Title: Towards a Phenomenology of Quantum Gravity?

Date: Nov 06, 2007 04:15 PM

URL: http://pirsa.org/07110046

Abstract: This talk will review proposed tests of ideas about quantum gravity, including searches for quantum decoherence, probes of the possible energy-dependence of the velocity of light, and the nature of vacuum energy. Motivations will be drawn from a non-critical string theory framework.

Work in Collaboration with:

Nick Mavromatos, Dimitri Nanopoulos & Giovanni Amelino-Camelia, Ignatios Antoniadis, Costas Bachas, CPLEAR Collaboration (Erwin Gabathuler, Noulis Pavlopoulos, Maria Fidecaro, Thomas Ruf, …), Kostas Farakos, John Hagelin, Jorge Lopez, Vasou Mitsou, Sasha Sakharov, Subir Sarkar, Edward Sarkisyan, Mark Srednicki, Michael Westmuckett, MAGIC Collaboration (Adrian Biland, Rudy Bock, Robert Wagner, …)

Outline

- Issues in quantum gravity

Outline

- Issues in quantum gravity
- Modification of quantum mechanics?

  experimental probes with kaons

Outline

- Issues in quantum gravity
- Modification of quantum mechanics?

  experimental probes with kaons
- **Non-critical string approach**

Outline

- Issues in quantum gravity
- Modification of quantum mechanics?

  experimental probes with kaons
- **Non-critical string approach**
- Modification of Lorentz invariance?

  astrophysical probes with GRBs, AGNs
- Violation of equivalence principle?

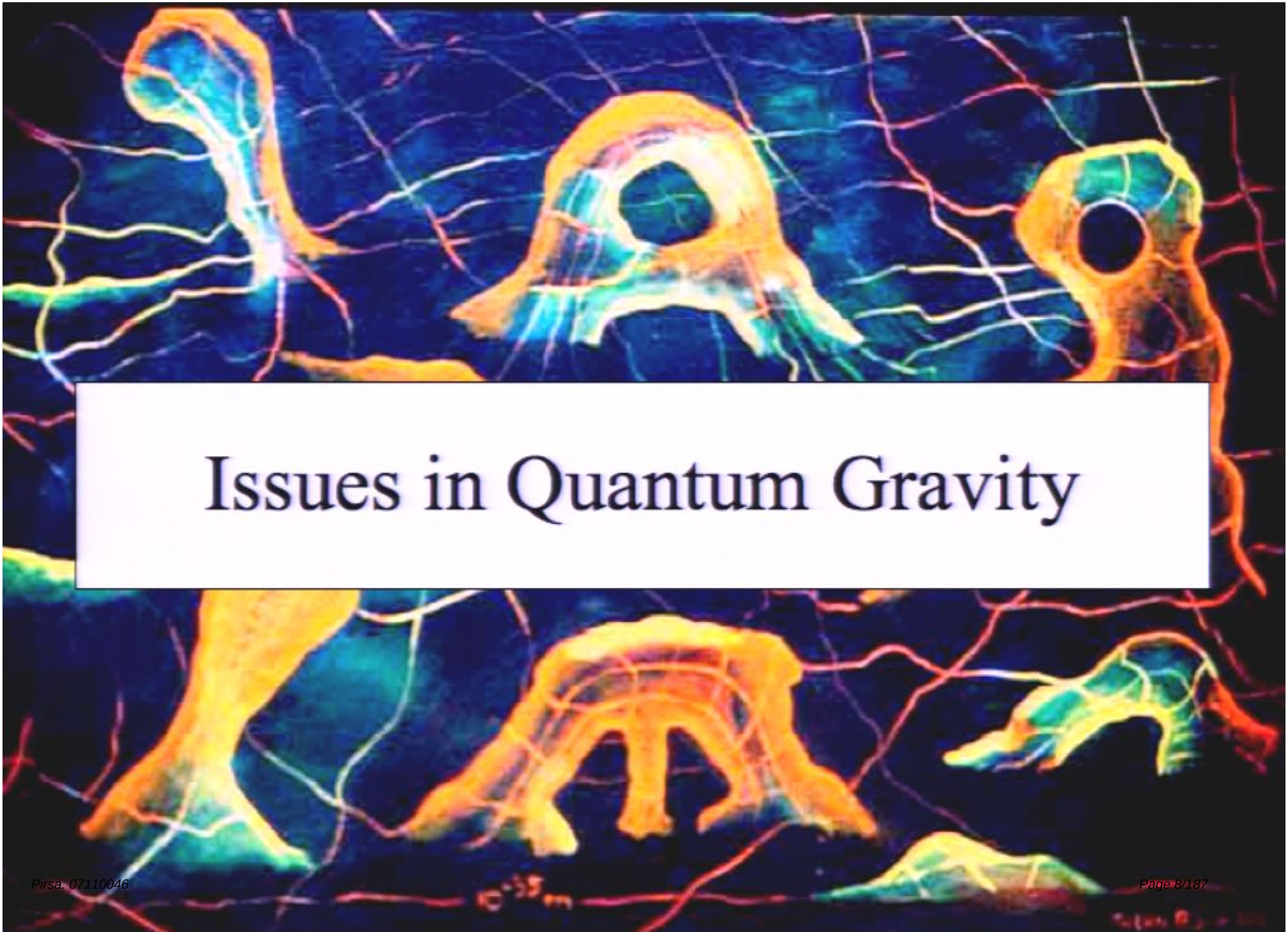
Outline

- Issues in quantum gravity
- Modification of quantum mechanics?

  experimental probes with kaons
- **Non-critical string approach**
- Modification of Lorentz invariance?

  astrophysical probes with GRBs, AGNs
- Violation of equivalence principle?
- Cosmological inflation
- Present-day dark energy

Issues in Quantum Gravity



Problems of Quantum Gravity

- Gravity grows with energy: $\sigma_G \sim E^2/m_P^4$
- Two-graviton exchange is infinite:

$$\int^{\Lambda\to\infty} d^4k \left(\frac{1}{k^2}\right) \leftrightarrow \int_{1/\Lambda\to 0} d^4x \left(\frac{1}{x^6}\right) \sim \Lambda^2 \to \infty$$

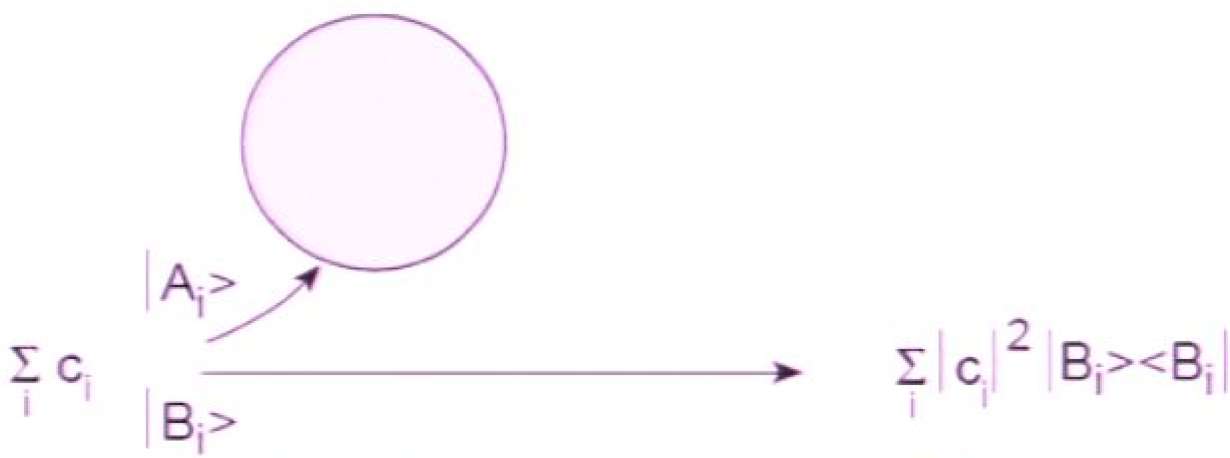
- **Gravity is a non-renormalizable theory**

Problems of Quantum Gravity

- Gravity grows with energy: $\sigma_G \sim E^2/m_P^4$
- Two-graviton exchange is infinite:

$$\int^{\Lambda\to\infty} d^4k \left(\frac{1}{k^2}\right) \leftrightarrow \int_{1/\Lambda\to 0} d^4x \left(\frac{1}{x^6}\right) \sim \Lambda^2 \to \infty$$

- **Gravity is a non-renormalizable theory**
- Pure states evolve to mixed states?



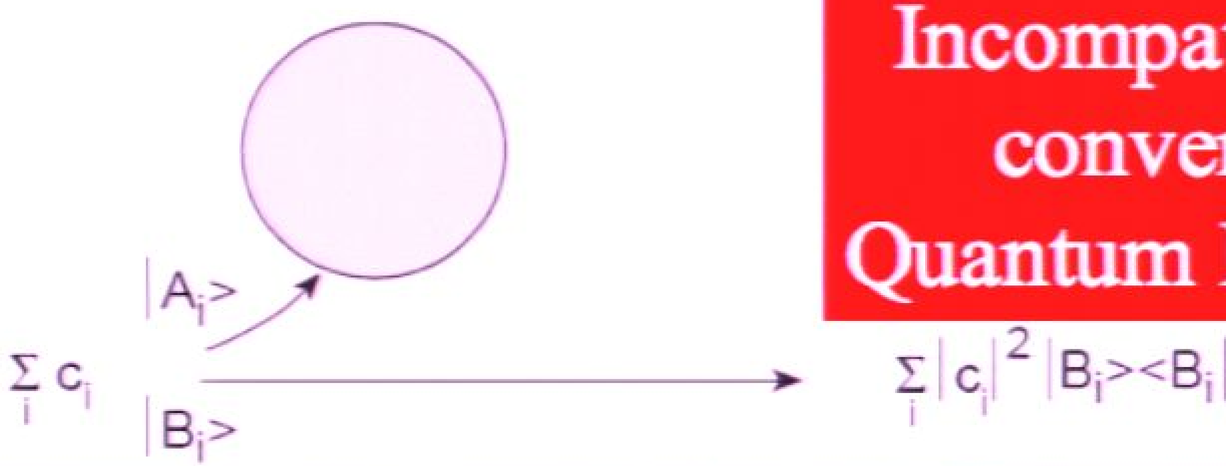
Problems of Quantum Gravity

- Gravity grows with energy: $\sigma_G \sim E^2/m_P^4$
- Two-graviton exchange is infinite:

$$\int^{\Lambda\to\infty} d^4k \left(\frac{1}{k^2}\right) \leftrightarrow \int_{1/\Lambda\to 0} d^4x \left(\frac{1}{x^6}\right) \sim \Lambda^2 \to \infty$$

- **Gravity is a non-renormalizable theory**
- Pure states evolve to mixed states?

Incompatible with conventional Quantum Mechanics



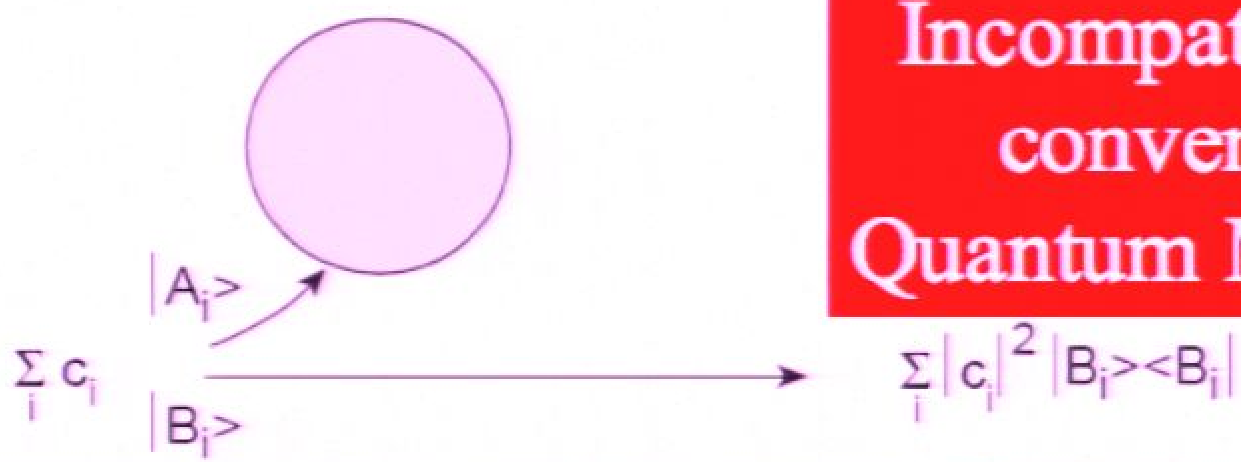
Problems of Quantum Gravity

- Gravity grows with energy: $\sigma_G \sim E^2/m_P^4$
- Two-graviton exchange is infinite:

$$\int^{\Lambda\to\infty} d^4k \left(\frac{1}{k^2}\right) \leftrightarrow \int_{1/\Lambda\to 0} d^4x \left(\frac{1}{x^6}\right) \sim \Lambda^2 \to \infty$$

- **Gravity is a non-renormalizable theory**
- Pure states evolve to mixed states?

Incompatible with conventional Quantum Mechanics

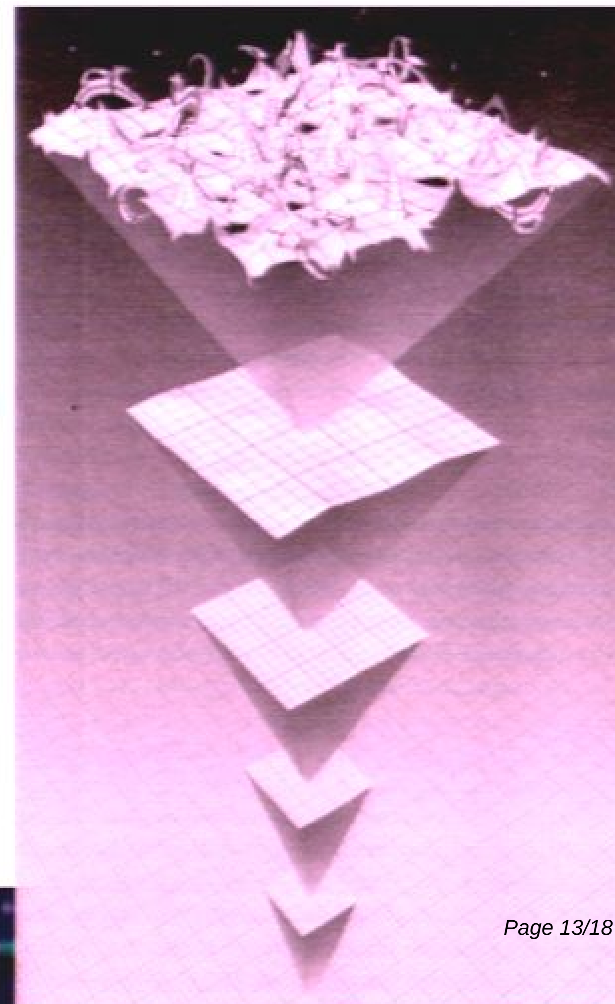


Nature of QG Vacuum

- Expect quantum fluctuations in fabric of space-time
- In natural Planckian units:

  $\Delta E, \Delta x, \Delta t, \Delta\chi \sim 1$

- Fluctuations in energy, space, time, topology of order unity
- **Space-time foam**

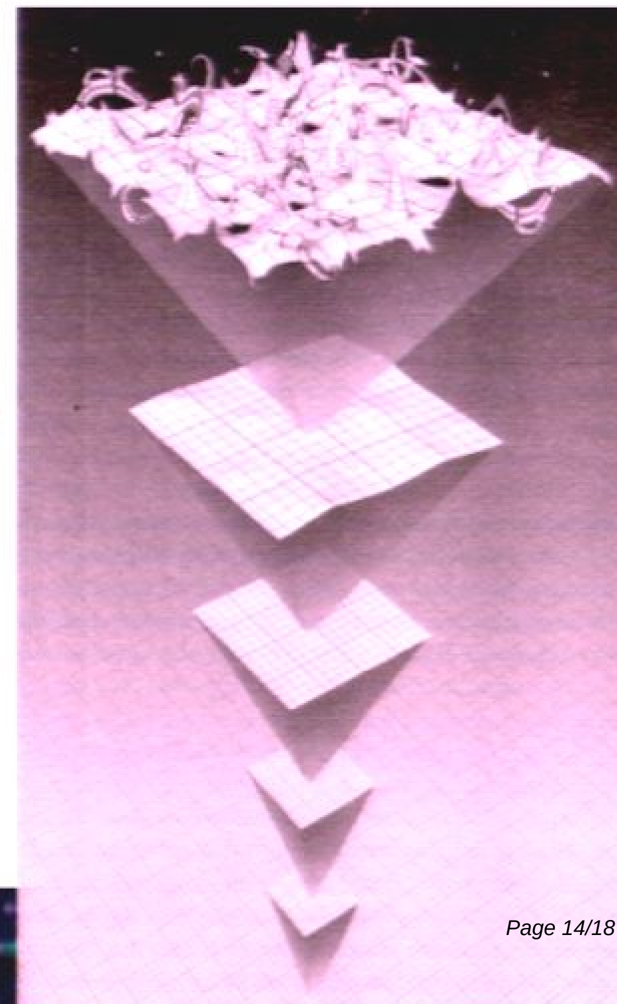


Nature of QG Vacuum

- Expect quantum fluctuations in fabric of space-time
- In natural Planckian units:

  $$\Delta E, \Delta x, \Delta t, \Delta\chi \sim 1$$

- Fluctuations in energy, space, time, topology of order unity
- **Space-time foam**
- **Manifestations?**



Reconciling General Relativity and Quantum Mechanics

- Unfinished business of 20th-century physics
- Primary task of 21st-century physics

Reconciling General Relativity and Quantum Mechanics

- Unfinished business of 20^{th}-century physics
- Primary task of 21^{st}-century physics
- One or the other – or both – must be modified?

Reconciling General Relativity and Quantum Mechanics

- Unfinished business of 20th-century physics
- Primary task of 21st-century physics
- One or the other – or both – must be modified?
- Modification of quantum mechanics?
- Violation of CPT?
- Modification of Lorentz invariance?
- Breakdown of equivalence principle?

Reconciling General Relativity and Quantum Mechanics

- Unfinished business of 20th-century physics
- Primary task of 21st-century physics
- One or the other – or both – must be modified?
- Modification of quantum mechanics?
- Violation of CPT?
- Modification of Lorentz invariance?
- Breakdown of equivalence principle?
- Search for distinctive signature not allowed in quantum field theory

String Theory

- Point-like particles → extended objects
- Simplest possibility: lengths of string
  no divergences in perturbation theory
- Quantum consistency fixes critical # dimensions:
  bosonic string: 26, superstring: 10

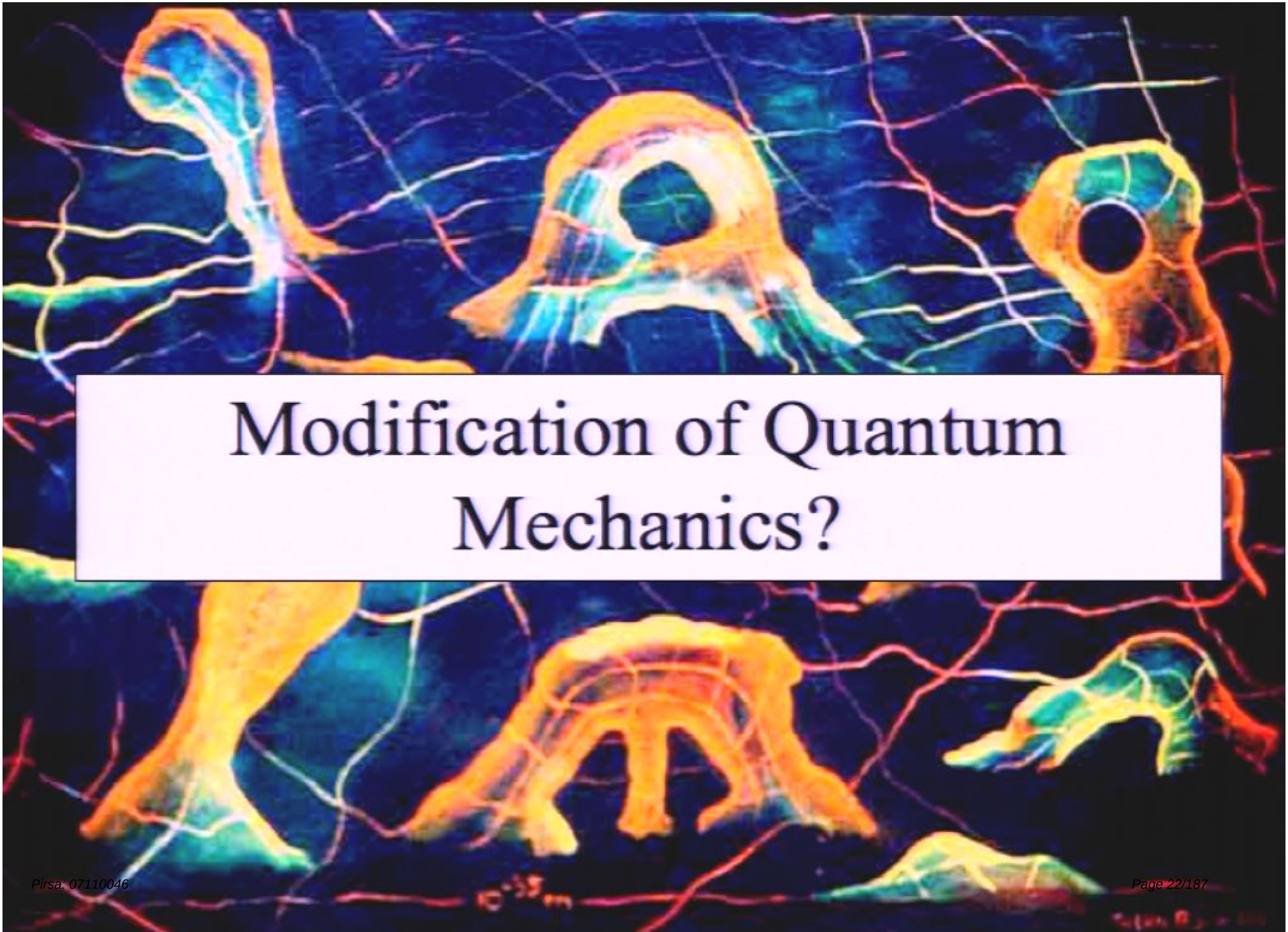
String Theory

- Point-like particles → extended objects
- Simplest possibility: lengths of string
  - no divergences in perturbation theory
- Quantum consistency fixes critical # dimensions:
  - bosonic string: 26, superstring: 10
- Non-perturbative configurations: D-branes
  - black-hole entropy = # of D-brane states

String Theory

- Point-like particles → extended objects
- Simplest possibility: lengths of string
  - no divergences in perturbation theory
- Quantum consistency fixes critical # dimensions:
  - bosonic string: 26, superstring: 10
- Non-perturbative configurations: D-branes
  - black-hole entropy = # of D-brane states
- Is critical string theory the whole story?

Modification of Quantum Mechanics?



Sic Transit Quantum Mechanics?

- Macroscopic black holes are mixed states:
  - thermodynamics: temperature, entropy
  - loss of information across horizon

Sic Transit Quantum Mechanics?

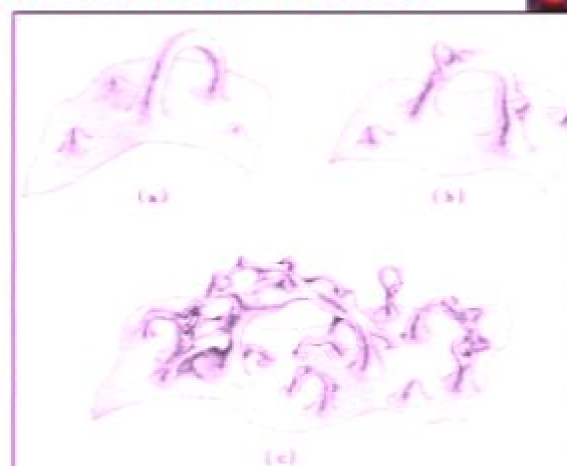
- Macroscopic black holes are mixed states:
  - thermodynamics: temperature, entropy
  - loss of information across horizon
- Could manufacture from pure initial state
- Pure states → mixed states: × Q. Mechanics!

Sic Transit Quantum Mechanics?

- Macroscopic black holes are mixed states:

  thermodynamics: temperature, entropy

  loss of information across horizon
- Could manufacture from pure initial state
- Pure states → mixed states: × Q. Mechanics!
- Also at microscopic level?
- Sum over foamy configurations: {f}
- Lose information in fluctuations?

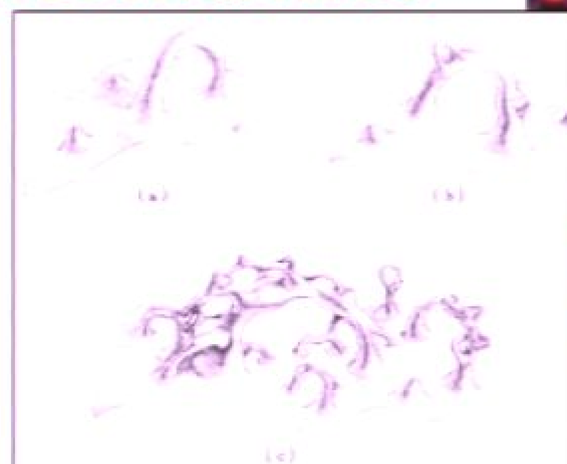


Sic Transit Quantum Mechanics?

- Macroscopic black holes are mixed states:

  thermodynamics: temperature, entropy

  loss of information across horizon
- Could manufacture from pure initial state
- Pure states → mixed states: × Q. Mechanics!
- Also at microscopic level?
- Sum over foamy configurations: {f}
- Lose information in fluctuations?
- Asymptotic scattering described by



$\rho_+{}^A{}_B = \$^A{}_{BC}{}^D \, \rho_-{}^C{}_D$: $\$ \neq S\, S^\dagger$: $\$ = \Sigma_f\, S_f\, S_f^\dagger$?

Historical Footnote

- Baryon number not conserved @ Planck scale?
  B not exact gauge symmetry → no B hair
- Proton decay via virtual black hole:
  dimension-6 operator → $\tau_p \sim 10^{46}$ y?

Hawking

Historical Footnote

- Baryon number not conserved @ Planck scale?
  B not exact gauge symmetry → no B hair
- Proton decay via virtual black hole:
  dimension-6 operator → $\tau_p \sim 10^{46}$ y?
- In presence of supersymmetry:
  dimension-5 operator → $\tau_p < 10^{34}$ y?
- If quantum mechanics modified @ black hole

see non-quantum-mechanical effect in proton decay?

