Charged Dark Matter and the H0 tension ?

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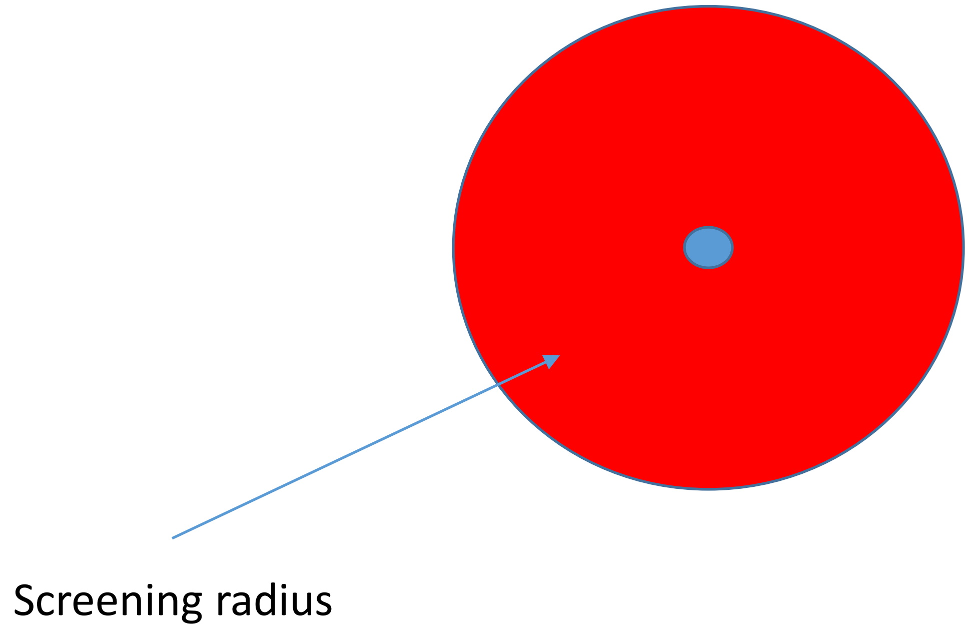
2004.13677
2007.11029
2103.03627

Non-linear effects in ***non-linear electromagnetism:***



A heuristic classical reasoning: if electromagnetism is non-linear then point-like particles belong to their **screening radius**:

$$Q_{\mathrm{eff}} = 0$$

Effectively point-like particle decouple from the U(1) field! Only ***macroscopic configurations*** will feel effects.

We will concentrate on *non-linear theories* with a single *charged dark matter* particle.

Charged dark matter?

- Dark matter, typically fermions, could be charged under a new U(1).
- Before acquiring a mass, must be careful about the anomaly condition. Not all charges allowed.
- At low energy, once dark matter acquires a mass, both particles and anti-particles of opposite charges may be present.

Standard scenario: freeze out and suppressed particle-antiparticle annihilation. See:
http://arxiv.org/abs/0810.5126

Here we will require an unknown period of ***dark matter genesis*** where only one type of charge remains.

Non-linear effects?

One brane could carry a U(1) gauge field.

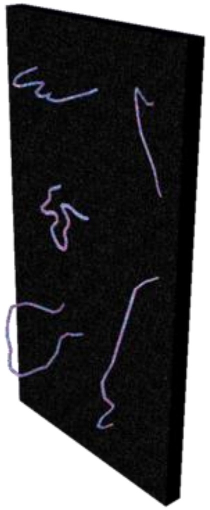
Dark matter could live on this brane and be charged

$$\mathcal{L} \propto \sqrt{-\det(\eta_{\mu\nu} + \frac{F_{\mu\nu}}{\Lambda^2})}$$

Born-Infeld theory

Screening of elementary charges guarantees a finite energy configuration

We will be agnostic about the origin of the models in the following: ***effective field theory approach***



Another brane could carry the baryons

Non-linear Electrodynamics: an ***effective approach***

$\mathcal{L} = Y$ Maxwell

$$\mathcal{L} = \mathcal{K}(Y, Z), \quad Y = -\frac{1}{4}F^2, \quad Z = -\frac{1}{4}F\tilde{F}$$

$$\tilde{F}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$$

$$Y = \frac{1}{2}(\vec{E}^2 - \vec{B}^2), \quad Z = \vec{E}.\vec{B}$$

Non-linear terms in powers of Y and *Z suppressed by scale Λ*. Non-linear regime when powers of Y and Z dominate over the linear term in Y.

