# Flat rotation curves, MOND-like behavior and CMB spectrum in the Dirac-Milne universe

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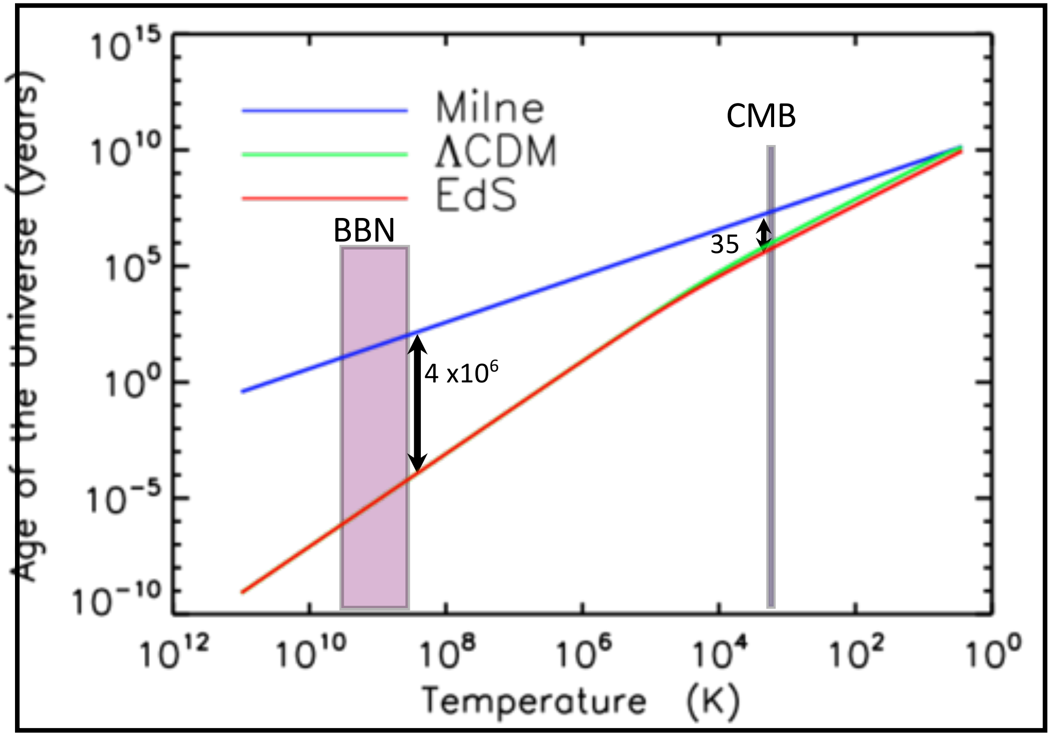
# The Dirac-Milne universe

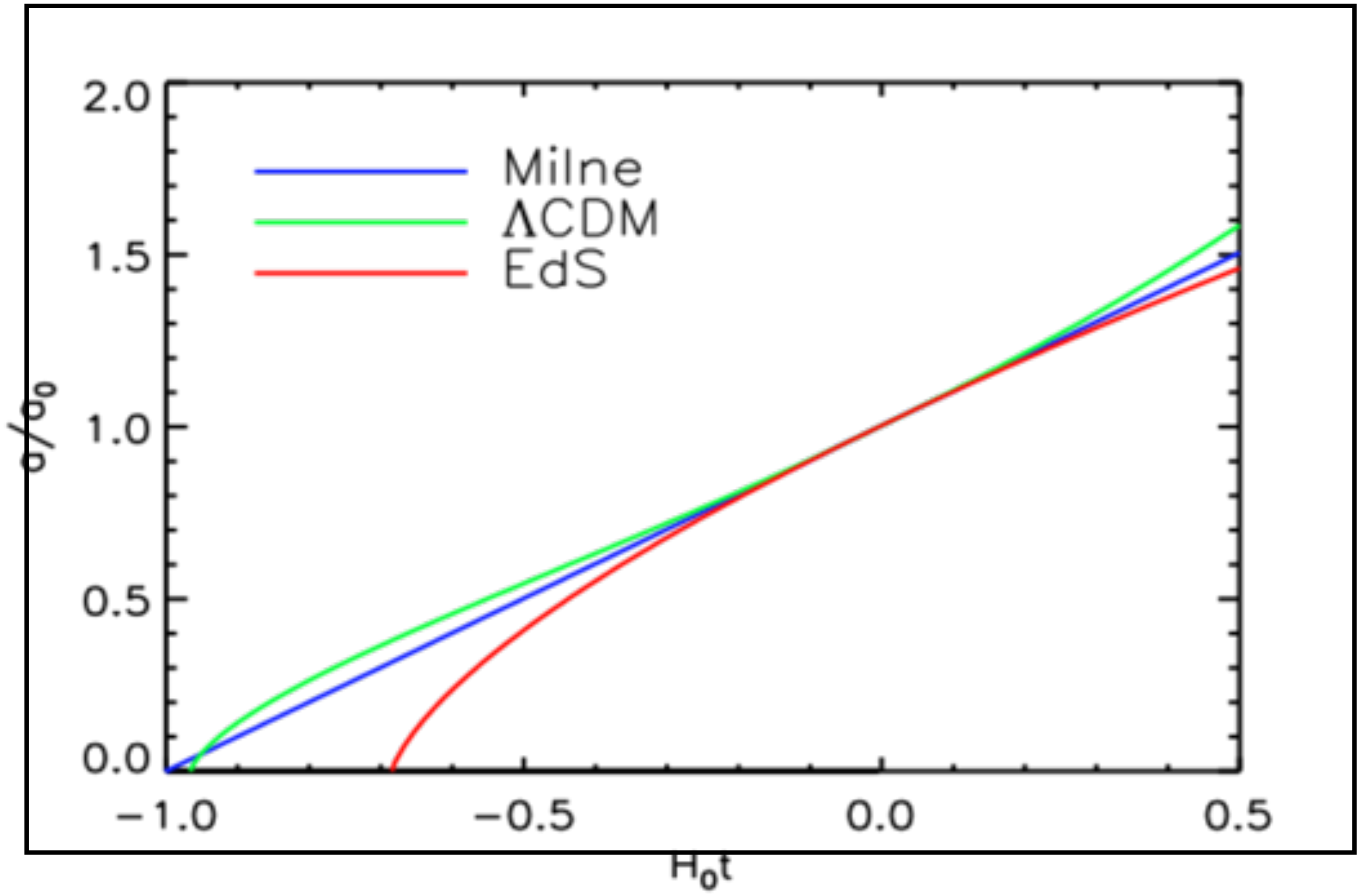
- Dirac-Milne : a universe with equal quantities of positive (matter) and « negative » (antiparticle) mass particles
- This is the Dirac « particle-hole » system, analog to electron-hole system in semiconductors, avoids annihilation between matter and antimatter (see simulations below)
- Dirac-Milne universe is a “ coasting ” universe (see review by Casado, Astrophys Space Sci 365:16 (2020))
- Age, luminosity distance (supernovae), and even nucleosynthesis are remarkably concordant
- What about the evidence for Dark Matter, BAO and CMB ?

# 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)

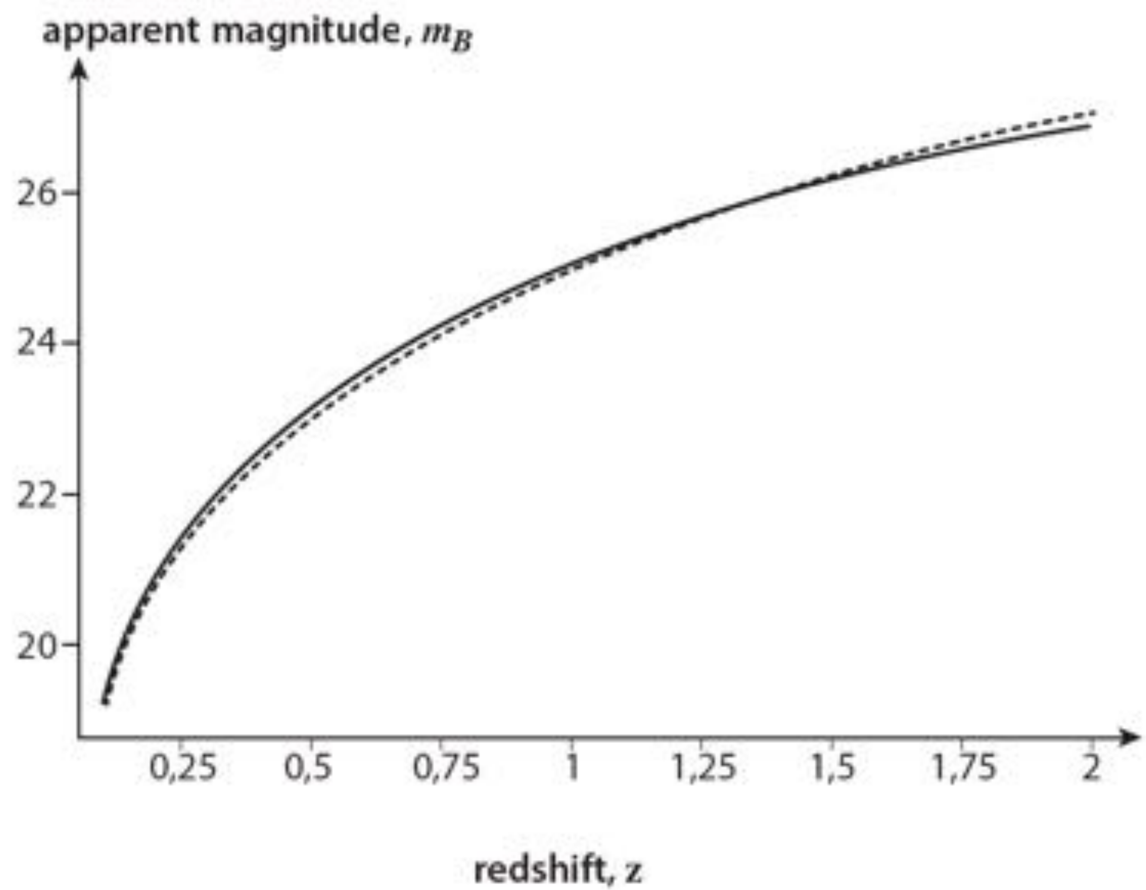


# Age of the Milne universe



# Supernovae SN1a

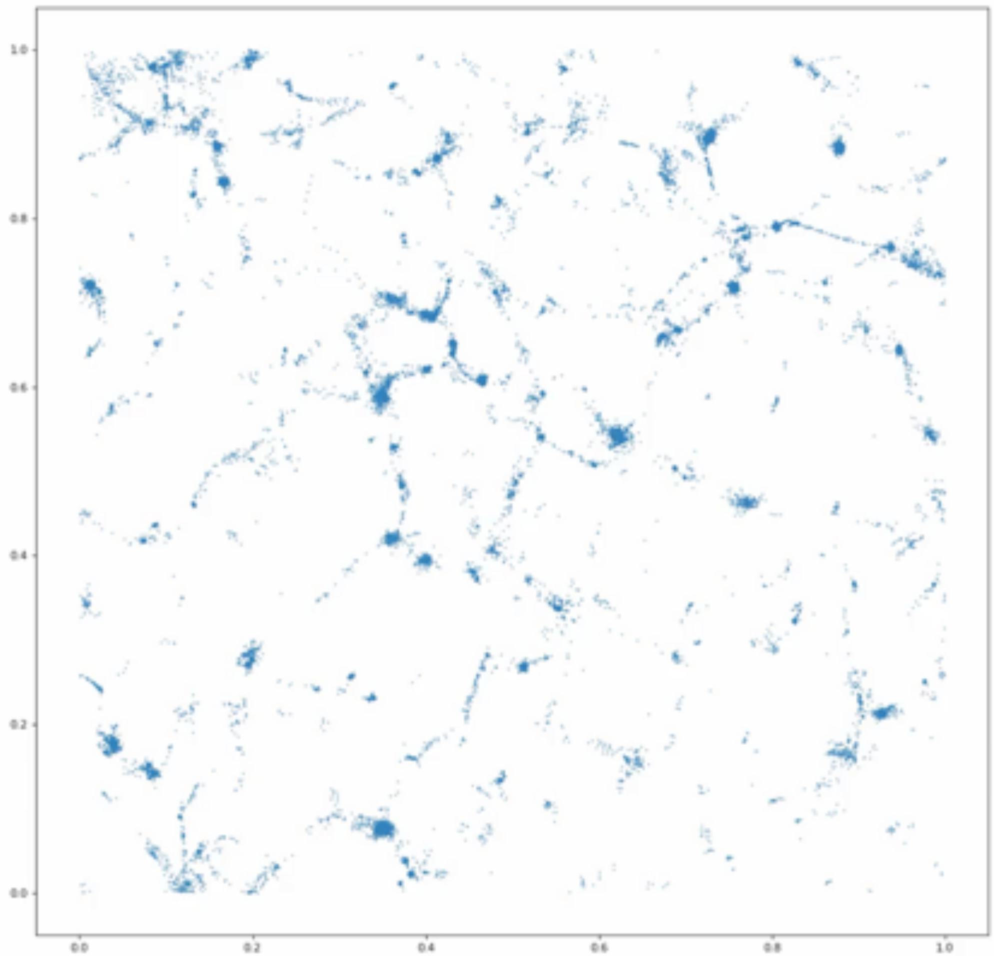
M. J. Chodorowski, « Cosmology under Milne's shadow »
Proc. Astron. Soc. Australia 22 (2005) 287



# Structure formation (1)

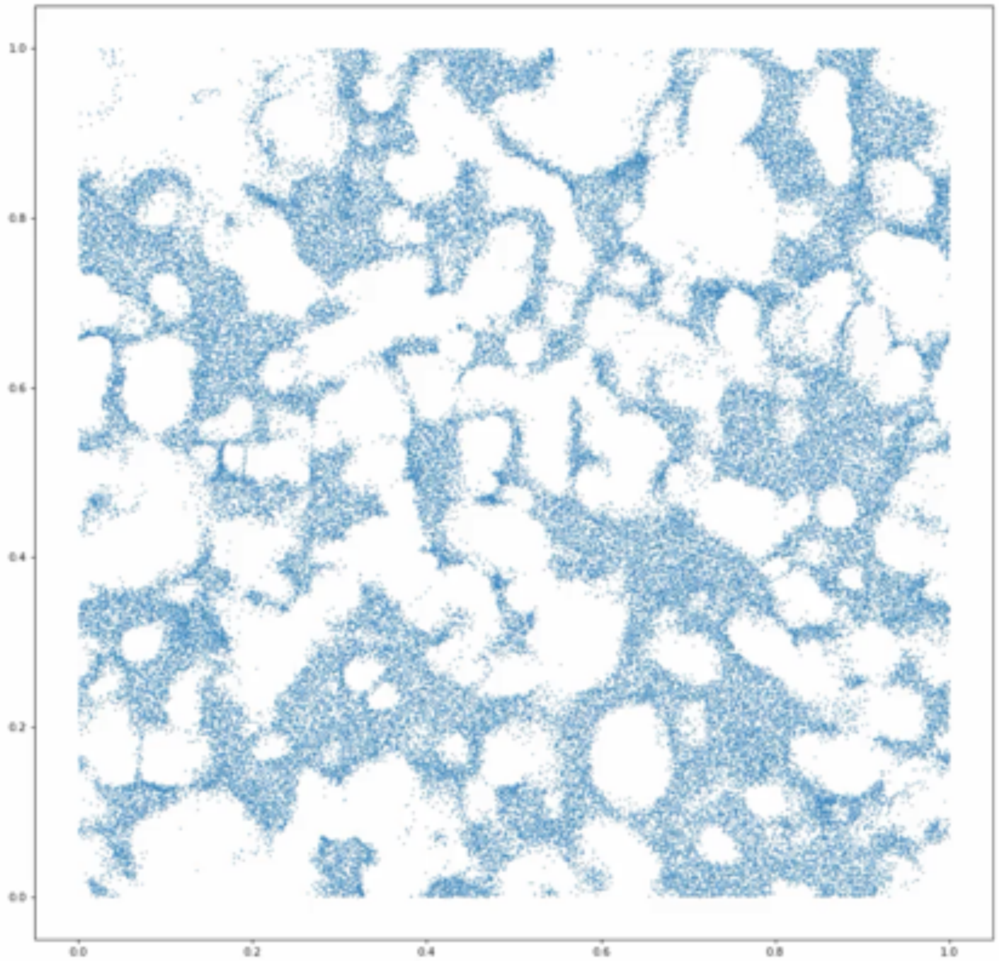
Immediately in the non-linear regime

Matter structure looks approximately as in standard model (nodes, filaments, planes and voids)



