Title: An Unparticle Solution to the Hierarchy Problem

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Abstract: The Planck-weak hierarchy is investigated in an extradimensional, soft-wall model originally proposed by Batell and Gherghetta. In this model the soft-wall is dynamically generated by background ï¬•elds that, in the Einstein frame, cause the metric factor to deviate from anti-de Sitter by a power-law of the conformal coordinate. This talk will demonstrate that in order to achieve the appropriate Planck-weak hierarchy, the power of the conformal coordinate must be less than one. This in turn implies that the gravitational sector contains scalar ï¬•elds that act like unparticles without a mass gap.

Unparticle Solution to Hierarchy

Nicholas Setzer
with T. Gherghetta

University of Melbourne

May 7, 2010

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- The BG Soft-Wall Model
- Achieving the Hierarchy
- Fluctuations
- Bulk Fields
- Summary

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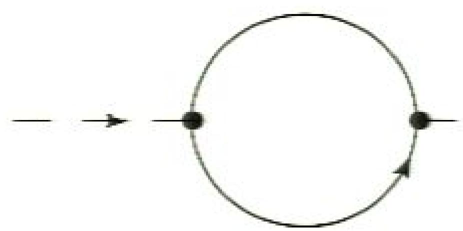

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- Warped Extra Dimension provides a way

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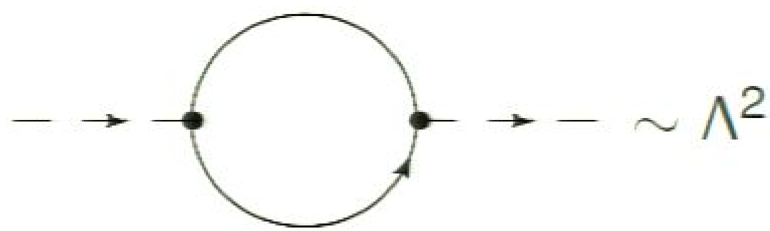

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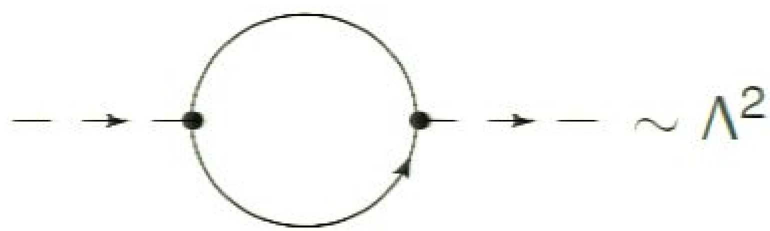

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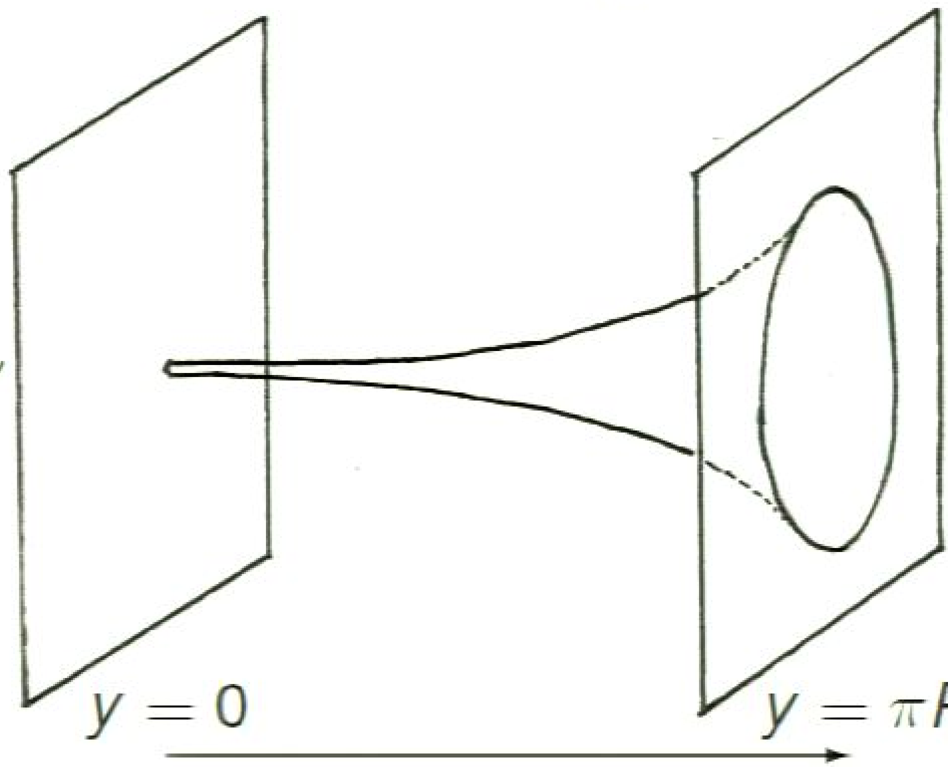

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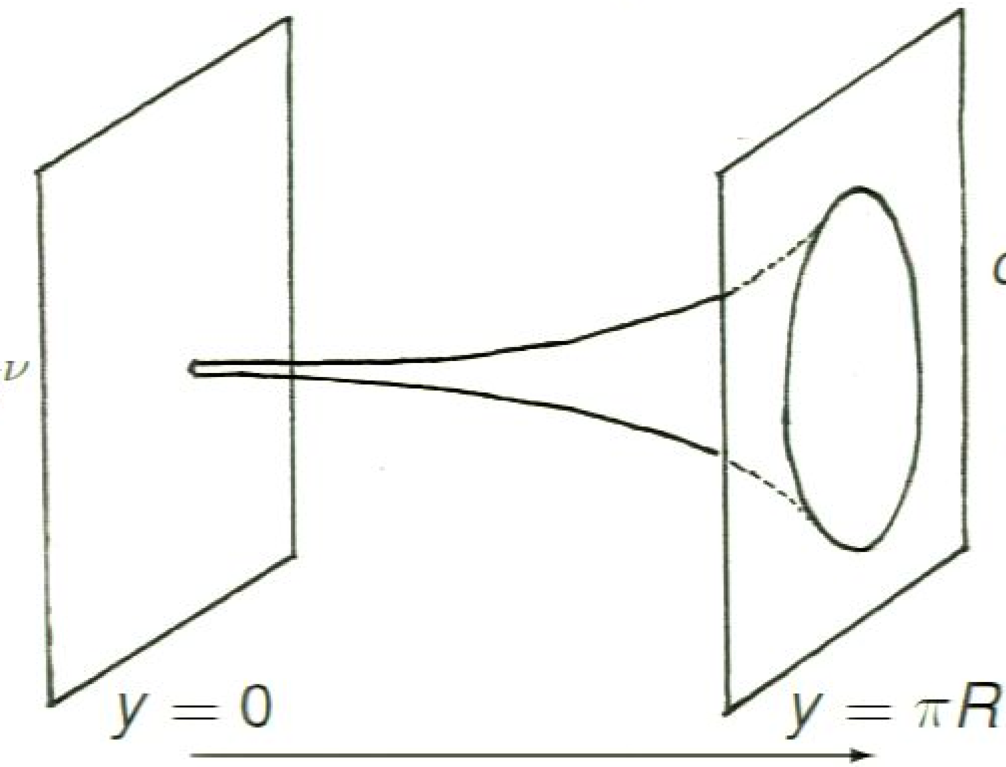

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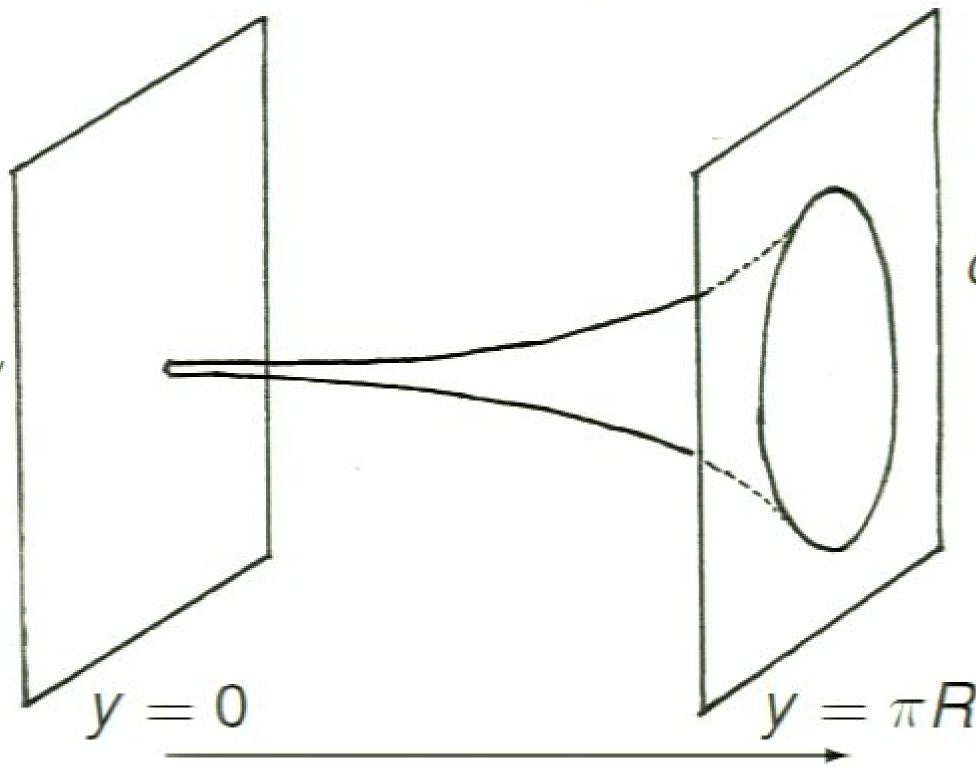

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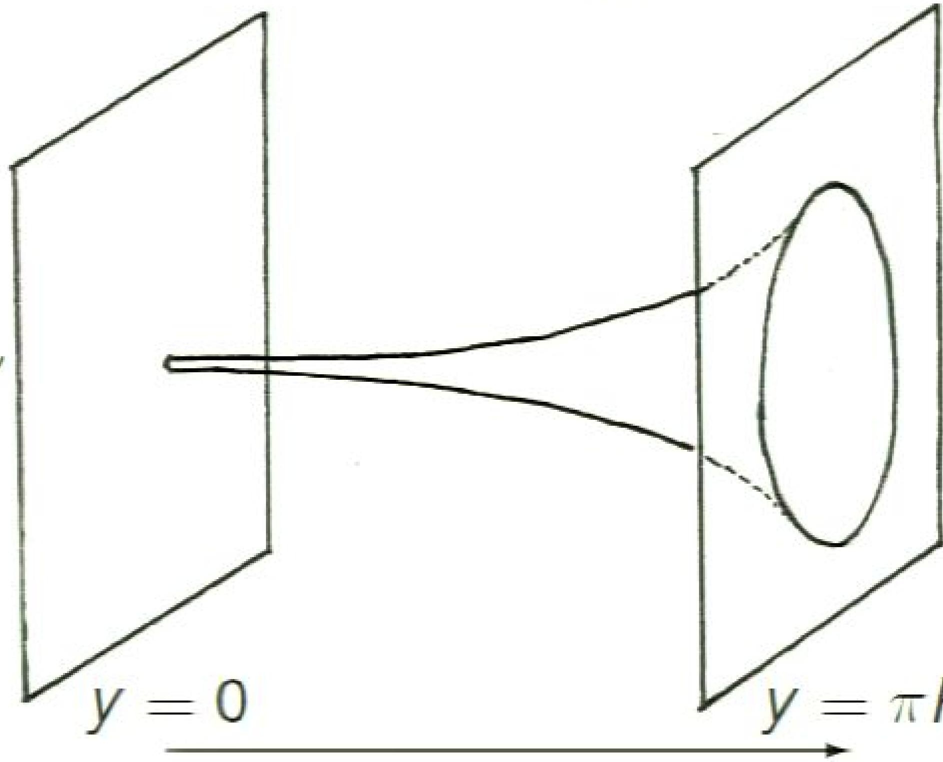

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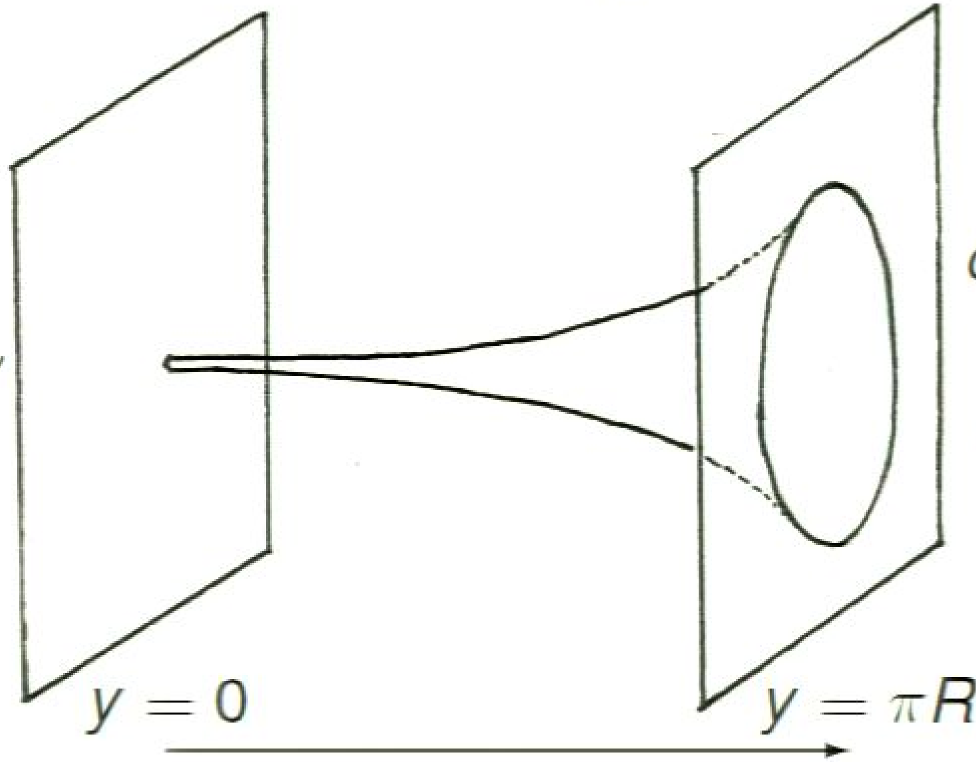

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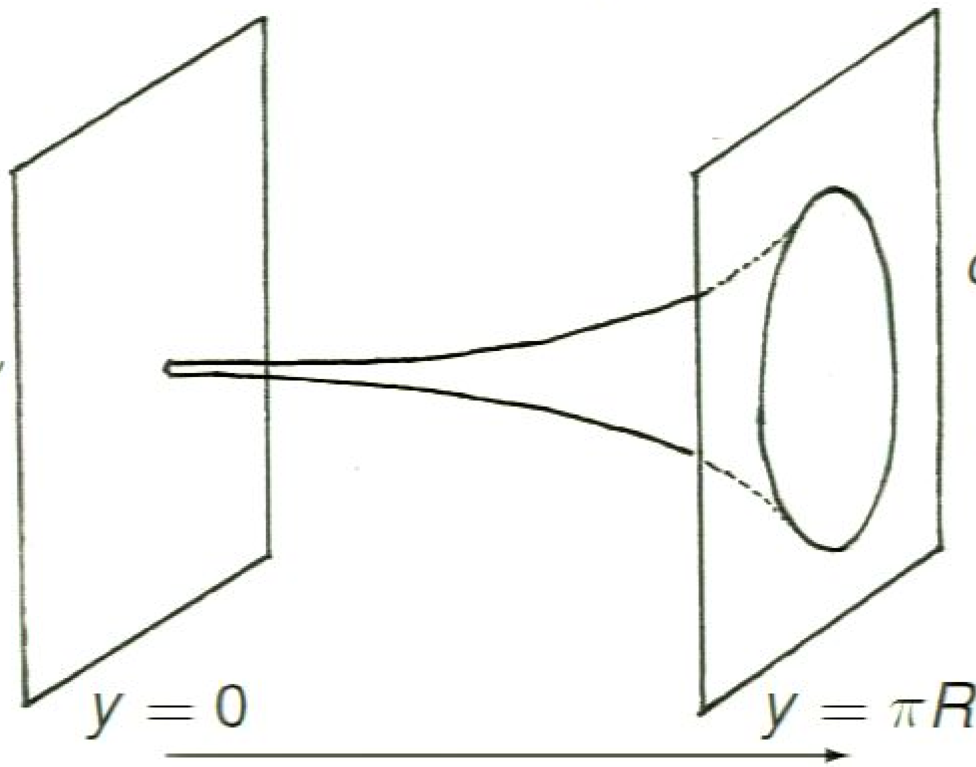

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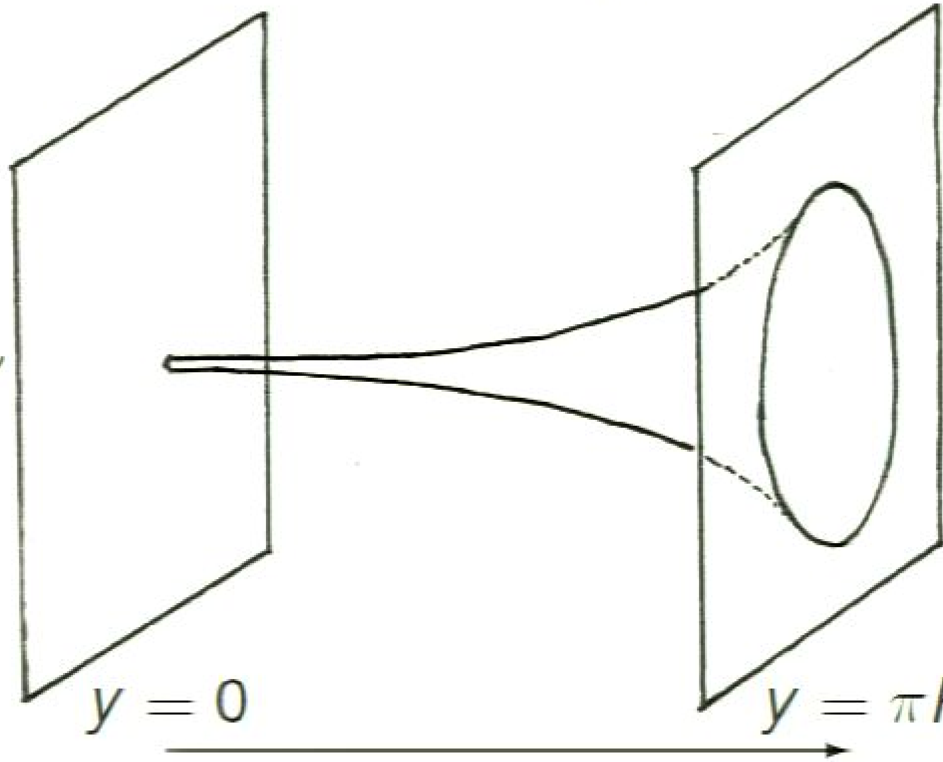

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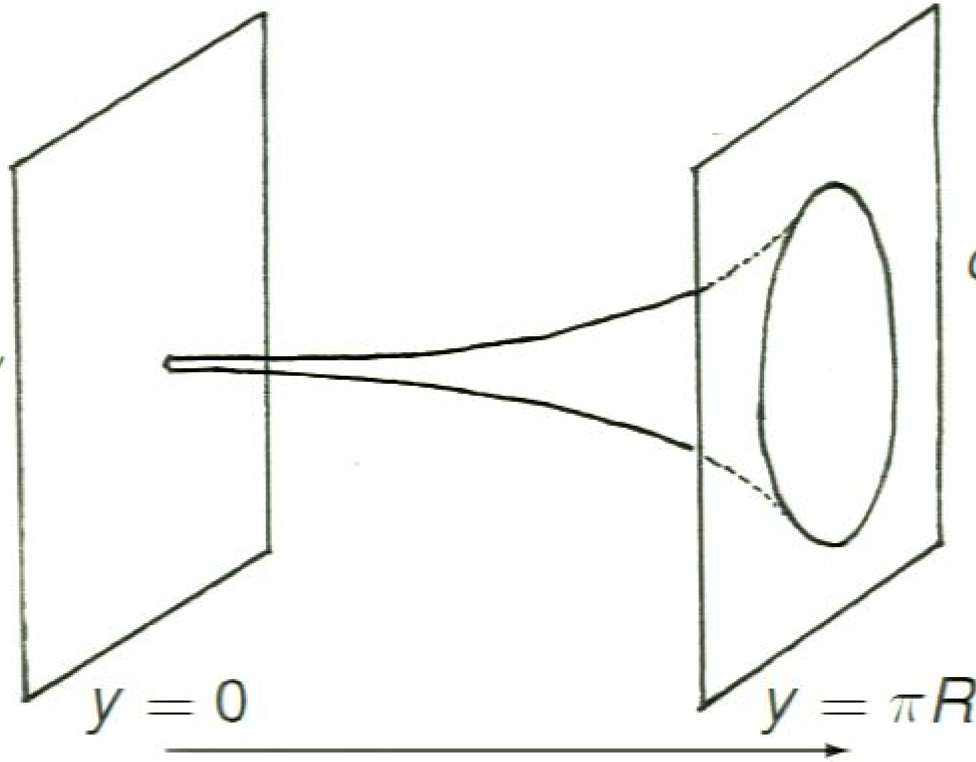

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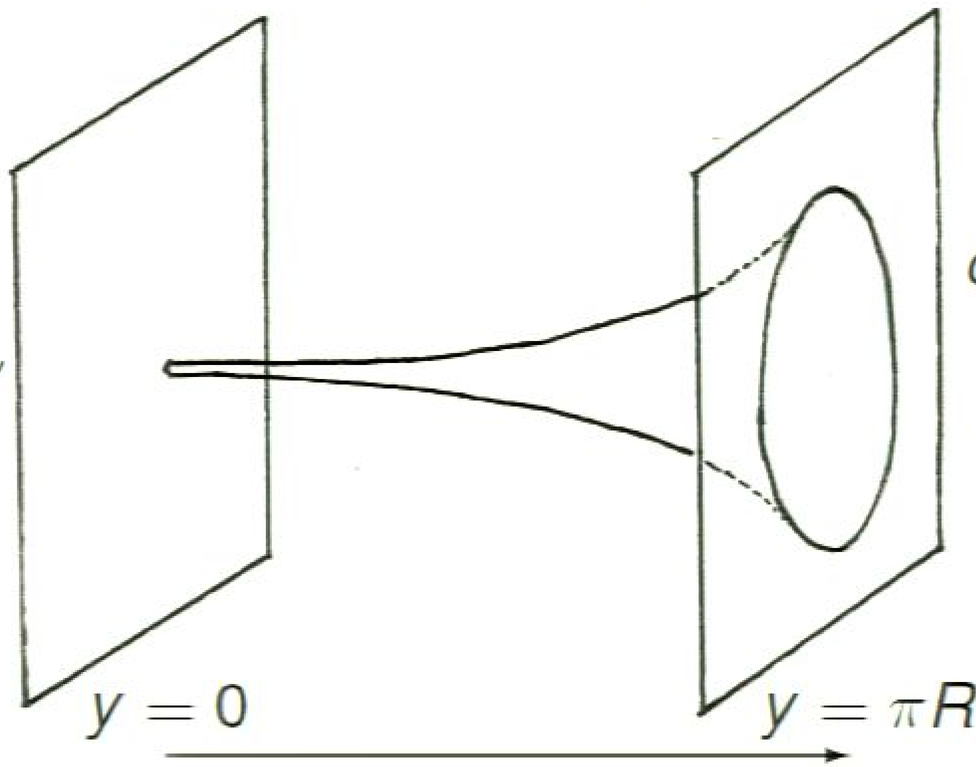

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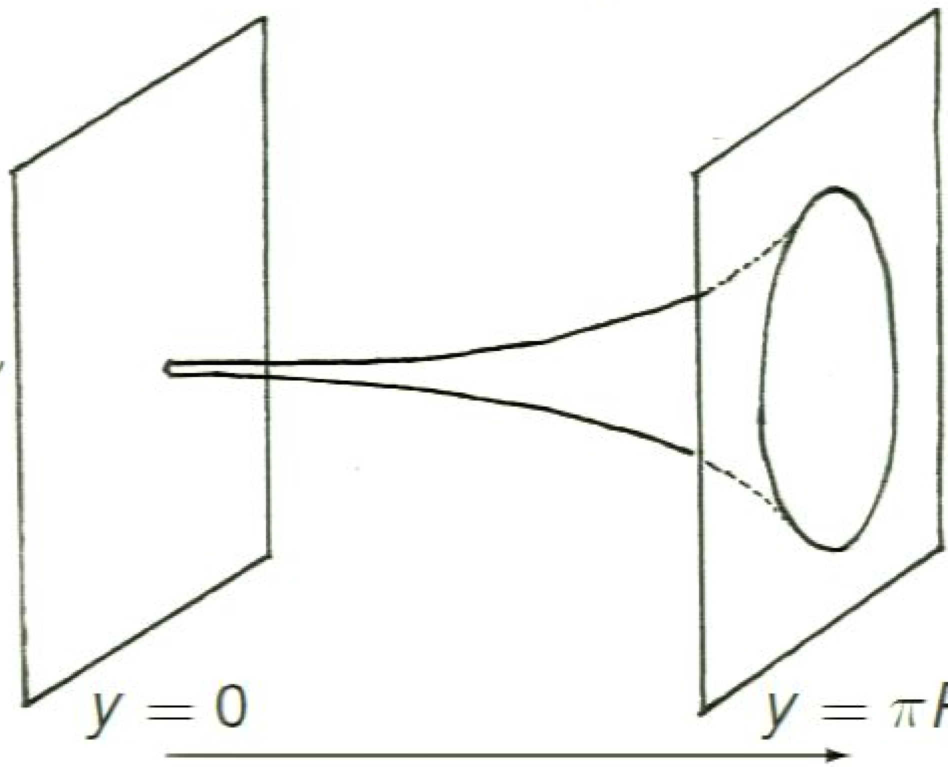

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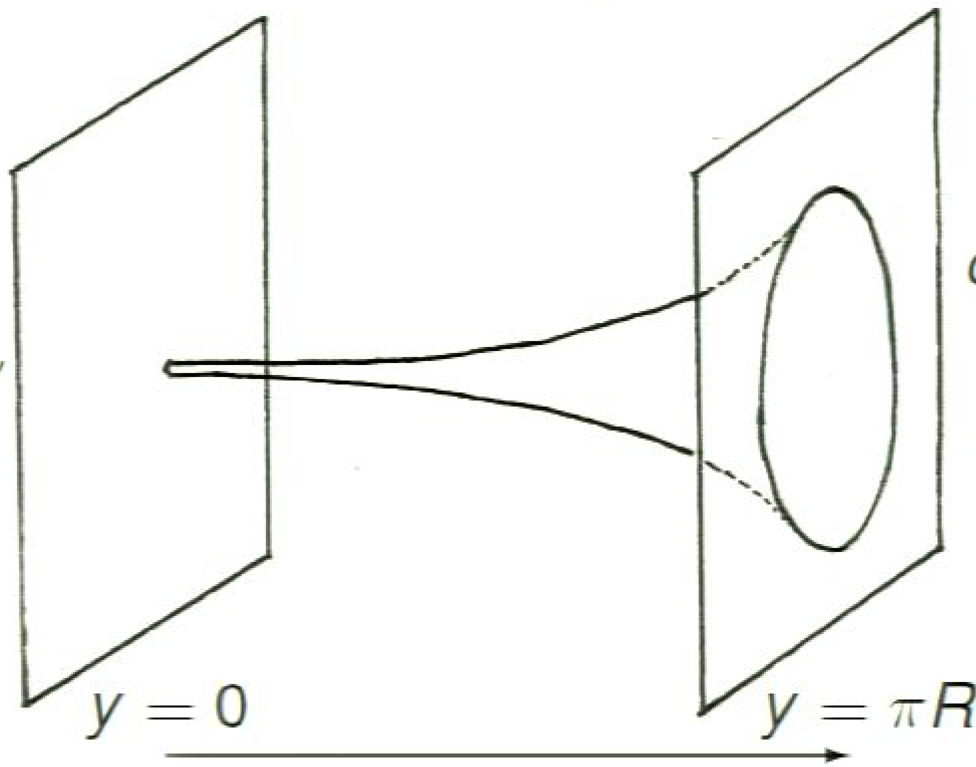

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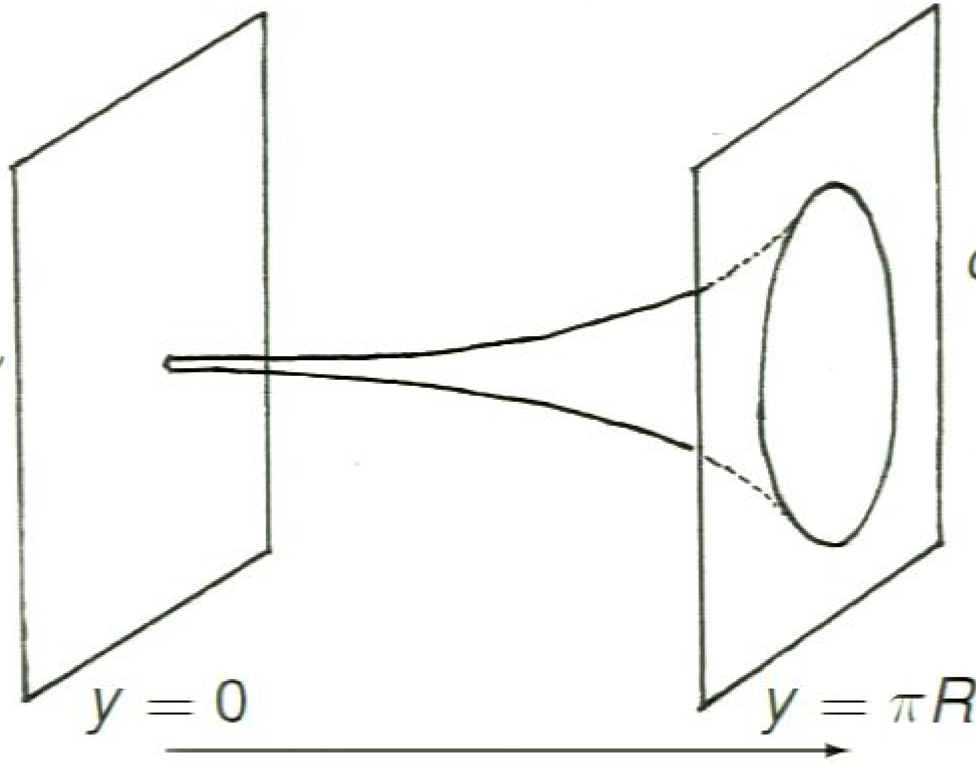

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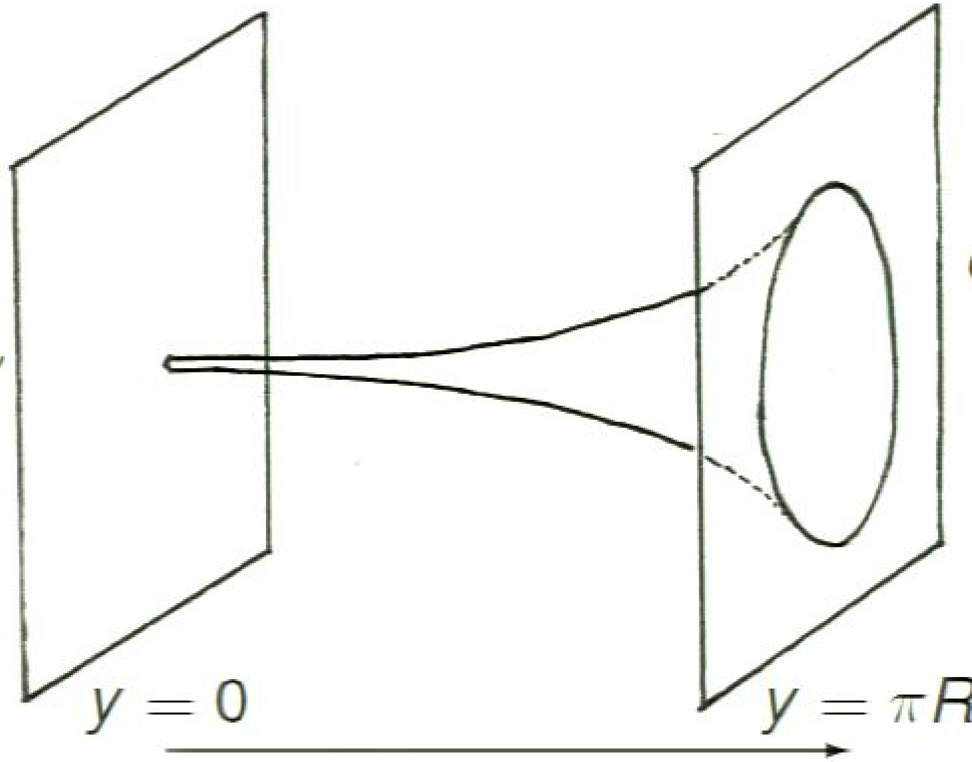

