Nouvelles de l'univers de Dirac-Milne

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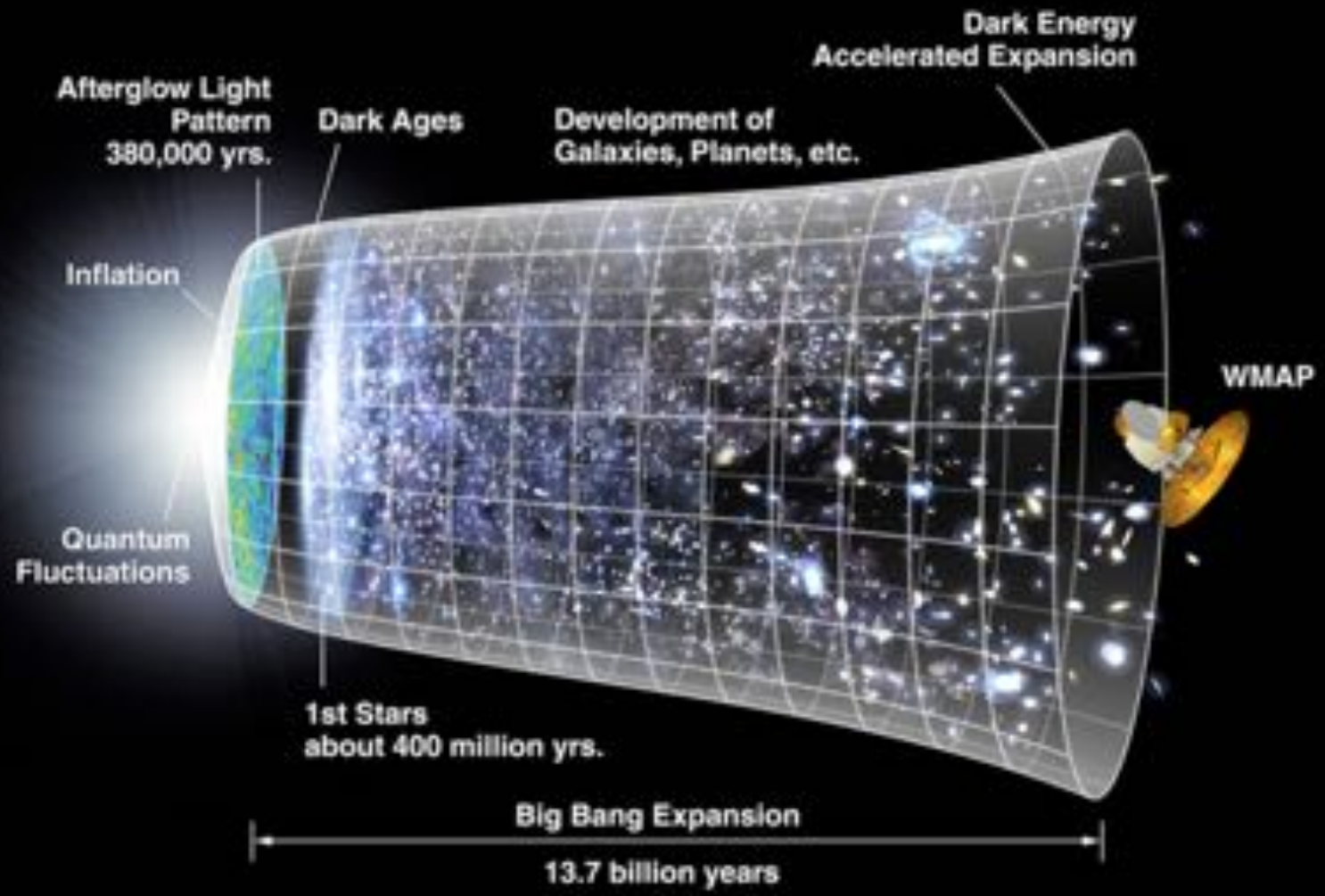
Introduction

- Shouldn’t it be obvious that antiparticles follows the same trajectories as particles ?
- As we will see, this depends on the expression that we provide for the Equivalence Principle…
- A bit of history and cosmology first
- For a review on the arguments against antigravity, see in particular : M.M. Nieto and T. Goldman, Phys. Rep., 205 (1991) 221-281
- Dark Energy and repulsive gravity
- Negative mass : which definition ?
- The Dirac-Milne universe
- Conclusions

References

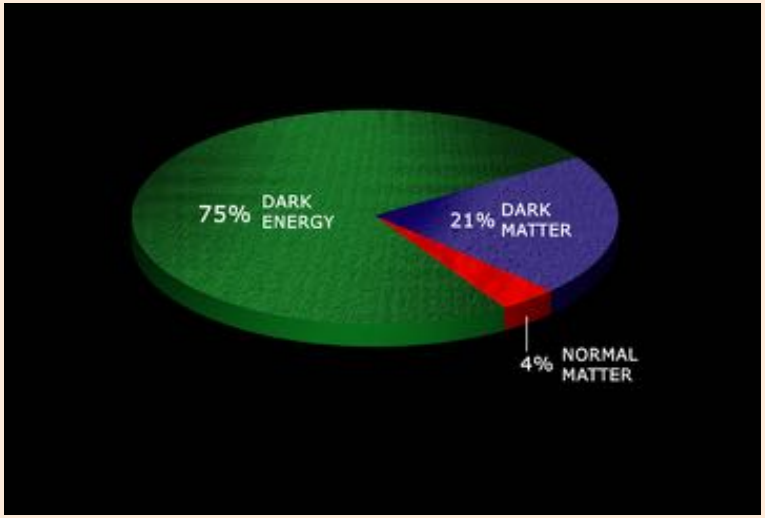
- **A. Benoit-Lévy and G. Chardin, , “ Introducing the Dirac-Milne-Universe ”, A&A 537 A78 (2012).**
- **G. Manfredi, J-L. Rouet, B. Miller, and G. Chardin, “ Cosmological structure formation with negative mass ”, Phys. Rev. D 98, 023514 (2018) ; https://arxiv.org/abs/1804.03067**
- **G. Chardin and G. Manfredi, "Gravity, antimatter and the Dirac-Milne universe", arXiv:1807.11198 (Proceedings LEAP 2018)**
- **G. Chardin, « L'insoutenable gravité de l'univers », Editions Le Pommier, Collection Idées, Mars 2018**

A very strange standard cosmological model



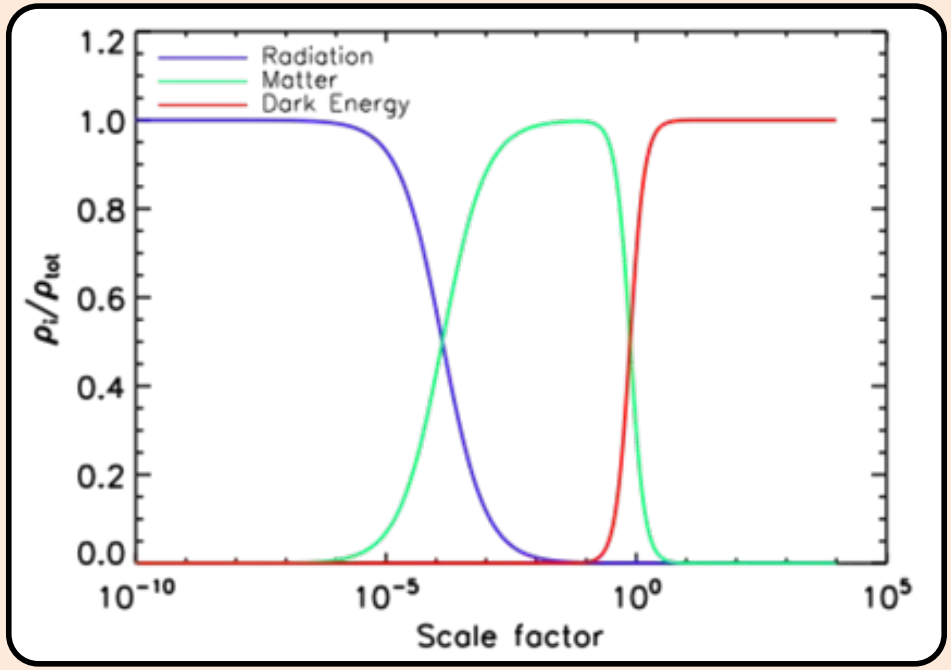
Good fit to the data, but several (≥ 6) free parameters. Alternative ?

- Dark Matter and Dark Energy (unidentified) represent ≈96 % of the Universe energy density !



- **(at least) six free parameters**

- Radiation, matter and dark energy are successively dominant, while the other two components are completely irrelevant…



Λ-CDM or coasting universe ?

- Several authors have noted that our Universe shares several aspects with a « coasting » or empty (Milne) universe
- Age, luminosity distance (supernovae), and even nucleosynthesis for He-4 and Li-7 (but not D)
- BAO (baryonic acoustic oscillations) and CMB initially appeared in contradiction with a coasting (empty) universe
- But surely our universe is not empty, and what could be the justification for a Milne universe anyway ?
- A universe with equal quantities of positive and negative mass…
- Dirac antimatter suggests symmetric matter-antimatter universe that avoids late annihilation

Coasting or Milne universe

- Several authors have noted that our Universe shares several aspects with a « coasting » or empty (Milne) universe
- A. Benoit-Lévy and G. Chardin, A&A, 537 (2012) A78.
- M. Sethi, Batra, A., & Lohiya, D. 1999, Phys. Rev. D, 60
- J. T. Nielsen, A. Guffanti, S. Sarkar, Scientific Reports, 6 (2016) 35596.
- I. Tutusaus, B. Lamine, A. Dupays, and A. Blanchard, A&A, 602 (2017) A73.
- F. Melia, and A. Shevchuk, MNRAS 419 (2012) 2579

Four statements

(all considered true 25 years ago)

- Negative mass is impossible (would lead to major instability) : E. Witten, R. Schoen and Shing-Tung Yau, Hawking
- Repulsive gravity is impossible (would violate energy conditions)
- Any violation of the equivalence principle, at the heart of GTR, must be very small (or zero)
- There is no indication of any difference between matter and antimatter in GTR

Negative mass is impossible…

- Negative mass is impossible (would lead to major instability) : R. Schoen and Shing-Tung Yau, E. Witten, Hawking and Ellis
- But negative mass is a useful tool in structure formation (and used in cosmological simulations)
- Examples of effective negative mass are known and observed : e.g. M. A. Khamehchi et al. (2017)
- Explicit (stable) negative mass solutions exist in expanding spacetimes (Paranjape et al. 2014)

