The bearable inhomogeneity of the baryon asymmetry

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Based on [arXiv: 2505.15904] with

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Baryon Asymmetry of Universe

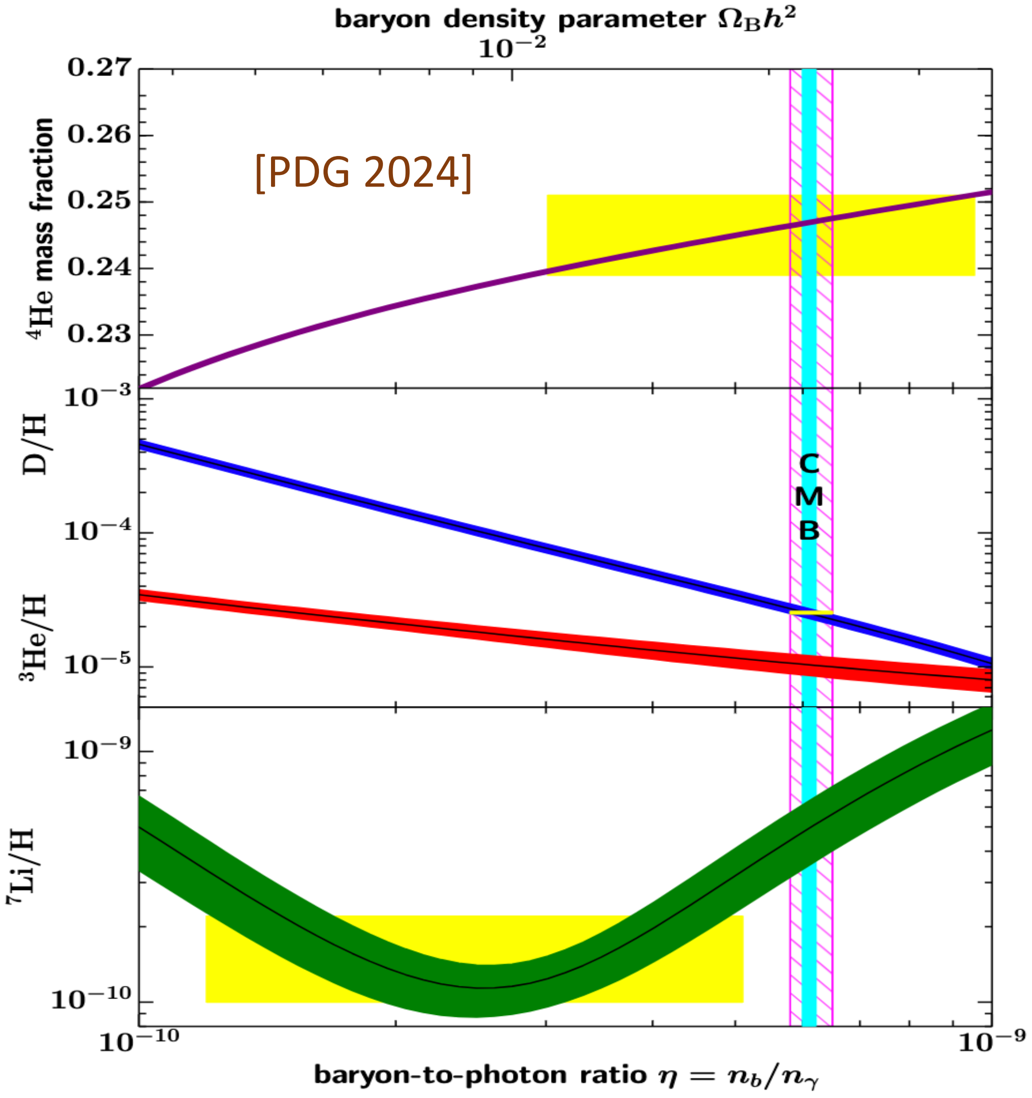
- From CMB:

$$\Omega_B\, h^2 = \; 0.02237 \; \pm \; 0.00012$$

- From BBN: Abundance of light elements depends on $\eta = \frac{n_B}{n_\gamma}$

$$\frac{n_B}{n_\gamma} \approx (6.04 \pm 0.2){\times}10^{-10}$$

- Most precise BBN determination from (D/H)



The idea

- The abundances of light elements at the end of BBN, at a given position x depends on the local value of $\eta(x)$
- The dependence on $\eta(x)$ is in general nonlinear
- For the average abundance, the linear variation drops out, sensitive to non-linear corrections
- $O(1\%)$ precison in D/H, in good agreement with CMB determination
- Expect bounding inhomogeneities at BBN to $O(10\%)$

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- Question: How early can the inhomogeneities be produced such that they can be probed by BBN? (in radiation domination)

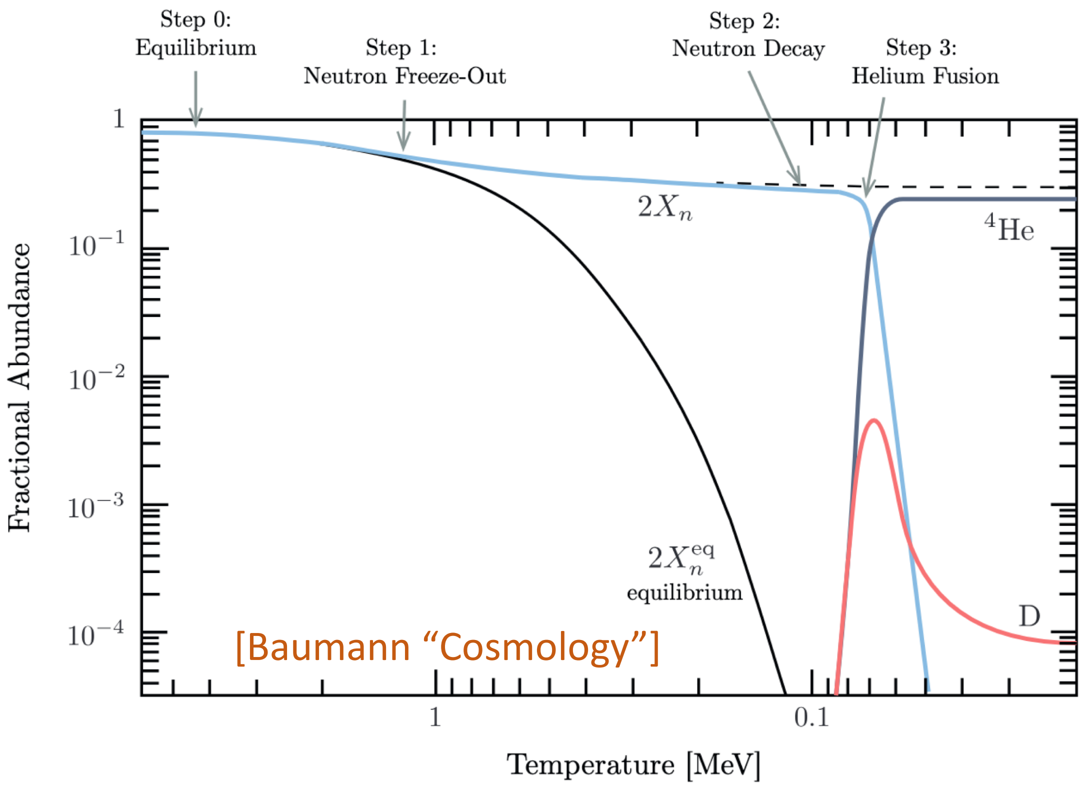
✓Inhomogeneities with comoving length scale larger than the Hubble length at $T \sim 3\ \mathrm{TeV}$ survive until BBN

