PTA SGWB from light KK resonances

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Based on works done in collaboration with:
T. Konstandin, E. Megías, G. Nardini, A. Wulzer (2006-2023)

Contents

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 scale $\Lambda_{\rm PTA} \sim 0.1 - 1$ 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?

- The simplest explanation is astrophysical. One possibility is that the SGWB is generated by super massive black hole binaries (SMBHB)

NANOGrav Collaboration, 2306.16219

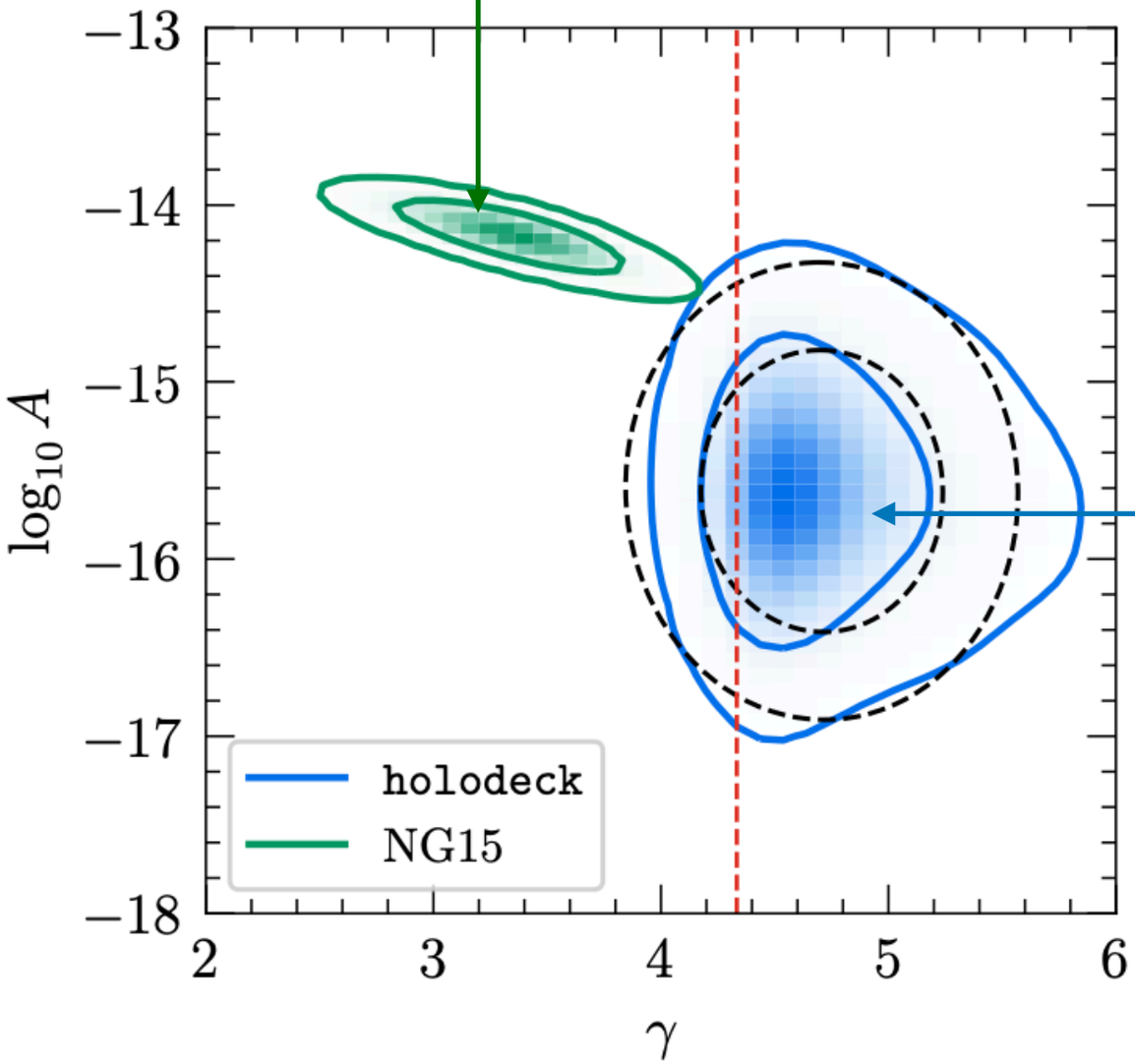
- According to current understanding of galaxy formation and evolution, the SMBHB population produces a SGWB with a strain following a power index $\gamma = 13/3$ and amplitude $A \sim 10^{-15}$ at frequency of $f \sim 32$ nH

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

- To reproduce the observed amplitude SMBHB models would require one or more of the astrophysical parameters describing the binaries' population to differ from expected values

Observed SGWB signal

NANOGrav Collaboration, 2306.16219



Astrophysical SMBHB prediction

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

New physics models without (or with) conventional SMBHB should better fit present data!

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

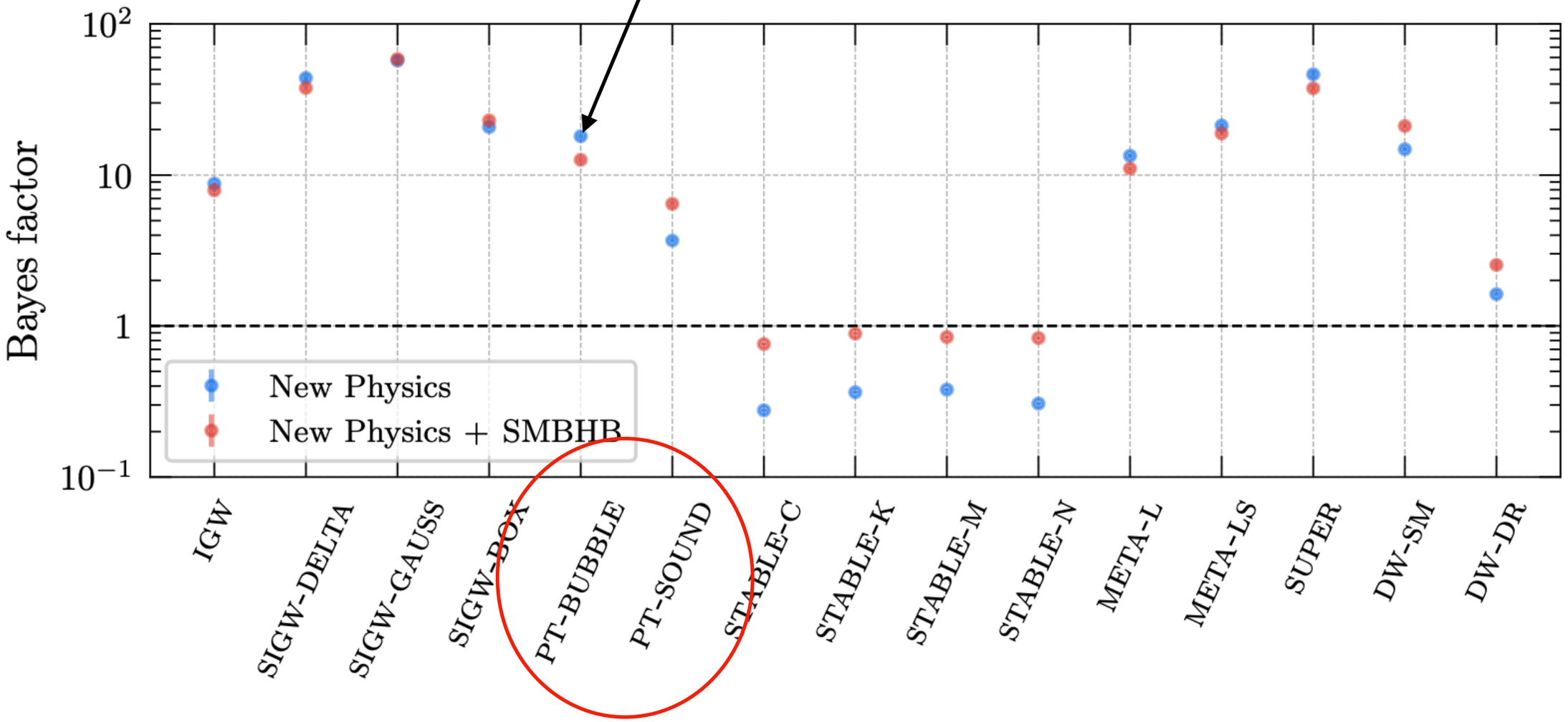
- They have been scrutinized in general by the NANOGrav collaboration: cosmic inflation (tensor perturbations), scalar induced (scalar perturbations), cosmic strings (1D topological defects typically from U(1)), domain walls (2D topological defects from breaking of discrete symmetry), cosmological first order phase transitions (FOPT): GW from bubble collisions, sound waves, turbulence
(talks by Konstandin, Mühlleitner, Lewicki,…)

- New Physics models discriminated by the Bayes factor: the ratio of the likelihood of observed data occurring under the given hypothesis over the likelihood of observed data under the null hypothesis.

