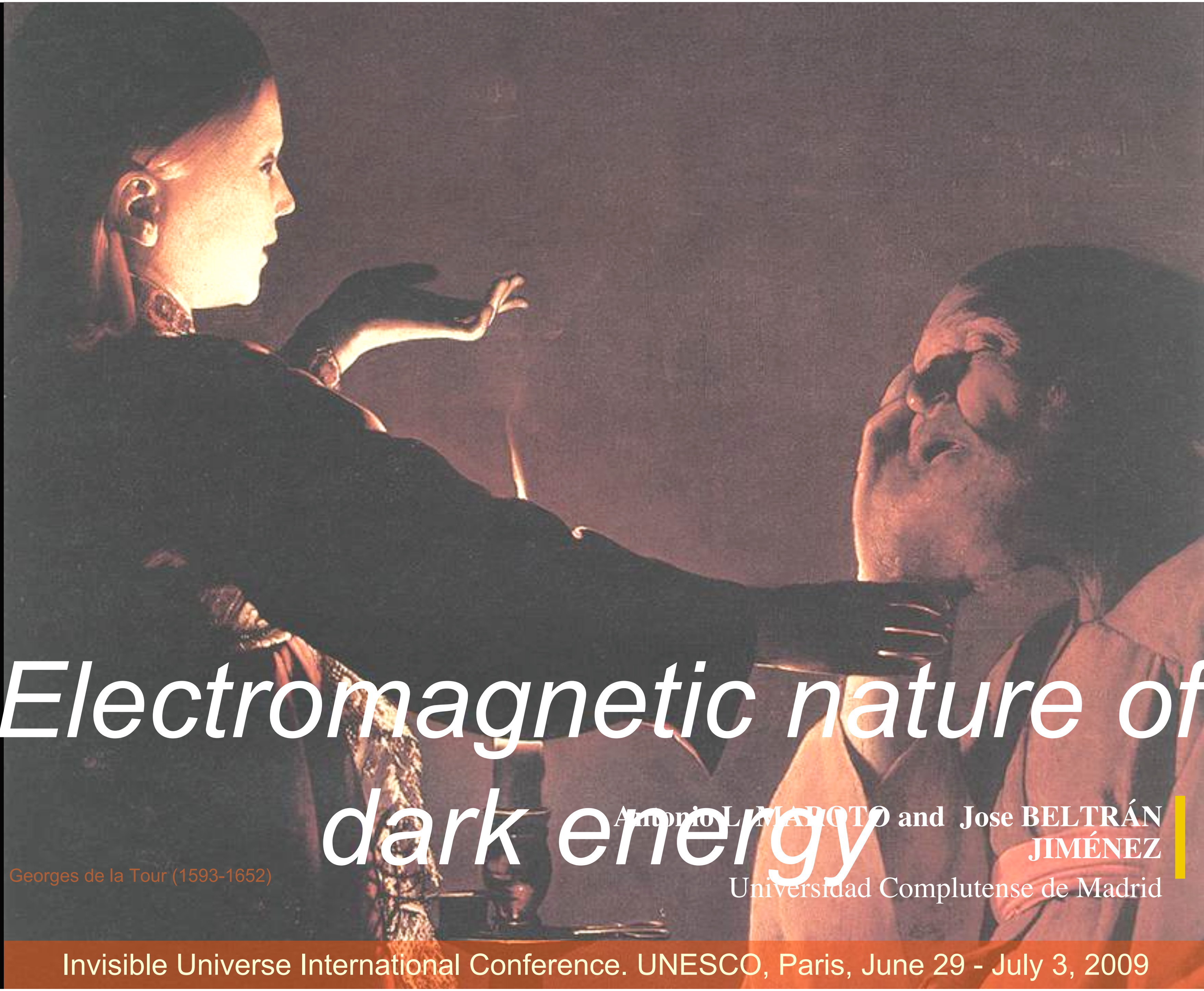

Electromagnetic nature of dark energy

Antonio L. MAROTO and Jose BELTRÁN JIMÉNEZ

Universidad Complutense de Madrid

Georges de la Tour (1593-1652)

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What is the nature of dark energy?

The standard cosmological constant explanation suffers from an important naturalness problem

$$\rho_\Lambda^{1/4} \sim (10^{-3}\ \mathrm{eV}) << M_P$$

Alternative models based on new physics plagued by:

- classical or quantum instabilities,
- fine tuning problems,
- inconsistencies with local gravity constraints.

