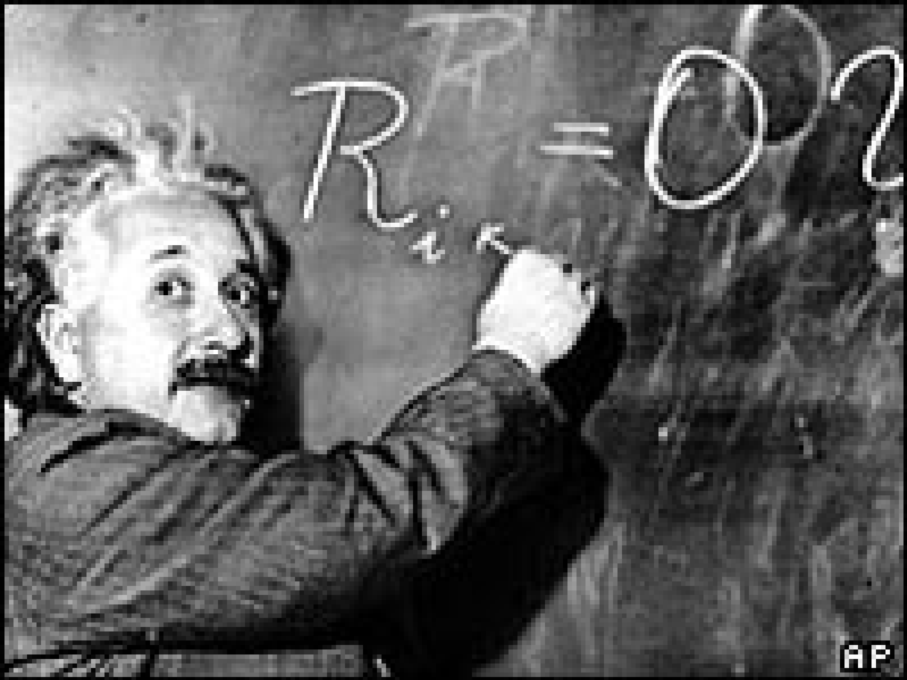
Einstein's Universe

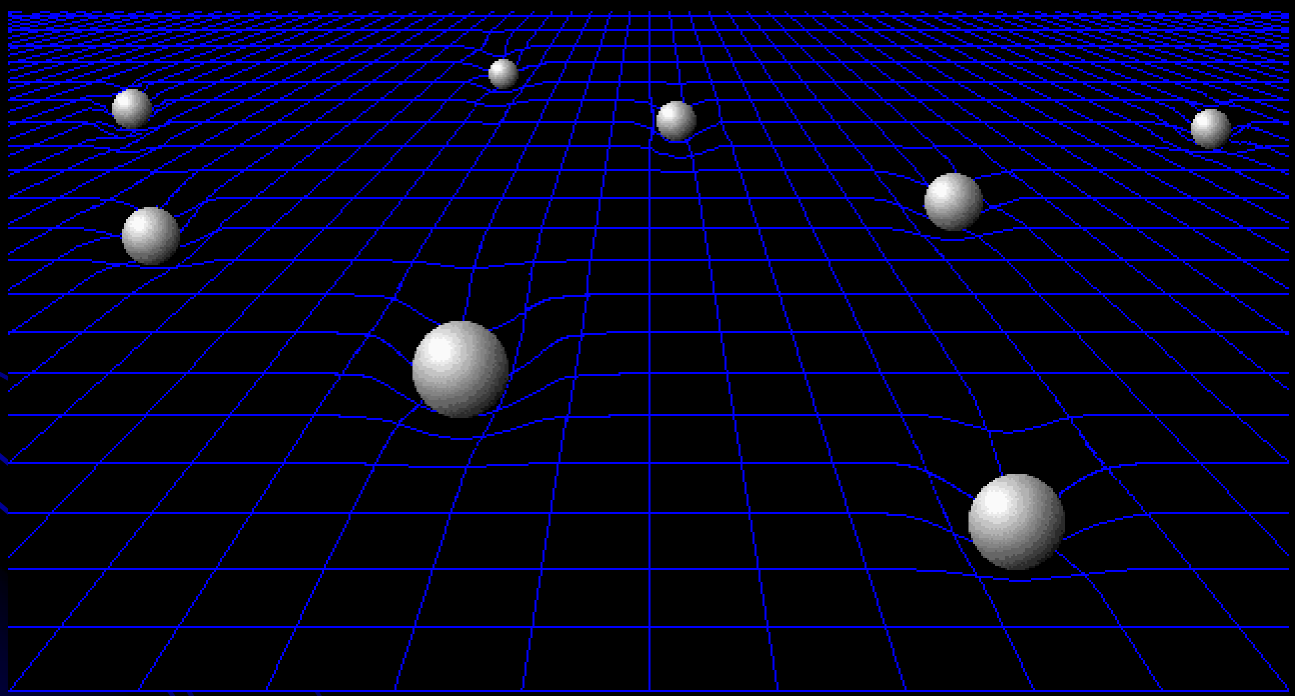


Fiona Speirits, Dept. of Physics and Astronomy

Einstein's Universe

- The shape of Spacetime – how do we know Einstein was right?
- Cosmology – from locally flat spacetime to a curved universe
- Measuring cosmological parameters
  - CMBR
  - Supernovae & GRBs
  - Baryon Acoustic Oscillations
- Is ΛCDM right?

"Matter tells spacetime how to curve… spacetime tells matter how to move"



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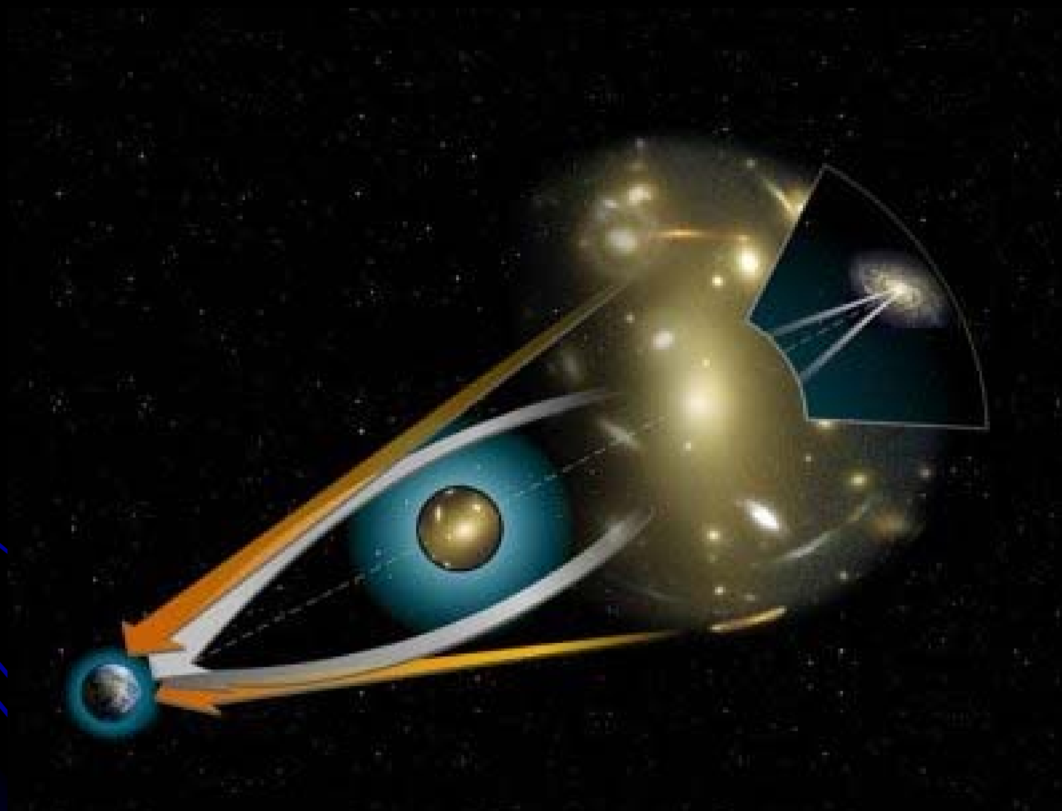
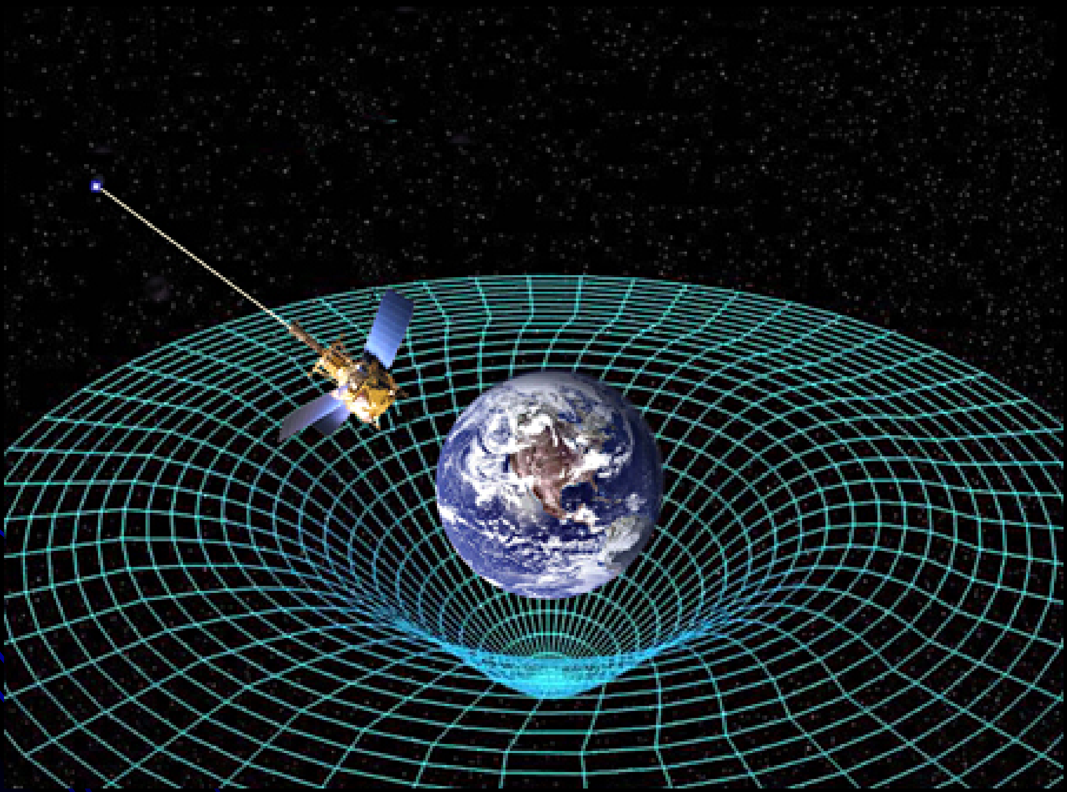


Gravitational Lensing

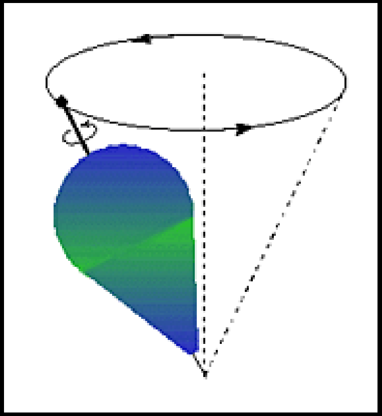
“Matter tells spacetime how to curve… spacetime tells matter how to move”



Gravity Probe B

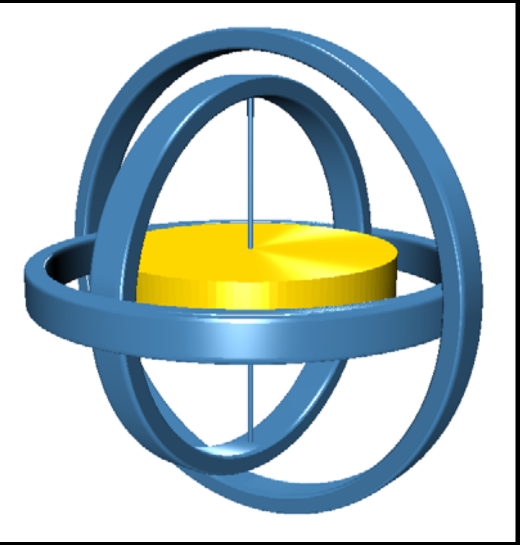
Gravity Probe B

Frame Dragging

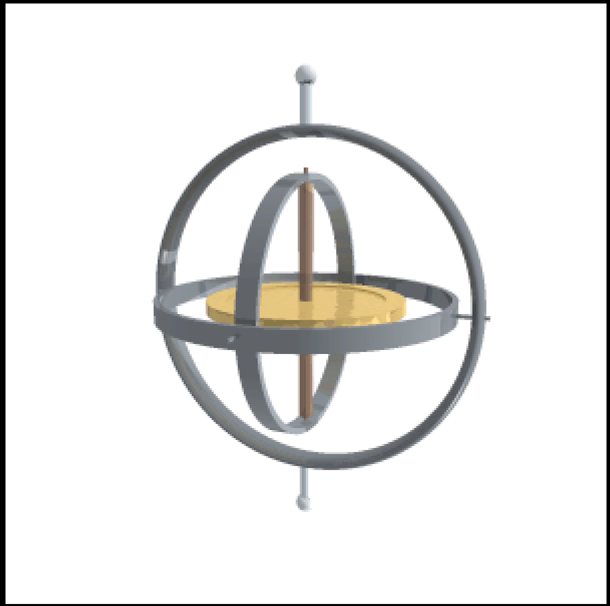


Geodetic Precession

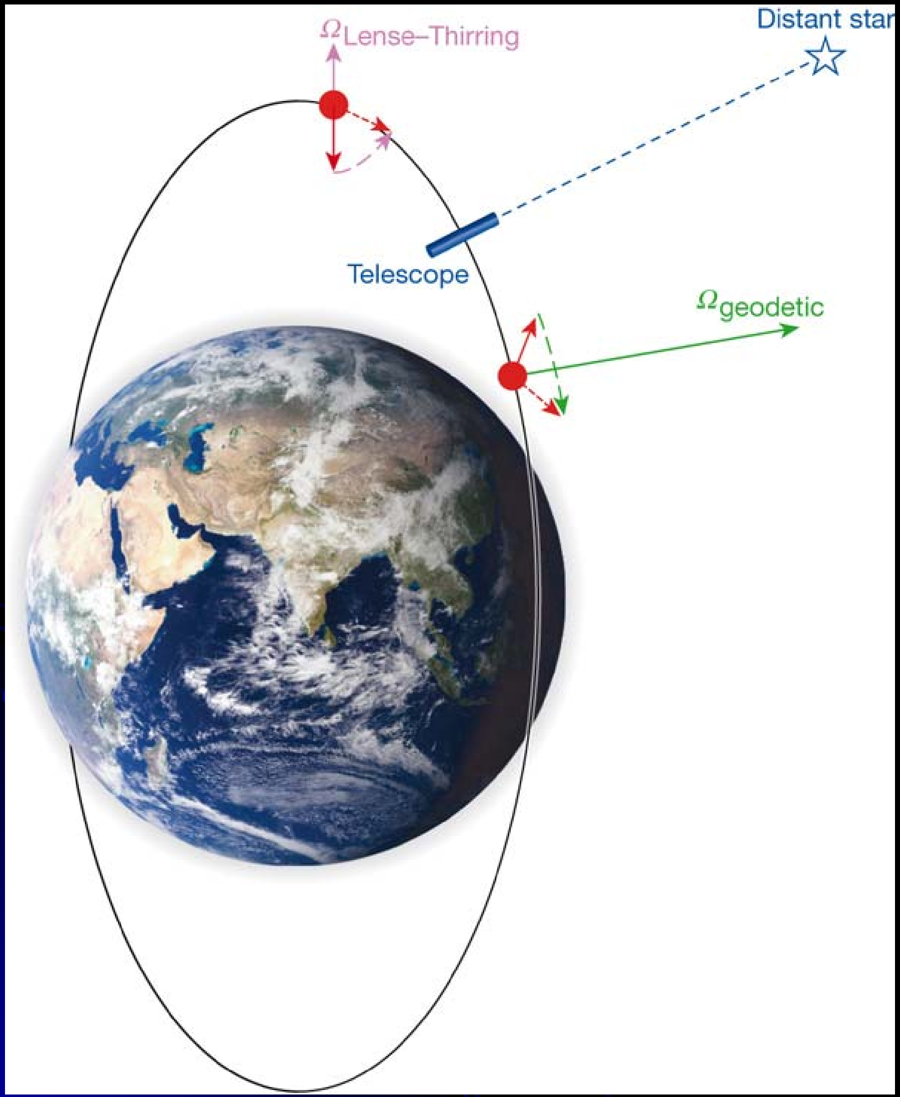
Gravity Probe B



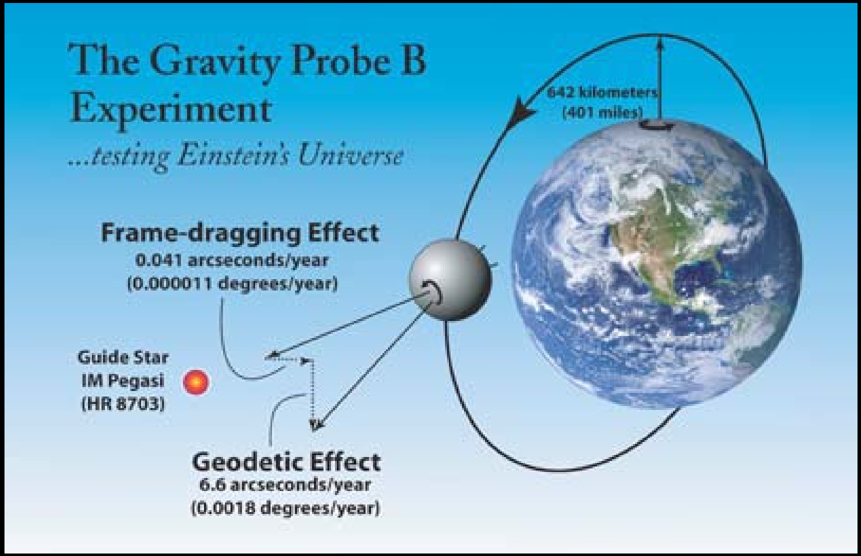
The world's most perfect sphere



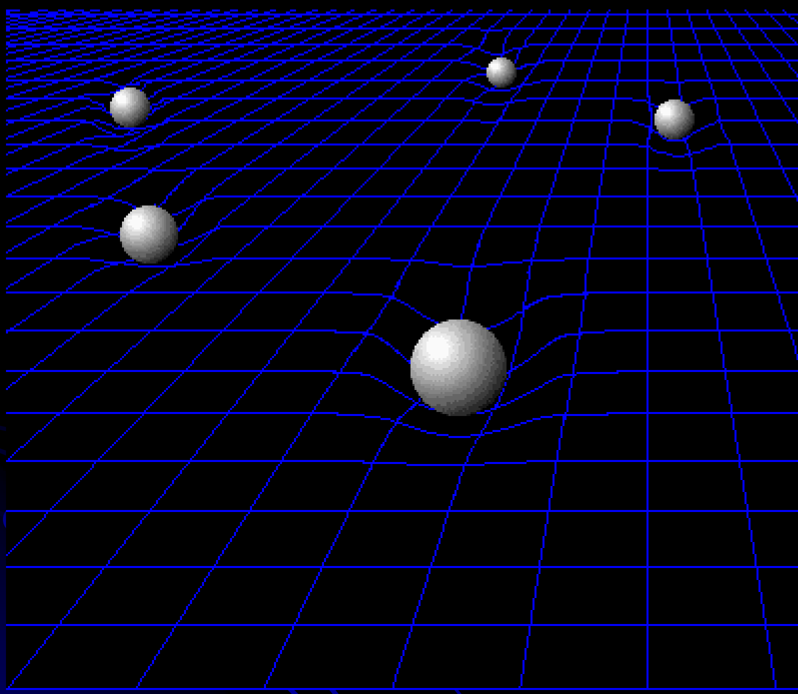
Gravity Probe B

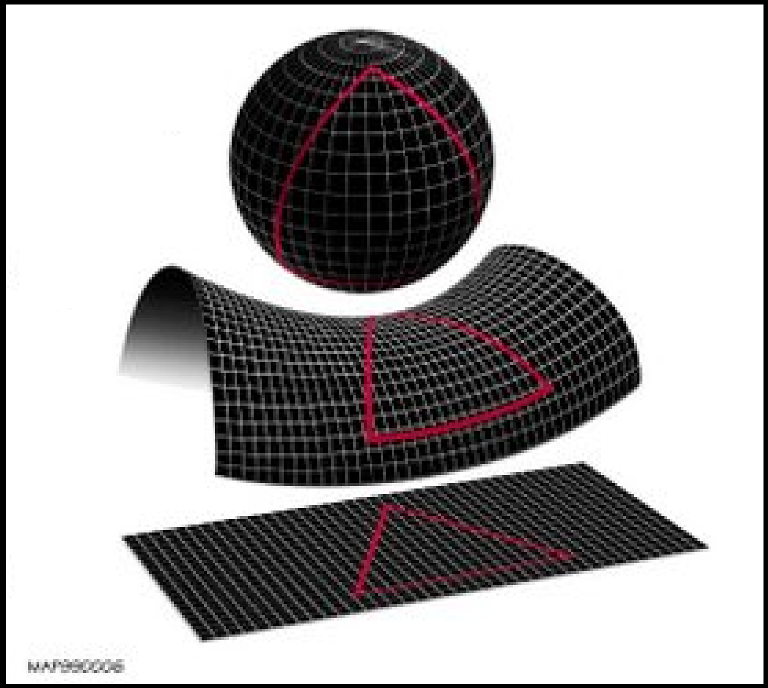


- Satellite in 642km polar orbit
- IM Pegasi used as guide star
- Preliminary results confirm geodetic effect to better than 1%