- If the Bayes factor is $\mathscr{B}$ then it means the alternative hypothesis is $\mathscr{B}$ times as likely as the null hypothesis given the data

- According to that if $\mathscr{B}$= 1 (no evidence), 1-3 (anecdotal evidence), 3-10 (moderate evidence), 10-30 (strong evidence), 30-100 (very strong evidence)

$\mathscr{B} = 18.1 \pm 0.6$

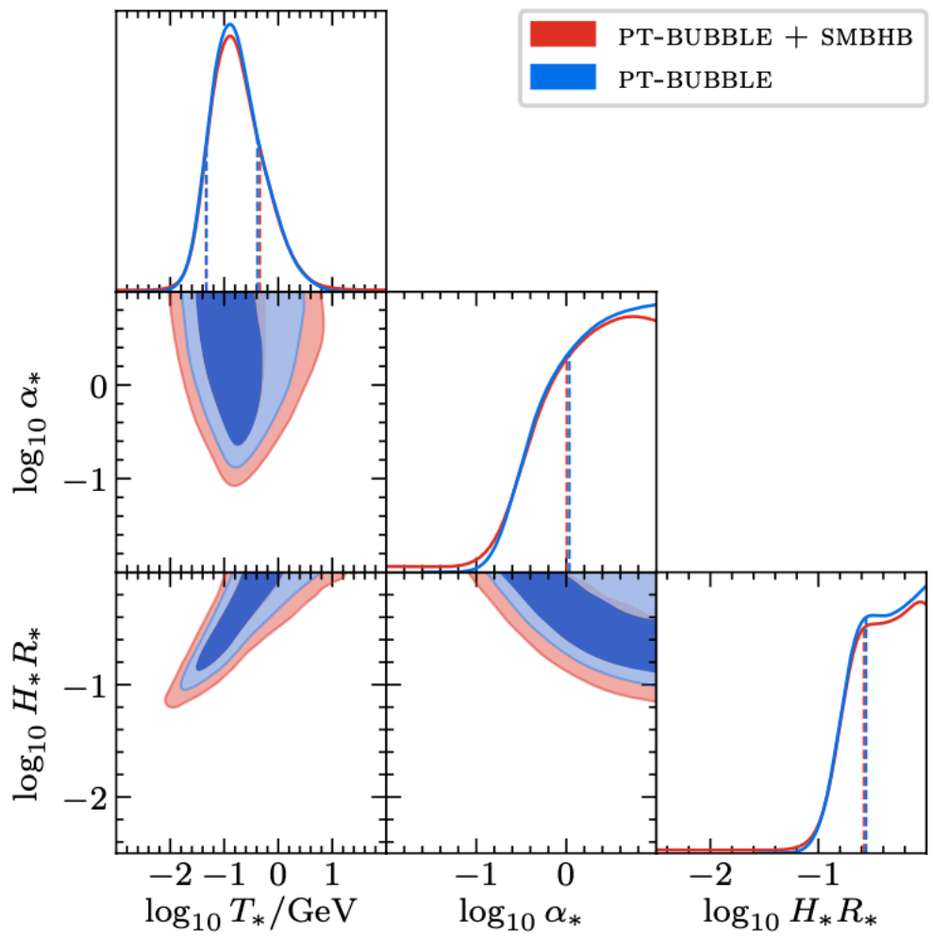


Cosmological FOPT

Cosmological FOPT

- NANOGrav signal 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 $\Lambda_{PTA} \sim 0.1 - 1$ GeV

- One possibility would be the QCD phase transition as $\Lambda_{PTA} \sim \Lambda_{QCD}$

- However the QCD phase transition is a crossover (unless $\eta_L \gg \eta_B$)

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

- These theories were proposed by L. Randall & R. Sundrum to solve the SM hierarchy problem

ii) Sterile neutrinos

- Another hint from the possible existence of a conformal sector with $\Lambda_{conf} = \Lambda_{PTA}$ is the possible existence of a *sterile neutrino* with a light Majorana mass: motivated by neutrino short baseline oscillation anomalies (under debate)

- A light Majorana mass can be obtained in a natural way if N_R is a composite object of a strongly coupled hidden sector

N. Arkani-Hamed, Y. Grossman, 9806223

- It is easily embedded into an AdS space if the profile of N_R is localized toward the IR (GeV) brane and $M_R \sim \rho \sim 1$ GeV

K. McDonald, 1010.2659

- The Dirac mass m_D can be very suppressed by the warp factor between the GeV brane and the Higgs brane, such that the seesaw applies

$$m_\nu = m_D^2 / M_R$$

The model

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

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

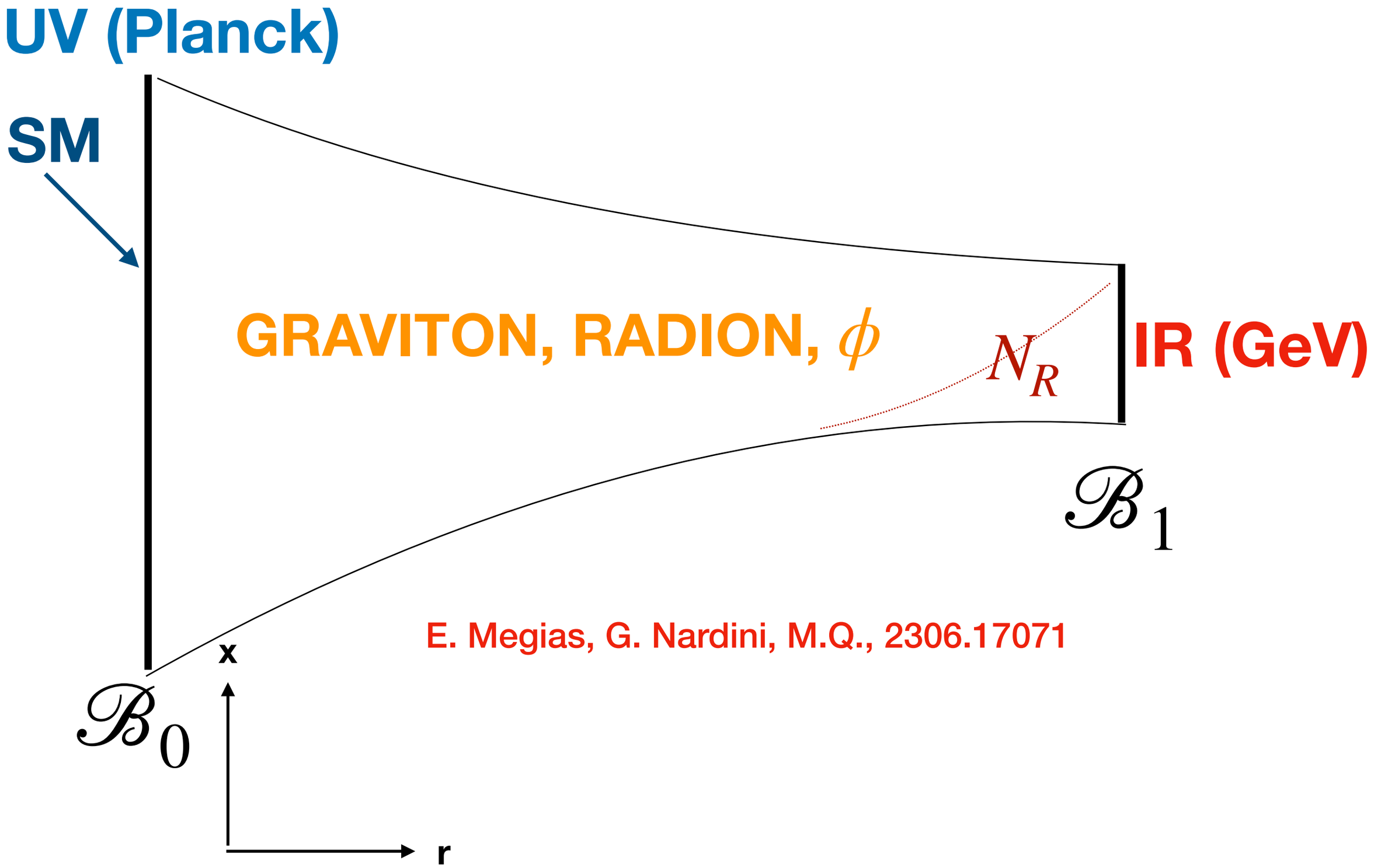
- The fundamental scale $\Lambda_{conf} \sim 10$ MeV $- 1$ GeV can be easily obtained from the Planck scale by a warp factor $\sim e^{-40}$

