Post-reheating Cosmology in a dilaton-Einstein-Gauss-Bonnet scenario of modified gravity

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Based on:
"WIMPs in dilatonic Einstein Gauss-Bonnet cosmology", Anirban Biswas, Arpan Kar, Bum-Hoon Lee, Hocheol Lee, Wonwoo Lee, S. S., Liliana Velasco-Sevilla and Lu Yin, JCAP 08 (2023) 024, e-Print: 2303.05813 [hep-ph]
"Gauss-Bonnet Cosmology: large-temperature behaviour and bounds from Gravitational Waves", Anirban Biswas, Arpan Kar, Bum-Hoon Lee, Hocheol Lee, Wonwoo Lee, Stefano Scopel, Liliana Velasco-Sevilla, Lu Yin, JCAP 09 (2024) 007, e-Print: 2405.15998 [hep-ph]

- hard to fit GR with other fundamental interactions
- naturalness problem (stabilitation of the Weak Scale under Quantum Corrections)

→ both General Relativity (GR) and the Standard Model of Particle Physics believed to be incomplete

- a new era of precision tests of GR from discovery of Gravitational Waves (GW) and direct measurement of merger events of compact objects
- an effective approach to probe extensions of GR using observational data is the use of **effective models**

Horndeski's theory: most general scalar-tensor theory having equations of motion with second-order time derivatives in four-dimensional spacetime, in which the theory does not have a ghost state
Einstein-Gauss-Bonnet (EGB): one of the simplest Horndeski's theories obtained by adding the Gauss-Bonnet term, a specific quadratic combination of the curvature → topological invariant not affecting the dynamics, unless the Gauss-Bonnet term is non-minimally coupled to a scalar field
→ **dilatonic Einstein Gauss-Bonnet (dEGB) scenario**

Dilatonic Einstein Gauss-Bonnet (dEGB) scenario

$$S = \int_{\mathcal{M}} \sqrt{-g}\, d^4x \left[\frac{R}{2\kappa} \underbrace{- \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - V(\phi)}_{\text{scalar field}} + \underbrace{f(\phi) R^2_{\rm GB}}_{\text{non-minimally coupled GB term}} + \mathcal{L}_m^{\rm rad} \right] ,$$

$\kappa \equiv 8\pi G = 1/M^2_{PL}$

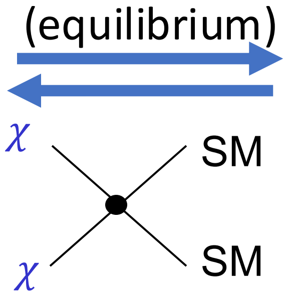
non-minimal coupling encoded in the f(ϕ) function (if $\phi' \equiv df/d\phi = 0$ the GB term does not affect the dynamics). In the following:

$$f(\phi) = \alpha e^{\gamma\phi}$$

(exponential form arises within theories where gravity is coupled to the dilaton)

→study the phenonology of WIMP decoupling in terms of the two free parameters α and γ

WIMP thermal decoupling



Boltzmann's equation

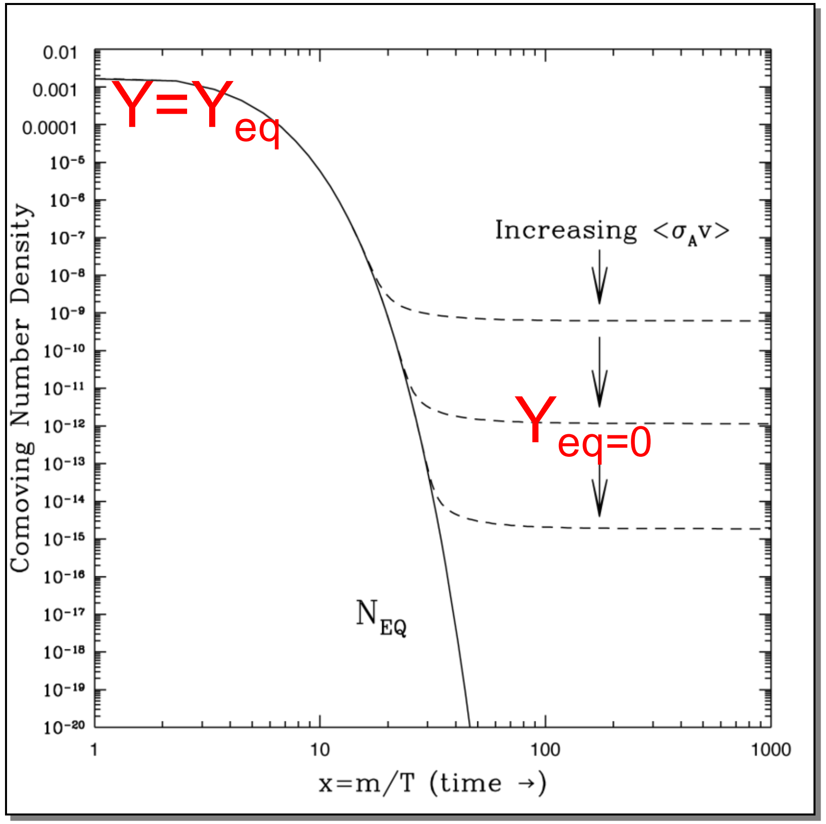
$$\frac{dn}{dt} + 3Hn = - < \sigma v > \left(n^2 - n_{eq}^2\right)$$ (Lee-Weinberg)

$$\frac{dY}{dx} = -\frac{xs}{H(T=m)} < \sigma v > \left(Y^2 - Y_{eq}^2\right)$$

x=m/T, m=WIMP mass, Y=n/s, n=WIMP number density, s=entropy density

$< \sigma v >$ =annihilation cross section time velocity of WIMP to SM particles

- at high temperature the WIMP number density follows its equilibrium value n_{eq}
- when T<m n_{eq} is exponentially suppressed and the WIMP decouples from the plasma
- from that moment Y=n/s almost constant until today
- today get $n_0=Y_0\ s_0$ with s_0 the present entropy density



x_f ~20

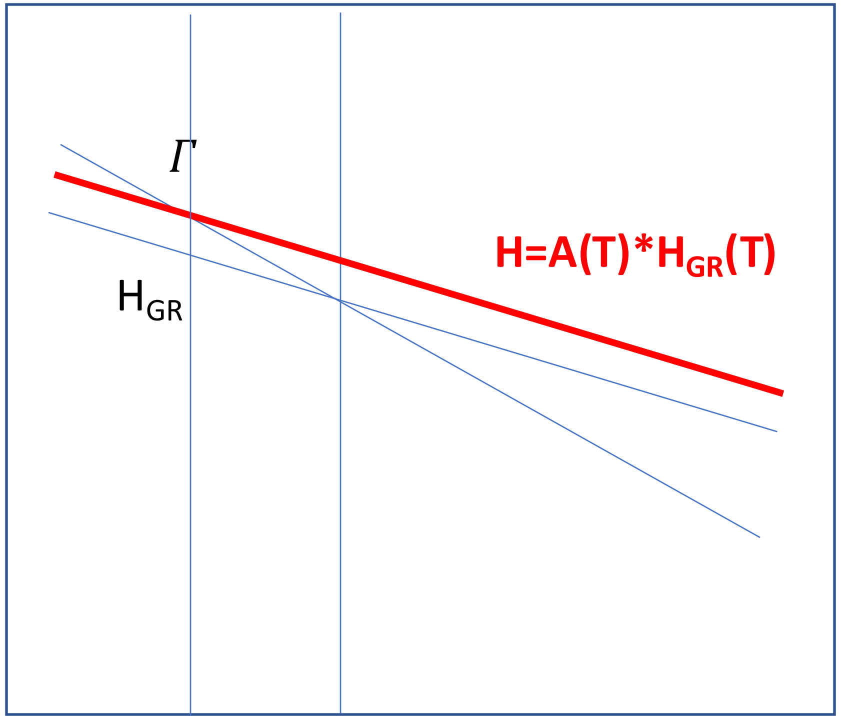
decoupling happens at T~m/20
→ Cold Dark Matter, i.e. the WIMP is non relativistic at decoupling and can start forming structures before baryons

Relic density for Dark Matter through thermal decoupling in non-standard Cosmology

$$\frac{dn}{dt} + 3Hn = - < \sigma v > (n^2 - n_{eq}^2)$$

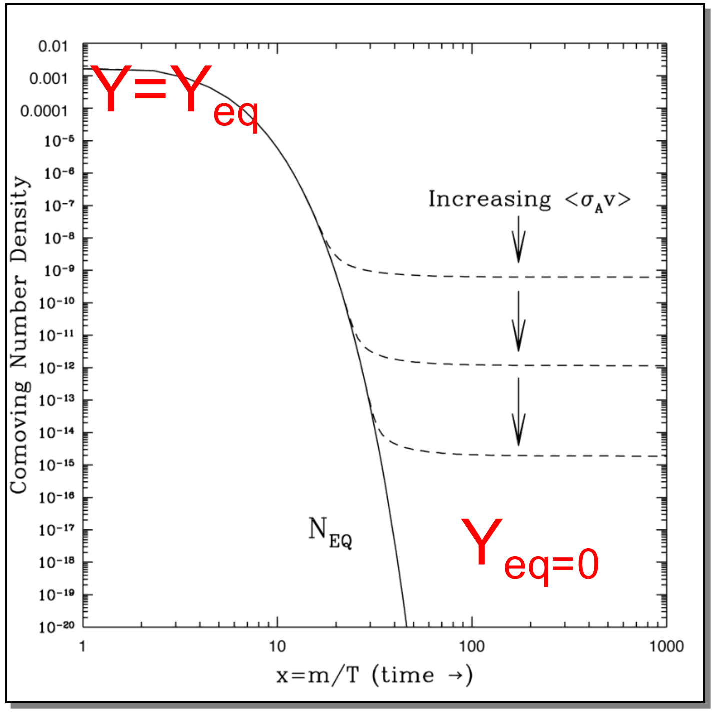
$\boxed{\Omega_X h^2 \sim 1/<\sigma v>}$ (for higher signals today lower relic density)

Typical value for $\Omega_X h^2 \sim 0.1$ in standard Cosmology→ **$<\sigma v> = 2.1\text{e-}26\ cm^3 s^{-1}$**



T_f T_f

Γ=annihilation rate
→Γ^{-1}=mean free path
H^{-1}=horizon



$x_f \sim 20$

Decoupling condition:

$\Gamma^{-1} > H^{-1} \rightarrow \Gamma < H$

Non-standard cosmology:

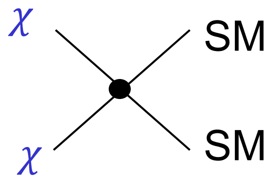
$H = A(T) * H_{GR}(T)$ **A≡enhancement parameter**

$H_{GR}(T)$=expansion rate in standard cosmology (radiation)

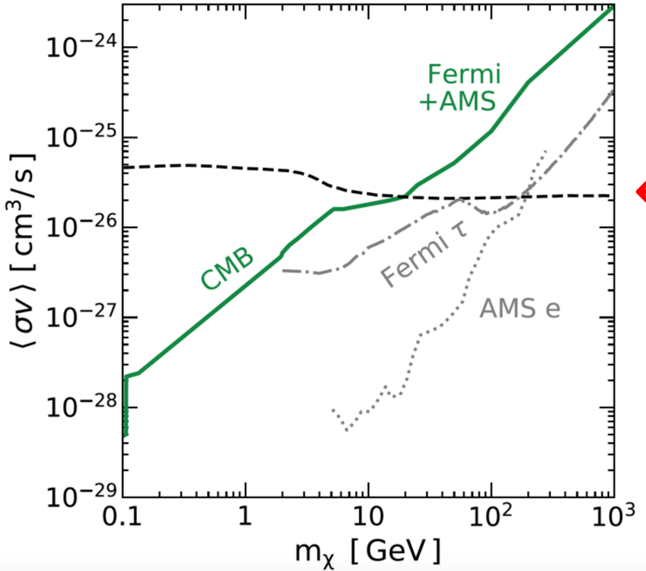
A>1→ earlier decoupling at same <σv> → larger relic density