Large-distance modifications of gravity suggested

What about electromagnetism on large scales?

EM quantization in Minkowski space-time

$$S = \int d^4x \left(-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + A_\mu J^\mu \right)$$

$$A_\mu \rightarrow A_\mu + \partial_\mu \Lambda$$
$$\partial_\mu J^\mu = 0$$

Gauge invariance

$$\partial_\nu F^{\mu\nu} = J^\mu$$

Maxwell's equations

BUT ....

- **Photon propagator?**
- **Negative energies**
- **"Unphysical" temporal and longitudinal photons**

→ **Coulomb's gauge**

→ **Covariant quantization**

EM quantization in Minkowski space-time

Coulomb's gauge

$$\partial_\mu A^\mu = 0$$

Lorenz condition

$$\begin{aligned} A_\mu &\rightarrow A_\mu + \partial_\mu \theta \\ \Box\theta &= 0 \end{aligned}$$

Residual gauge symmetry

$$\Box A_\mu = J_\mu$$

Maxwell's equations

$$\begin{aligned} A_0 &= 0 \\ \vec{\nabla}\cdot\vec{A} &= 0 \end{aligned}$$

Residual gauge (free fields)

2 physical states
Positive energies

Quantize

Covariant quantization

$$S = \int d^4x \left(-\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + \frac{\lambda}{2}(\partial_\mu A^\mu)^2 + A_\mu J^\mu \right)$$

Modified action: only residual symmetry

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

$$\Box(\partial_\nu A^\nu) = 0$$

Free field + boundary conditions= Lorenz condition

$$\partial_\nu A^{\nu\,(+)}|\phi\rangle = 0$$

$$\Updownarrow$$

$$(\mathrm{a}_0(\vec{k}) + \mathrm{a}_{||}(\vec{k}))|\phi\rangle = 0$$

$$\Updownarrow$$

$$n_0(k) = n_{||}(k)$$

2 physical states. Positive energies

EM quantization in an expanding universe

Covariant quantization

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

$$\nabla_\nu F^{\mu\nu} + \lambda \nabla^\mu (\nabla_\nu A^\nu) = J^\mu \longrightarrow \Box(\nabla_\nu A^\nu) = 0$$

Non-conformally coupled to gravity

$$\mathbf{a}_\lambda^{(in)}(\vec{k}) \to \sum_{\lambda'=0,\parallel} \left[\alpha_{\lambda\lambda'}(\vec{k}) \mathbf{a}_{\lambda'}^{(in)}(\vec{k}) + \overline{\beta_{\lambda\lambda'}(\vec{k})} \mathbf{a}_{\lambda'}^{(in)\dagger}(-\vec{k}) \right]$$

$$\Updownarrow$$

$\nabla_\nu A^\nu$ can be amplified from quantum vacuum fluctuations by the expanding background (e.g. during inflation) $\rightarrow$ **Lorenz condition?**

