Less Travelled Path of Dark Matter: Axions and PBHs

ICTS-TIFR, Bengaluru

INTRODUCTION TO DARK MATTER

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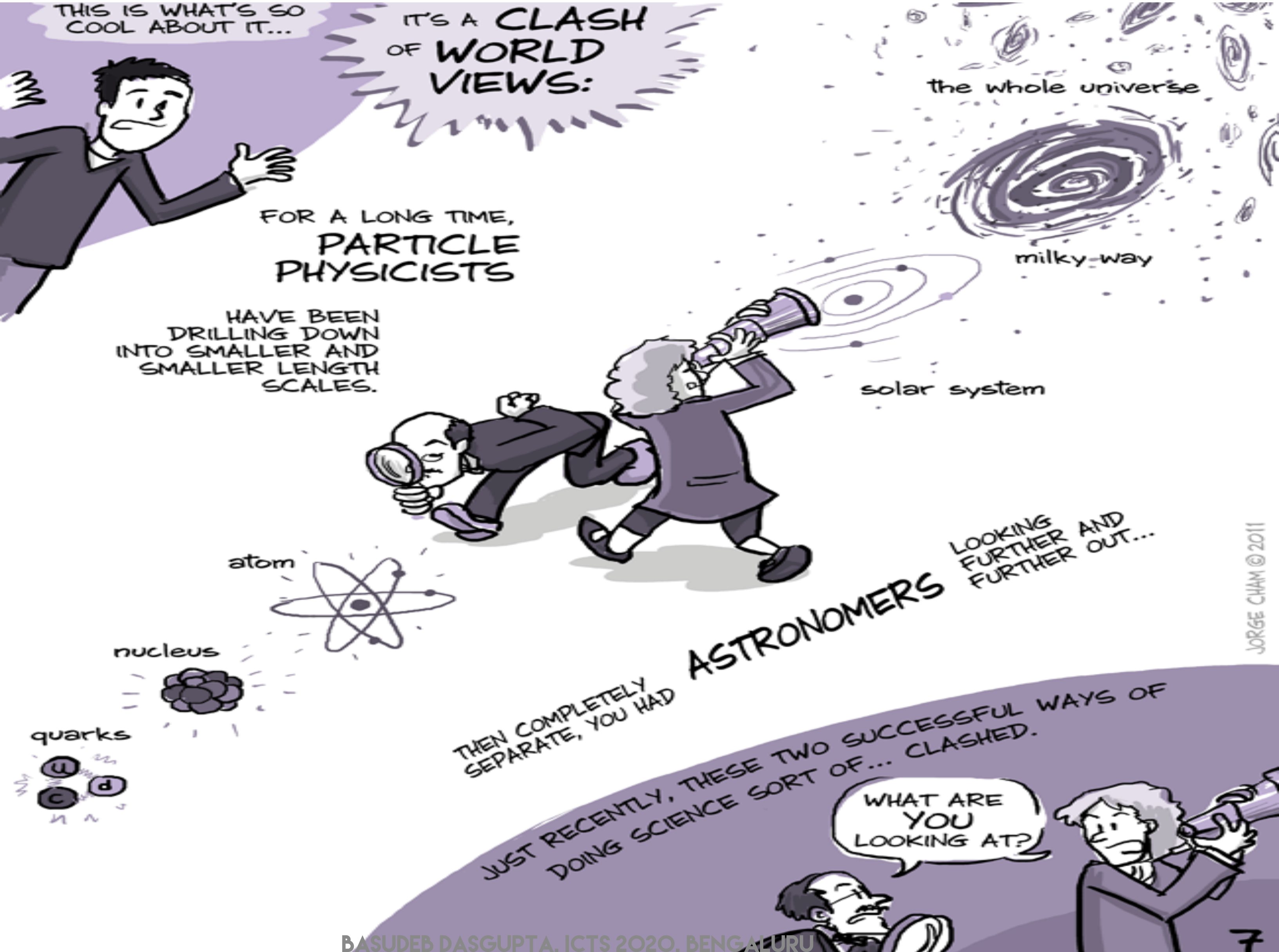
TIFR, Mumbai


THIS IS WHAT'S SO COOL ABOUT IT...
IT'S A CLASH OF WORLD VIEWS:
FOR A LONG TIME, PARTICLE PHYSICISTS
HAVE BEEN DRILLING DOWN INTO SMALLER AND SMALLER LENGTH SCALES.
atom
nucleus
quarks
u
d
c
the whole universe
milky way
solar system
THEN COMPLETELY SEPARATE, YOU HAD ASTRONOMERS LOOKING FURTHER AND FURTHER OUT...
JORGE CHAM © 2011
JUST RECENTLY, THESE TWO SUCCESSFUL WAYS OF DOING SCIENCE SORT OF... CLASHED.
WHAT ARE YOU LOOKING AT?
7

UNDERSTANDING OF "DARK AIR"

Lord Rayleigh
(Image: Nobel Prize Foundation)

When he compared nitrogen extracted from air with nitrogen extracted from chemical compounds, he found that the nitrogen from air was heavier. He concluded that the air must contain another, previously unknown substance.

Now called Argon.

THE 3 FOLD WAY

Thermodynamics		Cosmology
Kinetic Theory	$\approx$	Astrophysics
Chemistry		Particle Physics

REFERENCES

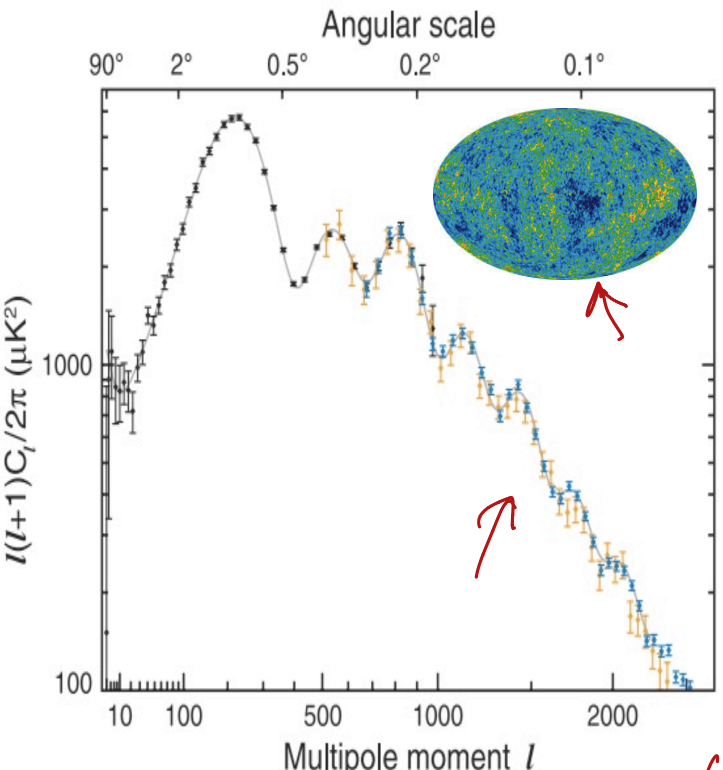
Textbooks:

1. Kolb and Turner (The Holy Bible)
2. Dodelson (Cosmology)
3. Profumo (DM)
4. Bernstein (Thermodynamics in Expanding Universe)

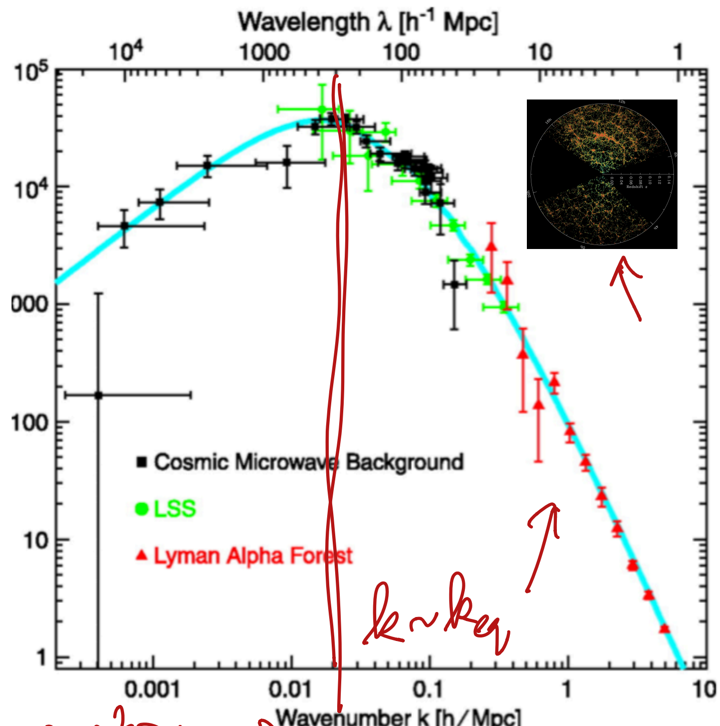
Notes/Papers:

1. BD/Paranjape/Mohanty (SERC School 2019)
2. Bauer and Plehn (DM)
3. Steigman, BD, Beacom (1204.3622, relic density)

COSMOLOGICAL PROBES OF DM



CMB



$k \sim k_{eq}$

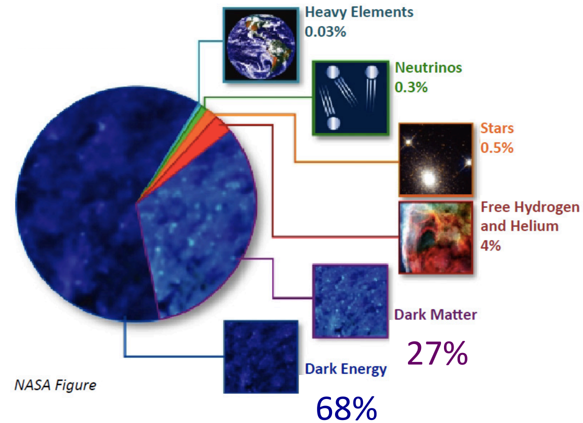
LSS

$$P(k)\,(2\pi)^3\,\delta(k-k') = \langle \delta(k)\,\delta(k') \rangle$$

ABUNDANCE AND DISTRIBUTION

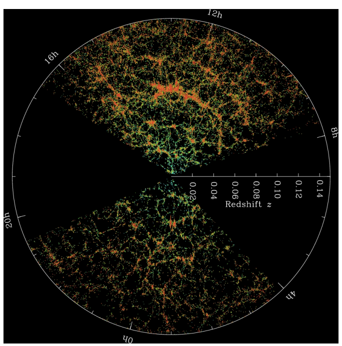
How much DM?

