A late baryogenesis in an ekpyrotic-like universe with a hidden CP violation

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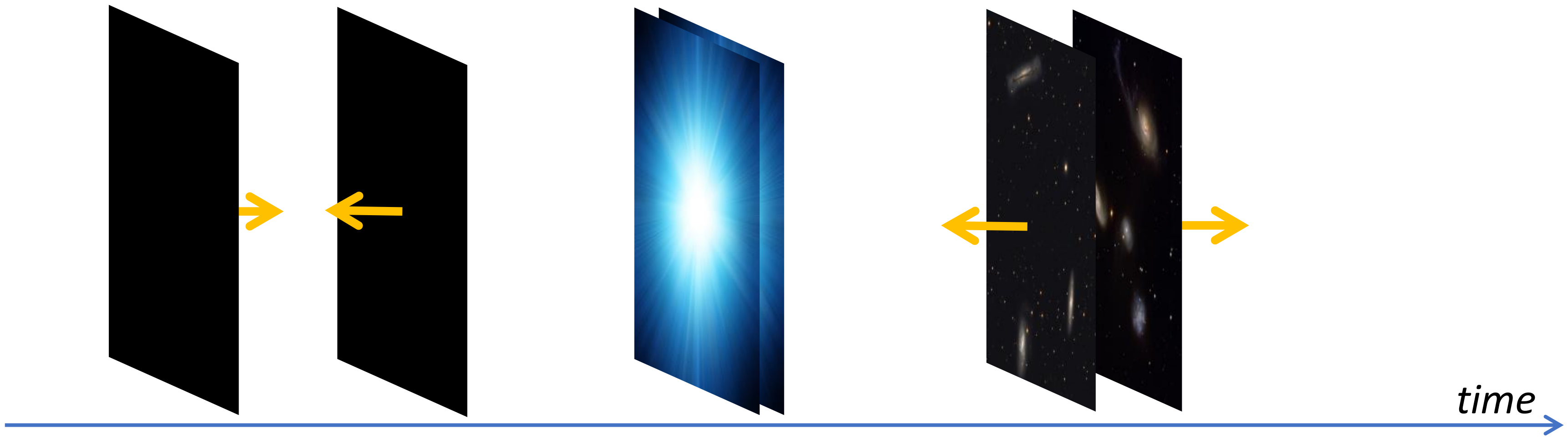
Big Bang as colliding braneworlds: Ekpyrotic-like scenarios

Our visible Universe: a 3D layer (3-brane) embedded in a N-dimensional hyperspace (N > 4)
an old and fruitful approach

V.A. Rubakov, M.E. Shaposhnikov, Physics Letters B 125 (1983) 136-138 ; J. Hughes, J. Liu and J. Polchinski, Physics Letters B 180 (1986) 370-374

The Big Bang triggered by the collision between two branes *(not necessarily the seminal string-inspired ekpyrotic approach)*



J. Khoury, B.A. Ovrut, P.J. Steinhardt, N. Turok, Phys. Rev. D64 (2001) 123522
J. Martin, P. Peter, N. Pinto-Neto & D. J. Schwarz, Phys. Rev. D 65, 123513 (2002)

$\rightarrow$ Can this allow to explain the baryogenesis?

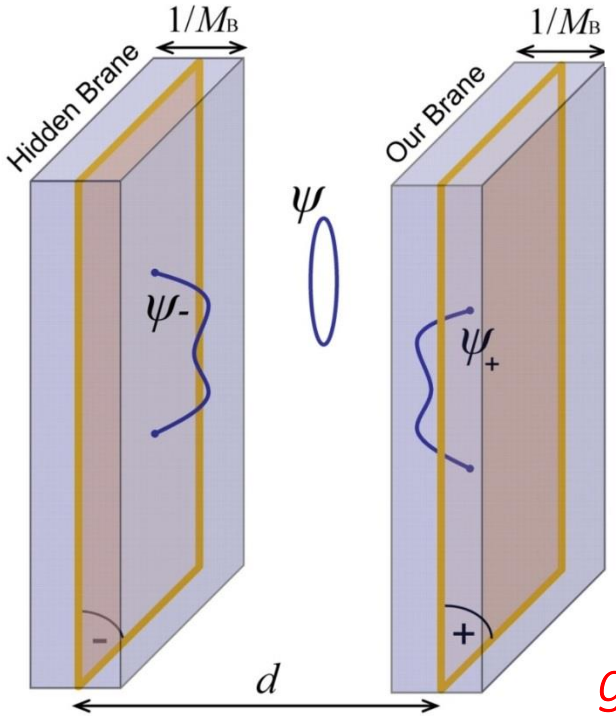
$\rightarrow$ Can we detect the hidden relic brane of the big bang?

Can matter exchange occur between braneworlds?