Not erased by diffusion until BBN if at such length scales even if produced at $T \lesssim O(\mathrm{TeV})$

Outline

- Quick review of BBN
- Baryon diffusion
- The bearable inhomogeneity at BBN
- What can we probe?
  - ➢ Inhomogeneities from baryogenesis
  - ➢ Other scenarios and correlation with gravitational waves

Quick review of BBN



- Neutrons and protons in chemical equilibrium for $T \gtrsim$ MeV

$$n + \nu_e \leftrightarrow p + e$$

Until neutrino decoupling at $T_\nu \approx 0.8$ MeV, $\quad X_n^{\rm eq} \approx 1/6$

- After T_ν, neutron decay is the only relevant process
- Until deuterium starts to build up $\quad n + p \leftrightarrow D + \gamma$
- $B_D = 2.2$ MeV, but as η is small, D abundance becomes sizeable only when $T \lesssim \frac{B_D}{\ln(\eta^{-1})} \sim 60$ keV

$$X_n \approx 1/8 \qquad \text{at} \quad t \sim 330\, s$$

Quick review of BBN

Neutron fraction at the onset of BBN, $T_{\rm BBN} \simeq 60$ keV:

$$X_n \approx 1/8 \qquad \text{at} \quad t \sim 330\, s$$

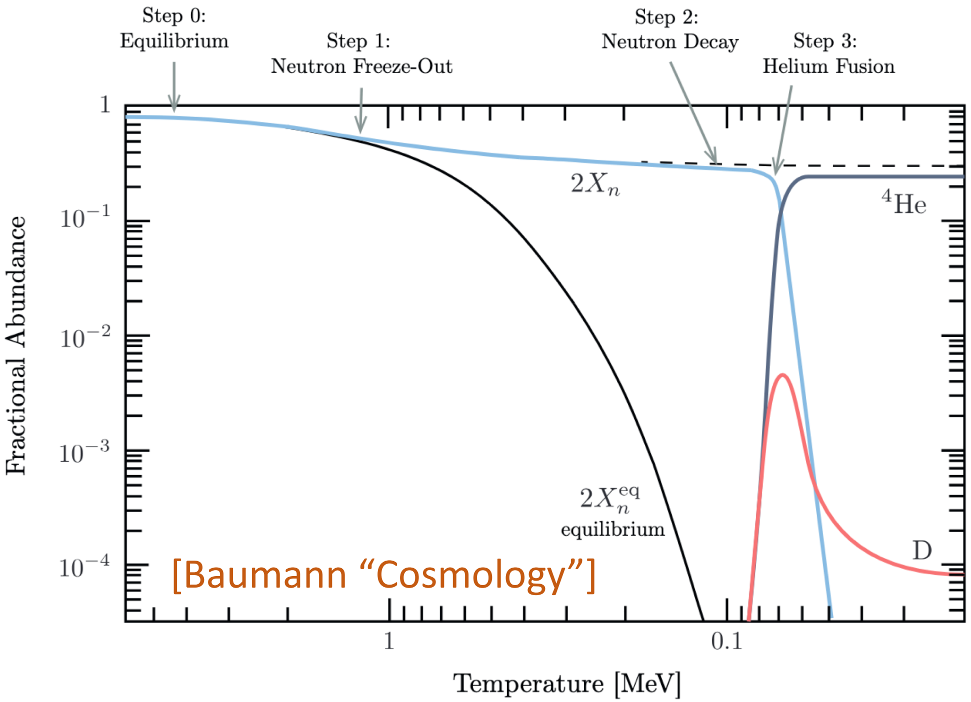
^{4}He is the most bound among the light nuclei

Almost all neutrons end up in ^{4}He

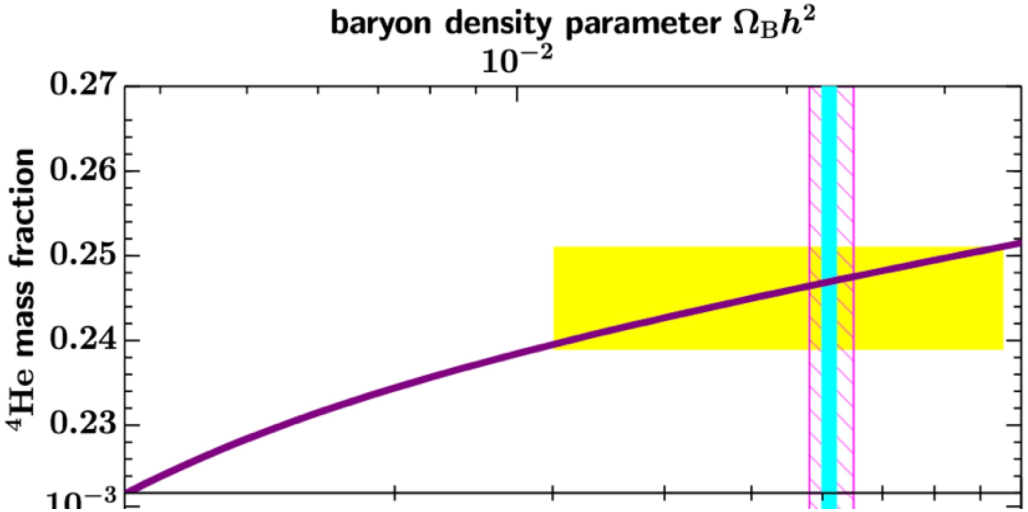
Helium mass fraction: $$\frac{4\, n_{^4\rm He}}{n_H} \approx 4 \frac{\tfrac{1}{2} X_n}{1 - X_n} \approx \frac{1}{4}$$

A sensitive probe of the expansion rate and therefore $N_{\rm eff}$

But only logarithmically sensitive to η



[Baumann "Cosmology"]



