Dark Matter Relic Abundance and Scalar-Tensor Dark Energy

astro-ph/0403614 with R. Catena, N. Fornengo, A. Masiero, and F. Rosati

Is Dark Energy telling us something about ...

- Gravity?

- Dark Matter?

- ... ?

Dynamical DE → ultra-light scalars → problems with Eq. Princ. !

EinsteinEquivalencePrinciple-respecting actions

$$S = S_G[g_{\mu\nu}, \Phi, \ldots] + S_{NG}[\psi_1, \psi_2, \ldots \psi_N, g_{\mu\nu}]$$

Matter fields

S_{NG} is obtained from the `usual' action of QFT (with constant non grav. couplings) by replacing:

1) $\eta_{\mu\nu}$ by $g_{\mu\nu}$;

2) `comma' by `semicolon';

3) $(-\eta)^{1/2}\, d^4x$ by $(-g)^{1/2}\, d^4x$.

Examples (differ by S_G): GR, Brans-Dicke, Scalar-tensor gravity

$$S_g = \frac{1}{16\pi}\int d^4x\sqrt{-\tilde{g}}\left[\Phi^2\tilde{R} + \right.$$
$$\left. + 4\,\omega(\Phi)\tilde{g}^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi - 4\tilde{V}(\Phi)\right]$$

define the ST theory

respects EEP and contains a scalar degree of freedom, Φ, possibly ultra-light: good for Dark Energy (Bartolo, M.P., '00)

$G \sim \Phi^{-2}$: what is the maximum variation of DM relic abundance compatible with BBN, CMB and GR tests?

Cosmology is easier in the `Einstein Frame':

$$\tilde{g}_{\mu\nu} \equiv A^2(\varphi) g_{\mu\nu}$$
$$\Phi^2 \equiv 8\pi M_*^2 A^{-2}(\varphi)$$
$$V(\varphi) \equiv \frac{A^4(\varphi)}{4\pi}\tilde{V}(\Phi)$$
$$\alpha(\varphi) \equiv \frac{d\log A(\varphi)}{d\varphi}.$$

← Measures the `distance' from GR

$$S_g = \frac{M_*^2}{2}\int d^4x\sqrt{-g}\left[R + g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - \frac{2}{M_*^2}V(\varphi)\right]$$

$$S_{NG}[\psi_1, ..., \psi_N, A^2(\varphi) g_{\mu\nu}]$$

$$\frac{\ddot{a}}{a} = -\frac{1}{6M_*^2}\left[\rho + 3\,p + 2M_*^2\dot{\varphi}^2 - 2V(\varphi)\right]$$
$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{1}{3M_*^2}\left[\rho + \frac{M_*^2}{2}\dot{\varphi}^2 + V(\varphi)\right]$$
$$\ddot{\varphi} + 3\frac{\dot{a}}{a}\dot{\varphi} = -\frac{1}{M_*^2}\left[\frac{\alpha(\varphi)}{\sqrt{2}}(\rho - 3p) + \frac{\partial V}{\partial\varphi}\right],$$

DE: $V \sim \varphi^{-\delta}$, if $\alpha(\varphi)$ vanish for $\varphi \to \infty$ then ST → GR !

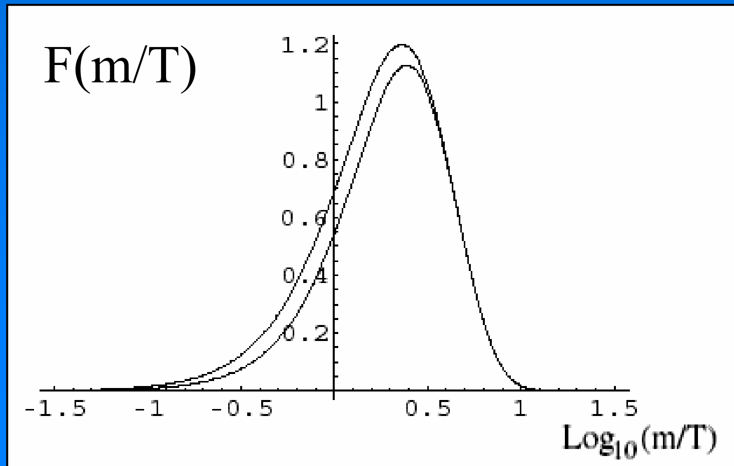
Cosmological field evolution:

$$\ddot{\varphi} + 3\frac{\dot{a}}{a}\dot{\varphi} = -\frac{1}{M_*^2}\left[\frac{\alpha(\varphi)}{\sqrt{2}}(\rho - 3p) + \frac{\partial V}{\partial \varphi}\right] ,$$

