DARK MATTER ON DARK BRANES

BASED ON:
F. Koutroulis, E. Megías, SP, M.Quiros, 2403.06276

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

DM AS A THERMAL RELIC?

RELIC ABUNDANCE OF A THERMAL RELIC χ (SOLVING THE BOLTZMAN EQUTIAN, e.g. KOLB&TURNER)

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

FOR COLD DM

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

SO WE NEED CROSS SECTIONS OF ORDER 1pb!

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

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

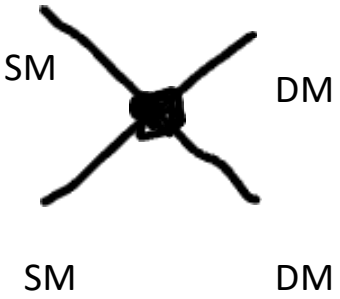
ON DIMENSIONAL GROUND

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

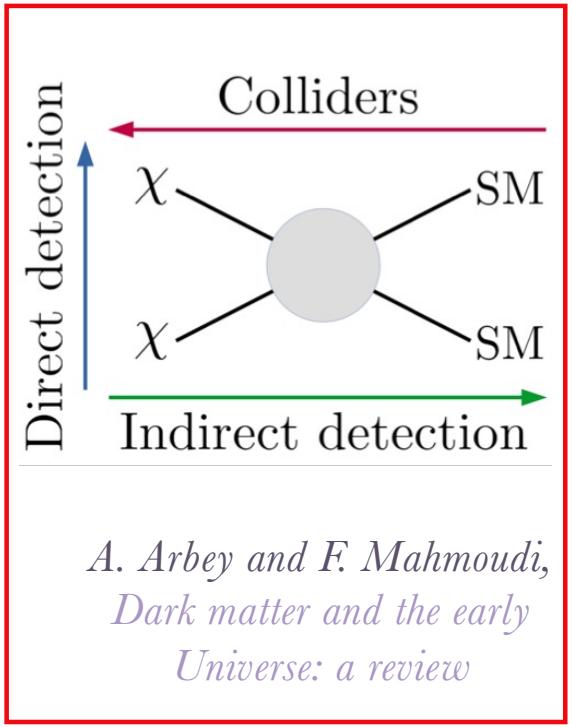
WHERE THOSE ARE THE CHARACTERISTIC FOR THE PROCESS COUPLING AND MASS

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.

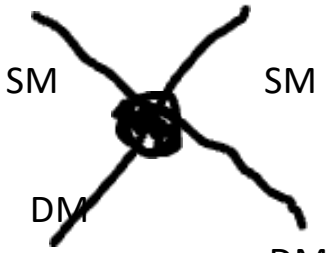
BUT THE PROBLEM IS THAT THE DETECTION EXPERIMENTS RELY ON DM INTERACTION WITH SM, TOO
(UP TO DETAILS THAT CAN BE DIFFERENT)



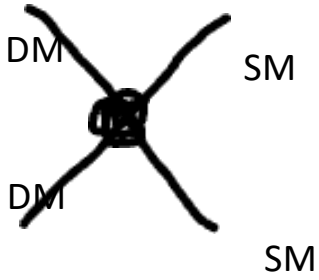
BUT DARK MATTER DETECTION EXPERIMENTS



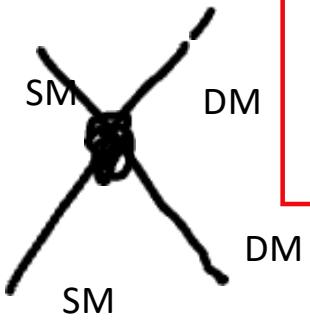
A. Arbey and F. Mahmoudi, Dark matter and the early Universe: a review



