RADION COSMOLOGY AND DARK MATTER

BASED ON:
F. Koutroulis, E. Megías, SP, M.Quiros,
2403.06276(Phys.Rev. D)

DM AS A THERMAL RELIC FREEZED OUT FROM A THERMAL BATH?

RELIC ABUNDANCE OF A THERMAL RELIC χ (SOLVING THE BOLTZMAN EQUTIAN, e.g. KOLB&TURNER FOR THE EVOLUTION OF ITS NUMBER DENSITY)

$$\Omega h^2 \approx 0.1 \frac{x_{FO}}{10} \frac{10^{-9} GeV^{-2}}{< \sigma v >} \qquad x_{FO} = \frac{m_\chi}{T_{FO}} >> 1$$

FOR COLD DM

BUT $$10^{-9} GeV^{-2} \approx 1pb = 10^{-36} cm^2$$

SO WE NEED ITS ANNIHILATION CROSS SECTIONS INTO PARTICLES IN THE BATH OF ORDER 1pb!

AND THE FREEZE-OUT TEMPERATURE IS DETERMINED BY THE STANDARD RELATION

$$< \sigma v > n_\chi(T_{FO}) \approx H(T_{FO}) \approx \frac{T_{FO}^2}{M_{PL}}$$

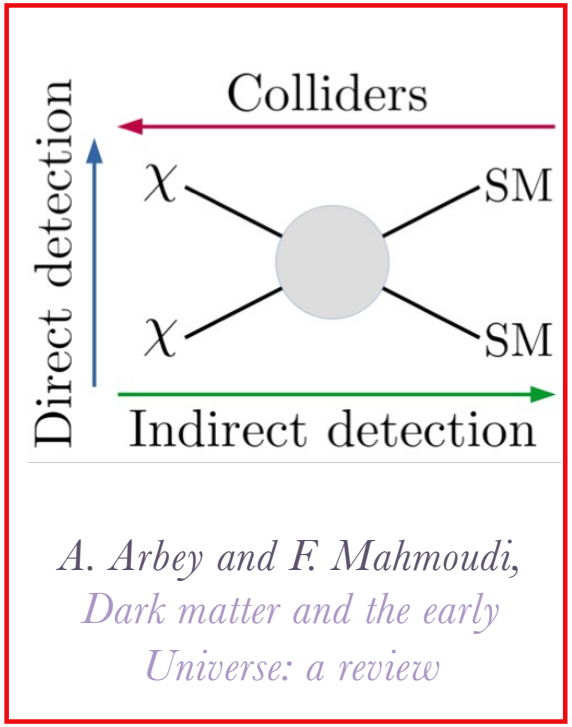
ON DIMENSIONAL GROUND

$$\sigma v \approx \frac{g^4}{m^2}$$

WHERE THOSE ARE THE CHARACTERISTIC FOR THE PROCESS COUPLING AND MASS

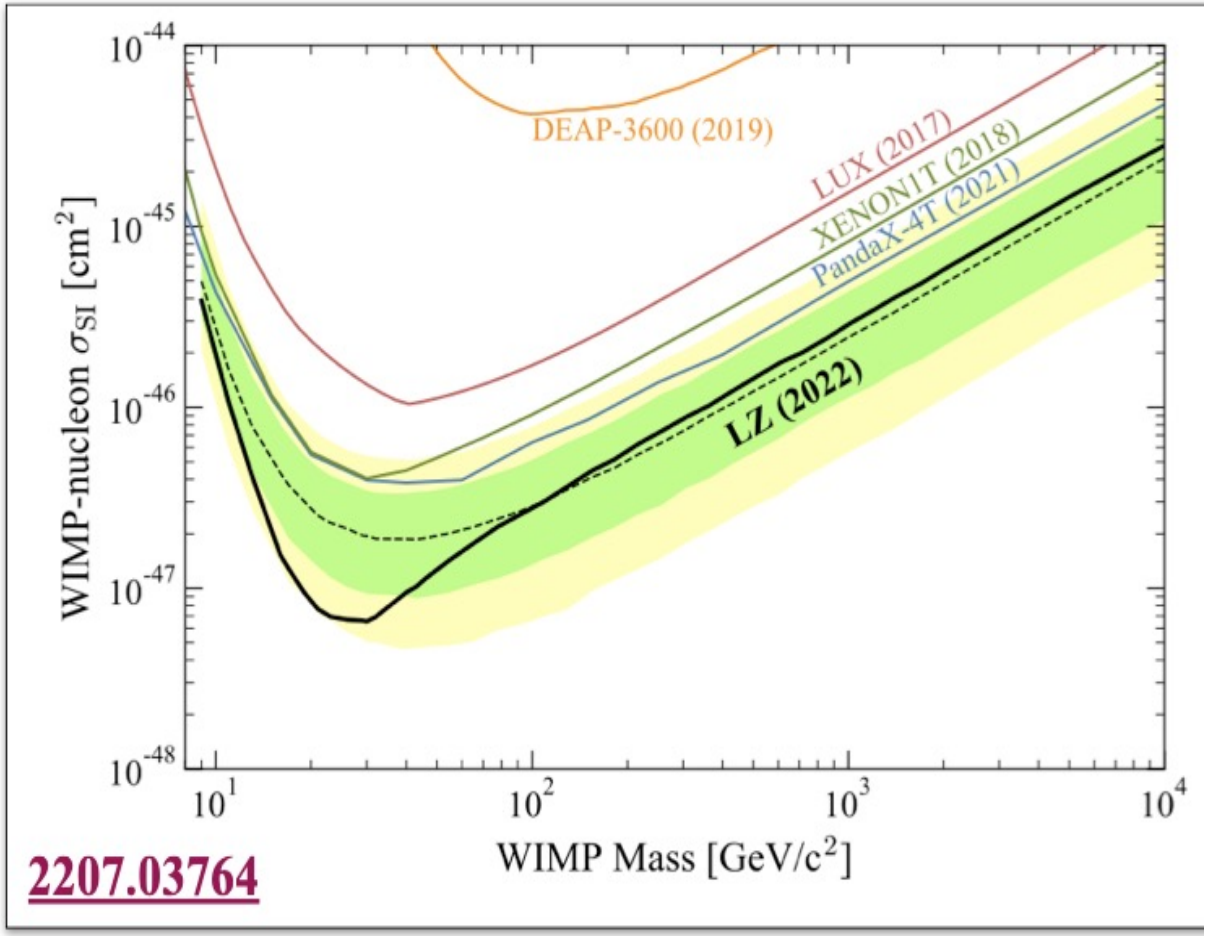
IT SO HAPPENS THAT WEAK COUPLING AND WEAK SCALE FIT TO THE PICTURE(WIMP MIRACLE) AND A NATURAL IDEA WOULD BE TO THINK ABOUT A FREEZE OUT FROM THE THERMAL EQUILIBRUM WITH THE SM PARTICLES.

BUT THE PROBLEM IS THAT THE DETECTION EXPERIMENTS RELY ON DM INTERACTION WITH SM, TOO
(UP TO DETAILS THAT CAN BE DIFFERENT)



A. Arbey and F. Mahmoudi,
Dark matter and the early Universe: a review

Direct Detection Bound



2207.03764

WIMP MIRACLE –AN ACCIDENTAL COINCIDENCE?

DETECTION SIGNATURES DEPEND ON THE DM INTERACTION WITH THE SM BUT THE

ANNIHILATION CROSS SECTION OF 1pb IS MORE “FLEXIBLE”:

$$\sigma v \approx \frac{g^4}{m^2}$$

DECREASING THE MASS SCALE AND THE COUPLING AND/OR MAKING THE ANNIHILATION CROSS SECTION DEPENDENT ON DIFFERENT SET OF PARAMETERS THAN THE DETECTION PROCESSES ONE CAN KEEP THE CROSS SECTION CONSTANT AND IT WOULD SOLVE THE PROBLEM

MANY IDEAS…

THERMAL UNIVERSE- SO MANY SUCCESSES…

Thermal production (freeze out) only with gravitational interactions?

CAN WE HAVE CORRECT RELIC ABUNDANCE AND AT THE SAME TIME SUPPRESSED, BUT STILL DETECTABLE INTERACTIONS OF DM WITH THE SM, WITH ONLY GRAVITATIONAL INTERACTIONS?

