Constraining sterile or hidden copies of the Standard Model as dark matter candidates with passing-through-walls neutron experiments

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GDR-InF ● Dark matter ● 2020

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Context of the research

Hidden sector

Hidden sector: extension of both the Standard Model of particles and the ΛCDM cosmological model.

Purpose: addressing some shortcomings as for instance question of **dark matter**.

Hidden sector

Duplication of the SM content: Mirror partners

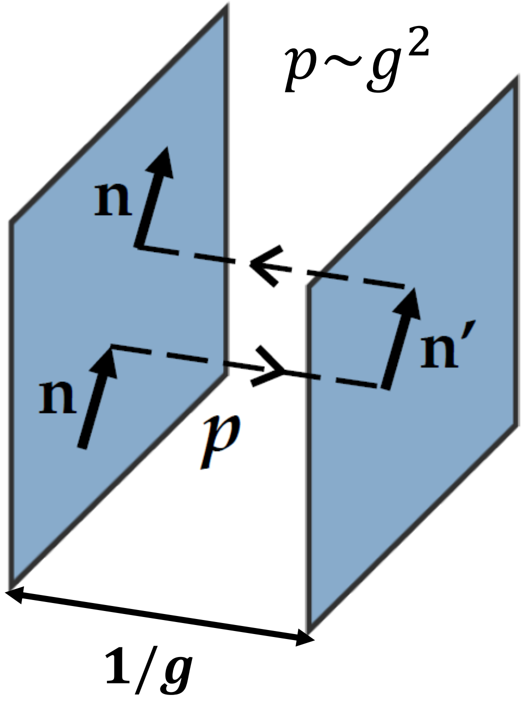
Geometrical sense: Braneworld hypothesis

Subclass of hidden sector models: fermions could exist in both the visible and the hidden states. In particular, a neutron n would have a sterile hidden state n'. Mixings between the two states could lead to $n \rightarrow n'$ transitions.

Passing-through-wall neutron

Braneworld models are often considered in the literature!

Neutrons could undergo fast oscillations between the two braneworlds!



M. Sarrazin, F. Petit, Phys. Rev. D81 (2010).

→ **Phenomenological way to probe braneworld scenarios with $n \rightarrow n' \rightarrow n$ transitions**

Parameter of interest:

$$g \sim \frac{m^2}{M_B}$$

With $M_B = \frac{1}{\xi}$ the energy scale of the brane (TeV or Planck scale?) and m the mass of a constituent quark (340 MeV)

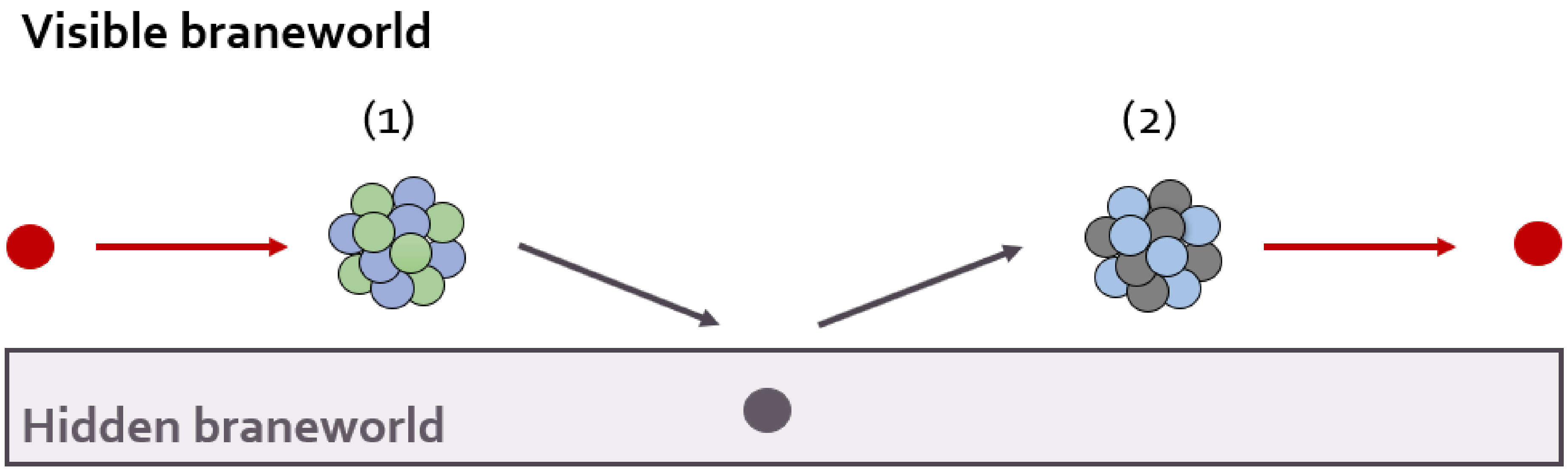
→ **New physics reachable even at the Planck scale!**

C. Stasser, M. Sarrazin, Int. J. Mod. Phys. A34 (2019) 1950029.

Passing-through-walls neutron experiment

Passing-through-wall neutron experiment

Neutron disappearance/reappearance toward/from a hidden brane can be induced thanks to nuclei with high scattering cross section.



(1) $\sigma\,(\text{vis. } n + \text{vis. nucleus} \longrightarrow \text{hid. } n) = \sigma_E\ (\text{vis. } n + \text{vis. nucleus} \longrightarrow \text{vis. } n) \cdot p/2$

(2) $\sigma\,(\text{hid. } n + \text{vis. nucleus} \longrightarrow \text{vis. } n) = \sigma_E\ (\text{vis. } n + \text{vis. nucleus} \longrightarrow \text{vis. } n) \cdot p/2$

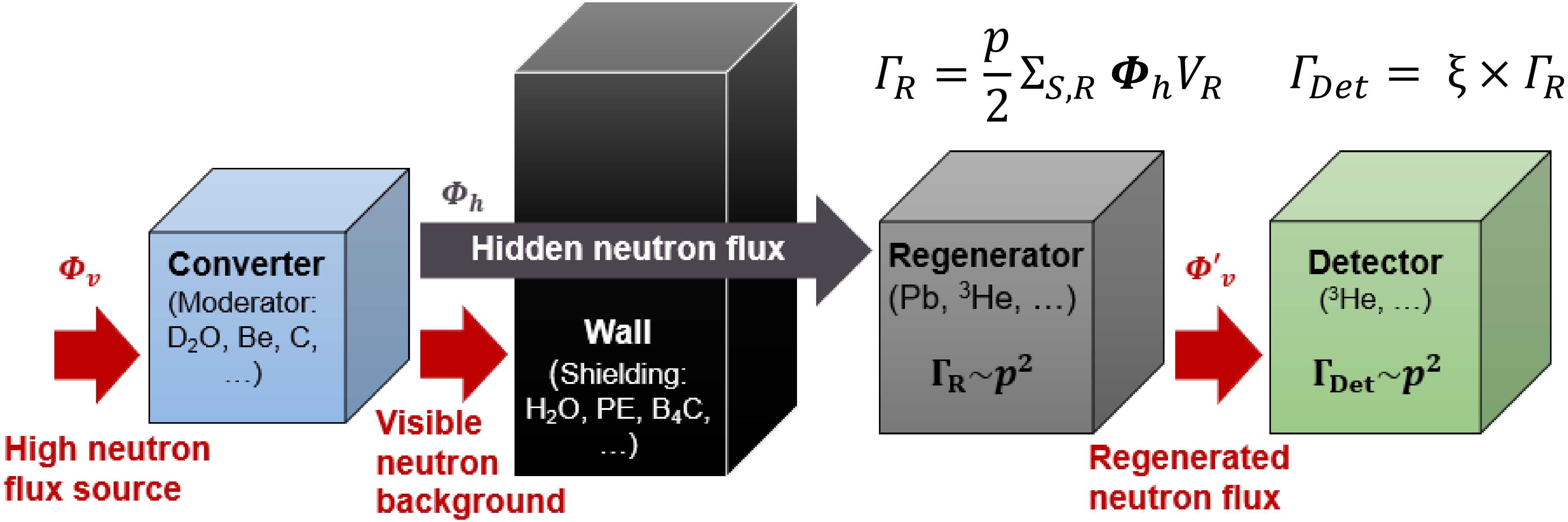
M. Sarrazin, G. Pignol, J. Lamblin, F. Petit, G. Terwagne, V. V. Nesvizhevsky, Phys. Rev. D91 (2015).

