

# Dark Matter Laboratory Searches

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Texel, NL

# Outline

1. The Evidence for Dark Matter
2. Dark Matter Detection Experimental Techniques
3. Dark Matter Search Status and Prospects
4. Neutrino Physics in Dark Matter Detectors

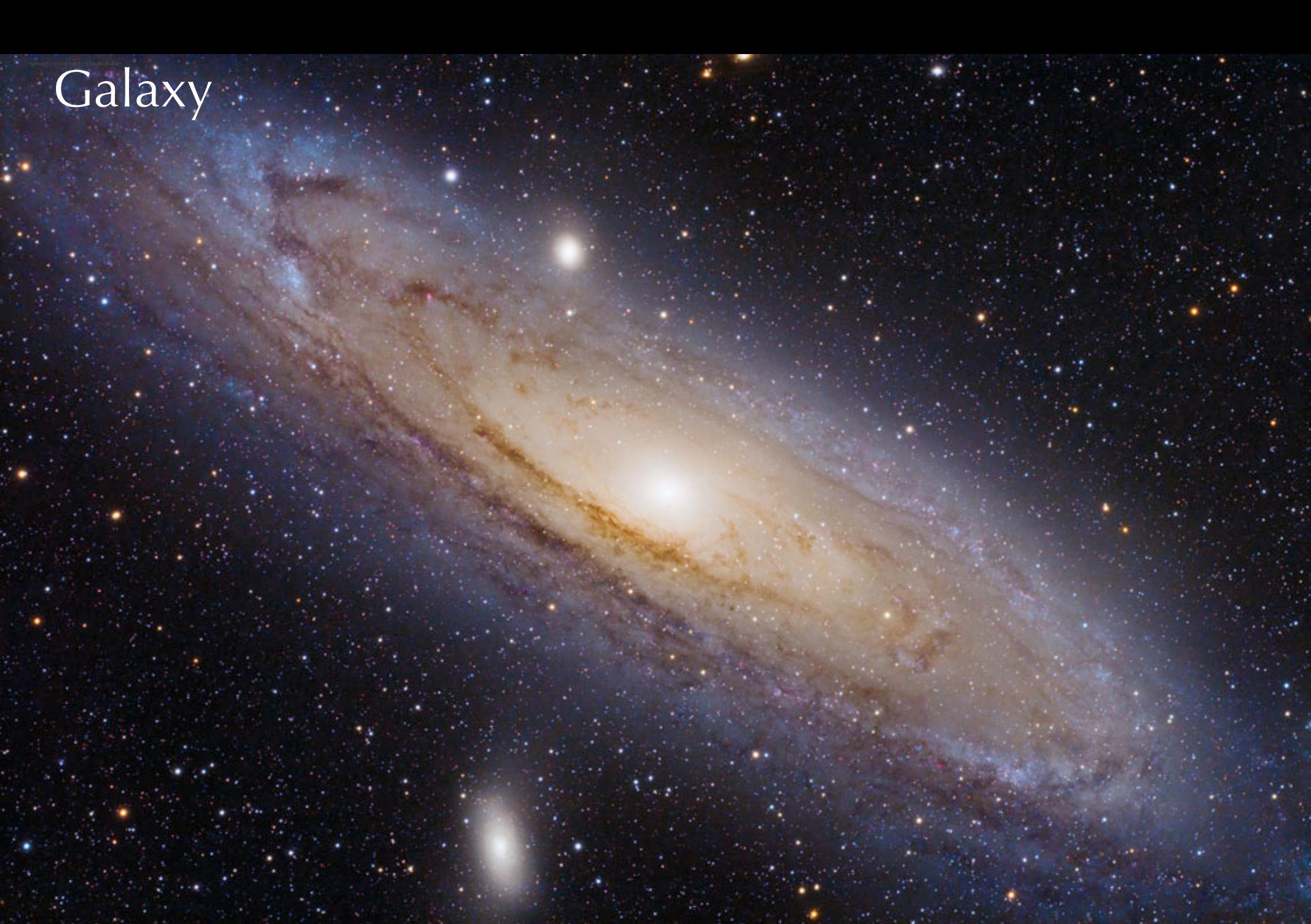
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I. Evidence for dark matter

- I • evidence for dark matter
- galaxy clusters
  - galactic rotation curves
  - gravitational lensing
  - LMB and large-scale structure

# Galaxy



# 1<sup>st</sup> Observation: 1930s



Fritz Zwicky

(Kitt Peak)

Virial Theorem: kinetic energy  $\propto$  potential energy  
*implies 400x more mass than visible!*



i) virial analysis of galaxy clusters



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virial theorem relates time-averaged  $\langle V \rangle + \langle KE \rangle$  of bound system of non-relativistic  $m_i$ , interacting via central force  $F(\vec{r}_i)$

$\vec{r}_i$  = vector from origin of coordinate system to each  $m_i$



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$\vec{r}_i$  = vector from origin of coordinate system to each  $m_i$

$$\begin{aligned} \text{virial } W &\equiv \sum \vec{p}_i \cdot \vec{r}_i \\ \frac{dW}{dt} &= \sum_i \vec{p}_i \cdot \ddot{\vec{r}}_i + \sum_i \vec{p}_i \cdot \dot{\vec{r}}_i \\ &= \sum_i m_i \ddot{\vec{r}}_i \cdot \vec{r}_i + \sum_i m_i |\vec{v}_i|^2 \\ &= \sum_i \vec{F}_i \cdot \vec{r}_i + 2 \sum_i KE_i \\ &= \sum_i \left( \frac{\partial V_i}{\partial r_i} \right) \cdot \vec{r}_i + 2 \sum_i KE_i \end{aligned}$$



$$= \sum_i \left( \frac{\partial \vec{v}_i}{\partial r_i} \right) \cdot \vec{r}_i + 2 \sum_i k \vec{e}_i$$



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we know  $\nabla_{\text{grav}} \propto -\frac{1}{r} \rightarrow \frac{\partial V}{\partial r} \cdot r = \left( \frac{1}{r^2} \hat{r} \right) \cdot r \hat{r} = \frac{1}{r}$

$$\downarrow = - \sum_i \vec{V}_i + 2 \sum_i k E_i$$



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$$\downarrow = - \sum_i \vec{v}_i + 2 \sum_i k E_i$$

time average  $\langle w \rangle = \frac{1}{T} \int \left( \frac{dw}{dt} \right) dt \rightarrow 0 \text{ as } T \rightarrow \infty$

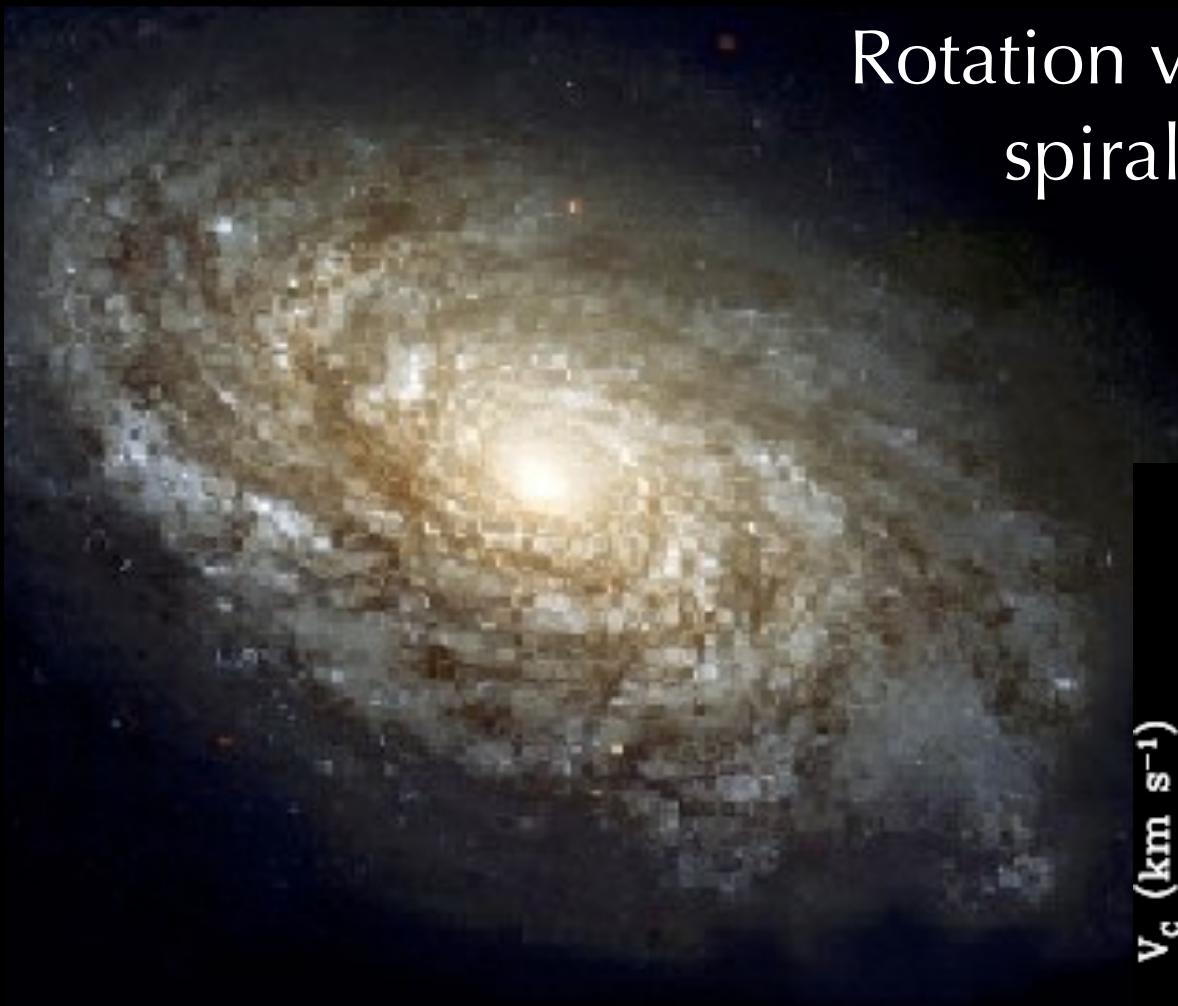
$$\therefore \langle v \rangle = 2 \langle k E \rangle$$

Zwicky applied this to coma cluster of galaxies, found  
 $\sim 500 \times$  more mass implied by  $2 \langle k E \rangle$  than was visible



# Confirmation: 1980s

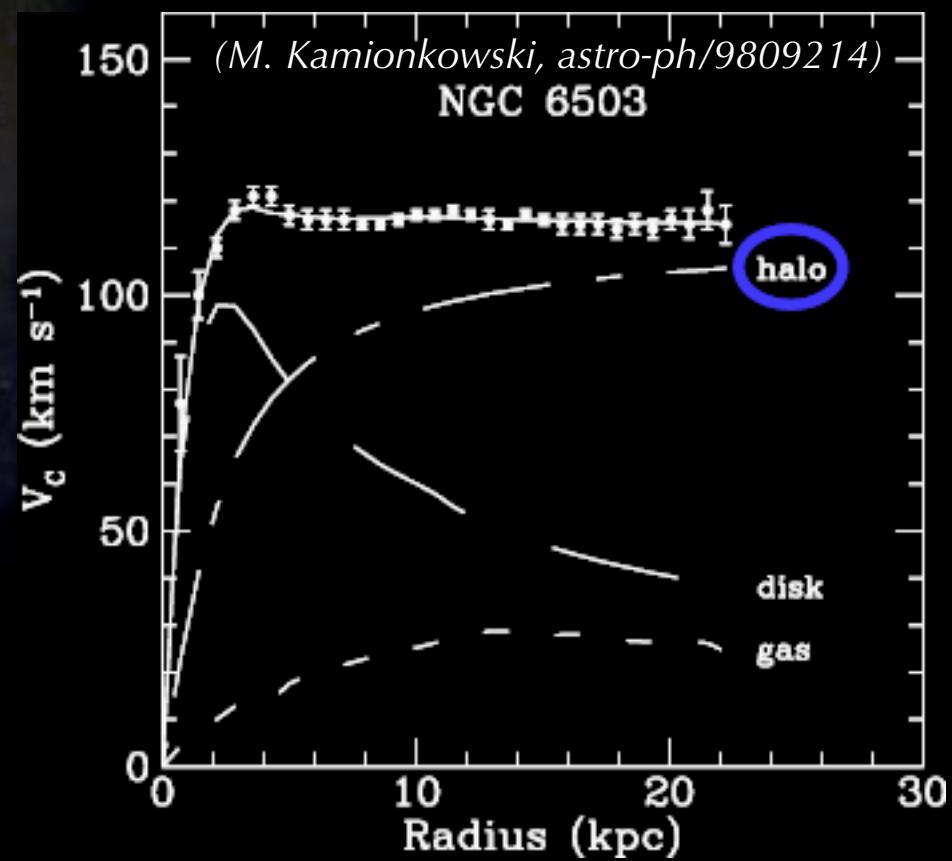
Vera Rubin



Rotation velocity  $v(r)$  of  
spiral galaxies



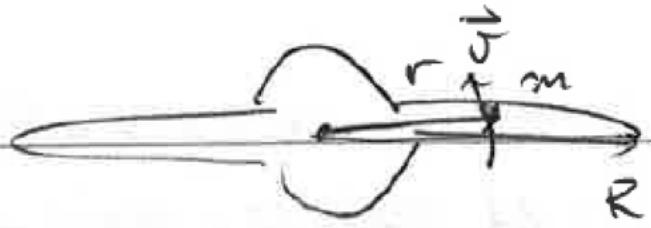
*implies 100x more mass  
than visible!*



2) rotation curves of spiral galaxies

orbit condition  $\vec{F}_c + \vec{F}_g = 0$

$$\frac{mv^2}{r} = \frac{GM(r)m}{r^2}$$



imagine  $\rho = \frac{M}{\frac{4}{3}\pi R^3} = \text{const.}$



2) rotation curves of spiral galaxies

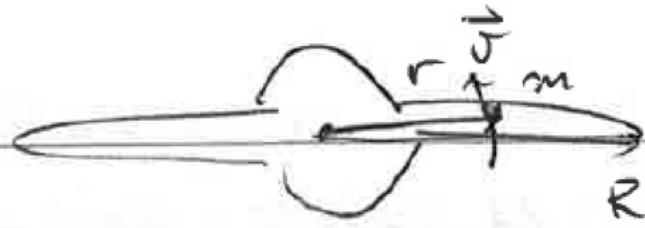
$$\text{orbit condition } \vec{F}_c + \vec{F}_g = 0$$

$$\frac{mv^2}{r} = \frac{GM(r)m}{r^2}$$

$$M(r) = \iiint_0^{\pi} \rho r^2 r^2 \sin\theta' dr' d\theta' d\phi' = \frac{4}{3}\pi r^3 \rho$$

$$\cdot \text{ if } r < R : M(r) = M\left(\frac{r^3}{R^3}\right), \omega^2 = \frac{GM}{r^2} \rightarrow \omega \propto \frac{1}{r}$$

$$\cdot \text{ if } r \geq R : M(r) = M, \omega^2 = \frac{GM}{r} \rightarrow \omega \propto \sqrt{\frac{1}{r}}$$



