Evolution of Non-comoving baryons and cold dark matter in cosmic voids

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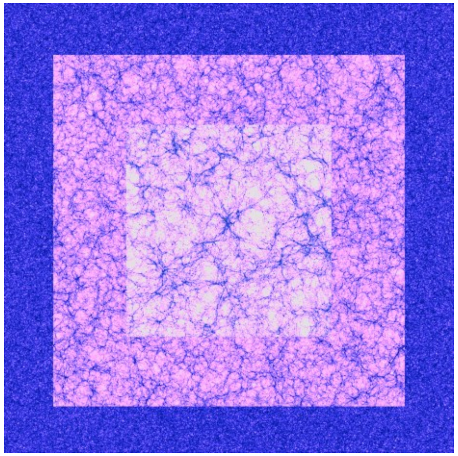
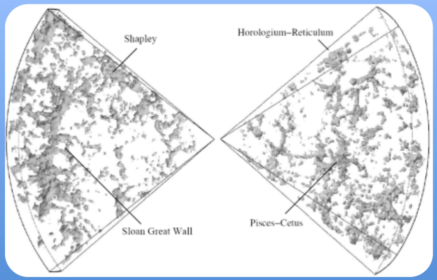
Relativistic Structures?

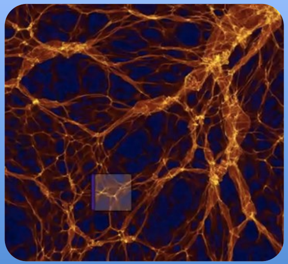
- The current era of "Precision Cosmology" requires a robust modeling clustering for the correct interpretation of data.
- Modeling of structures and analysis of observations mostly done in Newtonian gravity,



Teyser et al.
Astron.Astrophys. 497 (2009) 335



V Martínez, E Saar, E, Martínez-González, M. Pons-Bordería, Springer Verlag, Berlin, Lecture Notes on Physics 665 (2009)



C.S. Frenk and S.D.M. White, Ann Phys, 524, 507534 (2012)

Relativistic Structures?

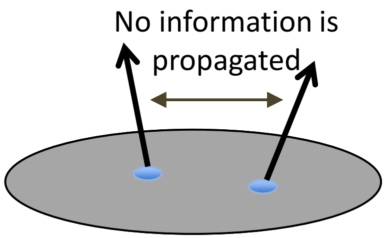
It’s widely assumed to be practically impossible to model minimally realistic cosmic structures by means of exact solutions of the Einstein’s equations

Large cosmic scale dynamics	⟶	linear perturbations on a FLRW background
Self–gravitational systems at galactic and galactic cluster scales	⟶	Newtonian gravity (perturbative and nonperturbative)

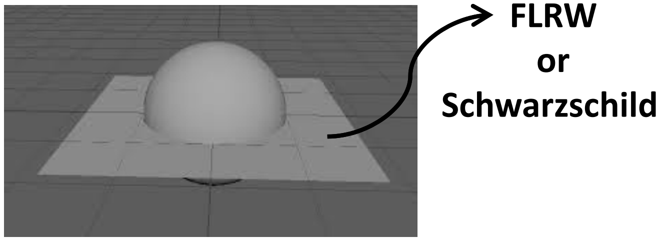
Can we hope to provide a “decent”, at least coarse grained, description of cosmic structures with semi-analytic or numerical solutions of Einstein’s equations?

Silent models

- **Silent universe:** Each worldline evolves independently of the others: there is no communication between different points of the universe (world-lines).

