# The $\Lambda$CDM Universe


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**Modern Cosmology**

**Bremen @ Oct-26-D10**

Goods Field
HST 2009

# Summary

The metric of the expanding Universe can be expressed in one of the 3 following ways:

$$ds^2 = -c^2 dt^2 + a^2(t)\left[d\chi^2 + \chi^2 d\Omega^2\right]$$

k=0 Infinite flat Universe

$$ds^2 = -c^2 dt^2 + a^2(t)\left[d\chi^2 + \sin^2\chi d\Omega^2\right]$$

k=1 Finite closed Universe

$$ds^2 = -c^2 dt^2 + a^2(t)\left[d\chi^2 + \sinh^2\chi d\Omega^2\right]$$

k=-1 Infinite, open Universe

# Hubble Function in terms of Ω's

- The generalized Friedmann equation governing evolution of *R(t)* is written in terms of the present Ω's (density parameter terms) as ➔ **Hubble Func**

$$H^2(z) = H_0^2\left[\Omega_R(1+z)^4 + \Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right].$$

- The only terms in this equation that vary with time are the scale factor *R* and its rate of change $\dot{R}$
- Once the constants **$H_0$, $\Omega_M$, $\Omega_\Lambda$, $\Omega_k$** are measured empirically (using observations), then the whole past and future of the Universe is determined by solving this equation!
- Solutions, however, are more complicated than for $\Lambda=0$.


18 December 1998
Science
Vol. 282 No. 5397
Pages 2141–2336 $7
THE ACCELERATING UNIVERSE
Breakthrough of the Year
… and the winner is ΛCDM
AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

# Topics

- The LCDM Universe – analytic solution for matter and Dark Energy;
- Transition from deceleration to acceleration;
- The **Fundamental Plane of Cosmology**;
- **Age of the Universe**, Age as a function of redshift, Look-back Time.
- **Luminosity distances** for particular models ➔ how to measure the Expansion with SN Ia.
- Apparent angular diameters in the expanding Universe.
- The Universe of **Dark Energy – how to probe Dark Energy?**
- **WMAP7 Results ➔ Concordance Model.**

# The ΛCDM Universe

$$\Omega_k = 0 \ , \quad \Omega_M + \Omega_\Lambda = 1$$

**Friedmann-Equation and its Solution ➔ Limiting cases**

$$\dot{a}^2 = H_0^2 \left( \frac{\Omega_M}{a} + \Omega_\Lambda\, a^2 + \cancel{1 - \Omega_M - \Omega_\Lambda} \right) .$$

$$a(t) = \left( \frac{\Omega_M}{\Omega_\Lambda} \right)^{1/3} \sinh^{2/3} \left( 3\sqrt{\Omega_\Lambda} H_0 t / 2 \right)$$

# The $\Lambda$CDM Exact Solution

$$a(t) = \left(\frac{\Omega_M}{\Omega_\Lambda}\right)^{1/3} \sinh^{2/3}\left(3\sqrt{\Omega_\Lambda} H_0 t/2\right)$$

**Applicable for 99.99% of the age of our Universe**

**Small t , t < < $t_0$: ➔ Einstein-deSitter**

$$a(t) \propto t^{2/3}, \quad \ddot{a}(t) \propto -t^{-4/3}, \quad H(t) \propto t^{-1}, \quad D_H(t) \propto t$$

**Large t: ➔ deSitter**

$$\ddot{a}(t) \propto a(t) \propto \exp\left(H_\infty t\right)$$

$$H_\infty = H(t = \infty) = H_0\sqrt{\Omega_\Lambda}$$

# The ΛCDM Turning Point

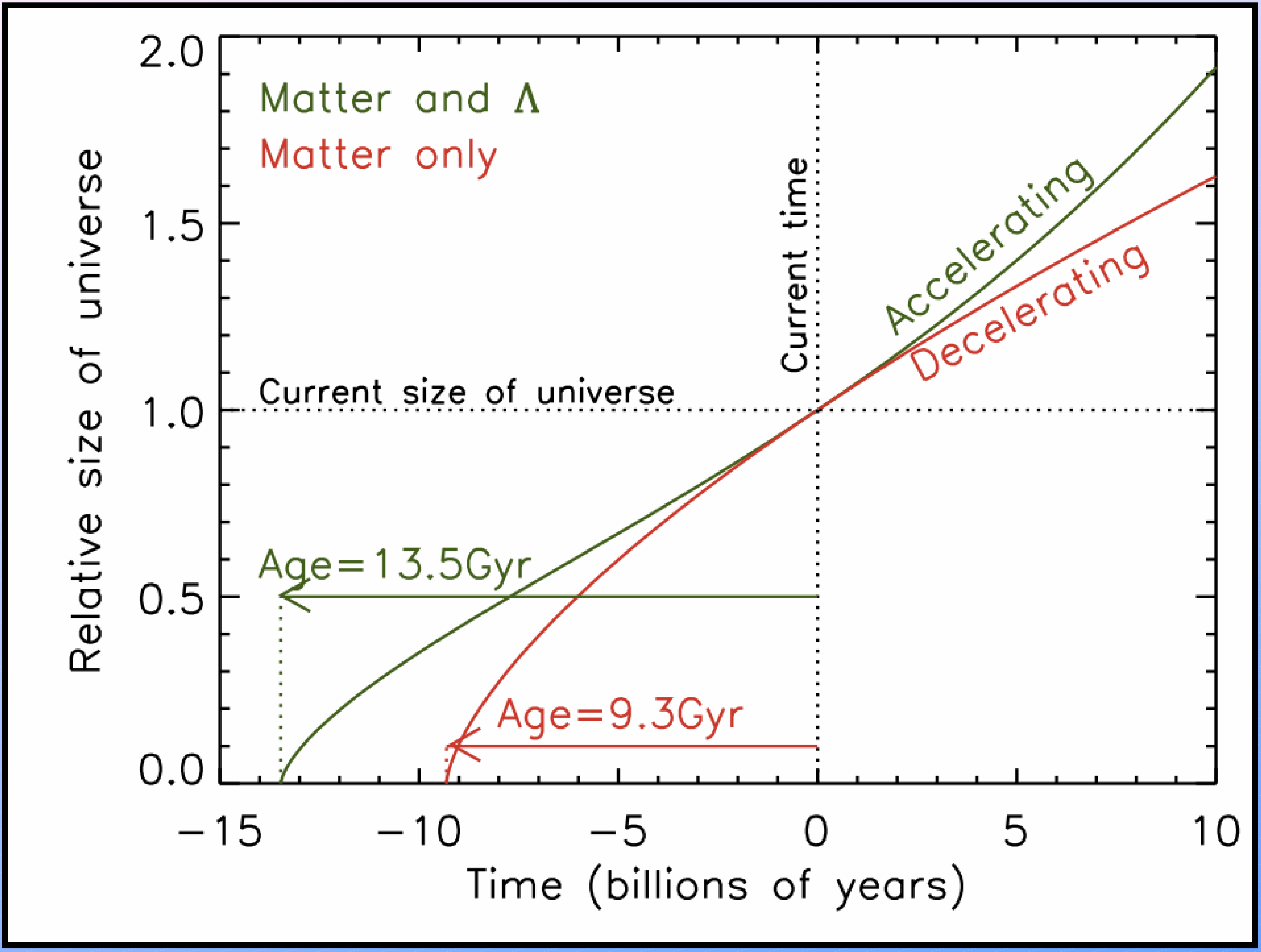
- There will a turning point **from deceleration to acceleration**, following from the 2nd Friedmann equation: $\ddot{a}_T = 0$

- $\ddot{a}/a = -4\pi G(\rho + 3P/c^2)/3 + c^2\Lambda/3 = 0$

✂➔ $-\frac{1}{2}\Omega_M/a^3_T + \Omega_\Lambda = 0$

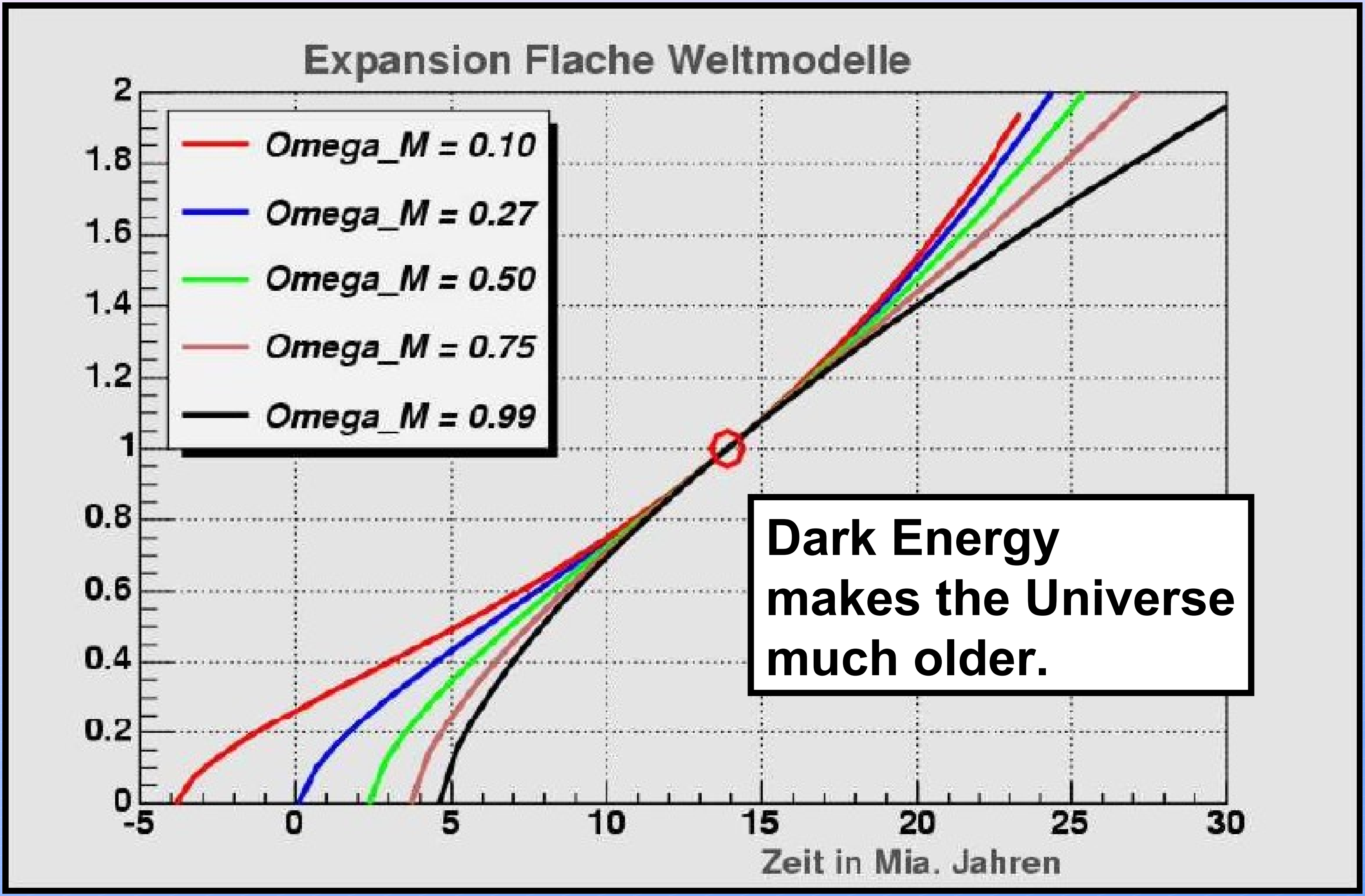
✂➔ $1 + z_T = (2\Omega_\Lambda/\Omega_M)^{1/3}$

✂➔ $z_T = 0.785$ **for the standard model.**



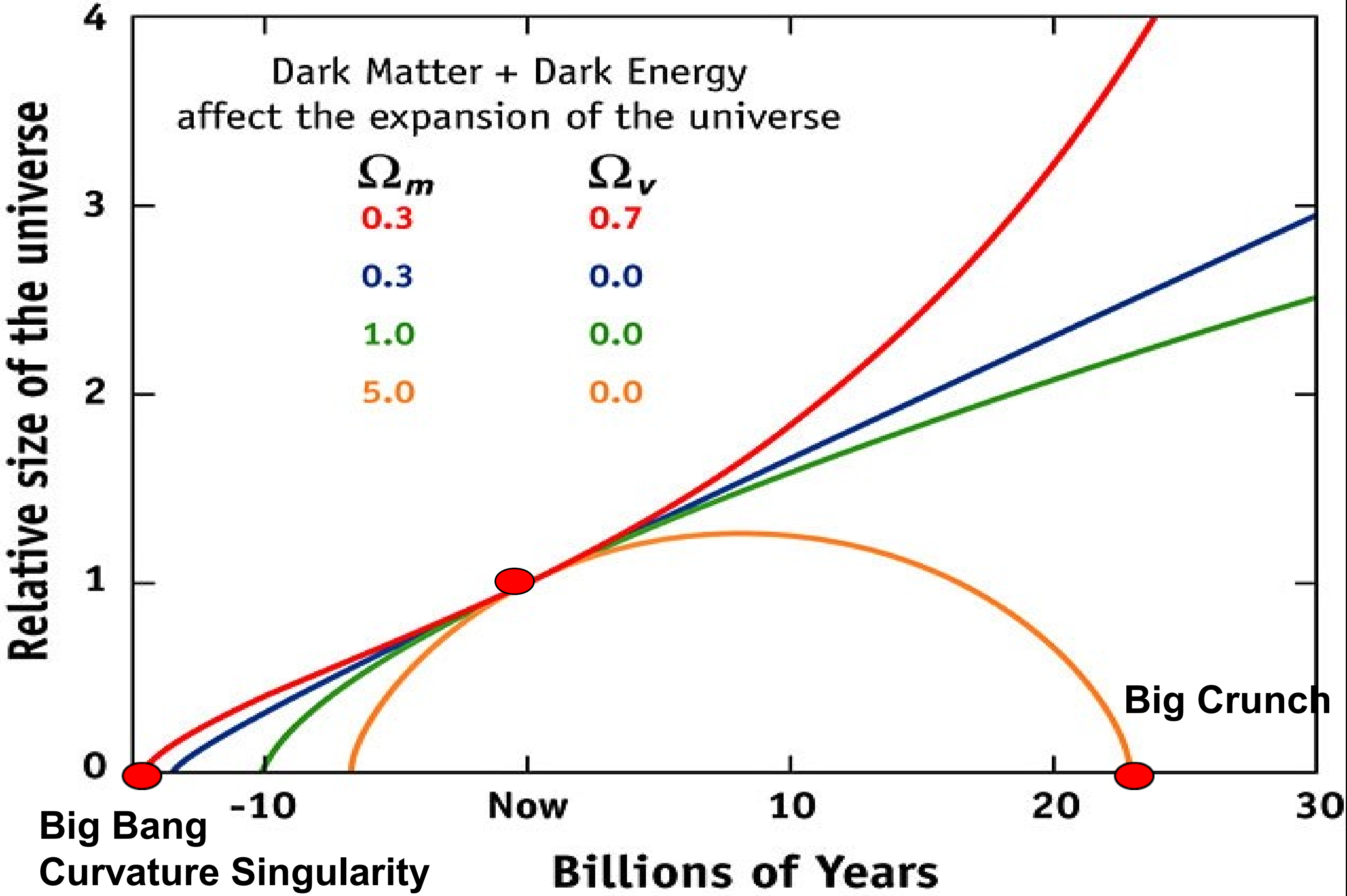
Matter and Λ
Matter only
Relative size of universe
2.0
1.5
1.0
0.5
0.0
Current time
Accelerating
Decelerating
Current size of universe
Age=13.5Gyr
Age=9.3Gyr
−15
−10
−5
0
5
10
Time (billions of years)

# The ΛCDM Universe




**Dark Energy makes the Universe much older.**

# Expansion of the Universe



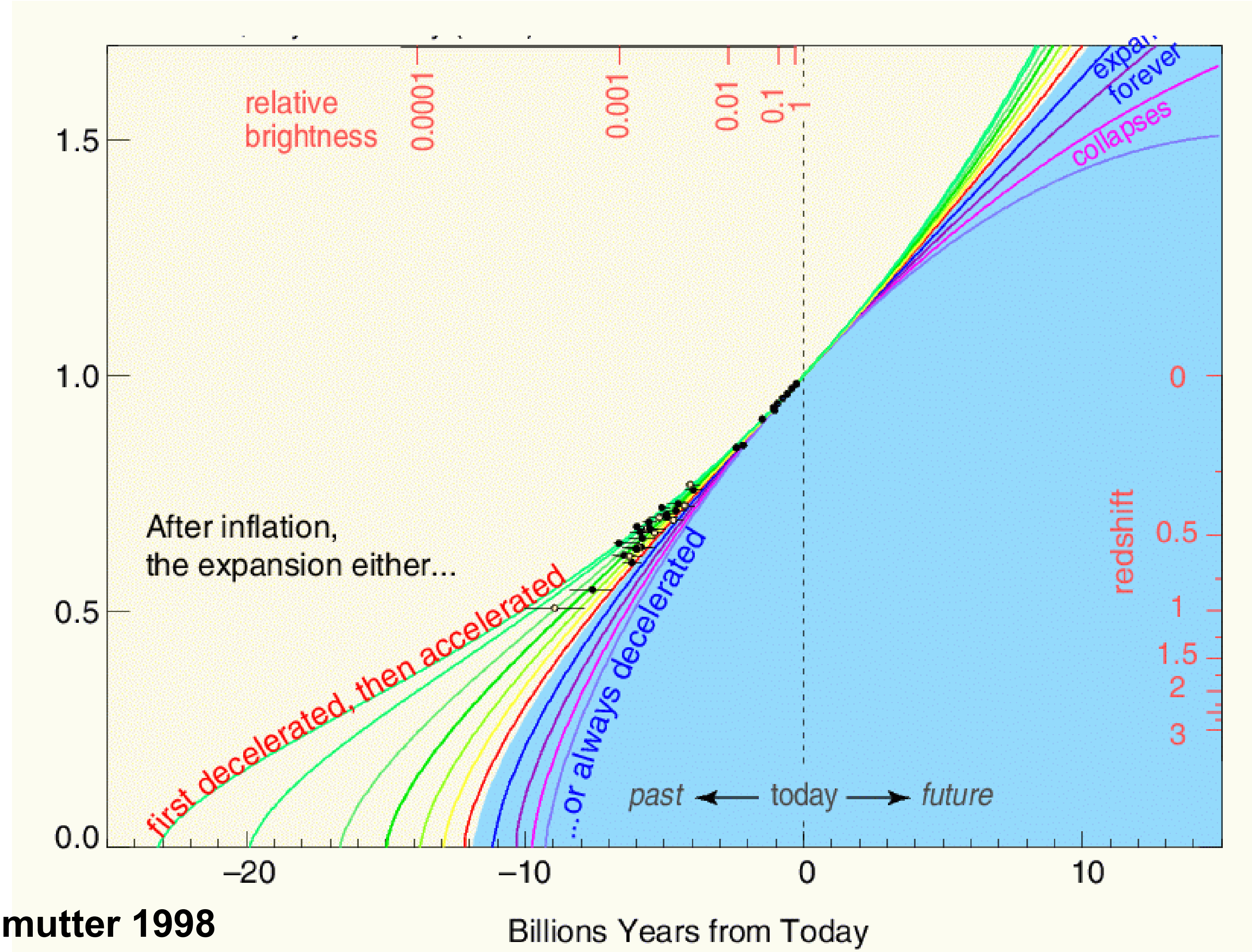
# The ΛCDM Universe - 1998

- Supernovae-Observations (Riess et al. 1997, …) ➔

The Expansion is accelerated!

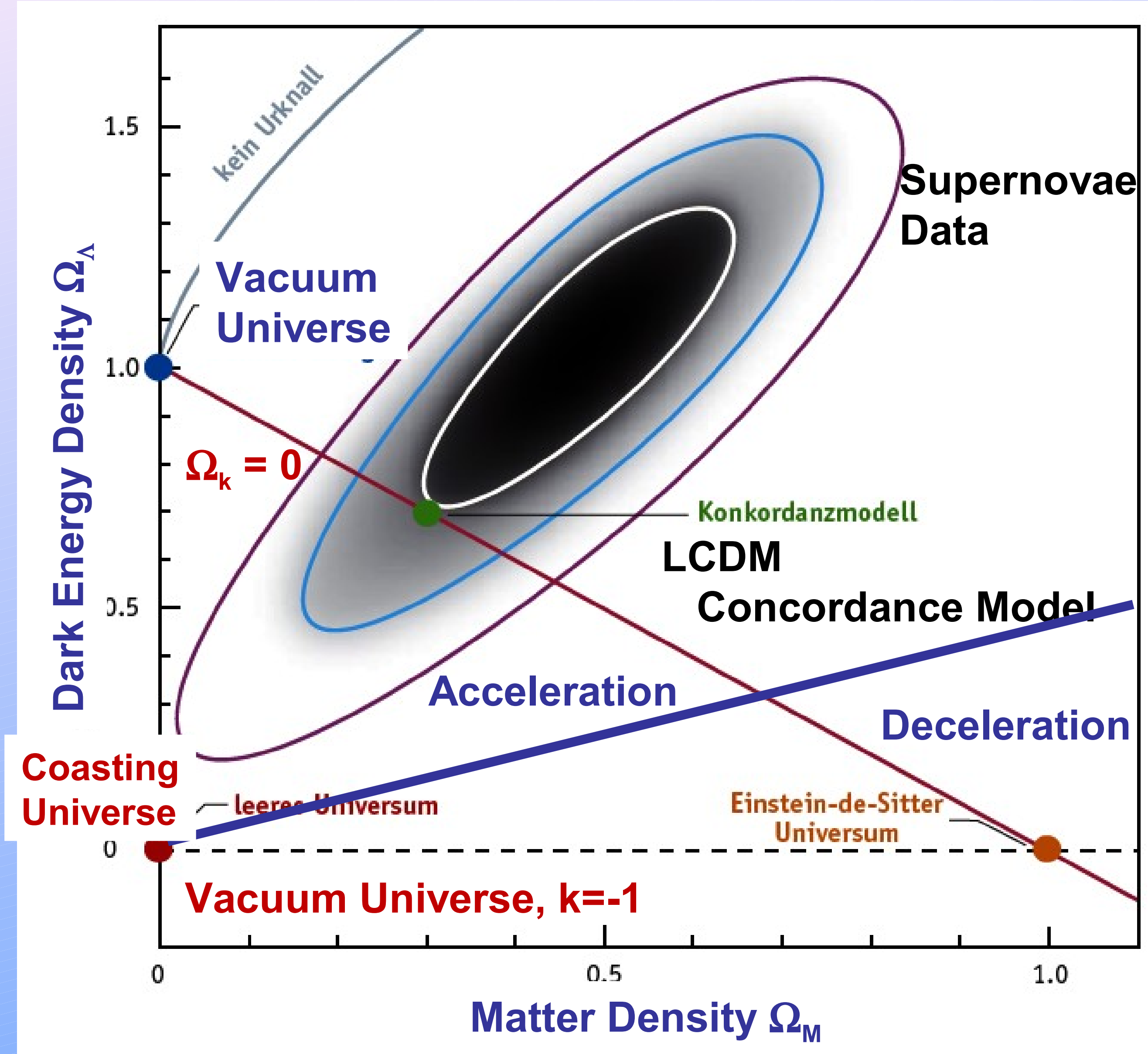
We need therefore a negative pressure like Λ !

# 1998 Discovery → Acceleration



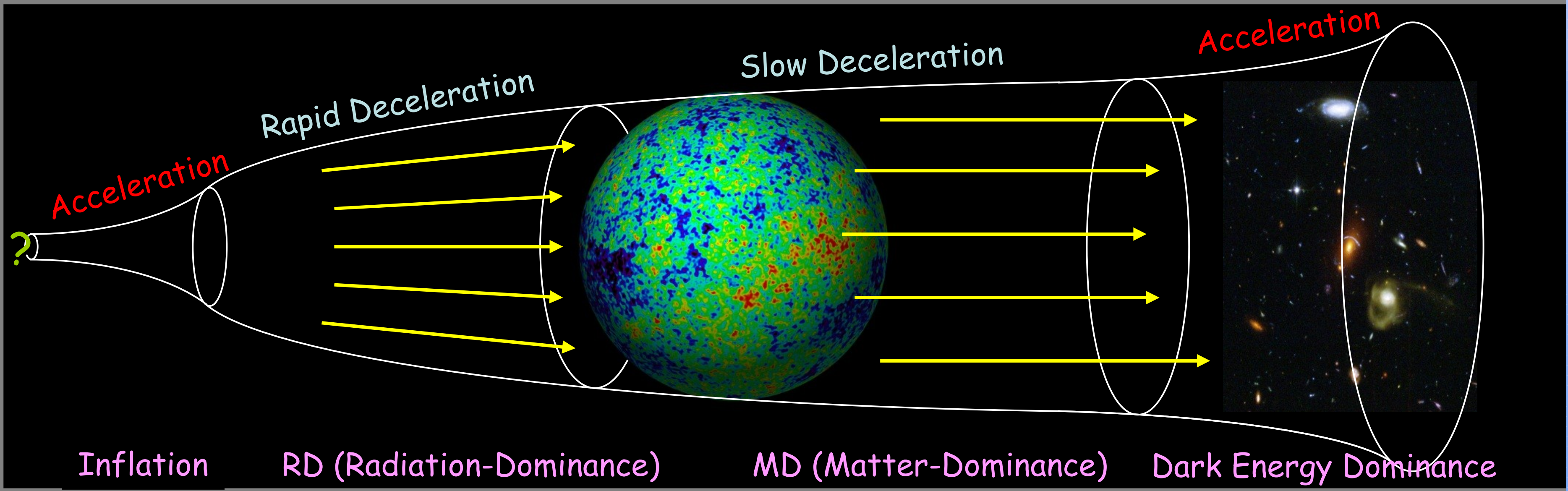

**Saul Perlmutter 1998**

# The Fundamental Plane of Cosmology



# Phases of Cosmic Expansion

$$\frac{\ddot{R}}{R} = -\frac{4\pi G(\rho c^2 + 3P)}{3c^2} + \frac{c^2\Lambda}{3}.$$



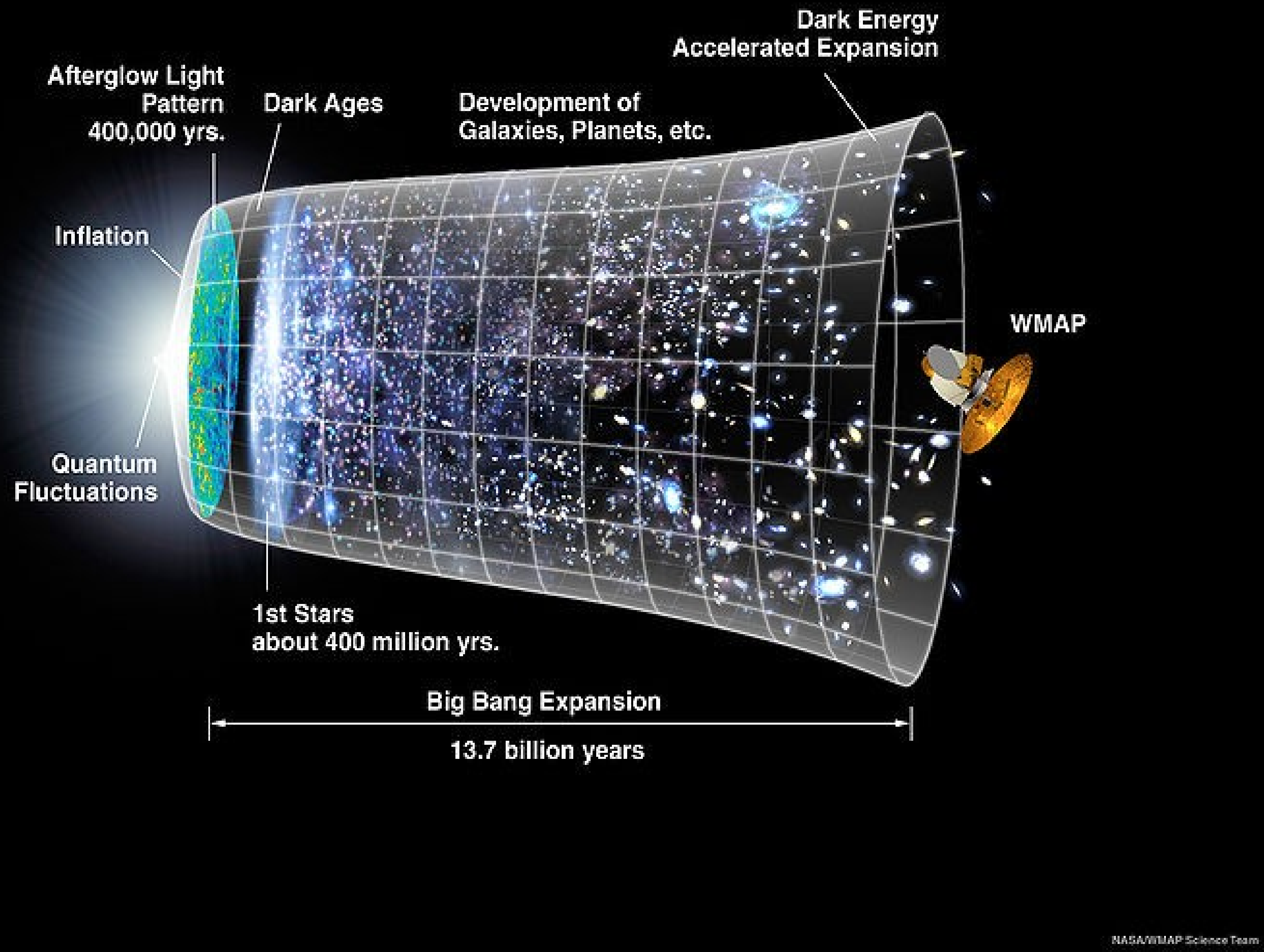

$a(t) \sim e^{Ht}$

$a(t) \sim t^{1/2}$

$a(t) \sim t^{2/3}$

→ **Time increases logarithmically**

# Phases of Cosmic Expansion



# The Age of the Universe

$$H^2 = H_0^2 \left(\Omega_m a^{-3} + \Omega_w a^{-3(1+w)}\right)$$

(without radiation, $\Omega_k = 0$ )

