Cosmological structure formation with negative mass

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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: $\ddot{\boldsymbol{r}} = -(m_p/m_i)\nabla\phi.$

EP: $m_p = m_i$

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

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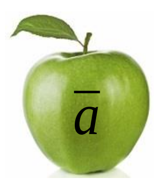
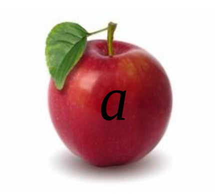
	D (antiinertia)	+	−	+

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 particles 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

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

General matrix formalism

$$\Delta\Phi = 4\pi G m \, \widehat{\mathsf{M}} \, \mathsf{n},$$

Matrix Poisson's equation

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

$$M_{ij} = \pm 1$$

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

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

Open question: how to incorporate this approach into General Relativity

- Bimetric theory?

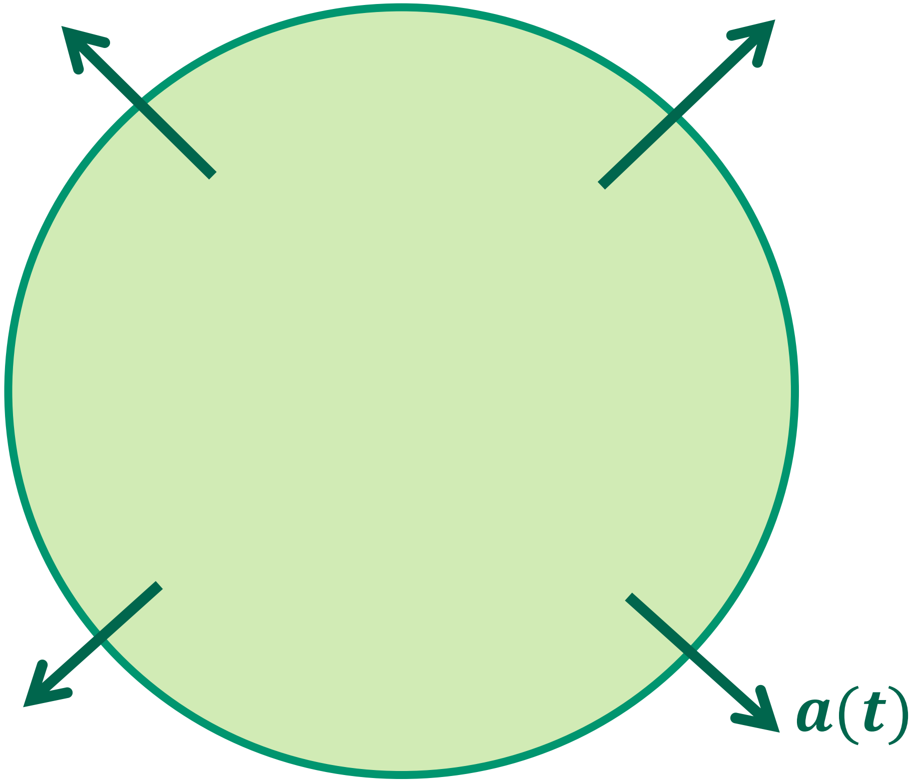
Expanding universe – Comoving coordinates