Curvature of the Universe





Curvature of the Universe

$$ds^2 = -\left(1 - \frac{2M}{r}\right) dt^2 + \frac{dr^2}{\left(1 - \frac{2M}{r}\right)} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2$$

Schwarzschild's solution for the spacetime metric exterior to a black hole

Curvature of the Universe

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Schwarzschild's solution for the spacetime metric exterior to a black hole

$$ds^2 = -dt^2 + R(t)^2 \left[\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right]$$

Robertson-Walker metric describes background cosmological model in a homogeneous, isotropic expanding or contracting universe

Curvature of the Universe

$$ds^2 = -dt^2 + R(t)^2\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

Curvature of the Universe

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$$\frac{R(t)}{R_0} = \frac{1}{1+z}$$

Scale factor

$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}}$$

Redshift

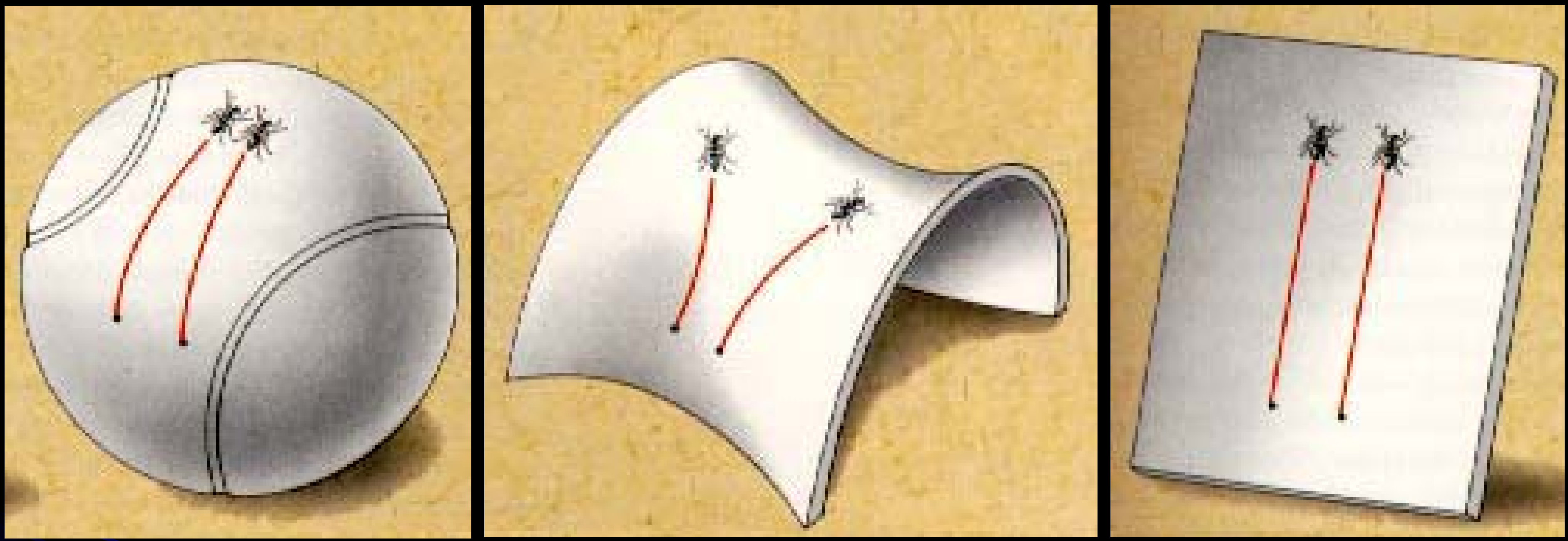
CURVATURE OF THE UNIVERSE

$$ds^2 = -dt^2 + R(t)^2 \left[\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right]$$

$$k = \begin{cases} -1, & \text{open} \\ 0, & \text{flat} \\ +1, & \text{closed} \end{cases}$$

Curvature constant

Curvature of the Universe



Closed Open Flat

$$k = \begin{cases} -1, & \text{open} \\ 0, & \text{flat} \\ +1, & \text{closed} \end{cases}$$

CURVATURE OF THE UNIVERSE

$$ds^2 = -dt^2 + R(t)^2\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

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We can solve this to give Friedmann's Equations:

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

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\left(\rho + 3P\right) + \frac{\Lambda}{3}$$

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Observables that we can measure, allowing us to determine 'k'

Curvature of the Universe

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Divide both sides by H^2

$$1 = \frac{8\pi G\rho}{3H^2} + \frac{\Lambda}{3H^2} - \frac{k}{R^2 H^2}$$

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Matter Density

Curvature of the Universe

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

Divide both sides by H^2

$$1 = \frac{8\pi G\rho}{3H^2} + \frac{\Lambda}{3H^2} - \frac{k}{R^2 H^2}$$

Energy Density

Curvature of the Universe

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

Divide both sides by H^2

$$1 = \frac{8\pi G\rho}{3H^2} + \frac{\Lambda}{3H^2} - \frac{k}{R^2 H^2}$$

Intrinsic Curvature

Curvature of the Universe

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

Divide both sides by H^2

$$1 = \frac{8\pi G\rho}{3H^2} + \frac{\Lambda}{3H^2} - \frac{k}{R^2H^2}$$

Recast as dimensionless parameters

$$1 = \Omega_m + \Omega_\Lambda + \Omega_k$$

Curvature of the Universe

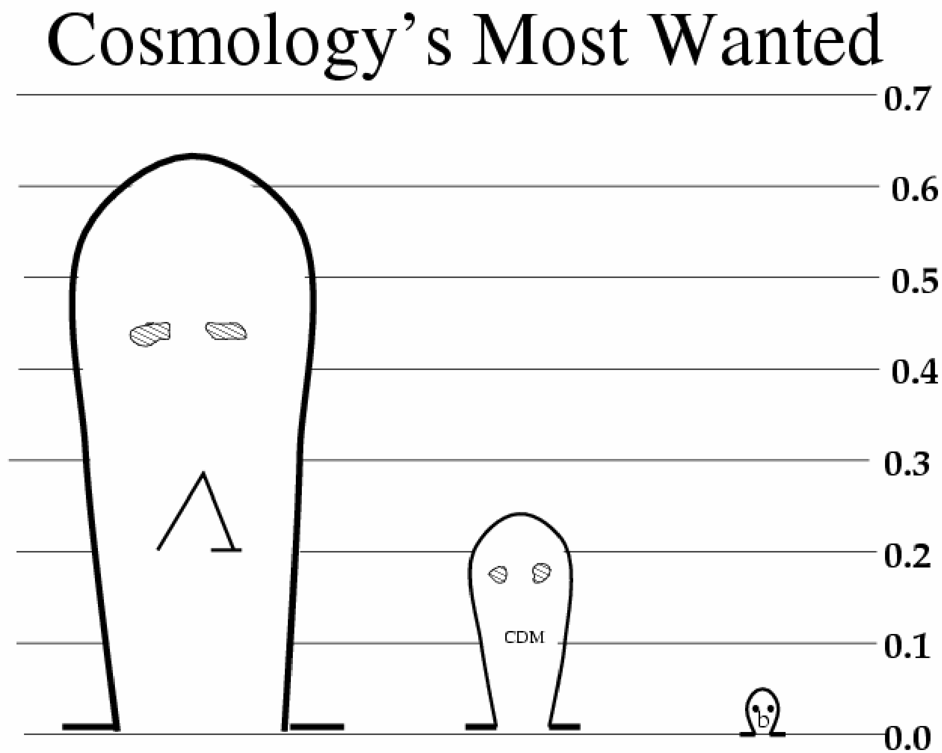
$$\Omega_m + \Omega_\Lambda + \Omega_k = 1$$

Matter, energy and intrinsic curvature

CURVATURE OF THE UNIVERSE

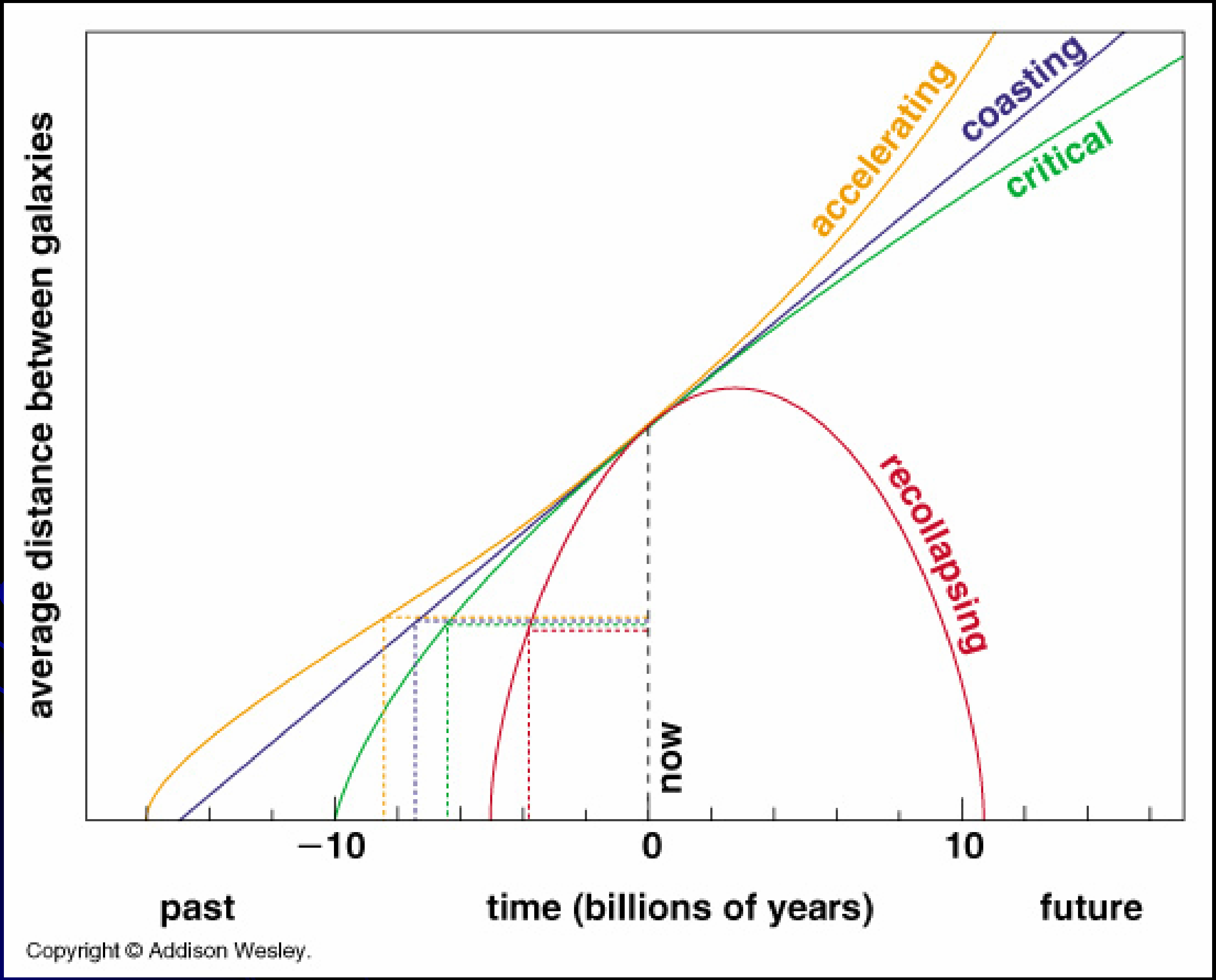
$$\Omega_m + \Omega_\Lambda + \Omega_k = 1$$

Figure 3. A line up of cosmological culprits Ω_Λ is the big shot controlling the Universe. He's going to make it blow up. Ω_{CDM} would like to make the Universe collapse but can't compete with Ω_Λ. Ω_b just follows Ω_{CDM} around. Like all dangerous criminals, one can never be sure of Ω_Λ until he is behind bars. The CMB police is being beefed up. Hundreds of heroic CMB observers are now planning his capture.

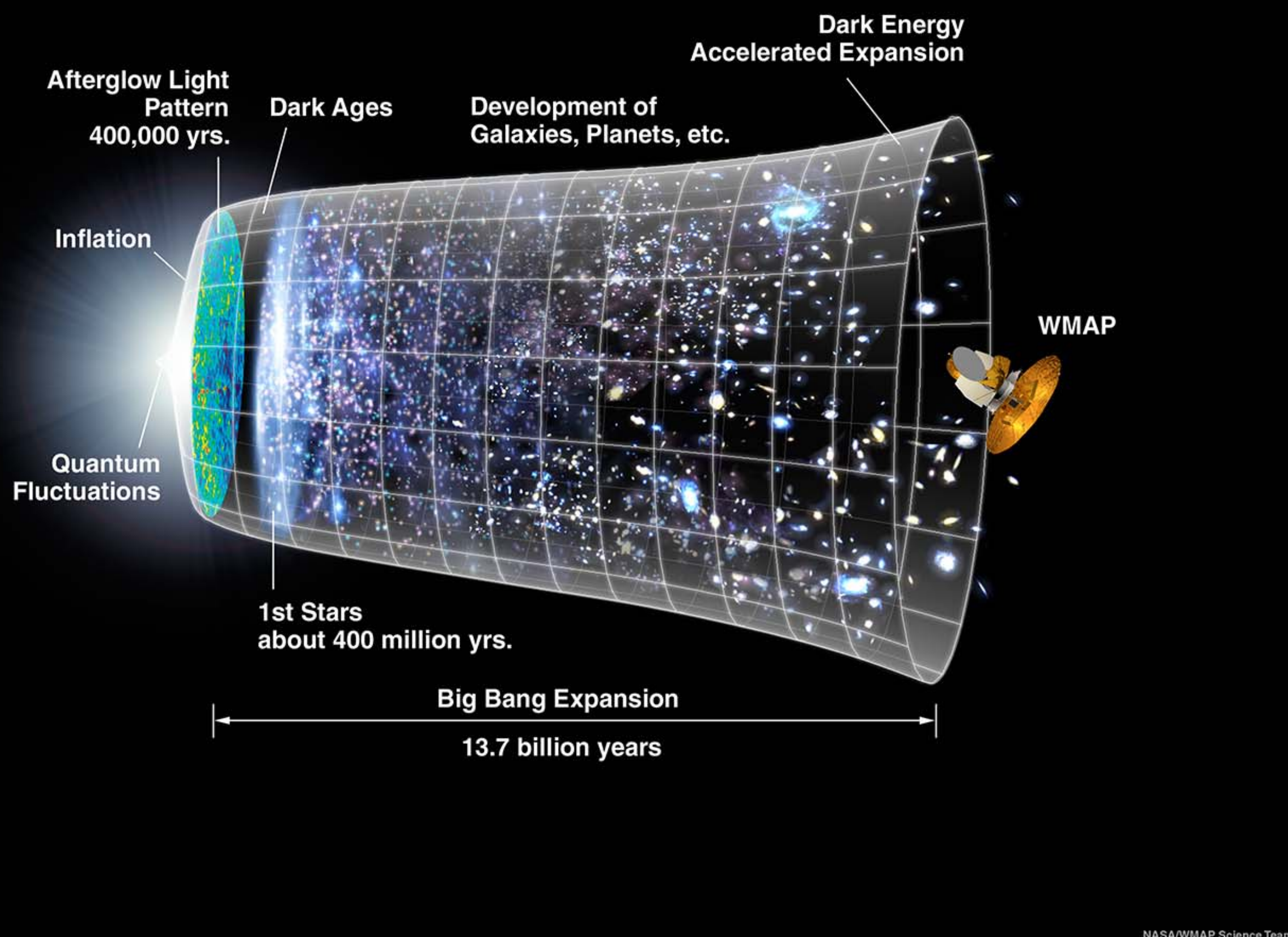


Ω_Λ	Ω_{CDM}	Ω_b
cosmological constant energy of the vacuum He never clumps His evil plan is to blow up the Universe	cold dark matter He likes to clump but has never been detected directly His evil plan is to make the Universe collapse	normal baryonic matter a pawn in the cosmic game who just follows CDM around. He thinks he's a complex life form but is really just a bunch of hydrogen

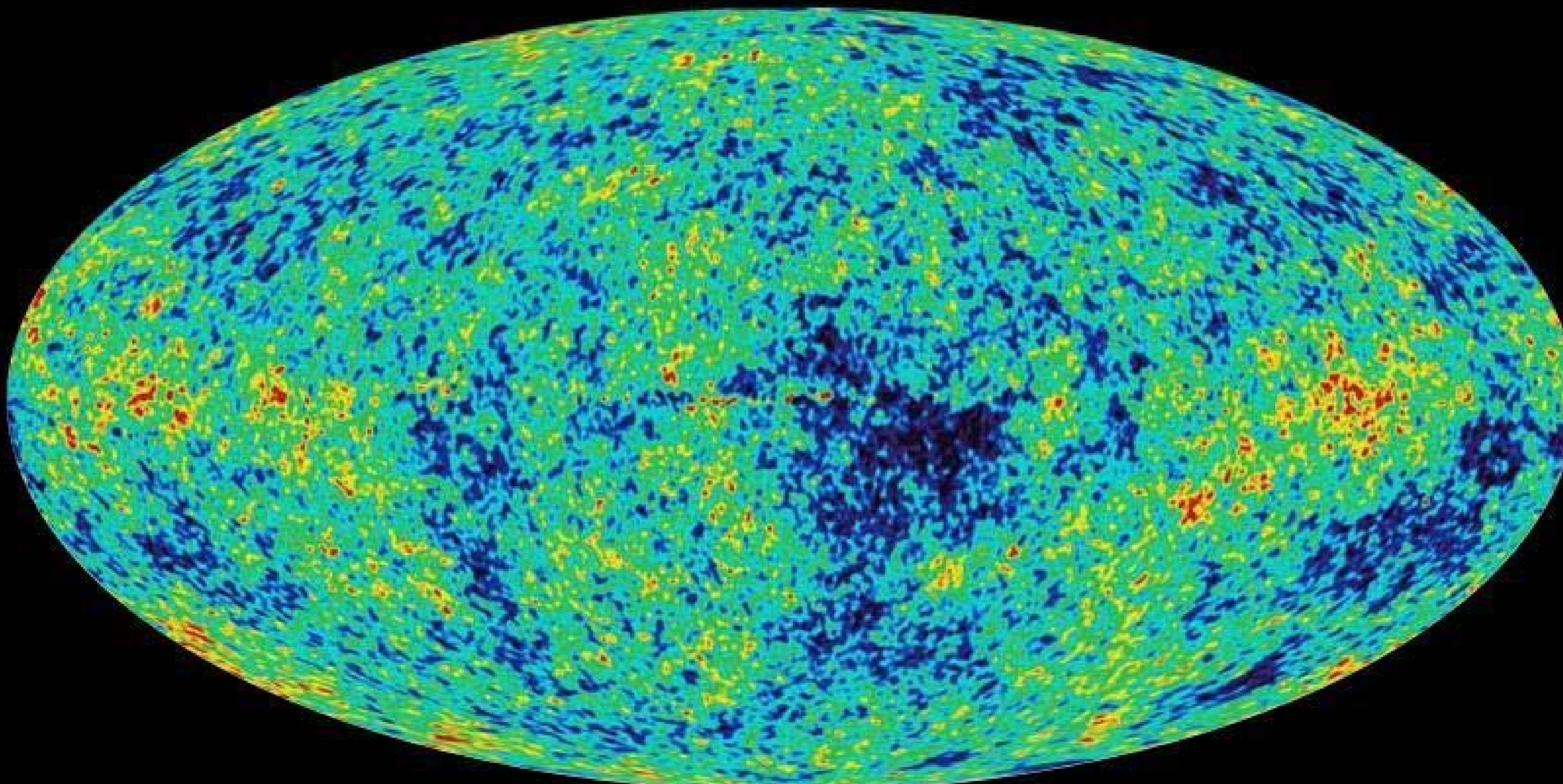
Why Does it Matter…?



