The History of Cosmological Star Formation:
Three independent Approaches and a Critical Test Using the Extragalactic Background Light

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astro-ph/0603257

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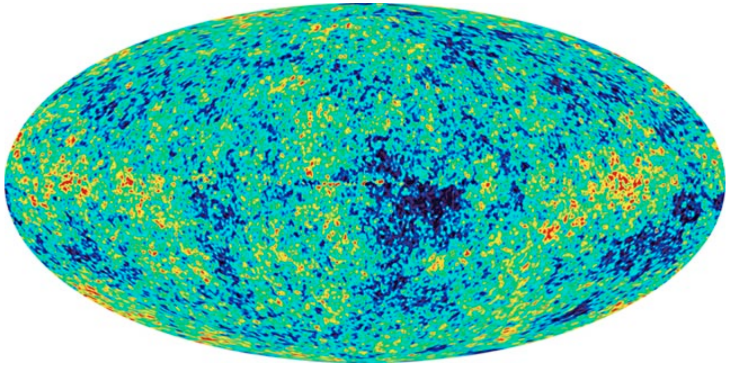
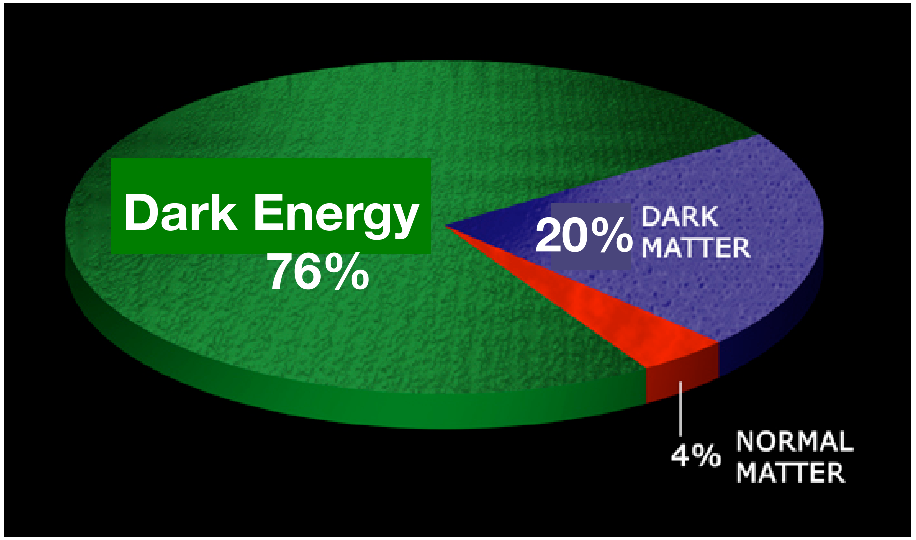
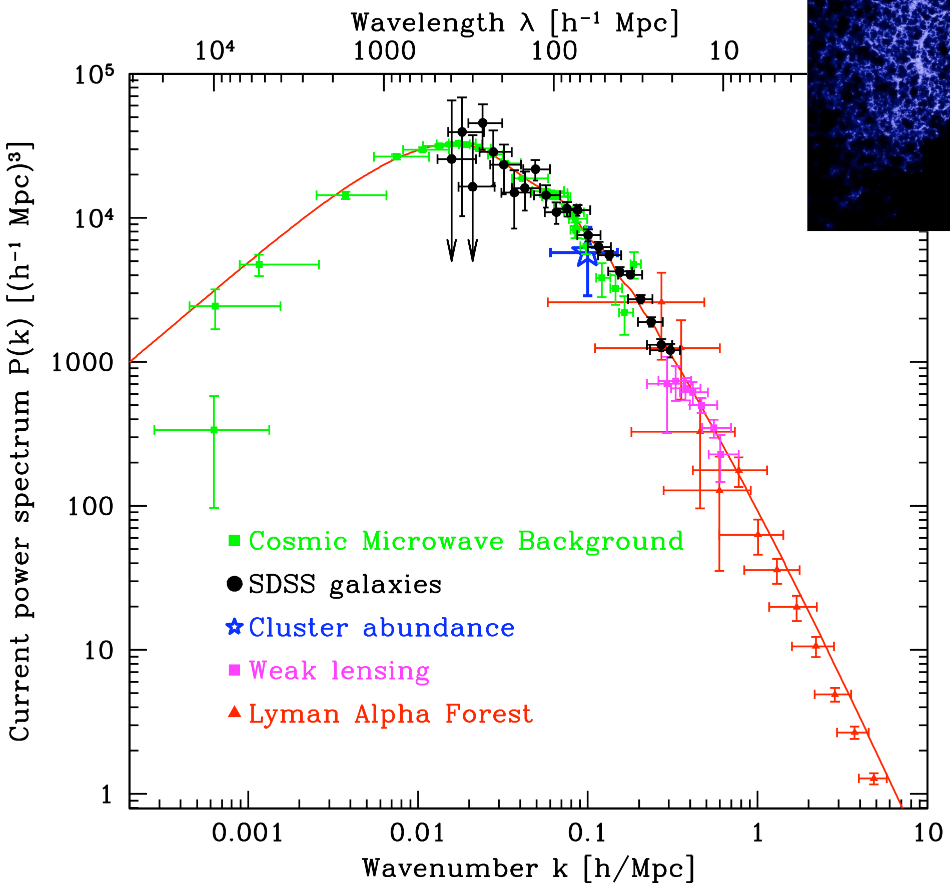
Overview: the concordance ΛCDM model

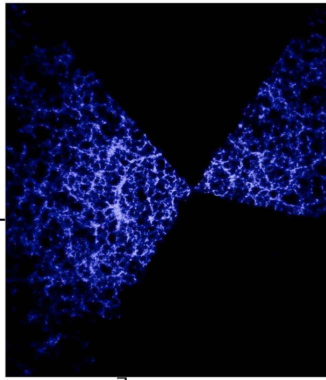
WMAP 3yr $(\Omega_M, \Omega_\Lambda, \Omega_b, h, \sigma_8, n_s) \approx (0.24, 0.76, 0.04, 0.73, 0.74, 0.95)$