$$F \simeq \Lambda^2$$

$$\vec{\nabla}(\mathcal{K}_Y \vec{E}) = \rho_q$$

Coulomb's law

Non-linear effect similar to K-mouflage for scalars

Electric charge

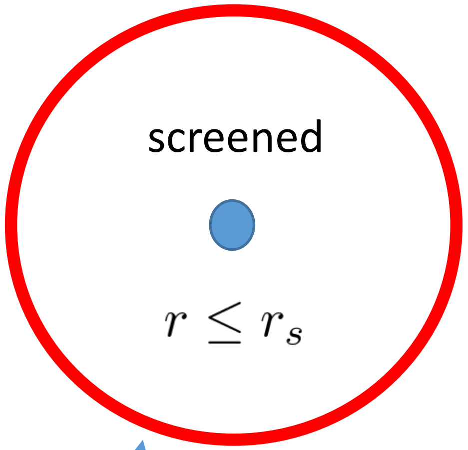
Point charges:

Screening when

$$\vec{E} = \frac{q}{4\pi \mathcal{K}_Y r^3}\vec{r}$$

$$\mathcal{K}_Y \gg 1$$

unscreened



$$E = \frac{q}{4\pi r^2}$$

$$r_s = \sqrt{\frac{q}{4\pi}}\Lambda^{-1}$$

Screening radius

If only one charged species, charge is proportional to mass:

$$E = \Lambda^2 \quad \text{at} \quad r = r_s$$

$$q = \beta \frac{m}{\sqrt{2}m_{\rm Pl}}$$

$$\vec{F} = -\frac{G_N m M}{r^3}\left(1 - \frac{\beta^2}{\mathcal{K}_Y}\right)\vec{r}$$

Repulsive force
Reduction of Newton's constant

The screening function:

$$\vec{E} = F(x)\frac{q}{4\pi r^3}\vec{r}$$

$$x = \frac{r}{r_s}$$

$$r_s \simeq \sqrt{\frac{m}{m_{\rm Pl}}}\Lambda^{-1}$$

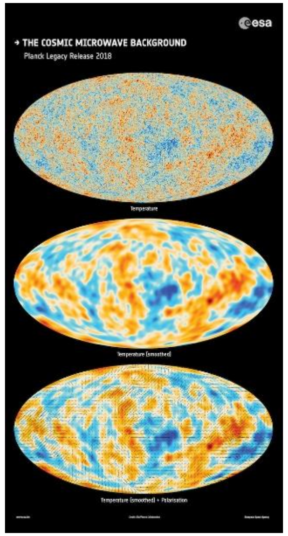
$$F(x) \ll 1,\ x \leq 1, \quad F(x) \simeq 1,\ x \geq 1$$

The screening radius goes like the square root of the mass!

Theory	Lagrangian	Function	Screening scale
Born-Infeld	$\frac{\mathcal{L}_{\rm BI}}{\Lambda_e^4} = 1 - \sqrt{-\det\left(\eta_{\mu\nu} + \frac{1}{\Lambda_e^2}F_{\mu\nu}\right)}$	$F(x) = \frac{1}{\sqrt{1+x^{-4}}}$	$r_s = \frac{1}{\Lambda_e}\sqrt{\frac{Q}{4\pi}}$
Quadratic	$\mathcal{L}_2 = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \left(\frac{F_{\mu\nu}F^{\mu\nu}}{4\Lambda_e^4}\right)^2$	$\left[1 + \frac{F(x)}{x^4}\right]F(x) = 1$	$r_s = \frac{1}{\Lambda_e}\sqrt{\frac{Q}{4\pi}}$

Some scales:

Energy at matter-radiation equality



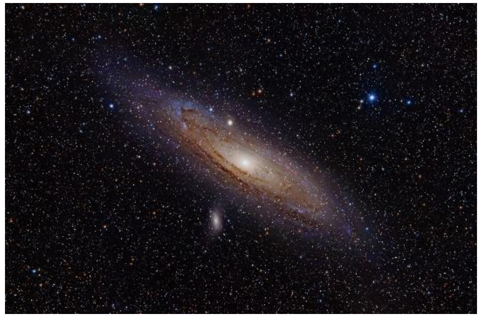
All the horizon at least till last scattering should be screened: $\Lambda \leq 1 \text{ eV}$

The screening radius of the horizon now should be smaller than the horizon: $\Lambda \geq 10^{-3}\text{eV}$

Dark energy scale

Clusters should be unscreened: $\Lambda \geq 10^{-4} \text{ eV}$

Galaxies should be unscreened: $\Lambda \geq 10^{-3} \text{ eV}$



Effects on late Universe only: $10^{-3} \text{ eV} \leq \Lambda \leq 1 \text{ eV}$

How to do cosmology with screened radiation?

Photons: Described by a ***relativistic fluid*** $T_{\mu\nu} = \mathrm{diag}(\rho, p, p, p)$

$$G_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

The cosmological principle allows one to describe the evolution of the Universe as the dynamics of ***co-moving shells***:

Eulerian (R(t),t) description of evolving shells

$$ds^2 = -dt^2 + a^2(t)dx^2 \qquad \frac{\dot{R}^2}{R^2} = \frac{\dot{a}^2}{a^2} \equiv H^2(a)$$

$$R(t) = a(t)r$$

(r,t) Lagrangian description foliated by the initial radii of the shells

Screened difficulties:

Field description:

Cosmological principle → $A_0(t) \Rightarrow F_{\mu\nu} \equiv 0$

Screening breaks homogeneity → $A_0(r,t) \Rightarrow E_r \neq 0$

Inhomogeneous models? Lemaitre!