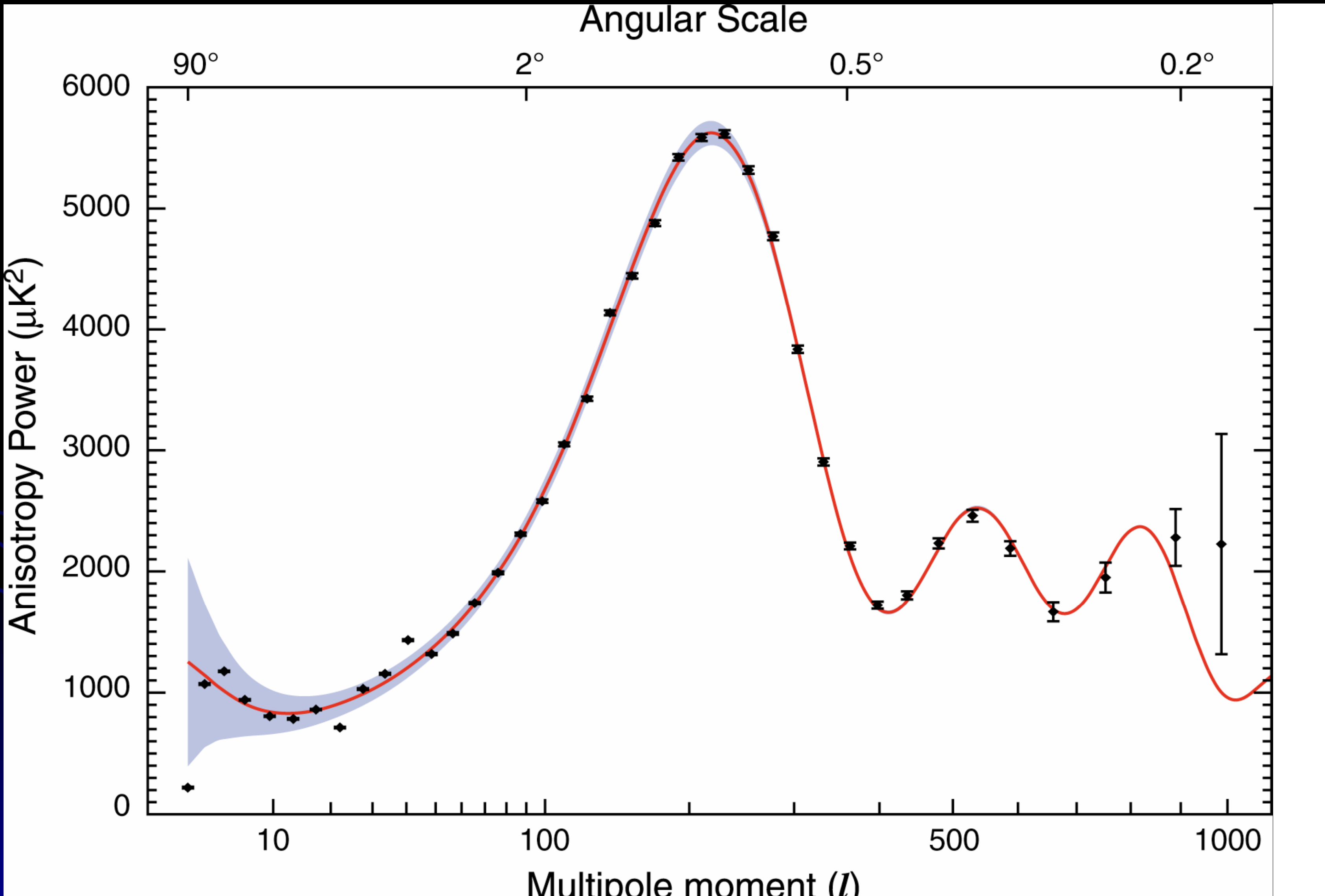
Cosmological Timeline



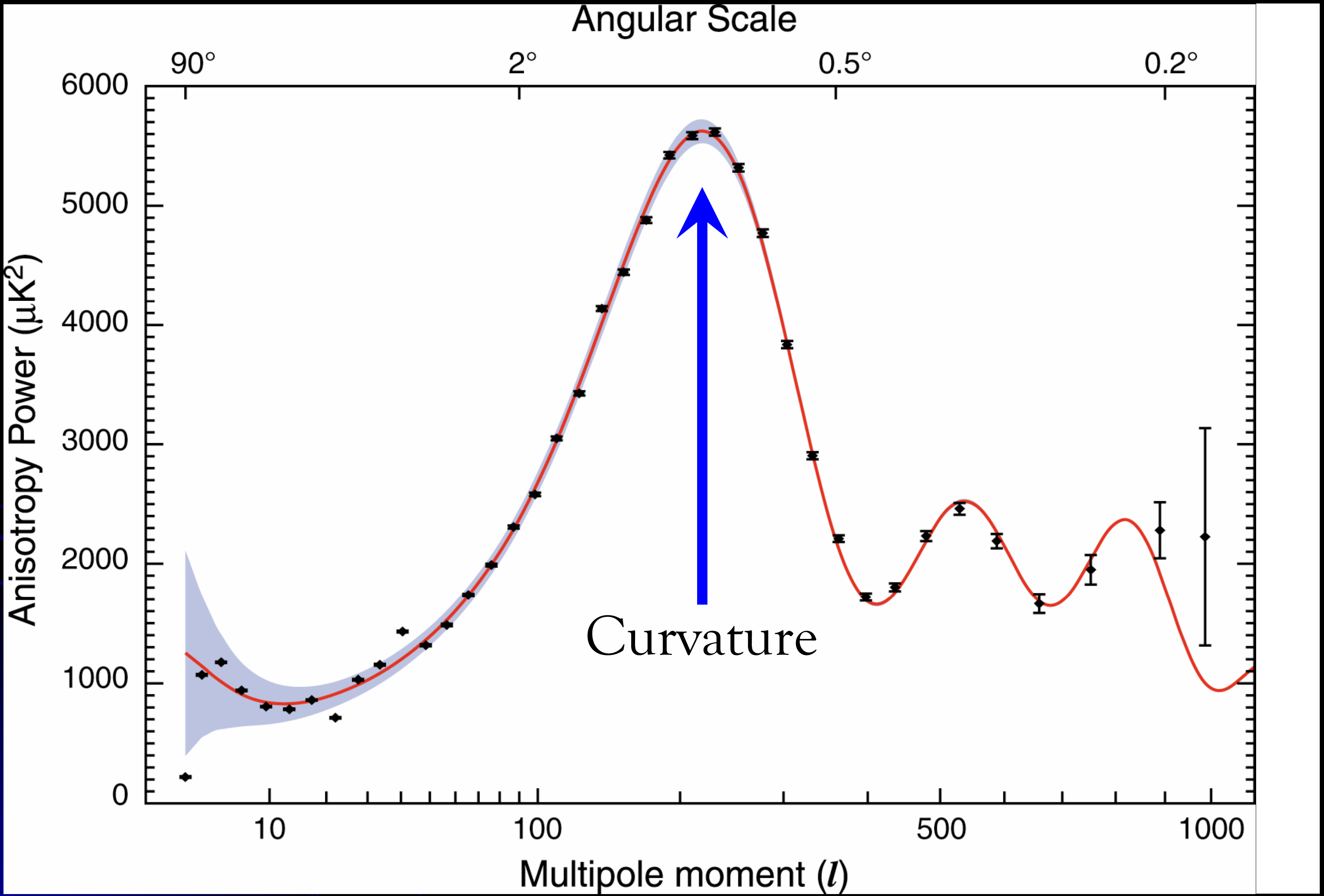
Cosmic Microwave Background Radiation



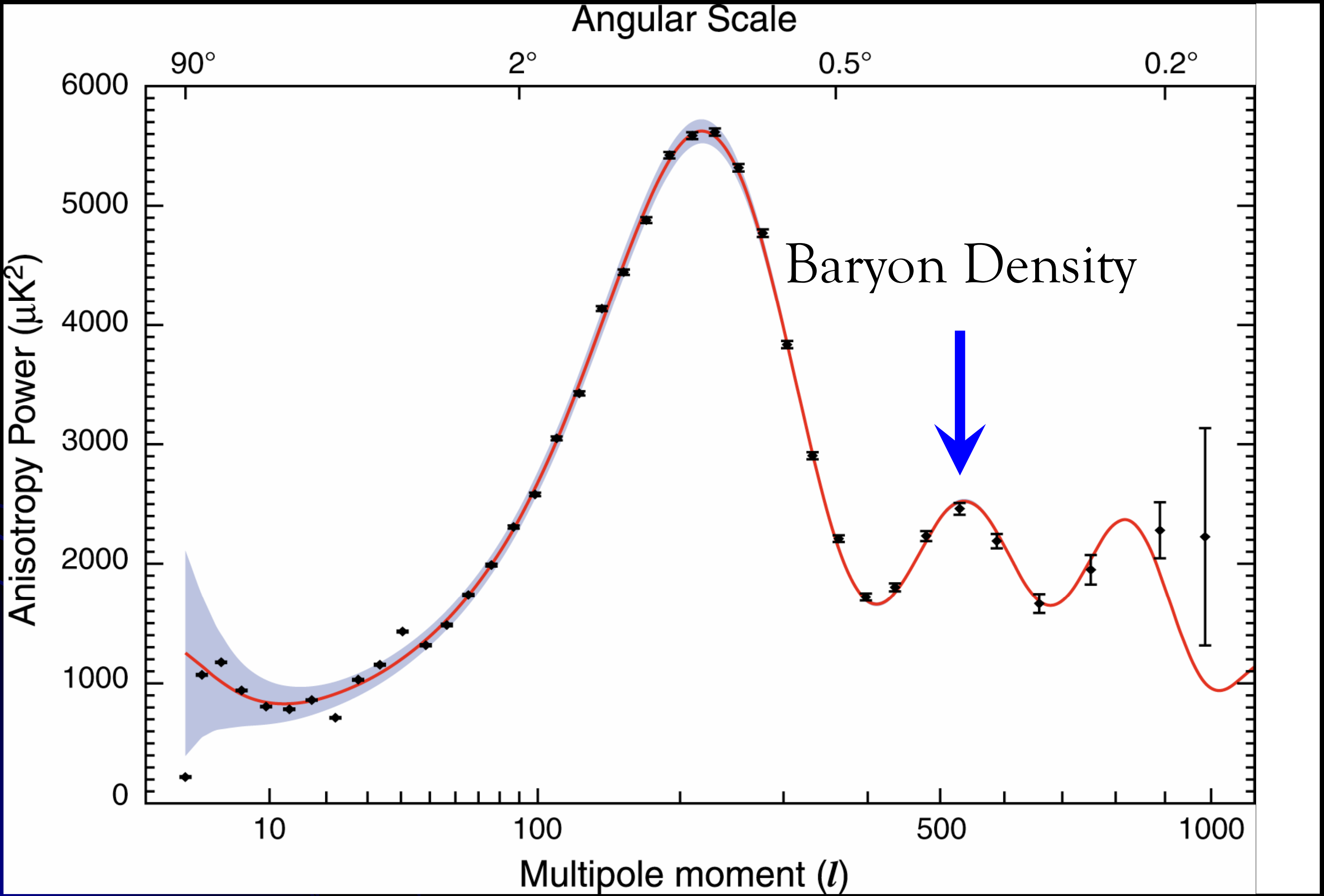
Cosmic Microwave Background Radiation



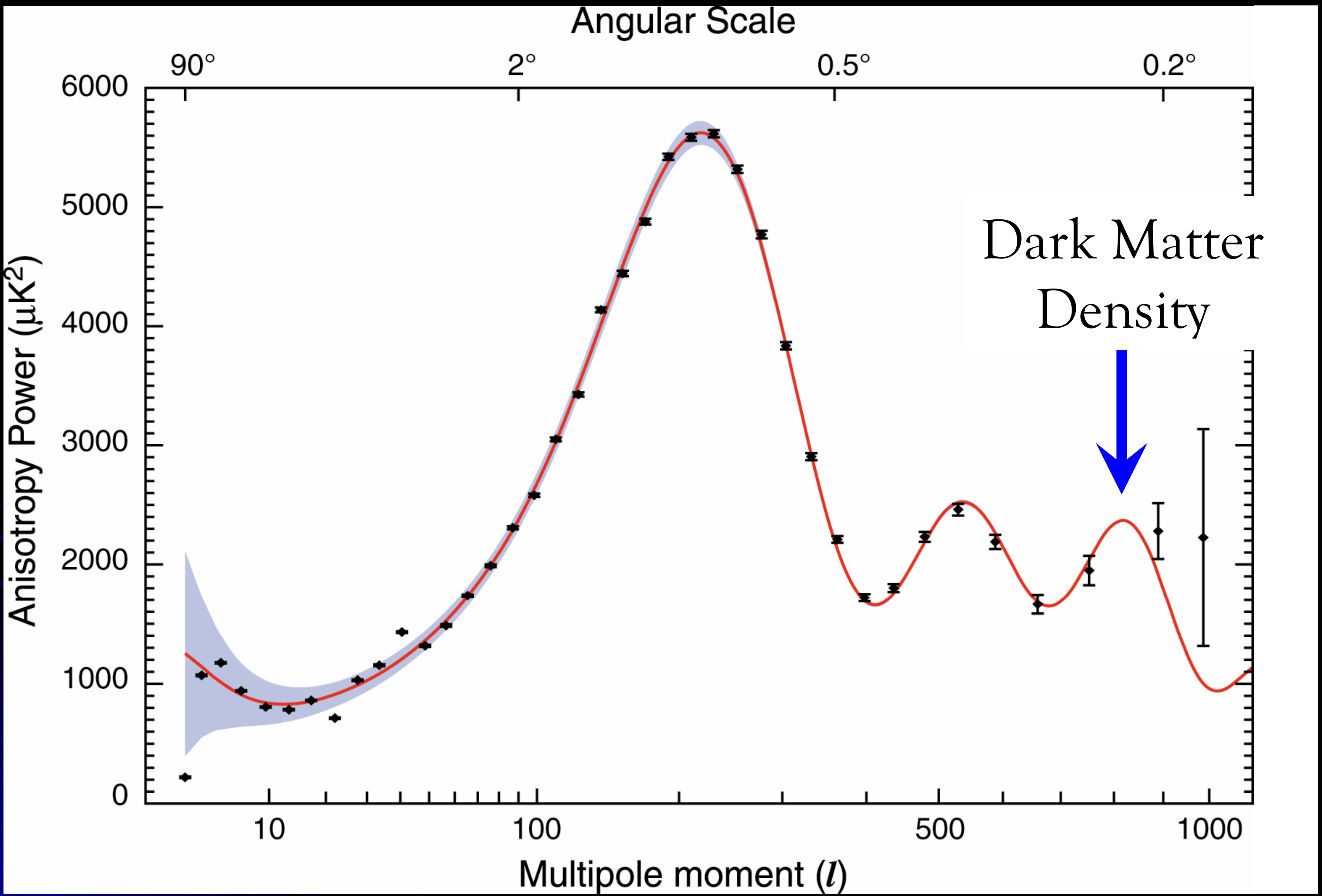
Cosmic Microwave Background Radiation



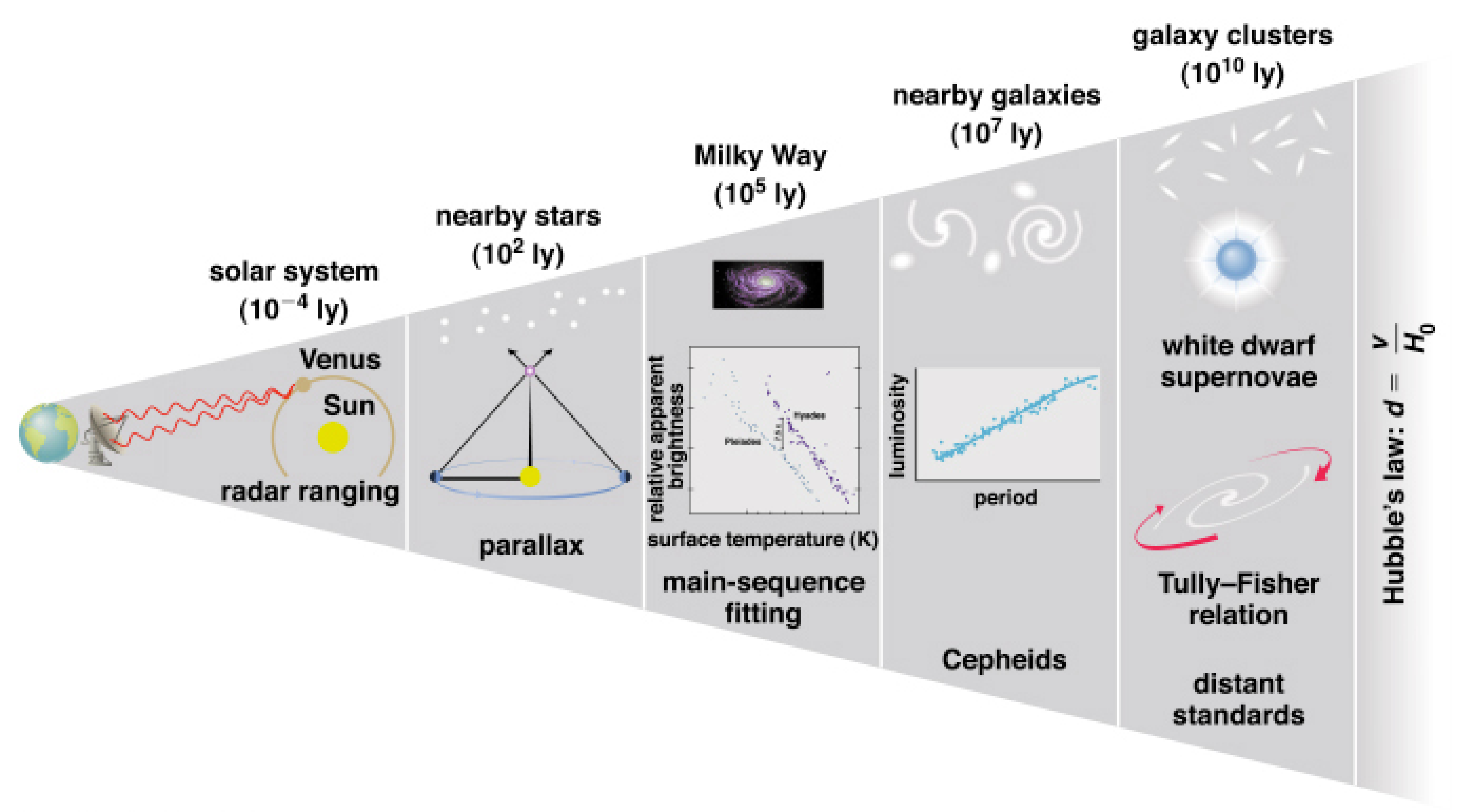
Cosmic Microwave Background Radiation



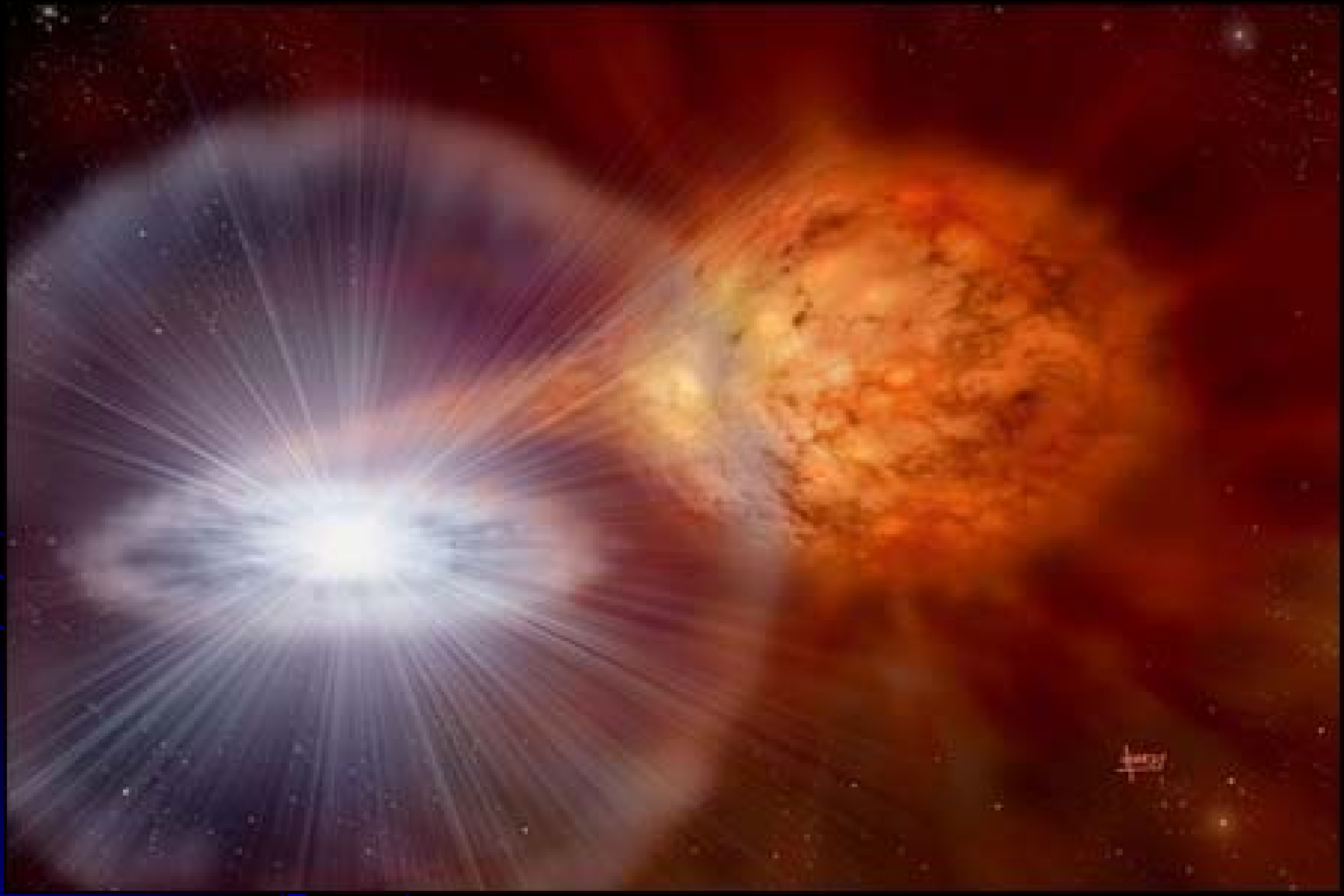
