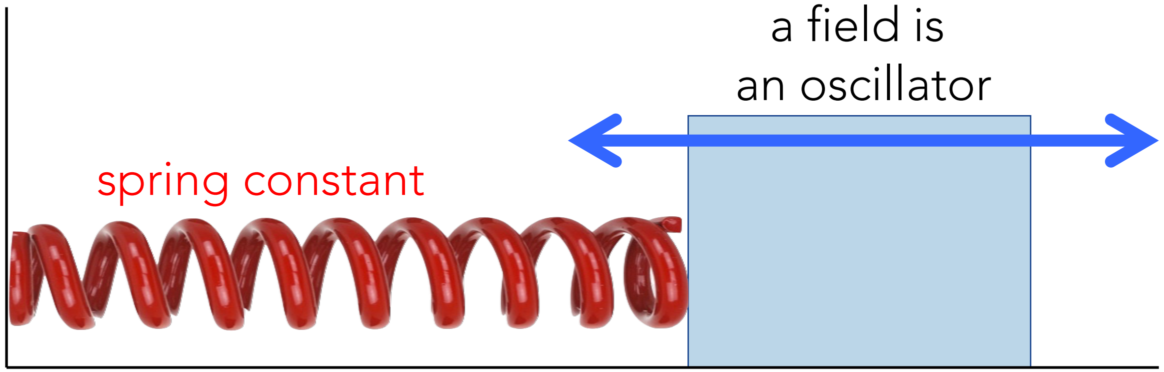
$$\mu = \ldots M_N^2) \qquad \Phi = \int_{-\infty}^{\eta}\mathrm{d}\eta'\sqrt{k^2 + a(\eta')^2 M_N^2}$$

number

$$\frac{\mathrm{d}^3\boldsymbol{p}}{(2\pi)^3}\,|\tilde\beta_p(\eta)|^2$$

original work: Parker (1969, 70)
fermions: Chung et. al. (2011)
review: Kolb & AL (2023)

An analogy with 1D quantum mechanics

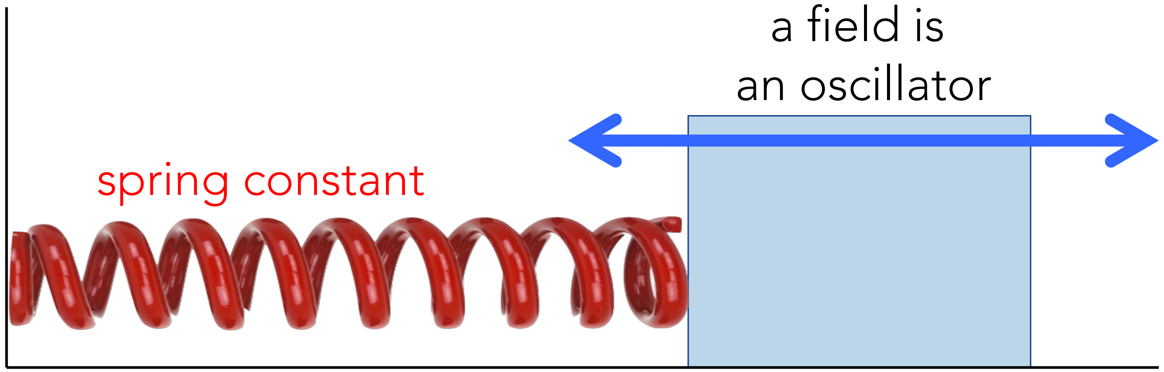


$$i\hbar \frac{\partial}{\partial t}\psi(x,t) = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi(x,t) + U(x,t)\,\psi(x,t)$$

$$U(x,t) = \tfrac{1}{2}k(t)x^2$$

$$k(t) = k_1 + \big(k_2 - k_1\big)\left[\frac{1+\tanh(t/\tau)}{2}\right]$$

An analogy with 1D quantum mechanics



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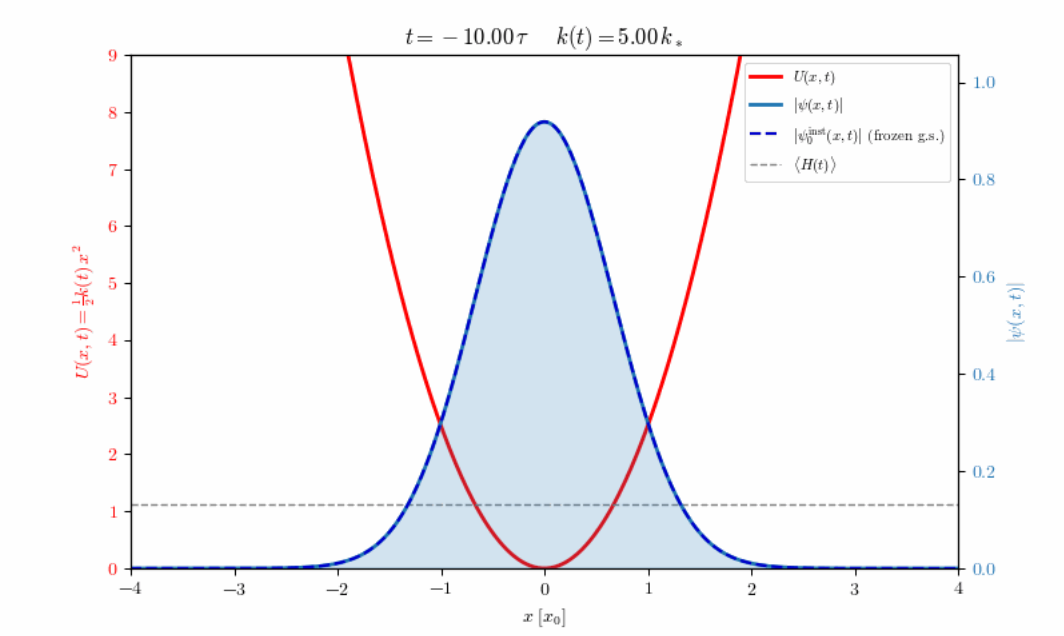
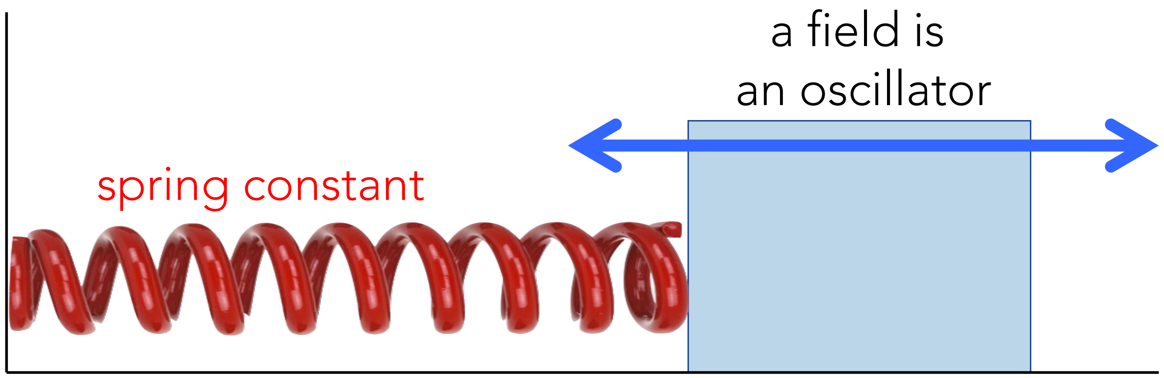
Spring constant is varied slowly (adiabatically)