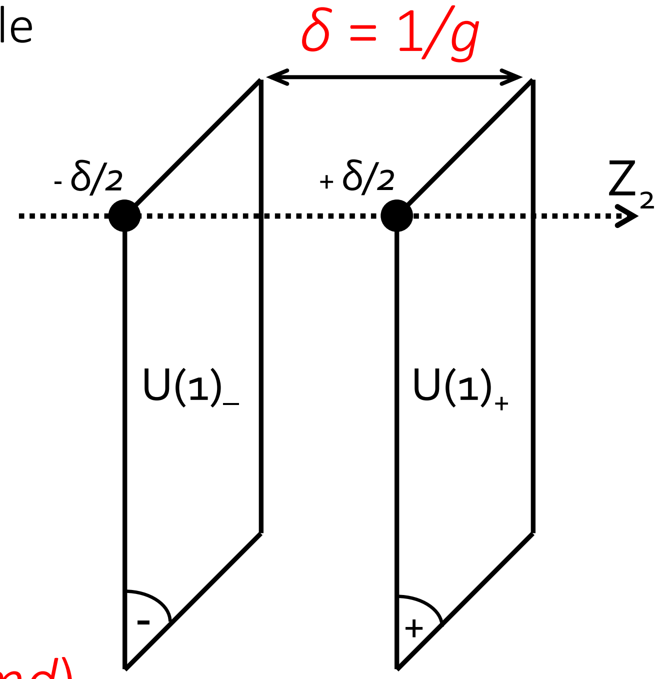
Conjecture *(M. Sarrazin, F. Petit, Acta Phys. Polon. B36 (2005) 1933-1950 ; F. Petit, M. Sarrazin, Phys. Lett. B 612 (2005) 105)*:

At low energy, the quantum dynamics of a fermion in a Universe with two 3-branes is the same as in a two-sheeted $M_4 \times Z_2$ spacetime in the formalism of the noncommutative geometry

Demonstrated for a domain-wall description and for a string-inspired description of a braneworld Universe
(M. Sarrazin, F. Petit, Phys. Rev. D 81 (2010) 035014 ; C. Stasser, M. Sarrazin, Int. J. Mod. Phys. A 34 (2019) 1950029)



M_B : Brane energy scale



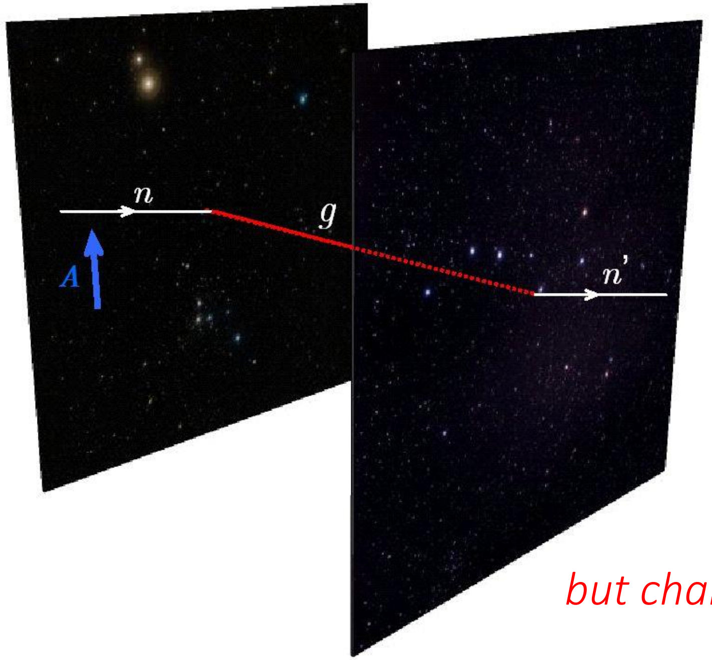
Neutron – hidden neutron coupling constant:

$$g \sim (m^2/M_B)\exp(-md)$$

$M_4 \times Z_2$ (Low-energy limit)

(m : Quark constituent mass ≈ 340 Mev)

Can matter exchange occur between braneworlds?



Fermion – hidden fermion geometrical mixing:

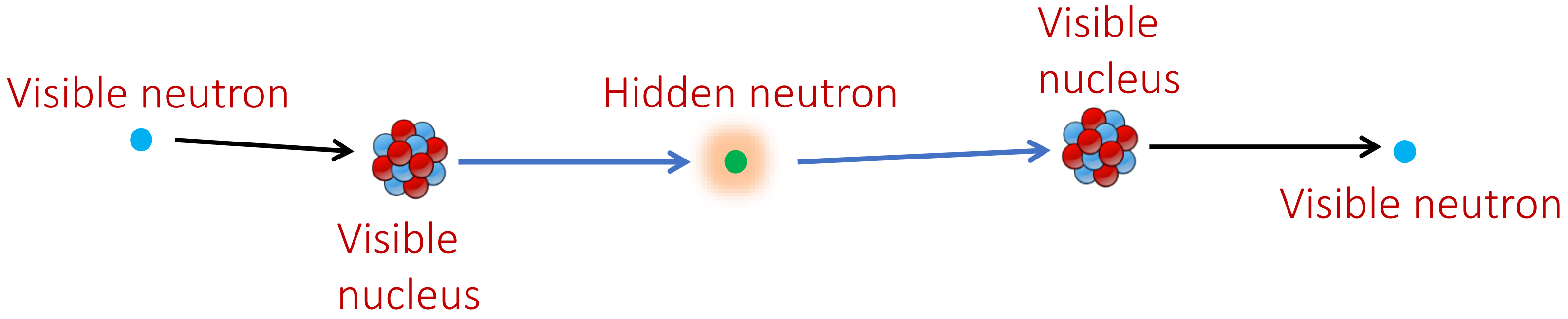
$$H = \begin{pmatrix} E_v & \varepsilon \\ \varepsilon & E_h \end{pmatrix}$$

≠ from neutron – mirror neutron mass mixing

- ✓ $\varepsilon = g\,\mu\,A$
- ✓ Diagonal terms → $\Delta E = E_v - E_h = V_+ - V_-$
  Gravitational contributions + Fermi potentials

allows neutron exchange between two branes: Our visible brane and a hidden one

but charged particles cannot swap between branes! *M. Sarrazin, F. Petit, Int. J. Mod. Phys. A22 (2007) 2629*



→ Neutron disappearance/reappearance toward/from a hidden brane can be tested with high-precision experiments

→ Need for a formalism of neutron - macroscopic matter interactions

Can matter exchange occur between braneworlds?

