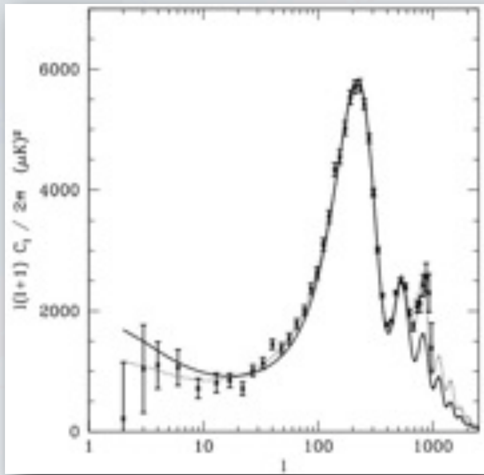
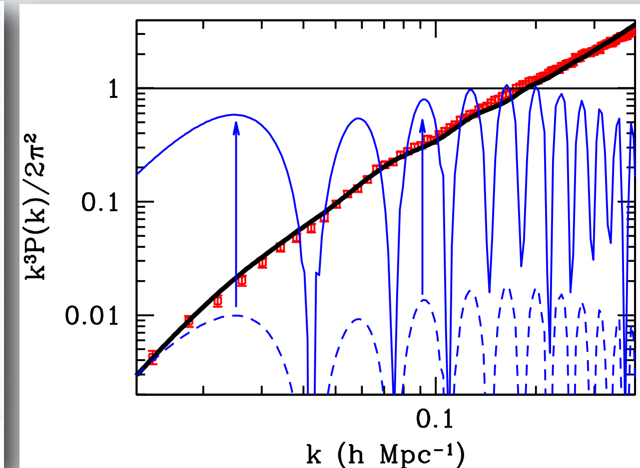
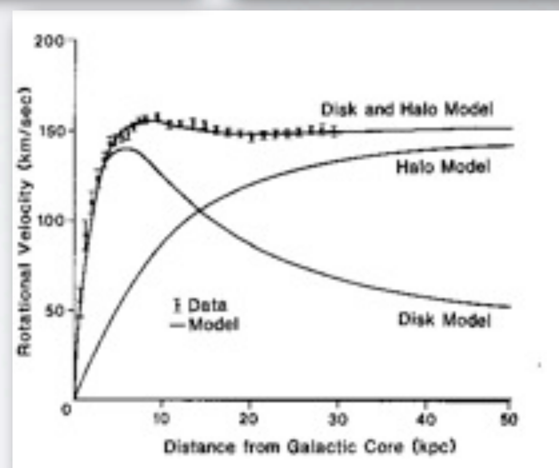
Astrophysical signals of dark matter:
I. Gravitational evidence & basic properties







Pasquale Dario Serpico

First ICTP Advanced School on Cosmology - 18-29/05/2016

OUTLINE & GOALS

Lecture one

- ***basic notions of cosmology for "particle astrophysics"***
- ***Gravitational evidence for Dark Matter (why are we so sure? Are we?)***
- ***A few 'particle physics' constraints from astro/cosmo observations***

Lecture two

- ***freeze-out (hot, cold), "WIMPs & their relatives"***
- ***Heuristic and more formal introduction of the Boltzmann eq. and its applications to DM-related problems***
- ***notions on direct detection***

Lecture three

- ***Indirect detection of dark matter, mostly focused on WIMPs (different channels, strategies, challenges)***

My Goals

To those who have basic notions, manual towards "working knowledge" of the problems
To those who have none, at least the key physical ideas and the tools needed to attack the problems

SOME REFERENCES

General references

- **The Early Universe", E. W. Kolb & M. S. Turner**
- **"Physical Foundations of Cosmology", V. Mukhanov**

...

Specific monographs

- **"Kinetic Theory in the expanding Universe", J. Bernstein**
- **"Neutrino Cosmology", J. Lesgourgues, G. Mangano, G. Miele, Pastor**
- **"Particle Dark Matter" Edited by Gianfranco Bertone (chapters on different particle physics candidates and probes)**

...

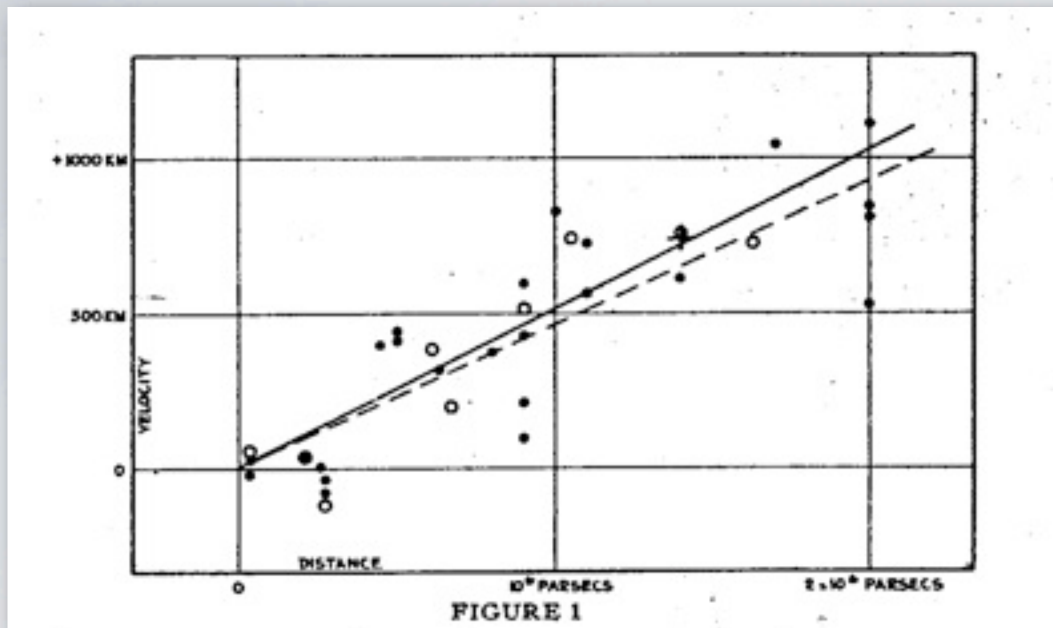
others will be introduced along the course

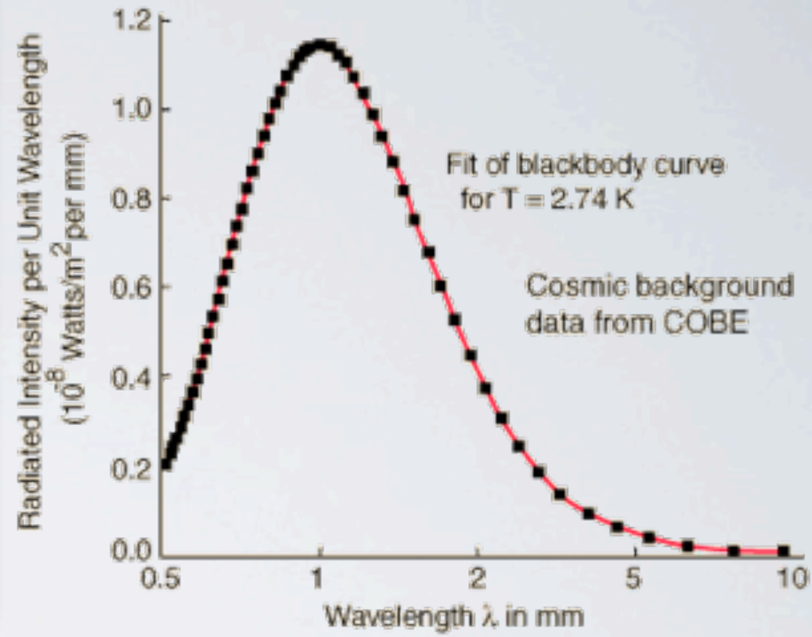
BASIC NOTIONS OF (SMOOTH) COSMOLOGY

Minimum you need to know to follow the rest of the lectures. Cannot replace a proper knowledge in cosmology needed to work on this subject!

Extra details in D. Weinberg's and M. Zaldarriaga's lectures

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)
- Yields of light elements (notably Deuterium and Helium) way larger than what expected from "stellar" phenomena.

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.

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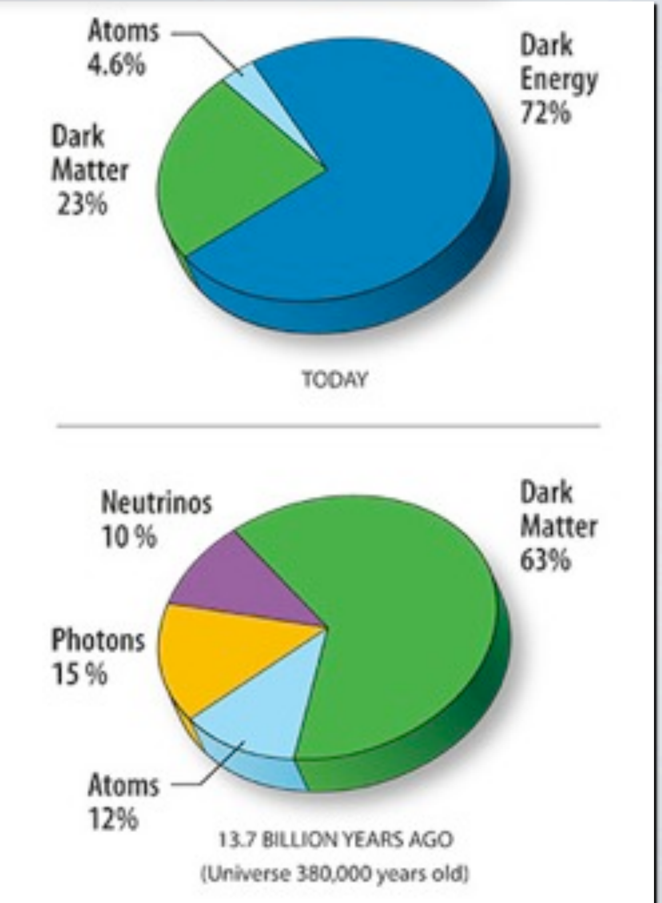
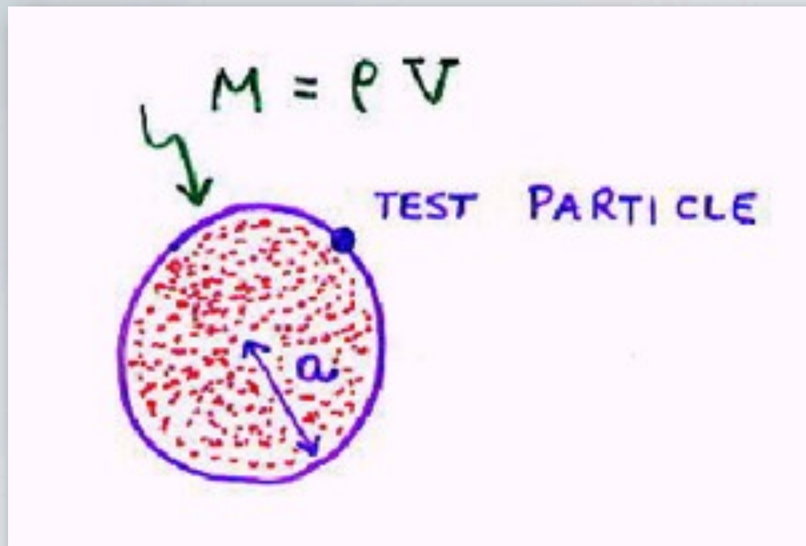
Evolving the expanding universe backwards in time → picture of hot Early Universe, made of a "gas" which has been cooling while expanding

