Title: Phenomenology of Massive Neutrinos

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Abstract:

PHENOMENOLOGY OF MASSIVE NEUTRINOS

(1998-2008 THE GOLDEN ν DECADE)

Concha Gonzalez-Garcia

(YITP-Stony Brook & ICREA-U Barcelona)

Pascos 08, June 3rd, 2008

PHENOMENOLOGY OF MASSIVE NEUTRINOS

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OUTLINE

Introduction: *The New Minimal Standard Model*

ν Masses and Mixing from Global ν-data Analysis

Beyond Masses and Mixing:

Testing How the Sun Shines

Constraints on Extensions of the NMSM

And what about LSND and MiniBooNE? (Next Talk)

Summary

Sources of ν's

$n_\nu = 330/\text{cm}^3$

$E_\nu = 0.0004$ eV

$E_\nu \sim$ MeV

The Sun

ν_e

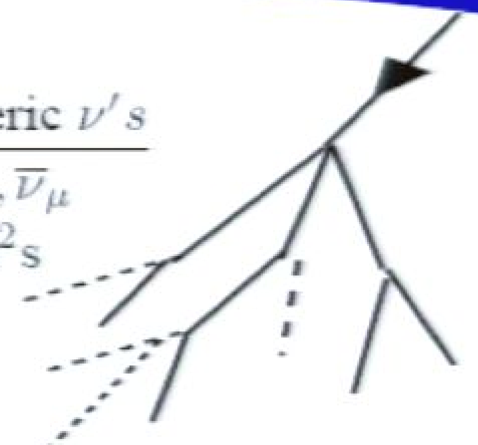
$\Phi_\nu^{Earth} = 6 \times 10^{10} \nu/\text{cm}^2\text{s}$

$E_\nu \sim 0.1\text{–}20$ MeV

Atmospheric ν's

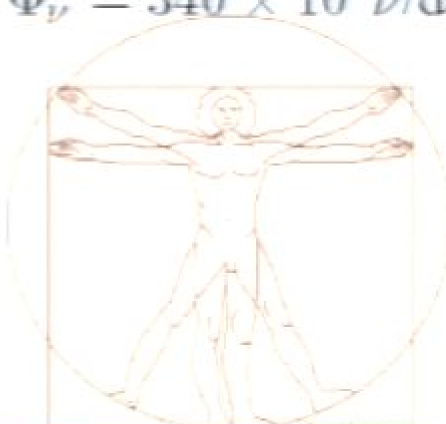
$\nu_e, \nu_\mu, \overline{\nu}_e, \overline{\nu}_\mu$

$\Phi_\nu \sim 1 \nu/\text{cm}^2\text{s}$



Human Body

$\Phi_\nu = 340 \times 10^6 \nu/\text{day}$



Nuclear Reactors

$E_\nu \sim$ few MeV

Earth's radioactivity

Accelerators

ν in the SM

- The SM is a gauge theory based on the symmetry group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

There is no ν_R

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$\Rightarrow$ Accidental global symmetry: $B \times L_e \times L_\mu \times L_\tau$

$\Rightarrow$ ν *strictly* massless

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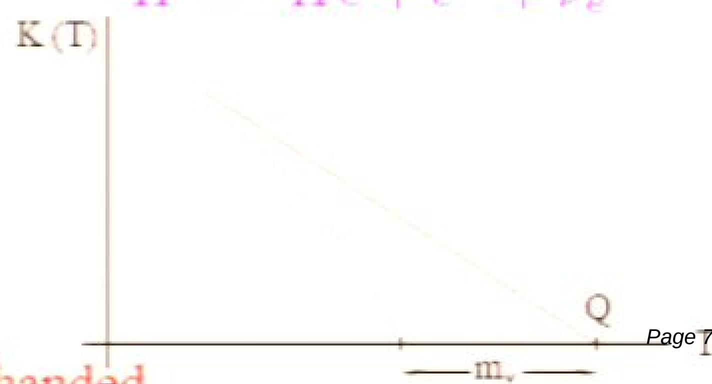
$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$

- When SM was built upper bounds on m_ν

$m_{\nu_e} < 2.2$ eV

$m_{\nu_\mu} < 190$ KeV $\quad (\pi \rightarrow \mu\nu_\mu)$

$m_{\nu_\tau} < 18.2$ MeV $\quad (\tau \rightarrow n\pi\nu_\tau)$



- Neutrinos are conjured to be massless and left-handed

- We have learned:
  - $*$ Atmospheric ν_μ disappear ($> 20\sigma$) most likely to ν_τ
  - $*$ K2K: accelerator ν_μ disappear at $L \sim 250$ Km with E-distortion (~ 2.5–4σ)
  - $*$ MINOS: accelerator ν_μ disappear at $L \sim 735$ Km with E-distortion ($\sim 5\sigma$)
  - $*$ Solar ν_e convert to ν_μ or ν_τ ($> 7\sigma$)
  - $*$ KamLAND: reactor $\overline{\nu_e}$ disappear at $L \sim 200$ Km with E-distortion ($\sim 5\sigma$ CL)
  - $*$ LSND found evidence for $\overline{\nu_\mu} \to \overline{\nu_e}$ (but not confirmed by Karmen nor MiniBooNE)

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All this implies that neutrinos are massive

- We have important information (mostly constraints) from:
  - * The line shape of the Z: $N_{\text{weak}} = 3$
  - * Limits from Short Distance Oscillation Searches at Reactor and Accelerators
  - * Direct mass measurements: $^3H \to ^3He + e^- + \bar{\nu}_e$ and ν-less $\beta\beta$ decay
  - * From Astrophysics and Cosmology: BBN, CMBR, LSS ...

Effects of ν Mass

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- Minimal Extensions to give Mass to the Neutrino:

  ∗ Introduce ν_R AND impose L conservation ⇒ Dirac ν:

  $$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \overline{\nu_L} \nu_R + h.c.$$

  ∗ NOT impose L conservation ⇒ Majorana ν

  $$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} M_\nu \overline{\nu_L} \nu_L^C + h.c.$$

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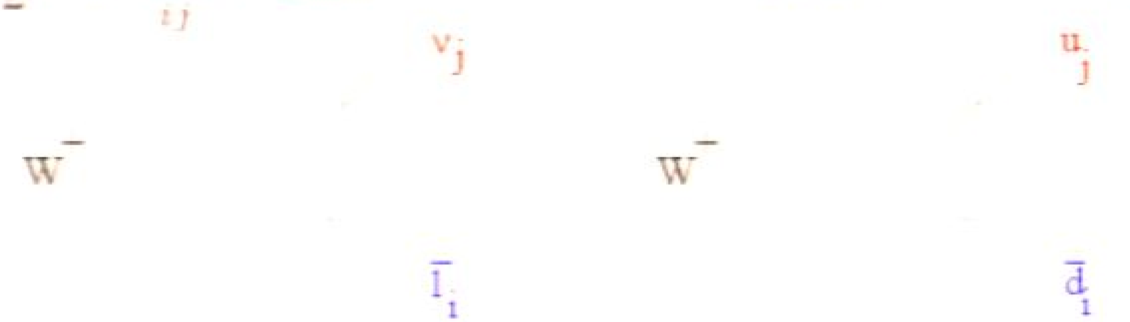
- The charged current interactions of leptons are not diagonal (same as quarks)

$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} \left(U_{LEP}^{ij}\, \overline{\ell^i}\, \gamma^\mu\, L\, \nu^j \;+\; U_{CKM}^{ij}\, \overline{U^i}\, \gamma^\mu\, L\, D^j \right) \;+\; h.c.$$



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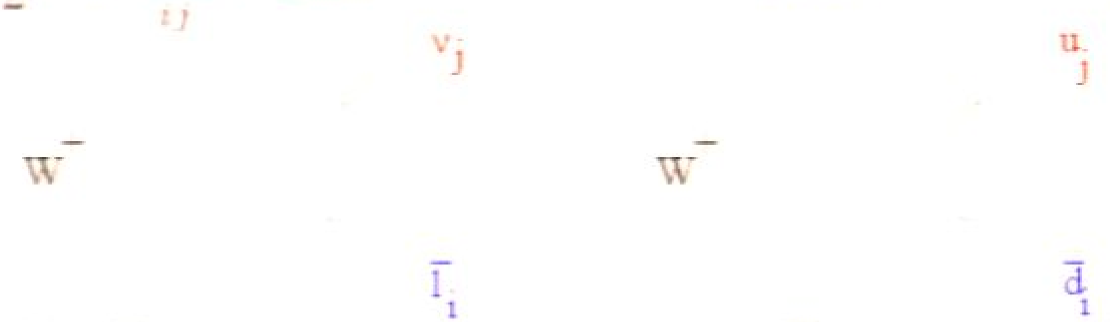

- In general for $N = 3 + m$ massive neutrinos U_{LEP} is $3 \times N$ matrix

$$U_{LEP} U_{LEP}^\dagger = I_{3\times3} \qquad \text{but in general} \qquad U_{LEP}^\dagger U_{LEP} \neq I_{N\times N}$$

- U_{LEP}: $3(N-2)$ angles + $2N-5$ Dirac phases + $N-1$ Majorana phases

Effects of ν Mass: Oscillations

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- If neutrinos have mass, a weak eigenstate $|\nu_\alpha\rangle$ produced in $l_\alpha + N \to \nu_\alpha + N'$

  is a linear combination of the mass eigenstates $(|\nu_i\rangle)$: $|\nu_\alpha\rangle = \sum_{i=1}^{n} U_{\alpha i}\, |\nu_i\rangle$

- After a distance L it can be detected with flavour β with probability

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j\neq i}^{n} \mathrm{Re}[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}] \sin^2\left(\frac{\Delta_{ij}}{2}\right) + 2\sum_{j\neq i} \mathrm{Im}[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}] \sin(\Delta_{ij})$$

$$\frac{\Delta_{ij}}{2} = \frac{(E_i - E_j)L}{2} = 1.27 \frac{(m_i^2 - m_j^2)}{\mathrm{eV}^2} \frac{L/E}{\mathrm{Km/GeV}}$$

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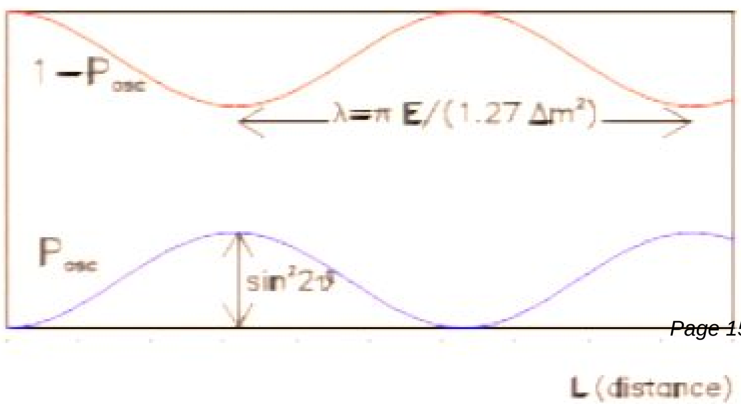
- For 2-ν:

$P_{\alpha\alpha} = 1 - P_{osc}$ Disappear

$P_{osc} = \sin^2(2\theta)\, \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$ Appear



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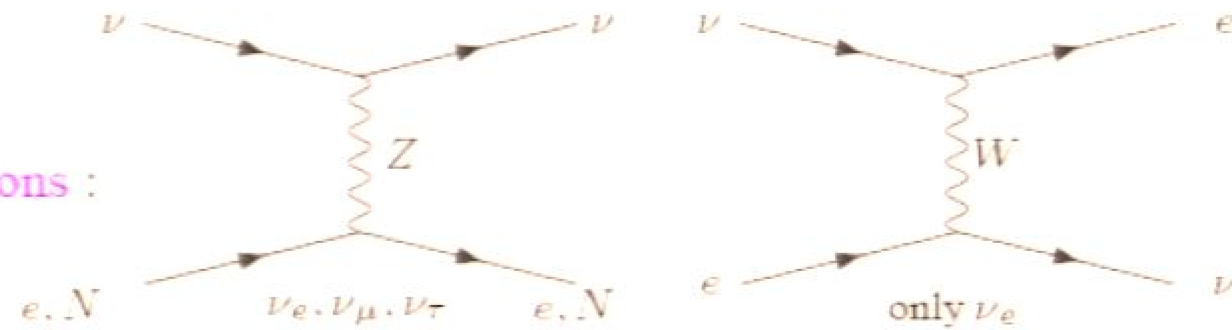
Matter Effects

- If ν cross matter regions (Sun, Earth...) it interacts *coherently*

  – But Different flavours have different interactions :



  – To include this effect: potential in the evolution equation: $V_e \neq V_\mu$

  $\Rightarrow$ *Modification of mixing angle and oscillation wavelength*

- The mixing angle in matter

$$\sin(2\theta_m) = \frac{\Delta m^2 \sin(2\theta)}{\sqrt{(\Delta m^2 \cos(2\theta) - A)^2 + (\Delta m^2 \sin(2\theta))^2}} \qquad A = 2\,E\,(V_\alpha - V_\beta)$$

  – When $\Delta m^2 \cos(2\theta) \sim A \Rightarrow$ Enhancement of Oscillation (MSW Effect)

ν Oscillations: Experimental Probes

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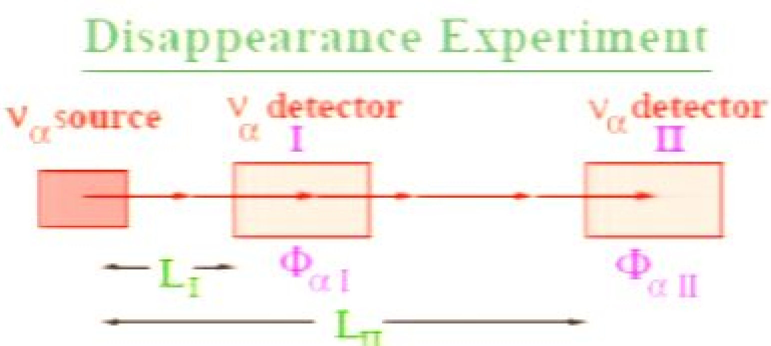

Compares $\Phi_{\alpha I}$ and $\Phi_{\alpha II}$ to look for loss

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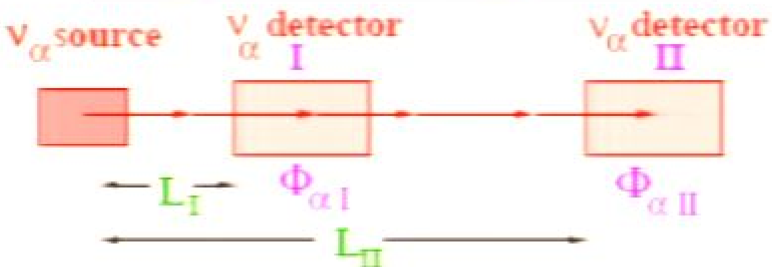
Disappearance Experiment



Compares $\Phi_{\alpha I}$ and $\Phi_{\alpha II}$ to look for loss

Appearance Experiment

Searches for β diff α

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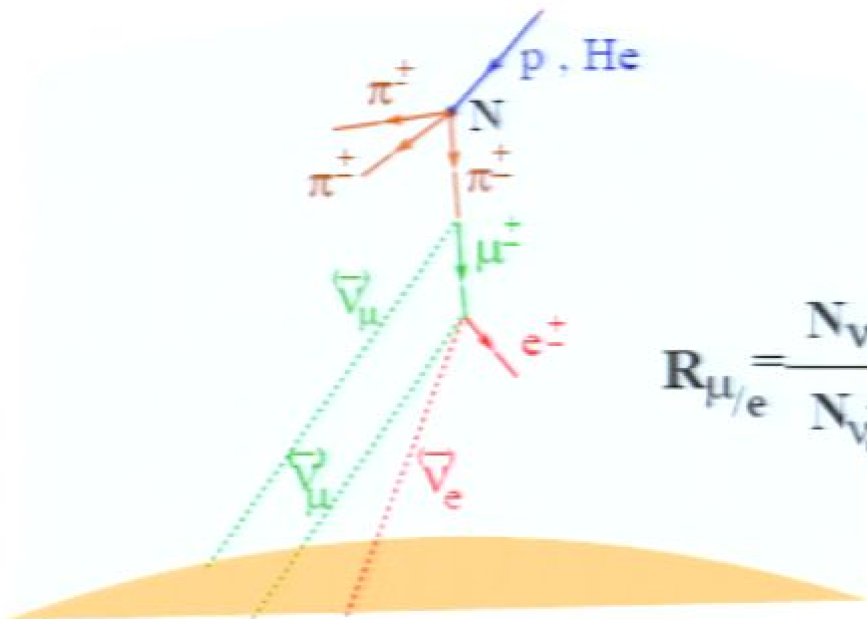
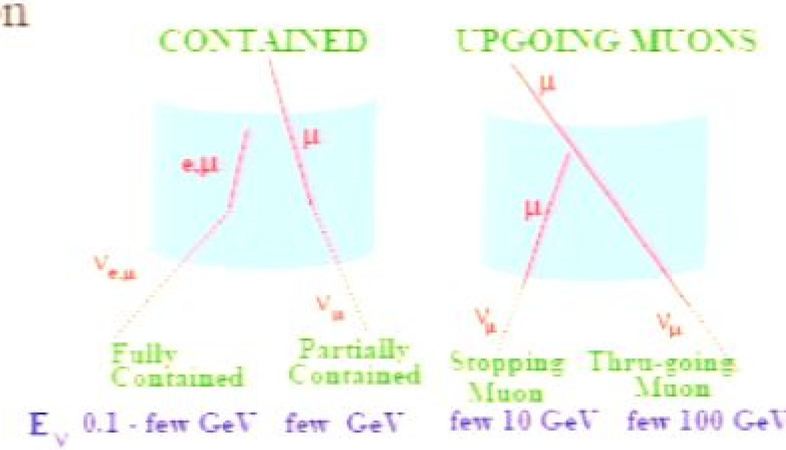
Atmospheric Neutrinos

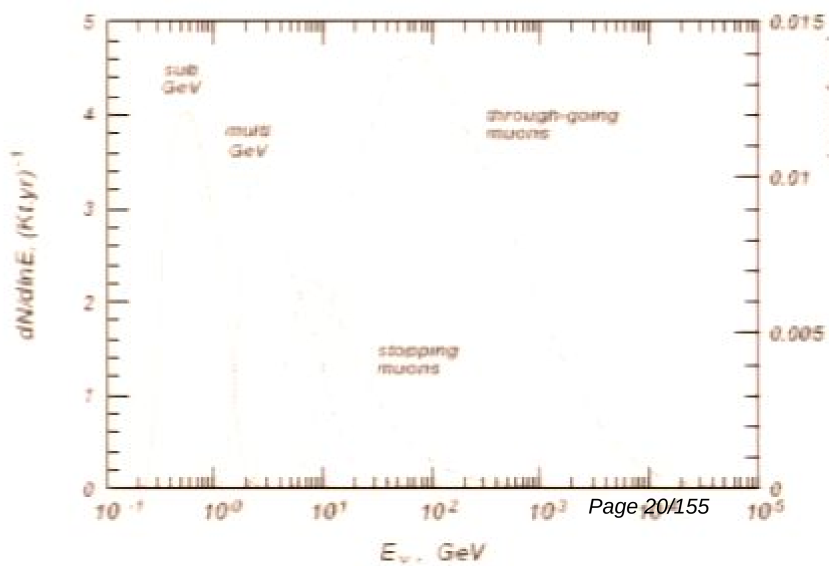
Atmospheric $\nu_{e,\mu}$ are produced by the interaction of cosmic rays (p, He ...) with the atmosphere



$$R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\overline{\nu}_\mu}}{N_{\nu_e} + N_{\overline{\nu}_e}} \sim 2$$

EVENT CLASSIFICATION





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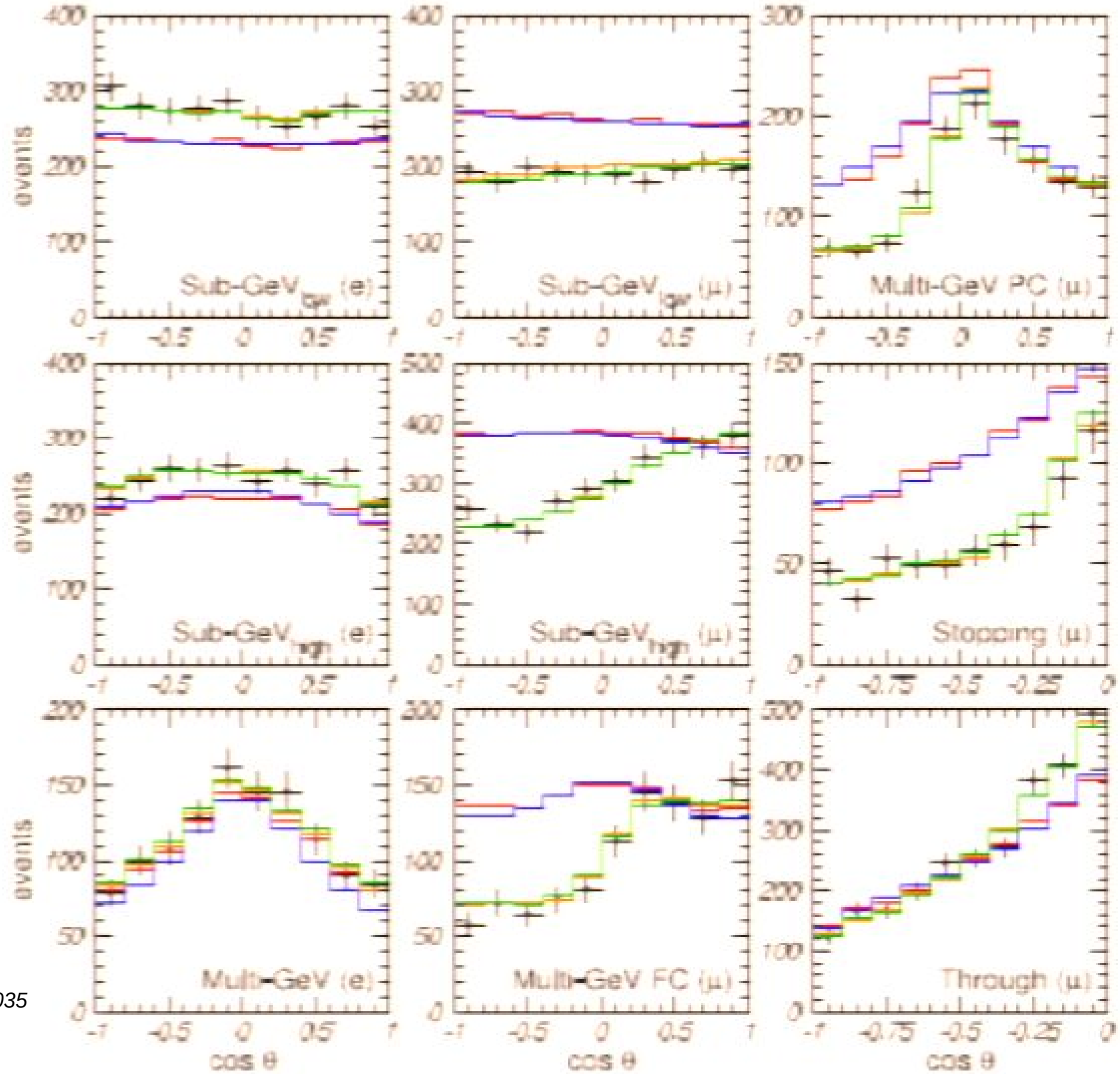
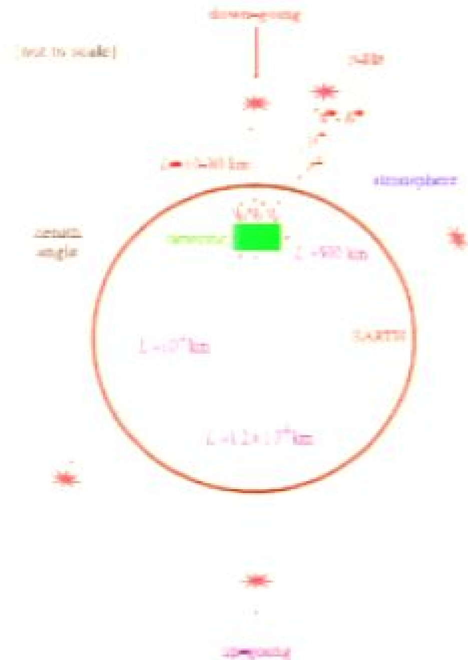
Atmospheric Neutrinos: Data

- Complete SKI−II data:





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Atmospheric Neutrinos: Data

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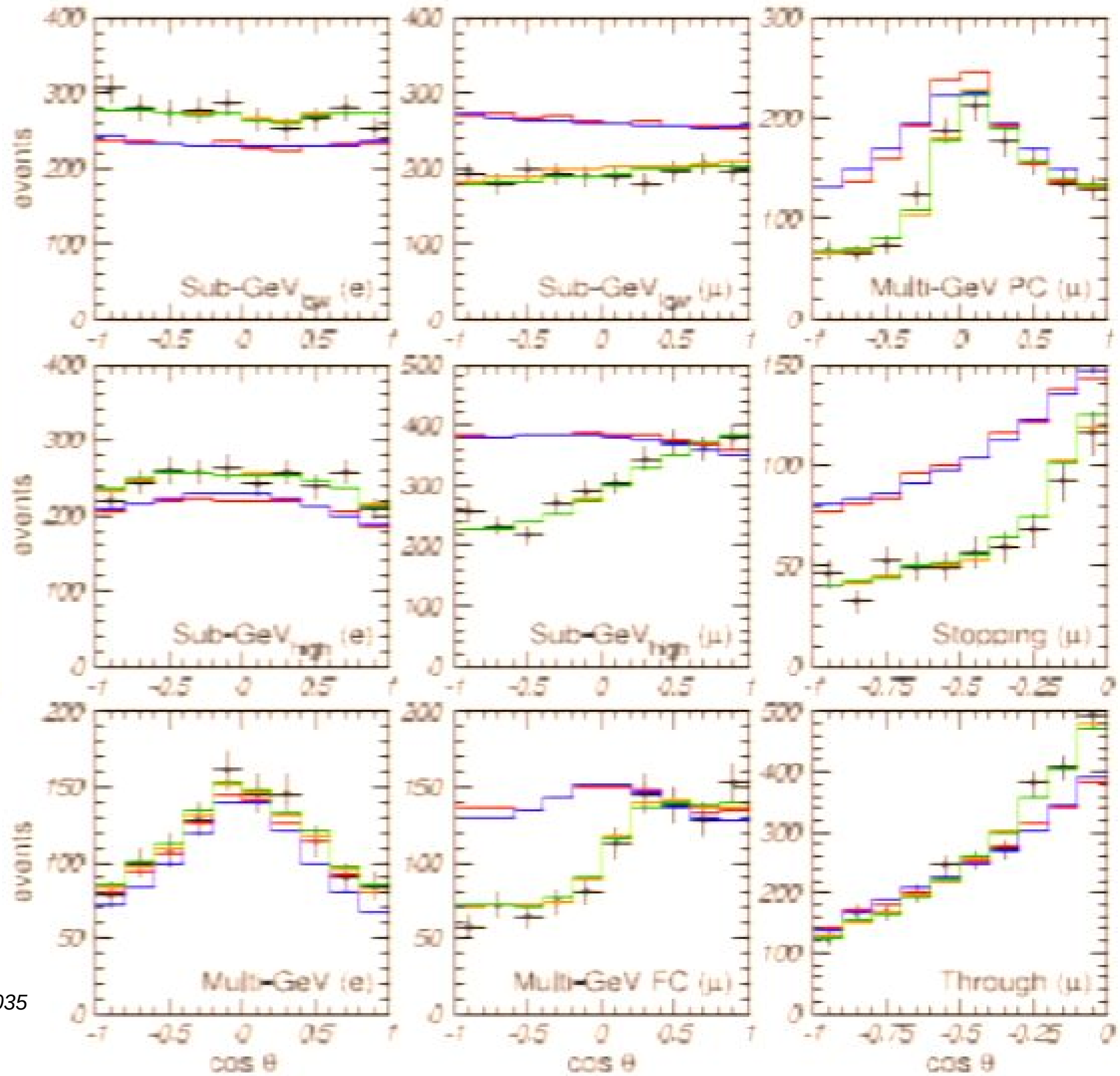
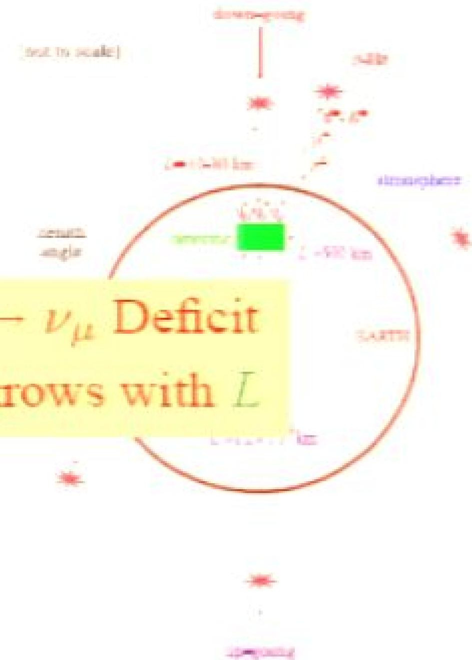
ν_e in agreement with SM



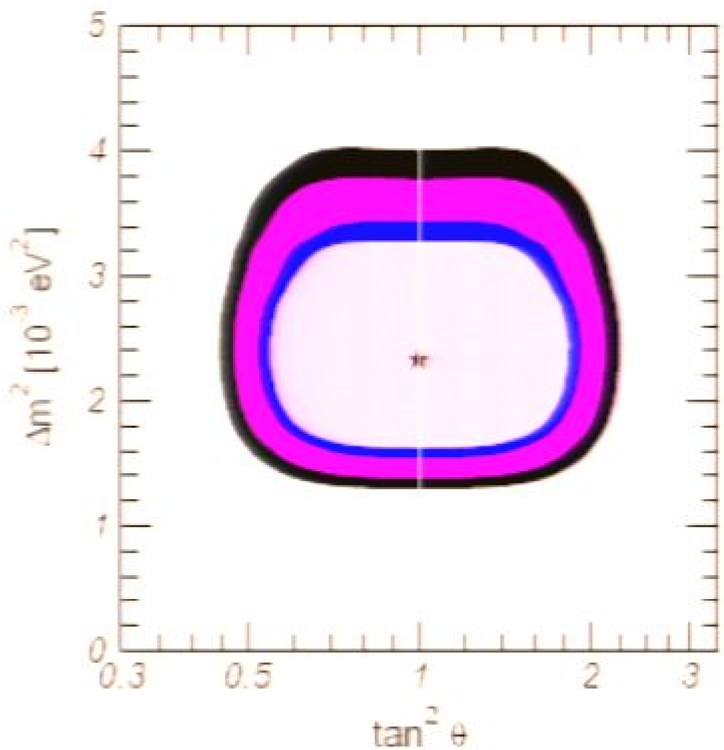


→ ν_μ Deficit grows with L

→ ν_μ Deficit decreases with E

Atmospheric Neutrinos: Oscillation Solutions

- $\nu_\mu - \nu_\tau$: best channel



Best fit

$\Delta m^2 = 2.35 \times 10^{-3}\ \mathrm{eV}^2$

$\tan^2\theta = 1$

ATM Test at Long Baseline Experiments

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K2K	ν_μ at KEK	SK	L=250 km
MINOS	ν_μ at Fermilab	Soundan	L=735 km
Opera	ν_μ at CERN	Gran Sasso	L=740 km

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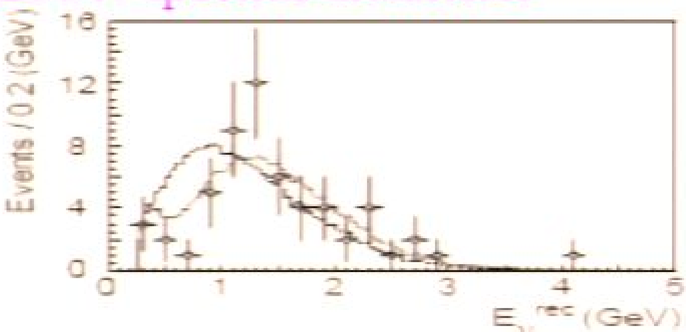
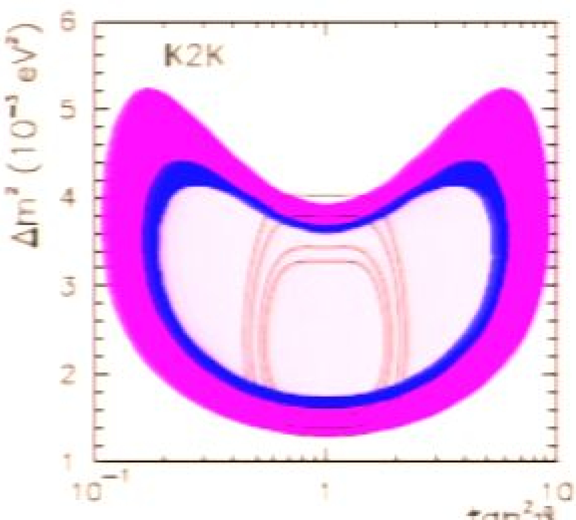
K2K 2004: spectral distortion



Confirmation of ATM oscillations



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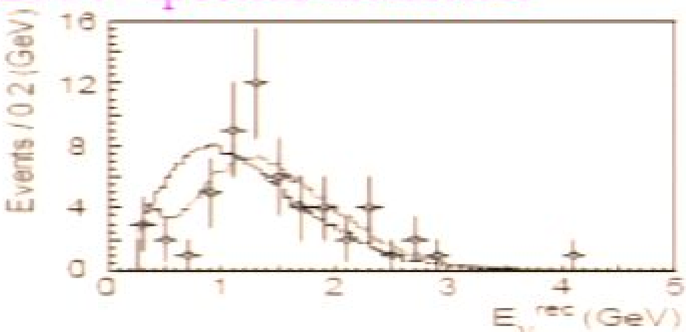
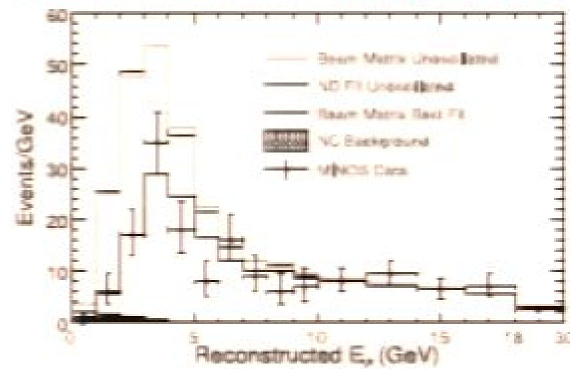