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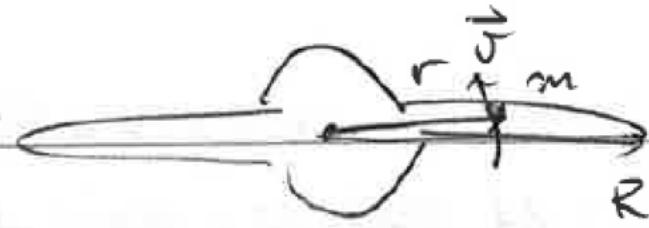
$$M(r) = \iiint_0^{\pi} \int_0^{2\pi} \rho r^2 \sin\theta' dr' d\theta' d\phi' = \frac{4\pi r^3}{3} \rho$$

if  $r < R$ :  $M(r) = M\left(\frac{r^3}{R^3}\right)$ ,  $\omega^2 = \frac{GM}{r^2} \rightarrow \omega \propto r$

if  $r \geq R$ :  $M(r) = M$ ,  $\omega^2 = \frac{GM}{r^2} \rightarrow \omega \propto \sqrt{\frac{1}{r}}$

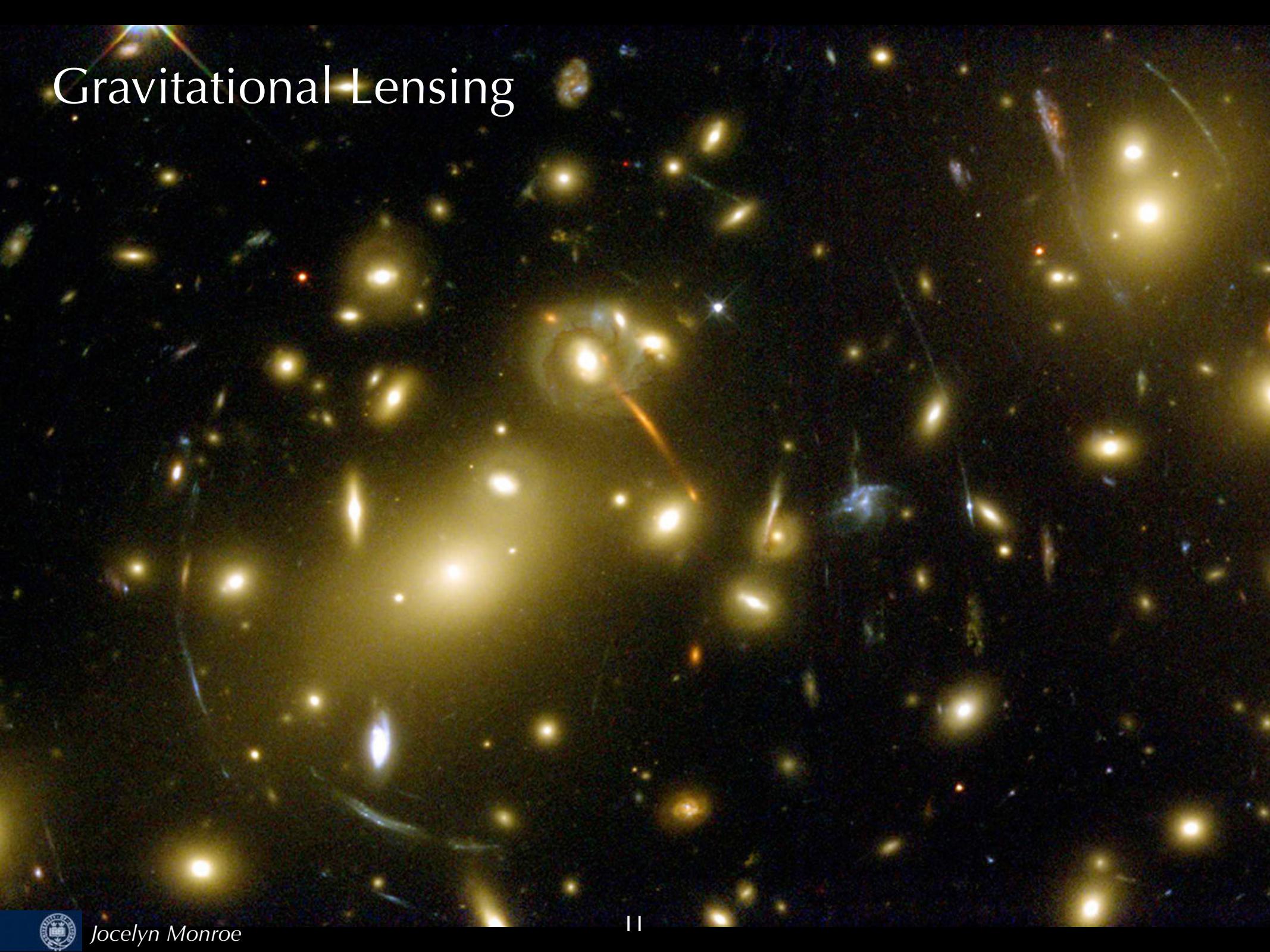
V. Rubin found 70-80% of spiral galaxies is "dark" matter, not luminous.

in other types (e.g. elliptical), dark matter can be ~99%!



$$\text{imagine } \rho = \frac{M}{\frac{4}{3}\pi R^3} = \text{const.}$$

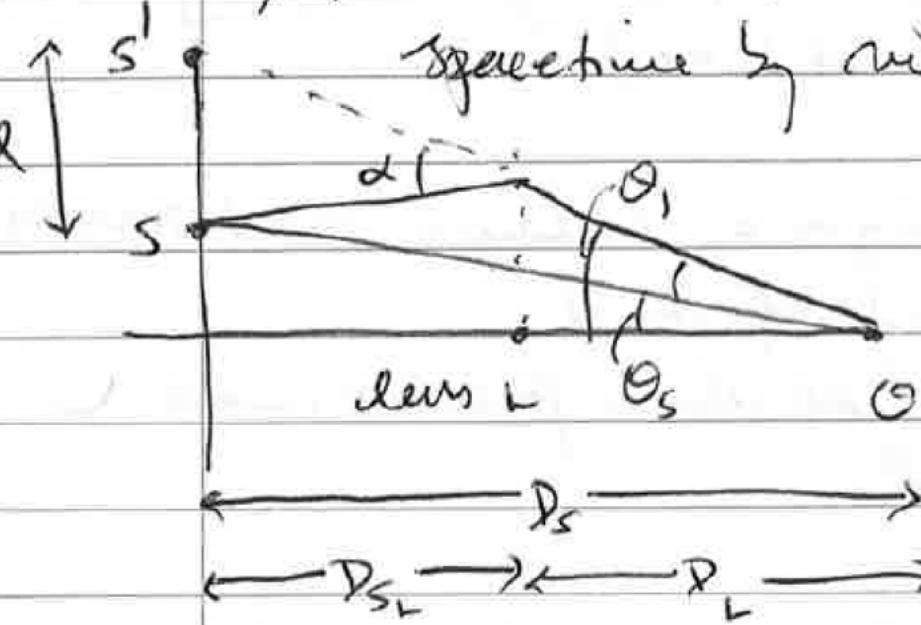
# Gravitational Lensing



3) Gravitational Lensing: deflection of photons by bending of  
space-time by massive, foreground object.

↑ s' q

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$d$  = deflection angle

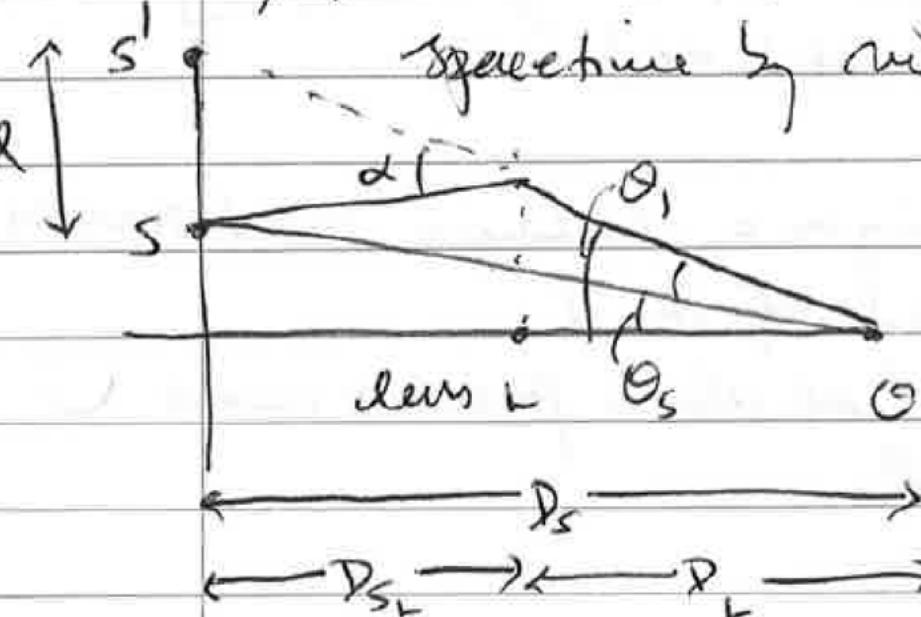
$b$  = impact parameter (distance of closest approach) =  $\theta_1 D_L$

$$\text{constant (PLW2)} \quad d = \frac{4GM}{c^2 b}$$

$$d = \alpha D_{LS}$$

find  $\theta_1$  = angle where "lensed" image appears.

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$$d = \alpha D_{LS}$$

find  $\theta_1$  = angle where "lensed" image appears.

$$d = \alpha D_{LS} = (\theta_1 - \theta_S)$$

solve for  $\theta_S$  =

$$\frac{\theta_1 D_S - \alpha D_{LS}}{D_S}$$

$$= \theta_1 - \left( \frac{4GM}{c^2 b} \right) \frac{D_{LS}}{D_S}$$

Subst for  $b$

$$= \theta_1 - \left( \frac{4GM}{c^2} \right) \frac{D_{LS}}{D_S} \left( \frac{1}{D_L \theta_1} \right)$$

$$= \theta_1 - \left( \frac{4\mu}{c^2} \right) \frac{D_{LS}}{D_S} \left( \frac{1}{D_L \theta_1} \right)$$

$$= \theta_1 - \left( \frac{4\pi M}{c^2} \right) \frac{D_{LS}}{D_S} \left( \frac{1}{D_L \theta_1} \right)$$

Solve for  $\theta_1 = \left[ \left( \frac{4\pi M}{c^2} \right) \left( \frac{D_{LS}}{D_S D_L} \right) \right] \gamma_2 \equiv \theta_E$  Elastohydro angle.

- in linear case,  $\theta_S = 0$ , see a ring!
- if not on-axis (general case)  $\theta_S \neq 0$ , get 2 images at  $\theta_{1,2} = \theta_S \pm \sqrt{\theta_S^2 + 4\theta_E^2}$
- for a point mass in plane S, L, O

$$= \Theta_1 - \left( \frac{4GM}{c^2} \right) \frac{D_{LS}}{D_S} \left( \frac{1}{D_L \Theta_1} \right)$$

Solve for  $\Theta_1 = \left[ \left( \frac{4GM}{c^2} \right) \left( \frac{D_{LS}}{D_S D_L} \right) \right]^{1/2} \equiv \Theta_E$  = Einstein ring  
angle.

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ex)  $M_{\text{cluster}} = 10^{14} M_\odot$ ,  $D_{LS} = D_L = \frac{D_S}{2} = 100 \text{ Mpc}$ ,  
 $\Theta_E = 65 \text{ arcsec}$ .

$M_{\text{cluster}} = 10 M_\odot$ ,  $D_{LS} = D_L = \frac{D_S}{2} = 2 \text{ pc}$   
 $\Theta_E = 0.065 \text{ arcsec}$  "microlensing"

# Direct Astrophysical Observation: 2006

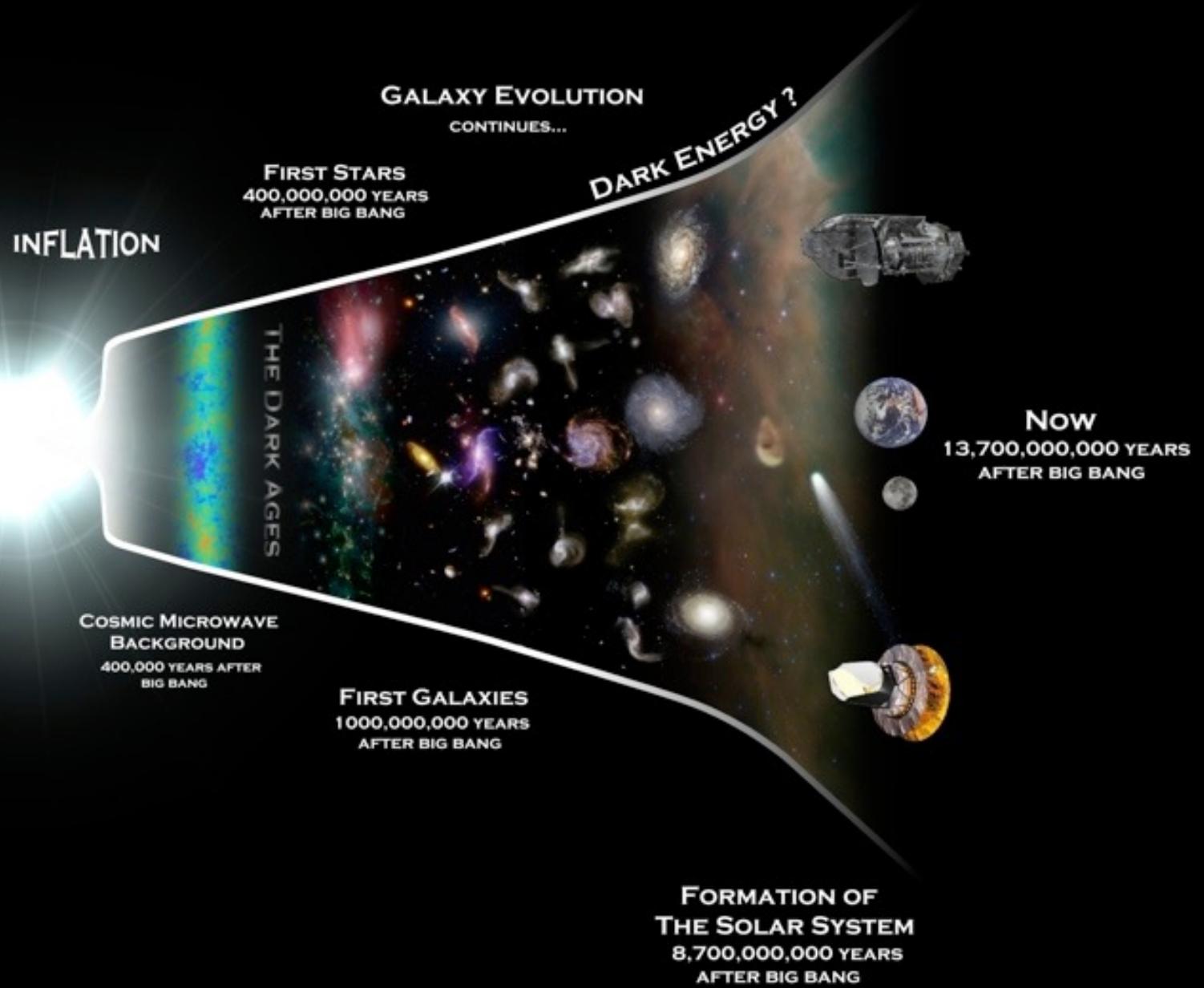


(NASA/Chandra/Magellan/Hubble)