Neutrons' collisional dynamics with surrounding matter and out of thermal equilibrium from the Lindblad equation:

$$\partial_t \rho = i(\rho H^\dagger - H\rho) + \sum_s \Gamma_s \left(C_s \rho C_s^\dagger - \frac{1}{2}\{\rho, C_s^\dagger C_s\} \right)$$

→ Neutron transition rate from one brane to another one: $\gamma = \dfrac{\varepsilon^2 \Gamma}{\Delta E^2 + 4\varepsilon^2 + (\Gamma/2)^2}$

Total collisional rate for both branes: $\Gamma = \Gamma_+ + \Gamma_-$

→ Hidden neutron source $S_- = \dfrac{1}{2} p \Sigma_E \Phi_+$ Neutron flux in the reactor

Macroscopic cross section of materials of the reactor

with $p = \dfrac{2\varepsilon^2}{\Delta E^2 + 4\varepsilon^2 + (\Gamma/2)^2}$

→ Regenerated neutron source (from hidden neutrons) $S_+ = \dfrac{1}{2} p \Sigma_s \Phi_-$ Hidden neutron flux

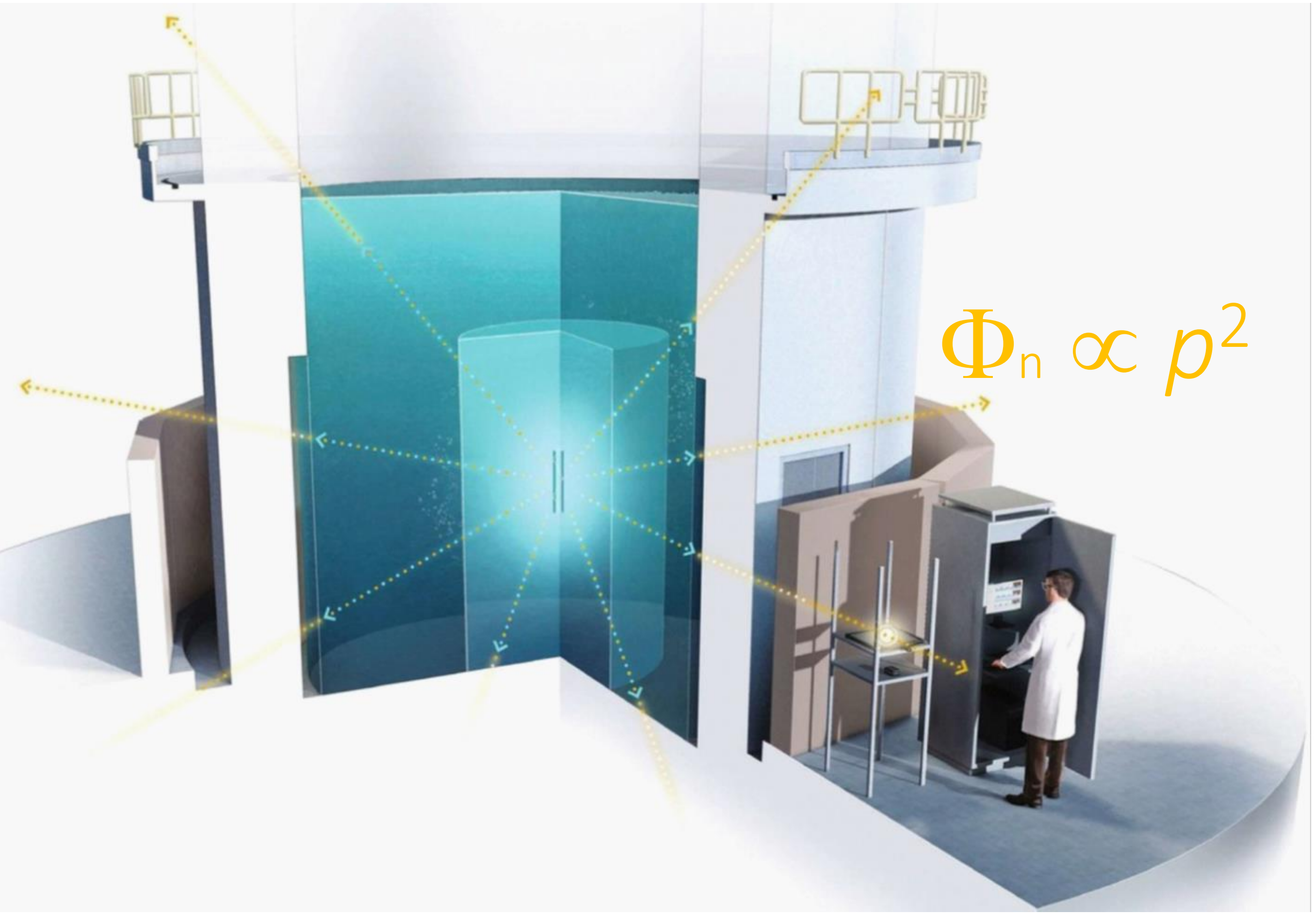
M. Sarrazin, G. Pignol, J. Lamblin, F. Petit, G. Terwagne, V. V. Nesvizhevsky, Phys. Rev. D 91 (2015) 075013

