Dark branes for PTA signal and dark matter

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Based on works done in collaboration with:
T. Konstandin, F. Koutroulis, E. Megías, G. Nardini, S. Pokorski, A. Wulzer (2006-2024)

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- Introduction
- The 5D model
- The phase transition & Stochastic Gravitational Waves Background (SGWB)
- The dark matter
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Introduction

- There are key relevant scales in Particle Physics normally associated with interactions:
  G_N (gravitational int.), G_F (electroweak int.), Λ_{QCD} (strong int.)

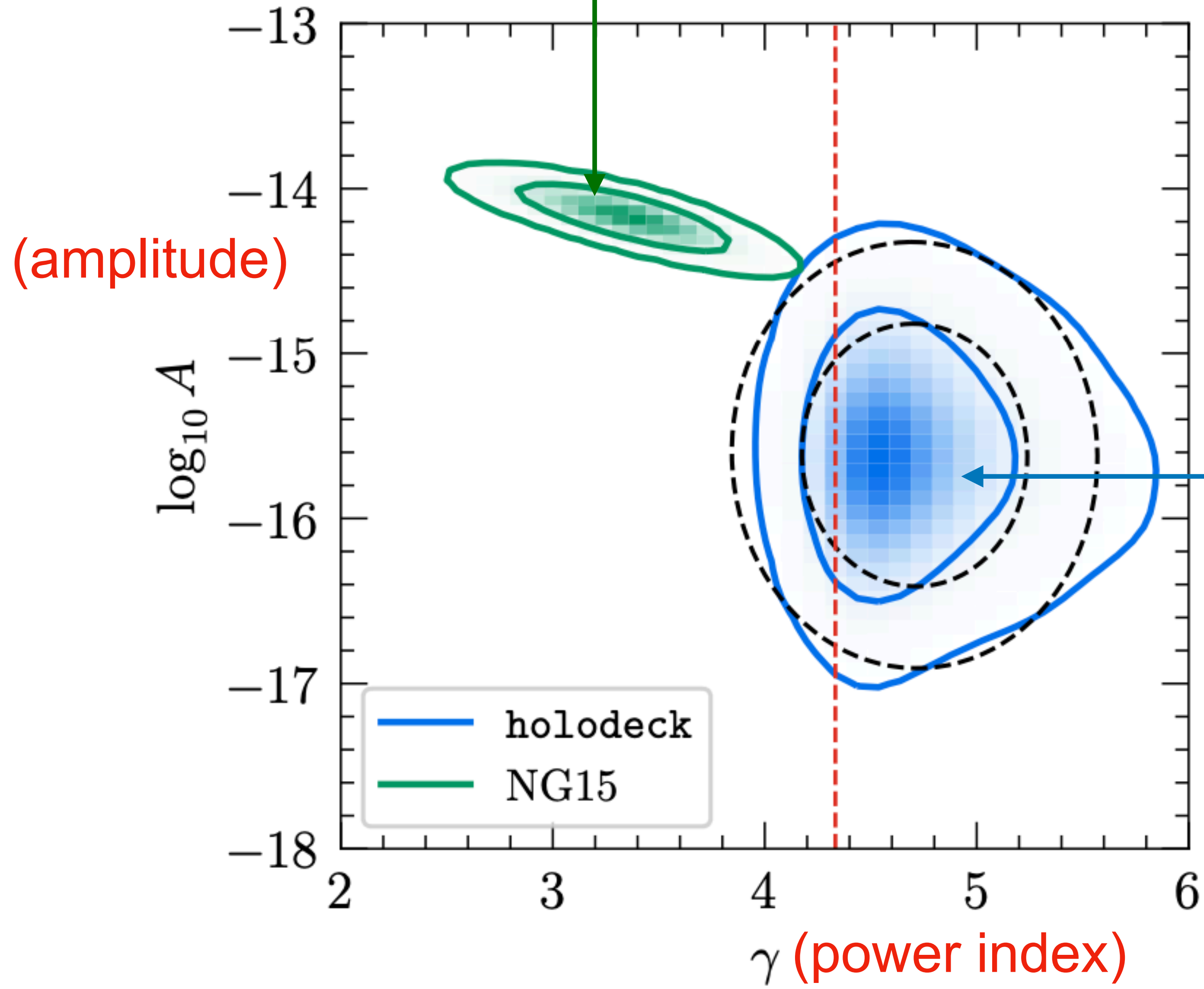
- Pulsar Timing Array (PTA) experiments have found a stochastic gravitational waves background (SGWB) that might be originated at a (new) scale $\Lambda_{\rm PTA} \sim 10$ MeV $- 10$ GeV

- PTA use the precise timing measurements of highly stable millisecond pulsars to detect modulations in the propagation of light caused by Gravitational Waves (GW). Such modulations are correlated with the angular separation of the pulsars as noted by Hellings and Downs

- Question: does Λ_{PTA} correspond to new BSM physics?

NANOGrav Collaboration, 2306.16219

Observed SGWB signal



Astrophysical SMBHB prediction

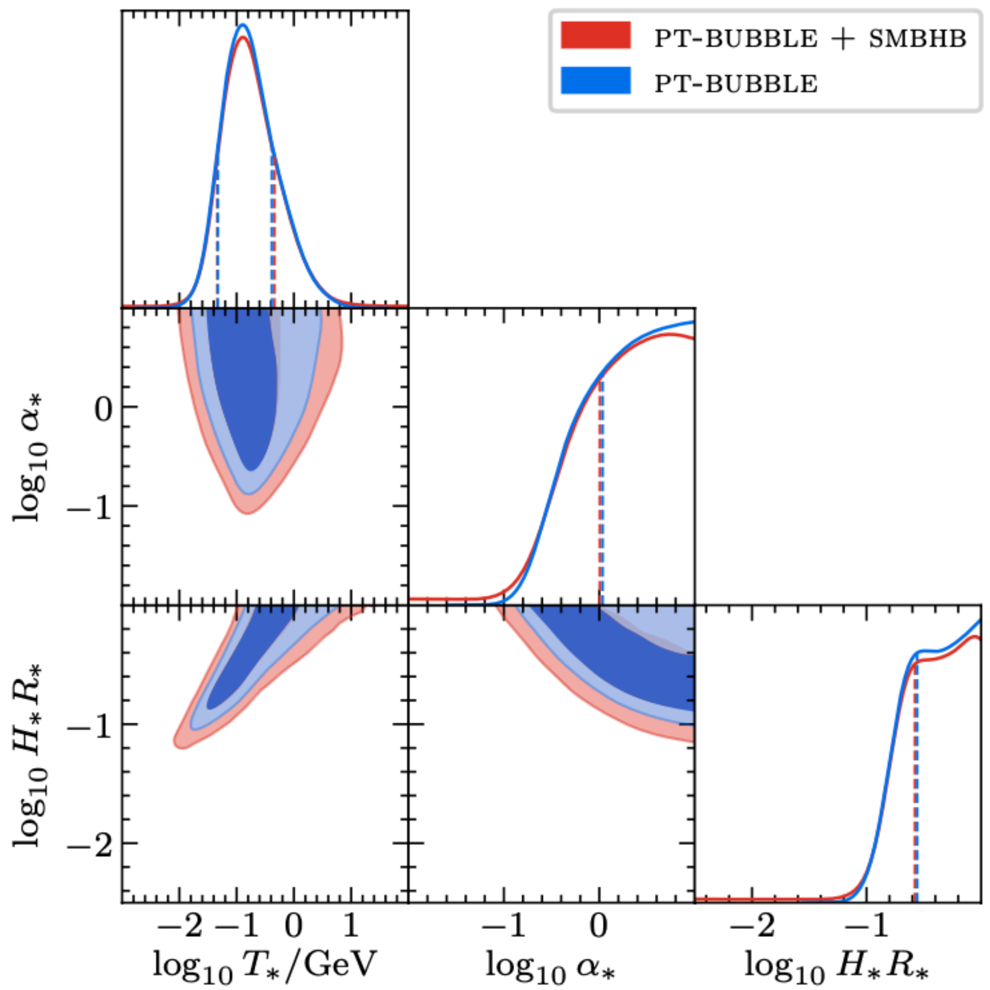
The 95% regions of the two distributions barely overlap: 2σ

There is a (mild) tension between the astrophysical prediction and the reconstructed spectral shape of the SGWB

- There are a number of new physics models that can generate a SGWB at nHz frequencies

- In particular cosmological first order phase transitions (FOPT): GW from bubble collisions, sound waves and turbulence

- NANOGrav signal mildly favors a FOPT over FOPT+SMBHB when SGWB comes mainly from bubble collisions after the phase transition