Spergel et al. '06





Tegmark et al. '03

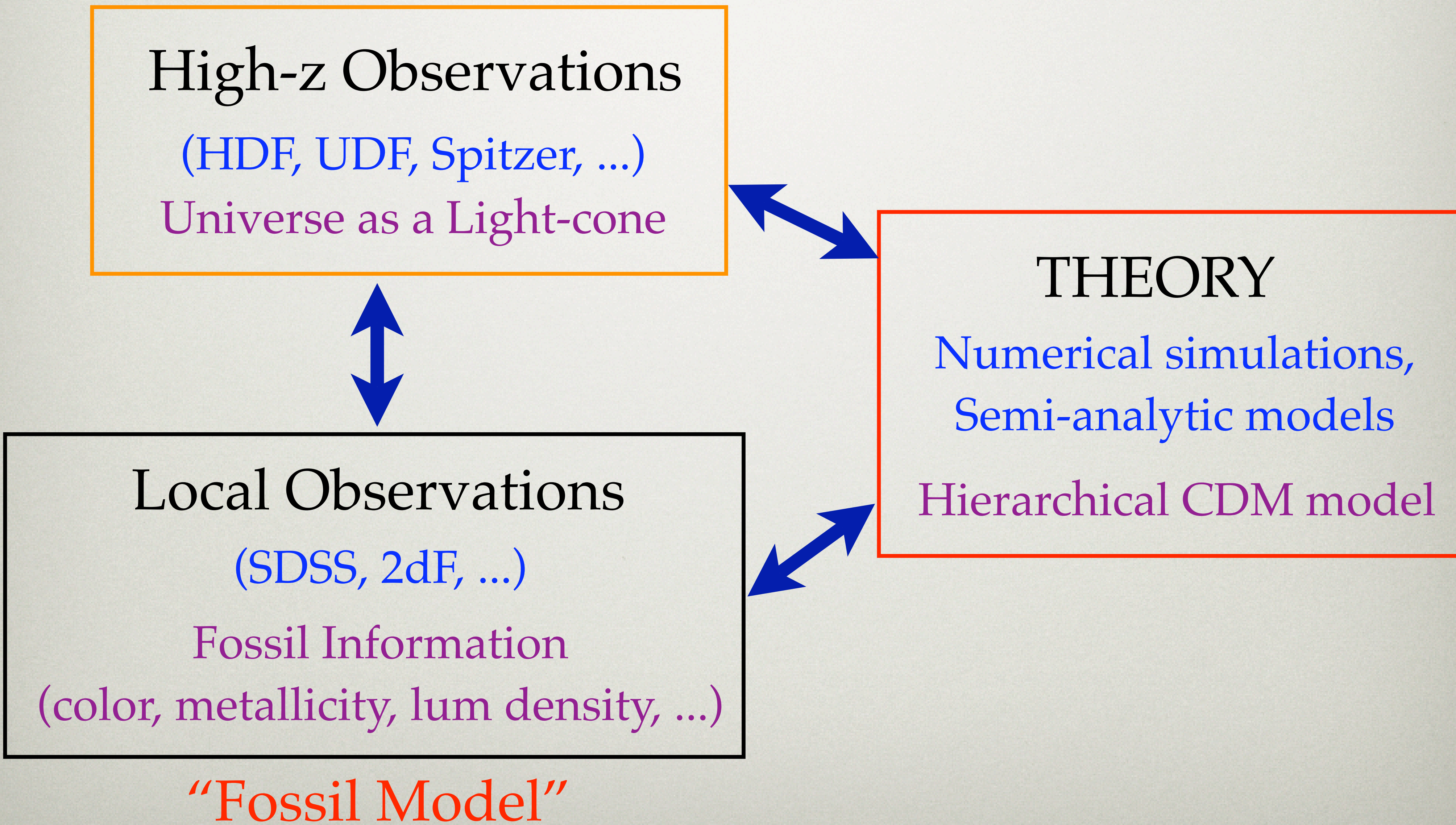
What are the Goals?

- Self-consistent model of galaxy formation (disk & bulge), and BH formation
- How did gas transform into stars?
- Can we build a model that is consistent with low-z & high-z observations?
- Does the hierarchical cold dark matter model work?

What We Derive

- Star Formation Rate: $\dot{\rho}_\star(z)$ $[\mathrm{M_\odot\,yr^{-1}\,Mpc^{-3}}]$
- Disk, Bulge Formation Rate: $\dot{\rho}_\star^{\mathrm{disk}}(z),\ \dot{\rho}_\star^{\mathrm{bulge}}(z)$
- Stellar Mass Density: $\Omega_\star(z)$ $[\mathrm{M_\odot\,Mpc^{-3}}]$
- Luminosity Density: $j(z)$ $[\mathrm{erg\,s^{-1}\,cm^{-3}}]$
- EBL (optical-IR, X-rays): I_{EBL} $[\mathrm{erg\,cm^{-3}}]$
- BH formation rate: $\dot{\rho}_{\mathrm{BH}}(z)$
- colors, etc....

Three Independent Approaches



Approach I
High-z Observation

Universe as a Time-Machine

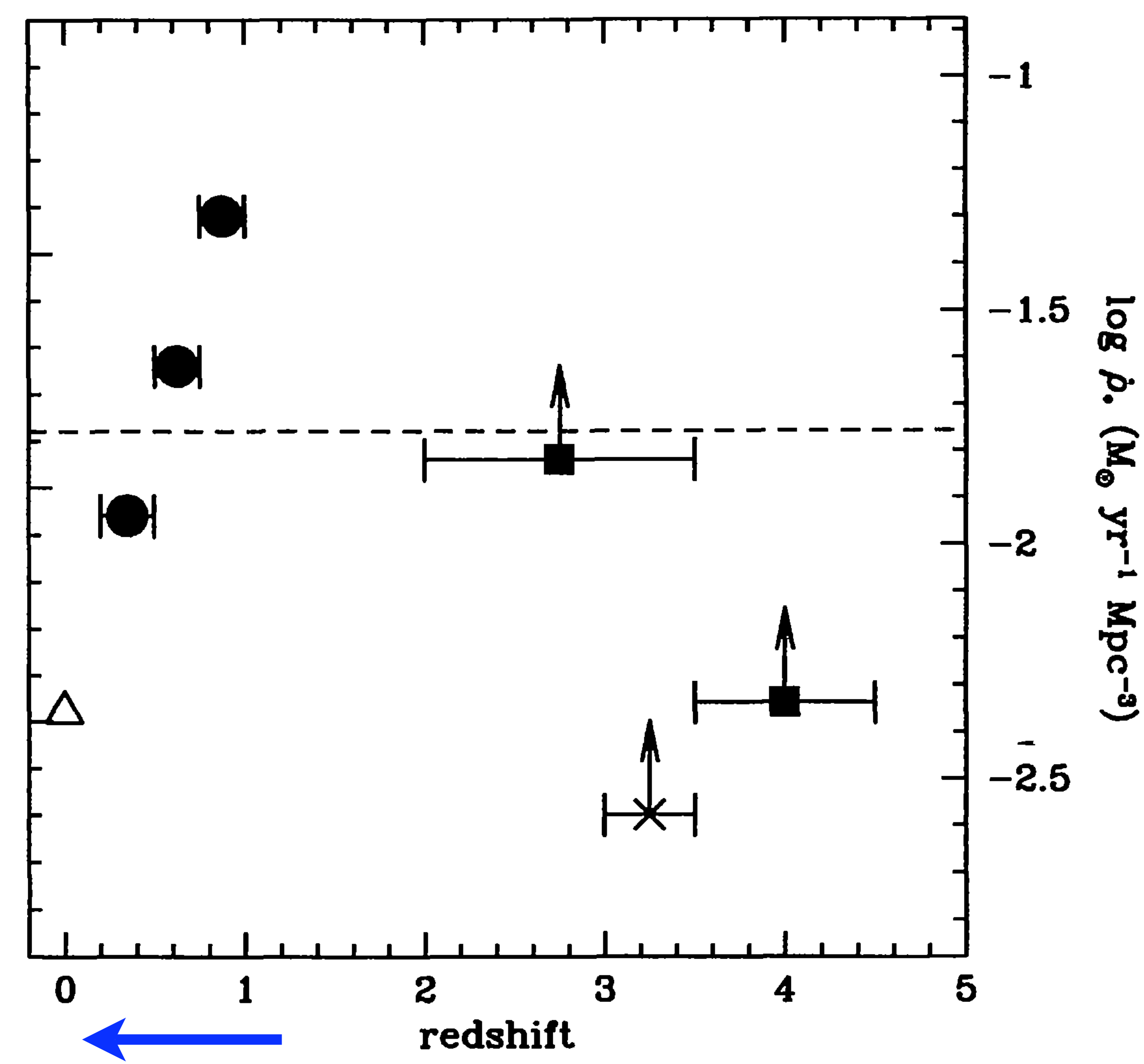
Mon. Not. R. Astron. Soc. **283,** 1388–1404 (1996) 1996

