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Electromagnetic nature of dark energy:

Cosmic magnetic fields

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The problem of cosmic magnetic fields

Magnetic fields with large coherence lengths $\lambda \sim 10$ kpc and strenghts $B \sim 10^{-6}$ G observed in galaxies and galaxy clusters. Origin is unknown

Two scenarios:

- Primordial field hypothesis: homogeneous fields present before galaxy formation with $B \sim 10^{-10}$ G amplified in the collapse of the protogalactic cloud
- Dynamo mechanism: weak seeds $B \sim 10^{-25}$ - 10^{-30} G at decoupling amplified by the galactic rotation

Several mechanisms proposed to generate seeds, but: dynamo unable to explain fields in young objects and *primordial* fields difficult to create.

General electromagnetism in curved space

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{\lambda}{2}(\nabla_\mu A^\mu)^2 + \underbrace{\sigma R_{\mu\nu}A^\mu A^\nu + \omega R A_\mu A^\mu}\right].$$

Non-minimal couplings

Weak-field limit

$$\begin{aligned} g_{\mu\nu} &= \eta_{\mu\nu} + h_{\mu\nu} \\ A_\mu &= \bar{A}_\mu + a_\mu \end{aligned}$$

$$\bar{A}_\mu = (\bar{A}_0, 0, 0, 0)$$

Background $\quad \bar{A}_0 \simeq 0.3 M_p$

Modified Maxwell's equations:

$$\partial_\nu F^{\mu\nu} + \lambda\partial^\mu(\nabla_\nu A^\nu)^{(1)} = J_g^\mu.$$

$$J_g^\mu = 2(\sigma\,{}^{(1)}R^{\mu\nu} + \omega\,{}^{(1)}R\eta^{\mu\nu})\bar{A}_\nu$$

General electromagnetism in curved space

Current conservation:

$$\partial_\mu J^\mu_g = 0 \Rightarrow \sigma = -2\omega$$

$$\Downarrow$$

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{\lambda}{2}(\nabla_\mu A^\mu)^2 + \sigma G_{\mu\nu}A^\mu A^\nu\right]$$

$$\partial_\mu(\partial_\nu F^{\mu\nu} + \lambda\partial^\mu(\nabla_\nu A^\nu)^{(1)}) = \partial_\mu J^\mu_g.$$

$$\Box(\nabla_\mu A^\mu)_{(1)} = 0 \longrightarrow$$

Lorenz condition

PPN parameters

$$\gamma - 1 \simeq -\sigma\bar{A}_0^2 \leq 2.3 \times 10^{-5} \quad \Rightarrow \quad |\sigma| \lesssim 10^{-5}$$

General electromagnetism in curved space

Classical stability

$h_{\mu\nu} \longrightarrow$ S + V + T

$a_\mu \longrightarrow$ S + V

Real propagation speeds for scalar, vector and tensor perturbations

$$c_s^2 = 1$$
$$c_v^2 \simeq 1 + 16\pi G\sigma^2 \bar{A}_0^2$$
$$c_t^2 \simeq 1 + 16\pi G\sigma \bar{A}_0^2$$

$\longrightarrow$ "Faster than light" photons?

$|\sigma| \ll 1$

Light cones for vectors and tensors

$$\mathcal{G}^{\mu\nu} k_\mu k_\nu = 0$$

$$\mathcal{G}^V_{\mu\nu} = \left[\left(1 + \frac{16\pi G\sigma^2 \bar{A}^2}{1 - \sigma A^2}\right)\eta_{\mu\nu} - \frac{16\pi G\sigma^2}{1 - \sigma A^2}\bar{A}_\mu \bar{A}_\nu\right]$$

$$\mathcal{G}^T_{\mu\nu} = \left[\left(1 + 16\pi G\kappa \bar{A}^2\right)\eta_{\mu\nu} - 16\pi G\kappa \bar{A}_\mu \bar{A}_\nu\right]$$

$\nabla_\mu t$ is timelike everywhere with respect to $(\mathcal{G}^{-1})_{\mu\nu}$

Hawking, Ellis, (1973)

Stable causality: no inconsistencies

General electromagnetism in curved space

Quantum stability

$$\rho = \left\langle T^{(2)}_{00} - \frac{1}{8\pi G} G^{(2)}_{00} \right\rangle$$