Quick review of BBN- Deuterium freeze out

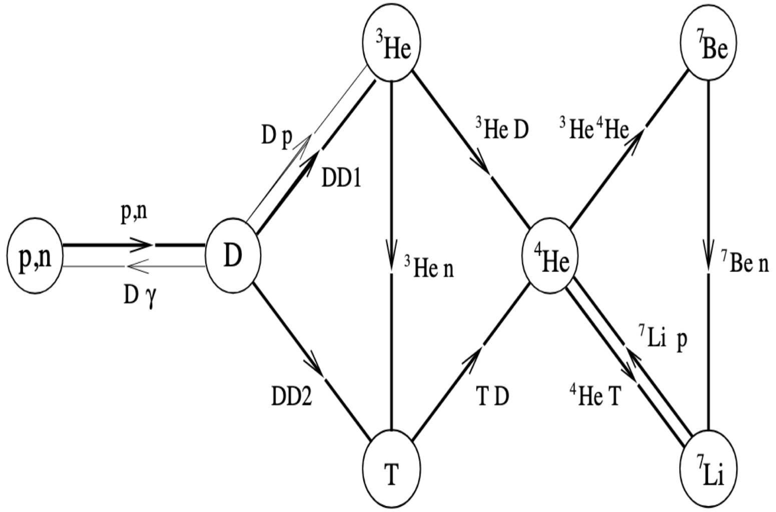
Mukhanov 2002

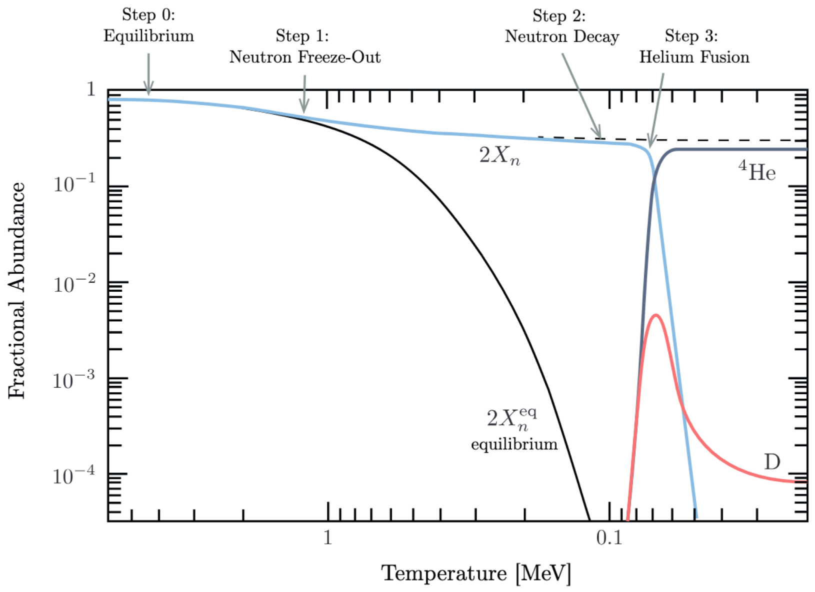
- Deuterium consumed mainly through processes:

$$D + D \rightarrow {}^3He + n \qquad D + D \rightarrow T + p$$
$$D + p \rightarrow {}^3He + \gamma$$

At the time of D freeze-out:

- If DD rates would dominate, the final D abundance would be independent of n_p $(\eta \ll 10^{-9})$
- If the Dp rate would dominate, the final D abundance would be exponentially sensitive to n_p (and therefore η) $(\eta \gg 10^{-9})$
- DD processes have larger cross sections but larger n_p makes the rates *comparable* at the time of D freeze out (for observed η)
- This makes deuterium sensitive to η and inhomogeneities





Diffusion

$$\partial_t n = D\nabla^2 n \qquad\qquad d \sim \sqrt{D\,t}$$

- Diffusion dominated by late time dynamics
  - Smaller T, smaller interaction rate, larger diffusion coefficient
  - Longer time $H \sim T^2/M_{\rm Pl}$

For example, consider particles strongly coupled to the plasma, so that $D \sim 1/T$

- Diffusion length during one e-fold of expansion: $\Delta d \sim \sqrt{D\,t} \sim \sqrt{D/H} \propto \sqrt{M_{\rm Pl}/T^3}$

  Note: $\Delta d/l_H = \Delta d\, H \sim \sqrt{T/M_{\rm Pl}} \ll 1$

- Diffusion is slow, homogenization happens on scales well with horizon only

Baryon Diffusion

See also Applegate, Hogan & Scherrer, 1987

- Diffusion generically dominated by late time dynamics: early diffusion of baryon number (carried by quarks) negligible compared to later diffusion of protons and neutrons
- Until neutrino decoupling T_ν, neutrons and protons in chemical equilibrium: a nucleon diffuses dominantly during the time it spends as a neutron
  - Dominant process: neutron-electron scattering via neutron magnetic moment

$$\sigma_{ne} \sim \frac{\alpha^2 \kappa^2}{m_n^2} \qquad D_{ne} \sim \frac{m_n^2}{\alpha^2 n_e}$$

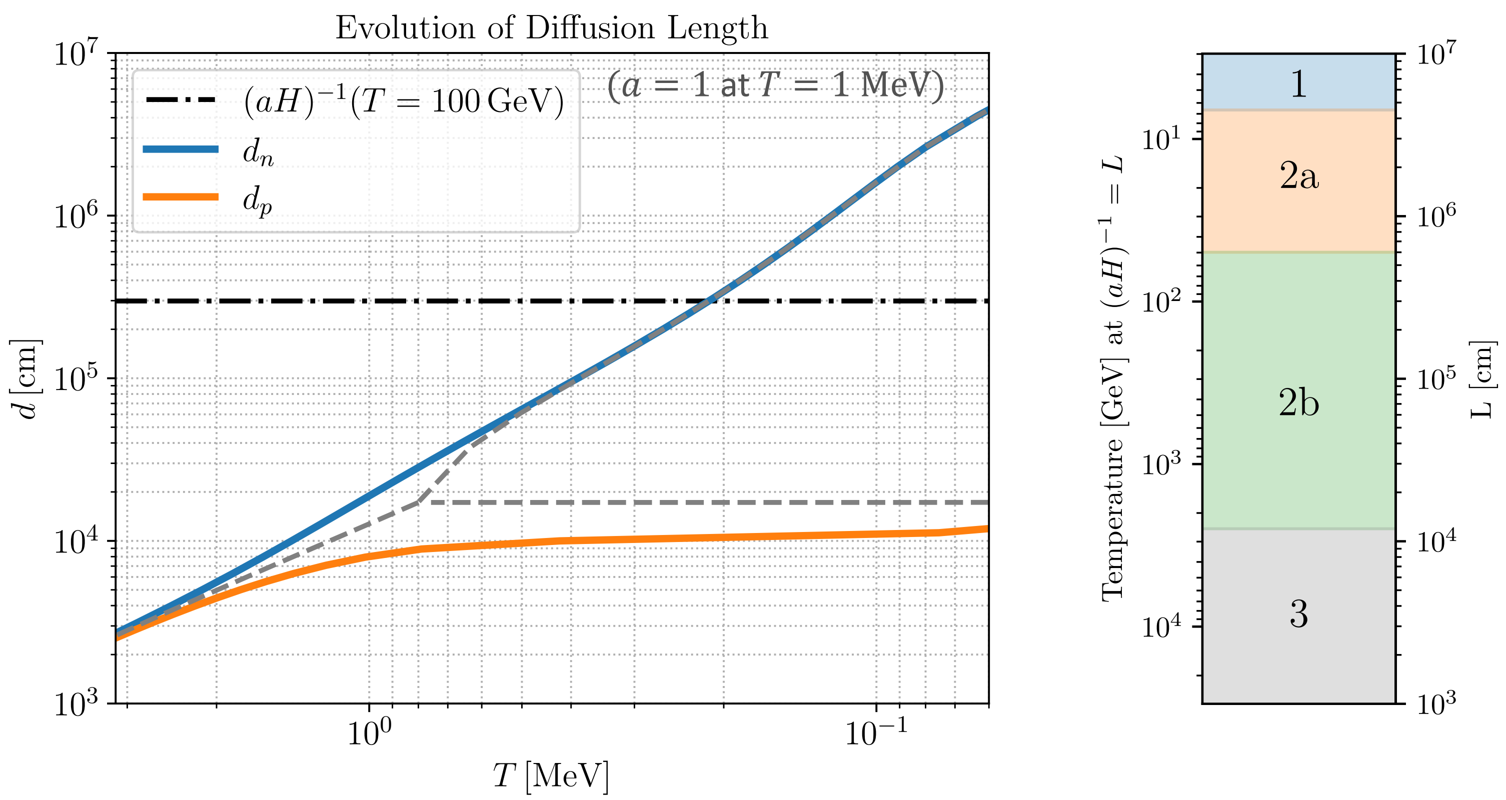
- After T_ν, effectively negligible diffusion of protons until BBN
- Can estimate proton diffusion length by that of the neutron at T_ν:

$$d_{\rm p} \sim \left[\sqrt{D_n/H}\,\right]_{T_\nu} \sim \sqrt{\frac{m_n^2 M_{\rm Pl}}{\alpha^2 n_e T_\nu^2}} \sim \sqrt{\frac{m_n^2 M_{\rm Pl}}{\alpha^2 T_\nu^5}}$$

