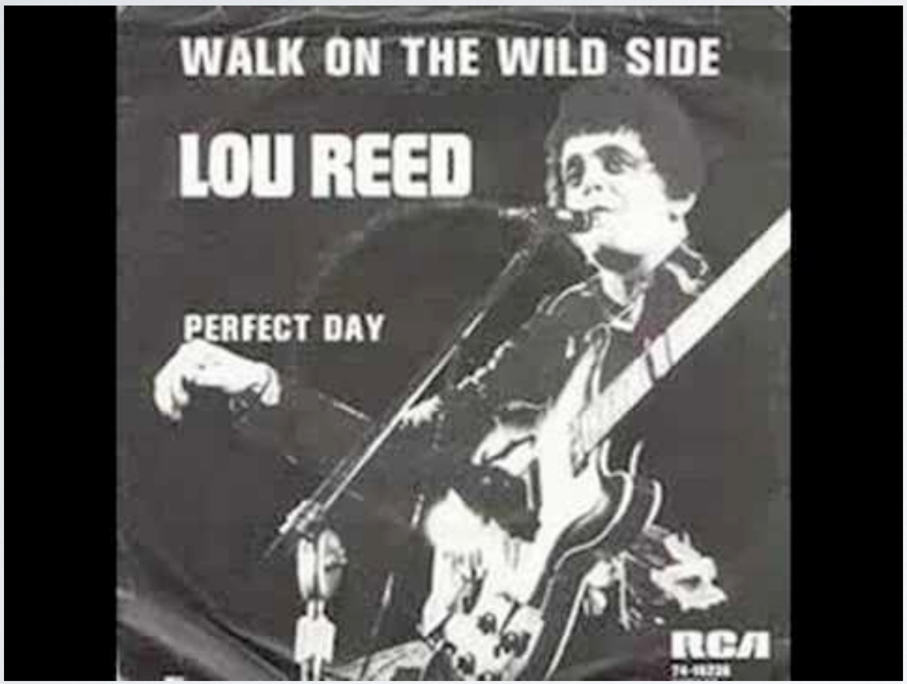
Astroparticle Theory I

aka "a walk on the dark side"



Pasquale Dario Serpico

GraSPA 2017 - 24/07/2016

OUTLINE OF THE 2 LECTURES

- *Basic notions of cosmology for "particle astrophysics"*
- *Gravitational evidence for Dark Matter*
- *A cosmological cross-check: BBN vs CMB*

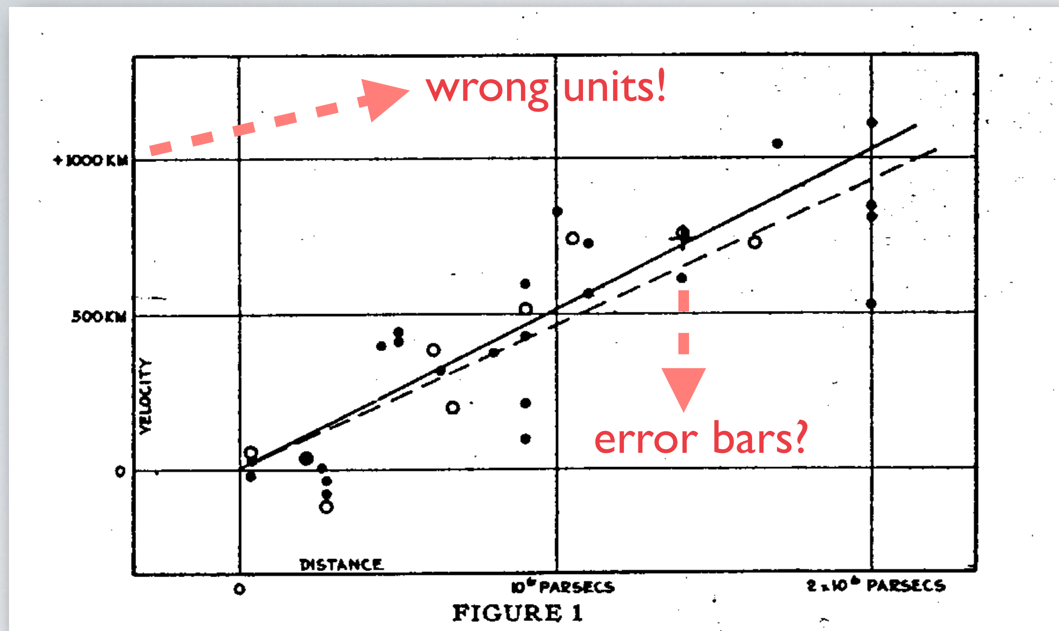
L. 1

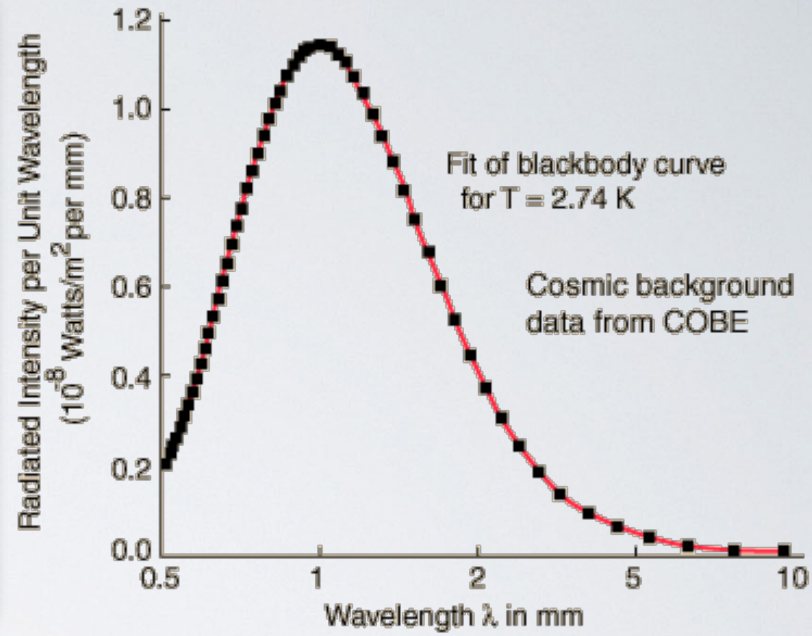
- *"Particle Cosmology": Classification & properties of DM candidates*
- *freeze-out production mechanism (hot, cold), WIMPs*
- *freeze-in*
- *asymmetric case (mentioning baryogengesis)*

L. 2

BASIC NOTIONS OF (SMOOTH) COSMOLOGY

PILLARS OF STANDARD COSMOLOGICAL MODEL





- Galaxies sufficiently far away from us recede with ***v=Hd*** (Hubble law)
- The Universe is permeated by an almost perfect blackbody radiation, with T~2.73 K (Cosmic Microwave Background, CMB)
- Yields of light elements (notably Deuterium and Helium) way larger than what expected from "stellar" phenomena: *if extrapolated way backwards, the early universe was a hot enough place to host thermonuclear reactions!*

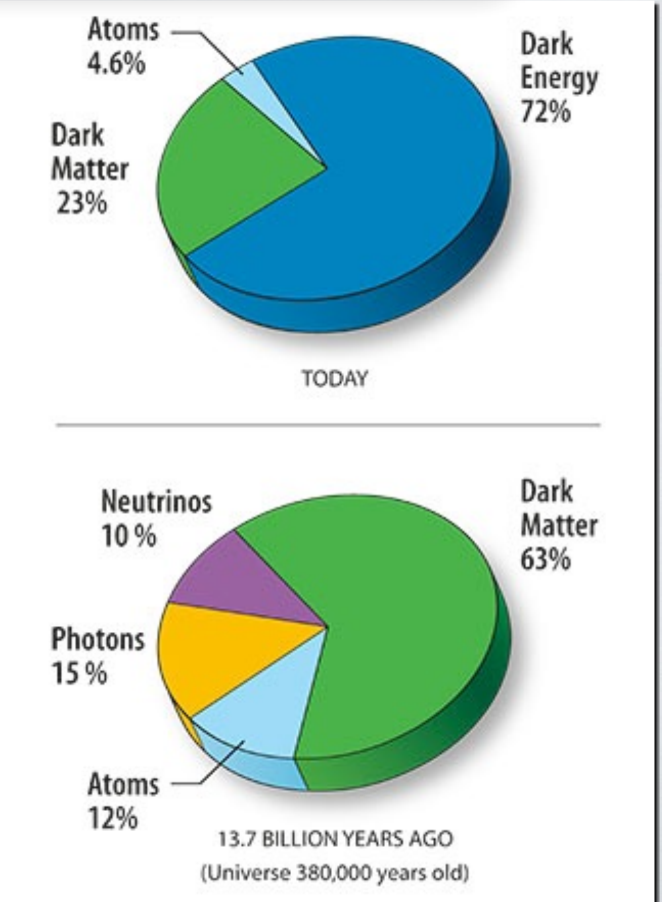
STANDARD COSMOLOGICAL MODEL

Based on:

- General Relativity (GR): metric theory of gravitation
- Cosmological Principle (*spatial homogeneity & isotropy on large scales*)
- "Standard Physics", in particular Kinetic Theory of Fluids, Particle & Nuclear Physics, Plasma Physics, Atomic Physics.

