Title: Particle Physics 1

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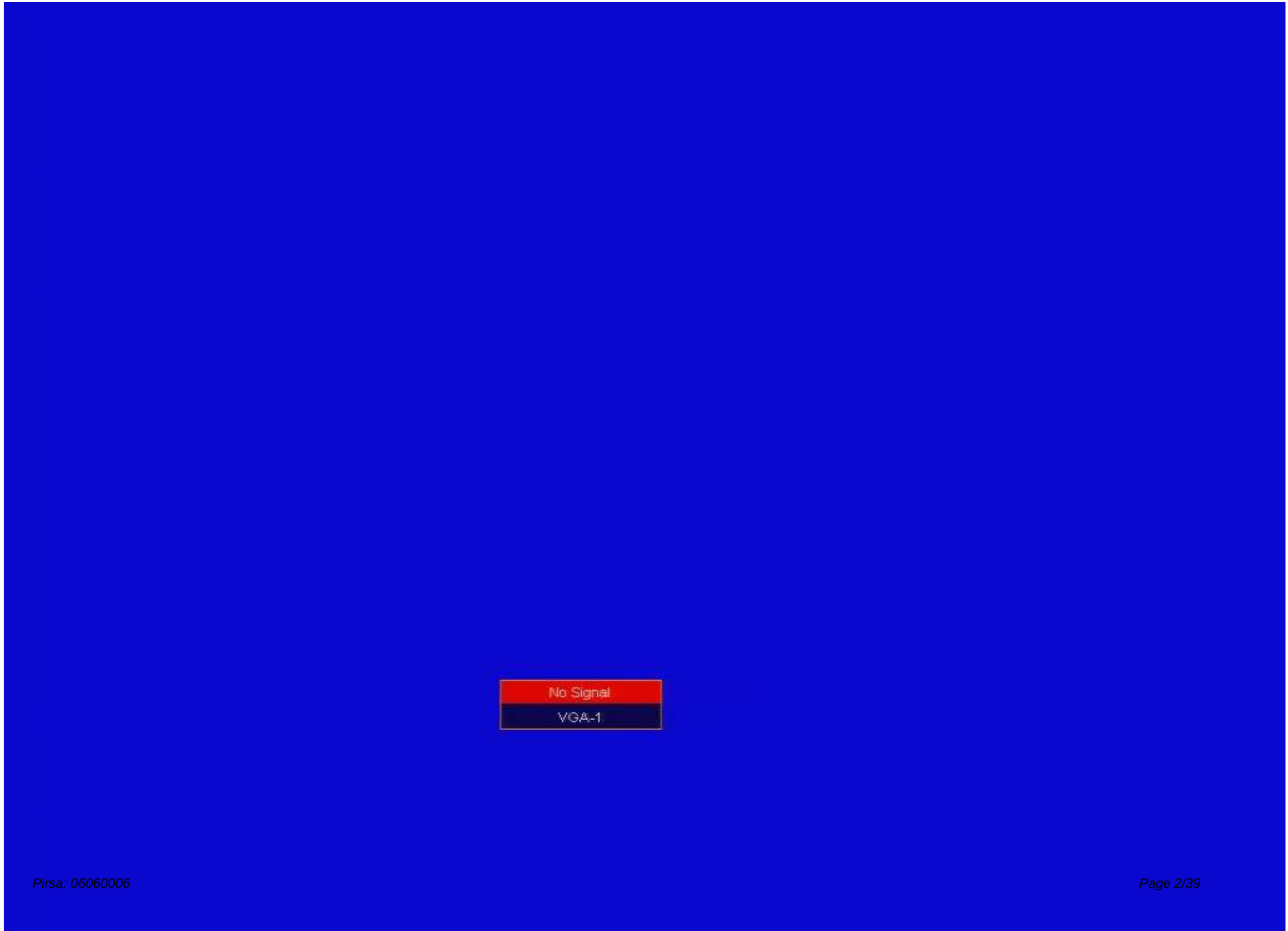
Abstract: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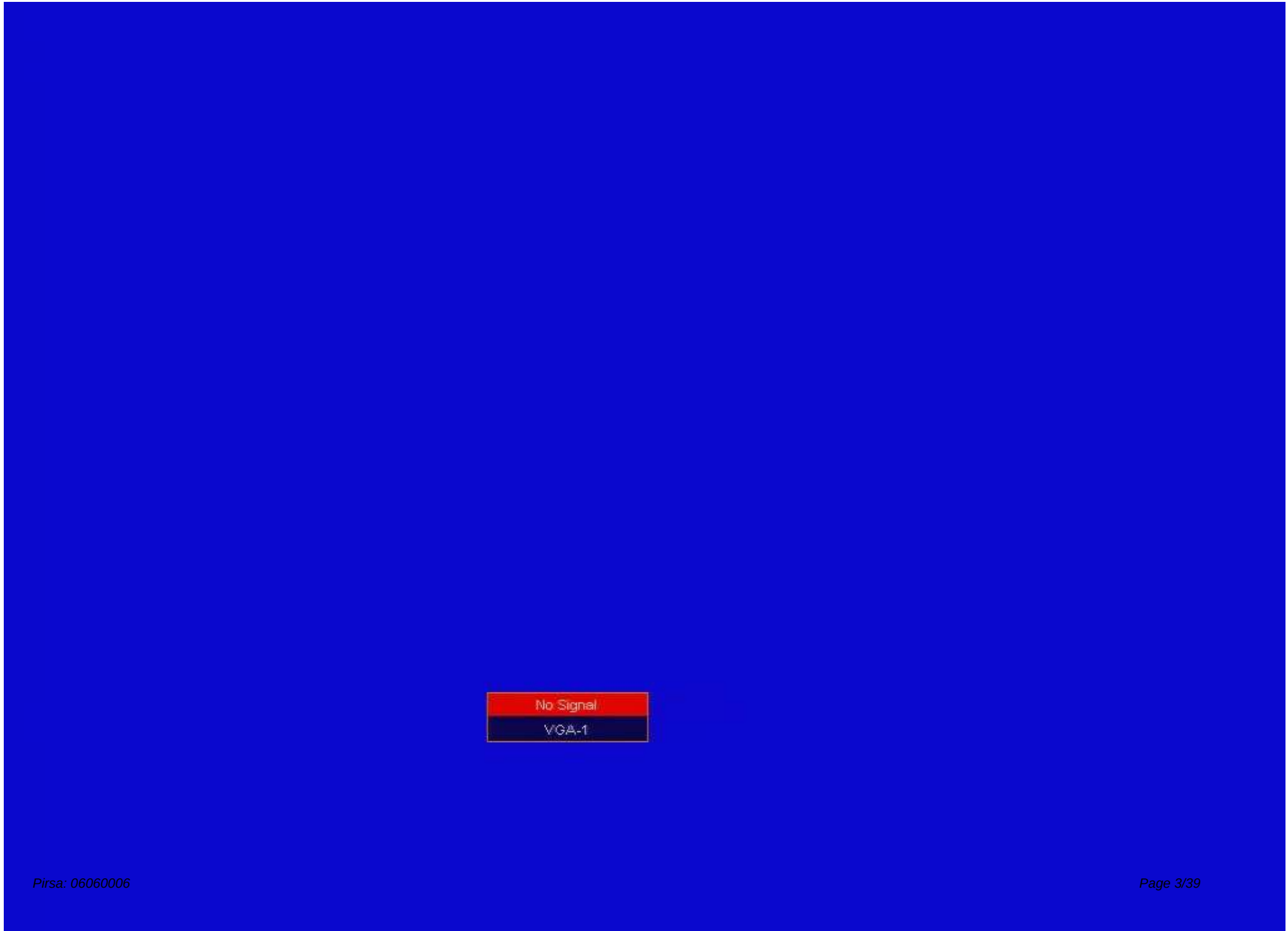
