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# *Realising DM and PTA via Dark Branes*

*The Dark Side of the Universe - DSU2024 10/09/2024*

• Compelling evidence for the existence of Dark Matter (DM) on different astrophysical scales



(galactic, clusters of galaxies, cosmological scale,…)

 $\bullet$  ~ 84% of the matter in the Universe is DARK

• DM candidate: **stable** (compared to the current age of the Universe), (dominantly) **Non-**

# **relativistic**, **electrically neutral** and **colorless**. (Only?) **gravitational interactions**

• Usual problem with DM candidates (e.g. WIMPs): **Conflict** between relic abundance and direct/indirect/accelerator searches because of **interactions with the SM**

*See Jan Heisig's talk earlier today*

# DM LANDSCAPE



### *Warped extra dimensional model with three 3-branes (extended Randall-Sundrum (RS) models)*









S.J. Lee et al., 2109.10938 *z* FK, E. Megías, S. Pokorski, M. Quiros, 2403.06276



E. Megías, G. Nardini, M. Quiros, 2306.17071





### The message

• DM interacts **only gravitationally** via radions and massive KK gravitons

• DM relic abundance obtained via **annihilation into radions** whereas its detection signatures via

# **interactions with the SM**

• Assuming that the PTA experiments have found a **new physics scale** around the GeV  $(\Lambda_{\text{PTA}} \sim \text{GeV})$  scale, our proposal would suggest that the new scale can be **provided by the dark matter sector** in our Universe





*A. Arbey and F. Mahmoudi, Dark* **S. Ferrante, A. Ism** *matter and the early Universe: a review*

matter experiments. In addition the relic density in addition the relic density in addition to the relic density in<br>In addition to relic density imposes strong constraints on dark matter on dark matter on dark matter on da

### *Two branes models*

B. von Harling and K. L. McDonald, JHEP 08 (2012) 048

H. M. Lee, M. Park and V. Sanz, Eur. Phys. J. C 74 (2014) 2715

M. G. Folgado, A. Donini and N. Rius, JHEP 01 (2020) 161

 A. de Giorgi and S. Vogl, JHEP 11 (2021) 036

A. de Giorgi and S. Vogl, JHEP 04 (2023) 032

*Three branes models*

S. Ferrante, A. Ismail, S. J. Lee and Y. Lee, JHEP 11 (2023) 186

### Radion interactions **In this subsection with a 5D profile radion interactions** *M*Pl p6 Radion interactions

*e*2*F*(*z,x*)

The wave function of the KK modes of the KK modes of the KK modes of the light radion can be decomposed as  $\alpha$ 

*<sup>f</sup>*(0)(*z*) ⌘ *<sup>f</sup>*(*z*). This mode is massless if we neglect the backreaction on the metrics. However, after the

We have introduced the dimensionless quantity ¯*v*↵ ⌘ *<sup>v</sup>*↵*/M*3*/*<sup>2</sup>

$$
\frac{e^{-2F(z,x)}\eta_{\mu\nu}dx^{\mu}dx^{\nu} + (1+2F(z,x))^{2}dz^{2}}{r(x)T_{b}(x)} \longrightarrow c_{r}(z_{b}) = \left(\frac{k}{M_{\text{Pl}}}\right)\frac{1}{\sqrt{6}}\frac{z_{b}^{2}}{z_{1}} \qquad \frac{m_{r}}{\tilde{\rho}_{1}} = \frac{2}{\sqrt{3}}\bar{v}_{1}u
$$
\n
$$
\text{SM brane}
$$
\n
$$
c_{r}(z_{T}) = \frac{\tilde{\rho}_{1}}{\sqrt{6}\tilde{\rho}_{T}^{2}}, \quad c_{r}(z_{1}) = \frac{1}{\sqrt{6}\tilde{\rho}_{1}}, \quad \text{and} \quad c_{r}(z_{T})c_{r}(z_{1}) = \frac{1}{6\tilde{\rho}_{T}^{2}}
$$
\n
$$
\downarrow
$$
\n
$$
\mathcal{L}_{\text{eff}} = a_{r}T_{\text{SM}}T_{\text{DS}}, \quad \text{where} \quad a_{r} = -\frac{c_{r}(z_{T})c_{r}(z_{1})}{q^{2} - m_{r}^{2}}
$$