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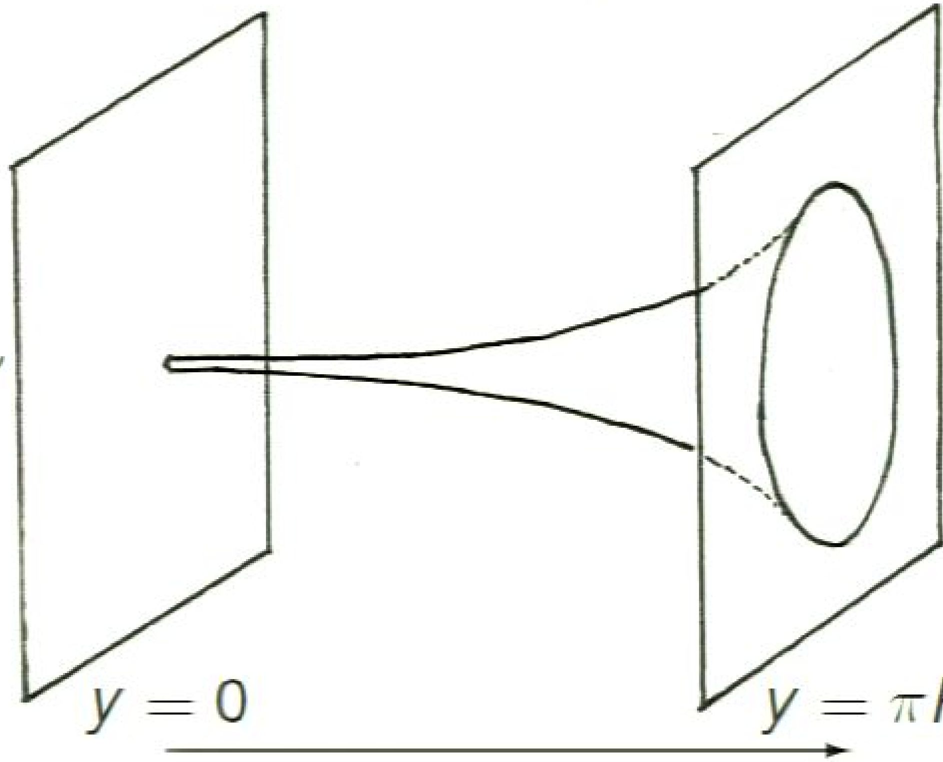

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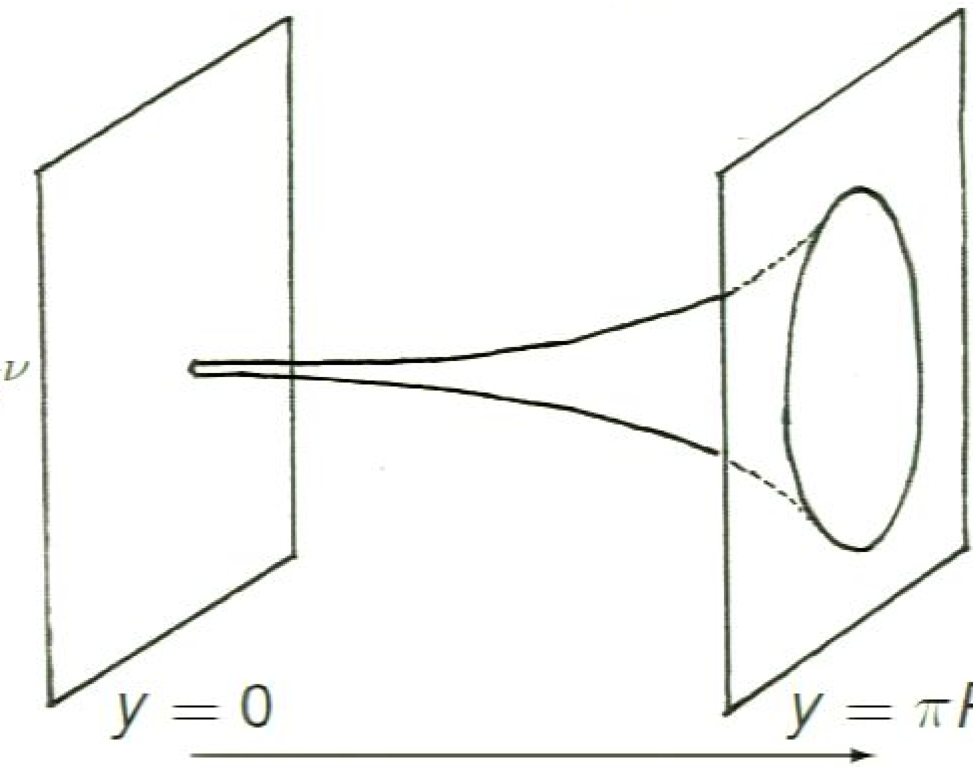

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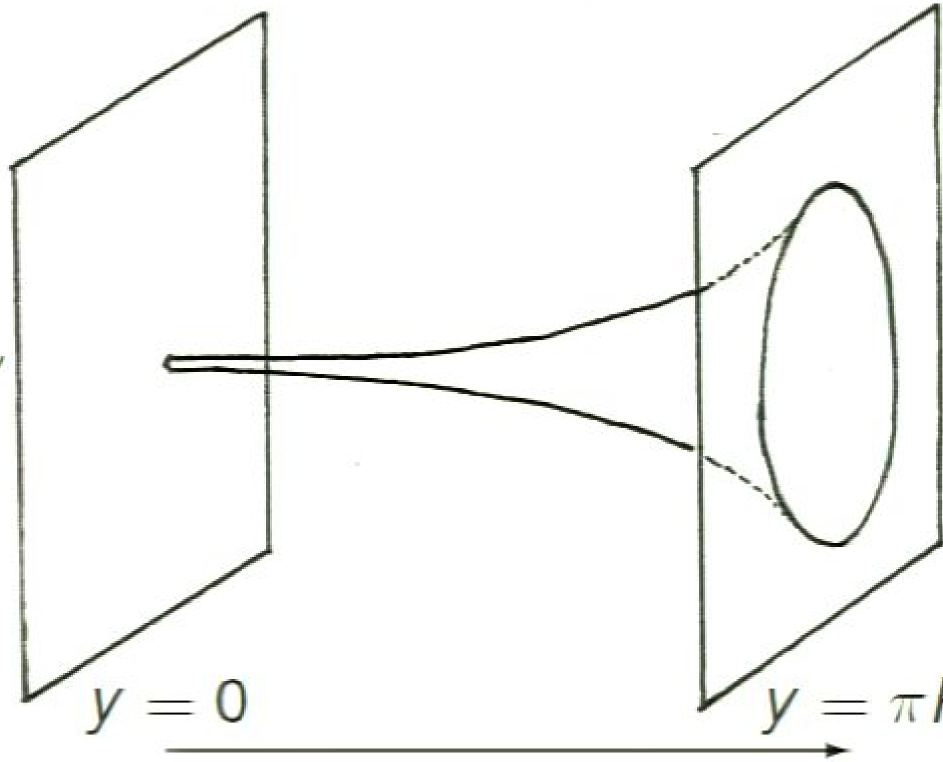

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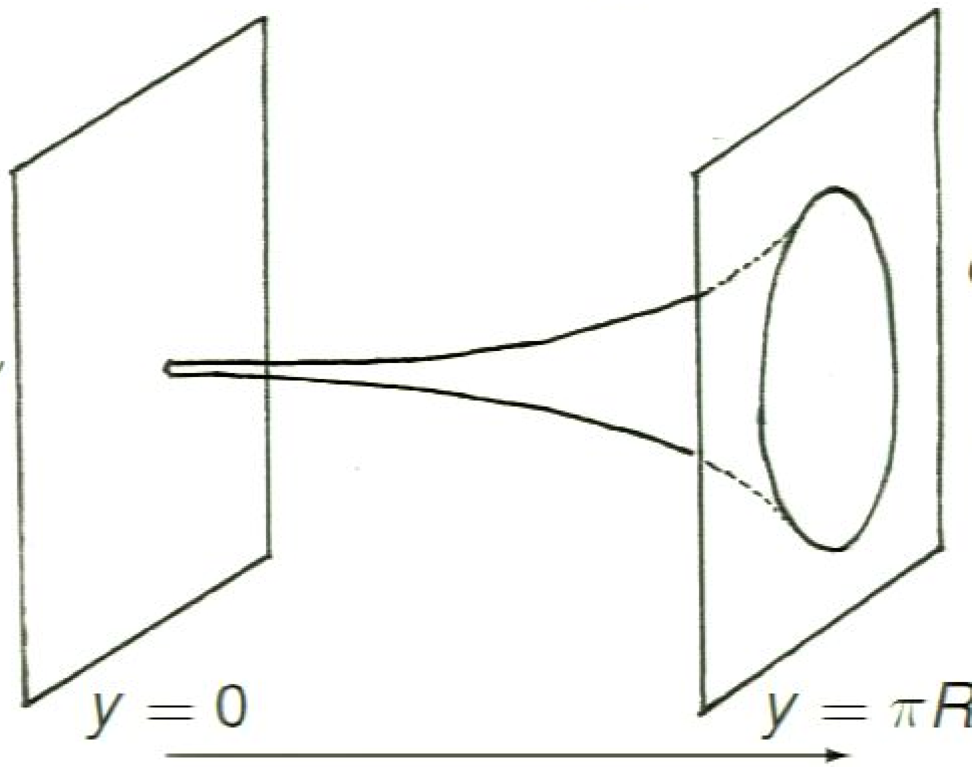

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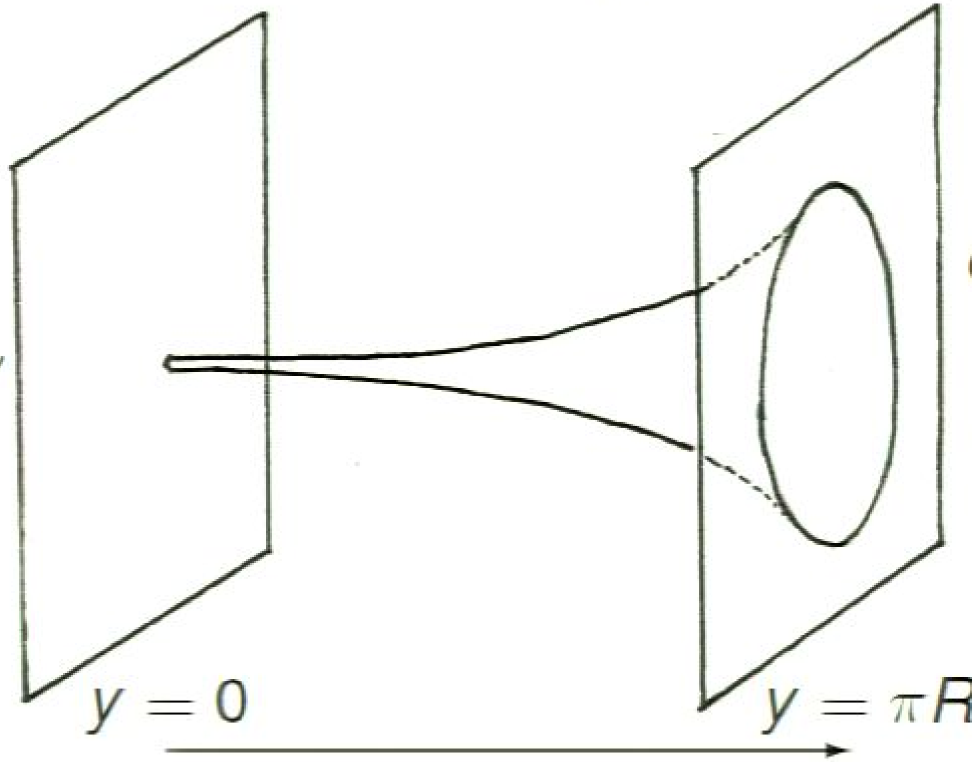

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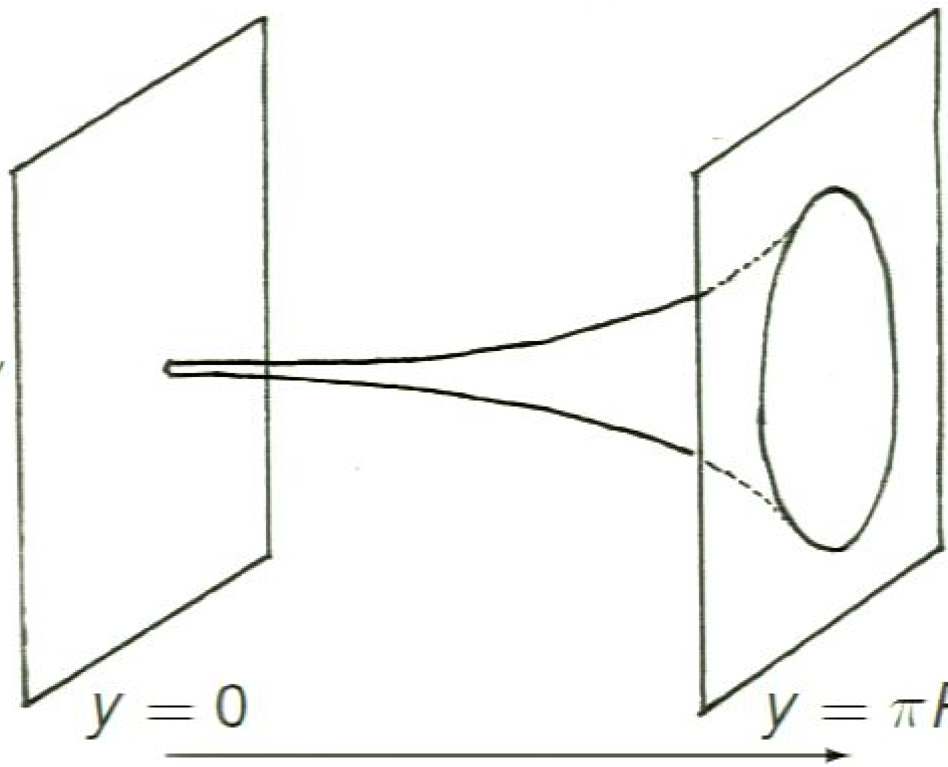

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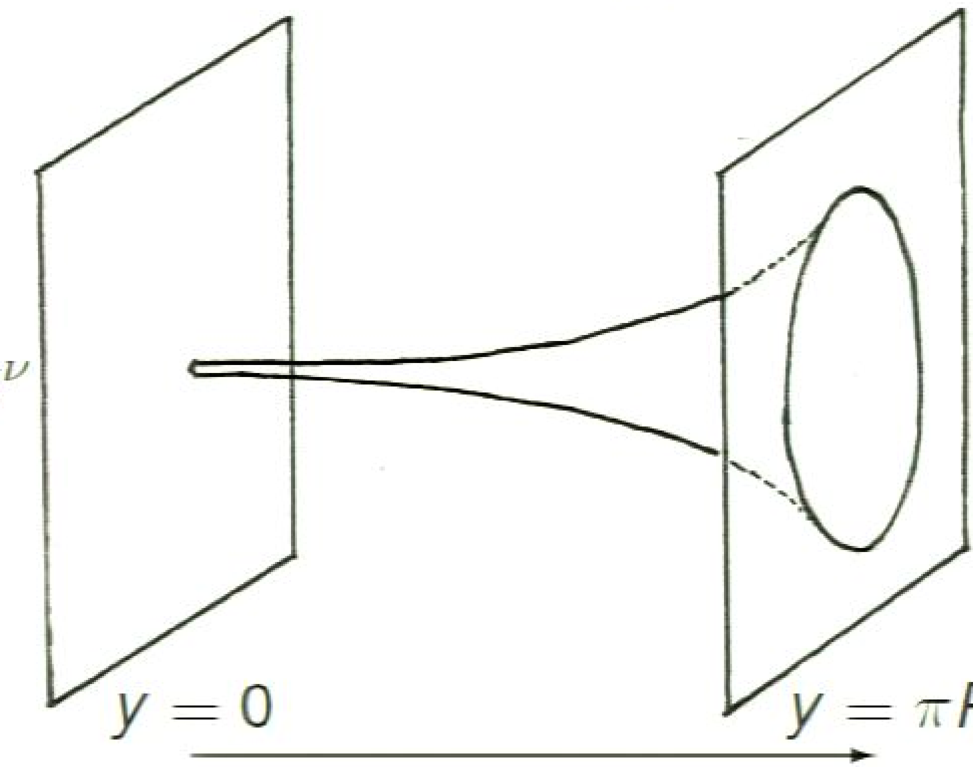

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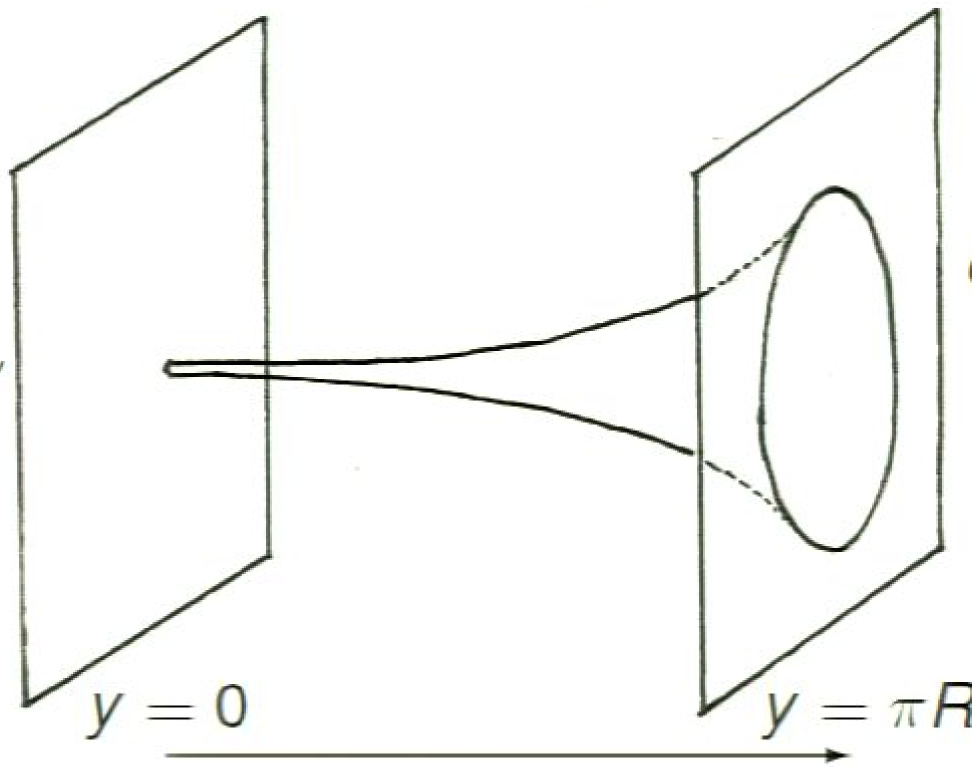

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- Continuum of tensor modes with $m^2 > 0$
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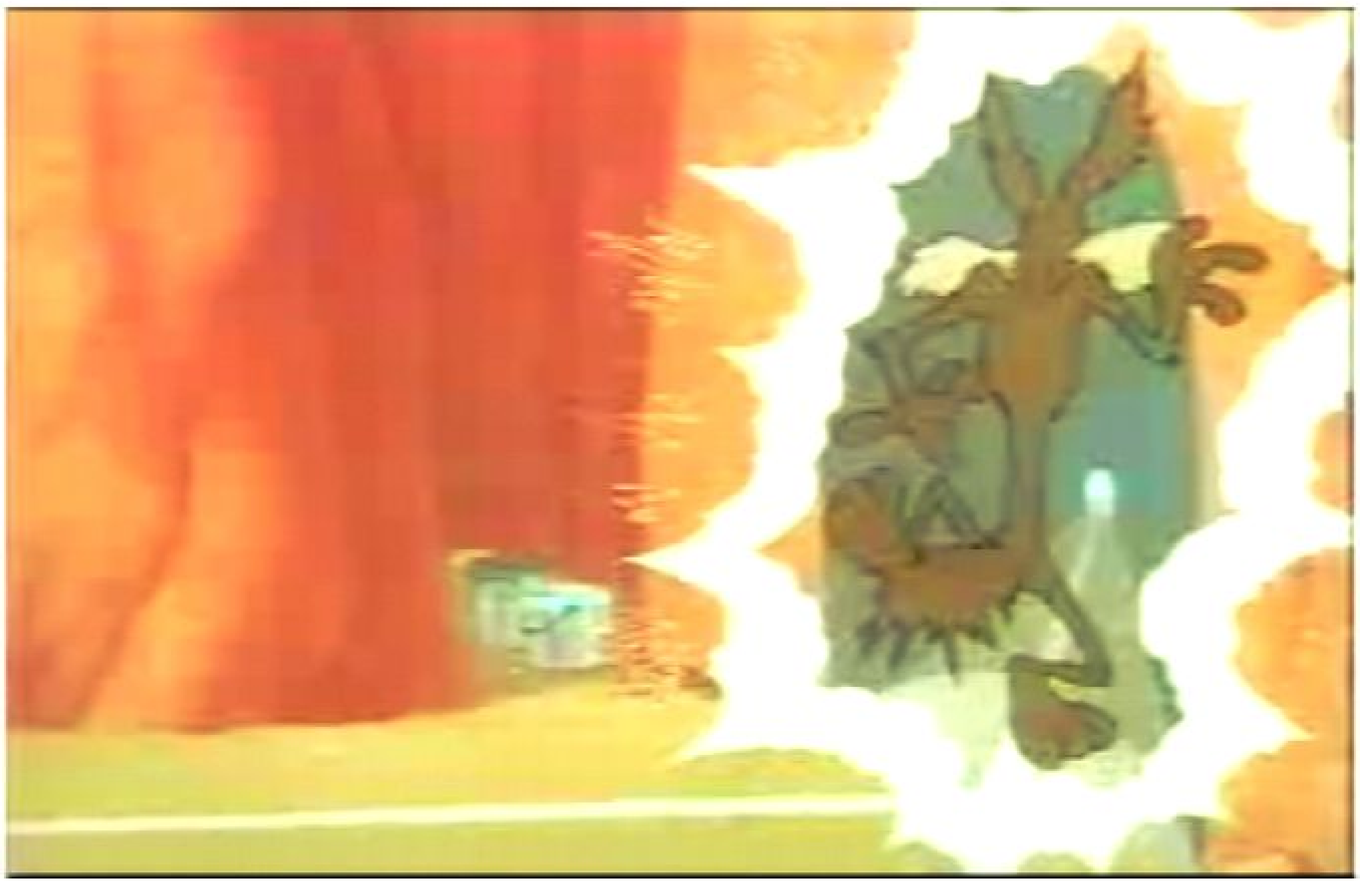

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- A Real Scalar (the “Dilaton”) with power-law VEV
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- Requires at least two real scalars (ϕ, T)

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metric factor: $$A(z) = \ln kz + \frac{2}{3}(\mu z)^\nu$$

dilaton: $$\langle\phi\rangle = \sqrt{\frac{8}{3}}(\mu z)^\nu$$

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- Requires at least two real scalars (ϕ, T)

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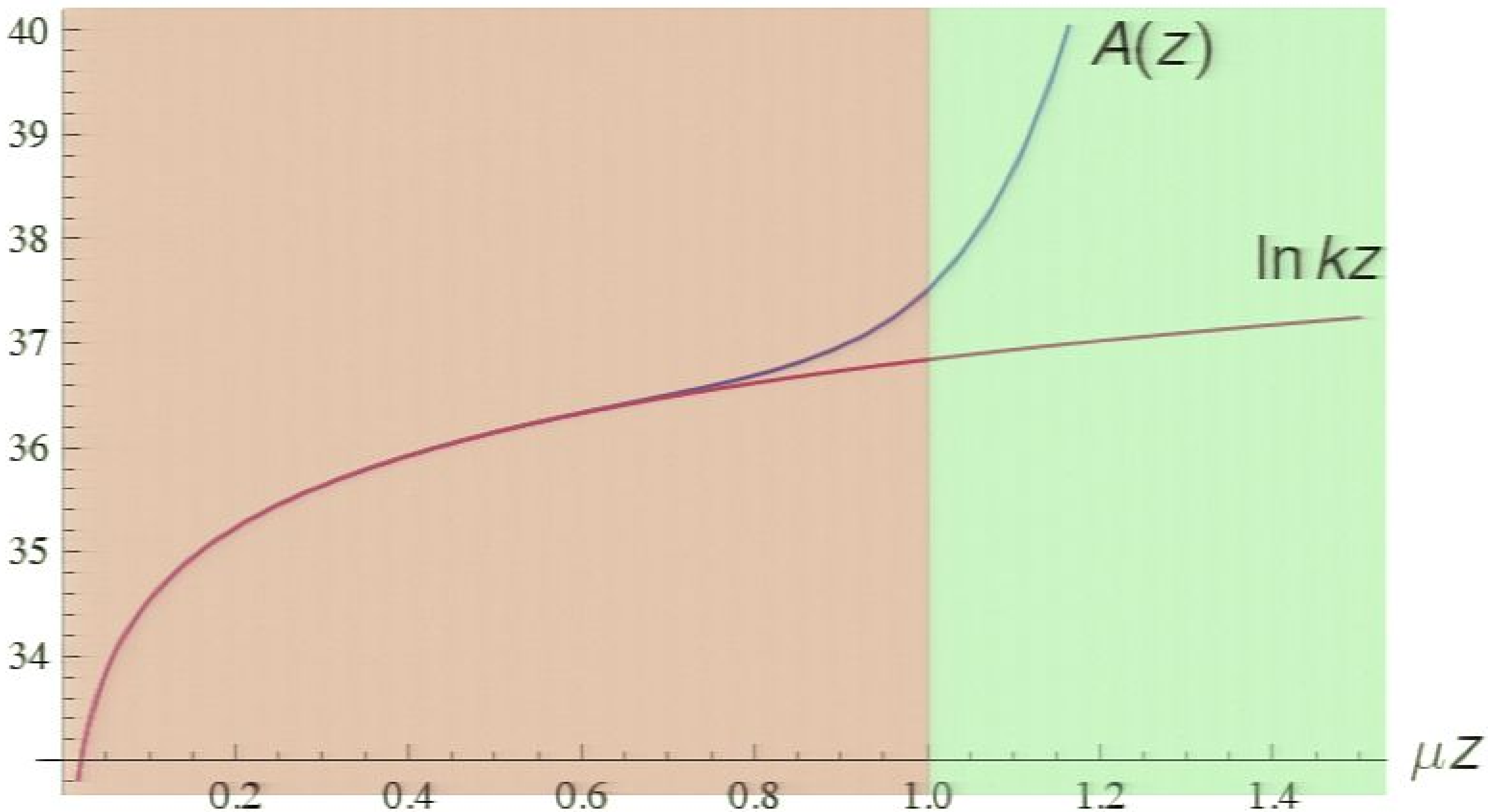

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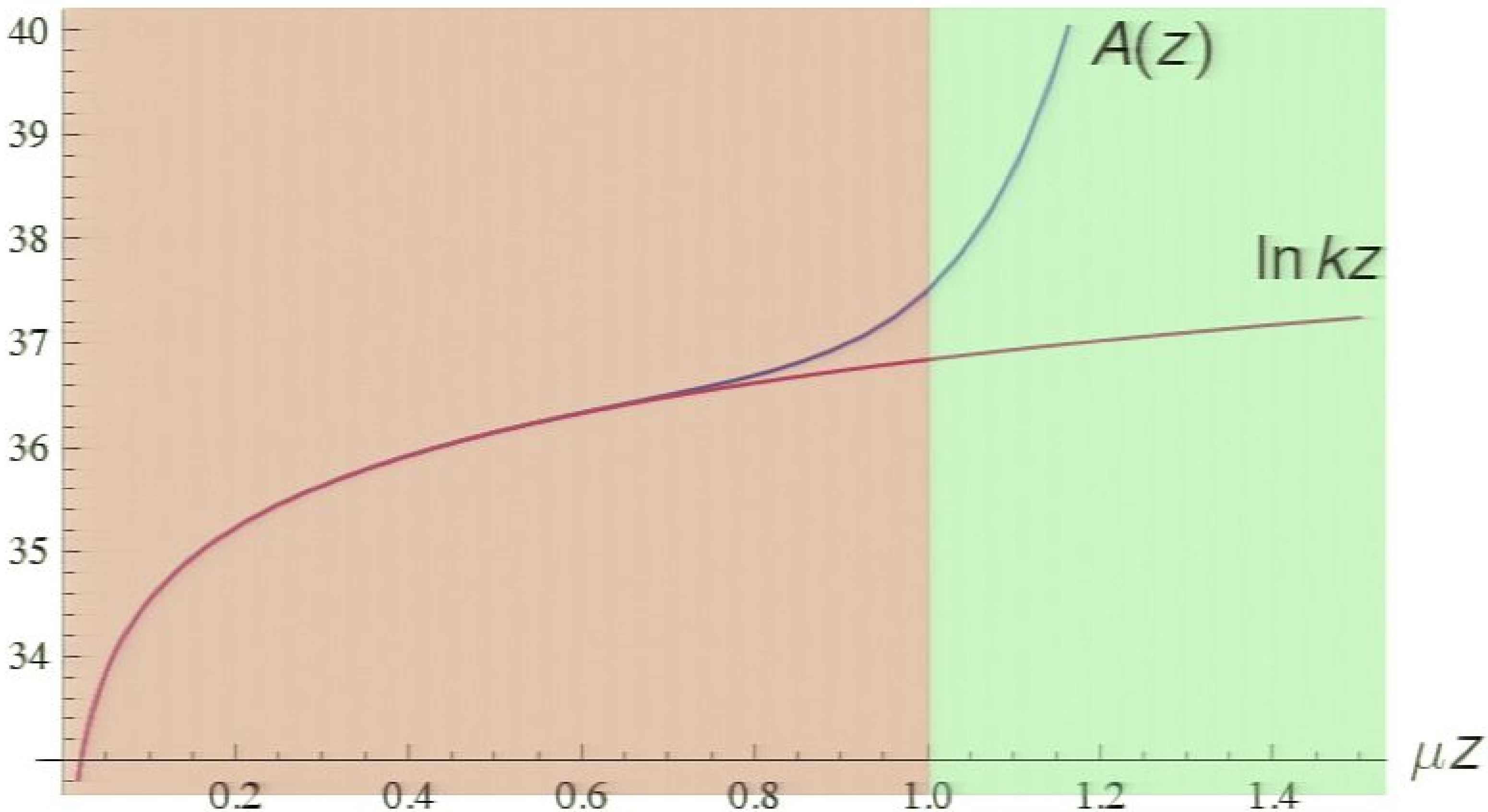