C. Stasser, et al., Eur. Phys. J. C 81, 17 (2021)

H. Almazán, et al., Phys. Rev. Lett. 128, 061801 (2022)

Passing-through-walls neutrons

Trying to detect neutrons bypassing the shielding of a reactor through a hidden brane.



$$\Phi_n \propto p^2$$

M. Sarrazin, G. Pignol, J. Lamblin, F. Petit, G. Terwagne, V. V. Nesvizhevsky, Phys. Rev. D 91 (2015) 075013

M. Sarrazin, et al., Phys. Lett. B758 (2016) 14-17

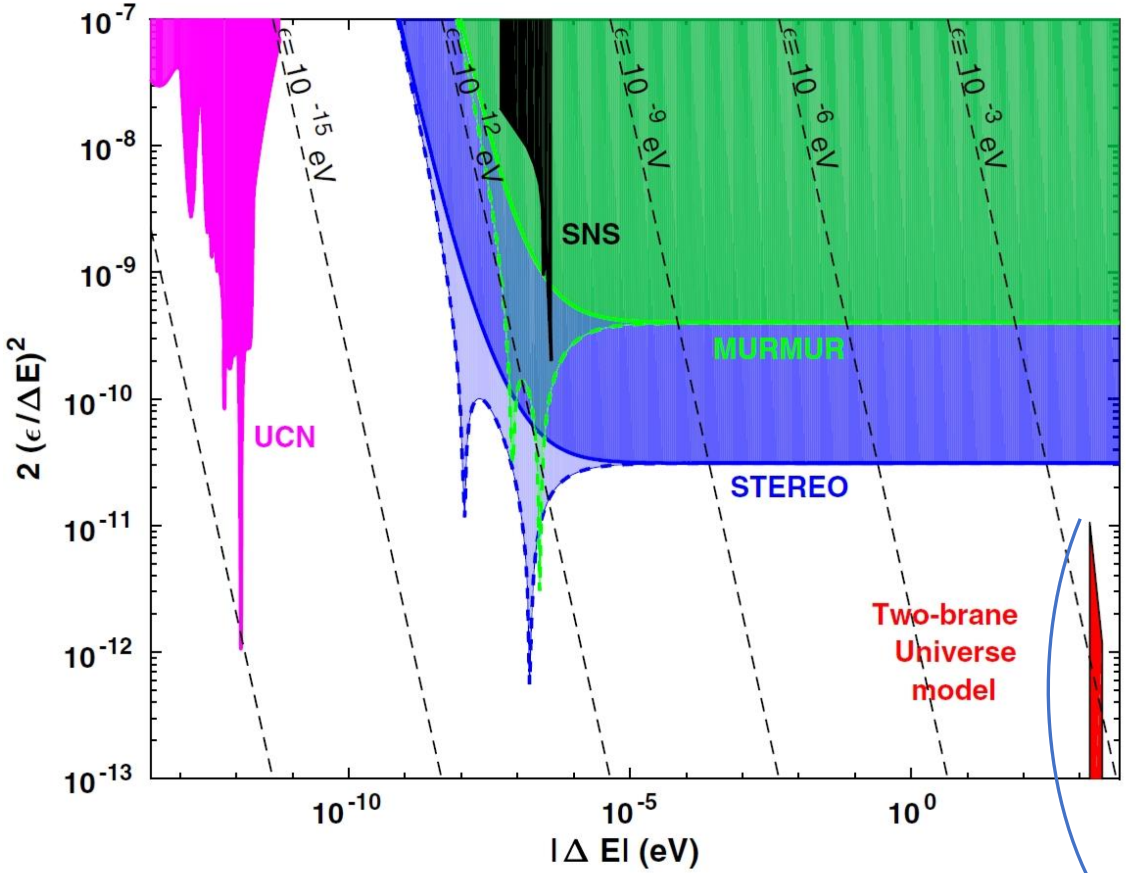
C. Stasser, et al., Eur. Phys. J. C 81, 17 (2021)