An analogy with 1D quantum mechanics



$$i\hbar\frac{\partial}{\partial t}\psi(x,t) = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi(x,t) + U(x,t)\,\psi(x,t)$$

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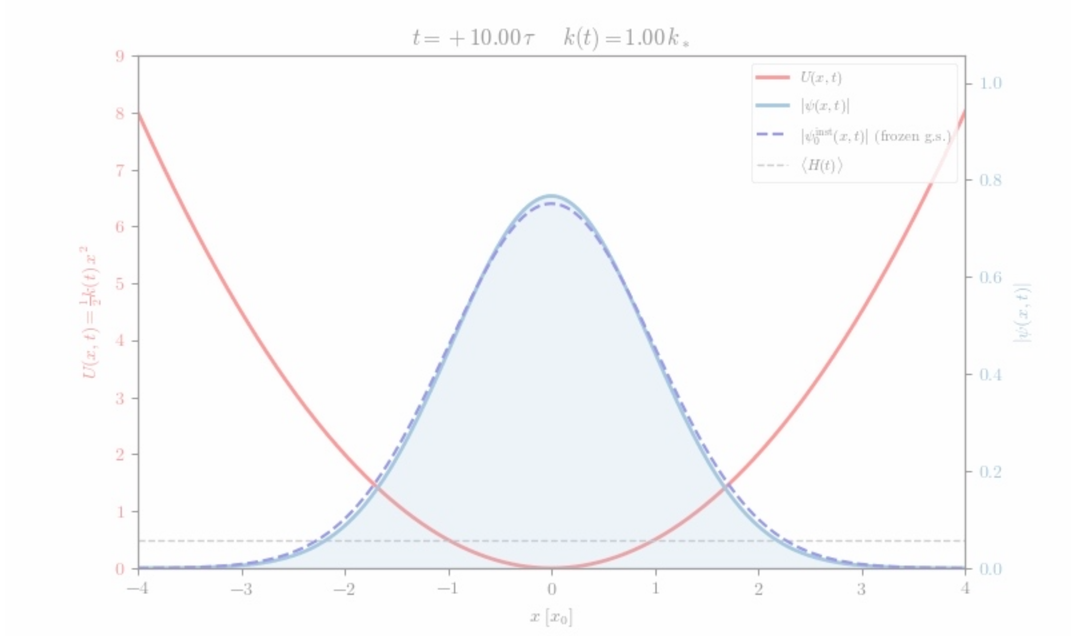
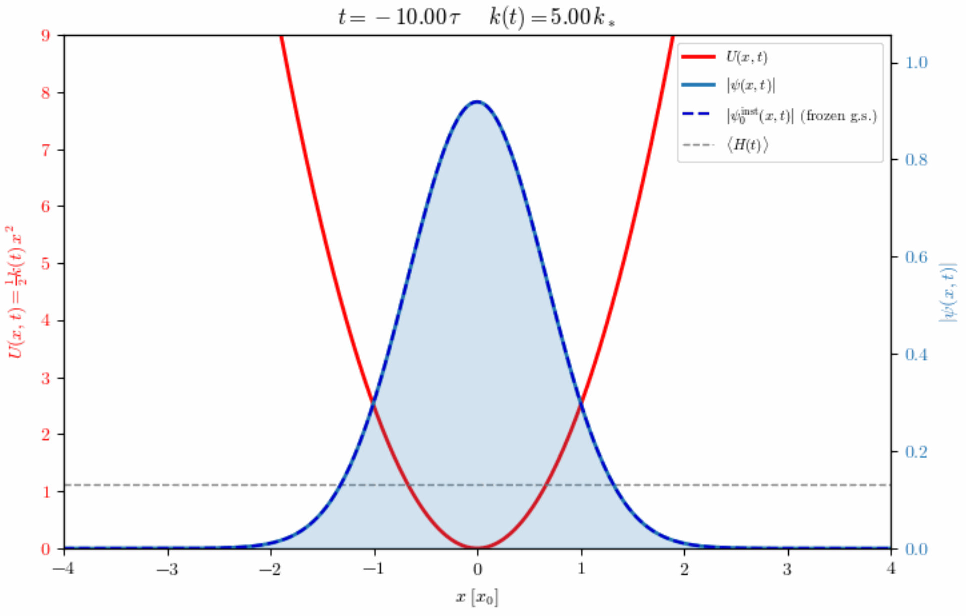
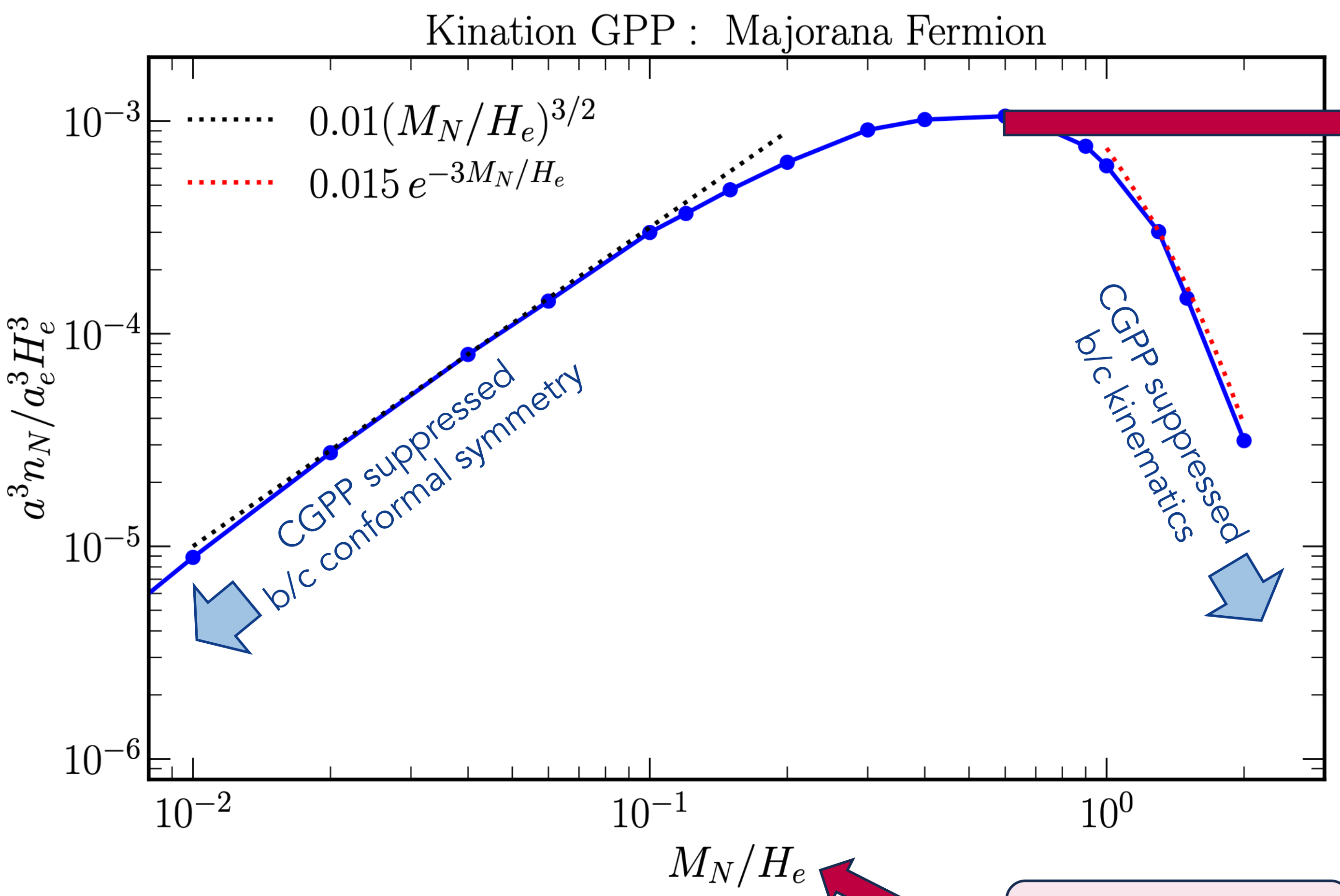
Spring constant is varied slowly (adiabatically)