Evolving the expanding universe backwards in time → picture of hot Early Universe, made of a "gas" which has been cooling while expanding. The CMB and light elements are the "atomic plasma" and "nuclear plasma" ashes of the early time

Basic (not unique!) task of cosmology: to understand what the universe is made of, now & in the past (the "mixture" can and does evolve with time…)



$$\text{Natural units} : c = \hbar = k_B = 1$$

Will use them, but for quoting some astrophysical results

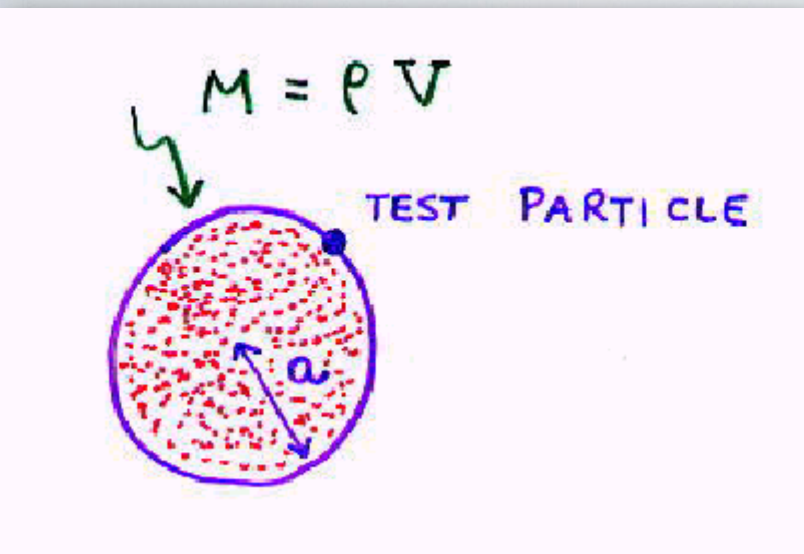
EXERCISE WITH NATURAL UNITS

If you are unfamiliar with them… or just for fun:

- Compute your typical body temperature (assuming you are still alive) in eV.
- Check the working frequency of your mobile phone. Rephrase it into eV.
- Compute your height in eV^{-1}
- Compute your age in eV^{-1}
- Compute your density in eV^4

(*Experimental guidance:* estimate within ~10% error from what happens when you jump into Annecy lake+ Archimedes law)

BACHELOR COSMOLOGY



Consider the Newtonian toy model of a sphere of dust. The acceleration is

$$\ddot{a} = -\frac{G_N M}{a^2}$$

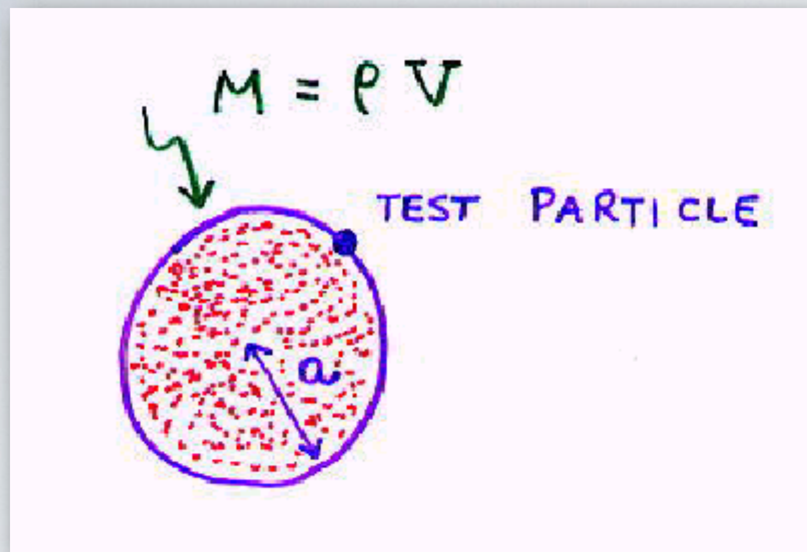
$$M = \frac{4\pi}{3} \rho a^3$$

by integration

$$\frac{\dot{a}^2}{2} = \frac{G_N M}{a} - \frac{k}{2}$$

In general relativity, the *spacetime* itself is *dynamical*, the key quantity is its *metric* (generalizing the Minkowski one $\eta_{\mu\nu}$) which responds to all types of energy (& *pressure*). Knowing the metric = restricted by the Cosmological principle to a single independent function of time, *a(t)*, describing the "stretching" of space as function of time, and a single number k=1,0,-1 describing the curvature of the 3D space.

BACHELOR COSMOLOGY



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$$\frac{\dot{a}^2}{2} = \frac{G_{\rm N} M}{a} - \frac{k}{2}$$

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi\, G_{\rm N}}{3}\rho - \frac{k}{a^2}$$

This naïve model reproduces correctly one of the 2 independent GR equations in the FLRW metric=(implementing the Cosm. Pr.)

$$\dot{\rho} + 3\frac{\dot{a}}{a}(\rho + P) = 0$$

The additional independent equation implements "energy conservation" and contains a peculiar GR term

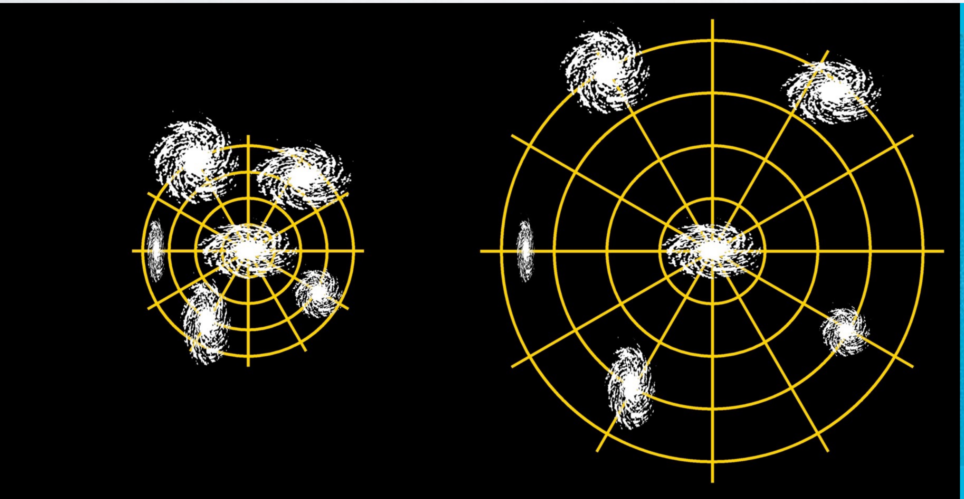
closed system if an Equation Of State P=P(ρ) is provided

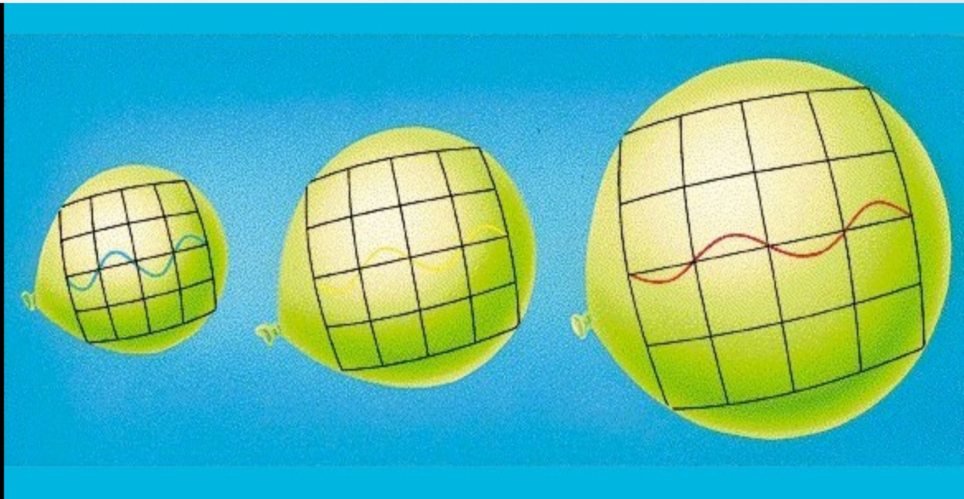
SOME GENERIC SOLUTIONS (K=0)

	Equation of State	Behaviour of ρ	Scale Factor
Matter	$P \simeq 0$ $(T \ll m)$	$\rho \propto a^{-3}$	$a \propto t^{2/3}$
Radiation	$P = \rho/3$	$\rho \propto a^{-4}$	$a \propto t^{1/2}$
Cosm. constant	$P = -\rho$	$\rho = \text{const.}$	$a \propto e^{H_0 t}$

conservation of particles per comoving volume
For radiation, further a-factor due to wavelength stretching, also called "redshift"

$$1 + z = \frac{\lambda_{\text{today}}}{\lambda_{\text{then}}} = \frac{a_{\text{today}}}{a_{\text{then}}}$$





GETTING FAMILIAR WITH JARGON…

Compositions usually expressed in Ω_i**'s**, ratios of density of i-species to "critical density"

$$\rho_c = \frac{3}{8\pi G_N} H_0^2$$

Ex: compute ρ_c for H_0=70 km/(s Mpc)

For a flat case (k=0), favoured by current data, we can simply write:

$$\frac{1}{H_0^2}\left(\frac{\dot{a}}{a}\right)^2 = \Omega_{m,0}\left(\frac{a_0}{a}\right)^3 + \Omega_{r,0}\left(\frac{a_0}{a}\right)^4 + \Omega_\Lambda$$

