Electromagnetic nature of dark energy: Theoretical aspects

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Outline

- Electromagnetic quantization in flat spacetime
- Electromagnetic quantization in an expanding universe: The Lorenz condition
- Electromagnetic quantization without the Lorenz condition
- Cosmological evolution: Solving the coincidence problem
- Consistency and viability
- Conclusions

EM quantization in flat space

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

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

Gauge invariance

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

Maxwell equations

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Maxwell equations

- Conjugate momentum of the temporal component?
- Commutation relations?
- Photon propagator?

EM quantization in flat space

Coulomb gauge

Covariant quantization

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$$\Box \theta = 0$$

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⇨ 2 physical states

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2 physical states

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

$$\left[\mathbf{a}_0(\vec{k}) + \mathbf{a}_{\parallel}(\vec{k})\right]|\phi\rangle = 0$$

$$n_0(\vec{k}) = n_{\parallel}(\vec{k})$$

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2 physical states

Quantize

EM quantization in an expanding universe

Covariant version of EM action in a curved spacetime

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

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Modified Maxwell equations

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Free scalar field non-conformally coupled to gravity

$$\Box\,(\nabla_\nu A^\nu) = 0$$

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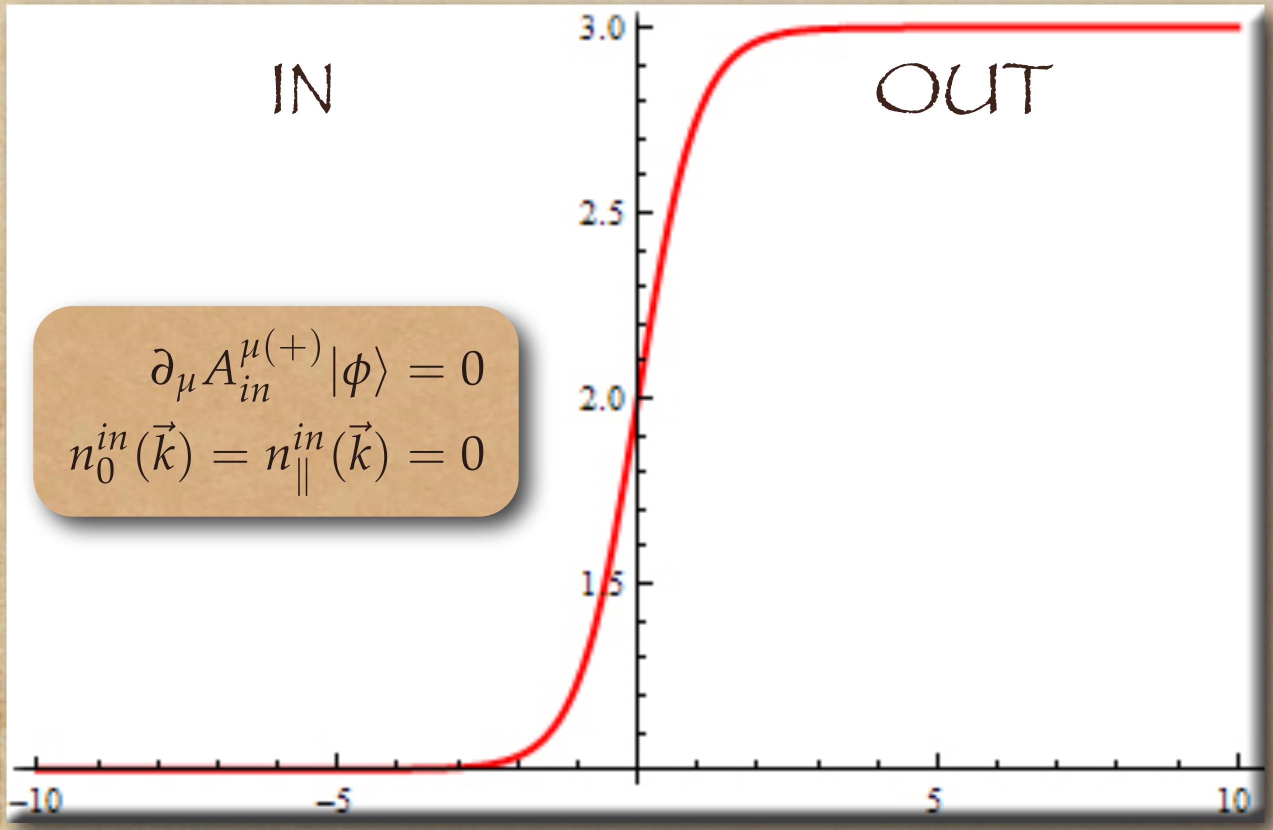
Lorenz condition?

