Cosmological structure formation with negative mass

Giovanni Manfredi

Centre National de la Recherche Scientifique

Institut de Physique et Chimie des Matériaux de Strasbourg

Gabriel Chardin, CNRS, France

Bruce Miller, Texas Christian University, USA

Jean-Louis Rouet, Université d'Orléans, France

Antimatter and gravitation

- **Why we see no antimatter in today's universe?**
  - Antimatter created in the primordial universe, but…
  - Observations exclude large amounts of antimatter in visible universe
    - ➢ No signature of gamma rays produced during annihilations
  - CP violation cannot explain observed asymmetry

- **Open questions on gravitation**
  - Acceleration of the expansion of the universe (1998) – *Dark Energy*
  - Matter content of the universe – *Dark Matter*
  - Primordial inflation (~1980) – *Inflaton field*

- **Gravitational behavior of antimatter**
  - Current experiments at CERN: GBAR, ALPHA-g, AEGIS

Cosmological models

- **The standard model: ΛCDM**
  - **Λ** → dark energy (70%) → accelerated expansion (≈ *repulsive gravity!*)
  - **CDM** (Cold Dark Matter): 25%
  - Ordinary matter (baryonic) : 5%
  - Scale factor:
    - ➢ $a(t) \sim t^{2/3}$ (matter-dominated age)
    - ➢ $a(t) \sim e^{\Lambda t}$ (Λ-dominated age)

- **Dirac-Milne universe** (see: A. Benoit-Lévy and G. Chardin, A&A 537, A78 (2012))
  - Matter-antimatter symmetric universe
    - ➢ Repulsion between matter and antimatter (negative mass)
    - ➢ Antimatter spreads almost uniformly across the universe
  - Total matter content = 0 ($\Omega_M = 0$)
  - No cosmological constant ($\Omega_\Lambda = 0$); No need for inflationary phase
  - Scale factor: $a(t) \sim t$

Mass in Newtonian mechanics

- Active gravitational mass m_a: $\Delta\phi = 4\pi G\rho = 4\pi G m_a n$
- Passive gravitational mass m_p: $\boldsymbol{F} = -m_p \nabla\phi$
- Inertial mass m_i: $\boldsymbol{p} = m_i \dot{\boldsymbol{r}}$
- Equation of motion: $\ddot{\boldsymbol{r}} = -(m_p/m_i)\nabla\phi.$

$\boxed{EP: \quad m_p = m_i}$

		Active grav. mass	Passive grav. mass	Inertial mass
matter	A (standard)	$+$	$+$	$+$
antimatter	B (antiplasma)	$-$	$-$	$+$
	C (Bondi)	$-$	$+$	$+$
	D (antiinertia)	$+$	$-$	$+$

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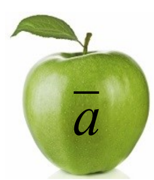
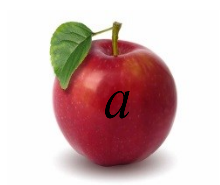
Bondi: runaway acceleration





Dirac-Milne scenario

- However, the above scenarios are not suited to model the Dirac-Milne universe
- **Antiplasma:**
  - Does not respect the EP
  - Allows formation of negative mass structures
- **Bondi:**
  - Requires negative inertial mass to ensure energy conservation
  - Unlikely features such as runaway acceleration

- We need a **generalization of Newtonian gravity** for two particle species

Type of matter	Type of matter	Interaction
$+$	$+$	Attraction
$-$	$-$	Repulsion
$-$	$+$	Repulsion
$+$	$-$	Repulsion

- **Antimatter spreads uniformly**
- **Matter coalesces into structures**

- Cannot be realized with a single Poisson's equation

$$\boxed{\begin{aligned} \Delta\phi_+ &= 4\pi G m(+n_+ - n_-), \\ \Delta\phi_- &= 4\pi G m(-n_+ - n_-) \end{aligned}}$$

General matrix formalism

$$\Phi = \begin{pmatrix} \phi_+ \\ \phi_- \end{pmatrix}, \quad \mathsf{n} = \begin{pmatrix} n_+ \\ n_- \end{pmatrix}, \quad \widehat{\mathsf{M}} = \begin{pmatrix} M_{++} & M_{+-} \\ M_{-+} & M_{--} \end{pmatrix} \qquad M_{ij} = \pm 1$$

Since $M_{++} = 1$, there are 2^3 = 8 possible cases (one trivial, with all elements = +1)

Antiplasma

$$\widehat{\mathsf{M}}_{\mathrm{ap}} = \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix},$$

Bondi

$$\widehat{\mathsf{M}}_{\mathrm{Bondi}} = \begin{pmatrix} 1 & -1 \\ 1 & -1 \end{pmatrix},$$

Anti-inertia

$$\widehat{\mathsf{M}}_{\mathrm{ai}} = \begin{pmatrix} 1 & 1 \\ -1 & -1 \end{pmatrix}.$$

Dirac-Milne

$$\boxed{\widehat{\mathsf{M}}_{\mathrm{DM}} = \begin{pmatrix} 1 & -1 \\ -1 & -1 \end{pmatrix}}$$

Open question: how to incorporate this approach into General Relativity

- Bimetric theory?

