Charging Dark Matter Up

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In collaboration with Dario Bettoni and Philippe Brax

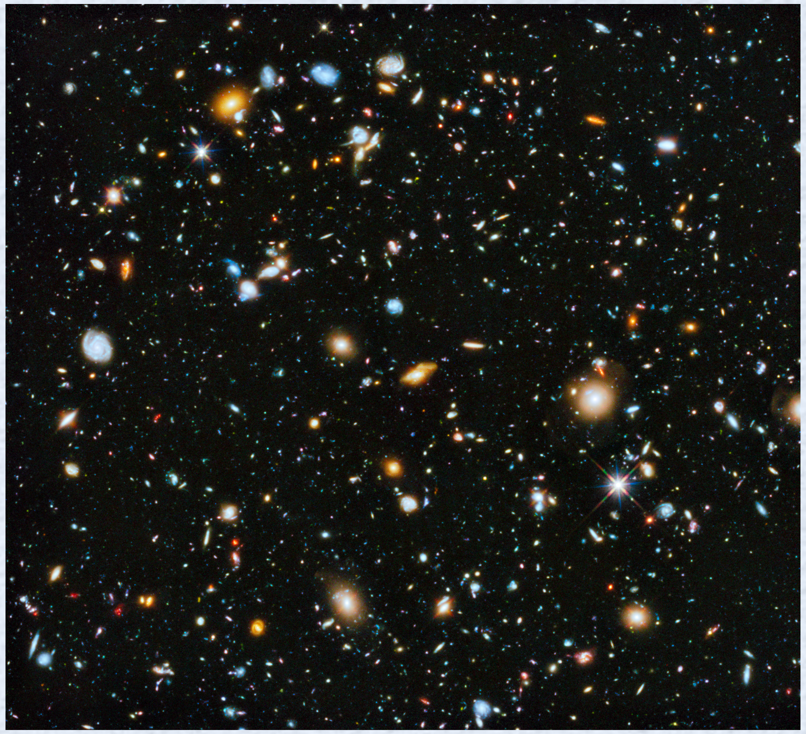
arXiv: 2004.13677

Cosmological forces

Gravity governs the large scale dynamics of the universe

Gravity is a long range force

Gravity couples universally



Are there other long-range forces in nature?

Yes! Electromagnetism

The universe is electrically neutral

No role in the cosmological evolution

Could there be a dark electromagnetism playing a non-trivial role?

Wouldn't that spoil the whole structure formation process?

Screening mechanisms

Screening mechanisms for cosmological models have been extensively explored in the last 20 years

IR modifications of gravity add new dof's which give rise to 5th forces that have never been detected.

$$\mathcal{L}_{\phi-\mathrm{matter}} = A(\phi)T \quad \Rightarrow \quad \Phi_{\mathrm{eff}} = -\frac{GM}{r}\left(1+\beta e^{-mr}\right)$$

We need to reconcile the absence of 5th forces on Solar system scales while having non-trivial effects on cosmological scales.

Screening mechanisms provided by non-linearities*

$$\boxed{\mathcal{L} = \frac{1}{2}\mathcal{Z}(\phi_b)\partial_\mu\delta\phi\partial^\mu\delta\phi - \frac{1}{2}m^2(\phi_b)\delta\phi^2 + g(\phi_b)\delta\phi T}$$

Vainshtein / Kinetic / K-mouflage   Chameleon   Symmetron / Dilaton

* NB: We have the obvious "screening" of canceling the coupling constant at all scales.

Screened electromagnetism?

Gauge fields are massless (required for long-range) ⇨ No chameleon/symmetron mechanism

No-go result for Galileon gauge fields ⇨ No Vainshtein mechanism (possible for massive fields)

Only remaining option, screening à la K-mouflage

$$\mathcal{L} = \mathcal{K}(Y, Z)$$

$$Y \equiv -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} = \frac{1}{2}\left(\vec{E}^2 - \vec{B}^2\right)$$

$$Z \equiv -\frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} = \vec{E} \cdot \vec{B}$$

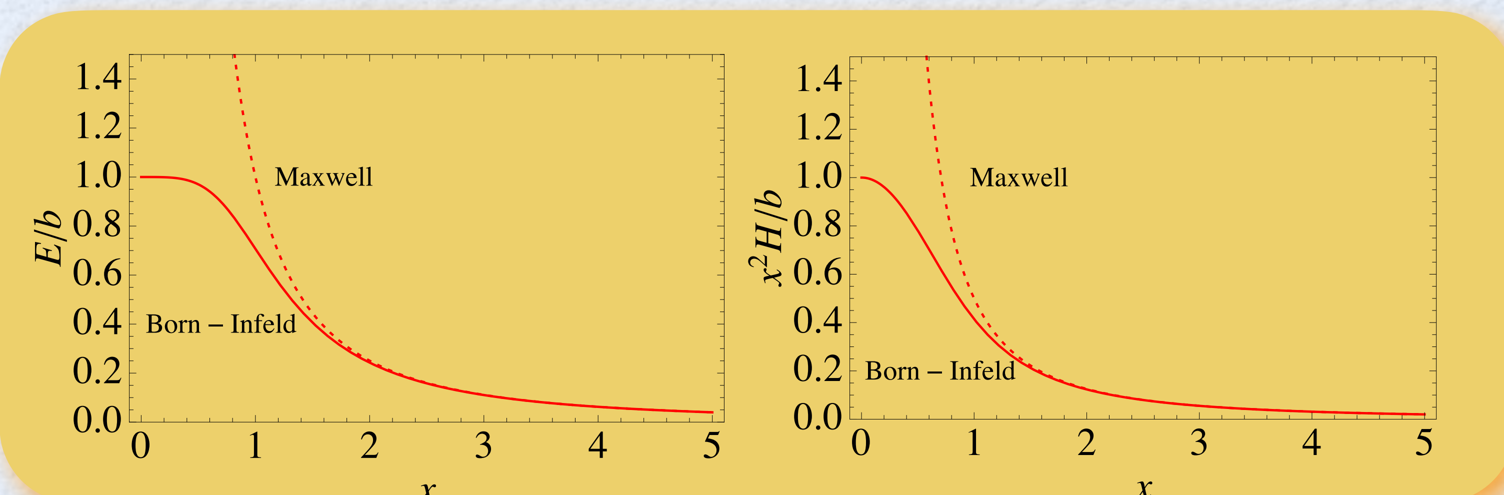
BORN-INFELD ELECTROMAGNETISM

$$\boxed{\mathcal{S}_{\mathrm{BIE}} = -\lambda^4 \int \mathrm{d}^4x \left[\sqrt{-\det\left(\eta_{\mu\nu} + \lambda^{-2} F_{\mu\nu}\right)} - 1 \right]}$$

