Disformal Dark D-brane Cosmology

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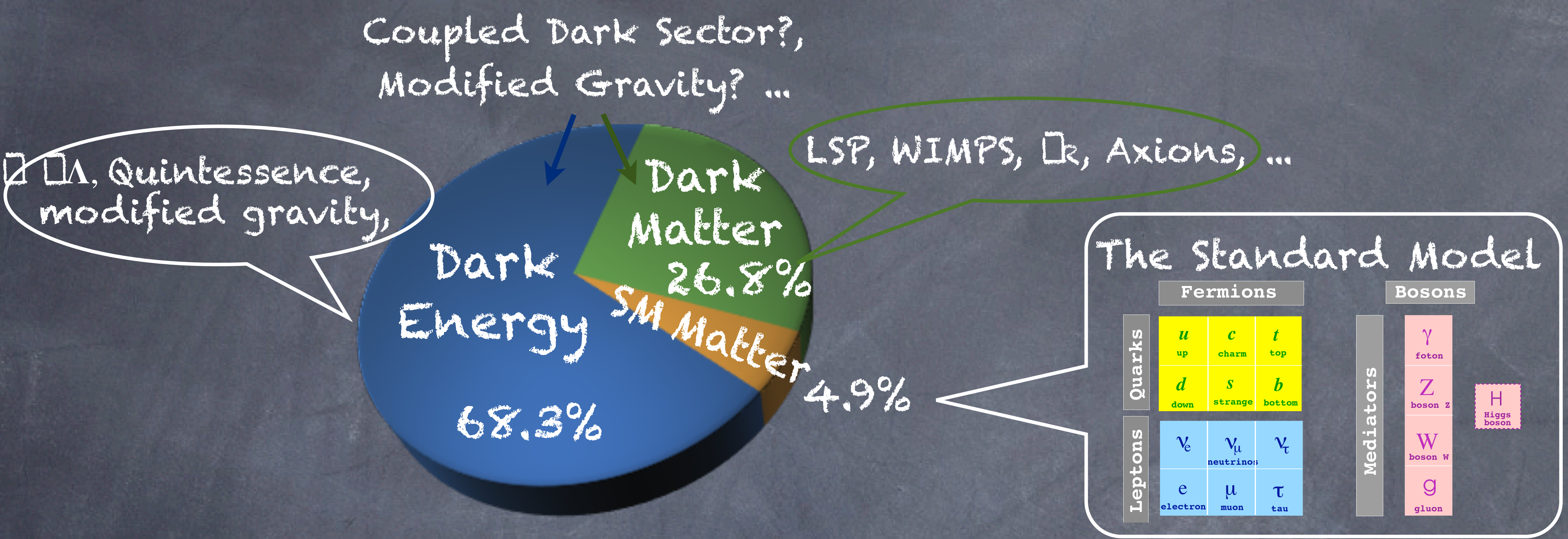
Collider and Dark Matter Physics Workshop

based on JCAP06(2014)036 w/Koivisto, Wills
and work in progress w/Dutta, Jimenez

The Dark Sector of the Universe



Dark Energy+Dark Matter: ~95% of density content!

Ordinary Matter: ~5% of density content!

What is CDM?: non-luminous weakly interacting particles (axions, wimps, neutrinos, etc).

What is DE?: permeates the universe uniformly causing the accelerated expansion of the universe (Λ, modified gravity, quintessence).

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- Given that we do not know the nature of either DE or DM, coupling between them is not excluded.
- Coupled models can aliviate the coincidence problem and have late time accelerating scaling solutions

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[Koivisto, Wills, IZ, '14]

Contents:

- Conformal and Disformal couplings
- The Disformal Coupling from D-branes
- The Coupled Dark Sector on a D3-brane
  - Late time background evolution
  - Early time effects
- Summary

Conformal and Disformal couplings

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$$\tilde{g}_{\mu\nu} = C(\phi) g_{\mu\nu} + D(\phi)\partial_\mu \phi \partial_\nu \phi$$

$C(\phi)$ conformal transformation (preserves angles)

$D(\phi)$ disformal transformation (distorts angles)

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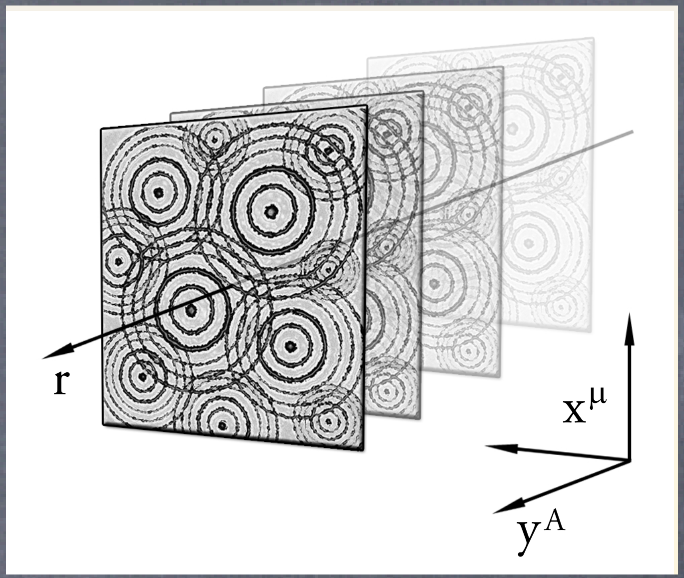
- A Disformal coupling among DE and DM arises naturally in D-brane models in string theory ⇨ coupling is determined by the theory.
- What can cosmology tell us about such couplings?

Dark D-brane Model

- Consider a moving D-brane in a higher dimensional spacetime. Dynamics described by DBI action:



$$S_{DBI} = -T_3 \int_{\mathcal{W}} d^4\xi \sqrt{-det(\gamma_{ab} + \mathcal{F}_{ab})}$$

($\gamma_{\mu\nu} = C(r)g_{\mu\nu} + D(r)\,\partial_\mu r \partial_\nu r$ induced metric on brane)

- Brane motion parameterised by the brane's position in extra dimension is identified with dark energy: DBI quintessence

- D-brane's matter can be identified with dark matter (massive fields) or dark radiation (massless fields).

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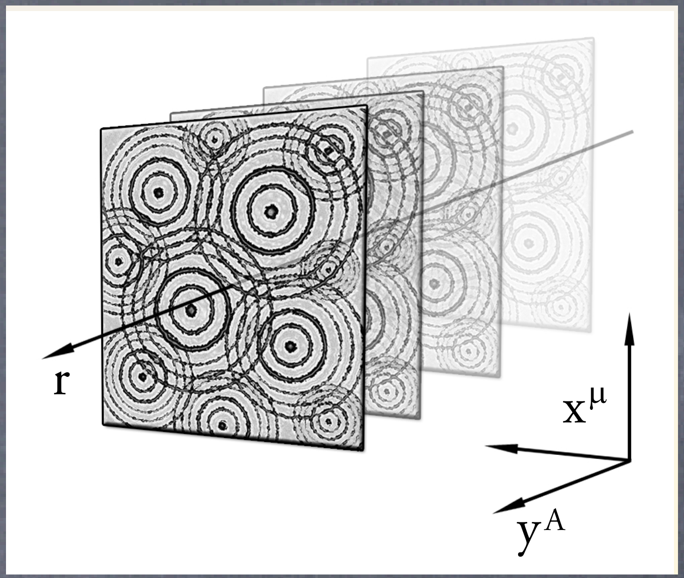

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- Dark Sector arises from same D-brane.