- $H_* R_* = (8\pi)^{1/3} v_\omega H_*/\beta$

- $H_* R_* > 1.1\ (0.29)\ 68\,\%\ (95\%)$

- $\alpha_* > 1.1\ (0.29)$

- $T_* = 0.05 - 0.4\ (0.023 - 1.75)$ GeV

NANOGrav Collaboration, 2306.16219

i) New conformal sector at GeV

- NANOGrav results can be accommodated in a strong FOPT at a scale $\Lambda_{PTA} \sim 10$ MeV $- 10$ GeV

- One appealing possibility is if there is a (new) conformal sector with confinement scale $\Lambda_{conf} = \Lambda_{PTA}$: this possibility is naturally realized by the IR brane of an AdS_5 space from the AdS/CFT duality

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

- The SM is located at the TeV brane separated from the Planck scale by around 35 e-folds

- PTA results suggest an extra Dark Brane in RS setup at the GeV scale separated from the Planck scale by around 40 e-folds

ii) Dark Matter in the Dark Brane

- The existence of the Dark Brane at the scale $\Lambda_{conf} = \Lambda_{PTA}$ suggests that the matter localized on it have 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: i) strong interactions with the radion to trigger thermal relic density; ii) feeble interactions with the SM to avoid direct detection experiments

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

The model

E. Megías, G. Nardini, MQ, 2306.17071

- Using the AdS/CFT correspondence one can easily model the previous setup

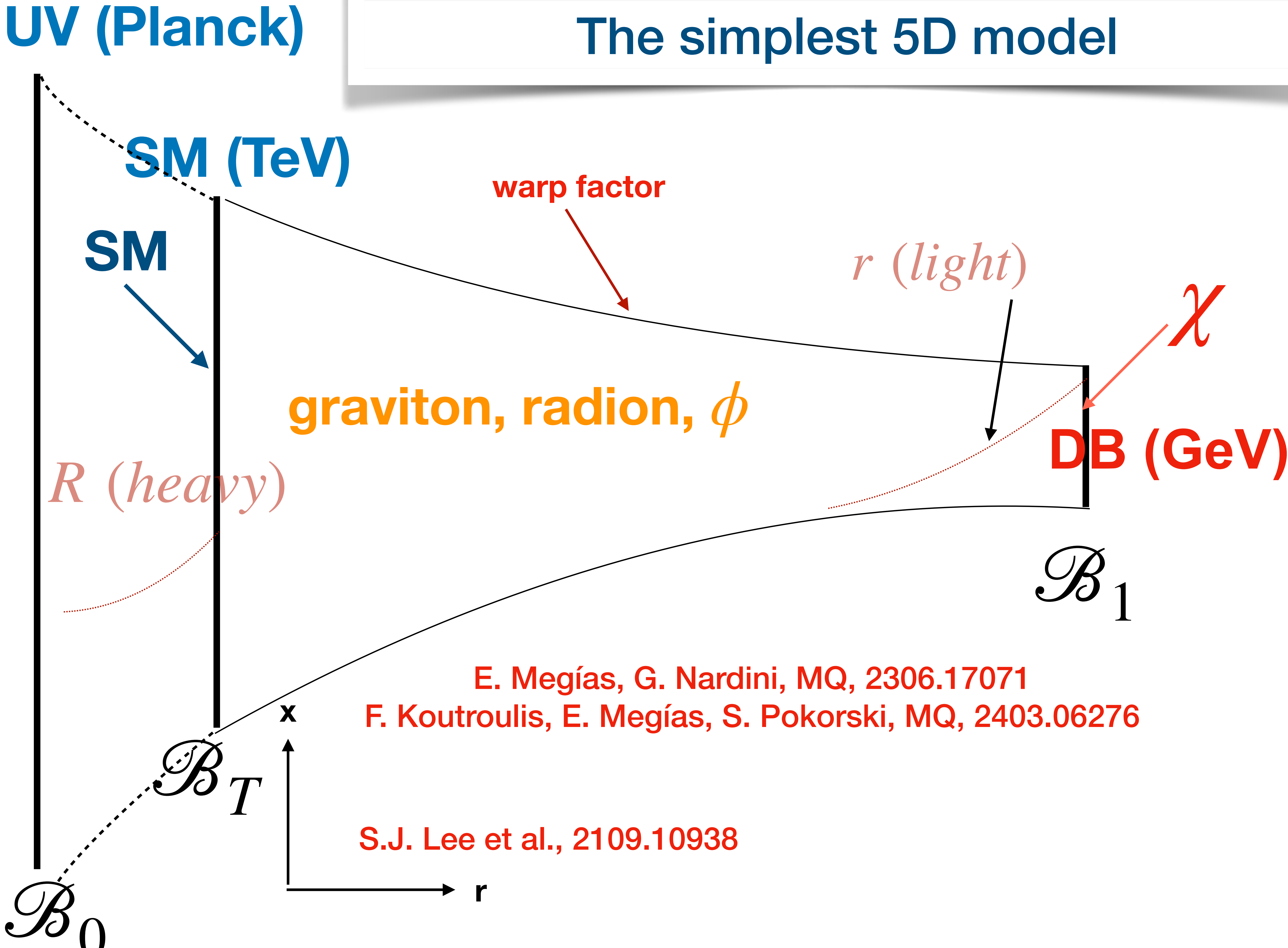
- The fundamental scale $\Lambda_{conf} \sim 10$ MeV $- \ 10$ GeV can be easily obtained from the Planck scale by a warp factor $\sim e^{-40}$

- The 4D (holographic) theory has a 5D (dual) theory by stabilizing an IR brane in AdS_5 at a distance in proper coordinates $ky_1 \sim 40$ from the Planck brane ($k \lesssim M_{\rm Pl}$ is related to the AdS curvature)

- The KK modes are at the GeV scale, so only the graviton, radion and the stabilizing field can propagate in the bulk of the fifth dimension

- The SM should be localized on the intermediate brane, at the TeV scale, to solve the SM hierarchy problem)

The simplest 5D model



E. Megías, G. Nardini, MQ, 2306.17071
F. Koutroulis, E. Megías, S. Pokorski, MQ, 2403.06276

S.J. Lee et al., 2109.10938

- The $\mathscr{B}_1$ 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 $\mathscr{B}_T - \mathscr{B}_1$ 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): $ds^2 = e^{-2A(r)}[h(r)dt^2 - d\vec{x}^2] - \frac{1}{h(r)}dr^2$

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

- RS confined phase (low T): $ds^2 = e^{-2A(r)}\eta_{\mu\nu}dx^\mu dx^\nu - dr^2$

The model parameters

- The values of ϕ at branes: $\phi(0) = v_0, \quad \phi(r_1) = v_1$

- From the potential on the IR brane: $\lambda_1 \simeq 1 + \ell(\kappa^2/6)\Lambda_1$
$\Lambda_1(\phi) = \Lambda_1 + \frac{1}{2}\gamma(\phi - v_1)^2, \quad \gamma \to \infty$ (stiff limit)