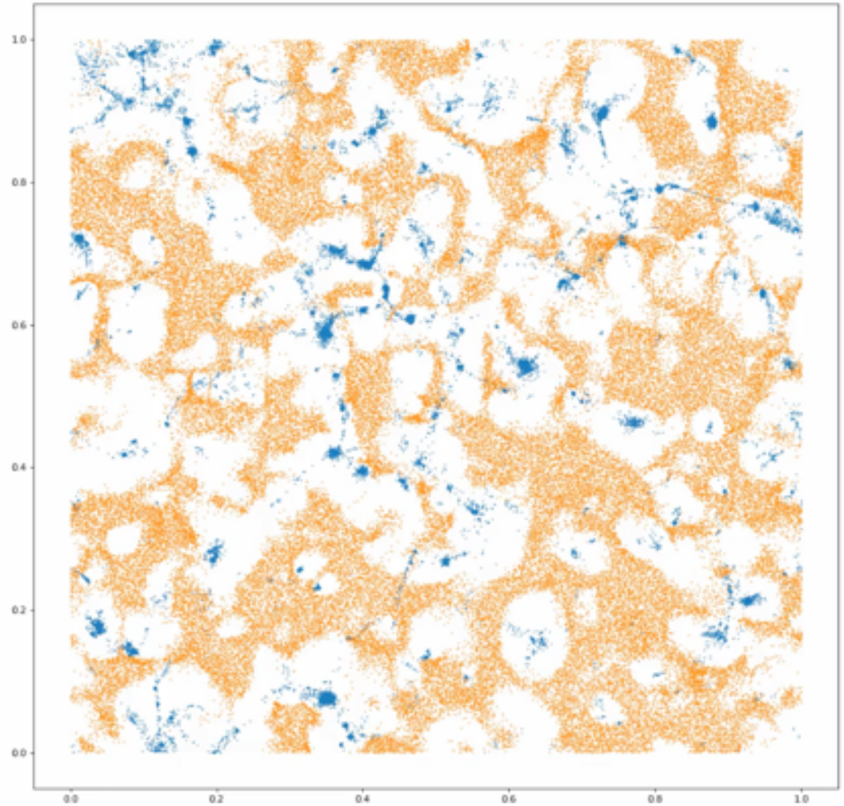
# Structure formation (2)

Antimatter is spread out with approx. constant density



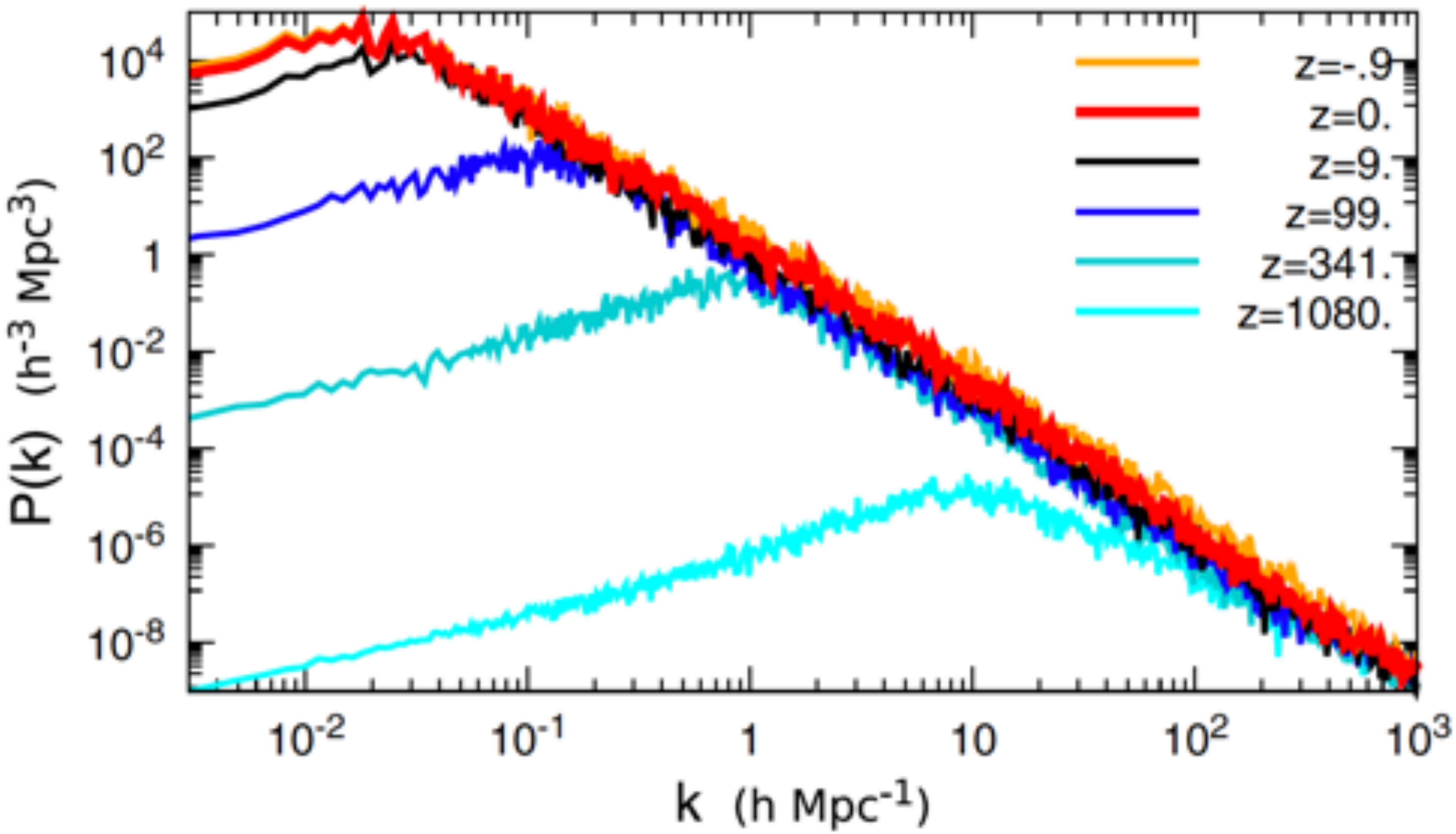
# Structure formation (3)

- The usual matter (condensed) structures (in blue)
- Two new fundamental elements:
  - Antimatter, of “ negative mass ” is spread out in homogeneous clouds (≈50% of the volume, in orange)
  - Depletion zones around matter structures (also ≈50% of the total volume)



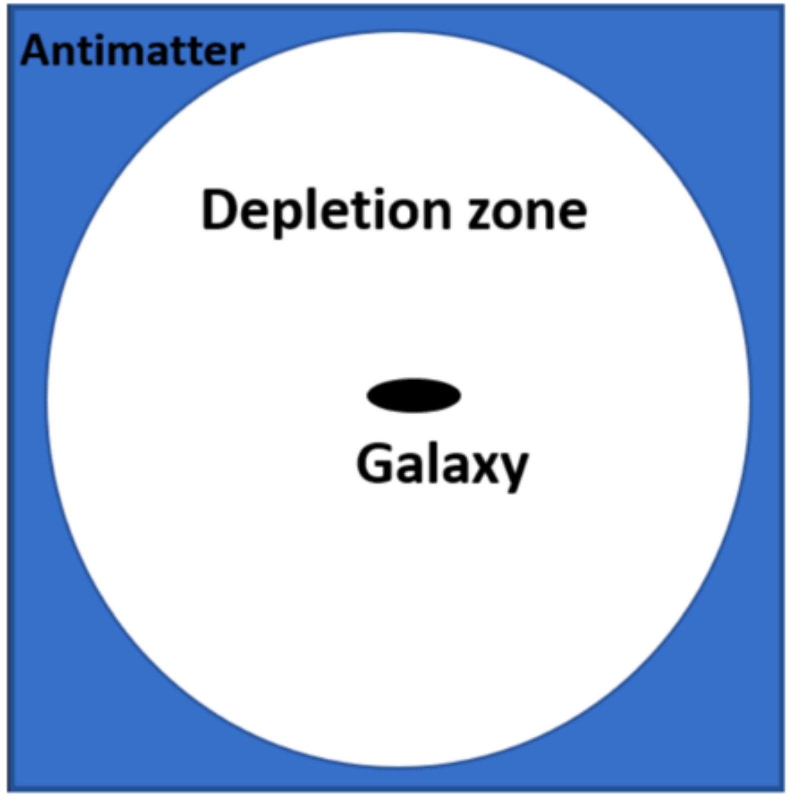
Evolution of power spectrum peak for Dirac-Milne ($k = 2\pi/\lambda$)

G. Manfred, J-L. Rouet, B. Miller, and G. Chardin, Phys. Rev. D 102, 103518 (2020)

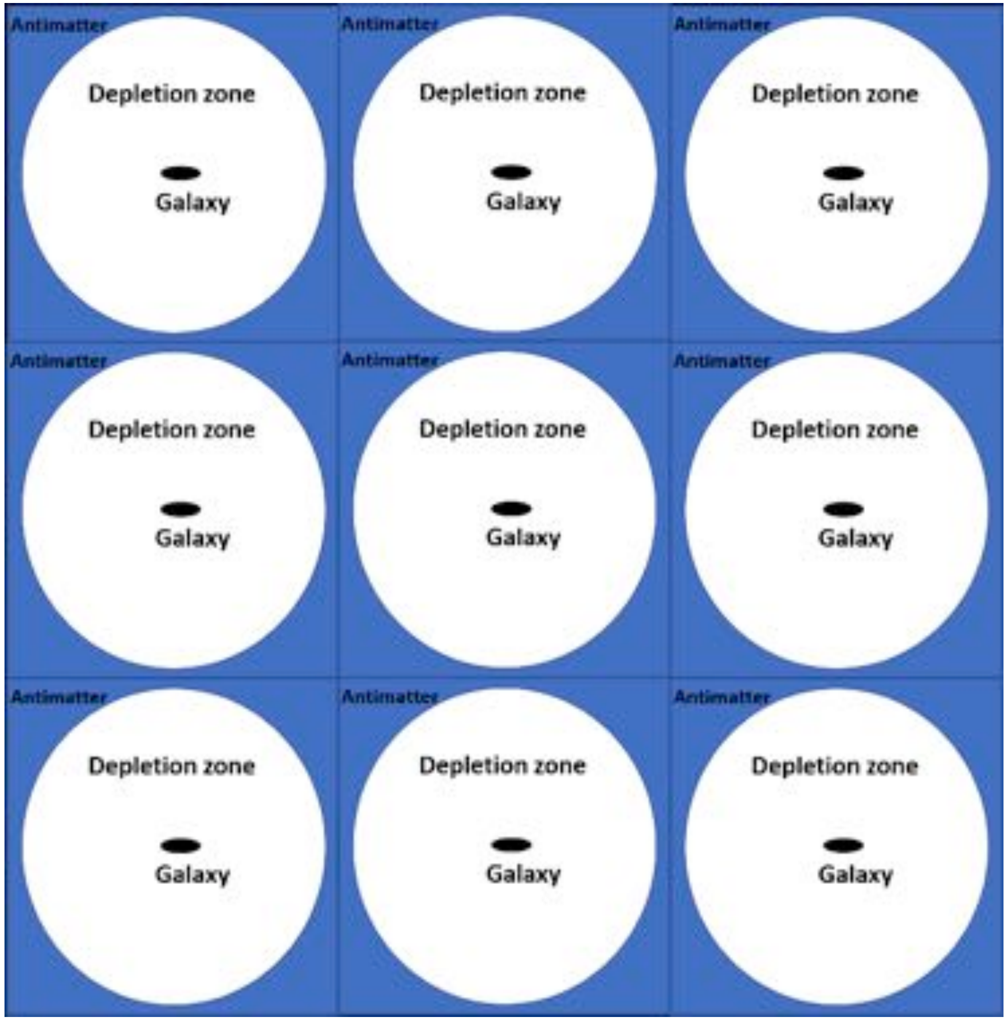


# Analytical approximation

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

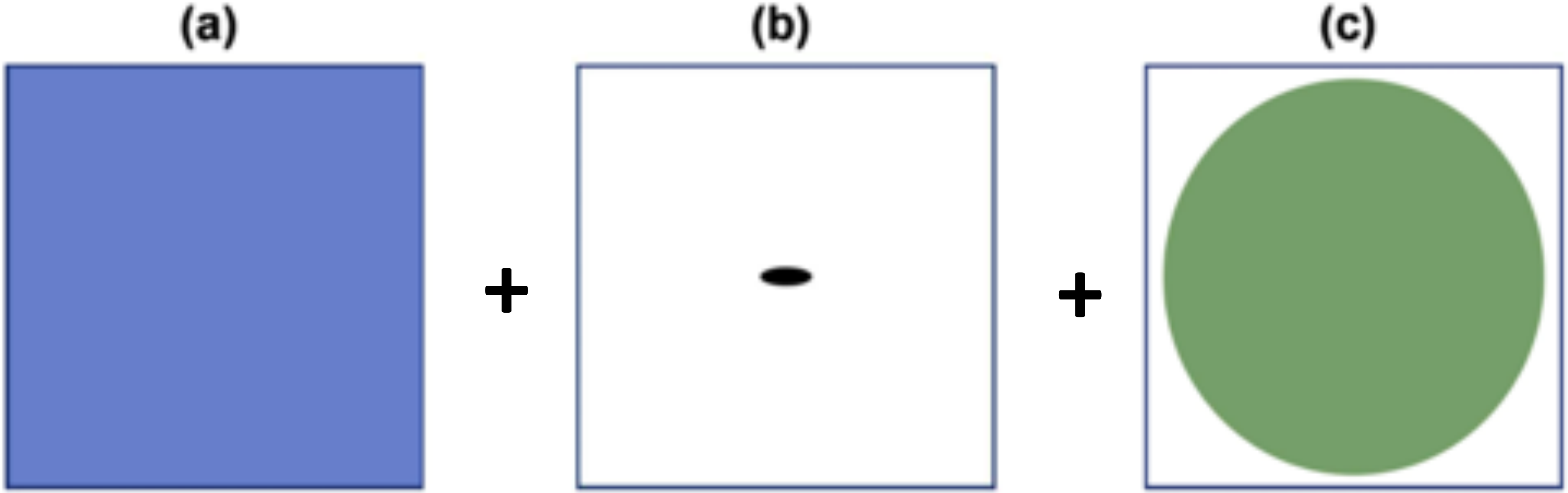


Beware : what we have in reality and in the simulation is really this periodic configuration