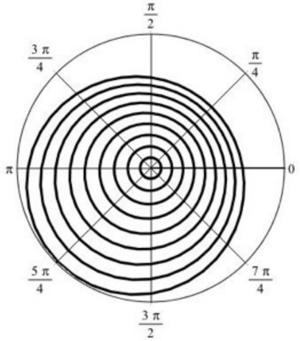


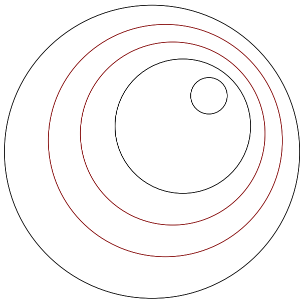
- The quasi-spherical Szekeres or LTB spacetime can be **matched** either **to an FLRW or Schwarzschild** spacetime.



- ❖ **Shell crossings:** These singularities occur when two shells of dust collide with each other leading to infinite values of the density. ShXs are considered weak singularities.

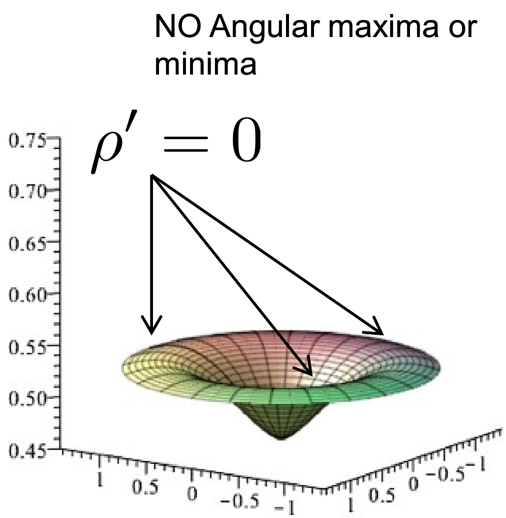
- ❖ **Local concavity inversions:** (from clumps to voids or vice versa) indicate that local maxima evolve into local minima and vice versa.

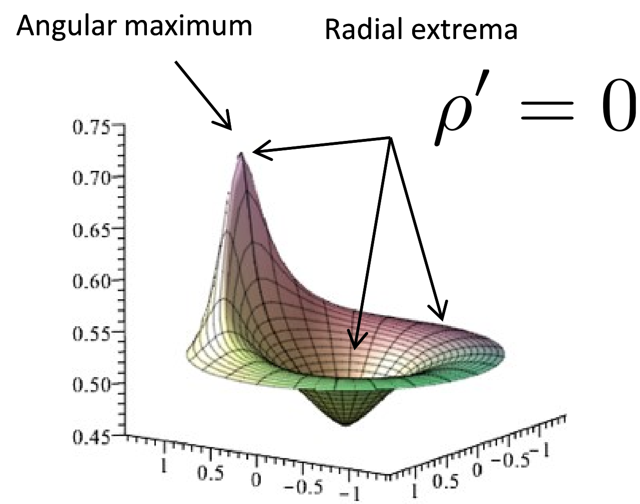




Coarse grained structure

- In order to account for structures using LTB and Szekeres models we associate the spatial maxima and minima of the density matter with “structures” representing overdensities and voids respectively.