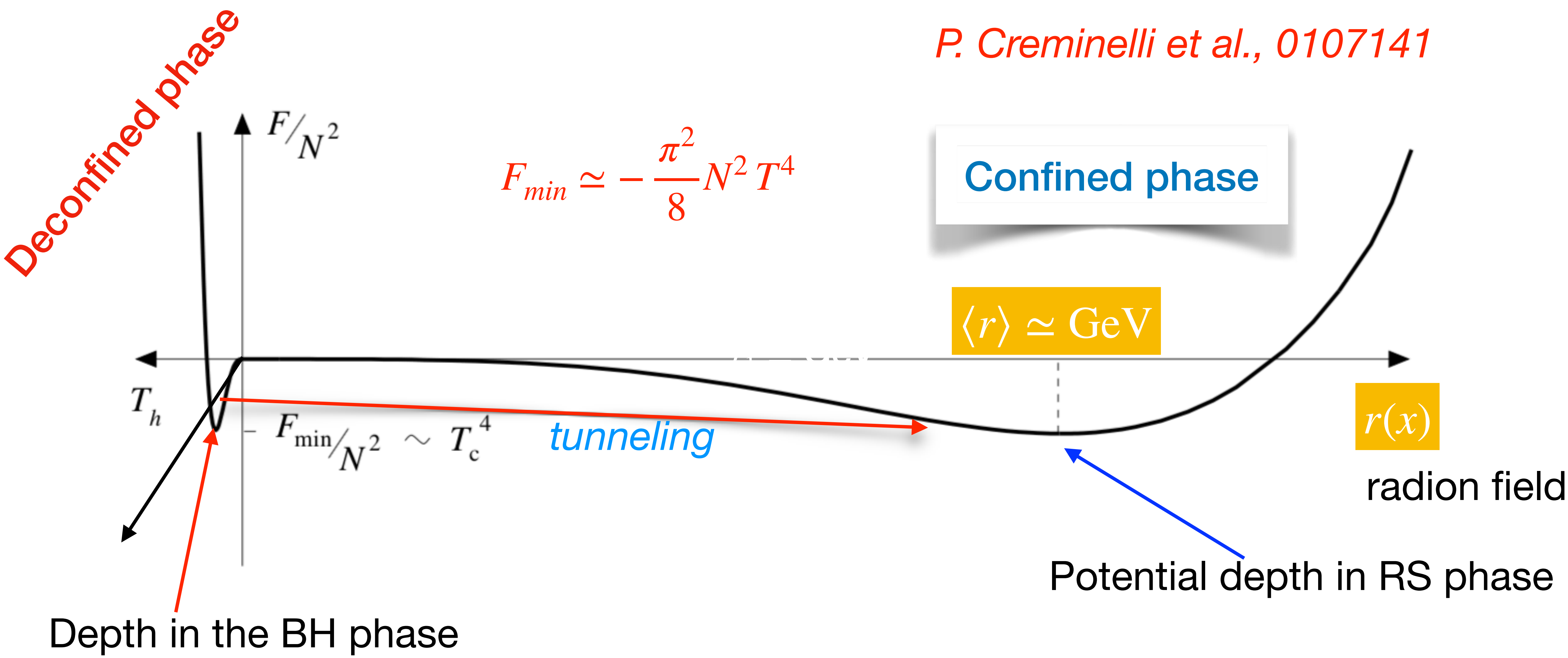
- N (# degrees freedom of holographic theory) Vs k:
$N = 4\pi M_{\mathrm{Pl}}\ell, \; \ell = 1/k$

- The brane scale ρ_1 (related to the interbrane distance by the warp factor): $\ell\rho_1 = e^{-r_1 k} \simeq (v_0/v_1)^{1/u}$