<sup>5</sup> , where ↵ refers to the *B*↵ brane. Therefore

$$
\mathcal{L}_{\text{eff}} = a_r T_{\text{SM}} T_{\text{DS}} ,
$$



$$
ds^{2} = e^{-2A(z)} \left[ e^{-2F(z,x)} \eta_{\mu\nu} dx^{\mu} dx^{\nu} + (1 + 2F(z,x))^{2} dz^{2} \right] \qquad F(z,x) = \sum_{n=0}^{\infty} f^{(n)}(z) r^{(n)}(x)
$$
  

$$
\mathcal{L} = -c_{r}(z_{b}) r(x) T_{b}(x) \longrightarrow c_{r}(z_{b}) = \left(\frac{k}{M_{\text{Pl}}}\right) \frac{1}{\sqrt{6}} \frac{z_{b}^{2}}{z_{1}} \qquad \frac{m_{r}}{\tilde{\rho}_{1}} = \frac{2}{\sqrt{3}} \bar{v}_{1} u
$$
  
**SM brane**  

$$
c_{r}(z_{T}) = \frac{\tilde{\rho}_{1}}{\sqrt{6} \tilde{\rho}_{T}^{2}}, \quad c_{r}(z_{1}) = \frac{1}{\sqrt{6} \tilde{\rho}_{1}}, \text{ and } c_{r}(z_{T}) c_{r}(z_{1}) = \frac{1}{6 \tilde{\rho}_{T}^{2}}
$$
  

$$
\downarrow
$$
  

$$
\mathcal{L}_{\text{eff}} = a_{r} T_{\text{SM}} T_{\text{DS}}, \text{ where } a_{r} = -\frac{c_{r}(z_{T}) c_{r}(z_{1})}{q^{2} - m_{r}^{2}}
$$

*z*1

*,* (2.17)

**3.** The radion mass  $m_r$ . We will assume that  $m_r < m_\chi$  and  $m_r \ll \tilde{\rho}_1$ . In this way the *radion decay*  $r \to \chi \bar{\chi}$  *is closed and only the channel*  $r \to SM + SM$  *is kinematically accessible* 

• The model has 3 free parameters:

**1.** The scale of the Dark Brane  $\tilde{\rho}_1 = \frac{\rho_1}{h} \rho_1$ . Its range to describe the PTA data is 10 MeV  $\leq \tilde{\rho}_1 \leq 10$  GeV, but in principle we also have considered a broader range  $M_{\rm pl}$  $\frac{P}{k}$  $\rho_1$ 

**2.** The DM mass  $m_{\chi}$ . We consider it in the range  $m_{\chi} < \tilde{\rho}_1$ . In this way the non*relativistic annihilation into gravitons*  $KK$  *modes*  $\chi \bar{\chi} \rightarrow G_n G_n$  *cannot take place* 