A toy model

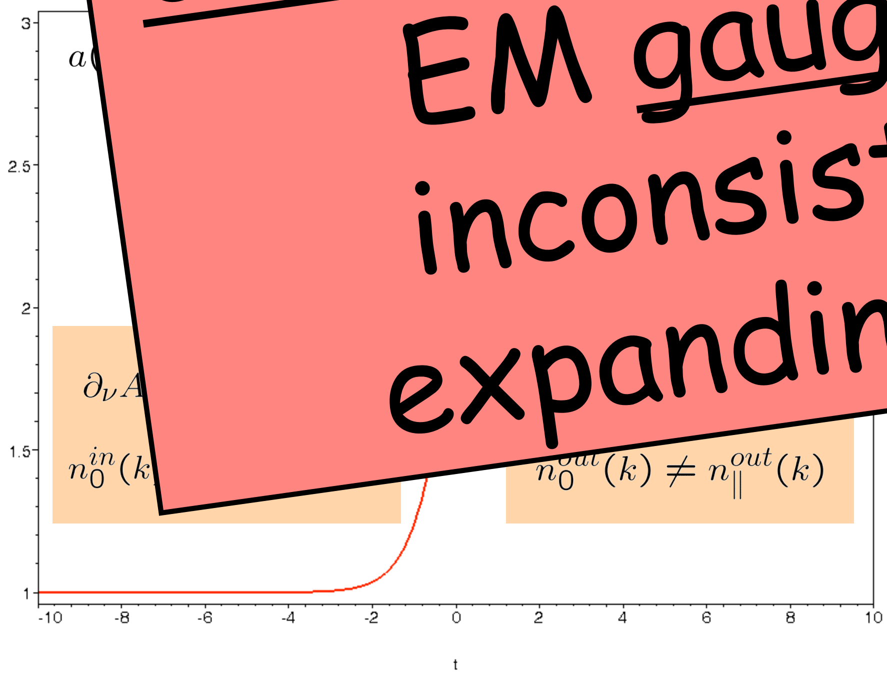
Flat Robertson-Walker metric

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

Mode equations

$\mathcal{A}''_{0k} - \left[\frac{k^2}{\lambda} - 2\mathcal{H}' + 4\mathcal{H}^2\right] \mathcal{A}_{0k} \; \ldots = 0$

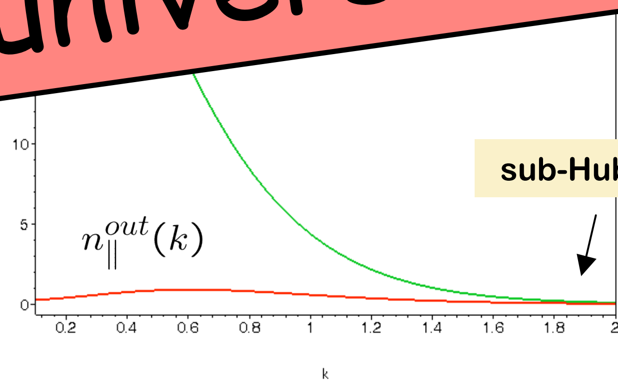
Covariant quantization of EM gauge theory inconsistent in an expanding universe



$\partial_\nu A$

$n_0^{in}(k$

$n_0^{out}(k) \neq n_\parallel^{out}(k)$



sub-Hubble OK

What if EM is not a gauge invariant theory?

Assume the fundamental theory of electromagnetism is not gauge invariant (no need for Lorenz condition):

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

General solution

$$A_\mu = \underbrace{A_\mu^{\perp(1)} + A_\mu^{\perp(2)}}_{\text{Photon}} + \underbrace{A_\mu^S}_{\text{New scalar state}} + \underbrace{\partial_\mu \theta}_{\text{Pure residual gauge}}$$

The pure gauge mode can be eliminated so that all the physical states have positive norm and canonical positive energy ($\lambda=1/3$)

Flat Robertson-Walker metric

$$\Box(\nabla_\nu A^\nu) = 0 \longrightarrow \nabla_\nu A_k^\nu = \begin{cases} \dfrac{C}{a(\eta)} e^{-ik\eta} & k\eta \gg 1 \longrightarrow \text{Negligible: Maxwell's eq. OK} \\ const. & k\eta \ll 1 \longrightarrow \text{DARK ENERGY} \end{cases}$$

A consistent gauge non-invariant EM theory

$$S=\int d^4x\sqrt{g}\left(-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}+\frac{1}{6}(\nabla_\mu A^\mu)^2+A_\mu J^\mu\right)$$

Consistent EM quantization with THREE physical states

- **New scalar state only coupled to gravity**
- **Electric charge is conserved (only EM gauge sector modified)**
- **No negative norm (energy) states**
- **Classical Maxwell's equations recovered on sub-Hubble scales (electromagnetism only tested below 1.3 AU)**
- **QED recovered in Minkowski space-time (ghosts play no role)**

Cosmological electromagnetic fields

$$\ddot{A}_0 + 3H\dot{A}_0 + 3\dot{H}A_0 = 0$$
$$\ddot{\vec{A}} + H\dot{\vec{A}} = 0$$

$H = p/t$ $\Rightarrow$

$$A_0(t) = A_0^+ t + A_0^- t^{-3p}$$
$$\vec{A}(t) = \vec{A}^+ t^{1-p} + \vec{A}^-$$

$$\frac{d}{dt}(\nabla_\mu A^\mu) = \frac{d}{dt}(\dot{A}_0 + 3HA_0) = 0$$

$$A_\mu = (A_0(t), \vec{A}(t))$$

$$\rho_{A_0} = \frac{\lambda}{2}\left(\dot{A}_0 + 3HA_0\right)^2 = const. \longrightarrow \text{Cosmological constant}$$