Spring constant is varied quickly (*non-*adiabatically)



Prediction for initial N abundance



superheavy!

$$a^3 n_N \simeq 10^{-3}\ a_e^3 H_e^3$$

about one N_1 particle for every 1000 Hubble volumes at the end of inflation

gravity gives us a population of heavy Majorana neutrinos “for free”

Putting the pieces together

Baryogenesis scenario: *LG from CGPP*

(1) Type-I seesaw

heavy Majorana neutrinos: $N_1,\ N_2,\ N_3$

interaction with SM: $\mathscr{L}_{\text{int}} = -y_{ij}\epsilon_{ab}\bar{L}_{a,i}N_j\Phi_b^* + \text{h.c.}$

appealing features: light ν masses, GUT embedding

possible generalizations: Type-II or Type-III seesaw

(2) Cosmological gravitational particle production

CGPP = particles are created by the expansion of the universe during inflation & at the end of inflation

preferred parameters: $M_1 \approx H_e < H_{\text{inf}} \ll M_2 < M_3$

typically: 10^{-3} particles per Hubble volume

(3) Nonthermal leptogenesis

LG = CP-violating decays of out-of-equilibrium N_1's create a lepton asymmetry & sphalerons convert to B

(4) Stiff phase

inflation is followed by a phase with $w \sim 1$

e.g., SUSY flat direction

(5) Reheating

inflaton's energy is converted into radiation

e.g., irruption

different implementations of *LG* from *CGPP*

Kobayashi, Yamaguchi, & Yokoyama (2010)
Hashiba & Yokoyama (2019)
Bernal & Fong (2021)
Co, Mambrini, & Olive (2022)
Fujikara, Hashiba, & Yokoyama (2022)
Barman, Clery, Co, Mambrini, & Olive (2022)
Flores & Perez-Gonzalez (2024)

What do we predict for the BAU?

