Victoria University of Wellington

Te Whare Wānanga o te Ūpoko o te Ika a Maui

Pedro's early work in general relativity (up to traversable wormholes)

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Abstract:

- Pedro started shifting the focus of his research from optics to general relativity in the early 1980's, with his early contributions being to bounds on black hole entropy and the connection between black holes and elementary particles.
- I shall survey some of this early work, up to the stage where Pedro became interested in traversable wormholes.

Topics:

Background

Background:

- Starting in the late-1970s early-1980s Pedro shifted his research focus to general relativity.
- Sabbatical at DAMPT (1987).
- Very strongly influenced by the "Hawking school"... (Euclidean quantum gravity.)
- Eventually Pedro published over 130 scientific articles relevant to general relativity.
- Eventually Pedro published 90 single-author scientific articles relevant to general relativity.
- So there is a lot to talk about...
- Inspires reports a (general relativity) citation count circa 2500.
- Inspires reports a (general relativity) h-index of 24.
- So Pedro had a significant influence on the field...

Background:

Pedro's most influential papers (other speakers will focus on these):

- P. F. Gonzalez-Diaz,
  "K-essential phantom energy: Doomsday around the corner?",
  Phys. Lett. B **586** (2004) 1; [astro-ph/0312579] (225 citations).
- P. F. Gonzalez-Diaz,
  "You need not be afraid of phantom energy",
  Phys. Rev. D **68** (2003) 021303; [astro-ph/0305559] (205 citations).
- M. Bouhmadi-Lopez, P. F. Gonzalez-Diaz and P. Martin-Moruno,
  "Worse than a big rip?",
  Phys. Lett. B **659** (2008) 1; [gr-qc/0612135] (148 citations).
- P. F. Gonzalez-Diaz and C. L. Siguenza,
  "Phantom thermodynamics",
  Nucl. Phys. B **697** (2004) 363; [astro-ph/0407421] (135 citations).

Early papers

Early papers 1:

Some of Pedro's earliest GR papers (I will focus on some of these):

- "Some additional results on the directional relationships between forces and accelerations in Special Relativity", Nuovo Cim. B **51** (1979) 104.
- "Black holes and elementary particles", Lett. Nuovo Cim. **31** (1981) 39.
- "Bounds on the Entropy", Phys. Rev. D **27** (1983) 3042.
- "Small-distance derivatives", Lett. Nuovo Cim. **41** (1984) 481.
- "Primordial Coleman–Weinberg inflation", Phys. Lett. **141B** (1984) 314.
- "On higher-derivative gravity interactions", Nuovo Cim. B **90** (1985) 65.
- "On the wave function of the universe", Phys. Lett. **159B** (1985) 19.
- "On the gravitational Lagrangian with R^2 terms", Phys. Lett. **151B** (1985) 405.

All of these are sole-author papers...

Early papers 2:

Some more of Pedro's early sole-author GR papers:

- "Primordial Kaluza-Klein inflation", Phys. Lett. B **176** (1986) 29.
- "Dynamics of the semiclassical Einstein Equations", Phys. Rev. D **33** (1986) 1835.
- "On the black hole internal physics", Annalen Phys. **43** (1986) 62.
- "Perdurance of higher dimensional De Sitter space", Phys. Rev. D **36** (1987) 3651.
- "Instability of higher dimensional De Sitter space", Phys. Lett. B **191** (1987) 263.
- "Quantized cosmological constant", Mod. Phys. Lett. A **2** (1987) 551.
- "The wave function of a stringy Universe", Phys. Rev. D **38** (1988) 2951.
- "Bubbles of false vacuum in General Relativity", Nuovo Cim. B **98** (1987) 37.

Early papers 3:

Some more of Pedro's early sole-author GR papers:

- "A heuristic particle geometry principle",
  Nuovo Cim. B **102** (1988) 115.
- "Correspondence principle in General Relativity",
  Nuovo Cim. B **102** (1988) 195.
- "Black holes and inflation",
  Annalen Phys. **45** (1988) 265.
- "Axion Instanton for Higher Derivative Quantum Gravity",
  Phys. Lett. B **233** (1989) 85.

