Gravity and Antimatter

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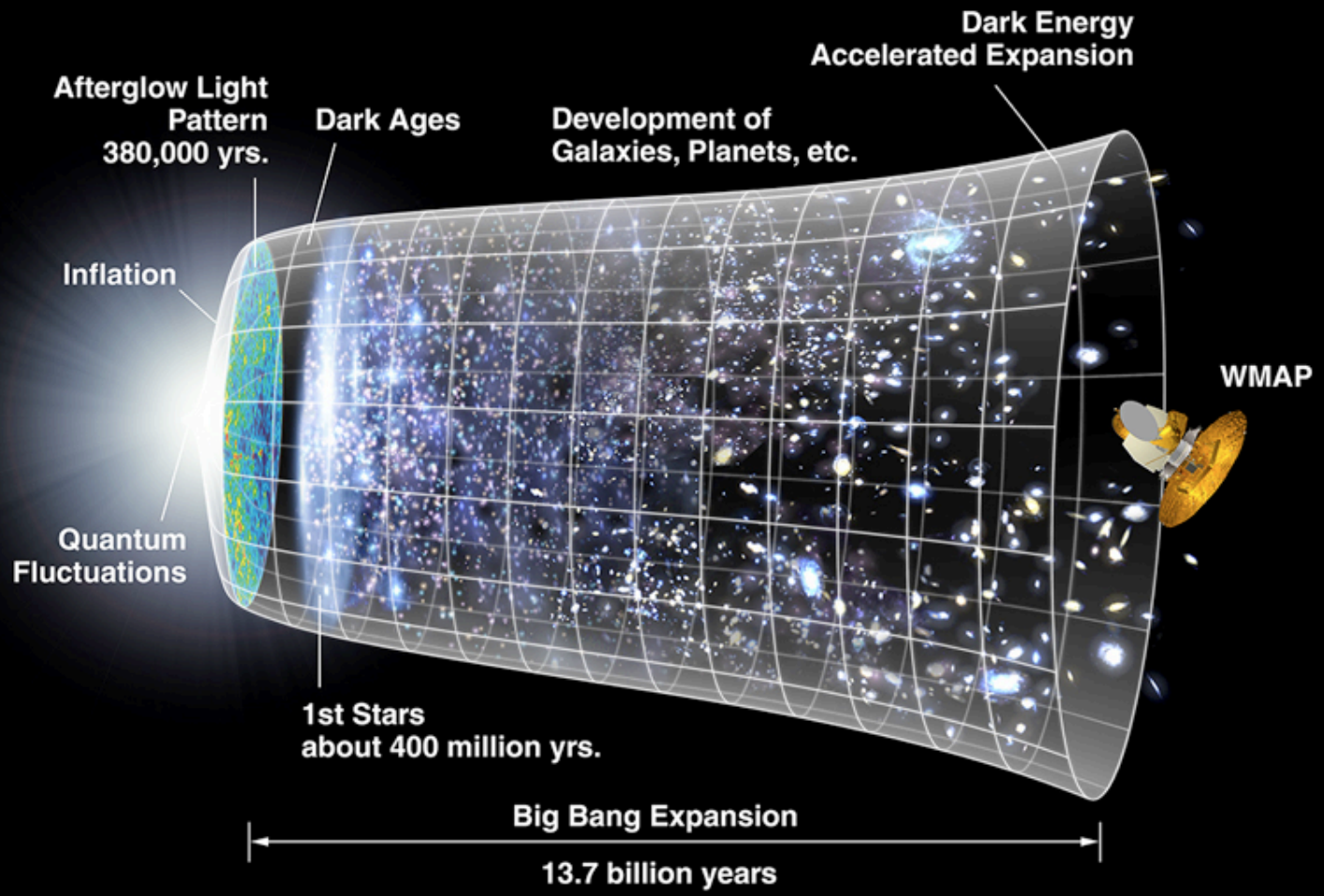
Why bother ?

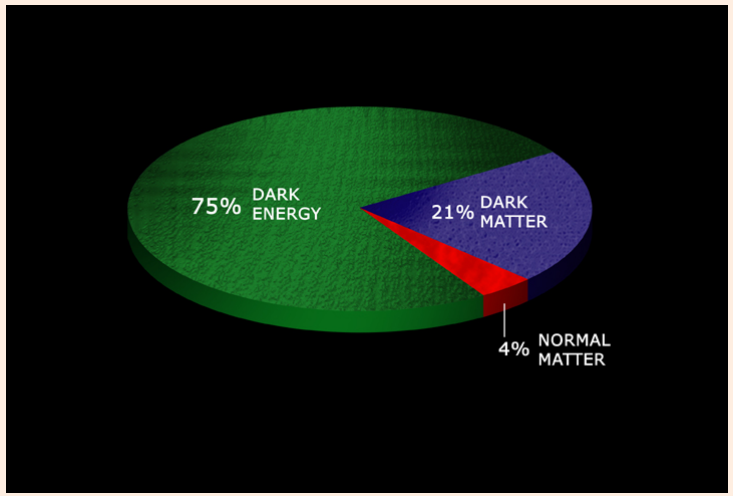
- Shouldn’t it be obvious that antiparticles follows the same trajectories as particles ?
- As we will see, this depends on the expression that we provide for the Equivalence Principle…
- A bit of history and cosmology first
- For a review on the arguments against antigravity, see in particular : M.M.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

A very strange standard cosmological model



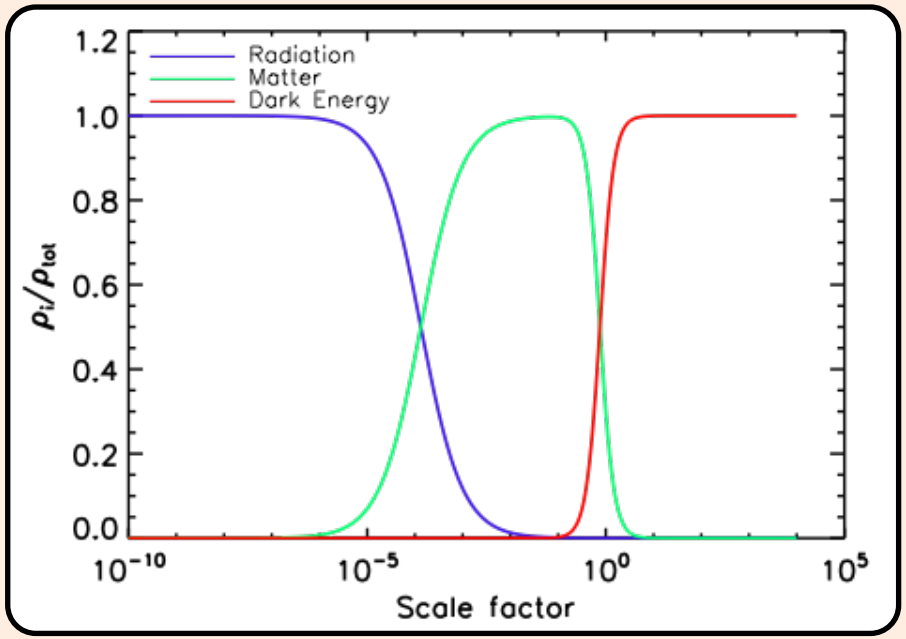
Good fit to the data, but several (≥ 6) free parameters. Alternative ?

- 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 ? 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

Negative mass in GTR (Bondi)