Antigravity would lead to instability

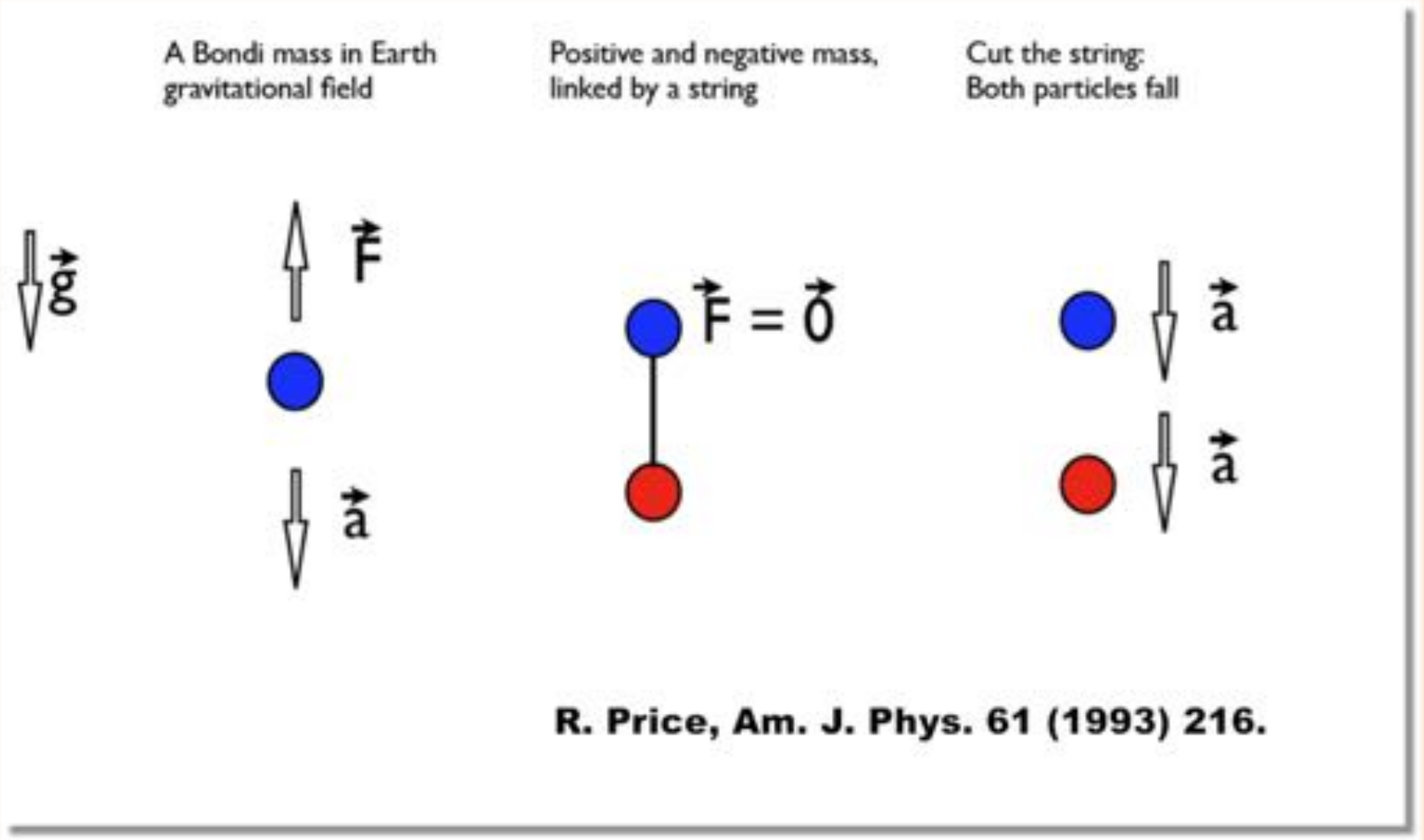
- P. Morrison, Am. J. Phys. 26 (1958) 358 : antigravity would lead to vacuum instability and apparent energy non-conservation
- J. Bekenstein (1972) and S. Hawking (1974) : vacuum ***is*** unstable (usually at extremely low rate) in the vicinity of a black hole
- G. Chardin, J-M. Rax (1992) : antigravity would provide the ***same instability*** (same formula) as black hole radiation of a black hole

Energy conditions and negative mass

- P. Morrison (1958)
- J. Scherk (1979)
- S. Hawking, H. Bondi, F. Hoyle (1965)
- Tension on age of Universe ≈ 1995 : cosmological constant
- SN1a Perlmutter, Riess and B. Schmidt 1998 : experimental demonstration of cosmological constant
- Matt Visser : counterexamples to essentially all expressions of energy conditions theorems
- Cosmological constant : $P < 0$ and $\rho = -P \Rightarrow \rho + 3P < 0$
- Paranjape et al. : negative mass « bubble » in de Sitter spacetime without violating energy conditions
- Electrons and holes as solid state analog : Dirac-Milne cosmology

R.H. Price, Am. J. Phys., 61, pp. 216-217 (1993)

Levitation and polarization predicted by GTR !

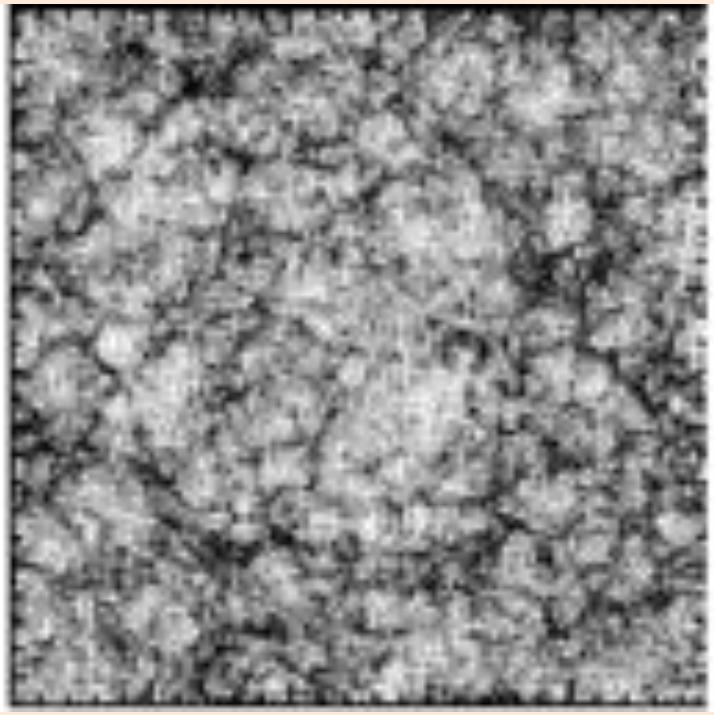


R. Price, Am. J. Phys. 61 (1993) 216.

A bound system +m –m levitates, is polarized
and in this sense violates maximally the equivalence principle …

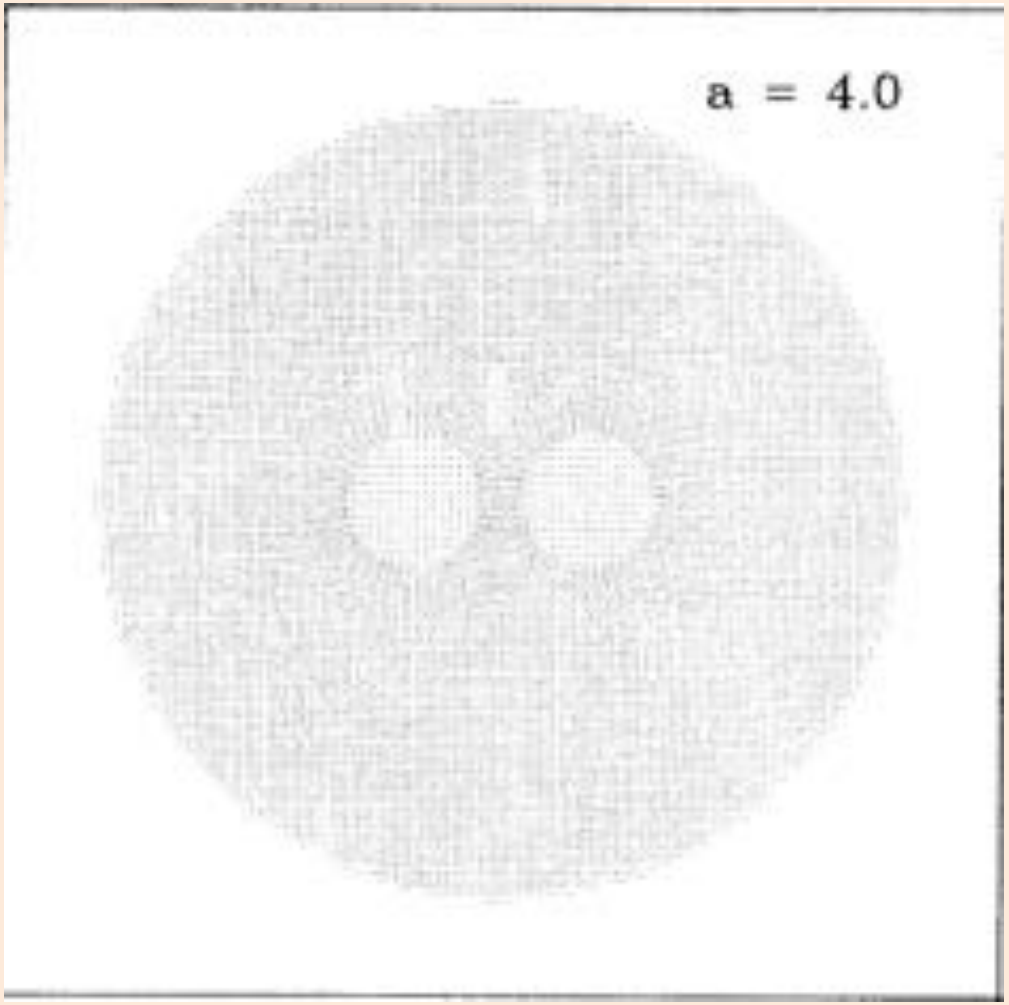
BAO and void evolution in the Λ-CDM and Dirac-Milne universes

- J. Dubinski, et al., ApJ. 410 (1993) 458
- T. Piran, Gen. Rel. Grav., 29 (1997) 1363
- R. K. Sheth and R. van de Weygaert, Mon. Not. R. Astron. Soc. 350, 517–538 (2004)
- Voids (underdense regions) act as negative mass and build structures of growing (comoving) size
- See also G. Manfredi's talk



Negative mass in GTR
(Piran (1997), Dubinski et al. (1993))

Negative mass in GTR (Dubinski et al.)



Symmetric Matter-antimatter cosmologies : are they excluded ?