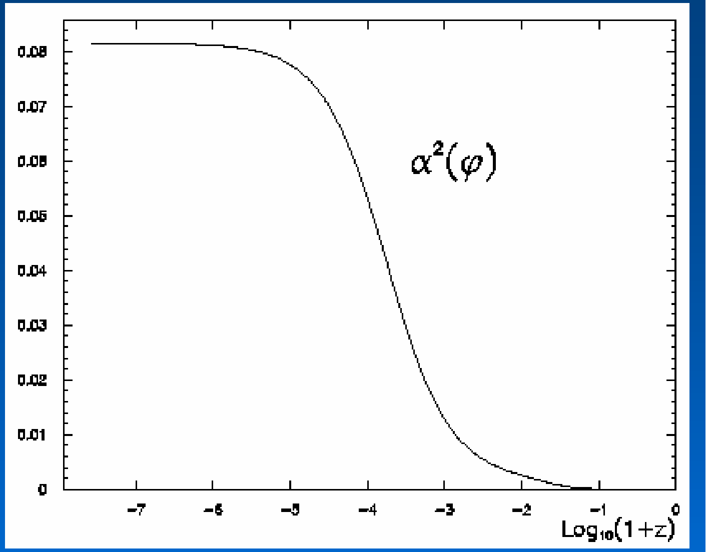
Radiation domination: V<< ρ, ρ - 3 p ≈ 0, but the field moves!

$$\frac{\tilde{\rho}_A - 3\tilde{p}_A}{\tilde{\rho}_{\rm tot}} \simeq \frac{15}{\pi^4}\frac{g_A}{g_\star}y_A^2 F[y_A]$$

$$y_A \equiv \tilde{m}_A/\tilde{T},$$

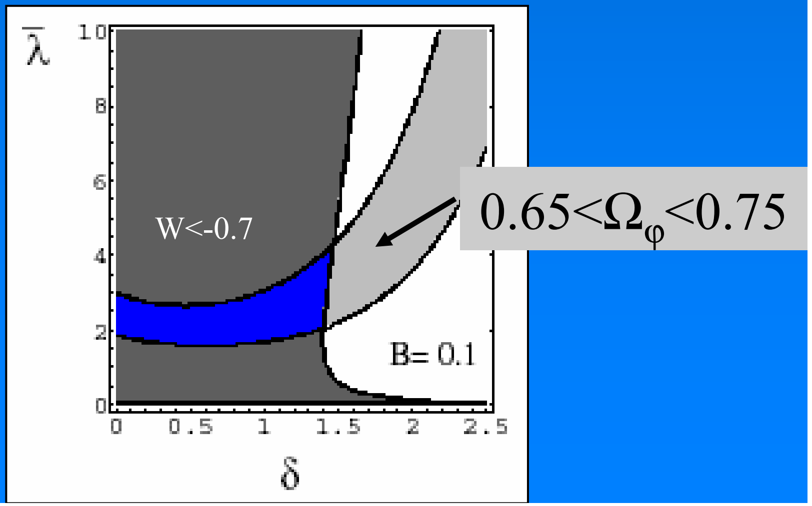


Matter domination: $V \ll \rho$, $p \approx 0$, $\alpha(\varphi)$ decreases:



$\alpha \to 0$: ST is attracted towards GR!!