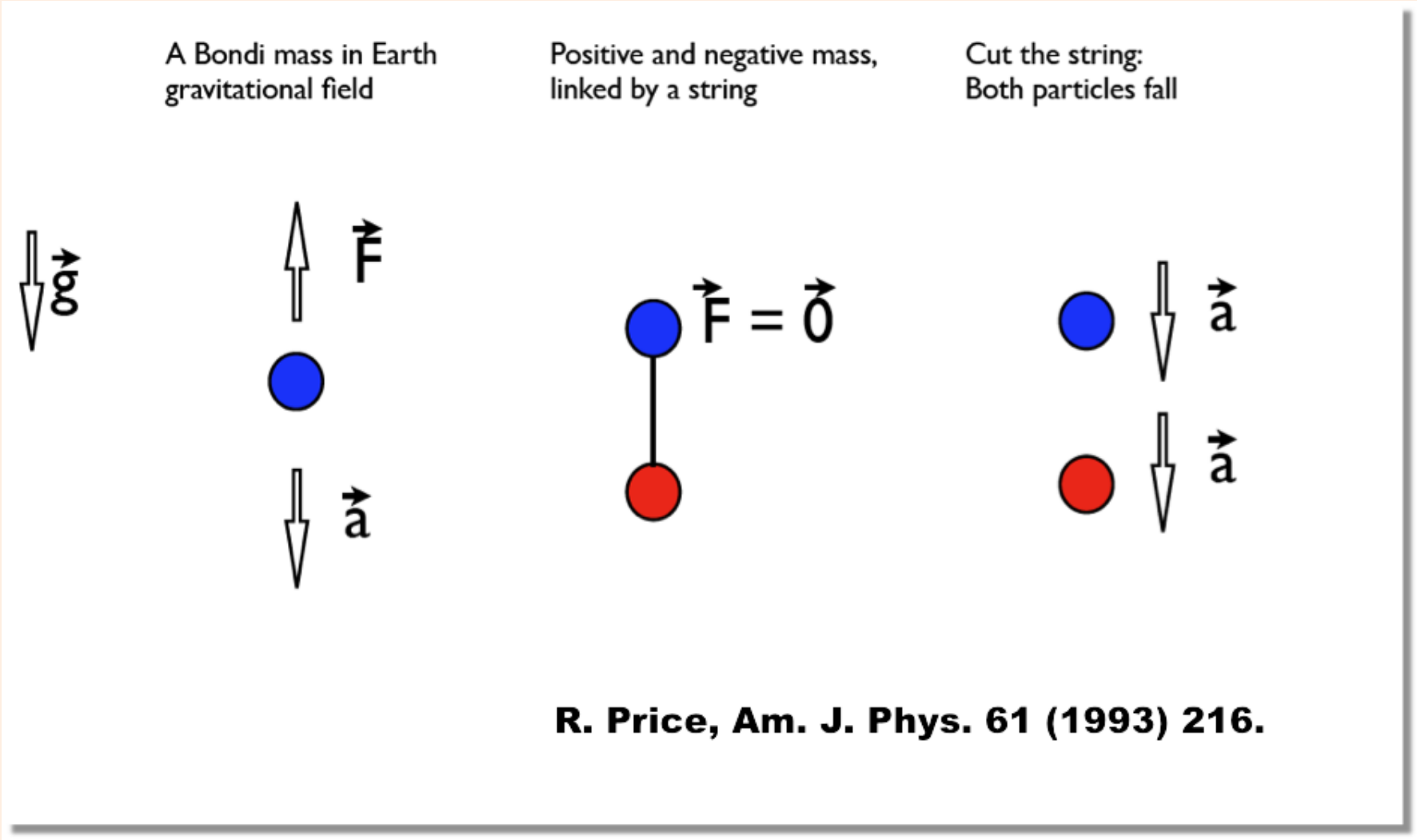
Two positive masses attract each other

Two negative masses repulse each other

One positive mass and one negative mass : runaway

Positive mass particle
Negative mass particle

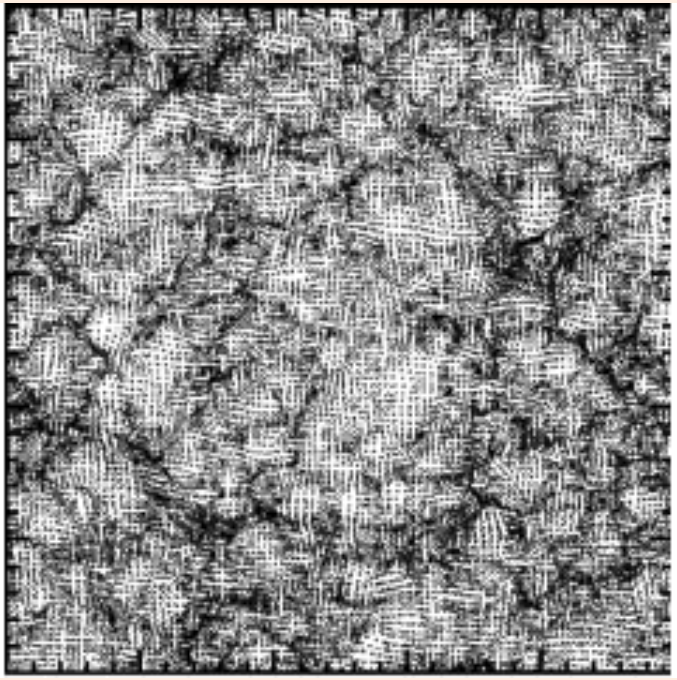
Levitation and polarization predicted by GTR !



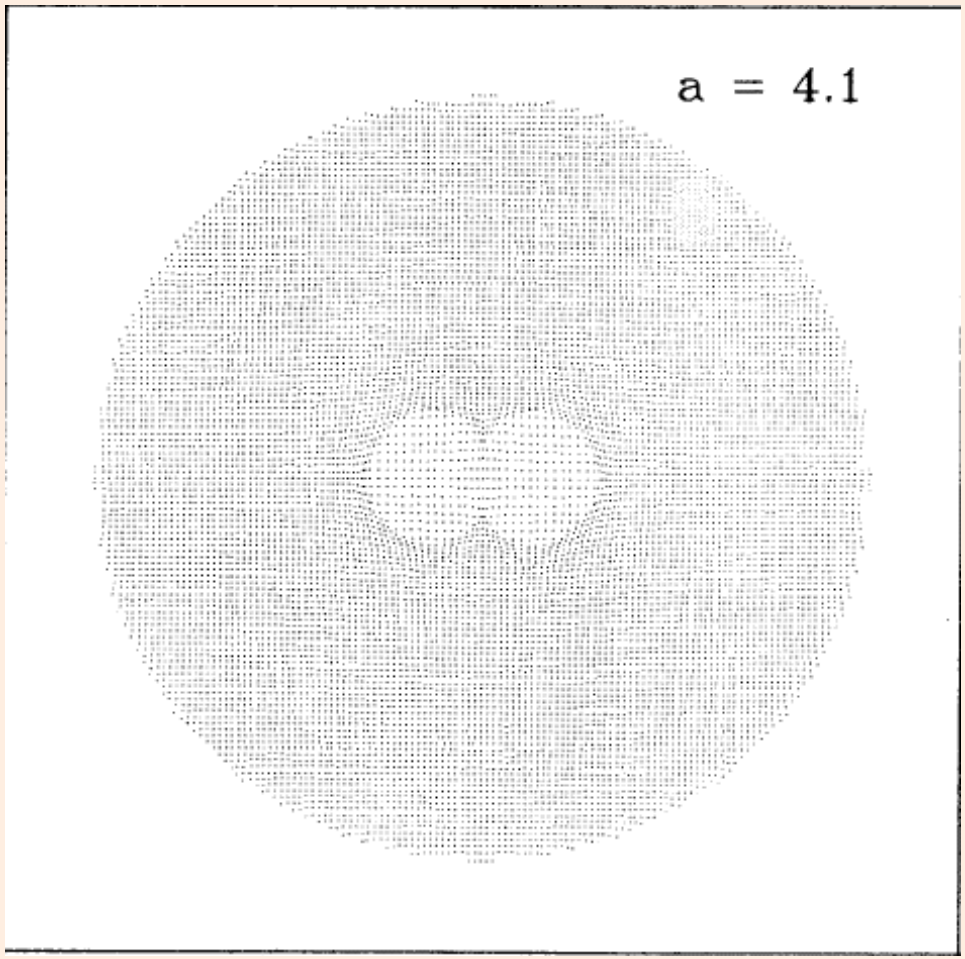
A bound system +m –m levitates, is polarized
and in this sense violates maximally the equivalence principle …

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

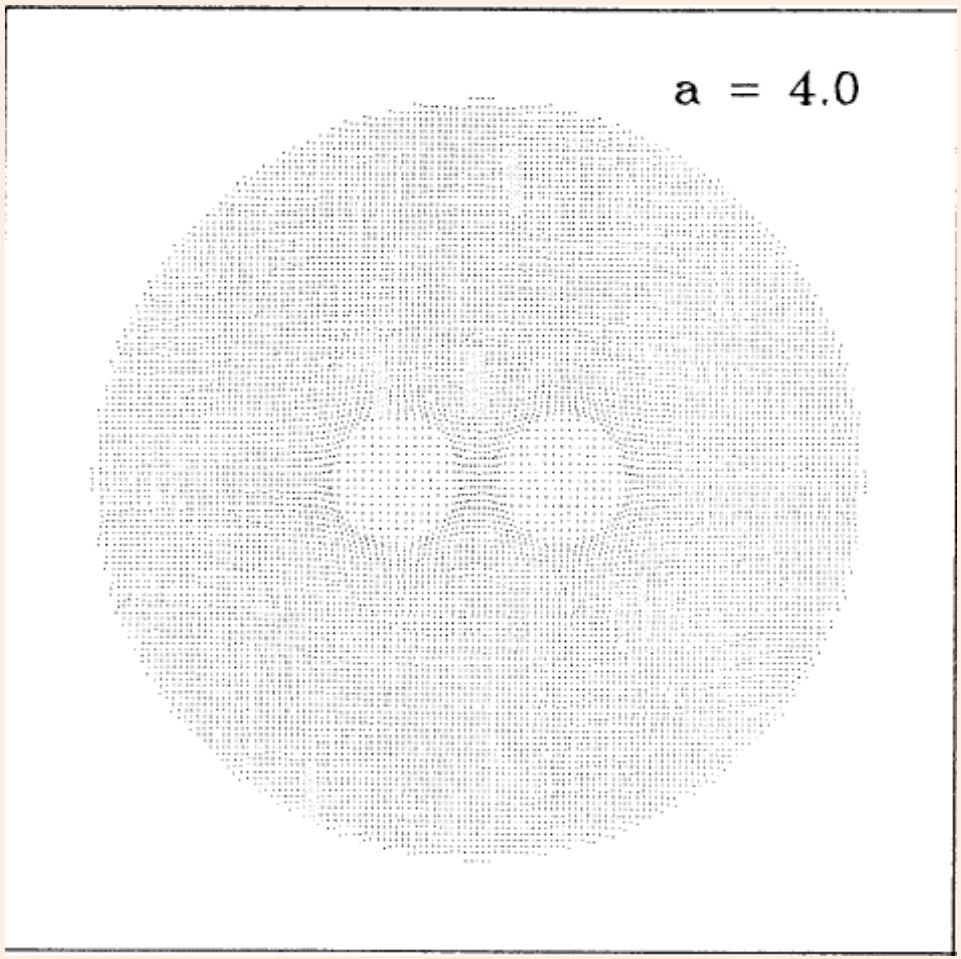
- J. Dubinski, et al., ApJ. 410 (1993) 458
- T. Piran, Gen. Rel. Grav., 29 (1997) 1363
- R. K. Sheth and R. van de Weygaert, Mon. Not. R. Astron. Soc. 350, 517–538 (2004)
- Voids (underdense regions) act as negative mass and build structures of growing (comoving) size
- See also G. Manfredi's talk