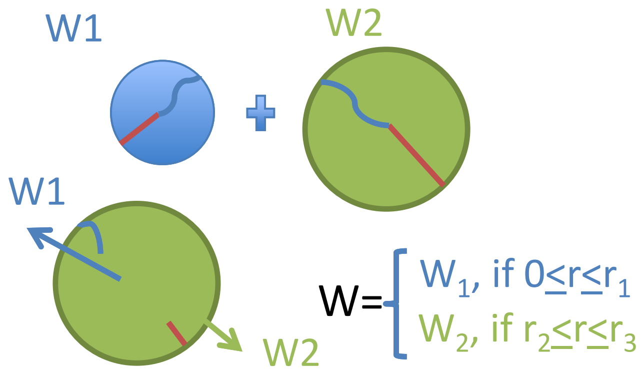


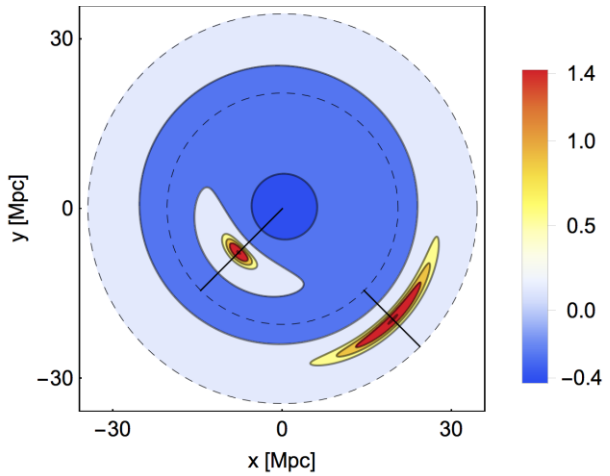


Coarse grained structure

- In order to model structures using Szekeres models we associate the spatial maxima and minima of the density matter with “structures” representing overdensities and voids respectively.

- There will be a radial extremum of the scalars In the radial interval between two Comoving Homogeneity Spheres.
- The “angular extrema” of the scalars coincide with the angular extrema of the dipole **W**, then they will lie along the curve of angular extrema

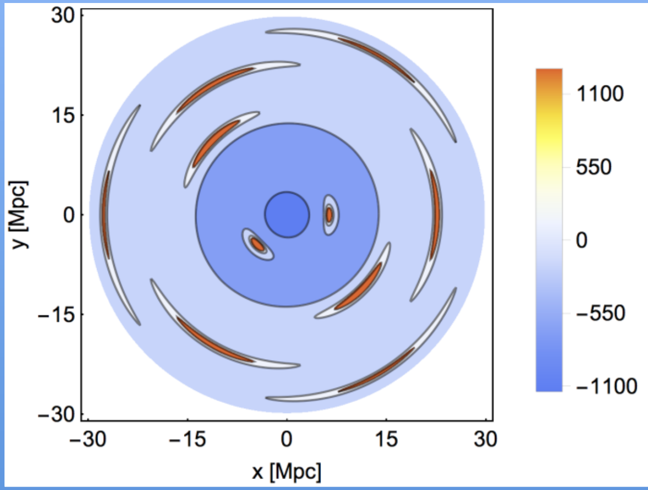




Numerical Example

Radial peculiar velocities of the structures relative to the background Hubble flow (identified with the CMB frame) [km/s].

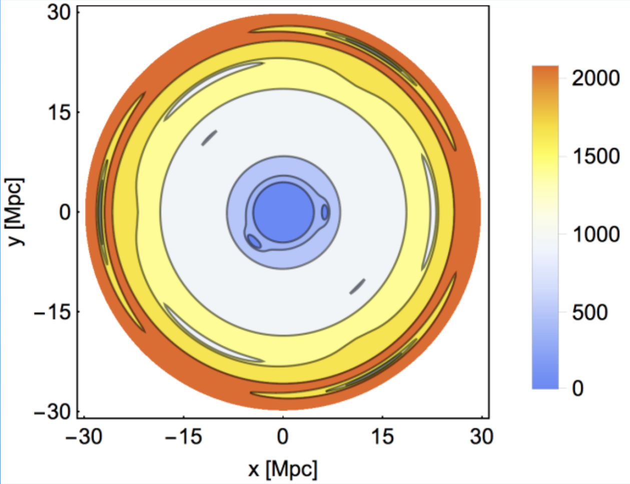
$$v_{\rm pec}^{\rm cmb} = [\mathcal{H}_0\, a_0 - \bar{\mathcal{H}}_0 \bar{a}_0](\chi - \chi_b)$$



- Low density regions expanding away from the background frame at ~ -1100 km/s.
- Over--densities fall into this frame (background) at ~ 1000 -1200km/s.
- The peculiar velocities of the over-densities in could be compared with the estimated infall velocity ~ 600 km/s of our local group with respect to the LCDM background.

