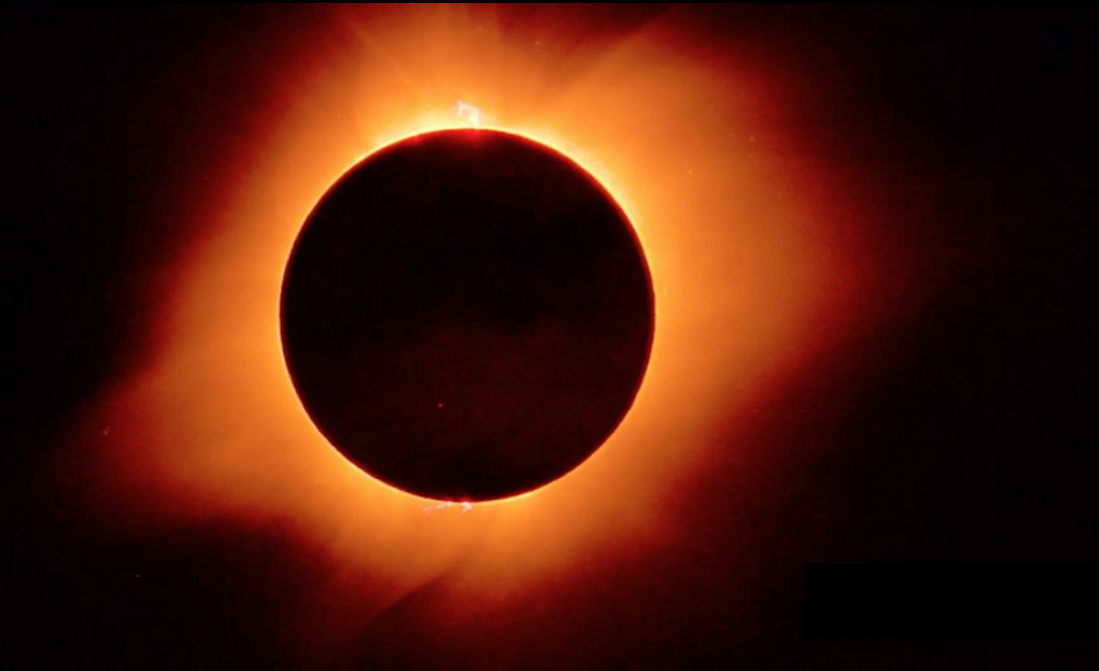


Trajectories in a dark universe



Luca Amendola
University of Heidelberg



1999

1994-1998

Weak Gravitational Lensing by Voids

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1998

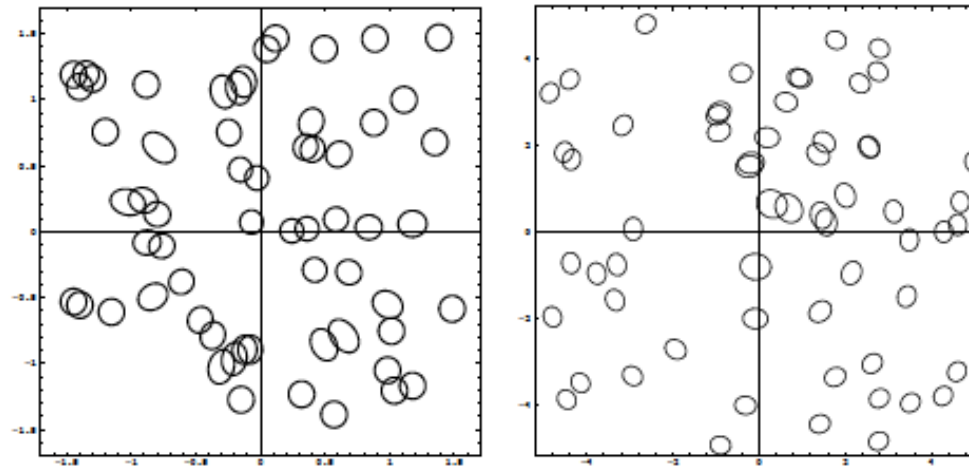


Figure 4. The appearance (ellipticity) of randomly distributed circular background galaxies in the case of void lensing (left panel) and for an isothermal lensing cluster (right panel).