Fluid description:

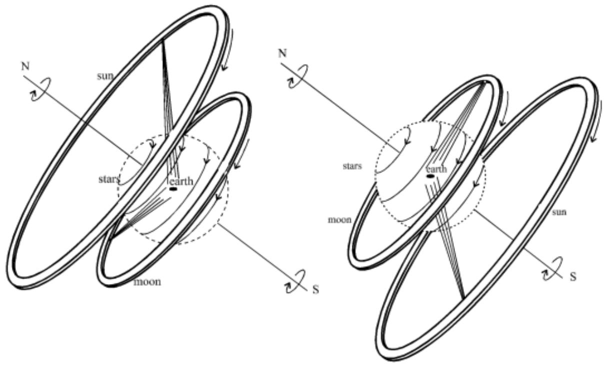
Inhomogeneous density and pressure? How to model it?

Newtonian Cosmology

$c_{\mathrm{dark}} \leq 1$

Restrict our description of the Universe to the **horizon** (domain of influence of the dark U(1)) as speed of light c=1 when unscreened (early in the Universe).

Initially foliate the Universe in shells of radius r inside the horizon.



$$\ddot{R}(t,r) = -\frac{G_N M(R(t,r))}{R^2(t,r)}\left(1-\beta^2 F\left(\frac{R(t,r)}{r_s}\right)\right)$$

Newton's law

Dark repulsion

For scalars, K-mouflage involves a plus sign! More gravity… similar type of modification…

Breaking the co-moving evolution

Breaking of co-moving evolution

Locally we can always define the scale factor of each shell:

$$a_s(r) = \frac{r_s(r)}{r}$$

$$R(t,r) = a(t,r)r$$

$$\mu = \frac{M}{r^3}$$

$$\ddot{R}(t,r) = -\frac{G_N M(R(t,r))}{R^2(t,r)}\left(1 - \beta^2 F\left(\frac{R(t,r)}{r_s}\right)\right)$$

$$\ddot{a}(t,r) = -\frac{G_N \mu(R(t,r))}{a^2(t,r)}\left(1 - \beta^2 F\left(\frac{a(t,r)}{a_s}\right)\right)$$

No shell crossing

$$\ddot{a}(t,r) = -\frac{G_N \rho_{\rm in}}{a^2(t,r)}\left(1 - \beta^2 F\left(\frac{a(t,r)}{a_s}\right)\right)$$

Explicit dependence on the scale factor when a **shell exits** its screening radius $a_s(r)$

Curvature and pressure

When mass is conserved, can integrate to get Friedmann's equation:

$$E(r) = \frac{\dot{a}^2}{2} - \frac{4\pi G_N \rho_{\rm ini}}{3a} + \mathcal{U}(a)$$

$$\mathcal{U}(a) = -\frac{4\pi\beta^2 G_N \rho_{\rm ini}}{3}\int_{a_{\rm ini}}^{a} \frac{F(a/a_s)}{a^2}da$$

Early Universe curvature

$$H^2 = \frac{8\pi G_N \rho_{\rm ini}}{3a^3} + 2\frac{E(r)-\mathcal{U}(a)}{a^2}$$

Acts like an effective curvature term or "pressure"…

Looks like Tolman-Bondi-Lemaitre…
not quite!

Curvature and pressure

Shells with small r exit their screening radius earlier.

For a sharp screening function:

$$\mathcal{U}(a) = 0,\ \ a \leq a_s$$

$$\mathcal{U}(a) = \frac{4\pi G_N \beta^2 \rho_{\rm ini}}{3}(\frac{a}{a_s} - 1)$$

$$\mathcal{U}_\infty = -\frac{4\pi G_N \beta^2 \rho_{\rm ini}}{3}$$

$$a_s \simeq \sqrt{r}$$

For shells outside their screening radius:

$$H^2(t,r) = \frac{8\pi(1-\beta^2)G_N\rho_{\rm ini}}{3a^3} + \frac{8\pi G_N \beta^2}{3a_s a^2}$$