MINOS 2006-2008: spectral distortion



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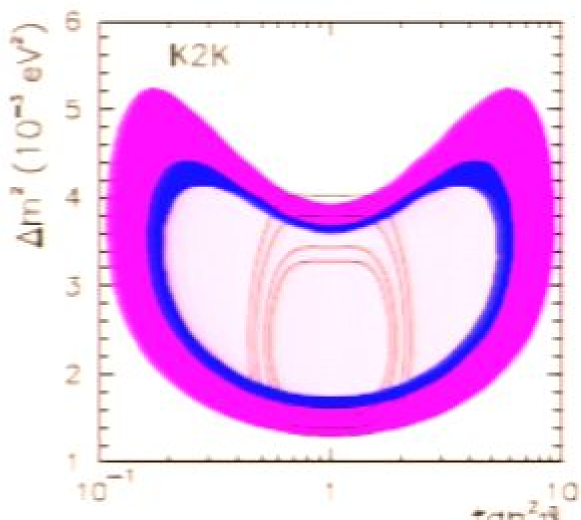
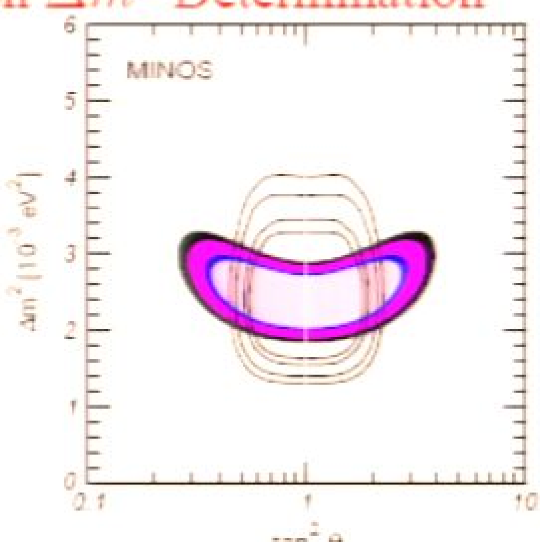


Impact on Δm^2 Determination



Solar Neutrinos: Fluxes

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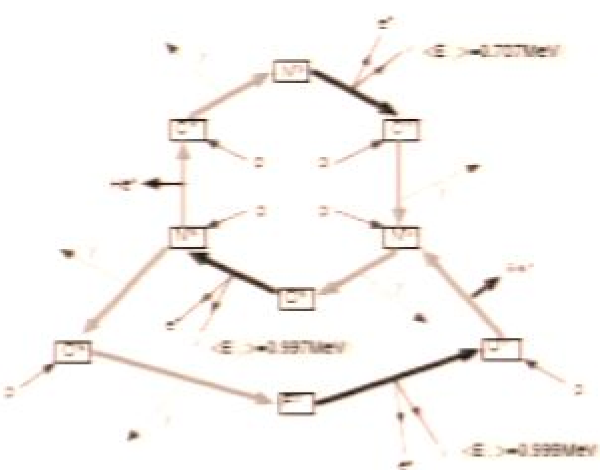
pp chain

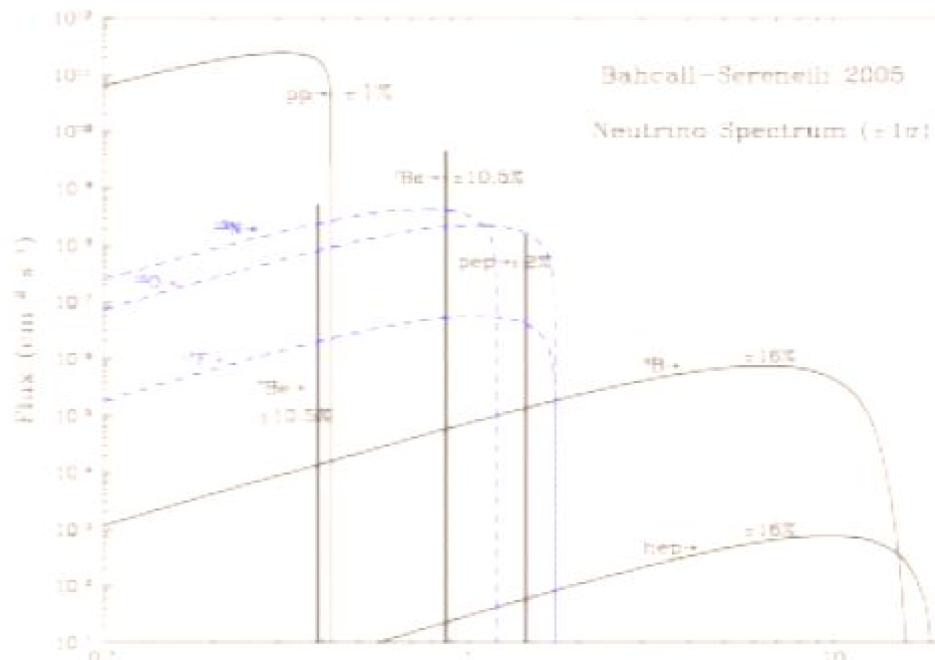
CNO cycle



- Sun shines by :

$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + \gamma$$

Solar Standard Model Fluxes



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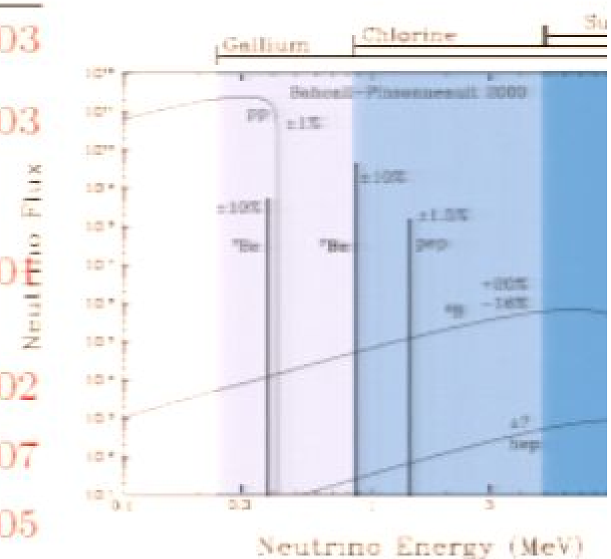
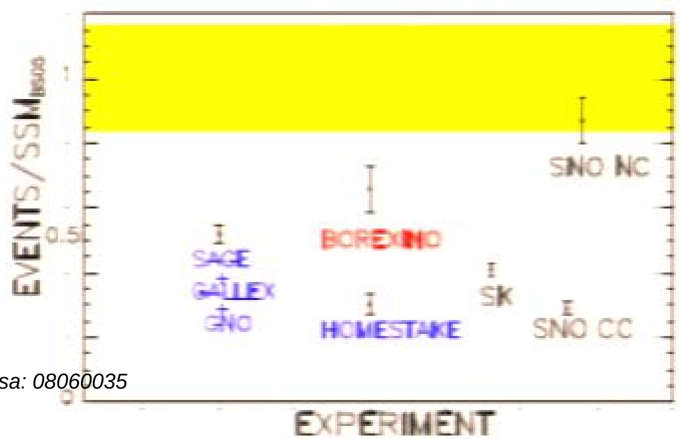
Solar Neutrinos: Data

	Experiment	Detection	Flavour	E_{th} (MeV)	$\frac{\text{Data}}{\text{BS05}}$
radio-chemical	Homestake	$^{37}Cl(\nu, e^-)^{37}Ar$	ν_e	$E_\nu > 0.81$	0.30 ± 0.03
	Sage + Gallex+GNO	$^{71}Ga(\nu, e^-)^{71}Ge$	ν_e	$E_\nu > 0.23$	0.52 ± 0.03
real time	Kam ⇒ SK	ES $\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$ $\left(\frac{\sigma_{\mu\tau}}{\sigma_e} \simeq \frac{1}{6}\right)$	$E_e > 5$	0.41 ± 0.01
	SNO	CC $\nu_e d \to p p e^-$	ν_e	$T_e > 5$	0.29 ± 0.02
		NC $\nu_x d \to \nu_x p\, n$	$\nu_e, \nu_{\mu/\tau}$	$T_\gamma > 5$	0.87 ± 0.07
		ES $\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$	$T_e > 5$	0.41 ± 0.05
	Borexino	$\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$	$E_\nu = 0.862$	0.66 ± 0.07





All experiments measuring mostly ν_e observed a deficit

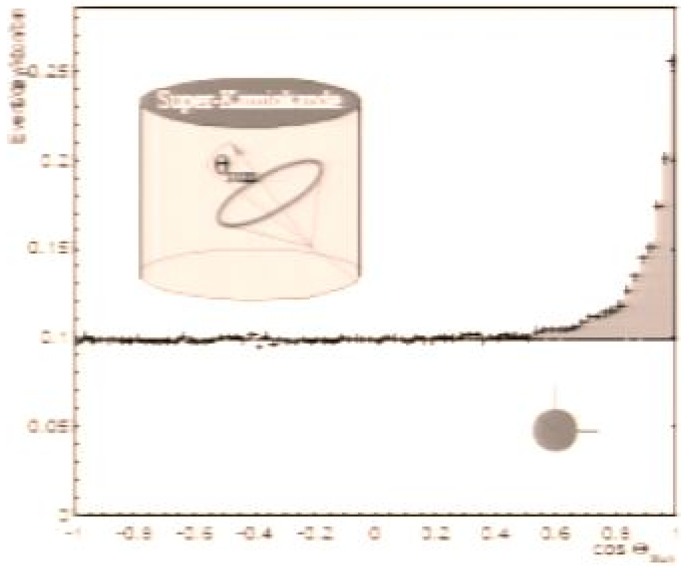
Deficit is energy dependent

Deficit disappears in NC

- Real Time experiments can also give information on Energy and Direction of $\nu's$ and can search for Energy and Time variations of the effect

ν's come from the SUN

- From SK (Confirmed by SNO)



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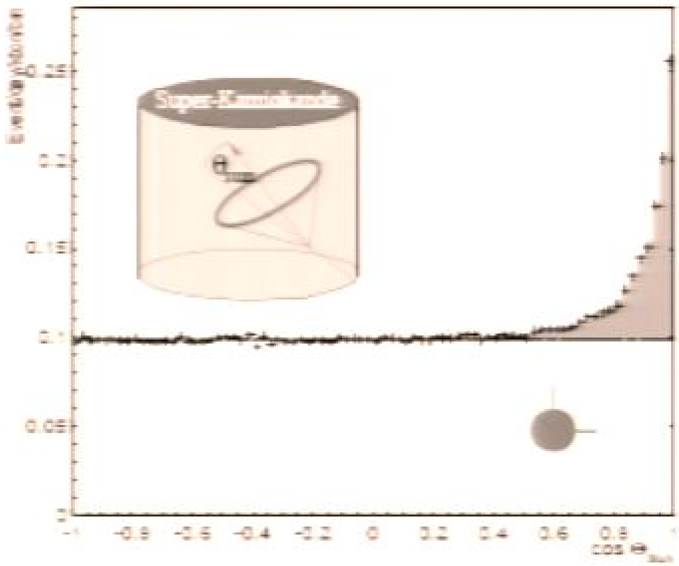
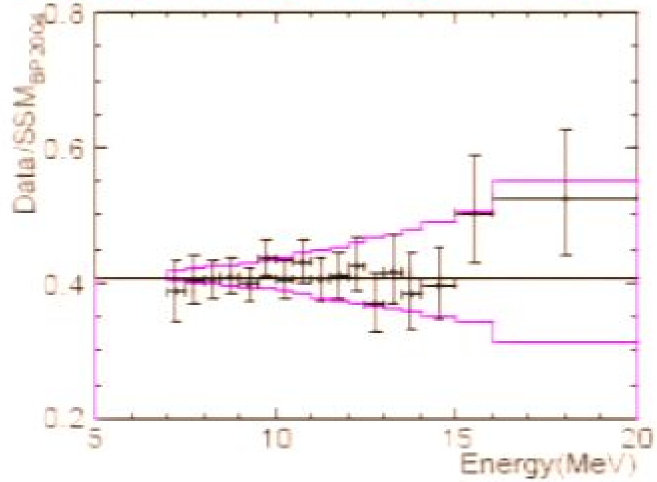


No Energy Distortion

Deficit indep $E_\nu \gtrsim 5$ MeV



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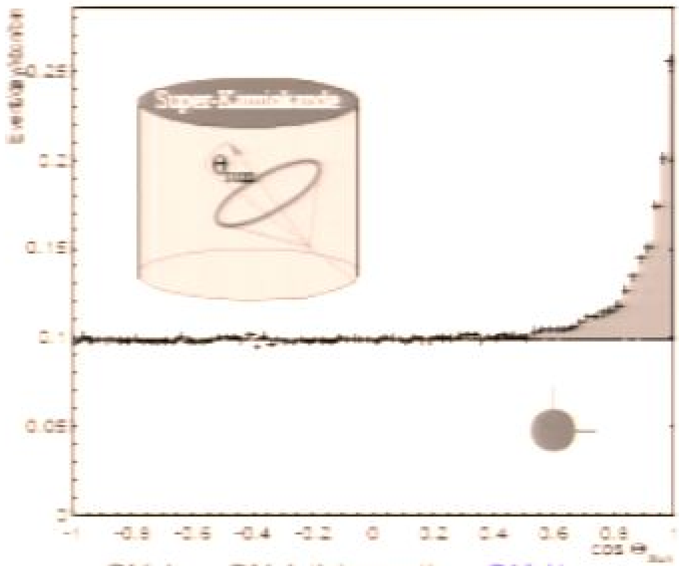

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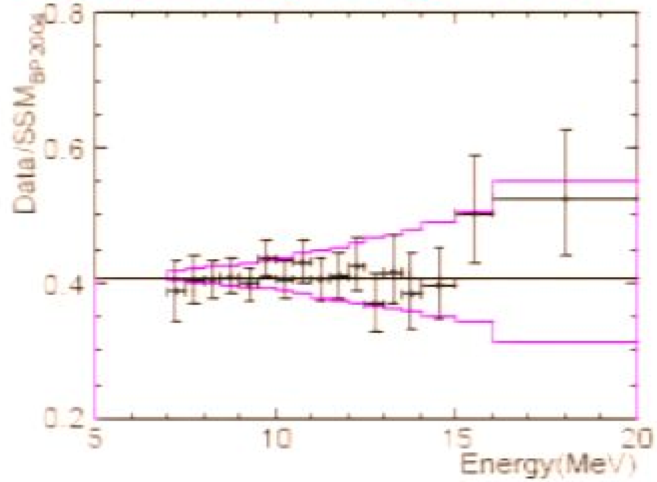

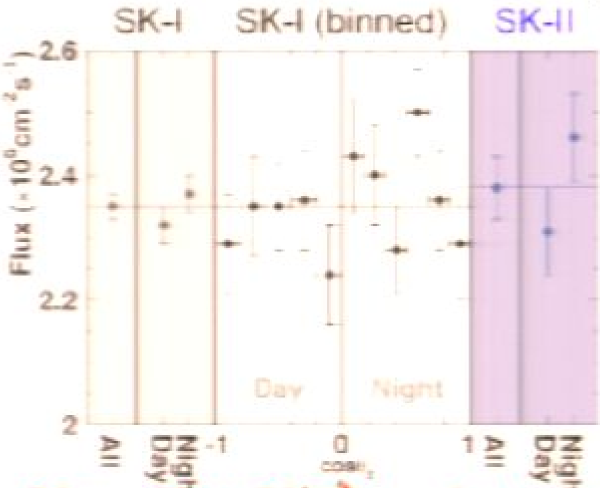

No Day-Night Asymmetry

$2\frac{N-D}{\ldots} = 0.021 \pm 0.025$

- Real Time experiments can also give information on Energy and Direction of $\nu's$ and can search for Energy and Time variations of the effect

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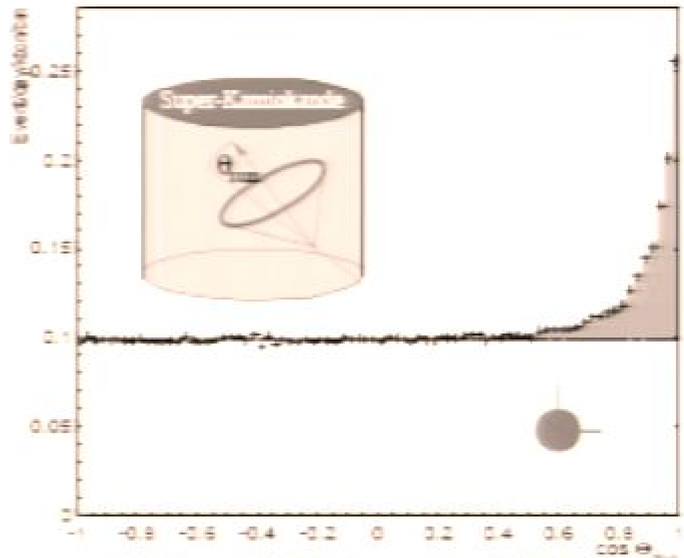

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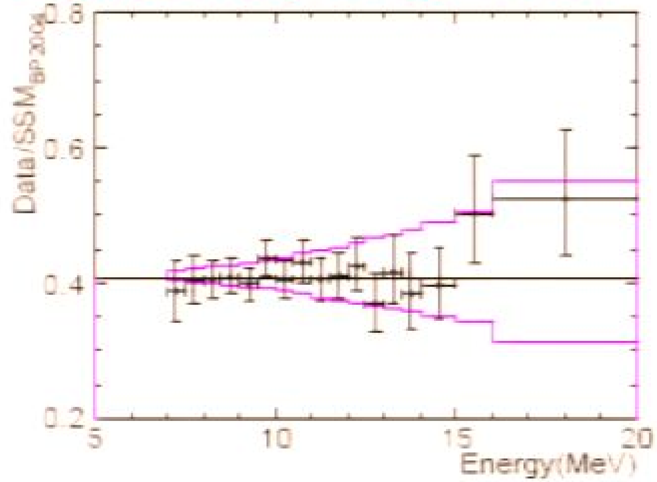

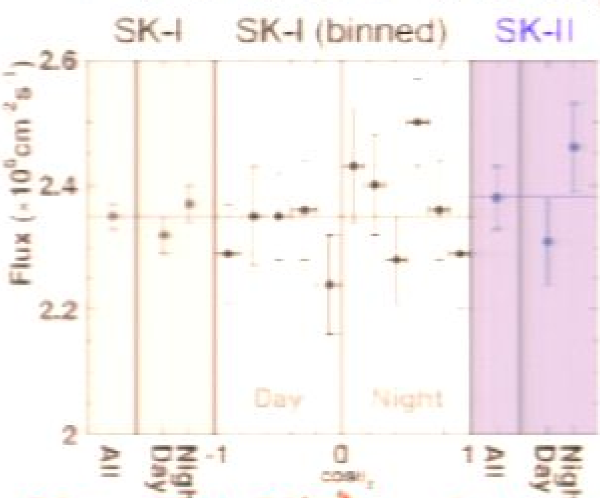

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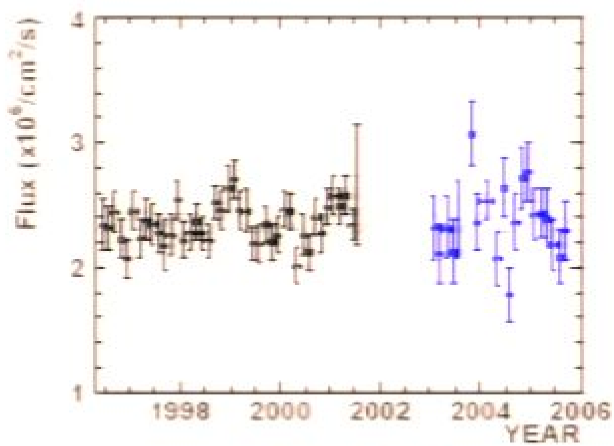
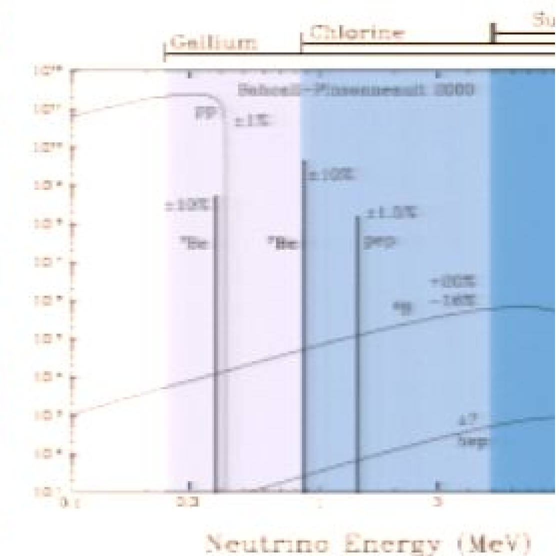


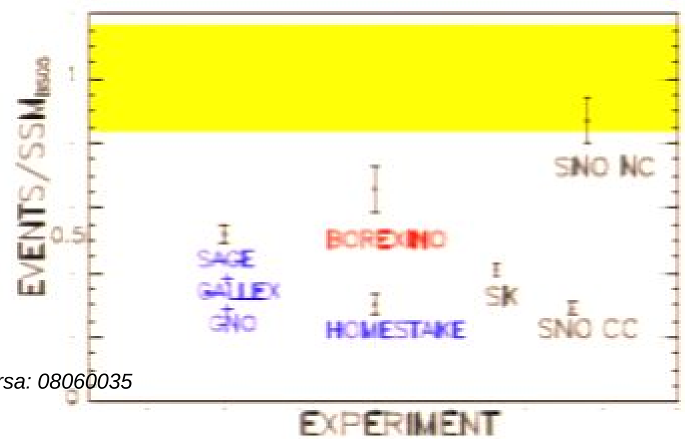
Seasonal Variation

Concha Gonzalez-Garcia

Solar Neutrinos: Data

	Experiment	Detection	Flavour	E_{th} (MeV)	$\frac{\text{Data}}{\text{BS05}}$
radio-chemical	Homestake	$^{37}Cl(\nu, e^-)^{37}Ar$	ν_e	$E_\nu > 0.81$	0.30 ± 0.03
	Sage + Gallex+GNO	$^{71}Ga(\nu, e^-)^{71}Ge$	ν_e	$E_\nu > 0.23$	0.52 ± 0.03
real time	Kam ⇒ SK	ES $\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$ $\left(\frac{\sigma_{\mu\tau}}{\sigma_e} \simeq \frac{1}{6}\right)$	$E_e > 5$	0.41 ± 0.01
	SNO	CC $\nu_e d \to p p e^-$	ν_e	$T_e > 5$	0.29 ± 0.02
		NC $\nu_x d \to \nu_x p n$	$\nu_e, \nu_{\mu/\tau}$	$T_\gamma > 5$	0.87 ± 0.07
		ES $\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$	$T_e > 5$	0.41 ± 0.05
	Borexino	$\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$	$E_\nu = 0.862$	0.66 ± 0.07





All experiments measuring mostly ν_e observed a deficit

Deficit is energy dependent

Deficit disappears in NC

- Real Time experiments can also give information on Energy and Direction of $\nu's$ and can search for Energy and Time variations of the effect

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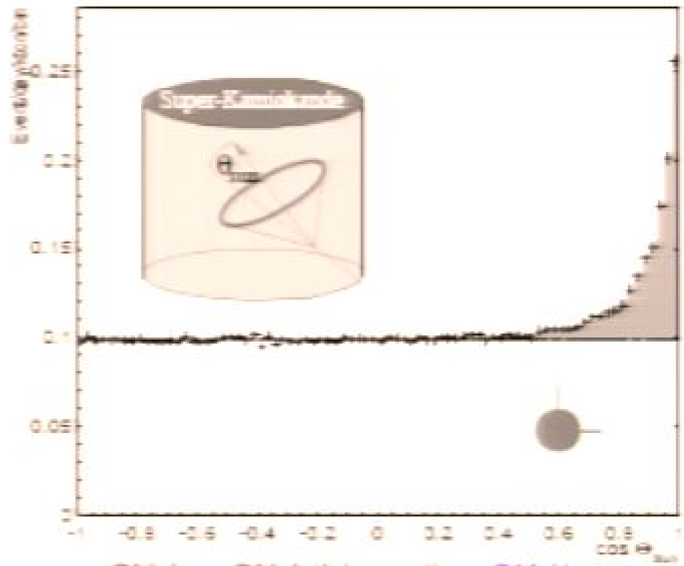

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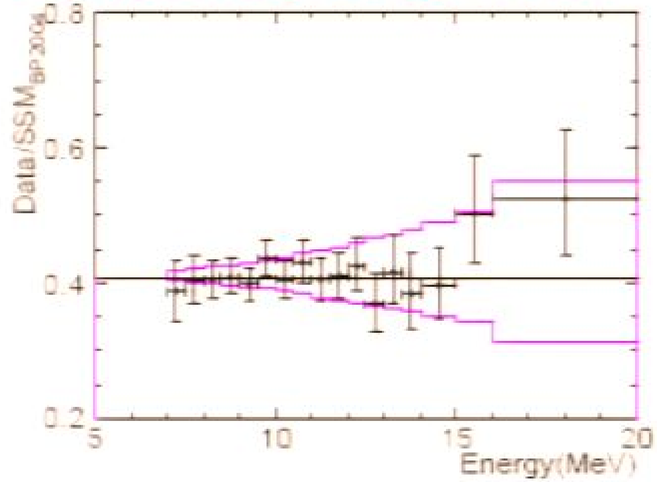

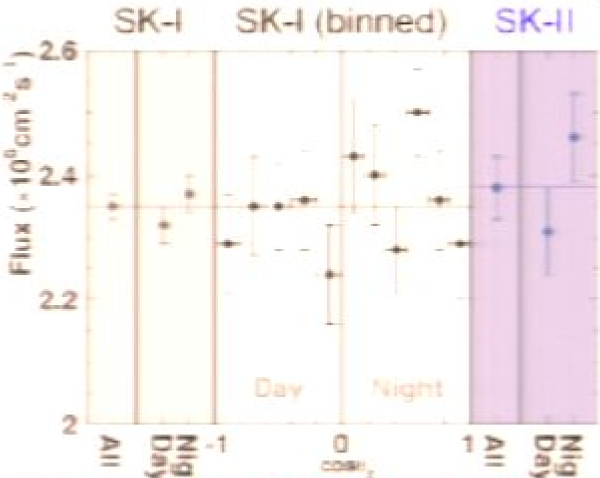

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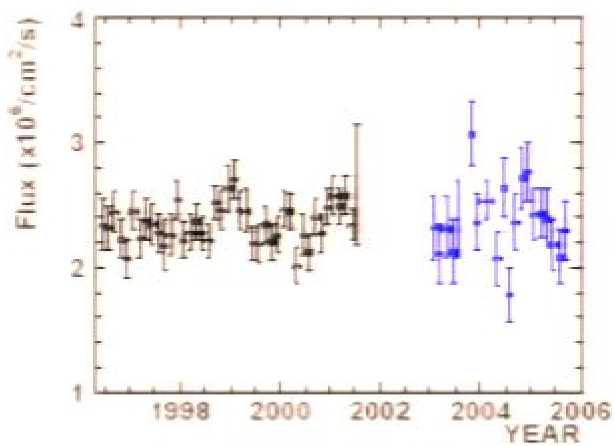

Seasonal Variation

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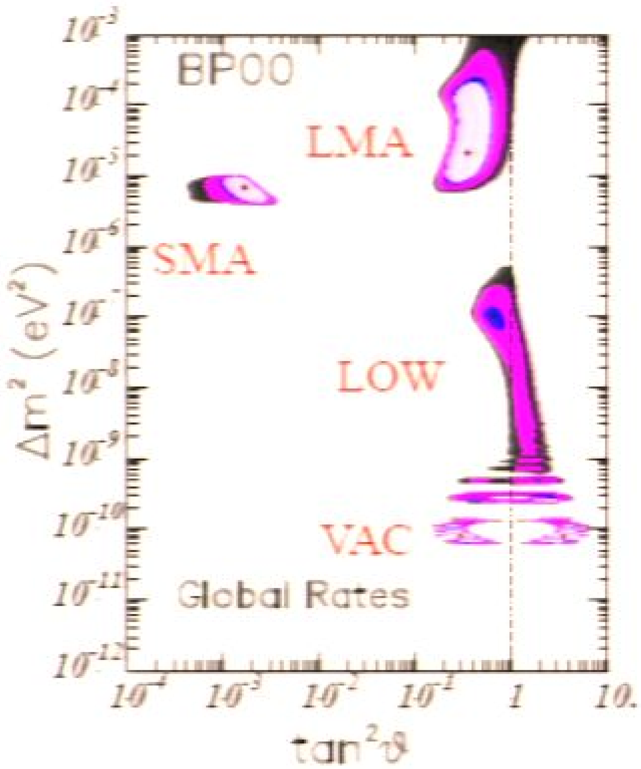
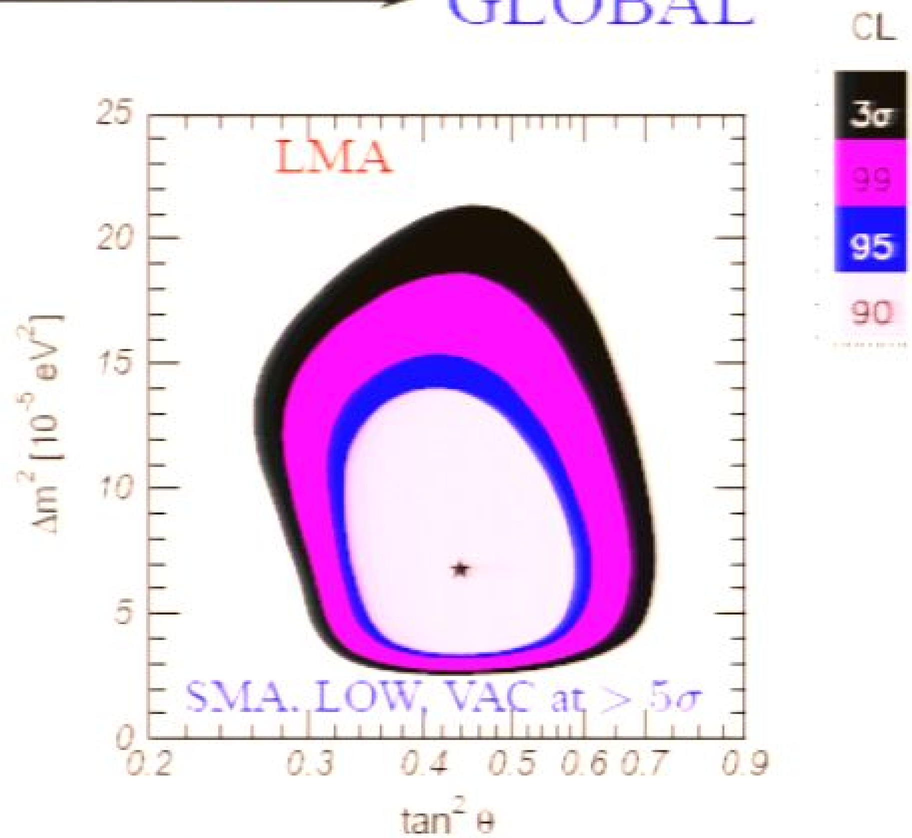
Solar Neutrinos: Oscillation Solutions

RATES ONLY —SK and SNO E and t dependence→ GLOBAL





Best fit

$\Delta m^2 = 6.8 \times 10^{-5}$ eV^2

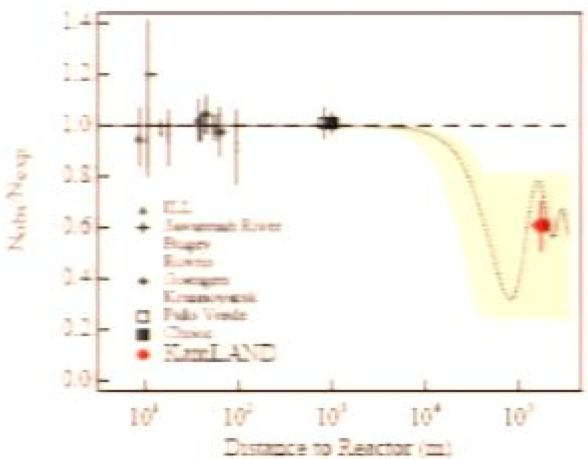
$\tan^2\theta = 0.43$

Terrestrial Test of LMA: KamLAND

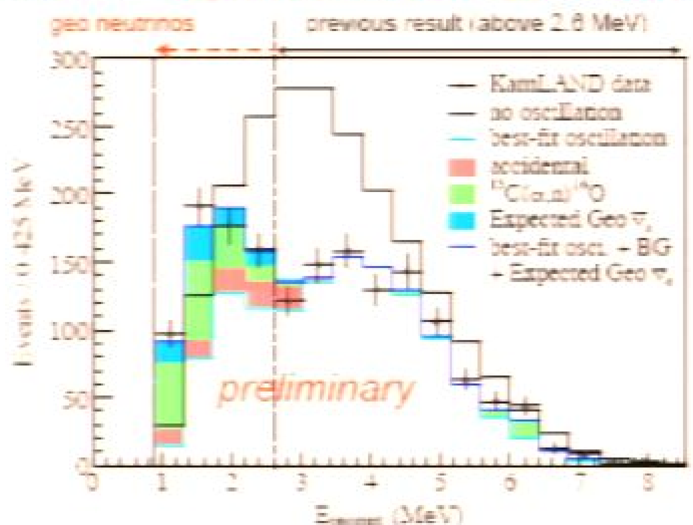
Gonzalez-Garcia

- Search on $\overline{\nu_e}$ at L ~ 180 km reactors. $E_{\bar\nu}$ ~ few MeV: $\bar\nu_e + p \to n + e^+$

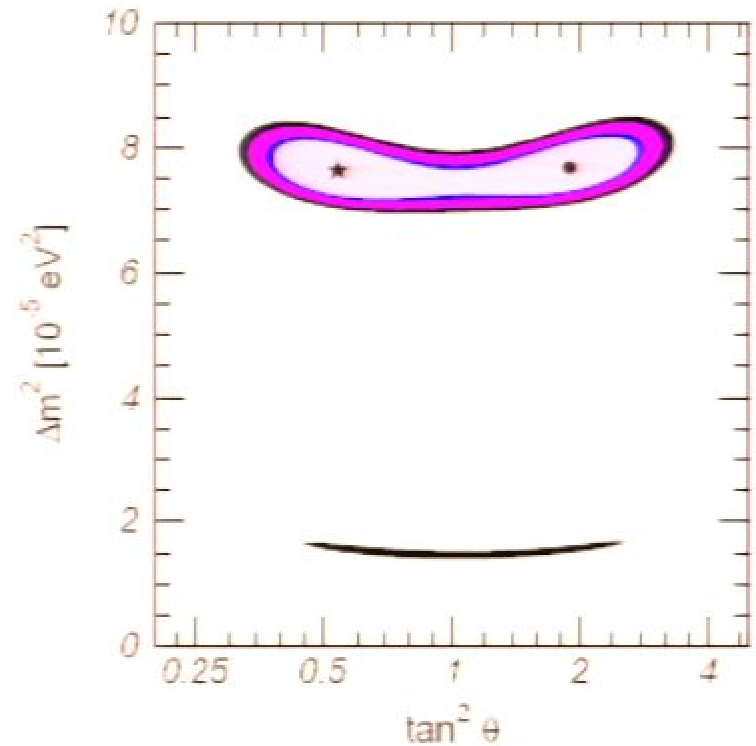
2002: Deficit $R_{\rm KLAND} = 0.611 \pm 0.094$



2004-2008: Significant Energy Distortion



Oscillation Analysis



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$\Delta m^2 = 7.7 \times 10^{-5}$ eV^2