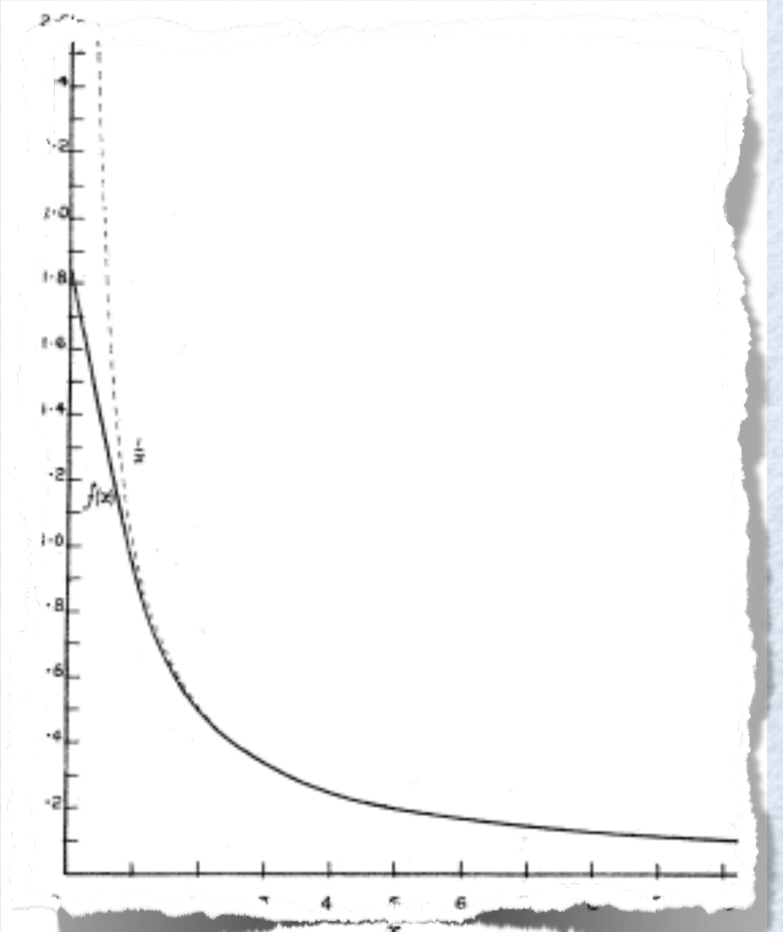
M. Born and L. Infeld.
Proc.Roy.Soc.Lond.
A144 .(1934)

$$\mathcal{S}_{\mathrm{BIE}} = -\lambda^4 \int \mathrm{d}^4x \left[\sqrt{1 + \frac{1}{2\lambda^4} F_{\mu\nu}F^{\mu\nu} - \frac{1}{16\lambda^8}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2} - 1 \right]$$

$$= -\lambda^4 \int \mathrm{d}^4x \left[\sqrt{1 - \frac{\vec{E}^2 - \vec{B}^2}{\lambda^4} - \frac{(\vec{E}\cdot\vec{B})^2}{\lambda^8}} - 1 \right]$$



$$|\vec{E}| = \frac{1}{\sqrt{1 + \left(\frac{Q}{4\pi\lambda^2 r^2}\right)^2}} \frac{Q}{4\pi r^2}$$

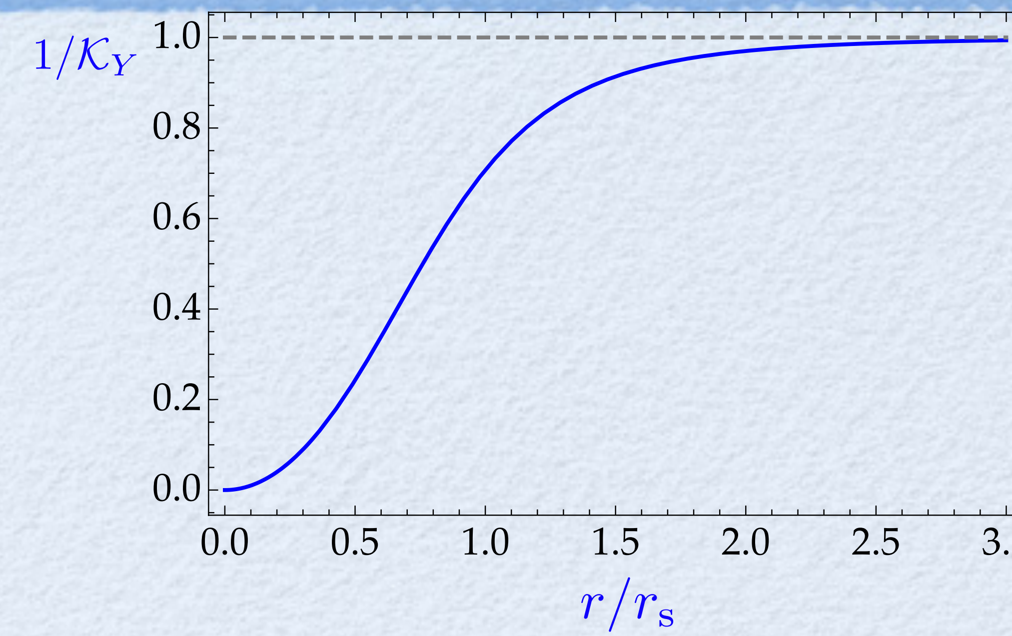


INCLUDING GRAVITY

Charge-to-mass ratio $\beta \equiv \frac{\sqrt{2} q M_{\rm Pl}}{m}$

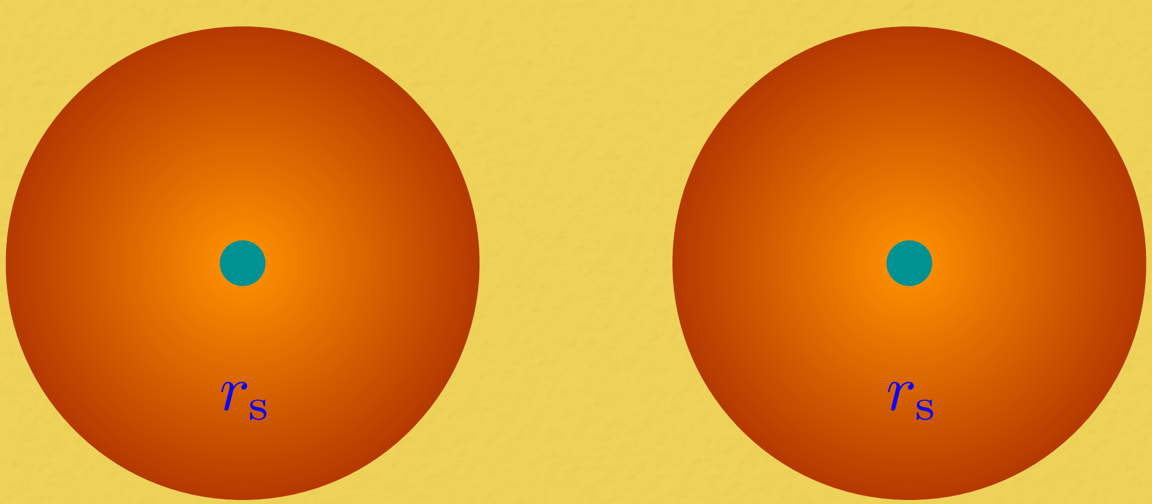
$$\vec{F} = -G\frac{mM}{r^3}\vec{r} + \frac{qQ}{4\pi \mathcal{K}_Y r^3}\vec{r} = -G\frac{mM}{r^3}\left(1 - \frac{\beta^2}{\mathcal{K}_Y}\right)\vec{r}$$

Repulsive nature



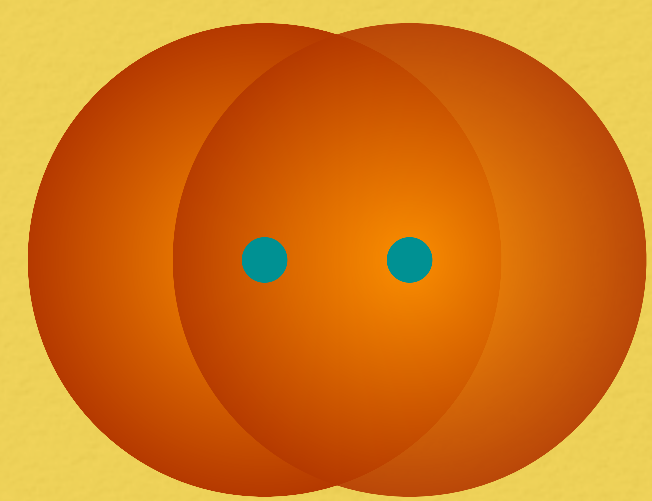
$r \gg r_{\rm s}$

$$G_{\rm eff} = \left(1 - \beta^2\right) G$$



$r \ll r_{\rm s}$

$$G_{\rm eff} \simeq G$$



NEWTONIAN COSMOLOGY

Let us study the evolution of spherically symmetric shells made out of identical charged (DM) particles