Wormholes:

Some of Pedro's early sole-author wormhole papers:

- "On the Tolman-Hawking wormhole", Phys. Rev. D **40** (1989) 4184.
- "What is really being lost in wormholes?", Phys. Rev. D **42** (1990) 3983.
- "Broken symmetry in wormholes", Mod. Phys. Lett. A **5** (1990) 2305.
- "Six-dimensional wormholes", Phys. Lett. B **247** (1990) 251.
- "The quantum wormhole", Mod. Phys. Lett. A **5** (1990) 1307.
- "The density matrix of wormholes", Nucl. Phys. B **351** (1991) 767.
- "New wormhole instanton", Nuovo Cim. B **106** (1991) 335.
- "Equivalence among wormhole instantons",
  Int. J. Mod. Phys. A **7** (1992) 2355.
- "Black body distribution for wormholes",
  Class. Quant. Grav. **10** (1993) 2505 [gr-qc/9309009].
- "Quantum theory of wormholes", Mod. Phys. Lett. A **8** (1993) 1089.

Wormholes:

Some more of Pedro's early sole-author papers:

- "Regaining quantum incoherence for matter fields",
  Phys. Rev. D **45** (1992) 499.
- "Nonclassical states in quantum gravity", Phys. Lett. B **293** (1992) 294.
- "Beyond the single universe", Nuovo Cim. B **108** (1993) 1197.
- "Is there gauge quantum hair?", Mod. Phys. Lett. A **8** (1993) 2539.
- "Gravitationally induced nonclassical effects",
  Class. Quant. Grav. **10** (1993) S219.
- "Quantum state and spontaneous symmetry breaking in gravity",
  Int. J. Mod. Phys. D **3** (1994) 191 [gr-qc/9309008].
- "The Quantum sphaleron", Phys. Lett. B **307** (1993) 362 [gr-qc/9305006].

Special relativity

Special relativity:

There is a sense in which the relativistic effective mass is a 3×3 matrix...

3-momentum:

$$\vec{p} = \frac{m_0 \vec{v}}{\sqrt{1 - v^2/c^2}}$$

3-force:

$$\vec{f} = \frac{d\vec{p}}{dt}$$

$\vec{f} = m\,\vec{a}$?

$$\vec{f} = \frac{m_0 \vec{a}}{\sqrt{1 - v^2/c^2}} + \frac{m_0 \vec{v}(\vec{v} \cdot \vec{a})/c^2}{(1 - v^2/c^2)^{3/2}}$$

That is

$$\vec{f} = m_0 \, \frac{1}{(1 - v^2/c^2)^{3/2}} \, \left[(1 - v^2/c^2)\, I + \vec{v} \otimes \vec{v} \right] \vec{a}$$

3-force not necessarily 3-parallel to 3-acceleration...

Special relativity:

In the 3-dimensional sense, effective mass is a 3×3 matrix:

$$m_{eff} = m_0 \, \frac{1}{(1 - v^2/c^2)^{3/2}} \, \left[(1 - v^2/c^2) \, I + \vec{v} \otimes \vec{v} \right]$$

- Longitudinal mass: $m_{||} = m_0 \, \gamma^3$.
- Transverse mass: $m_{\perp} = m_0 \, \gamma$.

Some people still get confused on this issue.

Special relativity:

Another perspective:

4-acceleration:

$$A^a = \frac{d^2 X^a}{d\tau^2} = \left(\gamma \frac{d}{dt}\right)^2 X^a$$

3-space part of 4-acceleration:

$$A^i = \left(\gamma \frac{d}{dt}\right)^2 X^i = \left(\gamma \frac{d}{dt}\right)(\gamma v^i) = \gamma^2 a^i + \gamma^4 v^i (\vec{v} \cdot \vec{a})/c^2.$$

That is:

$$A^i = \gamma^4 \; \left[(1 - v^2/c^2)\, I + \vec{v} \otimes \vec{v}\right]^i{}_j \; a^j.$$

3-space part of 4-acceleration need not be parallel to 3-acceleration...

Some people still get confused on this issue.

General relativity

General relativity: Madelung/Bekenstein

1981 — Madelung representation

$$\psi = \sqrt{\rho}\ \exp(-iS/\hbar)$$

Now much more mainstream.

1983 — Already in 1982/1983 Pedro argued that Bekenstein's 1981 bound

$$S/E \leq 2\pi R,$$

implies

$$S \leq \frac{1}{4}\, A,$$

with this bound being saturated by black holes.