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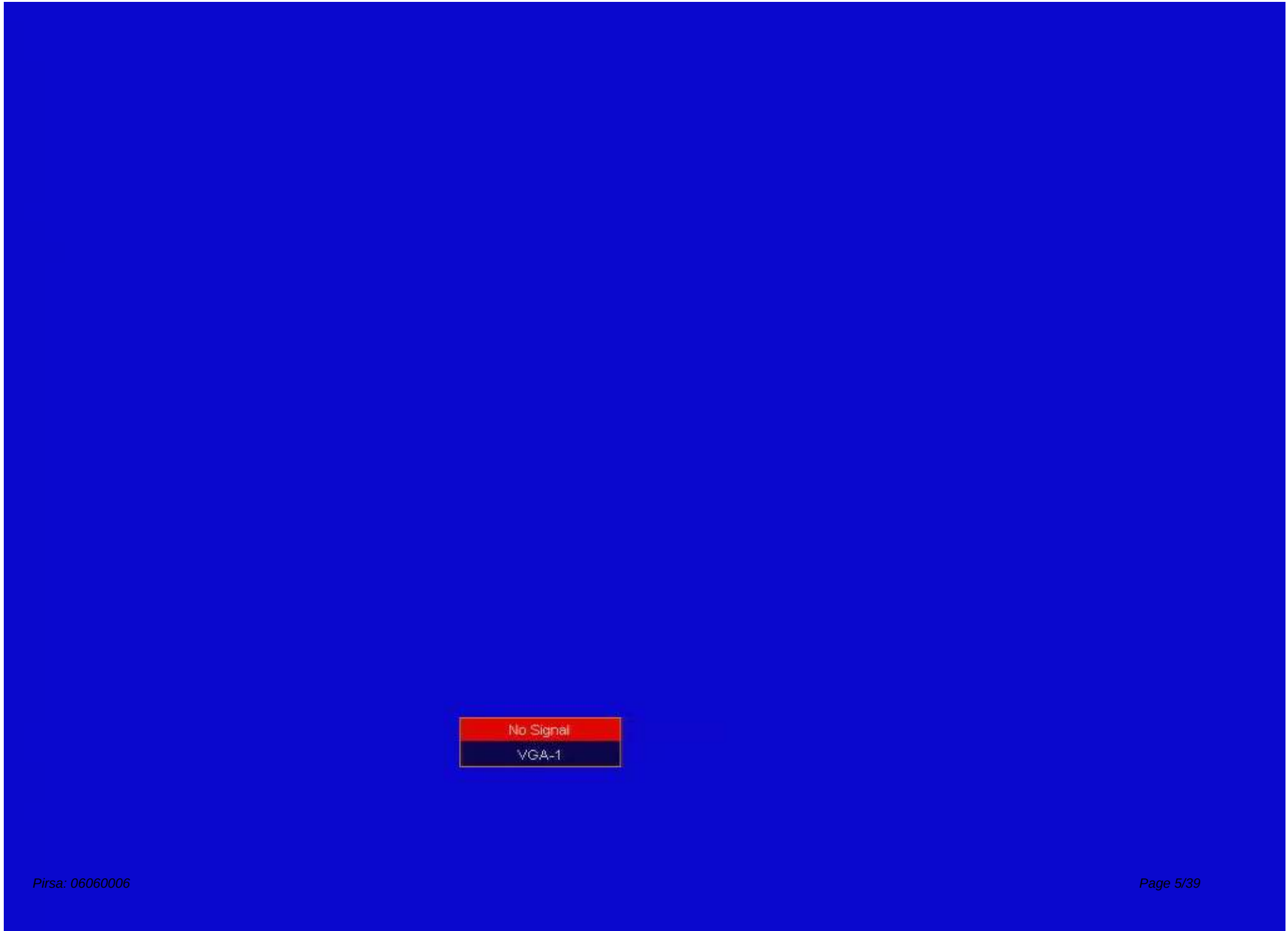
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The Nature of Naturalness