EM quantization in an expanding universe

We consider an expanding universe with two asymptotically Minkowski regions: $a(\eta) = 2 + \tanh(\eta/\eta_0)$



$$\partial_\mu A^{\mu(+)}_{in}|\phi\rangle = 0$$

$$n_0^{in}(\vec{k}) = n_{\parallel}^{in}(\vec{k}) = 0$$

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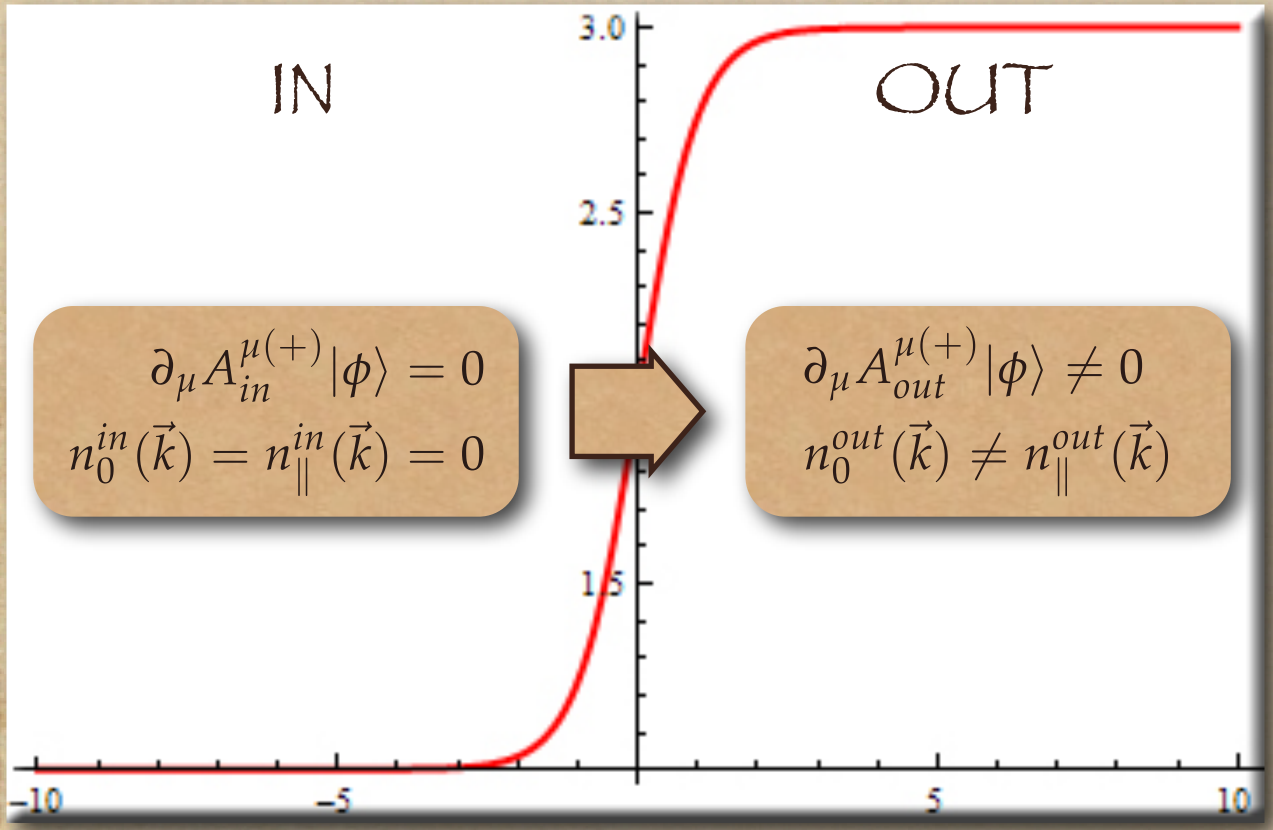

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$$n_0^{out}(\vec{k}) \neq n_\parallel^{out}(\vec{k})$$