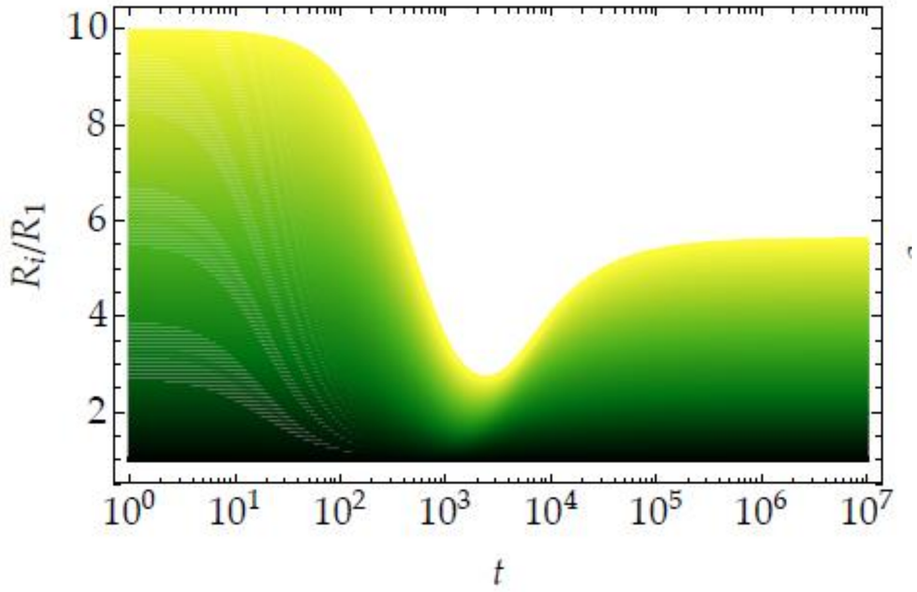
$$a(t) \simeq a_s(r)^{-1/2} t$$

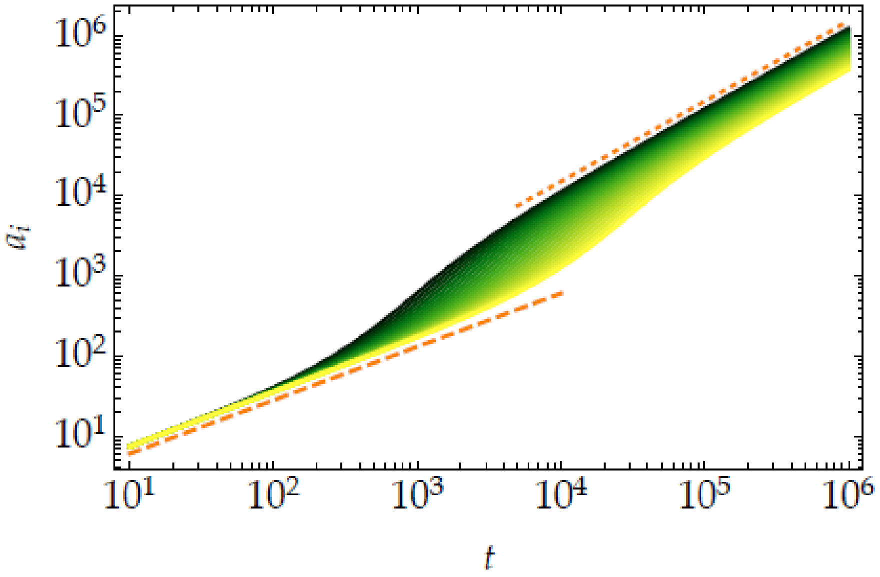
Repulsive effect

Asymptotic negative curvature

Dynamics of DM shells:

From yellow to Green: smaller and smaller initial radius r





When the different shell exit their screening radii (the innermost shells first), the evolution is not co-moving anymore. The inner shells catch the outer ones, resulting in a "compression" zone before relaxing a ending again co-movingly in a negatively curved Universe.

The initial co-moving evolutions breaks up as (green) inner shell exit their screening radii and feel the repulsive effect of the dark electric force. Eventually the curvature dominated phase starts whilst the transient regions sees a faster evolution of the innermost shells.

Equivalence with Lemaitre models (1933)

Absent in TLB models

Two fluid models:

dust and fluid with pressure

The line element is:

A=0 if no pressure

$$ds^2 = -e^{A(t,r)}dt^2 + e^{B(r,t)}dr^2 + R^2(r,t)d\Omega^2$$

Conservation of matter:

$$\dot{\rho} + (2\frac{\dot{R}}{R} + \frac{R'}{R})\rho = 0 \qquad \dot{\rho}_e + (2\frac{\dot{R}}{R} + \frac{R'}{R})(\rho_e + p_e) = -\frac{\dot{R}}{R'}p'_e$$

Electric pressure

Einstein equations:

$$e^B = \frac{R'^2}{1+2E(r)}e^{-\int A' \frac{\dot{R}}{R'} dt} \qquad A' = -\frac{2p'_e}{\rho+\rho_e+p_e}$$

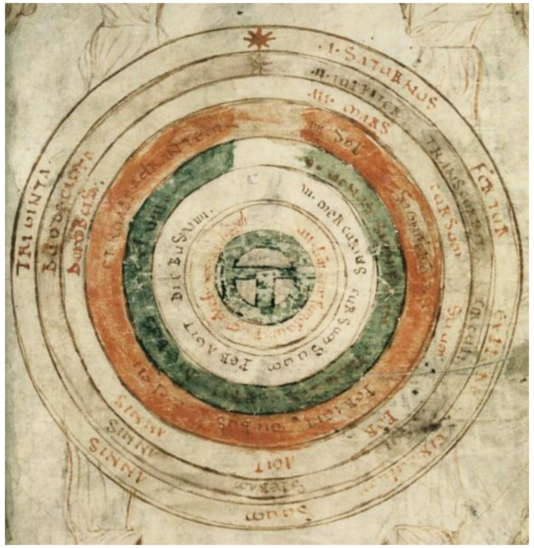
The H0 tension?

$$v = H_{\rm local} d$$

???