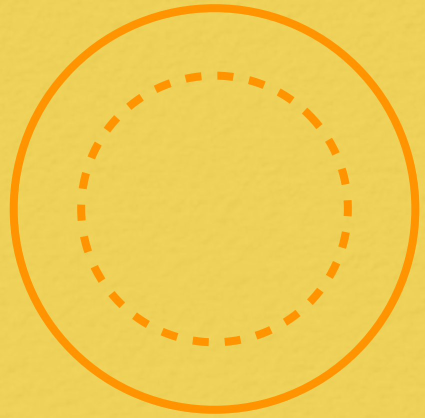
Lagrangian coordinates

$t_\star$

$r_\star$

$$\ddot{R}(t, r_\star) = -\frac{GM(R)}{R^2}\Big[\underbrace{1}_{\text{Gravitational attraction}} - \underbrace{\beta^2 F(R/r_{\rm s})}_{\text{Electric repulsion}}\Big]$$

t



$R(t, r_\star)$

Newtonian Cosmology

Let us study the evolution of spherically symmetric shells made out of identical charged (DM) particles

Eulerian coordinates: Local scale factor

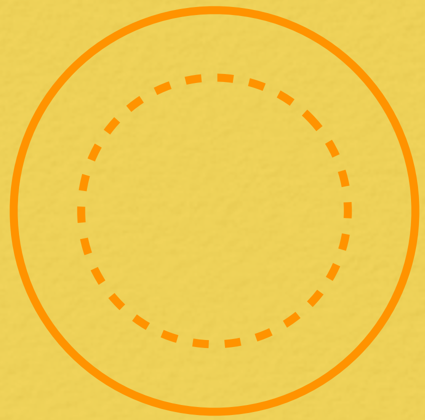
$t_\star$

$a(t_\star, r_\star) = 1$

$$a(t, r_\star) \equiv \frac{R(t, r_\star)}{r_\star}$$

$$\ddot{a}(t, r_\star) = -\frac{GMr_\star^{-3}}{a^2(t, r_\star)}\left[1 - \beta^2 F\left(\frac{a}{a_\mathrm{s}}\right)\right]$$

t



$a(t, r_\star)$

For an initially uniform density profile and no electric force:
Comoving motion (no shell-crossing)

Non-linearities in the electric force break the scale invariance.
Inhomogeneous evolution
(it does not imply shell crossing).

We neglect Lorentz forces due to magnetic fields.

NEWTONIAN COSMOLOGY

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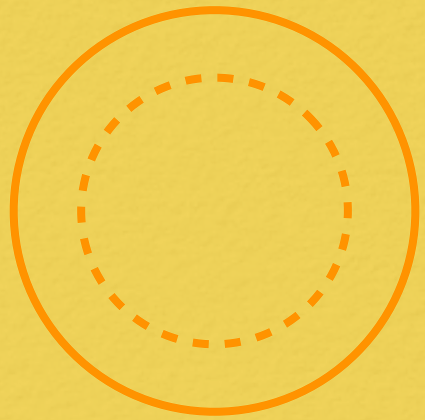
$$\ddot{a}(t, r_\star) = -\frac{GMr_\star^{-3}}{a^2(t, r_\star)}\left[1 - \beta^2 F\left(\frac{a}{a_\mathrm{s}}\right)\right]$$

$a_\mathrm{s} \propto \sqrt{r_\star}$

t



$a(t, r_\star)$

For an initially uniform density profile and assuming no-shell crossing:

$$\ddot{a} = -\frac{4\pi G\rho_\star}{3a^2}\left[1 - \beta^2 F(a/a_\mathrm{s})\right] \qquad \frac{\dot{a}^2}{a^2} = \frac{8\pi G\rho_\star}{3a^3} + 2\frac{E(r) - \mathcal{U}(a)}{a^2} \qquad \mathcal{U}(a) \equiv \mathcal{U}_\star - \frac{4\pi G\rho_\star}{3}\beta^2 \int_{a_\star}^{a} \mathrm{d}a \frac{F(a/a_\mathrm{s})}{a^2}$$