# Analytical approximation

equivalent to :

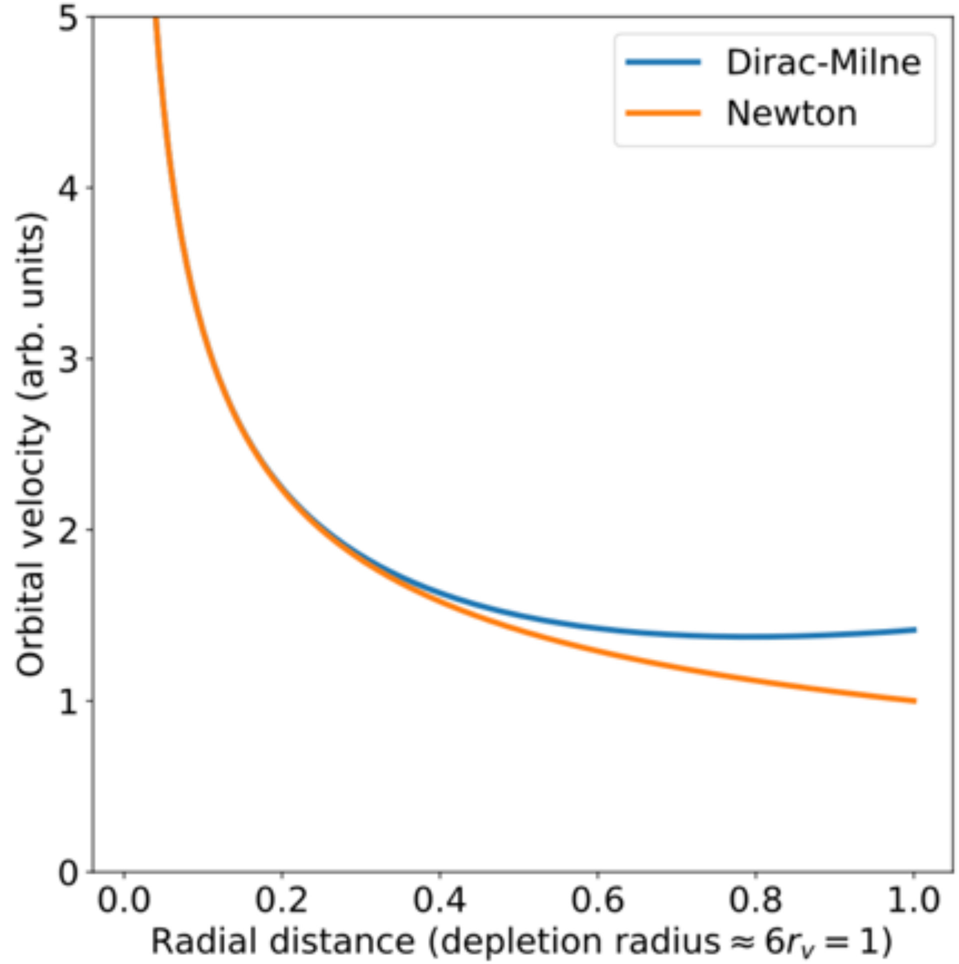


# Rotation velocity created by this configuration

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

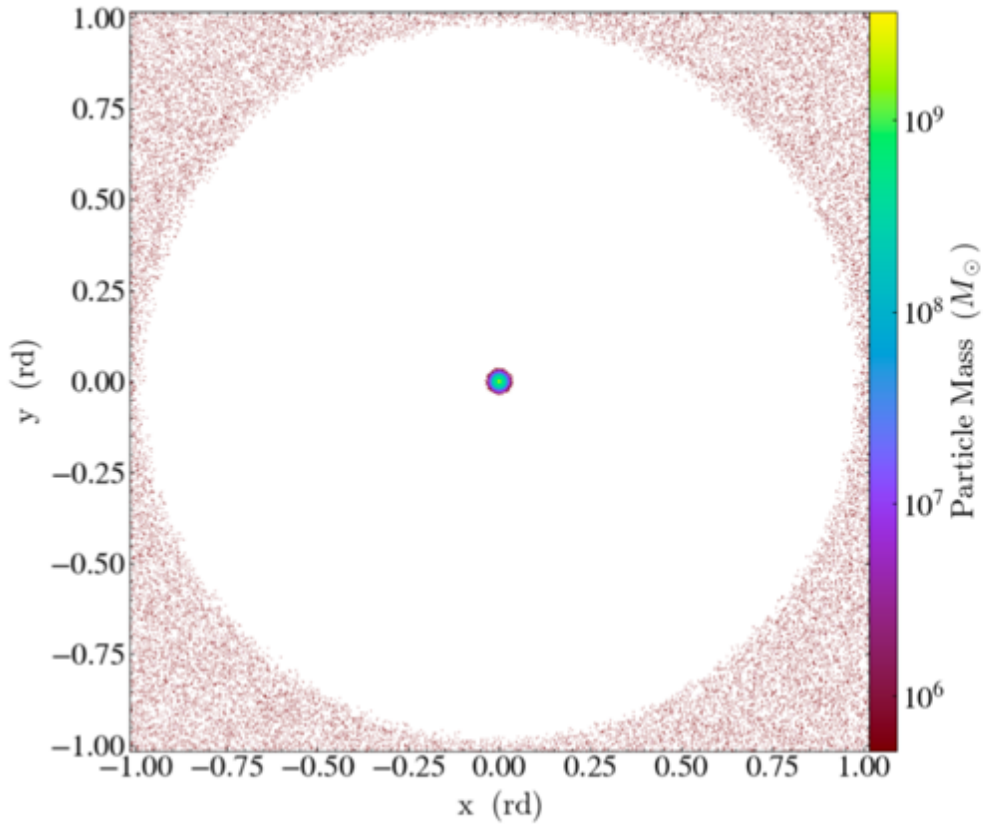
$$\frac{v^2}{r} = \frac{Gm}{r^2} + \frac{Gmr}{r_d^3}$$

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

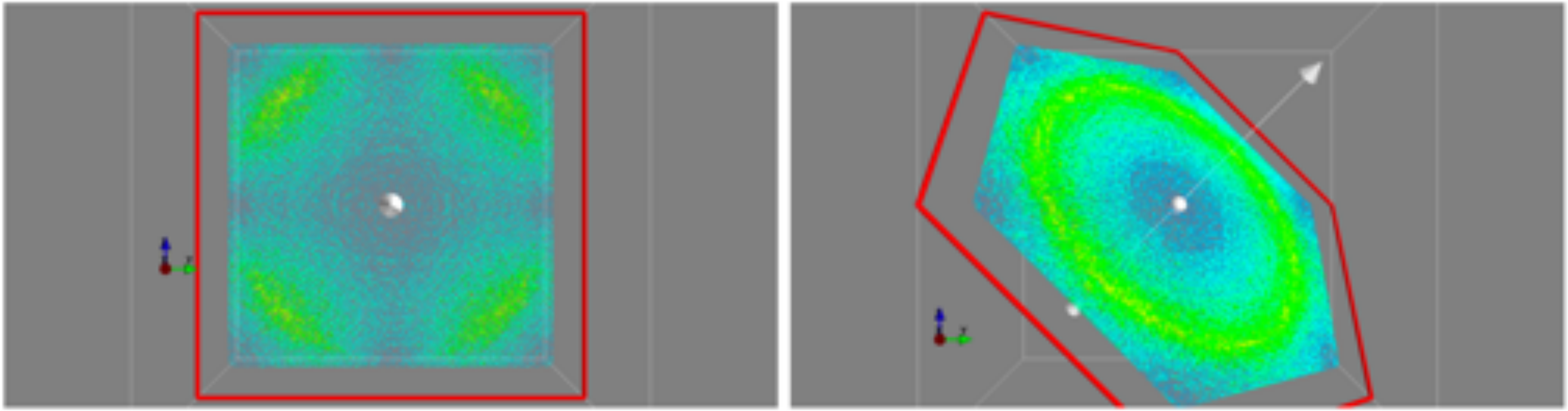


Check analytical approx with numerical simulation (RAMSES)

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

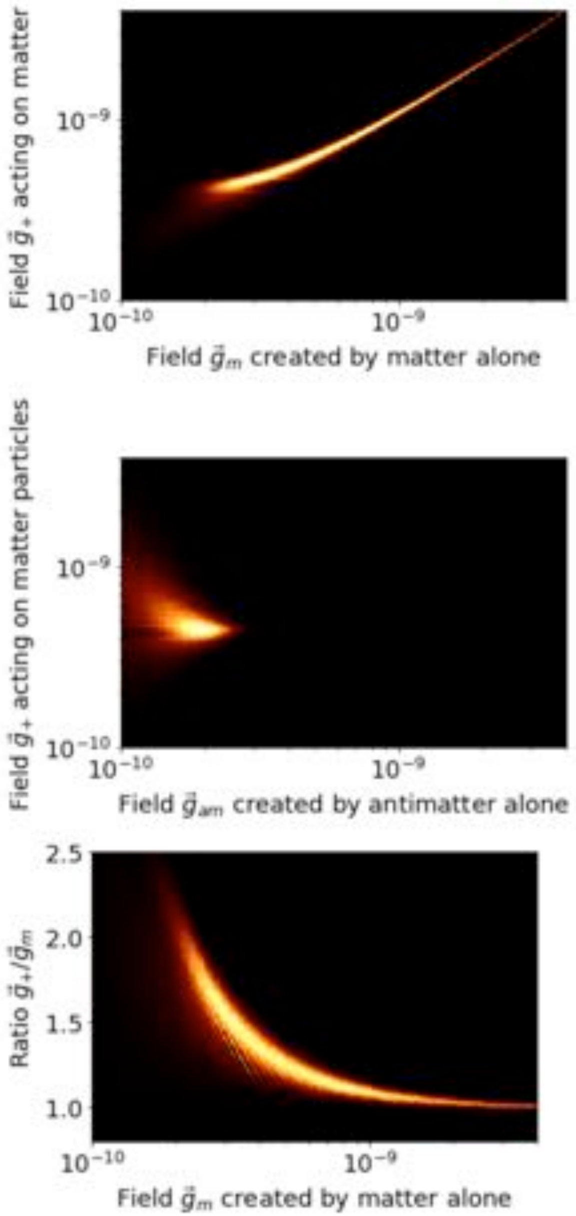


# Numerical simulation (RAMSES)



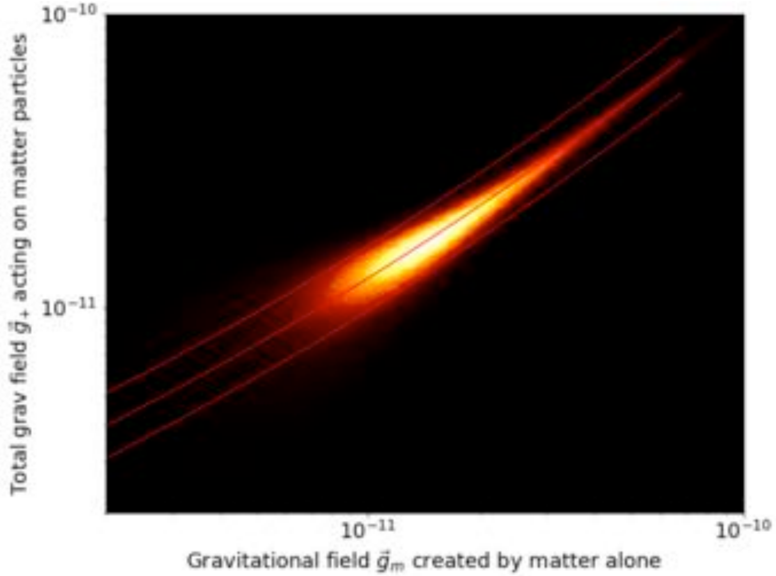
# MOND-like behavior

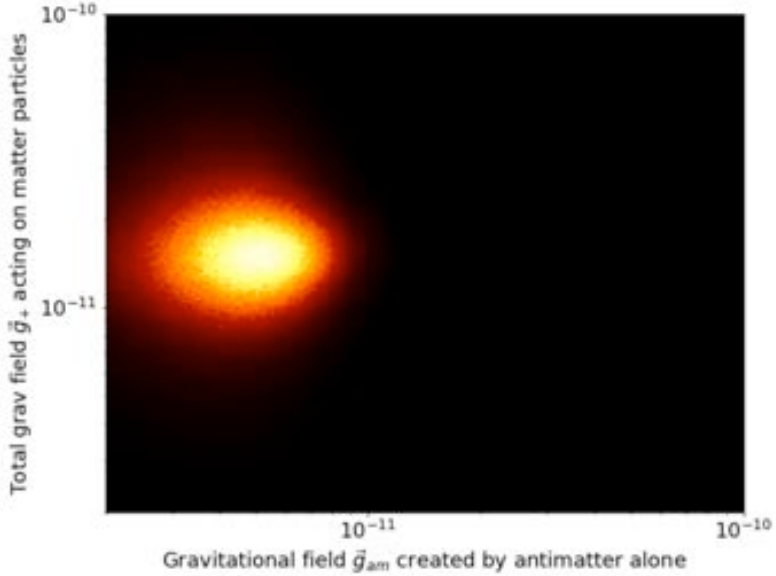
- Empty depletion zone (« heavier » than external m<0 antimatter) acts as almost uniform bubble of (non interacting !) Dark Matter
- Creates an extra confining field, quite uniform, ≈ few $10^{-11}$ m/s$^2$ at our epoch
- This will mimic a MOND behavior (figures on the right for idealized " spherical " galaxy)



# MOND and Dirac-Milne

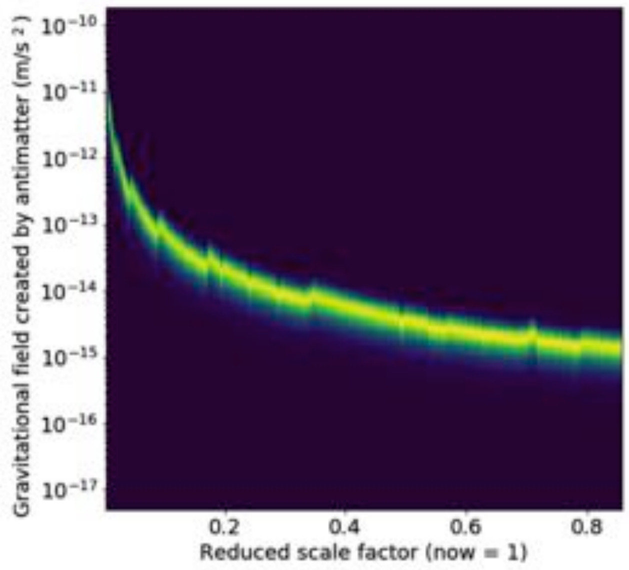
- Remarkably close to MOND for large collection of galaxies and clusters (≈ $10^3$ range of mass)
- Empty depletion zone acts as almost uniform bubble of non interacting Dark Matter
- There is an extra confining field, limited dispersion and ≈ few $10^{-11}$ $m/s^2$
- This mimics (quite remarkably) a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

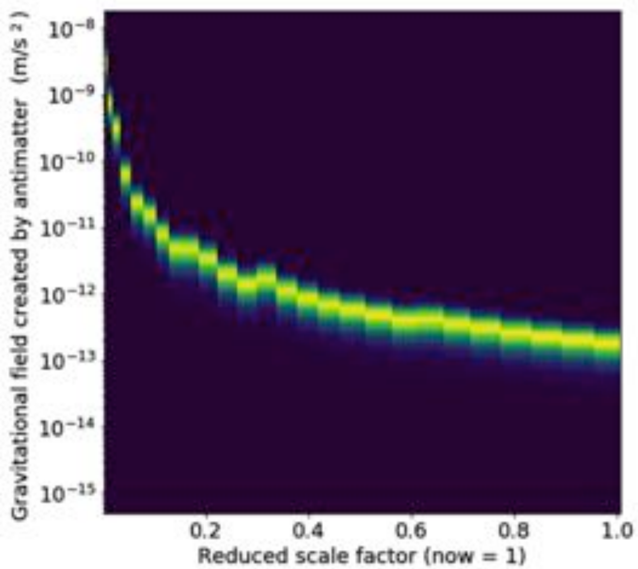


# Coherence of the antimatter field

- The gravitational field created by antimatter adds almost always its contribution to the matter field
- Its distribution is rather well-defined, with the same relative width whatever the redshift
- This will create in turn a rather well-defined ISW effect at any given z



# CMB in the standard model $\Lambda$CDM

- 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 as evidence for Dark Energy ?