COSMIC MICROWAVE BACKGROUND RADIATION



COSMOLOGICAL DISTANCE INDICATORS



Type 1A Supernovae



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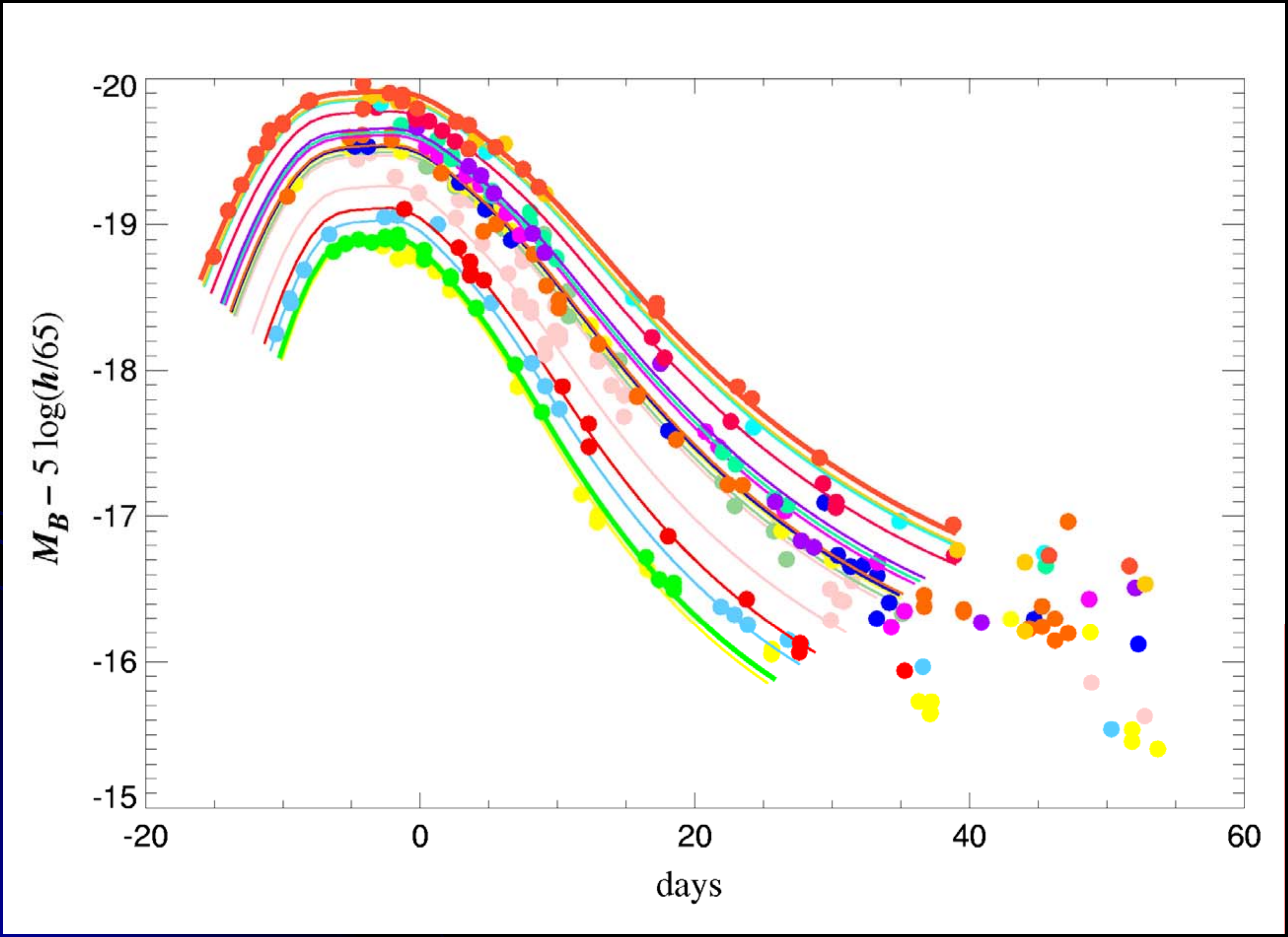

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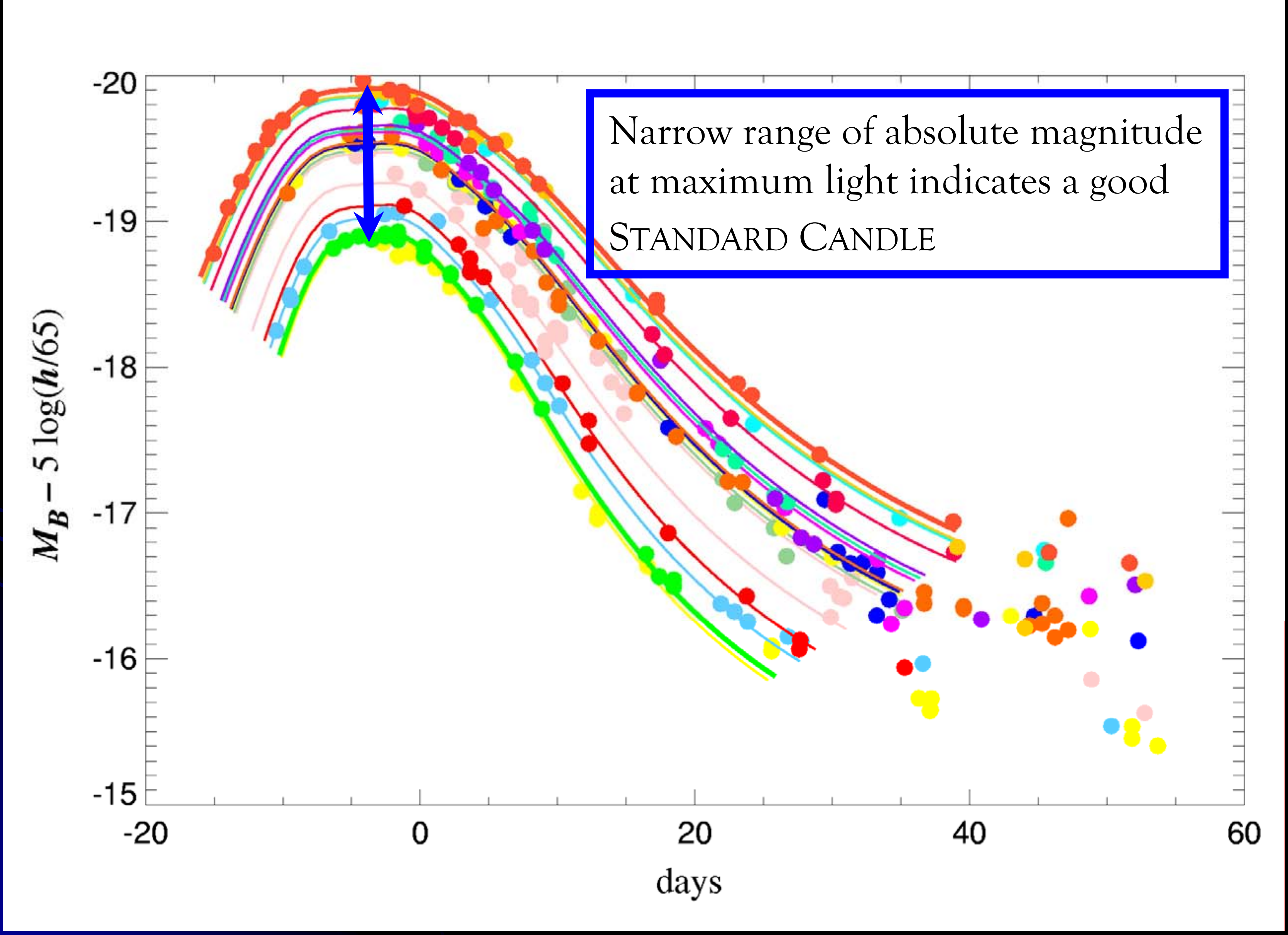
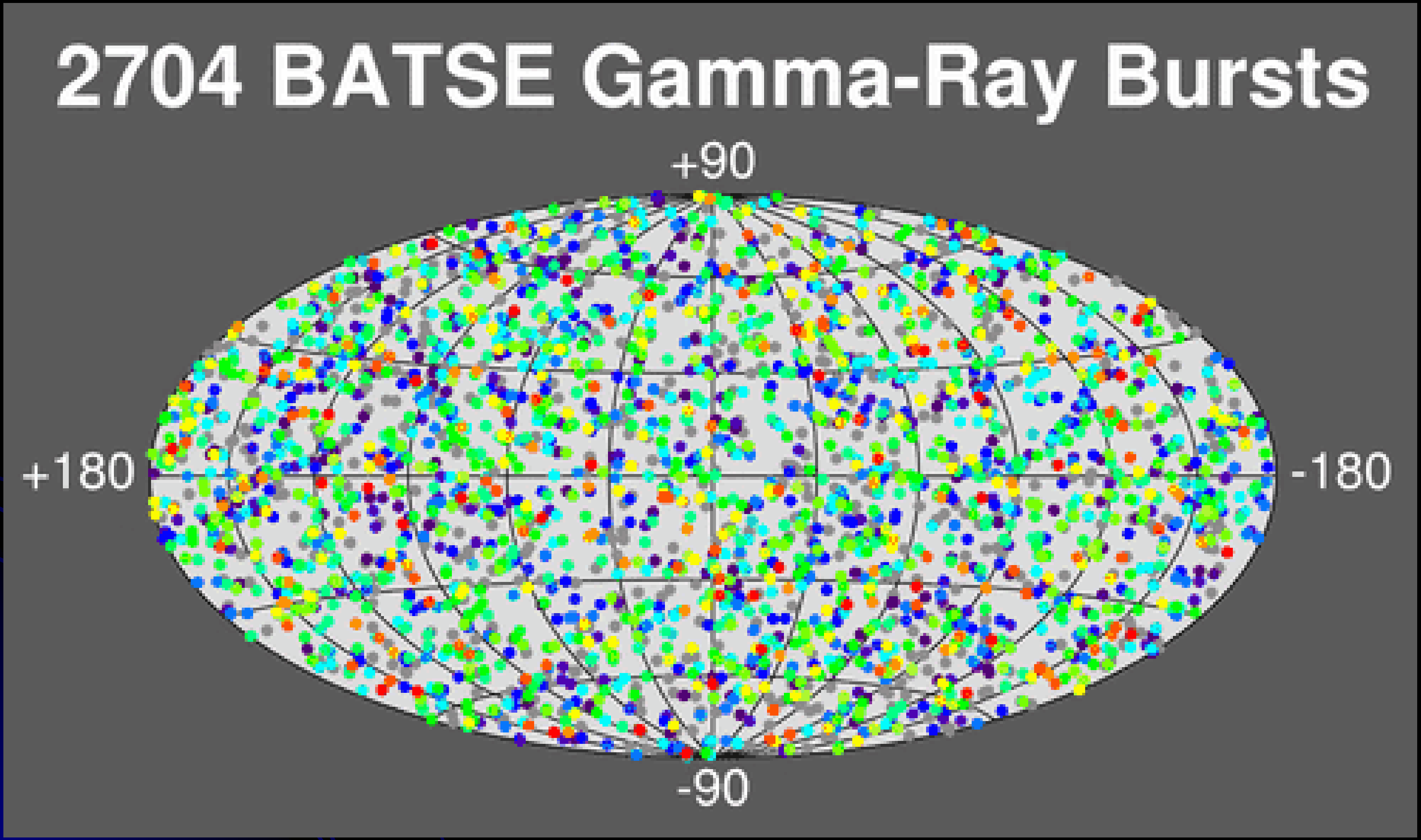


Gamma Ray Bursts



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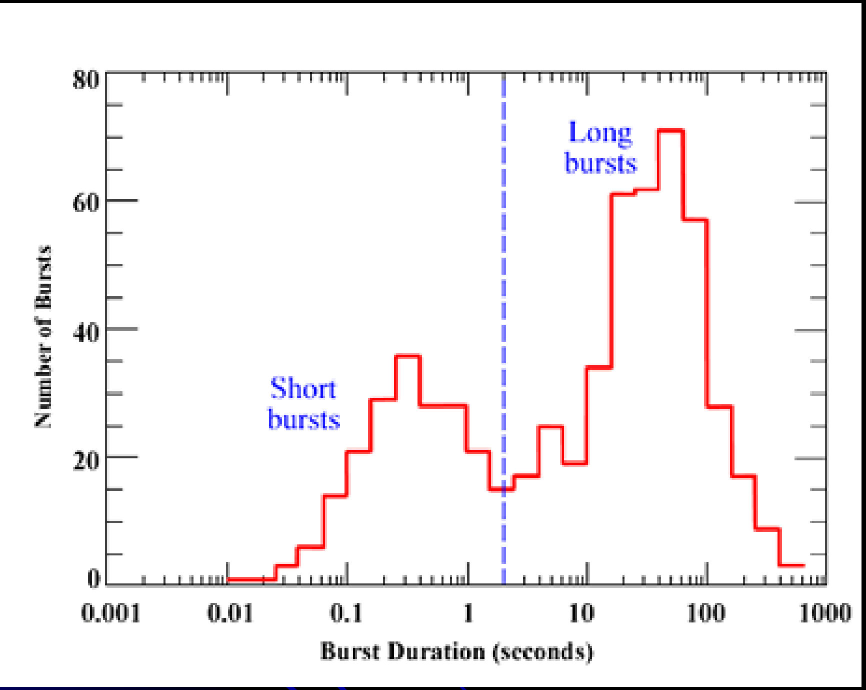