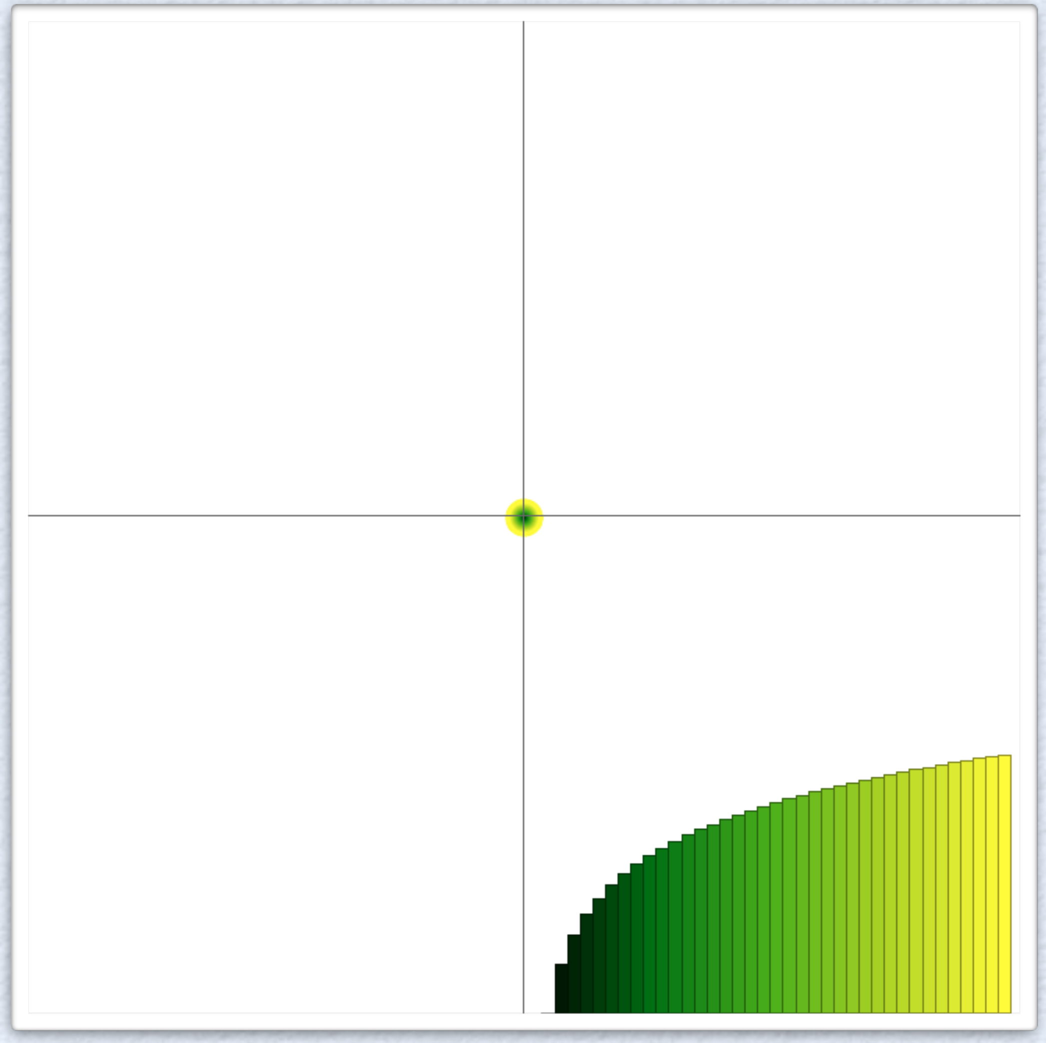
$F(x \gg 1) \simeq 1$

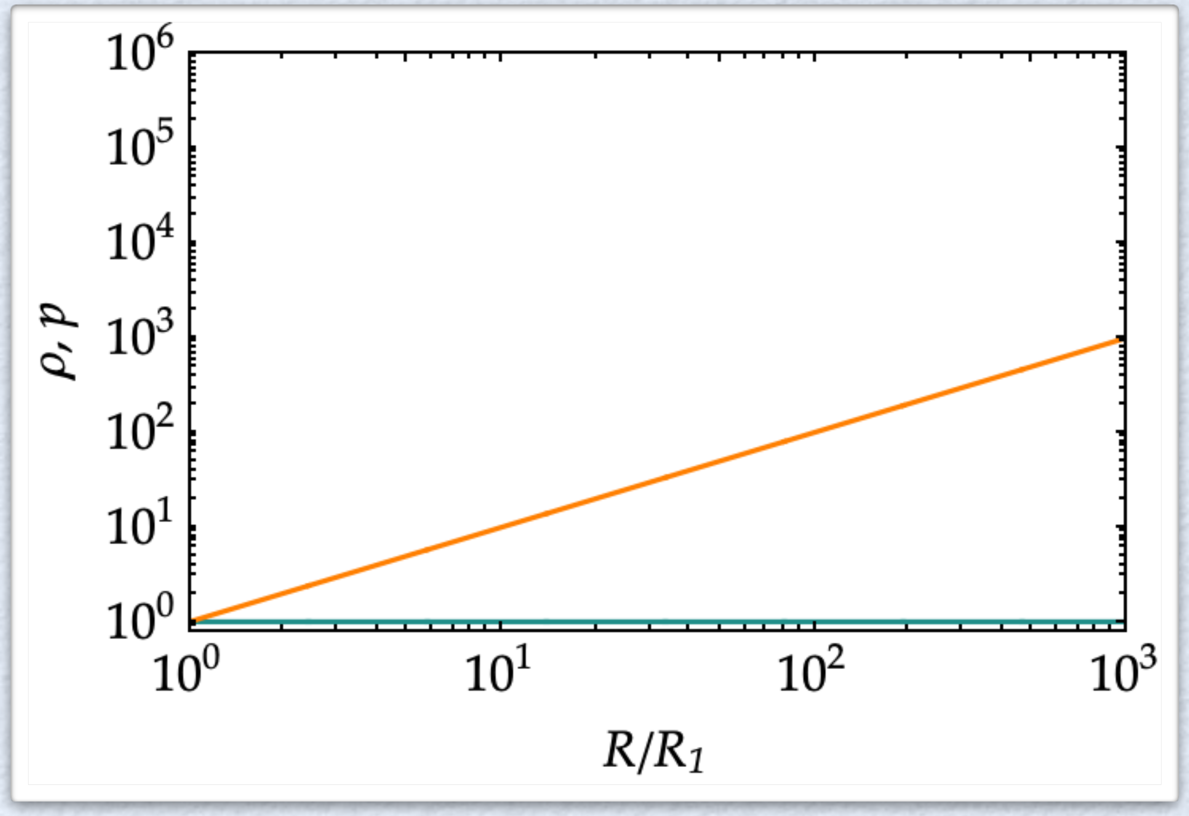
$F(x \ll 1) \simeq x^m$

$$\Rightarrow \quad \mathcal{U}(a) \simeq -\frac{4\pi G\rho_\star}{3a_\mathrm{s}}\beta^2\left[\frac{m}{m-1} - \frac{a_\mathrm{s}}{a}\right] \quad \Rightarrow \quad H^2(t, r) = \left(1 - \beta^2\right)\frac{8\pi G\rho_\star}{3a^3} + \frac{m}{m-1}\frac{8\pi G\rho_\star}{3a_\mathrm{s}}\beta^2 a^{-2}$$

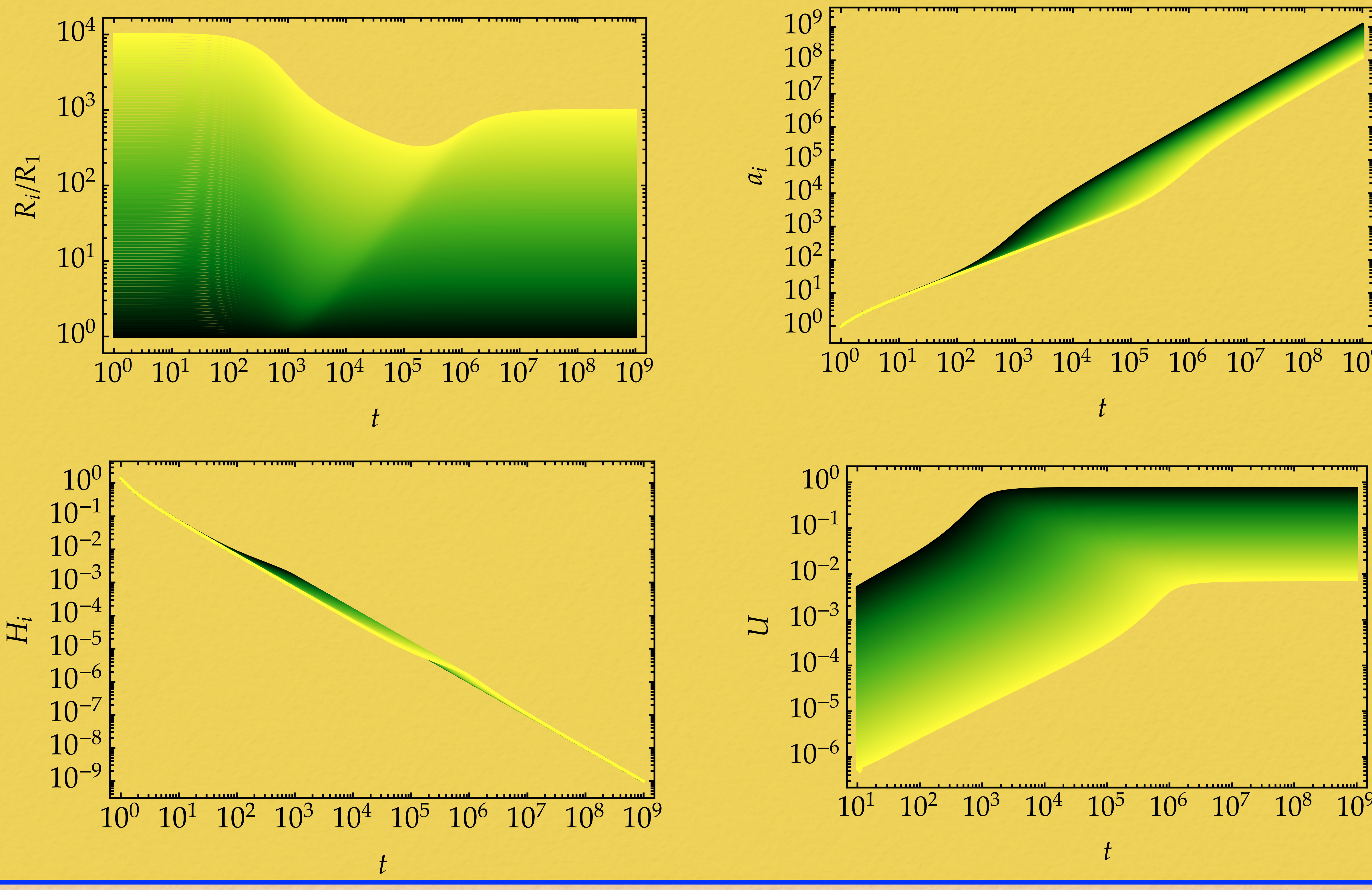
Asymptotically $\dot{a} \propto a_\mathrm{s}^{-1/2}(r)$ and H is homogeneous.