Hawking

JE, Hagelin, Nanopoulos + Tamvakis: 1983

Generalized Evolution Equation

- Consider subasymptotic time evolution, averaged over periods t >> Planck time t_P

JE, Hagelin, Nanopoulos + Srednicki: 1983

Generalized Evolution Equation

- Consider subasymptotic time evolution, averaged over periods t >> Planck time t_P
- Usually $\dot{\rho} = i\,[\rho, H]$ integrates to S-matrix

JE, Hagelin, Nanopoulos + Srednicki: 1983

Generalized Evolution Equation

- Consider subasymptotic time evolution, averaged over periods t >> Planck time t_P
- Usually $\dot{\rho} = i\,[\rho, H]$ integrates to S-matrix
- To get $: generalized Liouville equation:

$$\dot{\rho}^A{}_B = \not{H}^A{}_{BC}{}^D\ \rho^C{}_D\ :\ (\not{H}\,\rho)^A{}_B = i[\rho, H]^A{}_B + \delta\not{H}^A{}_{BC}{}^D\ \rho^C{}_D$$

JE, Hagelin, Nanopoulos + Srednicki: 1983

Generalized Evolution Equation

- Consider subasymptotic time evolution, averaged over periods t >> Planck time t_P
- Usually $\dot{\rho} = i\,[\rho, H]$ integrates to S-matrix
- To get $: generalized Liouville equation:

$$\dot{\rho}^A{}_B = \not{H}^A{}_{BC}{}^D\ \rho^C{}_D\ :\ (\not{H}\,\rho)^A{}_B = i[\rho, H]^A{}_B + \delta\not{H}^A{}_{BC}{}^D\ \rho^C{}_D$$

- Entropy increases in general:

$$\frac{1}{2}\,\frac{d}{dt}\,\mathrm{Tr}\,(\rho^2) = \mathrm{Tr}\,(\rho\,\dot{\rho}) = \rho^B{}_A\,\delta\not{H}^A{}_{BC}{}^D\,\rho^C{}_D \leq 0$$

JE, Hagelin, Nanopoulos + Srednicki: 1983

Generalized Evolution Equation

- Consider subasymptotic time evolution, averaged over periods t >> Planck time t_P
- Usually $\dot{\rho} = i\,[\rho, H]$ integrates to S-matrix
- To get $: generalized Liouville equation:

$$\dot{\rho}^A{}_B = \not{H}^A{}_{BC}{}^D \, \rho^C{}_D \; : \; (\not{H}\,\rho)^A{}_B = i[\rho, H]^A{}_B + \delta\not{H}^A{}_{BC}{}^D \, \rho^C{}_D$$

- Entropy increases in general:

$$\frac{1}{2}\,\frac{d}{dt}\,\mathrm{Tr}\,(\rho^2) = \mathrm{Tr}\,(\rho\,\dot{\rho}) = \rho^B{}_A \, \delta\not{H}^A{}_{BC}{}^D \, \rho^C{}_D \leq 0$$

JE, Hagelin, Nanopoulos + Srednicki: 1983

Generalized Evolution Equation

- Consider subasymptotic time evolution, averaged over periods t >> Planck time t_P
- Usually $\dot{\rho} = i\,[\rho, H]$ integrates to S-matrix
- To get \$: generalized Liouville equation:

$$\dot{\rho}^A{}_B = \not{H}^A{}_{BC}{}^D\, \rho^C{}_D \; : \; (\not{H}\,\rho)^A{}_B = i[\rho, H]^A{}_B + \delta\not{H}^A{}_{BC}{}^D\, \rho^C{}_D$$

- Entropy increases in general:

$$\frac{1}{2}\frac{d}{dt}\,\mathrm{Tr}\,(\rho^2) = \mathrm{Tr}\,(\rho\,\dot{\rho}) = \rho^B{}_A\, \delta\not{H}^A{}_{BC}{}^D\, \rho^C{}_D \leq 0$$

JE, Hagelin, Nanopoulos + Srednicki: 1983

Generalized Evolution Equation

- Consider subasymptotic time evolution, averaged over periods t >> Planck time t_P
- Usually $\dot{\rho} = i\,[\rho, H]$ integrates to S-matrix
- To get \$: generalized Liouville equation:

$$\dot{\rho}^A{}_B = \not{H}^A{}_{BC}{}^D\ \rho^C{}_D\ :\ (\not{H}\,\rho)^A{}_B = i[\rho, H]^A{}_B + \delta\not{H}^A{}_{BC}{}^D\ \rho^C{}_D$$

- Entropy increases in general:

$$\frac{1}{2}\,\frac{d}{dt}\,\mathrm{Tr}\,(\rho^2) = \mathrm{Tr}\,(\rho\,\dot{\rho}) = \rho^B{}_A\ \delta\not{H}^A{}_{BC}{}^D\,\rho^C{}_D \leq 0$$

- Possible magnitude of effect: E^2/m_P

JE, Hagelin, Nanopoulos + Srednicki: 1983

Generalized Evolution Equation

- Consider subasymptotic time evolution, averaged over periods t >> Planck time t_P
- Usually $\dot{\rho} = i\,[\rho, H]$ integrates to S-matrix
- To get \$: generalized Liouville equation:

$$\dot{\rho}^A{}_B = \not{H}^A{}_{BC}{}^D \rho^C{}_D : (\not{H}\rho)^A{}_B = i[\rho, H]^A{}_B + \delta\not{H}^A{}_{BC}{}^D \rho^C{}_D$$

- Entropy increases in general:

$$\frac{1}{2}\frac{d}{dt}\mathrm{Tr}\,(\rho^2) = \mathrm{Tr}\,(\rho\,\dot{\rho}) = \rho^B{}_A\,\delta\not{H}^A{}_{BC}{}^D \rho^C{}_D \leq 0$$

- Possible magnitude of effect: E^2/m_P

JE, Hagelin, Nanopoulos + Srednicki: 1983

Generalized Evolution Equation

- Consider subasymptotic time evolution, averaged over periods t >> Planck time t_P
- Usually $\dot{\rho} = i\,[\rho, H]$ integrates to S-matrix
- To get \$: generalized Liouville equation:

$$\dot{\rho}^A{}_B = \not{H}^A{}_{BC}{}^D\ \rho^C{}_D\ :\ (\not{H}\,\rho)^A{}_B = i[\rho, H]^A{}_B + \delta\not{H}^A{}_{BC}{}^D\ \rho^C{}_D$$

- Entropy increases in general:

$$\frac{1}{2}\frac{d}{dt}\,\mathrm{Tr}\,(\rho^2) = \mathrm{Tr}\,(\rho\,\dot{\rho}) = \rho^B{}_A\,\delta\not{H}^A{}_{BC}{}^D\,\rho^C{}_D \le 0$$

- Possible magnitude of effect: E^2/m_P

JE, Hagelin, Nanopoulos + Srednicki: 1983

Simplest Possible Example

- Consider two-state system: $E \pm \Delta E/2$
- Write density matrix in basis $(1, \sigma_{x,y,z})$:

$$H = E + \Delta E \sigma_z : h_0 = 2E, \ h_3 = \Delta E$$

$$\dot{\rho}_x = -\Delta E \, \rho_y \qquad \dot{\rho}_z = 0$$

$$\dot{\rho}_y = \Delta E \, \rho_x \qquad \dot{\rho}_0 = 0$$

JE, Hagelin, Nanopoulos + Srednicki: 1983

Simplest Possible Example

- Consider two-state system: $E \pm \Delta E/2$
- Write density matrix in basis $(1, \sigma_{x,y,z})$:

$$H = E + \Delta E \sigma_z : h_0 = 2E,\ h_3 = \Delta E$$

$$\dot{\rho}_x = -\Delta E\ \rho_y \qquad \dot{\rho}_z = 0$$

$$\dot{\rho}_y = \Delta E\ \rho_x \qquad \dot{\rho}_0 = 0$$

- Add non-quantum-mechanical term:

$$\not{h}_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & -\alpha & -\beta & 0 \\ 0 & -\beta & -\gamma & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\rho(t) \simeq \frac{1}{2} \begin{pmatrix} 1 & e^{-(\alpha+\gamma)t/2}\ e^{-i\Delta E t} \\ e^{-(\alpha+\gamma)t/2}\ e^{i\Delta E t} & 1 \end{pmatrix}$$

JE, Hagelin, Nanopoulos + Srednicki: 1983

Simplest Possible Example

- Consider two-state system: $E \pm \Delta E/2$
- Write density matrix in basis $(1, \sigma_{x,y,z})$:

$$H = E + \Delta E \sigma_z : h_0 = 2E, \; h_3 = \Delta E$$

$$\dot\rho_x = -\Delta E \, \rho_y \qquad \dot\rho_z = 0$$

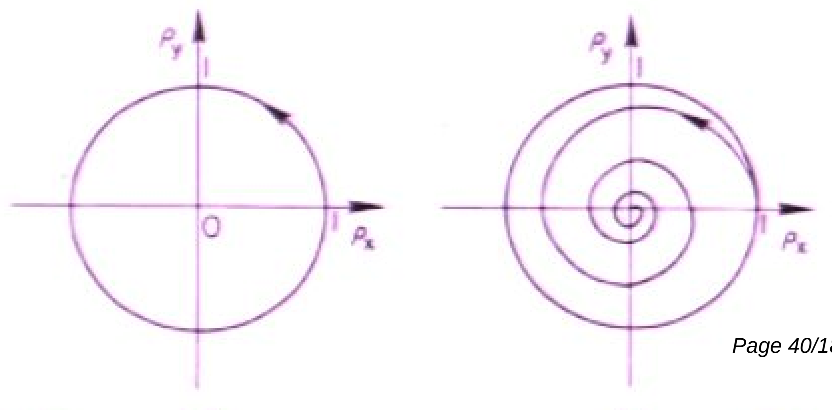
$$\dot\rho_y = \Delta E \, \rho_x \qquad \dot\rho_0 = 0$$

- Add non-quantum-mechanical term:

$$\not{h}_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & -\alpha & -\beta & 0 \\ 0 & -\beta & -\gamma & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\rho(t) \simeq \frac{1}{2} \begin{pmatrix} 1 & e^{-(\alpha+\gamma)t/2} \, e^{-i\Delta E t} \\ e^{-(\alpha+\gamma)t/2} \, e^{i\Delta E t} & 1 \end{pmatrix}$$

- Off-diagonal density matrix elements collapse



JE, Hagelin, Nanopoulos + Srednicki: 1983

Violation of CPT

- Non-trivial $ matrix entails CPT violation

Page; Wald; JE, Mavromatos + Nanopoulos

Violation of CPT

- Non-trivial \$ matrix entails CPT violation
- Standard CPT operator θ:

$\rho_{out}' = \Theta \rho_{in}$ $\rho_{in}' = \Theta^{-1} \rho_{out}$ where $\rho_{out} = \$ \rho_{in}$ $\rho_{out}' = \$ \rho_{in}'$

Page; Wald; JE, Mavromatos + Nanopoulos

Violation of CPT

- Non-trivial \$ matrix entails CPT violation
- Standard CPT operator θ:

$\rho_{out}' = \Theta \rho_{in} \quad \rho_{in}' = \Theta^{-1} \rho_{out}$ where $\rho_{out} = \$ \rho_{in} \quad \rho_{out}' = \$ \rho_{in}'$

- Hence $\Theta = \$ \Theta^{-1} \$$ and \$ matrix has inverse:

$$\$^{-1} = \Theta^{-1} \$ \Theta^{-1}$$

Page; Wald; JE, Mavromatos + Nanopoulos

Violation of CPT

- Non-trivial $ matrix entails CPT violation
- Standard CPT operator θ:

$\rho_{out}' = \Theta \rho_{in} \;\; \rho_{in}' = \Theta^{-1} \rho_{out}$ where $\rho_{out} = \not{S} \rho_{in} \;\; \rho_{out}' = \not{S} \rho_{in}'$

- Hence $\Theta = \not{S} \Theta^{-1} \not{S}$ and $ matrix has inverse:

$$\not{S}^{-1} = \Theta^{-1} \not{S} \Theta^{-1}$$

- This is impossible if $ matrix is singular, as in any framework allowing pure states to evolve into mixed states

Page; Wald; JE, Mavromatos + Nanopoulos

Application to Neutral Kaon System

- 2-state Hamiltonian in $K_1 - K_2$ basis

$$H = \begin{pmatrix} M - \frac{i}{2}\Gamma - \mathrm{Re}M_{12} + \frac{i}{2}\mathrm{Re}\Gamma_{12} & \frac{1}{2}\delta M - \frac{i}{4}\delta\Gamma - i\mathrm{Im}M_{12} - \frac{1}{2}\mathrm{Im}\Gamma_{12} \\ \frac{1}{2}\delta M - \frac{i}{4}\delta\Gamma + i\mathrm{Im}M_{12} - \frac{1}{2}\mathrm{Im}\Gamma_{12} & M - \frac{i}{2}\Gamma + \mathrm{Re}M_{12} - \frac{i}{2}\mathrm{Re}\Gamma_{12} \end{pmatrix}$$

JE, Hagelin, Nanopoulos + Srednicki: 1983

Application to Neutral Kaon System

- 2-state Hamiltonian in $K_1 - K_2$ basis

$$H = \begin{pmatrix} M - \frac{i}{2}\Gamma - \mathrm{Re}M_{12} + \frac{i}{2}\mathrm{Re}\Gamma_{12} & \frac{1}{2}\delta M - \frac{i}{4}\delta\Gamma - i\mathrm{Im}M_{12} - \frac{1}{2}\mathrm{Im}\Gamma_{12} \\ \frac{1}{2}\delta M - \frac{i}{4}\delta\Gamma + i\mathrm{Im}M_{12} - \frac{1}{2}\mathrm{Im}\Gamma_{12} & M - \frac{i}{2}\Gamma + \mathrm{Re}M_{12} - \frac{i}{2}\mathrm{Re}\Gamma_{12} \end{pmatrix}$$

- In the σ-matrix basis:

$$H_{\alpha\beta} = \begin{pmatrix} -\Gamma & -\frac{1}{2}\delta\Gamma & -\mathrm{Im}\Gamma_{12} & -\mathrm{Re}\Gamma_{12} \\ -\frac{1}{2}\delta\Gamma & -\Gamma & -2\mathrm{Re}M_{12} & -2\mathrm{Im}M_{12} \\ -\mathrm{Im}\Gamma_{12} & 2\mathrm{Re}M_{12} & -\Gamma & -\delta M \\ -\mathrm{Re}\Gamma_{12} & -2\mathrm{Im}M_{12} & \delta M & -\Gamma \end{pmatrix}$$

JE, Hagelin, Nanopoulos + Srednicki: 1983

Application to Neutral Kaon System

- 2-state Hamiltonian in $K_1 - K_2$ basis

$$H = \begin{pmatrix} M - \frac{i}{2}\Gamma - \mathrm{Re}M_{12} + \frac{i}{2}\mathrm{Re}\Gamma_{12} & \frac{1}{2}\delta M - \frac{i}{4}\delta\Gamma - i\mathrm{Im}M_{12} - \frac{1}{2}\mathrm{Im}\Gamma_{12} \\ \frac{1}{2}\delta M - \frac{i}{4}\delta\Gamma + i\mathrm{Im}M_{12} - \frac{1}{2}\mathrm{Im}\Gamma_{12} & M - \frac{i}{2}\Gamma + \mathrm{Re}M_{12} - \frac{i}{2}\mathrm{Re}\Gamma_{12} \end{pmatrix}$$

- In the σ-matrix basis:

$$H_{\alpha\beta} = \begin{pmatrix} -\Gamma & -\frac{1}{2}\delta\Gamma & -\mathrm{Im}\Gamma_{12} & -\mathrm{Re}\Gamma_{12} \\ -\frac{1}{2}\delta\Gamma & -\Gamma & -2\mathrm{Re}M_{12} & -2\mathrm{Im}M_{12} \\ -\mathrm{Im}\Gamma_{12} & 2\mathrm{Re}M_{12} & -\Gamma & -\delta M \\ -\mathrm{Re}\Gamma_{12} & -2\mathrm{Im}M_{12} & \delta M & -\Gamma \end{pmatrix}$$

- Conserve S, probability:

$$\delta \not{H}_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -2\alpha & -2\beta \\ 0 & 0 & -2\beta & -2\gamma \end{pmatrix} \quad \alpha, \gamma > 0, \qquad \alpha\gamma > \beta^2$$

JE, Hagelin, Nanopoulos + Srednicki: 1983

Application to Neutral Kaon System

- 2-state Hamiltonian in $K_1 - K_2$ basis

$$H = \begin{pmatrix} M - \frac{i}{2}\Gamma - \mathrm{Re}M_{12} + \frac{i}{2}\mathrm{Re}\Gamma_{12} & \frac{1}{2}\delta M - \frac{i}{4}\delta\Gamma - i\mathrm{Im}M_{12} - \frac{1}{2}\mathrm{Im}\Gamma_{12} \\ \frac{1}{2}\delta M - \frac{i}{4}\delta\Gamma + i\mathrm{Im}M_{12} - \frac{1}{2}\mathrm{Im}\Gamma_{12} & M - \frac{i}{2}\Gamma + \mathrm{Re}M_{12} - \frac{i}{2}\mathrm{Re}\Gamma_{12} \end{pmatrix}$$

- In the σ-matrix basis:

$$H_{\alpha\beta} = \begin{pmatrix} -\Gamma & -\frac{1}{2}\delta\Gamma & -\mathrm{Im}\Gamma_{12} & -\mathrm{Re}\Gamma_{12} \\ -\frac{1}{2}\delta\Gamma & -\Gamma & -2\mathrm{Re}M_{12} & -2\mathrm{Im}M_{12} \\ -\mathrm{Im}\Gamma_{12} & 2\mathrm{Re}M_{12} & -\Gamma & -\delta M \\ -\mathrm{Re}\Gamma_{12} & -2\mathrm{Im}M_{12} & \delta M & -\Gamma \end{pmatrix}$$

- Conserve S, probability:

$$\delta H\!\!\!/_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -2\alpha & -2\beta \\ 0 & 0 & -2\beta & -2\gamma \end{pmatrix} \quad \alpha, \gamma > 0, \qquad \alpha\gamma > \beta^2$$

- Observables:

$$\langle O_i \rangle = \mathrm{Tr}\,[O_i \rho] \qquad O_{2\pi} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \qquad O_{3\pi} \propto \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

JE, Hagelin, Nanopoulos + Srednicki: 198

Application to Neutral Kaon System

- 2-state Hamiltonian in $K_1 - K_2$ basis

$$H = \begin{pmatrix} M - \frac{i}{2}\Gamma - \mathrm{Re}M_{12} + \frac{i}{2}\mathrm{Re}\Gamma_{12} & \frac{1}{2}\delta M - \frac{i}{4}\delta\Gamma - i\mathrm{Im}M_{12} - \frac{1}{2}\mathrm{Im}\Gamma_{12} \\ \frac{1}{2}\delta M - \frac{i}{4}\delta\Gamma + i\mathrm{Im}M_{12} - \frac{1}{2}\mathrm{Im}\Gamma_{12} & M - \frac{i}{2}\Gamma + \mathrm{Re}M_{12} - \frac{i}{2}\mathrm{Re}\Gamma_{12} \end{pmatrix}$$

- In the σ-matrix basis:

$$H_{\alpha\beta} = \begin{pmatrix} -\Gamma & -\frac{1}{2}\delta\Gamma & -\mathrm{Im}\Gamma_{12} & -\mathrm{Re}\Gamma_{12} \\ -\frac{1}{2}\delta\Gamma & -\Gamma & -2\mathrm{Re}M_{12} & -2\mathrm{Im}M_{12} \\ -\mathrm{Im}\Gamma_{12} & 2\mathrm{Re}M_{12} & -\Gamma & -\delta M \\ -\mathrm{Re}\Gamma_{12} & -2\mathrm{Im}M_{12} & \delta M & -\Gamma \end{pmatrix}$$

- Conserve S, probability:

$$\delta \not{H}_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -2\alpha & -2\beta \\ 0 & 0 & -2\beta & -2\gamma \end{pmatrix} \quad \alpha, \gamma > 0, \qquad \alpha\gamma > \beta^2$$

- Observables:

$$\langle O_i \rangle = \mathrm{Tr}\,[O_i \rho] \qquad O_{2\pi} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \qquad O_{3\pi} \propto \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

JE, Hagelin, Nanopoulos + Srednicki: 1983

Application to Neutral Kaon System

- 2-state Hamiltonian in $K_1 - K_2$ basis

$$H = \begin{pmatrix} M - \frac{i}{2}\Gamma - \mathrm{Re}M_{12} + \frac{i}{2}\mathrm{Re}\Gamma_{12} & \frac{1}{2}\delta M - \frac{i}{4}\delta\Gamma - i\mathrm{Im}M_{12} - \frac{1}{2}\mathrm{Im}\Gamma_{12} \\ \frac{1}{2}\delta M - \frac{i}{4}\delta\Gamma + i\mathrm{Im}M_{12} - \frac{1}{2}\mathrm{Im}\Gamma_{12} & M - \frac{i}{2}\Gamma + \mathrm{Re}M_{12} - \frac{i}{2}\mathrm{Re}\Gamma_{12} \end{pmatrix}$$

- In the σ-matrix basis:

$$H_{\alpha\beta} = \begin{pmatrix} -\Gamma & -\frac{1}{2}\delta\Gamma & -\mathrm{Im}\Gamma_{12} & -\mathrm{Re}\Gamma_{12} \\ -\frac{1}{2}\delta\Gamma & -\Gamma & -2\mathrm{Re}M_{12} & -2\mathrm{Im}M_{12} \\ -\mathrm{Im}\Gamma_{12} & 2\mathrm{Re}M_{12} & -\Gamma & -\delta M \\ -\mathrm{Re}\Gamma_{12} & -2\mathrm{Im}M_{12} & \delta M & -\Gamma \end{pmatrix}$$

- Conserve S, probability:

$$\delta \not{H}_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -2\alpha & -2\beta \\ 0 & 0 & -2\beta & -2\gamma \end{pmatrix} \quad \alpha, \gamma > 0, \qquad \alpha\gamma > \beta^2$$

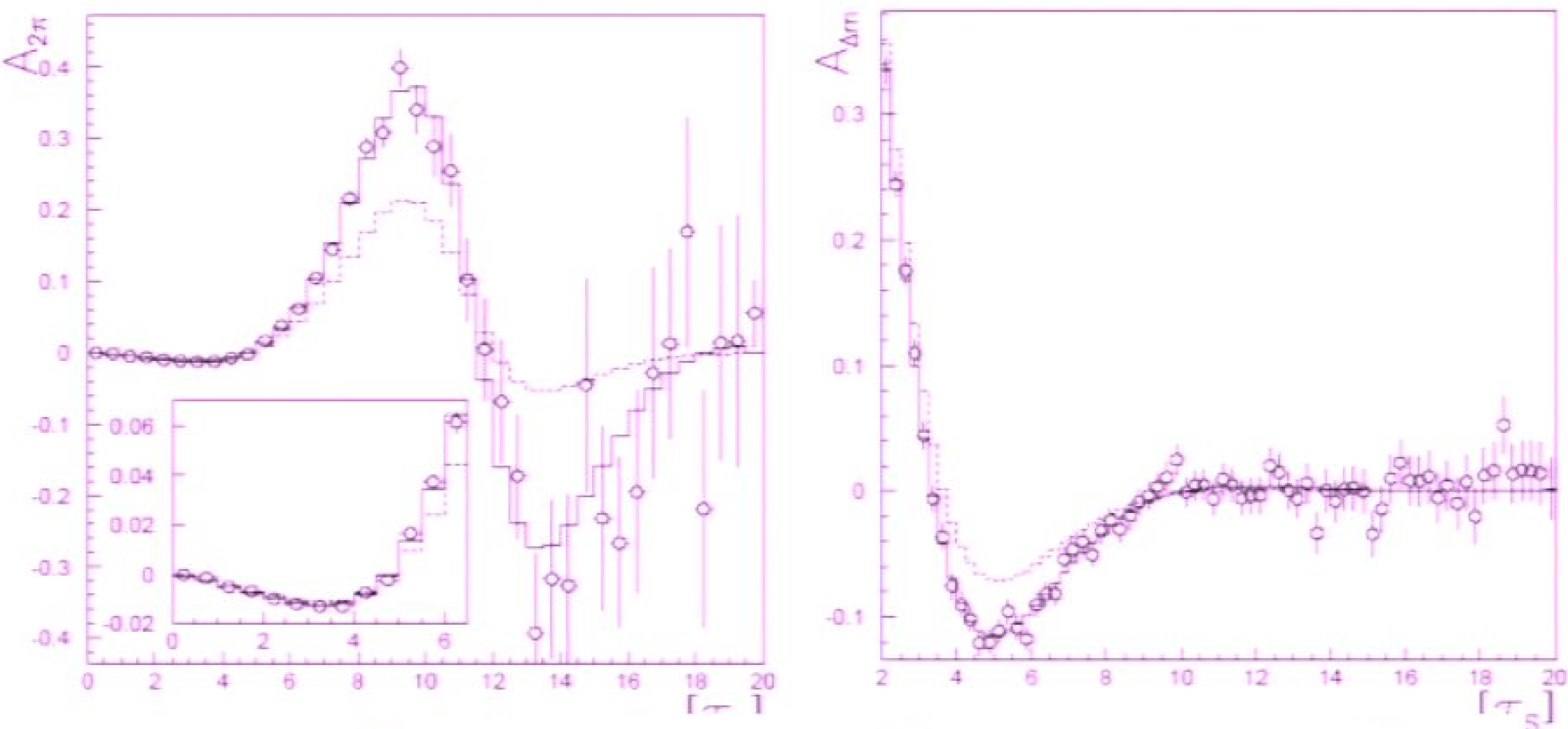
- Observables:

$$\langle O_i \rangle = \mathrm{Tr}\,[O_i \rho] \qquad O_{2\pi} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \qquad O_{3\pi} \propto \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

JE, Hagelin, Nanopoulos + Srednicki: 198

Probes of Quantum Mechanics using CPLEAR Data

- Using K →2π decays, K → πeν decays

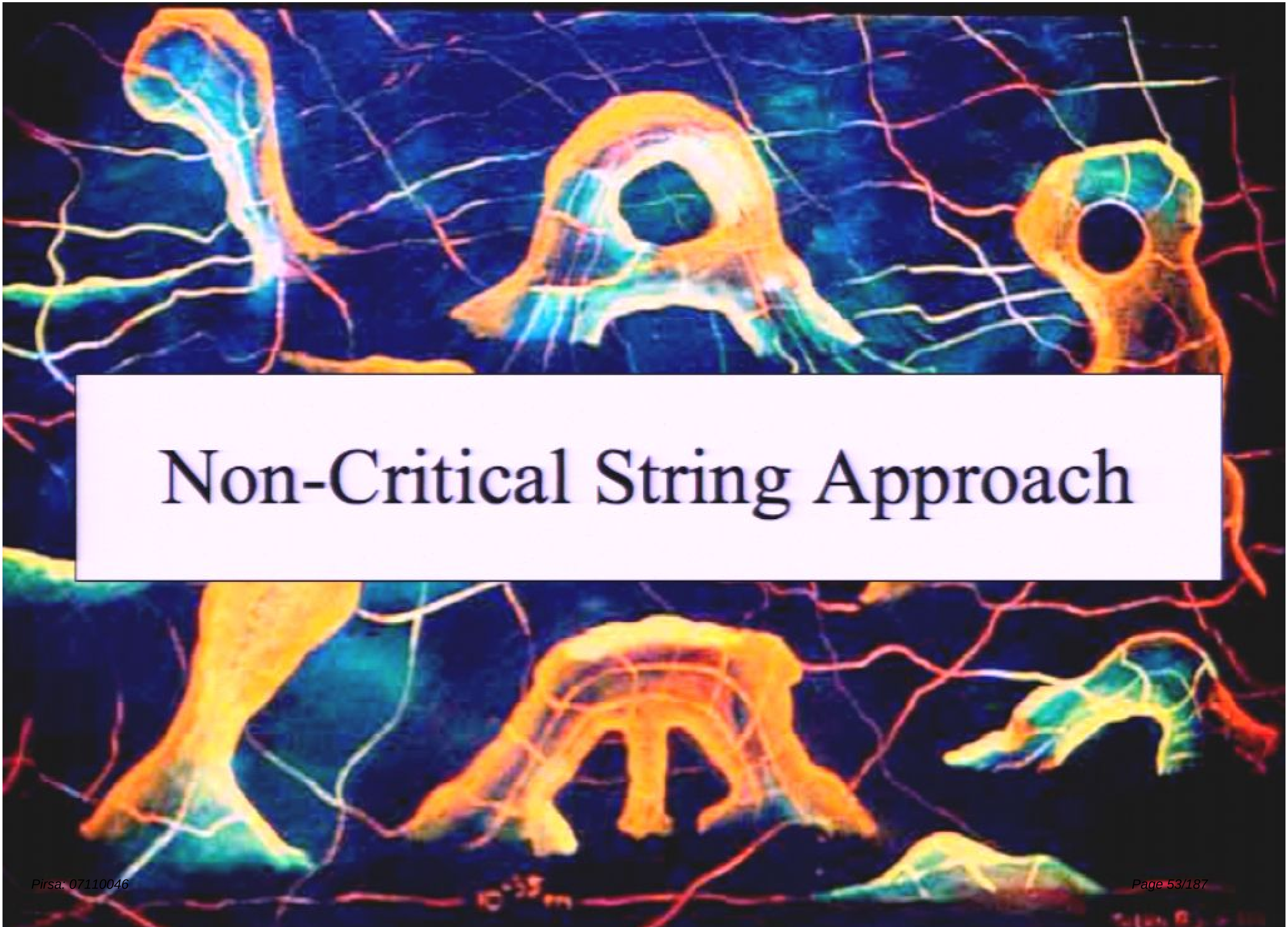


$\alpha < 4.0 \times 10^{-17}$ GeV $\quad |\beta| < 2.3 \times 10^{-19}$ GeV $\quad \gamma < 3.7 \times 10^{-21}$ GeV

JE, Lopez, Mavromatos, Nanopoulos

Non-Critical String Approach

Non-Critical String Approach



World-Sheet Formulation of Non-Critical Strings

- Consider perturbation of critical string model:

$$S = S_0(r) + g \int d^2 z V_g(r)$$

by operator g, vertex V_g, not exactly marginal:

scaling dimension: $\alpha_g = -gC_{ggg} + \ldots$

JE, Mavromatos + Nanopoulos: 1992

World-Sheet Formulation of Non-Critical Strings

- Consider perturbation of critical string model:

$$S = S_0(r) + g \int d^2 z V_g(r)$$

by operator g, vertex V_g, not exactly marginal:

scaling dimension: $\alpha_g = -gC_{ggg} + \ldots$

- Restore conformal invariance by dressing with Liouville field Φ: $\int d^2 z g V_g(r) \to \int d^2 z g e^{\alpha_g \phi} V_g(r)$

10^{-35}m

JE, Mavromatos + Nanopoulos: 1992

World-Sheet Formulation of Non-Critical Strings

- Consider perturbation of critical string model:

$$S = S_0(r) + g \int d^2 z V_g(r)$$

by operator g, vertex V_g, not exactly marginal: scaling dimension: $\alpha_g = -gC_{ggg} + \ldots$

- Restore conformal invariance by dressing with Liouville field Φ: $\int d^2 z g V_g(r) \to \int d^2 z g e^{\alpha_g \phi} V_g(r)$
- Non-trivial β functions for renormalized couplings:

$$g_R \equiv g - C_{ggg}\phi g^2 + \ldots \quad \beta_g = -C_{ggg} g_R^2 + \ldots$$

JE, Mavromatos + Nanopoulos: 1992

Equation of Motion for Density Matrix

- Density matrix function of g^i, momenta: $\rho(g^i, p_i)$

JE, Mavromatos + Nanopoulos: 1992

Equation of Motion for Density Matrix

- Density matrix function of g^i, momenta: $\rho(g^i, p_i)$
- Effective action is Zamolodchikov C function:

$\dot{g}^i = \beta^i(g)$: $\frac{\delta C(g)}{\delta g^i} = G_{ij}\beta^j$ where $C[g] = \int dt(p_i \dot{g}^i - E)$

JE, Mavromatos + Nanopoulos: 1992

Equation of Motion for Density Matrix

- Density matrix function of g^i, momenta: $\rho(g^i, p_i)$
- Effective action is Zamolodchikov C function:

$\dot{g}^i = \beta^i(g)$: $\frac{\delta C(g)}{\delta g^i} = G_{ij}\beta^j$ where $C[g] = \int dt(p_i \dot{g}^i - E)$

- Renormalizability of world-sheet σ model:

$$\frac{d}{dt}\rho[g^i, p_i, t] = 0 = \frac{\partial}{\partial t}\rho + \dot{g}^i \frac{\partial}{\partial g^i}\rho + \dot{p}_i \frac{\partial}{\partial p_i}\rho$$

JE, Mavromatos + Nanopoulos: 1992

Equation of Motion for Density Matrix

- Density matrix function of g^i, momenta: $\rho(g^i, p_i)$
- Effective action is Zamolodchikov C function:

$\dot{g}^i = \beta^i(g) \quad : \quad \frac{\delta C(g)}{\delta g^i} = G_{ij}\beta^j$ where $C[g] = \int dt(p_i \dot{g}^i - E)$

- Renormalizability of world-sheet σ model:

$$\frac{d}{dt}\rho[g^i, p_i, t] = 0 = \frac{\partial}{\partial t}\rho + \dot{g}^i \frac{\partial}{\partial g^i}\rho + \dot{p}_i \frac{\partial}{\partial p_i}\rho$$

- Reduces to equation of EHNS form:
- $\partial_t \rho = i[\rho, H] + \delta\!\!\!/ H \rho$: $\delta\!\!\!/ H \rho = G_{ij}\beta^j \frac{\partial \rho}{\partial p_i} = -iG_{ij}[\rho, g^i]\beta^j$