Direct

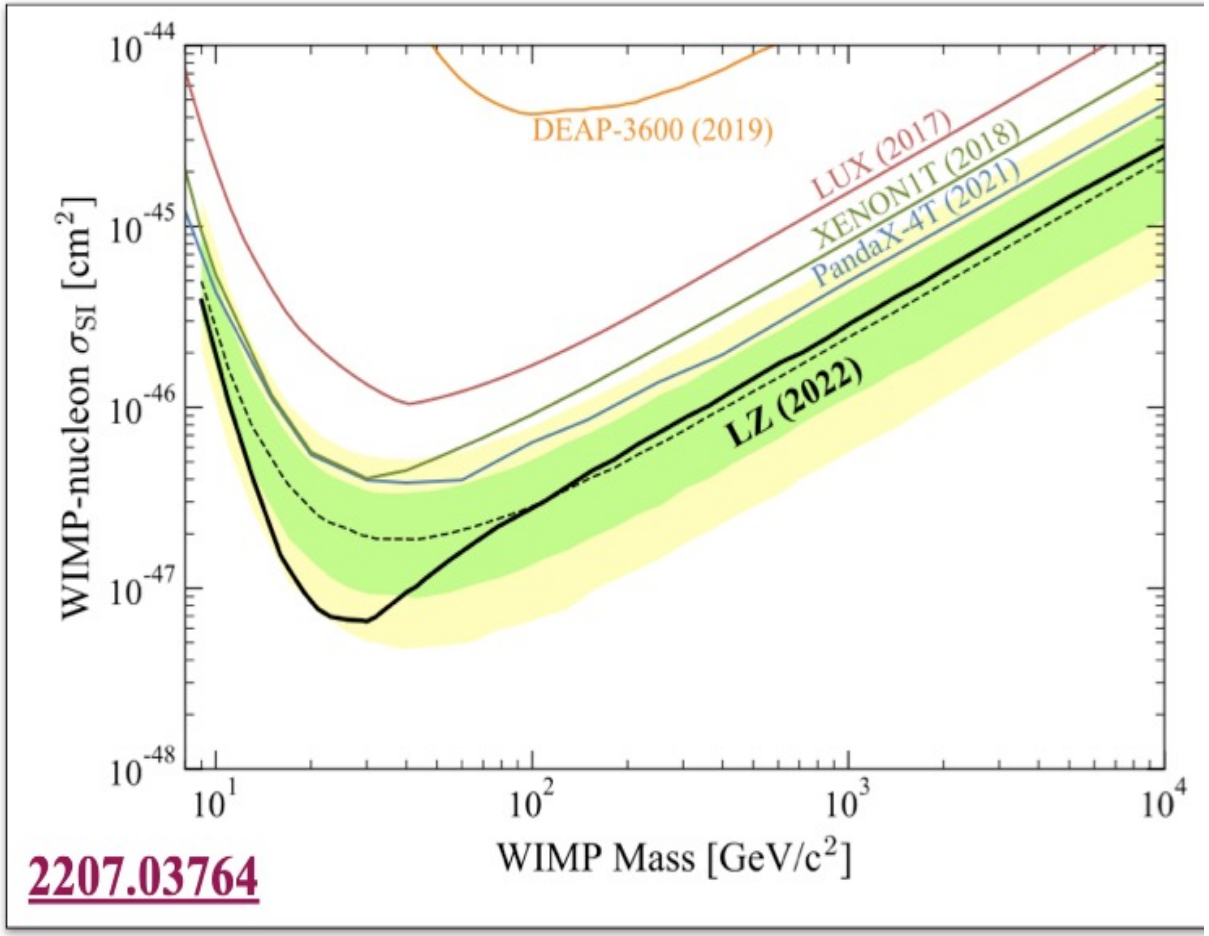


INDIRECT



COLLIDERS

Direct Detection Bound



2207.03764

WIMP MIRACLE –AN ACCIDENTAL COINCIDENCE?

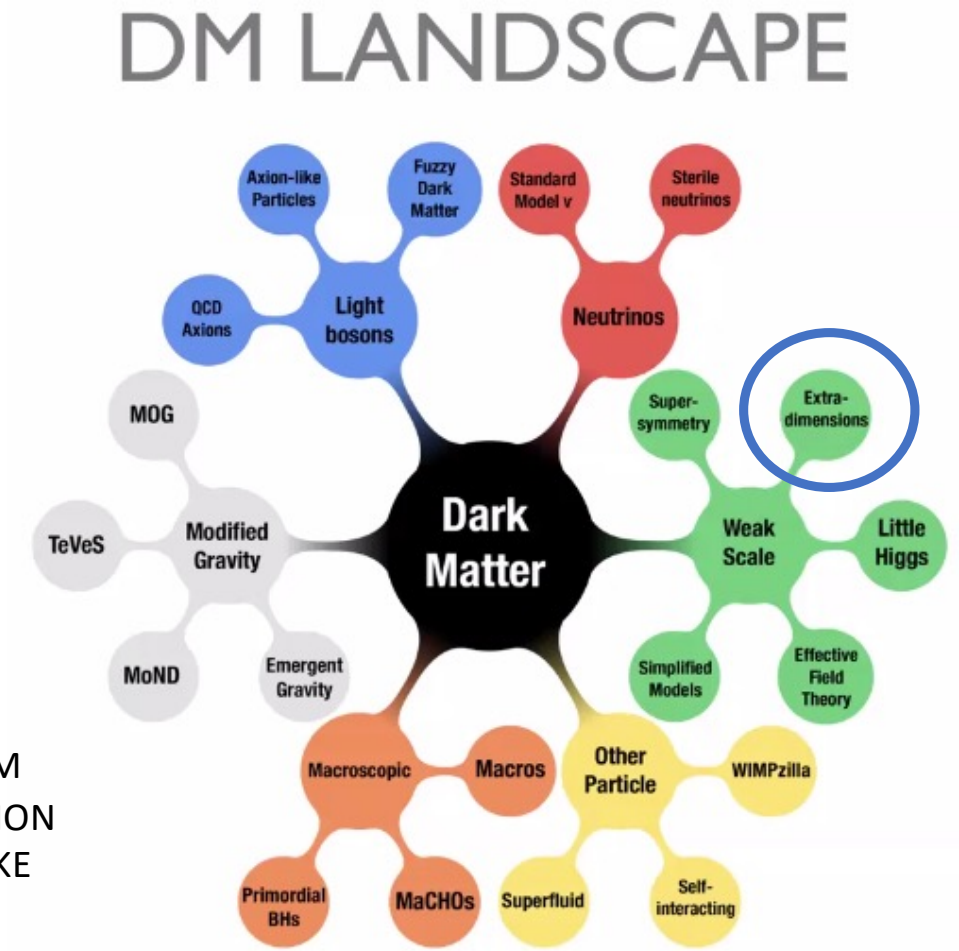
DETECTION SIGNATURES DEPEND ON THE DM INTERACTION WITH THE SM BUT THE

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…



I WOULD RATHER CLASSIFY DM ACCORDING TO ITS PRODUCTION MECHANISM …. BUT LET'S TAKE THIS ARTIST VIEW

Michele Redi talk

Undettered by the multitude of the proposals, we come up with our own

ACTUALLY, THE DIFFERENCE IS THAT WE DON'T INVENT A NEW MODEL, WE JUST TAKE AN EXISTING ONE AND CHECK IT'S PREDICTIONS FOR DM.