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



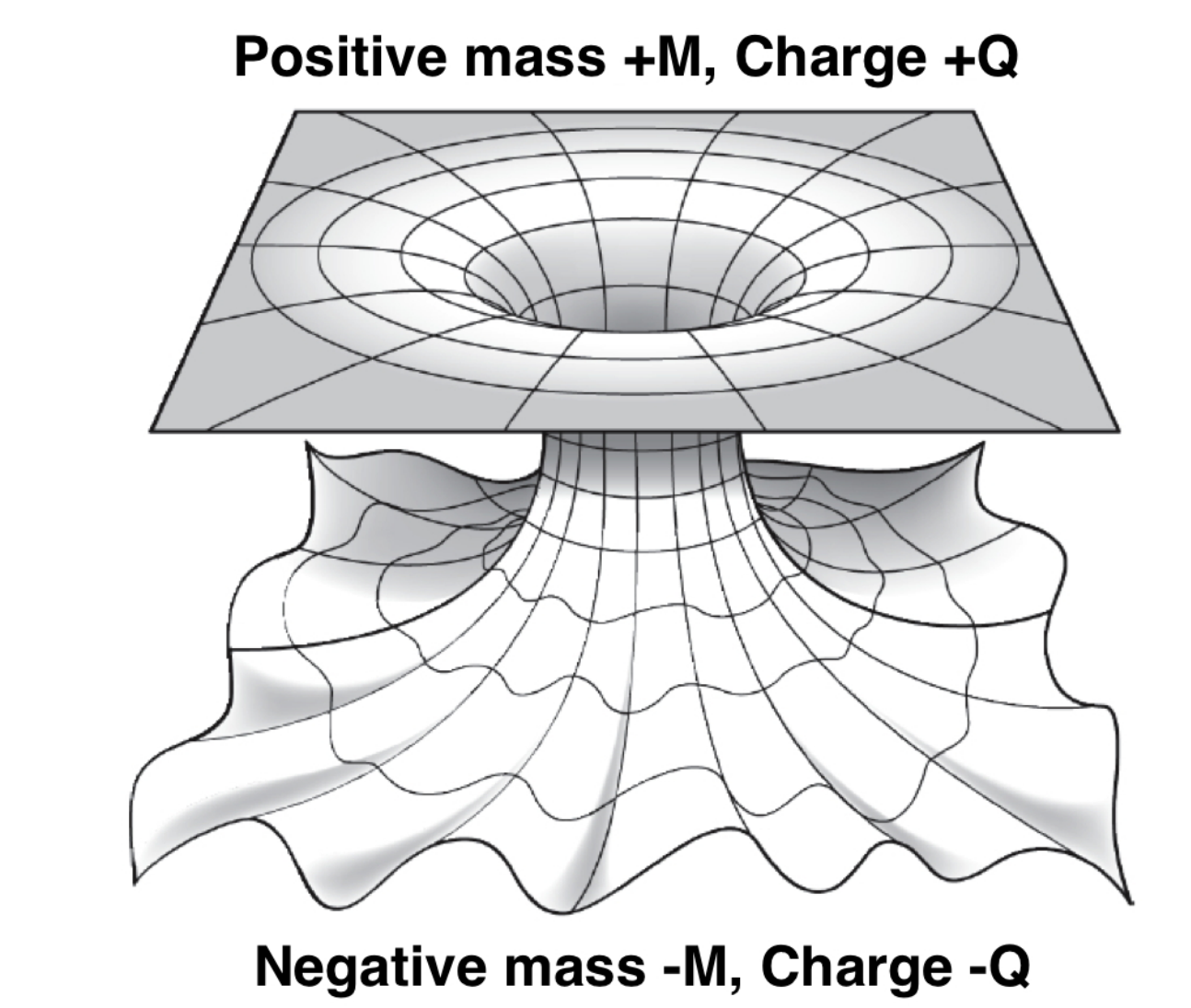
Negative mass in GTR (Dubinski et al.)



Charged and spinning black holes as particles (and antiparticles)

- B. Carter, Phys. Rev., 174 (1968) 1559 : charged and spinning black holes (Kerr-Newman) look very much like **elementary particles** (such as an eelctron)
- G. Chardin, Hyperfine Interactions, 109 (1997) 83 : charged and spinning black holes look like **particle-antiparticle pairs**
- H.I. Arcos, & J.G. Pereira, General Relativity and Gravitation, 36 (2004) 2441 : deep analogy with **Dirac equation and fermion-antifermion pair**

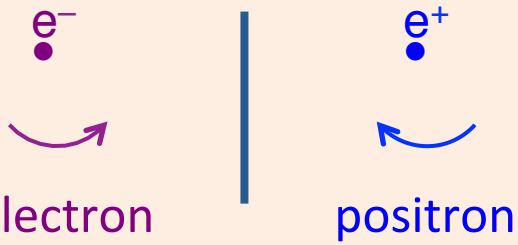
Carter 1966, 1968 : Kerr and Kerr-Newman geometry

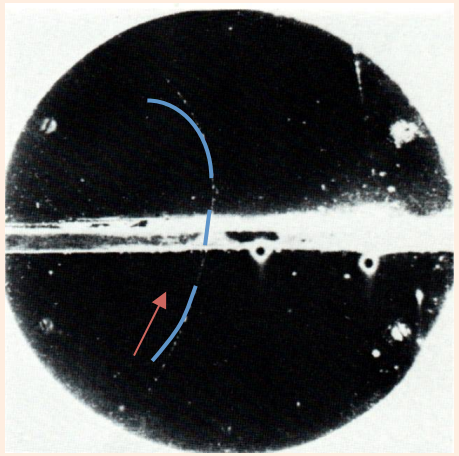


Dirac : antimatter as negative mass/energy

- Dirac equation has two solutions ± m
- What is the significance of the solution m < 0 :
  - nothing, aberrant unphysical solution ?
  - electron of negative energy ?
  - proton (but Weyl : m+ = m–) ?

Dirac 1930





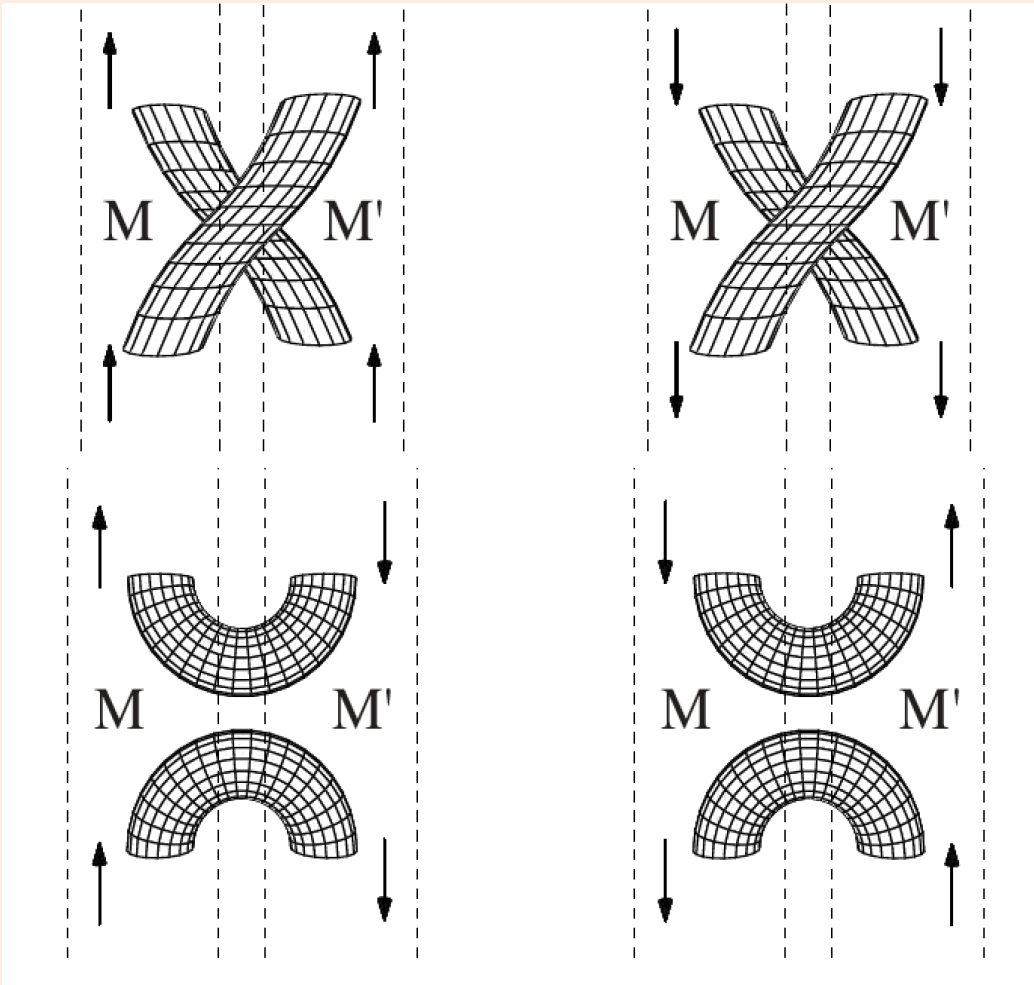
Plomb

1932 : Anderson discovers the positron in cosmic rays

Arcos and Pereira (2007) :

Kerr-Newman geometry has a deep relation with Dirac spinors

The four possible geometric configurations of KN states for a specific value of the electric charge.
The arrows indicate the sense of the spin vector.



