# Bound Dark Matter

Theoretical constructions, constraints and connections to observations


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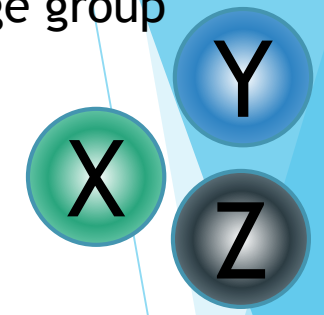
Cosmology on the Beach 2014

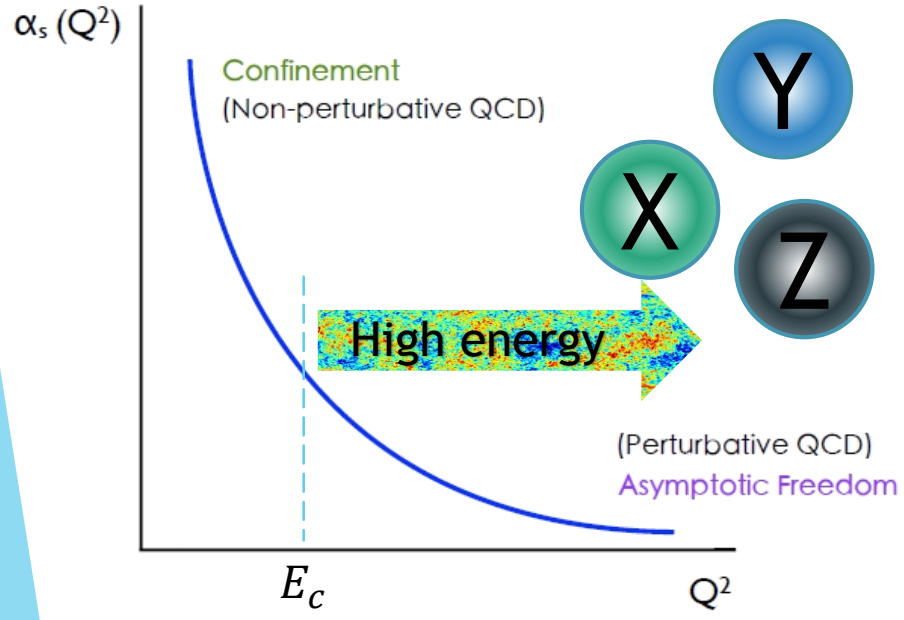
# The Model Bound Dark Matter

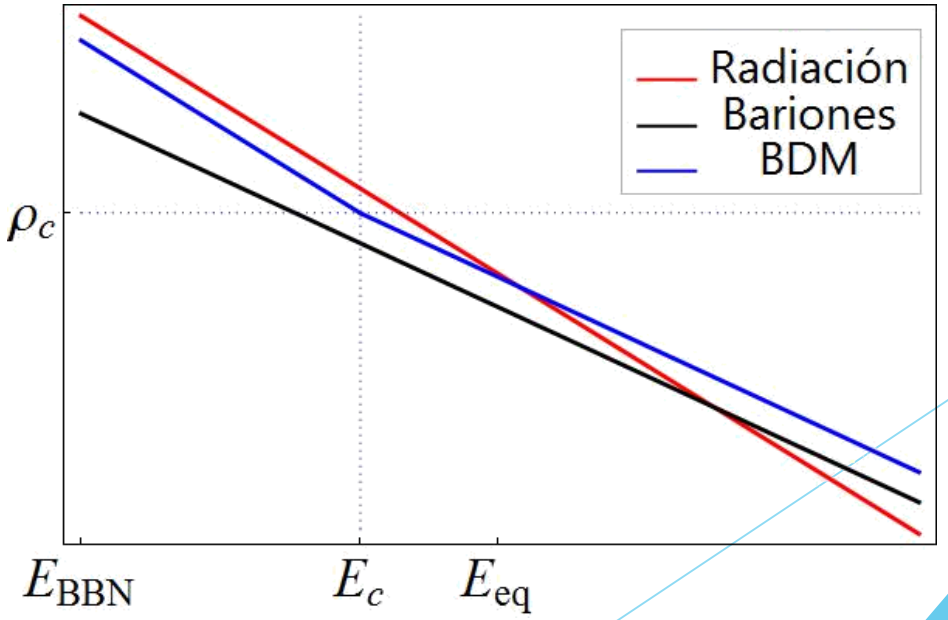
- Asymptotic Freedom

The model proposed that the dark matter is part of an asymptotically free gauge group

| | | | | |
|---|---|---|---|---|
| Asymptotic Freedom | $\alpha(E) \ll 1$ | $E > E_c$ | $m = 0$<br>$v \to c$ | $\rho = \rho_0 \left(\frac{a}{a_0}\right)^{-4}$ |
| Confinement | $\alpha(E) \geq 1$ | $E < E_c$ | $m \neq 0$<br>$v \to 0$ | $\rho = \rho_0 \left(\frac{a}{a_0}\right)^{-3}$ |




arXiv:0908.0571

# The Model Bound Dark Matter

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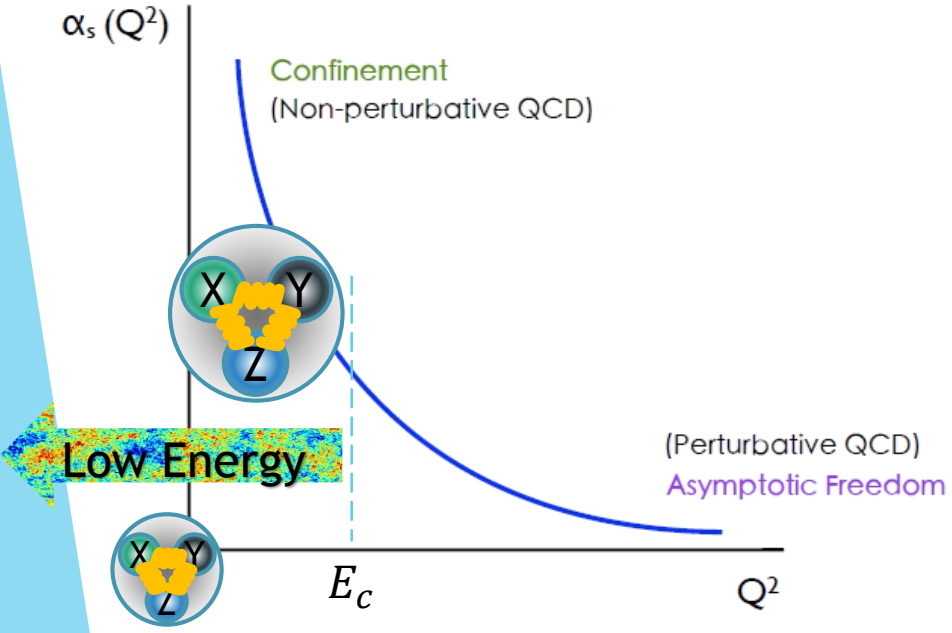
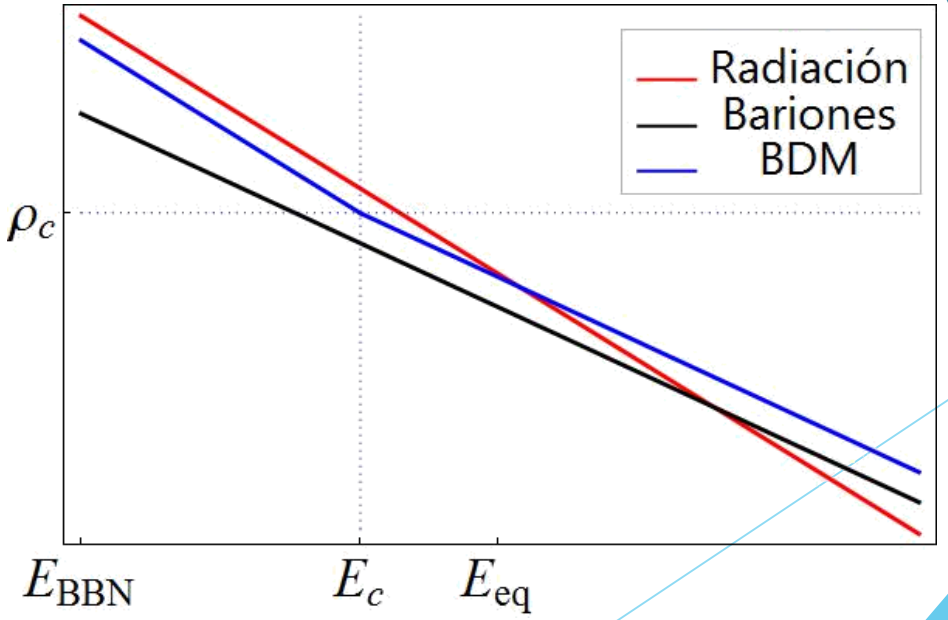
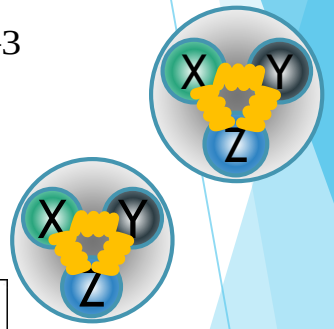


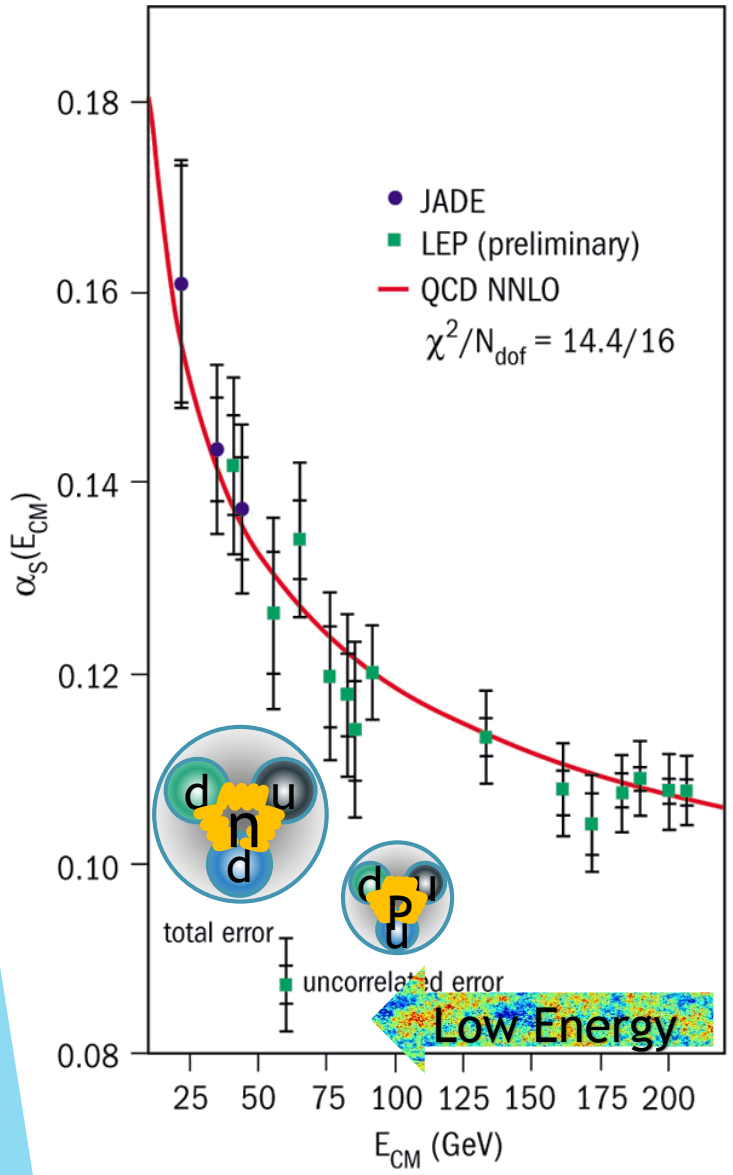




arXiv:0908.0571

# QCD Analogy

- SU(3)




