Non-canonical domain walls as a unified model of dark energy and dark matter

Fargiza A. M. Mulki

Hesti R. T. Wulandari

Taufiq Hidayat

Email: fargiza@as.itb.ac.id

ASTRONOMY RESEARCH GROUP

FACULTY OF MATHEMATICS AND NATURAL SCIENCES

INSTITUT TEKNOLOGI BANDUNG, INDONESIA

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Non-canonical Domain Wall as A Unified Model of Dark Energy and Dark Matter: I. Cosmic Dynamics[⋆,⋆⋆]

FAM Mulki[a,b,∗], H Wulandari[a,b] and T Hidayat[a,b]

[a]Astronomy Research Group, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung (ITB), Bandung, West Java, Indonesia
[b]Bosscha Observatory, Institut Teknologi Bandung (ITB), Lembang, West Java, Indonesia

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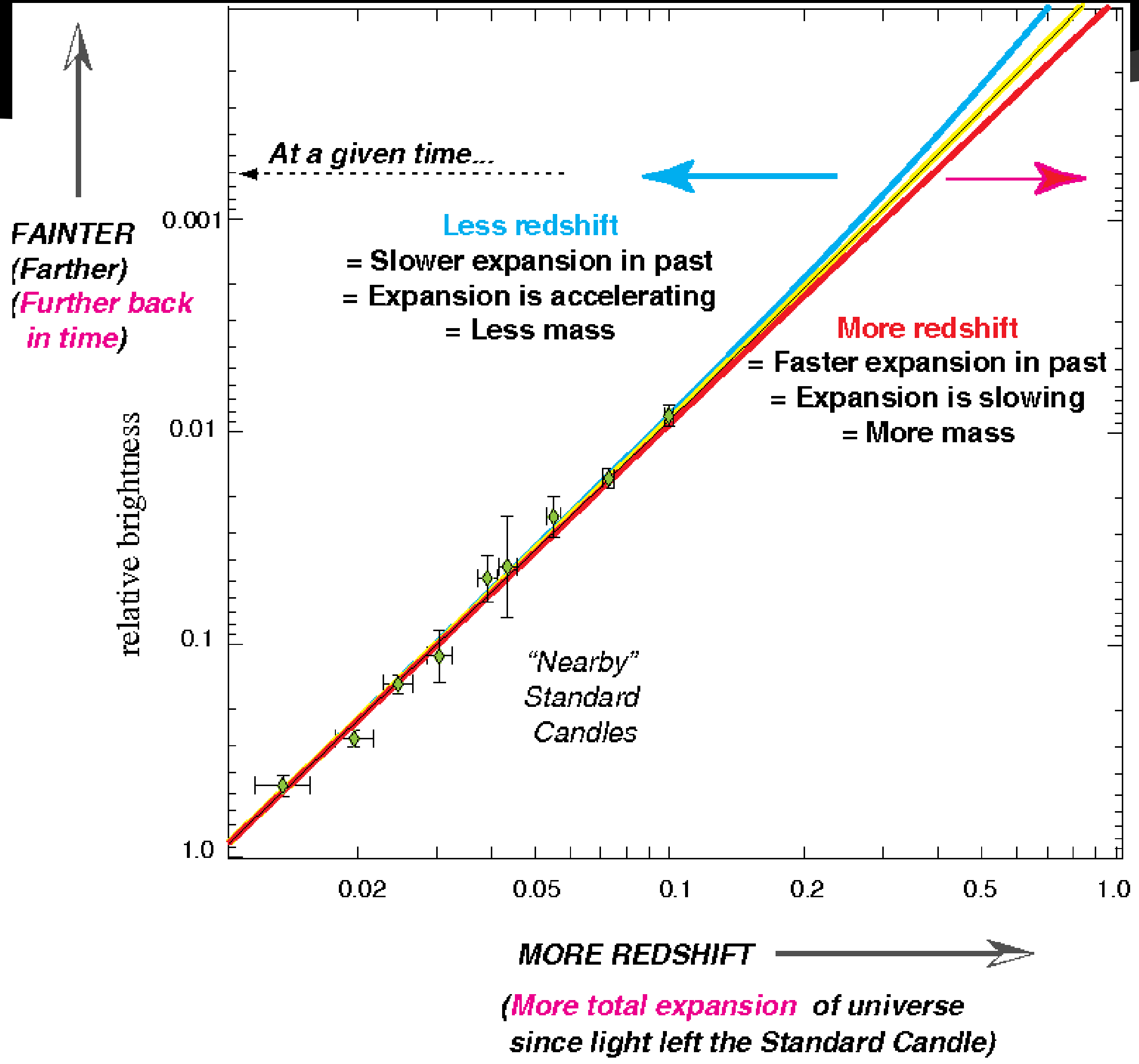
ABSTRACT