Dark D-brane Model

- A naturally coupled DM/DE emerges: System is described by action

$$S = S_{EH} + S_\phi + S_m$$

$$S_{EH} = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\,R$$

from 10D action
$(\kappa^2 = M_P^{-2} = (2\pi)^7 g_s^2/2M_s^2 V_6)$

$$S_\phi = -\int d^4x\sqrt{-g}\left[C^2(\phi)\left(\sqrt{1+\frac{D(\phi)}{C(\phi)}(\partial\phi)^2}-1\right)+\mathcal{V}(\phi)\right]$$

non-standard kinetic term from DBI action

$$S_{DM} = -\int d^4x\sqrt{-\tilde{g}}\,\mathcal{L}_{DM}(\tilde{g}_{\mu\nu})$$

disformal coupling between dark energy and dark matter on the D-brane

$(\tilde{g}_{\mu\nu} = C(\phi)g_{\mu\nu} + D(\phi)\partial_\mu\phi\partial_\nu\phi)$

(For a specific 10D background and D-brane, C, D have defined forms)

Late time evolution: scaling solutions

Consider FLRW metric $(g_{\mu\nu})$ $\quad ds^2 = -dt + a^2(t)dx^2$

- Einstein's and scalar equations are

$$H^2 = \frac{1}{3}(\rho_\phi + \rho)\,,$$

$$\dot{H} + H^2 = -\frac{1}{6}(\rho_\phi + 3P_\phi + \rho + 3P)\,,$$

$$\ddot{\phi} + 3H\gamma^{-2}\dot{\phi} + \frac{C}{2D}\left(\gamma^{-2}\left[\frac{5C'}{C} - \frac{D'}{D}\right] + \frac{D'}{D} - \frac{C'}{C}\right) + \frac{\gamma^{-3}}{CD}(V' + Q_0) = 0$$

where $$\gamma = \frac{1}{\sqrt{1 - \frac{D}{C}\dot{\phi}^2}}$$

$$Q_0 = \rho\left(\frac{\dot{\gamma}}{\dot{\phi}\gamma} + \frac{C'}{2C}(1 - 3\omega\gamma^2) - 3H\omega\frac{(1-\gamma^{-2})}{\dot{\phi}}\right)$$

- Total energy is conserved $\nabla_\mu (T_\phi^{\mu\nu} + T^{\mu\nu}) = 0$ but individual conservation equations are modified:

$$\dot{\rho} + 3H(\rho + P) = Q_0\,\dot{\phi}$$

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Note: in the lit

$$\dot\rho_{de} + 3H(1+\omega_{de})\rho_{de} = -\mathcal{Q}$$

$$\dot\rho_{dm} + 3H\rho_{dm} = \mathcal{Q}$$

where $\mathcal{Q}$ chosen phenomenologically. E.g.

$$\mathcal{Q} = \xi H \rho$$

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with $\omega^{eff} = \omega - \dfrac{Q_0\dot\phi}{3H\rho}$, $\omega_\phi^{eff} = \omega_\phi + \dfrac{Q_0\dot\phi}{3H\rho_\phi}$

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$\begin{cases} \omega^{eff} < 0 \\ \omega_\phi^{eff} > \omega_\phi \end{cases}$ DDM redshifts slower than a^{-3}
DE has less accelerating power

$\begin{cases} \omega^{eff} > 0 \\ \omega_\phi^{eff} < \omega_\phi \end{cases}$ DDM redshifts faster than a^{-3}
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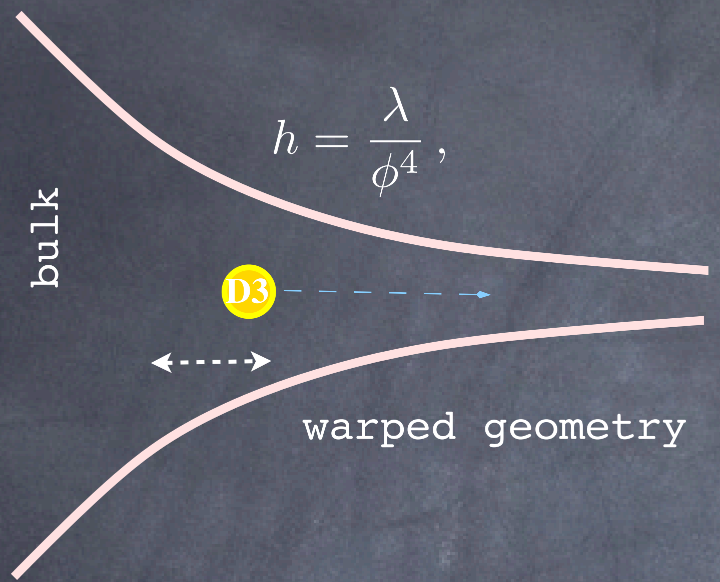
when $\omega^{eff} = \omega^{eff}_\phi < -1/3$ accelerating scaling solution

Explicit example: AdS5



- Scaling late time solutions can be found for

$$D = 1/C = h^{1/2}\,, \qquad h = \frac{\lambda}{\phi^4}\,, \qquad V = V_0\,\phi^2$$

this corresponds to a D3-brane moving in an AdS5 background. Dynamical system analysis:

$$\Omega_{kin} = \frac{\kappa^2\gamma^2\dot{\phi}^2}{3\,(\gamma+1)\,H^2}\,, \quad \Omega_{pot} = \frac{\kappa^2 V}{3\,H^2}\,, \quad \Omega_M = 1 - \Omega_{kin} - \Omega_{pot}$$

