Title: Some alternative unifying views on dark matter and dark energy

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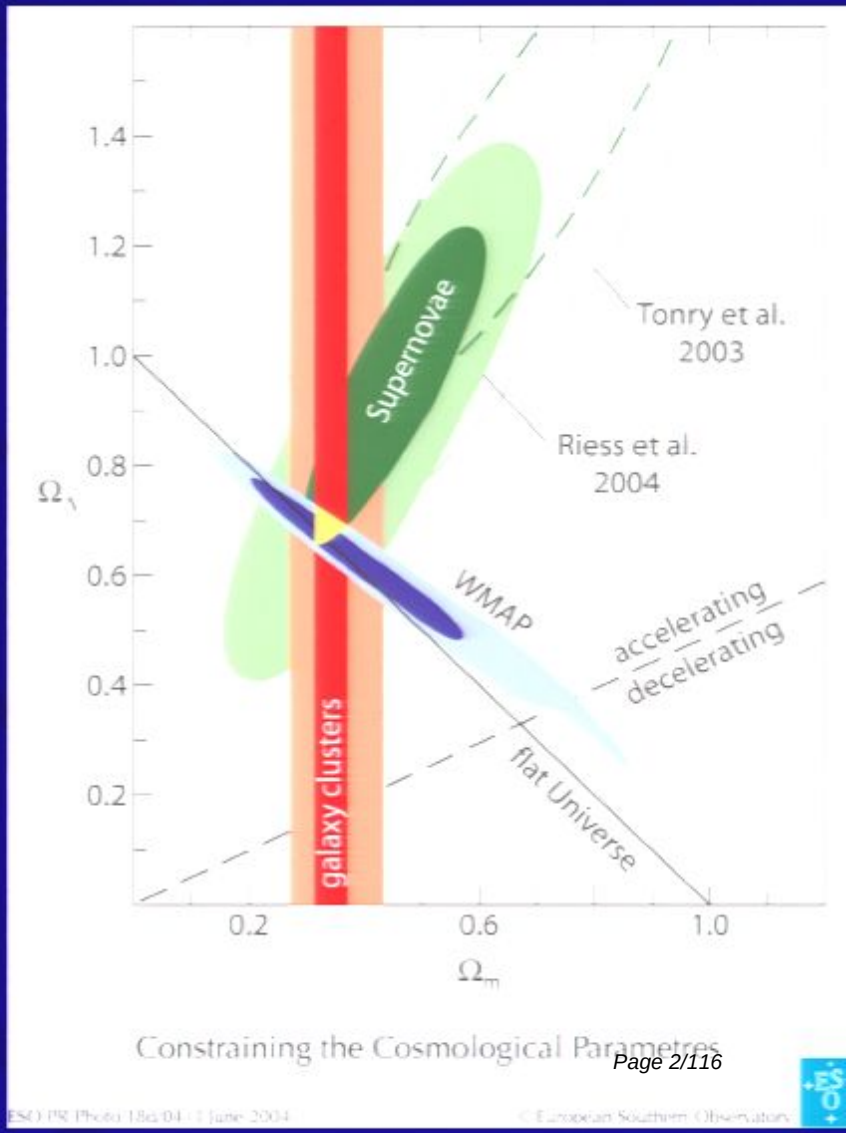
Abstract:

Alternative Unifying Approaches to Dark Matter and Dark Energy:

Grant J. Mathews
Center for Astrophysics
University of Notre Dame

Big Bang Nucleosynthesis and Particle Physics Workshop
Perimeter Institute
May 30-June 1, 2008



Alternative Views: Dark Matter produces Dark Energy

- Unified Dark Matter
- Chaplygin gas
- Brane-world /Inflowing Dark Matter
- Viscous/Decaying Dark Matter Relativistic
- Corrections to Friedmann Cosmology

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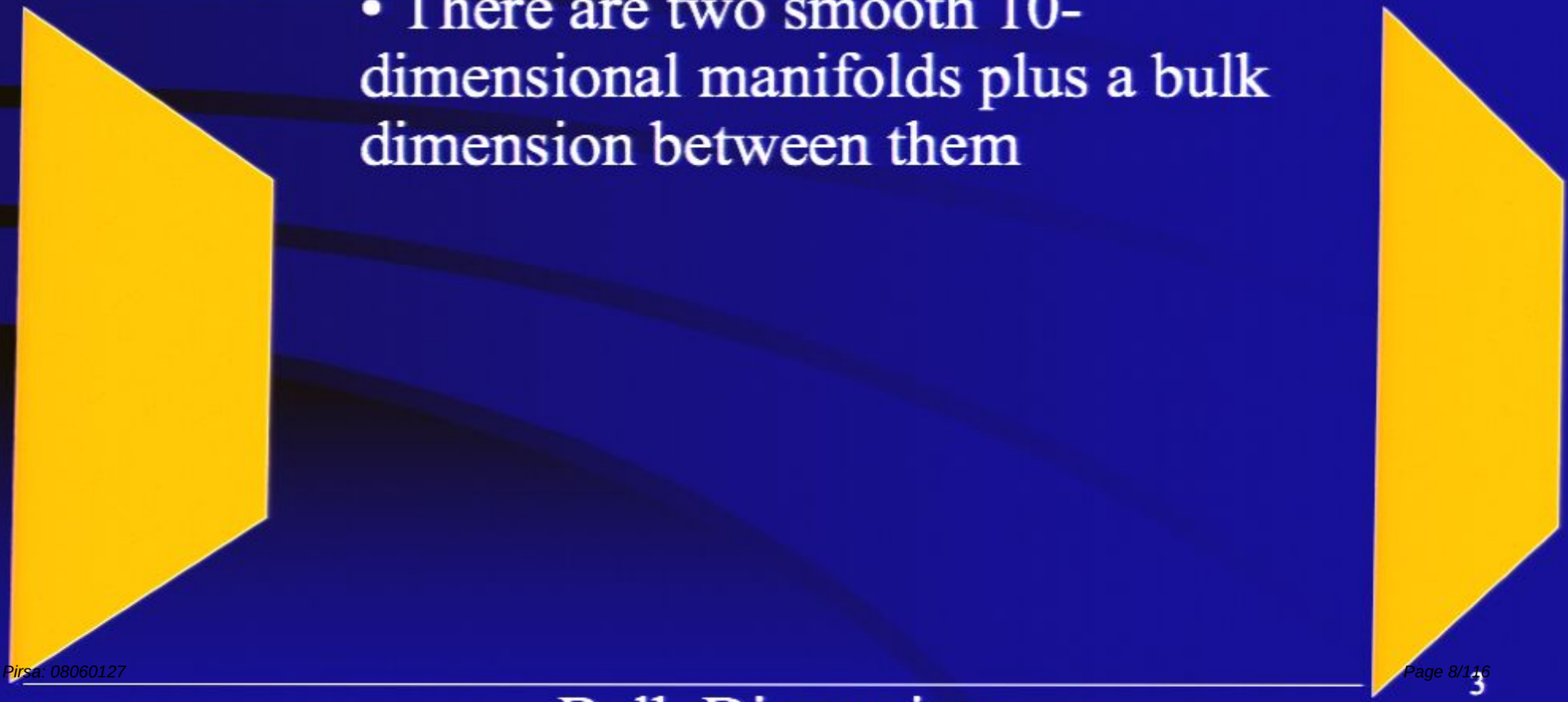
- There are two smooth 10-dimensional manifolds plus a bulk dimension between them



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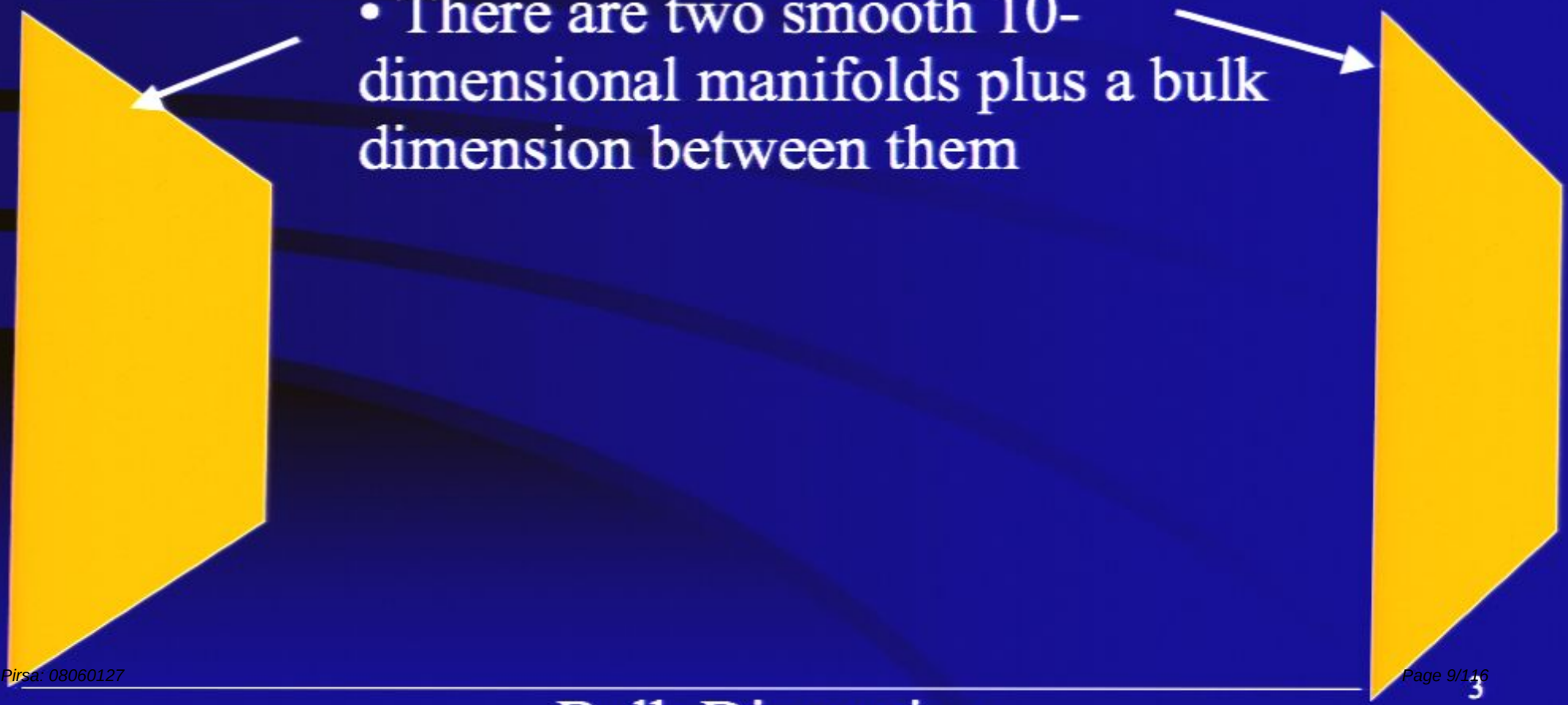

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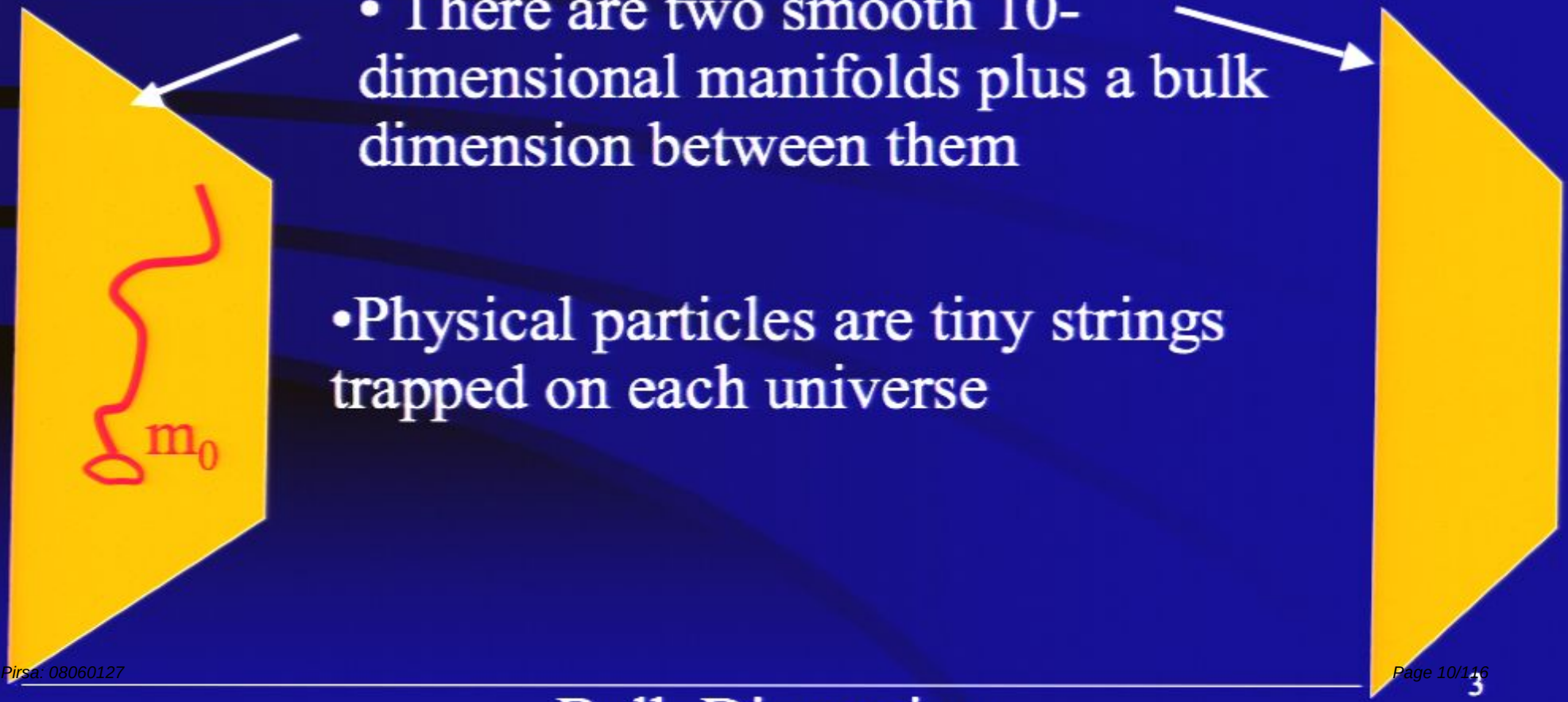

BBN in five Dimensional Gravity

- $G_{AB} = \kappa_5^2 T_{AB}$, $\kappa_5^2 = 1/2M_5^3$, $A,B = (0,1,2,3,5)$
- $ds^2 = e^{\{-2\mathbf{k}|z|\}} \eta_{\mu\nu} dx^\mu dx^\nu - dz^2$
- $T^A{}_B\,(brane) = (\delta(z)/b)\,diag(-\tau-\rho, -\tau+p, -\tau+p, -\tau+p, 0)$
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- Leads to a new Friedmann equation for cosmic expansion

$$H^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2} + \frac{\Lambda_4}{3} + \frac{\kappa_5^4}{36}\rho^2 + \frac{C}{a^4}$$

$G_N = \kappa_5^2\,\tau^2/48\pi$, $\Lambda_4 = \kappa_5^4\,\tau^2/12 + 3\,\Lambda_5/4$

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Dark Radiation

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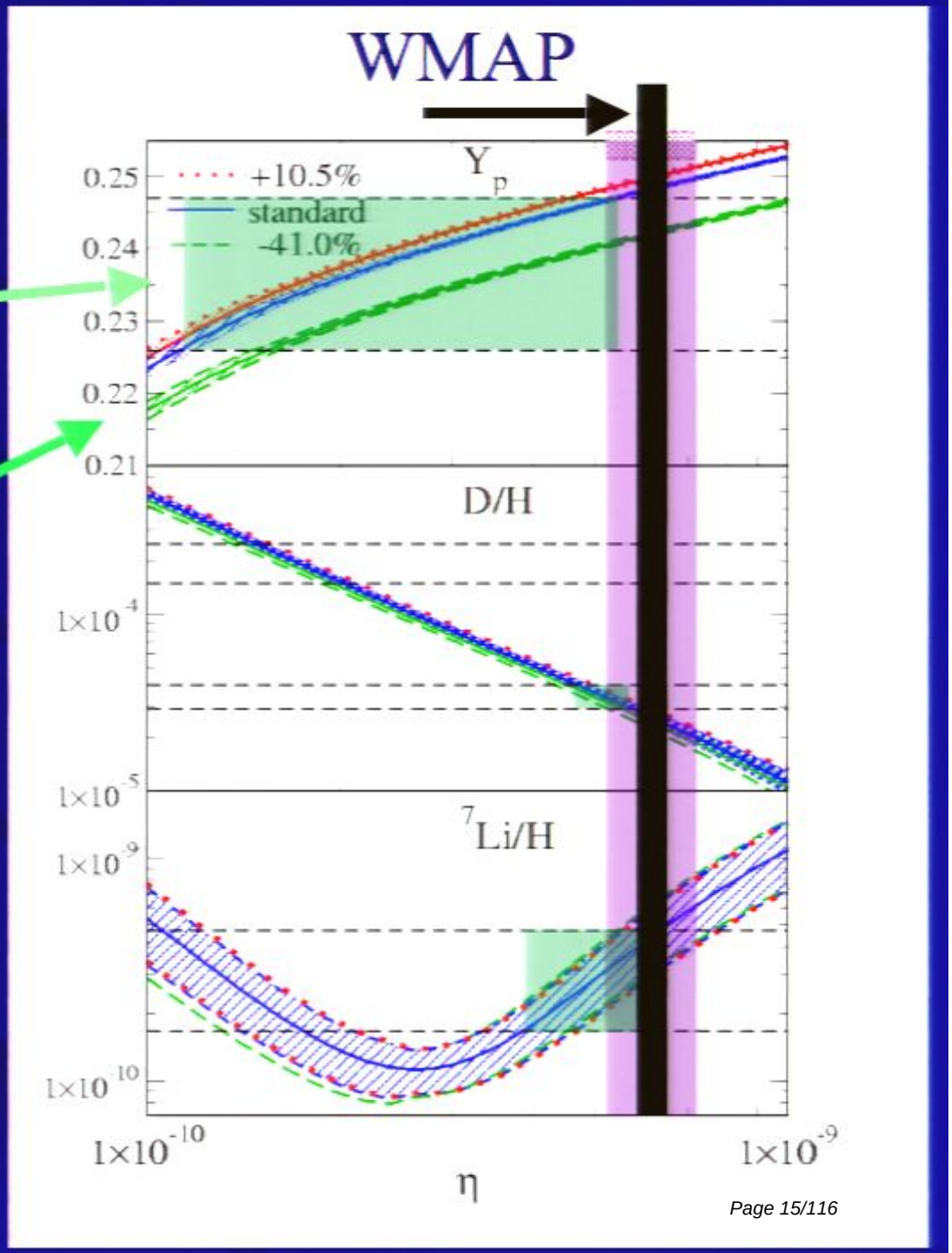
Standard BBN

Dark Radiation relaxes the tension between the CMB and ^{4}He limits on the baryon/photon ratio