- Integrated Sachs-Wolfe effect (due to the softening 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.
- Let us see what is the effect in the “ maximally open ” Dirac-Milne universe (flat **spacetime**, and not flat **space** => $\Omega_k$ = 1)

# CMB spectrum in the Dirac-Milne universe

- Matter and antimatter « domains » at $z \approx 1080$ are ≈ O(100) pc in dimension at that time
- Density at that time is $(1 + z)^3$ present density, about ≈ $3.5 \times 10^9$ protons/$m^3$
- Typical mass for domain at $z \approx 1080$: sphere 100 pc radius ≈ $4 \times 10^8$ $M_{sol}$
- Potential at border of domain : ≈ $10^{-7}$, small compared to 2 $10^{-5}$ (typical size of observed temperature and potential fluctuations)
- Temperature and potential fluctuations at last scattering surface are expected to be of the same order (virial theorem)
- Note that angular dimension of individual domains in D-M is extremely small (≈ **4 microradians** for 100 pc at $z = 1080$)
- **ISW (fluctuations of potential along the line of sight) is predominant in D-M**

# CMB spectrum in the Dirac-Milne universe

- **ISW (fluctuations of potential along the line of sight) requires to calculate:**

$$\Delta T(\hat{n}) = \frac{2}{c^2}\bar{T}_0 \int_{t_L}^{t_0} \dot{\Phi}(t, \hat{n})\, \mathrm{d}t, \tag{1}$$

where $t$ is cosmic time, $t_L$ the age of the universe at the last scattering surface, $t_0$ the present age, $\dot{\Phi}$ the time derivative of the gravitational potential, $\bar{T}_0$ the mean CMB temperature and $c$ the speed of light.

# Swiss cheese model (Szekeres solution)

- W. Valkenburg

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

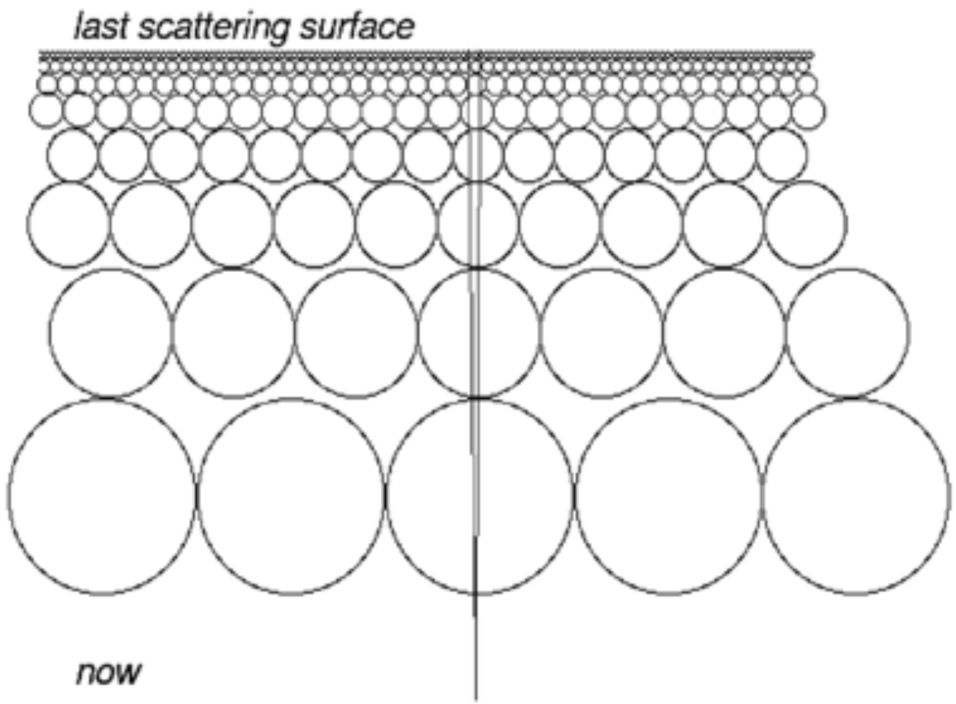



**Fig. 5** The schematic representation of the Swiss Cheese model. When two photons are propagating along a similar path the final temperature fluctuations are similar. If paths are different, then the final temperature fluctuations are also different and hence not correlated

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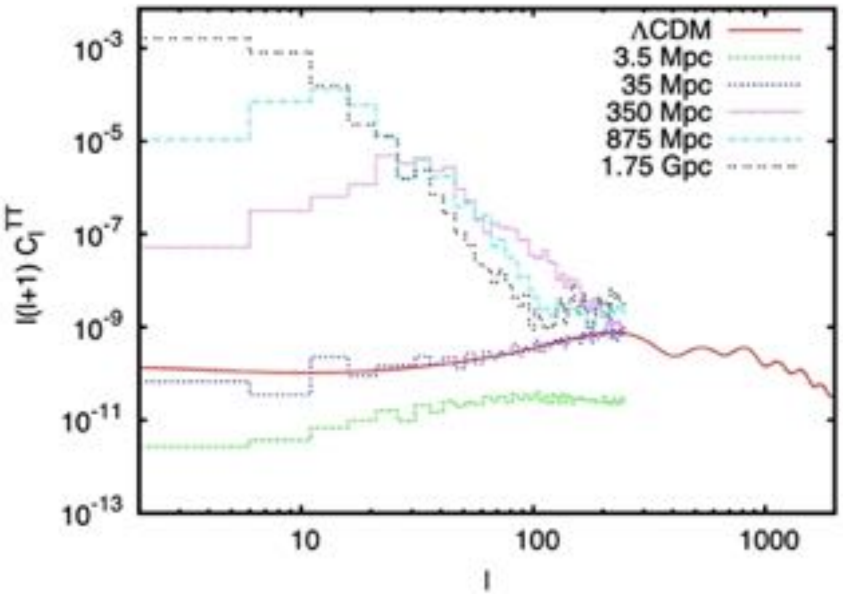
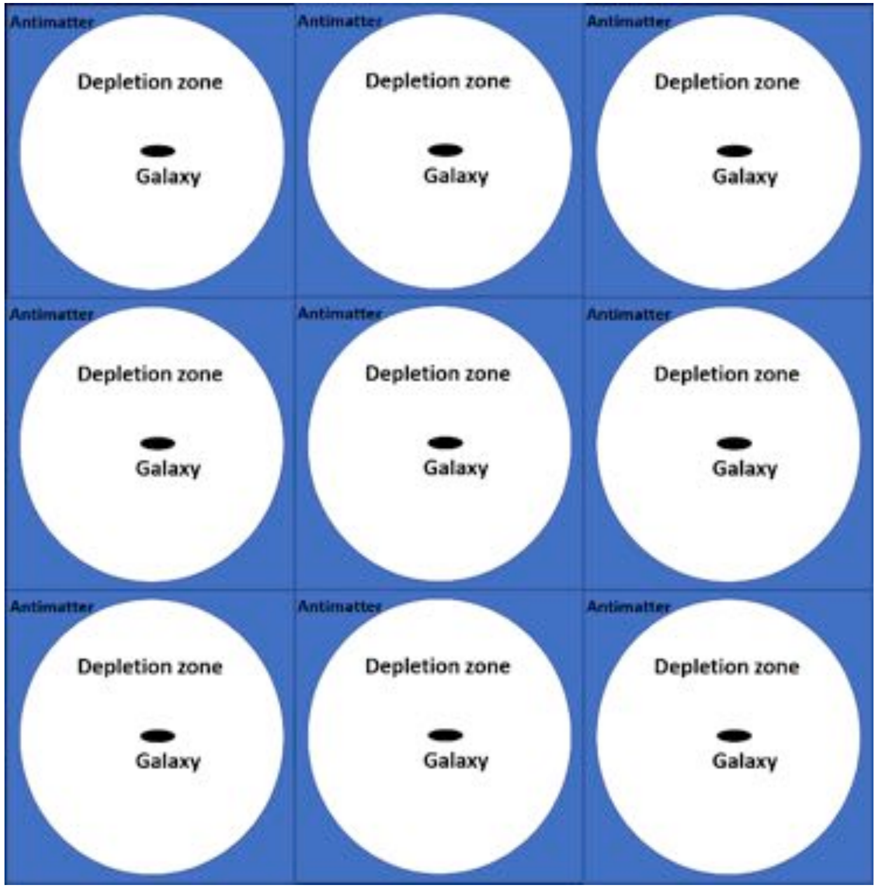



**Figure 4.** The $C_l^{\rm TT}$ of secondary anisotropies for different Swiss-Cheese cosmologies, in bins of 5 multipoles. For comparison we plot the full $C_l^{\rm TT}$-spectrum in a standard ΛCDM cosmology with $\Omega_{\rm baryon} = 0.045$, $\Omega_{\rm cdm} = 0.245$, $\Omega_{\rm k} = 0$, $\Omega_{\rm DE} = 0.71$, $h = 0.7$ (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.

# Dirac-Milne has several features of a Szekeres (Swiss-cheese) universe

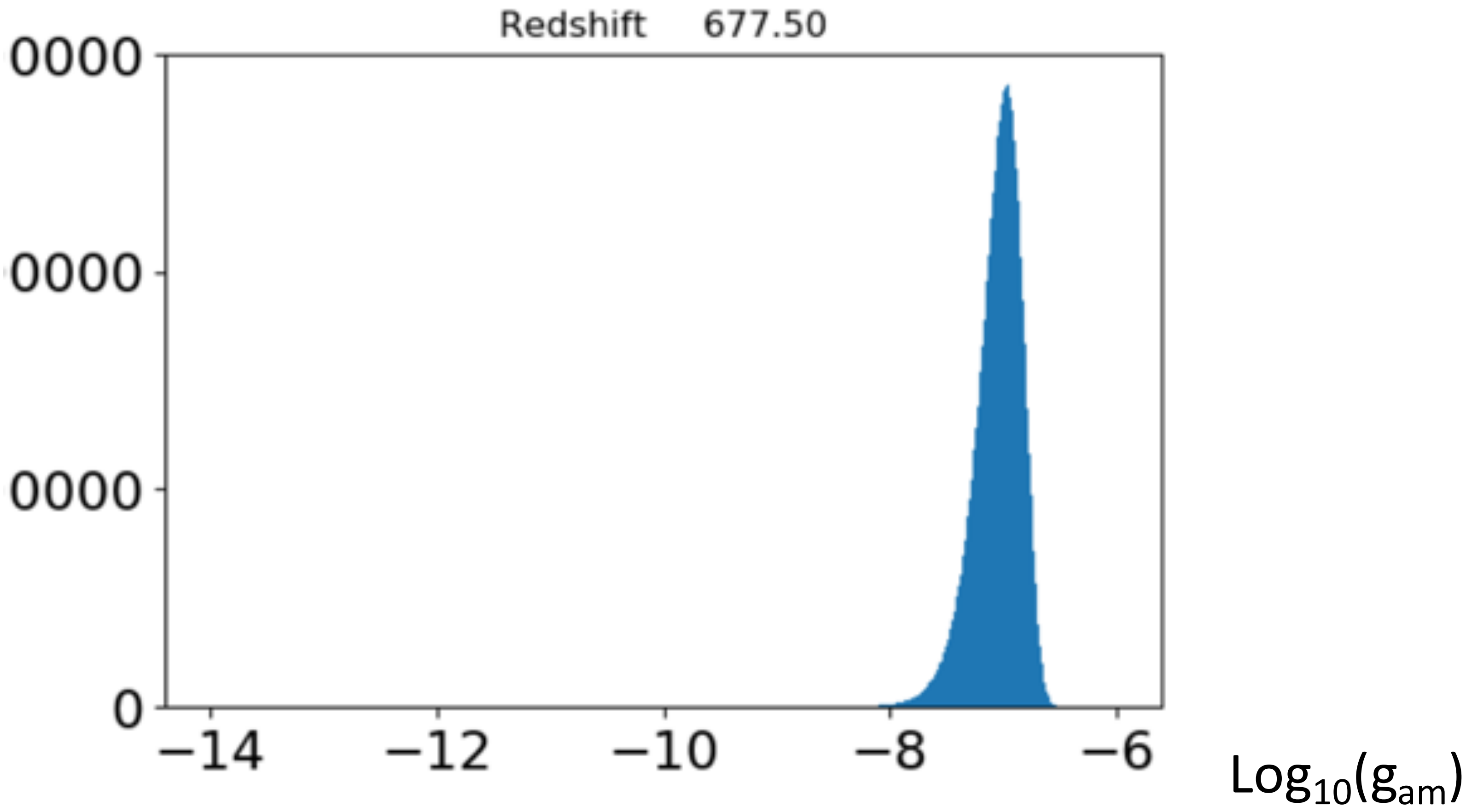
- Close to Swiss-cheese config
- Depletion zone (≈50% of the volume)
- Antimatter almost uniform and cold cloud (≈50% of the volume)



# CMB spectrum in the Dirac-Milne universe

- Rough simulation of a few successive « skies » (i.e. 4π steradians covered by ISW structures in small interval of z) provides an idea of the spectrum, and how it is built
- With WMAP resolution, integration between z = 0 and z = 10 is far sufficient, smoothing and windowing necessary for integration beyond this redshift as the spot angles becomes smaller than the experimental resolution of WMAP, and even than that of Planck
- Main peak in power spectrum clearly seen, together with harmonics
- What is the origin and intensity of the harmonics ?