Positive energies for vector and tensor perturbations.

$$\begin{aligned} \rho_s &= 0 \quad \longleftarrow \text{Lorenz condition} \\ \rho_v &\simeq 2k^2(1 - 16\pi G\sigma^3 \bar{A}_0^4)|\vec{C}|^2 \\ \rho_t &\simeq k^2(1 - 8\pi G\sigma \bar{A}_0^2)\left(|C_\oplus|^2 + |C_\otimes|^2\right) \end{aligned}$$

Cosmological evolution

$$ds^2 = dt^2 - a(t)^2 d\vec{x}^2$$

$$A_\mu = (A_0(t), 0, 0, A_z(t))$$

$$\ddot{A}_0 + 3H\dot{A}_0 + 3\left(\dot{H} - 2\frac{\sigma}{\lambda}H^2\right)A_0 = 0$$

$$\ddot{A}_z + H\dot{A}_z + \sigma(4\dot{H} + 6H^2)A_z = 0$$

$$A_0(t) \propto t^{1+\mathcal{O}(\sigma)}$$

Matter/radiation eras

Dark energy and cosmic magnetic fields

Effective electromagnetic current

$$J_g^\mu = 2\sigma G^{\mu 0} A_0 = 16\pi G\sigma T^{\mu 0} A_0$$

Einstein's equations

$$J_g^\mu = 16\pi G\sigma P^\mu A_0$$

Electromagnetic current density ⇦ Energy-momentum density

Dark energy and cosmic magnetic fields

$$T^{\mu\nu} = (\rho + p)u^{\mu}u^{\nu} - p\eta^{\mu\nu}$$

Electric charge density

$$\rho_g = J_g^0 = 16\pi G\sigma\rho\bar{A}_0$$

Current density

$$\vec{J}_g = 16\pi G\sigma(\rho + p)\vec{v}\bar{A}_0$$

$|\vec{v}| \ll 1$

Particle at rest with mass *m*

$$\Delta q = 16\pi G\sigma m\bar{A}_0 \simeq 15\sigma(m/M_P)$$

Modifies the active electric charge, but not the passive charge

Gravitational magnetism conjecture

Schuster (1912), Einstein (1924), Blackett (1947)

"The earth and sun have magnetic fields, the orientation and sense of which stand in approximate relationship with the axes of rotation . . . But it is hard to imagine that electrical conduction or convection currents of sufficient magnitudes are really present . . . It rather looks as if cyclic motions of neutral matter are producing magnetic fields". *A. Einstein (1924)*

$$dH = -C\, dm\, \vec{v} \times \vec{r}/r^3 \quad \rightarrow \quad q \sim m/M_P$$

"The constant C has the dimension (gravitational constant)$^{1/2}$/(speed of light). From this, one can estimate the order of magnitude of C: If one puts this numerical magnitude into the above formula, it will, applied to the rotating earth, give the right order of magnitude for the magnetic field. These relationships deserve consideration, but could be accidental."

Dark energy and cosmic magnetic fields

Electron-proton charge difference. Neutron charge

$$\Delta q \simeq 15\sigma m_n/M_p \simeq 4\sigma 10^{-18} e$$

Experimental limit: PDG (2008)

$$\Delta q < 10^{-21} e$$

Rotating compact objects

$$\vec{m} = \beta \frac{\sqrt{G}}{2c} \vec{L}$$

Schuster-Blackett law (planets, galaxies, neutron stars…)

$$\beta = 16\pi\sqrt{G}\sigma A_0 \lesssim 10^{-4}$$

Magnetic moment **Angular momentum**

Observations

$$\beta \sim 10^{-1} - 10^{-3}$$

Dark energy and cosmic magnetic fields

Blackett's experiment (1952)

Neutral sphere
Mass: 500 kg
Radius: 0.5 m
Rot. Freq: 100 Hz

$$B \sim \sigma 10^{-10}\ \mathrm{T} \lesssim 10^{-15}\ \mathrm{T}$$

Just below SQUID, SERF sensitivity

Typical spiral galaxy (without any amplification)

$$B_0 \sim \sigma 10^{-4}\ \mathrm{G} \lesssim 10^{-9}\ \mathrm{G}$$

"Primordial" field or dynamo seed

Conclusions

General electromagnetic theories in curved space-time including non-minimal couplings