Equation of motion

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

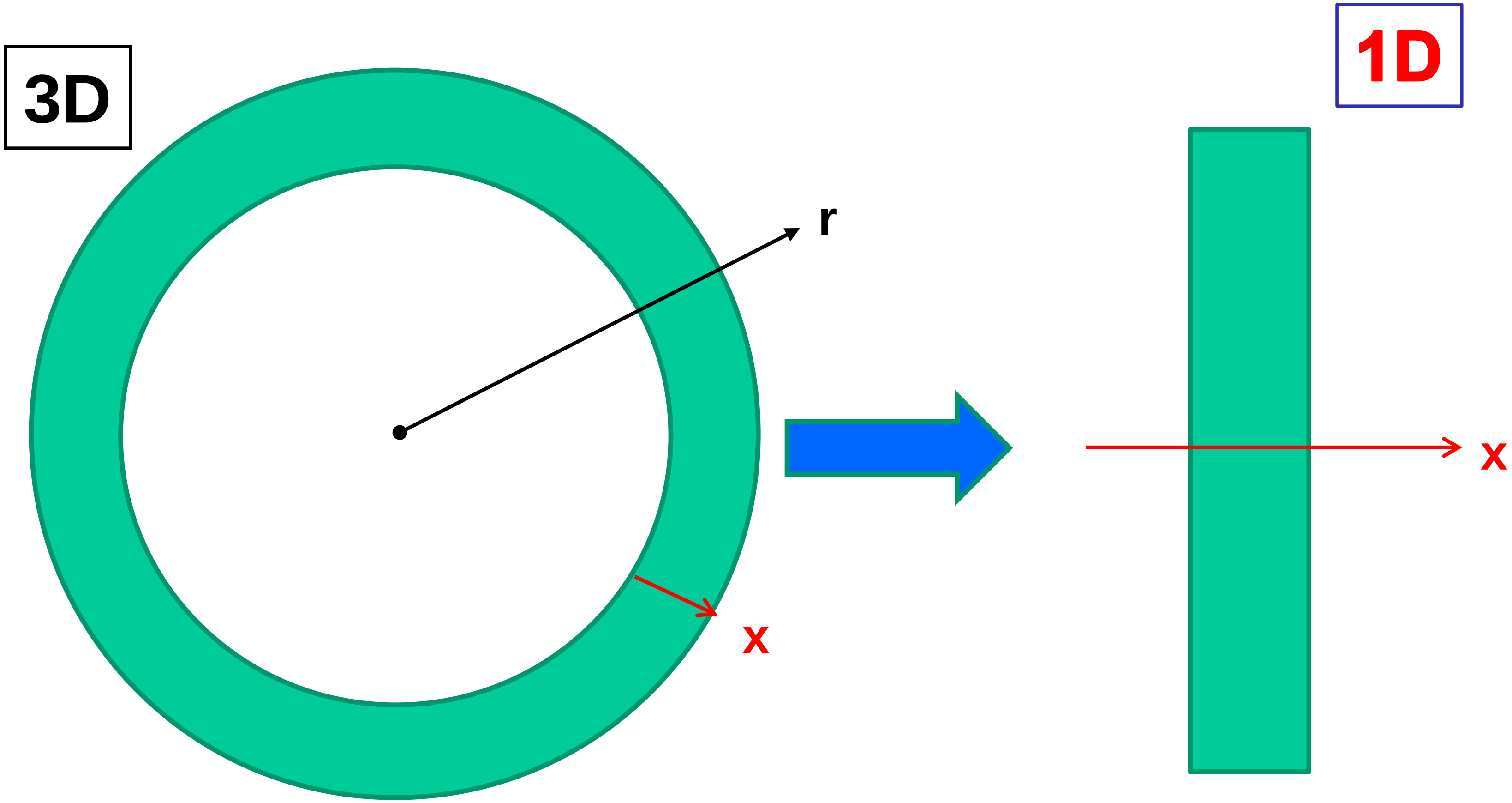
Scale factor

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



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

One-dimensional geometry