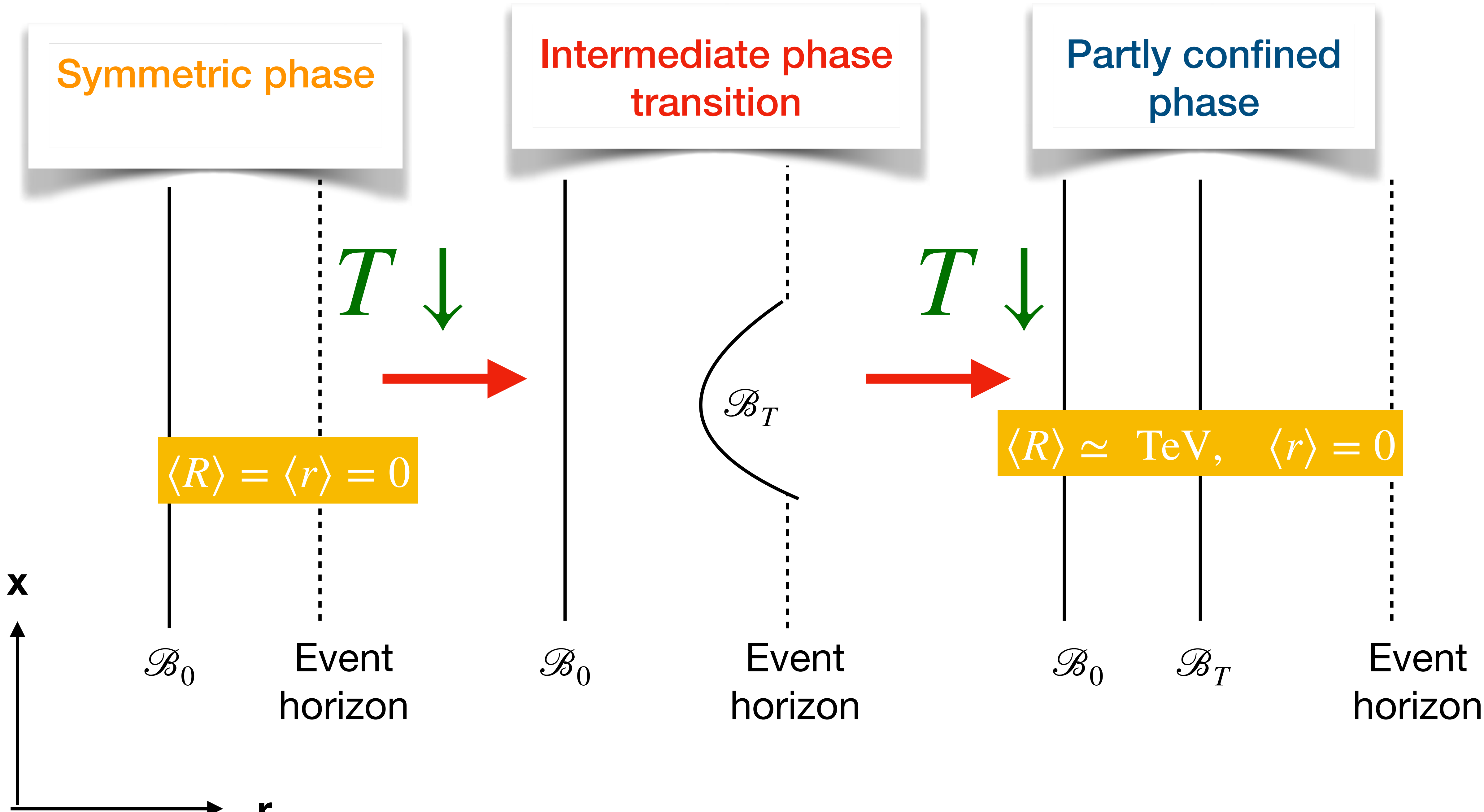
The phase transition: holographic view

Cartoon of free energies

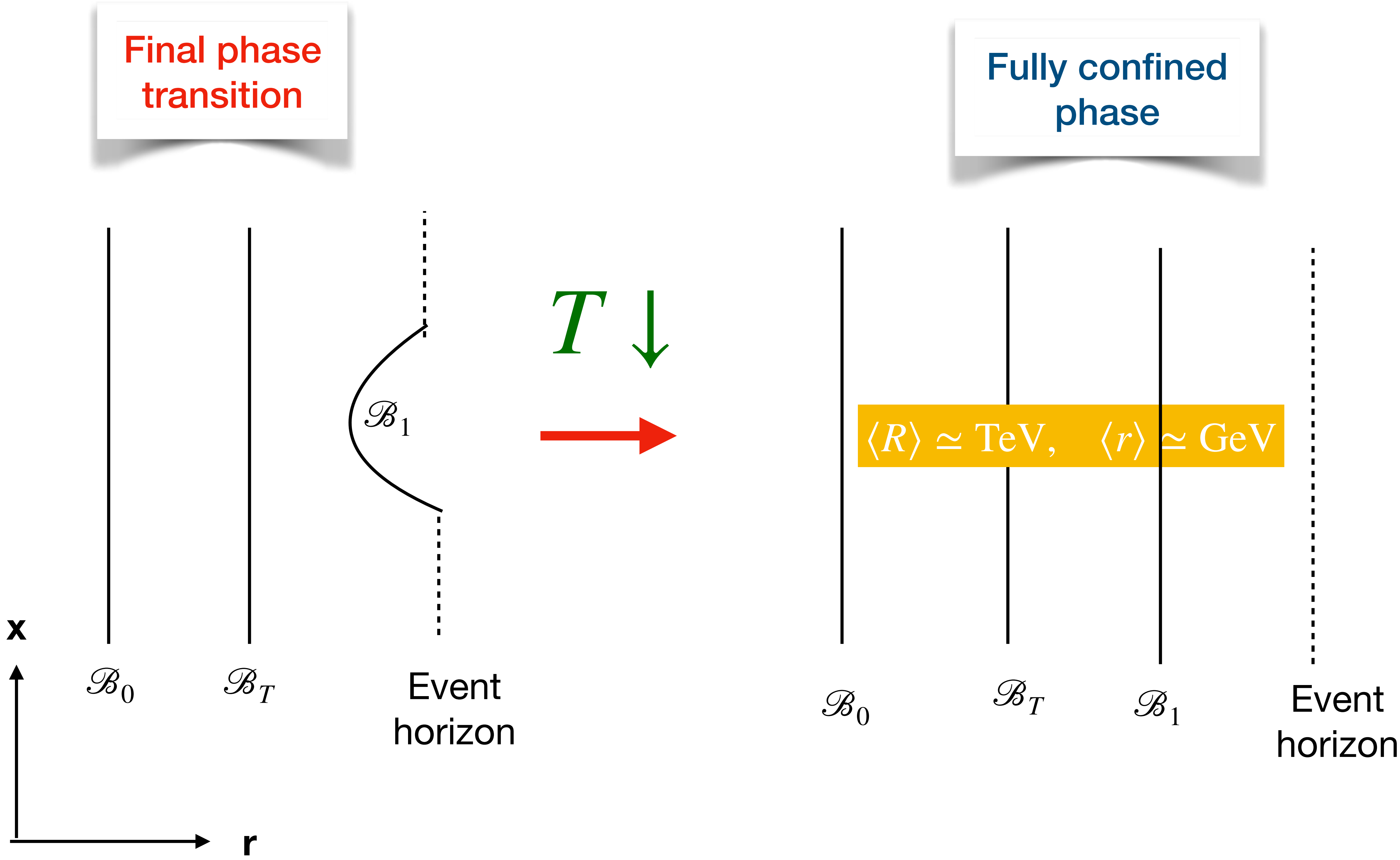
P. Creminelli et al., 0107141



The phase transition: dual view



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



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

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

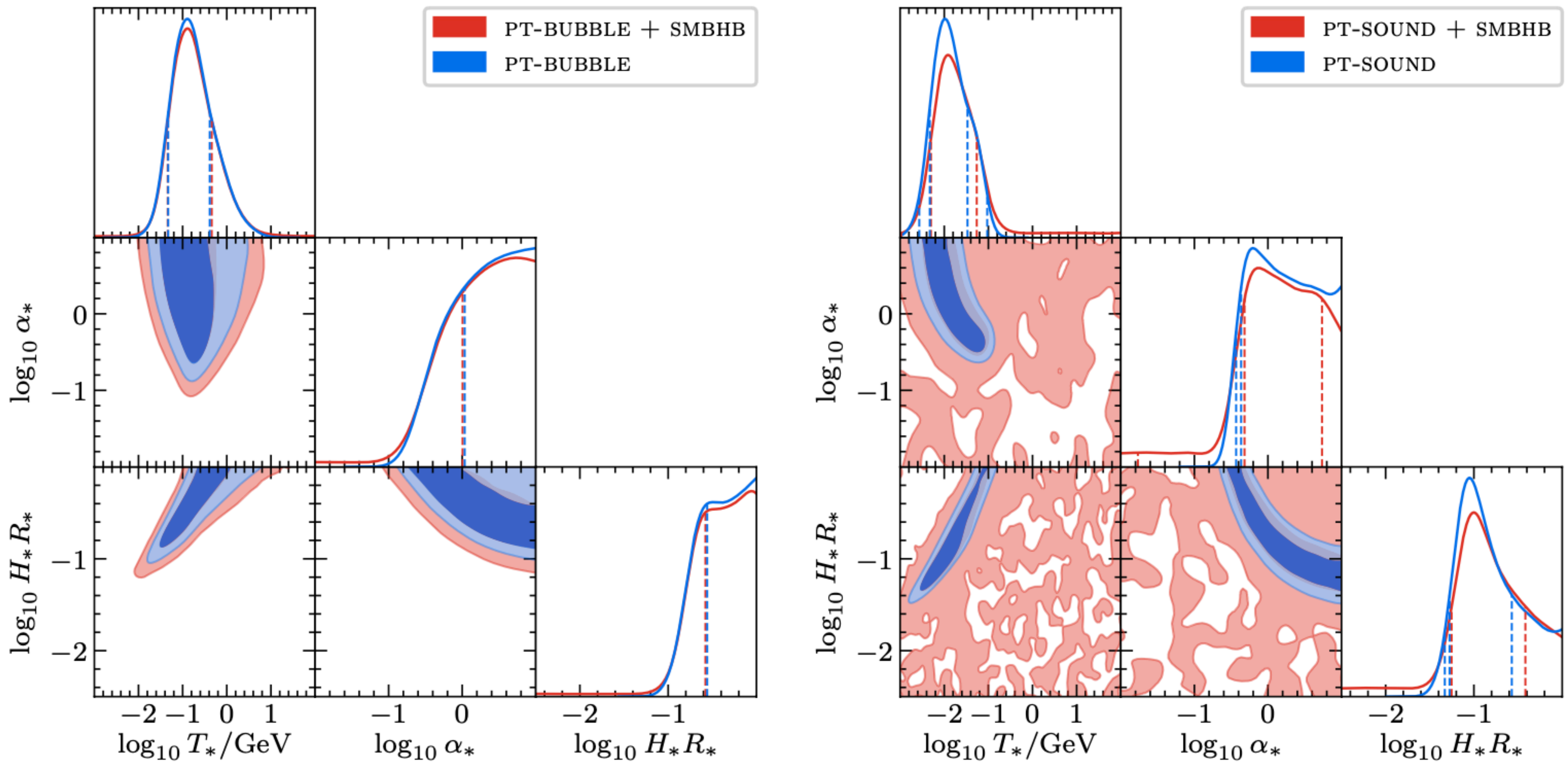
- The normalized inverse time duration of the phase transition

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

see G. Nardini's talk

Numerical results and comparison with NANOGrav data

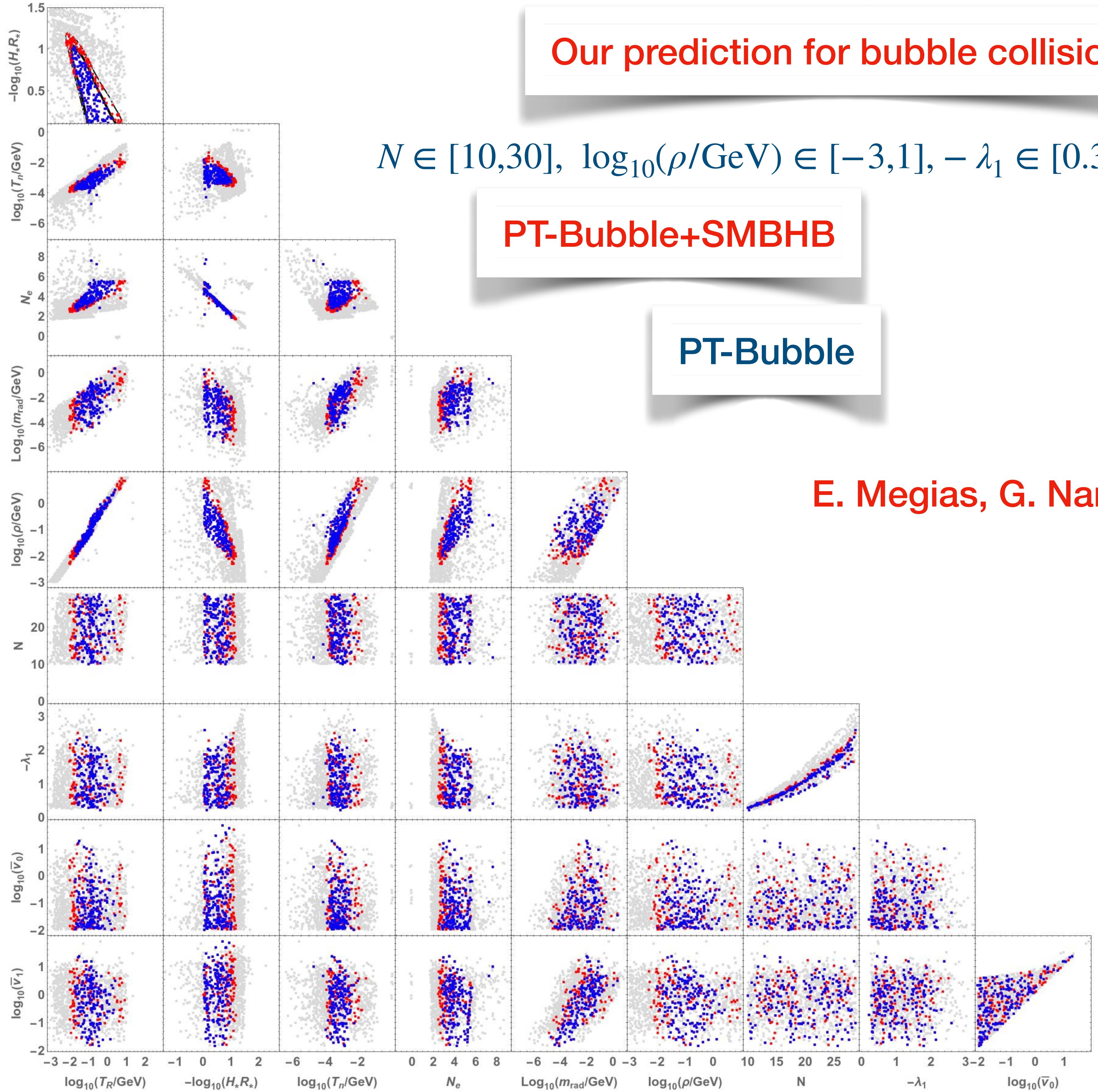
NANOGrav Collaboration, 2306.16219



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

NANOGrav results (95%): $T_R < 1.75$ GeV

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



Our prediction for bubble collisions

$$N \in [10,30],\ \log_{10}(\rho/\mathrm{GeV}) \in [-3,1], -\lambda_1 \in [0.3,2.7], \log_{10}(v_{0,1}\kappa)) \in [-2,2]$$