$$g^{-2}(E) = g_i^{-2} + \frac{\beta}{8\pi^2}\log\left(\frac{E}{E_i}\right)$$

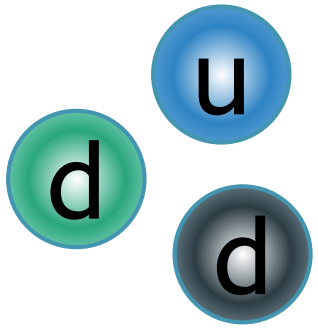
$$\alpha = \frac{g^2}{4\pi}$$

$$\beta(g) = -\left(\frac{11}{3}N_c - \frac{2}{3}N_f\right)$$

$N_f$: Fundamental part.

$N_c$: Charged part.

$$E_c = E_i e^{-8\pi^2/\beta g_i^2}$$




Low Energy

High energy

Example:

| | | |
|---|---|---|
| Proton | m = 938 MeV | n = 4.6 |
| Neutron | m = 940 MeV | n = 4.7 |
| Pion | m = 140 MeV | n = 0.7 |

$E_{QCD}$ = 200 MeV

$m_{up} = 2.3\ MeV$

$m_{down} = 4.8\ MeV$

For dimensional analysis we expect:

$$m_{bdm} = nE_c \qquad n \approx \vartheta(1)$$

The dark gauge group is not part of the SM of particles!

# BDM Model

- Free parameters

## 1. The energy (moment) of the transition $E_c$ $(a_c)$

In the theory of structure formation,is not only important the amount of DM, but also the qualities of the DM.

- Relativistic particles $T \gg m$

  $v \cong c$

- Non-relativistic particles $T \leq \frac{m}{3}$

  $v = v_c \frac{a_c}{a}$

## 2. The initial velocity $v_c$

Depending on the value of $E_c$ and $v_i$ the model can described cold, warm or bound DM

| | | |
|---|---|---|
| CDM | $E_c \gg MeV$ | |
| WDM | $100\ \mathrm{KeV} > E_c > KeV$ | $v_c \cong c$ |
| BDM | $E_c < KeV$ | $v_c < c$ |

# BDM Model

- Cosmological Scales

Massless, relativistic

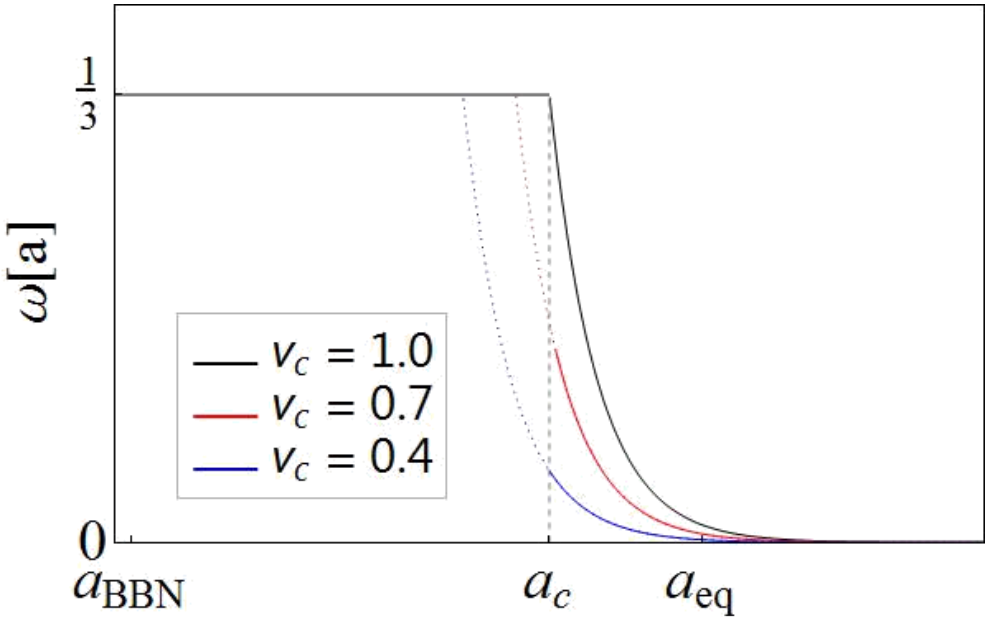
$E > E_c$ $\quad m = 0$ $\quad \omega = \frac{1}{3}$ $\quad \rho_{bdm} = \rho_c \left(\frac{a}{a_c}\right)^{-4}$

$a < a_c$ $\quad v \longrightarrow c$

Neutral, massive

$E < E_c$ $\quad m \neq 0$ $\quad \omega_{bdm} = \frac{v_{bdm}^2}{3}$ $\quad \rho_{bdm} = \rho_{bdm0} f(a) \left(\frac{a}{a_0}\right)^{-3}$

$a > a_c$ $\quad v \longrightarrow 0$ $\quad v_{bdm} = v_c \frac{a_c}{a}$




$$f(a) = \exp\left[\frac{3}{2}\,\omega_{bdm}(a)\left(1 - \frac{a^2}{{a_0}^2}\right)\right]$$

$$f(a) = \exp\left[\frac{1}{2}\left(\frac{v_c a_c}{a}\right)^2\left(1 - \frac{a^2}{{a_0}^2}\right)\right]$$

# Conection to Observations

- Equality and dark radiation

| | $\Omega_m$ | $z_{eq}$ | $N_{\rm eff}$ | $Y_p$ |
|---|---|---|---|---|
| Planck$^a$+ . . . . . | $0.308 \pm 0.010$ | $3366 \pm 39$ | – | – |
| Planck$^a$+ $N_{\rm eff}$ . . . . . | $0.304 \pm 0.011$ | $3354 \pm 42$ | $3.30 \pm 0.27$ | – |
| Planck$^a$+ $Y_p$ . . . . . | $0.306 \pm 0.011$ | $3373 \pm 40$ | – | $0.267 \pm 0.020$ |
| Planck$^a_\star$+ $N_{\rm eff}$ + $Y_p$ . . | $0.305 \pm 0.011$ | $3365 \pm 53$ | $3.19^{+0.54}_{-0.43}$ | $0.260^{+0.034}_{-0.029}$ |
| Planck$^b$+ $N_{\rm eff}$ . . . . . | $0.296 \pm 0.010$ | $3329 \pm 38$ | $3.52 \pm 0.24$ | – |
| WMAP9$^c$ . . . . . | $0.287^{+0.009}_{-0.009}$ | $3318 \pm 55$ | $3.55^{+0.49}_{-0.48}$ | $0.278^{+0.034}_{-0.032}$ |
| ACT$^d$. . . . . | $0.29 \pm 0.01$ | $3312 \pm 78$ | $3.50 \pm 0.42$ | $0.255^{+0.01}_{-0.11}$ |
| SPT$^e$. . . . . | $0.28 \pm 0.02$ | $3267 \pm 81$ | $3.86 \pm 0.42$ | $0.296^{+0.30}_{-0.30}$ |

arXiv:1303.7038

# Conection to Observations

- Equality and dark radiation

The dark radiation measured at the moment of equality is the remanent radiation of the BDM transition.

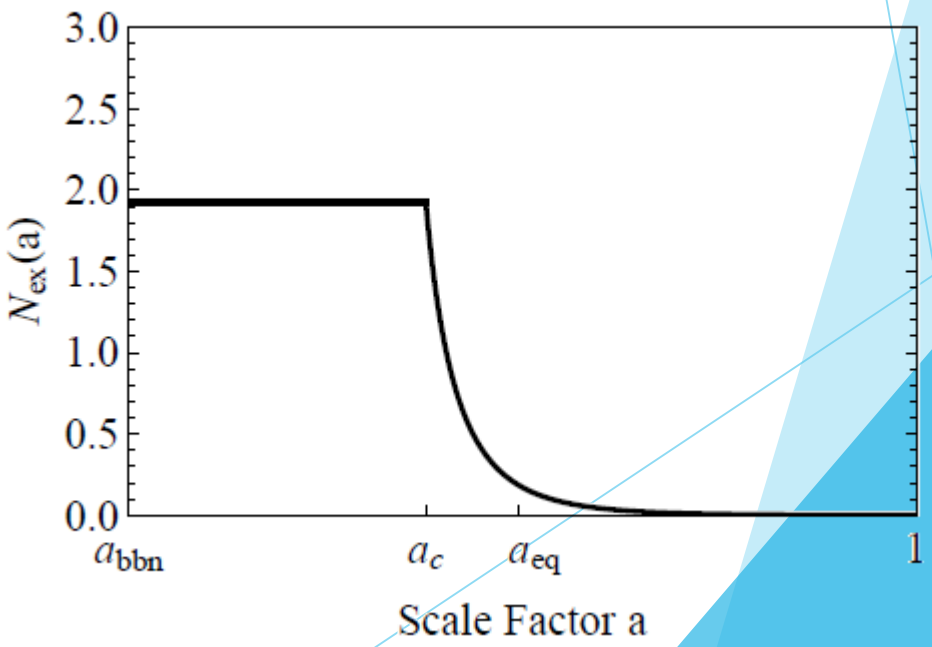
$$\tilde{\omega}_{tot} = \frac{P_{tot}}{\rho_{tot}} = \frac{\rho_r/3 + \omega_{bdm}\rho_{bdm}}{\rho_r + \rho_b + \rho_{bdm}}$$

$$\omega_{tot} = \hat{\omega}_{tot} = \frac{1}{6}$$

$$\frac{\tilde{a}_{eq}}{a_{eq}} = \frac{1}{1 + \frac{\Omega_{bdm0}}{\Omega_{m0}}\left[f(1 - 6\omega_{bdm}) - 1\right]}$$