Antigravity and CP violation

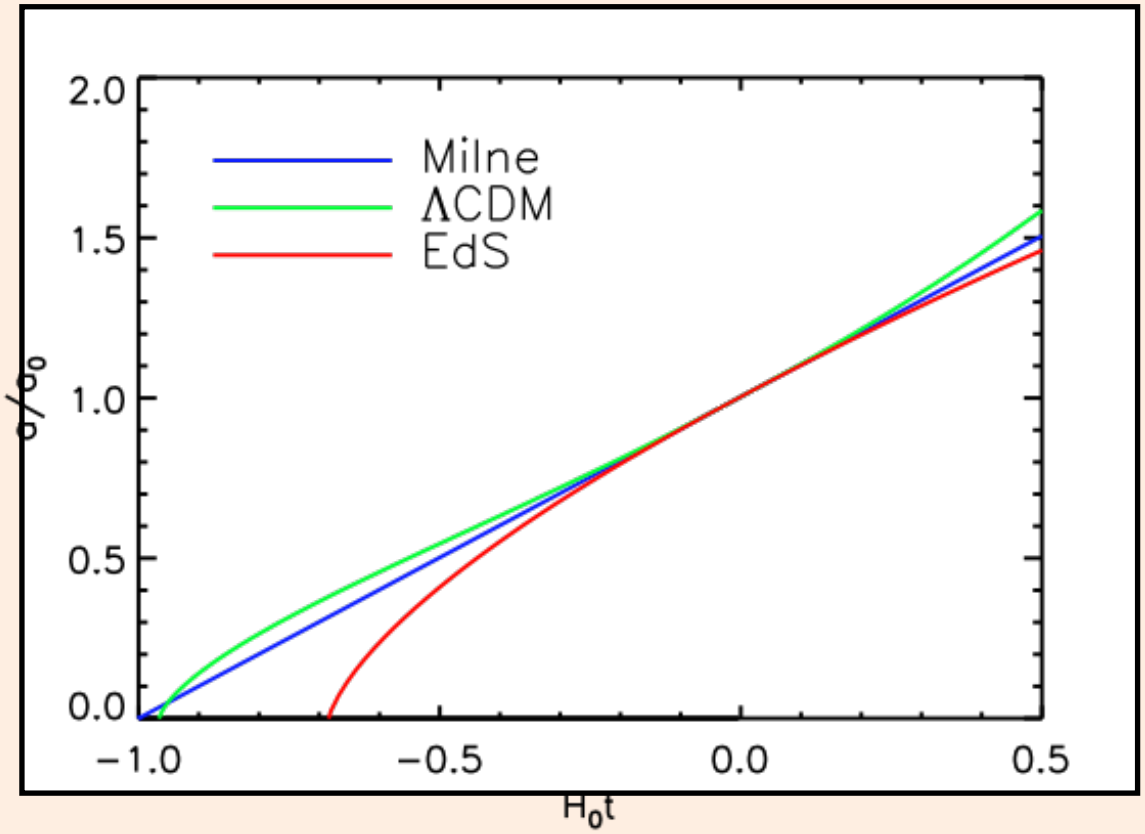
- M. Good (1961) : the neutral kaon system would have anomalous regeneration that is not observed (in fact, « **was not** in 1961 »…)
- G. Chardin and J-M. Rax (1992) : antigravity would give the amount of anomalous regeneration that we call CP violation (discovered in 1964, 3 years after Good's argument…)
- T. Goldman, M.M. Nieto and V. Sandberg (1992) : basically the same argument, but not taking into account adequately the mixing time of weak interactions

Symmetric Matter-antimatter cosmologies : are they excluded ?

- Symmetric matter-antimatter cosmologies : are they excluded ?
- 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

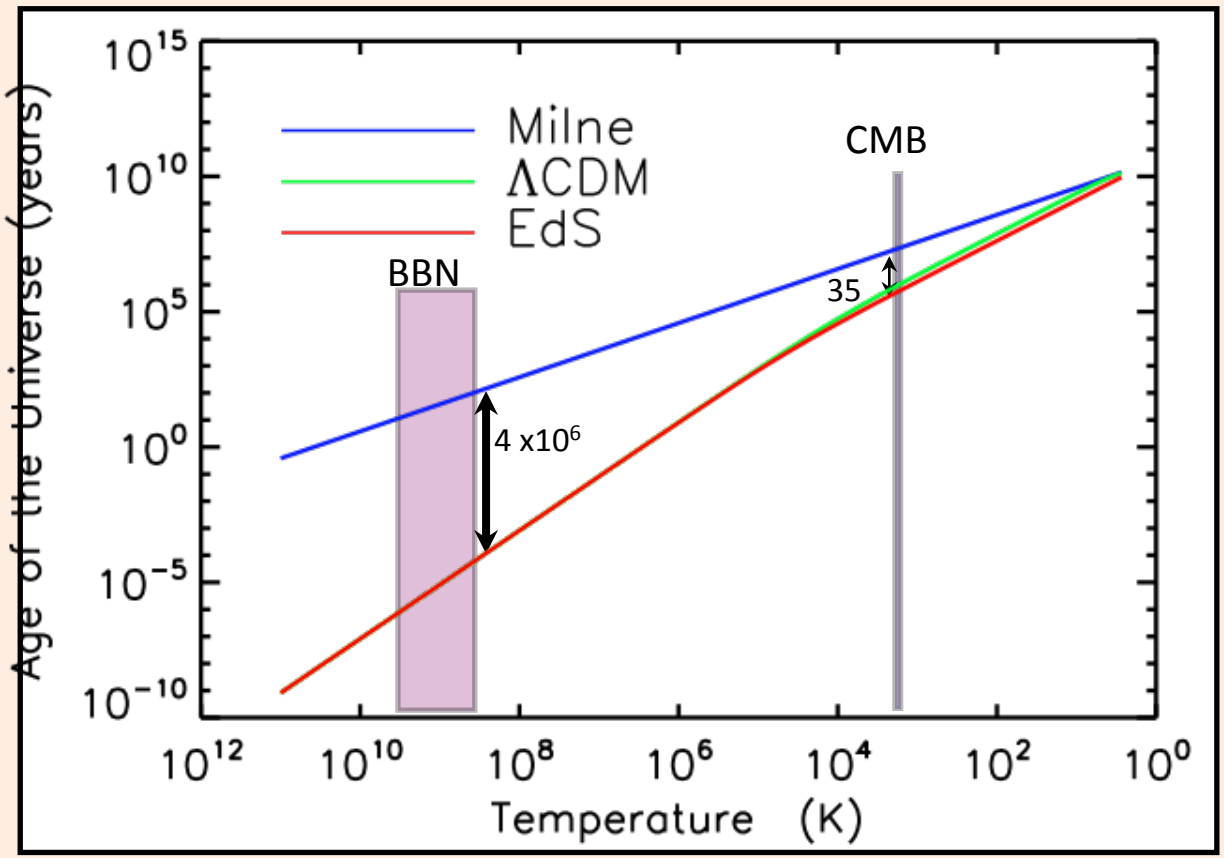
$$d_h(t) = a(t) \int_{t_0}^{t} \frac{dt'}{a(t')} \xrightarrow{t_0 \to 0} +\infty$$

- 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)

