Dark energy from various approaches

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Motivations

- Observational evidence for dark energy (present acceleration – supernovae); (weak lensing surveys); (CMB spectrum)
- Origin of dark energy: various candidates or mechanisms: *cosmological constant (theoretical difficulties); dynamical dark energy models (scalar fields motivated from unification scenarios); modified gravitational dynamics [f(R), MOND, braneworld, etc..];* numerous other scenarios…
- Three categories discussed here:

  (i) scalar field dynamics (unification of DE & DM)

  (ii) back reaction from inhomogeneties

  (iii) quantum entanglement and dark energy

Dark energy through scalar field dynamics

Quintessence -- potential energy driven acceleration

*[ASM, Phys. Rev. D **64**, 083503 (2001)]*

$$V(\varphi) >> \dot{\varphi}^2 \quad p = \dot{\varphi}^2 - V(\varphi) \approx -\rho \qquad a \sim \exp(t) \quad \ddot{a} > 0$$

K-essence – kinetic energy driven acceleration

*[N. Bose and ASM, Phys. Rev. D **79**, 103517 (2009); Phys. Rev. D **80**, 103508 (2009)]*

$$L = F(\dot{\varphi}^2) V(\varphi) \qquad F(\dot{\varphi}^2) >> 1 \quad \ddot{a} > 0$$

***Quintessence & k-* essence: Perspective**

- Inflationary models (kinetic– or potential energy driven) originally motivated from string theoretic (Born-Infeld), braneworld actions. *[c.f. Armendariz-Picon, Damour, Mukhanov, (1999)]*

- Subsequently, models for late time acceleration of the universe driven by scalar field kinetic / potential energy. *[c.f. Chiba et. al (1999), Steinhardt et. al. (2001), Chimento (2004)….]*

- Search for a single field (or similar mechanism) to generate the early and present era acceleration of the universe. *[c.f. quintessential inflation: Peebles (1999), Copeland (2000), Majumdar (2001), Sahni (2004)……]*

- Nature of both dark matter and dark energy are unknown. Could these be manifestations of the same entity ? *[c.f. unified models: ……Liddle et. al. (2008)]*

Dark energy in the brane-world scenario

(ASM, PRD 2001)

Early era inflation and late-time acceleration through same scalar field

$$V(\phi) = V_0[A \exp(-\alpha\phi/m_{pl}) + B \exp(-\beta\phi/m_{pl})]$$

Observational data:

(a) Inflationary era (CMBR observations, i.e., *COBE*)

(b) Intermediate era (e.g., nucleosynthesis)

(c) Present era (Red-shift *(supernovae)* , dark matter *(lensing)*

→ ***Constraints on potential parameters***

(Scalar field potential not directly measurable)

Constraints translate into restrictions on observable parameters such as H_0, q_0, w_0, z_T .....

K-essence Model-I (N. Bose and ASM, PRD 2009)

$$L = F(x)V(\varphi) \quad F(x) = Kx - m_{pl}^2 L\sqrt{x} + m_{pl}^4 M \quad V(\varphi) = 1 + e^{-\varphi/\varphi_c}$$

- *Inflationary era: (V ~ constant, or varies slowly)*

Field equation:

$$(2xF_{xx} + F_x)\dot{x} + 6HF_x x = 0 \quad \Rightarrow \sqrt{x}F_x = k/a^3$$

Energy conservation:

$$\Rightarrow \dot{\rho} = -3H(\rho + p) = -6HF_x xV$$

Fixed points of the eq. ($p = -\rho$ *) correspond to extrema of F.*

$$x = x_0 \equiv \left(0,\ m_{pl}^4 \frac{L^2}{4K^2}\right)$$ *is an attractor leading to exponential inflation.*