Radial peculiar velocities with respect to an observer at the void centre comoving with the origin [km/s].

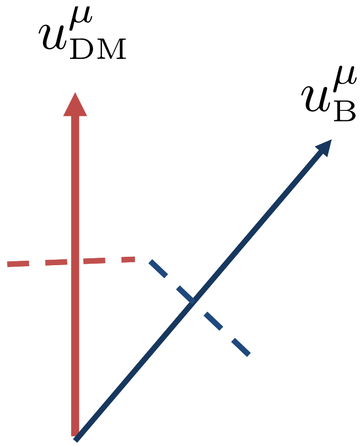
$$v_{\rm pec}^{\rm void} = (\mathcal{H} - \mathcal{H}|_{r=0})\, a_0 r$$



- Vs exhibit an expansion away that is roughly linearly proportional to the radial area distance to the void centre, reaching 2000 km/s for structures located ~ 30 Mpc away.
- Vs closely match the peculiar velocities observed for galaxies in the Virgo supercluster wrt. the centre of the local void.

Delgado-Gaspar, JCH, et al. **JCAP 1603 (2016) 012**

Beyond a single fluid system



- Consider a mixture of non-interacting baryons and CDM dust fluids, each evolving along a different 4-velocity. Our SS spacetime is characterized by the line element,

$$ds^2 = -N^2dt^2 + B^2dr^2 + Y^2(d\theta^2 + \sin^2(\theta)d\phi^2)$$

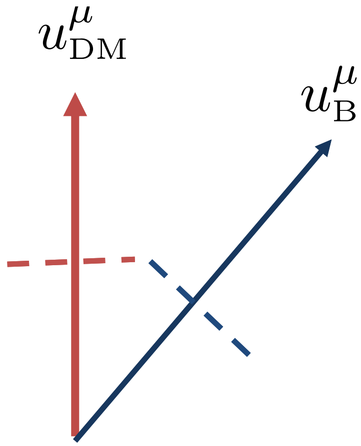
- Since CDM is the dominant clustering source, we choose a frame where fundamental observers are comoving with the dark matter:

$$u^\mu_{\rm DM} = \delta_t^{\ \mu} \qquad h_{\mu\nu} = g_{\mu\nu} + u_\mu u_\nu$$

- Baryon 4-velocity is related to the one of CDM via the relative velocity measured by the fundamental observers, which reads

$$u^\mu_{\rm B} = \gamma\left(u^\mu_{\rm DM} + v^\mu\right), \text{ with } \gamma = \left(1 - v^2\right)^{-\frac{1}{2}}, \text{ and } v_\mu = V\delta^r_\mu,$$

Description of Multiple fluids



- The energy-momentum tensor of the mixture is **not only the sum of two energy densities**, but a complicated tensor that contains effective pressures and energy flux terms associated with the relative velocity field

$$T^{\mu\nu} = T^{\mu\nu}_{\rm DM} + T^{\mu\nu}_{\rm B} = \rho\, u^{\mu} u^{\nu} + p h^{\mu\nu} + 2q^{(\mu} u^{\nu)} + \pi^{\mu\nu},$$

where *ρ, p, π* and *q* are determined by projecting the total energy-momentum tensor parallel and orthogonal to the four-velocity of the fundamental observers, which yields:

$$\rho = \rho_{\rm DM} + \rho_{\rm B}, \qquad p \equiv p_{\rm B} = \frac{1}{3}\gamma^2 v^2 \rho^*_{\rm B},$$

$$Q \equiv Q_{\rm B} = \gamma^2 \rho^*_{\rm B} V, \qquad \Pi \equiv \Pi_{\rm B} = \frac{1}{3}\gamma^2 \rho^*_{\rm B} v^2,$$

$$\rho_{\rm DM} \equiv \rho^*_{\rm DM}, \qquad \rho_{\rm B} = \gamma^2 \rho^*_{\rm B}.$$