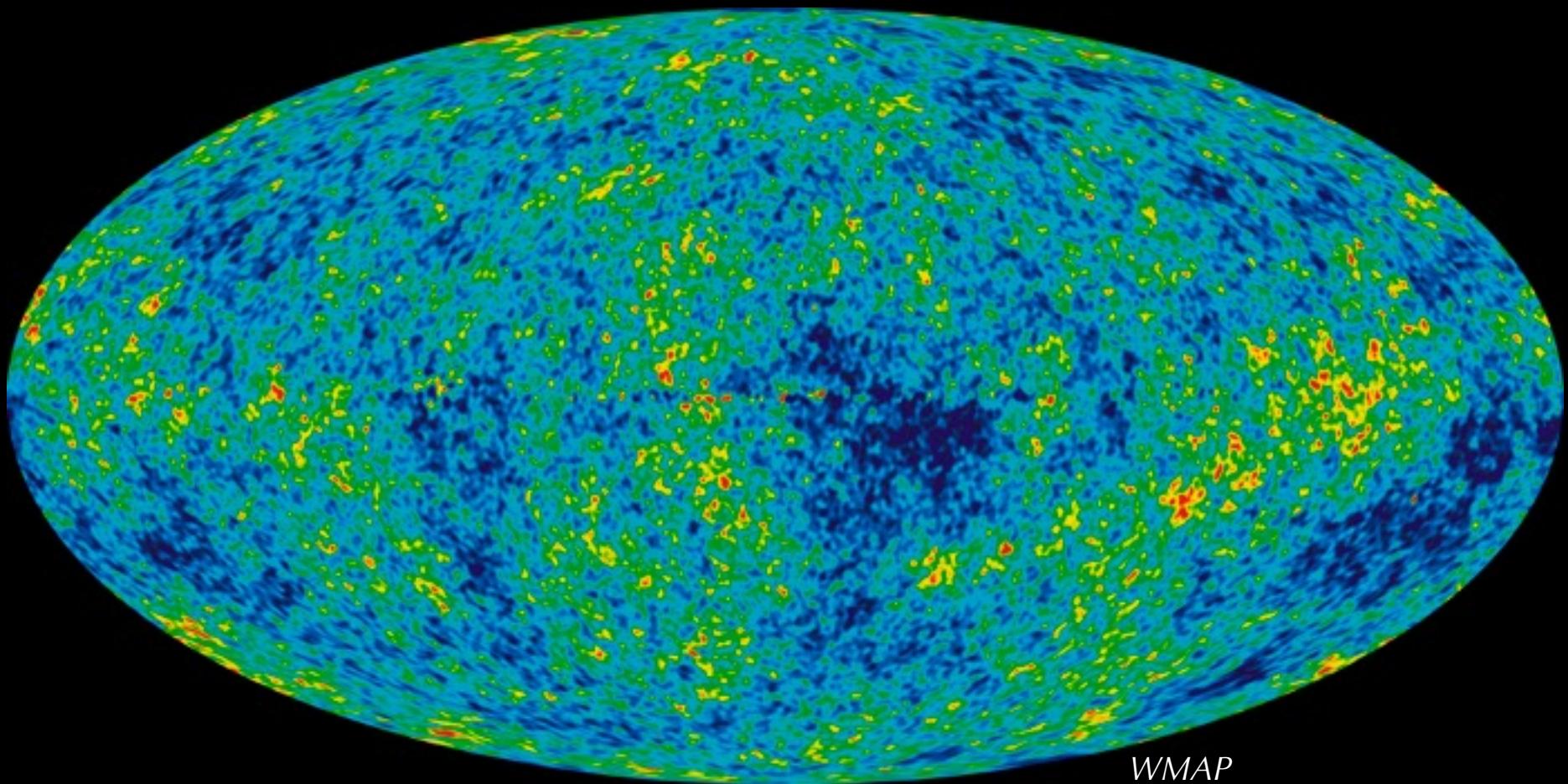
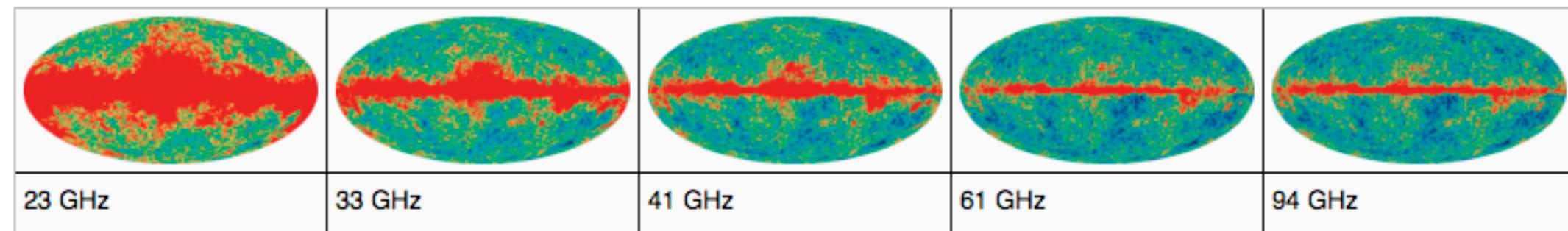
*“NASA Finds Direct Proof of Dark Matter”*



# THE BIG BANG

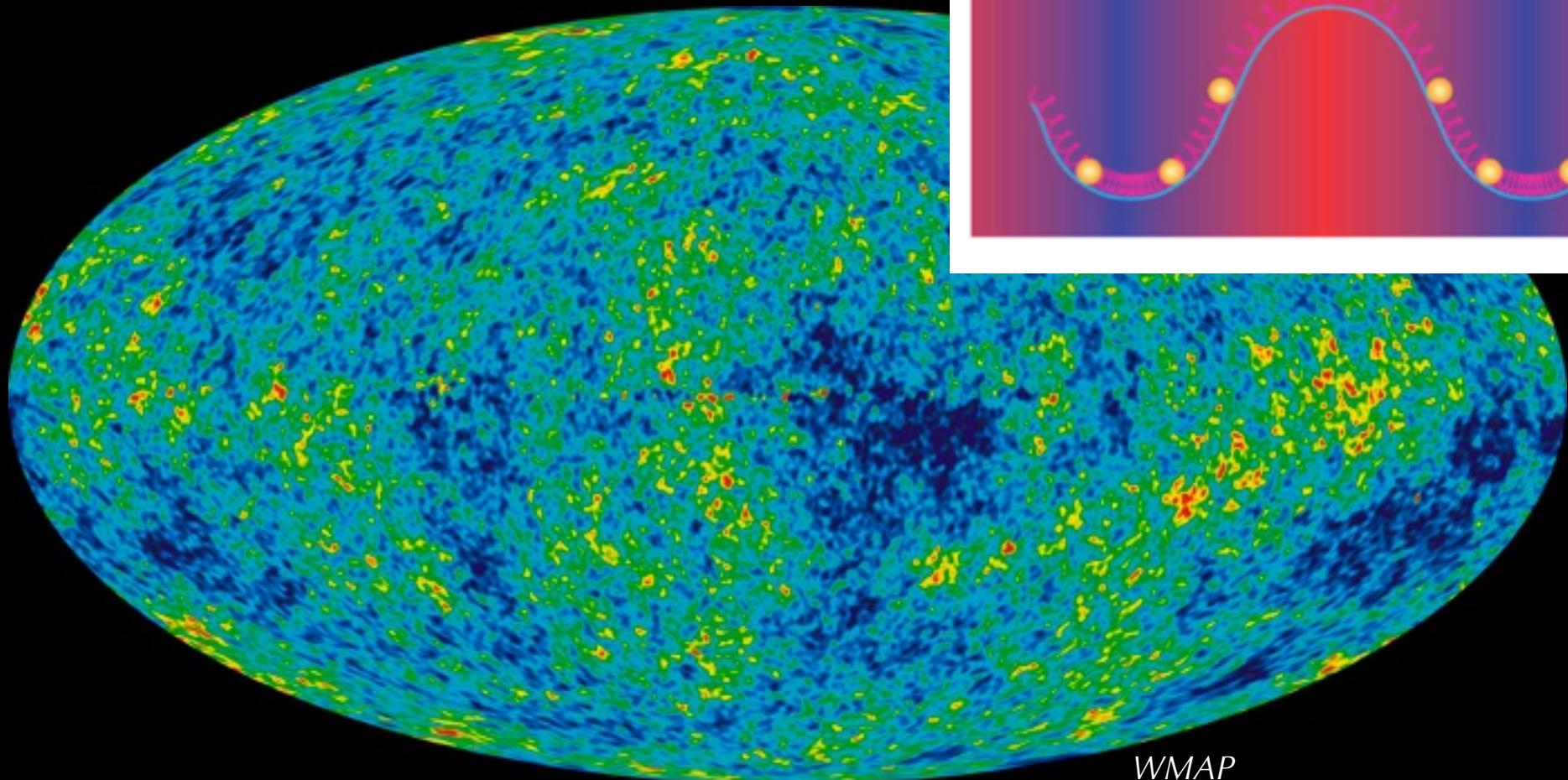


# Cosmic Microwave Background

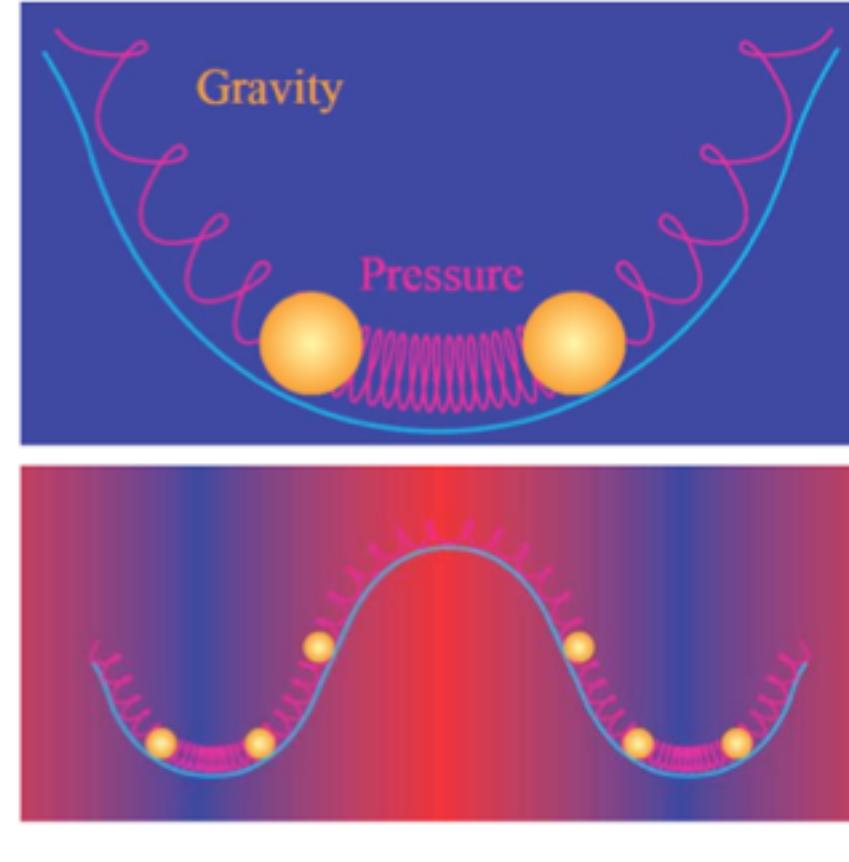


# Cosmic Microwave Background

fluctuations in the cosmic microwave background probe the composition of the early universe



WMAP



4) CMB Angular Spectrum of Anisotropies.

(Cosmology Aside...)