JE, Mavromatos + Nanopoulos: 1992

Equation of Motion for Density Matrix

- Density matrix function of g^i, momenta: $\rho(g^i, p_i)$
- Effective action is Zamolodchikov C function:

$$\dot{g}^i = \beta^i(g) \quad : \quad \frac{\delta C(g)}{\delta g^i} = G_{ij}\beta^j \text{ where } C[g] = \int dt(p_i \dot{g}^i - E)$$

- Renormalizability of world-sheet σ model:

$$\frac{d}{dt}\rho[g^i, p_i, t] = 0 = \frac{\partial}{\partial t}\rho + \dot{g}^i \frac{\partial}{\partial g^i}\rho + \dot{p}_i \frac{\partial}{\partial p_i}\rho$$

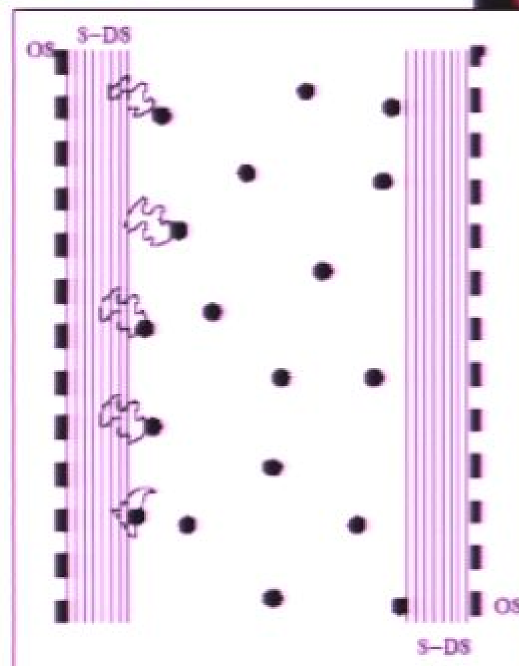
- Reduces to equation of EHNS form:
- $\partial_t \rho = i[\rho, H] + \not{\delta} H \rho$: $\not{\delta} H \rho = G_{ij}\beta^j \frac{\partial \rho}{\partial p_i} = -iG_{ij}[\rho, g^i]\beta^j$
- Higher-genus corrections ⟶ quantization

JE, Mavromatos + Nanopoulos: 1992

A Supersymmetric D-Brane Model for Space-Time Foam

JE, Mavromatos + Westmucket

- Two stacks, each of 8 coincident D8-branes attached to orientifold planes, D0 particles in bulk



Equation of Motion for Density Matrix

- Density matrix function of g^i, momenta: $\rho(g^i, p_i)$
- Effective action is Zamolodchikov C function:

$\dot{g}^i = \beta^i(g)$: $\frac{\delta C(g)}{\delta g^i} = G_{ij}\beta^j$ where $C[g] = \int dt(p_i\dot{g}^i - E)$

- Renormalizability of world-sheet σ model:

$$\frac{d}{dt}\rho[g^i, p_i, t] = 0 = \frac{\partial}{\partial t}\rho + \dot{g}^i\frac{\partial}{\partial g^i}\rho + \dot{p}_i\frac{\partial}{\partial p_i}\rho$$

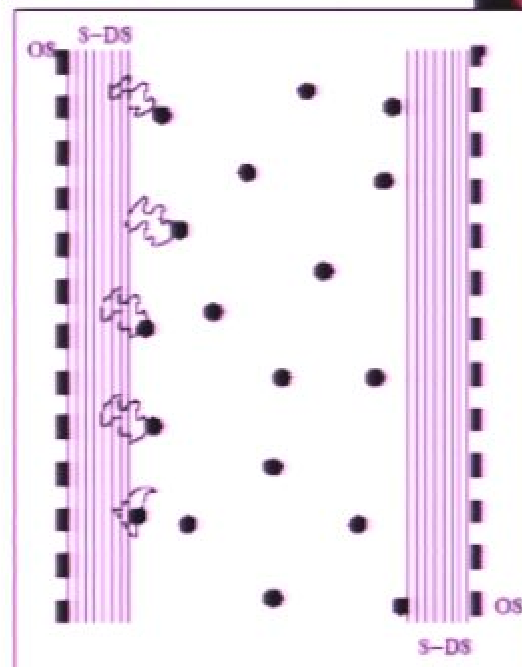
- Reduces to equation of EHNS form:
- $\partial_t \rho = i[\rho, H] + \delta\!\!\!/ H\rho$: $\delta\!\!\!/ H\rho = G_{ij}\beta^j\frac{\partial \rho}{\partial p_i} = -iG_{ij}[\rho, g^i]\beta^j$
- Higher-genus corrections ⟶ quantization

JE, Mavromatos + Nanopoulos; 1992

A Supersymmetric D-Brane Model for Space-Time Foam

JE, Mavromatos + Westmucket

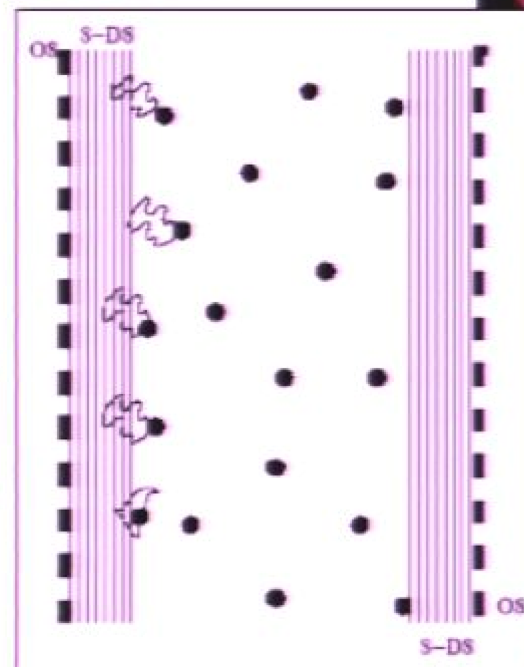
- Two stacks, each of 8 coincident D8-branes attached to orientifold planes, D0 particles in bulk



A Supersymmetric D-Brane Model for Space-Time Foam

JE, Mavromatos + Westmuckett

- Two stacks, each of 8 coincident D8-branes attached to orientifold planes, D0 particles in bulk



- Potential energy vanishes if static

$$\mathcal{V} = -\int \frac{dt}{2t}(8\pi^2\alpha' t)^{-1/2} e^{-R^2 t/2\pi\alpha'} \left[\frac{f_2^8(q) - f_3^8(q) + f_4^8(q)}{f_4^8(q)}\right]$$

- Minimum-energy state = vacuum

A Supersymmetric D-Brane Model for Space-Time Foam

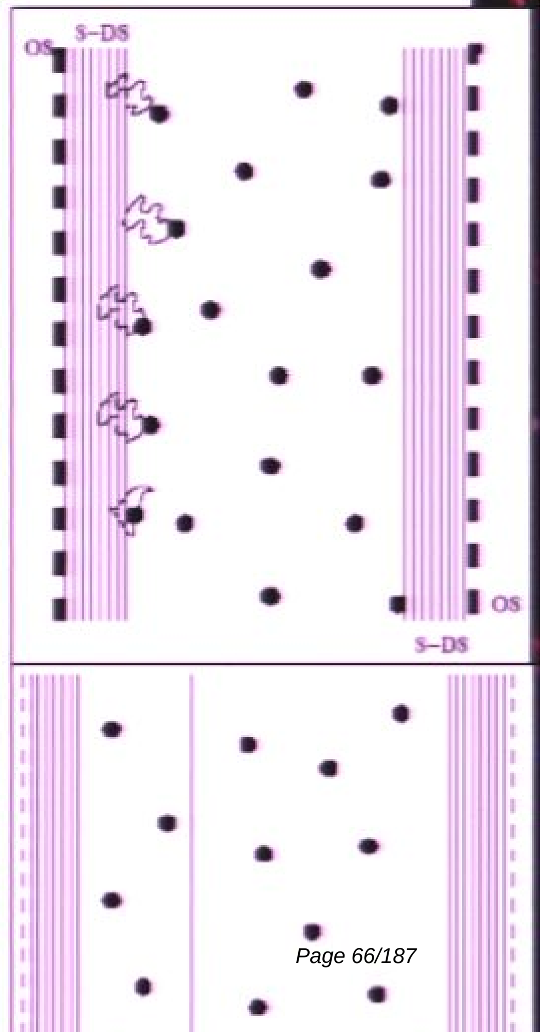
JE, Mavromatos + Westmuckett

- Two stacks, each of 8 coincident D8-branes attached to orientifold planes, D0 particles in bulk
- Potential energy vanishes if static

$$\mathcal{V} = -\int \frac{dt}{2t}(8\pi^2\alpha' t)^{-1/2} e^{-R^2 t/2\pi\alpha'} \left[\frac{f_2^8(q) - f_3^8(q) + f_4^8(q)}{f_4^8(q)}\right]$$

- Minimum-energy state = vacuum
- Non-zero potential if D8-brane moves: $\frac{V_8}{2^{13}\pi^9\alpha'^5}\left[v^4(R-2r)\right]$

where V_8 is volume, R, r distances



Applications of Formalism

- Apparent modification of quantum mechanics

  Quantum field theory on world-sheet

  Obstruction to elevation to space-time

Applications of Formalism

- Apparent modification of quantum mechanics
  - Quantum field theory on world-sheet
  - Obstruction to elevation to space-time
- (Black hole physics)

Applications of Formalism

- Apparent modification of quantum mechanics

  Quantum field theory on world-sheet

  Obstruction to elevation to space-time
- (Black hole physics)
- Violations of Lorentz invariance

  recoil of background due to energetic particle
- Violation of equivalence principle

  recoil effect depends on particle species

Applications of Formalism

- Apparent modification of quantum mechanics

  Quantum field theory on world-sheet

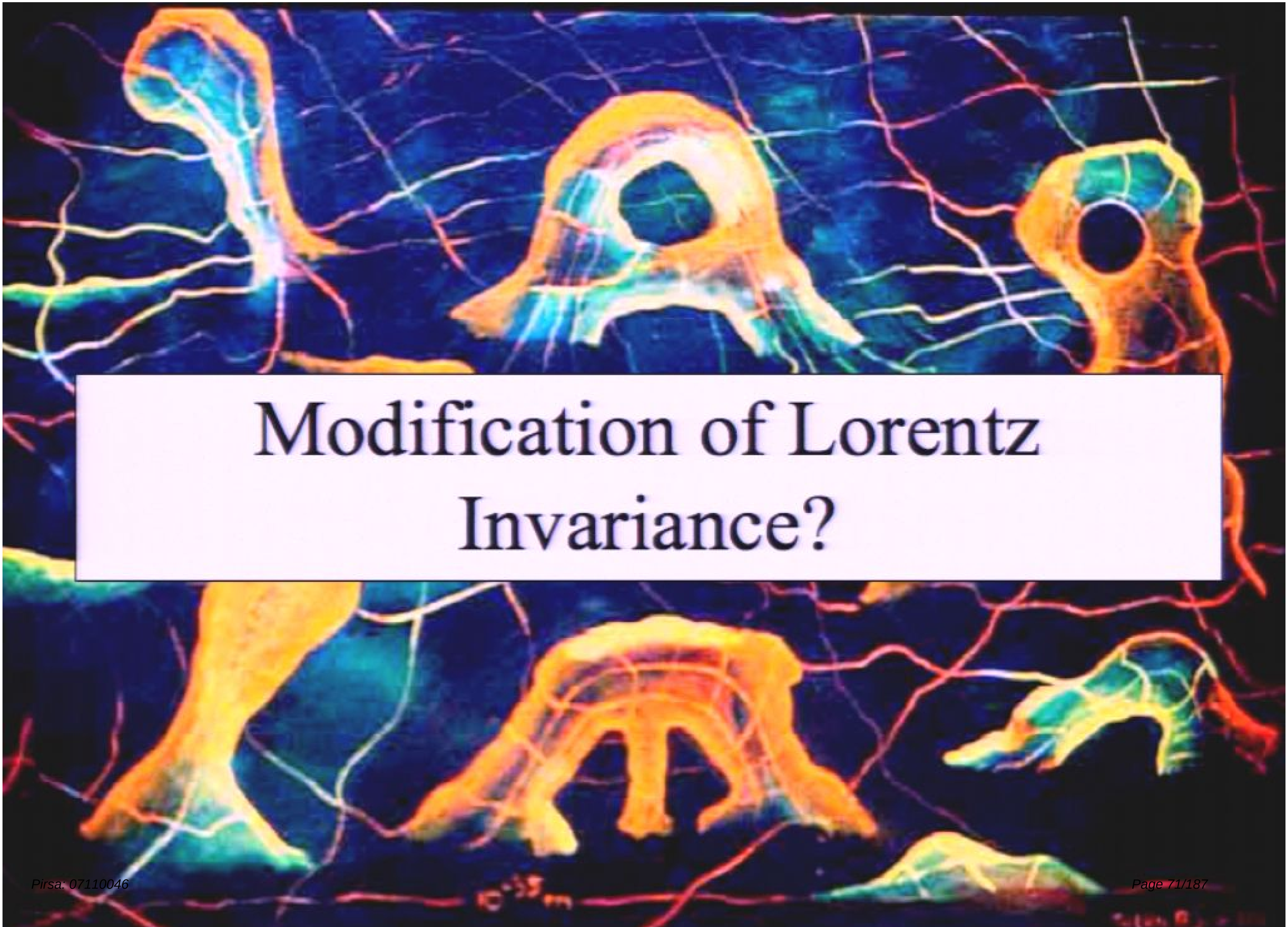
  Obstruction to elevation to space-time
- (Black hole physics)
- Violations of Lorentz invariance

  recoil of background due to energetic particle
- Violation of equivalence principle

  recoil effect depends on particle species
- Inflation and present-day dark energy

  Hubble expansion rate $\leftrightarrow$ departure from criticality

Modification of Lorentz Invariance?



Space-Time Foam as a Non-Trivial Medium

- Expect large intrinsic fluctuations at small scales
- Expect back-reaction due to energetic particles
- Non-trivial refractive index

Space-Time Foam as a Non-Trivial Medium

- Expect large intrinsic fluctuations at small scales
- Expect back-reaction due to energetic particles
- Non-trivial refractive index
- Effect on propagation that increases with energy:

$$c^2 \mathrm{p}^2 = E^2 \left[1 + \xi E/E_{\mathrm{QG}} + \mathcal{O}(E^2/E_{\mathrm{QG}}^2)\right] \qquad v = \frac{\partial E}{\partial p} \sim c\left(1 - \xi \frac{E}{E_{\mathrm{QG}}}\right)$$

Space-Time Foam as a Non-Trivial Medium

- Expect large intrinsic fluctuations at small scales
- Expect back-reaction due to energetic particles
- Non-trivial refractive index
- Effect on propagation that increases with energy:

$$c^2 \mathrm{p}^2 = E^2 \left[1 + \xi E / E_{\mathrm{QG}} + \mathcal{O}(E^2 / E_{\mathrm{QG}}^2) \right] \qquad v = \frac{\partial E}{\partial p} \sim c \left(1 - \xi \frac{E}{E_{\mathrm{QG}}} \right)$$

- Non-critical string model: $\xi = -1$
- $\xi = -1$ needed: avoid Čerenkov radiation *in vacuo*

Space-Time Foam as a Non-Trivial Medium

- Expect large intrinsic fluctuations at small scales
- Expect back-reaction due to energetic particles
- Non-trivial refractive index
- Effect on propagation that increases with energy:

$$c^2 p^2 = E^2 \left[1 + \xi E/E_{QG} + \mathcal{O}(E^2/E_{QG}^2)\right] \qquad v = \frac{\partial E}{\partial p} \sim c\left(1 - \xi \frac{E}{E_{QG}}\right)$$

- Non-critical string model: $\xi = -1$
- $\xi = -1$ needed: avoid Čerenkov radiation *in vacuo*
- Expect: $E_{QG} = O(M_P)$
- Related to $1/M_D$ in non-critical string model

Non-Critical String Description

- Consider energetic particle propagating through foam of D0-particles
- Interactions $\rightarrow$ D0-particle recoil

Non-Critical String Description

- Consider energetic particle propagating through foam of D0-particles
- Interactions → D0-particle recoil
- Recoil motion modifies flat-space metric:

$$G_{ij} = \delta_{ij},\ G_{00} = -1,\ G_{0i} = \epsilon^2 (Y_i + \overline{U}_i t)\Theta_\epsilon(t)$$

- Where $U_i \sim E/m_D$ is the recoil velocity

Non-Critical String Description

- Consider energetic particle propagating through foam of D0-particles
- Interactions → D0-particle recoil
- Recoil motion modifies flat-space metric:

$$G_{ij} = \delta_{ij},\ G_{00} = -1,\ G_{0i} = \epsilon^2 (Y_i + \overline{U}_i t)\Theta_\epsilon(t)$$

- Where $U_i \sim E/m_D$ is the recoil velocity
- Modified Maxwell equations:

$$\frac{1}{c^2}\frac{\partial^2}{\partial^2 t}B - \nabla^2 B - 2\left(\overline{U}.\nabla\right)\frac{1}{c}\frac{\partial}{\partial t}B = 0$$

$$\frac{1}{c^2}\frac{\partial^2}{\partial^2 t}E - \nabla^2 E - 2\left(\overline{U}.\nabla\right)\frac{1}{c}\frac{\partial}{\partial t}E = 0$$

JE, Farakos, Mavromatos, Mitsou + Nanopoulos

- Modified dispersion relation: $k^2 - \omega^2 - 2\overline{U}k\omega = 0$

Non-Critical String Description

- Consider energetic particle propagating through foam of D0-particles
- Interactions ⟶ D0-particle recoil
- Recoil motion modifies flat-space metric:

$$G_{ij} = \delta_{ij},\ G_{00} = -1,\ G_{0i} = \epsilon^2 (Y_i + \overline{U}_i t)\Theta_\epsilon(t)$$

- Where $U_i \sim E/m_D$ is the recoil velocity
- Modified Maxwell equations:

$$\frac{1}{c^2}\frac{\partial^2}{\partial^2 t}B - \nabla^2 B - 2\left(\overline{U}.\nabla\right)\frac{1}{c}\frac{\partial}{\partial t}B = 0$$

$$\frac{1}{c^2}\frac{\partial^2}{\partial^2 t}E - \nabla^2 E - 2\left(\overline{U}.\nabla\right)\frac{1}{c}\frac{\partial}{\partial t}E = 0$$

JE, Farakos, Mavromatos, Mitsou + Nanopoulos

- Modified dispersion relation: $k^2 - \omega^2 - 2\overline{U}k\omega = 0$
- Subluminal propagation: $c(E) = c\left(1 - \overline{U}\right) + \mathcal{O}\left(\overline{U}^2\right)$

Astrophysical Probes of Lorentz Violation

- Time delay from distant object:

$$\Delta t \sim \xi \frac{E}{E_{\mathrm{QG}}} \frac{L}{c}$$

Amelino-Camelia, JE, Mavromatos
Nanopoulos + Sarkar: 1997

Astrophysical Probes of Lorentz Violation

- Time delay from distant object:

$$\Delta t \sim \xi \frac{E}{E_{\mathrm{QG}}} \frac{L}{c}$$

Amelino-Camelia, JE, Mavromatos Nanopoulos + Sarkar: 1997

- Compare arrivals of photons of different energies from astrophysical source with small intrinsic δt
- Gamma-Ray Bursters, pulsars, active galaxies, …

Astrophysical Probes of Lorentz Violation

- Time delay from distant object:

$$\Delta t \sim \xi \frac{E}{E_{QG}} \frac{L}{c}$$

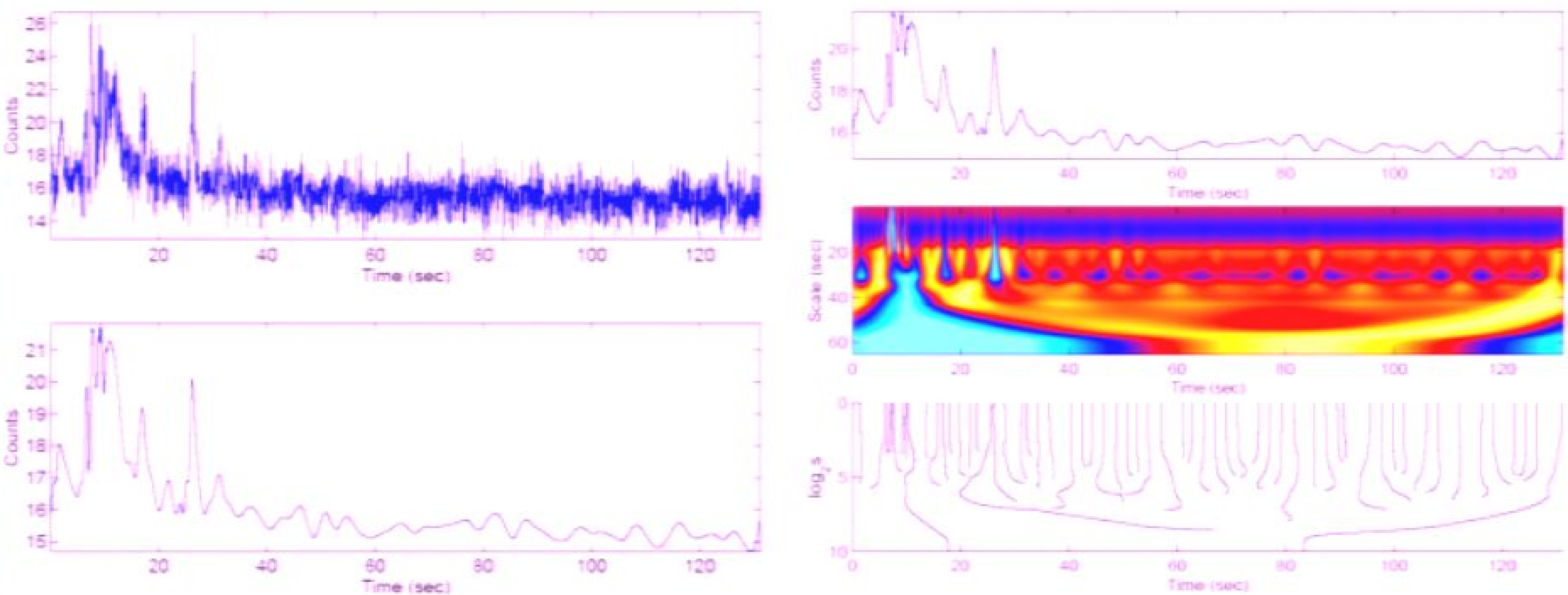
Amelino-Camelia, JE, Mavromatos Nanopoulos + Sarkar: 1997

- Compare arrivals of photons of different energies from astrophysical source with small intrinsic δt
- Gamma-Ray Bursters, pulsars, active galaxies, …
- Typical sensitivities:

Source	Distance	E	Δt	Sensitivity to M
GRB 920229 [a]	3000 Mpc (?)	200 keV	10^{-2} s	0.6×10^{16} GeV (?)
GRB 980425 [a]	40 Mpc	1.8 MeV	10^{-3} s (?)	0.7×10^{16} GeV (?)
GRB 920925c [a]	40 Mpc (?)	200 TeV (?)	200 s	0.4×10^{19} GeV (?)
Mrk 421 [b]	100 Mpc	2 TeV	280 s	$> 7 \times 10^{16}$ GeV
Crab pulsar [c]	2.2 kpc	2 GeV	0.35 ms	$> 1.3 \times 10^{15}$ GeV
GRB 990123	5000 Mpc	4 MeV	1 s (?)	2×10^{15} GeV (?)

Wavelet Analysis of GRB Data

- Optimal for finding significant time structures:



JE, Mavromatos, Nanopoulos + Sakharov: 2002

Astrophysical Probes of Lorentz Violation

- Time delay from distant object:

$$\Delta t \sim \xi \frac{E}{E_{QG}} \frac{L}{c}$$

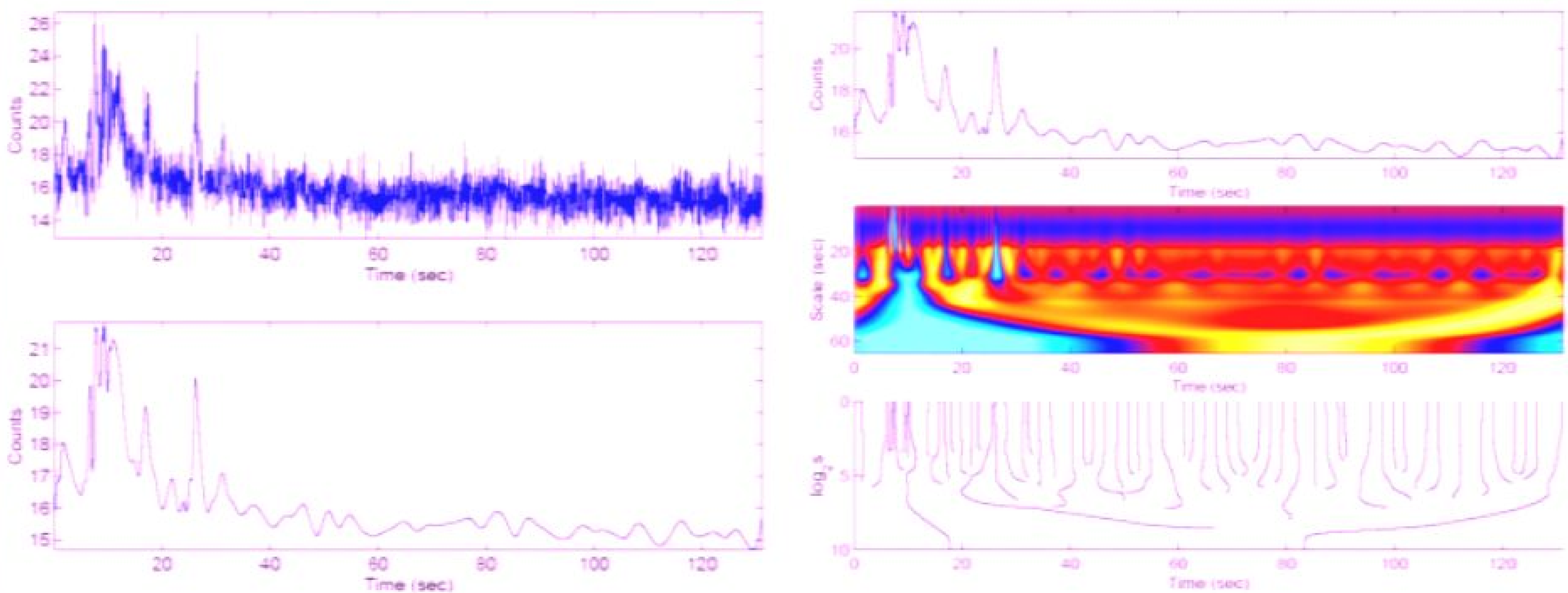
Amelino-Camelia, JE, Mavromatos Nanopoulos + Sarkar: 1997

- Compare arrivals of photons of different energies from astrophysical source with small intrinsic δt
- Gamma-Ray Bursters, pulsars, active galaxies, …
- Typical sensitivities:

Source	Distance	E	Δt	Sensitivity to M
GRB 920229 [a]	3000 Mpc (?)	200 keV	10^{-2} s	0.6×10^{16} GeV (?)
GRB 980425 [a]	40 Mpc	1.8 MeV	10^{-3} s (?)	0.7×10^{16} GeV (?)
GRB 920925c [a]	40 Mpc (?)	200 TeV (?)	200 s	0.4×10^{19} GeV (?)
Mrk 421 [b]	100 Mpc	2 TeV	280 s	$> 7 \times 10^{16}$ GeV
Crab pulsar [c]	2.2 kpc	2 GeV	0.35 ms	$> 1.3 \times 10^{15}$ GeV
GRB 990123	5000 Mpc	4 MeV	1 s (?)	2×10^{15} GeV (?)