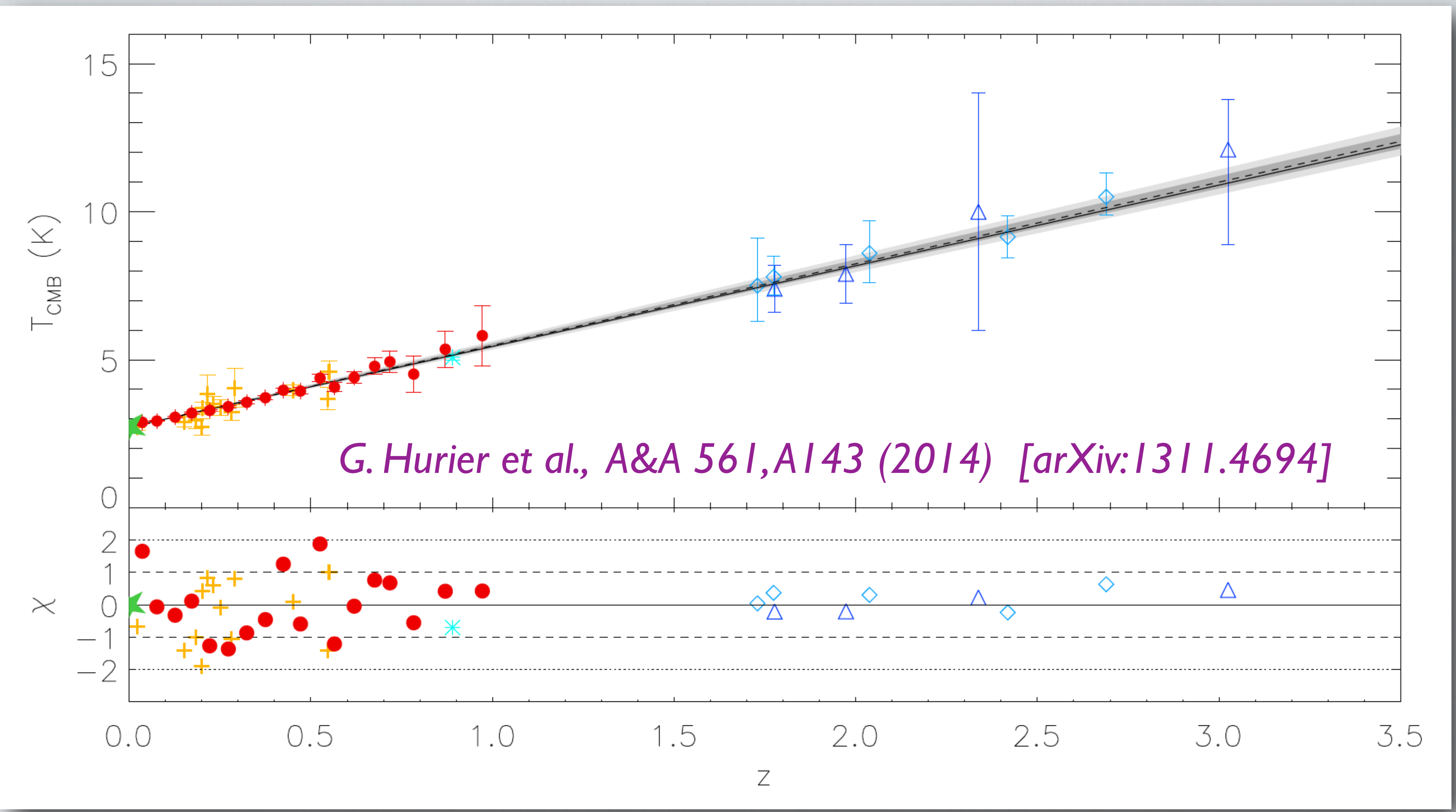
Ex: Knowing that today Ω_m~0.28 Ω_Λ~0.72, at which redshift z the matter and Cosmological constant contribution were equal?

$$1 + z = \frac{\lambda_{\rm today}}{\lambda_{\rm then}} = \frac{a_{\rm today}}{a_{\rm then}}$$

Ex. (postpone to later stage!)**:** Infer the current value of Ω_r from T_{CMB} ~2.73 K. At which z there is matter-radiation equality? What if you add to Ω_r neutrinos, assuming they share the same temperature of CMB? What if their temperature is 2 K?

Ex.: Plot the RHS of the above equation, expressed vs. 1+z, in log-log scale. Also, plot the ratio of each term to the total RHS

MODERN DATA ON BACKGROUND TEMPERATURE



Universe really hotter in the past!

T inferred via:

- distortion effect due to scattering of CMB photons by hot electrons in clusters;
- absorption in clouds where the pumping to excited level depends on T_{CMB}

“THERMODYNAMICS”

Let’s introduce the phase space density f describing the occupation number of microstates of different energies.

The Universe is not a system in equilibrium with an external bath, need nonequilibrium theory tools.

However, for sufficiently fast processes *(wrt expansion rate)* exchanging both energy & particles, locally the entropy gets maximized & “local equilibrium conditions” hold

$$f(E) = \frac{1}{\exp[(E-\mu)/T] \pm 1}$$

T and **μ**: parameters maximizing the entropy under given constraints on the ***energy*** and ***number of particles*** present per unit volume, respectively.

- If energy is exchanged rapidly, different species share the the same *T*
- Similarly, if particle changing reactions of the type $A + B \leftrightarrow C + D$ are fast enough

a conservation rule holds $\mu_A + \mu_B = \mu_C + \mu_D$

⇒ chemical potential μ vanishes for particles that can be freely created/annihilated, like photons; particles and antiparticles have opposite μ

USEFUL RECIPE FOR LTE

To know if LTE holds, compare

Rate of process of interest $\Gamma = n\,\sigma\,v$ vs. H Hubble expansion rate

Most of the interesting cosmological processes happen when those quantities become comparable ("freeze-out"): departures from equilibria!

- T~ 1 eV (@ t~10^{13} s)

$$e + p \leftrightarrow \gamma + H$$

freezes-out: recombination, photons nowadays forming CMB decouple

- T~ 0.1 MeV (@ t~10^{2} s)

$$p + n \leftrightarrow \gamma + D$$

freezes-out: the "nuclear statistical equilibrium" ends, BBN takes place

TD IN THE EXPANDING UNIVERSE

If f is the phase space distribution function, homogeneity and isotropy imply that it can only depend on t and $|\mathbf{p}|=p$

"Kinetic theory" demands a dynamical equation for f *(Boltzmann Eq.)*
However, in most applications the whole energy spectrum is not needed and one can work with moments of f *(and corresponding equations)*

current density of particles

internal (spin) dof

due to isotropy, only $n^0 \neq 0$

$$n^\mu = g \int f \frac{p^\mu}{p^0} \frac{d\vec{p}}{(2\pi)^3} \Rightarrow n = \int f \frac{d\vec{p}}{(2\pi)^3}$$

the covariant conservation of particle number follows

$$\nabla_\mu n^\mu = 0 \Rightarrow \nabla_\mu n^\mu = \frac{1}{a^3} \frac{\partial}{\partial t}(a^3 n) = 0$$

OK with physical intuition of previous cartoon

$$n \propto a^{-3} \propto V^{-1}$$

SECOND MOMENT

*In GR, the Einstein tensor depends on second moments of **f***

Stress-energy Tensor

$$T^{\mu\nu} = g \int f \frac{p^\mu p^\nu}{p^0} \frac{d\vec{p}}{(2\pi)^3}$$

Energy density

$$\rho = T^{00} = g \int f \, p^0 \frac{d\vec{p}}{(2\pi)^3}$$

Pressure

(note the isotropy assumption) →

$$-P\delta^{ij} = T^{ij} = -\delta^{ij} g \int f \frac{|\vec{p}|^2}{3E} \frac{d\vec{p}}{(2\pi)^3}$$

Bianchi identities (1 ind. eq.), "energy conservation"

$$\nabla_\mu T^{\mu\nu} = 0 \longrightarrow \frac{d\rho}{dt} = -3H(\rho + P)$$

We recover the second Friedmann equation!

If we express ***f*** in terms of "*T*", this equation provides a **time-temperature relation**!

EQUILIBRIUM EXPRESSIONS (**μ**=0)

Relativistic species

$$n = g\frac{\zeta(3)}{\pi^2}T^3 \times \left\{1(-), \frac{3}{4}(+)\right\}$$

$$\rho = g\frac{\pi^2}{30}T^4 \times \left\{1(-), \frac{7}{8}(+)\right\} \qquad P = \rho/3$$

applying comoving particle number conservation law we obtain a simple *t(T)*

$$a^3T^3 = \text{const.} \to T \propto a^{-1}$$

we can use e.g. **photon "temperature" as "clock variable"** for the epoch of the universe, at least after recombination when the # of photons does not change...

Non-relativistic species at LTE

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} \exp\left(-\frac{m}{T}\right) \qquad \rho = m\,n \qquad P = nT \ll \rho$$

ENTROPY

Remember Boltzmann's formula? It naturally suggests the following formula for the entropy density/current (classical limit)

$$s^\mu = -g \int f(\ln f - 1)\frac{p^\mu}{p^0}\frac{d\vec{p}}{(2\pi)^3} \Rightarrow s^0 = -g \int f(\ln f - 1)\frac{d\vec{p}}{(2\pi)^3}$$

Exercise: using *f~exp[(μ-E)/T] in the parenthesis*, check that at equilibrium & for a perfect fluid, this gives

$$s = \frac{\rho + P - \mu\, n}{T}$$

For relativistic species (entropy dominated by relativistic species!)

$$s \simeq \frac{4}{3}\frac{\rho}{T} \qquad s = \frac{2\pi^2}{45} h_{\rm eff}(T) T^3$$

$$h_{\rm eff}(T) = \sum_{i={\rm rel.bos.}} g_i \left(\frac{T_i}{T}\right)^3 + \frac{7}{8}\sum_{j={\rm rel.ferm.}} g_j \left(\frac{T_j}{T}\right)^3$$

ENERGY IN RELATIVISTIC ERA

similarly $$g_{\rm eff}(T) = \sum_{i={\rm rel.bos.}} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{j={\rm rel.ferm.}} g_j \left(\frac{T_j}{T}\right)^4$$

