Experimental tests of antigravity

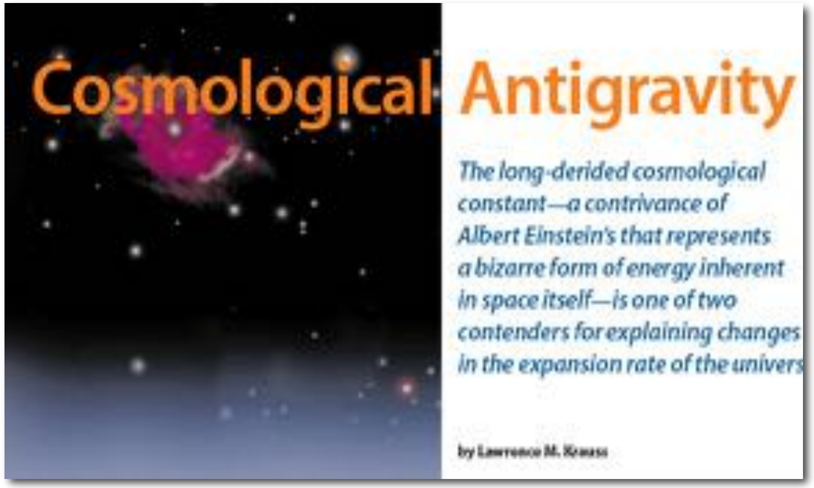
Gabriel CHARDIN
APC Laboratory, Université Paris-Cité and CNRS

Outline

- The strange history of the ΛCDM model
- Elements of concordance of a coasting universe
- What do we mean by antigravity ? A revolution or something that we should have expected ?
- Antigravity and cosmological tests
- A few notes on MOND (MOdified Newtonian Dynamics)
- Direct measurement at CERN: ALPHA, AEgIS and Gbar
- A note on antigravity and particle physics (CP violation)
- Conclusions and summary
- A few references

Dark Energy and Cosmological antigravity

- Repulsive gravity was considered as science-fiction until at least the mid-80s
- Dark Energy, dubbed here as cosmological antigravity by Riess and Krauss, is an accepted repulsive component, and one of the present major scientific questions
- A large part of the cosmological community is working at trying to characterize its properties and identify its equation of state
- But does it really exist ?



Cosmological Antigravity

The long-derided cosmological constant—a contrivance of Albert Einstein's that represents a bizarre form of energy inherent in space itself—is one of two contenders for explaining changes in the expansion rate of the univers

by Lawrence M. Krauss

Adventures in Antigravity

By Michael D. Lemonick

ADAM RIESS

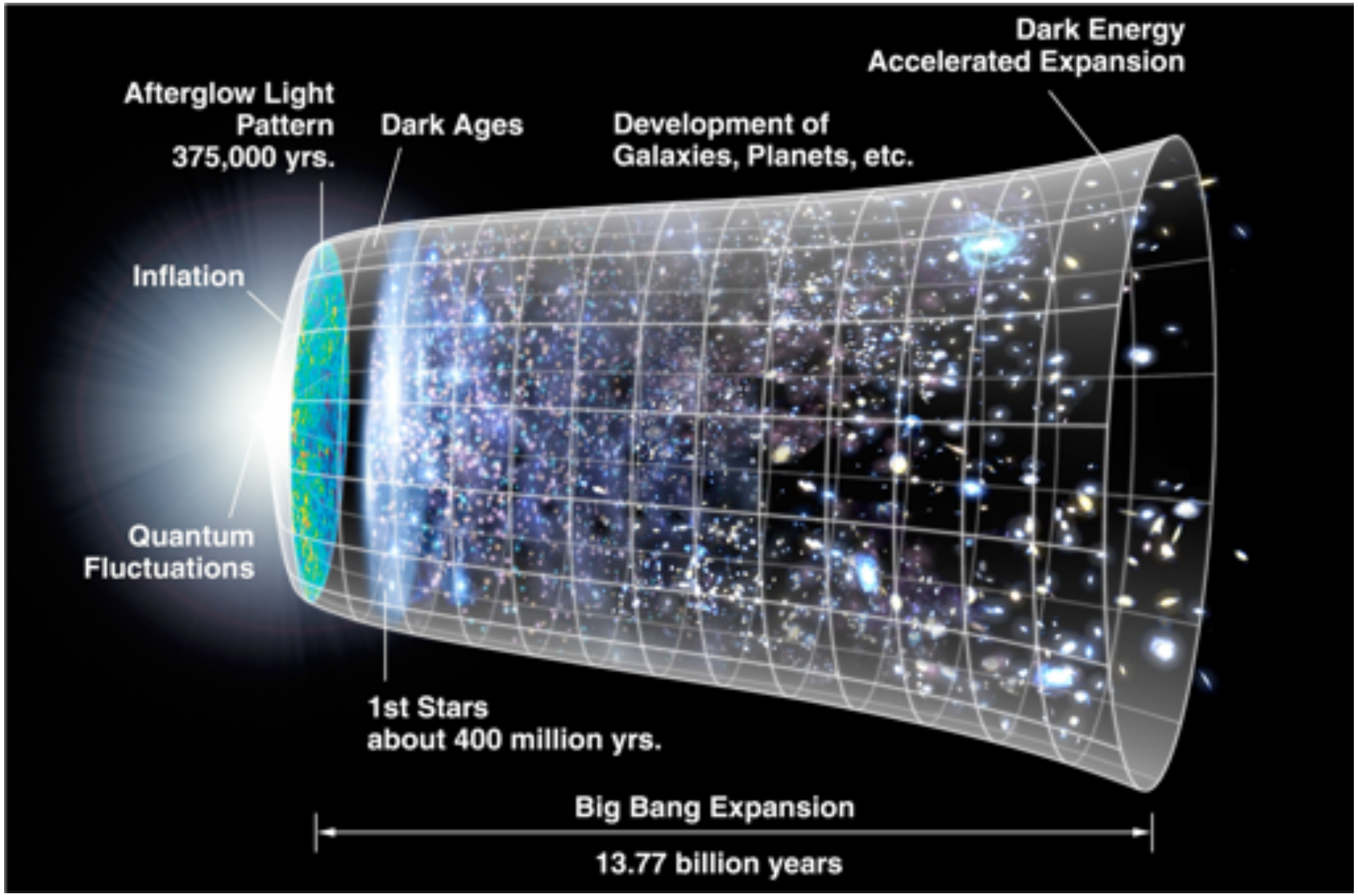
His calculations show that the universe seems to be expanding ever faster, suggesting the existence of the antigravity force first proposed, then abandoned, by Einstein.

Hard as it is for earthlings to imagine, astronomers have known for some time that the universe is expanding. They've never been able to figure out, though, whether it will balloon outward forever or slow under the combined gravity of its 100 billion galaxies, stop and fall back in on itself. Thanks in large part to Adam Riess, they're a lot closer to an answer—and it's not what they expected.

Riess was only 25 when he joined a prestigious group of scientists who set out in 1995 to measure what was expected would be a post Big Bang cosmic slowdown. The idea was to compare the expansion rate today with the rate billions of years ago by gauging the speeds of exploding stars called supernovas—Riess's grad—school specialty. But in January 1998, Riess saw something weird: the number he was getting for the slowdown kept coming out negative. The universe wasn't slowing down; it was speeding up! "This seemed to imply," he says, "that some force is acting against gravity." Crazy as antigravity sounds, the idea was originally suggested by Einstein as a kind of add-on to his General Theory of Relativity.

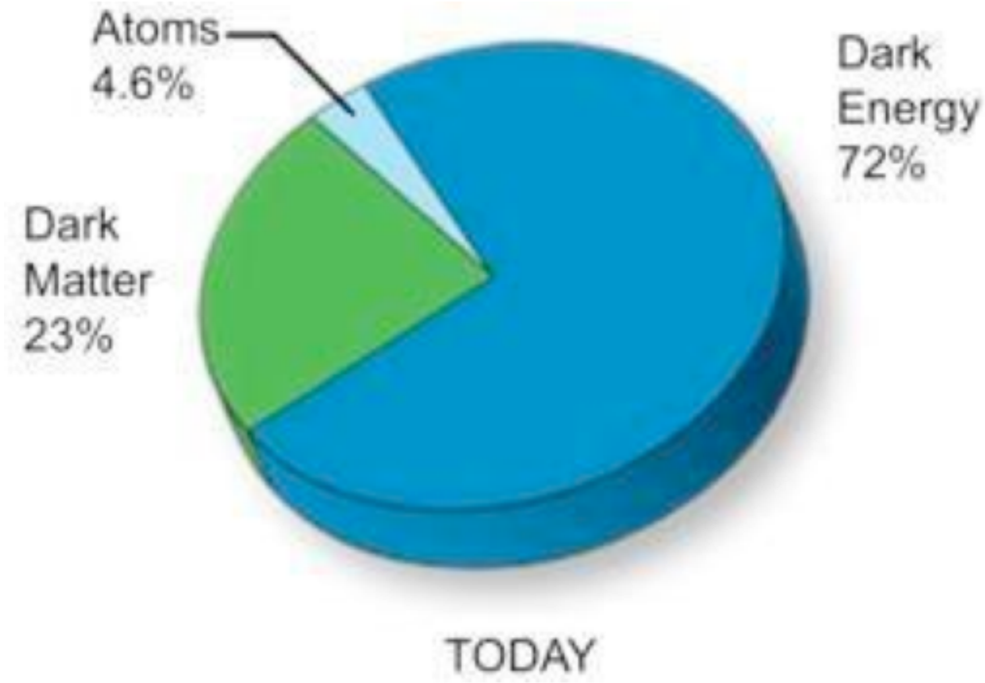
1 | 2

The very strange history of the ΛCDM Universe

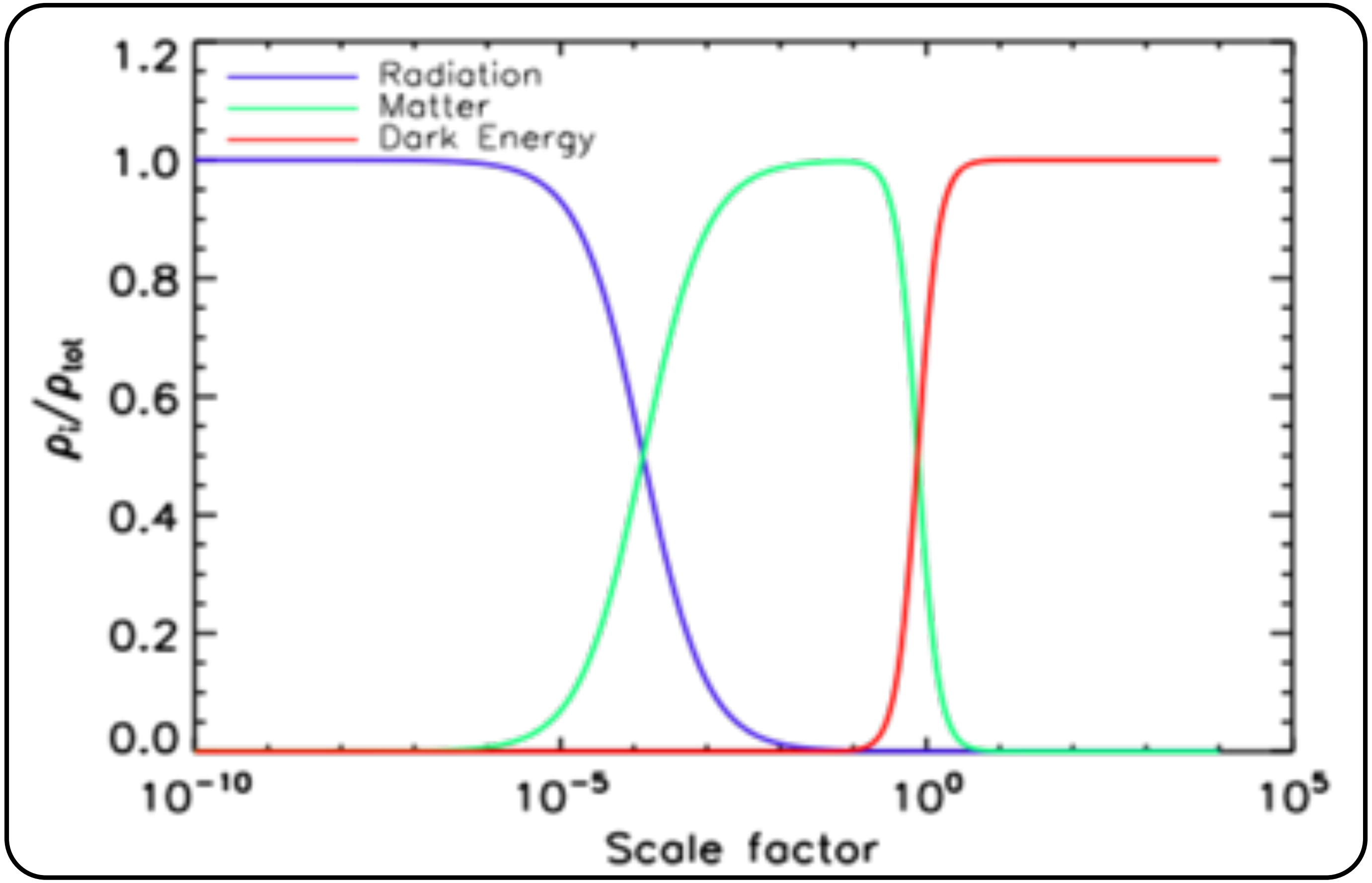


- Two, or maybe event three, episodes of deceleration /acceleration:
- Inflation
- Dark Energy
- And maybe even Early Dark Energy
- Epicycles ?

A very strange composition (see also variation in time of the main Universe components)…



Variation in time of matter, Dark Energy and radiation



The ΛCDM standard model

- An impressive fit of the data with a relatively small number of free parameters (Planck fit involves 6 parameters, plus some additional parameters marginalized in the fitting process)
- Might be dangerous to accept the principle that the correct model must be close to ΛCDM

Cosmology as a test for antigravity

- Large number of constraints for any candidate cosmology :
  - Age
  - SN1a luminosity distance
  - Primordial nucleosynthesis
  - Structure formation
  - What plays the role of Dark Matter and Dark Energy (if they don't exist in your theory?)
  - BAO constraints (and variation as a function of redshift z)
  - Above all, reproduce the CMB spectrum, which provides by far the most precise experimental contraints
  - Would be nice also to be able to predict some new features, and to alleviate the tensions on the LCDM model (Hubble tension, cold spot, age tension, structure history, intermediate mass black holes, …)

Coasting or Milne universe

- The Milne universe is a « zero total mass » and « coasting » universe, often used as a reference in cosmology plots
- Several authors have noted that our Universe looks quite close to such a « coasting » universe ; for a review see Casado, Astrophys Space Sci 365:16 (2020)
  - M. Sethi, Batra, A., & Lohiya, D. 1999, Phys. Rev. D, 60
  - A. Benoit-Lévy and G. Chardin, A&A, 537 (2012) A78.
  - F. Melia, and A. Shevchuk, MNRAS 419 (2012) 2579
  - 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.