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Friedmann Eqn:  $H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{R^2} \left( + \frac{\Lambda}{3} \right)$

$k$  = curvature parameter

from bending of Spectrum by mass

$\rho$  = energy density

$G$  = Newton's constant

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Sources of Energy Density,  $\rho_{tot} = \rho_{matter} + \rho_{rad.} + \rho_\Lambda$

$$\text{Friedman Eqn: } H(t)^2 = \frac{a_0 \pi g}{2} \left[ p_m(t) + p_r(t) + p_a(t) + p_e(t) \right]$$

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(dust & gases)  $\Rightarrow H_0^2 [\Omega_m(t) + \Omega_r(t) + \Omega_\lambda(t) + \Omega_{\nu_e}(t)]$

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(dust + radiation + dark energy + neutrinos)

$$= H_0^2 [\Omega_m(t) + \Omega_r(t) + \Omega_\lambda(t) + \Omega_\nu(t)]$$

- observe  $\dot{L} \approx 0$ ,  $\rightarrow$  define  $p_c \equiv \frac{3H^2}{8\pi G}$

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$$\Omega_{tot} = \Omega_m + \Omega_r + \Omega_\lambda + \Omega_\Lambda = 1$$

$$\Omega_m = \frac{p_m}{p_c}, \quad \Omega_r = \frac{p_r}{p_c}, \quad \Omega_\lambda = \frac{p_\lambda}{p_c} = \frac{1}{p_c} = \frac{1}{\frac{8\pi G}{3}} = \frac{3}{8\pi G}$$

$$\text{Friedmann Eqn: } H(t)^2 = \frac{8\pi G}{3} [p_m(t) + p_r(t) + p_\lambda(t) + p_k(t)]$$

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$$\Omega_m = \frac{p_m}{p_c}, \quad \Omega_r = \frac{p_r}{p_c}, \quad \Omega_\lambda = \frac{p_\lambda}{p_c} = \frac{1}{p_c} = \frac{\Lambda}{8\pi G}$$

$$\Omega_k = -\frac{kc^2}{H_0^2 R^2}$$

$\Lambda = \text{cosmological constant}$

4) CMB Angular Spectrum of Anisotropies.

recall, distance a photon travels (horizon distance  $D_H$ )

$$D_H = R(0)r = \frac{1}{H_0} \int_{z=0}^{z=z} -c dz$$
$$\left[ \Omega_m(0)(1+z)^3 + \Omega_r(0)(1+z)^4 + \Omega_\Lambda(0) \right]^{1/2}$$

in a flat universe  $z=10$  (we have set  $k=0$ ).



# 4) CMB Angular Spectrum of Anisotropies.

Real, distance a photon travels (horizon distance  $D_H$ )

$$D_H = R(0)r = \frac{1}{H_0} \int_{z=0}^{\infty} \frac{c dz}{[\Omega_m(z)(1+z)^3 + \Omega_r(z)(1+z)^4 + \Omega_\Lambda(z)]^{1/2}}$$

**Table 7.1** Luminosity distance versus redshift

Dominant component	$\Omega_m$	$\Omega_\Lambda$	$\Omega_k$	$D_L H_0/c$
Matter (Einstein-de Sitter universe)	1	0	0	$2(1+z)[1-(1+z)^{-1/2}]$
Empty universe	0	0	1	$z(1+z/2)$
Vacuum	0	1	0	$z(1+z)$
Flat, matter + vacuum	0.24	0.76	0	Numerical integration giving best fit to data (see Fig. 7.14)



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4) CMB Angular Spectrum of Anisotropies.

Overall, distance a photon travels (horizon distance  $D_H$ )

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in a flat universe ( $\lambda = 0$ ) (we have set  $k=0$ ).

can also define an acoustic horizon = distance sound travel

$$D_{AH} = \left(\frac{v_s}{c}\right) D_H, \quad v_s = \text{speed of sound}$$

$= \text{Speed at which pressure waves}$   
 $= \text{distance}$   
 $= \text{travel.}$

Should see "clumps" from baryon acoustic oscillations.



- matter-radiation interactions relate  $\left(\frac{\Delta p}{\bar{p}}\right)$  density fluctuations to  $\left(\frac{\Delta T}{\bar{T}}\right)$  temperature fluctuations



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before matter-radiation decoupling at  $\sim t = 400,000$  yrs, get anisotropy in CMB from pressure wave, arising because of inhomogeneities  $\rightarrow$  matter compresses by gravity, fights radiation pressure from photons. Pressure wave travels at  $c_S$ .  $\rightarrow$  measure  $\langle \frac{\Delta T}{T} \rangle$ , probe  $\langle \frac{\Delta p}{p} \rangle$ .



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expt: COBE (1992)  $\delta\Theta \sim 7^\circ$  (Smoot & Deans Nobel 2006)

WMAP (1998)  $\sim 15^\circ$

Planck (2003) look for polarization in B-modes  
for imprint of gravity waves in inflation.

result:  $S_2^{\text{far}} = 1 \pm 0.02$ ,  $S_{2m} = 0.27$ ,  $S_{2\lambda} = 0.49$



- WMAP (and COBE before) measure

$$\hat{n} \cdot \hat{m} = \cos \theta$$

$$\hat{m} \quad \hat{n}$$

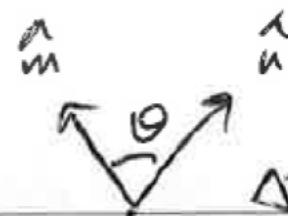


$$\frac{\Delta T(\hat{m})}{T} \text{ and } \frac{\Delta T(\hat{n})}{T}$$

two-pt. correlation  $\left\langle \left( \frac{\Delta T(\hat{m})}{T} \right) \left( \frac{\Delta T(\hat{n})}{T} \right) \right\rangle_{\text{same } \theta} =$

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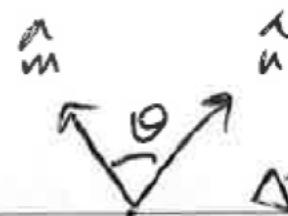
Report in terms of power spectrum  $\sum_l (2l+1) C_l \frac{P_l(\cos \theta)}{4\pi}$

$$P_l(\cos \theta) = \text{Legendre polynomials} = 0 \text{ at } \theta = \frac{n\pi}{2}/l \sim 200^\circ/l$$

$C_l$  = amplitude of fluctuations at multipole  $\ell$

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same  $\theta$

Report in terms of power spectrum

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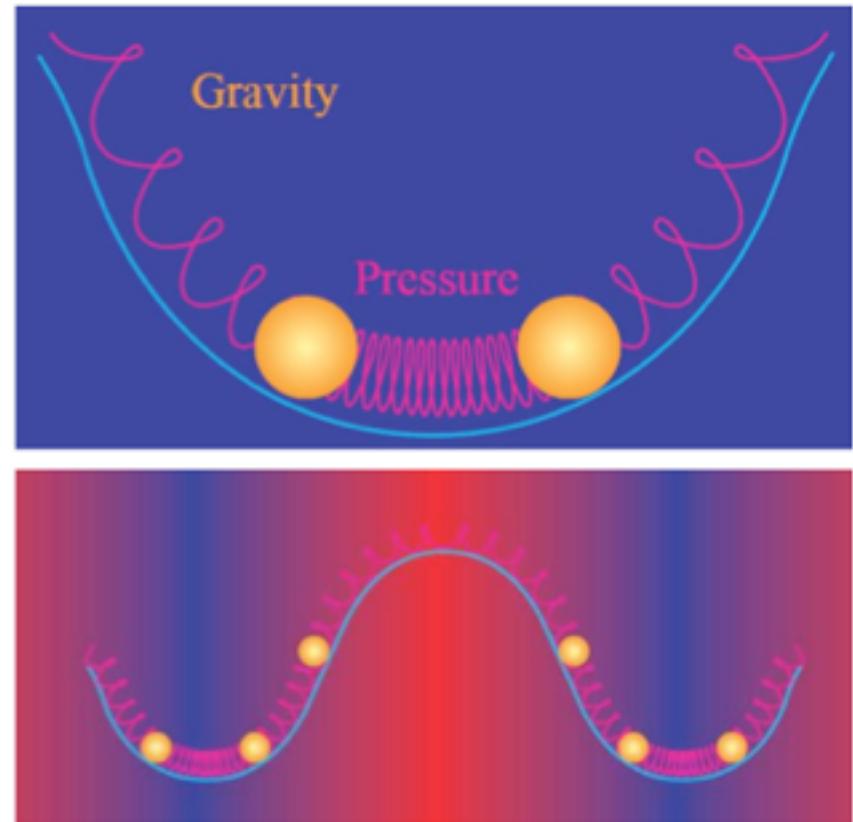
$C_l$  = amplitude of fluctuations at multipole  $\ell + l$

plot  $C_l$  vs.  $l$ , get 1<sup>st</sup> peak at acoustic horizon distance,  
amplitude related to  $S_{2m}$ ,  $k$ , etc. through  $D_H$ .

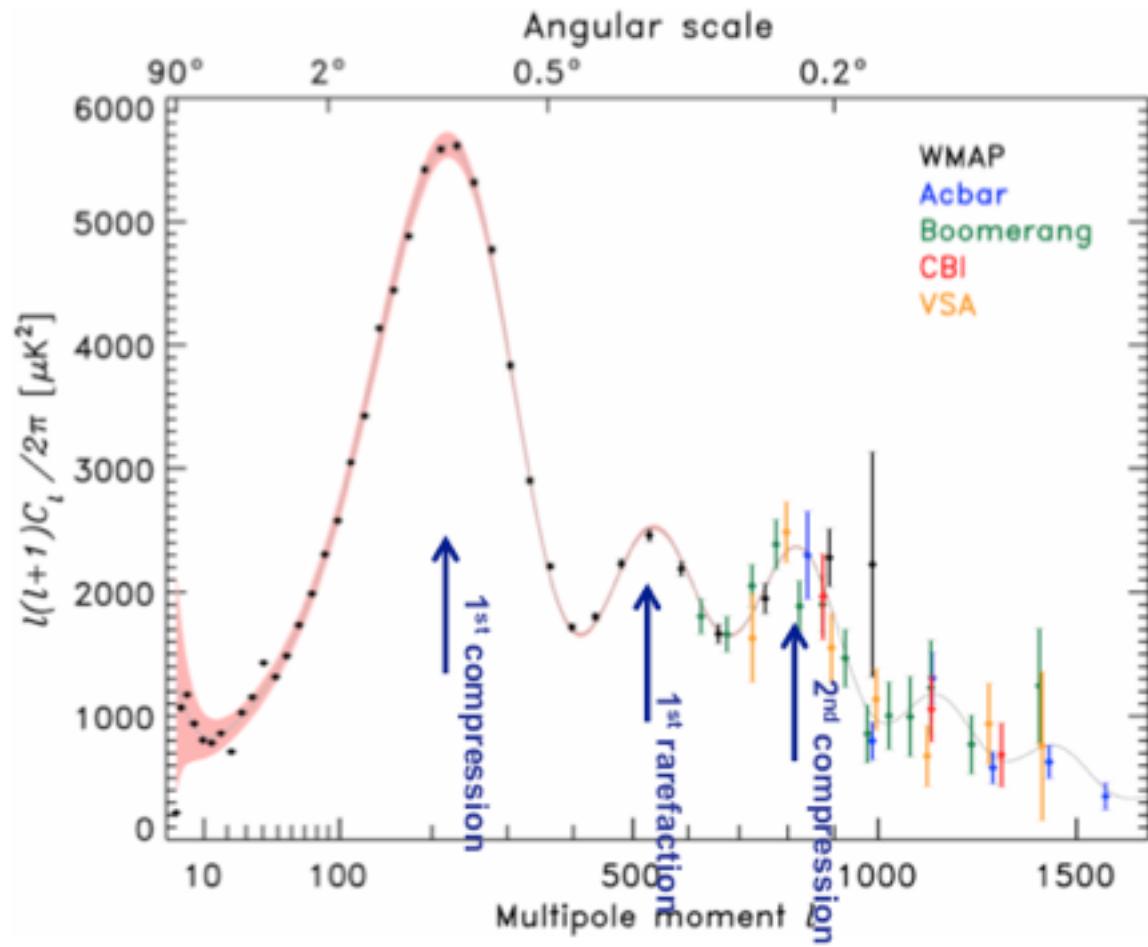
# CMB Acoustic Spectrum

## CMB “Baryometer”

From W. Wu (Chicago)



## Baryon Acoustic Oscillations



Baryons compress photon-baryon plasma at recombination,  
photons exert pressure, competition gives rise to pressure wave