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Concha Gonzalez-Garcia

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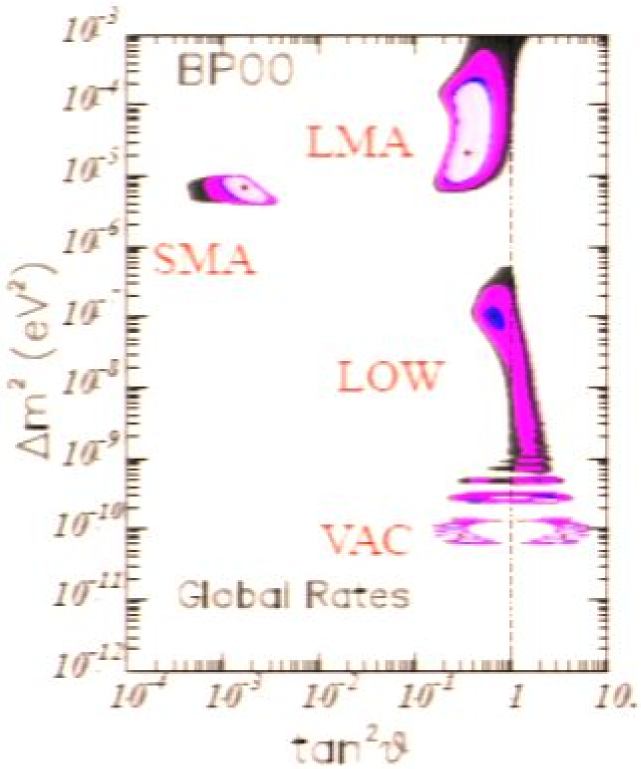

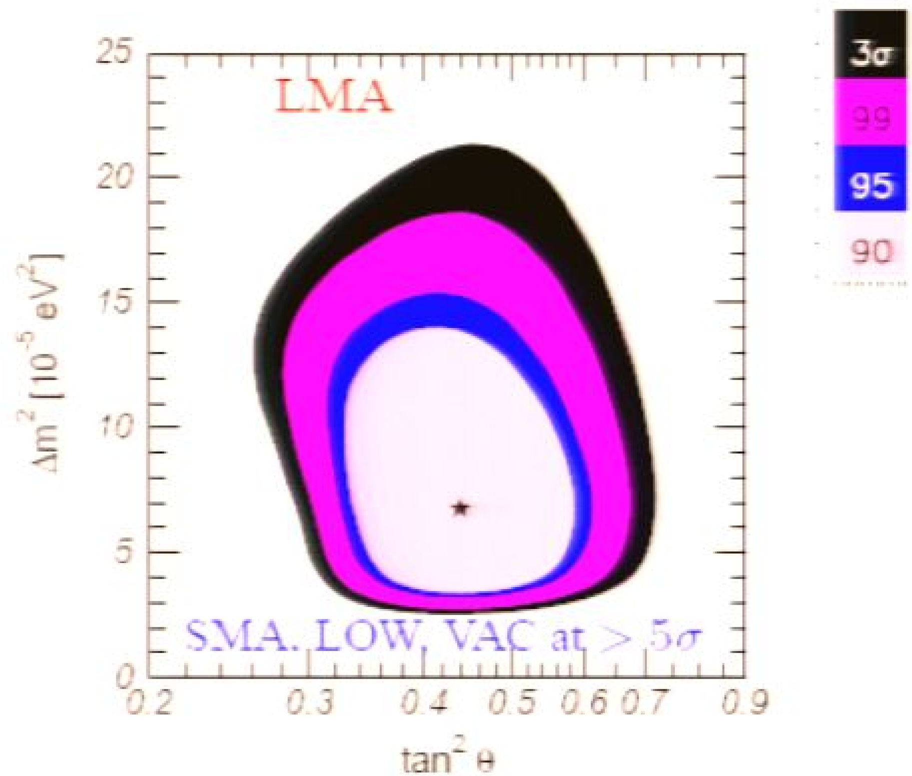

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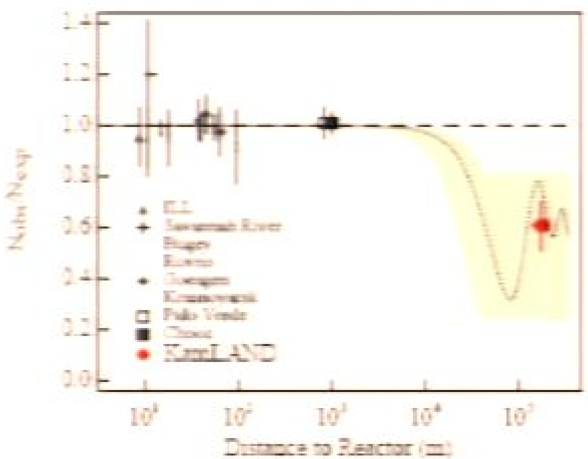

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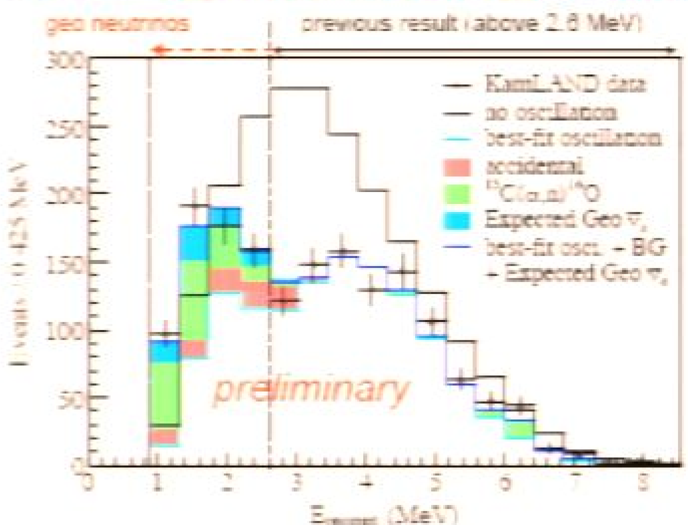

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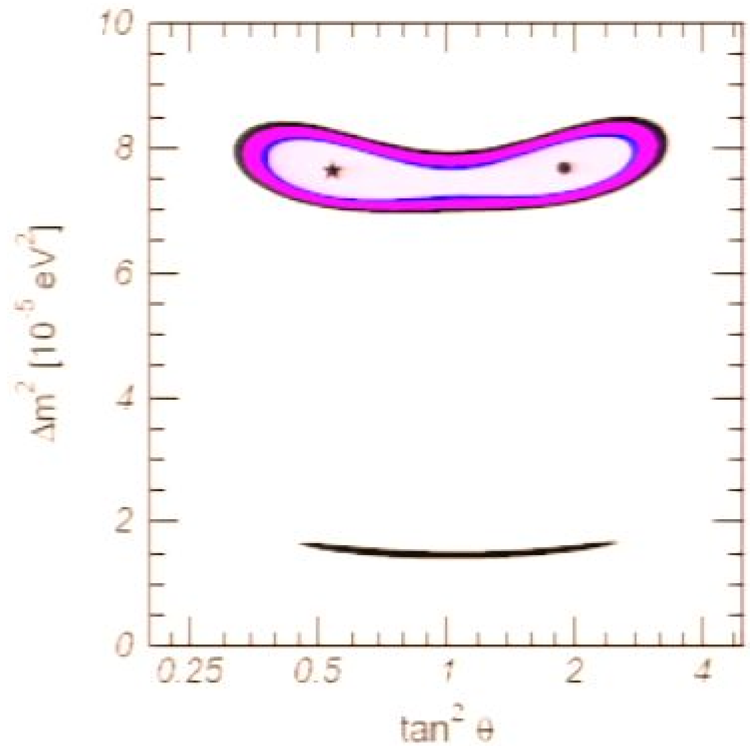

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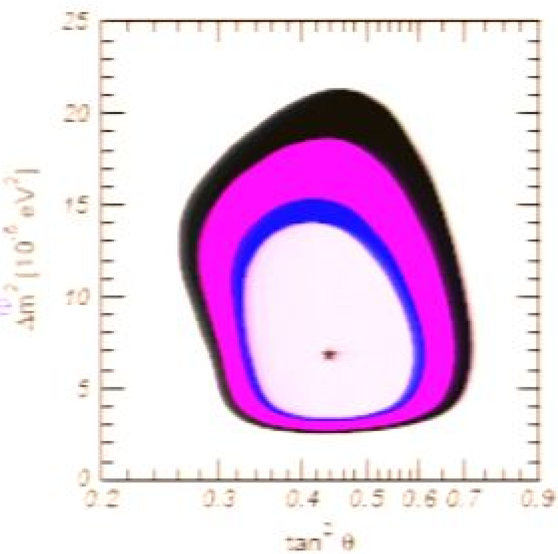
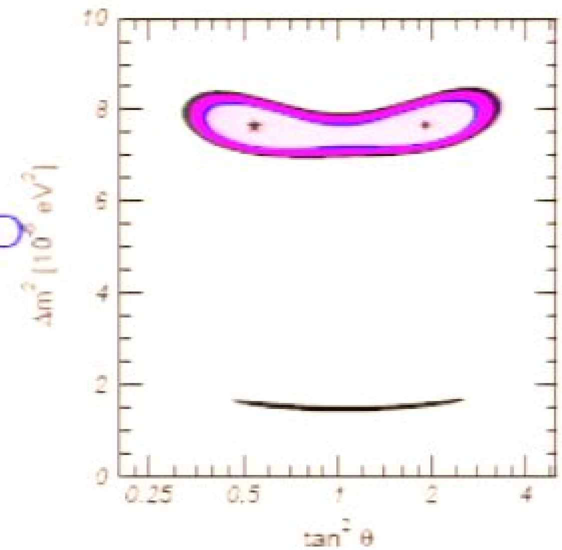
Solar

$\nu_e \to \nu_{\text{active}}$



– KamLAND

$\bar{\nu}_e \not\to \bar{\nu}_e$



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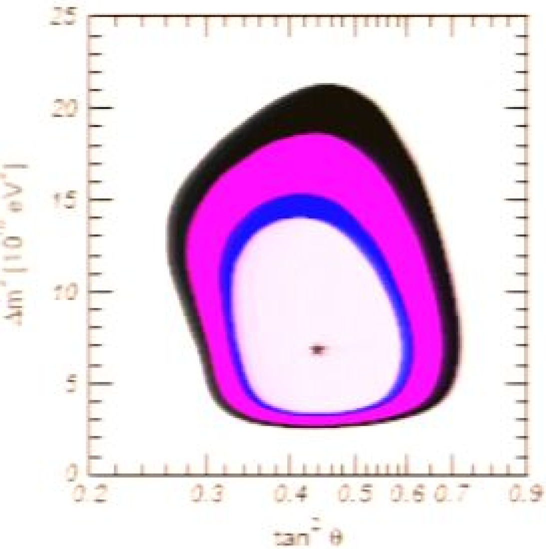

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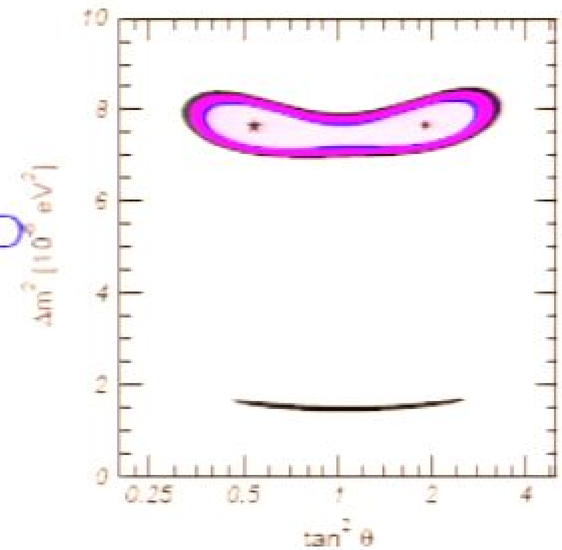
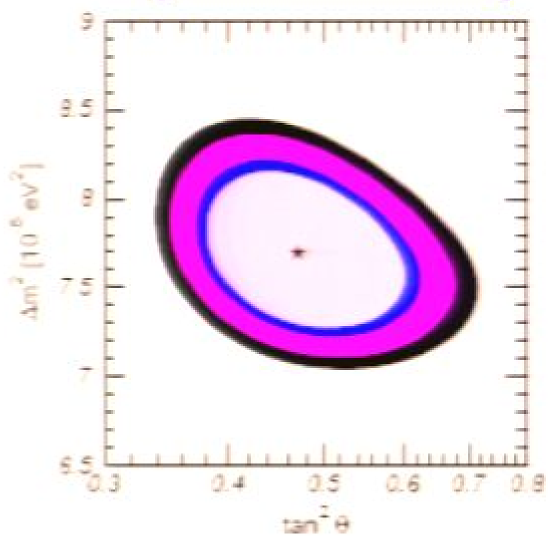


ν_e oscillation parameters compatible with $\overline{\nu}_e$: *Sensible* to assume CPT: $P_{ee} = P_{\bar{e}\bar{e}}$



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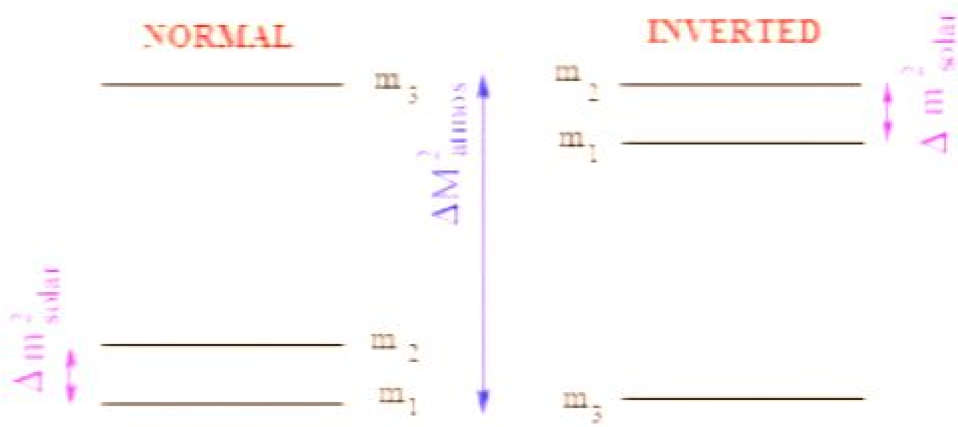
Solar+Atmospheric+Reactor+LBL 3ν Oscillations

U: 3 angles, 1 CP-phase
+ (2 Majorana phases)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Two mass schemes



2ν oscillation analysis $\Rightarrow \Delta m^2_{21} = \Delta m^2_{\odot} \ll \Delta M^2_{atm} \simeq \pm\Delta m^2_{32} \simeq \pm\Delta m^2_{31}$

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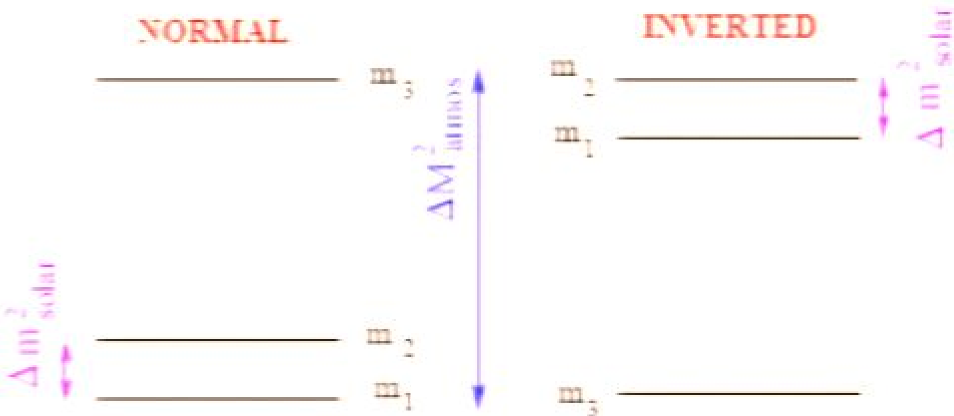
Two mass schemes



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Generic 3ν mixing effects:

– Effects due to θ_{13}

– Difference between Inverted and Normal

– Interference of two wavelength oscillations

– CP violation due to phase δ

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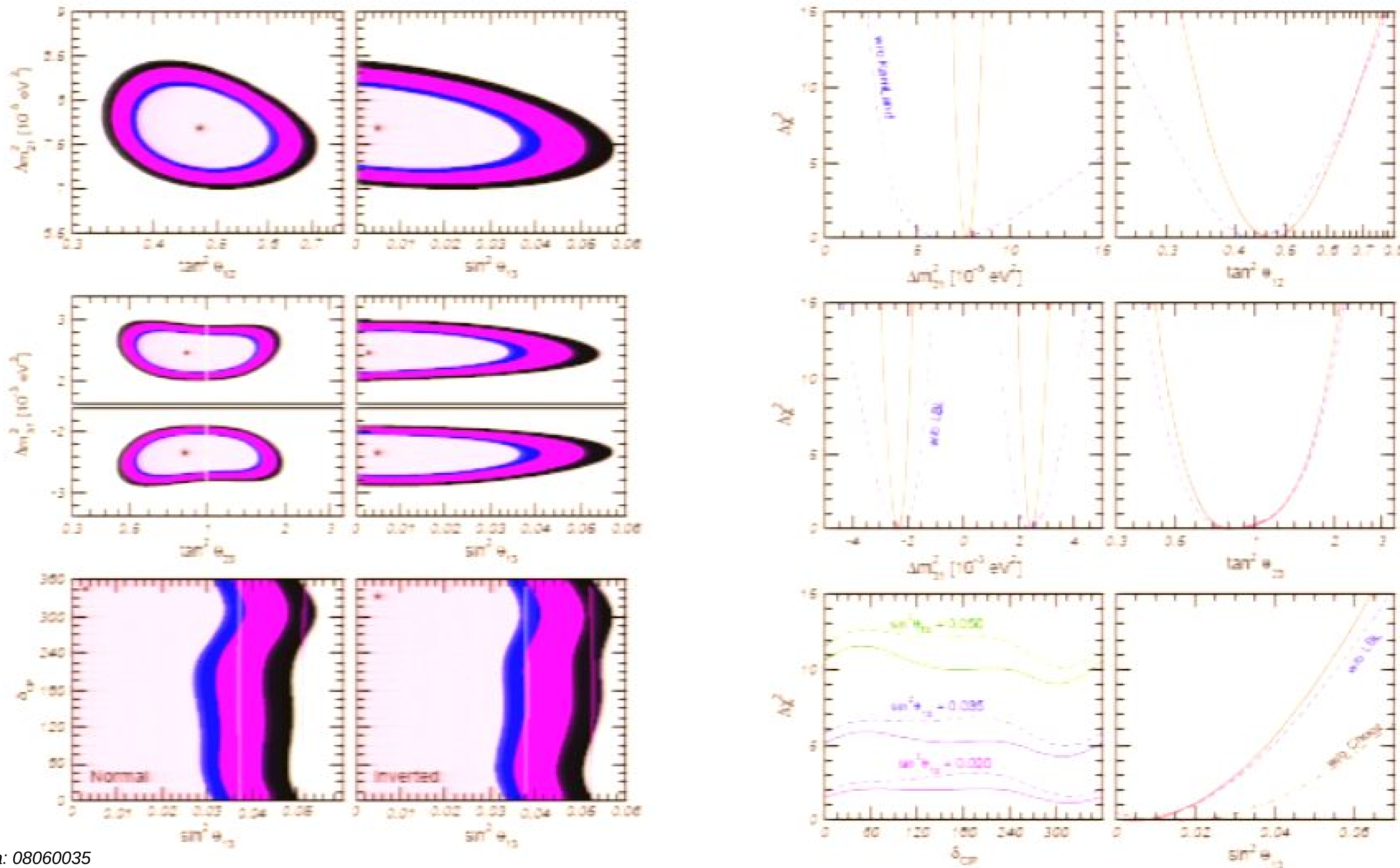
Global Analysis: Three Neutrino Oscillations

M.C. G-G. M.Maltoni. Phys. Rep. (2008)



Global Analysis: Three Neutrino Oscillations

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The derived ranges for the six parameters at 1σ (3σ) are:

$$\Delta m^2_{21} = 7.7\,^{+0.22}_{-0.21}\ \left(^{+0.67}_{-0.61}\right) \times 10^{-5}\ \mathrm{eV}^2 \qquad \left|\Delta m^2_{31}\right| = 2.37 \pm 0.17\,(0.46) \times 10^{-3}\ \mathrm{eV}^2$$

$$\theta_{12} = 34.5 \pm 1.4\ \left(^{+4.8}_{-4.0}\right) \qquad \theta_{23} = 42.3\,^{+5.1}_{-3.3}\ \left(^{+11.3}_{-7.7}\right)$$

$$\theta_{13} = 0\,^{+7.9}_{-0.0}\ \left(^{+12.9}_{-0.0}\right) \qquad \delta_{CP} \in [0,\ 360]$$

$$|U|_{3\sigma} = \begin{pmatrix} 0.77 - 0.86 & 0.50 - 0.63 & 0.00 - 0.22 \\ 0.22 - 0.56 & 0.44 - 0.73 & 0.57 - 0.80 \\ 0.21 - 0.55 & 0.40 - 0.71 & 0.59 - 0.82 \end{pmatrix}$$

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Open Questions

We still ignore:

(1) Is $\theta_{13} \neq 0$? How small?

(2) Is $\theta_{23} = \frac{\pi}{4}$? If not, is it $>$ or $<$?

(3) Is there CP violation in the leptons (is $\delta \neq 0, \pi$)?

(4) What is the ordering of the neutrino states?

(5) Are neutrino masses:

hierarchical: $m_i - m_j \sim m_i + m_j$?

degenerated: $m_i - m_j \ll m_i + m_j$?

(6) Dirac or Majorana?

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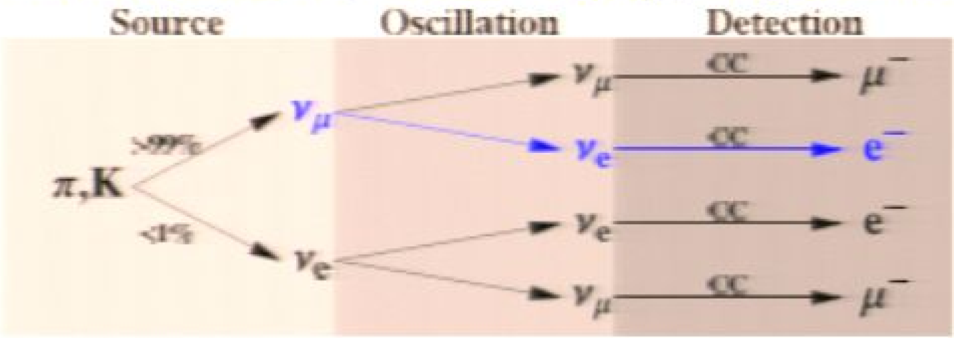
Future Experimental Set-ups: Next Decade(s)

- Conventional (=from π decay) Superbeams



	Exp	L	$\langle E \rangle$
Off-Axis	T2K (Japan, 2010)	295 km	0.76 GeV
	Noνa (Fermilab)	812 km	2.22 GeV

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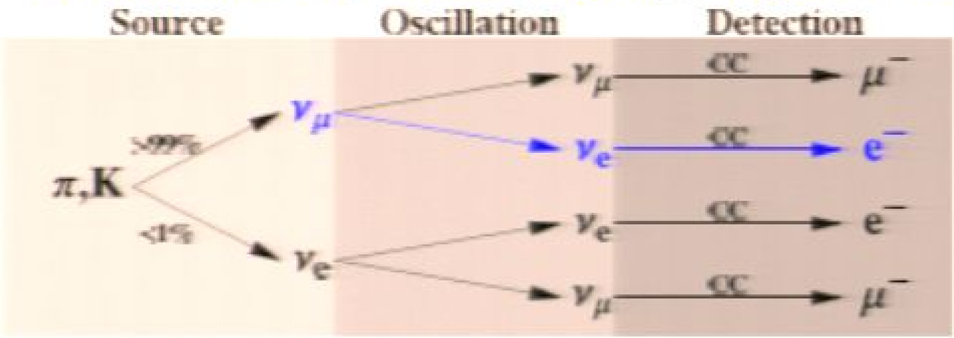

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- Reactor Experiment with 2 Detectors [only θ_{13}]

$$P(\nu_e \to \nu_e) \simeq 1 - \sin^2 2\theta_{31} \sin^2\left(\frac{\Delta_{31} L}{2}\right)$$

CHOOZII (France, 2009-11)

Daya-Bay (China, 2011)

$\langle E\rangle \sim 4$ MeV $\quad L \sim 1$–2 km

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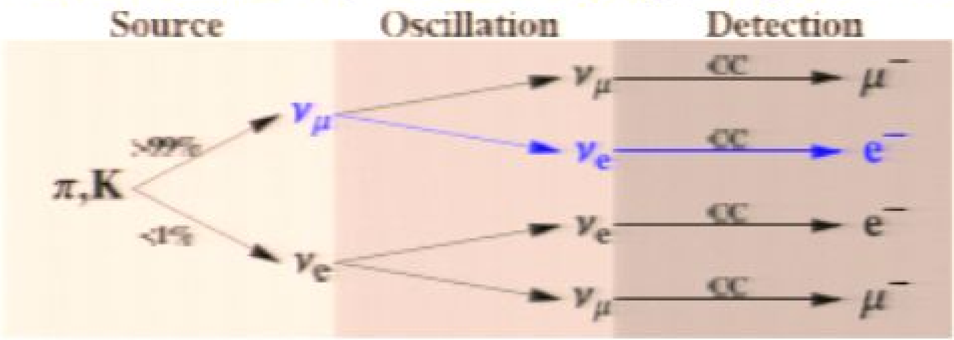

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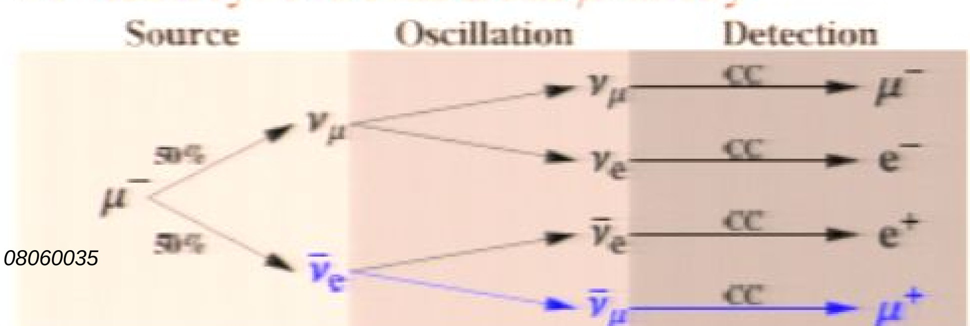
CHOOZII (France, 2009-11)

Daya-Bay (China, 2011)

$\langle E \rangle \sim 4$ MeV $\quad L \sim 1$–2 km

- β-beam : Beam of pure ν_e or $\overline{\nu}_e$ from radioactive ion decay: $^6_2He^{++} \to ^6_3 Li^{++}\, e^- \,\overline{\nu}_e$

- ν-factory: ν beam from μ decay



$\langle E \rangle \sim 20$–$50$ GeV

$L \sim 700$–7000 km

Neutrino Mass Scale: Tritium β Decay

- Fermi proposed a kinematic search of ν_e mass from beta spectra in ^3H beta decay

$$^3H \rightarrow ^3He + e + \overline{\nu}_e$$

- For "allowed" nuclear transitions, the electron spectrum is given by phase space alone

$$K(T) \equiv \sqrt{\frac{dN}{dT}\frac{1}{C\,p\,E\,F(E)}} \propto \sqrt{(Q-T)\sqrt{(Q-T)^2 - m_\nu^2}}$$

$T = E_e - m_e$, Q= maximum kinetic energy. (for ^3H beta decay $Q = 18.6$ KeV)

- $m_\nu \neq 0 \Rightarrow$ distortion from the straight-line at the end point of the spectrum

$$m_\nu = 0 \;\Rightarrow\; T_{\max} = Q$$
$$m_\nu \neq 0 \;\Rightarrow\; T_{\max} = Q - m_\nu$$

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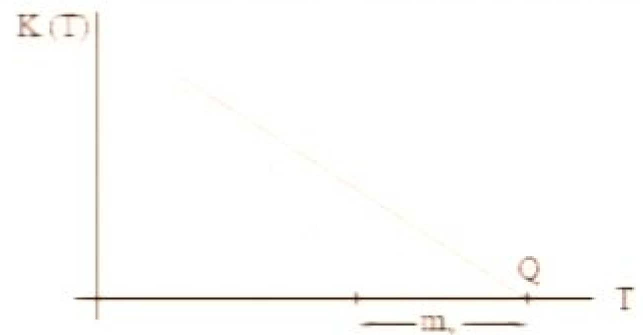

– At present only a bound: $m^3_{eff} \equiv \sqrt{\sum m_j^2 |U_{ej}|^2} < 2.2$ eV (at 95 % CL)
(Mainz & Troisk experiments)

– Katrin (starting 2009) proposed to improve present sensitivity to $m^3_{eff} \sim 0.3$ eV

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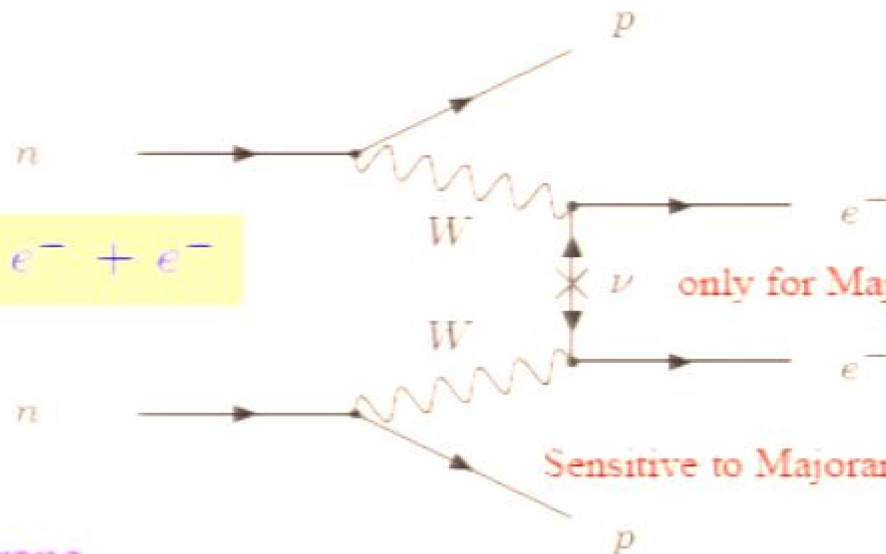
Neutrino Mass Scale: ν-less Double-β Decay

$(A, Z) \to (A, Z+2) + e^- + e^-$



- ν-less-$\beta\beta$ $\Leftrightarrow$ ν is Majorana
- But Majorana m_ν maybe not unique source of L breaking
- If only Majorana $m_\nu \Rightarrow (T^{0\nu}_{1/2})^{-1} = \frac{1}{m_e^2} G^{0\nu} |M^{0\nu}|^2 \langle m_{ee} \rangle^2$ with

$$\langle m_{ee} \rangle = |\sum U_{ej}^2 m_j|$$

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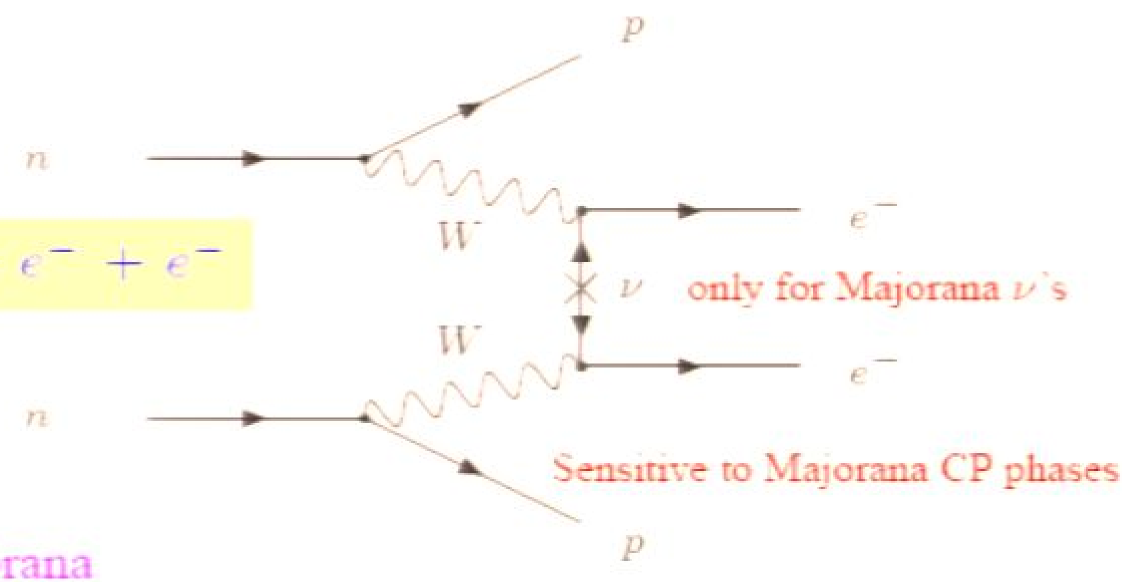

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Neutrino Mass Scale: ν-less Double-β Decay

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$$T^{0\nu}_{1/2} = 2.3^{+0.44}_{-0.31} \times 10^{25} \text{ yrs}$$

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- A new experiment, Cuorecino, has reported for ^{130}Te

$$T^{0\nu}_{1/2} > 2.5 \times 10^{25} \text{yrs (95\% CL)}$$

Within some theoretical models for nuclear matrix elements and uncertainties

$$\Downarrow$$

$$0.16 \leq m_{\beta\beta}/\text{eV} \leq 0.52 \qquad Evidence$$

$$0 \leq m_{\beta\beta}/\text{eV} \leq 0.23\text{–}0.85 \quad \text{Cuorecino}$$

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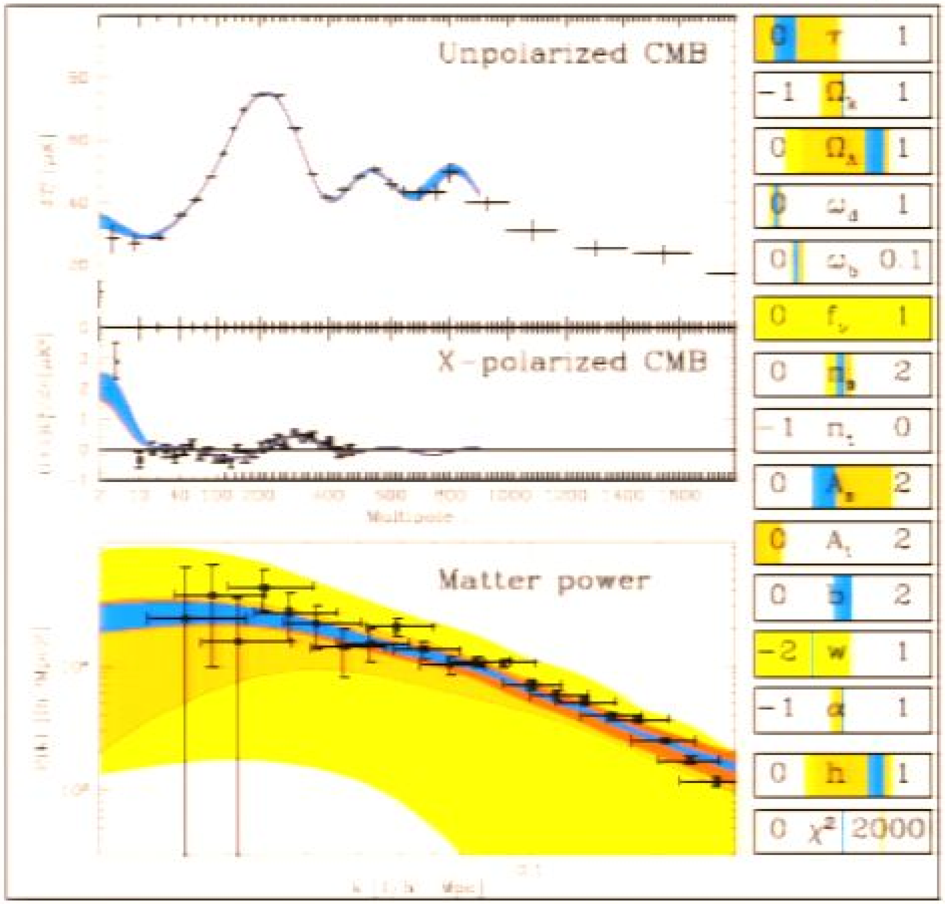
Neutrino Mass Scale in Cosmology

$\sum m_{\nu_i}$ has effects on:

Cosmic Microwave Background Temperature Fluctuations

Large scale structures



Problem: ∼ 10 parameters to be determined!!