High-redshift galaxies in the *Hubble Deep Field*: colour selection and star formation history to $z \sim 4$

Piero Madau,[1★] Henry C. Ferguson,[1★] Mark E. Dickinson,[1★] Mauro Giavalisco,[2★†]
Charles C. Steidel[3★‡§] and Andrew Fruchter[1★]

Stellar mass formed per unit time per unit volume

- 3 major uncertainties:
  - dust extinction
  - faint-end of LF (flux limit)
  - IMF



Updated "Madau" Plot

Extinction Correction:

z<2: x2.7

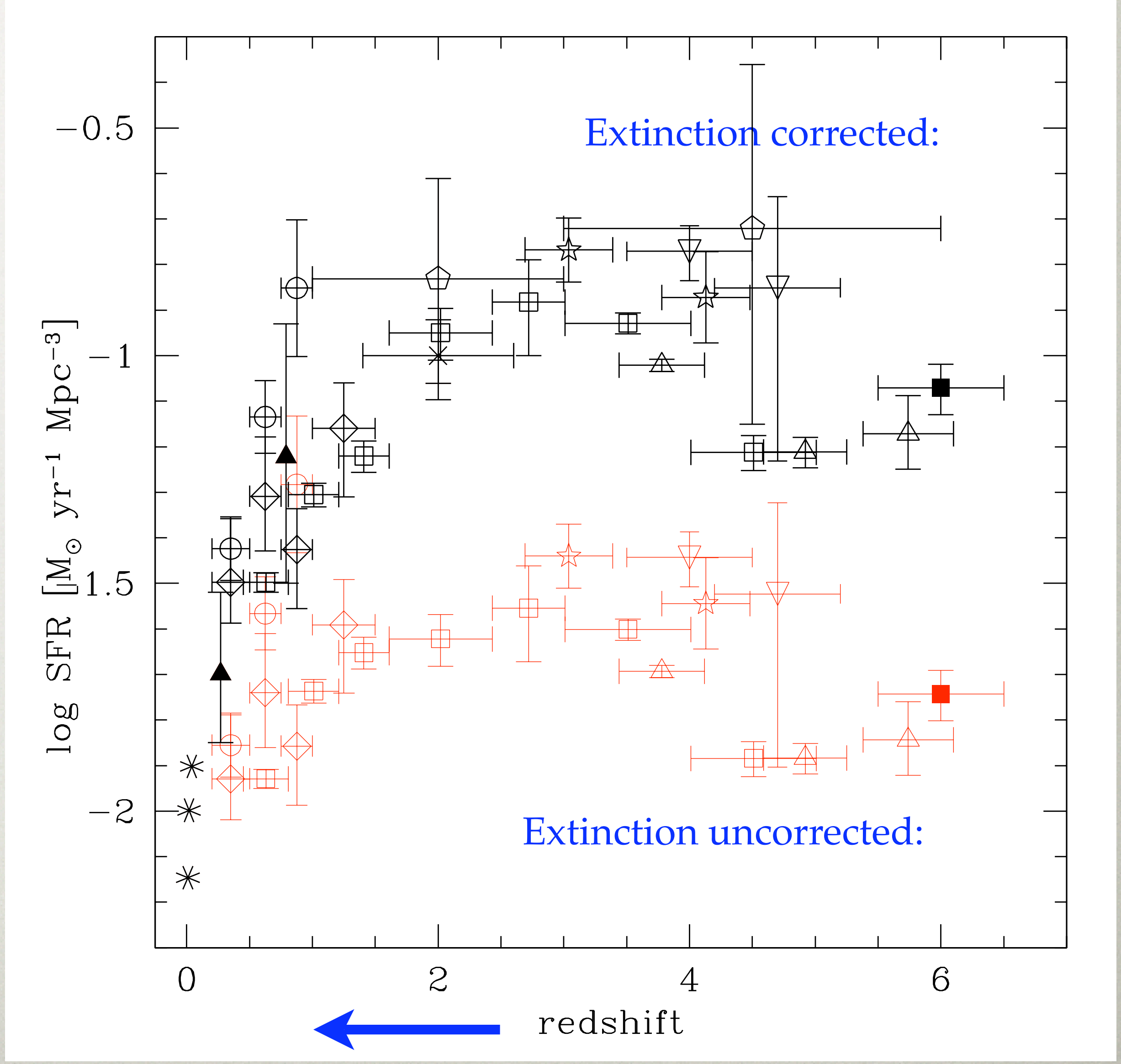
z>2: x4.7

E(B-V)~0.15 (Steidel+ '99)

$$\rho_{UV} = 8.0 \times 10^{27}\ \mathrm{SFR}$$

$[\mathrm{erg\ s^{-1}\ Hz^{-1}}]$ $[M_\odot\ \mathrm{yr}^{-1}]$

Salpeter IMF (Madau+ '98)