- The 4D (holographic) theory has a 5D (dual) theory by stabilizing an IR brane in AdS_5 at a distance $ky_1 \sim 40$ 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 eventually the SM singlets (e.g. sterile neutrino) can propagate in the bulk of the fifth dimension

- The SM should be localized on the UV brane (or an intermediate brane at the TeV scale to solve the SM hierarchy problem)

The simplest 5D model



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

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

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

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

The 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: $\lambda_1 \simeq 1 + \ell(\kappa^2/6)\Lambda_1$

$$\Lambda_1(\phi) = \Lambda_1 + \frac{1}{2}\gamma(\phi - v_1)^2, \quad \gamma \to \infty \text{ (stiff limit)}$$

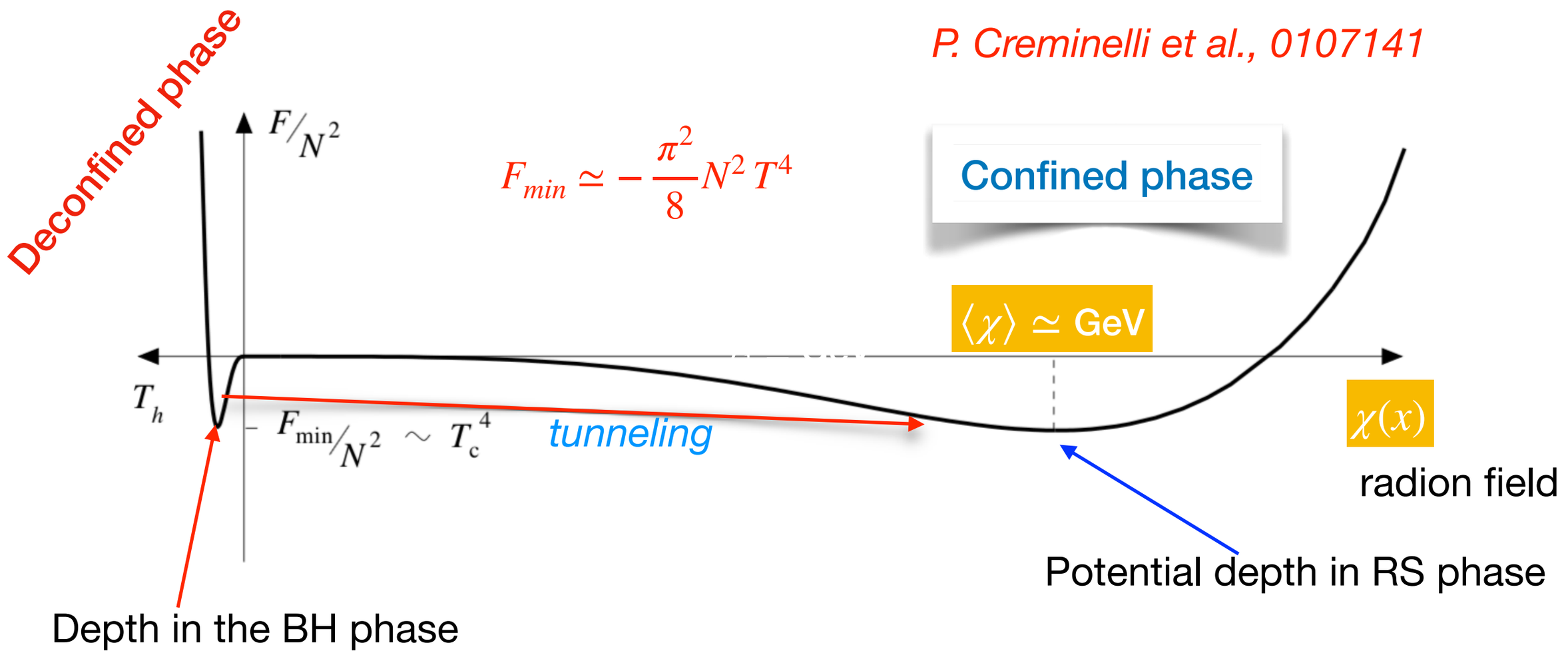
- N (# degrees freedom of holographic theory) Vs k:
$N = 4\pi M_{\rm Pl}\ell, \ \ell = 1/k$

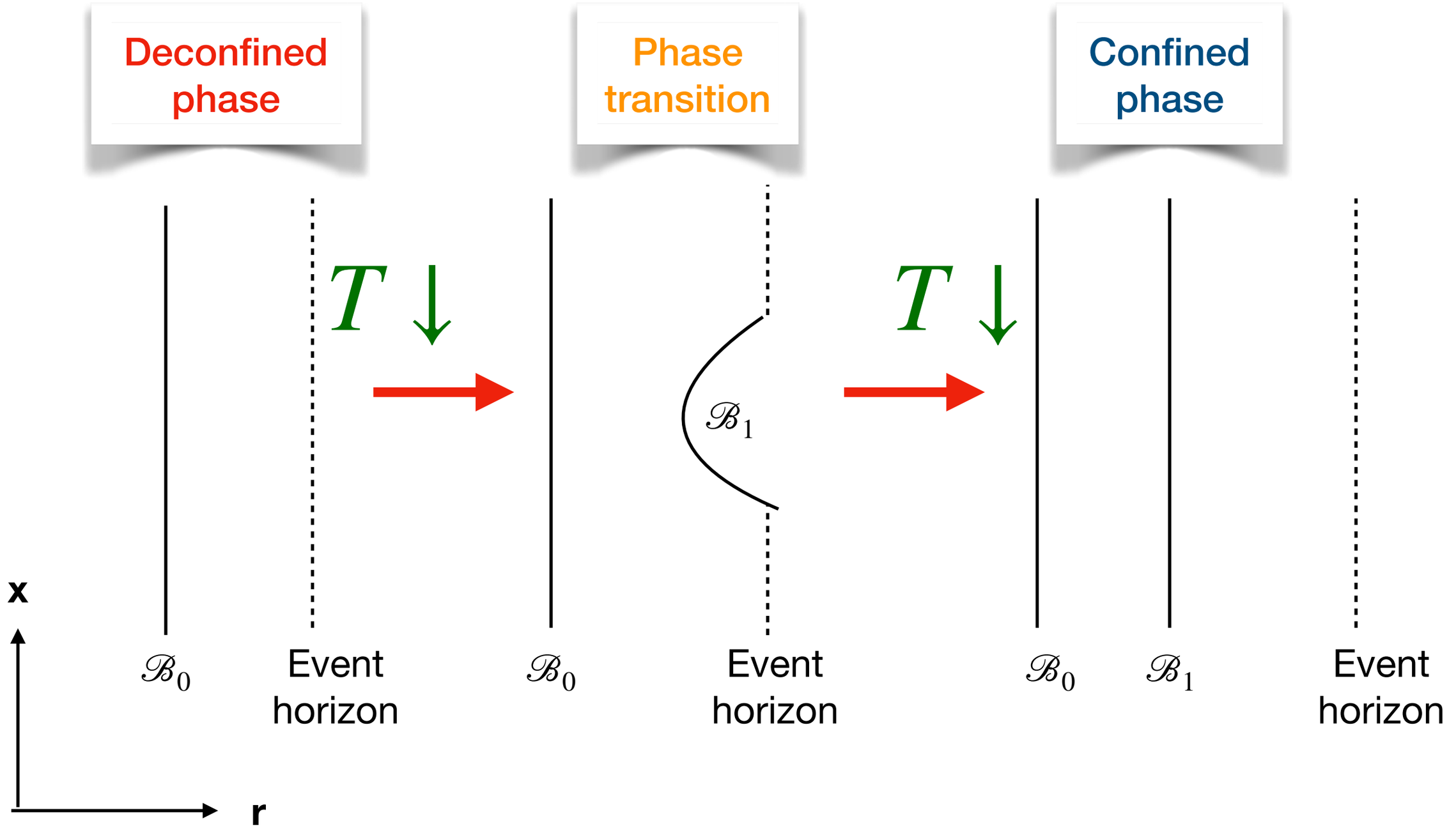
- The brane scale ρ (related to the interbrane distance by the warp factor): $\ell\rho = e^{-r_1 k} \simeq (v_0/v_1)^{1/u}$