initial N_1 abundance [comes from CGPP]

$$\left[a^3 n_N\right]_{\rm init}$$

CP-violating decays to leptons

$$\varepsilon \equiv \frac{\Sigma_{ab}\Sigma_i[\mathrm{Br}(N_1 \to L_{a,i}\Phi_b) - \mathrm{Br}(N_1 \to \bar{L}_{a,i}\bar{\Phi}_b)]}{\Sigma_{ab}\Sigma_i[\mathrm{Br}(N_1 \to L_{a,i}\Phi_b) + \mathrm{Br}(N_1 \to \bar{L}_{a,i}\bar{\Phi}_b)]}$$

predicted B-number

$$a^3(t) n_{\mathrm{B}}(t) = -\frac{28}{79}\,\varepsilon\,\left[a^3 n_N\right]_{\rm init}$$

predicted B-to-entropy

$$Y_{\mathrm{B}} = -\frac{28}{79}\,\varepsilon\,\frac{T_{\rm RH} H_e}{4 M_{\rm Pl}^2}\,\mathrm{e}^{3 w N_{\rm RH}} \left(\frac{[a^3 n_N]_{\rm init}}{a_e^3 H_e^3}\right)$$

upper bound (hierarchical spectrum)

$$|\varepsilon| < \varepsilon_{\rm DI} \equiv \frac{3}{8\pi}\frac{M_N m_\nu}{v^2} \approx 9.86 \times 10^{-4} \left(\frac{M_N}{10^{13}\,\mathrm{GeV}}\right)$$

stiff phase after inflation

$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \approx 1 \quad \Rightarrow \quad \dot{\phi}^2 \gg V(\phi)$$

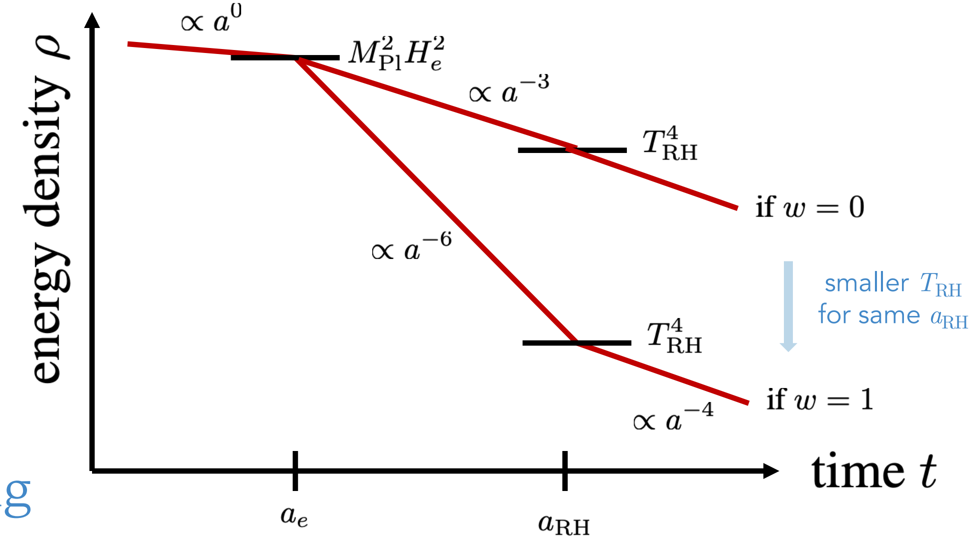
BAU prediction

$$Y_{\mathrm{B}} \simeq (1 \times 10^{-10}) \left(\frac{-\varepsilon}{10^{-1}\varepsilon_{\rm DI}}\right)\left(\frac{M_N}{10^{13}\,\mathrm{GeV}}\right) \times \left(\frac{H_e}{10^{13}\,\mathrm{GeV}}\right)^2 \left(\frac{T_{\rm RH}}{10^{9}\,\mathrm{GeV}}\right)^{-1} \left(\frac{[a^3 n_N]_{\rm init}/a_e^3 H_e^3}{10^{-3}}\right)$$

How does the stiff phase help?

The essential idea:

$$Y_{\mathsf{B}} \propto \frac{n_N}{s} \propto \frac{[a^3 n_N]_{\mathrm{init}}}{a_{\mathrm{RH}}^3 T_{\mathrm{RH}}^3} \quad \Rightarrow \text{larger } w \text{ implies } \begin{cases} \text{smaller } T_{\mathrm{RH}} \text{ for the same } a_{\mathrm{RH}} \\ \text{smaller } a_{\mathrm{RH}} \text{ for the same } T_{\mathrm{RH}} \end{cases}$$



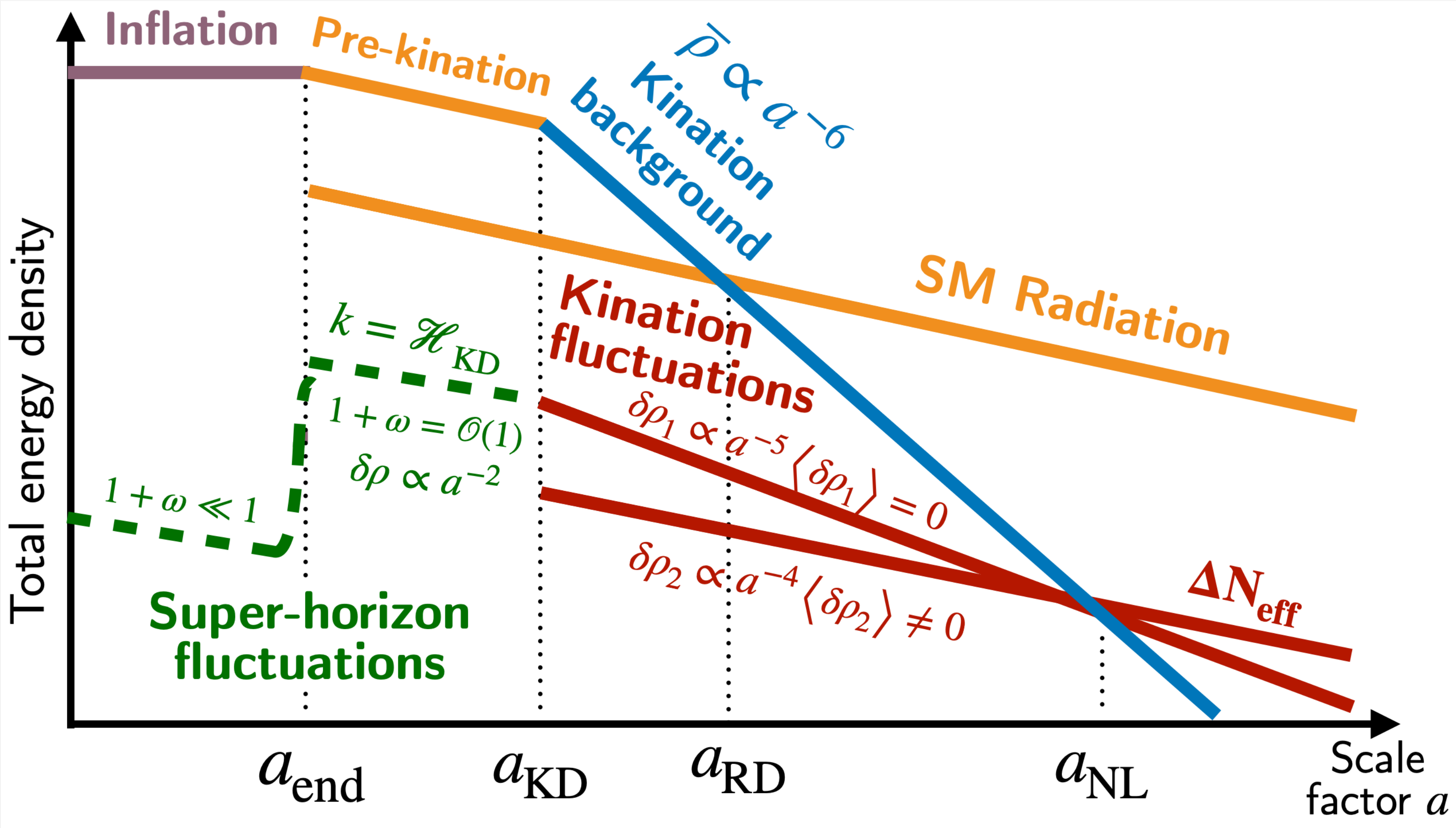
Varying the equation of state between inflation & reheating