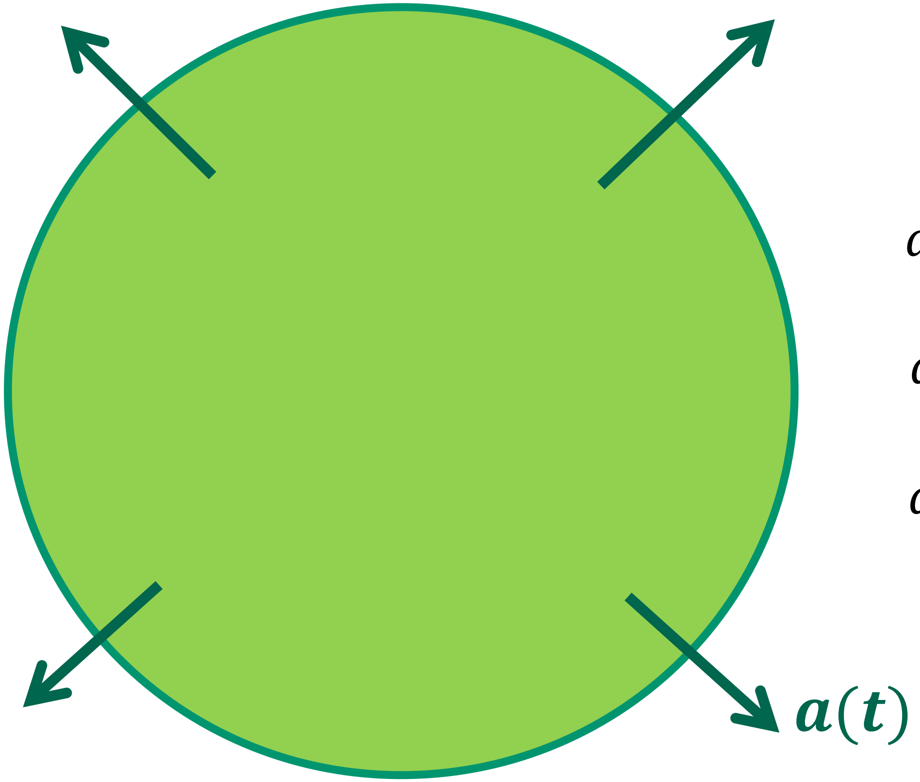
Expanding universe – Comoving coordinates