- **Integrate dt = da / (da/dt) = da / [a H(a)]**

$$t = \int_0^1 \frac{da}{aH(a)} = \int_0^1 \frac{da}{H_o(\Omega_m a^{-3} + \Omega_w a^{-3(1+w)})^{1/2}}$$

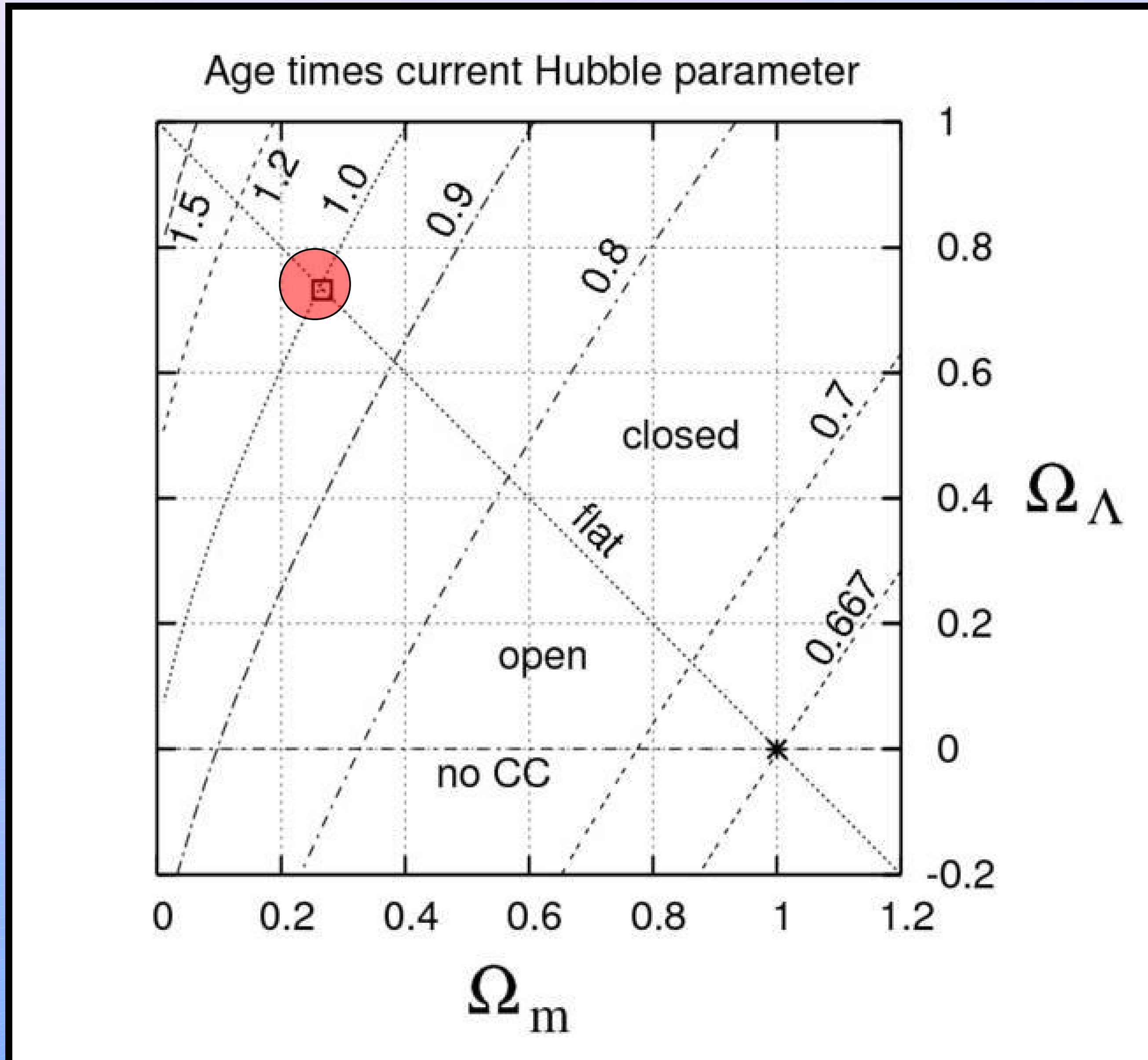
- **For w=-1 (d.h. $\Omega_{DE}=\Omega_\Lambda$):**

$$t_0 = \frac{2}{3H_0} \frac{\tanh^{-1}(\sqrt{\Omega_\Lambda})}{\sqrt{\Omega_\Lambda}}$$

- **Hubble Time: $1/H_0$ = 13,7 Gyears.**

# Fundamnetal Plane - Age of the Universe

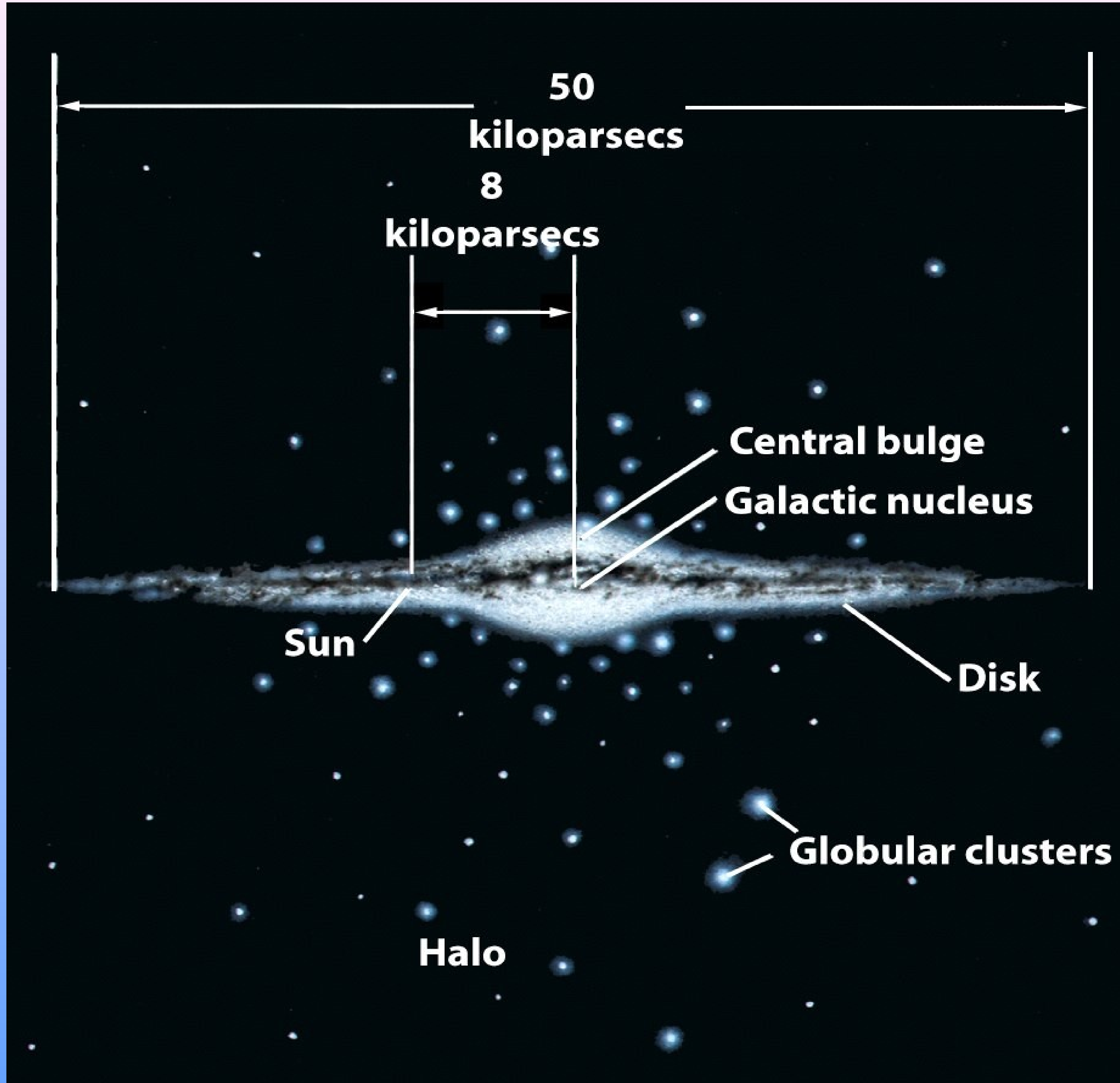
$$t_0 = \frac{1}{H_0} F(\Omega_r, \Omega_m, \Omega_\Lambda, \ldots)$$



# How to measure the Age

- Method of Globular Clusters (position of knee and horizontal branch in HR Diagramm).
- Cooling of White Dwarfs in the Galactic Disk ➔ T > 3000 K ➔ GAIA. Oldest WDs have cooled down to a surface temperature ~ 3000 K.
- Age of chemical elements in the Galaxy (somewhat inaccurate method).

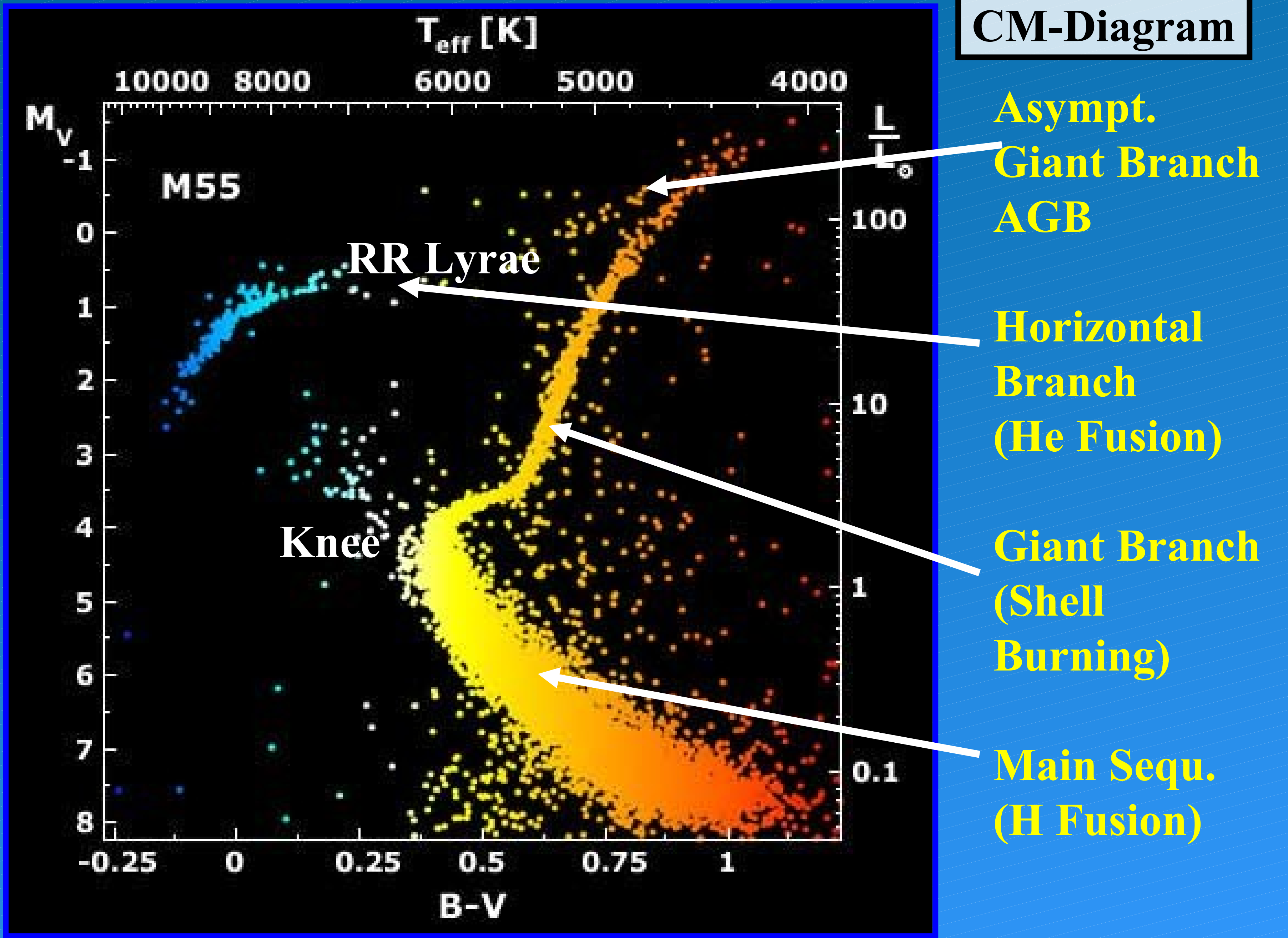
# Globular Clusters
## ~ 150 – oldest Objects



# Globular Clusters

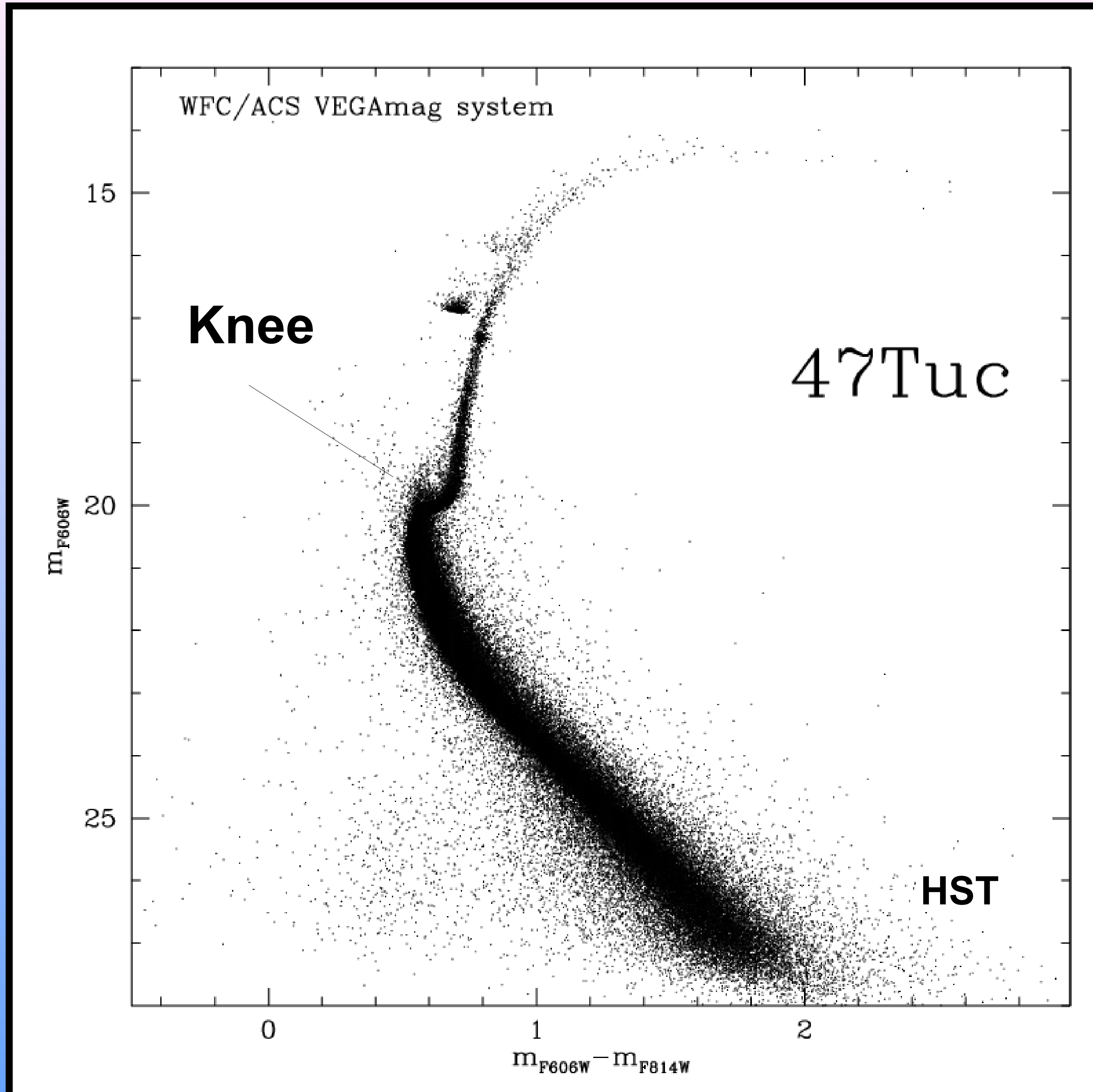
< 1 Mio Stars

# CM-Diagram



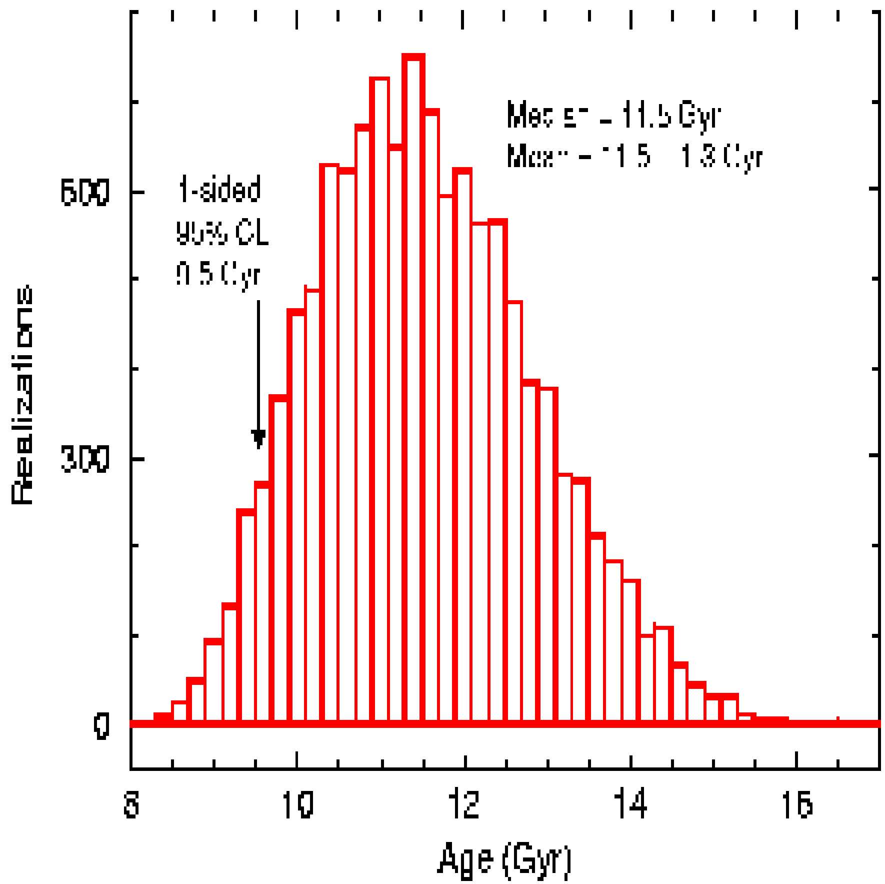
T_eff [K]
10000 8000 6000 5000 4000
M_V
-1
0
1
2
3
4
5
6
7
8
M55
RR Lyrae
Knee
L/L_⊙
100
10
1
0.1
-0.25 0 0.25 0.5 0.75 1
B-V
Asympt. Giant Branch AGB
Horizontal Branch (He Fusion)
Giant Branch (Shell Burning)
Main Sequ. (H Fusion)

# Globular Clusters Age Determination

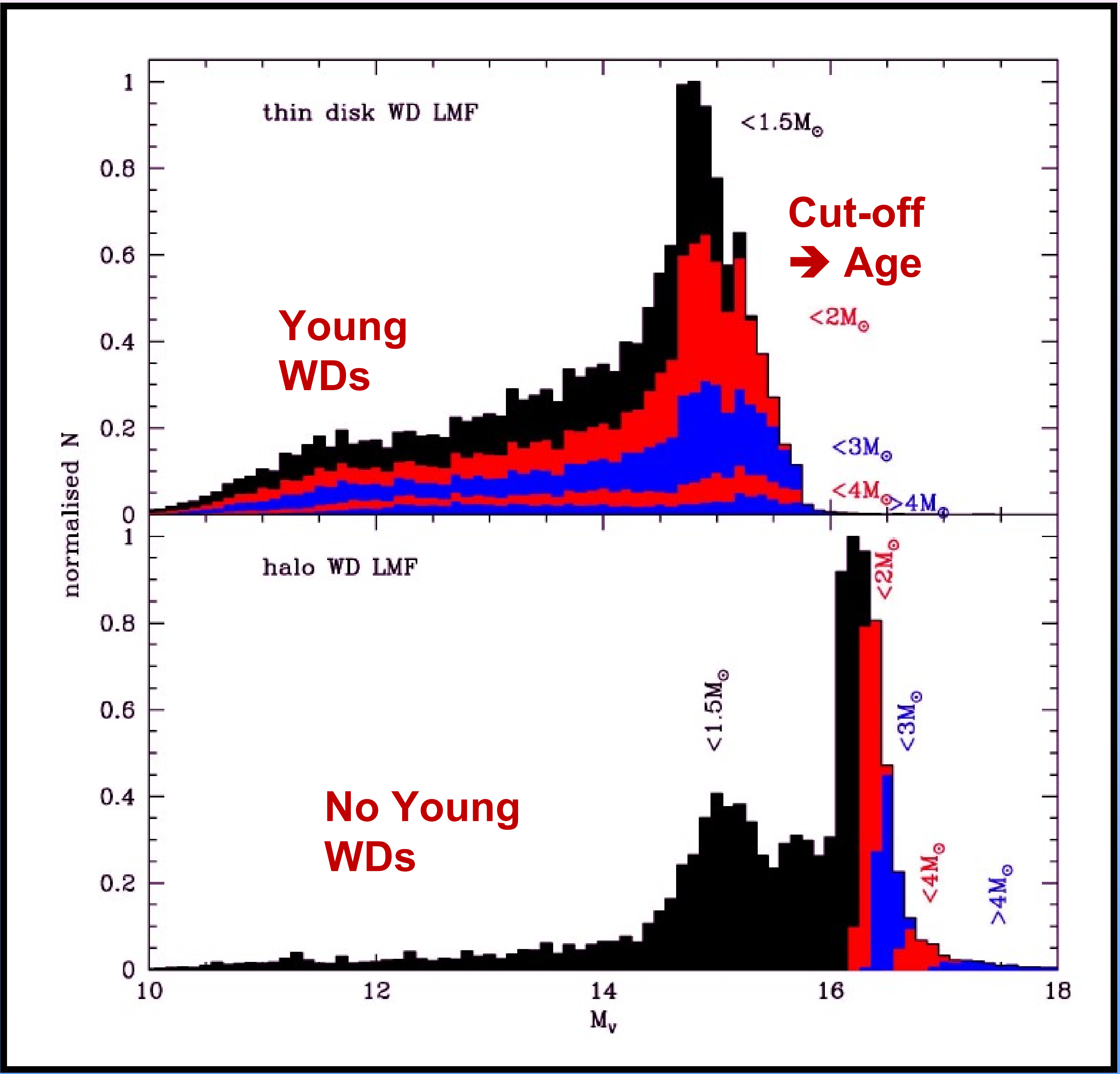


# Age Distribution of Globular Clusters

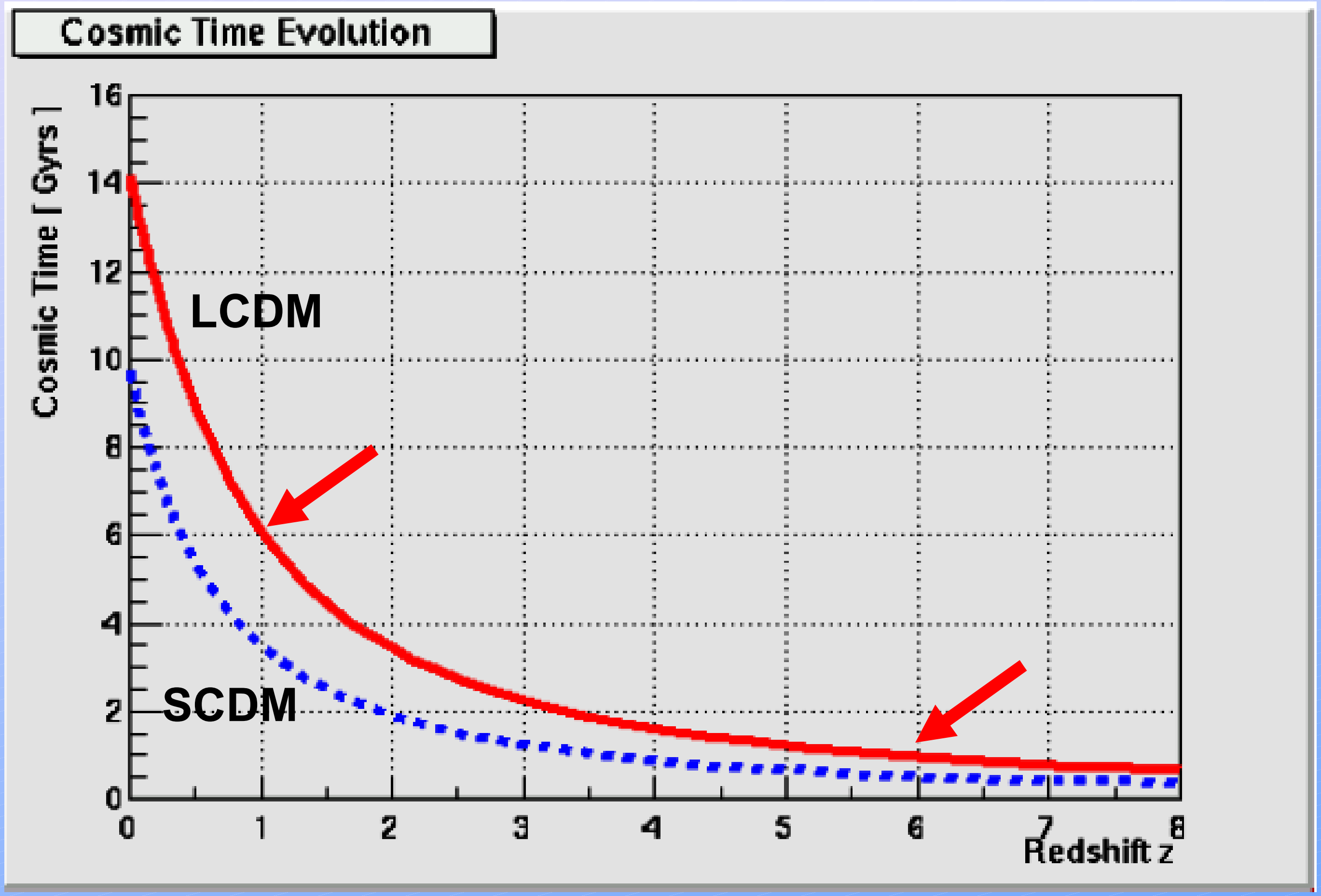
- Krauss + Chaboyer
  - stars age = 12.4 Gyr
  - estimate ~ 1 Gyrs min for formation
  - $t_0$>10.2 Gyr 95 per cent 1-tailed
- CMB + Flatness → $t_0$ ~ 13.7 Gyr



# White Dwarf Luminosity Function



# Age as Function Redshift



# How to Observe in the Friedmann Universe

Consider the propagation of photons under the Expansion of the Universe.