Approach II
Local Observation

The Fossil Model

THE ASTROPHYSICAL JOURNAL, **179**:427–438, 1973 January 15

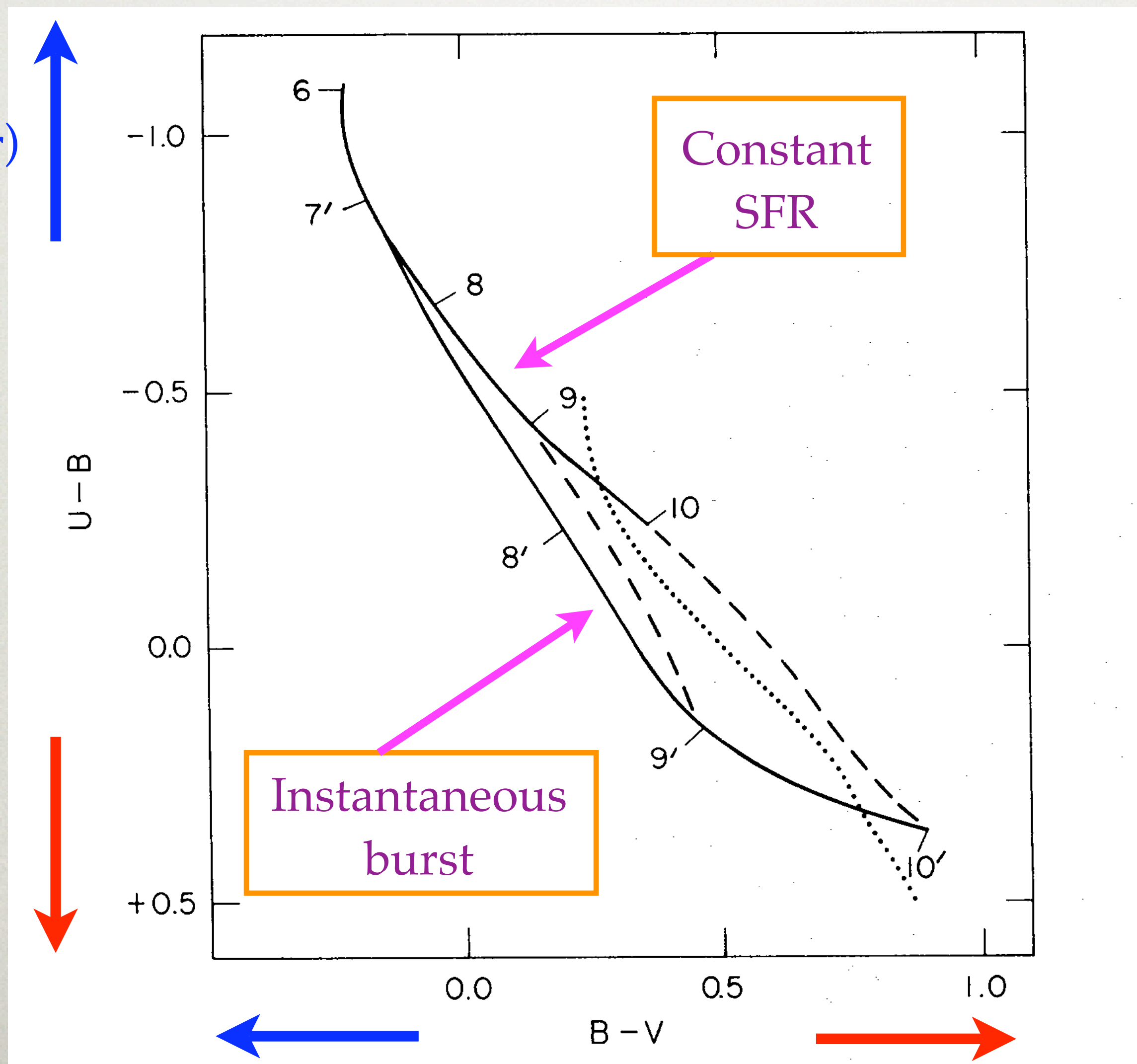
1973

THE HISTORY OF STAR FORMATION AND THE COLORS OF LATE-TYPE GALAXIES

LEONARD SEARLE, W. L. W. SARGENT, AND W. G. BAGNUOLO
Hale Observatories, Carnegie Institution of Washington, California Institute of Technology
Received 1972 June 13; revised 1972 August 9

bluer (younger)

redder (older)



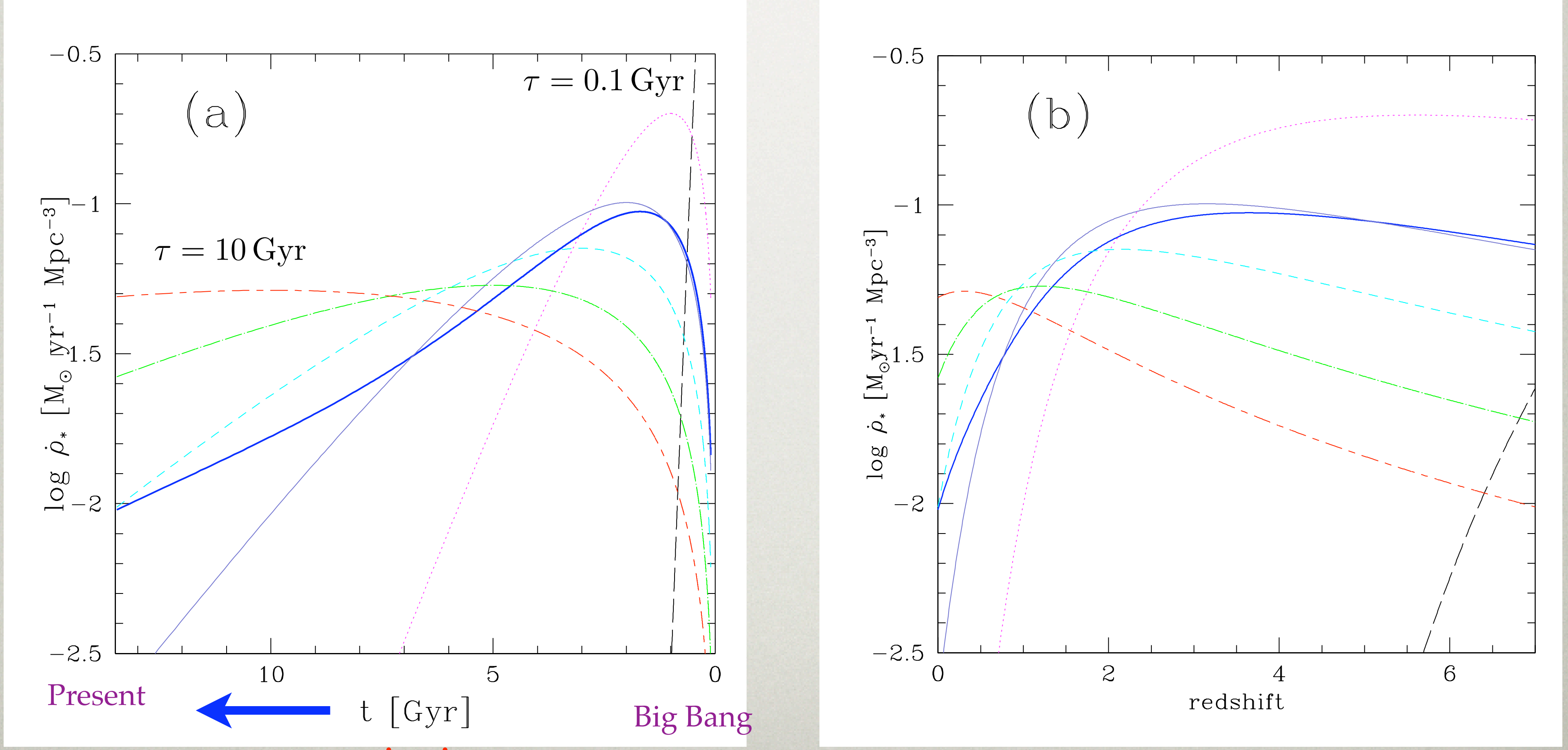
$$\dot{\rho}_\star \propto \exp(-t/\tau)$$