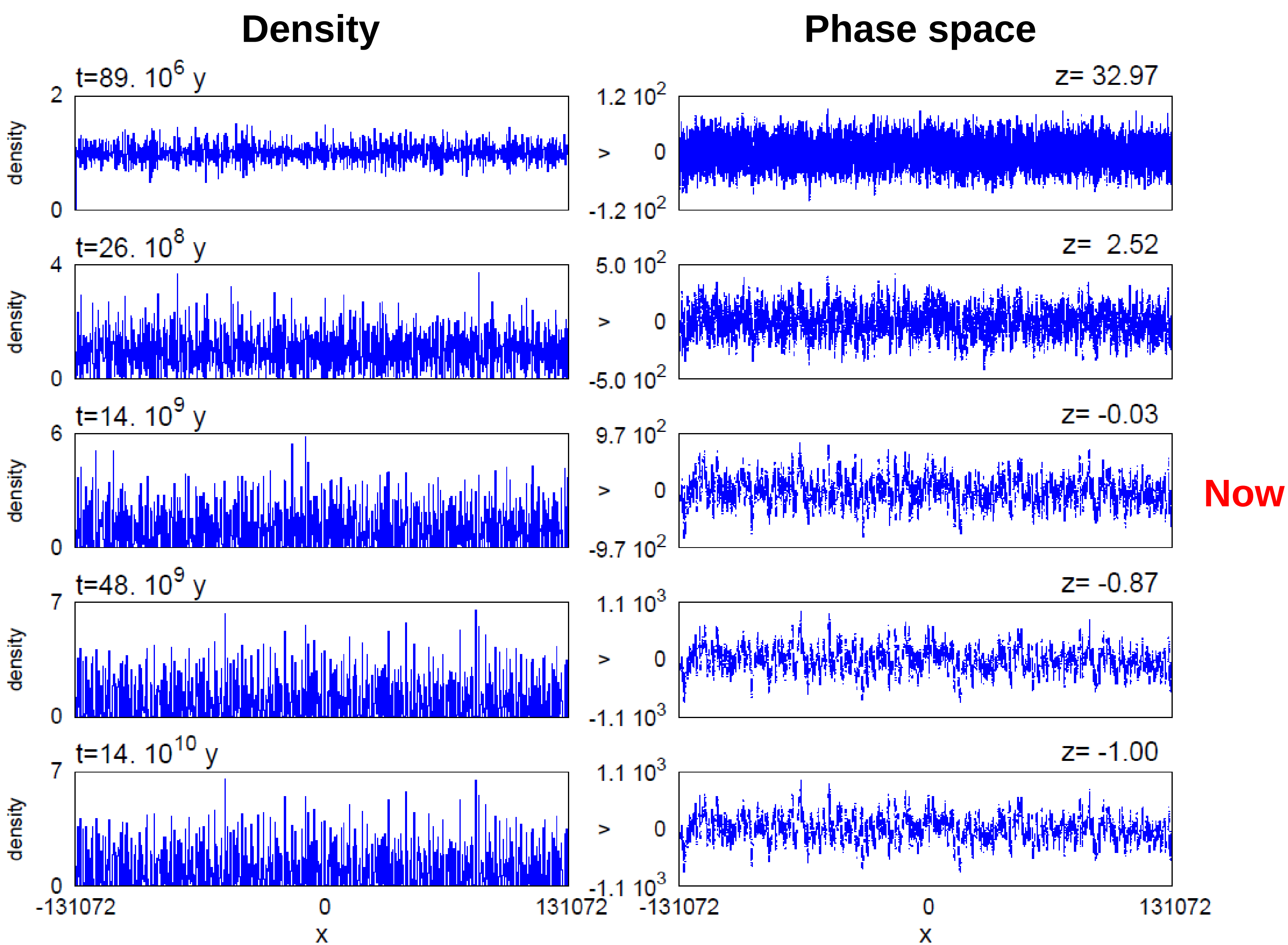
Dirac-Milne vs. Einstein- de Sitter

G. Manfredi, J.-L. Rouet, B. Miller, G. Chardin, Phys. Rev. D **98**, 023514 (2018)

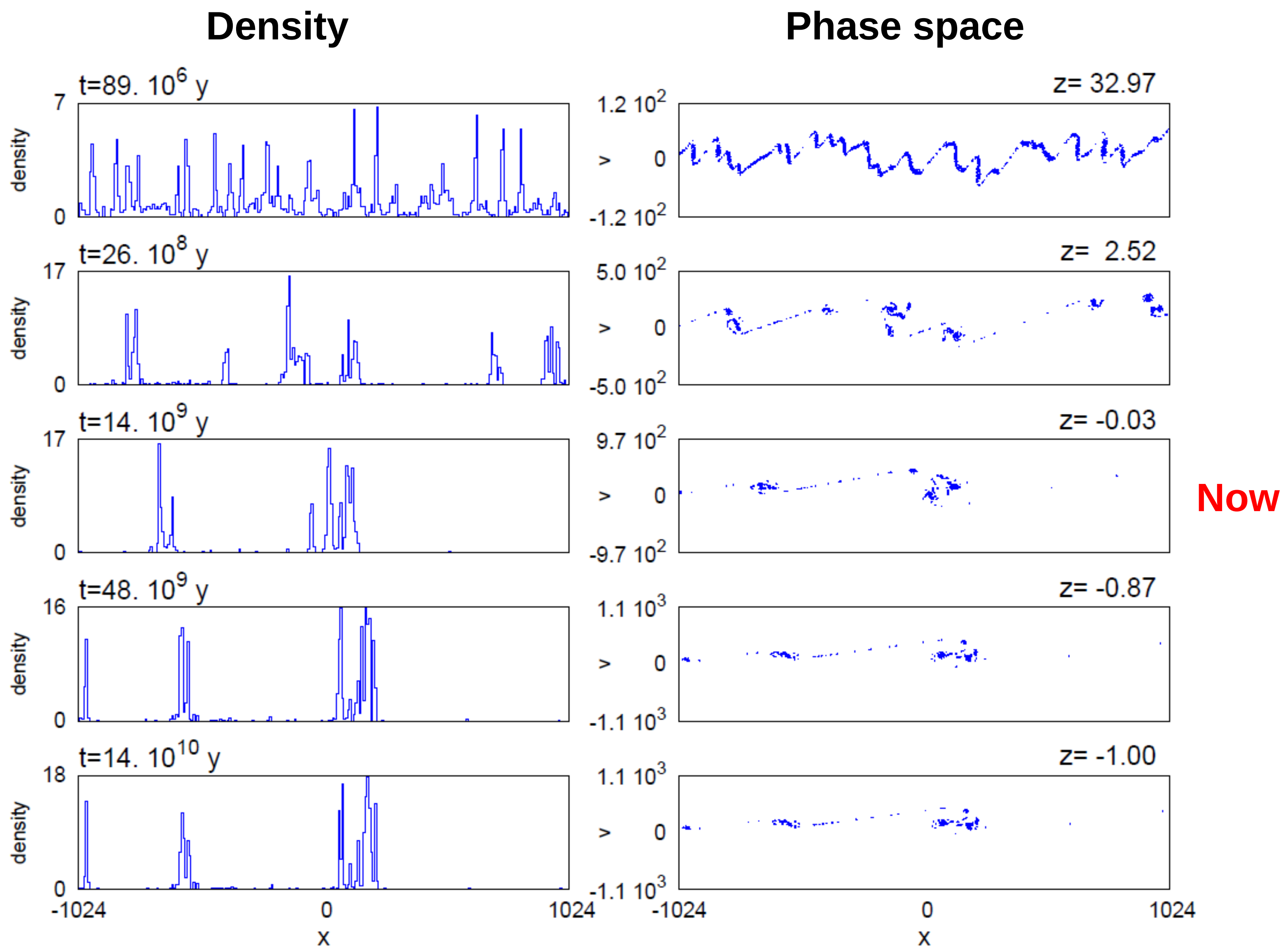
ArXiv 1804.03067

- (EdS: like ΛCDM , but with $\Lambda = 0$)
- Structure formation occurs for Dirac-Milne too
  - Earlier and faster compared to EdS
- Importantly, **structure formation in the Dirac-Milne universe stops after a few billion years**
  - Qualitatively similar to ΛCDM universe
- Direct comparison Dirac-Milne vs. ΛCDM is underway
- Today, I show some preliminary results.