## Thermal history of SM+DM+radion



$$
\begin{bmatrix}\n\text{SM} & \Leftrightarrow & \chi & T_d/m_\chi \\
\text{F}_\text{TO}/m_\chi & \Leftrightarrow & T_{\text{FO}}/m_\chi\n\end{bmatrix}\n\begin{bmatrix}\n\text{SM} \leftrightarrow \text{DM} \\
\text{SM} \leftrightarrow \text{DM} \\
\text{SM} \leftrightarrow \text{M} \\
\text{M}^2 \leftrightarrow \text{M}^2\n\end{bmatrix}
$$
\n
$$
\begin{bmatrix}\n\text{SM} & \Leftrightarrow & \chi \\
\text{SM} & \Leftrightarrow & \chi\n\end{bmatrix}\n\begin{bmatrix}\n\frac{dn_r}{dt} + 3Hn_r = -\langle \Gamma_r \rangle \left[ n_r - n_r^{\text{eq}} \right] - \\
\frac{\langle \sigma_r v \rangle \left[ n_r^2 - (n_r^{\text{eq}})^2 \right] + \langle \sigma_\chi v \rangle}{n_\chi^2 - (n_r^{\text{eq}})^2 n_r^2\n\end{bmatrix}
$$
\n
$$
\begin{bmatrix}\n\text{SM} & \Leftrightarrow & \chi \\
\text{SM} & \Leftrightarrow & \chi \\
\text{SM} & \Leftrightarrow & \chi\n\end{bmatrix}
$$
\n
$$
\begin{bmatrix}\n\frac{dn_r}{dt} + 3Hn_r = -\langle \Gamma_r \rangle \left[ n_r - n_r^{\text{eq}} \right] - \\
\frac{\langle \sigma_r v \rangle \left[ n_\chi^2 - (n_r^{\text{eq}})^2 n_r^2 \right]}{dt} - \langle \sigma_\chi v \rangle \left[ n_\chi^2 - (n_\chi^{\text{eq}})^2 n_r^2 \right] - \\
\frac{\langle \sigma_0 v \rangle \left[ n_\chi^2 - (n_\chi^{\text{eq}})^2 \right]}{(\sigma_0 v) \left[ n_\chi^2 - (n_\chi^{\text{eq}})^2 \right]}
$$





that h*v*i*n*(*T*FO) ' *H*(*T*FO), *H*(*T*) is the Hubble parameter and *g*⇤(*T*) is the e↵ective number of relativistic

$$
\Omega_{\chi} h^2 \simeq 0.1 \frac{x_{\rm FO}}{10} \sqrt{\frac{65}{g_*(T_{\rm FO})}} \frac{\langle \sigma v \rangle_c}{\langle \sigma v \rangle}
$$
\n
$$
\frac{\langle \sigma v \rangle n_{\chi}(T_{\rm FO}) \simeq H}{\langle \sigma v \rangle_c \sim 1.09 \times 10^{-9} \text{ GeV}^{-2}}
$$
\nFig.