⇒ limit on $\sum m_{\nu_i}$ depends on prior and data used to constraint other parameters

$\sum m_{\nu_i} \leq 0.2 - 1.3$ eV at 95 % CL

Fogli et al., 0805.2517

Learning How the Sun Shines

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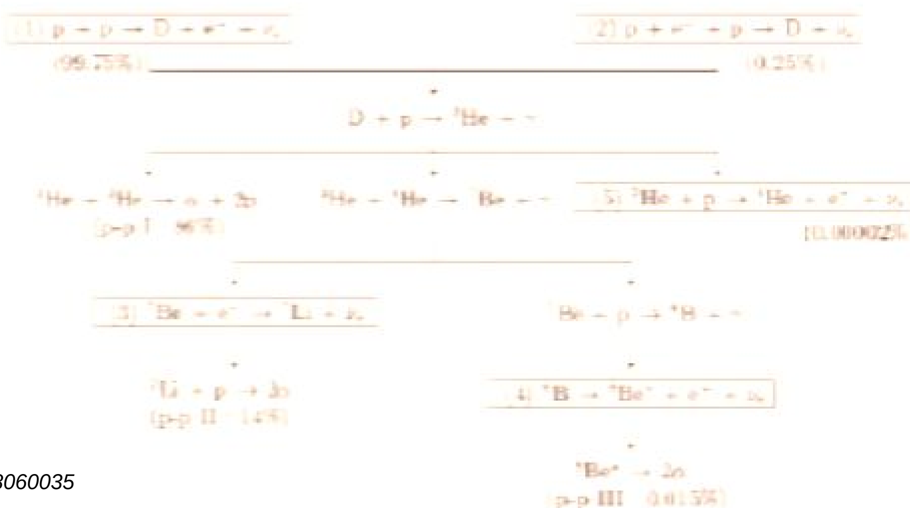
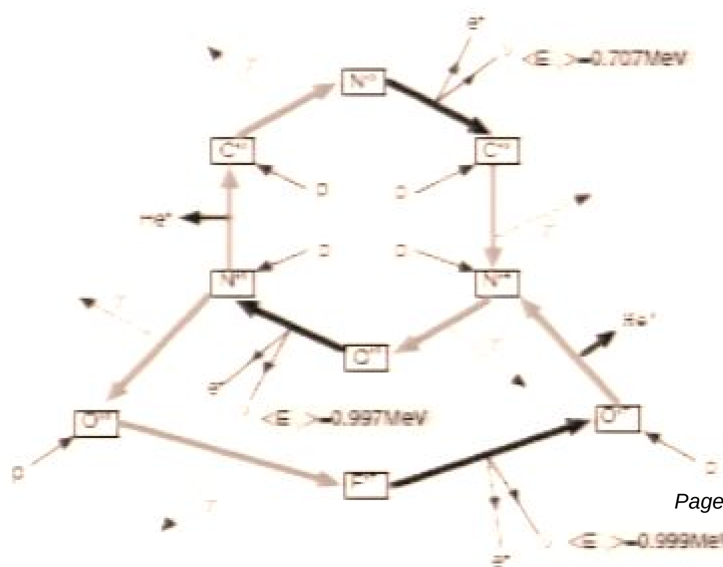
- The Sun shines converting protons into α, e^+ and $\nu's$

$4p \to {}^4He + 2e^+ + 2\nu_e + \gamma$

$4m_p - m_{^4He} - 2m_e \simeq 26$ MeV Thermal energy mostly in γ

pp chain: CNO cycle:





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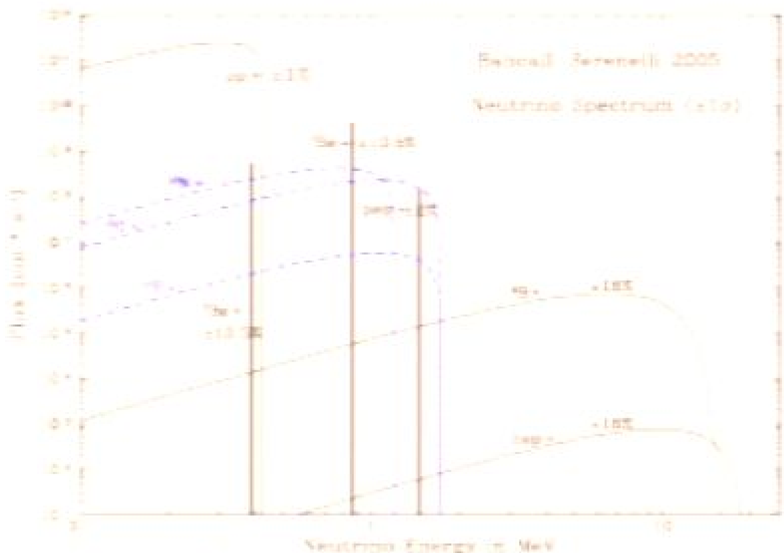
- SSM Fluxes



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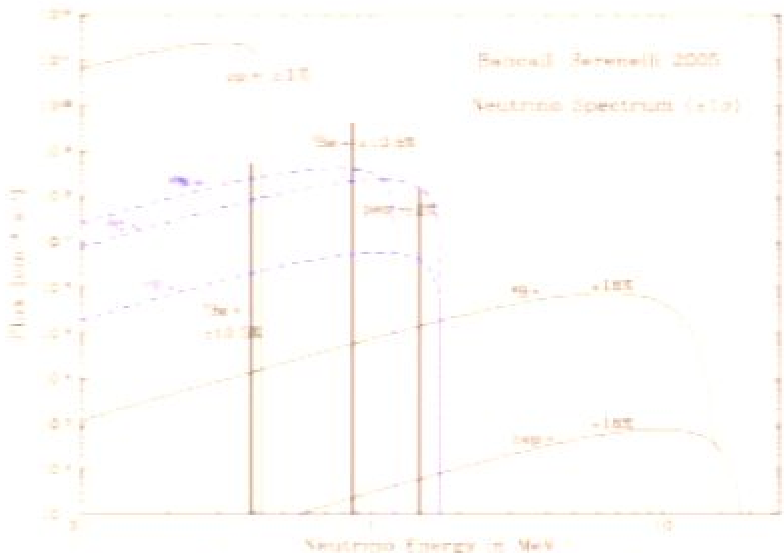

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- Can this be tested experimentally? Difficult

 – Radiochemical experiments sensitive to CNO fluxes
 But do not measure $E \Rightarrow$ only integrated flux above E_{th}
 – Oscillations modify the E dependence of detected fluxes
 – Possible suppression of CNO fluxes $\Rightarrow$ ANSWER TILL 2002: No limit

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How the Sun Shines? Present Answer

Bahcall, MCG-G, Peña-Garay, 03

- Fit solar (and KamLAND) data for:
  - 2ν oscillations Δm^2, $\tan^2\theta$ + 8 free solar ν fluxes under Luminosity constraint

$$\frac{L_\odot}{4\pi(A.U.)^2} = \sum_{i=1}^{8} \alpha_i \Phi_i \qquad \alpha_i \equiv \text{Energy released in reaction i}$$

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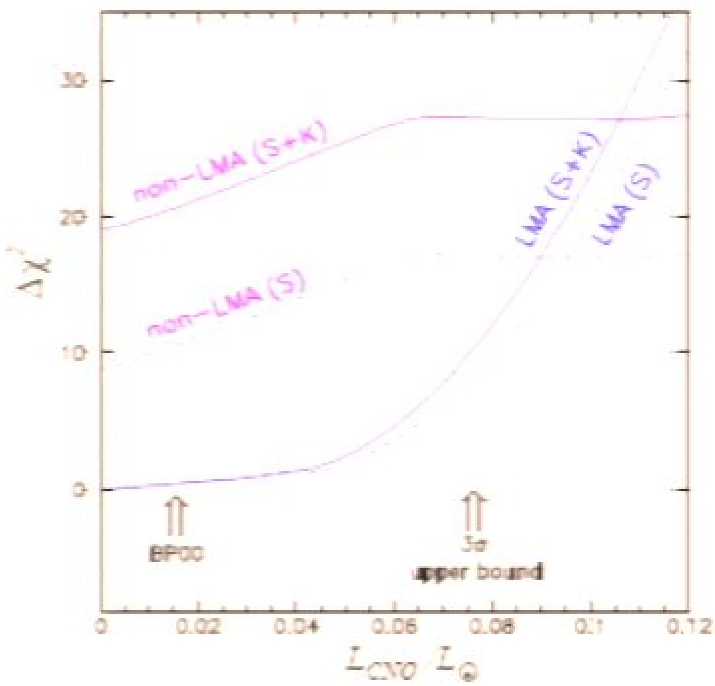
- Study the quality of fit as a function of: $L_{CNO} = \sum_{i=N,O,F} \alpha_i \Phi_i$



Resulting Limit:

$$\frac{L_{\rm CNO}}{L_\odot} < 6.2\,\%\ 3\sigma$$

Including latest Borexino ArXiv 0805.3843

Testing the Solar Luminosity with Neutrinos

$$\frac{L_\odot(\nu - \text{inferred})}{L_\odot} = 1.4^{+0.2}_{-0.3}\left(^{+0.7}_{-0.6}\right)$$

Some New Physics in ATM ν -Oscillations

- Oscillations are due to:
  - Misalignment between CC-int and propagation states: Mixing $\Rightarrow$ Amplitude
  - Difference phases of propagation states $\Rightarrow$ Wavelength. For Δm^2-OSC $\lambda = \frac{4\pi E}{\Delta m^2}$

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Non-standard ν interactions in matter: Wolfenstein 78

$G_F\varepsilon_{\alpha\beta}(\overline{\nu_\alpha}\gamma^\mu\nu_\beta)(\overline{f}\gamma_\mu f)$ $\lambda = \frac{2\pi}{2\sqrt{2}G_f\, N_f\, \sqrt{\varepsilon_{\alpha\beta}^2 + (\varepsilon_{\alpha\alpha}-\varepsilon_{\beta\beta})^2/4}}$

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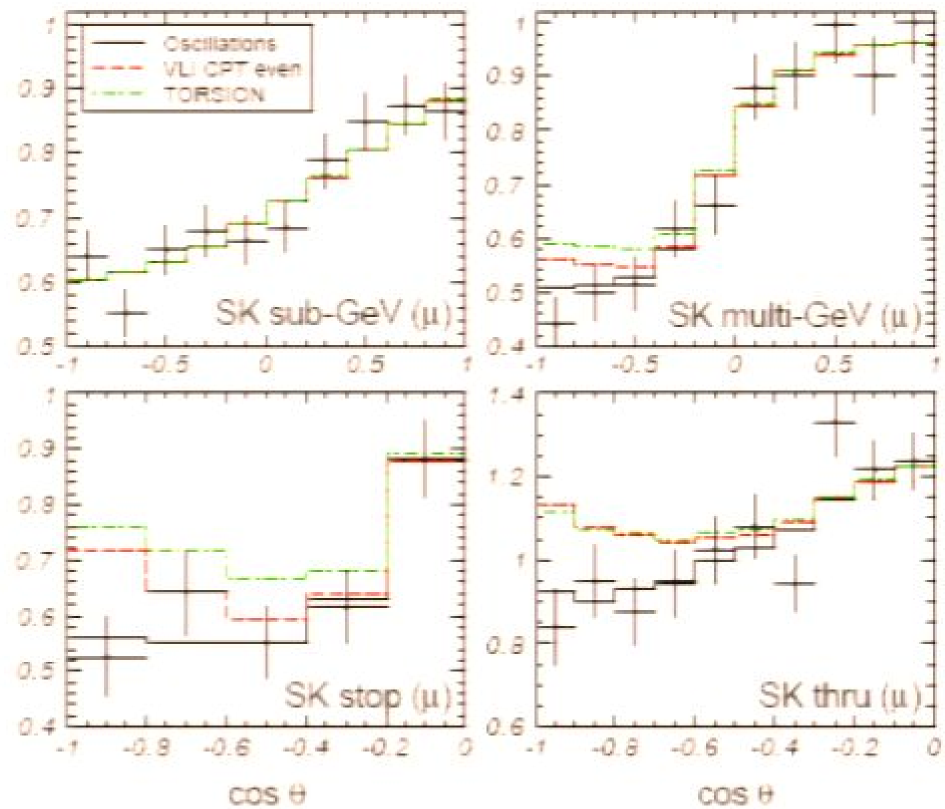
ATM ν's: Subdominant NP Effects

$$P_{\nu_\mu-\nu_\mu} = 1 - \sin^2 2\Theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\mathcal{R}\right)$$

$$\mathcal{R}\cos 2\Theta = \cos 2\theta + \sum_n R_n \cos 2\xi_n$$

$$\mathcal{R}\sin 2\Theta = \sin 2\theta + \sum_n R_n \sin 2\xi_n \, e^{i\eta_n}$$

$$R_n = \sigma_n^{+} \frac{\Delta\delta_n E^n}{2} \frac{4E}{\Delta m^2}$$



- Questions:
  - Do these effects affect our determination of oscillation parameters?
  - Can we limit these effects?

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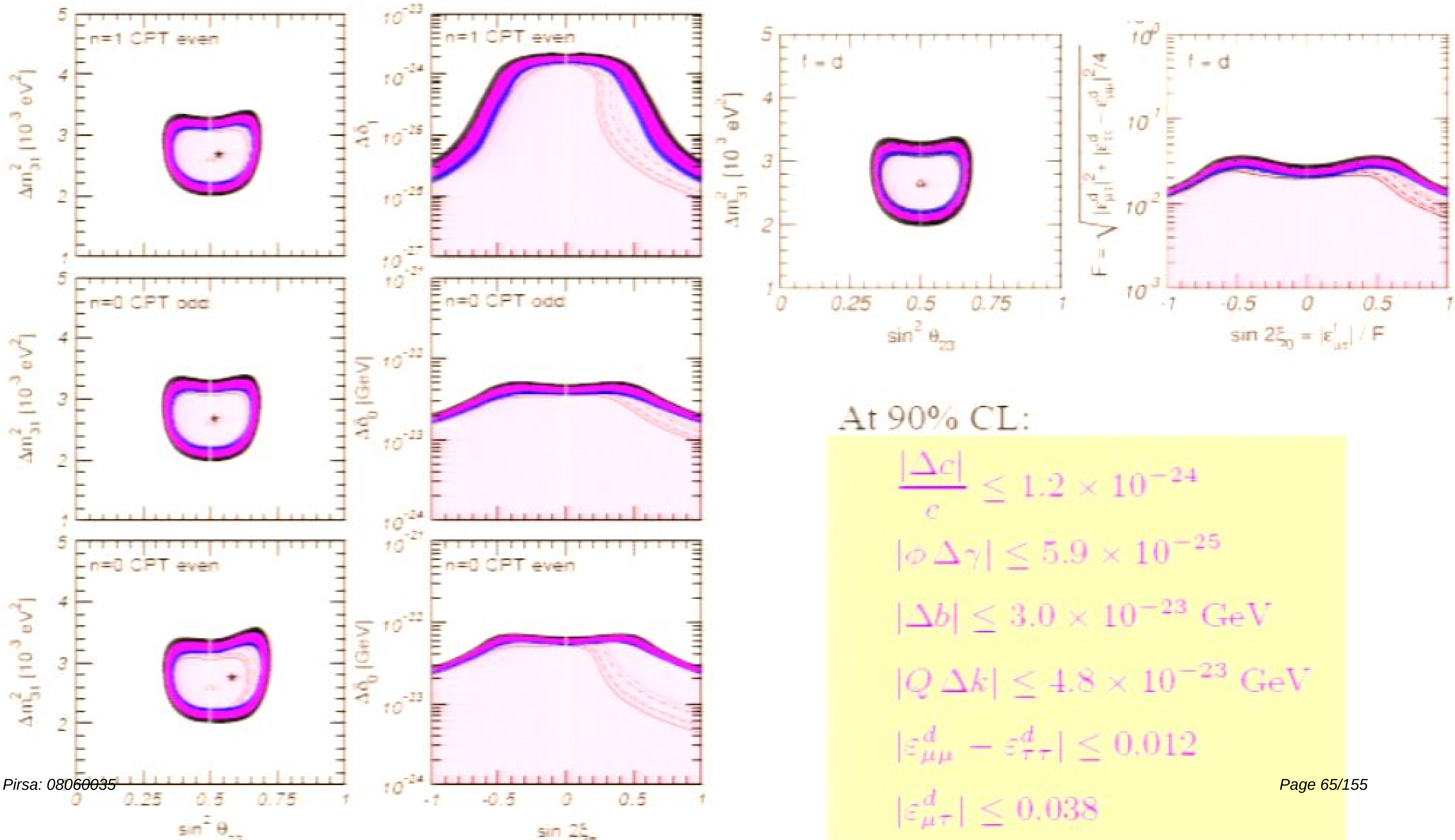
ATM ν's: Subdominant NP Effects

MCG-G. M. Maltoni 04.07



At 90% CL:

$$\frac{|\Delta c|}{c} \leq 1.2 \times 10^{-24}$$

$$|\phi \, \Delta\gamma| \leq 5.9 \times 10^{-25}$$

$$|\Delta b| \leq 3.0 \times 10^{-23} \text{ GeV}$$

$$|Q \, \Delta k| \leq 4.8 \times 10^{-23} \text{ GeV}$$

$$|\varepsilon^d_{\mu\mu} - \varepsilon^d_{\tau\tau}| \leq 0.012$$

$$|\varepsilon^d_{\mu\tau}| \leq 0.038$$

Unparticles: Framework

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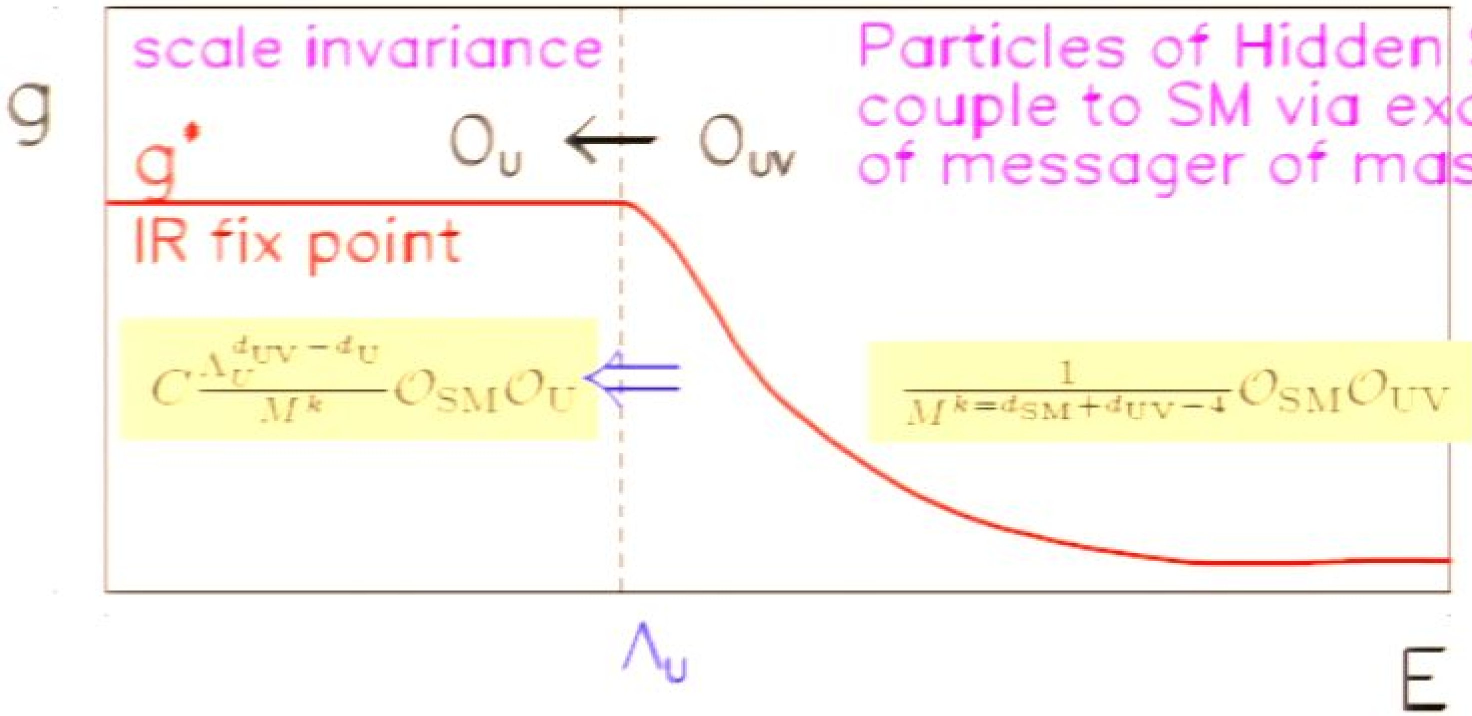
(H. Georgi, 2007)

Hidden sector
with gauge coupling g

Particles of Hidden Sector
couple to SM via exchange
of messager of mass M



- $d_U \equiv$ scaling dimension of unparticle operator $\mathcal{O}_U$. At $\Lambda_U \equiv$ scale invariance sets it.
- If $g^* >> 1 \Rightarrow C_U \sim \mathcal{O}(1)$ and d_U uncalculable
- Scale Invariance $\Rightarrow$ Unparticle of dimension d_U looks like a non-integral number d_U of massless invisible particles

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Unparticles and Solar Neutrinos

- If $\mathcal{O}_{SM} = \overline{f}\,\Gamma\, f$ and C^{ν}_{U} are non-universal

  Neutrino Decay: $\nu_i \to \nu_j\, U$

  L. Anchordoqui, H.Goldberg

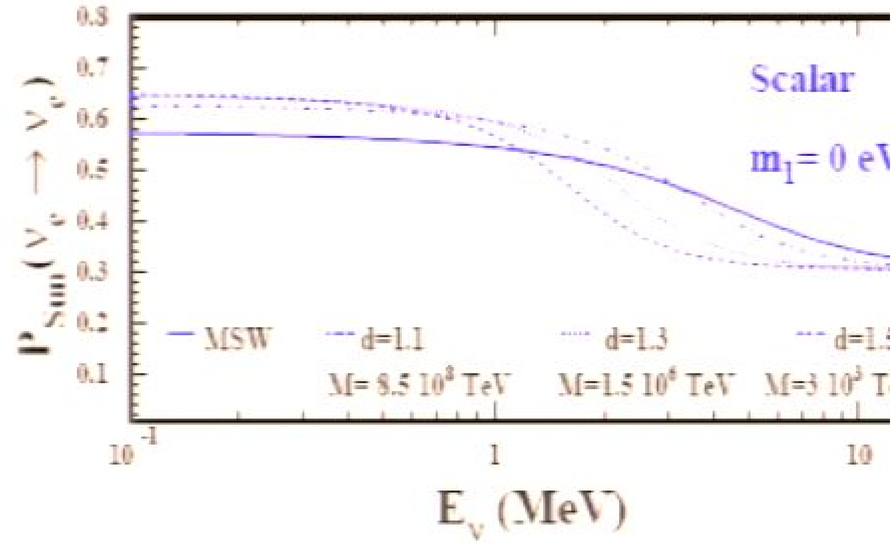
Unparticle exchange
— long range force between fermions
Unparticle exchange modifies matter potential and effective neutrino masses
— Modifies survival probability
— Strong constraints

De Holanda, M.C.G-G, Zukanovich

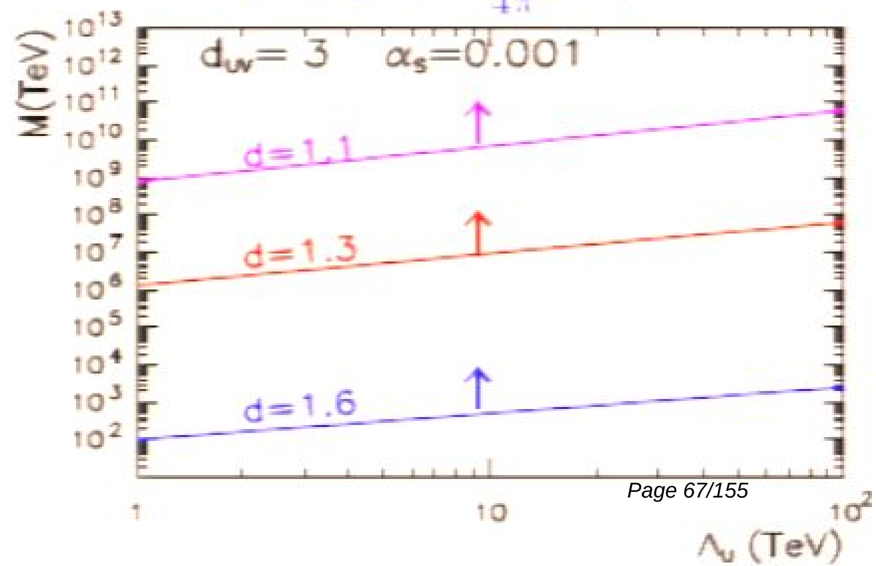
For $M = \Lambda_U$=1 TeV and $d_U = 1.1$–1.6

$$\frac{C^{\nu_e} - C^{\nu_\mu}}{C^{\nu_e}} \leq 10^{-37}\text{–}10^{-9}$$

Λ_u=1 TeV d_{UV}=3 α=10^{-3}



$$\alpha = C^{e}\,\frac{C^{\nu_e} - C^{\nu_\mu}}{4\pi}.$$



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Summary

- Big experimental effort has been devoted to proof ν oscillations beyond doubt
- Solar and atmospheric signals have been confirmed with "man-made" neutrino beams from reactor and accelerators.
- Solar. Reactor. Atmospheric and LBL data: Perfect in 3ν-oscillations
- After all existing experiments still many open questions:
  What is the value of θ_{13}?
  Is there CP violation in the leptons
  The absolute scale of neutrino mass
  Are neutrinos Dirac or Majorana particles?
- ν oscillation data already provides interesting constraints on:
  Solar Physics
  Extensions of the NMSM:
  Violation of Fundamental symmetries: LI. WEP. CPT
  Sterile Neutrino States. Neutrino decay. decoherence. new interactions
  Mass Varying Neutrinos
  Unparticles ...

C. ...nzalez-Garcia

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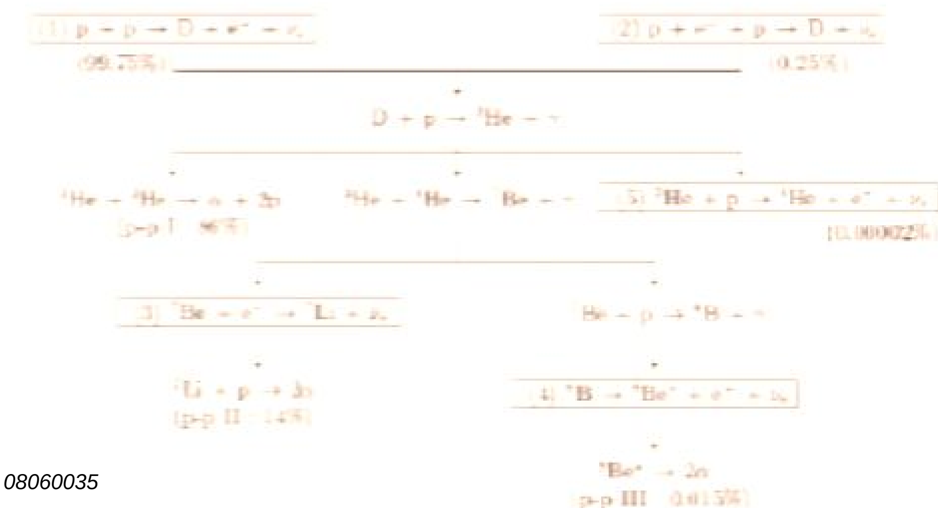
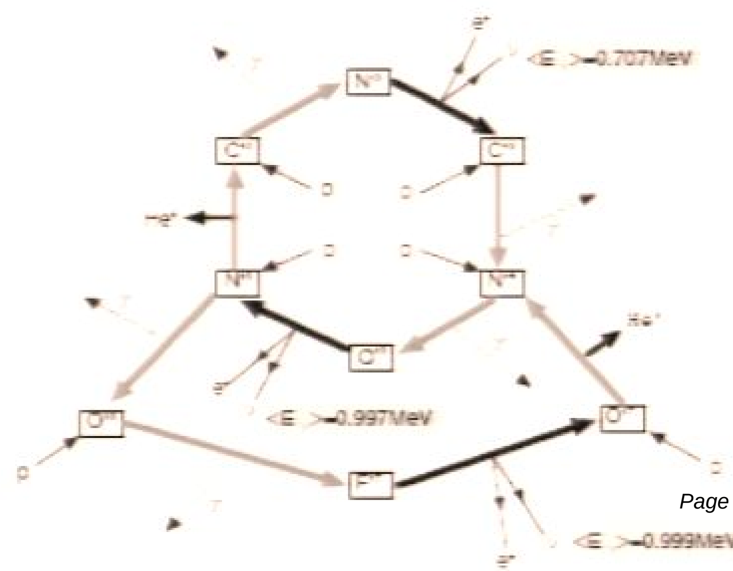


CNO cycle:



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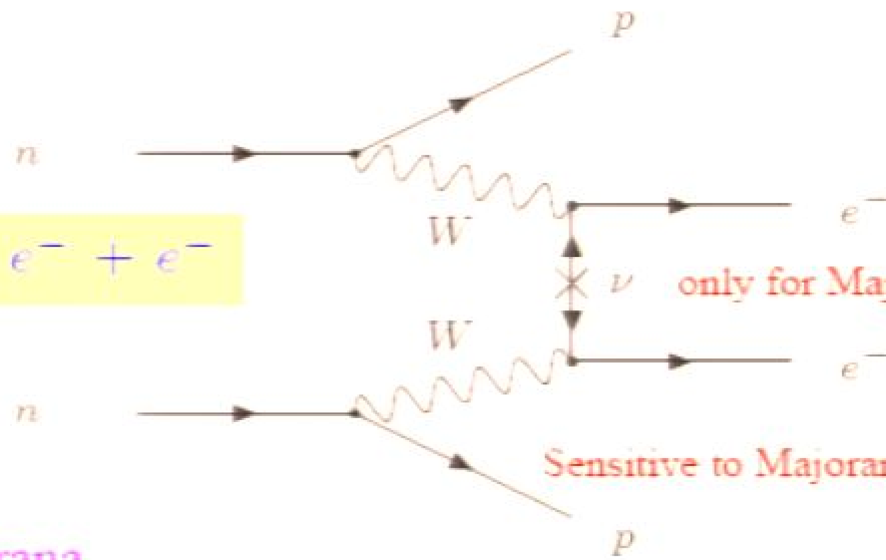

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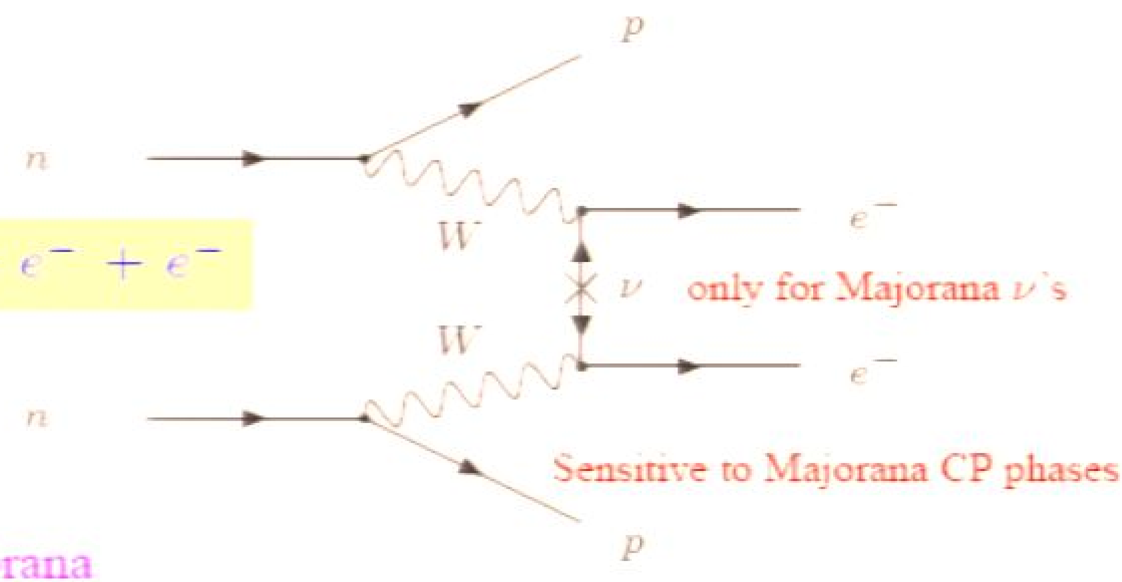