Wavelet Analysis of GRB Data

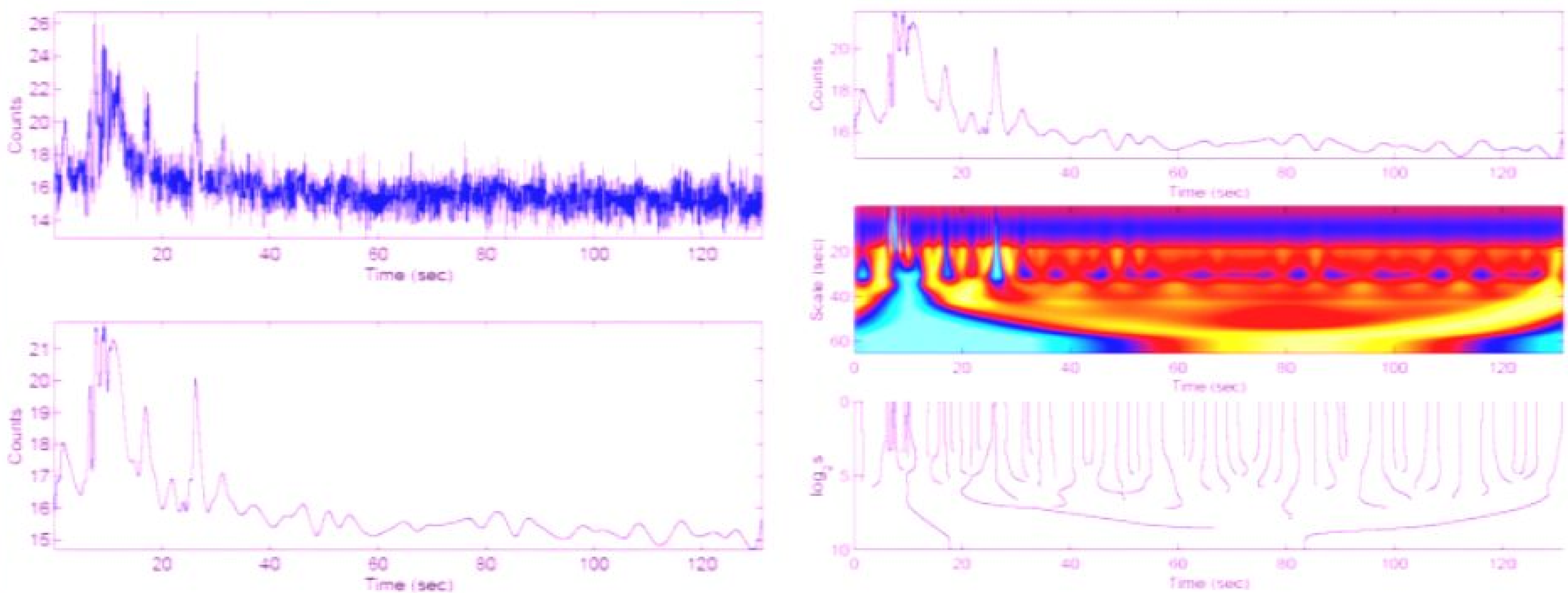
- Optimal for finding significant time structures:



JE, Mavromatos, Nanopoulos + Sakharov: 2002

Wavelet Analysis of GRB Data

- Optimal for finding significant time structures:

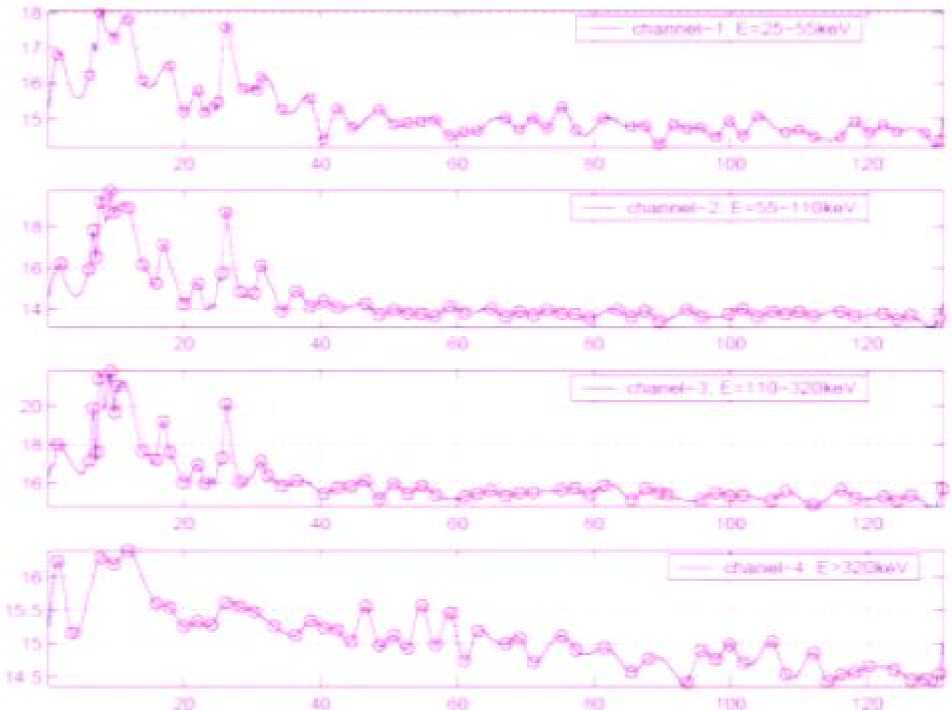


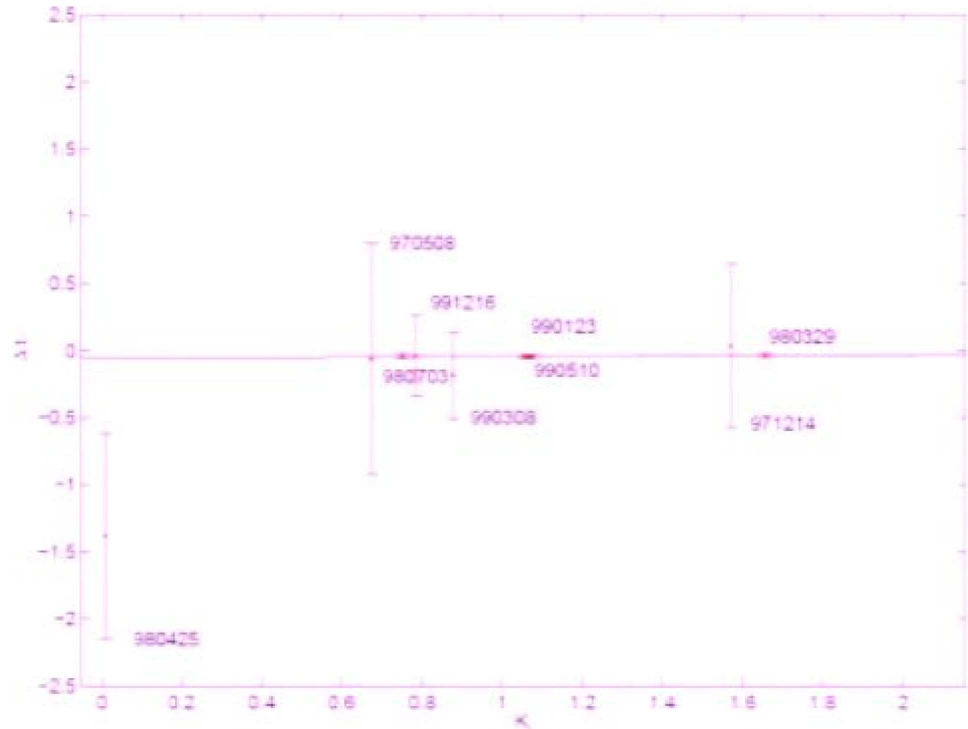
- Use data from BATSE and OSSE detectors on Compton Gamma-Ray Observatory satellite

JE, Mavromatos, Nanopoulos + Sakharov: 2002

Wavelet Analysis of GRB Data

- Compare time structures in different energy bands:

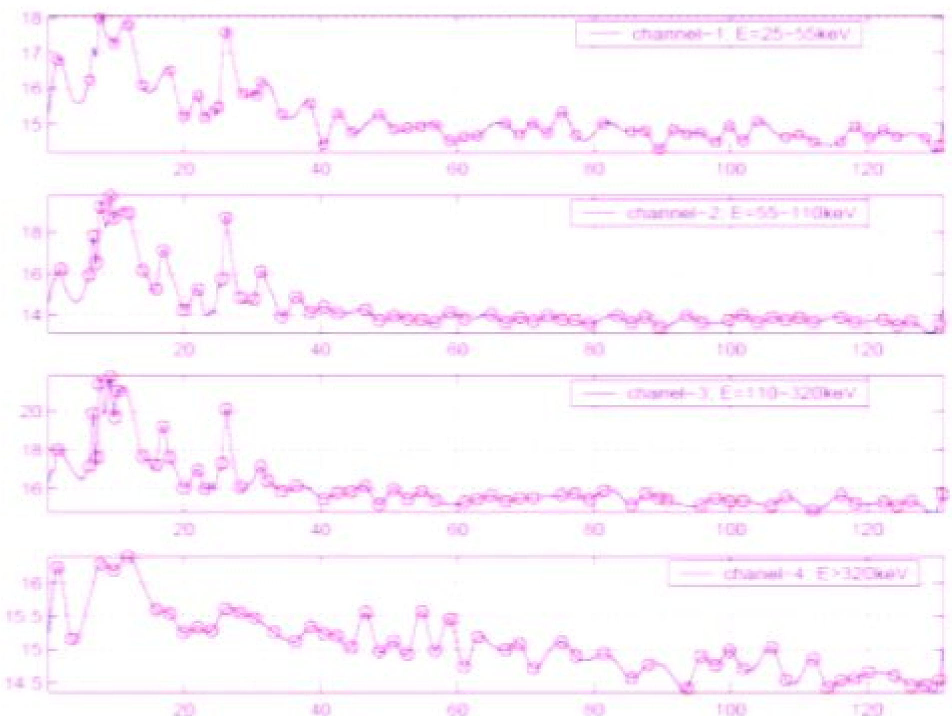


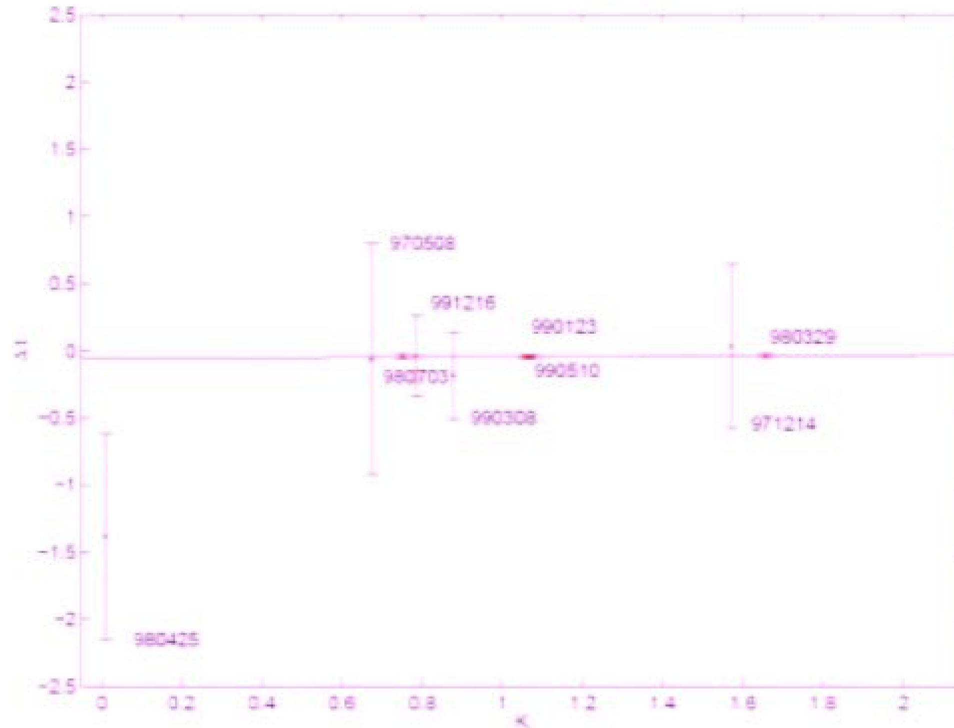


JE, Mavromatos, Nanopoulos + Sakharov: 2002

Wavelet Analysis of GRB Data

- Compare time structures in different energy bands:



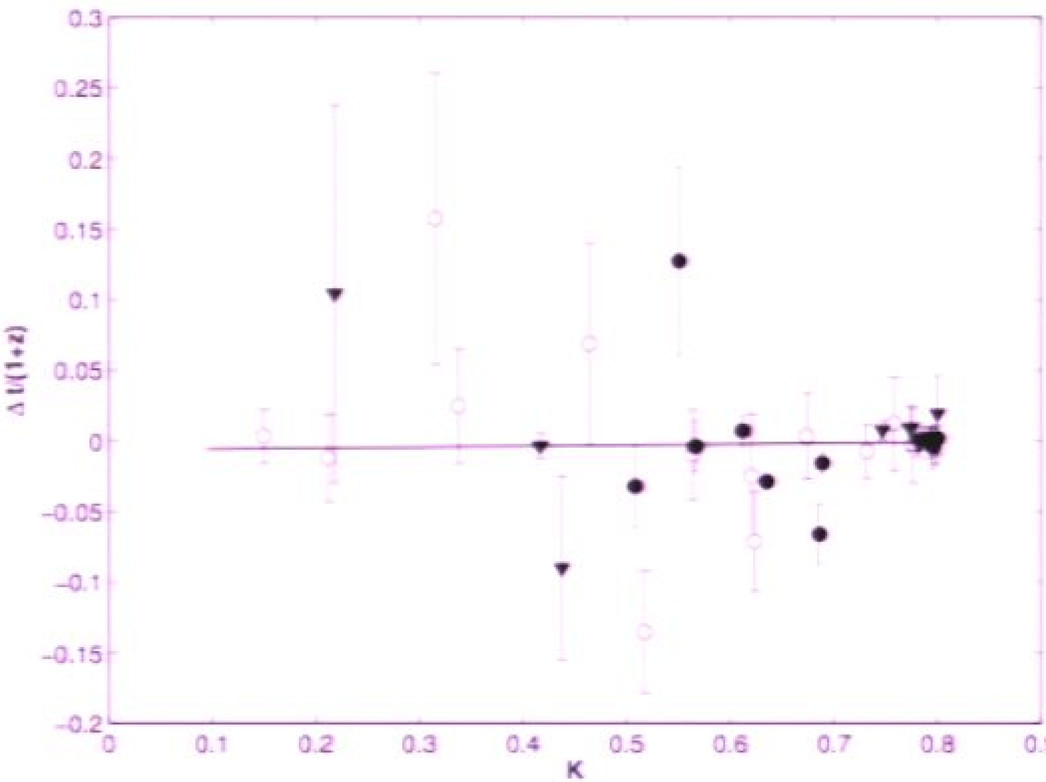


- No significant correlation of time-lags with redshift distance

JE, Mavromatos, Nanopoulos + Sakharov: 2002

Updated Analysis including HETE Data

- Corrected treatment of redshift



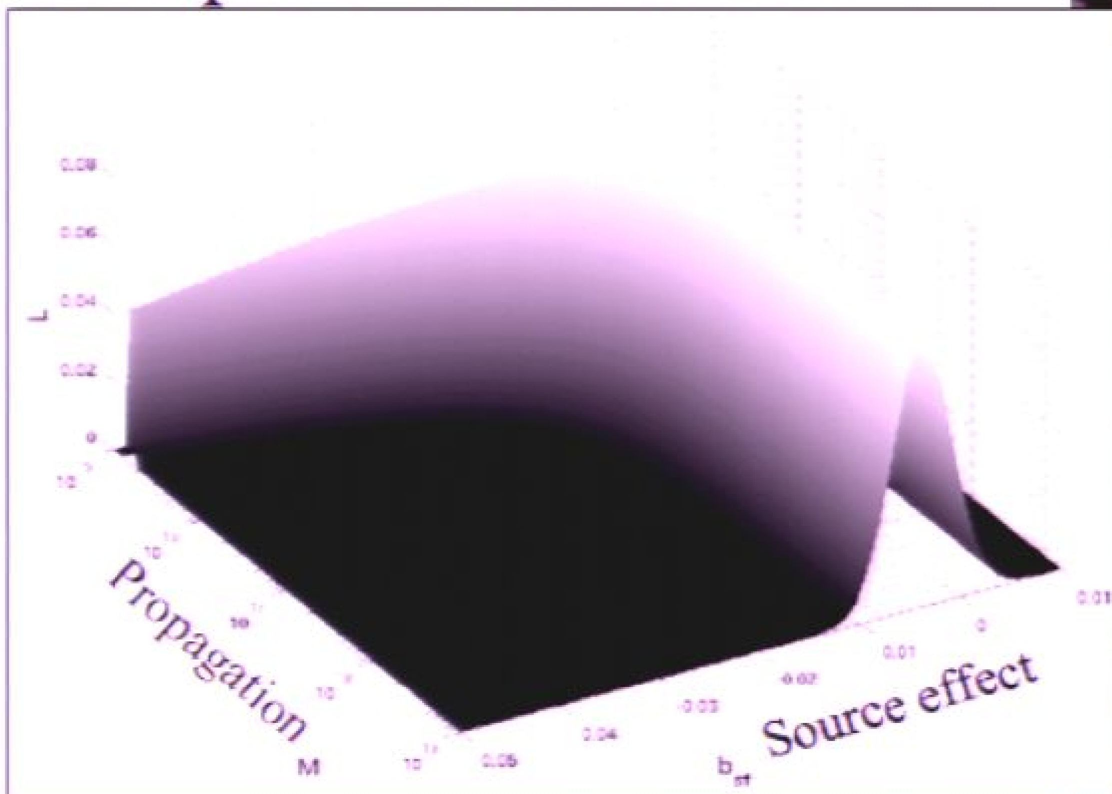
GRB	z	z Refs.	Δt [illegible] (s)
BATSE (64 ms)			
970508	0.835	24	-0.059±0.044
971214	3.418	25	-0.098±0.045
980329	3.9	23	-0.084±0.036
980703	0.966	26	0.138±0.053
990123	1.600	27	-0.155±0.041
990308	1.2	28	0.0188±0.0138
990510	1.619	29	-0.0017±0.0143
991216	1.020	30	-0.0091±0.0012
990506	1.3060	31	-0.0503±0.0075
HETE (164 ms)			
010921	0.45	32	0.0357±0.0585
020124	3.198	33	-0.0046±0.0455
020903	0.25	34	-0.0150±0.0386
020813	1.25	35	-0.1602±0.0794
020819	0.41	36	0.222±0.145
021004	2.33	37	-0.0402±0.1109
021211	1.01	23	-0.0202±0.0639
030226	1.99	23	-0.0227±0.0568
030323	3.372	38	-0.0148±0.0570
030328	1.52	23	0.00825±0.07661
030329	0.168	39, 23	0.0037±0.0219
030429	2.66	40	-0.0123±0.0965
040924	0.859	23	-0.2516±0.0801
041006	0.716	23	0.1179±0.1228
050408	1.2357	23	-0.0562±0.0989
SWIFT (64 ms)			
050319	3.24	41	0.0054±0.0109
050401	2.9	23	-0.0135±0.0285
050416	0.653	23	-0.1491±0.1075
050505	4.3	23	-0.0012±0.0561
050525	0.606	23, 42	0.1261±0.0150
050603	2.821	23	-0.0032±0.0047
050724	0.258	43	0.131±0.1681
050730	3.968	44	0.094±0.1361
050820	2.612	23	[illegible]±0.0569
050904	6.29	45	0.004±0.0852
050922	2.17	23	0.0231±0.0208

- Improved lower limit:

$$M \geq 1.4 \times 10^{16}\ \text{GeV}$$

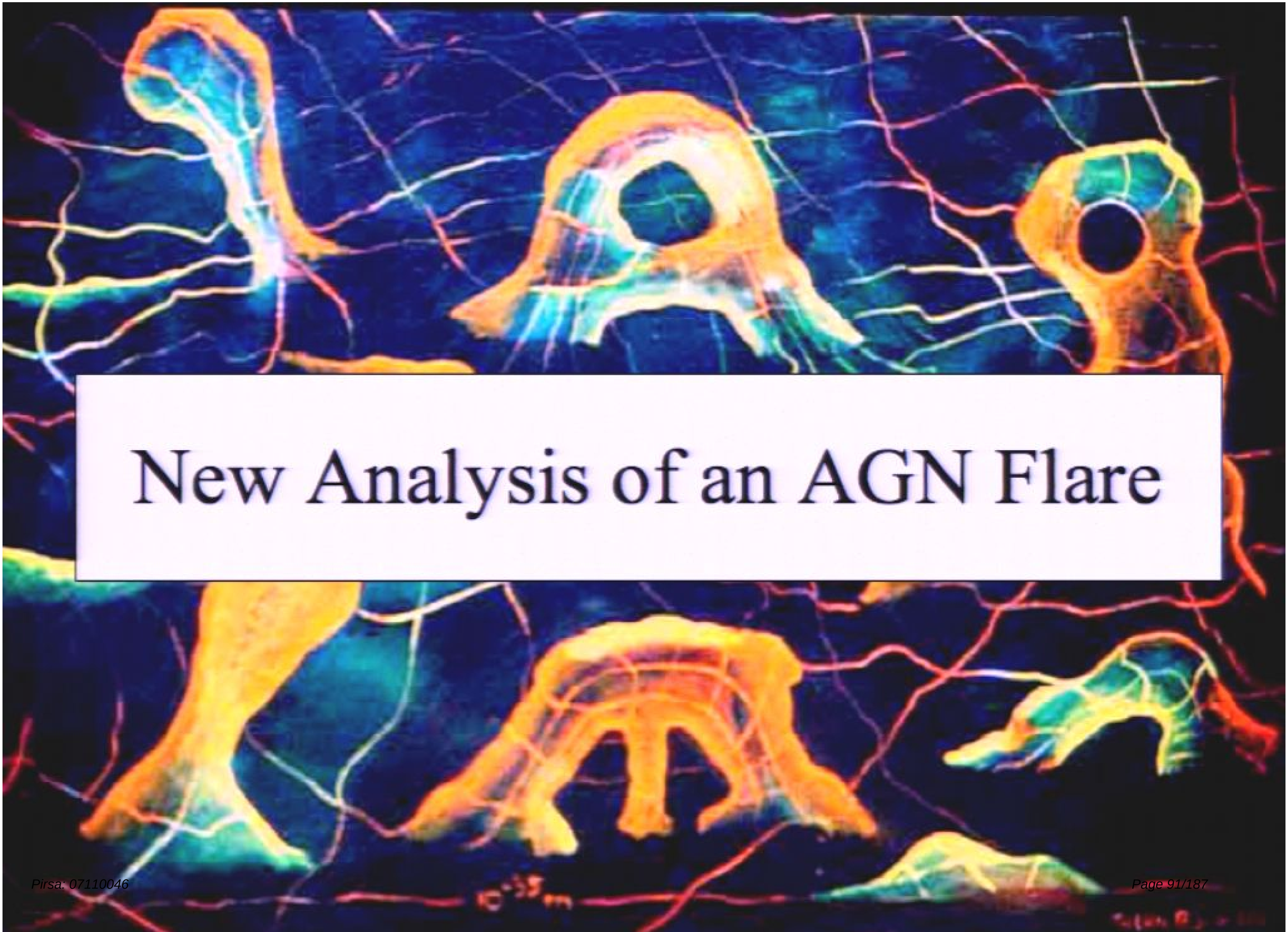
Source Effect vs Propagation Effect?

- Evidence for stochastic spread in intrinsic delays at sources
- Cannot distinguish with single source
- Need statistical techniques for multiple sources



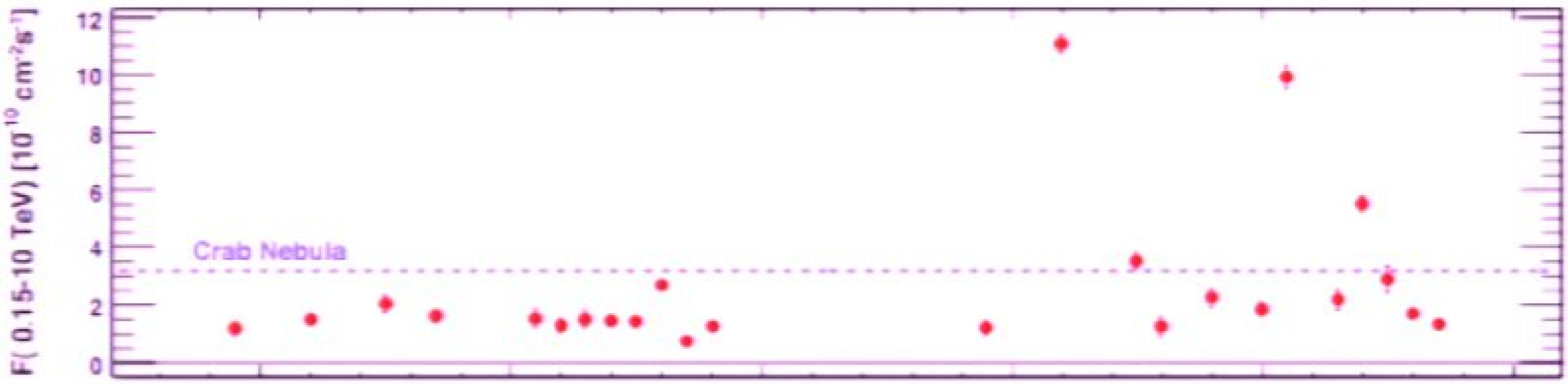
- Correlation between source and propagation effects: Need better understanding of GRBs!

New Analysis of an AGN Flare



Flaring of AGN Markarian 501

- AGN at redshift z = 0.034
- Flare on July 9th, 2005 with short rise/fall time

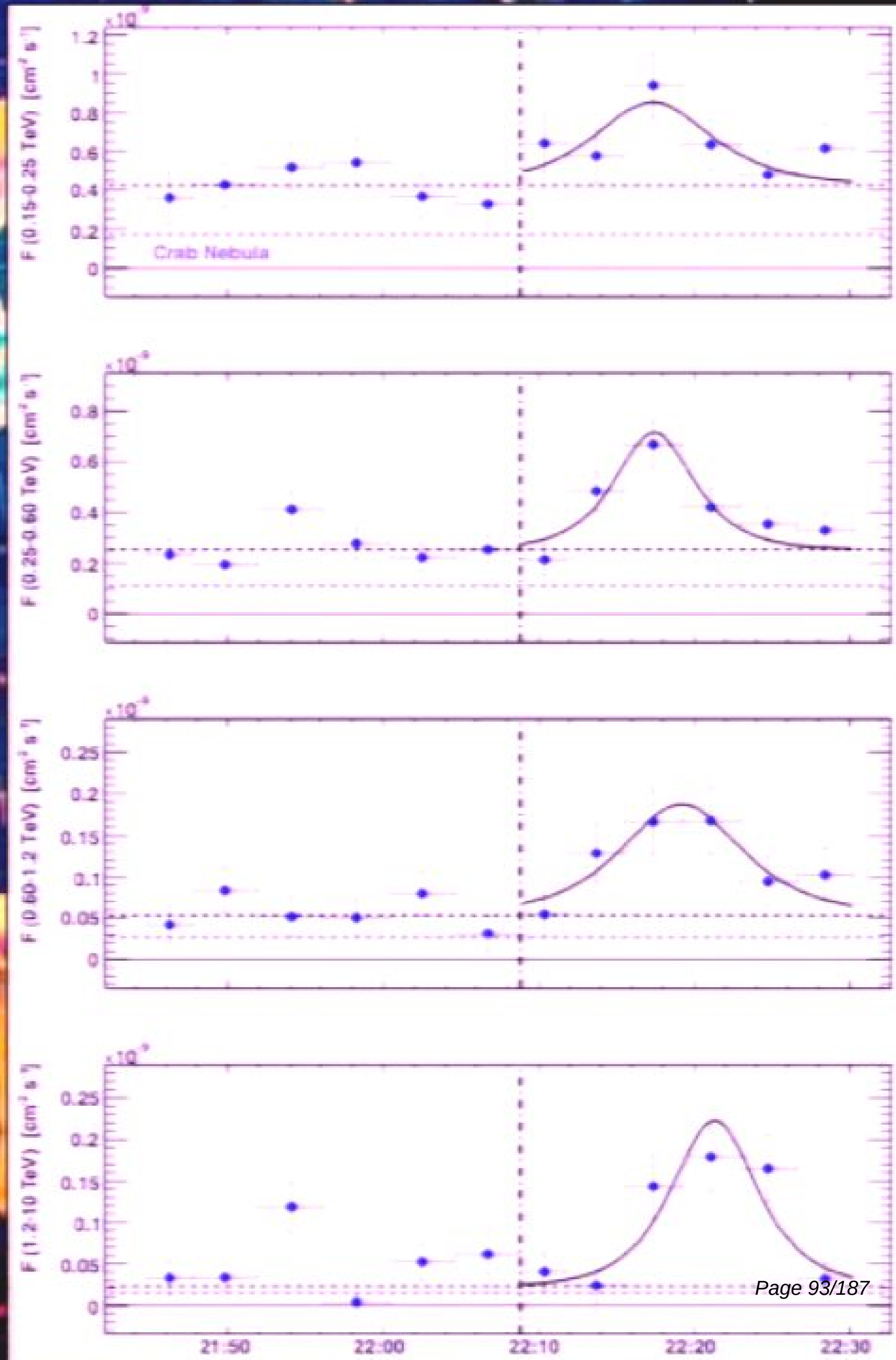


- Observed at energies from 150 GeV to ~ 10 TeV
- Earlier flare on June 30th not significant at high energies

MAGIC Collaboration: astro-ph/0702008

Time Delay from Markarian 501?

- Arrival time delay of ~ 4 minutes reported for photons in highest-energy bin
- Sensitive to $M_{QG1} \sim 10^{16}$ GeV



MAGIC Collaboration: astro-ph/0702008

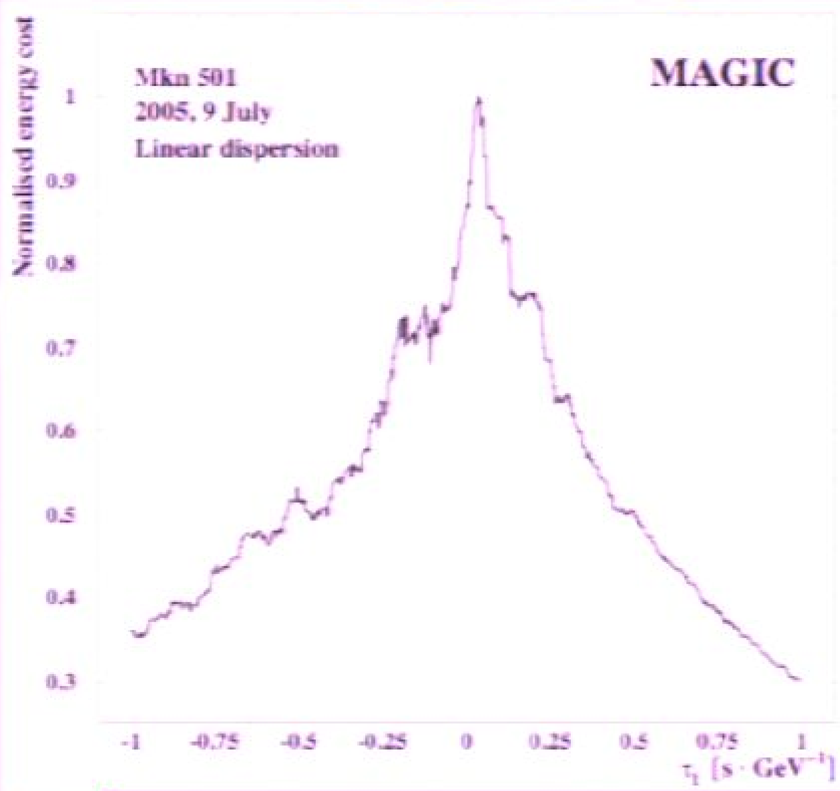
Analysis of AGN Markarian 501

- Non-trivial energy-dependent dispersion relation would tend to spread out any sharp structure
- Analyze individual photons, using measured energies E and arrival times t
- Use 1000 Monte Carlo samples to allow for ΔE
- Track back using many values of M_{QG}
- Determine value of M_{QG} that maximizes peaking of energy flow

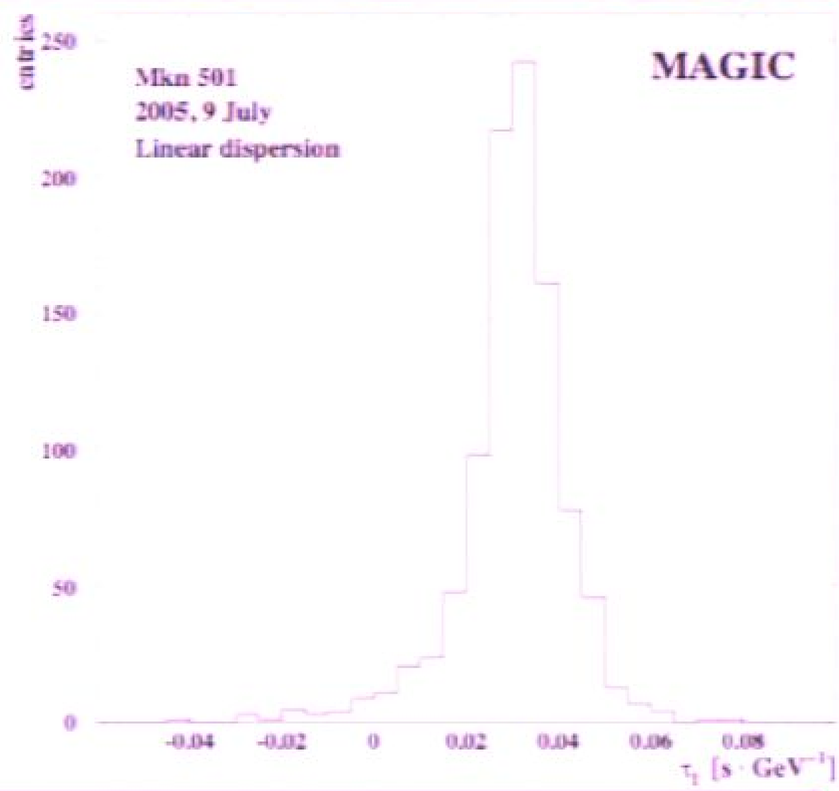
MAGIC Collaboration +
JE, Mavromatos, Nanopoulos, Sakharov, Sarkisyan:
arXiv:0708:2889 [astro-ph]

QG Analysis of AGN Markarian 501

Energy peaking for one Monte Carlo realization



Distribution of time delays for different realizations



MAGIC Collaboration + JE, Mavromatos, Nanopoulos, Sakharov, Sarkisyan:

QG Results for AGN Markarian 501

- Significance of time delay < 95%
- Linear dispersion: (E/M_{QG1})
  - One-σ range: $M_{QG1} = (0.34 \text{ to } 0.78) \times 10^{18}$ GeV
  - 95% CL lower limit: $M_{QG1} > 0.26 \times 10^{18}$ GeV
- Quadratic dispersion: $(E/M_{QG2})^2$
  - One-σ range: $M_{QG2} = (0.47 \text{ to } 1.1) \times 10^{11}$ GeV
  - 95% CL lower limit: $M_{QG2} > 0.27 \times 10^{11}$ GeV
- Cannot exclude initial time delay at source

MAGIC Collaboration + JE, Mavromatos, Nanopoulos, Sakharov, Sarkisyan: arXiv:0708:2889 [astro-ph]

Possible Source Effects?