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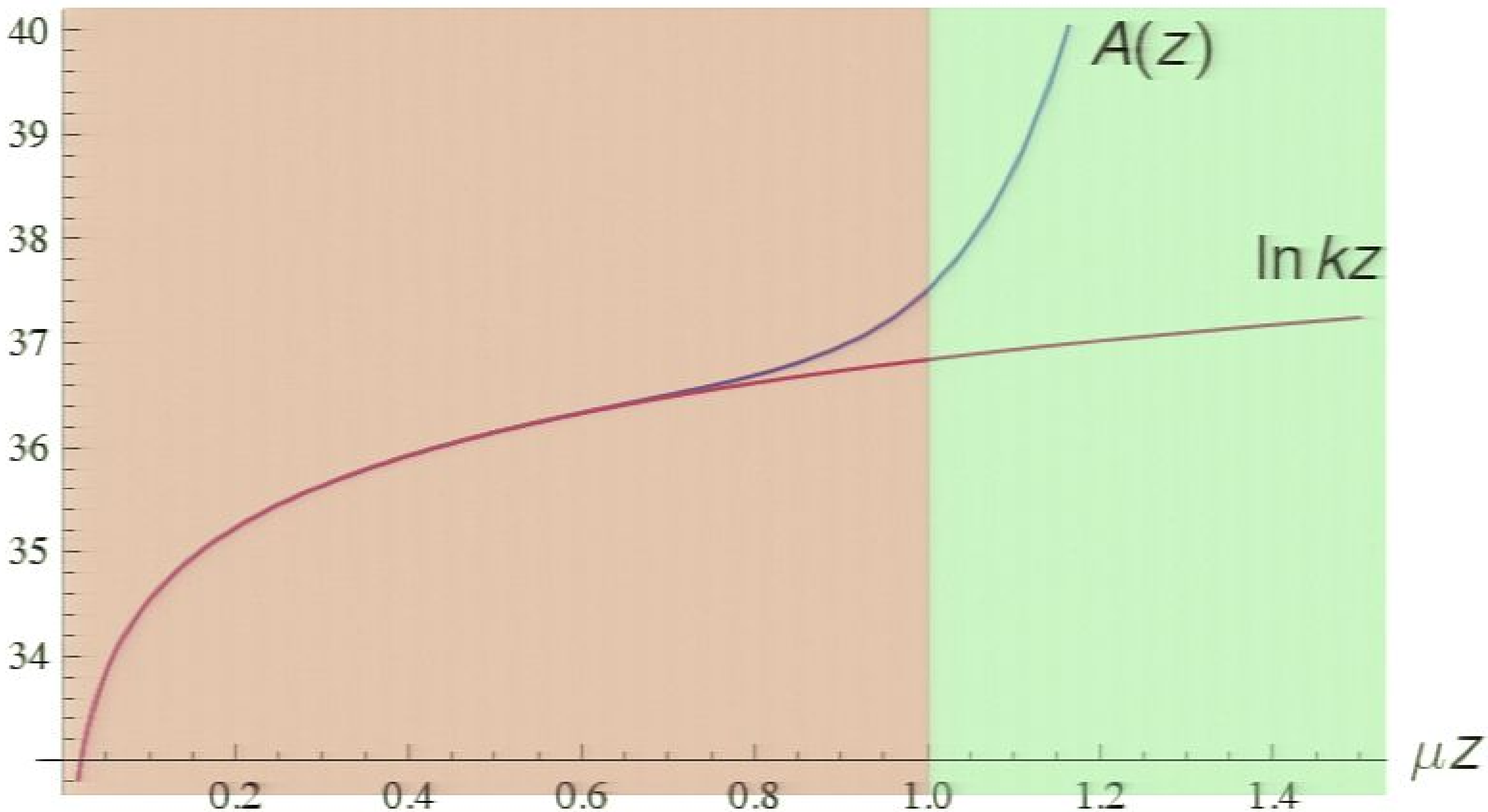

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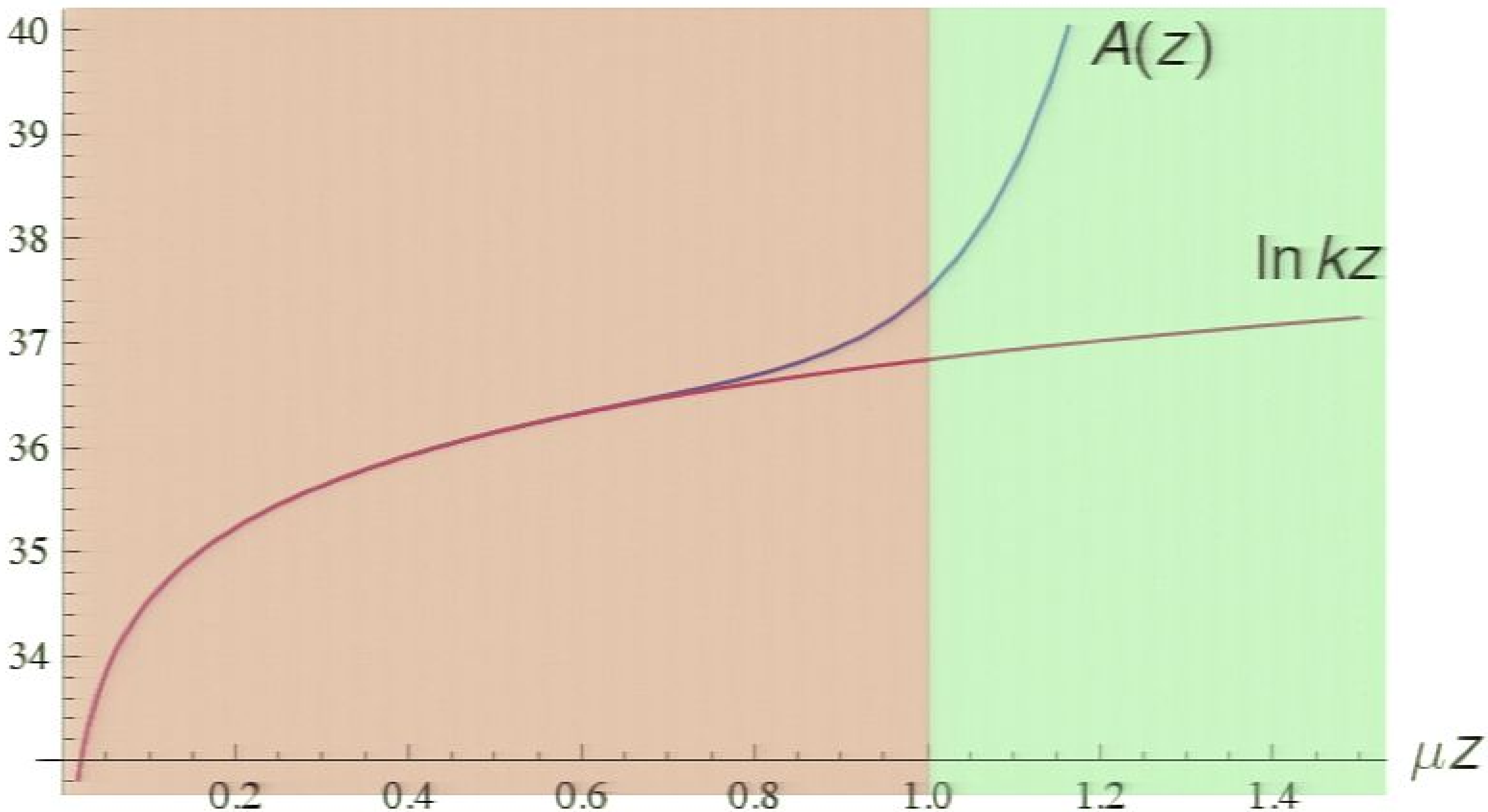

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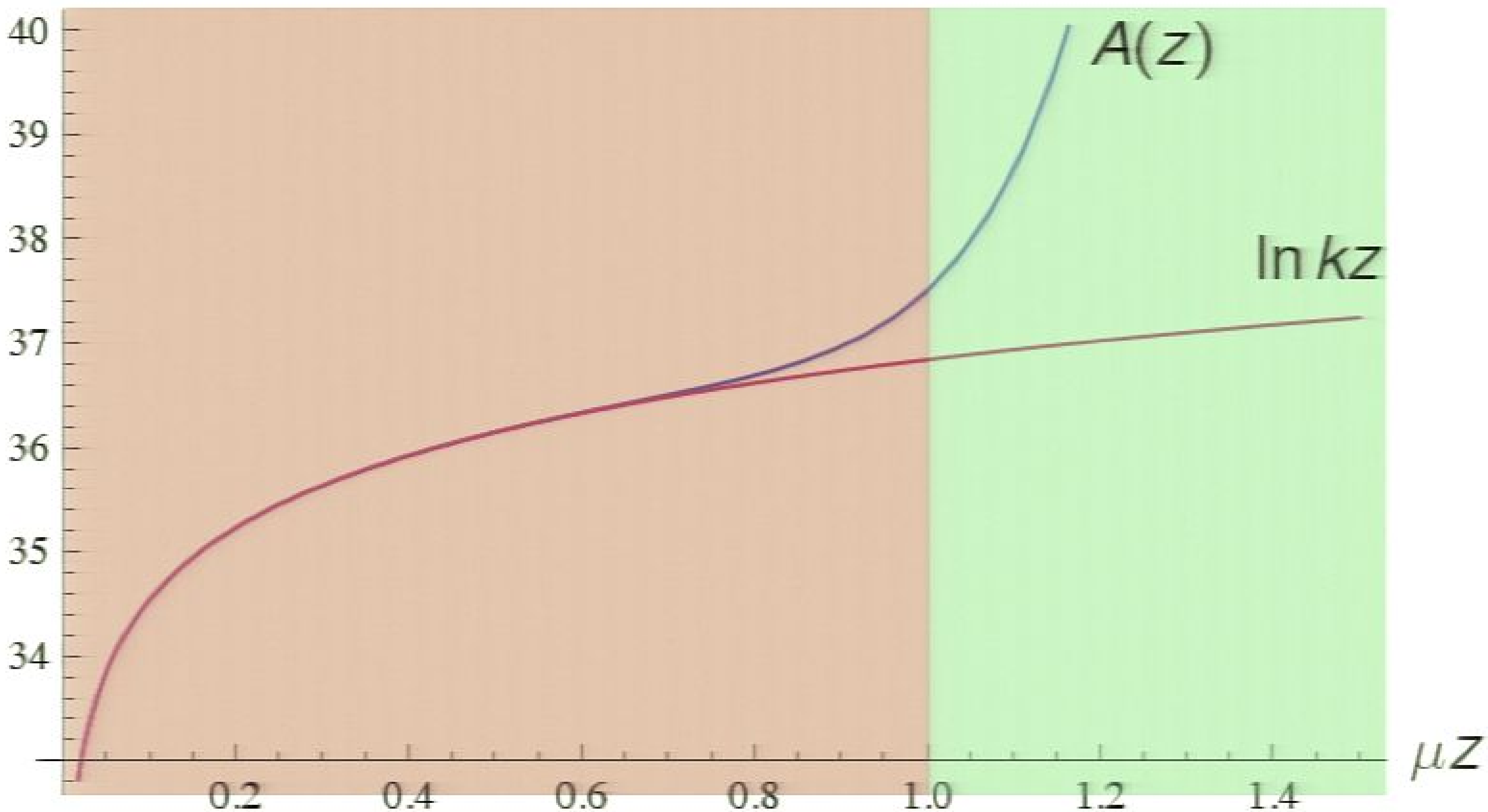

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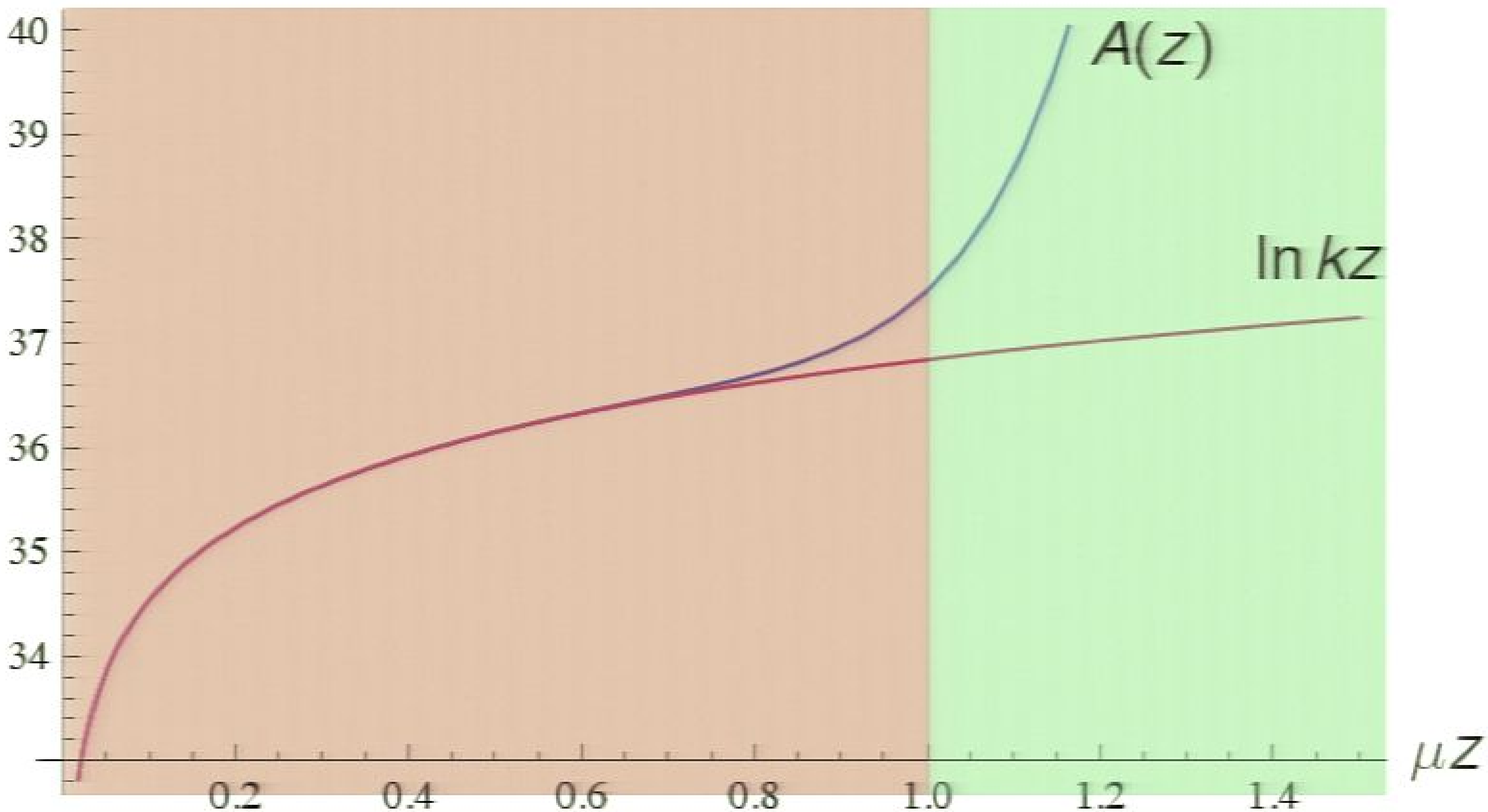

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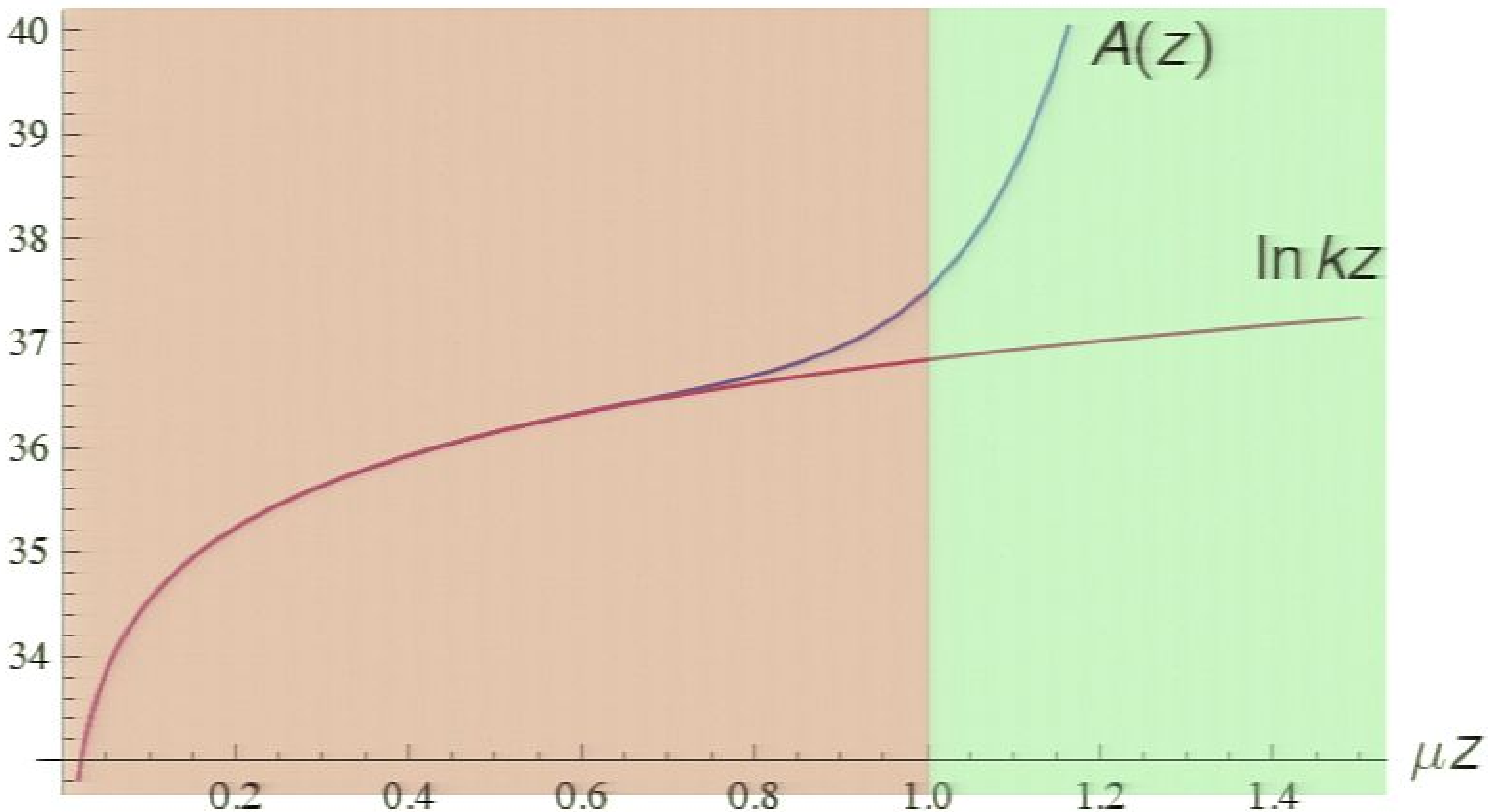

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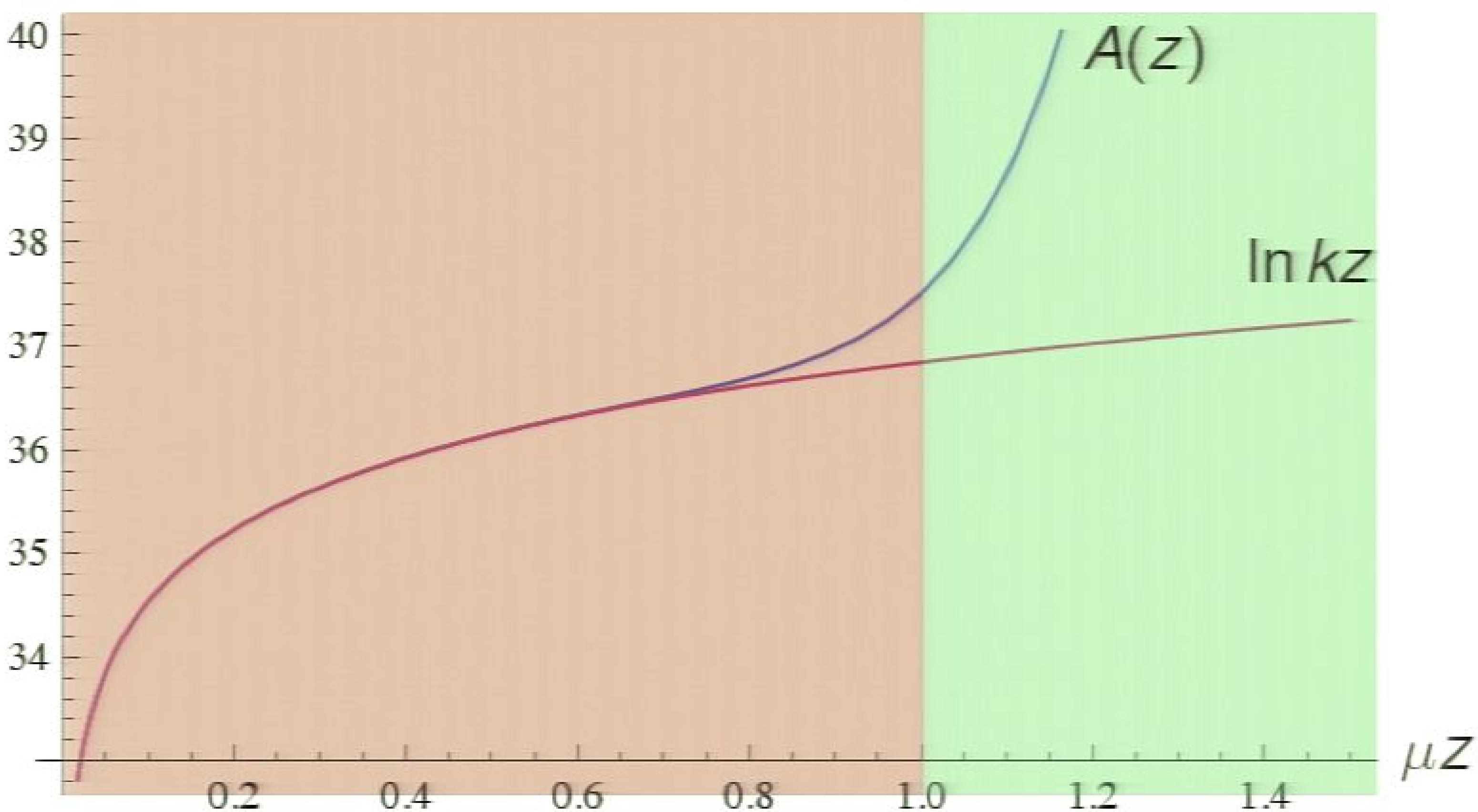

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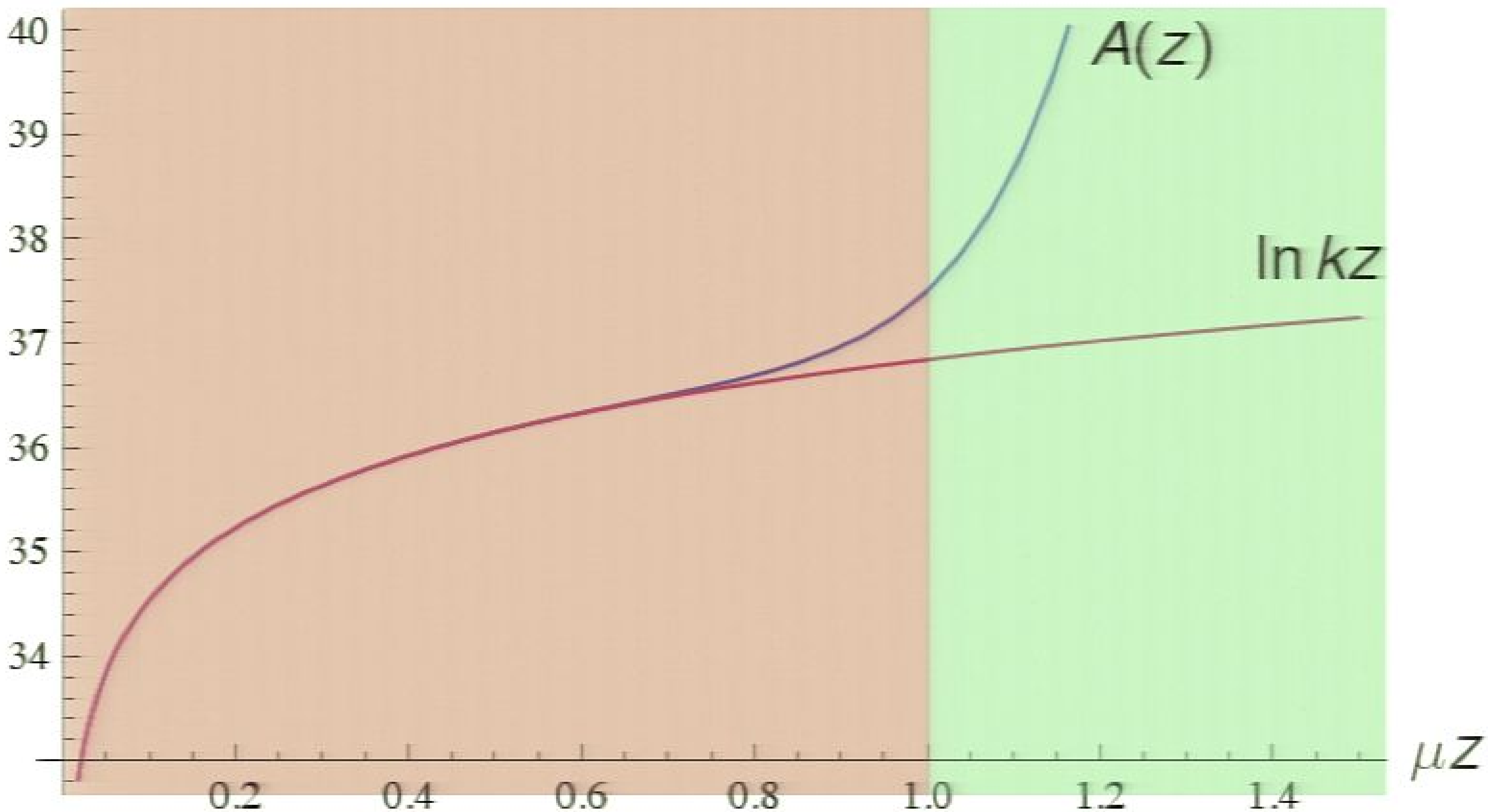

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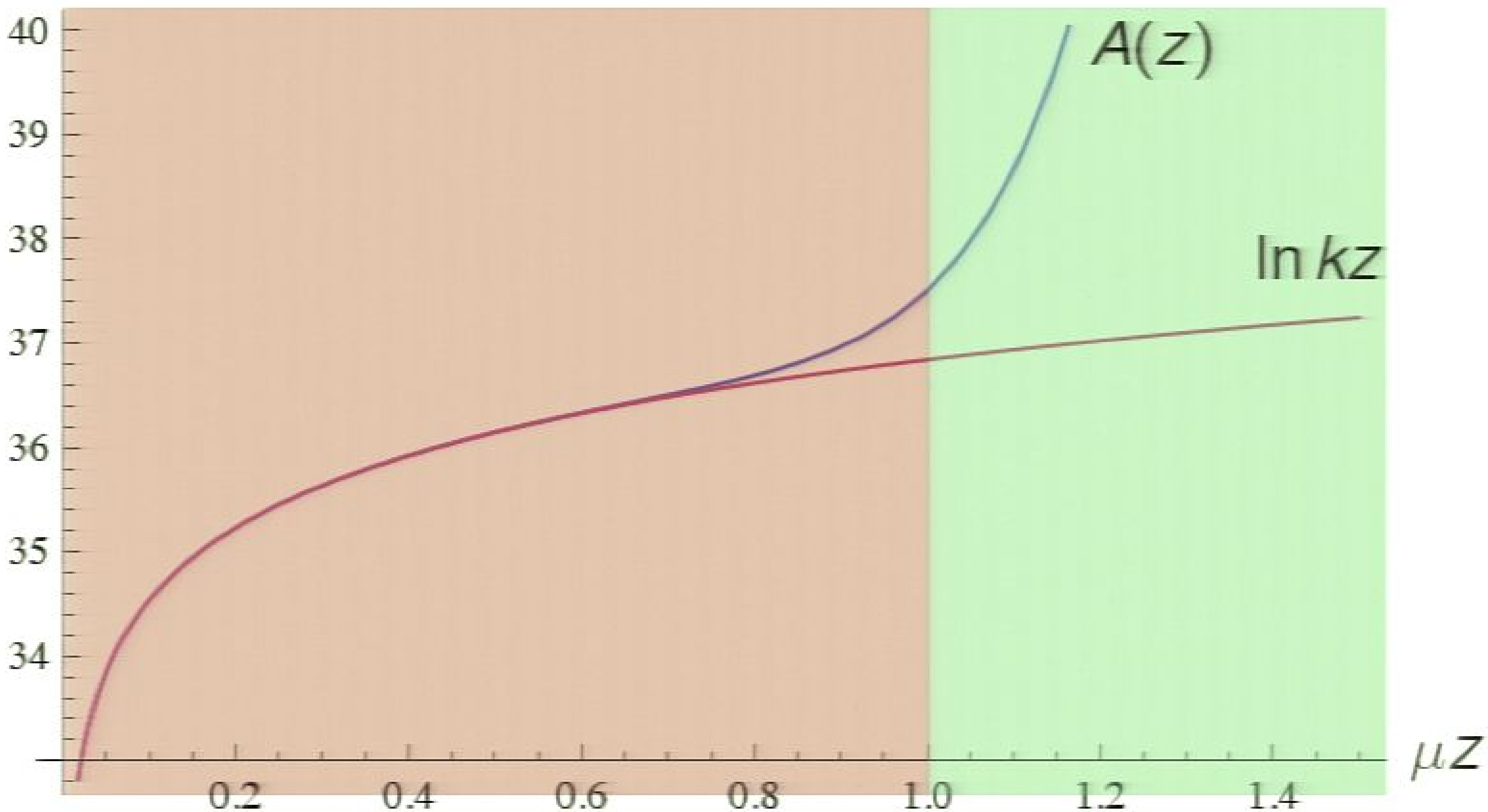

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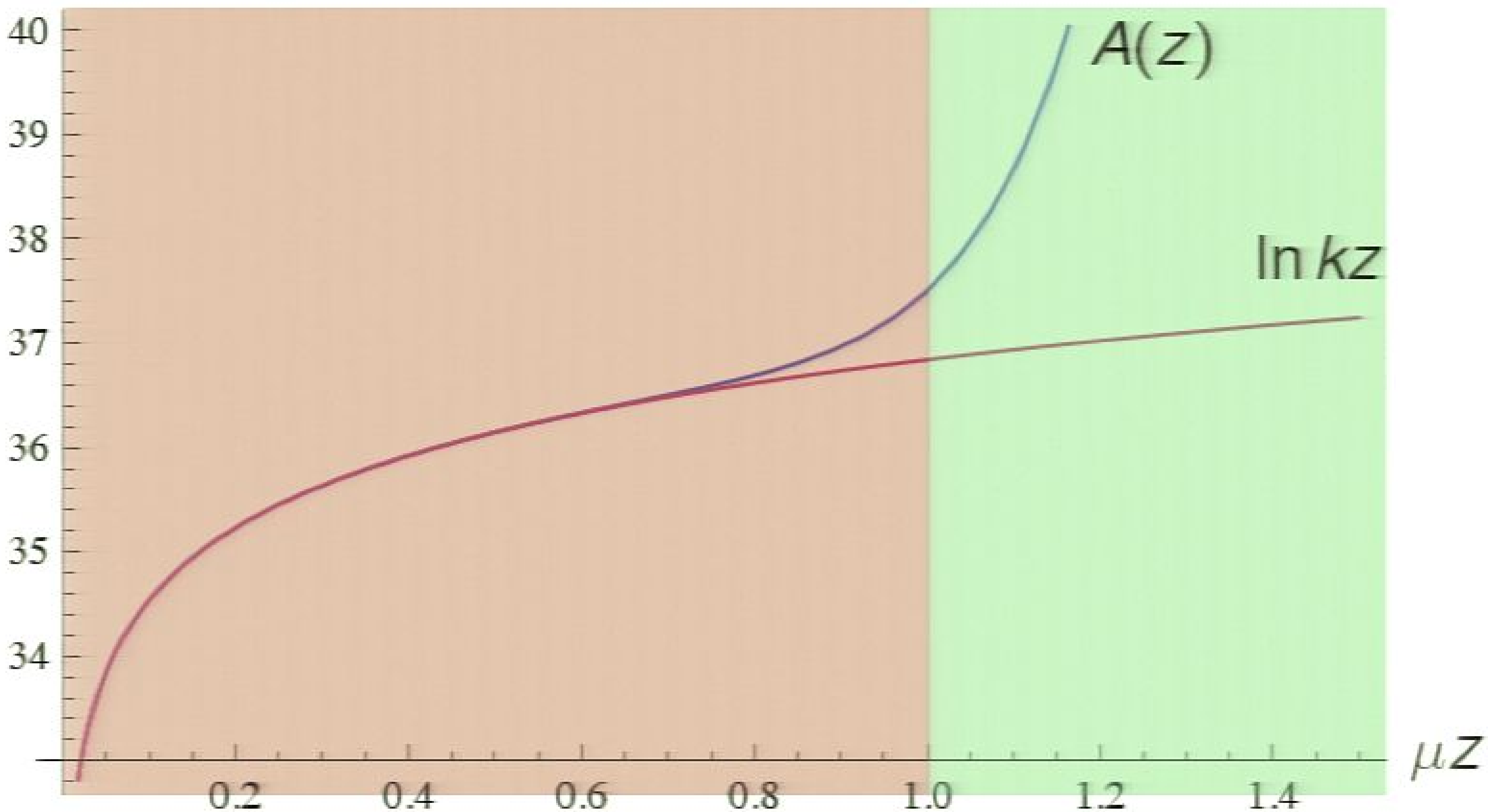

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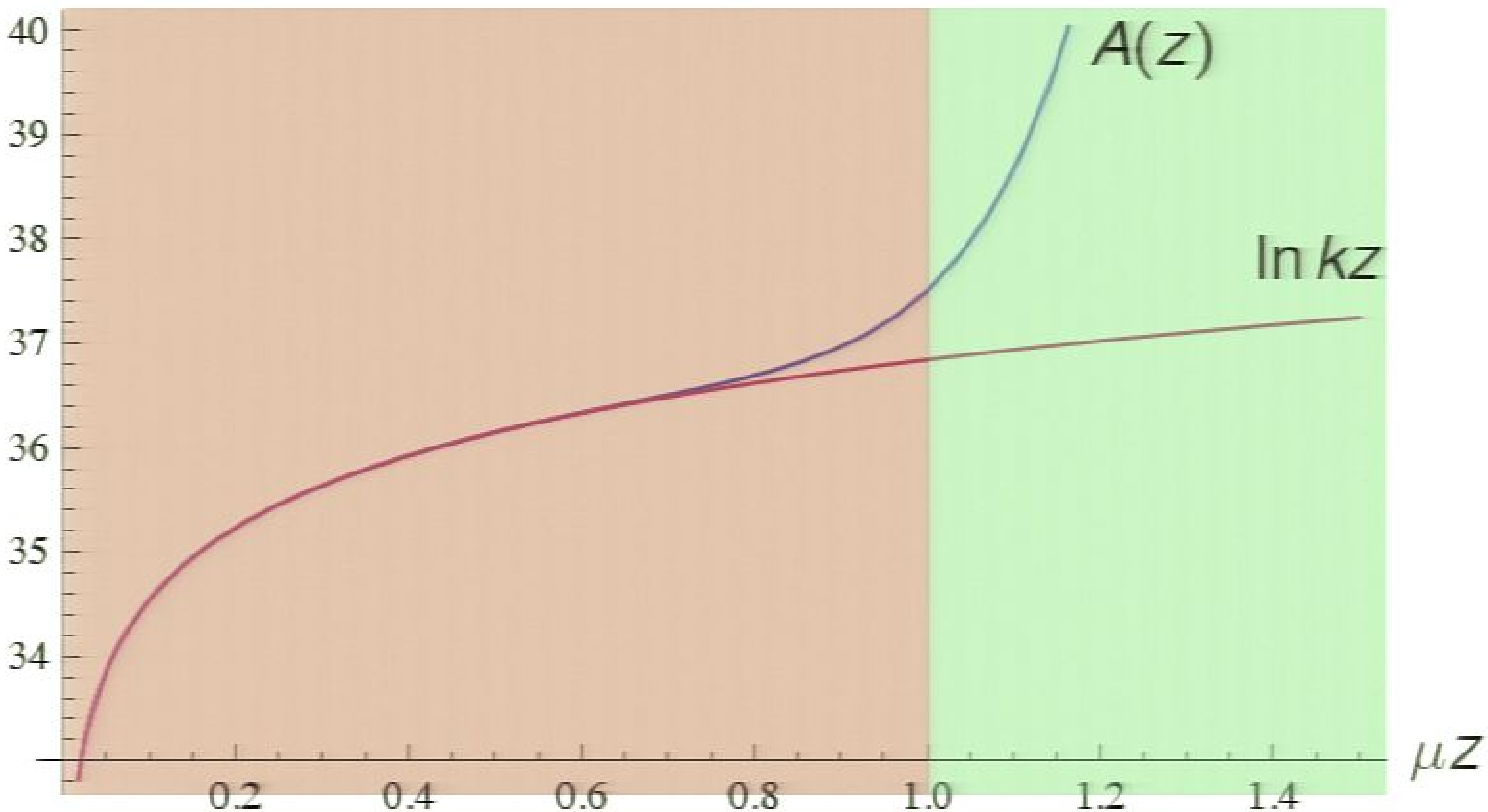

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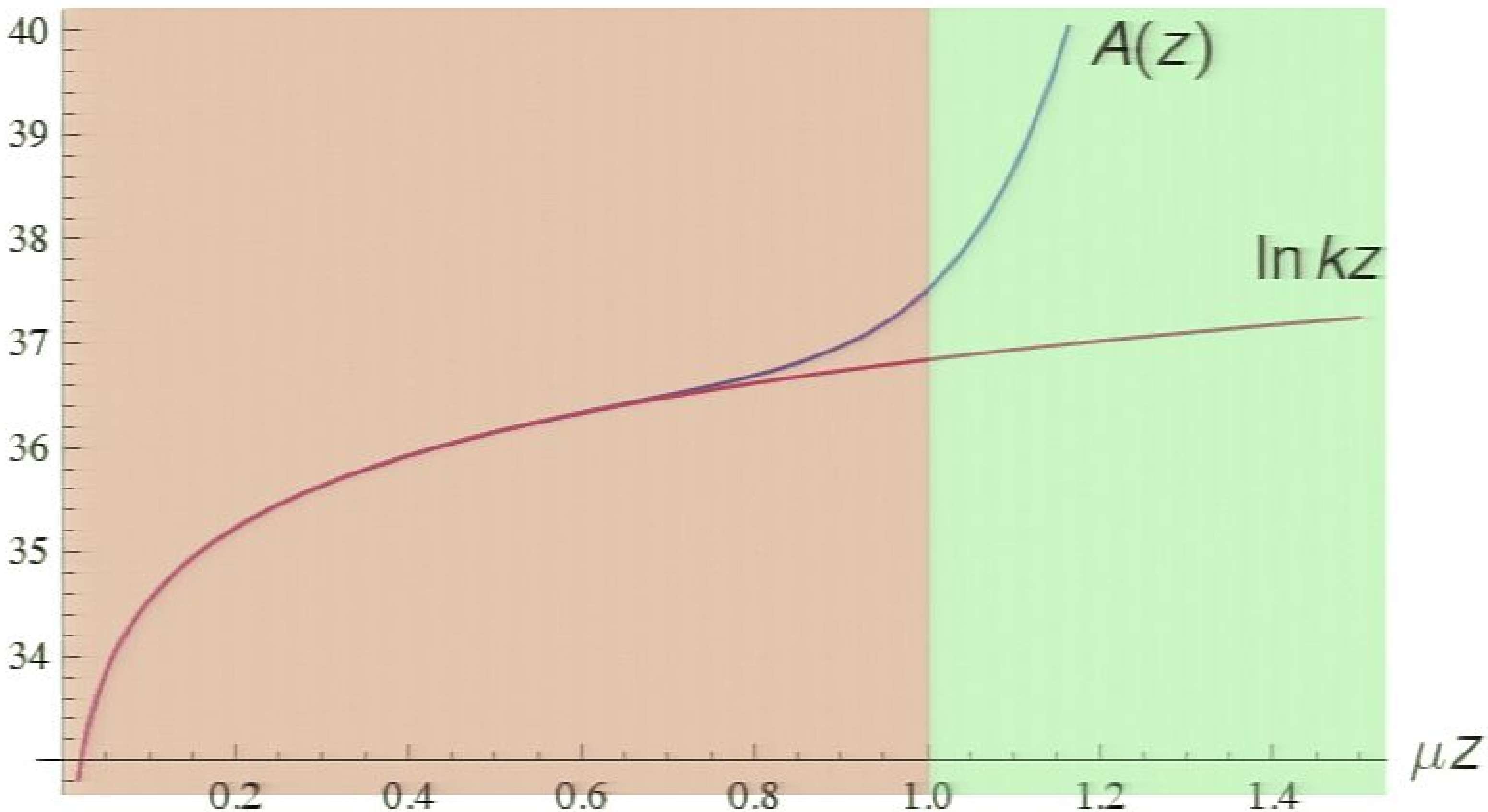

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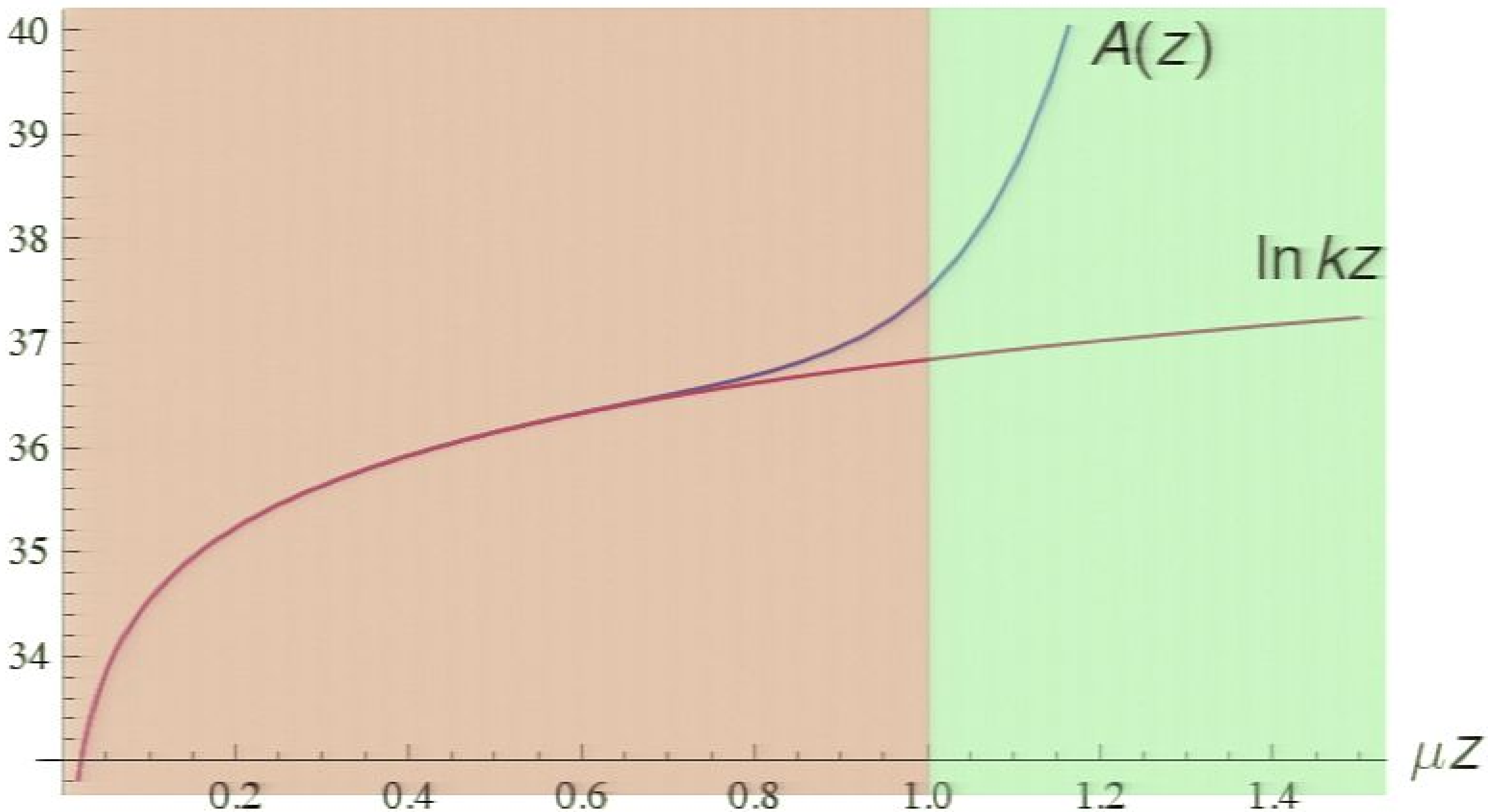

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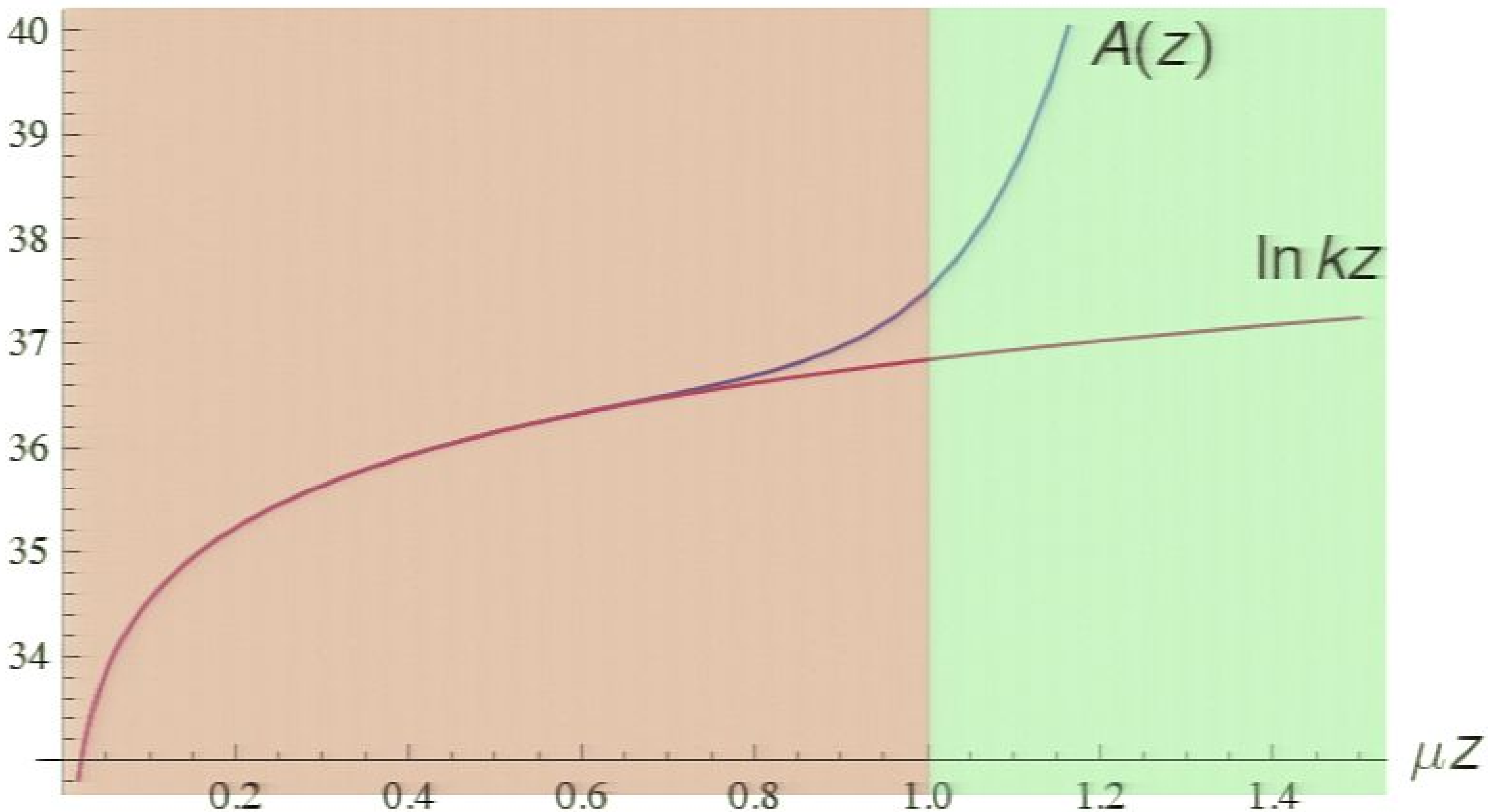

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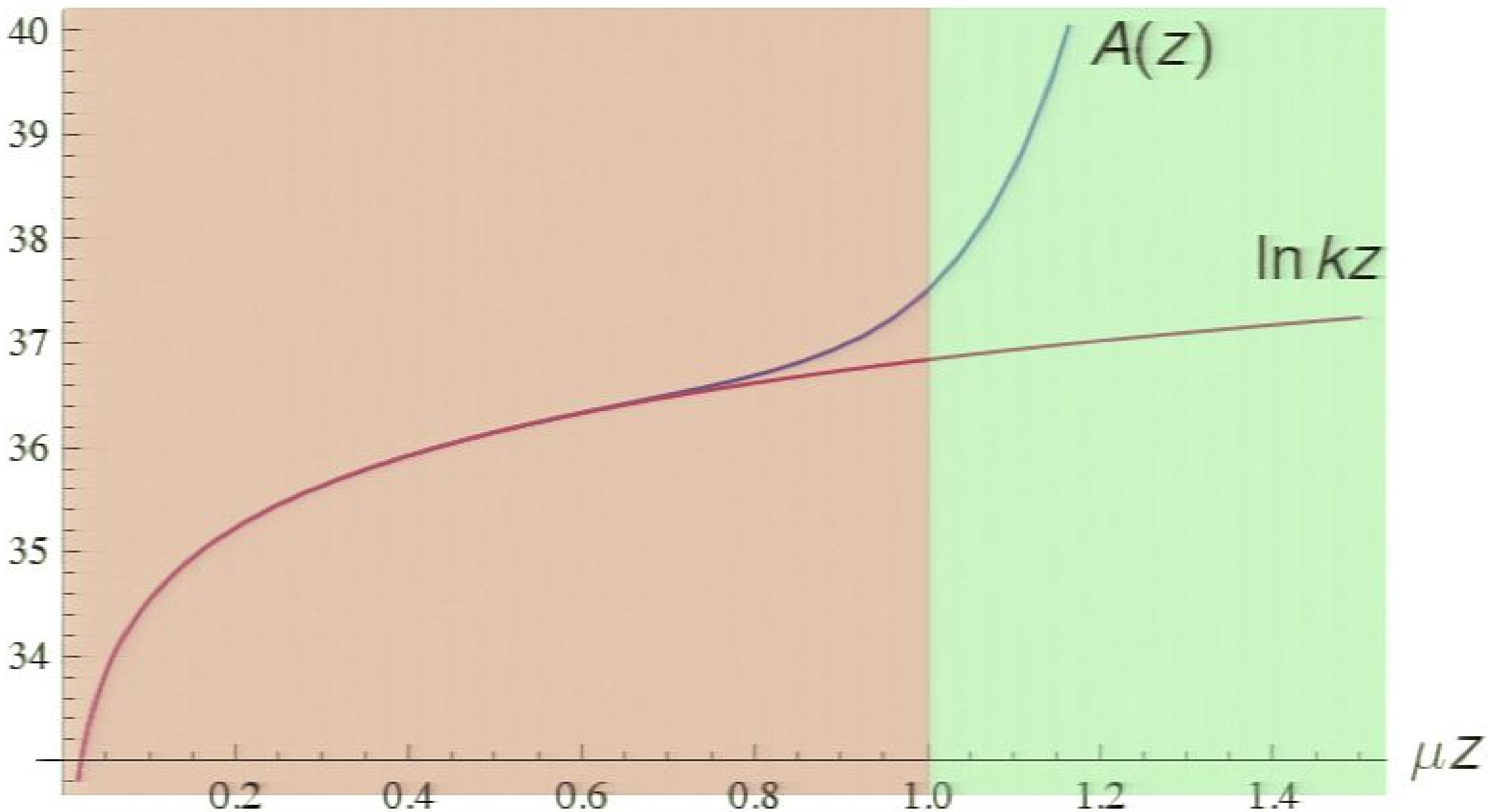

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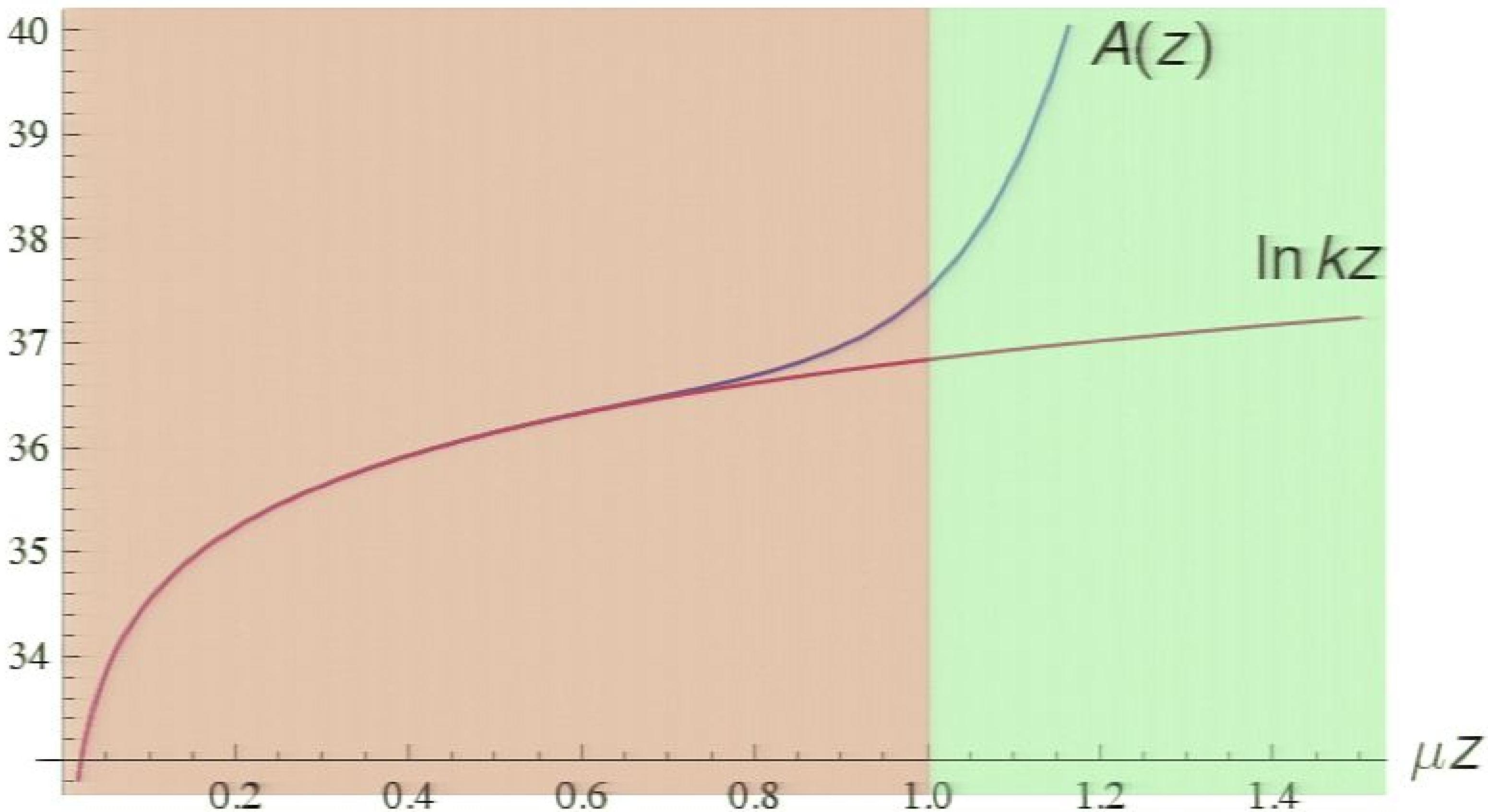

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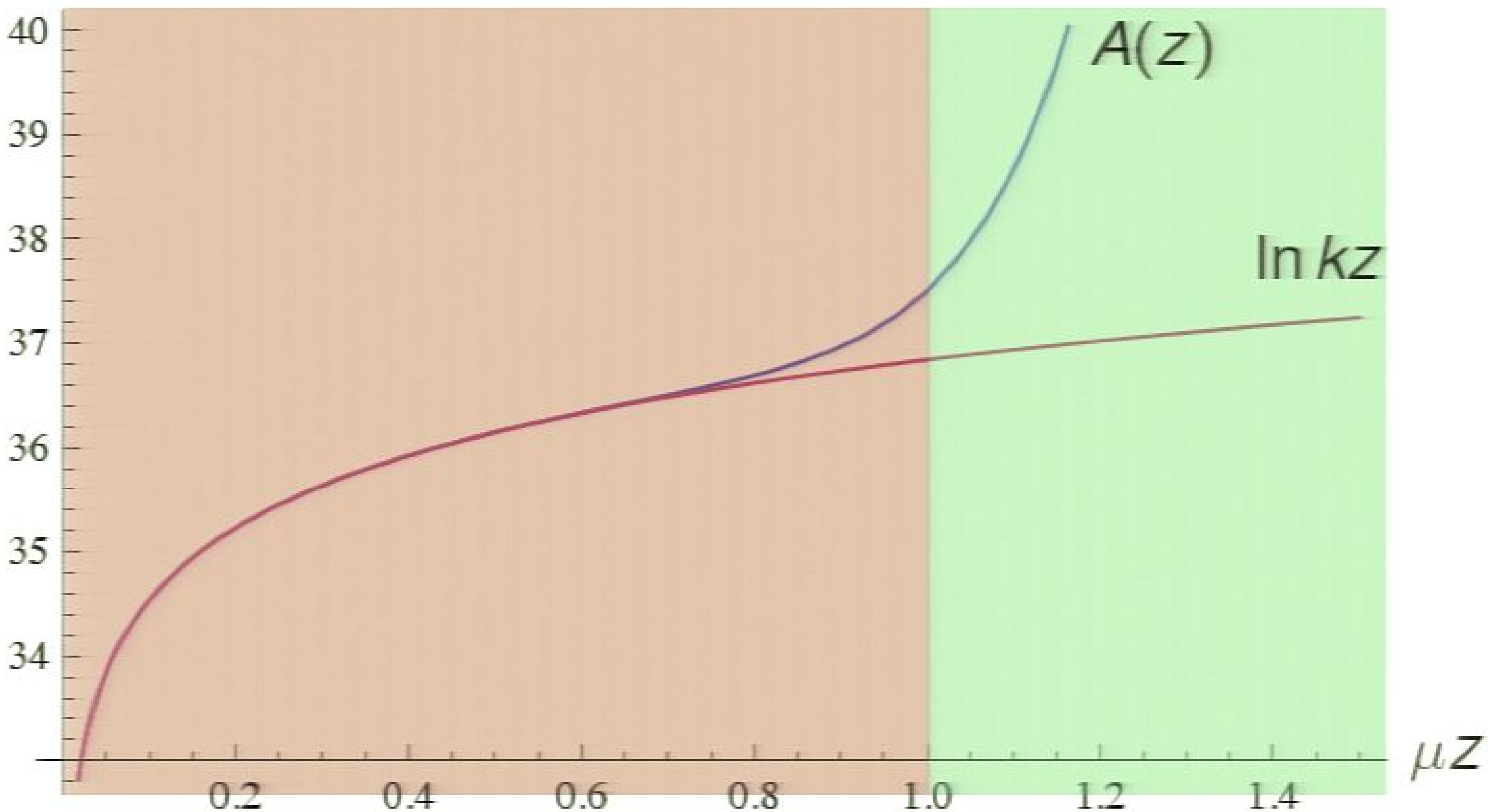

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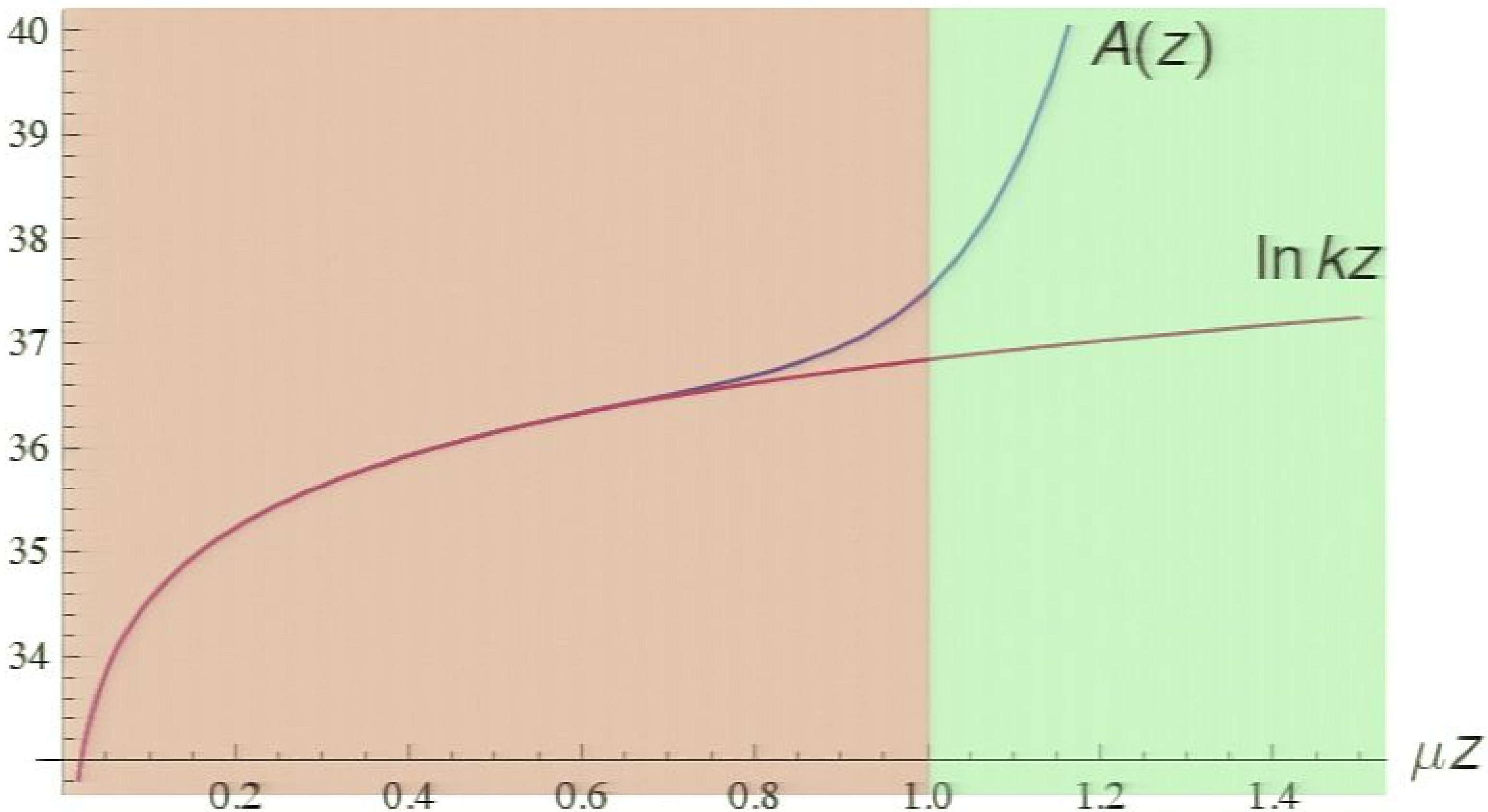