GO BEYOND THE EINSTEIN GRAVITY

RS-LIKE SCENARIOS WITH MULTIPLE BRANES

In theories with a warped fifth dimension, scales are naturally originating from the Planck scale by branes located at particular distances and stabilized by the Goldberger-Wise mechanism.

Gravitational sector contains scalars –radion KK modes.

MULTI-BRANE RS MODELS (NO DM):

Lykken&Randall, JHEP 06(2000)014;
Hatanaka et al., Prog.Theor.Phys. 102(1999)1213;
Kogan, Mouslopoulos,Papazoglou**, G.G.ROSS** and Santiago, Nucl. Phys.B584(2000)313;
Gregory, Rubakov and Sibiryakov, Phys.Rev.Lett. 84(2000)5928;
Kogan and **G.G.ROSS**, Phys.Lett.B485(2000)255;
Kogan, Mouslopoulos,Papazoglou and **G.G.ROSS** , Nucl. Phys.B595(2001)255;
Mouslopoulos, JHEP 05(2001) 038;
Kogan, Mouslopoulos,Papazoglou and **G.G.ROSS** , Nucl. Phys.B615(2001)191;
Oda, Phys.Lett. B472(2000),59;
Dvali and Shifman, Phys.Lett. B475(2000),295
…..

DM IN DARK SECTORS:

von Harling and McDonald,JHEP 08(2012) 048;
Foot and Vagnozzi, Phys.Rev. D91(2015) 02512;
Breitbach,,Kopp,Madge,Opferkuch and Schwaller, JCAP 07(2019) 007;
Fairbairn,Hardy and Wickens, JHEP 079 (2019) 044;
Brax,Fichet and Tanedo, Phys.Lett. B798(2019)135012;
Bento, Haber and Silva, Phys.Lett. B850(2024) 138501
…..

ONE INTERESTING MOTIVATION (e.g. K. AGASHE, P.DU, S. HONG and R. SUNDRUM - 1608.00526, JHEP)- PERFECT FRAMEWORK FOR:

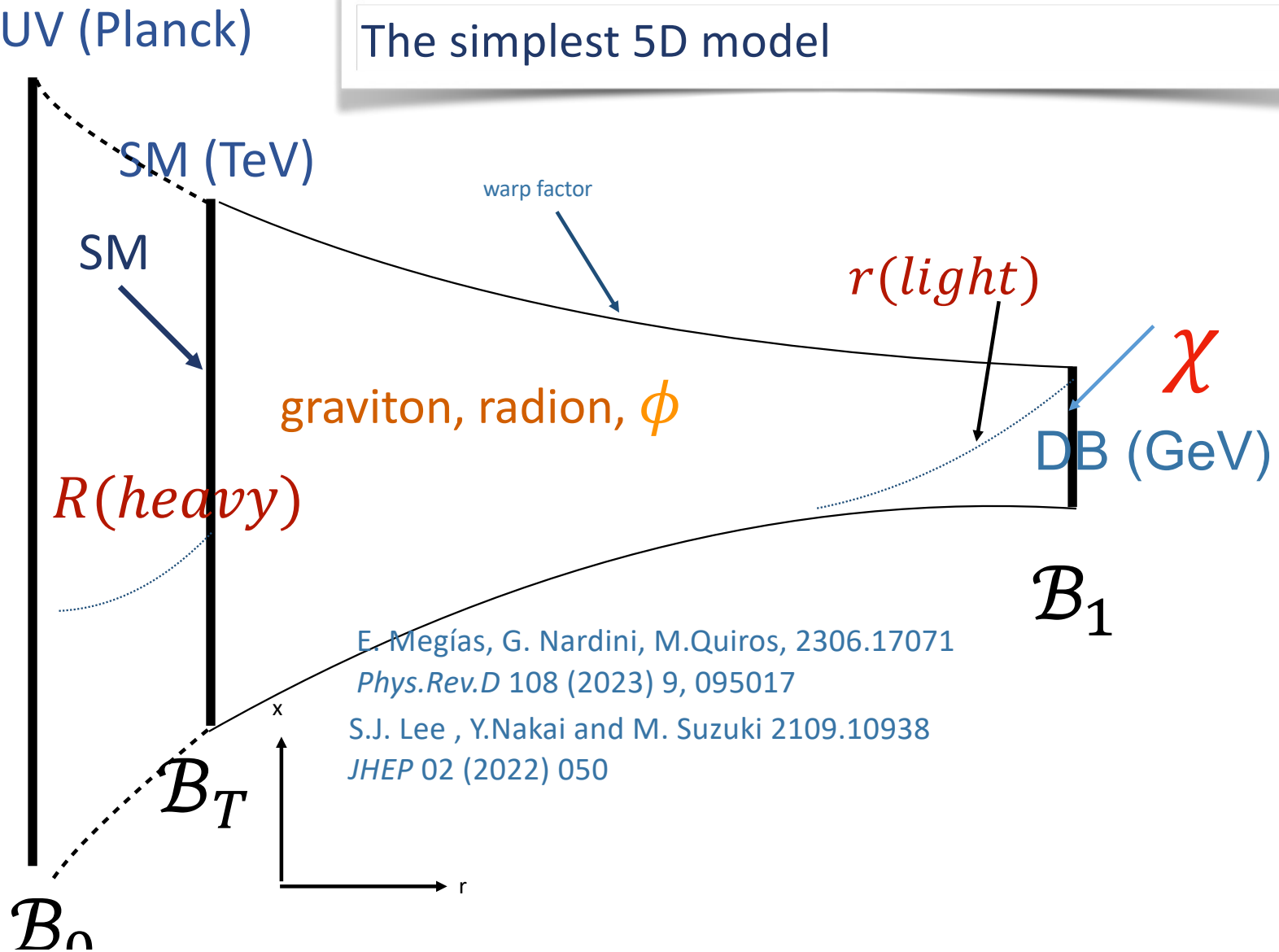
SEARCHING FOR A PHYSICS LYING BELOW THE SCALE AT WHICH THE HIERARCHY PROBLEM IS SOLVED (GIVEN ALL THE PRECISION AND FLAVOUR CONSTRAINTS), WHICH WOULD BE ALMOST (BUT NOT TOTALLY) DECOUPLED FROM THE SM AND WITHIN THE REACH OF NEAR FUTURE EXPERIMENTS

- "VESTIGES OF NATURALNESS"

ALSO 4D PERSPECTIVE (WITH EINSTEIN GRAVITY) = AdS/CFT DUALITY TO SEVERAL STRONG CONFINING SCALES AND NEW STATES (e.g.DILATONS)

DM IN 3-BRANE MODEL AS AN EXERCISE TO JUDGE SUCH POSSIBILITIES?

The simplest 5D model



E. Megías, G. Nardini, M.Quiros, 2306.17071
Phys.Rev.D 108 (2023) 9, 095017

S.J. Lee , Y.Nakai and M. Suzuki 2109.10938
JHEP 02 (2022) 050

The SM is located at the scale $\rho_T \approx 1\ TeV$ brane separated from the Planck scale by around 35 e-folds.

An extra Dark Brane at $\rho_1 \lesssim 100\ GeV << \rho_T$

scale separated from the Planck scale by around 40 e-folds.

BY THE WAY,

NANOGrav results can be accommodated in a strong FOPT at a scale 10 MeV-10 GeV

E. Megías, G. Nardini, M.Quiros, 2306.17071
Phys.Rev.D 108 (2023) 9, 095017

- Only the graviton and radion and the GW field can propagate in the bulk of the fifth dimension

That means that the matter localized on the Dark Brane has only "gravitational" interactions with the SM localized on the TeV brane

- That fits the properties of Dark Matter: mainly gravitational interactions with the SM to avoid experimental constraints

- Matter localized on the Dark Brane has strong enough interactions with the radion to trigger thermal relic density;

- A very simple DM model with a Dirac fermion χ localized on the Dark Brane with a mass m_χ

THE COUPLINGS OF THE RADION AND GRAVITONS TO BOTH BRANES ARE DETERMINED BY THE 5th DIMENSIONAL PROFILES

KK graviton couplings
In 4d effective theory

$$c_n(B) h_{\mu\nu}^{(n)}(x) T_B^{\mu\nu}$$

DIM [1/m]

$$c_1(B_1) \approx \frac{1}{\rho_1} \qquad c_1(B_T) \approx 4.6 \frac{1}{\rho_T} \left(\frac{\rho_1}{\rho_T}\right)^3$$