2006: DM-DE scalings

Challenges for scaling cosmologies

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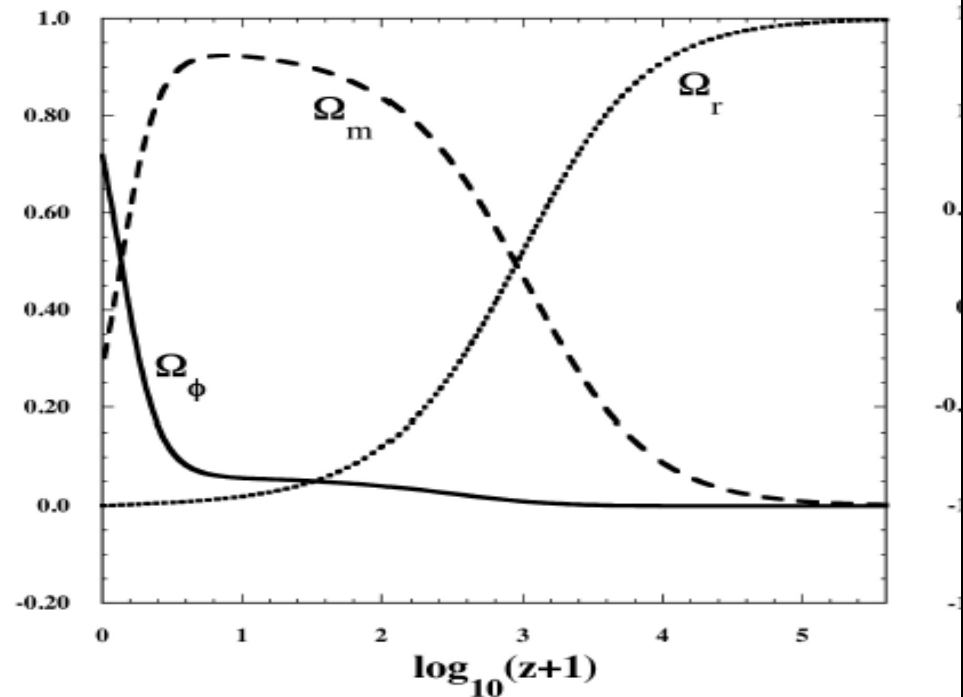
(Dated: 9th April 2018)

A cosmological model that aims at solving the coincidence problem should show that dark energy and dark matter follow the same scaling solution from some time onward. At the same time, the model should contain a sufficiently long matter-dominated epoch that takes place before acceleration in order to guarantee a decelerated epoch and structure formation. So a successful cosmological model requires the occurrence of a sequence of epochs, namely a radiation era, a matter-dominated era and a final accelerated scaling attractor with $\Omega_\varphi \simeq 0.7$. In this paper we derive the generic form of a scalar-field Lagrangian that possesses scaling solutions in the case where the coupling Q between dark energy and dark matter is a free function of the field φ . We then show, rather surprisingly, that the aforementioned sequence of epochs cannot occur for a vast class of generalized coupled scalar field Lagrangians that includes, to our knowledge, all scaling models in the current literature.