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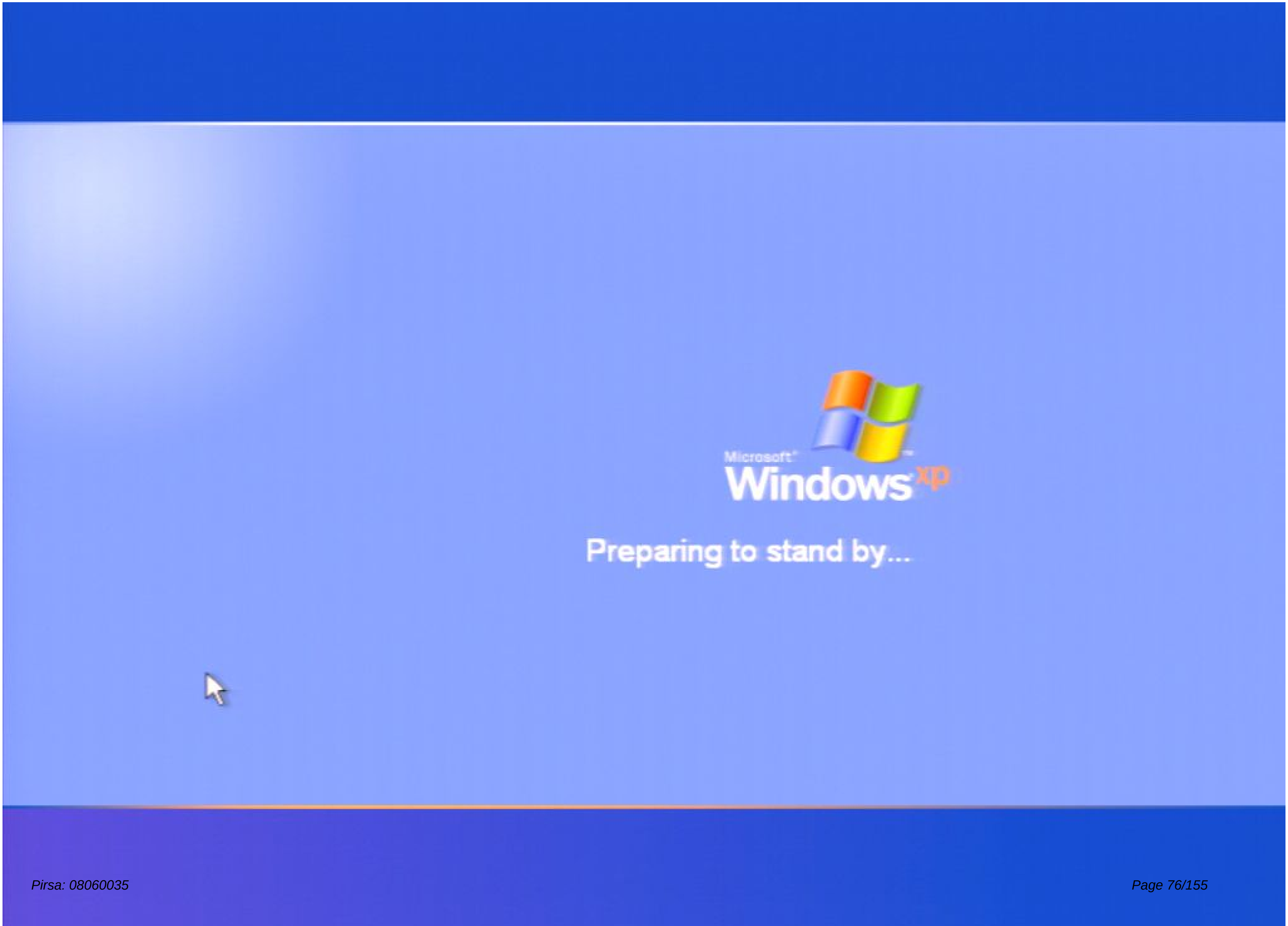
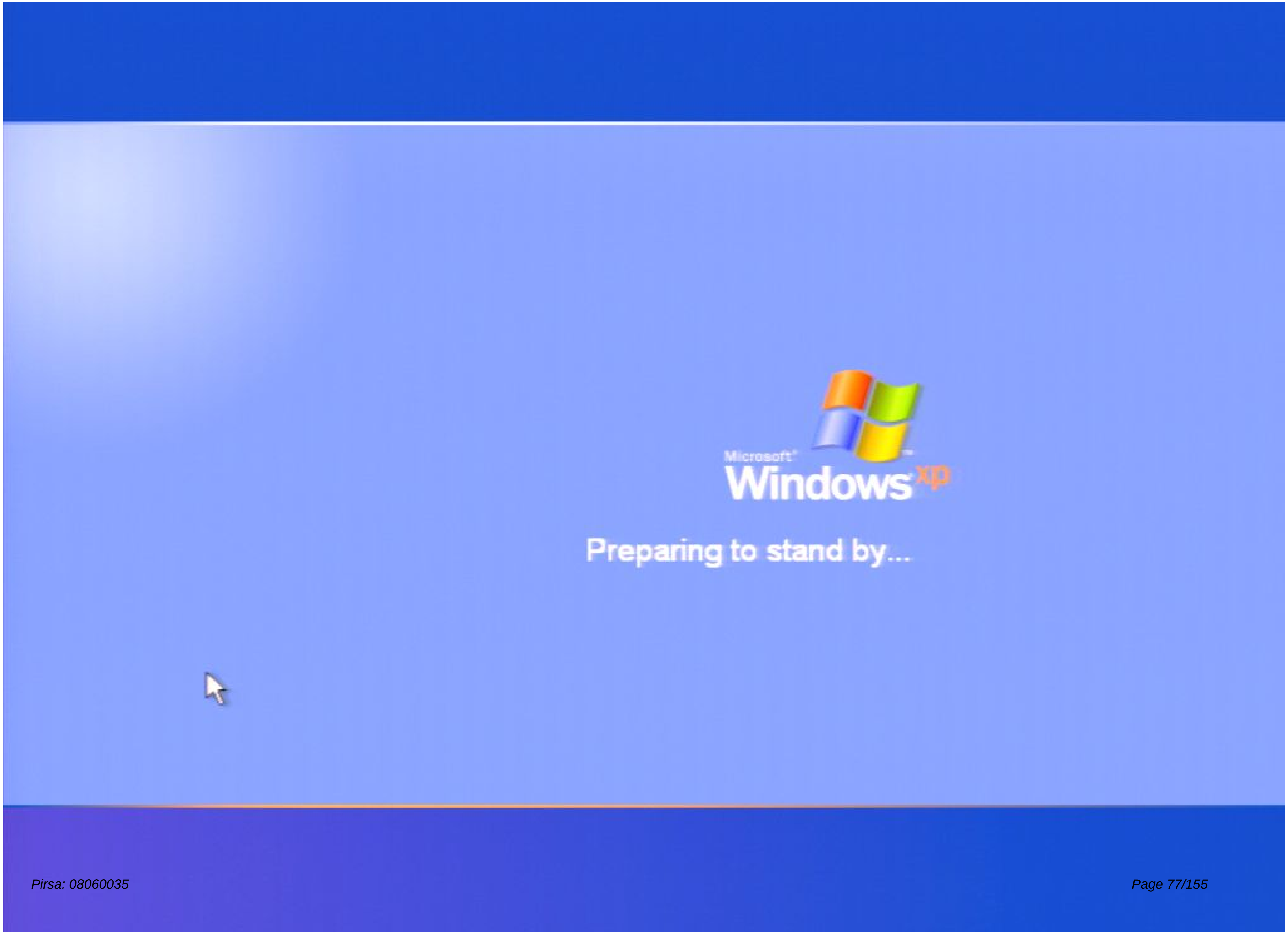

