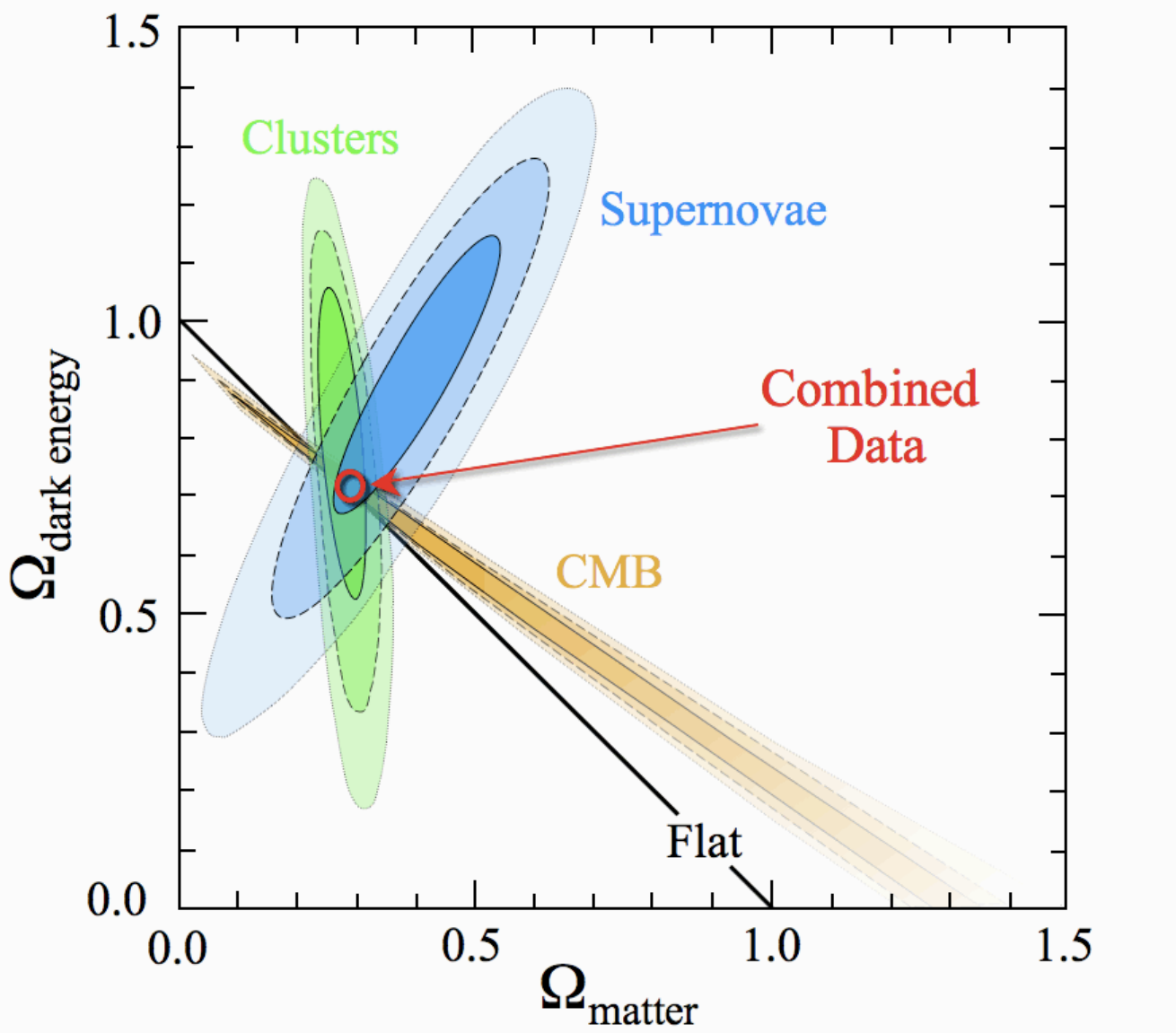
# The Cosmic Concordance



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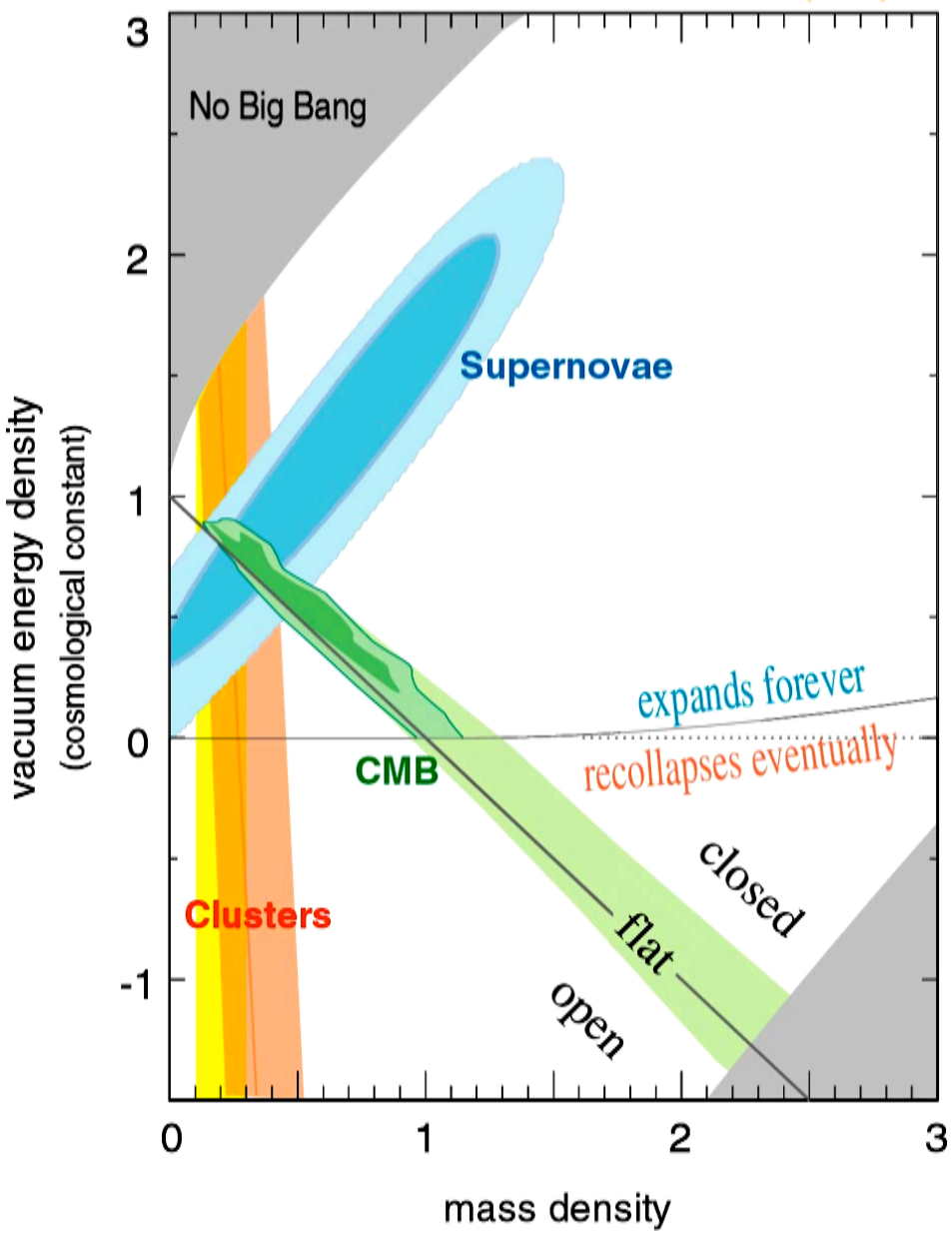