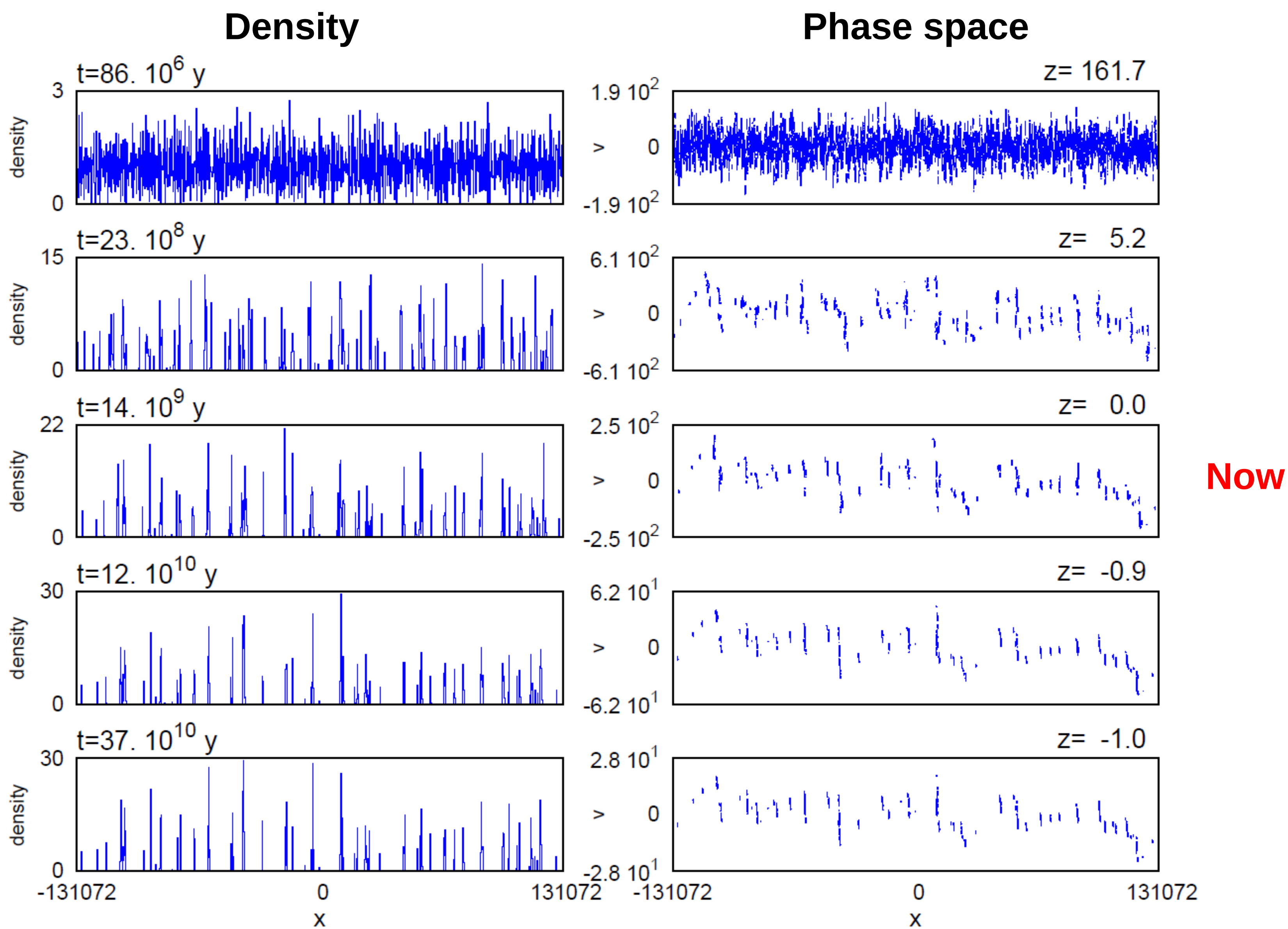
ΛCDM cosmology



ΛCDM cosmology (zooms)