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…)



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

EXAMPLES



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

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

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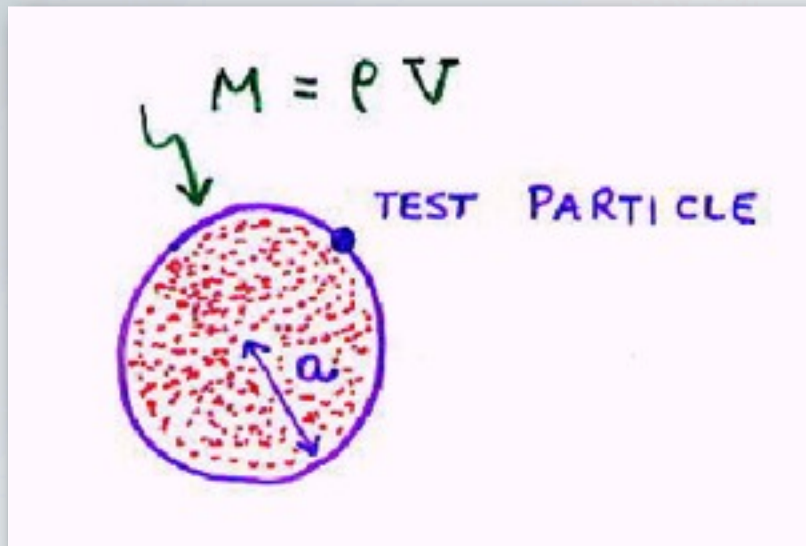

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$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2}$$

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

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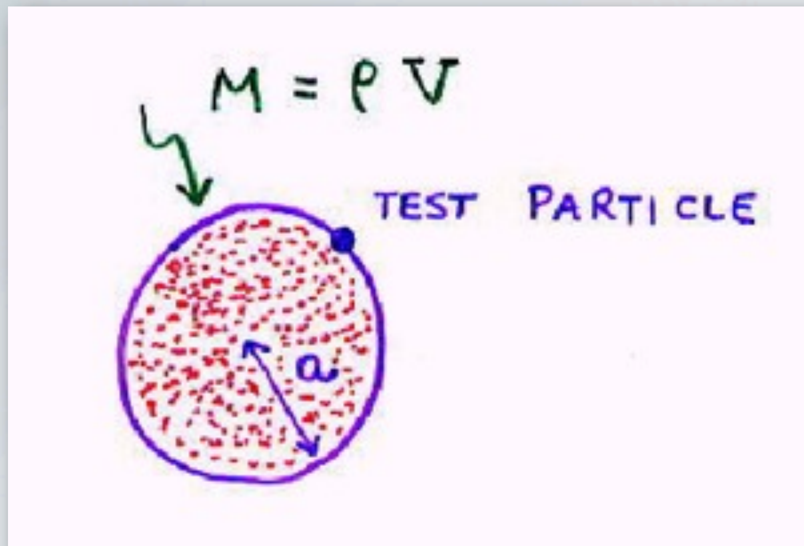

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Compositions usually expressed in Ω_i**'s**, ratios of density of i-species to "critical density"

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

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	$P = \rho/3$	$\rho \propto a^{-4}$	$a \propto t^{1/2}$
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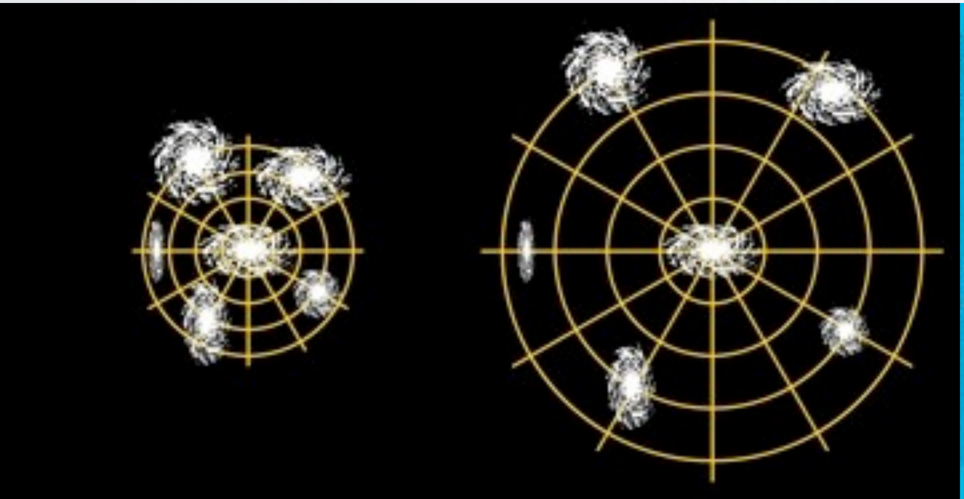
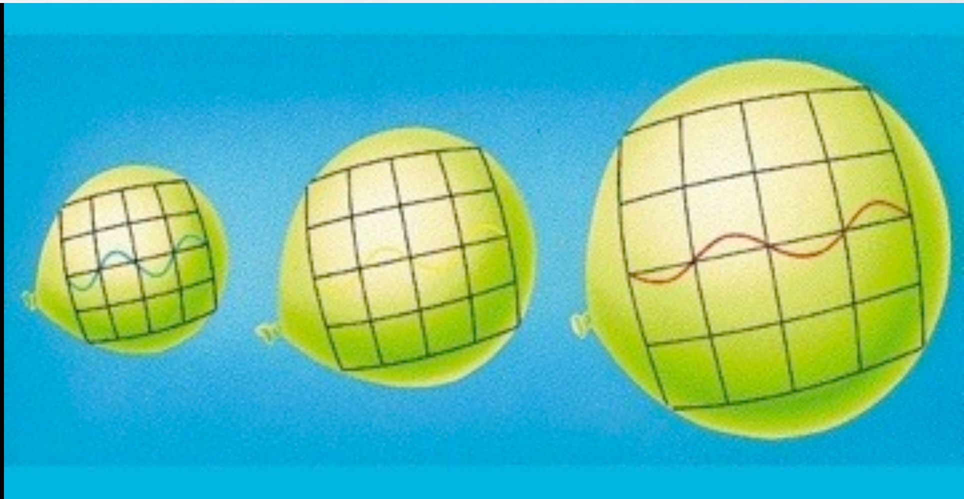
conservation of particles per comoving volume
For radiation, further a-factor due to wavelength stretching, also called "redshift"

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





“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 system 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.

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- 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)

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current density of particles

internal (spin) dof

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

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

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can be proven that the covariant conservation of particle number

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

OK with physical intuition of previous cartoon $\quad n \propto a^{-3} \propto V^{-1}$

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)

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

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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 "temperature", 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)*

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

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

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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

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For relativistic species (the entropy is 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 & ENTROPY IN RELATIV. ERA

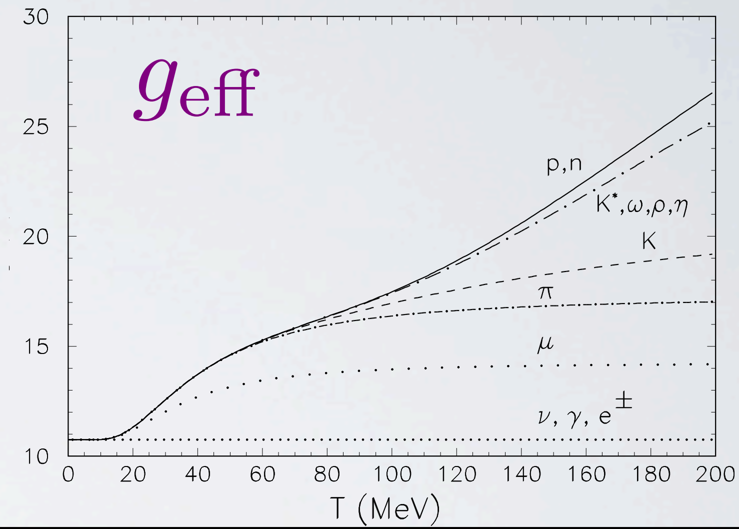
similarly
$$g_{\rm eff}(T) = \sum_{i={\rm rel.bos.}} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{j={\rm rel.ferm.}} g_j \left(\frac{T_j}{T}\right)^4$$

entering

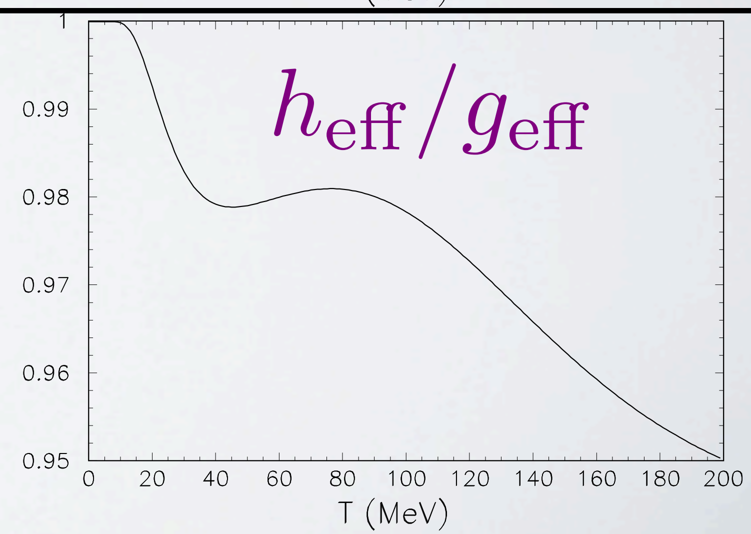
$$\rho_{\rm tot} = \frac{\pi^2}{30} g_{\rm eff}(T) T^4$$

&

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



compare with
$$s = \frac{2\pi^2}{45} h_{\rm eff}(T) T^3$$



they vary when species annihilate!

for reference, currently-accounting for photons and neutrinos-one has
$h_{\rm eff}$ ~ 2+3*2(4/11)*7/8~**3.91, T~2.73 K**

DARK MATTER ENTERS THE SCENE...