Graham Kribs

University of Oregon

Theory Canada @ PI

June 2006

PARTICLE PHYSICISTS

SEE THE UNIVERSE AS A SERIES OF

EFFECTIVE FIELD THEORIES

THAT HAVE A DOMAIN OF APPLICABI

DETERMINED BY THE ENERGY

PARTICLE PHYSICISTS

SEE THE UNIVERSE AS A SERIES OF

EFFECTIVE FIELD THEORIES

THAT HAVE A DOMAIN OF APPLICABILITY

DETERMINED BY THE ENERGY SCALE.

EACH FIELD THEORY IS CHARACTERIZED BY THE { FIELD CONTENT, SYMMETRIES / COUPLINGS

EXPRESSED IN TERMS OF A RELATIVISTIC ACTION:

$$S = \int d^4x \, \mathcal{L}(\phi, \psi, F_{\mu\nu}, R)$$

- R: RICCI SCALAR
- $F_{\mu\nu}$: GAUGE FIELD STRENGTH
- ψ: FERMIONS
- ϕ: SCALARS

THE RULES TO CONSTRUCT $\mathcal{L}$ FOR AN EFT ARE:

- WRITE ALL COMBINATIONS OF FIELDS CONSISTENT WITH THE SYMMETRIES
- COEFFICIENTS OF OPERATORS ARE $\mathcal{O}(\Lambda^{4-d})$ (d DIMENSIONAL)