PT-Bubble+SMBHB

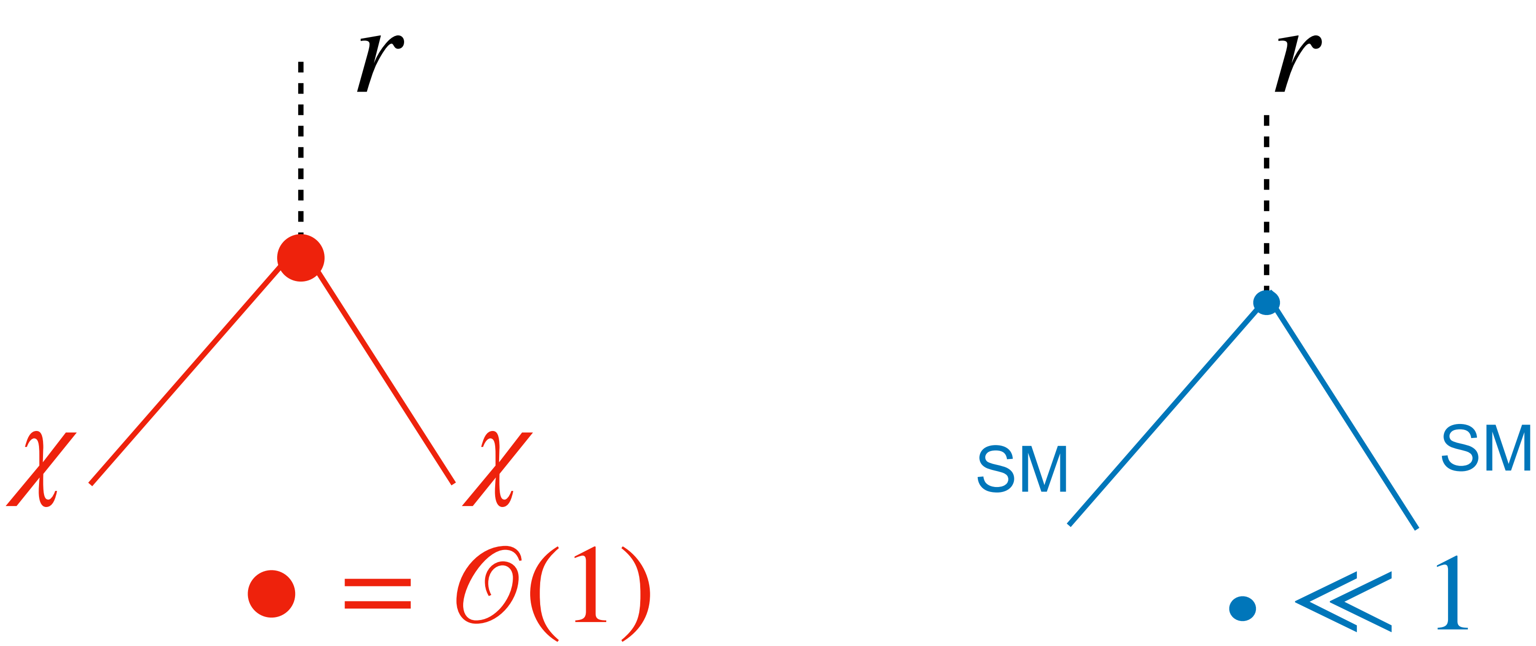
PT-Bubble

E. Megias, G. Nardini, M.Q. 2306.17071

The Dark Matter

F. Koutroulis, E. Megías, S. Pokorski, MQ, 2403.06276

- We can use the Dark Brane to support a Dark Sector without (essentially) 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:



- The model has 3 free parameters

- The scale of the Dark Brane $\rho_1 \equiv (k/M_{\rm Pl})\tilde{\rho}_1$. Its range to describe the PTA data is $\rho_1 \in [10 \text{ MeV}, 10 \text{ GeV}]$, but in principle we also have considered a broader range

- 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 $\chi\bar{\chi} \to G_n G_n$ 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 $r \to \chi\bar{\chi}$ is closed and only the channel $r \to \text{SM} + \text{SM}$ is kinematically accessible