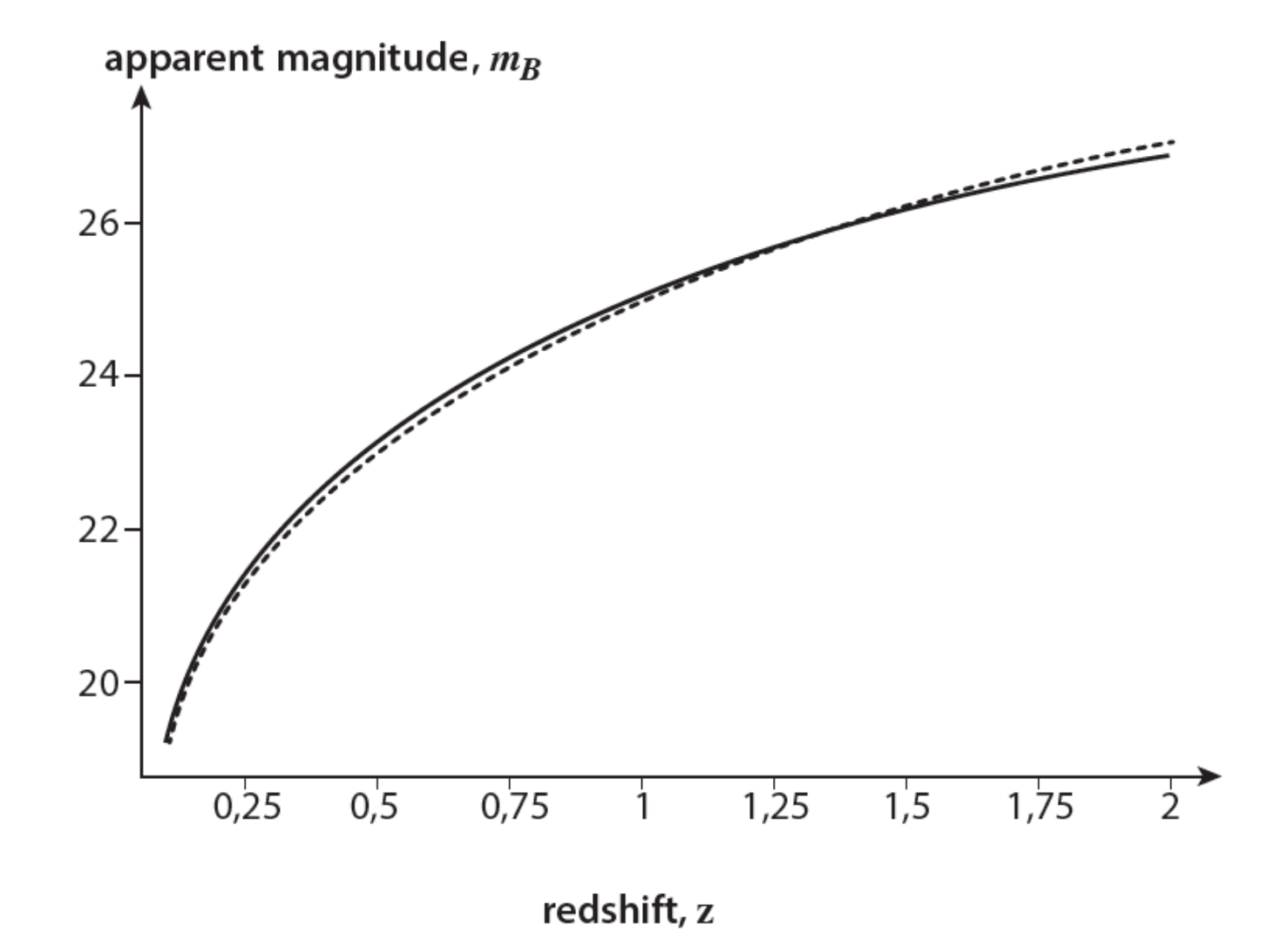


Supernovae SN1a

- 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

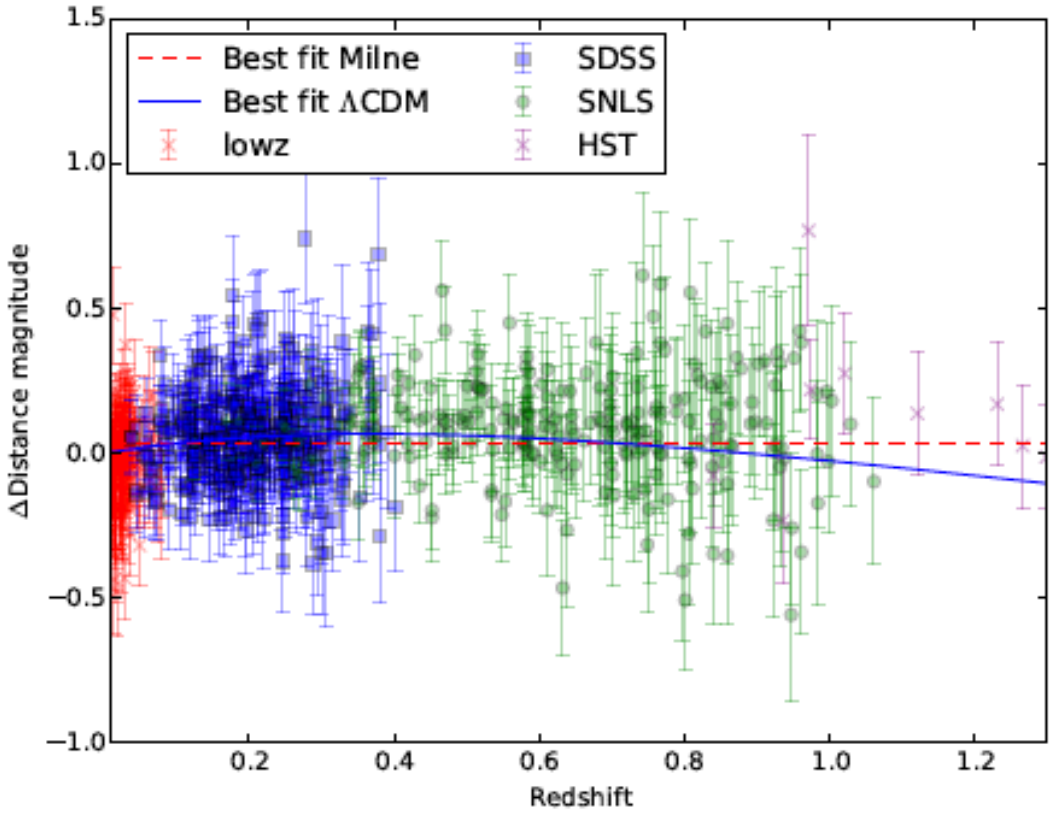
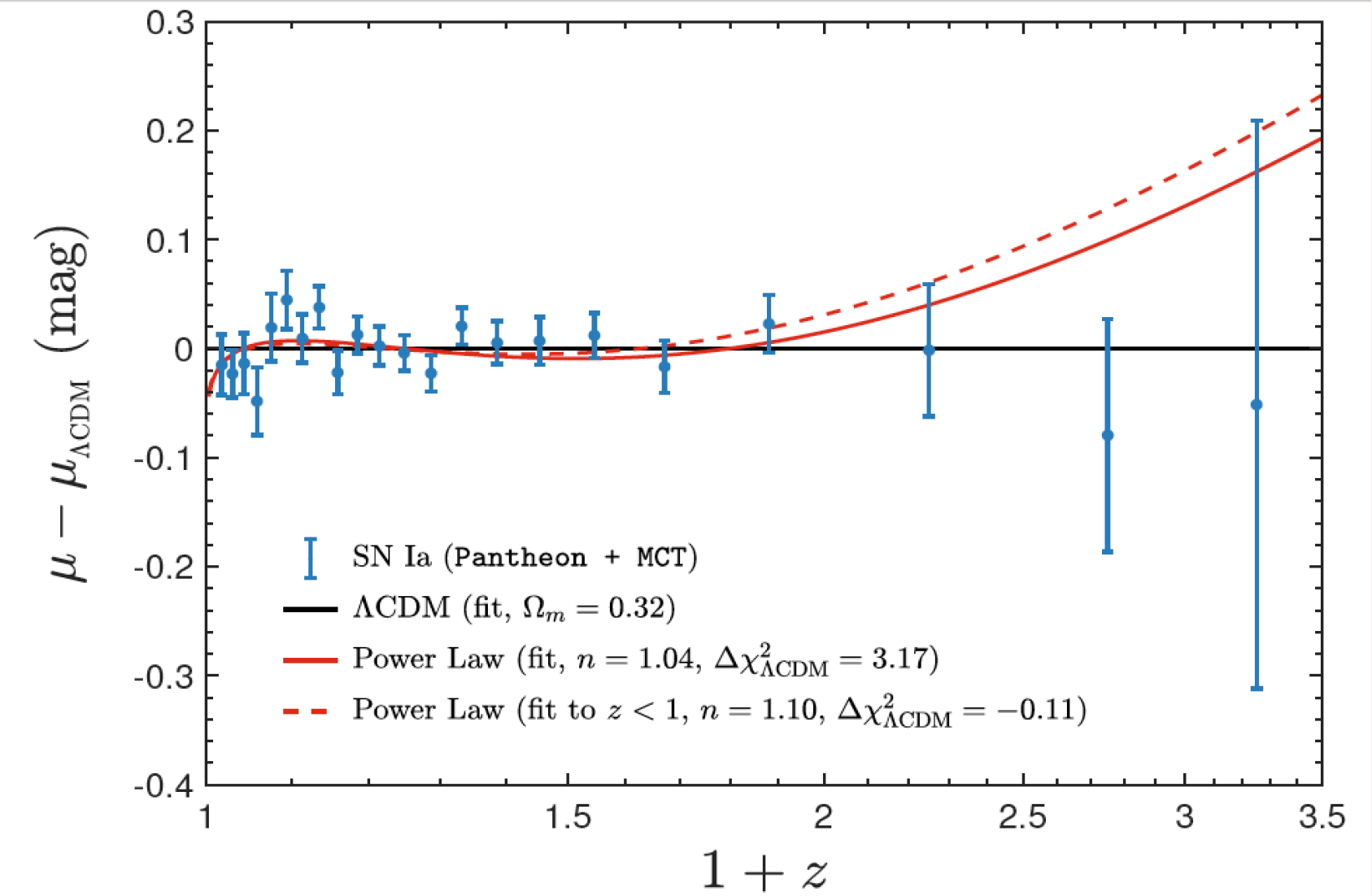