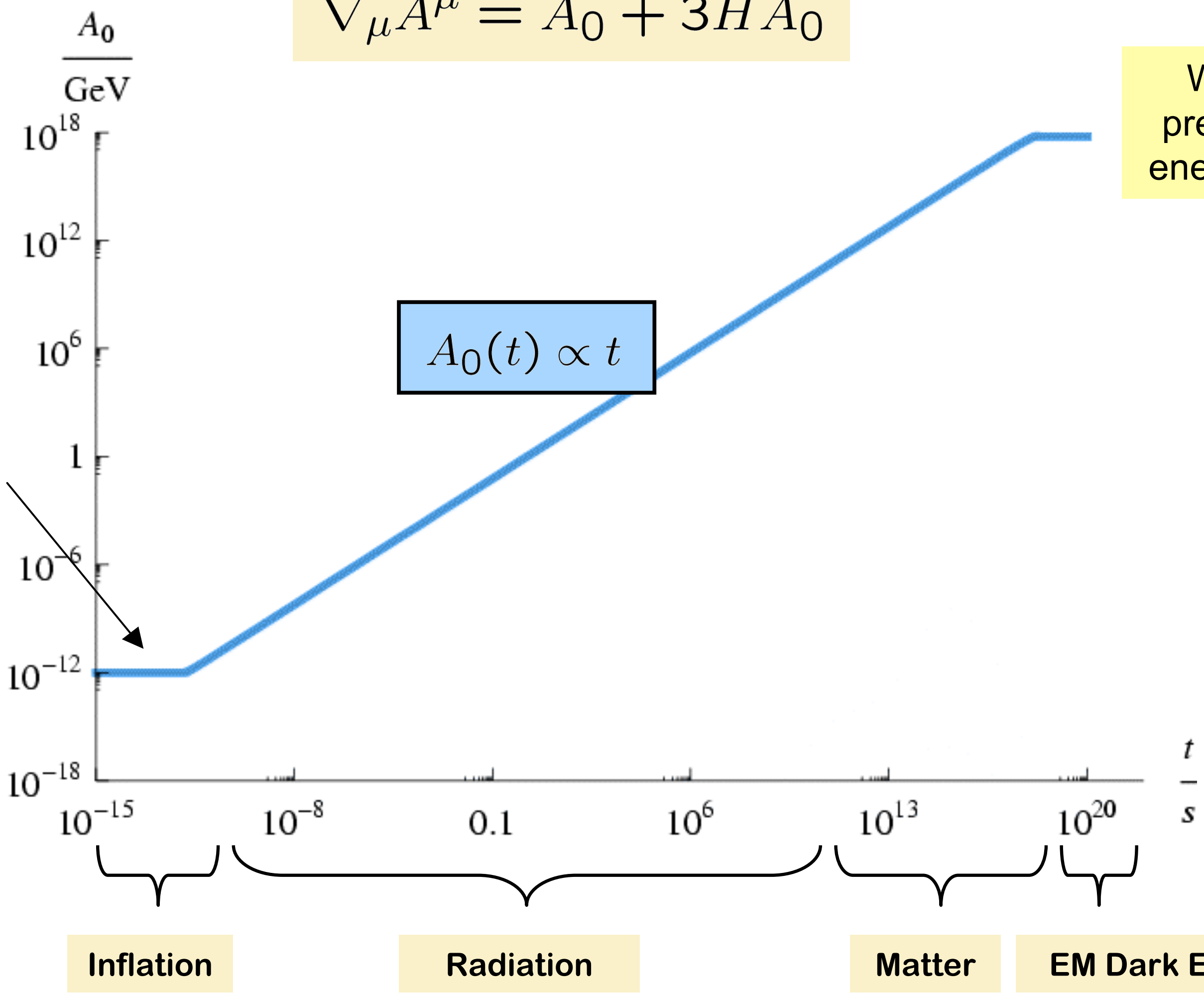
$$\rho_{\vec{A}} = \frac{1}{2a^2}\left(\dot{\vec{A}}\right)^2 \propto a^{-4} \longrightarrow \text{Isotropy OK}$$

The absolute cosmic electric potential

$$\nabla_\mu A^\mu = \dot{A}_0 + 3HA_0$$

What is the predicted dark energy density?

What is the field amplitude generated during inflation?