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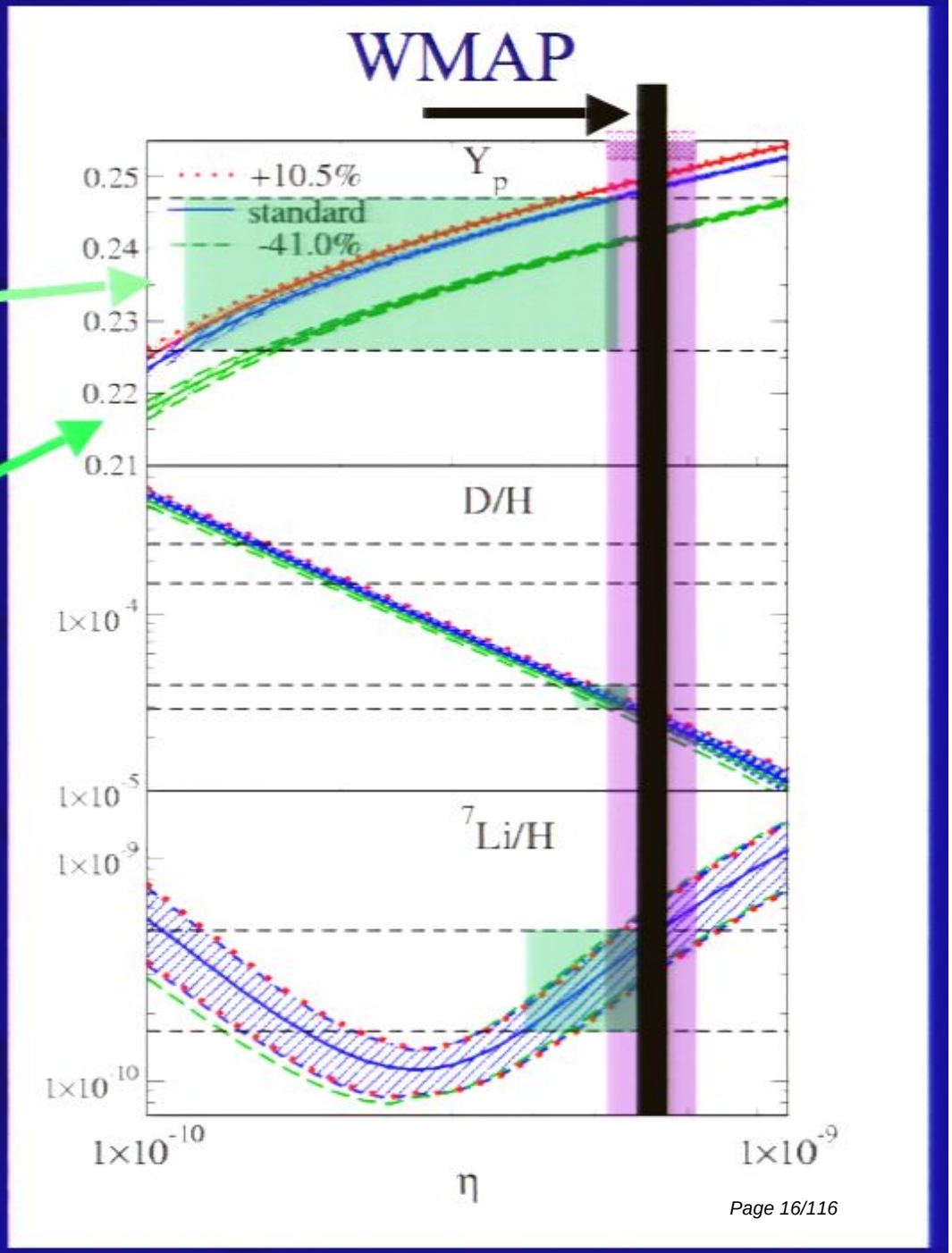
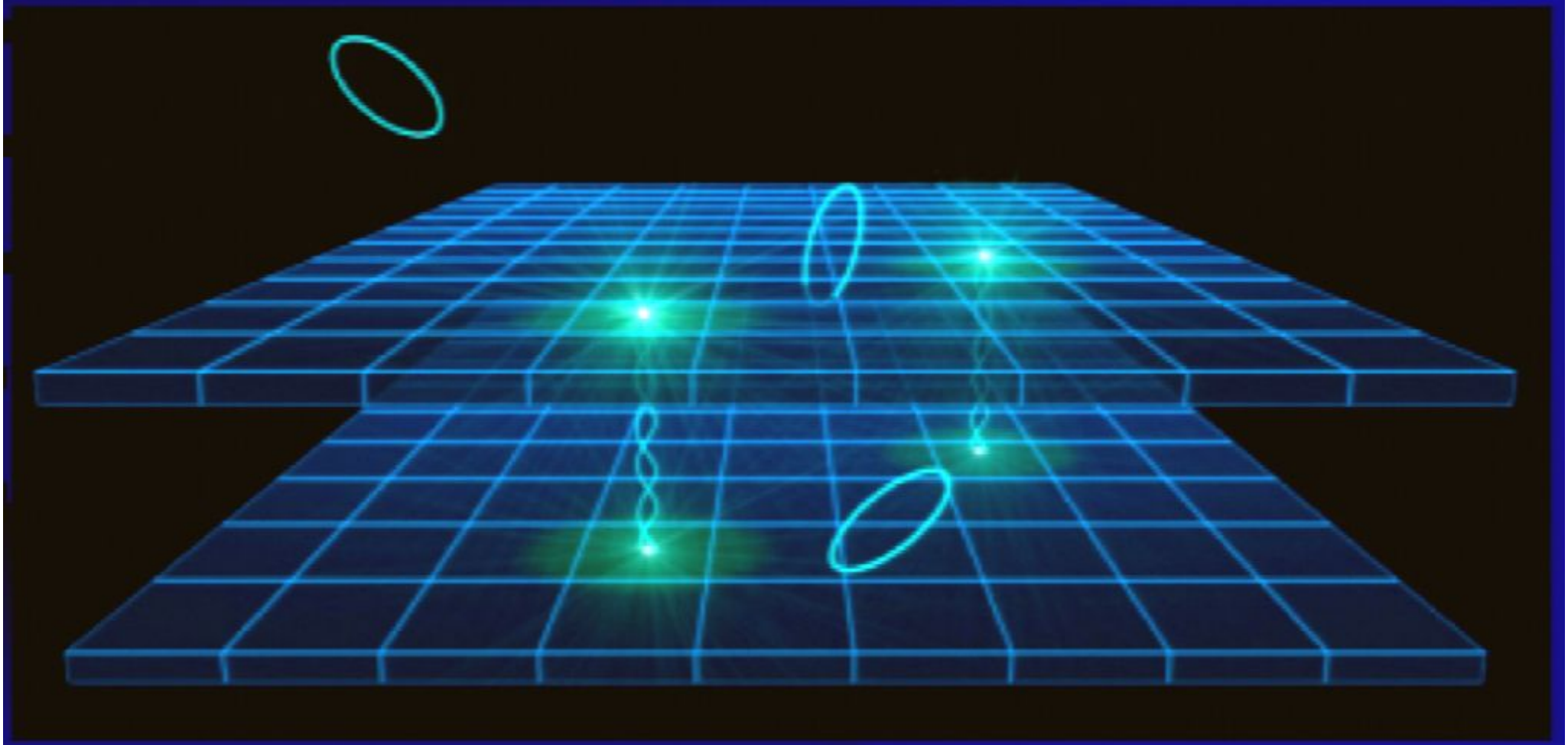


Matter might reside in the bulk dimension



Inflowing Dark Matter

Dark energy caused by inflow from a higher dimension

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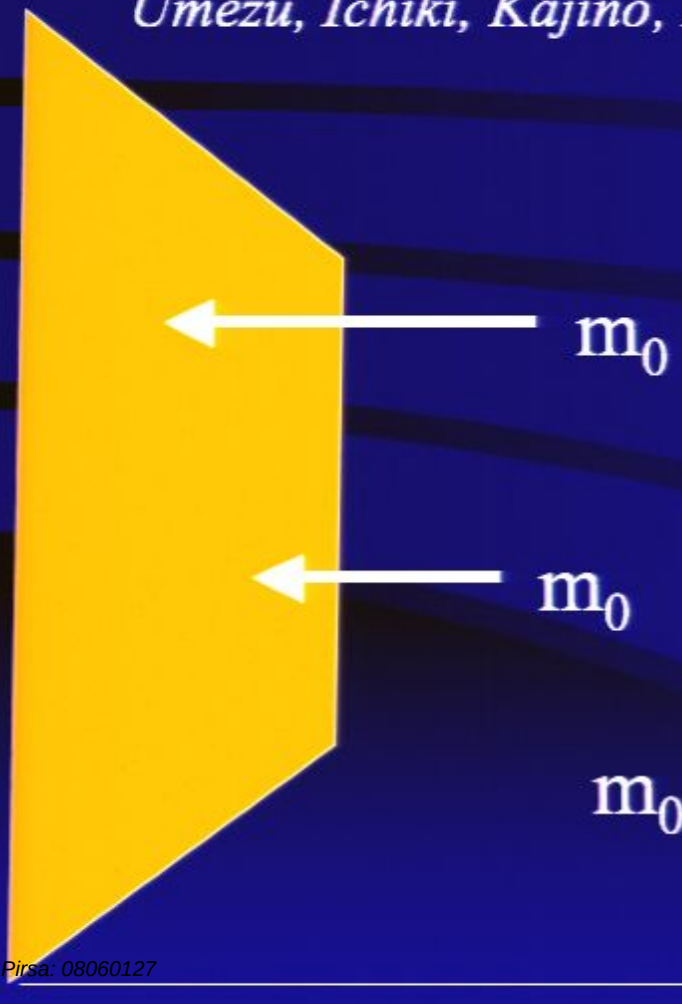

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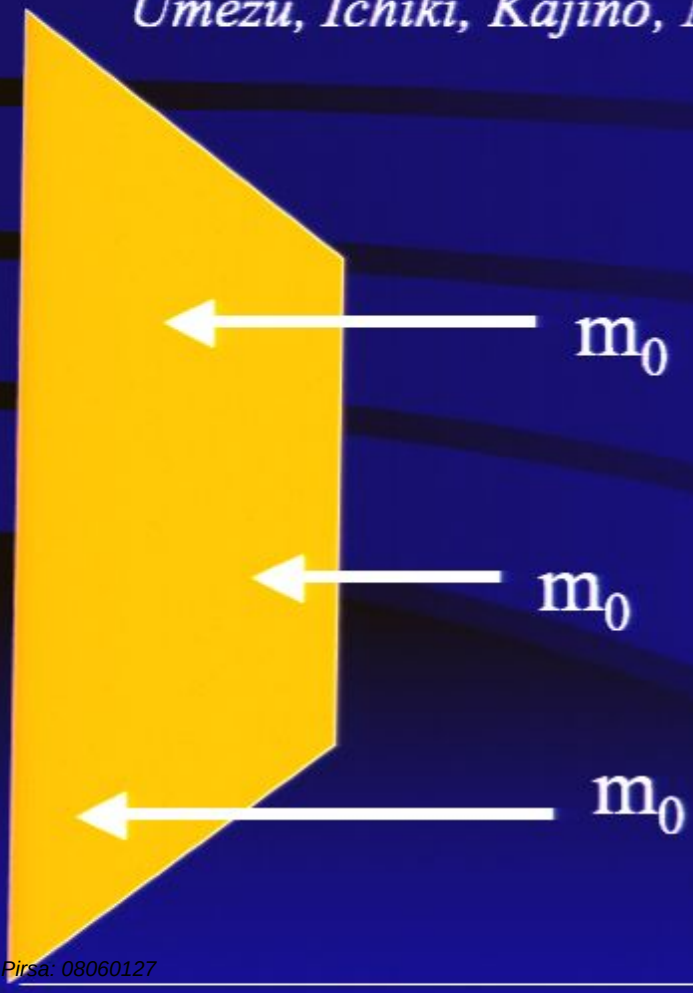

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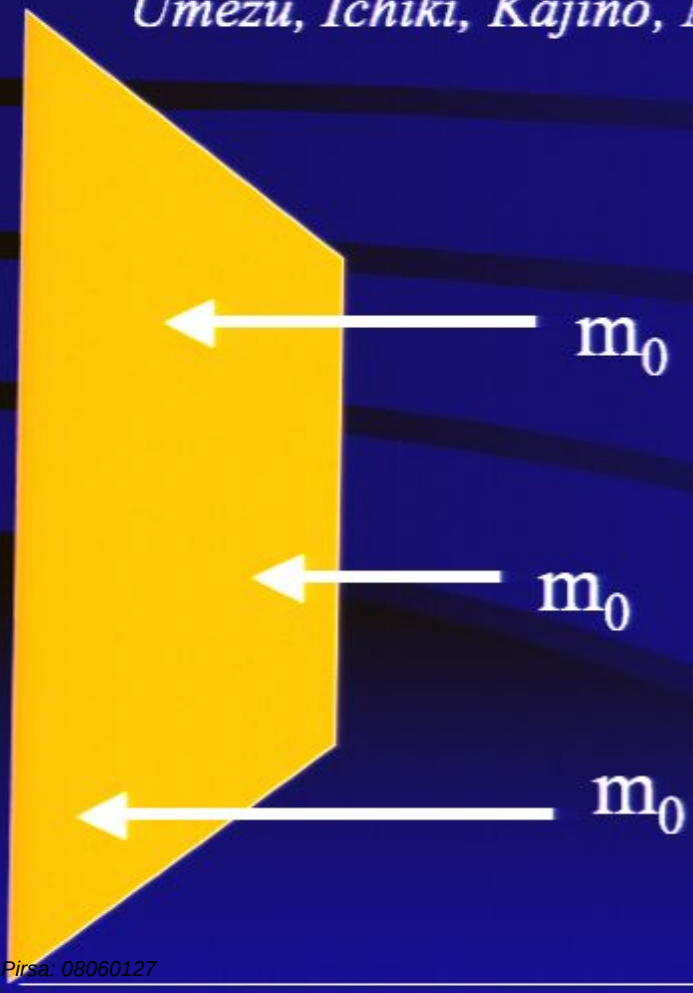

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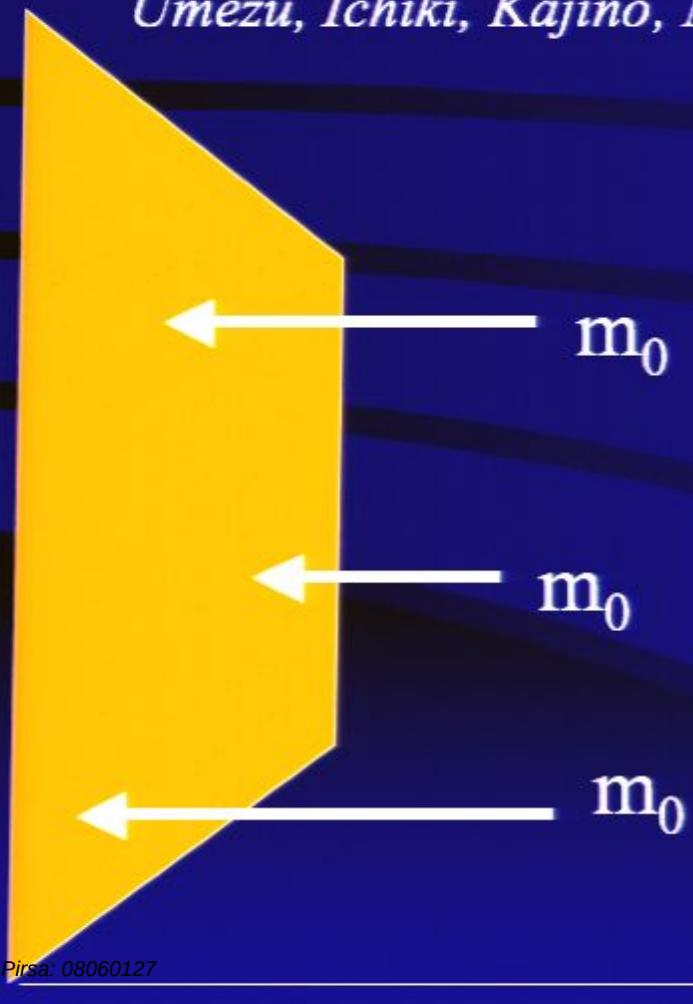

- The flow of matter into the 3-brane will appear as spontaneous matter creation

- Solution fixed point provides a constant energy density as the universe expands

Transfer from/to the Bulk leads to Modified Cosmic Expansion

$$H^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2} + \frac{\Lambda_4}{3} + \frac{\kappa_5^4}{36}\rho^2 + E$$

$$\rho = \rho_M + \rho_R + \rho_{DM}$$

$$\frac{\dot{\rho}}{\rho} + 3(1+w) = -2T^0{}_5$$

$$\frac{dE}{dt} + 4HE = \frac{\kappa_5^4 \tau}{9} T_0^5$$

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- E = "Dark Radiation" or Electric part of the bulk Weyl tensor

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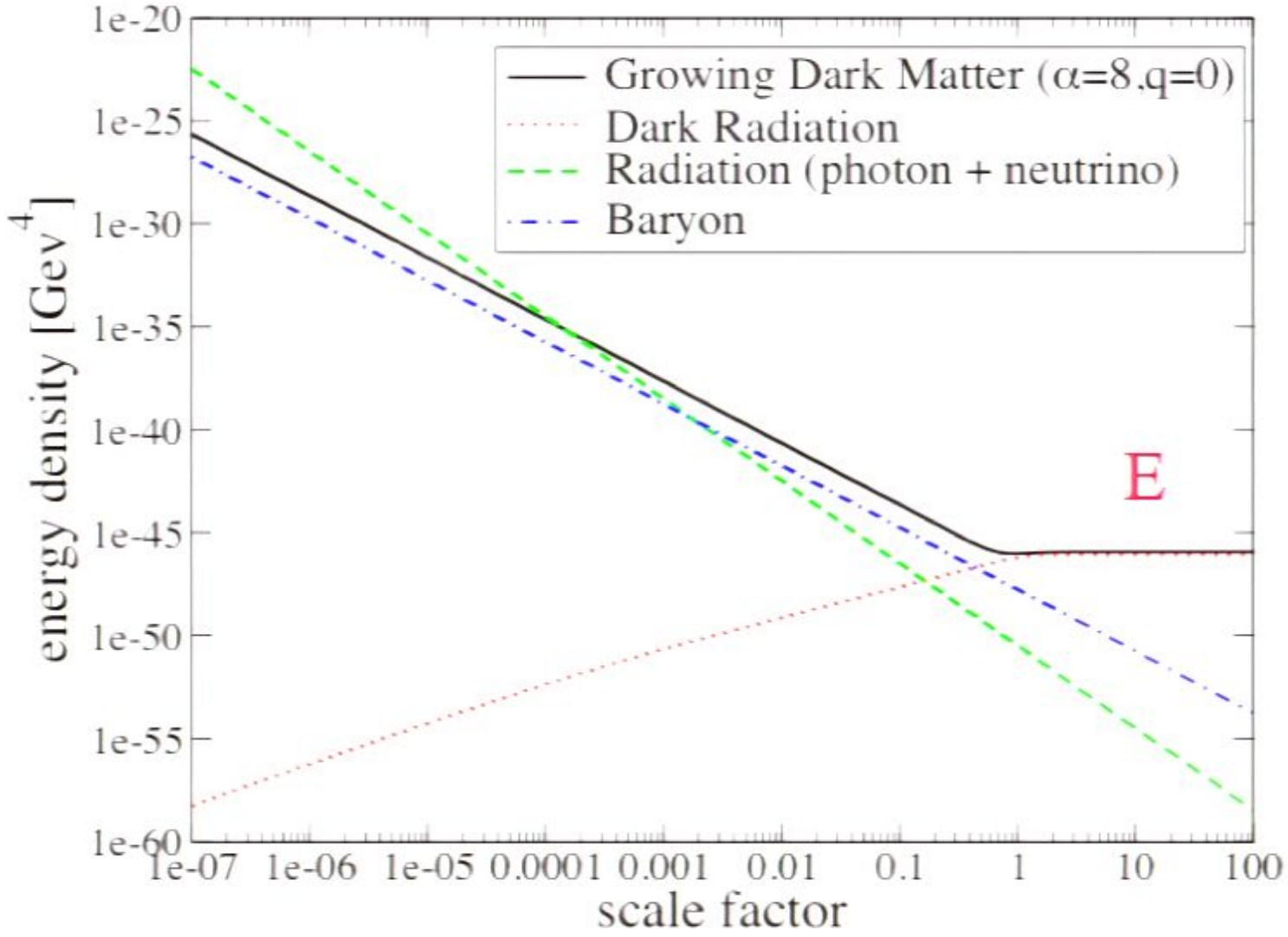
Accelerating Cosmology



Exchange between bulk and brane

Static bulk

Exchange between bulk and brane

$$T^0{}_5 = (\rho_{Bulk} + p_{Bulk})\, U_5$$

$$U_5 = -l\, H$$

Static bulk

Parametrize EOS of Matter in the Bulk

- $T_0^5 = (\alpha H/2)(\rho / a^q)$
- q = 4 Relativistic matter
- q = 3 Normal matter
- q = 1 Strings
- q = 0 Dark energy