$$\frac{\hat{a}_{eq}}{a_{eq}} = 1 + \frac{\xi N_{ex}}{1 + \xi N_v}$$

$$N_{ex}(a) = \frac{1 + \xi N_v}{\xi}\left(\frac{a}{a_{eq}}\frac{3\,\tilde{\omega}_{tot}(a)}{1 - 3\,\tilde{\omega}_{tot}(a)} - 1\right)$$




arXiv:1303.7038

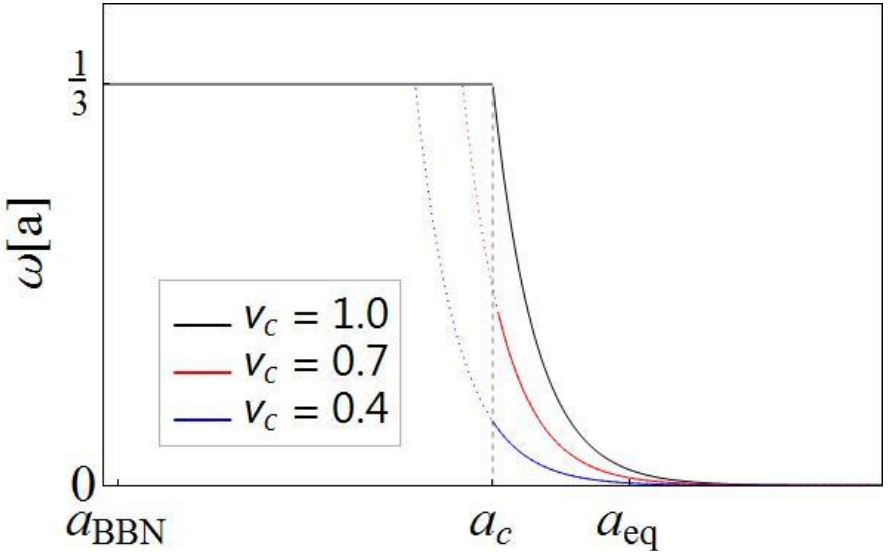
# Conection to Observations

- BBN and dark radiation

The abundance of neutral hidrogen ($Y_p$), taken into account non-standard expansion rate, is:

$$Y_p = 0.2485 + 0.0016[(\eta_{10} - 6) + 100(S - 1)]$$

$$S^2 = \left(\frac{\widetilde{H}}{H}\right)^2 \qquad \eta_{10} = 273.9\Omega_b h^2$$




Scale Factor a

MODELO BDM

$$S^2 = \frac{\tilde{\rho}_r}{\rho_r} = 1 + \frac{8}{43}\frac{\rho_{bdm}}{\rho_\gamma}$$

$$\rho_{bdm} = \rho_{bdm0}\frac{a_c}{a_0}\left(\frac{a}{a_0}\right)^4 e^{v^2{}_c/2}$$

We have extra radiation at the time of BBN due to the radiation behaviour of the BDM

EXTRA RADIATION

$$S^2 = \frac{\hat{\rho}_r}{\rho_r} = 1 + \frac{7}{43}N_{ex}$$

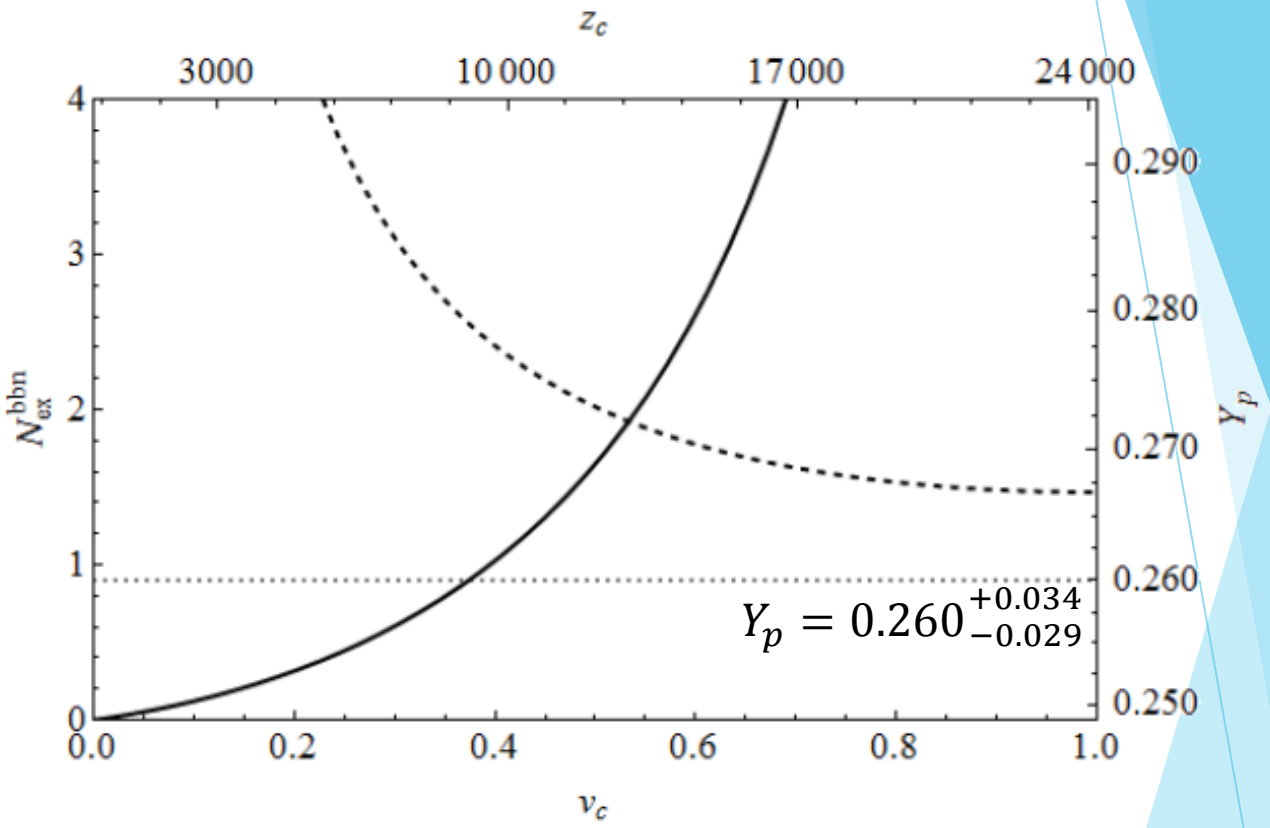
$$N_{ex}(a) = \frac{1}{\alpha}\frac{\Omega_{bdm0}}{\Omega_{\gamma 0}}\frac{a_c}{a_0}e^{v_c/2}$$

arXiv:1303.7038

# Conection to Observations

- BBN and dark radiation

The BDM model predicts the amount of $^4He$ at the time of BBN.




Equality

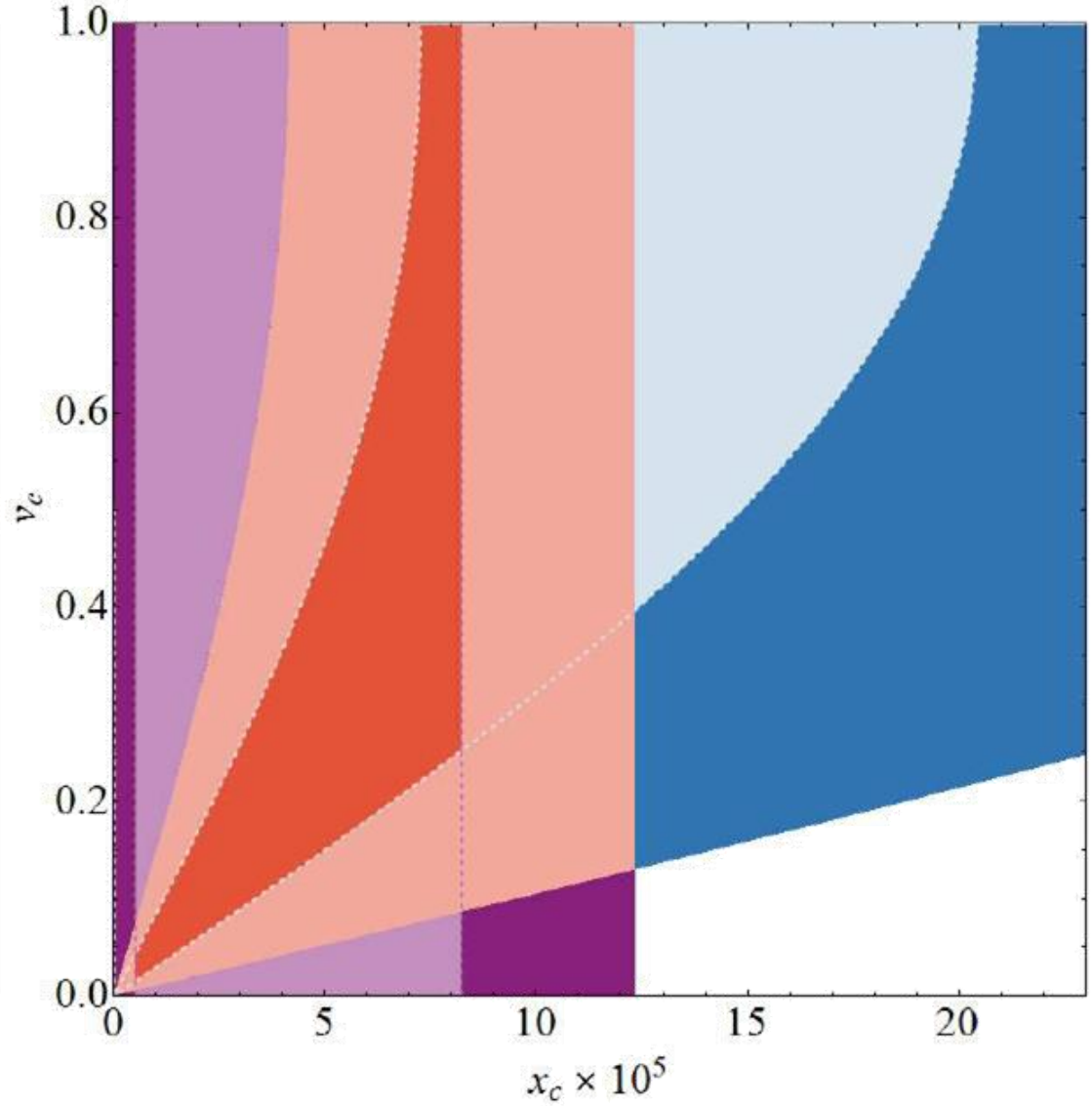
$$\omega_{tot} = \frac{1}{6} \qquad \text{———} \qquad N_{ex}(a_c) = \frac{1+\xi N_v}{\xi}\left(\frac{a_c}{a_{eq}}\frac{3\,\omega_{tot}(a_c\,,v_c)}{1-3\,\omega_{tot}(a_c\,,\ v_c)} - 1\right)$$