Equation of motion

$$\frac{d^2r}{dt^2} = E_r(r,t),$$

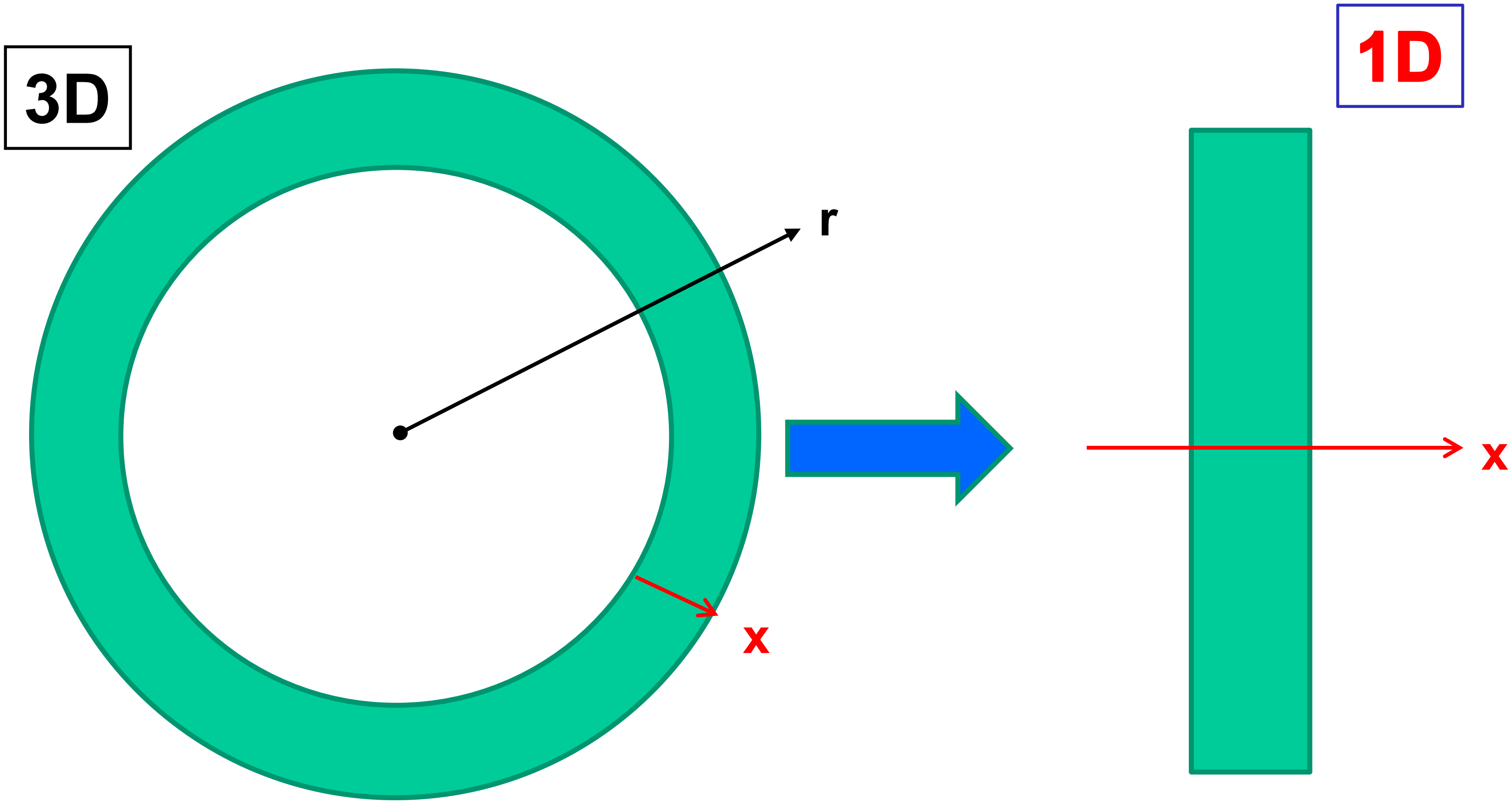
Scale factor

$$\boxed{r \;=\; a(t)\hat{r},}$$