C. Stasser, M. Sarrazin, G. Terwagne, EPJ Web Conferences (2019).

Passing-through-walls neutron experiment

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

$$\Gamma_R = \frac{p}{2}\Sigma_{S,R}\,\boldsymbol{\Phi}_h V_R \qquad \Gamma_{Det} = \xi \times \Gamma_R$$



C. Stasser, M. Sarrazin, G. Terwagne, EPJ Web Conferences (2019).

$$\boldsymbol{\Phi}_h(\boldsymbol{r}) = \frac{p}{8\pi}\int_C \frac{1}{|\boldsymbol{r}-\boldsymbol{r}'|^2}\,\Sigma_{S,C}(\boldsymbol{r}')\,\boldsymbol{\Phi}_v(\boldsymbol{r}')\,d^3\,r'$$

M. Sarrazin, G. Pignol, J. Lamblin, F. Petit, G. Terwagne, V. V. Nesvizhevsky, Phys. Rev. D91 (2015).

Passing-through-walls neutron experiment

First experiment of this kind at the ILL (France) in 2015: regenerator = detector (^3He counter).

$$p < 4.6\ 10^{-10} \text{ at 95\% CL.}$$

M. Sarrazin, G. Pignol, J. Lamblin, F. Petit, G. Terwagne, V. V. Nesvizhevsky, Phys. Rev. D91 (2015).

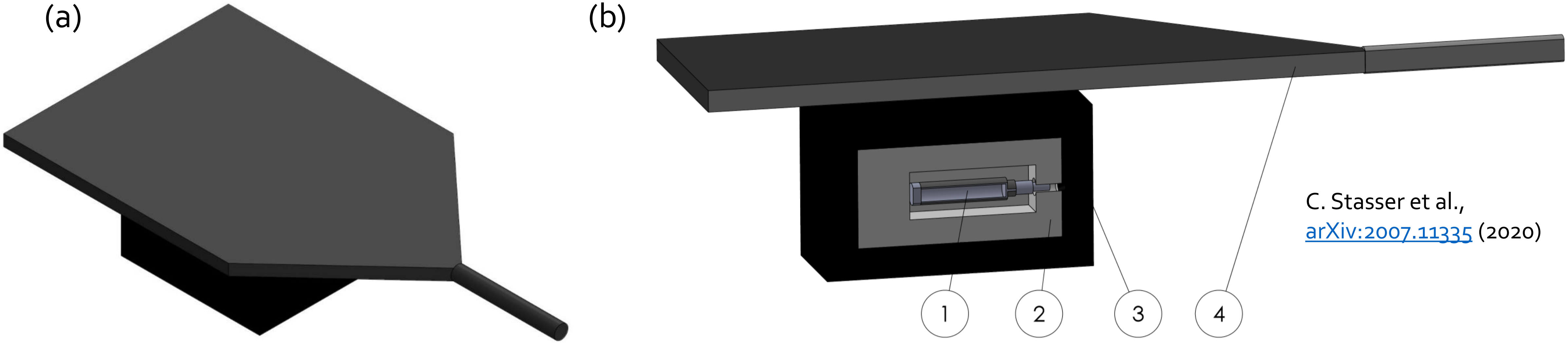
M. Sarrazin, G. Pignol, J. Lamblin, J. Pinon, O. Méplan, G. Terwagne, P.L. Debarsy, F. Petit and V. V. Nesvizhevsky, Phys. Lett. B758 (2016).

<u>MURMUR:</u> improved detector placed near the BR2 nuclear core at Mol in Belgium to constrain braneworld cosmological scenarios.

- Regenerator made of 50 kg of lead
- Noise substraction thanks to ON/OFF reactor measurements
- PSD
- Active veto
- Long acquisition time

The MURMUR detector

MURMUR detector

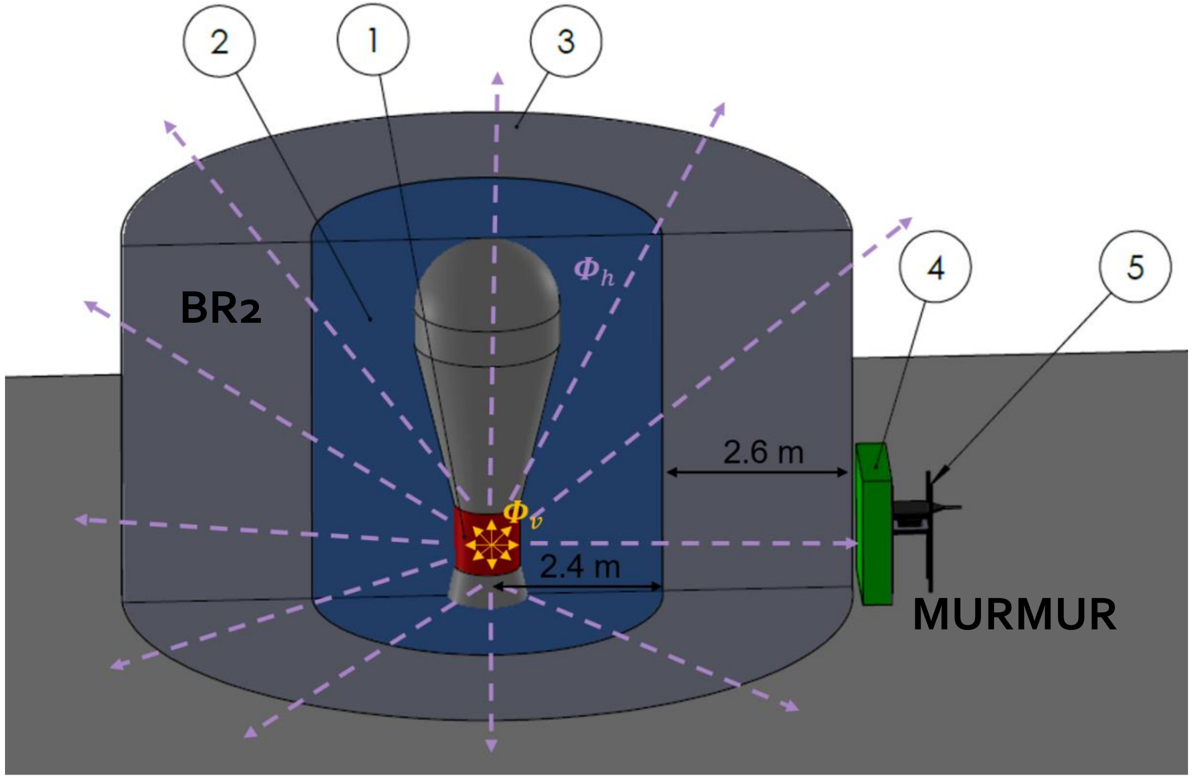


C. Stasser et al., arXiv:2007.11335 (2020)

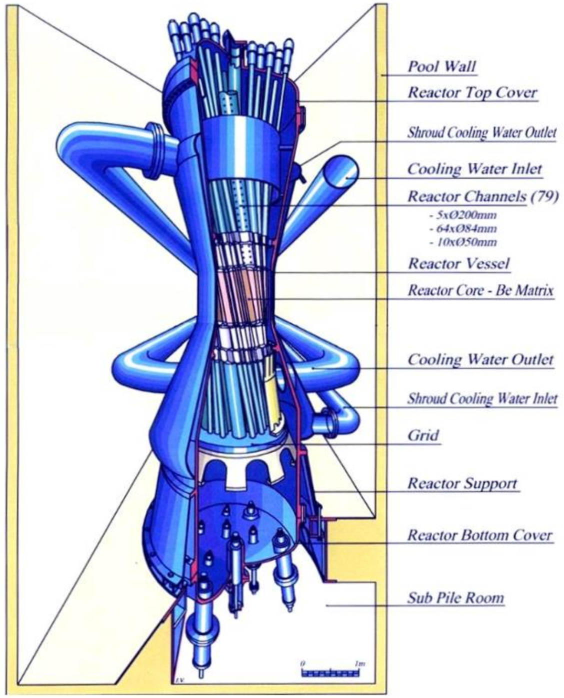
Design of the MURMUR detector: (a) complete view and (b) sectional view. 1. ^3He proportional counter, 2. Regenerator: $23.6 \times 17.7 \times 11.5\ cm^3$ of lead (50 kg), 3. Boron carbide box of $3.6\ cm$ of thickness, 4. plastic scintillator acting as a veto.