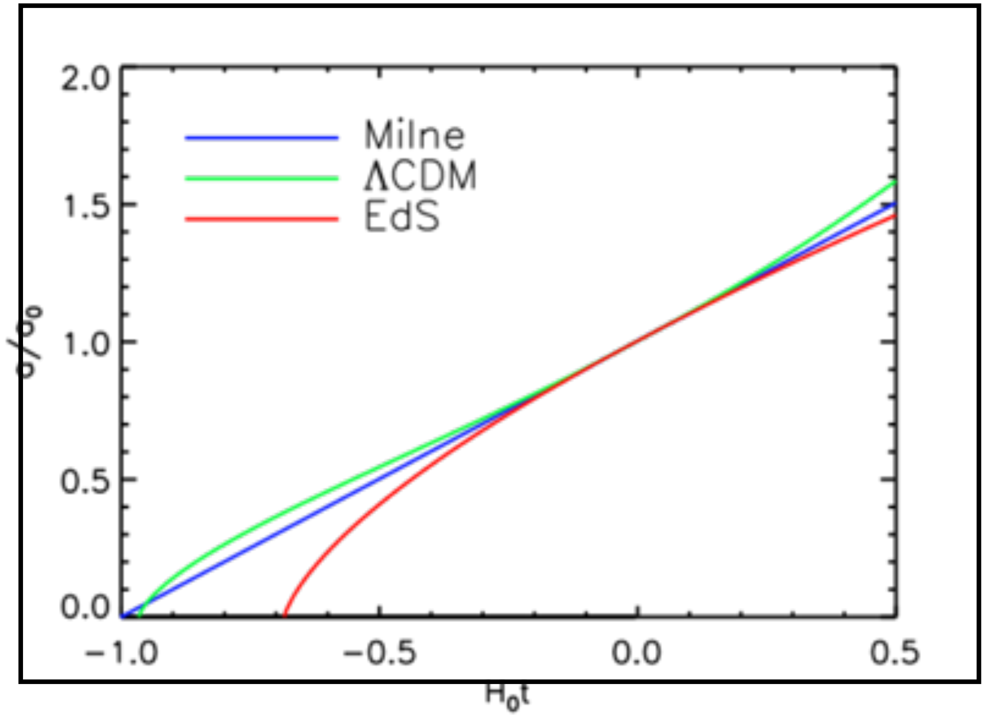
Elements of concordance of a coasting universe (independently of antimatter)

- Age, luminosity distance (supernovae), and even nucleosynthesis for He-4 and Li-7 (but not D) are extremely concordant
- Distance to horizon is infinite: no need for inflation
- BAO (baryonic acoustic oscillations) and CMB seem in contradiction with a coasting (empty) universe
- In any case, surely our universe is not empty, what could be then the justification for a Milne universe anyway ?

Age of the Universe

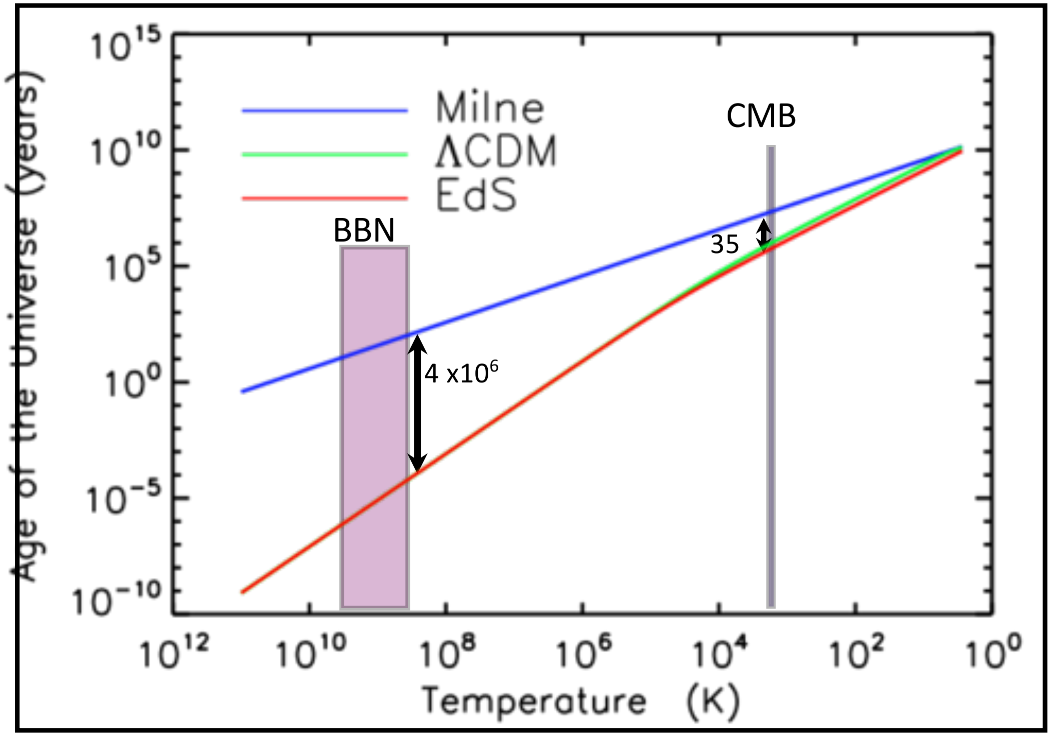
A. Dev, M. Safonova, D. Jain and D. Lohiya, PLB 548 (2002) 12-18.
M. Kutschera, and M. Dyrda. *Acta Physica Polonica* 38 (2007) 215.
A. Benoit-Lévy and G. Chardin, A&A 537 (2012) A78.

- Compared scale evolution for ΛCDM, Milne and Einstein-de Sitter
- Einstein-de Sitter universe (red curve) definitely too young (2/3 the age of the LCDM and the Milne universe)
- Linear evolution of the scale factor solves the initial age problem that led to the introduction of a fine-tuned cosmological constant



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 ≈ 35 years !
• QGP transition (T ≈ 170 MeV): 10^{10} slower !
(7 days vs. 30 μs)



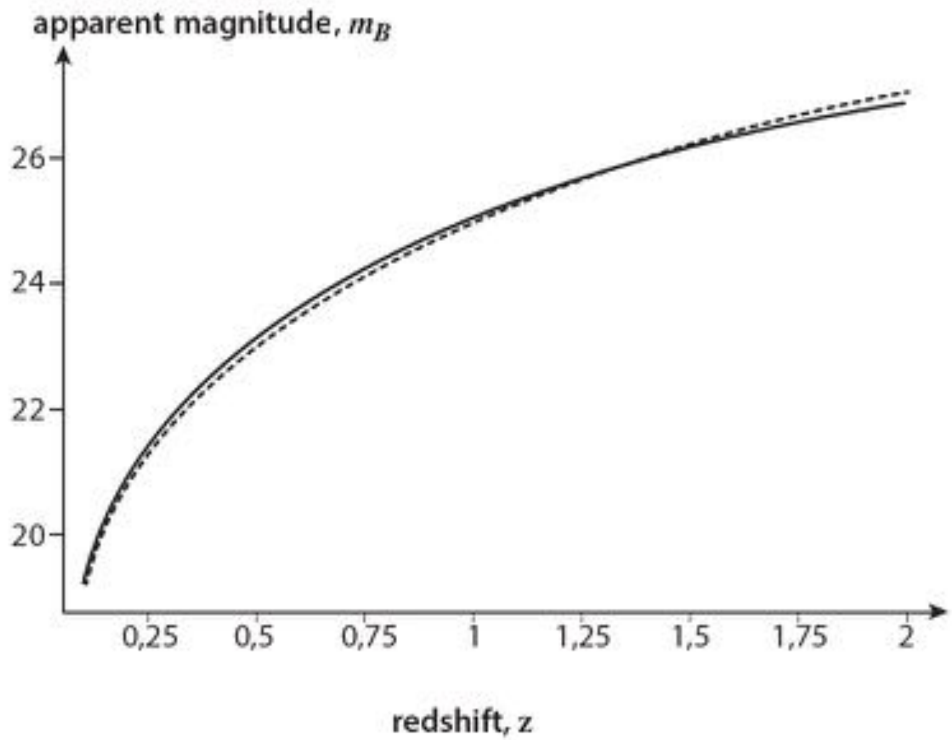
Coasting universe: nucleosynthesis

- Nucleosynthesis lasts for 35 years instead of 3 minutes !
- And still Helium-4 and lithium-7 are produced at adequate levels compared to hydrogen with $\eta = n_B/n_\gamma \approx 8\ 10^{-9}$
- Deuterium and helium-3 are destroyed, unless…
  - M. Sethi, A. Batra, & D. Lohiya, PRD 60 (1999) 108301.
  - A. Batra, D. Lohiya, S. Mahajan, "Nucleosynthesis in a universe with a linearly evolving scale factor." *International Journal of Modern Physics D* 9.06 (2000) 757.
  - A. Benoit-Lévy and G. Chardin, A&A (2012): deuterium (and Helium-3) are produced by (small) annihilation at border of matter-antimatter emulsion (almost exclusively matter jets)

SN1a luminosity distance

- SN1a data quite often considered as a proof that the present expansion is accelerating (Nobel prize 2011…)
- True if spatial curvature is zero
- Wrong if spacetime curvature is zero
- ΛCDM luminosity distance is remarkably similar to Milne's, while Milne luminosity distance has no free parameter
- Figure extracted from Chodorowski (2005), adequately titled « Cosmology under Milne's shadow »

Sethi, M., Batra, A., & Lohiya, D. PRD 60 (1999) 108301.
Dev, A., Sethi, M., & Lohiya, D., PLB 504 (2001) 207.
Benoit-Lévy, A., & Chardin, G, A&A 537 (2012) A78.
Nielsen, J. T., Guffanti, A., & Sarkar, S., Nat. Scient. Rep., 6 (2016) 1.
Tutusaus, I., Lamine, B., Dupays, A., & Blanchard, A., A&A 602 (2017) A73.

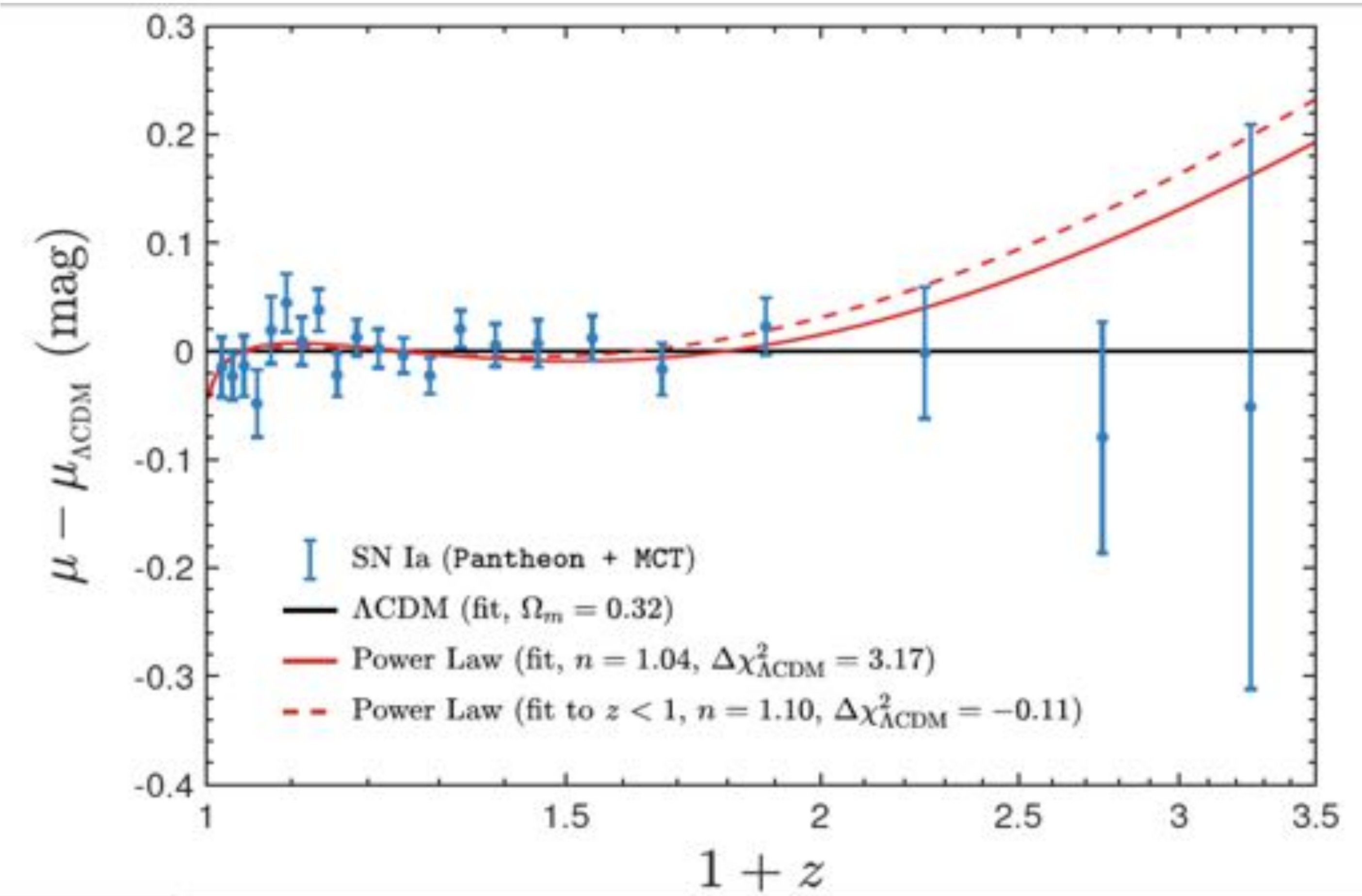


Supernovae SN1a (ff)

Riess et al. arXiv:1710.00844, HST + Pantheon

Note : data in this original figure 4 of Riess et al. are binned, there are 1048 SN1a in the Pantheon data sample