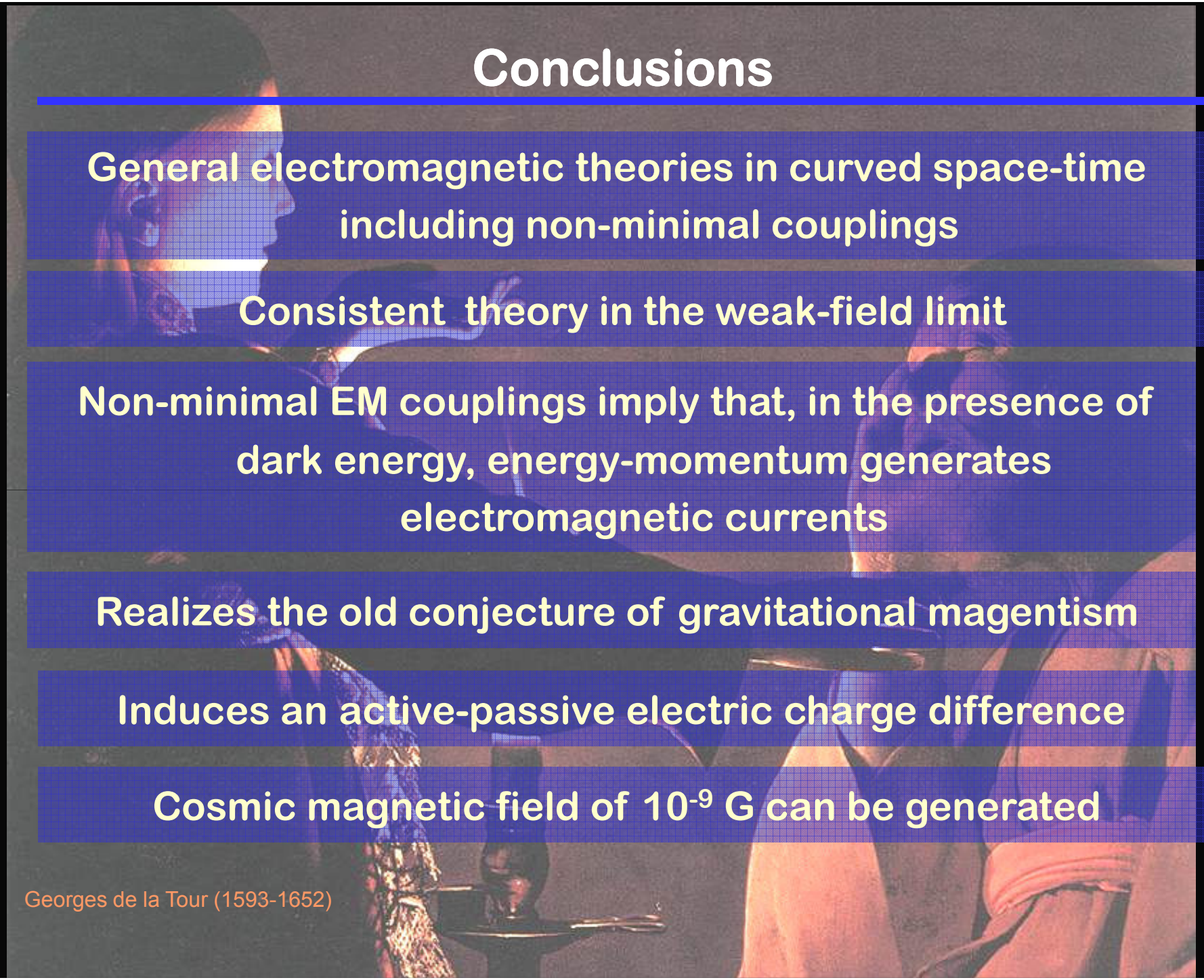
Consistent theory in the weak-field limit

Non-minimal EM couplings imply that, in the presence of dark energy, energy-momentum generates electromagnetic currents

Realizes the old conjecture of gravitational magentism

Induces an active-passive electric charge difference

Cosmic magnetic field of 10^{-9} G can be generated



Georges de la Tour (1593-1652)