The Dirac-Milne Universe
A Symmetric Matter-Antimatter Universe

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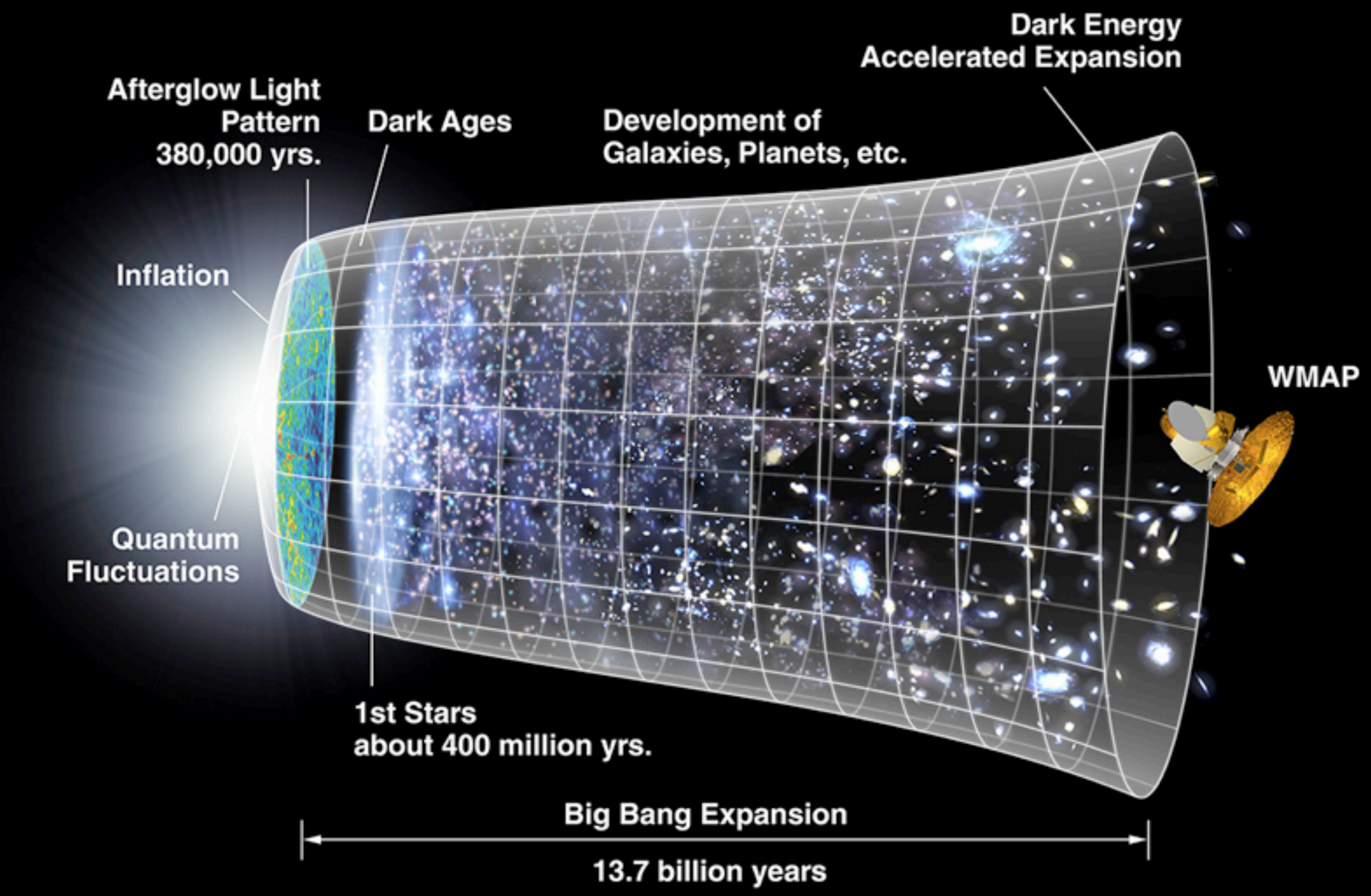
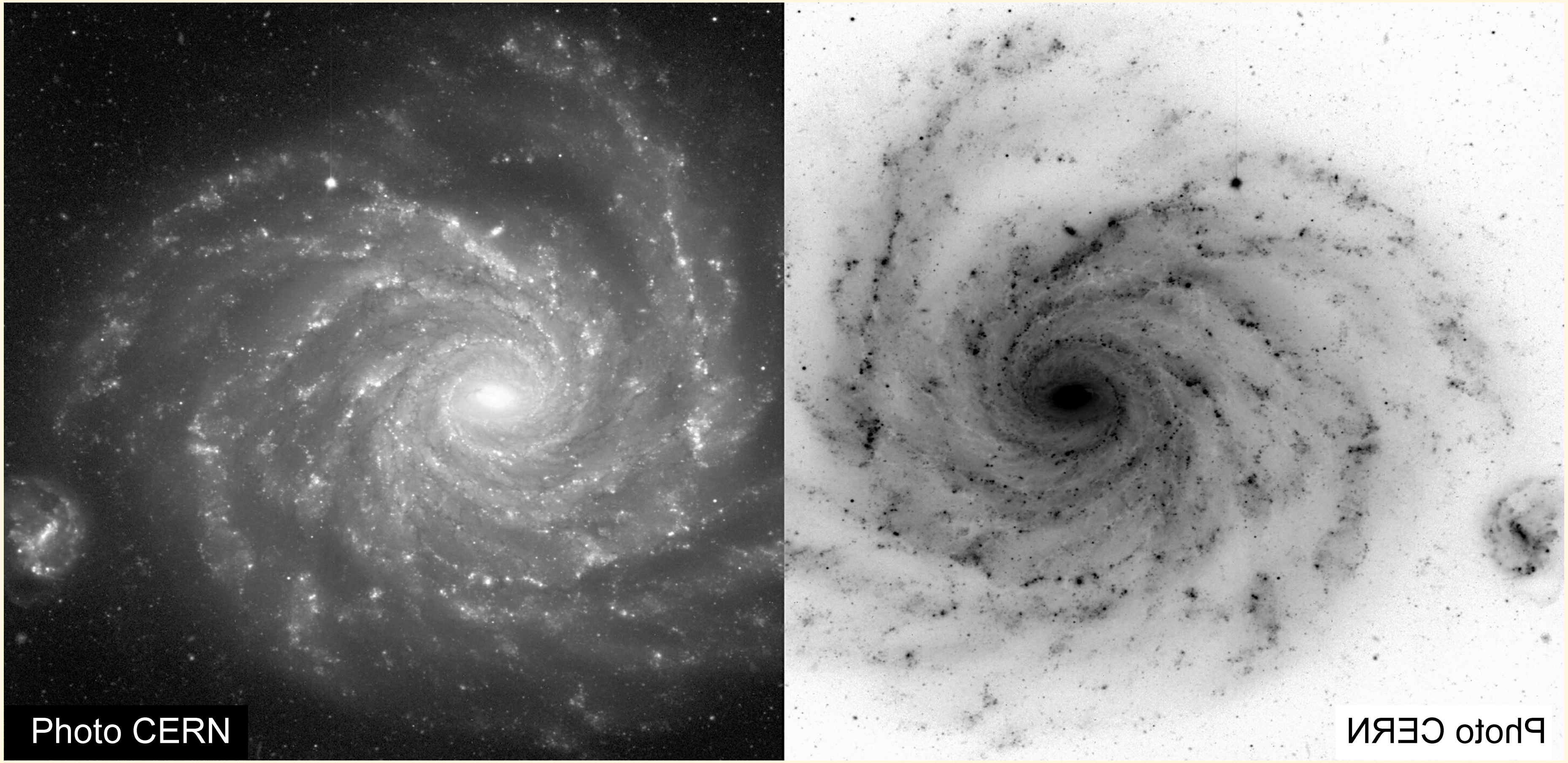
Le modèle de concordance de la cosmologie



Marche bien, mais peu naturel. Existe-t-il une alternative ?

NASA/WMAP Science Team

Où est passée l'antimatière ?



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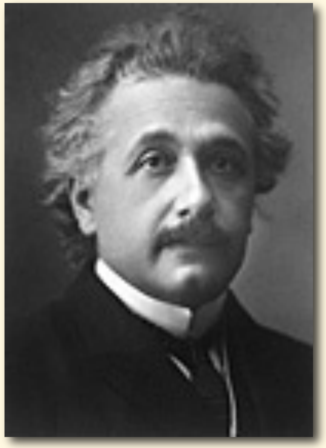
Petite histoire de l'antimatière

Maxwell

Électromagnétisme



1905 : Einstein

Relativité restreinte

1926 : Schrödinger

Mécanique Quantique

électron relativiste avec spin

1929 : Dirac

CNRS-IN2P3 et CEA-DSM-DAPNIA

Problème...

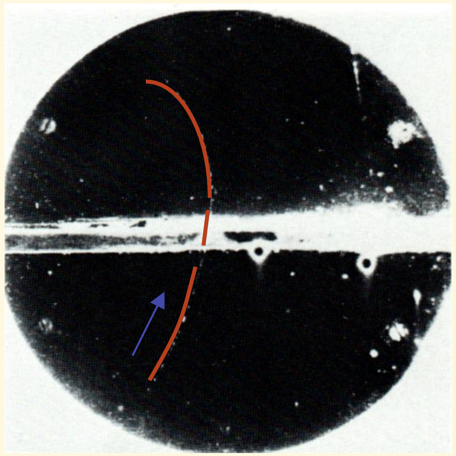
L'équation de Dirac a 2 solutions ! { l'électron / ????

Que signifie la deuxième solution ?

- Rien ?
- Électron d'énergie négative …
- Une particule de charge +1 ???
- Le proton ? Mais sa masse est 2000 fois plus grande

Dirac invente l'antiélectron en 1930

e^- électron | e^+ positron

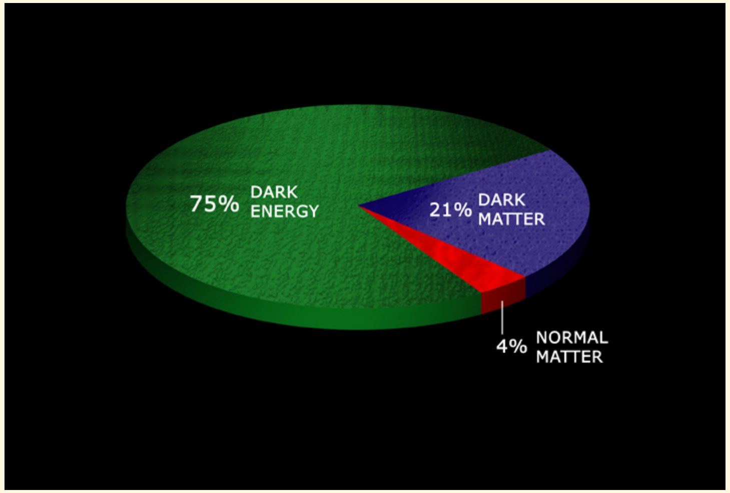


Plomb

1932 : Anderson découvre le positron dans les rayons cosmiques

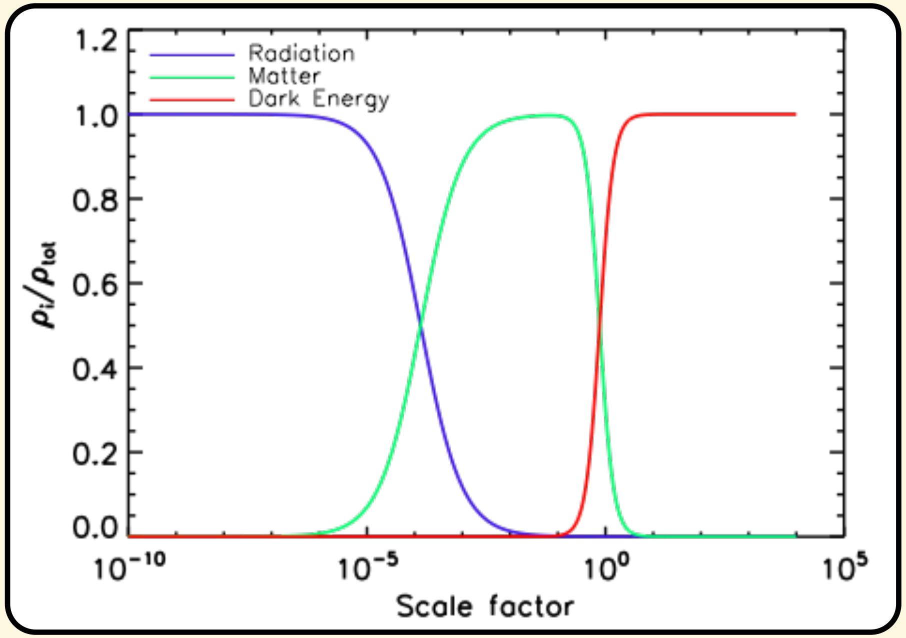
- La composition de l'Univers que semble indiquer le Modèle de Concordance est très surprenante: **moins de 5% de sa composition correspond à la matière ordinaire!**