### **Relic density** Timing Arrays (PTA) collaborations [11–14] with nanoHz frequencies, provided that ⇢<sup>1</sup> 2 [10 MeV*,* 10 GeV]. For the case of a thermal relic density today  $\mathcal{L}_{\text{F}}$  and  $\mathcal{L}_{\text{F}}$  and  $\mathcal{L}_{\text{F}}$  $\langle \sigma v \rangle n_\chi(T_{\rm FO}) \simeq H(T_{\rm FO})$  $\langle \sigma v \rangle_c \sim 1.09 \times 10^{-9}~{\rm GeV}^{-2}$ a holographic conformal theory [15, 35, 35, 40]. It was proven that the first order phase transition triggers a<br>It was provided to first order phase transition triggers and the first order phase transition triggers and the Timing Arrays (PTA) collaborations [11–14] with nanoHz frequencies, provided that ⇢<sup>1</sup> 2 [10 MeV*,* 10 GeV]. For the case of a thermal relic its energy density today ⌦ depends on its annihilation rate h*v*i as *,* (3.1) (see *e.g.* Ref. [41]),  $x_{\rm FO} = m_\chi/T_{\rm FO} \gg 1$ ⌦*h*<sup>2</sup> ' 0*.*1 where  $\overline{a}$  =  $\overline{a}$  =  $\overline{b}$  (typical of a cold thermal relic) is provided by the freeze-out temperature such the freeze-out temperature such the freeze-out temperature such the freeze-out temperature such temperat  $x_{\text{FO}} = m_v / T_{\text{FO}} \gg 1$ As the radion couples to the SM through the trace of the energy momentum tensor, the first candidates  $\sigma_{\rm 1}$  a<sub>r</sub>  $\sigma_{\rm 2}$   $\sigma_{\rm 3}$   $\sigma_{\rm 6}$   $\sigma_{\rm 7}$   $\sigma_{\rm 8}$   $\sigma_{\rm 7}$   $\sigma_{\rm 7}$   $\sigma_{\rm 8}$   $\sigma_{\rm$  $(1F()$  $\langle \sigma v \rangle_c \sim 1.09 \times 10$  GeV *mm<sup>f</sup> c z c*<sup>1</sup>  $\frac{1}{2}$   $\frac{1}{2$ radion, *<sup>c</sup>*1(*z<sup>T</sup>* )*/cr*(*z<sup>T</sup>* ) ' (3˜⇢1*/*⇢˜*<sup>T</sup>* )<sup>2</sup> ⌧ 1 for ˜⇢<sup>1</sup> ⌧ ⇢˜*<sup>T</sup>* . Moreover, given that we are using radion masses much smaller than the DM mass *m<sup>r</sup>* ⌧ *m*, the ratio of annihilation cross sections into the SM mediated by KK  $\sqrt{T}$ for DM annihilation into SM fields are fermions *f* with mass *m<sup>f</sup>* . *m/*2 and massless gauge bosons, the gluon and the photon. In fact the coupling between in the *B*<sup>1</sup> brane and the radion, *gr*¯, and the coupling  $\frac{\langle \sigma v \rangle n_{\chi} (I_{\text{FO}}) \simeq H(I_{\text{FO}})}{\sqrt{T_{\text{tot}}} N_{\text{tot}}^2}$  $\frac{1000}{1000}$  <del>1.00</del> ... 10 00 . between the SM fermion *f* in the *B<sup>T</sup>* brane and the radion, *grff*  $\overline{\phantom{a}}$  , are such that the such that that  $\overline{\phantom{a}}$ *.* (3.3) *mm<sup>f</sup>* !3*/*<sup>2</sup> for DM annihilation into SM fields are fermions *f* with mass *m<sup>f</sup>* . *m/*2 and massless gauge bosons, the gluon and the photon. In fact the photon. In the photon and the radion,  $\frac{1}{2}$  brane and the coupling between  $\frac{1}{2}$  brane and the coupling between  $\frac{1}{2}$  brane and the coupling brane and the coupling between  $\frac{$ between the SM fermion *f* in the *B<sup>T</sup>* brane and the radion, *grff*  $\sim$  are such that  $\sim$  $\frac{\sigma v}{2}$ *T*  $L(T_{\text{FO}}) \simeq H(T_{\text{FO}})$ The total cross-section for the process ¯ ! *<sup>f</sup>* ¯*<sup>f</sup>* mediated by the radion, is given by

**Only radion median** 
$$
\longrightarrow \chi + \bar{\chi} \rightarrow f + \bar{f}
$$

\n
$$
\underbrace{\sqrt{g_{r\chi\bar{\chi}}g_{rf\bar{f}}} \simeq \frac{m_{\chi}m_{f}}{6\tilde{\rho}_{T}^{2}}}_{\sigma_{f} \lesssim 10^{-4} \frac{m_{\chi}^{2}}{\tilde{\rho}_{T}^{4}}} \underbrace{\frac{1}{\tilde{\rho}_{T}} \left(1 - \frac{4m_{\chi}^{2}}{16\pi s} \right)^{1/2} \left(1 - \frac{4m_{\chi}^{2}}{s} \right)^{3/2}}_{\sigma_{f}v \lesssim 10^{-14} \text{ GeV}^{-2}} \times \frac{\chi + \bar{\chi} \rightarrow g + g}{\chi + \bar{\chi} \rightarrow \gamma + \gamma}
$$

between the SM fermion *f* in the *B<sup>T</sup>* brane and the radion, *grff*

between the DM and the DM and the DM and the SM. December 2000 is the SM. December 2000 is the SM. December 20<br>December 2000 is the SM. December 2<br>

<sup>1</sup> <sup>4</sup>*m*<sup>2</sup>

!1*/*<sup>2</sup>

<sup>1</sup> <sup>4</sup>*m*<sup>2</sup>

) are incoming (outcoming) momenta, are incoming (outcoming) momenta, are  $\alpha$ 