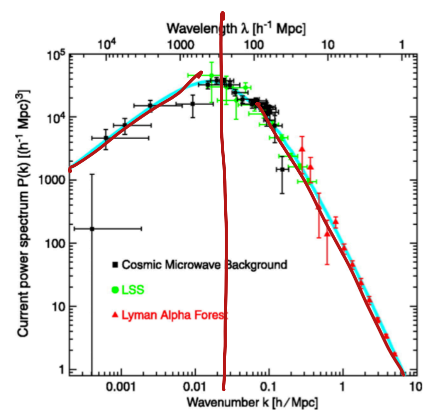
$$\frac{\rho_{dm}}{\rho_c} h^2 \approx \Omega_{dm} h^2 \approx 0.12$$



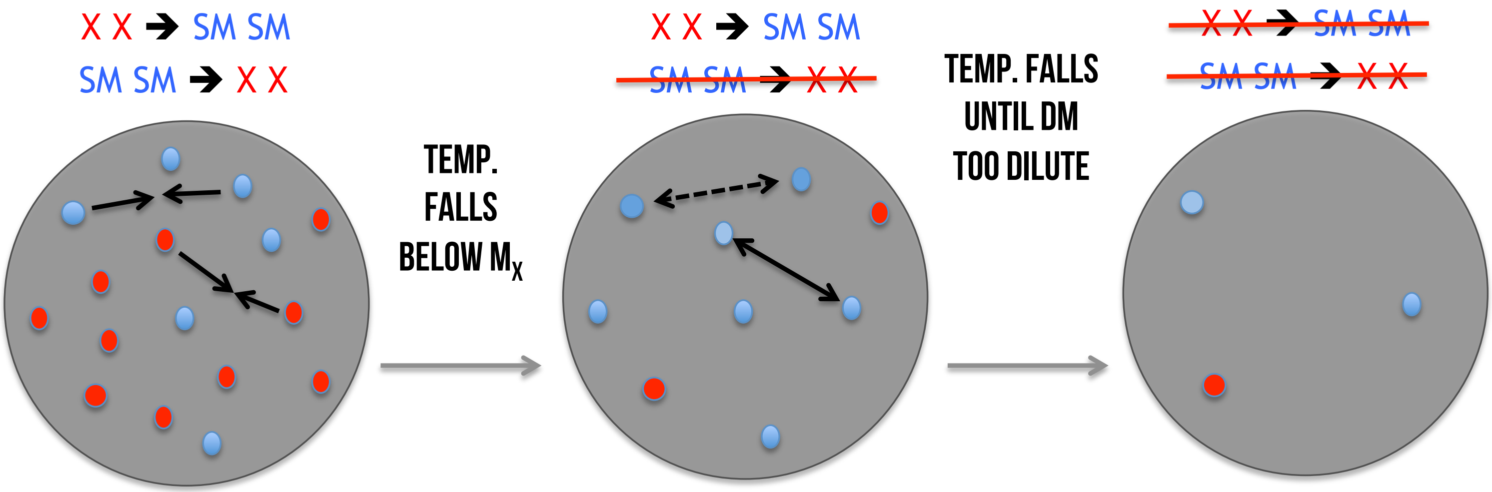
NASA Figure

How clumped?





IDEA 1 : THERMAL FREEZEOUT



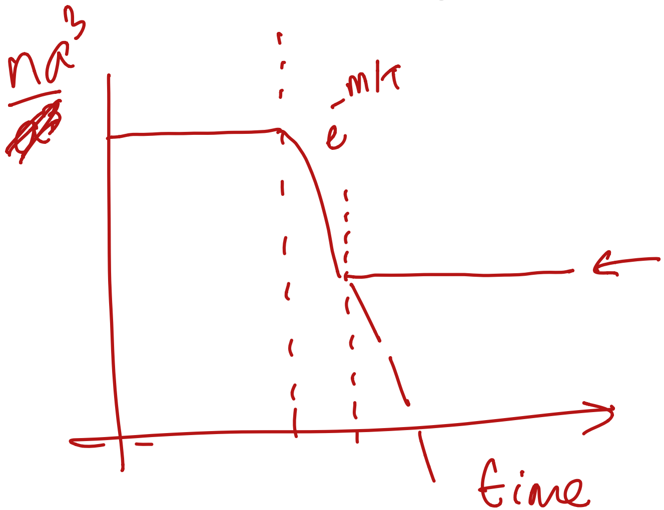
EQUILIBRIUM AT HIGH T

NO MORE PRODUCTION,
BUT ANNIHILATIONS CONTINUE

NO MORE ANNIHILATIONS,
AS NO PARTNERS AVAILABLE

Chemical Freeze-out sets DM Density

BOLTZMANN EQN

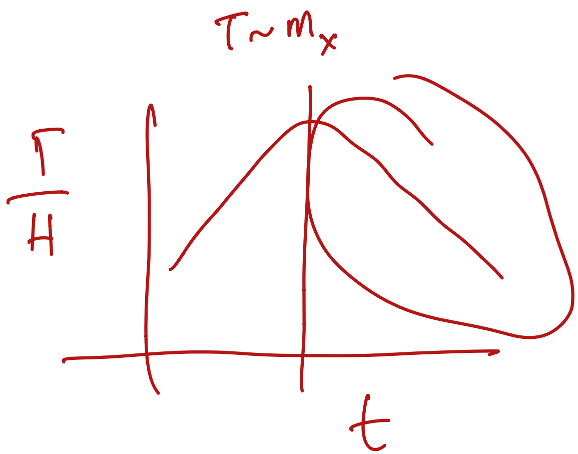


$$\Gamma \lesssim H$$

$$\Gamma \simeq n \sigma v$$

$$n \sim T^3$$

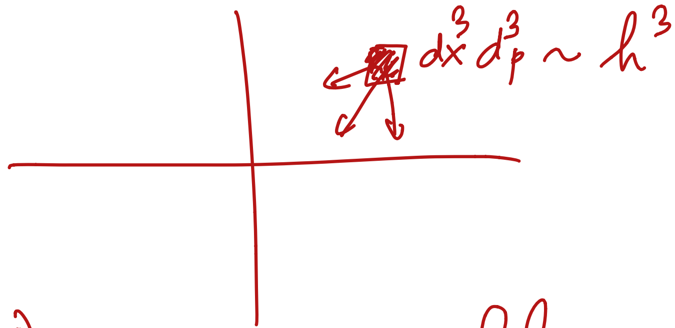
$$\sigma \sim \begin{cases} (g)^4\, 1/T^2 & T \gg m \\ \frac{m_x^2}{M^4_{med}} & T \ll m \end{cases}$$