***Supernovae alone***

**⇒ Accelerating expansion**

**⇒ Λ > 0**

***CMB alone***

**⇒ Flat universe**

**⇒ Λ > 0**

***Any two of SN, CMB, LSS***

**⇒ Dark energy ~70%**

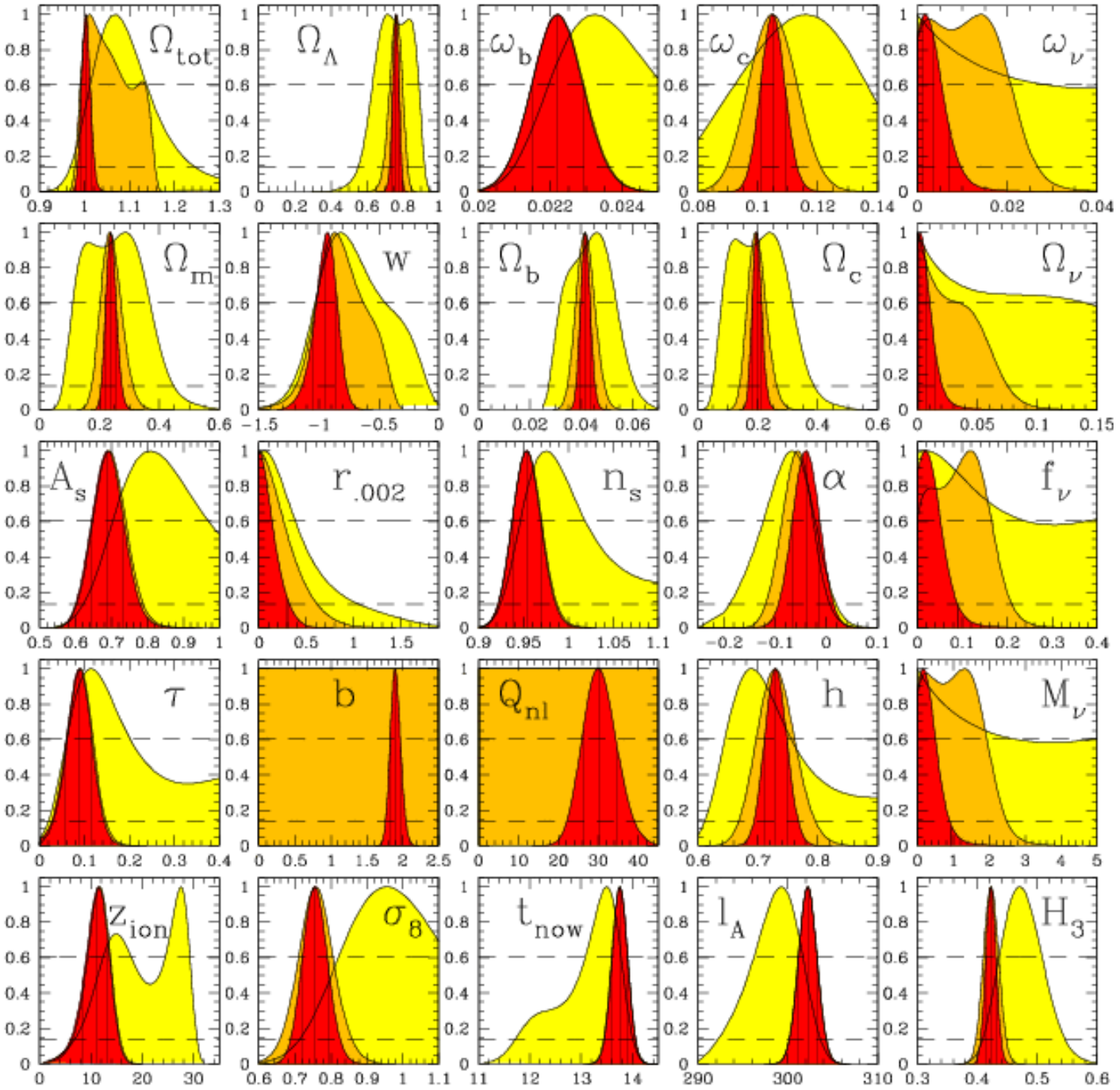
Also in agreement with the age estimates (globular clusters, nucleocosmochronology, white dwarfs)