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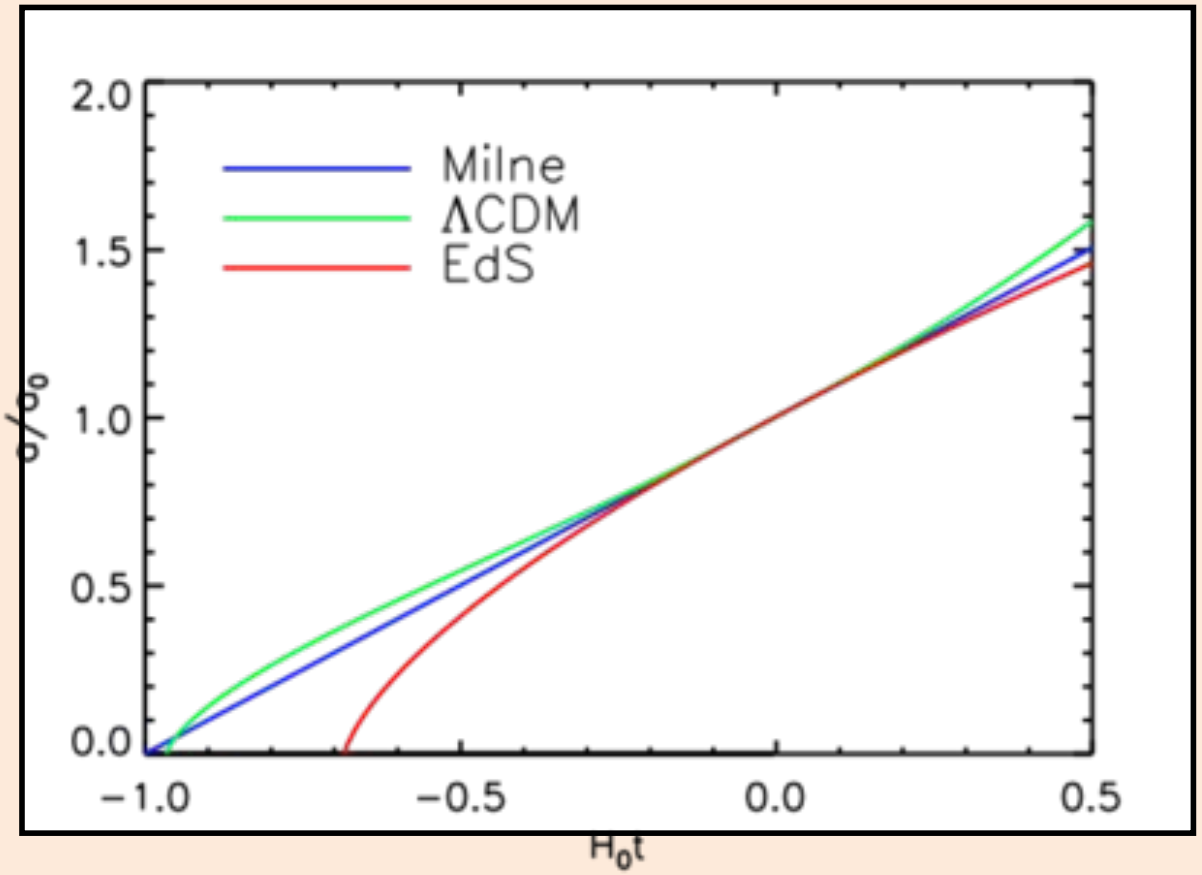
- R. Omnès, Phys. Rev. Lett. 23, (1969) 38
- J-J. Aly, A. Ramani (1971), etc.
- A.G. Cohen, A. de Rujula, & S. L. Glashow, ApJ, 495 (1998) 539
- Same conclusion : gamma-ray flux too high
- A. Benoit-Lévy and G. Chardin (2012) : the Dirac-Milne universe, where annihilation stops in the “ electron-hole ” system when the system cools down ($T \approx 30$ eV)

Age of the Milne universe

- No need for inflation in the Milne universe :
- it is permanently on the verge of inflation and has no horizon



Age of the Milne universe

- No need for inflation in the Milne universe : it is permanently on the verge of inflation

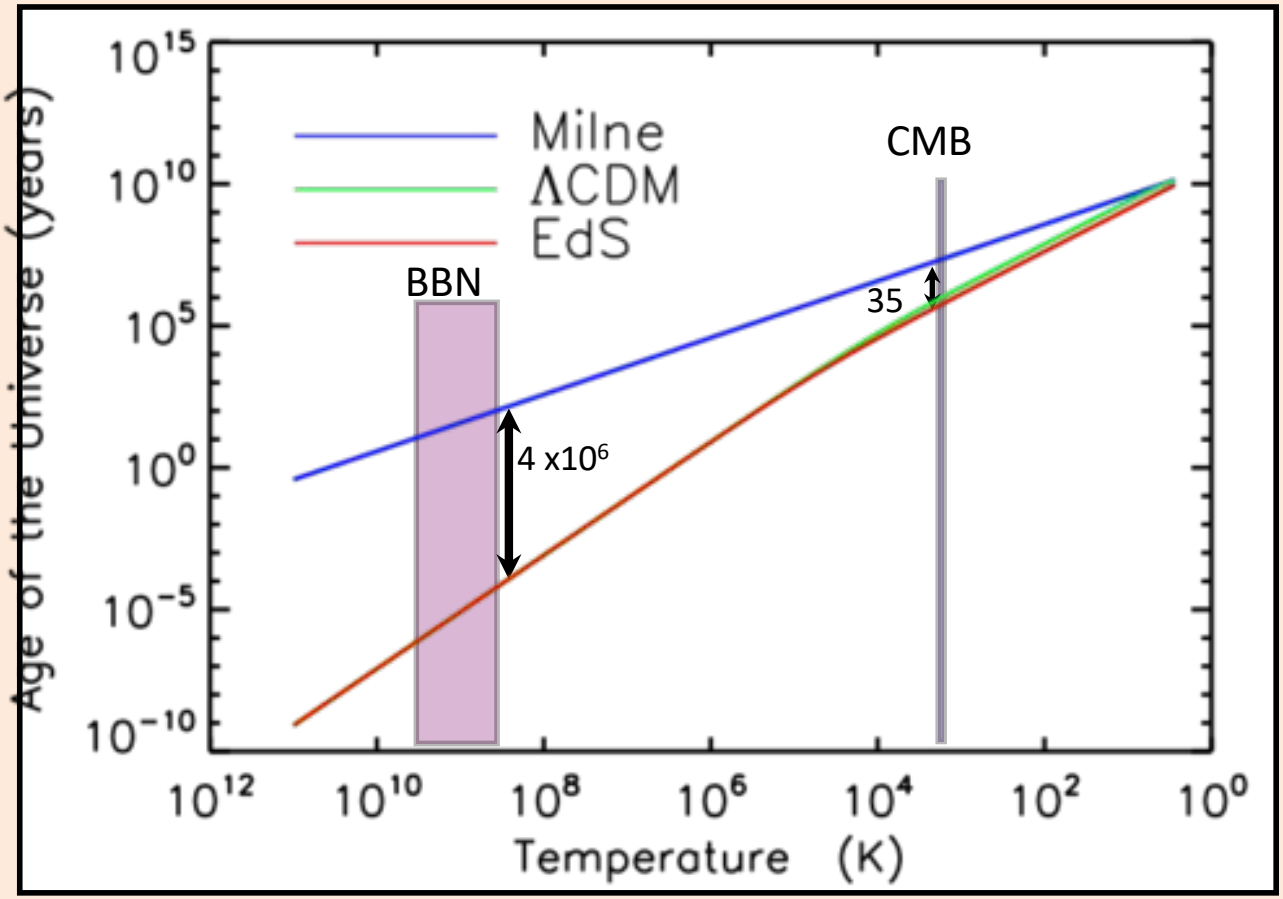
$$\boxed{d_h(t) = a(t) \int_{t_0}^{t} \frac{dt'}{a(t')} \overset{t_0 \to 0}{\longrightarrow} +\infty}$$

- Its age is almost exactly the same age as the Λ-CDM universe

$$t_0 = \frac{1}{H_0} = 13,9 \times 10^9 \text{ years, with } \mathrm{H}_0 = 70 \text{ km/s/Mpc}$$

Timescale(s) of the Milne universe

• Age of the Universe at recombinaison:
14 Gy/1000 ≈ 14 My
(compared to 0.38 My in ΛCDM)
• BBN duration:
Standard BBN ≈ 200 sec
Milne BBN ≈ 30 years !
• QGP transition
(T ≈ 170 MeV):
10^{10} slower !
(7 days vs. 3 10^{-5} s)

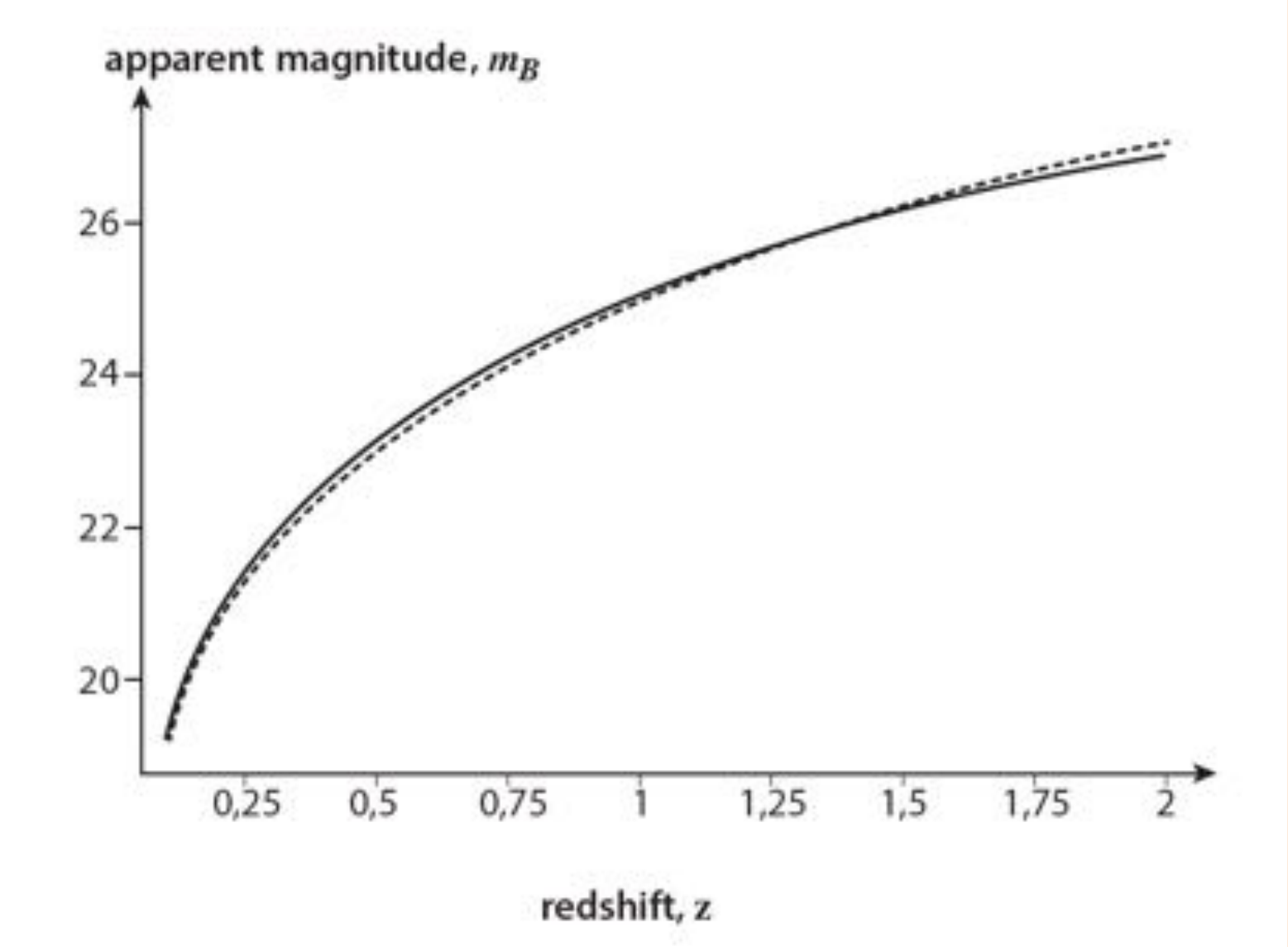


Supernovae SN1a

- A. Benoit-Lévy and G. Chardin, A&A 537 A78 (2012) : Milne and Lambda-CDM are basically indistinguishable for SN1a luminosity distance (small evolution factor of 0.05 magnitude is enough to make Milne better fit than Lambda-CDM !)
- JT Nielsen, A Guffanti, S Sarkar, Nature Sci. Rep. 6 (2016) 35596 : same conclusions, larger statistics
- Several rebuffing papers but consider the following figure…