$$n\sigma v \sim \begin{cases} T & T \gg m \\ \frac{m^2 T^3}{M^4_{med}} & T \ll m \end{cases}$$

$$H \sim T^2/M_{pl}$$

$$f(\bar{x}, \bar{p})$$



$$\int f \, d^3p \longrightarrow n(x)$$

$$= f_1 f_2 - f_3 f_4$$

$$\int d^3p \quad \left(\partial_t + \vec{v}\cdot\vec{\partial}_x\right) \underbrace{f(\bar{x}, \bar{p}, t)}_{} = 0$$

$$\underbrace{\left(\partial_t + \vec{v}\cdot\vec{\partial}_x\right)}_{\frac{d}{dt}} n = 0$$

$$\frac{d}{dt}(nV) = 0$$

$$\left(\frac{d}{dt} + 3\underbrace{\frac{\dot{a}}{a}}_{H}\right) n = 0 \qquad \approx \qquad \frac{d}{dt}\left(na^3\right) = 0$$

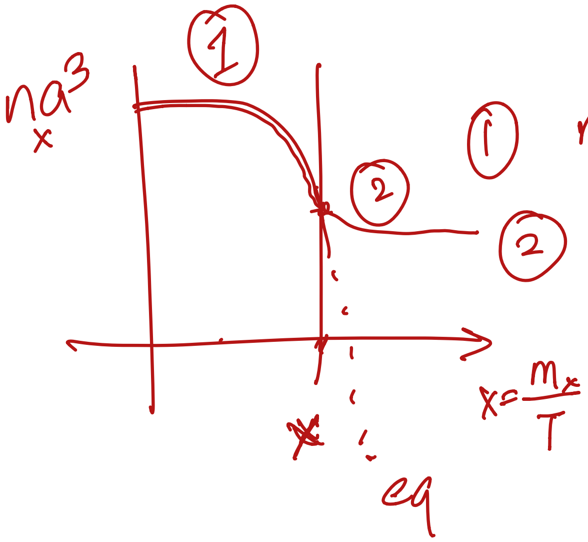
$$\boxed{\frac{dn_x}{dt} + 3 H n_x = 0}$$

$$XX \xrightarrow[\sigma]{} SS$$

$$\frac{\int d^3p_1\, d^3p_2\, e^{-(E_1+E_2)/T}\, \sigma}{\int d^3p_1\, d^3p_2\, e^{-(E_1+E_2)/T}} = \langle \sigma v \rangle$$

$\int d^3p_1\, d^3p_2\, e^{\dots}$

$$\frac{d}{dt} n_\chi + 3 H n_\chi = - \underbrace{\langle \sigma v \rangle}_{\Gamma} \left(n_\chi n_\chi - n_{eq}^2 \right)$$



(1) $n_\chi = n_{eq}(1 + \Delta)$ $\leftarrow \approx 0.5$

(2) $n_\chi \gg n_{eq}$

$$\boxed{\Omega h^2 = 0.12 \; \frac{x_*}{23} \; \frac{\sqrt{g_*}}{10} \; \frac{2 \times 10^{-26}\, \mathrm{cm^3/s}}{\langle \sigma v \rangle}}$$