$$^3_4He + {}^1_0n \rightarrow {}^1_1p + {}^3_1H + 764\ keV$$

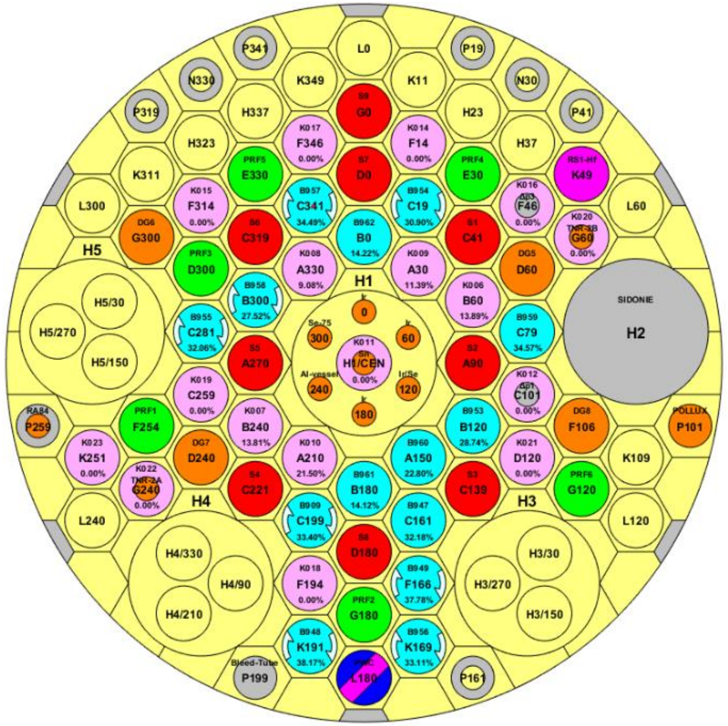
MURMUR near the BR2 core



(a)



(b)



MURMUR experiment near the BR2 core in the SCK·CEN at Mol in belgium. 1. BR2 core which has a beryllium moderator, 2. light water pool, 3. concrete wall, 4. paraffin wall, 5. MURMUR detector.

(a) Geometry of the BR2 nuclear core of the SCK·CEN at Mol in belgium. (b) Mid-plan of the BR2 core for the Cycle02/2019A. Orange: Fuel. Red: control roads in cadmium or hafnium.

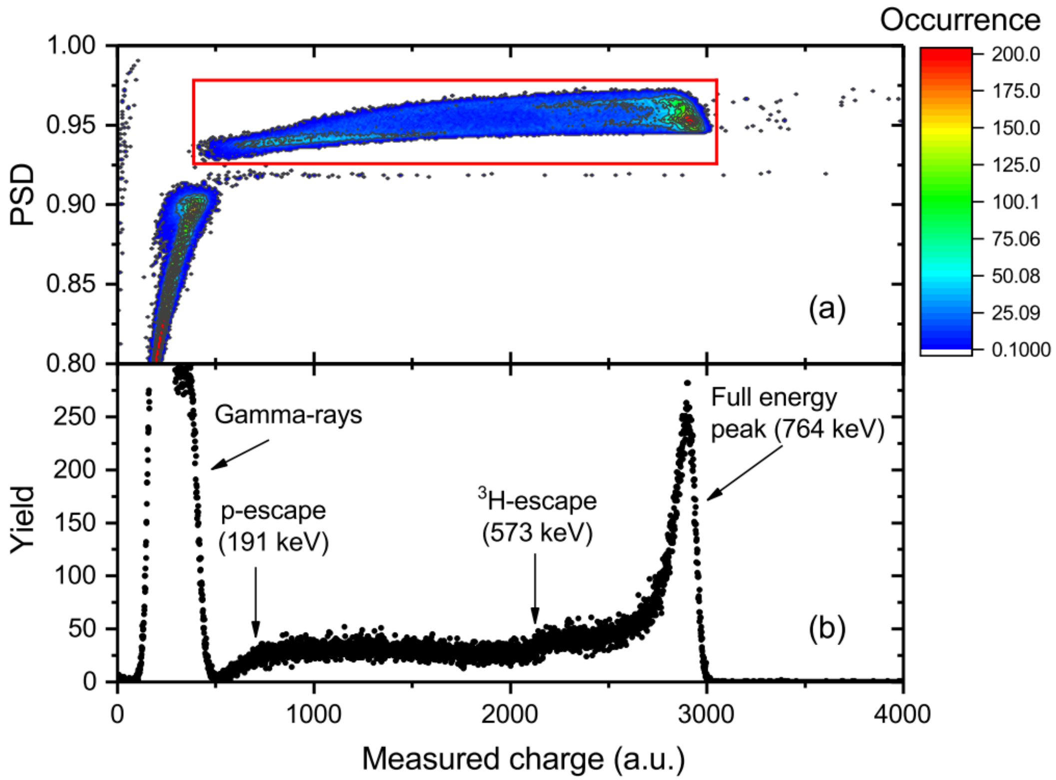
C. Stasser et al., arXiv:2007.11335 (2020)

First results

Neutron counting rate

(a) OFF1 ($\times 10^{-4}\ s^{-1}$)	(b) ON ($\times 10^{-4}\ s^{-1}$)	(c) OFF2 ($\times 10^{-4}\ s^{-1}$)
$3,09^{+0,17}_{-0,16}$	$3,10^{+0,18}_{-0,17}$	$2,88^{+0,15}_{-0,15}$

Neutron counting rate in the ^{3}He counter. (a) 831 hours of acquisition during the shutdown period (OFF) of the BR2 nuclear core of December 2018/January 2019. (b) 760 hours of acquisition during the Cycle02/2019A of April 2019. (c) 998 hours of acquisition during the shutdown period of May/June 2019.



(a) PSD quantity in function of the measured charge in the ^{3}He counter. (b) ^{3}He counter charge spectrum.

$\Gamma_{Det} < 3.3 \times 10^{-5}\ s^{-1}$ **at 95% CL**

C. Stasser et al., arXiv:2007.11335 (2020)

New constraint on p

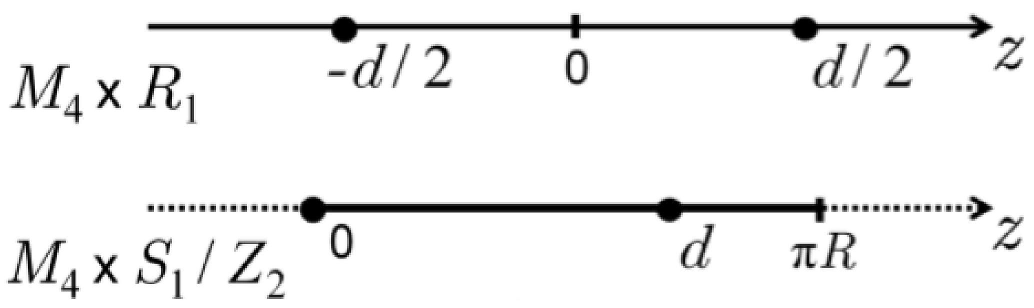
$p < 4.0 \times 10^{-10}$ at 95% CL

- The BR2 efficiency to produce hidden neutron flux is weaker than the ILL by a factor 8.
- Lead as regenerator material and noise substraction both make possible to give a similar constraint than the previous one found at the ILL despite a moderator less efficient to produce hidden neutrons.