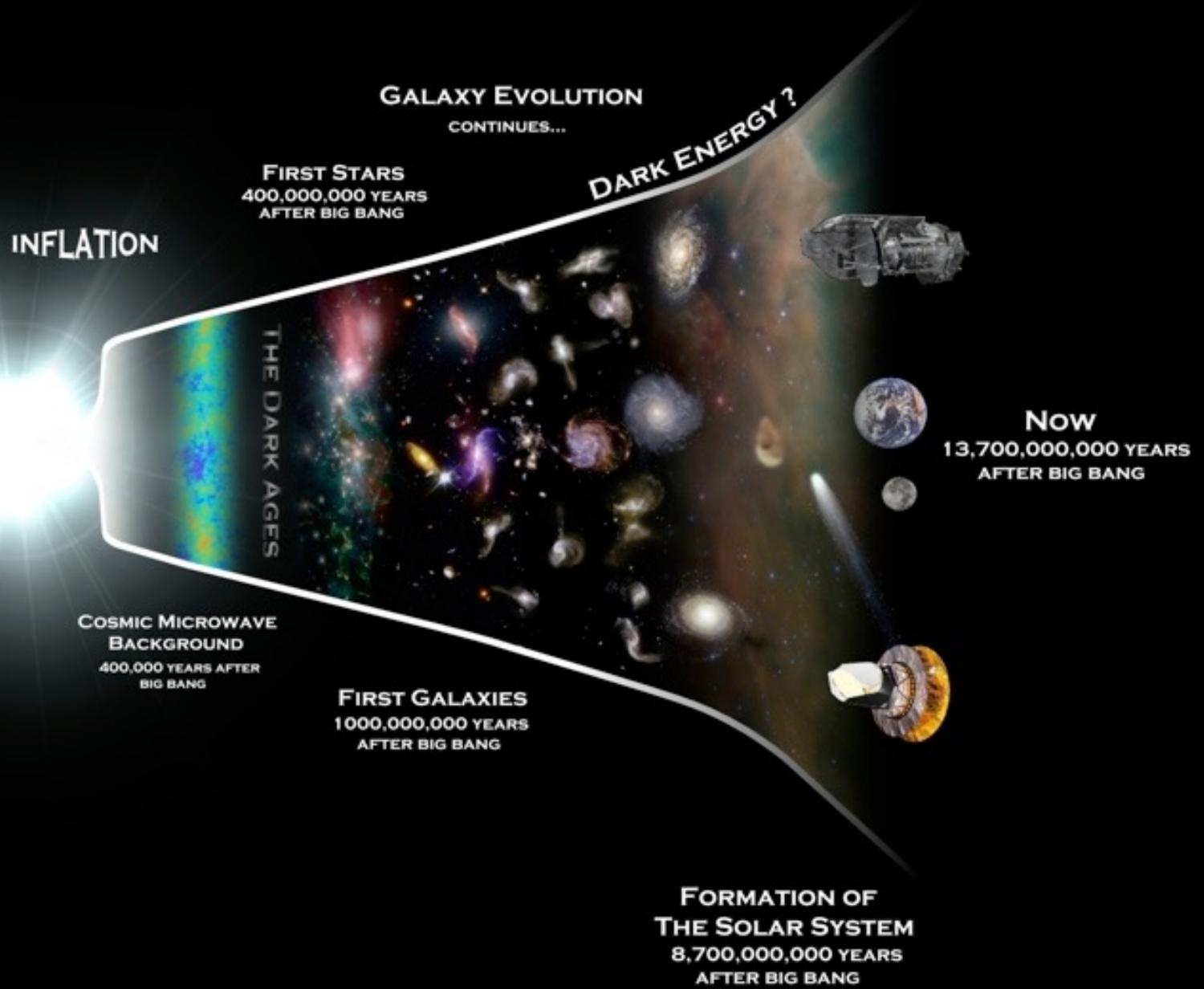
# Cosmological Parameters

Best-fit cosmological parameters from WMAP seven-year results<sup>[20]</sup>

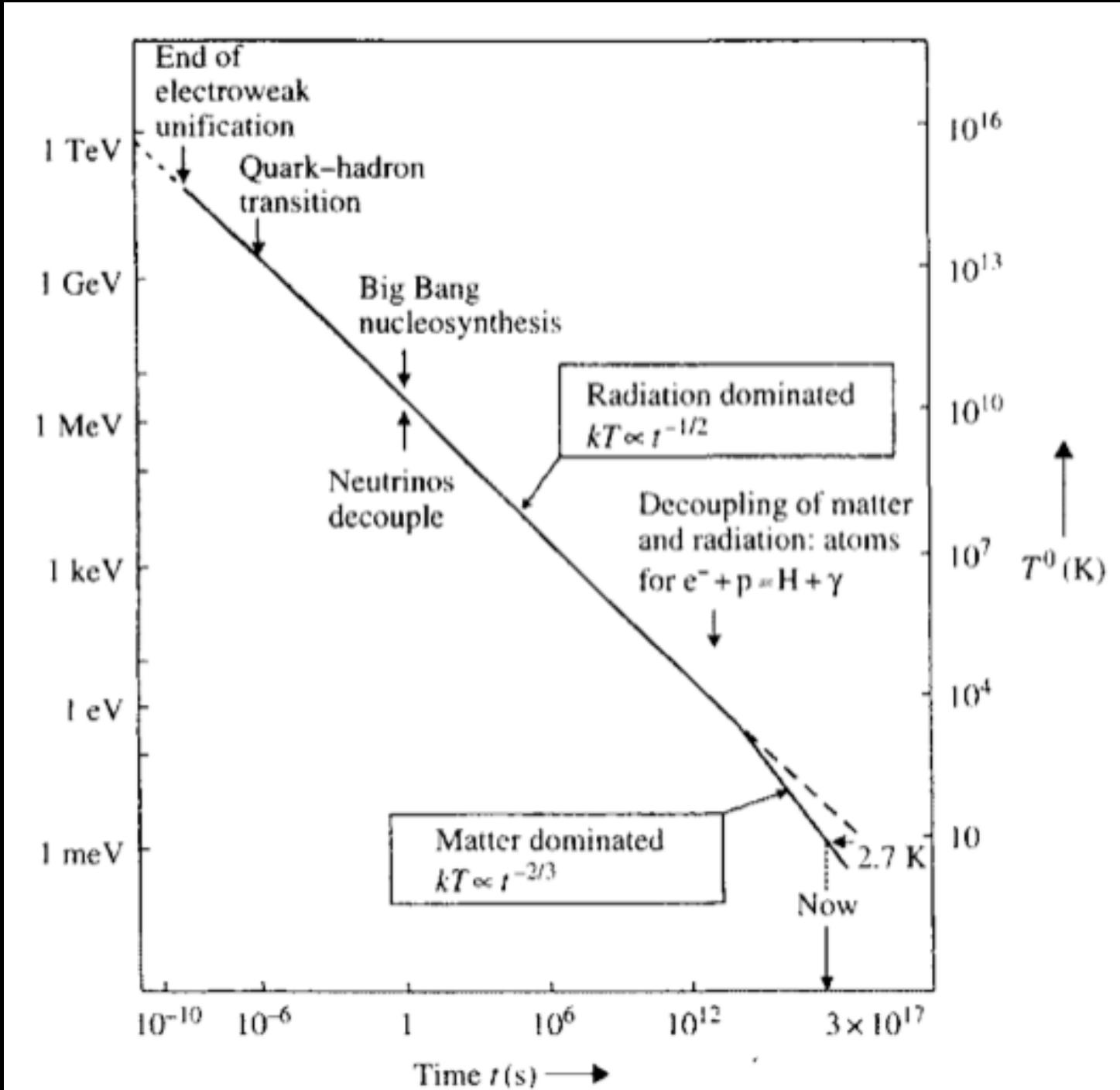
Parameter	Symbol	Best fit (WMAP only)	Best fit (WMAP + BAO <sup>[21]</sup> + H <sub>0</sub> <sup>[22]</sup> )
Age of the universe (Ga)	$t_0$	$13.75 \pm 0.13$	$13.75 \pm 0.11$
Hubble's constant (km/Mpc·s)	$H_0$	$71.0 \pm 2.5$	$70.4^{+1.3}_{-1.4}$
Baryon density	$\Omega_b$	$0.0449 \pm 0.0028$	$0.0456 \pm 0.0016$
Physical baryon density	$\Omega_b h^2$	$0.022\,58^{+0.000\,57}_{-0.000\,56}$	$0.022\,60 \pm 0.000\,53$
Dark matter density	$\Omega_c$	$0.222 \pm 0.026$	$0.227 \pm 0.014$
Physical dark matter density	$\Omega_c h^2$	$0.1109 \pm 0.0056$	$0.1123 \pm 0.0035$
Dark energy density	$\Omega_\Lambda$	$0.734 \pm 0.029$	$0.728^{+0.015}_{-0.016}$
Fluctuation amplitude at $8h^{-1}$ Mpc	$\sigma_8$	$0.801 \pm 0.030$	$0.809 \pm 0.024$
Scalar spectral index	$n_s$	$0.963 \pm 0.014$	$0.963 \pm 0.012$
Reionization optical depth	$\tau$	$0.088 \pm 0.015$	$0.087 \pm 0.014$

[20]

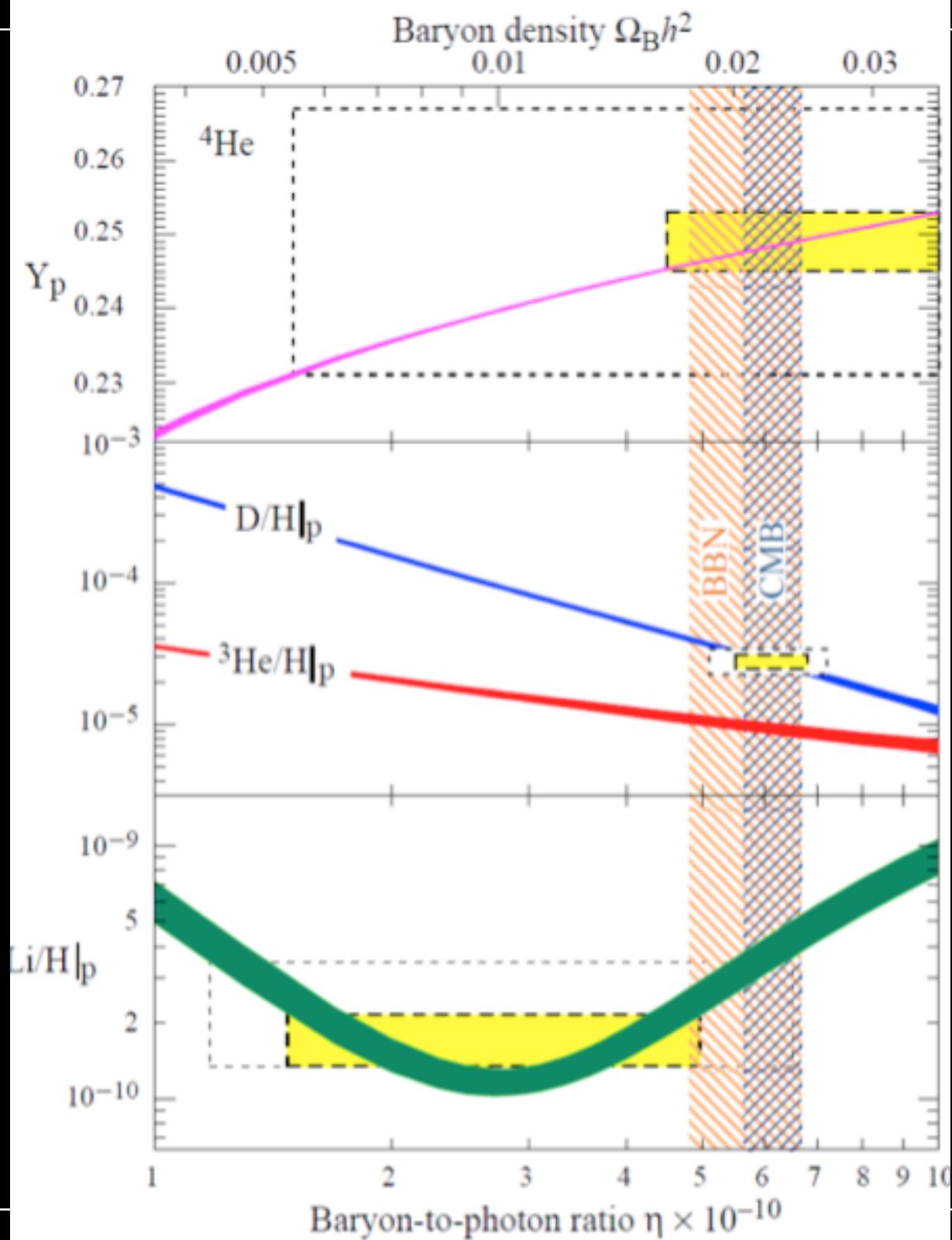
# THE BIG BANG



# Big Bang Nucleo-synthesis (BBN)



# BBN



lines =  
predicted  
light element  
abundances  
vs. baryon  
density

boxes =  
observed  
abundances  
(1, 2 sigma)

vertical band =  
CMB measure  
of baryon  
density  
(PDG)

The current baryon-to-photon ratio has been determined to be

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 5 \times 10^{-10}$$

Using this with  $H_0 = 70$  km/s/Mpc for the Hubble constant and approximating  $n_{\bar{B}} = 0$ , find the current value of  $\Omega_B = \rho_B/\rho_c$  and evaluate numerically.

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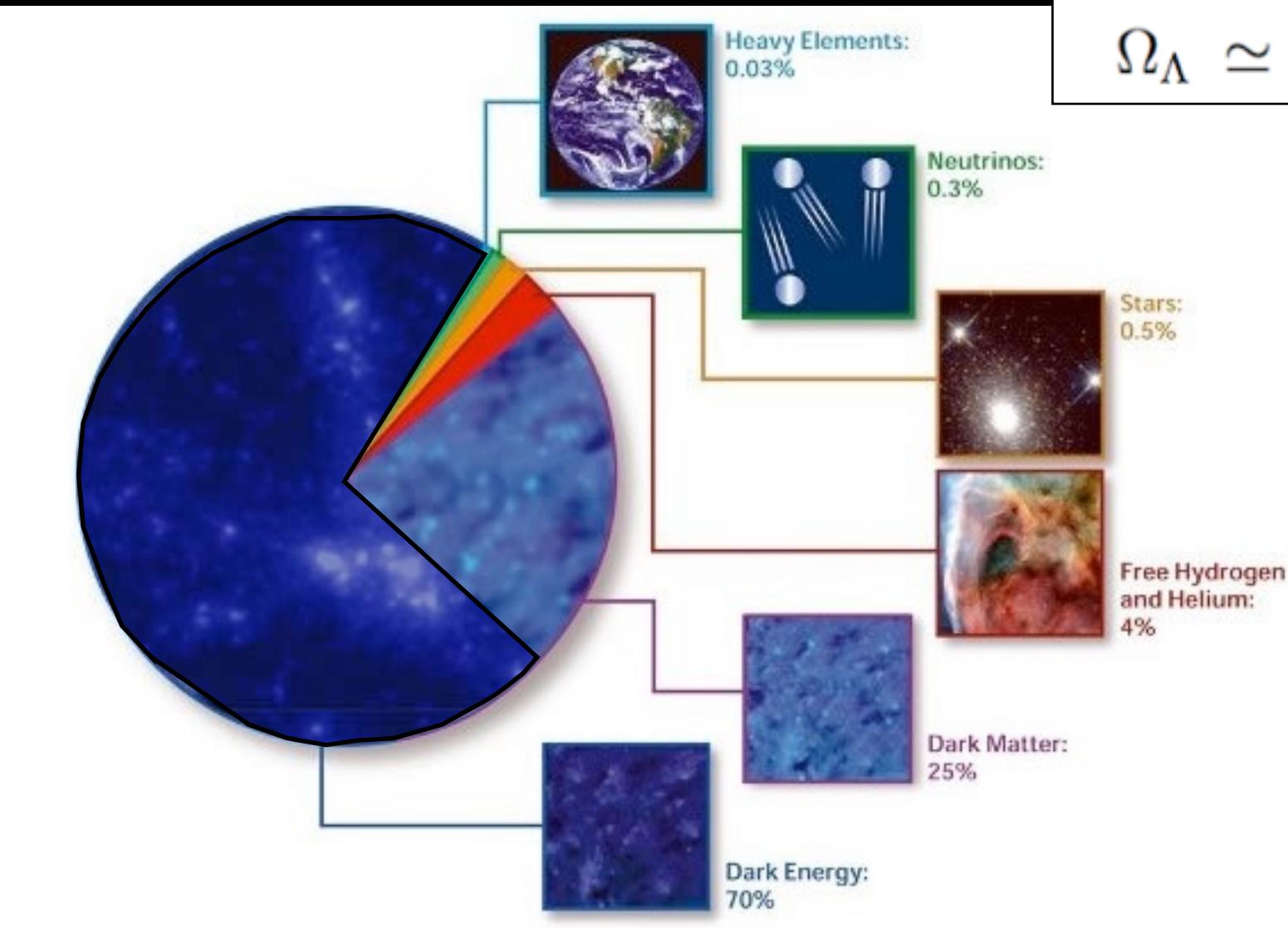
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The mass density  $\rho_B$  is then given by  $\rho_B = n_B \times m_B$ . Taking  $m_B$  as the proton mass is a good approximation. So to find the current value of  $\Omega$  we evaluate

$$\begin{aligned} \Omega_B &= \frac{\rho_B}{\rho_c} = \frac{m_B n_B 8\pi G}{3H_0^2} \\ &= \frac{(1.67 \times 10^{-27} \text{ kg})(2.055 \times 10^8 \text{ km}^{-3}) 8\pi (6.674 \times 10^{-20} \text{ km}^3 \text{ kg}^{-1} \text{ s}^{-2})}{3(2.16 \times 10^{-18} \text{ s}^{-1})^2} \\ &= 0.041 \end{aligned}$$

# The Standard Model of Cosmology

$$\Omega_B \simeq 0.0456 \pm 0.0016$$
$$\Omega_{DM} \simeq 0.227 \pm 0.014$$
$$\Omega_\Lambda \simeq 0.728 \pm 0.015 .$$



*E. Komatsu et al., Astrophys. J. Suppl 192 (2011) 18*

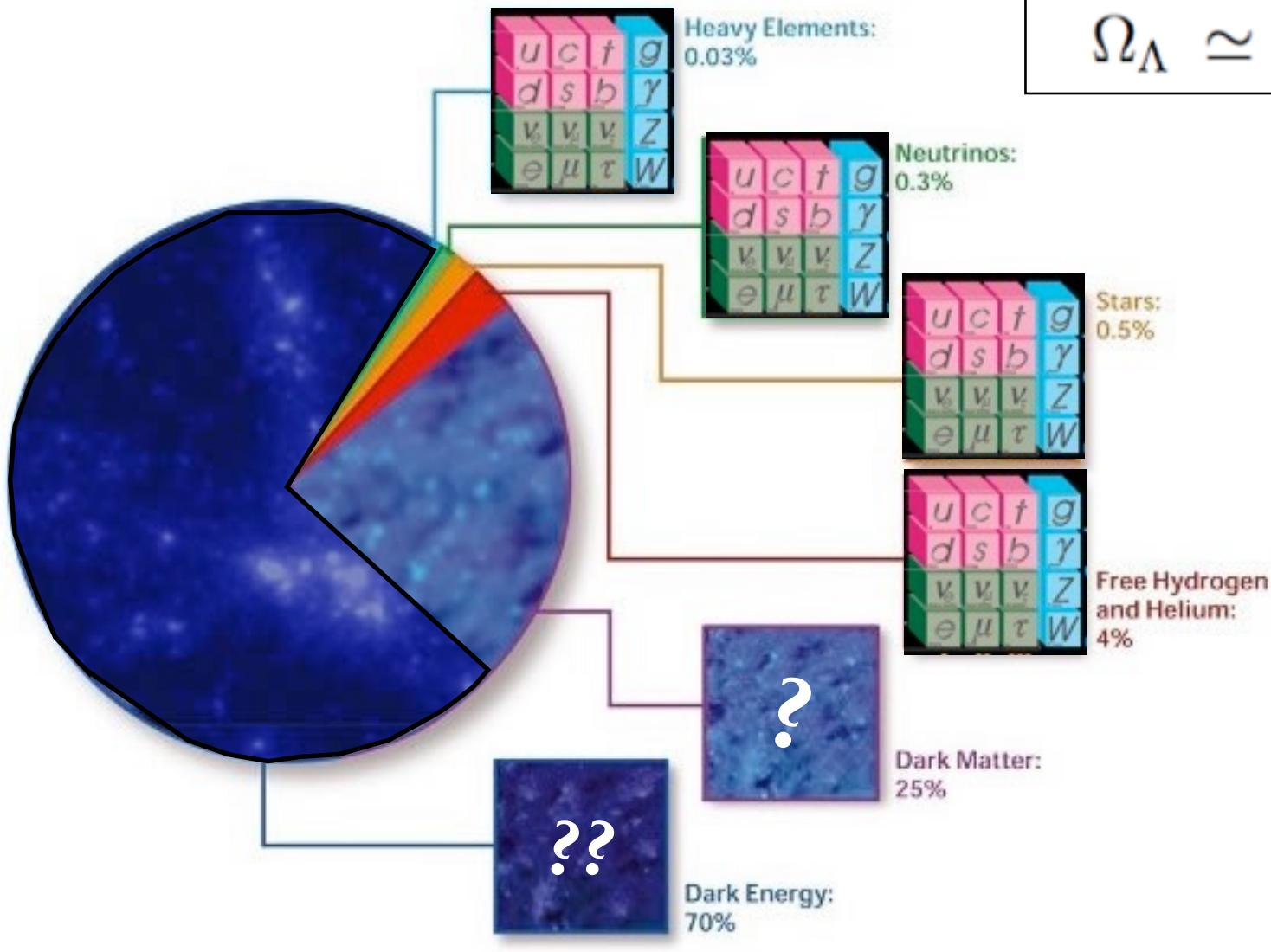
*Dark Matter is  $\sim 25\%$  of the universe.*



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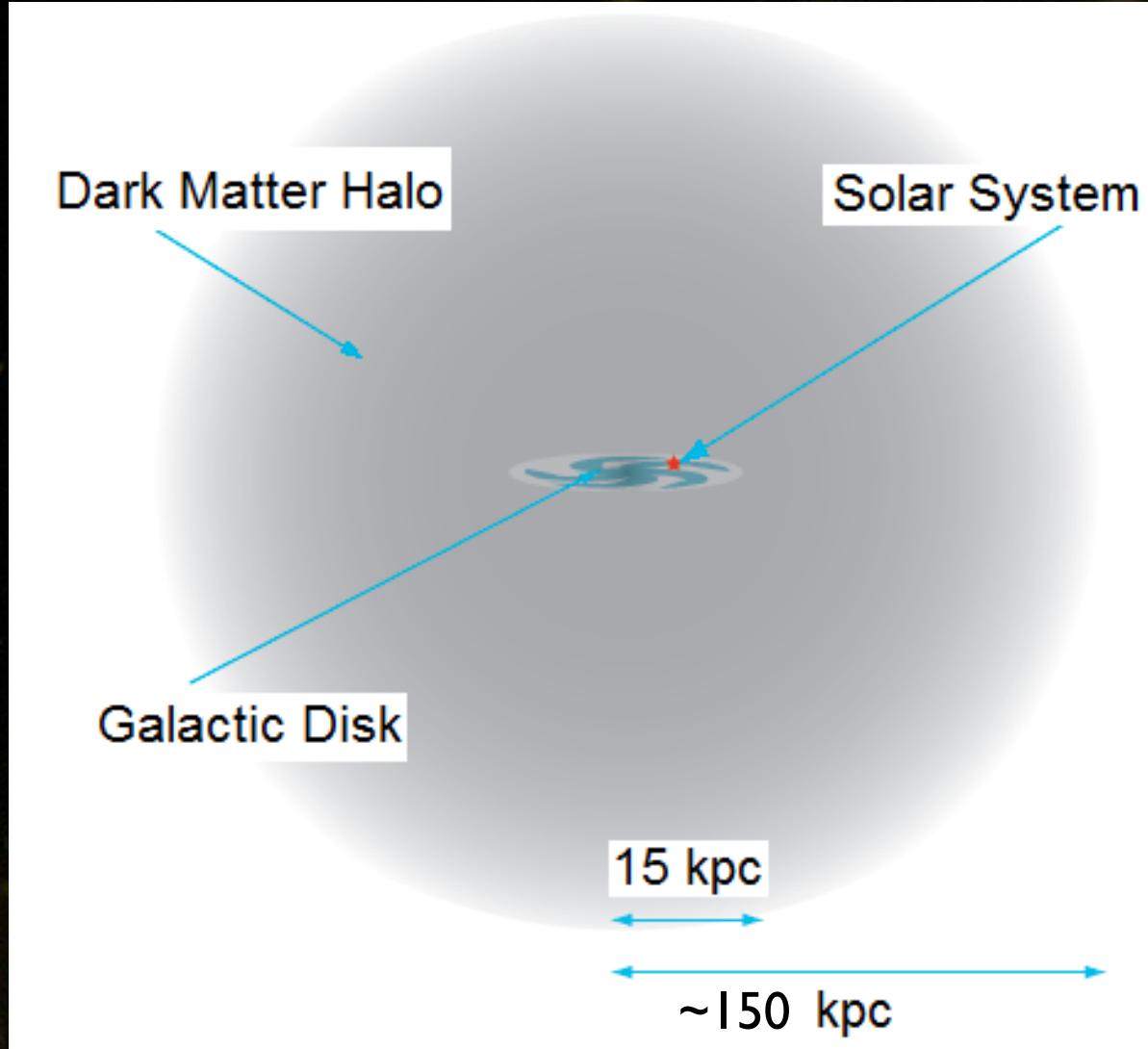
E. Komatsu et al., *Astrophys. J. Suppl* 192 (2011) 18



We only understand 4% of the universe!



# What do we know about Dark Matter?



~25% of the universe

optically dark

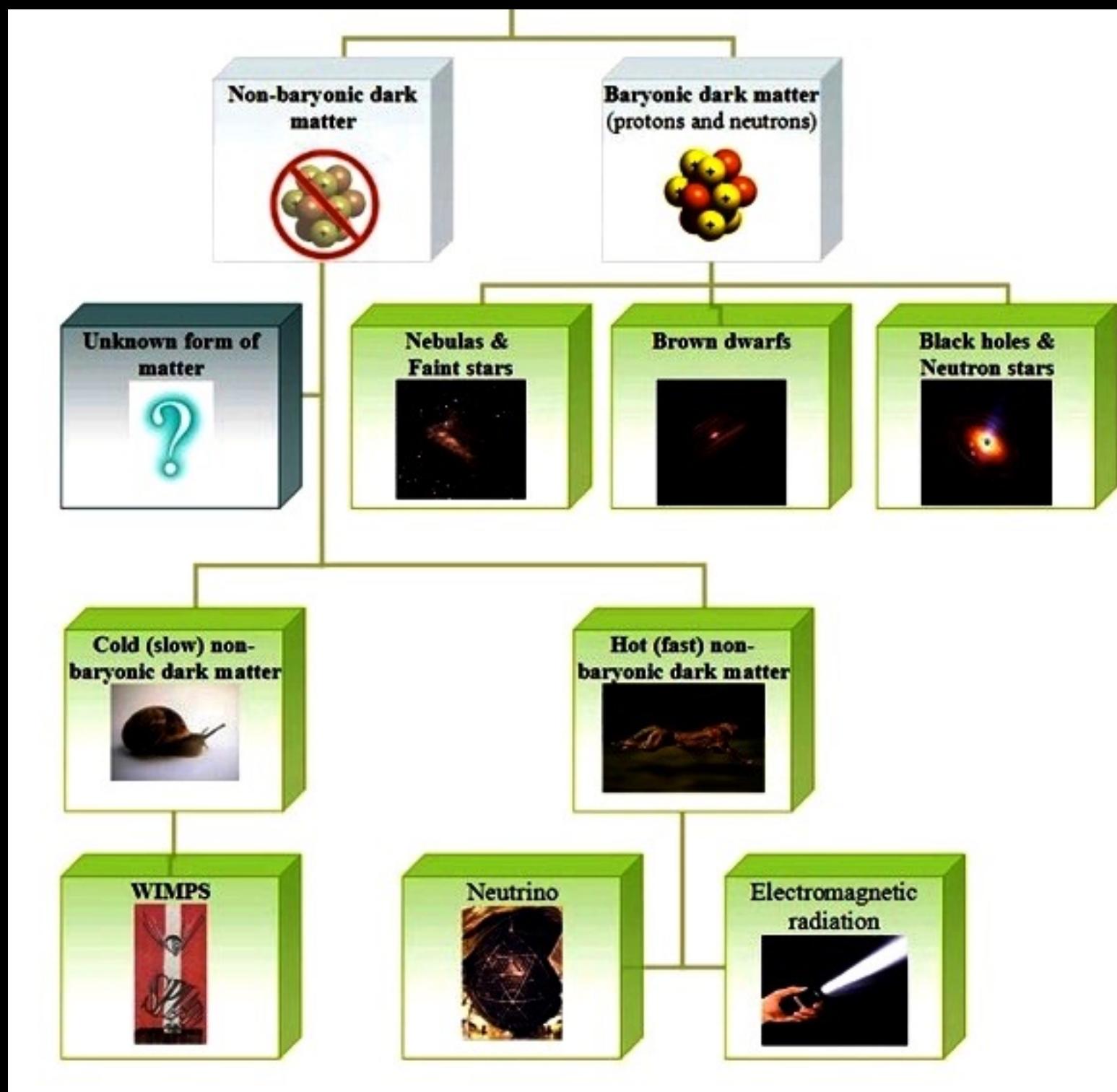
bound to our galaxy

density  $\sim 0.3 \text{ GeV/cm}^3$

interactions: very weak,  
~collision-less



# Candidates



## IV. Dark matter Candidates



## II. Dark matter Candidates

- baryonic :
  - dark stuff  $S2_{\text{dark}} = 0.01$ ,  $S2_b = 0.04$ , mostly gas  
MACS0025  $\lesssim 15\%$  of DM from microlensing
  - mini-black holes:  $m < 10^{11} \text{ kg}$  would evaporate  
by Hawking radiation in  $t < t_0$ .  
limit  $S2_{BH} < 10^{-7}$



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• neutrinos?  $N_{\nu_i} = \left(\frac{3}{11}\right) N_\gamma$  relic density at freeze-out.

for  $\rho_\nu = \rho_c$ , need  $\sum_i m_i c^2 = 47 \text{ eV}$

inconsistent w/ neutrino oscillation bounds  $\sum m_i c^2 < 0.1 \text{ eV}$

This assumes  $\nu$ s are in thermal equilibrium in early univ.

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- new particles?