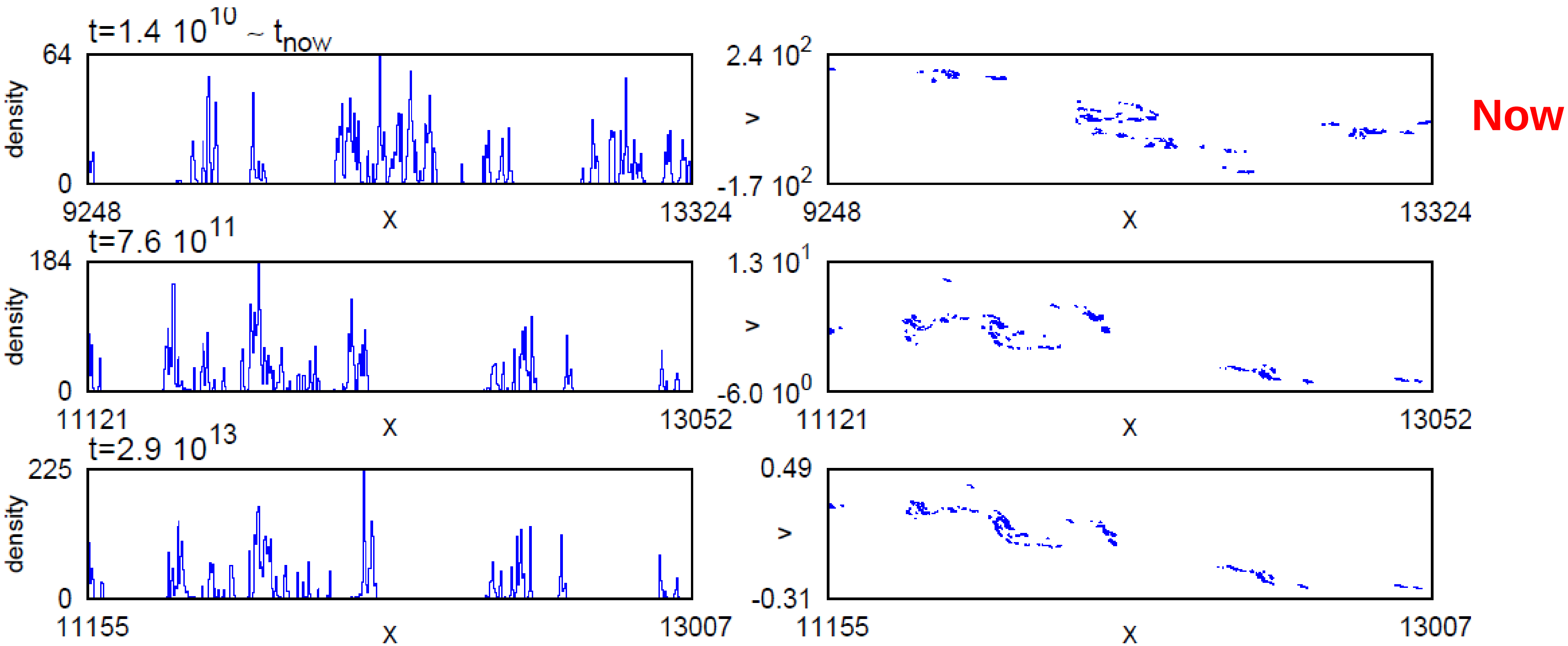


Dirac-Milne cosmology