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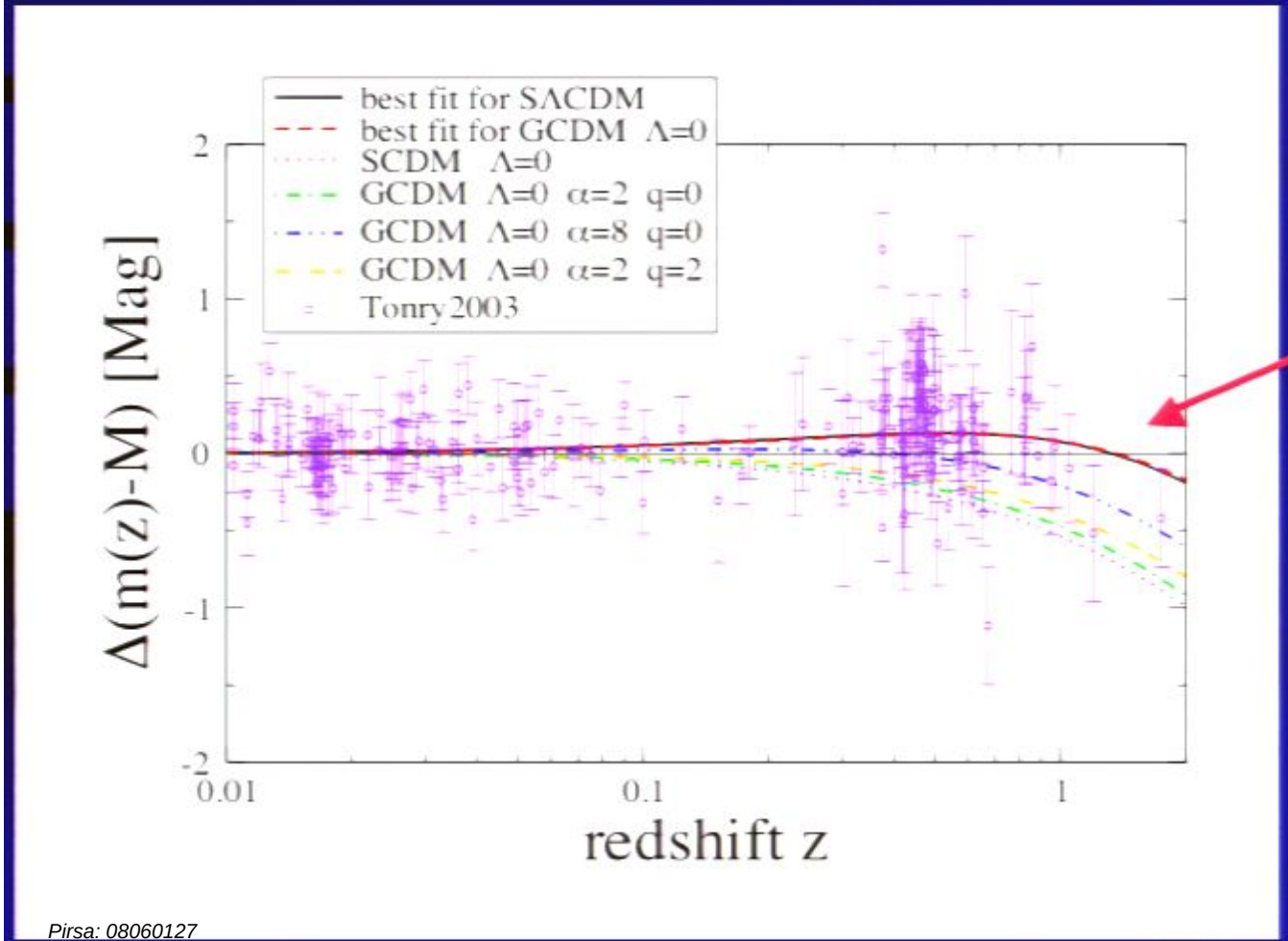
$\Omega_{DM} = 3.1$, $\Lambda = 0$

Inflowing Dark Matter Cosmology
Umezu, et al. (2006)

$T^0{}_5 = (\rho_{DM} + p)\, U_5 \;\; ; U_5 = -l\, H$

Supernovae

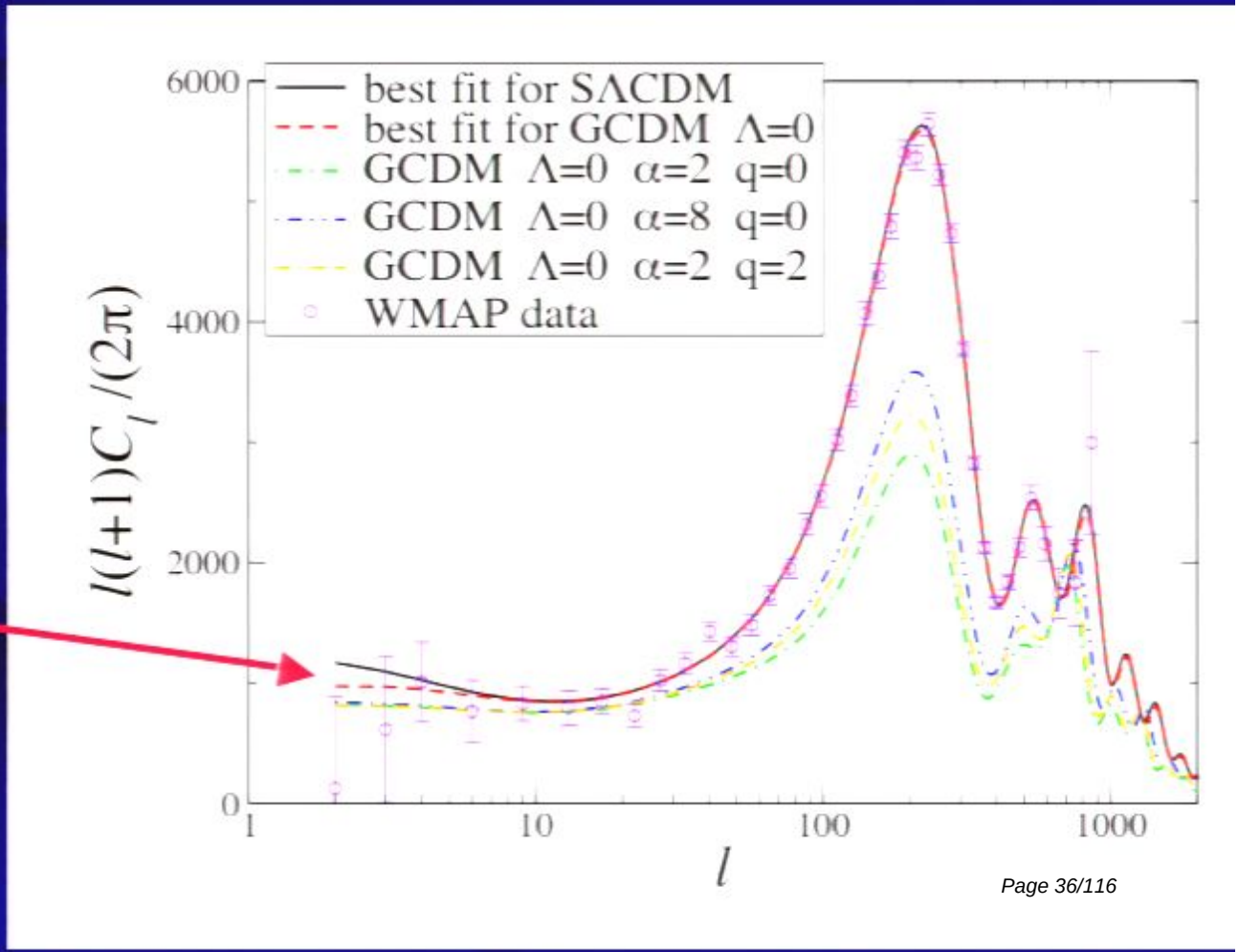


Supernovae are Fit with Λ=0

CMB Power Spectrum

Growing Dark Matter Cosmology
Umezu, et al. (2006)

Explains the diminished power for the lowest multipoles in the CMB fluctuations



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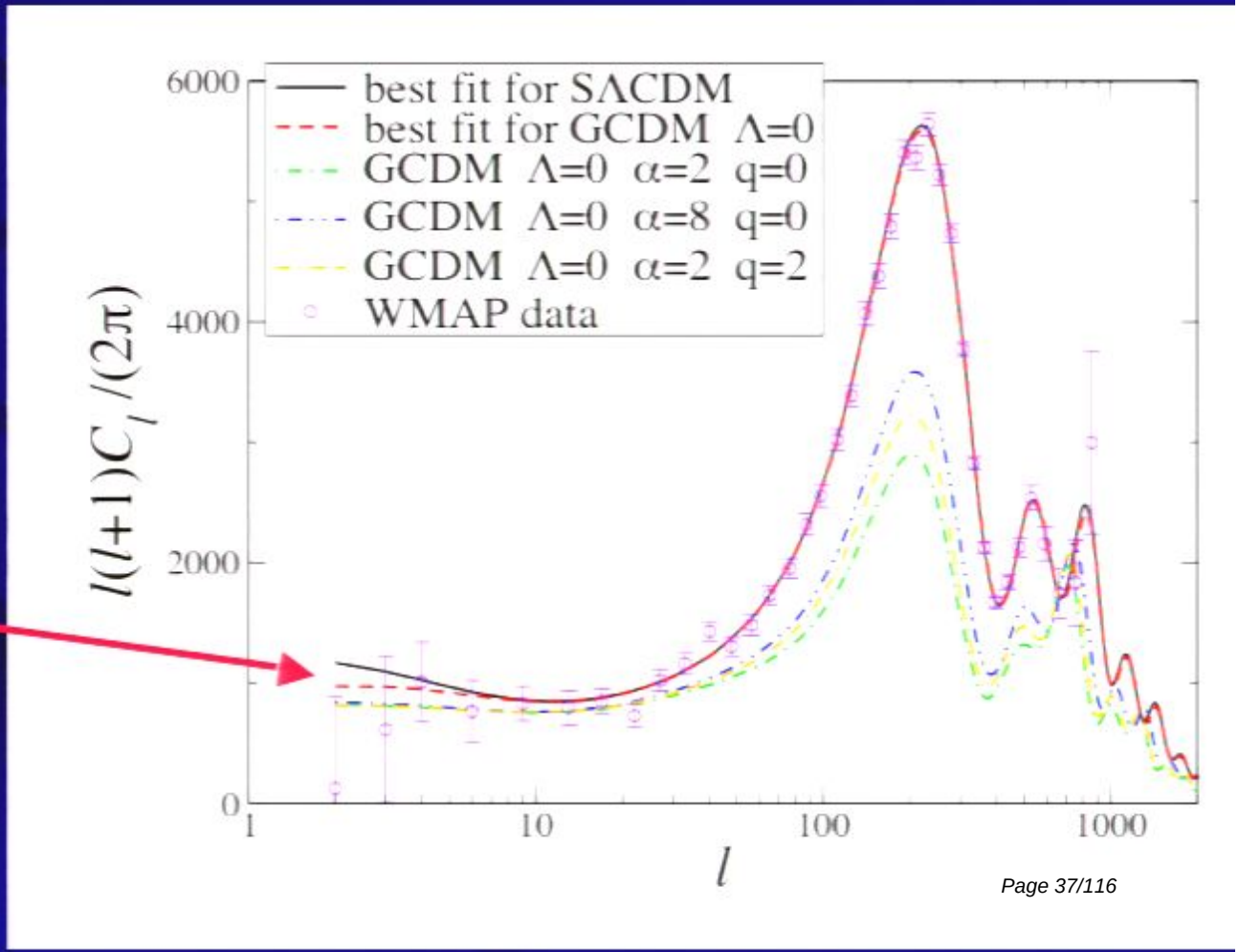
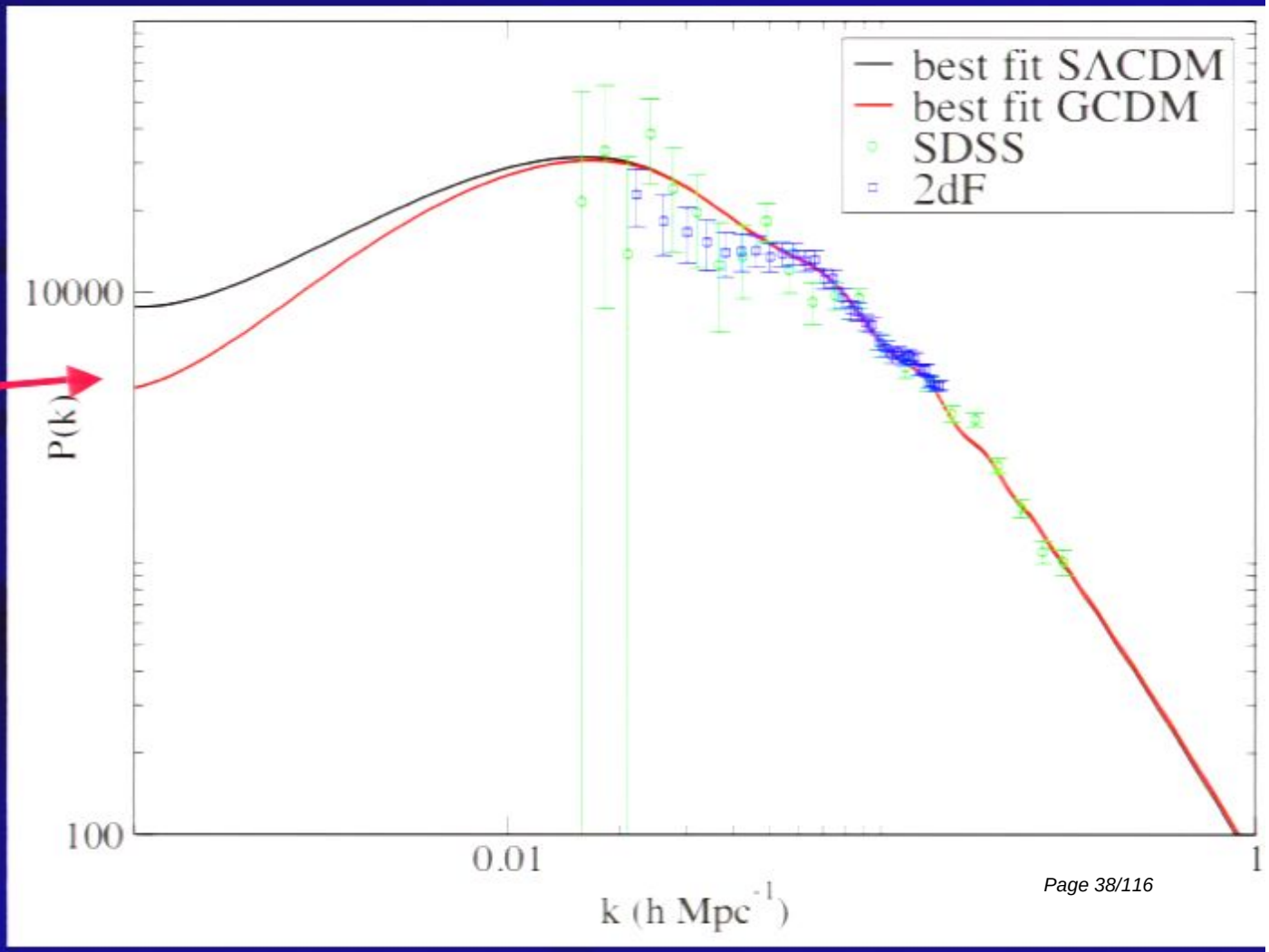


Matter Power Spectrum

Less power on the scales near the horizon



How to determine whether dark matter is flowing in from another dimension?

1. There should be an excess density of the dark matter particles compared to a standard cosmology
2. There should be diminished power for the largest structures near the scale of the horizon

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Bulk Viscosity and Decaying Dark Matter

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N. Q. Lan - Hanoi Univ. Ed.

PRD (2008); astro-ph/0801.0853

J. R. Wilson - LLNL, G. M. Fuller - UC San Diego

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1. Decaying dark matter leads to dissipative bulk viscosity in the cosmic fluid

2. This viscosity may account for some or all of the apparent cosmic acceleration

Viscous Dark Matter

Weinberg (1971)

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$$T^{\mu\nu} = (\rho + p)U^{\mu}U_{\nu} + g^{\mu\nu}p + \Delta T^{\mu\nu}$$

Viscous Dark Matter

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Bulk Viscosity

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Bulk Viscosity

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Viscous Dark Matter

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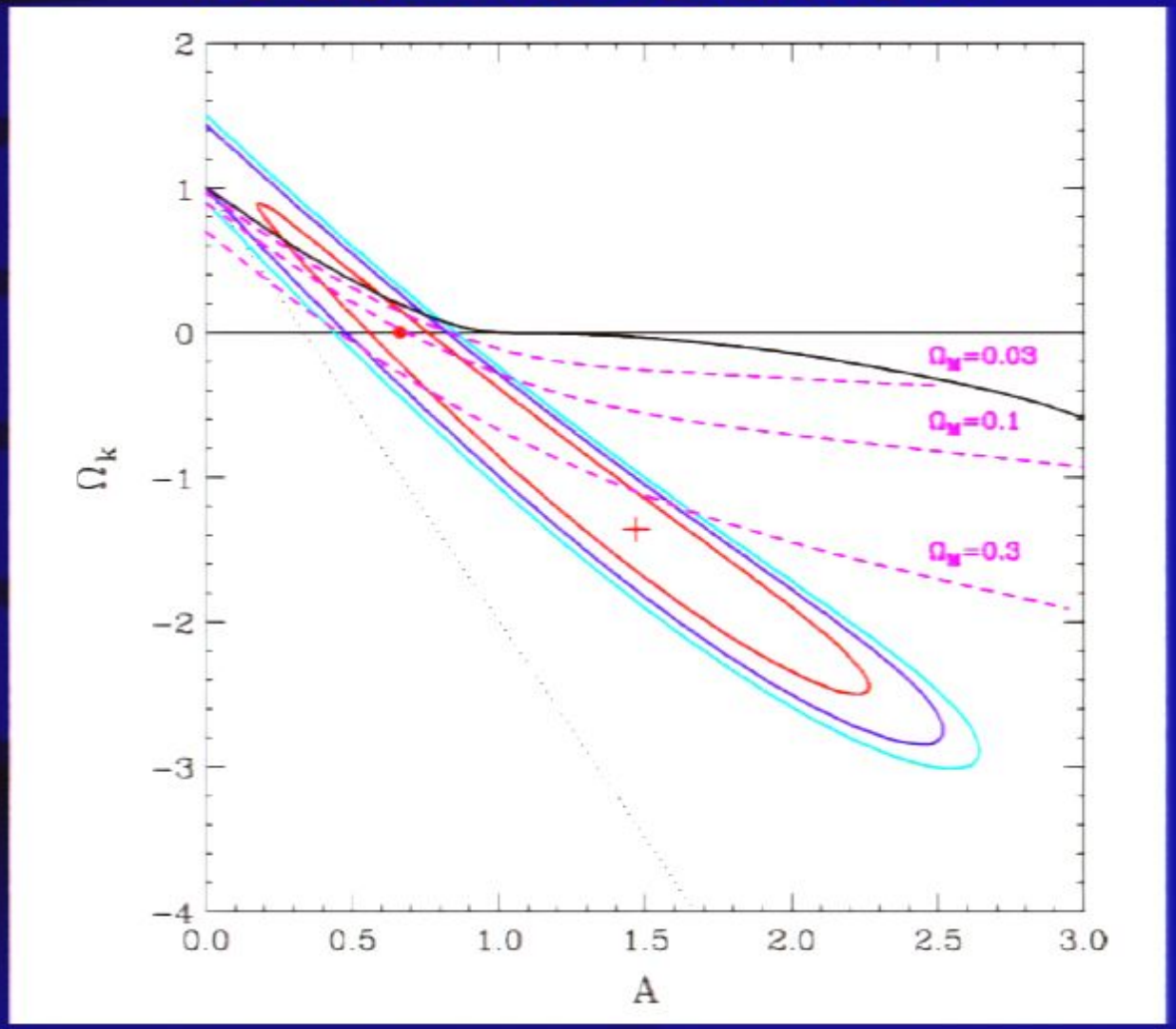
$$p_{eff} = p - \zeta 3\frac{\dot{a}}{a}$$