Note: Milne fit would be n = 1



Important note : Flat space and flat spacetime…

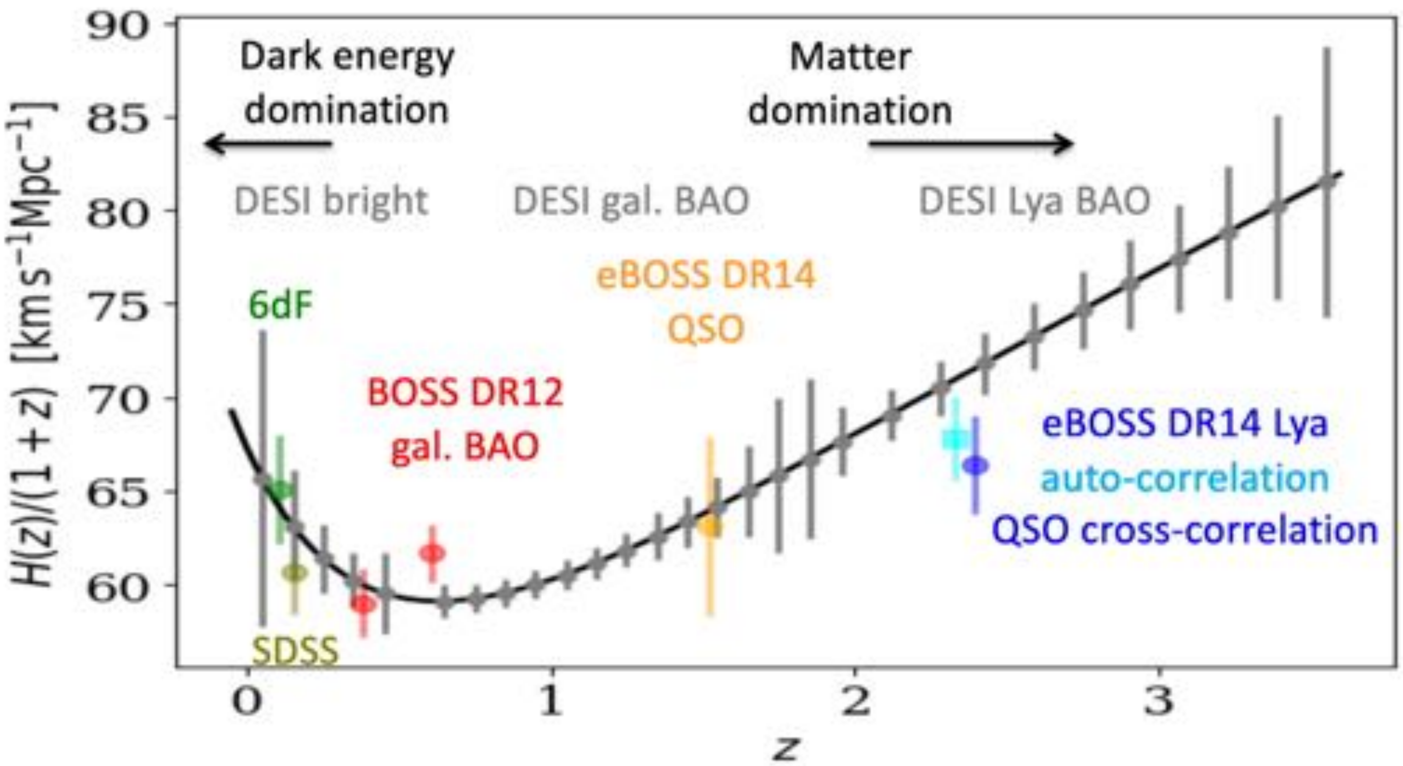
- We often see in present cosmology papers the sentence:

  " Assuming a flat Universe…"

- ΛCDM (and most present models) assume flat **space** **(at a given time)**, because inflation is assumed and near-exact flatness of space is natural
- But coasting universes (neither decelerating nor accelerating), and in particular the Dirac-Milne universe, are flat **spacetime**, not flat space…

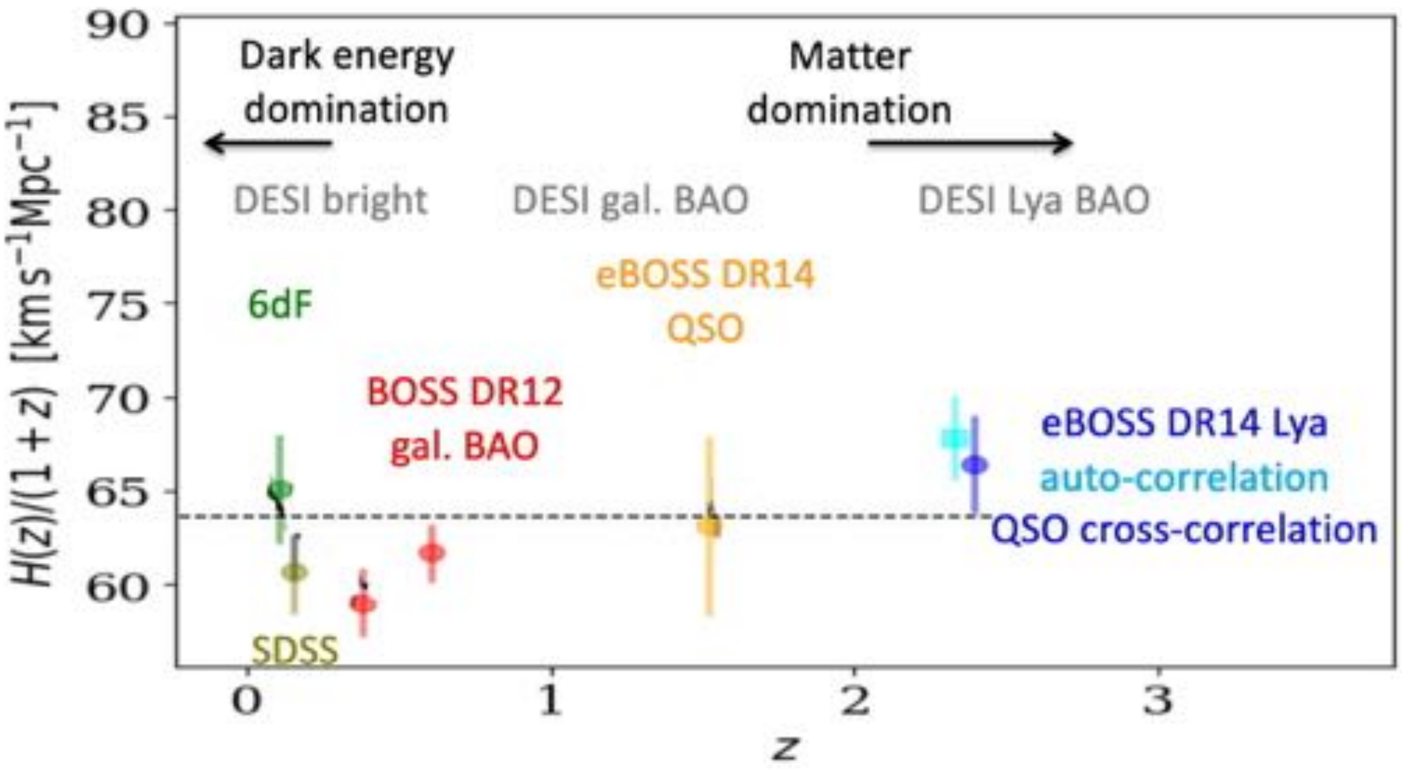
Hubble law and BAO data

- In a coasting (Milne) universe, H(z) follows a simple expression : $H(z) = H_0 (1 + z)$
- Fit to this expression provides low value for $H_0 \approx 63$ km/s/Mpc
- Almost the same chi-squared between LCDM and Milne universe in BAO measurements
- **Note : all grey points don't exist yet**



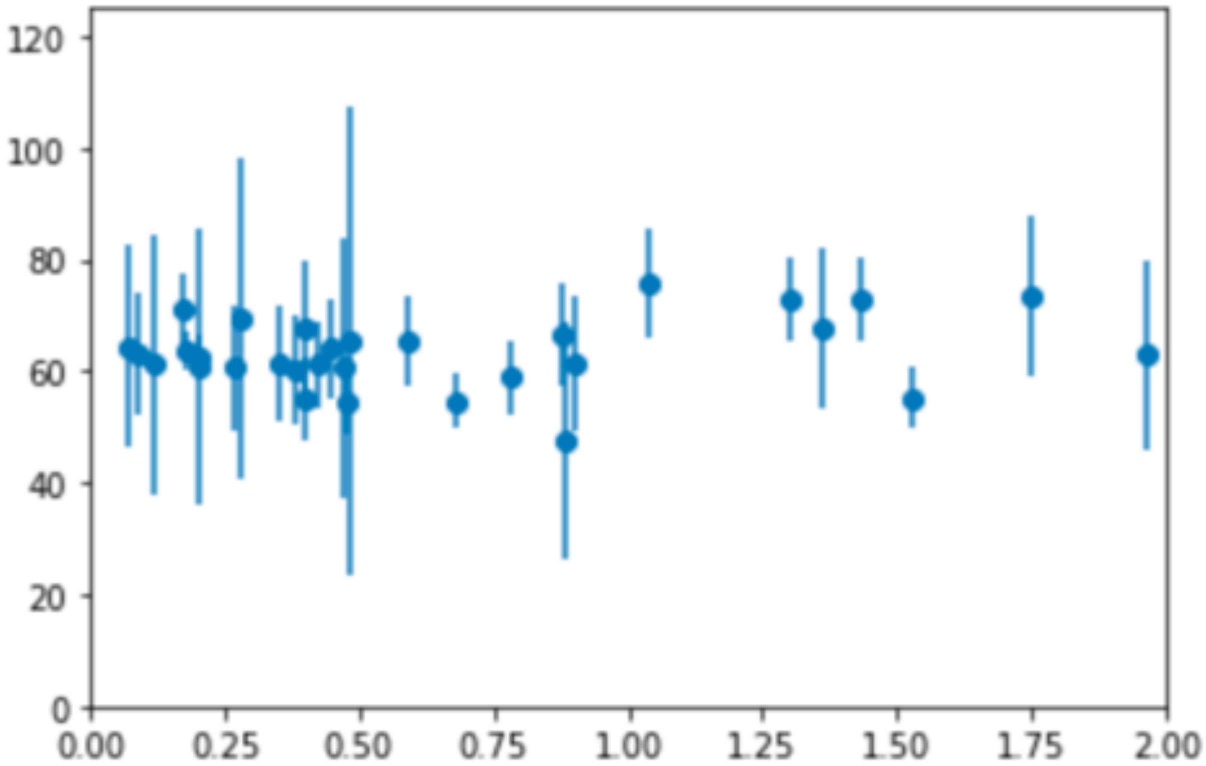
Same data plotted without the fit (and the future DESI points)

- In a coasting (Milne) universe, H(z) follows a simple expression : $H(z) = H_0 (1 + z)$
- Almost the same chi-squared between LCDM and Milne universe in BAO measurements
- Fit to this expression provides low value for $H_0 \approx 63$ km/s/Mpc



Cosmic chronometers
H(z)/(1+z) (constant for a Milne universe)

- Constant fit is excellent
- See arXiv:1911.12076 for the data, and [arXiv:1910.14024](), « Testing the R_h=*ct* Universe Jointly with the Redshift-dependent Expansion rate and Angular-diameter and Luminosity Distances » for an analysis
- For more recent data (but unchanged result), see arXiv:2201.07241
- Note: average (= H_0) is ≈ 63 km/s/Mpc, significantly lower than the H_0 value derived from Planck



What about antimatter antigravity then ?...

Matter-antimatter cosmologies

- It is well-known that symmetric matter-antimatter cosmologies are excluded by the non-observation of the diffuse gamma-ray flux at the borders of matter and antimatter domains, unless domains are >≈ few Gpc in size
- Two studies reached the same conclusion:
  - R. Omnès et al. (including J-L. Puget…) in the late 1960's-early 1970's, notably Phys. Rep. 3 (1972) 1, and references therein.
  - A. de Rujula, A. Cohen, S. Glashow, Ap. J. *495* (1998) 539.
- But what happens if there is gravitational repulsion between matter and antimatter?

The Dirac-Milne universe

- Dirac-Milne : a universe with equal quantities of positive (matter) and « negative » (antiparticle) mass particles
- By negative mass, we mean the Dirac « particle-hole » system, analog to electron-hole system in semiconductors, avoiding annihilation between matter and antimatter (see simulations below) by creation of a depletion zone
- Dirac-Milne universe is an instance of “ coasting ” universe :
  - $H(t) \propto 1/t$
- As we have seen, age, luminosity distance (supernovae), and even nucleosynthesis are remarkably concordant
- What about BAO, CMB and the evidence for Dark Matter, ?

Other coasting or matter-antimatter universes

- R_h = ct universe (Melia et al.): behaves at low z as a Milne universe, but is nevertheless supposed to have a zero spatial curvature and $\Omega = 1$
- Lattice matter-antimatter universe, proposed by Massimo Villata
  - Villata invokes CPT symmetry to justify similar structures for matter and antimatter. Antimatter, although repulsing matter, does not repulse itself and can therefore create galaxies and clusters
- References:

  - F. Melia, and A. Shevchuk, MNRAS 419 (2012) 2579
  - M. Villata, CPT symmetry and antimatter gravity in general relativity. *EPL 94 (2011)* 20001.
  - M. Villata, M., On the nature of dark energy: the lattice Universe. *Astrophysics and Space Science*, *345 (2013)* 1.
  - M. Villata (2015): The matter-antimatter interpretation of Kerr spacetime *Annalen der Physik*, *527* (2015) 507.

A short history of antigravity and negative mass

- Philip Morrison (1958) : gedanken experiment using the annihilation photons of an e+ e– pair to demonstrate (small) violation of the energy conservation
- Myron Good (1961) : antigravity would induce anomalous regeneration (i.e. CP violation) in the neutral kaon system (paper published 3 years before the discovery of CP violation)
- B. Carter (1968) : Kerr and Kerr-Newman solutions look very similar to particles, but allow time travel and CTCs (Carter calls them « vicious »)
- Kerr-Newman solutions look very much like **particle-antiparticle pair**s by their T and CP symmetries (Chardin (1997), Arcos and Pereira (2004), Burinskii (2008), see also Villata (2013)
- Chardin and Rax (1992) : criticism of the Good argument (used to explain observed CP violation!), and estimating vacuum instability (same temperature as Hawking radiation, so extremely slow)
- See also:
  - M.M. Nieto and T. Goldman, Phys. Rep. 205 (1991) 221.
  - E. Adelberger et al., Snowmass 2021 Spacetime Symmetries and Gravitational Physics, arXiv:2203.09691

Dirac-Milne scenario

G. Manfredi et al., PRD 98 (2018) 023514 ; and PRD 102 (2020) 103518

- Which combination of inertial, passive and active gravitational mass describes the Dirac particle-hole system ?