Radion couplings

$$c_r(B_T) r(x) T_T(x)$$

$$c_r(B_1) = \frac{1}{\sqrt{6}\rho_1} \qquad c_r(B_T) = \frac{1}{\sqrt{6}\rho_T} \left(\frac{\rho_1}{\rho_T}\right)$$

THE GRAVITON COUPLING TO THE SM BRANE IS MUCH SMALLER THAN THE RADION COUPLING. FORGET THE GRAVITON

- The model has 3 free parameters relevant for the DM calculation.
- The scale of the Dark Brane ρ_1.
- The DM mass m_χ. We consider it in the range $m_\chi < \rho_1$. In this way the non-relativistic annihilation into gravitons KK modes $\chi\overline{\chi} \to G_n G_n$ cannot take place
- The radion mass m_r. We take $m_r < m_\chi$ and $m_r \ll \rho_1$. In this way the radion decay $r \to \chi\overline{\chi}$ is closed and only the channel $r \to \mathrm{SM} + \mathrm{SM}$ is kinematically accessible

RADION AND DARK MATTER COSMOLOGY:
OUR SYSTEM IS THE SM THERMAL PLASMA + RADION r + DM χ

THE RELEVANT PROCESSES ARE

$$\chi\chi \to f\bar{f} \qquad \chi\chi \to gg \qquad \chi\chi \to \gamma\gamma$$

$$rr \to SMSM \qquad r \to SMSM$$

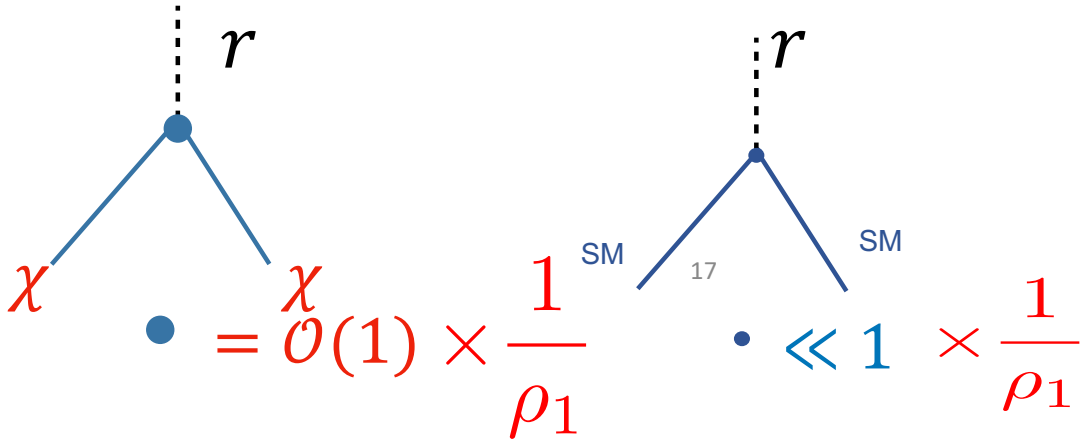
AND $\chi\bar{\chi} \to rr$

NEGLECTING IRRELEVANT KK GRAVITON EXCHANGE, THEY ARE ALL DETERMINED BY THE RADION COUPLINGS WITH THE SM AND IR BRANES

$$\mathcal{L} = -c_r(B) r(x) T_B(x) \qquad T_B(x) = \eta_{\mu\nu} T_B^{\mu\nu}$$

$$c_r(B_1) \approx \frac{1}{\rho_1} \qquad c_r(B_T) = \frac{1}{\sqrt{6}\rho_T}\left(\frac{\rho_1}{\rho_T}\right)$$

THE SMALL PARAMETER IS $c_r(B_T) \equiv c_r$



$$= \mathcal{O}(1) \times \frac{1}{\rho_1}$$

$$\ll 1 \times \frac{1}{\rho_1}$$

$$\Gamma(r \to SM + SM) \propto c_r^2$$

$$\sigma_r \equiv \sigma(rr \to SM + SM) \propto c_r^4$$

$$\sigma_0 \equiv \sigma(\chi\chi \to SM + SM) \propto c_r^2$$

$$\sigma_\chi \equiv \sigma(\chi\chi \to rr) \propto c_r^0$$

THE MAGNITUDE OF THOSE CROSS SECTIONS DETERMINES THE EVOLUTION OF NUMBER DENSITIES OF DM AND RADION (BOLTZMANN EQS)

TWO QUALITATIVELY DIFFERENT REGIONS

$m_r > 2m_e$ The decay r -→ SM SM plays important role in ensuring its equilibrum With the SM; simple qualitative picture of solutions to Boltzmann eqs. Short enough life-time for not to perturbed the BBN bound on light DOF

$m_r < 2m_e$ Requires more advanced analysis of BE; excluded by BBN bounds unless very Long lived; a candidate on DM in the latter case?

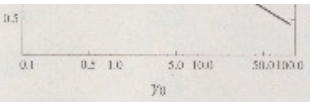


Figure 5: *The freeze-in temperature x_{fi} as a function of γ_0.*

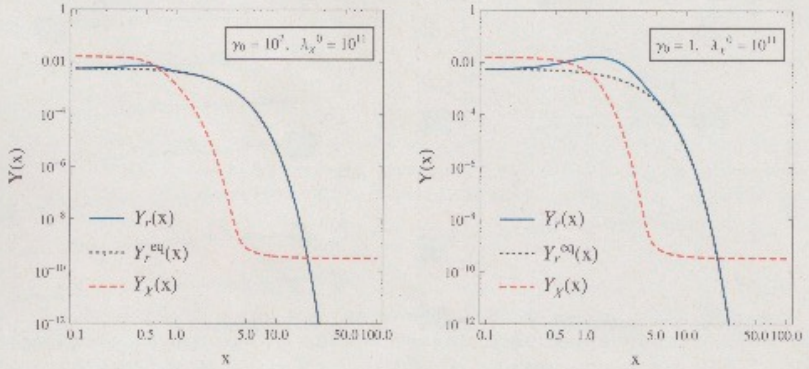


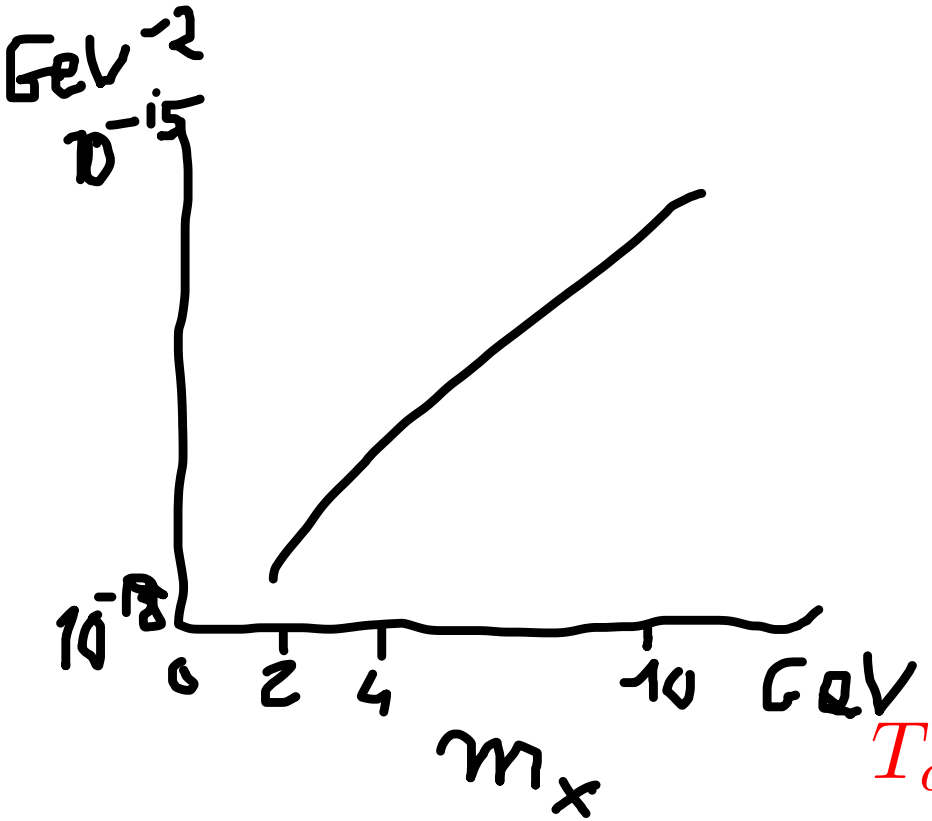
Figure 7: *Left panel: Plots of $Y_r(x)$ and $Y_\chi(x)$ from Eq. (6.6) for $\gamma_0 = 10^2$ and $\lambda_\chi^0 = 10^{11}$. Right panel: The same as in the left panel for $\gamma_0 = 1$. We have considered $m_\chi = 1\ GeV$ and $m_r = 0.2\ GeV$ in both panels.*

DM INTERACTION WITH THE SM BY ECHANGE OF THE RADION:

$$< \sigma v > << 10^{-9} GeV^{-2}$$

HUGE OVERABUNDANCE BUT NO PROBLEM WITH DETECTION?