THIS IS KNOWN AS A NATURAL EFFECTIVE FIELD THEORY

EXAMPLE: QED

ACTION: $S = \int d^4x \Big[m_e(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L) \Big]$ DIM-3

$+ \bar{\psi}_L \not{\partial} \psi_L + \bar{\psi}_R \not{\partial} \psi_R$

$+ F_{\mu\nu} F^{\mu\nu}$ DIM-4

$+ \frac{F^3}{\Lambda^2} + \frac{(\bar{\psi}\psi)^2}{\Lambda^2} + \cdots \Big]$ DIM ≥ 6

WHERE THE RANGE OF VALIDITY FOR QED:

$$m_e \lesssim E \lesssim \Lambda$$

Λ ← m_μ MUON MASS!

BUT THIS LEADS TO A PUZZLE:

NATURAL EFFECTIVE FIELD THEORIES HAVE ALL DIMENSIONFUL PARAMETERS SET BY Λ.

YET, $m_e \simeq 10^{-2} m_\mu = 10^{-2}\Lambda$.

SO WE MIGHT WORRY THAT QUANTUM CORRECTIONS SHIFT THE MASS OF THE ELECTRON THROUGH CUTOFF SCALE PHYSICS

$$m_e\Big|_{\substack{\text{QUANTUM}\\\text{CORRECTED}}} \overset{??}{=} m_e\Big|_{\text{BARE}} + \Lambda$$

IF THIS WERE TRUE, WE WOULD BE UNABLE TO SEPARATE SCALES WITHOUT FINE-TUNING $m_e|_{\text{BARE}}$ AGAINST Λ.

ALAS, QED IS SAFE:

m_e DOES NOT RECEIVE LINEAR QUANTUM CORRECTIONS $\propto \Lambda$

PERTURBATIVELY, THE QUANTUM CORRECTIONS

CAUSE THE ELECTRON TO BE MULTIPLICATIVELY RENORMALIZED:

$$\frac{d}{d\mu} m_e = m_e \cdot \left(\cdots \Lambda \right)$$

SO THAT THE LIMIT

$$m_e \longrightarrow 0$$

IS A FIXED POINT OF RENORMALIZATION SCALING.

't HOOFT REALIZED THAT THIS WAS NO ACCIDENT, NAMELY ('t HOOFT 1979)

$m_e \to 0$

CORRESPONDS TO AN EFT WITH AN

ENHANCED SYMMETRY

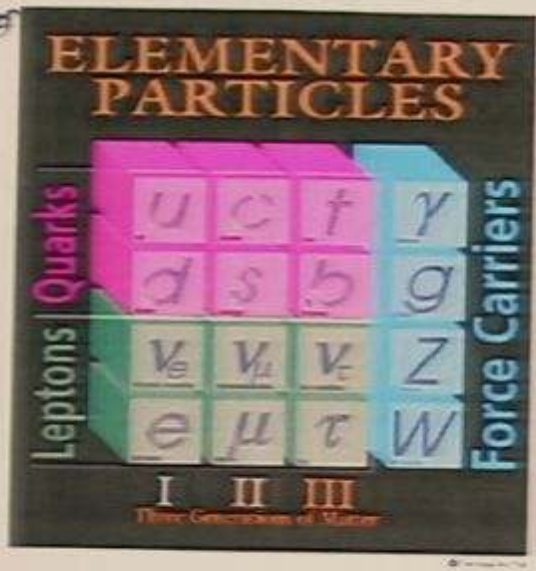
FOR m_e, THIS IS $U(1)_L \times U(1)_R$: INDEPENDENT CHIRAL ROTATIONS OF L- & R-HANDED ELECTRON

PARAMETERS OF EFTS WHERE

PARAMETER $\to 0$ LEADS TO ENHANCED SYMMETRY

ARE CALLED "TECHNICALLY NATURAL".

THE STANDARD MODEL OF PARTICLE PHYSICS IS AN EFFECTIVE FIELD THEORY VALID UP TO THE HIGHEST ENERGIES ATTAINED TO DATE.



MOST OF THE PARAMETERS OF THE STANDARD MODEL ARE TECHNICALLY NATURAL:

- FERMION MASSES (YUKAWA COUPLINGS)
- GAUGE COUPLINGS
- CKM ELEMENTS

AND ARE THUS NOT STRONGLY SENSITIVE TO CUTOFF SCALE PHYSICS.

