Experimental Techniques in Dark Matter and Neutrino Physics
Rare Event Searches

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Invisibles School 2023
Bad Honnef, DE

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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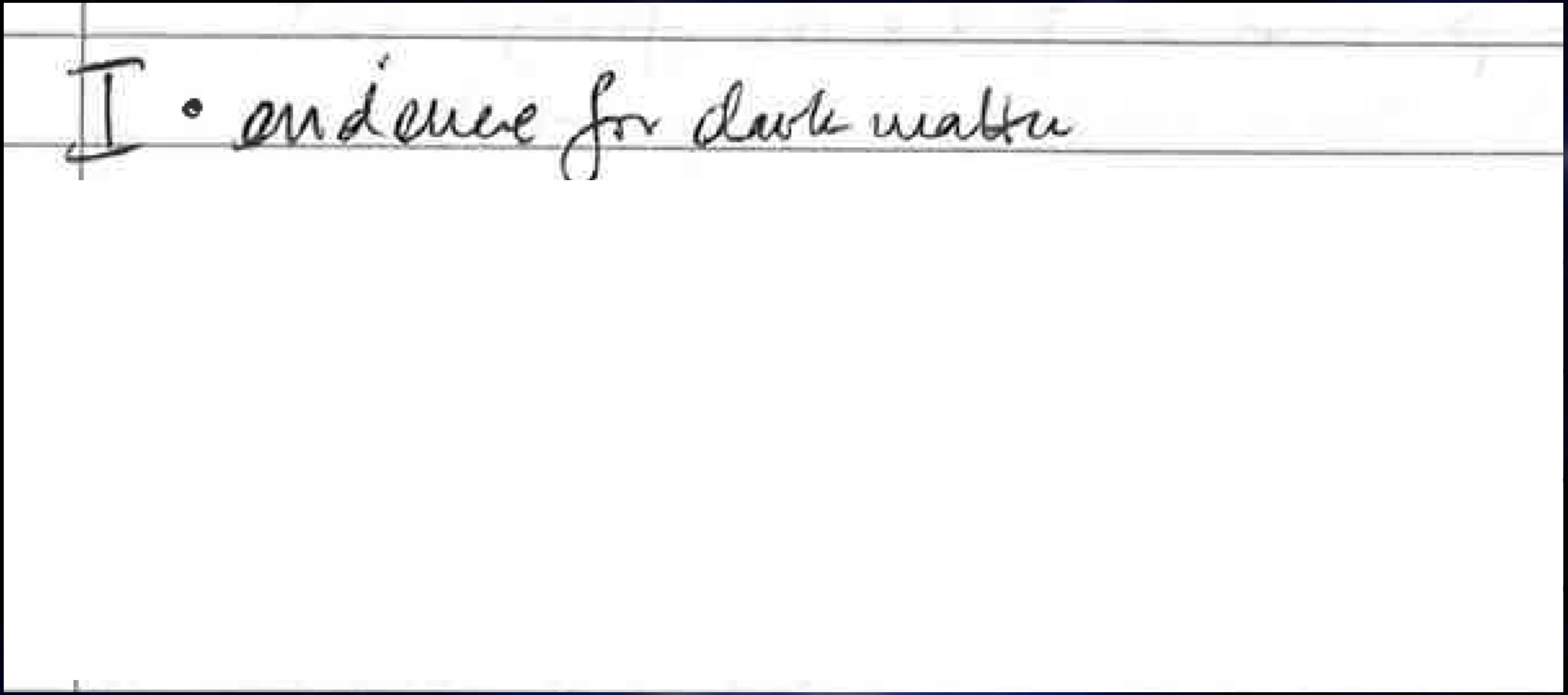
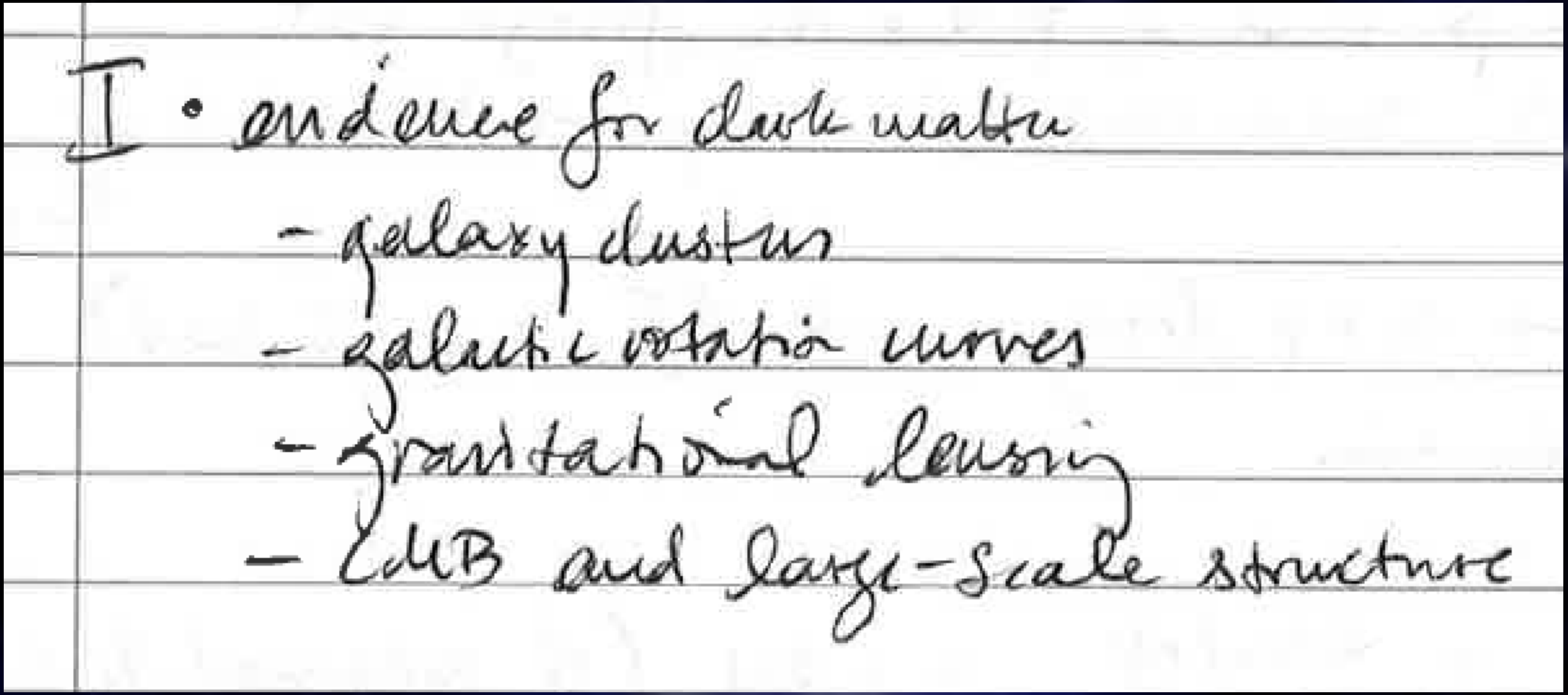


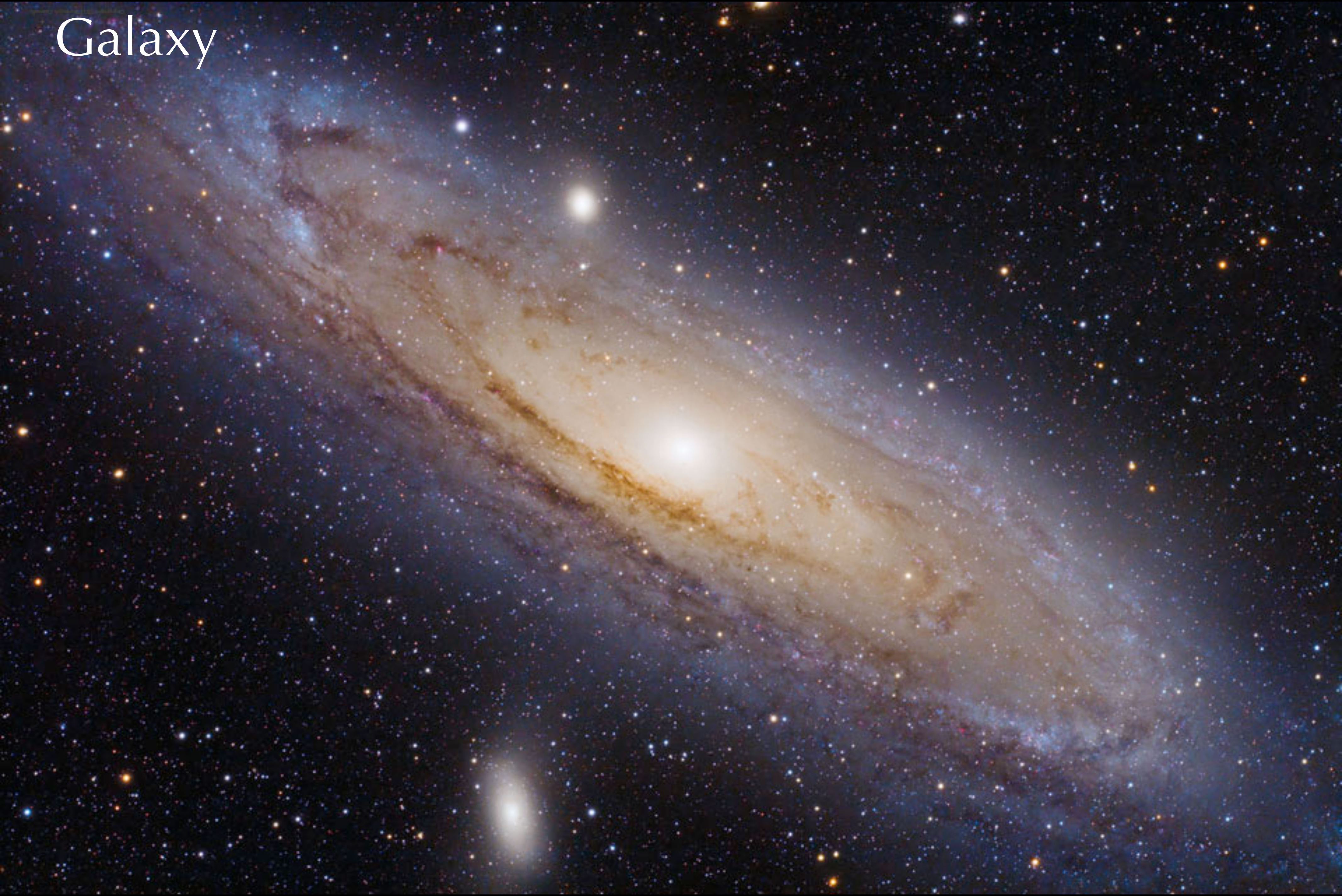
I • evidence for dark matter



I • evidence for dark matter

- galaxy clusters
- galactic rotation curves
- gravitational lensing
- CMB and large-scale structure

Galaxy



1st Observation: 1930s

Fritz Zwicky

(Kitt Peak)

Virial Theorem: kinetic energy ∝ potential energy

implies 400x more mass than visible!

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$$\text{virial } W \equiv \sum_i \vec{p}_i \cdot \vec{r}_i$$

$$\frac{dW}{dt} = \sum_i \dot{\vec{p}}_i \cdot \vec{r}_i + \sum_i \vec{p}_i \cdot \dot{\vec{r}}_i$$

$$= \sum_i m_i \ddot{\vec{r}}_i \cdot \vec{r}_i + \sum_i m|\vec{v}_i|^2$$

$$= \sum_i \vec{F}_i \cdot \vec{r}_i + 2\sum KE_i$$

$$= \sum_i \left(-\frac{\partial V_i}{\partial r_i}\right) \cdot \vec{r}_i + 2\sum_i KE_i$$

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

$$J = -\sum V_i + 2\sum KE_i$$

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$$J = -\sum_i V_i + 2\sum_i KE_i$$

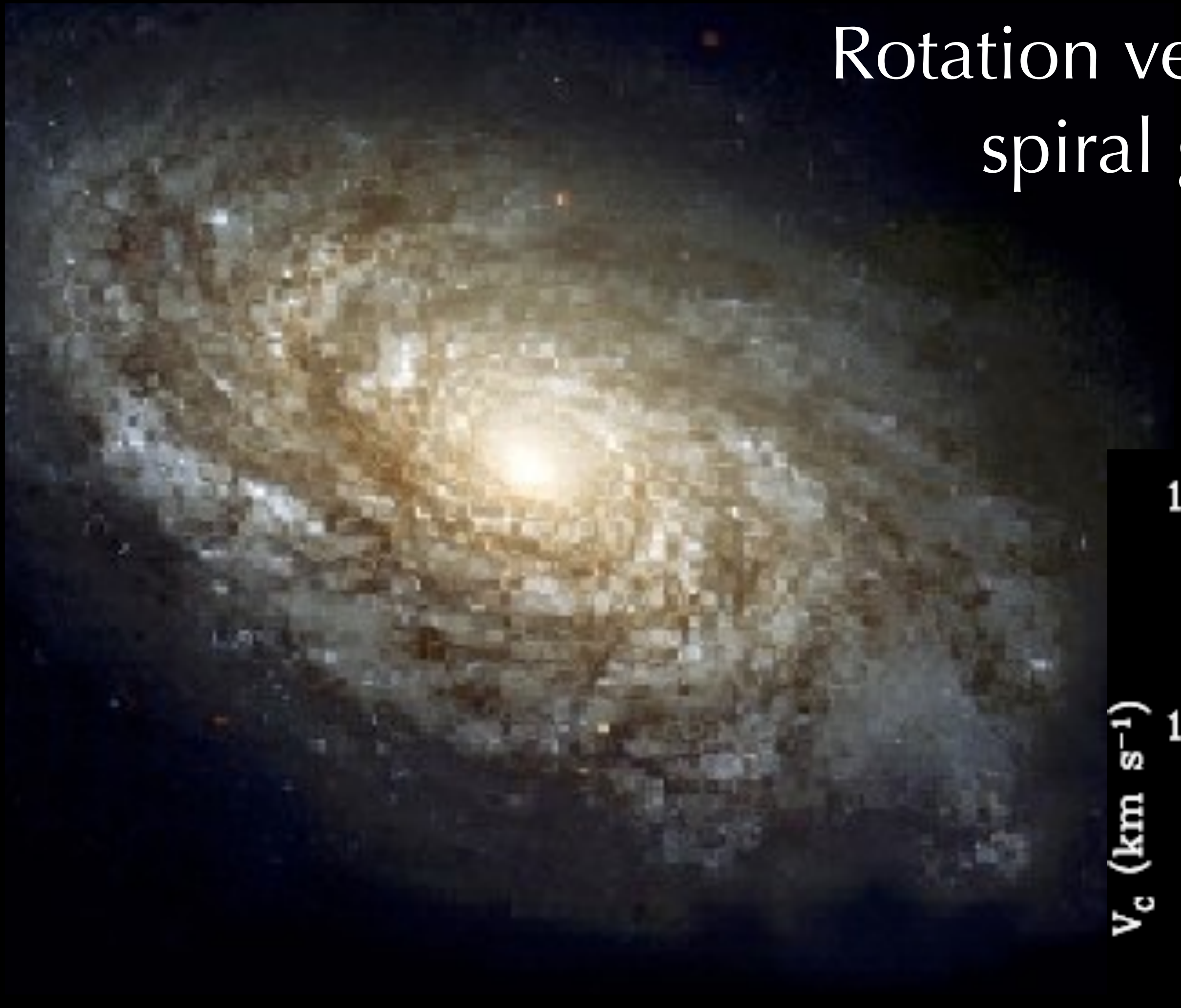
Time average $\langle W \rangle = \frac{1}{T}\int \left(\frac{dW}{dt}\right) dt \rightarrow 0$ as $T \rightarrow \infty$