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

- Where we require:
- Antimatter to spread uniformly
- Matter to coalesce in structures

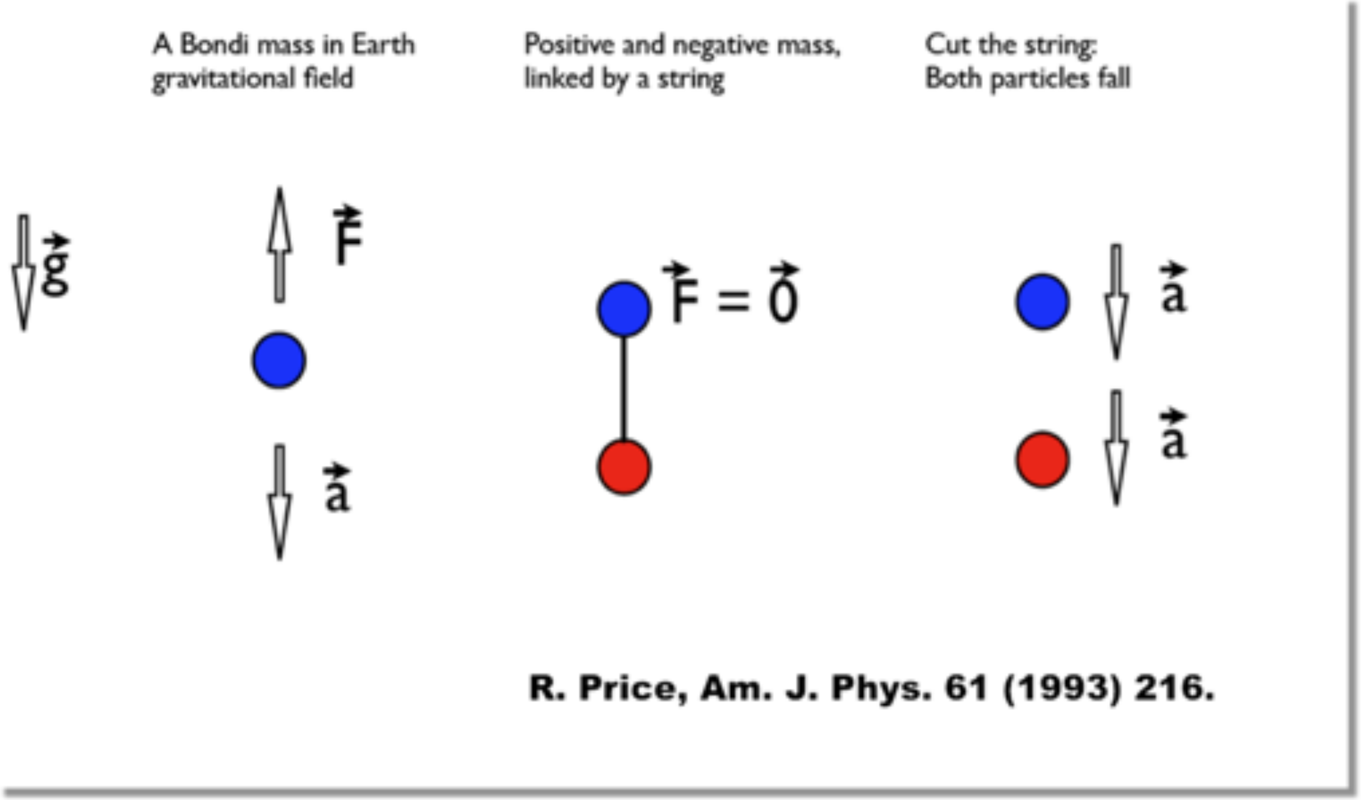
- None of them (!), this cannot be realized with a single Poisson's equation

$$\Delta\phi_+ = 4\pi G m(+n_+ - n_-),$$
$$\Delta\phi_- = 4\pi G m(-n_+ - n_-)$$

Bimetric formalism required to describe Dirac particle-hole system…

- Electrons and « holes » in a semiconductor (silicium, germanium): electrons gravitates, holes « antigravitates »
- A single electron in superfluid helium : vacuum bubble created around the electron, negative mass compared to the helium « vacuum »
- Motion of this « electron bubble » : acceleration exactly equal to +2*g* *(and not +g as you might have expected), see Landau and Lifshitz, Fluid Mechanics (1959)*
- « Voids » in large-scale structures can be considered (and have been considered) as negative mass objects (Dubinski et al. 1993, Piran 1997).
- This definition of a negative mass particle keeps the spirit of Einstein's equations (although violating the usual expression of the Equivalence Principle)

Counter-intuitive behavior of a bound system made of a negative and a positive (Bondi) mass (Price 1993) ?



A symmetric bound system +m –m *levitates and gets polarized* (b), violating the usual expression (100% !) of the Equivalence Principle…

Gravitational polarization also used by other authors

- Dipolar Dark Matter explains MOND:
  - L. Blanchet, Classical Quantum Gravity, 24 (2007) 3529
  - L. Blanchet, & Le Tiec, A., Phys. Rev. D, 80 (2009) 023524

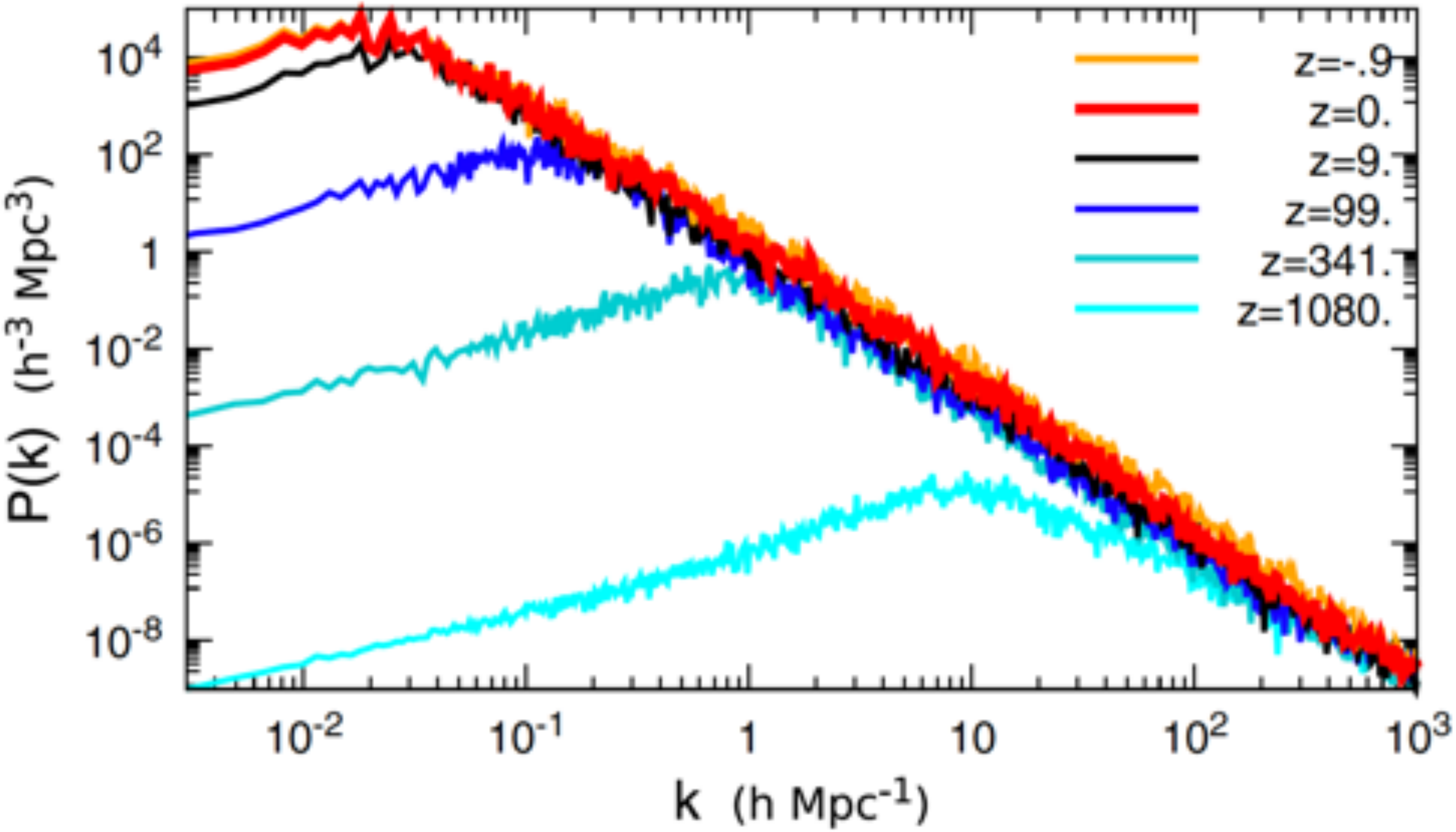
- Gravitational polarisation of vacuum mimics DM and DE
  - D.S. Hajdukovic, Astrophys. Space Sci., 334 (2011) 215
  - D.S. Hajdukovic, Phys. Dark Univ., 3 (2014) 34
  - D.S. Hajdukovic, MNRAS, 491 (2020) 4816

Structure formation in the Dirac-Milne universe:
a very short primer

- Density contrast $\delta\rho/\rho$ is O(1) right from the beginning, so structure formation starts immediately after transparency transition at z ≈ 1080, in the non-linear regime
- Very first clouds of matter to collapse are very « cold » and may produce very massive black holes. They will perturb a lot the surrounding clouds with their feedback
- Matter and antimatter « clouds » have physical dimensions of ≈200 pc at z ≈ 1080 (≈200 ckpc, and mass ≈ 10^9 solar masses)
- Their size grows in a bottom-up way by factor ≈500 to 1000 (in linear comoving dimensions), reaching a dimension today of ≈ 100 Mpc, the « BAO » scale, and a mass of a few 10^{17} solar masses, « Laniakea scale »)
  - G. Manfredi et al., PRD 98 (2018) 023514
  - G. Manfredi et al., PRD 102 (2020) 103518

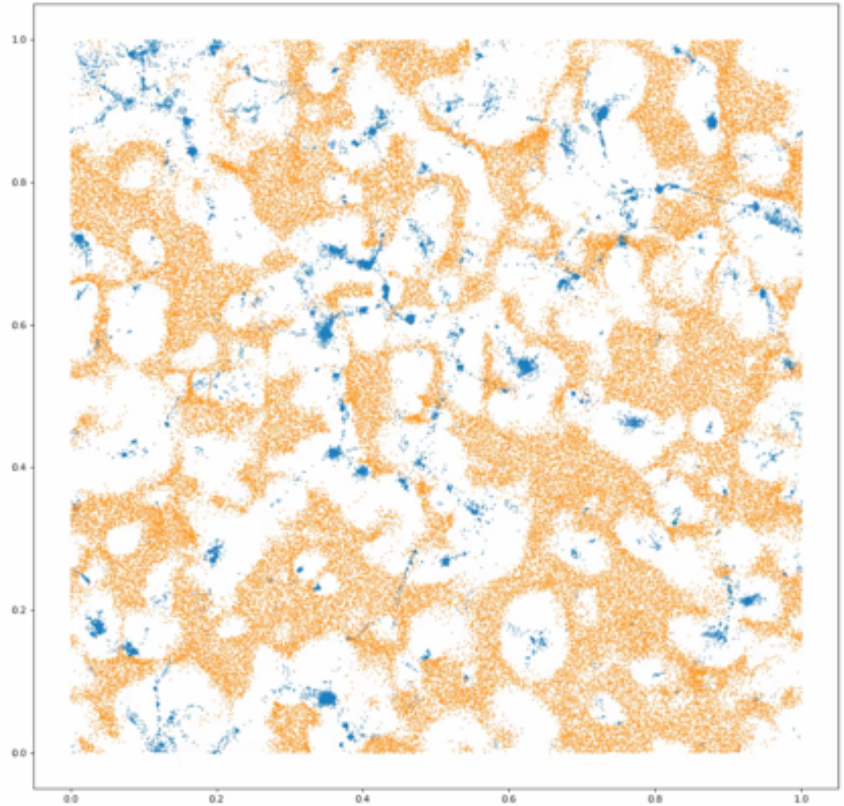
Structure formation starting at very high z in a non-linear regime

Evolution of power spectrum peak for Dirac-Milne ($k = 2\pi/ \lambda$)
G. Manfredi et al., PRD 102 (2020) 103518