Serge Claisse

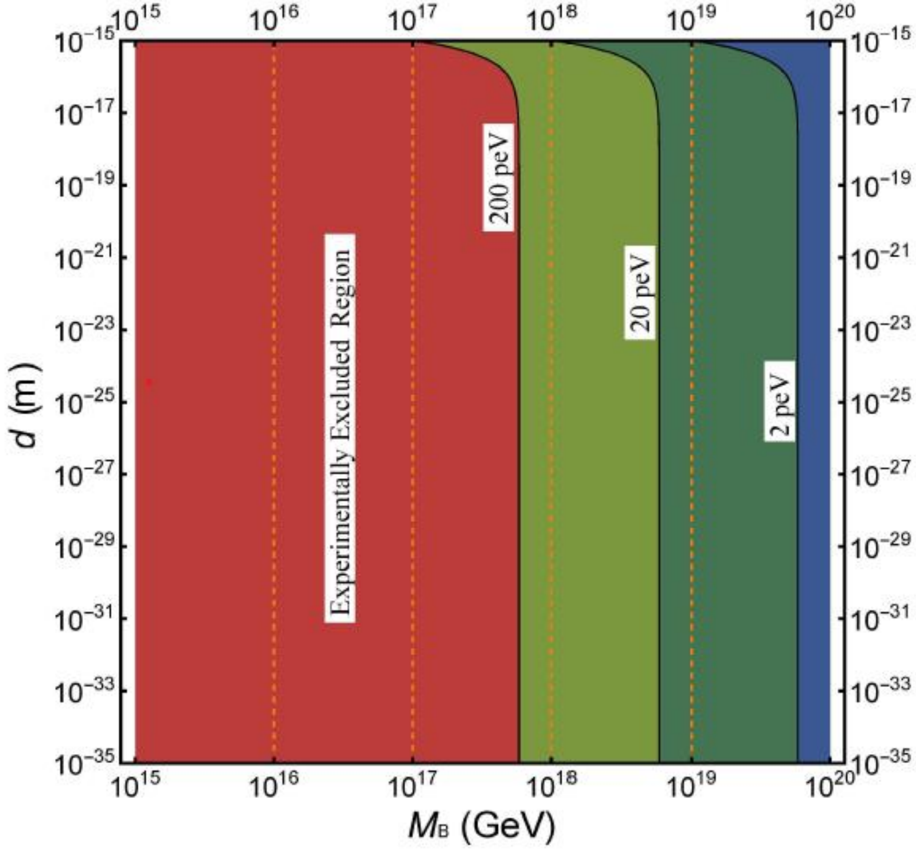
H. Almazán, et al., Phys. Rev. Lett. 128, 061801 (2022)

Passing-through-walls neutrons

Bounds on the coupling constant



Bounds on brane energy scale and interbrane distance



H. Almazán, et al., Phys. Rev. Lett. 128, 061801 (2022)

C. Stasser, et al., Eur. Phys. J. C 81, 17 (2021)

M. Sarrazin, et al., Phys.Lett. B758 (2016) 14-17

Experiments are not so far from the expected theoretical predictions

Matter exchange between braneworlds as a baryogenesis mechanism

The model allows:

- → Baryonic number violation
- → C/CP violation
- → Braneworlds not necessarily in thermal equilibrium

} Sakharov conditions

→ Reminiscent of models where visible and hidden sectors in our usual spacetime are not in thermal equilibrium

cf. Berezhiani et al. Phys. Lett. B503 (2001) 362-375, Int. J. Mod. Phys. A 19 (2004) 3775-3806

Matter exchange between braneworlds as a baryogenesis mechanism

The coupling between the neutron and the hidden neutron states is driven by:

$$g_n \widehat{\mu}_n = \sum_q g_q \widehat{\mu}_q$$

→ Summation on the dressed quark contents

with: $\widehat{\mu}_n = \sum_q \widehat{\mu}_q$

then: $g_n \approx g_{up} \approx g_{down}$ and $g = \dfrac{m^2}{M_B} e^{-md}$

- m → Quark constituent mass (dressed quark) ≈ 340 MeV
- d → Interbrane distance
- M_B → Brane energy scale

C. Stasser, M. Sarrazin, Int. J. Mod. Phys. A 34 (2019) 1950029

In the following, it is assumed that the distance between branes is such that: $g = \dfrac{m^2}{M_B}$

Matter exchange between braneworlds as a baryogenesis mechanism

What about the antineutron - hidden antineutron coupling?

Since: $$g_{\overline{n}}\widehat{\mu}_{\overline{n}} = \sum_q g_{\overline{q}}\widehat{\mu}_{\overline{q}}$$

One expects to (no C/CP violation): $g_{\overline{n}} \equiv g_n$ and $\mu_n \equiv \mu_{\bar{n}}$

but one could expect (C/CP violation): $g_{\overline{n}} \approx g_n$ or $\mu_n \approx \mu_{\bar{n}}$ (QCD origins?)

$\rightarrow$ The neutron - hidden neutron and antineutron - hidden antineutron swapping rates would present a slight difference needed for the baryogenesis

$\rightarrow$ If *g* only is concerned by the baryon/antibaryon asymmetry, the C/CP violation cannot be observed in our brane (except if one considers neutron or antineutron disappeareance/reappearance experiments)

$\rightarrow$ If μ is concerned too by the baryon/antibaryon asymmetry: one needs for antineutron magnetic moment measurements

Matter exchange between braneworlds as a baryogenesis mechanism

→ Let us modelize baryon-antibaryon populations between 160 MeV and 20 MeV: $n_n = n_p = (1/2)n_B$