entering

$$\rho_{\rm tot} = \frac{\pi^2}{30} g_{\rm eff}(T) T^4$$

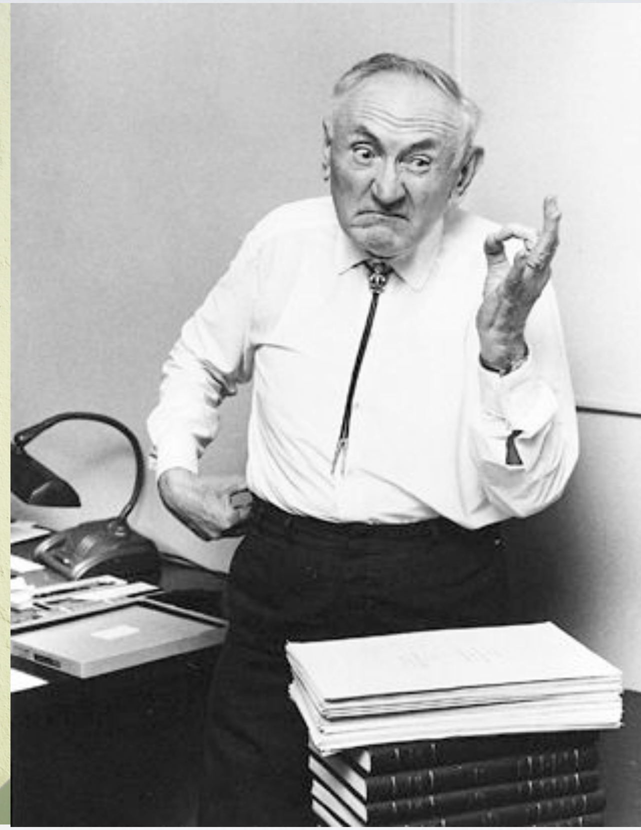
&

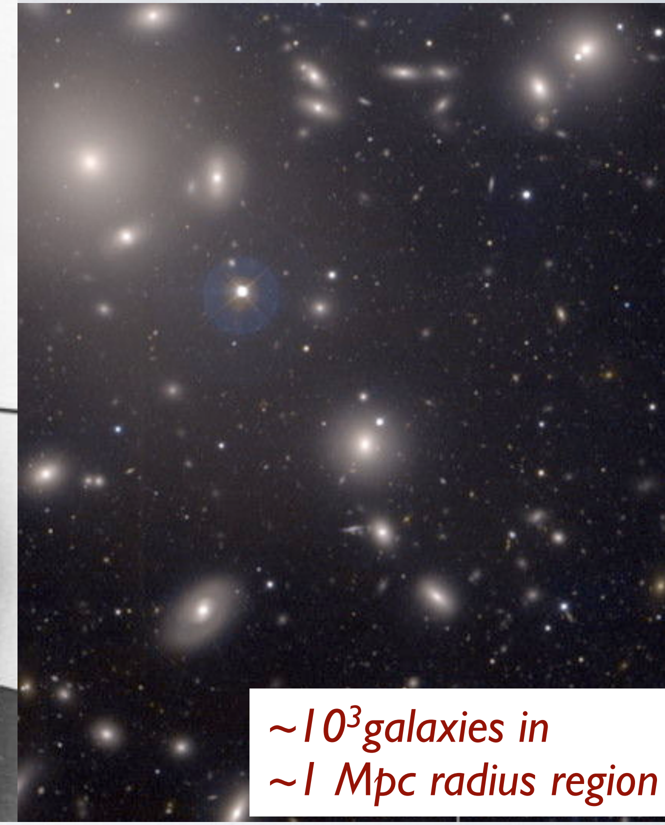
$$H^2 = \frac{8\pi}{3\,M_P^2}\rho_{\rm tot} = \frac{4\pi^3}{45\,M_P^2} g_{\rm eff} T^4$$

Exercise: List the particles of the Standard Model. Check that at T>>1 MeV (Hint 1: enough to check if true for the mostly weakly coupled ones) the typical energy exchange and pair production processes (draw some reactions and estimate σ's!) are at LTE. Compute and plot $g_{\rm eff}$ in the MeV-TeV range. (Hint 2: start from high T)

DARK MATTER ENTERS THE SCENE...

DM "DISCOVERY" IN COMA CLUSTER (~1933)





Remarkable application of Virial Theorem (basically pioneered in astronomy only by Poincaré, previously!) and **realized that this was a puzzle**.

Die Rotverschiebung von extragalaktischen Nebeln", Helvetica Physica Acta (1933) **6**, 110–127.*

"On the Masses of Nebulae and of Clusters of Nebulae", ApJ (1937) **86**, 217*

*Nebula=Early XXth century name for what we call now galaxy

Jan Oort had in fact found the need for "dark matter" already while studying the force ⊥ to the Galactic plane due to stars, but dismissively attributed to unaccounted gas or too dim bodies…

Bulletin of the Astronomical Institutes of the Netherlands 6, 249 (1932)

RECAP OF VIRIAL THEOREM

Given a system of N bodies/particles, define the function $$G = \sum_{k=1}^{N} \mathbf{r}_k \cdot \mathbf{p}_k$$

The average value of its time derivative must vanish if the system is bound (no particles "leave to infinity or acquire infinite velocity")

This condition is equivalent to $$2\langle T \rangle = -\sum_{k=1}^{N} \langle \mathbf{r}_k \cdot \mathbf{F}_k \rangle$$

For conservative forces coming from a potential U, $$\mathbf{F}_k = -\frac{\partial U}{\partial \mathbf{r}_k}$$

For the case $$U(r) = A\, r^n \Longrightarrow -\sum_{k=1}^{N} \langle \mathbf{r}_k \cdot \mathbf{F}_k \rangle = n \langle U_{tot} \rangle$$

For Gravity, U~ r $^{-1}$ $$2\langle T \rangle + \langle U_{tot} \rangle = 0$$

SKETCH OF THE METHOD

$$T = N\frac{m}{2}\langle v^2\rangle$$

$$\langle U_{tot}\rangle \simeq -\frac{N^2}{2} G_N \frac{m^2}{d}$$

~$N^2/2$ pairs of Galaxies

where m is the typical Galaxy mass, d the typical distance between Galaxies

$$M_{tot} \simeq N\, m = \frac{2\langle v^2\rangle\, d}{G_N}$$

e.g. *for N Galaxies in a sphere of radius R,* $d = \left(\frac{N}{V}\right)^{-1/3} = \left(\frac{4\pi}{3N}\right)^{1/3} R$

Alternatively, could directly estimate the gravitational potential energy of a self-gravitating homogeneous sphere of radius R

$$\langle U_{tot}\rangle \simeq -\frac{3}{5}\frac{G_N\, M^2}{R}$$

from doppler shifts in spectra ← $\langle v^2\rangle$

$$M_{tot} \simeq \mathcal{O}(1)\frac{\langle v^2\rangle R}{G_N}$$

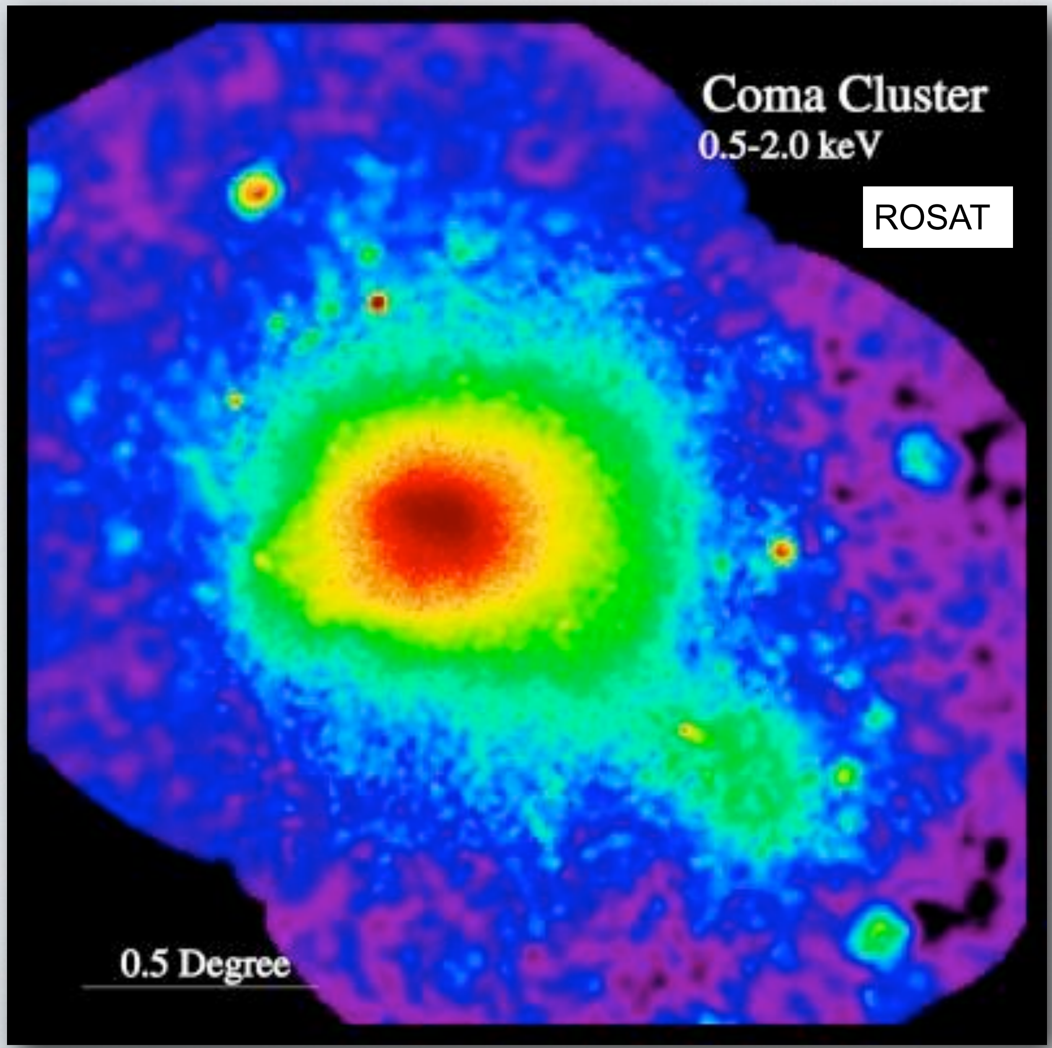
R → inferred from distance & angular size

$\mathcal{O}(1)$ → *weakly depends on geometry/distribution of Galaxies in the cluster*

Zwicky found 2-3 orders of magnitude larger M than expected from converting luminosity into mass!

MODERN PROOFS FROM CLUSTERS: X-RAYS

We know today that most of the mass in clusters (not true for galaxies!) is in the form of hot, intergalactic gas, which can be traced via X rays: X-luminosity and spectrum provide mass profile!



Again, a factor ~7 more mass than those in gas form is inferred (also its profile can be traced...)