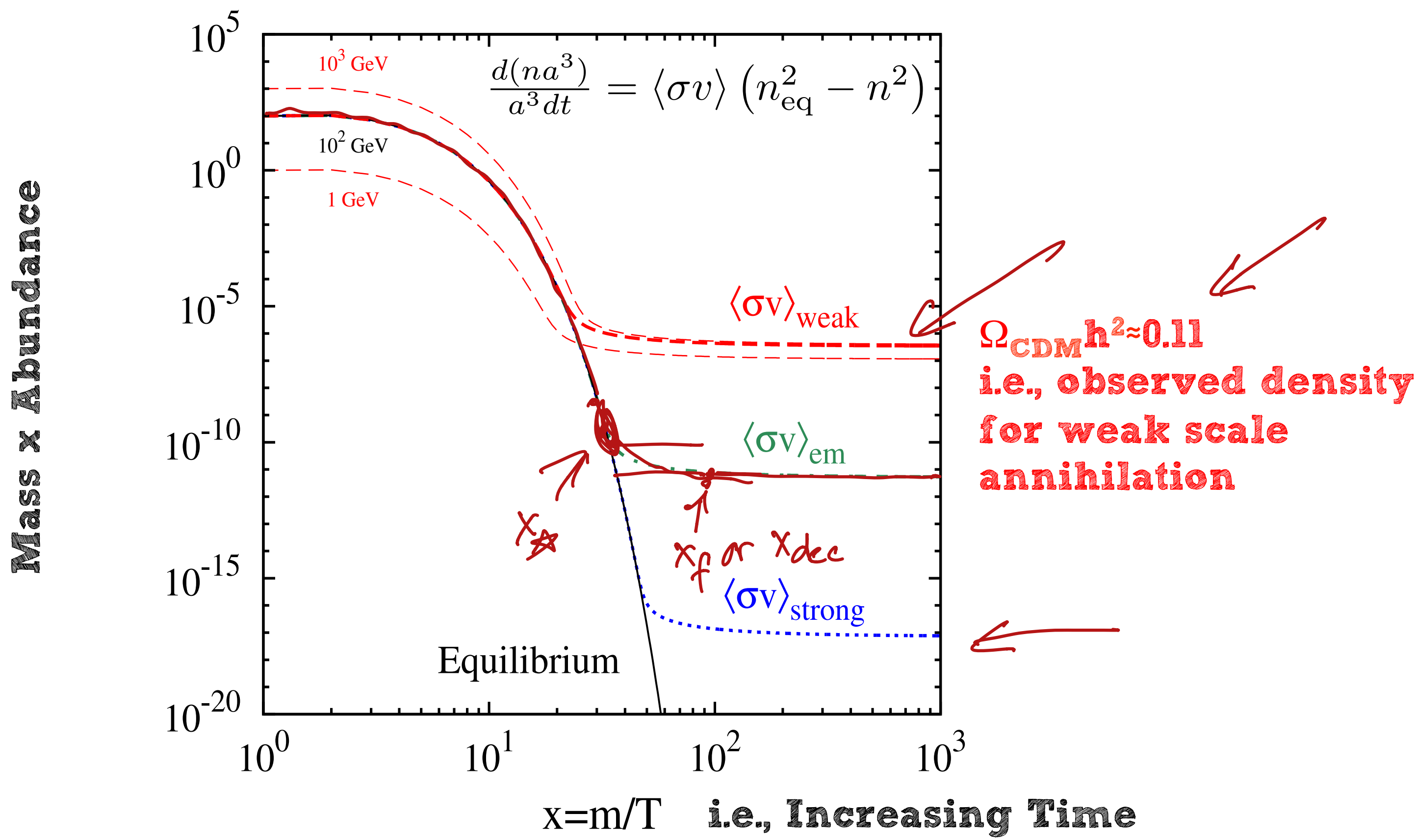
x_* is NOT where $\Gamma = H$

x_f is where $\Gamma = H$

So $x_* \lesssim x_f$

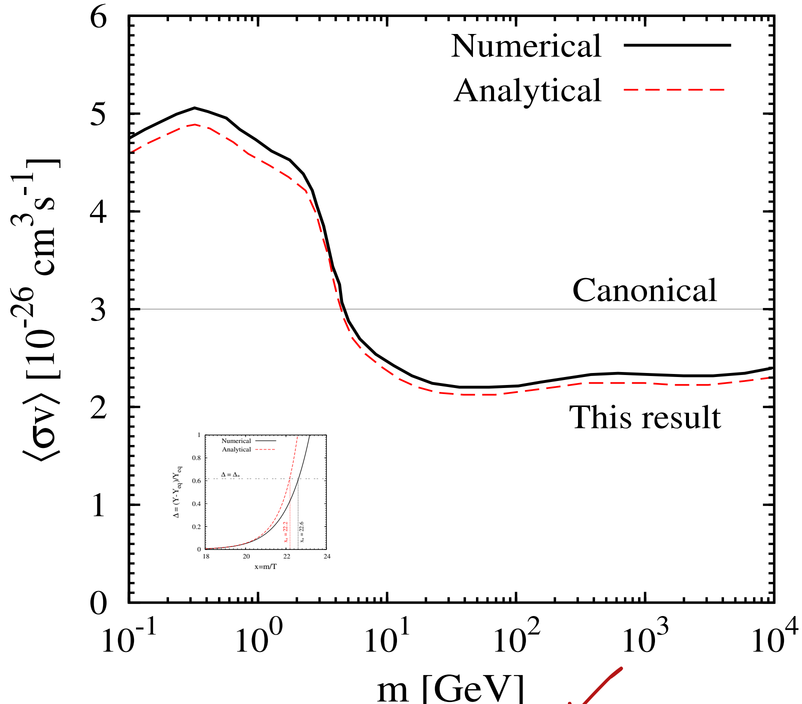
Y decreases by ~ 30 between x_* & x_f

FREEZE-OUT



Zeldovich (1965); Chiu (1966); Lee and Weinberg (1977); Hut (1977); Wolfram (1979); Steigman (1979).

PRECISION COMPUTATION



$$10^{26}\langle\sigma v\rangle = 0.902\left(\frac{0.11}{\Omega h^2}\right)\left(\frac{x_*}{g_*^{1/2}}\right)\left(\frac{(\Gamma/H)_*}{1+\alpha_*(\Gamma/H)_*}\right)$$