- Cannot exclude emission mechanism that delays higher-energy photons
- Can exclude conventional thermodynamic plasma effects:

$$\Delta t = D(\alpha^2 T^2 / 6q^2) \ln^2(qT/m_e^2)$$

T = temperature, D = size of emission region, q = photon momentum

Orders of magnitude too small for T ~10^{-2} MeV, D ~10^{9} km, q ~ 1 TeV

- Test with other AGNs (cf GRB analysis)

MAGIC Collaboration + JE, Mavromatos, Nanopoulos, Sakharov, Sarkisyan: arXiv:0708:2889 [astro-ph]

QG Results for AGN Markarian 501

- Significance of time delay < 95%
- Linear dispersion: (E/M_{QG1})
  - One-σ range: $M_{QG1} = (0.34 \text{ to } 0.78) \times 10^{18}$ GeV
  - 95% CL lower limit: $M_{QG1} > 0.26 \times 10^{18}$ GeV
- Quadratic dispersion: $(E/M_{QG2})^2$
  - One-σ range: $M_{QG2} = (0.47 \text{ to } 1.1) \times 10^{11}$ GeV
  - 95% CL lower limit: $M_{QG2} > 0.27 \times 10^{11}$ GeV
- Cannot exclude initial time delay at source

MAGIC Collaboration + JE, Mavromatos, Nanopoulos, Sakharov, Sarkisyan: arXiv:0708:2889 [astro-ph]

Possible Source Effects?

- Cannot exclude emission mechanism that delays higher-energy photons
- Can exclude conventional thermodynamic plasma effects:

$$\Delta t = D(\alpha^2 T^2/6q^2)\ln^2(qT/m_e^2)$$

T = temperature, D = size of emission region, q = photon momentum

Orders of magnitude too small for T ~10^{-2} MeV, D ~10^9 km, q ~ 1 TeV

- Test with other AGNs (cf GRB analysis)

MAGIC Collaboration + JE, Mavromatos, Nanopoulos, Sakharov, Sarkisyan: arXiv:0708:2889 [astro-ph]

QG Results for AGN Markarian 501

- Significance of time delay < 95%
- Linear dispersion: (E/M_{QG1})
  - One-σ range: $M_{QG1} = (0.34 \text{ to } 0.78) \times 10^{18}$ GeV
  - 95% CL lower limit: $M_{QG1} > 0.26 \times 10^{18}$ GeV
- Quadratic dispersion: $(E/M_{QG2})^2$
  - One-σ range: $M_{QG2} = (0.47 \text{ to } 1.1) \times 10^{11}$ GeV
  - 95% CL lower limit: $M_{QG2} > 0.27 \times 10^{11}$ GeV
- Cannot exclude initial time delay at source

MAGIC Collaboration + JE, Mavromatos, Nanopoulos, Sakharov, Sarkisyan: arXiv:0708:2889 [astro-ph]

Possible Source Effects?

- Cannot exclude emission mechanism that delays higher-energy photons
- Can exclude conventional thermodynamic plasma effects:

$$\Delta t = D(\alpha^2 T^2/6q^2)\ln^2(qT/m_e^2)$$

T = temperature, D = size of emission region, q = photon momentum

Orders of magnitude too small for T ~10^{-2} MeV, D ~10^{9} km, q ~ 1 TeV

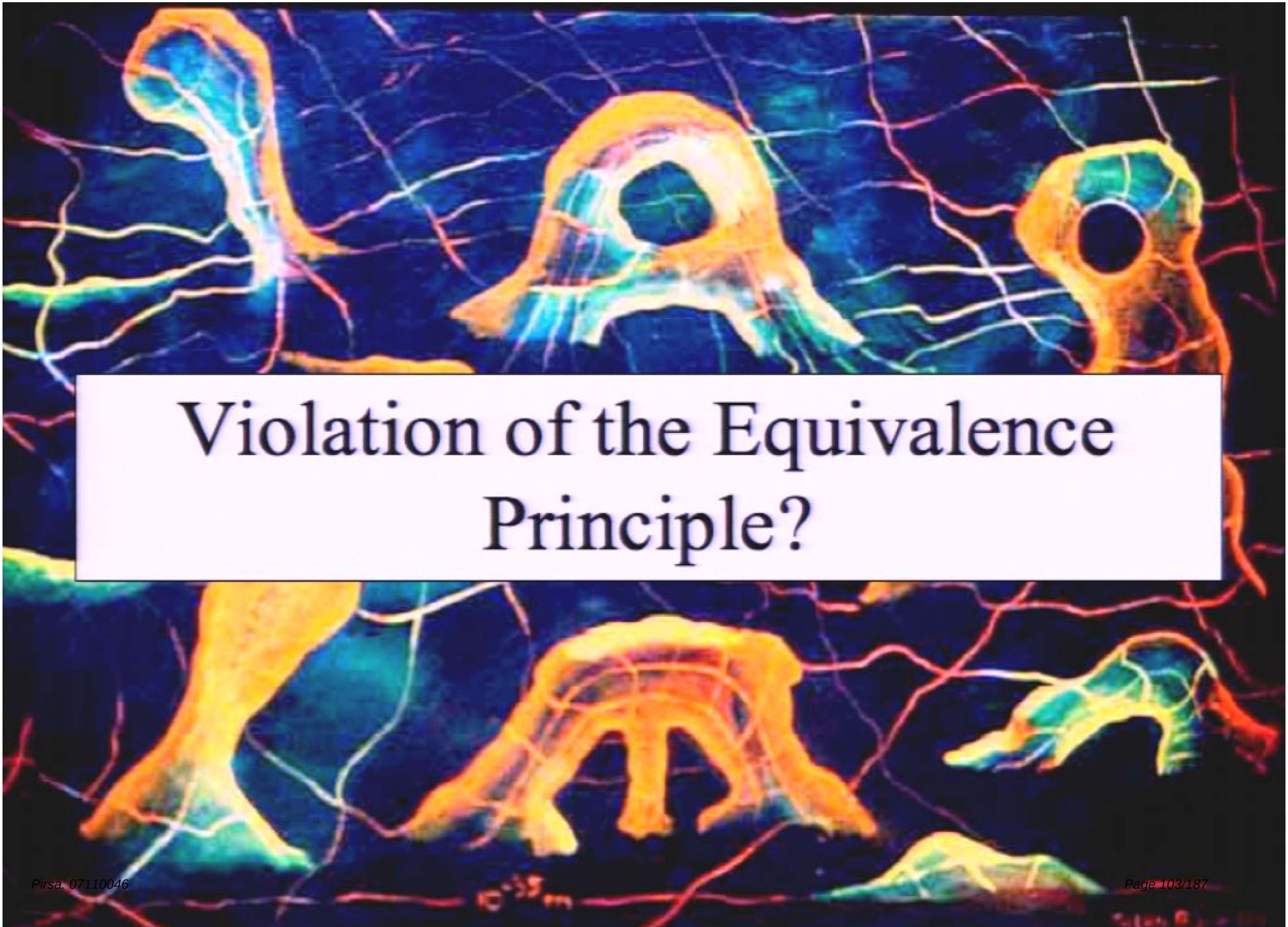
- Test with other AGNs (cf GRB analysis)

MAGIC Collaboration + JE, Mavromatos, Nanopoulos, Sakharov, Sarkisyan: arXiv:0708:2889 [astro-ph]

Analyze Other AGNs?

- E.g., observation by HESS of multiple flaring of AGN at larger redshift with more statistics

Violation of the Equivalence Principle?



Non-Universality of Lorentz Violation?

- Do all relativistic particles have same velocity?

Non-Universality of Lorentz Violation?

- Do all relativistic particles have same velocity?
- Not necessarily, if particle interactions with space-time foam are non-universal
- (Relativistic) departure from Principle of Equivalence

Non-Universality of Lorentz Violation?

- Do all relativistic particles have same velocity?
- Not necessarily, if particle interactions with space-time foam are non-universal
- (Relativistic) departure from Principle of Equivalence
- Suggested by astrophysics: limits on Lorentz violation for electrons >> m_P

Non-Universality of Lorentz Violation?

- Do all relativistic particles have same velocity?
- Not necessarily, if particle interactions with space-time foam are non-universal
- (Relativistic) departure from Principle of Equivalence
- Suggested by astrophysics: limits on Lorentz violation for electrons >> m_P
- Expected in non-critical string model of foam

Synchrotron Radiation Constraint from Crab Nebula

Jacobson, Liberati + Mattingly

- See 0.5 GeV γ: inverse Compton by > 50 TeV e
- Consider modified dispersion relations for both electrons e and photons γ:

$$\omega^2(k) = k^2 + \xi_\gamma \frac{k^3}{M_P} \qquad E^2(p) = m_0^2 + p^2 + \xi_e \frac{p^3}{M_P}$$

Synchrotron Radiation Constraint from Crab Nebula

Jacobson, Liberati + Mattingly

- See 0.5 GeV γ: inverse Compton by > 50 TeV *e*
- Consider modified dispersion relations for both electrons *e* and photons γ:

$$\omega^2(k) \;=\; k^2 + \xi_\gamma \frac{k^3}{M_P} \qquad E^2(p) \;=\; m_0^2 + p^2 + \xi_e \frac{p^3}{M_P}$$

- Lorentz-invariant: $\omega_c^{LI} = \frac{3}{2}\frac{eH}{m_0}\frac{1}{1-\beta^2}$

Synchrotron Radiation Constraint from Crab Nebula

Jacobson, Liberati + Mattingly

- See 0.5 GeV γ: inverse Compton by > 50 TeV e
- Consider modified dispersion relations for both electrons e and photons γ:

$$\omega^2(k) = k^2 + \xi_\gamma \frac{k^3}{M_P} \qquad E^2(p) = m_0^2 + p^2 + \xi_e \frac{p^3}{M_P}$$

- Lorentz-invariant: $\omega_c^{LI} = \frac{3}{2}\frac{eH}{m_0}\frac{1}{1-\beta^2}$
- QG modification: $\omega_c^{QG} = \frac{3}{\sqrt{2}}\frac{eH}{m_0}\frac{1}{(1+\sqrt{2-1/\eta^2})^{1/2}\left(\frac{m_0^2}{E^2}+(\alpha+1)\left(\frac{E}{\mathcal{M}}\right)^\alpha\right)}$

Synchrotron Radiation Constraint from Crab Nebula

Jacobson, Liberati + Mattingly

- See 0.5 GeV γ: inverse Compton by > 50 TeV e
- Consider modified dispersion relations for both electrons e and photons γ:

$$\omega^2(k) = k^2 + \xi_\gamma \frac{k^3}{M_P} \qquad E^2(p) = m_0^2 + p^2 + \xi_e \frac{p^3}{M_P}$$

- Lorentz-invariant: $\omega_c^{LI} = \frac{3}{2}\frac{eH}{m_0}\frac{1}{1-\beta^2}$
- QG modification: $\omega_c^{QG} = \frac{3}{\sqrt{2}}\frac{eH}{m_0}\frac{1}{(1+\sqrt{2-1/\eta^2})^{1/2}\left(\frac{m_0^2}{E^2} + (\alpha+1)\left(\frac{E}{\mathcal{M}}\right)^\alpha\right)}$

Synchrotron Radiation Constraint from Crab Nebula

Jacobson, Liberati + Mattingly

- See 0.5 GeV γ: inverse Compton by > 50 TeV e
- Consider modified dispersion relations for both electrons e and photons γ:

$$\omega^2(k) = k^2 + \xi_\gamma \frac{k^3}{M_P} \qquad E^2(p) = m_0^2 + p^2 + \xi_e \frac{p^3}{M_P}$$

- Lorentz-invariant: $\omega_c^{LI} = \frac{3}{2}\frac{eH}{m_0}\frac{1}{1-\beta^2}$
- QG modification: $\omega_c^{QG} = \frac{3}{\sqrt{2}}\frac{eH}{m_0}\frac{1}{(1+\sqrt{2-1/\eta^2})^{1/2}\left(\frac{m_0^2}{E^2}+(\alpha+1)\left(\frac{E}{\mathcal{M}}\right)^\alpha\right)}$
- For $\xi_e = (E/m_P)^\alpha$

data $\longrightarrow$ $|\xi_e| < \left(\frac{3eH}{m_0}\right)^{\frac{\alpha+2}{2\alpha}}\left(\frac{M_P}{m_0}\right)\left(\frac{2}{\alpha(\alpha+1)}\right)^{1/\alpha}\left(\frac{\alpha}{\alpha+2}\right)^{(\alpha+2)/2\alpha}$

Synchrotron Radiation Constraint from Crab Nebula

Jacobson, Liberati + Mattingly

- See 0.5 GeV γ: inverse Compton by > 50 TeV e
- Consider modified dispersion relations for both electrons e and photons γ:

$$\omega^2(k) = k^2 + \xi_\gamma \frac{k^3}{M_P} \qquad E^2(p) = m_0^2 + p^2 + \xi_e \frac{p^3}{M_P}$$

- Lorentz-invariant: $\omega_c^{LI} = \frac{3}{2}\frac{eH}{m_0}\frac{1}{1-\beta^2}$
- QG modification: $\omega_c^{QG} = \frac{3}{\sqrt{2}}\frac{eH}{m_0}\frac{1}{(1+\sqrt{2-1/\eta^2})^{1/2}\left(\frac{m_0^2}{E^2}+(\alpha+1)\left(\frac{E}{\mathcal{M}}\right)^\alpha\right)}$
- For $\xi_e = (E/m_P)^\alpha$

  data $\longrightarrow$ $|\xi_e| < \left(\frac{3eH}{m_0}\right)^{\frac{\alpha+2}{2\alpha}}\left(\frac{M_P}{m_0}\right)\left(\frac{2}{\alpha(\alpha+1)}\right)^{1/\alpha}\left(\frac{\alpha}{\alpha+2}\right)^{(\alpha+2)/2\alpha}$
- Lower bound on modification: $\alpha > 1.72$

Synchrotron Radiation Constraint from Crab Nebula

Jacobson, Liberati + Mattingly

- See 0.5 GeV γ: inverse Compton by > 50 TeV e
- Consider modified dispersion relations for both electrons e and photons γ:

$$\omega^2(k) = k^2 + \xi_\gamma \frac{k^3}{M_P} \qquad E^2(p) = m_0^2 + p^2 + \xi_e \frac{p^3}{M_P}$$

- Lorentz-invariant: $\omega_c^{LI} = \frac{3}{2}\frac{eH}{m_0}\frac{1}{1-\beta^2}$
- QG modification: $\omega_c^{QG} = \frac{3}{\sqrt{2}}\frac{eH}{m_0}\frac{1}{(1+\sqrt{2-1/\eta^2})^{1/2}\left(\frac{m_0^2}{E^2}+(\alpha+1)\left(\frac{E}{\mathcal{M}}\right)^{\alpha}\right)}$
- For $\xi_e = (E/m_P)^\alpha$

  data $\longrightarrow$ $|\xi_e| < \left(\frac{3eH}{m_0}\right)^{\frac{\alpha+2}{2\alpha}}\left(\frac{M_P}{m_0}\right)\left(\frac{2}{\alpha(\alpha+1)}\right)^{1/\alpha}\left(\frac{\alpha}{\alpha+2}\right)^{(\alpha+2)/2\alpha}$
- Lower bound on modification: $\alpha > 1.72$

- If $\alpha = 1$: $m_{QG} > 10^{26}$ GeV

Synchrotron Radiation Constraint from Crab Nebula

Jacobson, Liberati + Mattingly

- See 0.5 GeV γ: inverse Compton by > 50 TeV e
- Consider modified dispersion relations for both electrons e and photons γ:

$$\omega^2(k) = k^2 + \xi_\gamma \frac{k^3}{M_P} \qquad E^2(p) = m_0^2 + p^2 + \xi_e \frac{p^3}{M_P}$$

- Lorentz-invariant: $\omega_c^{LI} = \frac{3}{2}\frac{eH}{m_0}\frac{1}{1-\beta^2}$
- QG modification: $\omega_c^{QG} = \frac{3}{\sqrt{2}}\frac{eH}{m_0}\frac{1}{(1+\sqrt{2-1/\eta^2})^{1/2}\left(\frac{m_0^2}{E^2}+(\alpha+1)\left(\frac{E}{\mathcal{M}}\right)^\alpha\right)}$
- For $\xi_e = (E/m_P)^\alpha$

  data $\longrightarrow$ $|\xi_e| < \left(\frac{3eH}{m_0}\right)^{\frac{\alpha+2}{2\alpha}}\left(\frac{M_P}{m_0}\right)\left(\frac{2}{\alpha(\alpha+1)}\right)^{1/\alpha}\left(\frac{\alpha}{\alpha+2}\right)^{(\alpha+2)/2\alpha}$
- Lower bound on modification: $\alpha > 1.72$

- No constraint on dispersion relation for photon

Synchrotron Radiation Constraint from Crab Nebula

Jacobson, Liberati + Mattingly

- See 0.5 GeV γ: inverse Compton by > 50 TeV e
- Consider modified dispersion relations for both electrons e and photons γ:

$$\omega^2(k) = k^2 + \xi_\gamma \frac{k^3}{M_P} \qquad E^2(p) = m_0^2 + p^2 + \xi_e \frac{p^3}{M_P}$$

- Lorentz-invariant: $\omega_c^{LI} = \frac{3}{2}\frac{eH}{m_0}\frac{1}{1-\beta^2}$
- QG modification: $\omega_c^{QG} = \frac{3}{\sqrt{2}}\frac{eH}{m_0}\frac{1}{(1+\sqrt{2-1/\eta^2})^{1/2}\left(\frac{m_0^2}{E^2}+(\alpha+1)\left(\frac{E}{\mathcal{M}}\right)^\alpha\right)}$
- For $\xi_e = (E/m_P)^\alpha$

  data $\longrightarrow$ $|\xi_e| < \left(\frac{3eH}{m_0}\right)^{\frac{\alpha+2}{2\alpha}}\left(\frac{M_P}{m_0}\right)\left(\frac{2}{\alpha(\alpha+1)}\right)^{1/\alpha}\left(\frac{\alpha}{\alpha+2}\right)^{(\alpha+2)/2\alpha}$
- Lower bound on modification: $\alpha > 1.72$
- No constraint on dispersion relation for photon

Non-Universality in D-Brane Model

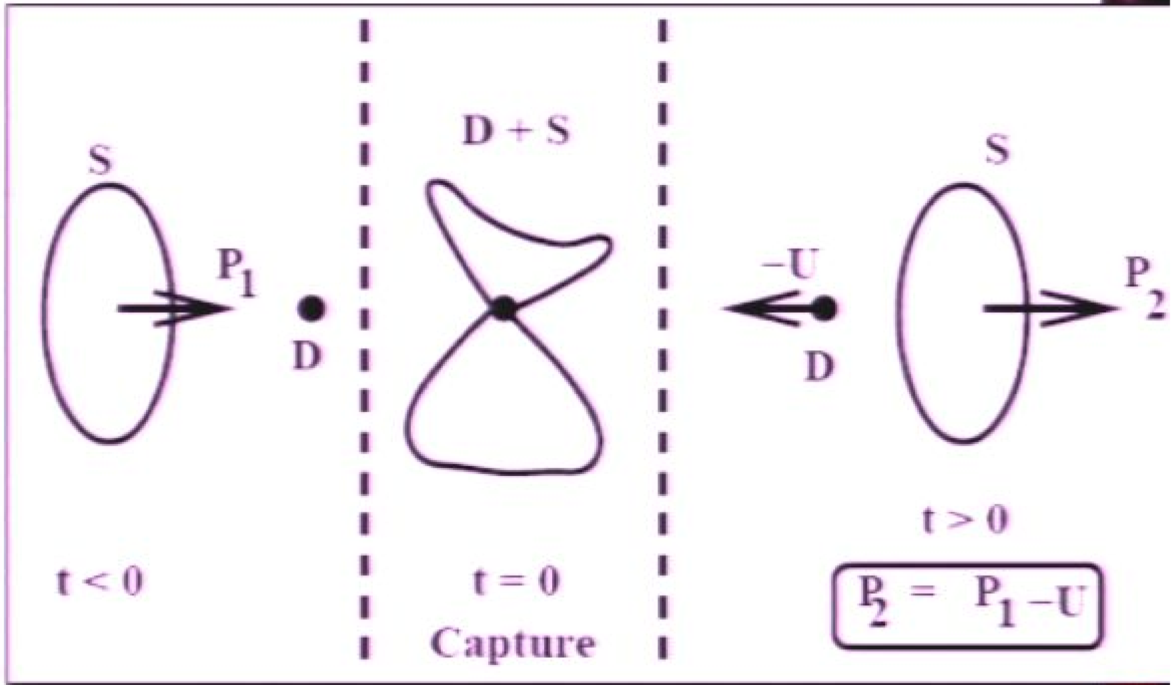
- D-branes carry only vacuum quantum numbers

JE, Mavromatos + Nanopoulo

Non-Universality in D-Brane Model

- D-branes carry only vacuum quantum numbers
- Only particles without conserved gauge charges interact with D particles,

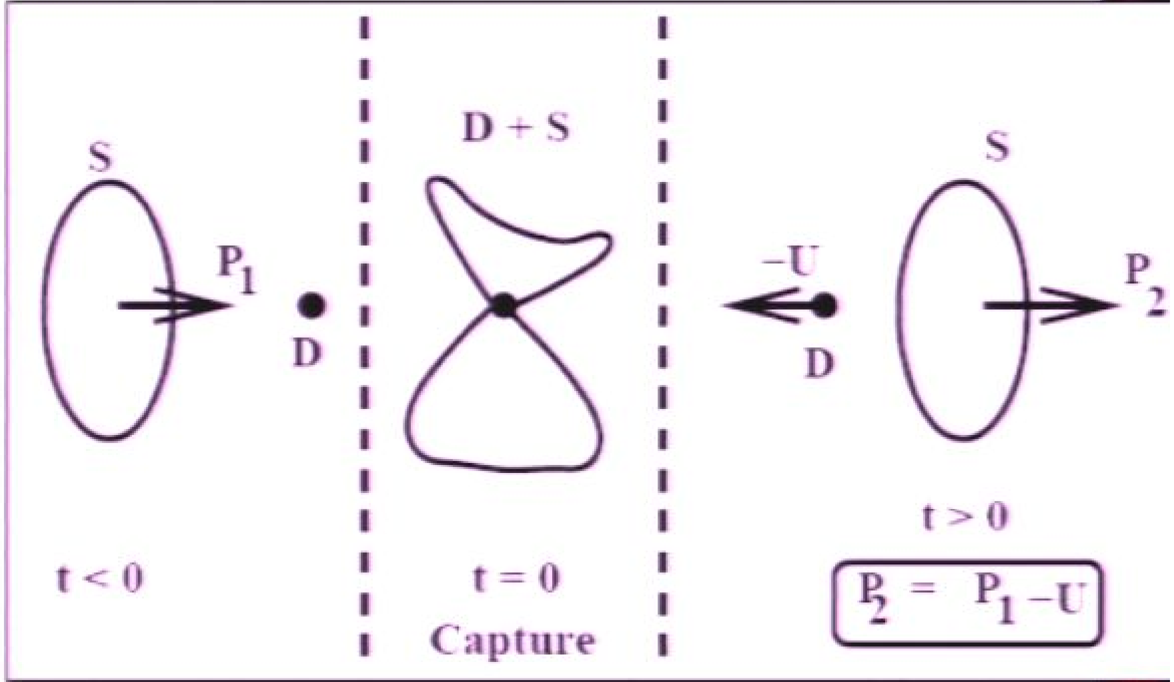
  e.g., photons



JE. Mavromatos + Nanopoulo

Non-Universality in D-Brane Model

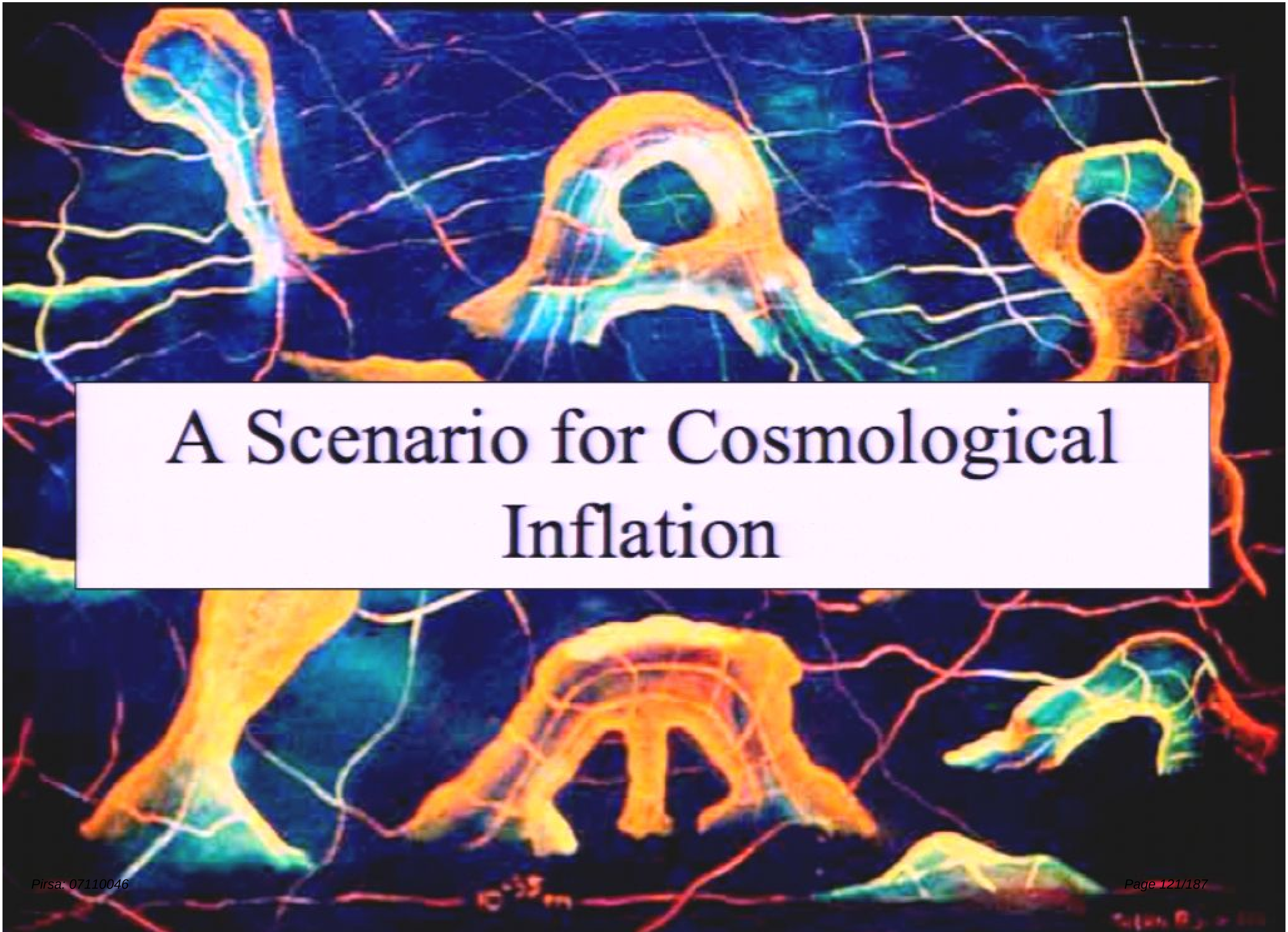
- D-branes carry only vacuum quantum numbers
- Only particles without conserved gauge charges interact with D particles, e.g., photons



- Charged particles such as electrons do not 'see' D-particle foam → propagate normally

JE, Mavromatos + Nanopoulo

A Scenario for Cosmological Inflation



Non-Critical String Description of Inflation

JE, Mavromatos + Nanopoulos

- Conventional field-theoretic inflation:

$$\ddot{\Phi}_c + 3H\dot{\Phi}_c - \mu^2\Phi_c = 0 \qquad \Phi_c \simeq exp(\frac{\mu^2}{3H}t)$$