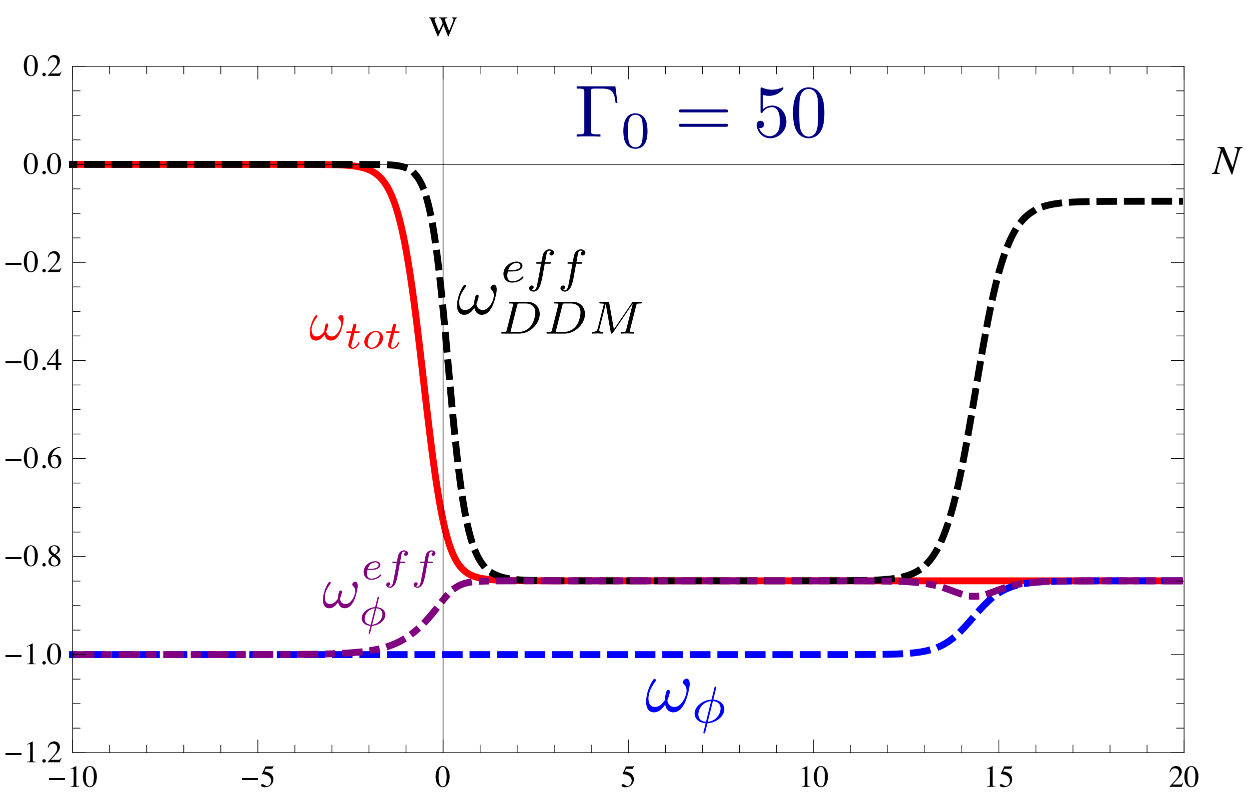
$$\omega_{tot} \equiv -\frac{2\dot{H}}{3H^2} - 1 = \gamma^{-1}\Omega_{kin} - \Omega_{pot}$$

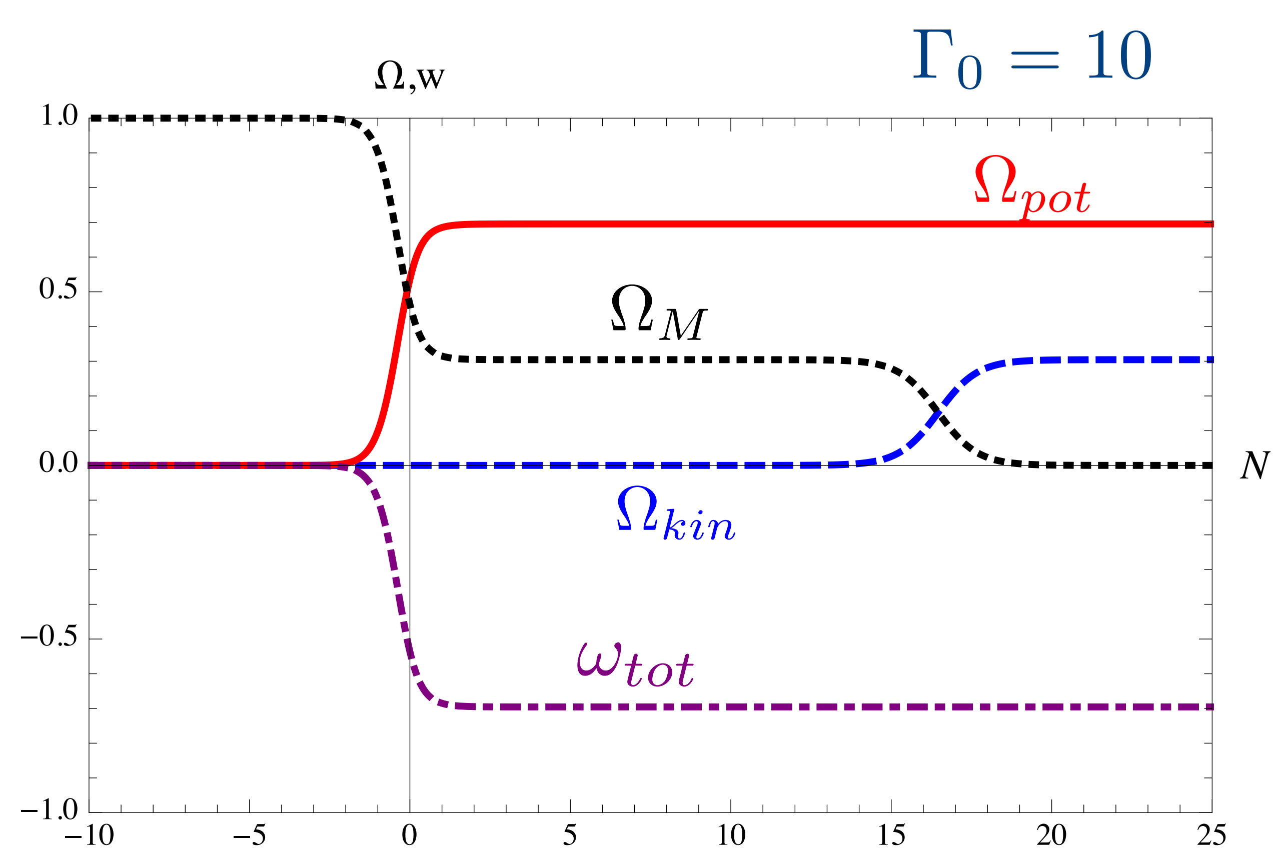
$\Gamma_0 = \lambda V_0$ determines the nature of the fixed points

The resulting fixed points for AdS5 are:

	Ω_M	Ω_{kin}	Ω_{pot}	ω_{tot}	γ	Stability
Matter Dominated	1	0	0	0	Any	Unstable
Potential Dominated	0	0	1	-1	1	Saddle
Matter Scaling	$\frac{2}{1+\sqrt{1+3\Gamma_0}}$	0	$\frac{-1+\sqrt{1+3\Gamma_0}}{\sqrt{3\Gamma_0}}$	$-\frac{\left(1-\sqrt{1+3\Gamma_0}\right)^2}{3\Gamma_0}$	∞	Attractor $\Gamma_0 < 1$
Kinetic Scaling	0	$\sqrt{\frac{2}{1+\sqrt{1+3\Gamma_0}}}$	$\frac{-1+\sqrt{1+3\Gamma_0}}{\sqrt{3\Gamma_0}}$	$-\frac{\left(1-\sqrt{1+3\Gamma_0}\right)^2}{3\Gamma_0}$	∞	Attractor $\Gamma_0 > 1$

Acceleration requires $\omega < -1/3 \;\Rightarrow\; \Gamma_0 > 1$





Other cases:

- for $C = 1/D = h = const.$ with inverse power law potential

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Accelerating solution: $\omega < -1/3 \quad \Rightarrow \quad \Gamma_0 > 1$

Early time effects?

