Dark matter

Before and after reheating

Diego Restrepo

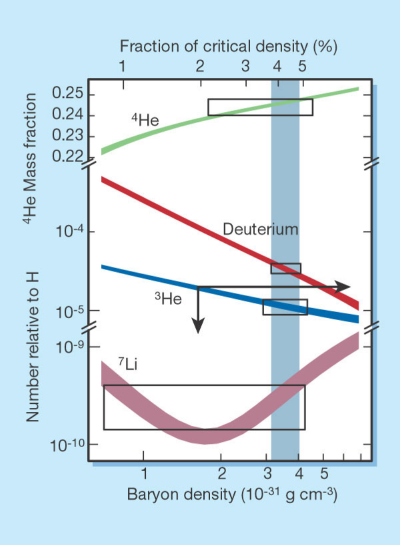
July 30, 2018

Instituto de Física
Universidad de Antioquia
Phenomenology Group
`http://gfif.udea.edu.co`

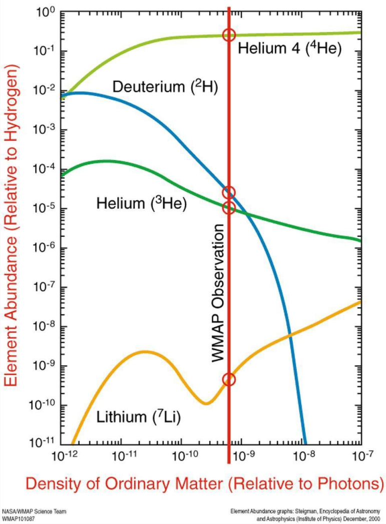
In collaboration with
Valentina Montoya

Gravitational evidence of dark matter

Big Bang Nucleosynthesys



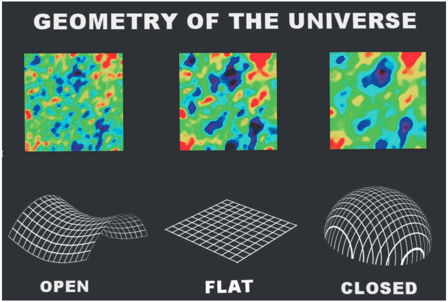
Credits: Chris Mihos ASTR/PHYS 328/428



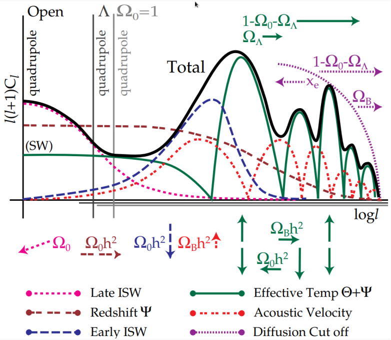
Credits: NASA/WMAP Science TEAM

Cosmic microwave background

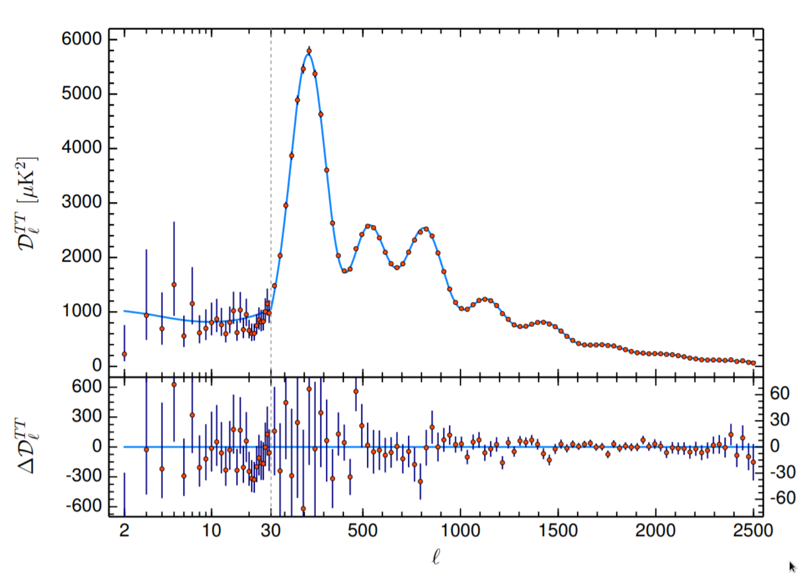
You are seeing the very photons that were emitted when the Universe was just 380,000 years old, and they display a spectrum indicative of a very precise temperature.