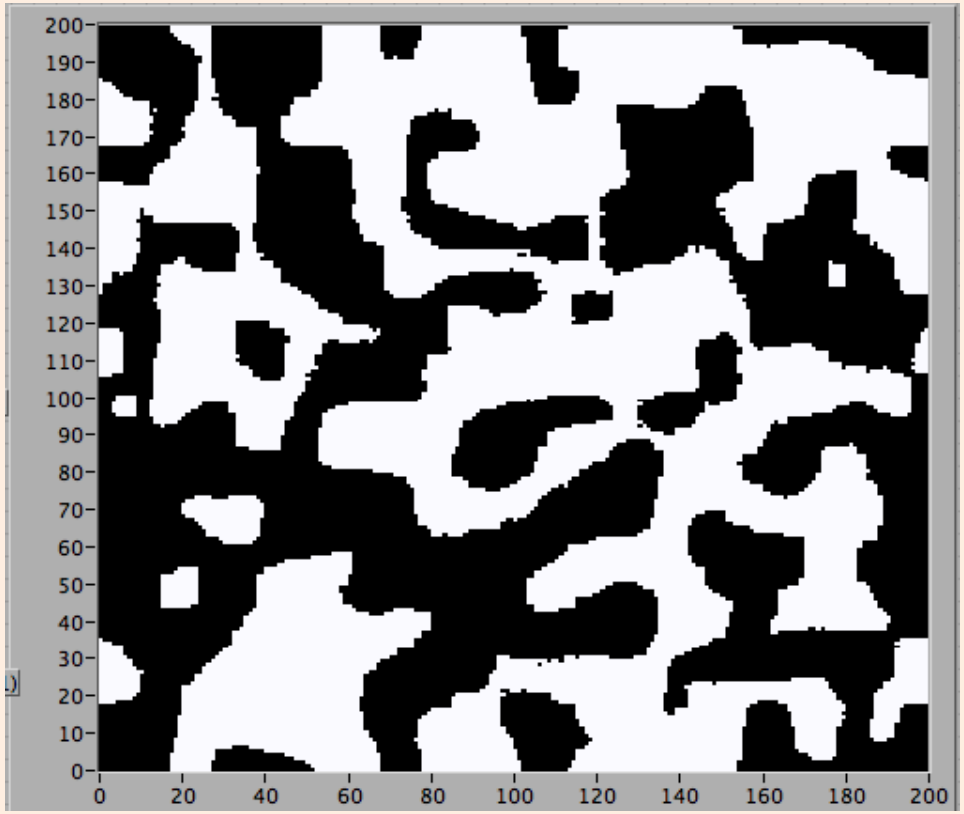
FIG. 4. Residuals relative to the Milne model for Fig. 3.

Supernovae SN1a (ff)

Riess et al. arXiv:1710.00844



So, why do we need antimatter, and a symmetric matter-antimatter universe ?

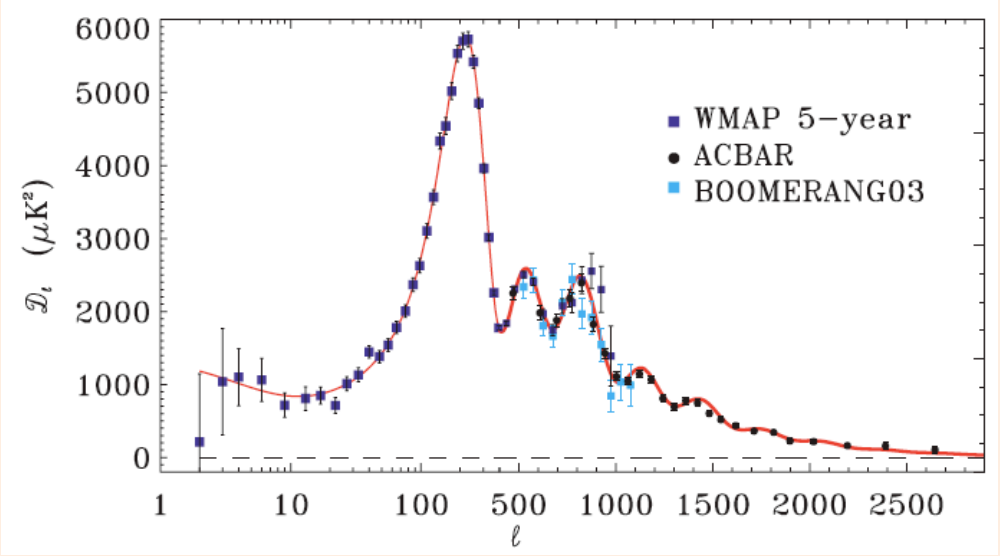


- Matter-antimatter emulsion in 3D : characteristic size grows linearly with annihilation at matter-antimatter interface
- Emulsion size at the end of annihilation completely determined, not a free parameter…
- Gravitational polarisation : annihilation stops at T ≈ 30 eV

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!

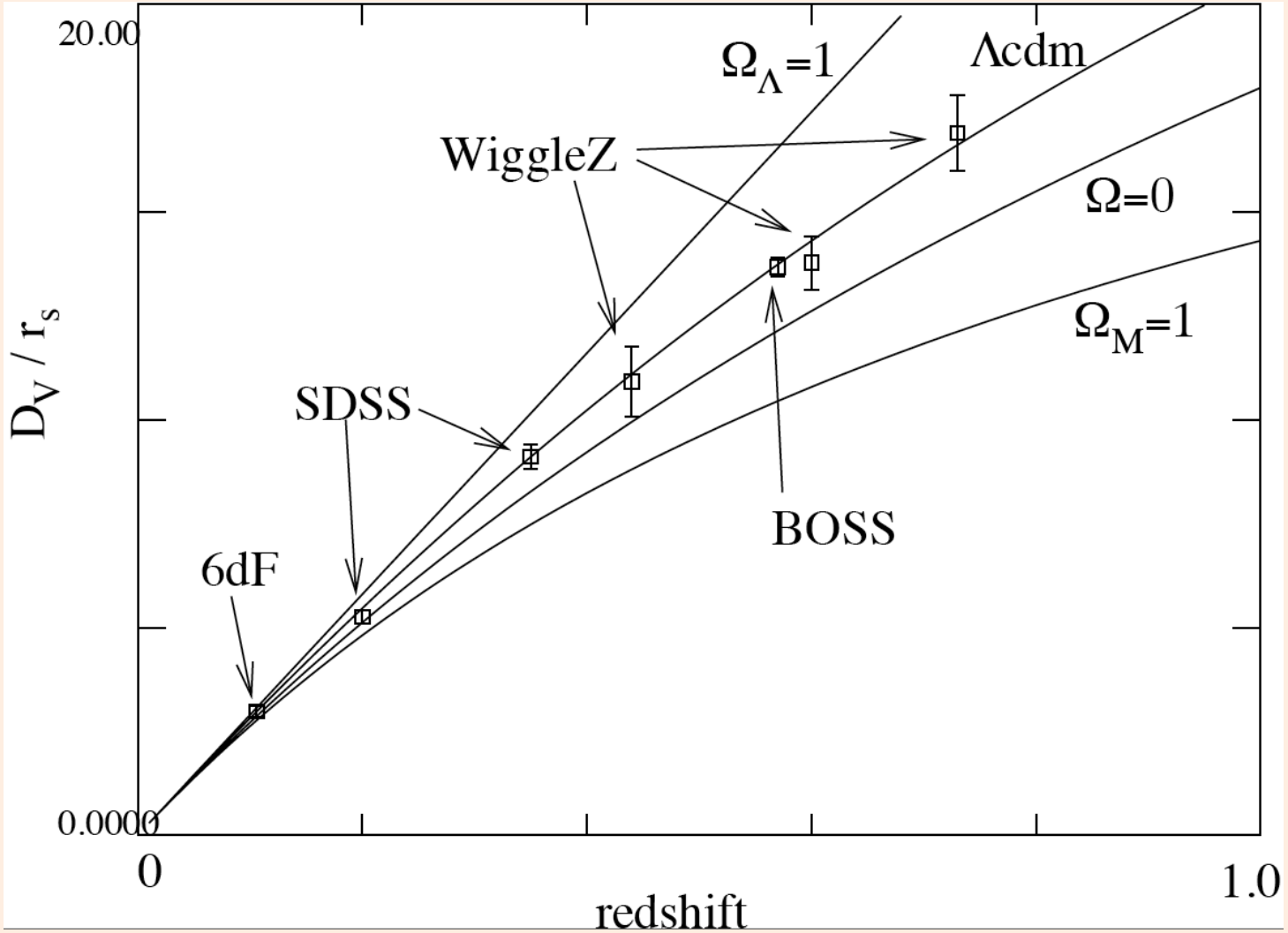
But, due to linear scale factor, sound horizon is much larger than in standard model

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

Integrating from 170 MeV to ~10 eV (end of annihilation, cf BBN) yields acoustic scale around 1º !