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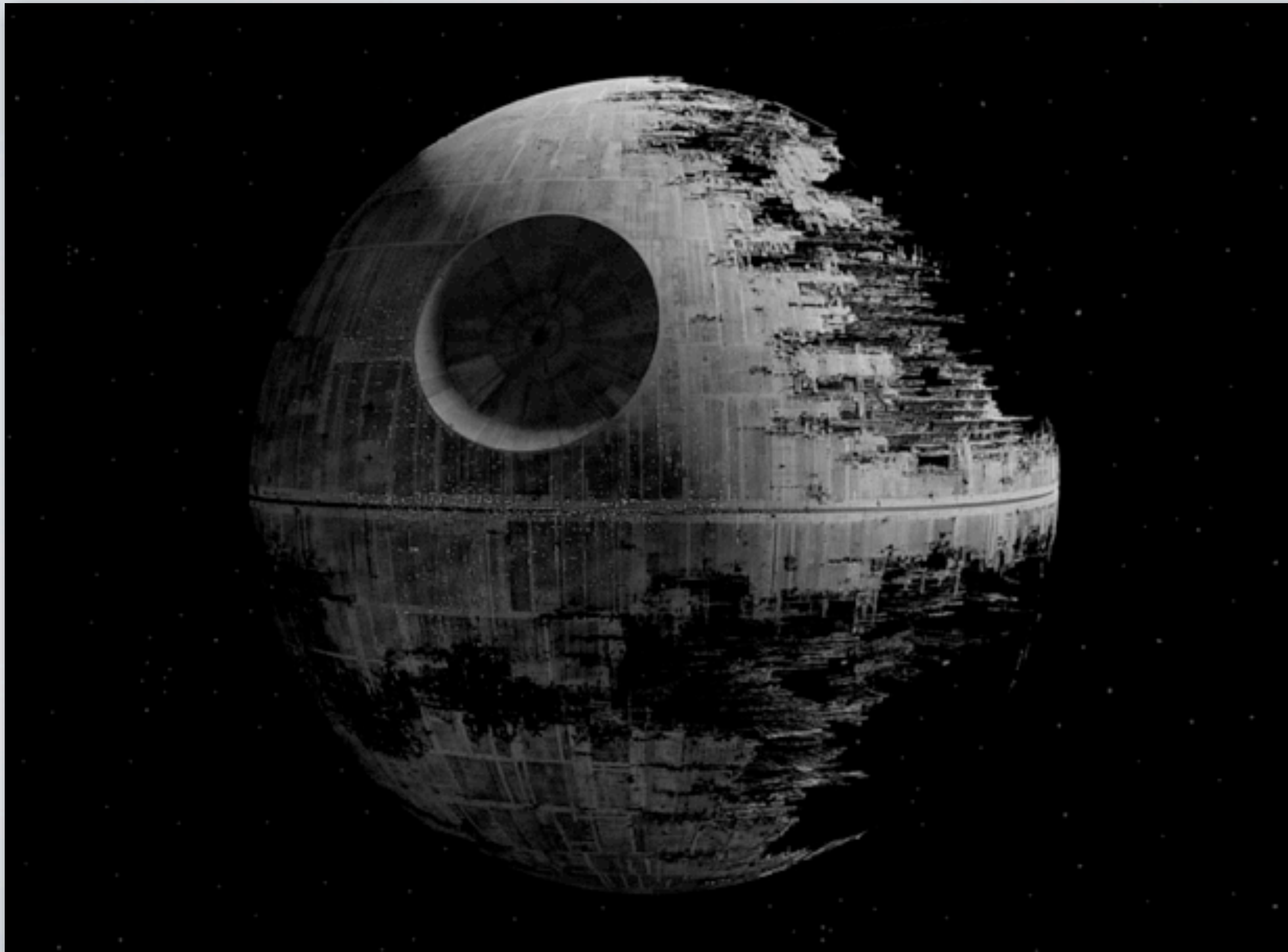
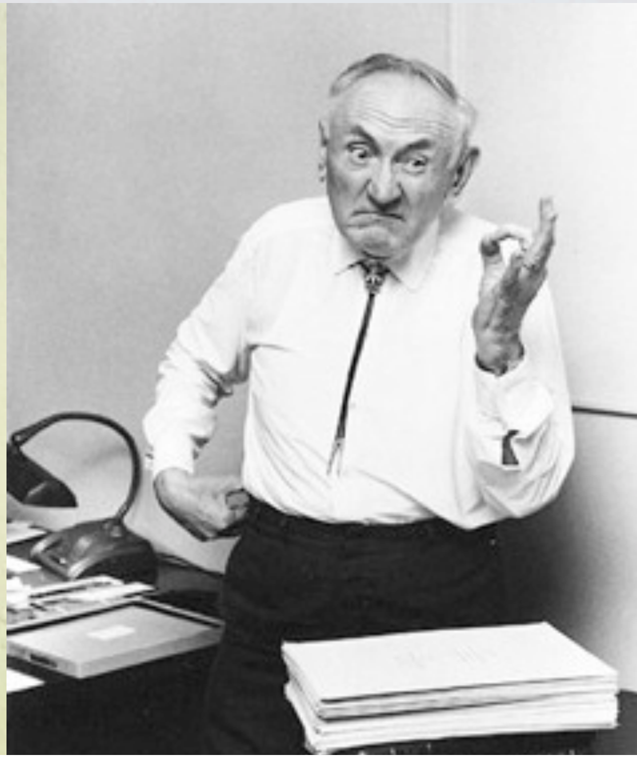


DM "DISCOVERY" IN COMA CLUSTER (~1933)

Varna, Bulgaria



~10^3 galaxies in ~1 Mpc radius region

We remember F. Zwicky here for two important discoveries:

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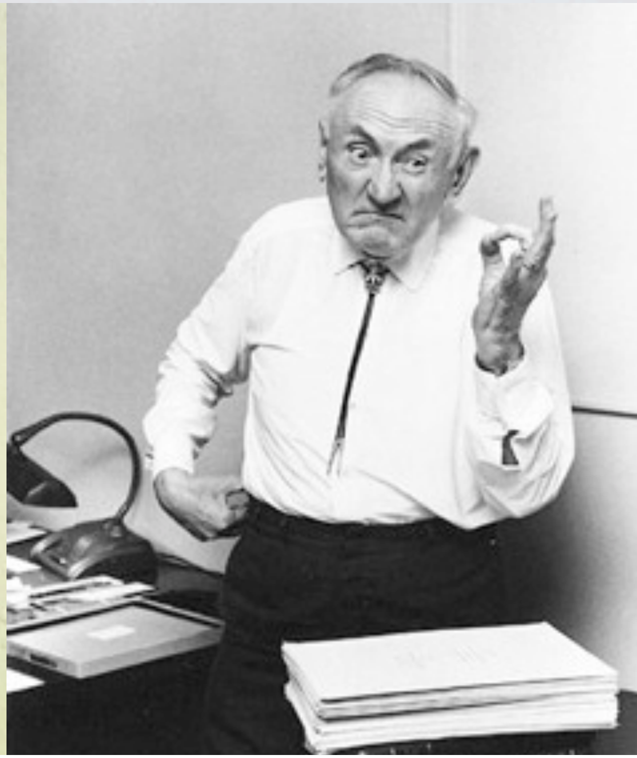

~10^3 galaxies in
~1 Mpc radius region

We remember F. Zwicky here for two important discoveries:

- "Astronomers are spherical bastards. No matter how you look at them they are just bastards."
- Inferred the mass of the Coma cluster from the proper motion of the Galaxies, finding that the required mass is much larger than what could be accounted for

Die Rotverschiebung von extragalaktischen Nebeln", Helvetica Physica Acta (1933)* ***6****, 110–127.*
"On the Masses of Nebulae and of Clusters of Nebulae", Astrophysical Journal (1937)* ***86****, 217*
*Nebula=Early XXth century name for what we call now galaxy

I. No "BSM" implications (yet)
II. How did he do it? Clever & original application of Virial Theorem

SKETCH OF THE METHOD

Expression of time average of total kinetic energy T of N particles bounded by conservative forces F

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

Average total potential energy <U>

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

For Gravity, U~ r $^{-1}$

$$2\langle T\rangle + \langle U_{tot}\rangle = 0$$

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$N^2/2$ pairs of Galaxies

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

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

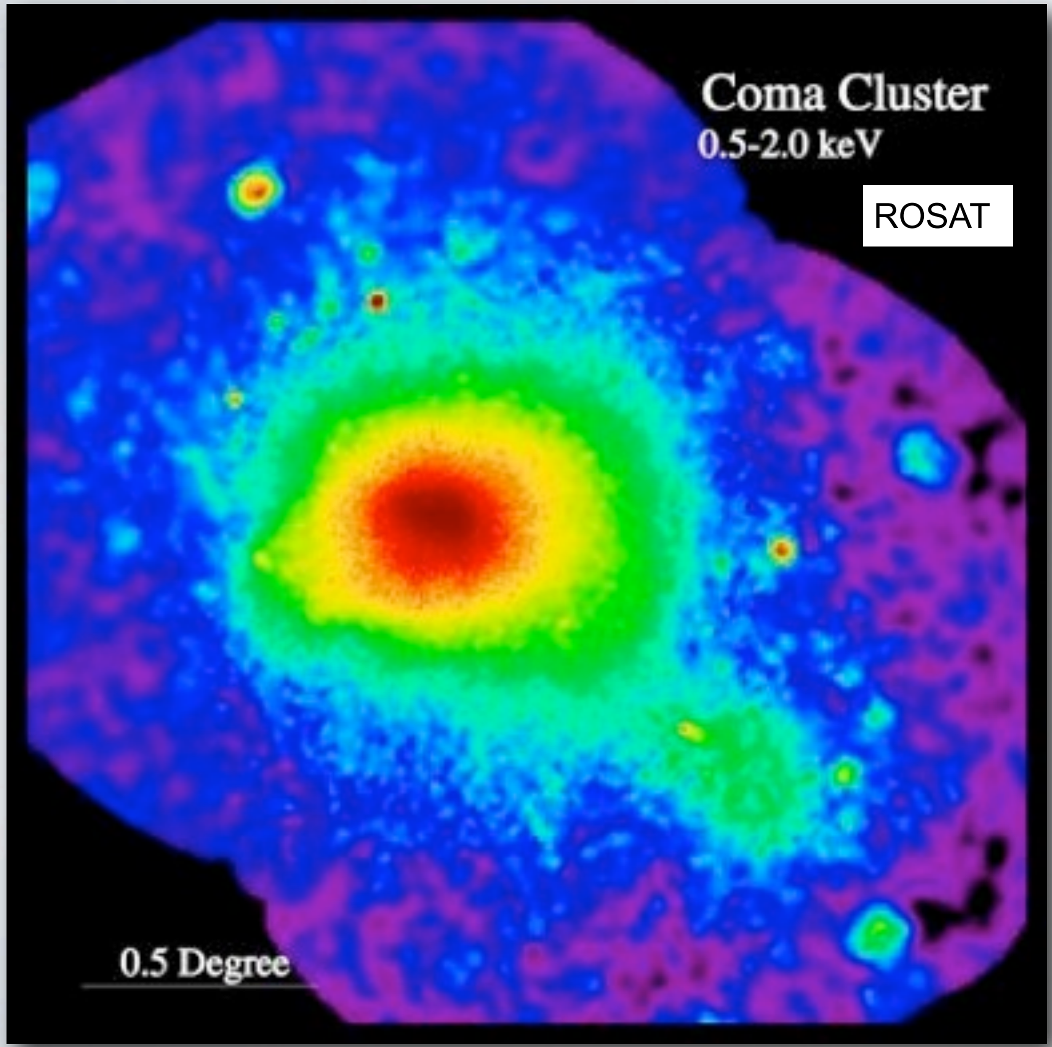
$$M_{tot} \simeq N\langle m\rangle \simeq -\frac{2\langle v^2\rangle\,\langle r\rangle}{G_N}$$

$\langle r\rangle$ → inferred geometrically

found a factor ~400 larger mass than the one 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: bolometric X-luminosity can be eventually converted into gas density maps, spectral info into pressure information (or potential depth)



$$\frac{dP_{gas}}{dr} = G_N \frac{M(< r)\rho_{gas}}{r^2}$$

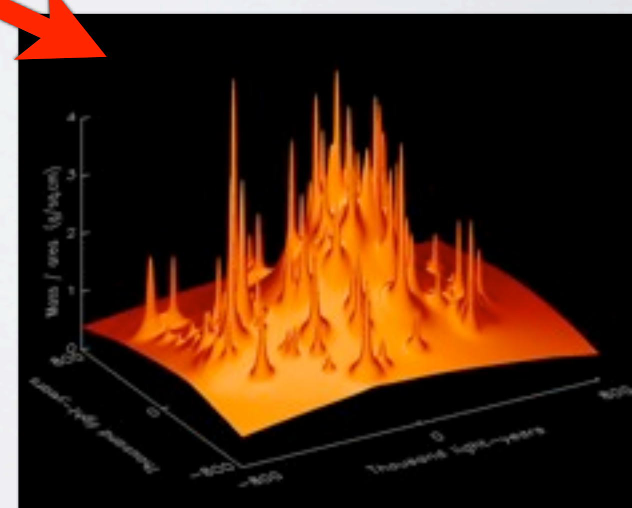
See for example
Lewis, Buote, and Stocke, ApJ (2003), 586, 135

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

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!

FLAT GALAXY ROTATION CURVES

- 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

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

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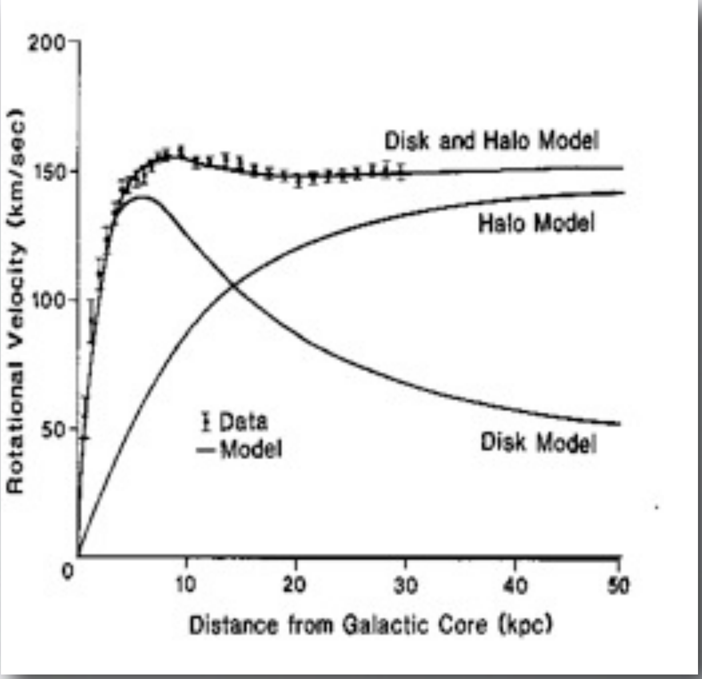
Data are well described by an additional component extending to distance >> visible mass scale, with a profile

$\rho(r) \propto r^{-2}$ (clearly not valid at asymptotically large r!)

Historically, only after these studies (in the ~'70-'80) people started to take the dark matter problem seriously



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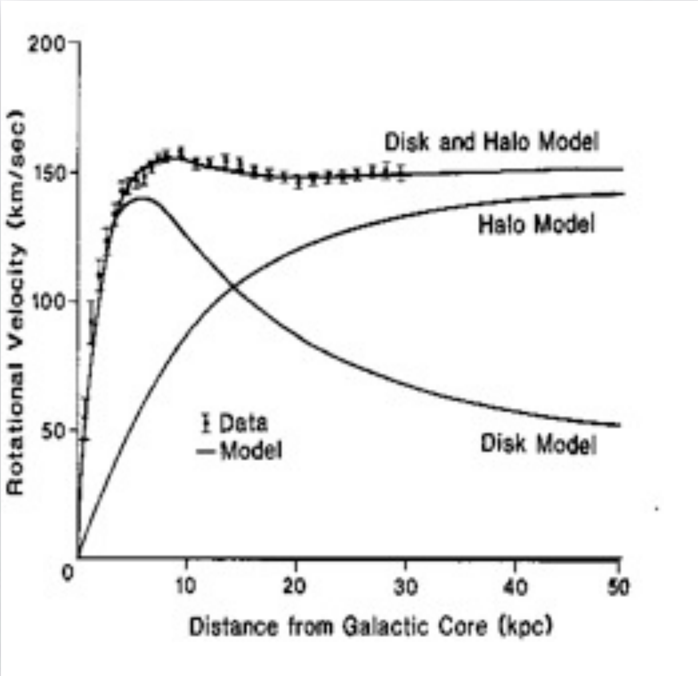
$$v_{rot}^2 \propto \frac{1}{R}$$

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!)

Historically, only after these studies (in the ~'70-'80) people started to take the dark matter problem seriously



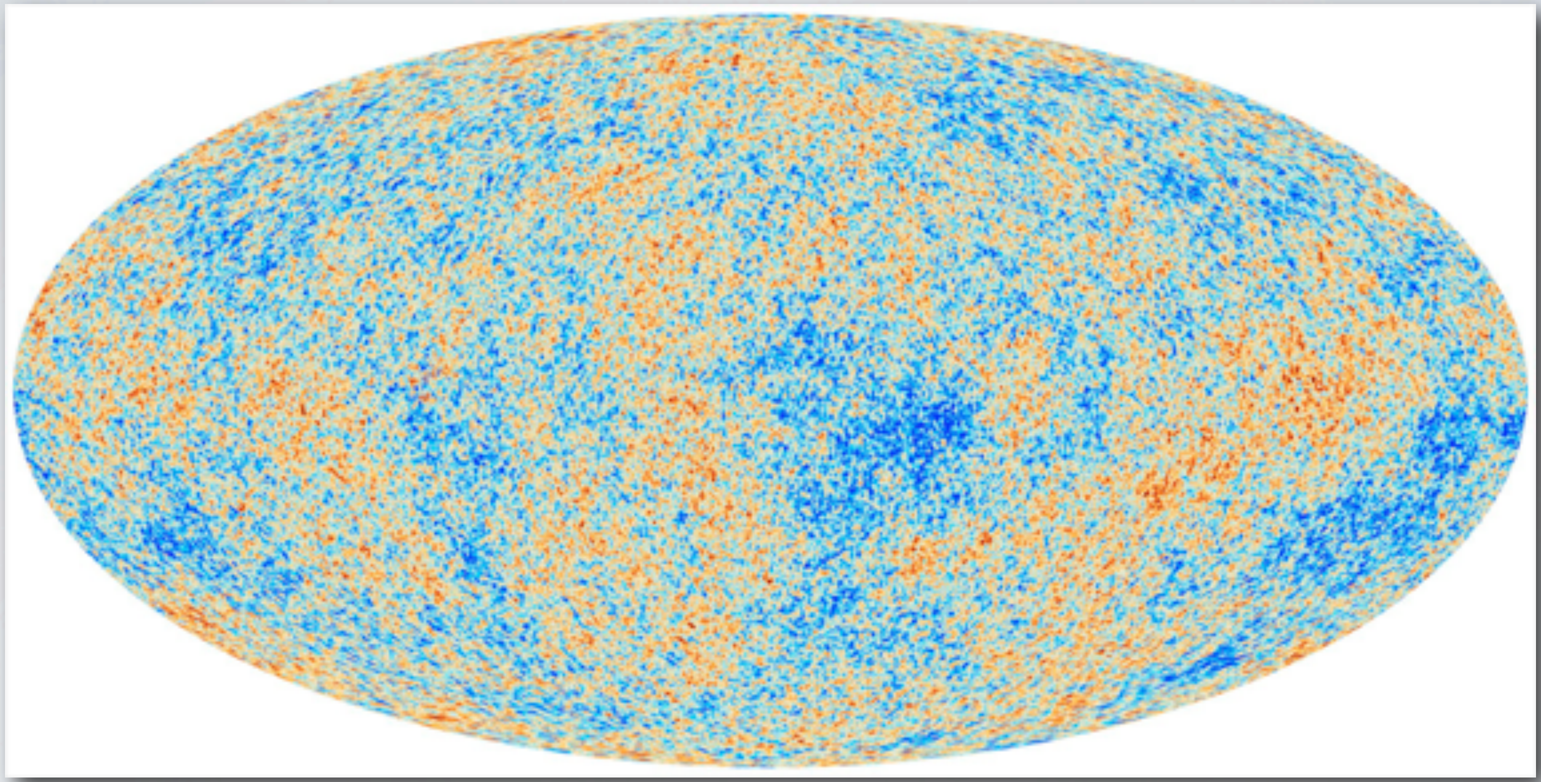
The determination of "local" (Galactic) DM properties require a multi-parameter fit including parameterizations for stellar disk, gas, bulge...

$$\rho_\odot \simeq 0.4\,\mathrm{GeV/cm^3}$$

Important for direct and indirect searches of DM, not so important/robust to infer its existence and properties

GROWTH OF STRUCTURES

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



Key argument

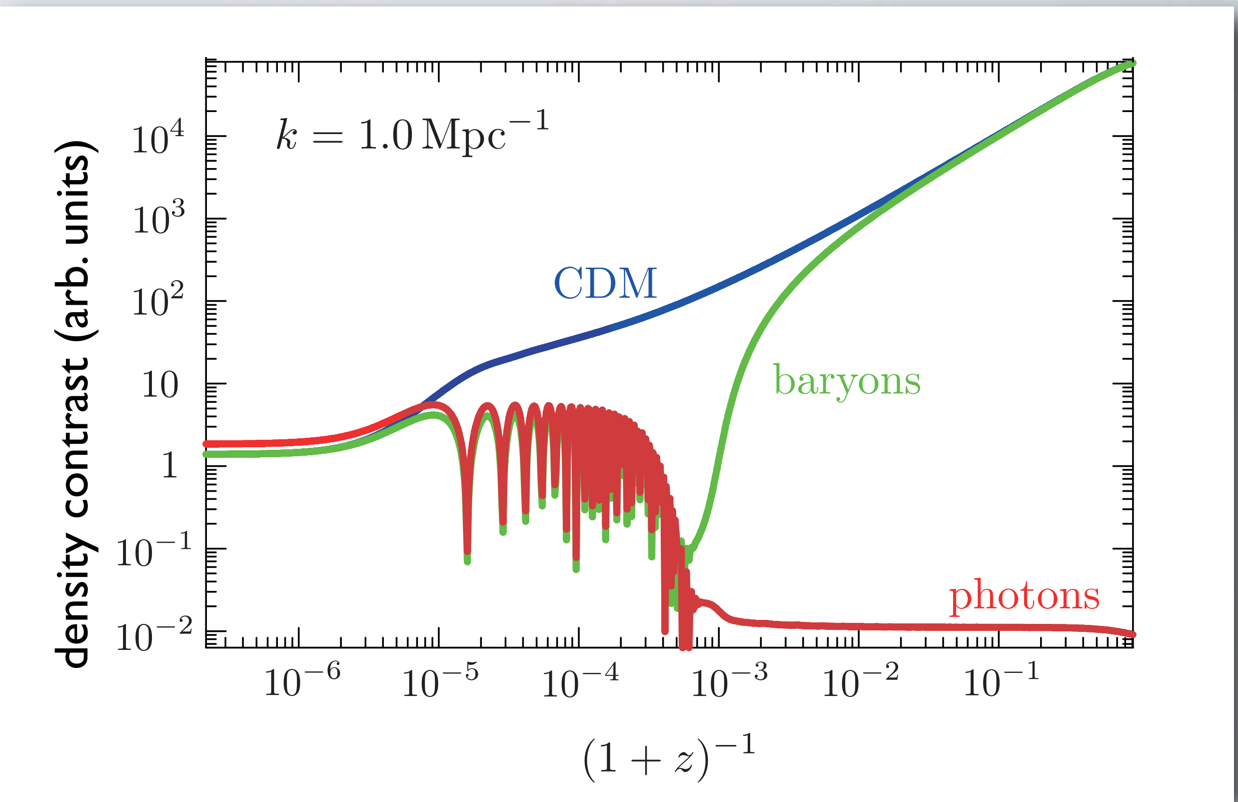
- Before recombination: baryons & photons coupled, "share perturbations"
- We measure amplitude ~10^{-5} at recombination (*picture above*)
- Evolving forward in time, insufficient to achieve collapsed structures as we see nowadays, unless lots of gravitating matter (not coupled to photons) creates deeper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