Dark Energy domination: $V > \rho$, $\alpha \ll 1$, $V=\Lambda^4 \varphi^{-\delta}$



Phenomenological bounds:

BBN: `physical' expansion rate

$$\tilde{H}^2 \simeq A^2(\varphi)\frac{1}{3M_*^2}\tilde{\rho}\,.$$

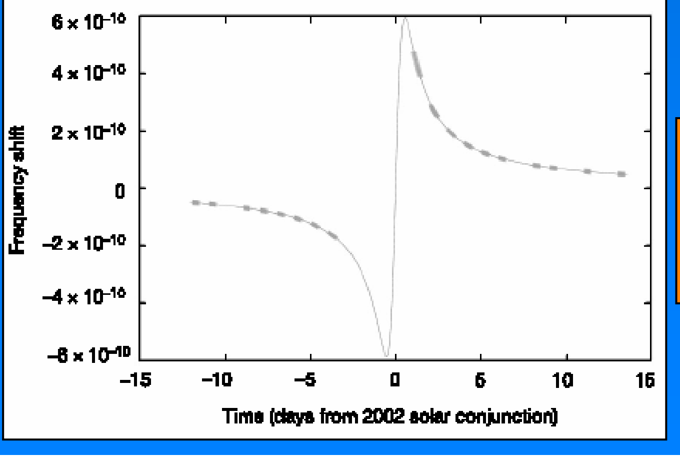
$$\rightarrow \quad \frac{\Delta\tilde{H}^2}{\tilde{H}^2}\bigg|_{\rm nuc} = \frac{A^2(\varphi_{nuc}) - A^2(\varphi_0)}{A^2(\varphi_0)}\,.$$

Analogous to the effect of extra neutrinos… $\Delta N<1 \rightarrow \frac{A(\varphi_{nuc})}{A(\varphi_0)} < 1.08\,.$

Solar system tests of GR: delay of radio signals

$$\Delta t = 2(1+\gamma)\frac{GM_S}{c^3}\ln\left(\frac{4r_1r_2}{b^2}\right)$$

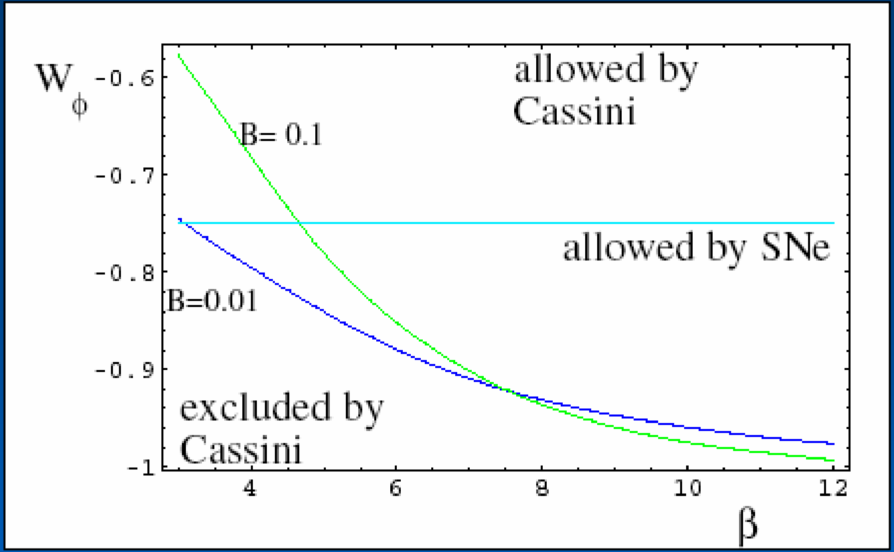
GR: $\gamma - 1 = 0$
ST: $\gamma - 1 = O(\alpha^2)$



Cassini spacecraft: $\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$
(Bertotti et al. '03)

ST manifestations vs. Wϕ:

$\alpha \sim -B\, e^{-\beta\varphi}$



If W=-1 then B<10^{-3}:

no ST evidence from CMB until today!

CMB:

$$\theta_{\rm peak} \sim \pi / l_{\rm peak} \sim v_s\, t_{\rm dec}\, z_{\rm dec} / d(z_{\rm dec})$$