C. Stasser et al., arXiv:2007.11335 (2020)

Some theoretical investigations…

$M_4 \times R_1$ and $M_4 \times S_1/Z_2$ bulks



C. Stasser, M. Sarrazin, Int. J. Mod. Phys. A34 (2019) 1950029.

C. Stasser, M. Sarrazin, arXiv:2009.12149 (2020)

- $M_4 \times S_1/Z_2$: Related to the 11D supergravity model of Horava-Witten at low energy.
- For braneworld located at the boundary of the orbifold, $g = 0$.

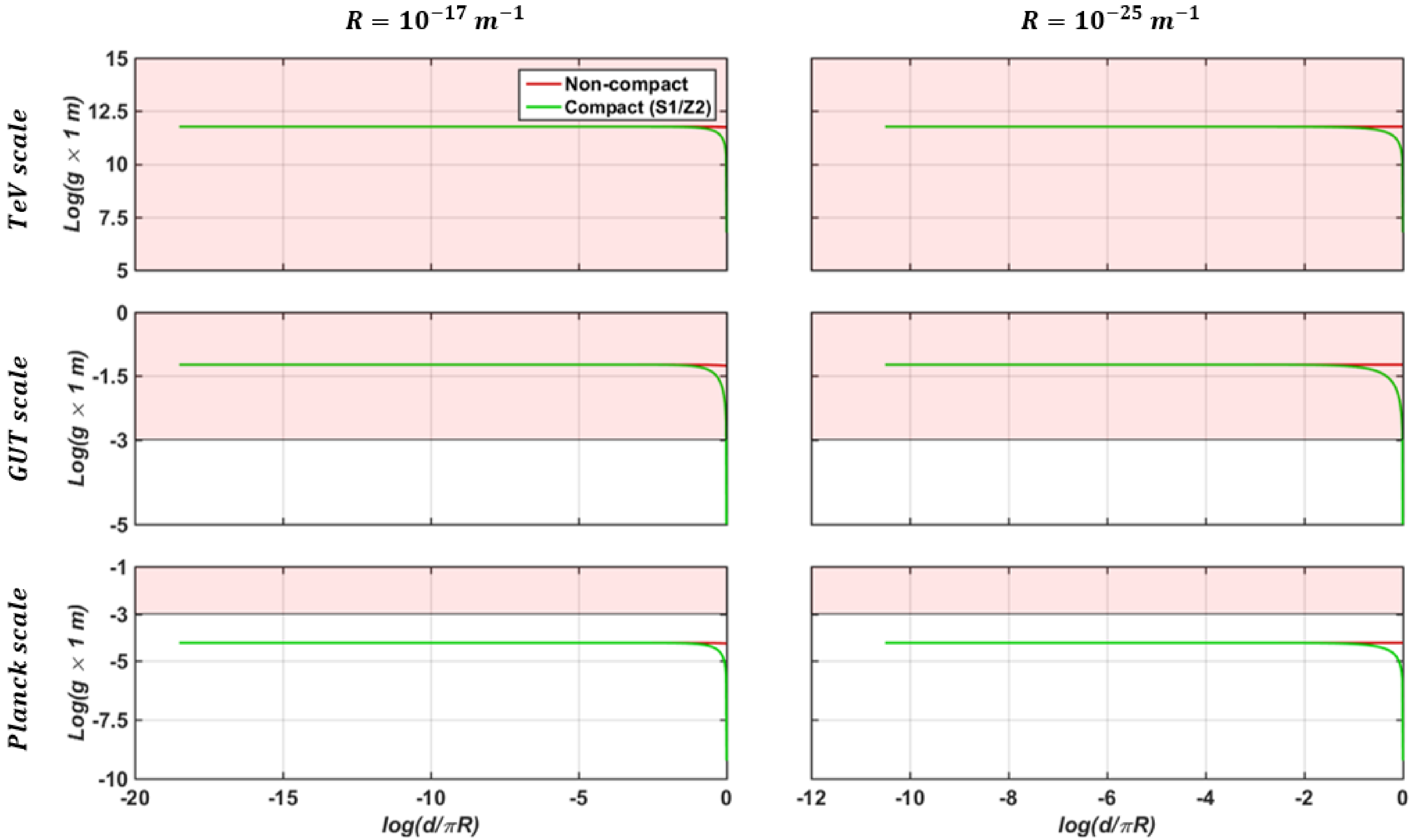
➡ Impossible to constrain HW scenario with p-t-w neutron experiments

➡ Interesting for some ekpyrotic scenarios

➡ TeV scale ruled out and GUT scale reachable by future experiments

➡ Planck scale for the compact case unreachable

$M_4 \times R_1$ and $M_4 \times S_1/Z_2$ bulks

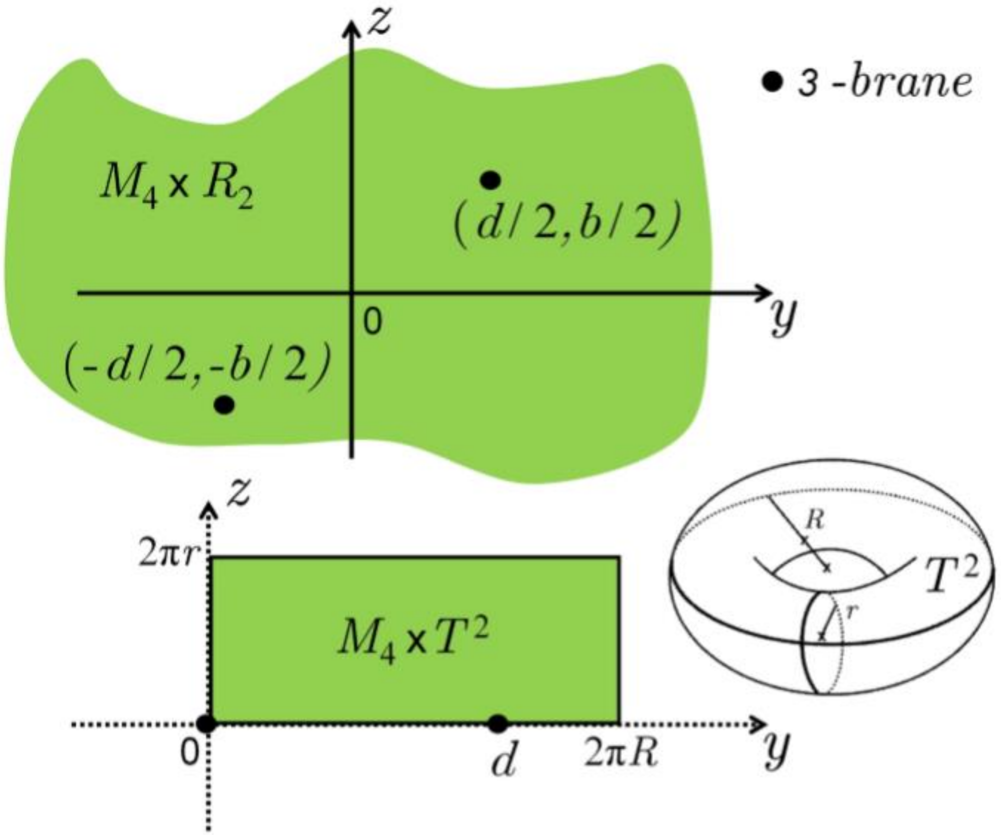


C. Stasser, M. Sarrazin, Int. J. Mod. Phys. A34 (2019) 1950029.

C. Stasser, M. Sarrazin, arXiv:2009.12149 (2020)

Neutron-hidden neutron coupling constant against interbrane distance d for a $M_4 \times R_1$ bulk (red lines) and a $M_4 \times S_1/Z_2$ bulk (green curves).