See for example
Lewis, Buote, and Stocke, ApJ (2003), 586, 135

SKETCH OF THE METHOD

Spherical symmetric, hydrostatic equilibrium for the gas:

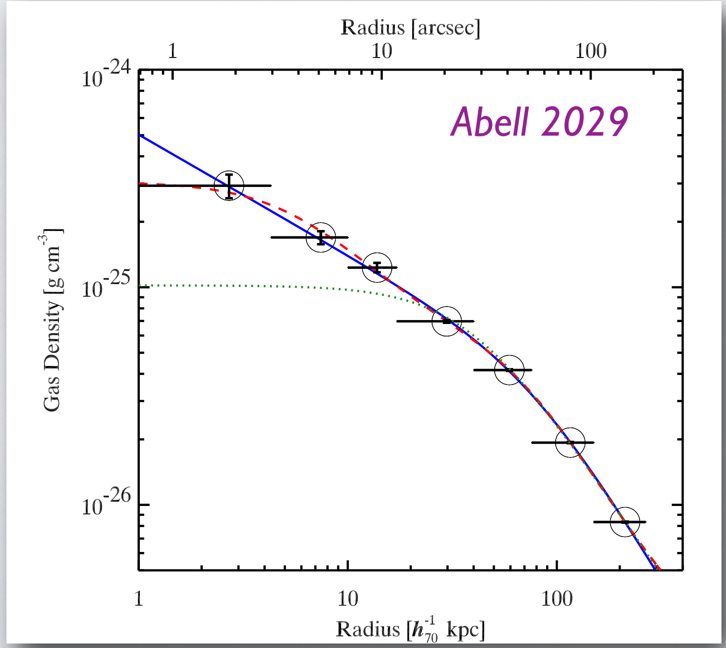
Newton's law in the fluid limit (shell)

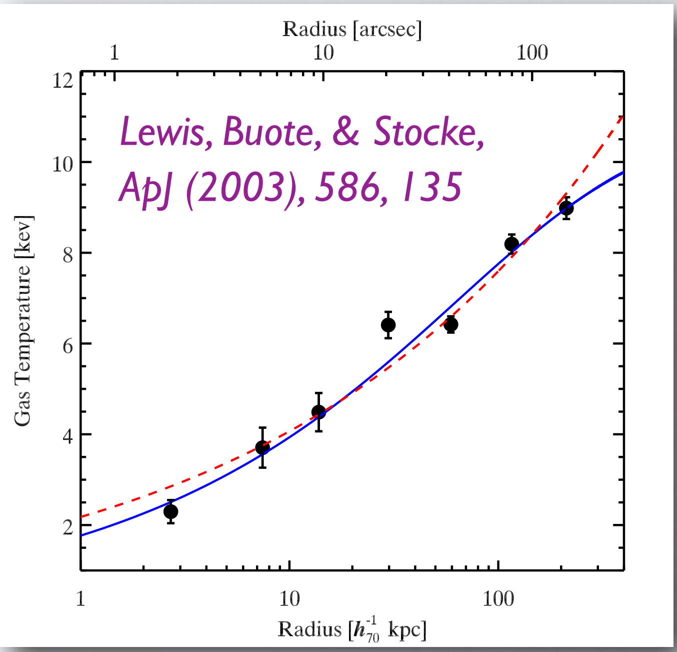
$$dF = -\frac{G_N\, M(r)\, \rho_g(r)\, S}{r^2} dr \quad \longrightarrow \quad \frac{dP_g}{dr} = -\frac{G_N\, M(r)\, \rho_g(r)}{r^2}$$

Use perfect gas EOS

$$P_g = \frac{\rho_g}{\mu\, m_p} k_B\, T_g \quad \longrightarrow \quad M(r) = -\frac{r\, k_B\, T_g}{G \mu m_p}\left[\frac{\mathrm{d}\log \rho_g}{\mathrm{d}\log r} + \frac{\mathrm{d}\log T_g}{\mathrm{d}\log r}\right]$$

The method ***does not depend on gas density normalization*** (which controls the baryonic mass)!

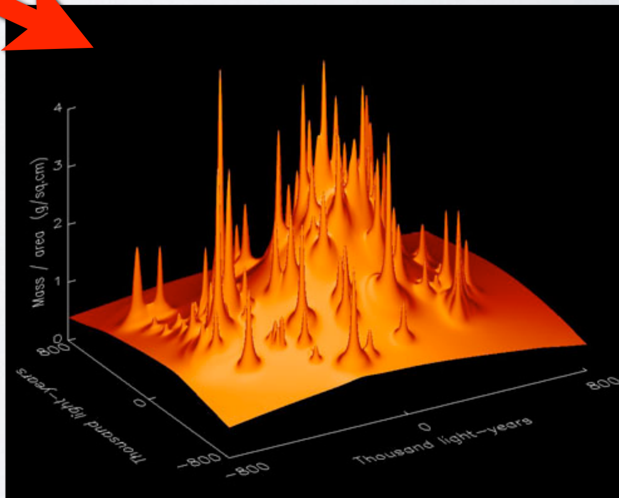




MODERN PROOFS FROM CLUSTERS: LENSING

CL0024+1654,
Hubble space telescope

its gravitating mass distribution
inferred from lensing tomography

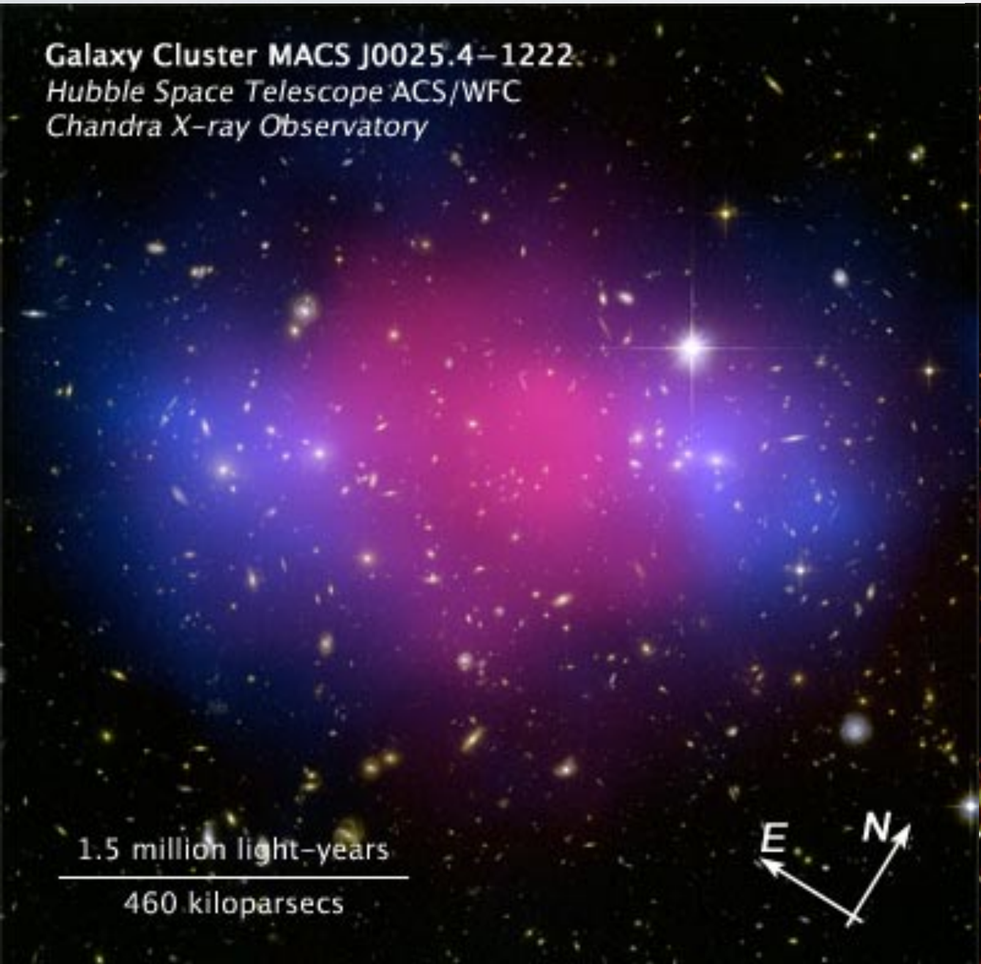


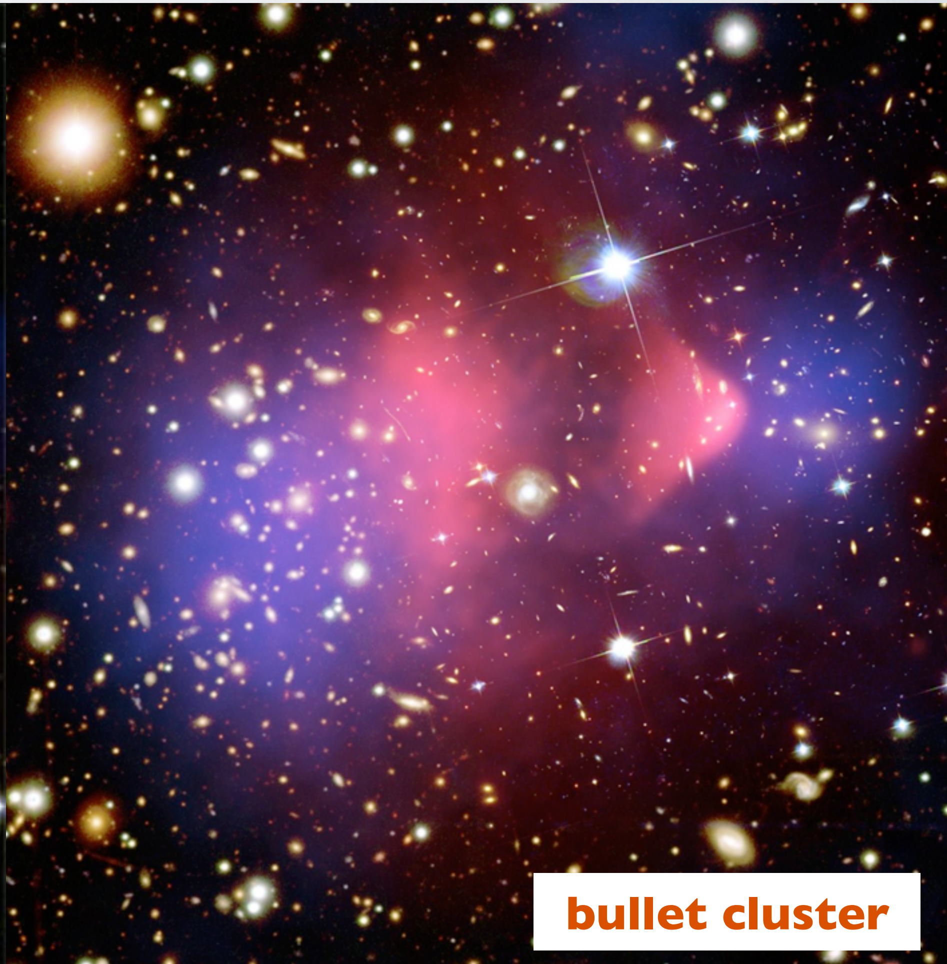
Consistent inference done from clusters of Galaxies:
Presence of Dark Matter smoothly distributed in-between galaxies is required
(and actually must dominate total potential)

MORE SPECTACULAR: SEGREGATION!