- Le rayonnement, la matière et une mystérieuse Energie Noire sont successivement (très) dominants, chacun à leur tour : **très peu naturel** ("fine tuning")



Avant d'accepter un univers aussi étrange, il semble nécessaire de considérer des cosmologies alternatives et si possible moins arbitraires

L'univers de Dirac-Milne: **un *espace-temps plat* sans Matière Noire ni Energie Noire**



- Présentation et motivations

- Confrontation aux observations cosmologiques, de plus en plus précises:
  - Supernovae de Type Ia
  - La nucléosynthèse (fabrication éléments)
  - Le fond diffus cosmologique (CMB)

Assumptions of the Symmetric Milne Universe

- A coasting Universe, with linear scale factor, could be an interesting alternative to a strong deceleration at early times and then a phase of exponential expansion. This Universe has a slower evolution at high temperature. Spends about 10^8 times more time at QGP transition.
- Universe very homogeneous above QGP transition. Separation of matter and antimatter shortly after phase transition (T$\approx$ 39 MeV), creating domains.
  Creation of large domains appears possible with such a long time available (cf Omnes 70's)
- Equal quantities of matter and antimatter. Antimatter has negative active gravitational mass
- Without Dark Energy or Dark Matter
- Gravitationally empty Universe at large scales, no acceleration and no deceleration. Scale factor evolves linearly with time: $a(t) \propto t$

$a(t) = t$ an $k = -1$ in FRW metric implies *flat space-time* and *open space*. Compared to usual assumption of *flat space*.

→ Milne Universe is the second "natural" universe

Motivations

- Symmetry in Kerr-Newmann geometry under space, mass and charge reversal.
  Two CP conjugate spaces connected by the ring
  Elementary particles as "black holes"
  B. Carter 1966&68, G. Chardin 1996, Arcos & Pereira 04

- SNIa observations reveals effective repulsive gravity which is still unexplained

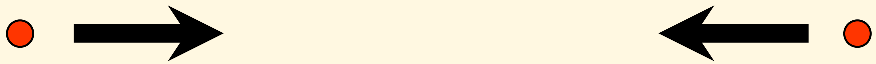
- High level of fine-tuning in standard model

- Removes need for inflation

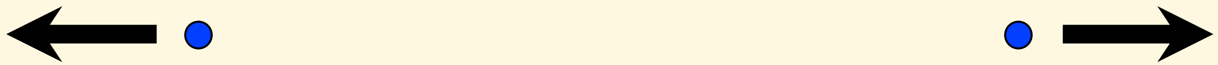
In the following, antimatter gravitational mass is taken negative.
We also suppose gravitational repulsion between matter and antimatter.
Analog situations in condensed matter: electrons and holes in gravitational field

Negative mass in GTR (Bondi) ?

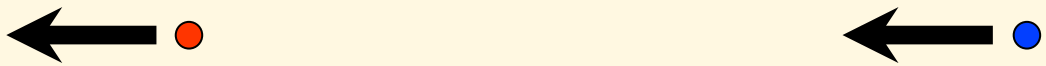
Two positive masses attract each other



Two negative masses repulse each other

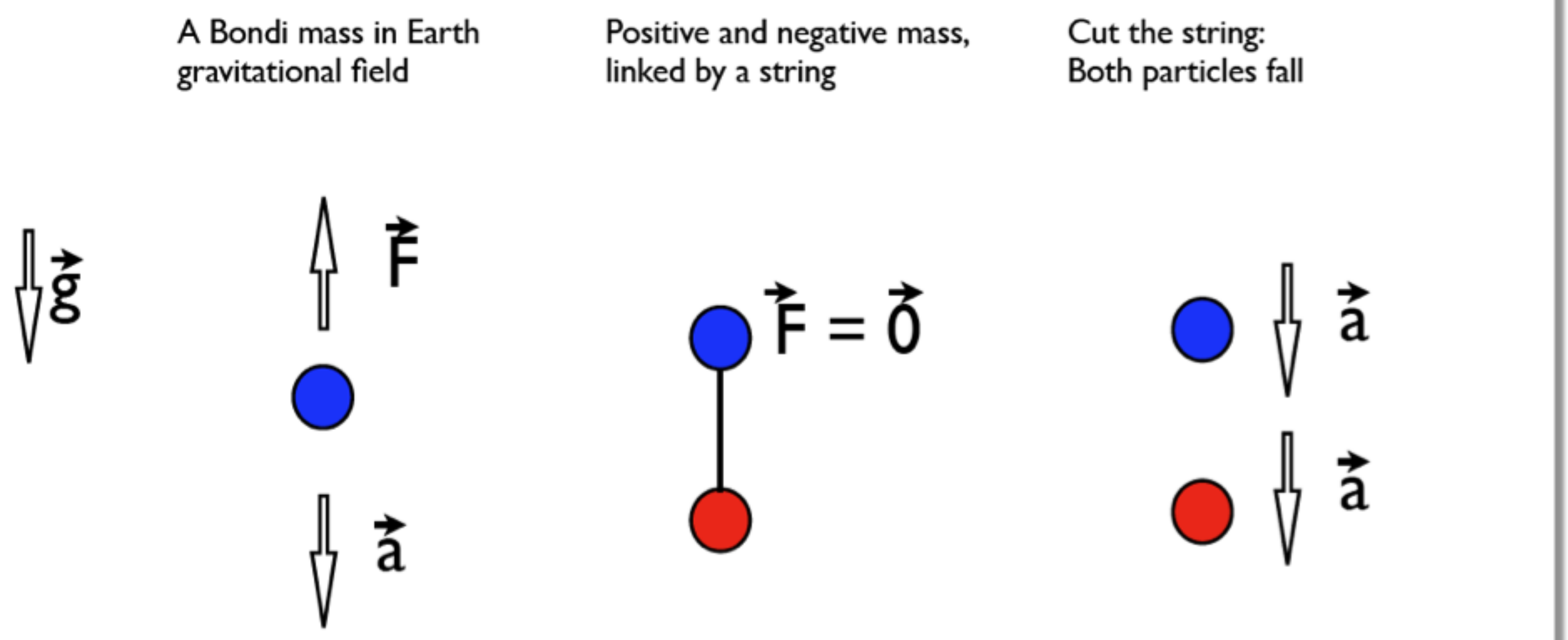


One positive mass and one negative mass : runaway



Positive mass particle
Negative mass particle

Negative mass in GTR (Bondi) ?



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

“antigravity”, a crazy idea ?

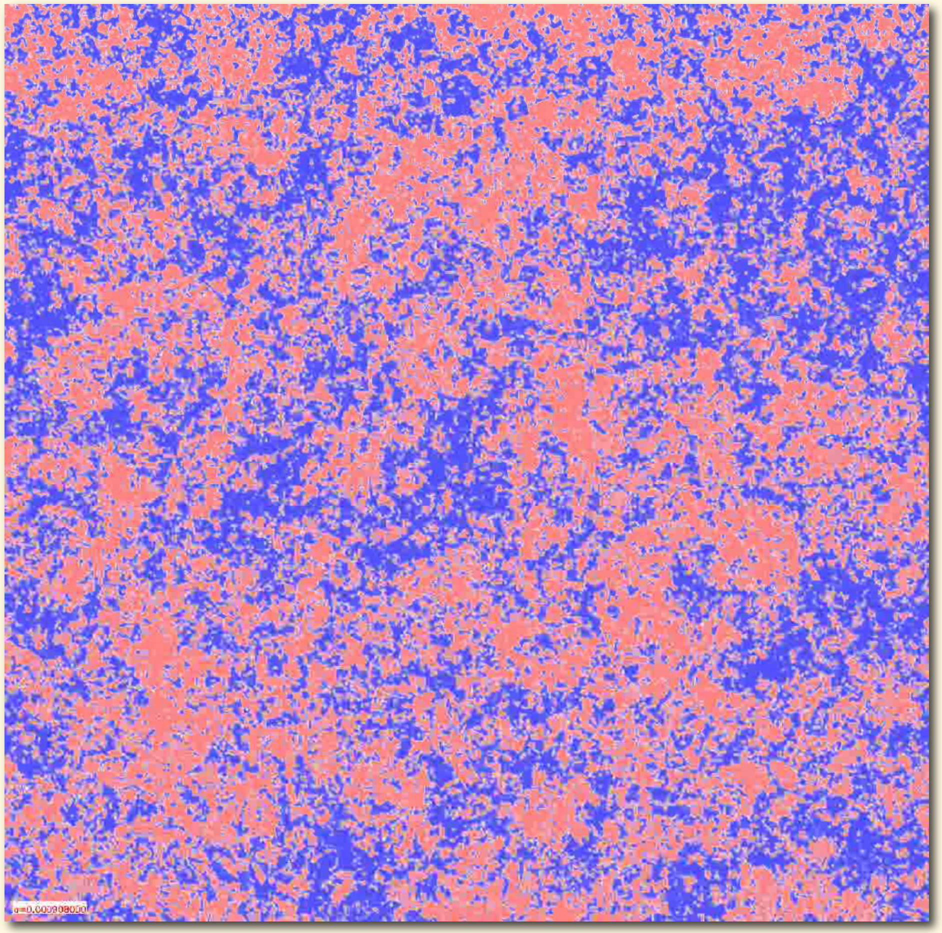
- Le génie de Newton a consisté à dire que la lune tombe alors que tout le monde voit bien qu'elle ne tombe pas. Paul Valéry
- One has to be an Einstein to notice that the Moon is not falling, when everyone sees that it falls. John Archibald Wheeler
- Changement de paradigme et influence ce qui paraît évident ou évidemment faux…

Classical examples of "antigravity"

- Analogy with solid state physics : electron-hole pairs, reminiscent of Dirac sea…
  Tolman experiments on sign of charge carriers
- Superfluid helium as a medium (static/Earth)
- Place an electron in this medium : vacuum bubble ➔ negative mass relative to He background medium
- Motion of this pseudoparticle : accelerates *upwards* with (nearly) perfect acceleration $+2g$
- Electrons ($+g$) and holes ($-g$) in a semiconductor as model
- Voids in large-scale structures seen as negative density with respect to background density (Dubinski et al. 93, Piran 97).

Simulation structures

- Simulation cosmologique 2D 2048 x 2048 (masses + et –)



The Symmetric Milne Universe

- As radial coordinate of a z redshift object: $\chi(z) \xrightarrow{z\to+\infty} +\infty$, a Universe with linear scale factor has no horizon. There is no need for an inflation scenario.