Description of Multiple fluids

- Dynamics determined from the first order "1+3" fluid flow representation of EFEs in terms of the quantities defined earlier plus the scalar expansion, the shear, and the electric Weyl tensor.

constraints

$$Y = l_* \mathscr{Y}, \quad r = l_* \xi, \quad \alpha = 1/(H_* l_*),$$

$$\mathscr{S} = \frac{\Sigma}{H_*}, \quad \mathscr{H} = \frac{H}{H_*}, \quad \mathscr{W} = \frac{W}{H_*^2}, \quad \chi = \mathscr{Y}_{,\xi},$$

$$\mu = \frac{\kappa\rho}{3H_*^2}, \quad \mathrm{p} = \frac{\kappa p}{3H_*^2},$$

$$\mathscr{M} = \frac{\kappa M}{3H_*^2}, \quad \mathscr{Q} = \frac{\kappa Q}{3H_*^2}, \mathscr{P} = \frac{\kappa \Pi}{3H_*^2},$$

$T_{\mu\nu}$ components

$$\mu_{\mathrm{B}} = \gamma^2 \mu_{\mathrm{B}}^*, \quad \mathrm{p} \equiv \mathrm{p}_{\mathrm{B}} = \frac{1}{3}\gamma^2 v^2 \mu_{\mathrm{B}}^*,$$

$$\mathscr{Q} \equiv \mathscr{Q}_{\mathrm{B}} = \gamma^2 \mu_{\mathrm{B}}^* V, \quad \mathscr{P} \equiv \mathscr{P}_{\mathrm{B}} = \frac{1}{3}\gamma^2 \mu_{\mathrm{B}}^* v^2,$$

$$\mu = \mu_{\mathrm{DM}} + \mu_{\mathrm{B}}.$$

Geometric scalars

$$\dot{u}_\mu = \tilde{\nabla}_\mu (\ln N) = A \delta^r_\mu$$

$$\sigma^\mu_{\ \nu} = \Sigma\, e^\mu_{\ \nu}, \quad E^\mu_{\ \nu} = W\, e^\mu_{\ \nu}.$$

Which are scalar functions of metric components

$$A \equiv \frac{N_{,r}}{N},$$

$$\Sigma = \frac{1}{3}\left(\frac{\dot{Y}}{Y} - \frac{\dot{B}}{B}\right), \quad W = -\Psi_2,$$

$$e^\mu_{\ \nu} = h^\mu_{\ \nu} - 3n^\mu n_\nu = \mathrm{Diag}[0,-2,1,1]$$

Description of Multiple fluids

- Evolution equations are cast as a first order ODE system with two constraints, Where the time derivative is

$$\hat{\Phi} = \frac{\dot{\Phi}}{H_*} = \frac{1}{H_*} u^{\mu} \nabla_{\mu} \Phi$$

Where characteristic scales are

$$H_* = H(t_*) \qquad l_* \sim 60\,\mathrm{Mpc}$$

constraints

$$\mathscr{H}^2 = \mu - k + \mathscr{S}^2, \quad \text{with} \quad k = \frac{\mathscr{K}}{H_*^2},$$

$$\mathscr{W} = -\frac{\mu}{2} + \frac{\mathscr{M}}{\mathscr{Y}^3} - \frac{3\mathscr{P}}{2},$$