IN GRAPHICAL TERMS

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

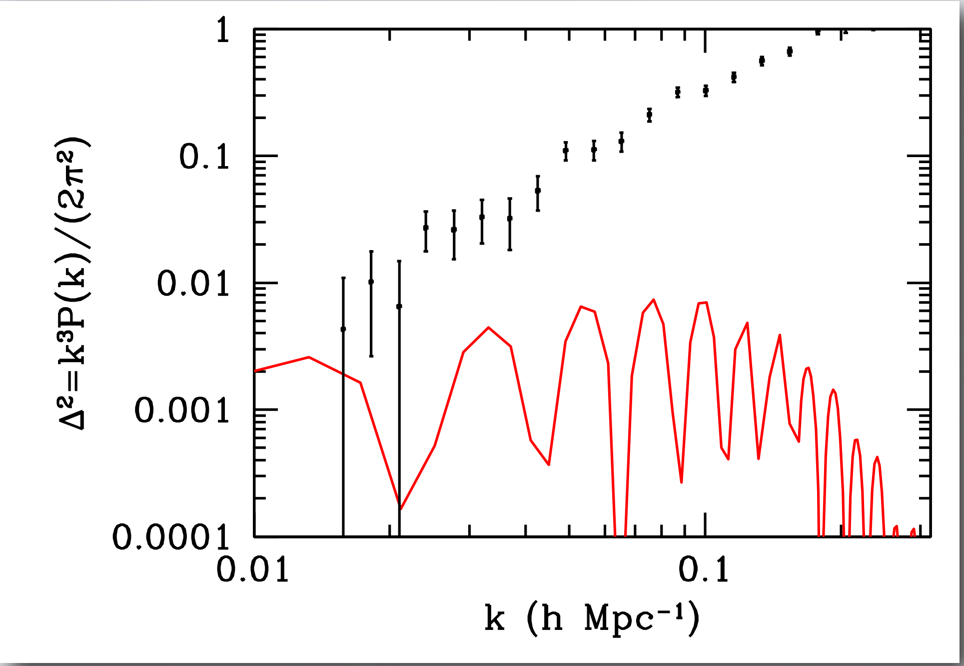
$$= \sum_{\mathbf{k}} \tilde{\delta}_{(\mathbf{k})} e^{i\mathbf{k}\cdot\mathbf{x}}$$

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 (before entering the Hubble horizon, gauge dependent).
- Upon horizon entry, as long as 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?



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

Even putative models of modified gravity that could "boost" growth (e.g. TeVeS...) have hard time to get the right shape!

See pedagogical discussion in Scott Dodelson, arXiv:1112.1320

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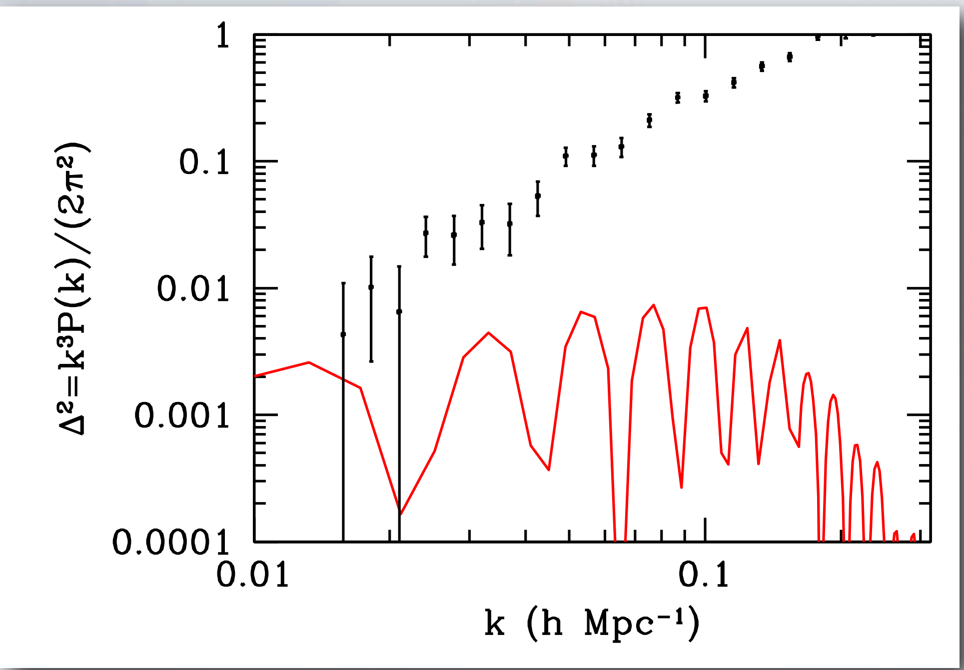

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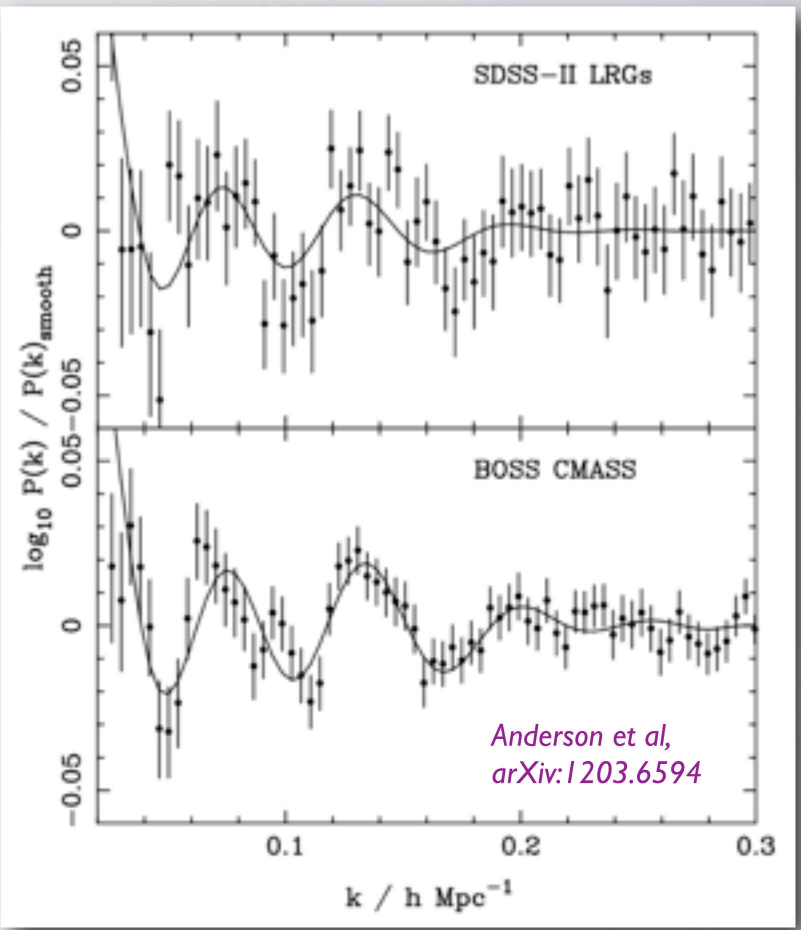

Credibility of our understanding reinforced since we see the residual "oscillations" due to coupling of subleading baryons with photons (BAO)!

EXERCISE (OR MINI-PROJECT)

Previous considerations can be easily made more quantitative (although quite advanced notions needed to justify rigorously some statements...)

1. Write down (Newtonian physics!) continuity, Euler equation & Poisson Equation

$$\frac{\partial \rho}{\partial t} + \partial_\alpha(\rho v^\alpha) = 0$$

continuity (mass conservation)

α=1,2,3

$$\frac{\partial v_\alpha}{\partial t} + v^\beta \partial_\beta v_\alpha + \frac{1}{\rho}\partial_\alpha p + \partial_\alpha \Phi = 0$$

Euler/Newton's law (momentum conservation)

$$\partial^2 \Phi - 4\pi G \rho = 0$$

Poisson Eq. (source Grav. potential)

Follow any cosmology perturbation theory course, or refs. such as C. G.Tsagas, astro-ph/0201405
D. Baumann's Cosmology Lectures, http://www.damtp.cam.ac.uk/user/db275/Cosmology/Lectures.pdf

EXERCISE

2. Consider expanding background case, previous equation write

$$\frac{\partial \rho}{\partial t} + 3H\rho + \frac{1}{a}\partial_\alpha(\rho u^\alpha) = 0$$

$$\frac{\mathrm{d}^2 a}{\mathrm{d}t^2} x_\alpha + \frac{\partial u_\alpha}{\partial t} + H u_\alpha + \frac{1}{a} u^\beta \partial_\beta u_\alpha + \frac{1}{a\rho}\partial_\alpha p + \frac{1}{a}\partial_\alpha \Phi = 0$$

$$\partial^2 \Phi - 4\pi G a^2 \rho = 0$$

where I defined a comoving set of coordinates (x^α) as opposed to "physical" ones (r^α)

$$r^\alpha = a(t) x^\alpha$$

physical velocity dr^α/dt: $$v^\alpha = H\, r^\alpha + u^\alpha$$ "Hubble flow" ($H\,r^\alpha$); "peculiar" velocity dx^α/dt (u^α)

derivative wrt r related to derivative wrt x

$$(\partial_\alpha)_{\mathrm{phys}} = (1/a)(\partial_\alpha)_{\mathrm{com}}$$

t-derivative at fixed r and fixed x related by

$$(\partial/\partial t)_{\mathrm{phys}} = (\partial/\partial t)_{\mathrm{com}} - H x^\alpha \partial_\alpha$$