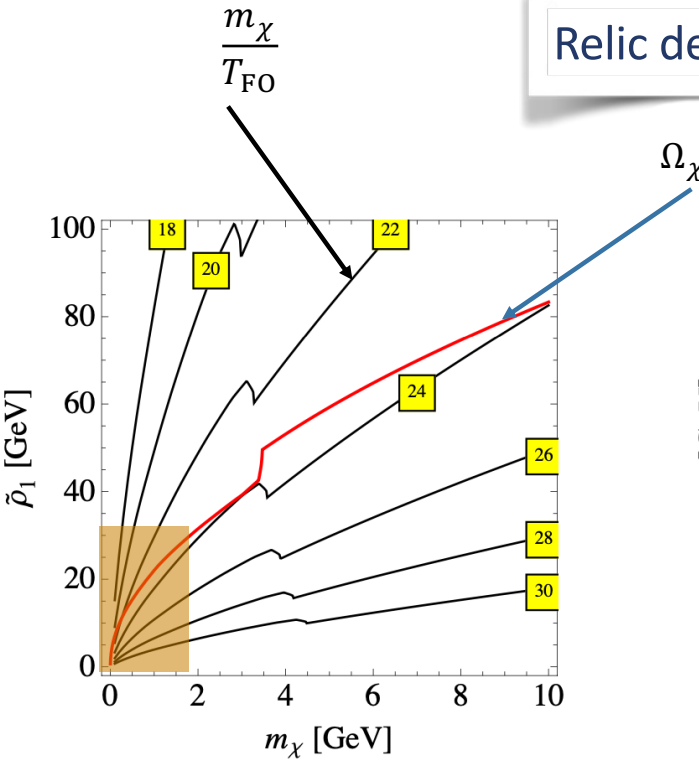
$$\chi\chi \to f\bar{f} \qquad \chi\chi \to gg \qquad \chi\chi \to \gamma\gamma$$

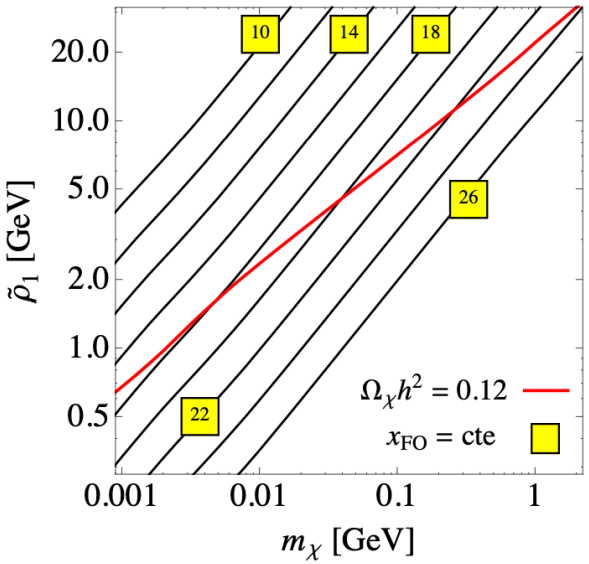


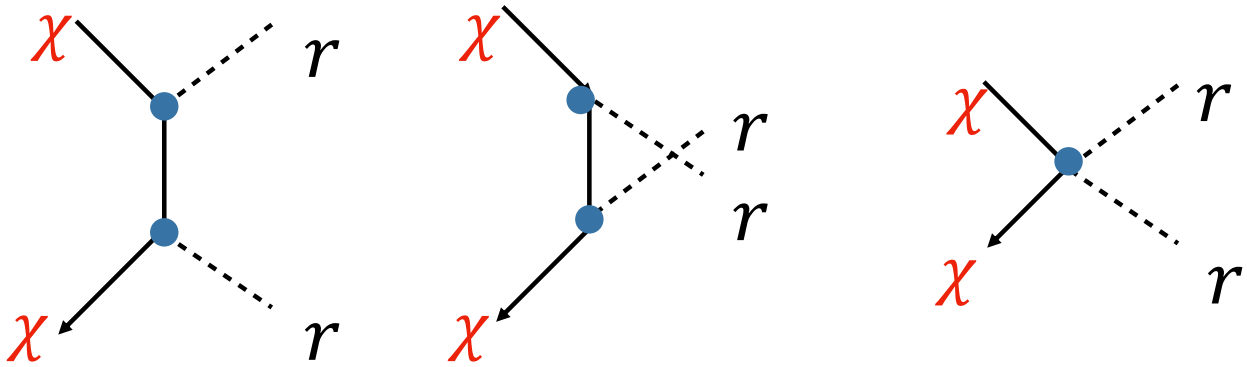
$$T_d \approx 0.2\ GeV + 0.1 m_\chi$$

Relic density

PTA region



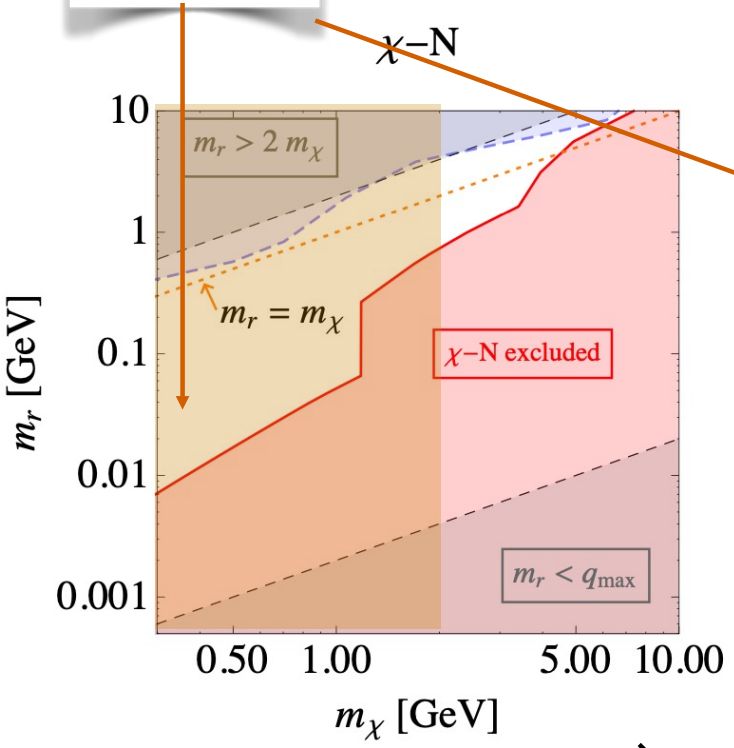


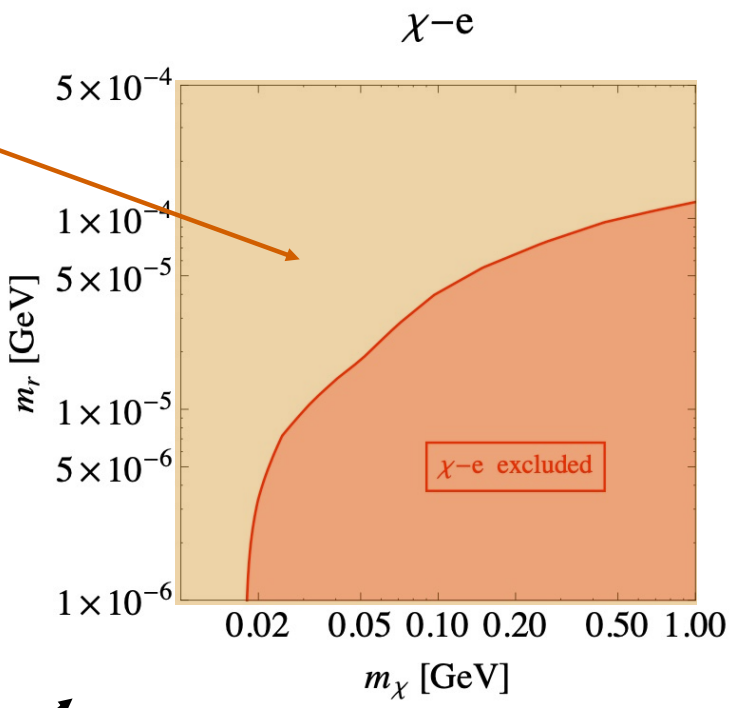


DM AND RADION AS “VESTIGES OF NATURALNESS”?