1st order ODEs

$$\hat{\mathscr{Y}} = \mathscr{Y}\left(\mathscr{H} + \mathscr{S}\right),$$

$$\hat{\chi} = -2\chi\mathscr{S} + \chi\mathscr{H} + \frac{3}{2\alpha}\mathscr{Q}\mathscr{Y},$$

$$\hat{B} = B\left(\mathscr{H} - 2\mathscr{S}\right),$$

$$\hat{\mathscr{H}} = -\mathscr{H}^2 - 2\mathscr{S}^2 - \frac{1}{2}(\mu + 3\mathrm{p}),$$

$$\hat{\mathscr{S}} = \mathscr{S}^2 - 2\mathscr{H}\mathscr{S} + \frac{3}{2}\mathscr{P} - \mathscr{W},$$

$$\hat{\mu}_{\mathrm{DM}} = -3\mu_{\mathrm{DM}}\mathscr{H},$$

$$\hat{\mu}_{\mathrm{B}} = -3(\mu_{\mathrm{B}} + p)\mathscr{H} - 6\mathscr{P}\mathscr{S} - \frac{2\alpha\mathscr{Q}\chi}{\mathscr{Y}B^2} - \frac{\alpha\mathscr{Q}_{,\xi}}{B^2} + \frac{\alpha\mathscr{Q}B_{,\xi}}{B^3},$$

$$\hat{\mathscr{Q}} = -3\mathscr{H}\mathscr{Q} - \alpha\mathrm{p}_{,\xi} + 2\alpha\mathscr{P}_{,\xi} + \frac{6\alpha\mathscr{P}\chi}{\mathscr{Y}},$$

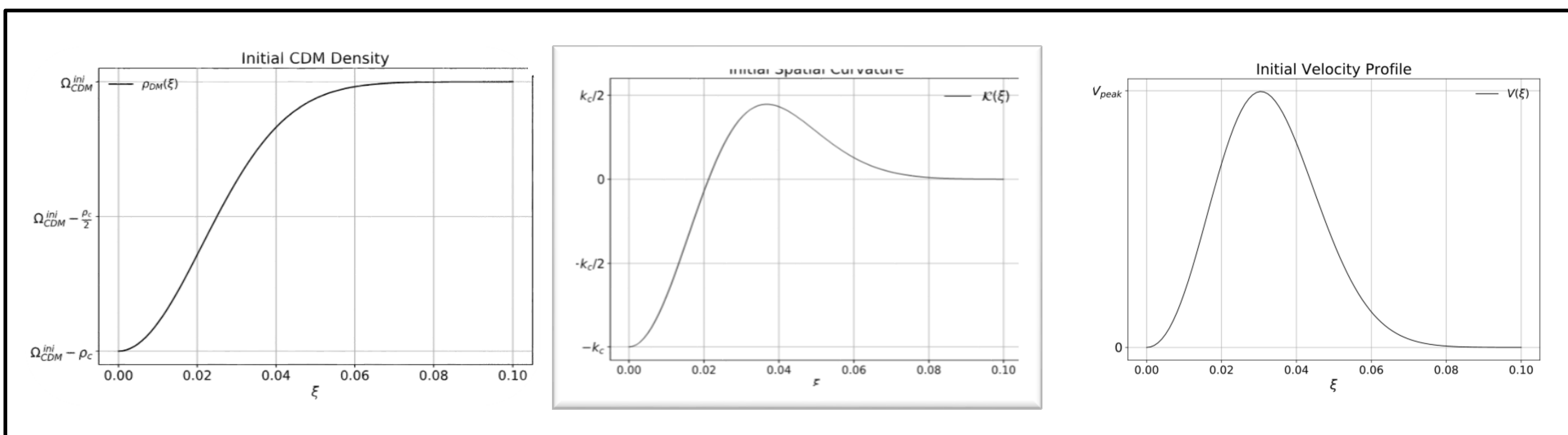
Multiple fluid approach on voids formation

- We examine the numerical solutions simulating a cosmic void of present-day radius ~ 60 Mpc. Starting from linear initial conditions at z=23.