BBN — — — —

$$N_{ex}(a) = \frac{1}{\xi}\frac{\Omega_{bdm0}}{\Omega_{\gamma 0}}\frac{a_c}{a_0}e^{v_c/2}$$

# Conection to Observations

- BBN and dark radiation




(b) Planck$_\star$

| | Planck$_\star$ [a] |
|---|---|
| $x_c \times 10^5$ . | $4.13^{+3.65}_{-4.13}$ |
| $N_{\rm ex}^{\rm bbn}$ . . . | $0.9^{+1.5}_{-0.9}$ |
| $v_c$ . . . . . | $0.37^{+0.18}_{-0.17}$ |
| $z_c$ . . . . . | $\geq 24217$ |
| $E_c^{\rm cos}[eV]$ . . | $\geq 3.89$ |

$x_c \stackrel{\rm def}{=} a_c\, v_c$

arXiv:1303.7038

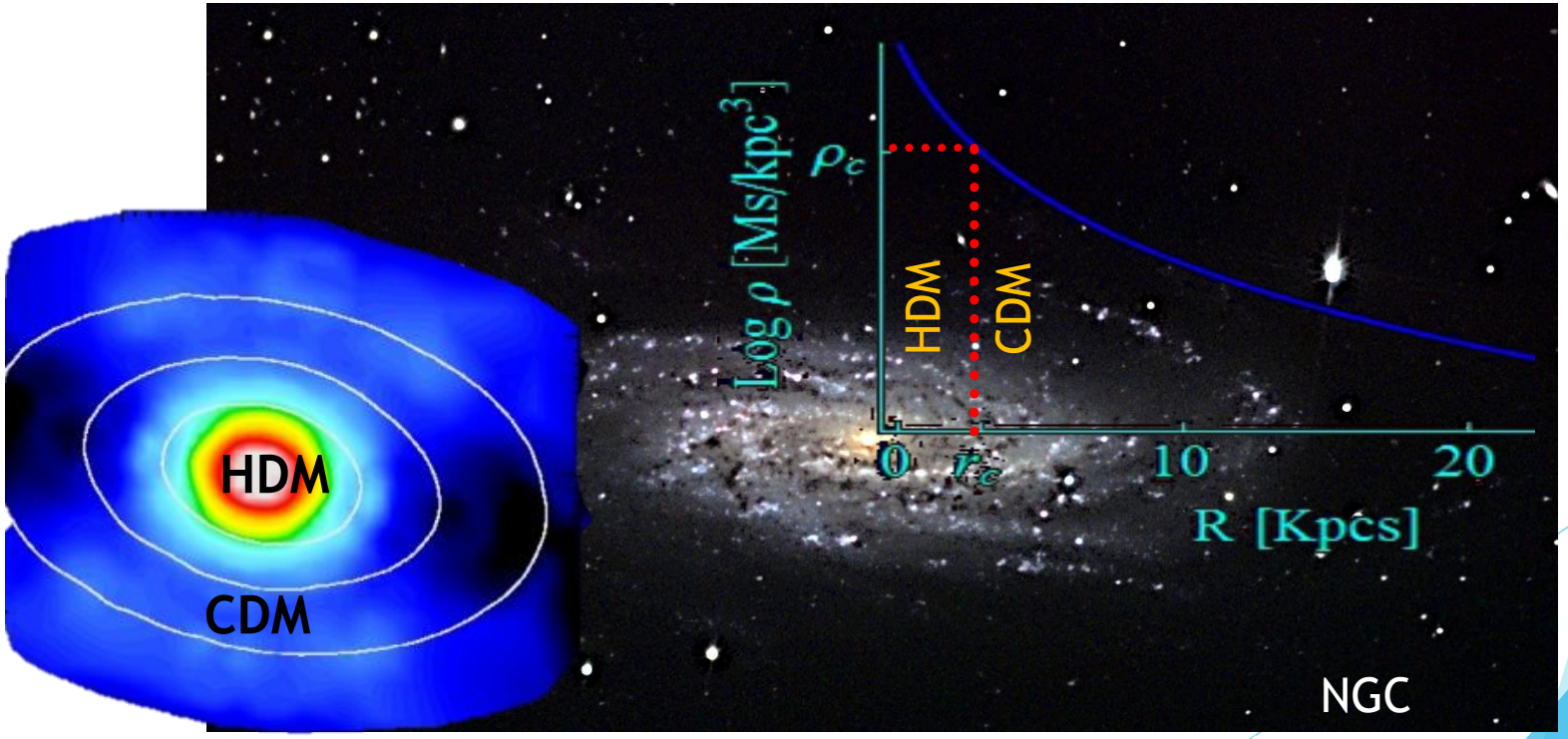
# Conection to Observations

- Galaxies

The BDM model predicts a DM core inside the galaxies.

In the outer galactic region we expect a NFW halo profile.

We constrain the value $E_c$ by fitting the RC of galaxies with a generic NFW profile.




arXiv:1107.5560

# Conection to Observations

- Galaxies

BDM

$$\rho_{BDM} = \frac{\rho_0}{\left(\frac{r_c}{r_s} + \frac{r}{r_s}\right)\left(1 + \frac{r}{r_s}\right)^2} = \frac{2\rho_c}{\left(1 + \frac{r}{r_c}\right)\left(1 + \frac{r}{r_s}\right)^2}$$

Transition energy

$$Ec^4 \propto \rho_{BDM}(r = r_c) \equiv \rho_c \qquad \rho_c = \frac{\rho_0 r_s}{2r_c}$$

Pseudo-Isotermal

$$\rho_{ISO} = \frac{\rho_0}{1 + \left(\frac{r}{r_s}\right)^2}$$

Burkert

$$\rho_B = \frac{\rho_0}{\left(1 + \frac{r}{r_s}\right)\left(1 + \left(\frac{r}{r_s}\right)^2\right)}$$

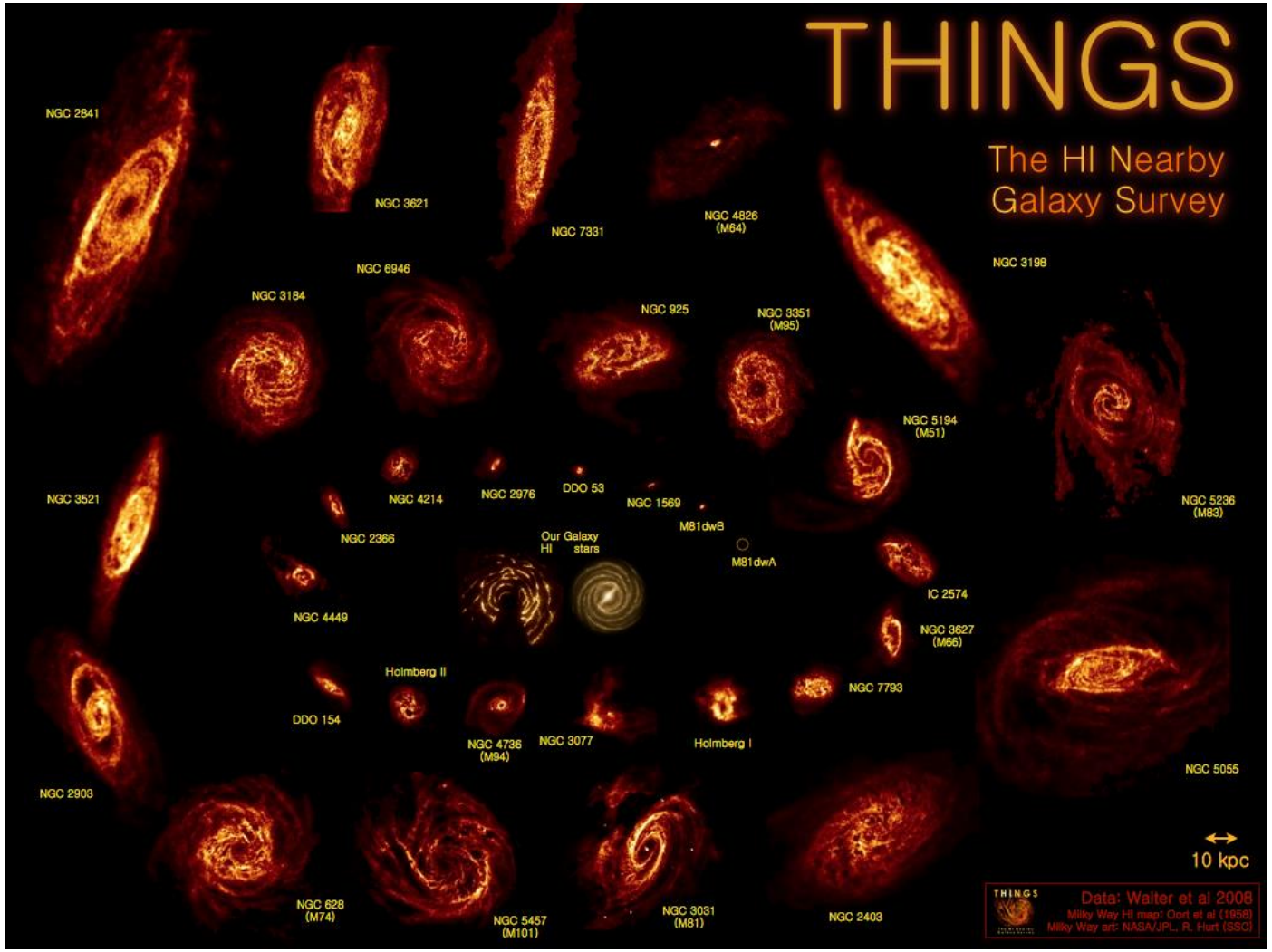
Navarro-Frenk-White

$$\rho_{NFW} = \frac{\rho_0}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$$

arXiv:1107.5560

# Conection to Observations

- Galaxies




- Great angular resolution
- Large number of galaxies
- Circular movements
- No elongation of dark matter halos

arXiv:1107.5560

# Conection to Observations

- Galaxies – Inner analysis

MOTIVATION

- A poor fit in the most inner data.
- The fitting is dominated by the external data.
- The data are good enough to do an inner analysis.