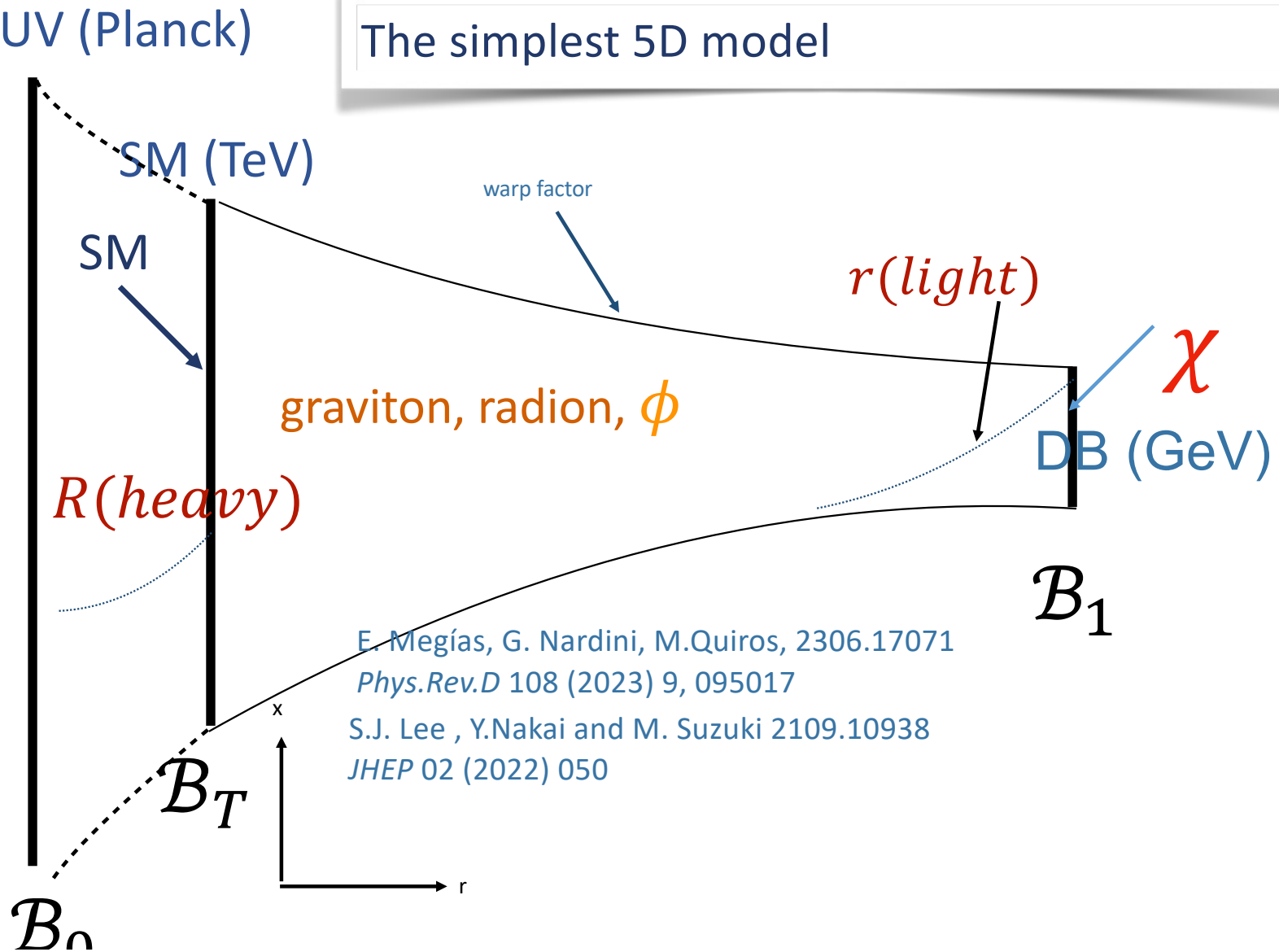
THIS IS SIMILAR TO WIMPS IN SUPERSYMMETRY (IN BOTH CASES THE MOTIVATION IS THE HIERARCHY PROBLEM)

THERMAL UNIVERSE- SO MANY SUCCESSES…

Thermal production (freeze out) but only gravitational interactions?

CAN WE HAVE CORRECT RELIC ABUNDANCE AND AT THE SAME TIME SUPPRESSED INTERACTIONS WITH THE SM, WITH ONLY GRAVITATIONAL INTERACTIONS?

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

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
…..

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

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

PTA results suggest an extra Dark Brane in RS setup at $\rho_1 \approx 1\ GeV$

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

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, radion and the stabilizing 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 Direct Detection experiments

- 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

- The model has 3 free parameters
- The scale of the Dark Brane ρ_1. Its range to describe the PTA data is $\rho_1 \in [10\mathrm{MeV}, 10\mathrm{GeV}]$, but we also have considered a broader range, up to 100 GeV
- 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 will assume that $m_r < m_\chi$ 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

KK graviton couplings

$$c_n(B_T)h^{(n)}_{\mu\nu}(x)T^{\mu\nu}_T \qquad c_1(B_T) \approx 4.6\frac{1}{\rho_T}(\frac{\rho_1}{\rho_T})^3$$

$$c_1(B_T)c_1(B_1) \approx 4.6\frac{1}{\rho_T^2}(\frac{\rho_1}{\rho_T})^2$$

Radion couplings

$$c_r(B_T)r(x)T_T(x) \quad c_r(B_T) = \frac{\rho_1}{\sqrt{6}\rho_T^2} \qquad c_r(B_1) = \frac{1}{\sqrt{6}\rho_1}$$

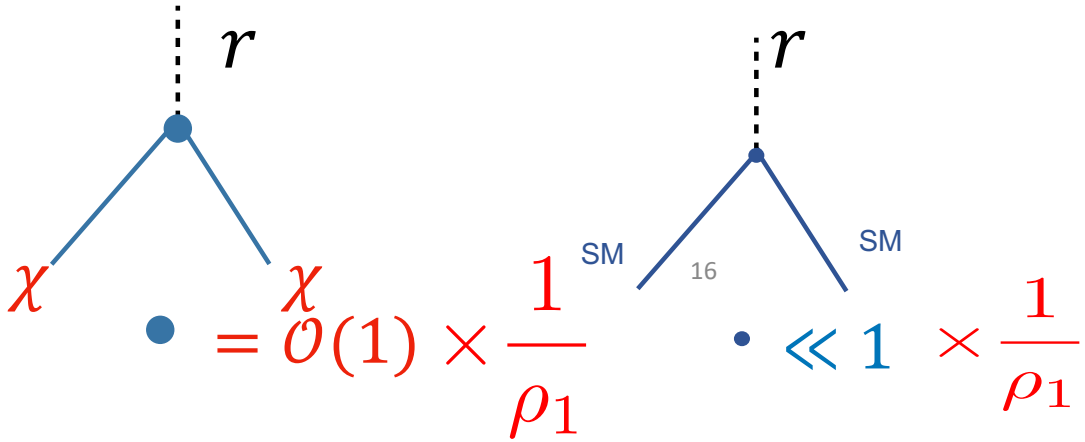
The Dark Matter

We can use the Dark Brane to support a Dark Sector (essentially) without perturbing the FOPT properties

The simplest possibility is assuming a Dirac fermion χ localized on the DB with a mass m_χ