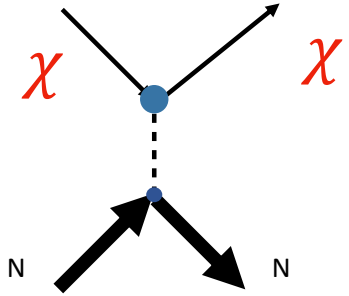
PTA region

Direct detection





FOR SUB-GeV DM ALMOST NO BOUNDS
FROM recoil experiments



ACCELERATOR SEARCHES, E.G. Z boson + Missing energy sensitive to

$$\mathcal{L} = \frac{m_q}{\Lambda^3}(q\bar{q})(\chi\bar{\chi})$$

(Z boson radiated from a quark)

EXP. Bound $\Lambda > 0.1GeV$

In the model $\Lambda = 1GeV$

$$\Lambda = (\frac{6m_r^2\rho_T^2}{m_\chi})^{1/3}$$

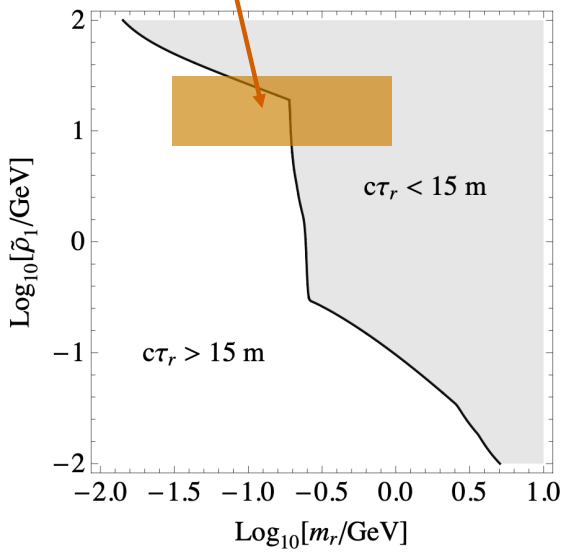
For

$$m_r = 1MeV,\ m_\chi = 6GeV,\ \rho_T = 1TeV$$

One gets $\Lambda = 1GeV$

PTA region

Accelerator searches



i) $m_e < m_r < m_p$ NA64 @ CERN SPS

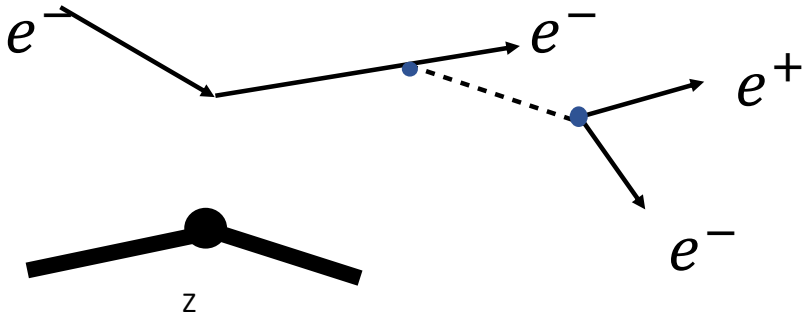
Our prediction is

$$g_{ree} = 2\times10^{-10}(\tilde{\rho}_1/GeV) \lesssim 10^{-9}$$

In agreement with present bounds, based on invisible decay of the messenger

$$r \to \chi\bar{\chi}$$

ii) The radion can decay inside or outside the detector depending on the values of the parameters m_r and ρ_1



SUMMARY

TRUE OR NOT, IT IS AMUSING… (GRAHAM ROSS)

ONLY “GRAVITATIONALLY” INTERACTING DM WITH CORRECT THERMAL ABUNDANCE, DETECTABLE BUT AVOIDING THE PRESENT BOUNDS.

4D INTERPRETATION, WITH SEVERAL STRONG CONFINIG SCALES?

$$\sigma_f \approx \frac{m_\chi m_f}{\rho_T^2} \frac{1}{16\pi s} \qquad \sigma_g \propto \frac{m_\chi}{\rho_T^2} \alpha_3^2$$

AT T ~ Td the DM decouples from the SM but keeps thermal equilibrum with radions through

$$\chi\chi \longleftrightarrow rr$$

to freeze out at Tfo~20-25

INTERESTING COSMOLOGICAL CONSTRAINTS (BBN)

ONE OBTAINS A LOWER BOUND ON THE DM MASS > 150 MEV FROM THE CONSTRAINT ON THE NUMBER OF RELATIVISTIC DEGREES OF FREEDOM* (IF THE RADION IS LIGHT AND DECOUPLES FROM THE EQUILIBRUM WITH THE SM TOGETHER WITH DM). Neff is inversly proportional to the number of the SM degrees of freedom at the radion decoupling temperature roughly equal Td(the dark fermion decoupling Temperature) and the later depends on its mass (see the figure).

- The constraint is due to the fact that the relation between the Hubble and the temperature Depends on the number of relativistic degrees of freedom. And that relation determines the temperature of decoupling of the nucleons via Gamma~H, so their abundanc

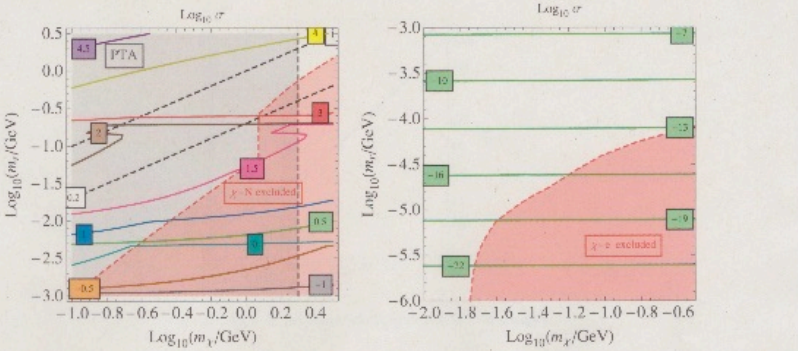


Figure 6: *Left panel: Contour lines of σ for $m_\sigma > 1$ MeV. We also display the area of $m_\chi \lesssim 2$ GeV where PTA results can be reproduced (shadowed gray area), and the forbidden region for the spin-independent DM-nucleon cross section (shadowed red area). The dashed straight lines correspond to fixed values of m_σ/m_χ. Right panel: Contour plots of σ for $m_\sigma < 1$ MeV. The forbidden region for the DM-electron collision is also displayed (shadowed red area).*

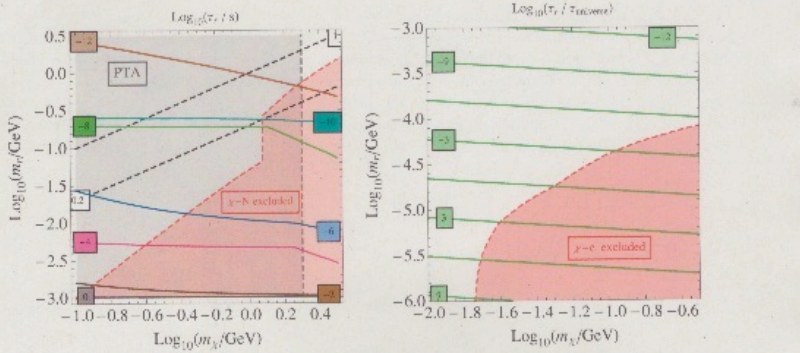


Figure 8: *Left panel: Contour lines of τ_σ/sec for $m_\sigma > 1$ MeV. The dashed straight lines correspond to fixed values of m_σ/m_χ. Right panel: Contour lines of $\tau_\sigma/\tau_{\rm universe}$ for $m_\sigma < 1$ MeV.*