$M_4 \times R_2$ and $M_4 \times T^2$ bulks



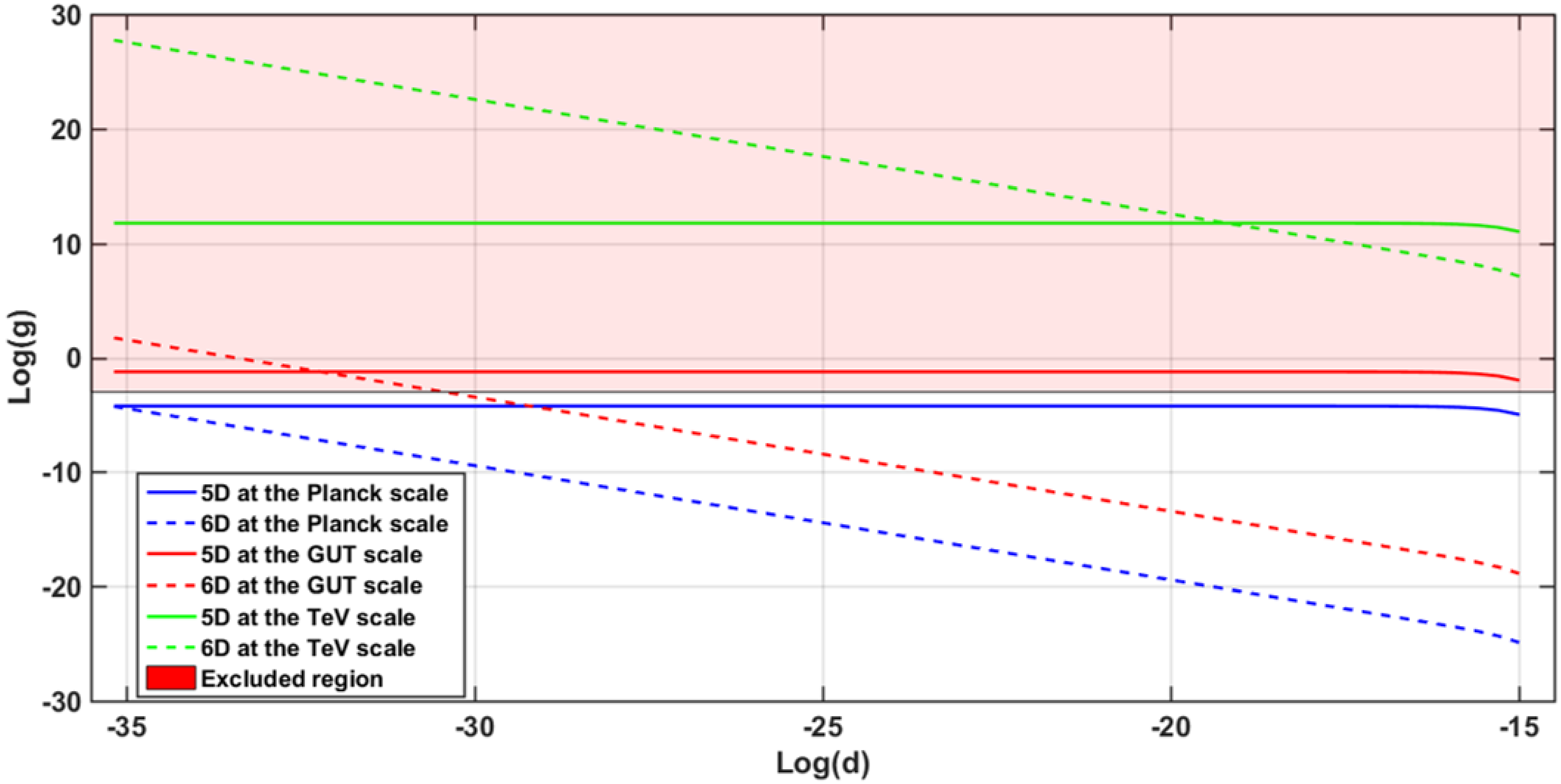
- The addition of more than one extra dimension significantly decreases the coupling constant values.

- 6D bulks can be constrained but not totally excluded!

C. Stasser, M. Sarrazin, Int. J. Mod. Phys. A34 (2019) 1950029.

C. Stasser, M. Sarrazin, arXiv:2009.12149 (2020)

$M_4 \times R_1$ VS $M_4 \times R_2$ bulks



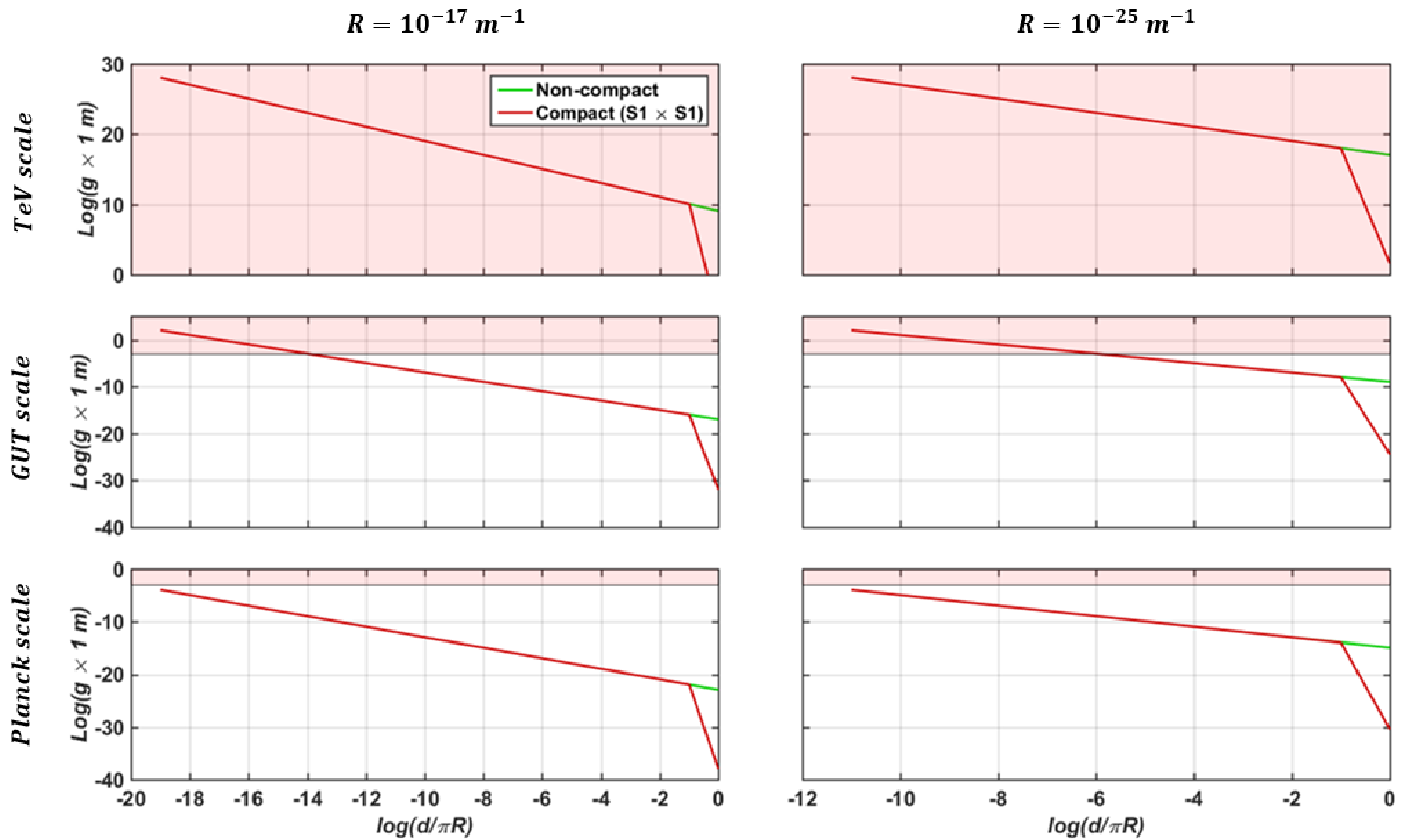
C. Stasser, M. Sarrazin, Int. J. Mod. Phys. A34 (2019) 1950029.

C. Stasser, M. Sarrazin, arXiv:2009.12149 (2020)

Neutron-hidden neutron coupling constant against interbrane distance d for a 5D $M_4 \times R_1$ bulk (solid curves) and a 6D $M_4 \times R_2$ bulk (dash curves).

MURMUR

$M_4 \times R_2$ and $M_4 \times \mathrm{T}^2$ bulks



C. Stasser, M. Sarrazin, Int. J. Mod. Phys. A34 (2019) 1950029.

C. Stasser, M. Sarrazin, arXiv:2009.12149 (2020)

Neutron-hidden neutron coupling constant against interbrane distance d for a 6D $M_4 \times R_2$ bulk (green lines) and a 6D $M_4 \times \mathrm{T}_2$ bulk (red curves).