## No DM relic density **but** freeze-out from SM  $\longrightarrow$   $\frac{m_{\chi}}{T}$

## Relic density

$$
\sigma_r = \frac{1}{1152\pi} \frac{m_\chi^2}{\tilde{\rho}_1^4} \left[ \frac{z^2(7 - 11z^2 - z^4)}{(1 - z^2)} \tanh^{-1}(\sqrt{1 - z^2}) + \frac{169 - 121z^2 - 8z^4}{8(1 - z^2)^{1/2}} \right] \quad \text{with} \quad z^2 = \frac{4m_\chi^2}{s}
$$

$$
x_{\text{FO}} = m_\chi/T_{\text{FO}}
$$



![](_page_11_Figure_2.jpeg)

![](_page_11_Figure_6.jpeg)

(*p*) ¯(*q*)*r*(*k*) ) *i*

 $x_{\rm FO} = m_\chi/T_{\rm FO}$ 

![](_page_11_Picture_9.jpeg)

## Relic density

![](_page_12_Figure_1.jpeg)

*Q*=*u,d,s m<sup>N</sup>*

*Q*=*u,d,s*

$$
m_N\left(1-\sum_{Q=u,d,s}f_{T_Q}^{(N)}\right)
$$

$$
h \t f_N \sim 1/m_r^2
$$

*Q*=*u,d,s*

$$
^{\prime }(m_{N}+m_{\chi })
$$

![](_page_13_Figure_0.jpeg)

= *c<sup>N</sup>*

![](_page_14_Figure_1.jpeg)

XENON1T, DarkSide, SENSEI

### Accelerator searches The most promising dark matter searches at the LHC in our model are in our model are in events with missing en<br>The LHC in events with missing energy and are in events with missing energy and are in events with missing ener *<u>Accelerator</u>* cearcher

![](_page_15_Picture_8.jpeg)

1) DM searches at the LHC for our model: **missing energy events** and mono-Z/jets ATLAS collab. 1211.6096, 1502.01518 AILAS COIIAD. 1211.0090, 1902.0<br> **1** consideration in the boundary in the boundary in the boundary in the boundary into the boundary into the boundary in<br>Considering to the boundary interest into the boundary interest in the boundary in the boundary interest missing *<sup>m</sup><sup>r</sup>* & <sup>10</sup><sup>5</sup> GeV ⇣ *<sup>m</sup>*

2) For 
$$
m_e \le m_\chi \le m_p
$$
 fixed-target experiments NA64  
\n(CERN SPS) and LDMX (SLAC) could probe  
\nnew boson (radion)  
\n
$$
g_{ree} = \frac{m_e \tilde{\rho}_1}{\sqrt{6} \tilde{\rho}_T^2}
$$
\n
$$
g_{ree} = 2 \times 10^{-10} \left( \frac{\tilde{\rho}_1}{1 \text{ GeV}} \right) < 2 \times 10^{-9}, \text{ for } \tilde{\rho}_1 < 10 \text{ GeV}
$$

![](_page_15_Picture_4.jpeg)

![](_page_15_Picture_3.jpeg)

*me*⇢ ˜

 $\int$ 

*m<sup>r</sup>* & 10<sup>5</sup> GeV

the region 1 GeV . 10 GeV . 10 GeV the 90% CL bound �� December 2007 CL bound in the model we are model we are<br>The model we are mo  $m_r \geq 10^{-1} \text{ GeV} \left( \frac{m_\chi}{\chi} \right)$ ⇤<sup>3</sup> (¯*qq*)( ¯)*,* where ⇤ <sup>=</sup>  $m_r \gtrsim 10^{-1} \text{ GeV} \left( \frac{\chi}{10.5 \text{ V}} \right)$  $1 \text{ GeV} \lesssim m_\chi \lesssim 10 \text{ GeV}$  the evidence of the evidence of  $100 \text{ eV}$ .  $m_r \gtrsim 10^{-1} \text{ GeV}$ *mχ*  $\overline{1{\rm GeV}}$  )  $1 \text{ GeV} \leq m \leq 10 \text{ GeV}$  .  $\frac{m_r \approx 10^{-9} \text{ GeV}}{1000}$ in our case, particle produced in the 100 GeV electron scattering o↵ nuclei (*A, Z*), *eZ* ! *eZr*, followed  $\begin{array}{c|c|c|c|c|c} \hline \end{array}$  in  $>10^{-1}$  GeV.  $\begin{array}{c|c|c} \hline m_\chi & m_\chi \end{array}$  $10 \text{ eV} \le m \le 10 \text{ GeV}$   $m_r \approx 10 \text{ GeV}$ 