→ SNe Ia Hubble-Diagrams, based on the Luminosity distance
→ Angular extensions of Galaxies
→ [ Number counts of galaxy clusters ]
→ [Weak Lensing by Dark Matter]

# The Comoving Distance

✂ ➔ **dx = c dt = a dr**   (k=0)

$$D_c = a_0 dr = a_0 \int \frac{cdt}{a} = a_0 \int \frac{da}{a\dot{a}} = a_0 \int \frac{da}{a^2 H(a)}$$

$$D_C(z) = \int_0^z \frac{dz'}{H(z')} = \int_0^z \frac{dz'}{H_0(\Omega_m (1+z')^3 + \Omega_w (1+z')^{3(1+w)})^{1/2}}$$

$$\frac{a}{a_0} = \frac{1}{1+z} \qquad \frac{da}{a^2} = \frac{dz}{a_0} \qquad \Omega_T = 1$$

$$\frac{H^2(z)}{H_0^2} = (\Omega_m (1+z)^3 + \Omega_w (1+z)^{3(1+w)})$$

**Hubble-Function**

# Luminosity Distances

**DeSitter Model:**

$$d_L(z) = \frac{c}{H} z(1+z) .$$

**Mattig Formula ($\Omega_\Lambda$ = 0, 1968):**

$$d_L = r_1 R_0 (1+z) = \frac{c}{H_0} \frac{1}{q_0^2} \left( q_0 z + (q_0 - 1)[\sqrt{1 + 2 q_0 z} - 1] \right) .$$

**FLRW ➔ no closed form:**

S(x) = x, k = 0
S(x) = sin(x), k=+1
S(x) = sinh(x), k=-1

$$D_L = \frac{(1+z)c}{H_0 \sqrt{|\Omega_\kappa|}} S\left\{ \sqrt{|\Omega_\kappa|} \int_0^z \left[ \Omega_\kappa (1+z')^2 + \Omega_M (1+z')^3 + \Omega_\Lambda \right]^{-1/2} dz' \right\}$$

# ΛCDM: Ue-Li Pen Approximation for Luminosity Distance

$$d_L(z) = \frac{c}{H_0}(1+z)\Big[\eta(0,\Omega_M) - \eta(z,\Omega_M)\Big]$$

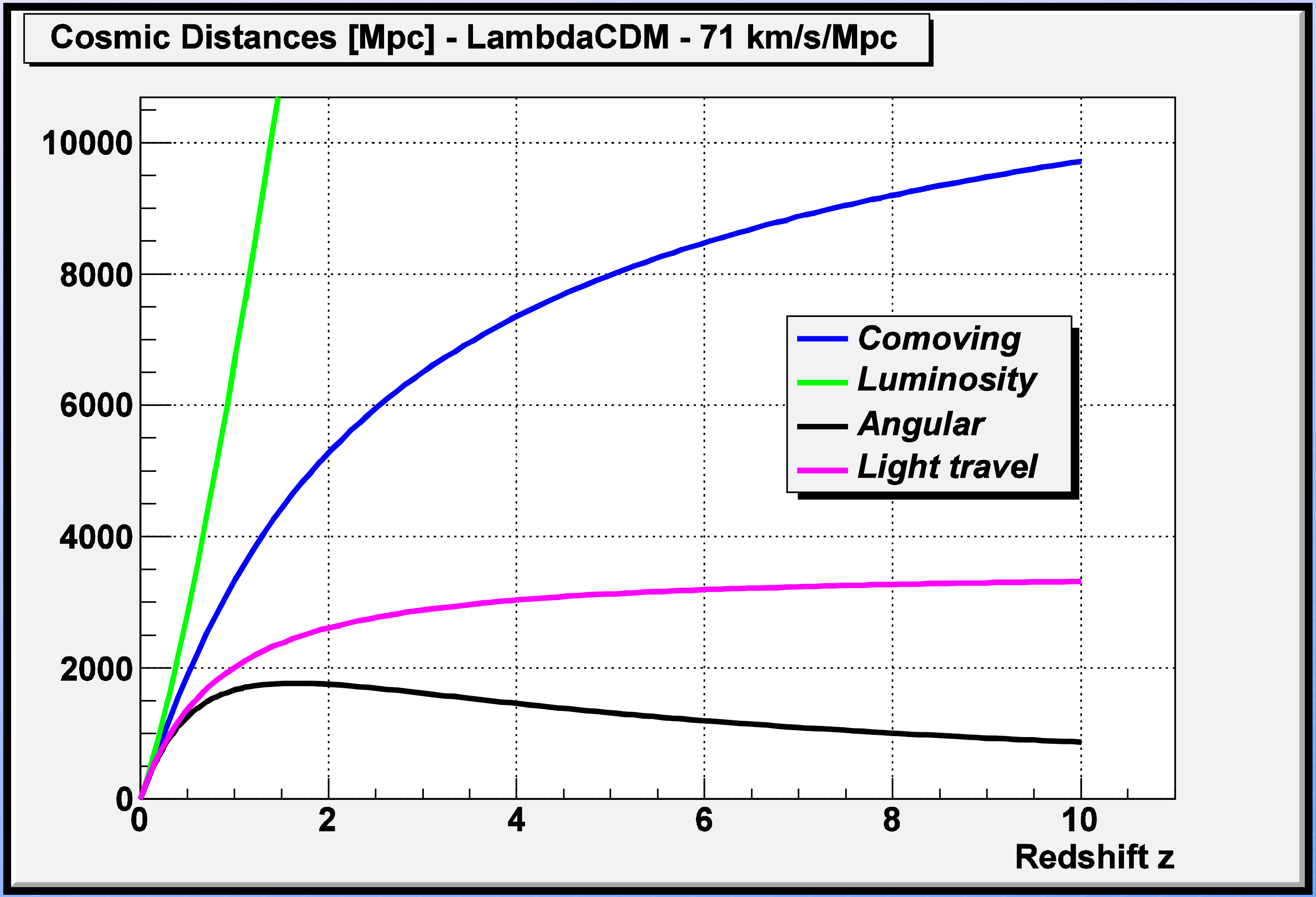
$$\eta(z,\Omega_M) = 2\sqrt{s^3+1}\Big[(1+z)^4 - 0,1540s(1+z)^3 + 0,4304s^2(1+z)^2 + 0,19097s^3(1+z) + 0,066941s^4\Big]^{-1/8}.$$

$s^3 = (1 - \Omega_m) / \Omega_m$

Ue-Li Pen 1999

$$d_A = \frac{d_L}{(1+z)^2} = \frac{D_C(z)}{(1+z)}$$

# Distances in LCDM

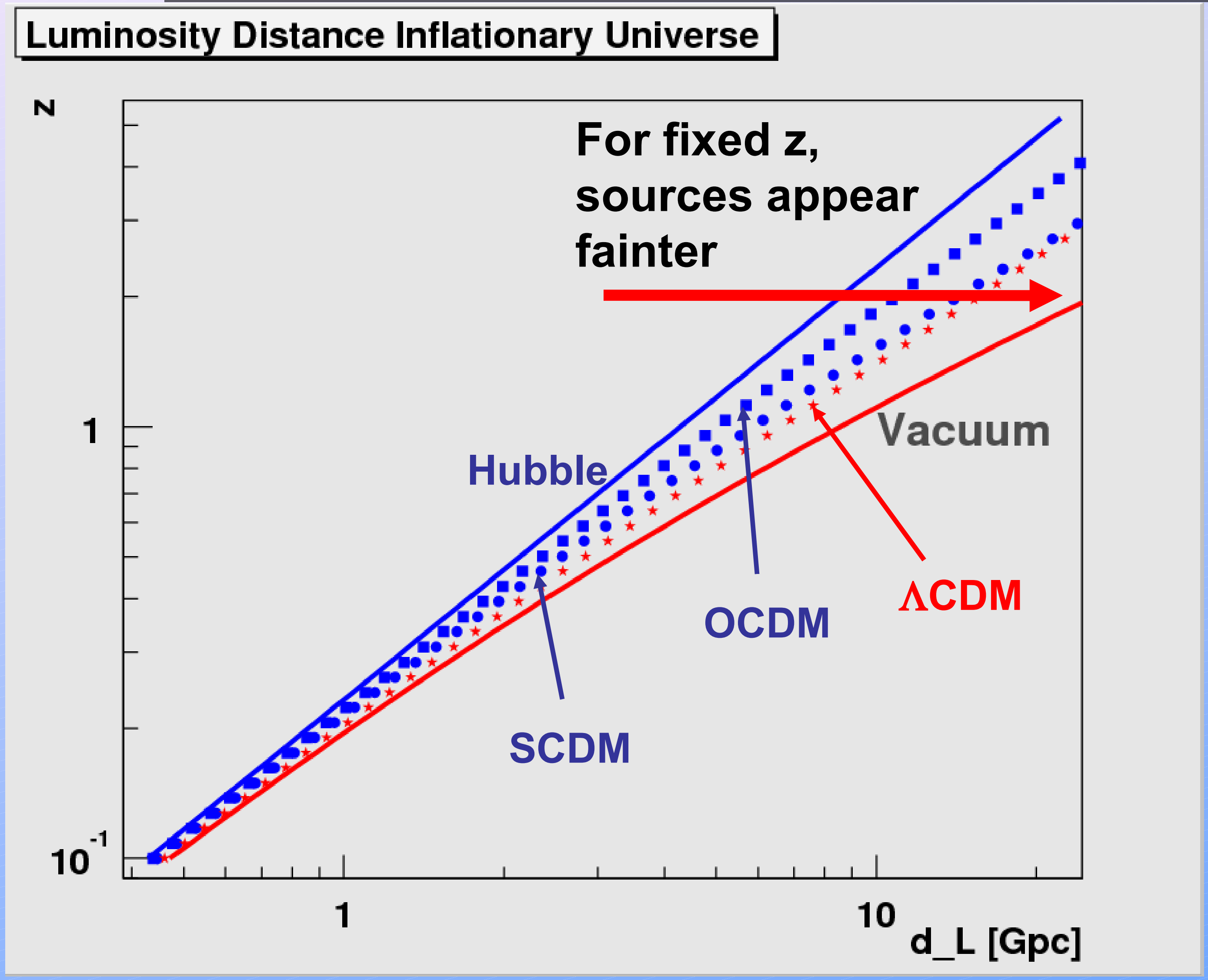



see Web Portal iCosmos

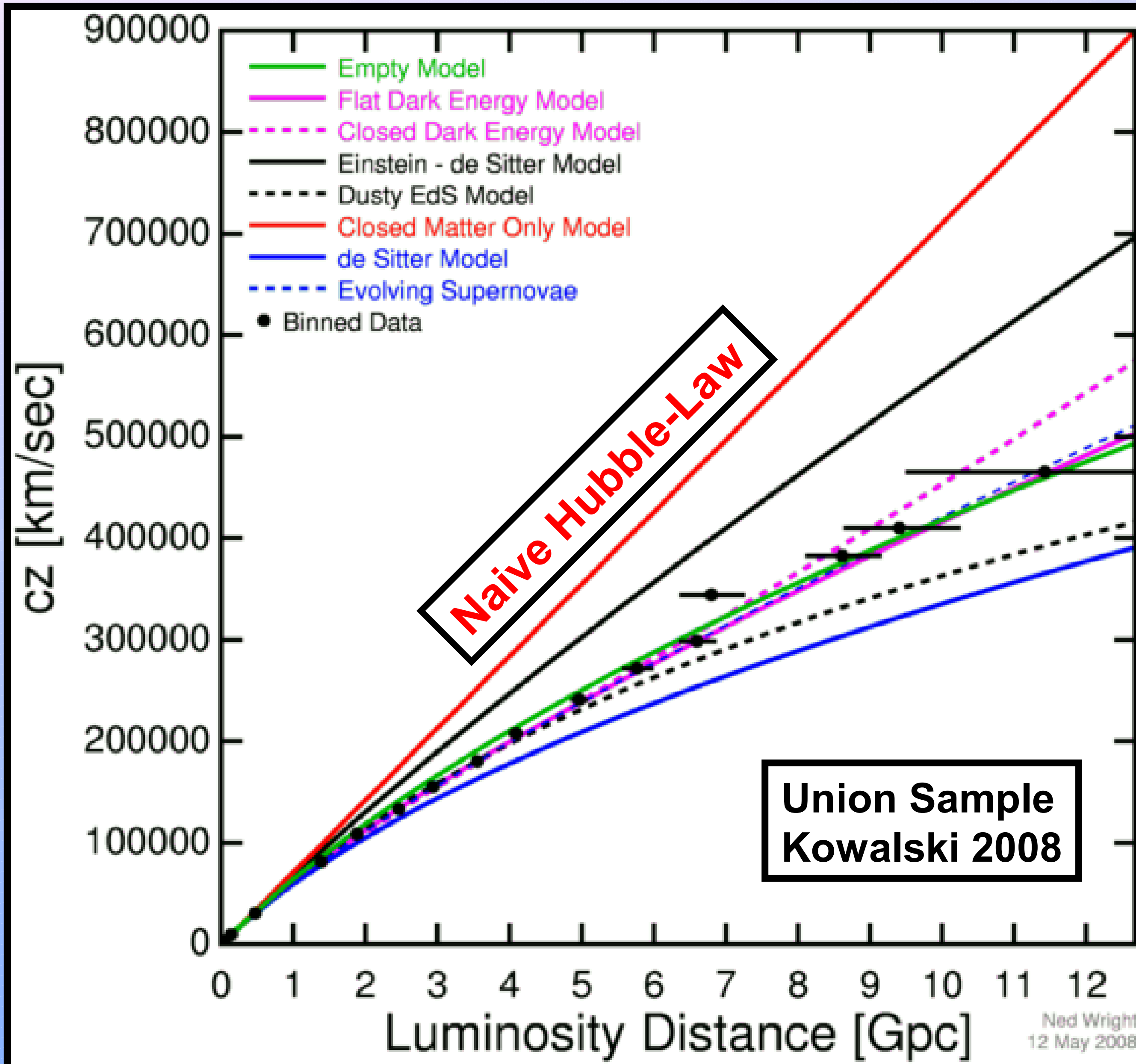
# Distances in LCDM

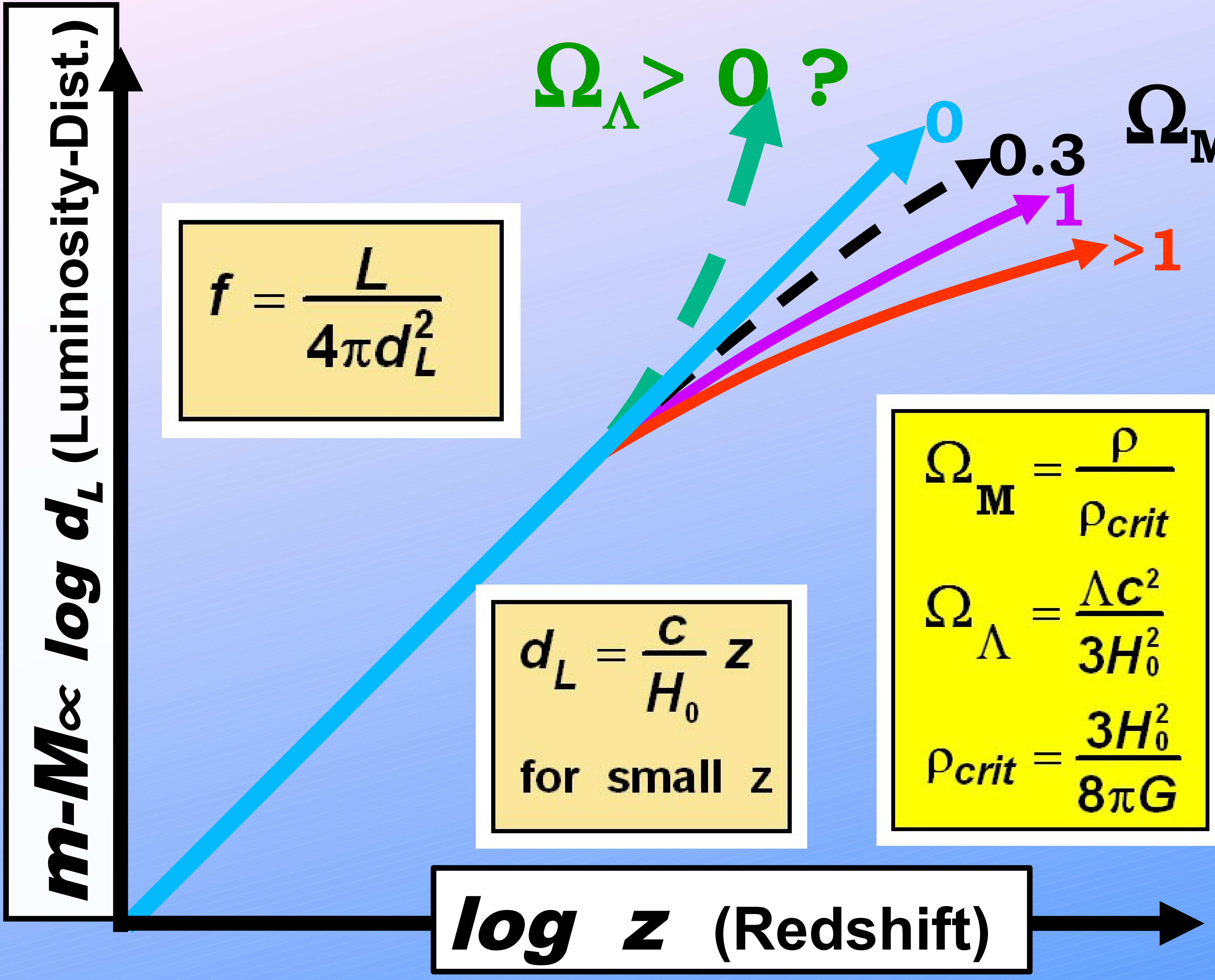
| Quantity | $z = 1$ | $z = 6$ | $z = 10$ |
|---|---|---|---|
| age at $z$ | 5.94 Gyr | 0.952 Gyr | 0.484 Gyr |
| lookback time | 7.73 Gyr | 12.7185 Gyr | 13.18 Gyr |
| Luminosity dist | 6635 Mpc | 58,972 Mpc | 106,308 Mpc |
| Angular dist | 1659 Mpc | 1203 Mpc | 878.6 Mpc |
| Comoving dist | 3317 Mpc | 8425 Mpc | 9664 Mpc |
| Comoving vol to $z$ | 153 $Gpc^3$ | 2505 $Gpc^3$ | 3781 $Gpc^3$ |
| 1 arcsec scale | 8.04 kpc | 5.83 kpc | 4.26 kpc |
| 1 kpc at $z$ | 0.124 arcsec | 0.17 arcsec | 0.23 arcsec |

# Distance Comparison



# Observed Supernovae Determine World Models

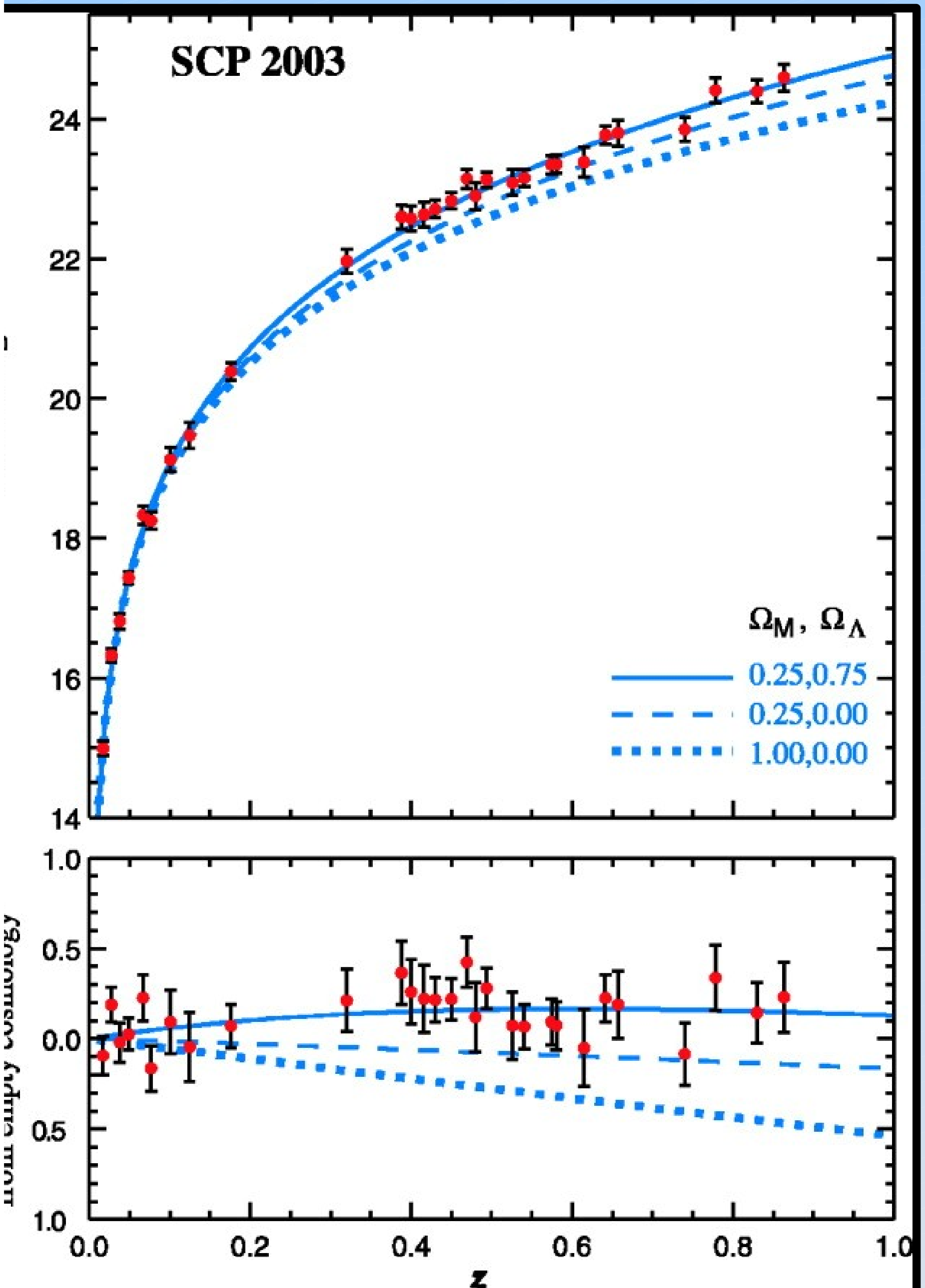




m-M ∝ log d_L (Luminosity-Dist.)
log z (Redshift)
Ω_Λ > 0 ?
Ω_M
0
0.3
1
>1
$f = \frac{L}{4\pi d_L^2}$
$d_L = \frac{c}{H_0} z$
for small z
$\Omega_M = \frac{\rho}{\rho_{crit}}$
$\Omega_\Lambda = \frac{\Lambda c^2}{3H_0^2}$
$\rho_{crit} = \frac{3H_0^2}{8\pi G}$

# Type Ia Supernovae
## (Knop et al. 2003)

How faint each object appears (when viewed from Earth)




≈ Distance

≈ Redshift

Redshift (amount universe “stretched” since the object’s light was emitted)

# Apparent Angular Diameter

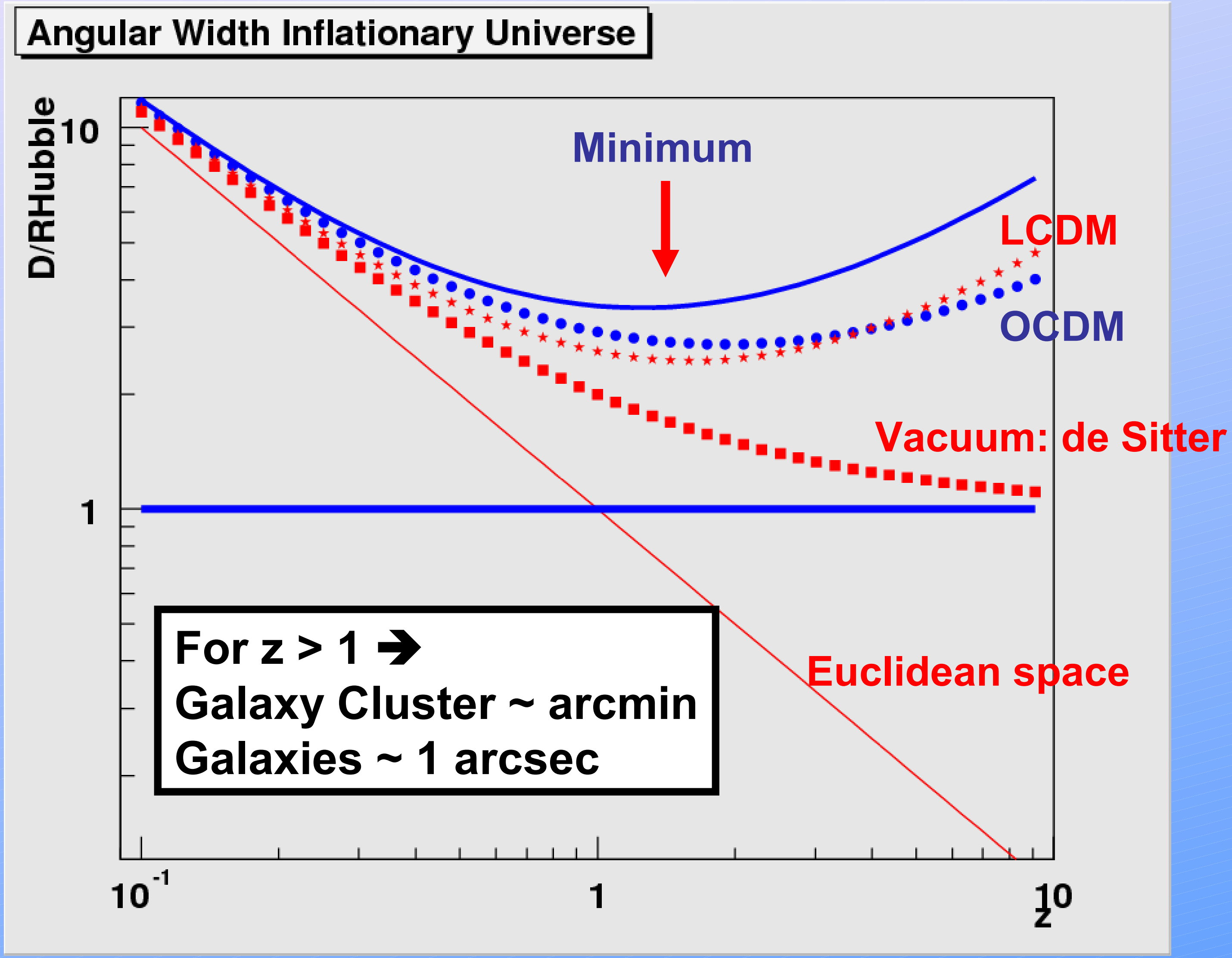
– Defined as $\theta = D / d_A = D\,(1+z)^2 / d_L$

- $D$ = physical Extension of the Object (Galaxy)
- $\theta$ = measured apparent angular diameter on Sky

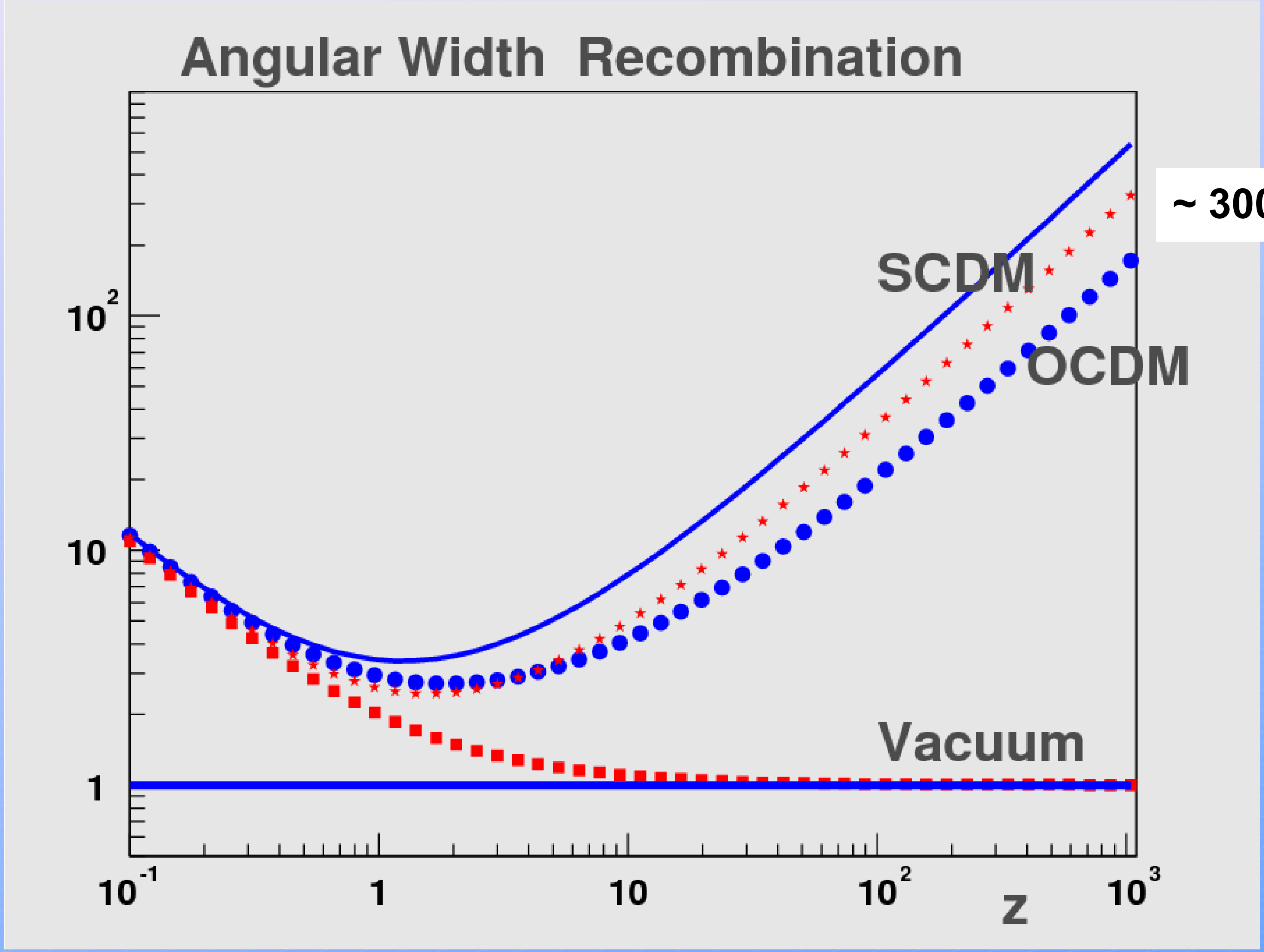
$$d_A = \frac{d_L}{(1+z)^2} = \frac{D_C(z)}{(1+z)}$$