To conclude…

- Passing-through-walls neutron experiments using lead as regenerator are promising to constrain the exitence of hidden copies of the SM.

- Future experiments like this could rule out a large parameter's range of 5D compact or non-compact braneworld scenarios and a certain proportion of 6D compact or non-compact braneworld scenarios.

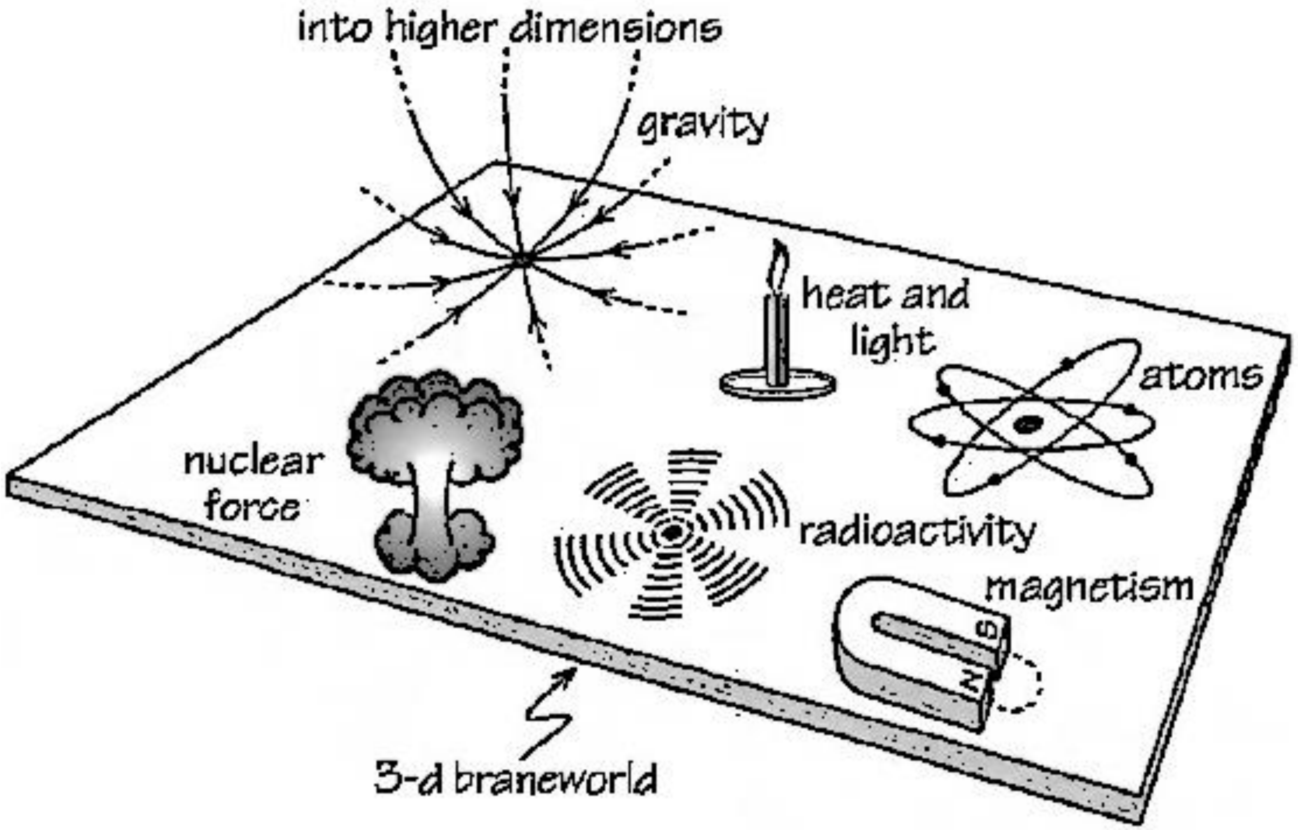
- While the existence of hidden braneworlds can be constrained, it will never be completely ruled out by passing-through-walls neutron experiments.

Thank you!

Braneworld

<u>Our visible world</u>: 3+1 hypersurface (a 3-brane) embedded in a hyperspace (the bulk) of more than 3+1 dimensions.

Many braneworlds could coexist in the bulk!



V.A Rubakov and M.E Shaposhnikov, Phys. Lett. 125B (1983) 126.

G. Dvali, G. Gabadadze, M. Shifman, Phys. Lett. B 497 (2001) 271.

D.J.H Chung and K. Freese, Phys. Rev. D62 (2000) 063513.

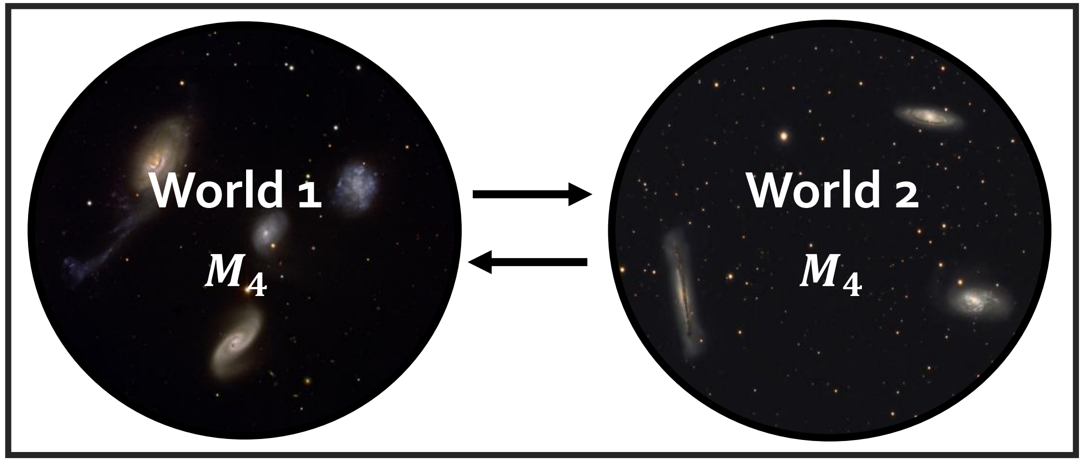
P. Horava and E. Witten, Nucl. Phys. B460 (1996) 506.

…

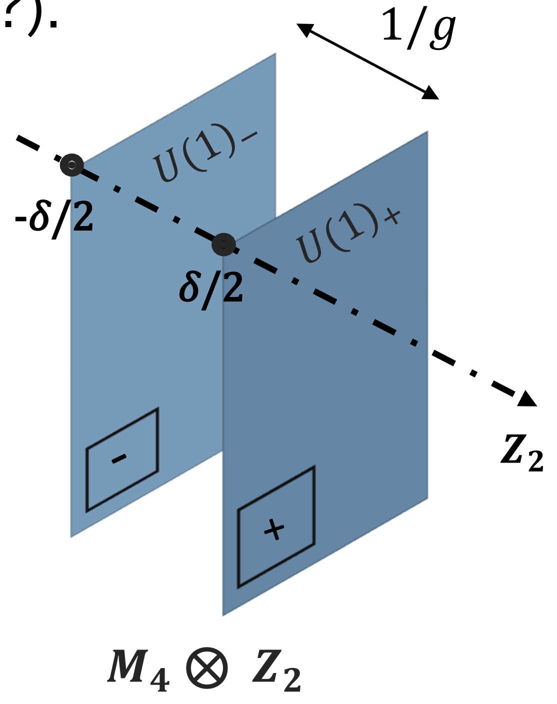
Framework

Problem: Many complex braneworld models to probe, ignoring which is the right one!

Solution: A two-brane universe is naturally described at low energy by a noncommutative two-sheeted system, whatever the nature of the branes (strings? Domain walls?) and the properties of the bulk (number of dimensions? Metric? Compact?).