$$Y_{\mathsf{B}} = -\frac{28}{79}\, \varepsilon\, \frac{T_{\mathrm{RH}} H_e}{4 M_{\mathrm{Pl}}^2}\, \mathrm{e}^{3wN_{\mathrm{RH}}} \left(\frac{[a^3 n_N]_{\mathrm{init}}}{a_e^3 H_e^3} \right)$$

$$Y_{\mathsf{B}} \approx \begin{cases} (1.5 \times 10^{-23}) \left(\frac{-\varepsilon}{10^{-1}\varepsilon_{\mathrm{DI}}}\right) \left(\frac{M_N}{10^{13}\,\mathrm{GeV}}\right) \left(\frac{H_e}{10^{13}\,\mathrm{GeV}}\right) \left(\frac{T_{\mathrm{RH}}}{10^{9}\,\mathrm{GeV}}\right) \left(\frac{[a^3 n_N]_{\mathrm{init}}/a_e^3 H_e^3}{10^{-3}}\right) & , \quad w = 0 \\ (3.9 \times 10^{-17}) \left(\frac{-\varepsilon}{10^{-1}\varepsilon_{\mathrm{DI}}}\right) \left(\frac{M_N}{10^{13}\,\mathrm{GeV}}\right) \left(\frac{H_e}{10^{13}\,\mathrm{GeV}}\right)^{3/2} \left(\frac{[a^3 n_N]_{\mathrm{init}}/a_e^3 H_e^3}{10^{-3}}\right) & , \quad w = 1/3 \\ (1.8 \times 10^{-13}) \left(\frac{-\varepsilon}{10^{-1}\varepsilon_{\mathrm{DI}}}\right) \left(\frac{M_N}{10^{13}\,\mathrm{GeV}}\right) \left(\frac{H_e}{10^{13}\,\mathrm{GeV}}\right)^{9/5} \left(\frac{T_{\mathrm{RH}}}{10^{9}\,\mathrm{GeV}}\right)^{-3/5} \left(\frac{[a^3 n_N]_{\mathrm{init}}/a_e^3 H_e^3}{10^{-3}}\right) & , \quad w = 2/3 \\ (1.0 \times 10^{-10}) \left(\frac{-\varepsilon}{10^{-1}\varepsilon_{\mathrm{DI}}}\right) \left(\frac{M_N}{10^{13}\,\mathrm{GeV}}\right) \left(\frac{H_e}{10^{13}\,\mathrm{GeV}}\right)^{2} \left(\frac{T_{\mathrm{RH}}}{10^{9}\,\mathrm{GeV}}\right)^{-1} \left(\frac{[a^3 n_N]_{\mathrm{init}}/a_e^3 H_e^3}{10^{-3}}\right) & , \quad w = 1 \end{cases}$$

How long can the stiff phase last?

Eroncel, Gouttenoire, Sato, Servant, & Simakachorn (2501.17226)



