FROM A WORLD OF COLOR
TOWARD A WORLD OF DARKNESS

I. INTRODUCTION

II. DARKNESS & GRAVITY

III. THE TOPOLOGICAL TERM IN FRW COSMOLOGY

IV. DARK ENERGY & THE COSMIC WEB

V. THE TOPOLOGICAL TERM NEAR A MATTER SOURCE

VI. VISUALIZING THE TOPOLOGICAL FLOW

VII. LIMITATIONS OF THE IDEA AND A POSSIBLE FIX

VIII. TOPOLOGICAL FLOW IN THE COSMIC WEB

IX. LESSONS FROM THE PAST
I. INTRODUCTION: THE OLD DAYS

MY TRAJECTORY:

Current Algebra
\[\rightarrow\]
Local sum rules
\[\rightarrow\]
Deep-inelastic scattering
\[\rightarrow\]
QCD & Color

Understanding the integrand

Intuition re constituents

Gell-Mann

Fubini Adler et al.

Feynman
II. DARKNESS & GRAVITY

• Two basic scales in gravitation
  Planck
  Cosmological

• One known “induced” scale
  Dark-energy density

• The proposal: a second “induced” scale
  Darkness density
II. DARKNESS & GRAVITY

• Two basic scales in gravitation
  
  **Planck**  \[ G_{\text{Newton}} \quad 10^{-33} \text{ cm.} \quad 10^{28} \text{ eV} \]
  
  **Cosmological**  \[ \Lambda \equiv \frac{H^2}{3} \quad 10^{28} \text{ cm.} \quad 10^{-33} \text{ eV} \]

• One known "induced" scale
  
  Dark-energy density  \[ \rho \sim \frac{\Lambda}{G_N} \sim H^2 M_{\text{Pl}}^2 \quad 10^{-3} \text{ cm.} \quad 10^{-3} \text{ eV} \]

• The proposal: a second "induced" scale
  
  Darkness density  \[ n \sim H M_{\text{Pl}}^2 \quad 10^{-13} \text{ cm.} \quad 10^8 \text{ eV} \]
WHAT IS DARKNESS?

• Density of topological structures in the gravitational vacuum

• It is a consequence of MacDowell–Mansouri’s extension of the first-order Einstein–Cartan GR

• It is an $O(4,1)$ Yang-Mills gauge theory

• $L \sim F^2$ (“almost topological”)

• Metric tensor is “emergent”

• $\Lambda > 0$ necessarily; $\Lambda = 0$ not possible

• Appropriate for Dirac particles
The $O(4,1)$ action is quadratic in field strength.

The gauge potentials carry the metric information.

The metric tensor is quadratic in the gauge potentials.

The $O(3,1)$ Einstein-Cartan action has 3 terms.
• The $O(4,1)$ action is quadratic in field strength:

\[ S \sim \frac{M^2}{H^2} \int d^4x \ \text{Tr} \ \gamma_5 \ F \cdot F \]

• The gauge potentials carry the metric information:

\[ A_\mu = \gamma_A \gamma_B A^A_{\mu} \equiv H e_\mu + \omega_\mu \quad (A, B = 0, 1, 2, 3, 5) \]

\[ H e_\mu = \gamma_5 \gamma_A A^A_{\mu} \quad \omega_\mu = \gamma_A \gamma_B \omega^{A\mu}_{B} \quad (A, B \neq 5) \]

• The metric tensor is quadratic in the gauge potentials

\[ g_{\mu \nu} = e^A_{\mu} e^B_{\nu} \eta_{AB} \leftarrow \text{Minkowski metric} \]

• The $O(3,1)$ Einstein-Cartan action has 3 terms:

\[ S \sim \frac{M^2}{H^2} \int d^4x \ \text{Tr} \ \gamma_5 \left[ R_\wedge R + H H e_\phi e_\phi R + H e_\phi e_\phi e_\phi e_\phi \right] \]

\[ F = dA + A_\wedge A \]

\[ R = dw + w_\wedge w \]
III. FRW Cosmology

- The scale factor is $a(t)$
- The comoving volume is $a^3(t)$
- The Gauss-Bonnet term is topological
- The darkness is $\alpha(t)$
- The darkness density is $\rho_{\alpha}$
The scale factor is $a(t)$

The comoving volume is $\sim a^3(t)$

The Gauss-Bonnet term is topological

The darkness is $\dot{a}(t)^3$

The darkness density is $\left(\frac{\dot{a}}{a}\right)^3$

$ds^2 = dt^2 - a^2(t)(d\xi)^2$

$V(t) = \int d^3x a(t) = a^3(t) \int d^3x$

$S_{GB} = 2\pi \int_{t_1}^{t_2} dt N(t) = 2\pi \left[ N(t_2) - N(t_1) \right] \sim \frac{M_{Pl}^2}{H^2} \int dt d^3x (\ddot{a} \dot{a} \dot{a})$

$N(t) \sim \frac{M_{Pl}^2}{H^2} (\dot{a})^3 \int d^3x$

$m(t) \sim \frac{M_{Pl}^2}{H^2} (\dot{a})^3$

$m(t) \sim \left\{ \begin{array}{ll} \frac{M_{Pl}^2}{H^2 t^3} \sim \left(\frac{10^{40}}{t}\right)^3 & \text{Earlier} \\ H M_{Pl}^2 \sim 10^{30} \text{cm}^{-3} & \text{Later} \end{array} \right.$

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IV. THE COSMIC WEB: EVOLUTION OF A VOID

*Density: □ High  □ Medium  □ Low  □ Dark

*The Newtonian limit suffices: $\sqrt{\frac{\partial}{\partial t} + \phi}$ vs. $H^3$

*In the heart of darkness there is no tidal deformation.