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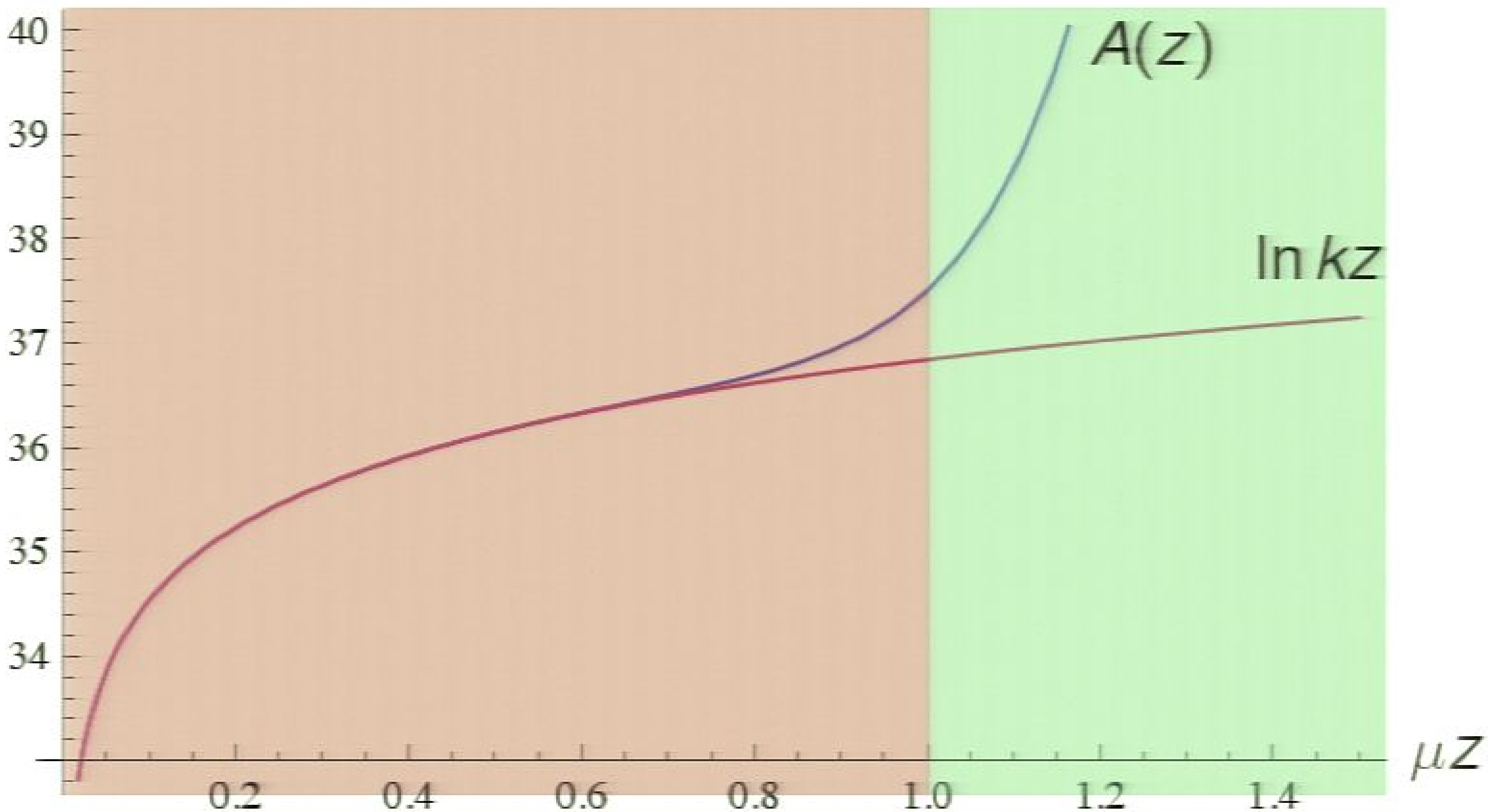

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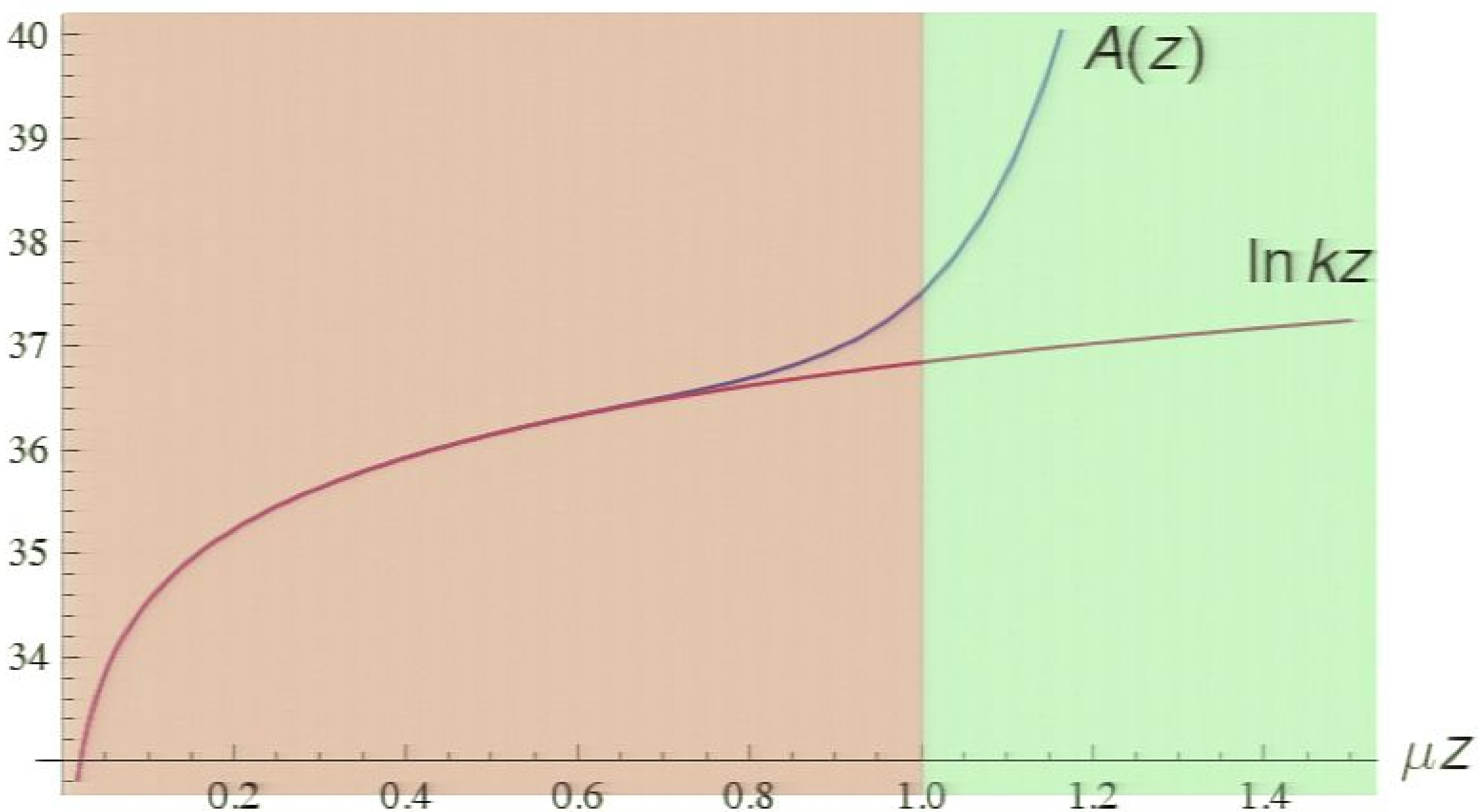

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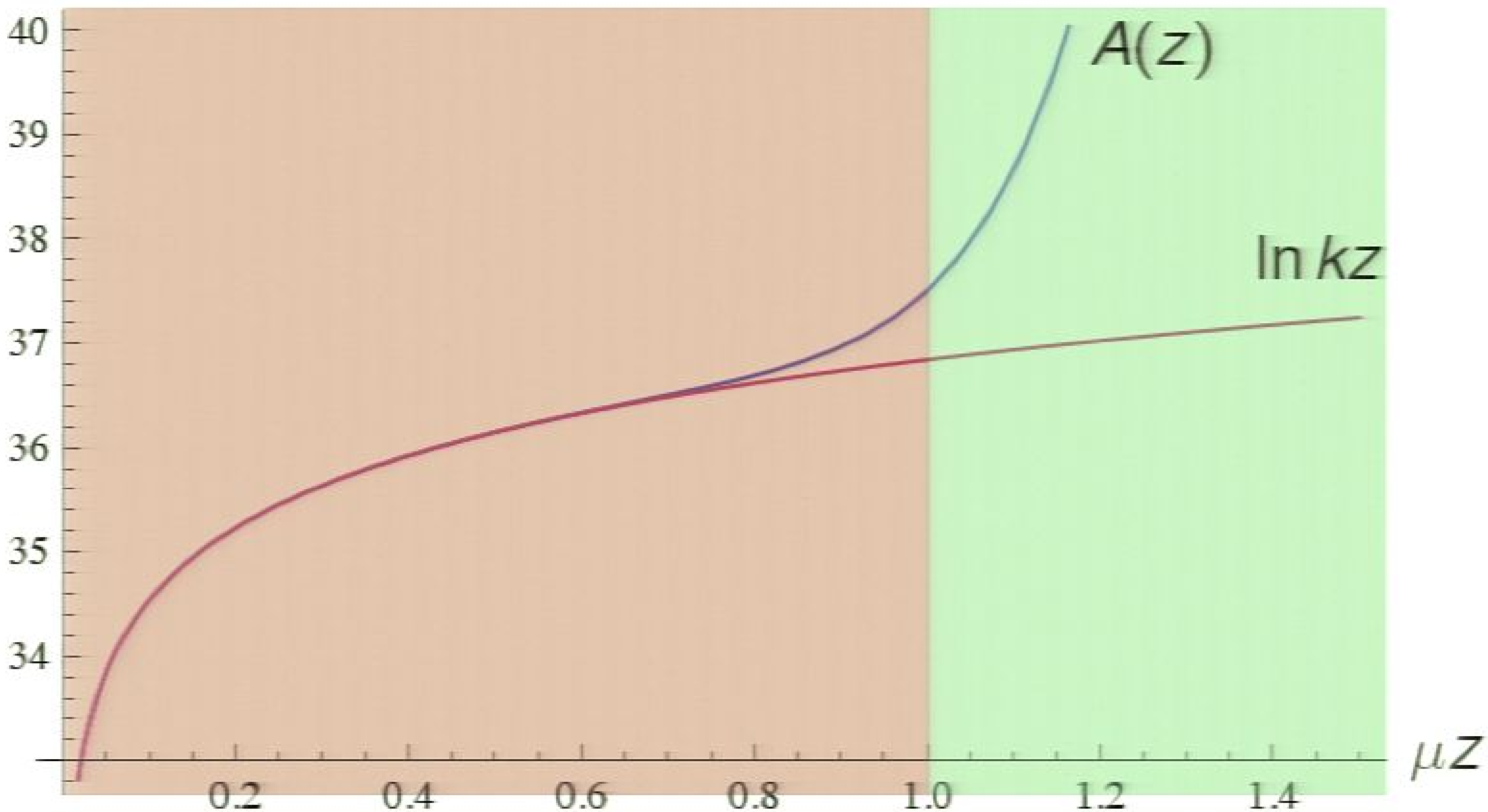

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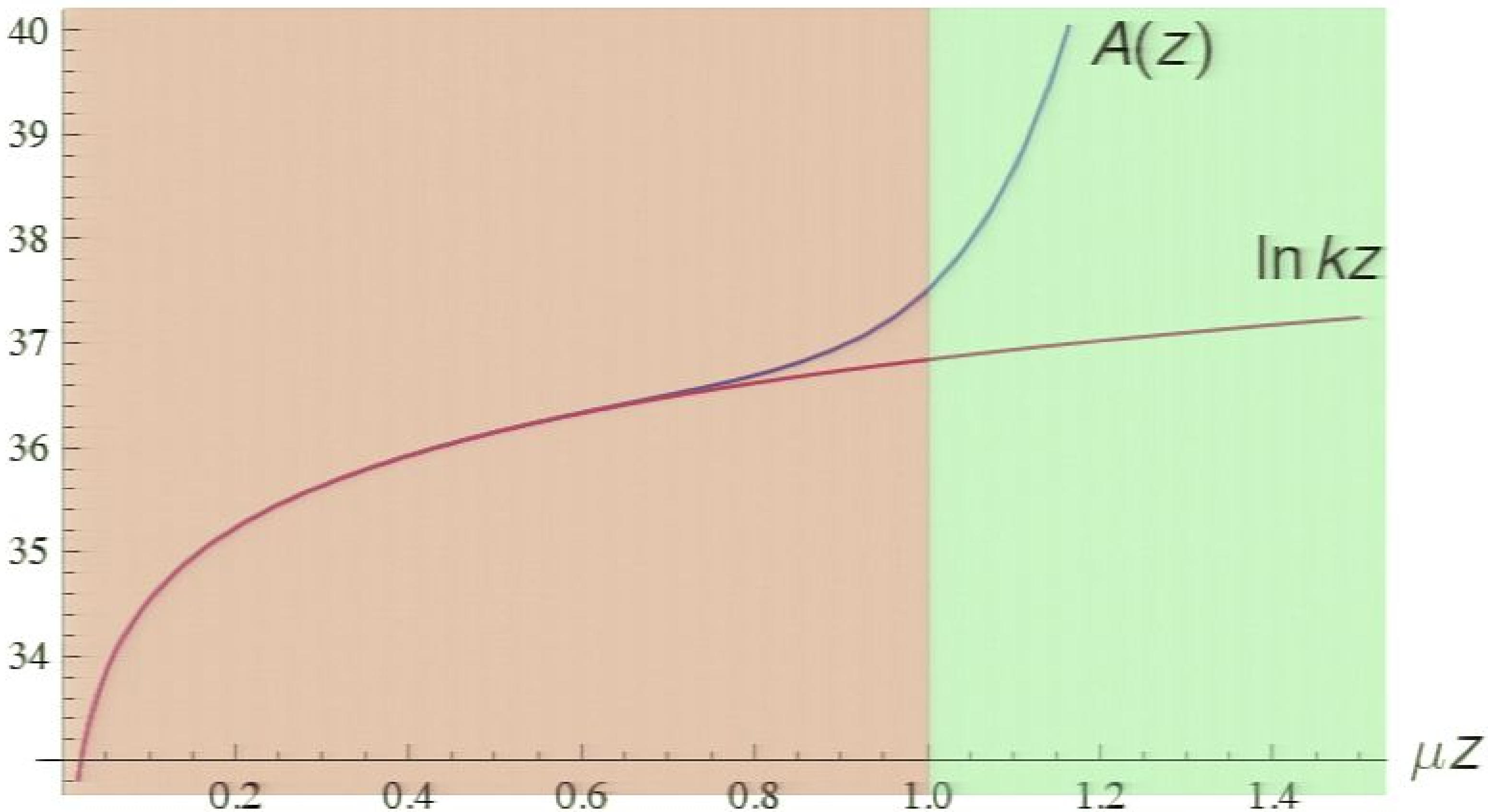

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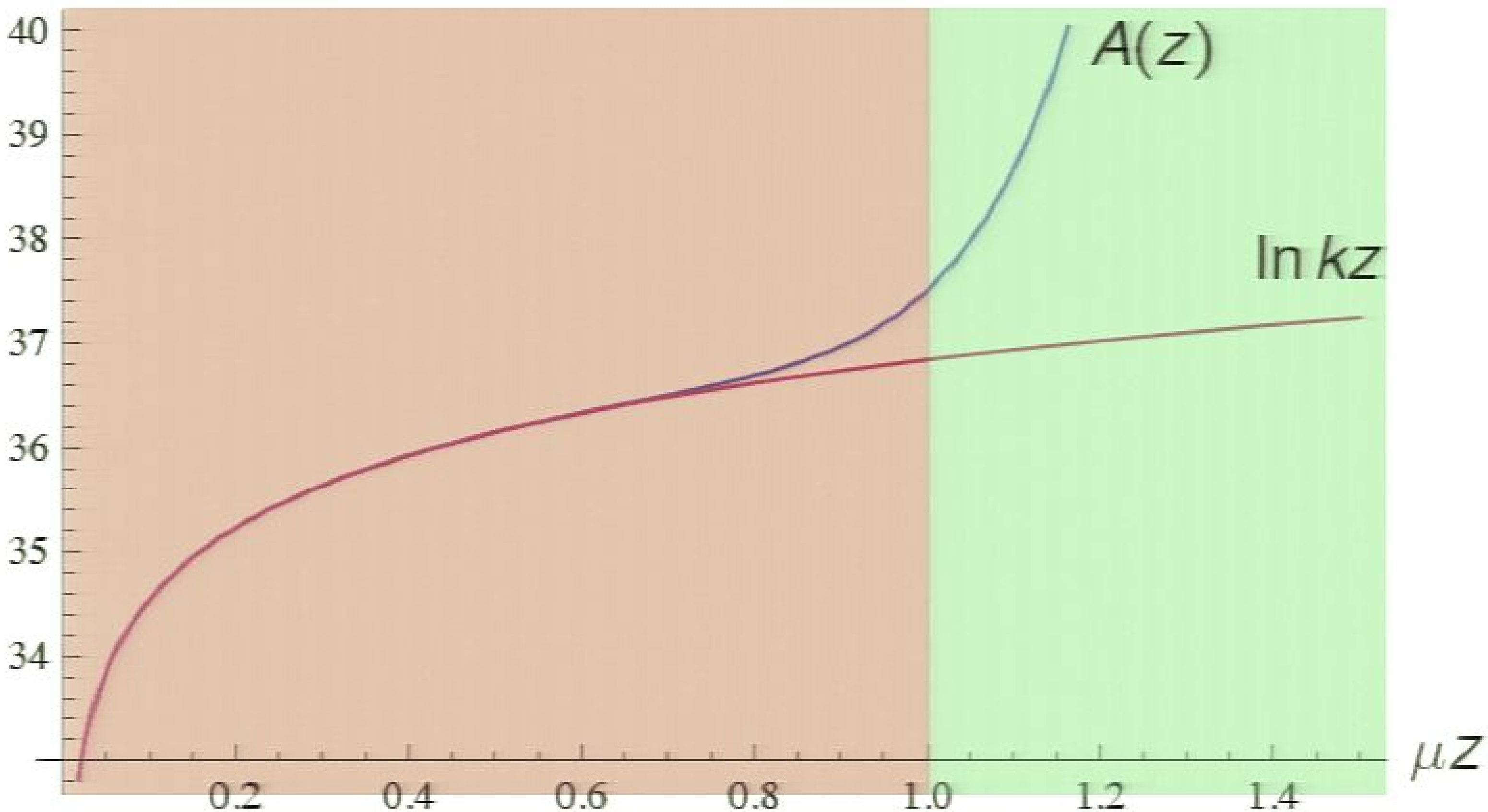

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$$S_{\text{BRANE}} = -M_5^3 \int d^4x \, \sqrt{-g_{\text{UV}}} \, \lambda_{\text{UV}}(\eta)$$

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$$\langle \eta \rangle = \pm\sqrt{3}\left(\frac{\nu+1}{\nu}\right) \left[\sqrt{\frac{2}{3}\frac{\nu}{\nu+1}(\mu z)^\nu + \left(\frac{2}{3}\frac{\nu}{\nu+1}(\mu z)^\nu\right)^2} + \sinh^{-1}\left(\sqrt{\frac{2}{3}\frac{\nu}{\nu+1}(\mu z)^\nu}\right) \right]$$

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$$S_{\text{BULK}} = M_5^3 \int d^5x \,\sqrt{-g}\left[R - g^{MN}(\partial_M\eta)(\partial_N\eta) - V(\eta)\right]$$

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$$\frac{d\eta}{d\beta} = \sqrt{3}\,\frac{\nu+1}{\nu}(\cosh 2\beta + 1) > 0$$

large $\beta \Leftrightarrow$ large η. Good since equations simplify for large β

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$$W = \frac{1}{2}k\nu\left[\frac{\nu+1}{2\nu}(1+\cosh 2\beta)-1\right]e^{(\nu+1)(\cosh 2\beta-1)/2\nu}$$

$$\eta = \pm\sqrt{3}\,\frac{\nu+1}{\nu}\left(\frac{1}{2}\sinh 2\beta+\beta\right)$$

Implicit function of η

Defines $\beta(\eta)$

G Soft-Wall Geometry, One Scalar

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$$W \sim \frac{1}{2\sqrt{3}} k \nu \eta e^{\eta/\sqrt{3}}$$

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w line element

$$ds^2 = e^{-2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

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- Boundary implies boundary terms
- Boundary terms mean equations of motion may change
- Need to ensure boundary terms vanish
  - Non-vanishing implies non-zero 4D cosmological constant
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superpotential grows asymptotically slower than $e^{2\eta/\sqrt{3}}$

symptotic form for superpotential:

$$W \sim \frac{1}{2\sqrt{3}} k \nu \eta e^{\eta/\sqrt{3}}$$

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- The value of the field at the UV brane is

$$\eta_0 = \pm\sqrt{3}\left(\frac{\nu+1}{\nu}\right)\left[\sqrt{\frac{2}{3}\frac{\nu}{\nu+1}\left(\frac{\mu}{k}\right)^{\nu} + \left(\frac{2}{3}\frac{\nu}{\nu+1}\left(\frac{\mu}{k}\right)^{\nu}\right)^2} + \sinh^{-1}\sqrt{\frac{2}{3}\frac{\nu}{\nu+1}\left(\frac{\mu}{k}\right)^{\nu}}\right]$$

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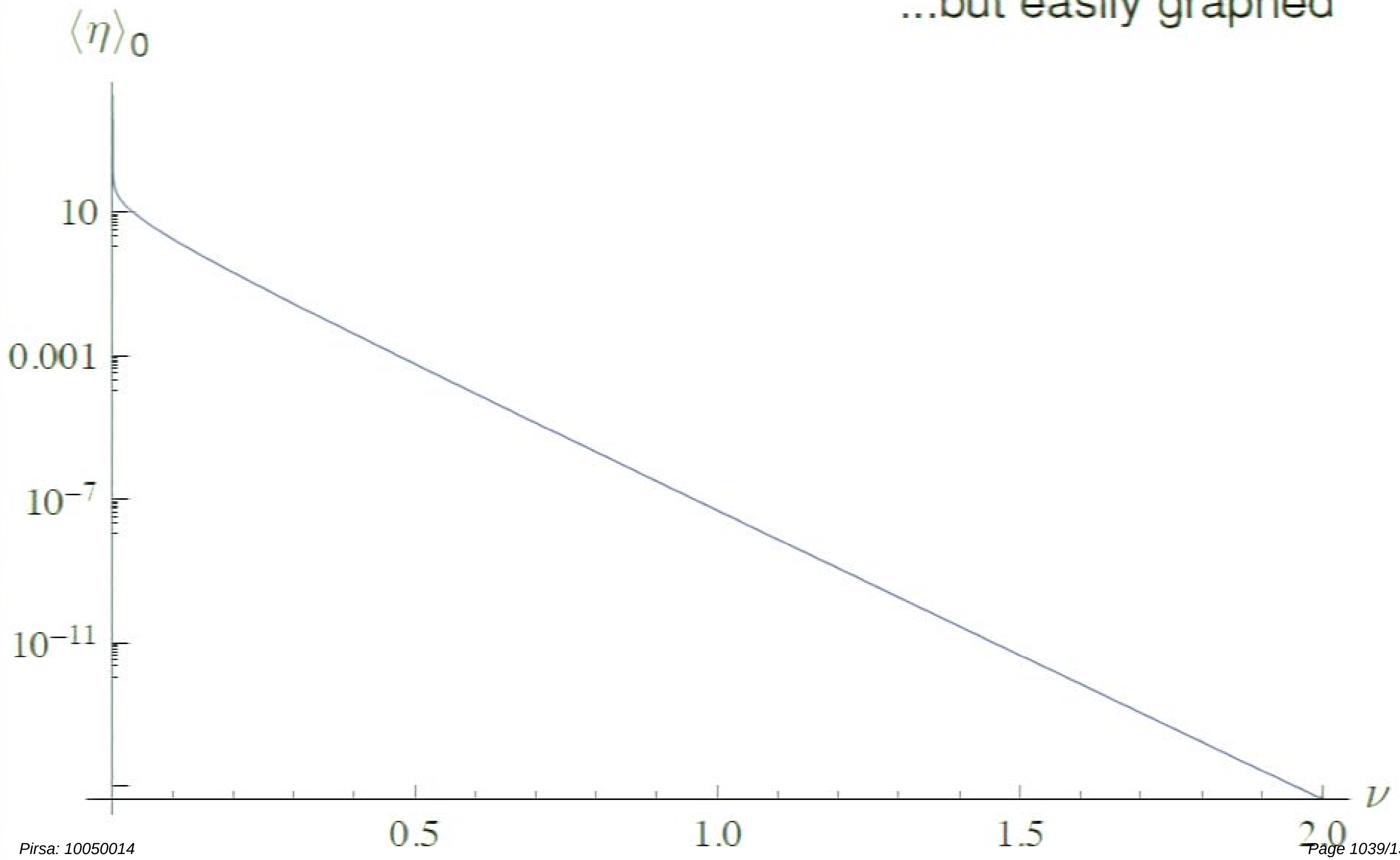

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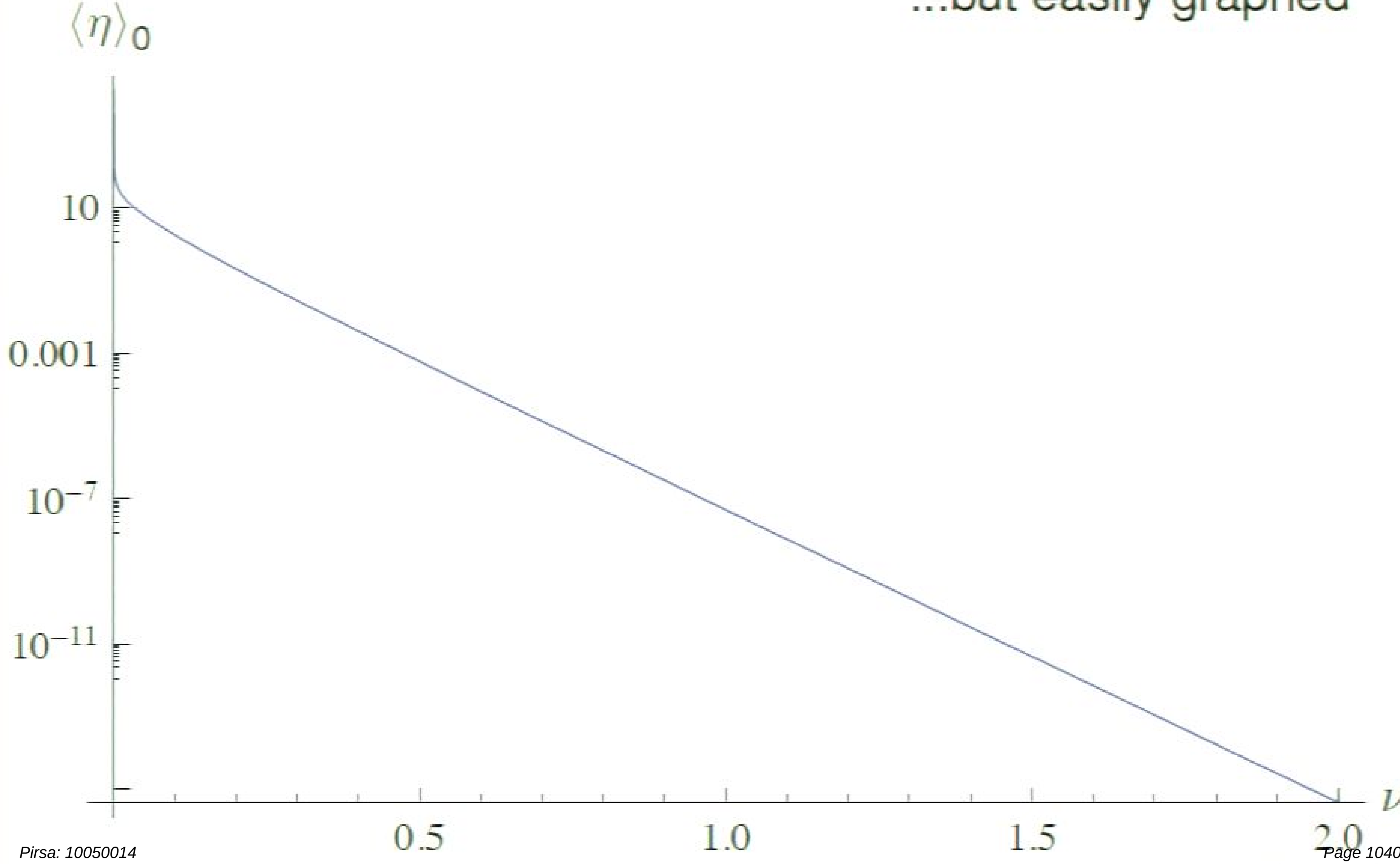

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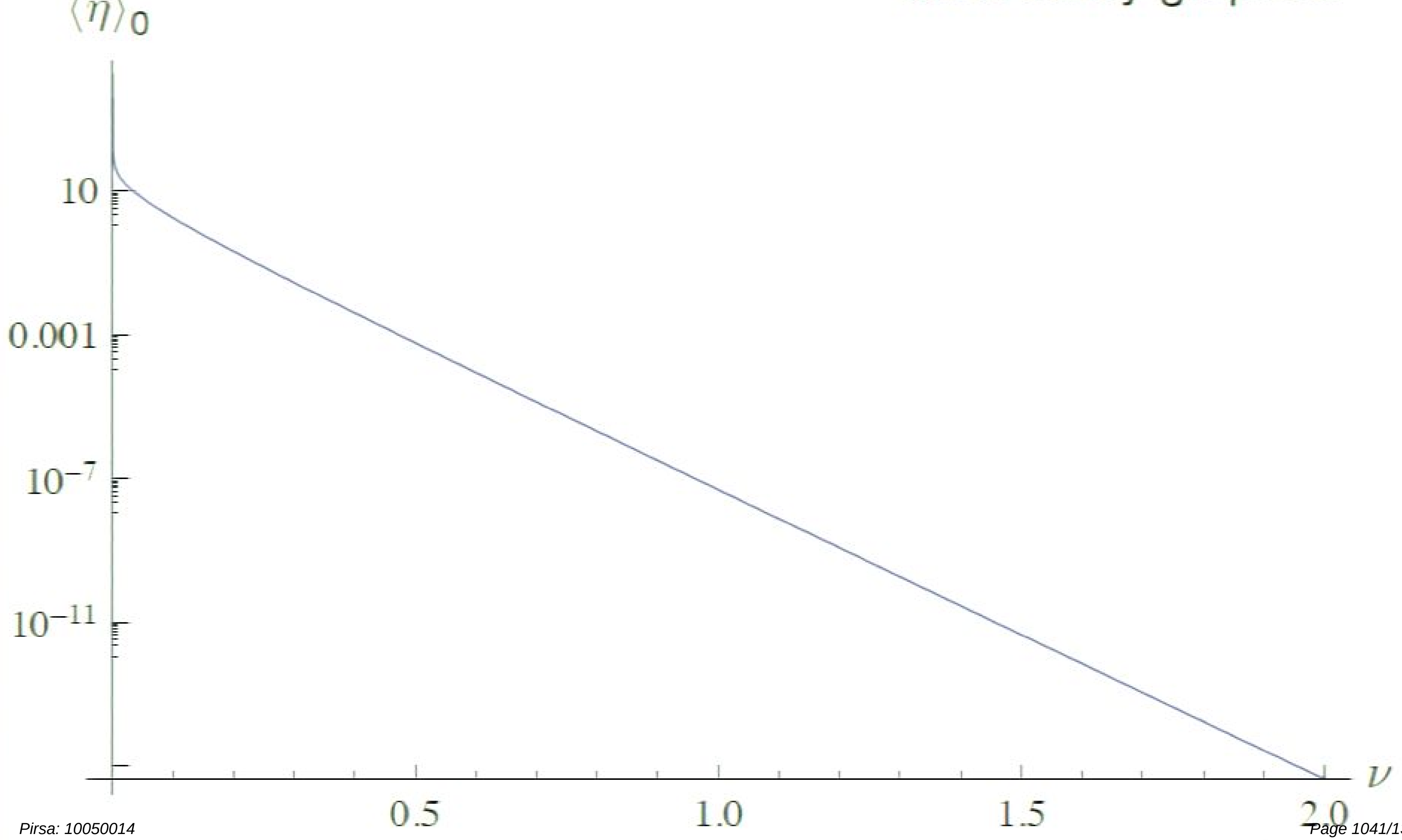