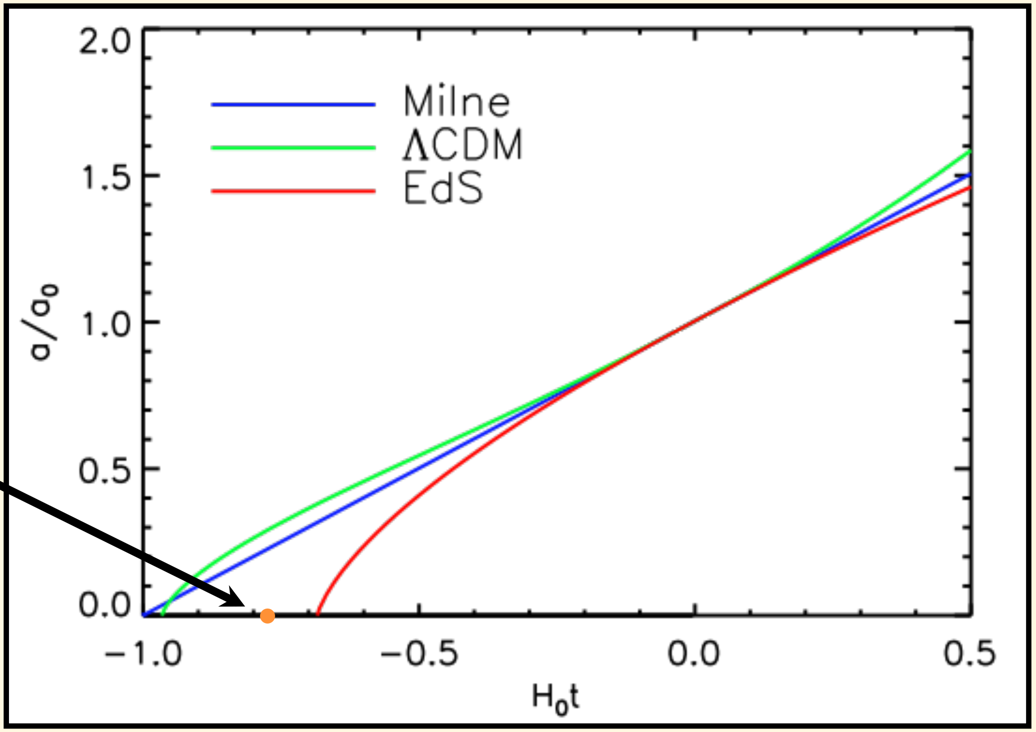
$$d_h(t) = a(t)\int_{t_0}^{t}\frac{dt'}{a(t')} \xrightarrow{t_0\to 0} +\infty$$

- Age of the Milne Universe is almost exactly the same as the age of ΛCDM Universe

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

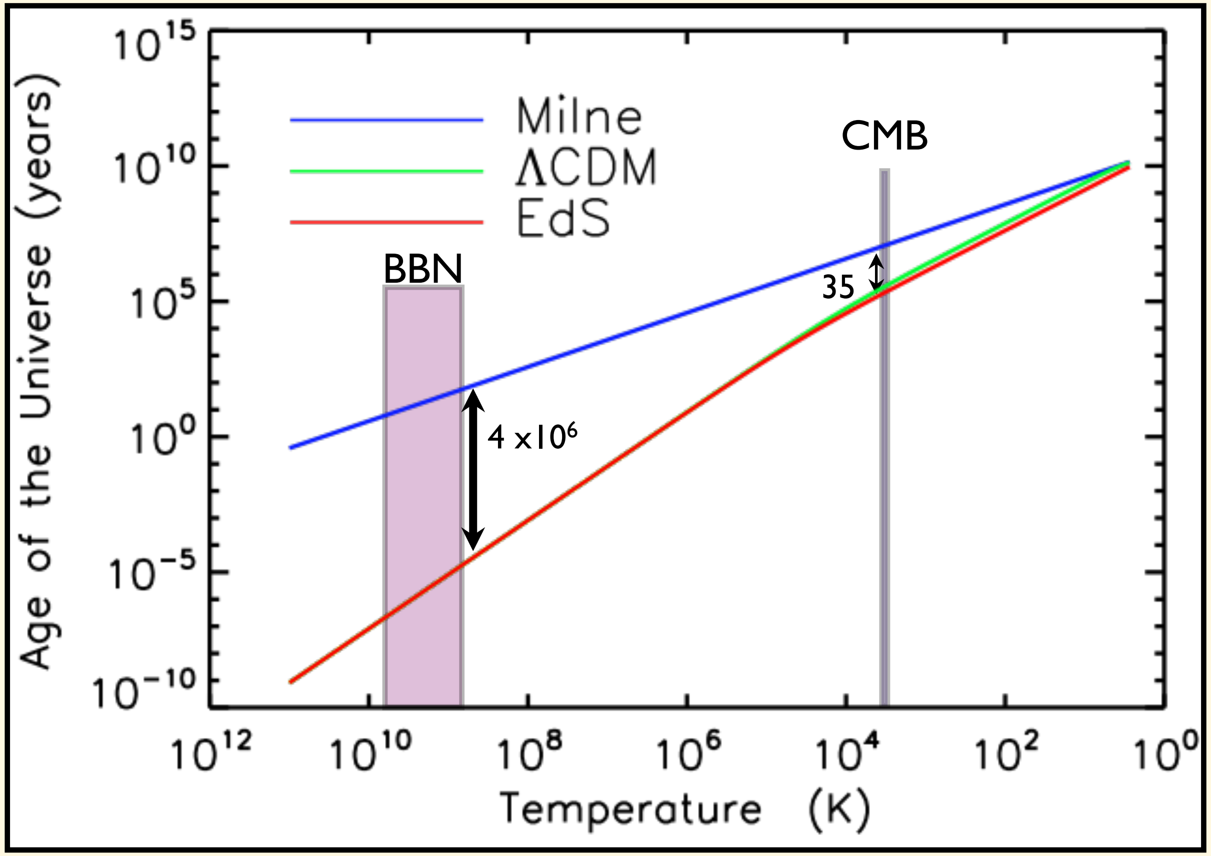
Age of the Universe was a problem for a Einstein-de Sitter model, which was solved by ΛCDM, but is also solved by Milne Universe

oldest globular clusters (Chaboyer et al.,98)



Time scale of primordial Universe is extremely different !

First noted by Dev et al. 02



Milne Universe spends much more time at high temperature than conventional Universe.

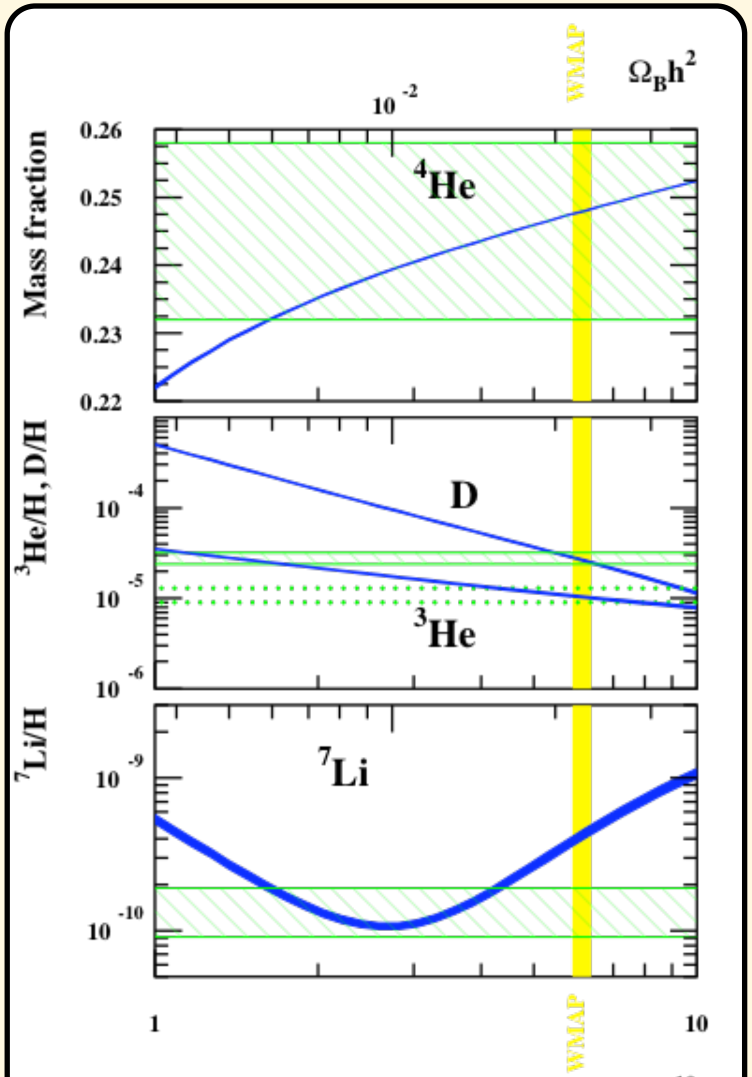
BBN duration:
Standard BBN ≈ 200 sec
Milne BBN ≈ 30 years

Age of the Universe at recombinaison:
14 Gy/1000 ≈ 14 My
(compared to 0.38 My in ΛCDM)

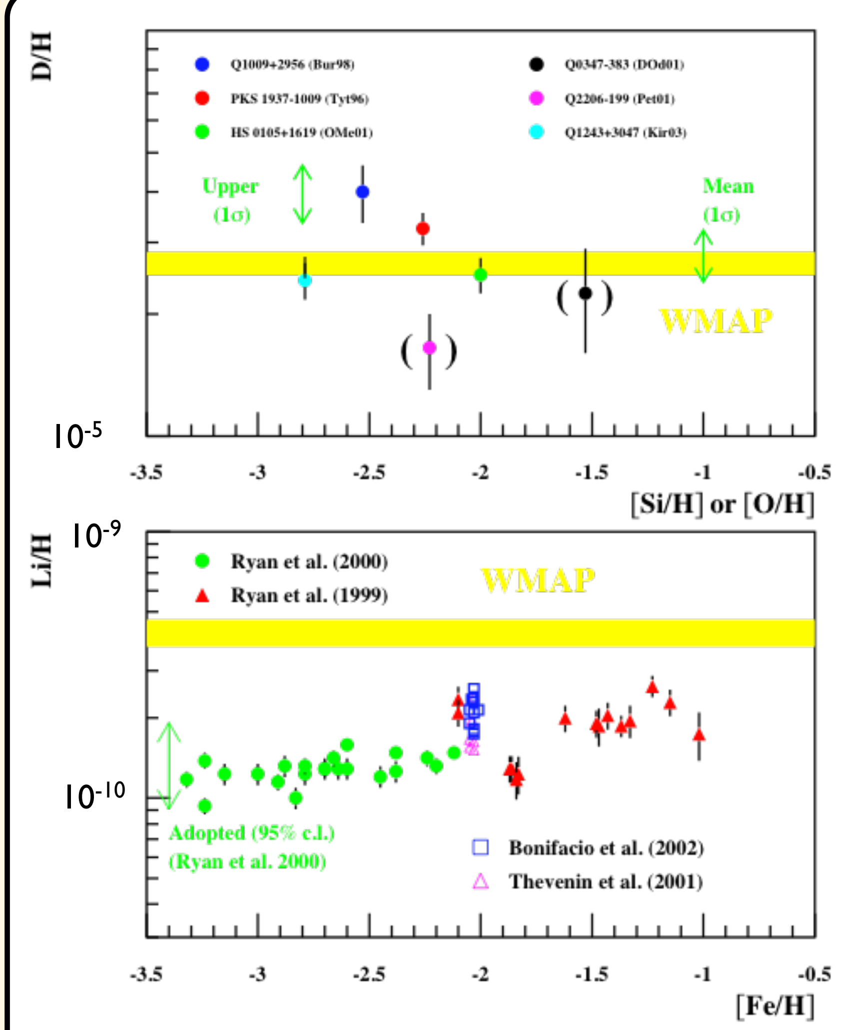
QGP transition (T~170 MeV):
if separation mechanism exists, much more time (7 days vs. 3 10^{-5} s) to create emulsion, compared to Omnès model