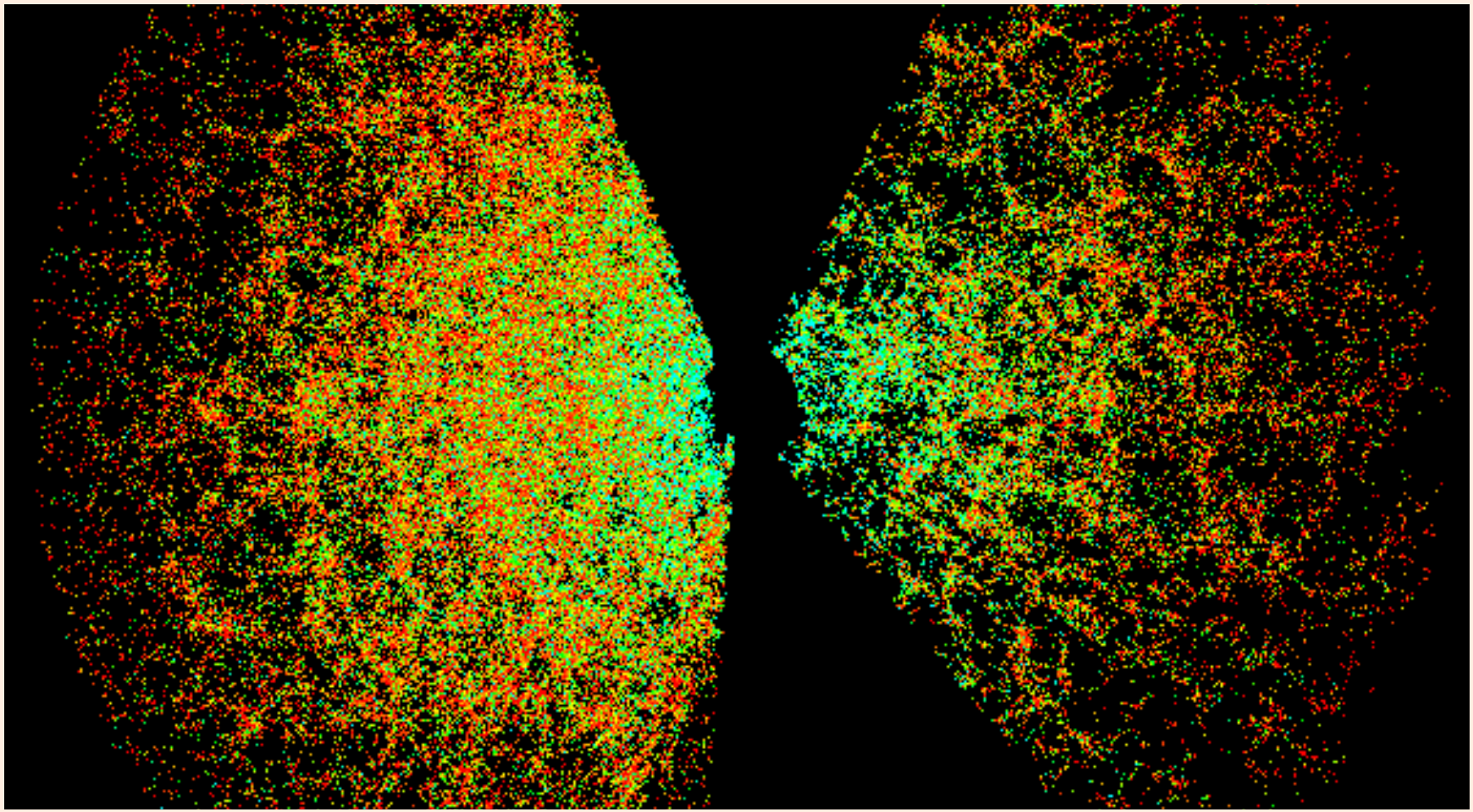
Clearly, BAO should not be observed in Dirac-Milne universe at the reported scale of ~150 Mpc.

BAO vs. cosmology

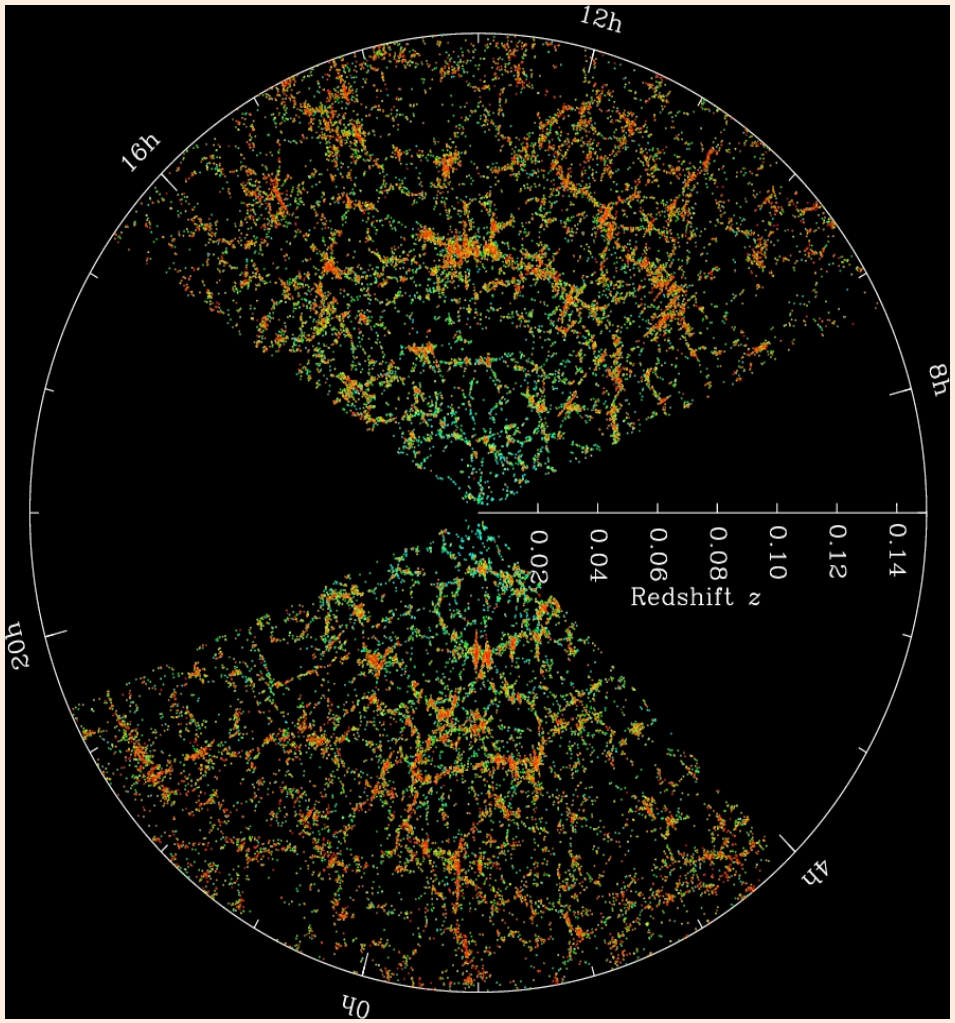


BAO Hubble linear Jim Rich

(Non linear) structures as seen by SDSS



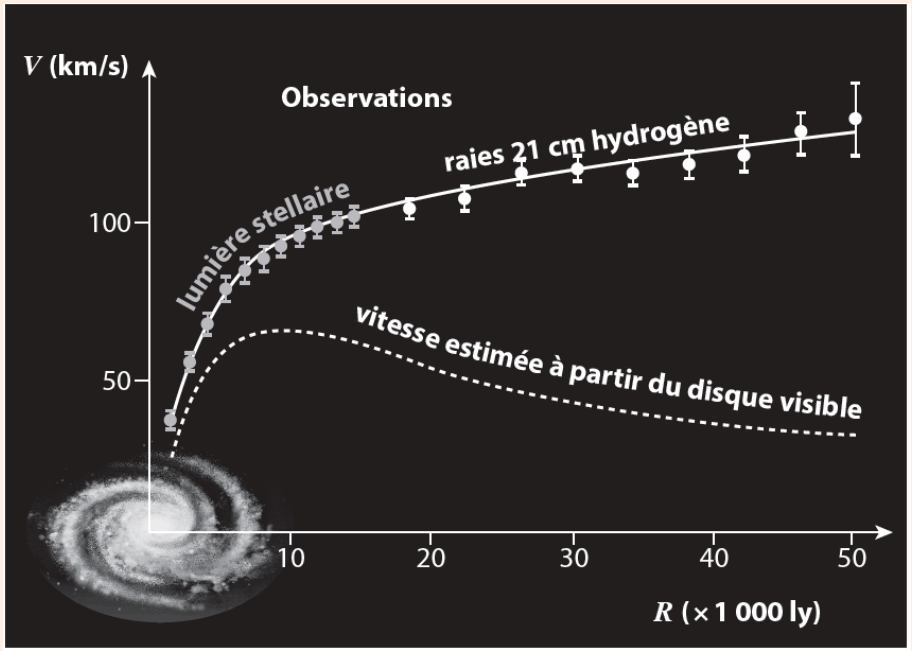
(Non linear) structures as seen by SDSS



- 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)