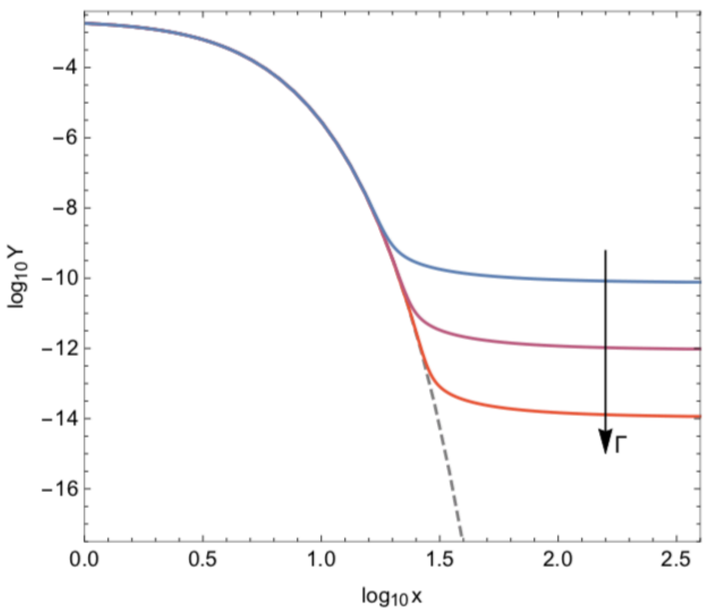
Depends modestly on Mass

Must take into account for low-mass WIMPs, below DM mass = 10 GeV

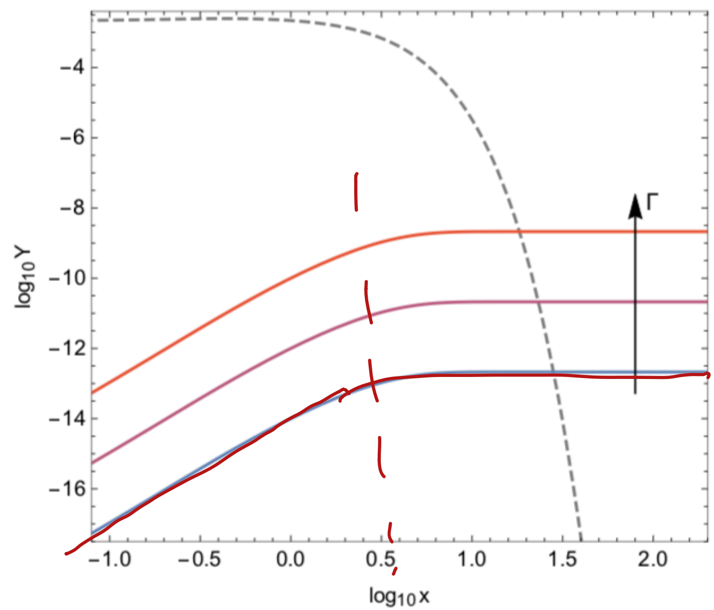
Steigman, BD, and Beacom (PRD, 2012)

Gary Steigman

IDEA 2: FREEZE IN



Freeze Out



Freeze In

$B \longrightarrow XX$

$e^{-m_B/T}$

$\Gamma_{B \to XX}$

Bernal et al (IJMP 2017)

STRUCTURE AS A PROBE OF DM

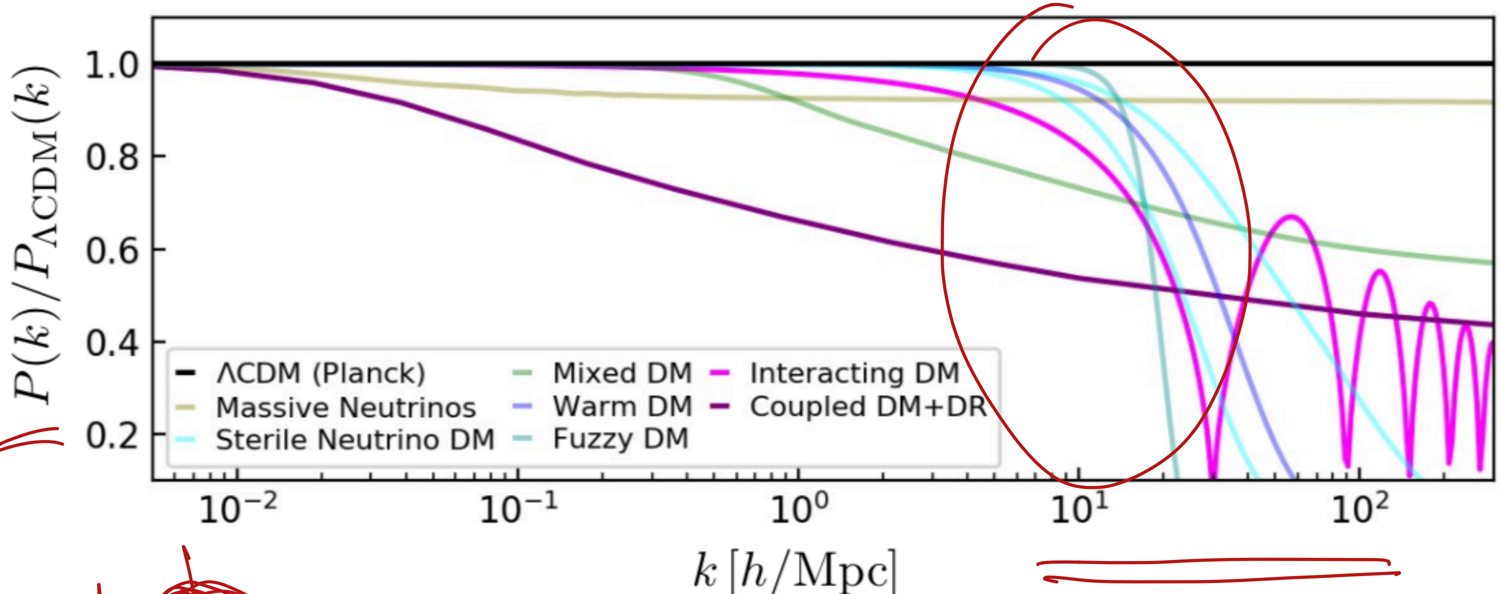
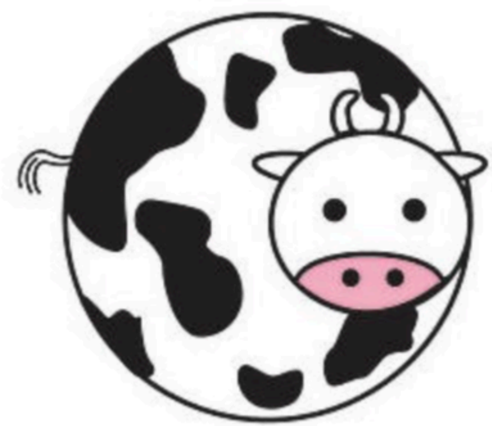
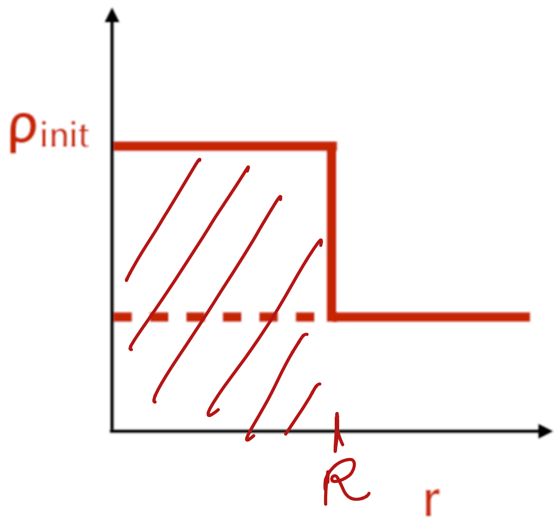