We propose a new model of dark energy inspired by Grand Unified Theories (GUT). We aim to decode the fundamental and classical problems of dark energy towards the search of nature of dark energy. These issues became less of attention now that tensions on the cosmological parameters are considered significant and more urgent to solve. We employ a non-canonical formalism to construct a non-canonical domain wall model of dark energy which is relevant to the existing constraints. We investigate the cosmic dynamics with such non-canonical domain walls and discover that the domain walls act as either dark energy or dark matter at different times. We obtain that the dark energy and dark matter behaviors of the non-canonical domain walls depend on the velocity v in the observer comoving frame. The velocities of the domain walls determine whether they are ordinary or phantom dark energy, or (at other times) hot or cold dark matter. We also find a single solution of the dynamics, in which for $v = 0$ (freezing non-canonical domain wall), can entering the phantom zone without having to experience ghost field instability, i.e., it has $w < -1$ without having to possess negative kinetic energy. These domain walls give rise to a late-time cosmic acceleration starting from $z \approx 0.8$ and result in $w_{dw} = -1.5$ with $w_{eff} = -1.03$ today. We also find that the equation of state (EoS) of non-canonical domain walls is independent of the potential form, since solitons globally have similar characteristics. In addition, we investigate the perturbation dynamics following the model. Using the best-fitting parameters of the ΛCDM model as input and assuming non-clustering domain wall, the power spectrum of dark matter decreased on the large scales, and the power spectrum of Cosmic Microwave Background (CMB) is shifted slightly to small l's. From our simulations, we obtain that the model we propose gives a smaller σ_8 compared to the ΛCDM model.

Requirement for dark energy

- SNe Ia observations (Riess et al., 1998 ; Perlmutter et al., 1999)
- Observations of cosmic microwave background (CMB), large scale structure (LSS), BAO, etc.
  - Baryonic matter and radiation only ~5% → ~26% dark matter (DM) & ~69% dark energy (DE) (see Planck Collaboration, 2016, 2019)



Perlmutter, 1999

Problems of Cosmological Constant

- Observation: $\rho_\Lambda \approx \frac{H_0^2 m_{pl}^2}{8\pi} \sim 10^{-47}\mathrm{GeV}^4$
- **Cosmological constant** $(w = -1 \ \rightarrow \mathrm{bestfit})$: theoretical prediction: $\rho_\Lambda \approx \frac{m_{pl}^4}{16\pi^2} \sim 10^{74}\mathrm{GeV}^4$ → fine tuning and coincidence problems
- Fine tuning? → low limit on effective field theory (Maziashvili, 2008)
- Coincidence? → antrophic principles, attractor solutions (see Amendola & Tsujikawa, 2010)
- **Slow-rolling canonical scalar field:** ex. **Quintessence** (Freezing, Thawing, Coupled, Assisted, etc.)
- **Non-canonical scalar field:** ex. **K-essence** (ordinary field, phantom field, string theory at low energy scale, Tachyon, etc.)

Cosmological parameters tensions: a possibility of new physics

- Significantly different result of H_0 and σ_8 measurement between Planck and direct measurements (Supernova Ia, galaxies/clusters survey, gravitational lensing, etc.)

New model of DE:

- Decaying dark energy to dark radiation (Pandey dkk., 2019)
- Modified Coupled quintessence (Baros, dkk., 2019)
- Early DE (Poulin dkk., 2019)
- Interacting dark energy to dark matter (Valentino dkk., 2017)
- Disappearing DE (Mortsell & Dawan, 2018)

Brightens dark energy: shop around GUT

- Sufficiently formal and well-motivated
- Topological defects (probably domain walls (DW) or kinks)
- Looking back in time:
  - $w_{DW} = -2/3$ (Kolb & Turner, 1990)
  - Fabris et al. (2000): effects of DW on structure formation
  - Friedland et al. (2003): Frustated DW
  - Volkas (2011): DW on Brane cosmology
  - Lazanu (2015): scaling solution of DW, CMB power spectra simulations
  - Peyravi (2017): spherical DW
- Challange: $w_{DW} \geq -2/3$ → cannot approach $w = -1$ (observations)

Non-canonical formalism for solitons

Lagrangian and field equation

- A simple non-canonical Lagrangian: $$L = \left(\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi\right)^n - V(\phi)$$

For $n = 2$:

- Equation of motion (EoM): $$\partial_\alpha \phi \partial^\alpha \phi \partial_\beta \partial^\beta \phi + 2 \partial^\alpha \phi \partial_\beta \partial_\alpha \phi \partial^\beta \phi + \partial_\phi V = 0$$
- Energy-momentum tensor:

$$T_{\alpha\beta} = g_{\alpha\beta} V + \partial_\alpha \phi \partial_\beta \phi \partial_\gamma \phi \partial^\gamma \phi - \frac{1}{4} g_{\alpha\beta} \partial_\gamma \phi \partial^\gamma \phi \partial_\delta \phi \partial^\delta \phi$$

Domain walls as a network of kinks

- Suppose a dense network of walls exist inside cosmic horizon
- It doesn't lose much energy from the time it was created till today
- It behaves like perfect fluid as good as isotropic field

$$\rho_{DW} = 4\langle V\rangle + \frac{3}{4}\langle\dot{\phi}^4\rangle - i\frac{3}{2}\left(\frac{4}{3}\right)^{1/2}\langle V^{1/2}\rangle\langle\dot{\phi}^2\rangle;$$

$$P_{DW} = -6a^2\langle V\rangle + \frac{1}{4}a^2\langle\dot{\phi}^4\rangle - i\frac{5}{2}\left(\frac{4}{3}\right)^{1/2}a^2\langle V^{1/2}\rangle\langle\dot{\phi}^2\rangle.$$

Lorentz invariant and phantom properties of DW

- Assume time-dependent of energy density and pressure are caused by Lorentz boost
- If observer's frame is $O(t, x, y, z)$ and DW frame is $D(t', x', y', z')$, hence the non-canonical kinetic term should be

$$\dot{\phi}^4 = -\frac{4}{3} v^4 V a^4$$

Unification of dark energy and dark matter

- Dark matter and dark energy: motivation for unification and its conceptual challange
- If $P_{DW} = w_{DW}\rho_{DW}$,

$$w_{DW}(a,v) = \frac{-6a^2 + \frac{10}{3}v^2a^4 - \frac{1}{3}v^4a^6}{4 + 2v^2a^2 - v^4a^4}$$

$$P_{DW} = -6\langle V\rangle a^2 + \frac{10}{3}\langle v^2\rangle\langle V\rangle a^4 - \frac{1}{3}\langle v^4\rangle\langle V\rangle a^6$$

$$\rho_{DW} = 4\langle V\rangle + 2\langle v^2\rangle\langle V\rangle a^2 - \langle v^4\rangle\langle V\rangle a^4,$$

- Non-relativistic domain walls ($v \ll 1$)
  - $a \ll 1 \rightarrow w_{DW} \approx 0$ and $a \approx 1 \rightarrow w_{DW} \approx -1.5$
- Relativistic domain walls ($v \approx 1$)
  - $a \ll 1 \rightarrow w_{DW} \approx 0$ and $a \approx 1 \rightarrow w_{DW} \approx -0{,}6$