- Neutrons continue to diffuse until BBN: $(d_{\rm n}/d_p)_{\rm BBN} \gg 1$
- Late time n diffusion controlled dominantly by $n\ p$ scattering

Baryon Diffusion

See also Applegate, Hogan & Scherrer, 1987

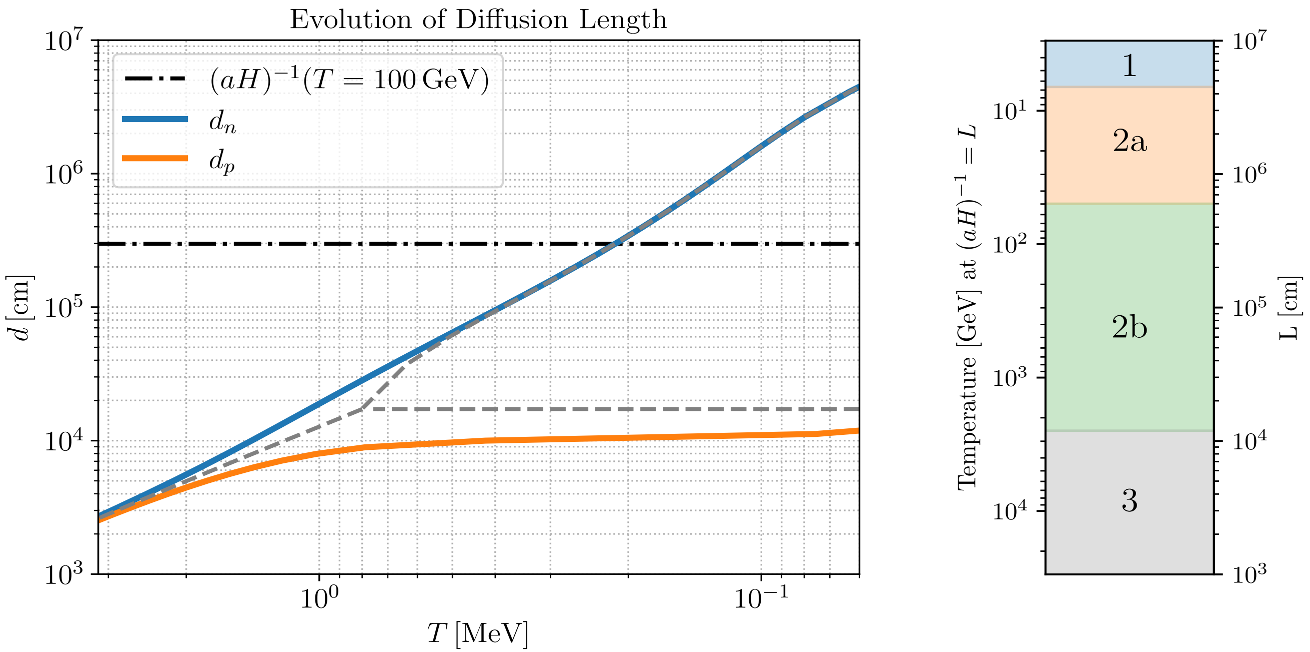


- To obtain the precise diffusion lengths we solve the coupled diffusion/ Boltzmann equations

  Comoving d_p at the onset of BBN = comoving Hubble length at $T \approx 3$ TeV

  Comoving d_n at the onset of BBN = comoving Hubble length at $T \approx 7$ GeV

Baryon Diffusion: Lengths scales and regimes for BBN



- (1) $L \gg d_n$ inhomogeneities in both neutrons and protons $n_p(x) \propto n_n(x) \propto \eta(x)$
- (2) $d_p \ll L \ll d_n$ neutrons homogenize by BBN but protons stay inhomogeneous:
  - (2a) $D_n\, L^{-2} \ll \langle \sigma_{np\to D\gamma} v \rangle n_p$ neutron diffusion during BBN can be ignored
  - (2b) $D_n\, L^{-2} \gg \langle \sigma_{np\to D\gamma} v \rangle n_p$ fast neutron diffusion during BBN keeps neutrons homogeneous
- (3) $L \ll d_p$ Baryon inhomogeneities are erased by BBN

The tolerable inhomogeneities at BBN

See also Inomata, Kawasaki, Kusenko & Yang 2018
Barrow & Scherrer 2018

Regime (1): $L > d_n$ (= comoving Hubble length at $T \approx 7$ GeV)

- Correlated inhomogeneities in $n_p(x) \propto n_n(x) \propto \eta(x)$
- Parameterize $\eta(x) = \eta_{\mathrm{CMB}}(1 + \epsilon(x))$ with $\langle \epsilon \rangle = 0$
- At each point: $D/H \propto (1+\epsilon)^{-1.67}$

$$\langle D \rangle / \langle H \rangle \propto \langle (1+\epsilon)^{-0.67} \rangle \approx 1 + 0.56\,\langle \epsilon^2 \rangle$$

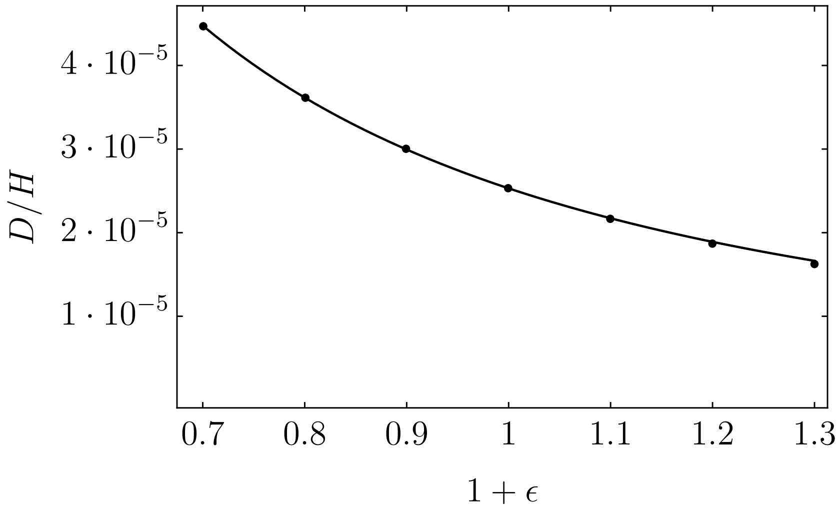
Overproduction of Deuterium compared to homogeneous BBN

Bound: $\epsilon_{RMS} = \sqrt{\langle \epsilon^2 \rangle} < 0.28$

Using CMB to determine η as input, homogeneous BBN predicts

$$D/H = (2.53 \pm 0.1) \times 10^{-5} \qquad \text{(4\% accuracy)}$$

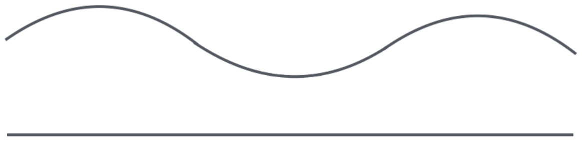
- Uncertainty dominated by nuclear reaction rates
- Observed $D/H = (2.55 \pm 0.003) \times 10^{-5}$ (1% precision)