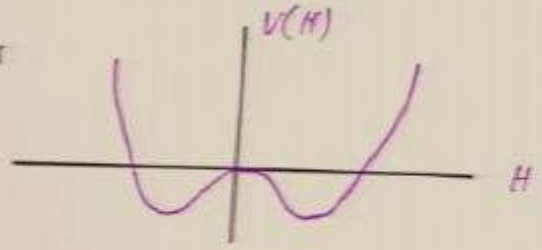
BUT, THERE ARE A HANDFUL OF STANDARD MODEL PARAMETERS THAT ARE

TECHNICALLY UNNATURAL !

- m_H^2 HIGGS SCALAR (MASS)^2
- Λ_{cc} COSMOLOGICAL CONSTANT
- θ_{QCD} QCD VACUUM ANGLE

THE HIGGS $(\text{MASS})^2$ PARAMETER

THE BREAKING OF ELECTROWEAK SYMMETRY IS ACCOMPLISHED WITH A HIGGS SCALAR FIELD w/ POTENTIAL:



WHERE THE SYMMETRY BREAKING SCALE IS DETERMINED BY THE HIGGS $(\text{MASS})^2$. QUANTUM CORRECTIONS SHIFT THE HIGGS $(\text{MASS})^2$:

SO THAT THE QUANTUM CORRECTED HIGGS $(\text{MASS})^2$:

$$m_H^2\Big|_{\substack{\text{QUANTUM}\\\text{CORRECTED}}} = m_H^2\Big|_{\text{BARE}} + \frac{\Lambda^2}{16\pi^2} f(g^2, g'^2, \lambda, \lambda_t^2 \ldots)$$

+ HIGHER LOOP CORRECTIONS...

ADDITIVE, NOT MULTIPLICATIVELY RENORMALIZED

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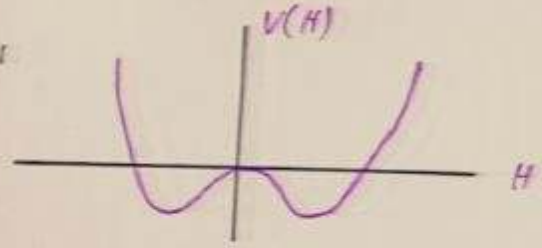

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MOREOVER, THERE ARE SEVERAL INDICATIONS THAT THE CUTOFF SCALE IS LARGE $|\Lambda|^2 \gg |m_H^2|$

- SCALE OF QUANTUM GRAVITY; $\Lambda \sim M_{Pl} \sim 10^{18}$ GeV
- NON-OBSERVATION OF PROTON DECAY $\frac{QQQL}{\Lambda^2}$; $\Lambda \gtrsim 10^{16}$ GeV
- OBSERVATION OF NEUTRINO MASS (ASSUMED MAJORANA) $\frac{(LH)^2}{\Lambda}$; $\Lambda \gtrsim 10^{13}$ GeV

THE STANDARD MODEL SEPARATES THESE MASS SCALES

$$m_H^2 \Longleftrightarrow \Lambda^2$$

ONLY BY FINE-TUNING

$$m_H^2\Big|_{\substack{\text{QUANTUM}\\ \text{CORRECTED}}} \approx -(100\ \text{GeV})^2$$

$$= -1000000000000000000000000000000\,10000 \quad \Big]\ \text{BARE}$$

$$+1000000000000000000000000000000000 \quad \Big]\ \text{LOOP CORRECTION}$$

NAMELY, 1 PART IN 10^{30} !!

MUCH OF THE PAST AND RECENT THEORETICAL EFFORT HAS BEEN DEVISING NEW PHYSICS THAT STABILIZES THE ELECTROWEAK BREAKING SCALE:

- NEW SYMMETRIES (AND FIELDS)
  - SUPERSYMMETRY
  - LARGER GLOBAL SYMMETRIES
  - ⋮
- NEW DYNAMICS
  - TECHNICOLOR
  - COMPOSITENESS
  - ⋮
- NEW CUTOFF SCALE
  - LARGE EXTRA DIMENSIONS
  - WARPED EXTRA DIMENSIONS
  - ⋮

FORTUNATELY THERE ARE ONGOING AND FUTURE EXPERIMENTS THAT WILL FIND OR RULE OUT THESE NEW PHYSICS IDEAS.