$$\therefore \langle V \rangle = 2\langle KE \rangle$$

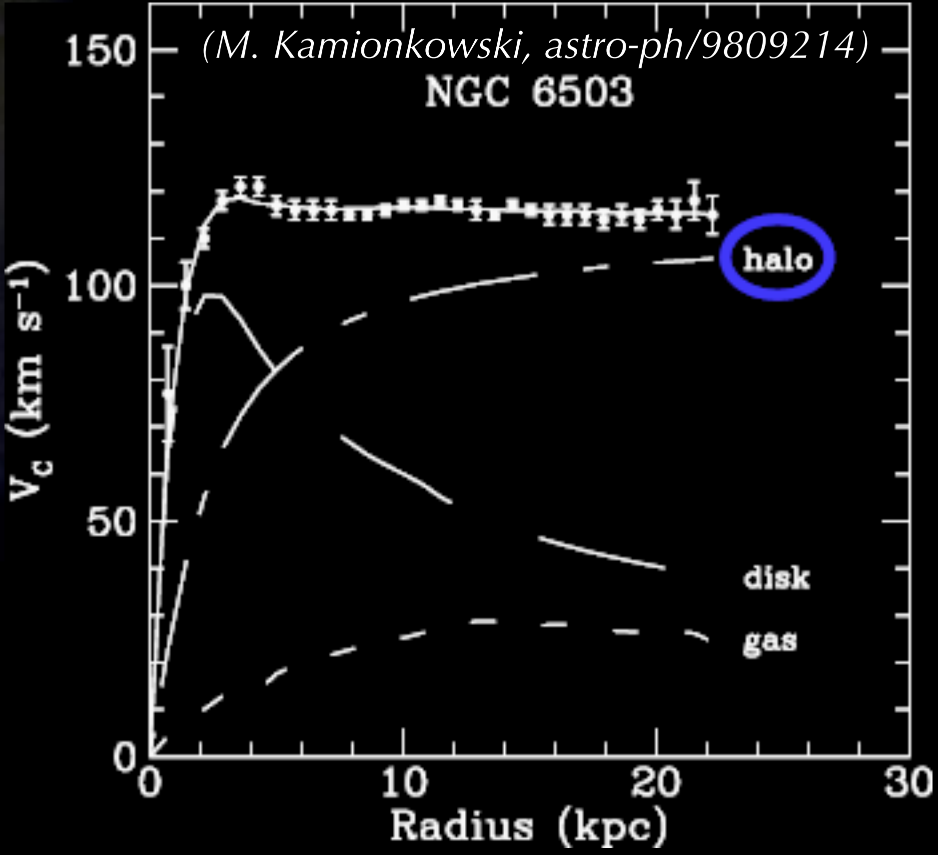
Zwicky applied this to coma cluster of galaxies, found ~500× more mass implied by $2\langle KE \rangle$ than was visible

Confirmation: 1980s

Vera Rubin



Rotation velocity v(r) of spiral galaxies

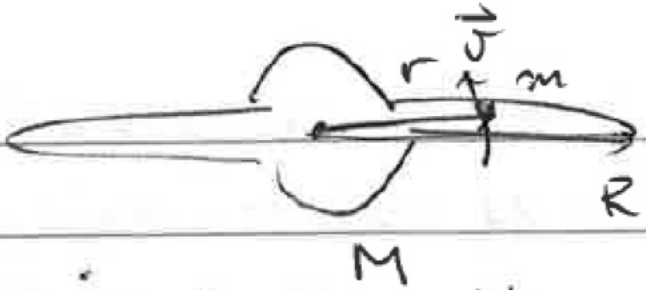


implies 100x more mass than visible!

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

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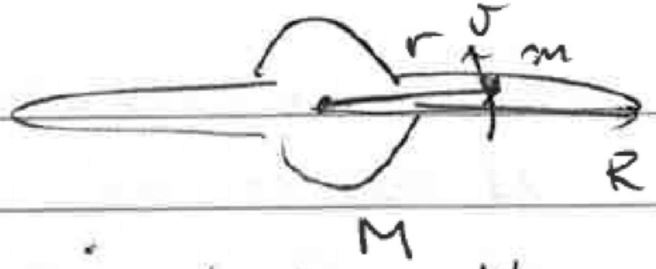

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$$M(r) = \int_0^r\int_0^\pi\int_0^{2\pi} \rho r'^2 \sin\theta' dr' d\theta' d\varphi' = \frac{4}{3}\pi r^3 \rho$$

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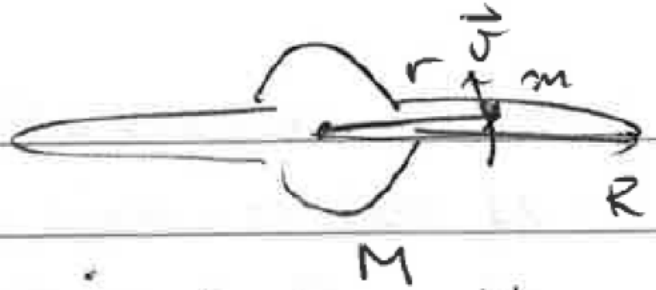

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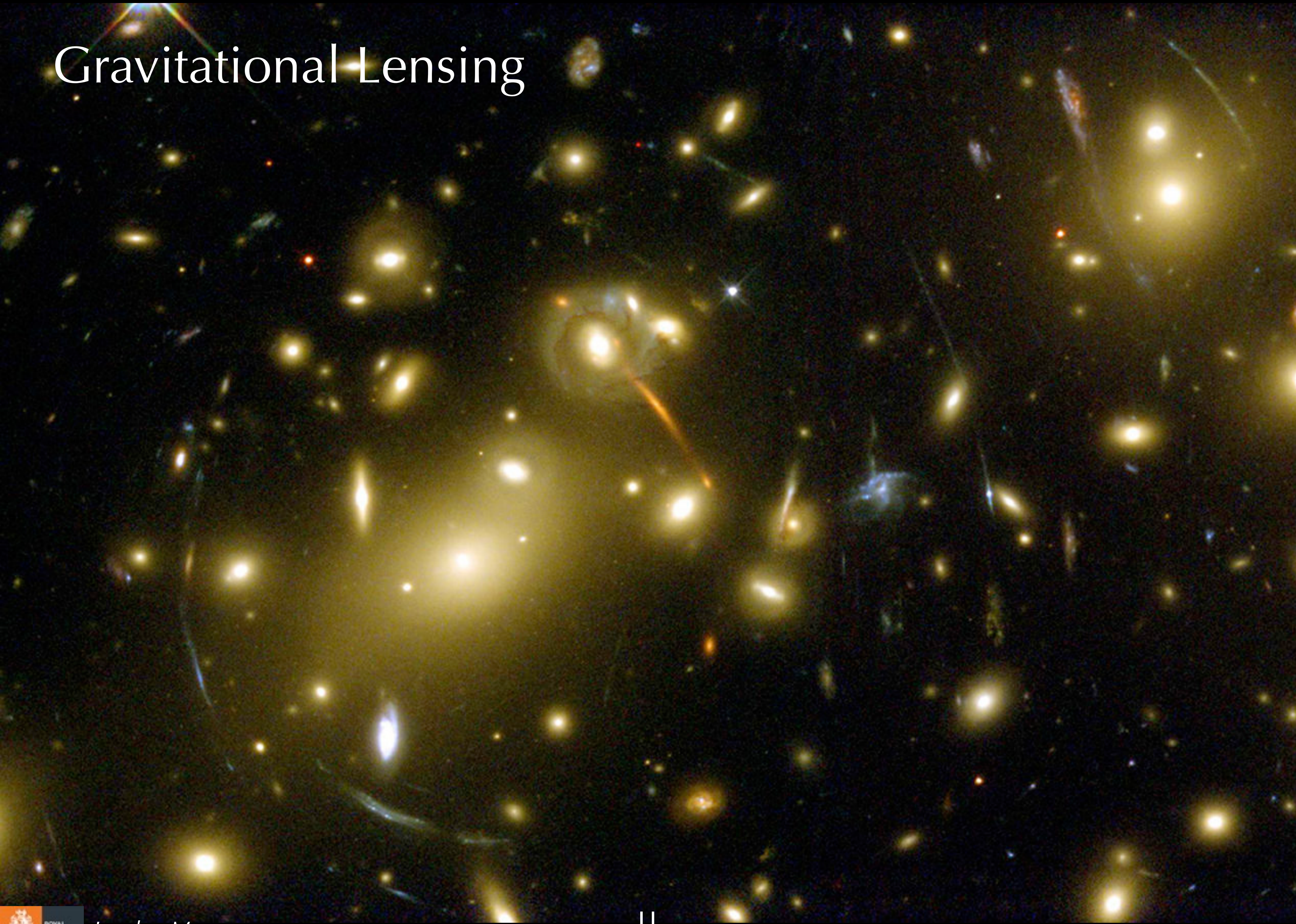
V. Rubin found 70-80% of spiral galaxies is "dark" matter, not luminous.

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

Gravitational Lensing



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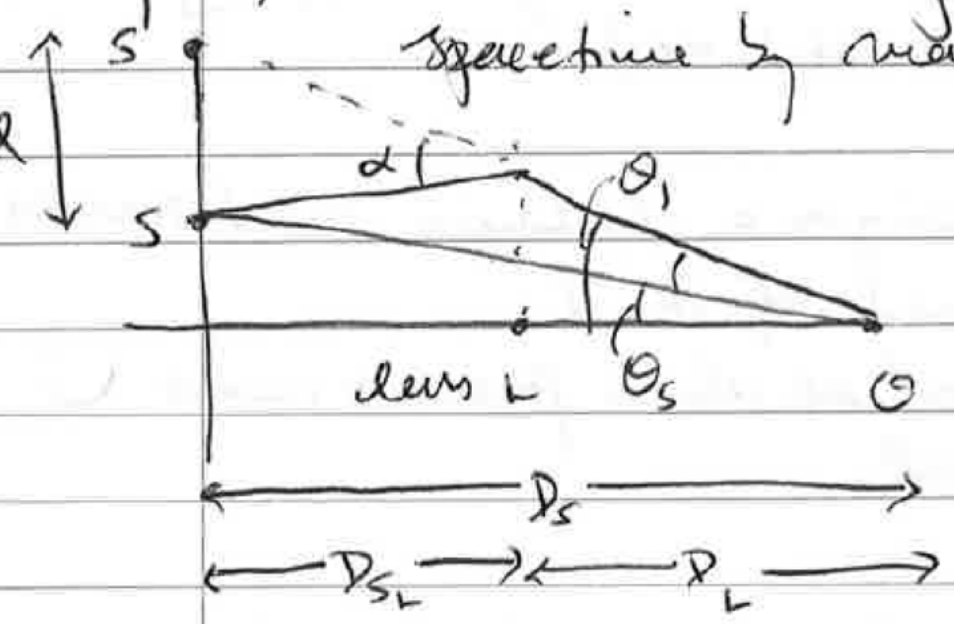

α = deflection angle

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

can show (PC2) $\alpha = \frac{4GM}{c^2 b}$

$l = \alpha D_{LS}$

find θ_1 = angle where "lensed" image appears.

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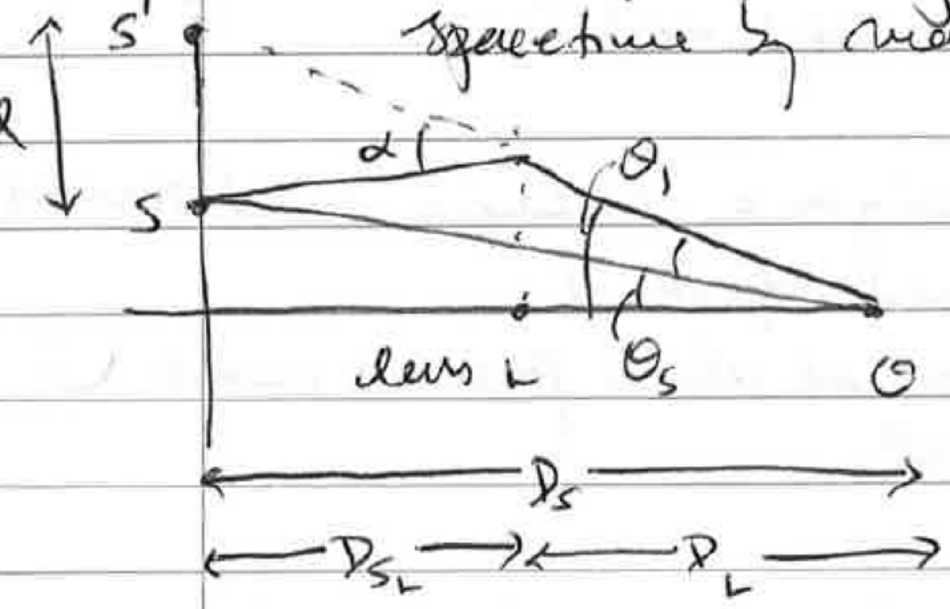

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$$l = \alpha D_{LS} = (\theta_1 - \theta_S)\,D_S$$

solve for $\theta_S = \dfrac{\theta_1 D_S - \alpha D_{LS}}{D_S}$

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

Subst for b

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

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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.