Toy model: only DM and no shell crossing.

We have seen that inner shells have a faster evolution than outer shells.



- The Hubble rate deduced at last scattering not influenced by dark U(1) (screening)
- At small redshift, closer objects from an observer have a larger expansion rate.
- Close objects have different Hubble rates on different shells

$$H^2 = \frac{8\pi G_N}{3}\left(\rho_o\left(\frac{a_o^3}{a^3}(1-\beta^2) + \beta^2 \frac{a_o}{a_s}\frac{a_o^2}{a^2}\right) + \rho_{\rm DE}\right)$$

observer

Close objects

$$a \simeq a_o$$

$$H_{\rm local} = H_0^{CMB}\left(1 - \frac{\beta^2}{2}\Omega_{m0} + \frac{\beta^2}{2}\Omega_{m0}\frac{a_o}{a_s}\right)$$

The H0 tension?

$$H_{\text{local}} = H_0^{CMB}(1 - \frac{\beta^2}{2}\Omega_{m0} + \frac{\beta^2}{2}\Omega_{m0}\frac{a_o}{a_s})$$

$$H_0^{\text{local}} \simeq H_0^{\text{CMB}}(1 + \frac{\beta^2}{2}\Omega_{m0} z_s)$$

$$z_s \leq 0.5$$

No discrepancy on BAO scale

10% effect for a coupling of order one and a cut-off scale:

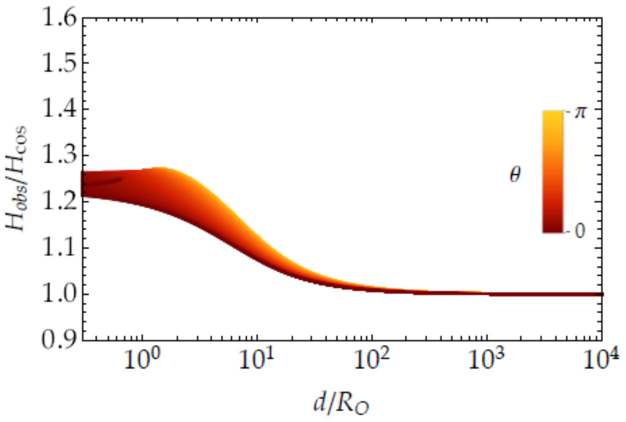
$$\Lambda \simeq 10^{-2} eV$$

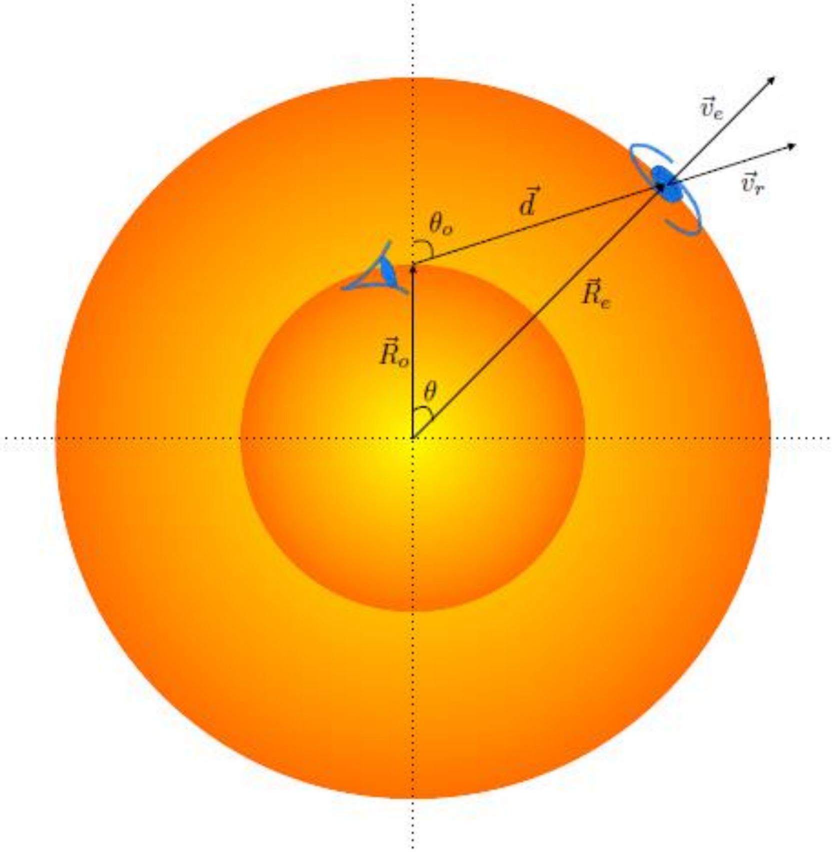
Anisotropy

When the observer is not at the centre of the shells, there is an anisotropic effect:

$$\frac{v_r}{|R_o - R_e|} = H_e \frac{1 + \frac{v_o R_o}{v_e H_e} - (\frac{R_o}{R_e} - \frac{v_o}{v_e}) \cos\theta}{1 + (\frac{R_o}{R_e})^2 - 2\frac{R_o}{R_e} \cos\theta}$$

Unity for comoving motion





$$v_r = (\vec{v}_o - \vec{v}_e).\frac{\vec{R}_o - \vec{R}_e}{|R_o - R_e|}$$

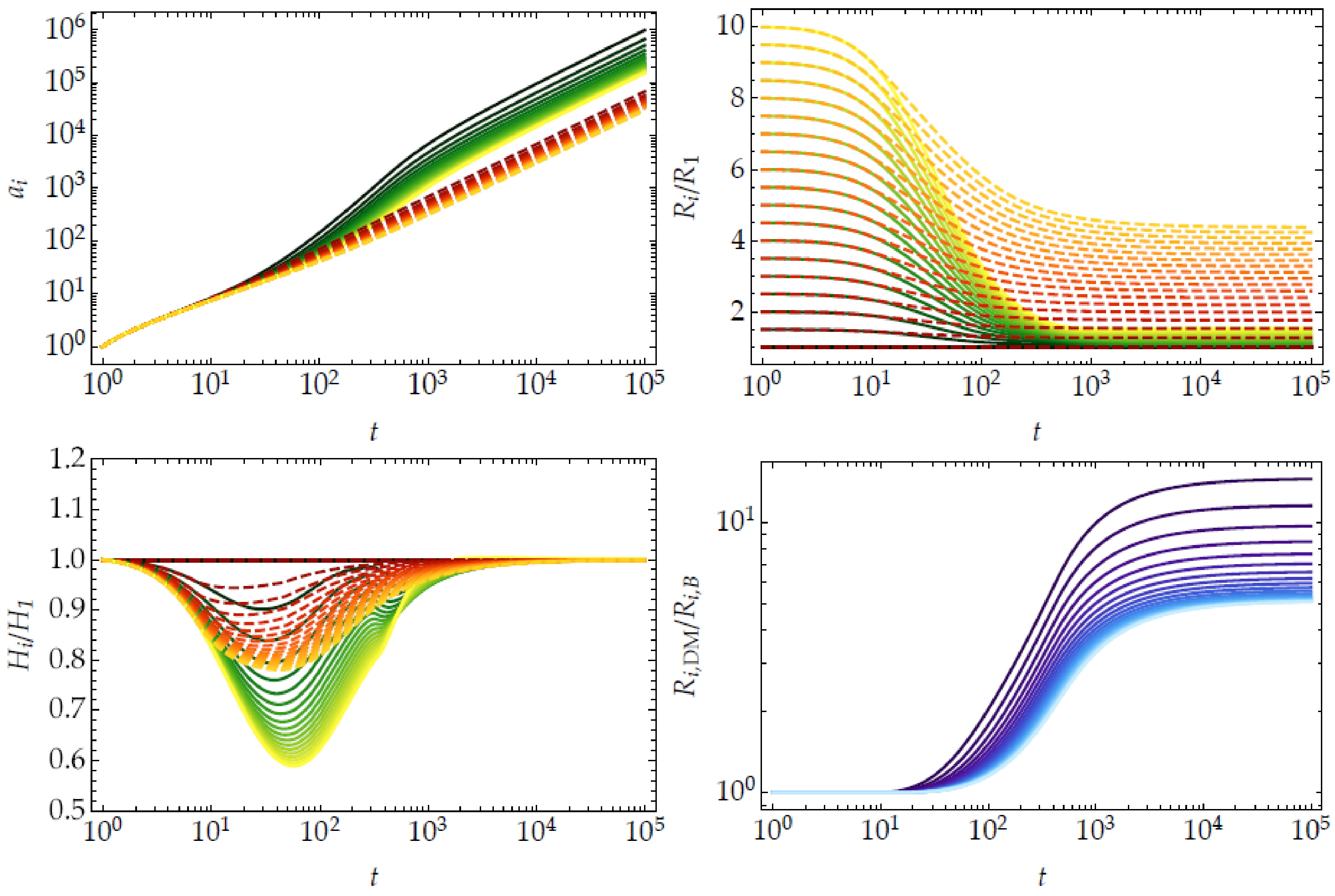
Time to conclude!