THE LARGE HADRON COLLIDER

POISED TO BEGIN IN ABOUT ONE YEAR (!!!)
WILL REACH COLLISION ENERGIES OF 14 TEV
THAT SHOULD (AFTER MUCH ANALYSIS AND EFFORT)
UNCOVER THE PHYSICS BEHIND ELECTROWEAK SYMMETRY BREAKING.

THE COSMOLOGICAL CONSTANT

THE MOST TROUBLING TECHNICALLY UNNATURAL PARAMETER IS THE COSMOLOGICAL CONSTANT.

⇒ LONG HISTORY GOING BACK TO BIG HC:

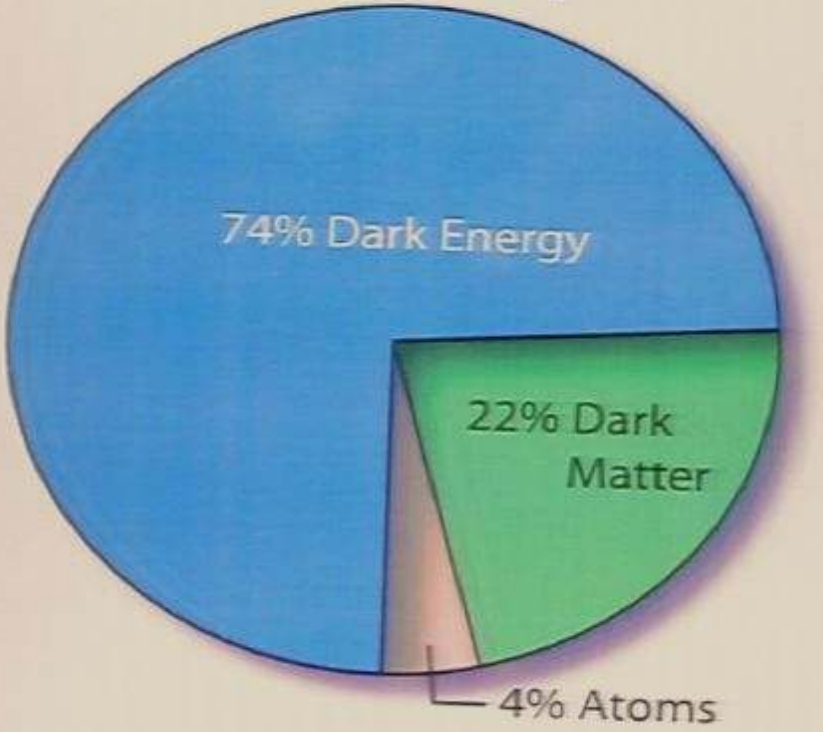
THE MOST TROUBLING TECHNICALLY UNNATURAL PARAMETER IS THE COSMOLOGICAL CONSTANT.

⇒ LONG HISTORY GOING BACK TO BIG HC:

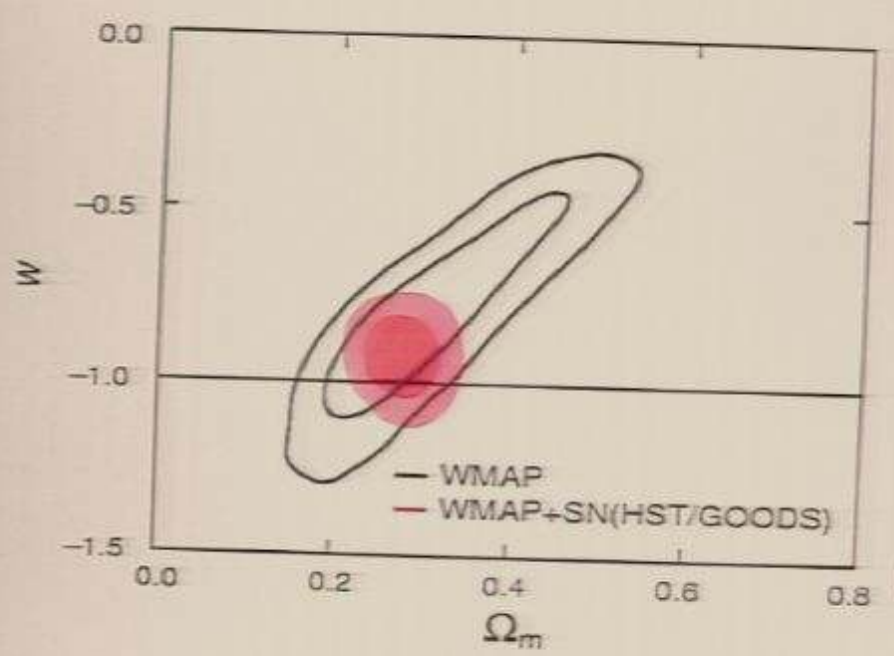
WHO WAS APPARENTLY PARAPHRASED BY KERRY,