All galaxies are ~>3 Gyrs old

Salpeter IMF

Delayed Exponential Model

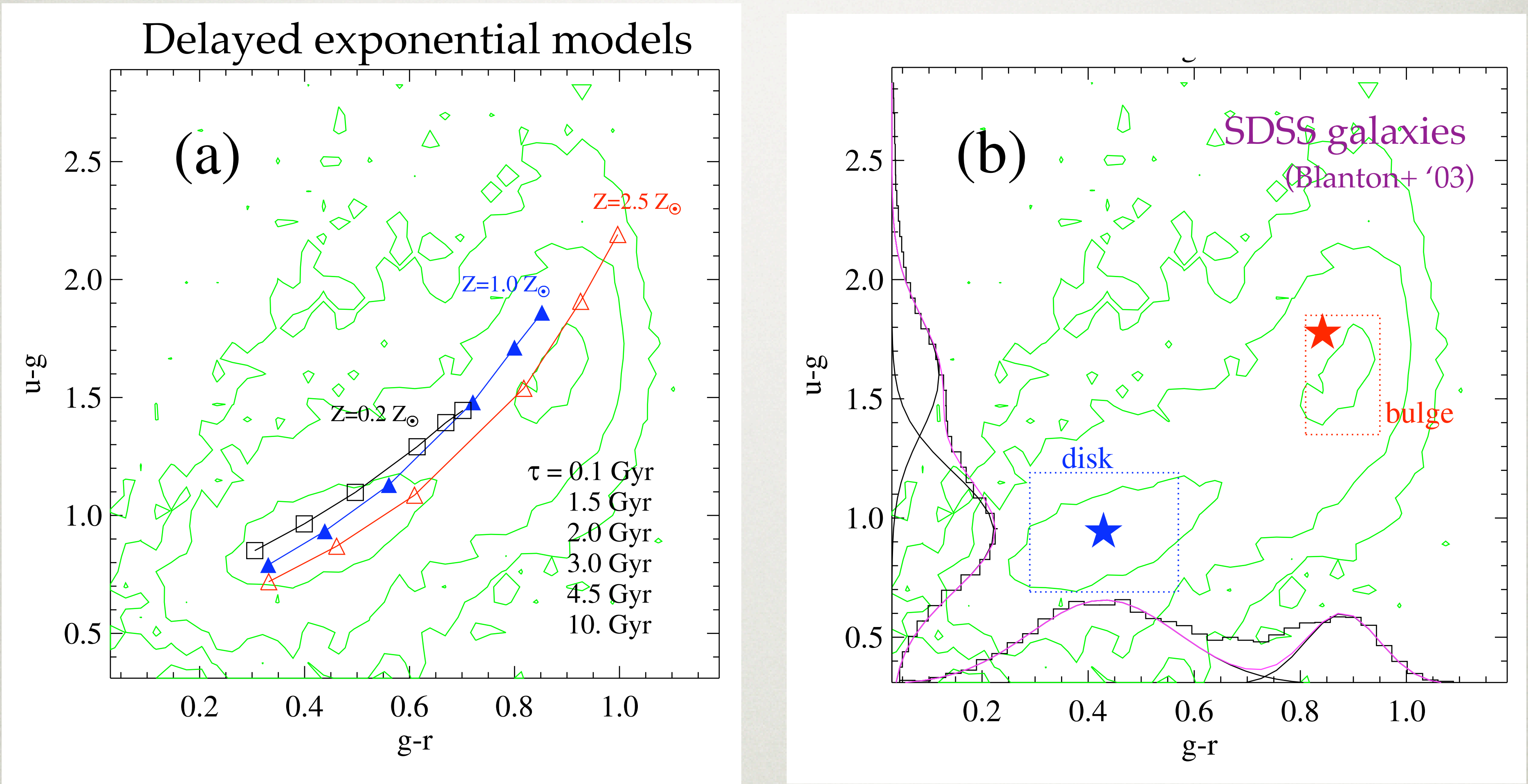
$$\dot{\rho}_\star \propto \left(\frac{t}{\tau}\right) \exp\left(-\frac{t}{\tau}\right) \qquad \tau = 0.1,\ 1,\ 2,\ 3,\ 5,\ 10\,\mathrm{Gyr}$$



cosmic time

redshift

2-Component Galaxies



Population synthesis model:
Bruzual & Charlot (2003)

Disk: $\tau = 4.5\,\mathrm{Gyr}$ $Z/Z_{\odot} = 0.8$

Bulge: $\tau = 1.5\,\mathrm{Gyr}$ $Z/Z_{\odot} = 1.5$

Properties of the Fossil Model

Population	$\Omega_\star$	τ [a]	$Z/Z_\odot$ [b]	$\langle t_{\rm age}\rangle$ [c]	$u-g$	$g-r$	$(M_\star/L_B)$ [d]	$(M_\star/L_r)$ [e]	$(M_\star/L_K)$ [f]
Bulge	0.00115	1.5	1.5	10.5	1.78	0.84	5.27	3.01	0.81
Disk	0.00083	4.5	0.8	7.0	0.94	0.43	1.13	1.11	0.52

$$\dot{\rho}_\star = A\left(\frac{t}{\tau}\right)\exp\left(-\frac{t}{\tau}\right),$$

(A, τ, Z)