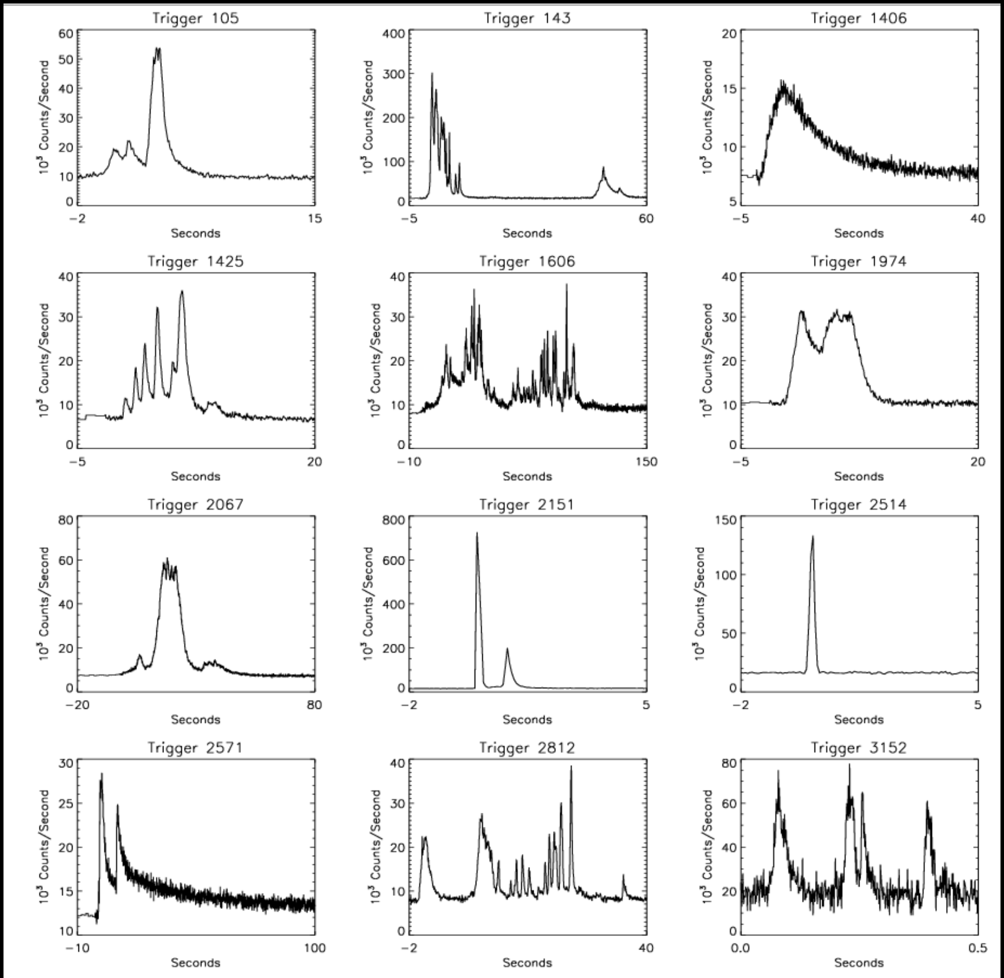

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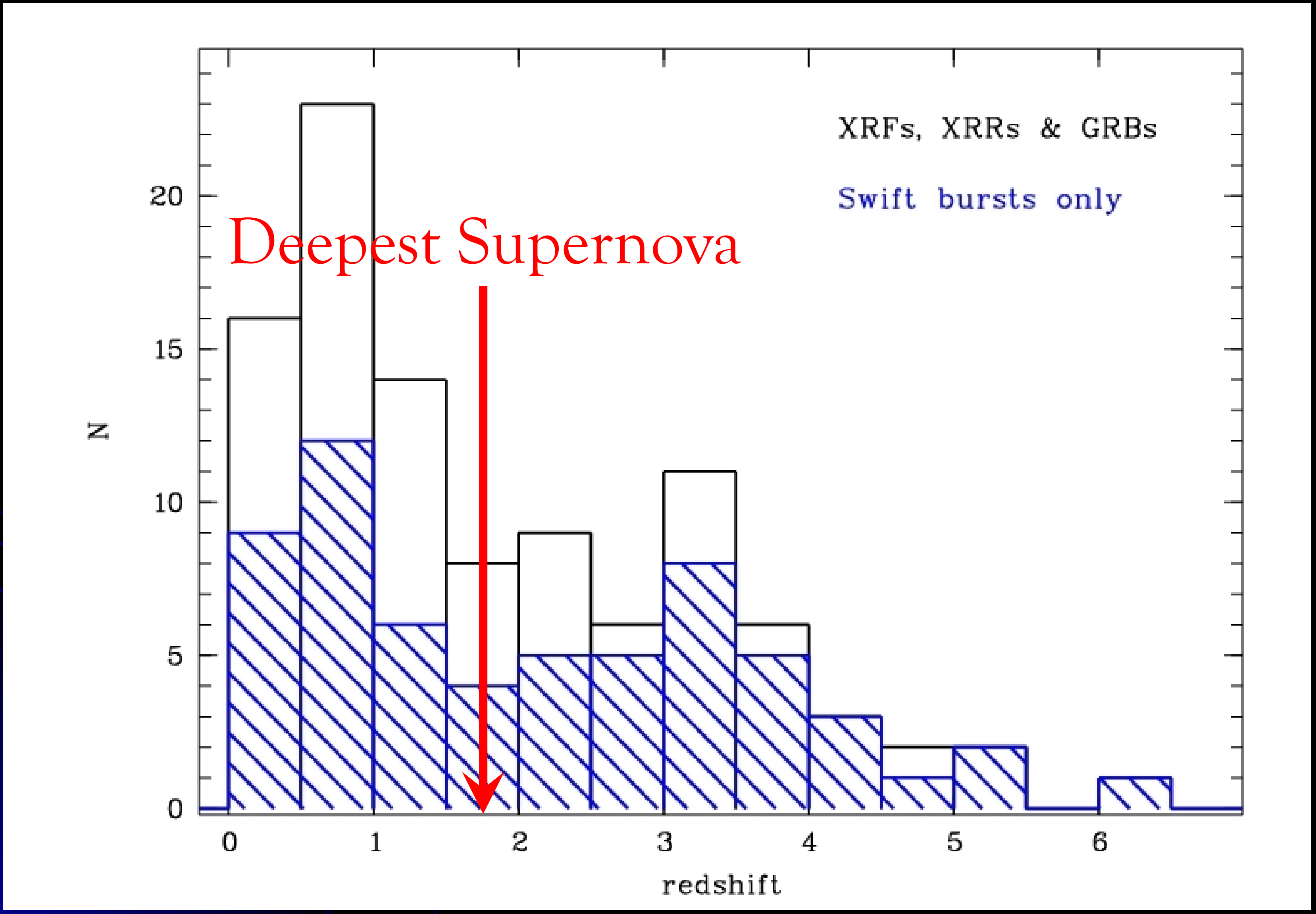
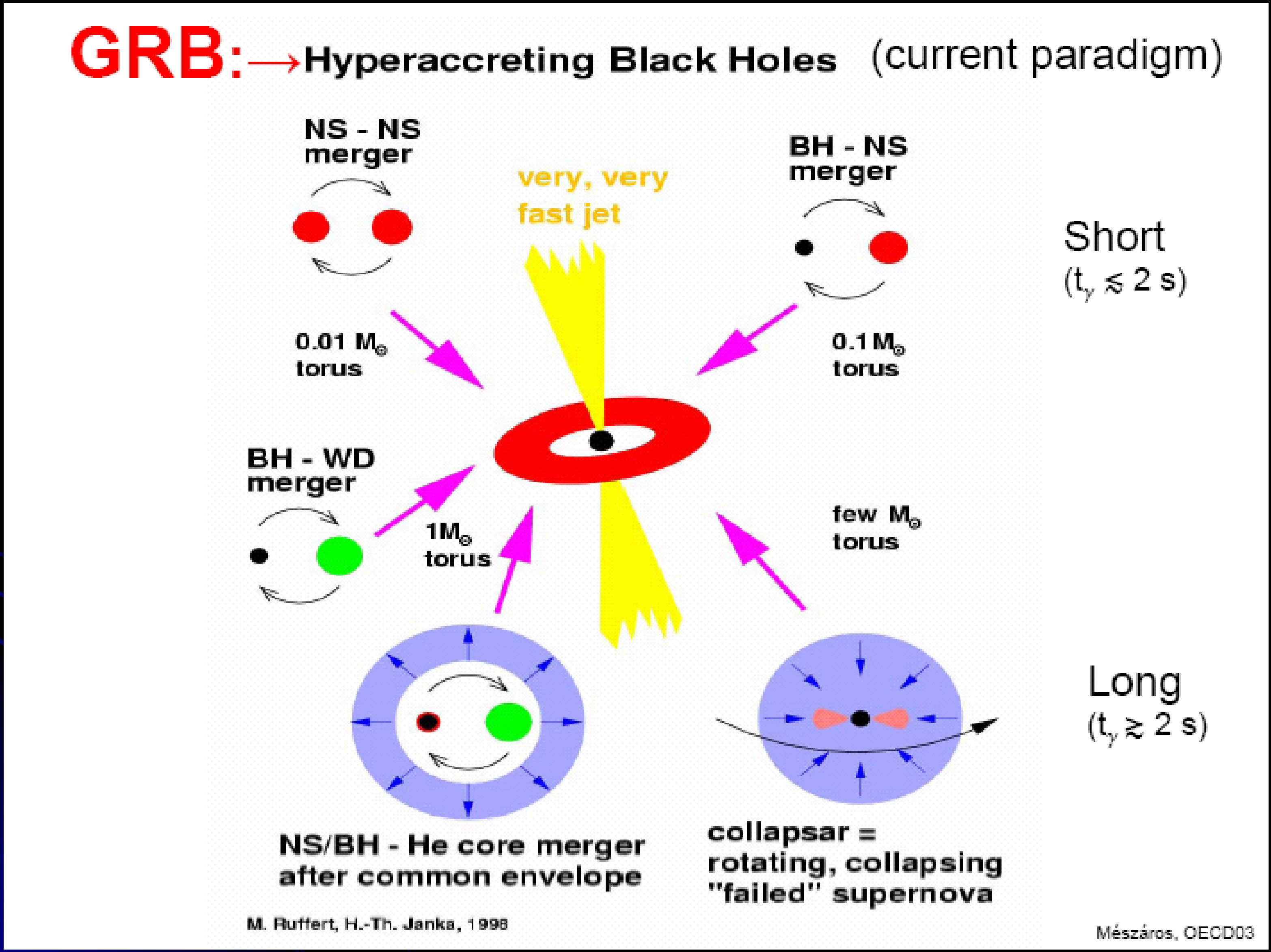
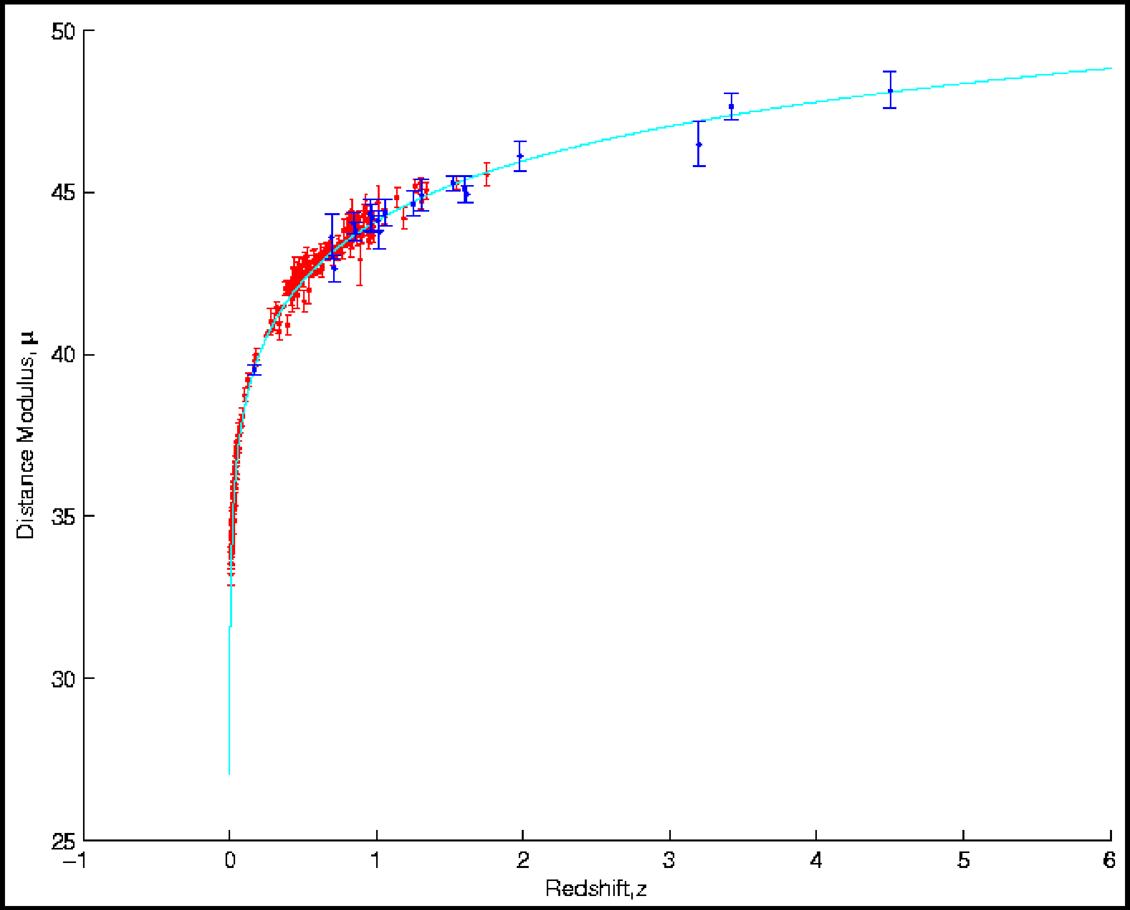


Gamma Ray Bursts



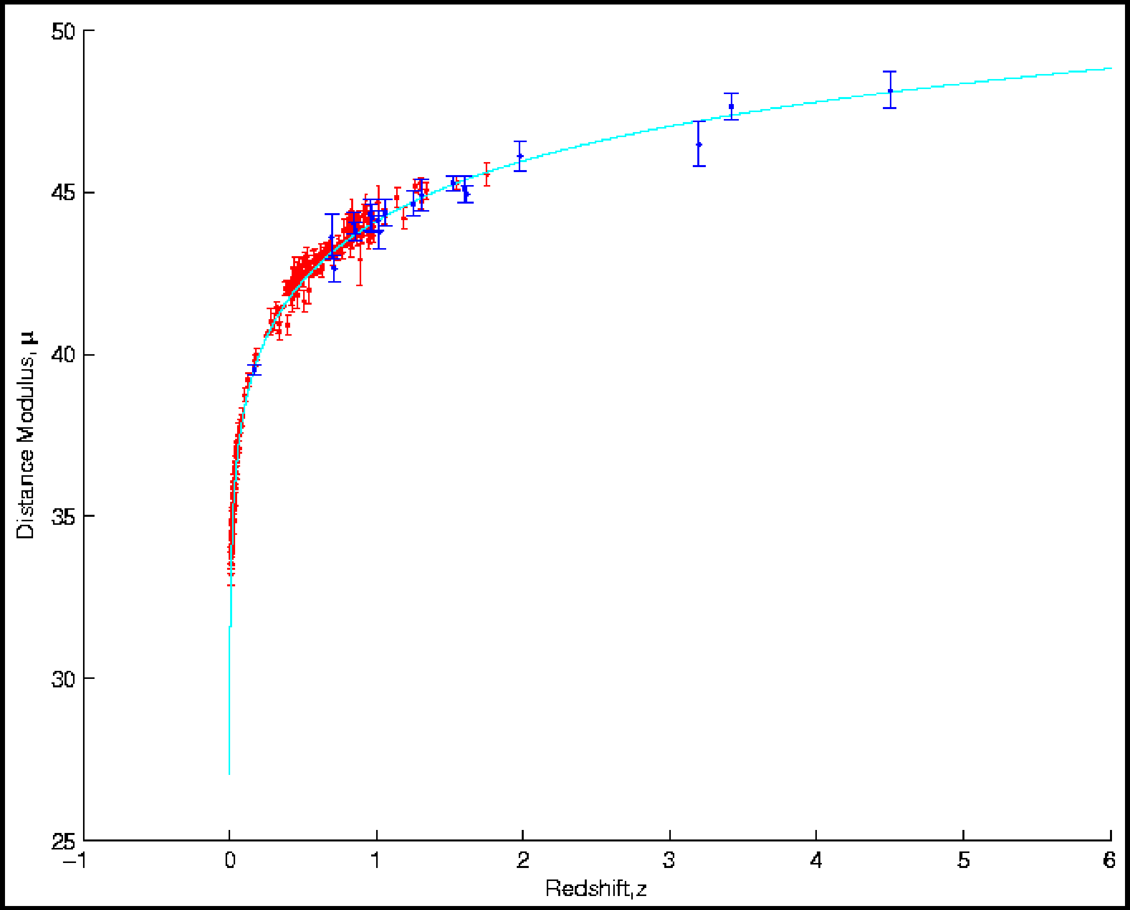
How Do We Use Standard Candles?



Hubble Diagram

How Do We Use Standard Candles?

$$\mu = m - M = 5\log d_L + 25$$



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$$\mu = m - M = 5\log d_L + 25$$

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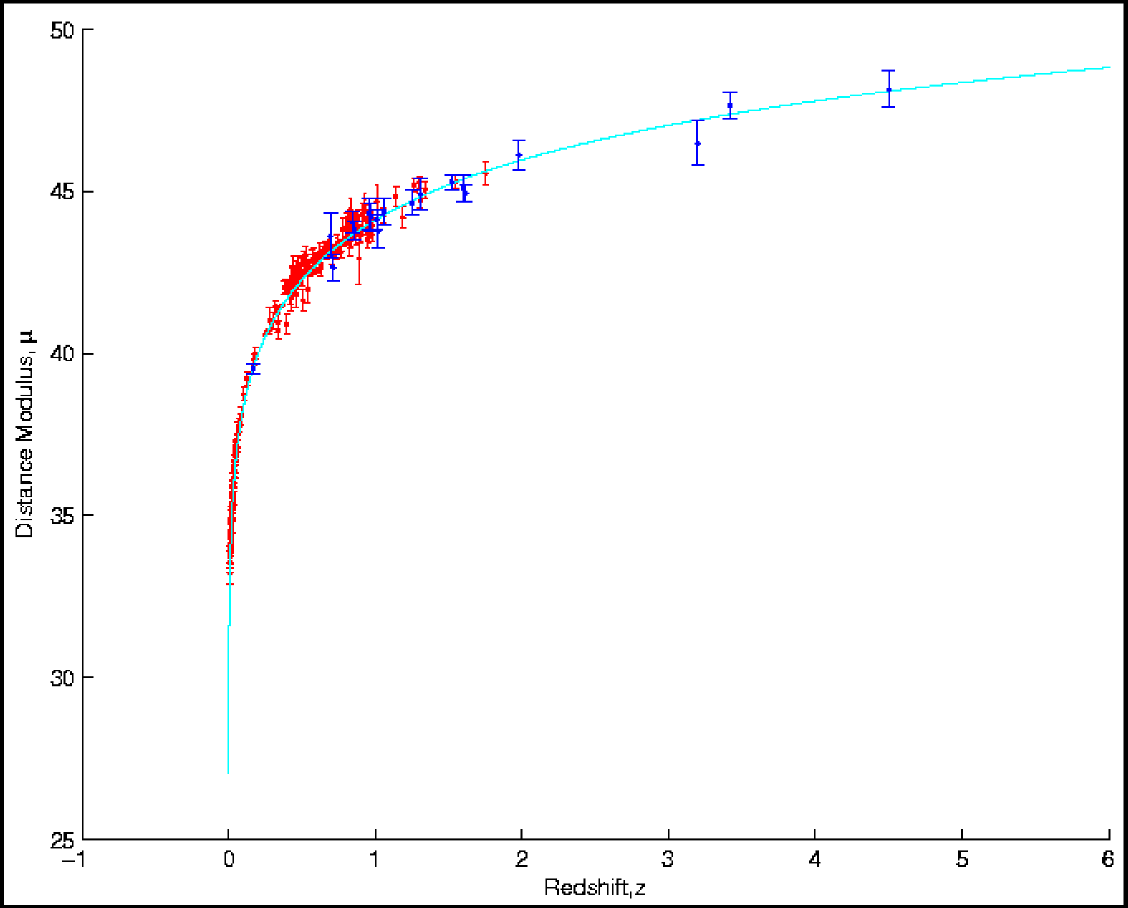

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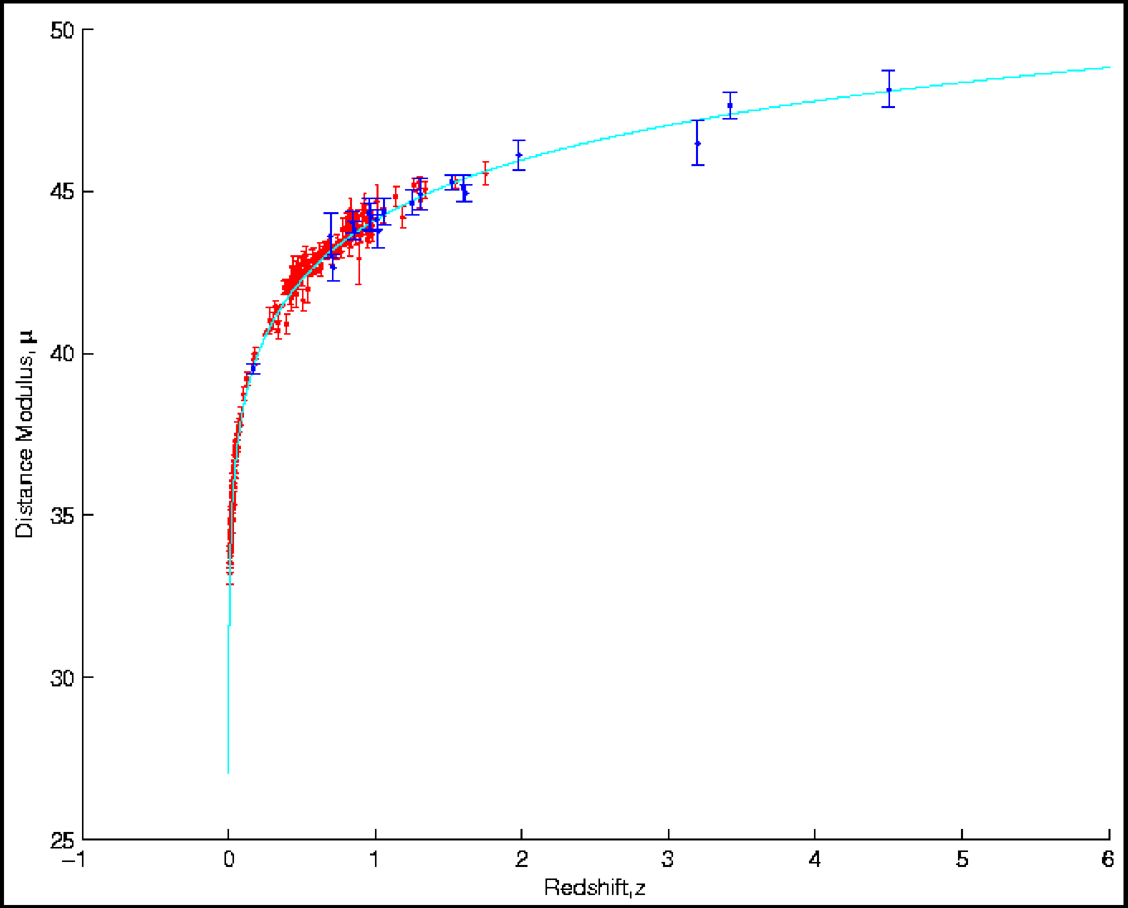
$$F = \frac{L}{4\pi d_L^{\,2}}$$

$$L_{obs} = \frac{L_{emitted}}{(1+z)^2}$$



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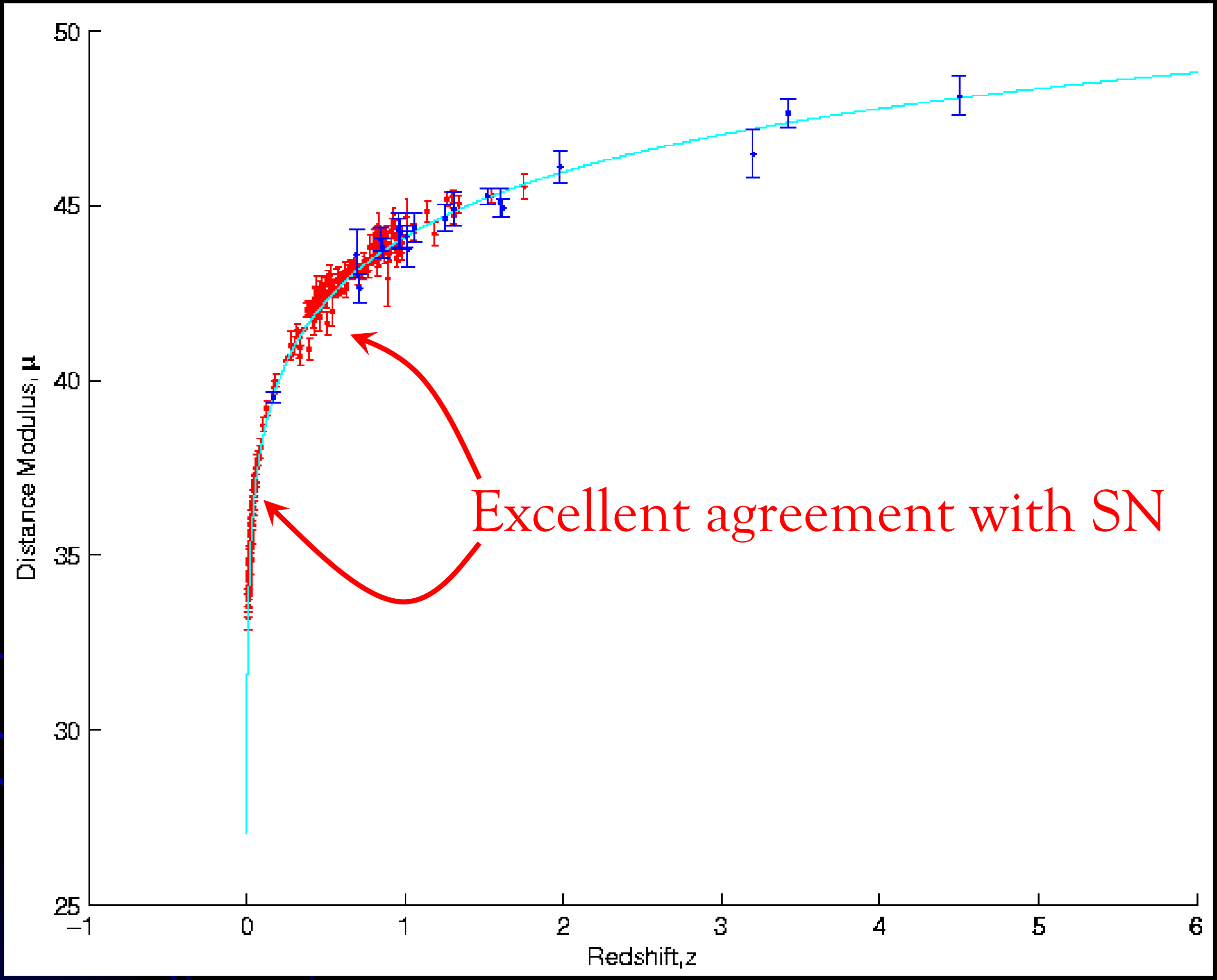