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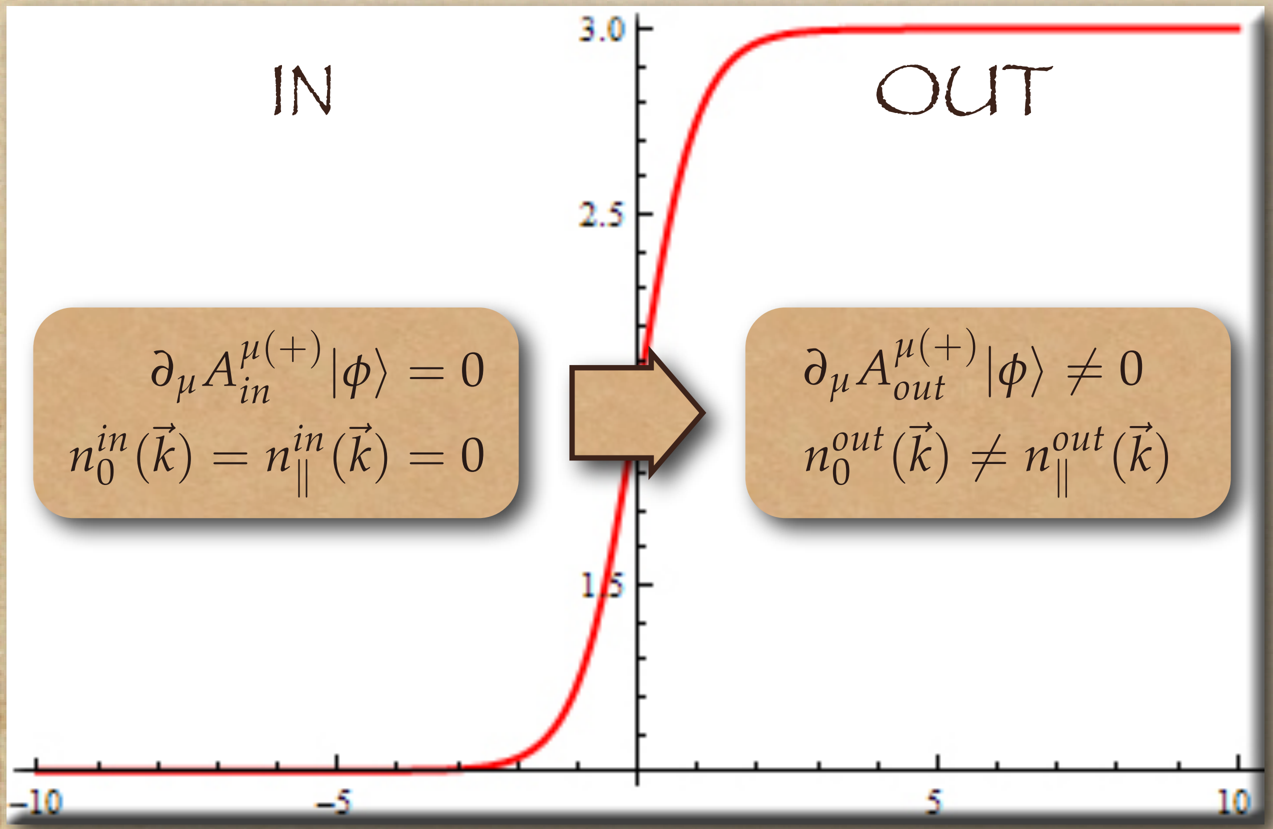
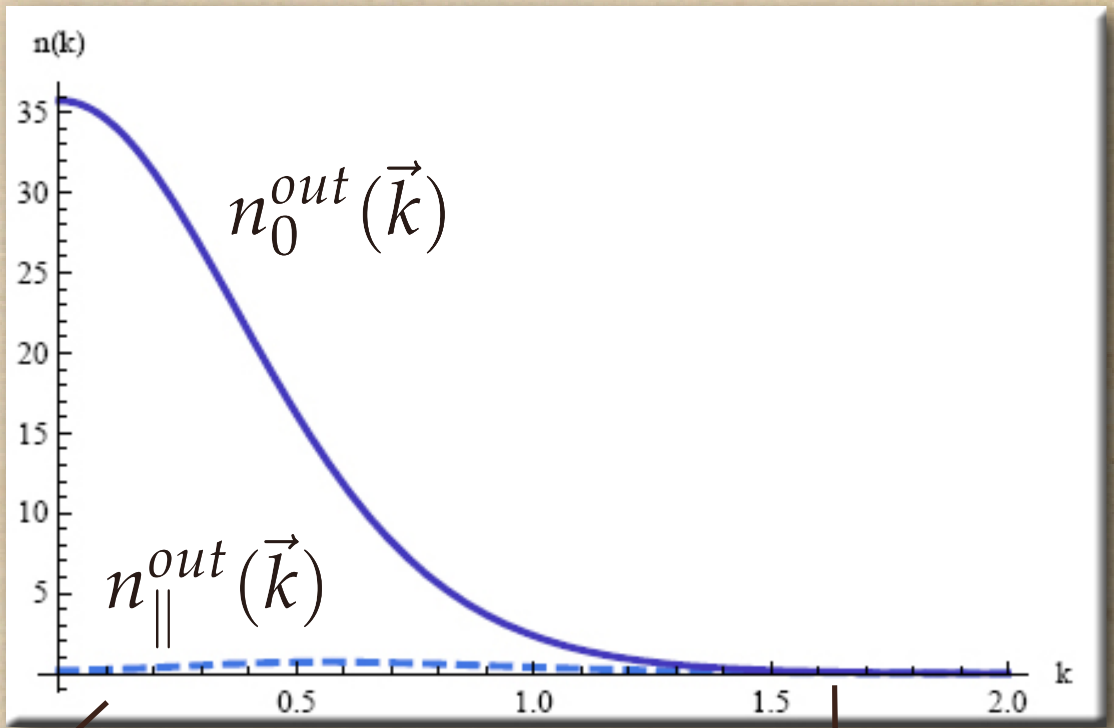