Big-Bang Nucleosynthesis

Predictions and observational status



A. Coc, 2007



A. Coc et al., 2004

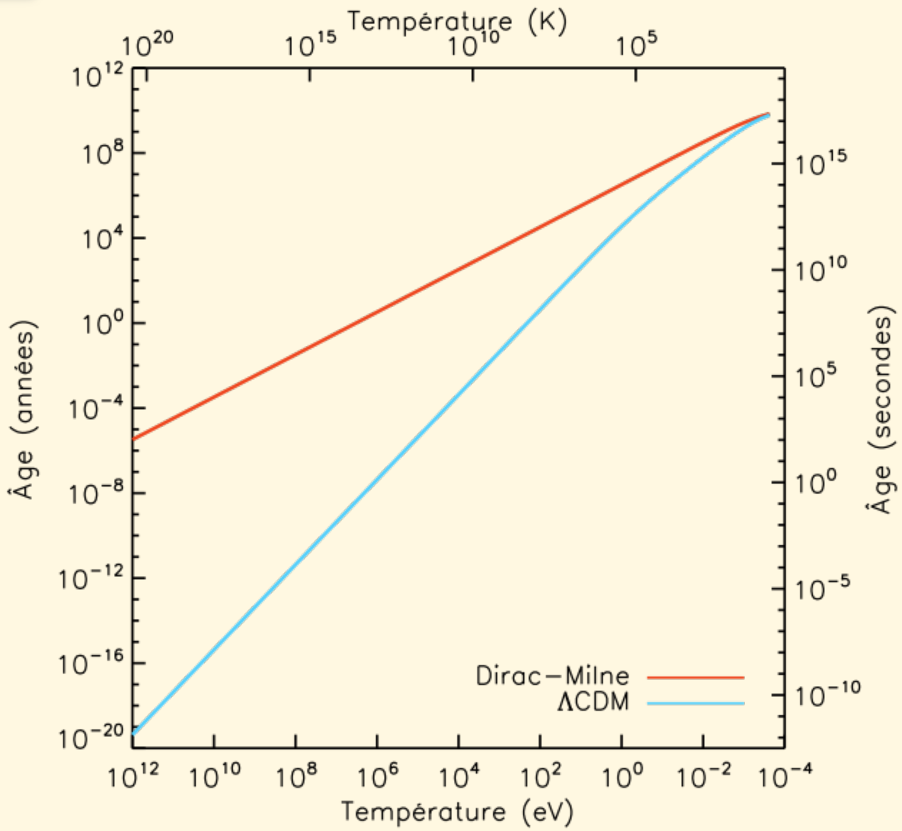
Time-temperature relation

Linear scale factor implies

$$T = \frac{T_0}{H_0}\frac{1}{t}$$

At high temperatures, Dirac-Milne universe is much older than Standard universe

	Standard Model	Dirac-Milne	Ratio
T= 170 MeV	3×10^{-5} sec	7 days	1.7×10^{10}
T = 1 MeV	1 sec	3.3 yr	10^8
T = 80 keV	~200 sec	41 yr	6.5×10^6
T = 3000 K	380 000 yr	12×10^6 yr	32



QGP transition (T~170 MeV):
if separation mechanism exists, much more time to create emulsion, compared to Omnès model

Different thermal history

Weak expansion rate implies late decouplings in Dirac-Milne universe

Weak interactions decoupling

Example of important changes induced by linear scale factor

Weak interactions decoupling:

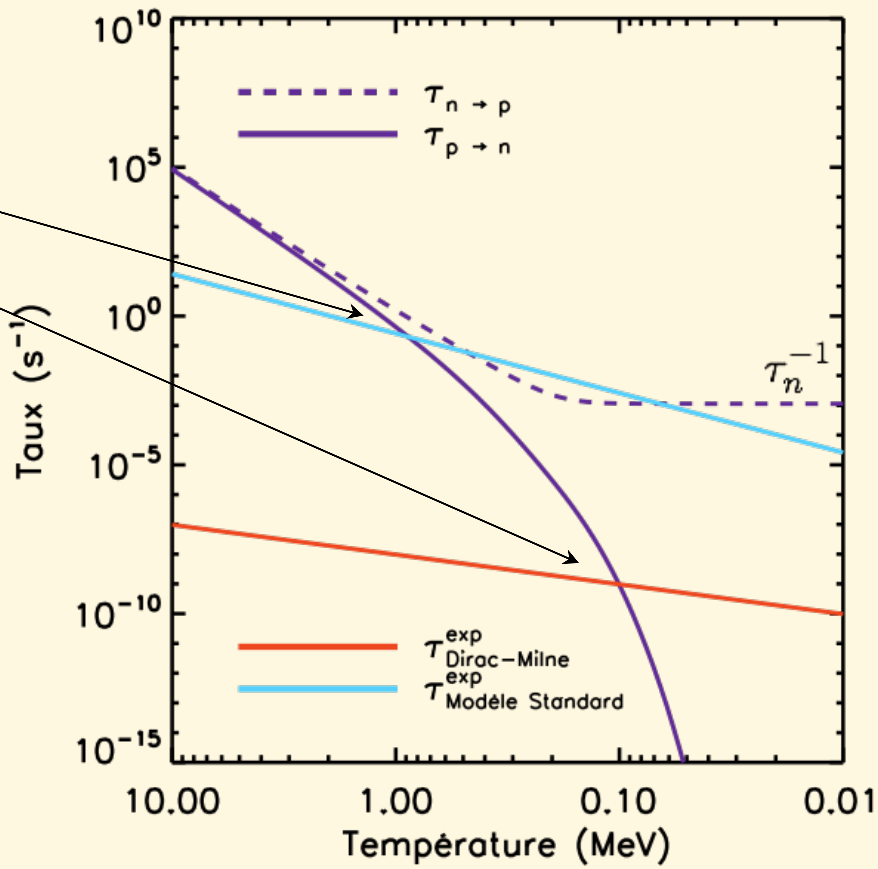
Standard model: 1 MeV
Dirac-Milne: 80 keV

Neutrinos decoupling after e^+e^- annihilation

Neutrino background temperature same as CMB
(Lohiya et al. 98)

Standard model $T_\nu = 1.94$ K

Dirac-Milne $T_\nu = T_{CMB} = 2.725$ K



Big-Bang Nucleosynthesis

Thermal episode : production of ^{4}He (Lohiya et al. 98 & Kaplinghat et al. 00) and ^{7}Li

Thermal nucleosynthesis mechanism largely different from standard one

$$\frac{n}{p} = e^{-Q/T}$$ down to 80 keV

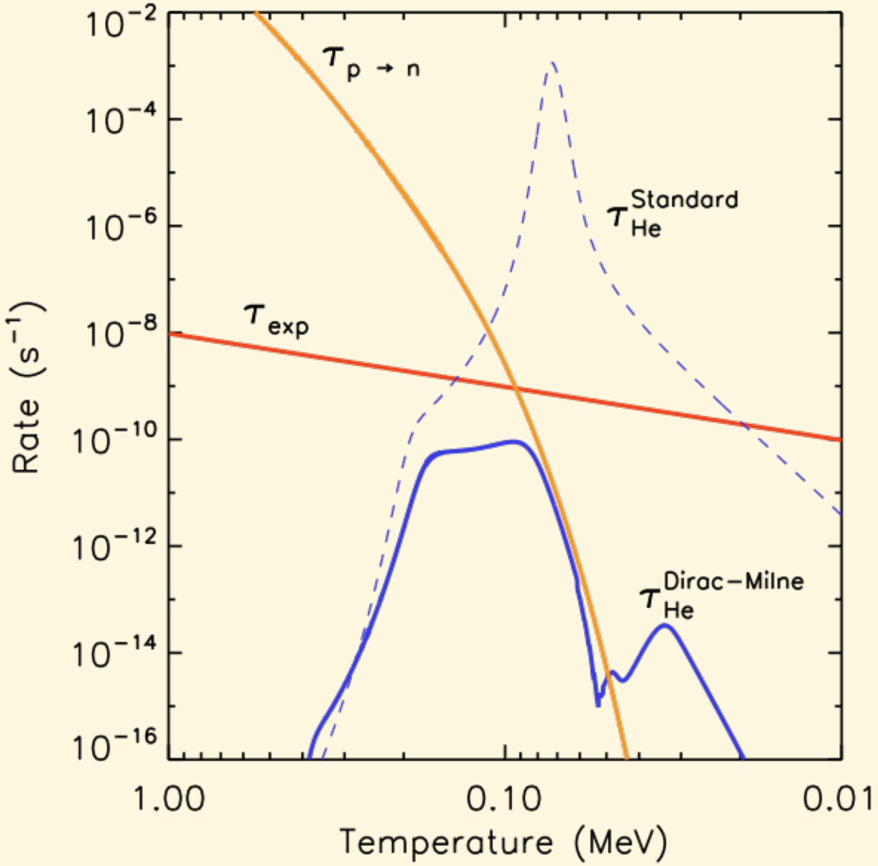
Still a small quantity, but very long time available (~40 yr)

Few neutrons are incorporated in nuclear network, but are regenerated from protons as weak interactions are maintained

Second branch of BBN: helium production at equilibrium

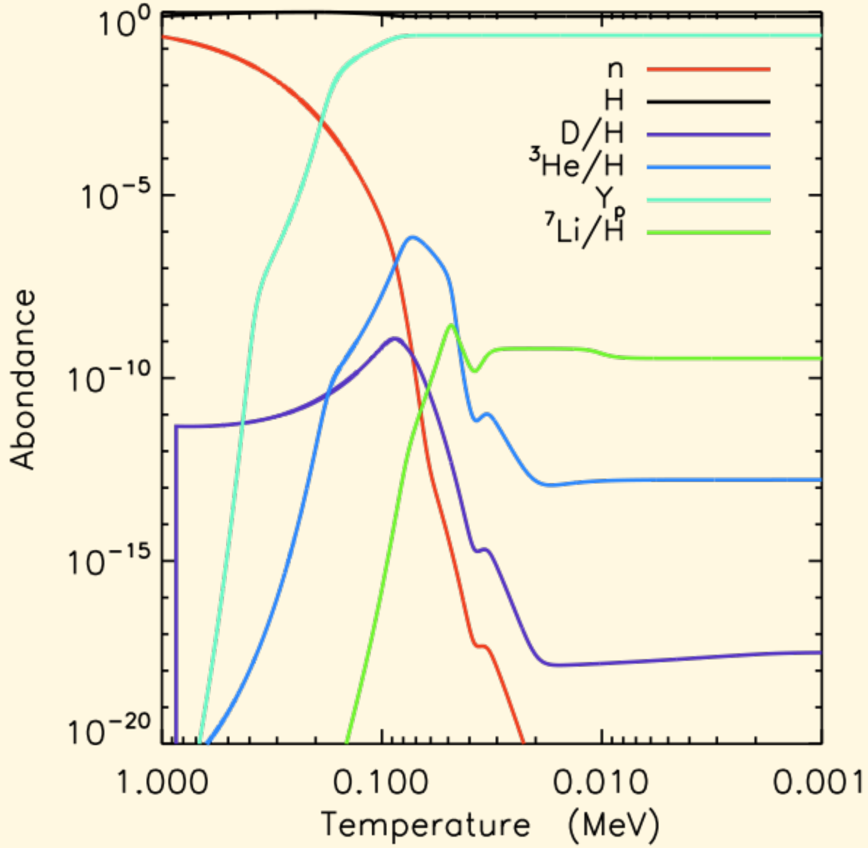
Modification of A. Coc's BBN code

Nuclear network up to ~40 nuclei and ~100 reactions. Needed because of long timescale.



10^{-10} s^{-1} x 40 yrs ~ 10^{-3} s^{-1} x 200 s

Big-Bang Nucleosynthesis

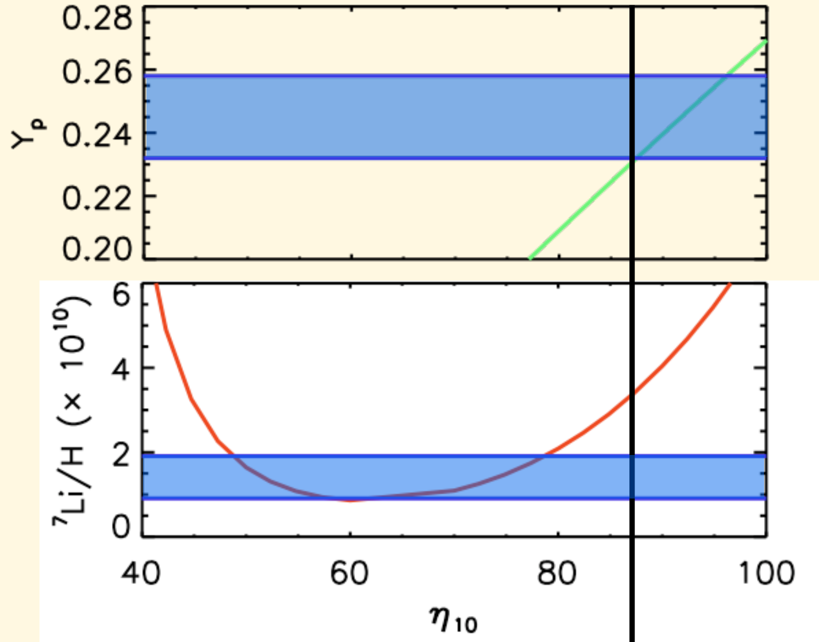


Confirms and extends previous studies (Lohiya et al. 98)

Concordant production of ^{4}He and ^{7}Li

D and ^{3}He almost totally depleted.