- Dark D-brane model good candidate for late time evolution.
- How about effect in early universe expansion?
- Departures from standard cosmology can arise due to the different expansion rate, $\tilde{H}$, determined by scalar evolution
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[Kamionkowski, Turner, '90]
[Salati, '03; Rosati, '03]
[Profumo, Ullio, '03]

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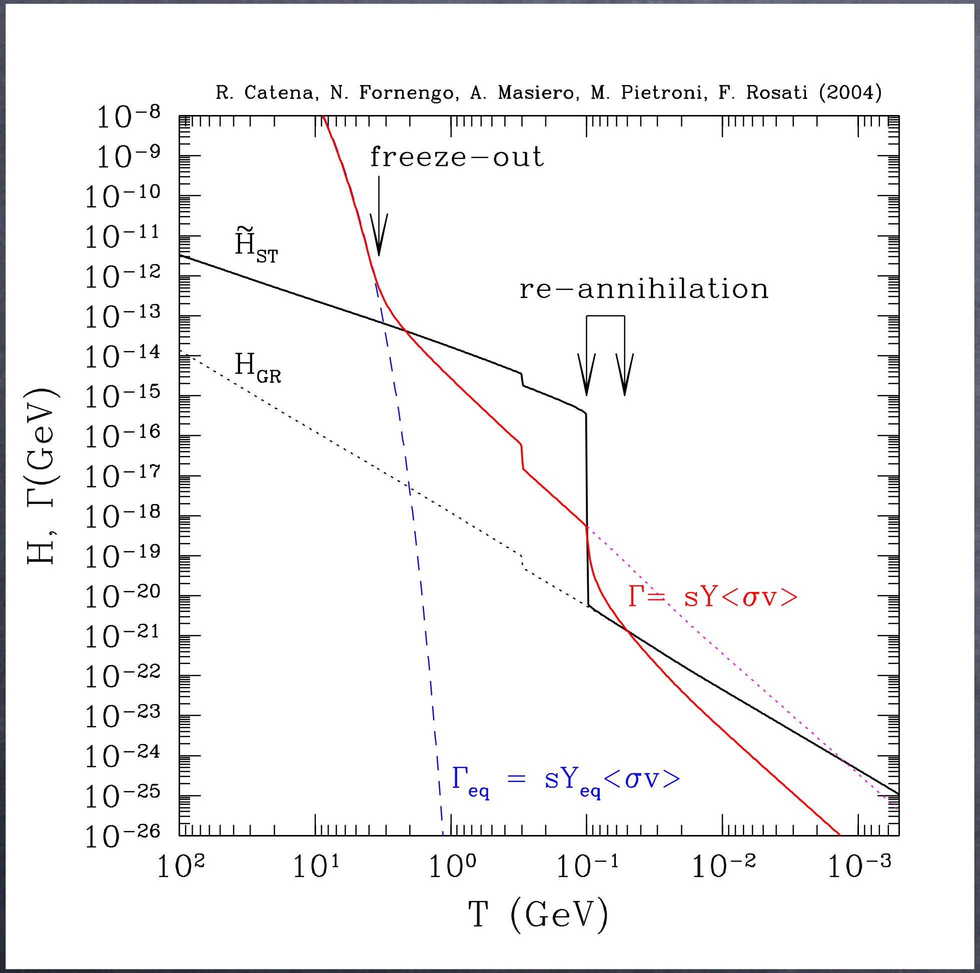

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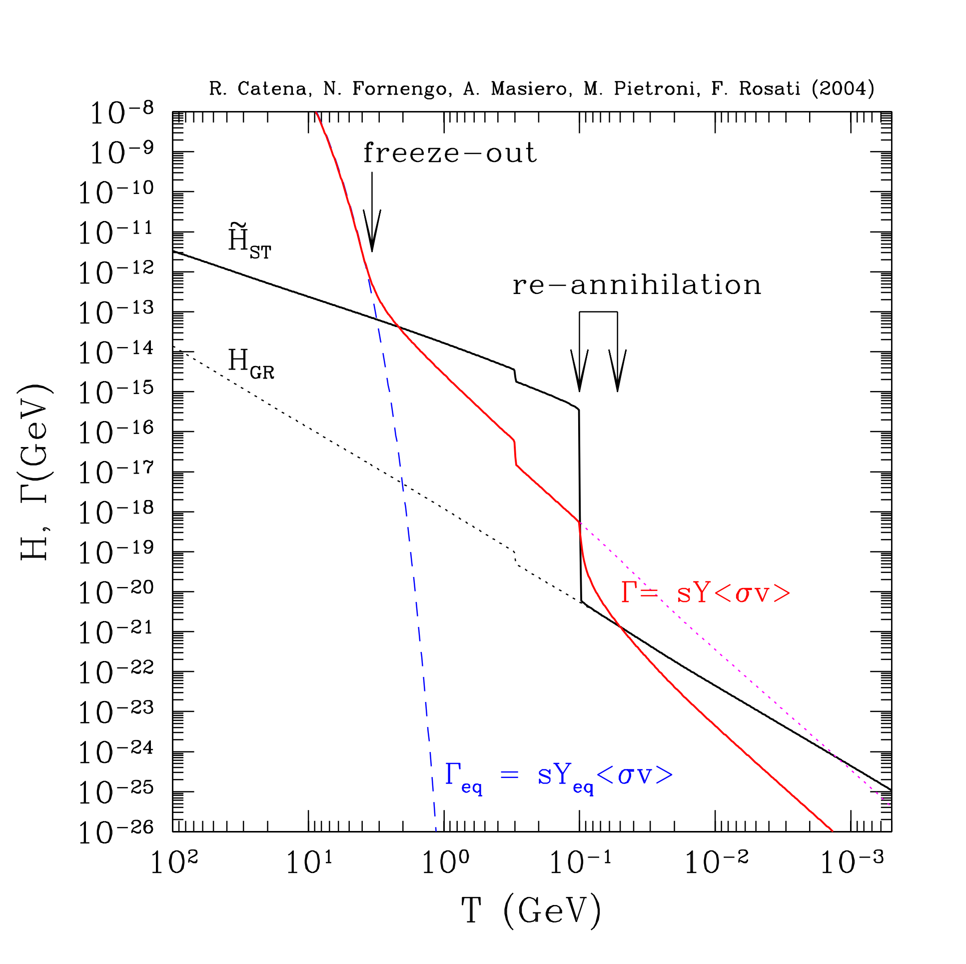