- Dark repulsion could have interesting effects at late time whilst preserving early time cosmology: a window on the H0 tension?
- Need to compare to data for Born-Infeld, best motivated model.
- How do structure form in these scenarios (spherical collapse…) ?
- N-body simulation should help!
- More funny properties (vanishing susceptibilities…)

Adding baryons:

The presence of baryons “induces” shell crossing of DM for models with no shell crossing at the DM level.

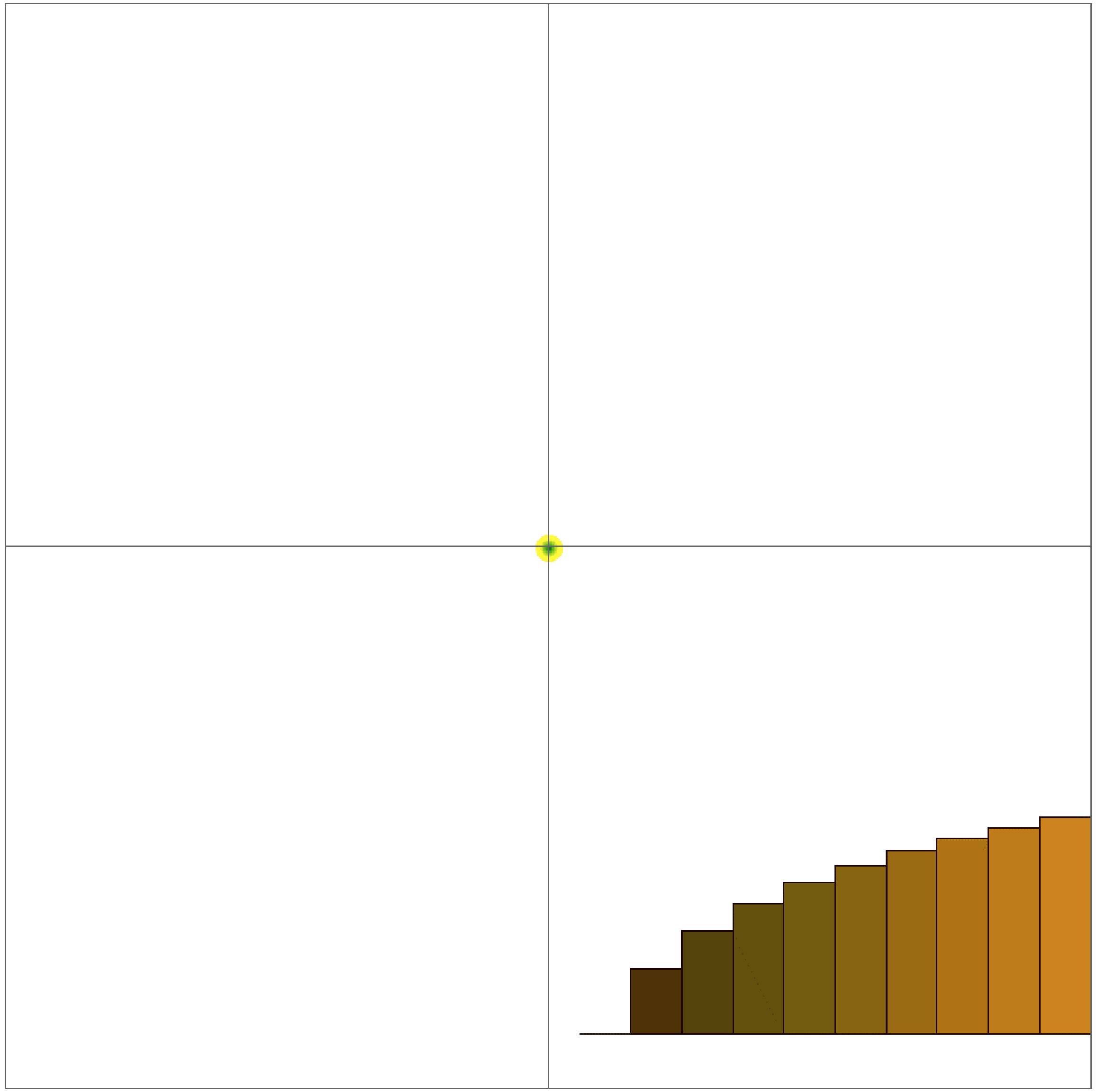
No shell crossing for baryons here.



The Hubble rate of baryonic shells follows the trend of DM, i.e. outer shells lag behind.

DM “pushed away” compared to baryons. Could leave DM depleted regions.