Baryonic gas gets "shocked" in the collision and stays behind. The mass causing lensing (as well as the subdominant galaxies) pass trough each other (non-collisional)

(most of the) Mass is not in the collisional gas, as would happen if law of gravity had been altered!





ANOMALOUS GALAXY ROTATION CURVES

age mass per cubic parsec is 0.98⊙. The total luminosity of M31 is found to be 2.1×10^9 times the luminosity of the sun, and the ratio of mass to luminosity, in solar units, is about 50. This last coefficient is much greater than that for the same relation in the vicinity of the sun. The difference can be attributed mainly to the very great mass calculated in the preceding section for the outer parts of the spiral on the basis of the unexpectedly large circular velocities of these parts.

H.W. Babcock (1939), PhD Thesis

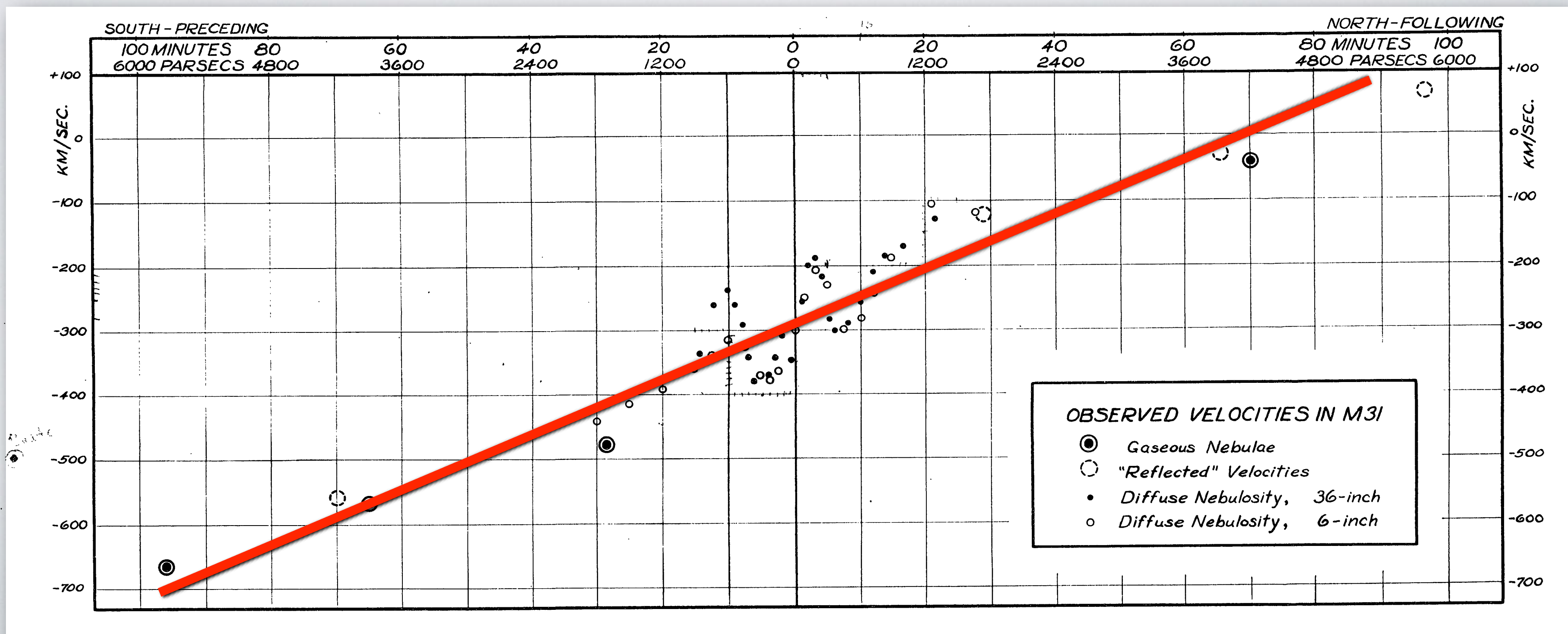
(& Lick observatory bulletin # 498 (1939) 41)

building upon works by Slipher (1914), Pease (1918)…

THE ROTATION OF THE ANDROMEDA NEBULA*

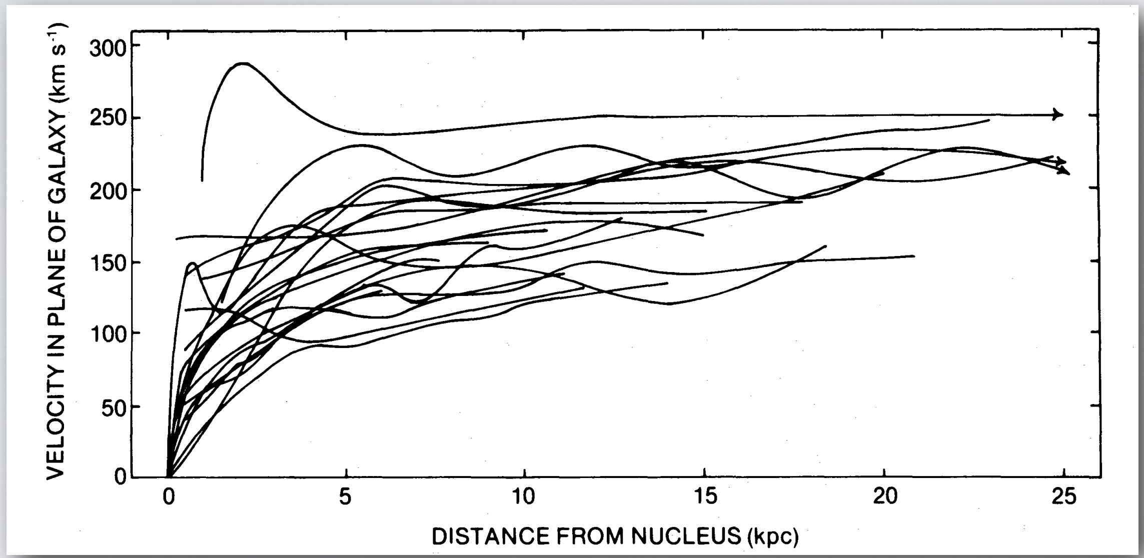
BY

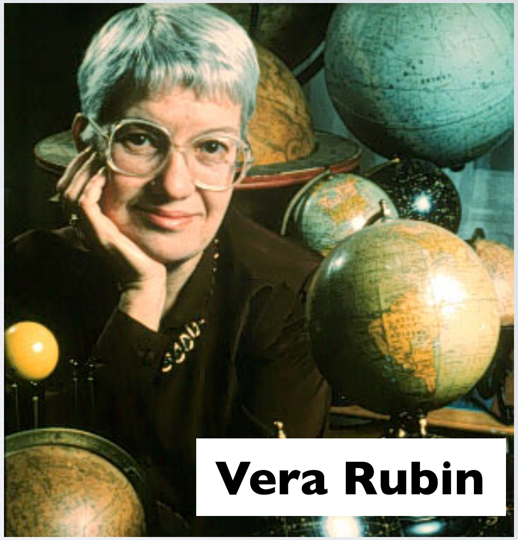
HORACE W. BABCOCK



FLAT GALAXY ROTATION CURVES

A few decades later, after a number of developments (radioastronomy, 21 cm indicators, improved spectroscopic surveys…) starting from around ~1970 astronomers like V. Rubin, W. K. Ford Jr. et al. embarked in a campaign to obtain rotational curves of Spiral Galaxies to their faint outer limits





V. C. Rubin and W. K. Ford, Jr.,
"Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions,"
ApJ 159, 379 (1970) […] V. C. Rubin, N. Thonnard and W. K. Ford, Jr.,
"Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 /R = 4kpc/ to UGC 2885 /R = 122 kpc/," ApJ 238, 471 (1980).

By the '80, many people started to take the dark matter problem seriously
(partly due to technical refinements, part sociology?)

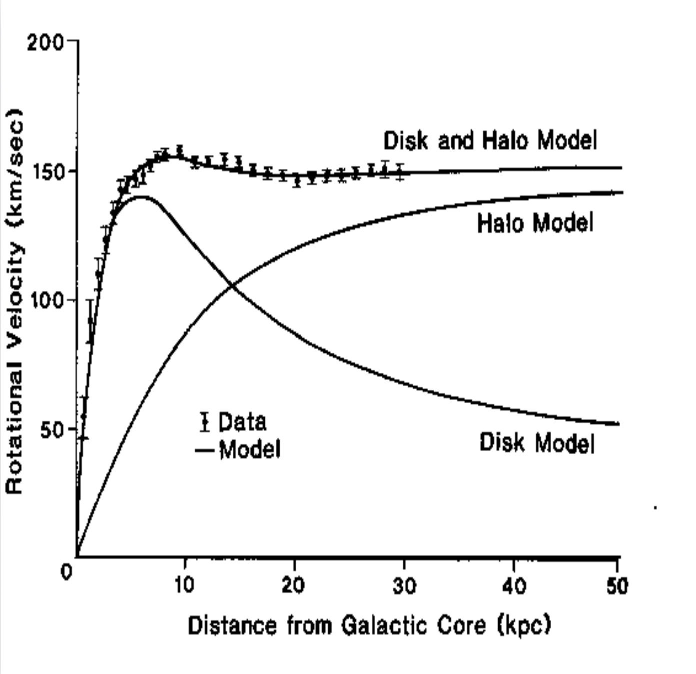
WHERE'S THE PROBLEM?

- observed (equate centripetal acc. & Newton's law)

$$v_{rot}^2 = \frac{G\,M(R)}{R} \simeq const. \qquad M(R) = \int_0^R 4\pi\, r^2\, \rho(r)\, d\,r$$

- predicted based on visible light

$$v_{rot}^2 \propto \frac{1}{R}$$



Data are well described by an additional component extending to distance >> visible mass scale, with a profile $\rho(r) \propto r^{-2}$ (clearly not valid at asymptotically large r!)