Considered as fatal in Kaplinghat et al. 00



$$\frac{^7\mathrm{Li}}{\mathrm{H}} = 3.45 \times 10^{-10}$$

$$8.8 \times 10^{-9} < \eta < 9.6 \times 10^{-9}$$

⇩

No longer need for *non-baryonic* Dark Matter

Big-Bang Nucleosynthesis

Production of deuterium and size of the emulsion

Annihilations at the border of domains can lead to D and ^{3}He production

$$\bar{p} + \alpha \rightarrow D, ^3He, ^3H$$

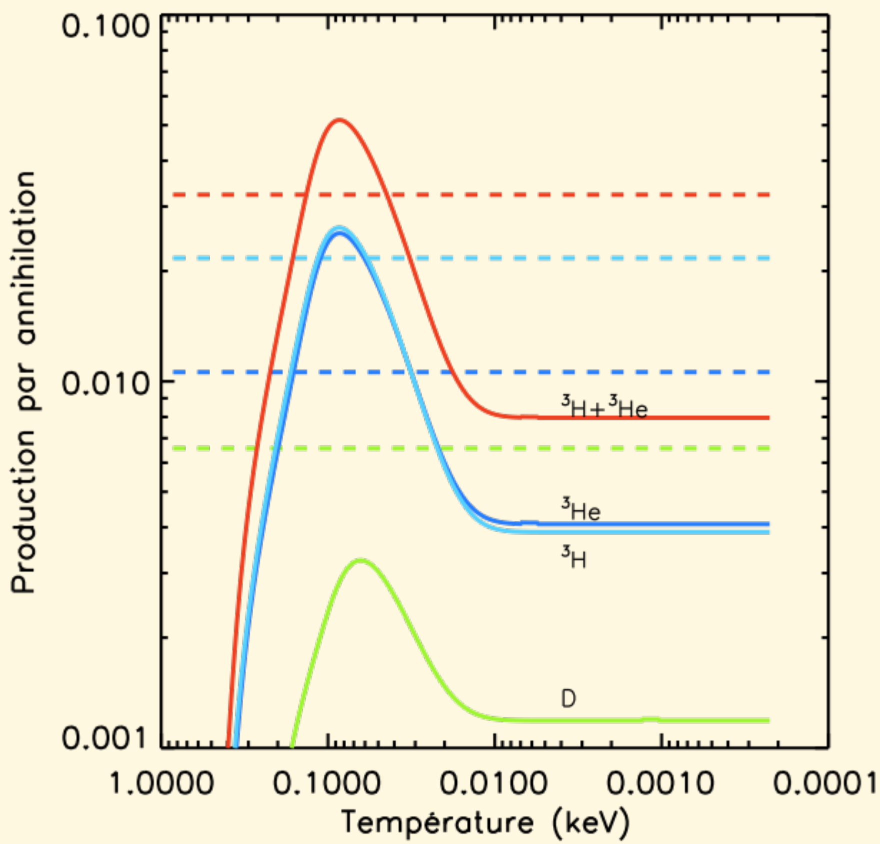
Nucleodisruption, ratios given by Balestra et al. 88

$$\bar{p} + p \rightarrow \gamma + \alpha \rightarrow D, ^3He, ^3H$$

Photodisintegration. γ, e^+e^- generates E.M. cascades

Photodisintegration starts at T~0.5 keV, when
$E_{cascade} > Q_{photo}$
Nucleodisruption is constant

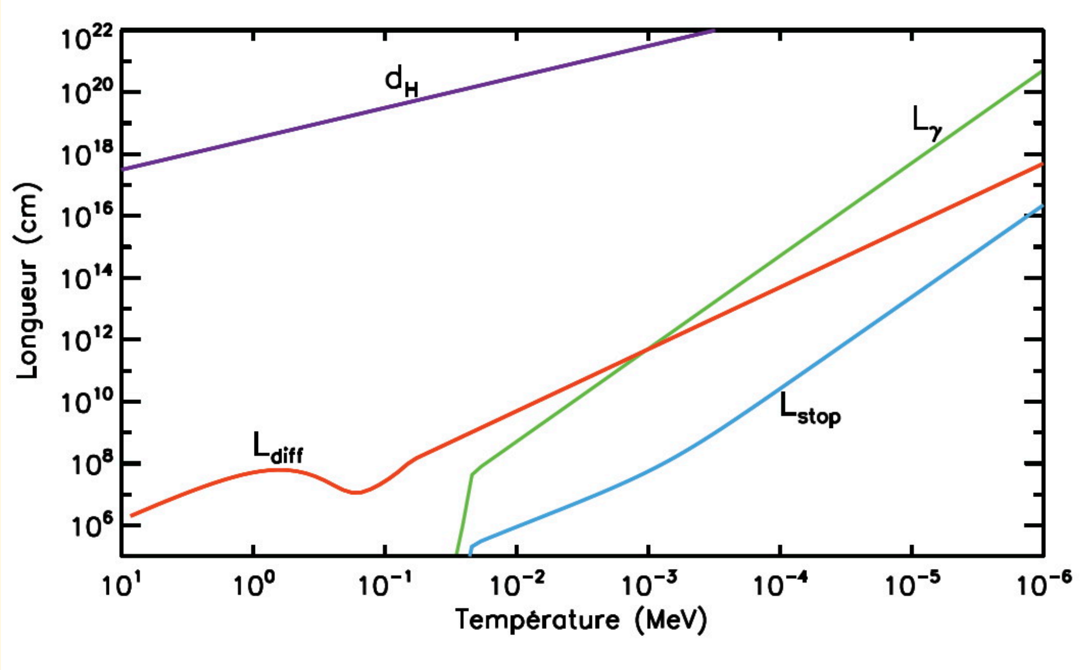
Annihilation rate ?



Big-Bang Nucleosynthesis: Deuterium

Approach based on diffusion following Combes et al. 75, Kurki-Suonio and Sihvola 00 & Rehm and Jedamzik 01

L_{diff} represents distance on which (anti)matter is annihilated in a Hubble time



L_{stop} is D stopping length

D produced by nucleodisruption (at the border) cannot survive

L_γ is 100 MeV- γ mean free path

Photodisintegration seems to be the only mean to produce deuterium

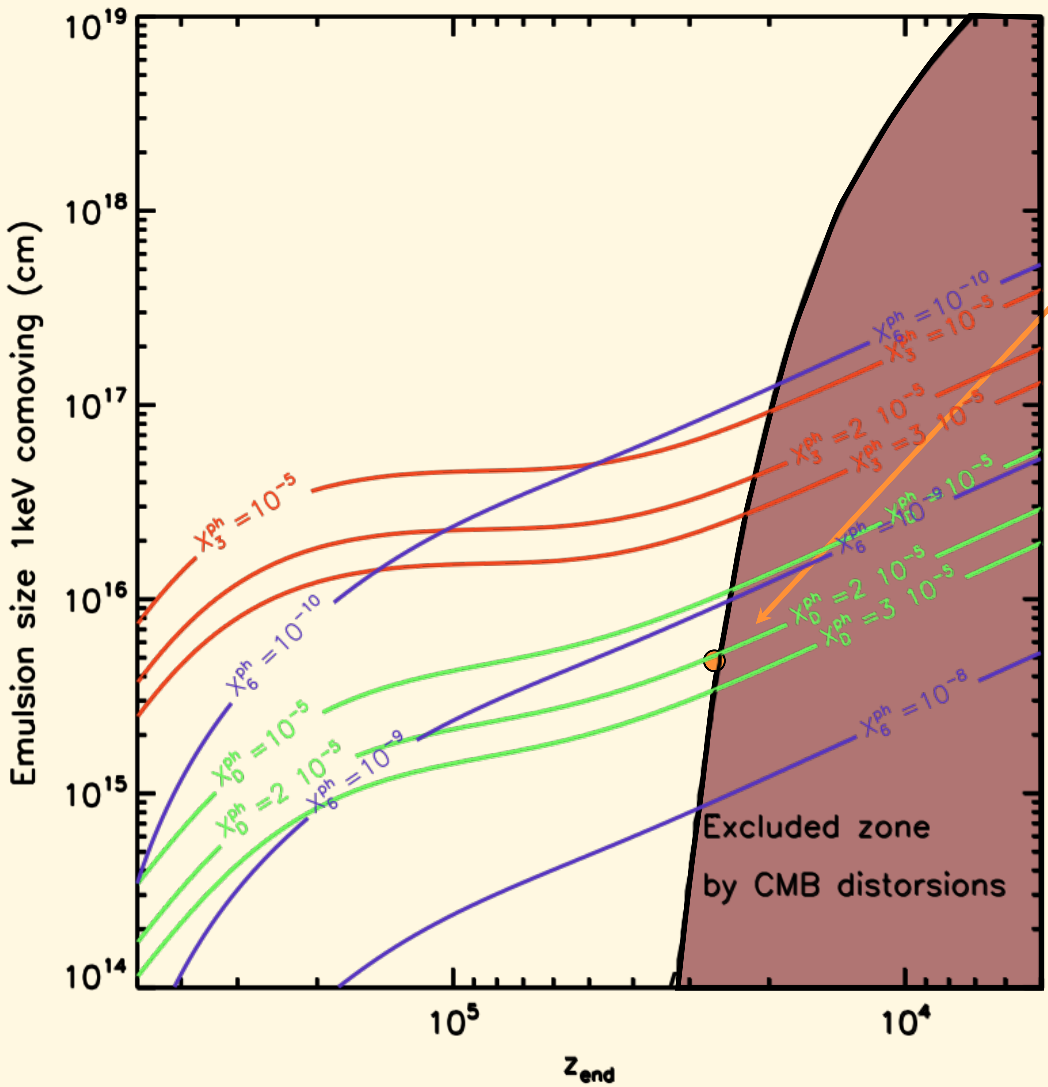
Redshift at which annihilations stop

$$X_{\rm D} = \frac{3 \times 10^{18}\ {\rm cm}}{L_{\rm 1keV}} \int_{z_*}^{z_{\rm fin}} N_{\rm D}(z) \frac{dz}{(1+z)^2}.$$

1 keV comoving size of emulsion

Redshift at which photodisintegration starts

Big-Bang Nucleosynthesis



Domain size ~7 kpc comoving, but size at the moment of production. Will evolve after recombination

^{3}He/D >> 1, possibly a constraint as ^{3}He/D is observed <1 (Sigl et al. 95)

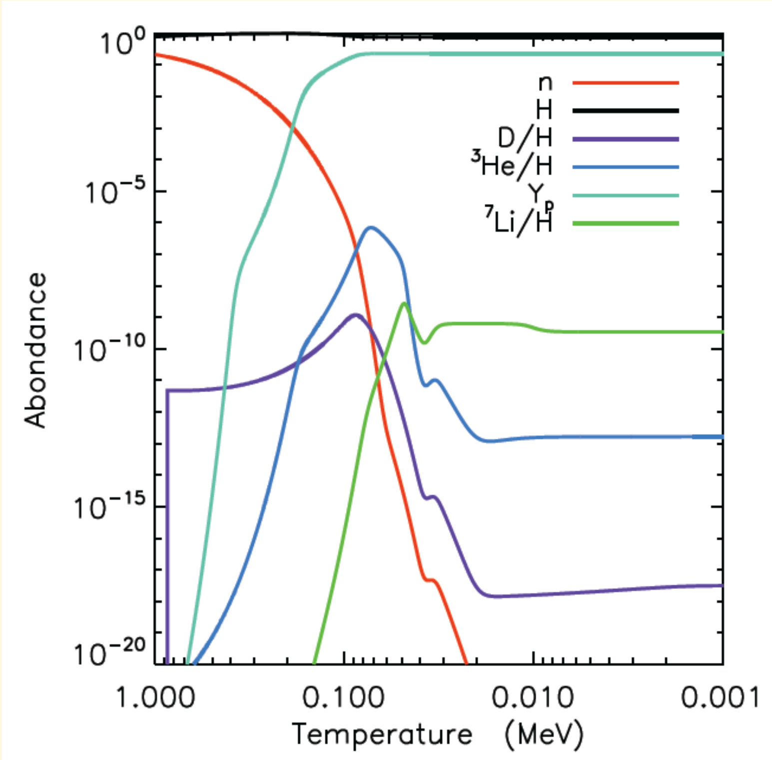
^{6}Li also probably too high:
^{6}Li/H ~2-3 x 10^{-9}