⇣ *m*

. <u>(5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.1) . (5.</u>

*r*⇢˜2

*T*

Using now data from ATLAS on  $\mathcal{I}_\mathcal{I}$  and  $\math$ 

 $\Lambda \gtrsim 40 \,\, \mathrm{GeV}$ 

 $1\,{\rm GeV}\,\lesssim\, m_\chi\,\lesssim\, 10\,$  GeV

 $\overrightarrow{ }$ 

 $\Lambda \gtrsim 40 \text{ GeV}$ 

 $\Lambda \gtrsim 40 \text{ GeV}$ 

2) For  $m_e \lesssim m_\chi \lesssim m_p$  fixed-target experiments NA64<br> *CERN SPS*) and LDMX (SLAC) could probe  $e^-Z \rightarrow e^-Zr$   $\longrightarrow$  invisible decay (CERN SPS) and LDMX (SLAC) could probe  $\rho$  and relatively large intensity large intensities: in particular the NA64 experiment at CERN SPS  $\alpha$  $f(x)$  For  $m \le m \le m$  fixed to rest experiments  $N164$ . in (CERN SPS) and LDMX (SLAC) could probe  $e^-Z \rightarrow e^-Zr$   $\longrightarrow$  in  $\epsilon^{-2}$  for  $m_e \gtrsim m_\chi \gtrsim m_p$  lixed-target experiments in A04<br>
(CERN SPS) and LDMX (SLAC) could probe  $e^-Z \rightarrow e^-Zr$   $\longrightarrow$  invisible decay

### Accelerator searches *i.e...* I.e. in the channel *accelerator* searches Accelerator searches *f*, such that *mr*  $\overline{a}$  ,  $\overline{b}$  ,  $\overline{c}$  , with a width a wid *mr*⇢˜<sup>2</sup> 1*m*<sup>2</sup>  $\overline{\phantom{a}}$ <sup>1</sup> <sup>4</sup>*m*<sup>2</sup> particular it will decay into the SM fermions *f*, such that *m<sup>r</sup> >* 2*m<sup>f</sup>* , with a width while lighter fermion contributions are highly suppressed. For values of  $\mathbb{R}^n$ ¯ = *N<sup>c</sup>* elerat *T* earches nes

!3*/*<sup>2</sup>

Otherwise, if *m<sup>r</sup> <* 2*m*, the invisible channel is forbidden and the radion decays into SM particles. In

particular it will decay into the SM fermions *f*, such that *m<sup>r</sup> >* 2*m<sup>f</sup>* , with a width

Τ

*f*

*f*

!3*/*<sup>2</sup>

*,* (5.6)

![](_page_16_Picture_5.jpeg)

![](_page_16_Picture_6.jpeg)

![](_page_16_Figure_1.jpeg)

**But** for  $m_r < 2m_\chi$  then  $r \rightarrow SM + SM$ **No** invisible decay and **no** bounds. Unless radion **decays** ut for  $m_{\nu} < 2m_{\nu}$  $r \rightarrow SM + SM$  bounds. Only stadion decays  $N$ <sup>*c*</sup> invisibl decay *T* <sup>1</sup> <sup>4</sup>*m*<sup>2</sup>  $2 \frac{m}{\sqrt{2}}$  while  $m_r < 2 m_\chi$  under  $m_r$  bounds. Unless radion decays *r*!*ff*  $\frac{1}{2}$  $r \rightarrow SM + SM$  outside the detector  $2 \left| \frac{1}{\sqrt{2\pi}} \right|$  **b** and **no c** *n also decay and no c a couple of*  $m_r < 2m_\chi$  *then decay into a couple of given decay into a couple of gas T* No invisible decay and no