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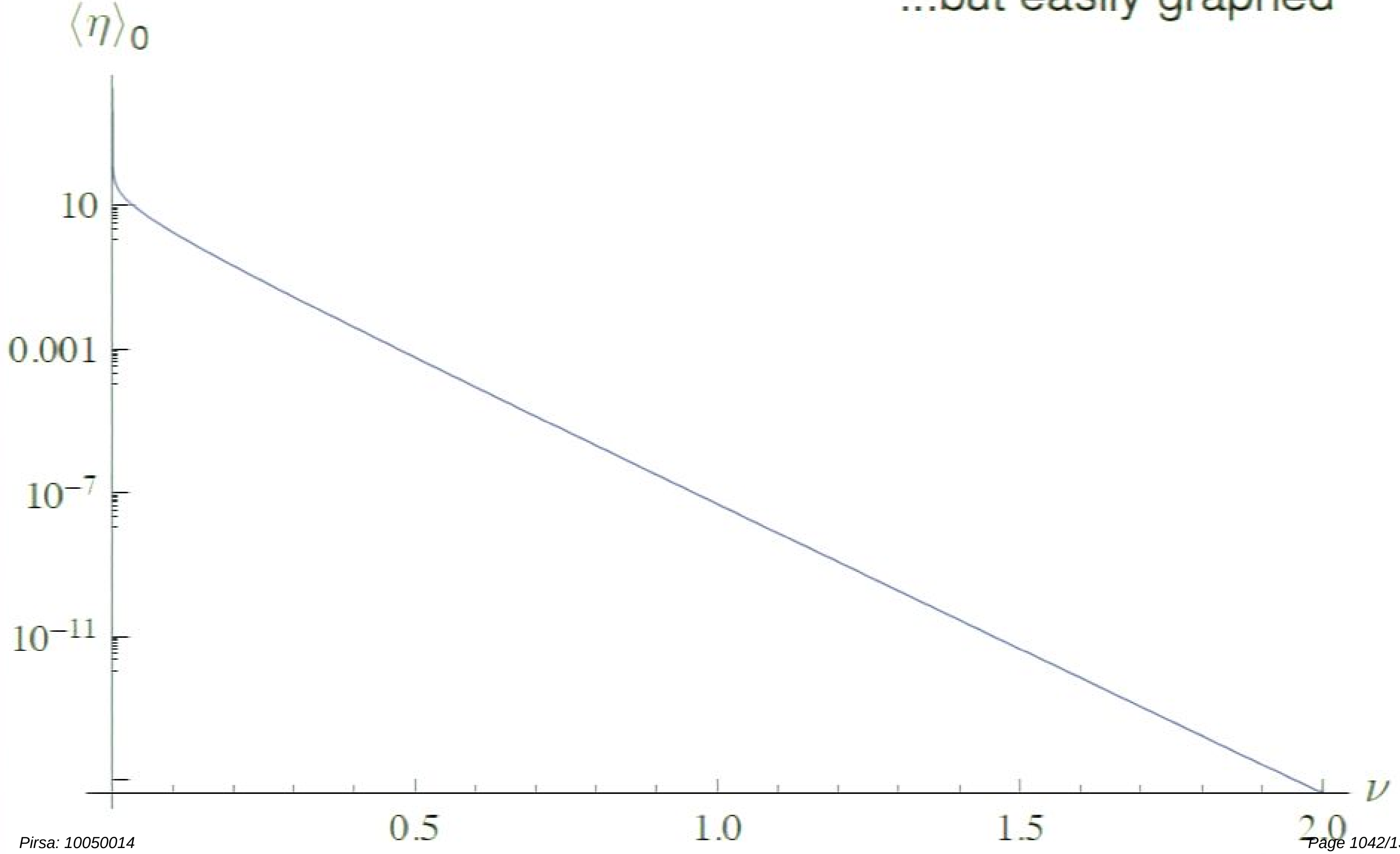

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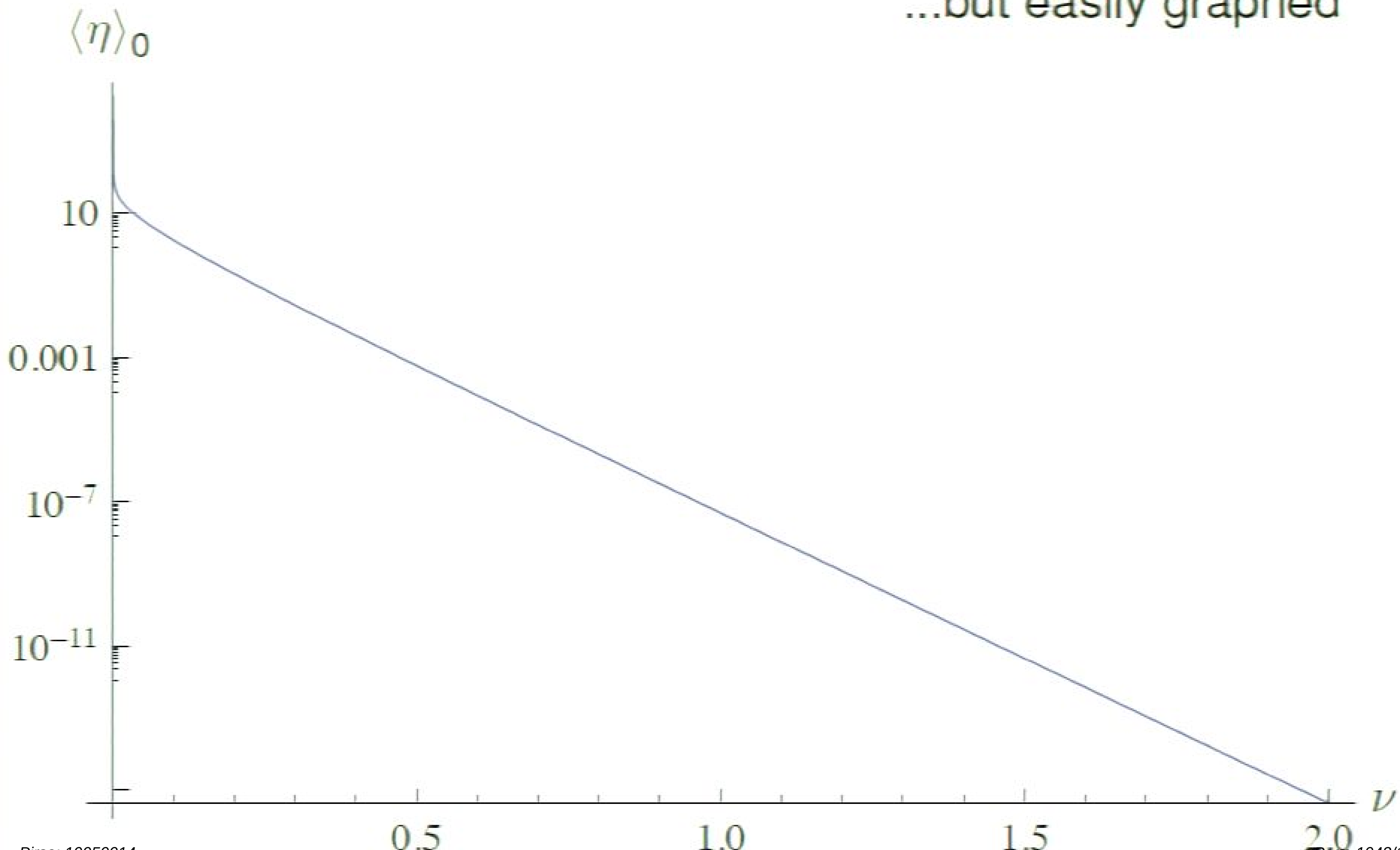

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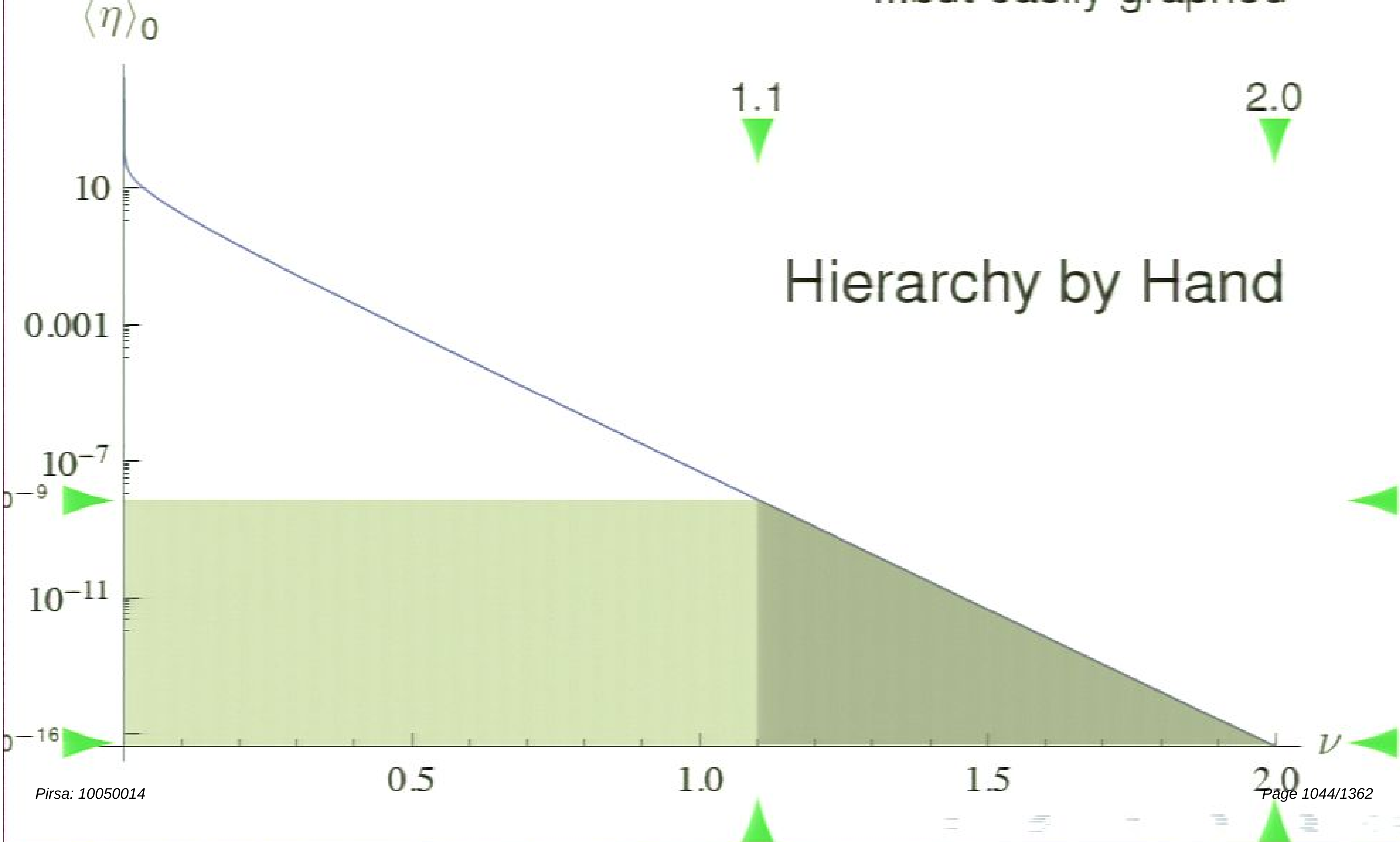

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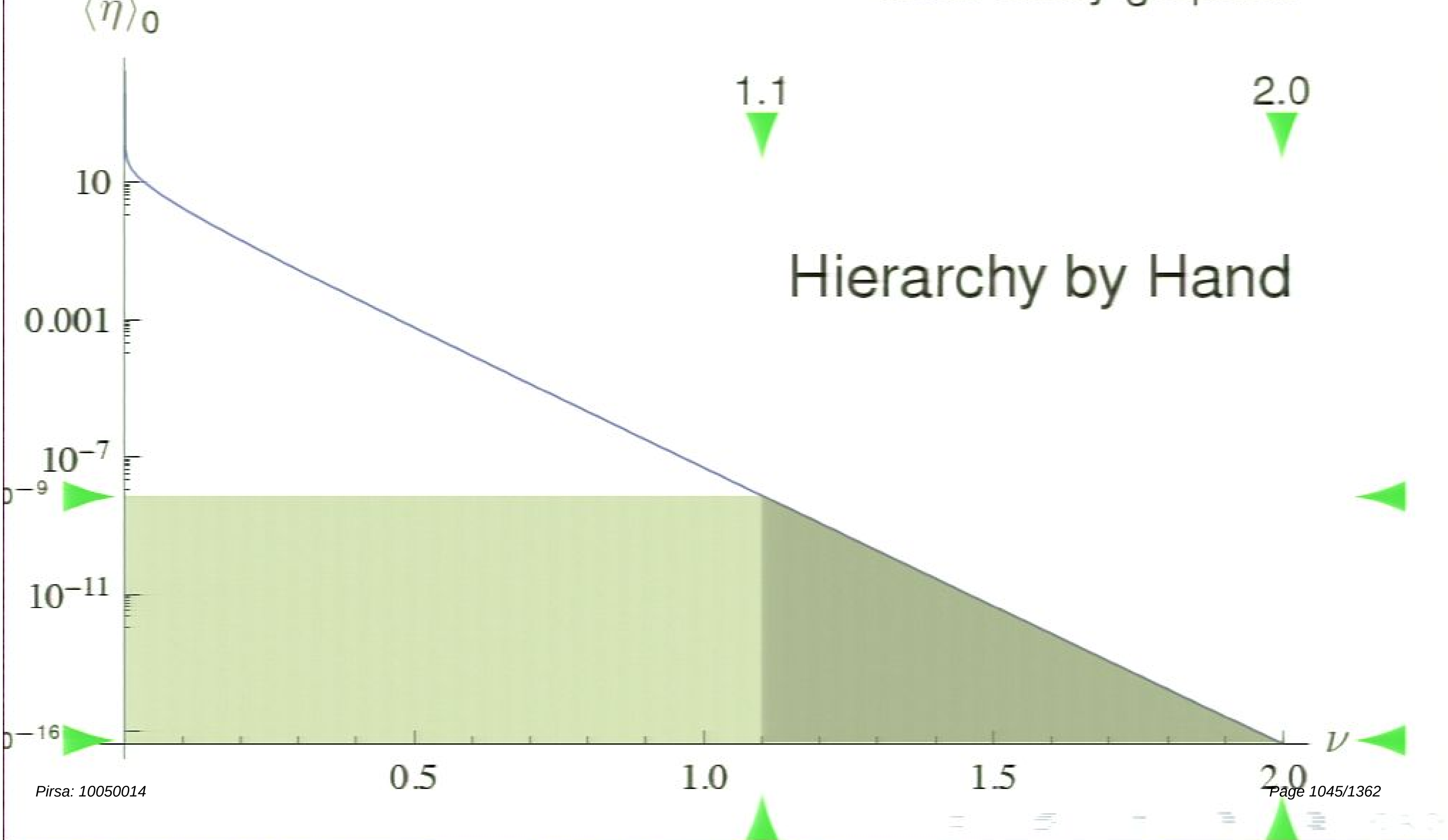

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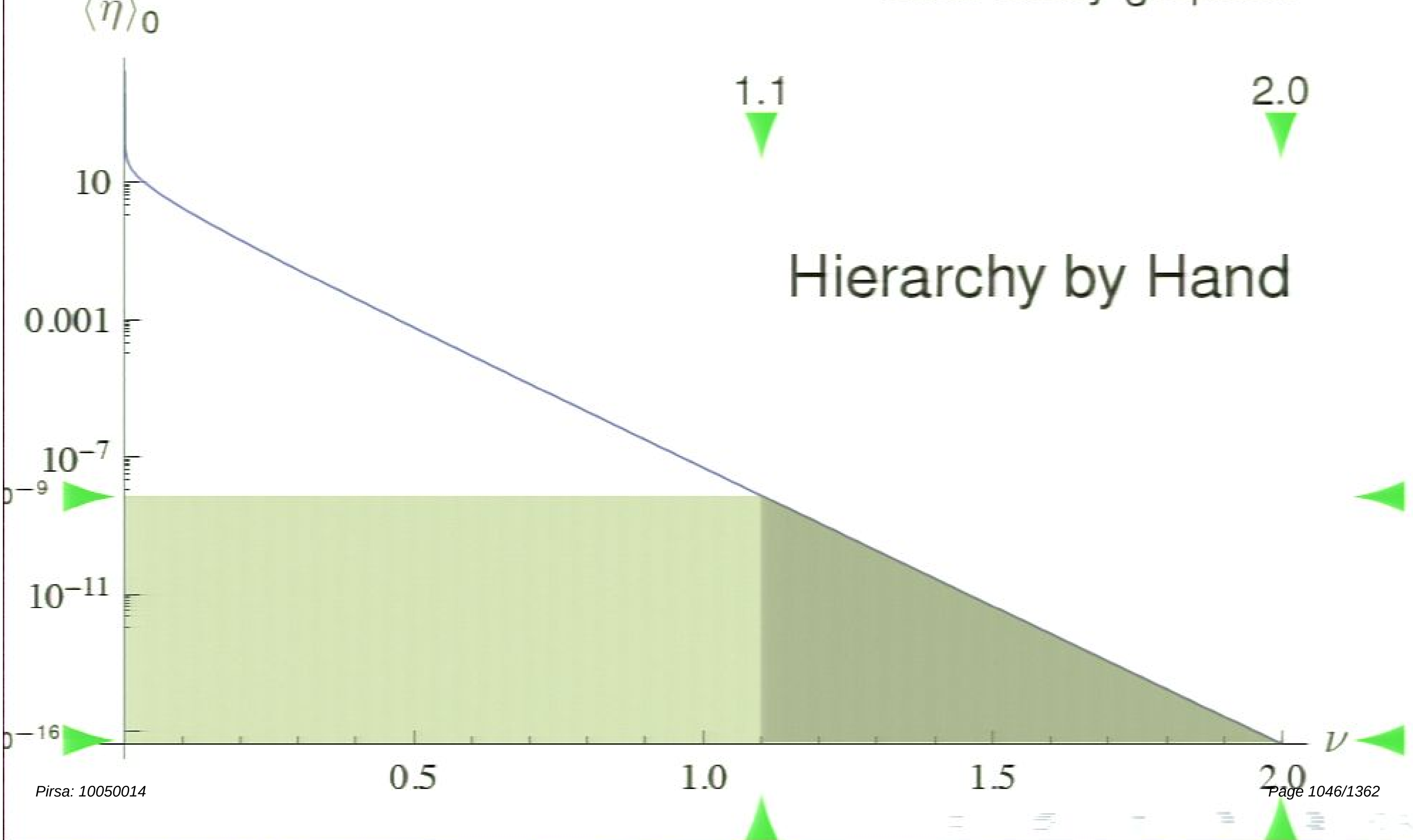

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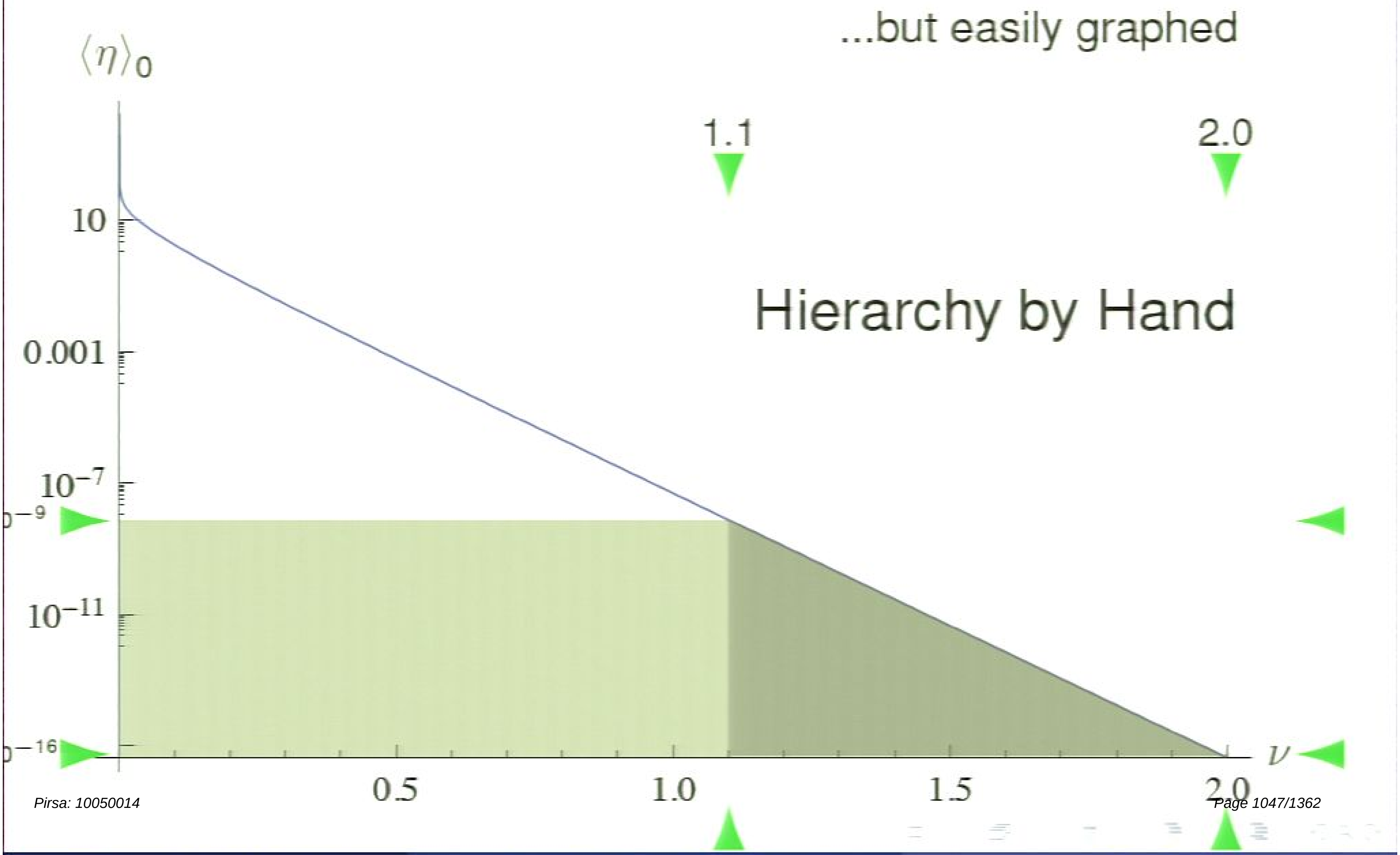

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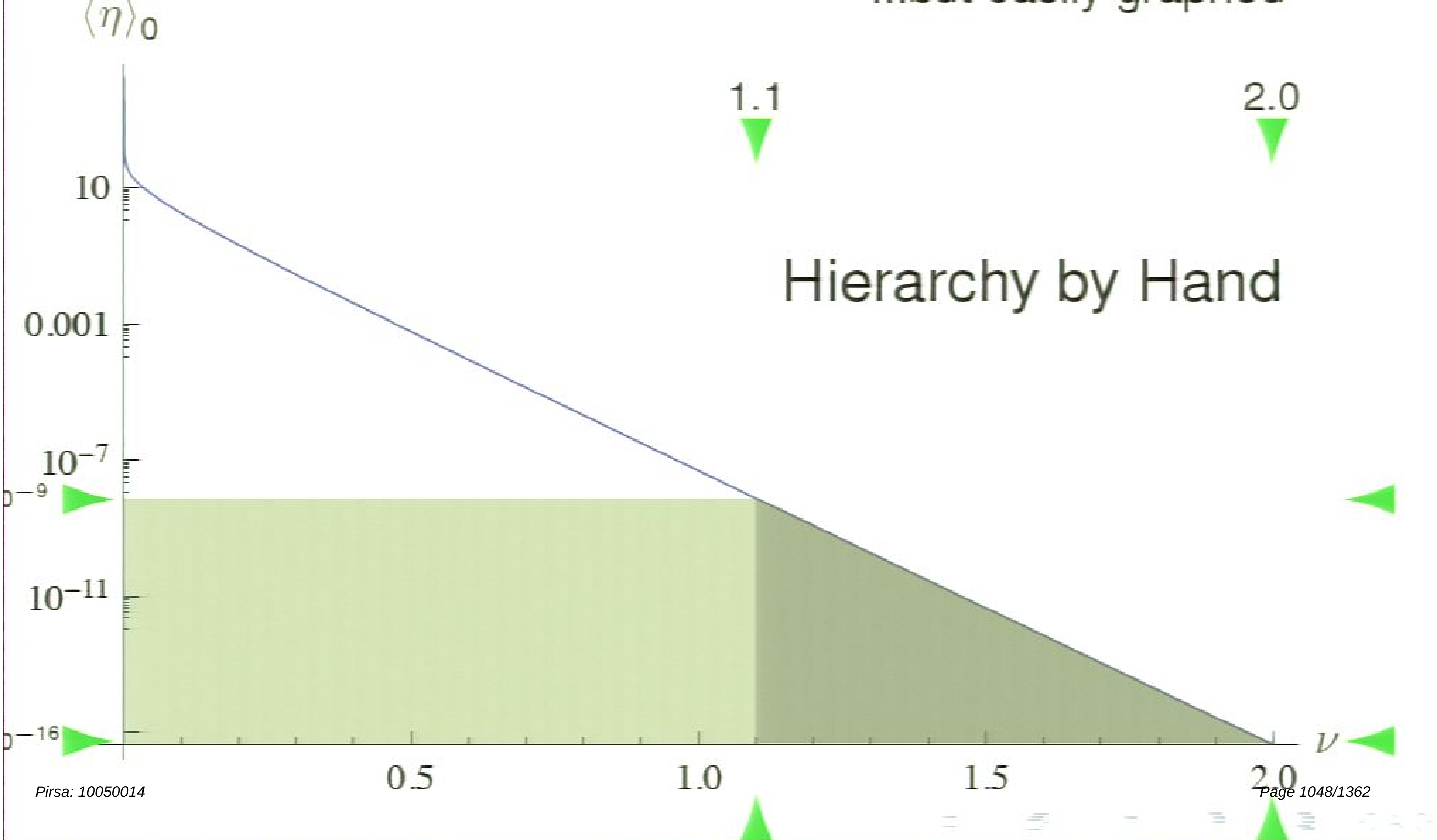

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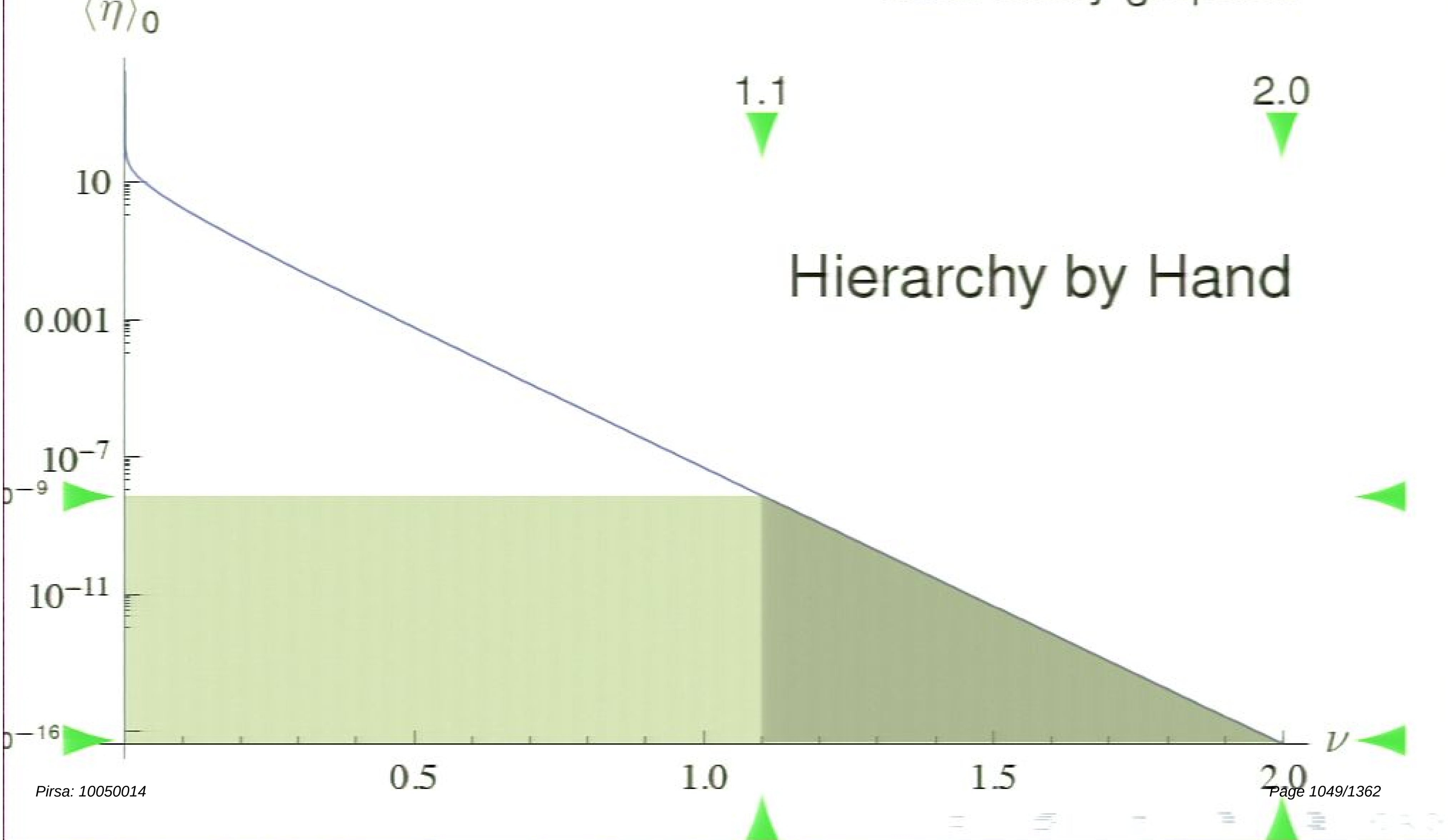

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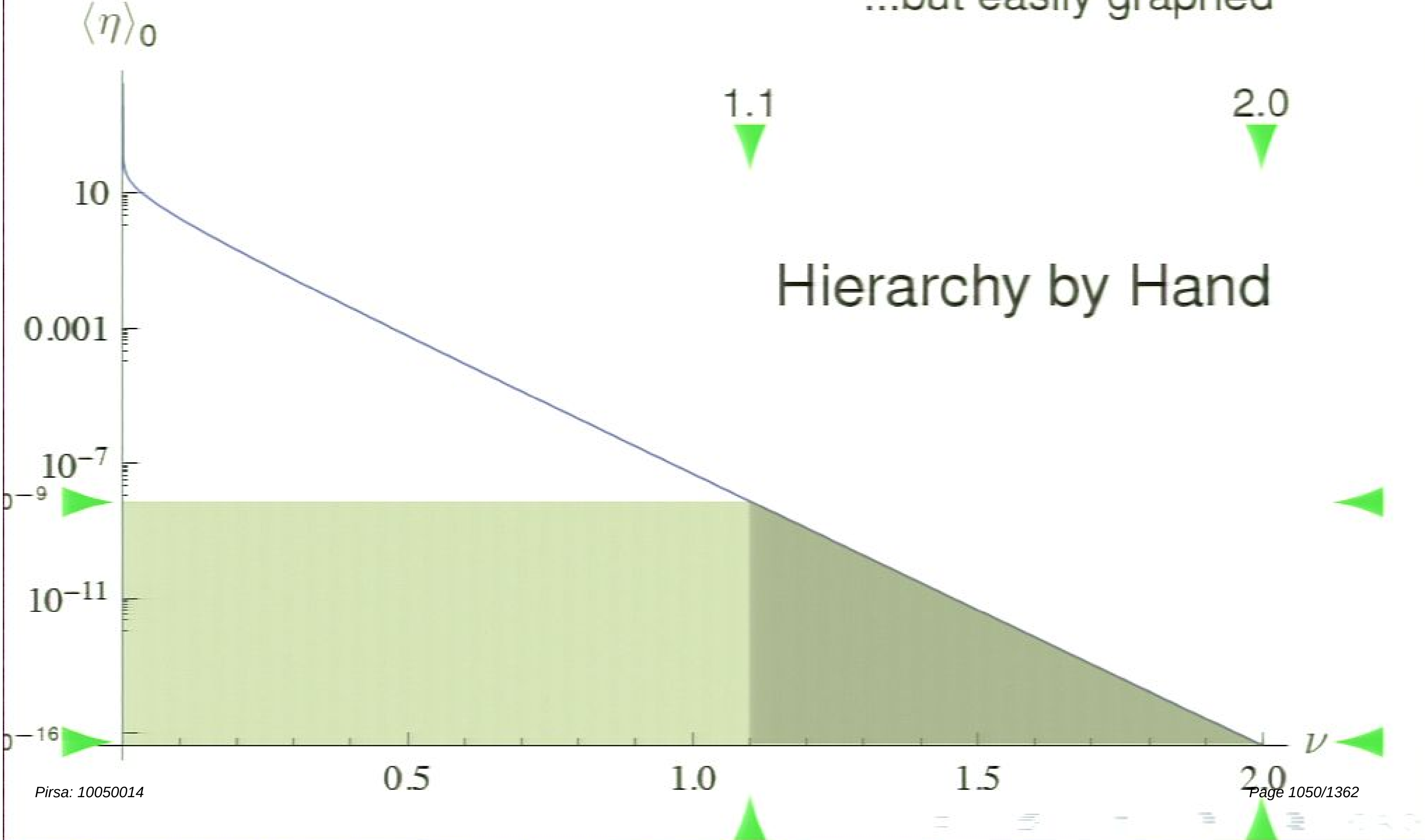