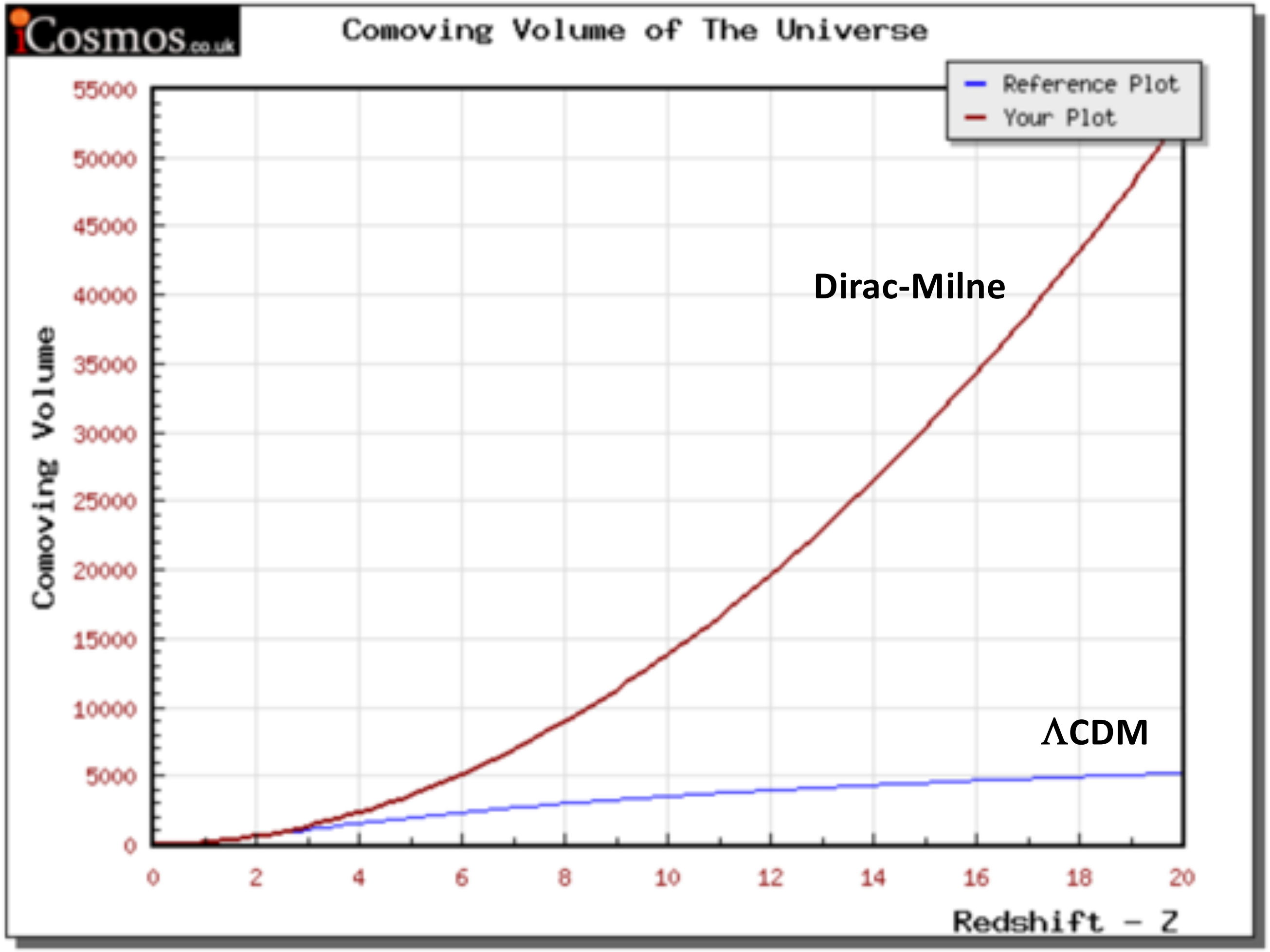
# Distribution of antimatter gravitational field



# Covolume as a function of redshift

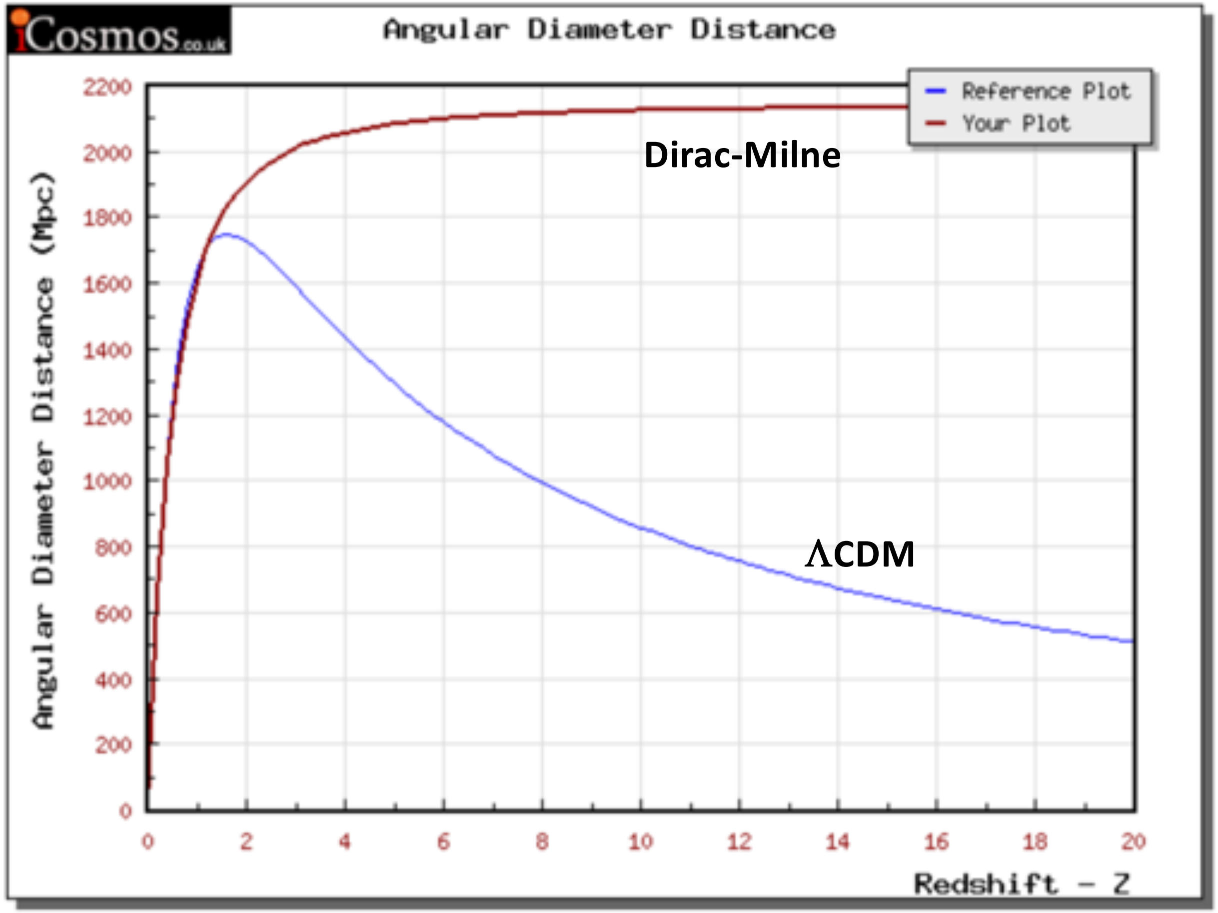
Covolume as function of redshift much larger in Dirac-Milne compared to $\Lambda$CDM

- Factor ≈4 at z = 10
- Factor ≈11 at z = 100



# Angular diameter distance

- Variation of angular diameter distance is also quite different between Dirac-Milne and $\Lambda$CDM
- Apparent size of structure of fixed size decreases faster in D-M compared to $\Lambda$CDM



# CMB spectrum in the Dirac-Milne universe

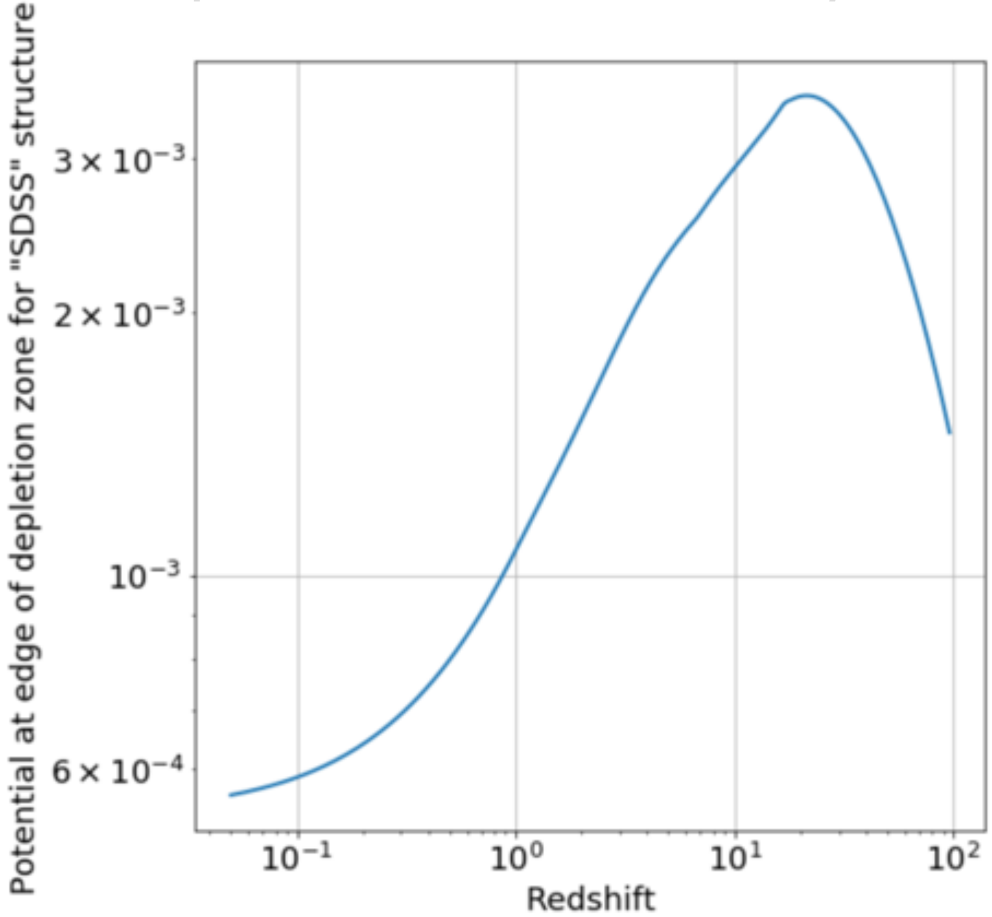
- ISW effect expected to be about twice as large as in LCDM at low redshifts (low \ell), factor to be checked
- … and increasingly larger at high redshifts, since the geometry is maximally open (while in $\Lambda$CDM, $\Omega_\Lambda$ becomes negligible above z ≈ 2-3, and therefore also ISW) and the volume of spatial slices becomes much larger in Dirac-Milne than in LCDM (figure)
- Note : at low \ell (below 100-200), Valkenburg has shown than domains of radius 35 Mpc in a Swiss-cheese configuration leads to spectrum similar to observed spectrum (his intention was to place a limit) (figure)

Why $\Delta T/T \approx 2 \times 10^{-5}$ ?

And why a peak at ≈ 1 degree scale ?

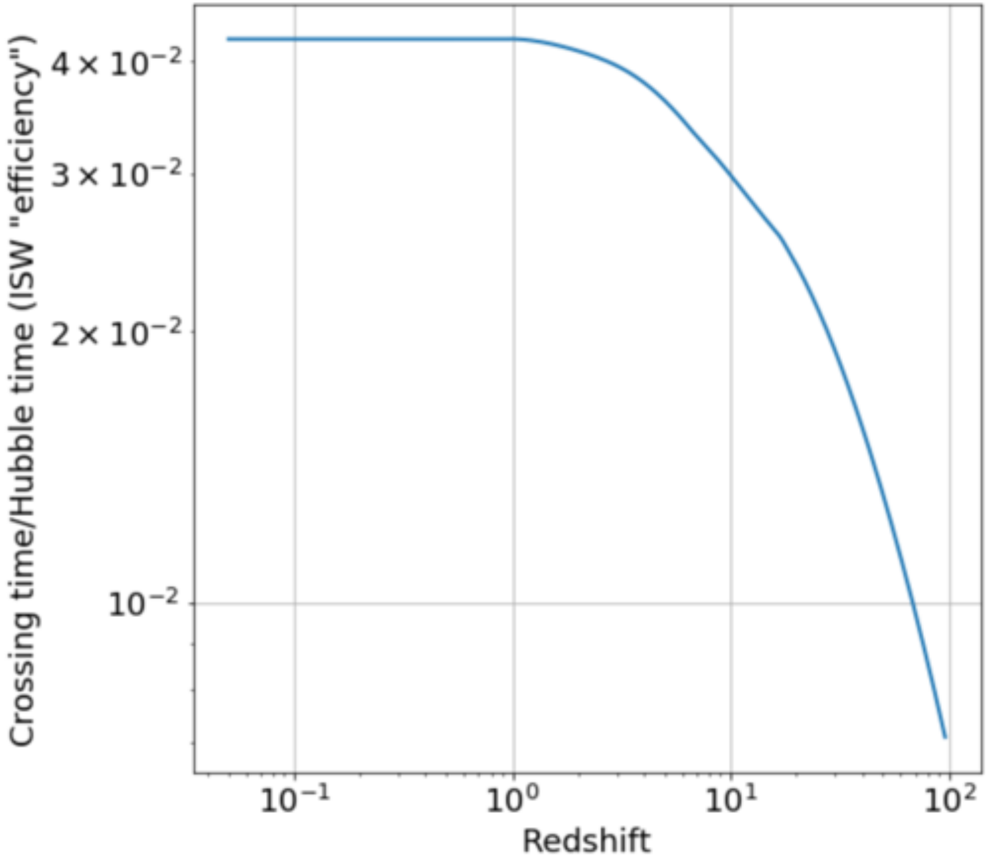
# Gravitational potential at edge of "SDSS" structure (100 Mpc scale at z = 0)

- Knowing the matter density in Dirac-Milne (≈3.5 GeV/m$^3$)
- and the size of the "SDSS" structures for a given z (Manfredi et al. PRD (2020)
- we can estimate the gravitational potential at the border of the depletion zone



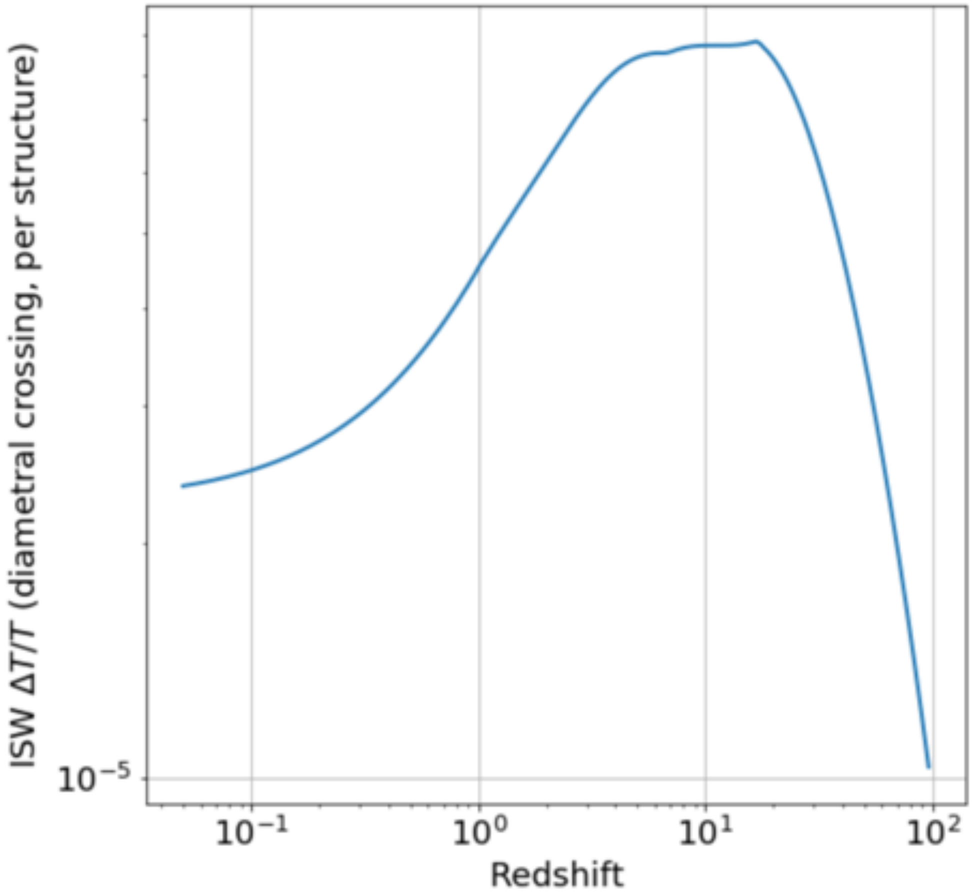
# Crossing time/Hubble time for a single “SDSS” structure