Credit: E. SIEGEL / BEYOND THE GALAXY



Credit: Hu, Sugiyama, Silk, astro-ph/9504057



Credit: Planck 2018

Why was the temperature of the CMB the same in all directions?
What was the origin of the small temperature fluctions?

Credit: Komatsu, ICTP Summer School on Cosmology 2018[1]

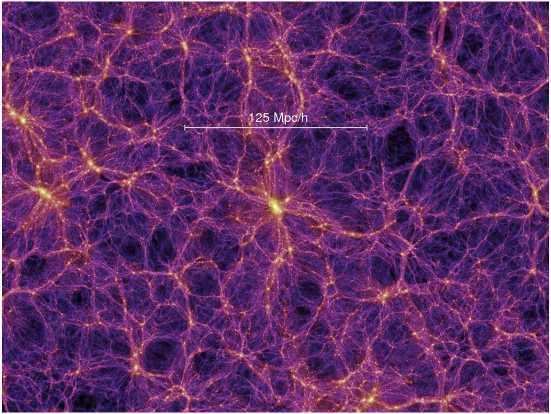
[1] Video avalaible

Credit: Komatsu, ICTP Summer School on Cosmology 2018[1]

[1] Video avalaible

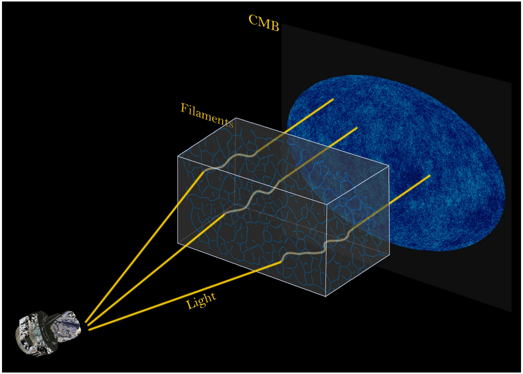
Cooking the soup: Cosmic web

Dark matter in the universe evolves through gravity to form a complex network of halos, filaments, sheets and voids, that is known as the cosmic web [arXiv:1801.09070]



Milenium simulation: `https://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/`

CMB filaments



Credits: Planck/ESA

A.C. Rodríguez, *et al* in arXiv:1801.09070 used data from the Baryon Oscillation Spectroscopic Survey, or BOSS, an Earth-based sky survey that captured light from about 1.5 million galaxies

Cosmic Anatomy

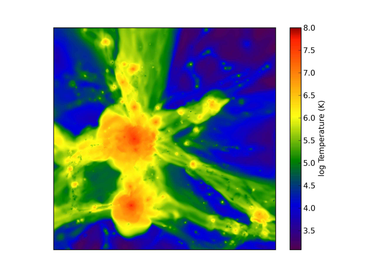
Baryons | Missing Baryons | Dark Matter

The muscles

Direct observations of filaments

Where are the Baryons? (Cen, Ostriker, astro-ph/9806281 [AJ])

> *Thus, not only is the universe dominated by dark matter, but more than one half of the normal matter is yet to be detected. (the muscles)*



Credit: Cen, arXiv:1112.4527 [AJ]

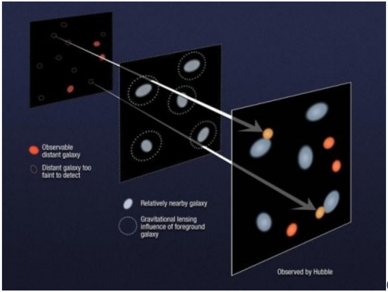
Warm-hot intergalactic medium (WHIM)
Density-weighted temperature projection of a portion of the refinement box of the C run of size $\left(18\,h^{-1}\mathrm{Mpc}\right)^3$.
Low temperature WHIM confirmed by O VI line that peak at $T \sim 3 \times 10^5$ K

New Hotter phases of the WHIM: **Observations of the missing baryons in the warm-hot intergalactic medium** (Nicastro, *et al.* arXiv:1806.08395 [Nature]).