Image: Schneider (2018)

SPHERICAL COLLAPSE





$$\frac{d^2R}{dt^2} = -\frac{GM(<R,t)}{R^2}$$

Assume no shell-crossing: $M(<R,t) = M(<R_{init},t_{init}) = \text{constant}$

Credit: Aseem Paranjape

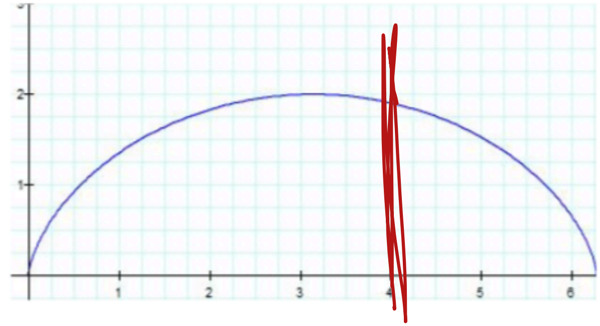
SPHERICAL COLLAPSE

Kolb & Turner

Nonlinear solution:

$$R \propto 1 - \cos\theta \quad ; \quad t \propto \theta - \sin\theta$$

$$\frac{\rho}{\bar{\rho}} = \frac{9}{2}\frac{(\theta - \sin\theta)^2}{(1-\cos\theta)^3}$$

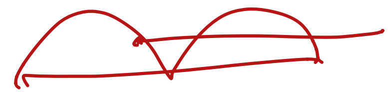


Linearly extrapolated value:

$$\delta_{\rm L} = \frac{3}{5}\left(\frac{3}{4}\right)^{2/3}(\theta - \sin\theta)^{2/3}$$

Value at collapse $\boxed{\delta_c = 1.686}$

Virialisation:



2 (K.E.) + (P.E.) = 0

Also **K.E. + P.E. = constant**

$R(t_{vir}) = R(t_{ta})$ / 2

$\Delta_{vir} = 18\pi^2 \simeq 178$

Erratum: $\delta_c = 1.686$ is density in spherical collapse if linear theory is (wrongly) extrapolated to time of collapse

Credit: Aseem Paranjape

LINEAR PERTURBATION THEORY

$f \to n, \rho, \vdots$

$$\frac{\partial \rho_m}{\partial t} = -\nabla \cdot (\rho_m \vec{u})$$ continuity equation

$$\left(\frac{\partial}{\partial t} + \vec{u} \cdot \nabla\right) \vec{u} = -\frac{\nabla p}{\rho_m} - \nabla \phi$$ Euler equation

$$\nabla^2 \phi = 4\pi G \rho_m$$ Poisson equation ,

$\delta > \cancel{O(0.3)}$

$O(1)$

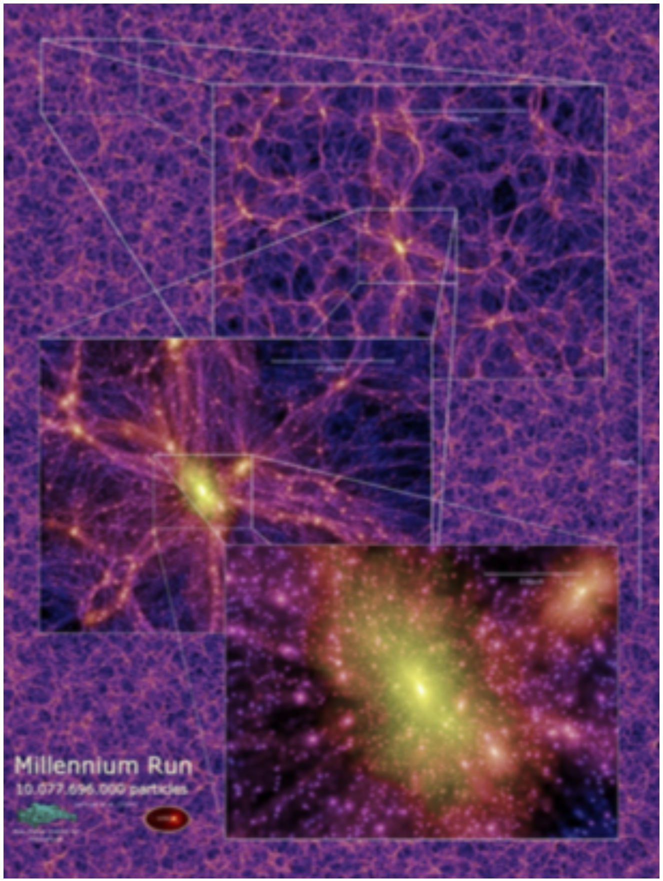
$\rho_m = \bar{\rho}(1+\delta_m)$

Gravity Collapse

Pressure

$$\ddot{\delta}_k + 2H\dot{\delta}_k = \delta_k \left[\frac{\bar{\rho}}{2M_{pl}^2} - \left(\frac{c_s\, k\, a_0}{a}\right)^2\right]$$

N BODY SIMULATIONS



Start with a box of particles, with initial conditions (x,v) consistent with CDM

Evolve their positions using collisionless Boltzmann equation

Various numerical issues/ techniques

One key issue: “particles” can be say, 10^6 − 10^7 solar masses!

Identify halos, merger trees, etc.

Predict clustering, substructure, merger histories, etc.

Some clarifications:

(1) Notion of $\delta_c = 1.686$ comes from asking what would be the density contrast in linear theory if it were to be extrapolated to time of collapse in spherical top hat model.