→ Comoving density (density/entropy ratio) : $Y_B = n_B/s$

→ Rates: $\gamma \sim \dfrac{4\varepsilon^2}{\Gamma}$ and $\gamma \sim \dfrac{4\bar{\varepsilon}^2}{\overline{\Gamma}}$ where

$$\begin{cases} \Gamma = \langle \sigma_{BB} v \rangle\, sY_B + \langle \sigma_{B\overline{B}} v \rangle\, sY_{\overline{B}} + \langle \sigma_{BB} v \rangle\ s'Y_{B'} + \langle \sigma_{B\overline{B}} v \rangle\ s'Y_{\overline{B}'}, \\ \overline{\Gamma} = \langle \sigma_{B\overline{B}} v \rangle\, sY_B + \langle \sigma_{BB} v \rangle\, sY_{\overline{B}} + \langle \sigma_{B\overline{B}} v \rangle\ s'Y_{B'} + \langle \sigma_{BB} v \rangle\ s'Y_{\overline{B}'}, \end{cases}$$

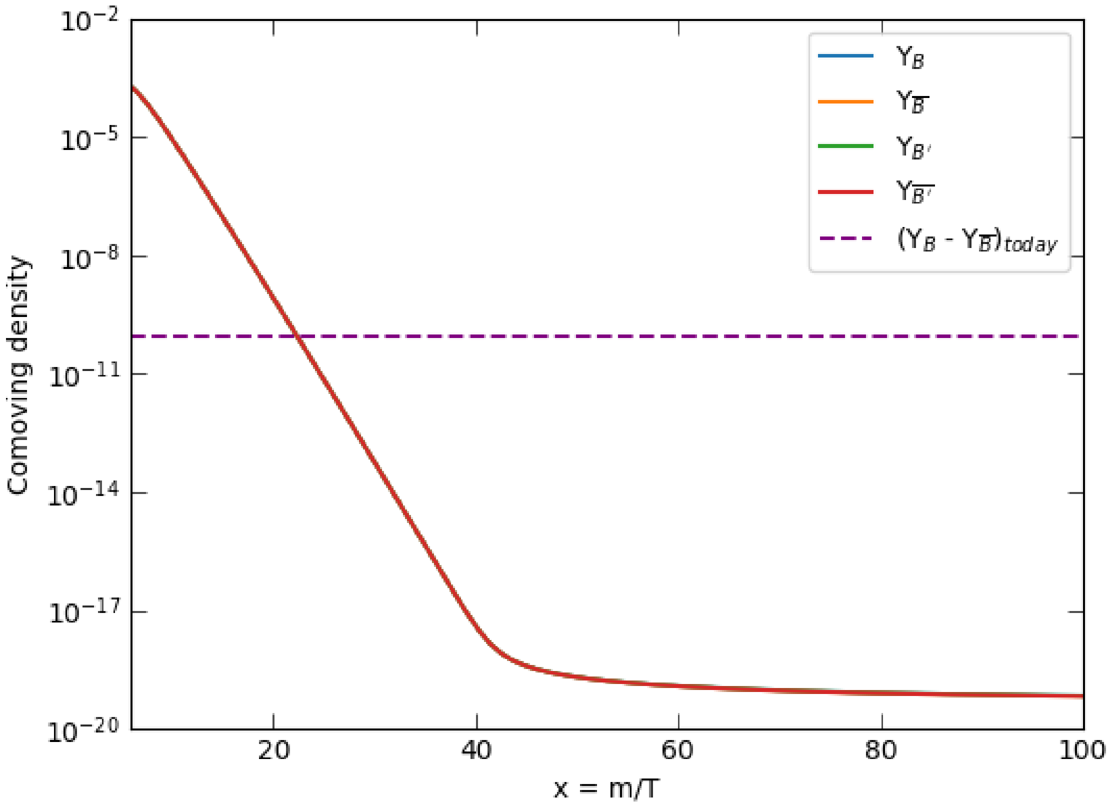
→ Boltzmann equations

$$\begin{cases} \dfrac{dY_B}{dx} = -\left\langle \sigma_{B\overline{B},ann} v \right\rangle \dfrac{s}{Hx} \left(Y_B Y_{\overline{B}} - Y_{B,eq} Y_{\overline{B},eq} \right) - (1/2)\dfrac{\gamma}{Hx} \left(Y_B - Y_{B'} \right) \\ \dfrac{dY_{\overline{B}}}{dx} = -\left\langle \sigma_{B\overline{B},ann} v \right\rangle \dfrac{s}{Hx} \left(Y_B Y_{\overline{B}} - Y_{B,eq} Y_{\overline{B},eq} \right) - (1/2)\dfrac{\overline{\gamma}}{Hx} \left(Y_{\overline{B}} - Y_{\overline{B}'} \right) \\ \dfrac{dY_{B'}}{dx} = -\left\langle \sigma_{B\overline{B},ann} v \right\rangle' \dfrac{\kappa s'}{H'x'} \left(Y_{B'} Y_{\overline{B}'} - Y_{B',eq} Y_{\overline{B}',eq} \right) + (1/2)\dfrac{\gamma\kappa}{H'x'} \left(Y_B - Y_{B'} \right) \\ \dfrac{dY_{\overline{B}'}}{dx} = -\left\langle \sigma_{B\overline{B},ann} v \right\rangle' \dfrac{\kappa s'}{H'x'} \left(Y_{B'} Y_{\overline{B}'} - Y_{B',eq} Y_{\overline{B}',eq} \right) + (1/2)\dfrac{\overline{\gamma}\kappa}{H'x'} \left(Y_{\overline{B}} - Y_{\overline{B}'} \right) \end{cases}$$