- Fokker-Planck evolution of quantum inflaton:

$$\partial_t \mathcal{P}(\Phi_<, t) = \frac{1}{8\pi^2}\frac{\delta}{\delta\Phi_<}(H^{\frac{3}{2}}\frac{\delta}{\delta\Phi_<}[H^{\frac{3}{2}}\mathcal{P}(\Phi_<, t)]) + \frac{1}{6}\frac{\delta}{\delta\Phi_<}[\frac{1}{H}\frac{\delta}{\delta\Phi_<}V(\Phi_<)\mathcal{P}(\Phi_<, t)]$$

Non-Critical String Description of Inflation

JE, Mavromatos + Nanopoulos

- Conventional field-theoretic inflation:

$$\ddot{\Phi}_c + 3H\dot{\Phi}_c - \mu^2\Phi_c = 0 \quad \Phi_c \simeq exp(\frac{\mu^2}{3H}t)$$

- Fokker-Planck evolution of quantum inflaton:

$$\partial_t \mathcal{P}(\Phi_<, t) = \frac{1}{8\pi^2}\frac{\delta}{\delta\Phi_<}(H^{\frac{3}{2}}\frac{\delta}{\delta\Phi_<}[H^{\frac{3}{2}}\mathcal{P}(\Phi_<, t)]) + \frac{1}{6}\frac{\delta}{\delta\Phi_<}[\frac{1}{H}\frac{\delta}{\delta\Phi_<}V(\Phi_<)\mathcal{P}(\Phi_<, t)]$$

- Non-critical string realization:

$$\ddot{\lambda}^i(\tau) + Q^2\dot{\lambda}^i(\tau) = -Q^2\beta^i(\lambda) = -Q^2\dot{\lambda}^i = -Q^2 G^{ij}\frac{\partial}{\partial\lambda^j}C(\lambda)$$

Non-Critical String Description of Inflation

JE, Mavromatos + Nanopoulos

- Conventional field-theoretic inflation:

$$\ddot{\Phi}_c + 3H\dot{\Phi}_c - \mu^2\Phi_c = 0 \quad \Phi_c \simeq exp(\frac{\mu^2}{3H}t)$$

- Fokker-Planck evolution of quantum inflaton:

$$\partial_t \mathcal{P}(\Phi_<, t) = \frac{1}{8\pi^2}\frac{\delta}{\delta\Phi_<}(H^{\frac{3}{2}}\frac{\delta}{\delta\Phi_<}[H^{\frac{3}{2}}\mathcal{P}(\Phi_<, t)]) + \frac{1}{6}\frac{\delta}{\delta\Phi_<}[\frac{1}{H}\frac{\delta}{\delta\Phi_<}V(\Phi_<)\mathcal{P}(\Phi_<, t)]$$

- Non-critical string realization:

$$\ddot{\lambda}^i(\tau) + Q^2\dot{\lambda}^i(\tau) = -Q^2\beta^i(\lambda) = -Q^2\dot{\lambda}^i = -Q^2G^{ij}\frac{\partial}{\partial\lambda^j}C(\lambda)$$

- Identify $H = Q/3$, potential Zamolodchikov C

Non-Critical String Description of Inflation

JE, Mavromatos + Nanopoulos

- Conventional field-theoretic inflation:

$$\ddot{\Phi}_c + 3H\dot{\Phi}_c - \mu^2\Phi_c = 0 \qquad \Phi_c \simeq exp(\frac{\mu^2}{3H}t)$$

- Fokker-Planck evolution of quantum inflaton:

$$\partial_t \mathcal{P}(\Phi_<, t) = \frac{1}{8\pi^2}\frac{\delta}{\delta\Phi_<}(H^{\frac{3}{2}}\frac{\delta}{\delta\Phi_<}[H^{\frac{3}{2}}\mathcal{P}(\Phi_<, t)]) + \frac{1}{6}\frac{\delta}{\delta\Phi_<}[\frac{1}{H}\frac{\delta}{\delta\Phi_<}V(\Phi_<)\mathcal{P}(\Phi_<, t)]$$

- Non-critical string realization:

$$\ddot{\lambda}^i(\tau) + Q^2\dot{\lambda}^i(\tau) = -Q^2\beta^i(\lambda) = -Q^2\dot{\lambda}^i = -Q^2 G^{ij}\frac{\partial}{\partial\lambda^j}C(\lambda)$$

- Identify *H* = *Q/3*, potential Zamolodchikov C
- String Fokker-Planck equation:

$$\partial_\tau \mathcal{P}(\lambda, \tau) = \frac{1}{\ldots}\frac{\delta}{\delta\lambda^i}Q^3\delta^{ij}\frac{\delta}{\delta\lambda^j}[Q^3\mathcal{P}(\lambda, \tau)] + \frac{\delta}{\delta\lambda^i}[\beta^i\mathcal{P}(\lambda, \tau)]$$

Brany Scenario for Inflation

- Generic non-critical string:

$$\ddot{g}^i + Q\dot{g}^i = -\beta^i(g) = -\mathcal{G}^{ij}\partial C[g]/\partial g^j$$

- Apply to metric tensor:

$$\ddot{G}_{ij} + Q\dot{G}_{ij} = -R_{ij} + \frac{1}{2}\beta^2 G_{ij}.$$

JE, Mavromatos, Nanopoulos + Sakharov

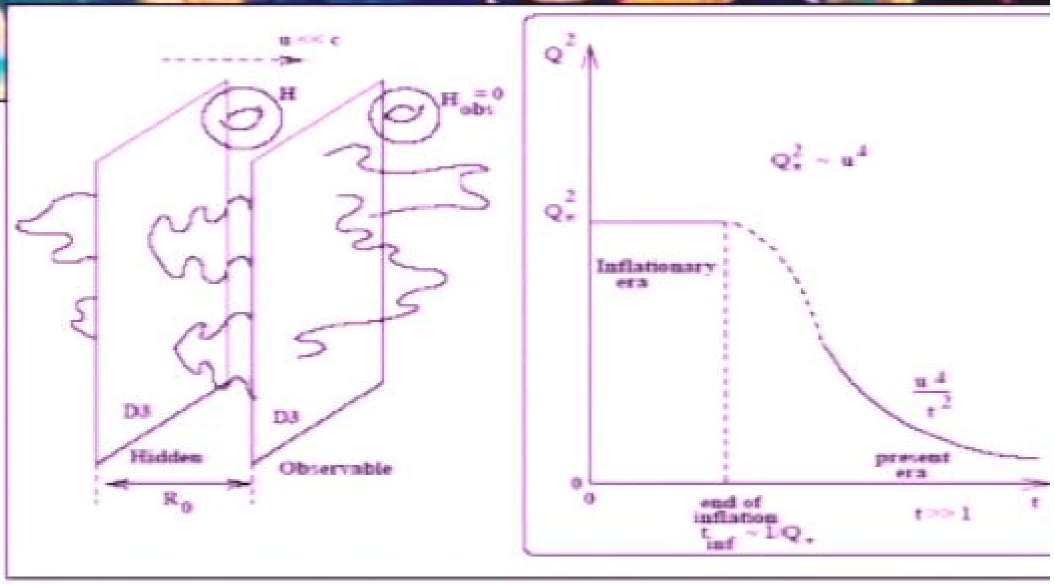
Brany Scenario for Inflation

- Generic non-critical string:

$$\ddot{g}^i + Q\dot{g}^i = -\beta^i(g) = -\mathcal{G}^{ij}\partial C[g]/\partial g^j$$

- Apply to metric tensor:

$$\ddot{G}_{ij} + Q\dot{G}_{ij} = -R_{ij} + \frac{1}{2}\beta^2 G_{ij}.$$



- Collision of two D-branes in a higher dimensional space?

JE, Mavromatos, Nanopoulos + Sakharov

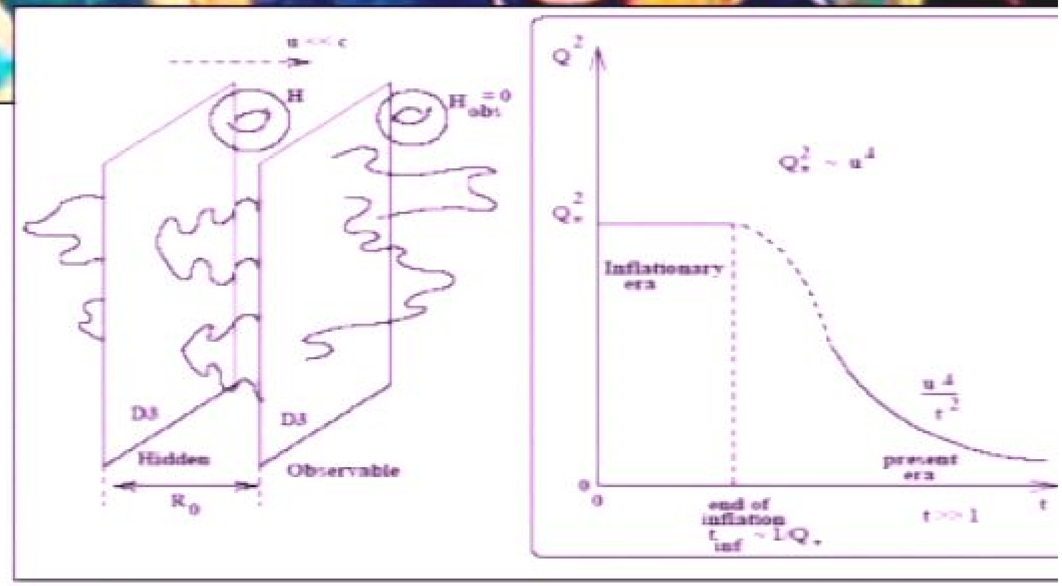
Brany Scenario for Inflation

- Generic non-critical string:

$$\ddot{g}^i + Q\dot{g}^i = -\beta^i(g) = -\mathcal{G}^{ij}\partial C[g]/\partial g^j$$

- Apply to metric tensor:

$$\ddot{G}_{ij} + Q\dot{G}_{ij} = -R_{ij} + \frac{1}{2}\beta^2 G_{ij}.$$



- Collision of two D-branes in a higher dimensional space?
- Motion of D-branes could provide energy driving inflation: departure from criticality ↔ velocity *v*: $Q^2 = \mathcal{O}\left(v^4\right) > 0$

JE, Mavromatos, Nanopoulos + Sakharov

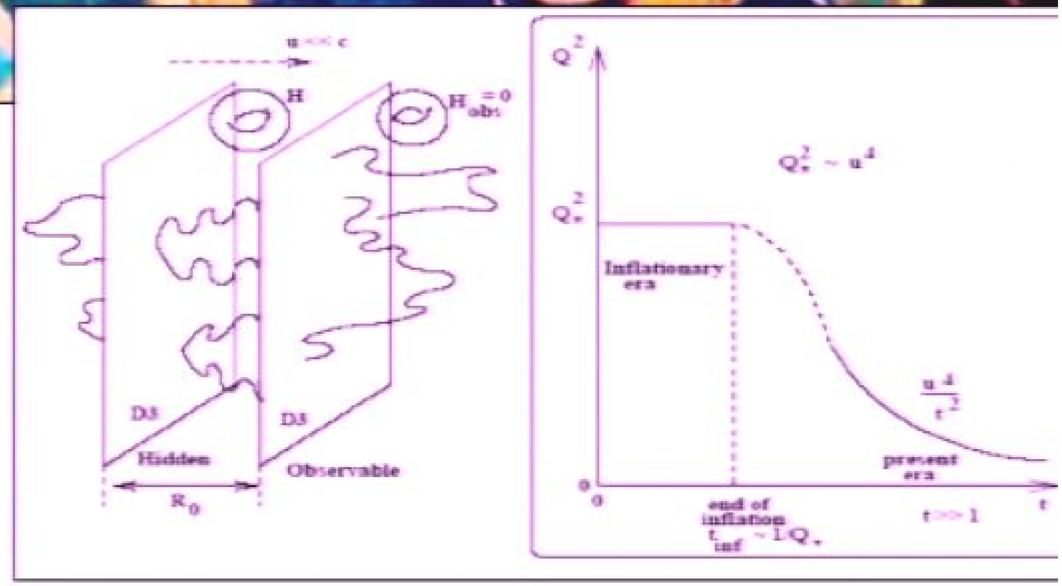
Brany Scenario for Inflation

- Generic non-critical string:

$$\ddot{g}^i + Q\dot{g}^i = -\beta^i(g) = -\mathcal{G}^{ij}\partial C[g]/\partial g^j$$

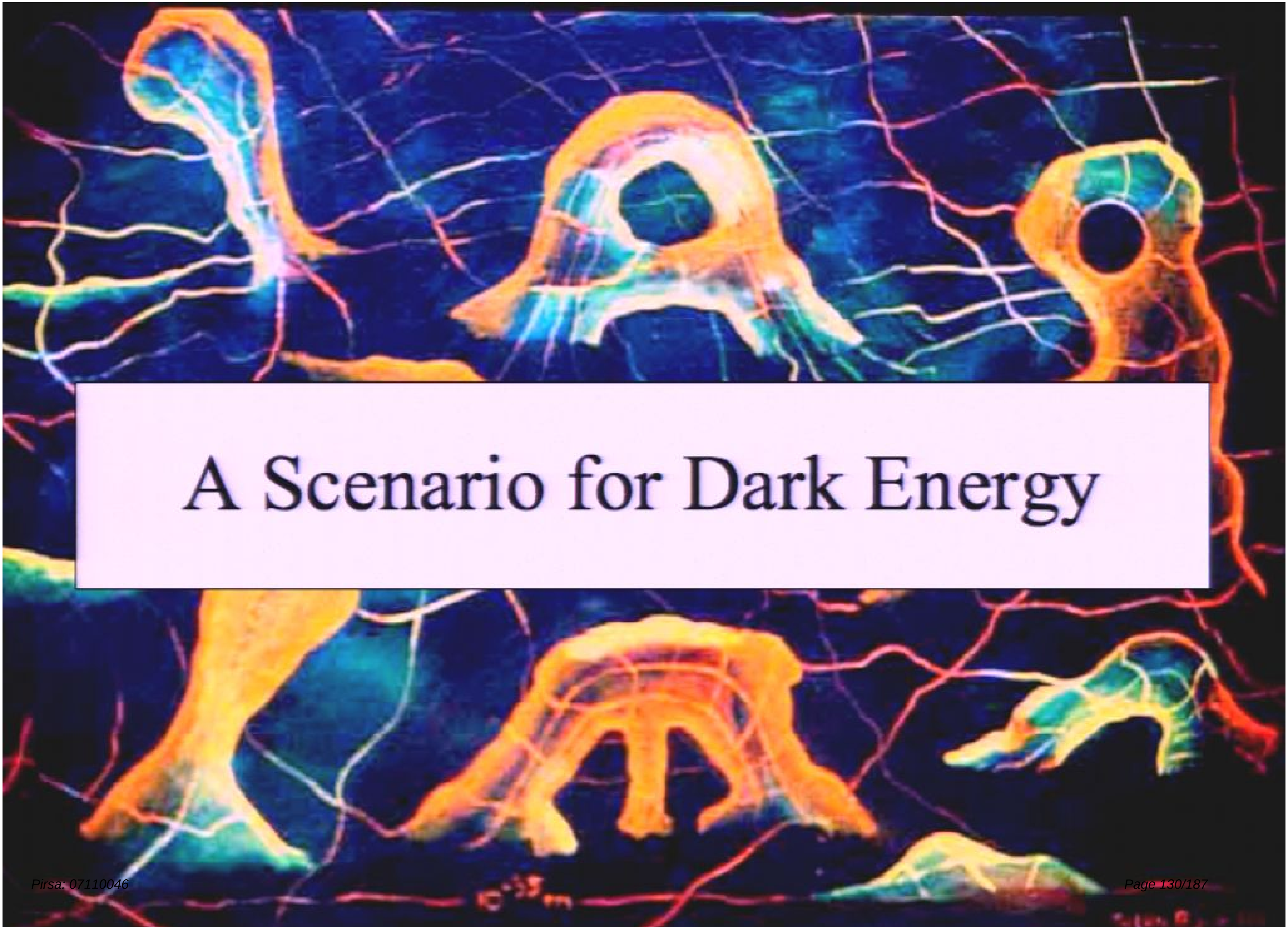
- Apply to metric tensor:

$$\ddot{G}_{ij} + Q\dot{G}_{ij} = -R_{ij} + \frac{1}{2}\beta^2 G_{ij}.$$



- Collision of two D-branes in a higher dimensional space?
- Motion of D-branes could provide energy driving inflation: departure from criticality ↔ velocity v: $Q^2 = \mathcal{O}\left(v^4\right) > 0$

JE, Mavromatos, Nanopoulos + Sakharov



A Scenario for Dark Energy

Comments on Dark Energy

- Many orders of magnitude smaller than expected contributions from 'known' physics: 10^{-48} GeV^4

Comments on Dark Energy

- Many orders of magnitude smaller than expected contributions from 'known' physics: 10^{-48} GeV^4

  QCD: $\Lambda_{QCD}{}^4 \sim 10^{-4}$ GeV^4

Comments on Dark Energy

- Many orders of magnitude smaller than expected contributions from 'known' physics: 10^{-48} GeV^4

  QCD: $\Lambda_{QCD}{}^4 \sim 10^{-4}$ GeV^4

  Higgs: $m_W{}^4 \sim 10^8$ GeV^4

Comments on Dark Energy

- Many orders of magnitude smaller than expected contributions from 'known' physics: 10^{-48} GeV^4

QCD:	$\Lambda_{QCD}^4 \sim 10^{-4}$ GeV^4
Higgs:	$m_W^4 \sim 10^8$ GeV^4
Broken susy:	$m_{susy}^4 \sim 10^{12}$ GeV^4
GUT:	$m_{GUT}^4 \sim 10^{64}$ GeV^4

Comments on Dark Energy

- Many orders of magnitude smaller than expected contributions from 'known' physics: 10^{-48} GeV^4

  QCD: $\Lambda_{QCD}^4 \sim 10^{-4}$ GeV^4

  Higgs: $m_W^4 \sim 10^8$ GeV^4

  Broken susy: $m_{susy}^4 \sim 10^{12}$ GeV^4

  GUT: $m_{GUT}^4 \sim 10^{64}$ GeV^4

  Quantum Gravity: $m_P^4 \sim 10^{76}$ GeV^4

Comments on Dark Energy

- Many orders of magnitude smaller than expected contributions from 'known' physics: 10^{-48} GeV^4

  QCD: $\Lambda_{QCD}^4 \sim 10^{-4}$ GeV^4

  Higgs: $m_W^4 \sim 10^8$ GeV^4

  Broken susy: $m_{susy}^4 \sim 10^{12}$ GeV^4

  GUT: $m_{GUT}^4 \sim 10^{64}$ GeV^4

  Quantum Gravity: $m_P^4 \sim 10^{76}$ GeV^4

- Need new physics!

Comments on Dark Energy

- Many orders of magnitude smaller than expected contributions from 'known' physics: 10^{-48} GeV^4

  QCD: $\Lambda_{QCD}{}^4 \sim 10^{-4}$ GeV^4

  Higgs: $m_W{}^4 \sim 10^8$ GeV^4

  Broken susy: $m_{susy}{}^4 \sim 10^{12}$ GeV^4

  GUT: $m_{GUT}{}^4 \sim 10^{64}$ GeV^4

  Quantum Gravity: $m_P{}^4 \sim 10^{76}$ GeV^4

- Need new physics!
- A great challenge for string theory

Comments on Dark Energy

- Many orders of magnitude smaller than expected contributions from 'known' physics: 10^{-48} GeV^4

  QCD: $\Lambda_{QCD}{}^4 \sim 10^{-4}$ GeV^4

  Higgs: $m_W{}^4 \sim 10^8$ GeV^4

  Broken susy: $m_{susy}{}^4 \sim 10^{12}$ GeV^4

  GUT: $m_{GUT}{}^4 \sim 10^{64}$ GeV^4

  Quantum Gravity: $m_P{}^4 \sim 10^{76}$ GeV^4

- Need new physics!
- A great challenge for string theory

Dark Energy & String Theory

- Cosmological constant or quintessence
  - → de Sitter space or similar
  - → event horizon
  - → loss of information
  - → $ matrix not S matrix
  - → inconsistent with critical strings

Dark Energy & String Theory

- Cosmological constant or quintessence
  - → de Sitter space or similar
  - → event horizon
  - → loss of information
  - → \$ matrix not S matrix
  - → inconsistent with critical strings

Dark Energy & String Theory

- Cosmological constant or quintessence
  - → de Sitter space or similar
  - → event horizon
  - → loss of information
  - → $ matrix not S matrix
  - → inconsistent with critical strings

Dark Energy & String Theory

- Cosmological constant or quintessence
  - → de Sitter space or similar
  - → event horizon
  - → loss of information
  - → $ matrix not S matrix
  - → inconsistent with critical strings

Dark Energy & String Theory

- Cosmological constant or quintessence
  - → de Sitter space or similar
  - → event horizon
  - → loss of information
  - → $ matrix not S matrix
  - → inconsistent with critical strings

Dark Energy & String Theory

- Cosmological constant or quintessence
  - → de Sitter space or similar
  - → event horizon
  - → loss of information
  - → $ matrix not S matrix
  - → inconsistent with critical strings

Dark Energy & String Theory

- Cosmological constant or quintessence
  - → de Sitter space or similar
  - → event horizon
  - → loss of information
  - → $ matrix not S matrix
  - → inconsistent with critical strings
- Natural possibility with non-critical strings

Dark Energy & String Theory

- Cosmological constant or quintessence
  - → de Sitter space or similar
  - → event horizon
  - → loss of information
  - → $ matrix not S matrix
  - → inconsistent with critical strings
- Natural possibility with non-critical strings

Dark Energy & String Theory

- Cosmological constant or quintessence
  - → de Sitter space or similar
  - → event horizon
  - → loss of information
  - → $ matrix not S matrix
  - → inconsistent with critical strings
- Natural possibility with non-critical strings

Non-Critical String Cosmology

Antoniadis, Bachas, JE + Nanopoulos: 198

- String coupling related to dilaton Φ : $g_s = e^{\Phi}$

Non-Critical String Cosmology

Antoniadis, Bachas, JE + Nanopoulos: 198

- String coupling related to dilaton Φ : $g_s = e^{\Phi}$
- Cosmology with time-dependent dilaton:

$\Phi = \text{constant} - Qt$ where t is world-sheet time

Non-Critical String Cosmology

Antoniadis, Bachas, JE + Nanopoulos: 198

- String coupling related to dilaton Φ : $g_s = e^{\Phi}$
- Cosmology with time-dependent dilaton:

$\Phi = \text{constant} - Qt$ where t is world-sheet time

- Cosmological time: $t_E = c_1 + \frac{c_0}{Q} e^{Qt}$

JE, Mavromatos + Nanopoulo

- Robertson-Walker-Friedman Universe:

$ds^2 = -dt_E^2 + a_E(t_E)^2 (dr^2 + r^2 d\Omega^2)$ where $a_E(t_E) \simeq \frac{\beta Q_0}{\gamma} \sqrt{1 + \gamma^2 t_E^2}$

Non-Critical String Cosmology

Antoniadis, Bachas, JE + Nanopoulos: 1988

- String coupling related to dilaton Φ : $g_s = e^{\Phi}$
- Cosmology with time-dependent dilaton:

  $\Phi \; = \; \mathrm{constant} - Qt$ where t is world-sheet time

- Cosmological time: $t_E \; = \; c_1 + \frac{c_0}{Q} e^{Qt}$

JE, Mavromatos + Nanopoulo

- Robertson-Walker-Friedman Universe:

$ds^2 \; = \; -dt_E^2 + a_E(t_E)^2(dr^2 + r^2 d\Omega^2)$ where $a_E(t_E) \simeq \frac{\beta Q_0}{\gamma}\sqrt{1+\gamma^2 t_E^2}$

- Q_0^2 departure from criticality, β & γ model-dependent constants
- Hubble expansion: $H(t_E) \simeq \frac{\gamma^2 t_E}{1+\gamma^2 t^2}$, $\Lambda_E(t_E) \simeq \frac{\gamma^2}{\beta^2(1+\gamma^2 t_E^2)}$

The String Coupling Accelerates the Expansion of the Universe

- Deceleration parameter:

$$q(t_E) = -\frac{(d^2 a_E/dt_E^2)\, a_E}{(da_E/dt_E)^2} \simeq -\frac{1}{\gamma^2 t_E^2}$$

- Directly related to string coupling:

$$q(t_E) = -\exp[2(\Phi - \mathrm{const})] = -g_s^2$$

JE, Mavromatos + Nanopoulos

The String Coupling Accelerates the Expansion of the Universe

- Deceleration parameter:

$$q(t_E) = -\frac{(d^2a_E/dt_E^2)\, a_E}{(da_E/dt_E)^2} \simeq -\frac{1}{\gamma^2 t_E^2}$$

- Directly related to string coupling:

$$q(t_E) = -\exp[2(\Phi - \text{const})] = -g_s^2$$

- Positivity of coupling² → $q_0 < 0$:

$$\boxed{q_0 \;=\; -g_s^2}$$

JE, Mavromatos + Nanopoulos

The String Coupling Accelerates the Expansion of the Universe

- Deceleration parameter:

$$q(t_E) = -\frac{(d^2 a_E/dt_E^2)\, a_E}{(da_E/dt_E)^2} \simeq -\frac{1}{\gamma^2 t_E^2}$$

- Directly related to string coupling:

$$q(t_E) = -\exp[2(\Phi - \text{const})] = -g_s^2$$

- Positivity of coupling^2 $\rightarrow$ $q_0 < 0$:

$$\boxed{q_0 = -g_s^2}$$

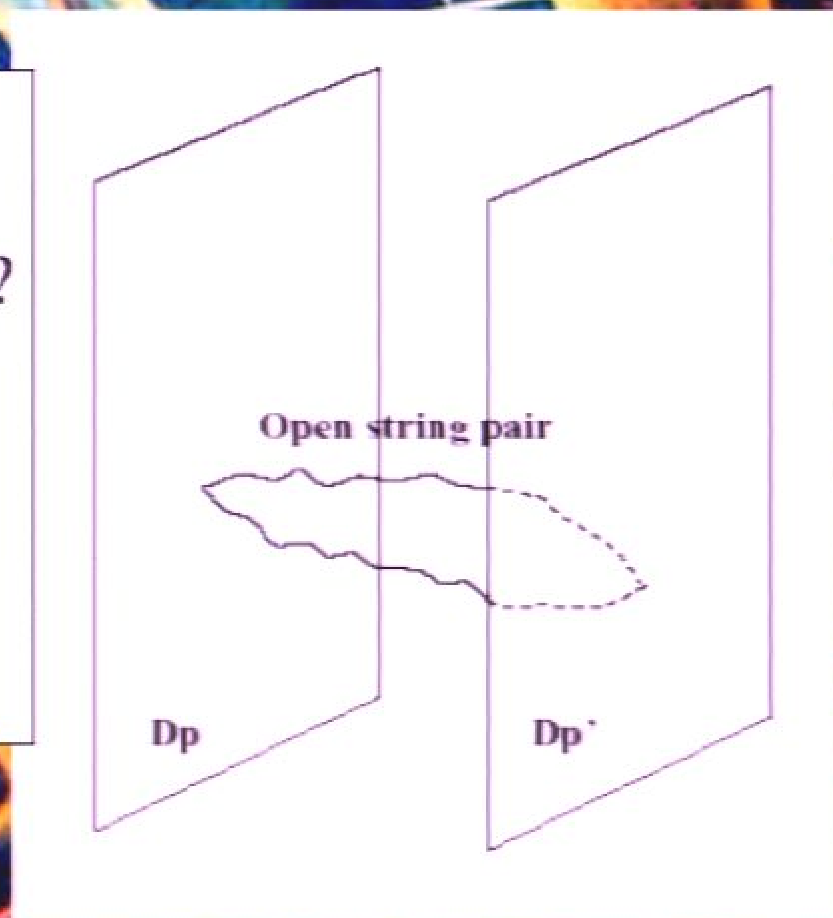
- The expansion of the Universe accelerates

Present data $\rightarrow$ $g_s^2 \sim 0.6$

JE, Mavromatos + Nanopoulos

One Possible 'Brany' Realization

- Maybe we live on a subspace in some higher-dimensional Universe (brane) populated also by other branes?

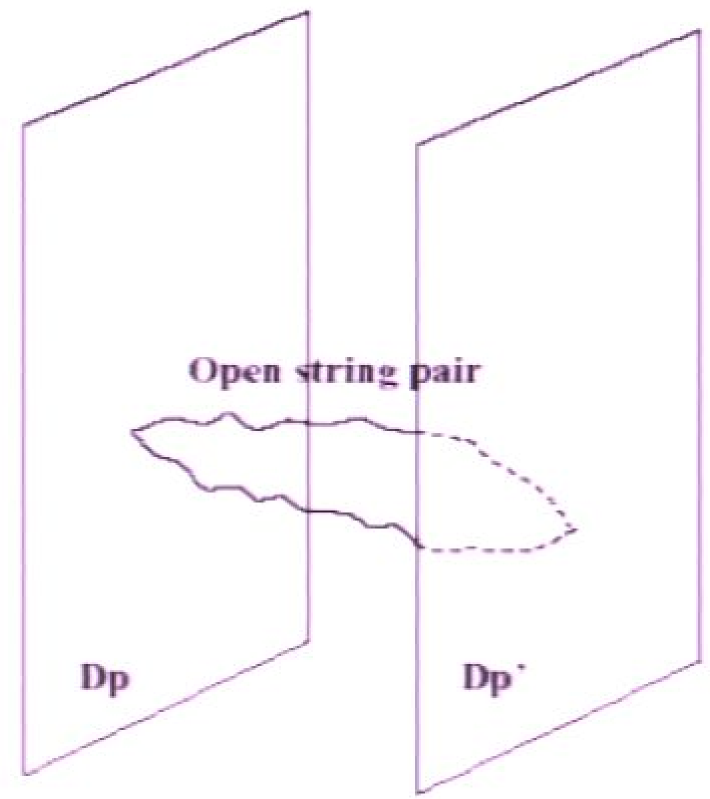


One Possible 'Brany' Realization

- Maybe we live on a subspace in some higher-dimensional Universe (brane) populated also by other branes?

- Maybe branes still moving apart?