The model parameters

- The values of ϕ at branes: $\phi(0) = v_0, \phi(r_1) = v_1$
- From the potential on the IR brane: $\lambda_1 \simeq 1 + \ell(\kappa^2/6)\Lambda_1$ $\Lambda_1(\phi) = \Lambda_1 + \frac{1}{2}\gamma(\phi - v_1)^2, \gamma \to \infty$ (stiff limit)
- N (# degrees freedom of holographic theory) Vs k: $N = 4\pi M_{\mathrm{Pl}}\ell, \ell = 1/k$
- The brane scale ρ (related to the interbrane distance by the warp factor): $\ell\rho = e^{-r_1 k} \simeq (v_0/v_1)^{1/u}$

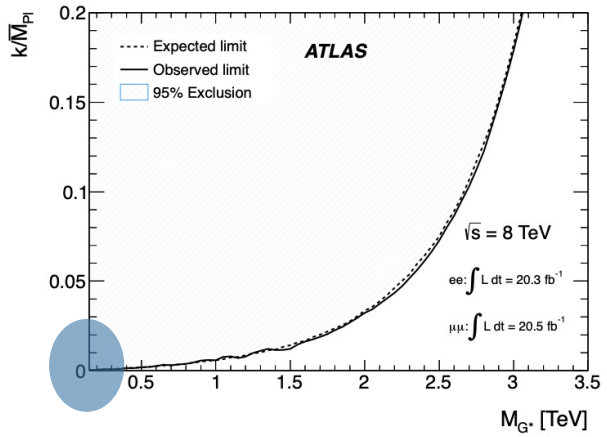
i) Deviation from Newtonian potential

$$V(R) = -\frac{m_1 m_2}{8\pi M_{\rm Pl}^2}\frac{1}{R}(1+\Delta R)), \Delta R \simeq \frac{4}{3}e^{-m_1 R}, \Rightarrow m_1 \gtrsim 10^{-11}\text{GeV}$$

ii) KK graviton production at the LHC

$$\mathcal{L} = -\frac{1}{M_5^{3/2}}h_{\mu\nu}(z_b, x)T^{\mu\nu}(x) = -\sum_n \frac{k z_b}{M_{\rm Pl}} \cdot \epsilon_n(z_b) \cdot h_{\mu\nu}^{(n)}(x)T^{\mu\nu}, \epsilon_n(z_b) = \frac{z_b}{z_1}\frac{J_2(x_n z_b/z_1)}{J_2(x_n)}, J_1(x_n) = 0$$

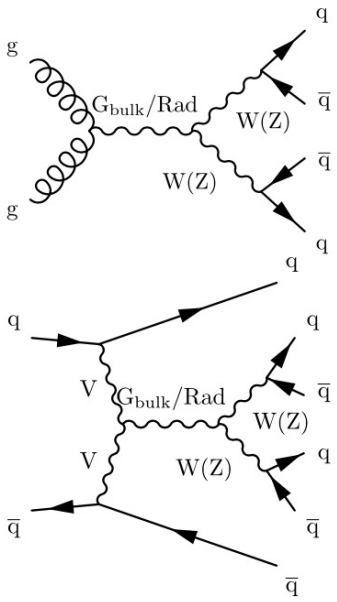
For $Z_b = Z_T$ there is a suppression factor with respect to the coupling in RS as $\epsilon(z_T) \simeq 5\times10^{-9}$ which brings the bounds to MeV-subGeV



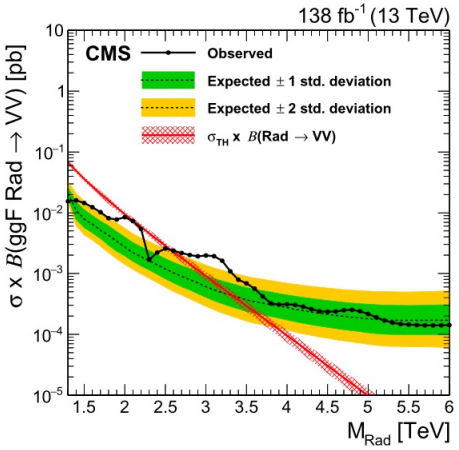
preliminary

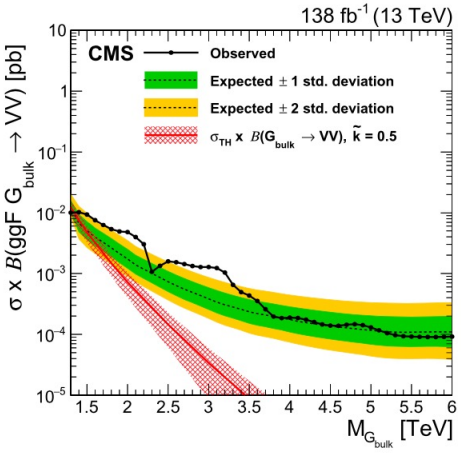
ATLAS Coll., 1405.4123

WHAT IS THIS?



CMS coll. 2210.00043





preliminary

$M^{\mathrm{rad}} > 2.7\mathrm{TeV}$ $M^{\mathrm{grav}} > 1.4\mathrm{TeV}$

Bounds only valid for $\epsilon_n(z_b) = 1$, for $\epsilon_n \ll 1$ the experiments do not have enough sensitivity

The model parameters

- The values of ϕ at branes: $\phi(0) = v_0, \phi(r_1) = v_1$
- From the potential on the IR brane: $\lambda_1 \simeq 1 + \ell(\kappa^2/6)\Lambda_1$ $\Lambda_1(\phi) = \Lambda_1 + \frac{1}{2}\gamma(\phi - v_1)^2, \gamma \to \infty$ (stiff limit)
- N (# degrees freedom of holographic theory) Vs k: $N = 4\pi M_{\rm Pl}\ell, \ell = 1/k$
- The brane scale ρ (related to the interbrane distance by the warp factor): $\ell\rho = e^{-r_1 k} \simeq (v_0/v_1)^{1/u}$

- The $\mathcal{B}_1$ location is stabilized by the Goldberger-Wise mechanism where a stabilizing bulk field ϕ is introduced
- The back-reaction of ϕ on the metric (creating the radion potential fixing the interbrane $\mathcal{B}_T - \mathcal{B}_1$ distance) is computed using the superpotential method with $W = 12M_5^3 k + uk\phi^2$ (M_5 is the 5D Planck mass and $u \ll 1$ a small parameter)
- There are two phases which are solutions of the 5D Einstein equations:
- BH deconfined phase (high T):
- RS confined phase (low T):

$$ds^2 = e^{-2A(r)}[h(r)dt^2 - d\vec{x}^2] - \frac{1}{h(r)}dr^2$$

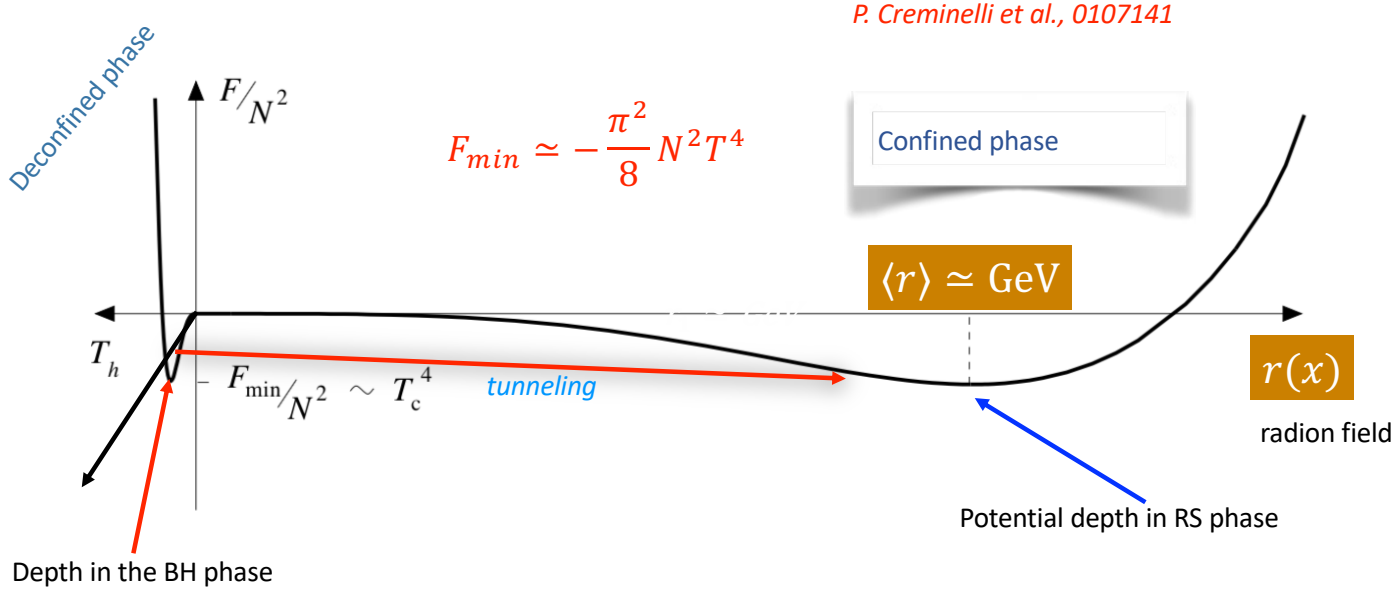
$$ds^2 = e^{-2A(r)}\eta_{\mu\nu}dx^\mu dx^\nu - dr^2$$