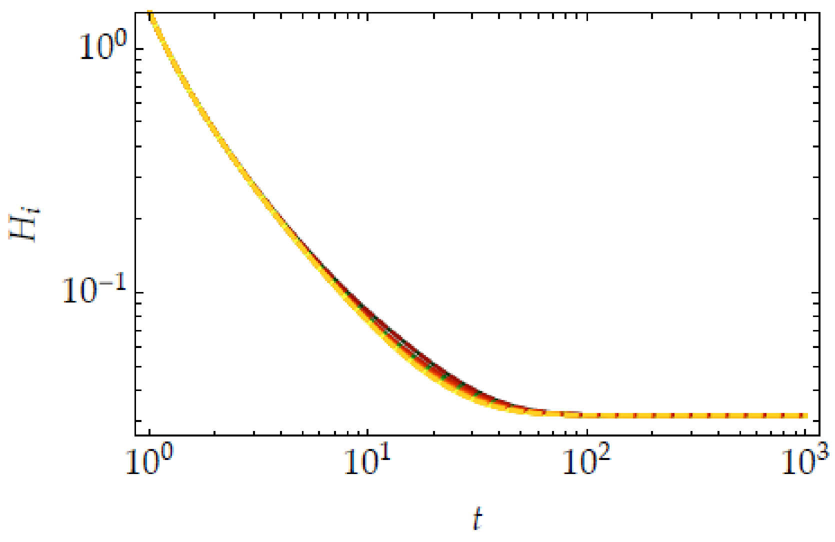
Dark matter and baryon shells in a DBI model.

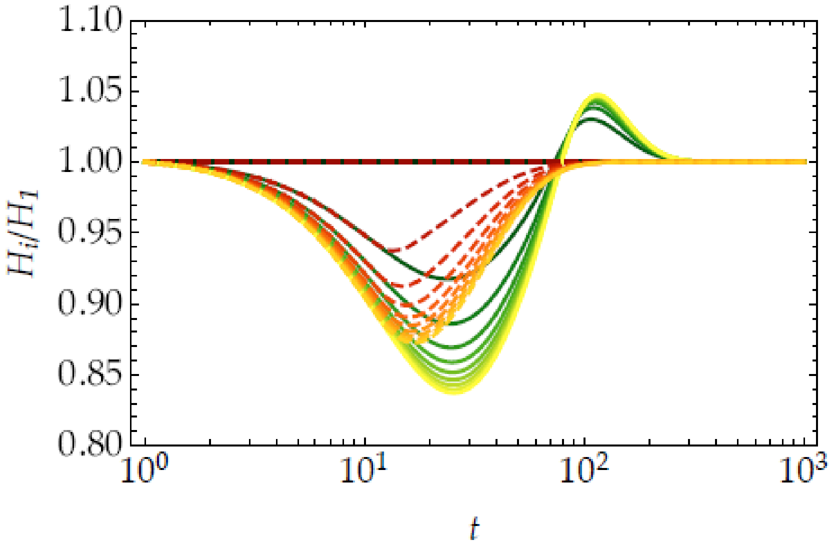


You can see the fact that the dark matter shells cross!

And the mass within each shell is not constant.

Adding Dark Energy:





Before complete dominance by DE, the inner shells still have a larger Hubble rate.

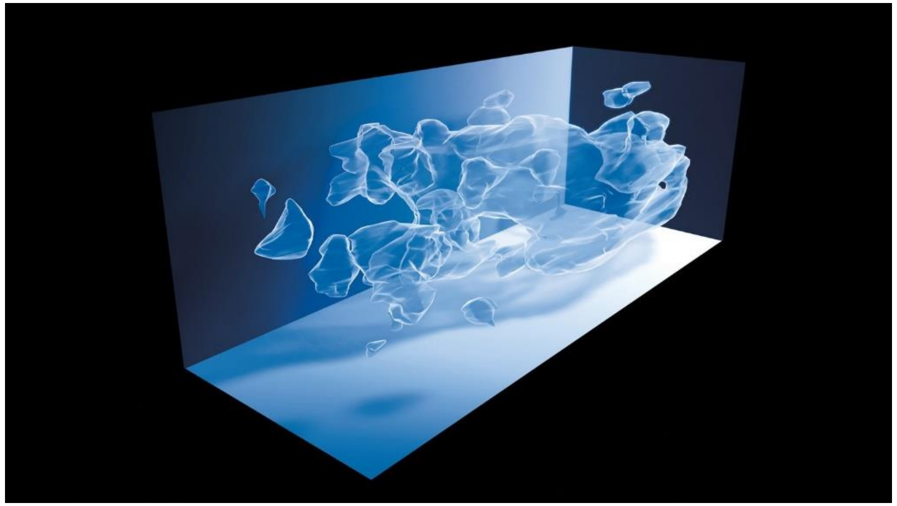
The inner shell baryons have a large Hubble rate when the Universe is not completely DE dominated.

Possible astrophysics effects:

If distribution of matter reconstructed from Newton's law and Newton's potential, then unaccounted for repulsion implies at least two possible effects:

$$\frac{\delta\sigma}{\sigma} = \beta^2$$

An increase of the velocity dispersion due to the repulsive effect of the dark repulsion?



$$\vec{v} \simeq \beta^2 \vec{\nabla} \Phi_N t_0$$

Possible large scale flows of galaxies pushed away by the dark repulsion ?