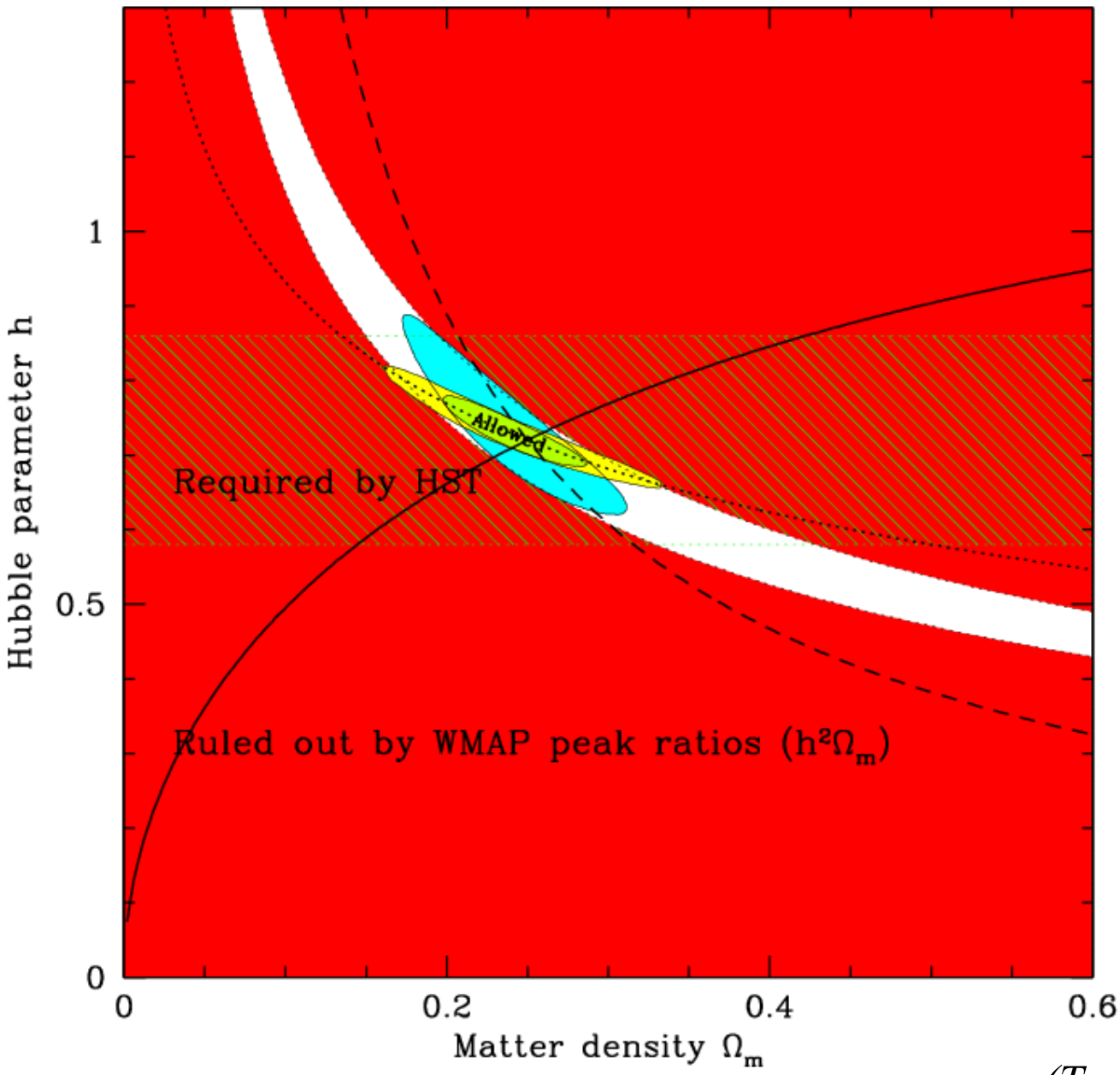
# Estimating Cosmological Parameters

- Many observables depend on complicated combinations of individual cosmological parameters; this is especially true for the analysis of CMB experiments
- Thus, one really gets probability contours or distributions in a multi-dimensional parameter space, which can then be projected on any given parameter axis
- Generally this entails a very laborious and computationally intensive parameter estimation
- It helps if one can declare some of the parameters to be fixed *a priori*, on the basis of our knowledge or prejudices, e.g., "We'll assume that the univese is flat", or "we'll assume the value of $H_0$ from the HST Key Project", etc.

Examples of probability distributions for various cosmological parameters, from a joint analysis of WMAP, SDSS, and other data