- *Exit from the inflationary era:* x slowly moves away from x_0

Inflation ends when

$$\frac{\delta x}{x_0} \approx 1$$

Post-inflationary evolution

- Stage of kinetic domination after inflation

  F.E.:

$$(2xF_{xx}+F_x)\ddot{\varphi}+3H F_x\dot{\varphi}=0 \qquad F(x)=B(1-2A\sqrt{x})^2-C$$

$$x=\frac{1}{16A^4B^2}\left(2AB+\frac{k}{a^3}\right)$$

recovering back effectively, kinetic *k-essence.*

- Energy density: $$\rho=C+\frac{k}{Aa^3}+\frac{k^2}{4A^2Ba^6}$$

- Eq. of state: $$w=\frac{\frac{k^2}{4A^2Ba^6}-C}{C+\frac{k}{Aa^3}+\frac{k^2}{4A^2Ba^6}}$$

post-inflation (before radiation domination): $w\approx 1$

matter domination: $w\approx 0$

- *late time evolution (* $a\to\infty$ *):* $w\to -1$

Constraints on model parameters

Observational requirements:

- Inflationary era: amplitude of density perturbations $\delta_H = 2\times 10^{-5}$; e-foldings $N > 60$
- Intermediate era: crossover from kinetic to radiation domination before nucleosynthesis; & matter domination subsequently
- Present era: transition to accelerated expansion after structure formation

Impose the constraints:

$$250\,(GeV)^{-2} \le A \le 10^{10}\,(GeV)^{-2}$$

$$10^{-22}(GeV)^4 \le B \le 10^{-6}(GeV)^4 \qquad C = 10^{-48}(GeV)^4$$

- **tensor-to-scalar ratio** $r \cong 0.12$ spectral index $n_s \cong 0.95$
- **Transition to acceleration** $Z_T \cong 0.81$ **present value of eq. state parameter** $w_0 \cong -0.75$

Summary (quintessence & *k*- essence)

[ASM, Phys. Rev. D (2001); N. Bose & ASM, Phys. Rev. D (2009); *ibid.*]

- We consider quintessence & *k-essence* models with the interplay of kinetic and potential terms ***(inspired from unified field theory, higher dimensional models)***.

- Our aim is to obtain inflation, dark matter & dark energy within a unified framework.

- **Predictions of w_0 and Z_T to be tested with upcoming probes.**

- Constraints on model parameters from phenomenological considerations *(typically, tuning of potential parameters)* ***Naturalness ? Multiplicity of models.***

Backreaction from inhomogeneities (motivation)

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$G_{\mu\nu} = < T_{\mu\nu} >$$

Einstein's equations: ***nonlinear***

$$< G_{\mu\nu}(g_{\mu\nu}) > = < T_{\mu\nu} > \neq G_{\mu\nu}(< g_{\mu\nu} >)$$

Einstein tensor constructed from average metric tensor will not be same in general as the average of the Einstein tensor of the true metric

Acceleration without additional phyics ?

_*Backreaction from inhomogeneities (perspective)*

[N. Bose & ASM, MNRAS Letters (2011); arXiv:1203.0125]

- Observations tell us that the Universe is inhomogeneous (< 100 Mpc)
- Backreaction from inhomogeneities could modify the evolution of the Universe. Averaging over inhomogeneities to obtain global metric
- Averaging procedure depends on chosen type of hypersurface: constant time or light cone ?
- Backreaction could lead to an accelerated expansion during the present epoch ?

The Backreaction Framework: Einstein equations:

$$3\frac{\ddot{a}_D}{a_D} + 4\pi G\langle\rho\rangle_D - \Lambda = Q_D \qquad 3H_D^2 - 8\pi G\langle\rho\rangle_D - \Lambda = -\frac{1}{2}\langle R\rangle_D - \frac{1}{2}Q_D$$

$$0 = \partial_t\langle\rho\rangle_D + 3H_D\langle\rho\rangle_D$$

where the average of the scalar quantities on the global domain D is

$$\langle f\rangle_D(t) = \frac{\int_D f(t, X^1, X^2, X^3)\, d\mu_g}{\int_D d\mu_g}$$

Global domain D is separated into sub-domains

Backreaction $\quad Q_D = \sum_\ell \lambda_\ell Q_\ell + 3\sum_{\ell \neq m} \lambda_\ell \lambda_m (H_\ell - H_m)^2$