The SM is localized on the TeV brane

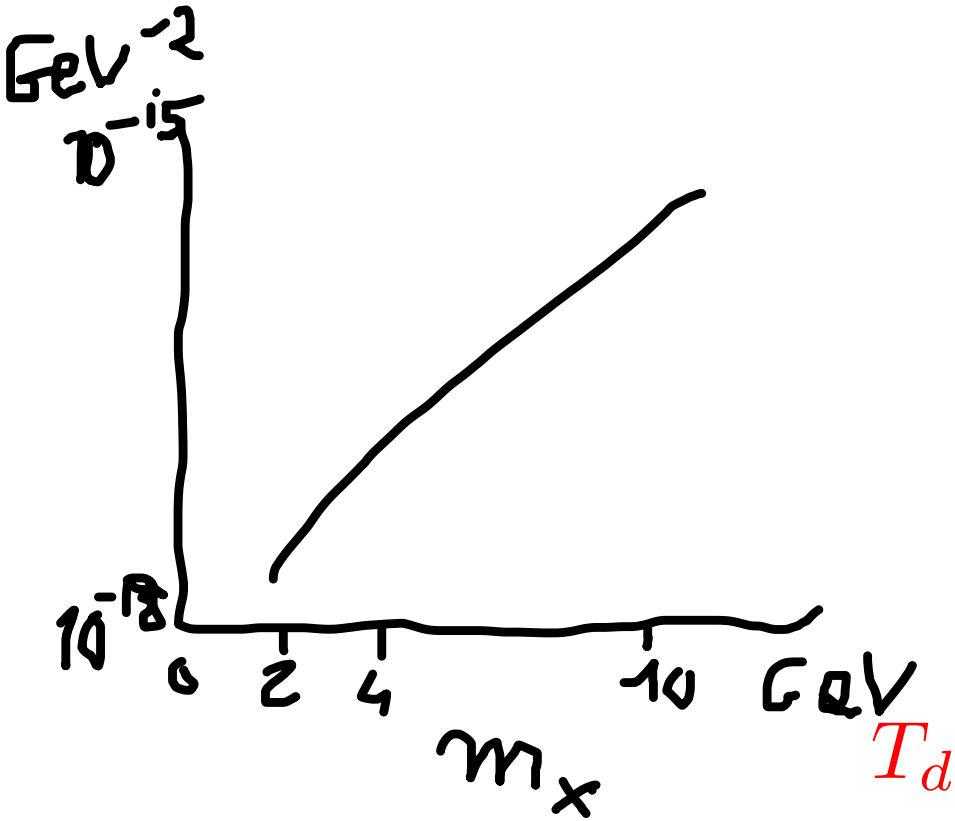
They are connected mainly via the radion with couplings:



RADION INTERACTION WITH THE SM: $< \sigma v ><< 10^{-9} GeV^{-2}$

HUGE OVERABUNDANCE BUT
NO PROBLEM WITH DETECTION?

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



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

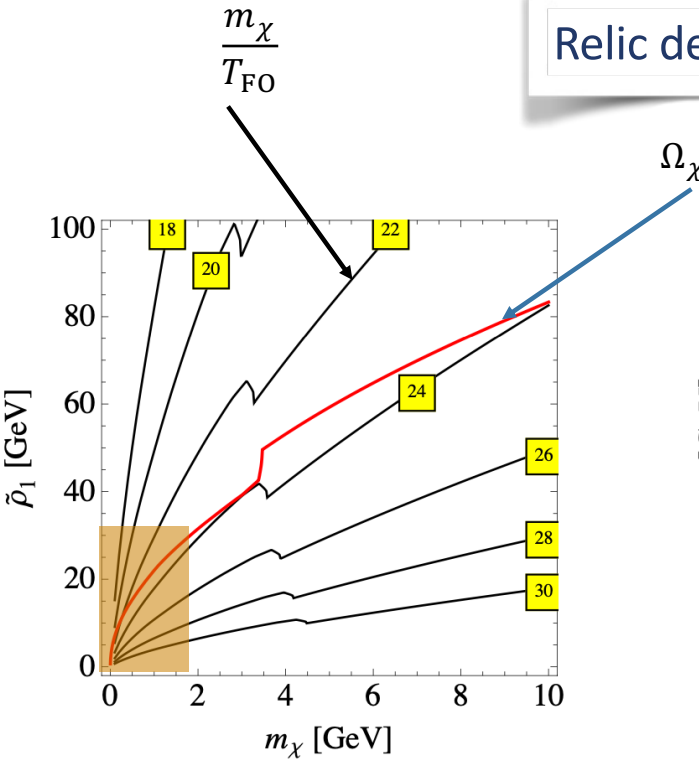
AT T ~ Td the DM decouples from the SM but keeps thermal equilibrum with radions through