DM-DE scalings

$$\Omega_\phi = \text{const}$$

$$\Omega_m = 1 - \Omega_\phi$$



DM-DE scalings

$$S = \int d^4x \sqrt{-g_M} \left[\frac{M_P^2}{2} R + p(X, \varphi) \right] + S_m[\varphi, \psi_i, g_{\mu\nu}],$$

$$p(X_\psi, \psi) = X_\psi g(X_\psi e^{\lambda\psi}),$$

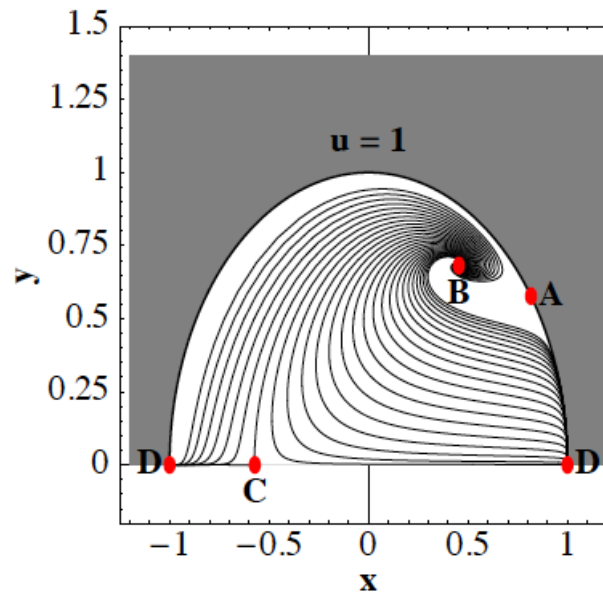
critical points

$$x = \frac{\dot{\varphi}}{\sqrt{6}H}, \quad y = \frac{e^{-\lambda\varphi/2}}{\sqrt{3}H}, \quad z = \frac{\sqrt{\rho_{\text{rad}}}}{\sqrt{3}H}.$$

Point	x	y	Existence	Stability	Ω_φ	w_{eff}
A	x_A	$(x_A^2/Y_A)^{1/2}$	$y_A \neq 0$ and $\Omega_\varphi = 1$	Stable node under conditions (46)	1	$-1 + \sqrt{\frac{2}{3}}\lambda x_A$
B	$\frac{\sqrt{6}}{2(Q+\lambda)}$	$(x_B^2/Y_B)^{1/2}$	$3(g+g_1) < (Q+\lambda)\lambda$	Stable node for $-\frac{Q}{Q+\lambda} \leq \Omega_\varphi < 1$ and $A > 0$	$\frac{Q(Q+\lambda)+3(g+g_1)}{(Q+\lambda)^2}$	$-\frac{Q}{Q+\lambda}$
C	$-\frac{\sqrt{6}Q}{3c_0}$	0	$ Q < \sqrt{(3c_0/2)}$ or $c_0 < 0$	Saddle point for $c_0 > 0$ Stable node for $c_0 < 0$ and $Q(Q+\lambda) > 3 c_0 /2$	$\frac{2Q^2}{3c_0}$	$\frac{2Q^2}{3c_0}$
D	$\pm \frac{1}{\sqrt{c_0}}$	0	$c_0 > 0$	Unstable node or saddle for $Q > 0$ Stable node for $Q < -\sqrt{3c_0/2}$	1	1