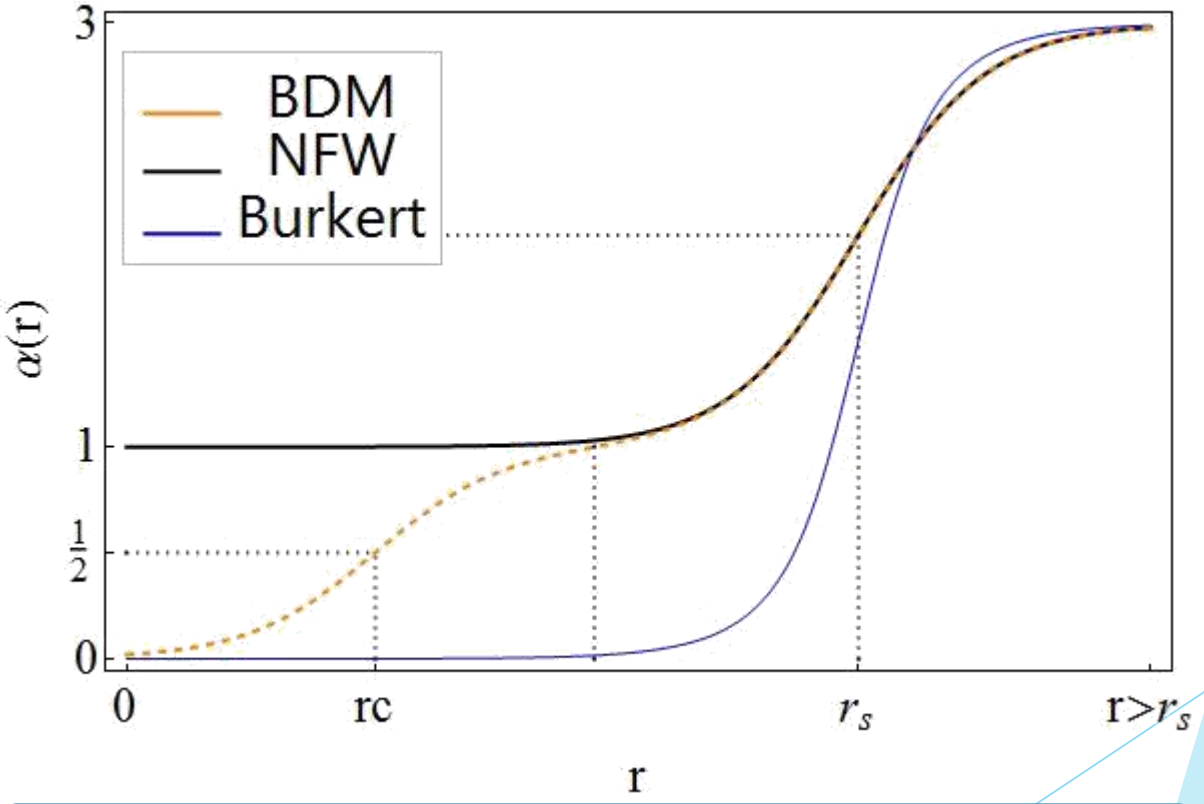
$$\rho_{BDM} = \frac{\rho_0}{\left(\frac{r_c}{r_s} + \frac{r}{r_s}\right)\left(1 + \frac{r}{r_s}\right)^2}$$

If $r \ll r_s$

$$\rho_{\text{int}} = \frac{\rho_c}{\left(1 + \frac{r}{r_c}\right)}$$

Ansatz:

$$\rho_\alpha = \rho_0 r^\alpha$$




If $\alpha < \frac{1}{2}$ we are in the core region $r < r_c$

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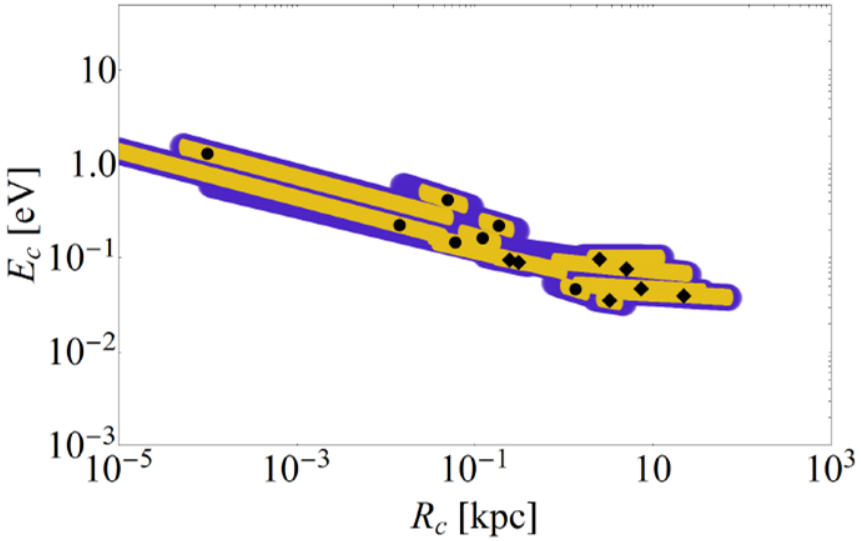
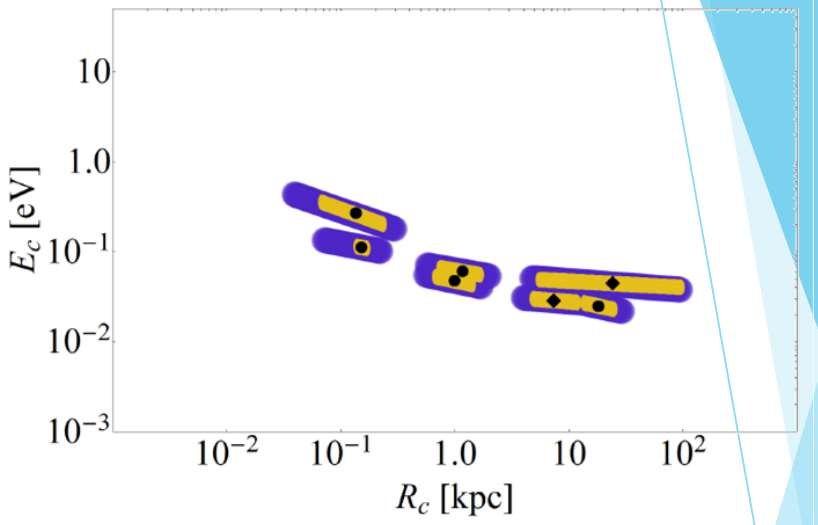
# Conection to Observations