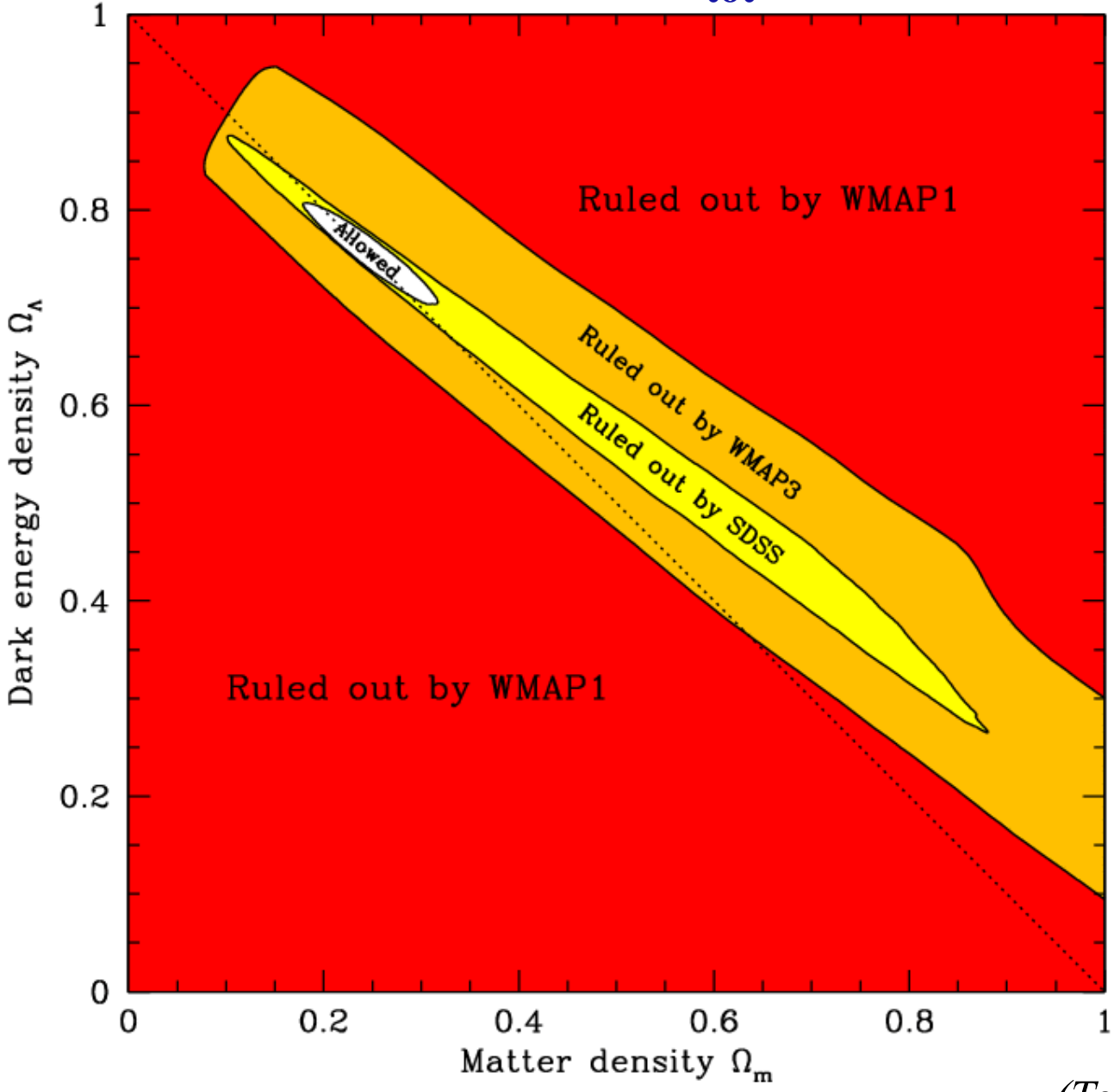
*(Tegmark et al.)*






*(Tegmark et al.)*

# How flat is space? $\Omega_{tot}=1.003 \pm 0.010$

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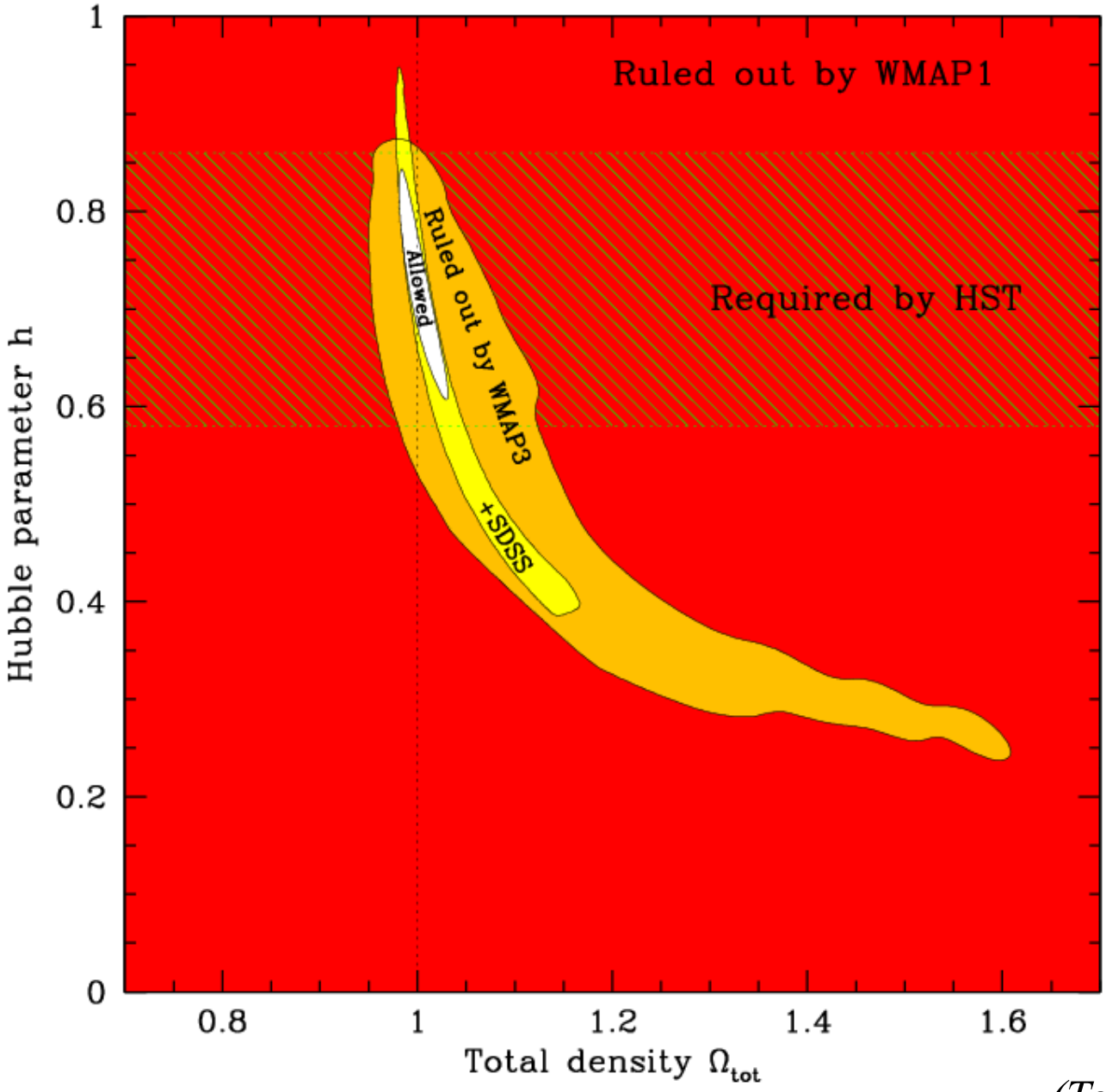