DM-DE interaction

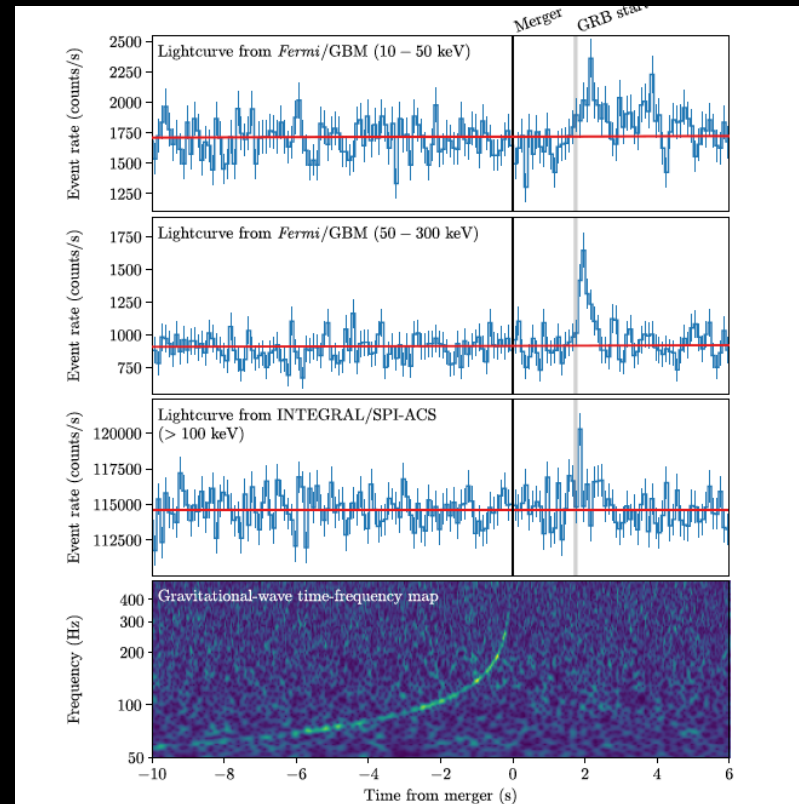
$$x = \frac{\dot{\phi}}{\sqrt{6}H}, \quad y = \frac{e^{-\lambda\varphi/2}}{\sqrt{3}H},$$



2006

GW speed constraints

$$c_T^2 = 1$$



2018: DM-DE interaction

Doppelgänger dark energy: modified gravity with non-universal couplings after GW170817

Luca Amendola,^a Dario Bettoni,^a Guillem Domènech^a and Adalberto R. Gomes^b

$$\begin{aligned}\mathcal{L}_2 &= G_2(\phi, X) \quad , \quad \mathcal{L}_3 = -G_3(\phi, X)\Box\phi, \\ \mathcal{L}_4 &= G_4(\phi, X)R + G_{4,X} \left[(\Box\phi)^2 - \nabla_\mu \nabla_\nu \phi \nabla^\mu \nabla^\nu \phi \right] , \\ \mathcal{L}_5 &= G_5(\phi, X)G^{\mu\nu} \nabla_\mu \phi \nabla_\nu \phi - \frac{1}{6}G_{5,X} \left((\Box\phi)^3 - 3\Box\phi \nabla_\sigma \nabla_\rho \phi \nabla^\sigma \nabla^\rho \phi + 2\nabla_\sigma \nabla_\rho \phi \nabla^\sigma \nabla^\mu \phi \nabla_\mu \nabla^\rho \phi \right) ,\end{aligned}\tag{3.1}$$

$$\begin{aligned}G_2(\phi, X) &= a_2(Y)\phi^{p_2} \quad , \quad G_3(\phi, X) = a_3(Y)\phi^{p_3} , \\ G_4(\phi, X) &= a_4(Y)\phi^{p_4} \quad , \quad G_5(\phi, X) = a_5(Y)\phi^{p_5} , \\ Y &\equiv X\phi^p .\end{aligned}$$