The skeleton

Credit: `https://www.disnola.com`

Weak gravitational lensing



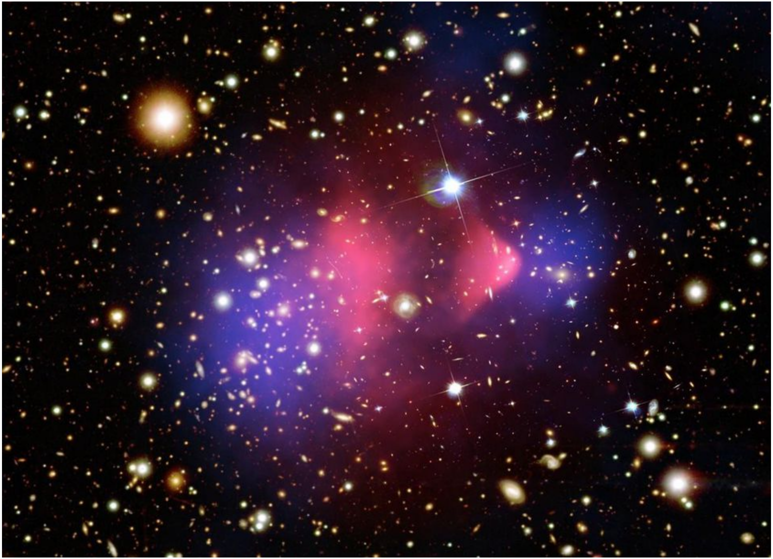
Credits: NASA/WMAP Science TEAM

Weak gravitational lensing.
This technique works somewhat like an X-ray: The ligth pass trough the dark matter until reach us.

Upcoming surveys will lead to the discovery of thousands of new gravitational lens systems

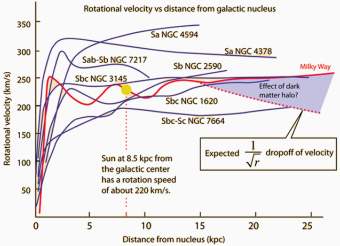
DM allows for a (free) factor of 10 increase in the discovery potential of very large telescopes that try to look at First Light objects

Bullet cluster



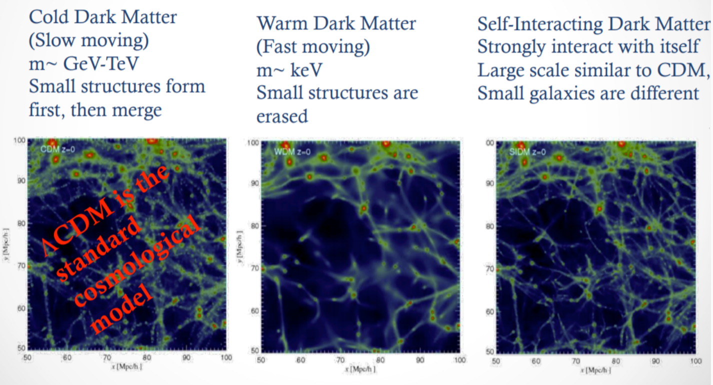
Further evidences

- For cluster of Galaxies
- For stars inside Galaxies
- Inside our Galaxy



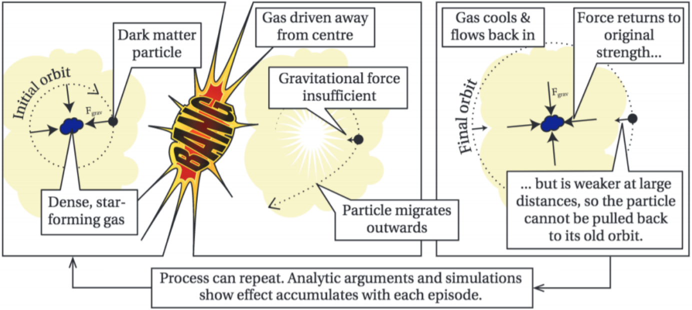
ΛCDM paradigm

Dark matter simulations



Credit: Arianna Di Cintio (Conference on Shedding Light on the Dark Universe with Extremely Large Telescopes, ICTP - 2018)