Big-Bang Nucleosynthesis in Milne Universe

Studied in Lohiya et al. (astro-ph/9902022) and Kaplinghat et al. (astro-ph/9805114)

BBN lasts in Milne Universe **lasts ≈30 years instead of ≈3 minutes**

Due to slower evolution, weak reactions decouple around 80 keV, maintaining equilibrium between protons and neutrons. Slowly, deuterium is formed and burnt into helium.
Neutrons are regenerated to restore equilibrium value



Production of adequate He-4 is possible in coasting BBN. It needs a greater baryon to photon ratio $\eta \approx 7 \times 10^{-9}$

Basically no deuterium (very fragile) left

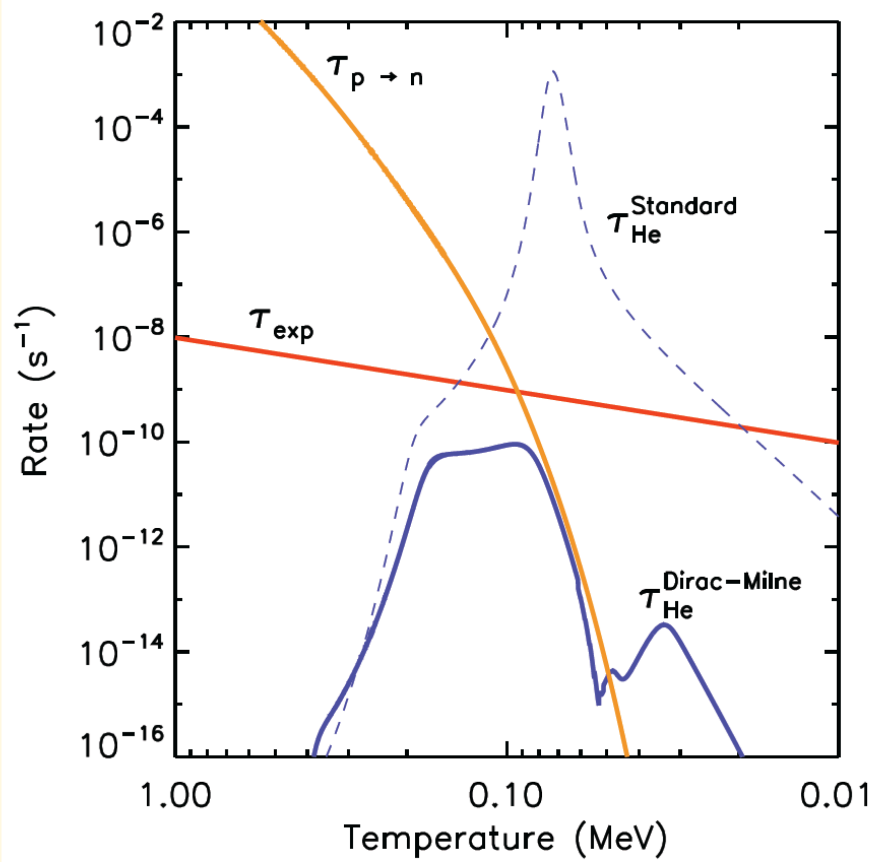
In collaboration with A. Coc (CSNSM/Orsay)

Big-Bang Nucleosynthesis in Milne Universe

Studied in Lohiya et al. (astro-ph/9902022) and Kaplinghat et al. (astro-ph/9805114)

BBN lasts in Milne Universe lasts 30 years instead of 3 minutes

Due to slower evolution, weak reactions decouple around 80 keV, maintaining equilibrium between protons and neutrons. Slowly, deuterium is formed and burnt into helium.
Neutrons are regenerated to restore equilibrium value



Production of adequate He-4 is possible in coasting BBN. It needs a greater baryon to photon ratio $\eta \approx 7 \times 10^{-9}$

No deuterium left

Type Ia Supernovae

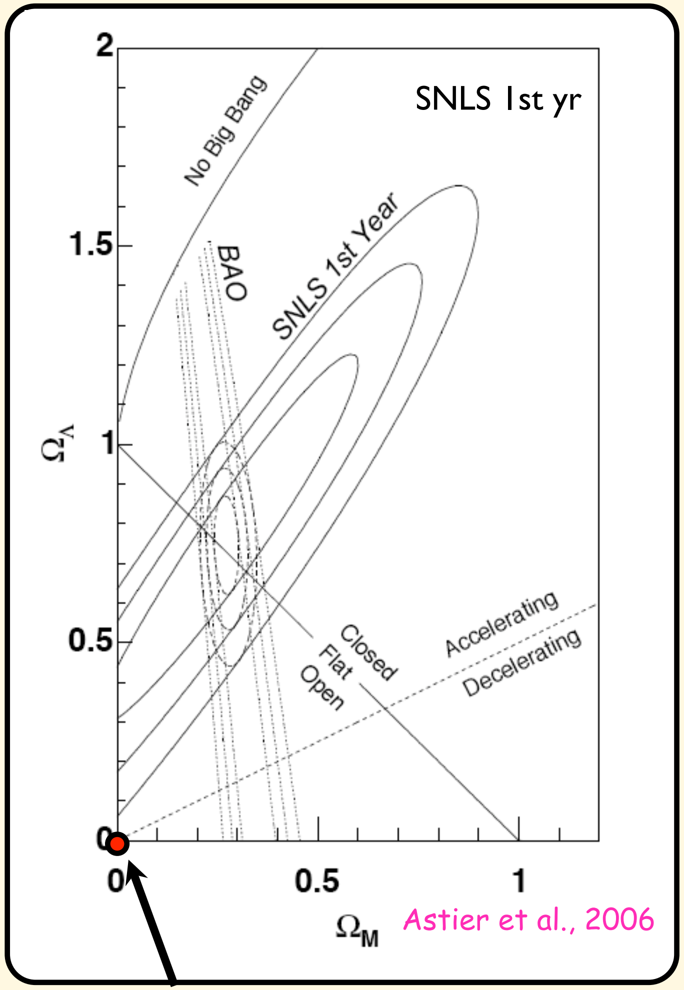
Type Ia Supernovae

Riess et al. 98 & Perlmutter et al. 99 discovered that distances measurements of SNe Ia are incompatible with an Einstein-de Sitter universe. Interpretation that our Universe is dominated by Dark Energy and that expansion is accelerating.

Type Ia SNe are commonly used to constrain cosmological parameters and possible Dark Energy redshift dependence

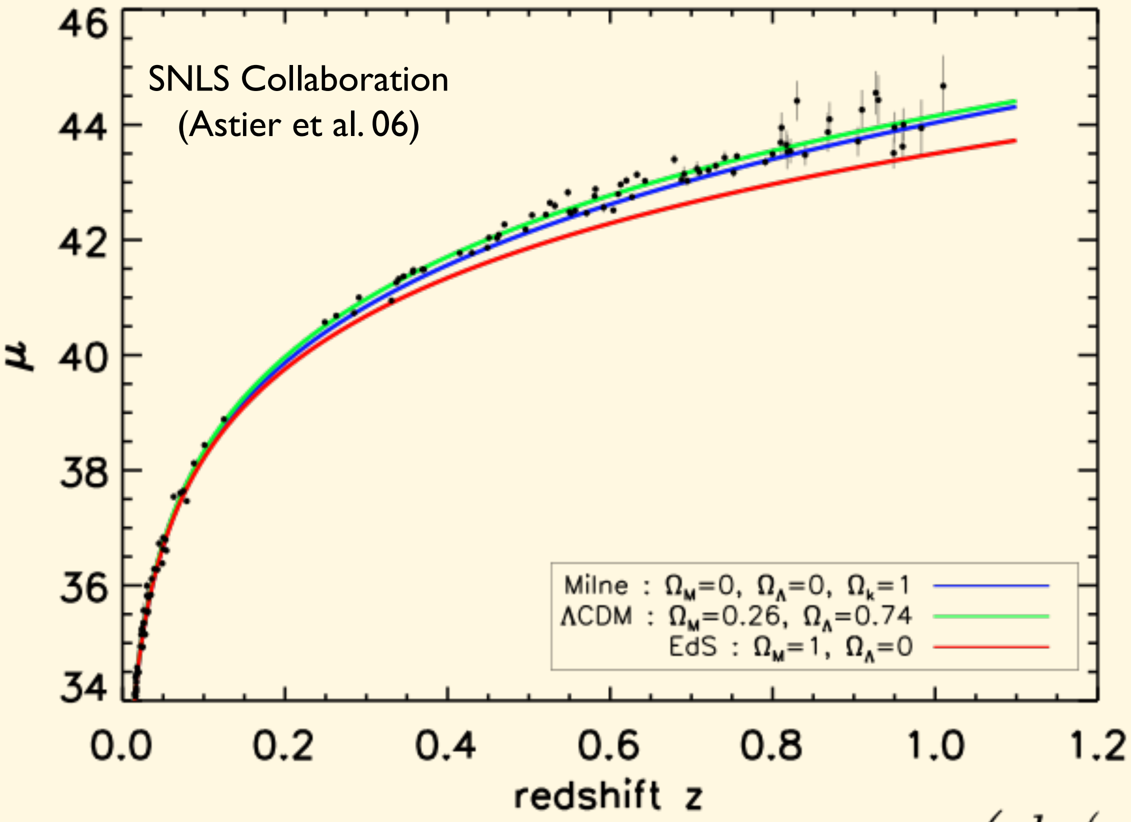
Dirac-Milne universe shows no acceleration nor deceleration

Are the data compatible ?



Dirac-Milne excluded at more than 3 σ

Hubble diagram of Type Ia Supernovae



Milne Universe (blue) is very close to ΛCDM (green) as noted in Perlmutter et al. 99

Einstein-de Sitter model seems totally ruled out

$$\mu = m - M = -5 + 5\log\left(\frac{d_L(z)}{1\text{pc}}\right)$$

Unknown parameter

Type Ia Supernovae

Cosmology with type Ia supernovae

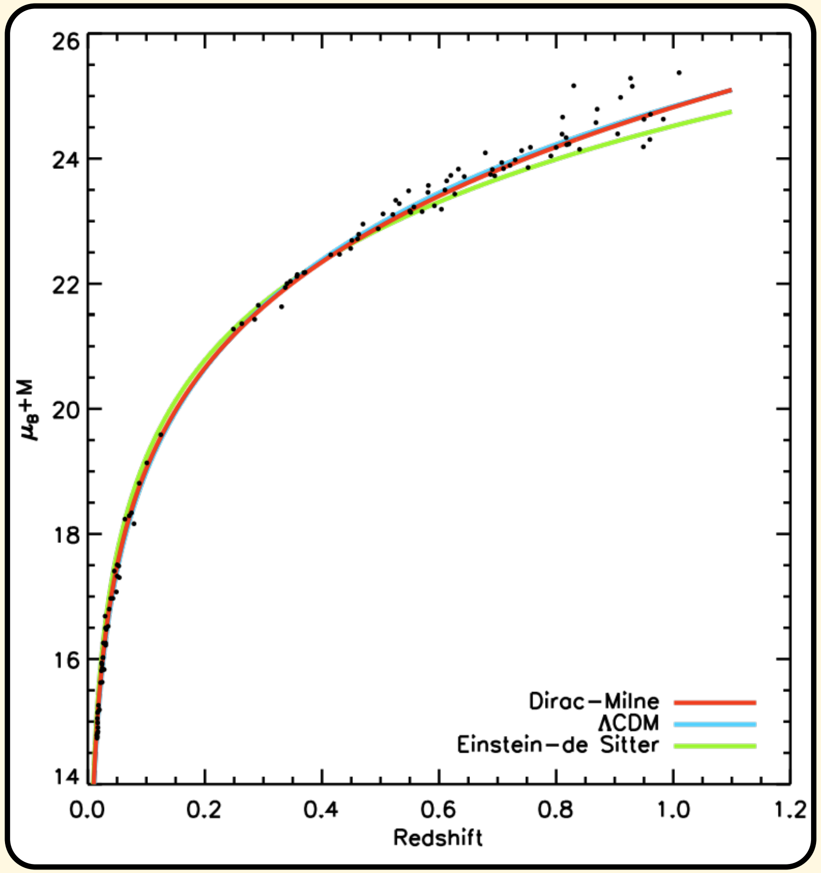
$$\mu = 5 \log \left(\frac{d_L(z)}{10 \text{ pc}} \right)$$