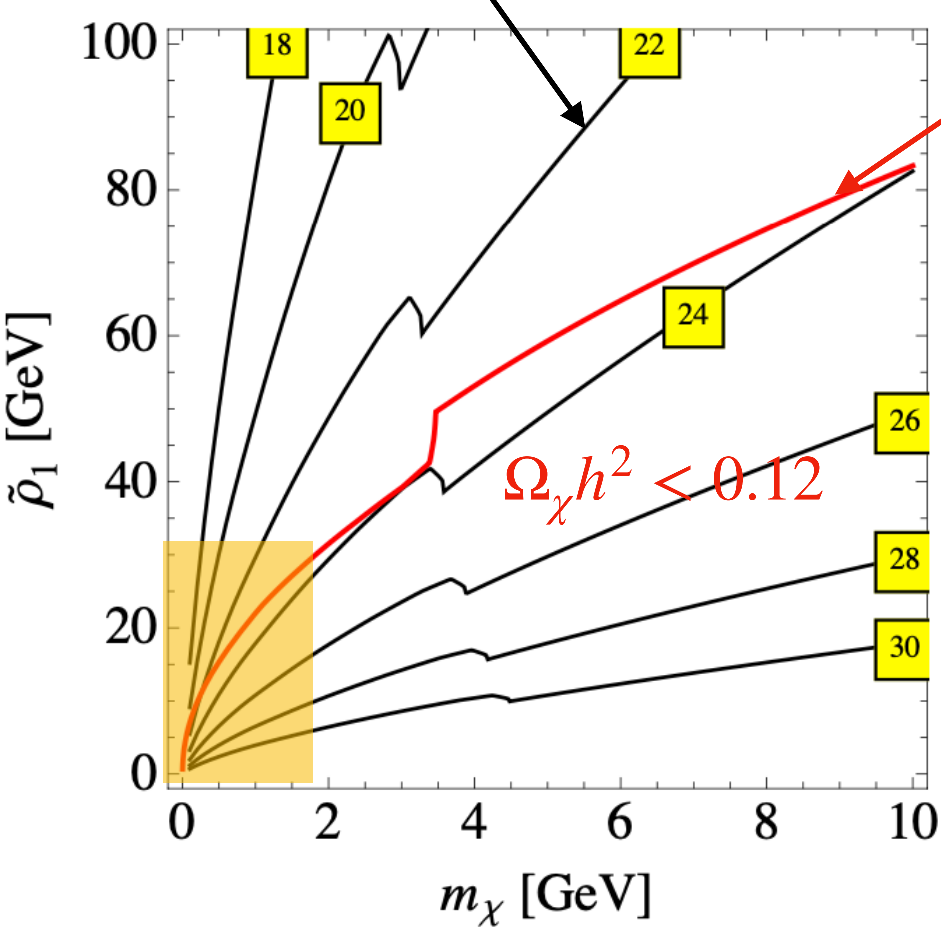
Relic density

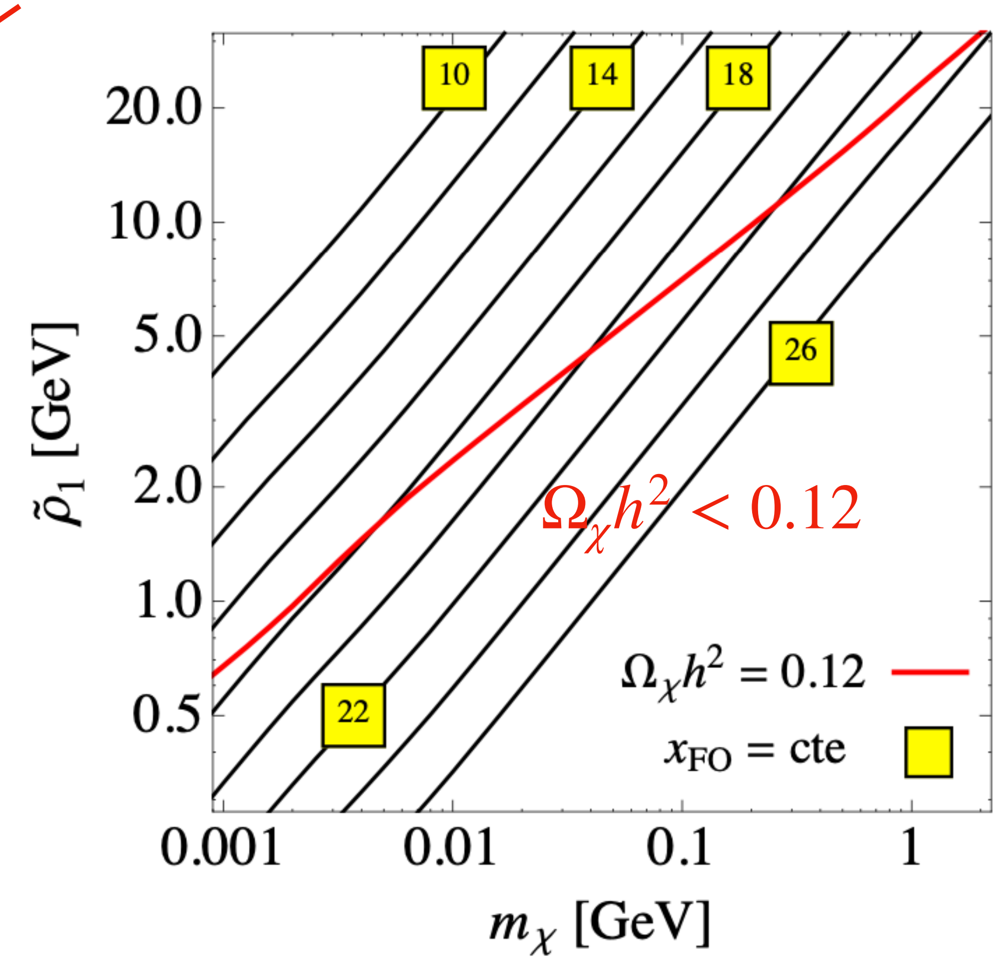
PTA region

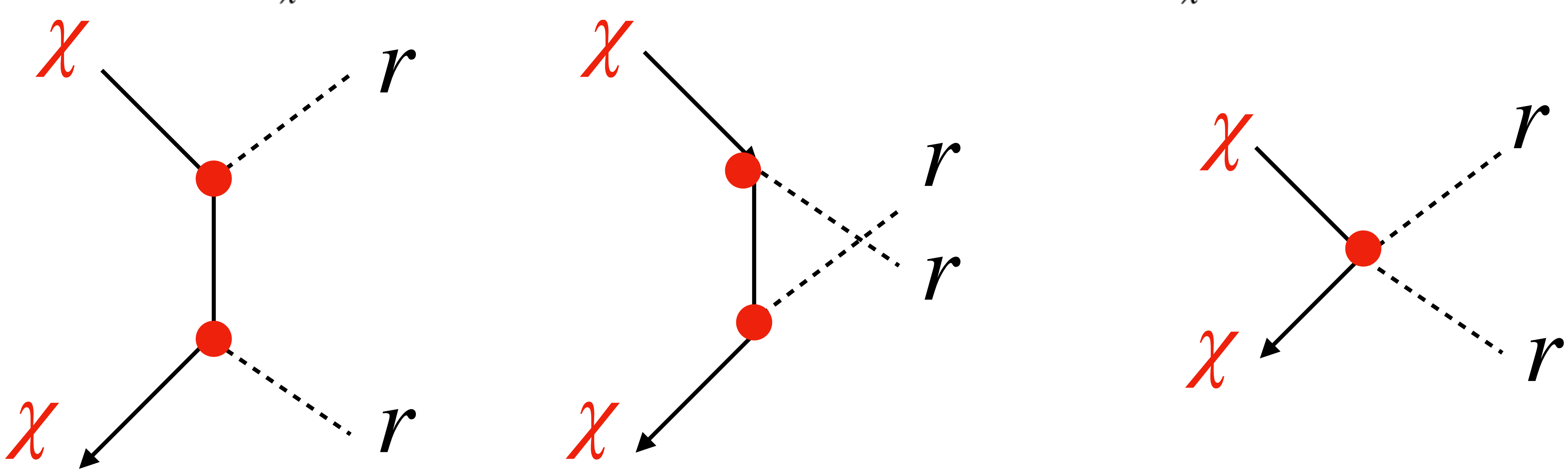
$$\frac{m_\chi}{T_{\rm FO}}$$

$$\tilde{\rho}_1 \equiv \frac{M_{\rm Pl}}{k}\rho_1$$

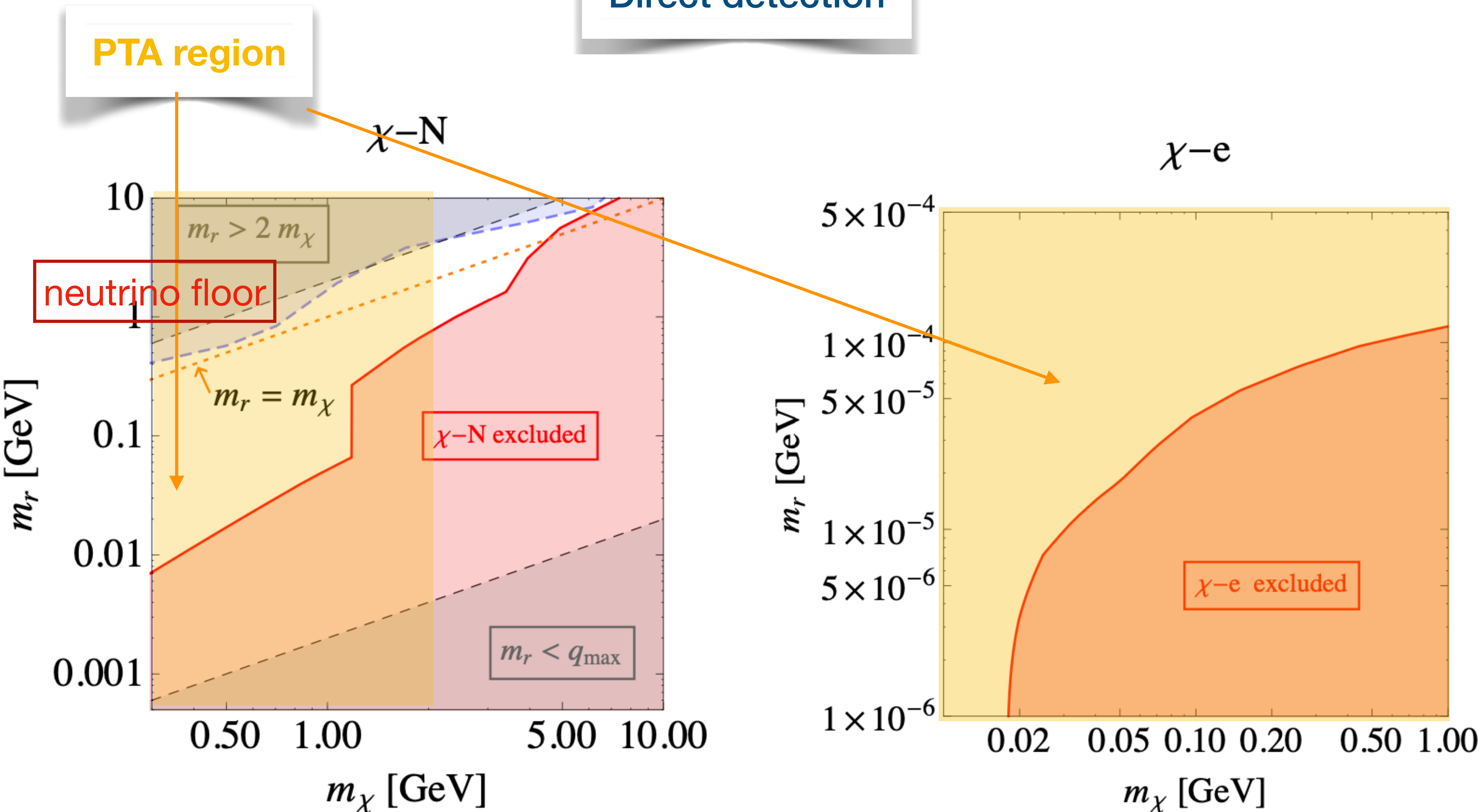
$$\Omega_\chi h^2 = 0.12$$

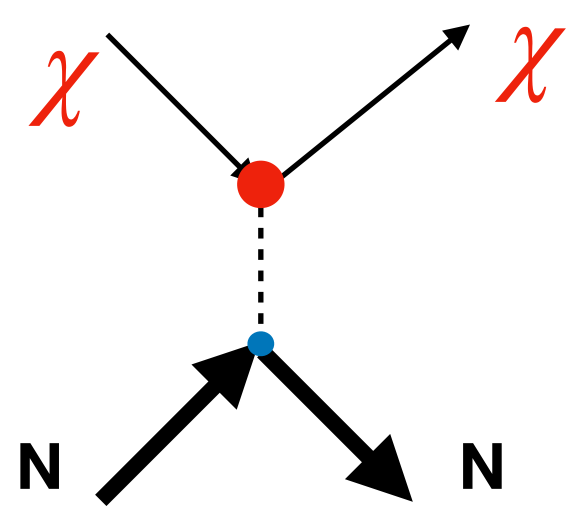




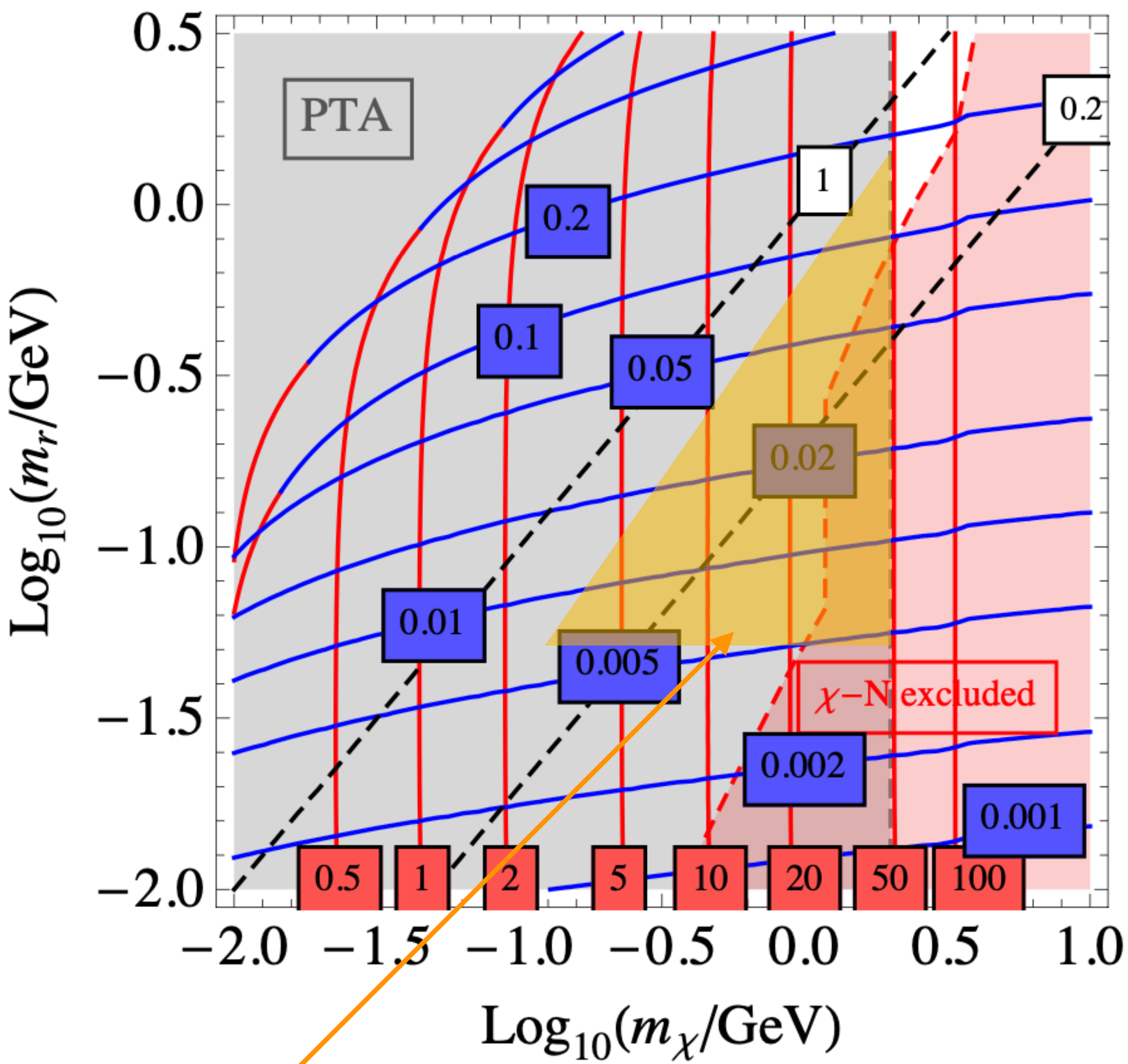


Direct detection





Indirect constraints



PTA region