For a non-standard cosmology with A>1 the annihilation cross section **<σv> needs to be larger that the standard value 2.1e-26 cm^{3}s^{-1}** to explain the data, corresponding to $\Omega h^2 << 0.1$ for a standard cosmology

Assuming s-wave annihilation **<σv> is the same in the early Universe and today**



In a non-standard Cosmology the value of **<σv>** corresponding to the correct relic abundance can be driven beyond the observational limits from **DM indirect searches**



← <σv> ~ 2.1e-26 cm^{3}s^{-1}

R. K. Leane,T.R. Slatyer,John F. Beacom,and K. C. Y. Ng, PRD 98, 023016 (2018)

Friedman equation in dEGB Cosmology:

$$H^2 = \frac{\kappa}{3}\left(\frac{1}{2}\dot{\phi}^2 + V - 24\dot{f}H^3 + \rho_{\rm rad}\right) ,$$

$$\dot{H} = -\frac{\kappa}{2}\left(\dot{\phi}^2 + 8\frac{d(\dot{f}H^2)}{dt} - 8\dot{f}H^3 + \rho_{\rm rad} + p_{\rm rad}\right)$$

$$\ddot{\phi} + 3H\dot{\phi} + V' - 24f'H^2(\dot{H} + H^2) = 0 .$$

Continuity equations:

$$\dot{\rho}_{\rm rad} + 3H(\rho_{\rm rad} + p_{\rm rad}) = 0.$$

(radiation)

$$\dot{\rho}_{\{\phi+{\rm GB}\}} + 3H\left(\rho_{\{\phi+{\rm GB}\}} + p_{\{\phi+{\rm GB}\}}\right) = 0.$$

(scalar field + GB)

N.B. Identify the term

$$\rho_{\rm GB} = -24\dot{f}H^3 = -24f'\dot{\phi}H^3 = -24\alpha\gamma e^{\gamma\phi}\dot{\phi}H^3.$$

as an energy density, although it can be negative (plot absolute value). Of course the total density of the Universe $\rho = \rho_{\Phi} + \rho_{\rm rad} + \rho_{\rm GB}$ remains positive.

We evolve the Friedmann equations numerically from Big Bang Nucleosinthesis to high temperatures - WIMP phenomenology is affected for T~m/20. For a WIMP mass 10 GeV<m<1 TeV this corresponds to **500 MeV<T<50 GeV**.

Boundary conditions at T_{BBN} ~ 1 MeV:

- $\dot{\phi}_{\rm BBN} \equiv \dot{\phi}(T_{BBN})$ so that $\rho_{\Phi,\rm BBN} = \frac{1}{2}(\dot{\phi}_{\rm BBN})^2 \leq 3 \times 10^{-2}\ \rho_{\rm rad,BBN}$ (from N_{eff} = 2.99 ± 0.17, radiation must dominate at T_{BBN} not to spoil BBN)
  ($\dot{\phi}_{\rm BBN} \rightarrow - \dot{\phi}_{\rm BBN}$ equivalent to $\gamma \rightarrow -\gamma$, **can fix $\dot{\phi}_{\rm BBN}$ >0 and study both signs of γ**)
- fixing $\phi_{\rm BBN}$ corresponds to a redefinition of the α parameter (gauge) in the dEGB function:

$$\phi'_{\rm BBN} = \phi_{\rm BBN} + \phi_0, \quad \alpha' = \alpha\, e^{-\gamma\phi_0}, \quad \gamma' = \gamma$$

so, without generality, can choose the gauge $\phi_{\rm BBN}$ =0 or, equivalently, can express the results in terms of the gauge-invariant parameter:

$$\tilde{\alpha} = \alpha\, e^{\gamma\phi_{\rm BBN}}$$

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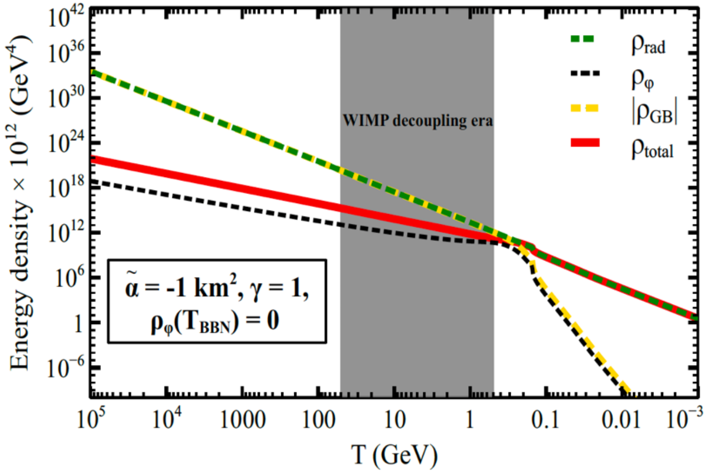
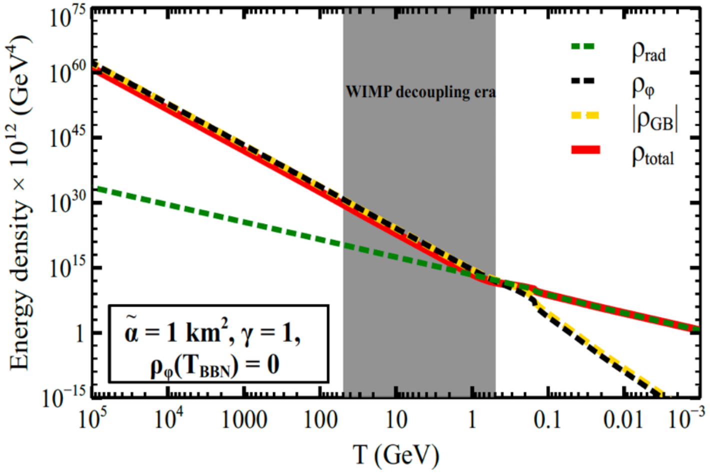
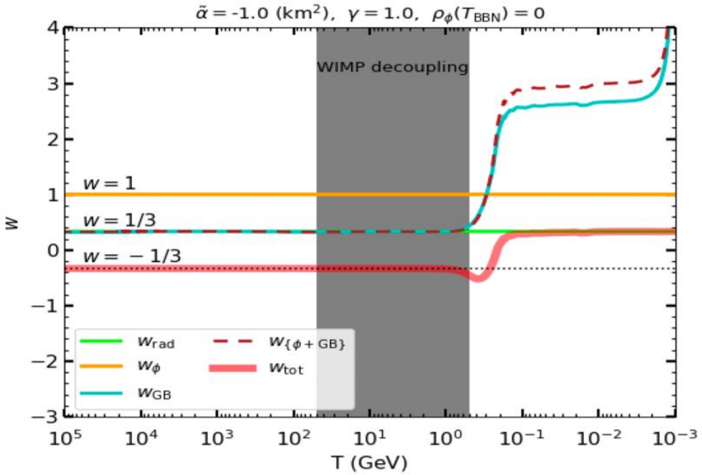
Example of evolutions of energy densities and equations of state for $\dot{\phi}_{\mathrm{BBN}}$ =0 (in this case the results are invariant when $\gamma \rightarrow -\gamma$)

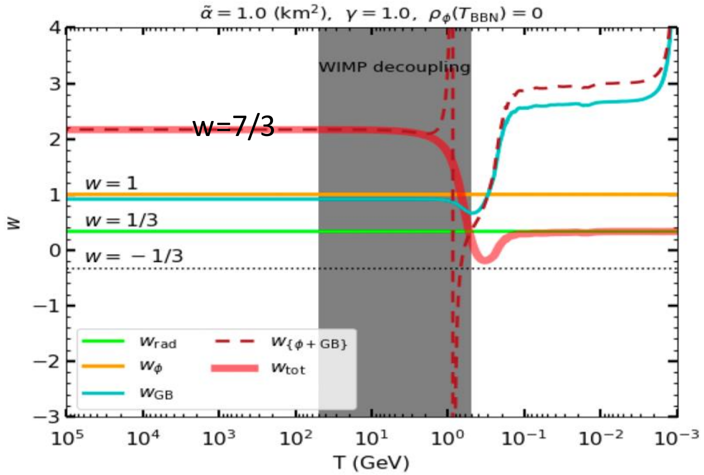
γ=1





energy densities





equation of state

$\tilde{\alpha}$=-1 km^2

$\tilde{\alpha}$=1 km^2

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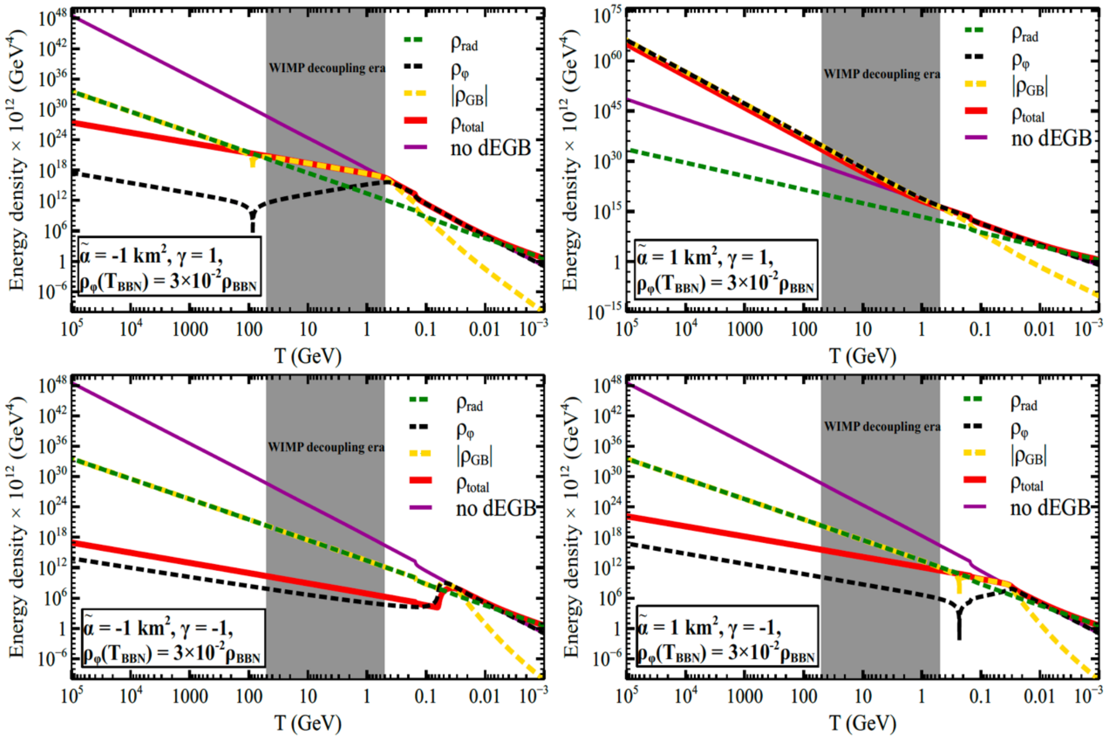
Example of evolutions of energy densities and equations of state for $\dot{\phi}_{\rm BBN} > 0$