- We would feel apparent dark energy
  ~ rate of separation

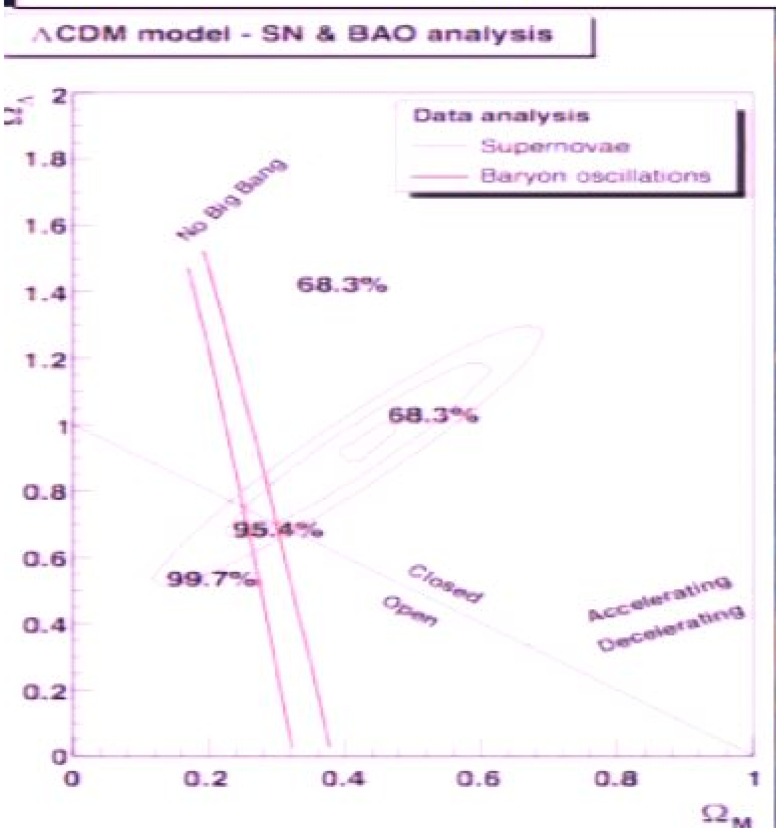


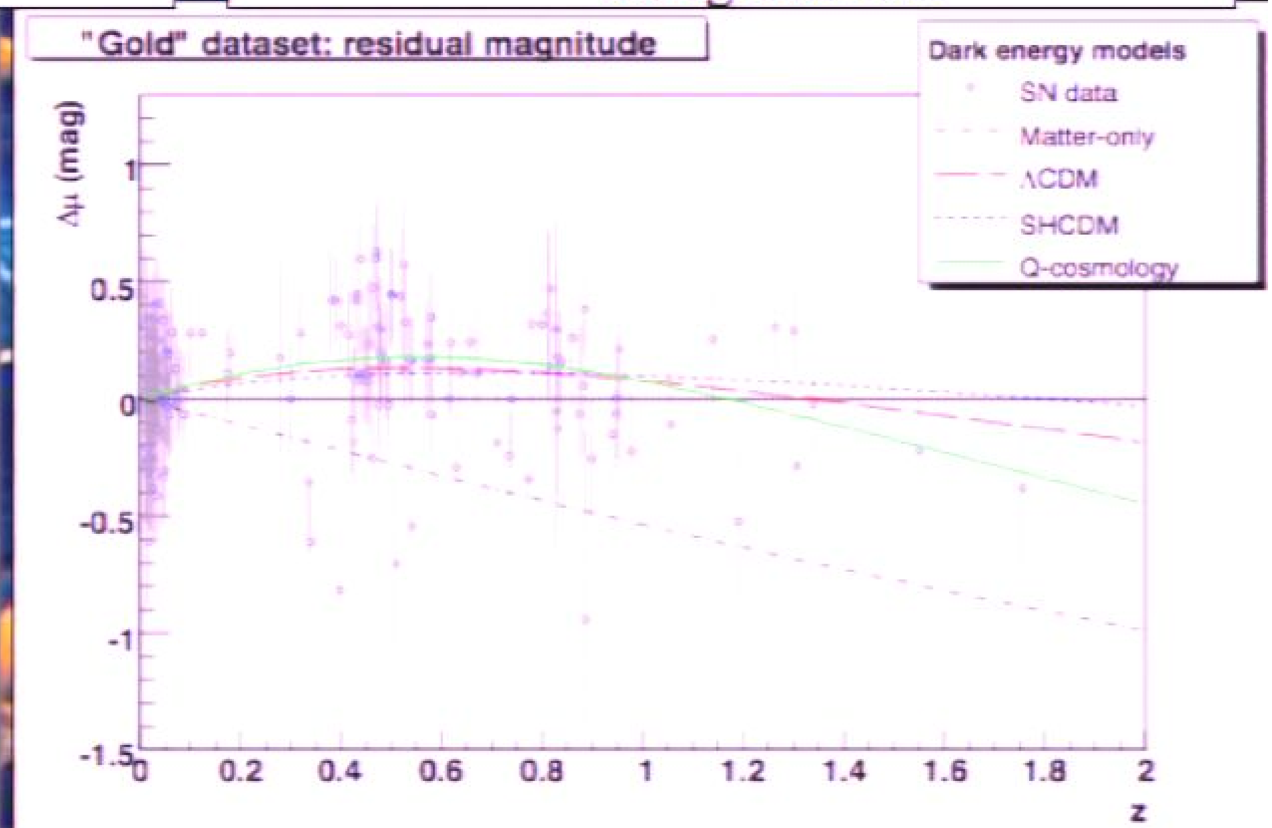
Fits to Cosmological Data

Standard ΛCDM

= Cosmo. Constant + cold dark matter

'Q- Cosmology' = time-dependent vacuum energy + off-shell string also OK





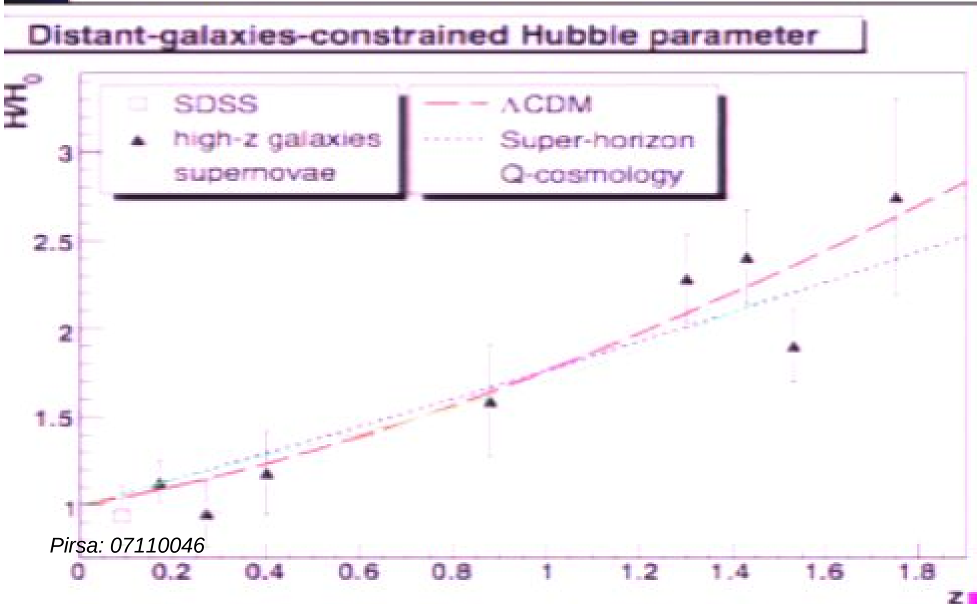
JE, Mavromatos, Mitsou, Nanopoulos: astro-ph/0604272

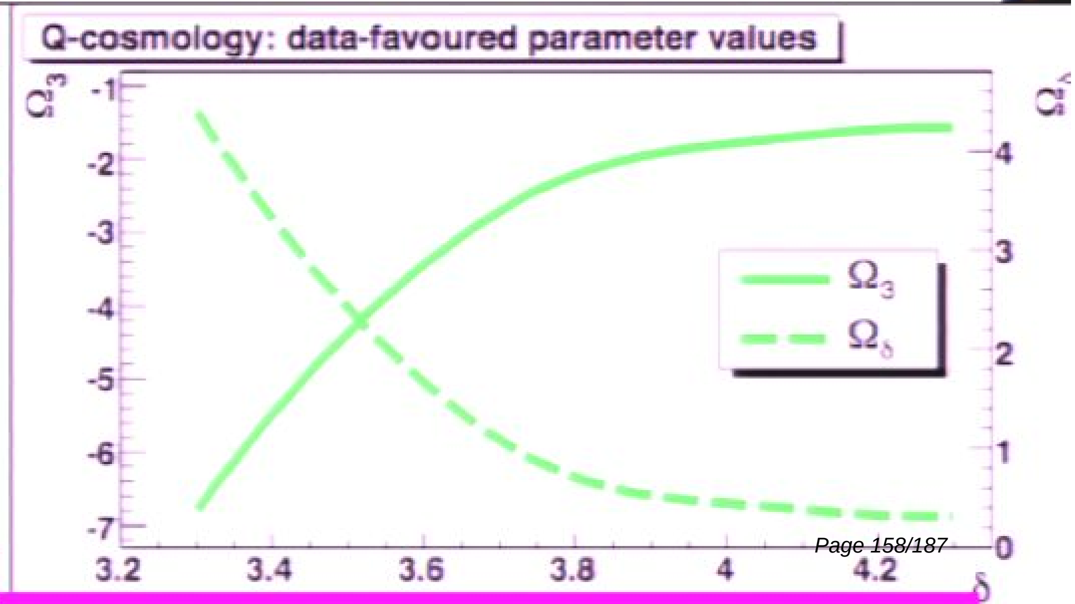
Time-Dependent Vacuum Energy: 'Q-Cosmology'

- 'Dust' + off-shell string contribution + varying vacuum energy:

$$H(z) = H_0 \left(\Omega_3(1+z)^3 + \Omega_\delta(1+z)^\delta + \Omega_2(1+z)^2\right)^{1/2}$$

- Fit to data with negative-energy dust





Summary & Prospects

- Think about possible experimental signatures of quantum gravity

Summary & Prospects

- Think about possible experimental signatures of quantum gravity
- Consider distinctive effects not allowed in usual quantum field theory

Summary & Prospects

- Think about possible experimental signatures of quantum gravity
- Consider distinctive effects not allowed in usual quantum field theory
- Only heuristic discussion yet possible
- Non-critical string theory is one proposal

Summary & Prospects

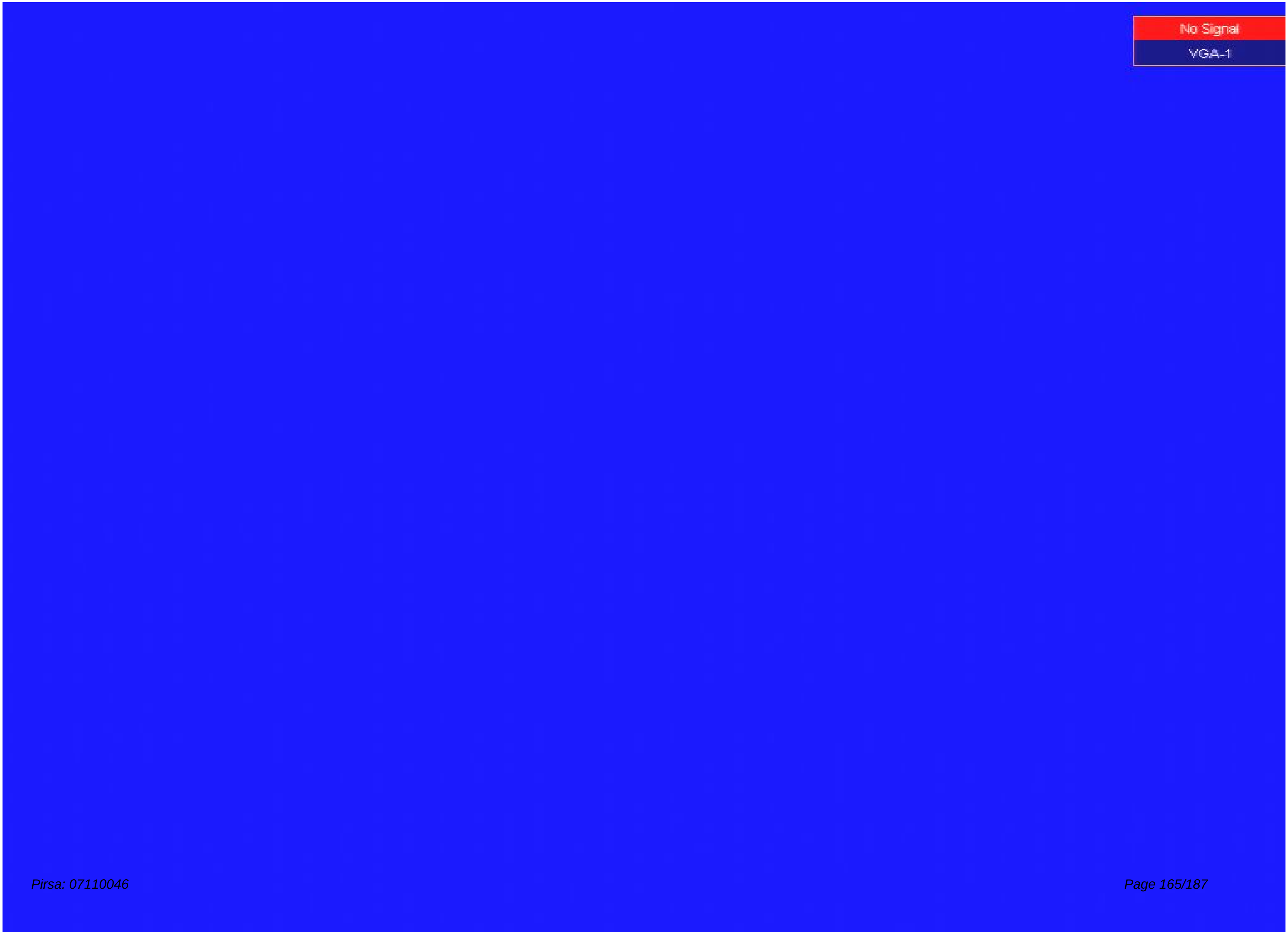
- Think about possible experimental signatures of quantum gravity
- Consider distinctive effects not allowed in usual quantum field theory
- Only heuristic discussion yet possible
- Non-critical string theory is one proposal
- ‘Violation’ of quantum mechanics?

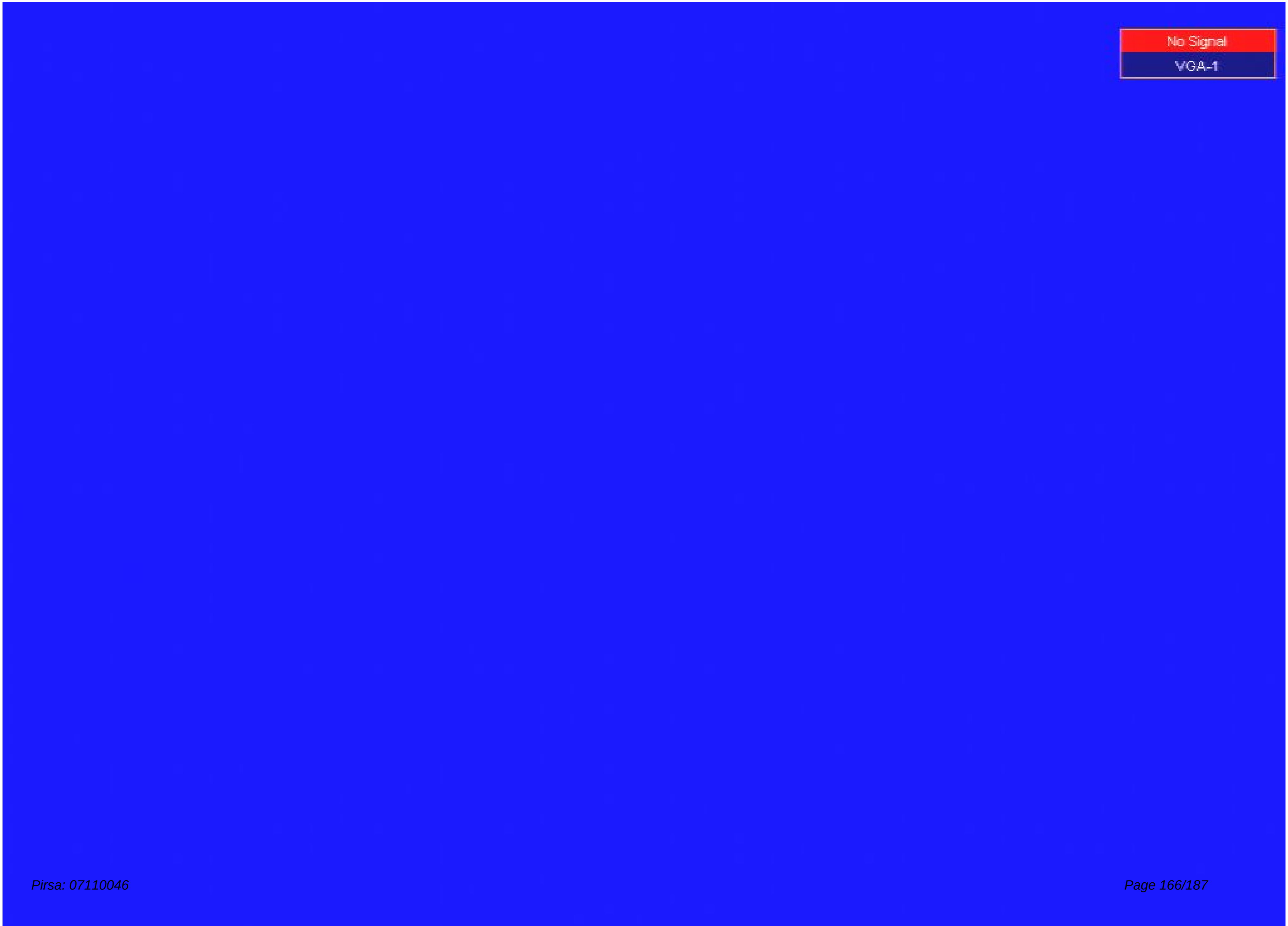
Summary & Prospects

- Think about possible experimental signatures of quantum gravity
- Consider distinctive effects not allowed in usual quantum field theory
- Only heuristic discussion yet possible
- Non-critical string theory is one proposal
- ‘Violation’ of quantum mechanics?
- Breakdown of Lorentz invariance?
- Violation of equivalence principle?

Summary & Prospects

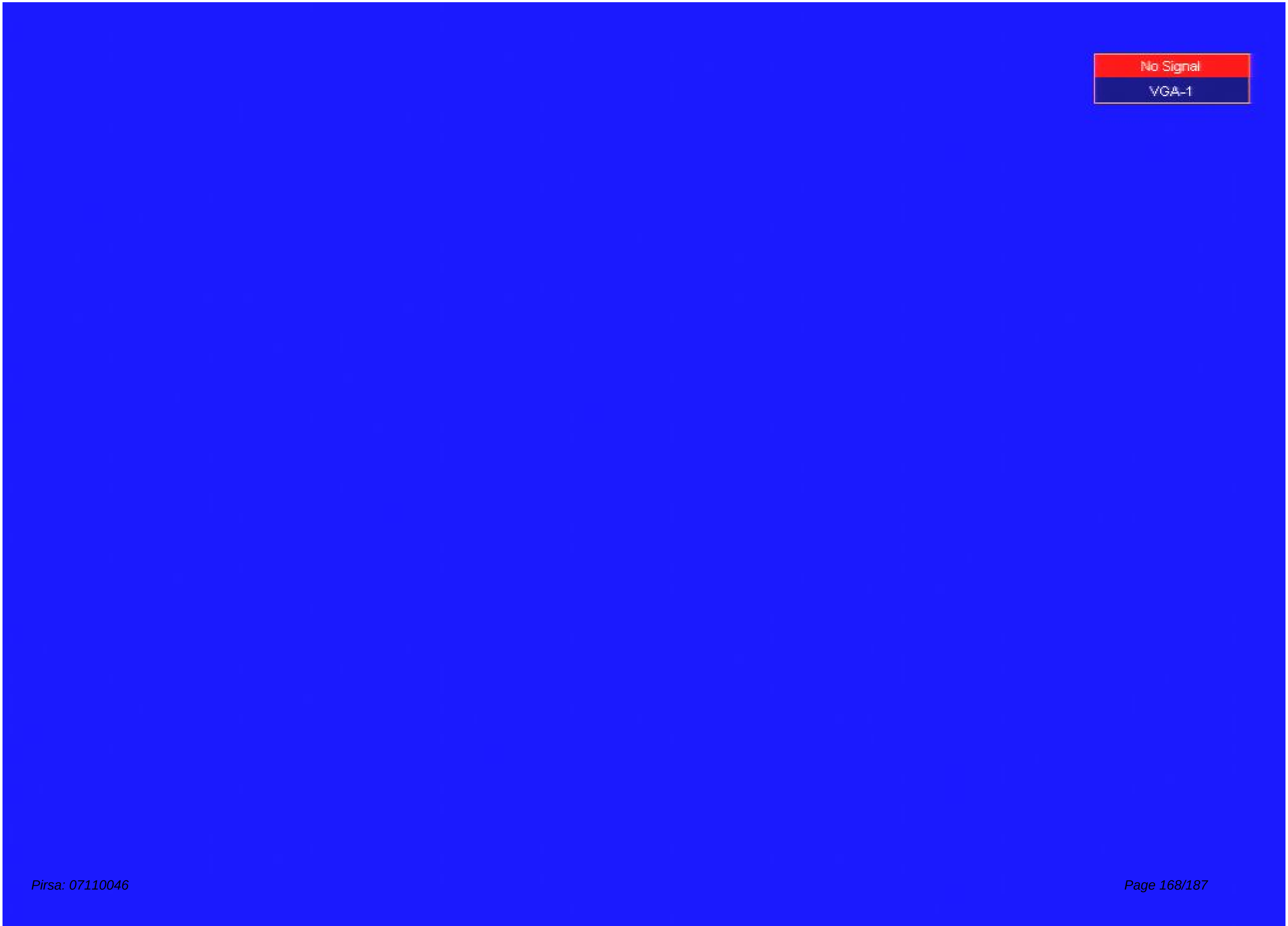
- Think about possible experimental signatures of quantum gravity
- Consider distinctive effects not allowed in usual quantum field theory
- Only heuristic discussion yet possible
- Non-critical string theory is one proposal
- 'Violation' of quantum mechanics?
- Breakdown of Lorentz invariance?
- Violation of equivalence principle?
- Cosmology is natural arena: inflation, dark energy