homogeneous inflaton ~ a^{-6}

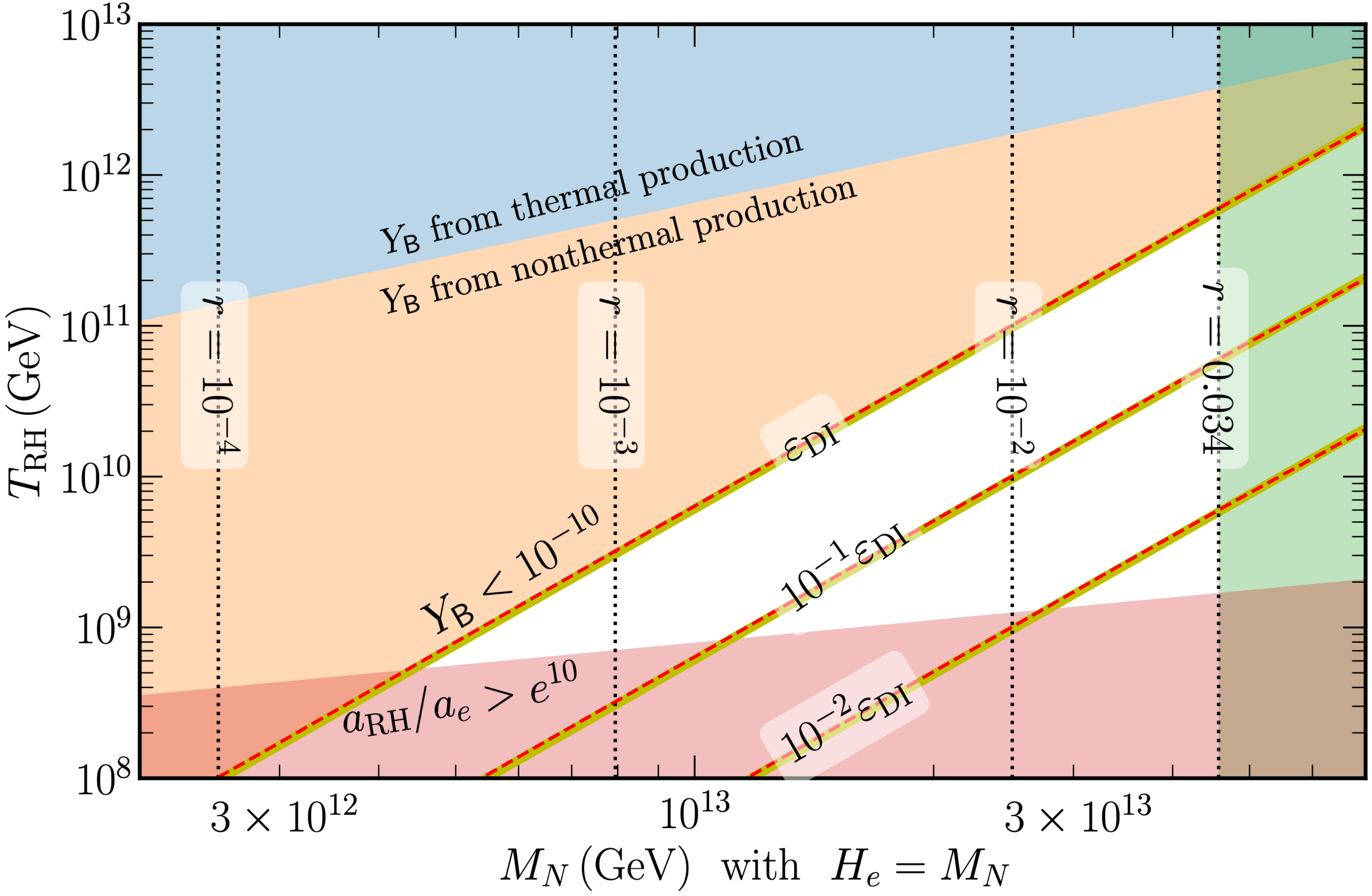
inflaton fluctuations ~ a^{-4}

Fluctuations dominate within ~10 e-foldings, and kination gives way to radiation domination.

$$N_{\mathrm{KD}} \lesssim 9.9 + 0.5 \ln\left(\frac{2.099 \times 10^{-9}}{\mathcal{P}_{\mathcal{R}}(k_\star)}\right) + 0.5 \ln n_s(k_{\mathrm{KD}}) + 0.5(1 - n_s(k_{\mathrm{KD}})) \ln\left(\frac{k_{\mathrm{KD}}}{k_\star}\right)$$

Viable parameters
& predictions

$$Y_{\mathrm{B}} = -\frac{28}{79}\,\varepsilon\,\frac{T_{\mathrm{RH}} H_e}{4M_{\mathrm{Pl}}^2}\,e^{3wN_{\mathrm{RH}}}\left(\frac{[a^3 n_N]_{\mathrm{init}}}{a_e^3 H_e^3}\right) \simeq (1\times 10^{-10})\left(\frac{-\varepsilon}{10^{-1}\varepsilon_{\mathrm{DI}}}\right)\left(\frac{M_N}{10^{13}\,\mathrm{GeV}}\right)\left(\frac{H_e}{10^{13}\,\mathrm{GeV}}\right)^2\left(\frac{T_{\mathrm{RH}}}{10^9\,\mathrm{GeV}}\right)^{-1}\left(\frac{[a^3 n_N]_{\mathrm{init}}/a_e^3 H_e^3}{10^{-3}}\right)$$



Plasma too hot at reheating.
Inverse decay creates N_1's.
Nonthermal LG not viable.

Kination phase is too short.
Reaching $\mathrm{Y_B} = \mathrm{Y_B^{obs}} = 10^{-10}$
would require $\varepsilon > \varepsilon_{\mathrm{DI}}$.

Kination phase is too long.
Inflaton field fluctuations
would dominate & terminate
kination after ~10 e-foldings.

Eroncel et. al. (2025)

Inflationary GW too strong.

white triangle = just right!

Summary & Discussion

summary

- A simple & testable scenario for baryogenesis: LG from CGPP
- Some abundance of heavy Majorana neutrinos are invariably produced at the end of inflation due to gravity alone
- Their CPV+OOE decays produce lepton number that leads to a baryon asymmetry
- If inflation is followed by a stiff phase (e.g., kination), the predicted baryon asymmetry can match the observed BAU

discussion

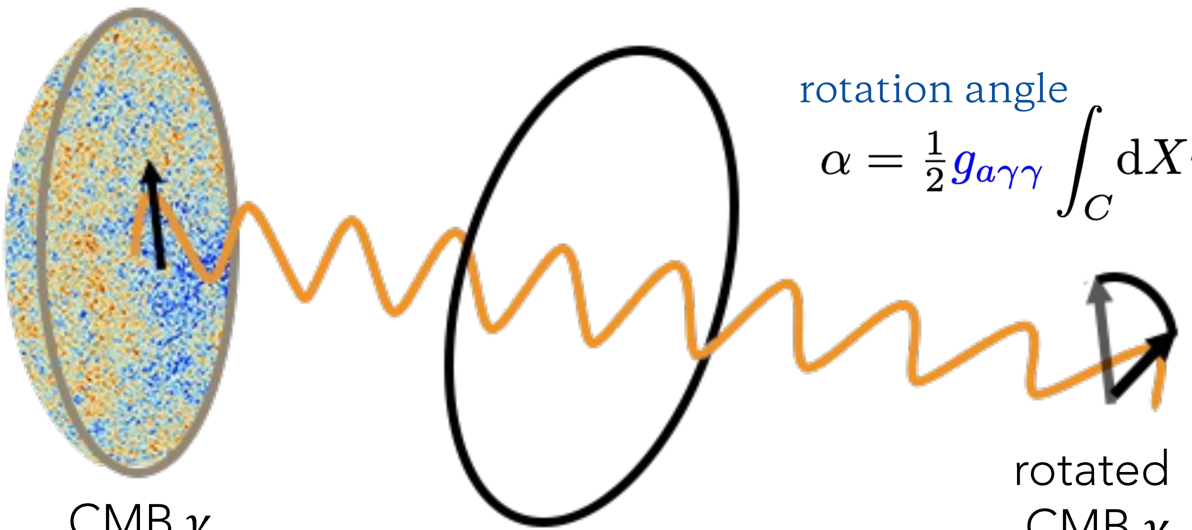
- Since N's arise gravitationally via CGPP, high-scale inflation is required to achieve a sufficient abundance
- High-scale inflation predicts strong primordial gravitational wave radiation
- This baryogenesis scenario brings a welcome element of falsifiability
- If future observations push the upper bound on r below 10^{-3}, it would severely constrain our scenario