BREAKING OF COMOVING MOTION

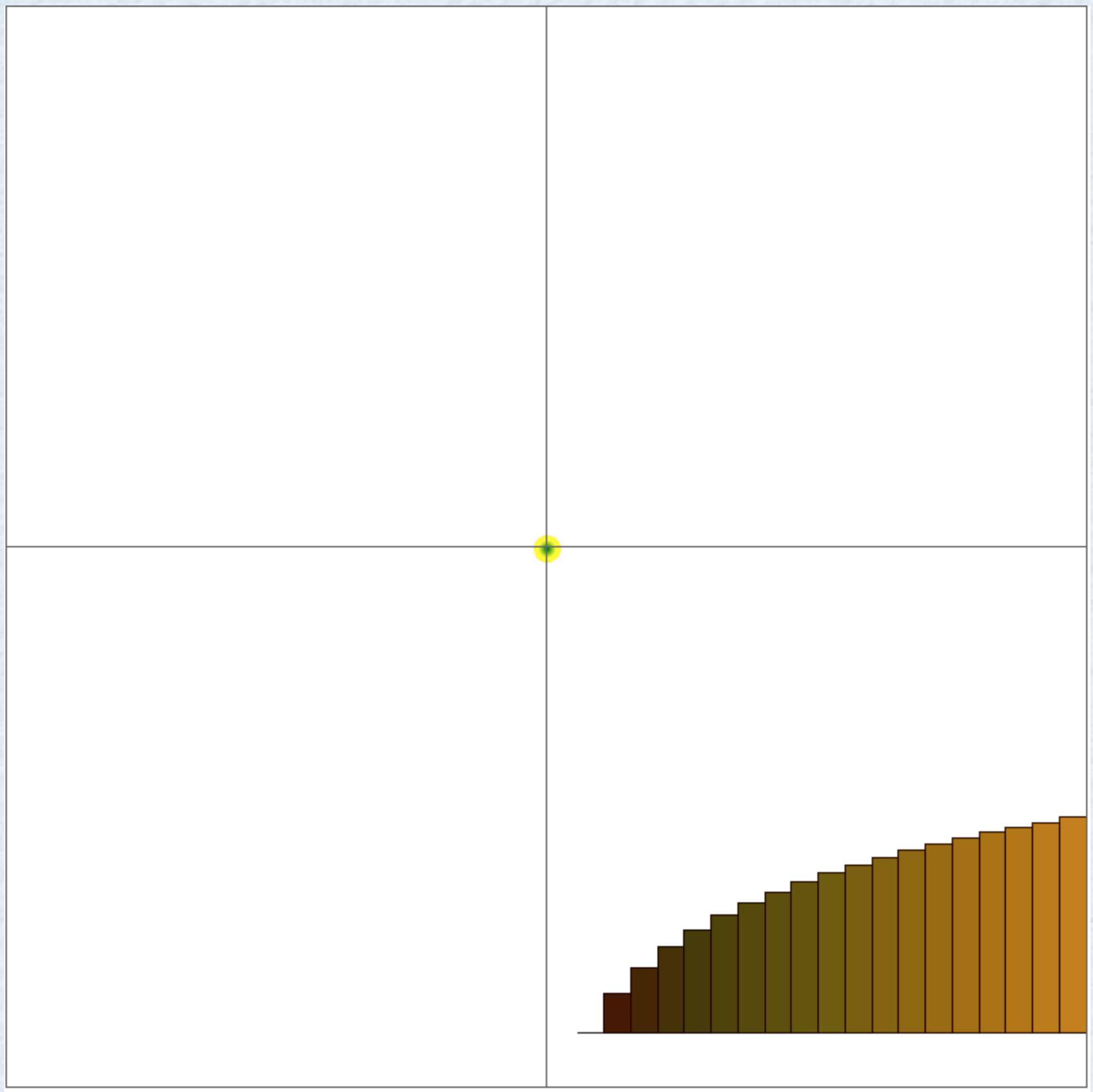


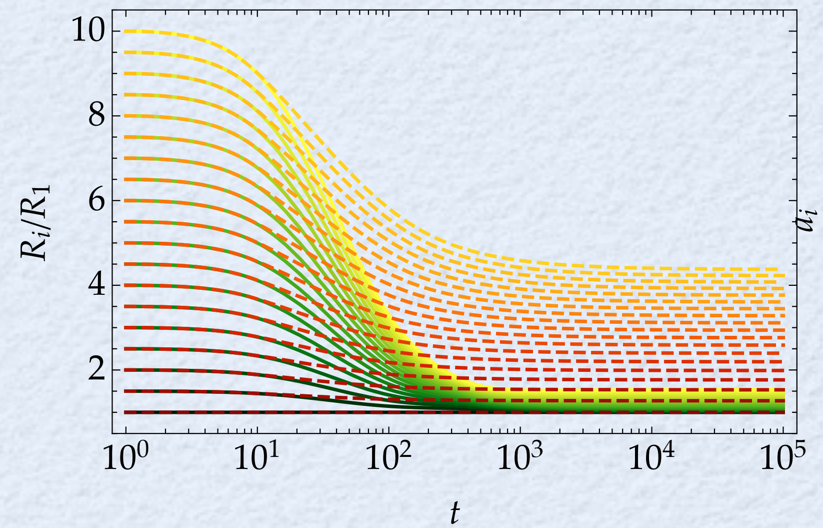


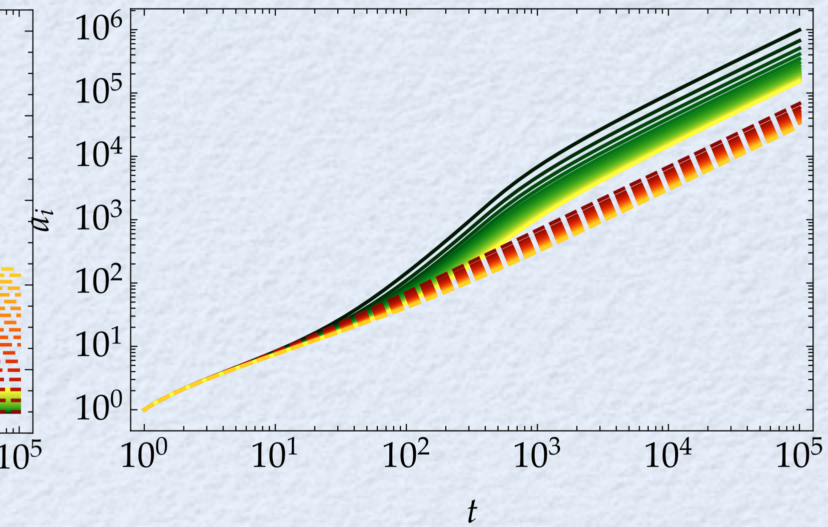
Breaking of Comoving Motion

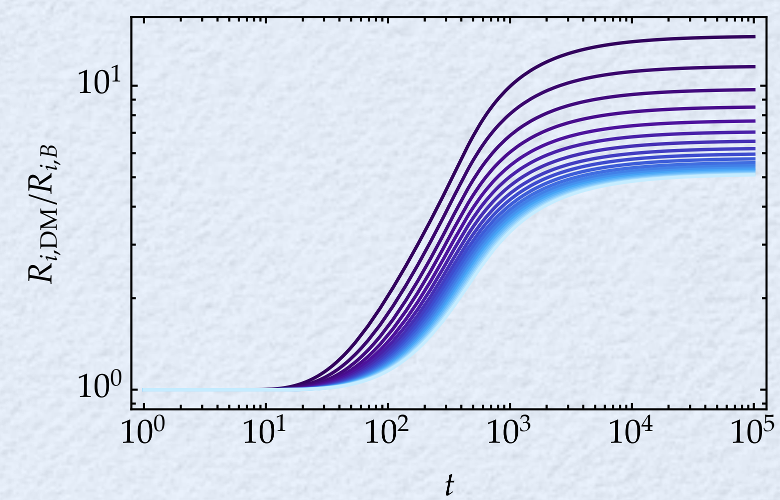


Adding uncharged baryons