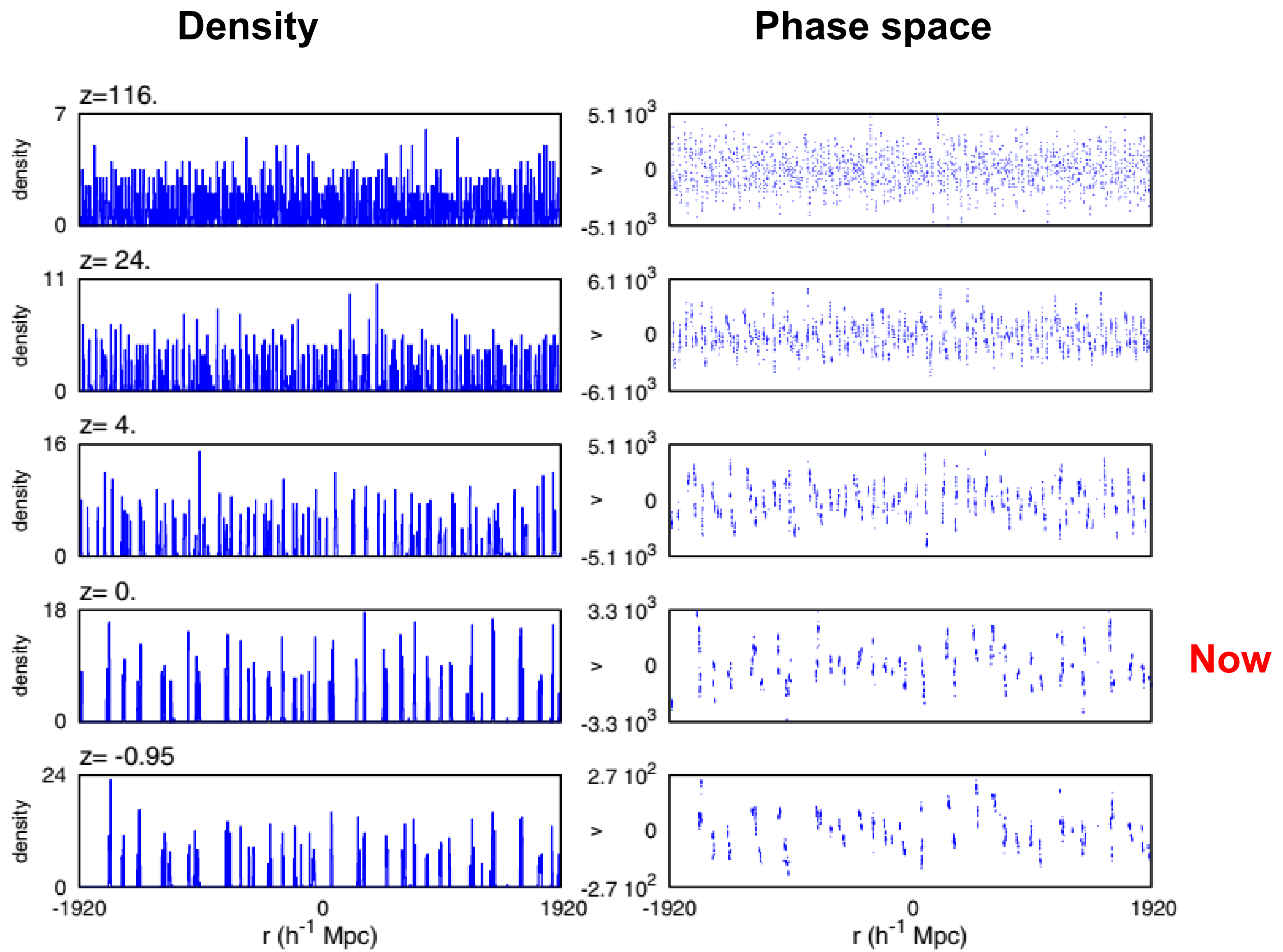


$a(t) \propto e^{\Lambda t}$	ΛCDM late times
$a(t) \sim t^{2/3}$	Einstein–de Sitter (ΛCDM early times)
$a(t) \sim t$	Dirac – Milne