The phase transition

Cartoon of free energies

P. Creminelli et al., 0107141





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

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

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

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

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

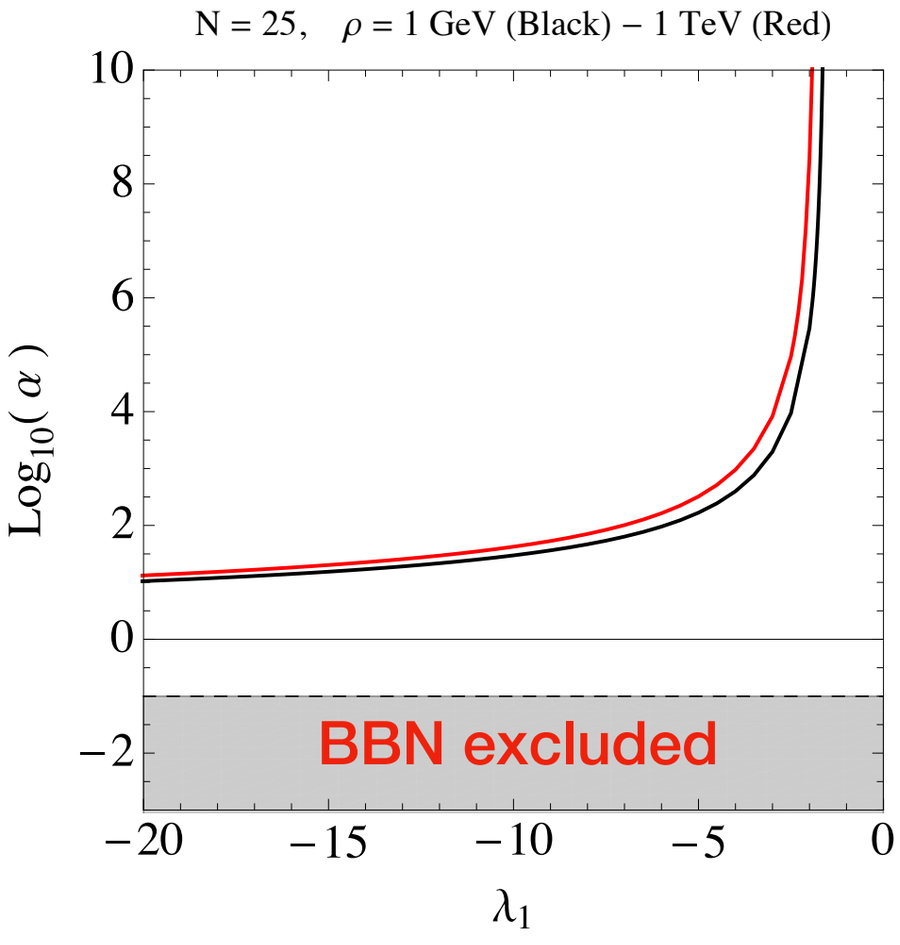
$$f_p \simeq 18\ \text{nHz}\ \frac{\beta}{H_*}\frac{T_R}{100\ \text{MeV}}g_c^{1/6}(T_R)$$

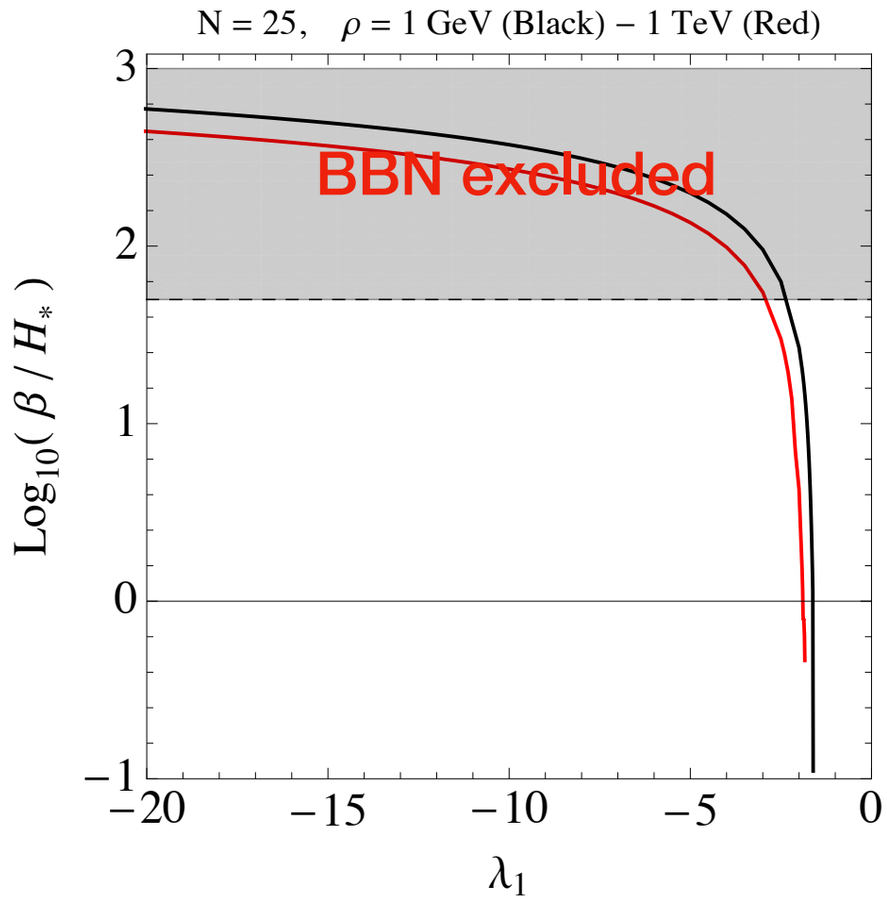
E. Megias, G. Nardini, M.Q., 2005.04127, 1806.04877