- The initial CDM density, spatial curvature, and the relative velocity profiles are taken as Gaussian functions of linear amplitude wrt the background parameters,

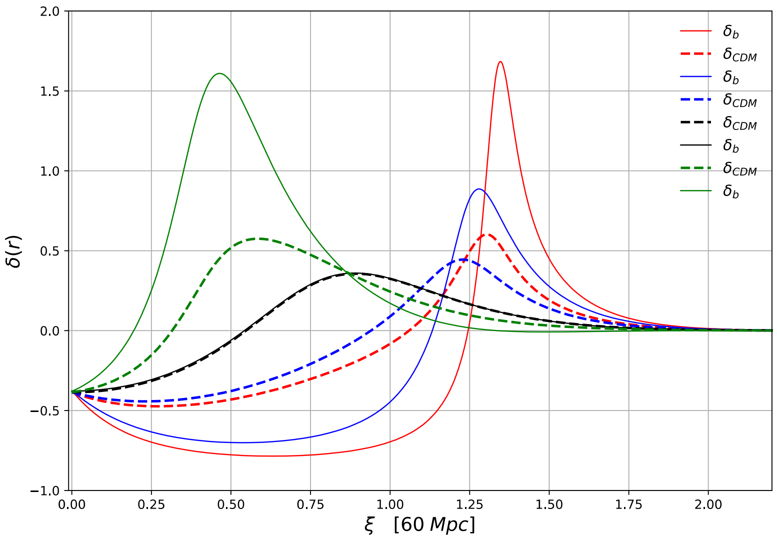
$$\left[\frac{8\pi}{3}\frac{\rho_{\rm DM}}{H^2}\right]_{\rm ini} = \Omega_{\rm DM}^{\rm ini} - \mu_c \exp\left(-\frac{\xi}{\sigma_\mu}\right)^2, \quad [K]_{\rm ini} = -k_c \xi^2 \exp\left(-\frac{\xi}{\sigma_K}\right)^2, \quad [V]_{\rm ini} = V_c \xi^2 \exp\left(-\frac{\xi}{\sigma_v}\right)^2.$$

- Take the baryonic density initially homogeneous with its value in the background.

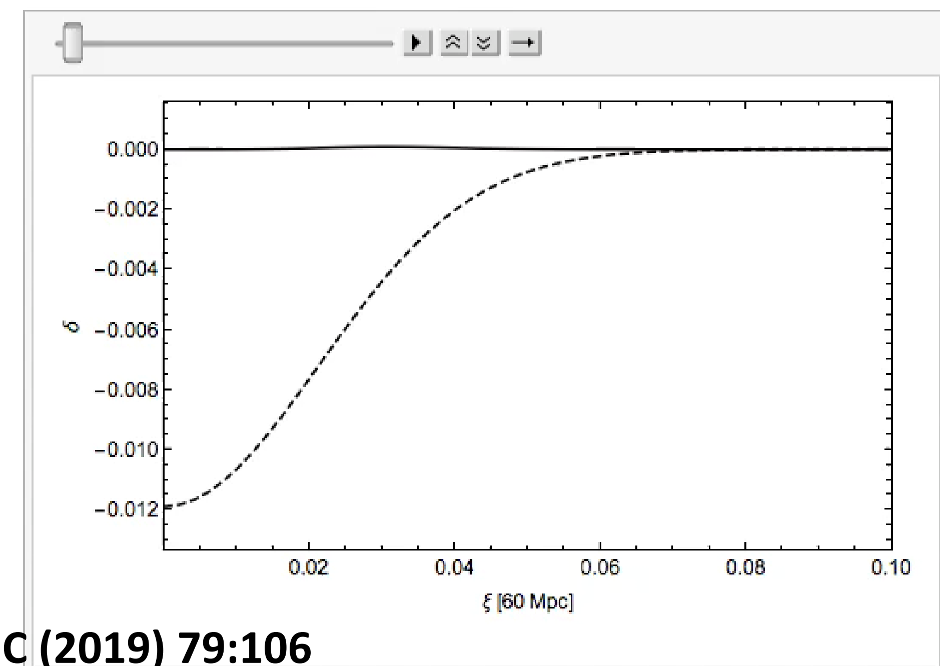


Multiple fluid approach on voids formation

- We perform a series of simulations with identical initial densities and curvature profiles, but vary the amplitude of the relative velocity (V_{peak}).