blackening factor $h(r_h) = 0$, event horizon (EH) r_h

The phase transition

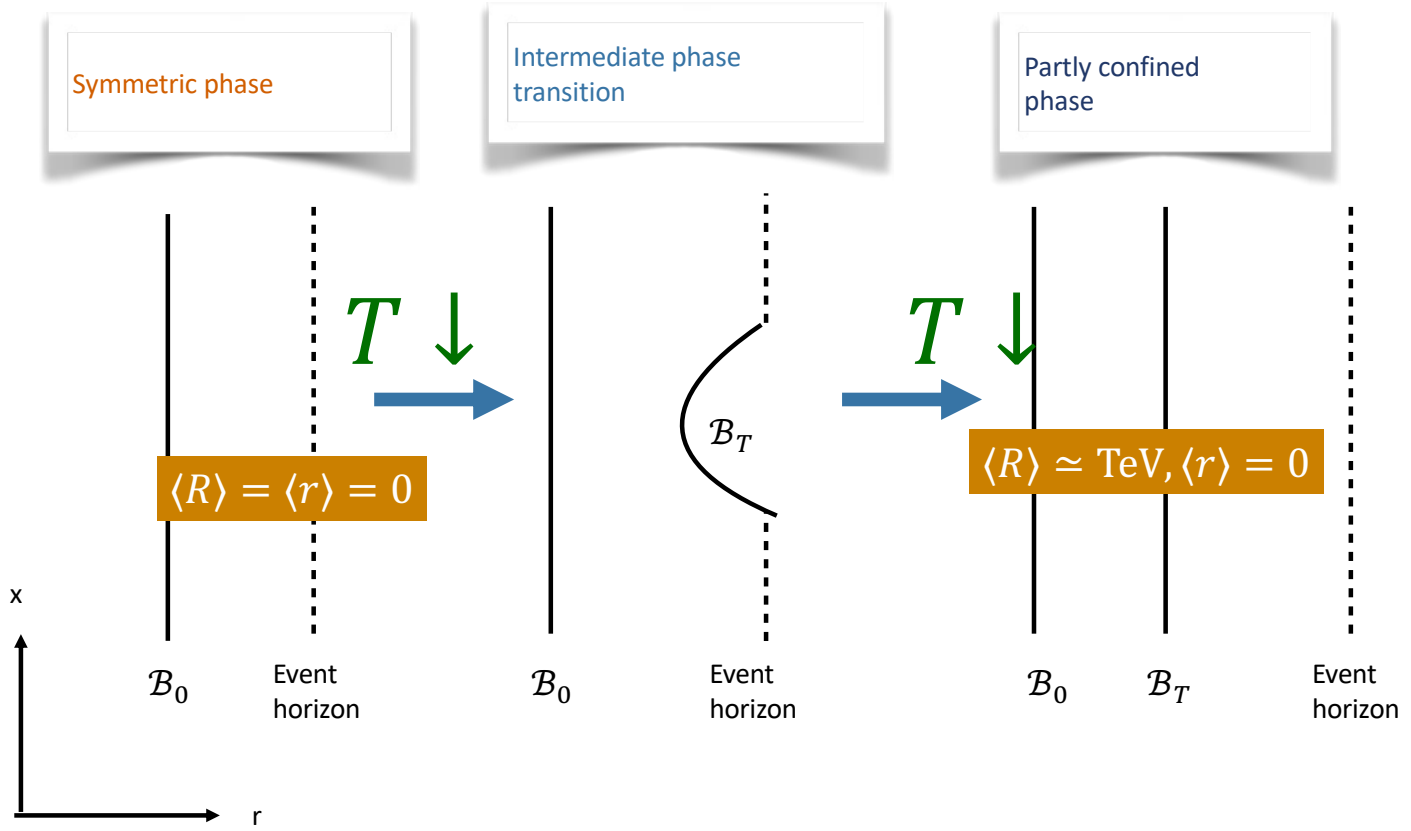
Cartoon of free energies

P. Creminelli et al., 0107141

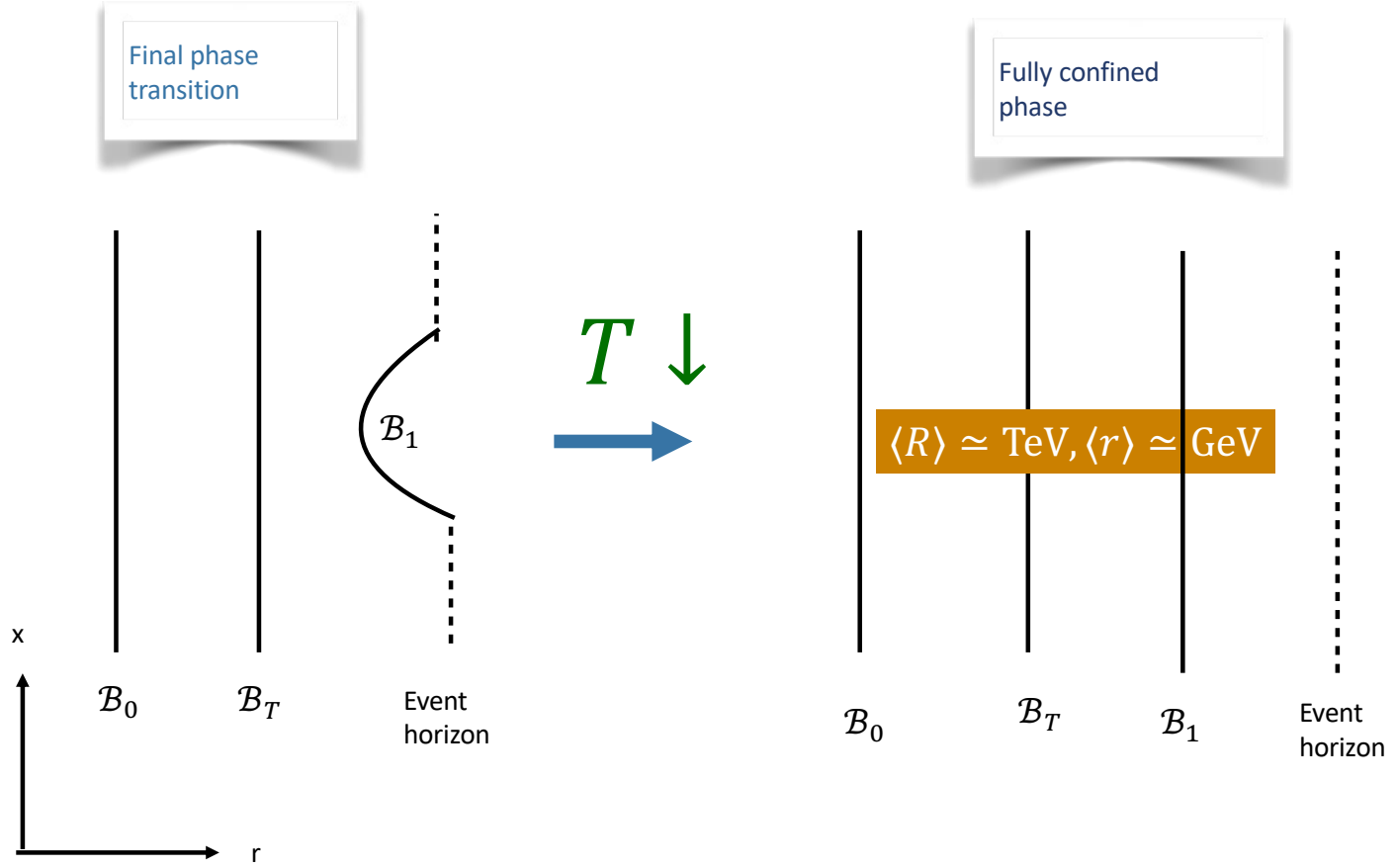


THE SCALAR PERTURBATIONS GIVE A TOWER OF RADION KK MODES. THE LIGHTEST MODE IS LOCALIZED

TOWARDS THE IR BRANE AND GIVES THE DOMINANT CONTRIBUTION TO THE INTERACTION BETWEEN THE FIELDS LOCALIZED ON THE IR AND INTERMEDIATE BRANES.