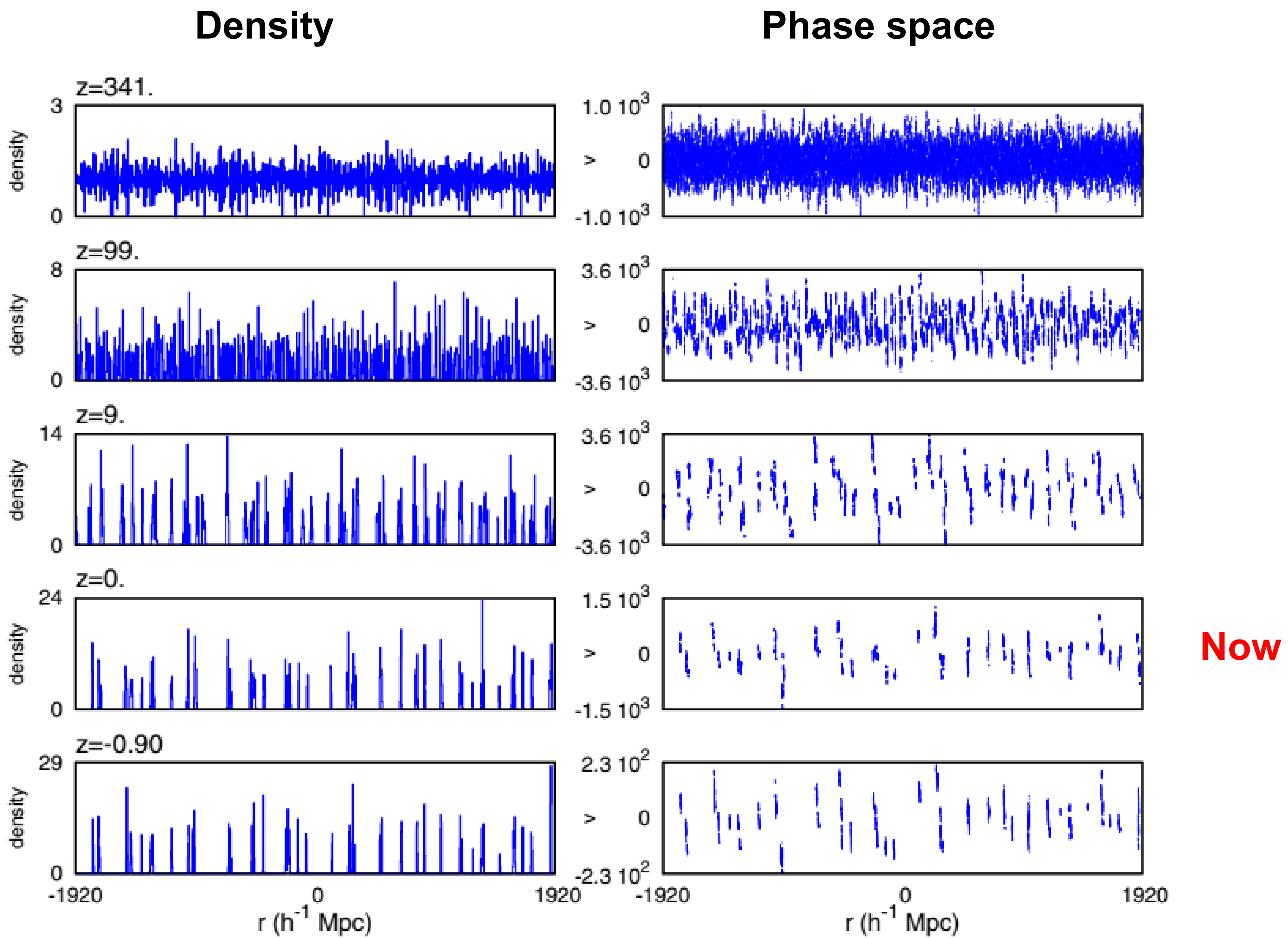
One-dimensional geometry



ΛCDM cosmology

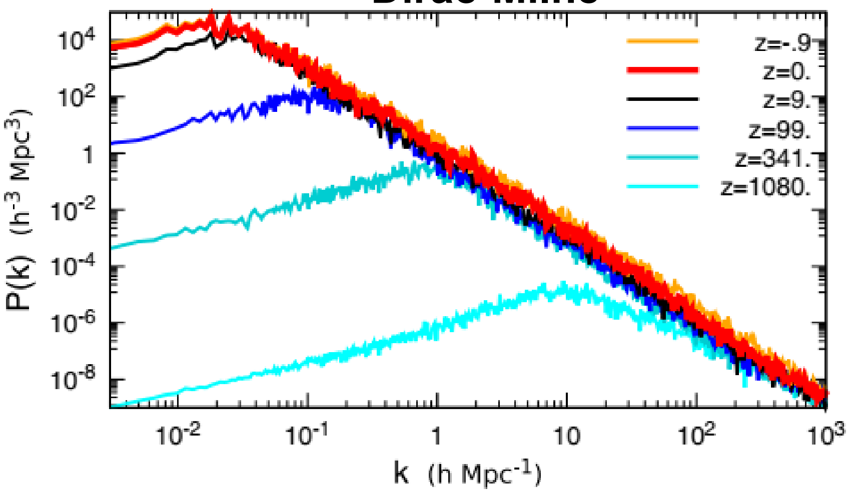


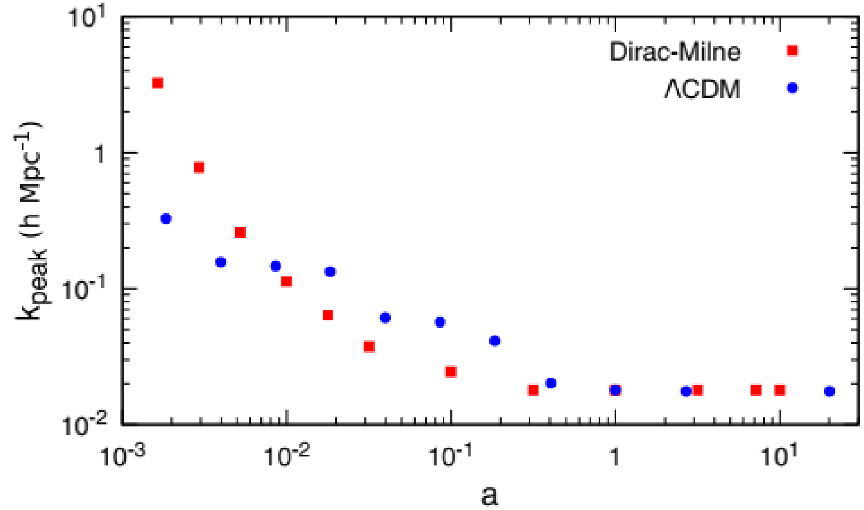
Dirac-Milne cosmology