DM-DE interaction

2002

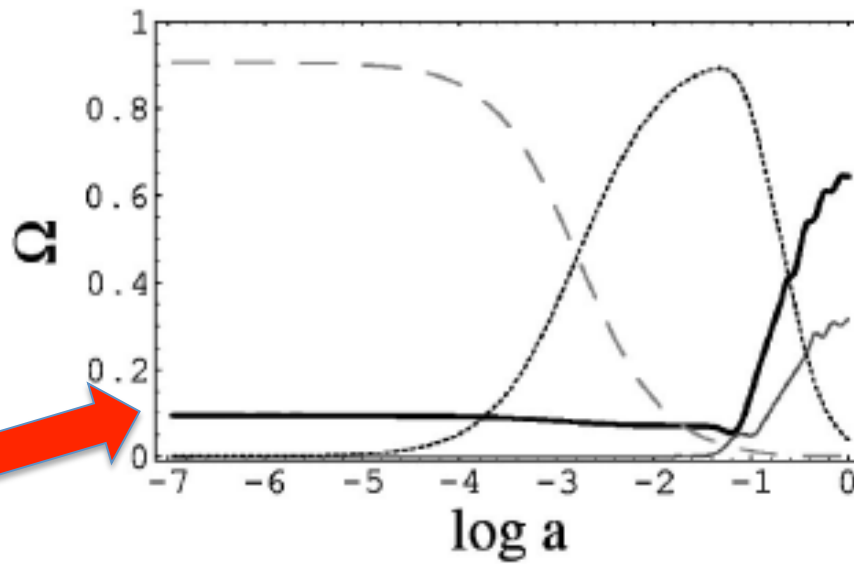
PHYSICAL REVIEW D, VOLUME 65, 063508

Stationary dark energy with a baryon-dominated era: Solving the coincidence problem with a linear coupling

Domenico Tocchini-Valentini* and Luca Amendola†

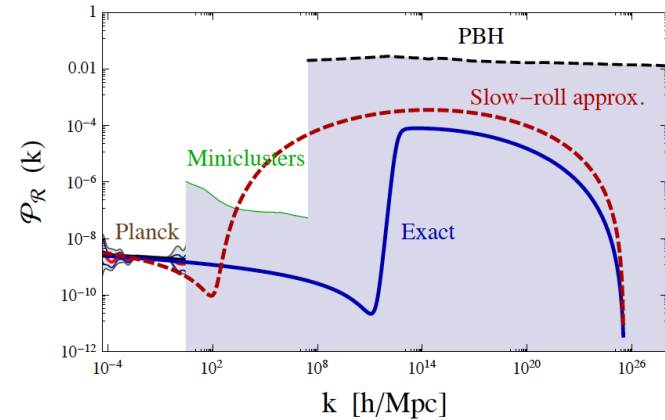
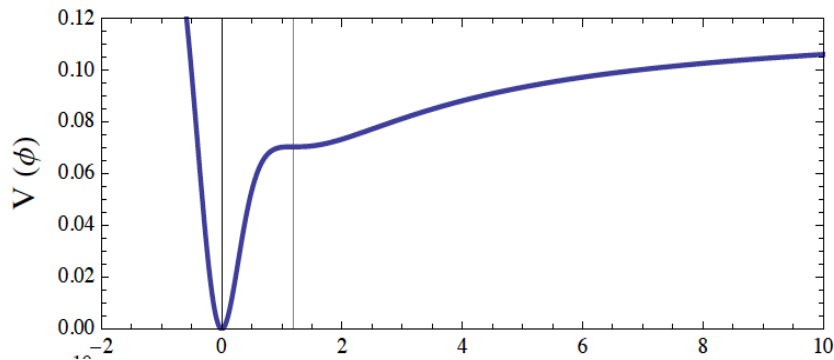
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(Received 11 August 2001; revised manuscript received 17 December 2001; published 28 February 2002)



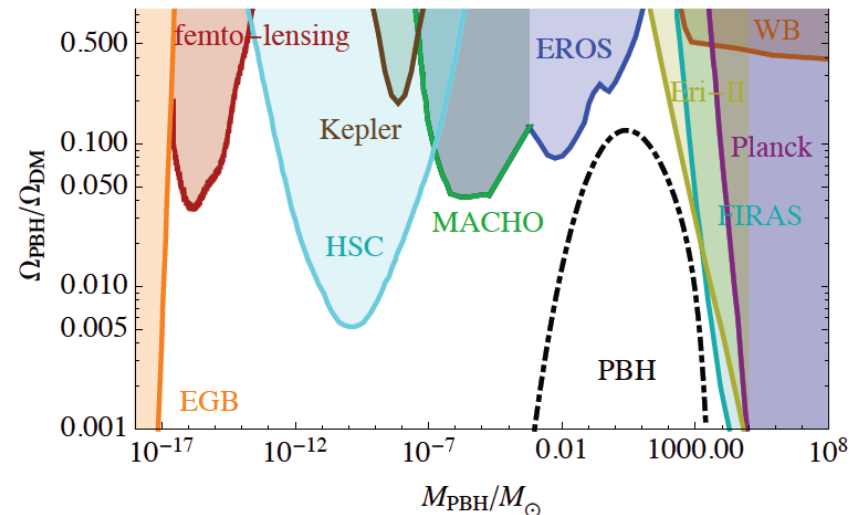
RDE attractor

PBH after inflation



PBH are normally assumed to form from spectral peaks due to features in slow-rolling inflation
Eg inflection in the potential

$$P \sim \frac{H^2}{\epsilon}$$



Growth during radiation era?