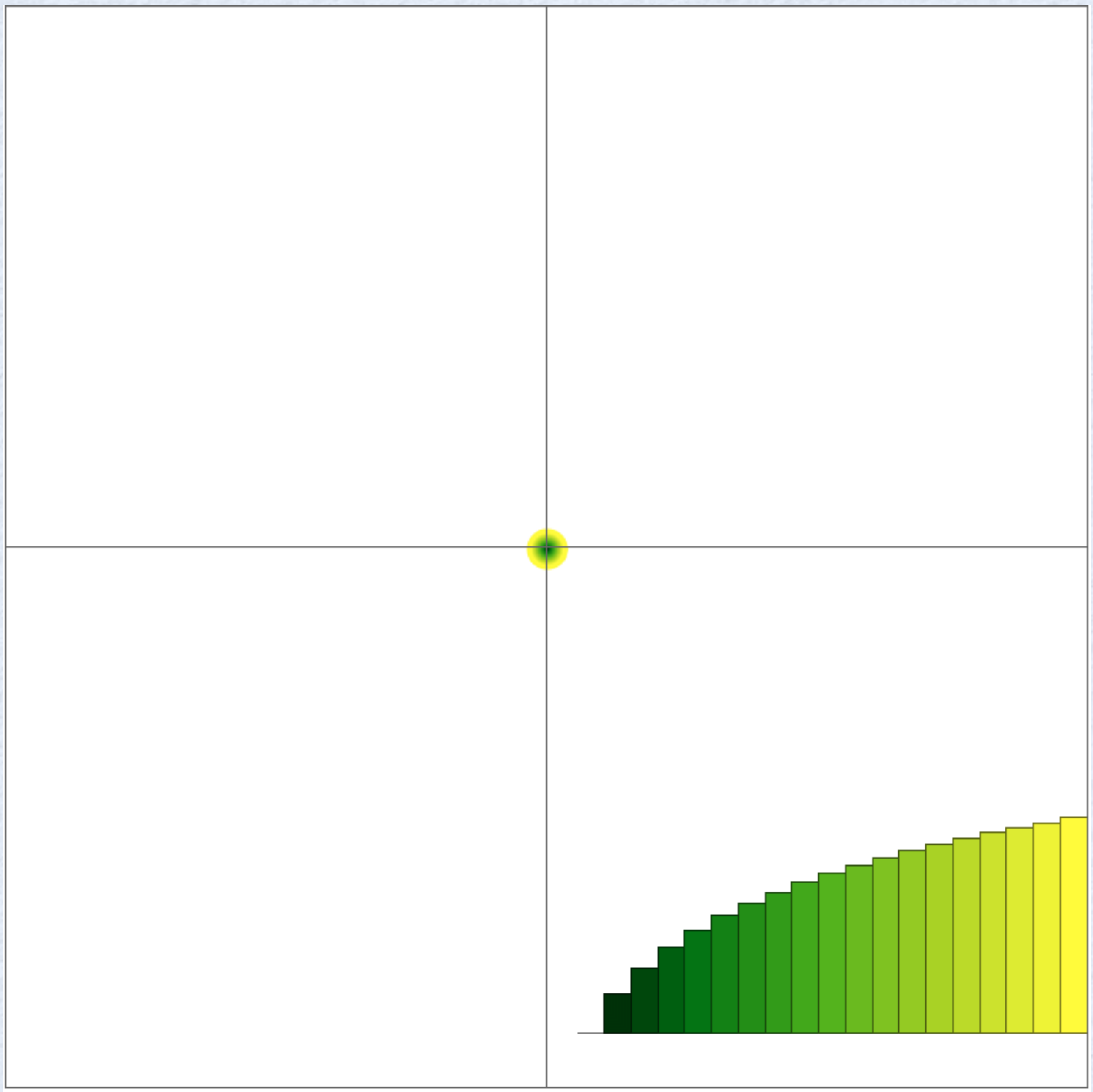


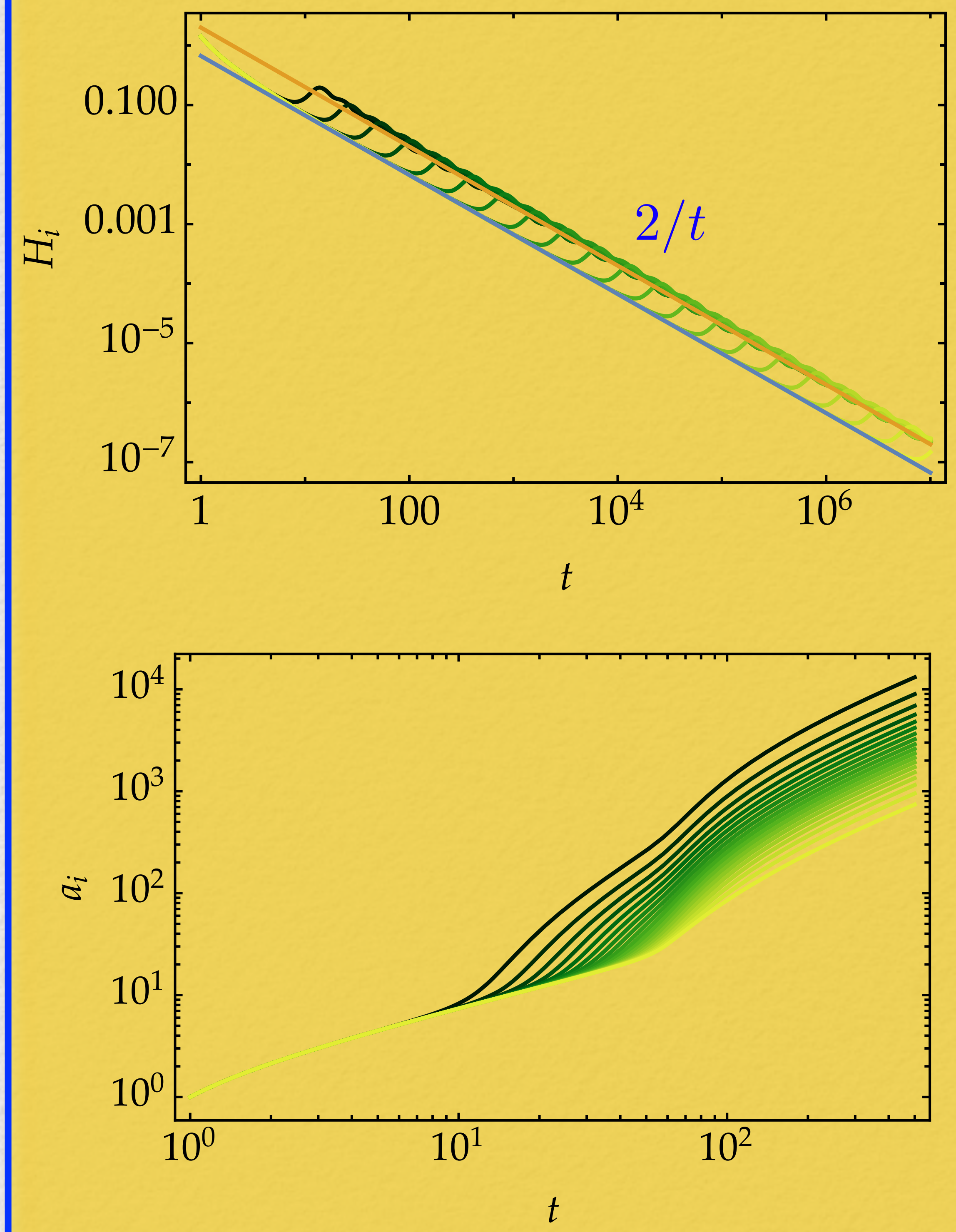




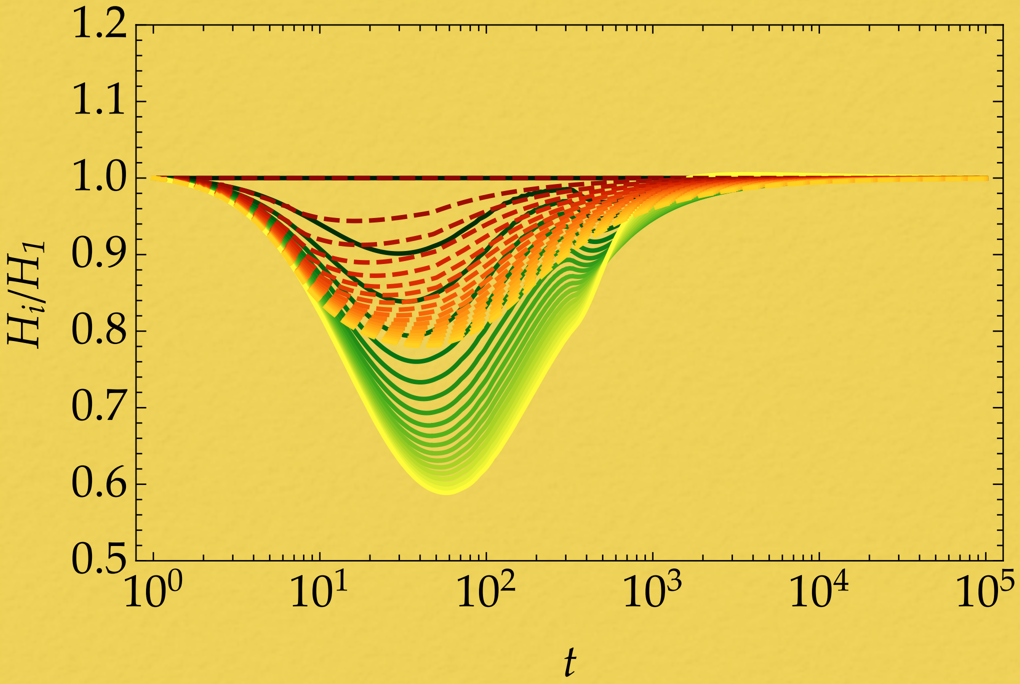
A little digression: Baryons and DM see different "metrics", which could be seen as a (fake) violation of the equivalence principle.