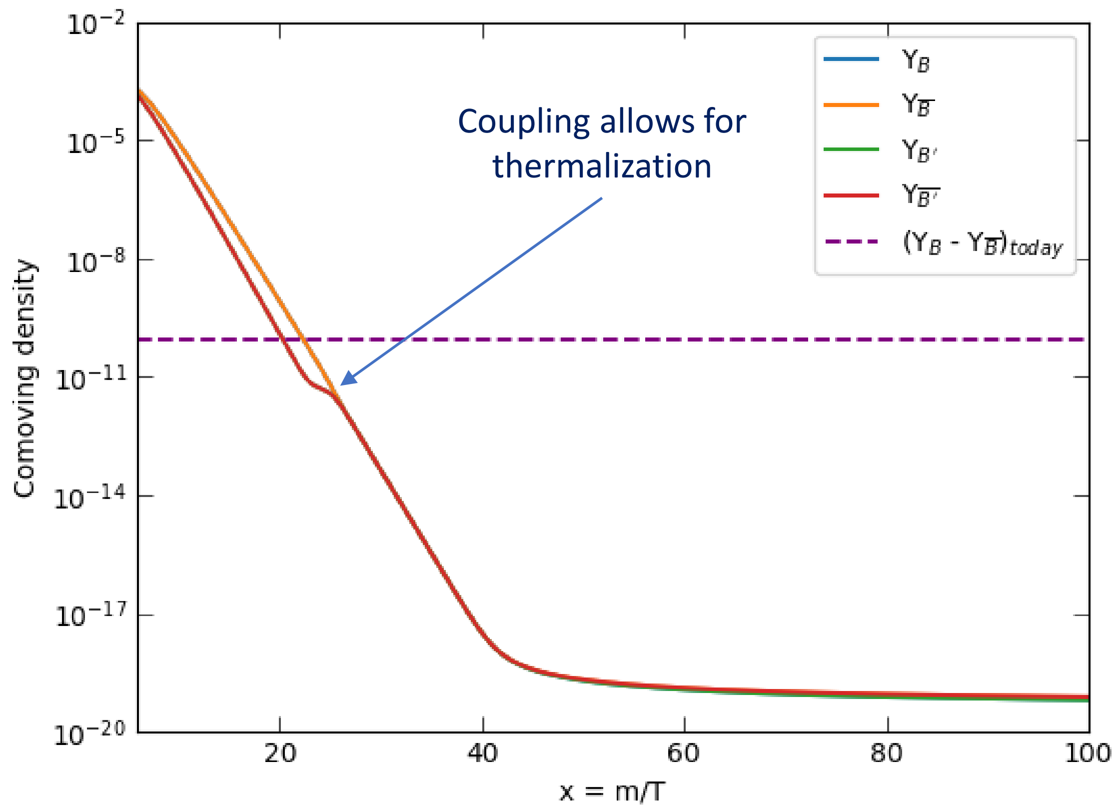
Late baryogenesis in a two-brane Universe with a hidden CP violation, in preparation (2023)

Some results…

- No coupling, same temperature ($T_{initial}$ = 160 MeV)
- Coupling, w or w/o matter-antimatter asymmetry, same temperature



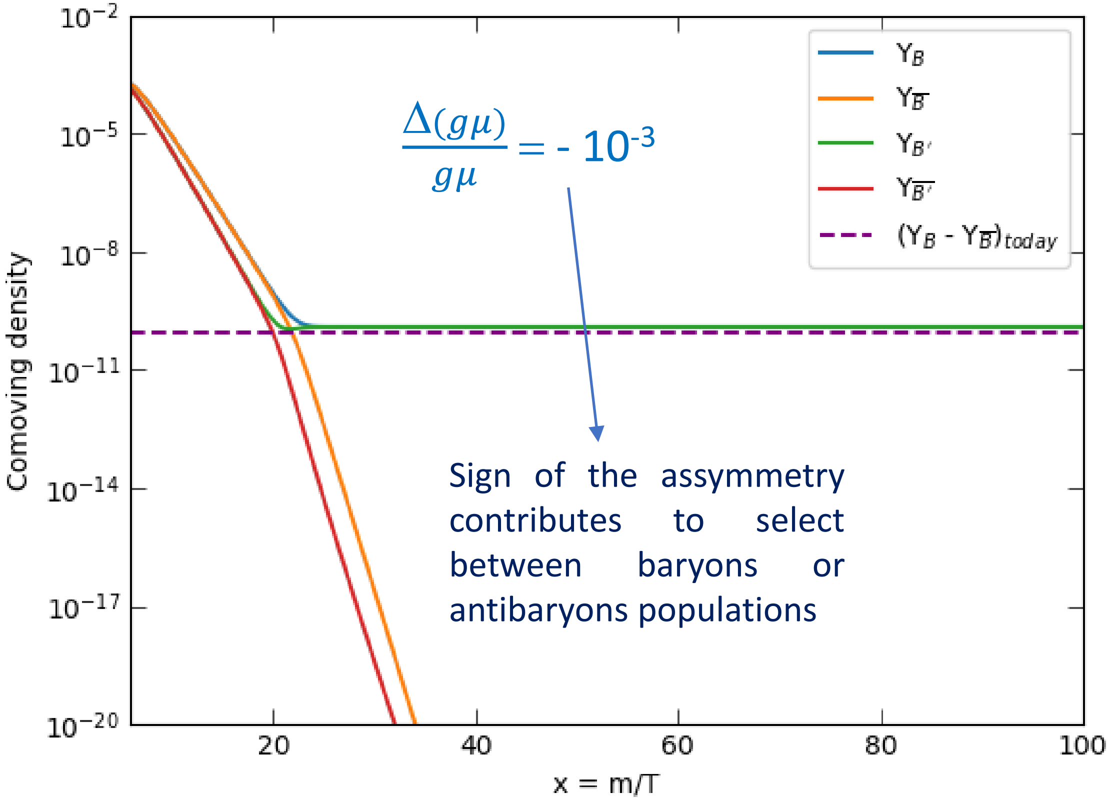
Coupling, no matter-antimatter asymmetry, different temperatures ($T_{initial}$ = 160 MeV and $T'_{initial}$ = 146 MeV)