Obtained using PRyMordial BBN code, varying η

The tolerable inhomogeneities at BBN

Regime (2a): $d_p < L_* < L < d_n$



Neutrons homogenized before BBN but $n_p(x)$ stays inhomogeneous

- Parameterize initially $\eta_i(x) = \eta_{\text{CMB}}(1 + \epsilon(x))$
- At the beginning of BBN

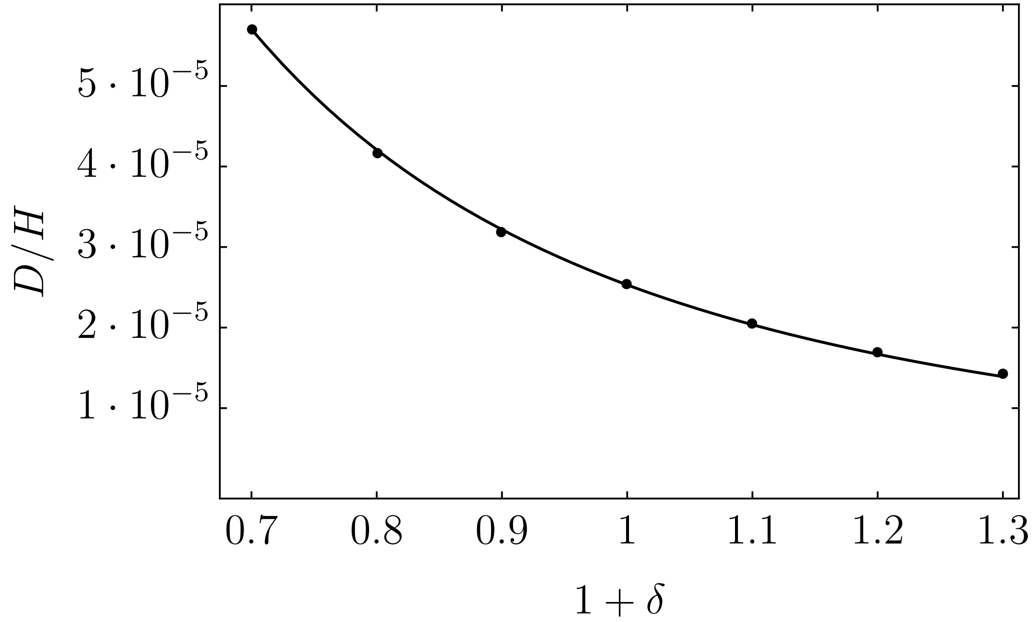
$$n_p(x) \propto (1 + \epsilon(x)),$$

$$\eta(x) = \eta_{\text{CMB}}\big(1 + \delta(x)\big) \qquad \delta \equiv \frac{\epsilon}{1+X_n(T_{\text{BBN}})}$$

- At each point: $D/H \propto (1+\delta)^{-2.3}$

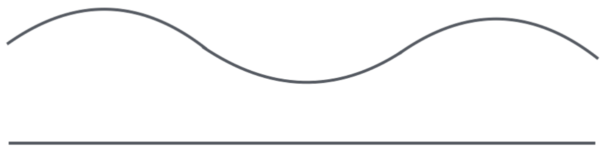
Bound: $\epsilon_{RMS} < 0.19$

Stronger bound since n_p is more inhomogeneous after ^4He formation



Obtained using PRyMordial BBN code, varying η , X_n, X_p (correlated)

The tolerable inhomogeneities at BBN



Regime (2b): $d_p < L < L_* < d_n$

- Neutrons homogenized before BBN but $n_p(x)$ stays inhomogeneous
- Higher rate of neutron consumption in the more proton-rich regions
- Neutron diffusion during BBN is efficient, keeps neutrons homogenous by transferring neutrons to the more proton-rich regions
- Parameterize initially $\eta_i(x) = \eta_{\mathrm{CMB}}(1 + \epsilon(x))$
- We fin that after helium formation, proton profile same as in regime (1), with initial $n_p(x) \propto n_n(x) \propto \eta(x)$ and no diffusion!

$$n_p(x) \propto (1 + \epsilon(x))$$

- Same bound as regime 1 with $L > d_n$

$$\epsilon_{RMS} < 0.28$$

Pointed out (but not studied) in Inomata, Kawasaki, Kusenko & Yang 2018

Prospects and limitations

- Currently observed D/H= $(2.55 \pm 0.003)\times10^{-5}$ (1% precision)
- Using CMB to determine η as input, homogeneous BBN predicts

$$D/H = (2.53 \pm 0.1)\times10^{-5}$$ (4% accuracy)

- Uncertainty dominated by nuclear reaction rates
- Most importantly: DD annihilation and Dp coannihilation rates
- Recent improvement, in 2020, in the measurements of Dp rates by LUNA
- Sizeable improvements expected in determination of η from CMB (Simons observatory and S4) and in D/H measurement (see e.g. [2409.06015])

$$D + D \to T + p$$
$$D + D \to {}^3He + n$$
$$D + p \to {}^3He + \gamma$$

What scenarios can we probe?

Scenarios of baryogenesis that produce large inhomogeneities

- Mesogenesis with SM CP Violation [Elor Houtz Ipek Ulloa 2024] $(\epsilon_{RMS} \sim 1, \ \mathrm{L} \gg \mathrm{d_p})$
- Electroweak Baryogenesis with domain walls [Azzla Matsedonskyi Weiler2024]
- Electroweak baryogenesis if slow enough ($\beta/H \lesssim O(10)$) $(\epsilon_{RMS} \gtrsim O(0.1), \ L \sim d_p)$

Scenarios that imprint inhomogeneities on a previously generated baryon asymmetry

Strong EW phase transition ($\beta/H \lesssim O(10)$)

Phase transitions proposed to explain the Pulsar Timing Array signal

Generic correlation with gravitational wave signals (from pHz to mHz frequency)

Primordial isocurvature perturbations (from inflation)

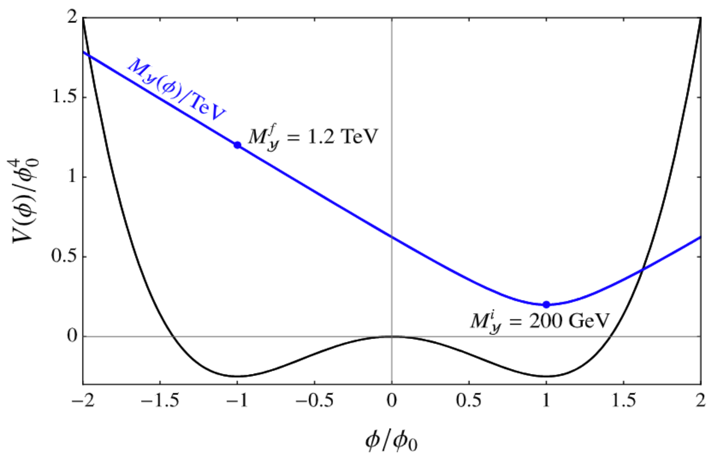
What scenarios can we probe?