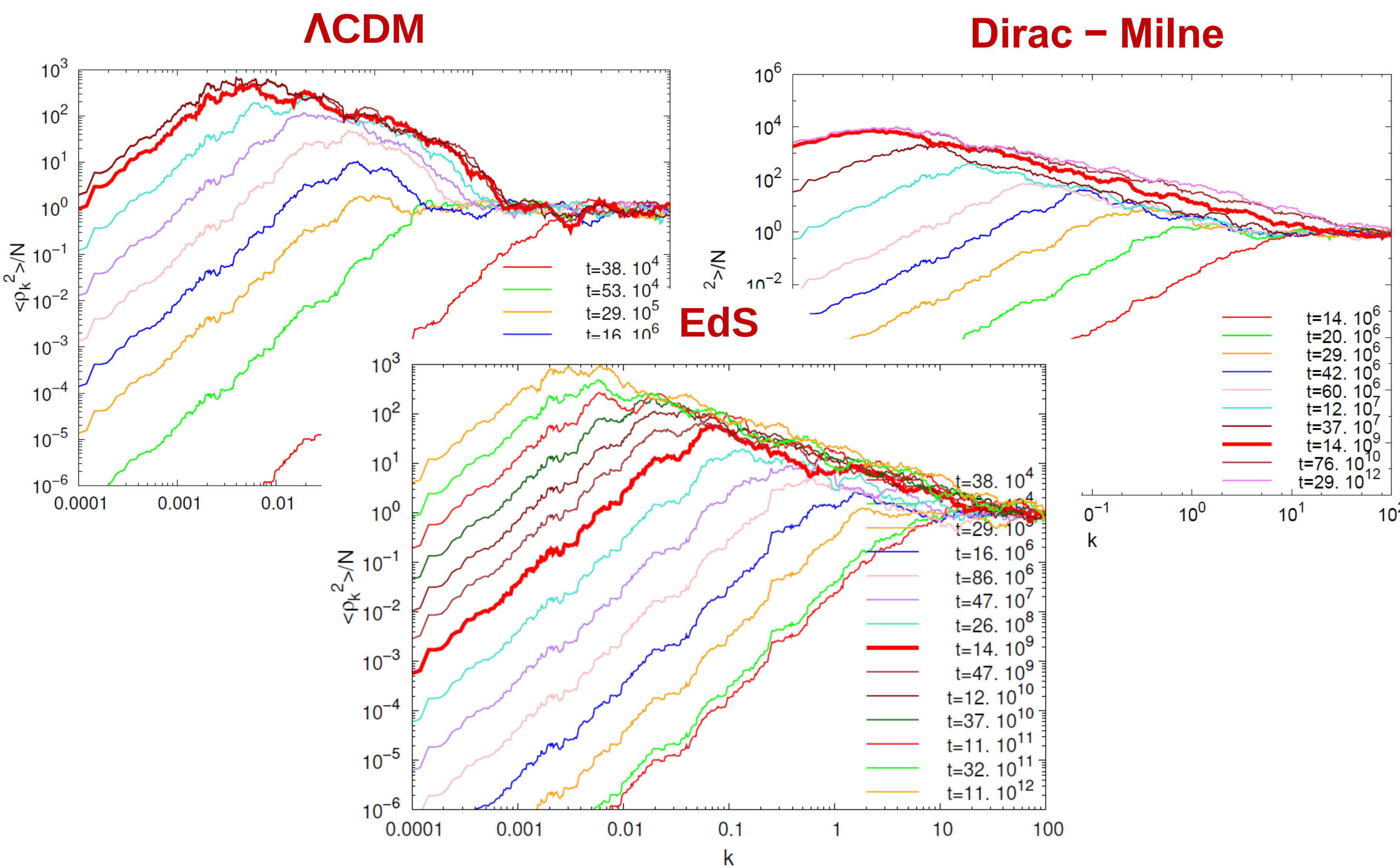


Dirac-Milne cosmology (zooms)