Tomography of structures in the Dirac-Milne universe

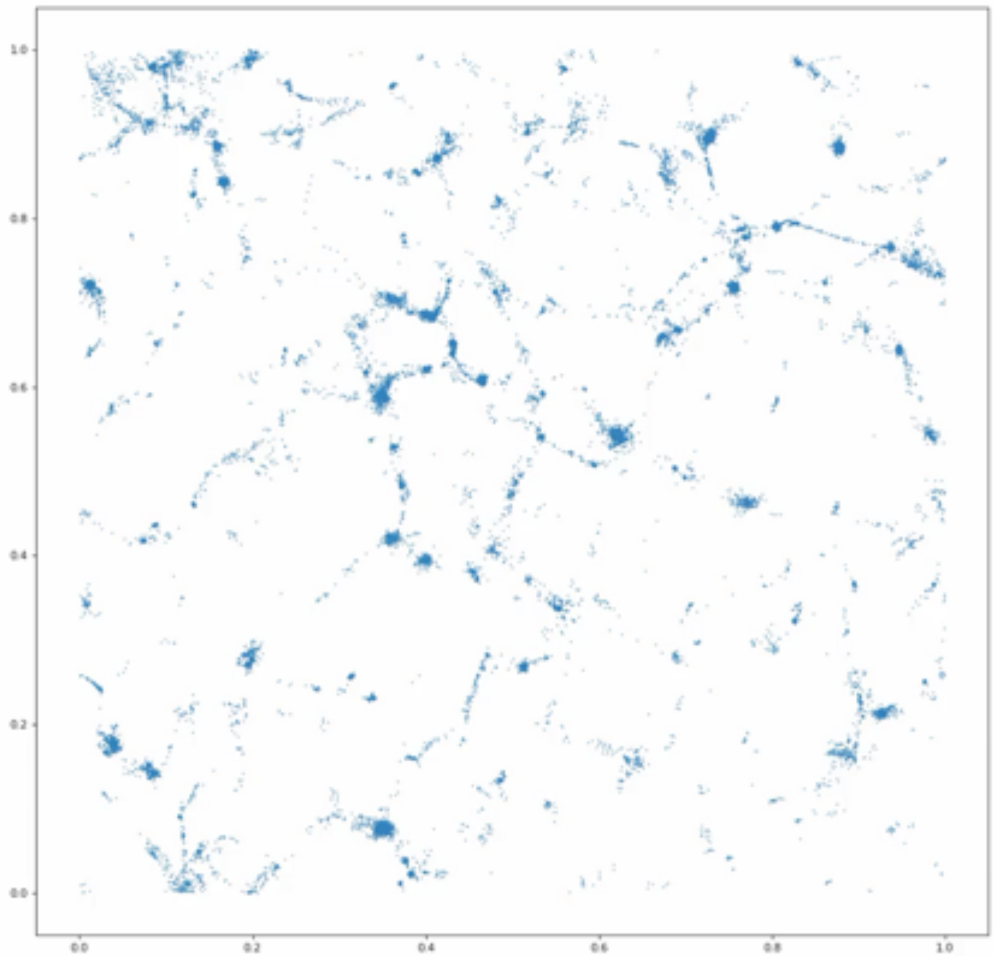
- Matter (condensed) structures (in blue)
- Two new fundamental elements:
  - Antimatter, of " negative mass " is spread out in **cold and homogeneous clouds** (≈50% of the volume, in orange)
  - **Depletion zones around matter structures** (also ≈50% of the total volume): **these « bubbles » will mimic Dark Matter**



Matter

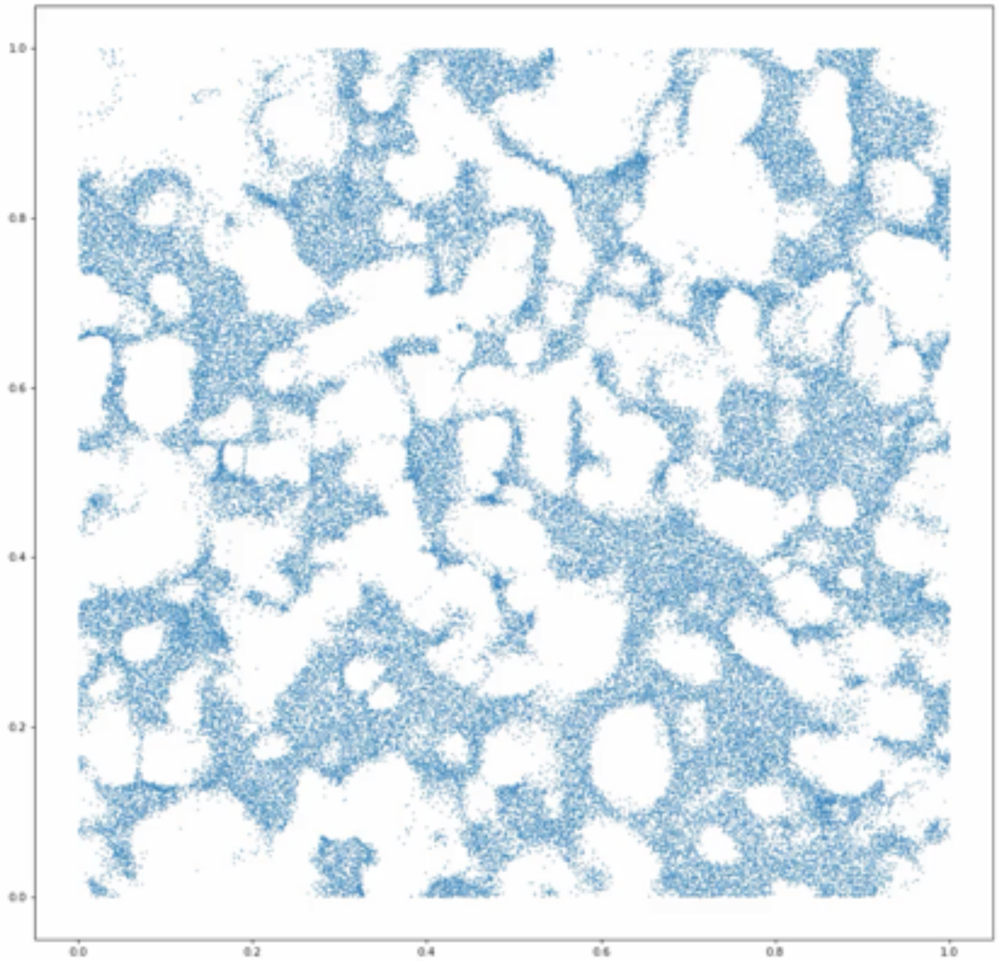
Immediately in the non-linear regime

Matter structure looks similar to ΛCDM structures (nodes, filaments, planes and voids)



Antimatter

Antimatter is spread out with approx. constant density over half of the volume, and repulsed by matter and by itself…

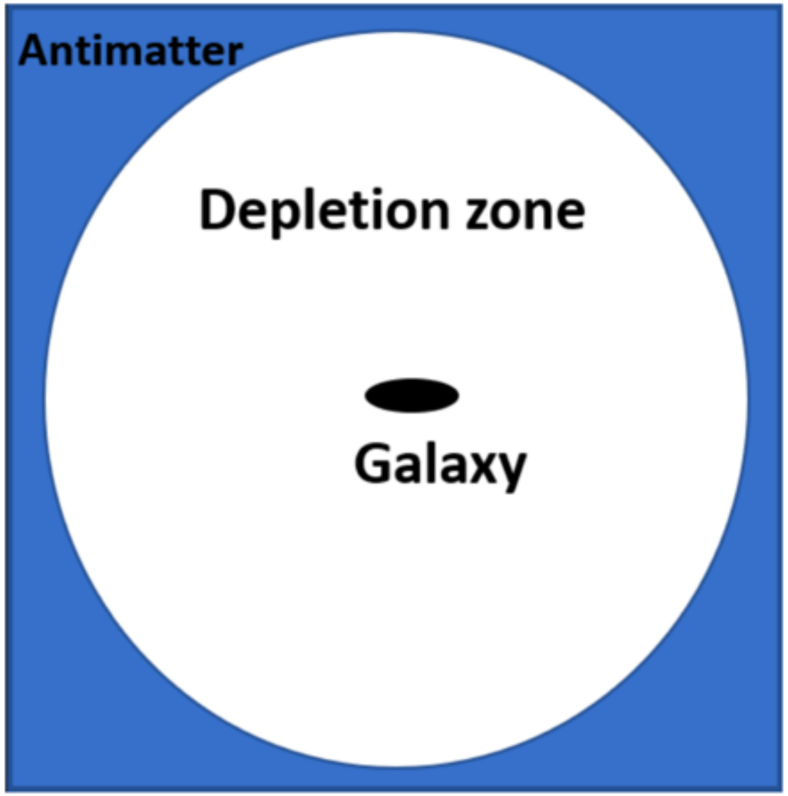


This will mimic MOND (or Dark Matter) and lead to flat rotation curves

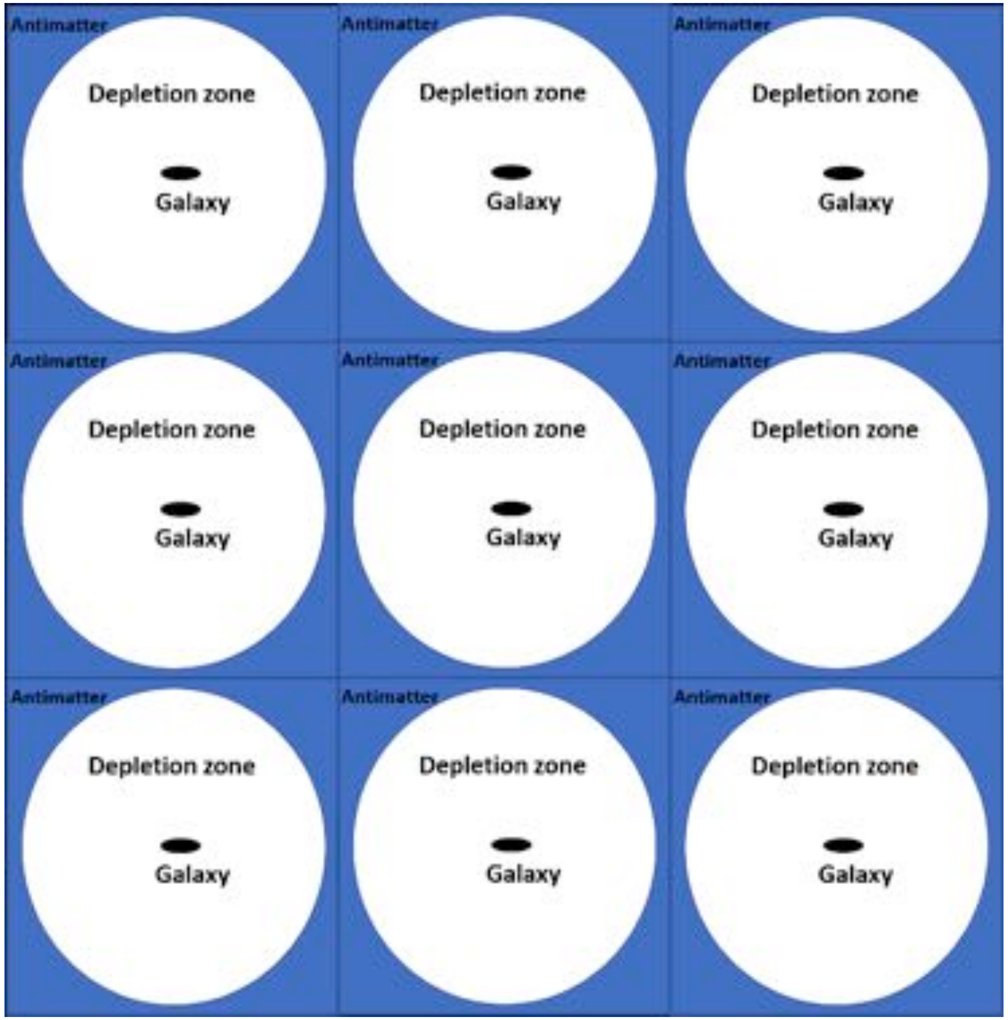
GC et al., A&A 652 (2021) A91

Idealized geometry:

- Point-like galaxy or cluster
- Depletion (empty) zone
- Uniform and cold antimatter cloud on the outskirts

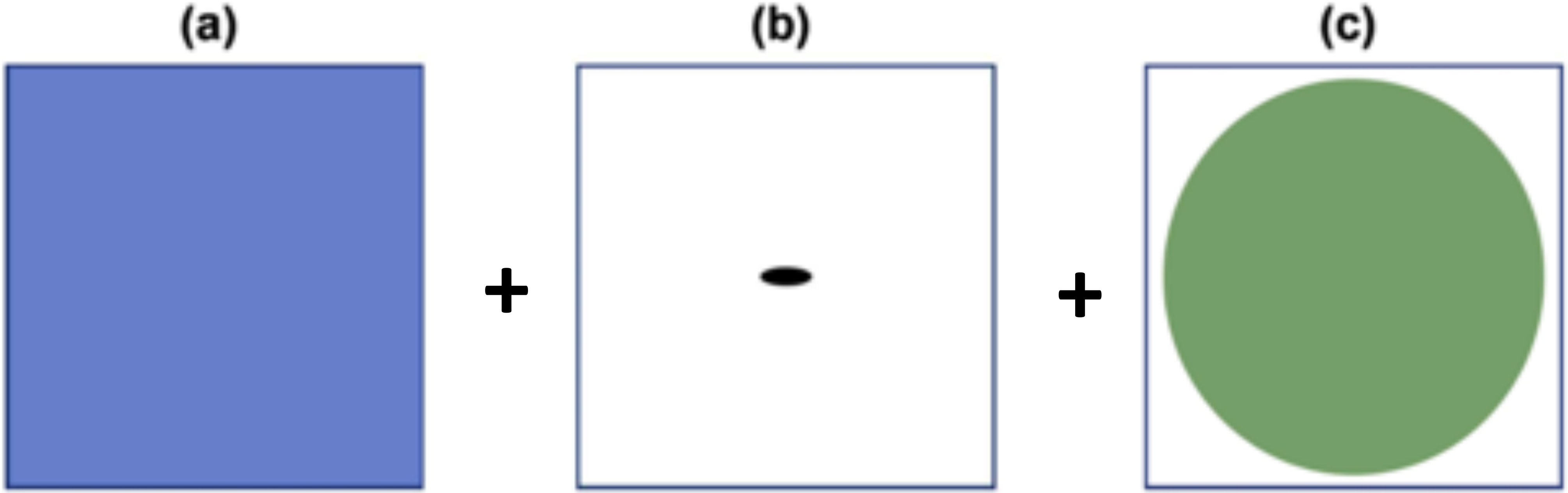


Beware : what we have in reality and in the simulation is really this periodic configuration



This configuration leads to **flat rotation curves without any free parameter (A&A 652 (2021) A91)**

It is equivalent to :