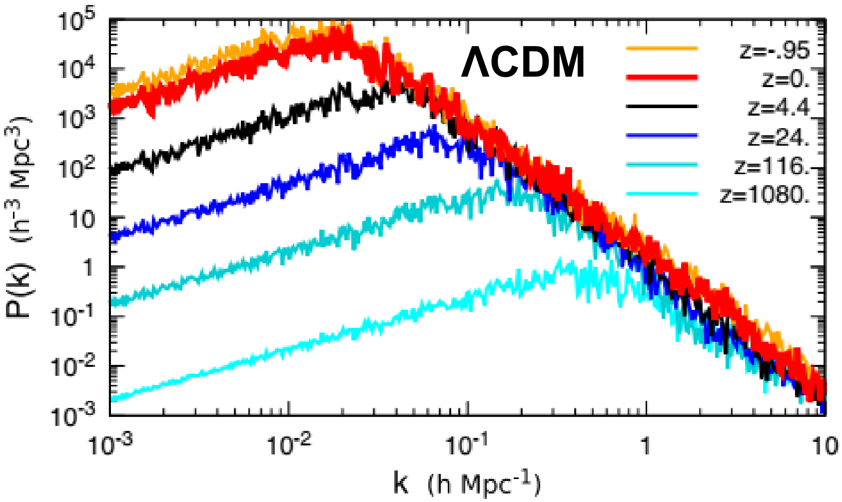


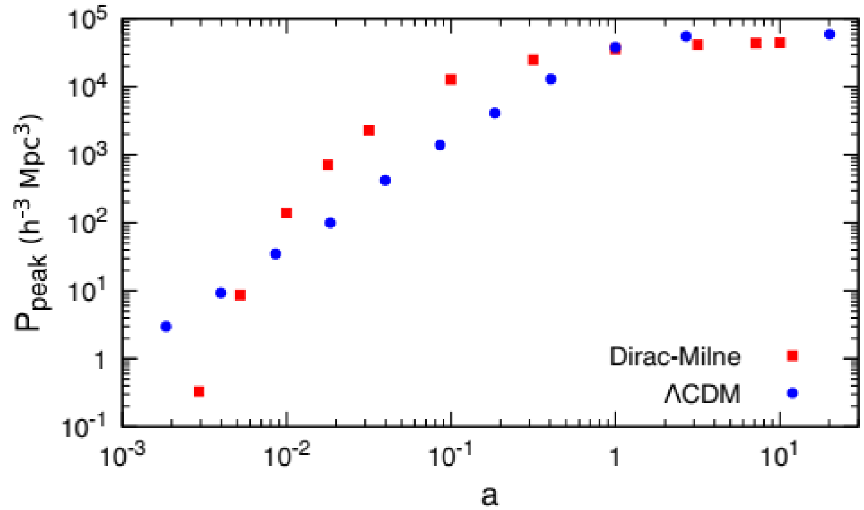
Matter-density power spectrum

Dirac-Milne

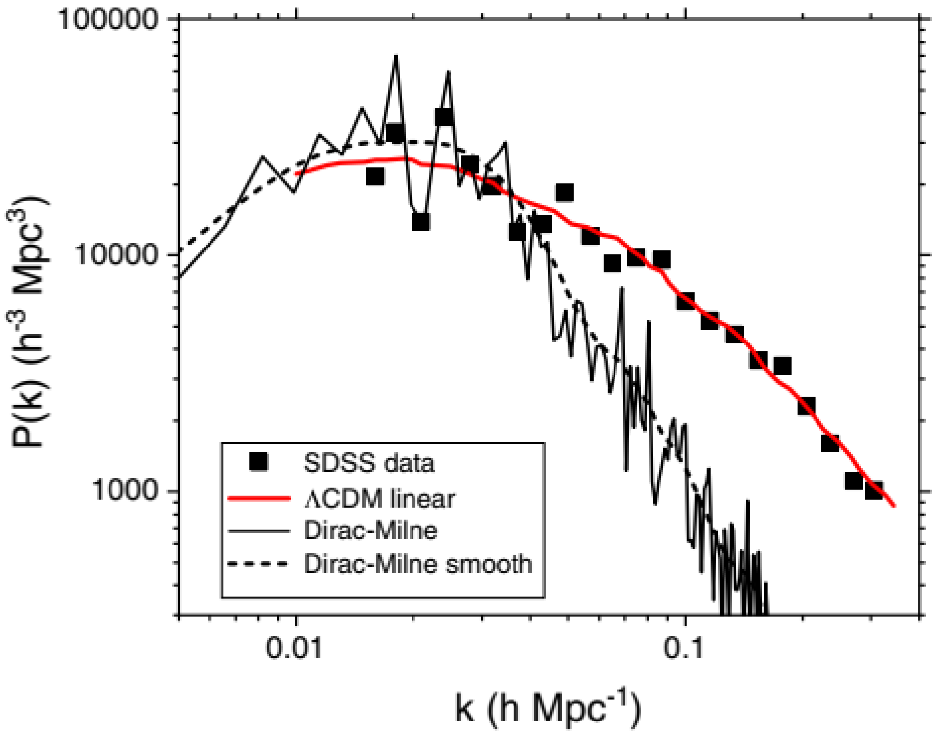