- 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

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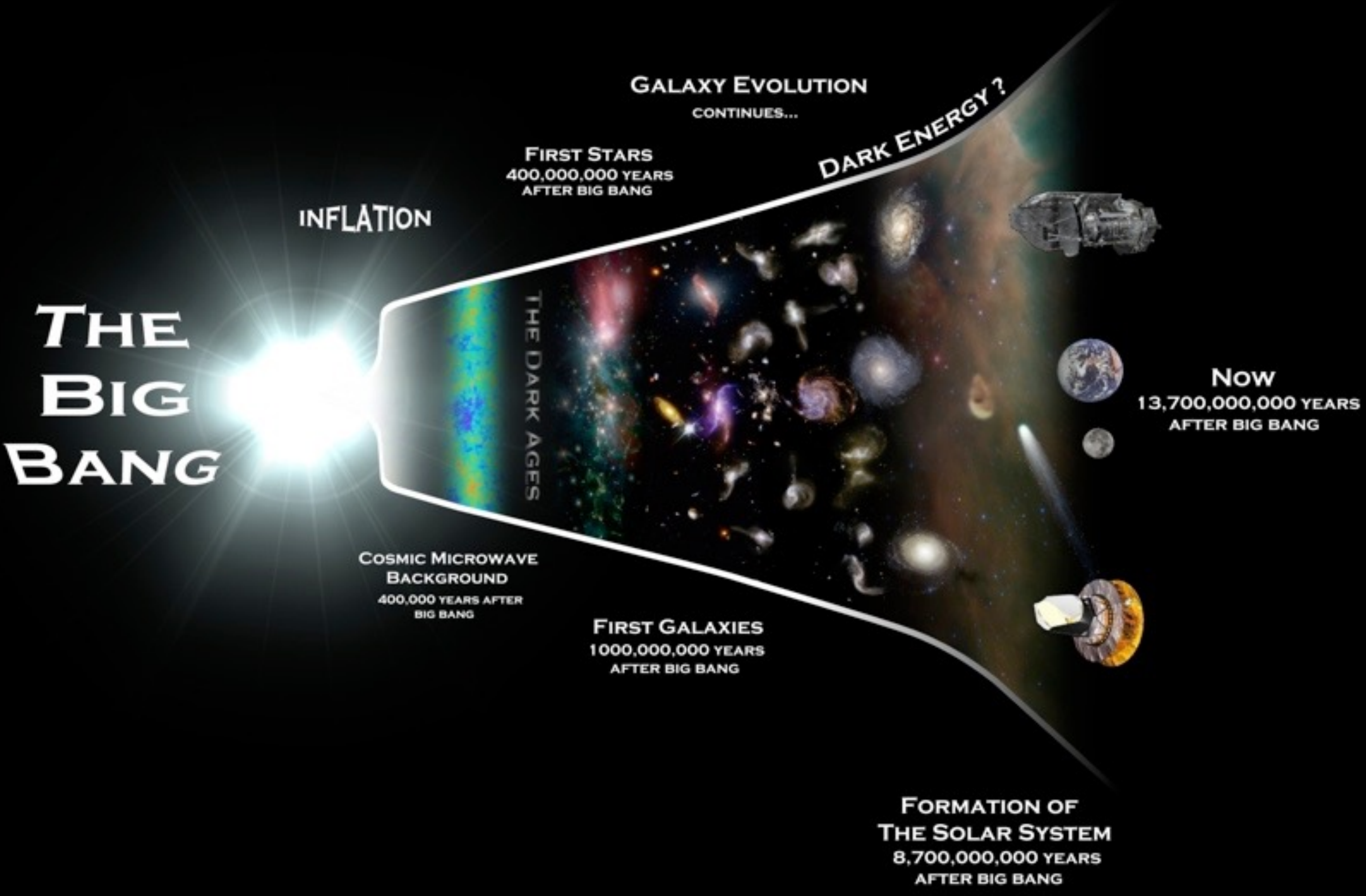
ex) $M_{cluster} = 10^{14} M_\odot$, $D_{LS} = D_L = \frac{D_S}{2} = 100$ Mpc,
$\theta_E = 65$ arcsec.

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

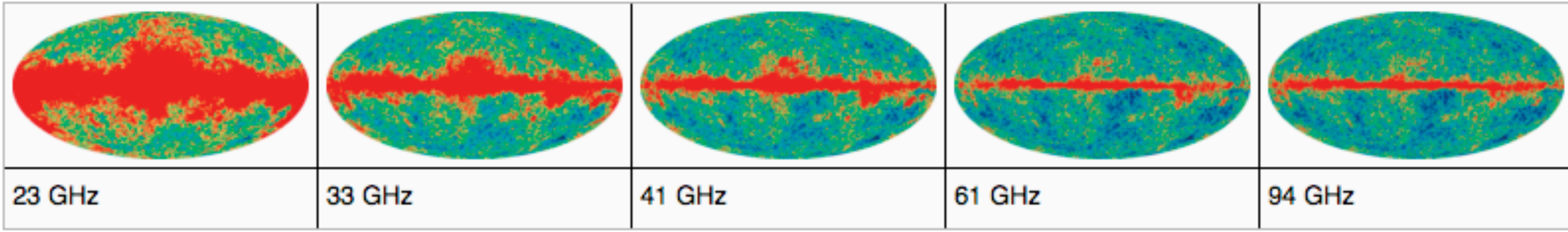
Direct Astrophysical Observation: 2006

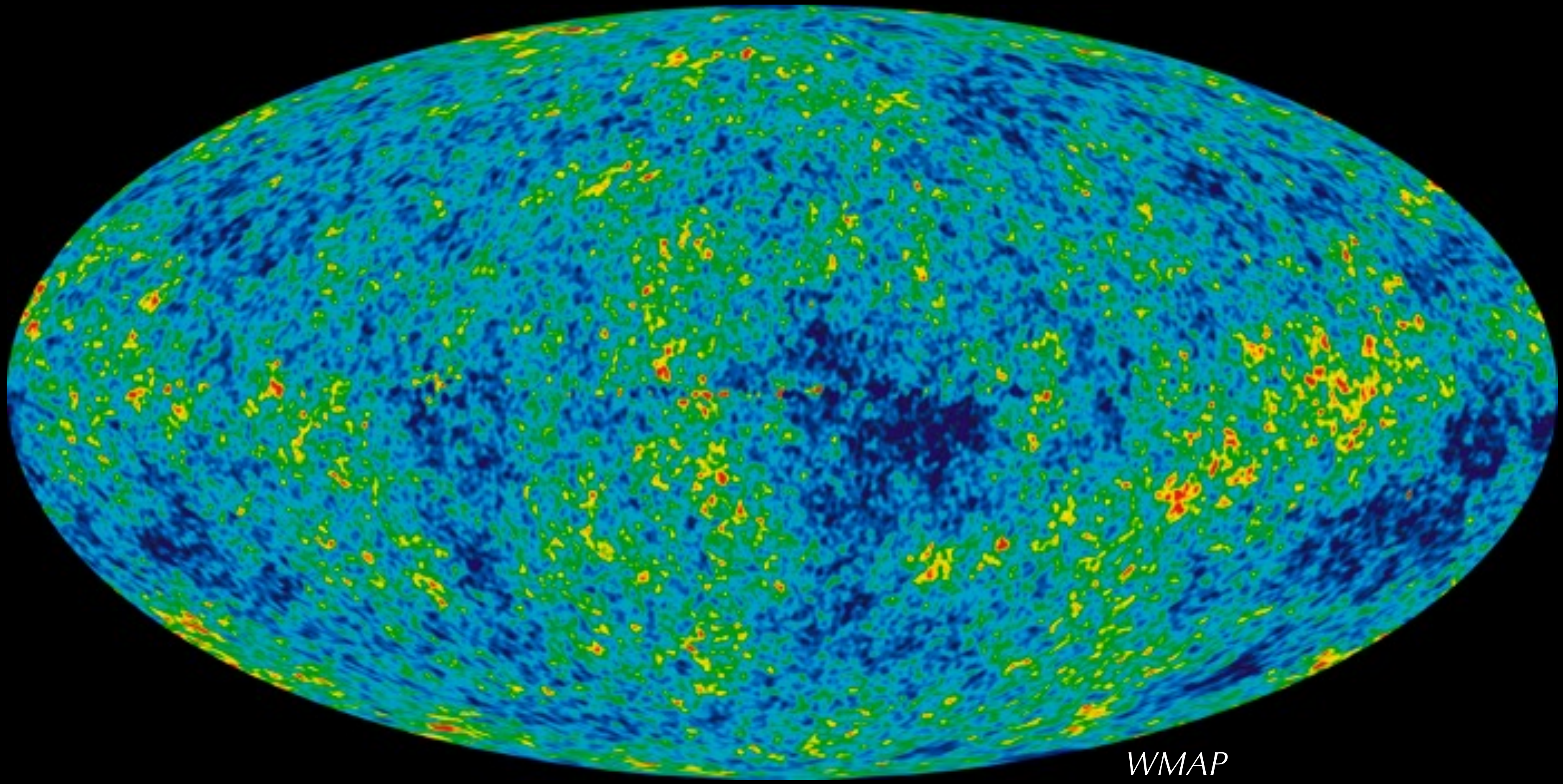
(NASA/Chandra/Magellan/Hubble)

“NASA Finds Direct Proof of Dark Matter”


THE BIG BANG
INFLATION
COSMIC MICROWAVE BACKGROUND
400,000 YEARS AFTER BIG BANG
THE DARK AGES
FIRST STARS
400,000,000 YEARS AFTER BIG BANG
FIRST GALAXIES
1000,000,000 YEARS AFTER BIG BANG
GALAXY EVOLUTION
CONTINUES...
DARK ENERGY ?
FORMATION OF THE SOLAR SYSTEM
8,700,000,000 YEARS AFTER BIG BANG
NOW
13,700,000,000 YEARS AFTER BIG BANG

Cosmic Microwave Background

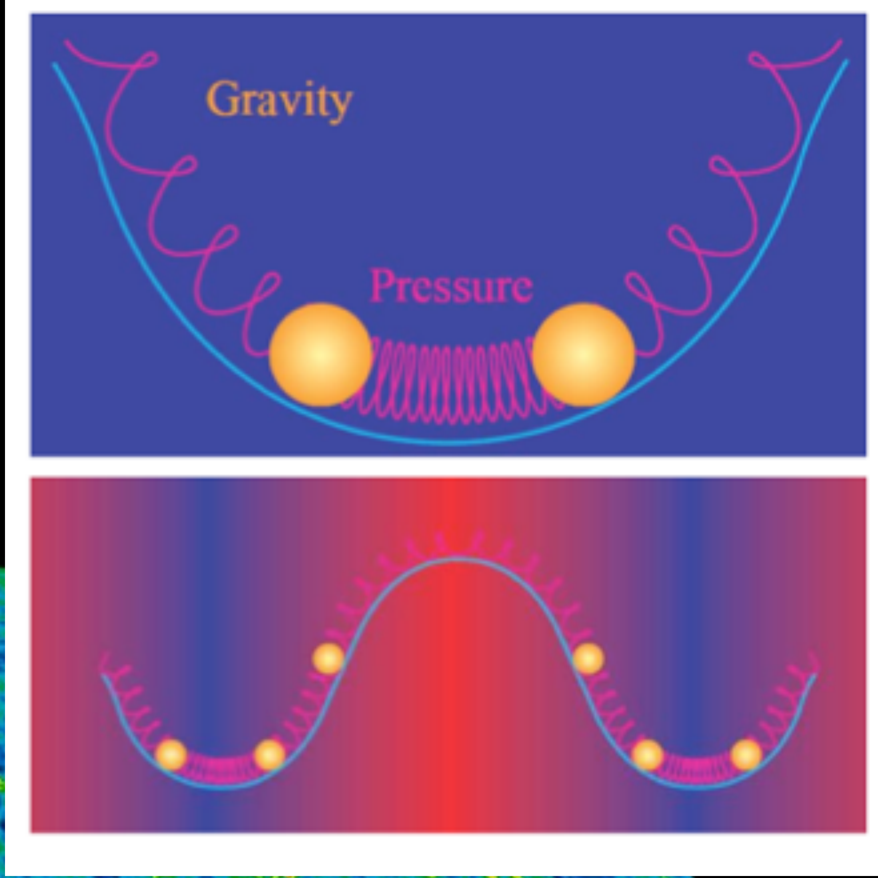


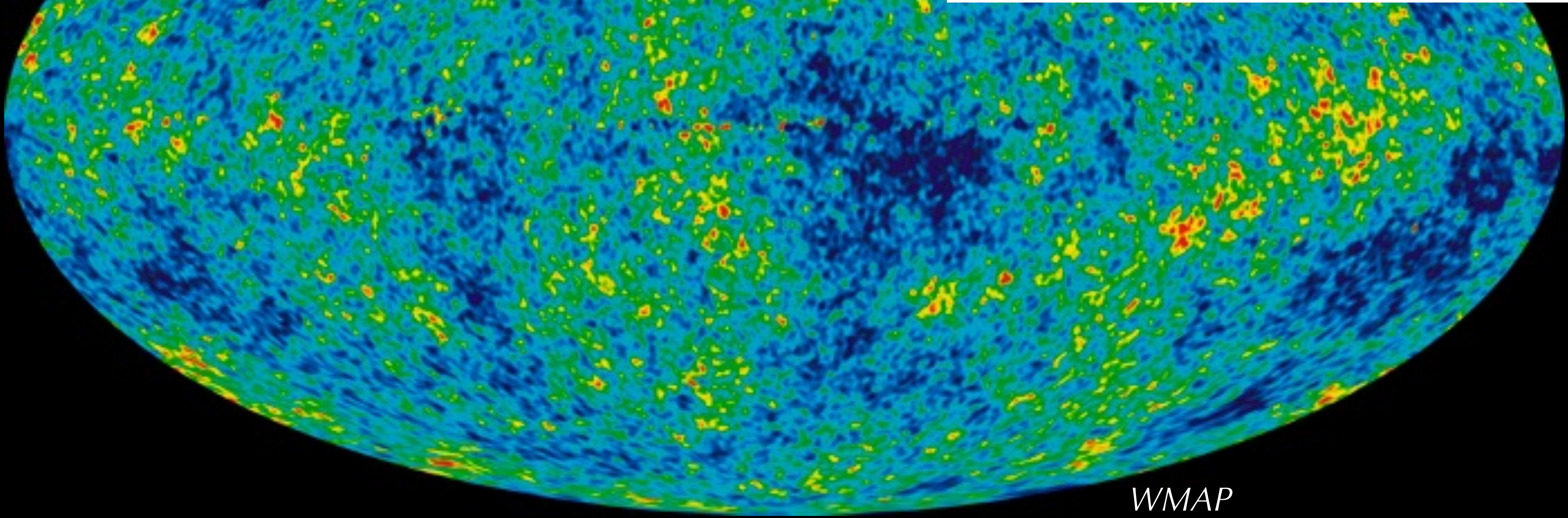


WMAP

Cosmic Microwave Background

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





WMAP

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(Cosmology Aside…)