Matter growth equations

$$\delta_m'' + \left(1 + \frac{H'}{H}\right)\delta_m' - \frac{3}{2}(\Omega_m\delta_m + \Omega_r\delta_r) = 0$$

Perturbation do not grow because

$$\begin{aligned}\Omega_m &\approx 0 \\ \delta_r &\approx 0\end{aligned}$$

interacting fields

Interacting fields ψ (heavy) and ϕ (light)

$$S = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R + \mathcal{L}_R + \mathcal{L}(\phi) + \mathcal{L}(\phi, \psi) \right] ,$$

$$\mathcal{L}(\phi, \psi) = i\bar{\psi} (\gamma^\mu \nabla_\mu - m(\phi)) \psi ,$$

coupling $\beta(\phi) = -M_P \frac{\partial \ln m(\phi)}{\partial \phi} .$

EOM

$$\dot{\rho}_\phi + 3H(\rho_\phi + p_\phi) = \frac{\beta}{M_P} (\rho_\psi - 3p_\psi) \dot{\phi} ,$$

$$\dot{\rho}_\psi + 3H(\rho_\psi + p_\psi) = -\frac{\beta}{M_P} (\rho_\psi - 3p_\psi) \dot{\phi} ,$$

interacting fields

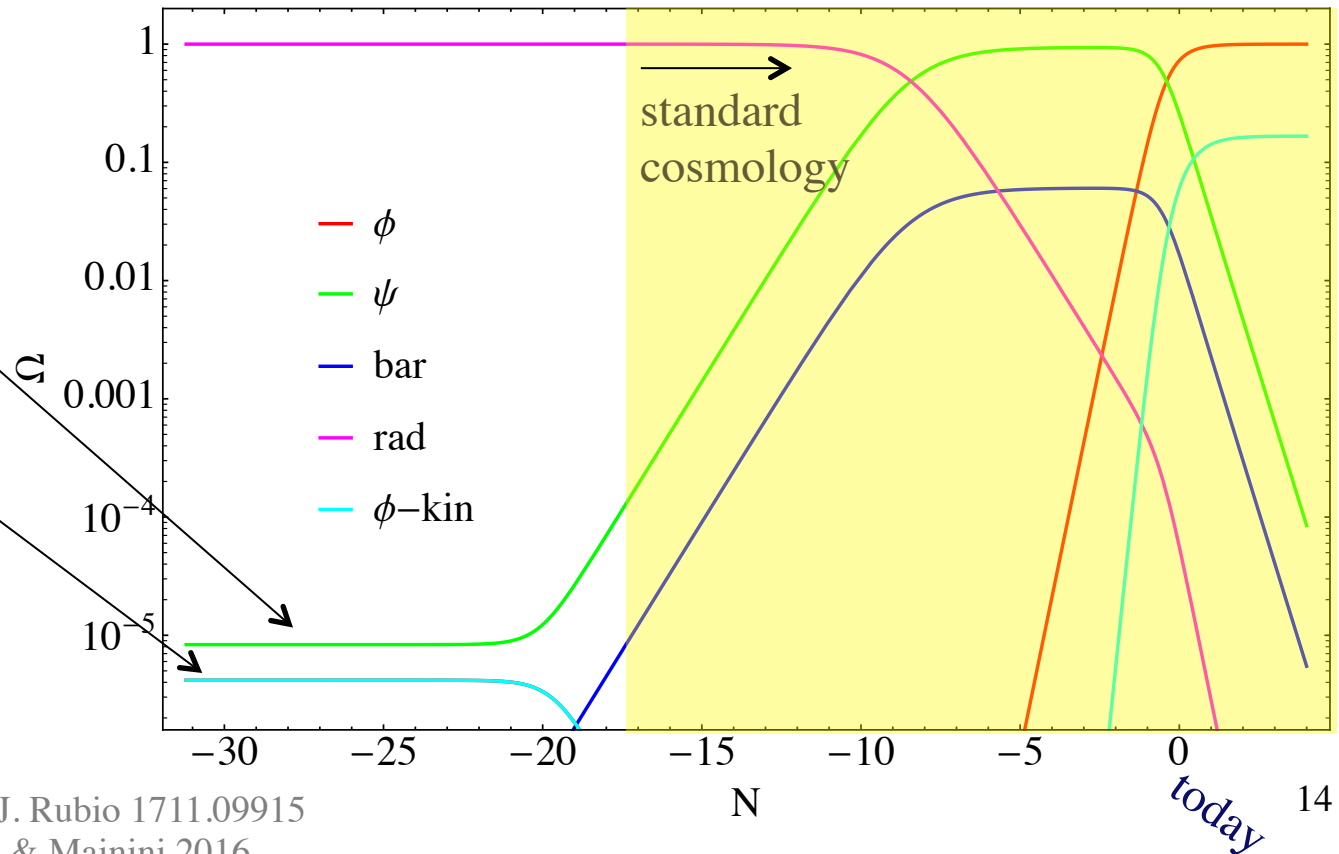
EOM

$$\dot{\rho}_\phi + 3H(\rho_\phi + p_\phi) = \frac{\beta}{M_P} (\rho_\psi - 3p_\psi) \dot{\phi},$$