Quantum fluctuations during inflation

De Sitter inflation

$$a(\eta) = -\frac{1}{H_I \eta}$$

$$\mathcal{A}_\mu = \int d^3\vec{k} \sum_{\lambda=1,2,s} \left[\mathbf{a}_\lambda(k) \mathcal{A}^{(\lambda)}_{\mu k} + \mathbf{a}^\dagger_\lambda(k) \overline{\mathcal{A}^{(\lambda)}_{\mu k}} \right]$$

Scalar mode

$$\begin{aligned}
\mathcal{A}^{(s)}_{0k} &= -\frac{1}{(2\pi)^{3/2}} \frac{i}{\sqrt{2k}} \left\{ k\eta e^{-ik\eta} + \frac{1}{k\eta} \left[\frac{1}{2}(1+ik\eta)e^{-ik\eta} - k^2\eta^2 e^{ik\eta} E_1(2ik\eta) \right] \right\} e^{i\vec{k}\vec{x}} \\
\mathcal{A}^{(s)}_{\parallel k} &= \frac{1}{(2\pi)^{3/2}} \frac{1}{\sqrt{2k}} \left\{ (1+ik\eta)e^{-ik\eta} - \left[\frac{3}{2} e^{-ik\eta} + (1-ik\eta) e^{ik\eta} E_1(2ik\eta) \right] \right\} e^{i\vec{k}\vec{x}}
\end{aligned}$$

Power spectrum on super-Hubble scales

$$\mathcal{P}_{A_0}(k) \equiv 4\pi k^3 \left| A_{0k} \right|^2 = \frac{H_I^2}{16\pi^2}$$

Initial conditions from inflation

Initial conditions from vacuum fluctuations during inflation

$$\langle A_0^2 \rangle \sim H_I^2$$

$$\rho_{A_0} \sim H^2 A_0^2 \sim \ const. \longrightarrow \rho_{A_0} \sim H_I^4 \longrightarrow \rho_{A_0} \sim \left(\frac{M_I^2}{M_P}\right)^4$$

Predicted dark energy density

Friedmann equation ($\boldsymbol{M_I}$ scale of inflation)

$$H_I^2 \sim \frac{M_I^4}{M_P^2}$$

$$\rho_{A_0} \sim \left(\frac{M_I^2}{M_P}\right)^4 \sim (10^{-3}\mathrm{eV})^4 \Rightarrow M_I \sim 1\,\mathrm{TeV}$$

The cosmological constant scale can be explained by physics at the electroweak scale

Natural solution to the coincidence problem

Stability and local gravity tests

PPN parameters

All parameters agree with GR for arbitrary A_0

$$\gamma = \beta = 1$$

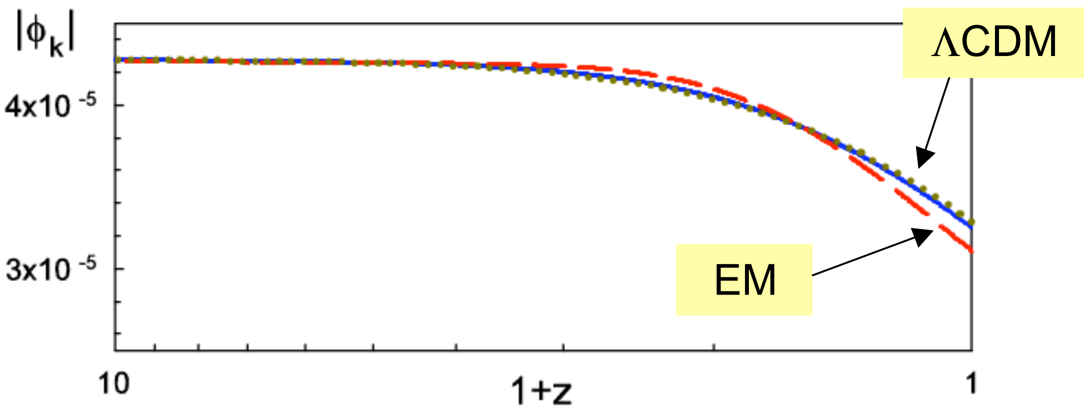
$$\alpha_1 = \alpha_2 = \alpha_3 = 0$$

Classical and quantum stability

v = c for scalar, vector and tensor perturbations. No ghosts.

Metric perturbations

Discriminating signal from ΛCDM in the ISW



Conclusions

Consistent EM quantization with three physical states

The new scalar state generates an effective cosmological constant

Compatible with local gravity tests and free from classical or quantum instabilities

Cosmological constant value naturally explained in the context of inflationary cosmology

No free parameters (simpler theory than ΛCDM)

Nature of dark energy is established without resorting to new physics

Vault of the old Salamanca University Library
Fernando Gallego (1440-1507)