Supernovae SN1a

M. J. Chodorowski, Proc. Astron. Soc. Australia 22 (2005) 287



Supernovae SN1a

- For a more detailed statistical analysis, see :
- A. Benoit-Lévy and G. Chardin, A&A 537 A78 (2012)
- JT Nielsen, A Guffanti, S Sarkar, Nature Sci. Rep. 6 (2016) 35596

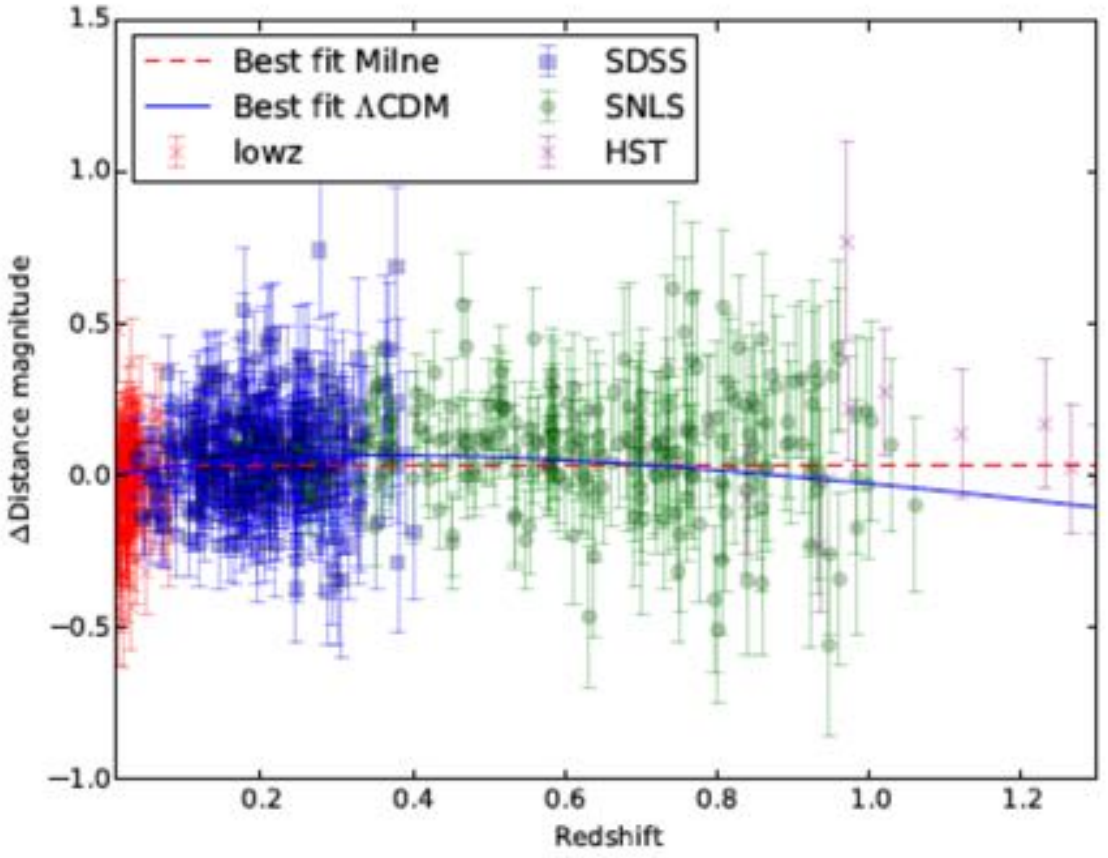
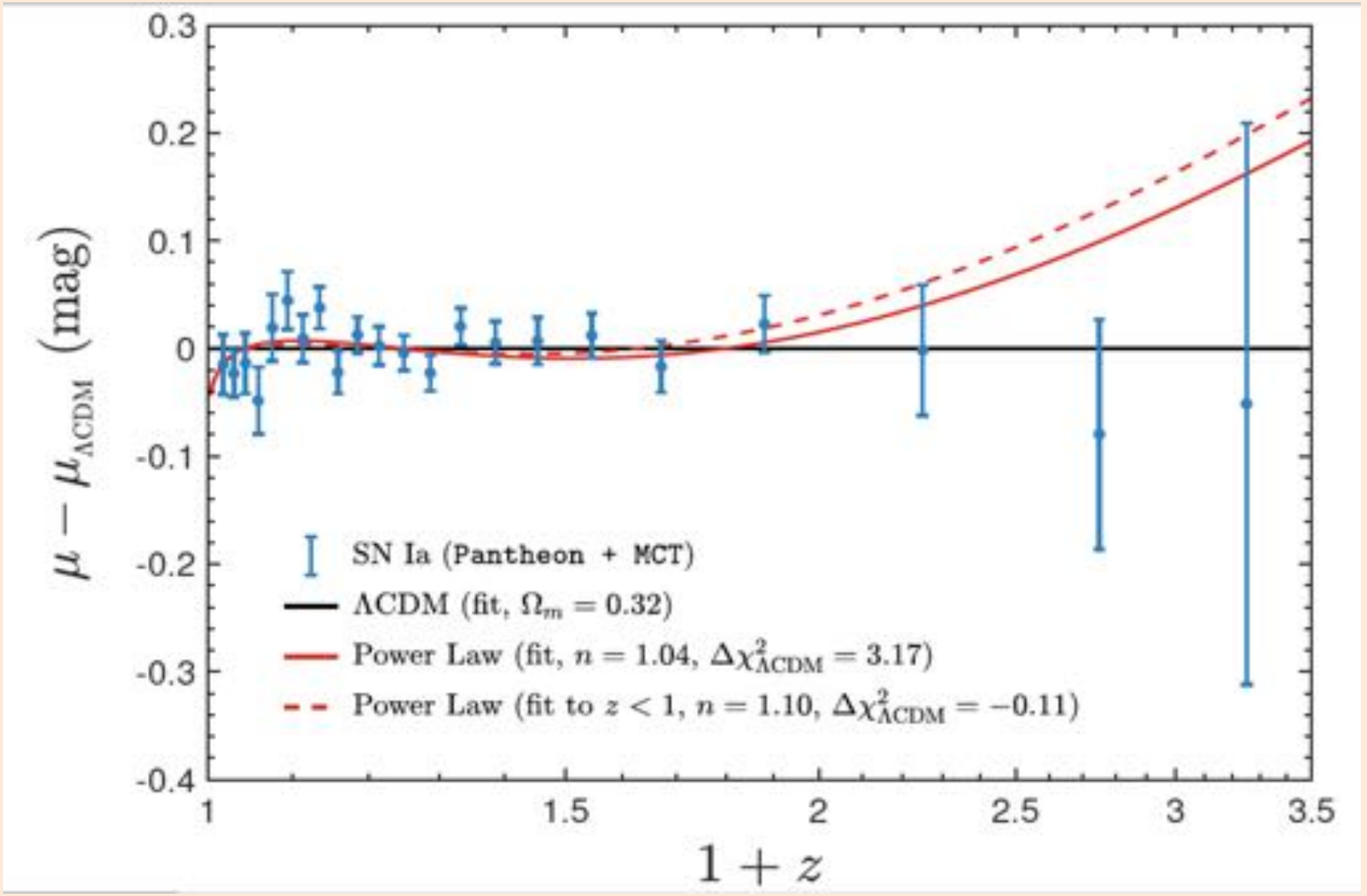


FIG. 4. Residuals relative to the Milne model for Fig. 3.

Supernovae SN1a (ff)

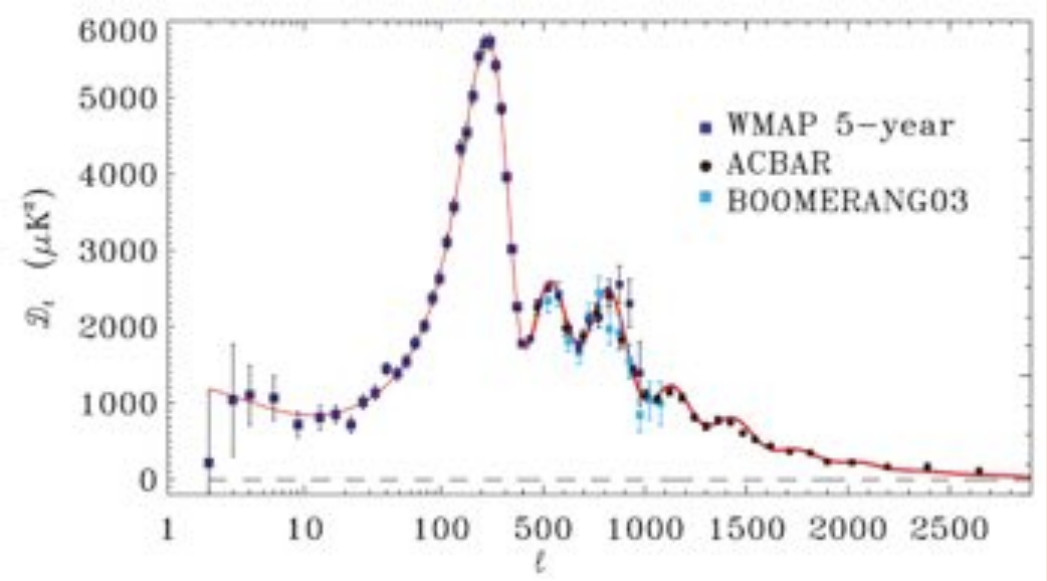
Riess et al. arXiv:1710.00844



Acoustic scale in CMB

First peak corresponds to acoustic scale given by sound horizon seen on last scattering surface.

$$\theta = \frac{r_s}{d_A}$$



For Dirac-Milne, angular distance

$$d_A(z) = H_0^{-1} \frac{1}{1+z} \sinh(\ln(1+z))$$

is 163 times larger than in ΛCDM.

one would expect a tiny angle!