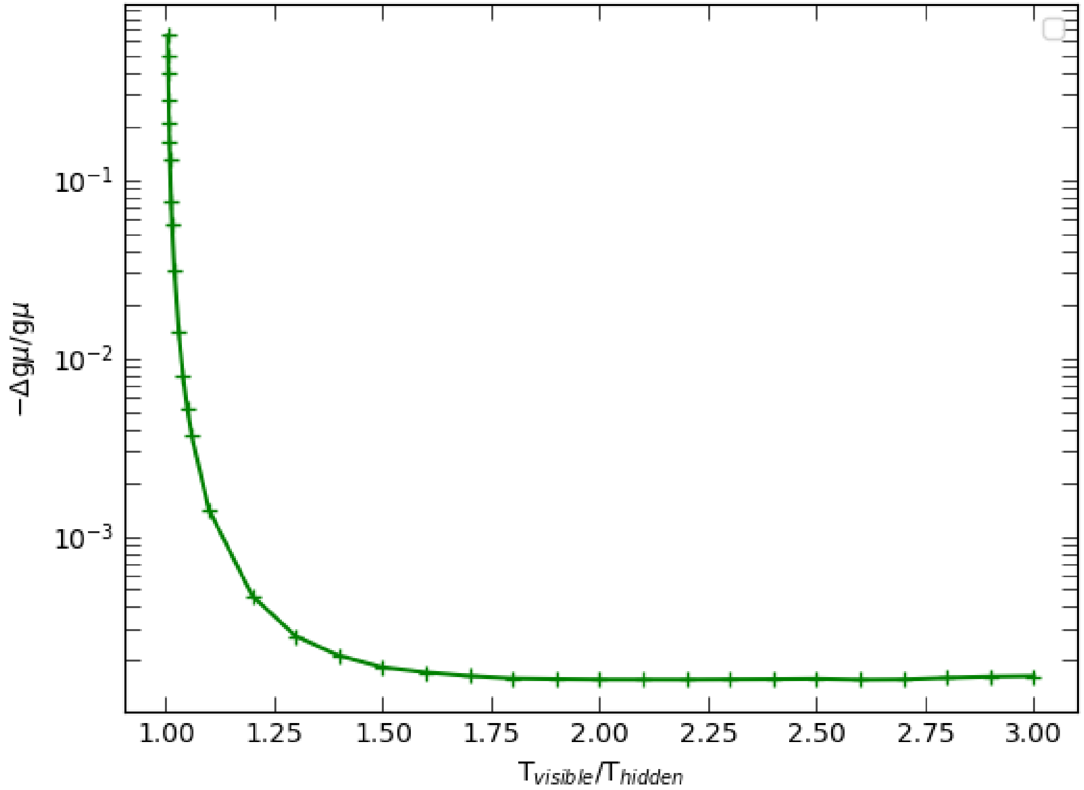
→ All the Sakharov conditions are required…

Some results...

Coupling, with matter-antimatter asymmetry, different temperatures ($T_{initial}$ = 160 MeV and $T'_{initial}$ = 144 MeV)



Global "coupling constant - magnetic moment" asymmetry against ratio of the temperature of each brane for $(Y_B - Y_{\overline{B}})_{today}$



→ A wide range of temperature differences and of matter-antimatter asymmetries easily allows to retrieve current baryon-antibaryon asymmetry

A late baryogenesis in an ekpyrotic-like universe

Inputs

- Baryogenesis can be supported by neutrons and antineutrons only

- A late baryogenesis mechanism: CP violation manifests right after the transition from the quark-gluon plasma to the hadron gas

- CP violation can be hidden in the interbrane coupling constant which could only be probed with *passing-through-walls-neutron* experiments

- Link with ekpyrotic scenarios and braneworld cosmologies allowing for dark matter and dark energy

Pending issues

- Justify the brane temperature asymmetry in terms of collision between branes (theoretical task)

- Find mechanisms to explain $\mu_n \neq \mu_{\bar{n}}$ or $g_n \neq g_{\bar{n}}$ (theoretical task)

- Antineutron magnetic moment versus neutron magnetic moment (experimental task)

- New disappearing (and/or reappearing) neutrons experiments needed (experimental task)

Many thanks to Patrick Peter (IAP - GReCO)
for the useful discussions on the topic!

Thank you for your attention!

Any questions?