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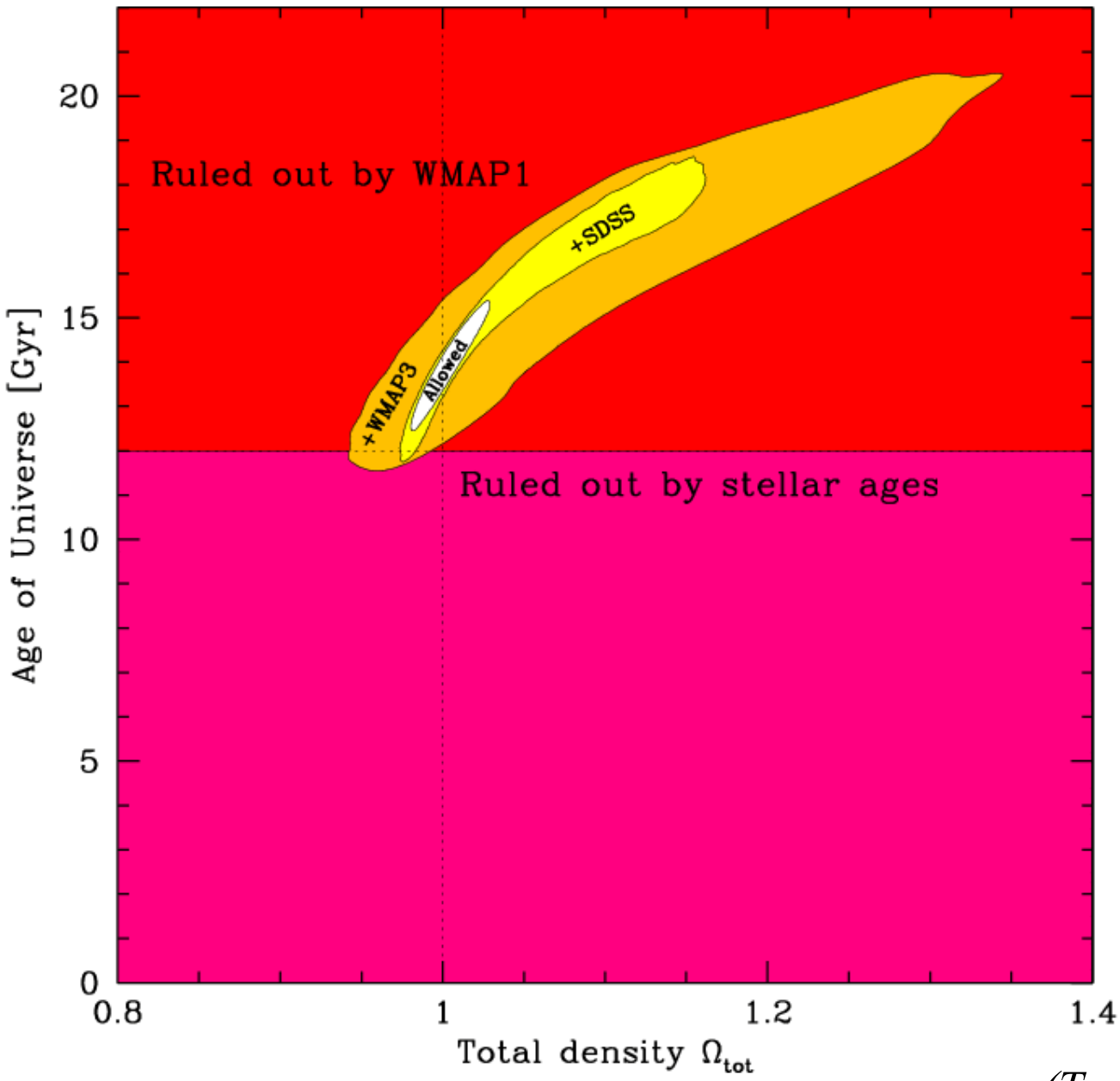