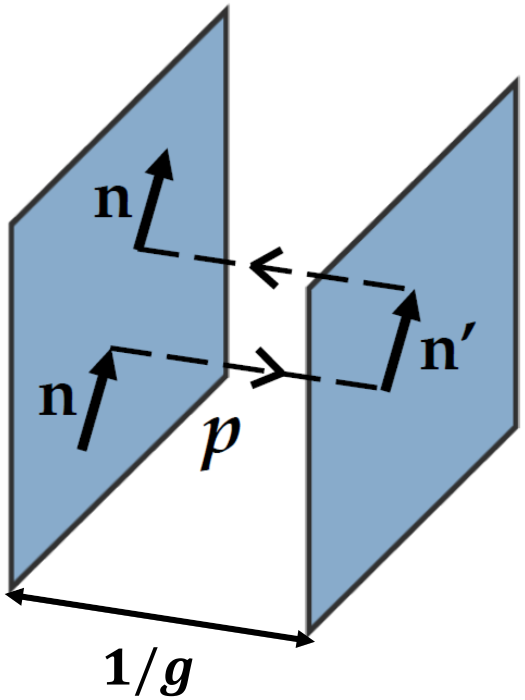


M. Sarrazin, F. Petit, Phys. Rev. D 81, 035014 (2010)



Passing-through-wall neutron

Neutrons could undergo fast oscillations between the two braneworlds!



M. Sarrazin, F. Petit, Phys. Rev. D81 (2010).

C. Stasser, M. Sarrazin, Int. J. Mod. Phys. A34 (2019) 1950029.

Mean value of the probability p:

$p = \frac{2\,{\Omega_P}^2}{{\Omega_0}^2}$ with $\Omega_0 = \frac{V_+ - V_-}{\hbar}$ and $\Omega_P = \frac{\mu g A}{\hbar}$, where $V_\pm$ is the energy of the particle in each brane.

→ Phenomenological way to probe braneworld scenarios with $n \to n' \to n$ transitions

Parameter of interest:

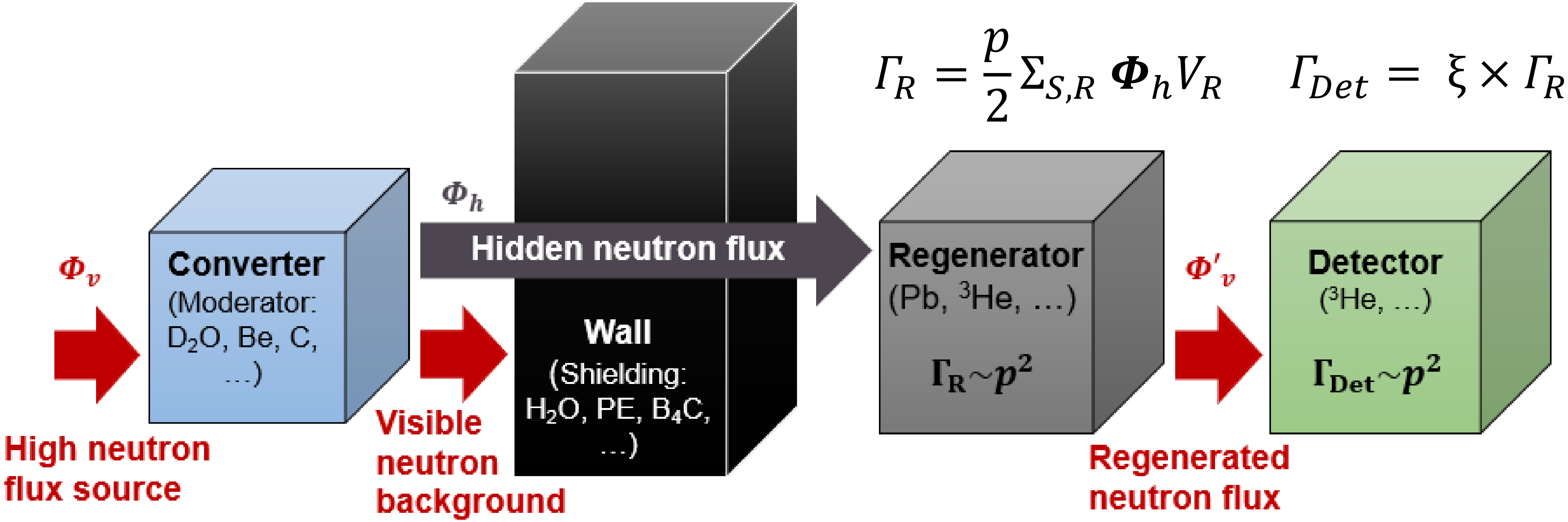
$$g \sim \frac{m^2}{M_B} \sim 10^{-4}\,m^{-1} \sim 0.01\,neV$$

→ New physics reachable even at the Planck scale ($M_B = \frac{1}{\xi} = M_{Planck}$)

Neutron passing-through-wall experiment

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

$$\Gamma_R = \frac{p}{2}\Sigma_{S,R}\,\boldsymbol{\Phi}_h V_R \qquad \Gamma_{Det} = \xi \times \Gamma_R$$



C. Stasser, M. Sarrazin, G. Terwagne, EPJ Web Conferences (2019).

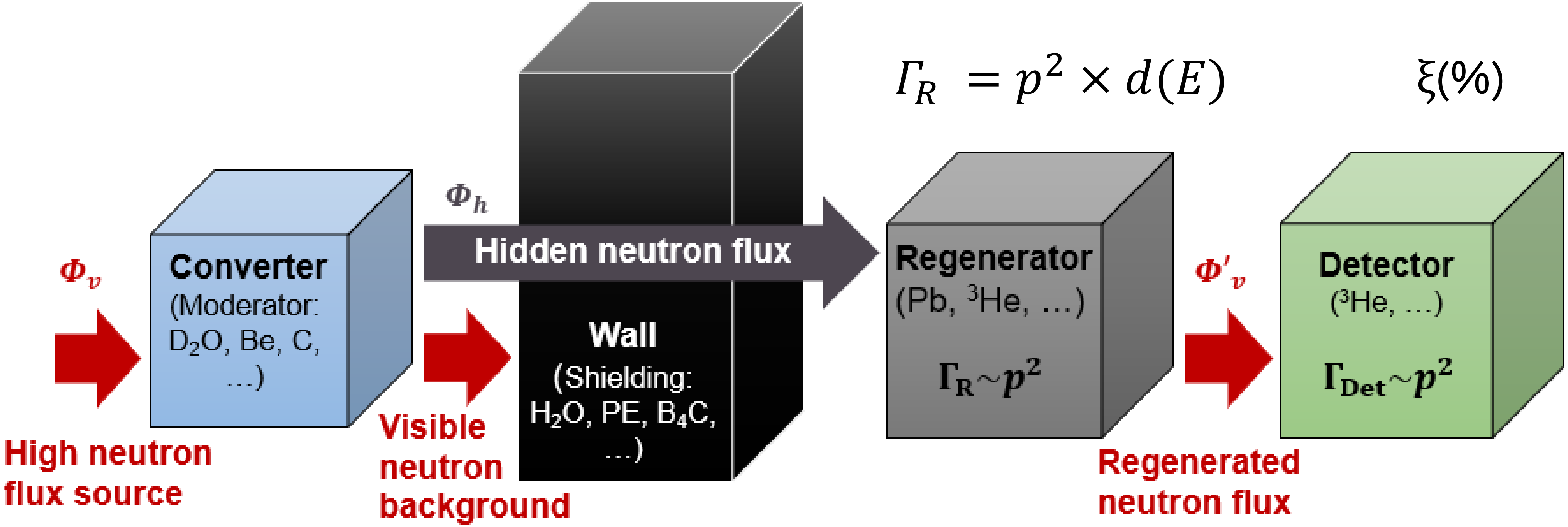
$$\boldsymbol{\Phi}_h(\boldsymbol{r}) = \frac{p}{8\pi}\int_C \frac{1}{|\boldsymbol{r}-\boldsymbol{r}'|^2}\,\Sigma_{S,C}(\boldsymbol{r}')\,\boldsymbol{\Phi}_v(\boldsymbol{r}')\,d^3\,r'$$