3-params set to local observation

Approach III
Theory

Numerical Simulations,
Semi-analytic Models

Theoretical Models

1. Cosmological Hydrodynamic Simulation

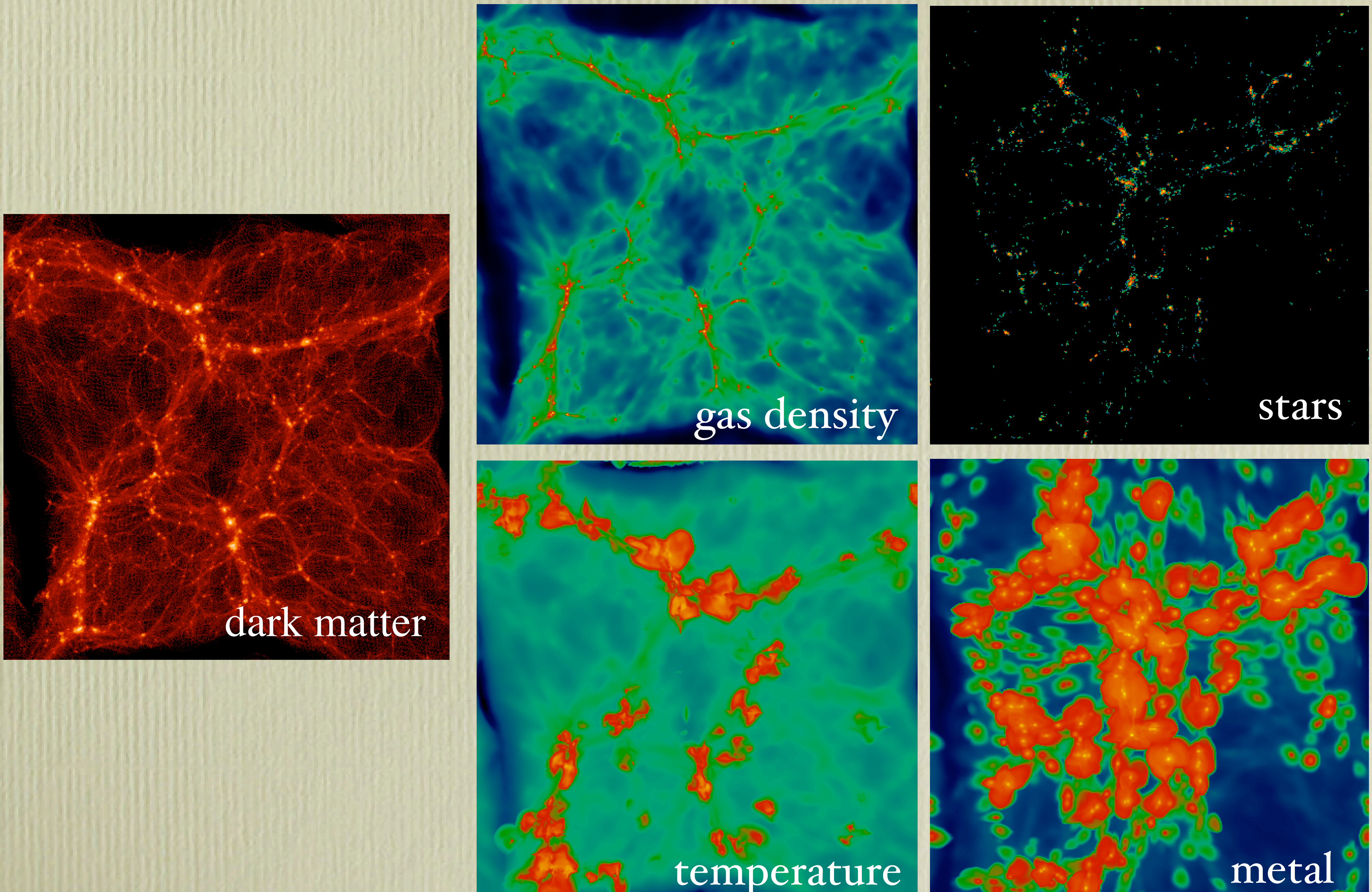
   Eulerian mesh code `TIGER' (Cen, Nagamine, & Ostriker '05)

2. Hernquist & Springel ('03) model (H&S model)

3. Semi-analytic model (SA model)

   (e.g. Kauffmann+ '93; Somerville+ '01; Cole+ '01, etc....)

Model Universe



Nagamine, Cen, Ostiker (2004)

Cosmological Hydro Simulation

Four criteria for SF in a cell

$\delta > \delta_c$	(overdense)
$\nabla \cdot \vec{v} < 0$	(converging flow)
$m_{\rm gas} > m_{\rm Jeans}$	(Jeans unstable)
$t_{\rm cool} < t_{\rm dyn}$	(cooling fast)

$$\Delta m_\star = c_\star \frac{m_{\rm gas}}{t_\star} \Delta t$$

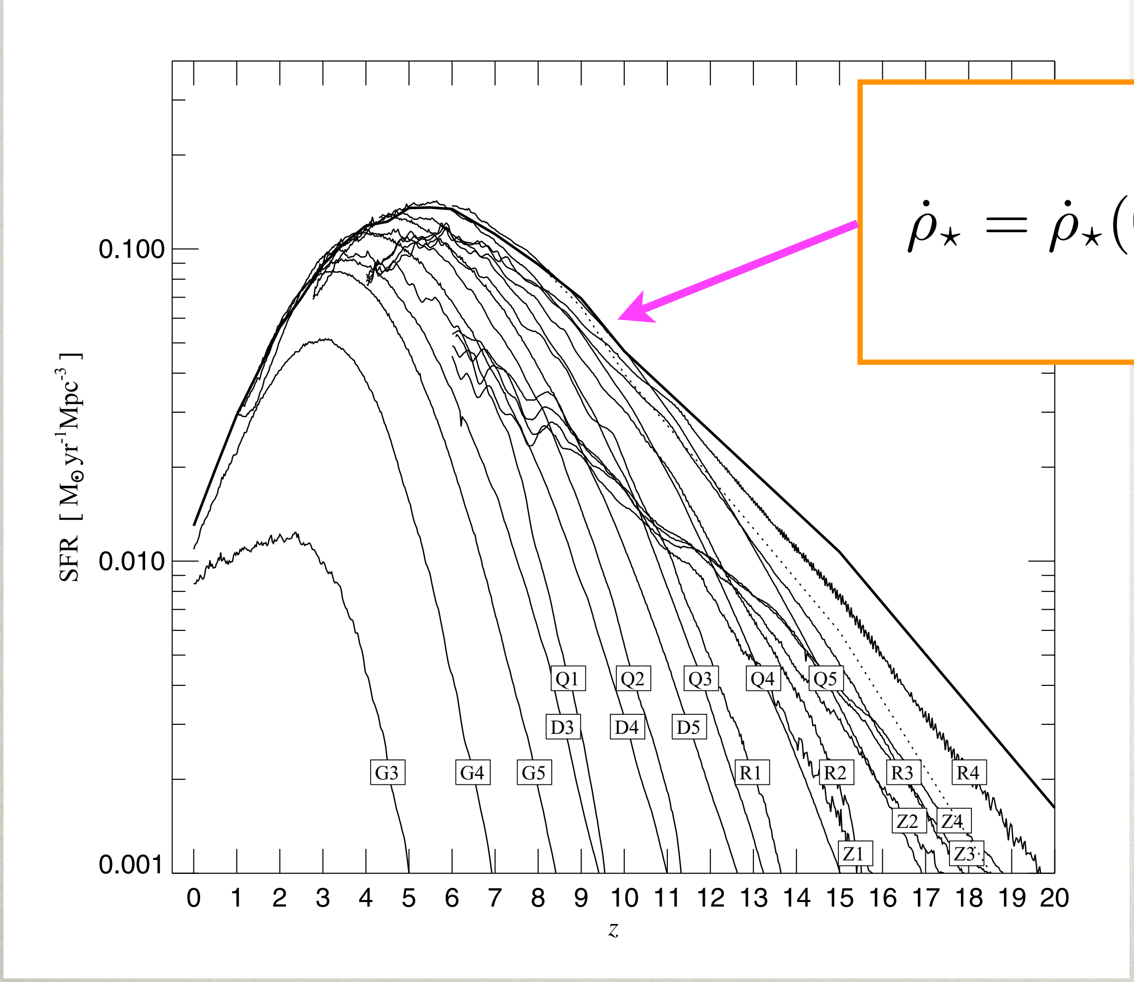
$$t_\star = \max(t_{\rm cool},\ t_{\rm dyn})$$