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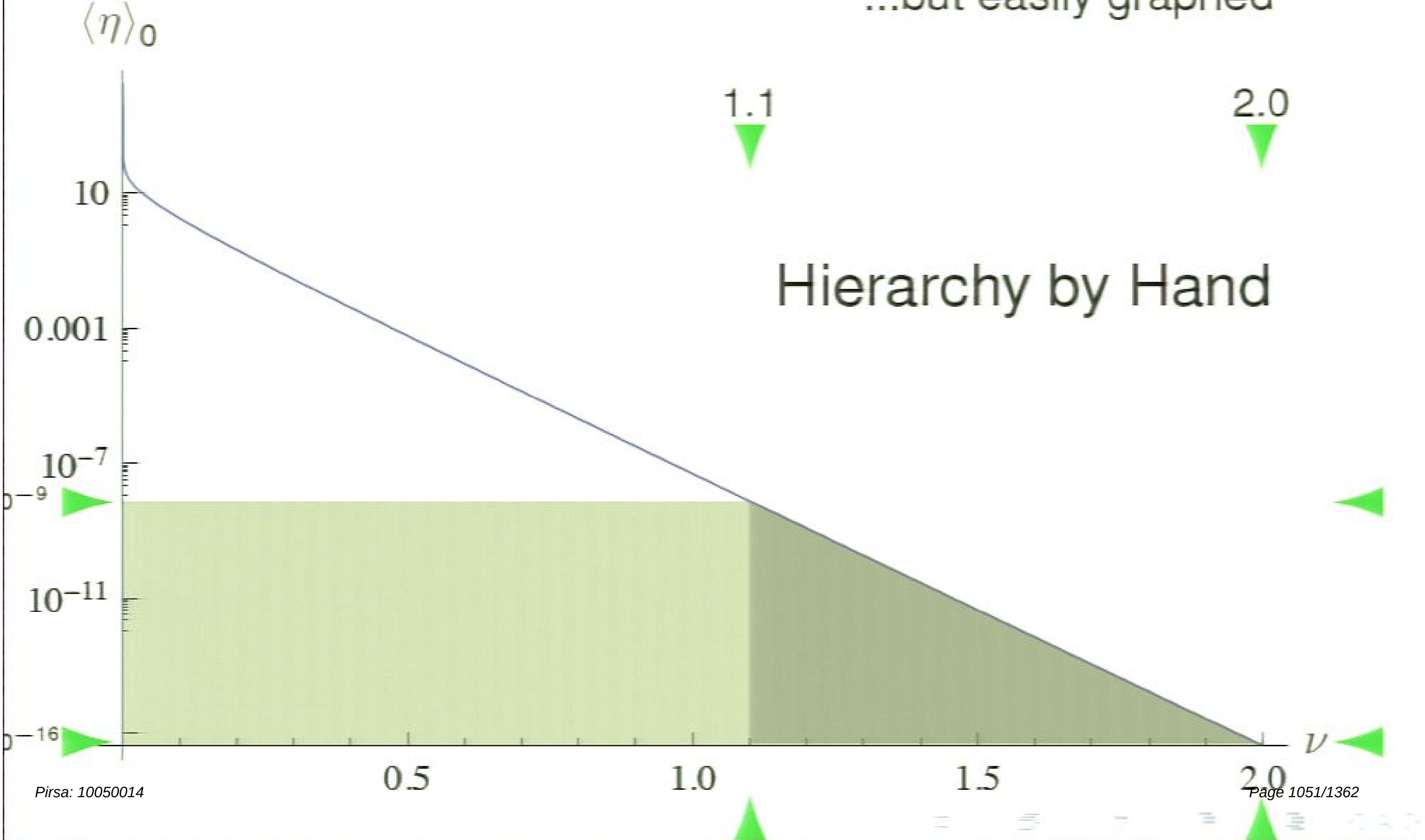

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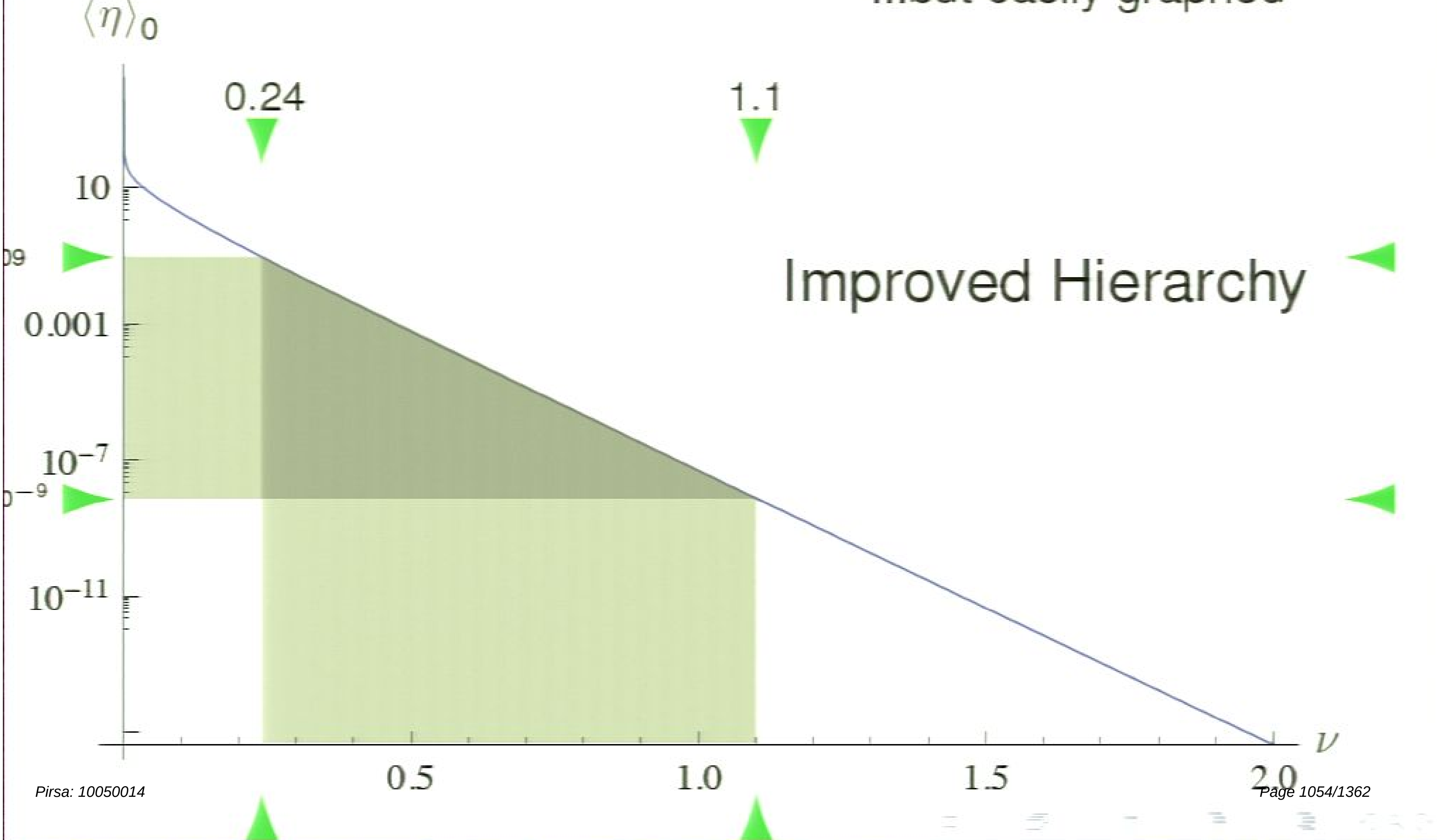

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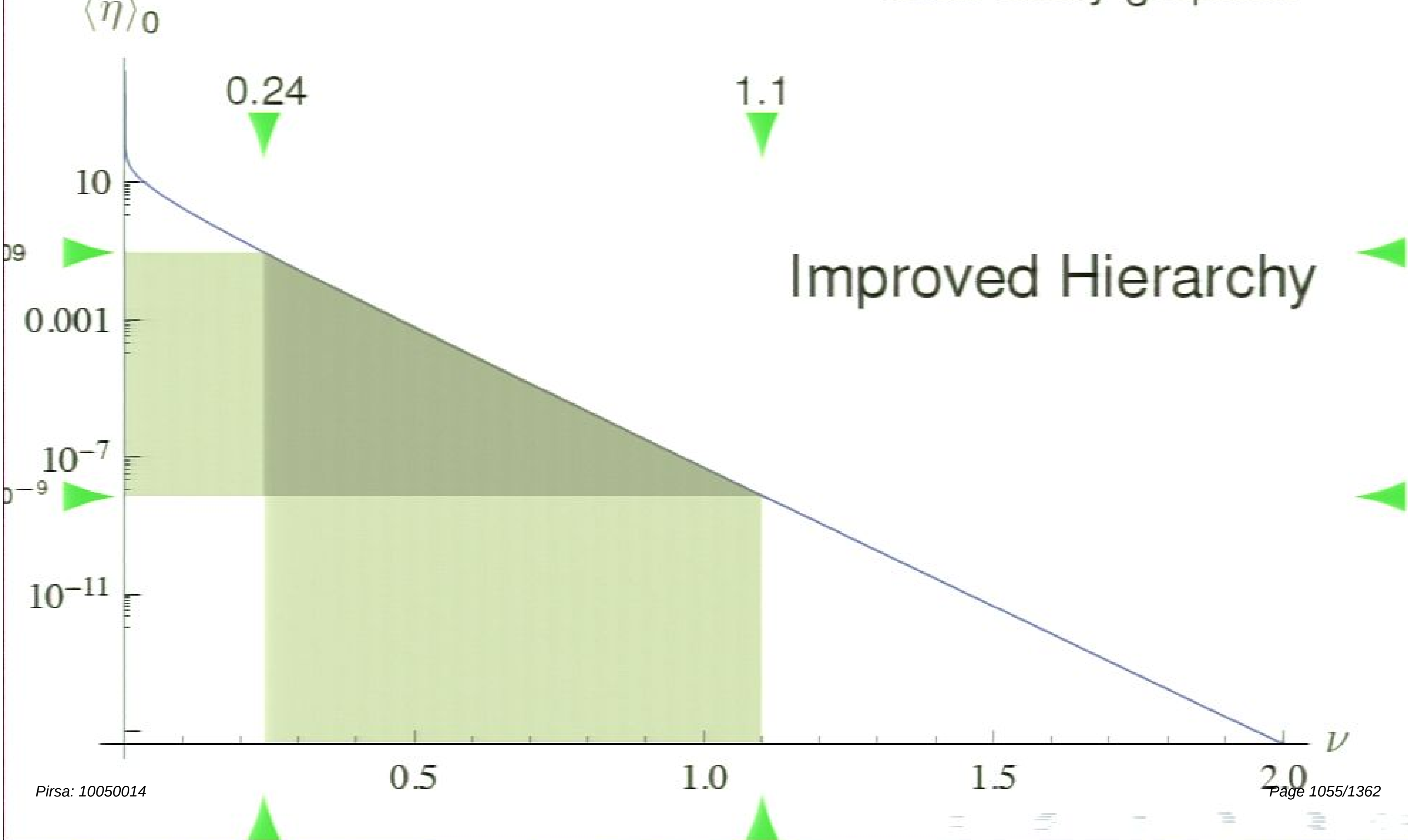

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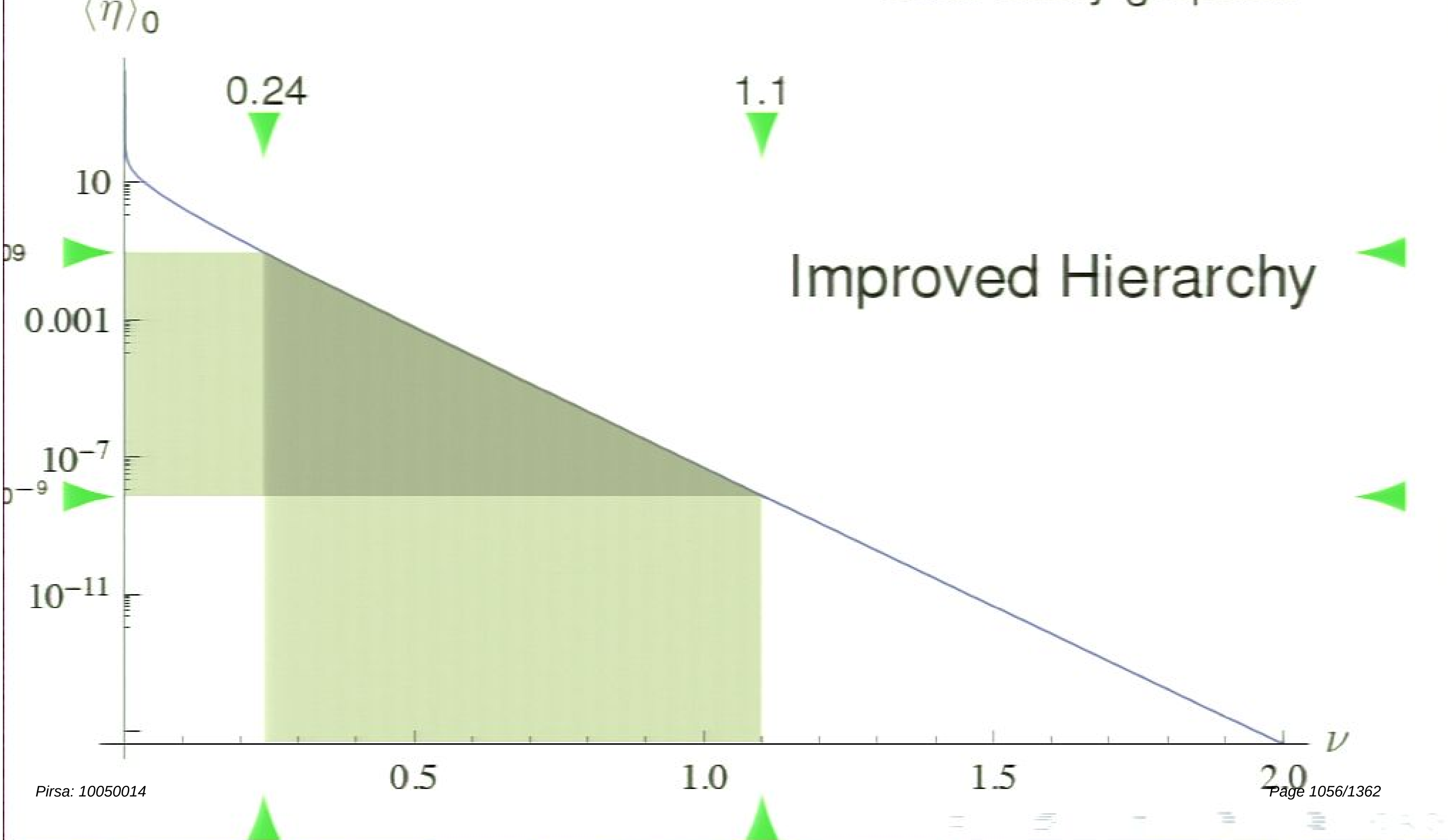

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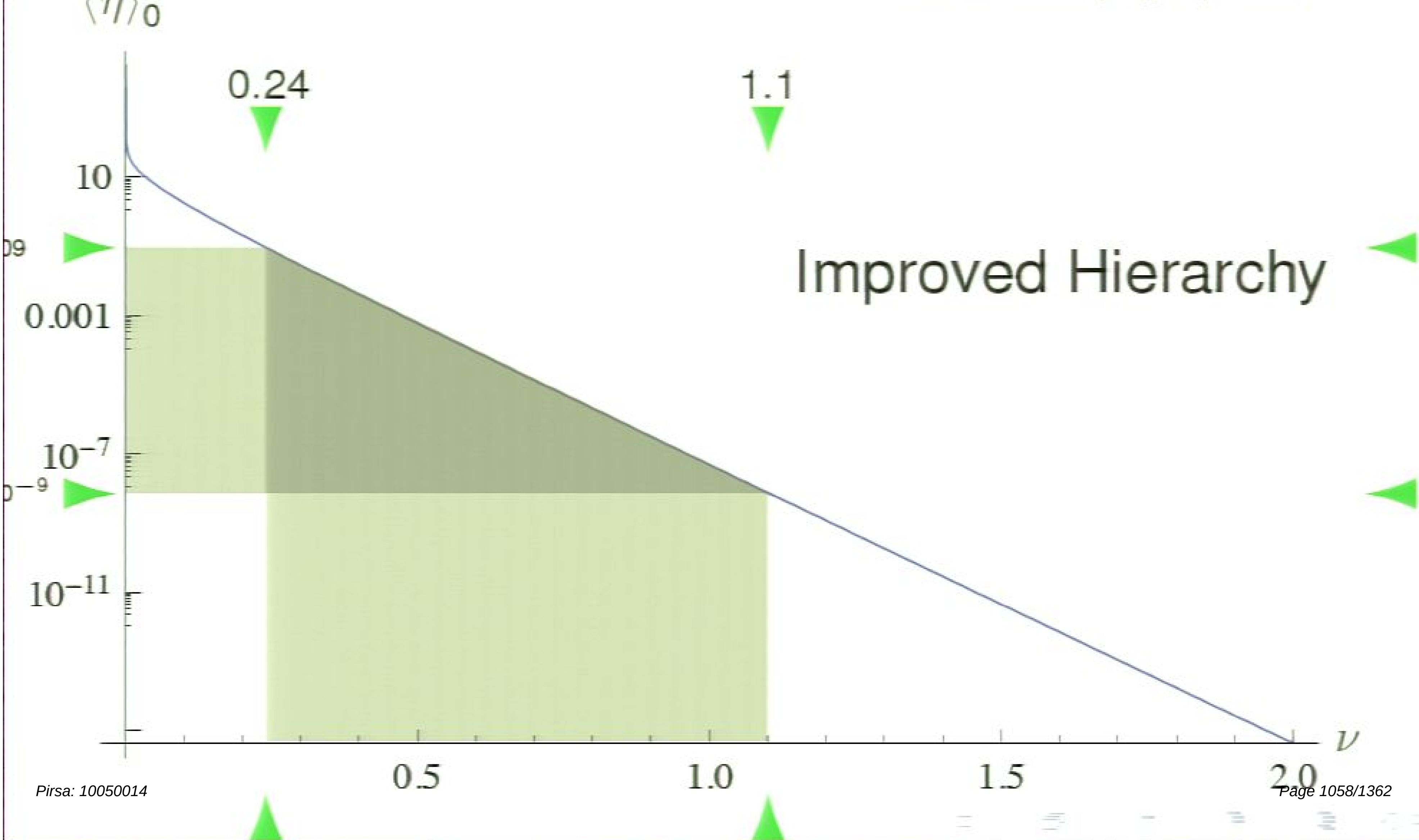

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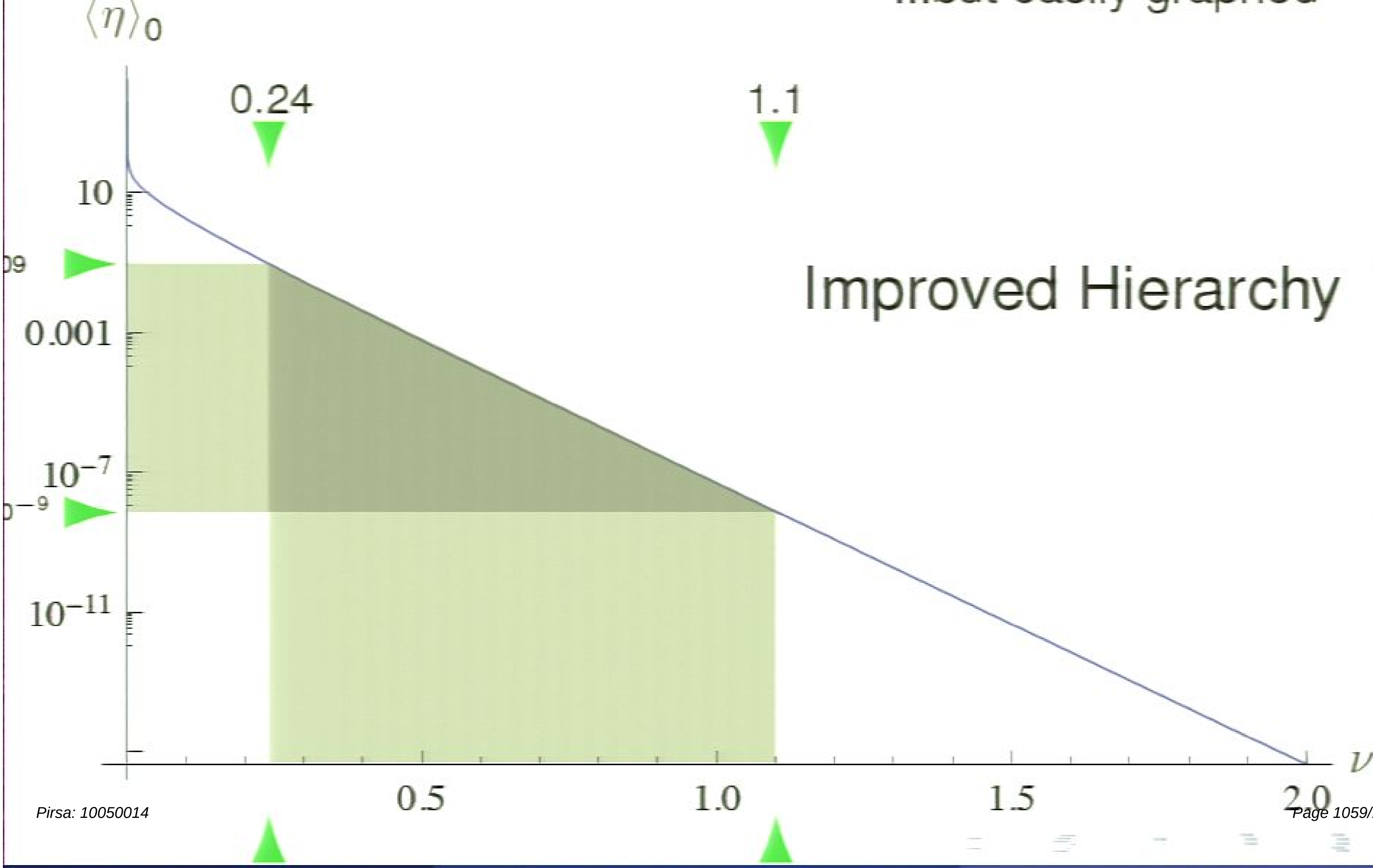

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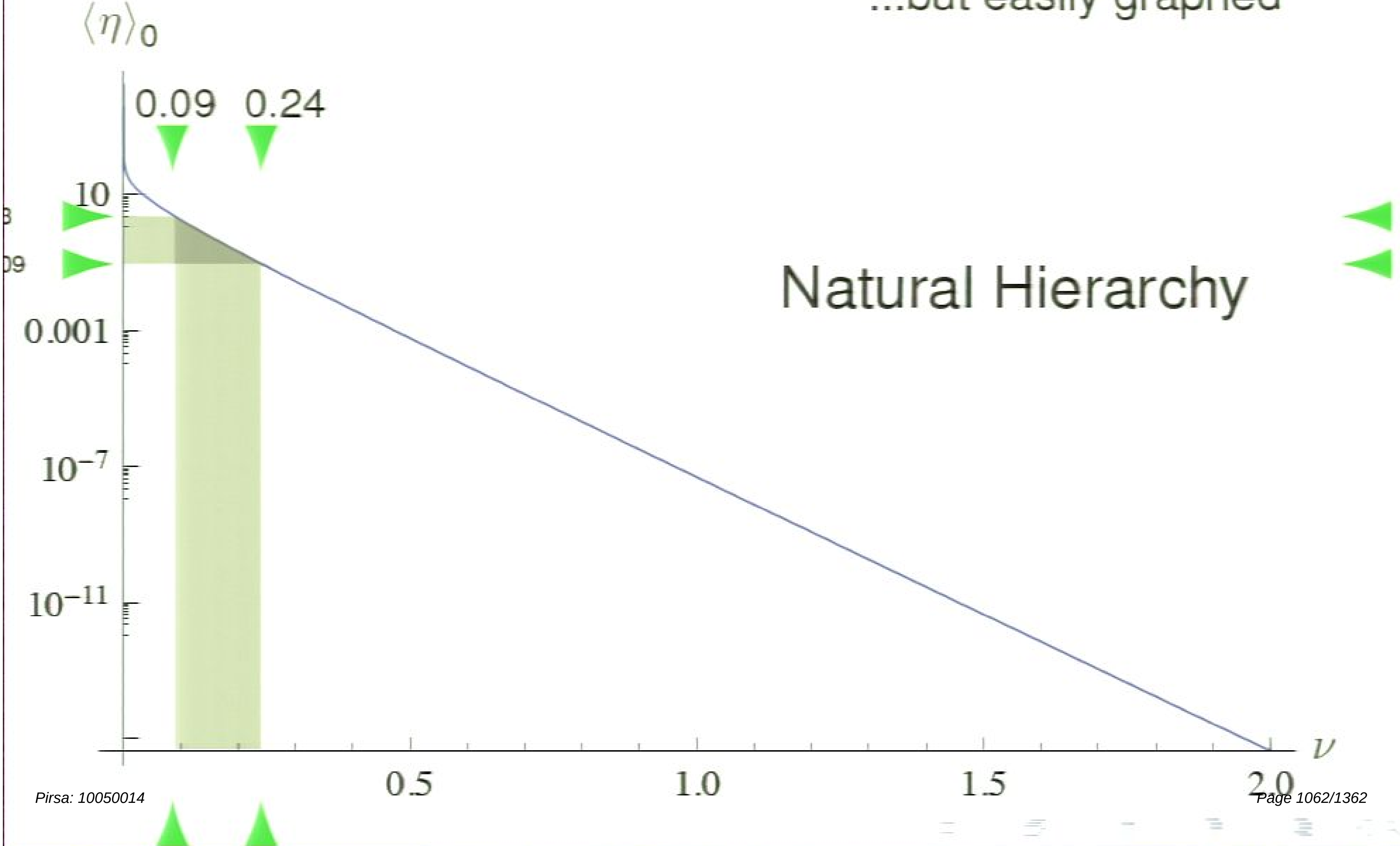

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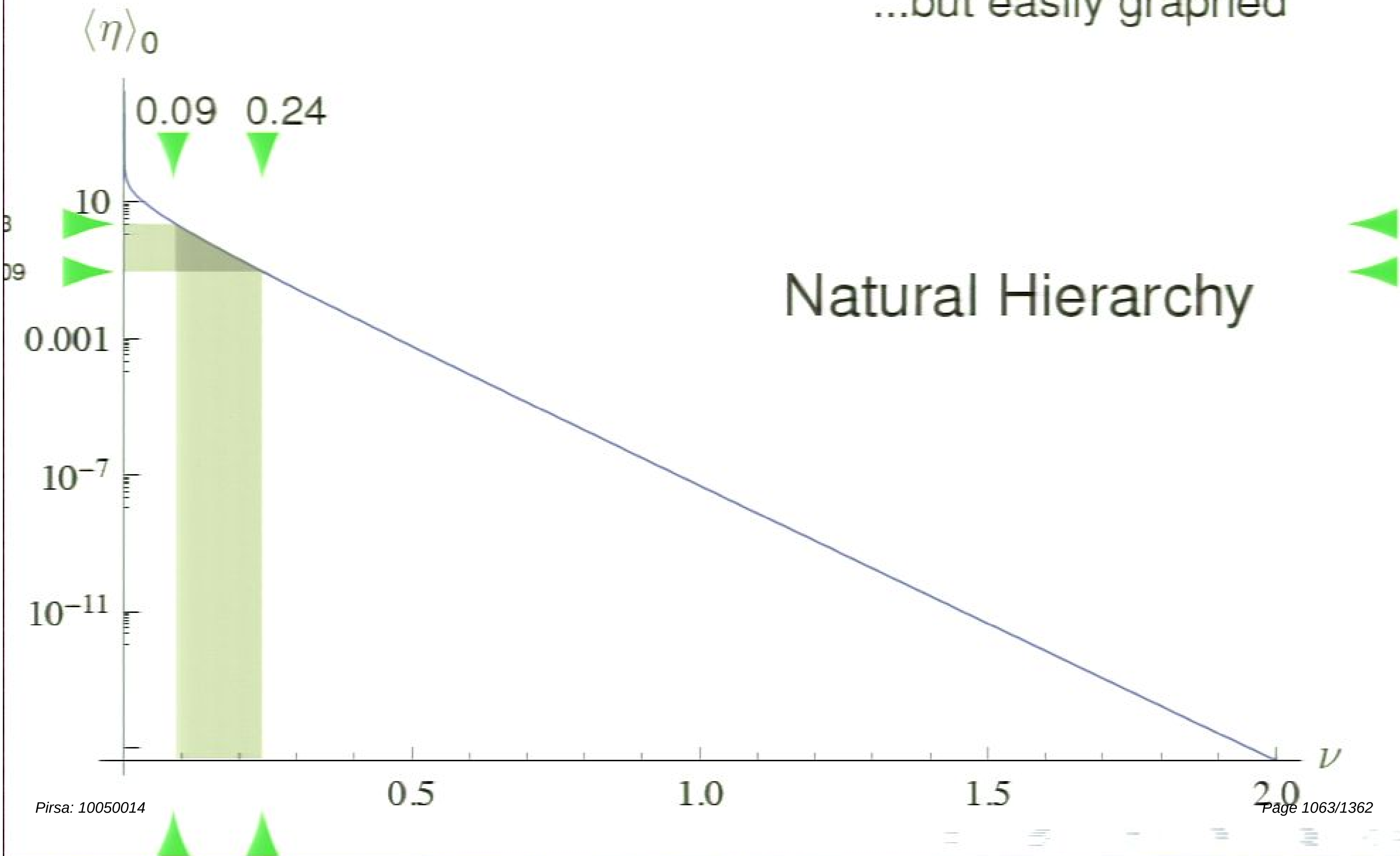