Shell-crossing: Acceleration?



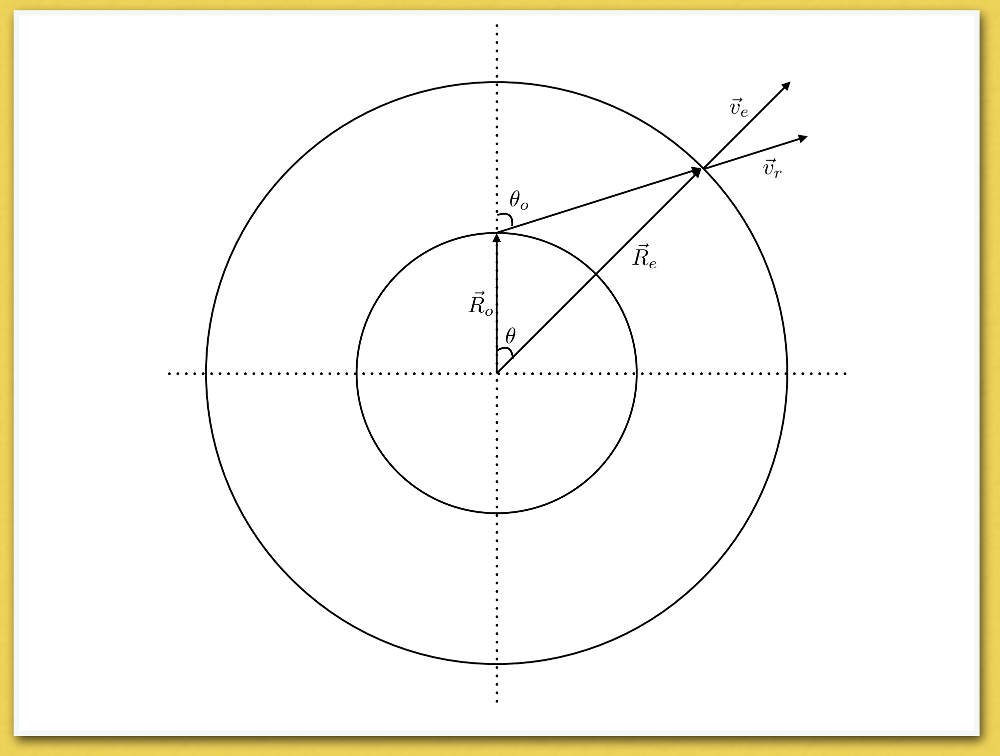


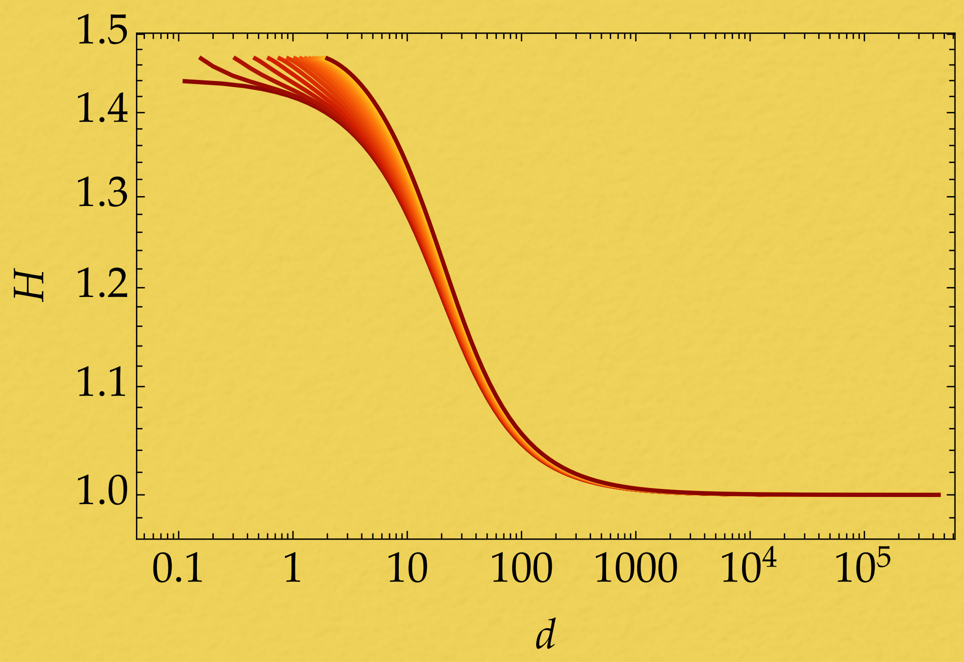
THE HUBBLE TENSION



The outer shells expand with a smaller Hubble expansion rate than the inner shells.