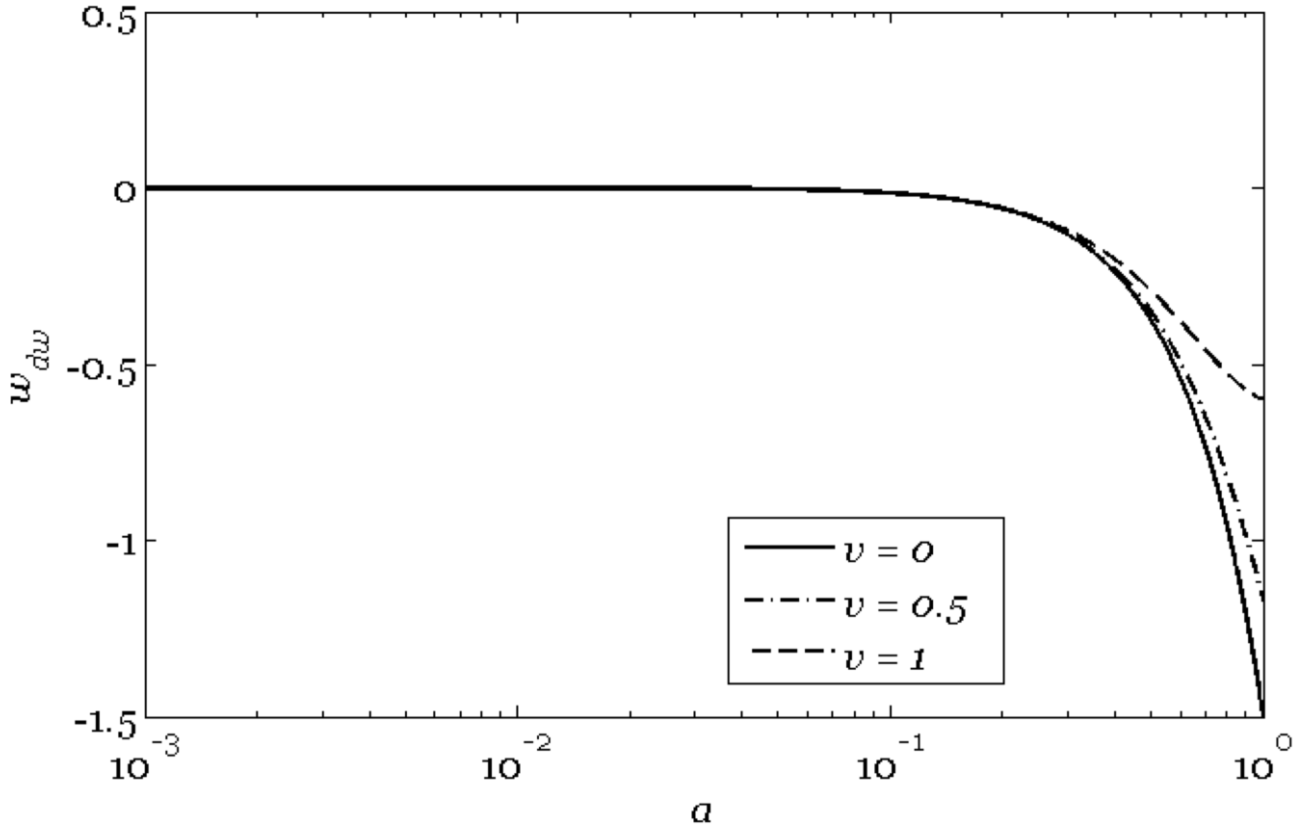
Phantom state and phantom zone

$v_{threshold}$ today: $0{,}605c$

TODAY:

- $v > v_{threshold}$ → $w_{DW} > -1$ (outside phantom zone), but $\dot{\phi}^4 < 0$ (inside phantom state)

- $v = 0$ → $w_{DW} = -1{,}5$ (inside phantom zone), but $\dot{\phi}^4 = 0$ (outside phantom state)



Stability

- Suppose a small perturbation, so that. $$\phi(t,x)=\phi_0(t,x)+\delta\phi(t,x)$$
- Perturbed Hamiltonian (see, Amendola & Tsujikawa, 2010):

$$\delta H=\left\{\partial_K L+2K\partial_K\left(\partial_K L\right)\right\}\frac{\left(\partial_t\delta\phi\right)^2}{2}+\partial_K L\frac{1}{2}g^{\mu\nu}\partial_\mu\delta\phi\partial_\nu\delta\phi-\partial_\phi\left(\partial_\phi L\right)\frac{\left(\delta\phi\right)^2}{2}$$

- It is stable for:

$$\xi_1\equiv\partial_K L+2K\partial_K\left(\partial_K L\right)\geq 0,$$
$$\xi_2\equiv\partial_K L\geq 0$$
$$\xi_3\equiv-\partial_\phi\left(\partial_\phi L\right)\geq 0$$

- Classical stability:

$$c_s^2\equiv\frac{\partial_K L}{\partial_K L+2K\partial_K\left(\partial_K L\right)}>0.$$

- Causality principle: $c_s^2<1$

Stability

This case:

- Hamiltonian:
  - Kinetic term: $\xi_1 = 6K \geq 0$ dan $\xi_2 = 2K \geq 0$, hanya dipenuhi oleh $v = 0$
  - Potensial term: $\xi_3 = -\partial_\phi\left(-\frac{\partial V(\phi)}{\partial\phi}\right) = \frac{\partial^2 V(\phi)}{\partial\phi^2} \geq 0$
- Classical dynamics: $c_s^2 = \frac{1}{3} > 0$, true for all v
- Causality: $c_s^2 < 1$ true for all v