*Dark-energy voids are important to study
I. Acceleration Toward Matter

- Proton sphere of influence is $R \approx 20$ cm.
- Orbital period at $R$ is $\sim 10$ Gyr.
- Darkness density increases as $R^{-9/2}$.
- It becomes Planckian when $R \sim 10^{13}$ cm.
- Darkness in proton neighborhood $\sim 10^{-6}$.
- This scales as $A^2$ (radii as $A^3$).
V. ACCELERATION TOWARD MATTER

- Proton sphere of influence is \( R \sim 20 \text{ cm} \).

- Orbital period at \( R \) is \( \sim 10 \text{ Gyr} \).

- Darkness density increases as \( r^{-9/2} \).

- It becomes Planckian when \( r \sim 10^{-13} \text{ cm} \).

- Darkness in proton neighborhood \( \sim 10^{60} \).

- This scales as \( A^{1/2} \) (radii as \( A^{3/2} \)).
VI. VISUALIZING THE TOPOLOGICAL FLOW

- The "gauge" (coordinate) choice seems to be important.
- A very intuitive gauge is Painleve-Gullstrand.

- Quasi-Newtonian
- Analog-gravity friendly
- In ADM lingo, it uses "shift"
- For gravity of a proton, we need a coordinate patch
- We only need nonrelativistic limit

- Is "darkness" in a state of stationary flow?
VI. VISUALIZING THE TOPOLOGICAL FLOW

- The "gauge" (coordinate) choice seems to be important.
- A very intuitive gauge is "Painlevé-Gullstrand".
- $\frac{\gamma^2 - 1}{2} = \frac{\dot{r}^2}{N^2} + 2\dot{r}\ddot{r}$
- Quasi-Newtonian
- Analog-gravity: friendly
- In ADM lingo, it 'uses shift'.

- For gravity of a proton, we need a coordinate patch.
- We only need nonrelativistic limit.
- Is "darkness" in a state of stationary flow?
VII. BEYOND THE EFFECTIVE FIELD THEORY

- Trouble when distances $\ll 10^{-13}\text{cm}$ (energies $\gg 100\text{MeV}$)
  - FRW Cosmology
  - Nuclear matter (stay away!)
- Origin of the problem?
  - Factor of $10^{20}$ in $L$
- A possible fix: 6 extra dimensions

- No KK modes should exist
  - No bulk excitations (including gravity)
  - Topological insulators are an analog system
VII. BEYOND THE EFFECTIVE FIELD THEORY

- Trouble when distances $<< 10^{13}$ cm (energies $>> 100$ MeV)
  - FRW Cosmology
  - Nuclear matter (stay away!)
  - Origin of the problem?
    - Factor of $10^{20}$ in $\mathcal{L}$
  - $\mathcal{L}_{GB} \sim 10^{12} \int d^4x F \Rightarrow 10^{12} \int d^4x R$ 
  - A possible fix: 6 extra dimensions
  - No KK modes should exist
  - No bulk excitations (including gravity)
  - Topological insulators are an analog system
VIII. Topological Flow in the Cosmic Web

- No spherical symmetry
- "No sources" (in simulations, at least)
- Newtonian limit suffices

The problem: How does darkness behave in this case?

- Darkness density $\rho$ and darkness current $\vec{j} = \rho \vec{v}$ can only depend on the Newtonian potential $\phi$

The Solution (I think): It looks like LQG.

- Non-abelian intuition is required
- My solution works for previous examples
VIII. **Topological Flow in the Cosmic Web**

- No spherical symmetry
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**The problem**: How does darkness behave in this case?

- Darkness density $\rho \propto$ darkness current $\vec{j} \propto \vec{n} \vec{v}$
  - Can only depend on the Newtonian potential $\phi$

**The Solution (I think)**: It looks like LQG.

\[ n \propto \frac{M_{Pl}^2}{H^2} \sqrt{\det \nabla \phi} \Phi \quad \text{and} \quad \vec{j} \propto \frac{M_{Pl}^2}{H^2} \nabla \left( \frac{\Phi}{2} \right) \]

- Non-abelian intuition is required
- My solution works for previous examples
IX. LESSONS FROM THE PAST

- 1950-2000: Triumph of gauge theories

- But they are all different:
  - QED
  - QCD (Confinement)
  - EW (Higgs)
  - Gravity (Topology)

- Choice of descriptive language is crucial
  - [QM: Hamilton-Jacobi vs. \( F = ma \)]

- A stepwise approach works best
  - [QM: Non-relativistic theory first]

- "The physics" is tougher than "the math"
  - [QM: deBroglie came late]

- The crossover from infrared to ultraviolet is crucial
  - [QCD: currents did the job]
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- 1950-2000: Triumph of gauge theories
- But they are all different:
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- Choice of descriptive language is crucial
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- A stepwise approach works best
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- “The physics” is tougher than “the math”
  - [QM: deBroglie came late]
- The crossover from infrared to ultraviolet is crucial
  - [QCD: currents did the job]
- Does non-Abelian intuition for Newtonian gravity make the darkness more colorful??