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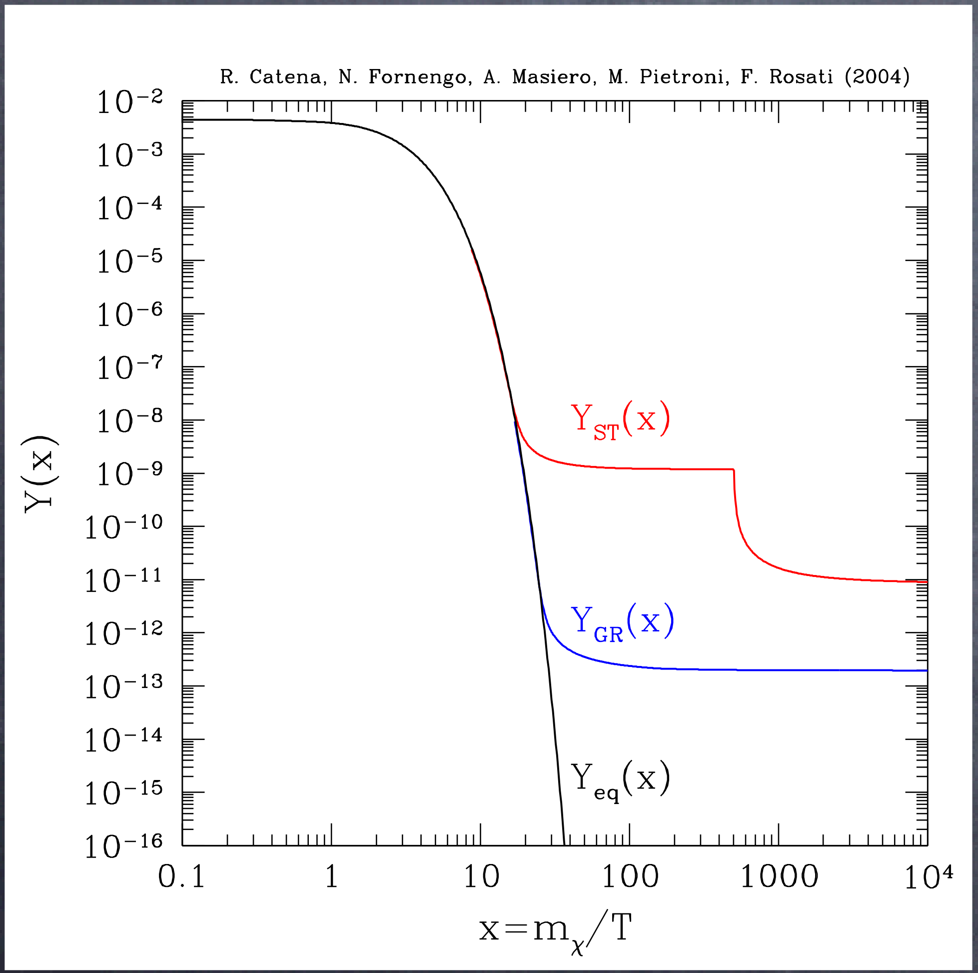

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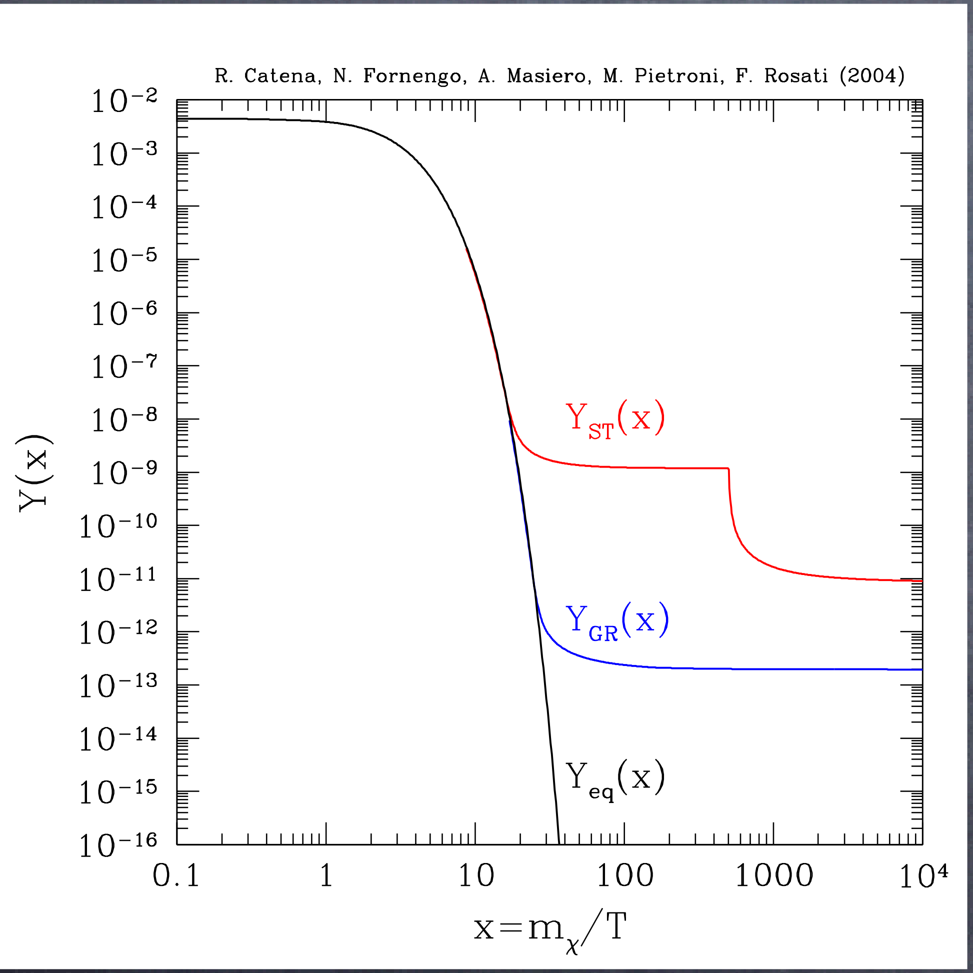