$\partial_\mu A_{in}^{\mu(+)}|\phi\rangle=0$

$n_0^{in}(\vec{k})=n_\parallel^{in}(\vec{k})=0$

$\partial_\mu A_{out}^{\mu(+)}|\phi\rangle\neq 0$

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



Breakdown of Lorenz condition on super-Hubble scales

Lorenz condition restored on sub-Hubble scales

EM quantization without Lorenz condition

Fundamental action for EM

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

General solution $A_\mu = A_\mu^{(1)} + A_\mu^{(2)} + A_\mu^{(s)} + \partial_\mu\theta$ Residual gauge mode

Photon New scalar state

EM quantization without Lorenz condition

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Potential problems

- Modified Maxwell equations
- Charge conservation
- Unobserved extra polarizations
- Modified interactions with charged particles

EM quantization without Lorenz condition

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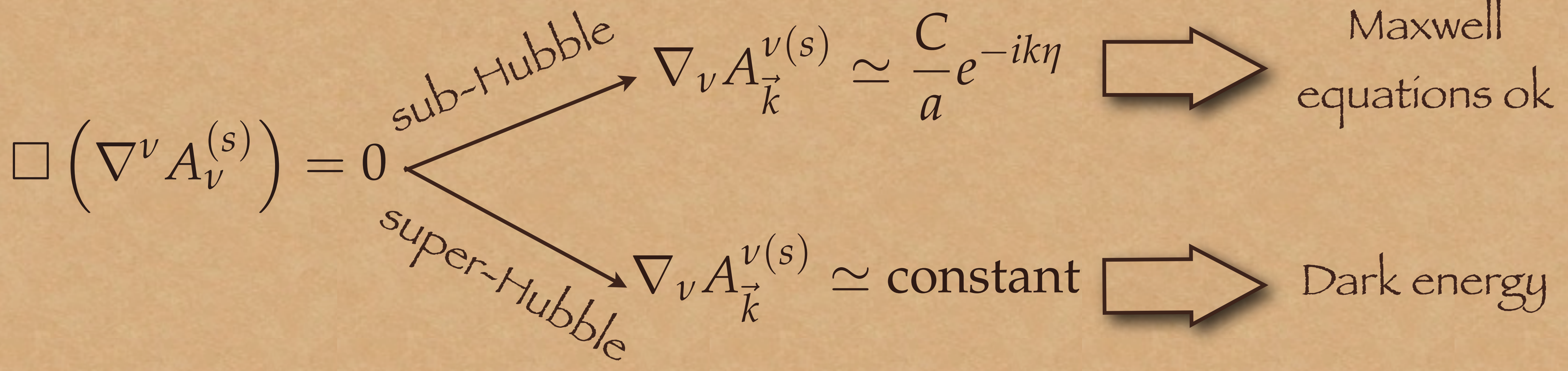

$$\Box\left(\nabla^\nu A_\nu^{(s)}\right)=0$$

$\nabla_\nu A_{\vec{k}}^{\nu(s)} \simeq \frac{C}{a}e^{-ik\eta}$ → Maxwell equations ok