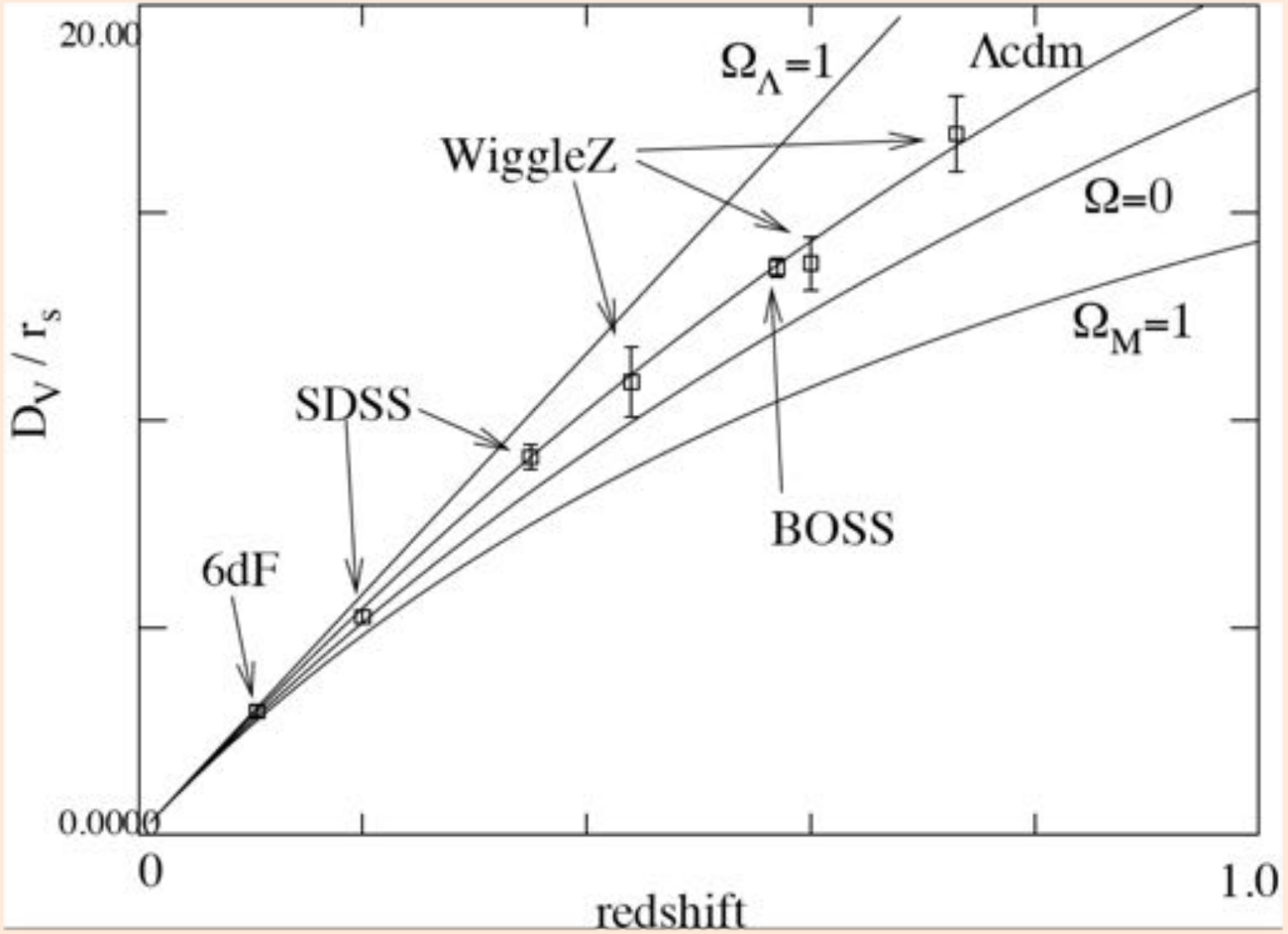
But, due to linear scale factor, sound horizon is much larger than in standard model

$$r_s = \int c_s \frac{dt'}{a(t')}$$

Integrating from 170 MeV to ~ 30 eV (end of annihilation, cf BBN) yields acoustic scale around 1º !

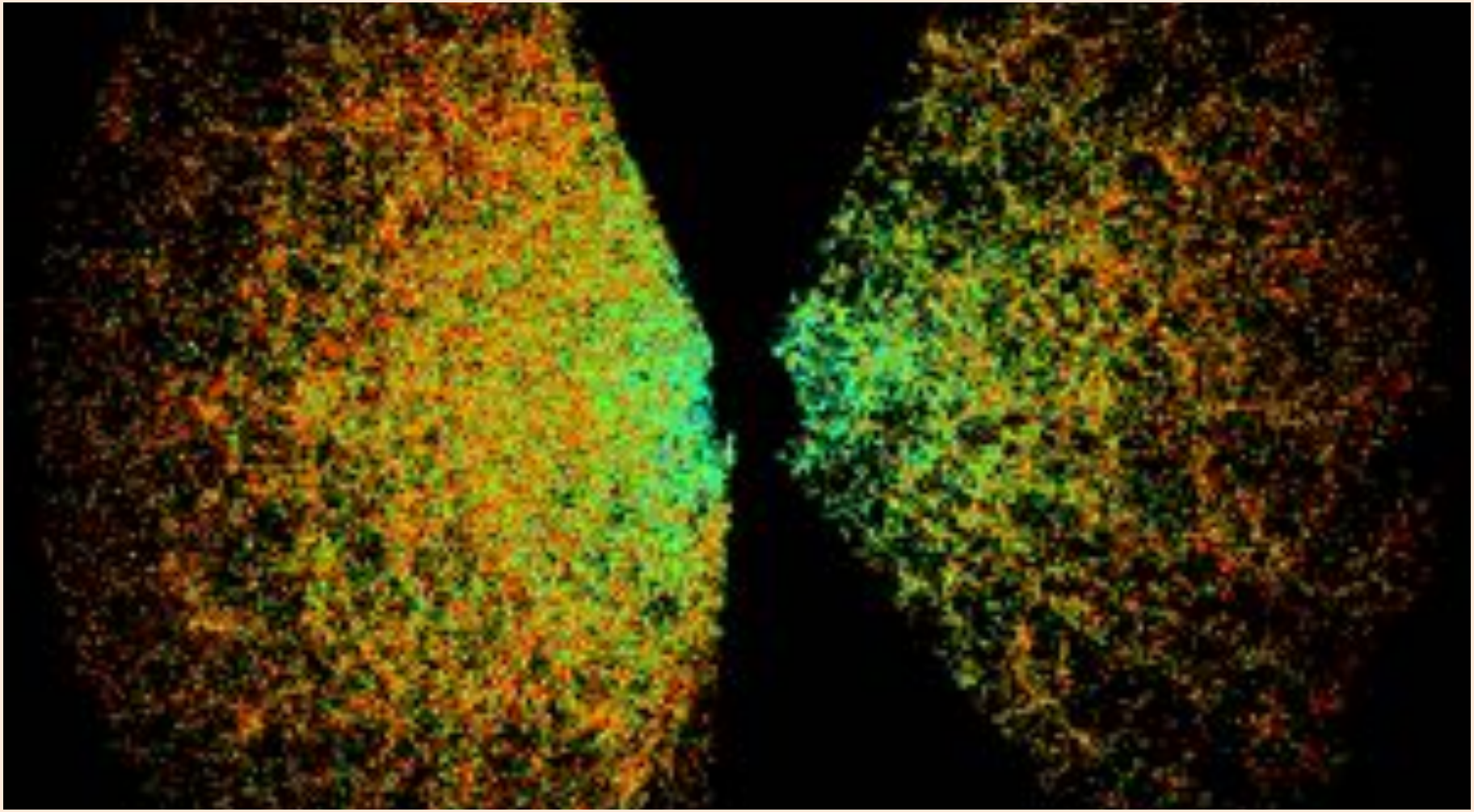
Clearly, BAO should not be observed in Dirac-Milne universe at the reported scale of ~150 Mpc.

BAO vs. cosmology



BAO Hubble linear Jim Rich

(Non linear) structures as seen by SDSS



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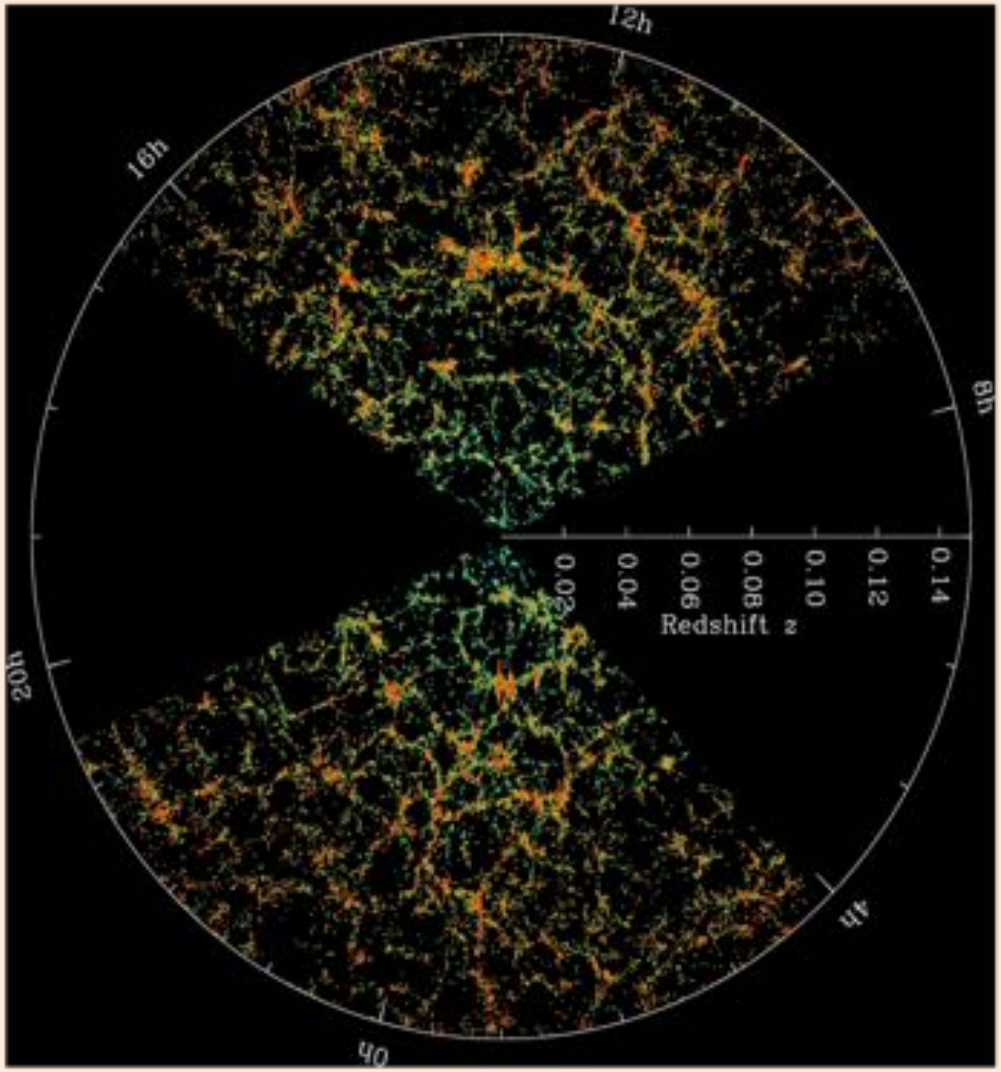