"I ACTUALLY VOTED FOR IT BEFORE I VOTED AGAINST IT"

TODAY, THE ENERGY BUDGET OF THE UNIVERSE IS KNOWN TO BE MADE UP DOMINANTLY OF UNKNOWNS:



COMBINING WMAP DATA WITH OTHER COSMOLOGICAL DATA, EQ OF STATE OF DARK ENERGY



[WMAP 2006]

IS TOTALLY CONSISTENT WITH A PURE COSMOLOGICAL CONSTANT.

WE ARE FACED WITH A MEASUREMENT OF THE COSMOLOGICAL CONSTANT

$$\Lambda_{cc} \sim (10^{-3}\ eV)^4$$

WHILE THE TECHNICAL UNNATURALNESS OF THIS PARAMETER SUGGESTS QUANTUM CORRECTIONS DRIVE THIS UP TO:

$$\Lambda_{cc} \sim \Lambda^4 \sim M_{Pl}^4 .$$

AND THUS A FINE-TUNING OF

1 PART IN 10^{120} !!!...

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THE PROBLEM IS EVEN WORSE THAN YOU THINK:

THERE IS NOW COMPELLING EVIDENCE,

$\Omega_{TOT} = 1$ (to within few %)

$n = 0.95$ (± 0.03)

THAT THE UNIVERSE UNDERWENT A PERIOD OF

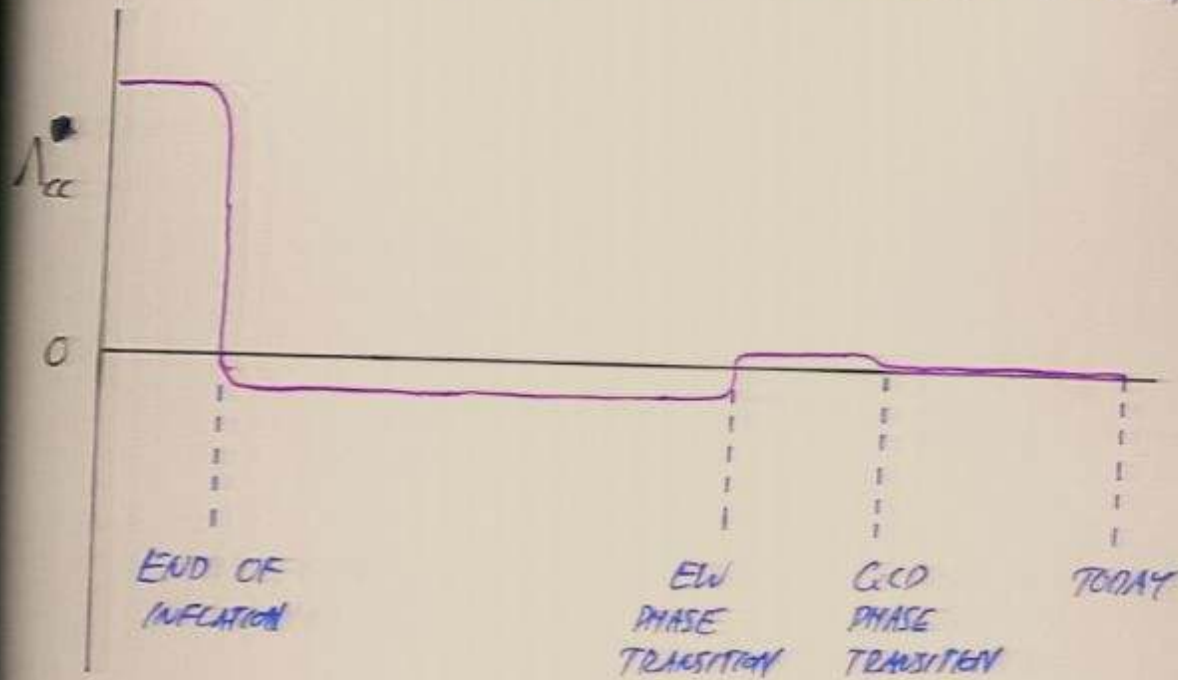
INFLATION

IN WHICH POSITIVE, LARGE VACUUM ENERGY CAUSED THE UNIVERSE TO EXPAND EXPONENTIALLY, EXPLAINING THE LARGE SCALE HOMOGENEITY & ISOTROPY (eg. OF THE CMB)