Numerical results

i) Our numerical results are in the ballpark of PTA results

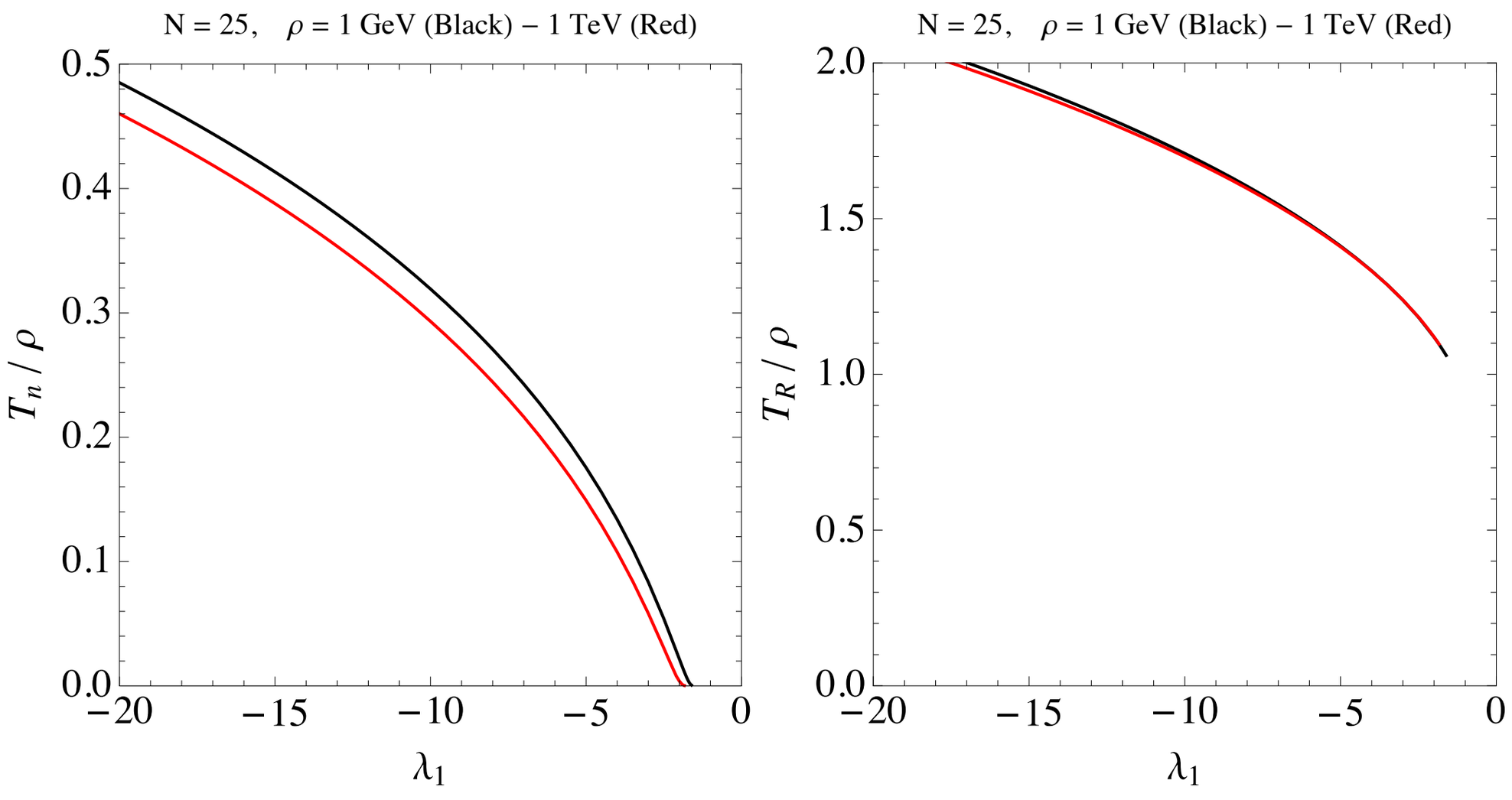
$$v_1\kappa = 2,\ v_0\kappa = 1$$





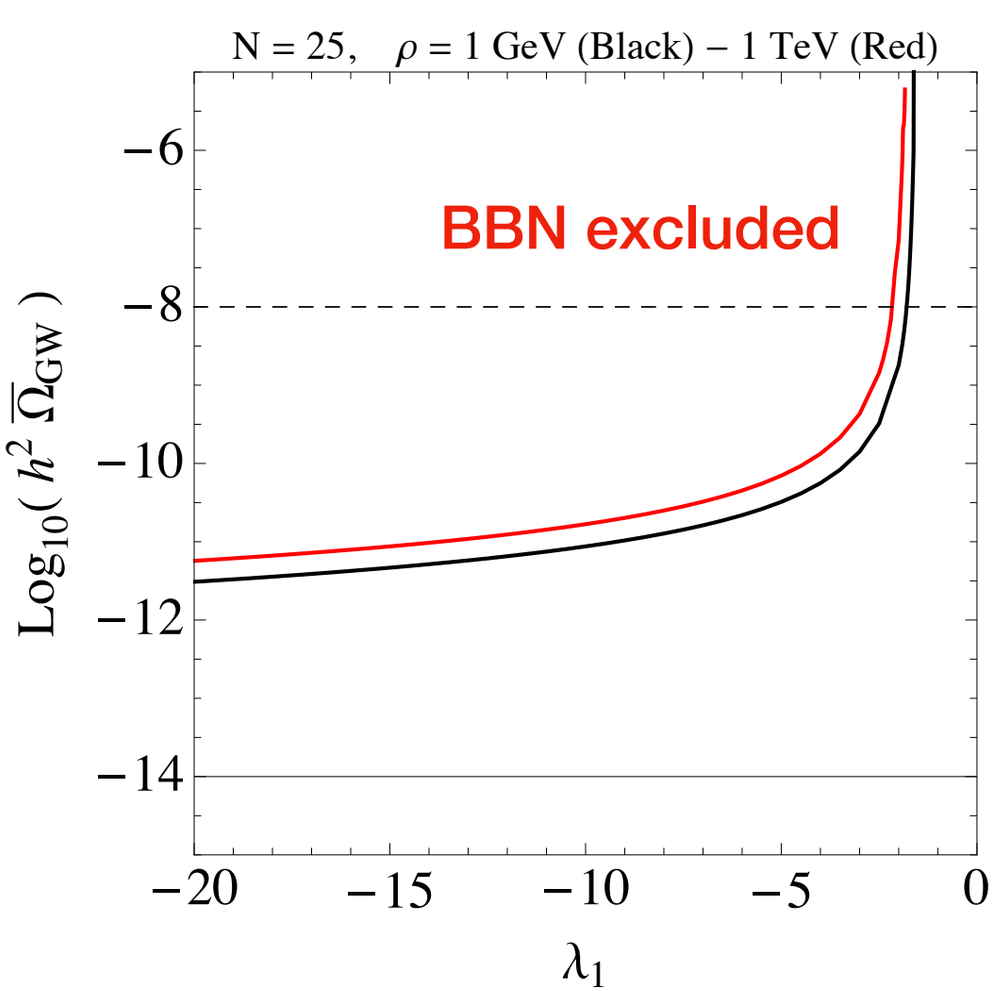
NANOGrav results (95%): $\log_{10}\alpha_* > -0.5, \quad \log_{10}(\beta/H_*) < 1$