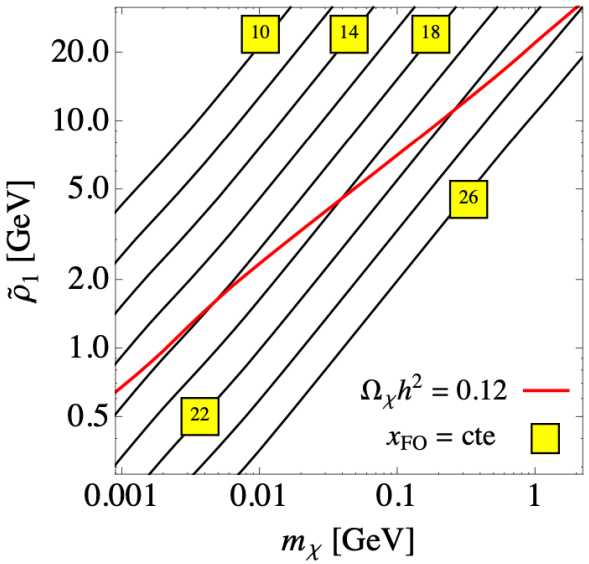
$$\chi\chi \longleftrightarrow rr$$

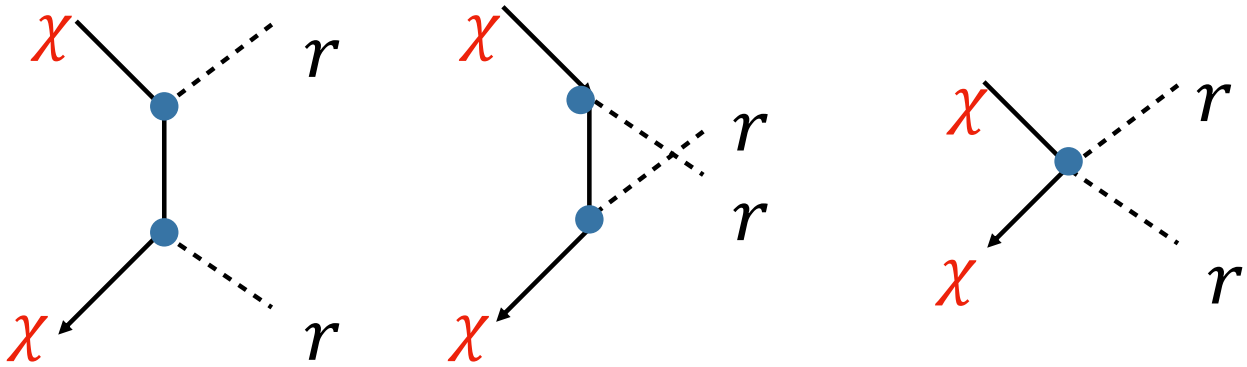
to freeze out at Tfo~20-25

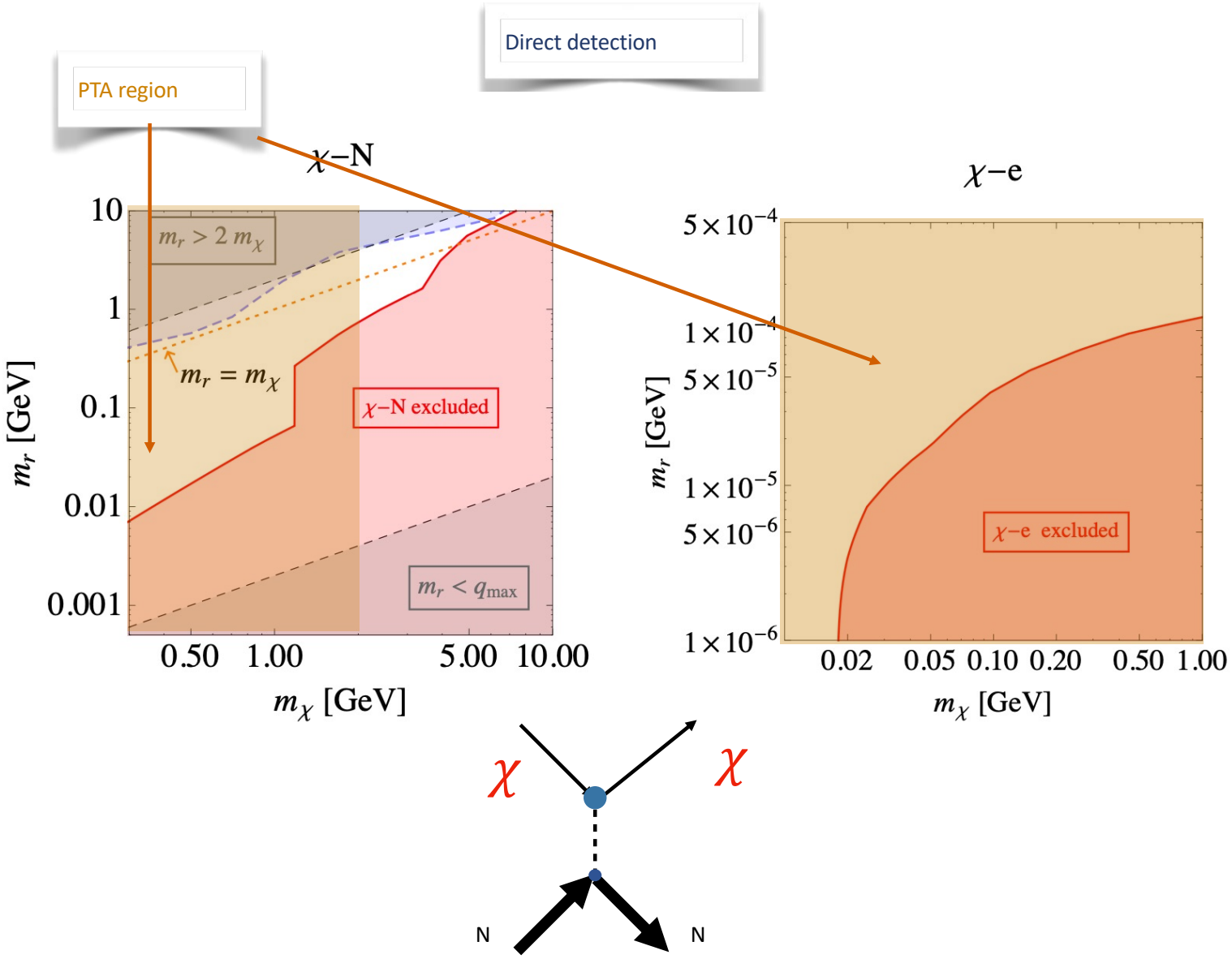
Relic density

PTA region



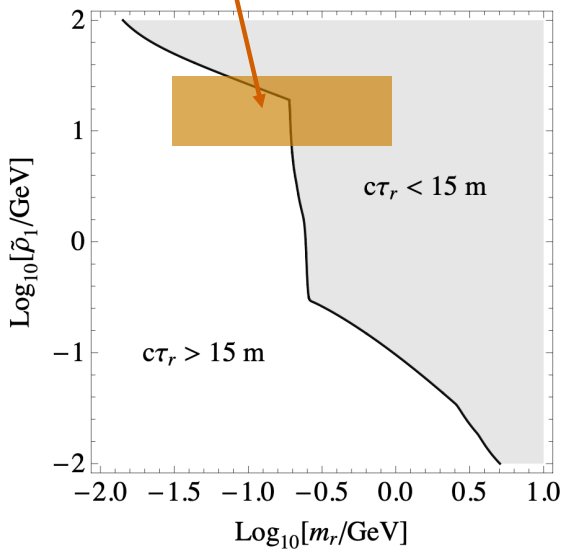





PTA region
Direct detection
χ–N
χ–e
$m_r > 2\,m_\chi$
$m_r = m_\chi$
$m_r < q_{\max}$
χ–N excluded
χ–e excluded
m_r [GeV]
m_χ [GeV]
10
1
0.1
0.01
0.001
0.50
1.00
5.00
10.00
5×10^{-4}
1×10^{-4}
5×10^{-5}
1×10^{-5}
5×10^{-6}
1×10^{-6}
0.02
0.05
0.10
0.20
0.50
1.00
χ
χ
N
N