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k = curvature parameter
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ρ = energy density

G = Newton's constant

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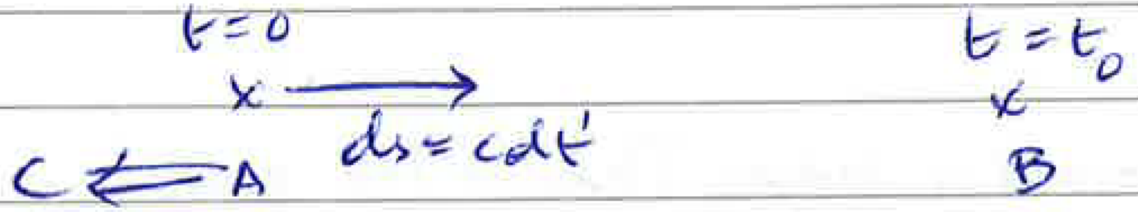

light emitted at A at $t=0$

by the time light arrives at B, A has moved to C

so $c\,dt'$ becomes $c\,dt'(1+z) = c\,dt'\left(\frac{R(0)}{R(t')}\right)$

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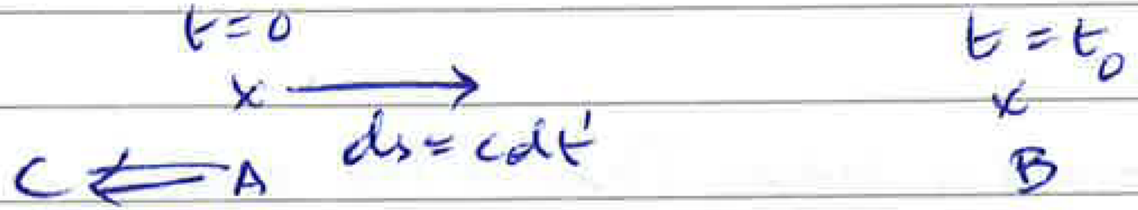

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because of Hubble expansion

$$D_H(t_0) = \int_0^{t_0} c\,dt'\left(\frac{R(0)}{R(t')}\right)$$

rewrite i.t.o. z and dz and quantities we can measure

$$D_H(t_0) = \int_0^{t_0} c\,dt' \left(\frac{R(0)}{R(t')}\right) = \int_0^{t_0} c\,dt' \,(1+z)$$

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Rewrite dt' in terms of dz:

$$H(t) = \frac{\dot{R}}{R} = \frac{1}{R}\frac{dR(t)}{dt} = \frac{1}{R(t)}\frac{d}{dt}\left(\frac{R(0)}{1+z}\right)$$

$$= \frac{R(0)}{R(t)}\,\frac{-1}{(1+z)^2}\,\frac{dz}{dt}$$

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

$$D_H(t_0) = \int_{z^*}^{\infty} \frac{c\,dz\,\cancel{(1+z)}}{H(t)\,\cancel{(1+z)}}$$

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from

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from $\rho = \left(H_0^2 + \frac{kc^2}{R^2}\right) \times \frac{3}{8\pi G}$

$= \left(H_0^2 + \frac{kc^2}{R^2}\right)\frac{\rho_c}{H_0^2}$

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

$$\Omega_m = \frac{\rho_m}{\rho_c},\quad \Omega_r = \frac{\rho_r}{\rho_c},\quad \Omega_\Lambda = \frac{\rho_\Lambda}{\rho_c} = \frac{1}{\rho_c}\left(\frac{\Lambda}{8\pi G}\right)$$

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

Λ = cosmological constant

Luminosity Distance

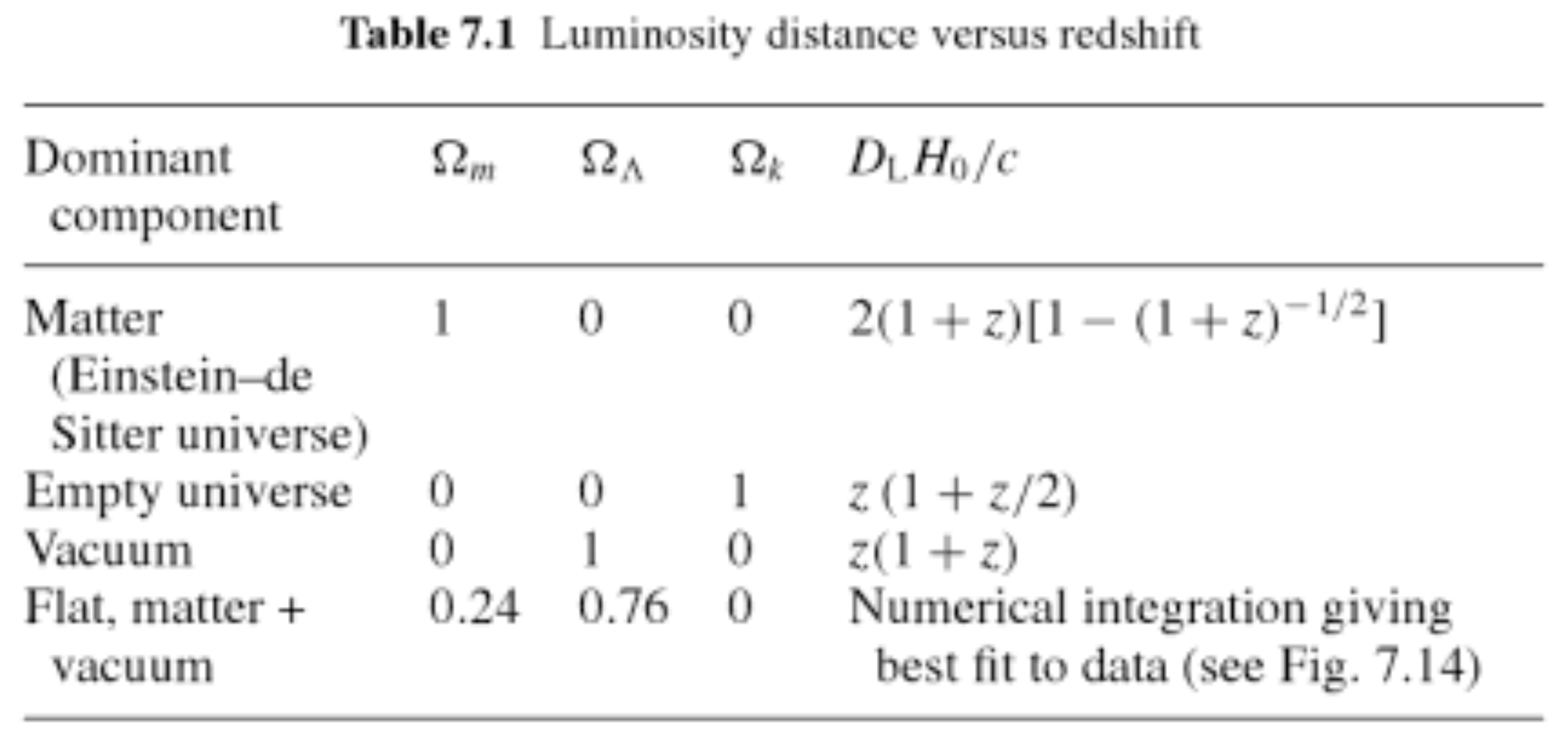

Table 7.1 Luminosity distance versus redshift

Dominant component	Ω_m	Ω_Λ	Ω_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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Recall, distance a photon travels (horizon distance D_H)

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

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

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in a <u>flat</u> universe (we have set $k=0$).

can also define an acoustic horizon = distance sound travels

$D_{AH} = \left(\frac{v_s}{c}\right) D_H$, v_s = speed of sound
= speed at which pressure waves travel.

= distance
over which
should see "clumps" from baryon acoustic oscillations.

- matter-radiation interactions relate $\left(\frac{\Delta\rho}{\rho}\right)$ density fluctuations to $\left(\frac{\Delta T}{T}\right)$ 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 → matter compresses by gravity, fights radiation pressure from photons. Pressure wave travels at v_s. → measure $\left(\frac{\Delta T}{T}\right)$, probe $\left(\frac{\Delta\rho}{\rho}\right)$.

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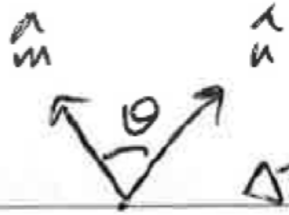
expts: COBE (1992) $\delta\Theta \sim 7^\circ$ (Smoot & Mather Nobel 2006)
WMAP (1998) $\sim 1/5^\circ$
PLANCK (2008) look for polarization in B-modes for imprint of gravity waves in inflation.

result: $\Omega_{tot} = 1 \pm 0.02$, $\Omega_m = 0.27$, $\Omega_\Lambda = 0.69$

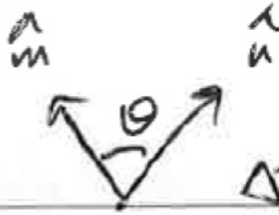
- WMAP (and COBE before) measure



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

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

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

- WMAP (and COBE before) measure  $\frac{\Delta T(\hat{m})}{T}$ and $\frac{\Delta T(\hat{n})}{T}$

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

report in terms of power spectrum $\sum_{\ell} (2\ell+1)\, C_\ell \, \frac{P_\ell(\cos\theta)}{4\pi}$

$P_\ell(\cos\theta)$ = Legendre polynomials $= 0$ at $\theta = \frac{n\pi}{2}/\ell \sim 200°/\ell$

C_ℓ = amplitude of fluctuations at multipole # ℓ

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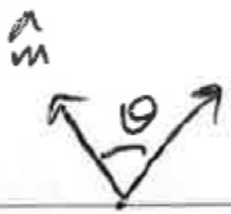

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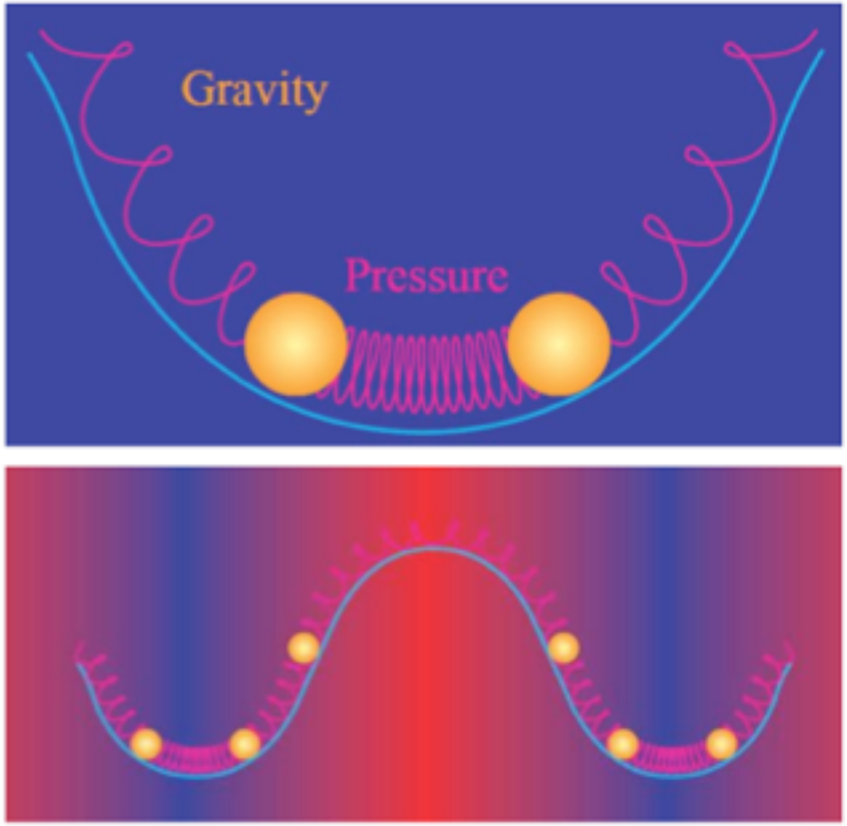
C_ℓ = amplitude of fluctuations at multipole # ℓ

plot C_ℓ vs. ℓ, get 1st peak at acoustic horizon distance, amplitude related to Ω_m, h, etc. through D_H.