$$\dot{\rho}_\psi + 3H(\rho_\psi + p_\psi) = -\frac{\beta}{M_P} (\rho_\psi - 3p_\psi) \dot{\phi},$$

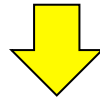
$$\Omega_\psi = \frac{1}{3\beta^2}$$

$$\Omega_\phi = \frac{1}{6\beta^2}$$



Growth during radiation era!

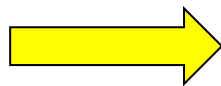
$$\delta_m'' + \left(1 + \frac{H'}{H}\right) \delta_m' - \frac{3}{2} (\Omega_m \delta_m + \Omega_r \delta_r) = 0$$



$$\delta_\psi'' + \left(1 + \frac{\mathcal{H}'}{\mathcal{H}} - \frac{\beta \phi'}{M_P}\right) \delta_\psi' - \frac{3}{2} (Y \Omega_\psi \delta_\psi + \Omega_R \delta_R) = 0. \quad Y = 1 + \beta^2$$

If a particle ψ strongly interacts with coupling $\beta \gg 1$ with a field ϕ , perhaps dark energy, then there are two consequences:

- 1) The effective gravitational force is large ($Y = 1 + \beta^2 \gg 1$)
- 2) The amount of ψ during radiation is larger ($\Omega_r \gg \Omega_\chi \gg \Omega_{\text{bar}}$)