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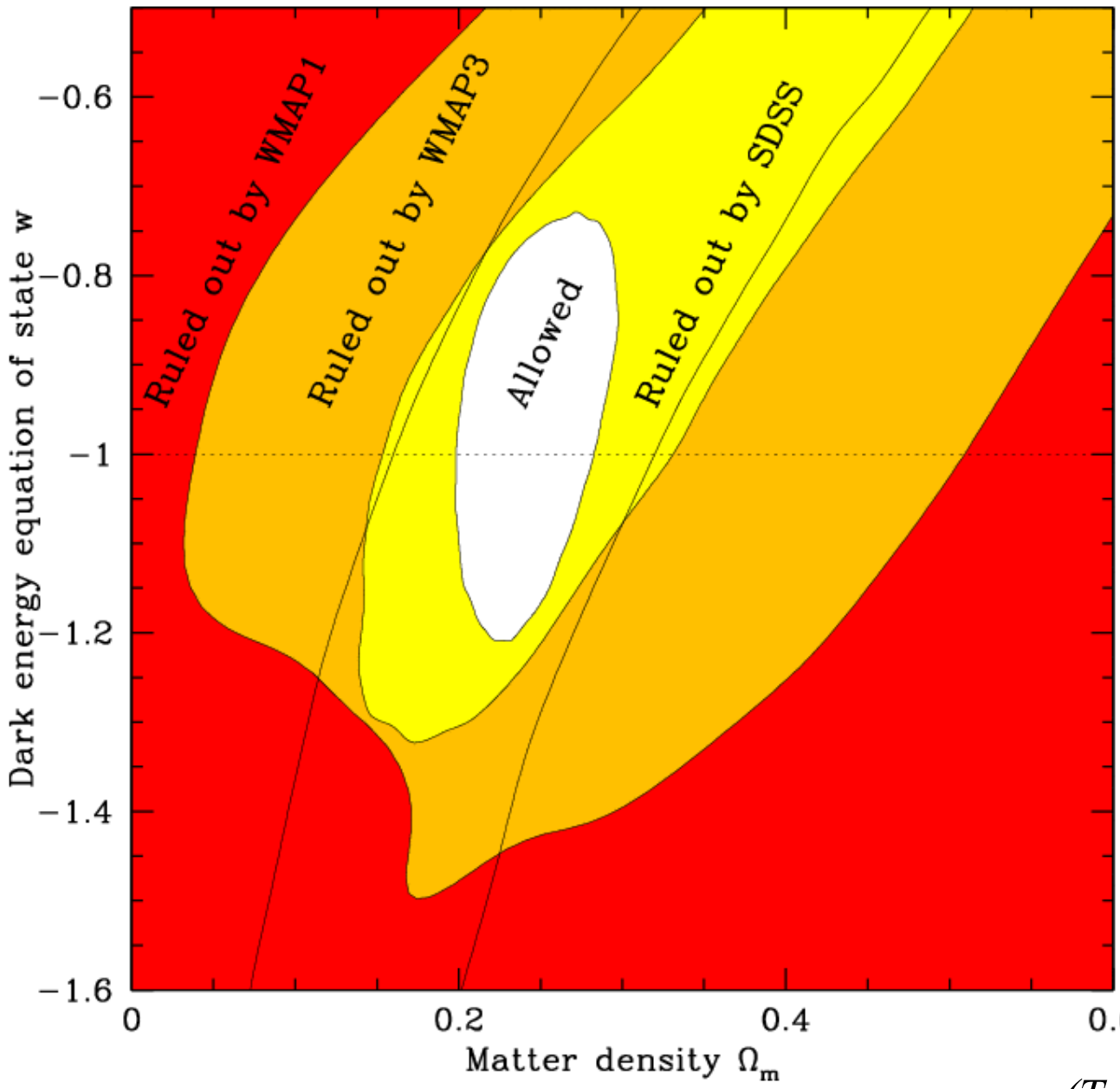
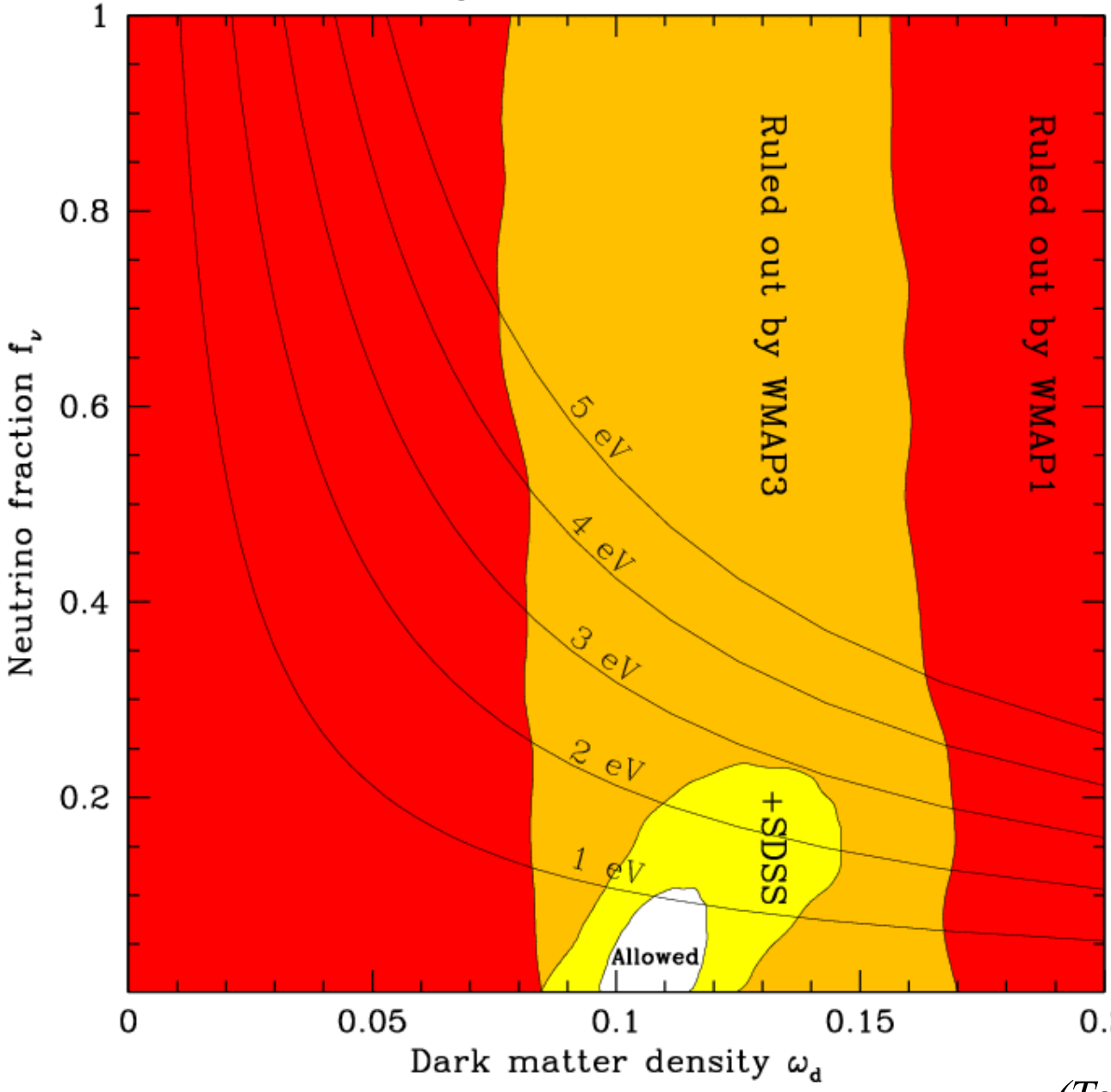