**Since $d_L(z)$ increases in general less steeply than ~ $z^2$**
**➔ Angular Diameter reaches a Minimum @ z ~ 1,4 !!!!**

# Angular Diameter in Models

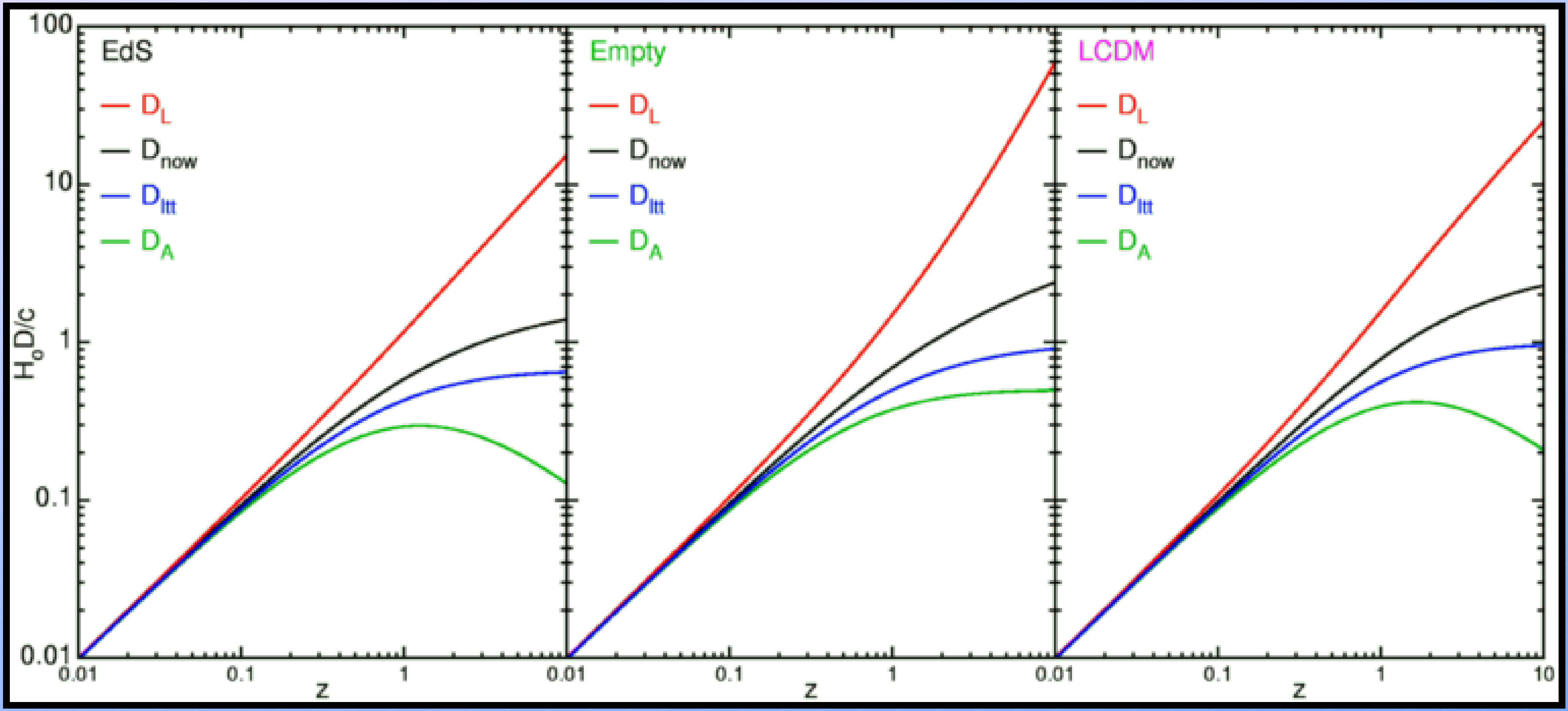


# Angular Diameter @ Recombination

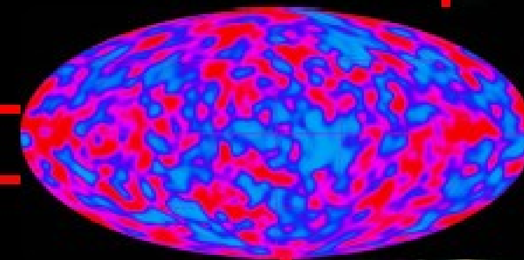



~ 300 $D/R_H$

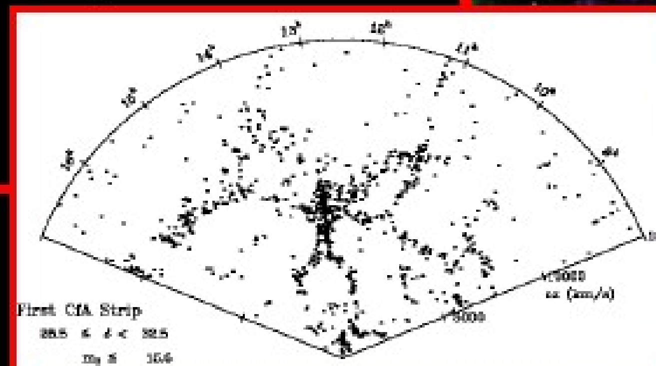
# Summary on Distances in Expanding Universe



# 1990s: Beginning of Data-driven Cosmology



- COBE! and CMB experiments
- Redshift surveys (CfA, IRAS, 2dF, SDSS)
- Large-scale velocity field measurements
- Gravitational lensing
- Big telescopes (Keck, …) with big CCD cameras
- X-ray, gamma-ray, IR, …




**E.L. Wright: Constraints … 2007: arXiv:0701.584**

# Physical Observables Probing Dark Energy

1. **Luminosity distance vs. redshift:** $d_L(z)$ $m(z)$

**Standard candles: SNe Ia**

**[2. Angular diameter distance vs. z:** $d_A(z)$

**Alcock-Paczynski test: Ly-alpha forest; redshift correlations]**

**3. Number counts vs. redshift:** $N(M,z)$

**probes:**

***Comoving Volume element** $dV/dz\, d\Omega$

***Growth rate of density perturbations** $\delta(z)$

**Counts of galaxy halos and of clusters; QSO lensing**

# Use Luminosity Distance

**Basic assumption:**
**homogeneous and isotropic Universe**
➔
**Null geodesics in Friedmann-Robertson-Walker metric:**

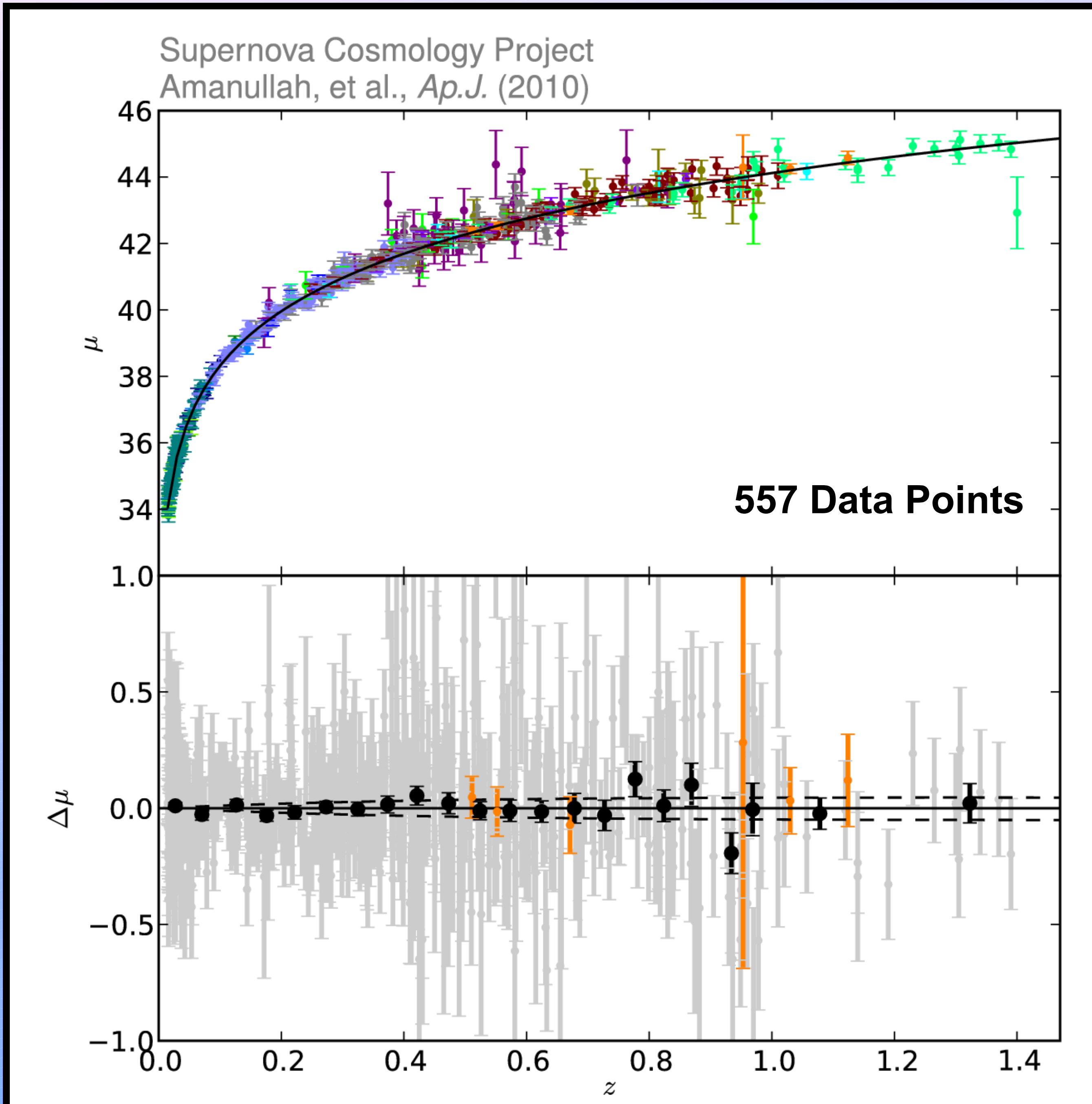
$$D_L = \frac{(1+z)c}{H_0\sqrt{|\Omega_\kappa|}} S\left\{ \sqrt{|\Omega_\kappa|} \int_0^z \left[ \Omega_\kappa (1+z')^2 + \Omega_M (1+z')^3 + \Omega_\Lambda \right]^{-1/2} dz' \right\}$$

$$\Omega_M = \frac{8\pi G}{3H_0^2}\rho_M \qquad \Omega_k = -\frac{kc^2}{R^2H_0^2} \qquad \Omega_\Lambda = \frac{\Lambda c^2}{3H_0^2}$$

**$\Omega_M$: Matter Density** **$\Omega_k$: Curvature** **$\Omega_\Lambda$: Cosmological Constant**

# Hubble Diagram SNe Ia

## $\mu = 5 \log(D_L/\mathrm{Mpc}) + 25$

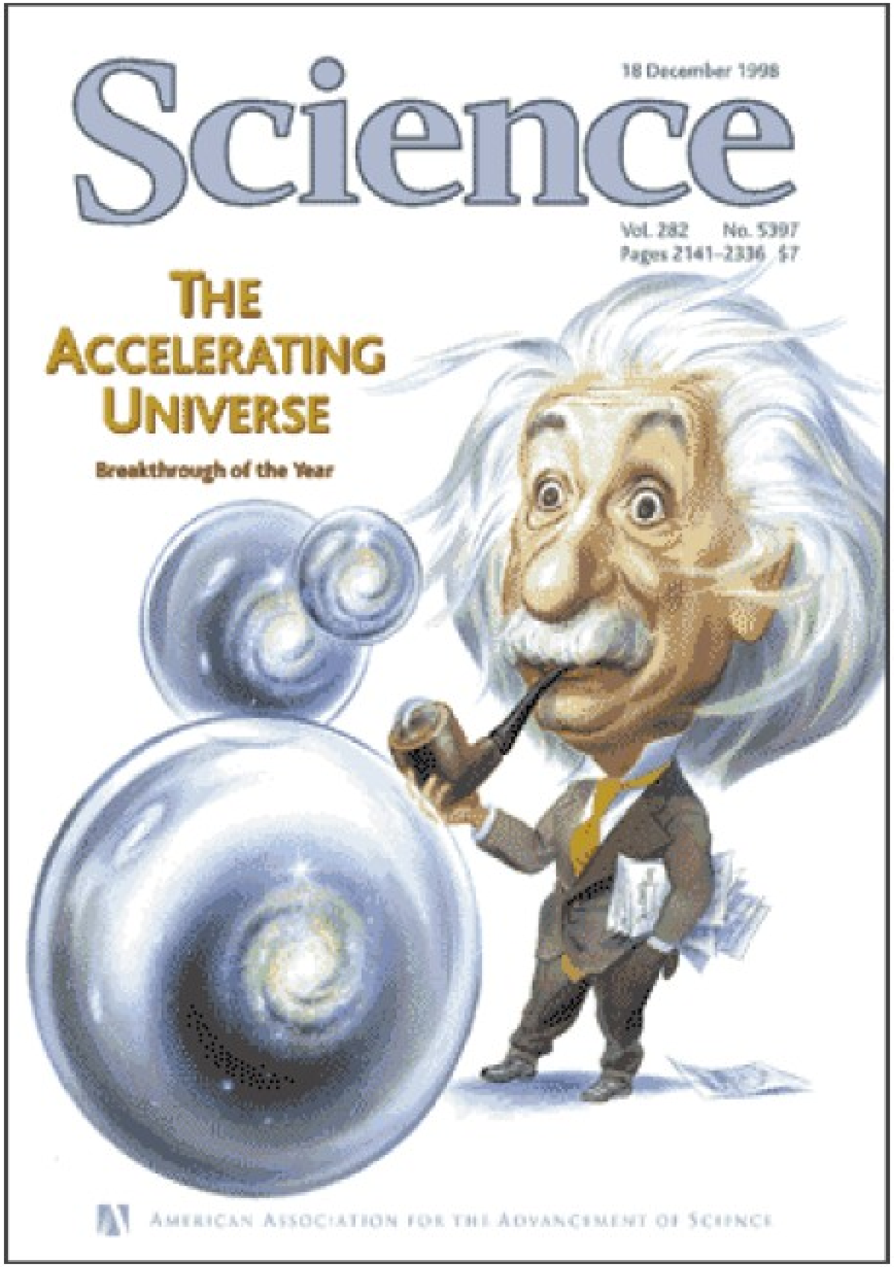


# Accelerating Universe: 1998

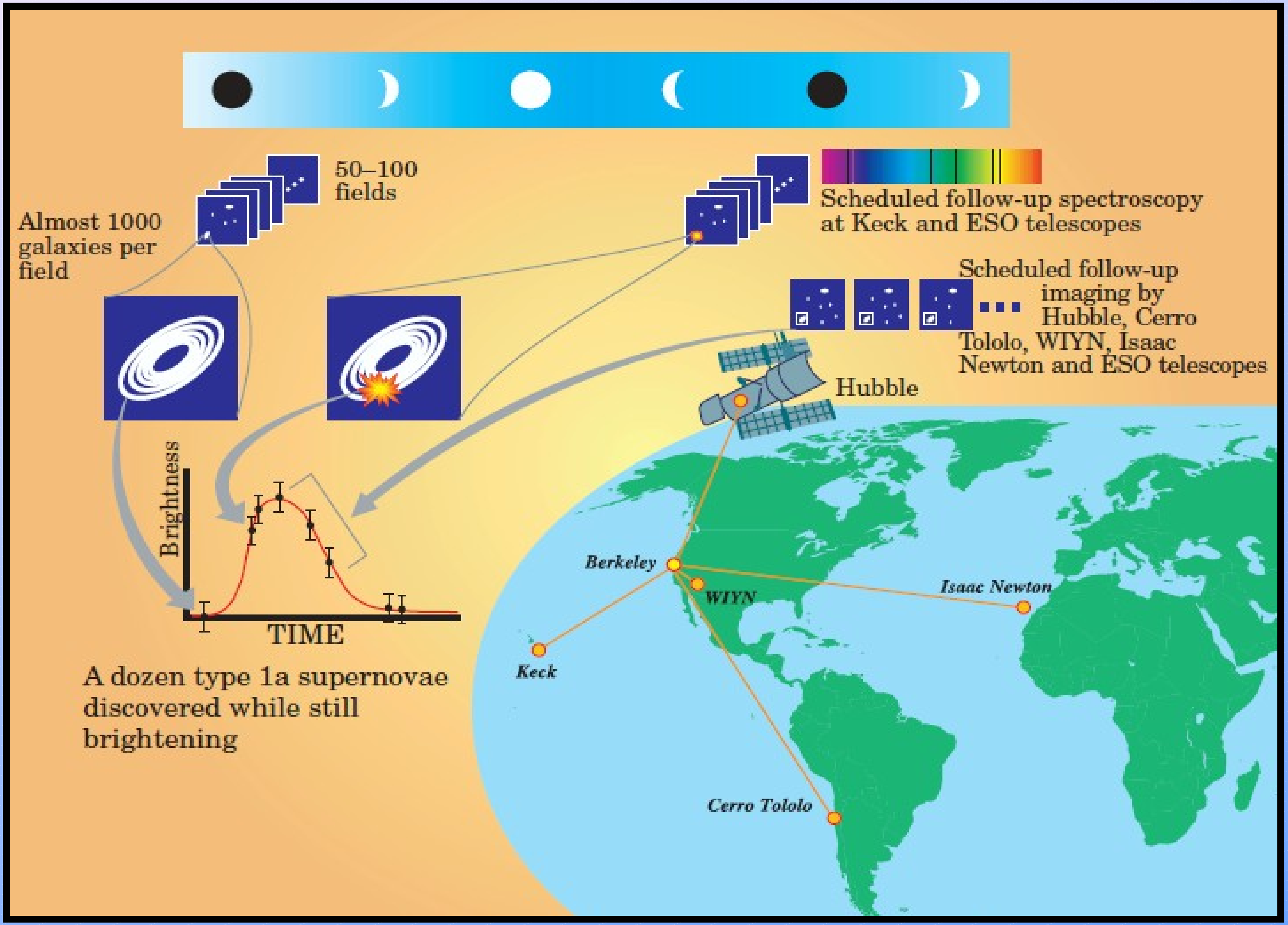
Distant (high z) supernovae fainter than expected.

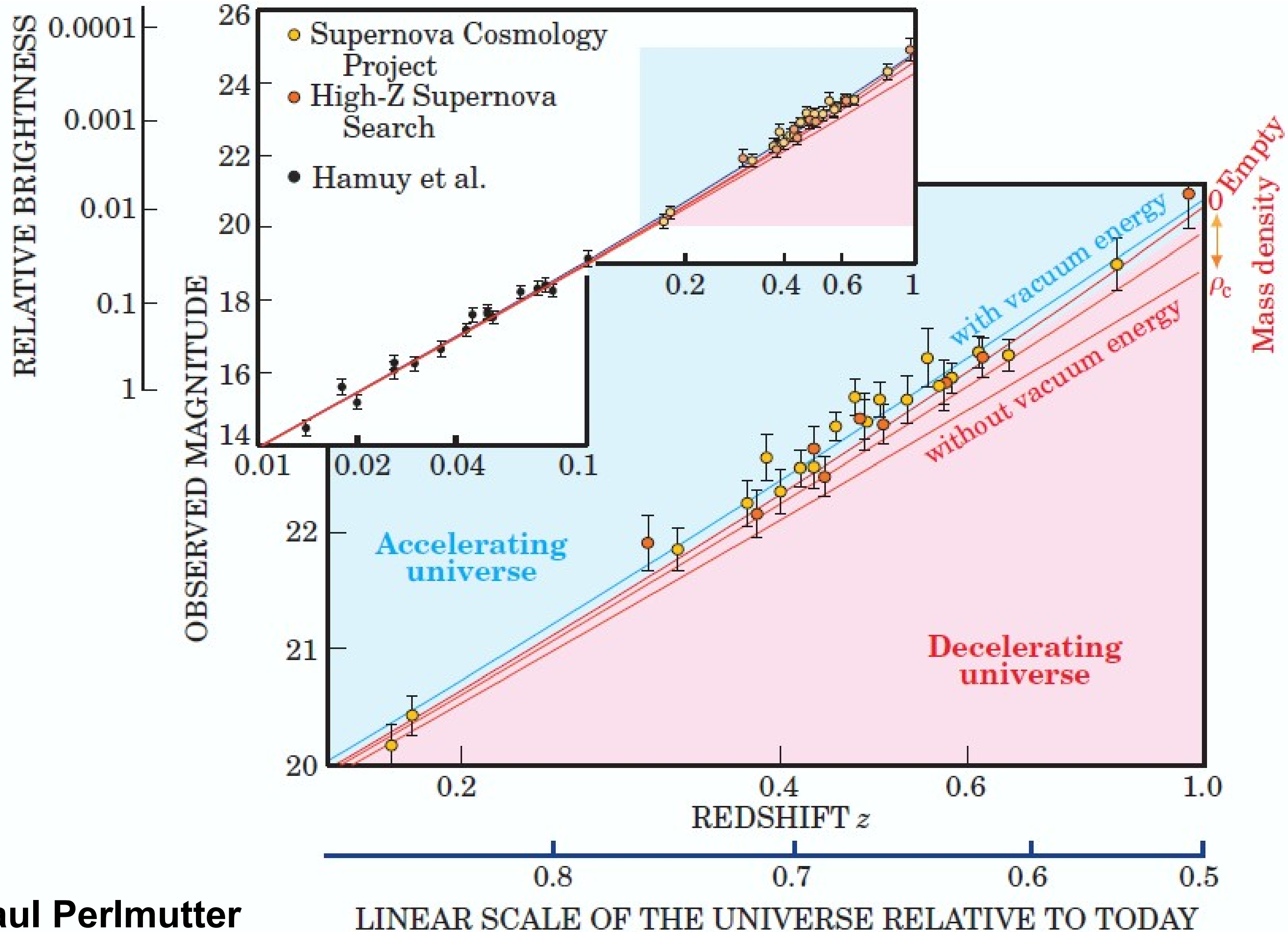
This was the AAAS discovery of the year in 1998.

$\Lambda$ causes acceleration!