The SM CP violation is enough(?)

[Elor Houtz Ipek Ulloa 2024]

- A recent attempt for baryogenesis using the CP violation of only the SM
- CP violation in B meson oscillations
- B violation: B mesons decay to a particle in the dark sector and a baryon (total baryon number conserved but B violation in the visible sector)
- The collider bounds limit the branching fractions (today) below what is needed to reproduce the observed baryon asymmetry
- To enhance it at early times: Considered changing the mass of the particle mediating the decay in some domains and not the others

  Domain wall network persisting until $T \sim 10$ MeV
- Considerable baryon asymmetry generated in only some domains
- $O(1)$ inhomogeneities with comoving length scale larger than both neutron and proton diffusion lengths



What scenarios can we probe?

Electroweak baryogenesis

Deserves a dedicated study, only estimates here

- Production of the baryon asymmetry takes a time of order β^{-1}
- Temperature changes during this time $\frac{\Delta T}{T} \simeq H/\beta$
- Baryon symmetry produced at different points depends on T, expect $\epsilon \propto \frac{\Delta T}{T} \simeq H/\beta$
- The precise amplitude of inhomogeneities generally depends on the model/parameters, e.g much more sensitive if $\langle h \rangle/T$ near 1
- Characteristic length scale: typical bubble separation $L \sim v_w \, \beta^{-1}$
- $L_{\text{comoving}} > d_p$ corresponds to $\beta/H \lesssim 30$
- Sensitivity drops quickly for larger β/H (smaller L)

What scenarios can we probe?

Strong first order phase transitions

Consider a supercooled PT with $\alpha \gtrsim 1$

- Phase transition starts at different times at different points, same for reheating after the PT
- Temperature variation of of size $\Delta T/T \sim H/\beta$ (Needs a dedicated study, only estimates here)
- Variations in the baryon-to-photon ratio $\Delta\eta/\eta \simeq 3\,\Delta T/T$
- T fluctuations damp, but $\Delta\eta/\eta$ survive when the oscillations are underdamped
- This is the case unless PT close to the MeV scale: near neutrino decoupling, heat transfer very efficient, oscillation of sound waves are overdamped and the induced inhomogeneity in η suppressed
- Sensitive to PTs with $\beta/H \lesssim O(10)$, relevant to both EW PT and PTs at $T \sim 100\ \mathrm{MeV}$ proposed to explain the PTA signal if the energy transferred to the visible sector (see [NANOGrav 2306.16219])
- If energy transferred to dark sector radiation only, in conflict with N_{eff}

Summary and Conclusions

- Novel bounds on the inhomogeneities in the baryon asymmetry at BBN
- Baryon diffusion leaves inhomogeneities with length scale larger than comoving Hubble length at a few TeV
- Can probe inhomogeneities produced as early as the electroweak scale
- Complementary to gravitational wave searches
- Improvements in measurements of D/H and CMB determination of η expected
- Currently precision limited by the nuclear reaction rates, (how much) future improvement possible?

Thank you!

Extra Slides

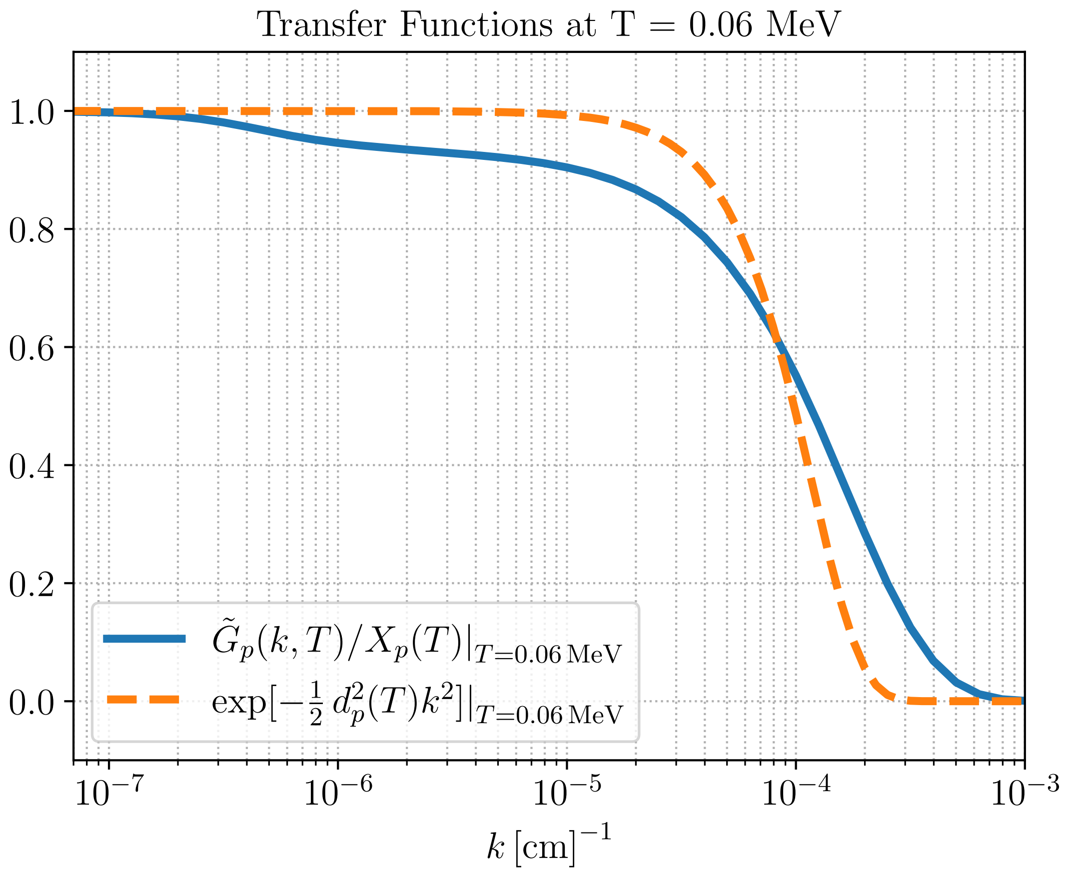
Baryon Diffusion: transfer function

- To obtain the precise diffusion lengths and transfer functions need to solve the coupled diffusion/ Boltzmann equations

- If not coupled, transfer function is simply a Gaussian

$$\tilde{n}(k,t) \; = \; e^{-\frac{1}{2}\left(d_p(t)\,k\right)^2}\tilde{n}(k,0)$$