PTA region

Accelerator searches



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

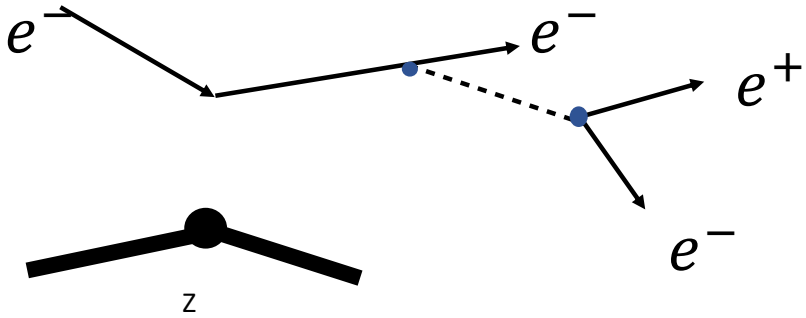
Our prediction is

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

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



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

SUMMARY

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

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

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): $\ell\rho = e^{-r_1 k} \simeq (v_0/v_1)^{1/u}$

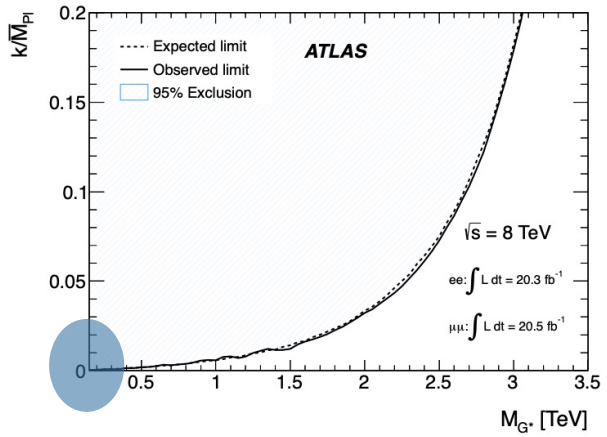
i) Deviation from Newtonian potential

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

ii) KK graviton production at the LHC

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

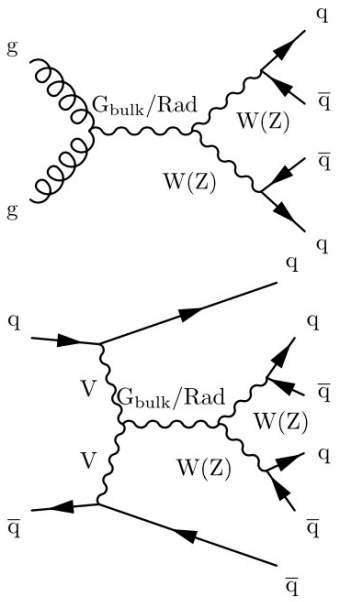
For $Z_b = Z_T$ there is a suppression factor with respect to the coupling in RS as $\epsilon(z_T) \simeq 5\times10^{-9}$ which brings the bounds to MeV-subGeV



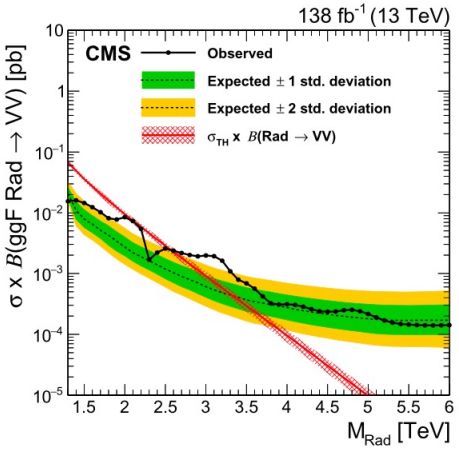
preliminary

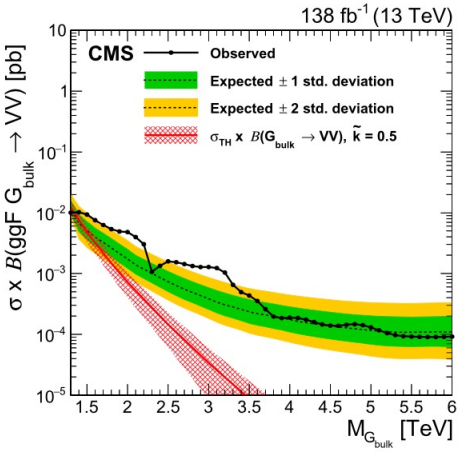
ATLAS Coll., 1405.4123

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: $N = 4\pi M_{\mathrm{Pl}}\ell, \ell = 1/k$
- The brane scale ρ (related to the interbrane distance by the warp factor): $\ell\rho = e^{-r_1 k} \simeq (v_0/v_1)^{1/u}$

- 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):

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

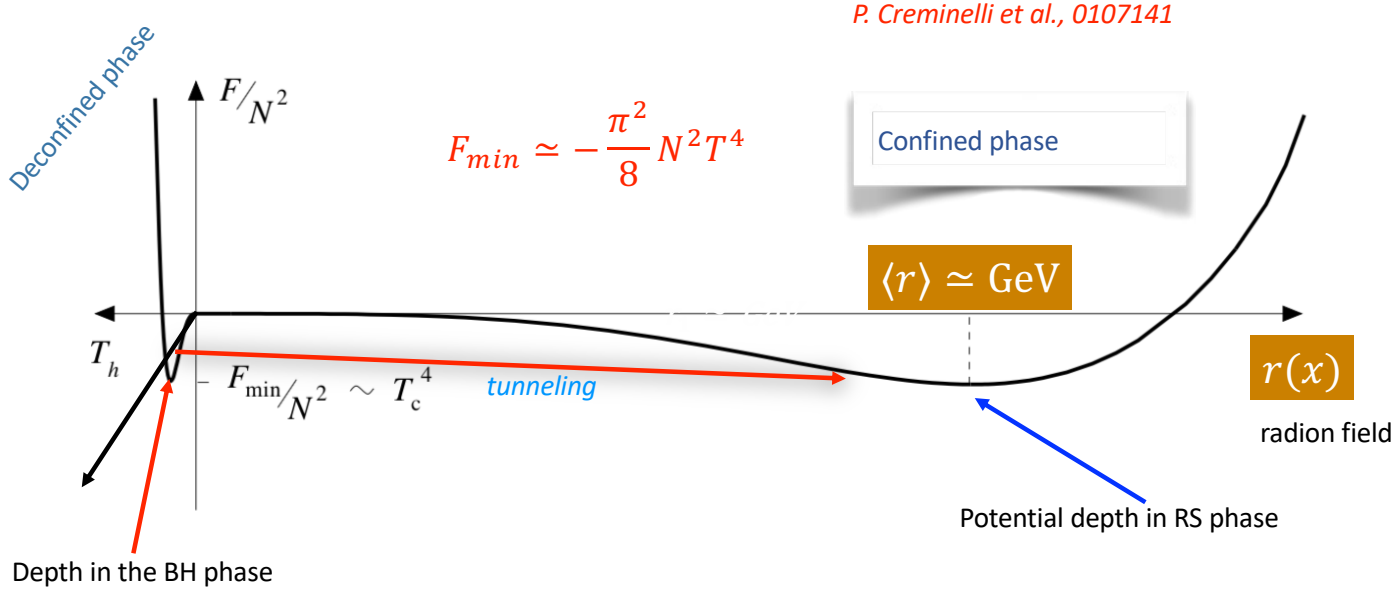
$$ds^2 = e^{-2A(r)}\eta_{\mu\nu}dx^\mu dx^\nu - dr^2$$