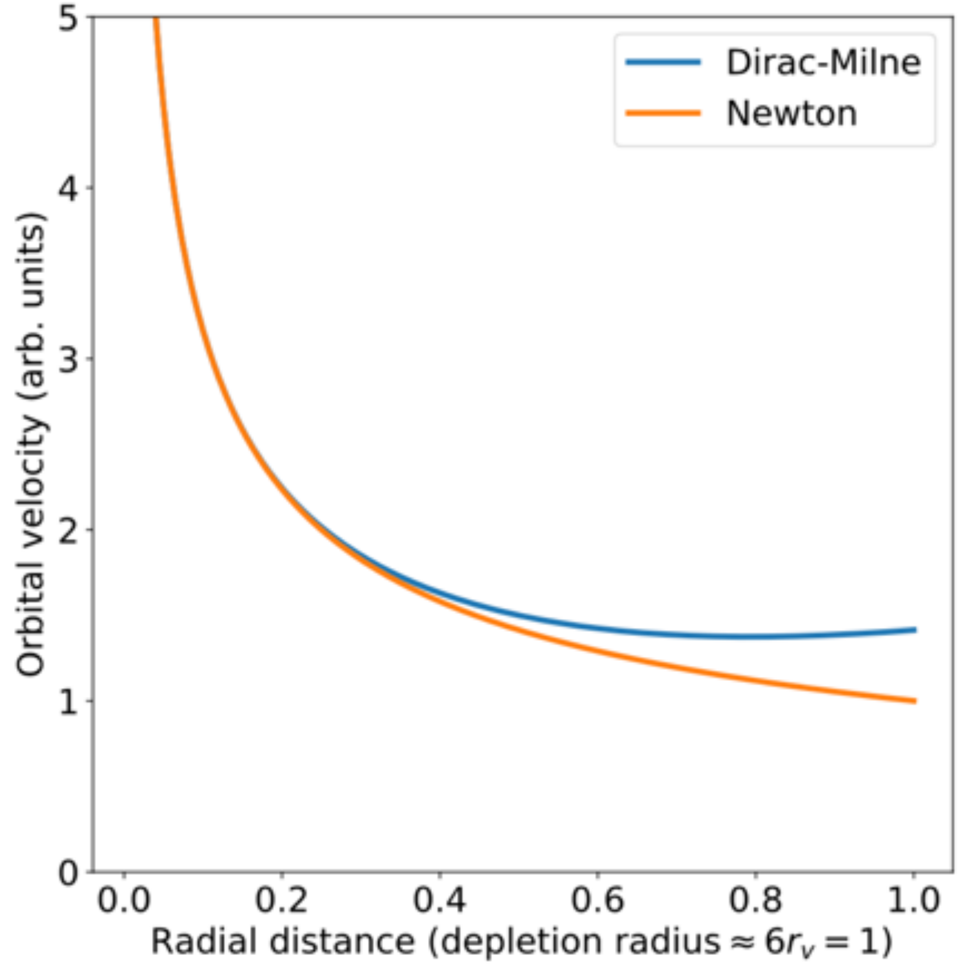


Rotation velocity created by this configuration

$$\vec{g}_+ = -\frac{Gm\vec{r}}{r^3} - \frac{Gm\vec{r}}{r_d^3}$$

$$\frac{v^2}{r} = \frac{Gm}{r^2} + \frac{Gmr}{r_d^3}$$

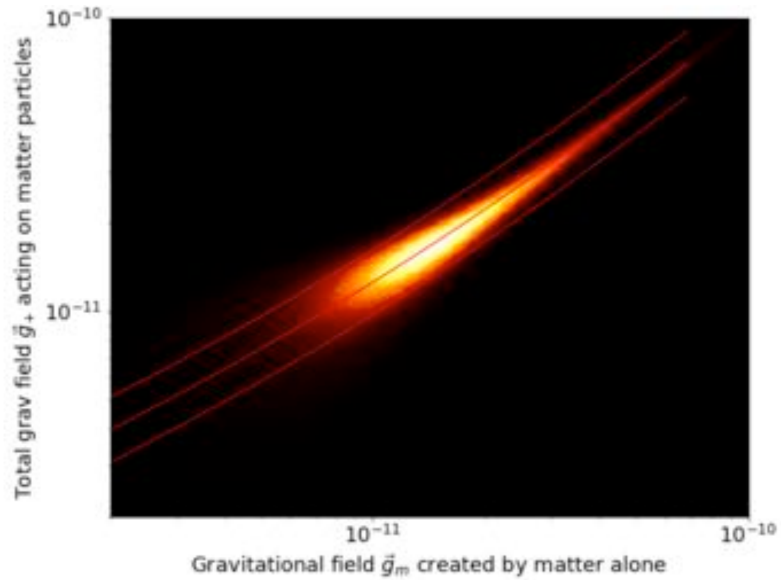
$$v(r) = \sqrt{\frac{Gm}{r} + \frac{Gmr^2}{r_d^3}}$$

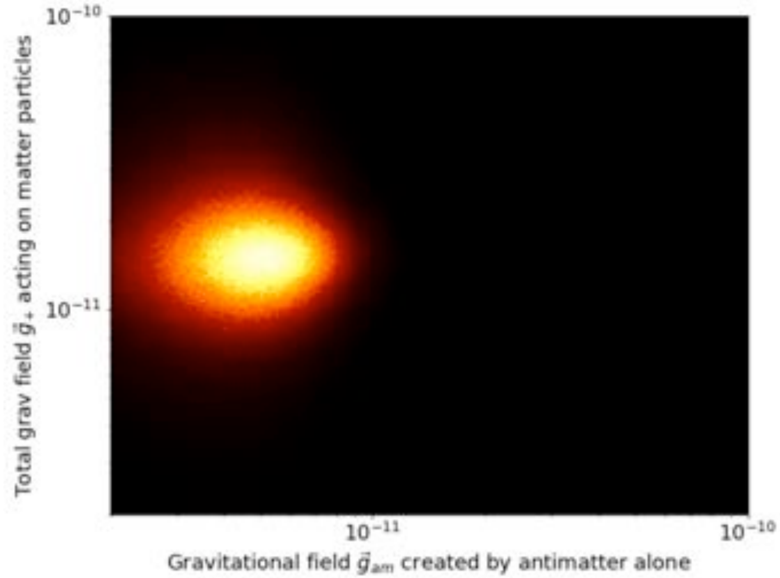


MOND and Dirac-Milne

GC et al., A&A 652 (2021) A91.

- Remarkably close to MOND for large collection of galaxies and clusters (≈ 10^3 range of mass)
- Empty depletion zone acts as almost uniform bubble of non interacting Dark Matter
- Extra confining field, of ≈ few 10^{-11} m/s^2 is antimatter field
- This mimics (quite remarkably) a MOND behavior (see upper figure with the MOND fit and error bars from Lelli et al. (2019) (red lines)





Compare this behavior to MOND
(McGaugh et al., External Field Effects, arXiv2009.11525)

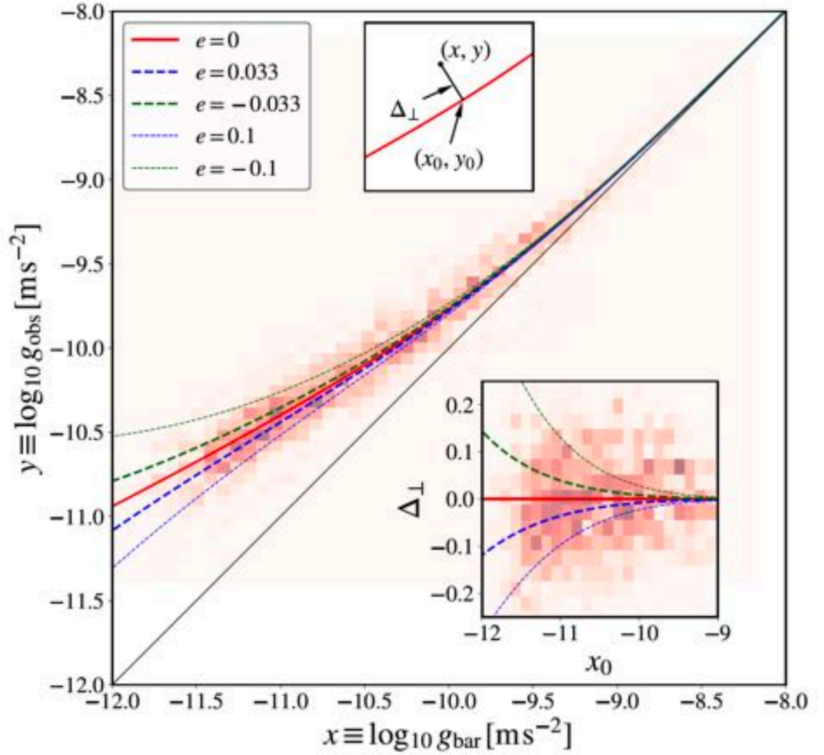
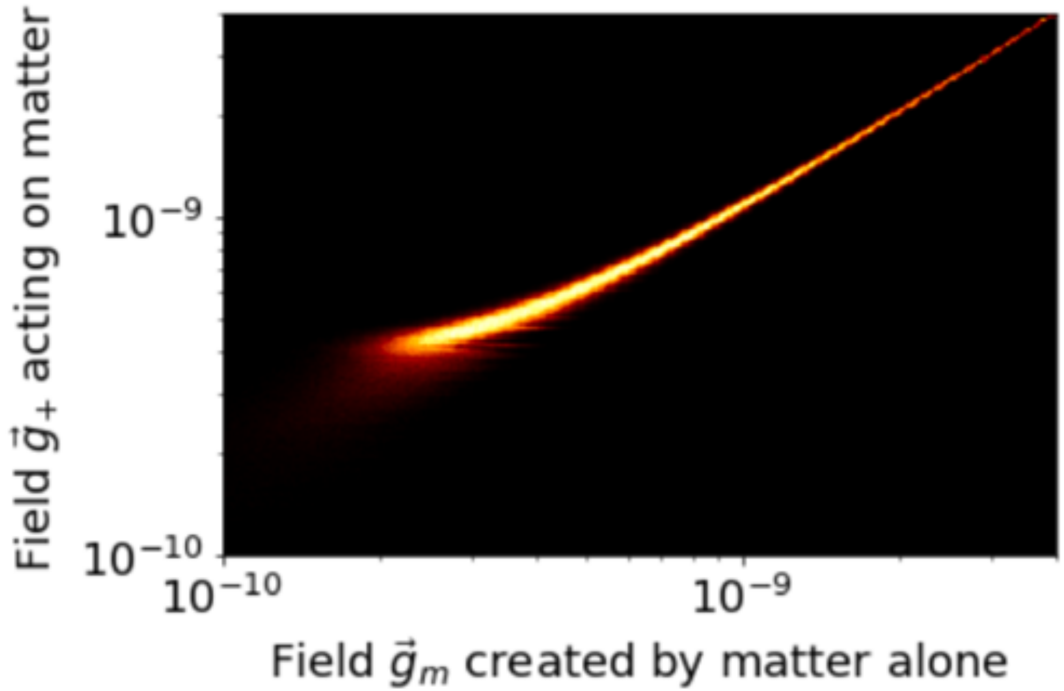


Figure 1. The external field effect in the weak-field limit of the radial acceleration relation.



Addition of antimatter field creates MOND-like behavior

CMB in the standard model ΛCDM

- Observed temperature fluctuation spectrum is the sum of:
  - Doppler effect between observer and source
  - Temperature fluctuations on last scattering surface, at z = 1080
  - Gravitational potential variations at last scattering surface, z = 1080
  - Integral of gravitational potential variations along the line of sight (Integrated Sachs-Wolfe effect)
  - Similar effect but in the non-linear regime (Rees-Sciama effect), usually at very small angles

$$1 + z = \underbrace{\frac{a_{\text{obs}}}{a_{\text{src}}}}_{\text{background}} \left(1 + \underbrace{\mathbf{n} \cdot \mathbf{v}_{\text{obs}} - \mathbf{n} \cdot \mathbf{v}_{\text{src}}}_{\text{Doppler}} + \underbrace{\psi_{\text{obs}} - \psi_{\text{src}}}_{\text{time dilation}} \underbrace{- 2 \int_{\text{src}}^{\text{obs}} \frac{\partial \psi}{\partial \tau} d\chi}_{\text{ISW effect}} \right),$$

Integrated Sachs-Wolfe: profiting of the expansion of the universe

ISW, evidence for Dark Energy ?

- Integrated Sachs-Wolfe effect (ISW, due to the variations of the potential along the trajectory of a CMB photon) is usually considered as a small secondary effect (zero to first order in an Einstein-de-Sitter universe), and **a demonstration of the existence of Dark Energy**
  - R.G. Crittenden and N. Turok, " Looking for a Cosmological Constant with the Rees-Sciama Effect ", PRL 76 (1996) 575.
- However, Kamionkovsky noted that this effect could be **even larger in an open universe**
  - M. Kamionkowski , " Matter-microwave correlations in an open universe ", Phys. Rev. D 54 (1996) 4169.
- ISW is by far the dominant effet in the Dirac-Milne universe (flat **spacetime**, and not flat **space** => $\Omega_k = 1$)

Swiss cheese model (Szekeres solution)

- W. Valkenburg

" Swiss cheese and a cheesy CMB ", JCAP 6, (2009) 10.

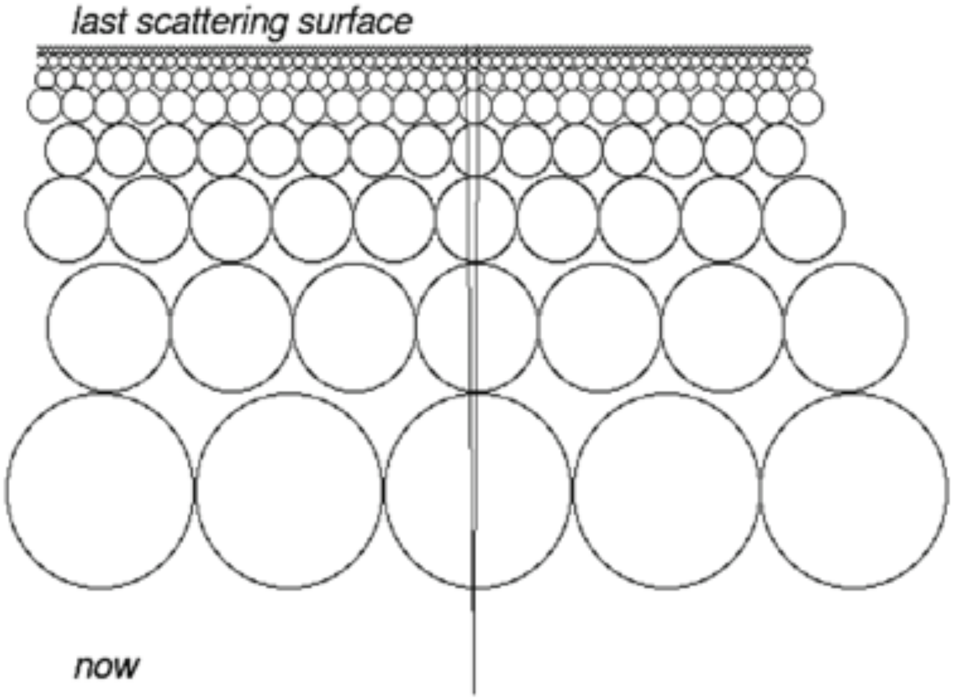


Fig. 5 The schematic representation of the Swiss Cheese model. When two photons are propagating along a similar path the final temperature fluctuations are similar. If paths are different, then the final temperature fluctuations are also different and hence not correlated