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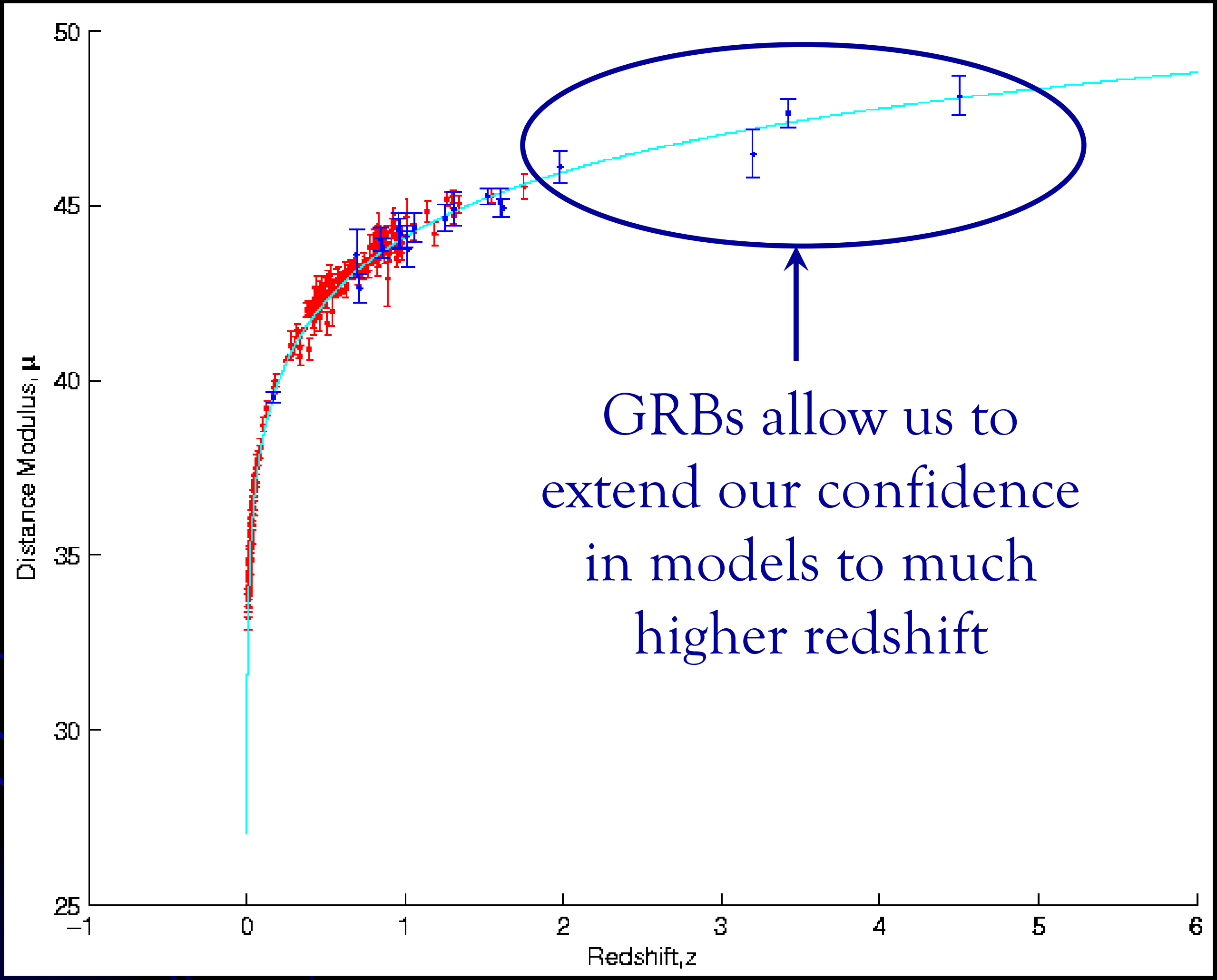
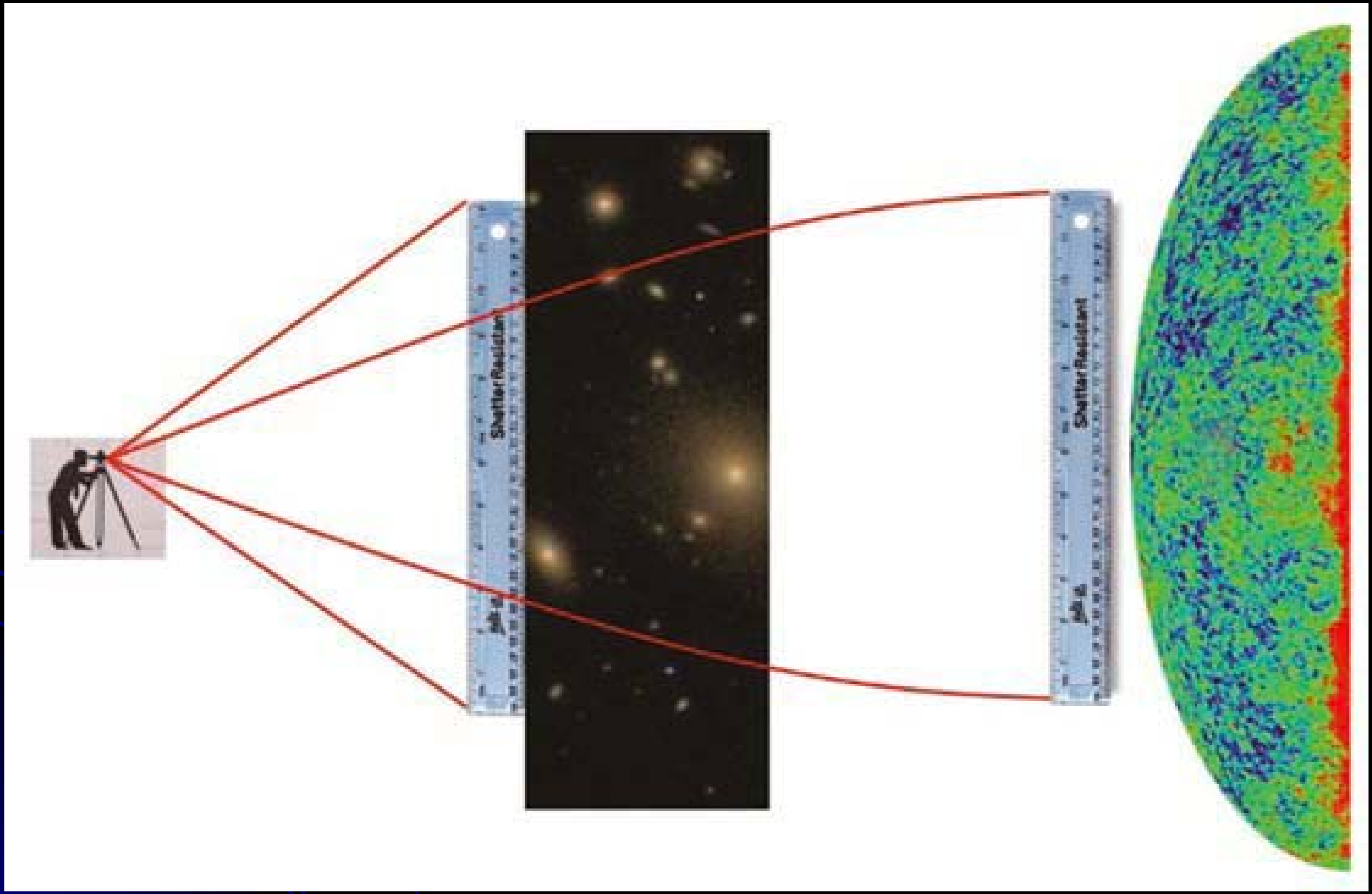
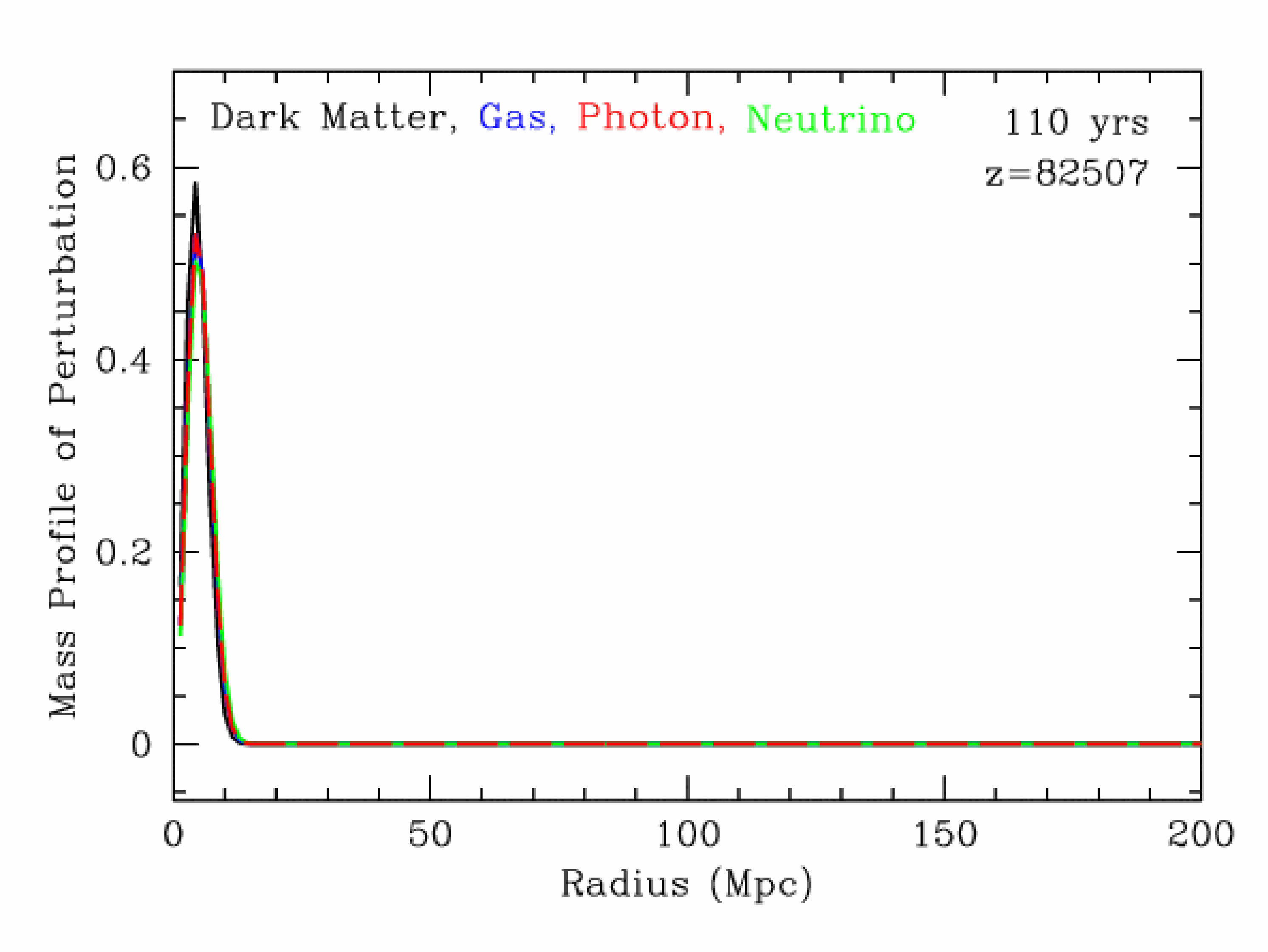