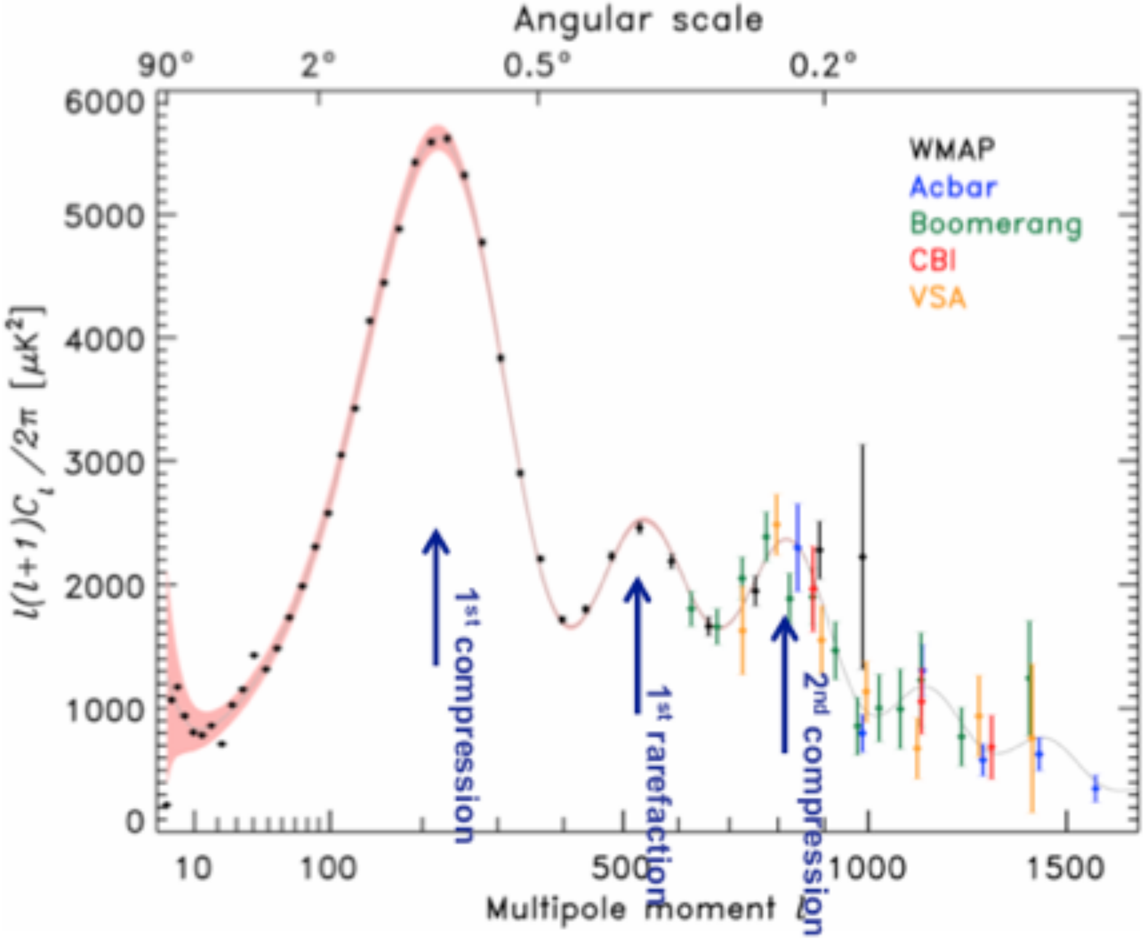
CMB Acoustic Spectrum

CMB "Baryometer"

From W. Wu (Chicago)

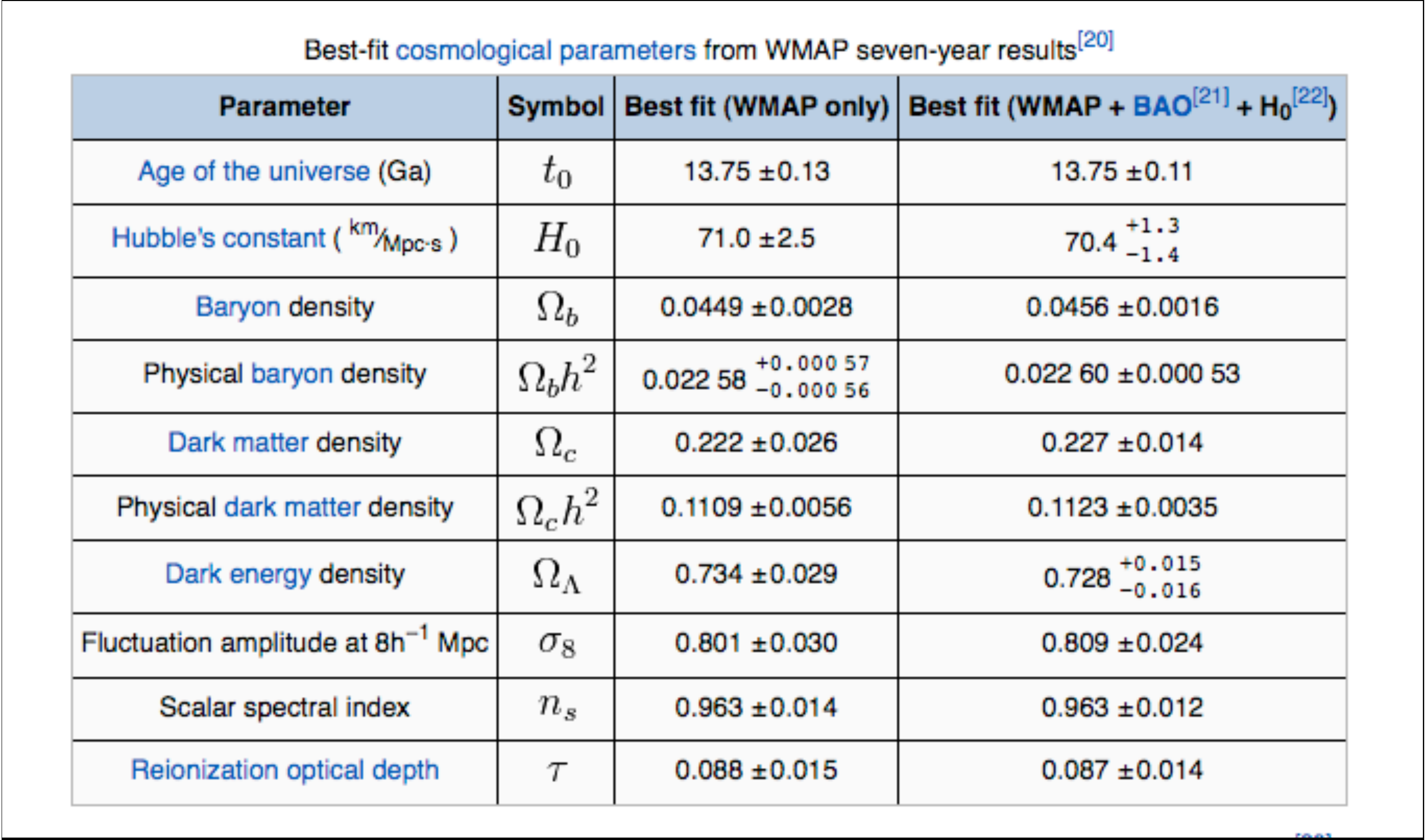


Baryon Acoustic Oscillations



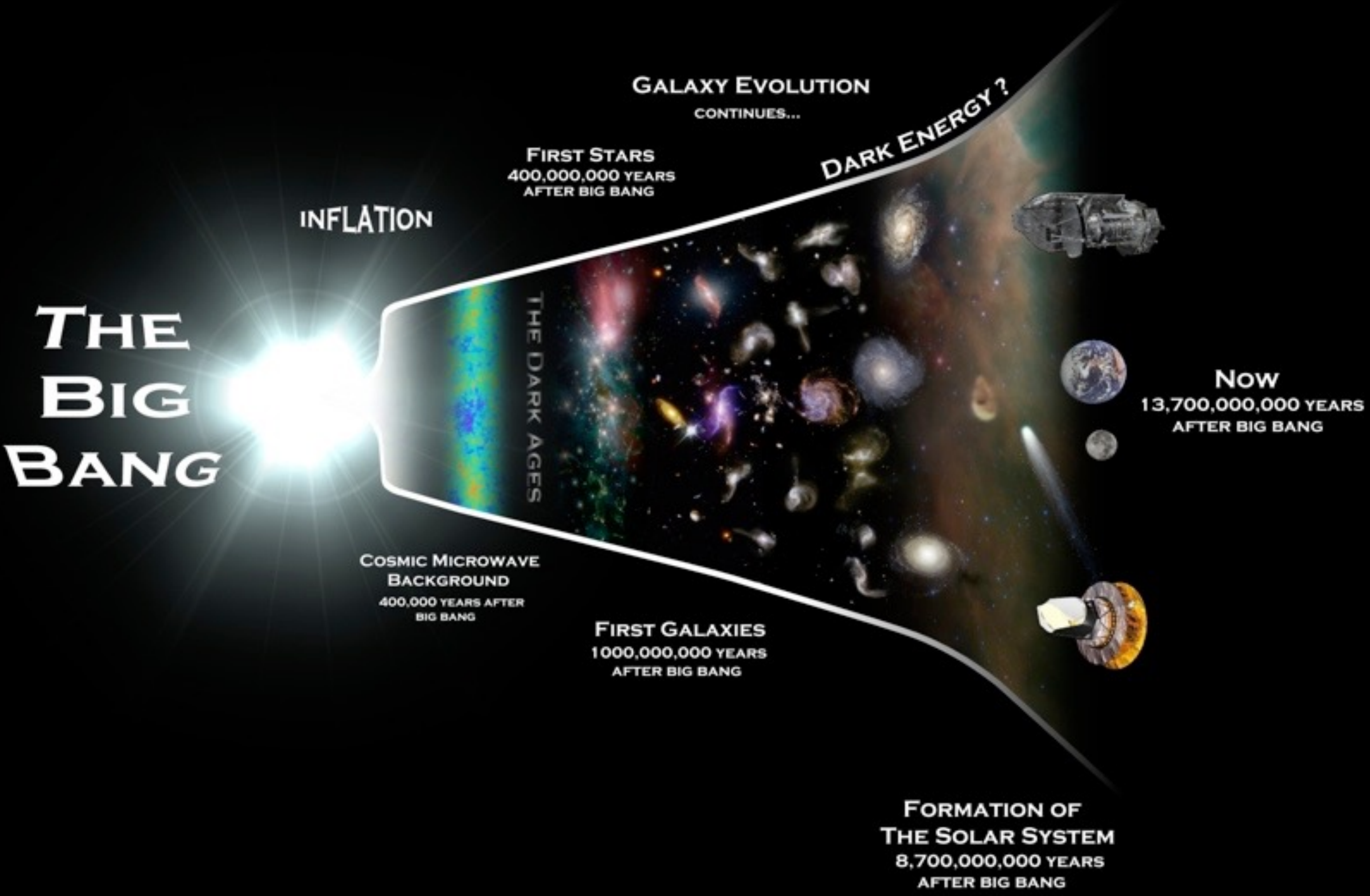
Baryons compress photon-baryon plasma at recombination, photons exert pressure, competition gives rise to pressure wave

Cosmological Parameters

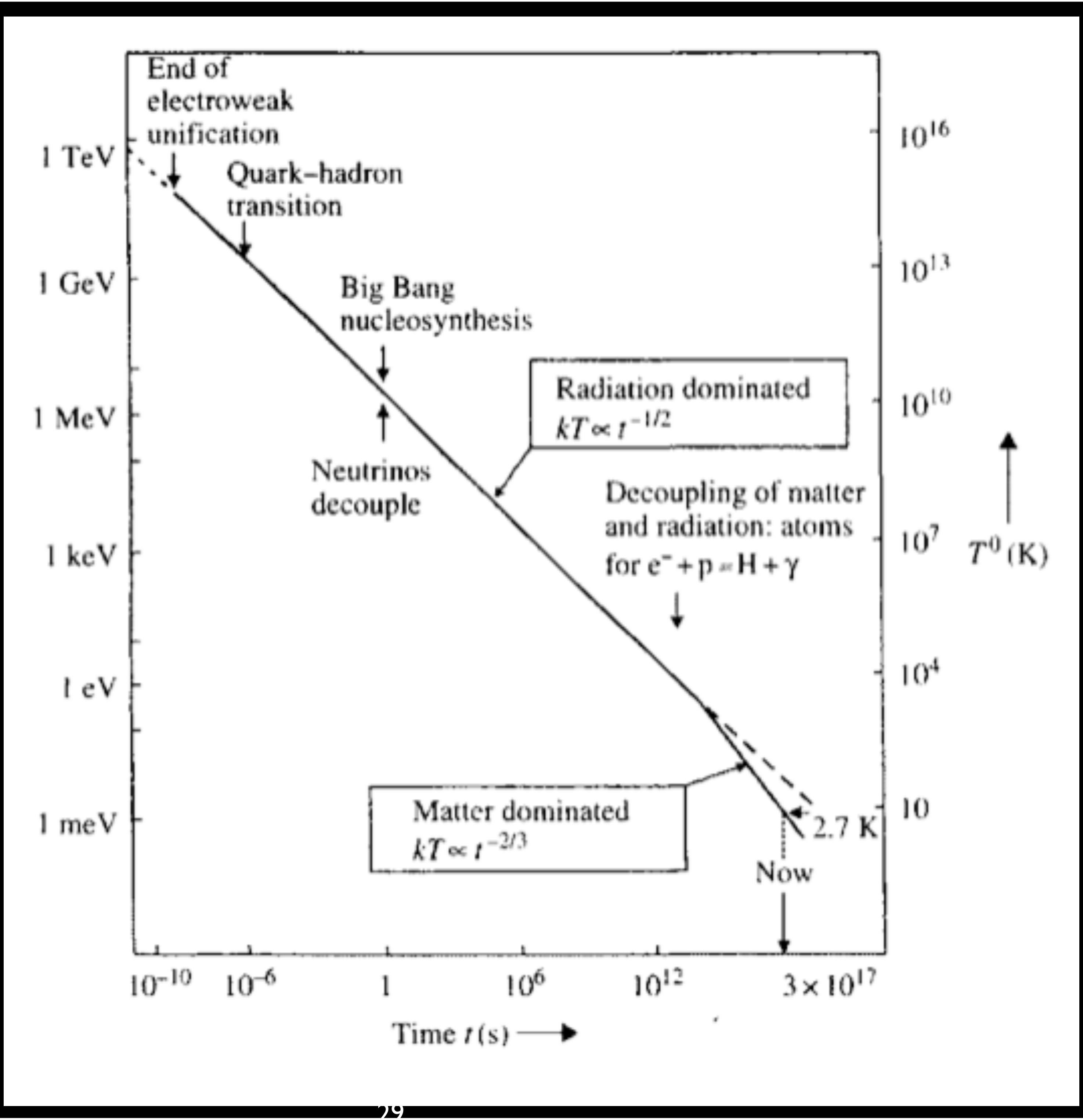


Best-fit cosmological parameters from WMAP seven-year results[20]

Parameter	Symbol	Best fit (WMAP only)	Best fit (WMAP + BAO[21] + H_0[22])
Age of the universe (Ga)	t_0	13.75 ±0.13	13.75 ±0.11
Hubble's constant (km/Mpc·s)	H_0	71.0 ±2.5	$70.4^{+1.3}_{-1.4}$
Baryon density	Ω_b	0.0449 ±0.0028	0.0456 ±0.0016
Physical baryon density	$\Omega_b h^2$	$0.022\,58^{+0.000\,57}_{-0.000\,56}$	0.022 60 ±0.000 53
Dark matter density	Ω_c	0.222 ±0.026	0.227 ±0.014
Physical dark matter density	$\Omega_c h^2$	0.1109 ±0.0056	0.1123 ±0.0035
Dark energy density	Ω_Λ	0.734 ±0.029	$0.728^{+0.015}_{-0.016}$
Fluctuation amplitude at $8h^{-1}$ Mpc	σ_8	0.801 ±0.030	0.809 ±0.024
Scalar spectral index	n_s	0.963 ±0.014	0.963 ±0.012
Reionization optical depth	τ	0.088 ±0.015	0.087 ±0.014