Swiss cheese model (Szekeres solution)

- W. Valkenburg

 " Swiss cheese and a cheesy CMB ", JCAP 6, 10-19 (2009)

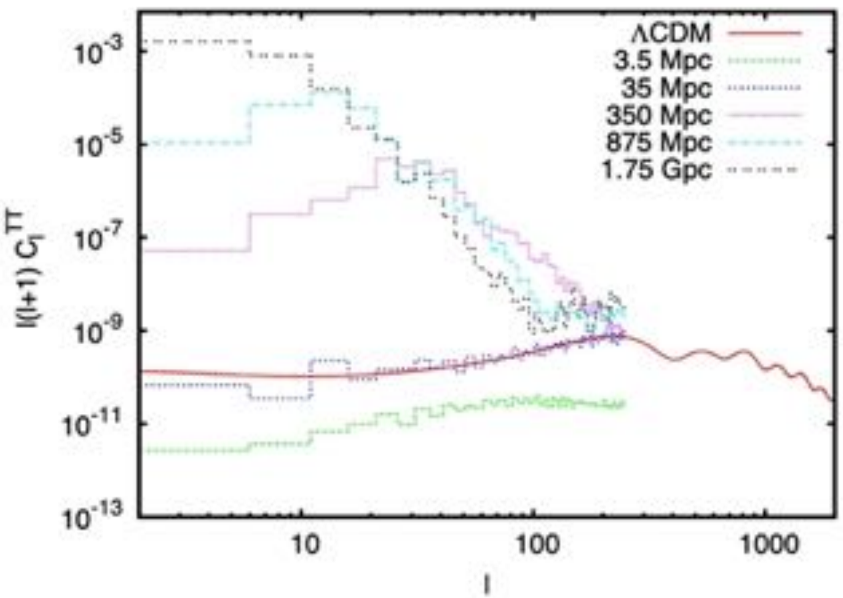
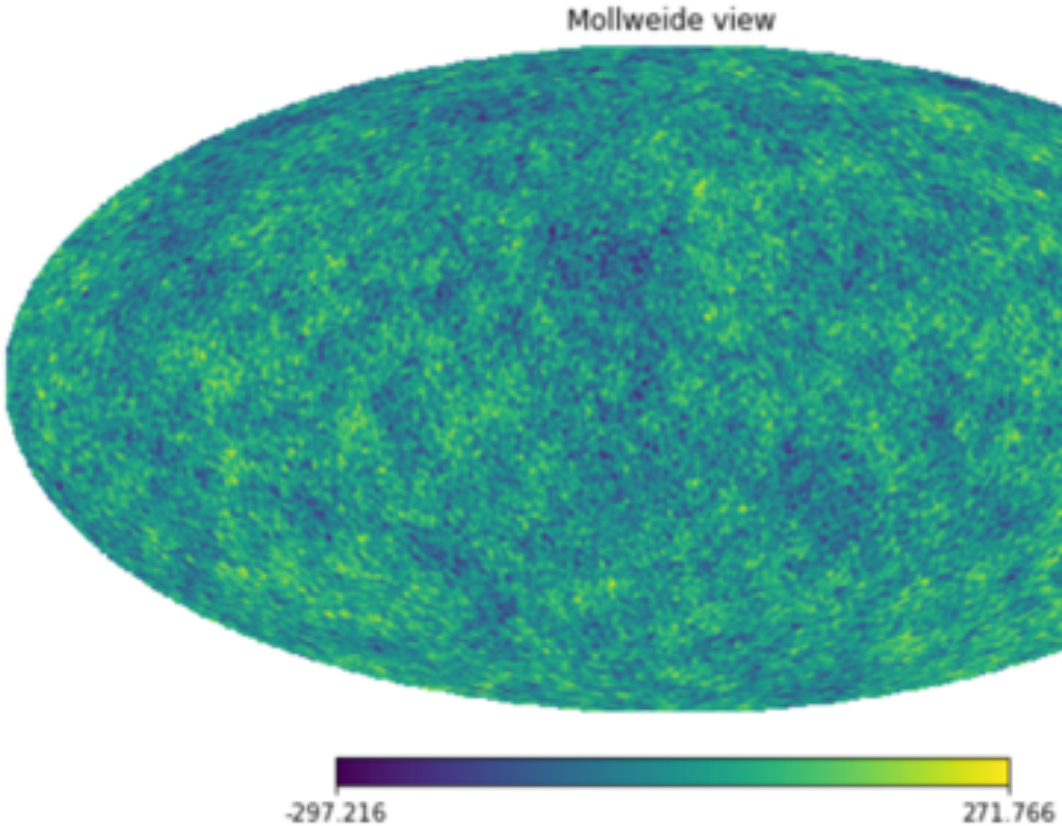


Figure 4. The C_l^{TT} of secondary anisotropies for different Swiss-Cheese cosmologies, in bins of 5 multipoles. For comparison we plot the full C_l^{TT}-spectrum in a standard ΛCDM cosmology with $\Omega_{baryon} = 0.045$, $\Omega_{cdm} = 0.245$, $\Omega_k = 0$, $\Omega_{DE} = 0.71$, $h = 0.7$ (red solid line, unbinned). A Swiss-Cheese universe with holes of radius smaller than 35 Mpc, potentially leaves the CMB unaltered with respect to the standard cosmological model. Note the numerical limitations beyond the ankle at high $l \sim 100$, as discussed in the text.

Example of an ISW sky in Dirac-Milne
(integration between z=0 and z = 30, 256-cube RAMSES simulation)

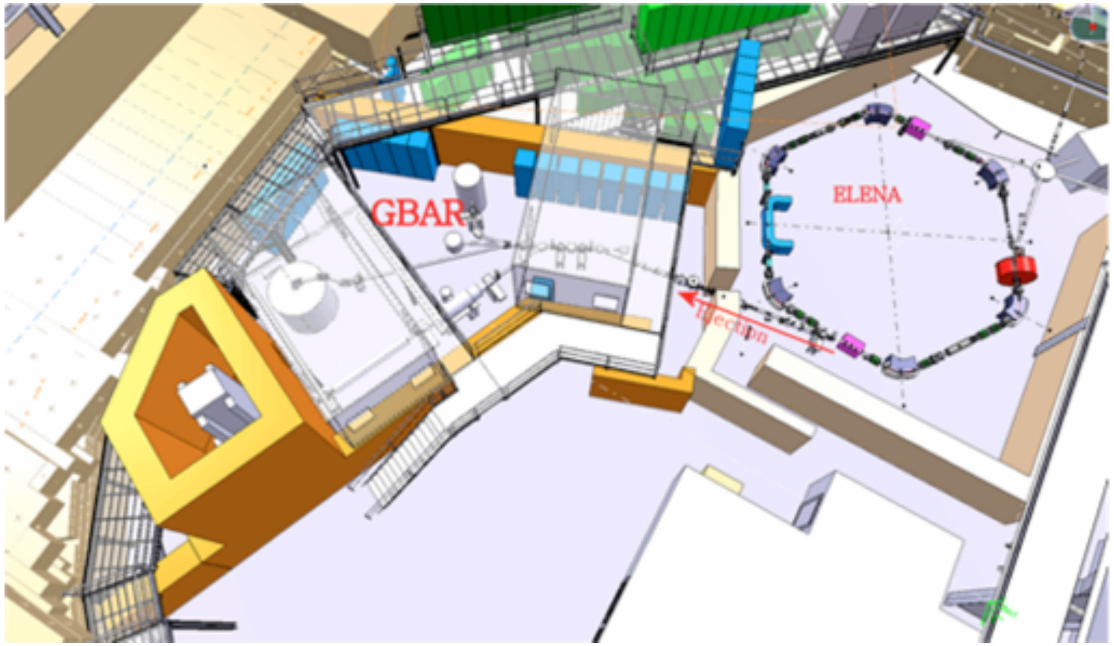
- Aim: reproduce the amplitude and position of the first three peaks with only the scale of the antimatter « waves » (which plays the role of the BAO scale in Dirac-Milne) as a free parameter



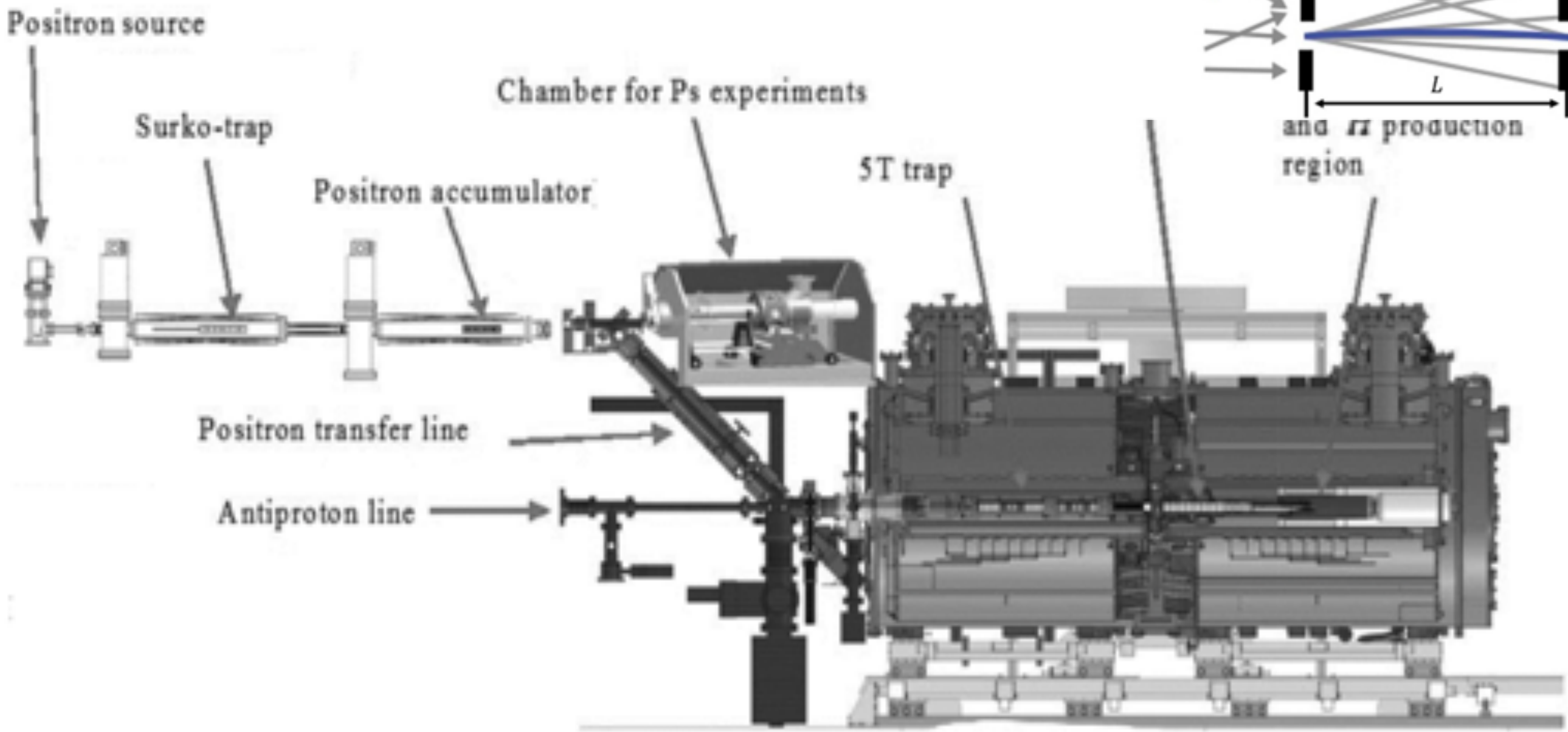
Direct measurements of the gravitational mass of antihydrogen…

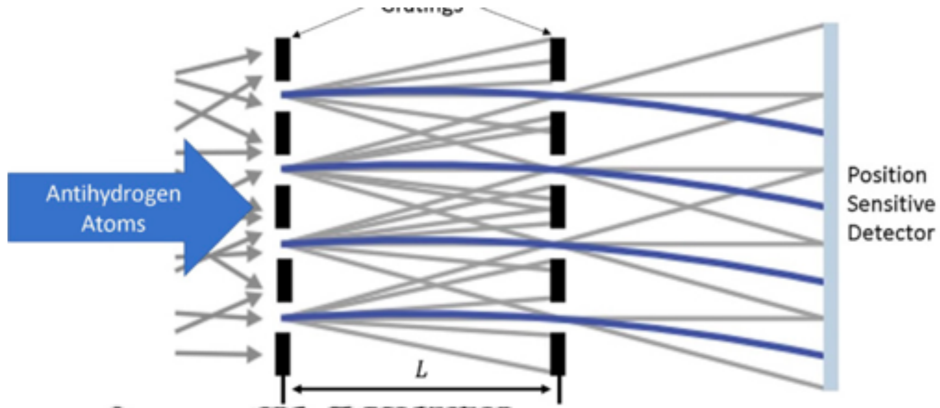
Direct measurement at CERN

- Three experiments at CERN : Gbar, AEgIS, ALPHA-g are aiming at the measurement of the gravitational field of the Earth on antihydrogen atoms