# Dark Matter Candidates

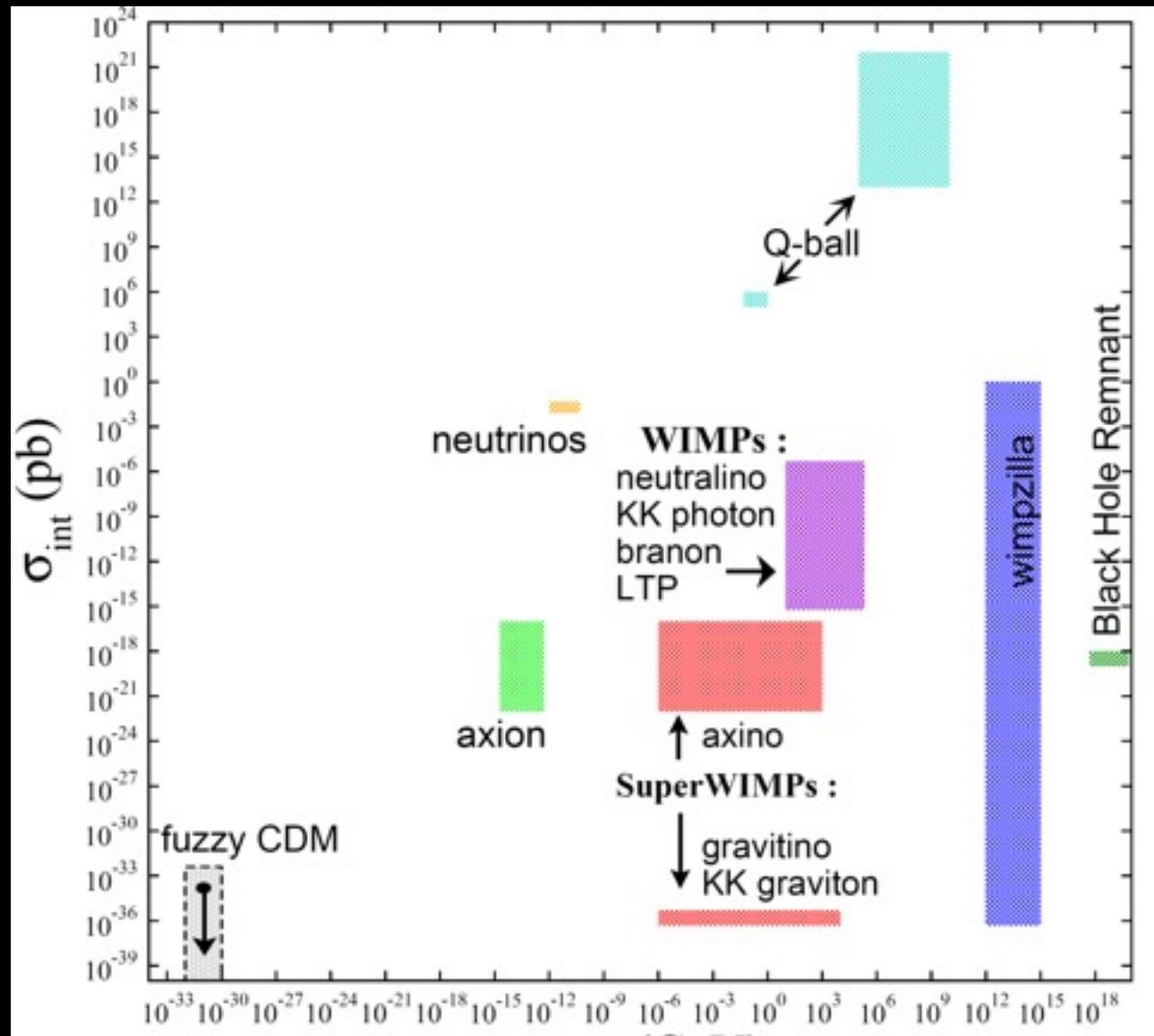
interaction strengths

strong e.m.

weak

gravity

↑



masses



neutrino?

electron

t-quark



Jocelyn Monroe

Axions: new particle postulated to solve Strong CP problem.  
( $n_{\text{Edd}} < 10^{-9} \times \text{prediction if CP}$ )

$\varphi$  arises from Spontaneous Symmetry breaking of new  
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- can draw  $\varphi \rightarrow \gamma\gamma$   $f_\pi = 93 \text{ MeV}$



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- $m_{\text{axion}} \approx 0.5 m_\pi \frac{f_\pi}{f_a}$   $m_\pi = 140 \text{ MeV}$   
 $= \frac{6 \text{ eV}}{[f_a / 10^6 \text{ GeV}]}$   $f_a = 6 \times 10^6 \text{ if } m_a = 1 \text{ eV}$



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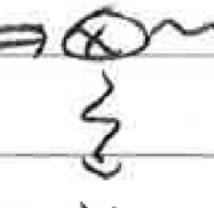
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 $= \frac{6 \text{ eV}}{[f_a / 10^6 \text{ GeV}]}$   $f_a = 6 \times 10^6 \text{ if } m_a = 1 \text{ eV}$
- decay rate: lifetime  $\tau > t_0$  if  $m_a < 10 \text{ eV}$  ✓ stable
- weakly coupled so not in thermal equilibrium before freeze-out



- limits:
  - in stars  $\varphi \rightarrow \infty$  would change cooling rate of red dwarfs  $\rightarrow m_a < 0.01 \text{ eV}$
  - $\overline{B}$  field coupling

$$\text{magnetic field} \rightarrow \varphi \quad \text{or} \quad \varphi = \text{magnetic field}, \quad m_a < 0.001 \text{ eV}$$





from sun, or laser



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from sun, or laser

- for  $p_\chi = p_c$ , need  $m_\chi \sim 10^{-3} - 10^{-5} \text{ eV}$



WIMPs: new particle postulated in models that address the hierarchy problem in the Standard Model leading to ~~and~~ contender: Supersymmetry (SUSY)



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e.g.  $\tilde{X}\tilde{X}$ , so lightest susy particle is stable.  
(LSP)

LSP: neutralino  $\chi_0 = \text{mix of photino, zino, 2 higgsinos}$   
predicted to interact via the weak force, with  $10^{-16, 000}$  g/cm  
mean, and  $10^{-40} - 10^{-48} \text{ cm}^2$  cross sections of nucleons.



- abundance at freeze-out?



• abundance at freeze-out?

freeze out when  $\bar{e}e$  annihilation rate  $\leq$  expansion rate

$$\langle N = 5 \rangle \leq H$$

comment: weaker interaction  
= earlier freeze out



• abundance at freeze-out?

freeze out when  $\bar{X}X$  annihilation rate  $\leq$  expansion rate

$$\langle N = \nu \rangle \propto H$$

comment: weaker interaction

= earlier freeze out

= higher abundance

= more DM =

larger contribution to  
closure parameter

$\rightarrow$  Thermal DM

(non-relativistic solution)

$$N(T) = \left( \frac{M T}{2\pi} \right)^{3/2} \exp \left\{ - \frac{M}{k_B T} \right\}$$

weak interaction,  $\sigma_{X\bar{X}} \sim \sigma_{\text{weak}} \sim g_F^2 S$

$$\sim g_F^2 M^2$$

means  $\sigma(Xp) > 10^{-48} \text{ cm}^2$

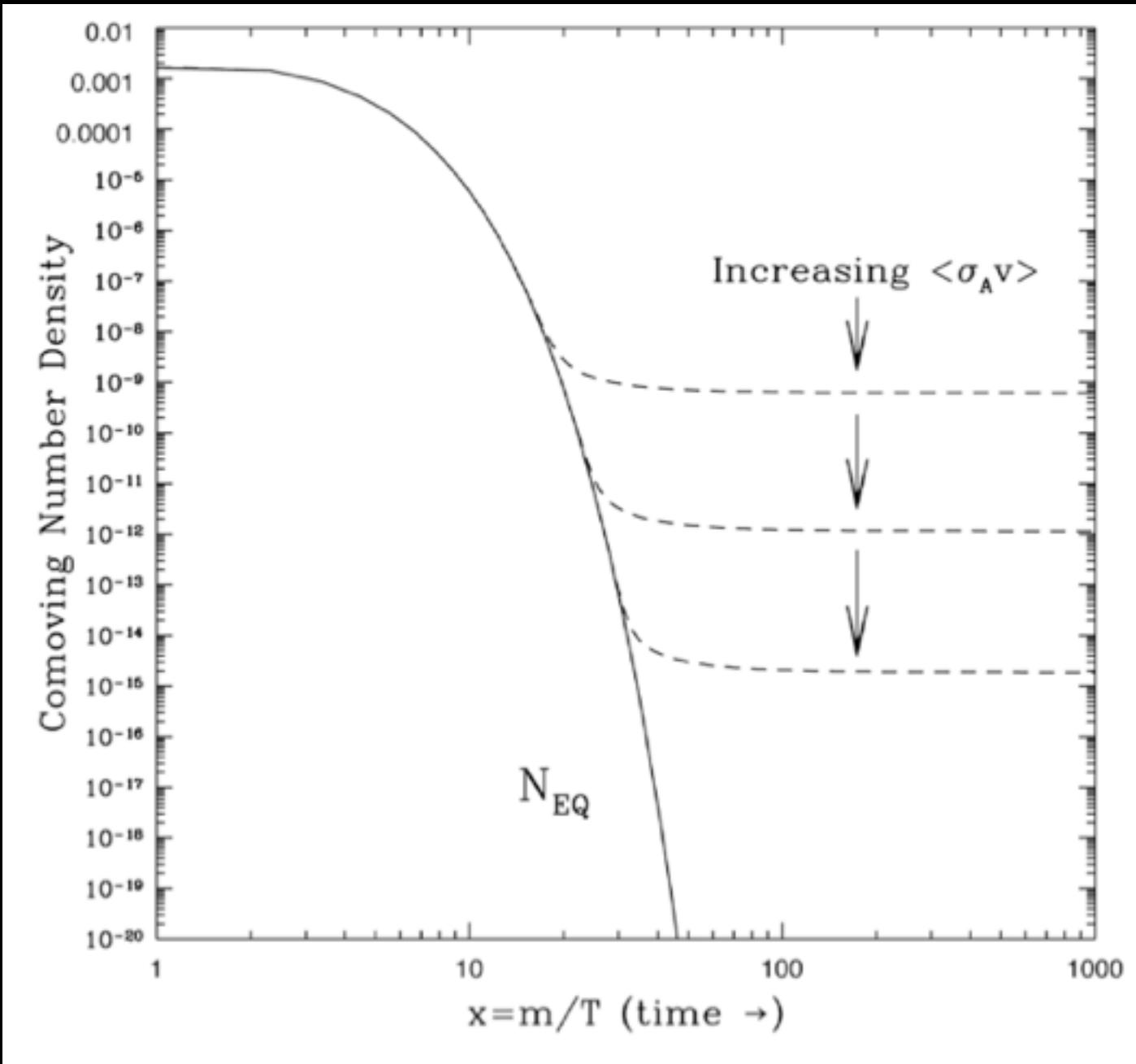
$$g_F = 10^{-5} \text{ GeV}^{-2}$$

Hubble expansion:  $H(T) \propto \frac{f T^2}{M_{pl}}$ ,  $f = \text{constant} \sim 100$

$$M_{pl} = \sqrt{\frac{8\pi G}{3}} = 10^{19} \text{ GeV}$$



# WIMP Number Density



D. H. Perkins, Particle Astrophysics (2004)

freeze out condition:

$$(MT)^{3/2} \exp\left\{-M/e_0 T\right\} \cdot g_F^2 M^2 \leq \frac{\rho T^2}{M_{pl}}$$

Plug in constants, find  $\frac{M}{T} \approx 25$  at freeze-out  $\equiv P$

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Plug in constants, find  $\frac{M}{T} \approx 25$  at freeze-out  $\equiv P$

co-moving number density:  $N(T) \frac{H(T)}{\langle v \rangle}$ ,  $N(0)v(0) = N(T)v(T)$   
after freeze-out

$$N(0) = N(T) \times \left(\frac{v(T)}{v(0)}\right) \quad \sqrt{\alpha R^3} \propto \left(\frac{1}{T}\right)^3$$

$$= \left(\frac{fT^2}{M_{pl}}\right) \frac{1}{\langle v \rangle} \times \left(\frac{T_0}{T}\right)^3 = \frac{f}{M_{pl}} \frac{1}{\langle v \rangle} \frac{T_0^3}{T}$$

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$$N(0) = N(T) \times \left(\frac{v(T)}{v(0)}\right) \propto R^3 \propto \left(\frac{1}{T}\right)^3$$

$$= \left(\frac{fT^2}{M_{pl}}\right) \frac{1}{\langle v \rangle} \times \left(\frac{T_0}{T}\right)^3 = \frac{f}{M_{pl}} \frac{1}{\langle v \rangle} \frac{T_0^3}{T}$$

• contribution to energy density:  $\rho_{\text{WIMP}} = MN(0) = f \frac{PT_0^3}{M_0 \langle v \rangle}$

$$\text{for closure: } \Omega_w = \frac{\rho_w}{\rho_c} = \frac{10^{-25} \text{ cm}^2 \text{ s}^{-1}}{\langle \sigma v \rangle} = \frac{6 \times 10^{-31} [\text{GeV s}^{-1}]}{\langle \sigma v \rangle} \left[ \text{cm}^3 \text{ s}^{-1} \right]^{\text{pk}}$$

(estimate  $\sigma$  so we can get  $\sigma$ )



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at freeze-out, non-relativistic ("cold" dark matter)

$$\frac{1}{2} M v^2 = \frac{3}{2} T \rightarrow v = \sqrt{\frac{3T}{m}} = \sqrt{\frac{3}{P}} (\approx 0.3 c)$$