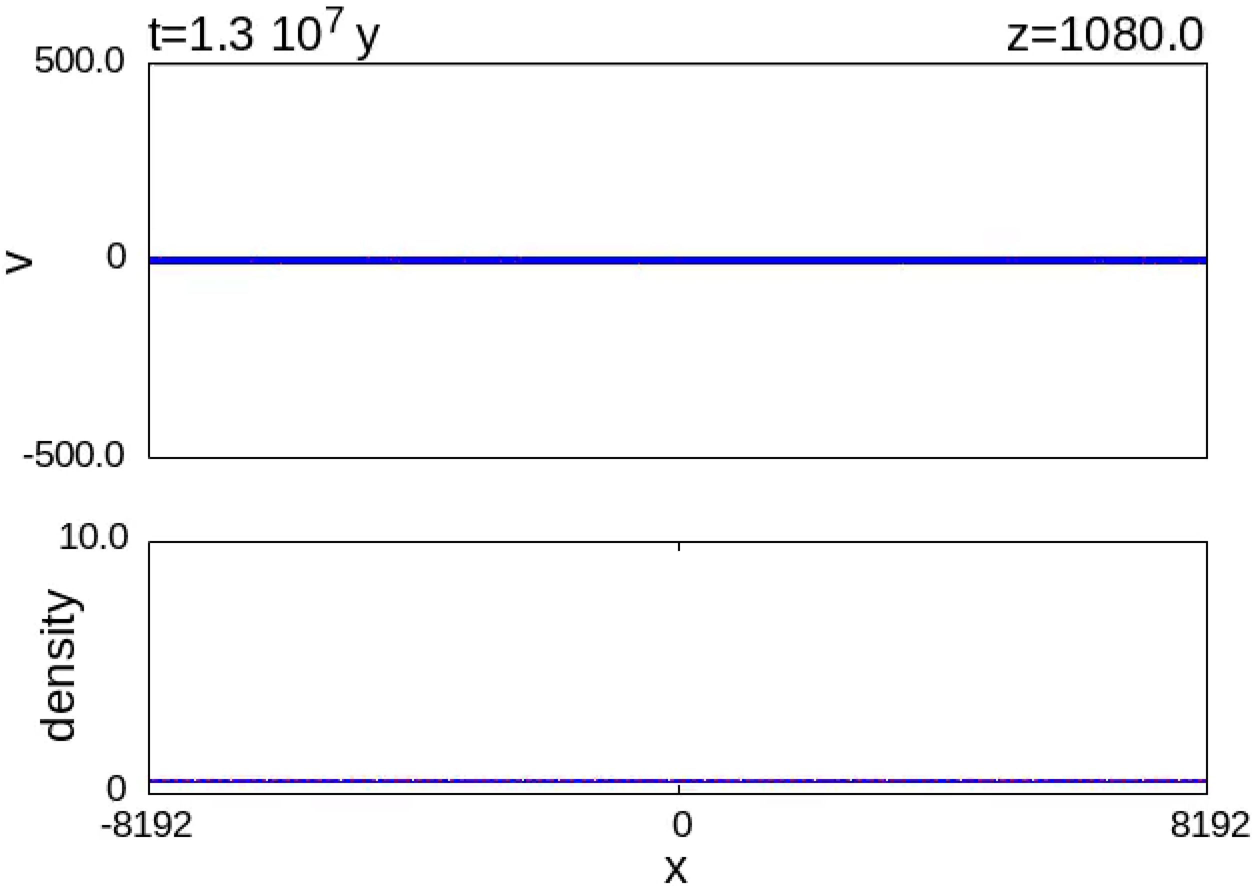


Matter-density power spectrum



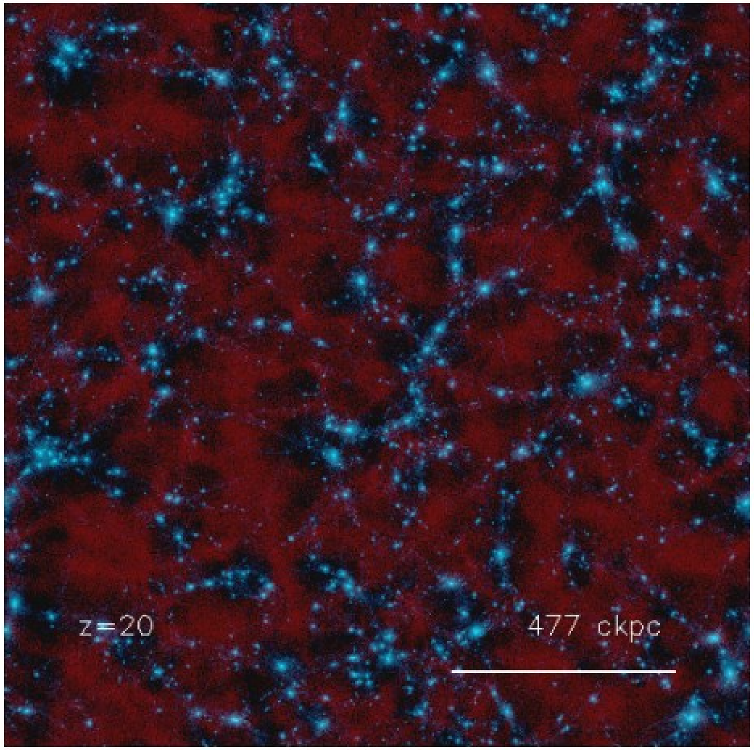
ΛCDM data from: M. Tegmark et al., Astrophys. J. **606**, 702 (2004)