Microsoft Windows xp
Preparing to stand by...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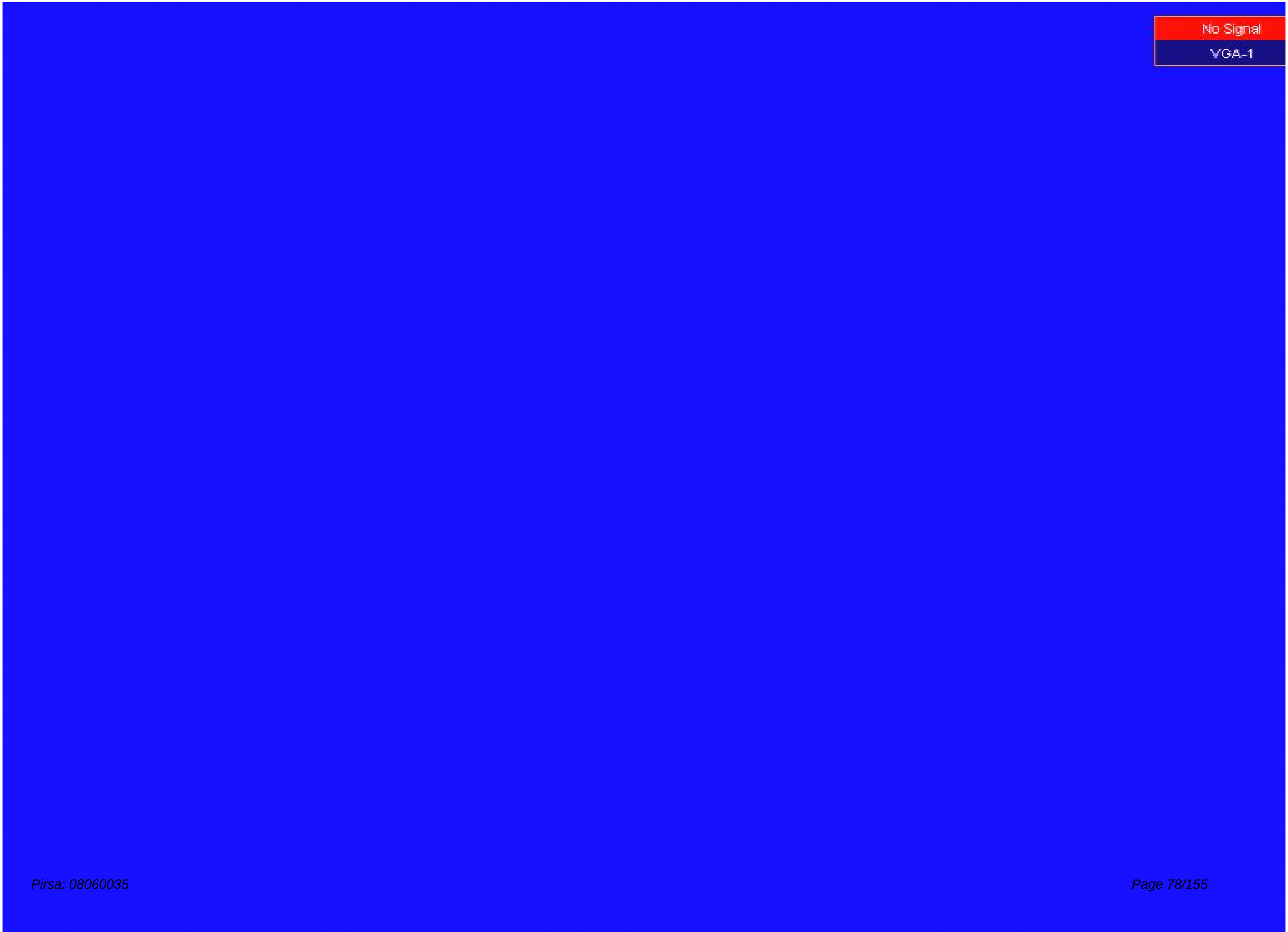
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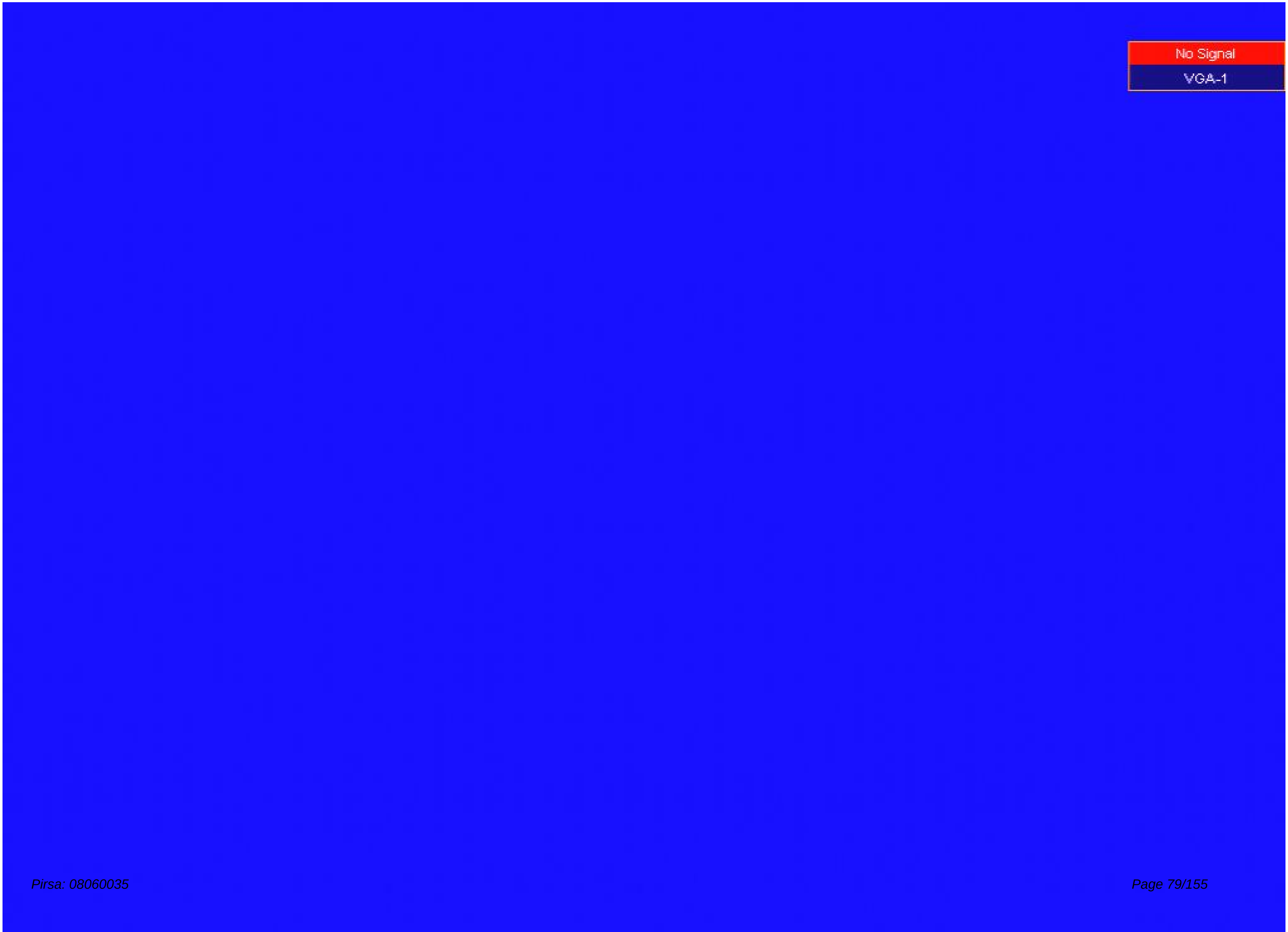
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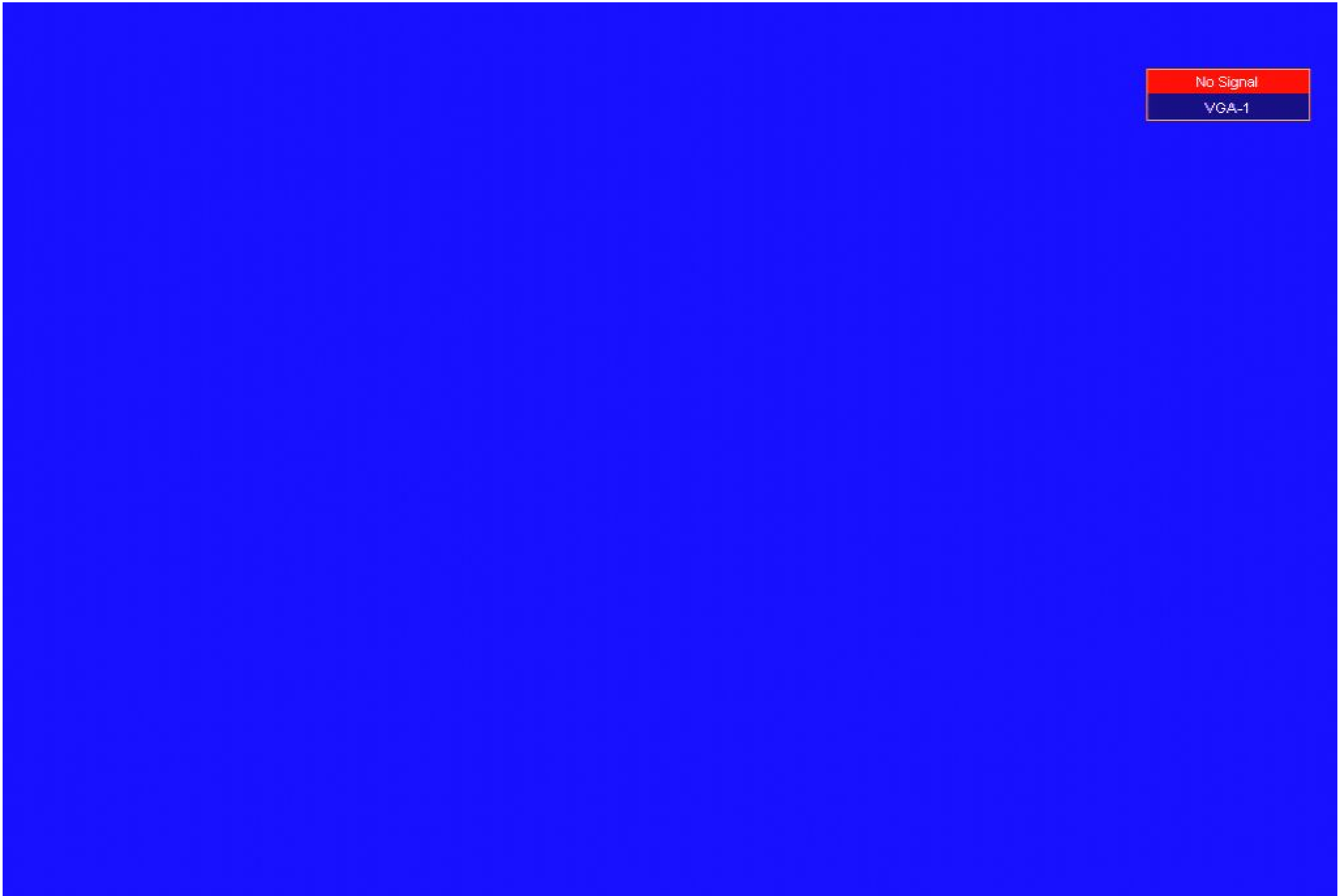
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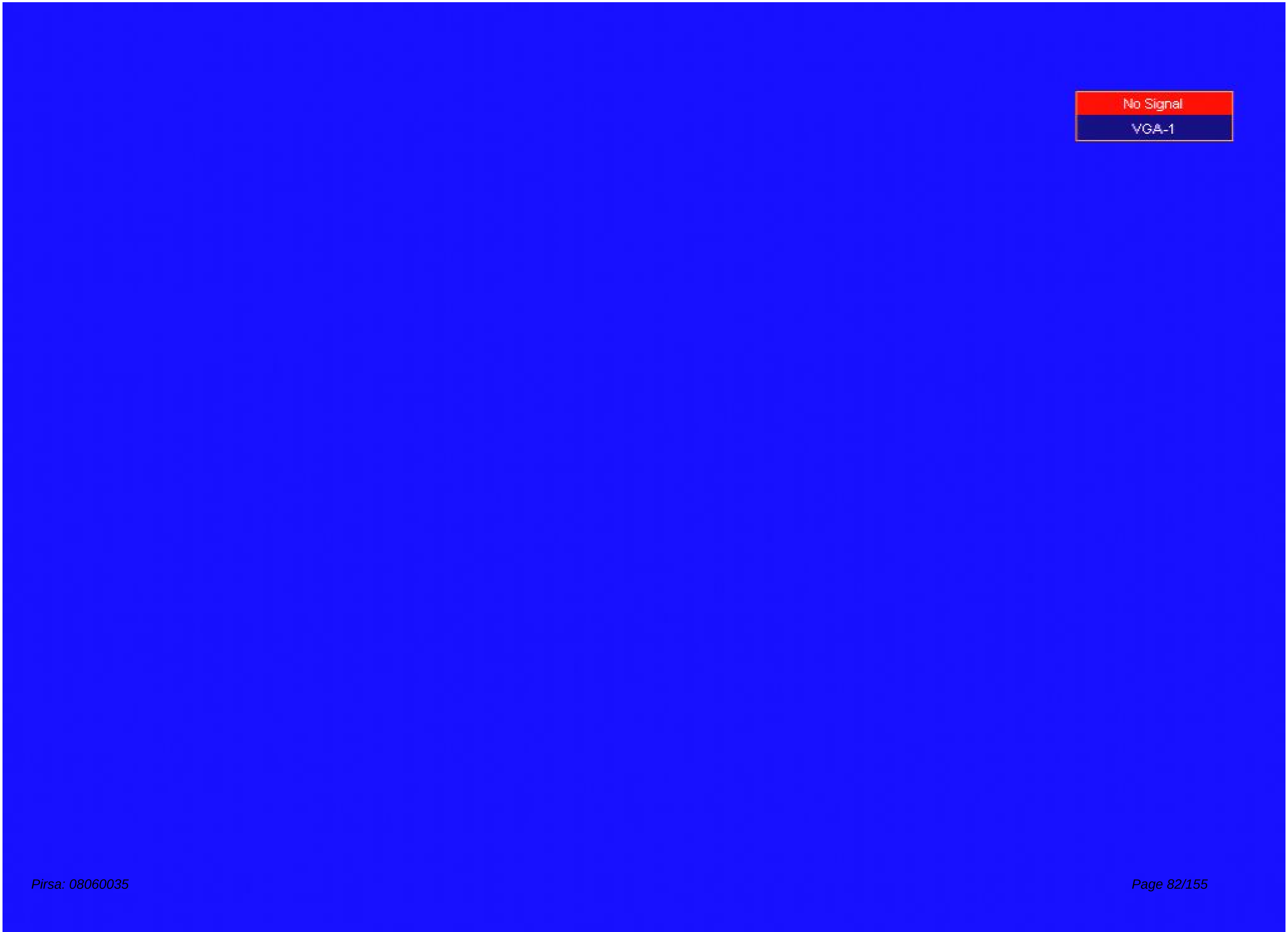
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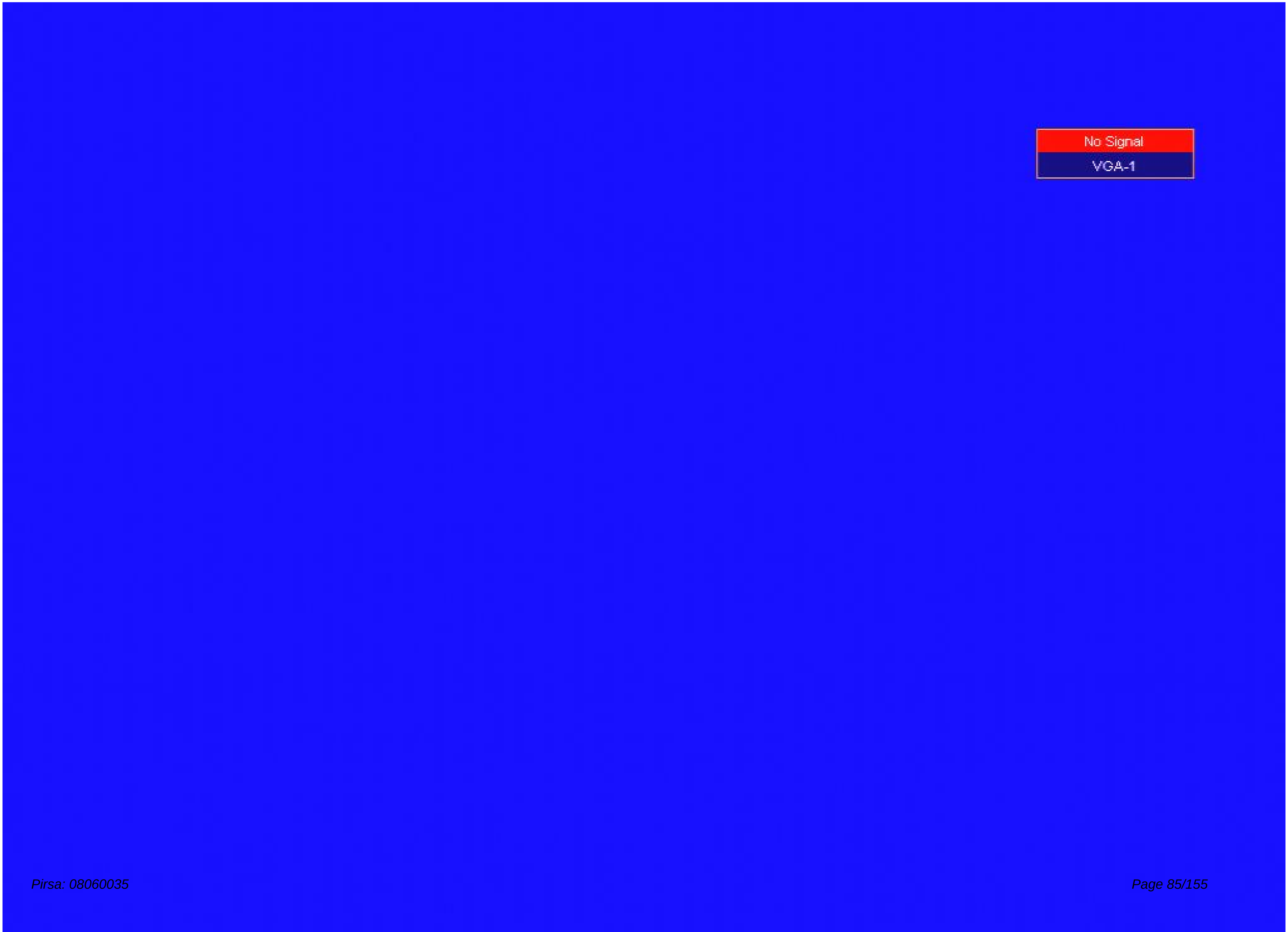
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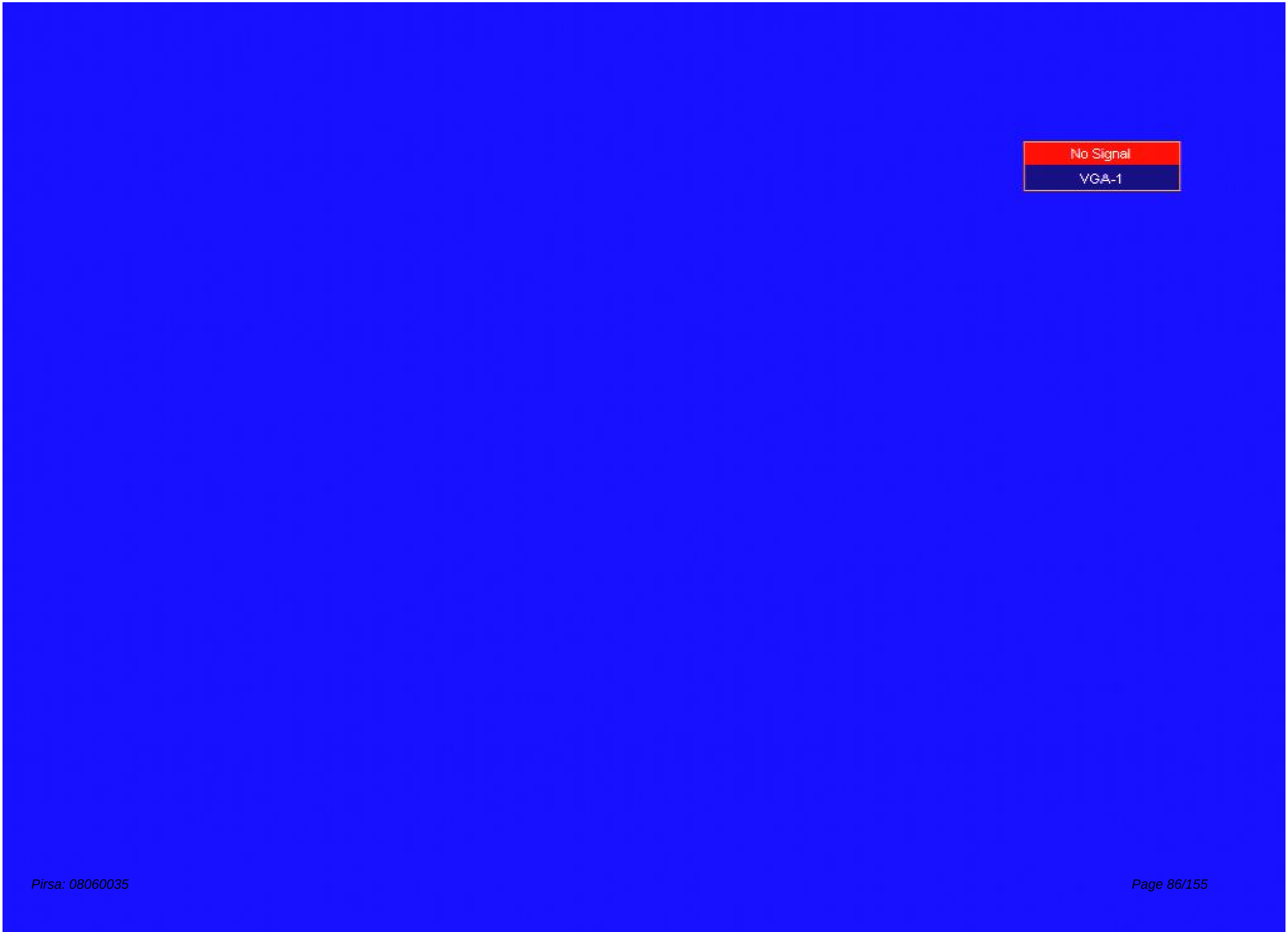
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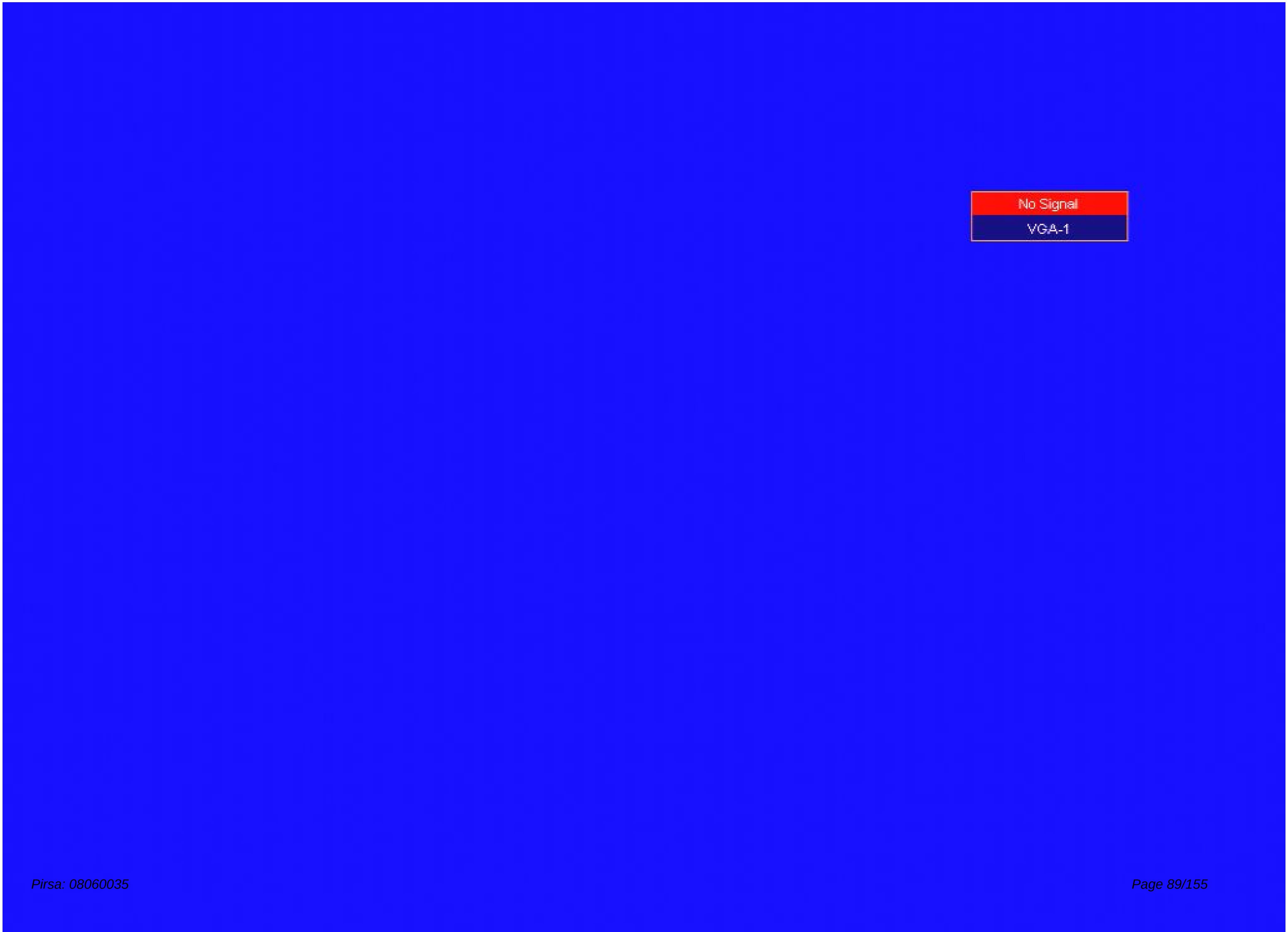
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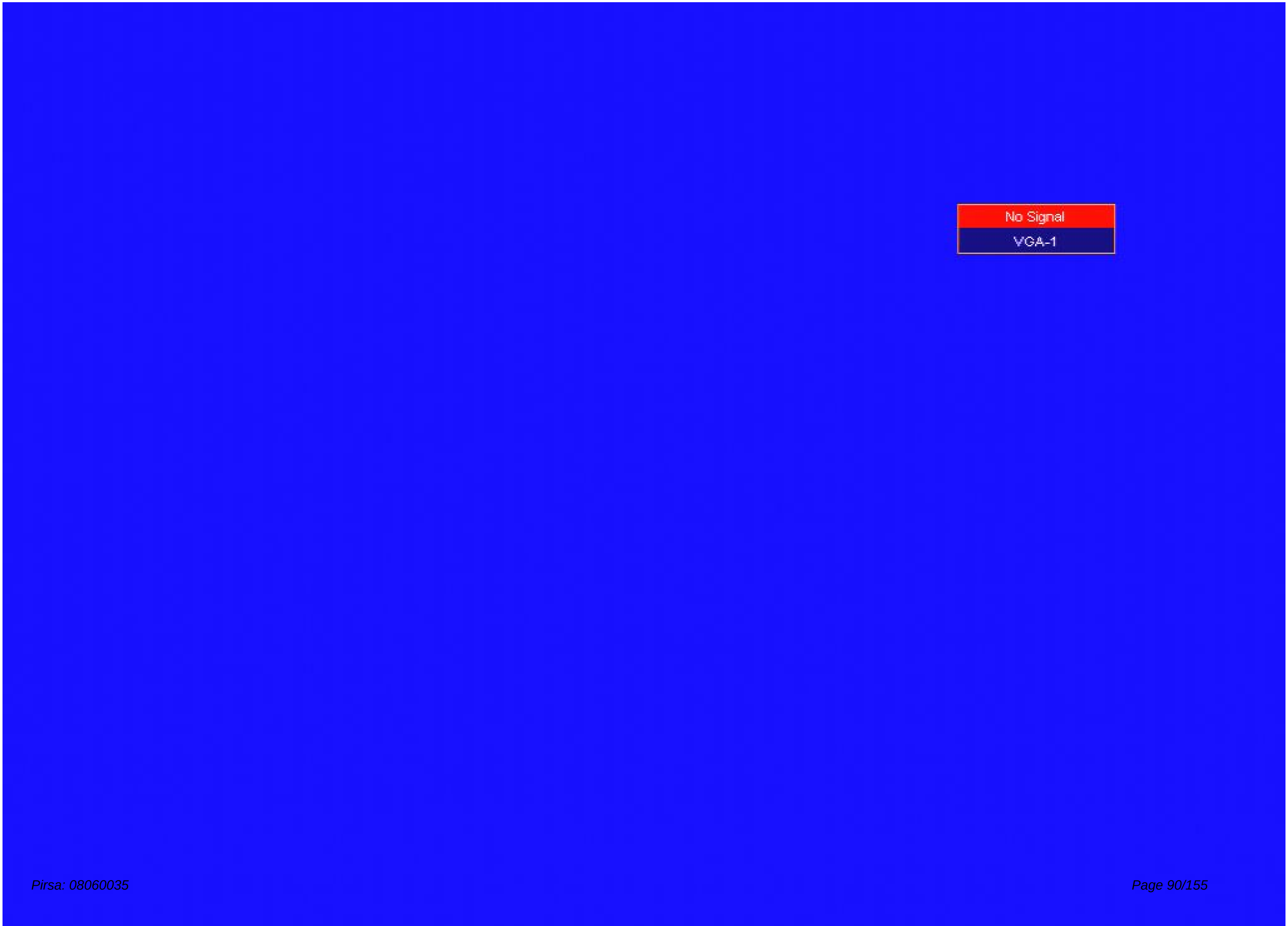
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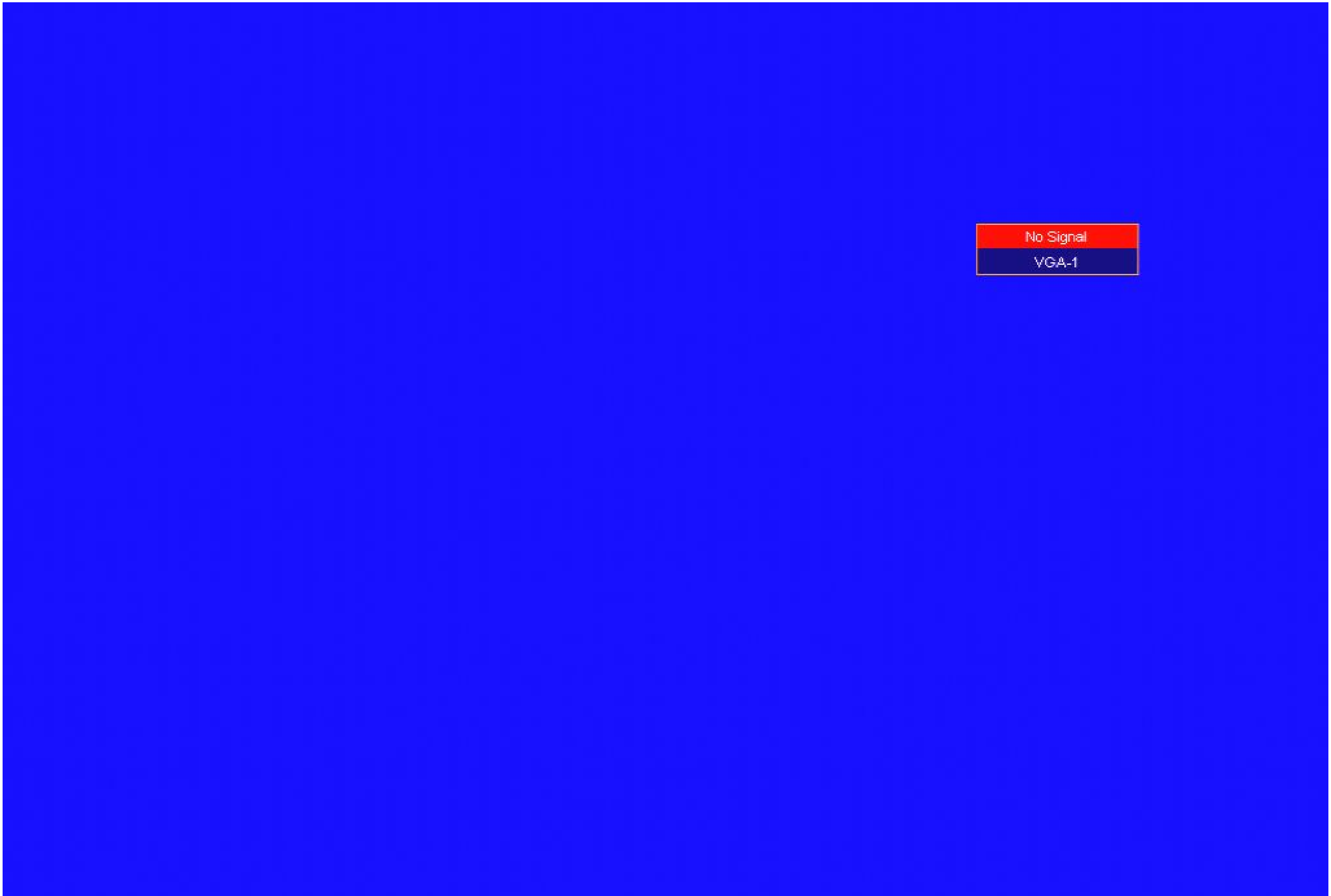
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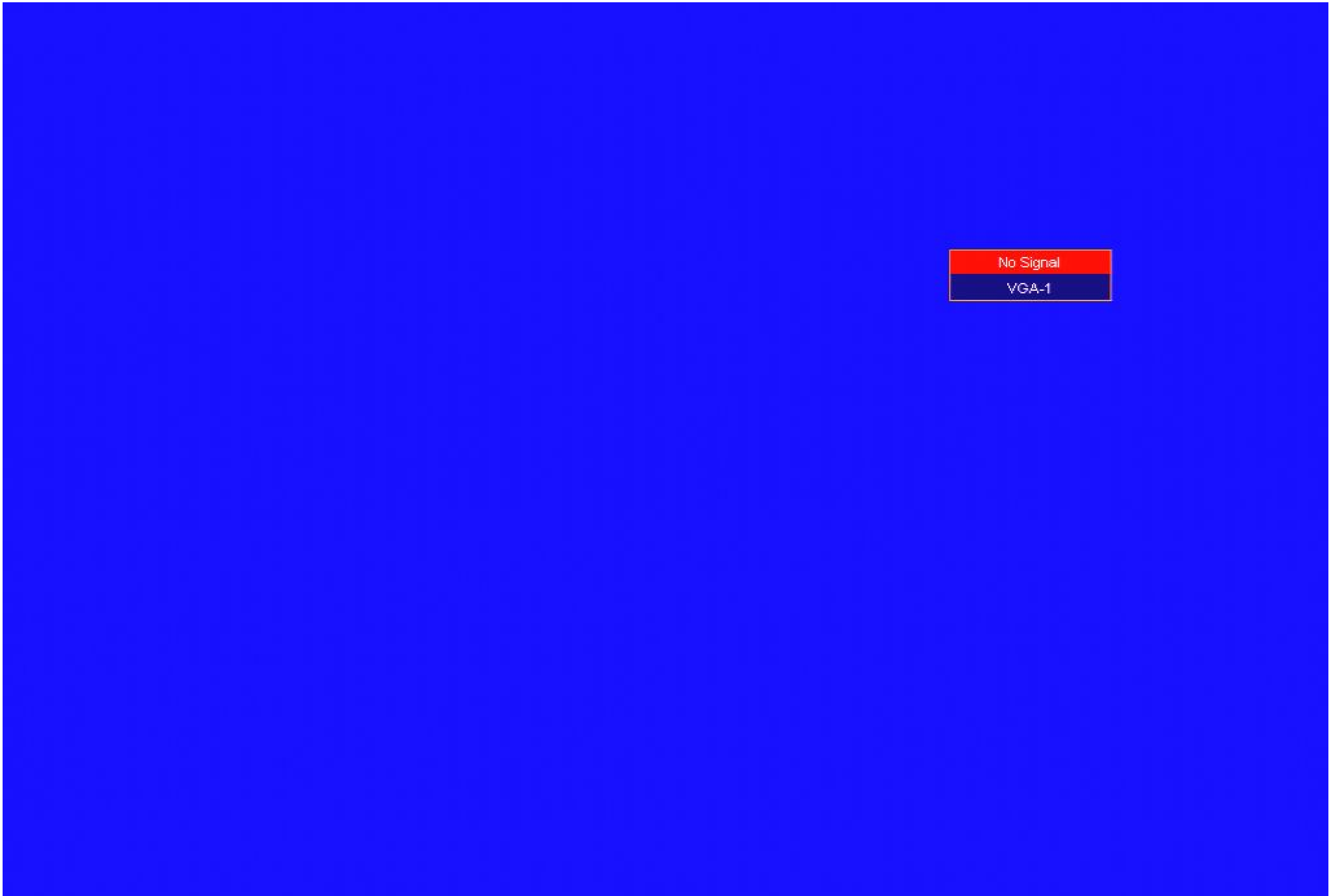
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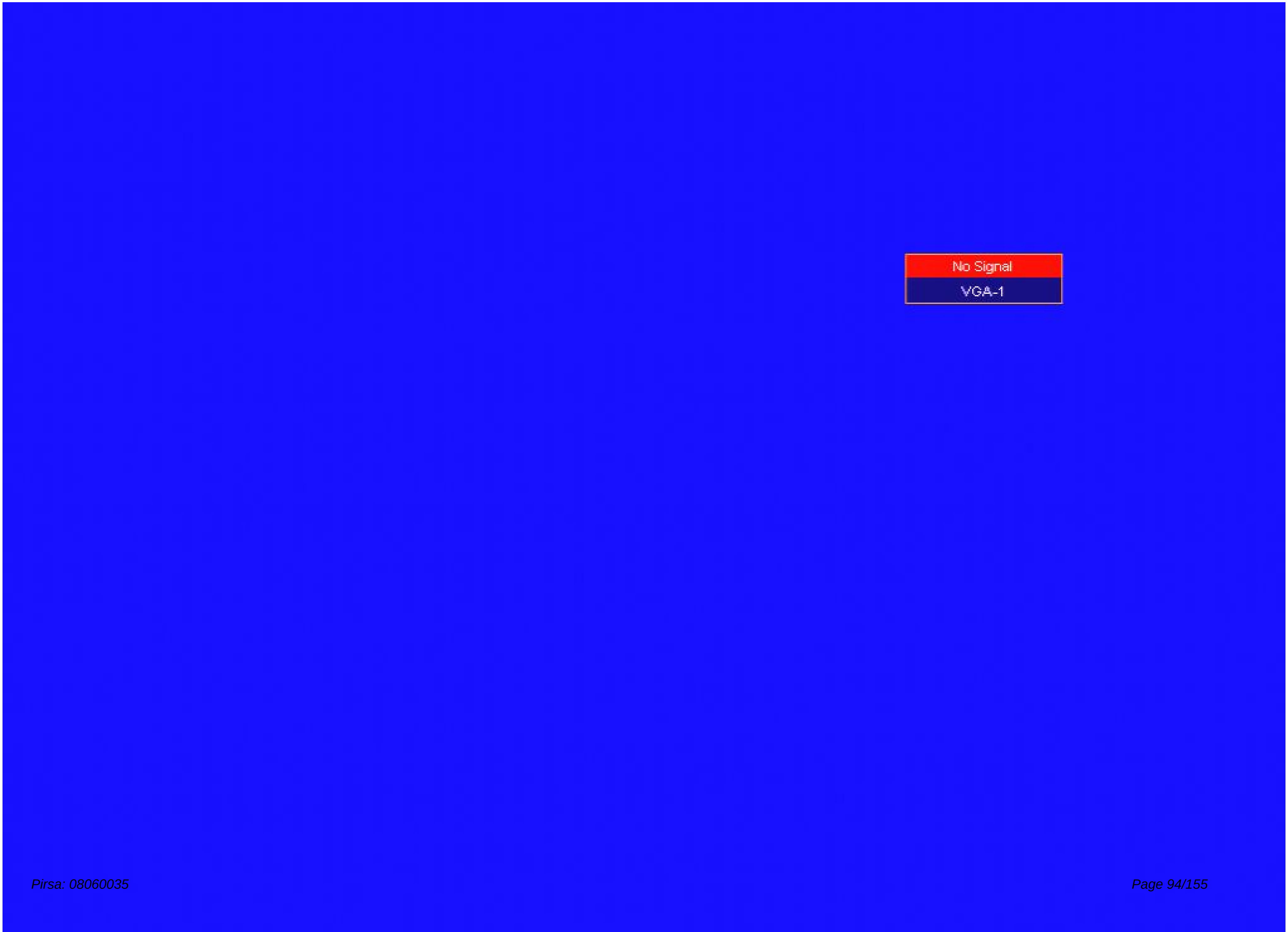
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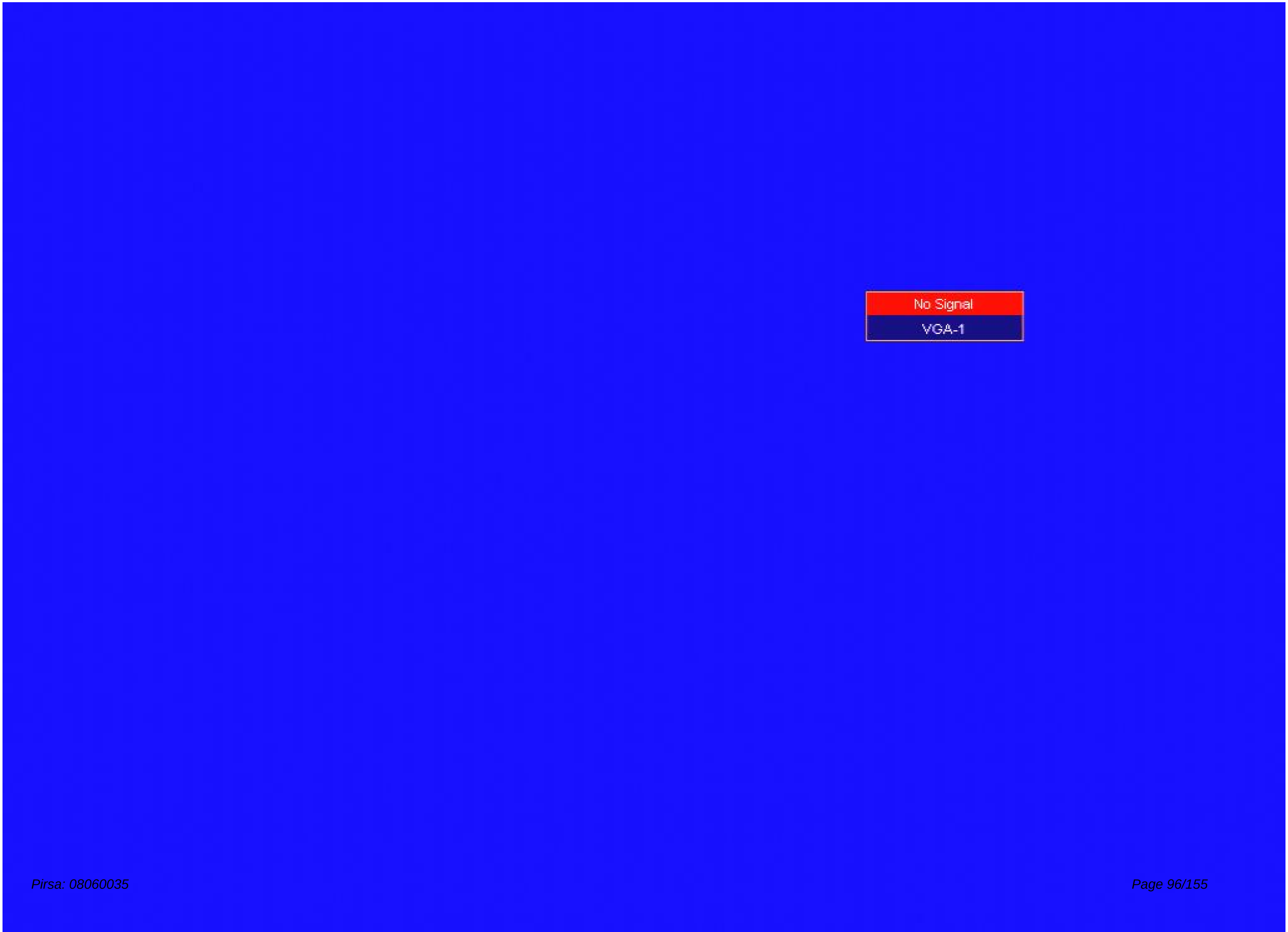