- On this projection of the SDSS survey, there is clearly a non linear scale at $\Delta z \approx 0.03$
- With $H_0 \approx 70$ km/s/Mpc, this gives a ≈100 Mpc scale
- This is impressively close to the (linear) BAO scale
- There is no explanation of this coincidence in the standard model
- On the other hand, this non linear scale is expected in the Dirac-Milne universe (see Manfredi's talk)

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

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

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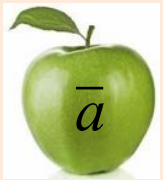
Bondi: runaway acceleration



Dirac-Milne scenario

- However, the above scenarios are not suited to model the Dirac-Milne universe

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

Type of matter	Type of matter	Interaction
+	+	Attraction
−	−	Repulsion
−	+	Repulsion
+	−	Repulsion

- Cannot be realized with a single Poisson's equation

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

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

General matrix formalism

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

Matrix Poisson's equation

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

$$\mathcal{L}(\phi_+, \phi_-) = \frac{\nabla\Phi^T \cdot \nabla\Phi}{8\pi G} + \Phi^T \, \widehat{\mathsf{M}} \, \Phi$$

(can be obtained from Lagrangian)

$$\widehat{\mathsf{M}}_{\rm plasma} = \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix}, \quad \widehat{\mathsf{M}}_{\rm Bondi} = \begin{pmatrix} 1 & -1 \\ 1 & -1 \end{pmatrix} \qquad \widehat{\mathsf{M}}_{\rm DM} = \begin{pmatrix} 1 & -1 \\ -1 & -1 \end{pmatrix}$$

Expanding universe

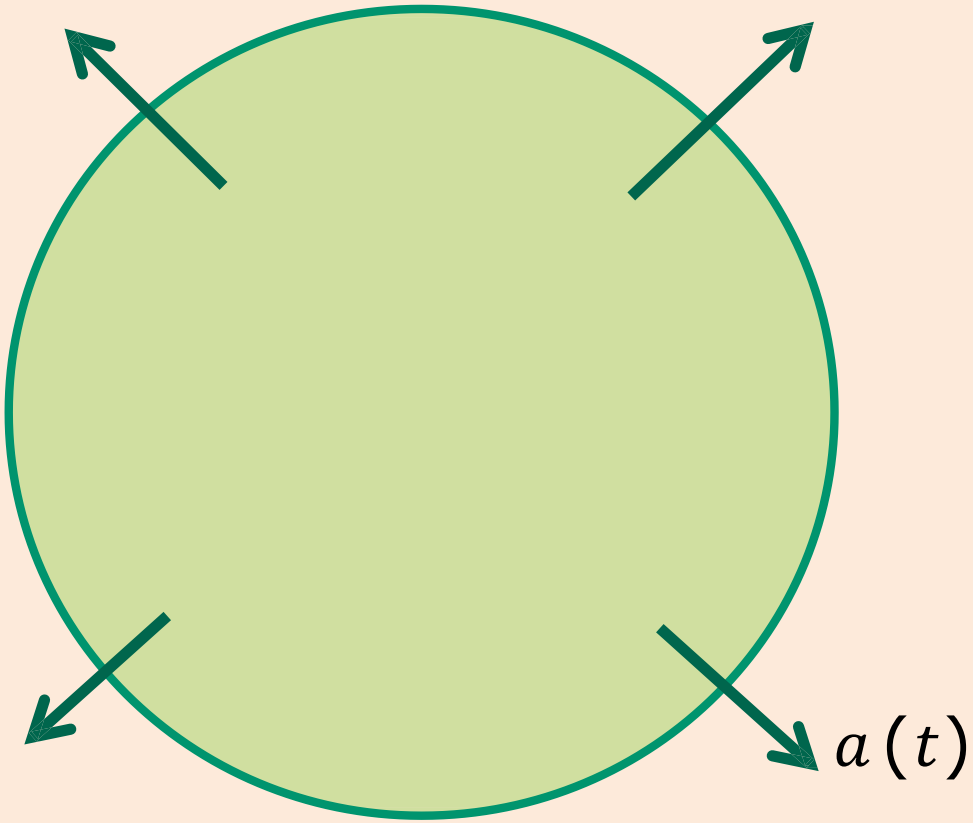
Comoving coordinates

Equation of motion

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

Scaling factor

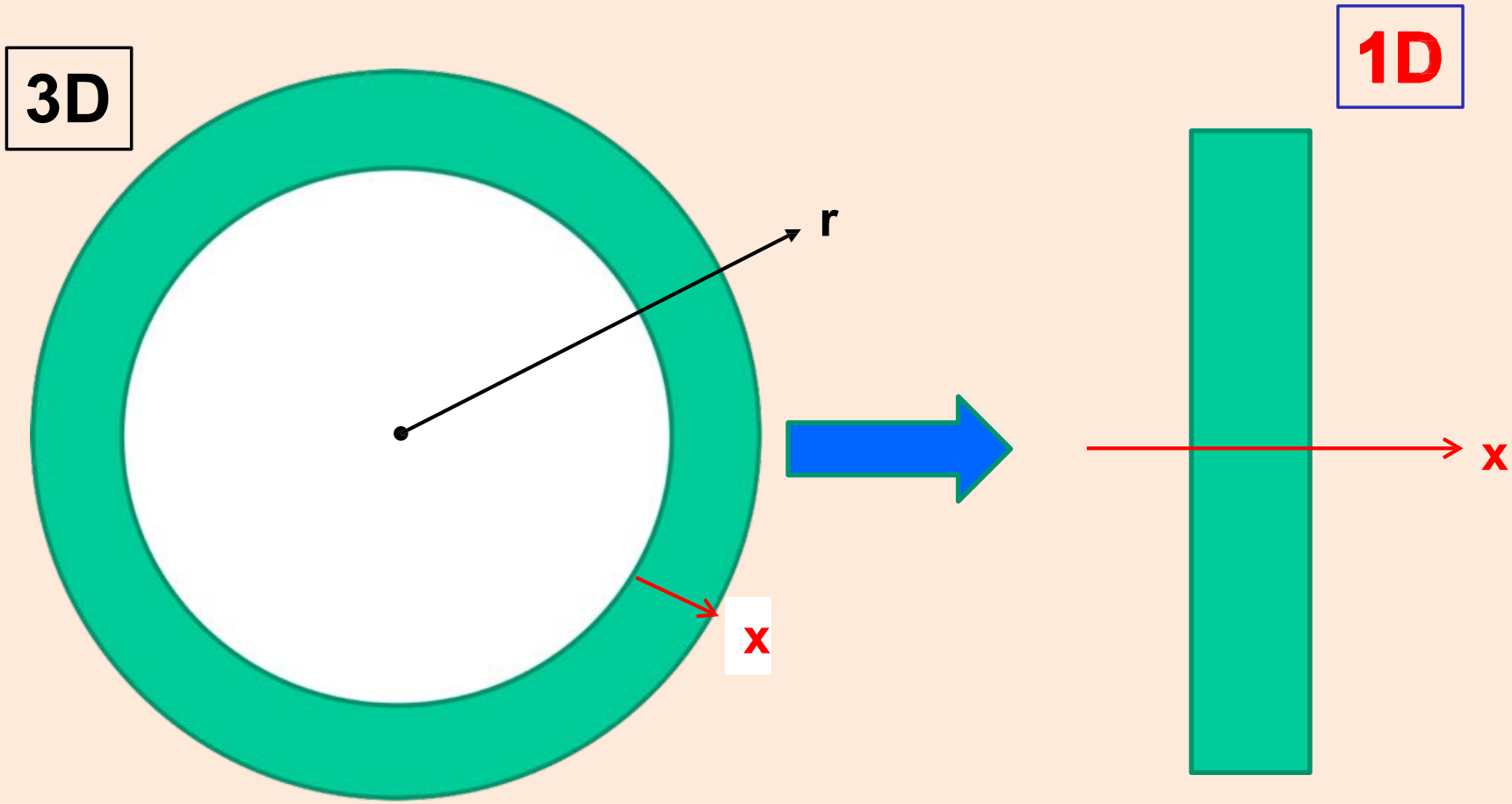
$$r = a(t)\hat{r},$$



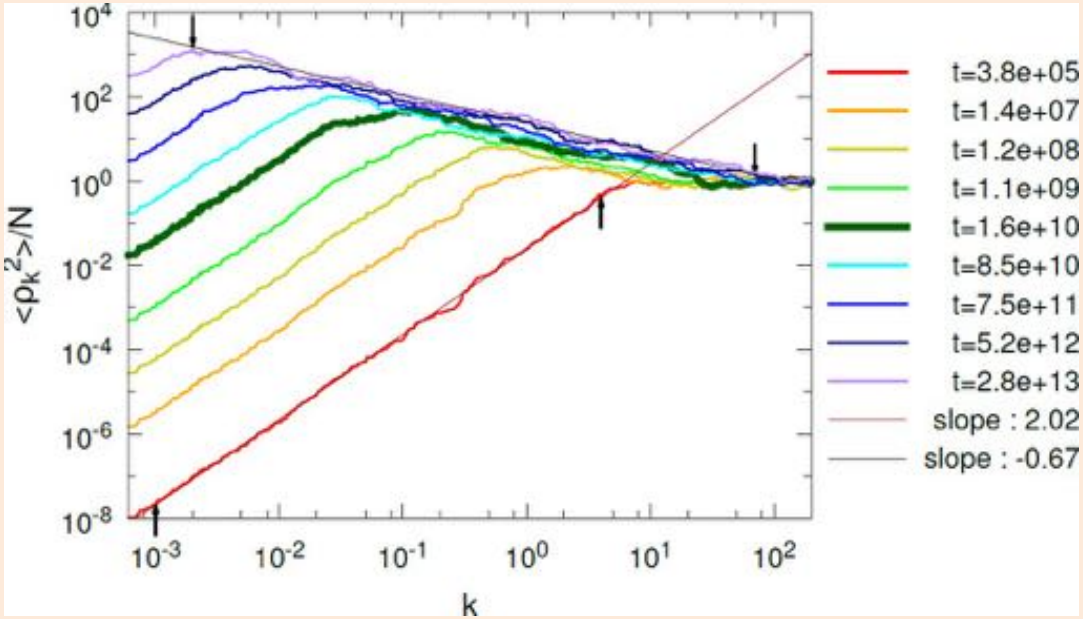
$a(t) \sim t^{2/3}$ Einstein – de Sitter universe (matter dominated)