Measured data

$$\mu = m - M + \alpha (s - 1) - \beta c$$

Unknown parameters. Same for all SNe Ia

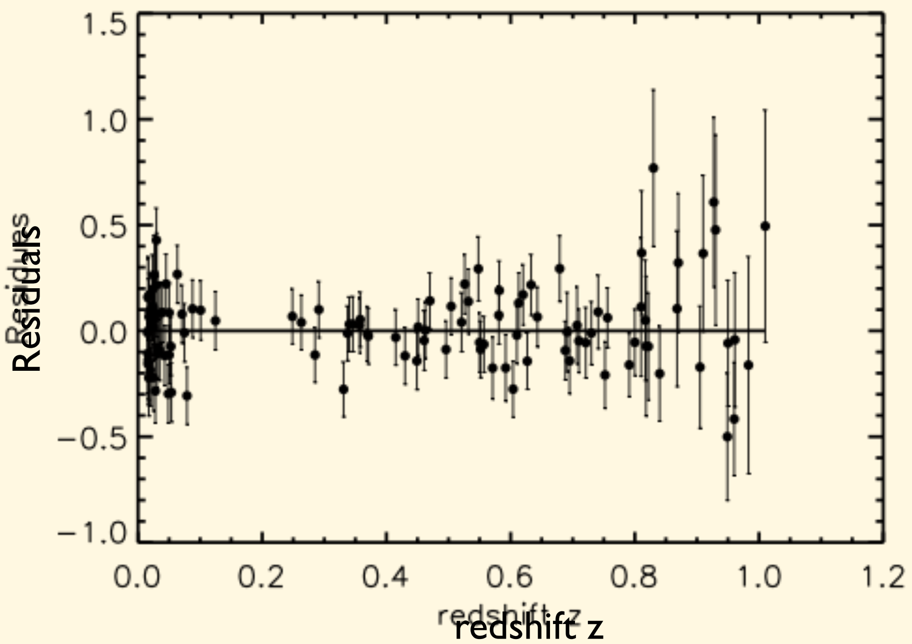
M is SN Ia absolute magnitude.
M will be different for each fit, i.e. different for each model.
Hubble diagram should be ...

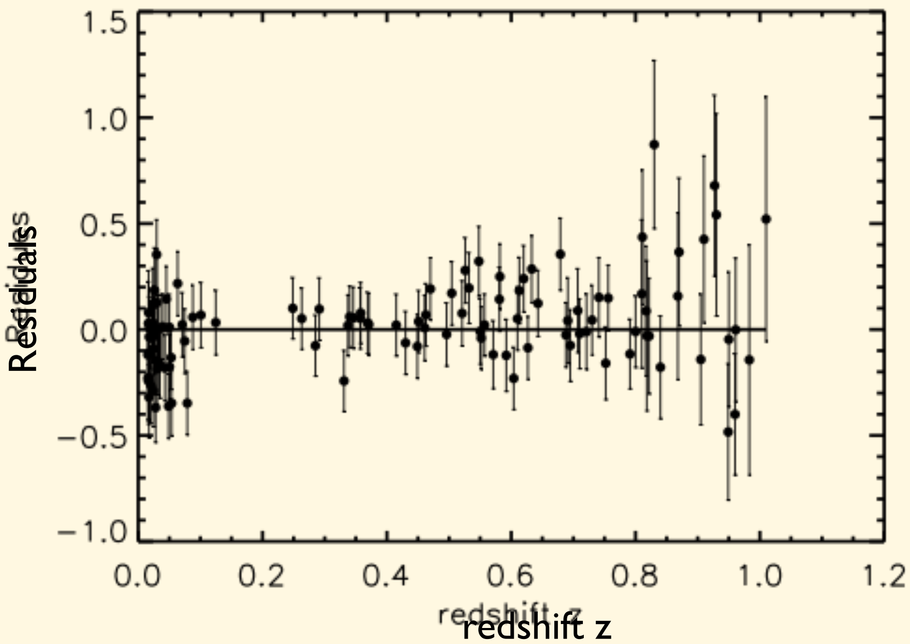


Residuals of Hubble diagram for the two models

Absolute magnitude parameter M unconstrained for Milne

Which one is Milne ? Which one is ΛCDM ?

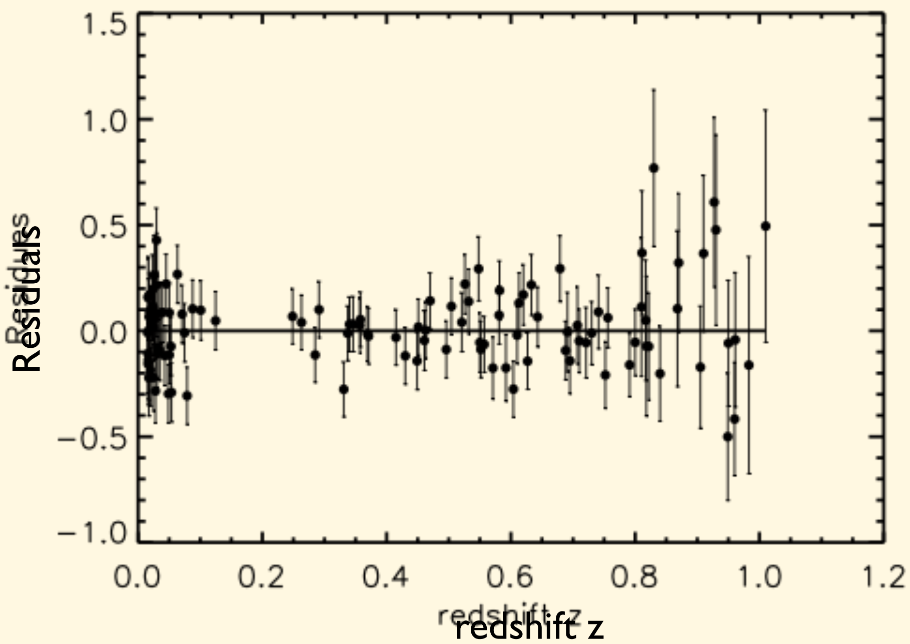




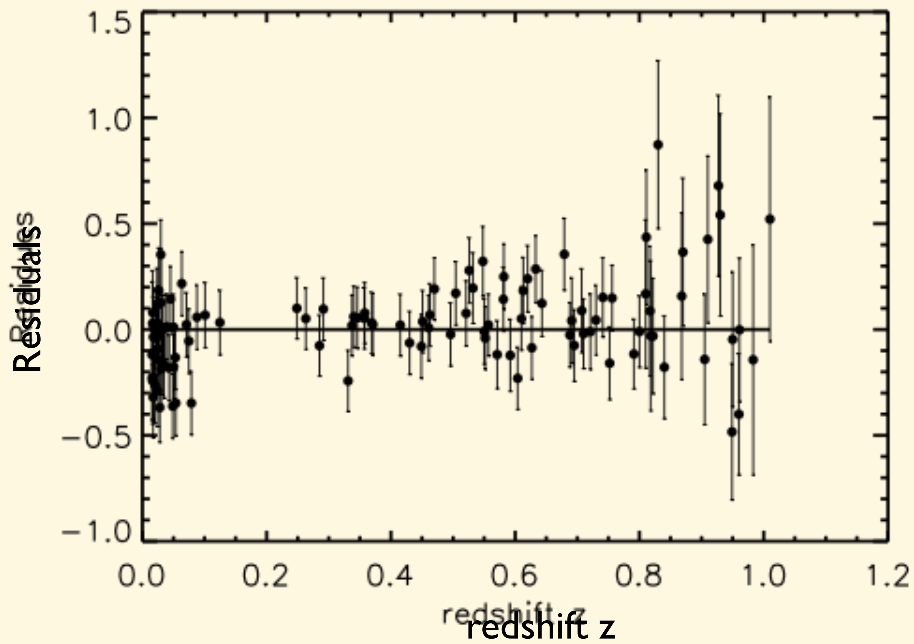
Residues of Hubble diagram for the two models

Absolute magnitude parameter M unconstrained for Milne

LCDM Best fit



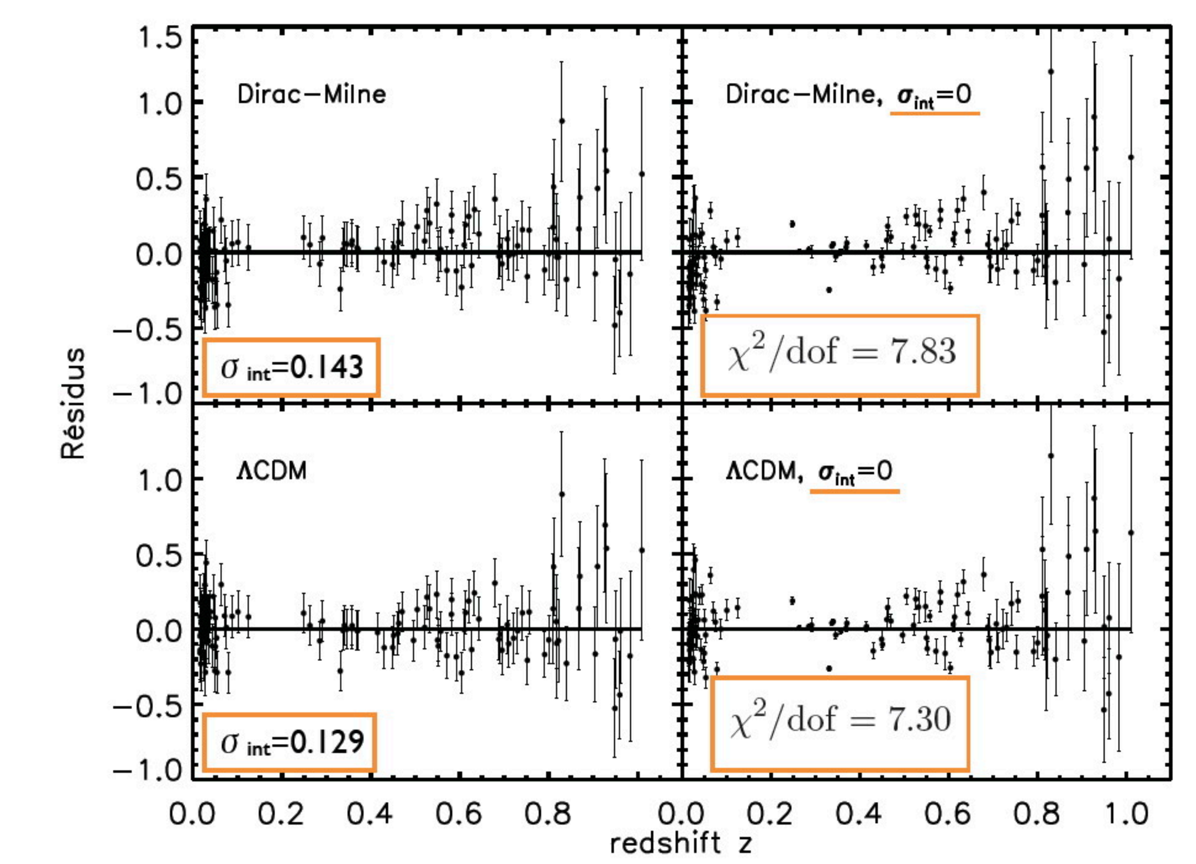
Milne - our analysis



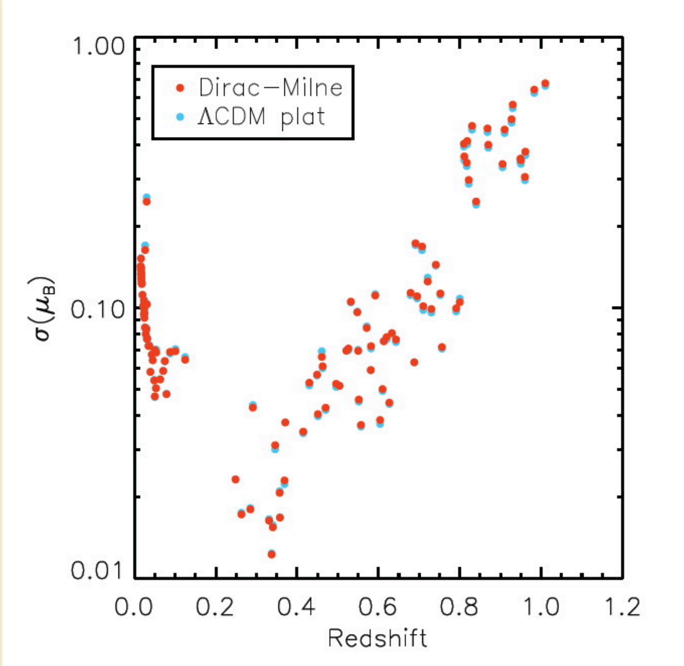
Type Ia SN test most probably does not allow to exclude the Milne model !