M. Sarrazin, G. Pignol, J. Lamblin, F. Petit, G. Terwagne, V. V. Nesvizhevsky, Phys. Rev. D91 (2015).

Numerical computations

$$\Gamma_R = p^2 \times d(E)$$

$\xi(\%)$

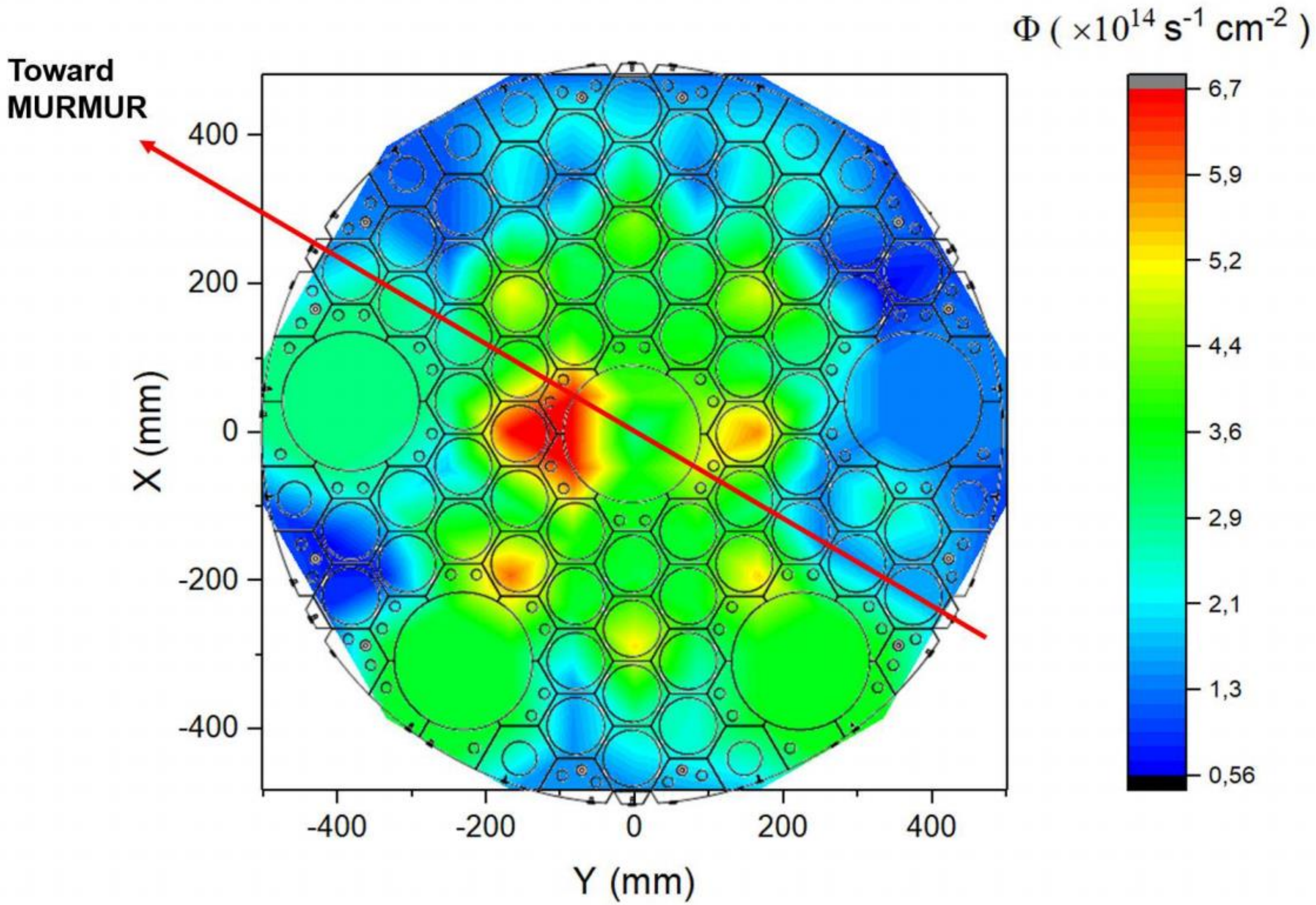


$$d = \frac{\Sigma_{S,Pb}}{16\pi} \int_C \frac{\Sigma_{S,C}(\boldsymbol{r}')\boldsymbol{\Phi}_v(\boldsymbol{r}', E) d^3 r'}{|\boldsymbol{r} - \boldsymbol{r}'|^2}$$

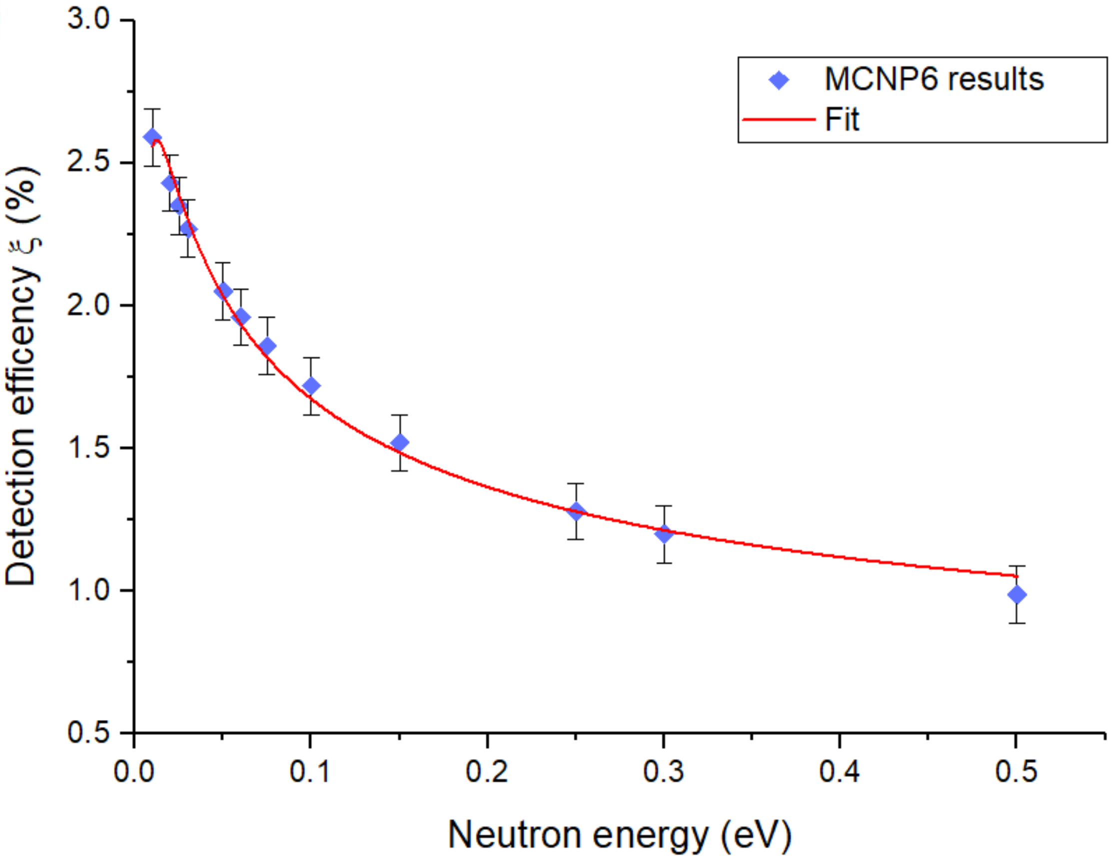
$$p < \sqrt{\frac{\Gamma_{Det}}{\xi(E) \times d(E)}}$$

First results

Numerical computations



Map of the thermal neutron flux Φ in the mid-plan of the BR2 core calculated thanks to MCNP6 simulations.



Regenerated neutron detection efficiency ξ(%) in function of the neutron energy calculated with MCNP6. Fit function in red: $\frac{A}{E} + \frac{B}{\sqrt{E}} + C$.

Perspectives

Prospects for the futur…

- Improvements of the experimental setup:
  - Addition of cadmium as shielding to reduce the epithermal neutron background.
  - Addition of PE to reduce the fast neutron background.
  - Addition of plastic scintillators by the sides of the experiment to reduce neutron background due to muons in lead.
- Test of the detector near the high flux nuclear core of the ILL.