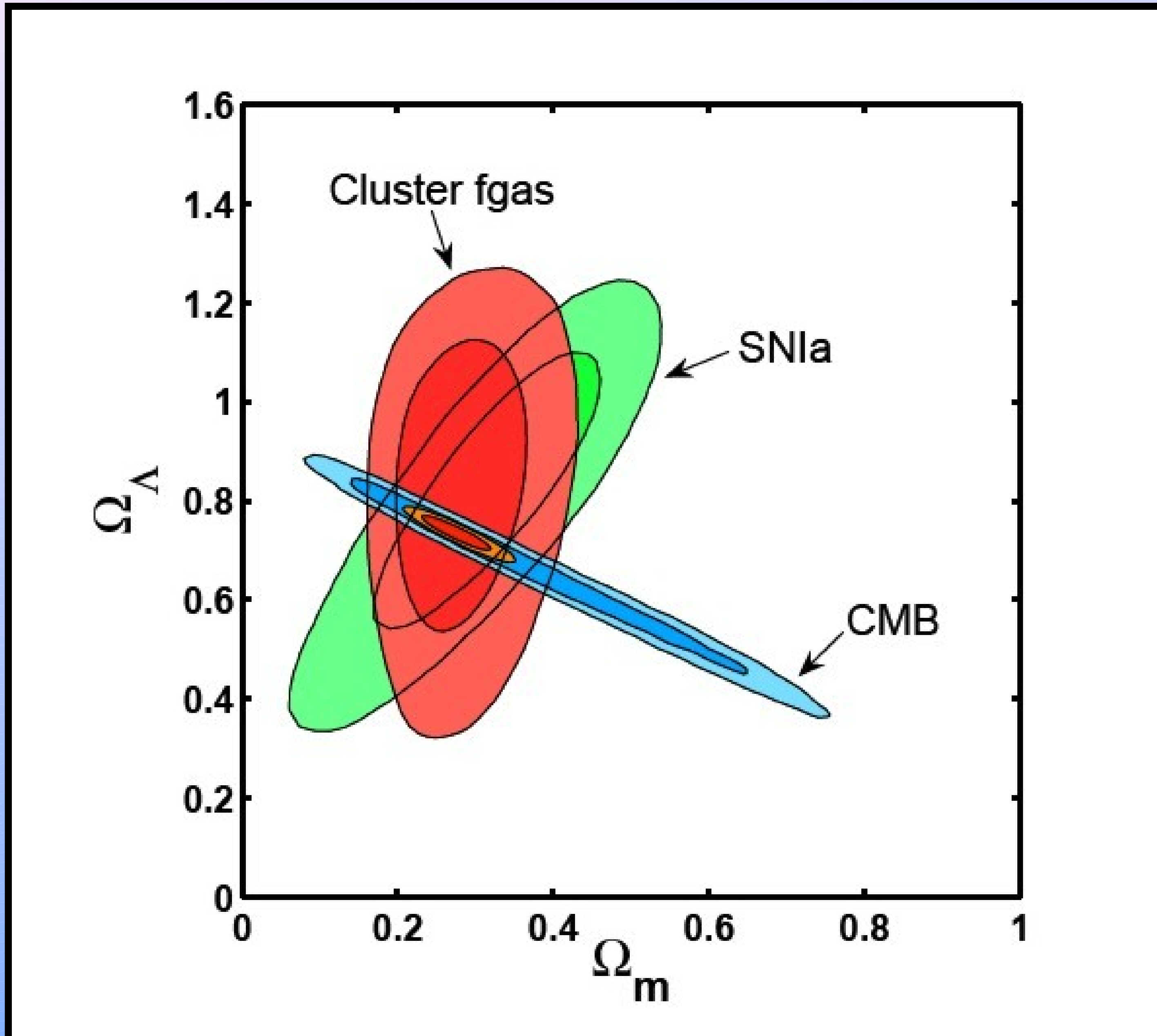
# Observing Strategy 1998



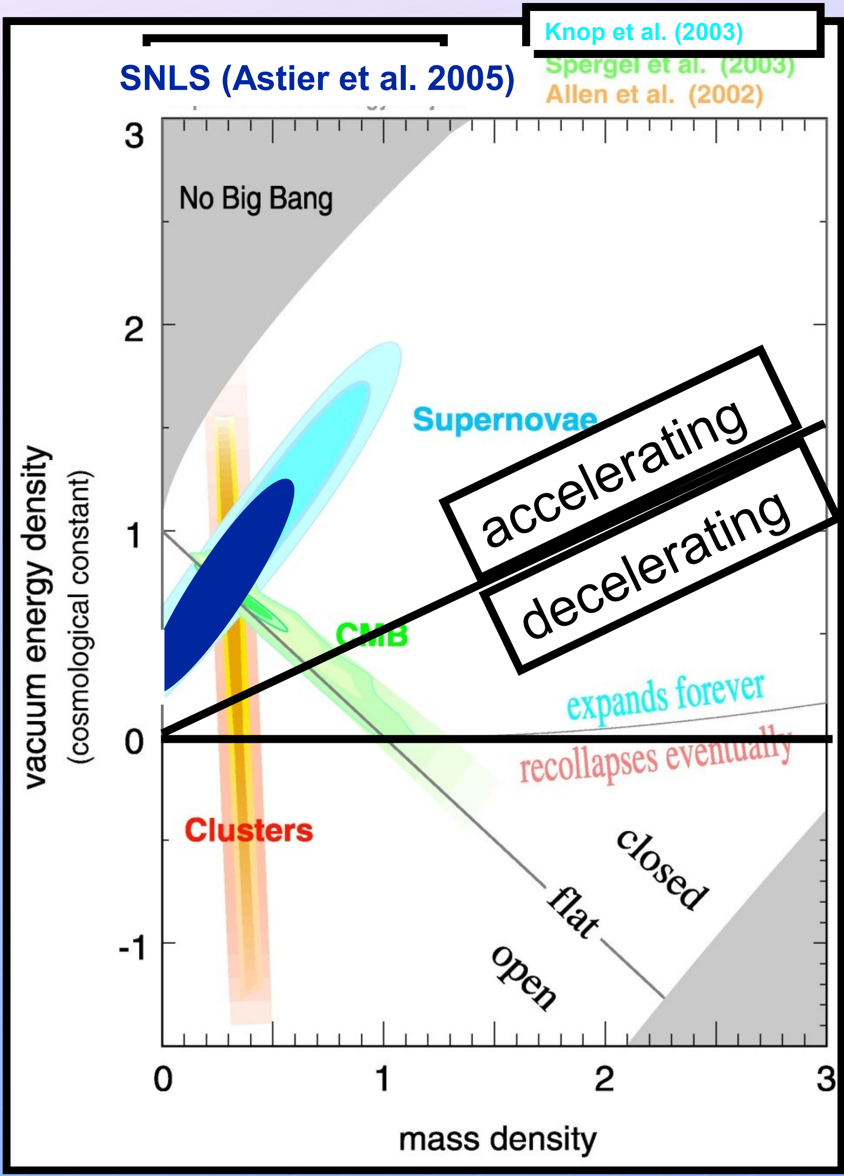



**Saul Perlmutter**
**Physics Today 1998**

# Fundamental Plane of Cosmology



# Concordance Model $\Omega_k=0$




- *Supernovae alone*

  ⇒ **Accelerating expansion**

  ⇒ **$\Lambda$ > 0**

- *CMB (plus LSS)*

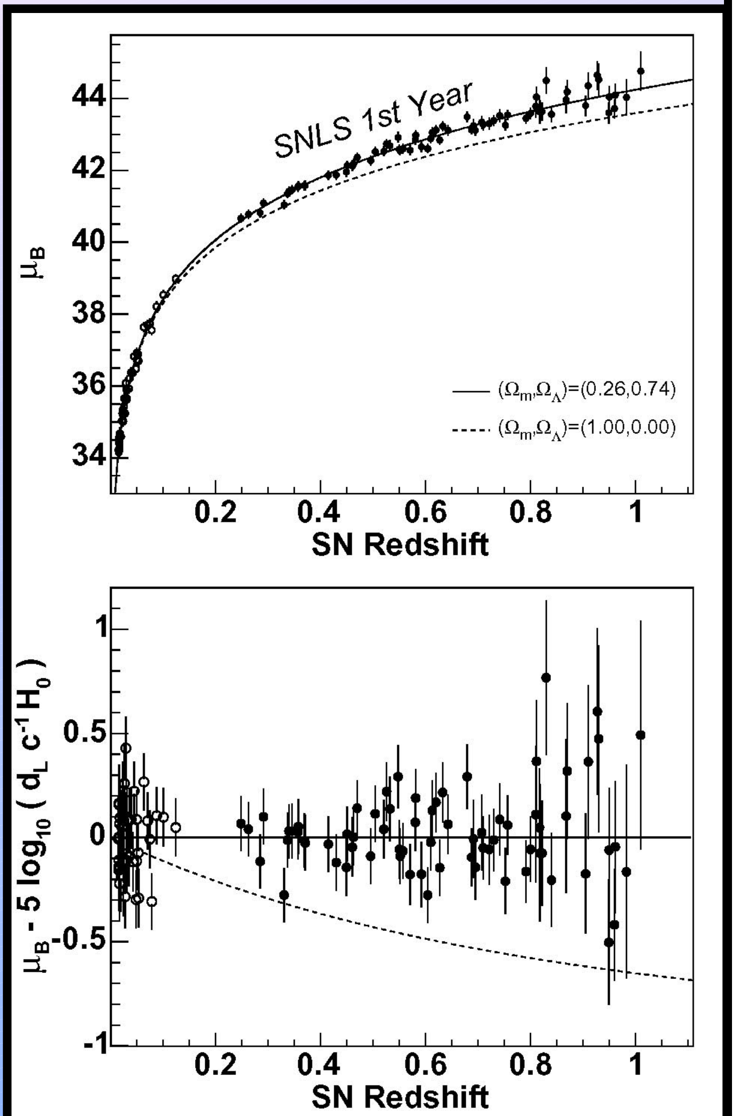
  ⇒ **Flat universe**

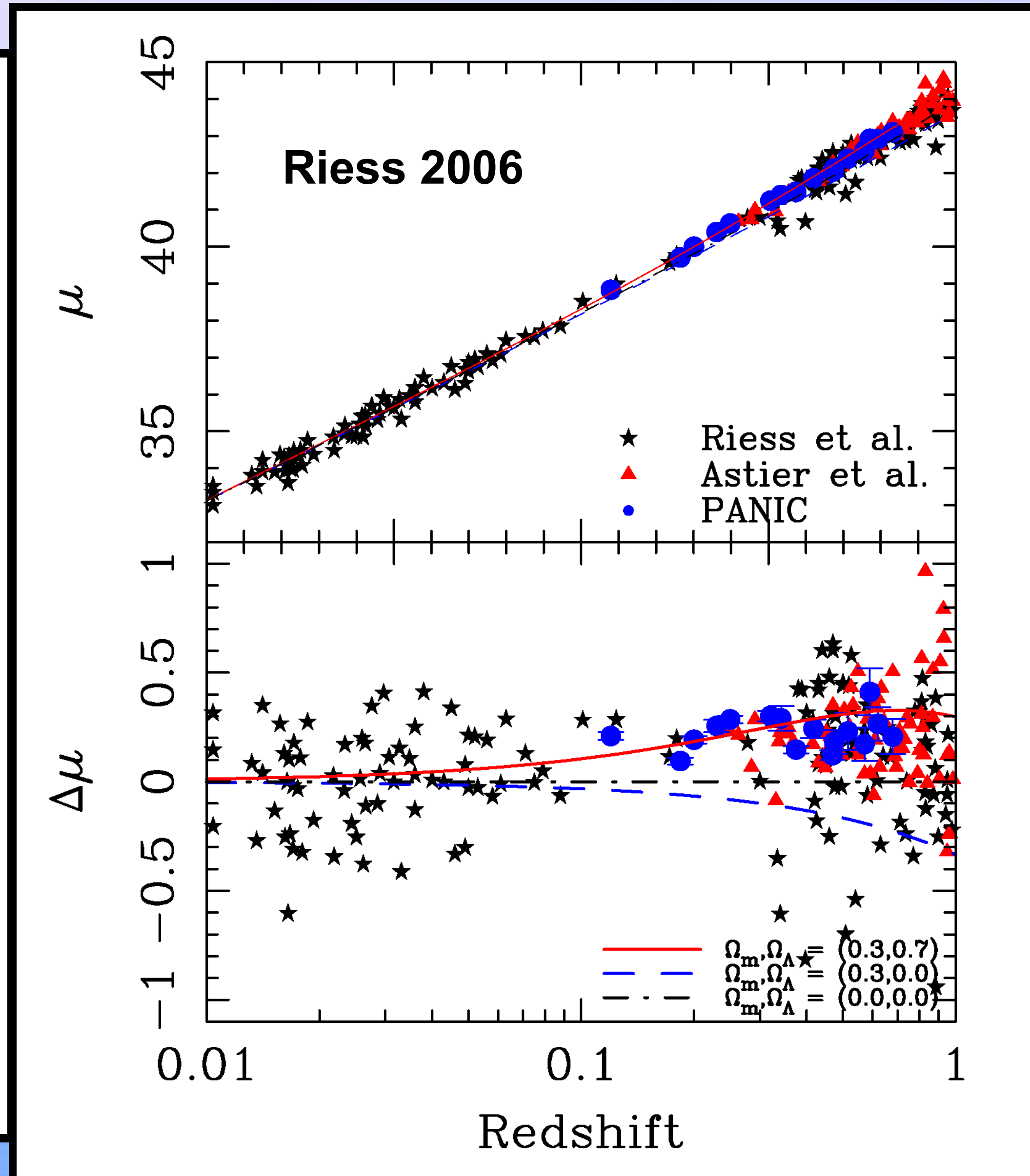
  ⇒ **$\Lambda$ > 0**

- *Any two of SN, CMB, LSS*

  ⇒ **Dark energy ~75%**

# Hubble Diagram SNe Ia - 2006



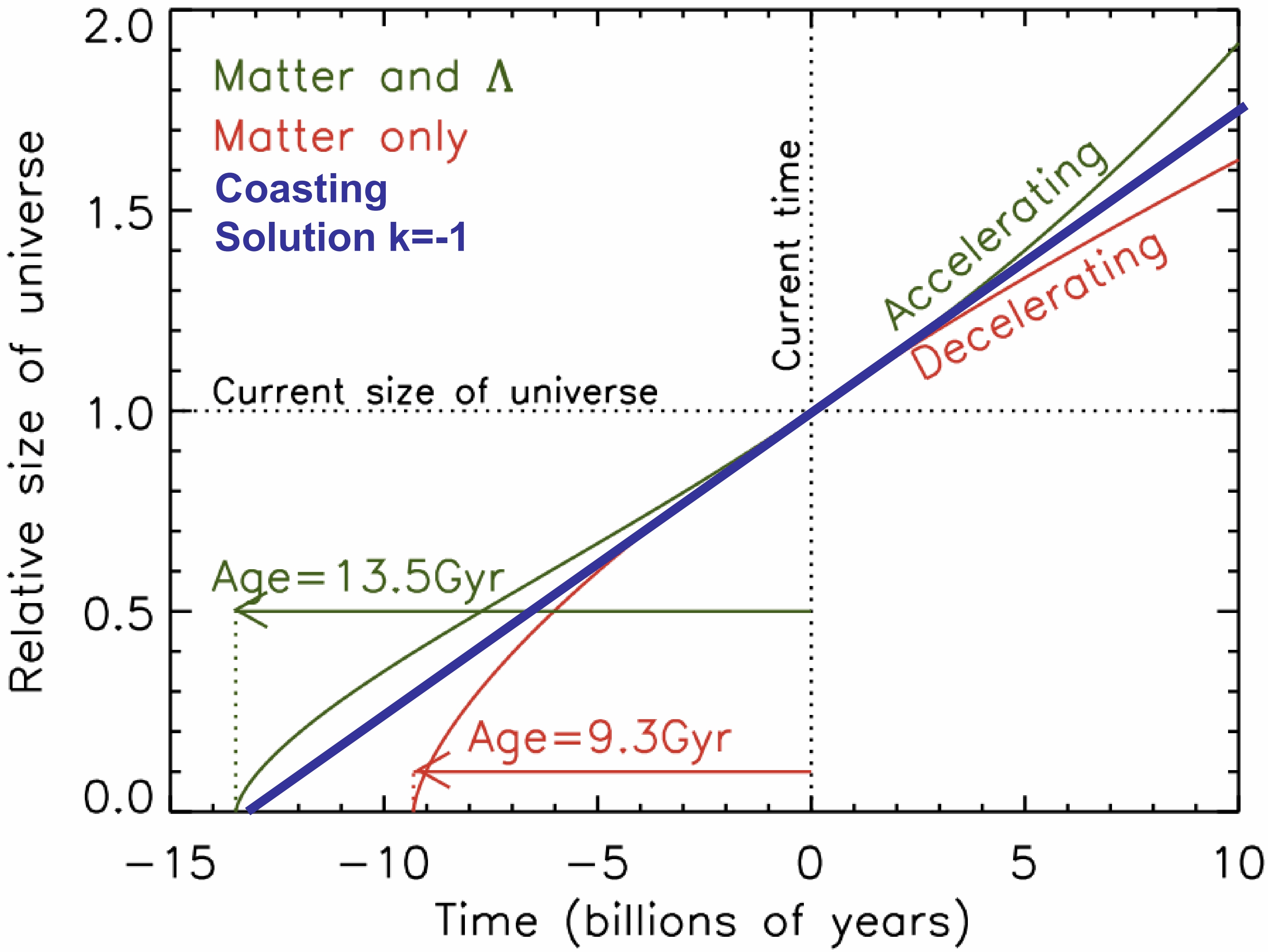



# Coasting Universe – a Reference Model k = -1

$(\dot{a}/a)^2 = H_0^2 \, ( \Omega_k \, / \, a^2 )$ ; $\Omega_k = - \, k R_H^2 / R_0^2$

➔ $a(t) = R_0 \, (t/t_0)$ : linear

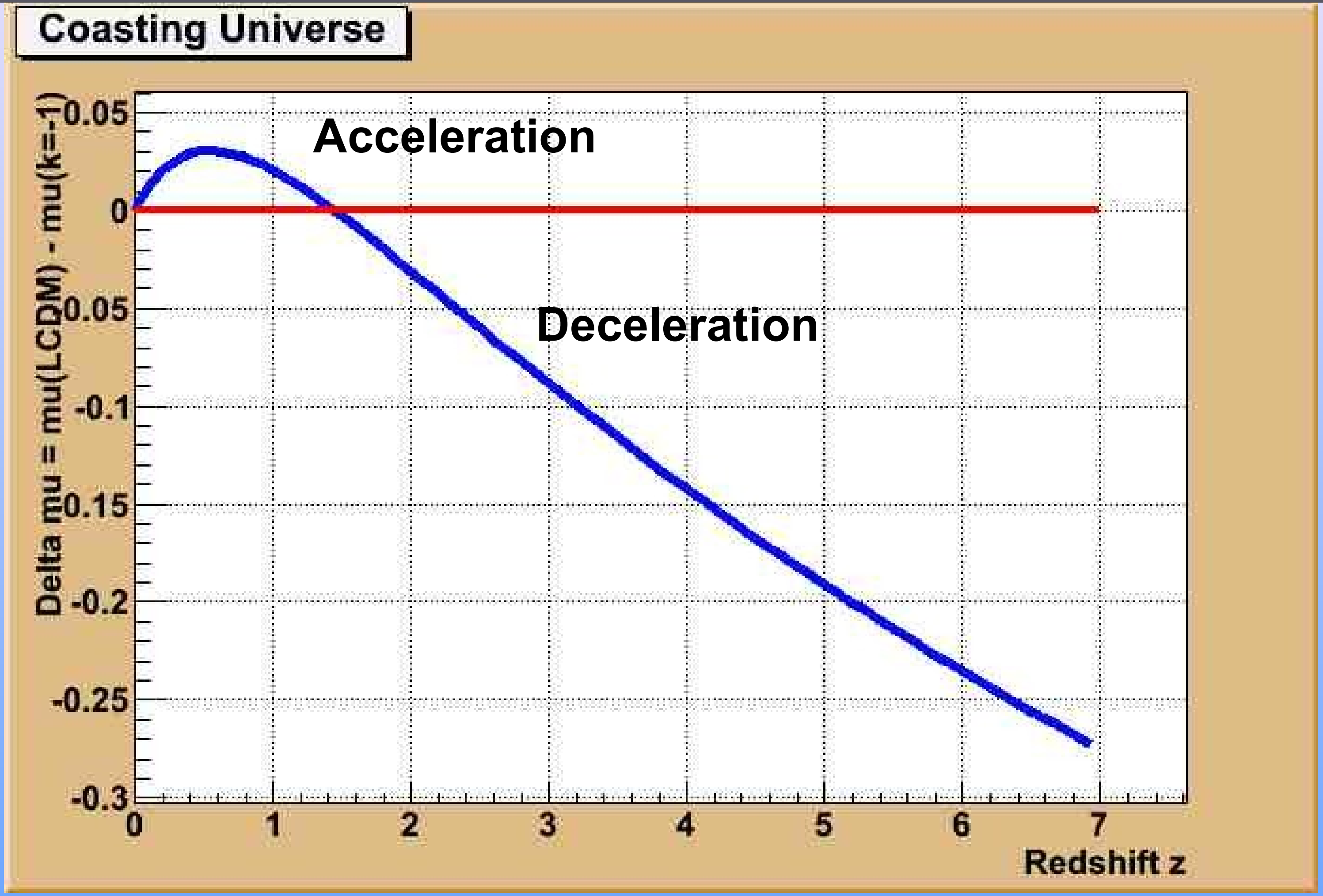
➔ $d_L(z) = (c/H_0) \, (z + z^2/2)$



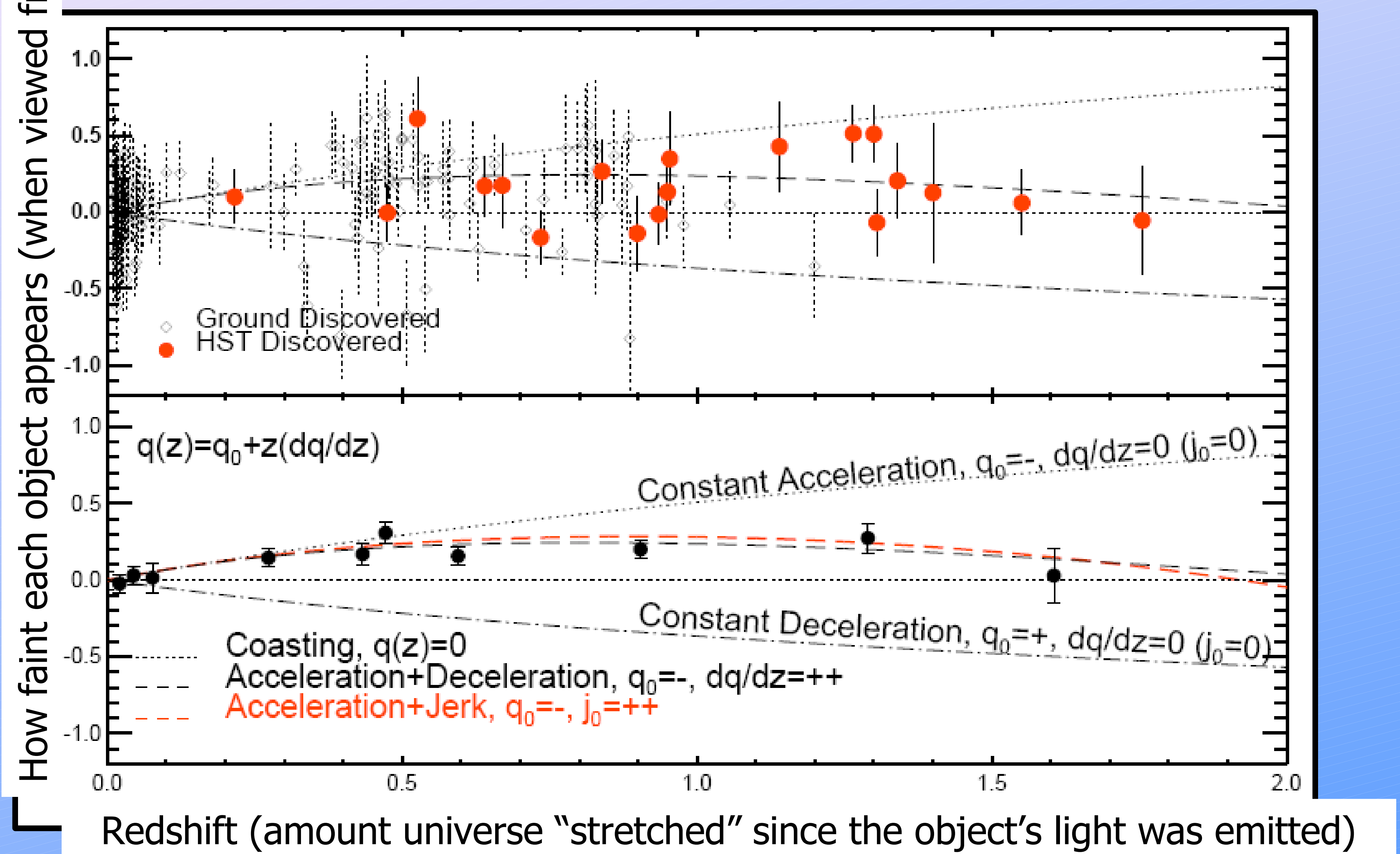
Matter and Λ
Matter only
Coasting
Solution k=-1
Current time
Current size of universe
Accelerating
Decelerating
Age=13.5Gyr
Age=9.3Gyr
Relative size of universe
0.0
0.5
1.0
1.5
2.0
−15
−10
−5
0
5
10
Time (billions of years)

# Coasting Universe – Ref Model

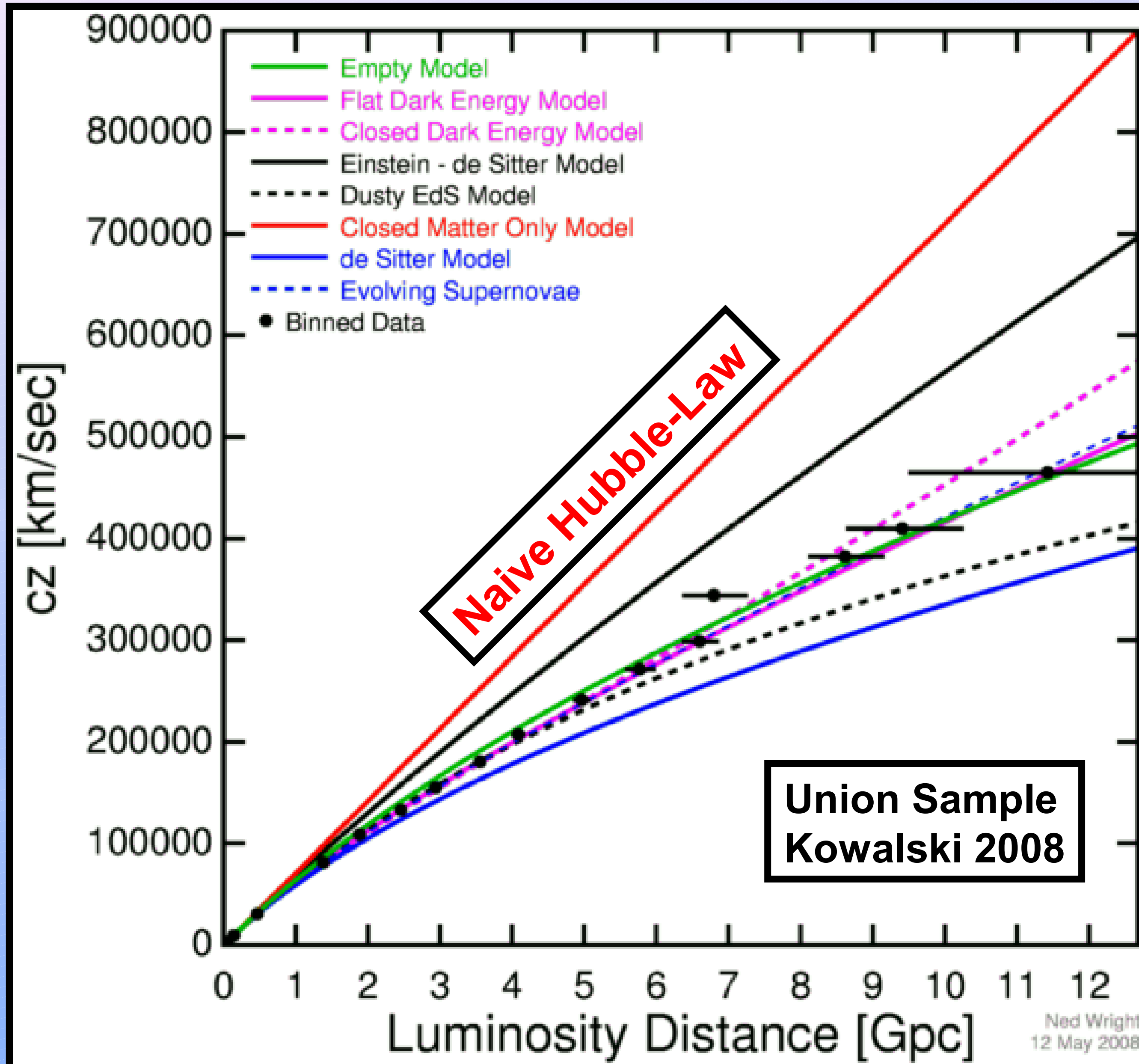
## Neither Acceleration nor Deceleration



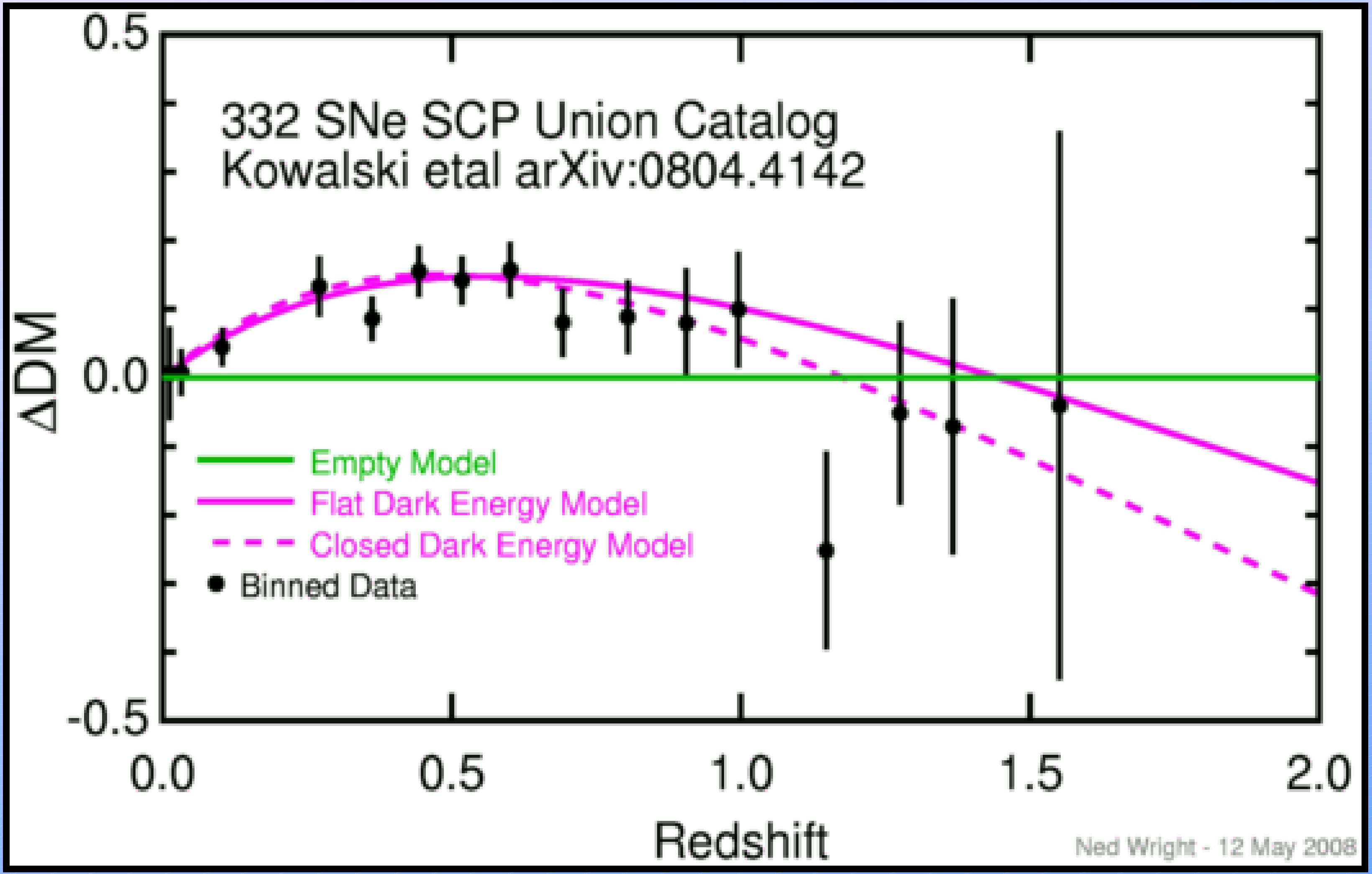
# Type Ia Supernovae
## (Riess et al. 2006)