$$kr_h \simeq -\log(\pi T/k)$$



$$kr_h \simeq -\log(\pi T/k)$$

Conclusion

CHANGE IT

We have found a 5D setup for explaining the NANOGrav SGWB at nanoHz frequencies and a simple model for Dark Matter

We have introduced an Dark Brane in the RS setup at the GeV scale associated with the presence of a new conformal sector

At the confinement scale of the conformal theory the radion gets a VEV in a FOPT with gravitational waves fitting the PTA data

Dark matter is localized in the Dark Brane so that in the holographic interpretation is a composite state at the confinement phase transition.

Consistency between PTA data and DM relic density plus all constraints is achieved in a region of the parameter space (ρ_1, m_χ, m_r)

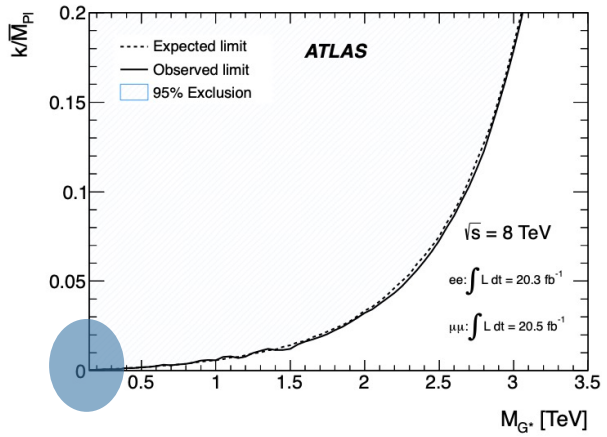
i) Deviation from Newtonian potential

$$V(R) = -\frac{m_1 m_2}{8\pi M_{\rm Pl}^2}\frac{1}{R}(1+\Delta R)), \Delta R \simeq \frac{4}{3}e^{-m_1 R}, \Rightarrow m_1 \gtrsim 10^{-11}\text{GeV}$$

ii) KK graviton production at the LHC

$$\mathcal{L} = -\frac{1}{M_5^{3/2}}h_{\mu\nu}(z_b, x)T^{\mu\nu}(x) = -\sum_n \frac{k z_b}{M_{\rm Pl}} \cdot \epsilon_n(z_b) \cdot h_{\mu\nu}^{(n)}(x)T^{\mu\nu}, \epsilon_n(z_b) = \frac{z_b}{z_1}\frac{J_2(x_n z_b/z_1)}{J_2(x_n)}, J_1(x_n) = 0$$

For $Z_b = Z_T$ there is a suppression factor with respect to the coupling in RS as $\epsilon(z_T) \simeq 5\times10^{-9}$ which brings the bounds to MeV-subGeV



preliminary

ATLAS Coll., 1405.4123

Gravitational waves

- A cosmological first order phase transition produces a SGWB whose power spectrum depends on the dynamics of the bubbles and their interactions with the plasma
- The amplitude of GW $h^2\Omega_{GW}$ and the peak frequency f_p depend on parameters of the phase transition
- The strength of the phase transition
- The normalized inverse time duration of the phase transition

$$\alpha_* = \frac{|F_d(T_R) - F_c(T_R)|}{\rho_d(T_R) - E_0}$$

$$\frac{\beta}{H_*} = T_R \frac{dS_E(T_R)}{dT_R}$$

and by interactions with the plasma (sound waves and hydrodynamic turbulence)

- The SGWB for very strong phase phase transitions $\alpha_* > 1$ is expected to be dominated by bubble collisions
- For bubble collisions the spectrum is given by $(v_\omega \simeq 1, T_* \simeq T_R)$

$$h^2\Omega_{GW} = h^2\overline{\Omega}_{GW}\frac{3.8(f/f_p)^{2.8}}{1+2.8(f/f_p)^{3.8}}, h^2\overline{\Omega}_{GW} \simeq 0.6\times10^{-5}\left(\frac{H_*}{\beta}\frac{\alpha_*}{1+\alpha_*}\right)^2$$

$$f_p \simeq 18\text{nHz}\frac{\beta}{H_*}\frac{T_R}{100\text{MeV}}g_c^{1/6}(T_R)$$

E. Megias, G. Nardini, M.Q., 2005.04127, 1806.04877

Compelling evidence for the existence of Dark Matter,

On different astrophysical scales
(galactic, clusters of galaxies, cosmological scale,…)

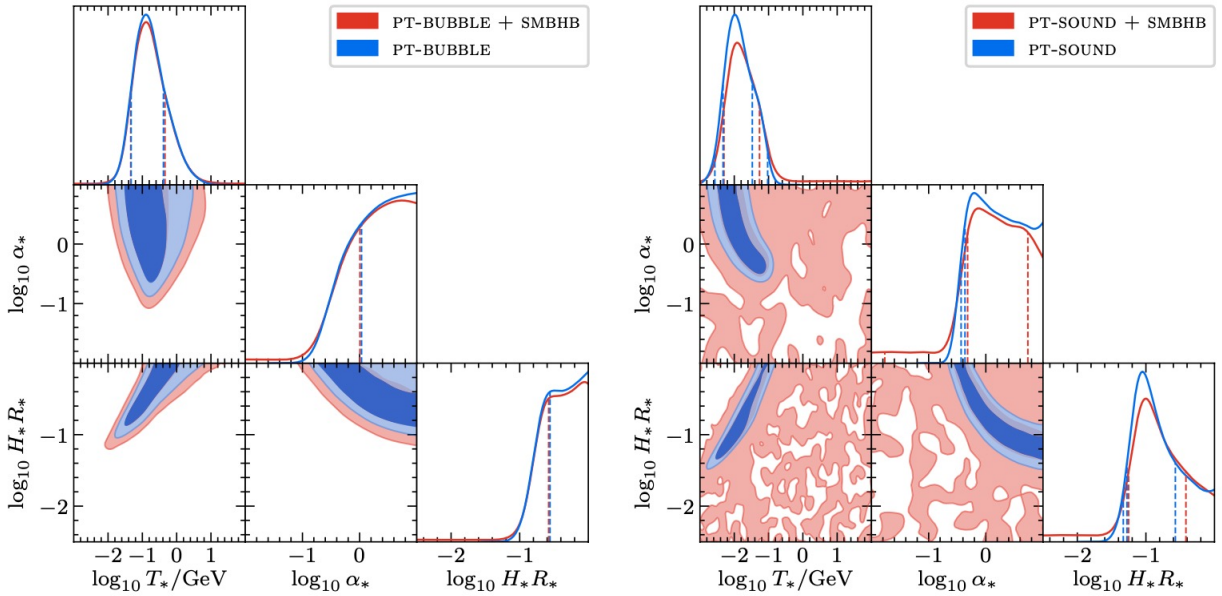
84% of the matter in the Universe is DARK
Stable (DM life time bigger than the current age of the Universe, $\rho_\chi(t_0) \sim \rho_\chi(t_{\rm cmb})$)

(dominantly)Non-relativistic

"Weakly" interacting with the SM

Numerical results and comparison with NANOGrav data

NANOGrav Collaboration, 2306.16219



NANOGrav results (95%): $\log_{10}\alpha_* > -0.5, \log_{10}(\beta/H_*) < 1$

NANOGrav results (95%): $T_R < 1.75\mathrm{GeV}$

NANOGrav results: $h^2\Omega_{GW} \lesssim 10^{-6}, f_p \gtrsim 10^{-8}\mathrm{Hz}$