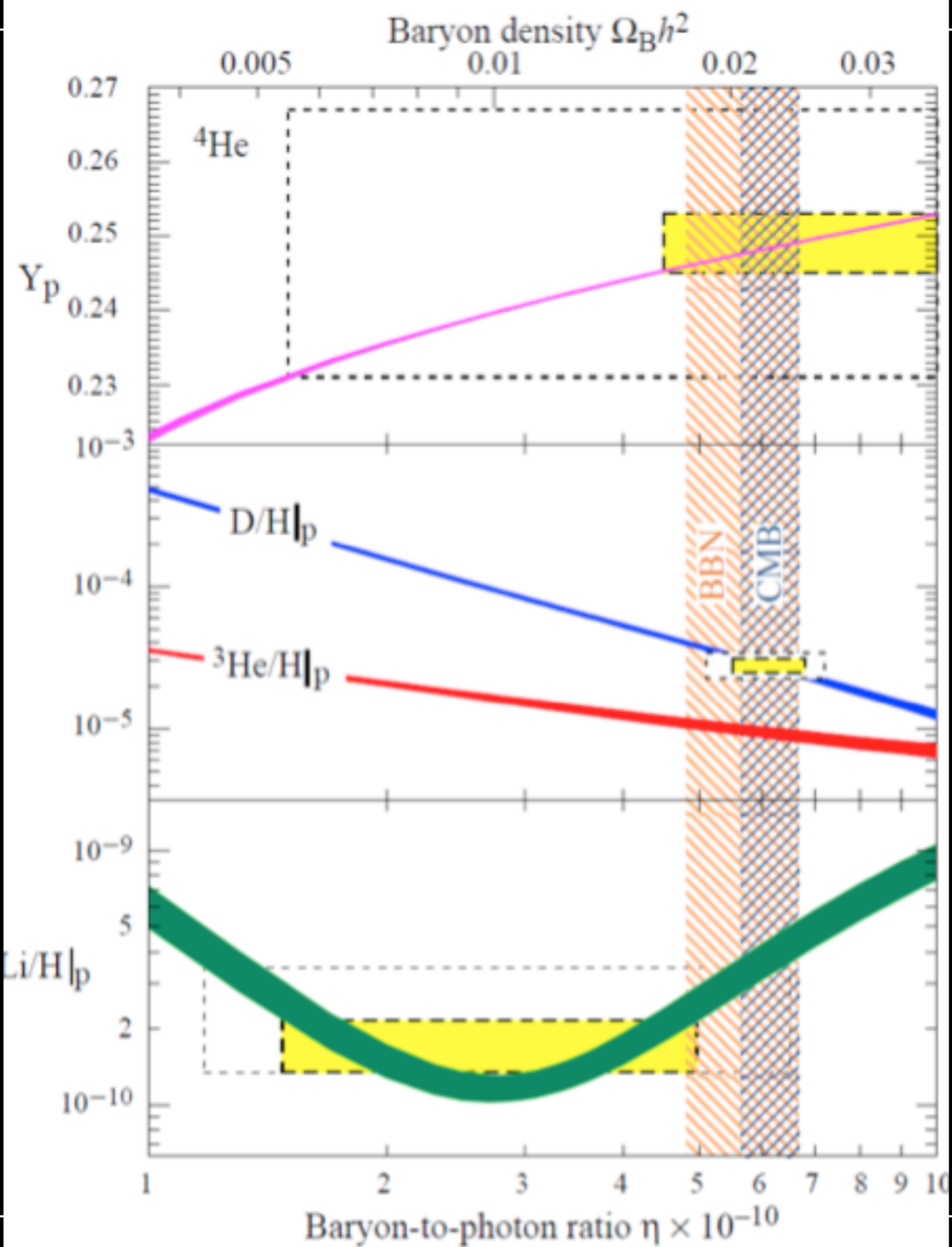
THE BIG BANG
INFLATION
FIRST STARS
400,000,000 YEARS
AFTER BIG BANG
GALAXY EVOLUTION
CONTINUES...
DARK ENERGY ?
THE DARK AGES
COSMIC MICROWAVE BACKGROUND
400,000 YEARS AFTER BIG BANG
FIRST GALAXIES
1000,000,000 YEARS
AFTER BIG BANG
NOW
13,700,000,000 YEARS
AFTER BIG BANG
FORMATION OF THE SOLAR SYSTEM
8,700,000,000 YEARS
AFTER BIG BANG

Big Bang Nucleo-synthesis (BBN)



D. H. Perkins, Particle Astrophysics (2004)

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

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

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

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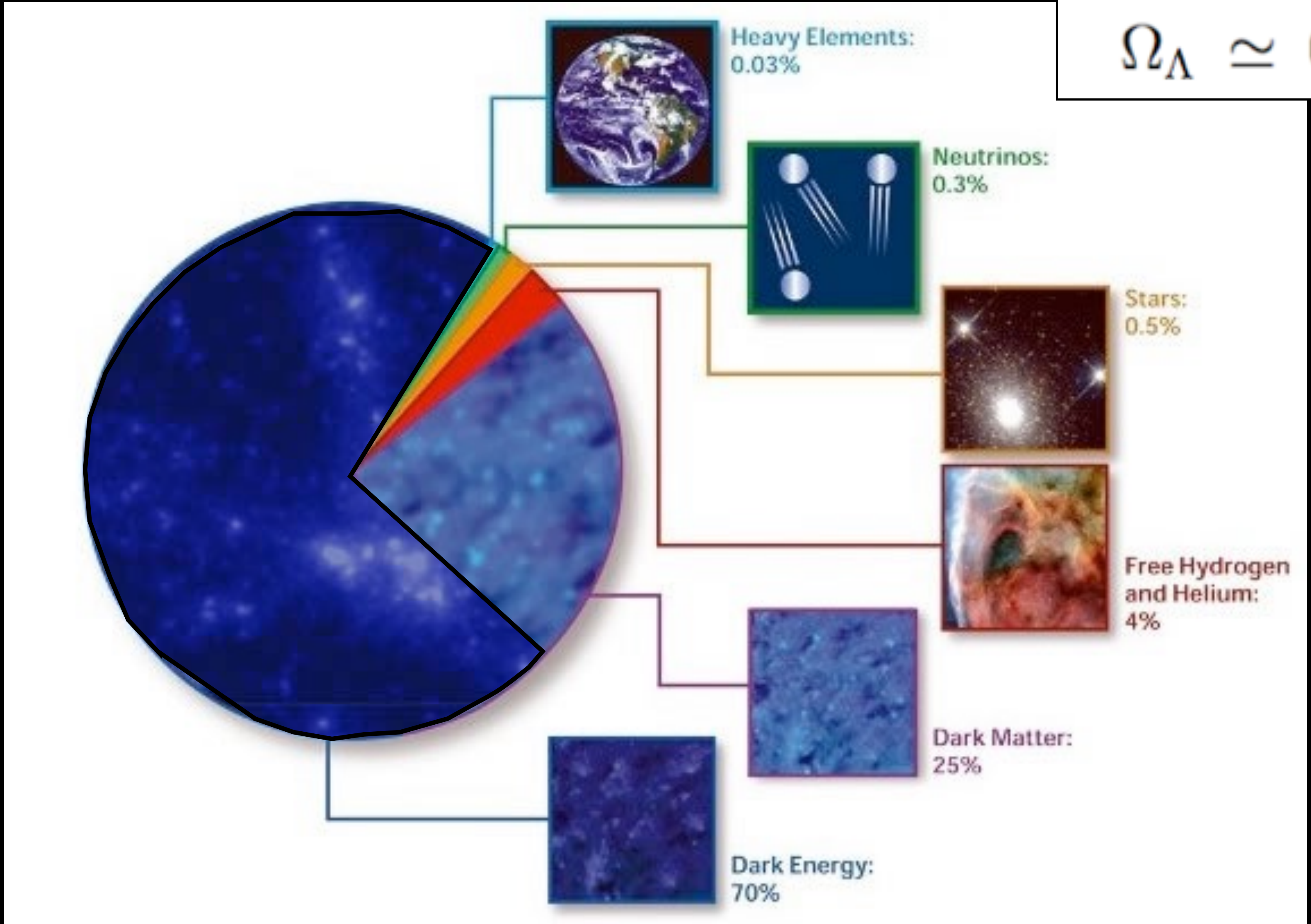
The mass density ρ_B is then given by $\rho_B = n_B \times m_B$. Taking m_B as the proton mass is a good approximation. So to find the current value of Ω we evaluate

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

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 ~25% of the universe.

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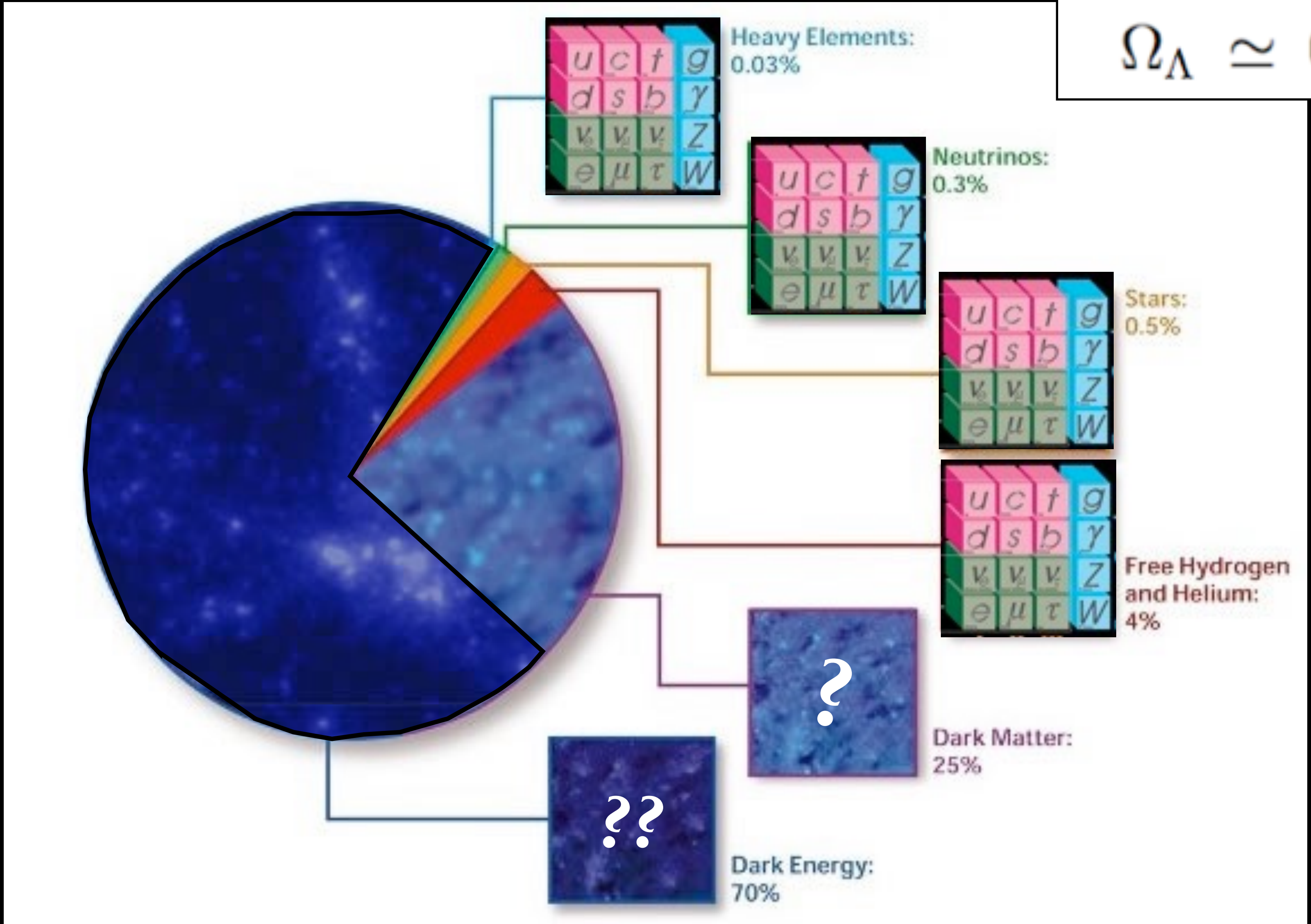
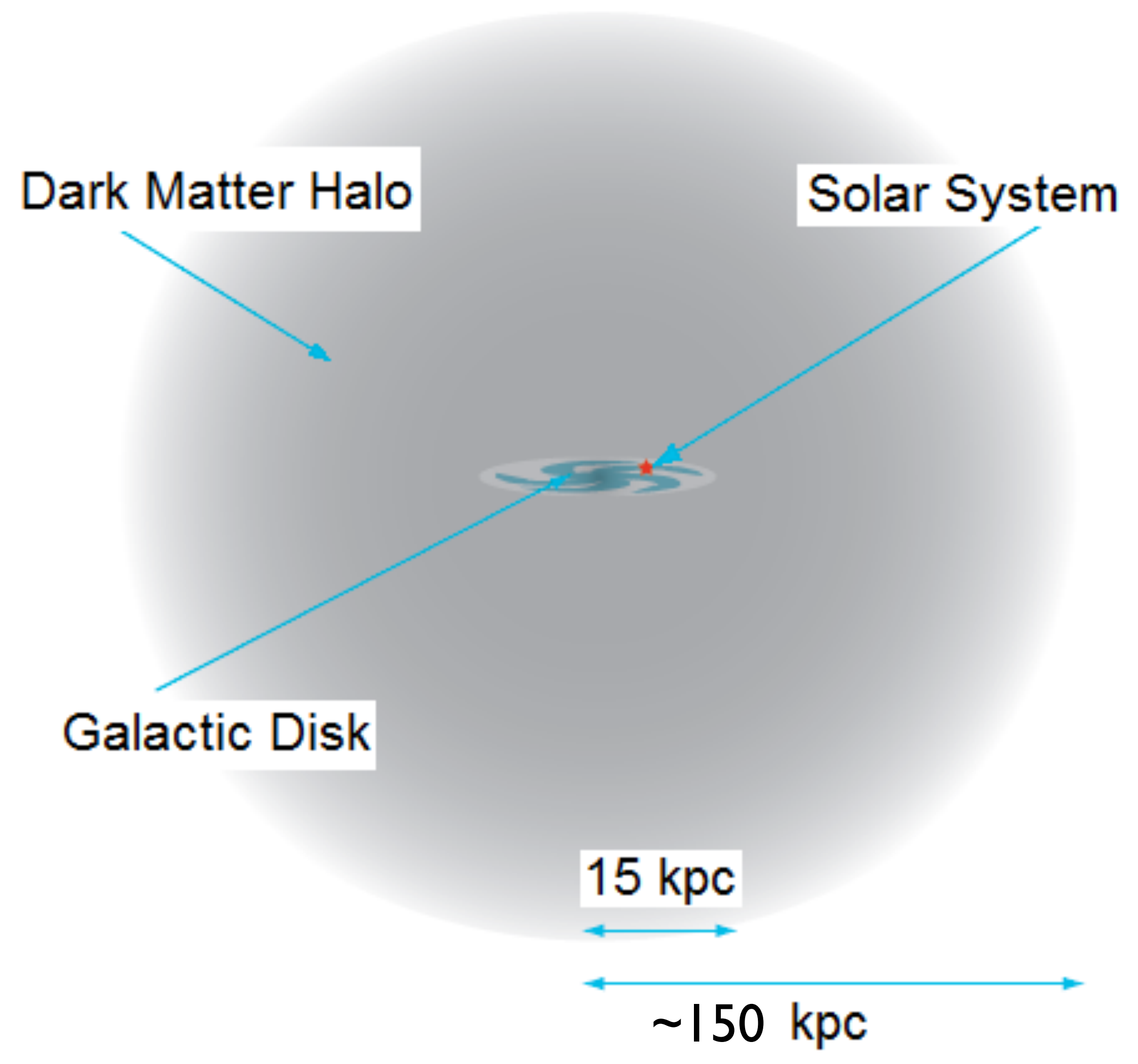