# Observed Supernovae Determine World Models

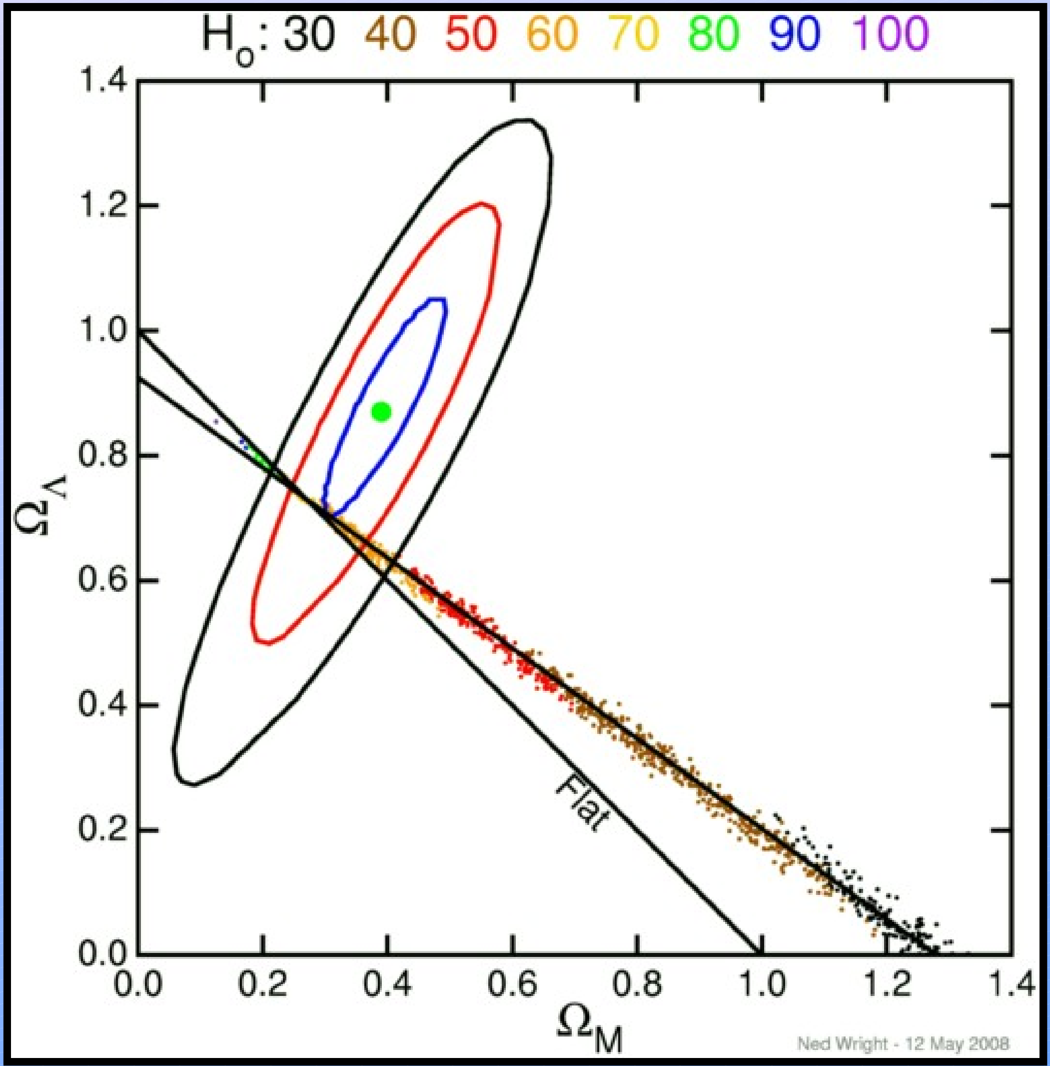


# Hubble Diagram SNe Ia 2008

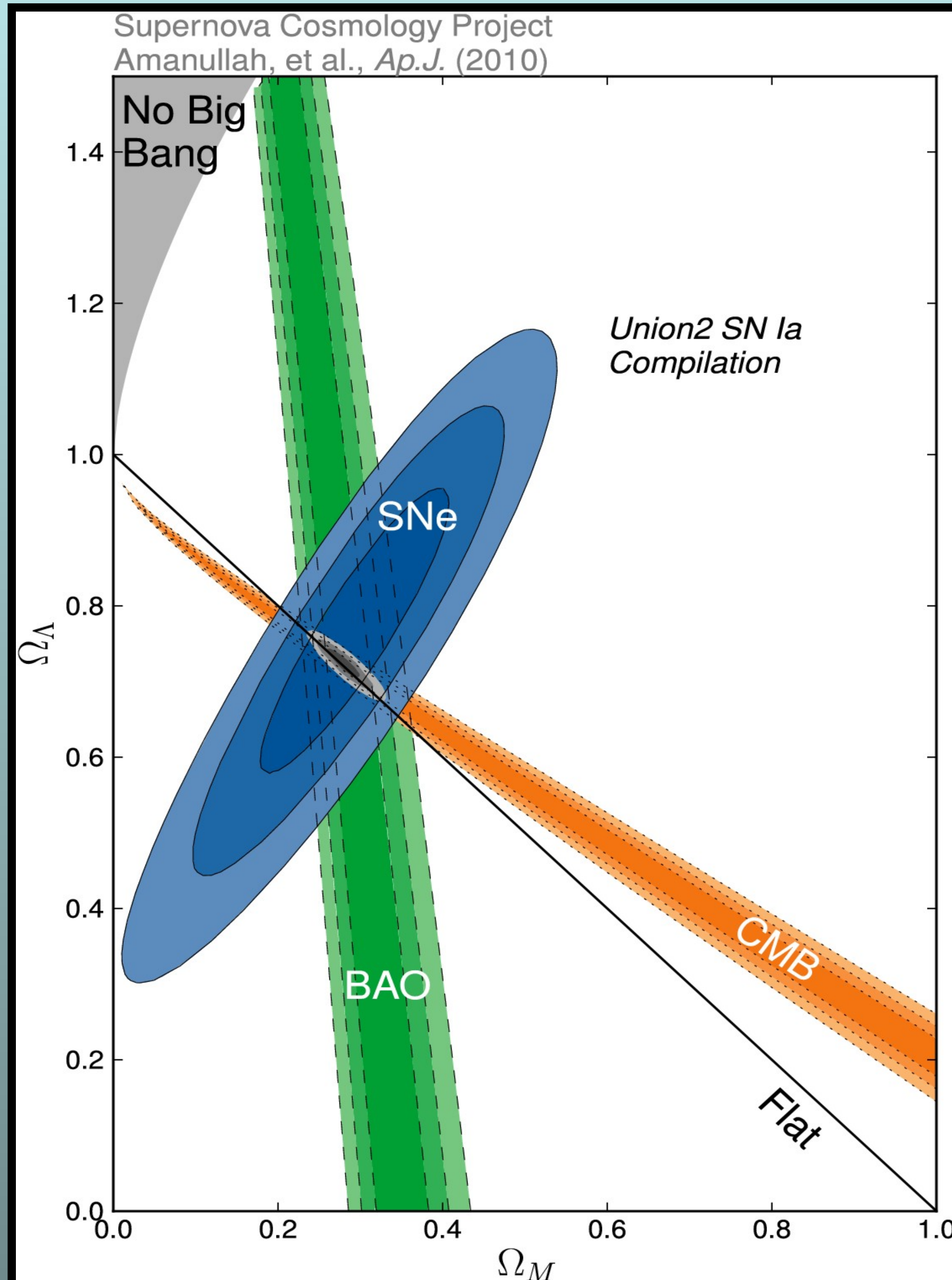


# Union Sample 2008

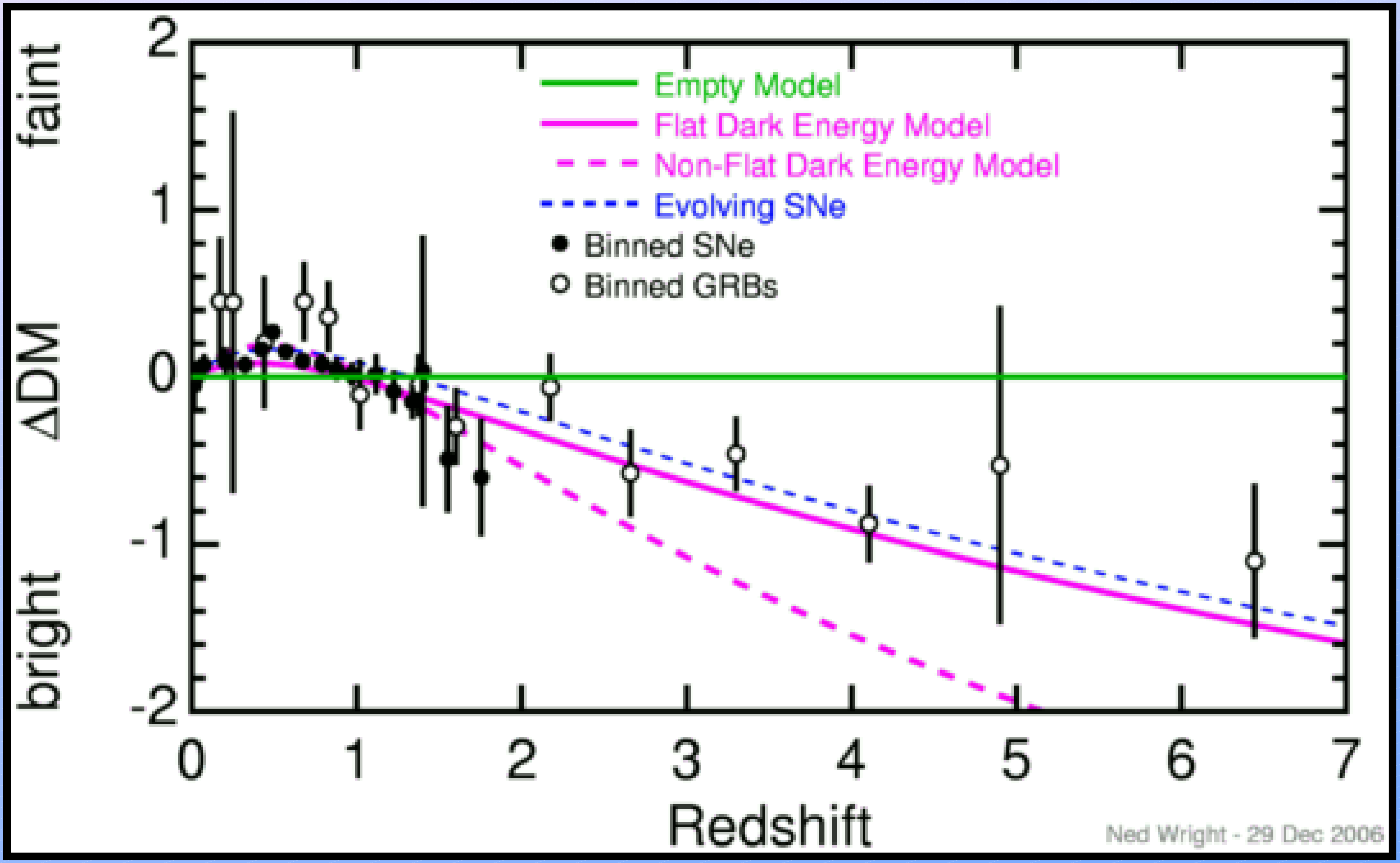
**The addition of high redshift supernovae has had two effects on the supernova error ellipse. The long axis of the ellipse has gotten shorter, and the slope of the ellipse has gotten higher. The best fit model has gotten closer to the CMB degeneracy track in absolute terms, and it has also gotten closer in terms of standard deviations in the Kowalski *et al.* *(2008)* dataset.**



# Fundamental Plane
# SNe Ia – 2010
## SCP Union2 Sample – 557 SNe
## Amanullah et al. 2010

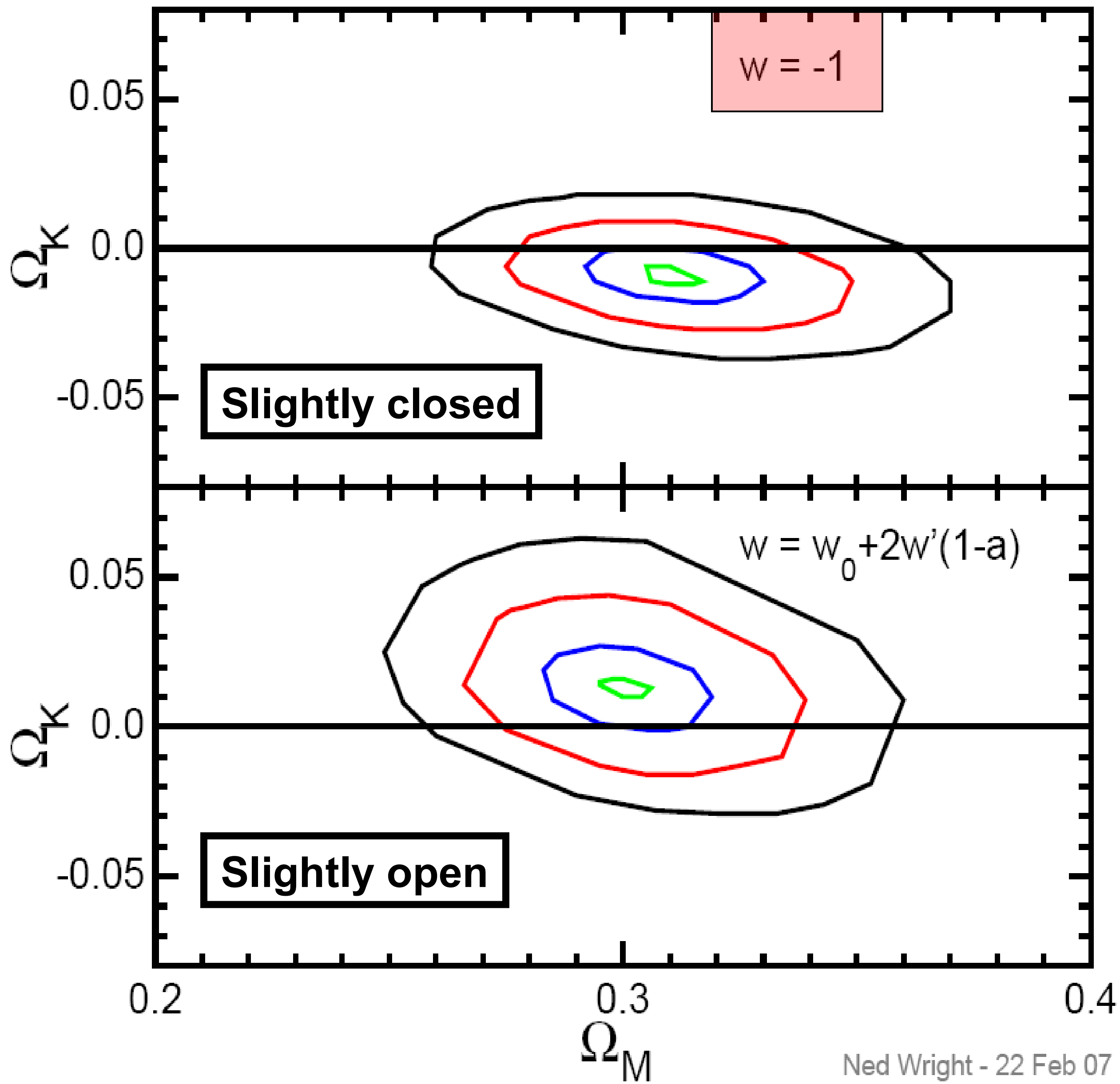


# GRBs in Expanding Universe



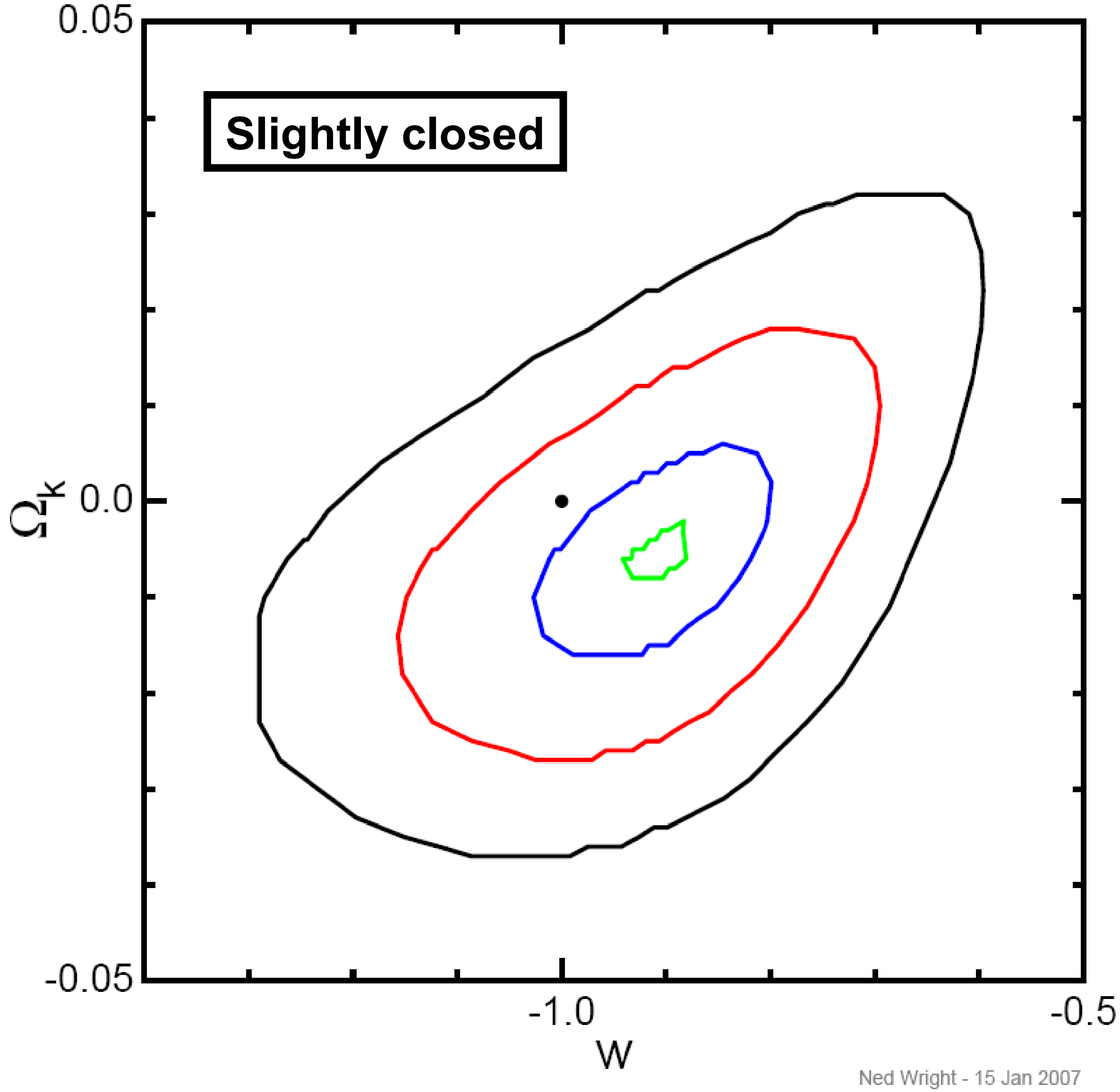

**Data: Schaefer 2006**

# Curvature Constraints



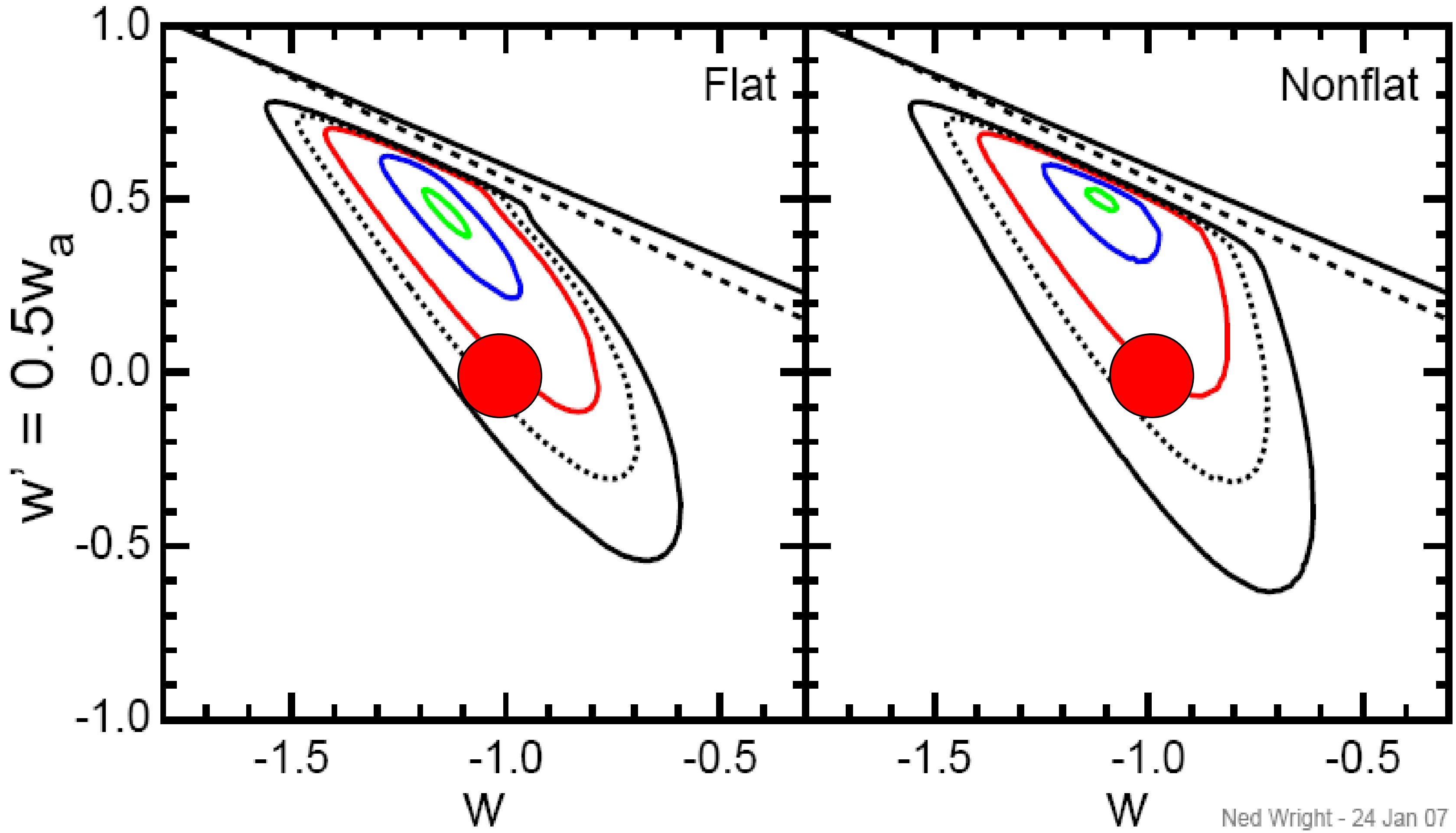

**Wright 2007**

# Curvature vs DE Constraints

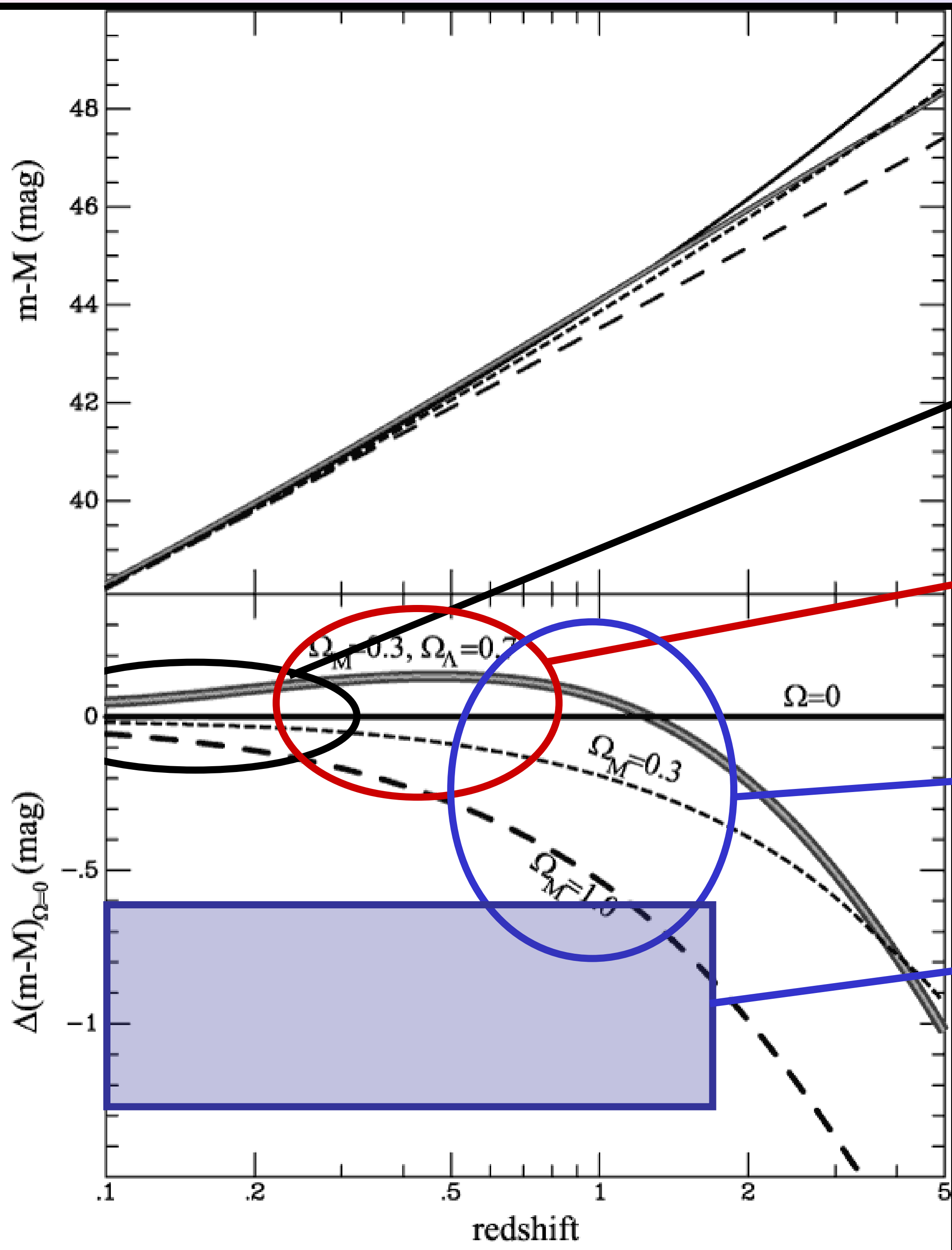



**Wright 2007**

# Constraints on Vacuum EoS



# Supernova Projects




**SN Factory**
**Carnegie SN Project**
**SDSSII**

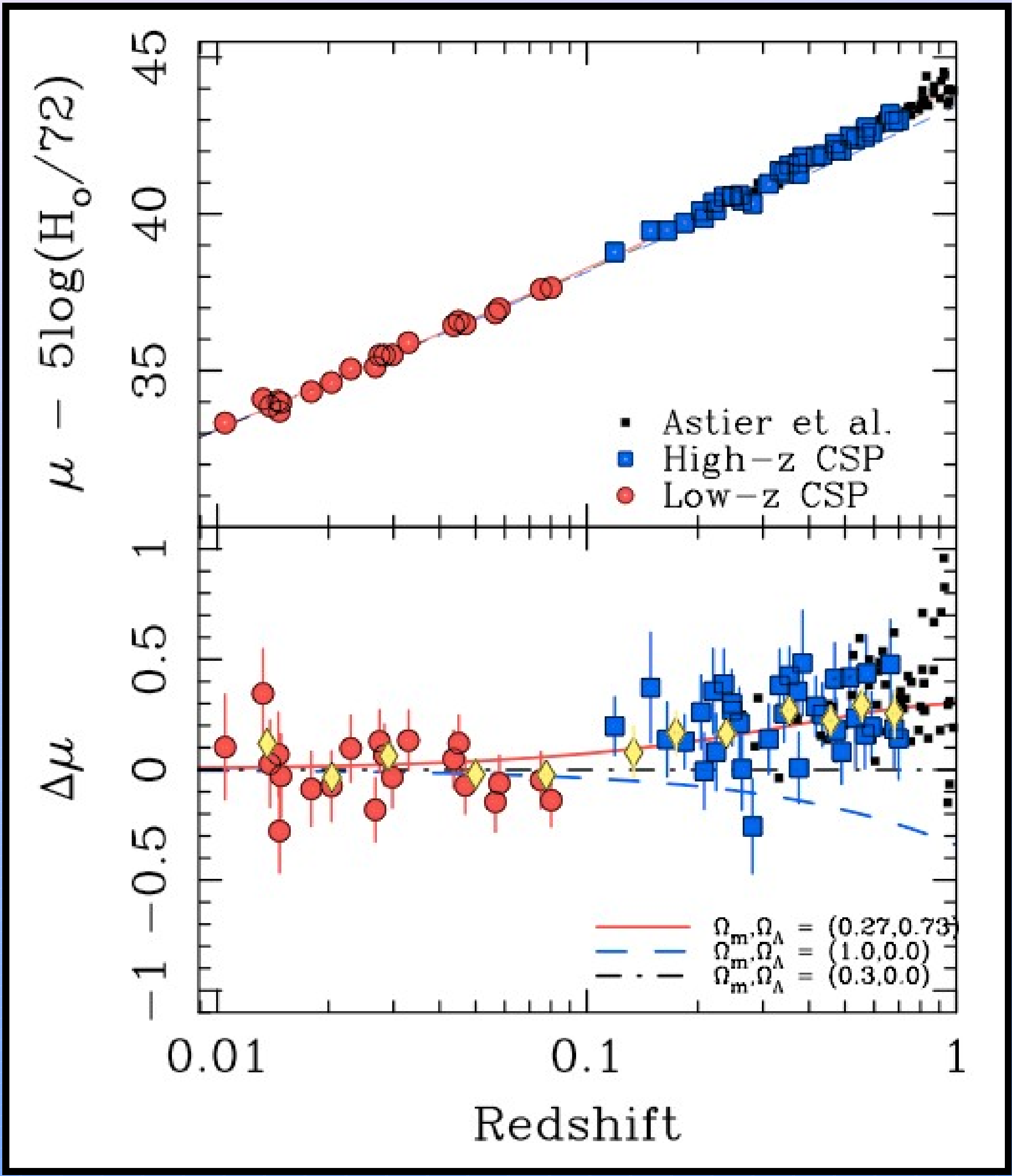
**ESSENCE**
**CFHT Legacy Survey**

**Higher-z SN Search (GOODS)**

**JDEM/LSST**

**Plus the local searches: LOTOSS, CfA, ESC**

# Carnegie SN Project - Hubble Diagram to z ~ 0.7



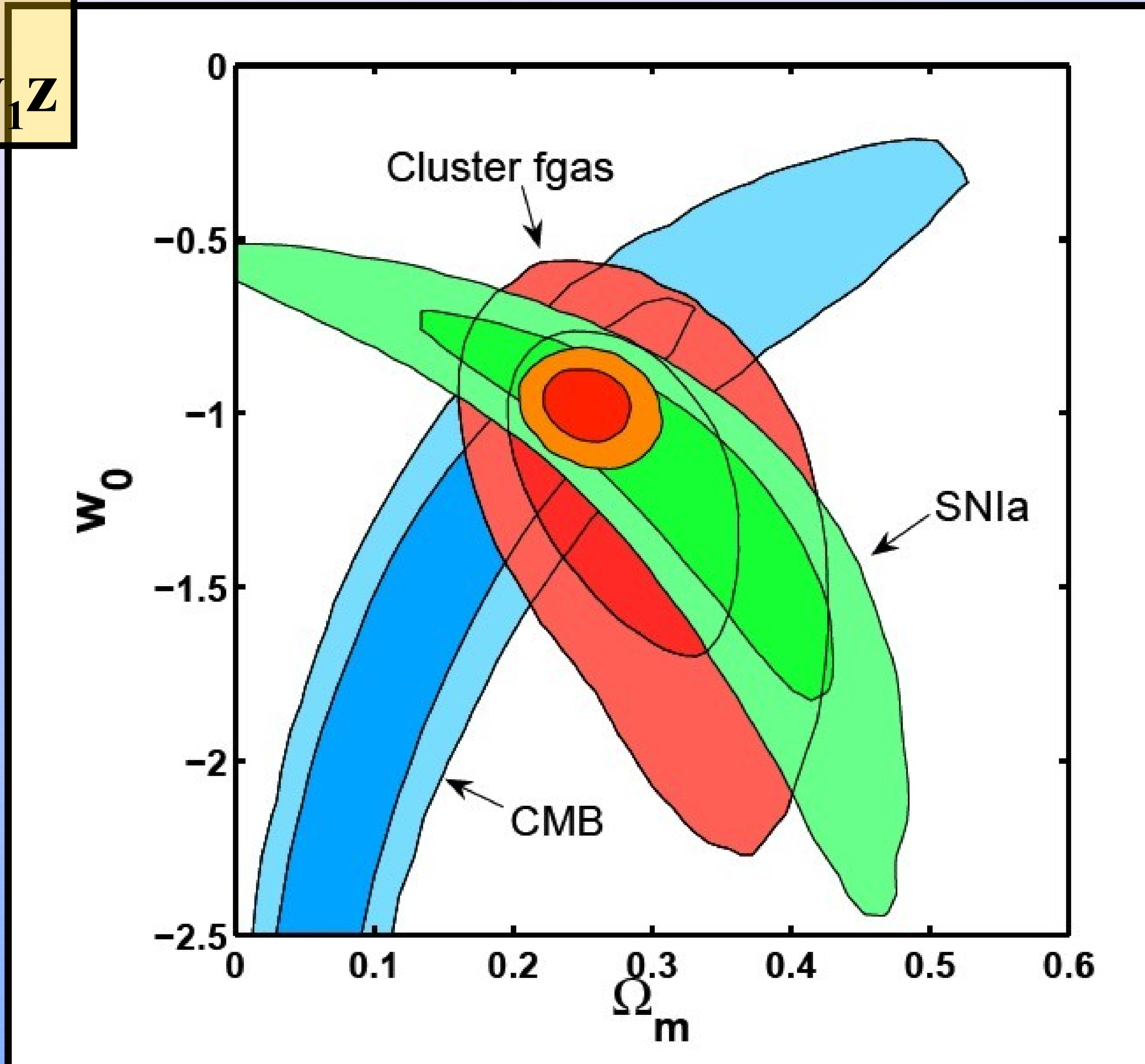
# Essence

- World-wide collaboration to find and characterise SNe Ia with $0.2 < z < 0.8$
- Search with CTIO 4m Blanco telescope.
- Spectroscopy with VLT, Gemini, Keck, Magellan
- Goal: Measure distances to 200 SNe Ia with an overall accuracy of 5%
  → determine w to 10% overall.