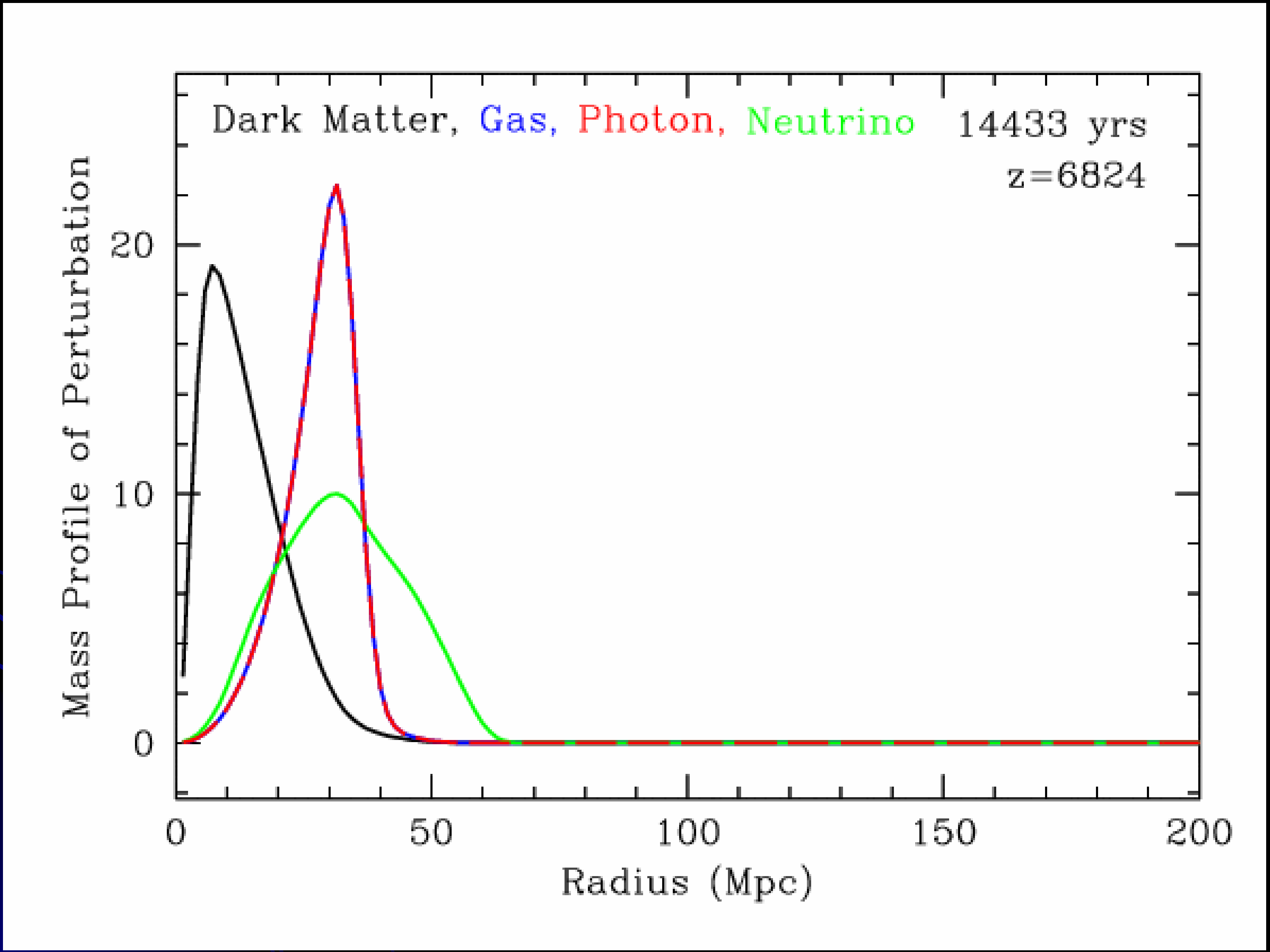
STANDARD RULERS



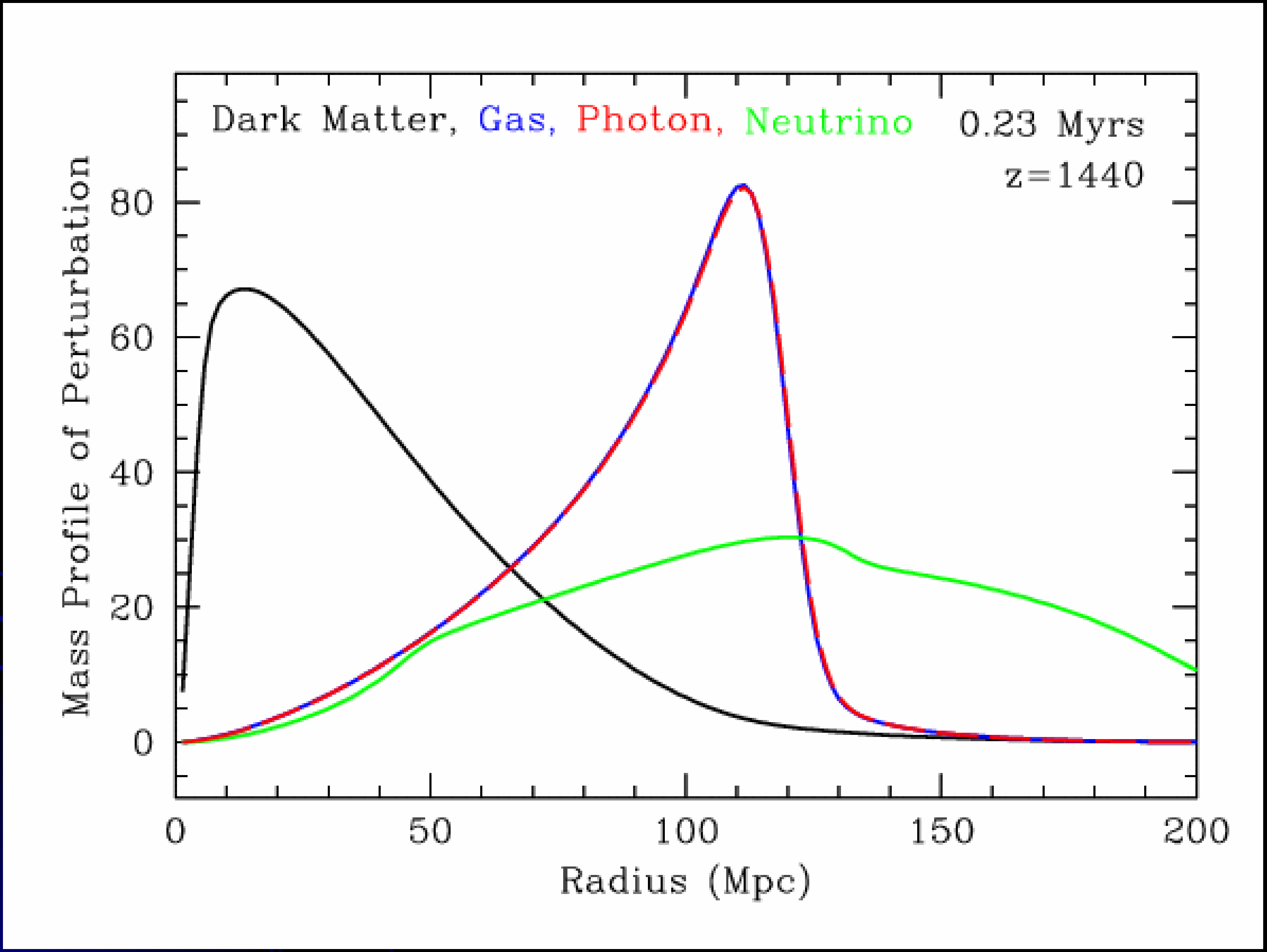
BARYON ACOUSTIC OSCILLATIONS



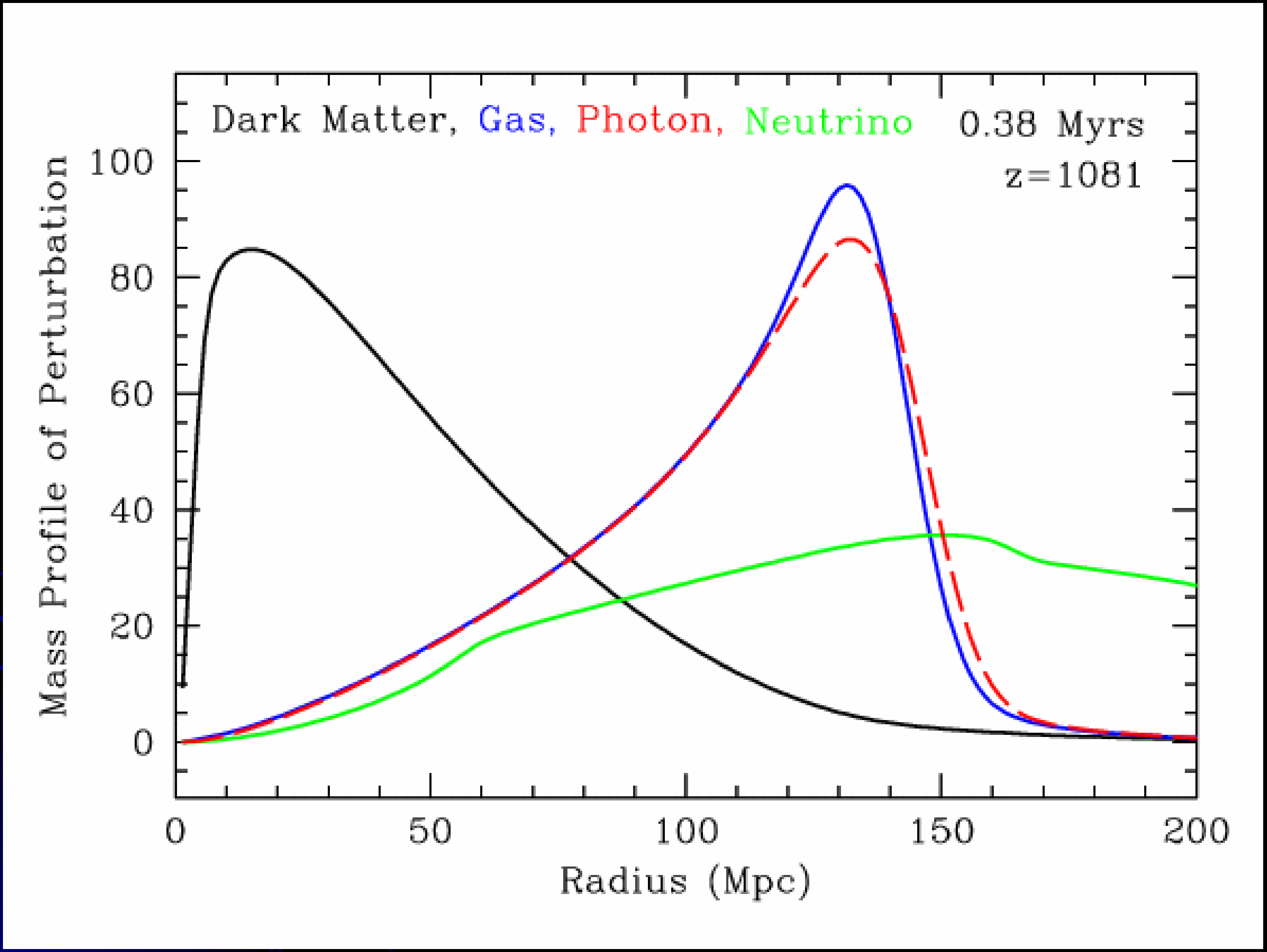
Baryon Acoustic Oscillations



Baryon Acoustic Oscillations



Baryon Acoustic Oscillations



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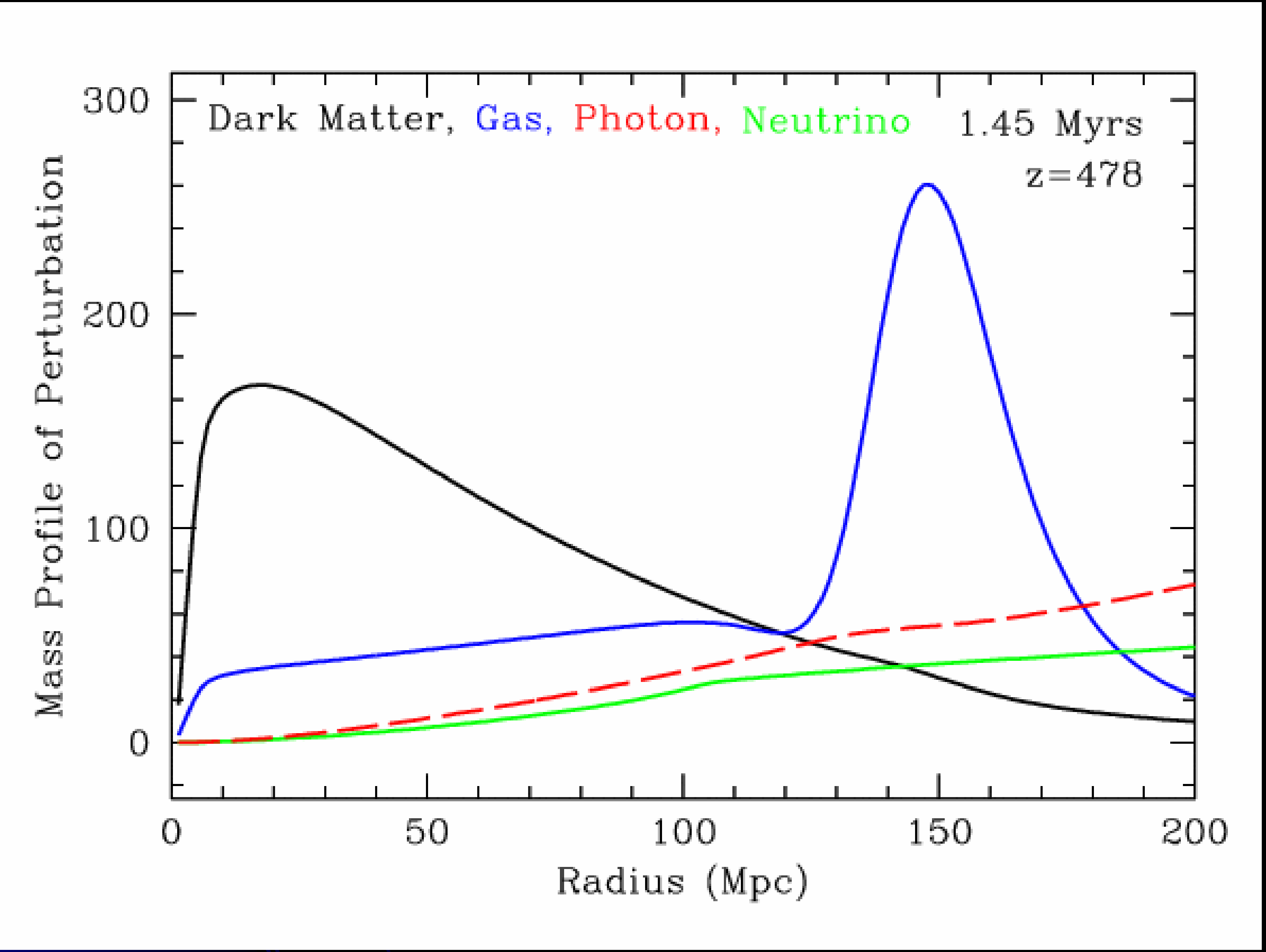

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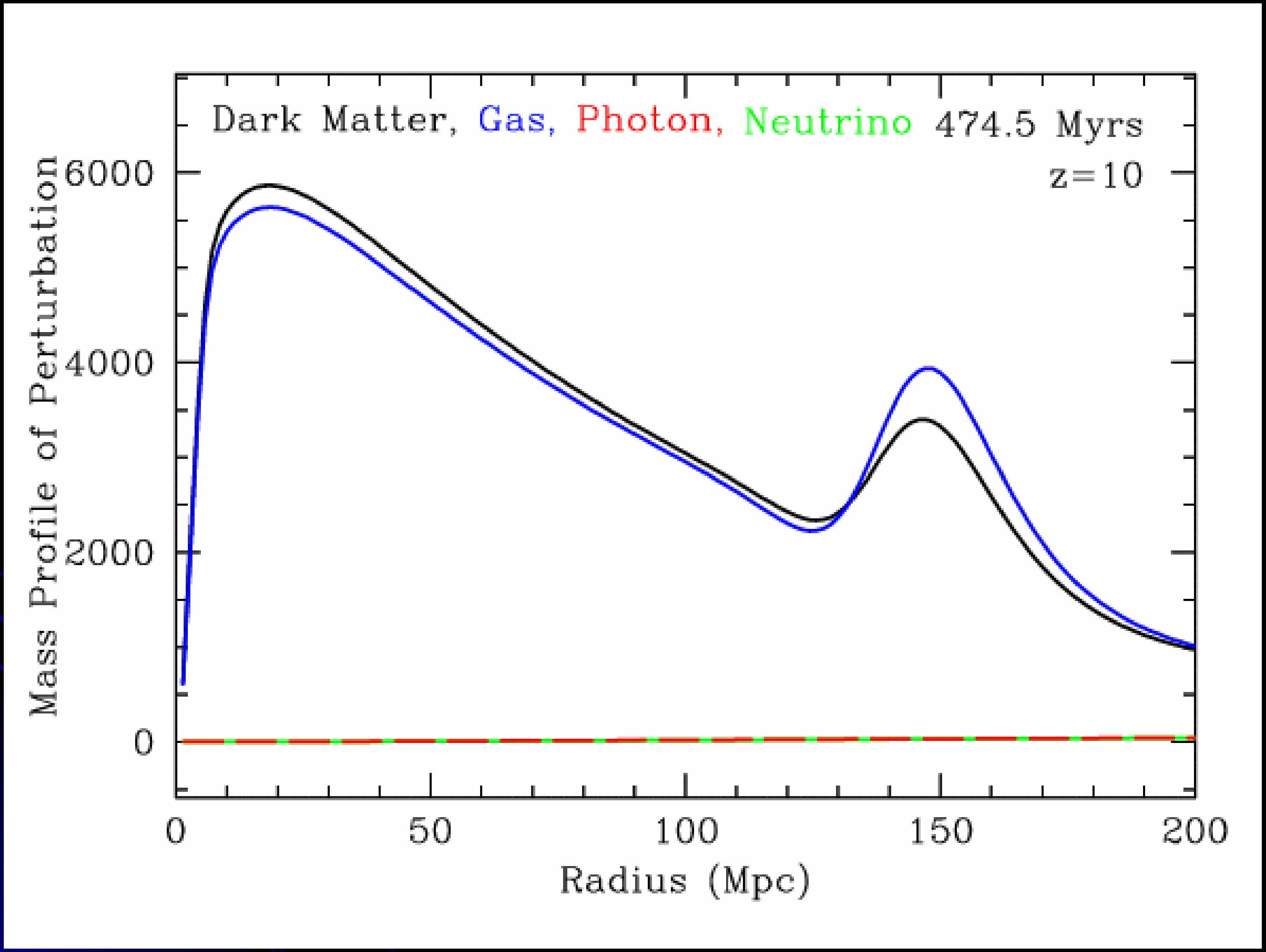

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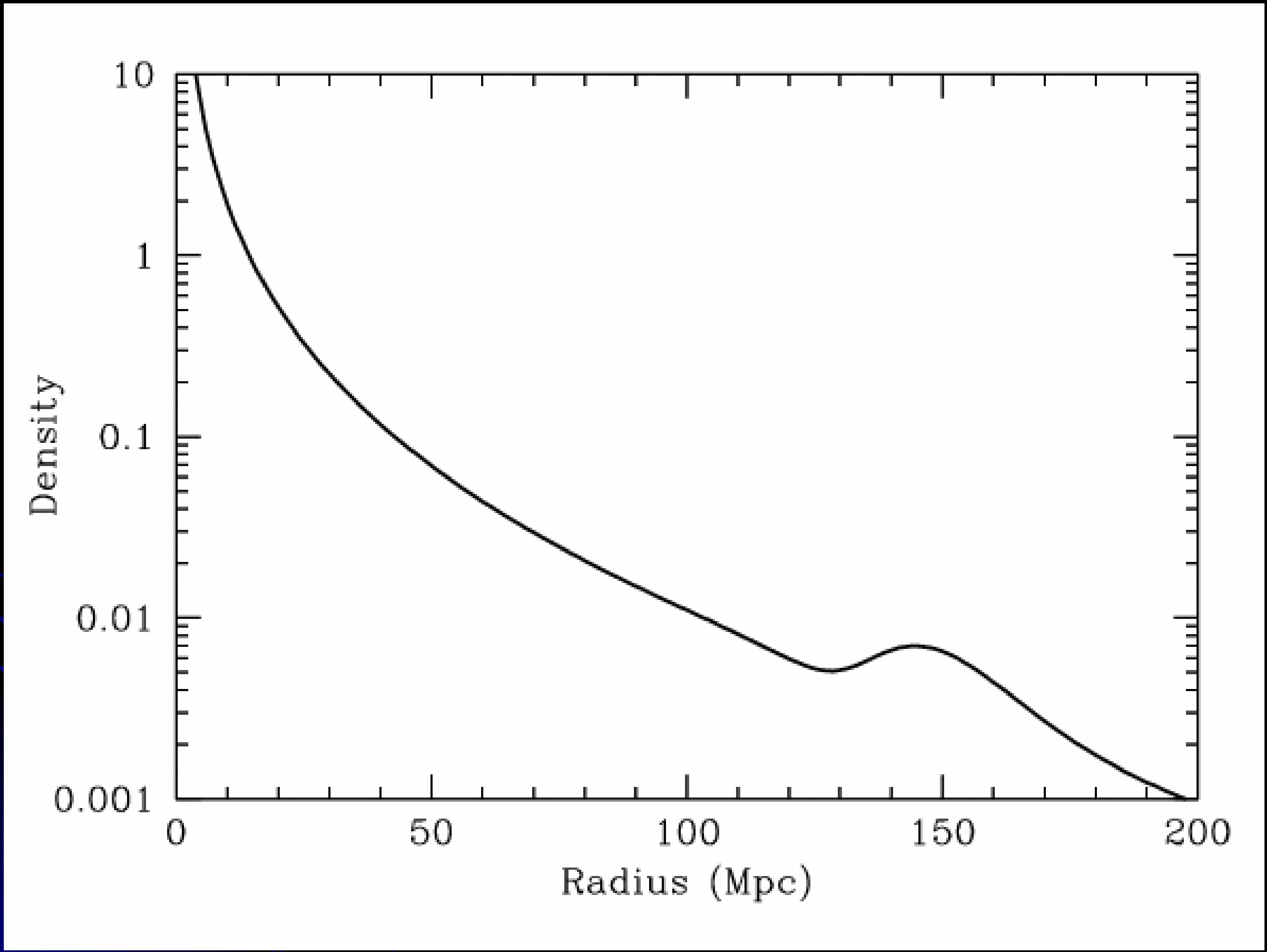
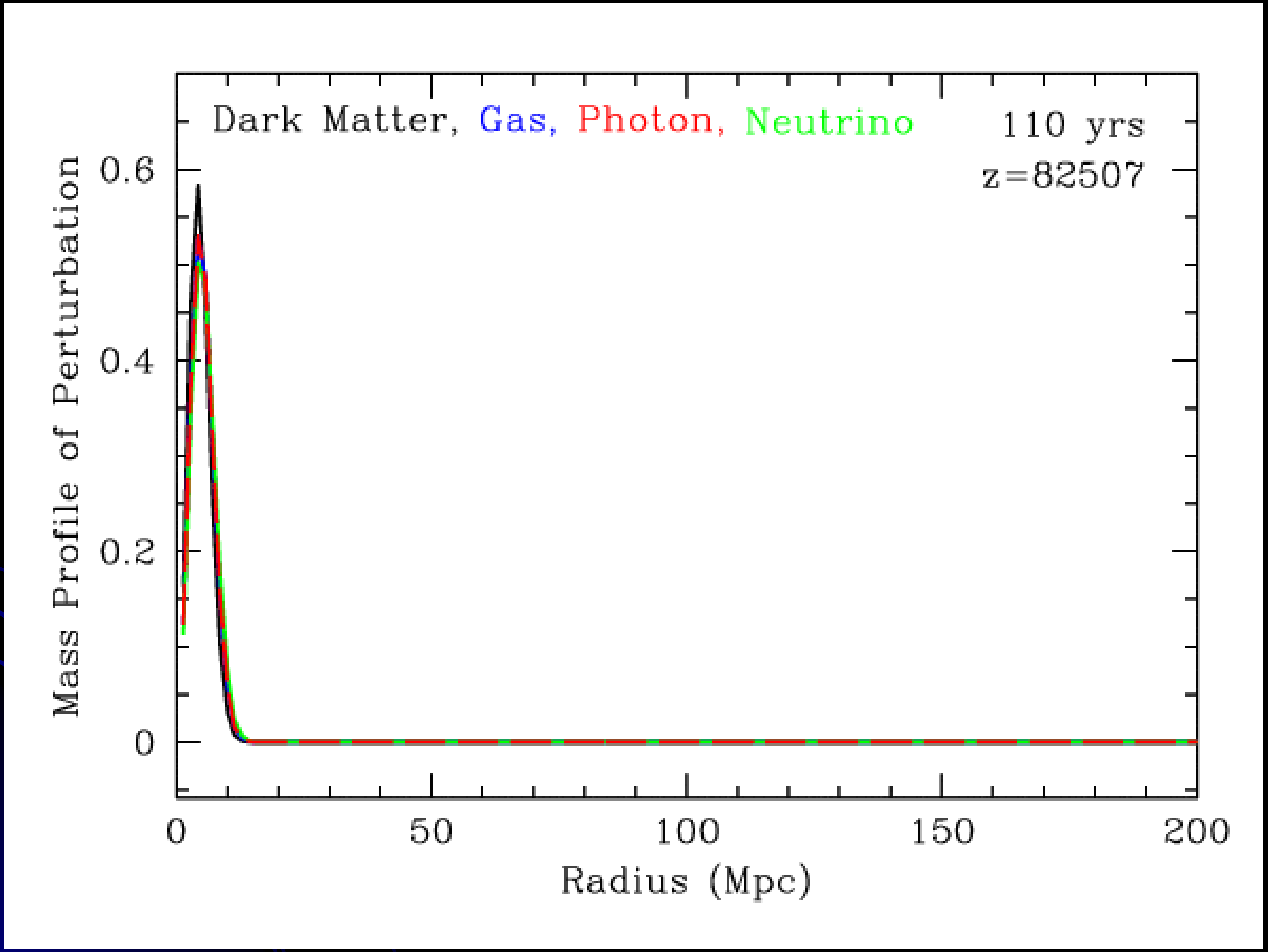
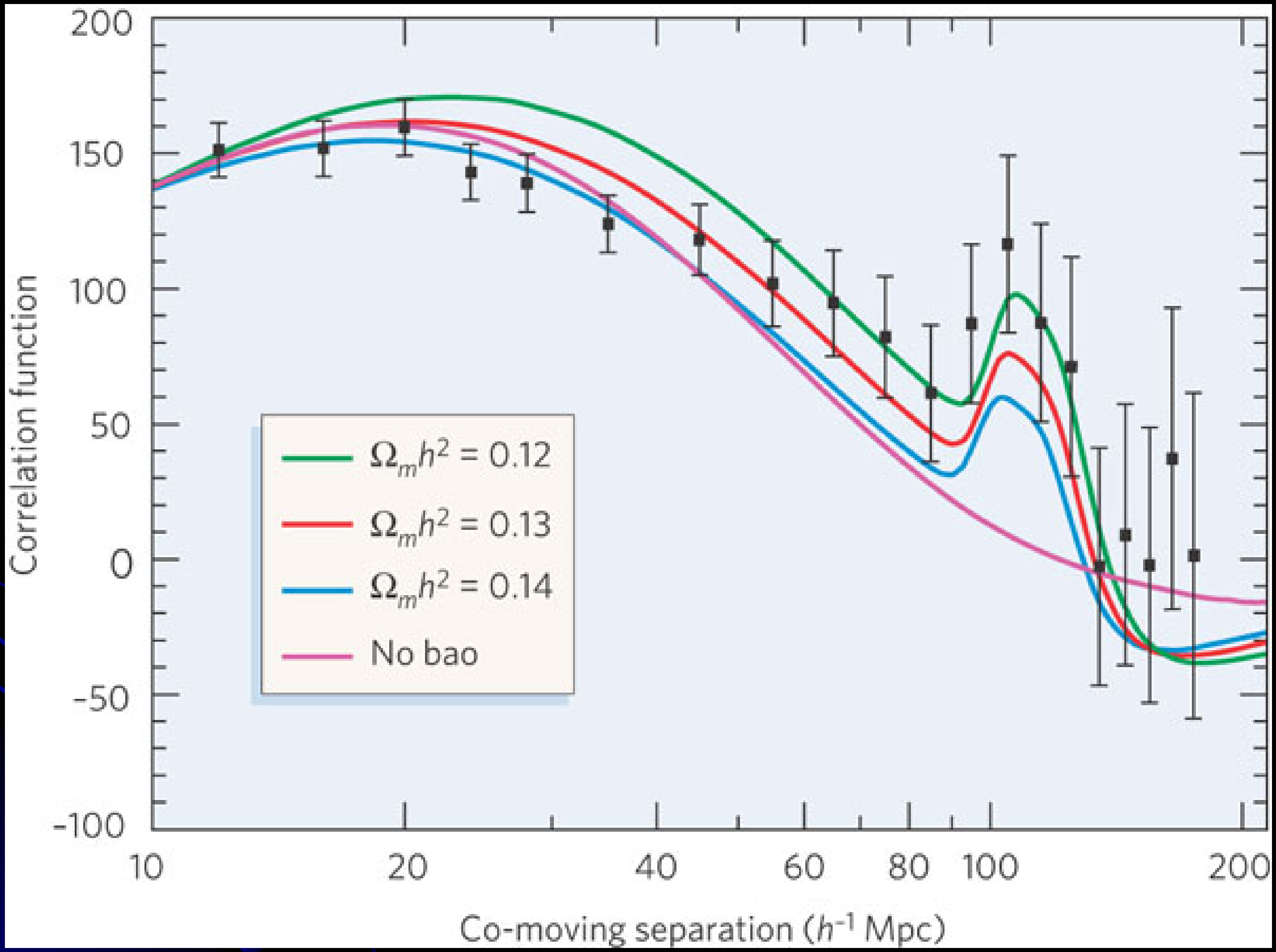