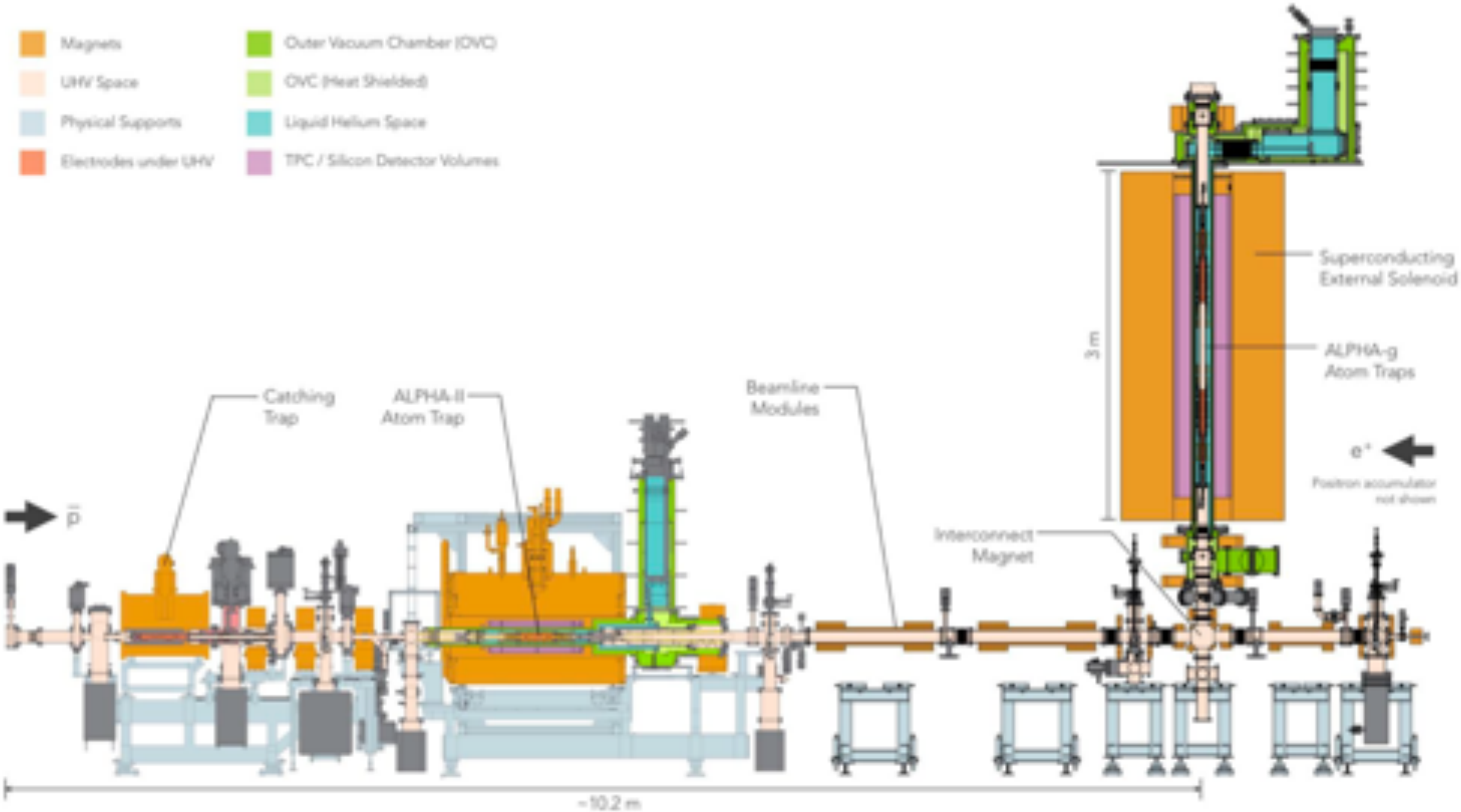
AEgIS





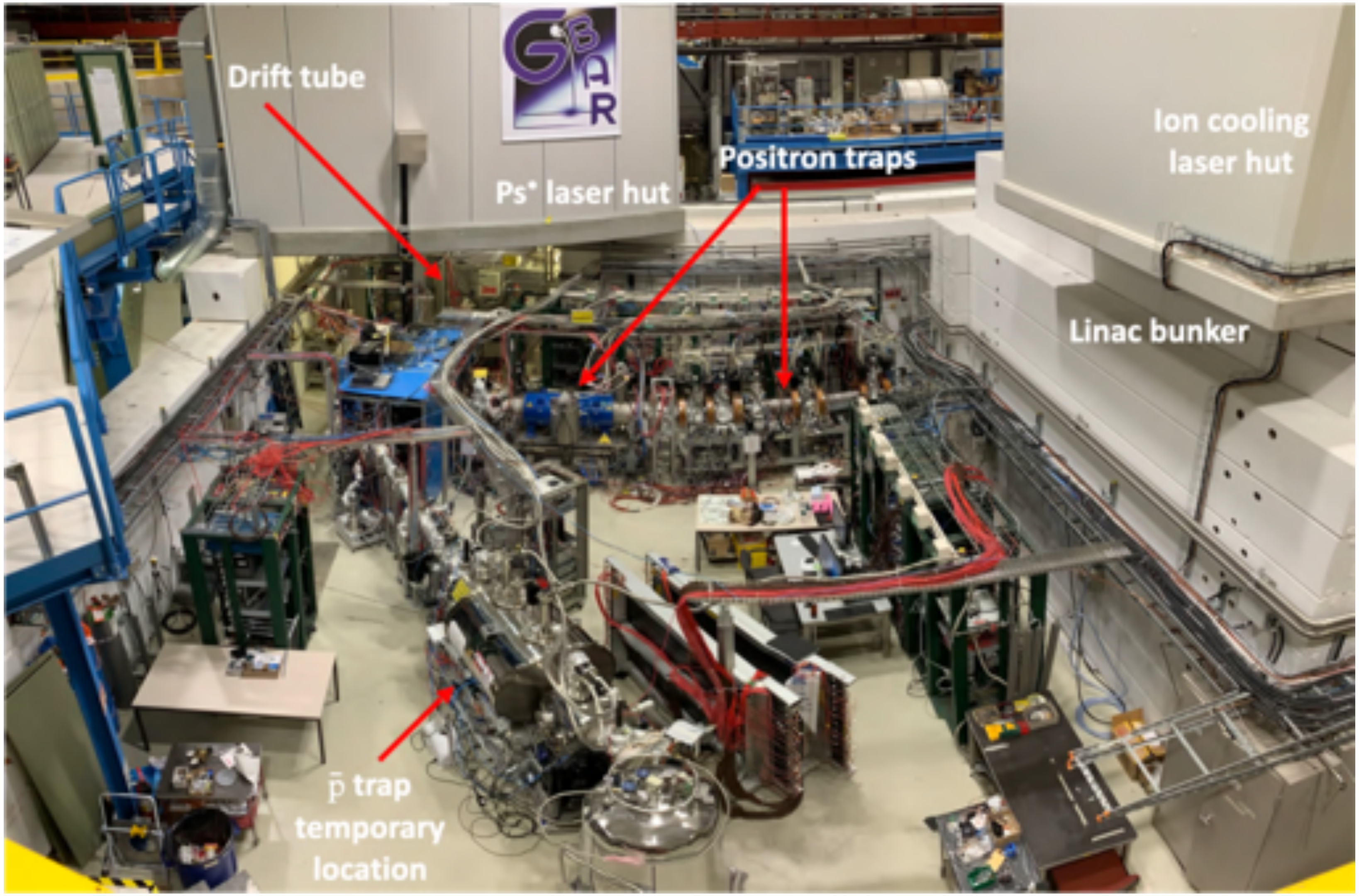
Proof of principle of the Moiré deflectometer with fast antiprotons:
Nature Commun **5,** 4538 (2014)

ALPHA-g



First measurement in 2013, a factor ≈65 from testing antigravity:
A.E. Charman, et al., Nature communications, 4 (2013) 1.
ALPHA-g (2022) : **expected improvement of precision by a factor ≈1000.**

Gbar



First gravitational measurement on antihydrogen atoms expected in 2024-2025

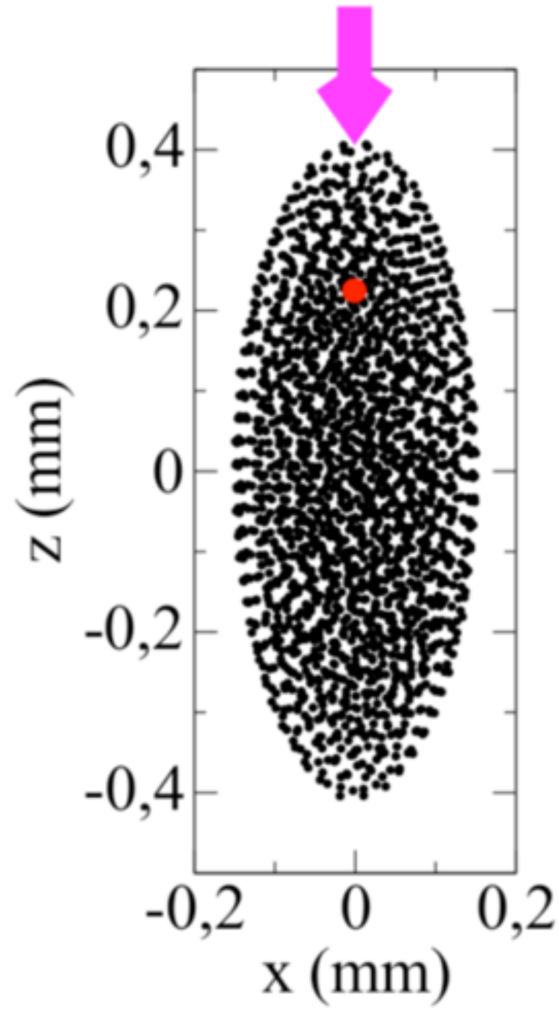
Gbar

- Use method proposed by J. Walz and T. Hänsch, GRG 36 (2004) 561.

- Intermediate cooling using antihydrogen ion : ultracold Be+ ions thermalize antihydrogen ions (1 antiproton, 2 positrons, same charge as Be ions)

- After cooling to tens of μK, horizontal laser kick, to strip ion of its extra positron

- First gravitational measurement on antihydrogen atoms expected in 2024-2025



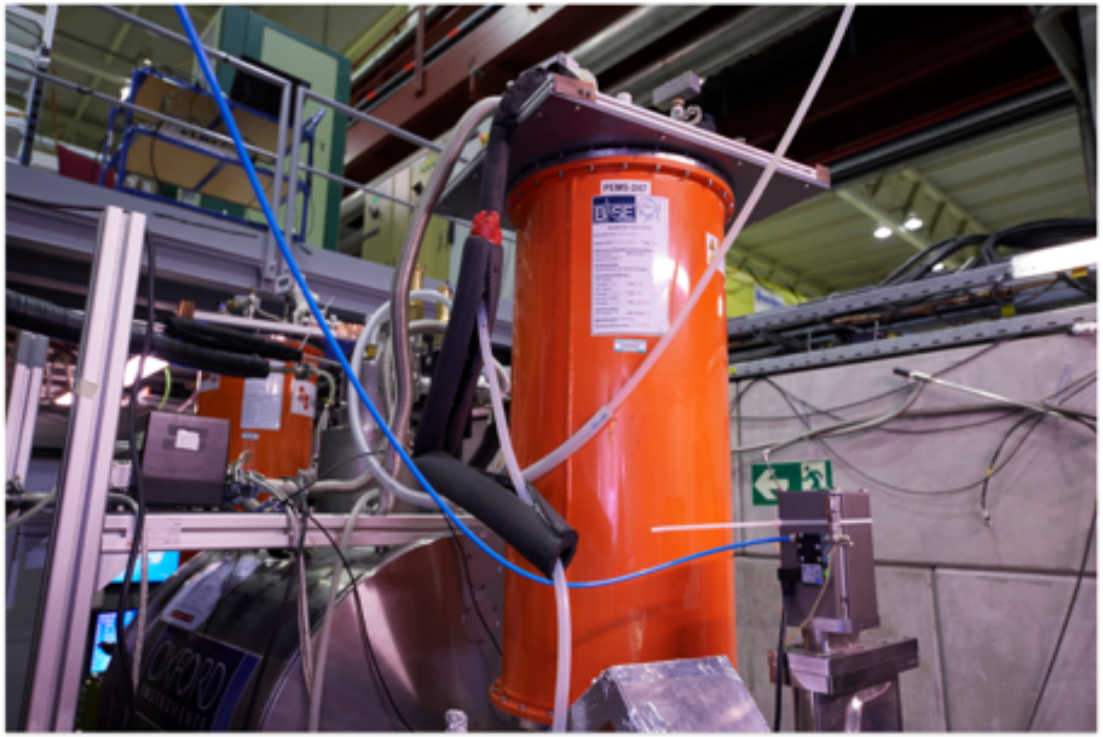
The BASE experiment

- Very nice and precise measurement of the **inertial** mass of the antiproton
- On the other hand, it is **not** possible to measure the tiny variation of the gravitational field of the Earth around the Sun with a bound system using a charged particle (here an ion in a trap)
- Similarly, **the universe expansion cannot be detected in galaxies, atoms or any bound system**
- See R.H. Price AJP 80, 376 (2012)
- and P. D. Noerdlinger and V. Petrosian, Ap. J. 168, 1–9 (1971).
- See also V. Bouchiat, GC, MH. Devoret, D. Estève, Hyper. Int. 109 (1997) 345.
- T.W. Darling, et al., RMP 64 (1992) 237.

BASE breaks new ground in matter–antimatter comparisons

The collaboration has made the most precise comparison yet between protons and antiprotons and tested whether or not they behave in the same way under the influence of gravity

5 JANUARY, 2022



View of the BASE experiment (Image: CERN)

In a paper published today in the journal *Nature*, the BASE collaboration at CERN reports the most precise comparison yet between protons and antiprotons, the antimatter counterparts of protons.

A note on CP violation

- If the Dirac-Milne scenario is correct, we should look again at the possibility that “ CP ” violation is in fact a manifestation of this antigravity
- Remarkably, the epsilon (ε) parameter of CP violation is of the same order as the ratio between the separation $g(\Delta\tau)^2$ induced by antigravity during the $K^0 K^0 bar$ oscillation time $\Delta\tau$ and the Compton wavelength of the kaon

- This is most probably an indication that “ CP-violation ” might be just another experimental test of antigravity.

- Note also that the only inclined kaon beam (Fermilab) has a measurement of the epsilon CP parameter deviating from 9 sigma from the world average

Conclusions

- The Standard Cosmological Model is based on the existence of several (yet ?) unobserved items: inflation, Dark Matter, Dark Energy, the last two representing ≈95% of the Universe in ΛCDM
- Antimatter, matter going backward in time (Feynman and Wheeler) is the « usual suspect » for a « negative mass » component, mimicking Dark Energy
- Coasting universes are already impressively concordant
- Age, nucleosynthesis, luminosity distance are extremely similar between the ΛCDM and a Milne Universe
- In addition, gravitational polarization mimicks a MOND behavior, or the presence of Dark Matter, keeping the spirit of General Relativity
- The MOND field is then simply the field created by antimatter (which varies in time and is therefore not a fundamental parameter)

Conclusions

• This hypothesis, which may appear provocative, would allow to explain several strange features of the ΛCDM Universe, without requiring Dark Matter nor Dark Energy (nor Inflation…)

• Experimental test at CERN expected in the near future (result published end 2022 ?) for the ALPHA-g experiment, and circa 2025 for Gbar and AEgIS

• Keep posted for more precise results about the CMB and BAO spectra in the Dirac-Milne universe, and for the first results of the ALPHA-g experiment, hopefully this year