Each star ptcl is tagged w/

$$(m_\star, t_{\rm form}, Z/Z_\odot)$$

H&S model

Based on cosmological SPH simulations

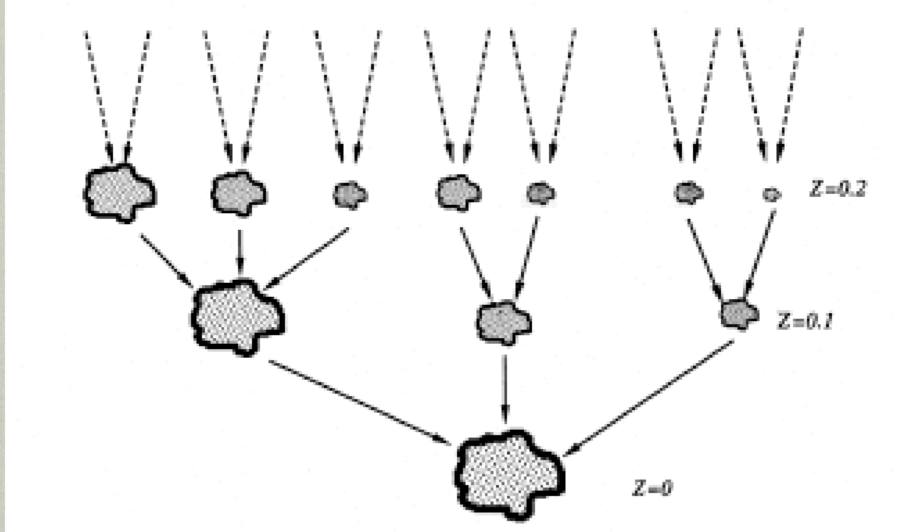


$$\dot{\rho}_\star = \dot{\rho}_\star(0)\,\frac{\chi^2}{1+\alpha(\chi-1)^3\exp\left(\beta\chi^{7/4}\right)}$$

$$\chi(z) \equiv \left[\frac{H(z)}{H_0}\right]^{\frac{2}{3}},$$

Hernquist & Springel (2003)

Semi-analytic Models



Dark matter halo merger tree

Monte Carlo, extenden Press-Schechter, etc...
(e.g. Cole '91; Kauffmann '93
Somerville & Kollatt '99)

e.g.

$$\rho_{\rm cool} = 3.52 \times 10^7 \frac{k_{\rm B} T}{\tau_{\rm cool} \Lambda_{23}(T)},$$

$$\dot{m}_* = \frac{m_{\rm cold}}{\tau_*(V_{\rm c})},$$

$$\tau_*(V_{\rm c}) = \tau_*^0 \left(\frac{V_{\rm c}}{V_0}\right)^{\alpha_*},$$

Somerville+ '01

$$\tau_* = \begin{cases} \tau_*^0[1+\beta(V_{\rm circ})] \\ \tau_*^0[1+\beta(V_{\rm circ})]\left[\frac{\tau_{\rm dyn}(z)}{\tau_{\rm dyn}(0)}\right](1+z)^\sigma \end{cases}$$