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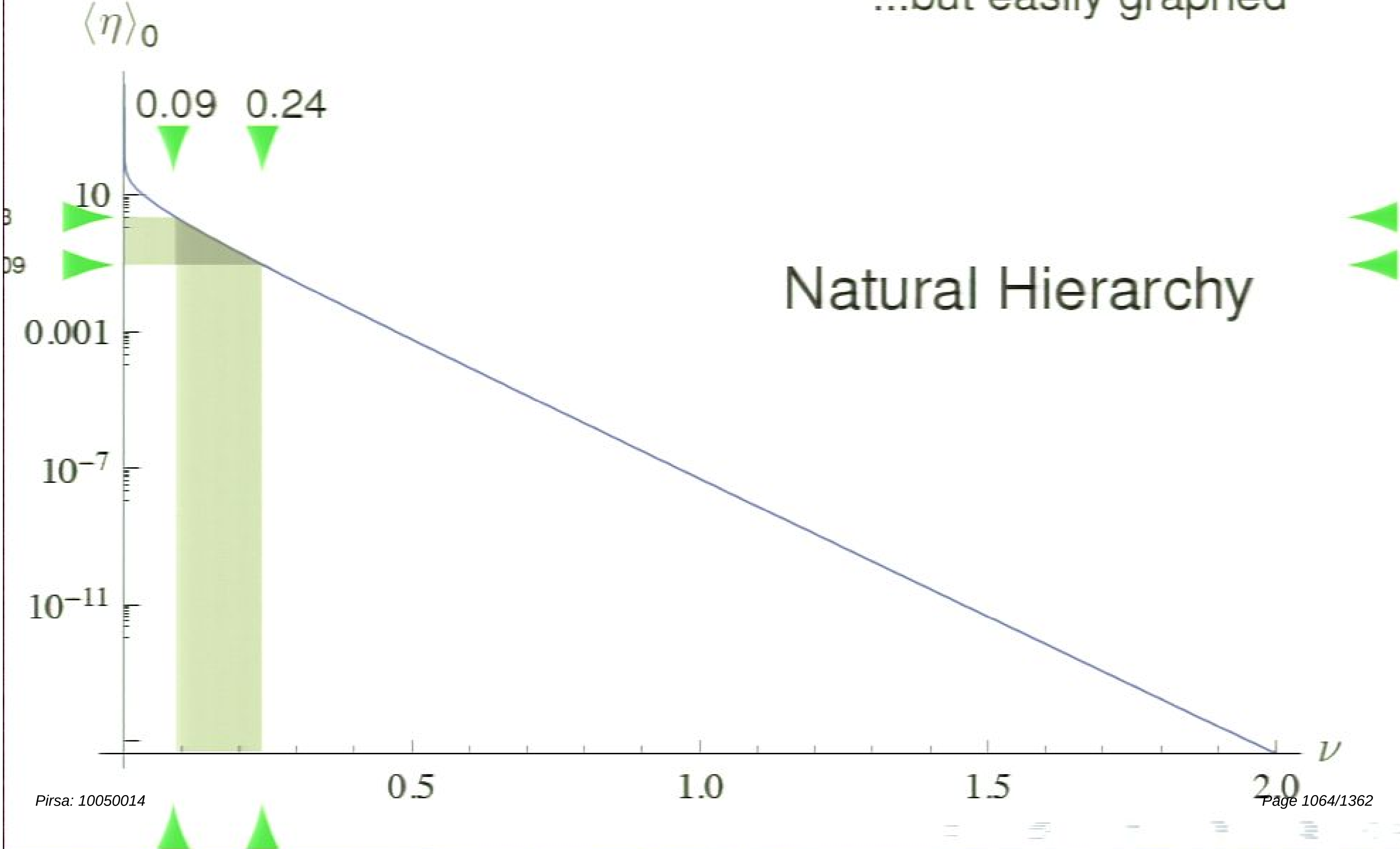

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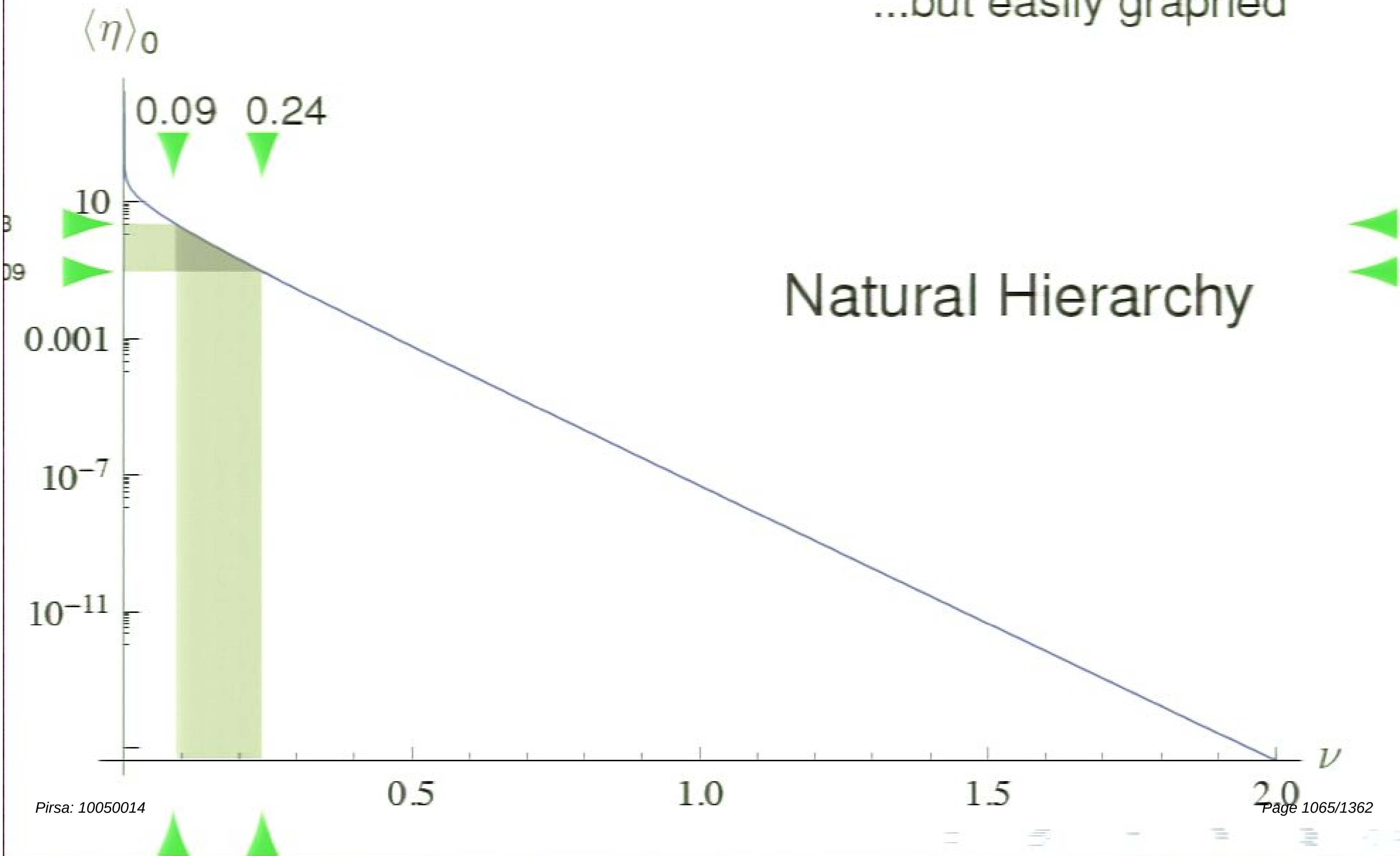

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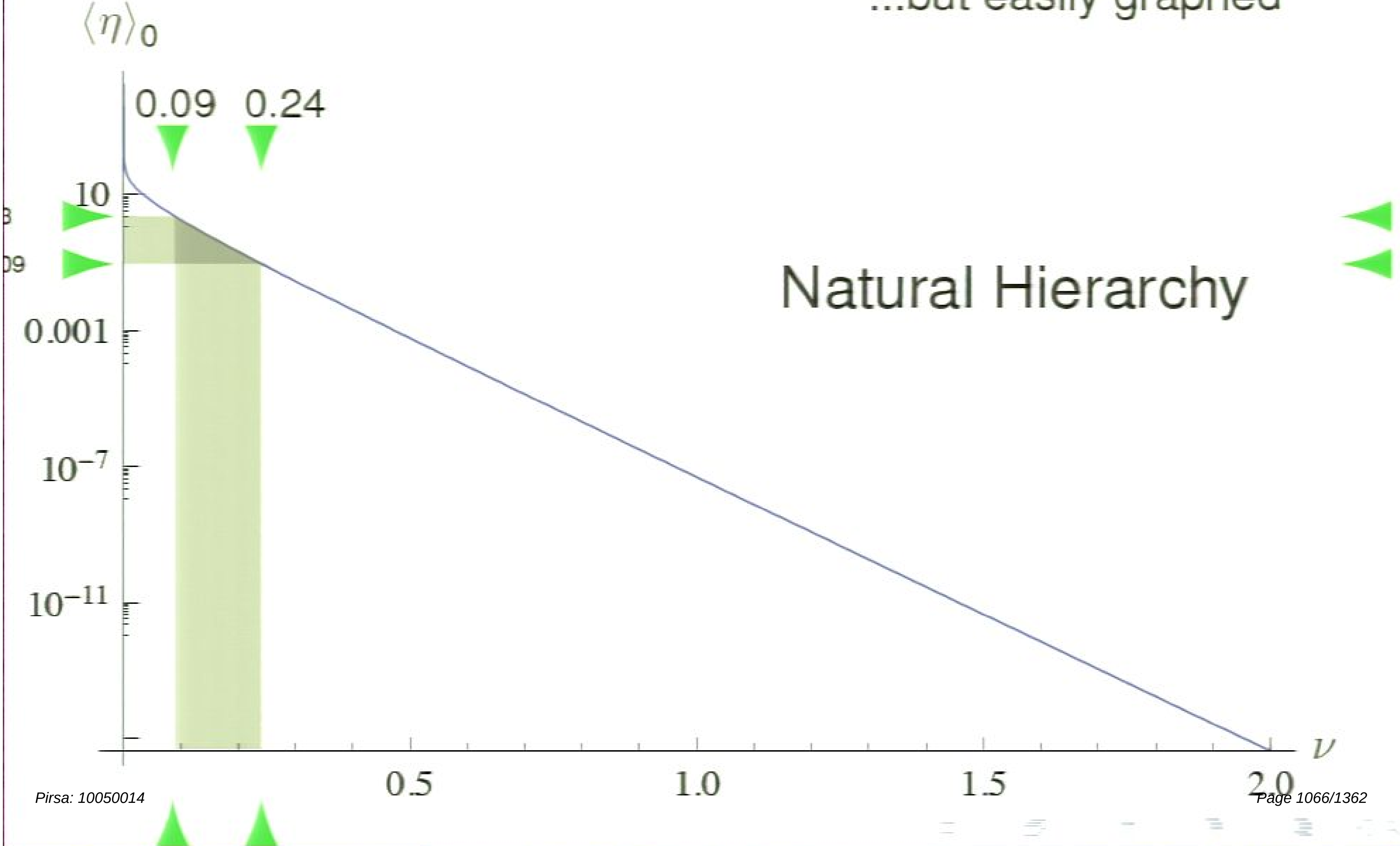

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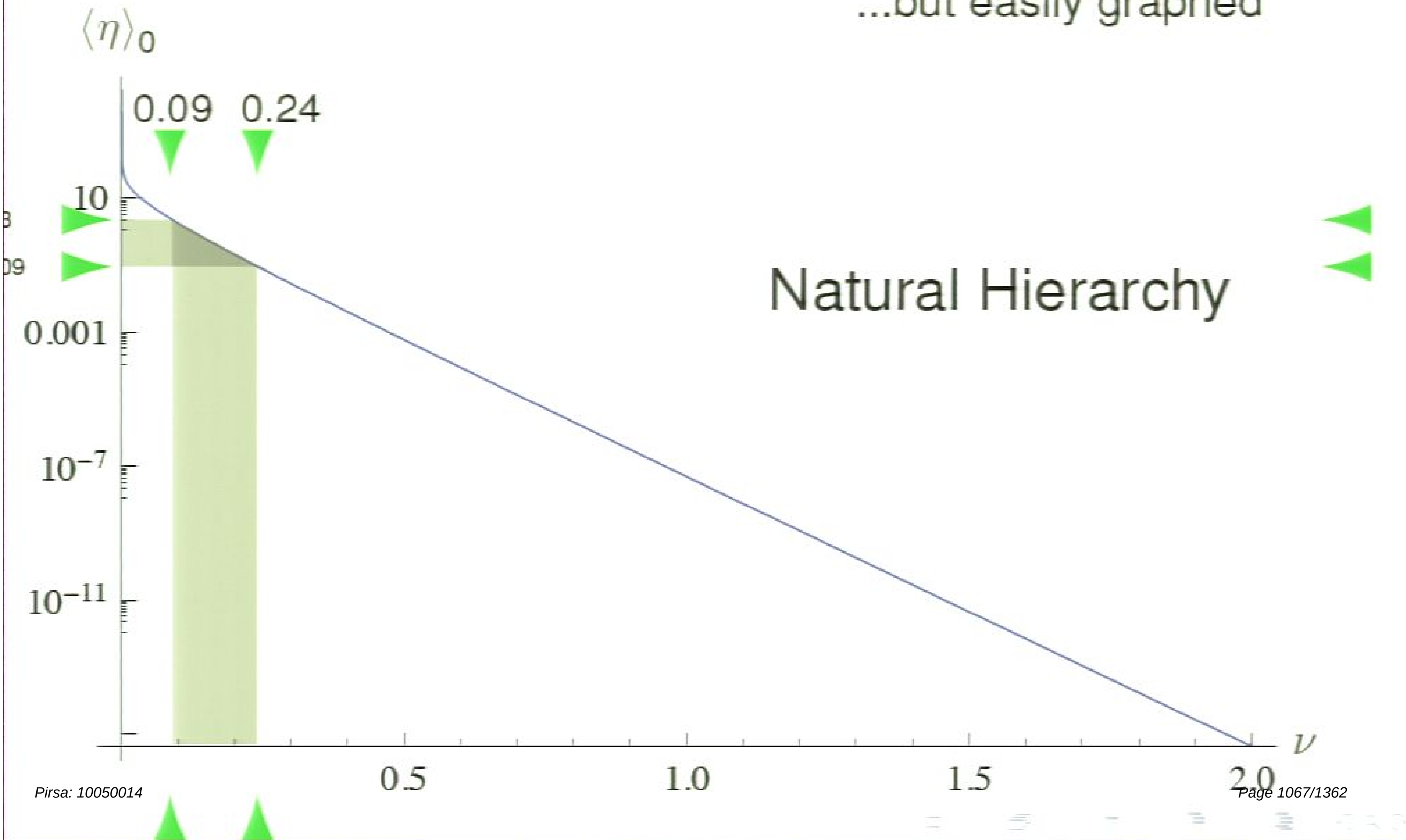

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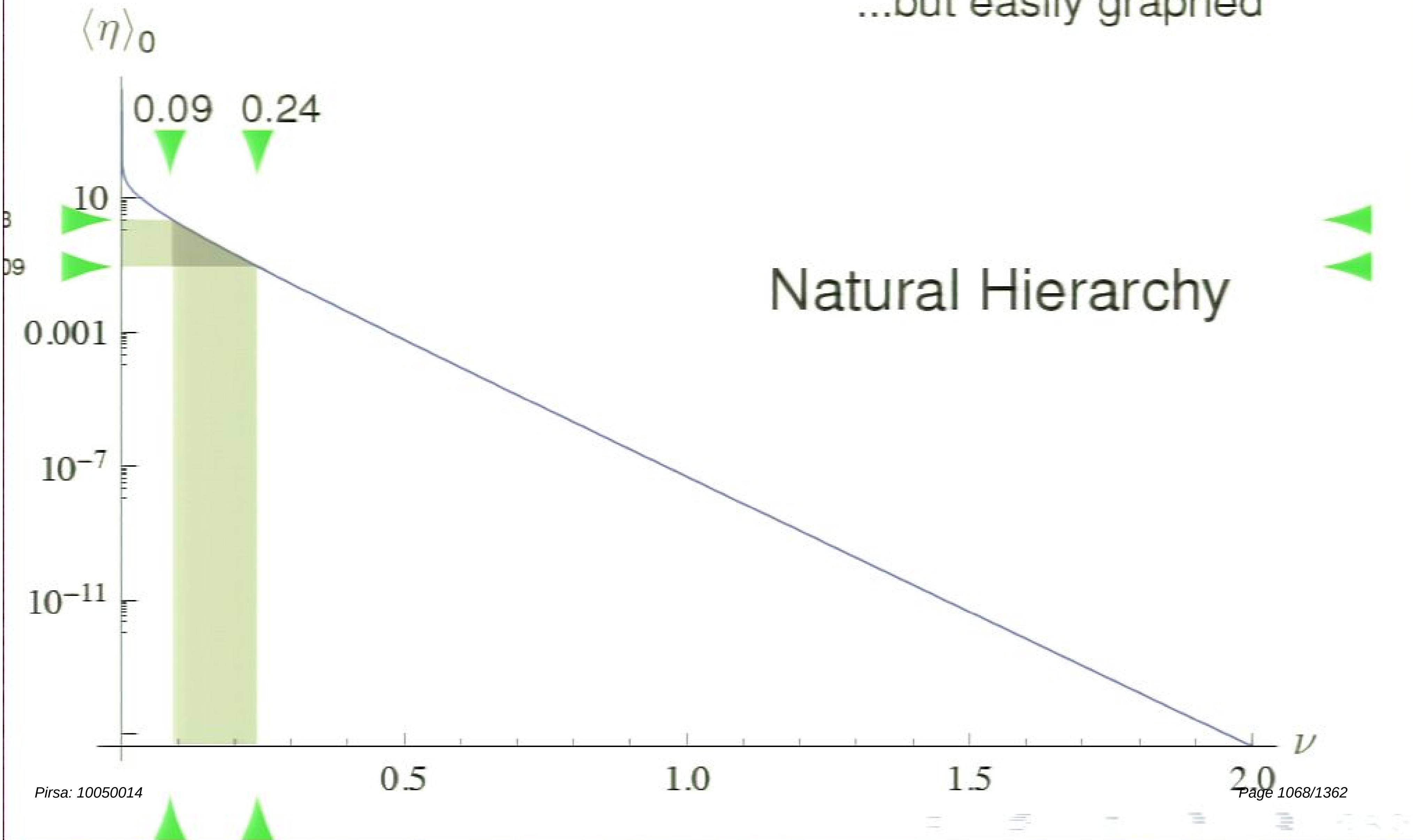

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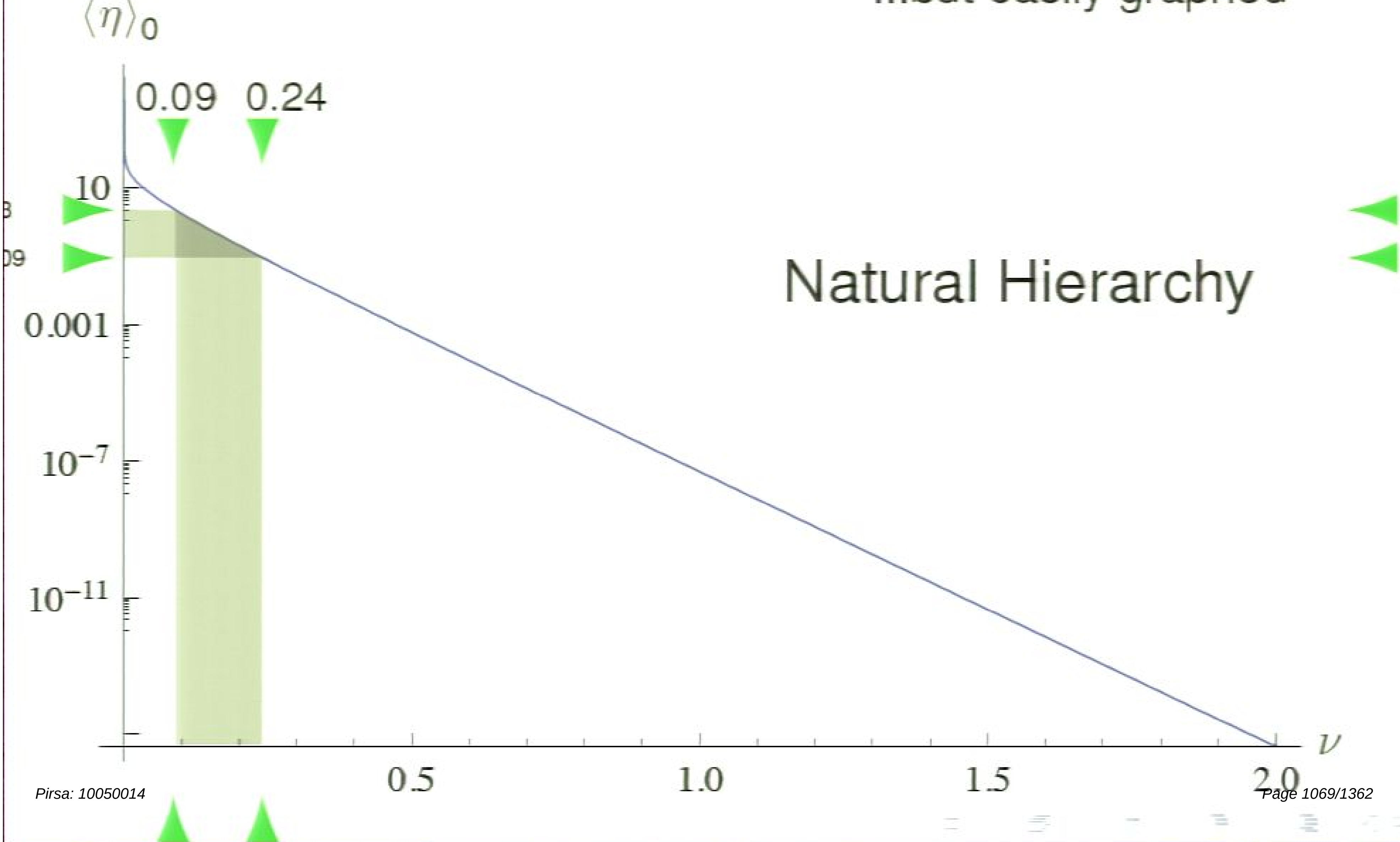

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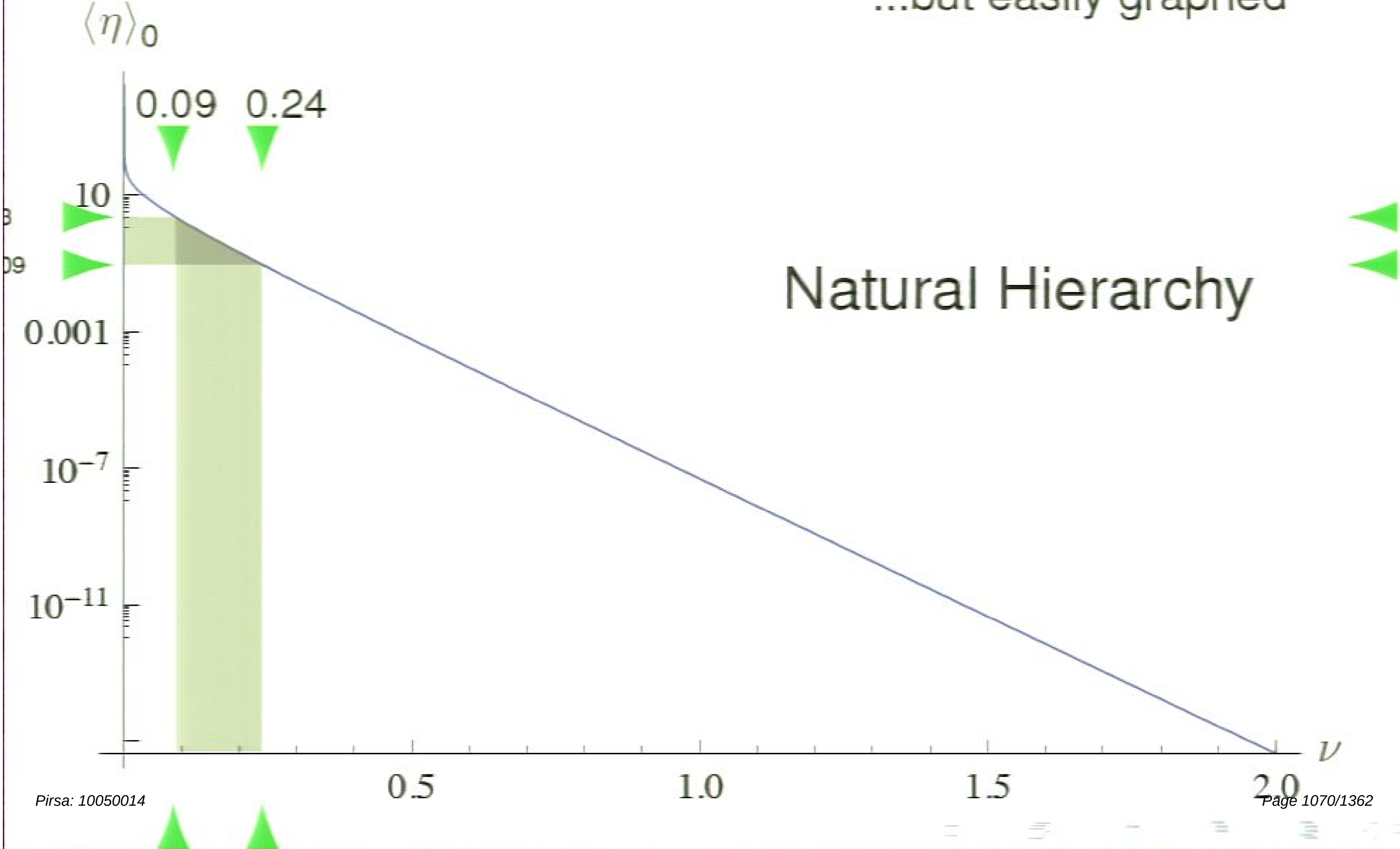

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$$\eta_0 = \pm\sqrt{3}\left(\frac{\nu+1}{\nu}\right)\left[\sqrt{\frac{2}{3}\frac{\nu}{\nu+1}\left(\frac{\mu}{k}\right)^{\nu}+\left(\frac{2}{3}\frac{\nu}{\nu+1}\left(\frac{\mu}{k}\right)^{\nu}\right)^2}\right.$$
$$\left.+\sinh^{-1}\sqrt{\frac{2}{3}\frac{\nu}{\nu+1}\left(\frac{\mu}{k}\right)^{\nu}}\right]$$

- Not easily inverted...

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$$\eta_0 = \pm\sqrt{3}\left(\frac{\nu+1}{\nu}\right)\left[\sqrt{\frac{2}{3}\frac{\nu}{\nu+1}\left(\frac{\mu}{k}\right)^{\nu} + \left(\frac{2}{3}\frac{\nu}{\nu+1}\left(\frac{\mu}{k}\right)^{\nu}\right)^2} + \sinh^{-1}\sqrt{\frac{2}{3}\frac{\nu}{\nu+1}\left(\frac{\mu}{k}\right)^{\nu}}\right]$$

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an also ask how sensitive $\langle\eta\rangle_0$ is to μ/k (and vice-versa).

	% change in $\langle\eta\rangle_0$ for 1% change in weak scale
$\sim 1/4$	0.1% (fairly robust)
$\leq \nu \leq 3$	1% (robust)
$\gg 1$	very sensitive to variation

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perator Dimension

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Hierarchy by Hand	$\nu > 1$	$\Delta > \frac{5}{2}$
Improved Hierarchy	$\nu \sim 1$	$\Delta \sim \frac{5}{2}$
Natural Hierarchy	$0 < \nu < 1$	$2 < \Delta < \frac{5}{2}$

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ok at potential

$$V(\eta) = -12k^2 - k^2\nu\left(1 - \frac{\nu}{8}\right)\eta^2 + \cdots$$

ves η's mass as

$$m_\eta^2 = -2k^2\nu\left(1 - \frac{\nu}{8}\right)$$

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lanck Weak Hierarchy Robustness

an also ask how sensitive $\langle\eta\rangle_0$ is to μ/k (and vice-versa).

	% change in $\langle\eta\rangle_0$ for 1% change in weak scale
$\sim 1/4$	0.1% (fairly robust)
$\leq \nu \leq 3$	1% (robust)
$\gg 1$	very sensitive to variation

course, ν has other consequences...

lanck Weak Hierarchy

...but easily graphed

lanck Weak Hierarchy

- The value of the field at the UV brane is

$$\eta_0 = \pm\sqrt{3}\left(\frac{\nu+1}{\nu}\right)\left[\sqrt{\frac{2}{3}\frac{\nu}{\nu+1}\left(\frac{\mu}{k}\right)^{\nu} + \left(\frac{2}{3}\frac{\nu}{\nu+1}\left(\frac{\mu}{k}\right)^{\nu}\right)^2} + \sinh^{-1}\sqrt{\frac{2}{3}\frac{\nu}{\nu+1}\left(\frac{\mu}{k}\right)^{\nu}}\right]$$

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$$\eta_0 = \pm\sqrt{3}\left(\frac{\nu+1}{\nu}\right)\left[\sqrt{\frac{2}{3}\frac{\nu}{\nu+1}\left(\frac{\mu}{k}\right)^{\nu}+\left(\frac{2}{3}\frac{\nu}{\nu+1}\left(\frac{\mu}{k}\right)^{\nu}\right)^2} + \sinh^{-1}\sqrt{\frac{2}{3}\frac{\nu}{\nu+1}\left(\frac{\mu}{k}\right)^{\nu}}\right]$$

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lanck Weak Hierarchy Robustness

an also ask how sensitive $\langle\eta\rangle_0$ is to μ/k (and vice-versa).

	% change in $\langle\eta\rangle_0$ for 1% change in weak scale
$\sim 1/4$	0.1% (fairly robust)
$\leq \nu \leq 3$	1% (robust)
$\gg 1$	very sensitive to variation

course, ν has other consequences...

calar's Potential

ok at potential

$$V(\eta) = -12k^2 - k^2\nu\left(1 - \frac{\nu}{8}\right)\eta^2 + \cdots$$

ves η's mass as

$$m_\eta^2 = -2k^2\nu\left(1 - \frac{\nu}{8}\right)$$

dS/CFT correspondence says operator dimension is

$$\Delta = 2 + \sqrt{4 + \frac{m_\eta^2}{k^2}} = 2 + \frac{1}{2}|4 - \nu|$$

)perator Dimension

ıe breakdown is

Hierarchy by Hand	$\nu > 1$	$\Delta > \frac{5}{2}$
Improved Hierarchy	$\nu \sim 1$	$\Delta \sim \frac{5}{2}$
Natural Hierarchy	$0 < \nu < 1$	$2 < \Delta < \frac{5}{2}$

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Fluctuations

luctuations Parameterized

$$ds^2 = e^{2(F - A(z))}\left[\left((1-2F)\eta_{\mu\nu} + h_{\mu\nu}\right)dx^\mu dx^\nu + 2A_\mu dx^\mu dz + dz^2\right]$$

$$\eta = \langle \eta \rangle + \tilde{\eta}$$

- Tensor Modes
  - Discussed in arXiv:0808.3977 [Batell et al.]
  - massless zero mode and KK tower
- Vector Modes
  - only zero mode: higher modes eaten by massive tensors
- Scalar Modes
  - gravi-scalar: F
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  - two massless modes

$$\zeta = -\frac{1}{2}F + \frac{A'(z)}{\langle\eta\rangle'}\tilde{\eta} \qquad \& \qquad \sigma = -\frac{A'(z)}{\langle\eta\rangle'}\tilde{\eta}$$

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- Gravi-scalar mixes with scalar η
- Careful decomposition required [Kiritsis & Nitti]
  - must treat massless and massive modes separately
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- Massive modes Schrödinger Potential
  - Behavior similar to massive tensors

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calar Modes - No Massless - Physical Reason

- Can better understand lack of massless modes
- Consider theory without UV brane
  - Work in y coordinate

FGK Model

$$V = -12k^2 + \frac{1}{2}m_\phi^2\phi^2 - \frac{\lambda}{12}\phi^4$$

$$\lambda_{\text{UV}} = 12k^2 - u\phi_{\text{UV}} - 2u\phi_{\text{UV}}(\phi - \phi_{\text{UV}}) + \frac{1}{2}\mu_{\text{UV}}(\phi - \phi_{\text{UV}})^2$$

$$m_\phi^2 = 4ku + u^2$$

$$\lambda = u^2$$

$$A(y) = ky + \frac{1}{24}\left(\langle\phi\rangle^2 - \langle\phi\rangle_{\text{UV}}^2\right)$$

$$\langle\phi\rangle = \phi_{\text{UV}}e^{-uy}$$

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- Examined Planck weak Hierarchy for Batell-Gherghetta Soft-Wall
- Found natural hierarchy for $\nu < 1$
- $\nu < 1$ corresponds to fractional-dimension operators in dual theory
- $\nu < 1$ also implies a continuum of modes in the $5D$ theory
- Thus, natural hierarchy implies unparticles
- Furthermore, can get phenomenologically viable Standard Model Fields

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