- Galaxies - Results




(a) $R_c vs E_c^{\rm gal}$ : Minimal Disk




(c) $r_c$ vs $E_c^{\rm gal}$ : Kroupa

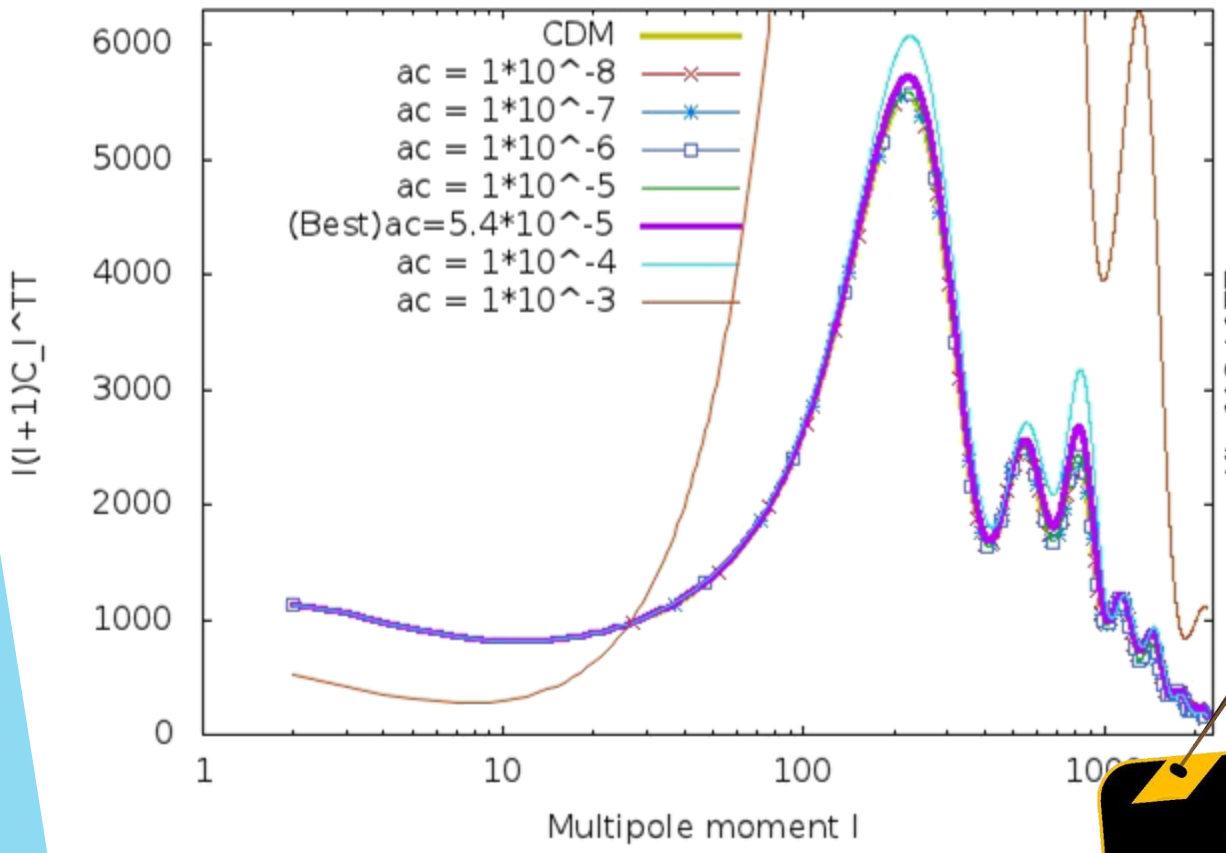
BDM Statistics

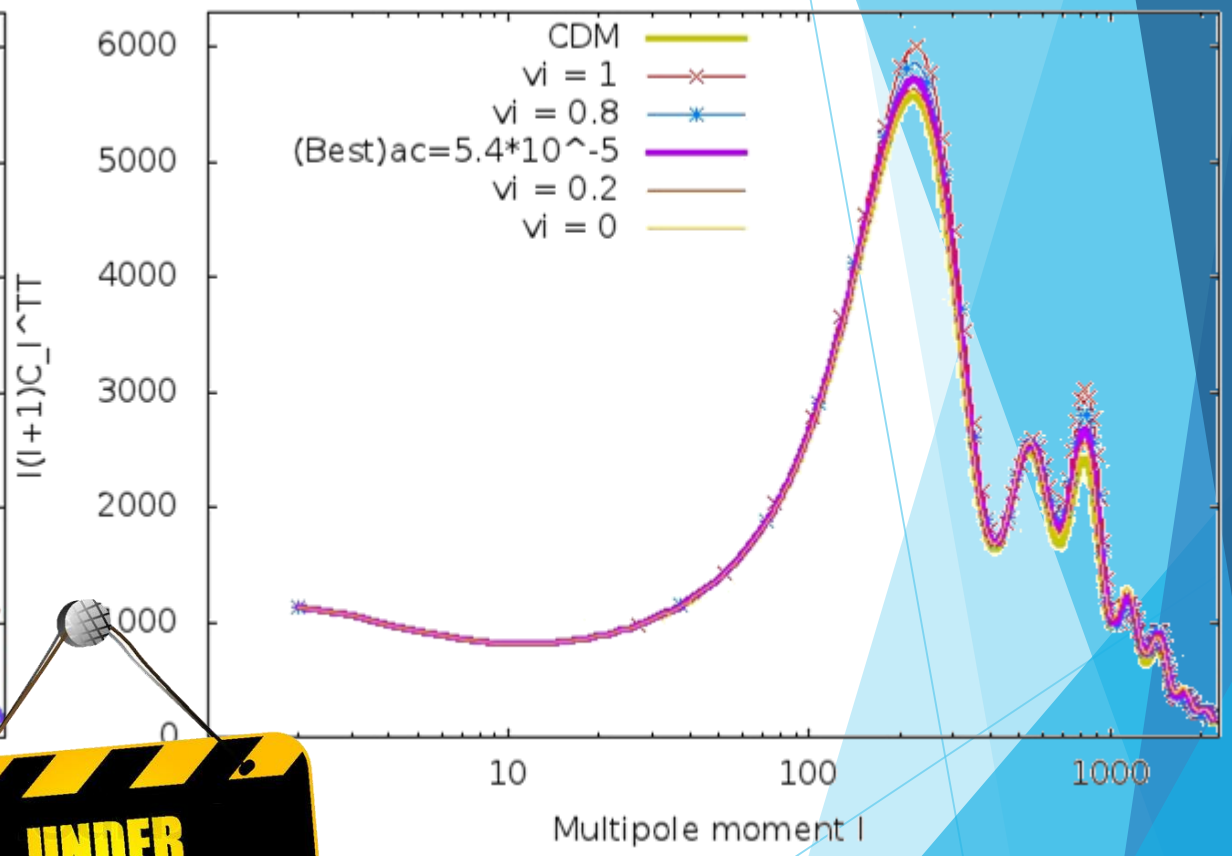
| Mass Models | Energy $E_c^{\rm gal}$ | | | | | | Core $r_c$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\tilde{E}_{c_n}$ | $E_{c_-}$ | $E_c^{\rm gal}$ | $E_{c_+}$ | $\sigma(E_c^{\rm gal})$ | $\log_{10}\rho_c$ | $\tilde{r}_{c_n}$ | $r_{c_-}$ | $\hat{r}_c$ | $r_{c_+}$ | $\sigma(r_c)$ |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
| Min.Disk | 0.21 | 0.04 | 0.11 | 0.33 | 0.46 | 8.85 | 3.02 | 0.01 | 0.30 | 7.02 | 1.37 |
| Min.Disk+gas | 0.10 | 0.05 | 0.08 | 0.15 | 0.25 | 8.35 | 3.81 | 0.15 | 0.98 | 6.60 | 0.83 |
| Kroupa | 0.08 | 0.03 | 0.06 | 0.13 | 0.33 | 7.65 | 6.59 | 0.16 | 1.48 | 13.73 | 0.97 |
| diet-Salpeter | 0.13 | 0.02 | 0.07 | 0.21 | 0.47 | 7.92 | 5.85 | 0.17 | 1.70 | 17.37 | 1.01 |

arXiv:1107.5560

# Conection to Observations

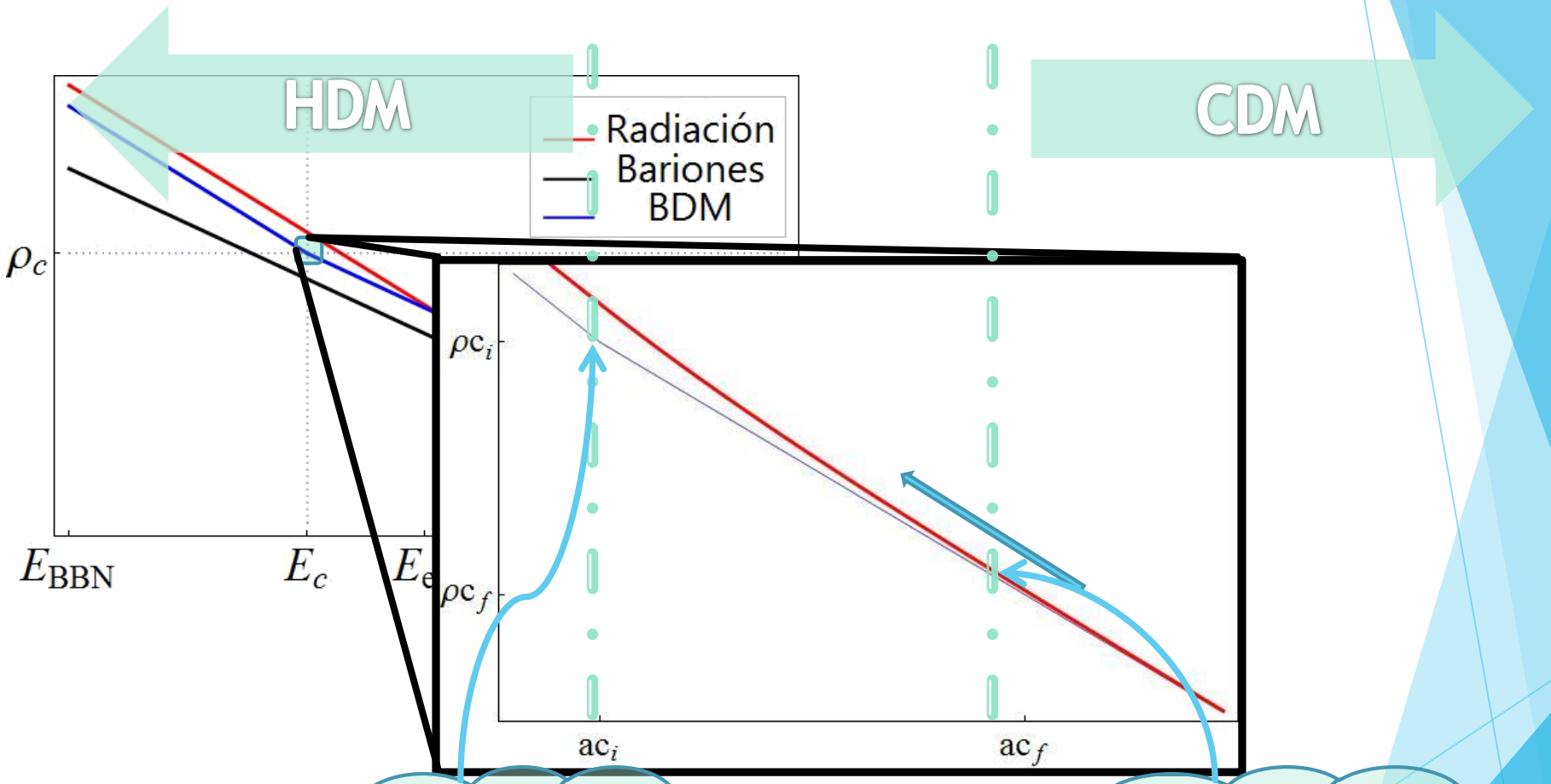
- CMB



# Conclusions

- The transition energy $E_c$ constrained by time of BBN and the moment of equality is $E_c = \vartheta(10)\ eV$.
- The amount of $^4He$ that BDM model predicts is within 1σ error data of CMB.
- The extra radiation, and different fitted values at BBN and equality, can be explained with an equation of state that depends of the scale factor.
- The energy transition constrained by the rotation curves is $E_c = \vartheta(0.1)\ eV$.
- El BDM profile, taking $\rho_c$ as a fundamental constant, and two free parameters given by the morphology on the galaxies, can fit better (6/4) than NFW profile.
- The model predict an average cores of 2.3 kpc in DM halos.




BBN, Equality, CMB, LSS

RC, Cluster of galaxies

# Equality

SM:

$(N_\upsilon = 3.046)$

$$\rho_r = (1 + \xi\, N_\nu)\rho_\gamma$$

$$\xi = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}$$

$$\frac{a_{eq}}{a_0} = \frac{\rho_{r0}}{\rho_{m0}}$$

$$\omega_{tot}(a) = \frac{P_{tot}}{\rho_{tot}} = \frac{1}{3}\frac{a_{eq}}{a_{eq} + a}$$

Radiación extra:

$$\hat{\rho}_r = (1 + \xi N_{eff})\rho_\gamma$$

$$N_{eff} = N_\nu + N_{ex}$$

$$\frac{\hat{a}_{eq}}{a_0} = \frac{\hat{\rho}_{r0}}{\rho_{m0}}$$

$$\frac{\hat{a}_{eq}}{a_{eq}} = 1 + \frac{\xi N_{ex}}{1 + \xi N_\nu}$$

$$\hat{\omega}_{tot}(a) = \frac{P_{tot}}{\rho_{tot}} = \frac{1}{3}\frac{\hat{a}_{eq}}{\hat{a}_{eq} + a}$$

We define equivalence when

$$\boxed{\omega_{tot}(a_{eq}) = \hat{\omega}_{tot}(\hat{a}_{eq}) = \frac{1}{6}}$$

$$\rho_{BDM} = \frac{\rho_0}{\left(\frac{r_c}{r_s}+\frac{r}{r_s}\right)\left(1+\frac{r}{r_s}\right)^2} = \frac{2\rho_c}{\left(1+\frac{r}{r_c}\right)\left(1+\frac{r}{r_s}\right)^2}$$

Estadística de BDM-Fijo

| Mass Model | $E_c^{gal}$ | $\tilde{r}_c$ | $r_{c-}$ | $r_c$ | $r_{c+}$ | $\sigma(r_c)$ | $\tilde{r}_s$ | $r_{s-}$ | $r_s$ | $r_{s+}$ | $\sigma(r_s)$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
| Min.Disk | 0.11 | 0.81 | 0.11 | 0.46 | 1.85 | 0.61 | 4.71 | 0.51 | 2.64 | 13.44 | 0.71 |
| Min.Disk+gas | 0.08 | 1.86 | 0.40 | 1.28 | 4.11 | 0.51 | 3.25 | 1.03 | 2.41 | 5.62 | 0.37 |
| Kroupa | 0.06 | 2.01 | 0.44 | 1.27 | 3.65 | 0.46 | 13.84 | 2.90 | 8.56 | 25.26 | 0.47 |
| diet-Salpeter | 0.07 | 1.59 | 0.25 | 0.85 | 3.50 | 0.62 | 11.99 | 2.80 | 7.84 | 22.01 | 0.45 |