- ISW ΔT/T effect is not related to the potential itself, but to its variation (softening) of potential while the CMB photons cross the structure
- Basically, the “efficiency” factor is: **crossing time/Hubble time**, which needs to be multiplied by the potential
- In Dirac-Milne, this “efficiency factor” is almost constant for z <≈2, and then decreasing with z, but rather smoothly



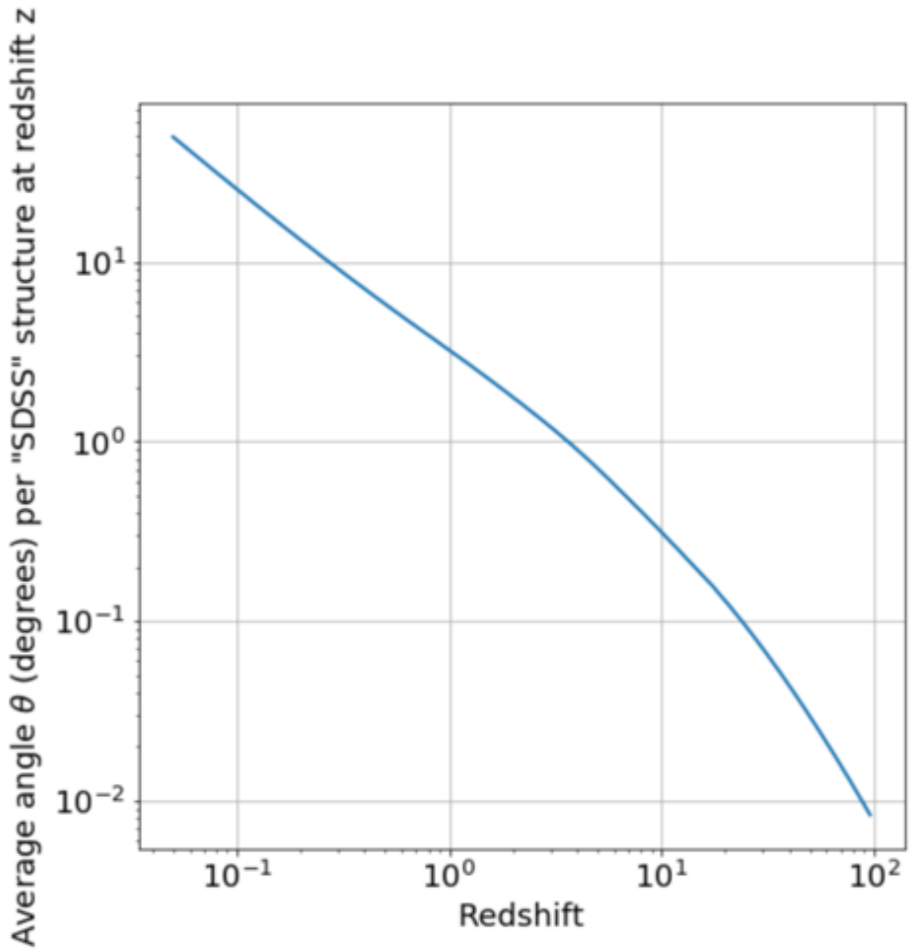
# ISW variation ΔT/T for a single "SDSS" structure

- Multiplying the potential at edge of depletion zone by the variation of the potential due to expansion while crossing the structure results in the following figure (right)
- Typical factor is ≈ $10^{-5}$, peak value is ≈ 4 $10^{-5}$
- Angle at maximum is ≈ 0.5°

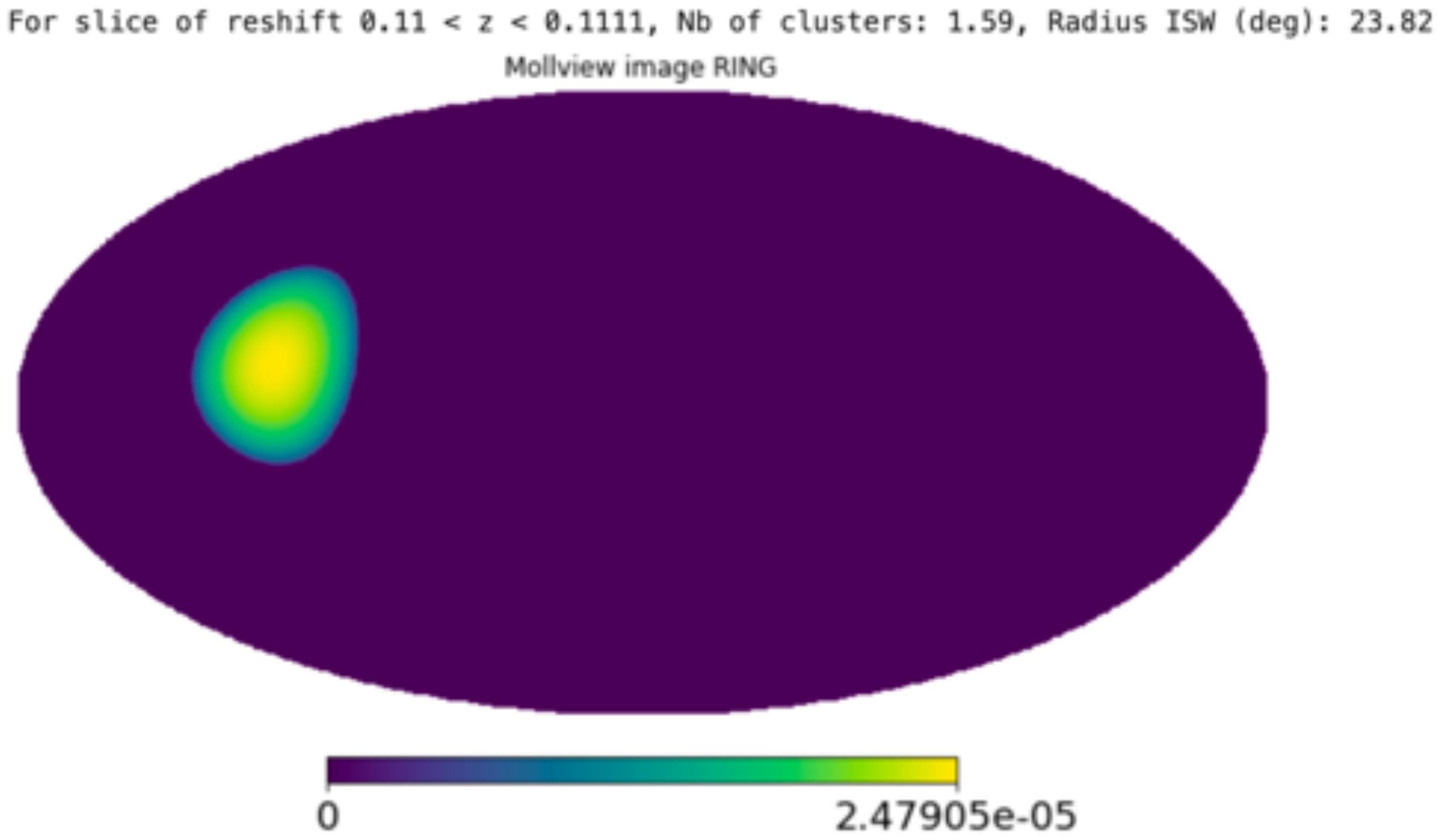


# Variation of angular size of average ISW spot

- Several tens of degrees for z <≈ 0.1
- Angle is ≈ 0.5 degree at maximum ISW “efficiency”
- Large additional power at high \ell (smaller angles), but will be hardly detected by present experiments
- Note also, incoherent superposition of skies at high \ell



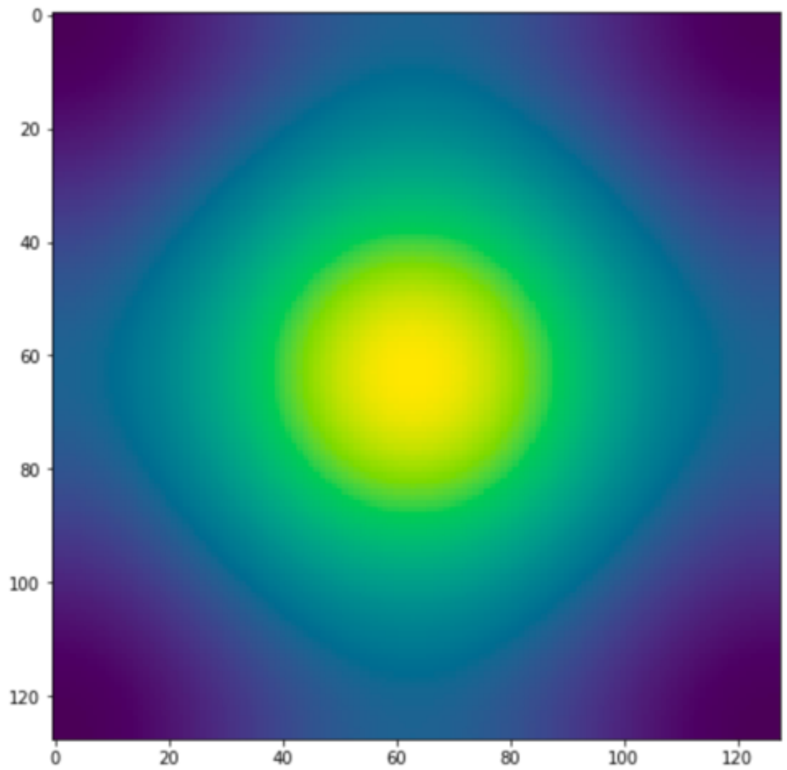
# Individual ISW spot at low z

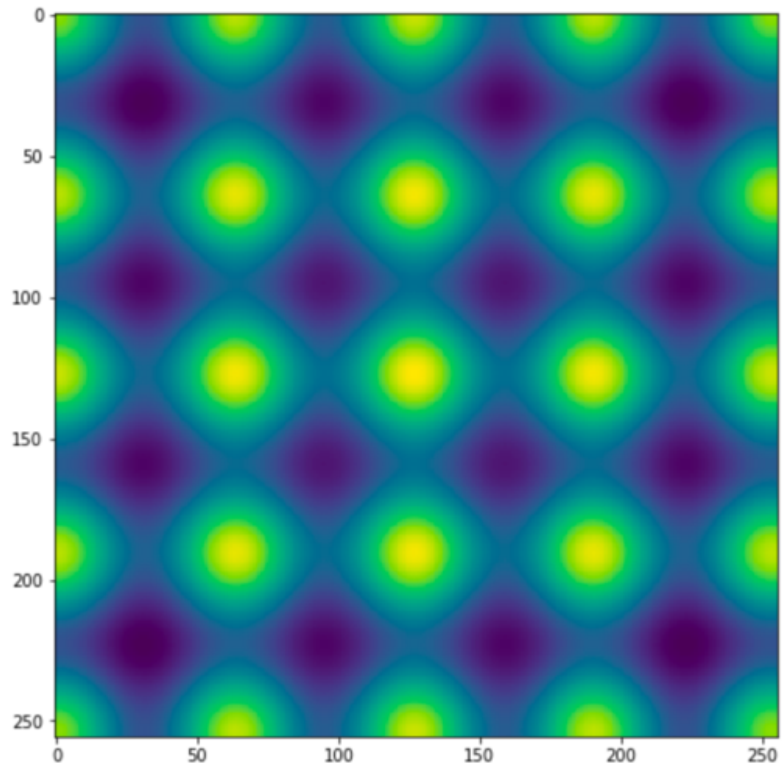


# The ISW temperature spot

- Gravitational potential for an infinite plane of periodic galaxies + antimatter clouds, used to normalize the ISW “spot”

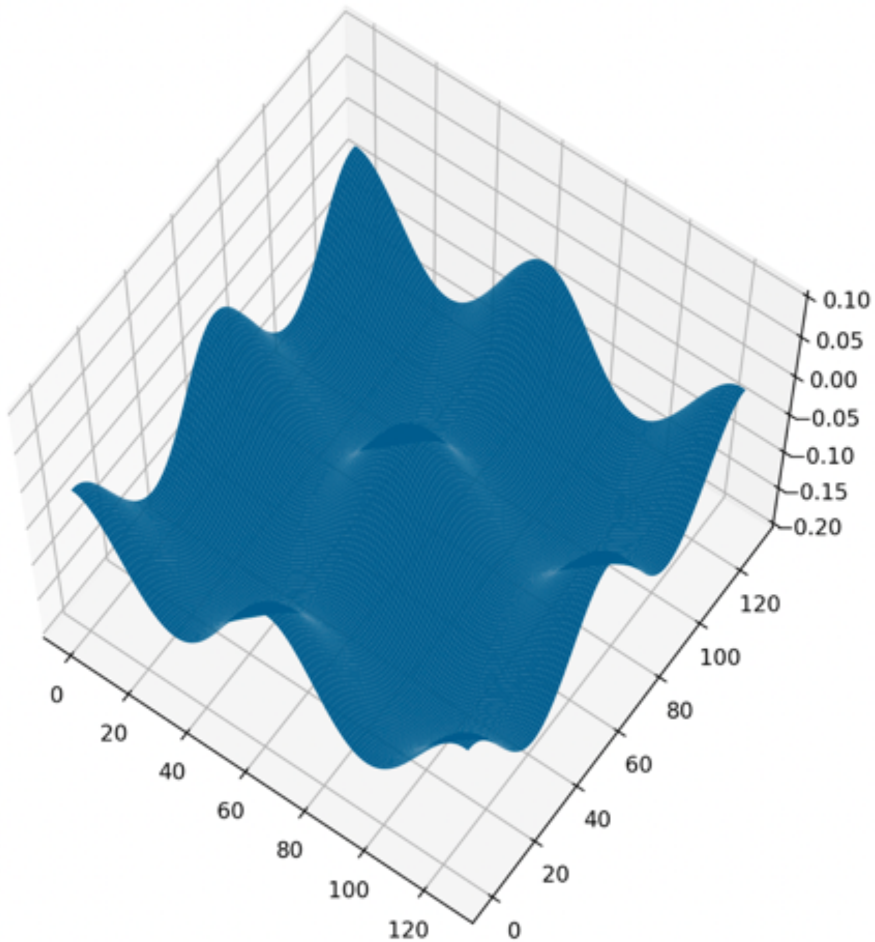
<matplotlib.image.AxesImage at 0x7fe448866b10>