The cosmological expansion would correspond to the outermost shells, while the local measurements of the Hubble constant would probe the inner shells.





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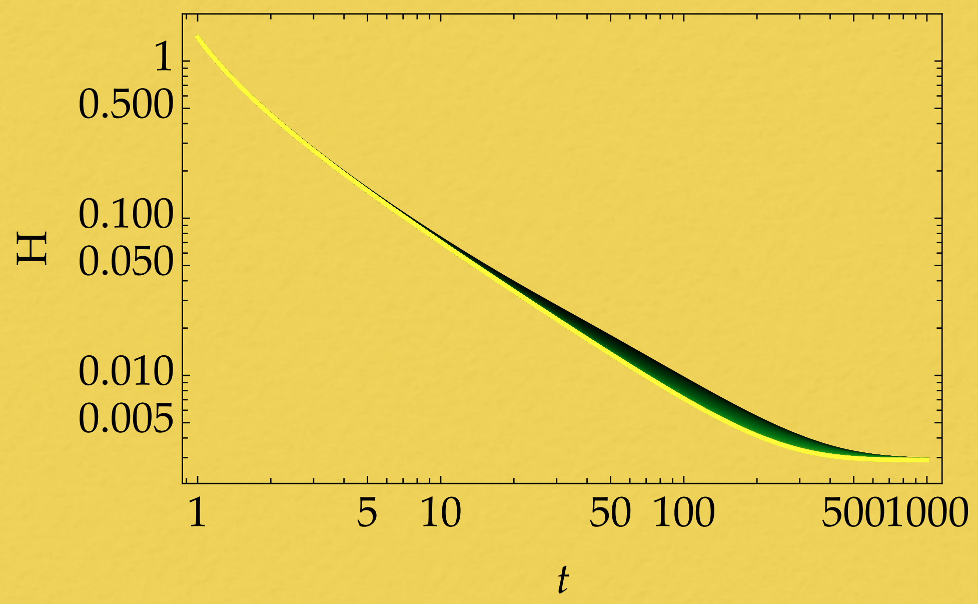
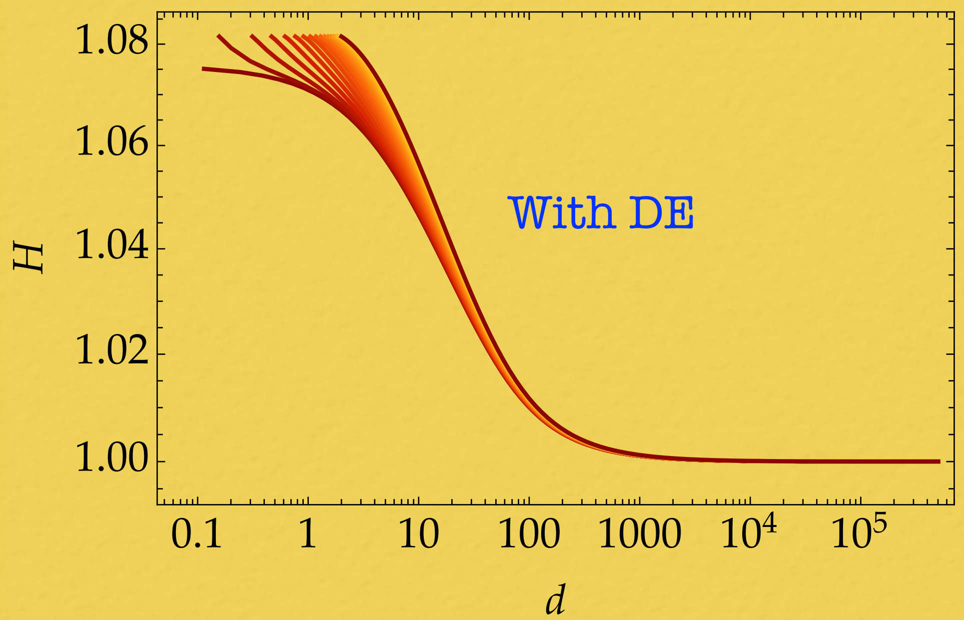
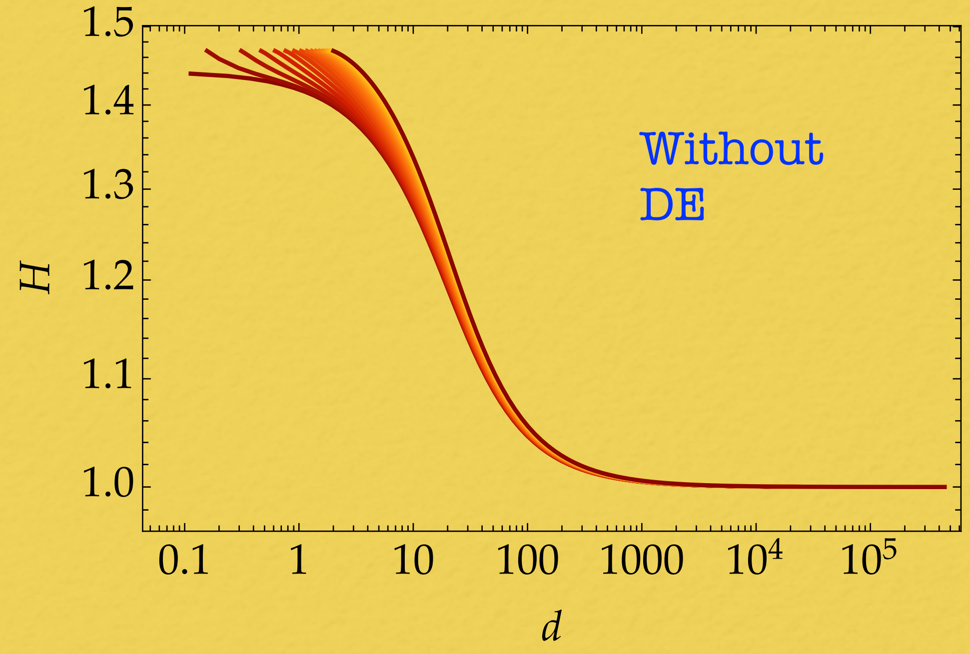


DE stops the generation of inhomogeneities.

DE does not change the picture, but it can actually help.





Conclusions/Prospects

- DM can be charged under a dark non-linear electromagnetic field without spoiling the core of structure formation.
- The dark electric force can affect the late-time evolution with potentially interesting effects on the Hubble constant and structure formation (dark flows?).
- A fully relativistic description in terms of inhomogeneous (Lemaître) models.
- N-body simulations should help clarifying the exact effects on structure formation. Spherical collapse.
- A proper comparison to data is needed.