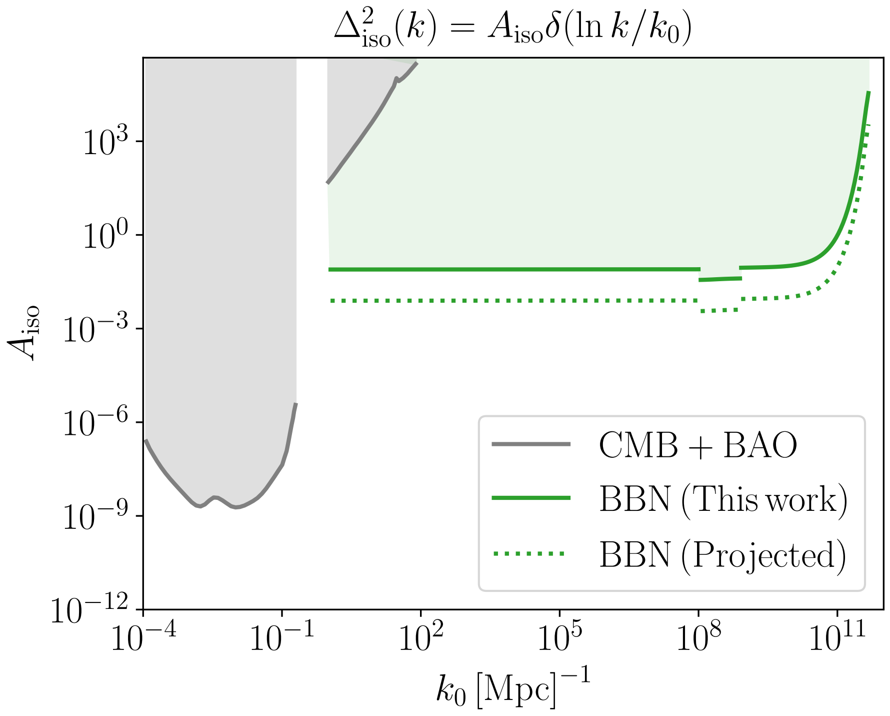
- For protons, deviates from a Gaussian, less washout of inhomogeneities at smaller distances
- The inhomogeneities are suppressed by a factor of 10 for k =comoving Hubble scale at 10 TeV

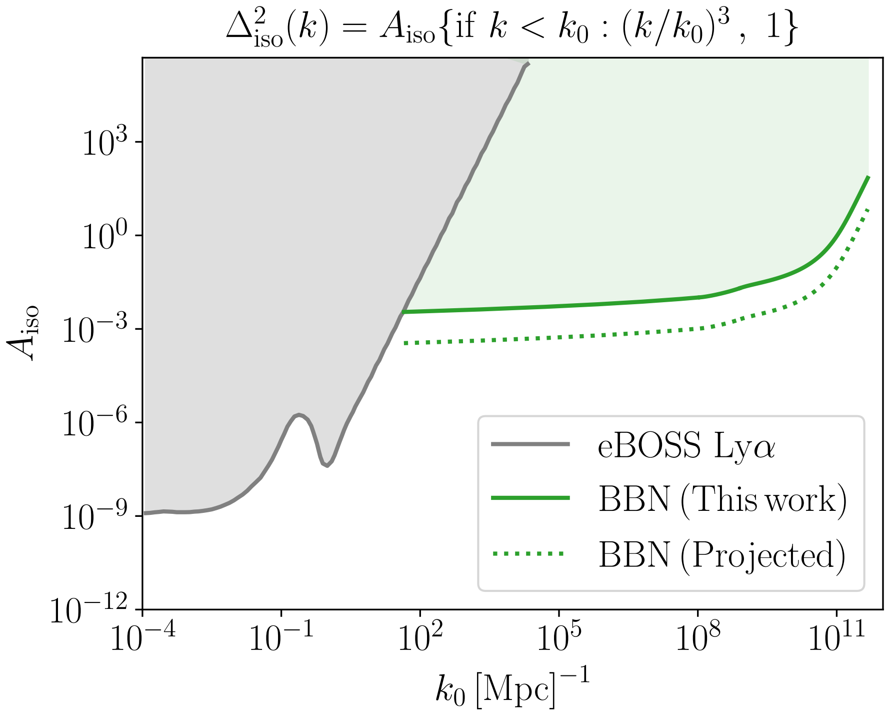


Bounds on baryon inhomogeneities (isocurvature)

Strong bounds from CMB and at large scales

Our BBN constraints dominate for smaller length scales, up to comoving horizon scale at $T \lesssim 10$ TeV





What scenarios can we probe?

Electroweak baryogenesis

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- Temperature changes during this time $\frac{\Delta T}{T} \simeq H/\beta$
- Baryon symmetry produced at different points depends on T, expect $\epsilon \propto \frac{\Delta T}{T} \simeq H/\beta$
- In general depends on the model/parameters:
- As example consider a case where $\frac{v_c}{T_c} \lesssim 1$ inside the bubble so that the washout by sphalerons is not negligible, then exponentially sensitive: $\frac{\Delta\Gamma_{\rm sph}}{\Gamma_{\rm sph}} \simeq e^{-\Delta\left(\frac{E_{sph}}{T}\right)} \sim e^{\frac{2g}{\alpha_w}\Delta(v/T)}$
- 3% change in v/T near $\frac{v_c}{T_c}$ ≈1 during the PT changes $\Gamma_{\rm sph}$ by a factor of e, can lead to $\epsilon \sim O(1)$ even for $\frac{\beta}{H} \sim 30$

What scenarios can we probe?

Electroweak baryogenesis with domain walls

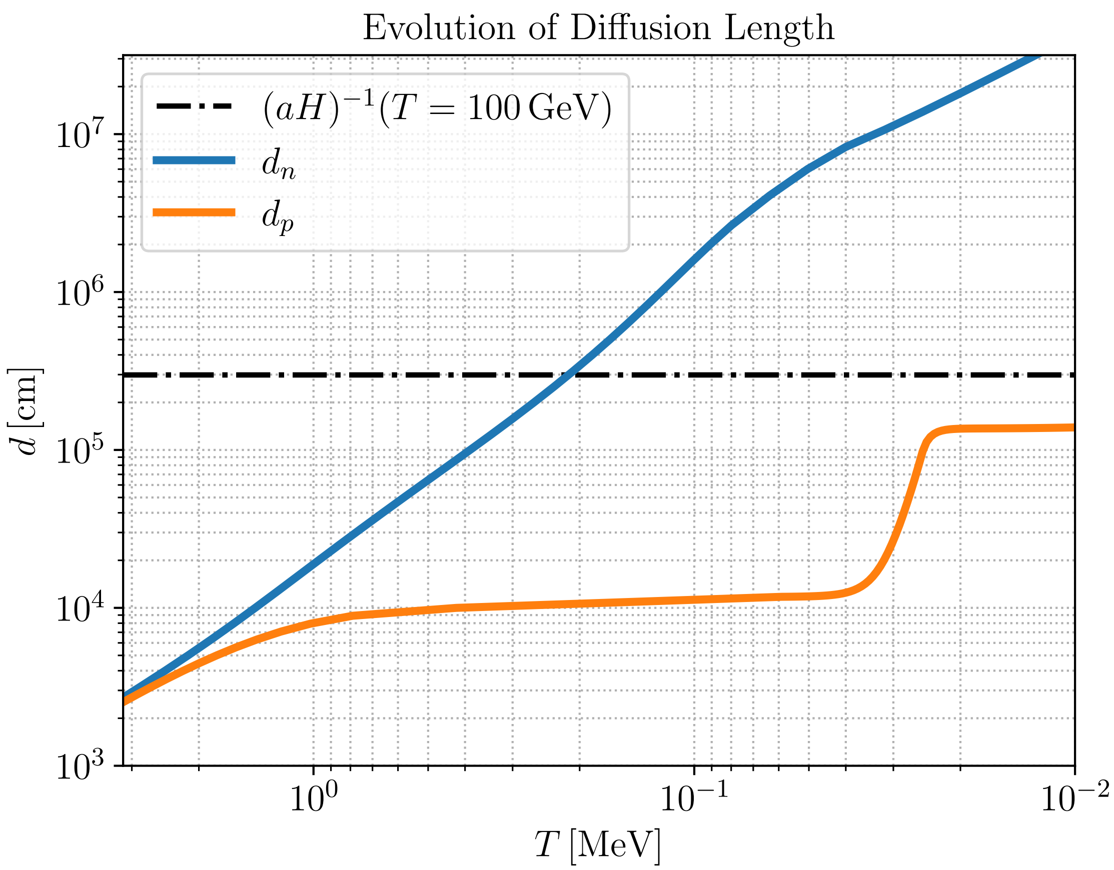
[Azzla Matsedonskyi Weiler2024]

- Scaling regime, few domains per Hubble at EW scale
- Inhomogeneities generated on large enough distances
- Why inhomogeneities?