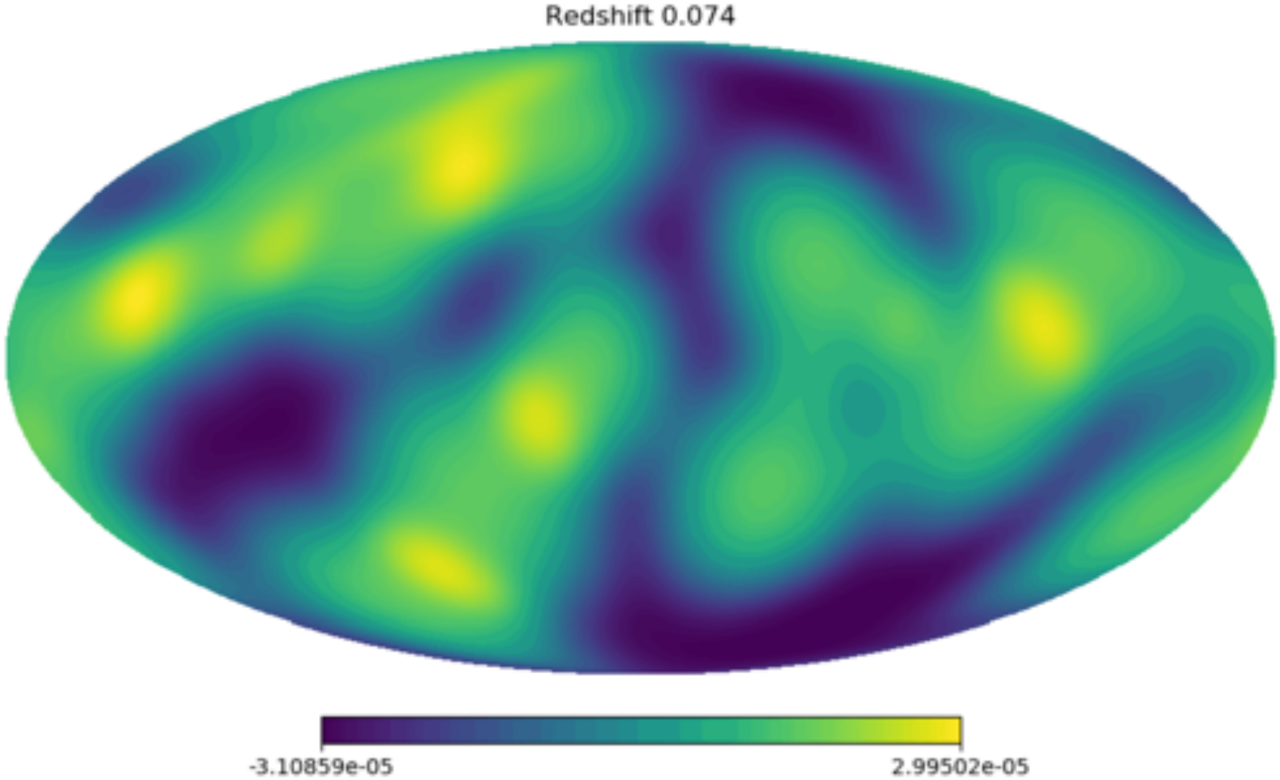
# The ISW temperature spot

- Note that this structure has a central hot spot (matter structure), but also satellite peaks acting as cold spots (zones of antimatter)
- Difficult to define a spherical spot (edge effects)



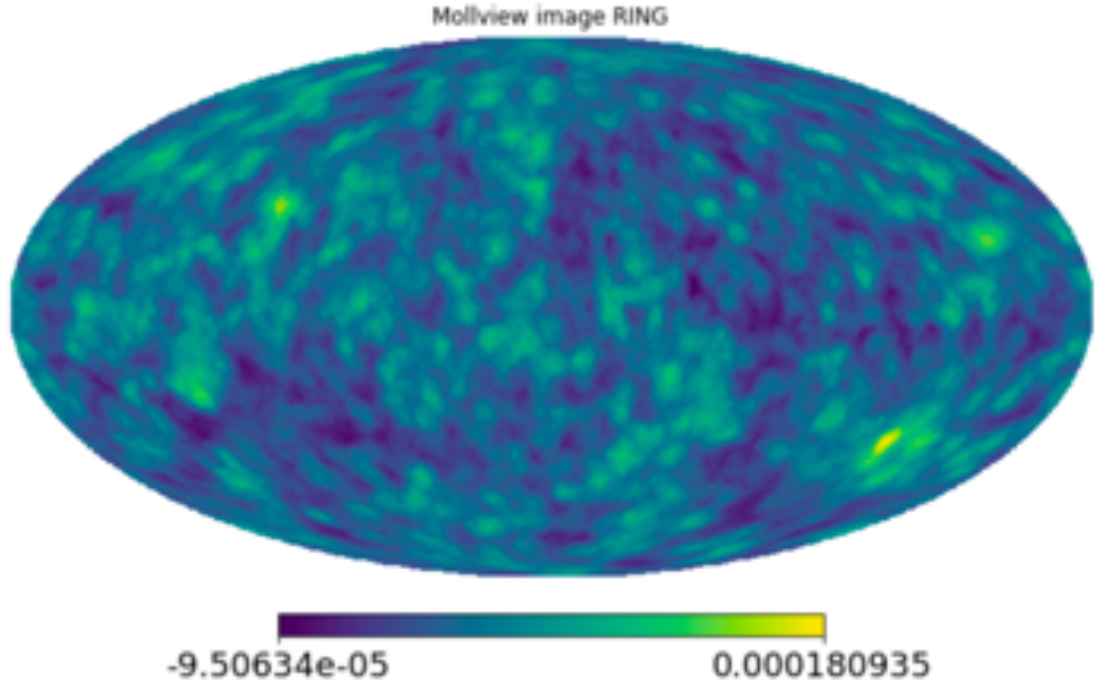
# CMB sky from the sum of contributions of all « skys »

Note: (partially) excluded volume between adjacent ISW spots

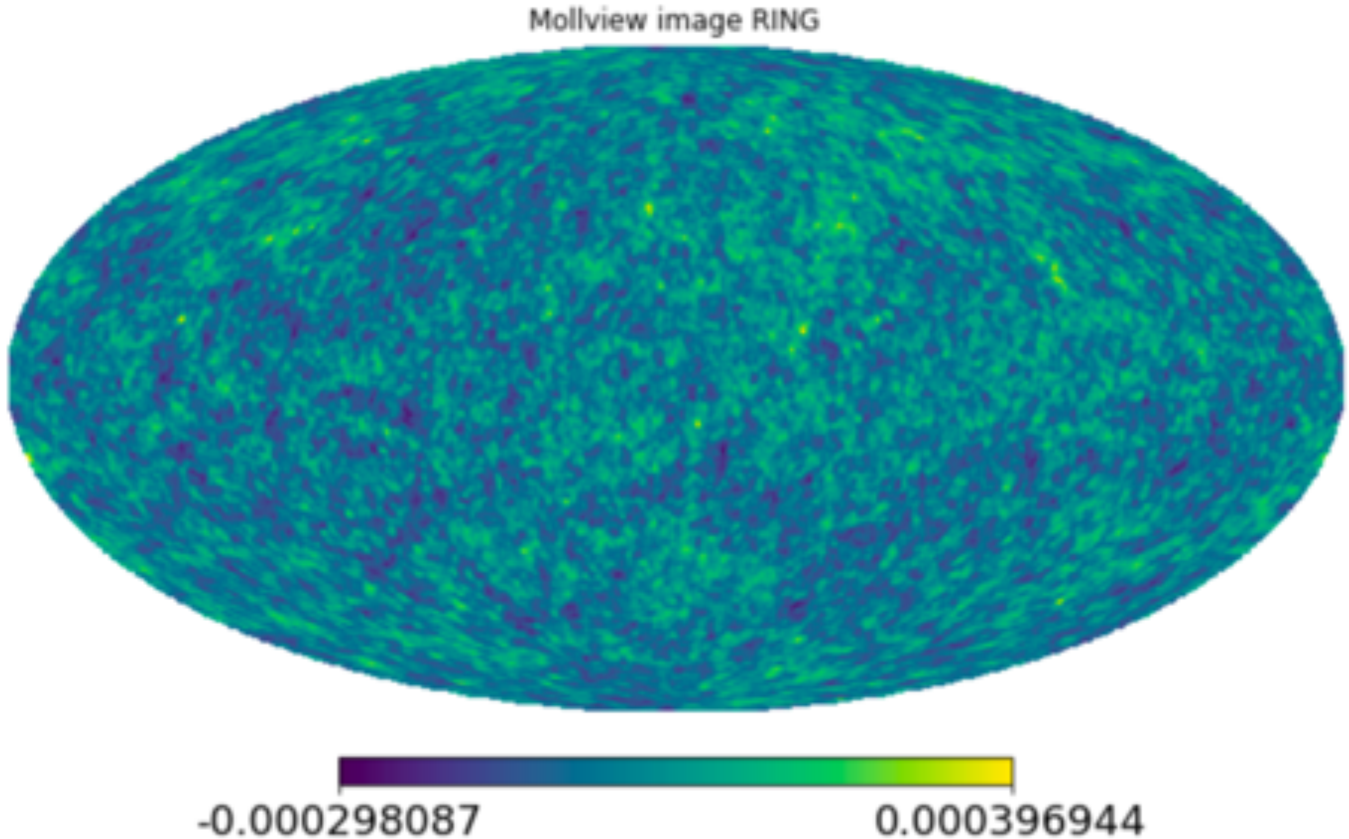


# Sum of randow ISW spots for z between 0.05 and 1.05

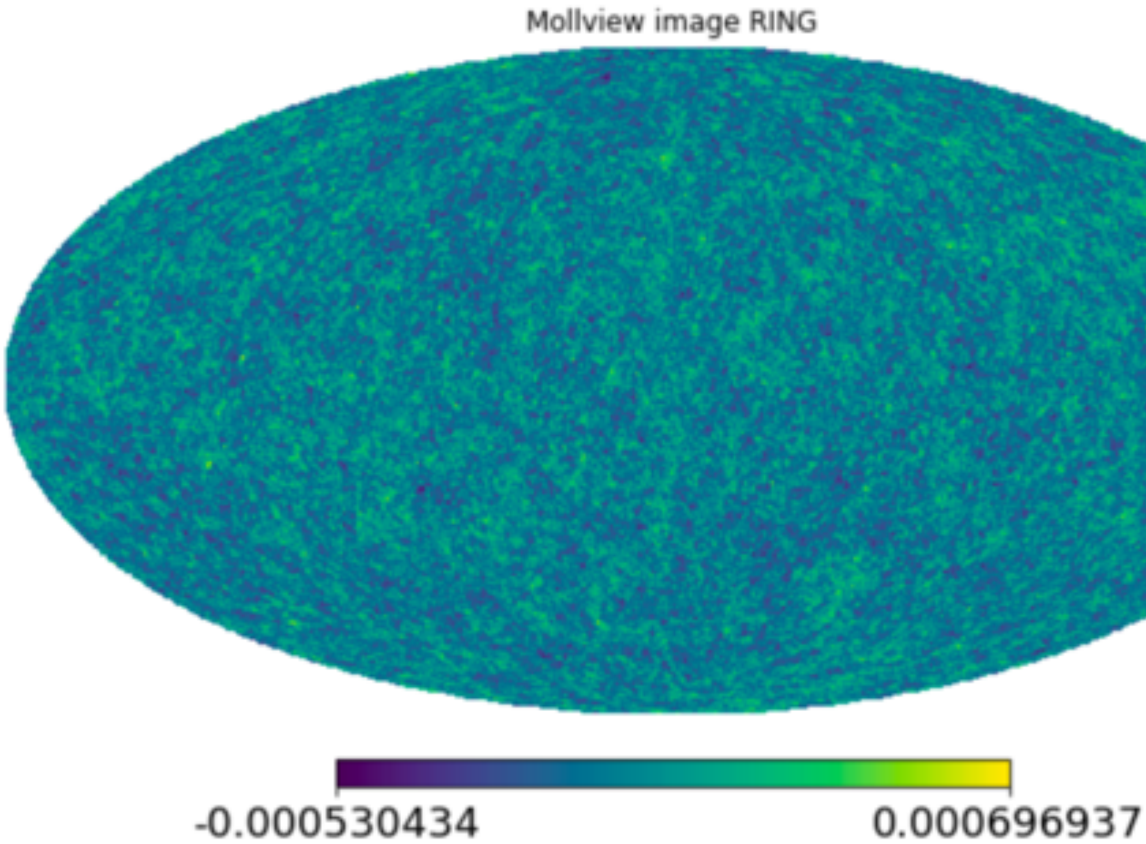
```
For slice 0.05 < z < 0.15, Nb clusters: 34.67, Radius ISW (deg): 49.66, Total ISW solid angle (ster):76.82,
For slice 0.15 < z < 0.25, Nb clusters: 112.1, Radius ISW (deg): 17.29, Total ISW solid angle (ster):31.8,
For slice 0.25 < z < 0.35, Nb clusters: 215.3, Radius ISW (deg): 10.77, Total ISW solid angle (ster):23.84,
For slice 0.35 < z < 0.45, Nb clusters: 333.1, Radius ISW (deg): 7.956, Total ISW solid angle (ster):20.15,
For slice 0.45 < z < 0.55, Nb clusters: 458.9, Radius ISW (deg): 6.375, Total ISW solid angle (ster):17.83,
For slice 0.55 < z < 0.65, Nb clusters: 588.8, Radius ISW (deg): 5.357, Total ISW solid angle (ster):16.16,
For slice 0.65 < z < 0.75, Nb clusters: 720.4, Radius ISW (deg): 4.643, Total ISW solid angle (ster):14.86,
For slice 0.75 < z < 0.85, Nb clusters: 852.5, Radius ISW (deg): 4.113, Total ISW solid angle (ster):13.79,
For slice 0.85 < z < 0.95, Nb clusters: 984.0, Radius ISW (deg): 3.702, Total ISW solid angle (ster):12.9,
For slice 0.95 < z < 1.1, Nb clusters: 1.115e+03, Radius ISW (deg): 3.373, Total ISW solid angle (ster):12.13,
```



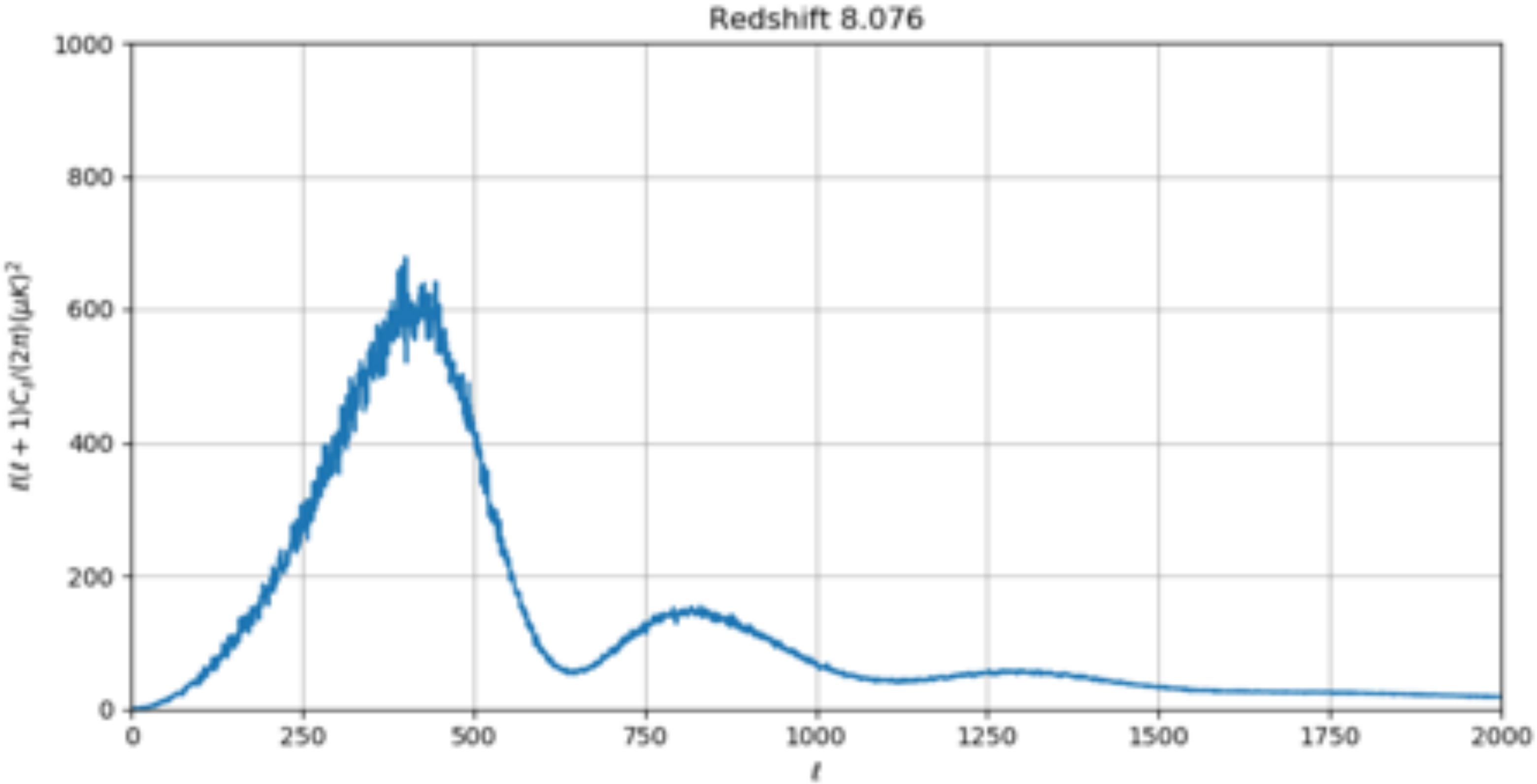
# Sum of randow ISW spots for z between 0.05 and 4.05