We only understand 4% of the universe!

What do we know about Dark Matter?



~25% of the universe

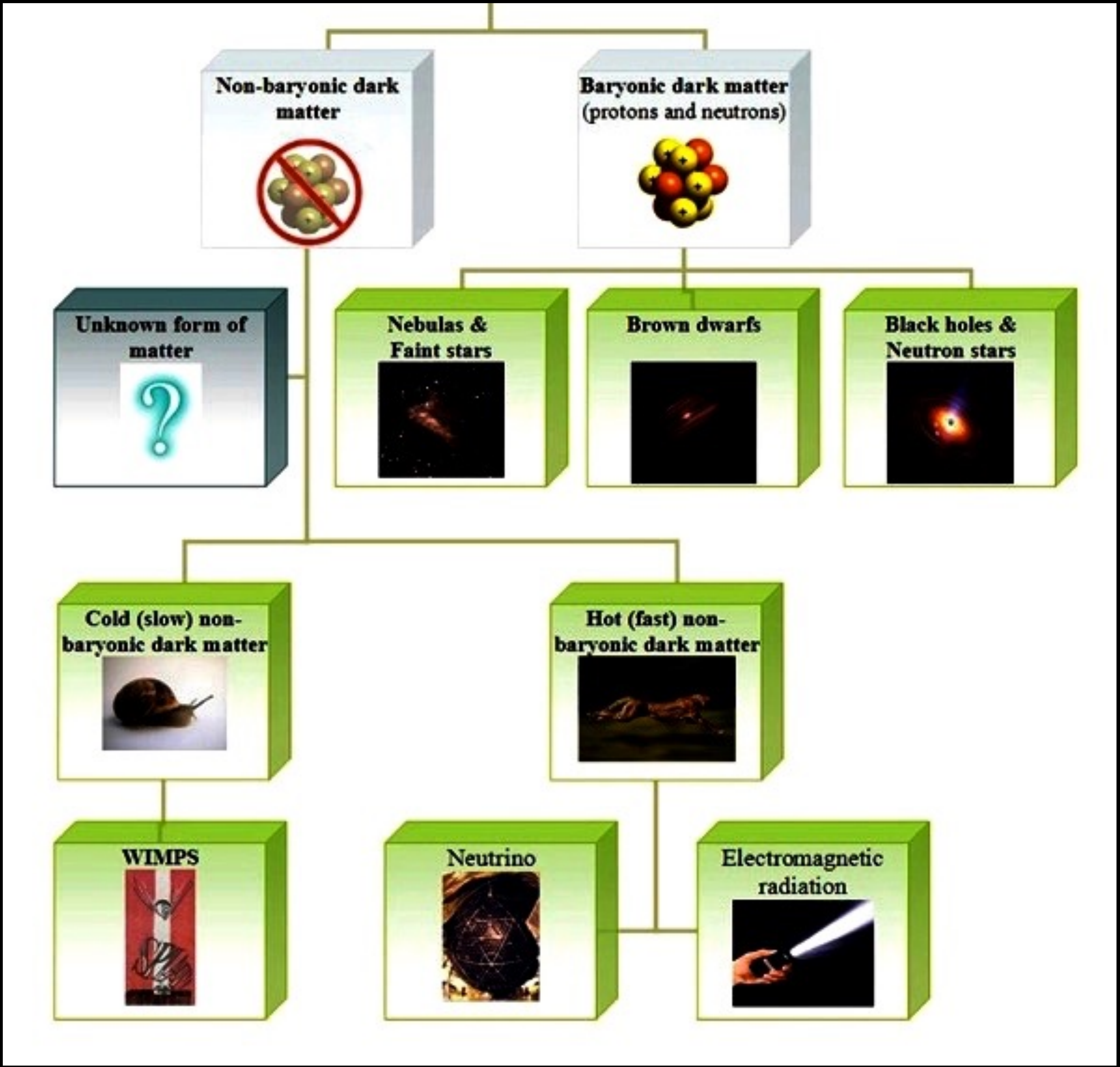
optically dark

bound to our galaxy

density ~ 0.3 GeV/cm^3

interactions: very weak,
~collision-less

Candidates


Non-baryonic dark matter
Baryonic dark matter (protons and neutrons)
Unknown form of matter
Nebulas & Faint stars
Brown dwarfs
Black holes & Neutron stars
Cold (slow) non-baryonic dark matter
Hot (fast) non-baryonic dark matter
WIMPS
Neutrino
Electromagnetic radiation

II. Dark Matter Candidates

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– baryonic : • dim stuff $\Omega_{lum} = 0.01$, $\Omega_b = 0.04$, mostly gas

MACHOS $< 15\%$ of DM from microlensing

• mini-black holes: $m < 10^{11}$ kg would evaporate by Hawking radiation in $t < t_0$.

limit $\Omega_{BH} < 10^{-7}$

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

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  inconsistent w/ neutrino oscillation results $\sum_i m_i c^2 < 0.1 eV$

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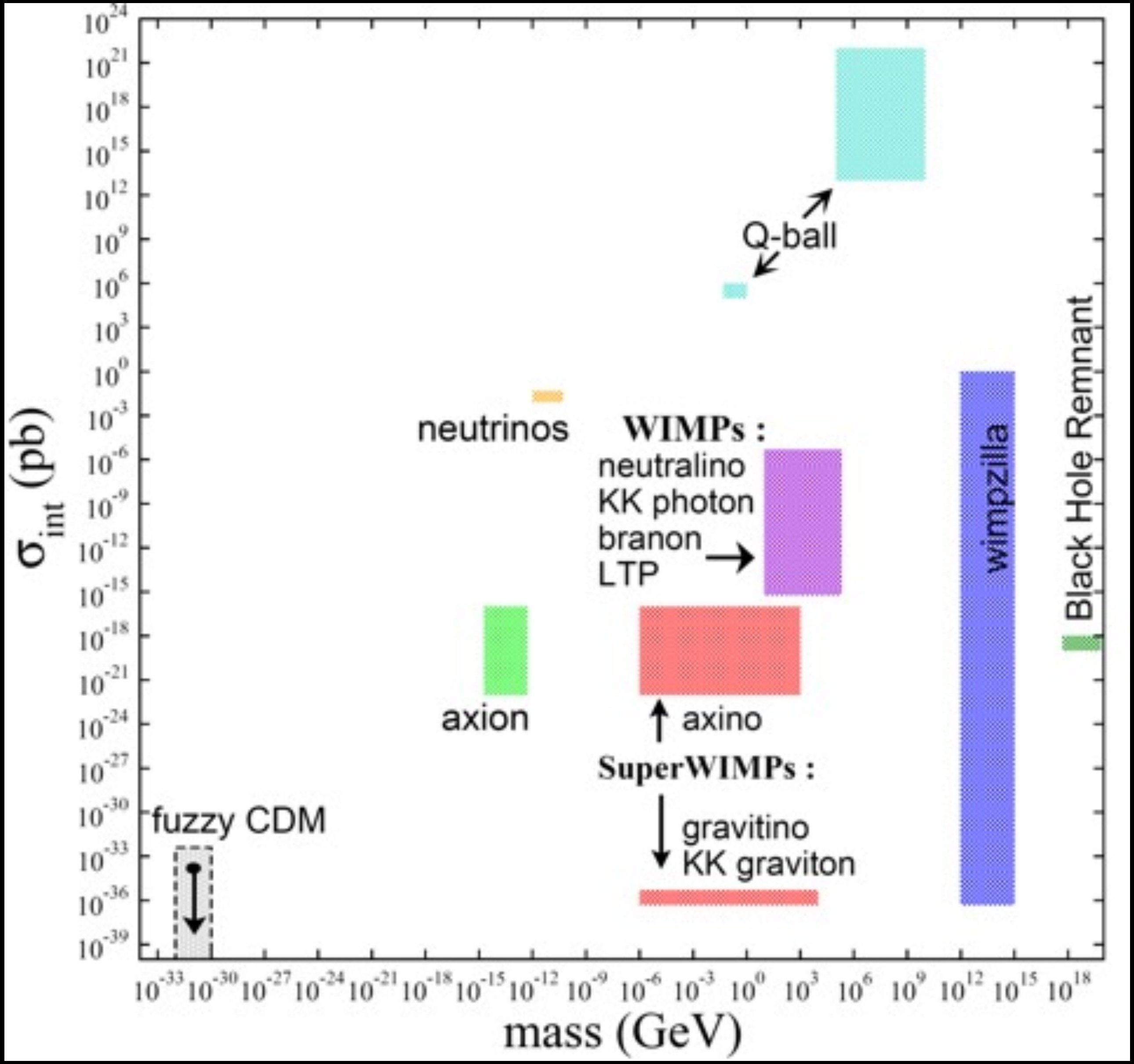
- new particles ?

Dark Matter Candidates



strong

e.m.

weak

interaction strengths

gravity

masses

neutrino?

electron

t-quark

HEPAP/AAAC DMSAG Subpanel (2007)

<u>Axions</u>: new particle postulated to solve Strong CP problem.

($nEDM < 10^{-9}$ x prediction if $\not{CP}$)

a arises from spontaneous symmetry breaking of new $U(1)$ symmetry.

- can decay $a \to \gamma\gamma$ $f_\pi = 93$ MeV

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- $$m_{axion} \approx \frac{0.5\, m_\pi f_\pi}{f_a} = \frac{6 \text{ eV}}{[f_a / 10^6 \text{ GeV}]}$$

$f_\pi = 93$ MeV
$m_\pi = 140$ MeV
$f_a = 6 \times 10^6$ if $m_a = 1\,\text{eV}$

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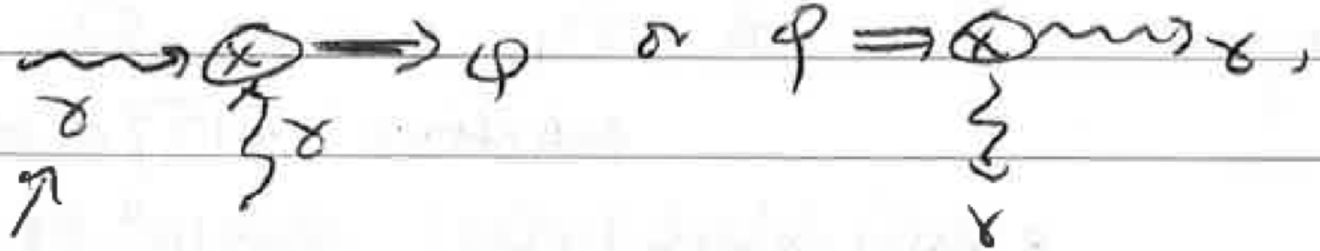
$m_\pi = 140$ MeV

$f_a = 6 \times 10^6$ if $m_a = 1_{eV}$

- decay rate: lifetime $\tau > t_0$ if $m_a < 10$ eV ✓ stable
- weakly coupled so not in thermal equilibrium before freeze-out

- limits:
  - in stars $\varphi \to \gamma\gamma$ would change cooling rate of red dwarfs $\to m_a < 0.01$ eV
  - $\vec{B}$ field coupling



$m_a < 0.001$ eV

from sun, or laser

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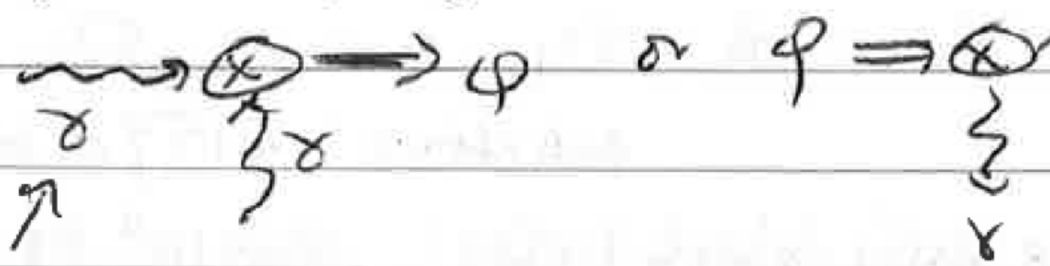

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from sun, or laser

- for $\rho a = \rho c$, need $m_a \sim 10^{-3} - 10^{-5}$ eV

WIMPs: new particle postulated in models that address the hierarchy problem in the Standard Model

leading contender: Supersymmetry (SUSY)

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R-Parity in SUSY means SUSY ptcls produced in pairs, e.g. $\chi\bar{\chi}$, so lightest SUSY particle (LSP) is stable.