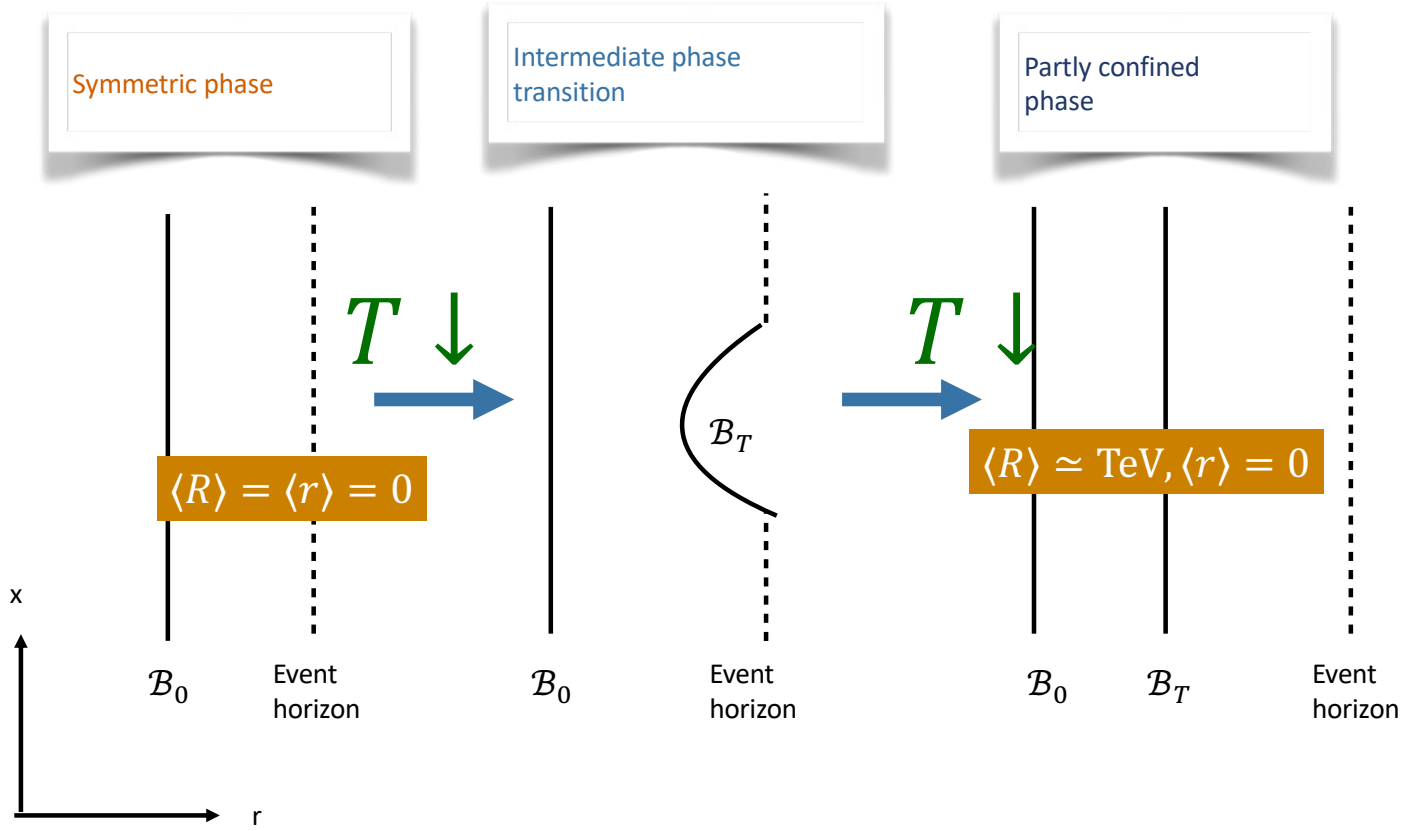
blackening factor $h(r_h) = 0$, event horizon (EH) r_h