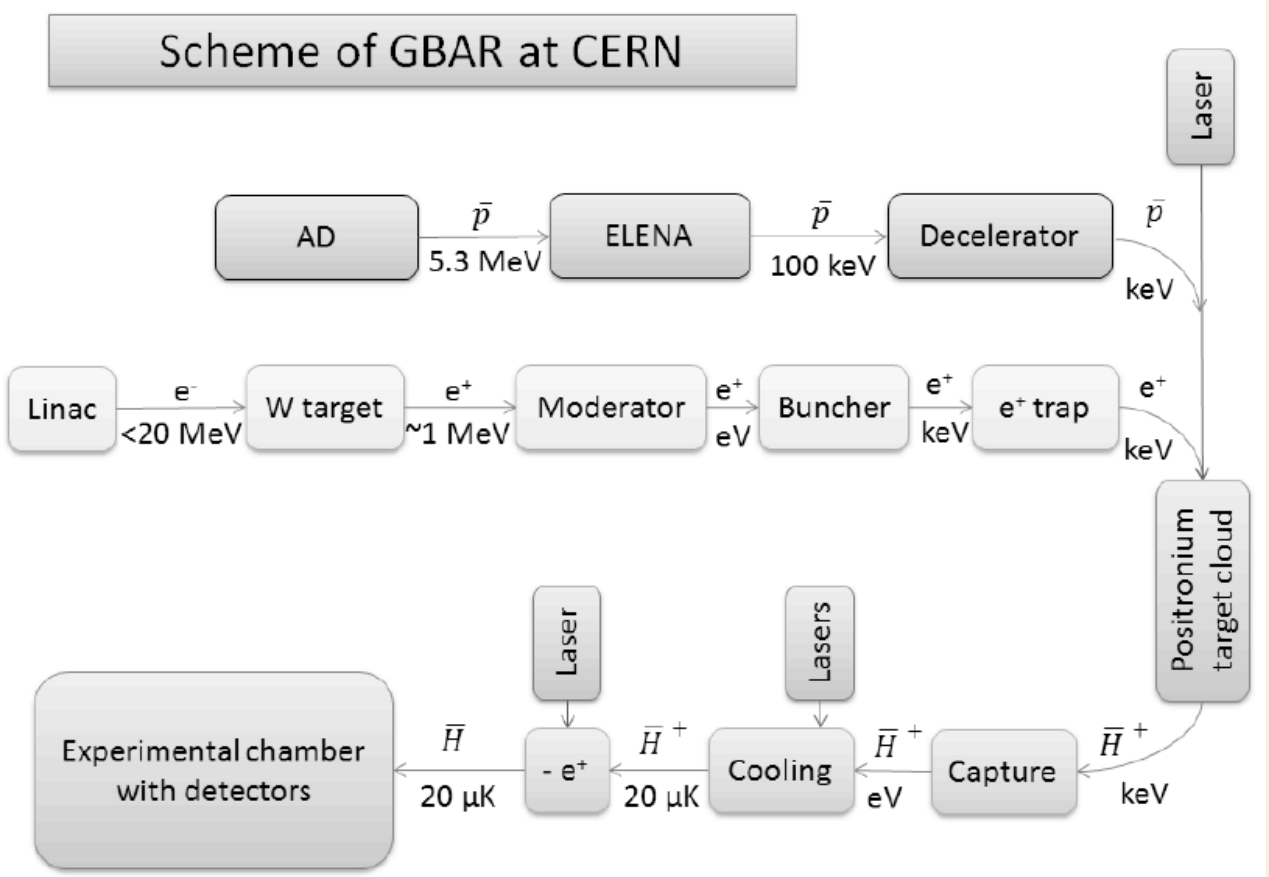
Note : Dark Matter and MOND

- 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



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



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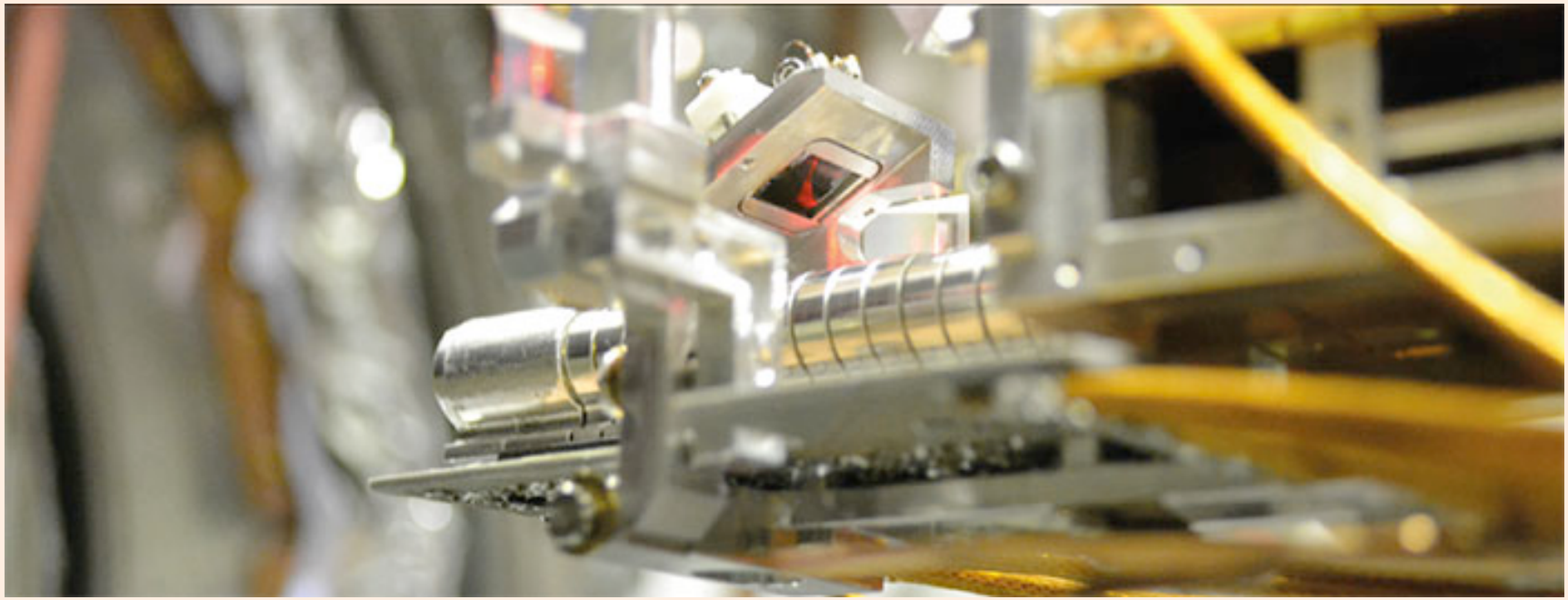

Direct test in the laboratory

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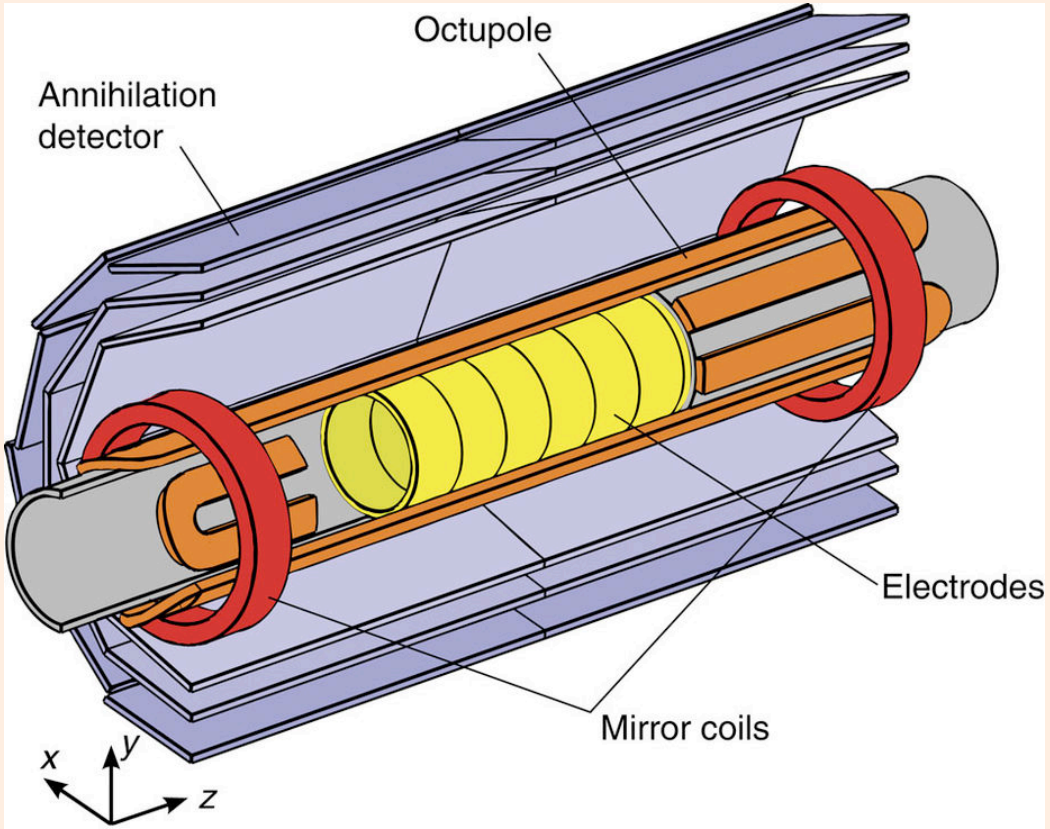
The 2013 ALPHA apparatus that was used to derive a limit ≈ 65 x antigravity in a first measurement.

The ALPHA-g experiment is expected to improve this precision by nearly three orders of magnitude,
and to be able to test antigravity with a precision of ≈ 10% in a first stage, and ≈ 1% in a second stage.



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 (MOND ?) (Note : vacuum disruption at the horizon of black holes, solving the “ firewall paradox ” ?)
- Negative mass, as proposed by Piran, is present by construction in simulation codes of cosmological evolution : voids take as much space as they can (no Newtonian expression, see Mandredi !)

Summary (2)

- There is a physical system (the electron-hole system in a semiconductor) that implements the 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

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