Q_ℓ *backreaction in subdomain*

λ_ℓ *volume fraction of subdomain*

Two-scale (interaction-free) void-wall model

M – collection of subdomains with initial **overdensity** (called “Wall”)

E — collection of subdomains with initial **underdensity** (called “Void”)

(power law evolution in subdomains: $a_E = c_E t^{\alpha}\,;\; a_M = c_M t^{\beta}$

acceleration equation

$$\frac{\ddot{a}_D}{a_D} = \frac{c_M^3 t^{3\beta}}{r_h^3}\frac{\beta(\beta-1)}{t^2} + \left(1 - \frac{c_M^3 t^{3\beta}}{r_h^3}\right)\frac{\alpha(\alpha-1)}{t^2}$$

$$+2\frac{c_M^3 t^{3\beta}}{r_h^3}\left(1 - \frac{c_M^3 t^{3\beta}}{r_h^3}\right)\left(\frac{\beta}{t} - \frac{\alpha}{t}\right)^2$$

Effect of event horizon *(Event horizon forms at the onset of acceleration)*

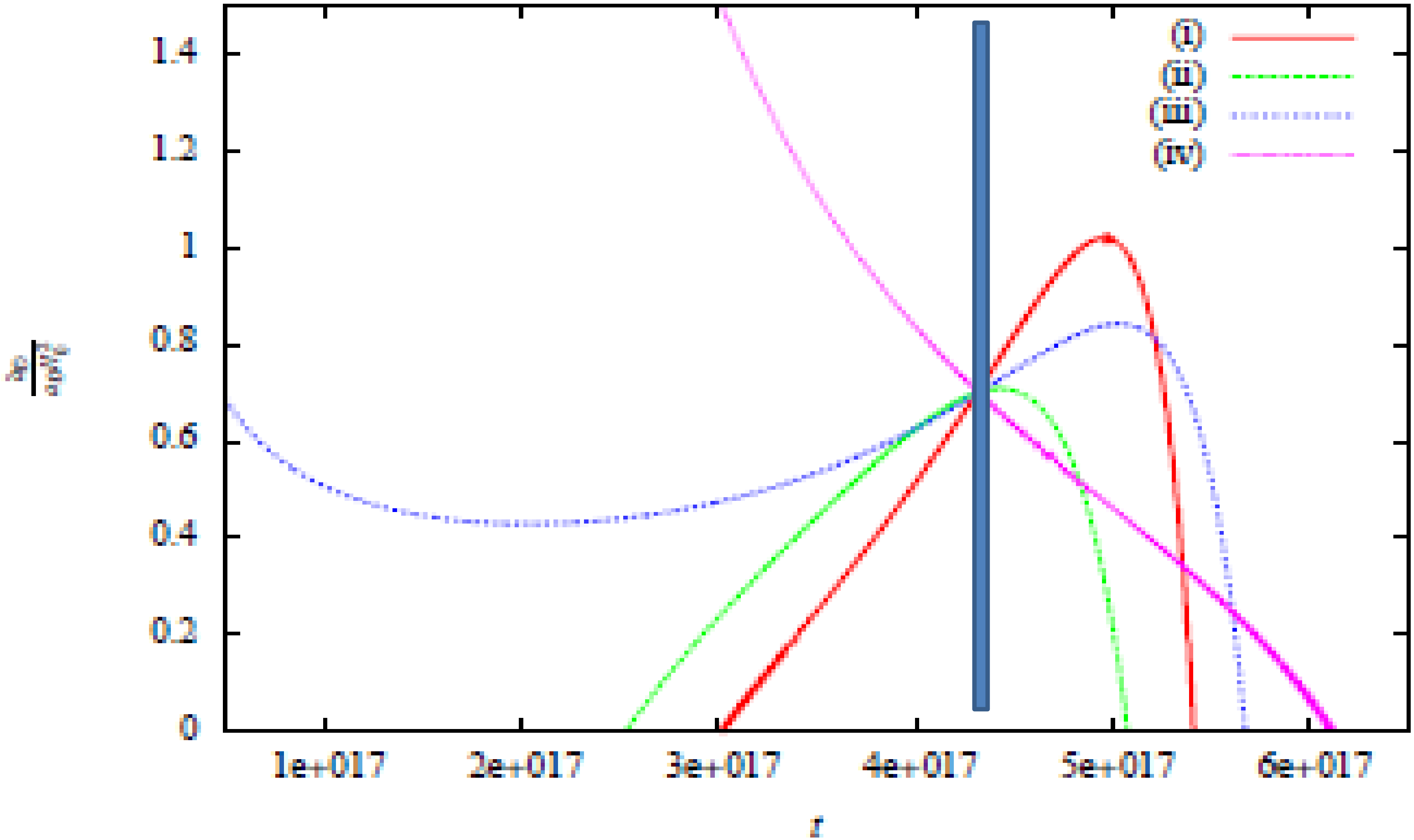
$$r_h = \int_t^{\infty} \frac{dt'}{a_D(t')}$$