Baryonic effects

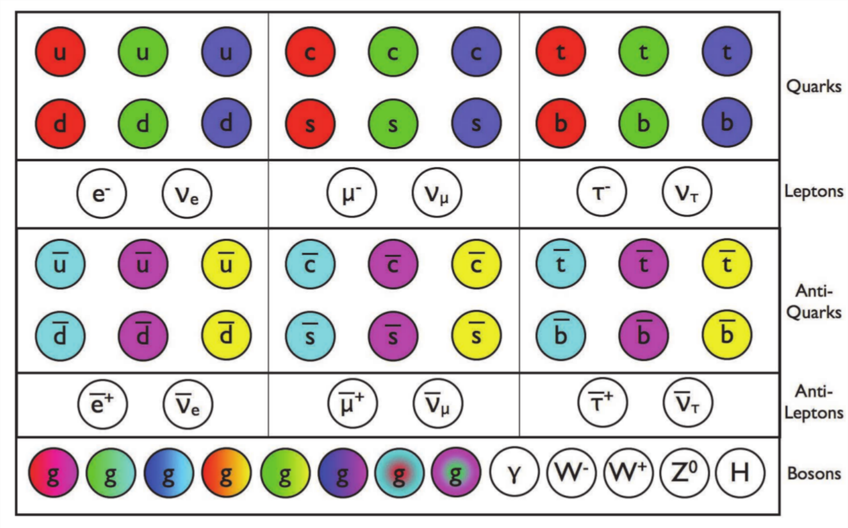


Pontzen & Governatp 14

Once the effect of baryonic physics is included, it is hard to distinguish between WDM/SIDM/CDM

Dark matter interpretations

SM



E. SIEGEL / BEYOND THE GALAXY

Z_2 Singlet scalar dark matter

Minimal number of fields:

SM (even) + Real Scalar singlet (odd)

$$\mathcal{L} = \mathcal{L}_{\text{SM}} \frac{1}{2}\partial_\mu S \partial^\mu S - \lambda_{HS} H^\dagger H\, S^2 - {M_S}^2\, S^2 - \lambda_S S^4\,.$$

S is stable and a dark matter particle

WIMP

At some high temperature after reheating the scalar dark matter particle is in thermal equilibrium with the standard model plasma. We rather high yield. We need the Higgs portal interaction to exponetial decrease the abundance until the correct relic density value. Freeze-out at $M_S/T \sim 20$

See `http://bit.ly/singletscalar`

requieres $\lambda_{HS} \sim 0.1$ (weak-like annihilation cross sections) https://colab.research.google.com/drive/1xeN7waRalplV1mlWcwNtKdd1BulosJmM#scrollTo=0Ox2eXrZk7bX

CODE TEXT CELL CELL CONNECT EDITING

Dark Matter Boltzmann equation

This program is made to reproduce the behavior of dark matter yield in WIMP and FIMP frameworks based on Chapter 5th, Kolb Turner (Early Universe)

```
[ ] %pylab inline
    import numpy as np
    from numpy import arange
    from scipy.integrate import odeint
```

```
[ ] # parameters

    Ms = 100                                #GeV Singlet Mass
    Mp = 1.22e19                            #GeV Planck Mass
    g = 100                                 # Degrees of freedom
    gs = 106.75                             # Entropy degrees of freedom
    H0 = 2.133*(0.7)*1e-42                   # GeV Hubble parameter (unused)
```

Boltzmann equation

The general expresion for the thermal evolution of DM is as follows (see eq (5.26) Kolb and Turner):

$$\frac{x}{Y_{EQ}(x)}\frac{dY}{dx} = -\frac{n_{EQ}(x)\langle\sigma v\rangle}{H(x)}\left[\left(\frac{Y}{Y_{EQ}(x)}\right)^2 - 1\right],$$

donde

$$n_{EQ}(x) = 2\left(\frac{M^2}{2\pi x}\right)^{3/2} e^{-x}$$

and []see (eq 5.16) Kolb & Turner]

$$H(x) = 1.67x^{-2}g_*^{1/2}\frac{M^2}{Mp}$$

The equilibrium distribution of this particles is consider for the non-relativistic case, as follows (see eq 5.25):

$$Y_{EQ}(x) = \frac{45}{2\pi^4}\frac{g}{g_{*s}}x^{3/2}e^{-x} = 0.145\frac{g}{g_{*s}}x^{3/2}e^{-x}\,,$$

where $x = M/T$ and $M = 100$ GeV is the singlet mass taken as constant.