For pbh δ_c is simply what is overdensity that causes BH-formation (in rad-dom phase). There is no linear theory assumption here

(2) $P(k)$ was wrongly interpreted as giving "which scales are most likely to have structure". This is not totally correct.

$$P(k) \sim \int e^{-ikx} \underbrace{\int \delta(x_0)\, \delta(x_0+x)\, dx_0}_{\langle \delta(x)\, \delta(0) \rangle}$$

Suppose $\langle \delta(x)\, \delta(0) \rangle \sim \cos(k' x)$

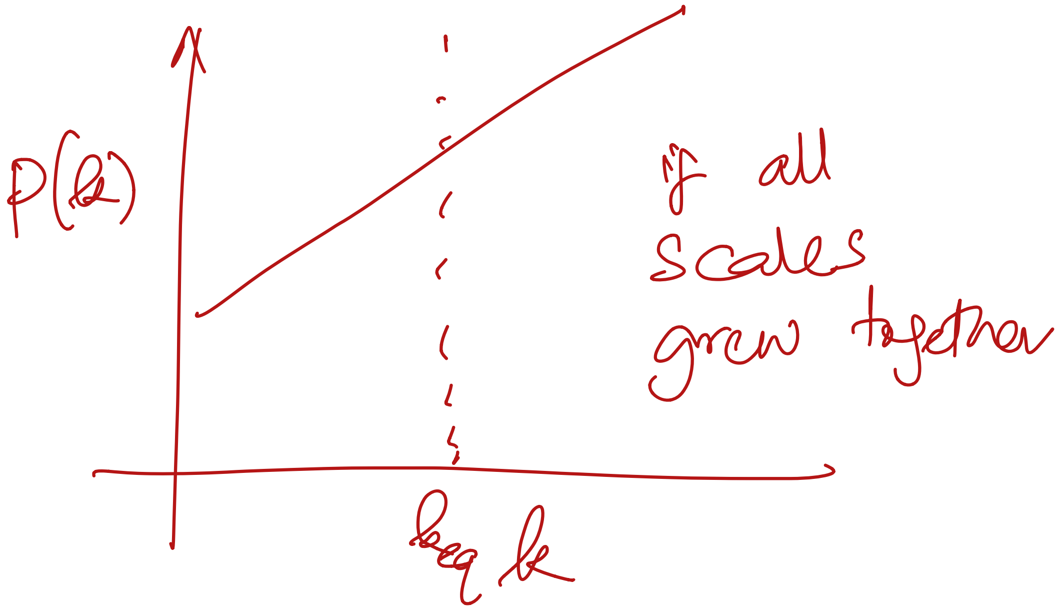
$$P(k) \sim \int e^{-ikx}\, e^{+ik'x}\, dx$$

$\sim \delta(k-k')$

So it is true that $P(k)\neq 0$ does say "where" there is power.

BUT $P(k)$ also depends on <u>amplitude</u> of the fluctuations at scale $2\pi/k$.

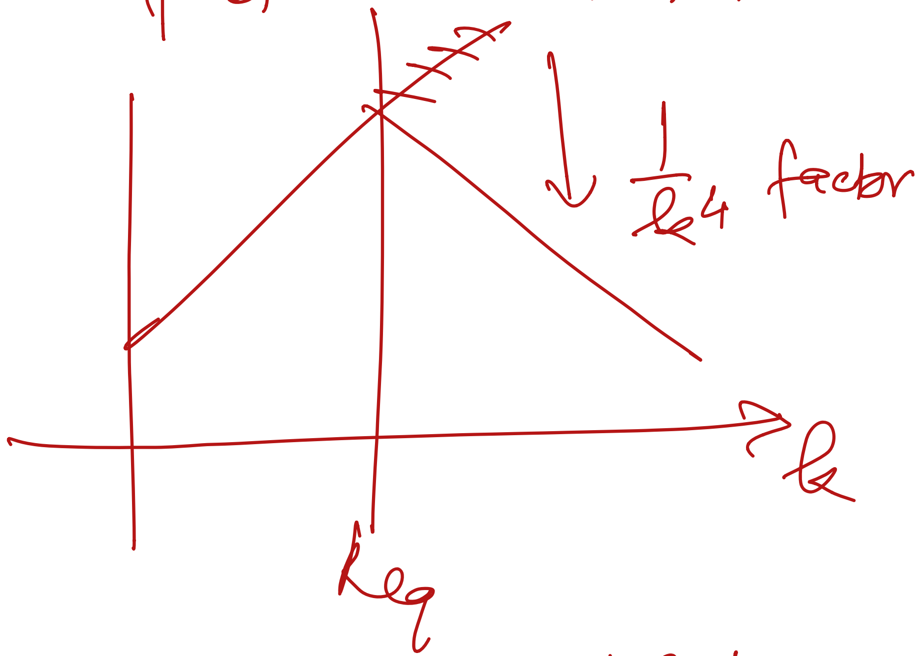
In cosmology $P(k)$ <u>would have</u> looked like



BUT small scales ($k>k_{eq}$) only grow after <u>equality</u>

So they have to wait by a factor $\left(\frac{a}{a_{eq}}\right)^2$, and $P(k)$

gets a factor k^4 ...



Overall scaling with 'k' depends on definition of "$P(k)$" in 3 dimensions.

One can say $P(k)$ is fourier transform of the autocorrelation fn.

$$\xi(x) = \int \frac{dx_0}{L}\, \delta(x_0)\, \delta(x_0 + x)$$

<u>In 3D</u>:

$$\Delta^2 \simeq \frac{k^3 P(\vec{k})}{2\pi^2} \quad \text{is dim-less}$$

$P(\vec{k})$ has dimension of L^3.