LSP: neutralino χ_0 = mix of photino, zino, 2 higgsinos
predicted to interact via the weak force, with 10-10,000 GeV mass, and $10^{-40} - 10^{-48}$ cm^2 cross sections w/ nucleons.

- abundance at freeze-out?

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

$\langle N \sigma v \rangle \leq H$

comment: weaker interaction

= earlier freeze out

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

$$\langle N \sigma v \rangle \leq H$$

comment: weaker interaction
= earlier freeze out
= higher abundance
= more DM =
larger contribution to
closure parameter
→ Thermal DM

Boltzmann relation:

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

(non-relativistic solution)

weak interactions, $\sigma_{\chi\bar{\chi}} \sim \sigma_{weak} \sim G_F^2 s$

$$\sim G_F^2 M^2$$

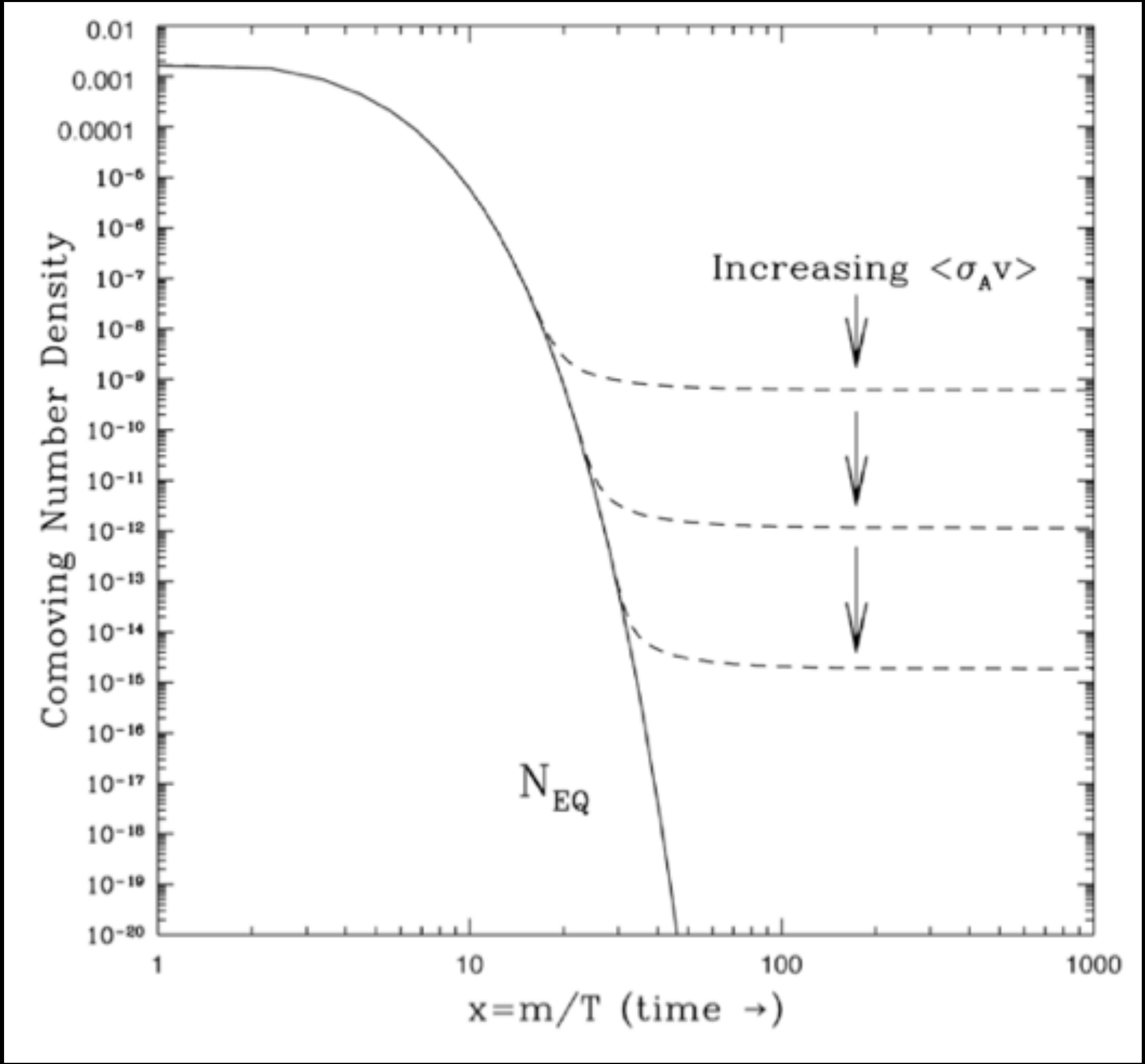
means $\sigma(\chi p) > 10^{-48}\,cm^2$

$G_F = 10^{-5}\,GeV^{-2}$

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

$$M_{pl} = \sqrt{\frac{\hbar c}{G}} = 10^{19}\,GeV$$

WIMP Number Density



D. H. Perkins, Particle Astrophysics (2004) freeze out condition:

$$(MT)^{3/2} \exp\left\{-M/k_B T\right\} \cdot G_F^2 M^2 \leq \frac{f T^2}{M_{pl}}$$

plug in constants, find $\frac{M}{T} \sim 25$ at freeze-out Ξ P freeze out condition :

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

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

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

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- contribution to energy density : $\rho_{WIMP} = M N(0) = f \frac{P T_0^{\,3}}{M_{pl} \langle \sigma v \rangle}$

for closure: $\Omega_w = \frac{\rho_w}{\rho_c} = \frac{10^{-25}\ cm^2 s^{-1}}{\langle \sigma v \rangle}$ $= \frac{6\times10^{-31}}{\langle \sigma v \rangle}[GeV s^{-1}]$ $\leftarrow [cm^3 s^{-1}]$

(estimate v so we can get σ)

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

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

called the "WIMP miracle"

[more like WIMP "nice coincidence" since there is broad range of coupling constants to e.g. Higgs field giving rise to particle masses ranging from eV to GeV]

WIMP Mass Range

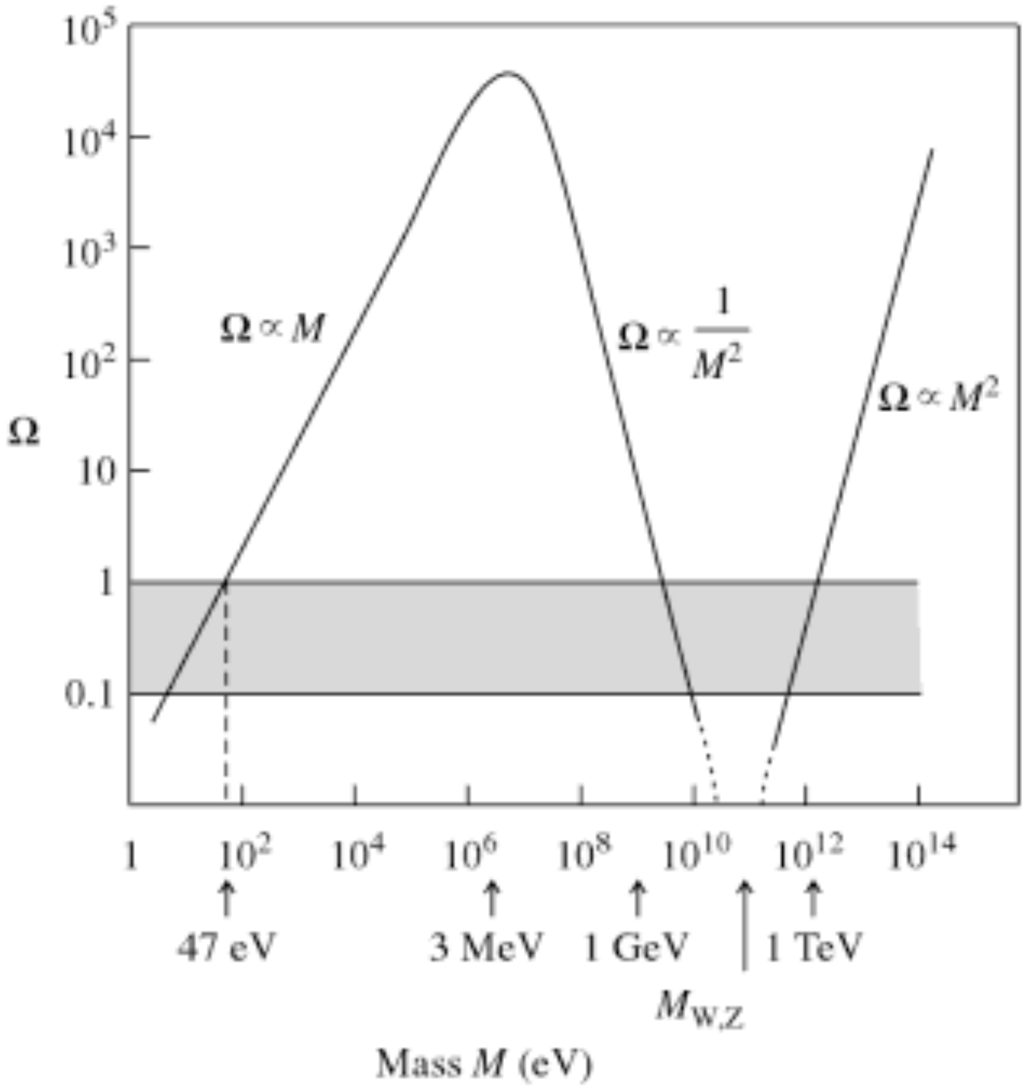
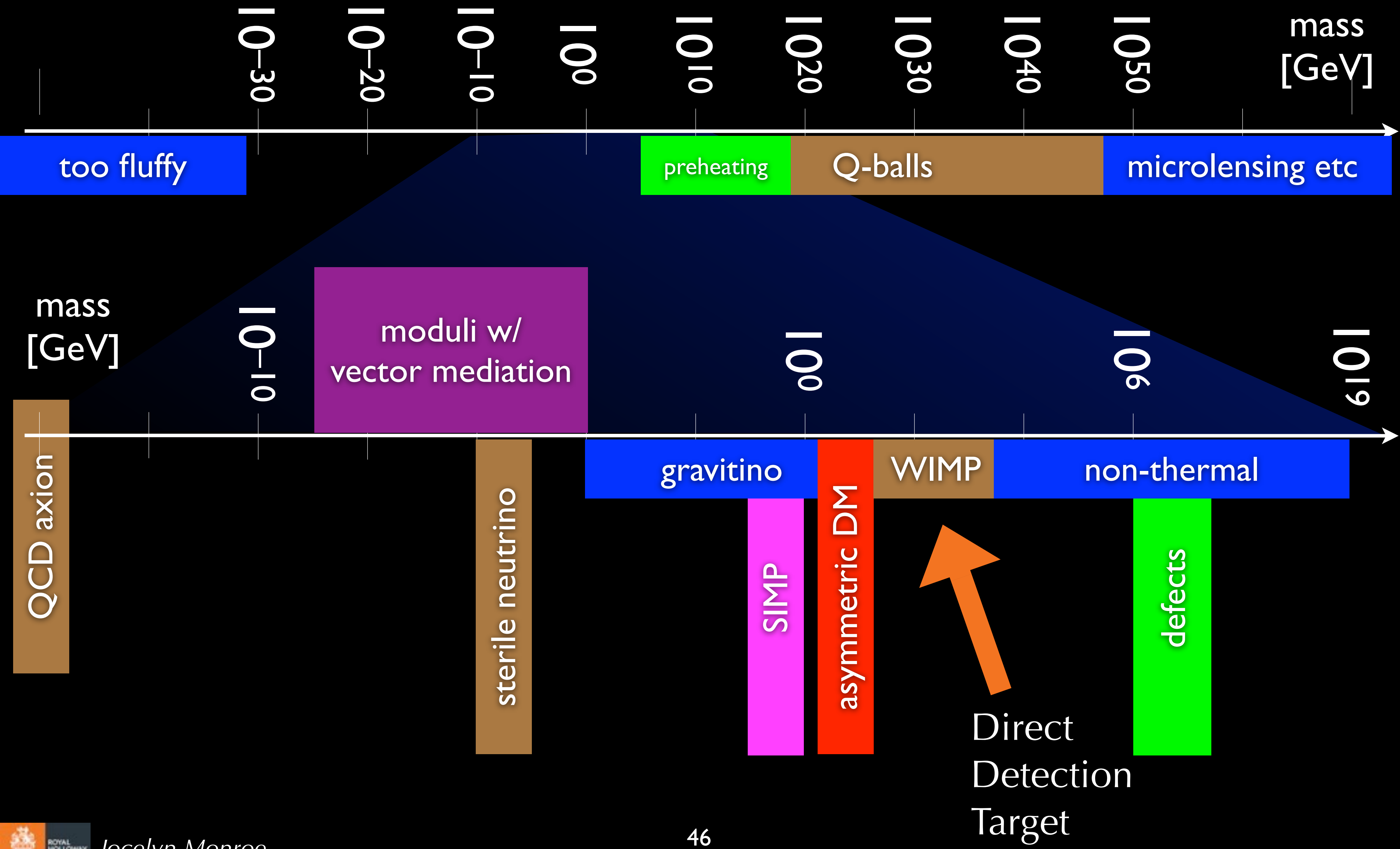


Fig. 7.11 Variation of the closure parameter with WIMP mass, assuming conventional weak coupling. The shaded region, corresponding to $\Omega = 0.1 - 1$, is that in which the contribution to the closure parameter from massive neutrinos or WIMPs must lie, thus excluding the range of masses 100 eV–3 GeV. Accelerator experiments suggest that WIMPs must have masses exceeding $M_Z/2 = 45\,\mathrm{GeV}$, 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)



mass [GeV]

10^{-30} 10^{-20} 10^{-10} 10^{0} 10^{10} 10^{20} 10^{30} 10^{40} 10^{50}

too fluffy

preheating

Q-balls

microlensing etc

mass [GeV]

10^{-10} 10^{0} 10^{6} 10^{19}

moduli w/ vector mediation

QCD axion

sterile neutrino

gravitino

SIMP

asymmetric DM

WIMP

non-thermal

defects

Direct Detection Target

Model Space: Theorist's View

(thanks to H. Murayama)