WIMP

The initial condition to solve the evolution equation is $Y(x_i) = Y_{EQ}$, where $x_i = 0.01$, such that $T_i = M/x_i = 10^4$ GeV.

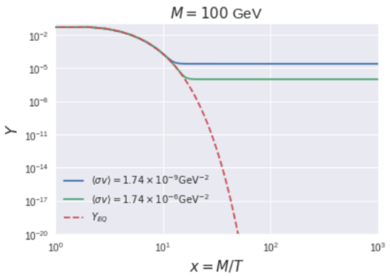
```
[7] def Yeq(x):
        return 0.145*(g/gs)*(x)**(3/2)*np.exp(-x)

    xi=1E-4
    xe=1000
    npts=3000
    # For several order of magnitude:
    x = np.linspace(0.01, 1000, 1000)
```

```
sigmav=[1.7475568196239999e-09,1.7475568196239999e-06]
def eqd(yl,x,Ms = 100,σv = sigmav[0]):
    '''
    Ms  [GeV]     : Singlet Mass
    σv: [1/GeV^2] : ⟨σv⟩
    '''

    Mp = 1.22e19
    g = 100                                 # Degrees of freedom
    gs = 106.75                             # Entropy degrees of freedom

    H = 1.67*g**(1/2)*Ms**2/Mp

    dyl = -2*(((Ms**2/(2*np.pi*x))**(3/2)*np.exp(-x))*σv/(x**(-2)*H*x))*(yl**2 - (0.145*(g/gs)*(x)**(3/2

    return dyl
```

[9]
```
#Initial conditions
y0 = Yeq(x[0])
yl =  odeint( eqd, y0, x,args=(Ms,sigmav[0]) )
yl1 = odeint( eqd, y0, x,args=(Ms,sigmav[1]) )
```

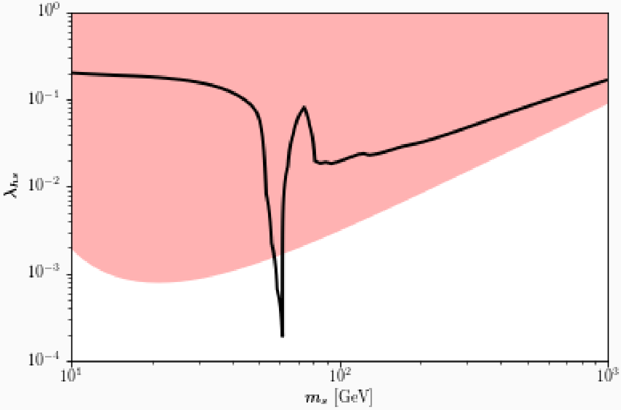
The following plot can be find in the reference book (Figure 5.1)

[10]
```
plt.loglog(x,yl, label = r'$\langle σ v\rangle = 1.74 \times 10^{-9} {\rm GeV}^{-2}$')
plt.loglog(x,yl1, label = r'$\langle σ v\rangle = 1.74 \times 10^{-6} {\rm GeV}^{-2}$')
plt.loglog(x,Yeq(x), '--', label = '$Y_{EQ}$')
plt.ylim(ymax=0.1,ymin=1e-20)
plt.xlim(xmax=1e3,xmin=1)
plt.xlabel('$x = M/T$', size= 15)
plt.ylabel('$Y$', size= 15)
plt.title('$M = 100$ GeV', size= 15)
plt.legend(loc='best',fontsize=10)
plt.grid(True)
```



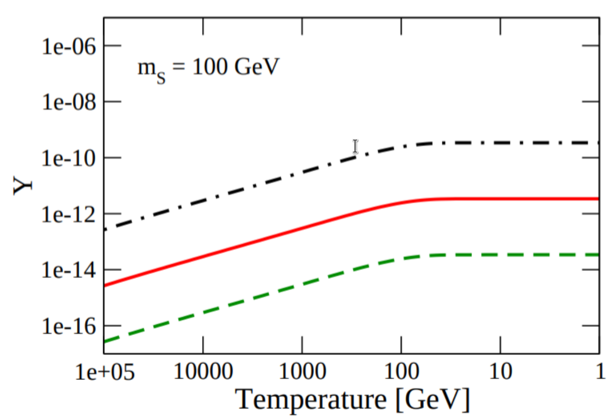
Full wimp parameter space

Restricted by direct detection cross section Xenon1T (arXiv:1805.12562)