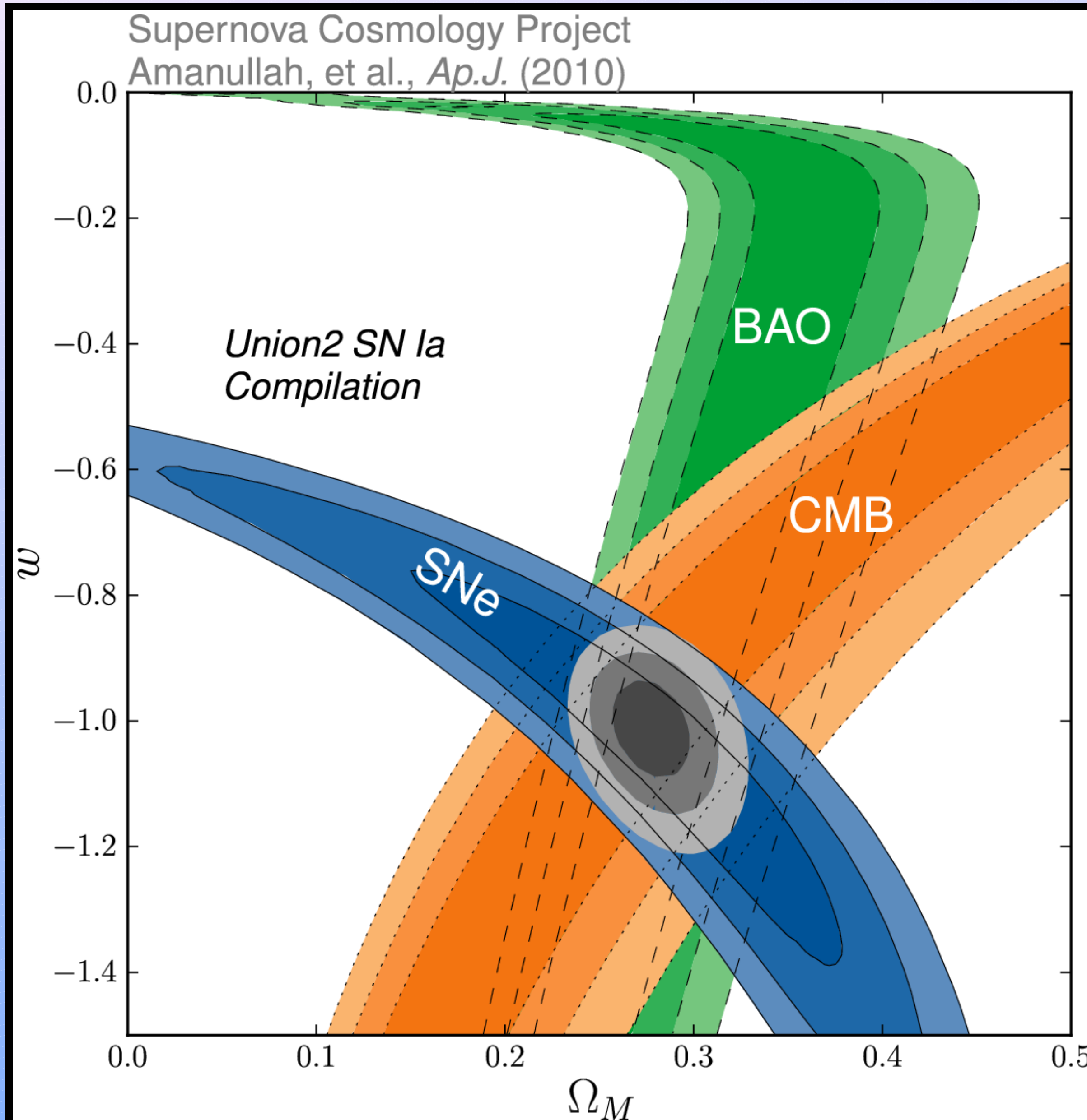
$$P_V = w\,\rho_V$$

$$w \sim w_0 + w_1 z$$

# Is Dark Energy Vacuum Energy ?



# Is Dark Energy Vacuum Energy ?



# WMAP – 7 Years Results

- **Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations**: Sky Maps, Systematic Errors, and Basic Results
  Jarosik, N., et.al., 2010, ApJSup, astro-ph
- **Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations**: Galactic Foreground Emission
  Gold, B., et.al., 2010, ApJSup, astro-ph
- **Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations**: Power Spectra and WMAP-Derived Parameters
  Larson, D., et.al., 2010, ApJSup, astro-ph
- **Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations**: Are There Cosmic Microwave Background Anomalies?
  Bennett, C., et.al., 2010, ApJSup, astro-ph
- **Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations**: **Cosmological Interpretation**
  Komatsu, E., et.al., 2010, ApJSup, astro-ph

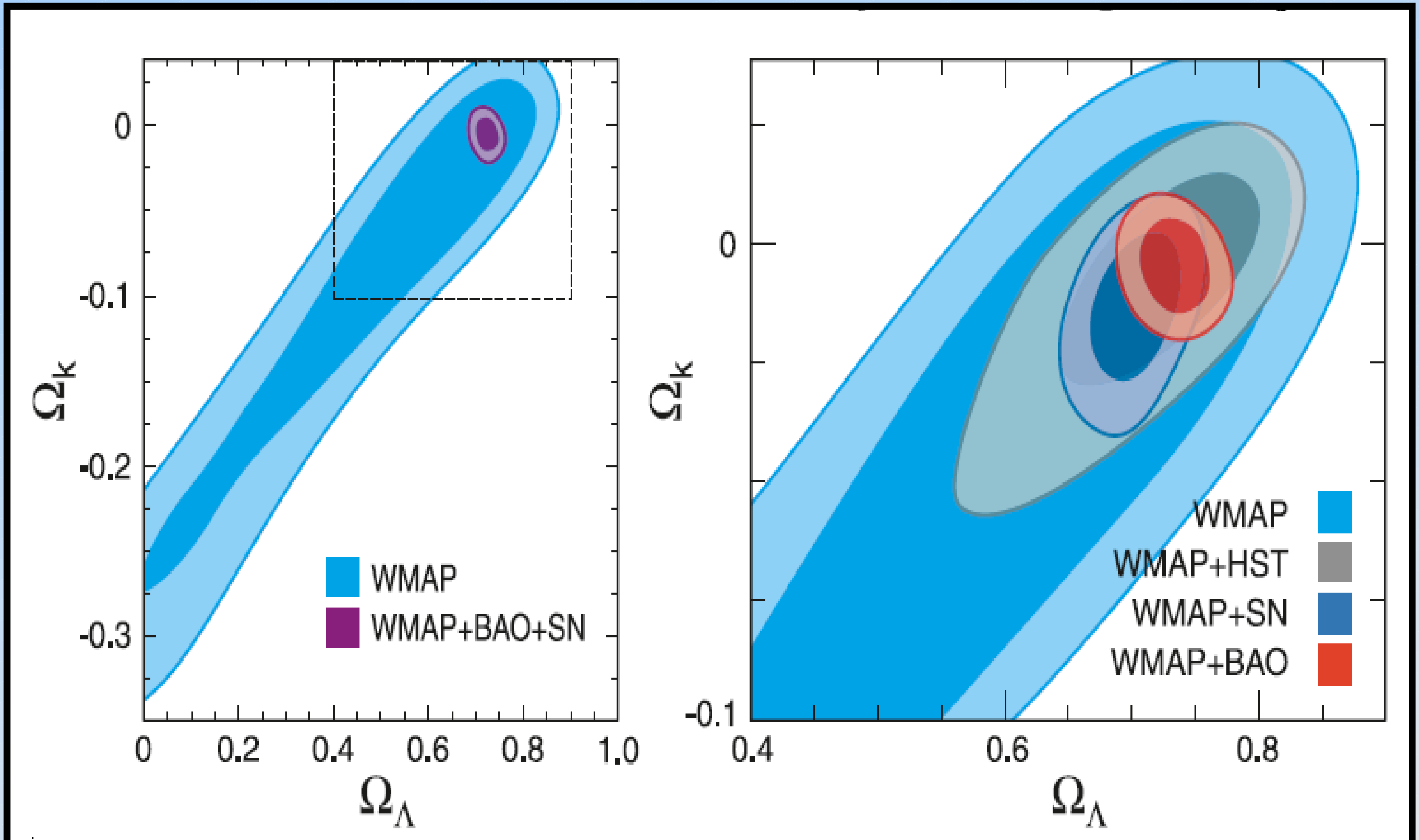
# WMAP – 7 Years Results

## 9 global FLRW Parameters:

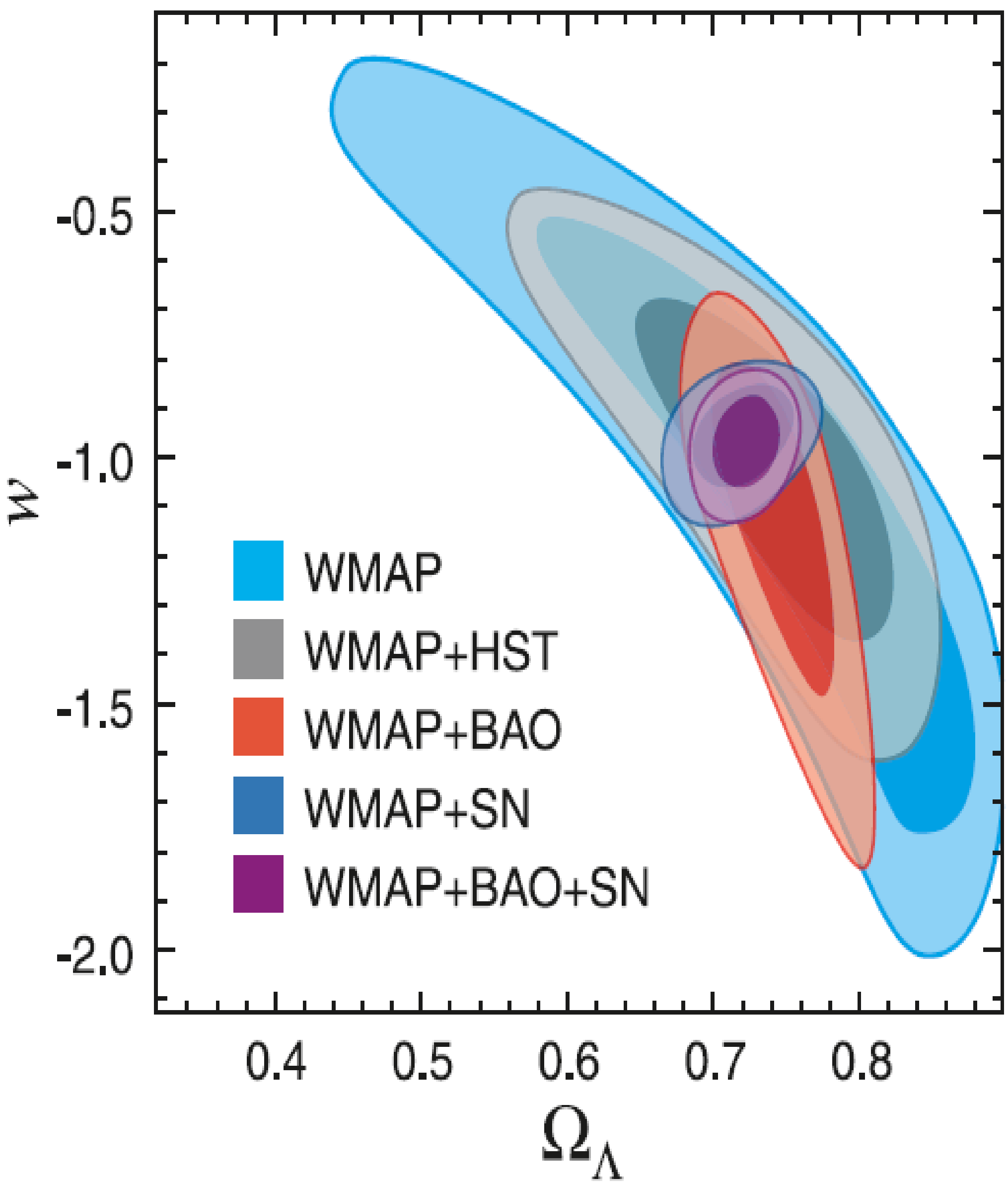
| | | |
|---|---|---|
| $H_0$ | 71+/-2 km/sec/Mpc | Expansion rate |
| $q_0$ | -0.67 +/- 0.15 | Deceleration parameter |
| $t_0$ | 13.75 +/- 0.17 | Age of the Universe |
| $T_0$ | 2.725 +/- 0.001K | CMB Temperature |
| $\Omega_k$ | - 0.01 +/- 0.005 | Curvature → k = +1 ? |
| $\Omega_B$ | 0.0449 /- 0.0028 | Baryons |
| $\Omega_M$ | 0.266 +/- 0.029 | DM+B |
| $\Omega_\nu$ | < 0.002 | Massive Neutrinos |
| $\Omega_{DE}$ | 0.734 +/- 0.029 | Dark Energy DE |

WMAP7 + SNIa + Lensing

# WMAP7 Data – Curvature

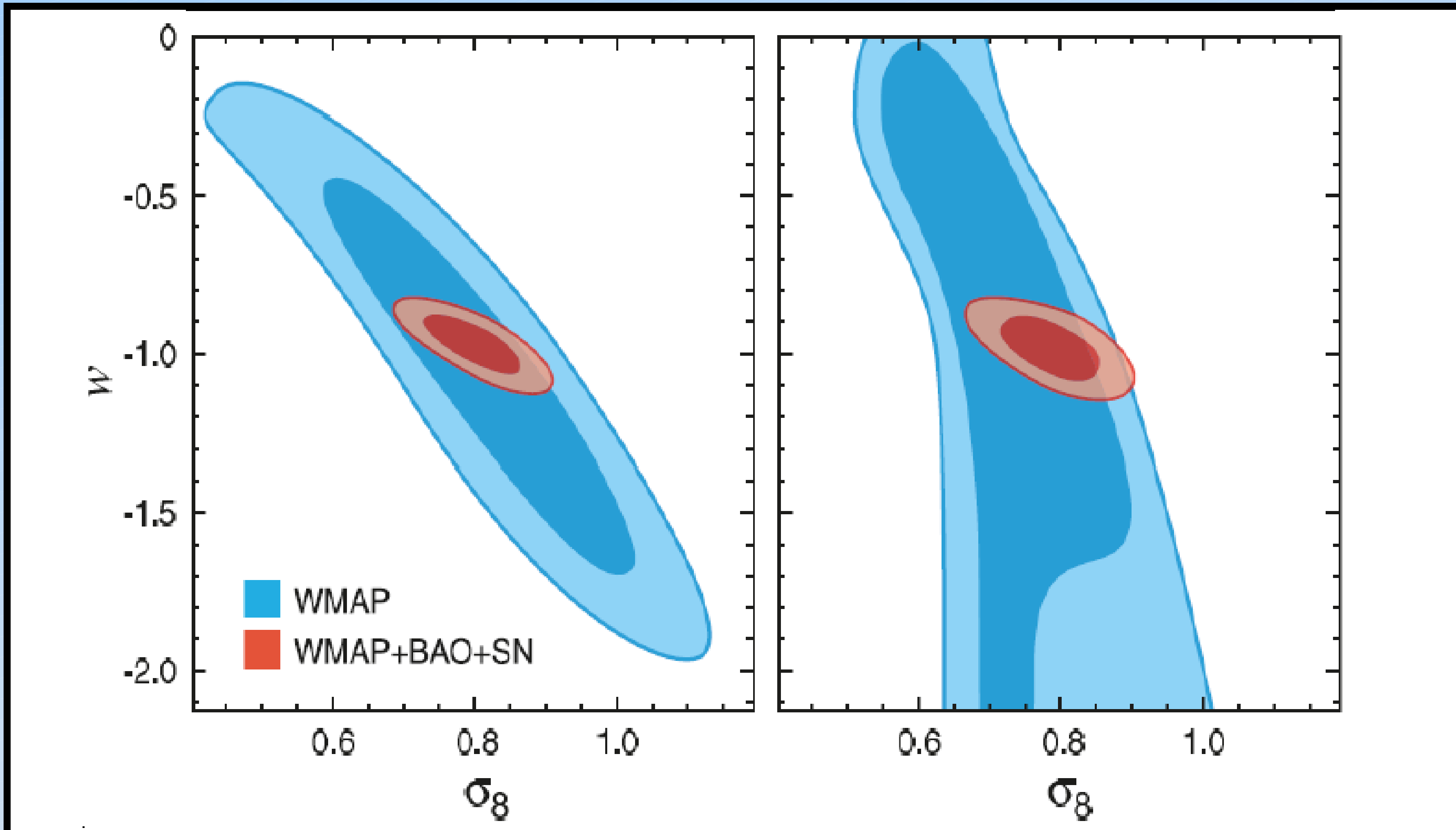


# WMAP7 Data DE w EoS

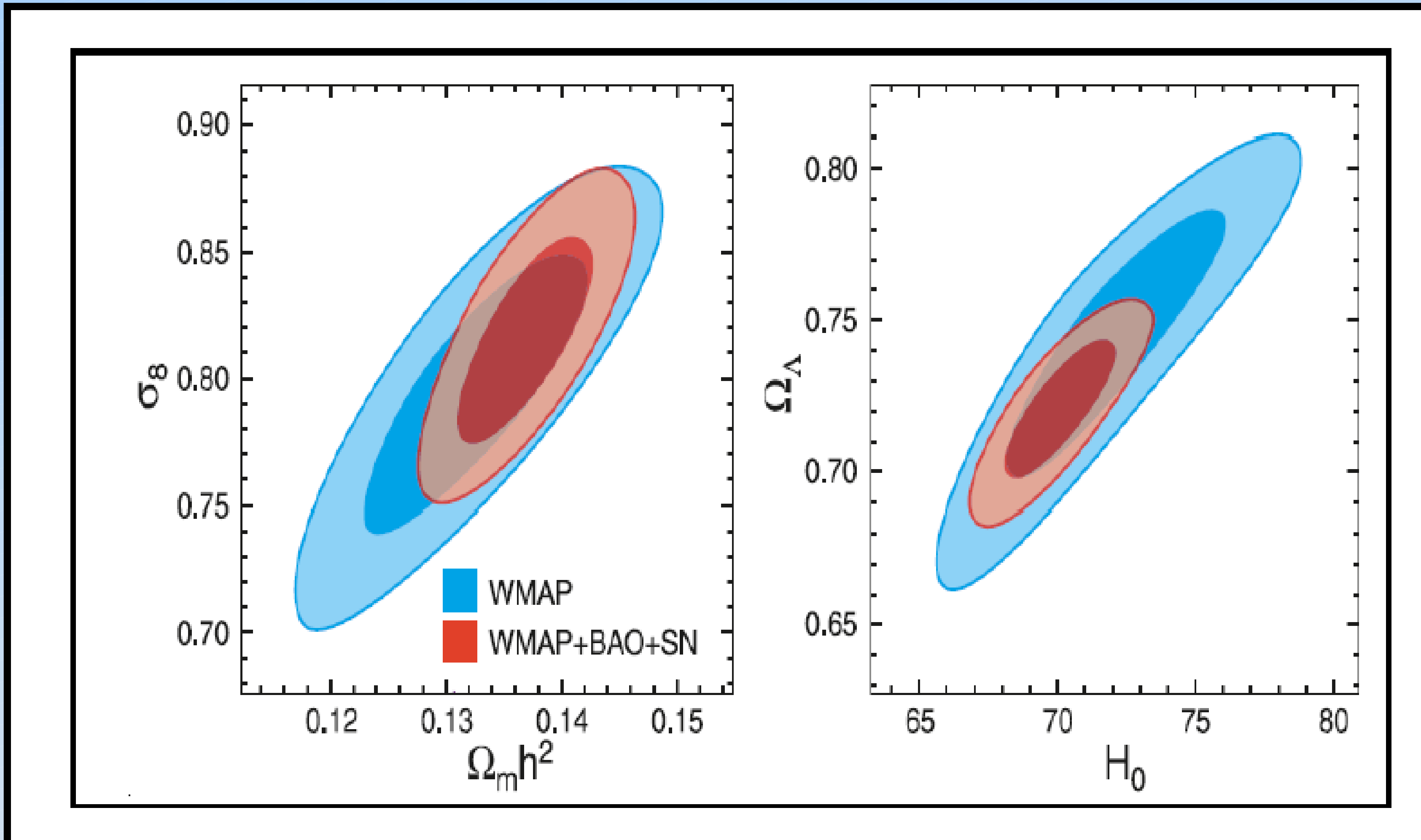



$$P_V = w\,\rho_V$$
$$w \sim w_0 + w_1 z$$

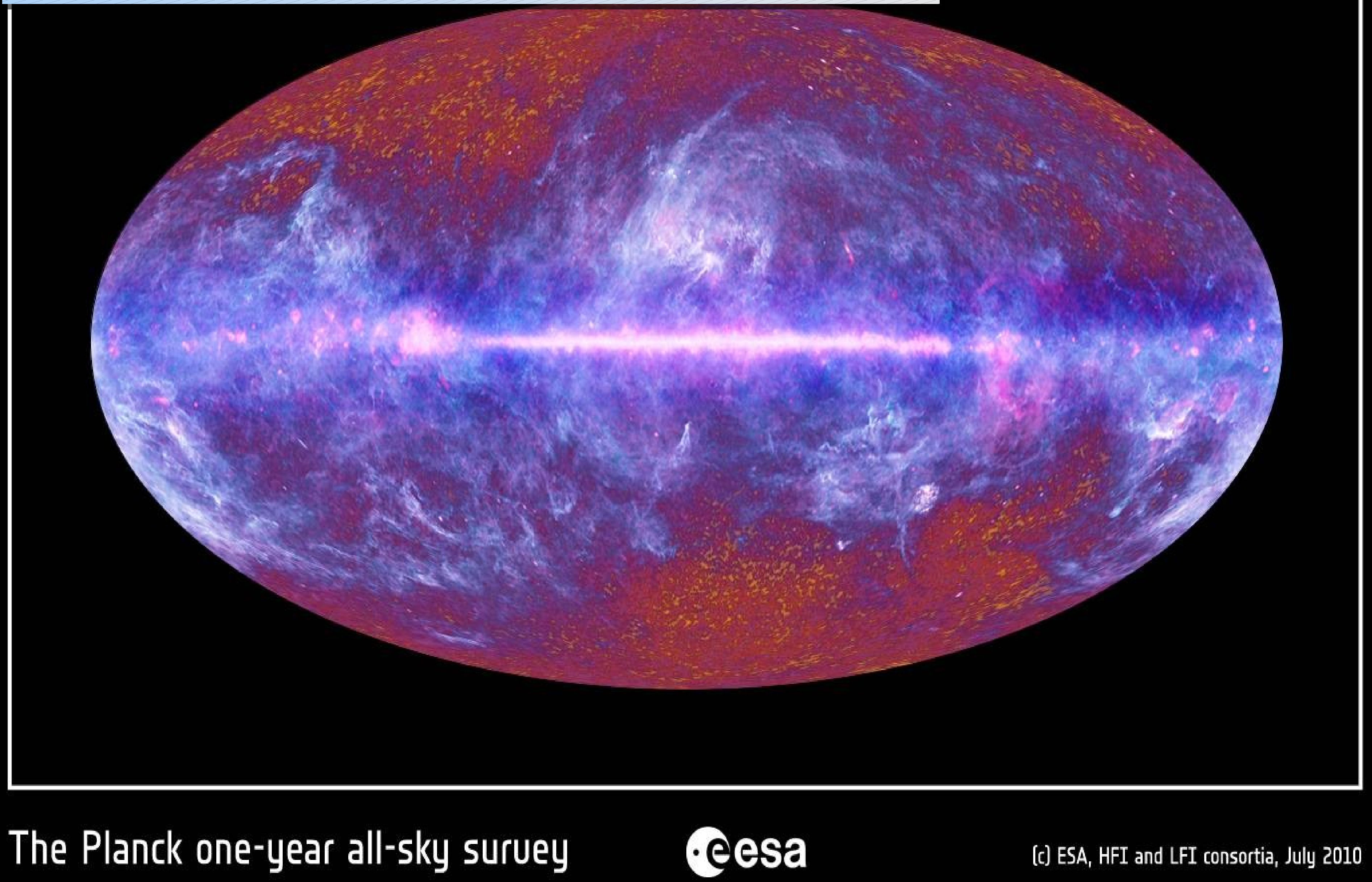
# WMAP7 Data – Fluctuations



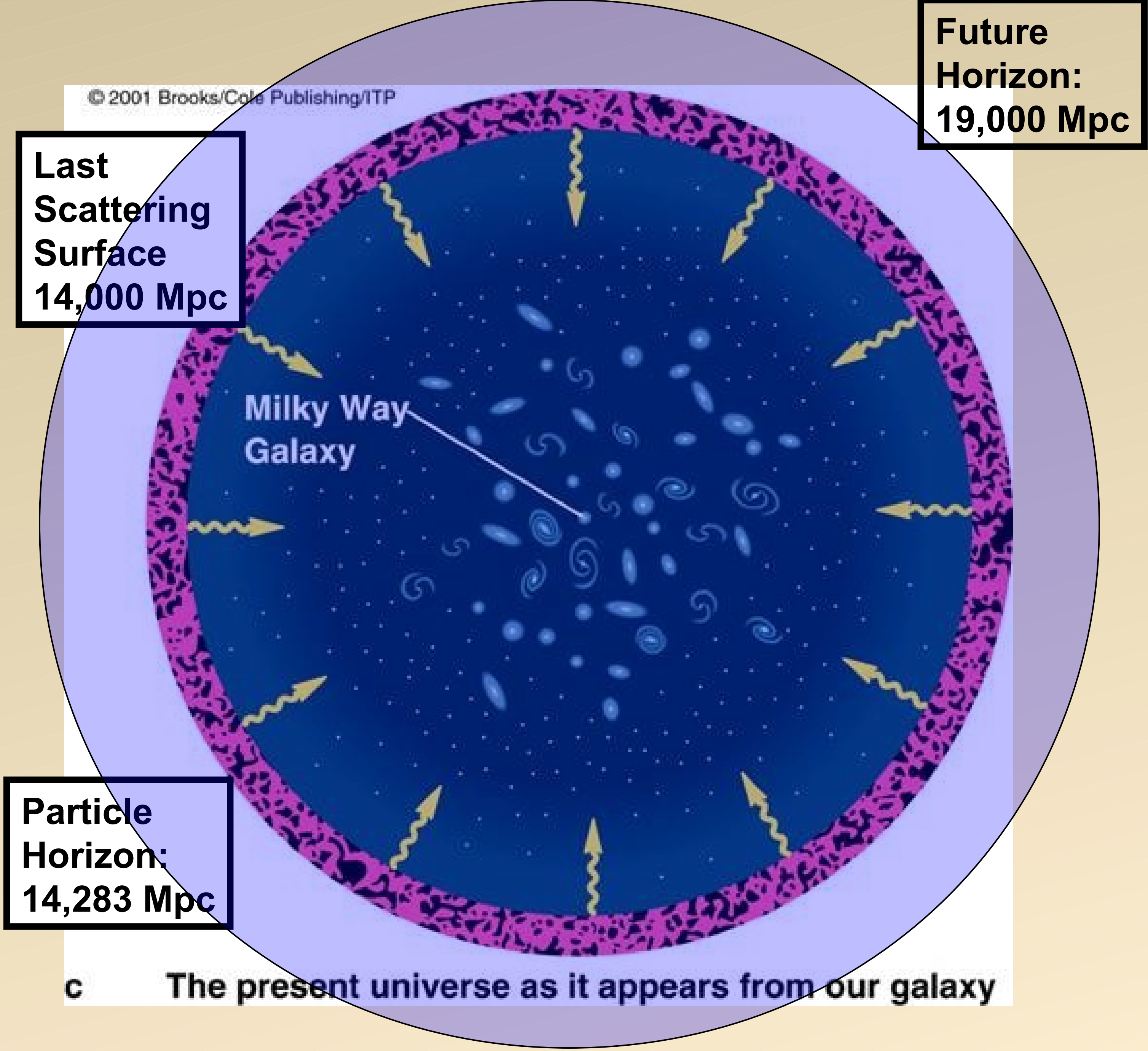
# WMAP7 Data – Hubble Const



# Future: Planck ~ 2012



# The Observable Universe



# Conformal Time

$$ds^2 = -dt^2 + a^2(t)(d\chi^2 + \sin^2\chi(d\theta^2 + \sin^2\theta d\phi^2)), \quad k = +1$$
$$ds^2 = -dt^2 + a^2(t)(d\chi^2 + \chi^2(d\theta^2 + \sin^2\theta d\phi^2)), \quad k = 0$$
$$ds^2 = -dt^2 + a^2(t)(d\chi^2 + \sinh^2\chi(d\theta^2 + \sin^2\theta d\phi^2)), \quad k = -1$$

**Use conformal time $d\eta = dt/a$: $\eta(t_0) = 3.38$ present value**

$$\eta(t) = \int_0^t \frac{dt}{a} = \int_0^{a(t)} \frac{da}{a^2 H(a)} = \frac{1}{H_0}\int_0^{a(t)} \left[\Omega_r + \Omega_m a + \Omega_k a^2 + \Omega_\Lambda a^4\right]^{-1/2} da \quad (4.178)$$

➔ **Particle horizon scale:**

$$\chi R_{H_0} = 3.38 R_{H_0} = 14,300\,\mathrm{Mpc}\,.$$

Gott et al. 2003

# Particle & Future Horizon

**Particle Horizon:**

$$\tilde{r}_P = a(t) \int_0^t \frac{dt}{a(t)}.$$

**Particle horizon** is the maximum distance from which particles could have traveled to the observer in the age of the universe. It represents the portion of the Universe, which we could have conceivably observed at the present day.