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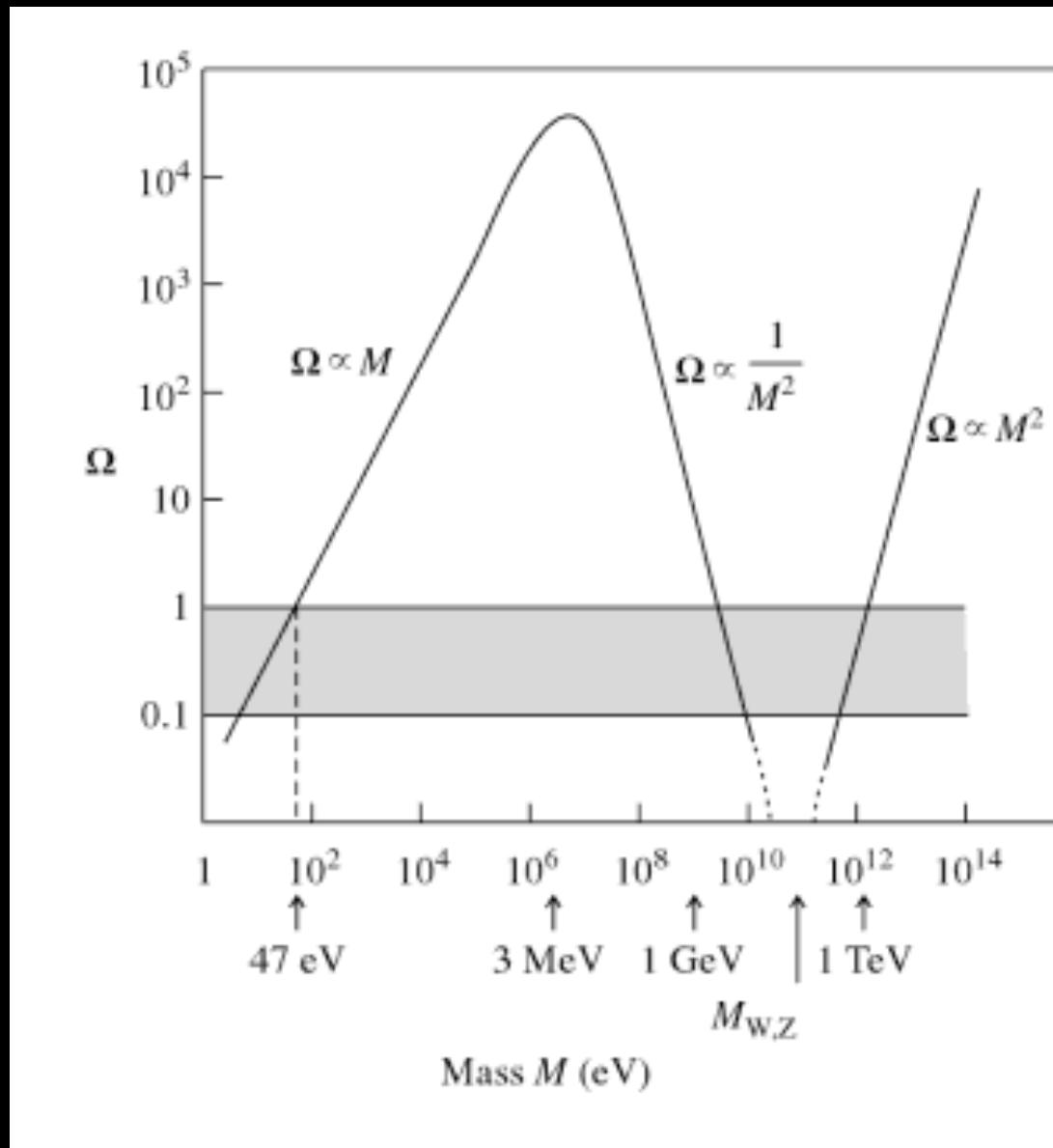
plug in, find need  $\sigma \approx 10^{-35} \text{ cm}^2$  for  $\rho_w = \rho_c$ .

called the "WIMP miracle"

[more like WIMP "nice coincidence" since there is broad range of coupling constants for e.g. Higgs field giving us a particle masses ranging from  $1 \text{ eV}$  to  $1 \text{ GeV}$ ]



# WIMP Mass Range

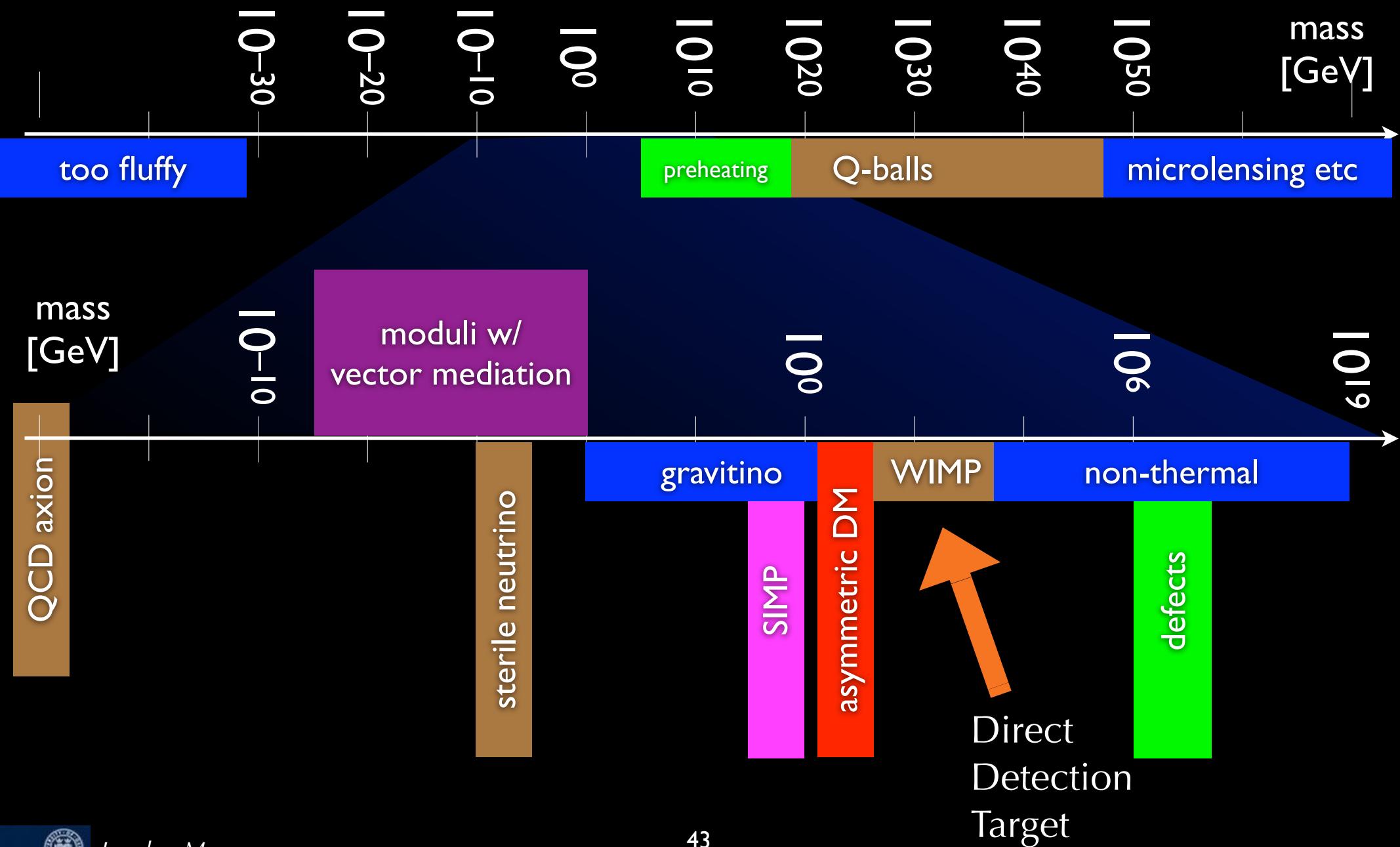


**Fig. 7.11** Variation of the closure parameter with WIMP mass, assuming conventional weak coupling. The shaded region, corresponding to  $\Omega = 0.1 - 1$ , is that in which the contribution to the closure parameter from massive neutrinos or WIMPs must lie, thus excluding the range of masses 100 eV–3 GeV. Accelerator experiments suggest that WIMPs must have masses exceeding  $M_Z/2 = 45 \text{ GeV}$ , otherwise  $Z$  bosons could decay into WIMP–antiWIMP pairs. However, for masses which are large compared with the  $Z$  boson mass, the weak cross-section falls rapidly because of propagator effects, so that WIMPs in the TeV mass range are possible dark matter candidates, depending on the precise values of the WIMP coupling.



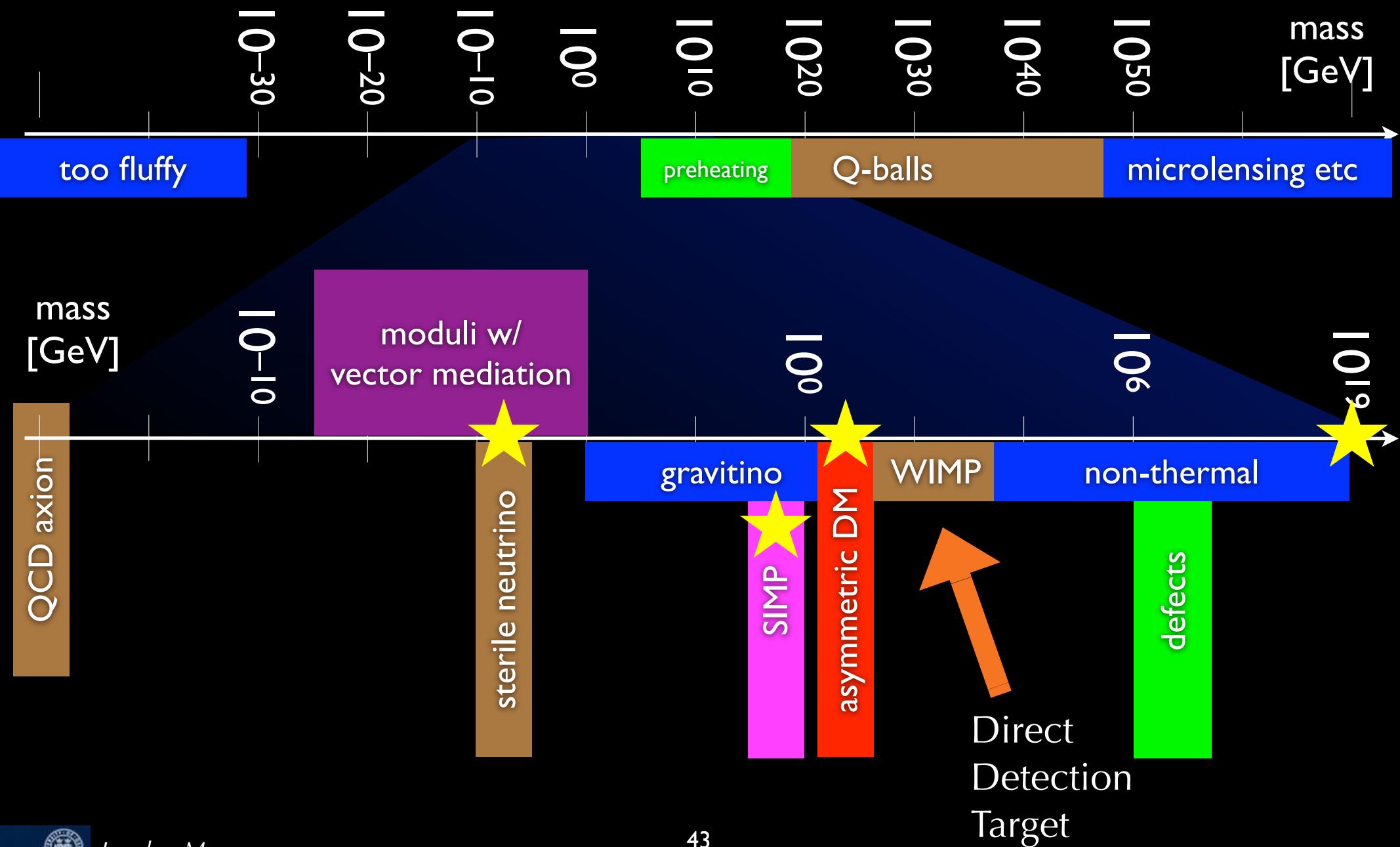
# Model Space: Theorist's View

(thanks to H. Murayama)



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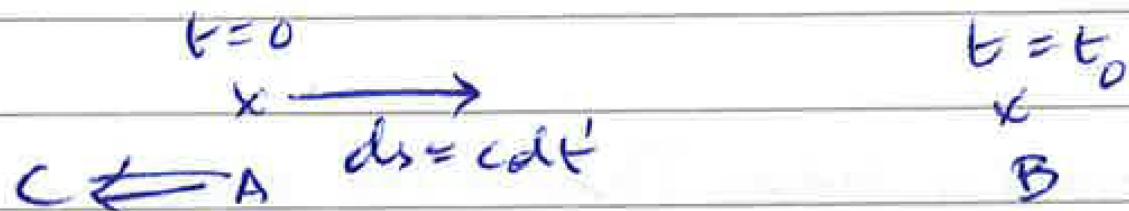
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and  $R(0) > R(t)$



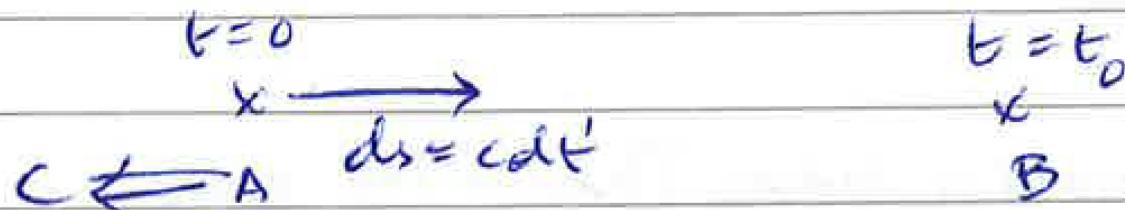
light emitted at A at  $t=0$

by the time light arrives at B, A has moved to C  
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because of Hubble expansion

$$D_H(t_0) = \int_{t_0}^{\infty} cdt' \left( \frac{R(0)}{R(t')} \right)$$

quantity i.t.o.  $z$  and  
 $d_3$  and quantities we can  
measure

$$D_n(t_0) = \int_0^{t_0} c dt' \left( \frac{f(c)}{R(t')} \right) = \int_0^{t_0} c dt' (1 + 3)$$

$$D_n(t_0) = \int_{t_0}^{t_1} dt' \left( \frac{R(0)}{R(t')} \right) = \int_{t_0}^{t_1} dt' \left( 1 + z \right)$$

Write  $dt'$  in term of  $dz$ :

$$\begin{aligned} H(t) &= \frac{i}{R} = \frac{1}{R} \frac{dR(t)}{dt} = \frac{1}{R(t)} \frac{d}{dt} \left( \frac{R(0)}{1+z} \right) \\ &= \frac{R(0)}{R(t)} \cdot \frac{-1}{(1+z)^2} \frac{dz}{dt} \end{aligned}$$

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$$= \frac{\dot{R}(t)}{R(t)} = \frac{-1}{(1+z)^2} \frac{dz}{dt}$$

$$\downarrow dt = (1+z) \left( -\frac{1}{(1+z)^2} \right) dz \quad \frac{1}{H(t)} = -\frac{dz}{H(t)(1+z)}$$

$$D_H(t_0) = \int_{z_0}^{\infty} \frac{cdz}{H(t)(1+z)}$$