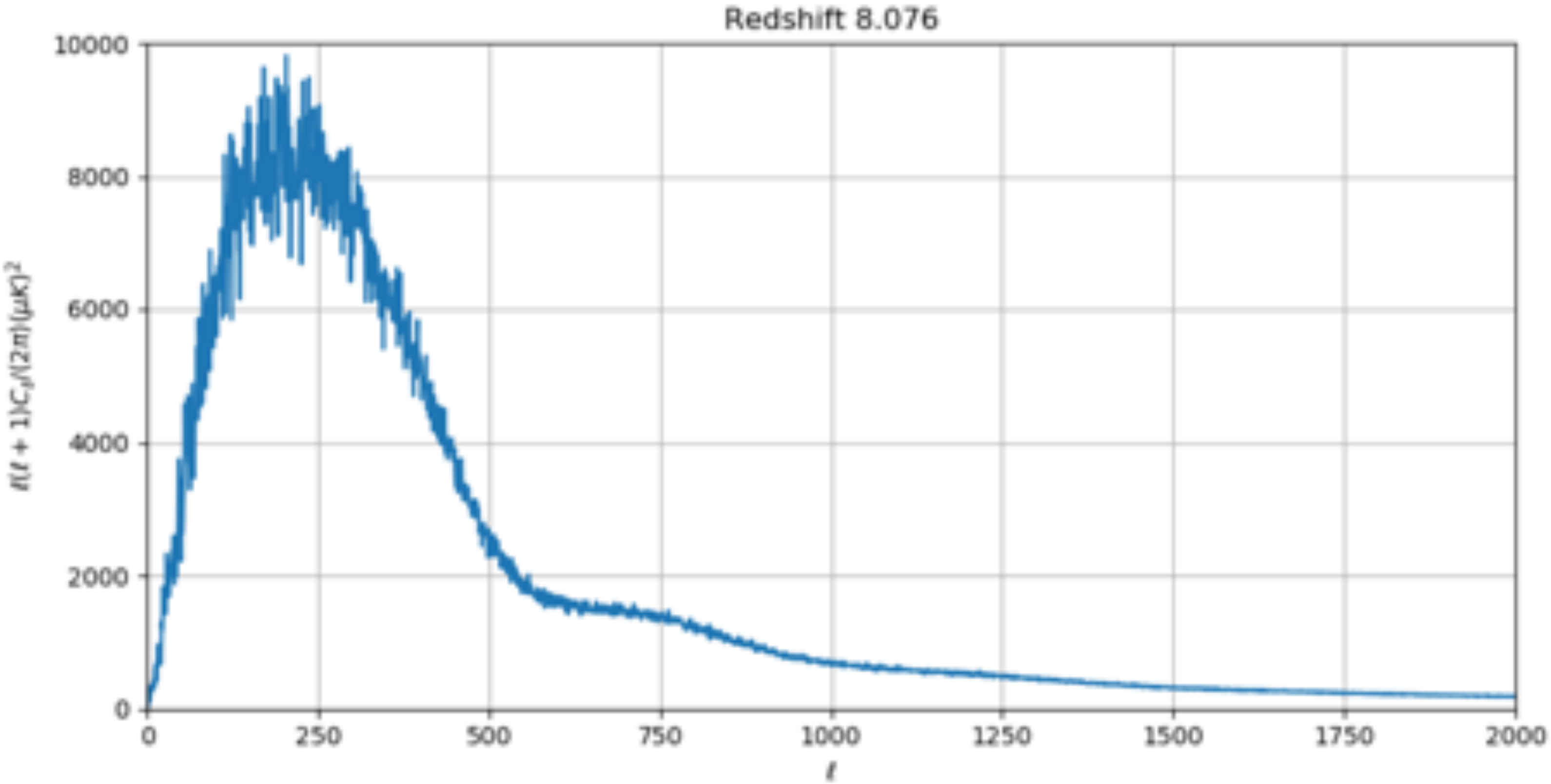
Sum of randow ISW spots for z
(integration between between 0.05 and 15.05)



# Cl spectrum of individual skies (starting from z = 0)

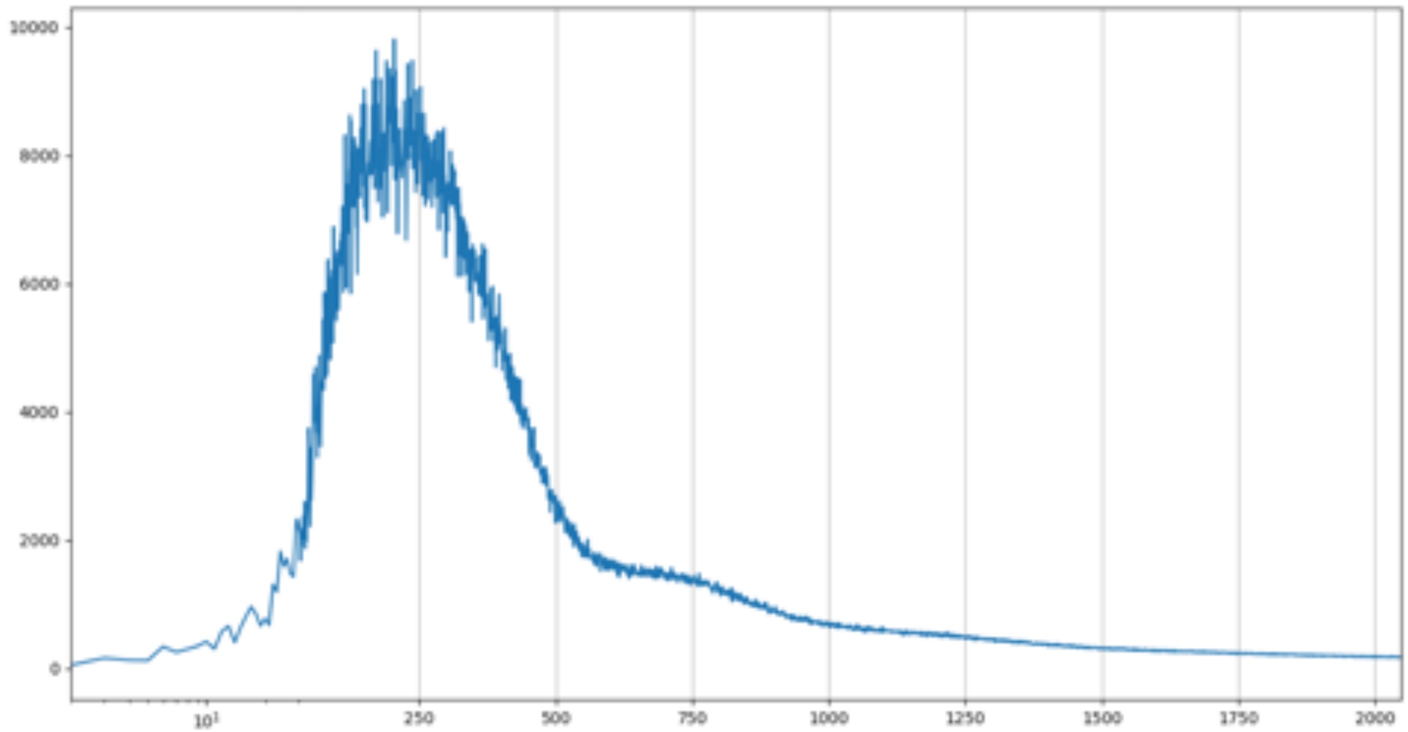


# Cl spectrum for summed (amplitude) skies

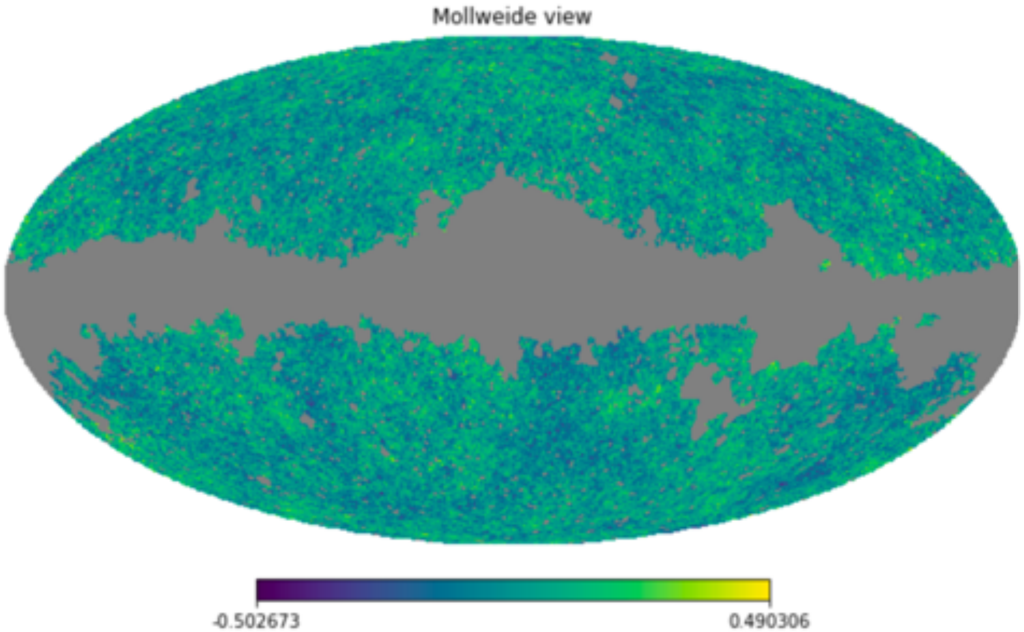


# Cl spectrum for summed (amplitude) skies

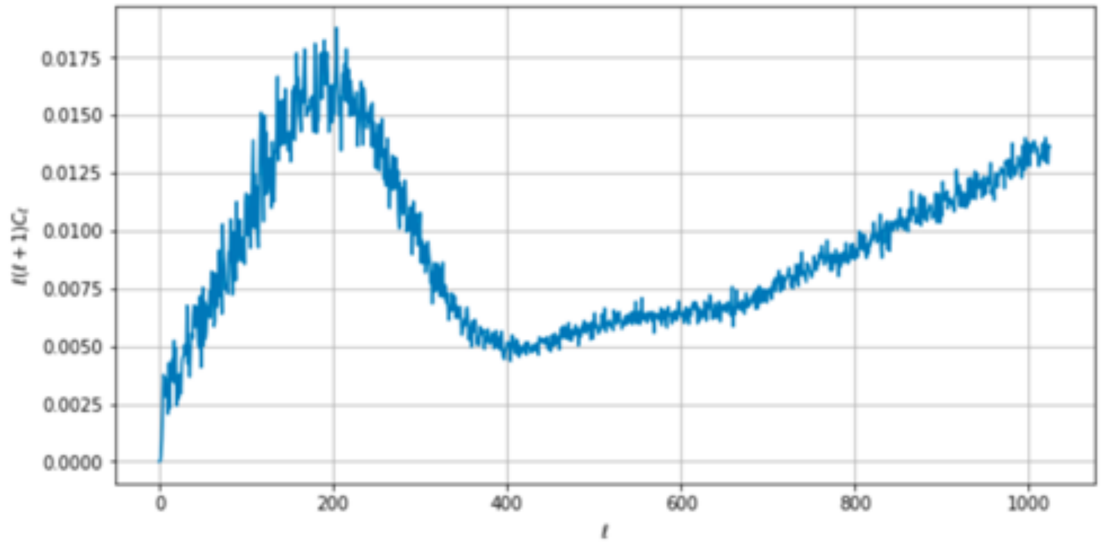
- Note: usual presentation of c_l spectrum looks different at low \ell because it is usually represented with a logarithmic horizonta scale at low ell (≤30), and a linear scale at higher ell (>30)



# For comparison, WMAP masked map and $c_l$




```python
plt.figure(figsize=(10, 5))
plt.plot(ell, ell * (ell + 1) * cl)
plt.xlabel("$\ell$")
plt.ylabel("$\ell(\ell+1)C_{\ell}$")
plt.grid()
#hp.write_cl("cl.fits", cl, overwrite=True)
```



# What remains to be done

- Scan the 3 parameters of simulation (size of domains, width of power spectrum, and contrast parameter, $\sigma_{50}$ , the analog of $\sigma_8$, relevant for antimatter)
- In principle, only 3 parameters, compared to ≥ 6 for Planck modeling
- Constrain size of matter/antimatter “ domains ” at z = 1080 by mass distribution of objects (and notably black holes, see LIGO/VIRGO)
- Study the ISW integral of grav potential in 1D (very high resolution possible)
- Dedicated study at large \ell ([500-3000]) to check consistency with SPT measurements
- Dedicated study at low \ell ([2-30]) with CosmicFlows (or other) « nearby » maps (cold spot)
- Make the full calculation of the integral of the time derivative of the gravitational potential in 3D:
  - Ramses adapted to Dirac-Milne
  - DEUS-FUR (Rasera, Alimi et al.), based on Ramses
- Test at CERN of the gravitational mass of antihydrogen with ALPHA-g, Gbar and AEgIS

# Conclusions

- With basically no free parameters, the Dirac-Milne universe is astonishingly concordant, although very different ($\Omega_k$ = 1, flat spacetime) from LCDM
- Age, SN1a luminosity distance, nucleosynthesis were already known to present strong elements of concordance
- In addition, we have shown that flat rotation curves are generic in the Dirac-Milne universe
- …and that the antimatter field creates a MOND-like behavior, effectively explaining MOND
- This antimatter field varies with the redshift, and is therefore not a fundamental constant, as in MOND
- In Dirac-Milne, the CMB spectrum seen today (z=0) comes almost exclusively from the ISW effect, much larger in the Dirac-Milne universe than in the LCDM universe, due to its “ Swiss cheese ” structure and open geometry
- The angular scale and amplitude predicted seem very similar to those of our universe

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