$a(t) \sim t$ Dirac-Milne universe

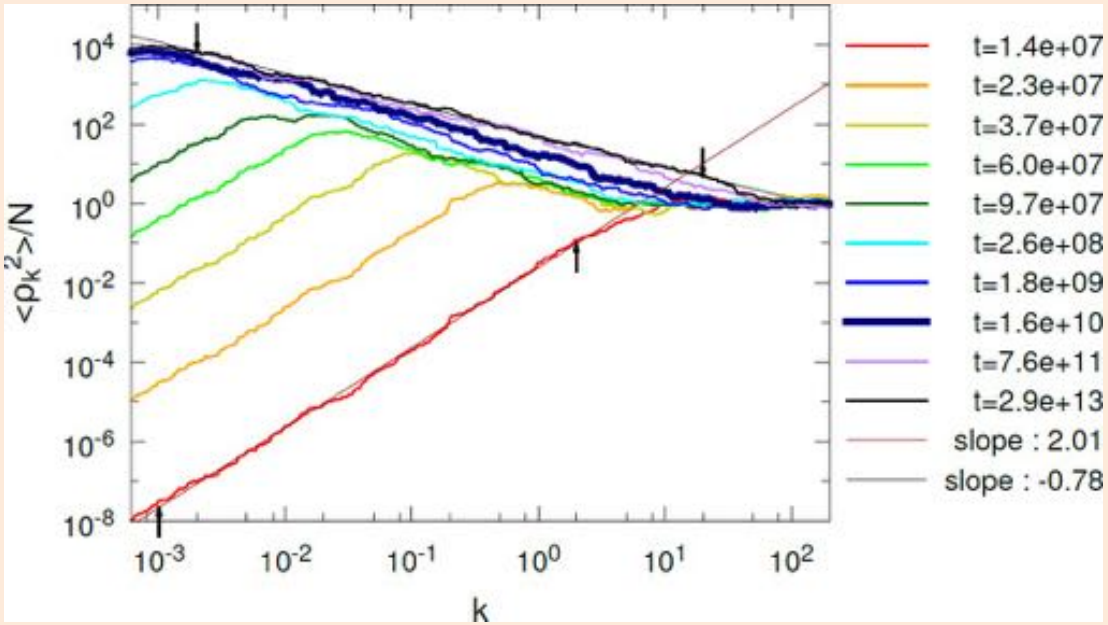
One-dimensional geometry



Matter-density power spectrum



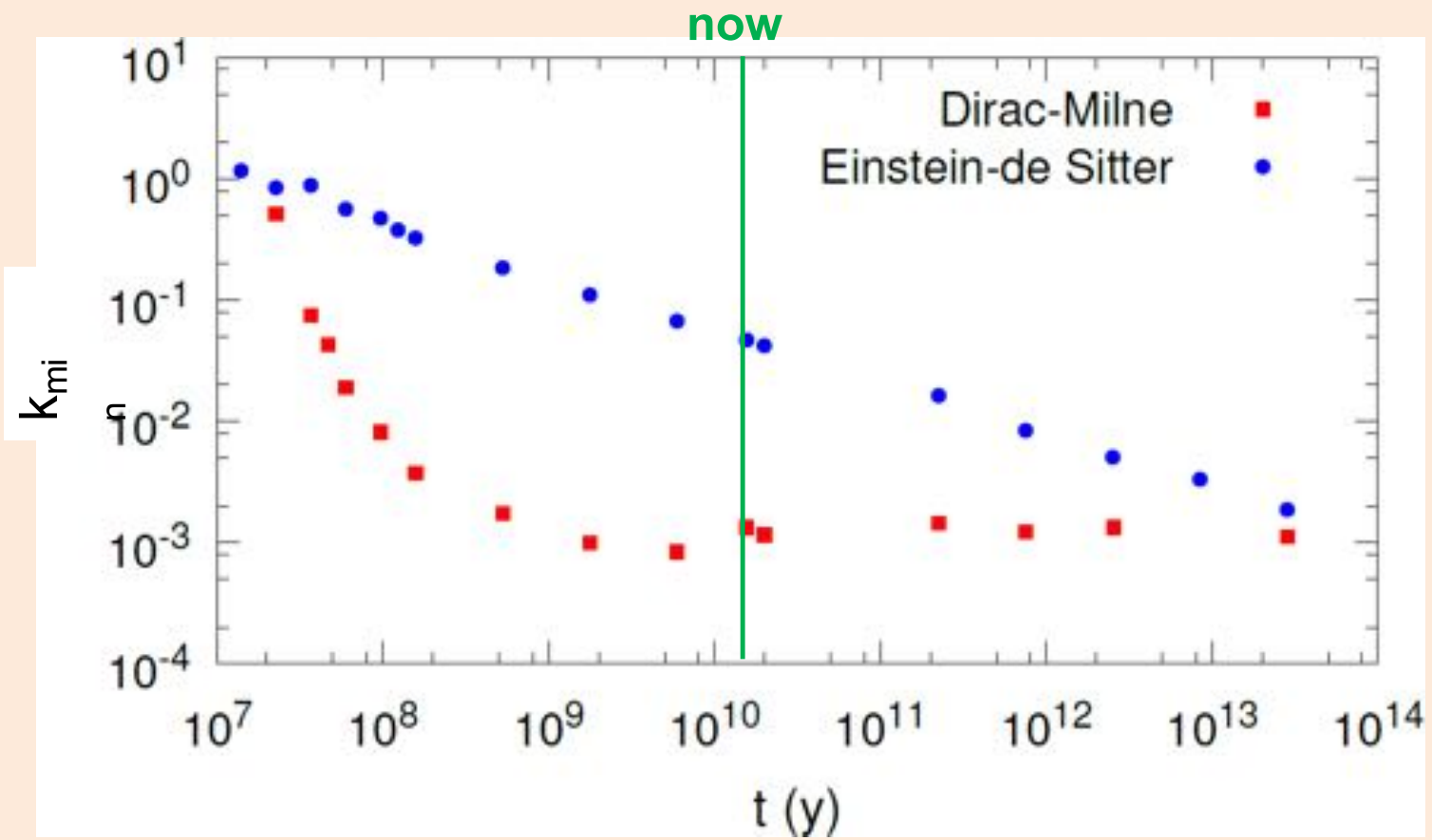
Einstein – de Sitter



Dirac-Milne

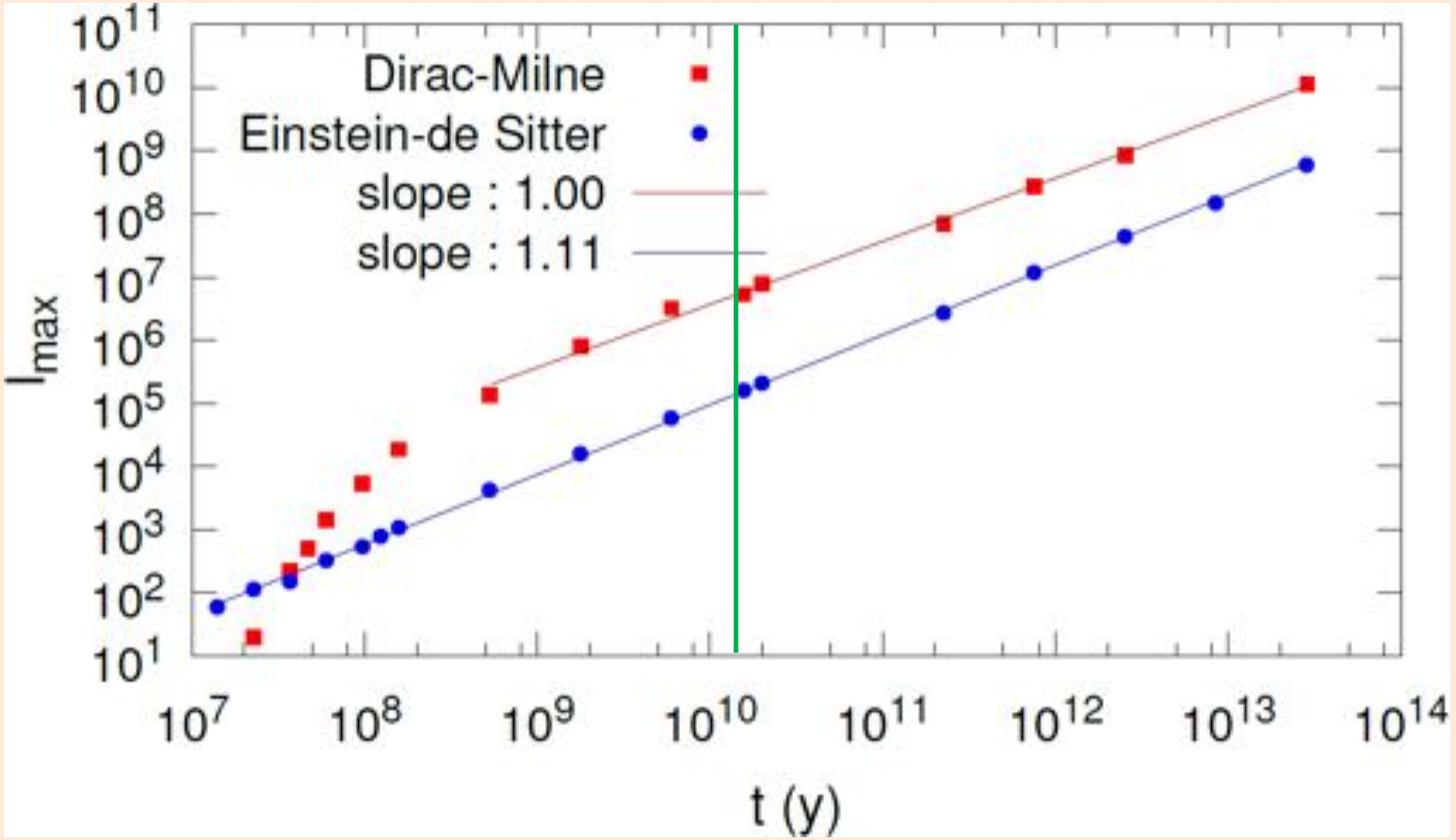
Evolution of power spectrum peak

k_{min} in comoving coordinates



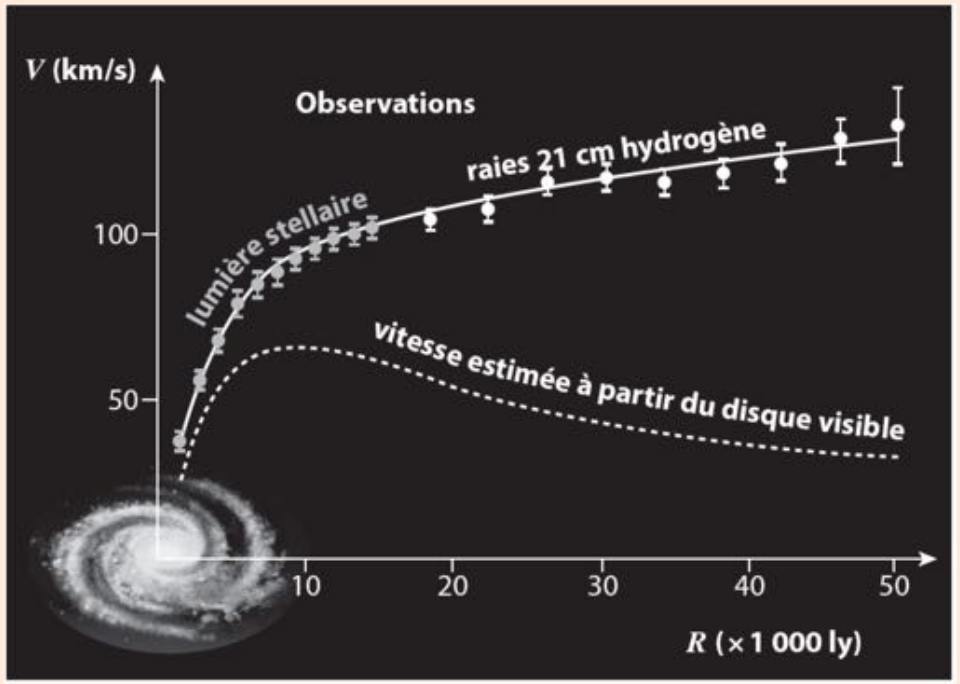
Typical cluster size

$l_{max} = \frac{2\pi at}{k_{min}}$ in fixed (non comoving) coordinates

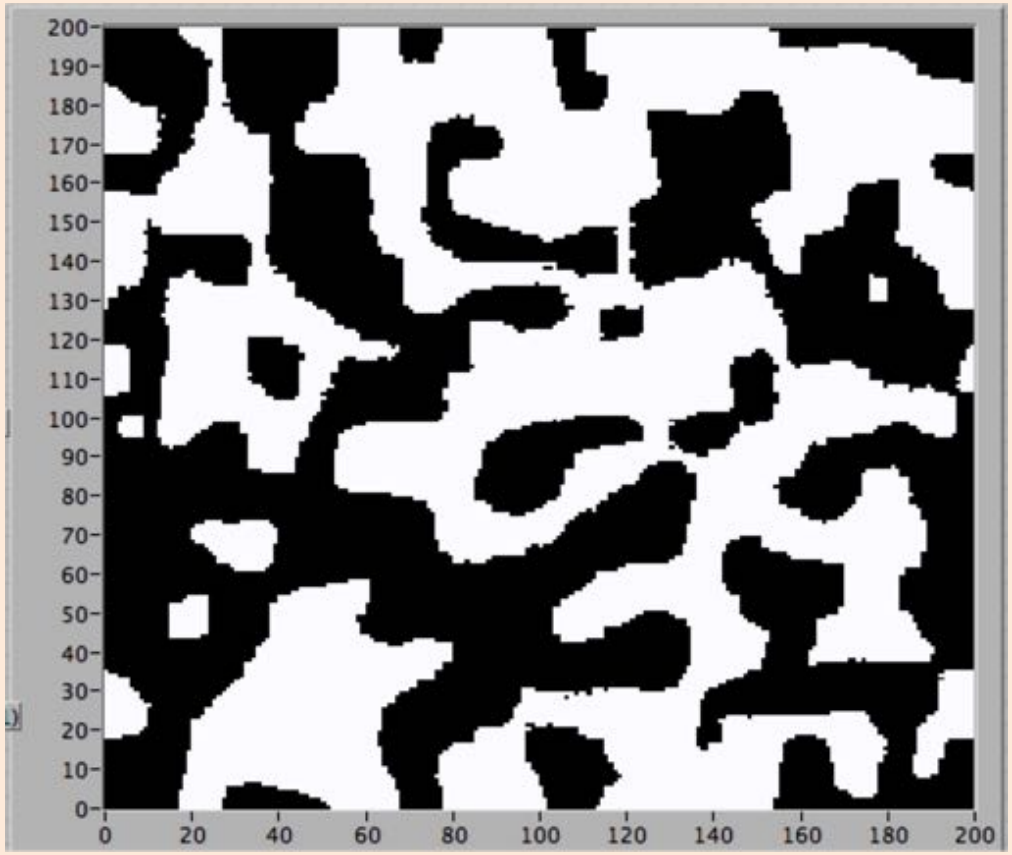


Note : Dark Matter and MOND

- M. Milgrom, ApJ., 270, (1983) 365
- L. Blanchet and A. Le Tiec (2007-2008) :
dipolar dark matter may explain MOND (analog to Maxwell's equations in matter)
- Negative mass in GTR will do just that…
- MOND may just be General Relativity with polarization induced by the presence of m <0



Evolution of a symmetric matter-antimatter universe : $\eta = n_B/n_\gamma$



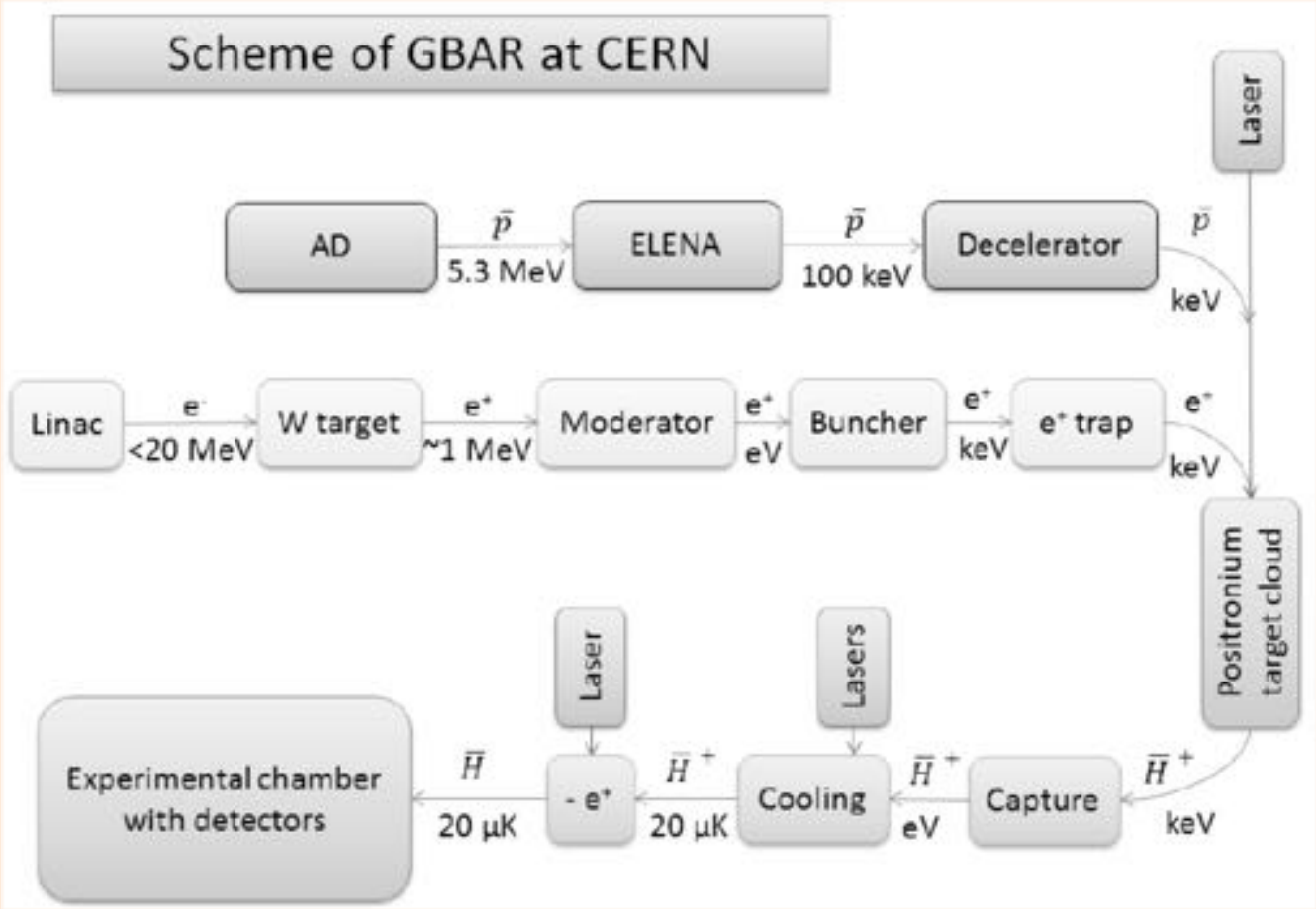
- Matter-antimatter emulsion in 3D : characteristic size grows linearly with annihilation at matter-antimatter interface
- Emulsion size at the end of annihilation completely determined, not a free parameter…
- Gravitational polarisation : annihilation stops at T ≈ 30 eV

Helium-3 overproduction ?

- Robert T. Rood, T. M. Bania, Dana S. Balser, Ap. J., 280 (1984) 629 : « If this difference is due to the general chemical evolution of the galaxy, our result for He-3 is exactly the *opposite* of what one would expect (…) The utility of 3He/H as a probe of the cosmological baryon-to-photon ratio rests on the resolution of this puzzle. »
- « He-3 (…) was most abundant where it was least expected… », Science 295 (2002) 804

Direct test in the laboratory

- Three experiments at CERN : Gbar, AEgIS, ALPHA-g are attempting to measure the trajectory of cold antihydrogen atoms in the gravitational field of the Earth