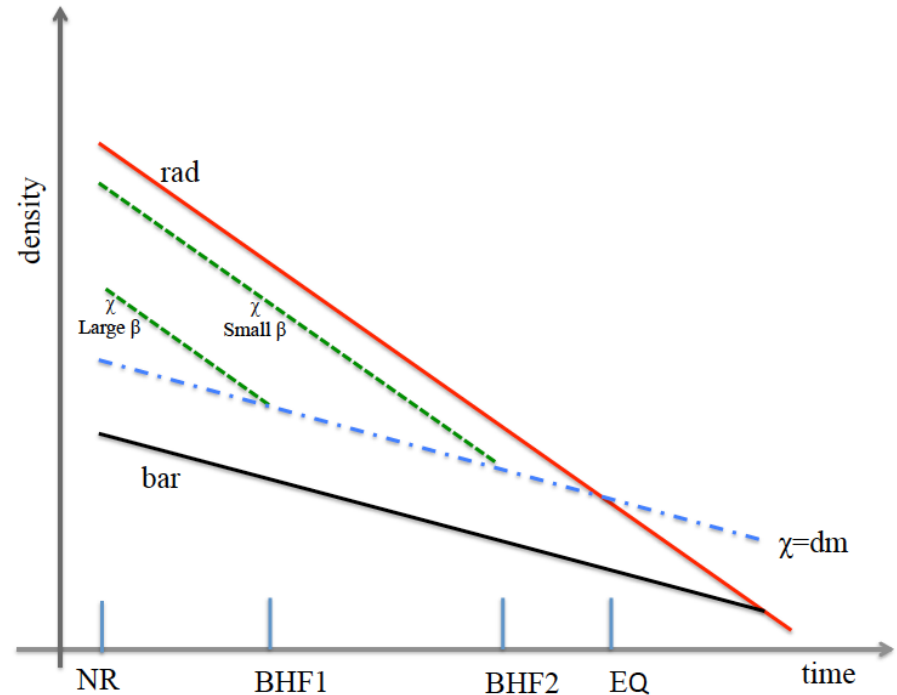
$$\delta_\psi'' - \delta_\psi' - \delta_\psi = 0.$$

Growth during radiation era

Growth as $\delta_\chi \sim a^{1.6}$ after horizon reenter
during radiation:
formation of BHs or DM-balls

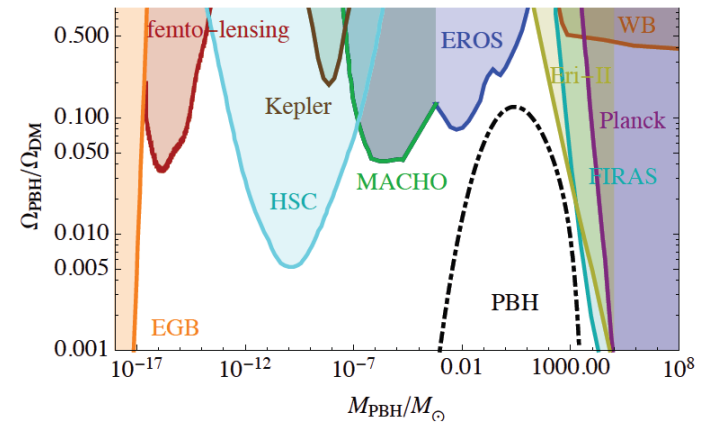
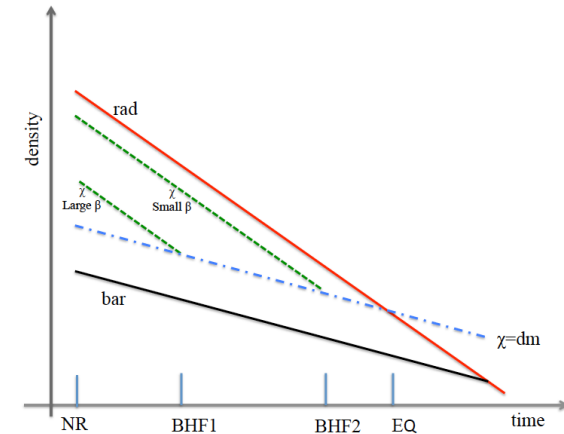
Simple relation between BH mass and
coupling parameter β

$$|\beta_c| = 585 \left(\frac{M_{\text{BH}}}{M_\odot} \right)^{-1/6}$$



Growth during radiation era

- No need of special features on the inflationary spectrum
- Do these objects become BHs or do they virialize into DM-balls?
- Is the coupling fully screened?
- If DM-balls, they escape the strong constraints on PBHs
- Dark matter ψ remains confined into these structures



Conclusions

there's more darkness to discover
out there!