The phase transition

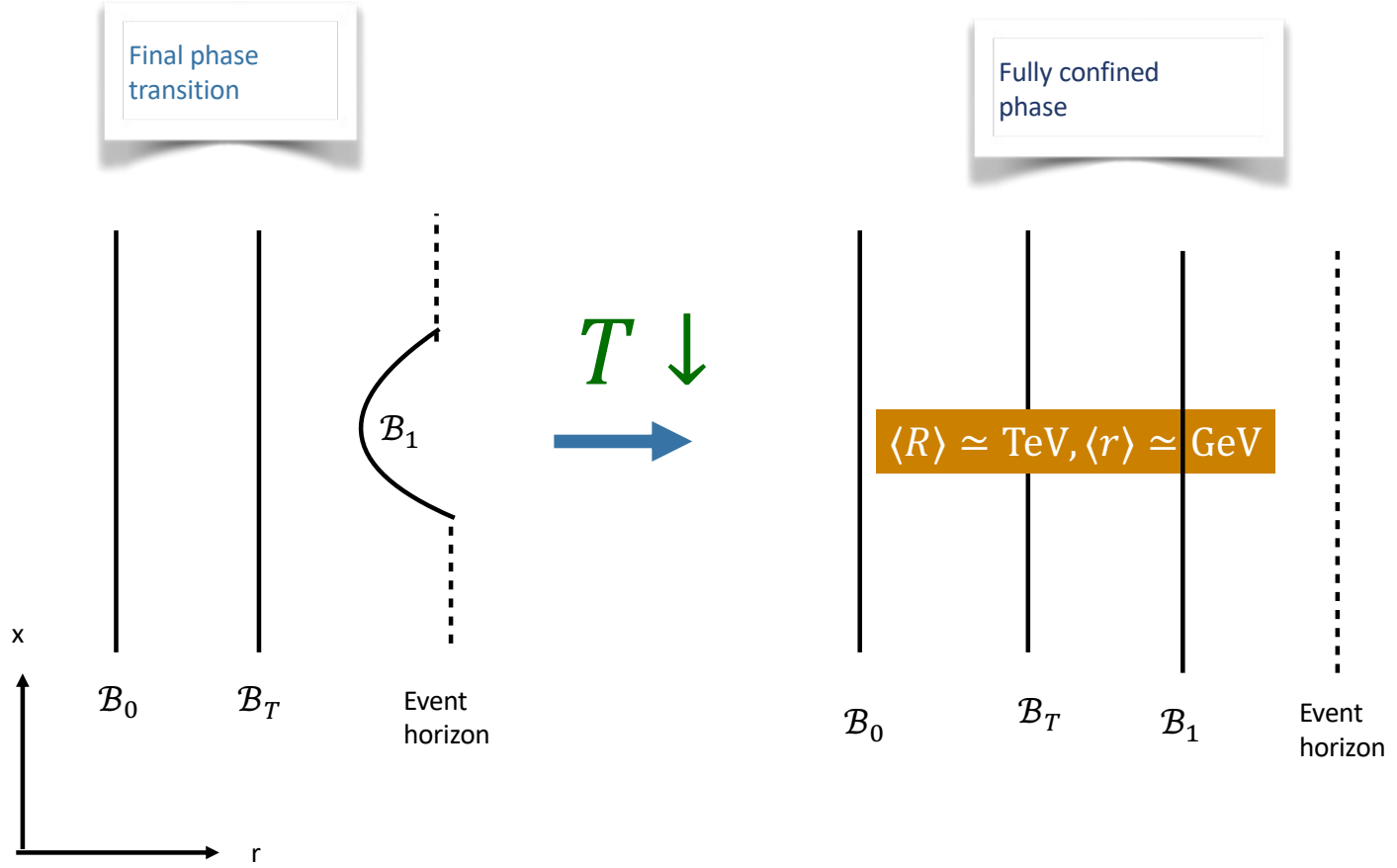
Cartoon of free energies

P. Creminelli et al., 0107141





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



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

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)

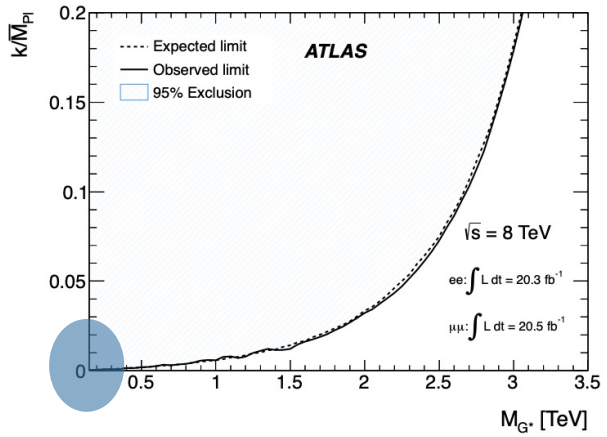
i) Deviation from Newtonian potential

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

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 $(v_\omega \simeq 1, T_* \simeq T_R)$

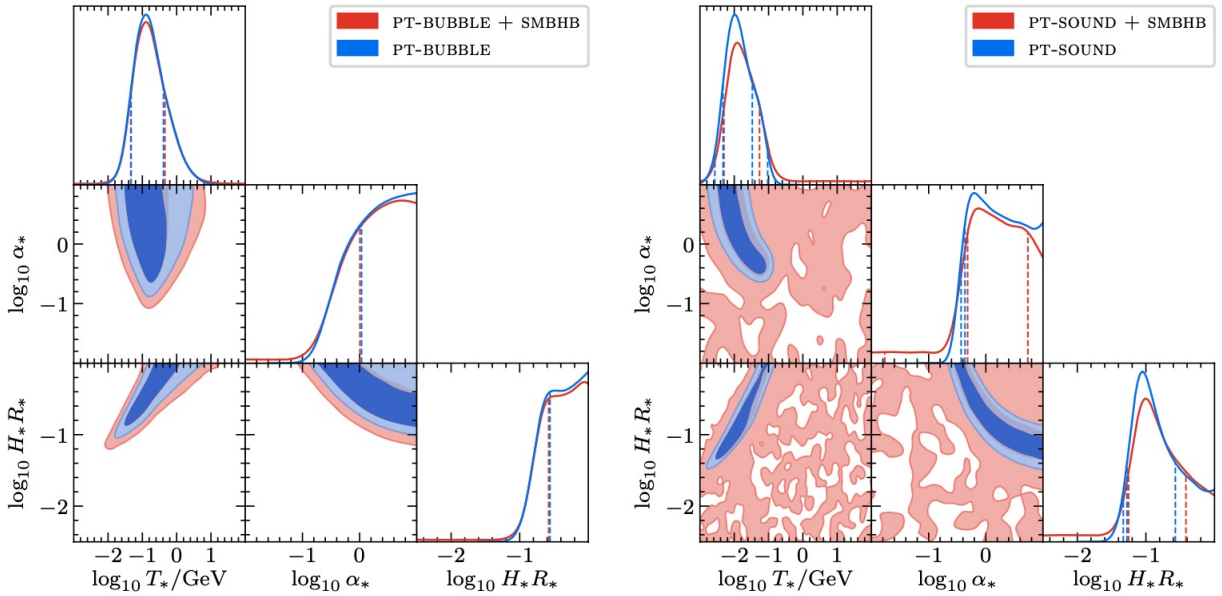
$$h^2\Omega_{GW} = h^2\overline{\Omega}_{GW}\frac{3.8(f/f_p)^{2.8}}{1+2.8(f/f_p)^{3.8}}, h^2\overline{\Omega}_{GW} \simeq 0.6\times10^{-5}\left(\frac{H_*}{\beta}\frac{\alpha_*}{1+\alpha_*}\right)^2$$

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

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

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