Proof: $(\partial/\partial t)_r = (\partial/\partial t)_x + (\partial x/\partial t)_r (\partial/\partial x) = (\partial/\partial t)_x + (\partial a^{-1} r/\partial t)_r (\partial/\partial x)$

EXERCISE

3. solve the cases of a "smooth" background

4. Linearize these equations for small perturbation around the smooth solutions.

5. Write them down also in Fourier space.

6. Extension to multi-fluid case is also possible.

7. Which perturbation grow? *(Concept of Jeans length)*

8. How do perturbation grow in the radiation-dominated era?

9. How do they grow in the matter-dominated era?

10. How do they grow in the cosmological constant-dominated era?

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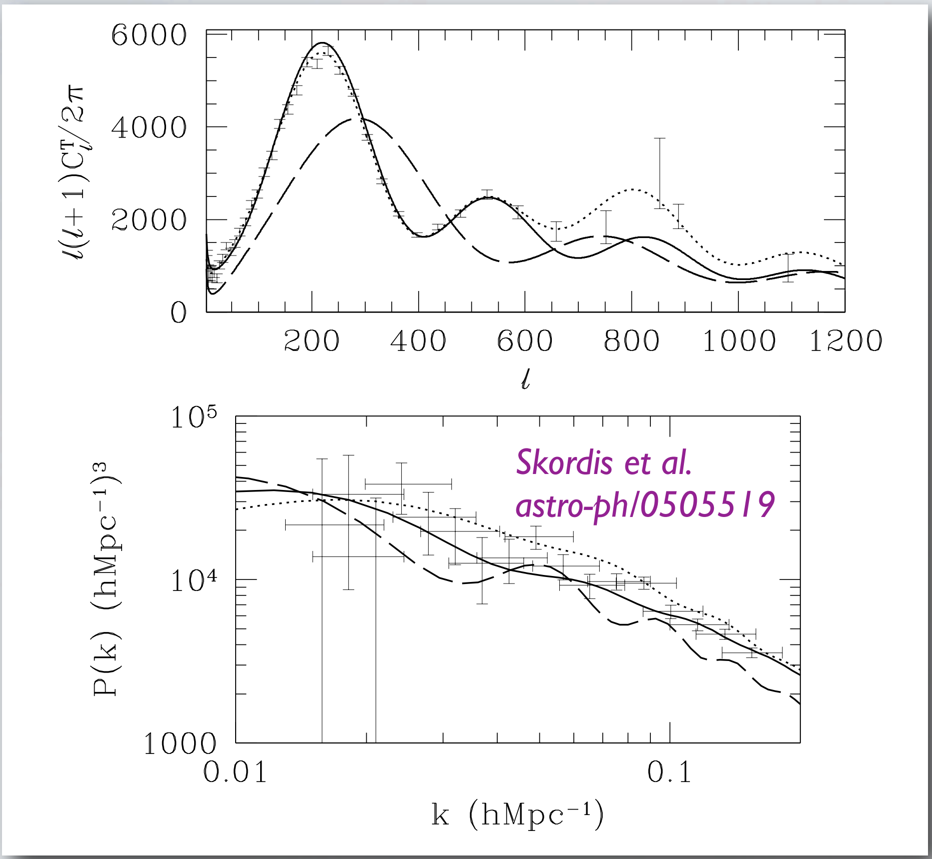
SIMILAR ISSUES WITH CMB...

A few years ago, modified gravity models could still accommodate data (with large Ω_ν)



MOND universe (with $a_0 \simeq 4.2\times10^{-8}$cm/s^2) with Ω_Λ = 0.78 and Ω_ν = 0.17 and Ω_b = 0.05 (solid line), for a MOND universe Ω_Λ = 0.95 and Ω_b = 0.05 (dashed line) and for the ΛCDM model (dotted line)

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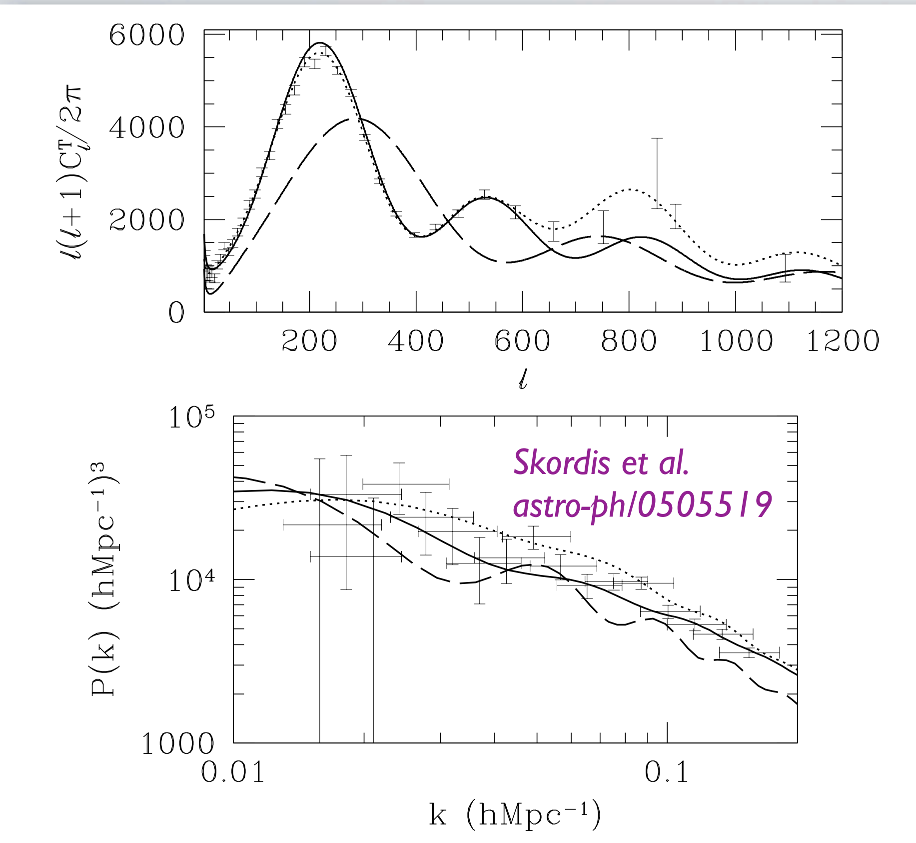
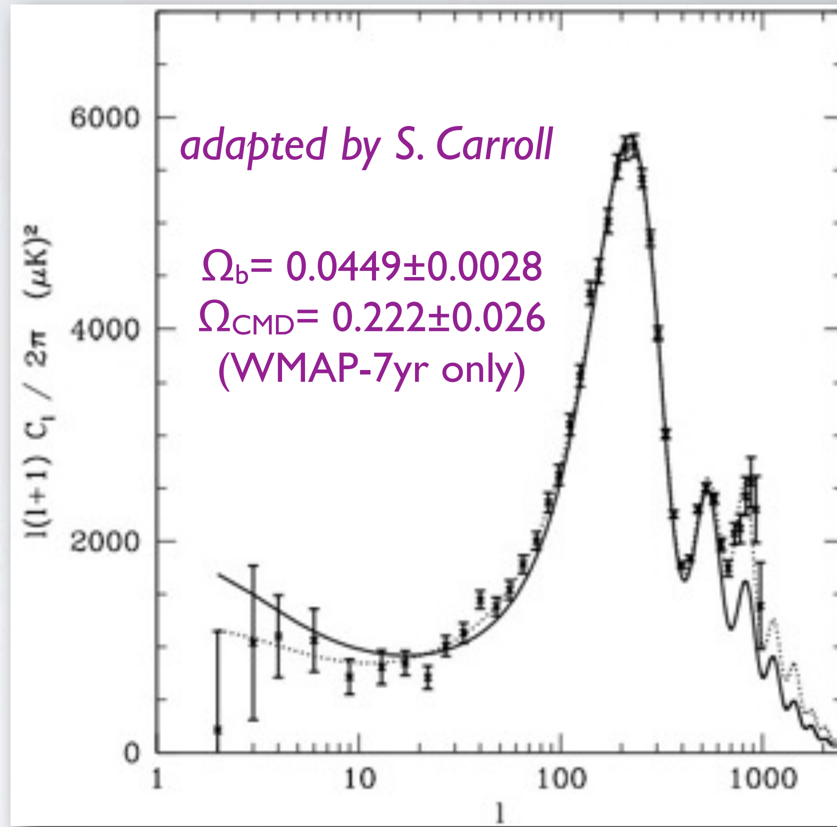
recent data inconsistent with these "old" proposals: e.g. CMB 3rd peak, baryon acoustic oscillations...





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Ω_b^{CMB} (from atomic physics) is also in agreement with Ω_b^{BBN}, sensitive to total number of nucleons in the plasma at T~0.01-1 MeV (nuclear physics)

Great success of cosmology!

WHY COSMO EVIDENCE IS IMPORTANT

***I.** It is essentially based on exact solutions or linear perturbation theory applied to simple physical systems (gravity, atomic physics…): credible and robust!*

***II.** It suggests additional species, rather than a modification of gravity.*

***III.** Because it tells us that the largest fraction of required dark matter is non-baryonic, rather than brown dwarf stars, planets, etc.*

Only (even more radical) way out: modify cosmology to allow "collapsed" objects at very early times (e.g. primordial Black Holes, But very constrained/on the verge of exclusion, see e.g. F. Capela, M. Pshirkov, P. Tinyakov, PRD 90, 083507 (2014) [arXiv:1403.7098]. and refs. therein)

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But neutrinos (at least known ones) do not work!

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But neutrinos (at least known ones) do not work!

This implies that Dark Matter requires "new physics", beyond the theories known today. Only a handful of similar indications: explains the interest of particle physicists!

NEUTRINOS AS DARK MATTER?

Condition 1. Must be massive (which is already a departure from SM...)

Fulfilled! Oscillations established, at least 2 massive states, measured splitting implies at least one state heavier than 0.05 eV

$$\Delta m^2_{\rm atm} \simeq 2.4 \times 10^{-3}\,{\rm eV}^2$$

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Condition 2. Must match cosmological abundance

Failed! Direct mass limits combined with splittings from oscillation experiments impose upper limit of about 7 eV to the sum (After KATRIN, potentially improved to ~0.7 eV)

$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} \simeq \frac{\sum_i m_i}{45\,{\rm eV}}$$

$\Omega_{DM} \approx 0.3$(Planck)$\Rightarrow \Sigma m_i \approx 15$ eV

we will perform this computation in lecture 2.

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Condition 3. Must allow for structure formation (of the right kind)

Failed! We will see shortly why it is so... which applies to more general classes of candidates.

AN IMPORTANT NUMBER...

Recent determination (Planck 2015, 68% CL)

$\Omega_c h^2$=0.1188±0.0010, i.e. Ω_c~0.26

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$$\rho_{X,0} = M_X\, n_{X,0} = M_X\, s_0\, Y_0$$

$$\rho_c = \frac{3H_0^2}{8\pi G_N} = 1.054 \times 10^{-5} h^2 \mathrm{GeV\,cm}^{-3}$$

$$s_0 = 2889 \left(\frac{T_{\gamma,0}}{2.725}\right)^3 \mathrm{cm}^{-3}$$

where $\mathbf{h_{eff}}$ ~ 2+3×2(4/11)×7/8~**3.91** comes from accounting for γ's & ν's

$$\Omega_X h^2 = 2.74 \times 10^8 \left(\frac{M_X}{\mathrm{GeV}}\right) Y_0$$

[Main] Goal: *compute value of number to entropy density ratio, Y_0*

IN ADDITION MUST BE SURE THAT DM...

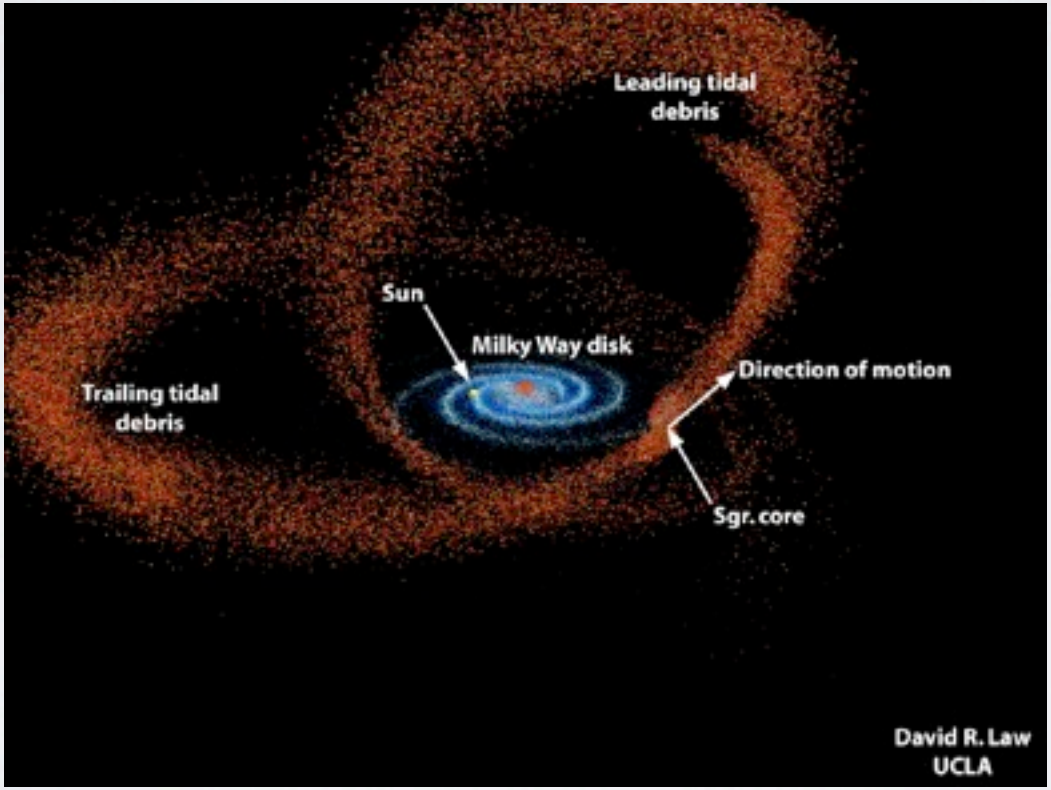
...also fulfills some basic requirements from astro/cosmo

- ***Dark matter... is dark, and dissipationless***
- ***Dark matter is collisionless (or not very collisional)***
- ***Dark matter is smoothly distributed (at astrophysical scales)***
- ***Dark matter behaves as a classical fluid at astrophysical scales***
- ***Dark matter is not "hot" (non-relativistic velocity distribution)***

Let's detail them one by one: they have more or less stringent particle physics implications

1) DM IS... DARK AND DISSIPATIONLESS

- DM must not couple "much" to photons (perturbation shape & amplitude argument, invisibility in e.m. channels...)
- *<u>DM forms extended, triaxial halos</u>*, while baryons "sink" in inner halo parts, form disks, etc. since they can dissipate energy by e.m. emission. At Galactic scale, evidence from tidal streams of satellite galaxies



e.g. D. R. Law, S. R. Majewski, K.V. Johnston, "Evidence for a Triaxial Milky Way Dark Matter Halo from the Sagittarius Stellar Tidal Stream" Astrophys. J. 703, L67 (2009)

2) DM IS... COLLISIONLESS (WRT BARYONIC GAS)

- if DM-DM interaction too strong, spherical structures would be obtained rather than triaxial. From actual clusters, one can derive $\sigma/m<0.02$ cm^2/g

  *Jordi Miralda-Escudé ApJ **564** 60 (2002)*

but different levels of robustness...

- From Bullet cluster, $\sigma/m<0.7$-1.3 cm^2/g,

  S. W. Randall et al. ApJ 679, 1173 (2008)

- similar bounds from different arguments, for a compilation see e.g.

System	v_0[km/s]	σ/m_χ [cm^2/g]	References
Bullet Cluster	1000	1.25	[41, 43]
Galactic Evaporation	1000	0.3	[45]
Elliptic Cluster	1000	0.02	[46]
Dwarf Evaporation	100	$0.1^\star$	[45]
Black Hole	100	$0.02^\star$	[59]
Mean Free Path	44 – 2400	0.01 – 0.6	[57]
Dwarf Galaxies	10	0.1	[56]

From M. R. Buckley and P. J. Fox, Phys. Rev. D 81, 083522 (2010) (=v-dependent)*

- Very loose from particle physics standard (barn level!), but much less than atomic or molecular cross sections characteristic of gas.

$$\frac{\text{cm}^2}{\text{g}} = 1.78\,\frac{\text{barn}}{\text{GeV}}$$

NEW BOUNDS COMING OUT "EVERY DAY"...

Science 27 March 2015:
Vol. 347 no. 6229 pp. 1462-1465
DOI: 10.1126/science.1261381

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REPORT

The nongravitational interactions of dark matter in colliding galaxy clusters

David Harvey[1,2,*], Richard Massey[3], Thomas Kitching[4], Andy Taylor[2], Eric Tittley[2]

± Author Affiliations

*Corresponding author. E-mail: david.harvey@epfl.ch

arXiv:1503.07675

ABSTRACT | EDITOR'S SUMMARY

Collisions between galaxy clusters provide a test of the nongravitational forces acting on dark matter. Dark matter's lack of deceleration in the "bullet cluster" collision constrained its self-interaction cross section $\sigma_{DM}/m < 1.25$ square centimeters per gram (cm^2/g) [68% confidence limit (CL)] (σ_{DM}, self-interaction cross section; m, unit mass of dark matter) for long-ranged forces. Using the Chandra and Hubble Space Telescopes, we have now observed 72 collisions, including both major and minor mergers. Combining these measurements statistically, we detect the existence of dark mass at 7.6σ significance. The position of the dark mass has remained closely aligned within 5.8 ± 8.2 kiloparsecs of associated stars, implying a self-interaction cross section $\sigma_{DM}/m <$ 0.47 cm^2/g (95% CL) and disfavoring some proposed extensions to the standard model.

3) DM IS... SMOOTHLY DISTRIBUTED

DM has a "continuum" (fluid limit), rather than having "granular" structure.

✤ Granular distribution would provide time-dependent gravitational potentials, distrupting bound systems of different sizes (function of "grain mass")

- thickness of disks: $M_X < 10^6\ M_{sun}$
  satellites, globular clusters: $M_X < 10^3\ M_{sun}$

H-W.Rix and G. Lake, astro-ph/9308022 & refs. therein

- Halo-wide binaries: $M_X < 43\ M_{sun}$

J. Yoo, J. Chaname and A. Gould, Astrophys. J. 601, 311 (2004)

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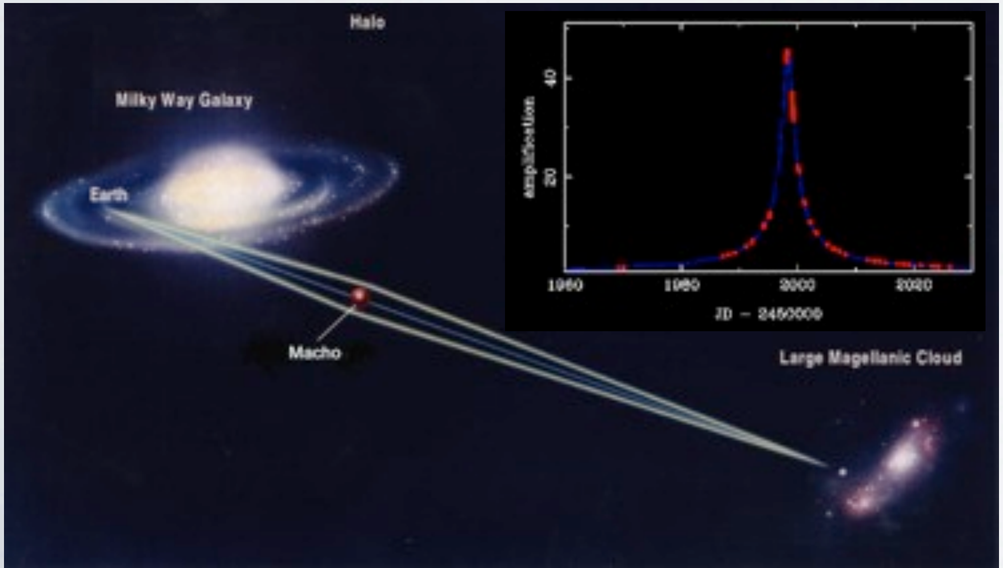
✤Several searches (EROS, OGLE...) for µlensing events towards Magellanic Cloud exclude dominant MACHOs component as halo DM for 10^{-7} to $10\ M_{sun}$