$\nabla_\nu A_{\vec{k}}^{\nu(s)} \simeq$ constant → Dark energy

EM quantization without Lorenz condition

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The gauge-fixed QED effective action in the path-integral formalism in flat spacetime is:

$$e^{iW} = \int [dA][dc][d\bar{c}][d\psi][d\bar{\psi}]e^{i\int d^4x\left(-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}+\frac{\xi}{2}(\partial_\mu A^\mu)^2+\partial_\mu\bar{c}\,\partial^\mu c+\mathcal{L}_F\right)}$$

$$\propto \int [dA][d\psi][d\bar{\psi}]e^{i\int d^4x\left(-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}+\frac{\xi}{2}(\partial_\mu A^\mu)^2+\mathcal{L}_F\right)}$$

which coincides with the considered action for flat spacetime.

EM quantization without Lorenz condition

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Potential problems

- Modified Maxwell equations ✔
- Charge conservation ✔
- Unobserved extra polarizations ✔
- Modified interactions with charged particles ✔

Cosmological evolution

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

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

$$\rho_{A_0} = \frac{\xi}{2}\left(\dot{A}_0 + 3HA_0\right)^2 = \text{constant}$$

$$\rho_{\vec{A}} = \frac{1}{2a^2}(\dot{\vec{A}})^2 \propto \frac{1}{a^4}$$

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

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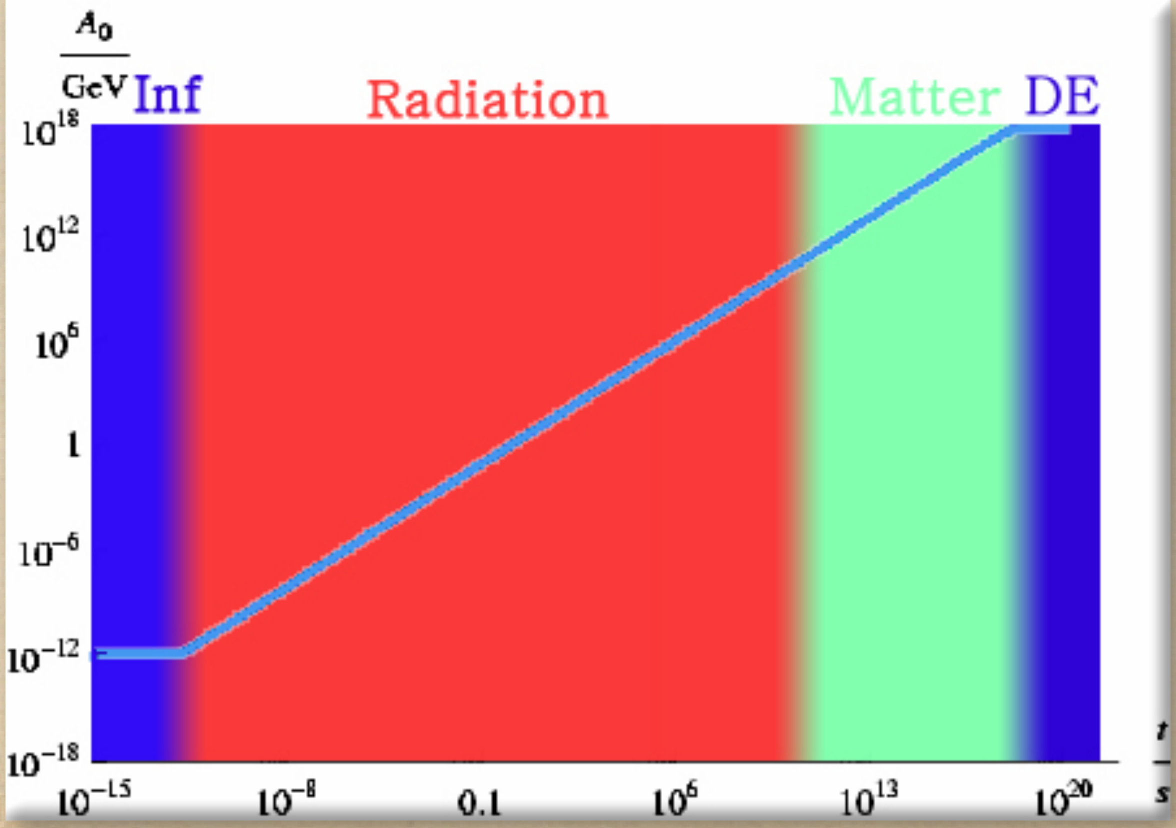

$$\Omega_\Lambda \simeq 0.7$$

$$A_0 \simeq 0.3\ \mathrm{M_P}$$

Initial amplitude?