$$
\sum_{\substack{0 \leq x \\ 0 \leq y \\ 0 \leq y \\ 0 \leq x \leq 15}} \frac{1}{\sqrt{1 - \left(1 - \frac{4m_f^2}{m_f^2}\right)^{3/2}} \left(1 - \frac{4m_f^2}{m_r^2}\right)^{3/2}}}{\sqrt{1 - \left(1 - \frac{4m_f^2}{m_r^2}\right)^{3/2}} \left(1 - \frac{4m_f^2}{m_r^2}\right)^{3/2}} \sum_{\substack{0 \leq x \\ 0 \leq x \leq 15 \\ -2, 0 - 1.5 - 1.0 - 0.5 - 0.0 - 0.5 - 1.0} \log_{10}[m_r/\text{GeV}]}
$$
\n
$$
\sum_{\substack{0 \leq x \\ 0 \leq x \leq 10 \\ 0 \leq x \leq 15 \\ \sqrt{1 - \left(1 - \frac{4m_f^2}{m_f^2}\right)^{3/2}} \sqrt{1 - \left(1 - \frac{4m_f^2}{m_f^2}\right)^{3/2}} \log \frac{1}{\sqrt{1 - \left(1 - \frac{4m_f^2}{m_f^2}\right)^{3/2}} \log \frac{1}{\sqrt{1 - \left(1 - \frac{4m_f^2}{m_f^2}\right)^{3/2}}}{\sqrt{1 - \left(1 - \frac{4m_f^2}{m_f^2}\right)^{3/2}} \left(1 - \frac{4m_f^2}{m_f^2}\right)^{3/2}}
$$
\n
$$
\sum_{\substack{0 \leq x \\ 0 \leq x \leq 15 \\ \sqrt{1 - \left(1 - \frac{4m_f^2}{m_f^2}\right)^{3/2}} \log \frac{1}{\sqrt{1 - \left(1 - \frac{4m_f^2}{m_f^2}\right)^{3/2}}}{\sqrt{1 - \left(1 - \frac{4m_f^2}{m_f^2}\right)^{3/2}}}
$$

regime of the strong coupling, the radion can also decay into a couple of gluons *r* ! *gg* with a width

*,* (5.6)

### Indirect constraints at the temperature *<sup>T</sup>*FO the distribution *<sup>Y</sup>*, provided by Eq. (6.3), goes to a constant value ⇠ <sup>2</sup>*x*2(*T*FO)*/*. To summarize, the radion enters thermal equilibrium with the SM at the temperature *T*FI = *mr/x*FI, while  $\mathcal{A}$  assuming the radion is already in the thermal bath) the DM  $\mathcal{A}$  and  $\mathcal{A}$ To solve numerically the system (6.3) we can make some approximations. Given that *<sup>r</sup>* ⌧ and at the temperature  $T$  the distribution  $\Box$ To solve numerically the system (6.3) we can make some approximations. Given that *<sup>r</sup>* ⌧ and **r** *r*, *r*, *c r constraints* indirect constraints *n*eq

![](_page_17_Figure_1.jpeg)

as its equilibrium distribution, until the freeze-out temperature *<sup>T</sup>*FO *< T<sup>d</sup>* for which */x*2(*T*FO) ⌧ 1. Then

di↵erent cross-sections are defined as: *<sup>r</sup>* ⌘ (*rr* ! SM+SM) ⇠ *<sup>c</sup>*<sup>4</sup>

be written changing variable to *Y<sup>r</sup>* = *nr/s* and *x* = *mr/T* as

*dt* + 3*Hn* <sup>=</sup> h*v*<sup>i</sup>

where  $r$  is a second contract of the small  $r$  is a second contract of the small  $r$ 

*<sup>r</sup>* is the decay width defined in Eqs. (5.6), (5.7) and (5.8) <sup>8</sup>, while the