Negative pressure
=> Dark Energy

Bulk Viscosity can fit the SNIa redshift relation

Fabris et al. 2005 astro-ph/0503362



$A = 8\pi G\, \zeta / H_0$

Need a Physical Model for Bulk Viscosity

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If a gas is out of pressure equilibrium as it expands or contracts a bulk viscosity is generated

$$\zeta 3\frac{\dot{a}}{a} = \Delta p$$

Particle decay

Particle decay

Pressureless DM → relativistic particles $P = \rho/3$

→ Out of temperature and pressure equilibrium

→ Dissipation & Bulk Viscosity

During decay, matter and relativistic particles are out of pressure and temperature equilibrium

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$$\zeta = 3\,\rho_h \tau_{eq}[(1/3) - (\partial P/\partial \rho]$$

Weinberg (1971)

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$P = (\rho_l + \rho_\gamma)/3$

$\rho = \rho_{DM} + \rho_b + \rho_h + \rho_\gamma + \rho_l$

Candidates for Decaying Dark Matter

sneutrino $\tilde{\nu} \rightarrow \tilde{g}+\nu_e$

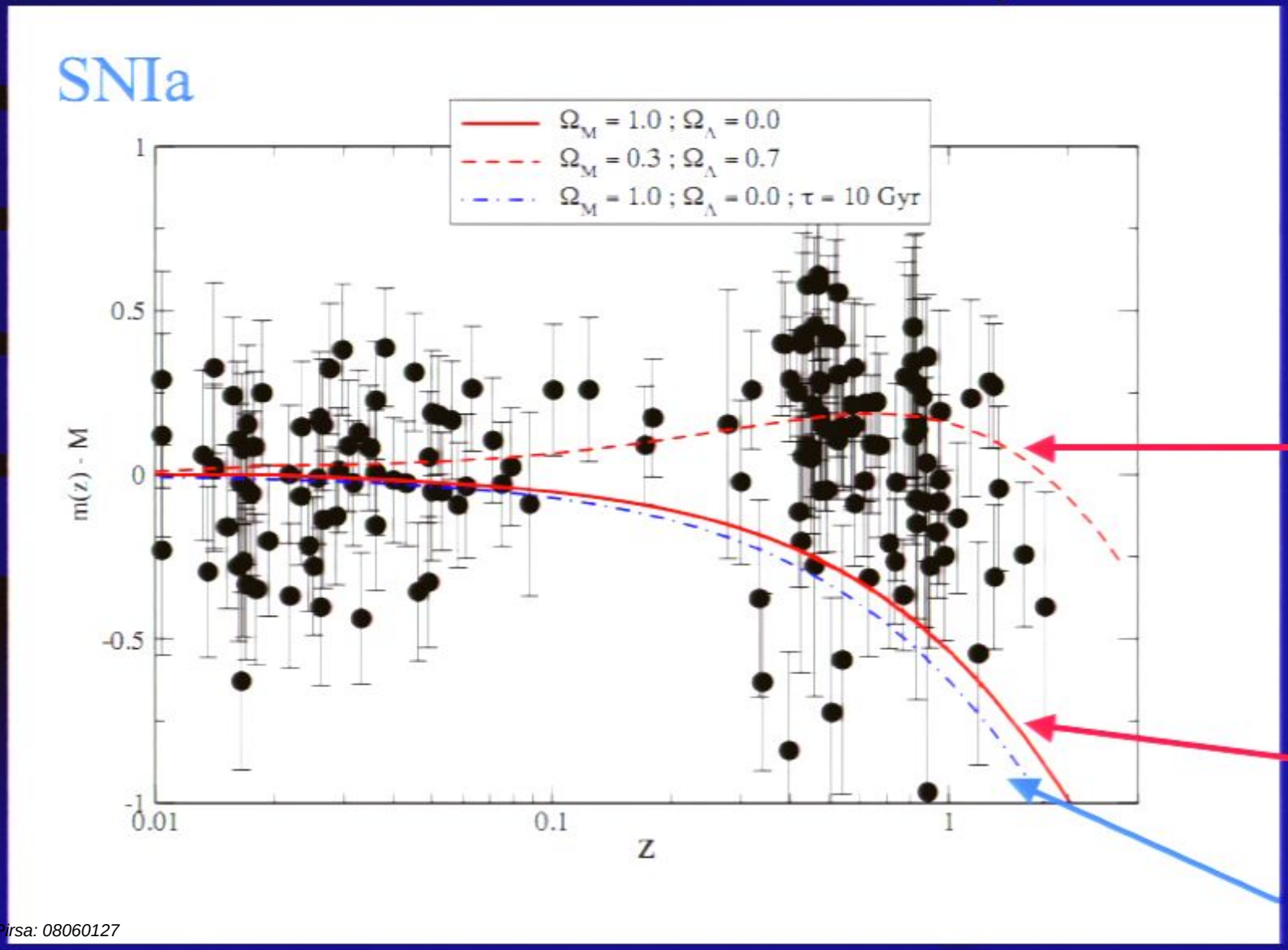
Gauge mediated supersymmetry breaking

$\tilde{\phi} \rightarrow \nu_R + \nu_R$

Decaying massive sterile neutrino

$\nu_S \rightarrow \nu_e$

Particle decay

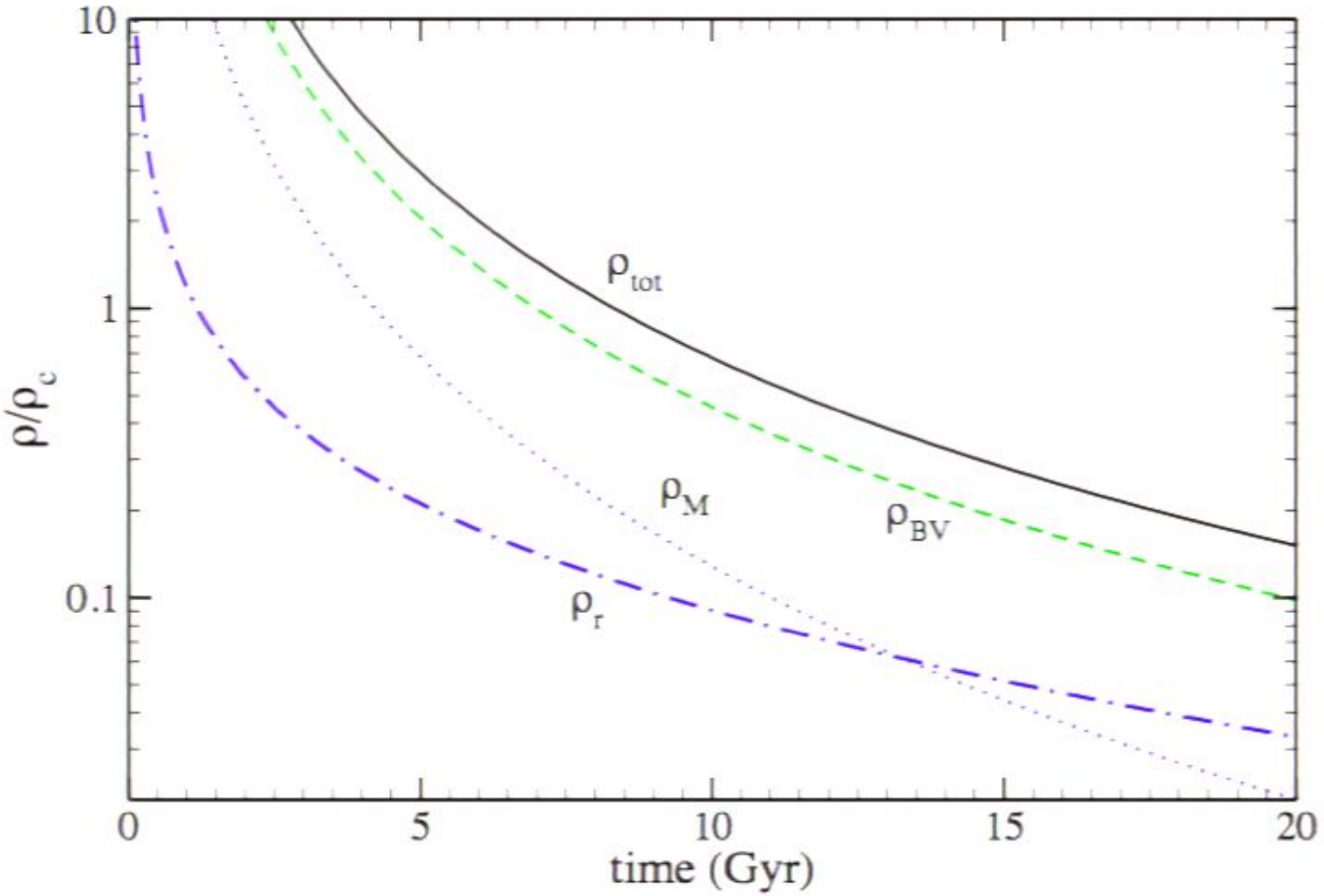


ΛCDM

$\Omega_M = 1.0$

BV $\tau = 10$

Why this does not work



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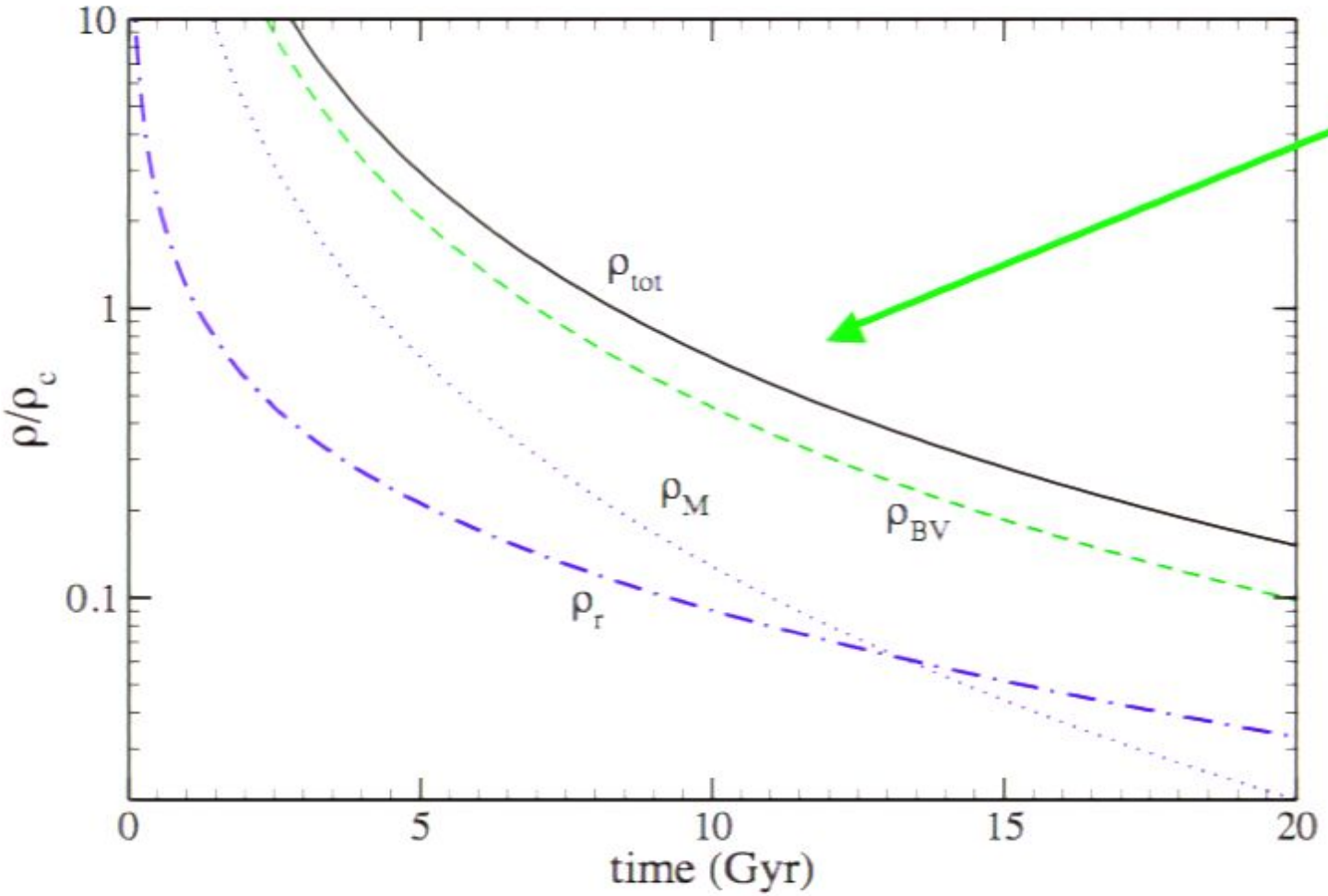

ρ_{tot} falls off too rapidly with time

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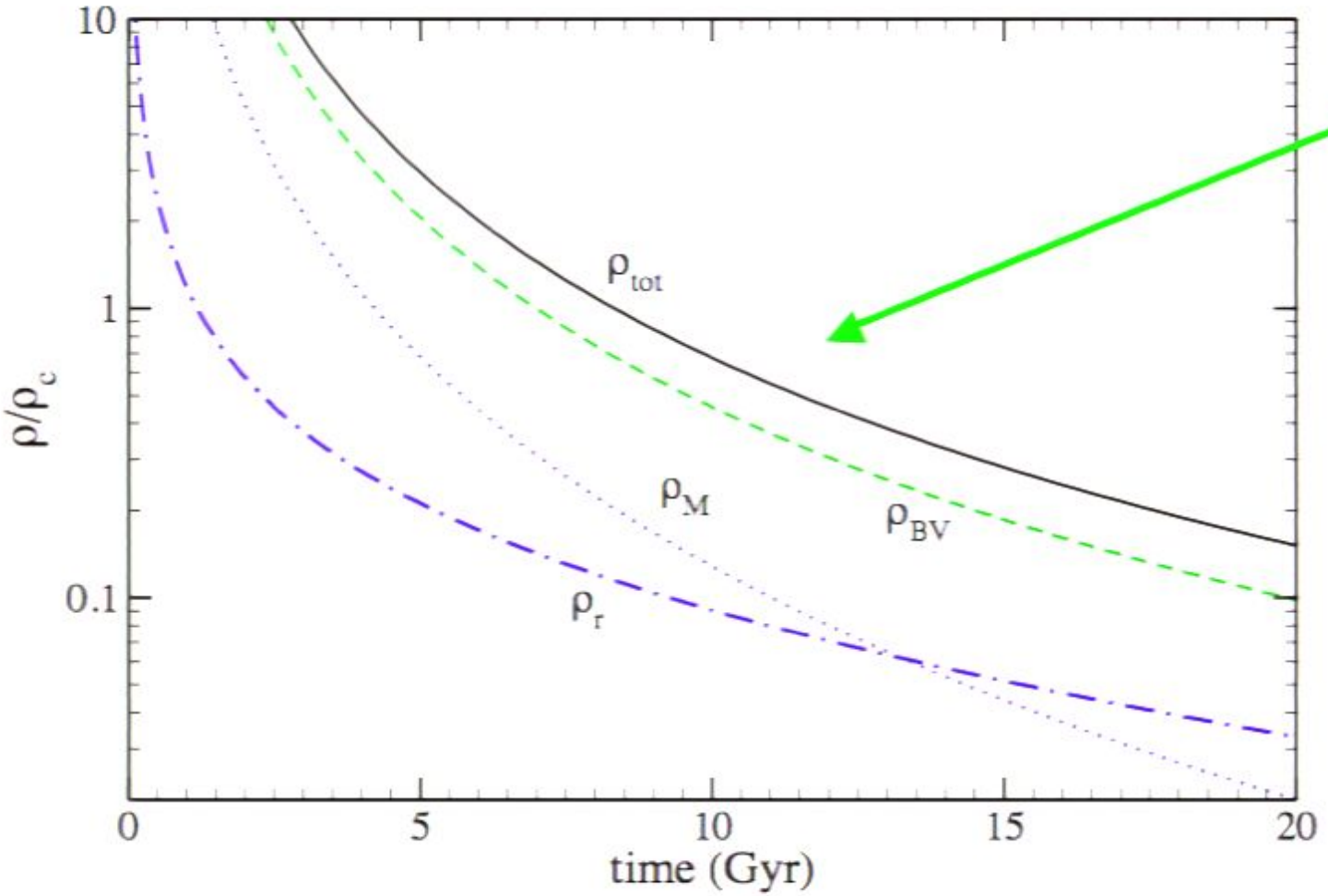

ρ_{tot} falls off too rapidly with time

Need constant ρ_{tot}

How to fix this?

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Late decays:

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Late decays:

Cascading decays: Sterile neutrinos

$\nu_1 \rightarrow \nu_2 \rightarrow \nu_3 \rightarrow \nu_4 \rightarrow \nu_5 \rightarrow \nu_6 \rightarrow$ regular neutrinos

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Late decays:

Cascading decays: Sterile neutrinos

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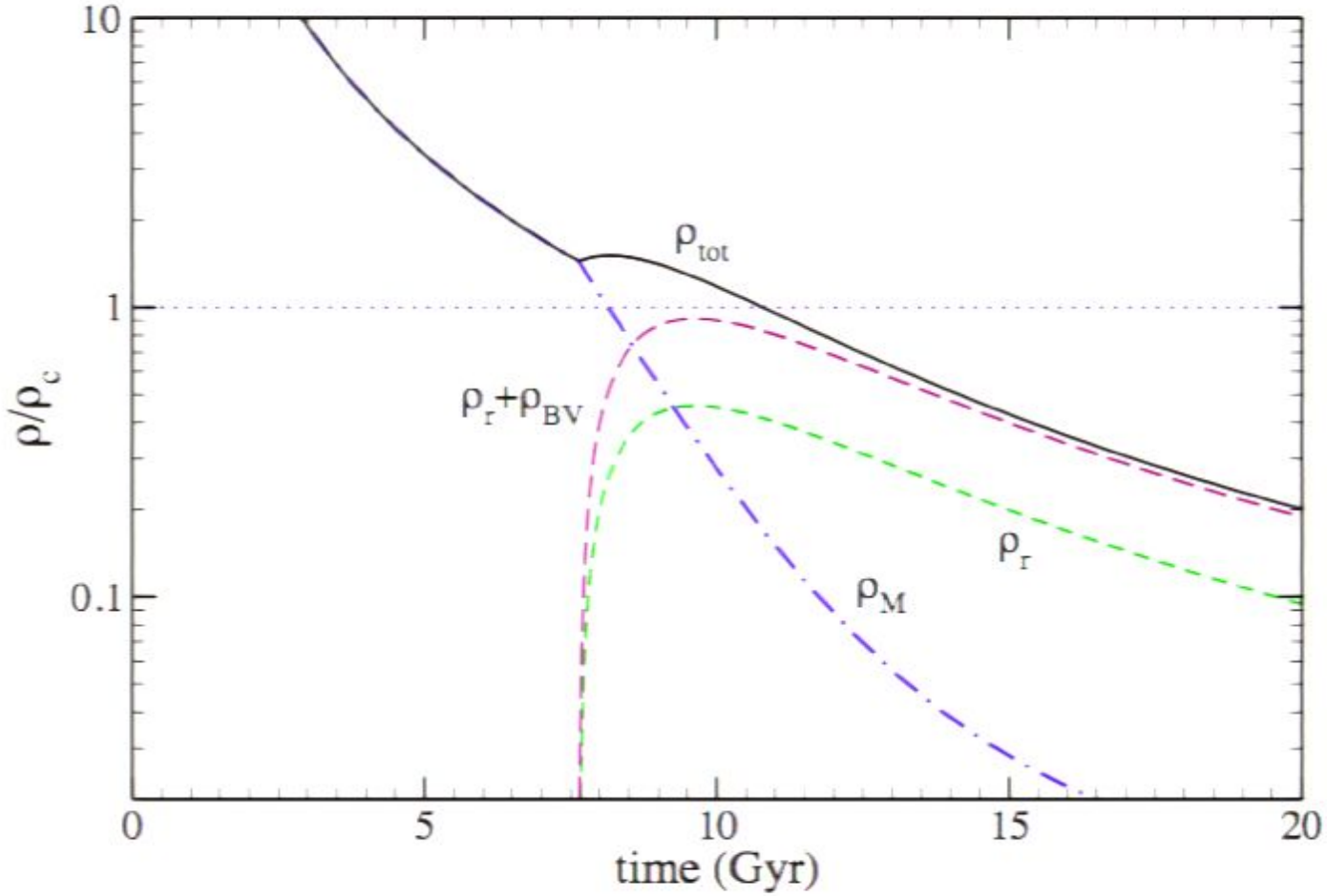
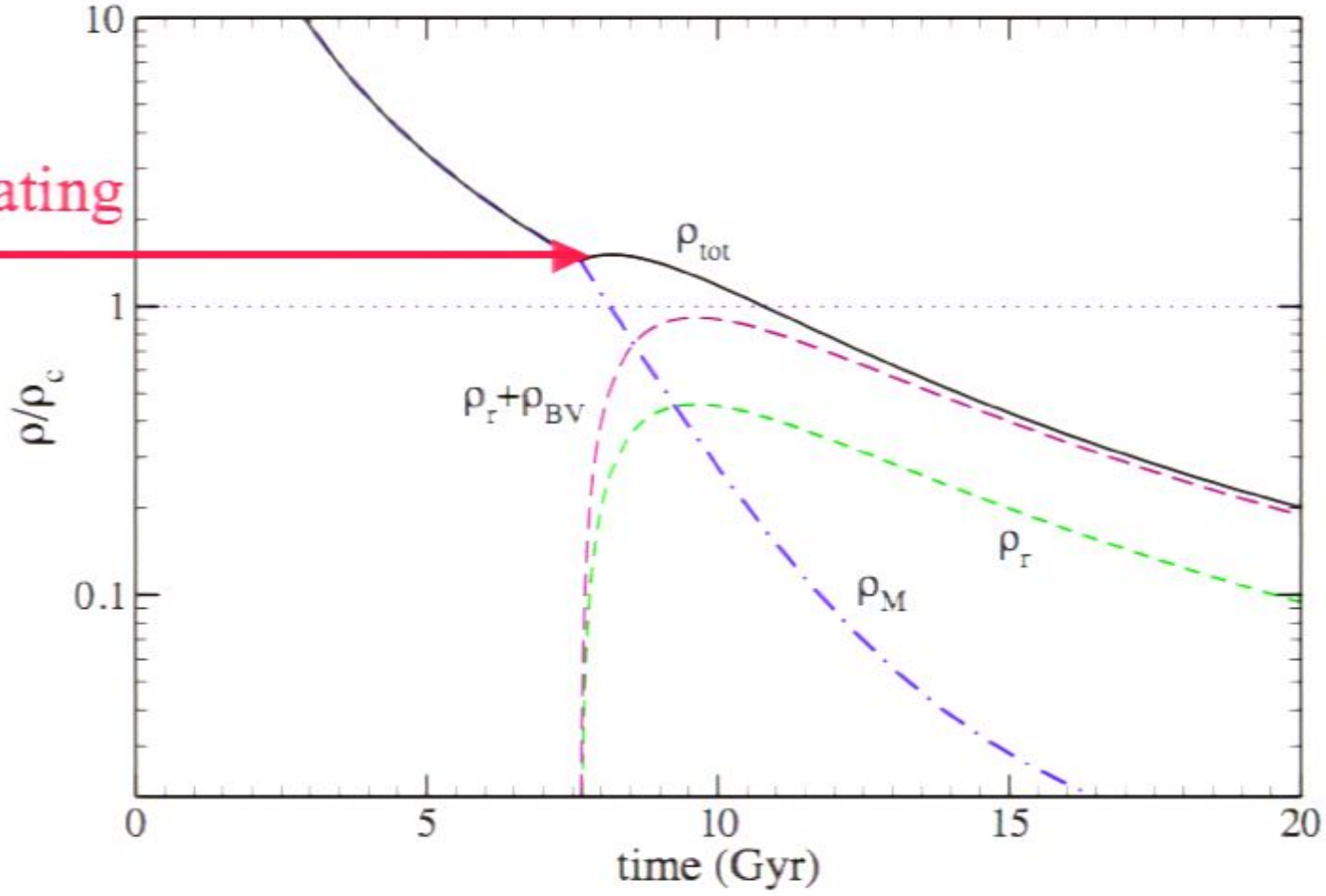
Late decays due to time varying mass or a late phase transition

Late Decaying Particles



Late Decaying Particles

Accelerating



Late Decaying Particles

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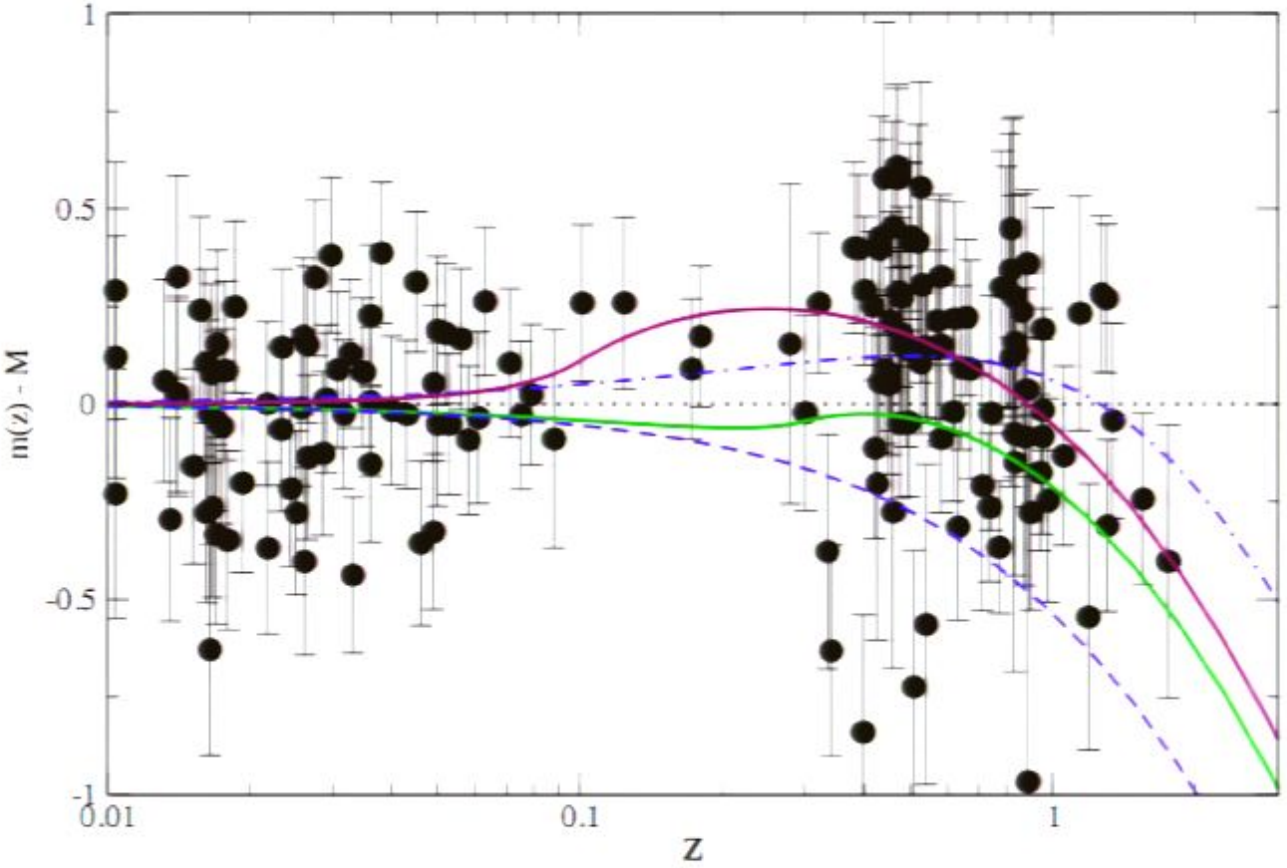

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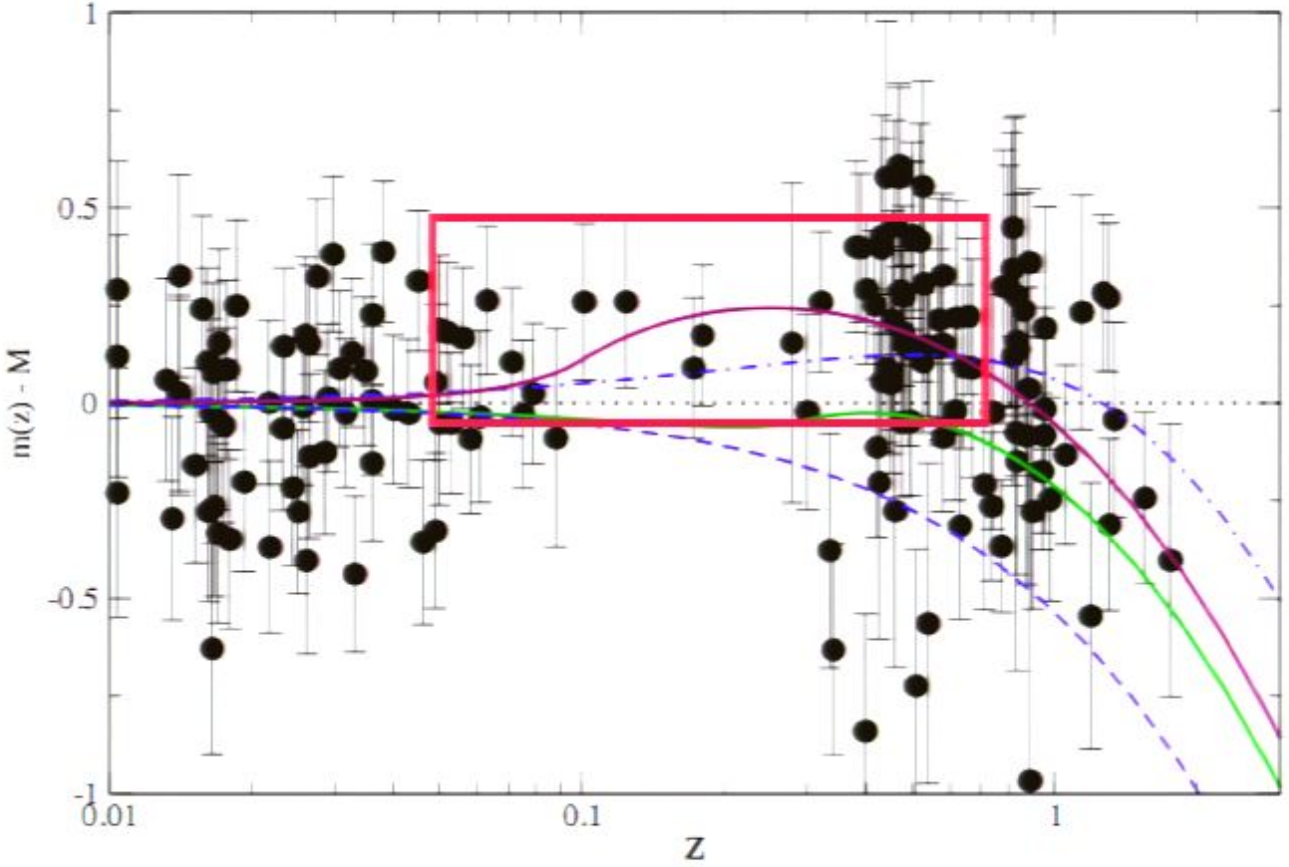

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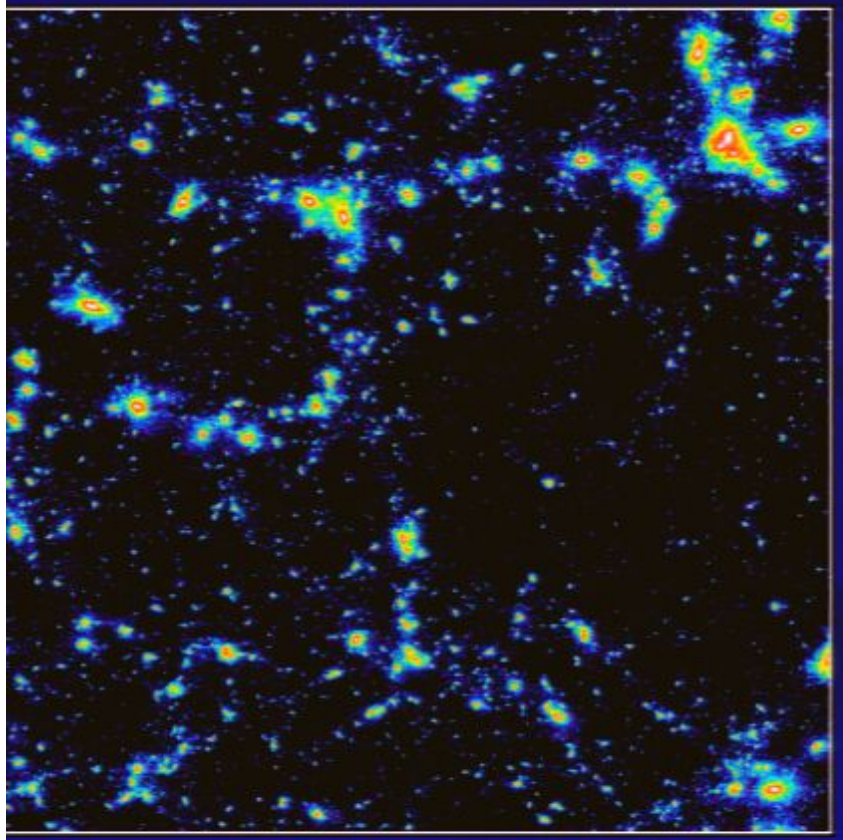

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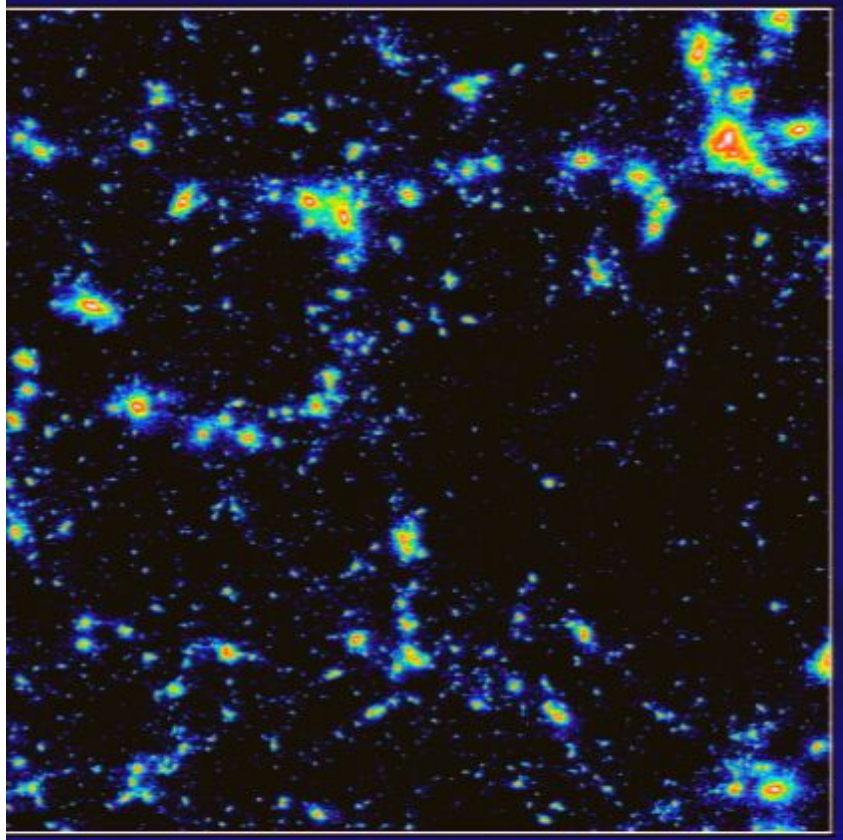

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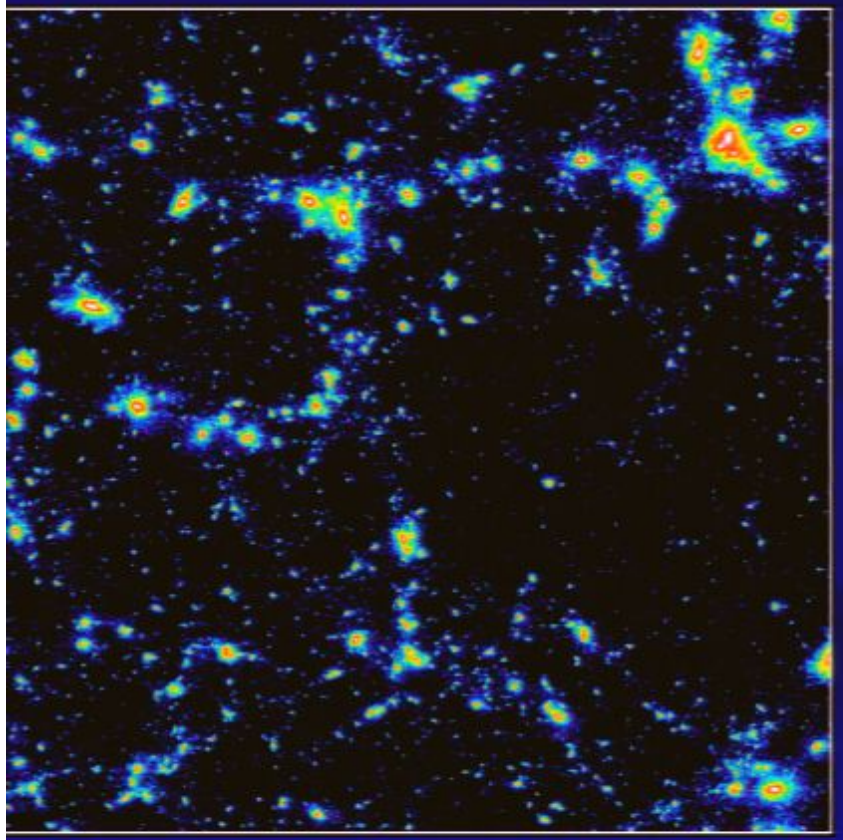

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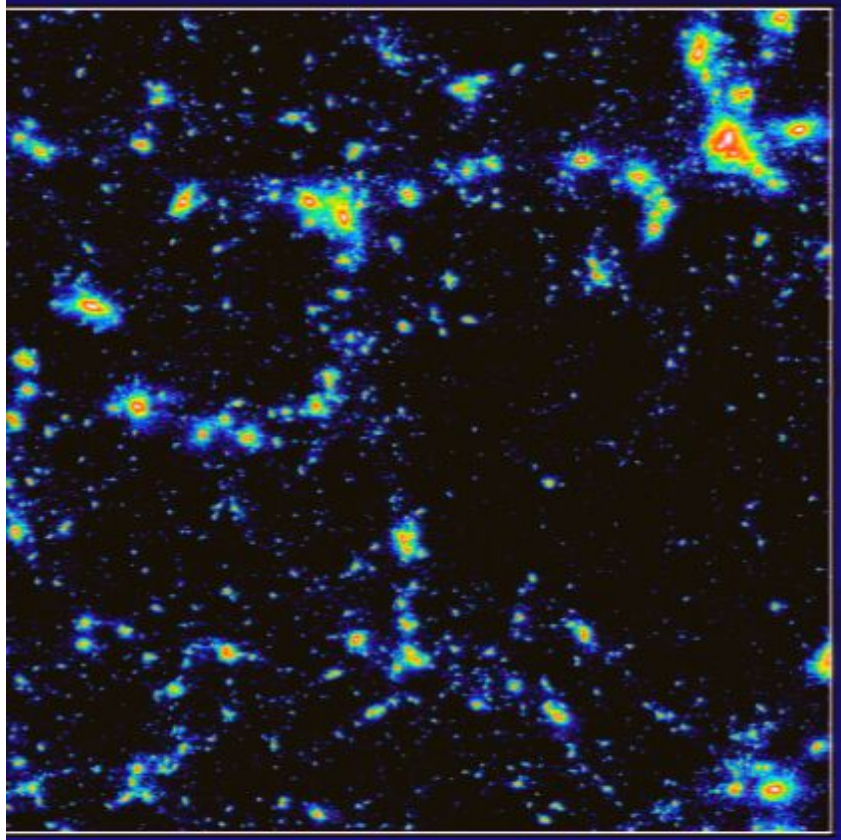

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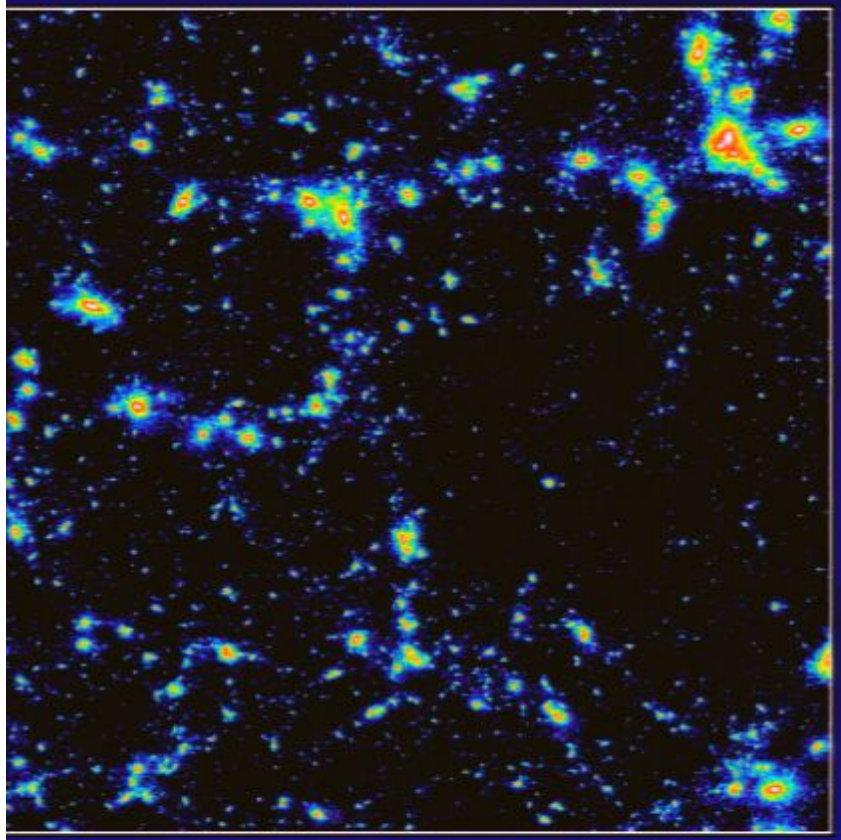

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This can produce acceleration: (e.g. Kolb 2005; 2006, Celerier 2006; Burchert 2007)

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Needs to be tested without the ambiguities of perturbative schemes, averaging, or special symmetry

Goals

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2. Follow null surfaces through the evolving space-time to construct the effective expansion rate and luminosity distance seen by an observer who assumes a Friedmanian cosmology

ADM (3+1)

The Metric

$$ds^2 = -(\alpha^2 - \beta_i \beta^i)dt^2 + 2\beta_i dx^i dt + \gamma_{ij} dx^i dx^j$$

Einstein Equations

$$\dot{\gamma}_{ij} = -2\alpha K_{ij} + D_i \beta_j + D_j \beta_i$$

$$\dot{K}_{ij} = -D_i D_j \alpha + \alpha \left[R_{ij} - 2K_{il}K^l{}_j + K K_{ij} - 8\pi S_{ij} - 4\pi \gamma_{ij} \left(\rho_H - S \right) \right]$$
$$+ \beta^l D_l K_{ij} + K_{il} D_j \beta^l + K_{lj} D_i \beta^l$$

$$\dot{K} = -D_i D^i \alpha + \alpha \left[R + K^2 \right] + 4\pi\alpha [S - 3\rho_H] + \beta^l D_l K$$

Hamiltonian Constraint

$$G_{\mu\nu} n^\mu n^\nu = \frac{1}{2} \left(R + K^2 - K_{ij} K^{ij} \right) = 8\pi \rho_H$$

Momentum Constraint

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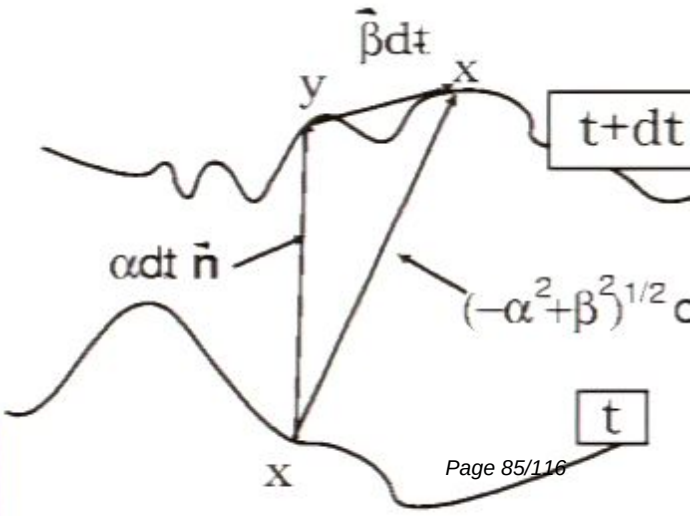

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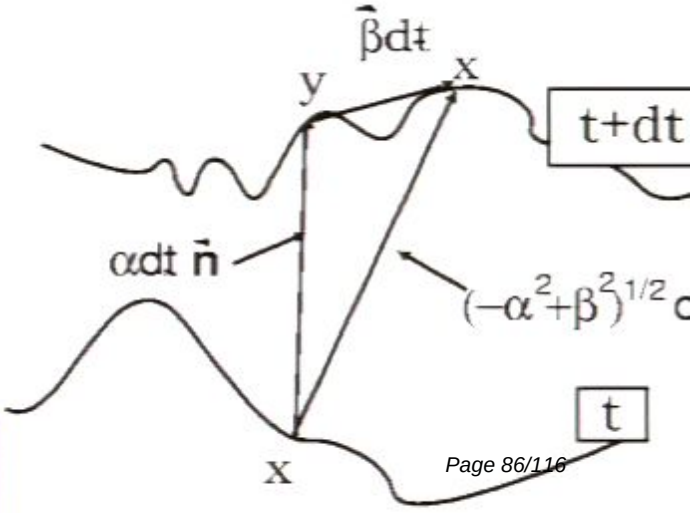

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$$\beta_i = 0$$

$$ds^2 = -\alpha^2 dt^2 + a^2(t)\Phi^4(x.t)\delta_{ij}dx^i dx^j$$

$$w^2 - 1$$

$$\alpha - 1 - \Phi_N \quad \Phi^4 - 1 + \frac{\Phi_N}{2}$$

$$K_{ij} = -\frac{1}{2\alpha}\dot{\gamma}_{ij} = -\frac{1}{2\alpha}[2a\dot{a}\Phi^4\delta_{ij} + 4a^2\Phi^3\dot{\Phi}\delta_{ij}]dx^i dx^j = -\frac{1}{\alpha}[\frac{\dot{a}}{a} - 2\frac{\dot{\Phi}}{\Phi}]\gamma_{ij}$$

$$K = -\frac{3}{\alpha}[\frac{\dot{a}}{a} + 2\frac{\dot{\Phi}}{\Phi}$$

$$K^2 = \frac{9}{\alpha^2}[\frac{\dot{a}}{a} + 2\frac{\dot{\Phi}}{\Phi}]$$

Hamiltonian Constraint

$${}^3R + K^2 - K_{ij}K^{ij} = 16\pi\rho_H$$

$${}^3R = -\frac{8\nabla^2\Phi}{\Phi^5} \quad {}^3R = -\frac{8a^{\frac{1}{2}}\nabla^2\Phi}{a^{\frac{5}{2}}\Phi^5} = -\frac{8\nabla^2\Phi}{a^2\Phi^5}$$

So Hamiltonian Constraint becomes

$$-\frac{8\nabla^2\Phi}{a^2\Phi^5} + \frac{9}{\alpha^2}[\frac{\dot{a}}{a} + 2\frac{\dot{\Phi}}{\Phi}]^2 - \frac{3}{\alpha^2}[\frac{\dot{a}}{a} + 2\frac{\dot{\Phi}}{\Phi}]^2 = 16\pi\rho w^2$$

$$\frac{6}{\alpha^2}[\frac{\dot{a}}{a} + 2\frac{\dot{\Phi}}{\Phi}]^2 = 16\pi\rho w^2 - \frac{8\nabla^2\Phi}{a^2\Phi^5}$$

$$\frac{\dot{a}}{a} = \alpha[\frac{8}{3}\pi\rho w^2 + \frac{4}{3}\frac{\nabla^2\Phi}{a^2\Phi^5}]^{\frac{1}{2}} - 2\frac{\dot{\Phi}}{\Phi}$$

Mathews et al J Mod Phys. A (2008)

Modified Friedman Equation

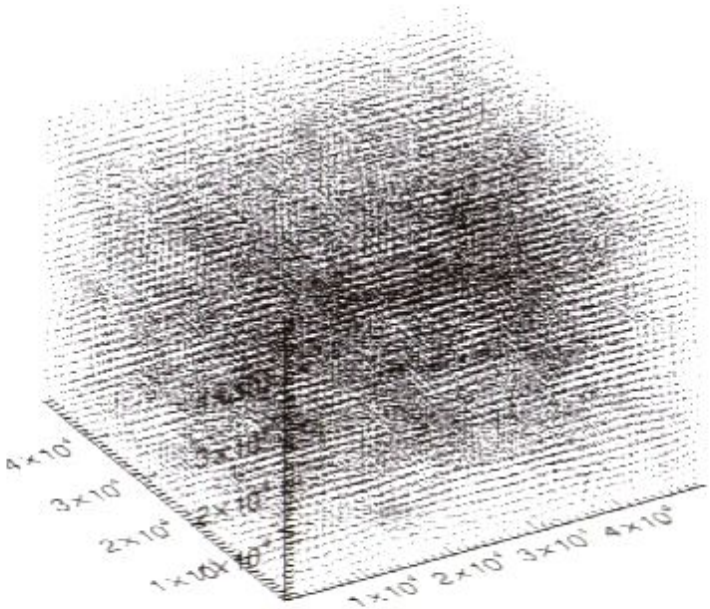
(conformal Newtonian gauge)

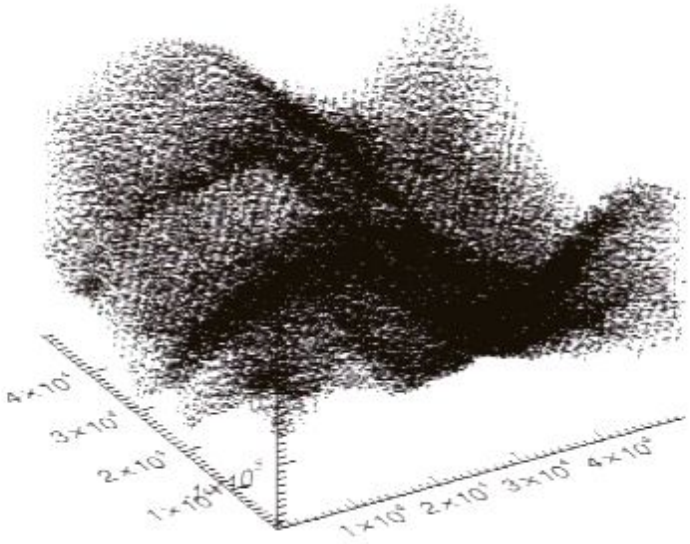
$$\frac{\dot{a}}{a} = (1+2\Phi)^{\frac{1}{2}}[\frac{8\pi\rho}{3} + \frac{4\nabla^2(1-2\Phi)^{\frac{1}{4}}}{3a^2(1-2\Phi)^{\frac{5}{4}}}]^{\frac{1}{2}} - \frac{\dot{(1-2\Phi)^{\frac{1}{4}}}}{(1-2\Phi)^{\frac{1}{4}}}$$

SPH calculation of the evolution of structure and Newtonian potential for an $\Omega_M=1$ cosmology

Φ_N

ρ





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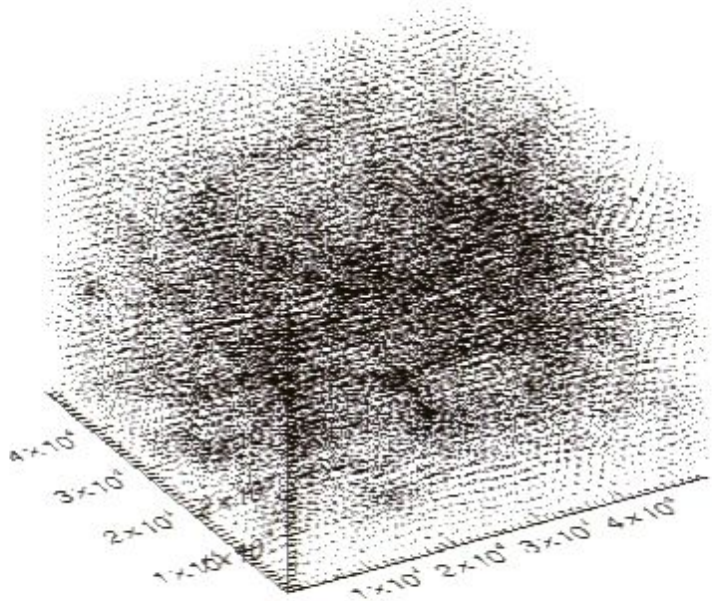

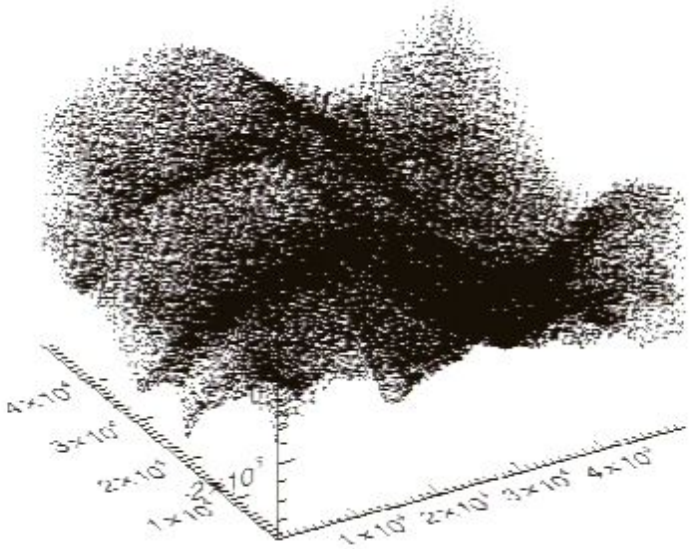

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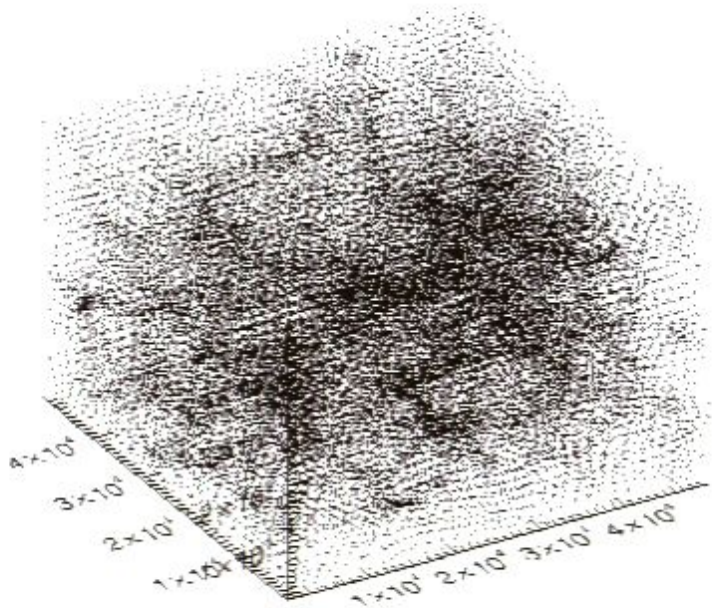

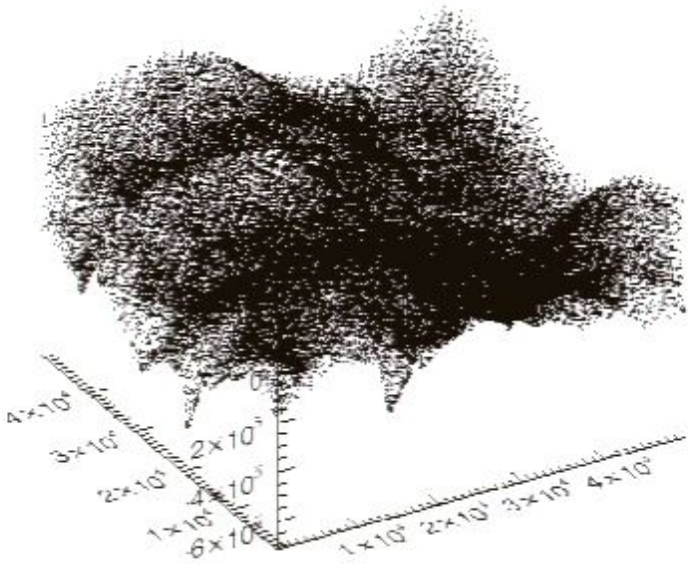

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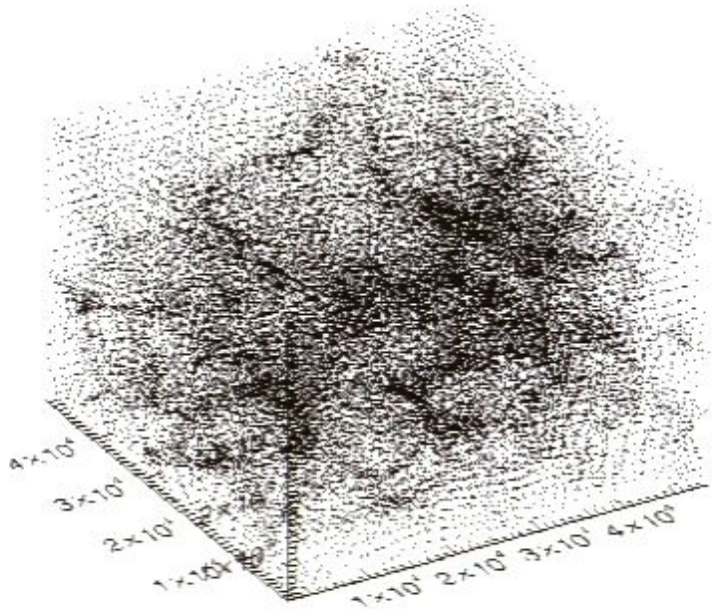

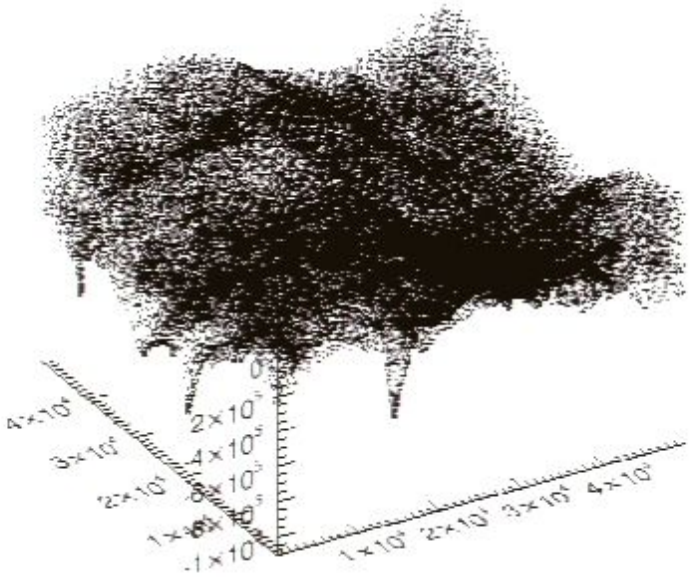

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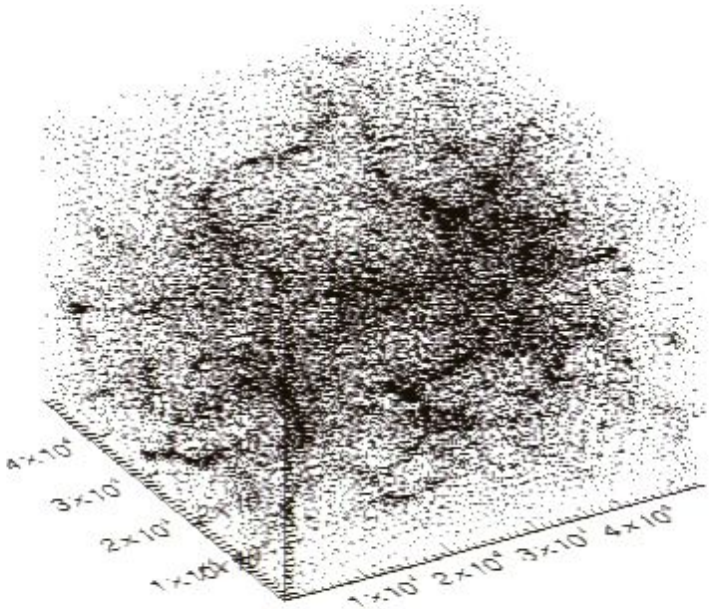

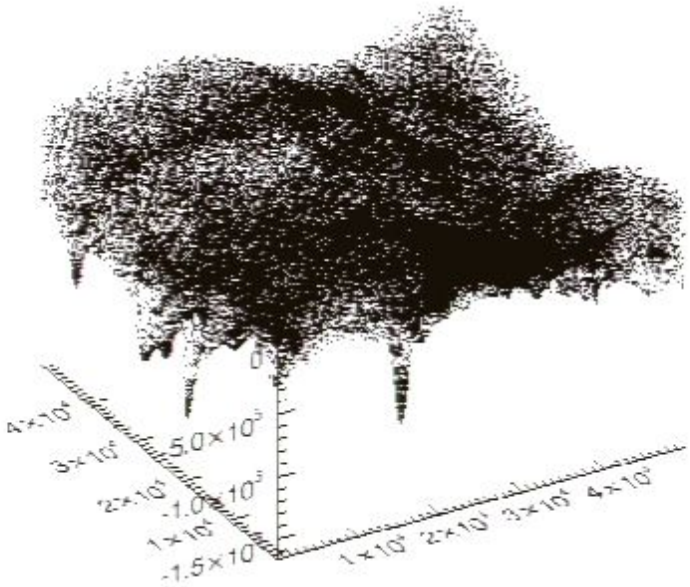

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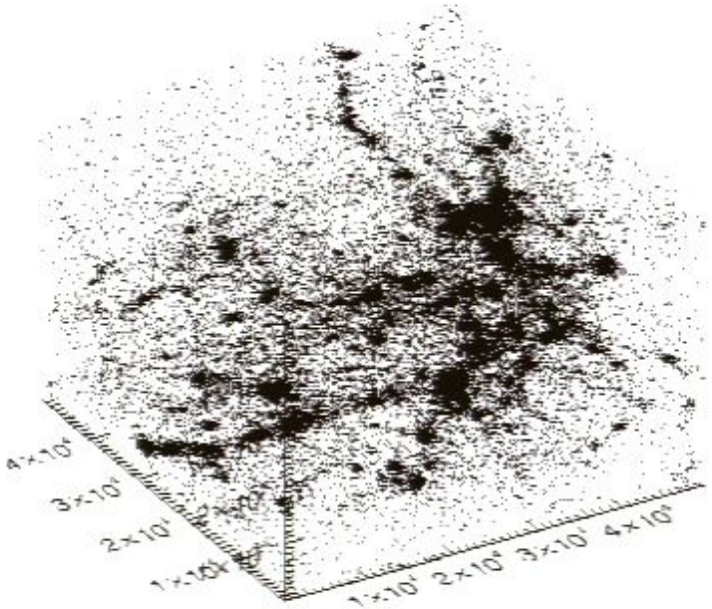

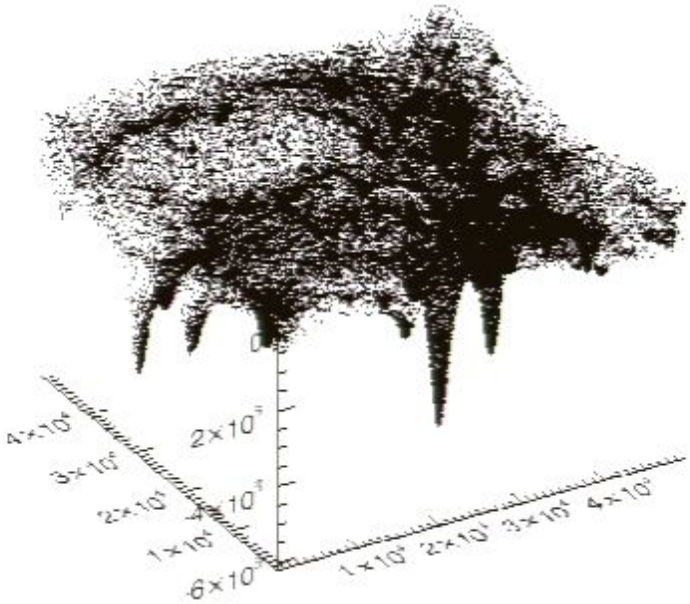

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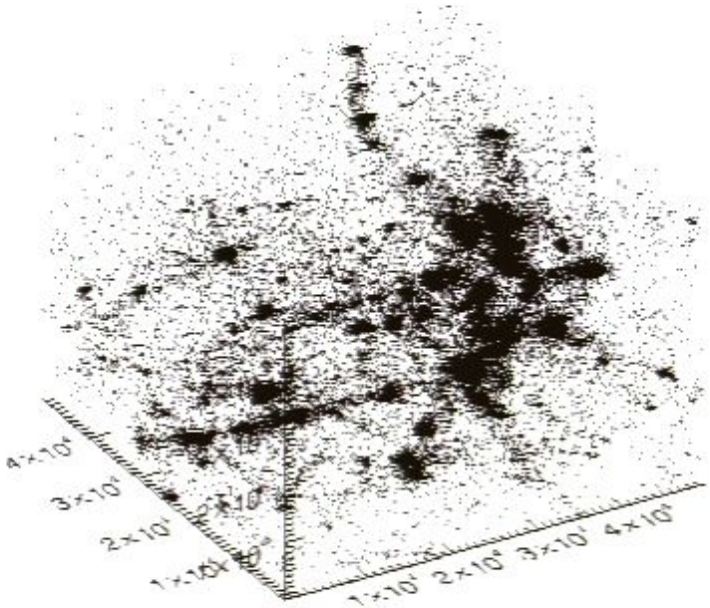

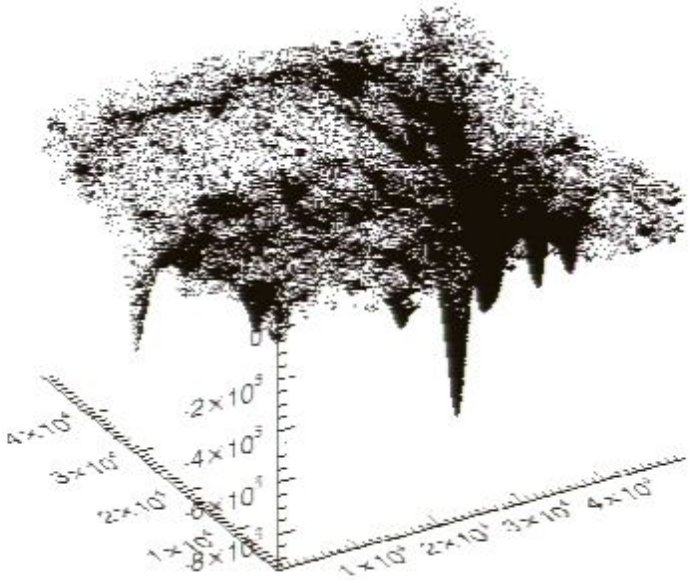

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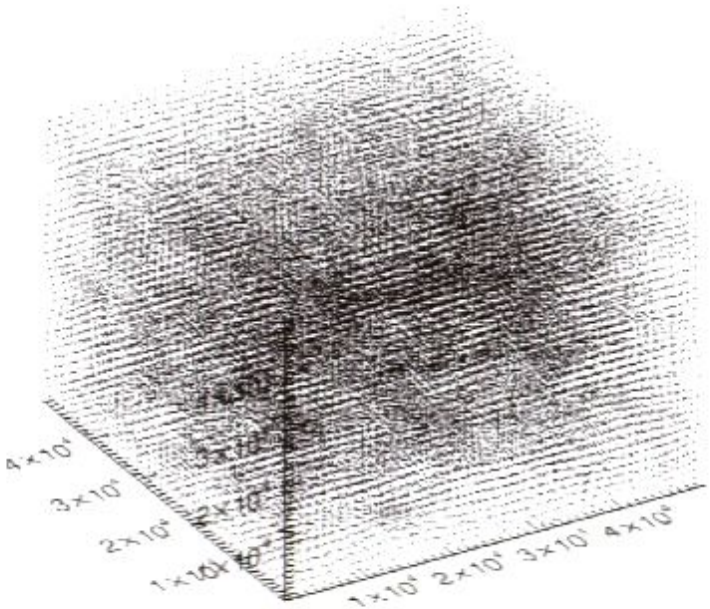

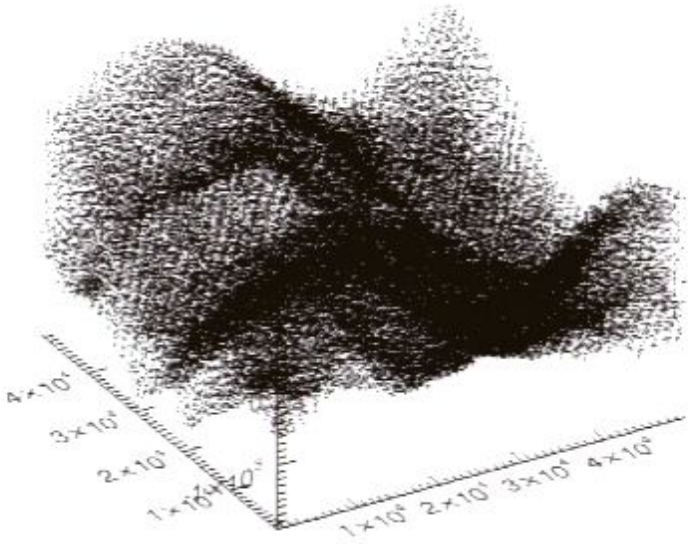

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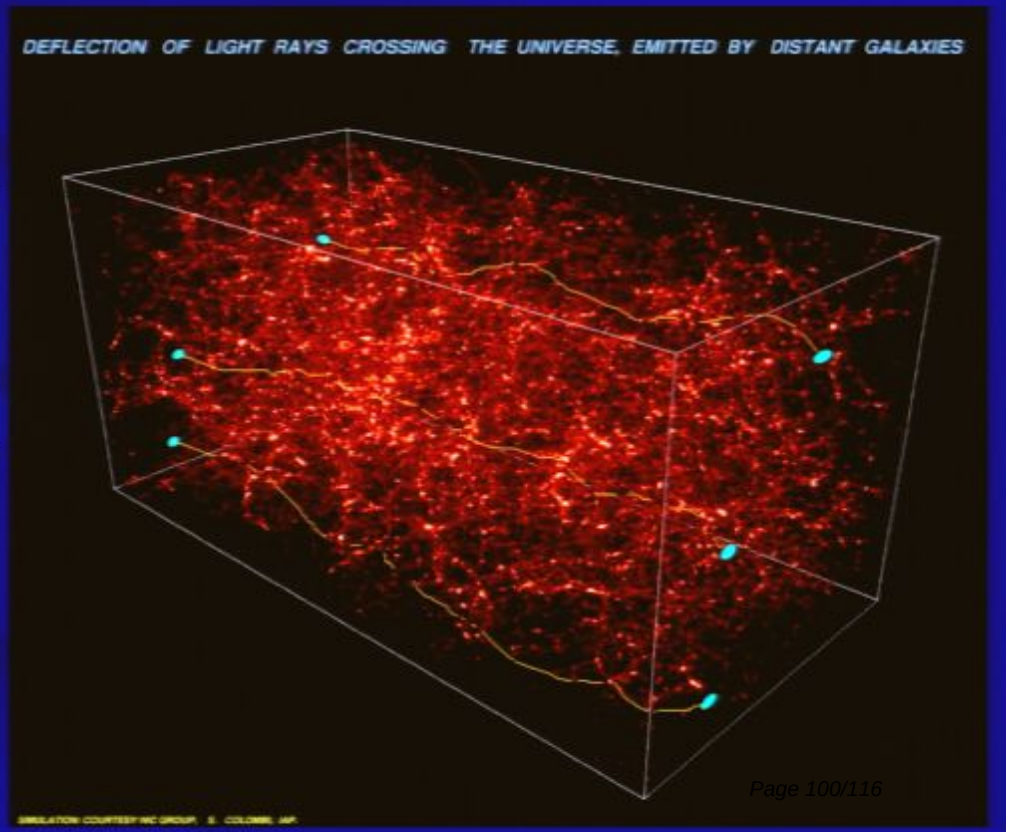

Effects on cosmic acceleration are large

Can recover an accelerating cosmology with Lambda = 0

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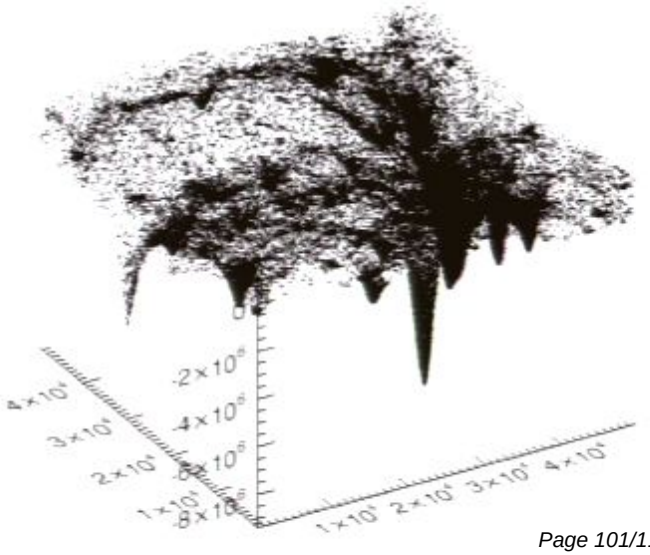
Φ_N



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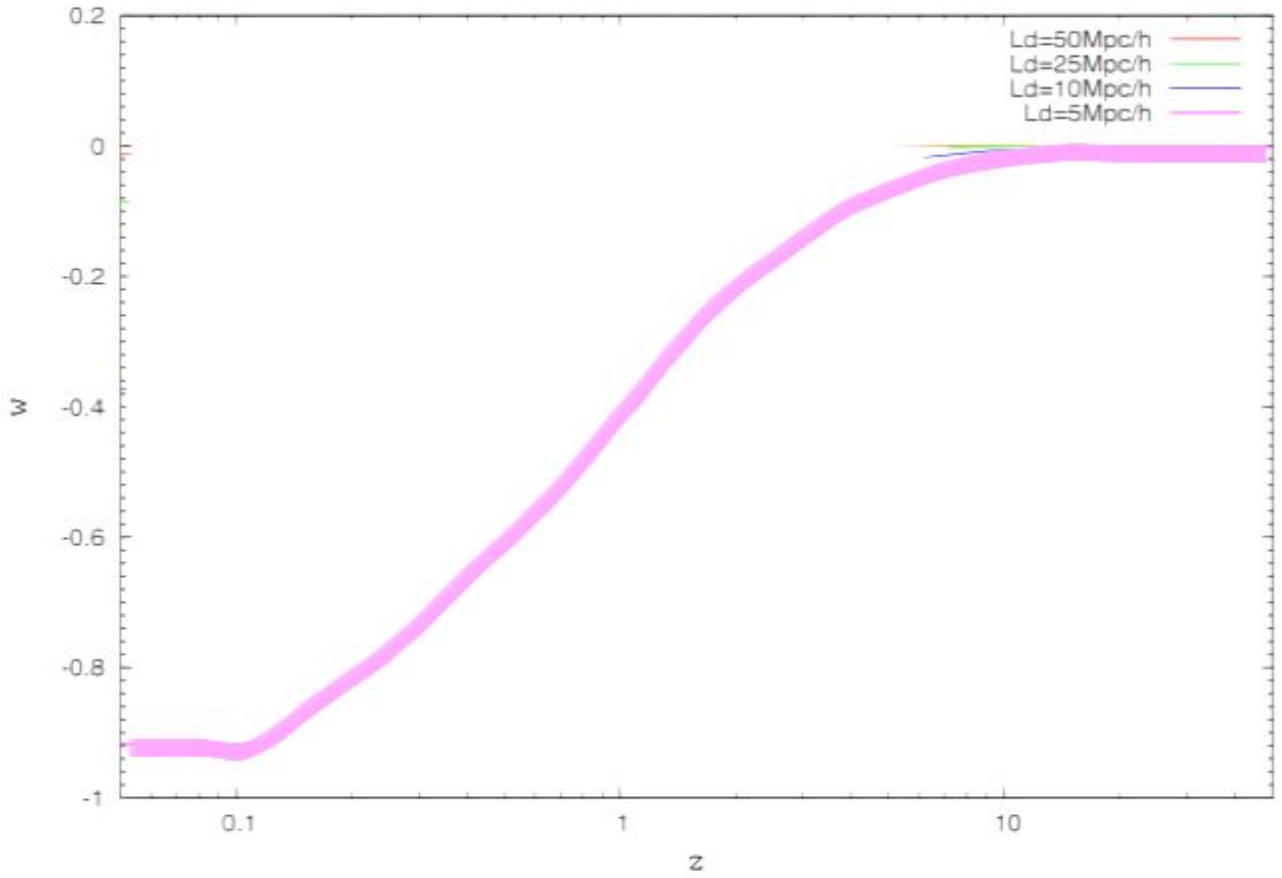

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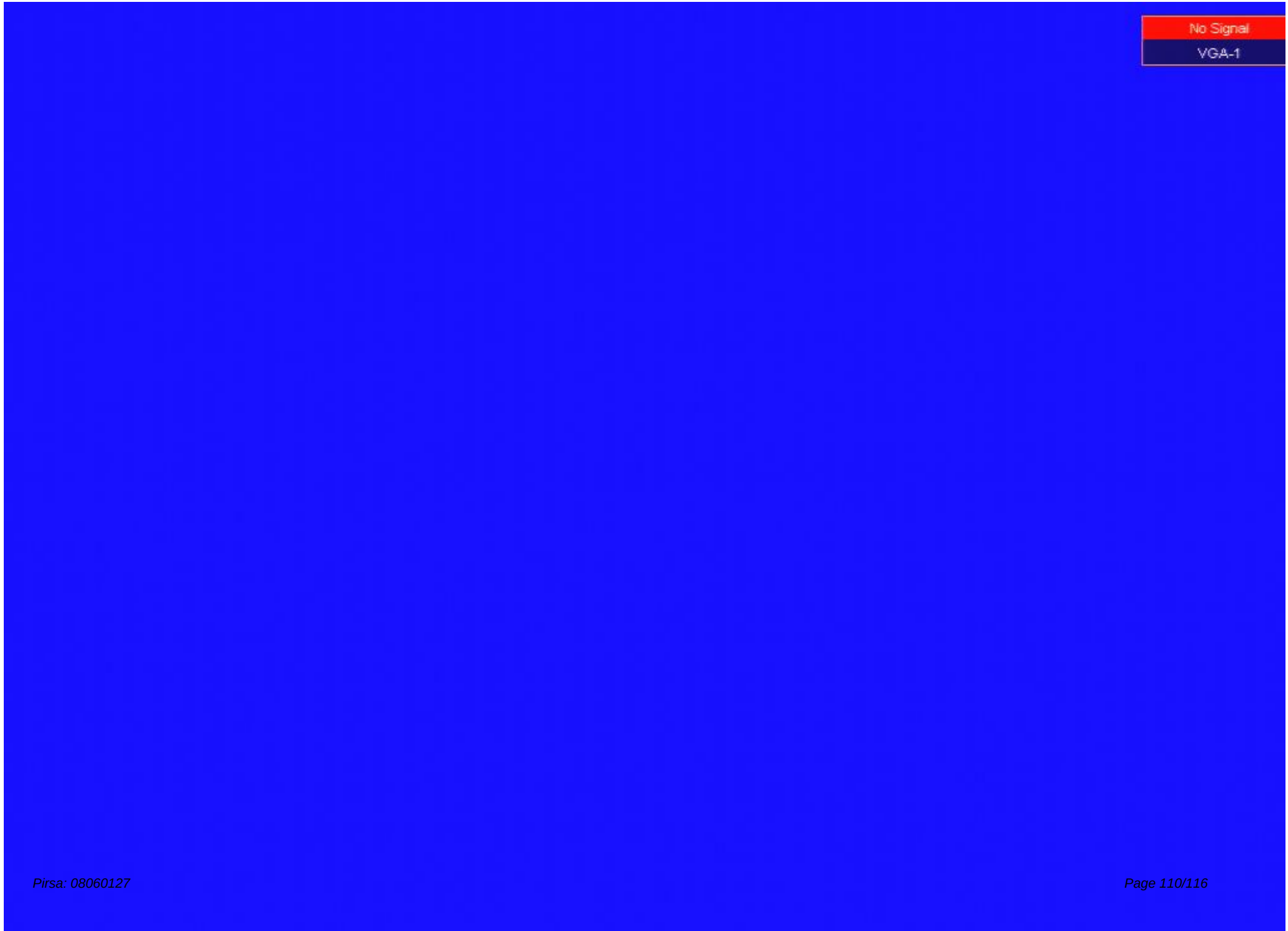
- Corrections for an inhomogeneous Friedmann equation remain a possibility to explain the dark energy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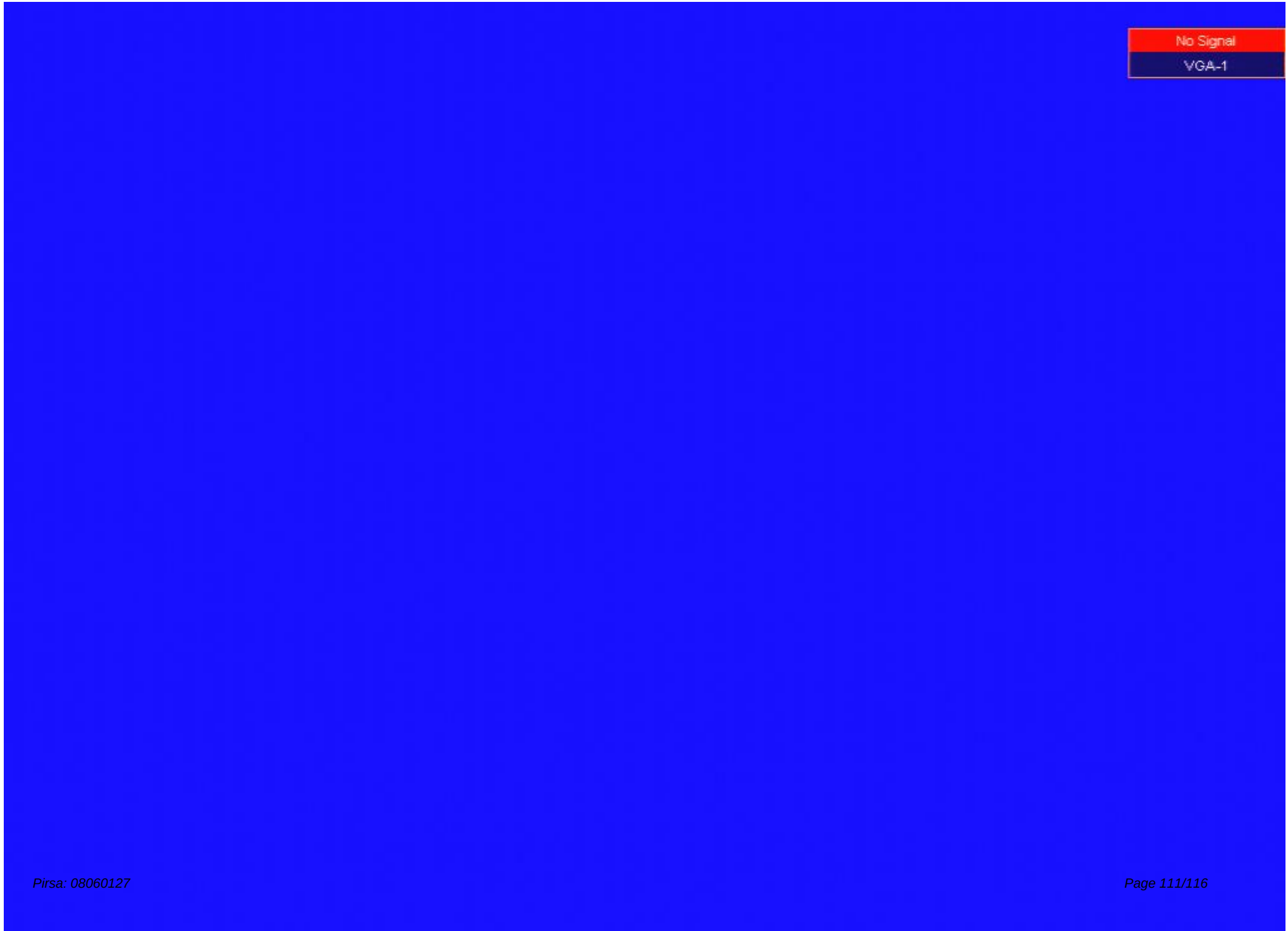
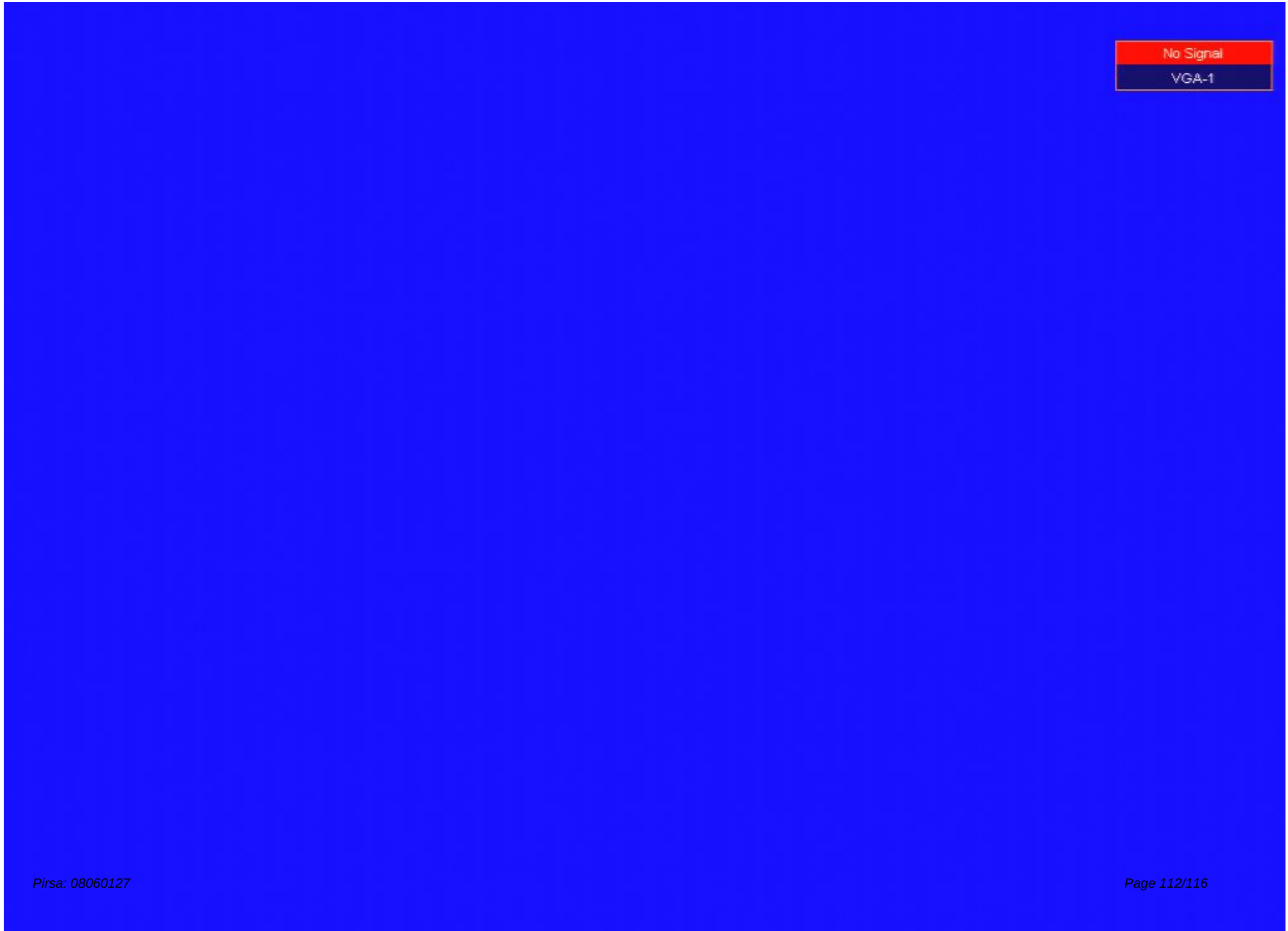
VGA-1


No Signal
VGA-1


No Signal
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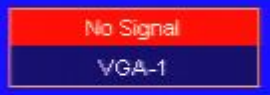
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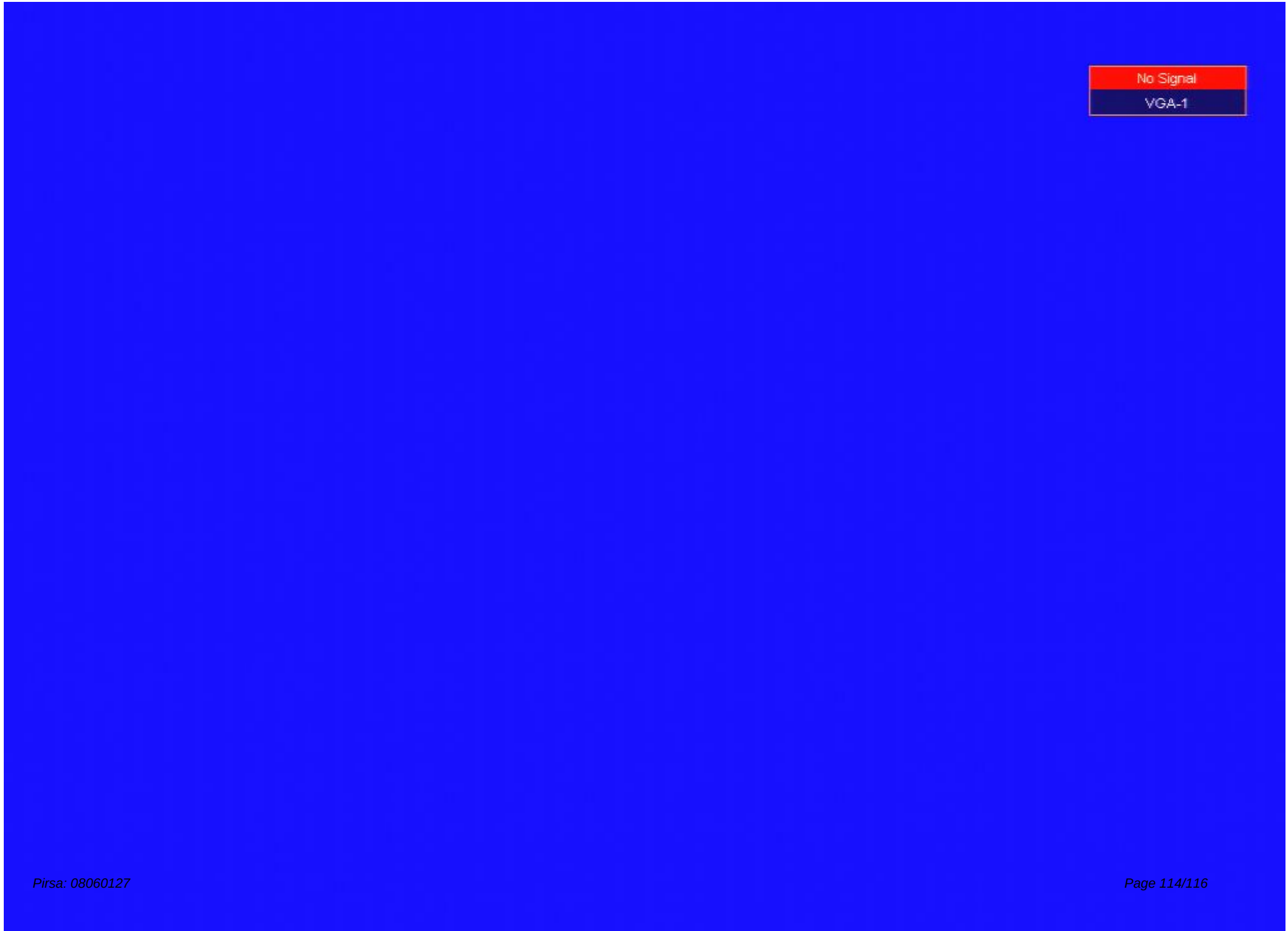
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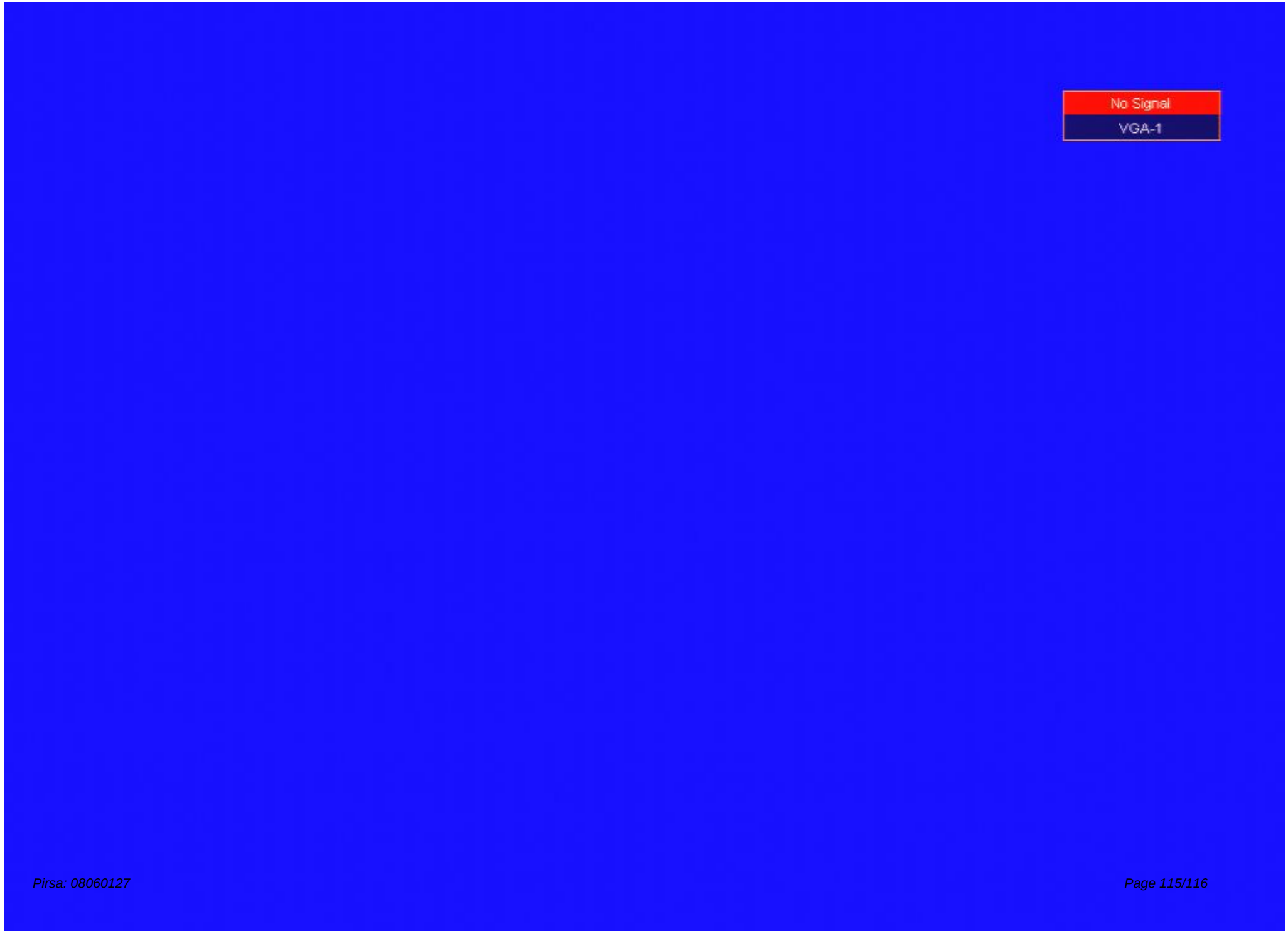
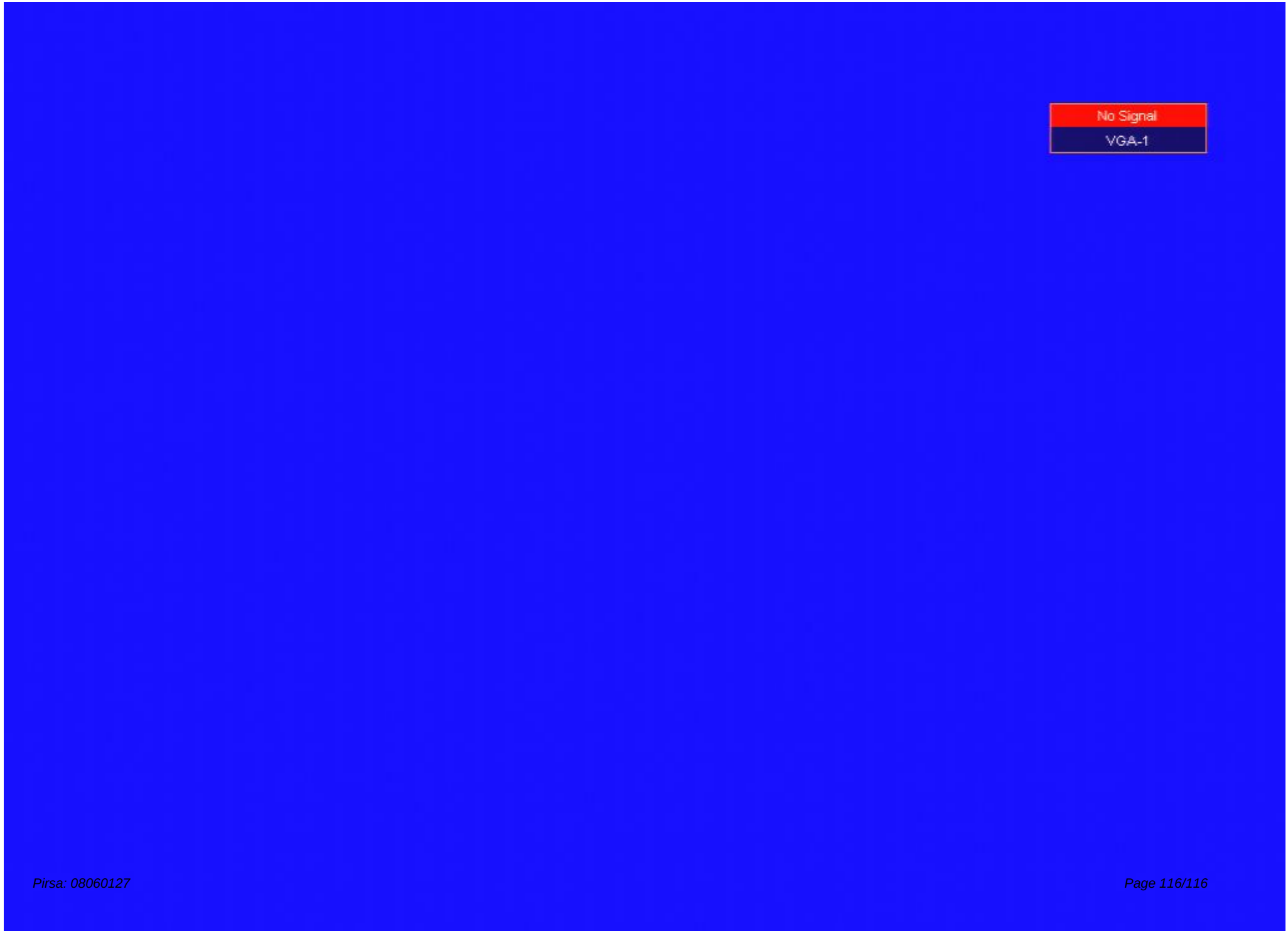

No Signal
VGA-1


No Signal
VGA-1