Initial conditions during inflation

Power spectrum generated during inflation from quantum fluctuations

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

Initial amplitude set by Hubble constant during inflation

$$A_{0I}^2 \sim H_I^2$$

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Initial amplitude set by Hubble constant during inflation

$$A_{0I}^2 \sim H_I^2$$

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

$$\rho_{A_0} \sim H^2 A_0^2 \sim H_I^2 A_{0I}^2 \sim H_I^4 \simeq \left(\frac{M_I^2}{M_P}\right)^4$$

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$$\rho_{A_0} \sim H^2 A_0^2 \sim H_I^2 A_{0I}^2 \sim H_I^4 \simeq \left(\frac{M_I^2}{M_P}\right)^4$$

$\Rightarrow$

$M_I \sim 1\ TeV$

Electroweak scale

Viability and consistency

Local gravity tests

PPN parameters exactly the same as GR for any value of A_0, so it has the same small scales behavior.

Stability

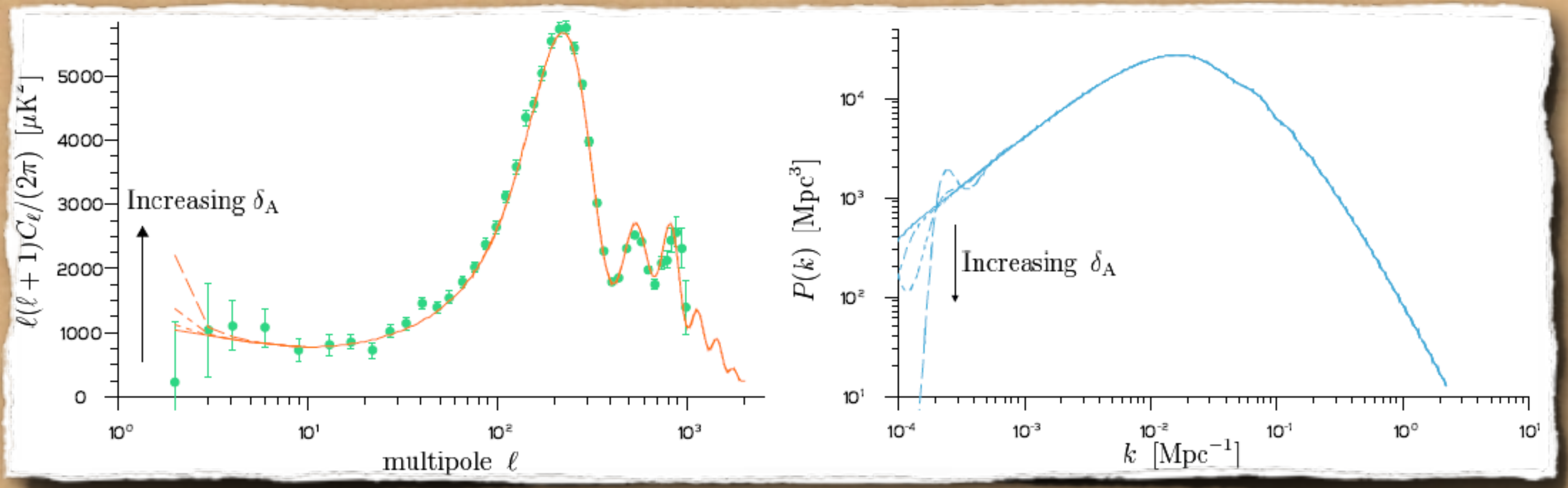
Classical

All the modes propagate at the speed of light.

Quantum

The three physical states carry positive energy.

CMB and LSS



Compatible as long as the initial perturbation is not too large, implying a reduction in the inflation scale by a factor of 15.

Conclusions

- EM field can be consistently quantized with three physical states without the need of Lorenz condition.
- Quantum fluctuations of the new state during an inflationary epoch at the electroweak scale give rise to an effective cosmological constant on large scales with the correct value.
- The model satisfies all the viability conditions and it is in agreement with CMB and LSS measurements.
- The true nature of dark energy can be established without resorting to new physics.
- For generation of cosmic magnetic fields see next talk.