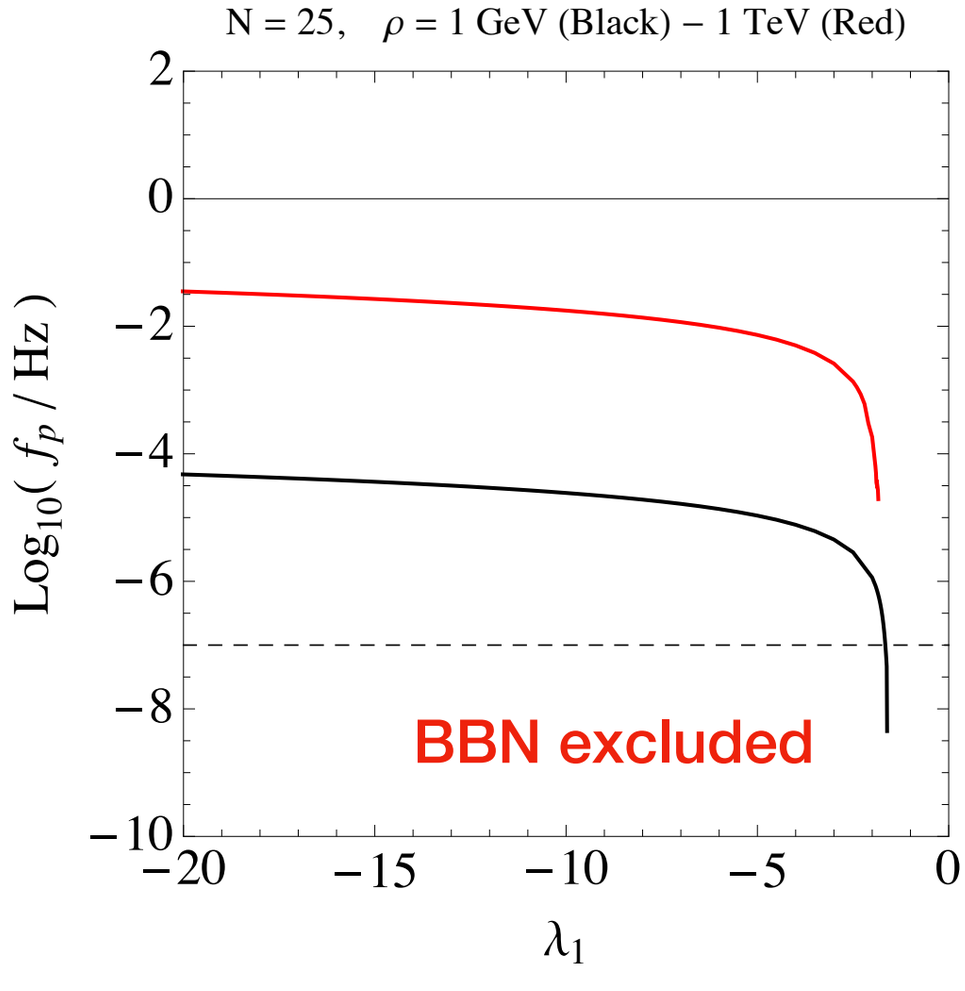
$$v_1\kappa = 2,\ v_0\kappa = 1$$



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

$$v_1\kappa = 2,\ v_0\kappa = 1$$

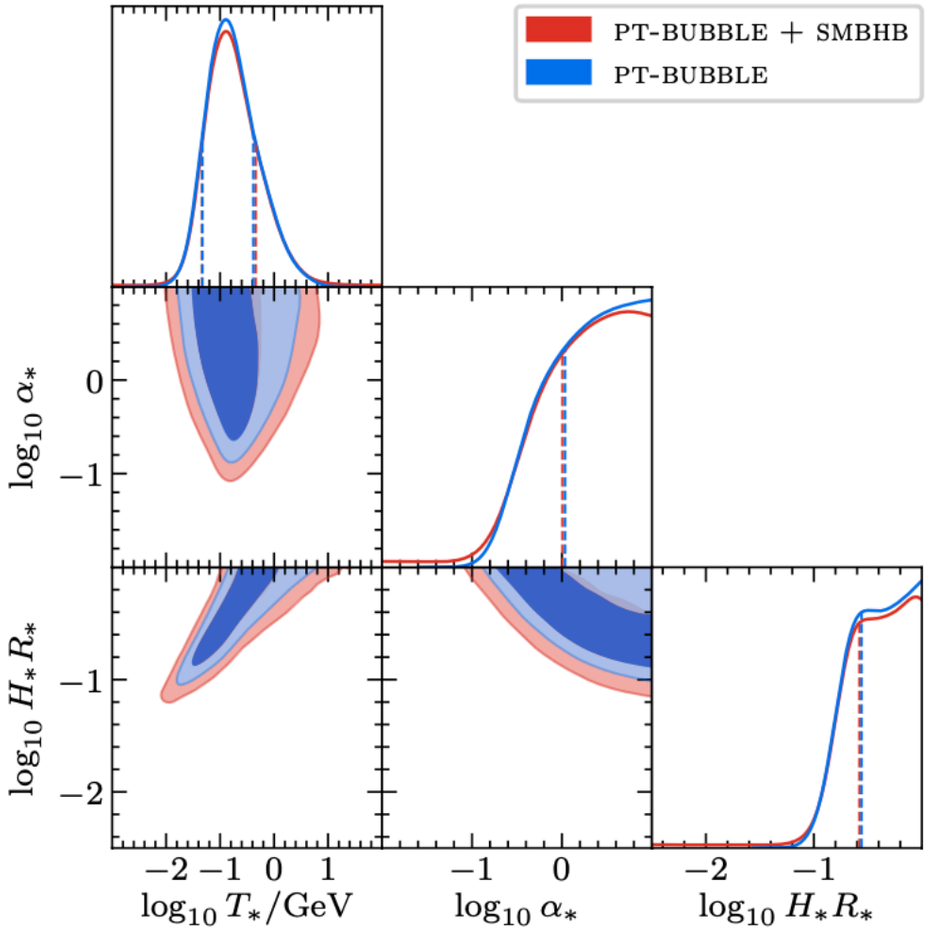


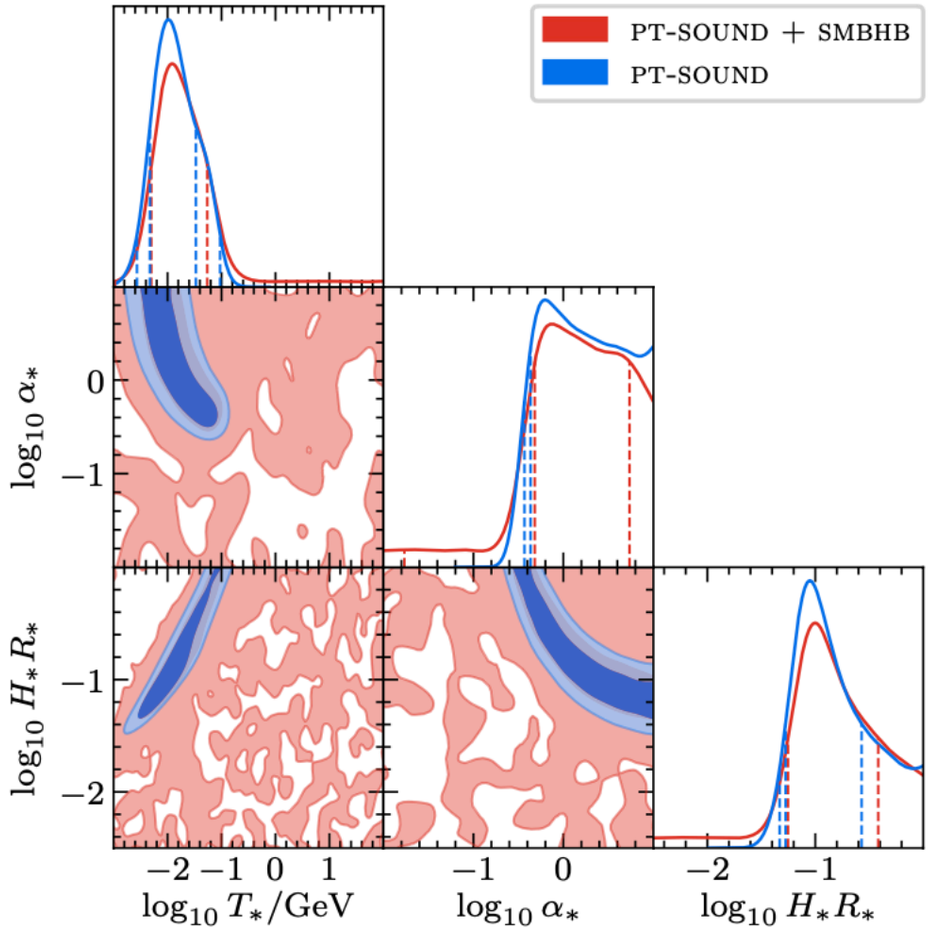


NANOGrav results: $h^2\Omega_{GW} \lesssim 10^{-6},\ f_p \gtrsim 10^{-8}\,\mathrm{Hz}$