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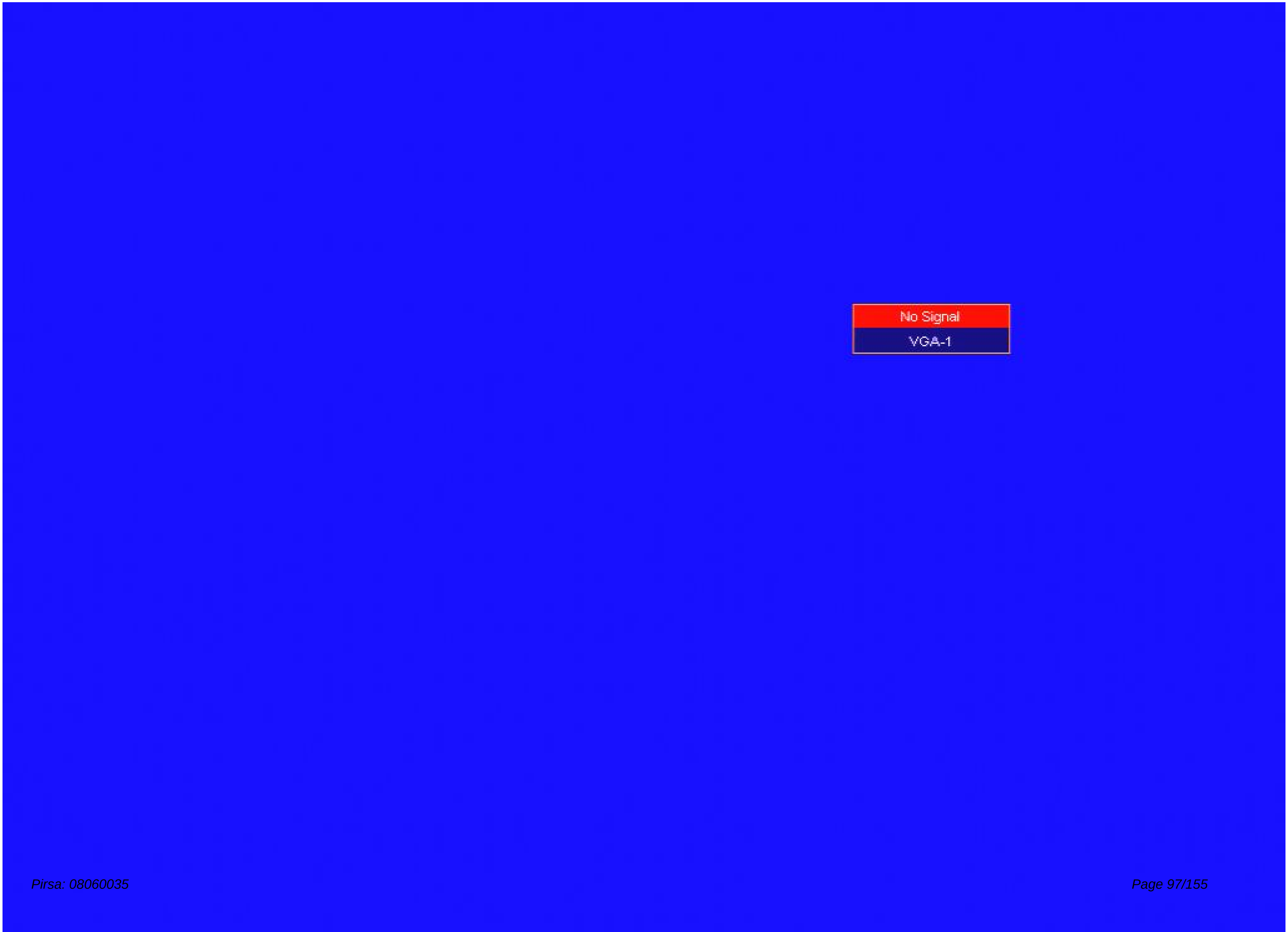
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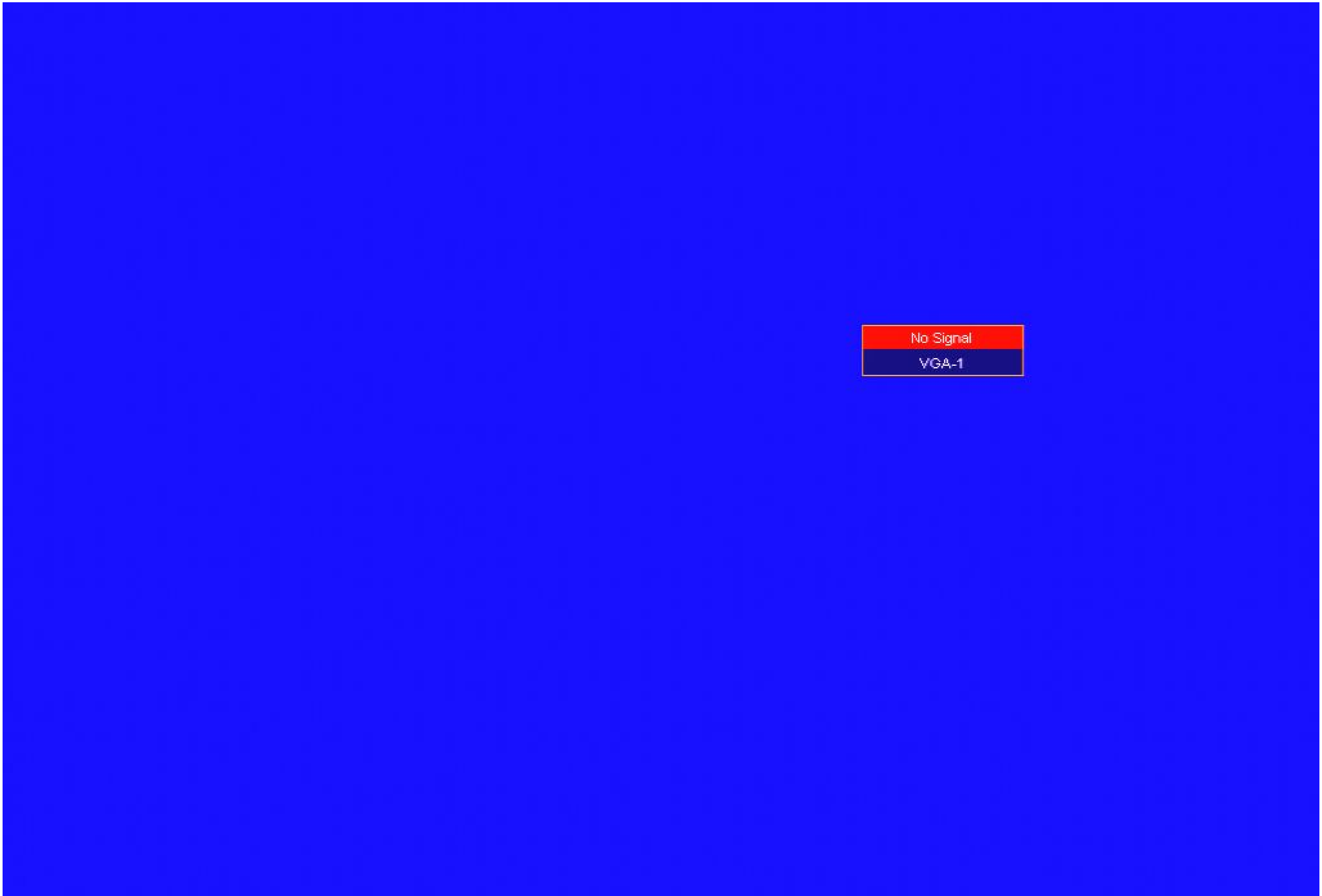
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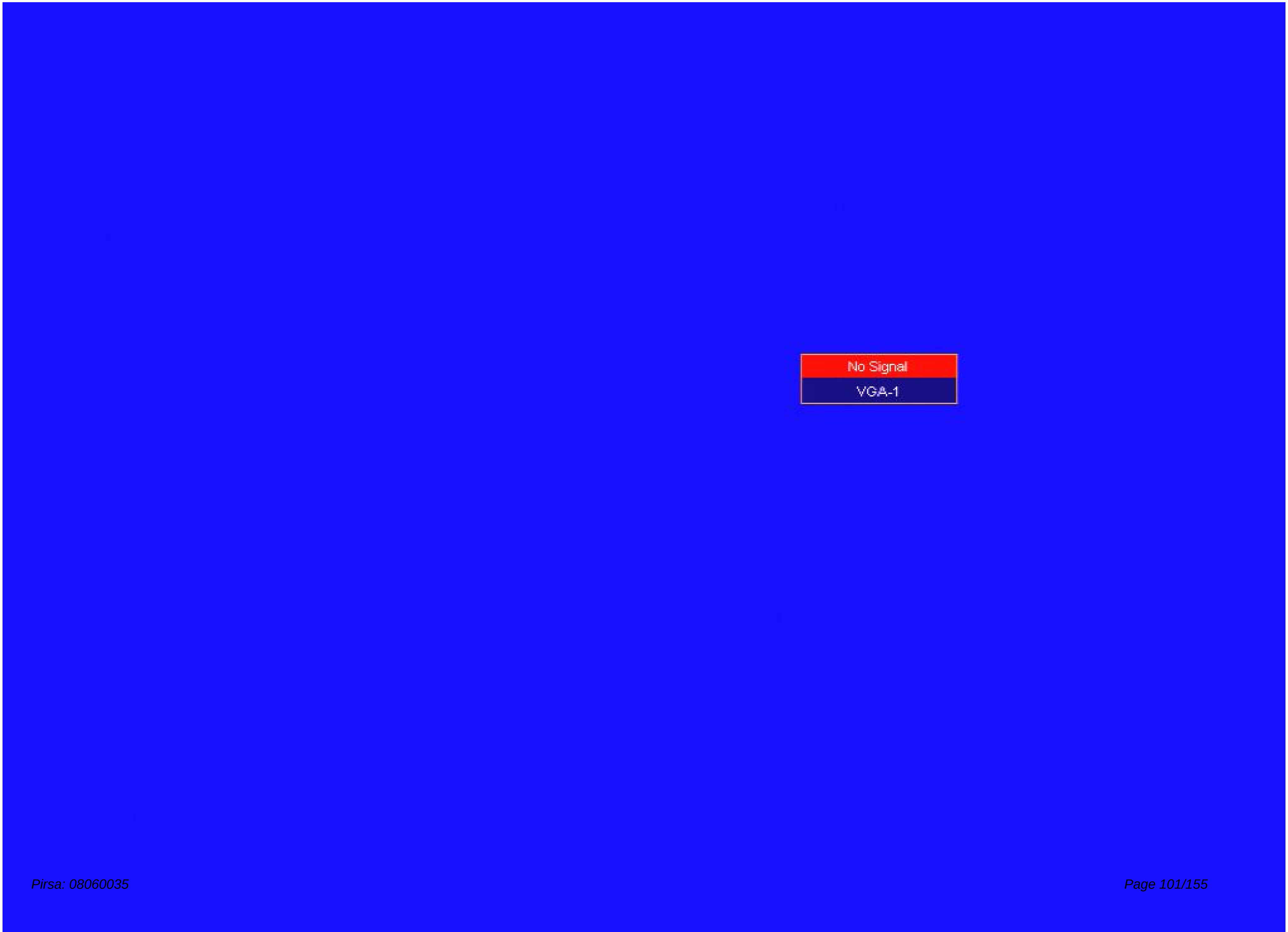
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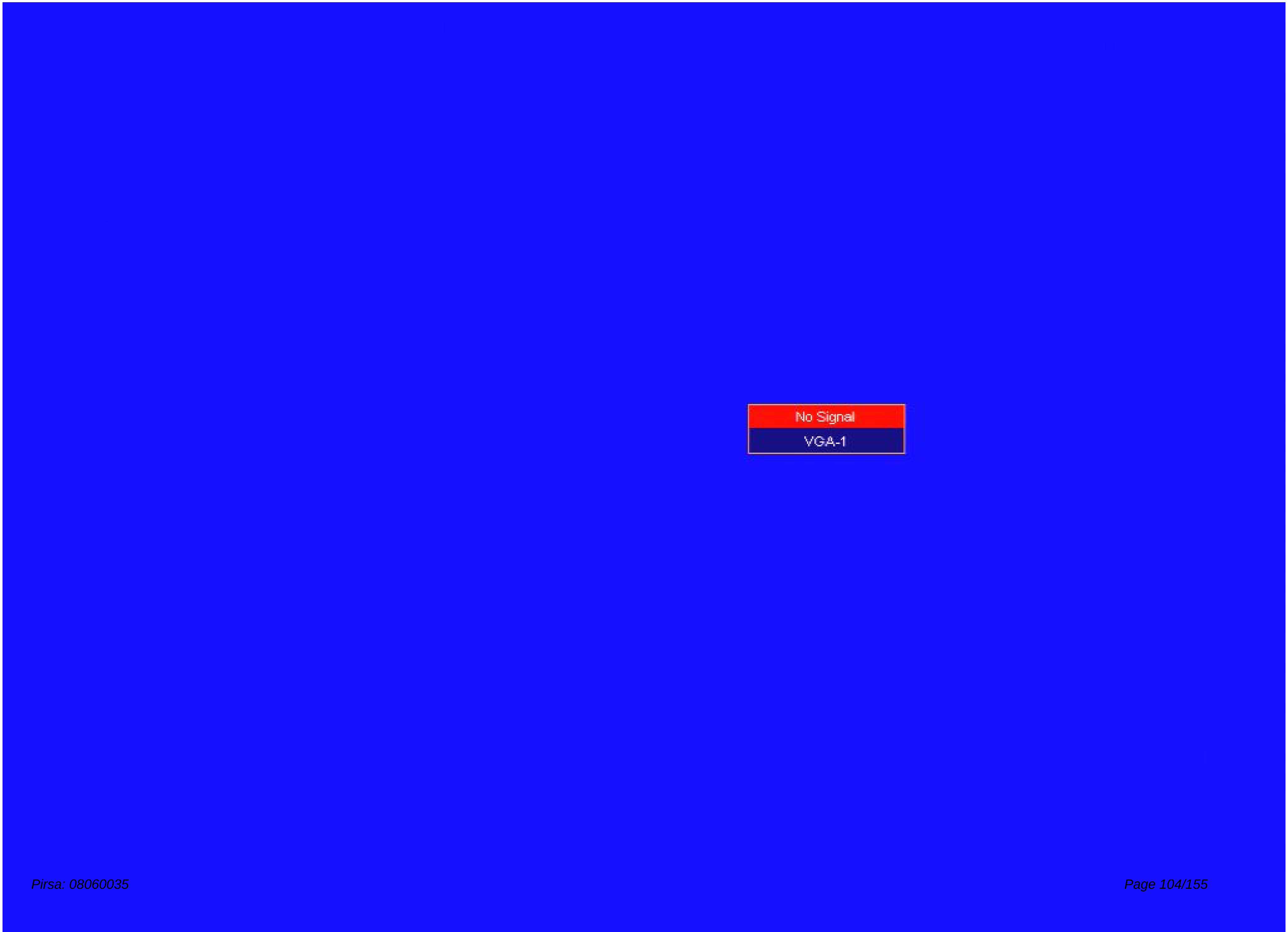
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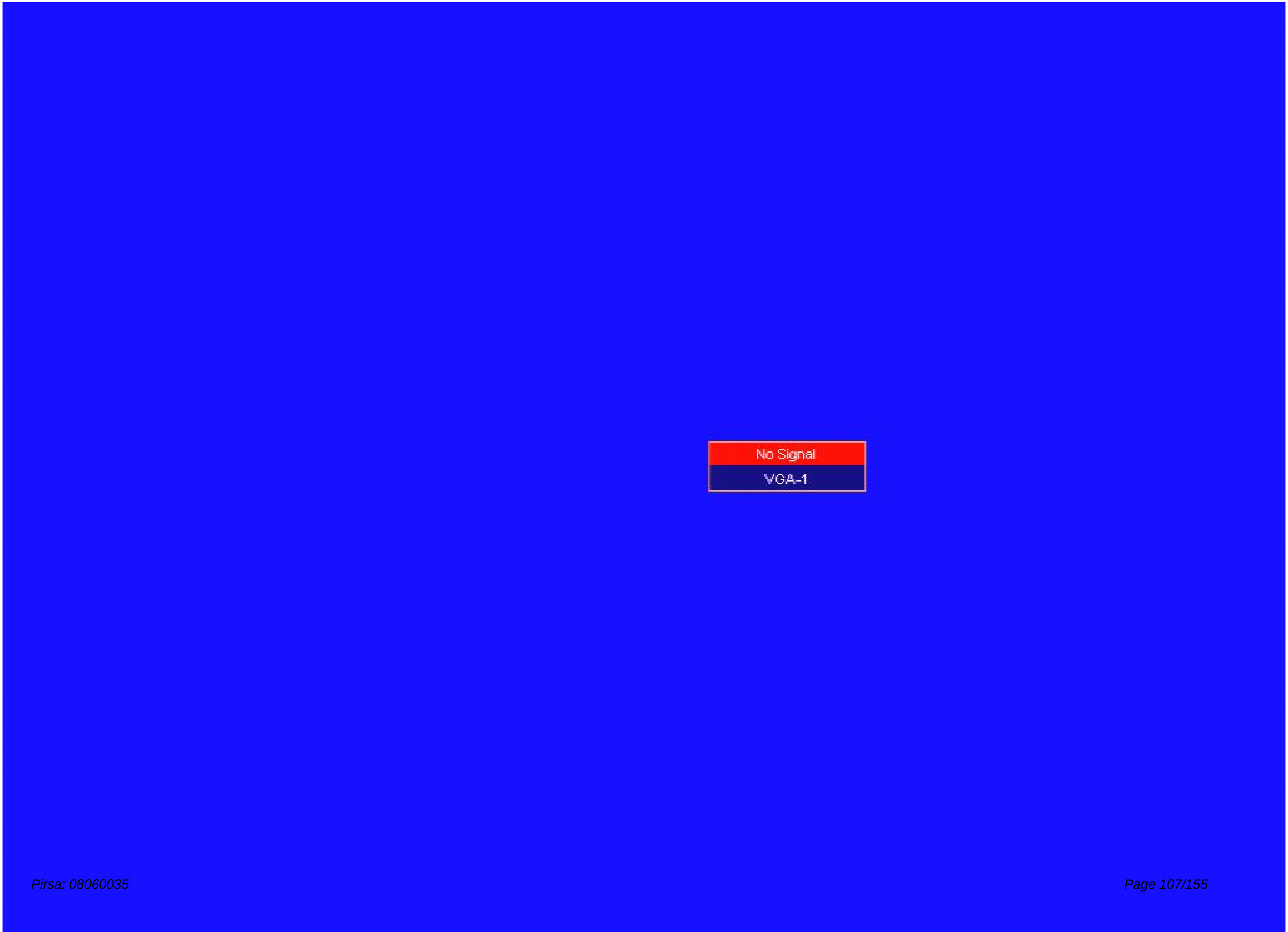
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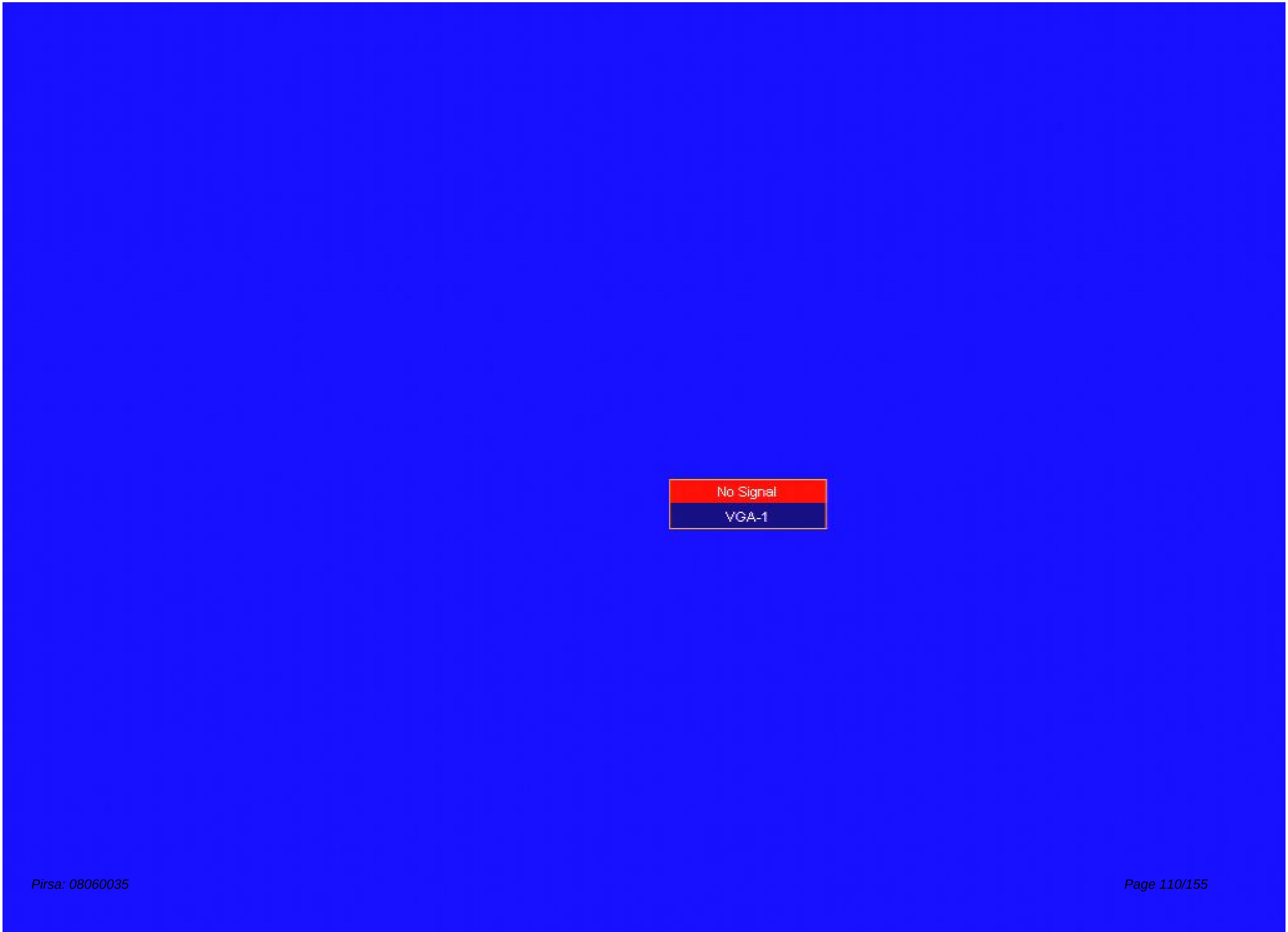
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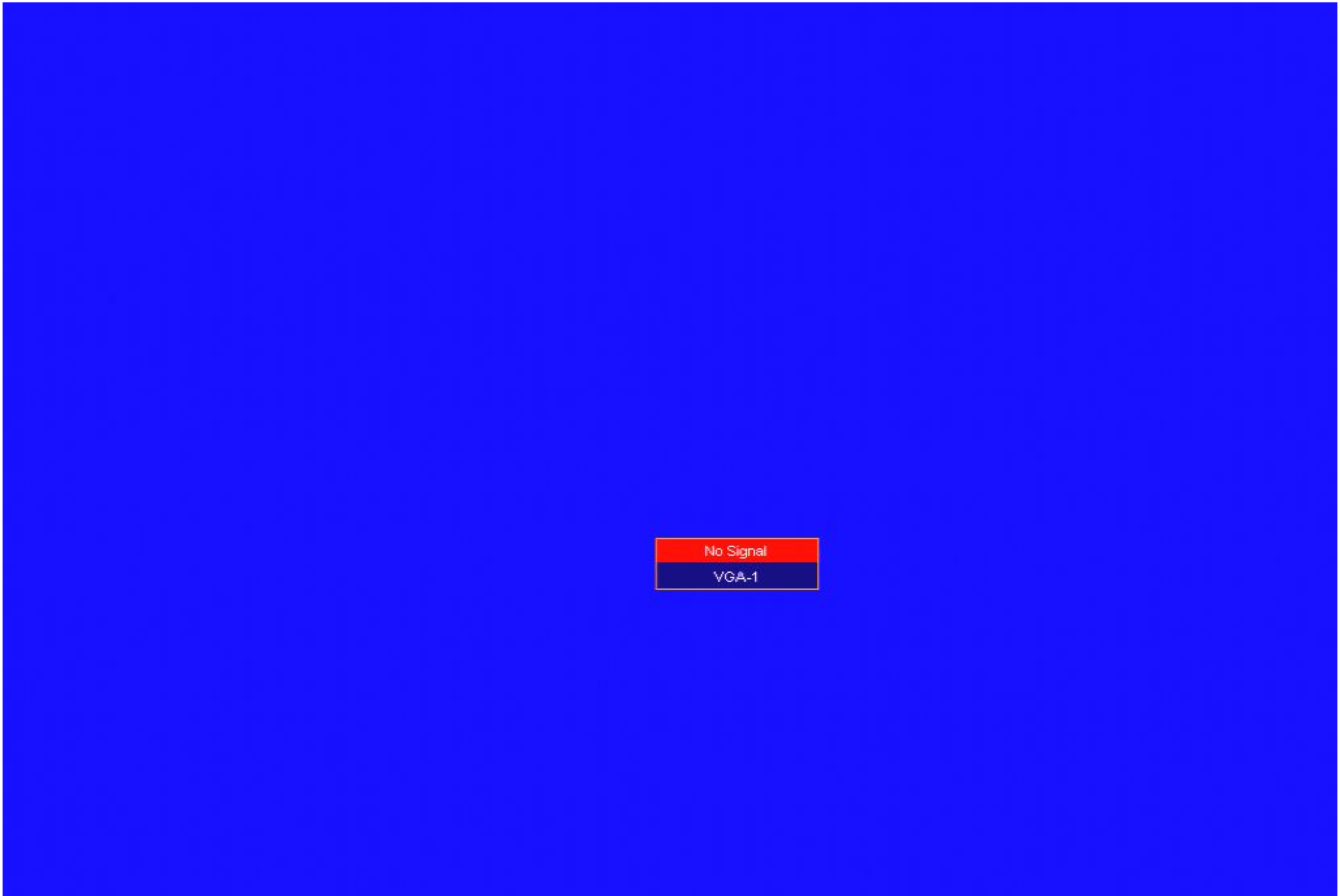
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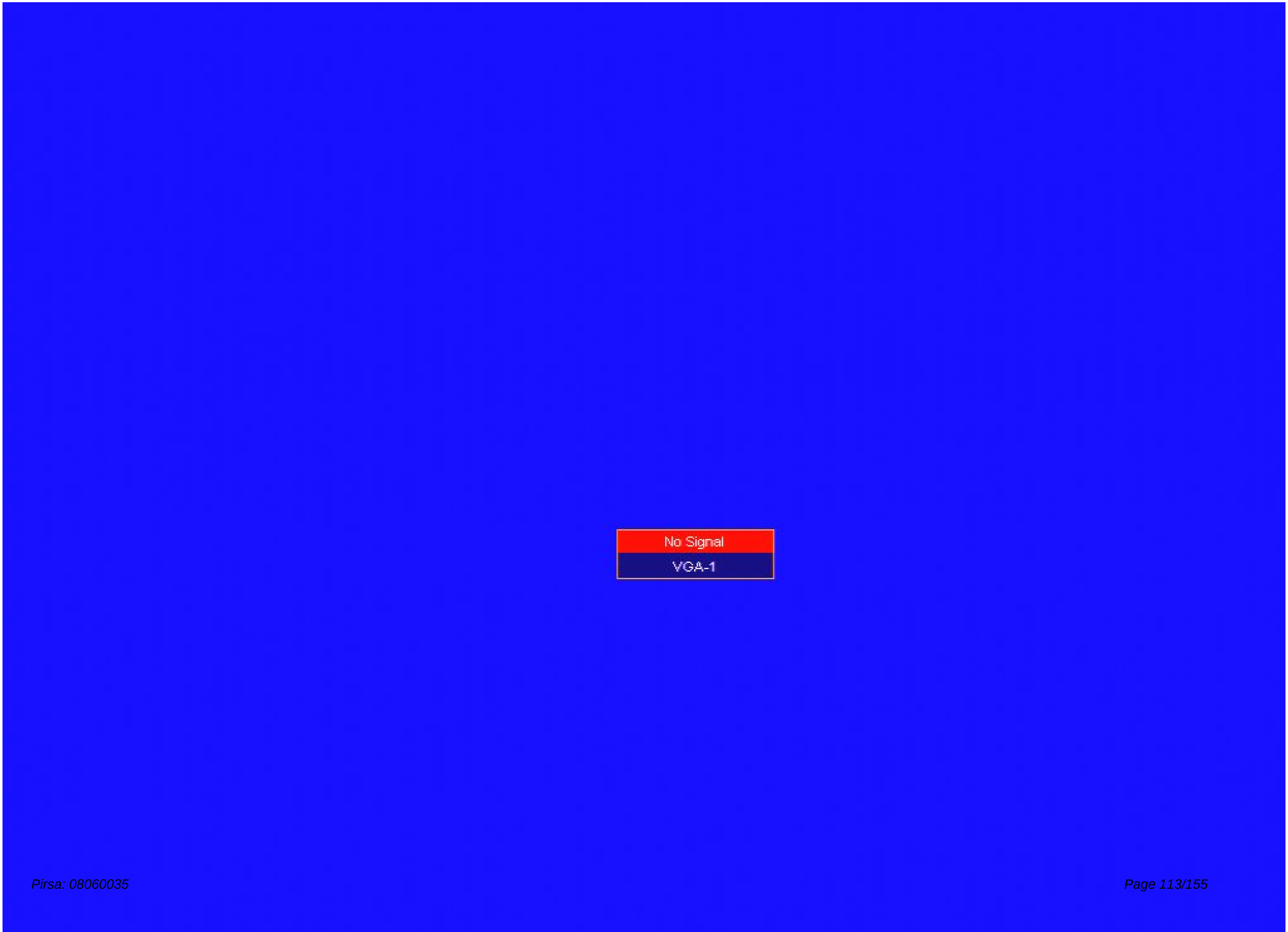
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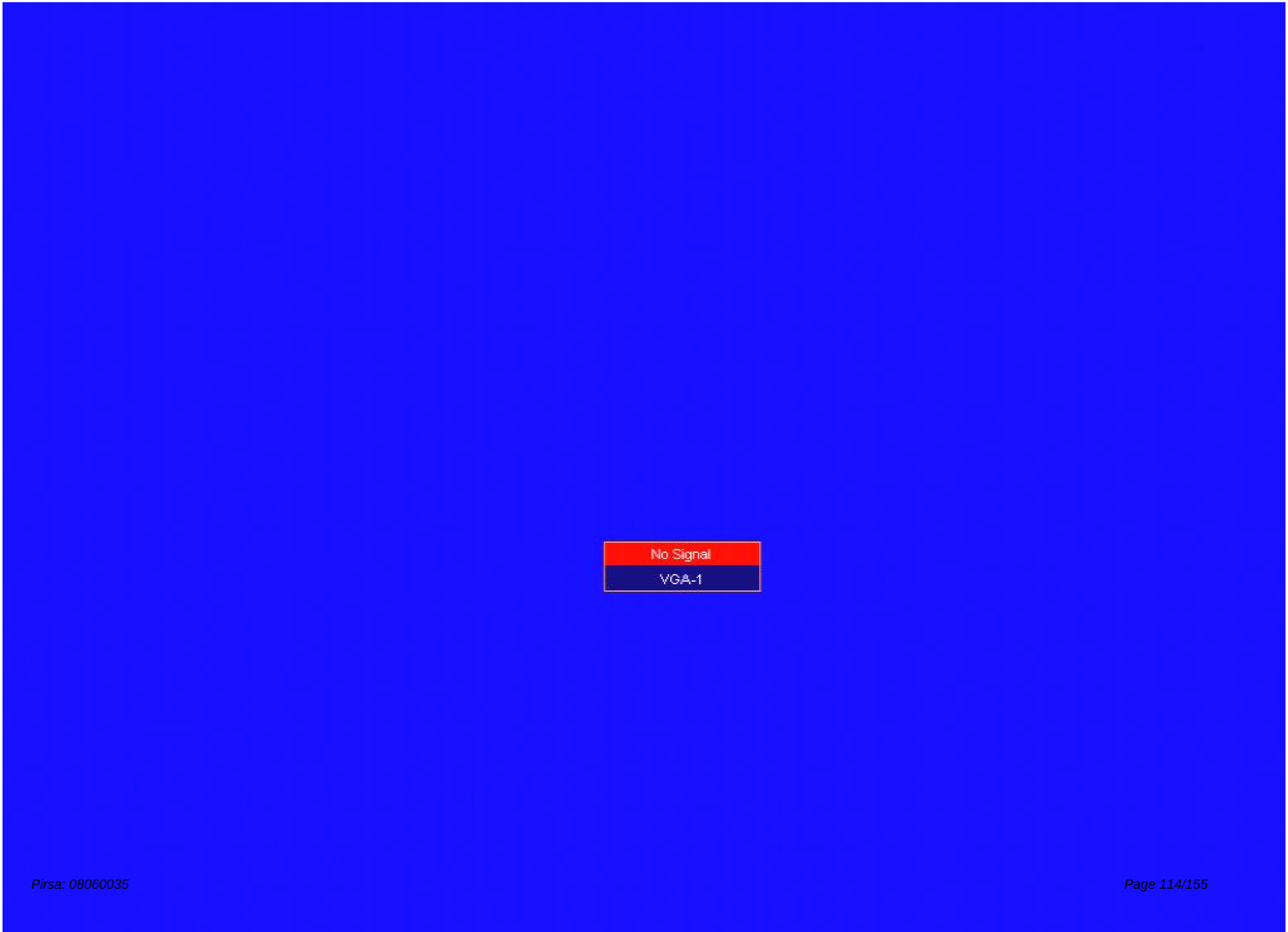
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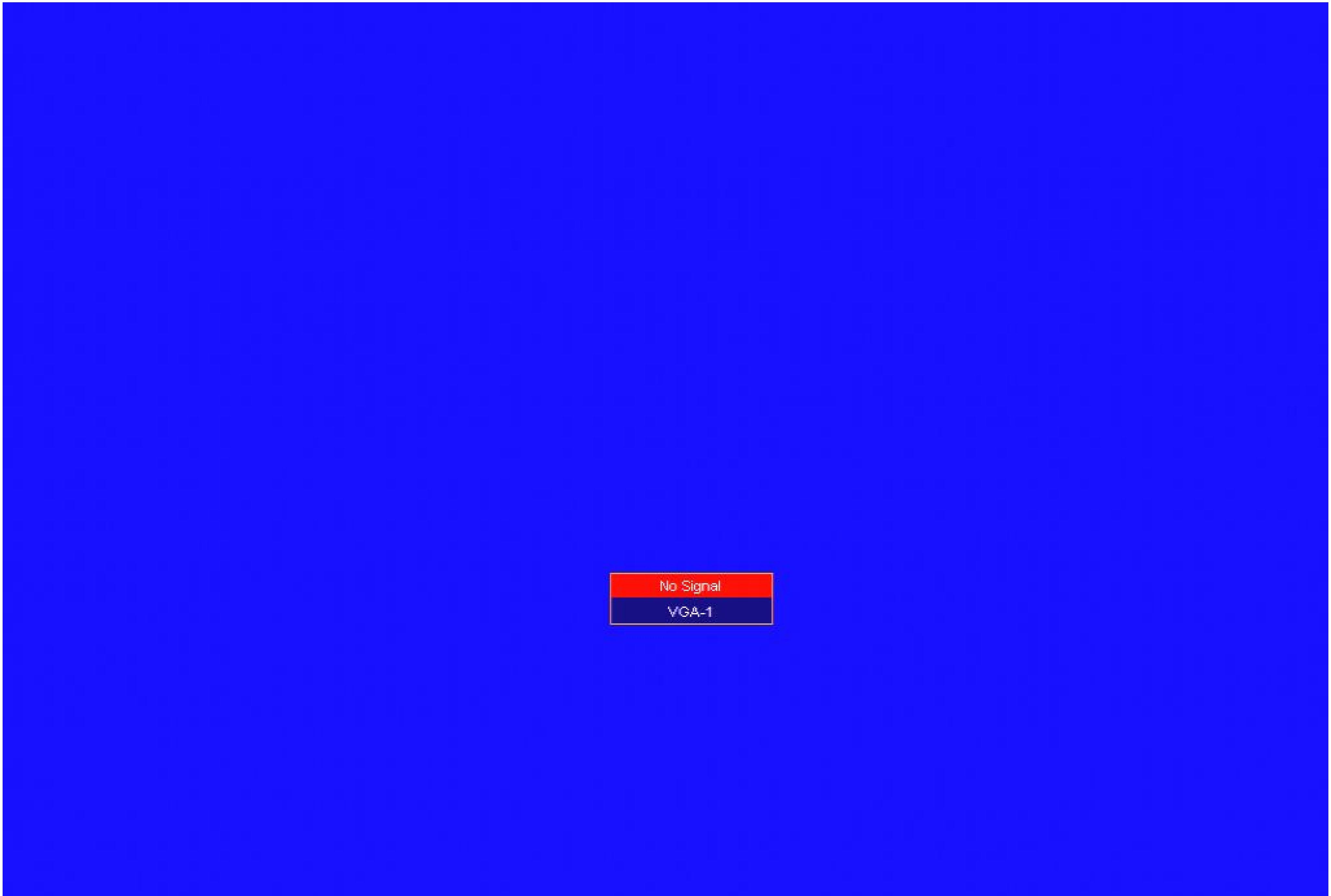
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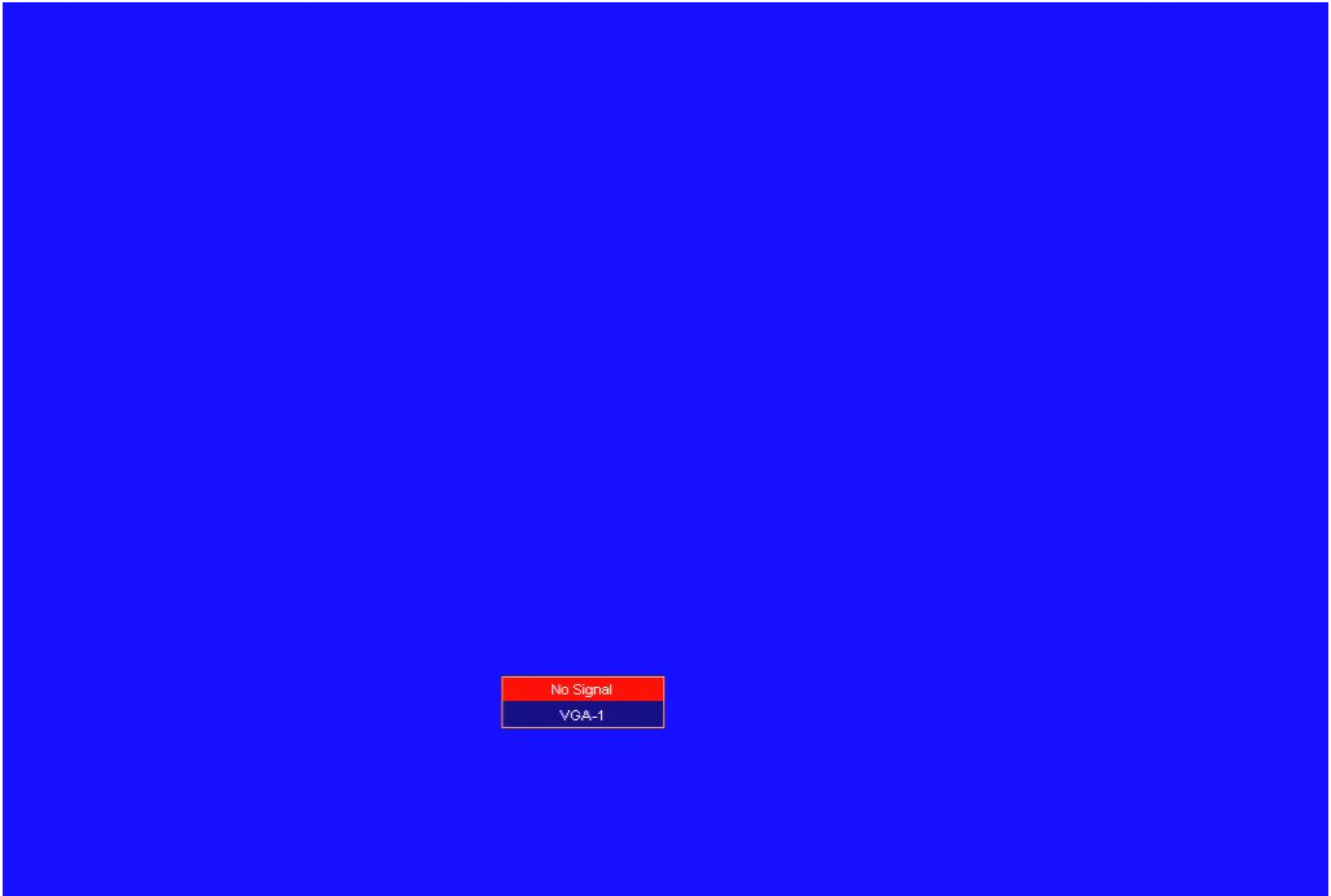
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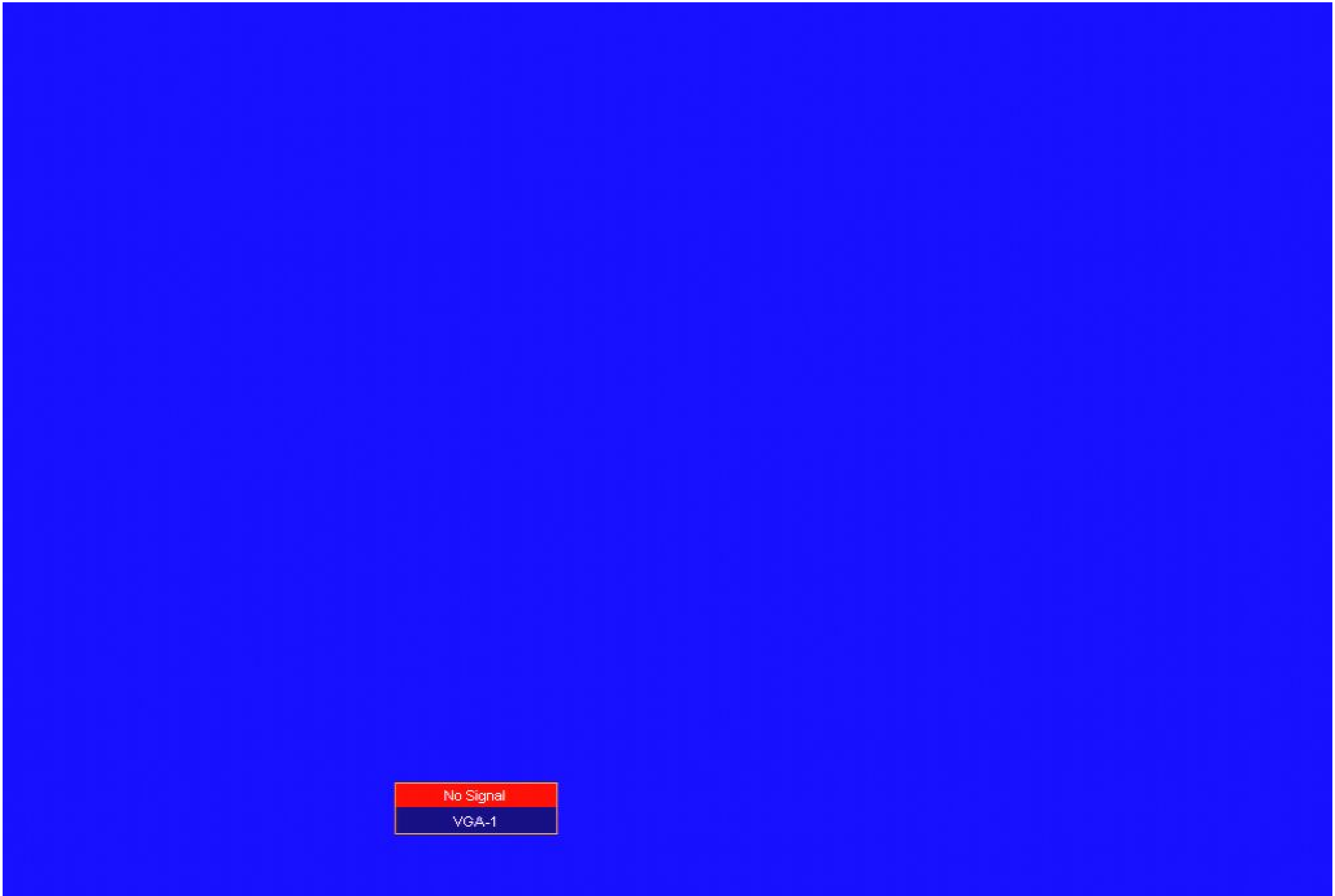
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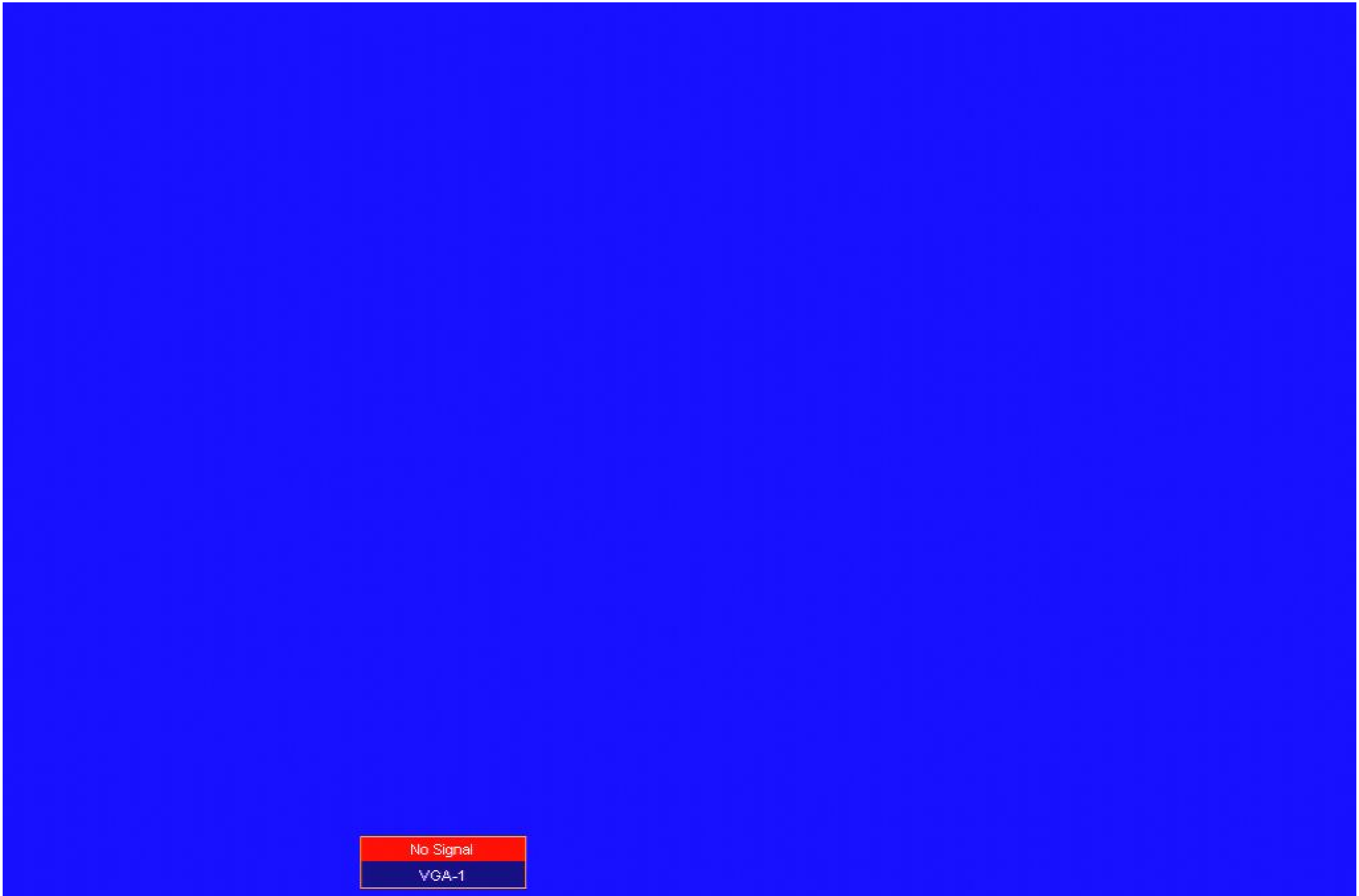