*(Tegmark et al.)*

# Cosmological neutrino bounds

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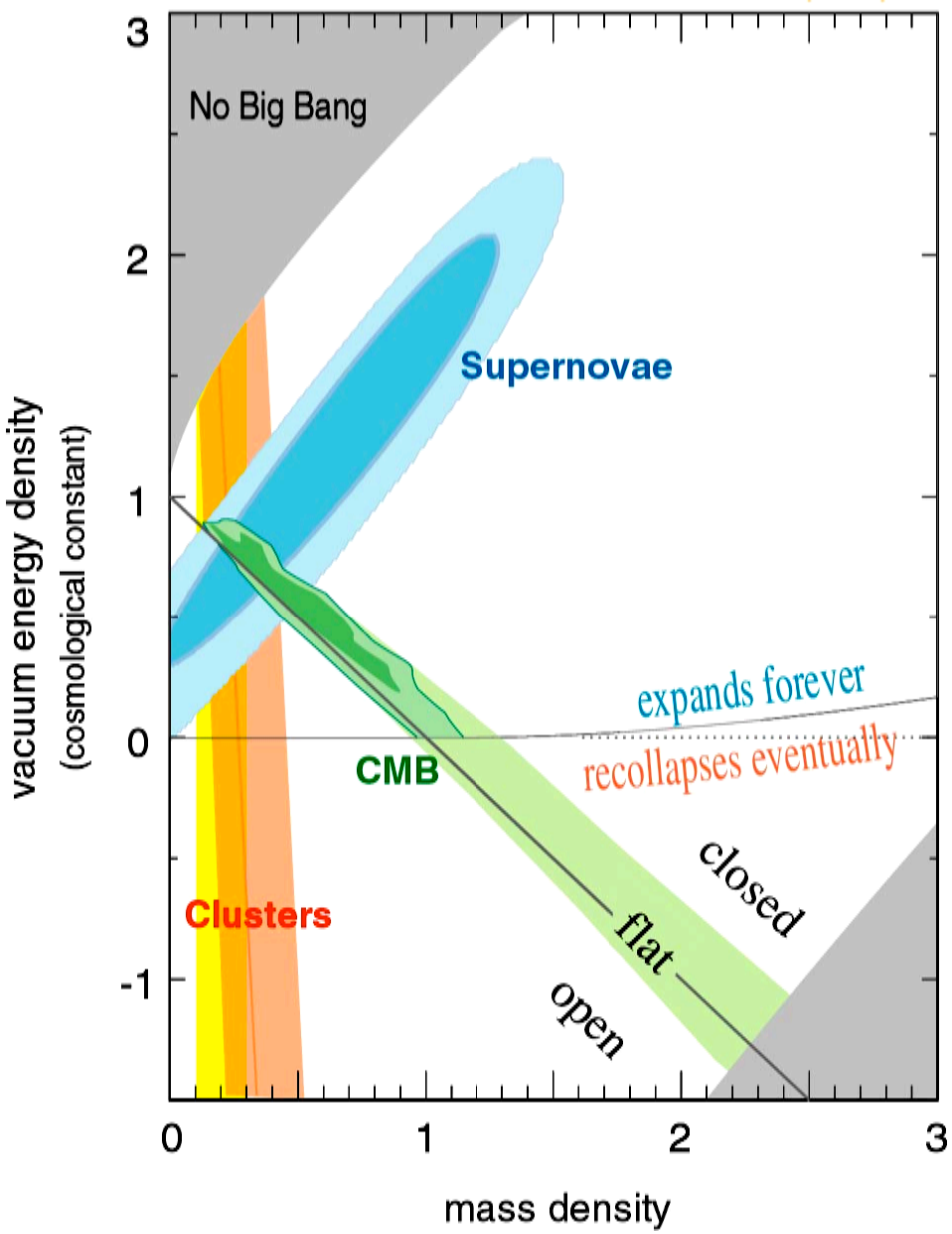


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# This is Not Exactly New …

*Nature Vol. 257 October 9 1975*

## An accelerating Universe

**James E. Gunn***

Hale Observatories, California Institute of Technology, Carnegie Institution of Washington, Pasadena, California 91125