Demarcates causally connected regions

Future deceleration due to cosmic backreaction in presence of the event horizon *[N. Bose, ASM; MNRAS 2011]*

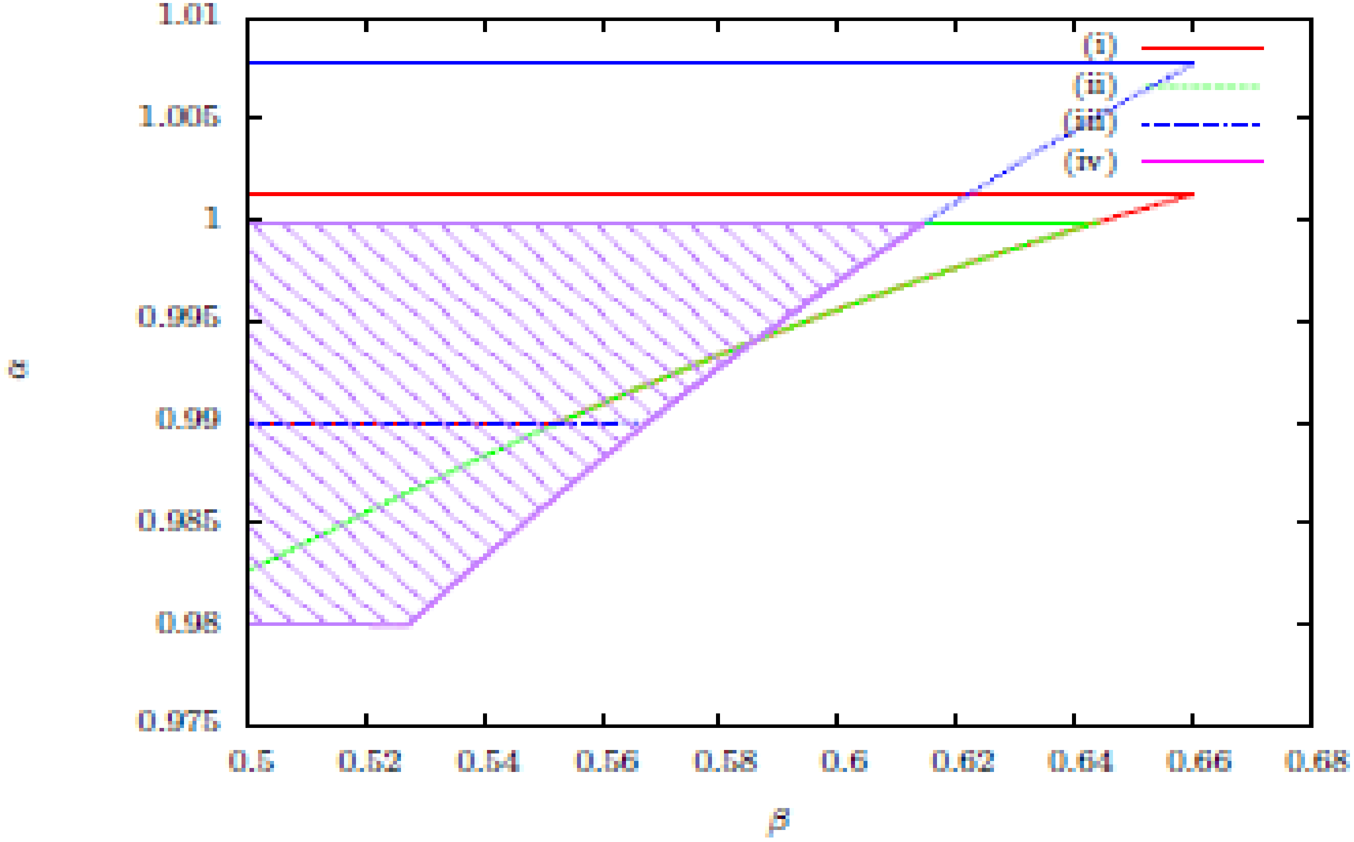
(i) α = 0.995, β = 0.5 , (ii) α = 0.999, β = 0.6 ,
(iii) α = 1.0, β = 0.5 , (iv) α = 1.02, β = 0.66 .