FIMP

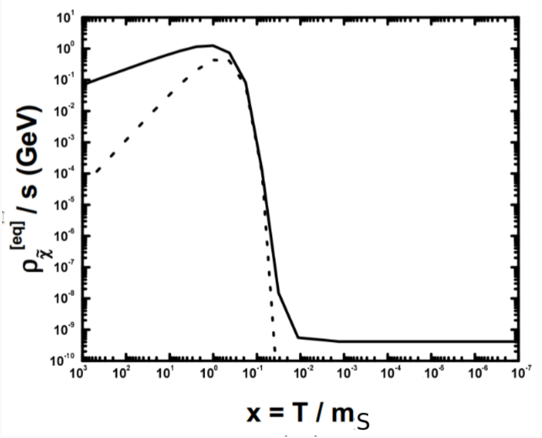
At some high temperature after reheating the abundance of scalar dark matter particle is zero. A feebly interaction allows the Higgs to produce dark matter particles until $M_S/T \sim 1$ where the freeze-in is reached. See C. Yaguna arXiv:1105.1654 [JHEP]



$\lambda_{HS} = 10^{-10}$, 10^{-11} , 10^{-12}. Not signals at all!

WIMP during reheating

The freeze-out occurs at $M/T_{\rm RH} \sim 10^3$. Very slow reheating for $M \sim 1TeV$- After reheating the dark matter particle not longer termalize and the freeze out is kept. See C. Pallis hep-ph/0402033 [APP]



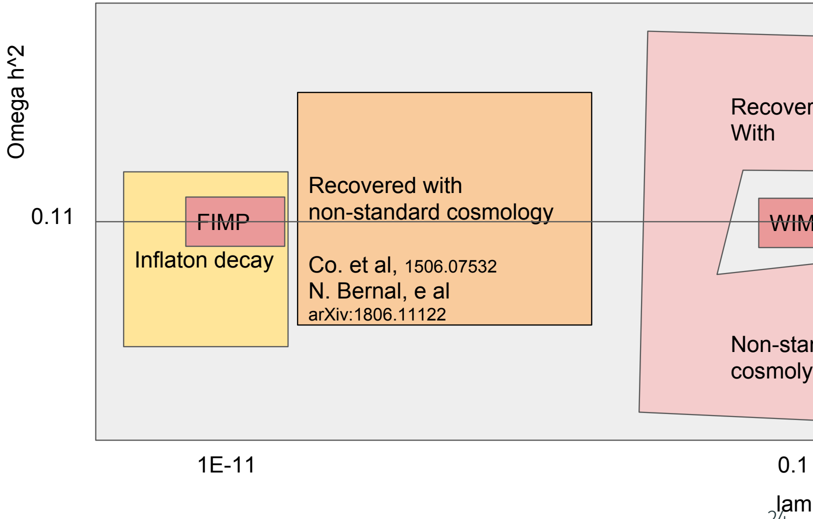
$M_\phi = 10^6$ GeV, $M_S = 350$ GeV $T_{\rm RH} = 5$ GeV $N^i_S = 1.4 \times 10^{-7}$. λ_{HS} fixed to be compatible with direct dection constrains

FIMP during reheating

Produced abundance can be an initial condition for the FIMP after reheating.

See poster session (Valentina Montoya)

Space


Omega h^2
0.11
FIMP
Inflaton decay
Recovered with
non-standard cosmology
Co. et al, 1506.07532
N. Bernal, e al
arXiv:1806.11122
Recover
With
WIM
Non-sta
cosmoly
1E-11
0.1
lam

Conclusions

Even a simple model like the Singlet Sccarlar Dark matter model can span many orders the maginuted in mass and in the strength of the interactions (Higgs portal λ_{HS}, self-interaction λ_S) afert non-thermal and non-standard cosmology scenarios are considered

Mass: fev MeV to PeV λ_{SH}: 10^{-16} to 10

May be the window to search for dark matter is too wide