More boldly, Pedro argued that for elementary particles

$$S \leq 2\pi.$$

General relativity: Coleman–Weinberg

1984 — Modified Coleman–Weinberg:

Conformal coupling: $$L \propto R + \frac{1}{6} R\phi^2$$

Effective potential:

$$V_{eff} = A + B\phi^2 + C\phi^4 + D\phi^4 \ln(\phi^2/\mu^2)$$

Tune to:

$$V_{eff} = A + C\phi^4 + D\phi^4 \ln(\phi^2/\mu^2)$$

Tune to:

$$V_{eff} = A + D\phi^4 \ln(\phi^2/\phi_*^2)$$

Tune to:

$$V_{eff} = -\frac{D\phi_*^4}{2e} + D\phi^4 \ln(\phi^2/\phi_*^2)$$

General relativity: Black hole entropy

1986 — black holes as bubbles of false vacuum...

$$L \propto R\left\{1 + (R/R_0)[1 - \ln(R/R_0)]\right\}$$

- Early version of $f(R)$ gravity...
- Early version of "gravastars"...

1987 — quantized cosmological constant...

$$\Lambda \sim \frac{m_P^2}{n} \sim \frac{1}{L_P^2\, n}; \qquad n \sim \left(\frac{c}{H_0\, L_P}\right)^2 \sim 10^{123}.$$

1987 — Euclidean baby universes...

...instantons; loss of quantum coherence (Coleman)...

Wormholes

Wormholes:

Wormholes come in several varieties:

- Euclidean wormholes (instantons; QFT; Euclidean quantum gravity).
- Lorentzian wormholes (bridges across space and time):
  - Traversable (Morris–Thorne).
  - Non-traversable (Einstein–Rosen).

Do not attempt to cross an Einstein–Rosen bridge — you will die...

- Pedro's early work on wormholes was mainly in the Euclidean regime...
- Prof Lobo will talk about Pedro's later work on Lorentzian wormholes...

1989 — Tolman–Hawking wormholes:

...the usual suspects:

...Hawking, LaFlamme, Coleman, Giddings, Strominger.

... yet another Euclidean instanton.

... causality?

Wormholes:

1990 — lost in Euclidean wormholes:

...the usual suspects:

...Hawking, LaFlamme, Coleman, Giddings, Strominger.

... yet another Euclidean instanton.

... causality?

1991 — baby universe $\iff$ BH interior...

Euclidean Schwarzschild:

$$ds^2 = +(1 - 2m/r)dt^2 + \frac{dr^2}{(1 - 2m/r)} + r^2 d\Omega^2$$

(4+0) dimensions $\iff$ (2+2) dimensions...

Maximal extension?

1991 — Euclidean wormhole density matrix?

GR superspace — divide the manifold in two across a hyper-sphere

— factorize (or not) the wavefunction... density matrix?

Wormholes:

1992 — nonclassical states in quantum gravity...

- squeezed states $\rightarrow$ wormholes?

1992 — Euclidean wormholes $\rightarrow$ quantum decoherence?

- Coleman-esque...
- Hawking, LaFlamme, Giddings, Strominger, usual suspects...
- Non-factorizable density matrices...
- Causality...

1993 — black-body distribution for wormholes?

- Still Euclidean...
- Bi-local vertex operators for QFT?
- Planckian distribution for QFT amplitudes?

Wormholes:

1993 — my first visit to Madrid (and Spain for that matter).
1993 — my first seminar at the CSIC in Serrano (Lorentzian wormholes).
1993 — my first meeting with Pedro.

1996 — wormholes and (euclideanized) thermodynamics.

- Solve the problem of the end-state of Hawking evaporation?
- (Idea currently undergoing somewhat of a resurgence)...
- Lorentzian versus Euclidean?
- Euclidean thermodynamics $\Rightarrow$ Lorentzian thermodynamics?
- Questions of scale?

1999 — warp drive spacetime...

- by now firmly in the Lorentzian regime...
- see talk by Francisco Lobo...

Summary

Summary:

- Pedro's work in general relativity spanned some 35 years...
- Pedro's work in general relativity spanned some 130 papers...
- Pedro's work in general relativity spanned some 10 PhD students...

End: