Dark Matter in Cosmology and Astrophysics

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Evidence for Dark Matter

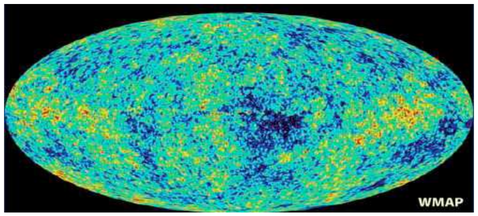
Cosmological Parameters

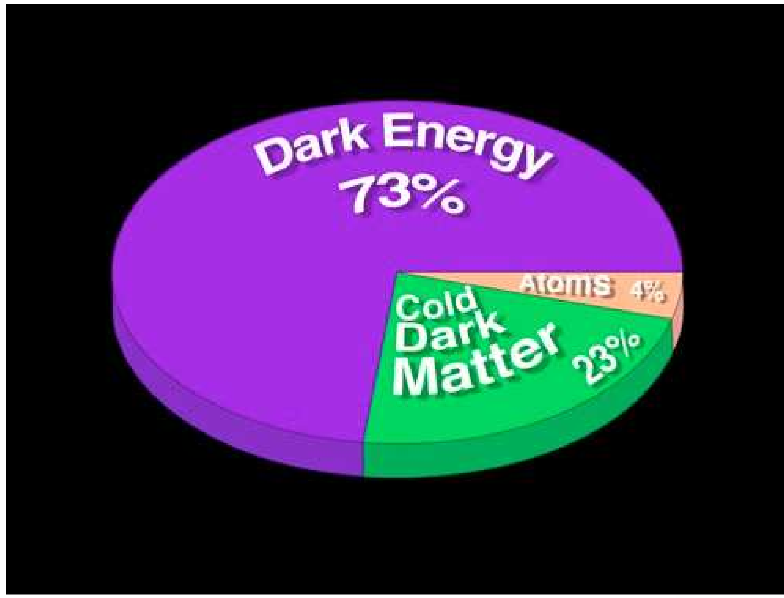
Candidates for Dark Matter

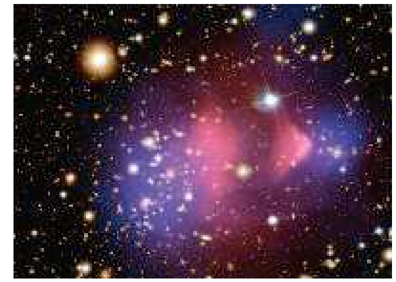
How can we detect them?

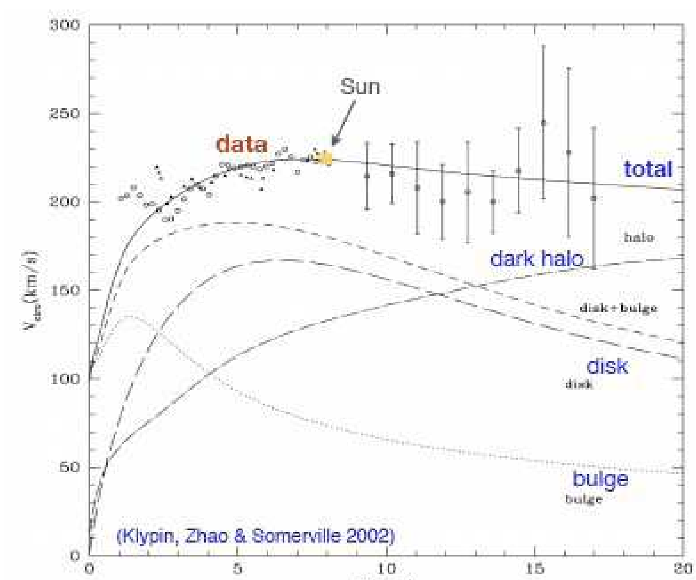
Annual Oscillation as Example

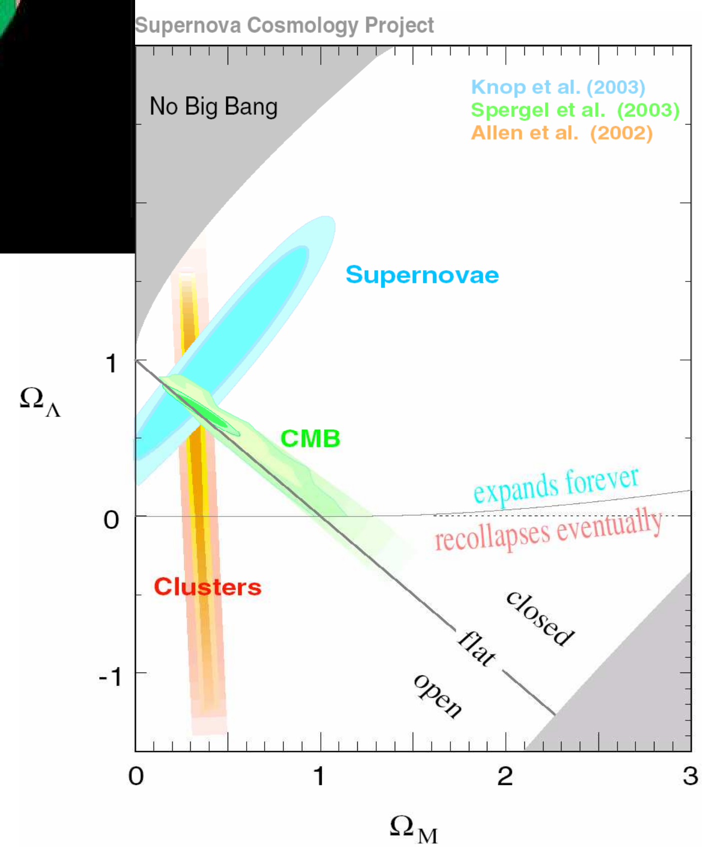
Evidence for Existence of Dark Matter

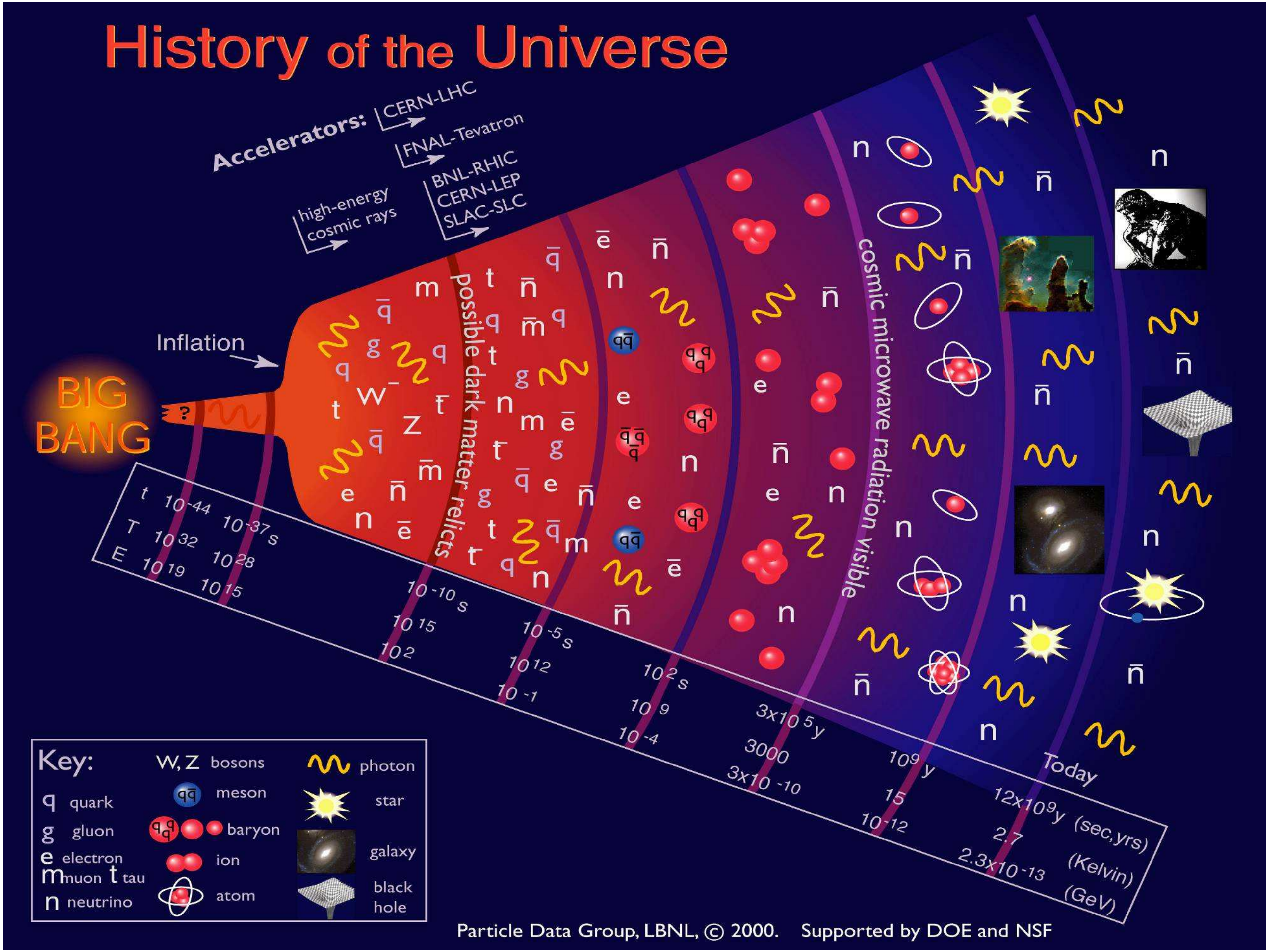












Supported by DOE and NSF

Rotation Curves

Lensing

Hot Gas Clusters

Why are we not content with what we see?

Flat rotation curves were seen – so, must be more.

How much more – that is, what is the density of the Universe.

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

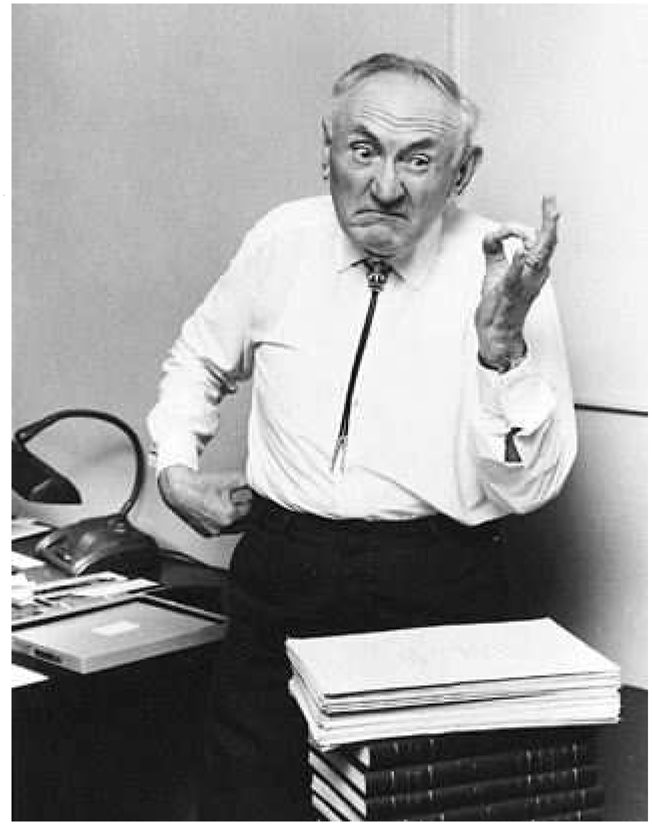
(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.

Original: Helvetica Physica Acta 6 (1933) 110-127.

Republished in English:

Gen Relativ Gravit 41 (2009) 207-224.

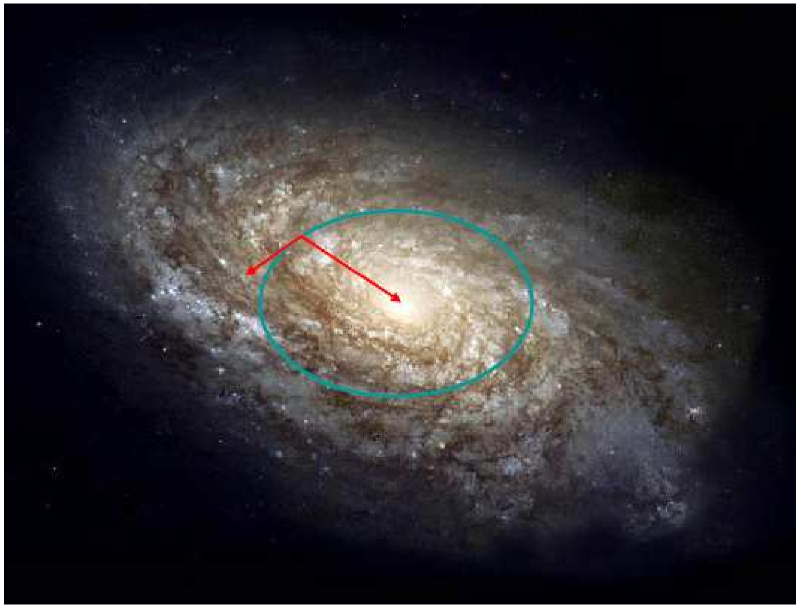


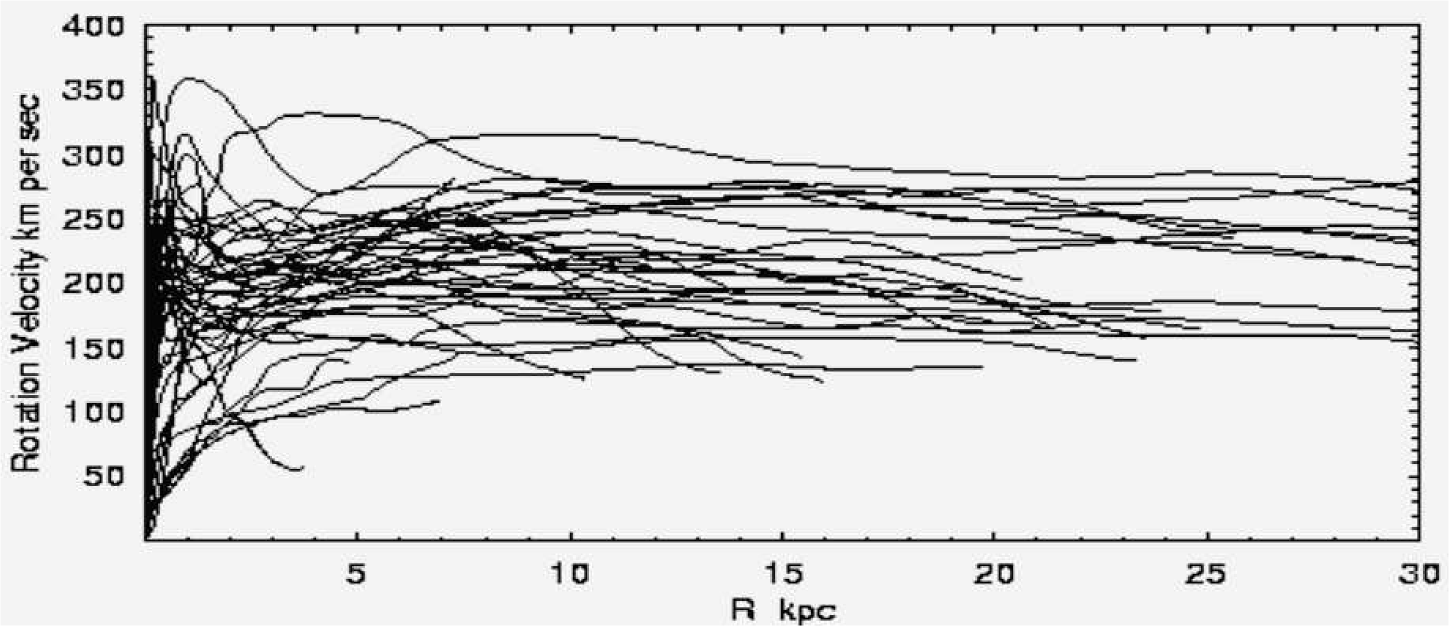
Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

DARK MATTER

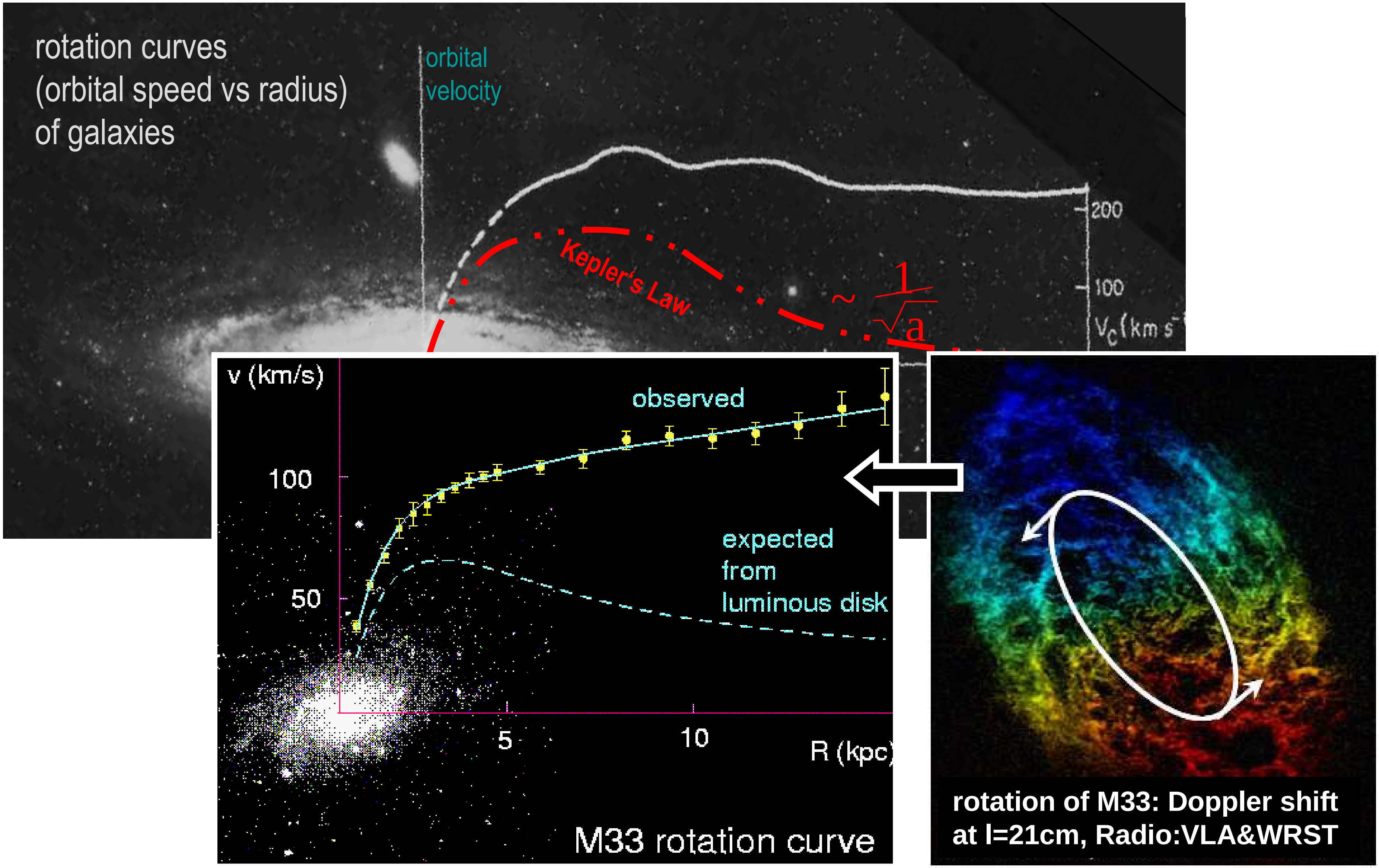
More on Rotation Curves (1970s)

Vera Rubin





Astronomical evidences for DM



Astronomical evidences for DM

Kepler´s law:
rotation velocity v_{rot} of a star of mass m around a central inner mass M_r :

$$F = \frac{G M_r m}{r^2} = m \cdot a$$

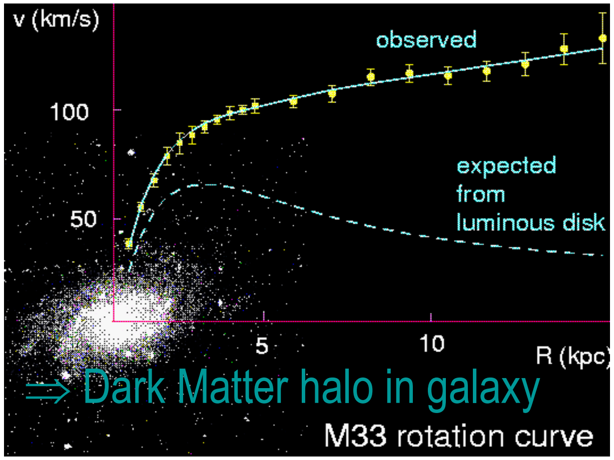
$$a = \frac{v_{rot}^2}{r} = \frac{G M_r}{r^2}$$

$$\Rightarrow v_{rot}(r) = \sqrt{\frac{G M_r}{r}}$$

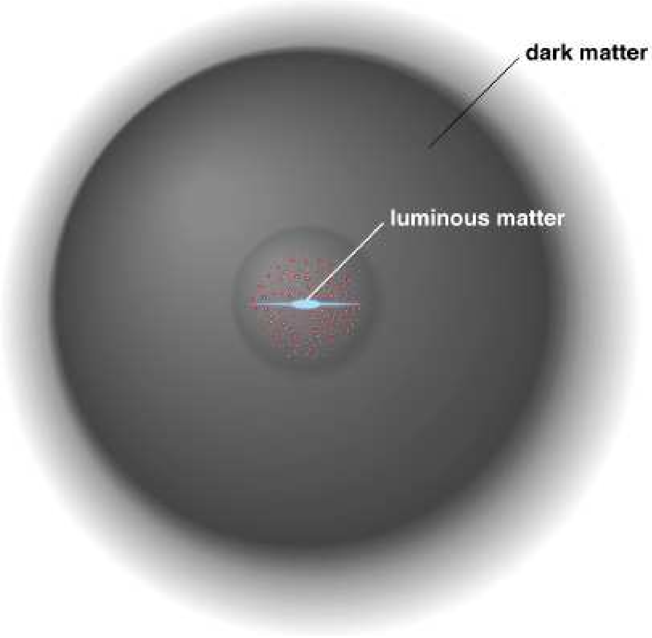
$$M_r = \int \rho(r) dV$$

(galactic bulge: $\rho(r)=\rho_0$=const. r<5kpc
outside: $\rho(r)\sim 0$ → M_r=const. → $v_{rot} \sim r^{-1/2}$)

v_{rot} ~ const. → $\rho(r) \sim r^{-2}$ outside bulge

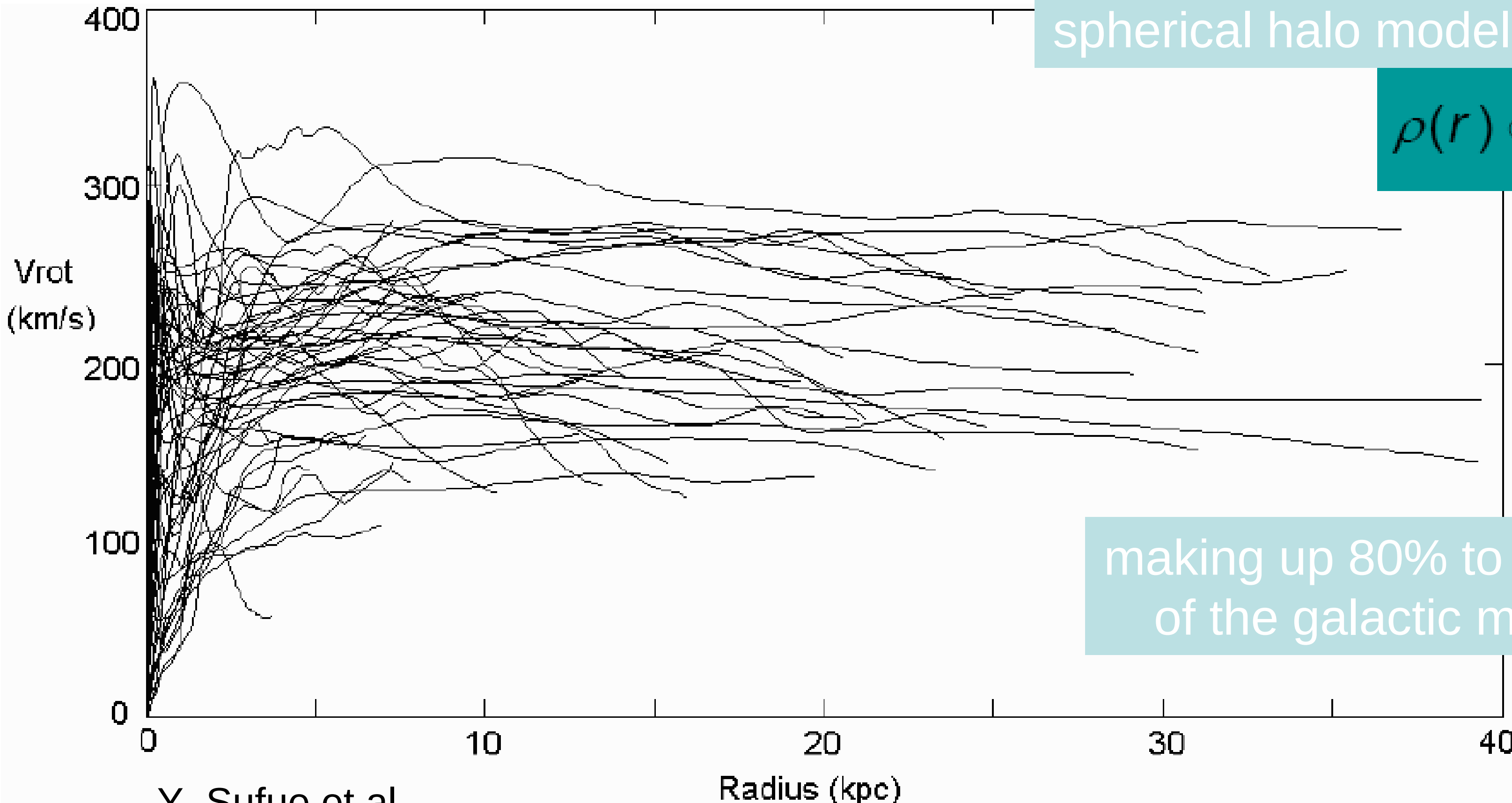


or better:
luminous matter in DM halo



Astronomical evidences for DM

multitude of galaxy rotation curves



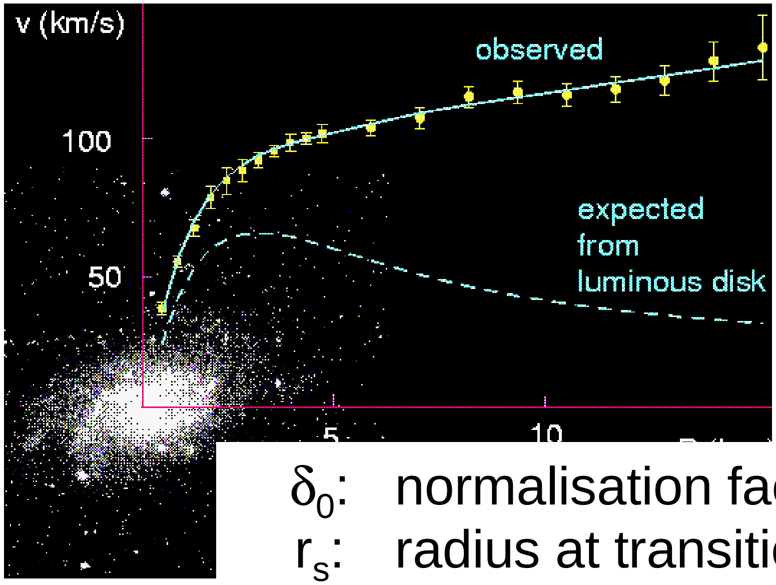
spherical halo model with

$$\rho(r) \propto \frac{1}{r^2}$$

making up 80% to 90% of the galactic matter

Y. Sufue et al.,
Central rotation curves of spiral galaxies, Astrophys. J. 523 (1999) 136–146

Galactic DM halo models



generic spherical description for all galaxies

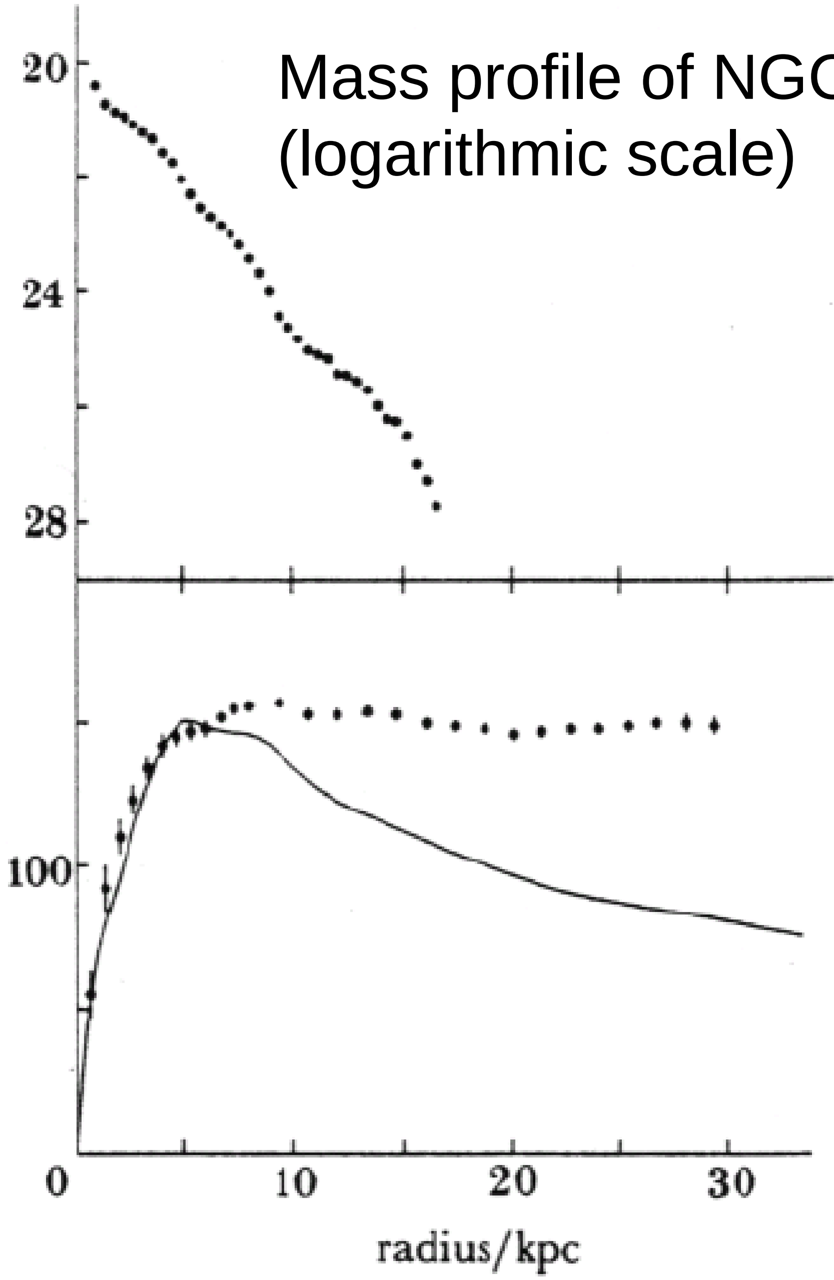
$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)^{\gamma}[1+(r/r_s)^{\alpha}]^{(\beta-\gamma)/\alpha}}$$

Navarro,Frenk&White, Astrophys.J. **490**, 493 (1997):
halo shape spherical, independent on halo mass

δ_0: normalisation factor
r_s: radius at transition of ´cusp´ to galactic plane ~20 kpc
γ: slope of the inner halo (central cusp) [~1.0]
(difficult to determine since ρ_{baryon} is dominant)
β: slope of the outer halo (often ~ r^{-3}) [~3.0]
α: transitory slope from inner to outer halo [~1.0]

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

Infer mass profile and how much DM



Mass profile of NGC3198 (logarithmic scale)

$$v(R) = \sqrt{\frac{GM(R)}{R}}$$

Rotation curves don't fall off as expected but remain flat.

Typical velocities can be much higher, inferring ~10 times more mass than seen directly.

DARK MATTER the only solution?

MOdified Newtonian Dynamics an Alternative?

$$F = \frac{GMm}{r^2} = m\mu\left(\frac{a}{a_0}\right)a$$

Assuming that at large distance *r*, *a* is smaller than a_0

$$\mu\left(\frac{a}{a_0}\right) \approx \frac{a}{a_0}$$

$$\frac{GM}{r^2} = \frac{a^2}{a_0} \text{ thus: } a = \frac{\sqrt{GMa_0}}{r} \text{ and } a = \frac{v^2}{r}$$

$$\text{Therefore: } v = \sqrt[4]{GMa_0}$$

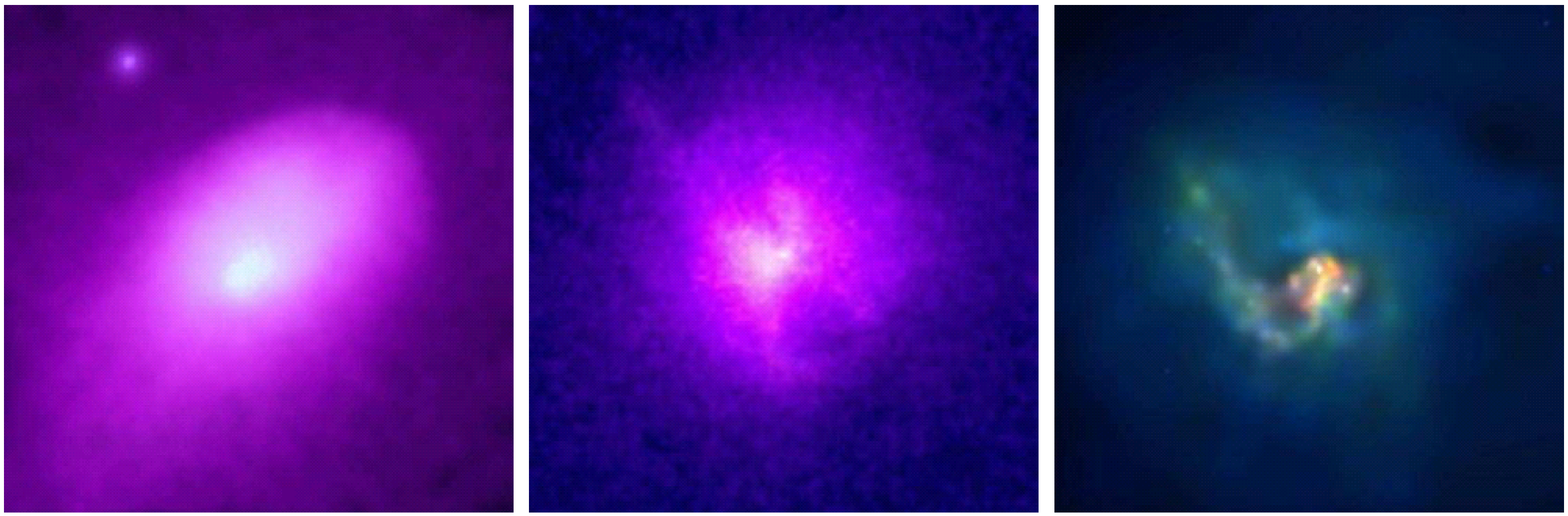
Independent of r at large radii.

Fits many rotation curves.

Plenty of literature available, but Dark Matter appears more attractive to many.

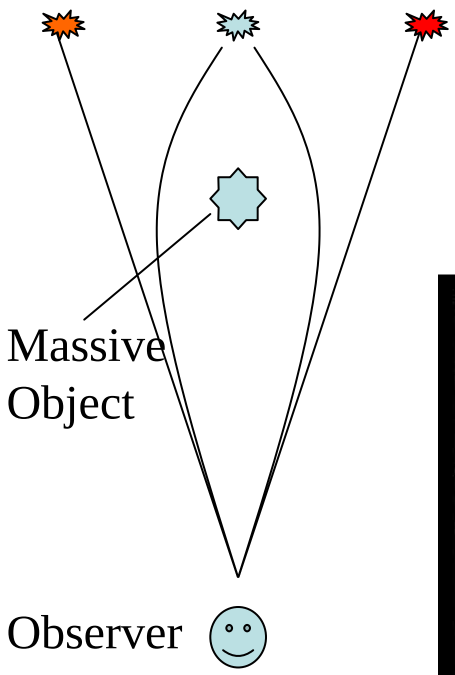
Local universe (low redshift): observe intracluster medium ($T \sim 10^7$ to 10^8 K) through its x-ray emission. Only 5 – 10% of baryons are in stars. Intracluster medium.

X-ray emission from clusters as seen with Chandra



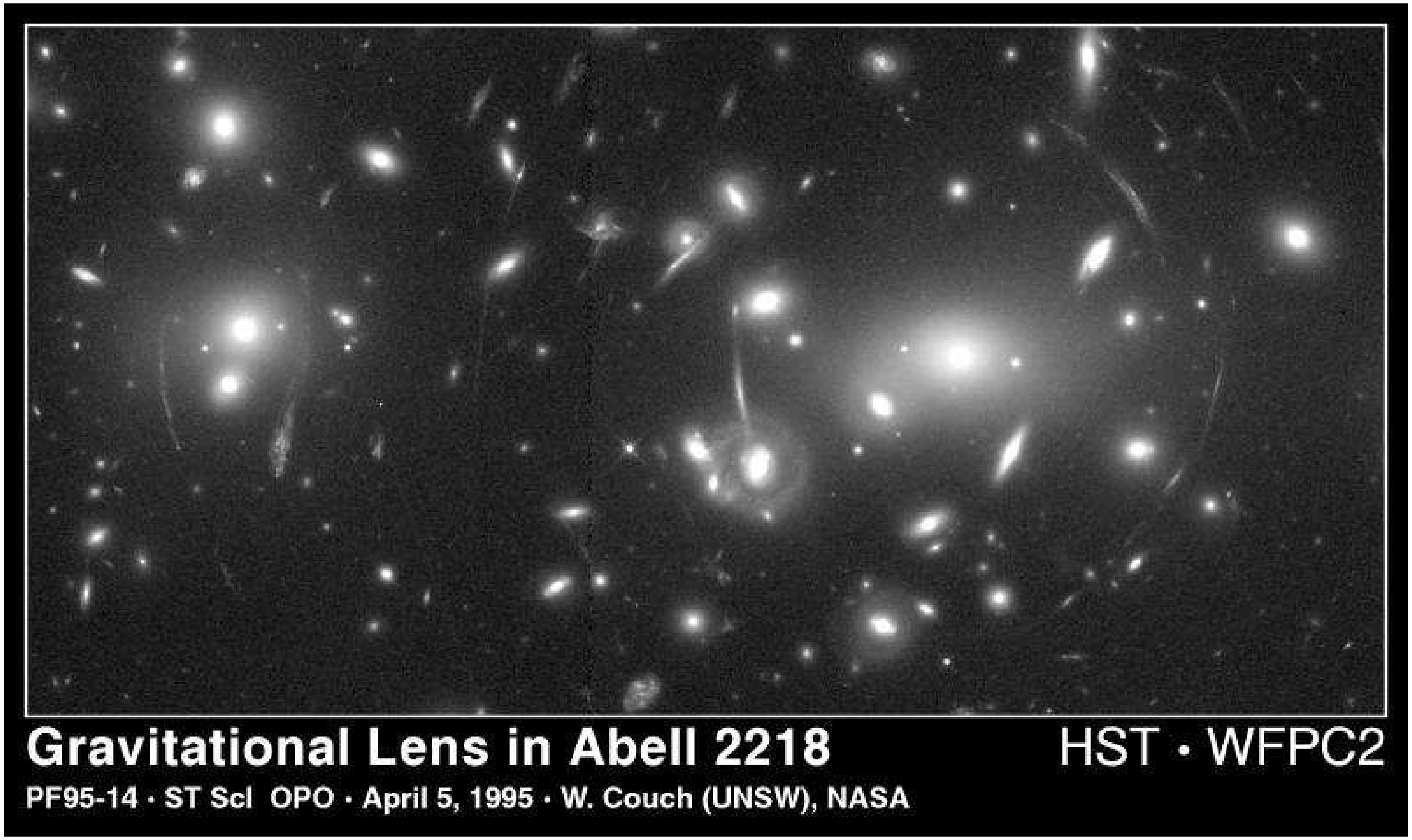
Also: simulations predict a large fraction of baryons in the intergalactic medium. Detect this at high redshift.

Evidence from Gravitational Lensing



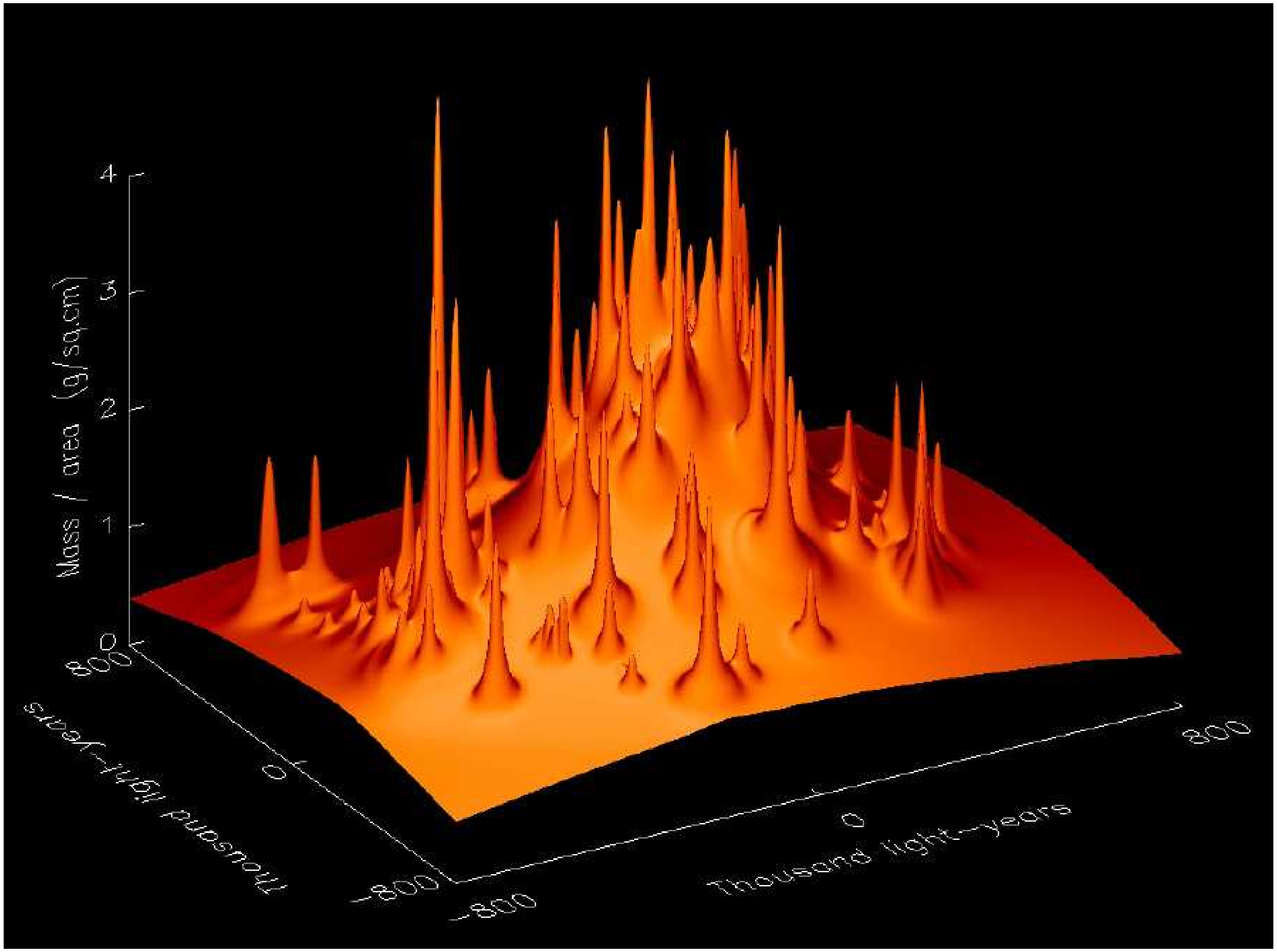
(Dark) Matter makes light bend:

Feature-rich image (7 multiple systems)



Credits: W.Couch (University of New South Wales), R. Ellis (Cambridge University), and NASA

Reconstructing the Mass Distribution

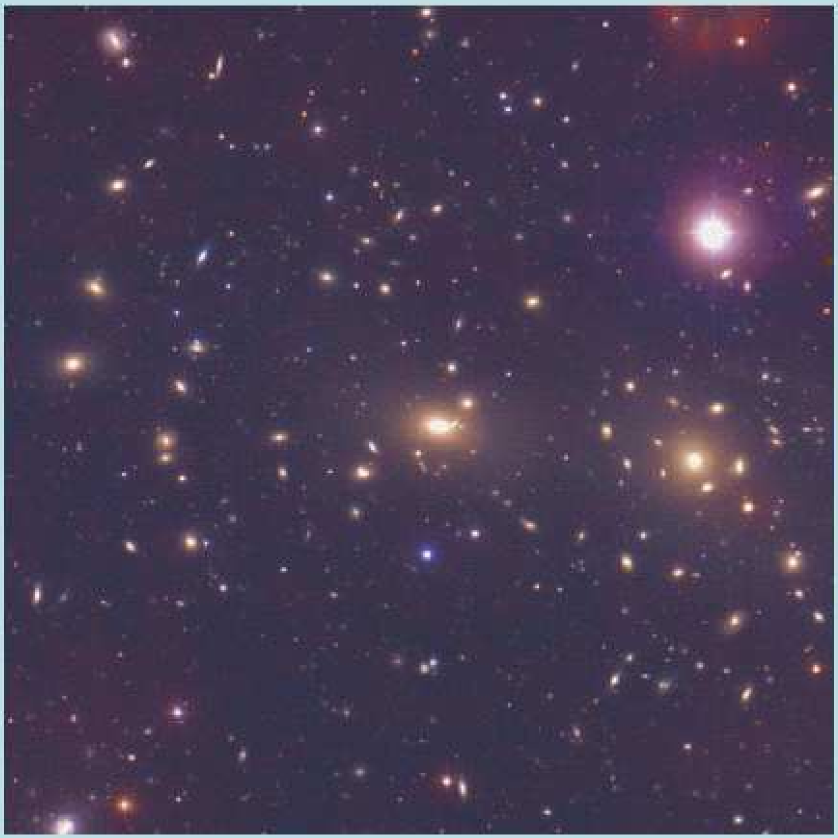


Smooth background component, not accounted for by mass of luminous objects.

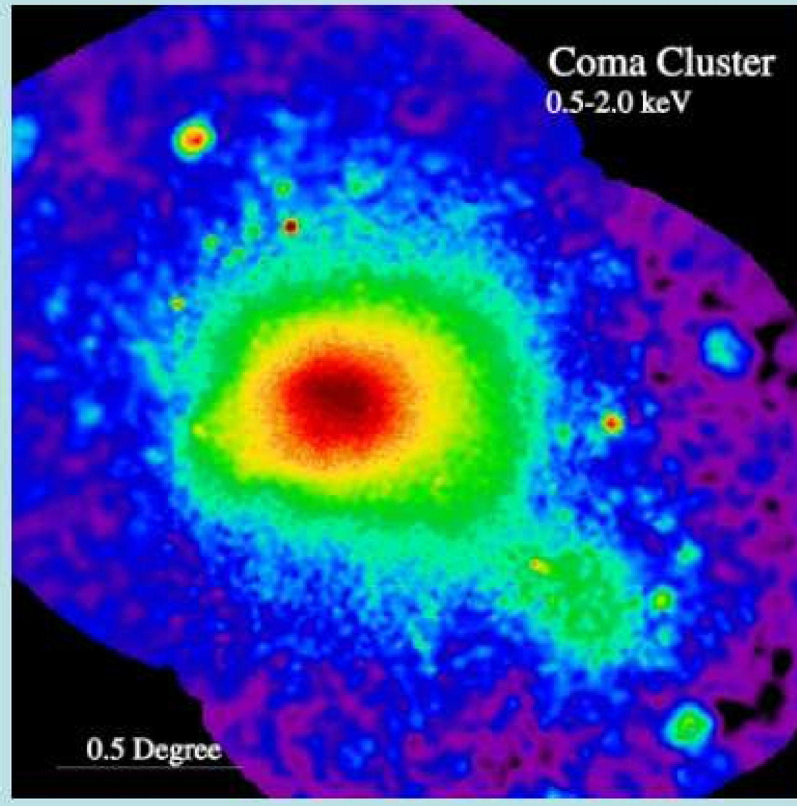
From K Freese's talk

Hot Gas in Clusters: the COMA Cluster

Without Dark Matter, the gas would evaporate



Optical Image



ROSAT X-ray Image

From K Freese's talk

The Bullet Cluster

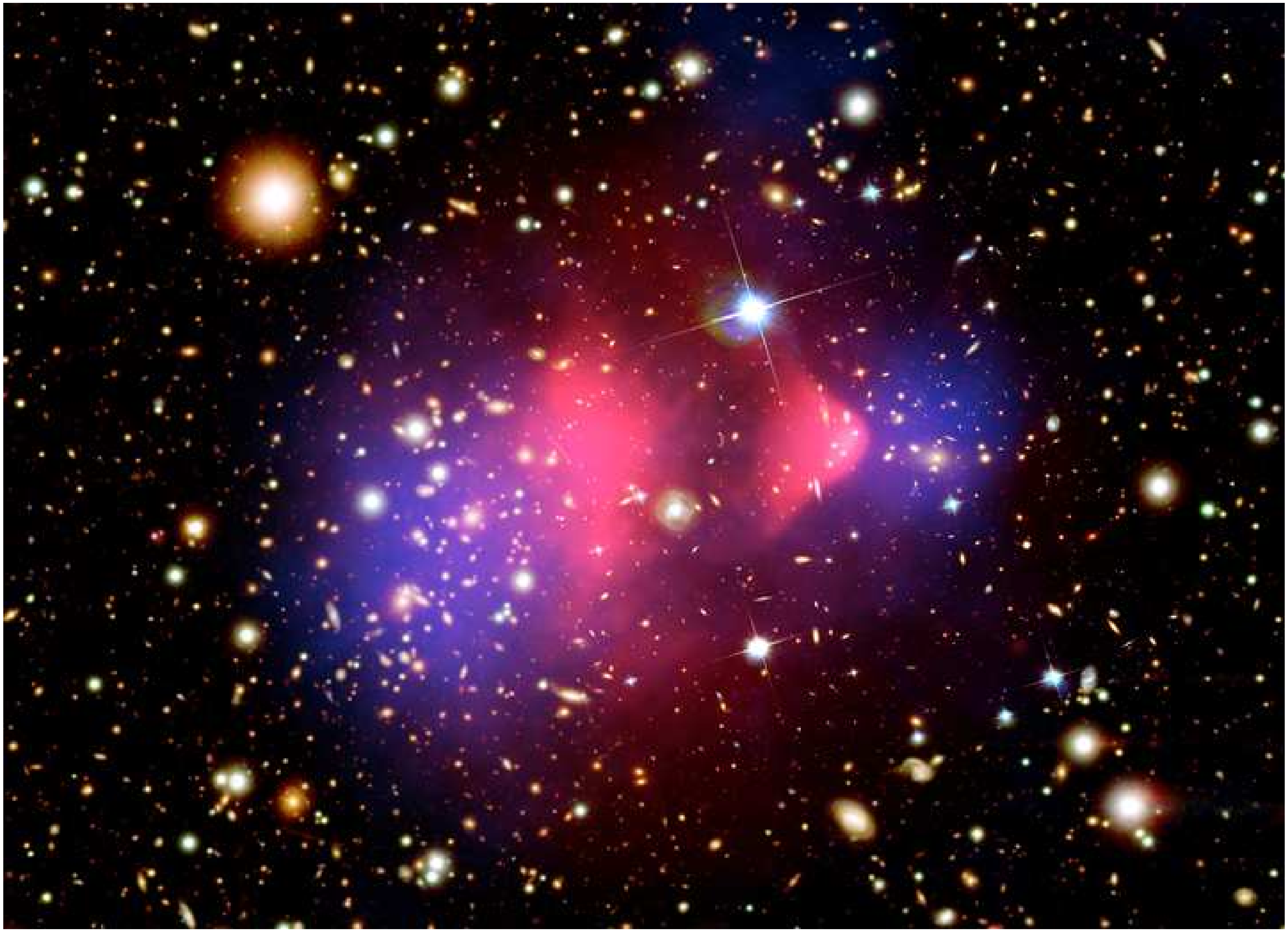


Image credit:NASA/CXC/M.Markevitch et al.
Optical: NASA/STScI; Magellan/U.Asizona/D.Clowe et al.
Lensing map: NASA/STSCI; ESOWFI; Magellan/U.Arizona/D.Clowe et al.

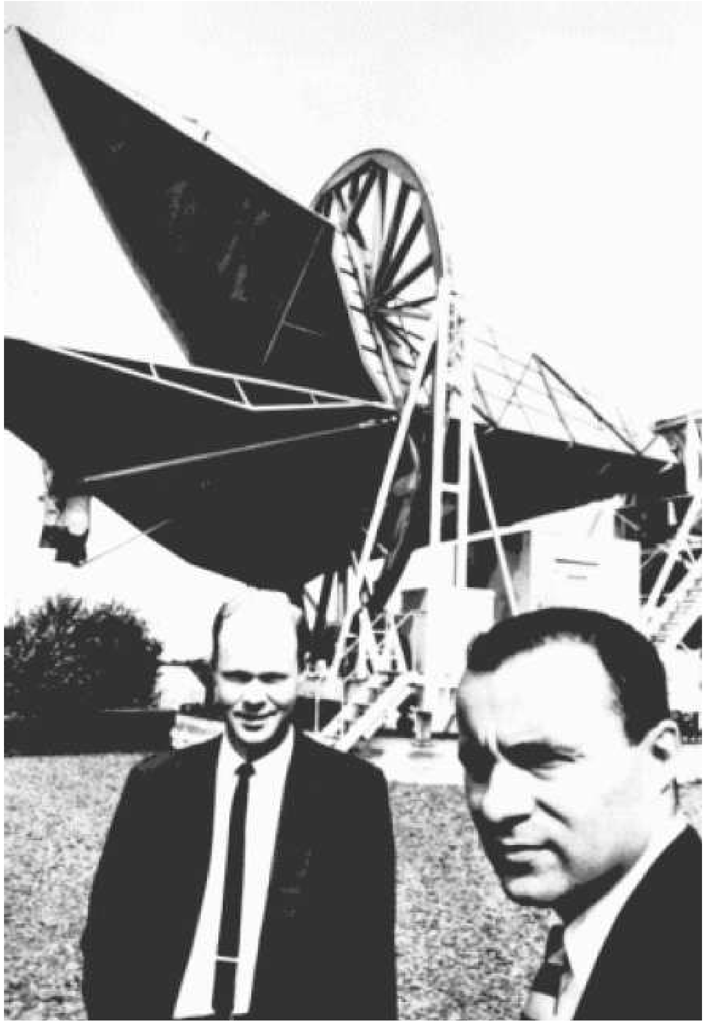
The Cosmic Microwave Background

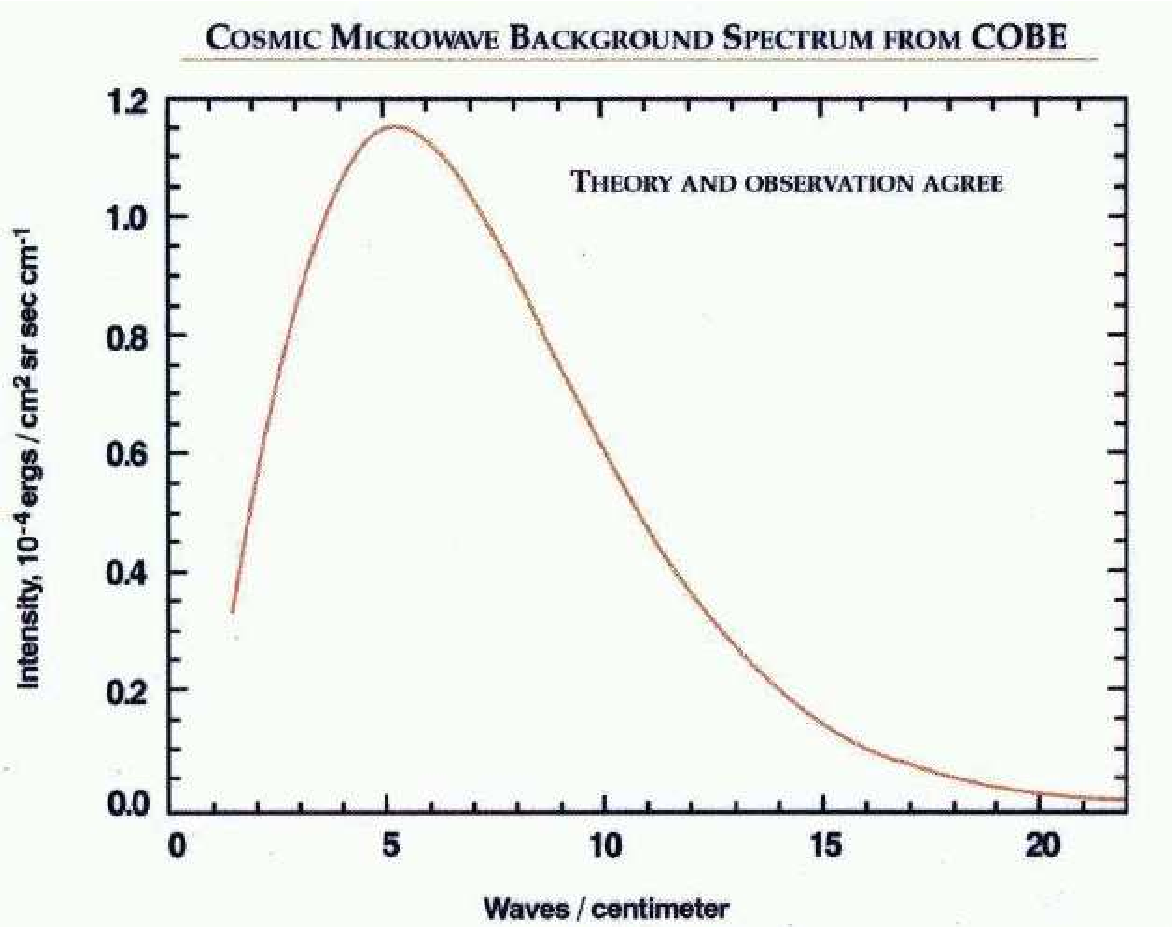
Big Bang Nucleosynthesis

Dark Energy

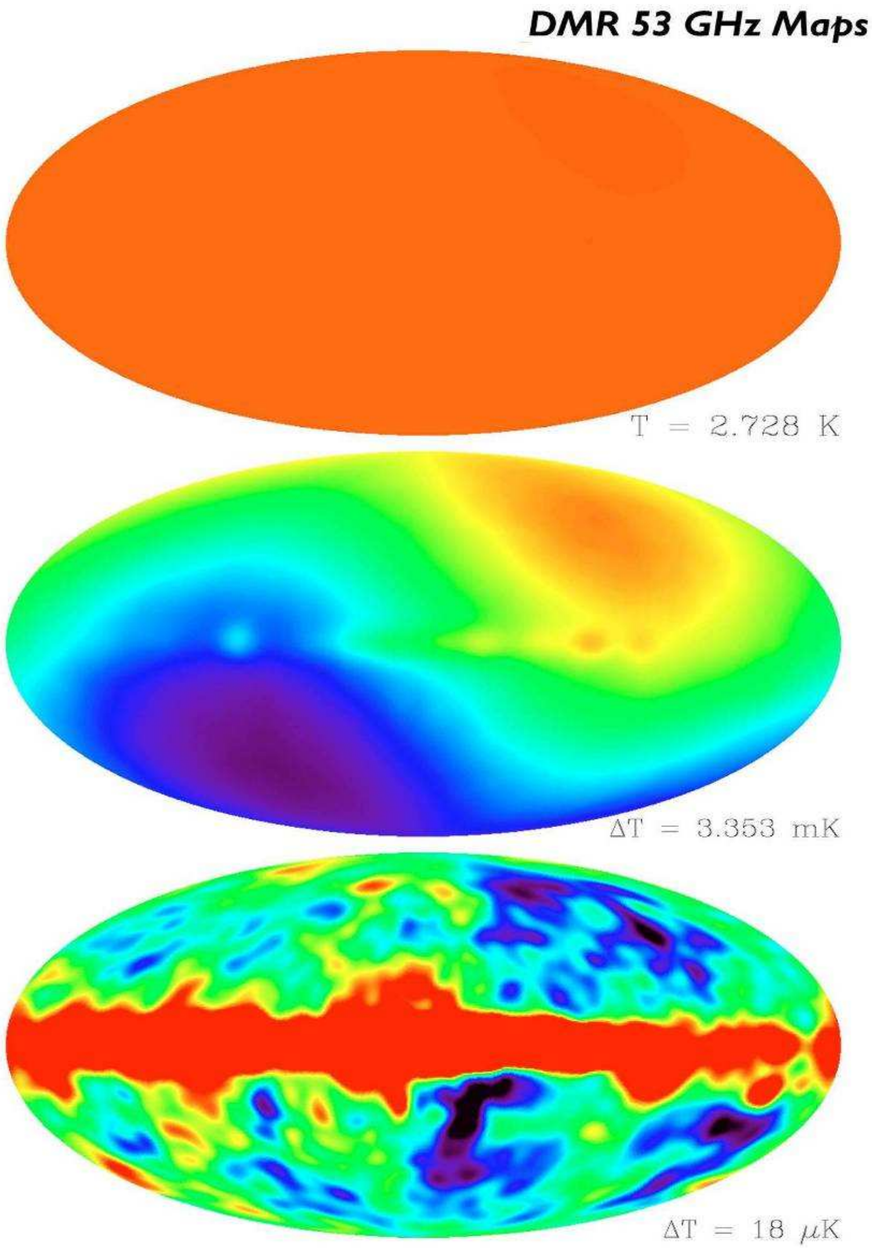
The Cosmic Microwave Background

Measured in the 1990's by the COsmic Background Explorer satellite: almost perfect black body with T=2.725K





The Cosmic Microwave Background

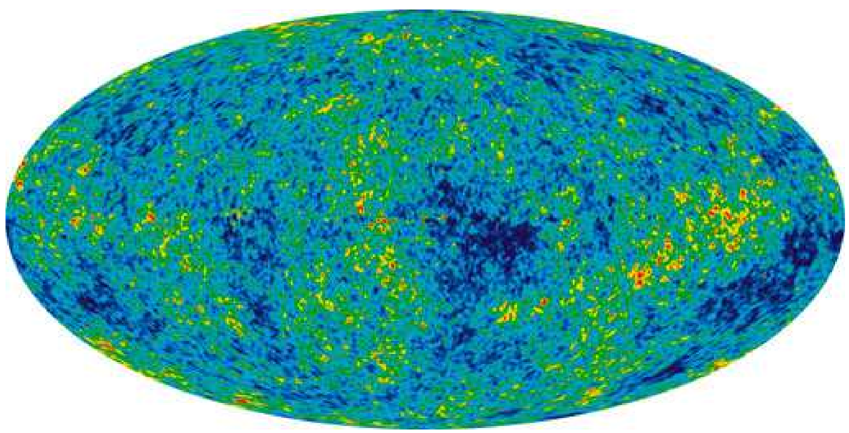


Subtract black body spectrum for T = 2.725K

Dipole is not of cosmologic origin. COBE finds v = 371 +/− 1 km/s for the absolute velocity of the Earth.

Leaves fluctuations (resolved in COBE to ~7 degree)

Much better resolution with WMAP (below) ~15’

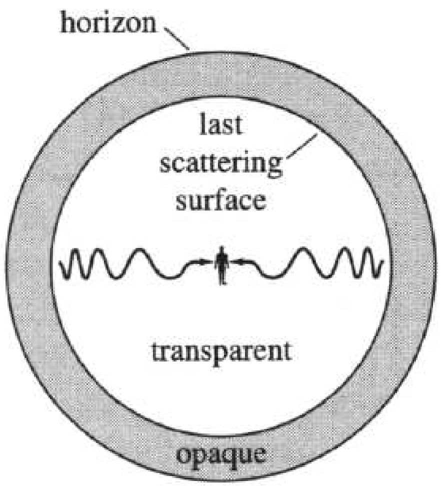


About the Cosmic Microwave Background

Universe was so hot and dense in the past that it was almost a perfect black body with all ionized particles and photons in thermal equilibrium.

Early Universe was opaque: mean free path of radiation small, mainly due to Thomson scattering. It cooled through expansion and eventually electrons and protons recombined to form atoms. At recombination, the Universe becomes transparent, and matter and photons decouple and evolve separately.

The photons we observe come from surface of last scattering.



Not really a perfect black body.

Observed at redshift ~1000.

Fluctuations at 1 in 10^5 level.

These are the seeds of structure formation.

Interpretation of the CMB

Temperature is Doppler boosted:

$$T_{obs} = \frac{T_0}{\gamma\left[1-\left(\frac{v}{c}\right)\cos\theta\right]}$$

Expand this into a power series:

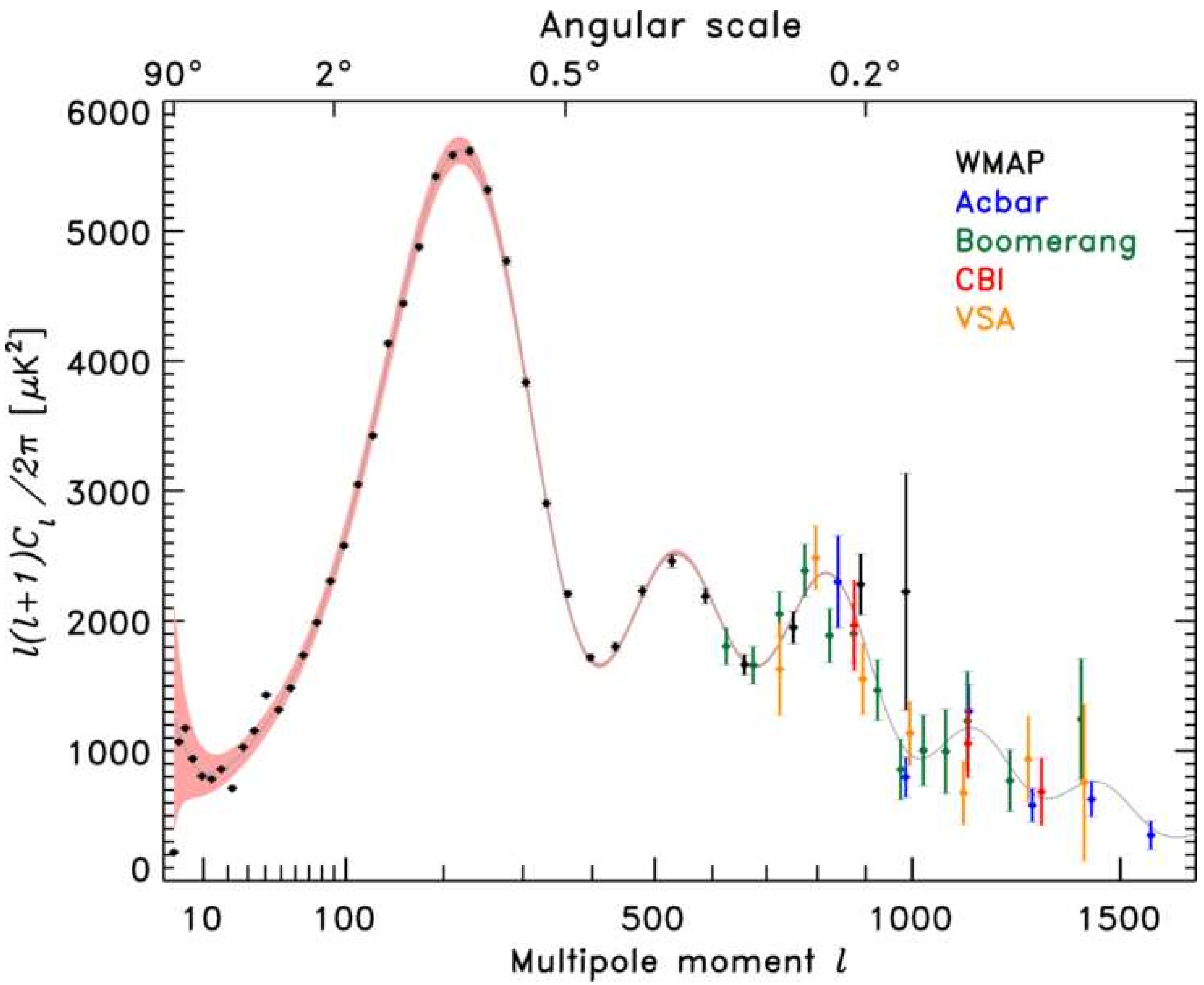
$$T_{obs} = T_0\left[1+\tfrac{v}{c}\cos\theta+\tfrac{1}{2}\left(\tfrac{v}{c}\right)^2\cos 2\theta+O\left(v^3\right)\right]$$

$$C(\theta)=\left\langle \frac{\delta T}{T}(\alpha)\frac{\delta T}{T}(\alpha+\theta)\right\rangle$$

Express this as sum of Legendre polynomials

$$C(\theta)=\frac{1}{4\pi}\sum_{l=2}^{\infty}a_l^2\left(2l+1\right)P_l\left(\cos\theta\right)$$

CMB Power Spectrum



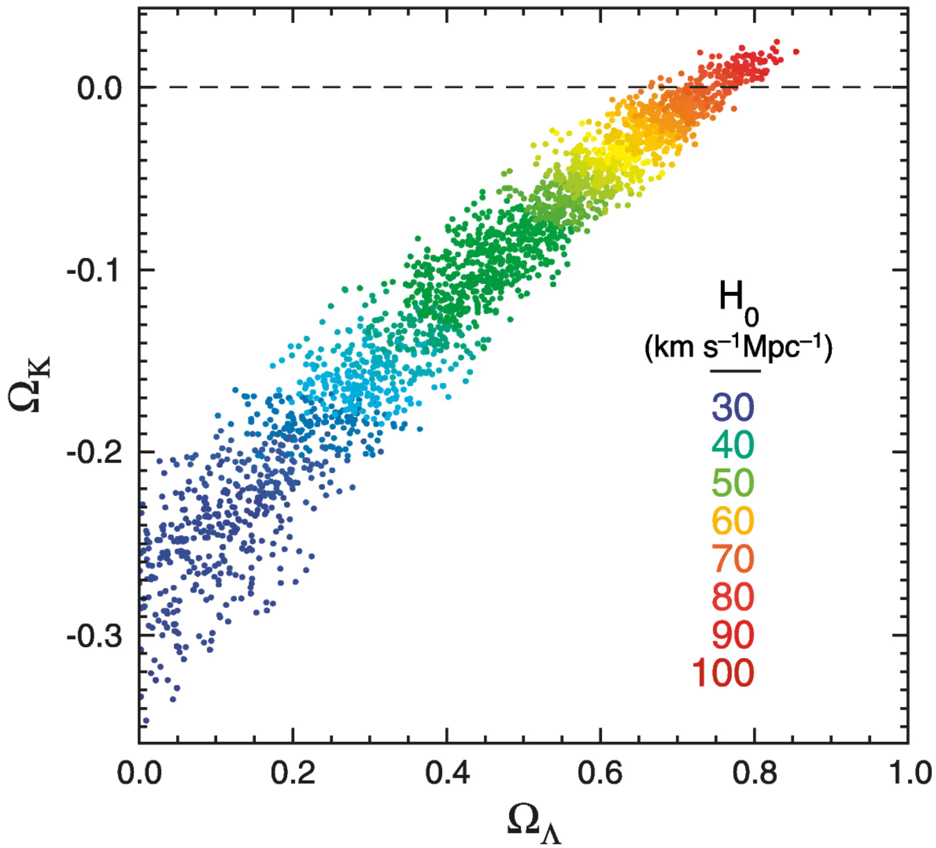
Position of first peak: probes spatial geometry.

Ratio of peaks: relative height of peaks probes baryon density.

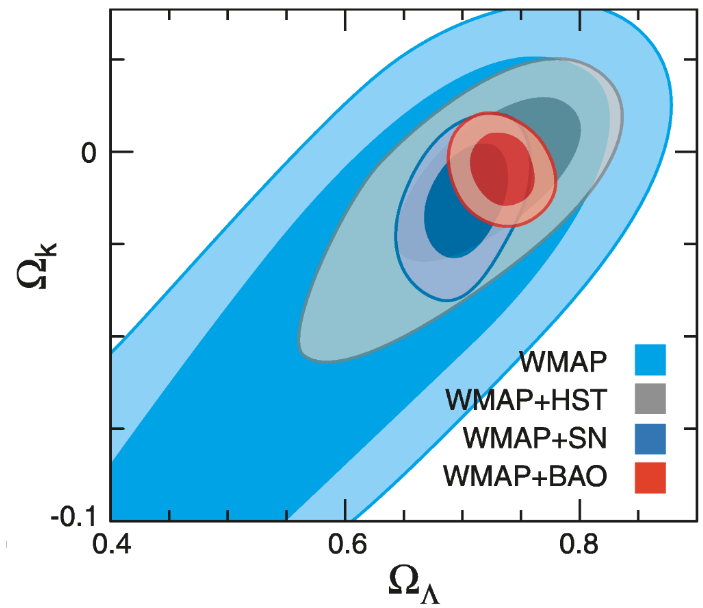
Summary of Parameter Determination

Dunkley et al. 0803.0586, simple 6 parameter fit (3 shown):

Baryons	(2.27 +/− 0.06) / h^2 %
Cold DM	(10.99 +/− 0.62) / h^2 %
Dark Energy	0.742 +/− 0.036



Komatsu *et al*., 803.0547



$$-0.018 < \Omega_k < 0.007$$

Big Bang Nucleosynthesis

p (n,γ) D

→ D (p, γ) ^{3}He

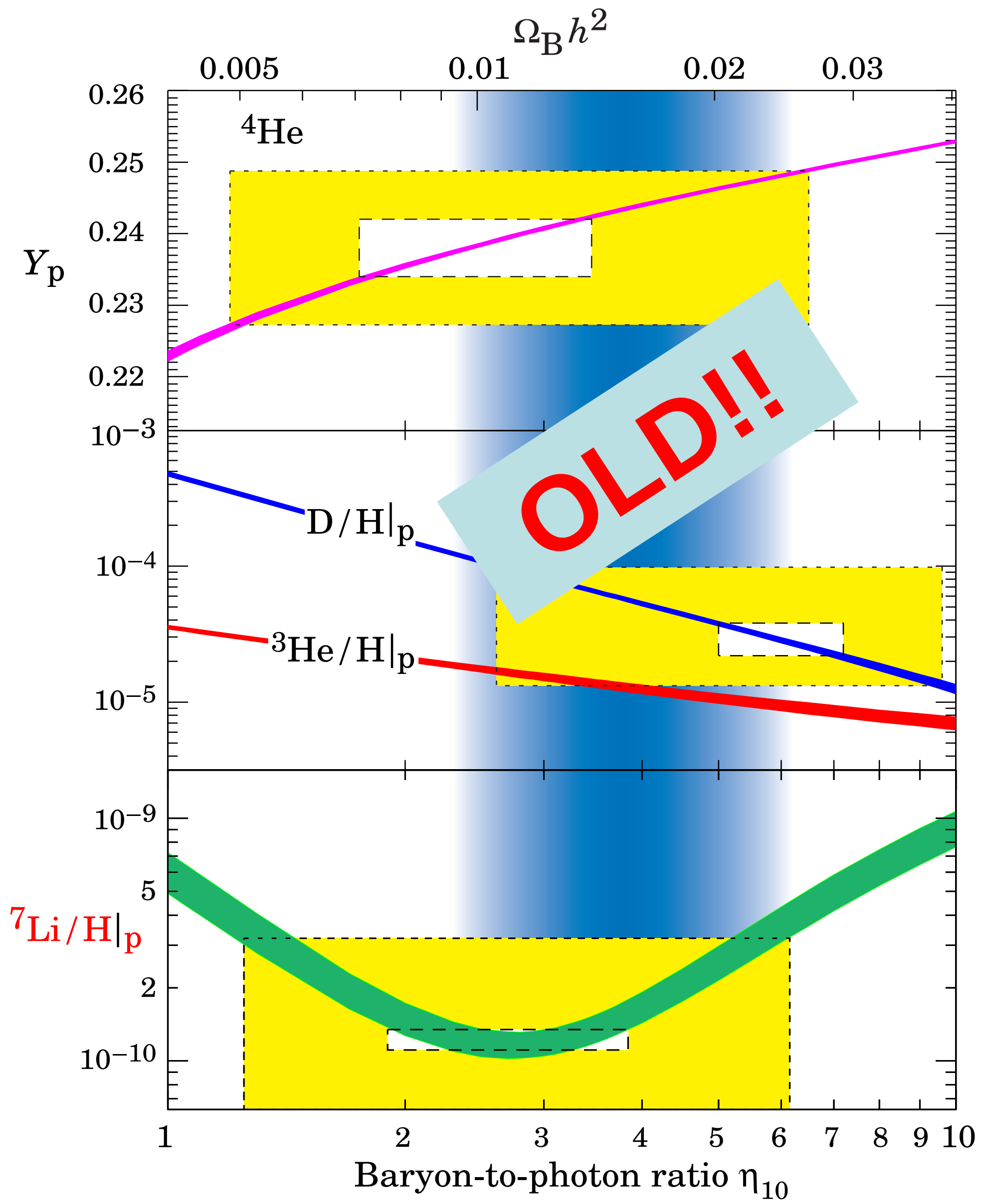
→ ^{3}He (D,p) ^{4}He

No stable element with A = 5 or 8

$$\frac{n}{p} = \exp\left(-\frac{Q}{T_{fr}}\right) \simeq \frac{1}{6} \xrightarrow{\beta\text{-decay}} \frac{1}{7}$$

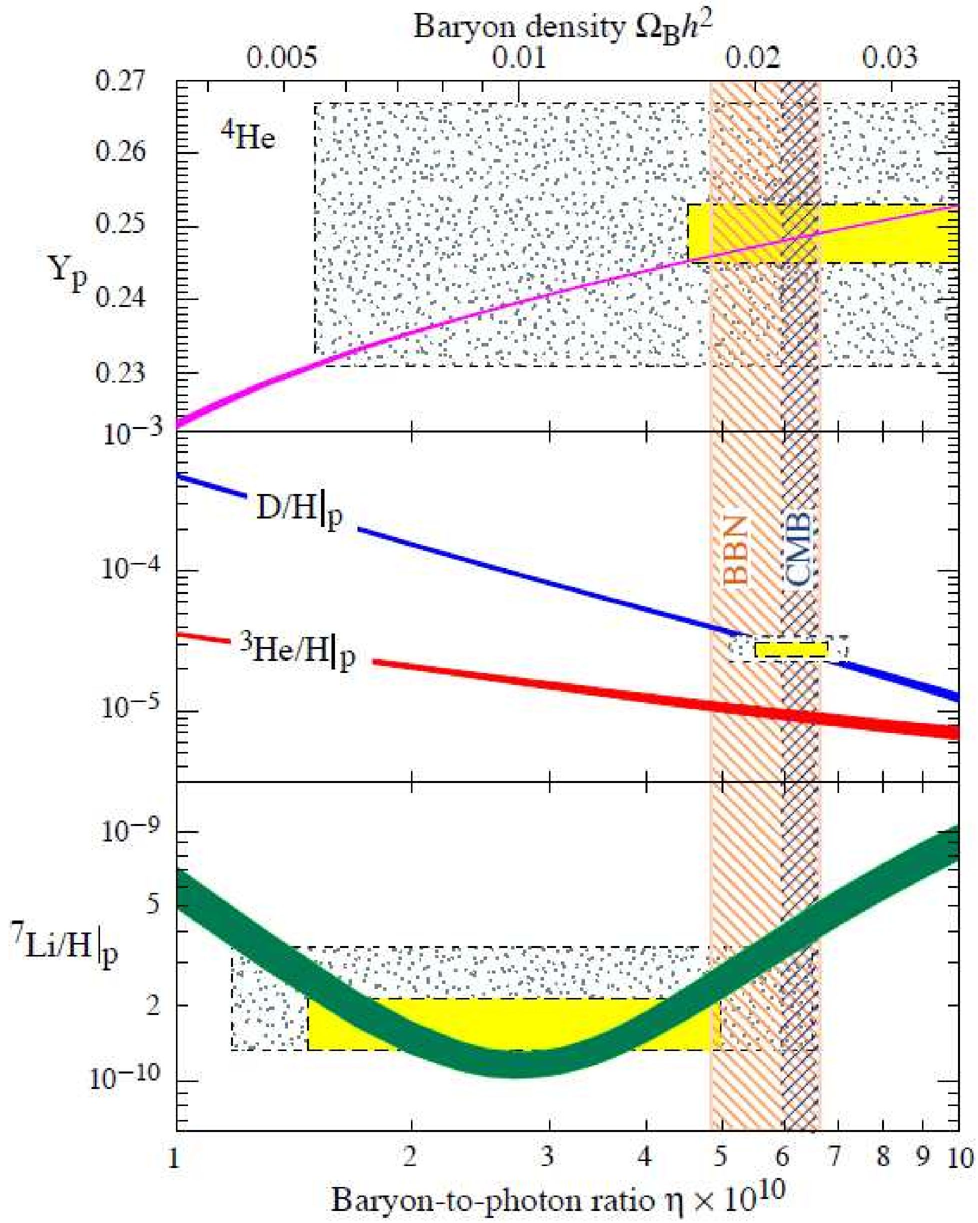
$$Y_P = \frac{2\, n/p}{1 + n/p} \approx 0.24$$

$$\Omega_B = (4 \pm 1)\%$$

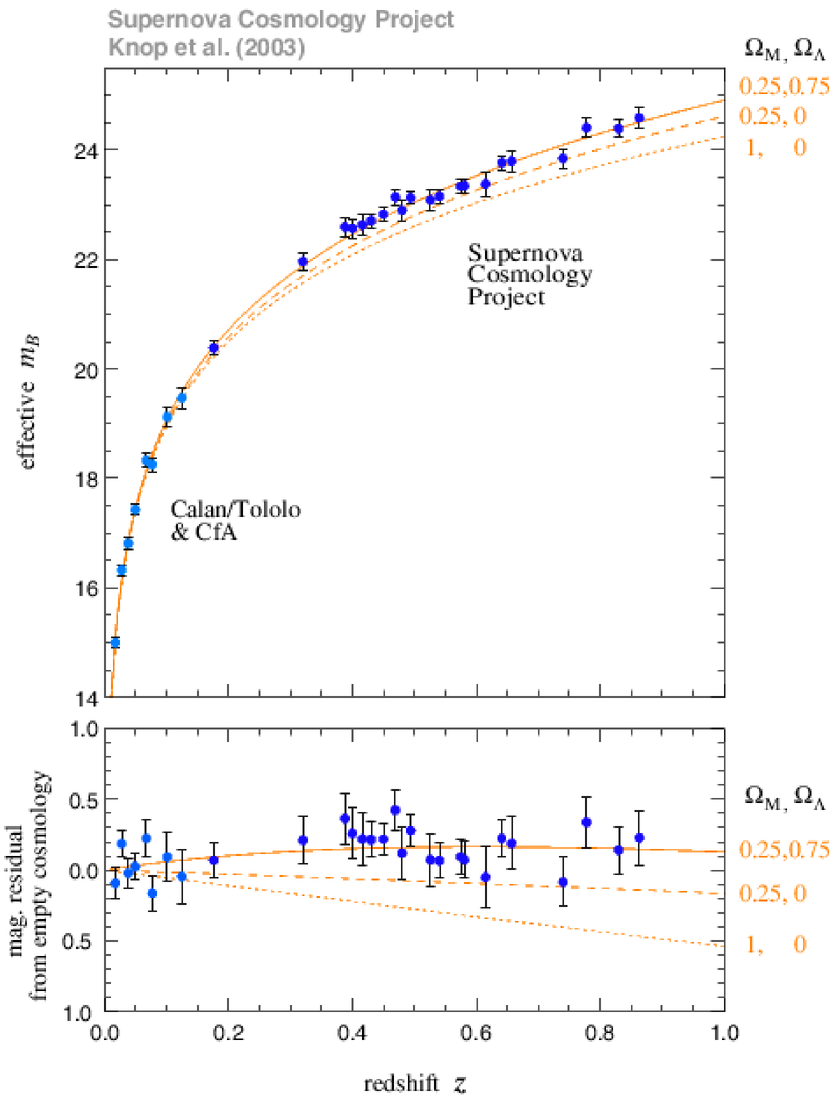


Big Bang Nucleosynthesis

The baryon-to-photon ratio is the only free parameter in calculating nuclear fusion models of the first few minutes. The WMAP constraint agrees with direct measurements of primordial abundance (if you ignore lithium).



Dark Energy



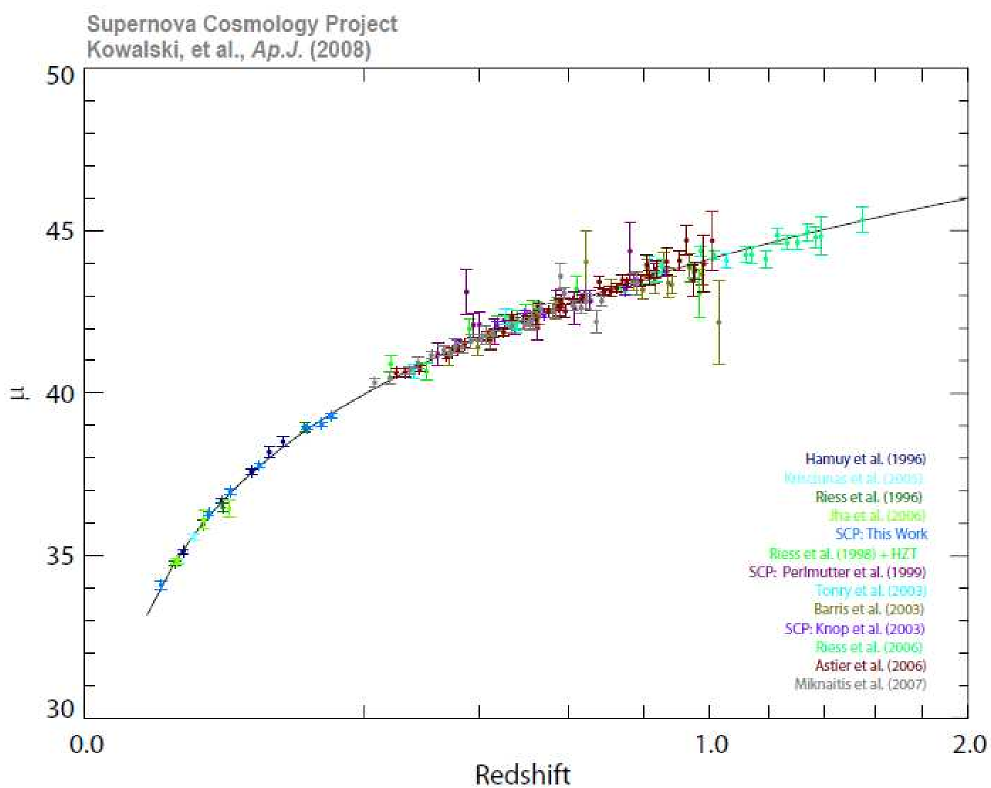
Observation of distant supernovae

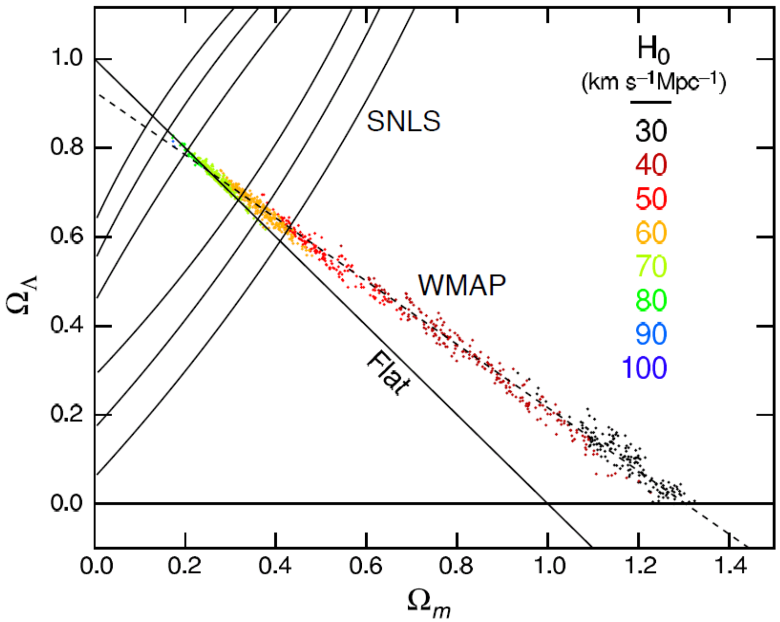
Standard candles

Further away than anticipated

Expansion of Universe accelerates

Vacuum energy

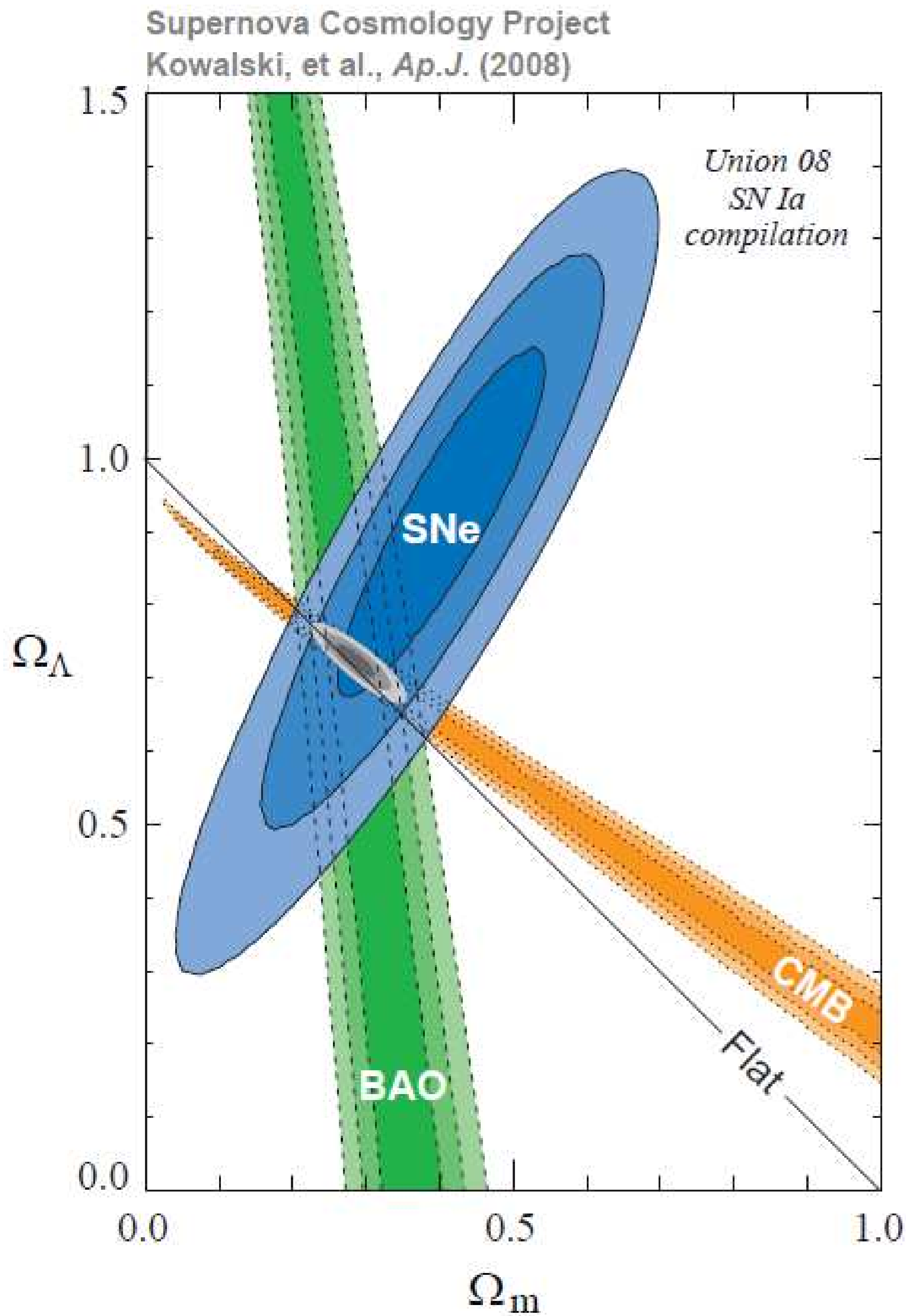




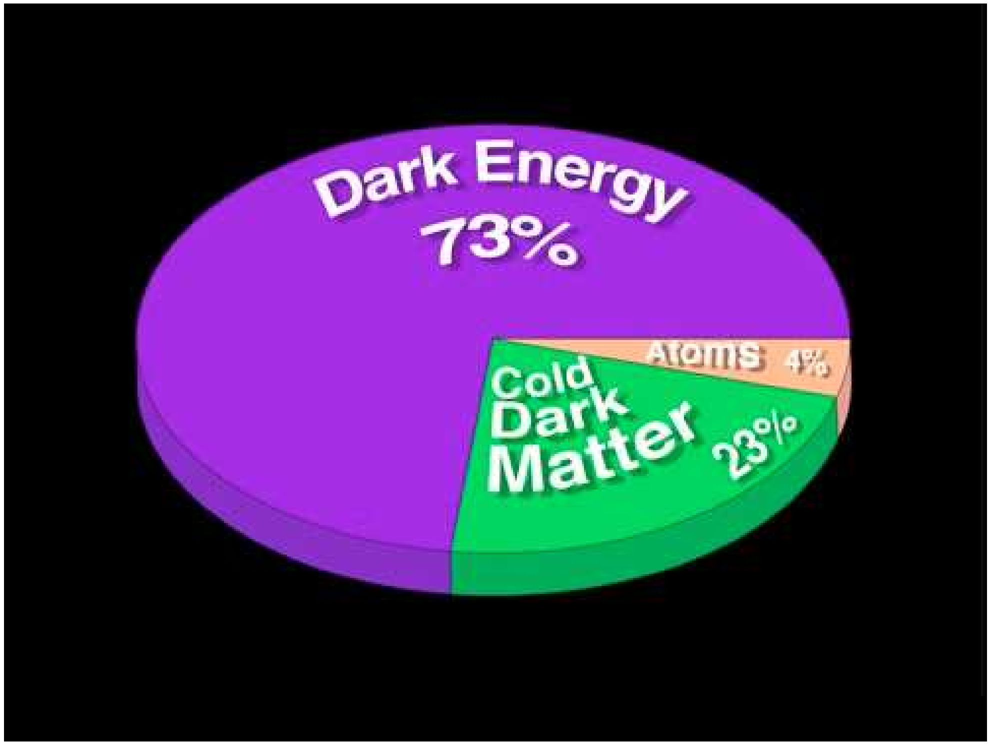
74% Dark Energy

23% Dark Matter

4% Baryonic Matter



A Summary of Cosmological Parameters



Flat Universe

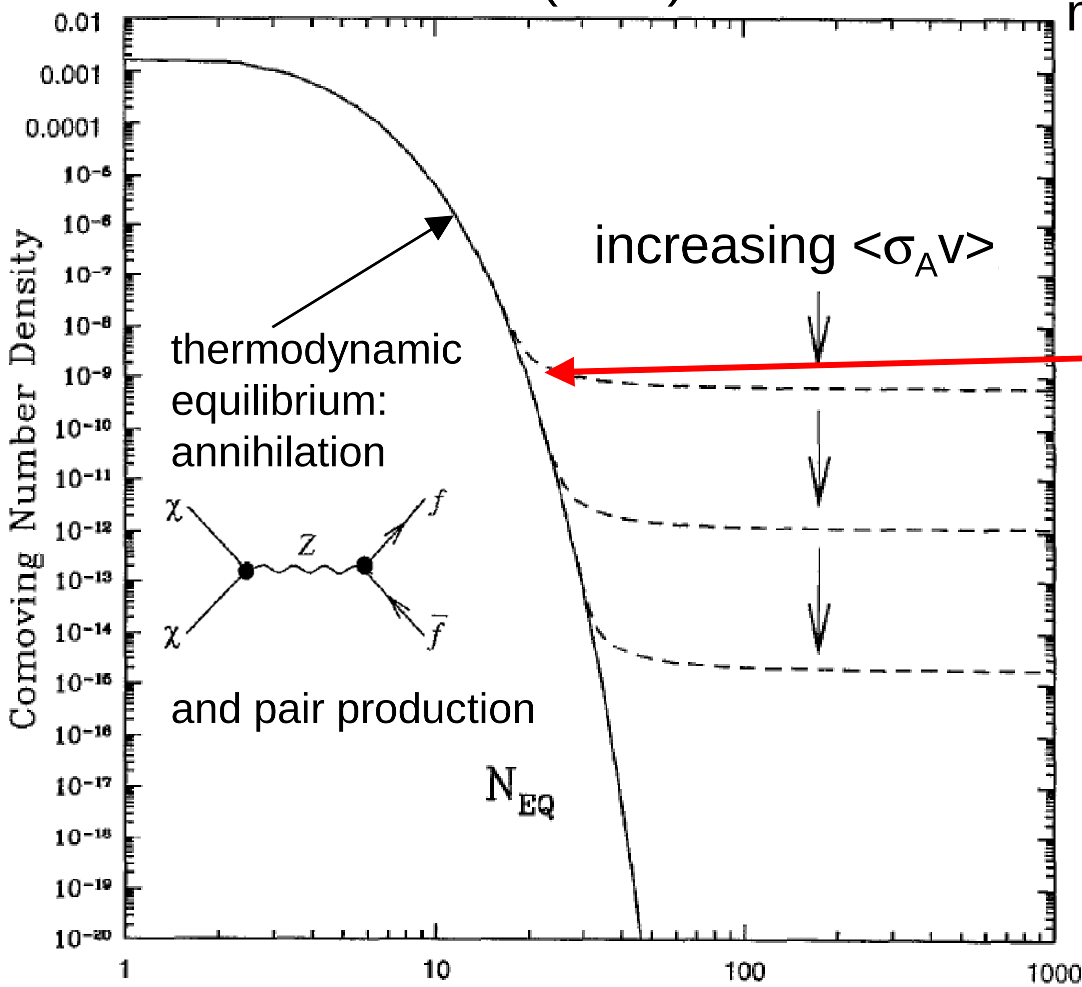
Local DM density:

$$\rho_\chi \approx 0.3 \text{ GeV/cm}^3$$

Need a candidate for Cold Dark Matter

CDM as particle Dark Matter

time t ($t \sim T^{-2}$) →



$x = m_\chi / T$

freeze-out of a weakly interacting massive particle (WIMP χ) when reaction rate drops below expansion rate

$T_{freeze\text{-}out} \sim 1/20 \times m(\text{WIMP})$

Cold Dark Matter:

- non-relativistic

"survival of the weakest"

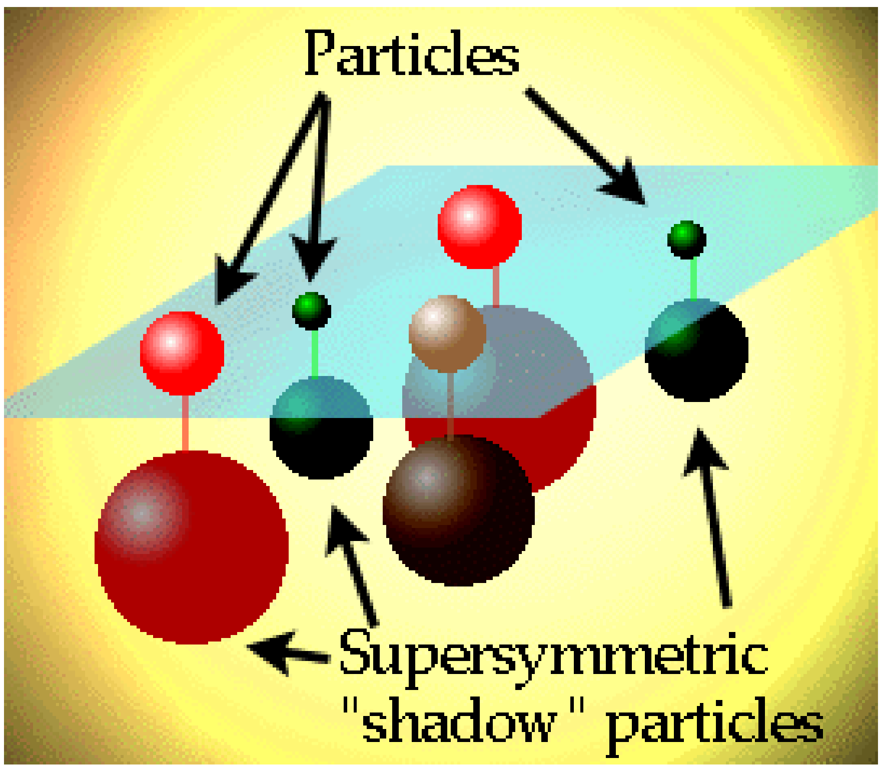
At or below the weak scale

$$\Omega_\chi h^2 \approx \frac{m_\chi n_\chi}{\rho_c} \approx \frac{3\times 10^{-27}\,\text{cm}^3/\text{sec}}{\langle \sigma_A v \rangle}$$

Supersymmetry SUSY

Particles:
half-integer spin

Carriers of forces:
integer spin



FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

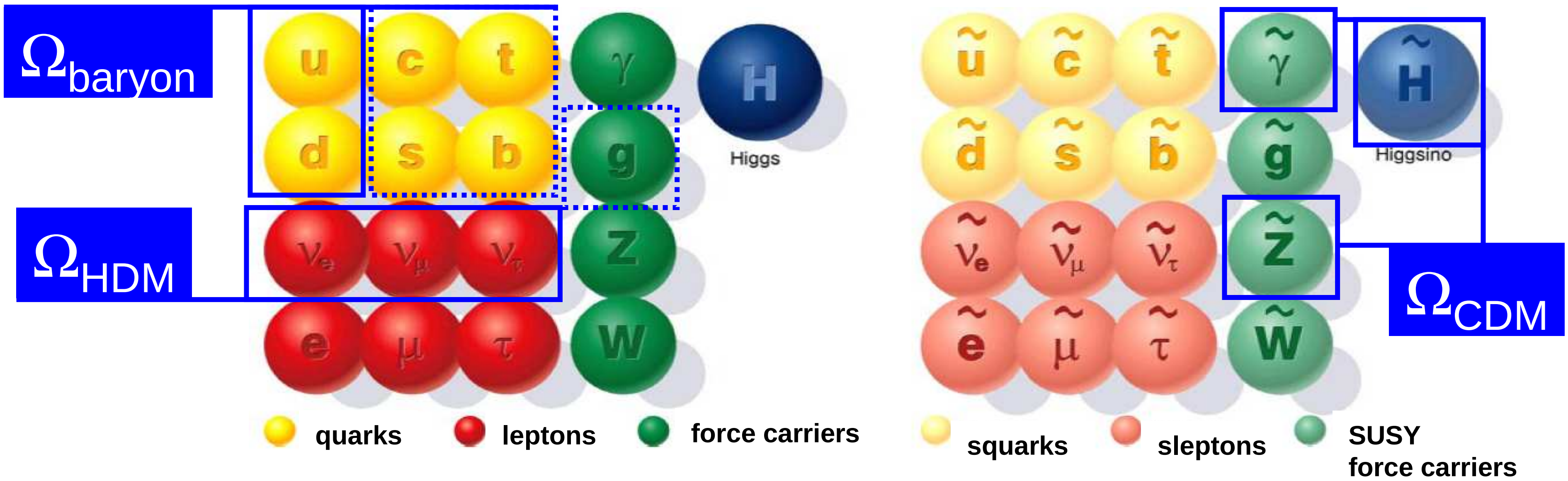
BOSONS force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

WIMP ≡ LSP (lightest SUSY particle)?

SUSY in a nutshell:



Requirements on LSP to be a WIMP:

- R parity conservation
- LSP must be neutral (→ superposition of $\tilde{\gamma}$, $\tilde{Z}$ and $\tilde{H}$ or $\tilde{G}$)
- LSP must be stable (or lifetime ~ age of the Universe)

to be detectable:

- interaction cross section $\sigma \sim 10^{-3} \ldots 1\ \sigma_{ew}$
- $50 < m(\chi) < 1000$ GeV

CDM as Particle Dark Matter

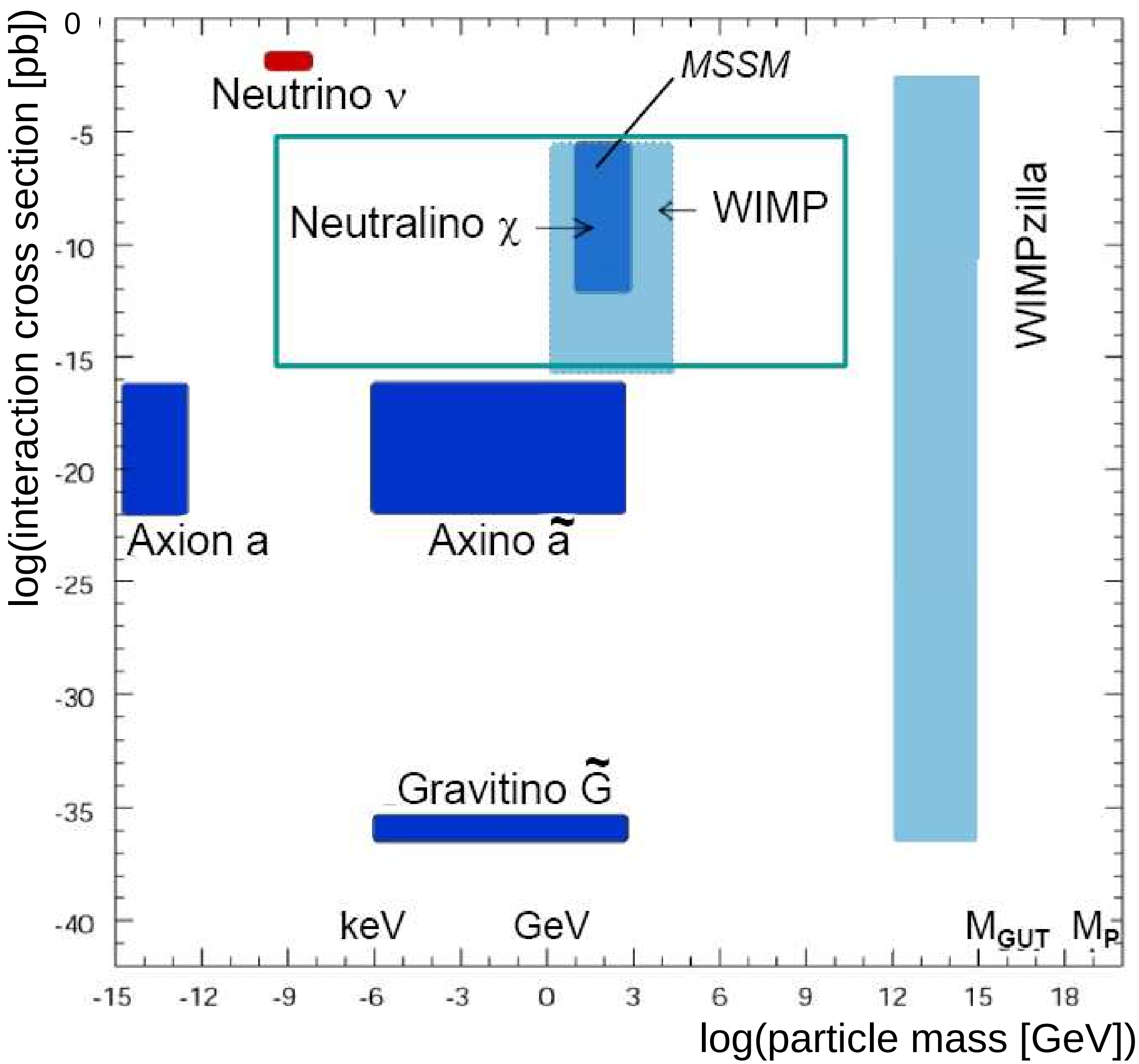
axion:
light WIMP produced non-thermally (to solve CP violation via Peccei-Quinn)

axino:
SUSY partner of axion, produced via decays of sparticles

gravitino:
SUSY partner of graviton, interacts only via gravitation

WIMPzilla:
extremely massive non-thermal relicts (from space curvature)

neutralino χ:
lightest (neutral) SUSY particle
$\sigma \sim 1 \ldots 10^{-2}\, \sigma_{electroweak}$



WIMP as CDM-Candidate

- Neutral
- Stable
- Small Cross section

SUSY → LSP = neutralino?

$$\tilde{\chi}_0^1 = a\widetilde{B} + b\widetilde{W}^3 + c\widetilde{H}_1^0 + d\widetilde{H}_2^0$$

Coherent interaction:

$$\sigma_{Coh.} \propto A^2$$

→ Heavy nuclei

Spin-dependent interaction:

$$\sigma_{spin-dependent} \propto \left[a_p \langle \mathbf{S_p} \rangle + a_n \langle \mathbf{S_n} \rangle \right] \cdot \frac{J+1}{J}$$

Only significant for light-weight nuclei

Focus on WIMPs

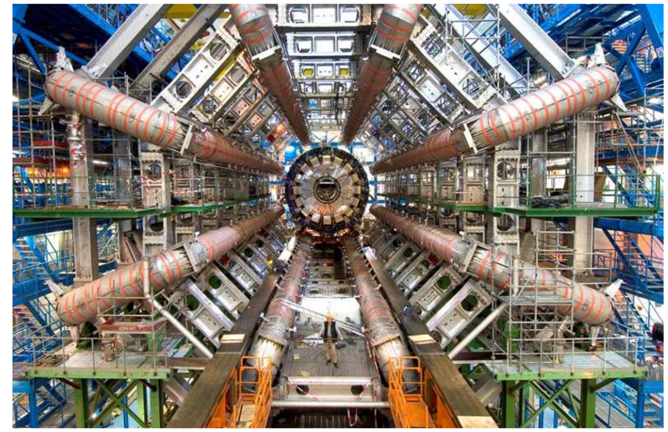
Production at the LHC

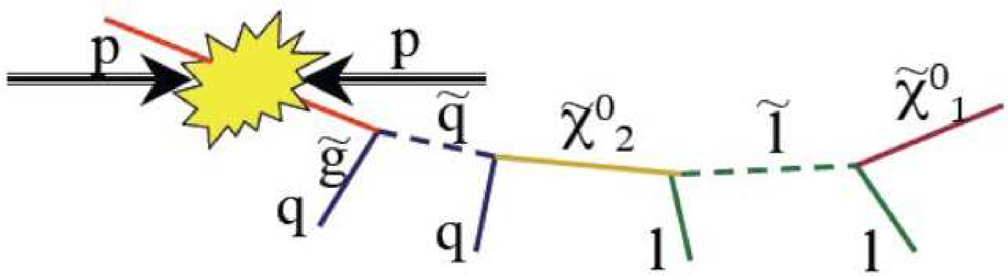
Indirect Detection

Direct Detection

Production at Accelerators

Heavy strongly-interacting SUSY states (squarks, gluinos) produced copiously in p-p collisions





Cascade decays through lighter states to invisible LSP (Dark Matter)

Theoretical models needed for interpretation.

Collider measurements are complementary to direct and indirect measurements.

Indirect Detection

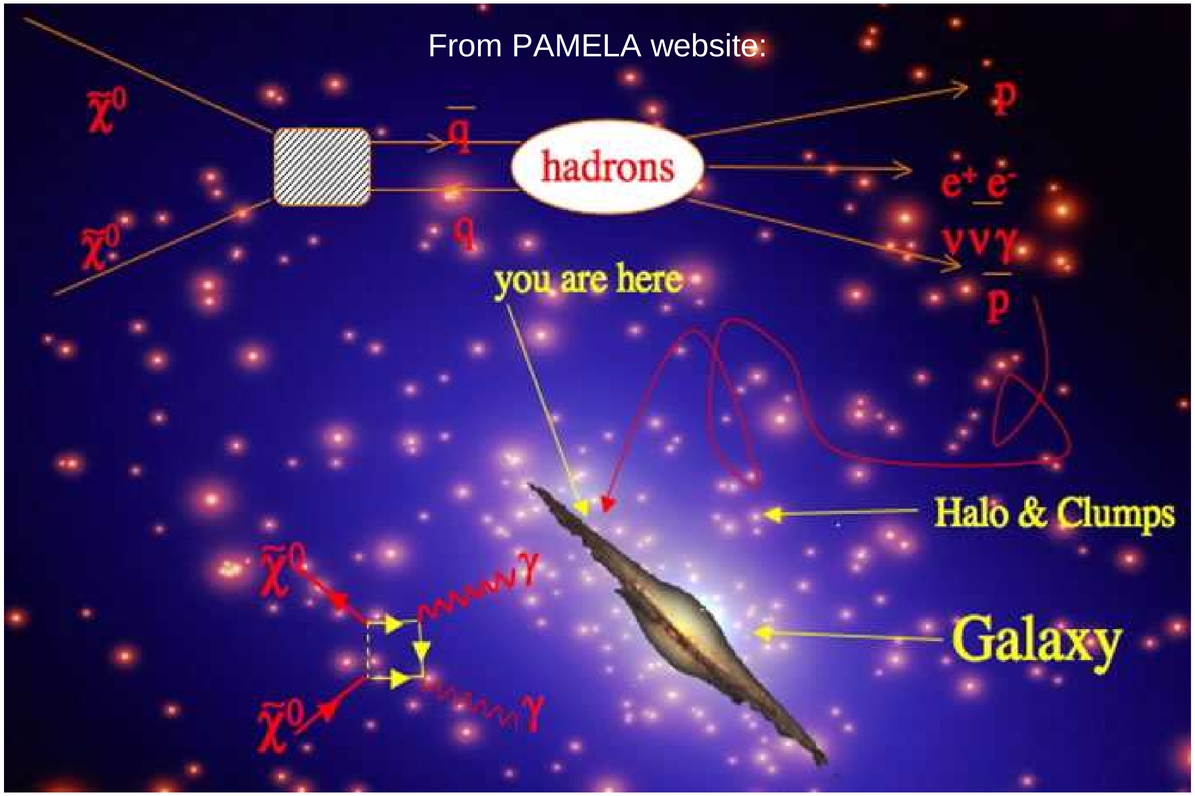
WIMP annihilation in regions for high DM density $\text{Rate} \propto \rho^2$

Probes for:

Sun
Earth
Milky Way Halo / Galactic Centre
External galaxies
Stars

Messengers:

High-energy neutrinos
Gamma ray
Antiprotons
Positrons



Indirect Detection

The signature: how to detect indirectly? Standard particles, charged messengers and gamma rays and neutrinos.

Assume: neutralinos captured and accumulated in celestial bodies (Sun, Earth).

What to look at: galactic centre, sub-structures

Experiments:

Neutrino final states: AMANDA II (South pole since 2001); ANTARES (Mediteranian, completed), IceCube (in 2011).

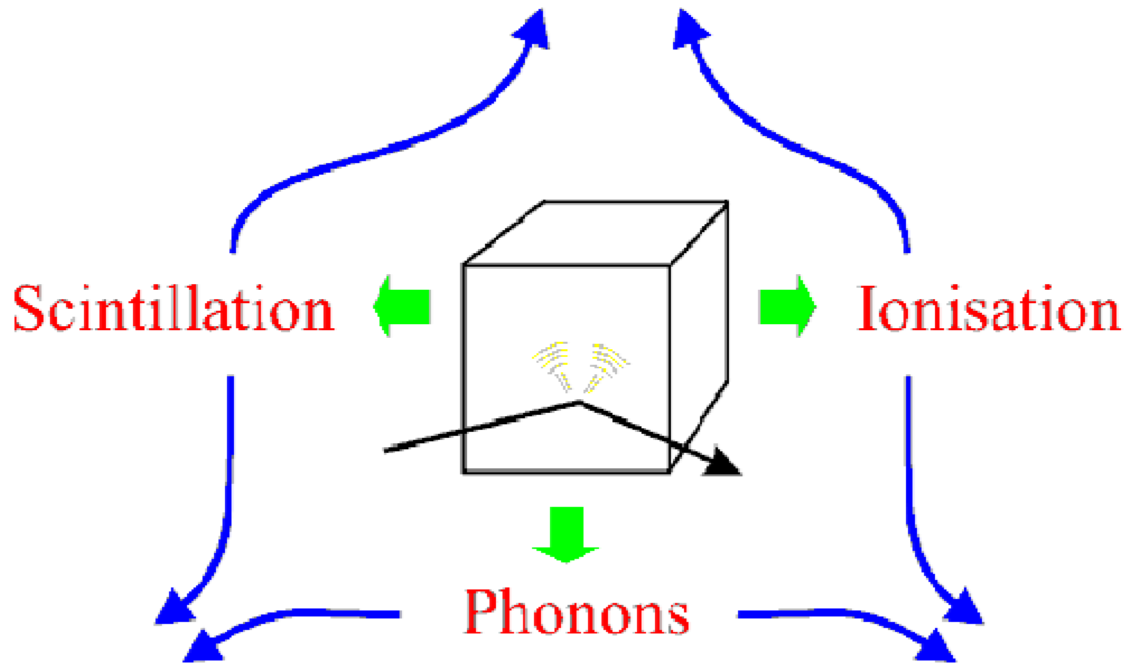
Gamma final states: EGRET, GLAST/FERMI, HESS, MAGIC

Charged final states: PAMELA, AMS.

Direct Detection Techniques

Ar, Xe
ArDM, WARP, XENON, LUX, ZEPLIN

NaI, Ar, Xe
DAMA/LIBRA
ANAIS
NAIAD
KIMS
XMASS
DEAP/CLEAN



Ge
HDMS
GERDA
MAJORANA
IGEX

$CaWO_4$, $ZnWO_4$
CRESST II
ROSEBUD

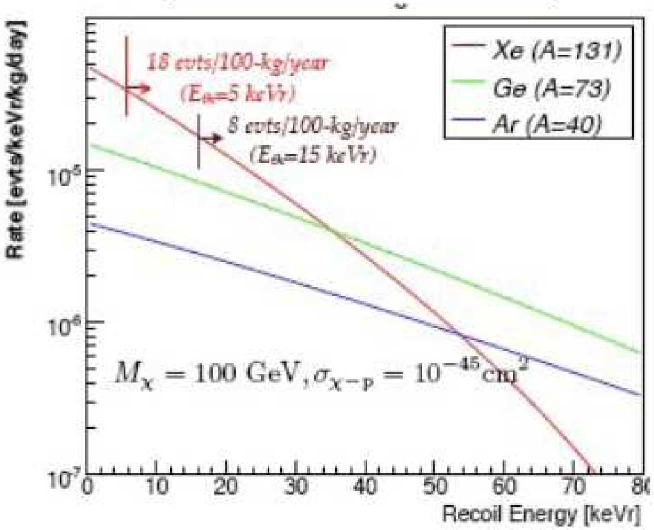
Al_2O_3 and others
CRESST I
CUOPP
PICASSO

Si, Ge
CDMS
EDELWEISS

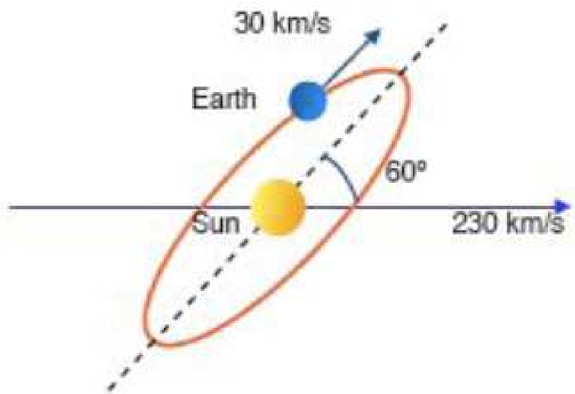
Displacement / tracking: DRIFT, Newage, MIMAC, DM-TPC

Direct Detection Signals

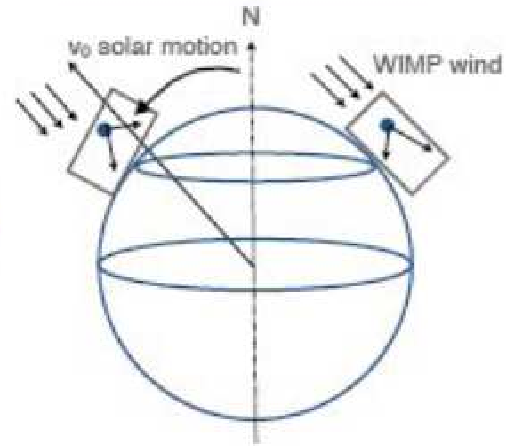
Recoil Spectra



Annual Modulation



Directionality

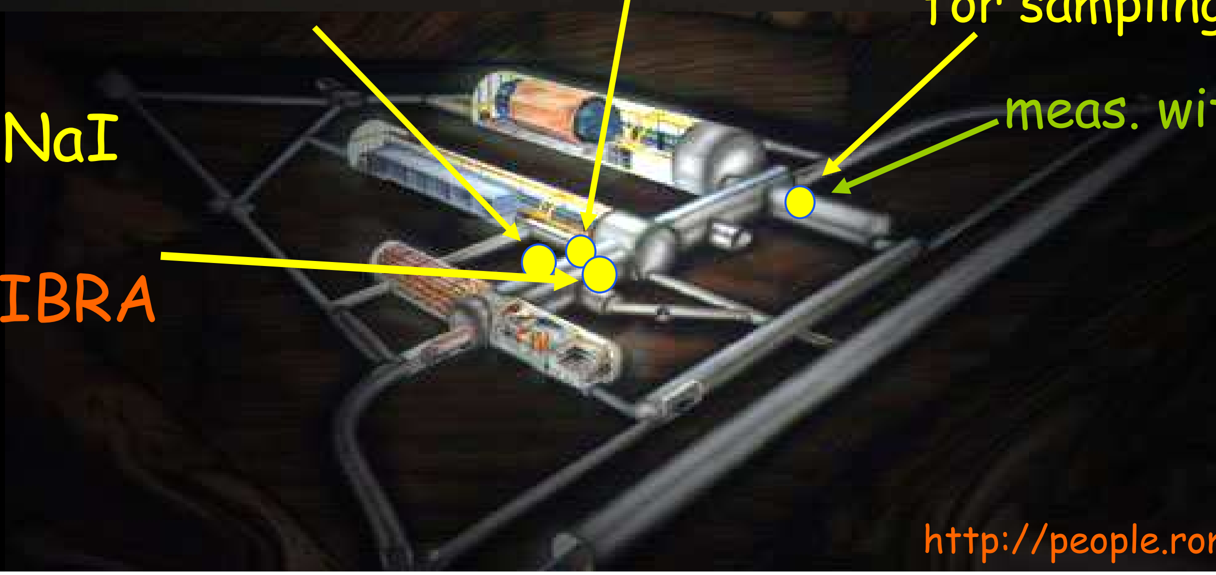


- Annual modulation of flux and spectrum (few % effect at threshold)
- Recoil direction modulation (large diurnal effect, requires gas target)
- Target dependence (depends on A^2, form factor; neutron rejection)
- Spectral shape (exponential form, but can look like typical background)
- Interaction characteristics (nuclear recoils; single hits, uniform distribution)

Roma2,Roma1,LNGS,IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev
+ neutron meas.: ENEA-Frascati
+ in some studies on ββ decays (DST-MAE project): IIT Kharagpur, India

DAMA: an observatory for rare processes @LNGS



http://people.roma2.infn.it/dama

The new DAMA/LIBRA set-up ~250 kg NaI(Tl)
(Large sodium Iodide Bulk for RAre processes)

As a result of a second generation R&D for more radiopure NaI(Tl)
by exploiting new chemical/physical radiopurification techniques
(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

installing DAMA/LIBRA detectors

assembling a DAMA/ LIBRA detector

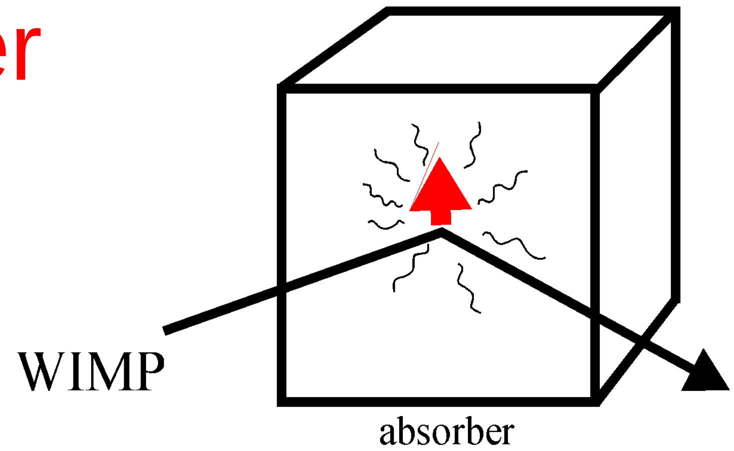
detectors during installation; in the central and right up detectors the new shaped Cu shield surrounding light guides (acting also as optical windows) and PMTs was not yet applied

filling the inner Cu box with further shield

closing the Cu box housing the detectors

view at end of detectors' installation in the Cu box

Elastic Scattering of WIMPs by Nuclei in an Absorber



Measure Recoil Energies

$$E_R = E_0\, r \cdot \tfrac{1}{2}\left(1-\cos\theta_{\mathrm{CM}}\right)$$

Local density: $\rho_{\mathrm{W}} \approx 0.3\ \mathrm{GeV/cm^3}$

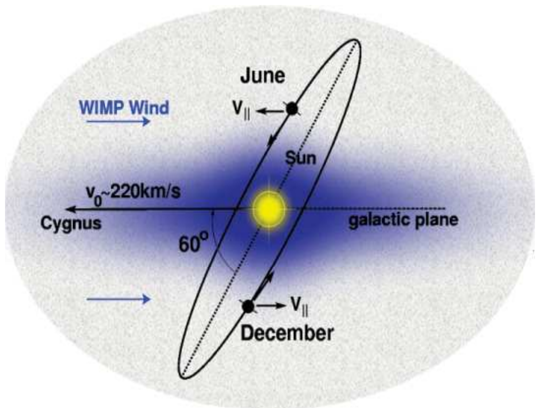
Maxwellian v-distibution: $\mathrm{v}_{\mathrm{rms}} \approx 270\ \mathrm{km/s}$

$$\frac{dR}{dE_R} = 2\frac{\rho_W}{m_W}\cdot\frac{1}{m_W m_N r}\cdot\sigma_0\cdot F^2\left(q^2\right)\cdot\int d\mathbf{v}\,\frac{f\left(\mathbf{v}\right)}{v}$$

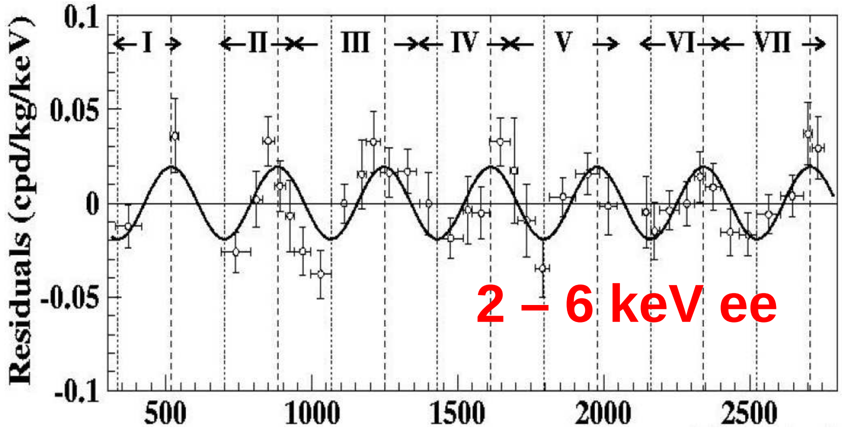
… in an Earth bound frame of reference

$$E = \tfrac{1}{2}mv^2 = \tfrac{1}{2}mc^2\cdot\left(\tfrac{v}{\mathrm{c}}\right)^2 \;\Rightarrow\; \sim 10\mathrm{GeV}\cdot 10^{-6} \;\rightarrow\; \sim 10\mathrm{keV}$$

DAMA / LIBRA



- Data taking completed in July 2002
- Total exposure of 107,731 kg.d
- See annual modulation at 6.3σ
- Claims model-independent evidence for WIMPs in the galactic halo
- 2nd phase: LIBRA 250 kg



WIMP candidate, using standard halo parameters:

$M_X = (52\ ^{+10}_{-8})$ GeV and

$\sigma_{X\text{-}N} = (7.2\ ^{+0.4}_{-0.9})\ .10^{-6}$ pb

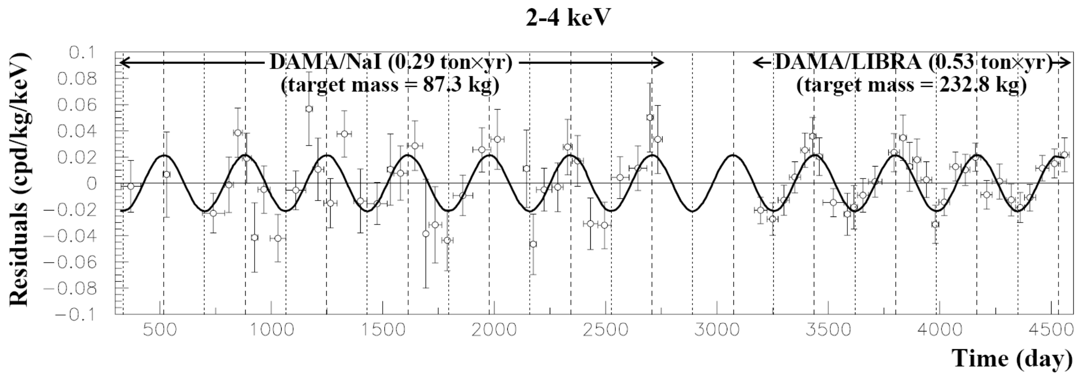
DAMA / LIBRA running 250 kg; wait at least until 2008 …

Model Independent Annual Modulation Result

DAMA/NaI (7 years) + DAMA/LIBRA (4 years)   Total exposure: 300555 kg×day = 0.82 ton×yr

experimental single-hit residuals rate vs time and energy

arXiv:0804.2741
to appear on EPJC



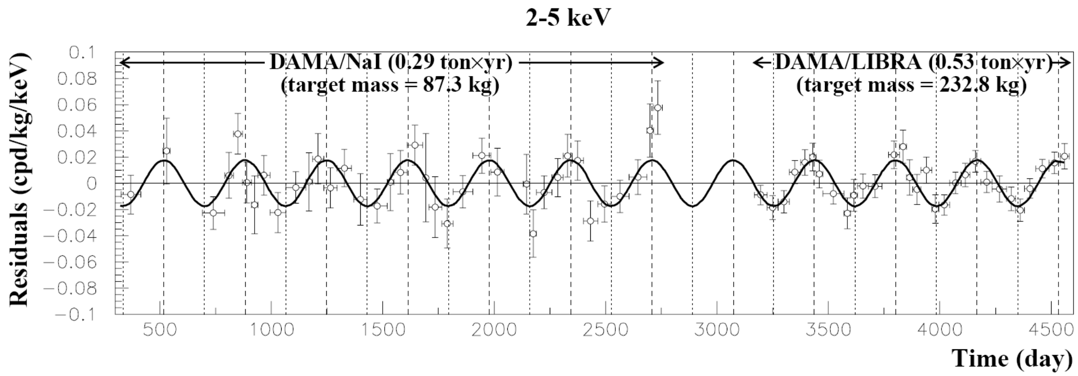
2-4 keV

A=(0.0215±0.0026) cpd/kg/keV

χ^2/dof = 51.9/66   **8.3 σ C.L.**

Absence of modulation? No

χ^2/dof=117.7/67 ⇒ P(A=0) = 1.3×10^{-4}



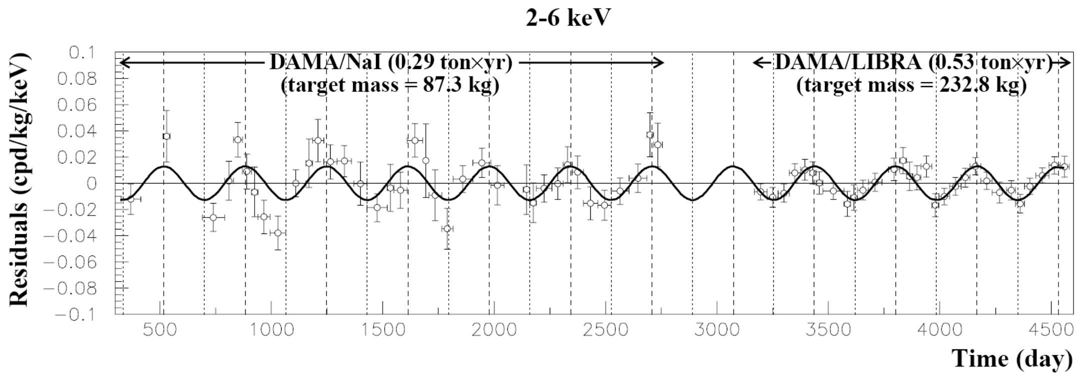
2-5 keV

A=(0.0176±0.0020) cpd/kg/keV

χ^2/dof = 39.6/66   **8.8 σ C.L.**

Absence of modulation? No

χ^2/dof=116.1/67 ⇒ P(A=0) = 1.9×10^{-4}



2-6 keV

A=(0.0129±0.0016) cpd/kg/keV

χ^2/dof = 54.3/66 **8.2 σ C.L.**

Absence of modulation? No

χ^2/dof=116.4/67 ⇒ P(A=0) = 1.8×10^{-4}

Taken from P Belli's talk at IDM2008

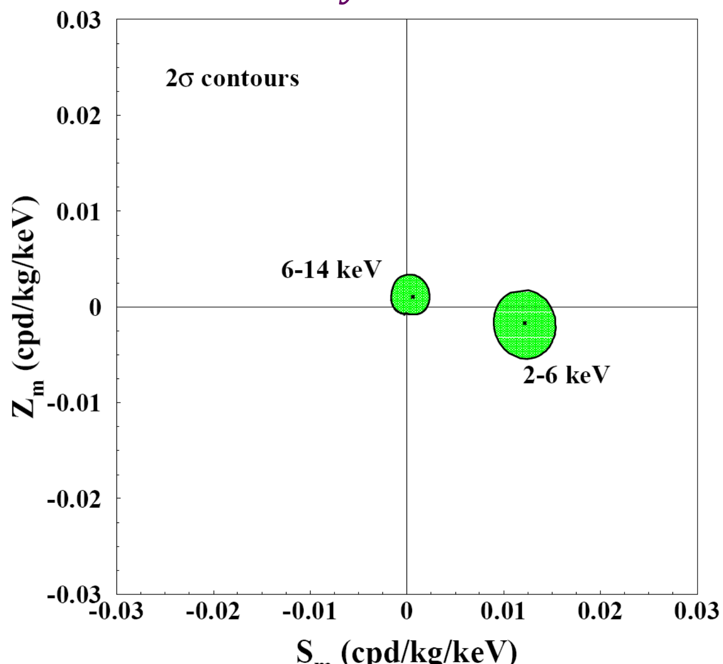
Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?

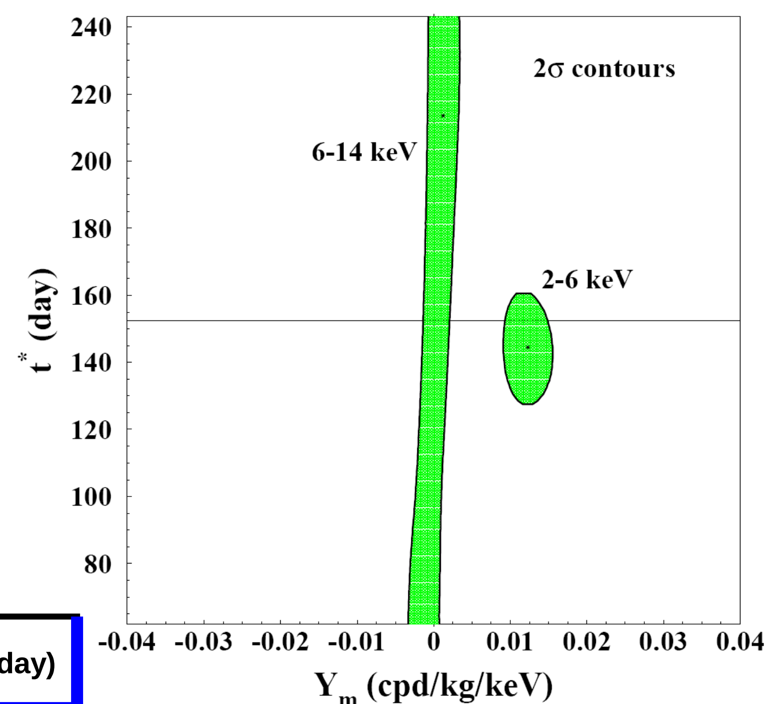
$$R(t) = S_0 + S_m \cos[\omega(t-t_0)] + Z_m \sin[\omega(t-t_0)] = S_0 + Y_m \cos[\omega(t-t^*)]$$

For Dark Matter signals:

- $|Z_m| \ll |S_m| \approx |Y_m|$
- $t^* \approx t_0 = 152.5d$
- $\omega = 2\pi/T$
- $T = 1$ year

Slight differences from 2nd June are expected in case of contributions from non thermalized DM components (as e.g. the SagDEG stream)

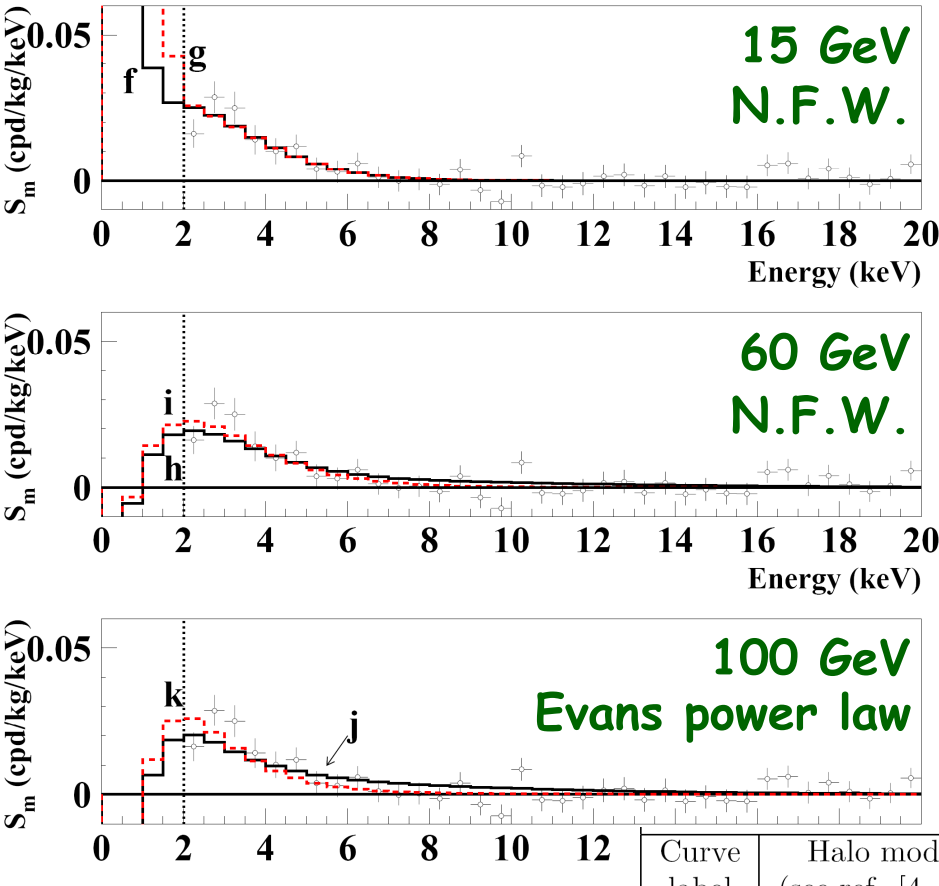




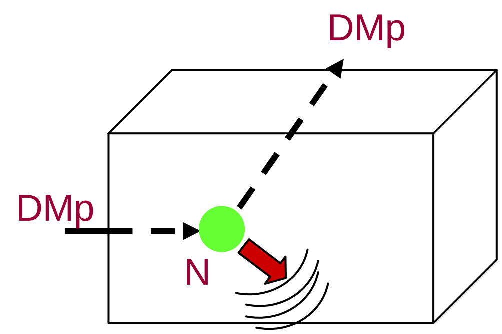
E (keV)	S_m (cpd/kg/keV)	Z_m (cpd/kg/keV)	Y_m (cpd/kg/keV)	t* (day)
2-6	0.0122 ± 0.0016	-0.0019 ± 0.0017	0.0123 ± 0.0016	144.0 ± 7.5
6-14	0.0005 ± 0.0010	0.0011 ± 0.0012	0.0012 ± 0.0011	--

from P Belli's talk at IDM2008

Examples for few of the many possible scenarios superimposed to the measured modulation amplitues $S_{m,k}$



WIMP DM candidate (as in [4])
Elastic scattering on nuclei
SI & SD mixed coupling
v_0 = 170 km/s



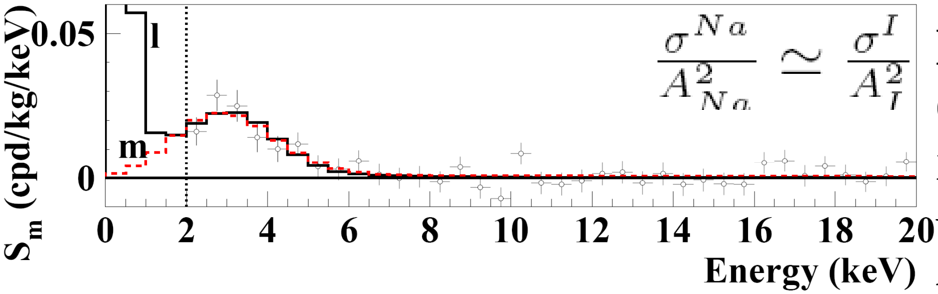
About the same C.L.

...scaling from NaI

Curve label	Halo model (see ref. [4, 34])	Local density (GeV/cm^3)	Set as in [4]	DM particle mass	$\xi\sigma_{SI}$ (pb)	$\xi\sigma_{SD}$ (pb)
f	A5 (NFW)	0.2	A	15 GeV	10^{-7}	2.6
g	A5 (NFW)	0.2	A	15 GeV	1.4×10^{-4}	1.4
h	A5 (NFW)	0.2	B	60 GeV	10^{-7}	1.4
i	A5 (NFW)	0.2	B	60 GeV	8.7×10^{-6}	8.7×10^{-2}
j	B3 (Evans power law)	0.17	A	100 GeV	10^{-7}	1.7
k	B3 (Evans power law)	0.17	A	100 GeV	1.1×10^{-5}	0.11

[4] RNC 26 (2003) 1; [34] PRD66 (2002) 043503

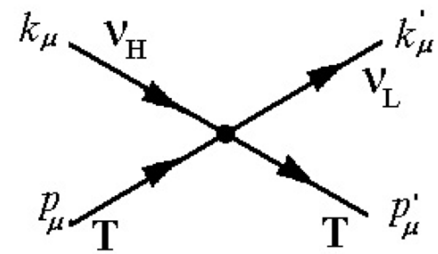
Examples for few of the many possible scenarios superimposed to the measured modulation amplitues $S_{m,k}$

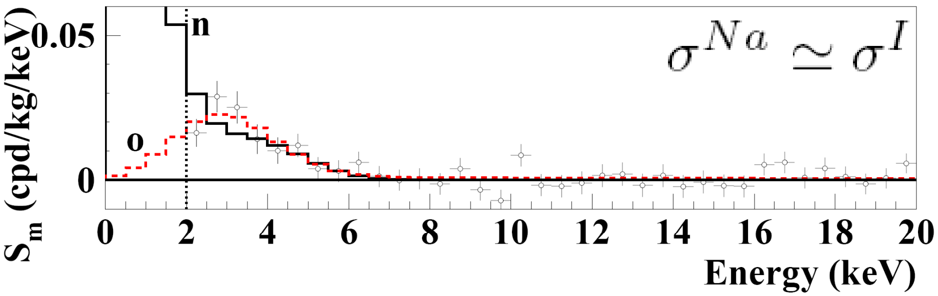


LDM candidate

(as in arXiv:0802.4336):

inelastic interaction with electron or nucleus targets

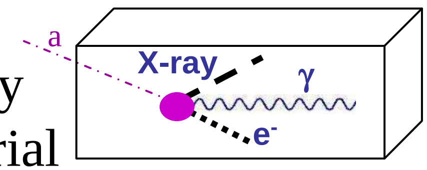


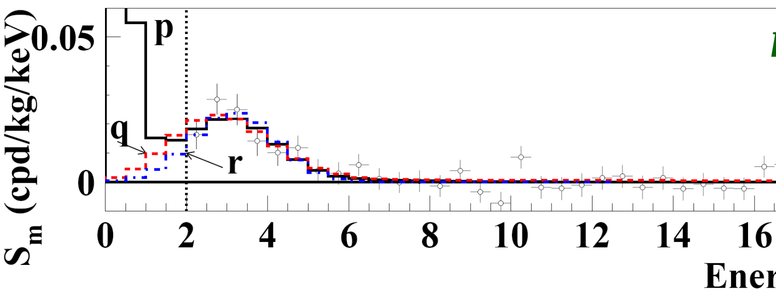


Light bosonic candidate

(as in IJMPA21(2006)1445):

axion-like particles totally absorbed by target material





About the same C.L.

(NFW) halo model as in [4, 34], local density = 0.17 GeV/cm^3, local velocity = 170 km/s

Curve label	DM particle	Interaction	Set as in [4]	m_H	Δ	Cross section (pb)
l	LDM	coherent on nuclei	A	30 MeV	18 MeV	$\xi\sigma_m^{coh} = 1.8 \times 10^{-6}$
m	LDM	coherent on nuclei	A	100 MeV	55 MeV	$\xi\sigma_m^{coh} = 2.8 \times 10^{-6}$
n	LDM	incoherent on nuclei	A	30 MeV	3 MeV	$\xi\sigma_m^{inc} = 2.2 \times 10^{-2}$
o	LDM	incoherent on nuclei	A	100 MeV	55 MeV	$\xi\sigma_m^{inc} = 4.6 \times 10^{-2}$
p	LDM	coherent on nuclei	A	28 MeV	28 MeV	$\xi\sigma_m^{coh} = 1.6 \times 10^{-6}$
q	LDM	incoherent on nuclei	A	88 MeV	88 MeV	$\xi\sigma_m^{inc} = 4.1 \times 10^{-2}$
r	LDM	on electrons	–	60 keV	60 keV	$\xi\sigma_m^{e} = 0.3 \times 10^{-6}$

curve *r*: also pseudoscalar axion-like candidates (e.g. majoron)
m_a=3.2 keV g_{aee}= 3.9 10^{-11}

[4] RNC 26 (2003) 1; [34] PRD66 (2002) 043503

Summary

Conclusive Evidence for Cold Dark Matter

Viable Theories for Particle Candidates

Some “Indication” in Experiments

An Exciting and Lively Field