Cosmic dynamics

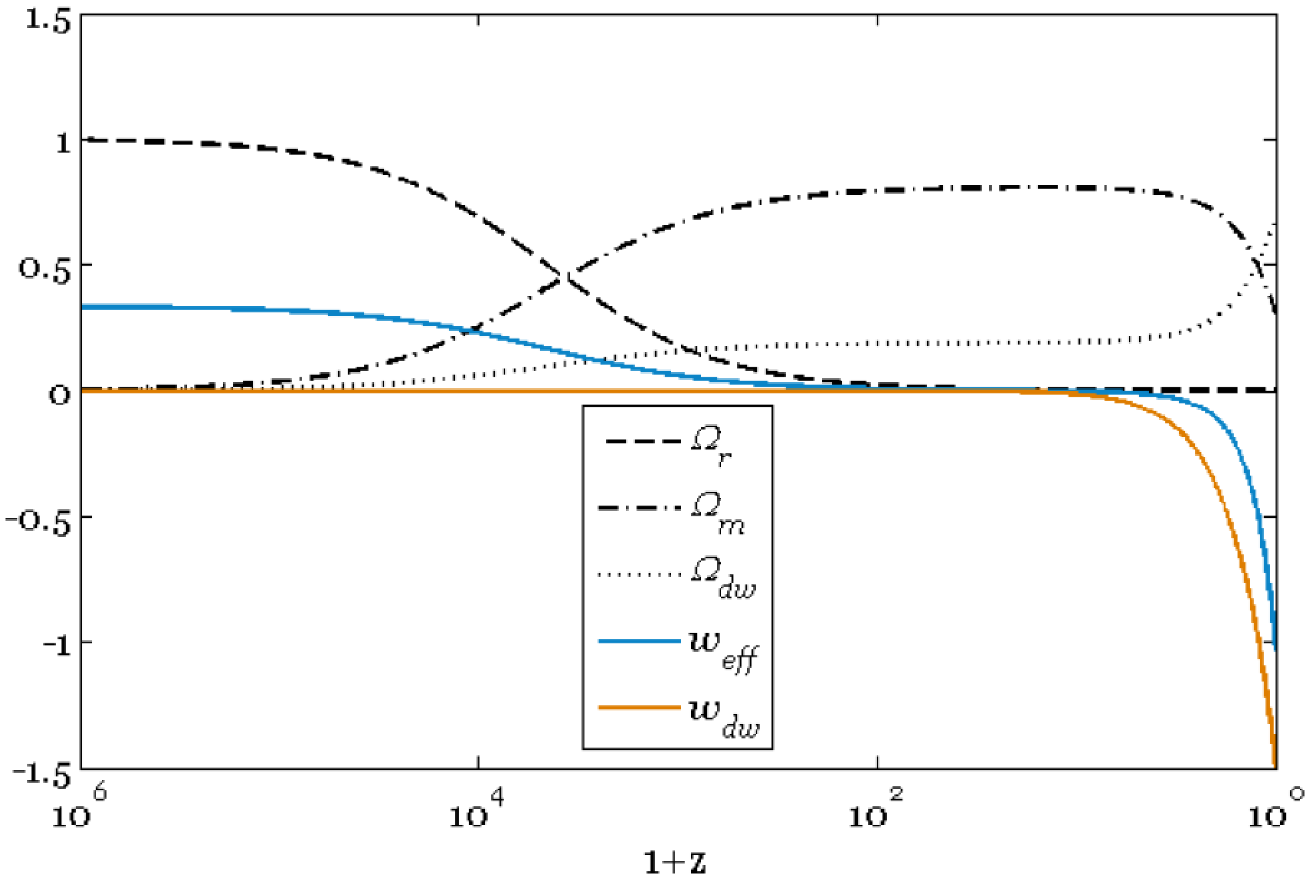
- Suppose a flat universe contains matter, radiation, and freezing domain walls
- Set of cosmic dynamics equations:

$$H^2 = \frac{8\pi G}{3}\rho_T; \quad \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho_T + 3P_T\right); \quad \dot{\rho}_X + 3H\left(\rho_X + P_X\right) = 0;$$

- Globally all constituents evolve independently

Cosmic evolution

- Input: $\Omega_{m,0} = 0.31$ (Planck Collaboration, 2019) and $\Omega_{r,0} = 8{,}4 \times 10^{-5}$ (see Ryden, 2017)
- $z_{mDW} \approx 0.24$ ($a_{mDW} \approx 0.8$). $a_{m\Lambda} \approx 0.75$
- $w_{DW}(a_0) \approx -1.5$
- $w_{eff}(a_0) \approx -1.03$



Summary

- The EoS of non-canonical domain walls depends on its velocity measured by the observer
- For all allowed values, non-canonical domain walls might become a candidate for the unifying dark energy and dark matter
- Domain walls with a velocity greater than v_{ph} behave like an ordinary scalar field with $w_{dw} > -1$, and domain walls with $v < v_{ph}$ at the late time possess phantom field properties with $w_{dw} < -1$
- Domain walls as dark energy generate late-time cosmic acceleration precisely starting from $z_{mdw} \approx 0.24$, which is slightly later than that of the cosmological constant