$$q_o = -0.7$$



Parameter space for future deceleration

[N. Bose & ASM; arXiv:1203.0125]



Backreaction in presence of event horizon (Summary)

[N. Bose and ASM, MNRAS Letters (2011); arXiv:1203.0125]

- Effect of backreaction due to inhomogeneities on the evolution of the universe

- The cosmic event horizon impacts the role of inhomogeneities on the evolution, causing the acceleration to slow down significantly with time.

- Backreaction could be responsible for a decelerated era in the future. ***(Avoidance of big rip !)*** *more realistic models required.*

- What is the origin for the onset of acceleration ? No clear answer provided by the backreaction framework

Quantum entanglement and dark energy

Does quantum mechanics (entanglement) play any role in the dynamics of the large-scale universe ?

Two approaches:

- (i) decoherence of quantum wave function (dynamical state vector reduction models) **[ASM, D. Home & S. Sinha, Phys. Lett. B (2009)]**
- (ii) holographic dark energy from trapped domains (strange quark nuggets) **[ASM, S. Sinha, …., *under preparation]***

Quantum entanglement & Dark Energy (status)

- Two approaches: breaking of quantum entanglement results in dynamical dark energy.

- i) Spontaneous localization of matter wave function (energy exchange with fluctuating scalar field) : using the standard model parameters, DE emerges if the process starts at EW era. [ASM, D. Home, S. Sinha, PLB (2009)]

  (comparison with other decoherence models)

- Ii) Holographic dark energy due to trapped baryons in strange quark nuggets (associated with QCD phase transitions). [ASM, S. Sinha, …, under preparation]

Required amount of DE leads to constraints on model parameters (DM—DE scenario).

Summary *(Dark energy from various approaches)*

- Dark energy : various observations; theoretical puzzle
- Several scenarios – different perspectives
- Category I: ***no modification of gravitational model; no extra particle physics***, e.g., back reaction from observed inhomogeneities – curious feature – present acceleration may be transient (event horizon)
- Category II: ***Inputs from quantum physics – quantum entanglement and its breaking***, e.g., decoherence : (a) spontaneous localization models (b) holographic effects due to trapped domains
- Category III: ***Scalar field dynamics inspired by unification scenarios***

predictions for w, z_T, etc. to be tested by upcoming probes

Some references

- ***Dark energy (unification scenarios)***
- ASM, Phys. Rev. D **55**, 6092 (1997); ASM, Phys. Rev. D **64**, 083503 (2001)
- N. Bose & ASM, Phys. Rev. D **79**, 103517 (2009); Phys. Rev. D **80**, 103508 (2009)

- ***Dark energy (quantum entanglement)***
- ASM, D. Home, S. Sinha, Phys. Lett. B **679**, 167 (2009)

- ***Dark energy (backreaction from inhomogeneities)***
- N. Bose & ASM, Mon. Not. R. Astron. Soc. Letters **418**, L45 (2011); arXiv:1203.0125