i) $m_r < 2m_e \Rightarrow \; r = \text{Dark Radiation}$

$\Delta N_{\rm eff} < 0.17 \Rightarrow m_\chi \gtrsim 150\ \text{MeV}$

ii) $m_r > 2m_e \Rightarrow \; r \to e^+e^-$,

Radion decays provided that $\Gamma_r > H$

Radion is in equilibrium with electrons

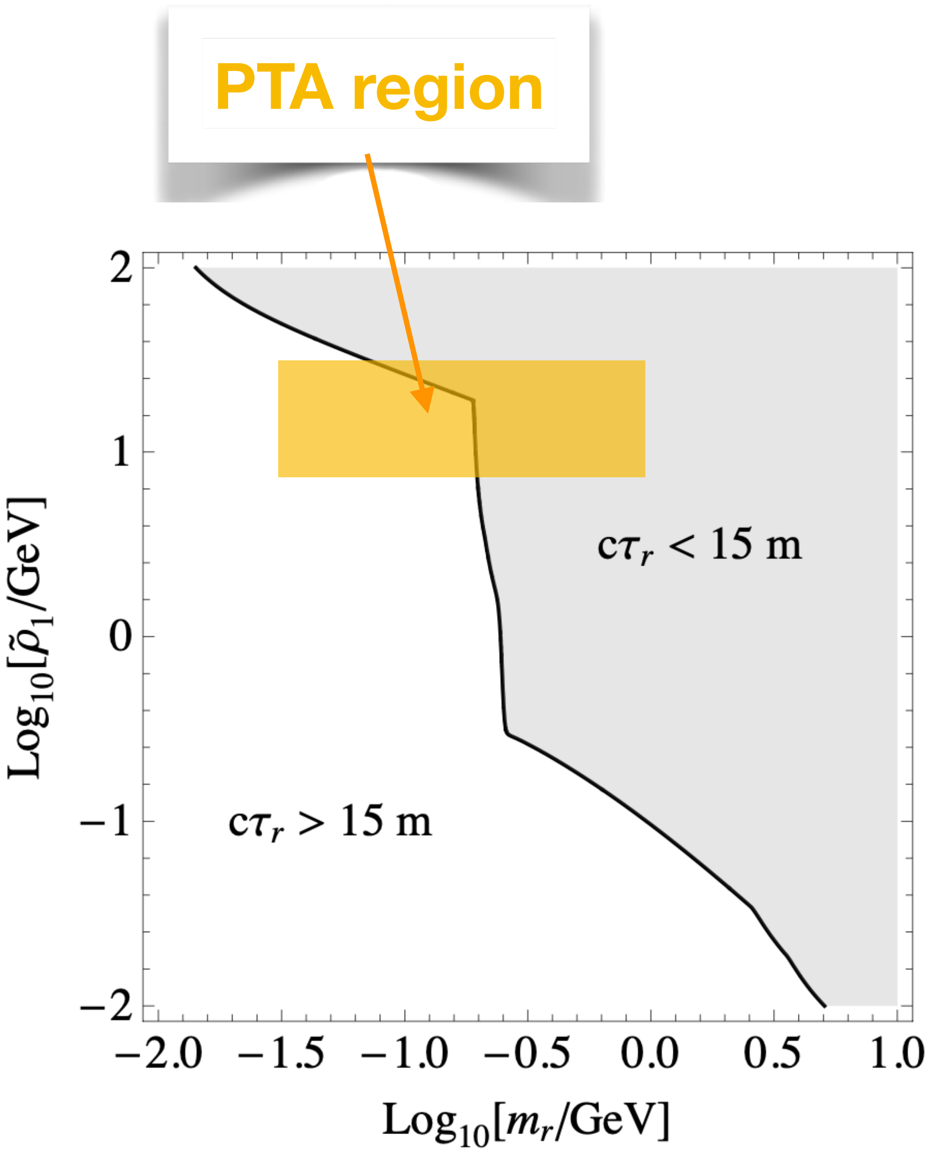
$r \leftrightarrow e^+e^-$

until freeze out when $e^+e^- \not\to r$

BBN should then imposes that

$T_{\rm FO} \gtrsim \mathcal{O}(\text{few})\ \text{MeV} \Rightarrow m_\chi \gtrsim 100\ \text{MeV}$