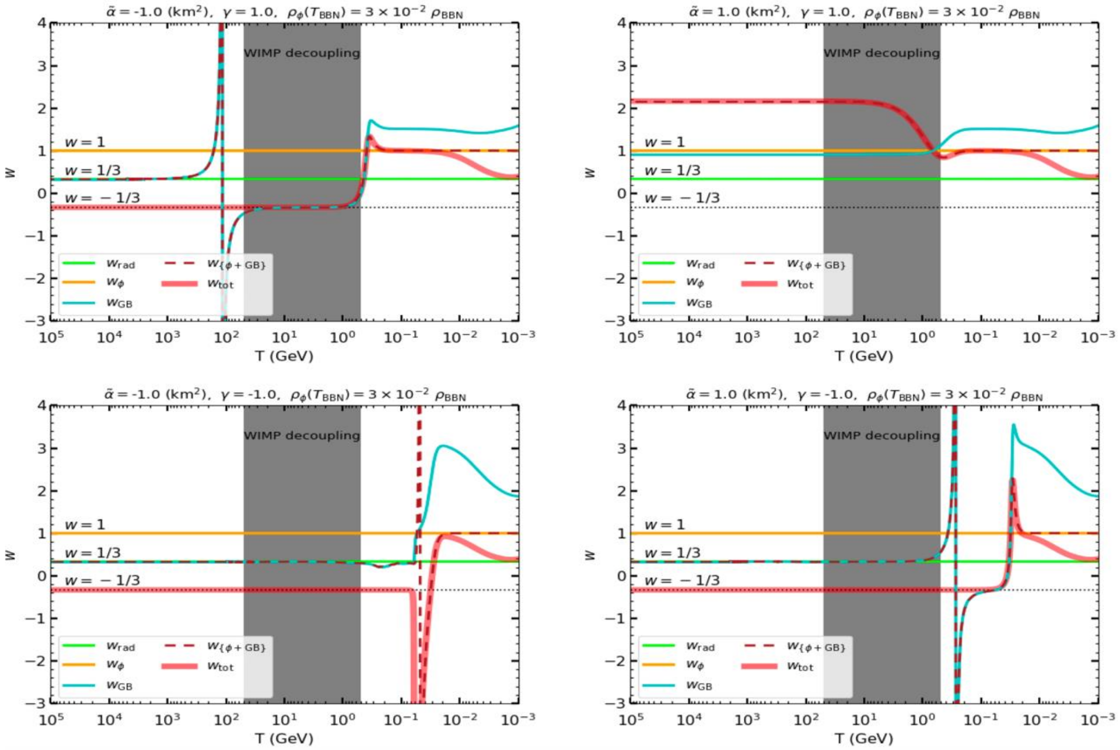
energy densities

equation of state

γ=+1

γ=-1





$\tilde{\alpha}$=-1 km^2 $\tilde{\alpha}$=+1 km^2 $\tilde{\alpha}$=-1 km^2 $\tilde{\alpha}$=+1 km^2

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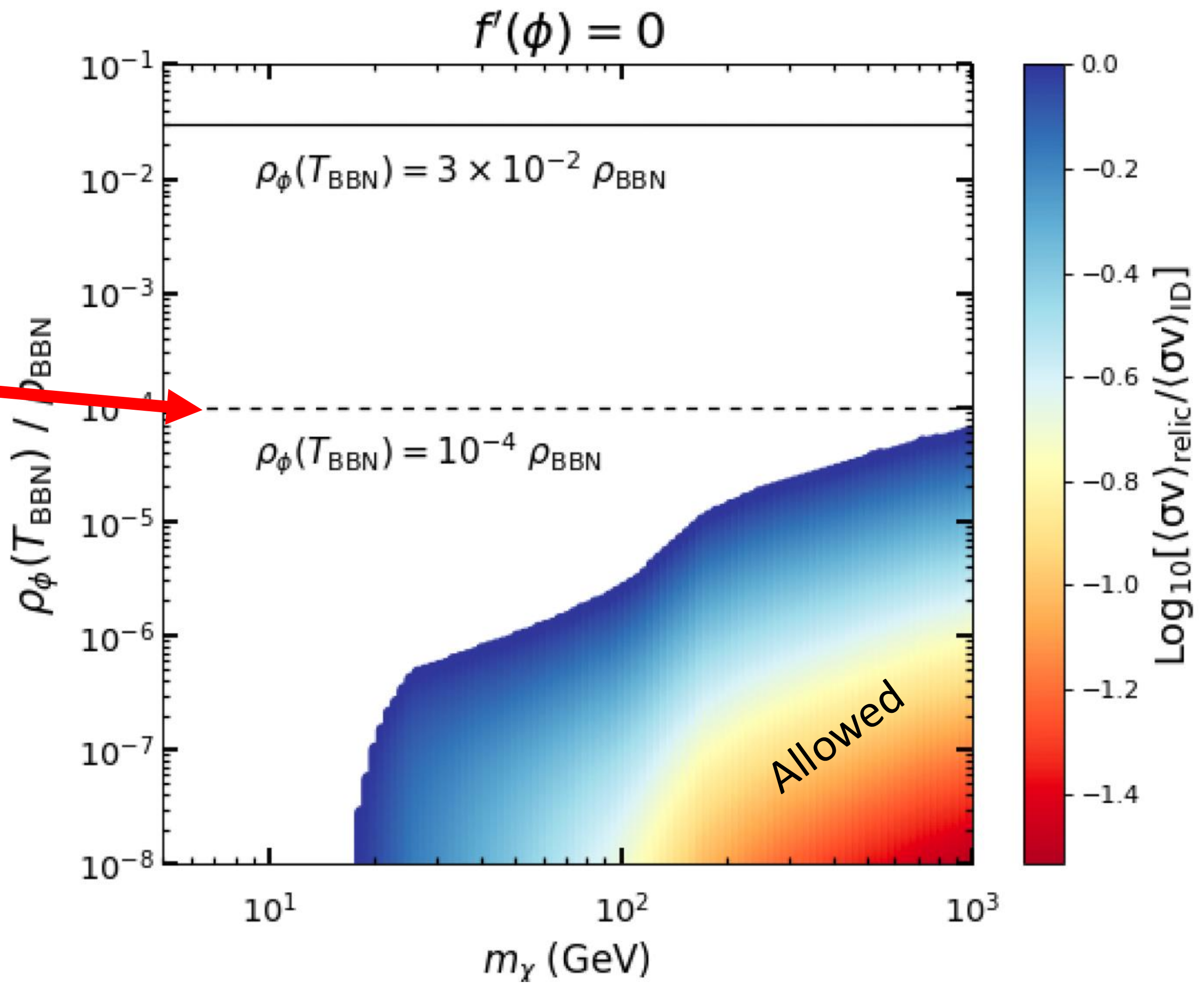
N.B. for f'(ϕ)=0 (no GB term, only kination) WIMP indirect detection already excludes $\rho_{\Phi,\mathrm{BBN}} = 3 \times 10^{-2}\, \rho_{\mathrm{rad,BBN}}$ for any WIMP mass m

also this intermediate value of $\rho_{\Phi,\mathrm{BBN}}$ is excluded at all m



what is the effect of the dEGB term?

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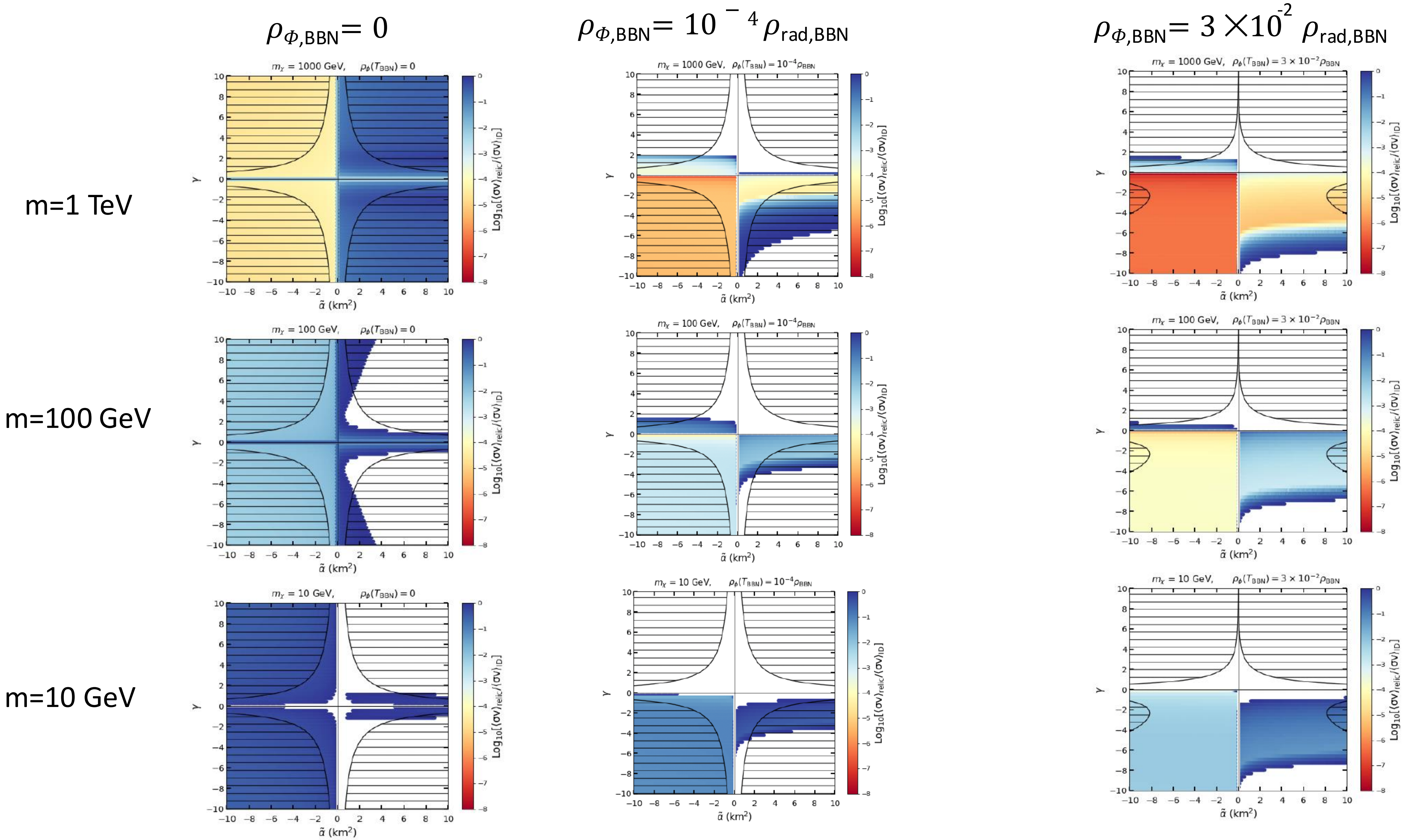

white regions: excluded by WIMPs; **shaded regions**: excluded by GW from compact-binary mergers; **non-white regions**:allowed;

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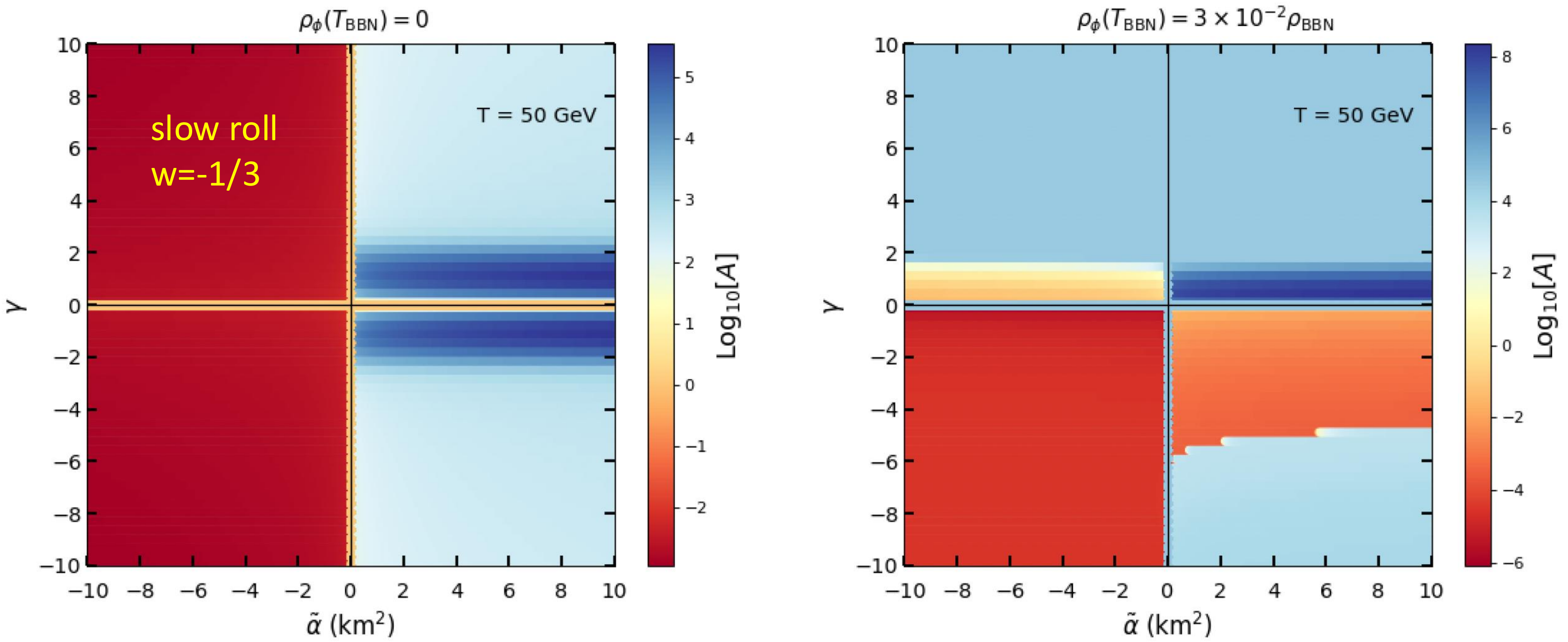
Enhancement factor $A=H/H_{GR}$



A can be very large (10^5), however the corresponding enhancement of <σv> is more moderate because annihilations can remain sizeable after freeze-out when $\Gamma/H \sim T^{3-\alpha}$ and $\alpha>3$ (F. D'Eramo, N. Fernandez and S. Profumo, JCAP 05 (2017) 012, [1703.04793]).