No Signal
VGA-1


No Signal
VGA-1

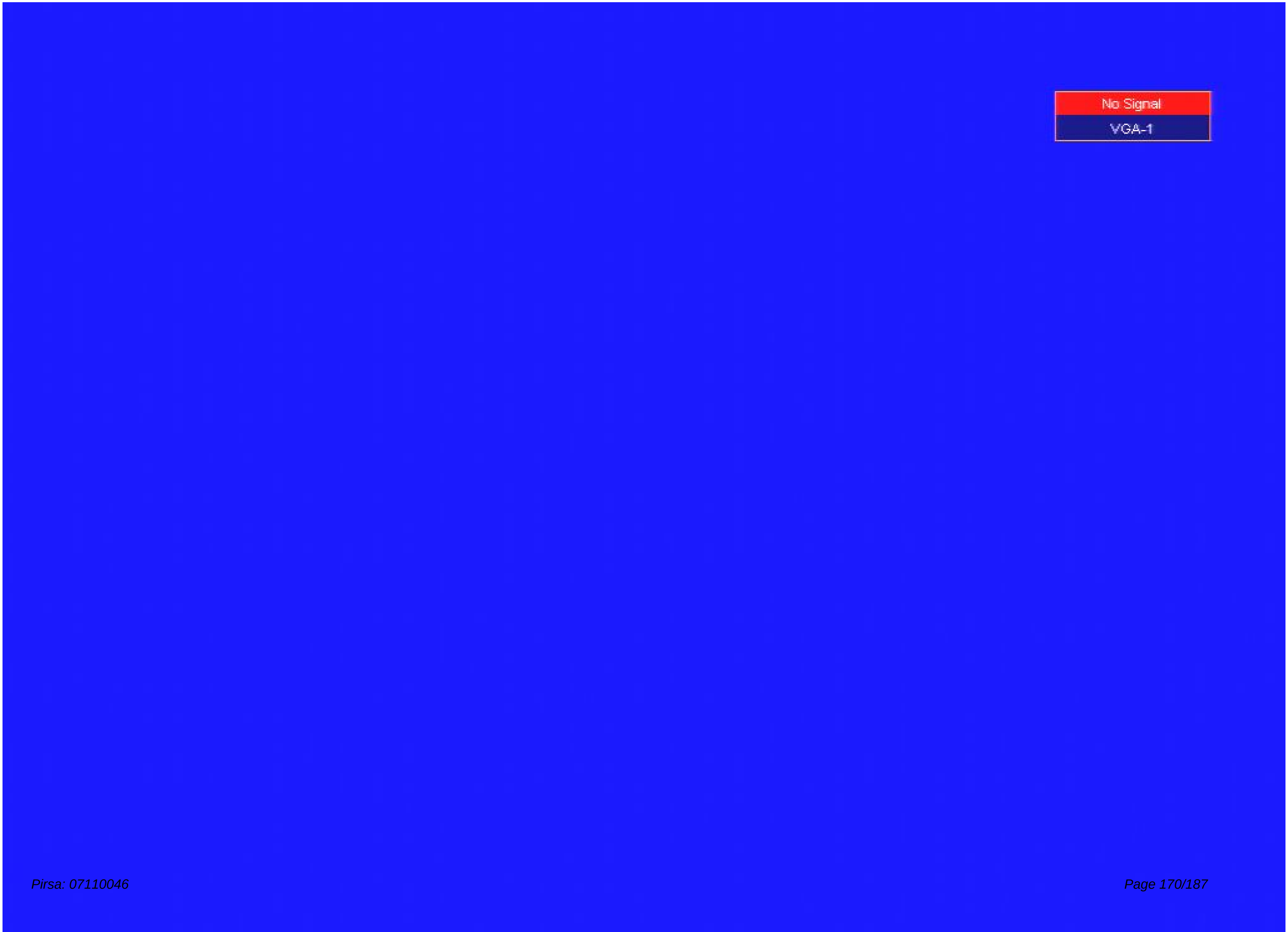
No Signal

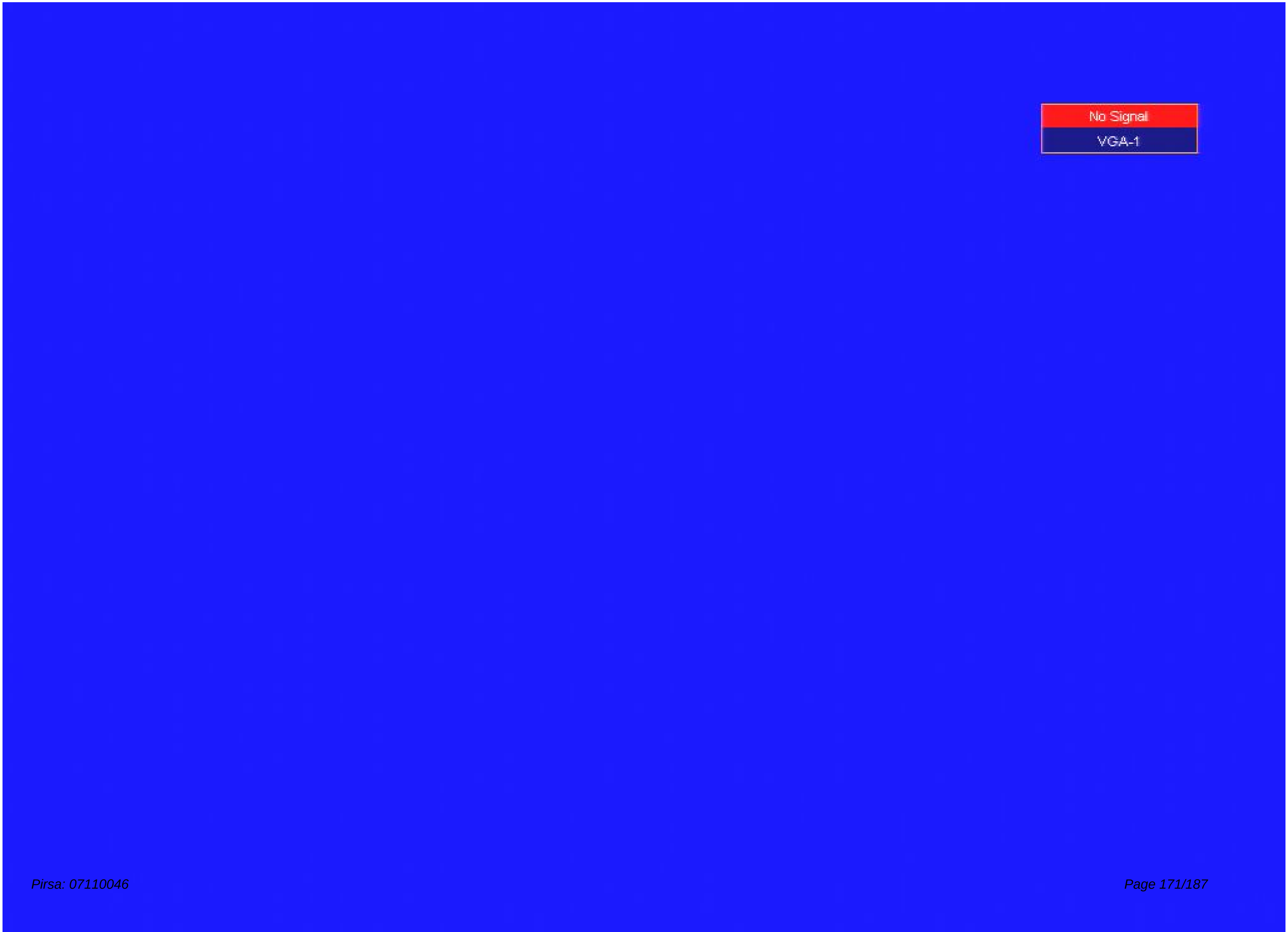
VGA-1

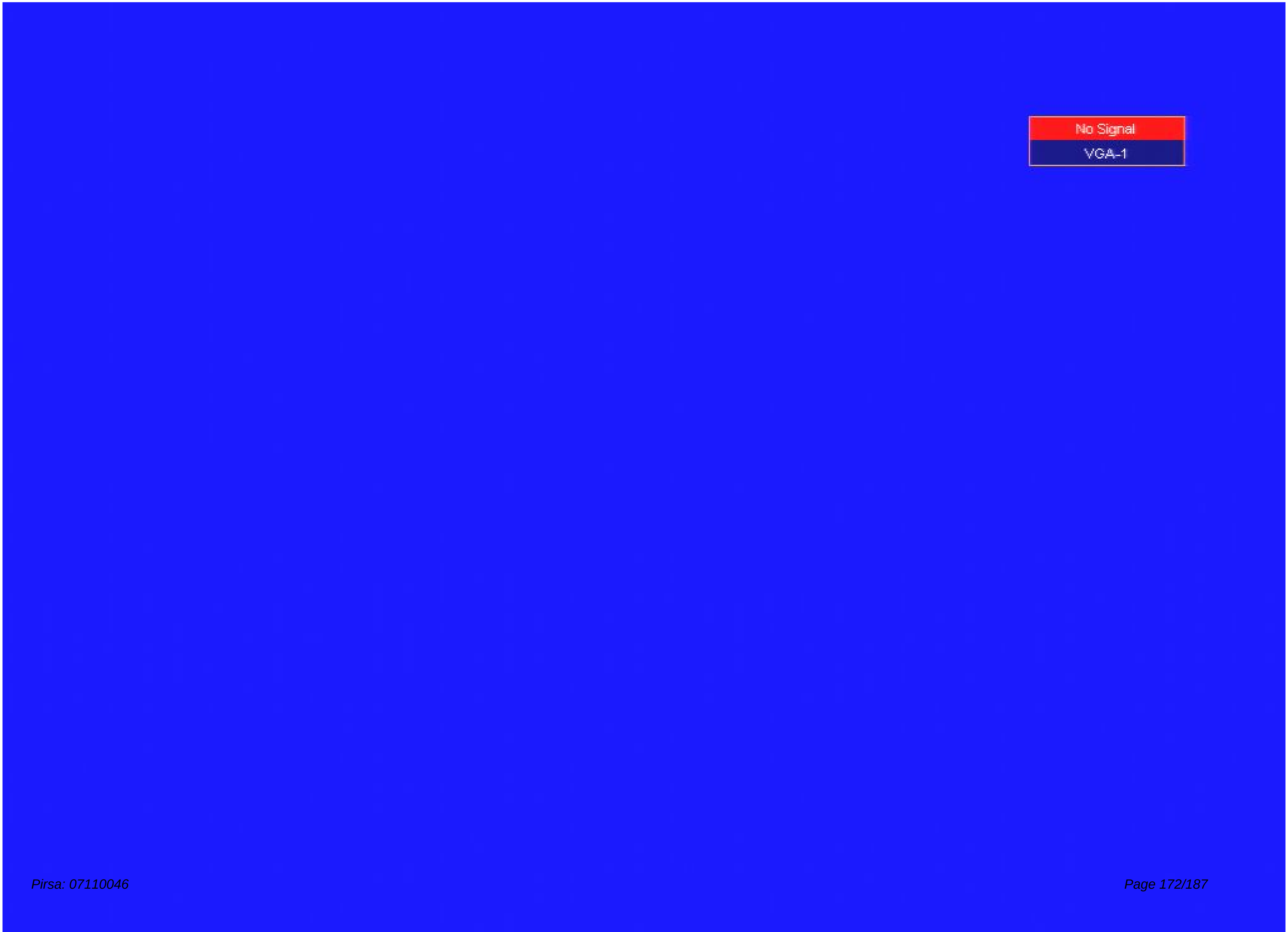

No Signal
VGA-1

No Signal

VGA-1


No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1

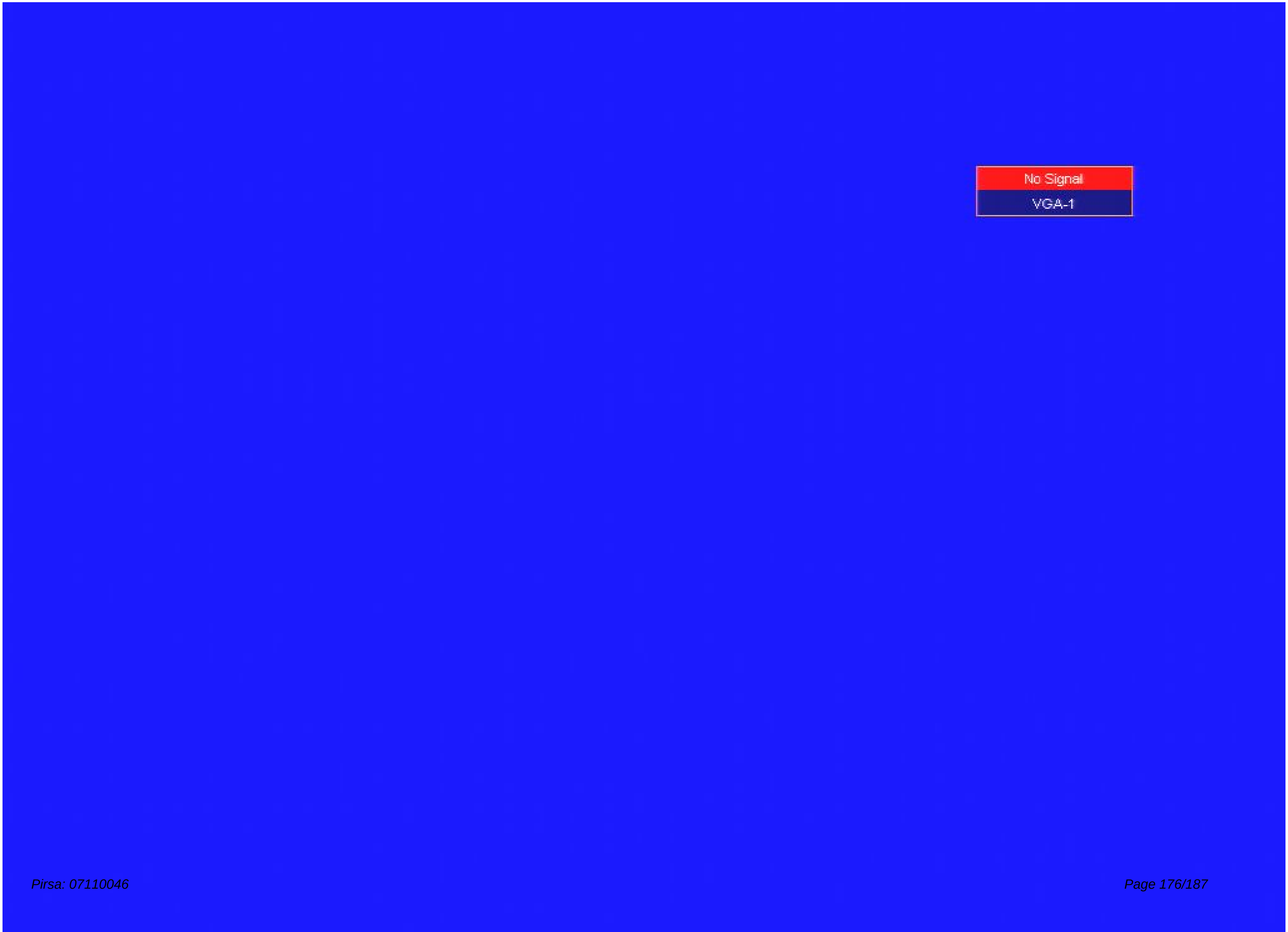
No Signal

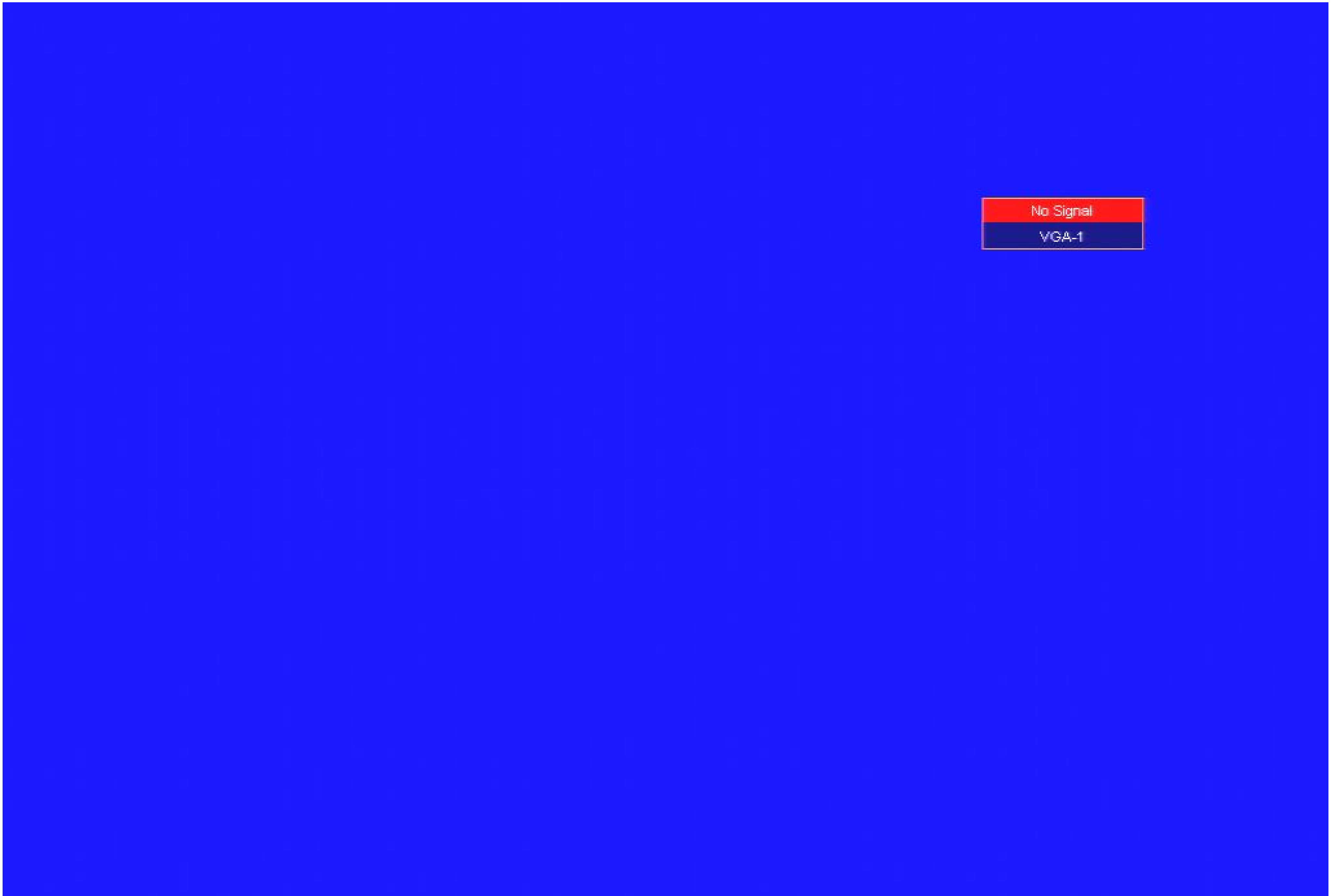
VGA-1

No Signal

VGA-1

No Signal
VGA-1


No Signal
VGA-1

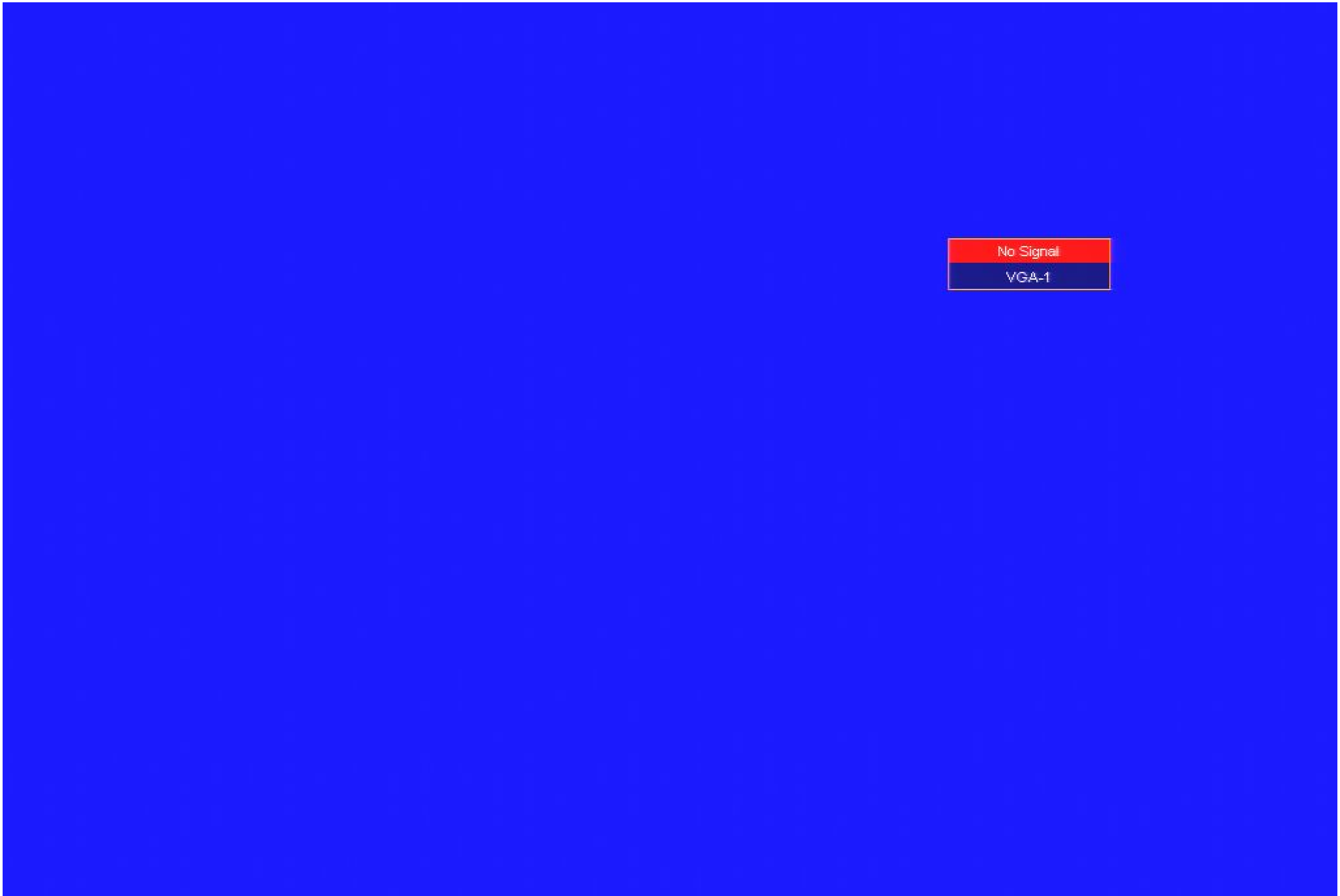

No Signal
VGA-1

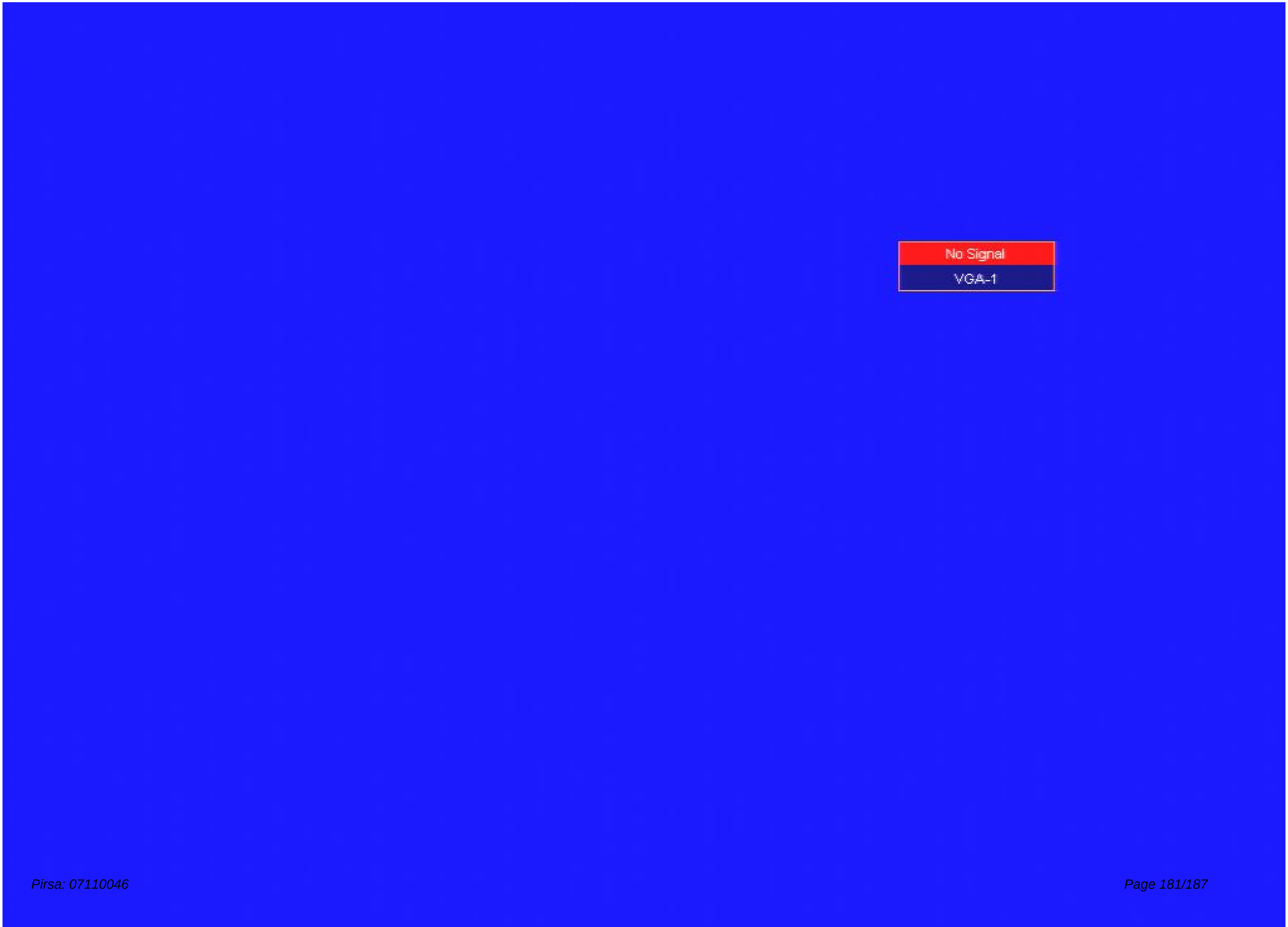
No Signal

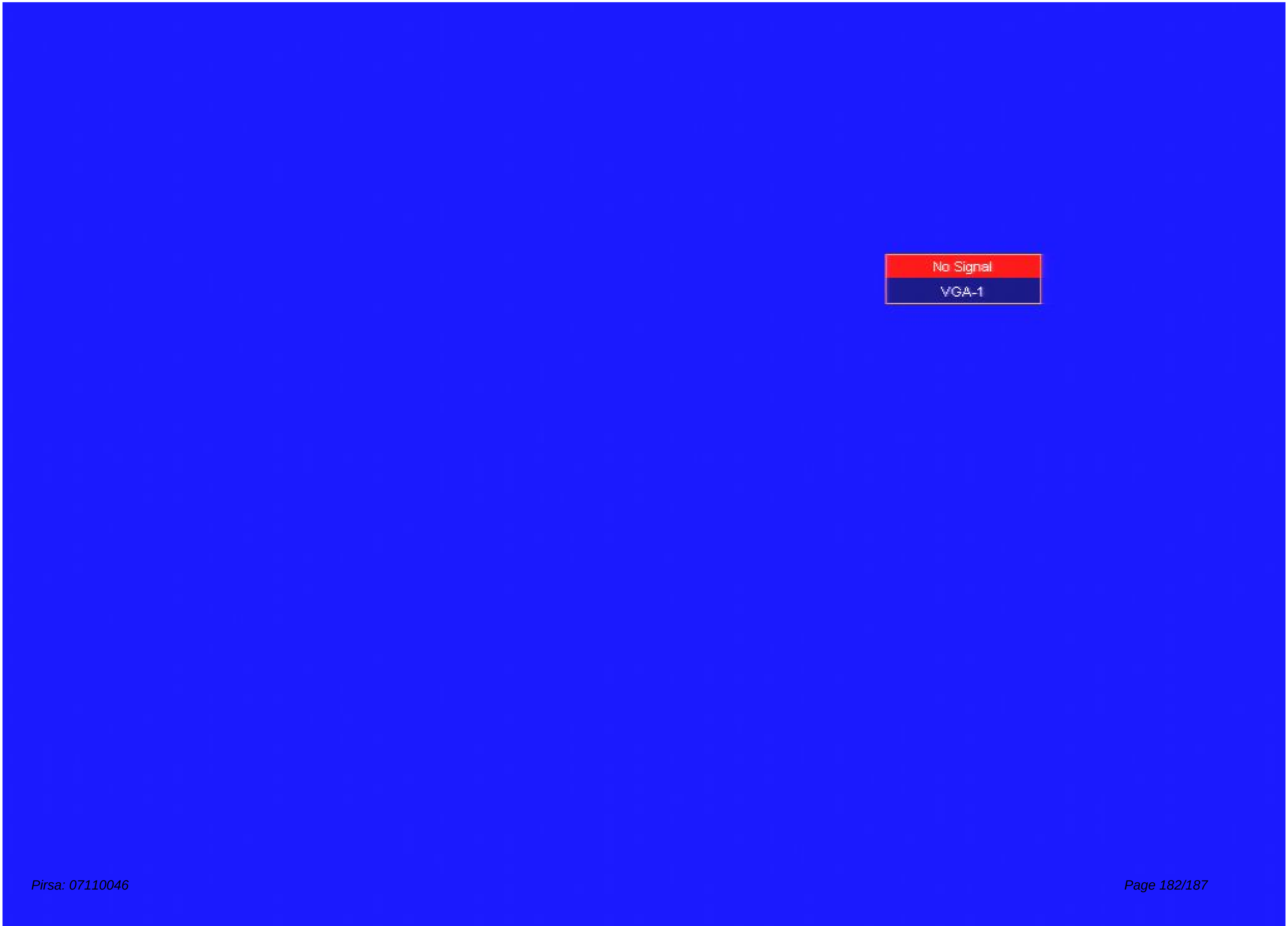
VGA-1

No Signal

VGA-1

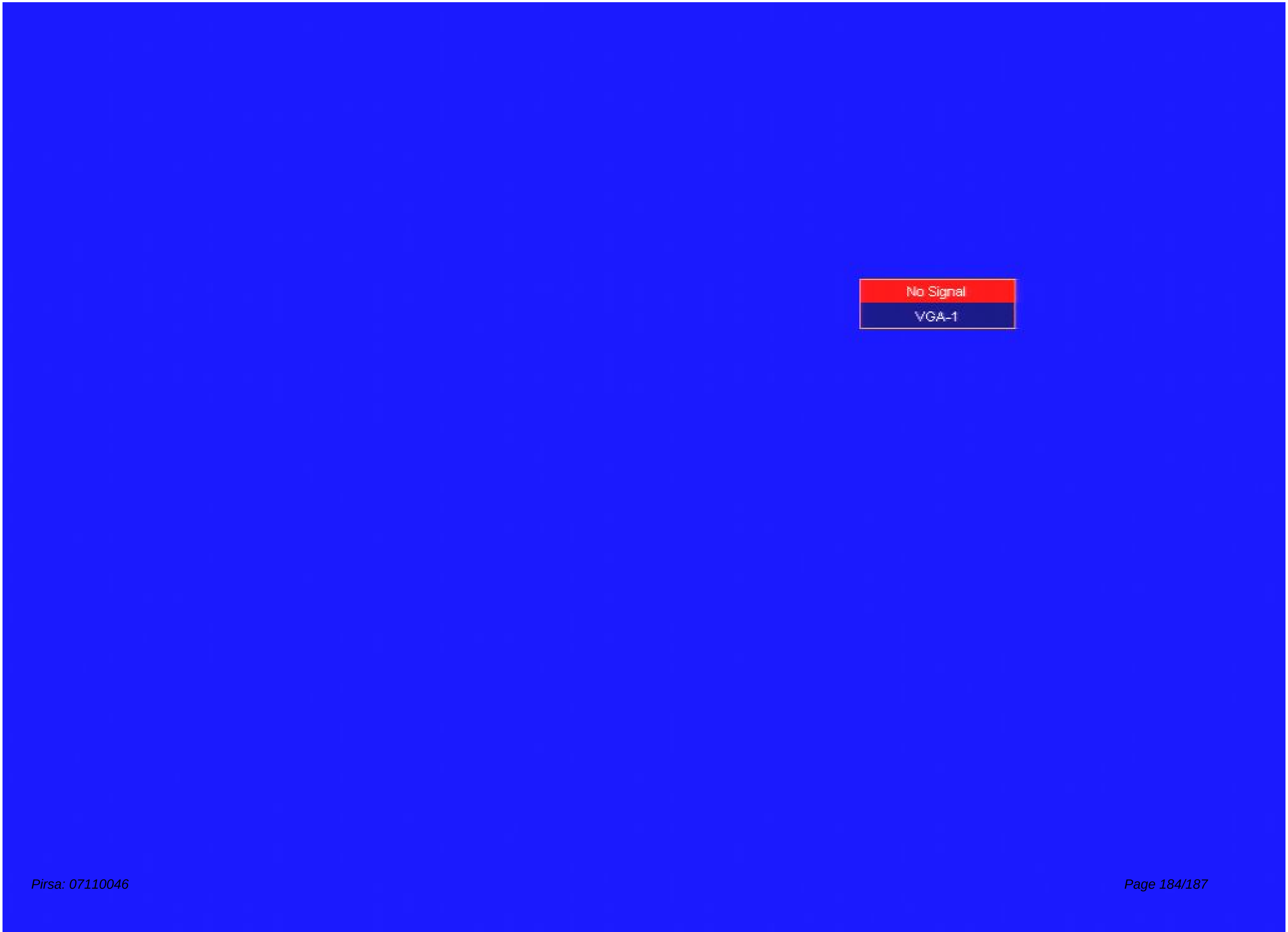

No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1

No Signal

VGA-1

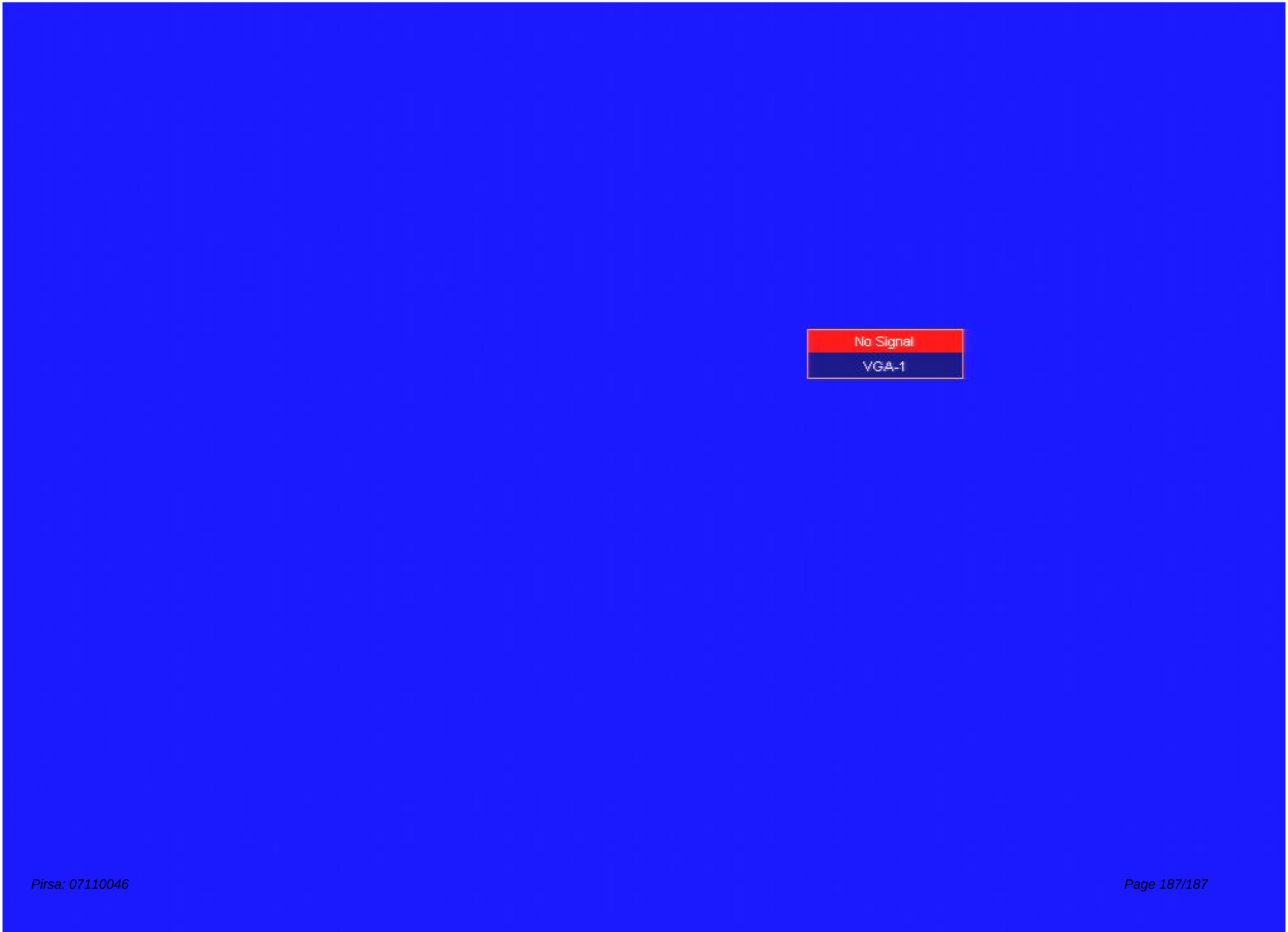

No Signal
VGA-1

No Signal

VGA-1

No Signal

VGA-1


No Signal
VGA-1