Accelerator searches



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

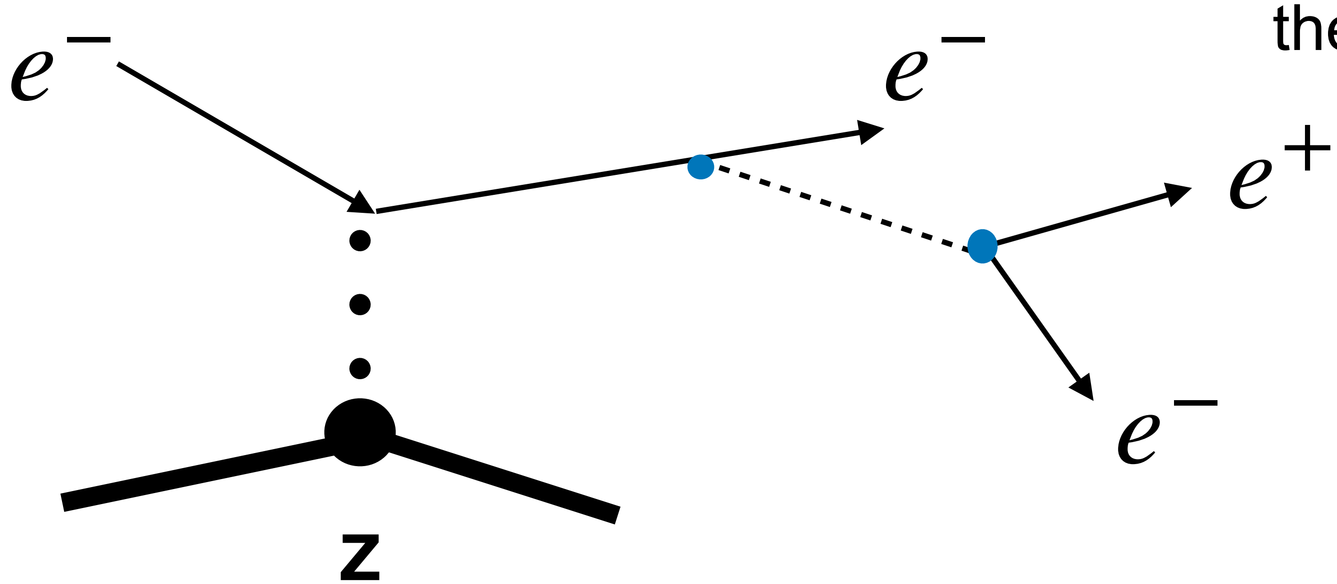
Our prediction is

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

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

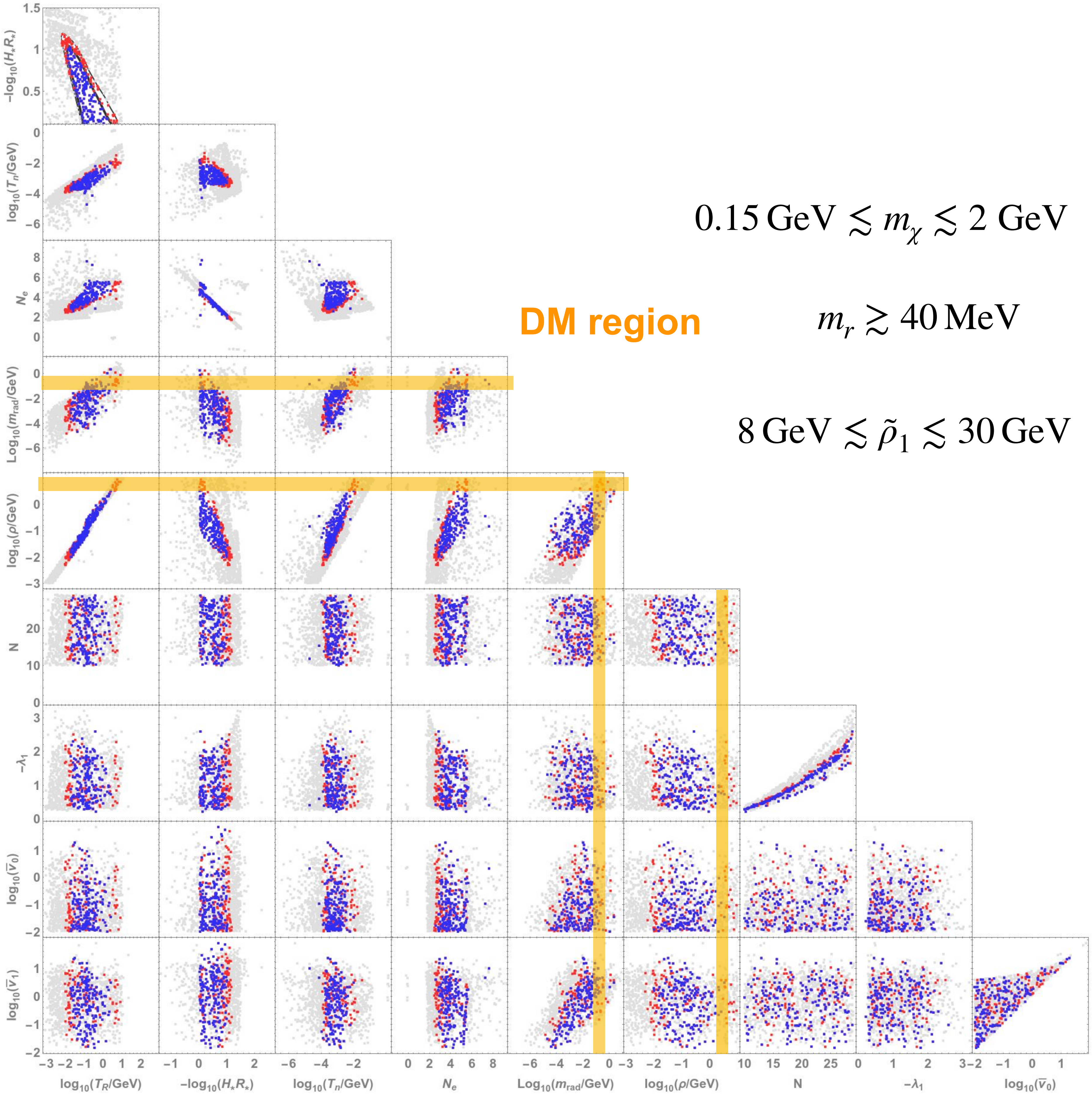
$$r \to \chi\bar{\chi}$$

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



Conclusion

- 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)


DM region
$0.15\,\mathrm{GeV} \lesssim m_\chi \lesssim 2\ \mathrm{GeV}$
$m_r \gtrsim 40\,\mathrm{MeV}$
$8\,\mathrm{GeV} \lesssim \tilde{\rho}_1 \lesssim 30\,\mathrm{GeV}$
$\log_{10}(T_R/\mathrm{GeV})$
$-\log_{10}(H_* R_*)$
$\log_{10}(T_n/\mathrm{GeV})$
N_e
$\mathrm{Log}_{10}(m_{\mathrm{rad}}/\mathrm{GeV})$
$\log_{10}(\rho/\mathrm{GeV})$
N
$-\lambda_1$
$\log_{10}(\bar{v}_0)$
$\log_{10}(\bar{v}_1)$

Thank you

- The SGWB can be produced by bubble collisions 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 $(v_\omega \simeq 1,\ T_* \simeq T_R)$

$$h^2\Omega_{GW} = h^2\bar{\Omega}_{GW}\frac{3.8\,(f/f_p)^{2.8}}{1+2.8\,(f/f_p)^{3.8}}, \qquad h^2\bar{\Omega}_{GW} \simeq 0.6\times 10^{-5}\left(\frac{H_*}{\beta}\frac{\alpha_*}{1+\alpha_*}\right)^2$$

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

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

Our prediction for sound waves

$N \in [10,30],\ \log_{10}(\rho/\mathrm{GeV}) \in [-3,1], -\lambda_1 \in [0.3,2.7], \log_{10}(v_{0,1}\kappa)) \in [-2,2]$

PT-Sound

E. Megias, G. Nardini, M.Q., 2306.17071