Two-component Dirac-Milne system

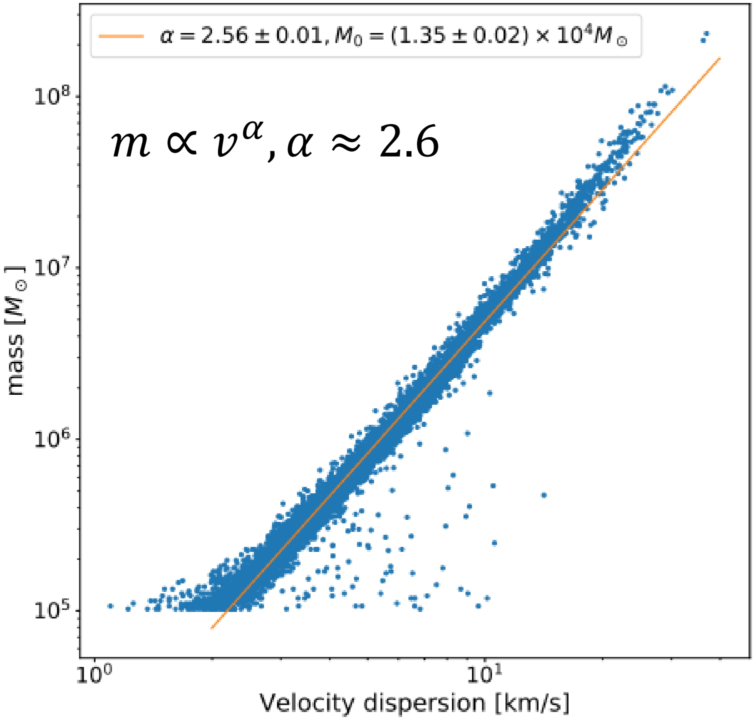


3D simulations and dark matter/MOND

RAMSES code simulation



Faber-Jackson relation



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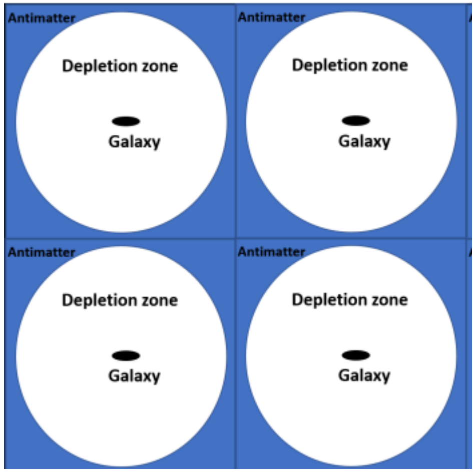
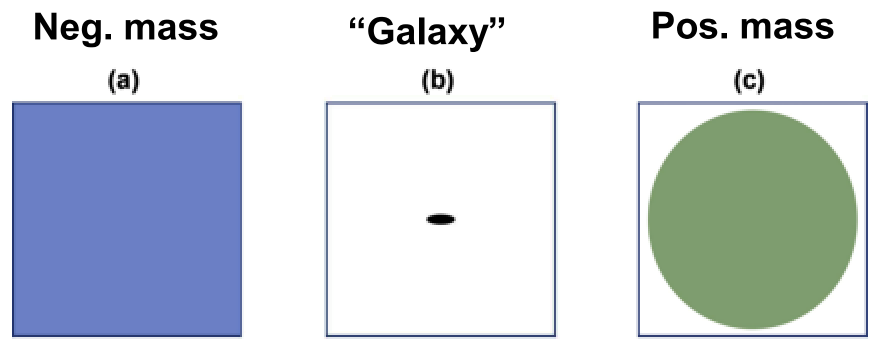
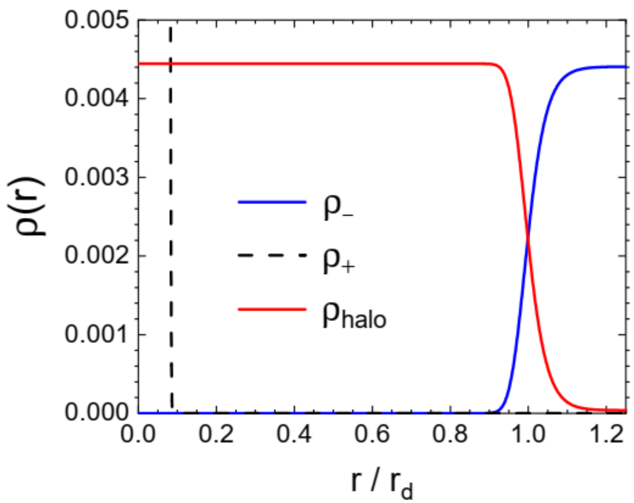
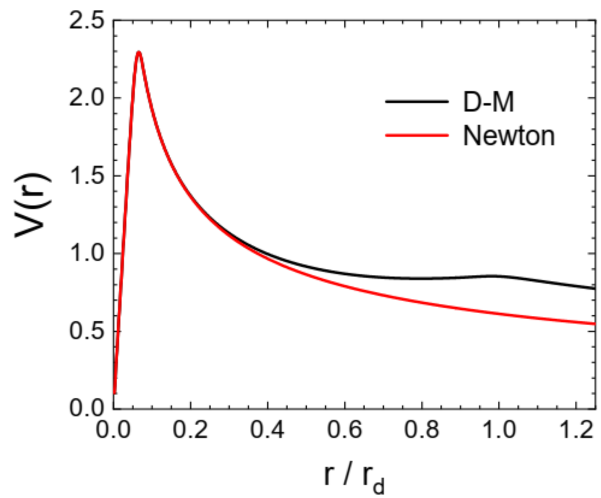




$$\nabla^2\phi_+ = 4\pi G(\rho_+ - \rho_-),$$
$$\nabla^2\phi_- = 4\pi G(-\rho_+ - \rho_-).$$

$$\rho_-(r) = \rho_0 \exp\left(\frac{-m\phi_- + \mu}{k_B T}\right),$$





Conclusions

- **Newtonian gravity with negative mass**
  - Standard cases with various choices of m_i, m_a, m_p (Bondi, antiplasma,…)
  - Alternative “bimetric” theories → Dirac-Milne
- **Cosmological structure formation with negative mass**
  - Comparison between ΛCDM and Dirac-Milne
  - In Dirac-Milne universe, structure formation begins at an earlier epoch and freezes before ≈ 10^{10} Gy
  - Present power spectra are qualitatively similar to ΛCDM
- **Local MOND-like behavior**
  - 3D simulations show depletion zone and antimatter halos
  - Compatible with Faber-Jackson relation with exponent 2.6
  - Flattening of rotation curves

Bibliography

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