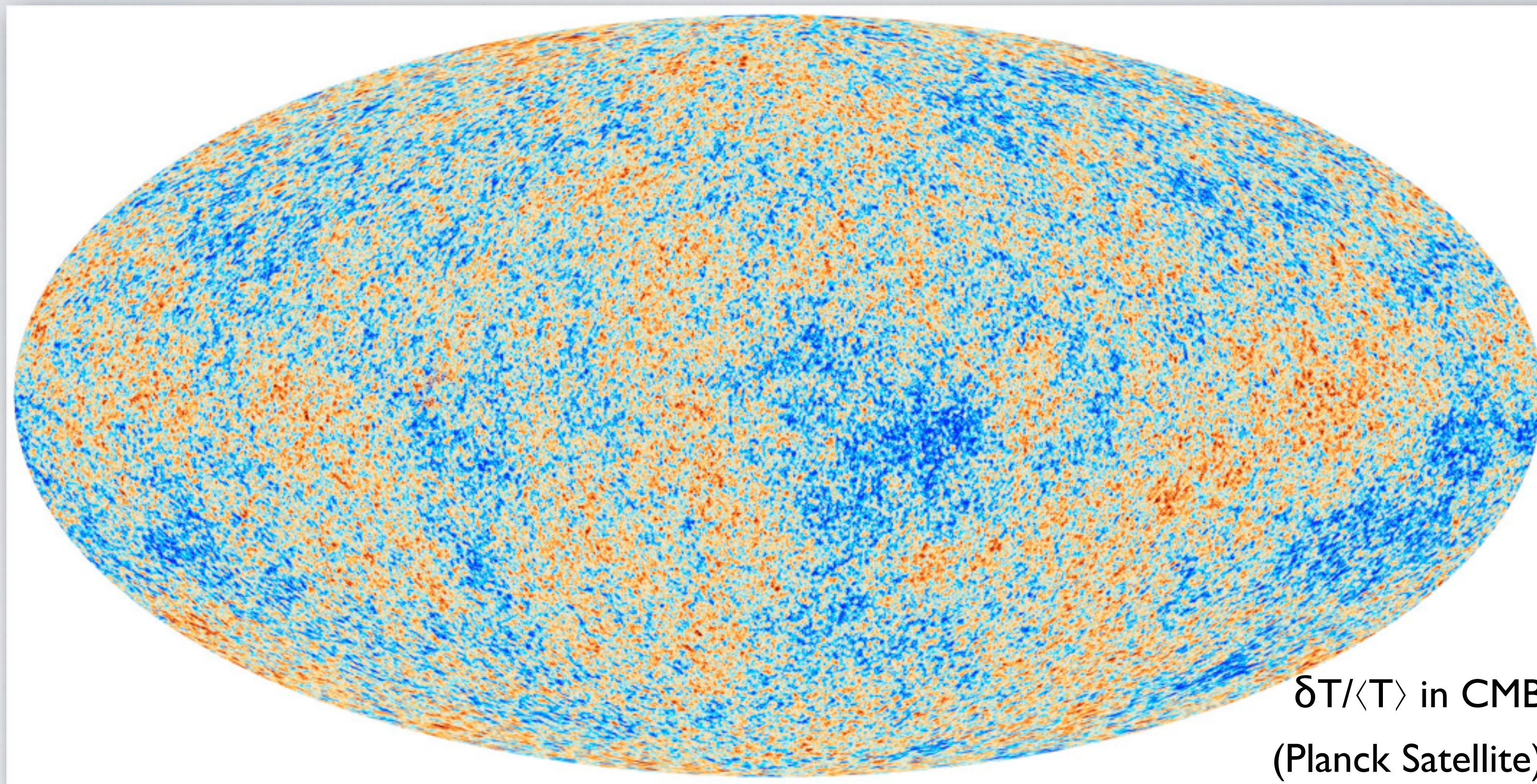
The determination of "local" (Galactic) DM properties requires a multi-parameter fit including stellar disk, gas, bulge yielding $\rho_\odot \simeq 0.4\,\mathrm{GeV/cm^3}$

Such techniques, as well as analogous ones used to infer DM in other systems (like dwarf Galaxies) are extremely important for ***direct and indirect searches*** of DM, *but people often forget about it…*

not the most crucial or unambiguous ones to infer DM existence and properties *…yet often presented as "smoking gun"!*

GROWTH OF STRUCTURES

This picture, plus some (linear) theory is a robust proof for the existence of DM!



Key argument

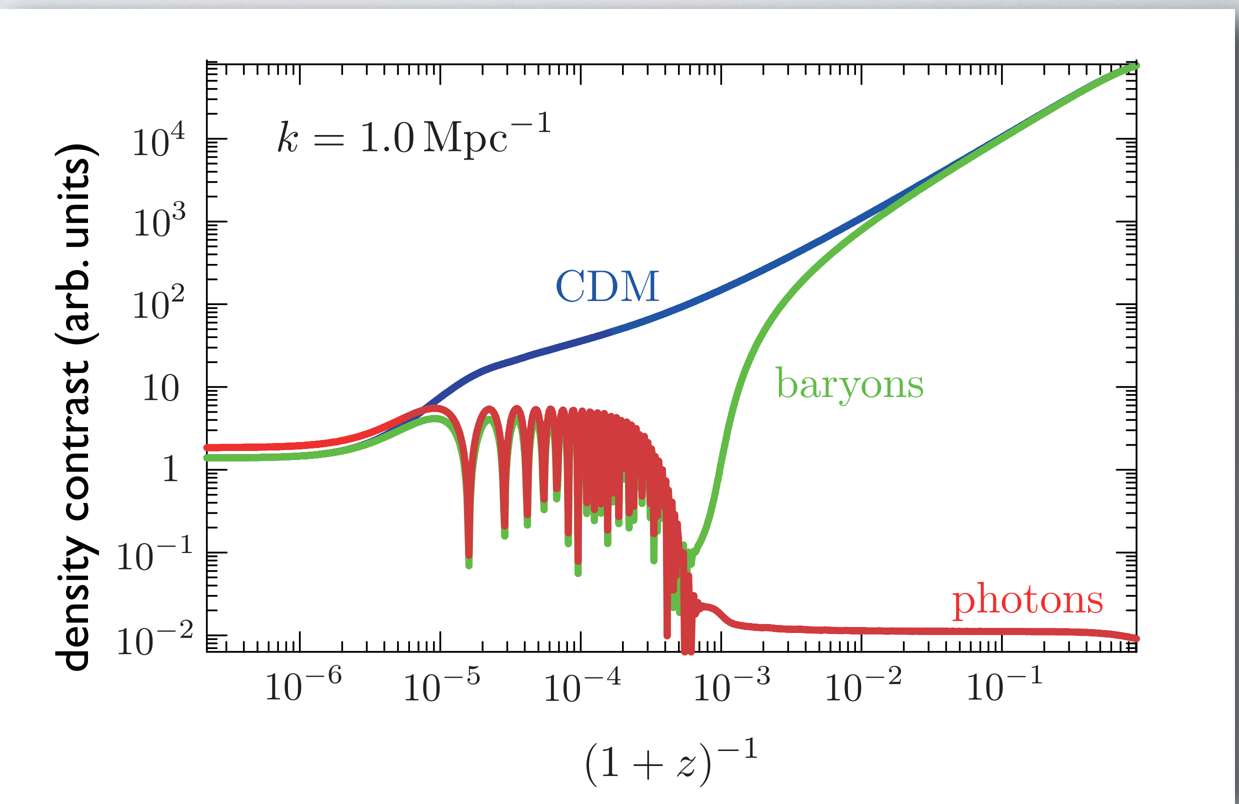
- Before recombination: baryons & photons coupled, "share perturbations"
- We measure amplitude ~10^{-5} at recombination, i.e. when e and *p* form atoms (*picture above*)
- Evolving forward in time, insufficient to achieve collapsed structures as we see nowadays, unless lots of gravitating matter (not coupled to photons) creates deeper potential wells!

IN GRAPHIC TERMS

$$\delta = \frac{\rho}{\langle\rho\rangle} - 1$$

$$= \sum_{\mathbf{k}} \tilde{\delta}_{(\mathbf{k})} e^{i\mathbf{k}\cdot\mathbf{x}}$$

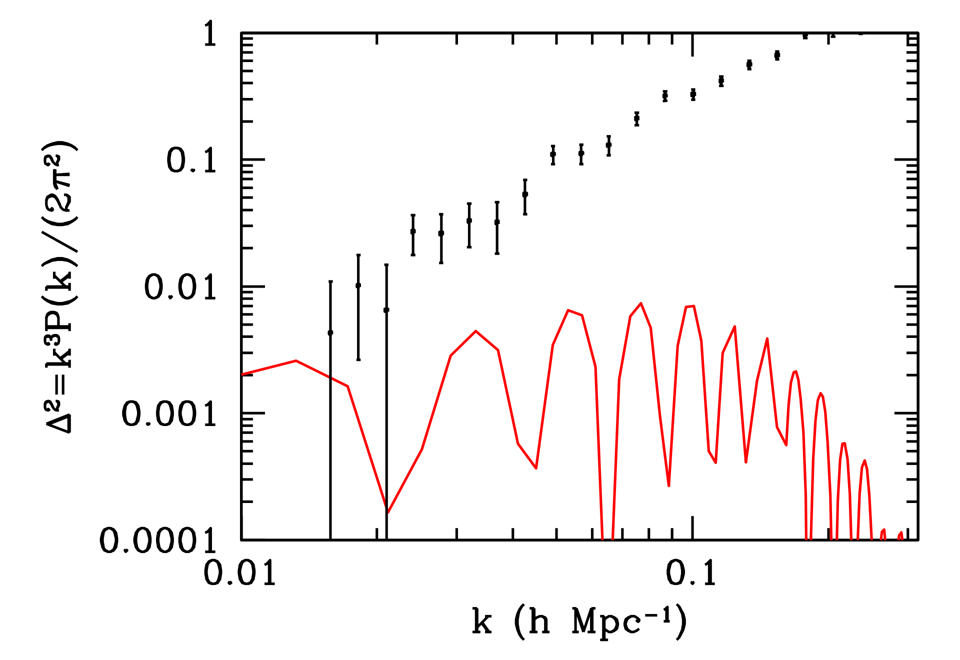
Density contrast for a "mode" (in Fourier space). Indep. evolution in linear theory, its "variance" is the power spectrum *P(k)*



- Ignore evolution at very early times (stuff not in causal contact).
- When causally connected, until the baryonic gas is ionized, it is coupled to radiation & oscillates, as pressure prevents overdensities from growing. The (uncoupled, pressureless) CDM mode instead grows, first logarithmically during radiation domination, then linearly in the matter era.
- After recombination, baryons behave as CDM, quickly fall in their "deep" potential wells... but, had not been for CDM, they would need much longer to reach the same density contrast!