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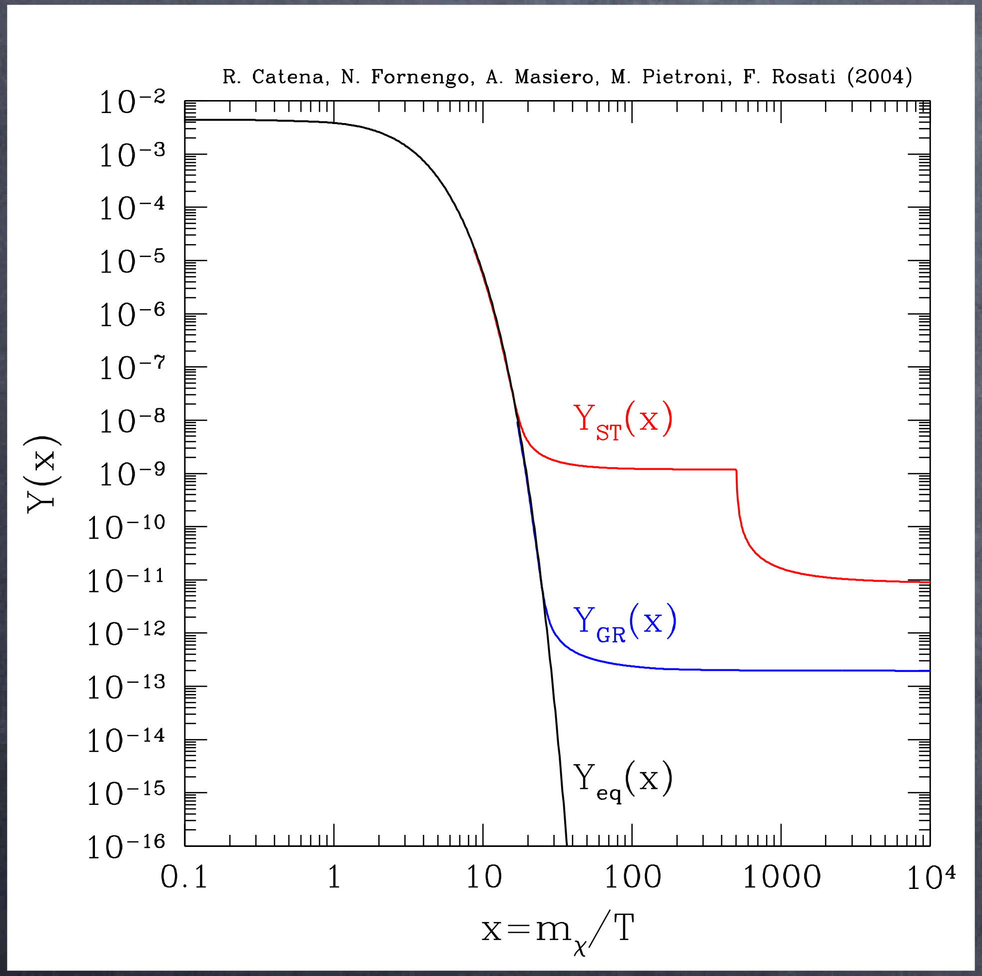

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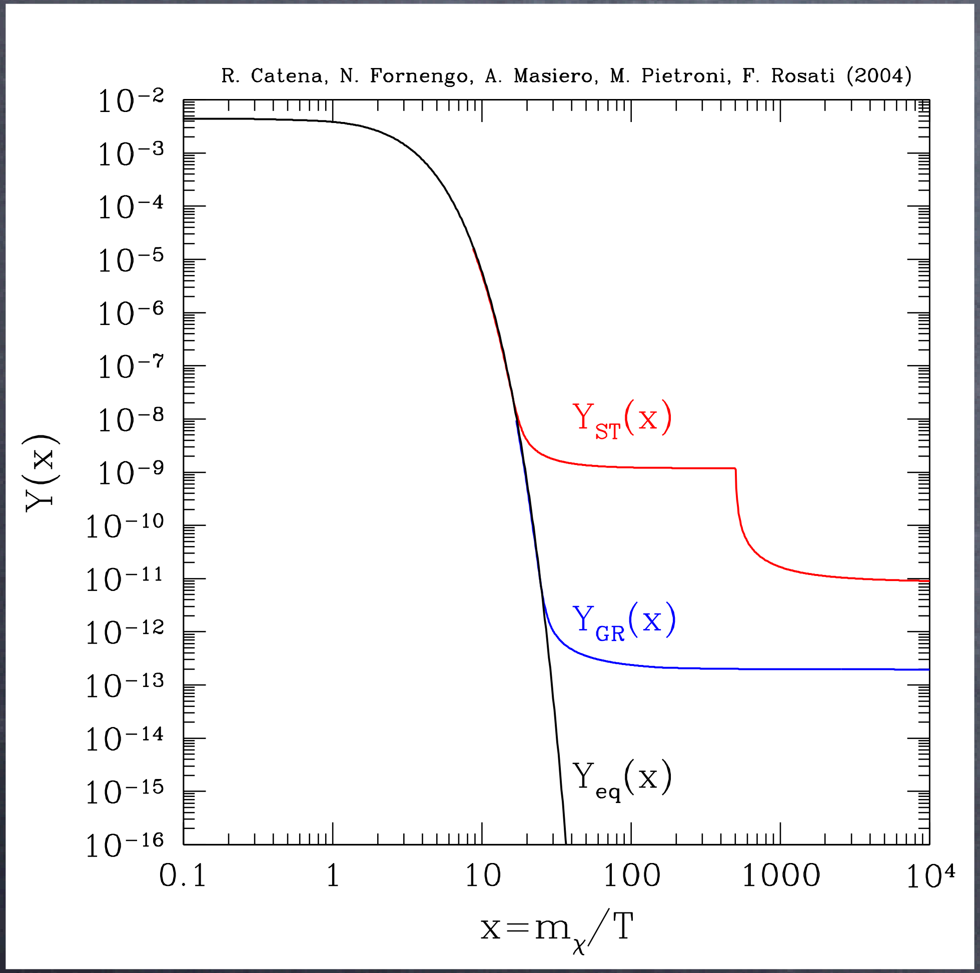

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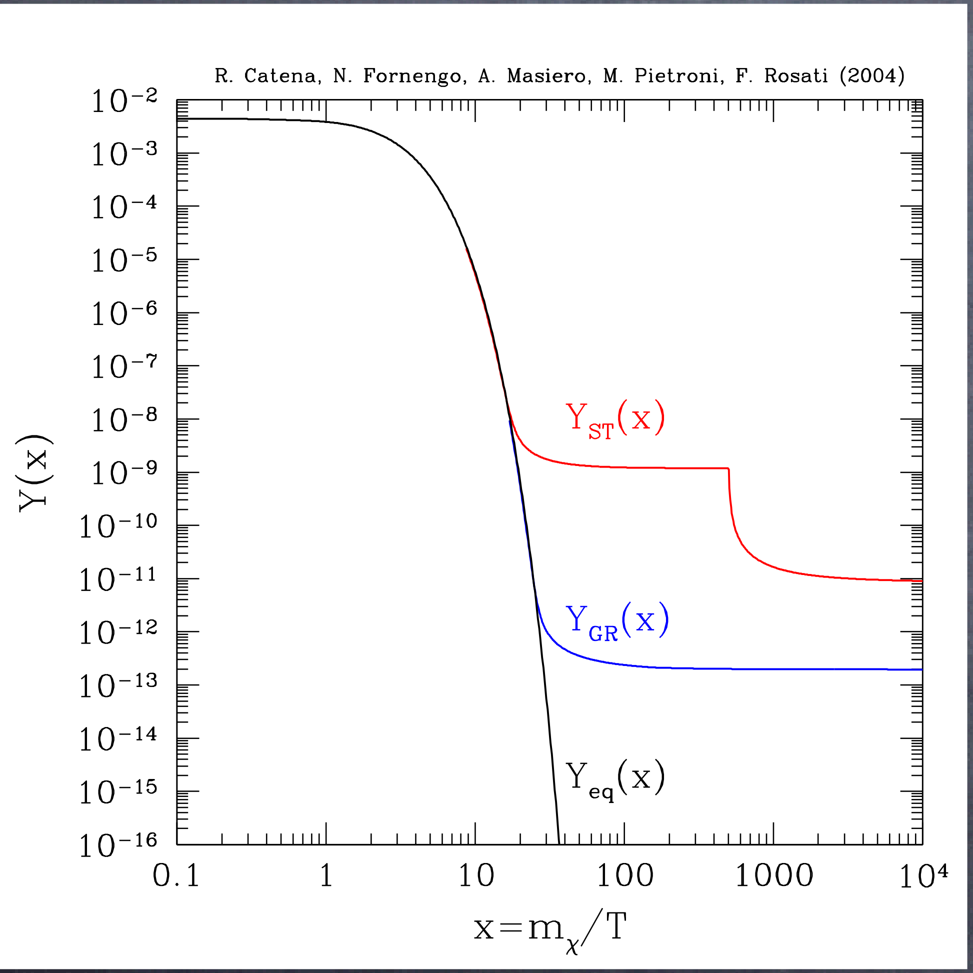