ii) Scatter plot of results and comparison with NANOGrav data

NANOGrav Collaboration, 2306.16219



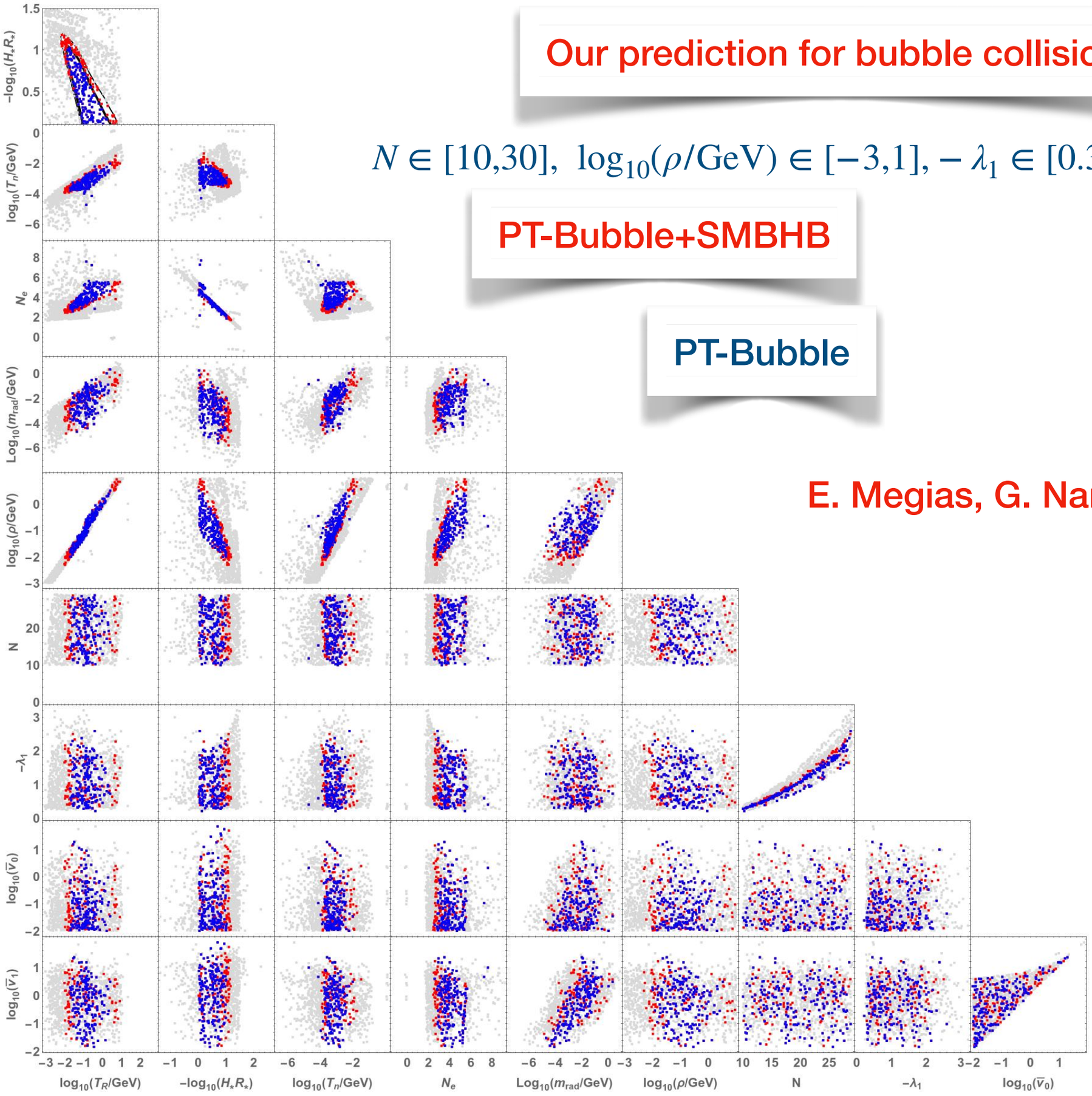


Our prediction for bubble collisions

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

PT-Bubble+SMBHB

PT-Bubble



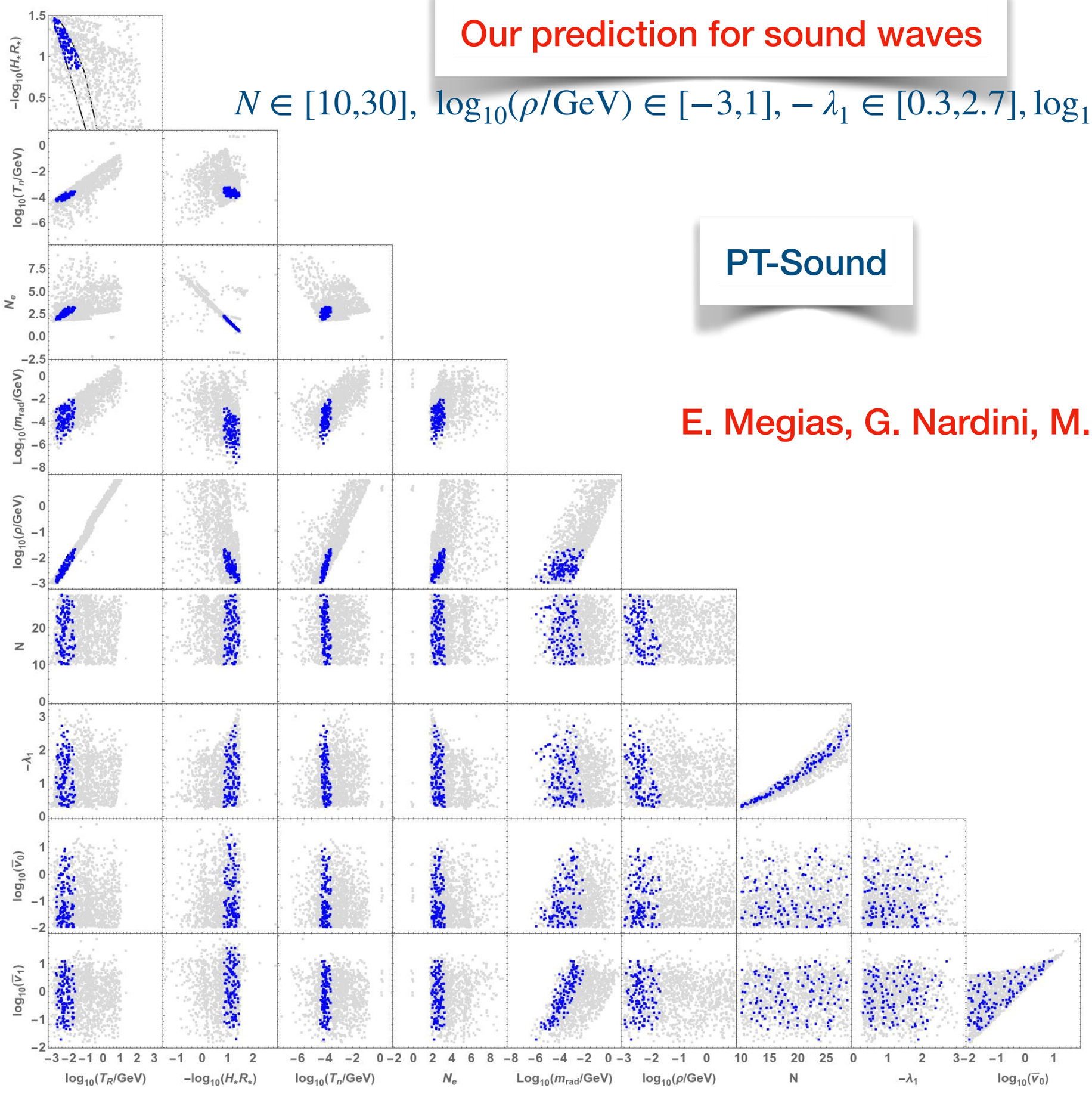
E. Megias, G. Nardini, M.Q. 2306.17071

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

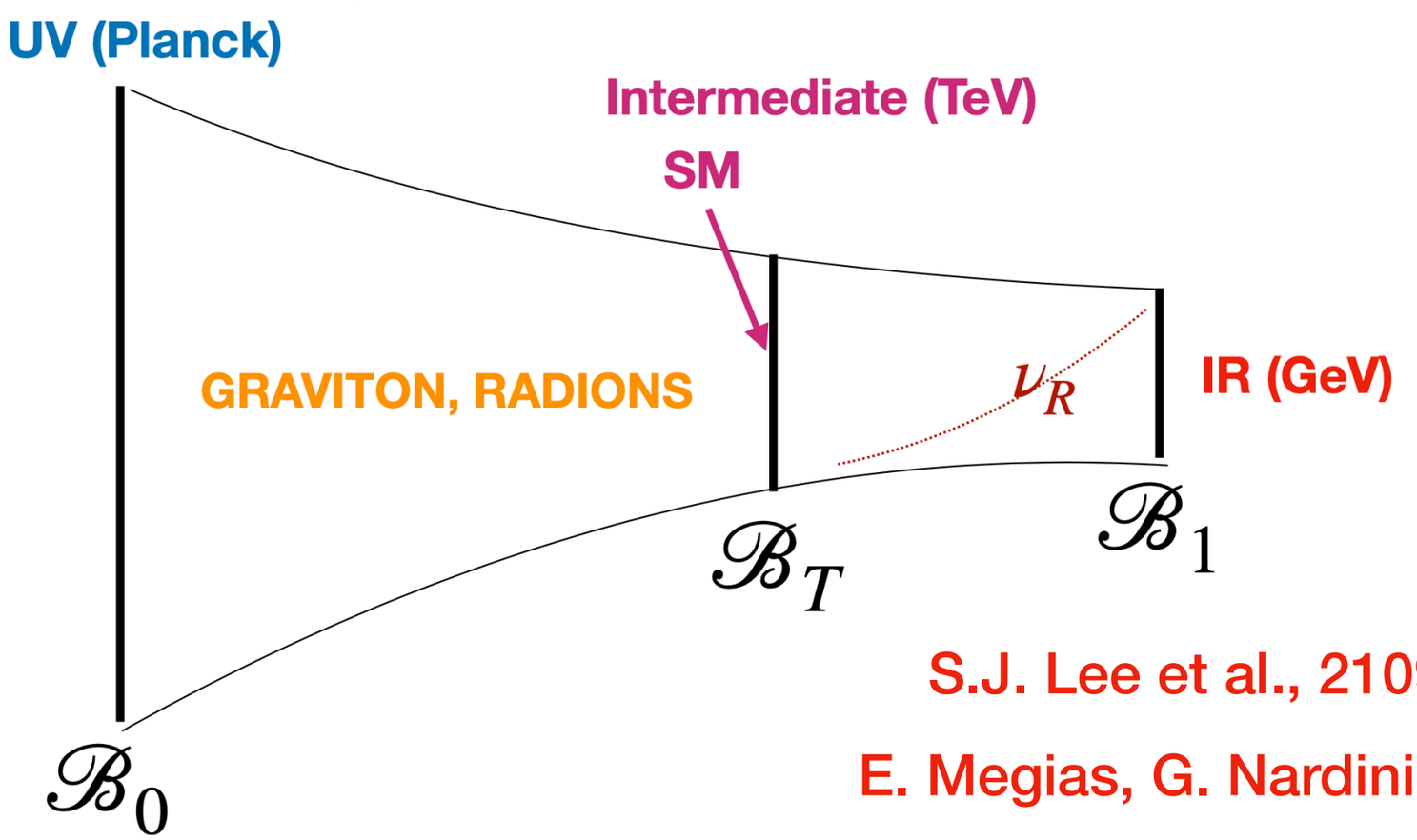
E. Megias, G. Nardini, M.Q., 2306.17071



Phenomenological constraints

- A complete theory could be one with an intermediate brane at the TeV, where the SM is localized, and thus providing an explanation of the hierarchy problem

- The comparison with PTA data is the same as it only depends on the $\mathscr{B}_1$ brane



S.J. Lee et al., 2109.10938

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

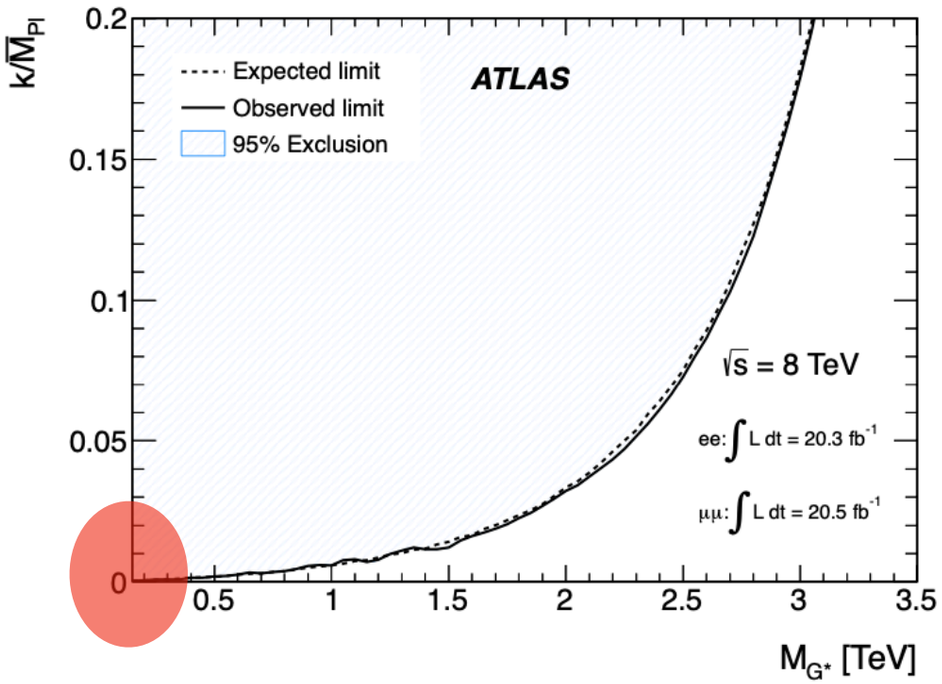
i) Deviation from Newtonian potential

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

ii) KK graviton production at the LHC

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

For $z_b = z_T$ there is a suppression factor with respect to the coupling in RS as $\epsilon(z_T) \simeq 5\times 10^{-9}$ which brings the bounds to MeV-subGeV



ATLAS Coll., 1405.4123

Conclusion

- There is a SGWB at nHz frequencies found by PTA experiments
- The SMBHB explanation, for the moment needs to stretch some astrophysical parameters outside their range
- Otherwise it could be a FOPT new physics (among other candidates)
- An obvious possibility is, in theories solving the hierarchy problem with a warp dimension, a new IR brane at the GeV scale
- The SM can be either in the UV brane (thus not solving the hierarchy problem) or on an intermediate TeV brane (thus solving the hierarchy problem)
- The IR brane at the GeV scale points toward a corresponding conformal sector possibly with a light sterile neutrino whose lightness is natural

BACKUP SLIDES

iii) the H_0 puzzle

- Additional radiation produced just before the BBN by an unstable sterile neutrino can alleviate the Hubble tension by increasing ΔN_{eff}

- In the presence of large lepton asymmetry sterile neutrinos with masses in the 150-500 MeV range can increase ΔN_{eff} by 0.2-0.4 and reduce the Hubble tension

G. Gemini et al., 2005.06721

Planck 2018, 1807.06209