$$t_{dec} = \int_0^{1/(z_{dec}+1)} \frac{d\tilde{a}}{\tilde{a}\tilde{H}}$$

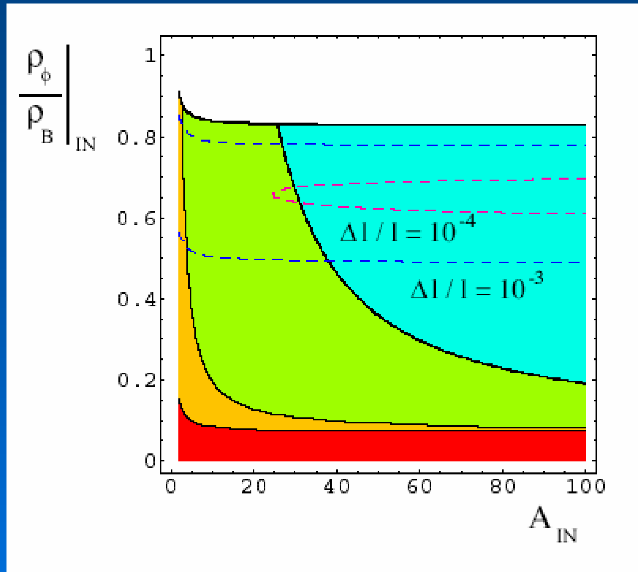
→

$$\frac{\Delta l_{\rm peak}}{l_{\rm peak}} \simeq \frac{4}{3}\frac{A(\tilde{a}_{\rm dec}) - 1}{A(\tilde{a}_{\rm dec})},$$

Typically less than O(10^{-3})
(once BBN bounds have been imposed)

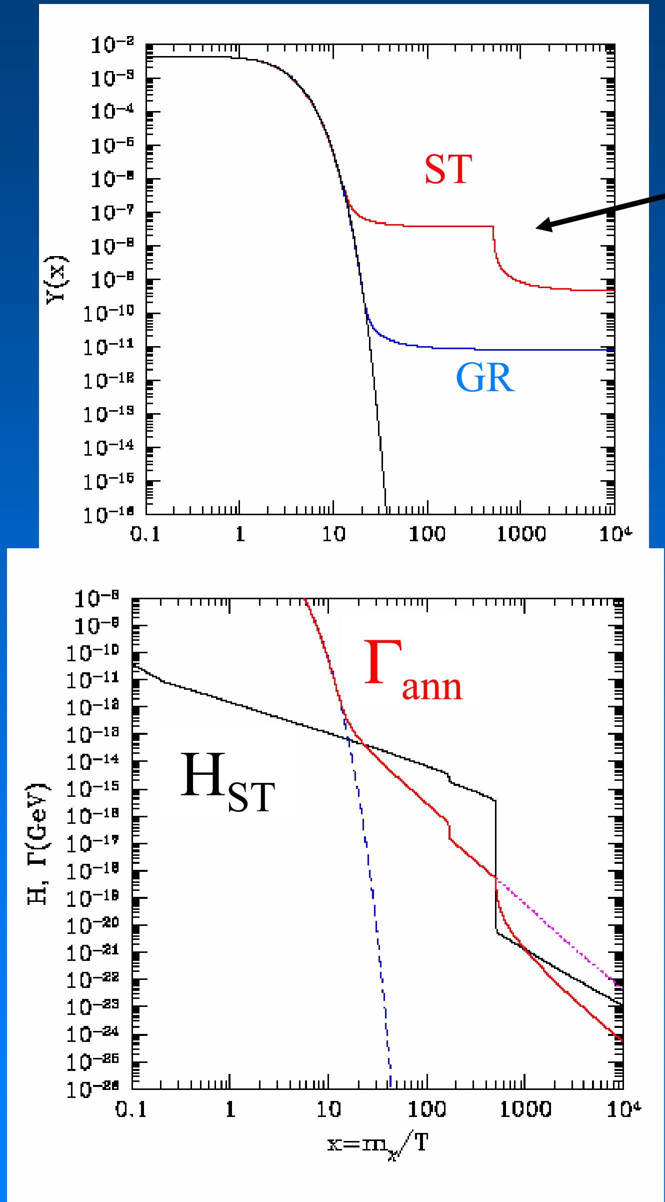
Speed-up factor: $\left.\frac{H_s}{H_s^{GR}}\right|_{10\,GeV}$

Up to $O(10^5)$ compatibly with all the bounds!