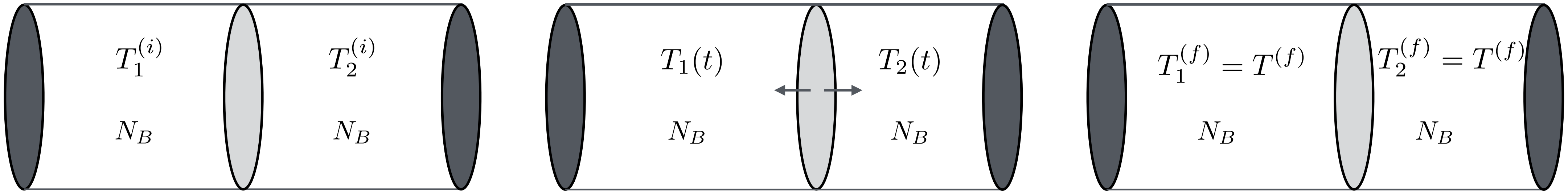
Baryons generated at domain wall, slowly moving through space

- Temperature changes while wall swipes through space , therefore number densities, velocity and sphaleron rate change

Proton diffusion during BBN



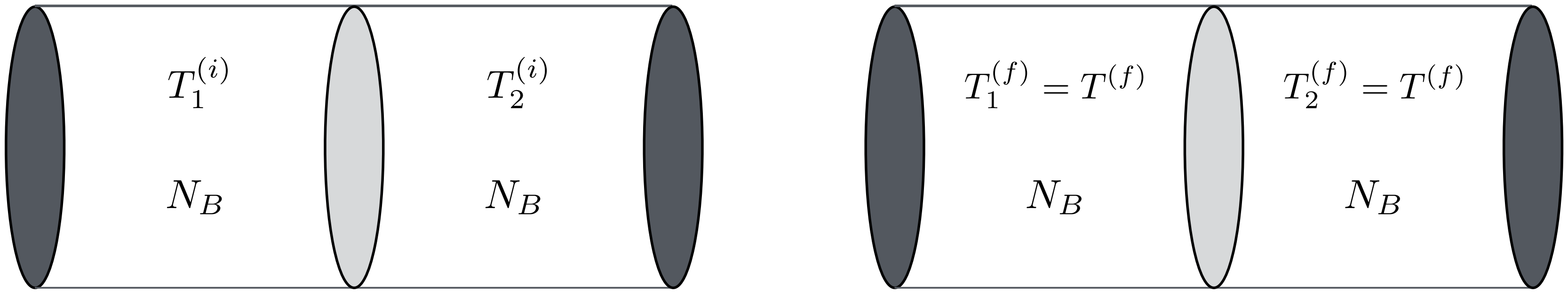
Toy model for evolution of T fluctuations Slow heat transfer



Neglect the pressure from baryons

- The fluctuations in T lead to fluctuations in volume and number densities
- The local volume/pressure oscillate around the equilibrium value (sound wave)
- Oscillation gradually damped due to viscosity (friction in the toy model) and heat transfer and the system relaxes with homogenized P and T
- At the "equilibrium" point the B density inhomogeneous

Toy model for evolution of T fluctuations efficient heat transfer



- The efficient heat transfer homogenizes T and P before considerable motion
- No final inhomogeneity induced in baryons

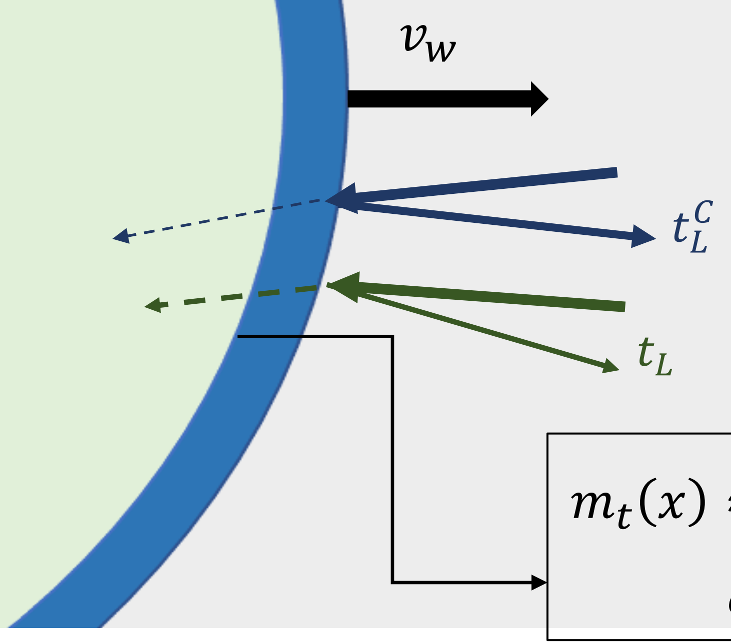
EW baryogenesis

$\langle h \rangle \neq 0$

- $\Gamma_{\text{sph}} \propto e^{-\frac{E_{sph}}{T}}, E_{\text{sph}} \sim \frac{2g\langle h \rangle}{\alpha_w}$
- $\Gamma_{\text{sph}} \lesssim H$
- $\frac{g\,\langle h \rangle}{T} \gtrsim \frac{\alpha_w}{2} \ln \frac{M_{Pl}}{T} \sim 0.6$
- $\langle h \rangle / T \gtrsim 1$, to avoid washout

$\langle h \rangle = 0$

- $\Gamma_{\text{sph}} \sim 20\, \alpha_w^5\, T \sim 10^{-6}\, T$
- $Y_B = Y_L \propto \frac{\delta_{\text{CP}}\, \alpha_w^5}{g_*}$



$$m_t(x) \approx \frac{y_t}{\sqrt{2}} h(x) e^{ib\,\eta(x)}$$
$$\delta_{\text{CP}} \sim b\Delta\eta$$

Diffusion

$$\partial_t n = D\nabla^2 n \qquad\qquad d \sim \sqrt{D\,t}$$

- Diffusion dominated by late time dynamics
  - ➢ Smaller T, smaller interaction rate, larger diffusion coefficient
  - ➢ Longer time $H \sim T^2/M_{\rm Pl}$

For example, consider particles strongly coupled to the plasma, so that $D \sim 1/T$

- ➢ Diffusion length during one e-fold of expansion: $\Delta d \sim \sqrt{D\,t} \sim \sqrt{D/H} \propto \sqrt{M_{\rm Pl}/T^3}$
- ➢ Contribution to comoving diffusion lengths: $\Delta d^2_{\rm comoving} \propto M_{\rm Pl}/T$

Also note: $\Delta d/l_H = \Delta d\ H \sim \sqrt{T/M_{\rm Pl}} \ll 1$

- Diffusion is slow, homogenization happens on scales well with horizon only