- the presence of the dEGB term slows down the scalar field evolution when w→-1/3 (non-accelerated Cosmology, "slow ϕ roll") recovering allowed configurations when $\boldsymbol{\tilde{\alpha}}$, $\boldsymbol{\gamma<0}$ and $\boldsymbol{\tilde{\alpha}*\gamma<0}$

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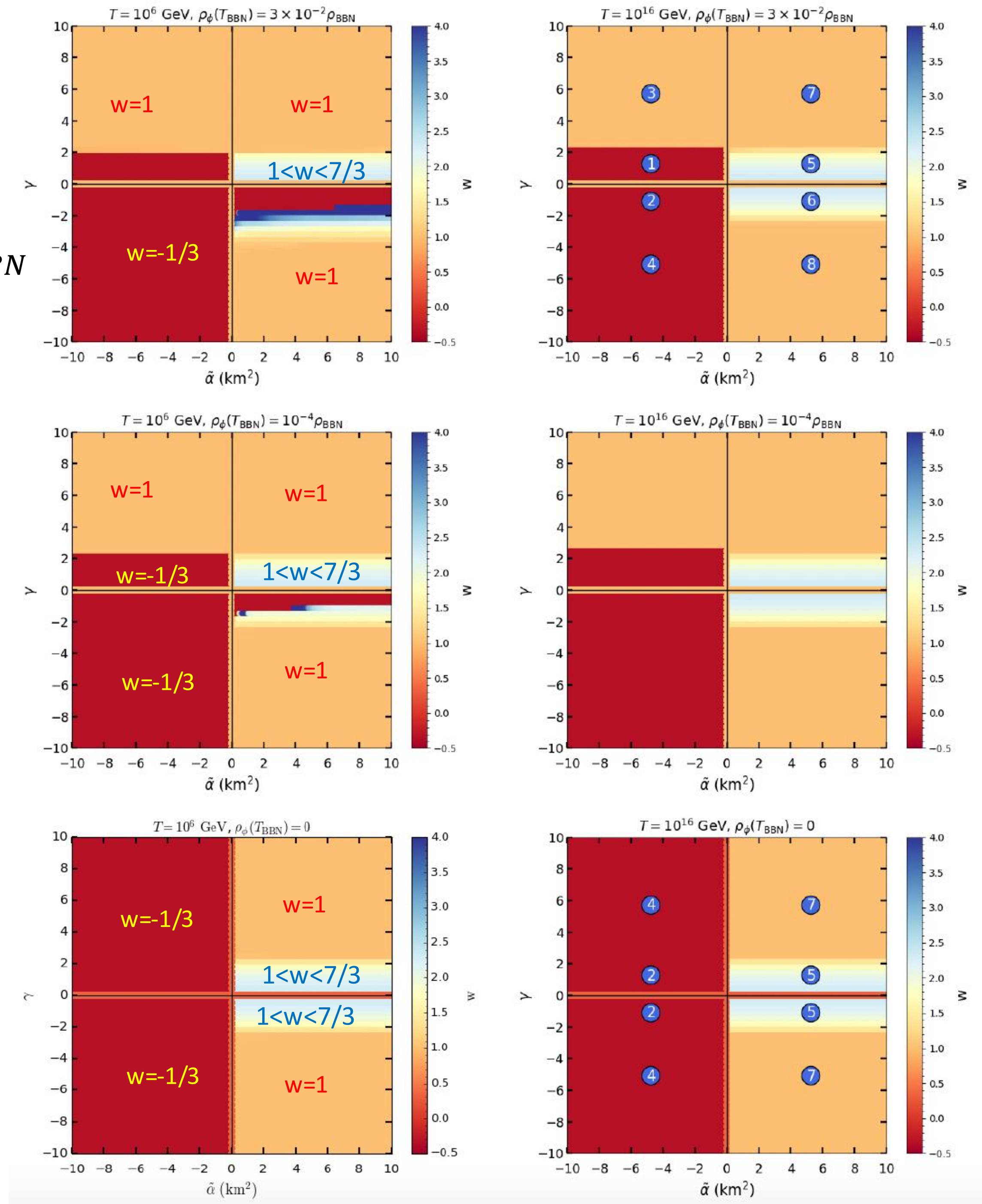
in spite of a high degree of non linearity and phenomenological complexity at low temperatures, at large-enough temperatures dEGB exhibits only <u>very few asymptotic behaviours</u> – attractor solutions?

- w=1
- w=-1/3
- 1<w<7/3

$$\dot{\varphi} = 3\text{x}10^{-2}\rho_{BBN}$$

$$\dot{\varphi} = 10^{-4}\rho_{BBN}$$

$$\dot{\varphi} = 0$$



Introduce the following non-dimensional variables:

$$x \equiv \frac{\rho_\phi}{\rho} = \frac{\kappa}{6}\left(\frac{\dot{\phi}}{H}\right)^2 ,$$

$$y \equiv \frac{\rho_{\rm rad}}{\rho} = \frac{\kappa g_* \pi^2}{90}\frac{T^4}{H^2} ,$$

$$z \equiv \frac{\rho_{\rm GB}}{\rho} = -8\kappa \dot{f} H = -8\kappa \frac{\partial f}{\partial \phi}\dot{\phi} H$$

with the constraint:

$$x + y + z = 1$$

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can express the Friedmann equations in terms of two independent variables (x and z):

$$\begin{cases} x' = 2\left[\epsilon(x,z) - 3\right] x + \left[\epsilon(x,z) - 1\right] z \equiv F(x,z), \\ z' = 2x + \left[\epsilon(x,z) - 3\right] z + 2\left[2 - \epsilon(x,z)\right] \equiv G(x,z) \\ \left(' = \frac{d}{dN} = \frac{d}{d\ln a} = \frac{1}{H}\frac{d}{dt}\right) \end{cases}$$

autonomous equations
(do not depend explicitly on N)

N=# of e-foldings (”time” parameter)

$$\epsilon \equiv -\frac{\dot{H}}{H^2} = 1 + q = \frac{4x^2 + 8x + z^2 + 2\sqrt{\frac{6}{\kappa}}\mathrm{sign}(\alpha)|\gamma||z|x^{3/2}}{4x - 4xz + z^2}$$

$q = -\frac{a\ddot{a}}{\dot{a}}$ =deceleration parameter

N.B. the $\boldsymbol{\epsilon}$ parameter is directly related to the equation of state:

$$w = \frac{2}{3}\epsilon - 1$$

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the two equations describe a velocity field in the x-z plane

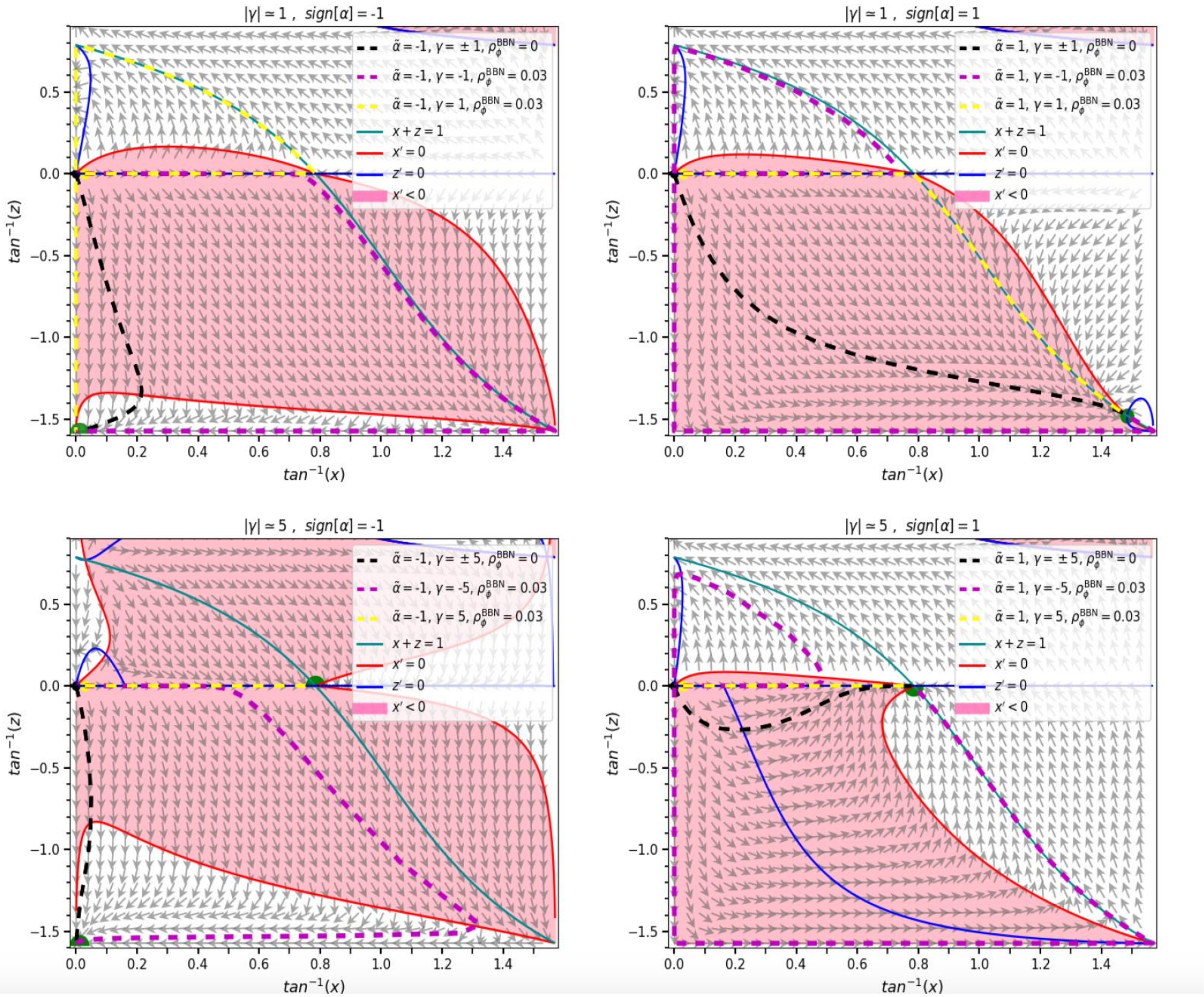
critical points: $x'=z'=0$

three types of critical points:

- stable → attractors
- unstable → saddle points
- repelling nodes

In a stable critical point (attractor) at $N \to -\infty$ the differential equations saturate at $x,z \to x_c,z_c$ and so also the equation of state since $\varepsilon=\varepsilon(x_c,z_c)$

this explains the asymptotic behaviours at large T



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Critical points for finite x,z:

$$\begin{cases} \dfrac{dx}{dN} = 0 \\ \dfrac{dz}{dN} = 0 \end{cases} \Rightarrow \quad x_c = \frac{\epsilon - 1}{5 - \epsilon}, \quad z_c = -2\frac{\epsilon - 3}{5 - \epsilon}$$

(implicit, ε depends on x,z)

substituting back x_c, z_c in $\varepsilon(x,z)$:

$$(\epsilon - 1)(\epsilon - 3)\left(\sqrt{\frac{6}{\kappa}}|\gamma|\mathrm{sgn}(\alpha z_c)\sqrt{\frac{\epsilon - 1}{5 - \epsilon}} + 2\epsilon\right) = 0,$$

three solutions:

- **ε=1** , (x_c,z_c)=(1,0) (kination)
- **ε=3** , (x_c,z_c)=(0,1) (Gauss Bonnet)

always present, do not depend on the parameters α and γ

- $(x_c,z_c)=(x_{fp},z_{fp})$ solution of cubic equation:

$$2\epsilon^3 - 10\epsilon^2 + \frac{3}{\kappa}\gamma^2\epsilon - \frac{3}{\kappa}\gamma^2 = 0.$$

  with $x_{fp}+z_{fp}$ =1. Only when sign(αz_c)<0, which implies:

- $|\gamma|<\sqrt{6\kappa}$ when α>0 (in this case z_{fp}<0 and ε>3
- $|\gamma|>\sqrt{6\kappa}$ when α<0 (in this case z_{fp}>0 and ε<3

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Critical points at infinity:

expand $\varepsilon(x,z)$ in the leading term in O(x/z)→0 ("slow-roll" regime):

$$\epsilon = \frac{1+\mathcal{O}(\frac{x^{3/2}}{z})}{1-4\frac{x}{z}+\mathcal{O}(\frac{x}{z^2})} \simeq 1+4\frac{x}{z}$$
$$\Rightarrow \quad (\epsilon-1)z \to 4x,$$

substituting back in the differential equation one gets x'=0.

N.B. combining x'=0 with x'+y'+z'=0 implies y'+z'=(y+z)'=0
However, the evolution of radiation is : y'=-2y≠0
This implies that y'=-z'≠0 with a **large cancelation** between y and z

In this regime $\varepsilon\to1$ and w=-1/3, so the density of the Universe evolves as $\rho \sim T^2$. However the density of radiation is still evolving as as $\rho_{rad} \sim T^4$. This implies that also $\rho_{GB} \sim T^4$

$$\rho \sim \rho_{rad}+\rho_{GB} \to T^4 - T^4 = T^2$$

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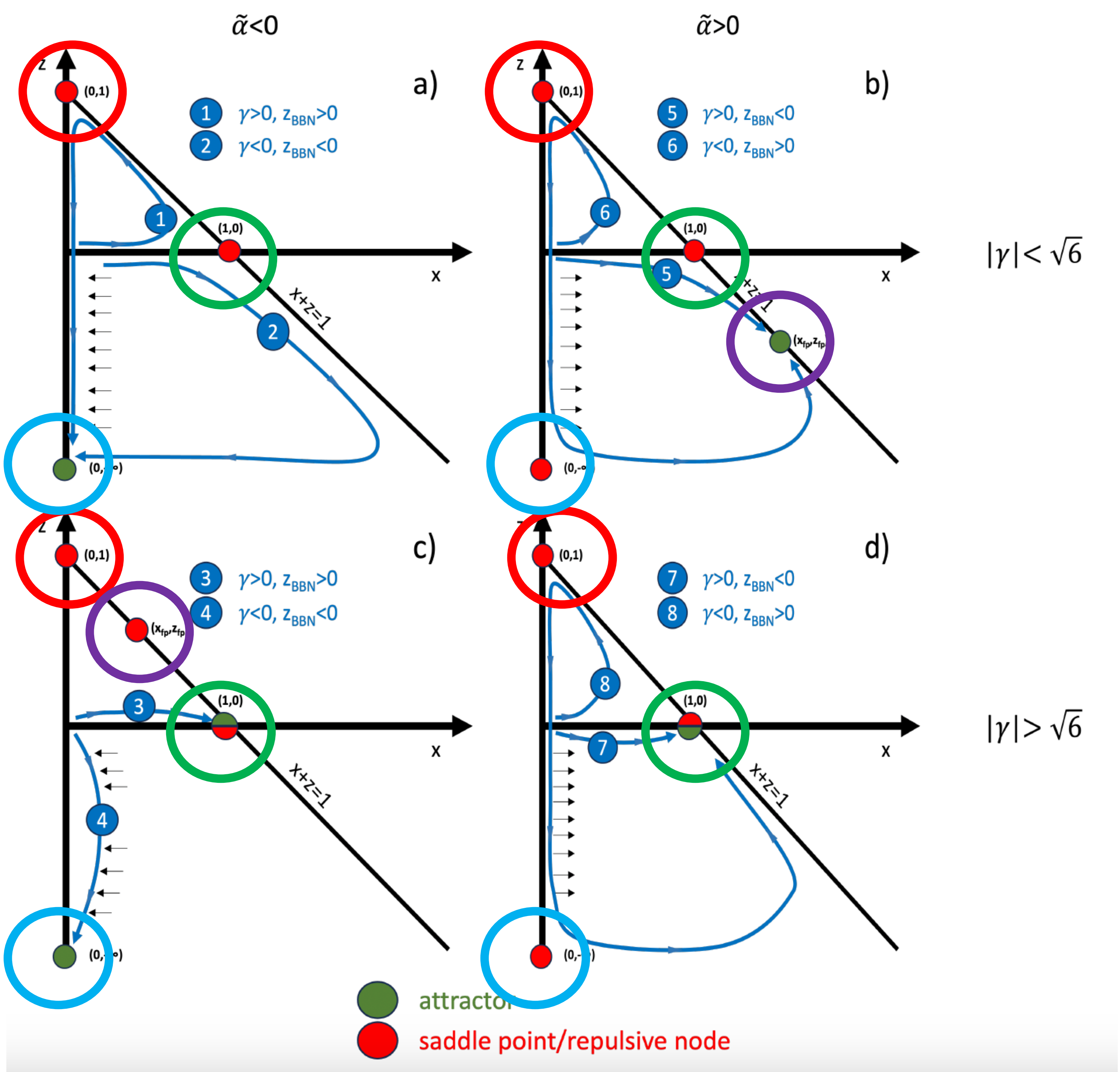
Schematic view of the critical points:

w=-1/3, Gauss Bonnet (0,1)

w=1, kination (1,0)

1<w<7/3, fast roll (x_{fp},z_{fp})
only for sign(αz_{fp})<0

w=-1/3, slow roll (0,-∞)



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Stability of critical points

Need to study the sign of the eigenvalues of the Jacobian of the differential equations in the vicinity of the critical point:

expand at linear order close to the critical point:

$$x' = F(x,z) \simeq F(x_c, z_c) + \frac{\partial F}{\partial x}(x - x_c) + \frac{\partial F}{\partial z}(z - z_c)$$
$$z' = G(x,z) \simeq G(x_c, z_c) + \frac{\partial G}{\partial x}(x - x_c) + \frac{\partial G}{\partial z}(z - z_c)$$

$$\Rightarrow \quad X' = J(X - X_c)$$

with:

$X=(x,z)$, $X_c=(x_c,z_c)$

$$J = \begin{pmatrix} \frac{\partial F}{\partial x} & \frac{\partial F}{\partial z} \\ \frac{\partial G}{\partial x} & \frac{\partial G}{\partial z} \end{pmatrix}_{(x,z)=(x_c,z_c)}$$

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A total of 8 qualitative approaching paths to the attractors, determined by three dichotomies:

$\alpha > 0$
$\alpha < 0$

$\gamma < 0$
$\gamma > 0$

$|\gamma| < \sqrt{6\boldsymbol{\kappa}}$
$|\gamma| > \sqrt{6\boldsymbol{\kappa}}$

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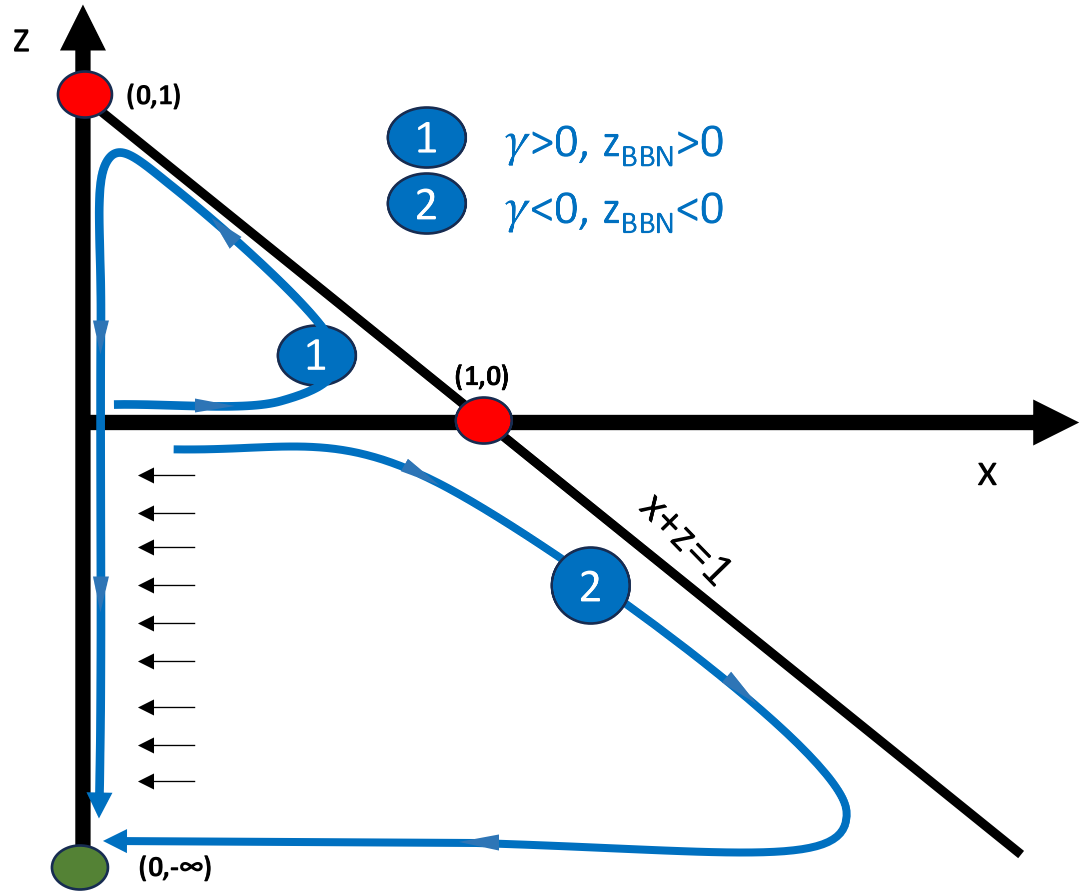
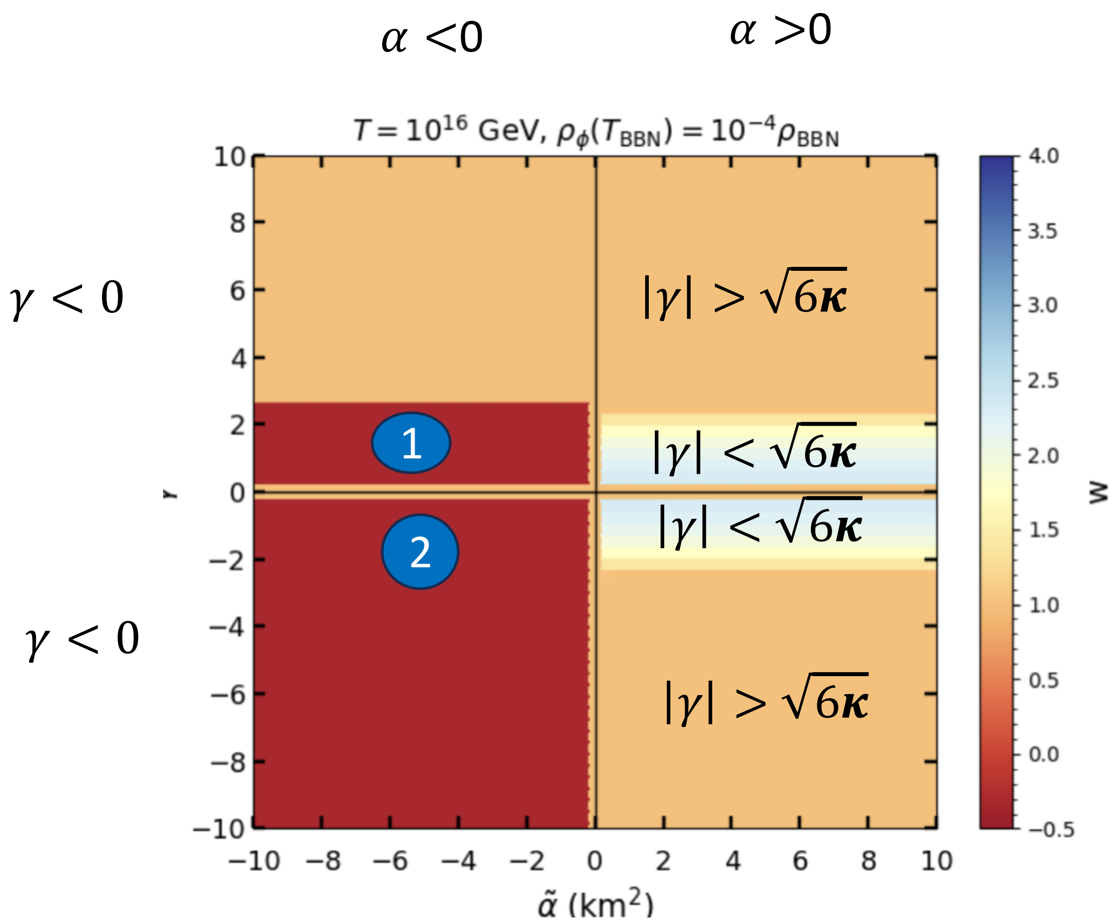
A total of 8 qualitative approaching paths to the attractors, determined by three dichotomies:

$\tilde{\alpha}<0 \quad |\gamma|<\sqrt{6}$





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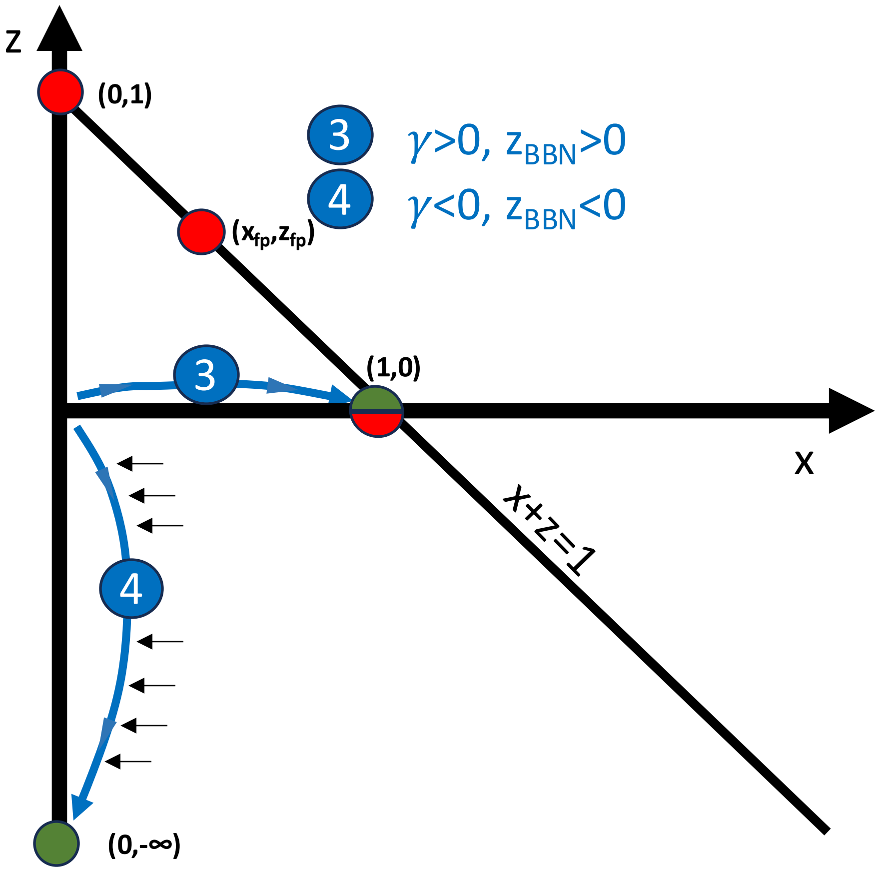
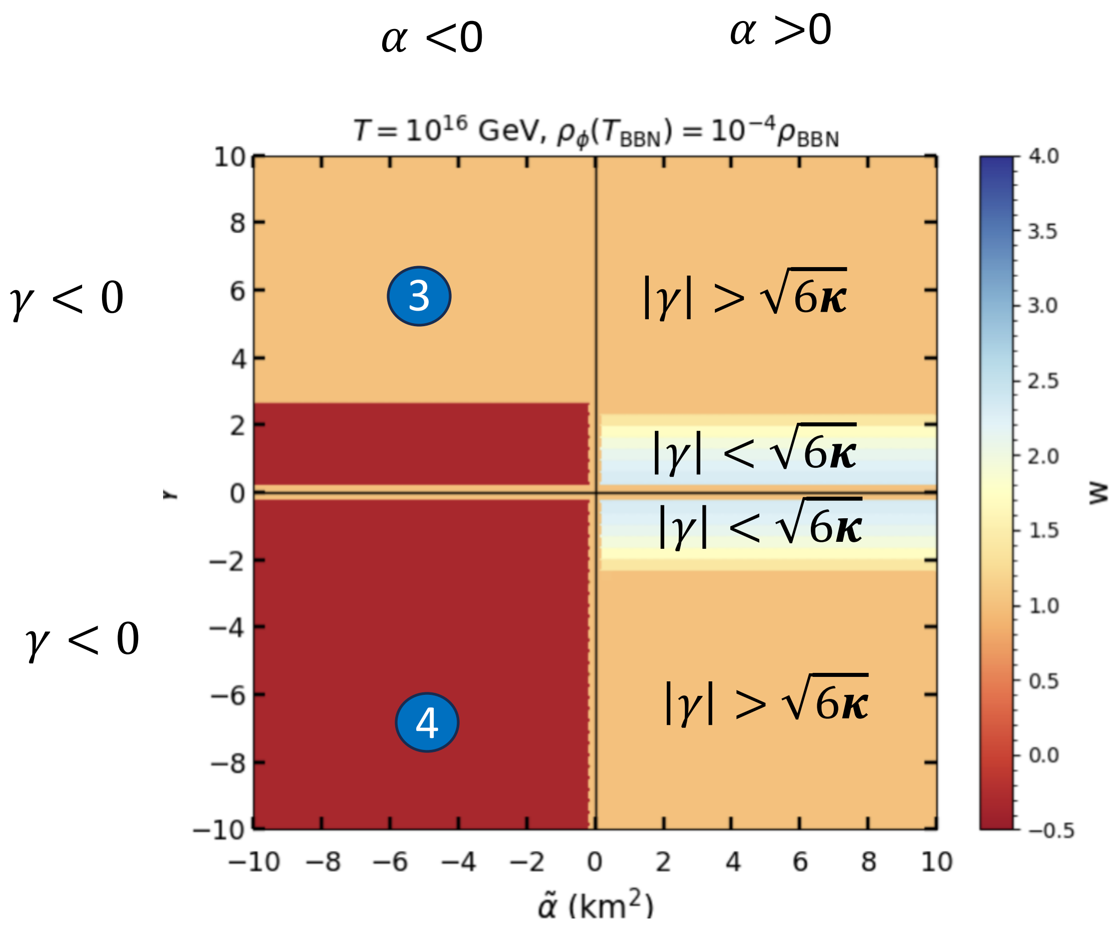
A total of 8 qualitative approaching paths to the attractors, determined by three dichotomies:

$\tilde{\alpha}<0 \qquad |\gamma|>\sqrt{6}$





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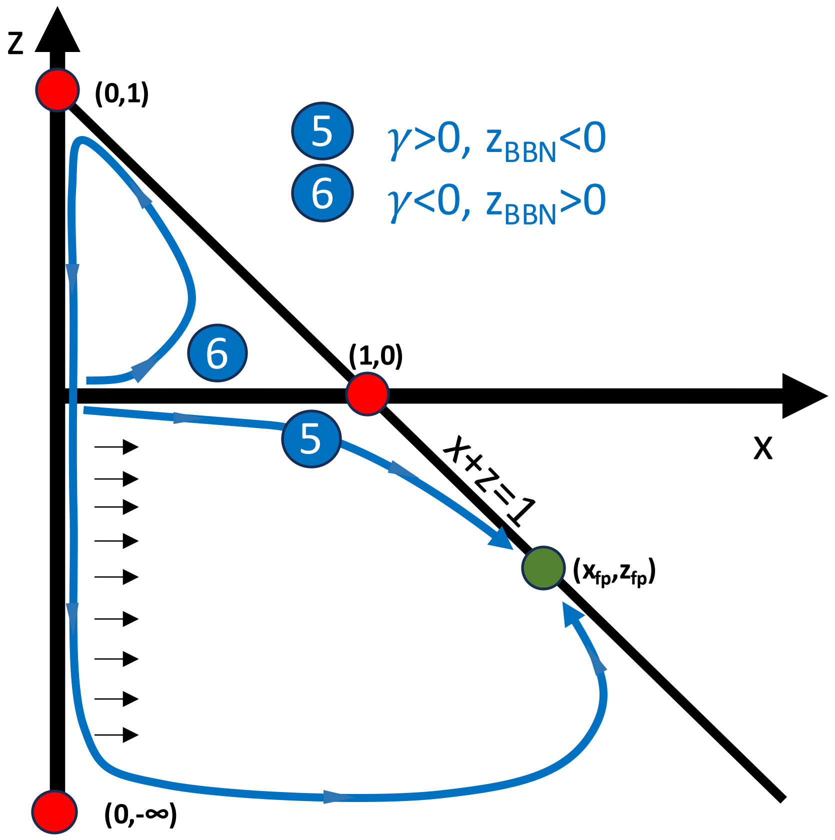
A total of 8 qualitative approaching paths to the attractors, determined by three dichotomies:

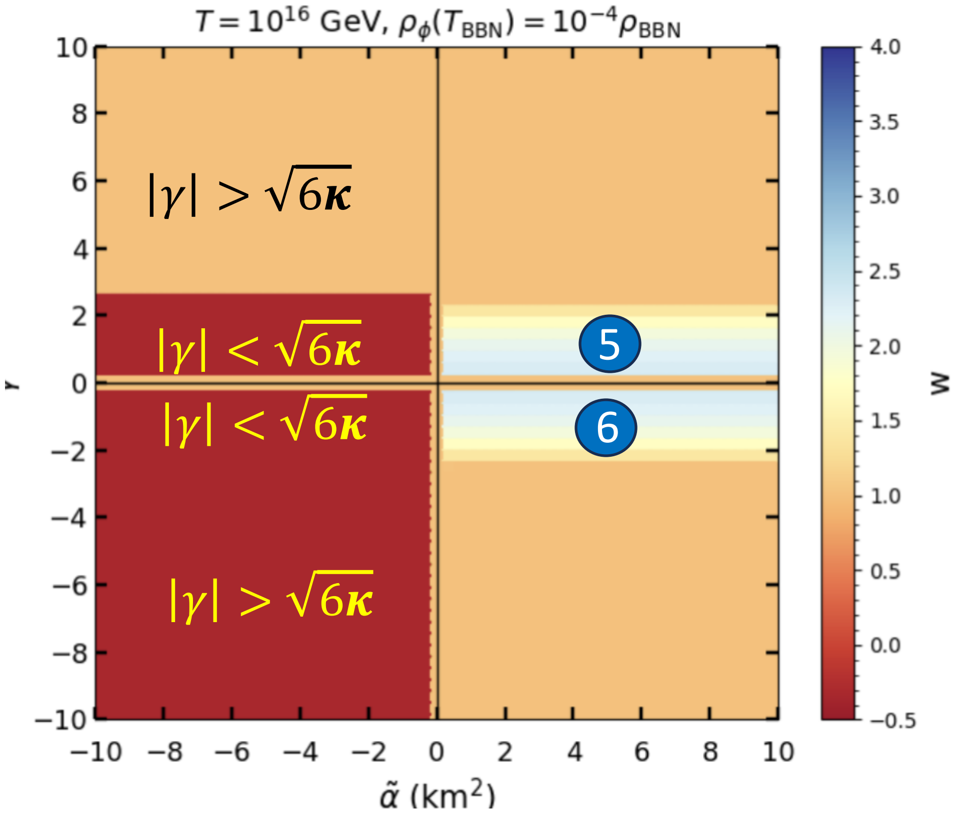
$\tilde{\alpha} > 0 \quad |\gamma| < \sqrt{6}$



$\alpha < 0 \quad \alpha > 0$

$\gamma < 0$

$\gamma < 0$



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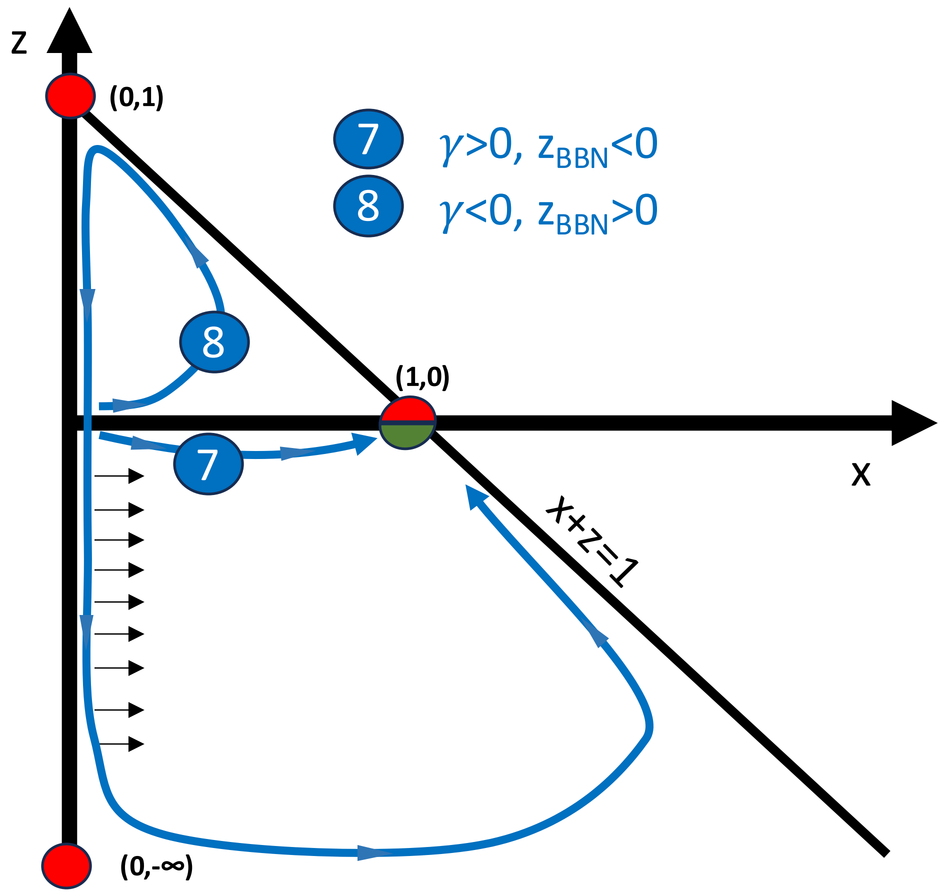
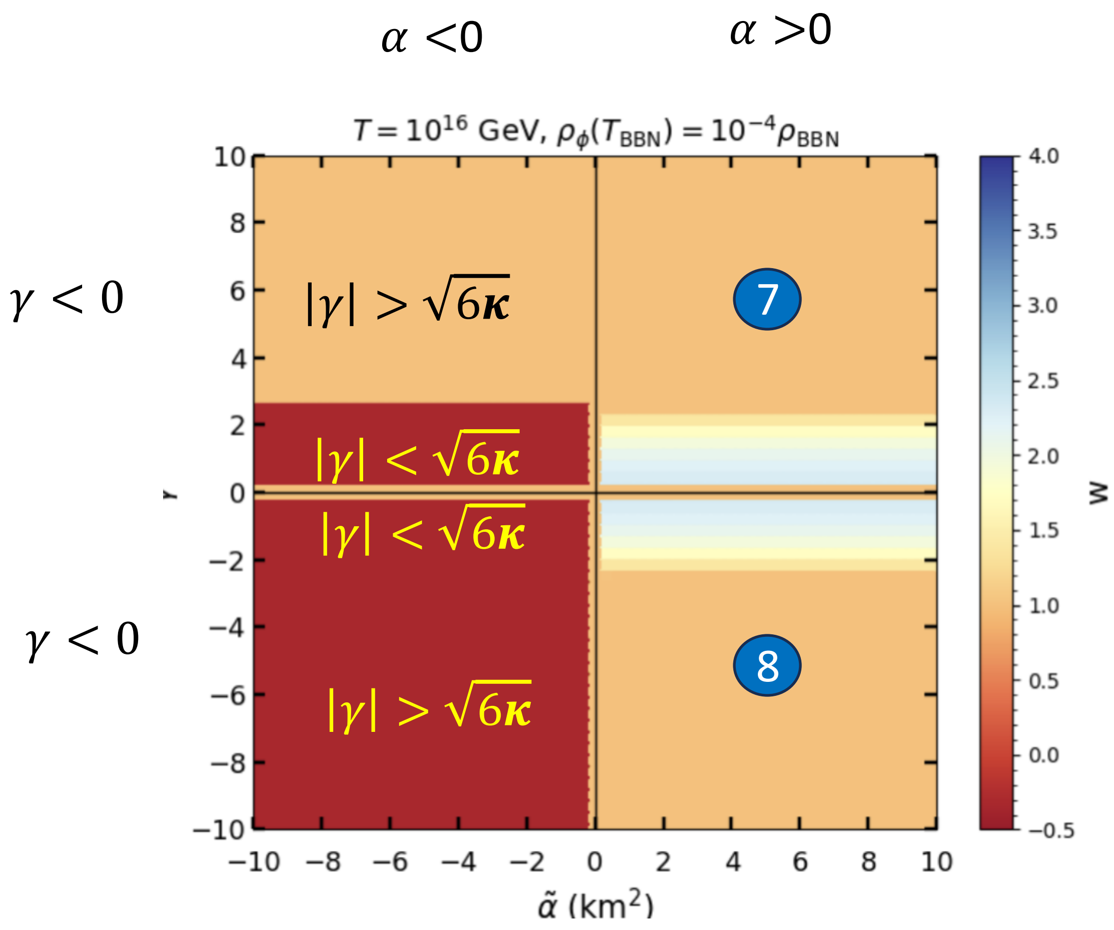
$\tilde{\alpha} > 0 \quad |\gamma| > \sqrt{6}$





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Stochastic background of gravitational waves

- Any plasma of relativistic particles in thermal equilibrium emits a stochastic background of gravitational waves, which in the case of the Standard Model is expected to peak at a frequency of around 80 GHz
- present detectors are only sensitive to frequencies of the order of few Hertz, some proposals exist to extend the experimental reach to the GHz range
- <u>such background can be presently constrained using BBN bounds</u>

$$\frac{1}{a^4}\frac{d}{dt}\left(a^4\rho_{\mathrm{GW}}(t)\right) = \left(\frac{\partial}{\partial t} + 4H\right)\rho_{\mathrm{GW}}(t) = 4\frac{T^4}{M_{\mathrm{PL}}^2}\int\frac{d^3k}{(2\pi)^3}\eta(T,k)$$

evolution of GW density according to the Cosmological model

sheer viscosity of plasma (GW production)

$$\eta(\hat{k},T) = \begin{cases} \frac{1}{8\pi}\frac{16}{g_1^4\ln(5T/m_{D_1})}, & k \lesssim \alpha_1^2 T, \\ \eta_{\mathrm{HTL}}(\hat{k},T) + \eta^T(\hat{k},T), & k \gtrsim 3T, \end{cases}$$

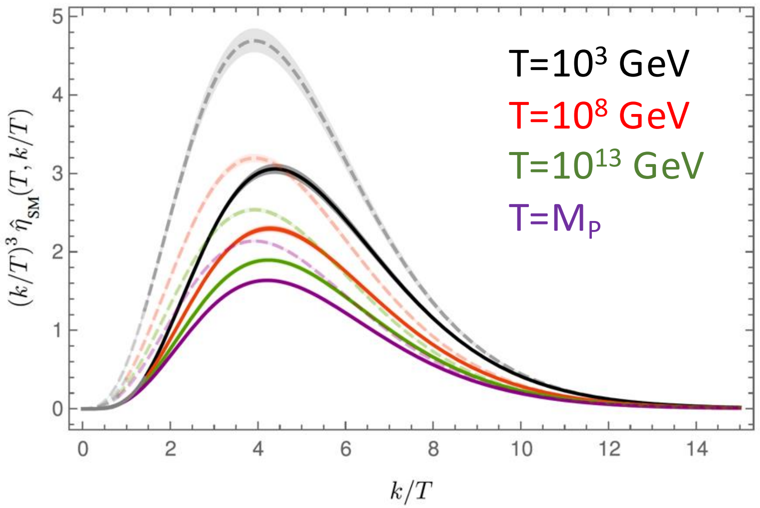
$$\hat{m}_{D_i} = \frac{m_{D_i}}{T}, \quad m_{D_i}^2 = \begin{cases} d_1\frac{11}{6}g_1^2T^2, & d_1 = 1, \\ d_2\frac{11}{6}g_2^2T^2, & d_2 = 3 \\ d_3 2g_3^2T^2, & d_3 = 8. \end{cases}$$

$$\Omega_{\mathrm{GW}}(f,T_0)h^2 = \Omega_{\gamma_0}h^2\frac{\lambda}{M_{\mathrm{PL}}}\int_{T_{\mathrm{EWCO}}}^{T_{\mathrm{Max}}} dT\left(\frac{g_{*0}}{g*(T)}\right)^{4/3} T^2\,\hat{k}(f,T)^3\frac{\eta(\hat{k},T)}{\sqrt{\rho(T)}}\beta(T)$$

For a plasma of standard model particles GW production at all epochs is peaked at:

$$\frac{k}{T} = \hat{k}(f,T) = \left[\frac{g_{*s}(T)}{g_{*s}(T_0)}\right]^{\frac{1}{3}}\frac{2\pi f}{T_0}. \sim 3.92$$

A. Ringwald et al., JCAP 03 (2021), 054



$$\Omega_{\rm GW}(f,T_0)h^2 = \Omega_{\gamma_0}h^2\frac{\lambda}{M_{\rm PL}}\int_{T_{\rm EWCO}}^{T_{\rm Max}} dT\left(\frac{g_{*0}}{g*(T)}\right)^{4/3} T^2\,\hat{k}(f,T)^3\frac{\eta(\hat{k},T)}{\sqrt{\rho(T)}}\,\beta(T)$$

- ultra-violet dominated, i.e. the integral is driven by the contribution of the GWs emitted at high temperature
- dominated by the highest temperature where the energy density of the Universe is driven by the plasma of relativistic particles
- In the SM this is usually assumed all the way up to the reheating temperature of the Universe – in such case the signal is diluted as a^{-4} (scale factor)
- However, in the case of the slow-roll asymptotic solution (w=-1/3) found in GB Cosmology, one has:

$$\rho\sim\rho_{rad}+\rho_{GB}\rightarrow T^4\text{-}T^4=T^2$$

radiation domination at high temperatures **but dilution as a^{-2}** → enhanced signal compared to SM!