AND NOW FOR SOMETHING COMPLETELY DIFFERENT
(a brief advertisement for 2608.Tuesday)

CMB birefringence from axion strings

[Harvey & Naculich (1989)], [Carroll, Field, Jackiw (1990,91)], [Harari, Sikivie (1992)]
[Fedderke, Graham, Rajendran (2019)], [Agrawal, Hook, Huang (2019)]
[Yin, Dai, Ferraro (2021) & (2023)]

axion-induced birefringence:
an electromagnetic wave
traveling through a varying axion field
has its plane of polarization rotated



rotation angle

$$\alpha = \frac{1}{2} g_{a\gamma\gamma} \int_C \mathrm{d}X^\mu \, \partial_\mu a(X)$$

assume interaction with electromagnetism:
standard Chern-Simons coupling

$$\mathscr{L}_{\text{int}} = -\frac{1}{4} g_{a\gamma\gamma} a F \tilde{F}$$

$$g_{a\gamma\gamma} = -\mathcal{A} \frac{\alpha_{\text{em}}}{\pi f_a}$$

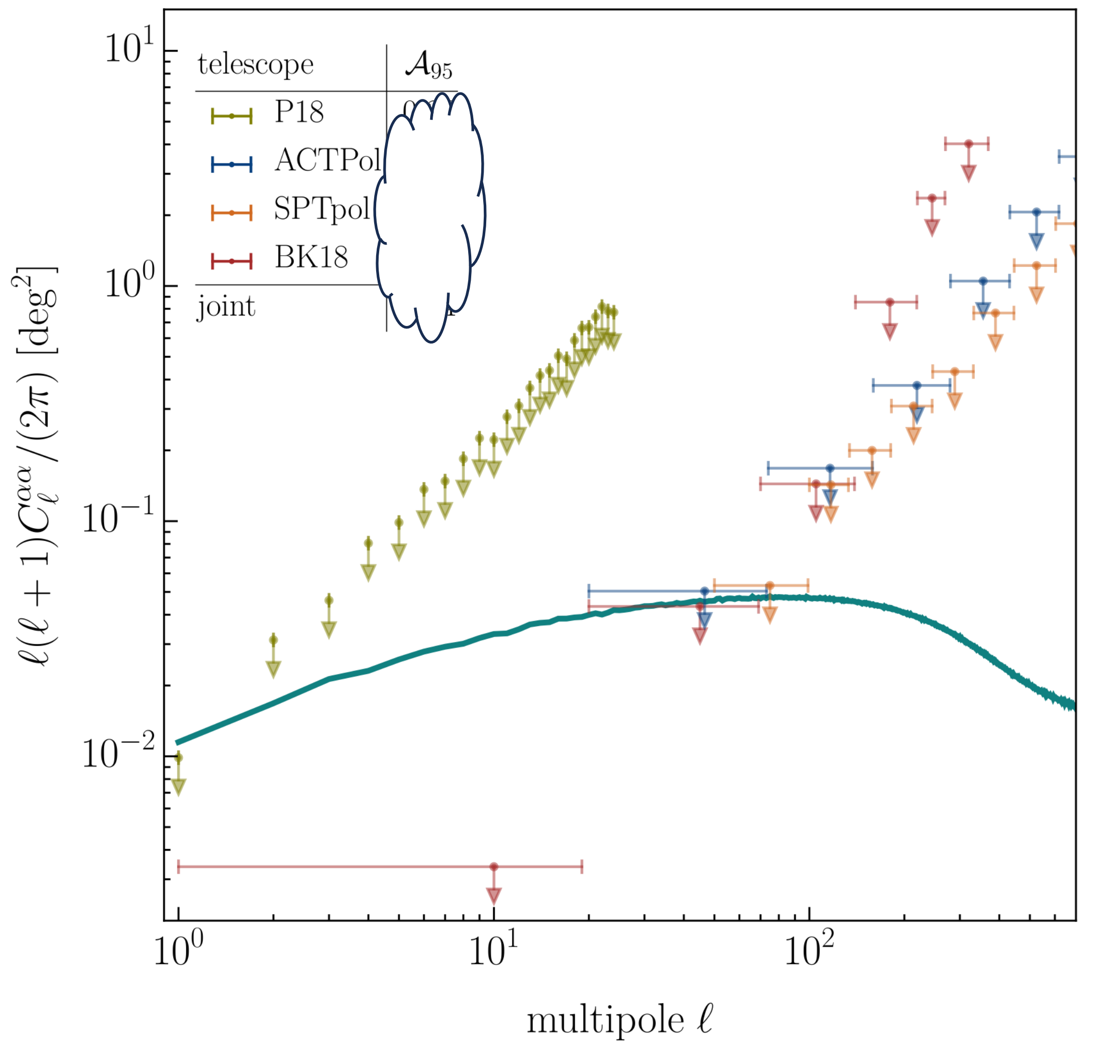
$$\mathcal{A} = \sum Q_{\text{PQ}} Q_{\text{em}}^2 \sim \#/9$$

$$\boxed{\begin{aligned} \alpha &= g_{a\gamma\gamma} \pi f_a \\ &\equiv -\mathcal{A} \alpha_{\text{em}} \\ &\approx -0.42^\circ \, \mathcal{A} \end{aligned}}$$