**ONLY DM**

8 Galaxies $\chi^2_{BDM} < \chi^2_{NFW}$

8 Galaxies $\chi^2_{BDM} \approx \chi^2_{NFW}$

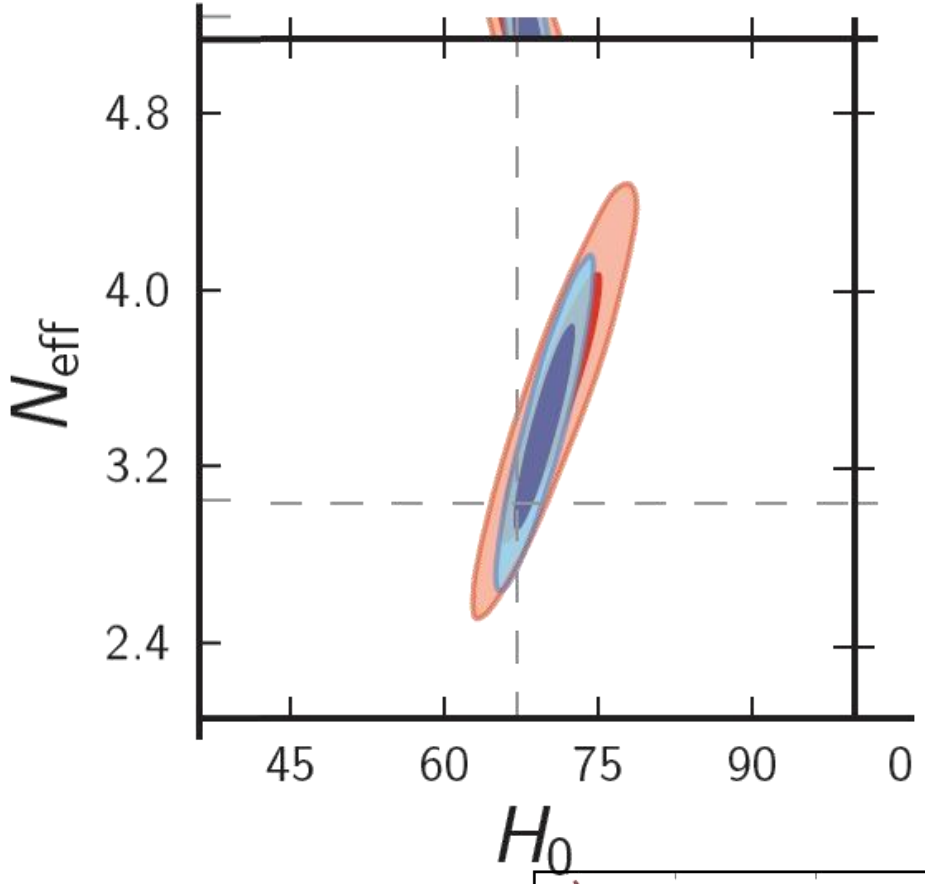
2 Galaxies $\chi^2_{BDM} > \chi^2_{NFW}$

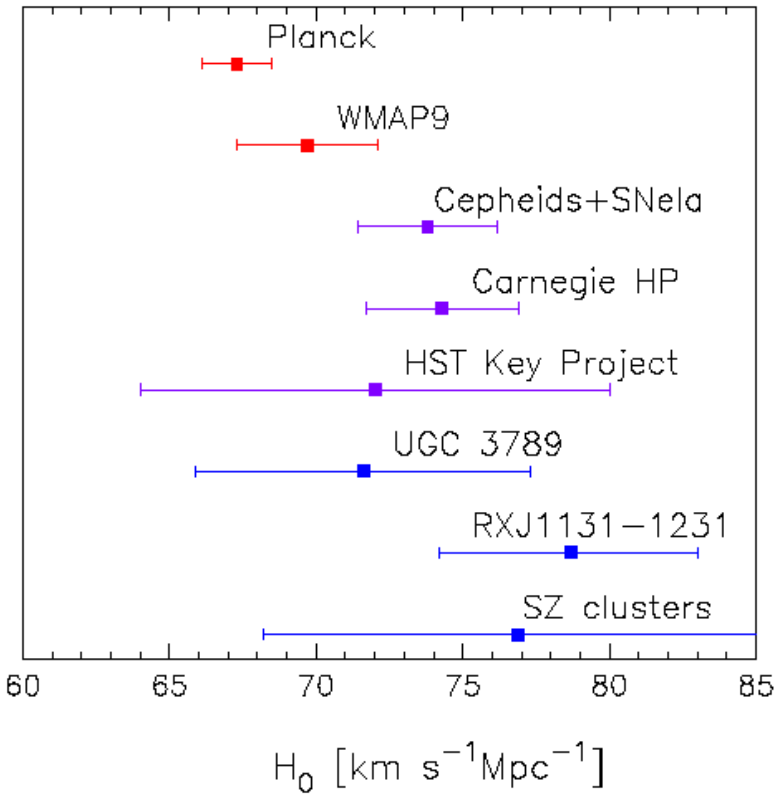
**KROUPA**

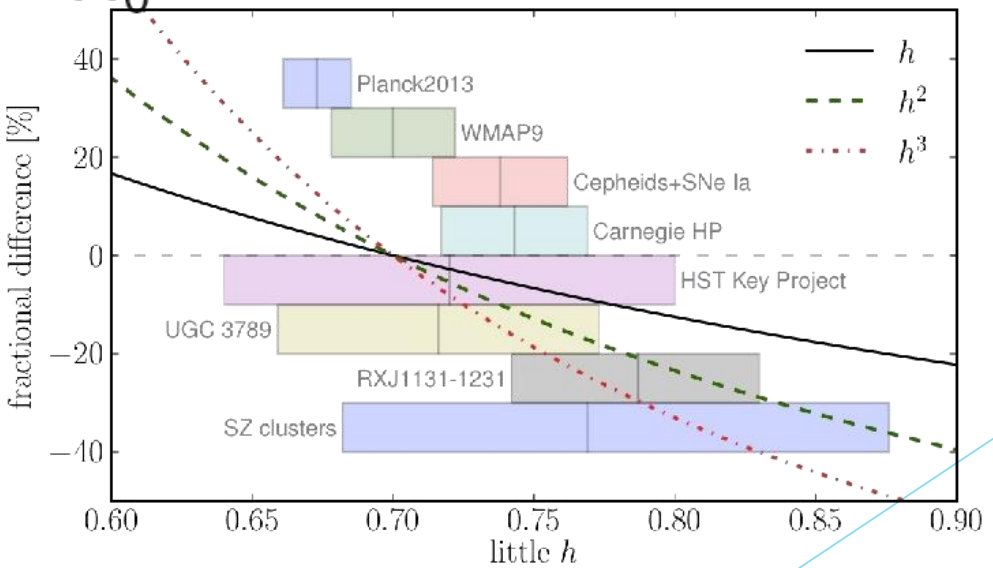
6 Galaxies $\chi^2_{BDM} < \chi^2_{NFW}$

7 Galaxies $\chi^2_{BDM} \approx \chi^2_{NFW}$

4 Galaxies $\chi^2_{BDM} > \chi^2_{NFW}$


4.8
4.0
3.2
2.4
$N_{eff}$
45
60
75
90
0
$H_0$


Planck
WMAP9
Cepheids+SNeIa
Carnegie HP
HST Key Project
UGC 3789
RXJ1131−1231
SZ clusters
60
65
70
75
80
85
$H_0$ [km s$^{-1}$Mpc$^{-1}$]


Planck2013
WMAP9
Cepheids+SNe Ia
Carnegie HP
HST Key Project
UGC 3789
RXJ1131-1231
SZ clusters
$h$
$h^2$
$h^3$
40
20
0
−20
−40
fractional difference [%]
0.60
0.65
0.70
0.75
0.80
0.85
0.90
little $h$

$$P = \frac{n\langle p^2 \rangle}{3\langle E \rangle}$$

$$E = \gamma\, m_0$$

$$p = \gamma\, m_0\, v$$

$$\rho = n\langle E \rangle$$

$$\omega = \frac{P}{\rho} = \frac{\langle p^2 \rangle}{3\langle E \rangle^2} = \frac{v^2}{3}$$

En el límite no relativista $m \gg T$

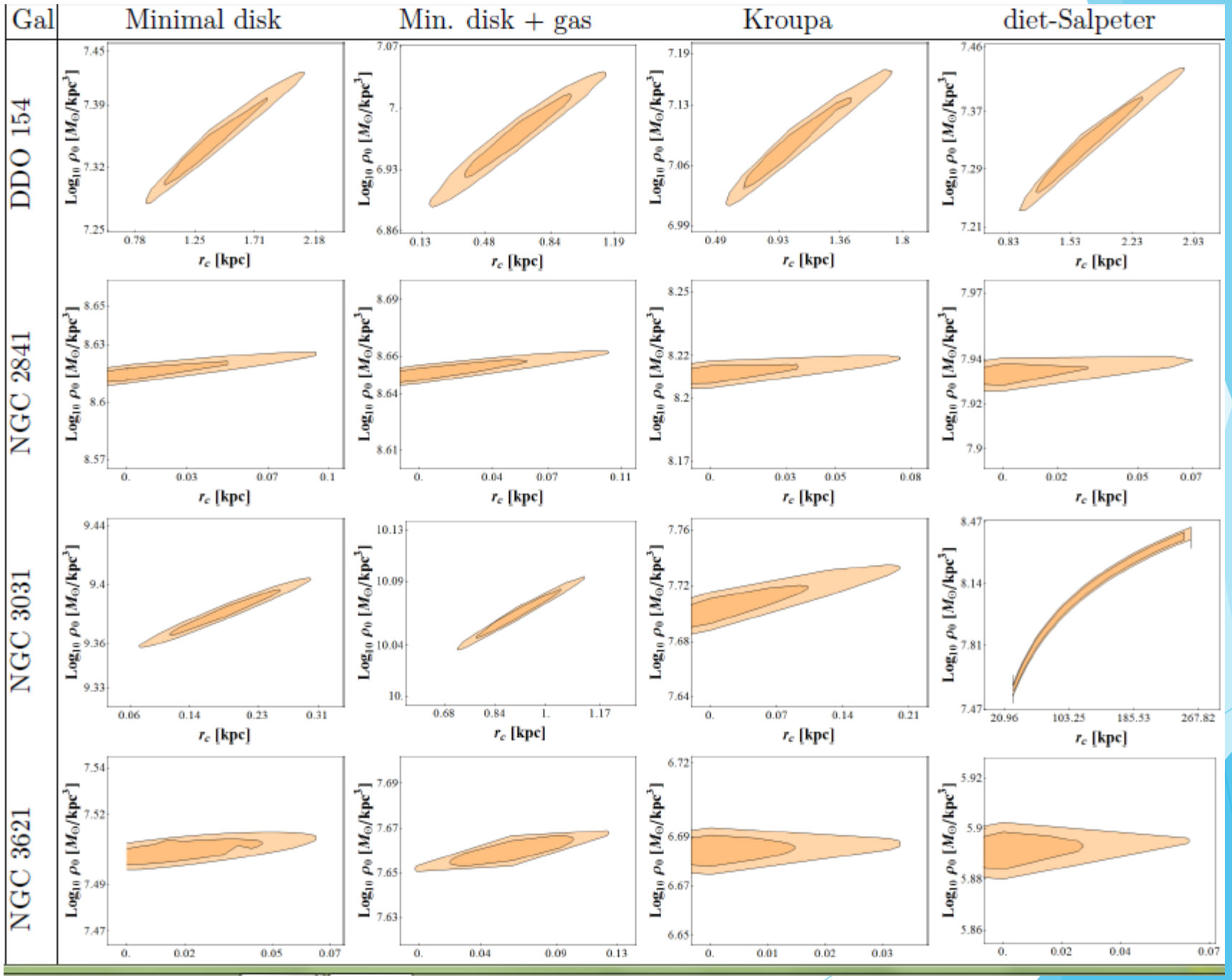
$$\rho = mn$$

$$P = Tn$$

$$\omega = \frac{P}{\rho} = \frac{T}{m}$$

$$T \propto a^{-2} \qquad v \propto a^{-1}$$

$$v = v_c \frac{a_c}{a}$$


Gal
Minimal disk
Min. disk + gas
Kroupa
diet-Salpeter
DDO 154
NGC 2841
NGC 3031
NGC 3621
$\mathrm{Log}_{10}\,\rho_0\,[M_\odot/\mathrm{kpc}^3]$
$r_c$ [kpc]