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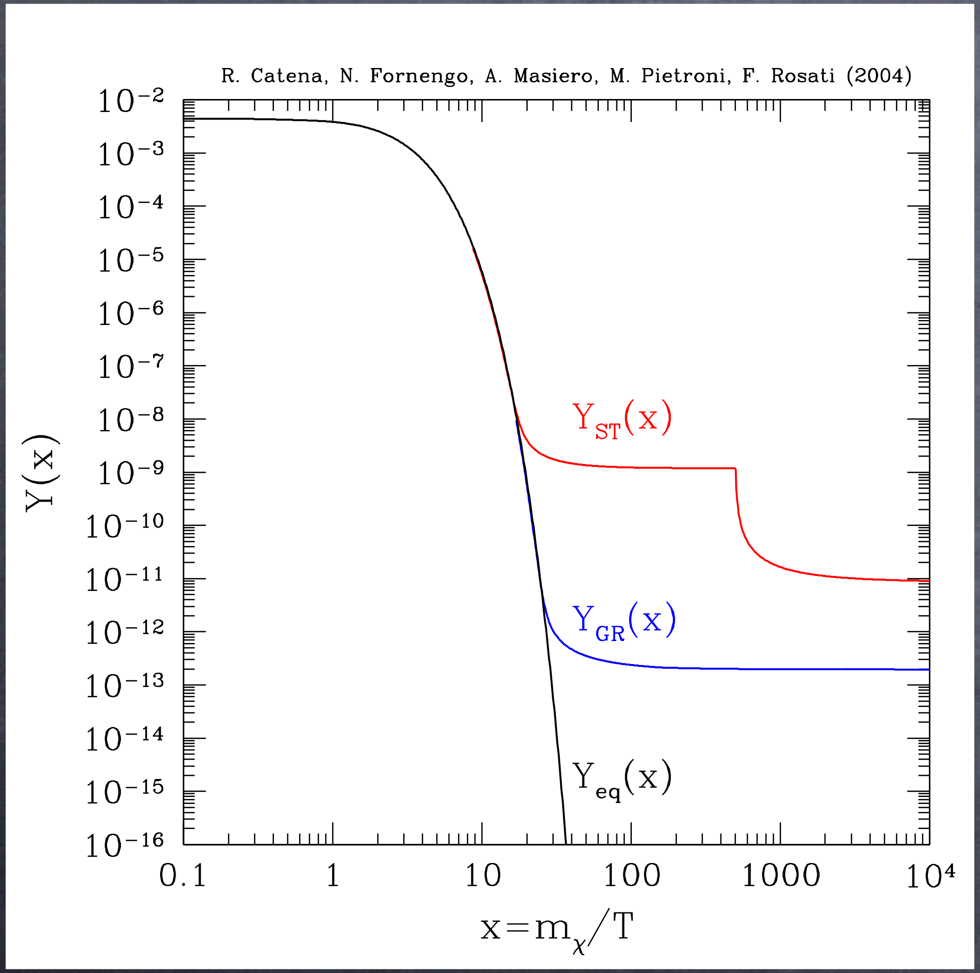

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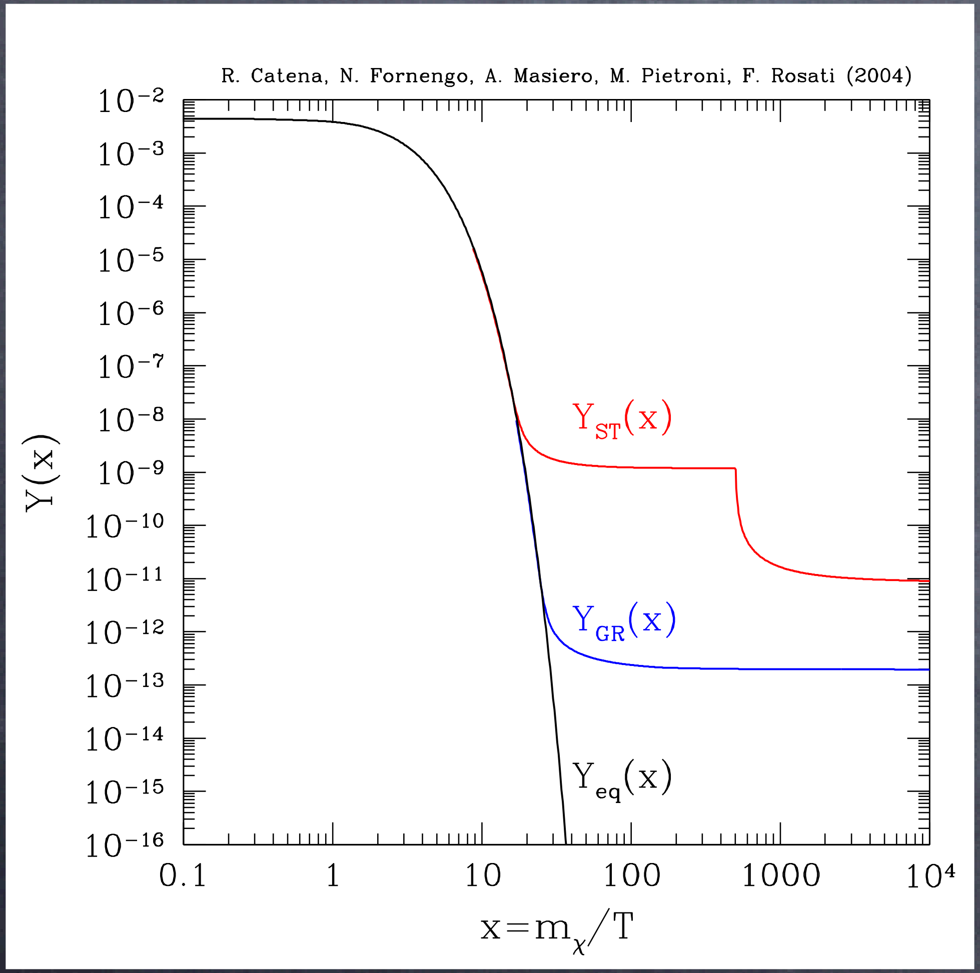