WHAT IF ONLY BARYONS PRESENT?

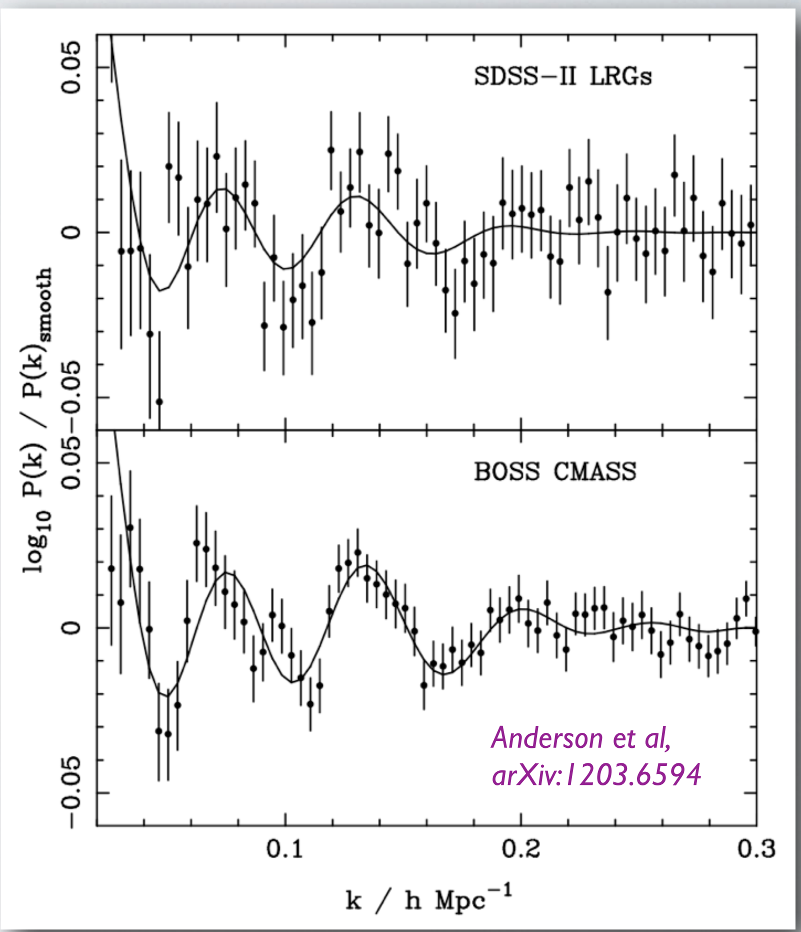
Power spectrum: Fourier transform of 2 point correlation function ("variance") of large scale structures, as traced by Galaxies)



No structure non-linear by now & pattern of "clumpiness" would be very different!

Models where "baryonic gravity is enhanced" so to "boost" growth have do not get the right shape!

See pedagogical discussion in S. Dodelson, 1112.1320



Credibility of our understanding reinforced since we see the residual "oscillations" due to coupling of subleading baryons with photons (BAO)!

AN INDEPENDENT TEST: BBN

CMB data sensitive to baryons via e.m. coupling with photons (plus gravity)

But the baryon/photon number density ratio η also determines at which T nuclei depart from thermal nuclear equilibrium, eventually determining the pattern of light nuclei emerging from primordial plasma.

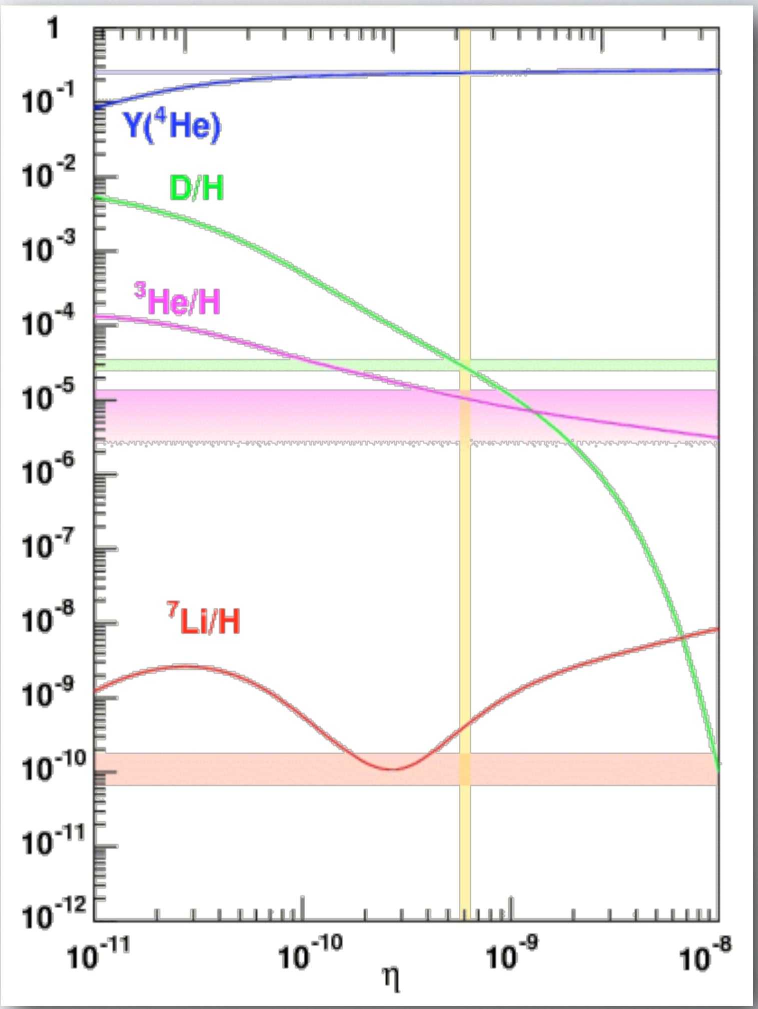
Exercise: prove $\eta \equiv n_b/n_\gamma = 2.74 \times 10^{-8}\Omega_b h^2$

$h=H_0/100$ km /s/Mpc ~0.7

CMB provides a measurement η^{CMB}**~6x10^{-10}** (from atomic physics, T~eV)

Big Bang Nucleosynthesis theory, plus spectroscopic observation e.g. of deuterium/hydrogen abundance in old clouds systems, determines η^{BBN} (from nuclear physics, T~0.1 MeV)

The agreement between the two is a
Great success of cosmology!



INITIAL CONDITIONS AND NSE

- T>> 1 MeV: nucleons & nuclei are in thermal (kinetic & chemical) equilibrium

✓ high entropy per baryon → negligible fractions of all but *p* & *n* (which in turn easily intercovert into each other)

$$n_A = g_A \left(\frac{m_A T}{2\pi}\right)^{3/2} \exp\left(-\frac{m_A}{T} + \frac{\mu_A}{T}\right)$$

Boltzmann thermal distribution

$$\begin{aligned} m_A &= Z\, m_p + (A-Z)\, m_n - B_A \\ \mu_A &= Z\, \mu_p + (A-Z)\, \mu_n \end{aligned}$$

Impose mass balance and chemical equilibrium

$$X_A \equiv \frac{n_A}{n_b} = \left(\frac{2\zeta(3)}{\sqrt{\pi}}\right)^{A-1} \frac{g_A}{2} A^{\frac{3}{2}} \left(\frac{n_p}{n_b}\right)^Z \left(\frac{n_n}{n_b}\right)^{A-Z} \left(\frac{T}{m_N}\right)^{\frac{3(A-1)}{2}} \eta^{A-1} e^{\frac{B_A}{T}}$$

Abundance mostly controlled by

B_A= binding energy ≅ few MeV x A

$\eta \equiv n_b/n_\gamma = 2.74 \times 10^{-8} \Omega_b h^2$

DEUTERIUM BOTTLENECK

D formation crucial for triggering further nuclear reactions, since multi-body (as opposed to 2-body) processes as $2n+2p \rightarrow {}^4He$ are inhibited by the low density: @T=0.1 MeV baryon density ~ air density

Two competing processes

- fusion: $n+p \rightarrow D+\gamma$
- photodissociation: $\gamma+D \rightarrow n+p$

One expects that when T drops below ~ B_D= 2.23 MeV, photodissociation processes become ineffective. However: too many photons!!

$$\frac{X_D}{X_p X_n} = \frac{12\,\zeta(3)}{\sqrt{\pi}} \left(\frac{T}{m_N}\right)^{3/2} \eta\, e^{\frac{B_D}{T}}$$

D formation starts only when $\eta \exp(B_D/T_*) \sim 1 \Rightarrow T_* \sim B_D/(23 - \ln \eta_{10}) \sim 0.1$ MeV

Despite availability of high-T, **BBN starts late and ends soon**, it's an incomplete/inefficient combustion, leaving fragile nuclear ashes behind! **η controls what's left**!

SUMMARY OF WHAT WE LEARNED

- A number of observations, collected over the past century, show the need for "some dark stuff" contributing dominantly to the dynamics of bound objects from sub-Galactic to Cluster scales, and which is also needed to explain the timely formation of non-linear scales via gravitational instabilities starting from tiny fluctuations as inferred from CMB temperature perturbations.

- Whatever it is, it cannot be made by "hidden baryons" (like dim stars, gas, planets) because we can measure the amount of baryons at a time where the universe was smooth (no stars, no planets…) via electromagnetic/gravitational coupling and via purely nuclear effects: the measurements agree, and point to a too low amount of baryons

- We can anticipate that this stuff must have quite peculiar properties, since it behaves so differently from ordinary stuff. In the following, we'll learn what astrophysical and cosmological observations tell us about those!