- Even no relativistic values of relative velocities exert non-trivial effects on present-day configurations as density contrasts become non-linear.



- The void size depends on the sign of radial component of the velocity, so that smaller voids result from initially negative values for the relative velocity

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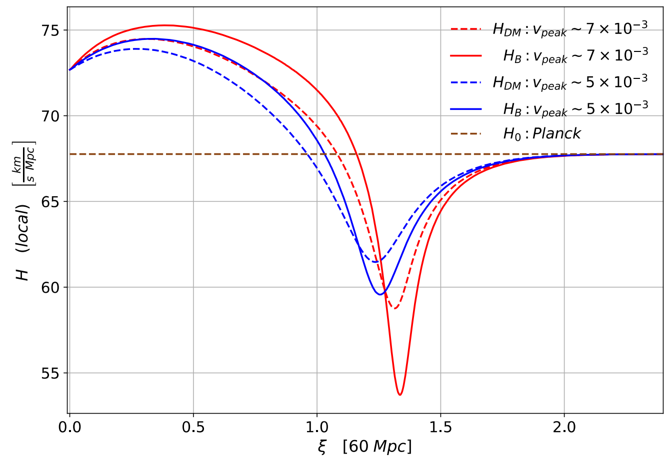
Multiple fluid approach on voids formation

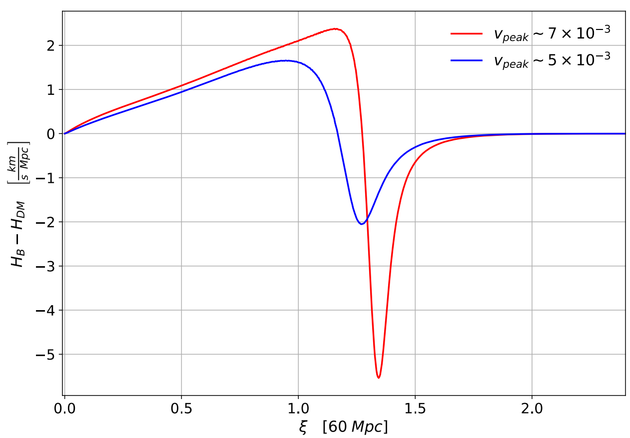
- Due to a change of frame, the local expansion of CDM will depart from the expansion of the baryonic matter H_B, which is given by :

$$3H_B = \Theta_B = h_{B\mu}^{\ \nu}\nabla_\nu u_B^\mu, \quad \Rightarrow \quad 3(H_B - H_{DM}) \simeq \left(\frac{2\chi}{Y} - \frac{B_{,r}}{B}\right)\frac{V}{B^2} + \frac{V_{,r}}{B^2} + V\dot{V}$$



- Difference of a few km/(s Mpc) at the maximum of the baryonic matter density

Difference between local expansions



- **Clue (?)** to better understand discrepancies between H_0 values reported by CMB and SNe observations. Considering a relative velocity between baryons and CDM may provide new interesting local effects.

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Conclusions

- It was shown how to model astrophysical and cosmological structures using the spatial extrema of Szekeres models.
  - ✧ Regions surrounding the spatial maxima of the matter density ⟶ Over-densities
  - ✧ Regions surrounding the spatial minima of the matter density ⟶ Voids
- networks of structures can be modelled, obtaining numerical solutions with values of order of magnitude of the observations.
- In the evolution of two non-commoving fluids, voids sizes may be altered through relative velocities of components
- The resulting difference between velocity profiles yields values of order the inconsistencies observed between local and CMB scales.

IN PROGRESS:

- ❖ Relative speeds between components may provide a smoking gun for Λ.
- ❖ We are working to simulate the relativistic evolution of the BAO feature.

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