**Beatrice M. Tinsley*†**

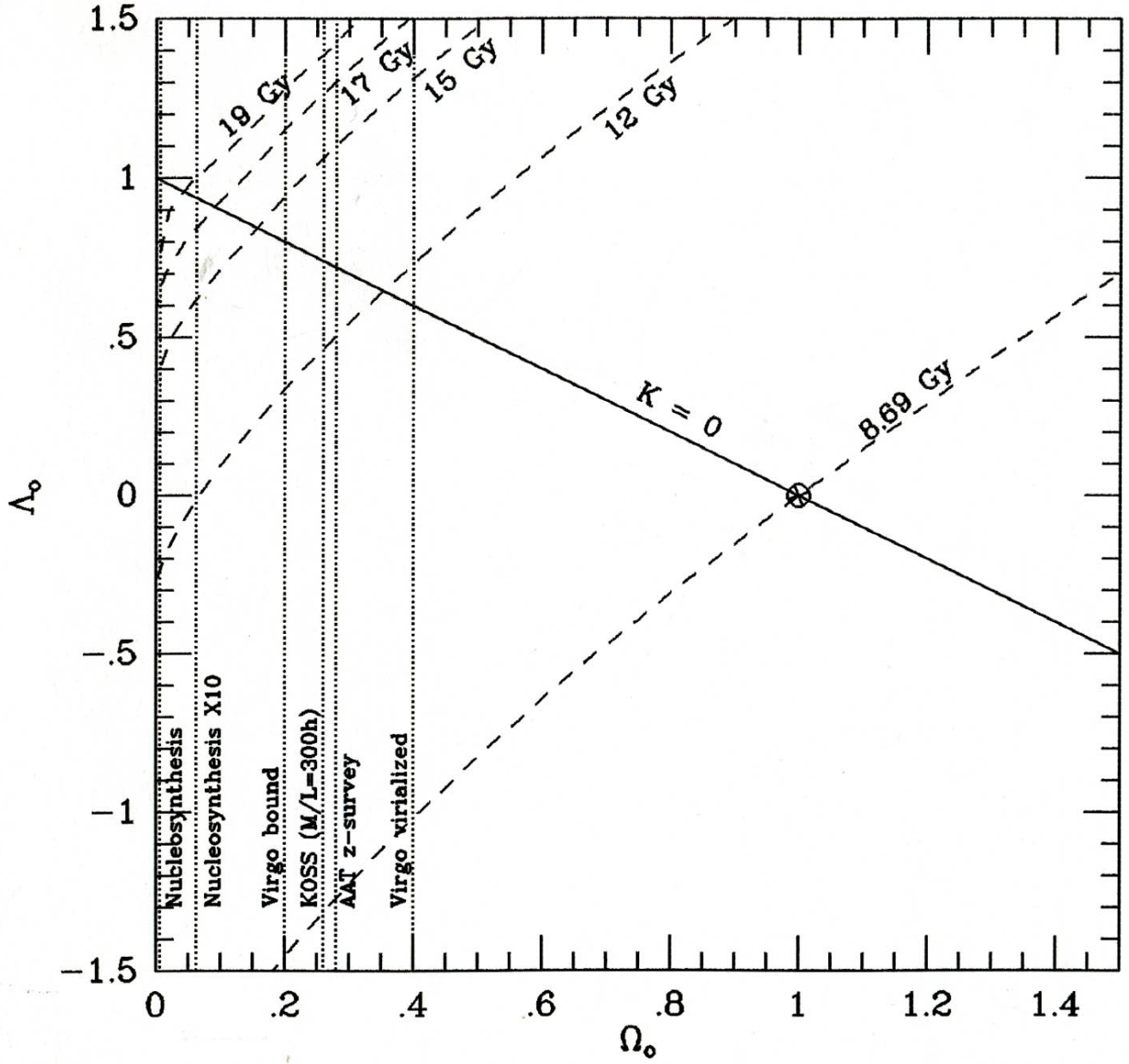
**B. Tinsley, *Nature Vol. 273 18 May 1978***

## Accelerating Universe revisited

They were driven to this conclusion by the combination of data on the Hubble constant, ages of globular clusters, Hubble diagram, and density measurements … just like today

**For the next 20 years, cosmological constant was invoked mainly as a means to solve the apparent conflict between the ages of globular clusters and chemical elements, and the age of the universe derived from the $H_0$ and density parameter**

# Concordance Cosmology, Circa 1985




$H_o$ = 75 km/s/Mpc

Globular cluster ages, dynamical measurements of matter density, and $H_0$, all consistent with the newly fashionable, flat ($k$=0) inflationary universe

*(Djorgovski 1985, unpublished)*

# Today's Best Guess Universe

**Age:**

$t_0 = 13.7 \pm 0.2$ Gyr

Best fit CMB model - consistent with ages of oldest stars

**Hubble constant:**

$H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$

CMB + HST Key Project to measure Cepheid distances

**Density of ordinary matter:**

$\Omega_{baryon} = 0.04$

CMB + comparison of nucleosynthesis with Lyman-a forest deuterium measurement

**Density of all forms of matter:**

$\Omega_{matter} = 0.27$

Cluster dark matter estimate CMB power spectrum

**Cosmological constant:**

$\Omega_\Lambda = 0.73$

Supernova data, CMB evidence for a flat universe plus a low matter density

# The Component Densities

at z ~ 0, in critical density units, assuming $h \approx 0.7$

**Total matter/energy density:** $\Omega_{0,tot} \approx 1.00$ From CMB, and consistent with SNe, LSS

**Matter density:** $\Omega_{0,m} \approx 0.27$ From local dynamics and LSS, and consistent with SNe, CMB

**Baryon density:** $\Omega_{0,b} \approx 0.05$ From cosmic nucleosynthesis, and independently from CMB

**Luminous baryon density:** $\Omega_{0,lum} \approx 0.005$ From the census of luminous matter (stars, gas)

**Since:** $\Omega_{0,tot} > \Omega_{0,m} > \Omega_{0,b} > \Omega_{0,lum}$

There is baryonic dark matter

There is non-baryonic dark matter

There is dark energy

# Cosmological Tests Summary

- Tests of the global geometry and dynamics: correlate redshifts (~ scale factors) with some relative measure of distance (~ look back time); could use:
  - "standard candles" (for luminosity distances; e.g., SNe)
  - "standard rulers" (for angular diameter dist's; e.g., CMBR fluc's)
  - "standard abundances" (for volume-redshift test; e.g., rich clusters)
- Get matter density from local dynamics or LSS
- Combine with constraints from the $H_0$, ages
- There are often parameter couplings and degeneracies, especially with the CMB alone
- Multiple approaches provide cross-checks, break degeneracies
- Concordance cosmology is now fairly well established


Next:
The Early
Universe