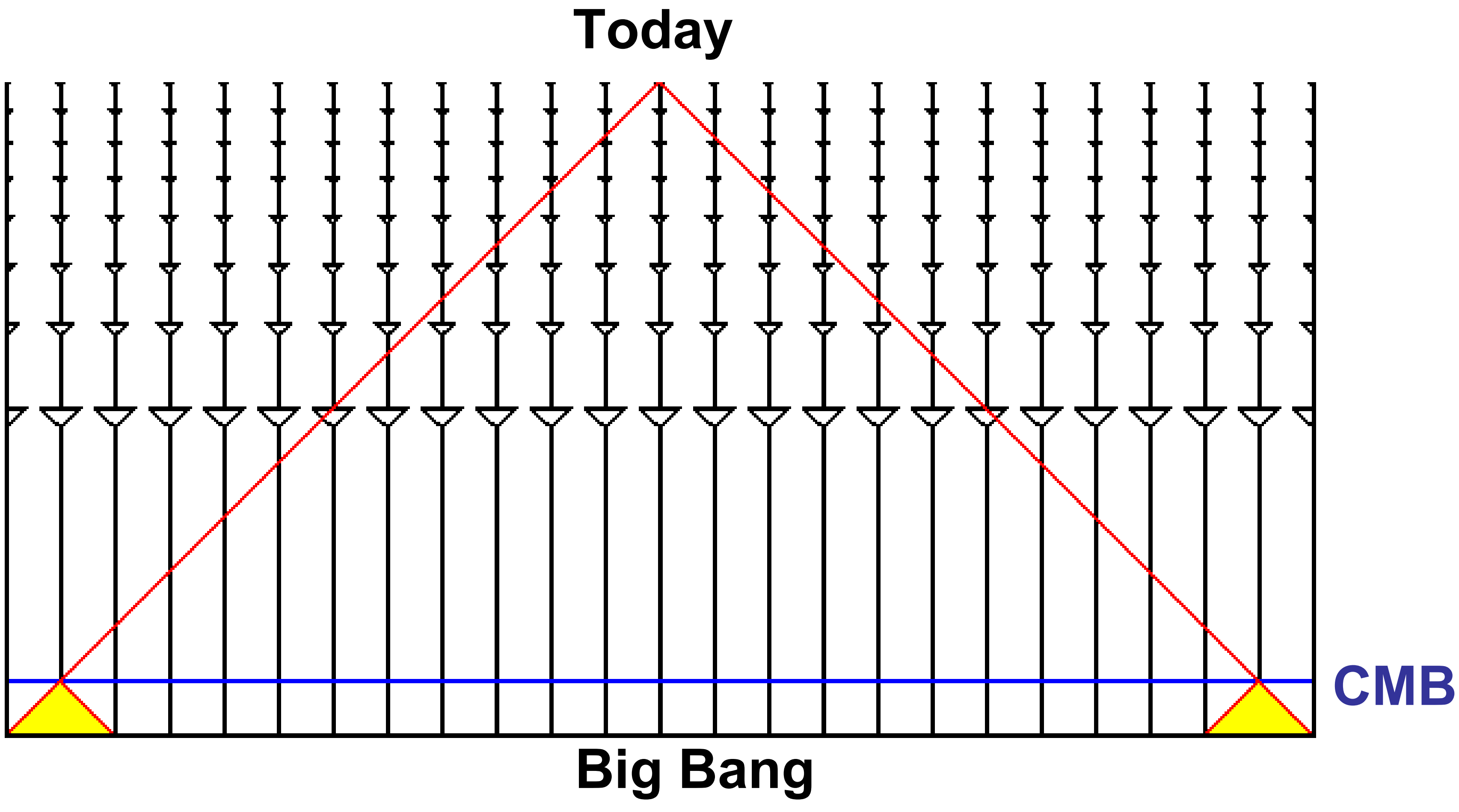
**Event Horizon:**

$$\tilde{r}_E = a(t) \int_t^\infty \frac{dt}{a(t)},$$

A **cosmological horizon** marks a limit to the observability, and marks the boundary of a region that an observer cannot see into directly due to cosmological effects.

# Universe in Conformal Time

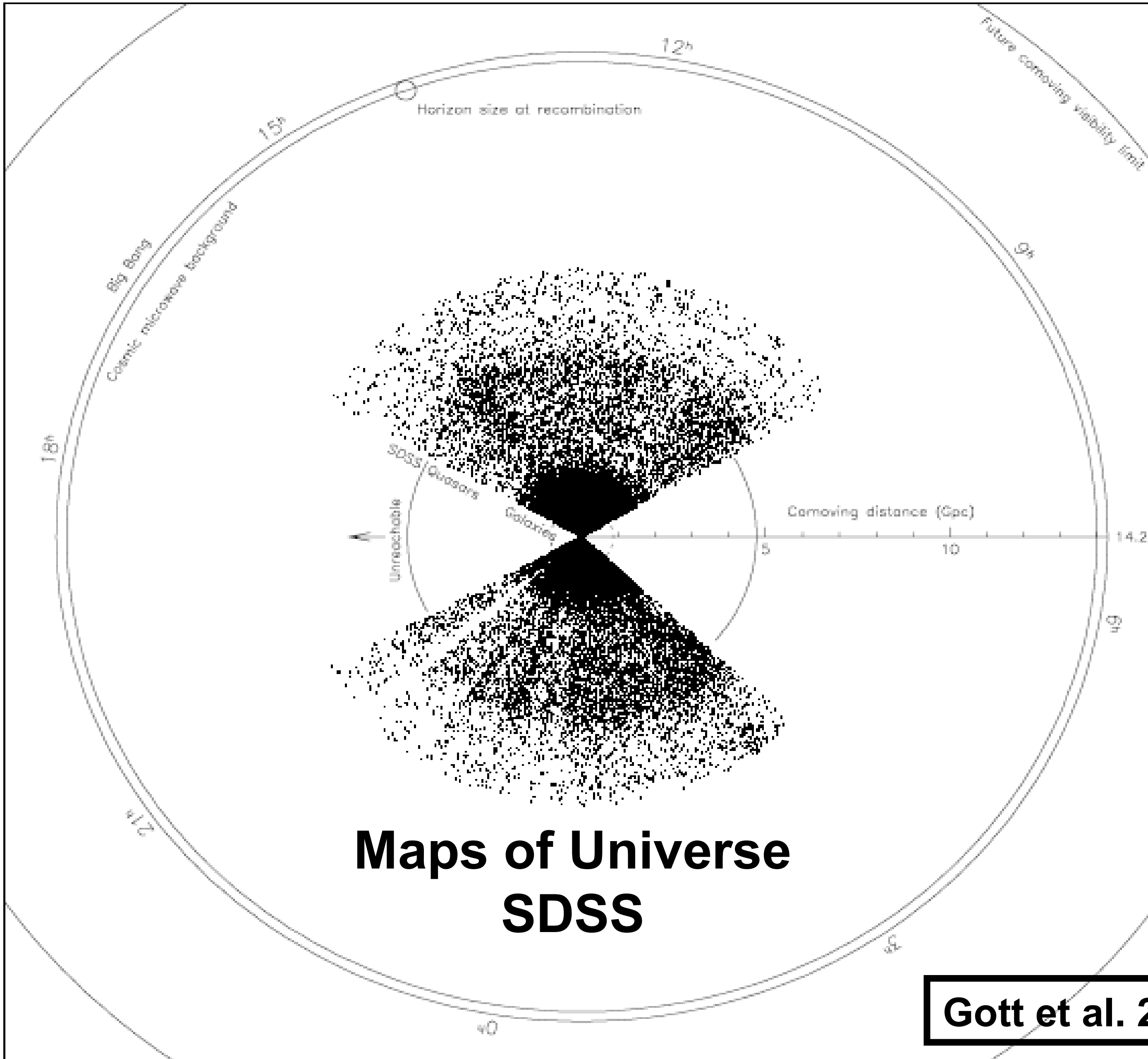
$$ds^2 = R^2(\eta)\,[d\eta^2 - d\sigma^2]$$



# Comoving Distance

| **Redshift** $z$ | $r(z)$ **(Mpc)** | **Remark** |
|---:|---:|---|
| $\infty$ | 14,283 | Big Bang (end of inflationary period) |
| 3233 | 14,165 | Equal matter and radiation density epoch |
| 1089 | 14,000 | Recombination |
| 6 | 8,422 | |
| 5 | 7,933 | |
| 4 | 7,305 | |
| 3 | 6,461 | |
| 2 | 5,245 | |
| 1 | 3,317 | |
| 0.5 | 1,882 | |
| 0.2 | 809 | |
| 0.1 | 413 | |

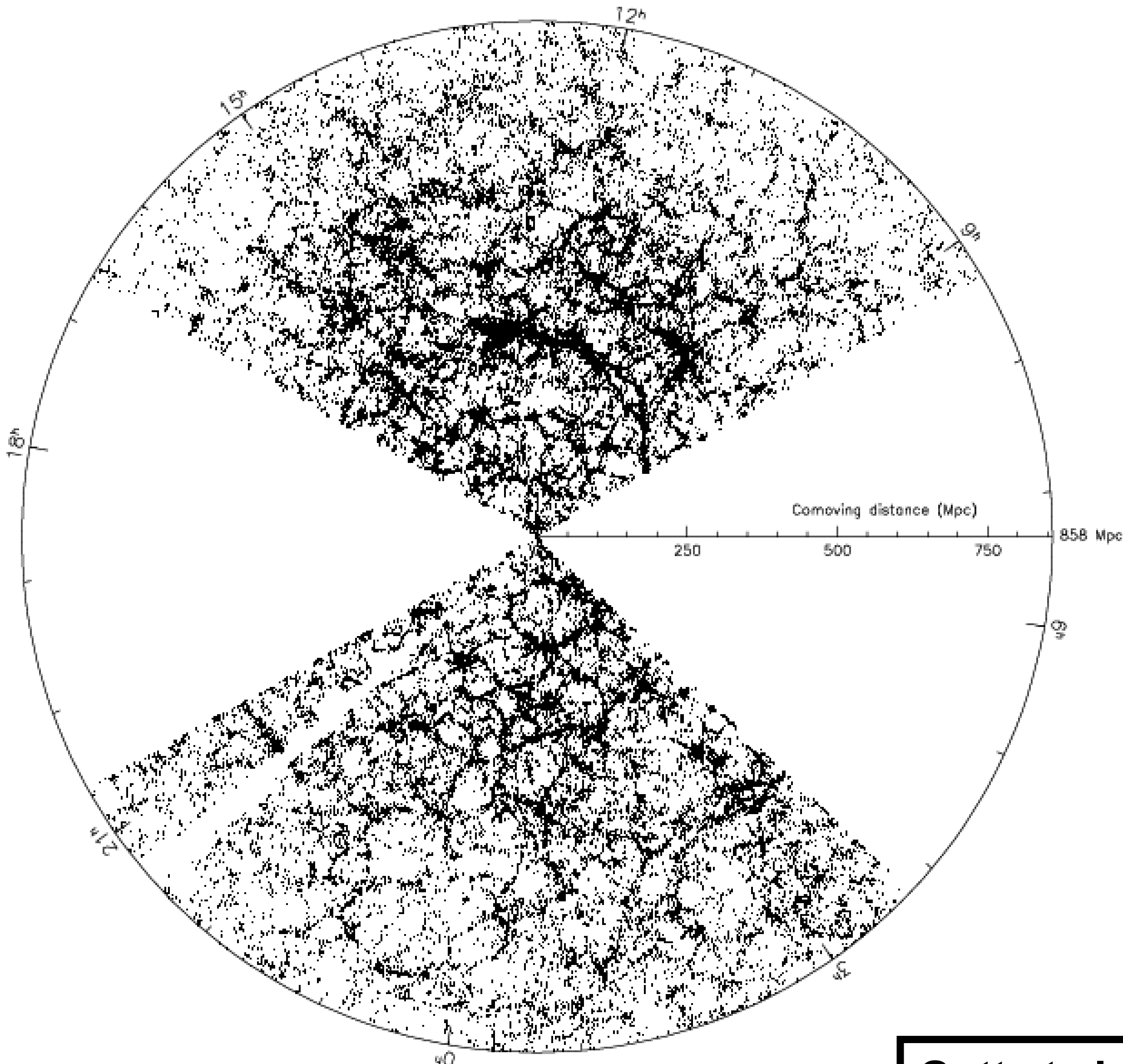
# Universe in Comoving Distance




**Maps of Universe**
**SDSS**

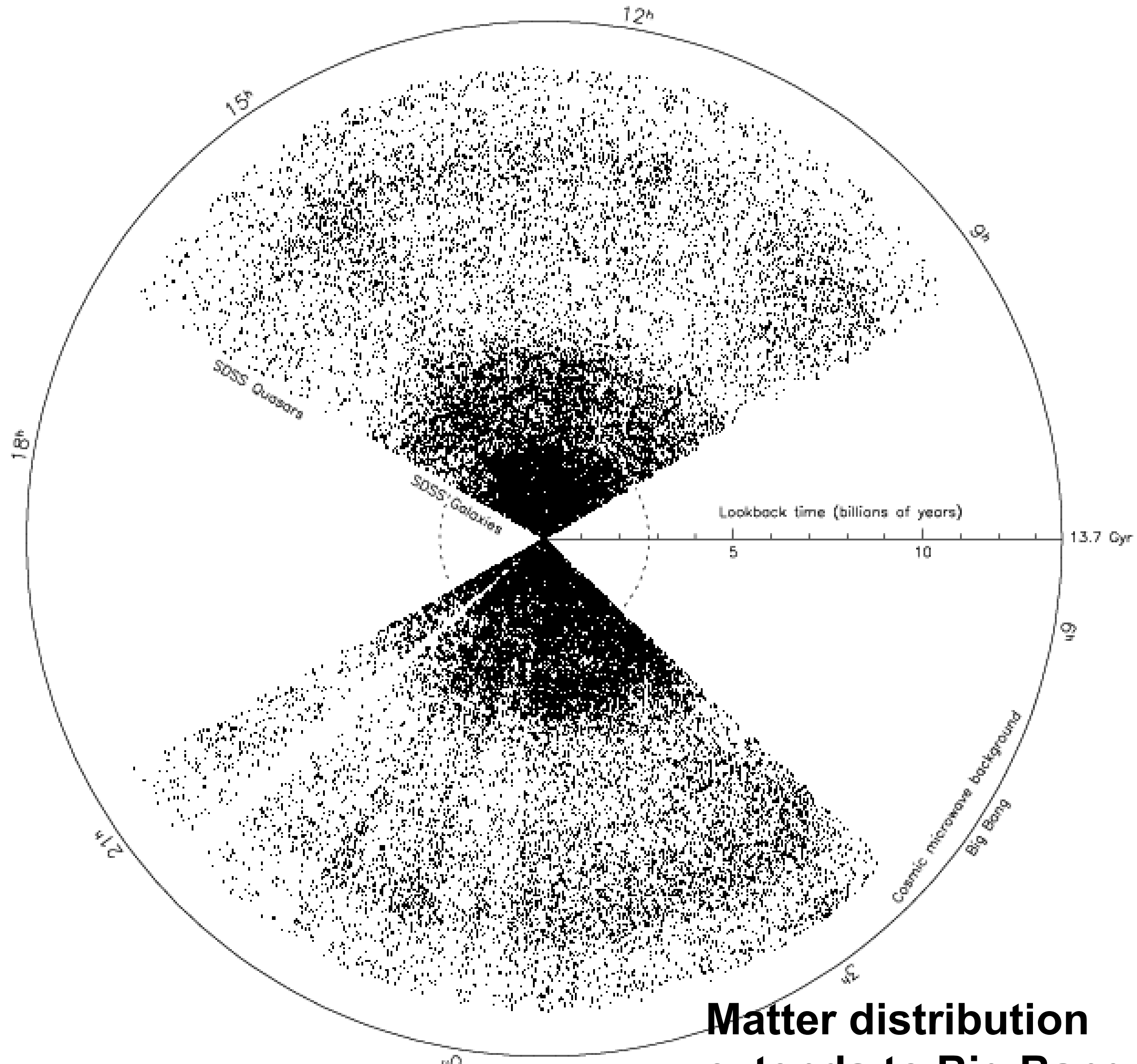
**Gott et al. 2003**

# Universe zoomed in Comoving Distance




Gott et al. 2003

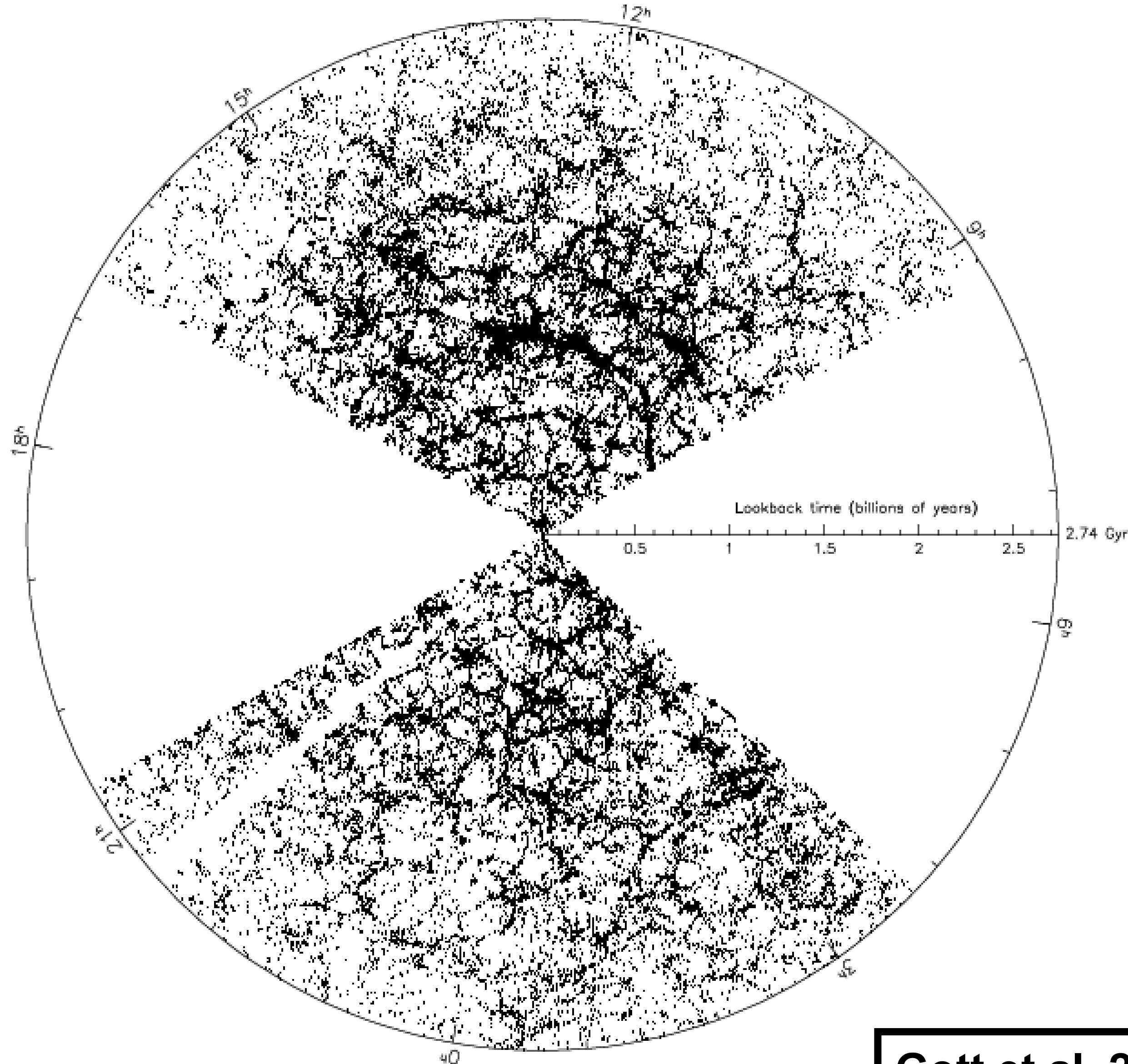
# Universe in in Look-Back Coords




Gott et al. 2003

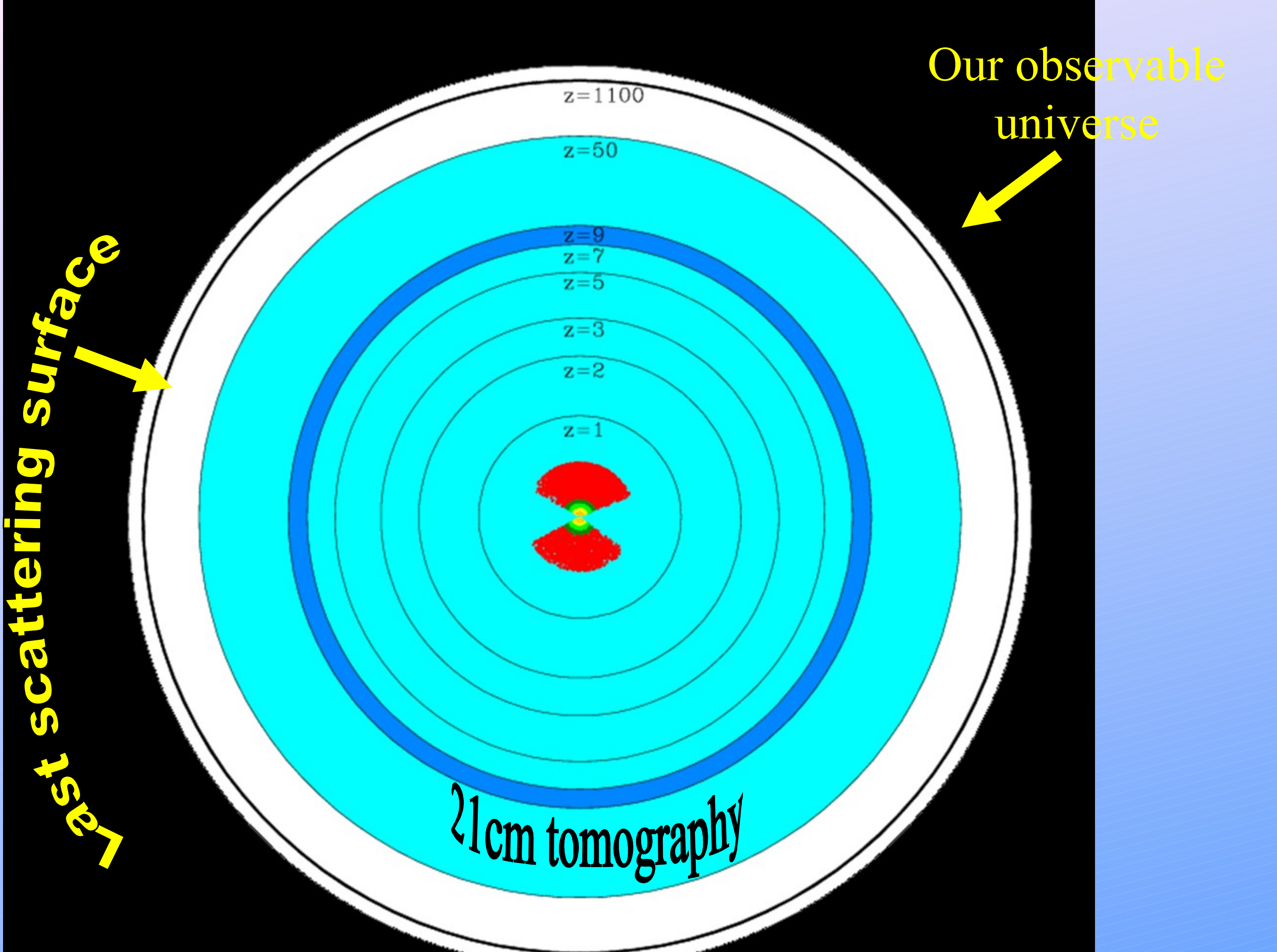
**Matter distribution extends to Big Bang**
**➔ Wrong impression**

# Universe in In Look-Back Coords




Gott et al. 2003

# Future: 21 cm Tomography



# Unsolved Problem: What is Dark Energy ?

- **Constant of Nature**

= cosmological constant **Λ** à la Einstein**? – No!**

- **Vacuum Energy (Quantum effects)?**

to be expected, but at the moment not predictable

**Consequence of „quantized“ Space (Loop-Quantum Gravity LQ)? – yes ?**

- **Quintessence? New scalar Field ≈ Λ(t) ?**
- **Some effect from existence of future Horizon? (~ Hawking radiation) - ???**

# Summary

- LCDM **Relativistic Cosmos** is a good approx.
- 2 Friedmann-Equations determine the **Expansion of the Universe for given EoS**.
- **Matter in the present Universe** consists of various components: **Baryons, Photons, Neutrinos, Dark Matter and Dark Energy (w)**.
- Expressed in terms of **Omega-parameters**.
- Since 1997, Supernovae observations give evidence for an accelerated expansion ➔ **Dark Energy is therefore required and $\Omega_k$ ~ 0**.
- **EoS w** of Dark Energy is one of crucial problem.