MOREOVER, AS THE UNIVERSE COOLED IT UNDERWENT A SERIES OF PHASE TRANSITIONS THAT SHIFTED THE VACUUM ENERGY:

- ELECTROWEAK PHASE TRANSITION
- QCD PHASE TRANSITION

A POSSIBLE TIME-DEPENDENT HISTORY OF THE EFFECTIVE SIZE OF THE COSMOLOGICAL CONSTANT:



NOT ONLY DO WE HAVE NO COMPELLING IDEAS TO EXPLAIN A SMALL Λ_{cc}, WE DON'T WANT A TIME-INDEPENDENT SMALL Λ_{cc} (SINCE ... INFLATION!)

ANTHROPIC NATURALNESS ?

THE ONLY RATIONALE FOR A SMALL COSMOLOGICAL CONSTANT THAT APPEARS SUCCESSFUL IS:

- REQUIRE EXISTENCE OF LARGE SCALE STRUCTURE IN THE UNIVERSE CAPABLE OF SUPPORTING OBSERVERS

THEN WE GET A BOUND

$$\Lambda_{CC} \lesssim \mathcal{O}(100)\,\rho_c$$

SUCH THAT DENSITY PERTURBATIONS [WEINBERG PRL] HAVE TIME TO GROW AND GO NON-LINEAR (COLLAPSE)

MOREOVER, GIVEN A FLAT PROBABILITY DISTRIBUTION EXPECT Λ_{CC} TO BE OF ORDER THE BOUND.

(WHICH IT IS, TO WITHIN 10^{-2})

IS AN ANTHROPIC RATIONALE FOR A FUNDAMENTAL PARAMETER NATURAL? IS IT SCIENTIFIC?

- CERTAINLY NO ONE WOULD THINK THAT OUR EXISTENCE ON EARTH, THAT RELIES ON

CRITICAL DISTANCE TO ALLOW LIQUID WATER, IS SURPRISING GIVEN BILLIONS OF STARS & GALAXIES

- IF QUANTUM GRAVITY IS REALIZED IN STRING THEORY, THERE MAY BE A LANDSCAPE OF VACUA TO CHOOSE FROM, $\mathcal{O}(10^{500})$

IF THE ... IS TAKEN TO BE

"ANTHROPICALLY NATURAL"

WHAT ABOUT THE OTHER UNNATURAL PARAMETERS?

WE STUDIED THIS QUESTION IN DETAIL,

CONSIDERING THE MOST EXTREME SCENARIO:

arXiv:hep-ph/0604027 v1 4 Apr 2006

A Universe Without Weak Interactions

Roni Harnik[1], Graham D. Kribs[2], and Gilad Perez[3]

[1]*Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309 and Physics Department, Stanford University, Stanford, CA 94305*

[2]*Department of Physics and Institute of Theoretical Science University of Oregon, Eugene, OR 97403*

[3]*Theoretical Physics Group, Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720*

RESULT? FOR A GENERIC EFT, WE SHOWED THAT EW INTERACTIONS ARE UNNECESSARY, TO GET A CALC[illegible] UNIVERSE WITH BBN, LARGE SCALE STRUCTURE, STARS [illegible] FOR BILLIONS OF YEARS, UP TO IRON. [illegible] ELEMENTS INTO SN (IA SN)

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NATURALNESS SCORECARD

	ANTHROPIC?	EFT MECHANISM TO NATURALIZE?
$\emptyset_{QCD}$	NO	YES
m_H^2	~~YES~~ NO	YES
Λ	YES	NO

SO IT APPEARS THAT THE

COSMOLOGICAL CONSTANT PROBLEM

IS QUALITATIVELY DIFFERENT FROM THE

OTHER TECHNICALLY UNNATURAL PARAMETERS

IS NATURE NATURAL ?

ONGOING, EXTREMELY ACTIVE AREA OF RESEARCH

WITH A REMARKABLE SYNERGY BETWEEN

THEORY & EXPERIMENT.