*<sup>f</sup>* the radion lifetime is shorter and the BBN bound is Dominant channel  $r \rightarrow w$  and  $\mathcal{L}_{\mathcal{F}}$  $\rightarrow$   $T_{\rm FO} \gg T_{\rm FI}$  $\sigma \sim m_r \ll 1$   $\tau_r > 10 \text{ sec}$ Dominant channel  $r \to \gamma \gamma$  and <br>  $\sigma \sim m_r \ll 1$  *T*FO  $\gg T_{\text{FI}}$   $\rightarrow$   $\left(\begin{array}{ccc} I_r \ll I_r \ I_r \ll I_r \end{array}\right)$ Excluded by **BBN**  $\Gamma_r \ll Y_r^{\text{eq}}$  $Y_r \ll Y_r^{\text{eq}}$ <br> $\tau_r > 10 \text{ sec}$ Contour lines of the parameter are plotted in the right panel of Fig. 6, where it is shown that ⌧ 1,  $\text{Domain channel } r \to \gamma \gamma \text{ and }$   $\tau \to \tau \gamma$  and  $Y_r \ll Y_r^\text{eq}$  $\frac{r}{r}$  , see Fig. 5. In the case we can see Fig. 5. In the case we can see Fig. 5. In the case we can see Fig. 5. In the case of  $r$ 

![](_page_18_Figure_0.jpeg)

$$
\tau_r \simeq 0.4 \sec \left(\frac{\tilde{\rho}_T}{\text{TeV}}\right)^4 \left(\frac{\text{GeV}}{\tilde{\rho}_1}\right)^2 \left(\frac{\text{MeV}}{m_r}\right)^2 \text{ Dominant channel}
$$
\n
$$
r \to e^- e^+
$$

 $\langle \mathcal{A} \rangle$  **N**egion  $m_r$  $2a)$  Region  $m_r < 2m_e$   $\longrightarrow$  Dominant chan 2a) Region *mr* < 2*me*  $\sigma \sim m_r \ll 1$ 

### $\text{Log}_{10}(V_{\text{R}})$  $\frac{H}{L} \mathbf{K}$  is  $\mathbf{K}$  is  $\mathbf{K}$ . In particular, in the region where the region  $\mathbf{K}$ . If  $\mathbf{K}$  . If  $\mathbf{K}$  is  $\mathbf{K}$ . If  $\mathbf{K}$  is  $\mathbf{K}$ . If  $\mathbf{K}$  is  $\mathbf{K}$ . If  $\mathbf{K}$  is  $\mathbf{K}$ . If  $\mathbf{K}$  $Log_{10}(m_{\nu}/$ GeV)  $10(2018)$  0. Log to Convasced VI Log<sub>10</sub>(m<sub>x</sub>/GeV) HHFP 10 (2018) 050 M. Kawasaki, K. Kohri, T. Moroi and Y. Takaesu, *Phys. Rev. D 97 (2018) 023502*

*D* OIIIIIIdiil Chamici Dominant channel  $r \rightarrow e^-e^+$ 

![](_page_18_Picture_9.jpeg)

## Indirect constraints

![](_page_19_Figure_1.jpeg)

 $Log_{10} \sigma$ 

![](_page_19_Figure_3.jpeg)

### Indirect constraints

![](_page_20_Figure_1.jpeg)

![](_page_20_Figure_2.jpeg)

## Radion Cosmology

A **relic background** of radions from the time of their decoupling exists with temperature  $T_r(T_0) \approx 1.16 \text{ K} < T_{CMB}$ 

![](_page_21_Figure_1.jpeg)

*See Pokorski's talk on* **Saturday!!!**

![](_page_22_Figure_11.jpeg)

![](_page_22_Figure_12.jpeg)

• DM interacts **only** gravitationally (via radions) with the SM and its **relic density** and **detection** 

• The scale provided by the DM sector could explain the nanoHz SGWB from the PTA experiments. The dark matter mass window,  $m_\chi \in [0.15 \text{ GeV}, 2 \text{ GeV}]$ , consistent with all direct and indirect constraints **will** 

**constraints** processes are **decoupled** 

**allow to sharply concentrate** the experimental searches

• A spinoff is the **prediction of a light radion** which, in the future, **can be detected** in present fixed

target experiments, as NA64 at the CERN SPS, and the future LDMX at SLAC

• Future plans: **Ultra-light** radion cosmology, concrete **Inflationary** scenario in the multi-brane set up

# THANK YOU!!!