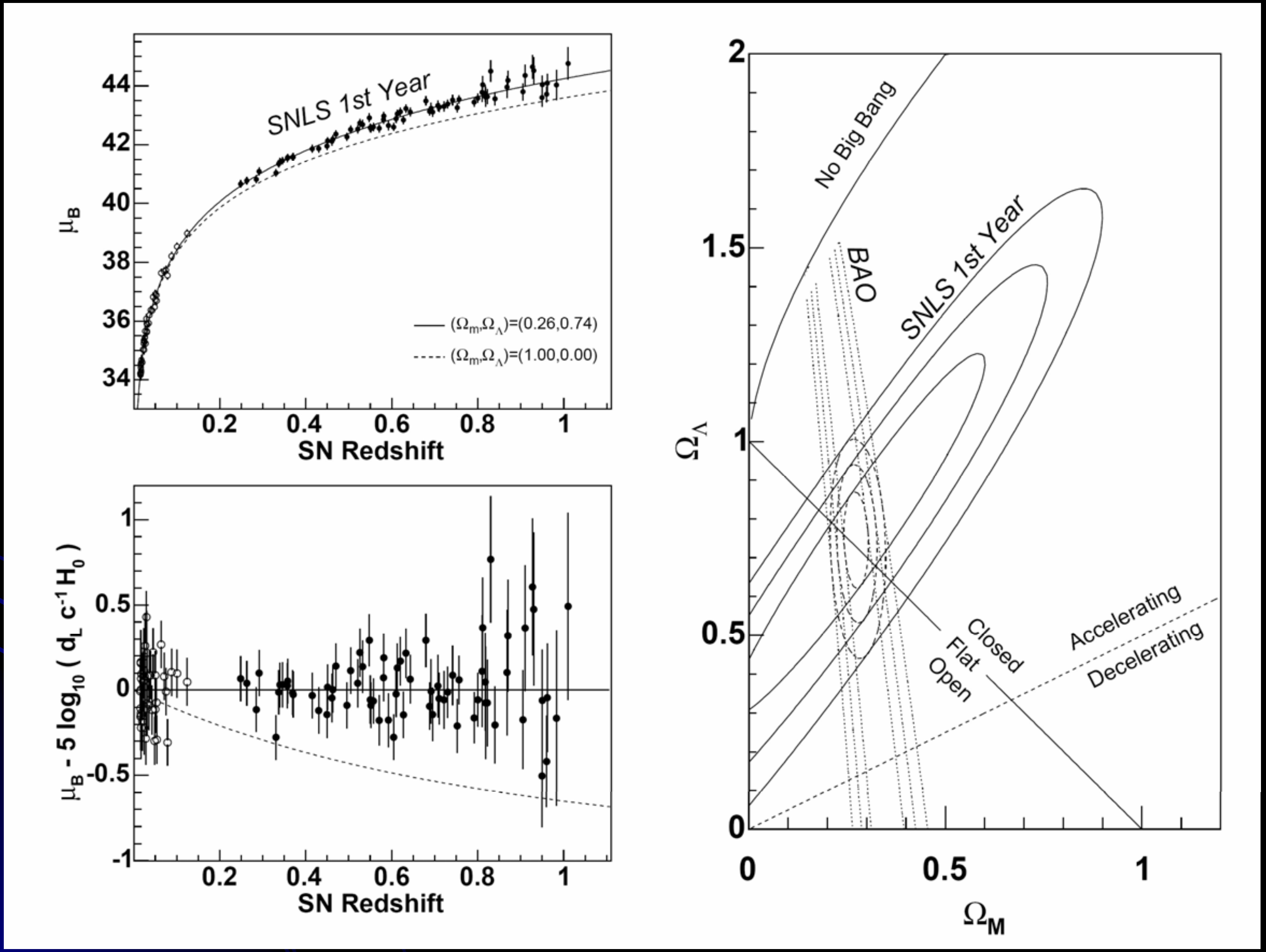
Baryon Acoustic Oscillations



Baryon Acoustic Oscillations

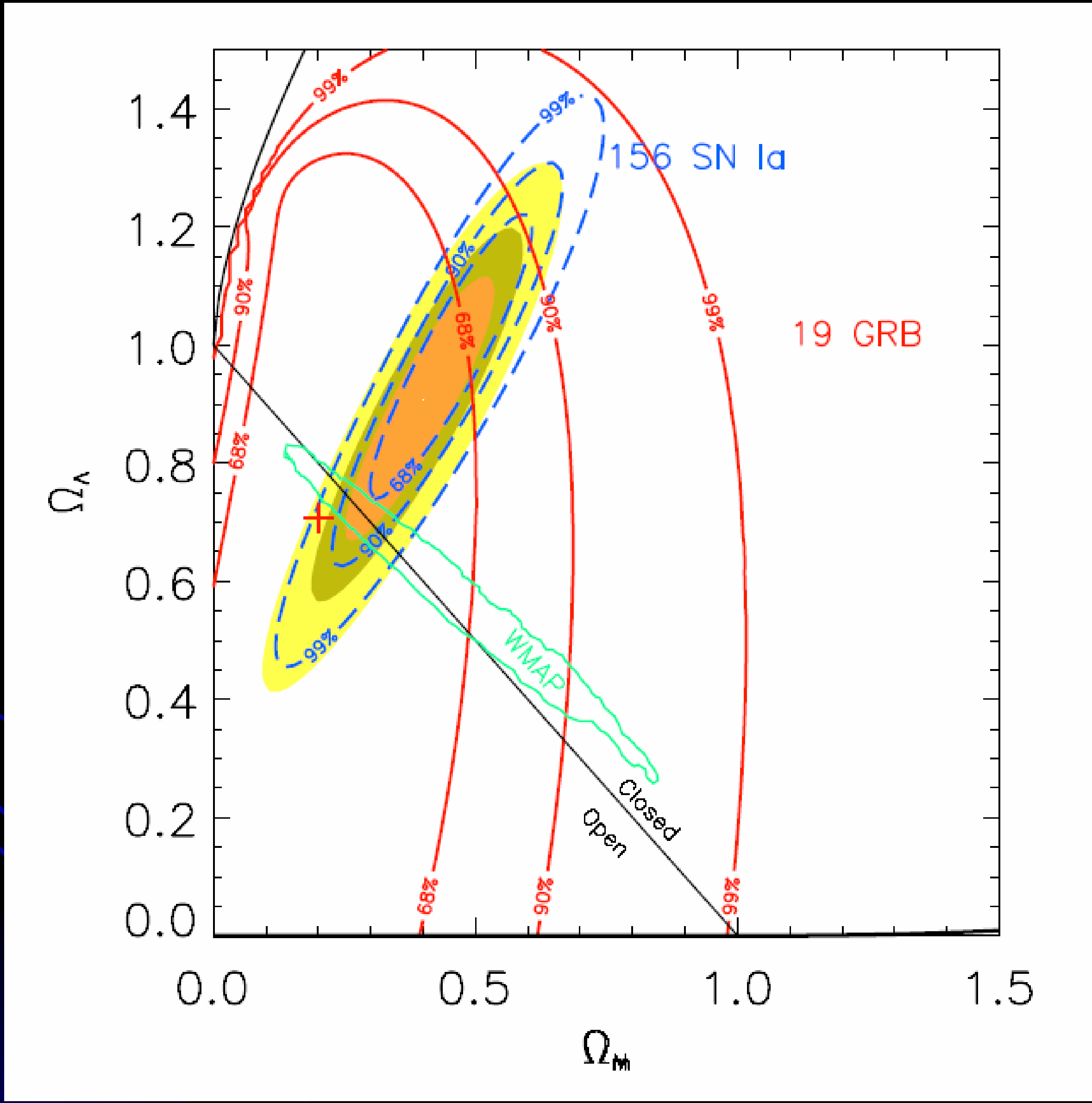


Results



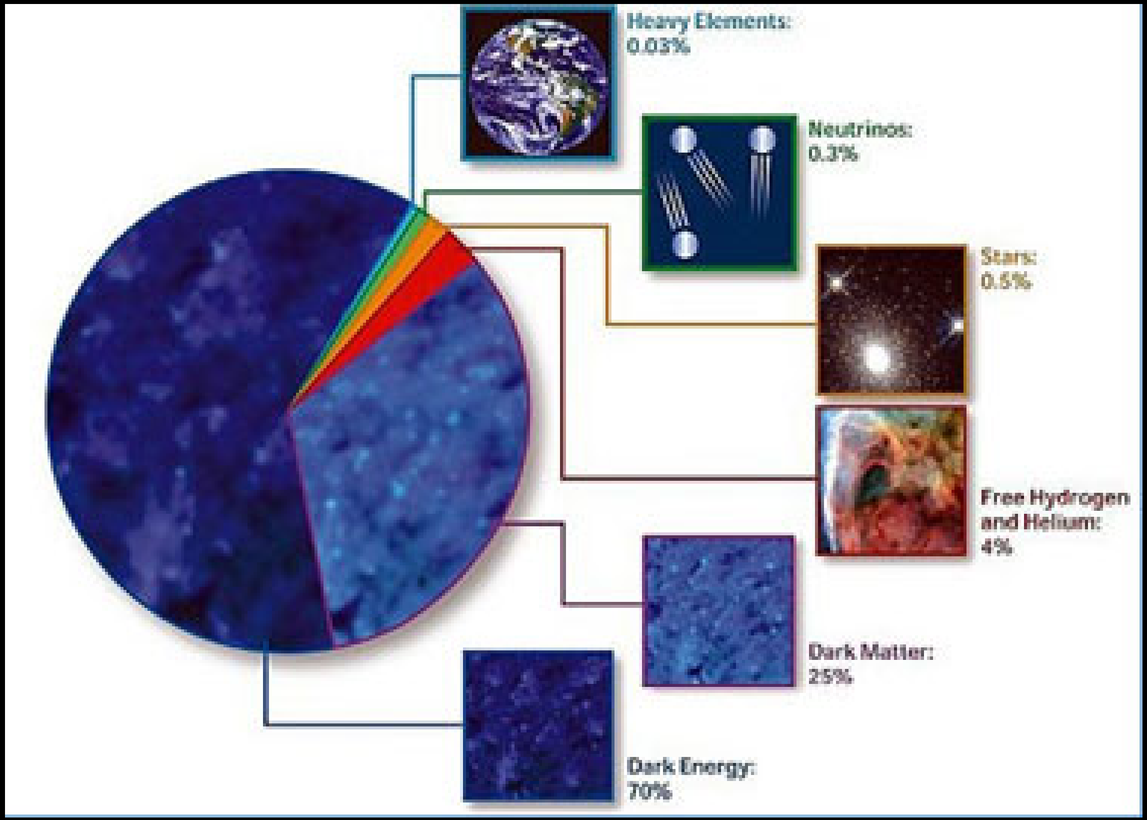
SNLS 1st Year
μ_B
SN Redshift
$(\Omega_m,\Omega_\Lambda)=(0.26,0.74)$
$(\Omega_m,\Omega_\Lambda)=(1.00,0.00)$
$\mu_B - 5\log_{10}(d_L c^{-1} H_0)$
SN Redshift
No Big Bang
BAO
SNLS 1st Year
Closed
Flat
Open
Accelerating
Decelerating
Ω_Λ
Ω_M

RESULTS



1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
Ω_Λ
Ω_M
156 SN Ia
19 GRB
WMAP
Closed
Open
99%
90%
68%

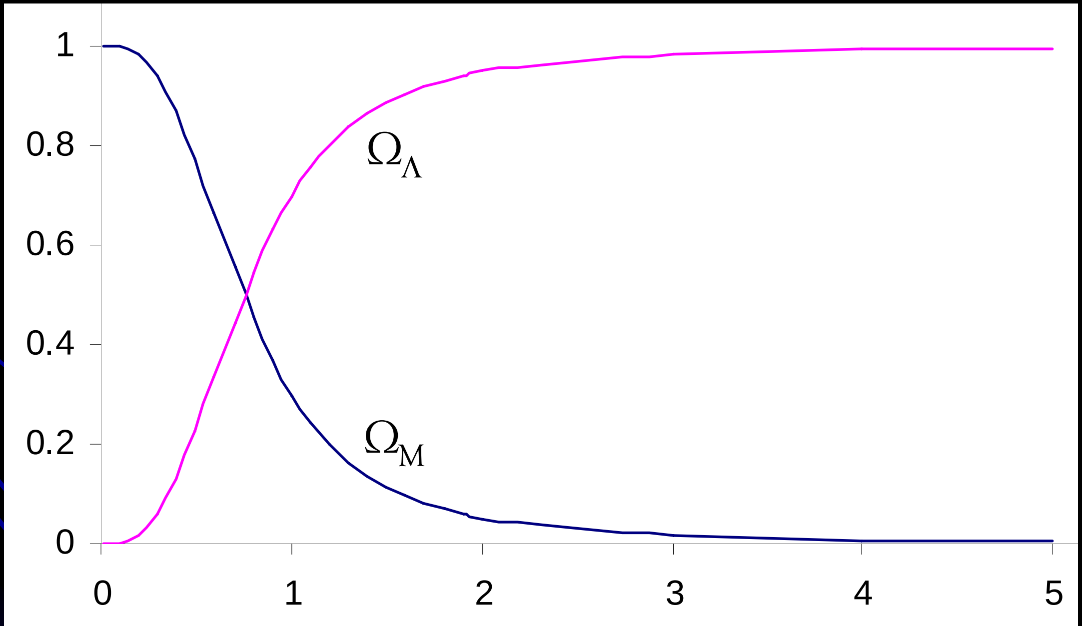
Results



- $H_0 = 73 \pm 0.03\ km^{-1}s^{-1}Mpc$
- $\Omega_M = 0.24 \pm 0.03$
- $\Omega_\Lambda = 0.72 \pm 0.04$
- $\Omega_k = -0.010\ (+0.016, -0.009)$

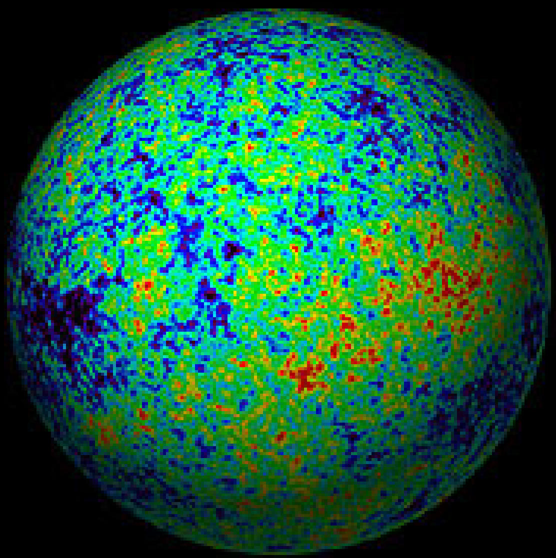
Could We Be Wrong?

- ΛCDM is a *model* not a *theory*
- Pioneer Anomaly
- Fine tuning of parameters – 'why now?' problem

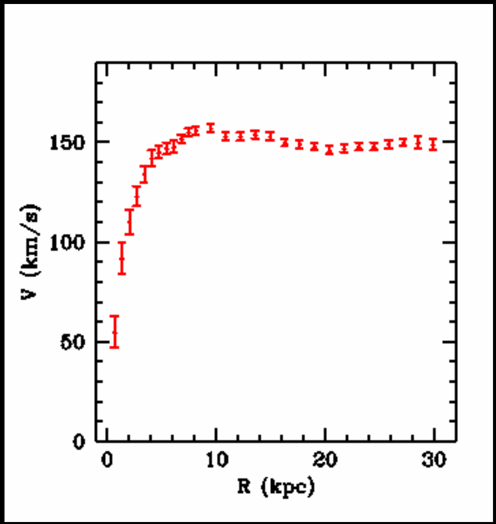


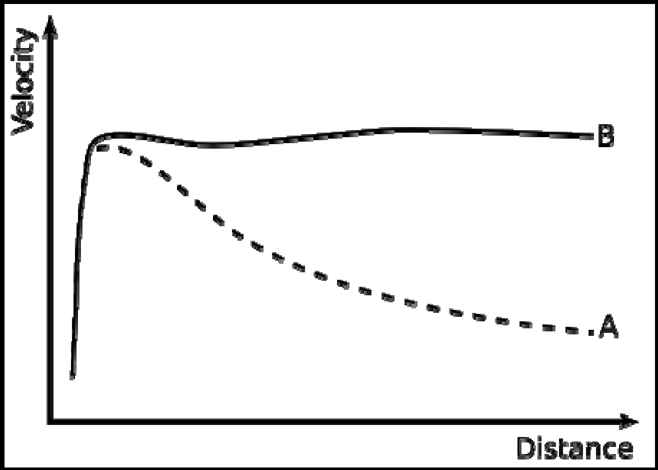
R/R_0

Could We Be Wrong?



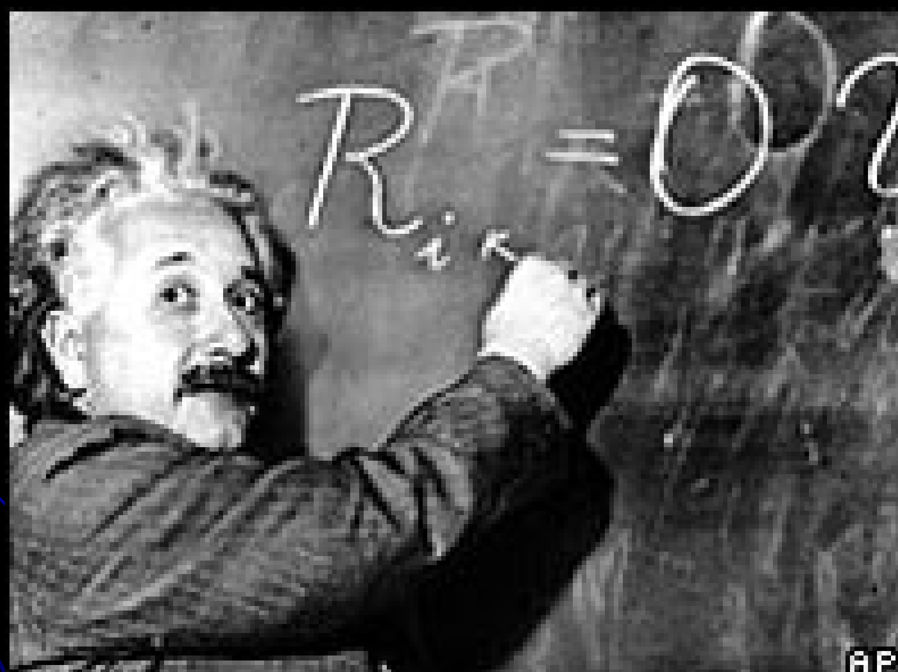
Cosmic Microwave Background Radiation (CMBR)





Galaxy Rotation Curves

Einstein's Universe



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