Future work

- **Extend 1D simulations to Λ-CDM (instead of Einstein-de Sitter)**
- **3D simulations + feedback (SN explosion, reionization, …) instead of 1D simulations**
- **Calculation of $\eta = n_B/n_\gamma$ (integral of annihilation between T ≈170 MeV and T ≈30 eV) : ≈10^{-9} ?**
- **He-3 overproduction : is this really a problem ? See Rood, Bania and Baiser**

Summary (1)

- “ Cosmological antigravity ” (i.e. repulsive gravity, or Dark Energy) is in Λ-CDM the main component (≈70%) of the universe
- Negative mass solutions can be built in GTR in a de Sitter or inflating universe without creating disasters
- There exists a deep relation between the Kerr-Newman geometry with its charge-mass symmetry and Dirac particles
- If negative mass particles exist, even at virtual state, they will induce polarization (and MOND ?)
- Negative mass, as proposed by Piran, is present by construction in simulation codes of cosmological evolution : voids take as much space as they can and stay away from positive mass (no Newtonian expression, see Mandredi !)

Summary (2)

- The electron-hole system in a semiconductor implements this negative mass scheme first proposed by Piran, keeping the spirit of the Equivalence Principle
- The Dirac-Milne « coasting » or « empty » universe, a symmetric matter-antimatter universe, is impressively concordant (age, SN1a, nucleosynthesis, CMB) with our universe
- The (non-linear) growth of structure (voids) in the Dirac-Milne universe leads to the same length scale as the (linear) BAO (baryonic acoustic oscillations) ; see Manfredi's talk for more about this
- He-3 is overproduced in Dirac-Milne, but is this really a problem ?
- Three experiments at CERN will test in the near future, and possibly already before the long shutdown in 2019-2020, the Dirac-Milne antigravity hypothesis