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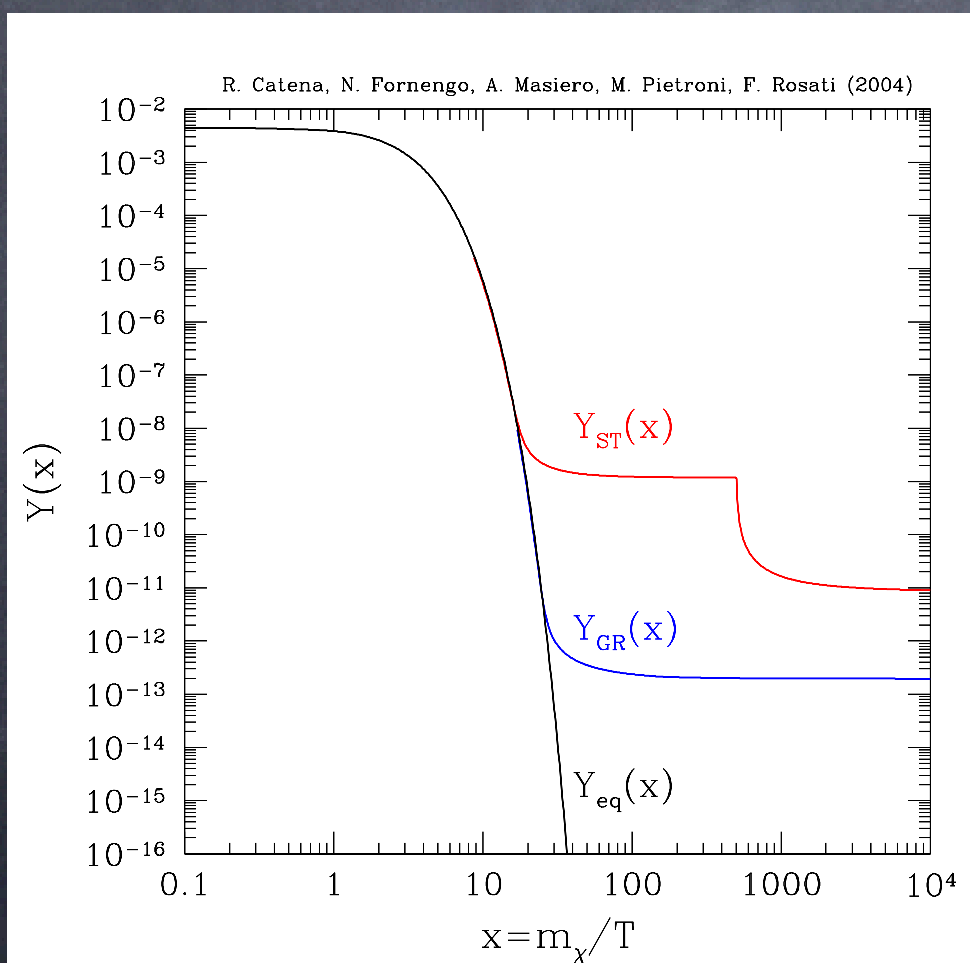

$$\frac{dY}{dx} = -\frac{1}{x}\frac{s}{\tilde{H}}\langle\sigma_{ann}v\rangle(Y^2 - Y_{eq}^2)$$

In the disformal case

$$\tilde{H} = \frac{H\gamma}{C^{1/2}}\left(1 + \frac{d\ln C}{2\,d\phi}\frac{d\phi}{dN}\right)$$

-How does conformal/disformal terms affect expansion rate?

-Effect of for relic abundance?

- A conformally coupled DM/Quintessence model was considered by Catena et al.

[Catena et al. '04]
[Lahanas et al. '06]

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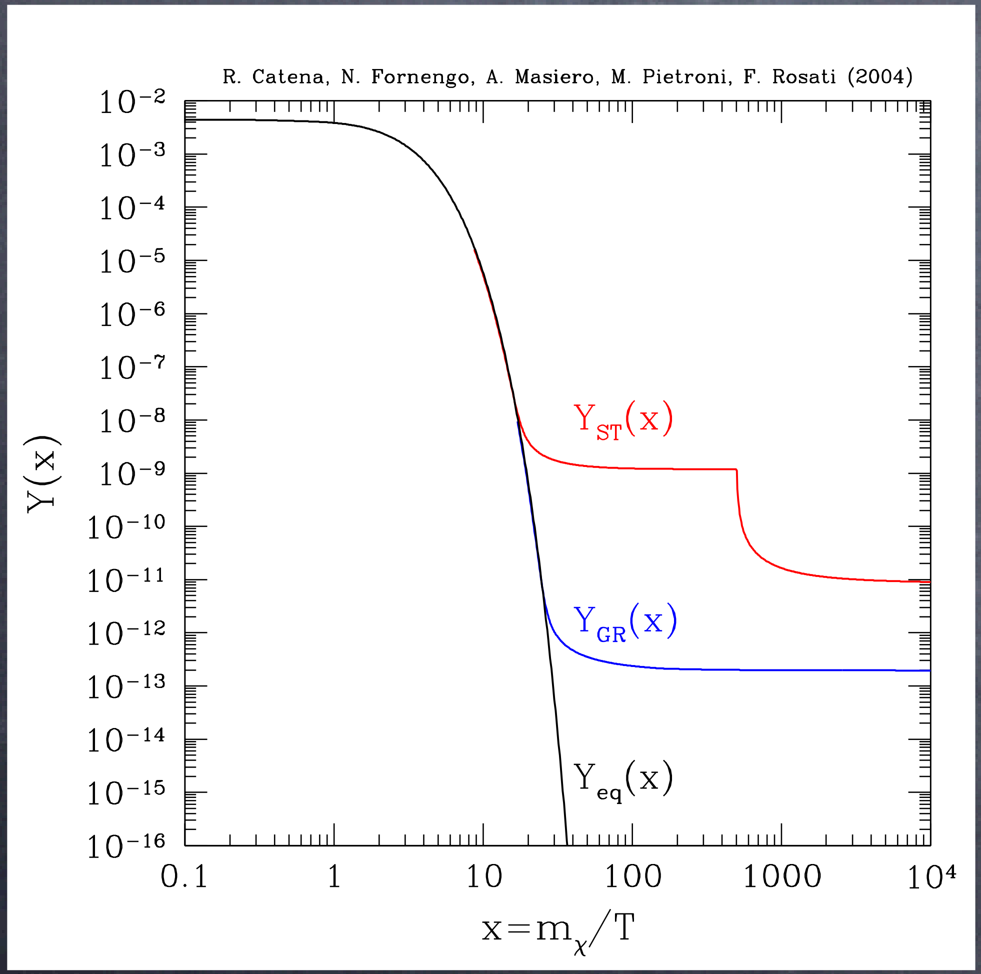

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-How does conformal/disformal terms affect expansion rate?

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- Particles which were not considered suitable to play a significant role in CDM scenarios can be rescued because of their enhanced number density.

- While particles (regions of the parameter space for given WIMP candidate), which in usual GR scenarios are promising CDM candidates, would be excluded because their boosted number would overclose the Universe.

- What can we learn about Dark D-brane models of coupled DM/DE?

Summary

- Coupled DM/DE models are attractive solution to coincidence problem
- Disformal coupling between D-brane matter and DE offers an interesting possibility: coupling is dictated by theory
- Assessing early time consequences important for DM searches and to constraint parameters of Dark D-brane model