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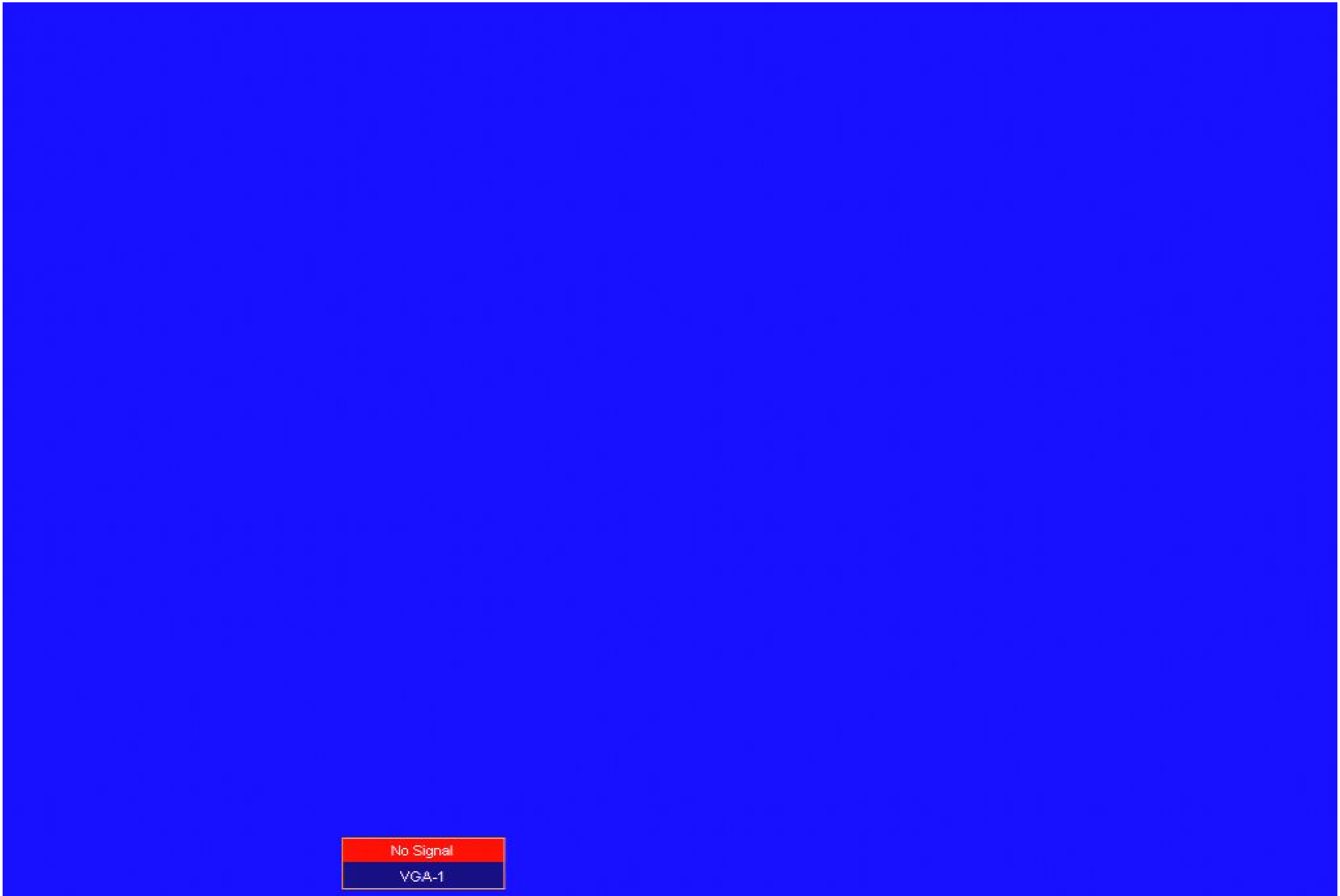
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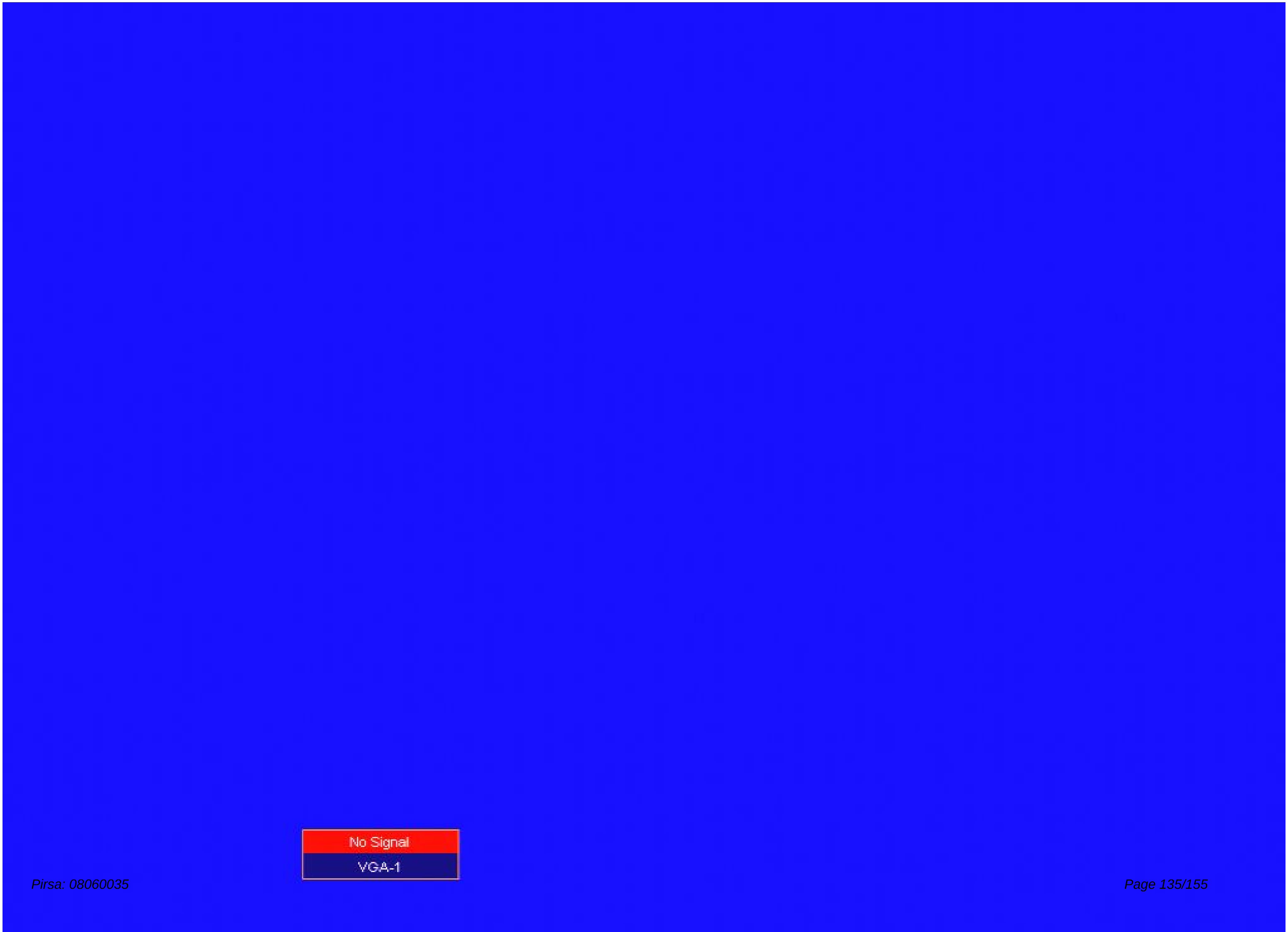
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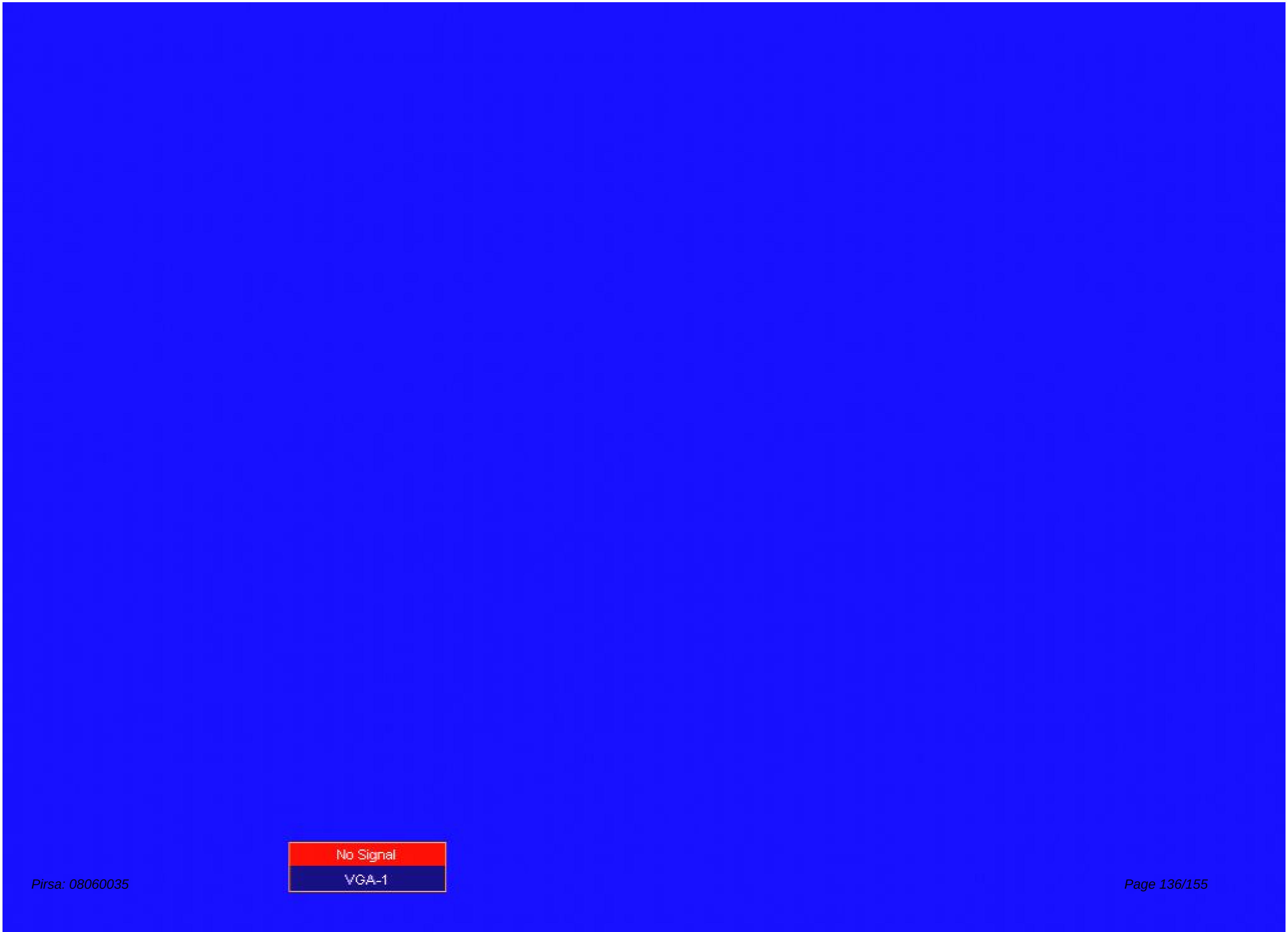
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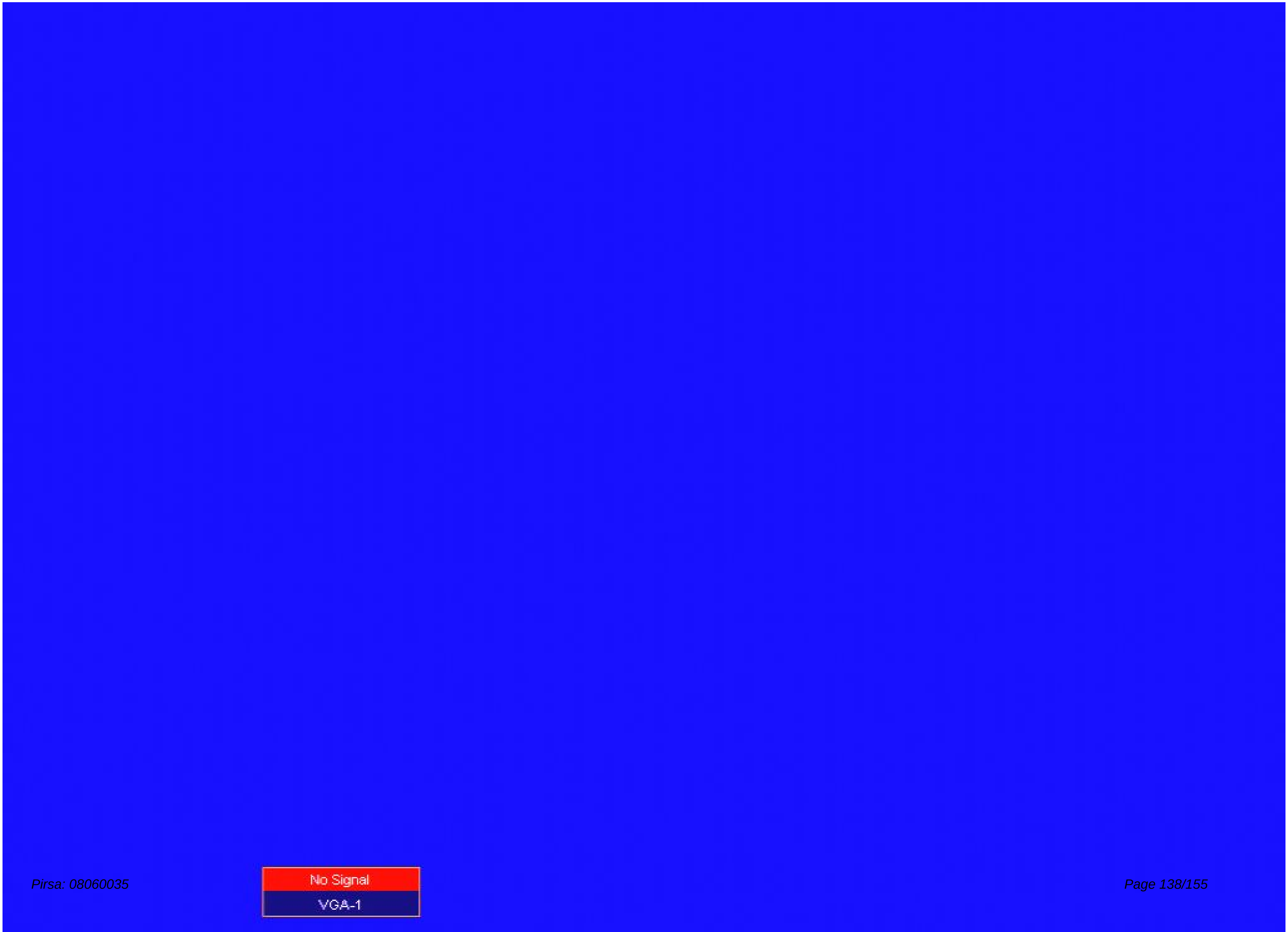
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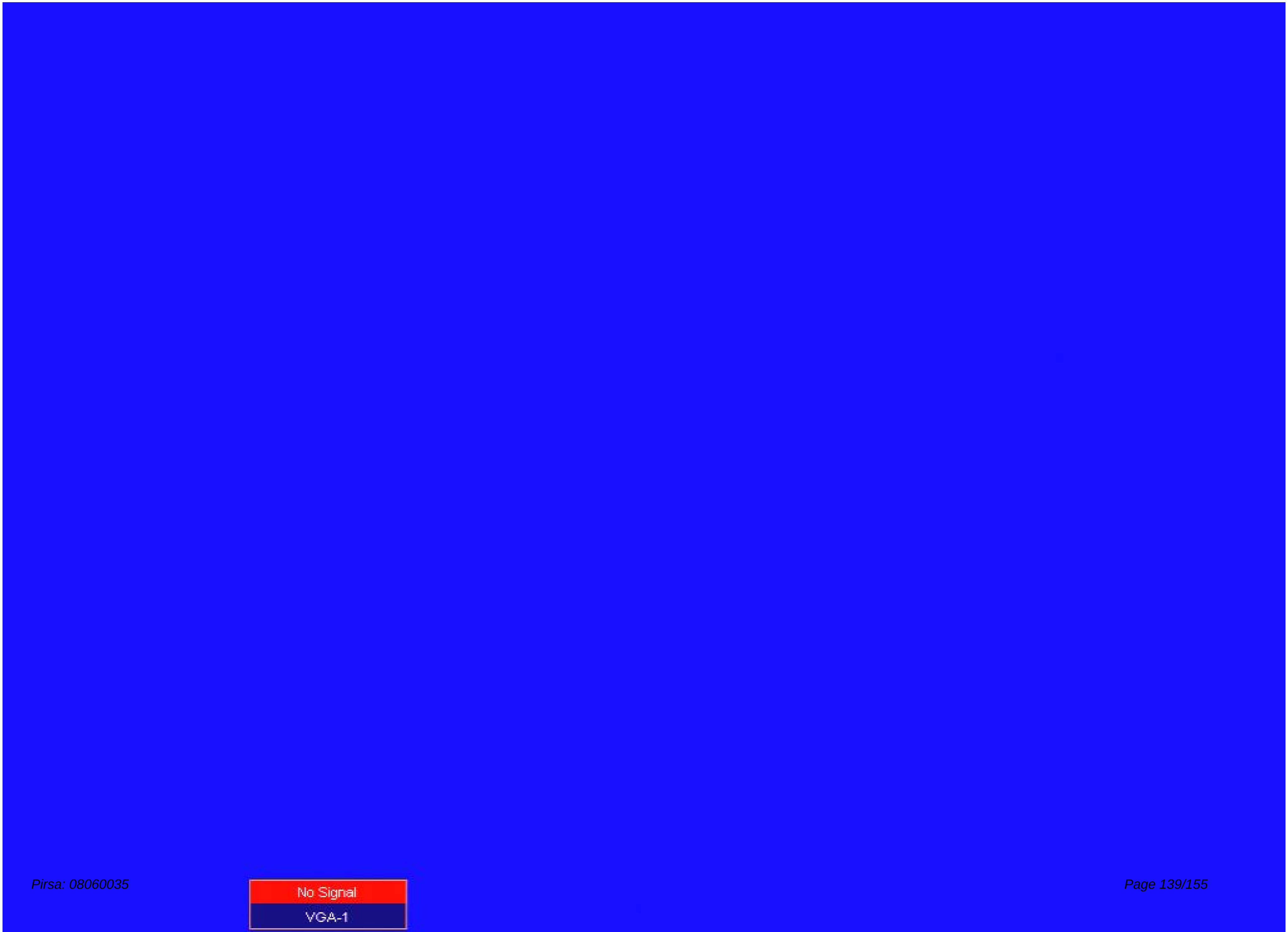
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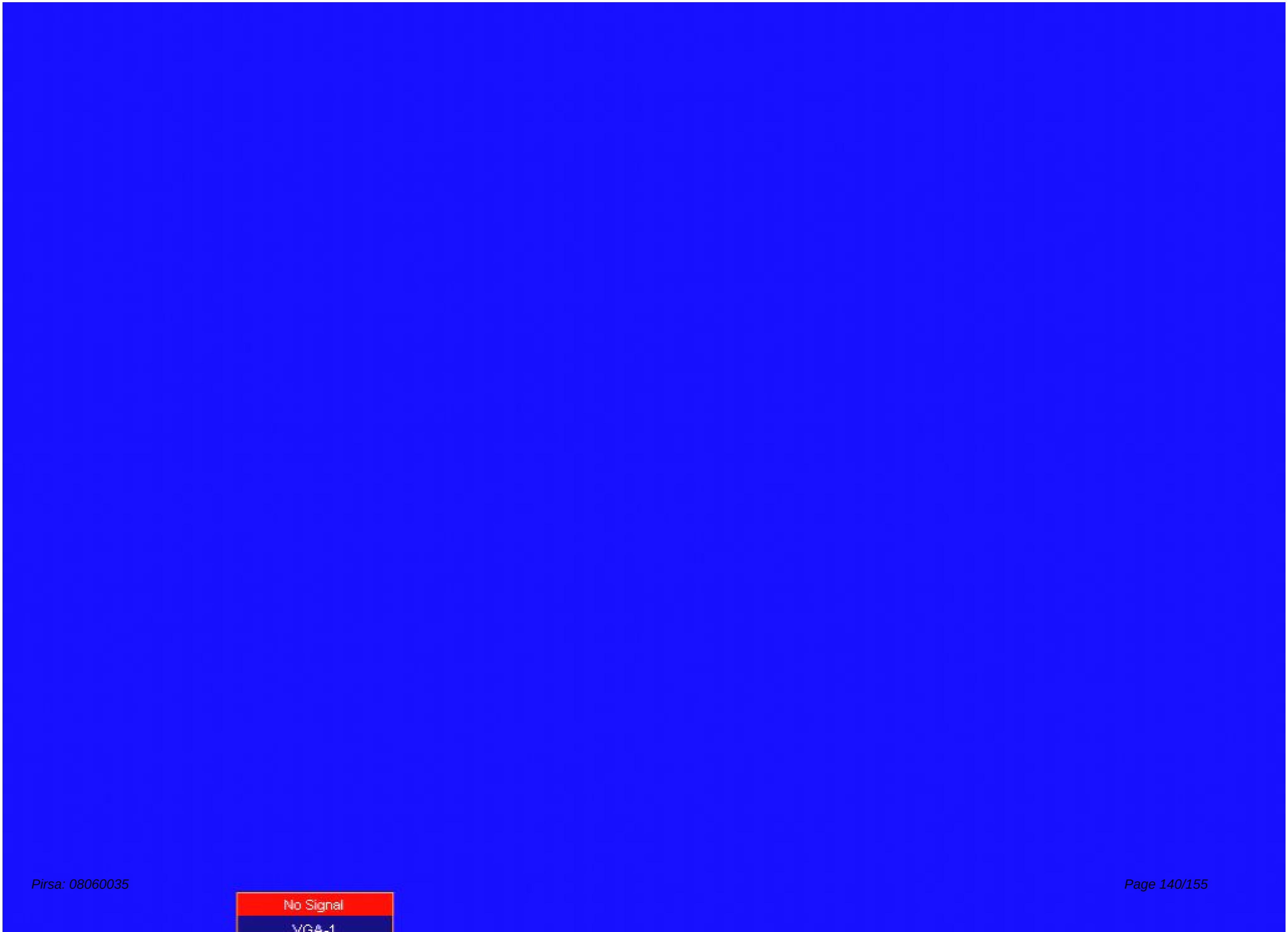
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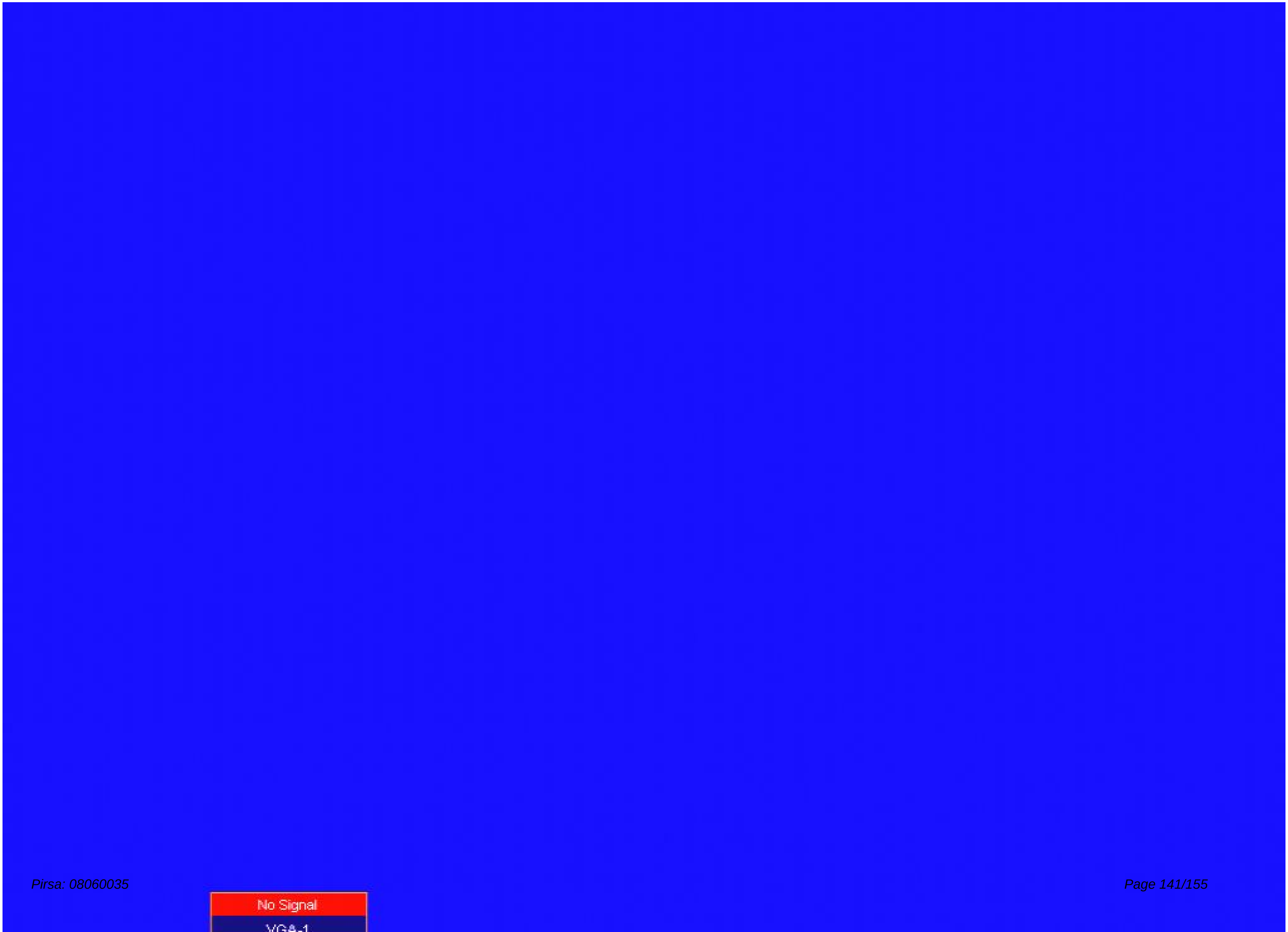
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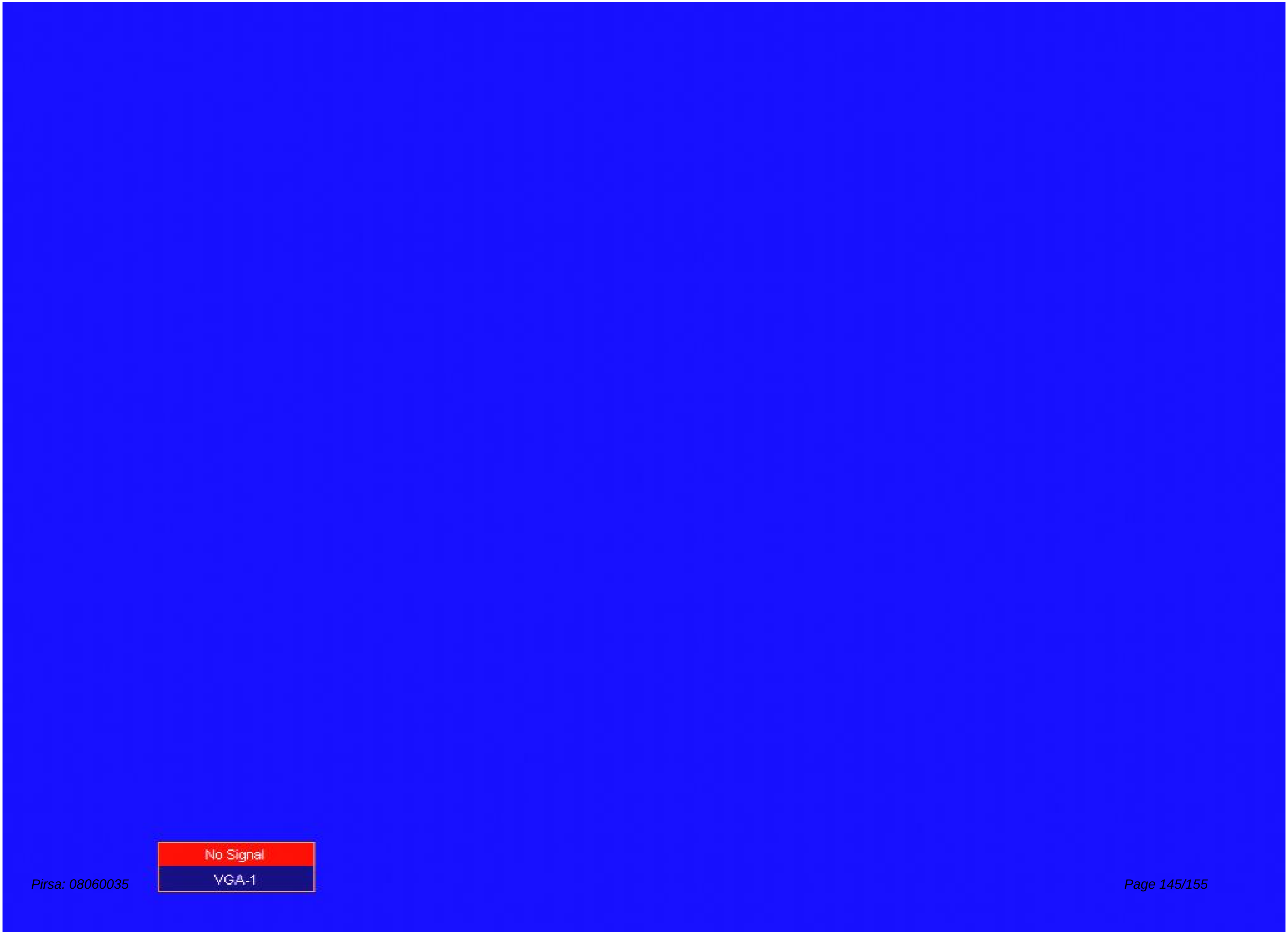
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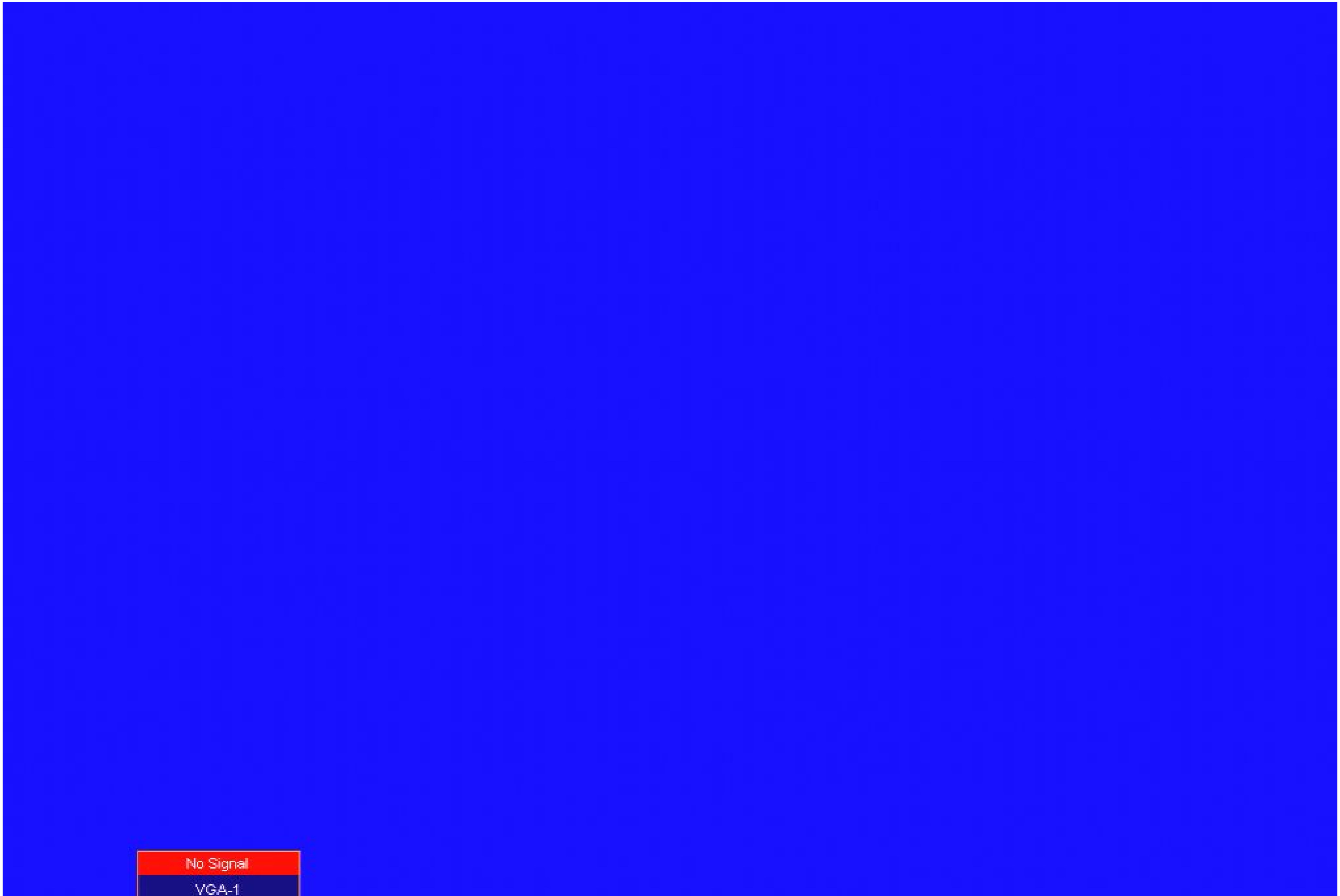
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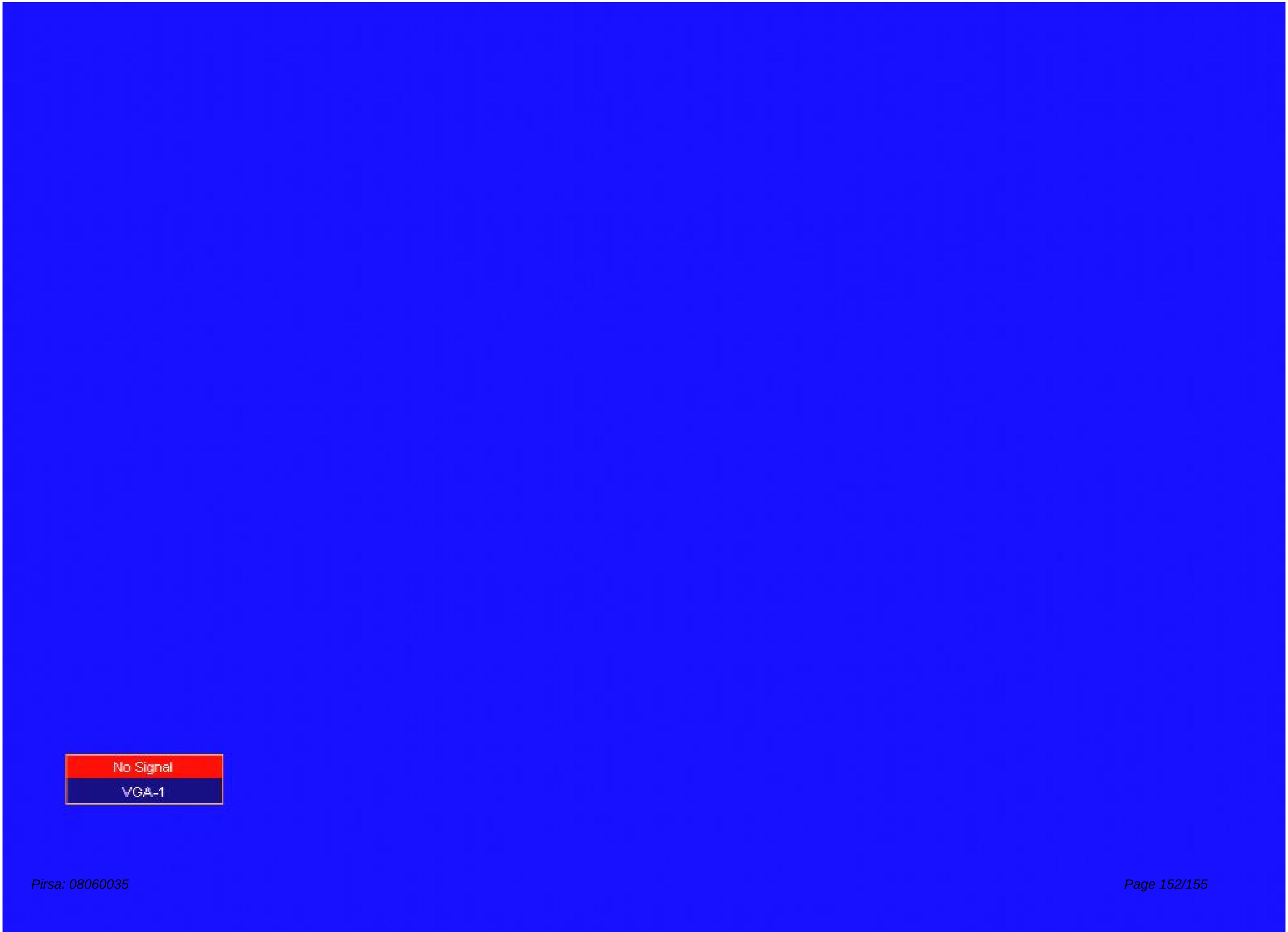
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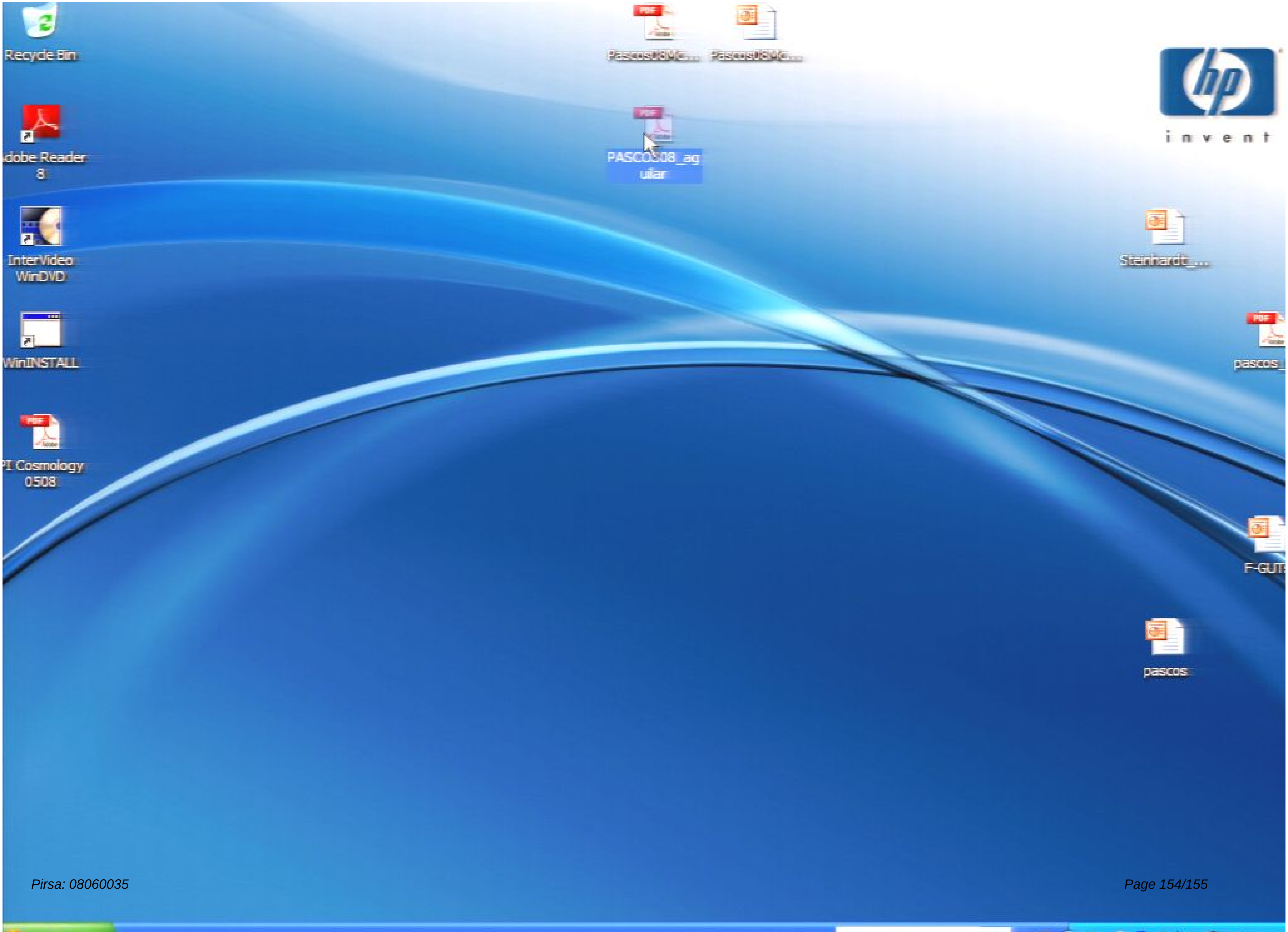
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Results from the MiniBooNE Experiment

Alexis A. Aguilar-Arévalo
for the MiniBooNE Collaboration

June 3, 2008, PASCOS '08