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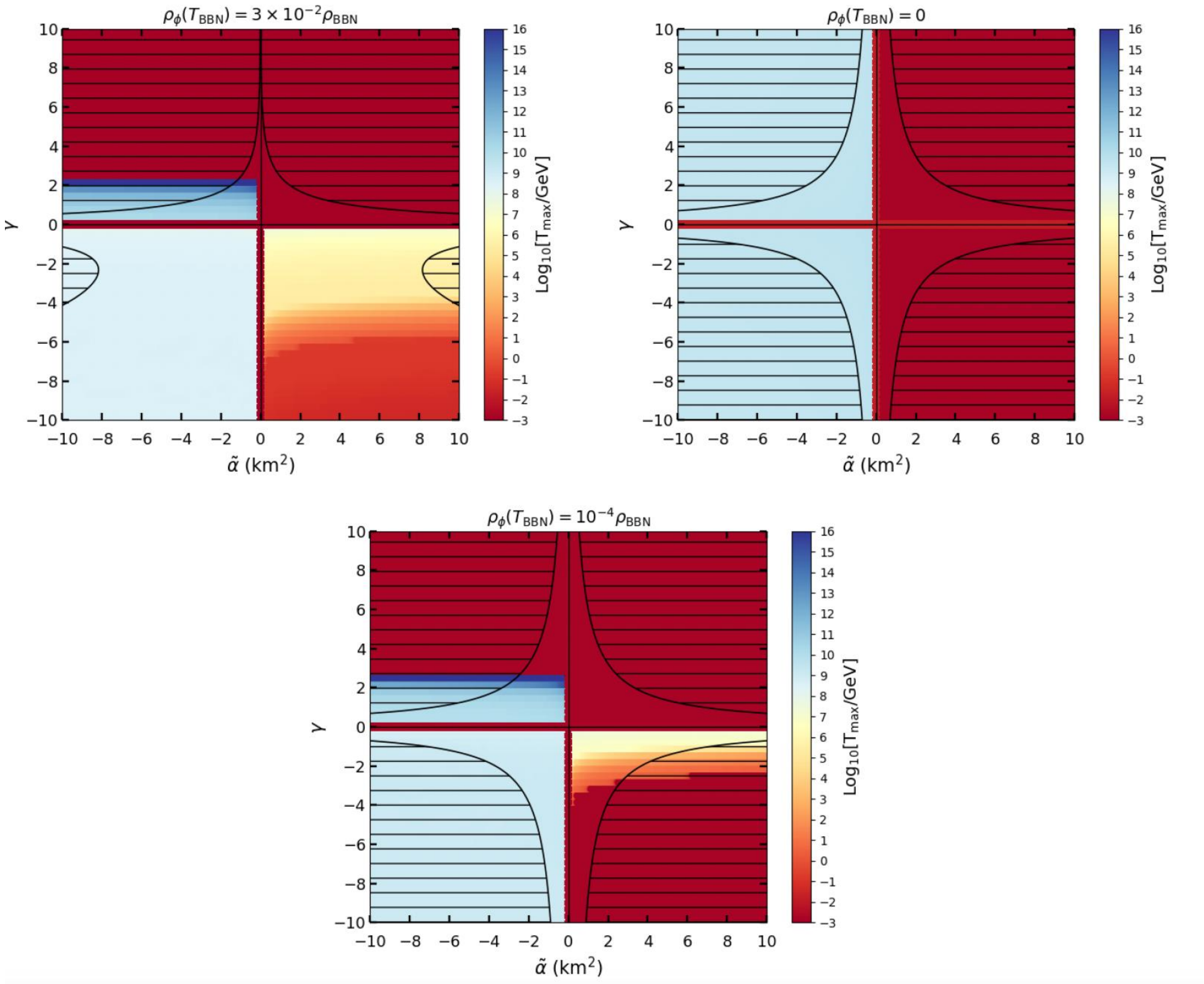
Bounds on T_{max}~ reheating temperature (cyan/blue) or maximal temperature of GW production (red)



hatched regions: GW bounds from BH-BH and BH-NS mergers

- In Standard Cosmology the GW stochastic background is never at the level of the BBN bounds, even for T_{RH}~10^{16} GeV.
- **On the other hand, in GB Cosmology BBN puts sensible bounds on $T_{RH} \simeq 10^8$–10^9 GeV $\ll 10^{16}$ GeV whenever w=-1/3 ("slow-roll" solutions)**
- complementarity between bounds from stochastic background and those from BH-BH and BH-NS mergers

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Constraints from Gravitational Waves from BH-BH and BH-NS merger events at $T=T_L$

(Z. Lyu, N. Jiang and K. Yagi, Phys. Rev. D 105 (2022) 064001 [2201.02543])

TABLE I. Astrophysical bounds on EdGB gravity. We show bounds from a LMXB, NSs ($\sim 2\, M_\odot$ NSs), GWs from BBHs, and NSBHs (this work). The one in brackets comes from GW190814 assuming that it is a BBH, which has some uncertainty. For NSBH, we present the bound from GW200115 and that by combining NSBHs (GW200115, GW200105, and GW190814; assuming the last one as a NSBH is a conservative choice) and BBHs from [26].

			GW (BBH)		GW (NSBH) (this work)	
	LMXB	NS	O1–O2	O1–O3	GW200115	Combined
$\sqrt{\alpha_{\mathrm{GB}}}$ (km)	1.9 [30]	1.29 [45]	5.6 [25], 1.85 [46], 4.3 [47]	1.7 [26], 4.5 [48], (0.4) [48]	1.33	1.18

$$f(\phi) = f(\phi(T_L)) + f'(\phi(T_L))\,\Delta\phi + \mathcal{O}((\Delta\phi)^2)$$

(linearized perturbation close to the system)

$$|f'(\phi(T_L))| \leq \sqrt{8\pi}\,\alpha_{\mathrm{GB}}^{\mathrm{max}}$$

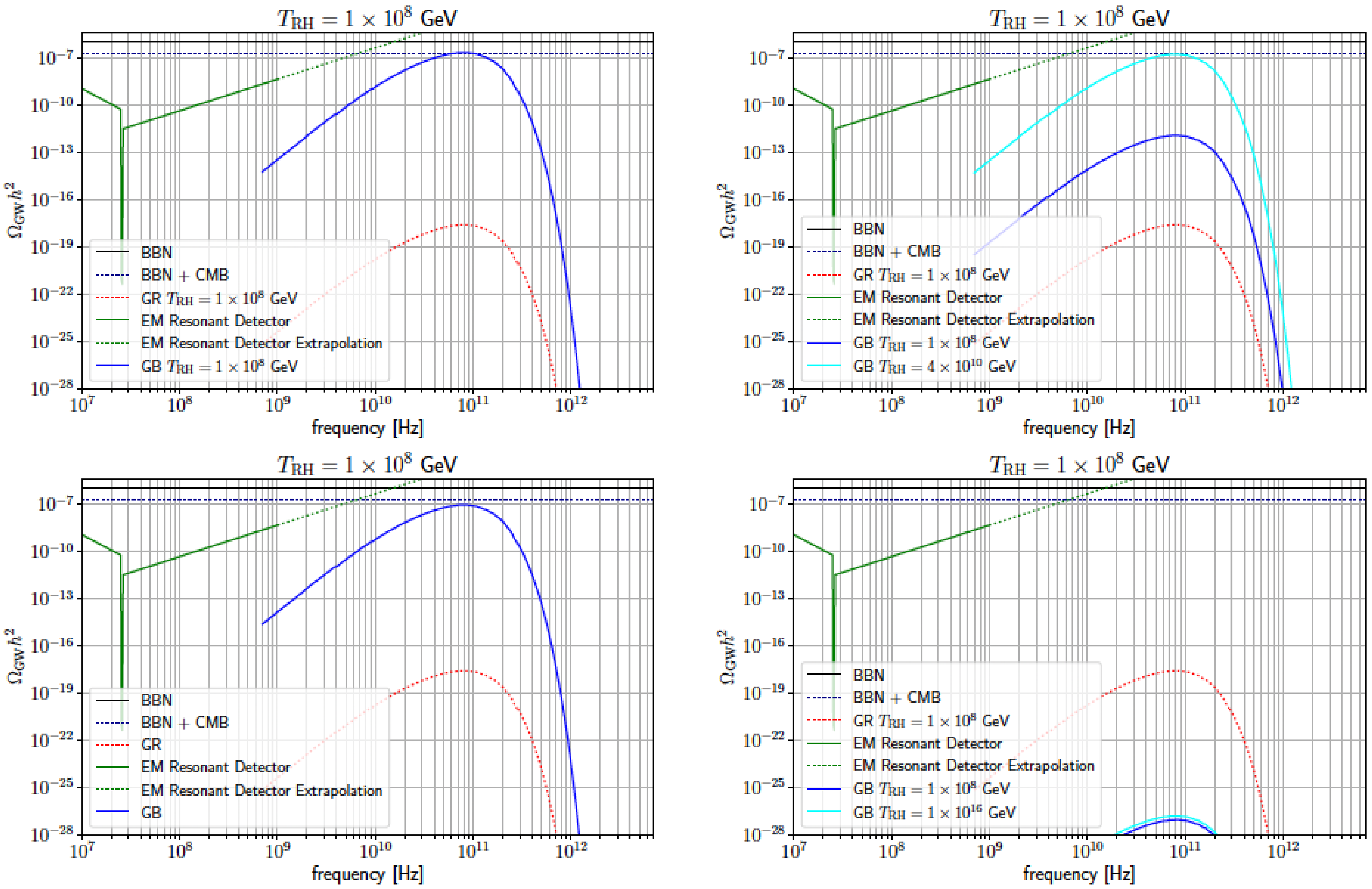
N.B. Residual evoution of ϕ after BBN can be non-zero for ”fast-roll” solutions (modify cosmological value $f(\phi(T_L))$).
In this case the value of $\phi(T_L)$ can be displaced compared to ϕ_{BBN} :

$$\phi(T_L) \simeq \phi_{\mathrm{BBN}} + \frac{\dot{\phi}_{\mathrm{BBN}}}{H_{\mathrm{BBN}}}$$

$\tilde{\alpha}$=-1 km^2

γ=-1 γ=+1

BBN bound



γ=-5 γ=5

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Conclusions

we analized WIMP relic density and indirect signals in GB Cosmology

- the simple kination case (only scalar field) is already disfavored by WIMP indirect searches unless $\dot{\phi}_{BBN}$
- the dEGB term is even more disfavoured for $\tilde{\alpha}, \boldsymbol{\gamma}$**>0**, when w=7/3
- however, the presence of the dEGB term can slow down the scalar field evolution when w→-1/3 (non-accelerated Cosmology, "slow ϕ roll") recovering allowed configurations when $\tilde{\alpha}, \boldsymbol{\gamma}$**<0** and $\tilde{\alpha} * \boldsymbol{\gamma}$**<0**
- bounds from WIMPs complementary to those from GW from compact-binary mergers

we also studied the equation of state of the Universe at high temperatures in GB Cosmology

- only few asymptotic equations of state at high temperature: w=1 (kination), w=-1/3 (slow roll), 1<w<7/3 (fast roll)
- clear interpretation in terms of three attractors (stable critical points) of a set of autonomous differential equations
- in the "slow-roll" w=-1/3 regime the GW stochastic backround from the plasma of relativistic particles is enhanced compared to standard Cosmology and reaches the level of the BBN bound for T_{RH}~10^8-10^9 GeV