Density | **Phase space**



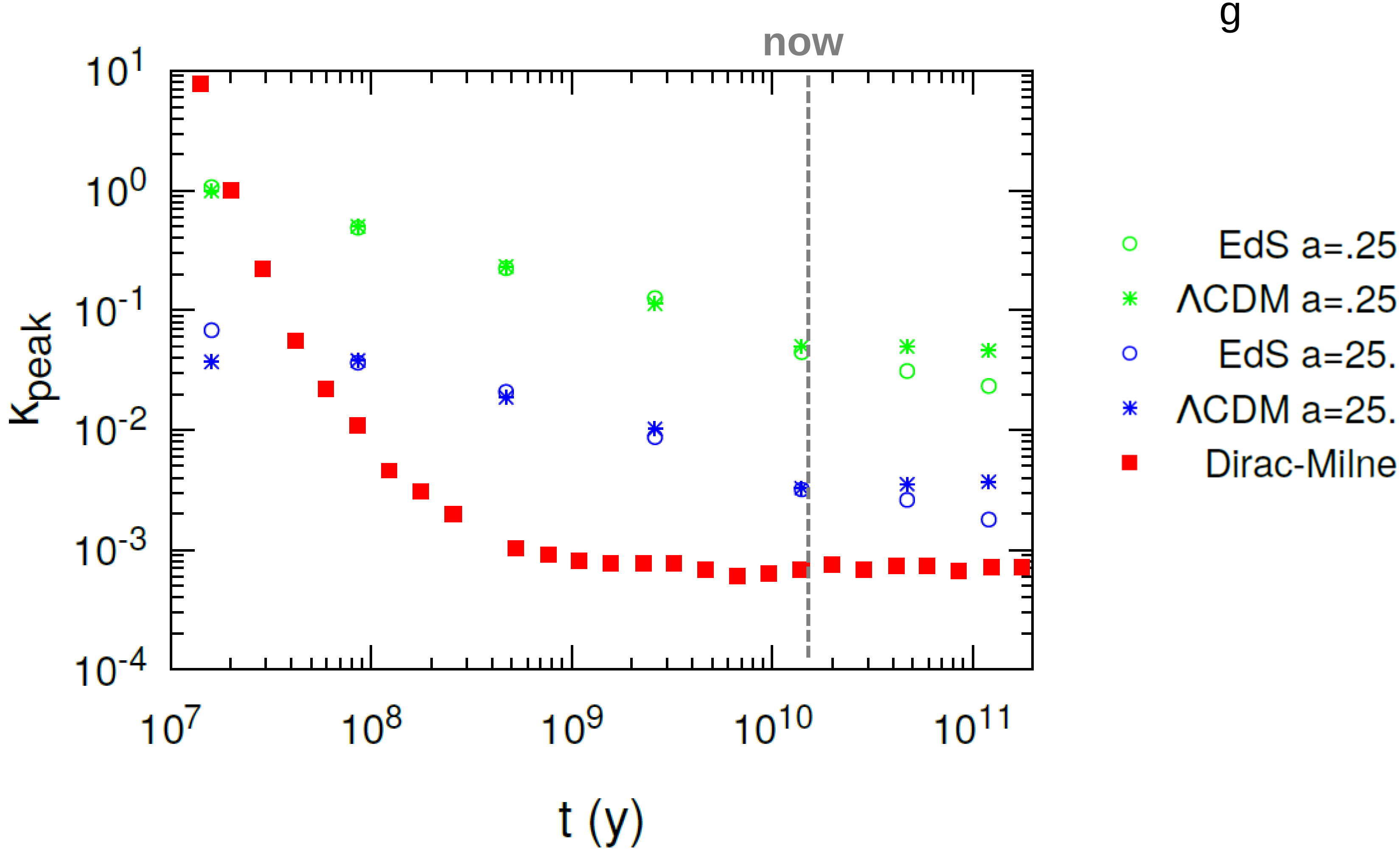
Matter-density power spectrum



Evolution of power spectrum peak

k_{peak} in comoving coordinates

g



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 Einstein-de Sitter and Dirac-Milne
    - ➢ G. Manfredi, J.-L. Rouet, B. Miller, G. Chardin, Phys. Rev. D **98**, 023514 (2018)
  - **Here, comparison between ΛCDM and Dirac-Milne**
  - **In the Dirac-Milne universe, structure formation begins at an earlier epoch and freezes before ≈10^{10} Gy**
  - Qualitatively similar to ΛCDM
- **Future developments**
  - 3D simulations of Dirac-Milne cosmologies
  - Development of general-relativistic bimetric gravity yielding Dirac-Milne in the Newtonian limit.