e.g. L.Wyrzykowski et al., arXiv:1106.2925 & refs. therein



idea: constrain the frequency of a peculiar magnification pattern

$$A(u) = \frac{u^2+2}{u\sqrt{u^2+4}}$$

$u = \theta/\theta_E$

ang. distance source-lens

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{d_S - d_L}{d_S d_L}}$$

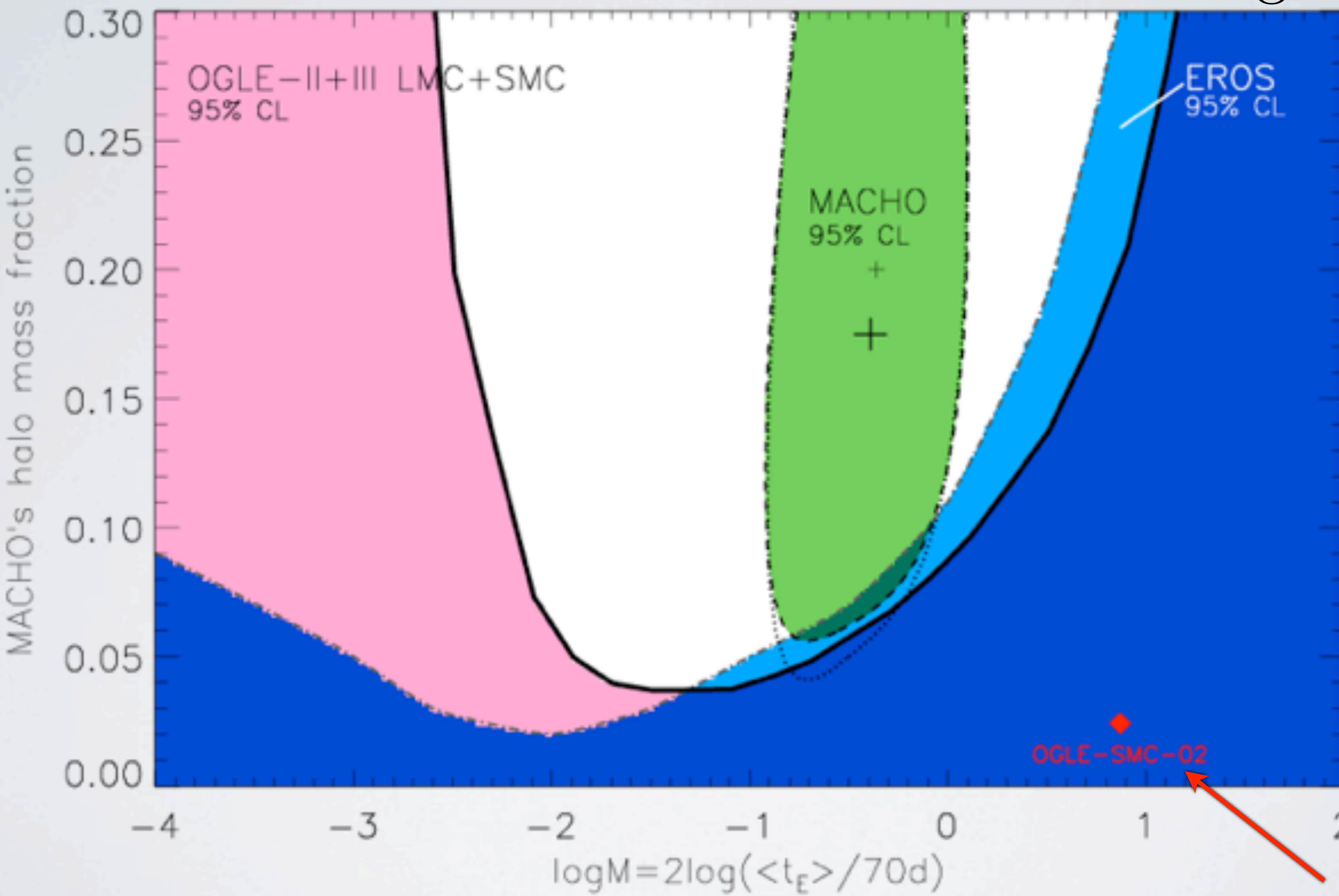
depends on lens mass and Geometry

$$u(t) = \sqrt{u_{min}^2 + \left(\frac{t-t_0}{t_E}\right)^2}$$

t_E =time to cross einstein angular size

MICROLENSING CONSTRAINTS

← goes to $\simeq 10^{26}\mathrm{g}$ $2 \times 10^{34}\mathrm{g}$



some events expected due to stellar BH

4) DM IS... CLASSICAL (AT GAL. SCALES, AT LEAST)

dark matter is confined/detected at least at astrophysical scales, hence must be "localized" and behave classically there.

$$\lambda_{De\,Broglie} = \frac{h}{m\,v} \lesssim \mathrm{kpc} \Longrightarrow m \gtrsim 10^{-22}\,\mathrm{eV}\;(v \simeq 100\,\mathrm{km/s})$$

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For *fermions* a much stronger bound holds, due to the fact that their quantum nature emerges more easily, so to speak, thanks to Pauli principle/Fermi-Dirac statistics

$$f \leq \frac{g}{h^3}$$

Conservation of phase space density of a non-interacting fluid (Liouville Eq.) + condition that any observable, coarse grained p.s. density must be lower than the real one, in turn lower than the above maximum, one derives

$$m > \mathcal{O}(10 - 100)\,\mathrm{eV}$$

S. Tremaine and J. E. Gunn, Phys. Rev. Lett. 42, 407 (1979)

updated lower limit around ~400 eV

A. Boyarsky, O. Ruchayskiy and D. Iakubovskyi, JCAP 0903, 005 (2009)

5) DM IS NOT "HOT" (IT IS NOT RELATIVISTIC)

dark matter is not "hot": cannot have a relativistic velocity distribution (at least from matter-radiation equality for perturbation to grow)

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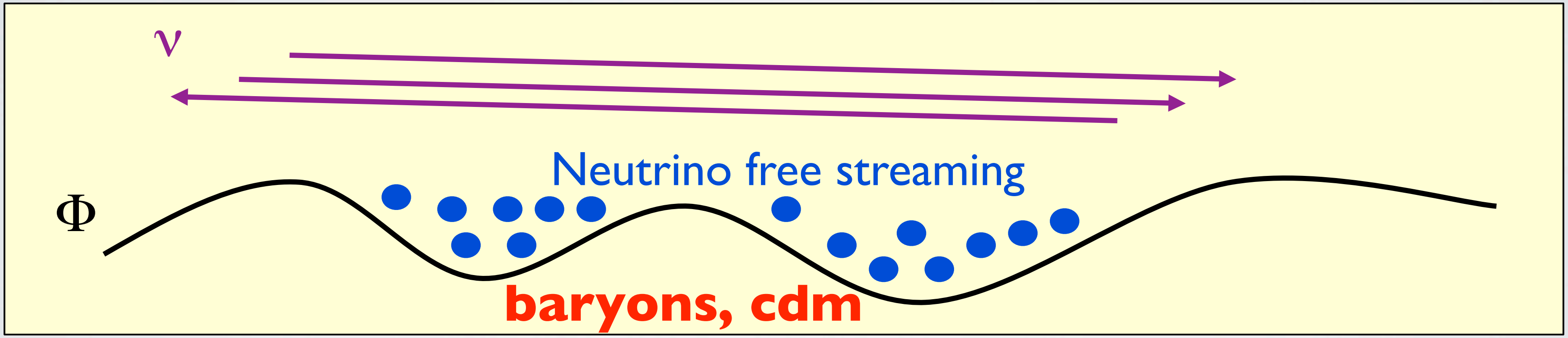
This is the more profound reason why neutrinos would not work as DM, even if they had the correct mass: they were born with relativistic velocity distribution which prevents structures below O(100 Mpc) to grow till late!

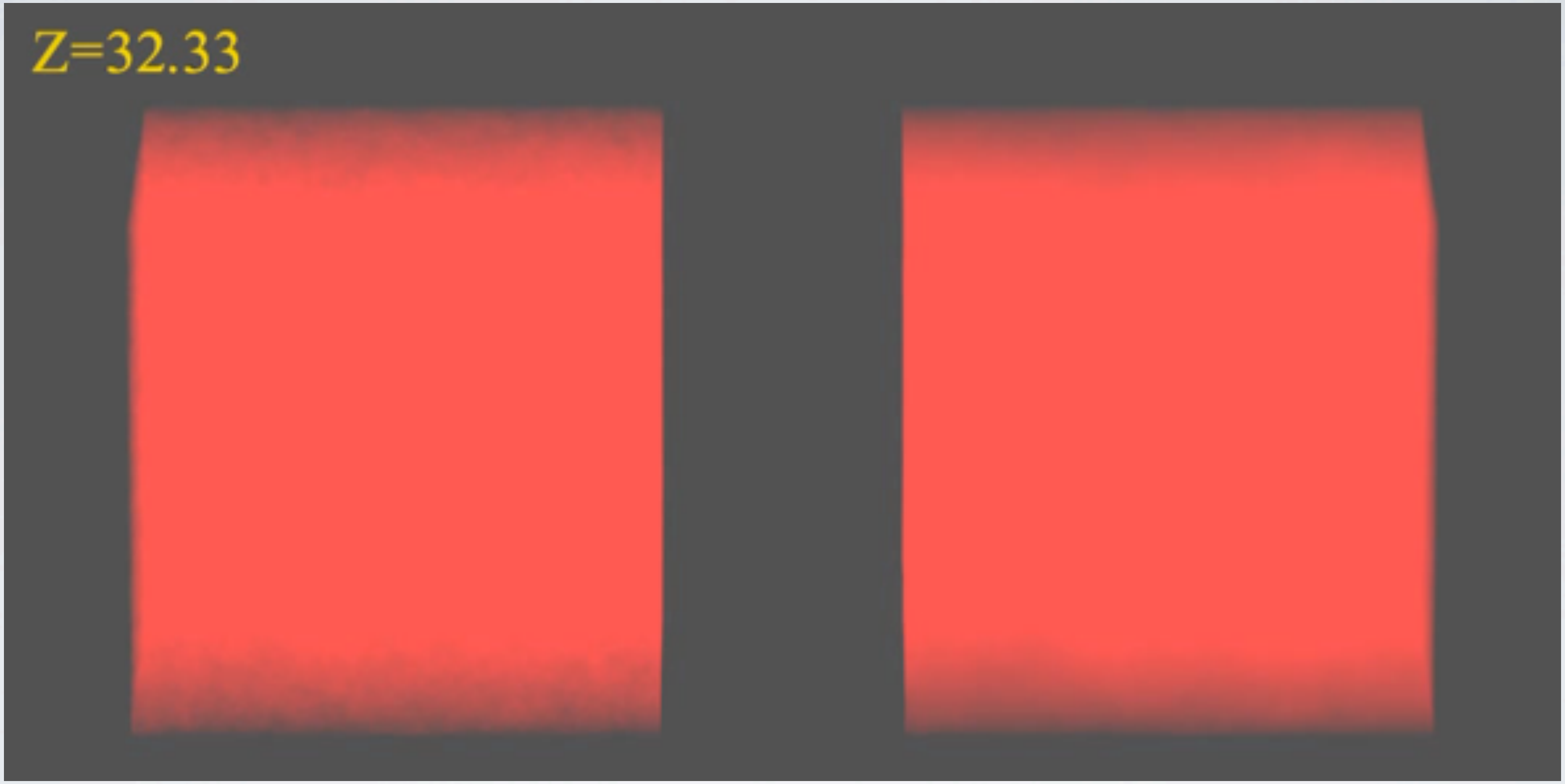


Cartoon Picture:

ν's "do not settle" in potential wells that they can overcome by their typical velocity: compared with CDM, they suppress power at small-scales

THE NUMERICAL PROOF

ΛCDM run vs. cosmology including neutrinos (total mass of 6.9 eV)



simulation by Troels Haugbølle, see

http://users-phys.au.dk/haugboel/projects.shtml

SUMMARY OF WHAT WE LEARNED

✤ Numerous observations tell us that we need some degree of freedom, gravitating as ordinary matter but with otherwise suppressed couplings.

✤ It turns out that this requires **new physics**, with some specific properties. Justifies the enormous amount of attention particle physicists devote to it!

✤ Unfortunately, "gravity is universal" ➙ *it does not tell us what kind of physics it is*.

✤ We need some "strategy" to identify what DM is. For that, first we need some extra input/constraint ➙ must necessarily come from theory (at very least to conceive what we should be looking for!)

✤ Notice that I have not mentioned (yet!) neutralinos, nor "WIMPs", these aspects belong to theoretical creativity... & prejudice. While defining some ***theoretical context*** (and will do it in ***Lec. 2***!) is necessary to engage in ***identification strategies*** (see ***Lec. 3***), please decouple the validation of specific particle physics theories (e.g. electroweak scale SUSY at the LHC) from the DM problem.