Residuals of Hubble diagram for the two models

Compared χ^2 for ΛCDM and Dirac-Milne



Compared errors vs. redshift



CMB

Thermalization of energy injection in CMB radiation

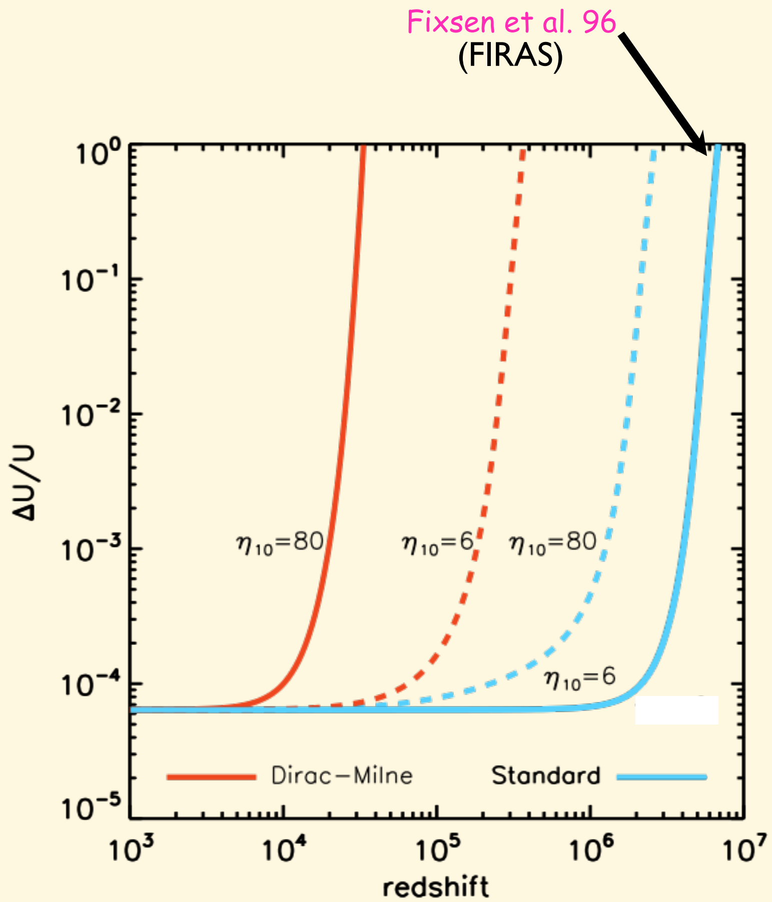
Distorsions parametrized by chemical potential

$$\mu = 1.4 \frac{\Delta U}{U} \qquad f_{\mathrm{BE}} = \frac{1}{e^{x_e+\mu} - 1}$$

Compton scattering	$\gamma + e \leftrightarrow \gamma + e$
Bremsstrahlung	$e + N \leftrightarrow e + N + \gamma$
Double Compton scattering	$e + \gamma \leftrightarrow e + \gamma + \gamma$

These radiative processes create/destroy/redistribute photons to restore spectrum towards Planck distribution

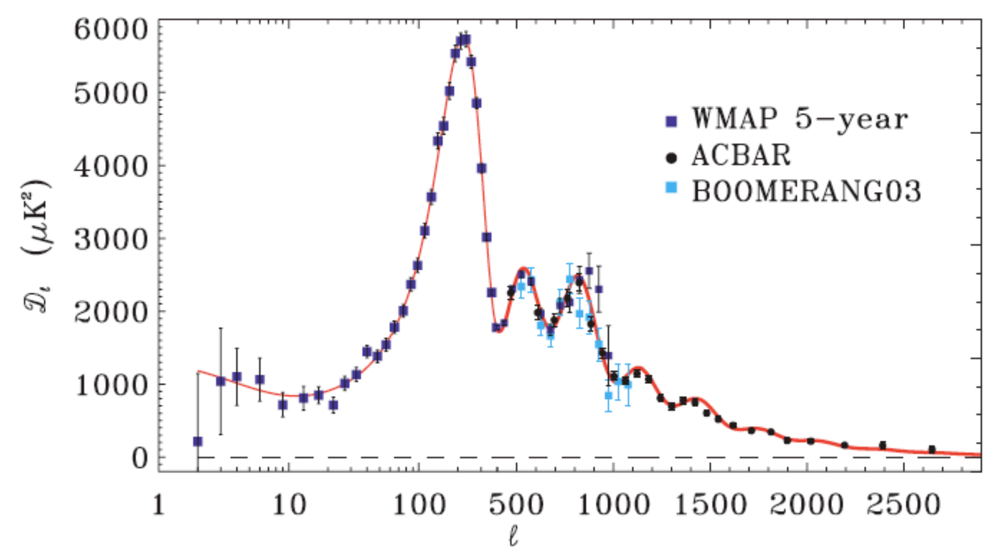
In Dirac-Milne universe, due to slow evolution and more baryons it is possible to inject energy in CMB down to z ~ 3 x 10^4



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 40 MeV to ~7 eV (end of annihilation, cf BBN) yields acoustic scale around 1°

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

Conclusions (1)

Dirac-Milne constitue un modèle d'univers assez remarquablement concordant et naturel
Il permet d'éliminer plusieurs problèmes fondamentaux (constante cosmologique, fine-tuning, causalité et inflation) du Modèle Standard cosmologique

Mais plusieurs questions ouvertes ou contraintes fortes:
- transition QCD vers 170 MeV: pas de crossover (avis assez général), mais transition de premier ordre (sinon disparition presque totale de la matière)
- si transition QCD du premier ordre, beaucoup plus favorable que modèle d'Omnès (taille des domaines)
- nucléosynthèse primordiale remarquablement concordante, mais produire le deutérium observé engendre trop d'hélium-3 (facteur 5 à 10) (mal mesuré ?

Conclusions (2)

- Coïncidence à nouveau étonnante: l'horizon sonore dans l'univers de Dirac-Milne est d'environ 1 degré comme observé dans le CMB
- mais pour le moment juste un calcul d'ordre de grandeur
- le BAO (Baryon Acoustic Oscillations) est difficile à expliquer dans l'univers de Dirac-Milne ; il ne peut pas correspondre à la longueur de l'horizon sonore (longueur énorme)
- il doit correspondre à une longueur d'évolution dans le régime non-linéaire (exemple des simulations de Dubinski)
- la taille des domaines matière ou antimatière au moment où l'univers devient transparent n'est pas un paramètre libre (même s'il n'est pas facile de la calculer exactement)
- la masse concernée pour un domaine est de l'ordre d'une fraction de masse solaire à quelques dizaines de masses solaires
- Fuutur: test direct via l'expérience Gbar ?

Quelques références

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BACKUP SLIDES

Position of the first acoustic peak in Milne Universe

Angular scale of first peak corresponds to the angle under which is seen sound horizon at decoupling

Angular distance

In Milne Universe, spacetime is flat. Therefore space is hyperbolic, angular distance is drastically changed. An object in the sky will be seen with a much smaller angle than in standard cosmology

$$\frac{\theta_{\Lambda CDM}}{\theta_{\rm Milne}} = \frac{d_A^{\rm Milne}(z)}{d_A^{\Lambda CDM}(z)} \overset{z=1100}{=} \sharp \quad 173$$

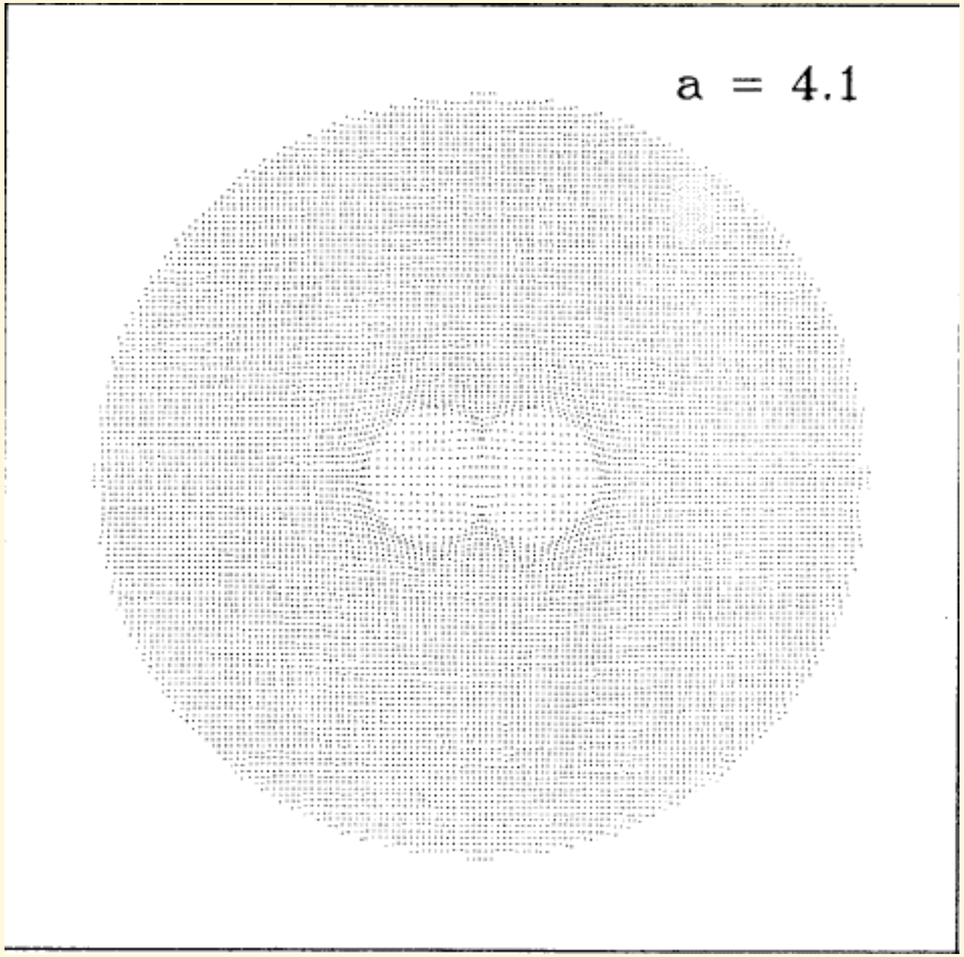
Sound horizon

Sound generation during QGP transition, caused by matter-antimatter annihilation

$$r_s = \int_{t_{170\rm MeV}}^{t_{\rm rec}} c_s \frac{dt}{a(t)}$$

Finally, we obtain $\theta_{\rm Milne} \approx 1.2^\circ$. One degree scale, just like the observed scale !

Negative mass in GTR (Dubinski et al.)



Negative mass in GTR (Dubinski et al.)