* birefringence can be measured through E-B cross correlation

CMB birefringence from axion strings

[Amin, Jain, Long, Pugsley, Venegas, Whelley (Tuesday)]



these measurements
place powerful
constraints
on axion strings
in the Universe today

see talk by Moira Venegas
(Wednesday, P6 CMB)

backup slides

Davidson-Ibarra bound

Yukawa interaction

$$\mathscr{L}_{\text{int}} = -y_{ij}\epsilon_{ab}\bar{L}_{a,i}N_j\Phi_b^* + \text{h.c.}$$

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Total decay rate

$$\Gamma = (yy^\dagger)_{11} M_N / 8\pi$$

CP-violation parameter

$$\varepsilon \equiv \frac{\Sigma_{ab}\Sigma_i[\mathrm{Br}(N_1 \to L_{a,i}\Phi_b) - \mathrm{Br}(N_1 \to \bar{L}_{a,i}\bar{\Phi}_b)]}{\Sigma_{ab}\Sigma_i[\mathrm{Br}(N_1 \to L_{a,i}\Phi_b) + \mathrm{Br}(N_1 \to \bar{L}_{a,i}\bar{\Phi}_b)]}$$

If the spectrum is hierarchical

$$\varepsilon = -\frac{3}{16\pi}\frac{1}{(yy^\dagger)_{11}}\sum_{i=2,3}\mathrm{Im}[(yy^\dagger)_{1i}^2]\frac{M_1}{M_i}$$

Meanwhile, seesaw mass relation

$$m_\nu \sim y^2 v^2 / M_N$$

In combination:

$$|\varepsilon| < \varepsilon_{\mathrm{DI}} \equiv \frac{3}{8\pi}\frac{M_N m_\nu}{v^2} \approx 9.86 \times 10^{-4}\left(\frac{M_N}{10^{13}\,\mathrm{GeV}}\right)$$

may be interesting to
explore nonhierarchical N's
→ resonant enhancement?

Hamaguchi, Murayama, & Yanagida (2002)
Davidson & Ibarra (2002)
Buchmuller, Di Bari, & Plumacher (2003)
Hambye, Lin, Notari, Papacci, & Strumia (2003)

Boltzmann equations

reactions involving N_1 and leptons

$$\text{decay:} \quad \begin{cases} N_1 \to L_{a,i} + \Phi_b \\ N_1 \to \bar{L}_{a,i} + \bar{\Phi}_b \end{cases}$$

$$\text{inverse decay:} \quad \begin{cases} L_{a,i} + \Phi_b \to N_1 \\ \bar{L}_{a,i} + \bar{\Phi}_b \to N_1 \end{cases}$$

$$\Delta \mathsf{L} = \pm 2 \text{ scattering:} \quad \begin{cases} L_{a,i} + \Phi_b \leftrightarrow \bar{L}_{c,j} + \bar{\Phi}_d \\ L_{a,i} + L_{b,j} \leftrightarrow \bar{\Phi}_c + \bar{\Phi}_d \\ \bar{L}_{a,i} + \bar{L}_{b,j} \leftrightarrow \Phi_c + \Phi_d \end{cases}$$

$$\Delta \mathsf{L} = \pm 1 \text{ scattering:} \quad \begin{cases} N_1 + L_{a,i} \to \bar{\Phi}_b^* \to \mathrm{SM} + \mathrm{SM} \\ N_1 + \bar{L}_{a,i} \to \Phi_b^* \to \mathrm{SM} + \mathrm{SM} \end{cases}$$

number density of lepton number

$$n_{\mathsf{L}} \supset \Sigma_{a,i} \big(n_{L_{a,i}} - n_{\bar{L}_{a,i}} \big)$$

Boltzmann equations

$$\tfrac{\mathrm{d}}{\mathrm{d}t} n_N + 3 H n_N = -(n_N - n_N^{\mathrm{eq}}) \big[\Gamma + 2\, n_\gamma^{\mathrm{eq}} \langle \sigma v \rangle_1 \big]$$

$$\tfrac{\mathrm{d}}{\mathrm{d}t} n_{\mathsf{L}} + 3 H n_{\mathsf{L}} = \varepsilon \Gamma \big(n_N - n_N^{\mathrm{eq}} \big) - n_{\mathsf{L}} \frac{n_{\mathsf{L}}^{\mathrm{eq}}}{n_\ell} \Gamma - 2 n_{\mathsf{L}} n_N \langle \sigma v \rangle_1 - 4 n_{\mathsf{L}} n_\Phi^{\mathrm{eq}} \langle \sigma v \rangle_2$$

transport coefficients

we adopted the rates & cross sections from Buchmuller, Di Bari, & Plumacher's Leptogenesis for Pedestrians (hep-ph/0401240)

thermal environment

we suppose that CGPP creates a plasma of SM particles with

$$T_e \approx H_e / 2\pi g_*^{1/4}$$

at the end of inflation

take away

scattering & inverse decay are negligible across the viable parameter space (i.e., the white triangle)

Evolution of densities via Boltzmann eqns

Boltzmann equations

$$\frac{\mathrm{d}}{\mathrm{d}t}n_N + 3Hn_N = -(n_N - n_N^{\mathrm{eq}})\left[\Gamma + 2\,n_\gamma^{\mathrm{eq}}\,\langle\sigma v\rangle_1\right]$$

$$\frac{\mathrm{d}}{\mathrm{d}t}n_{\mathsf{L}} + 3Hn_{\mathsf{L}} = \varepsilon\Gamma\left(n_N - n_N^{\mathrm{eq}}\right) - n_{\mathsf{L}}\frac{n_{\mathsf{L}}^{\mathrm{eq}}}{n_\ell}\Gamma - 2n_{\mathsf{L}}n_N\langle\sigma v\rangle_1 - 4n_{\mathsf{L}}n_\Phi^{\mathrm{eq}}\langle\sigma v\rangle_2$$

across the viable parameter space:
inv. decays & washout = negligible