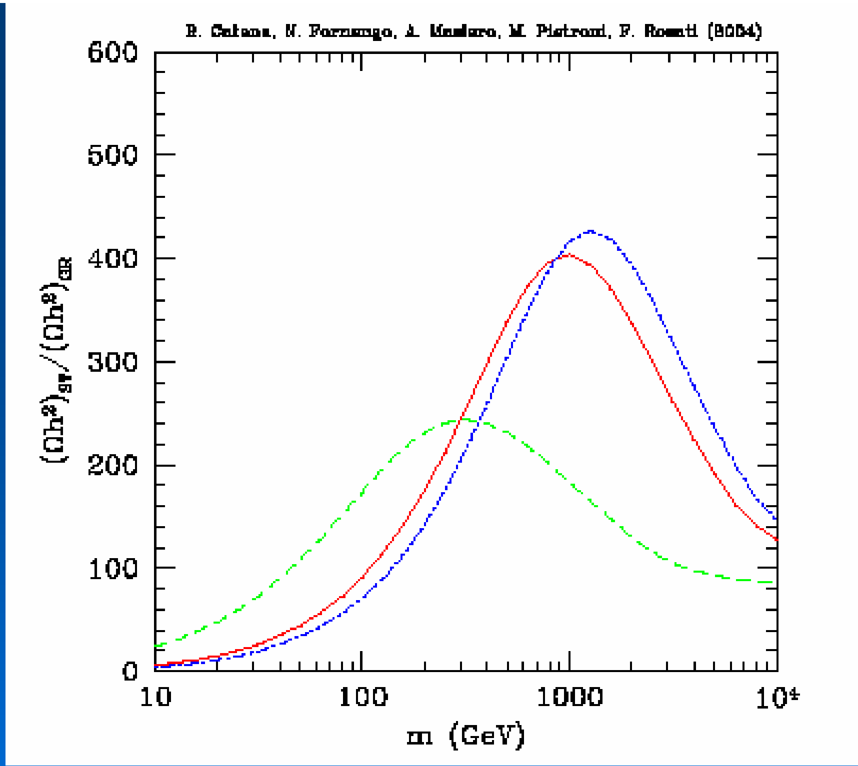


Wimps might have decoupled in a much more violent Universe!

Impact on the relic abundance

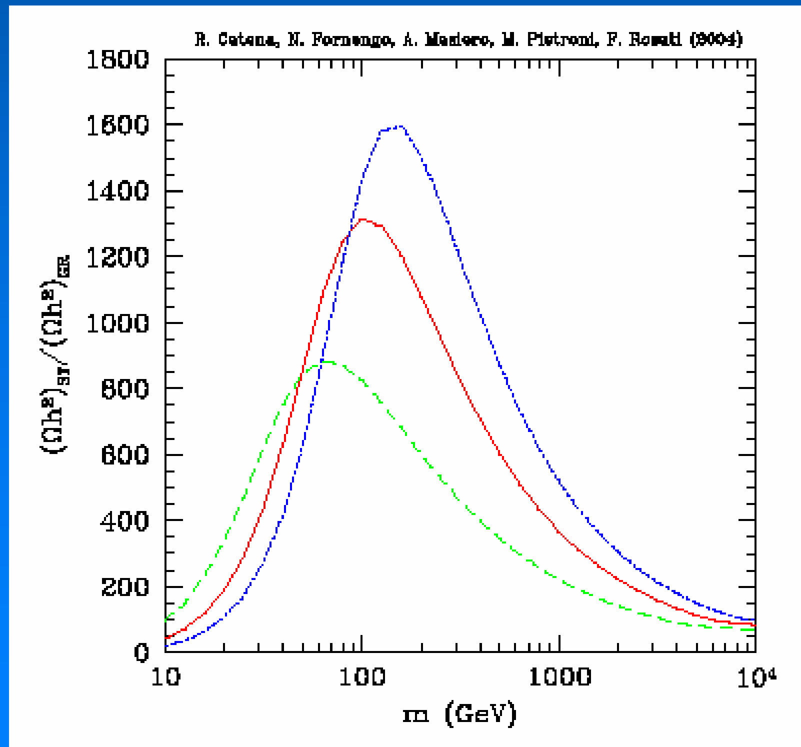


Re-annihilation



$\langle \sigma_{ann} v \rangle$ = const

$\langle \sigma_{ann} v \rangle$ = const $\times$ T/m



CONCLUSIONS

- Dark Energy models generally require light scalars: ST Gravity can safely accommodate them

- Strong constraints from BBN, CMB, and solar system tests of gravity

- If W=-1 then it is unlikely that post CMB cosmology will show sizable deviations from GR

- Dark matter may have decoupled in a much more violent Universe. Reanalyze WIMP parameter space ! (Neutralino… see Profumo's talk)