BDM

| | Galaxia | MINIMAL DISK | | | MINIMAL DISK+GAS | | |
|---|---|---|---|---|---|---|---|
| | | $r_c$ | $\log_{10}\rho_c$ | $E_c$ | $r_c$ | $\log_{10}\rho_c$ | $E_c$ |
| G.A | DDO154 | $1.35^{+0.04}_{-0.04}$ | $7.20^{+6.18}_{-6.17}$ | $0.05^{+0.001}_{-0.001}$ | $0.66^{+0.04}_{-0.04}$ | $7.42^{+6.54}_{-6.53}$ | $0.05^{+0.002}_{-0.002}$ |
| | NGC2841 | $0.001^{+0.01}_{-0.01}$ | $12.98^{+15.}_{-11.08}$ | $1.29^{+0.004}_{-0.004}$ | $< 0.01$ | – | – |
| | NGC3031 | $0.19^{+0.01}_{-0.01}$ | $9.90^{+8.74}_{-8.02}$ | $0.22^{+0.004}_{-0.001}$ | $0.91^{+0.01}_{-0.01}$ | $9.14^{+7.74}_{-7.73}$ | $0.14^{+0.001}_{-0.001}$ |
| | NGC3621 | $0.01^{+0.01}_{-0.01}$ | $9.94^{+9.87}_{-9.83}$ | $0.22^{+0.05}_{-0.04}$ | $0.06^{+0.01}_{-0.01}$ | $9.36^{+8.76}_{-8.74}$ | $0.16^{+0.01}_{-0.01}$ |
| | NGC4736 | $0.05^{+0.01}_{-0.01}$ | $11.01^{+10.2}_{-8.9}$ | $0.41^{+0.016}_{-0.001}$ | $0.40^{+0.009}_{-0.005}$ | $9.71^{+8.61}_{-7.61}$ | $0.20^{+0.004}_{-0.0004}$ |
| | NGC6946 | $0.12^{+0.02}_{-0.01}$ | $9.37^{+8.53}_{-8.46}$ | $0.16^{+0.006}_{-0.005}$ | $0.15^{+0.01}_{-0.01}$ | $9.30^{+8.33}_{-8.32}$ | $0.16^{+0.004}_{-0.004}$ |
| | NGC7793 | $0.06^{+0.01}_{-0.01}$ | $9.18^{+8.51}_{-8.49}$ | $0.15^{+0.007}_{-0.007}$ | $0.06^{+0.01}_{-0.01}$ | $9.21^{+8.56}_{-8.55}$ | $0.15^{+0.008}_{-0.008}$ |
| G.B | IC2574 | $3.26^{+0.33}_{-0.33}$ | $6.72^{+5.74}_{-5.72}$ | $0.04^{+0.001}_{-0.001}$ | $2.22^{+0.2}_{-0.2}$ | $6.71^{+5.73}_{-5.76}$ | $0.03^{+0.001}_{-0.001}$ |
| | NGC2366 | $7.40^{+0.74}_{-0.74}$ | $6.32^{+5.68}_{-5.72}$ | $0.03^{+0.002}_{-0.002}$ | $3.23^{+0.3}_{-0.3}$ | $6.02^{+6.03}_{-6.05}$ | $0.02^{+0.006}_{-0.006}$ |
| | NGC2903 | $1.70^{+0.17}_{-0.17}$ | $8.12^{+7.26}_{-7.26}$ | $0.08^{+0.003}_{-0.003}$ | $1.66^{+0.2}_{-0.2}$ | $8.12^{+7.27}_{-7.27}$ | $0.08^{+0.003}_{-0.003}$ |
| | NGC2976 | $0.25^{+0.025}_{-0.025}$ | $8.44^{+7.46}_{-7.45}$ | $0.09^{+0.003}_{-0.002}$ | $0.20^{+0.02}_{-0.02}$ | $8.31^{+7.52}_{-7.51}$ | $0.09^{+0.004}_{-0.004}$ |
| | NGC3198 | $0.22^{+0.021}_{-0.021}$ | $8.48^{+7.49}_{-7.49}$ | $0.10^{+0.003}_{-0.003}$ | $0.20^{+0.02}_{-0.02}$ | $8.52^{+7.53}_{-7.53}$ | $0.10^{+0.003}_{-0.003}$ |
| | NGC3521 | $2.42^{+0.242}_{-0.242}$ | $8.15^{+7.36}_{-7.36}$ | $0.08^{+0.003}_{-0.003}$ | $5.32^{+0.5}_{-0.5}$ | $8.47^{+7.0}_{-7.0}$ | $0.10^{+0.001}_{-0.001}$ |
| | NGC925 | $11.01^{+1.1}_{-1.1}$ | $6.65^{+5.87}_{-5.87}$ | $0.03^{+0.001}_{-0.001}$ | $8.02^{+0.7}_{-0.7}$ | $6.52^{+5.92}_{-5.92}$ | $0.03^{+0.002}_{-0.002}$ |

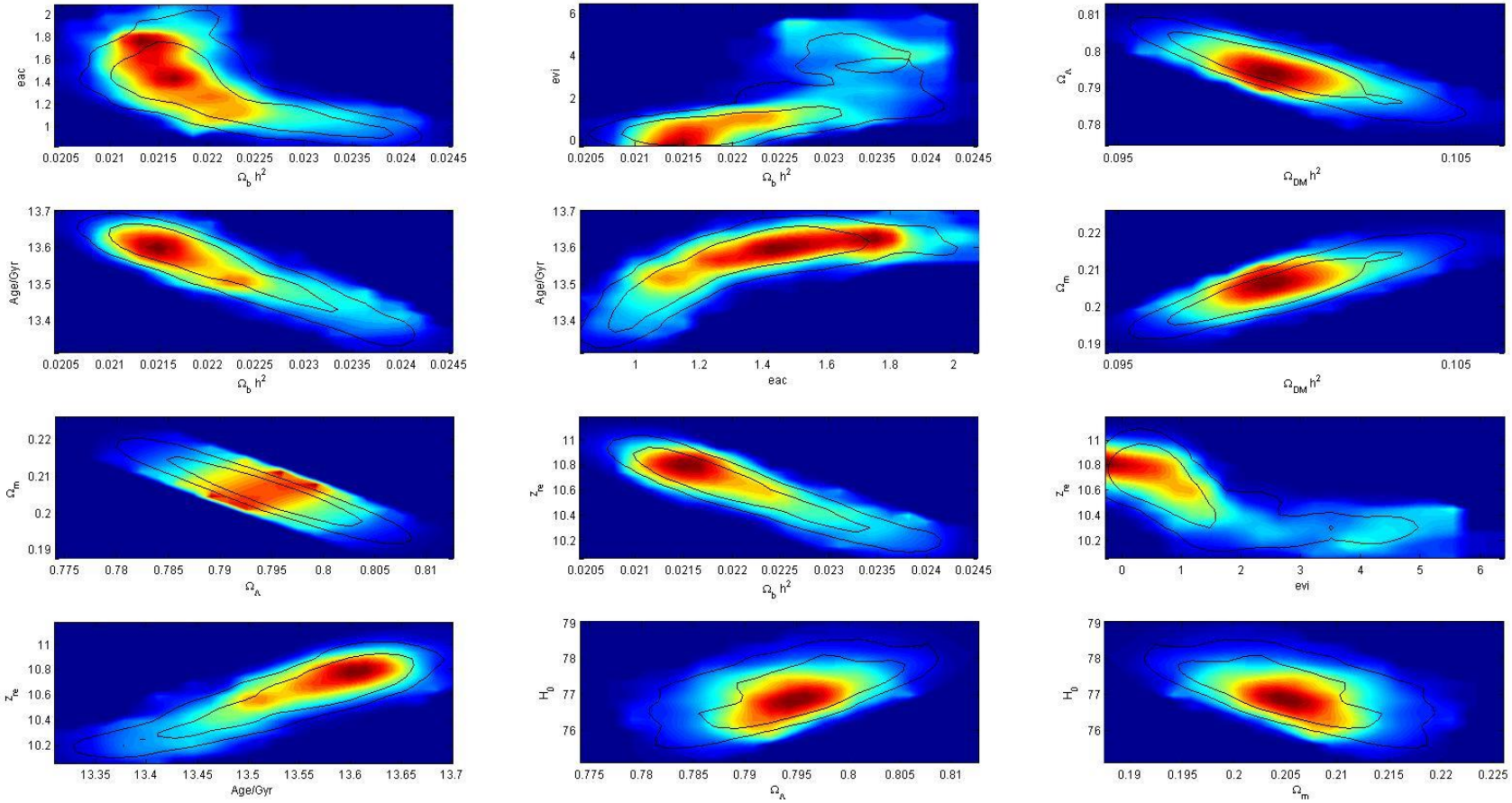
- Anisotropies on the CMB

$$a < a_c \quad \begin{cases} \dot{\delta} = -\frac{4}{3}\theta - \frac{2}{3}\dot{h} \\ \dot{\theta} = \frac{1}{4}k^2\delta \end{cases}$$

$$a > a_c \quad \begin{cases} \dot{\delta} = -(1-\omega)\left(\theta + \frac{\dot{h}}{2}\right) - \frac{2\omega}{\omega+1}H\delta \\ \dot{\theta} = \left(\frac{\omega(3\omega+4)-1}{1+\omega}\right)\theta + \omega\left(\frac{5+3\omega}{3(1+\omega)}\right)k^2\delta \end{cases}$$

$$Ec \approx O(60)eV$$

$$\omega \propto v_{bdm}$$


eac
$\Omega_b h^2$
evi
$\Omega_\Lambda$
$\Omega_{DM} h^2$
Age/Gyr
$\Omega_m$
$z_{re}$
$H_0$