Nagashima+ '05

Results of All Models

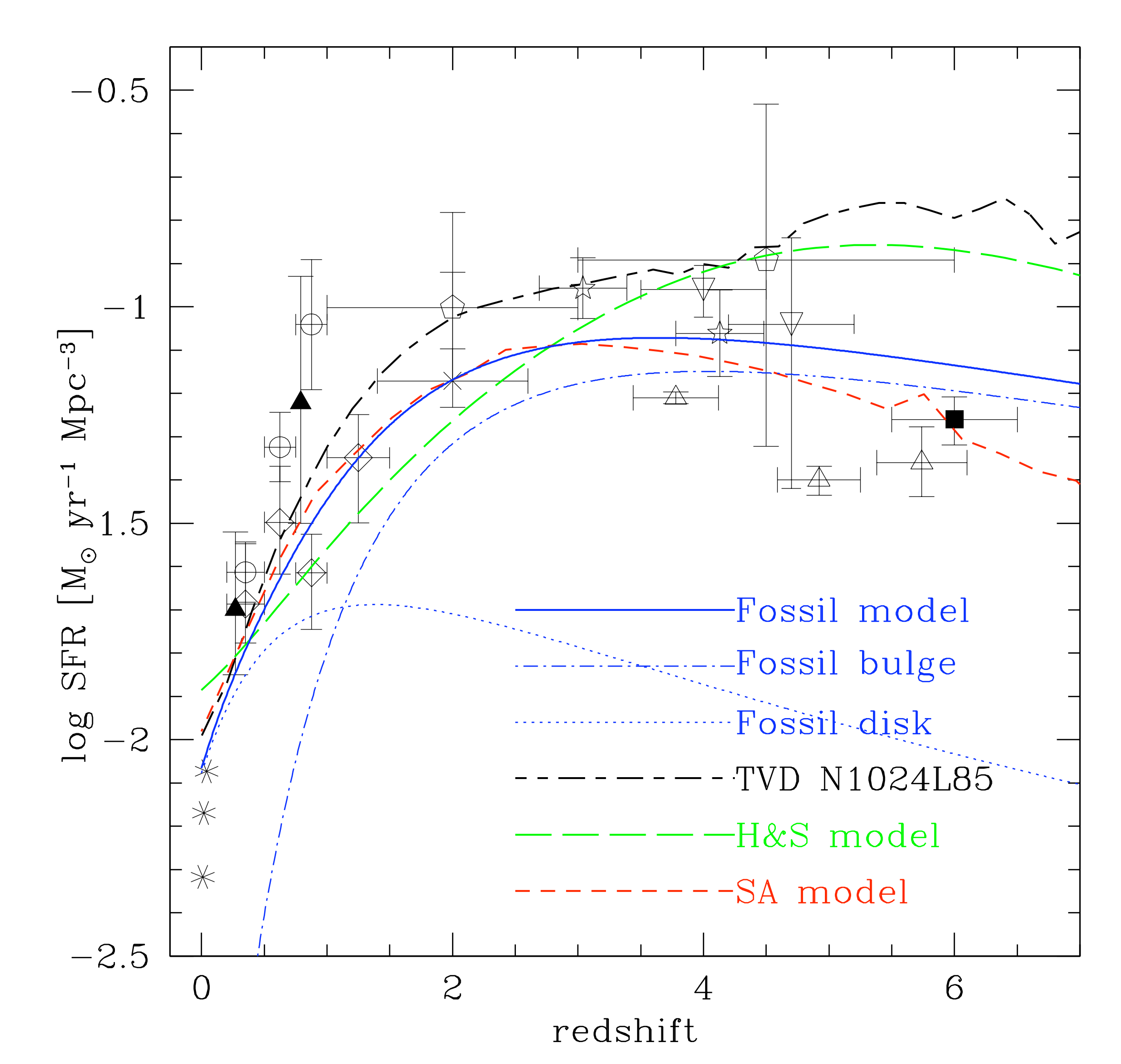
Cosmological SF History

Models agree w/ extinction corrected data to within factor ~2

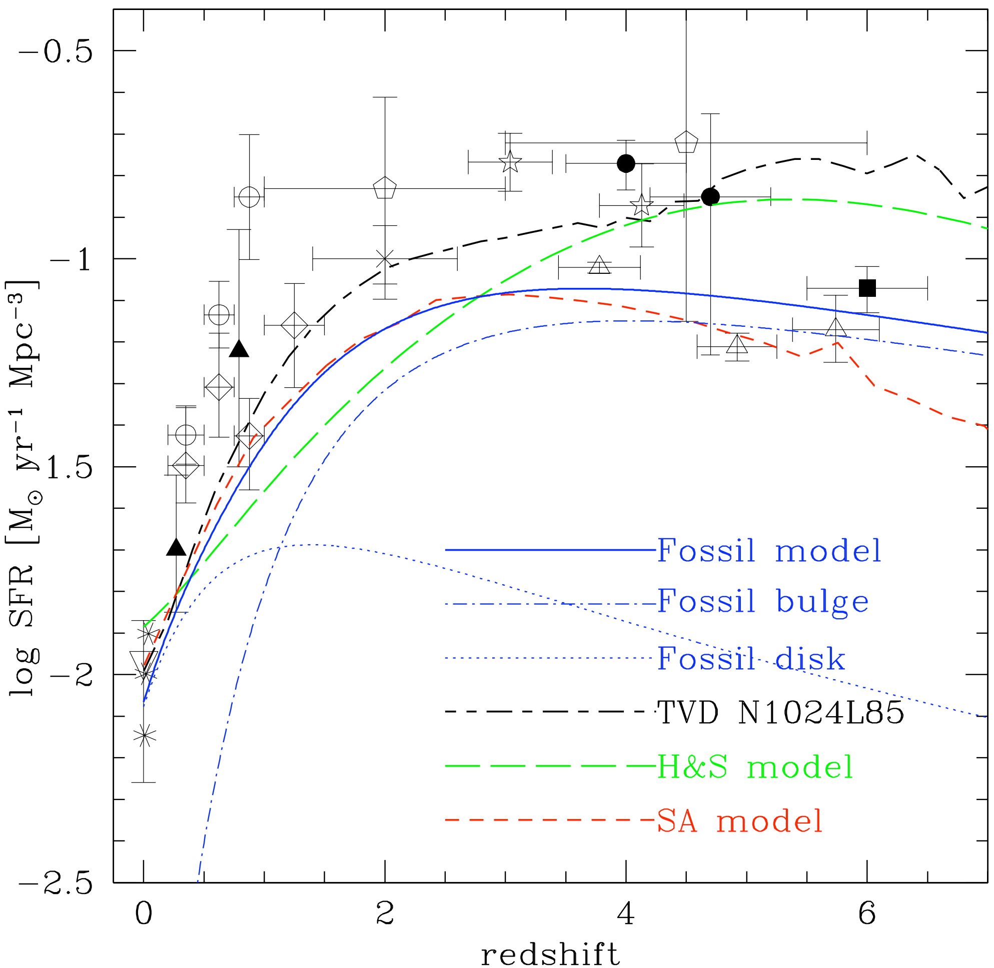
Chabrier IMF $[0.01, 100]\ M_\odot$

$$\rho_{\rm UV} = 1.24 \times 10^{28}\ {\rm SFR}$$

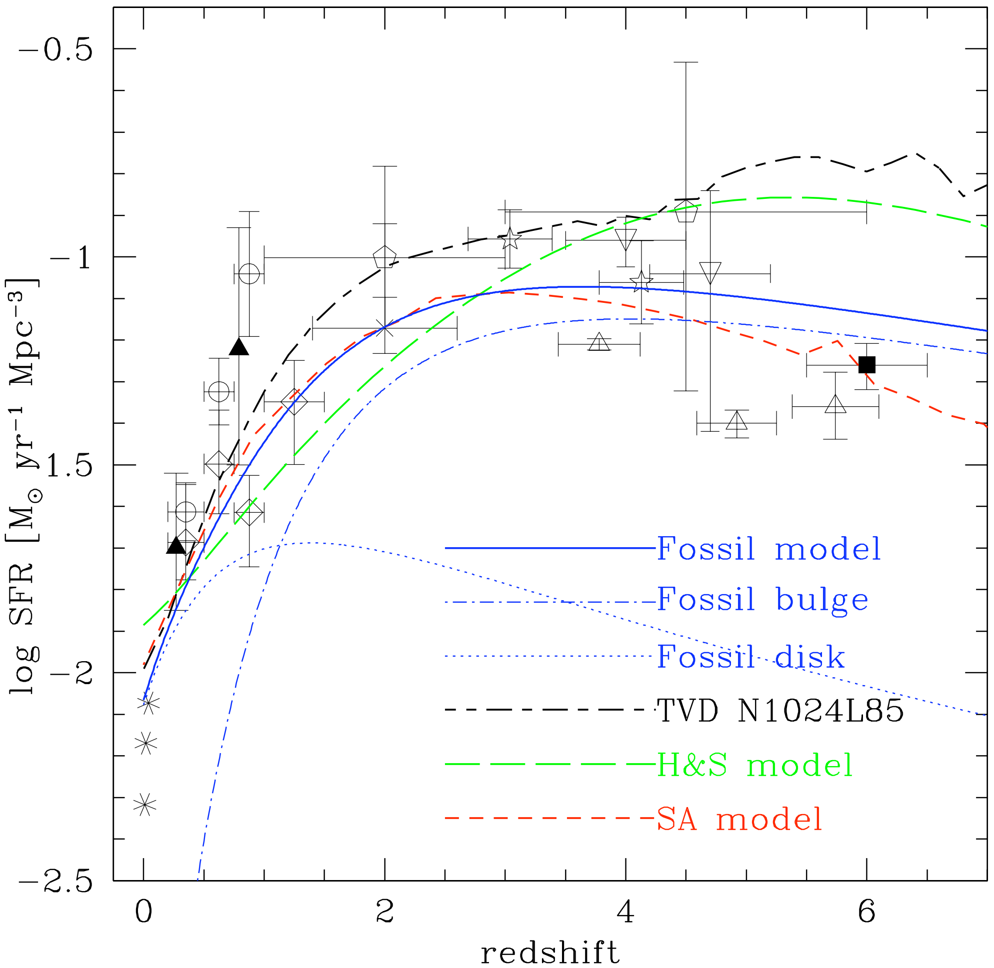
$[{\rm erg\ s^{-1}\ Hz^{-1}}]$ $[{\rm M_\odot\ yr^{-1}}]$



Comparing Two IMFs



Salpeter IMF



Chabrier IMF

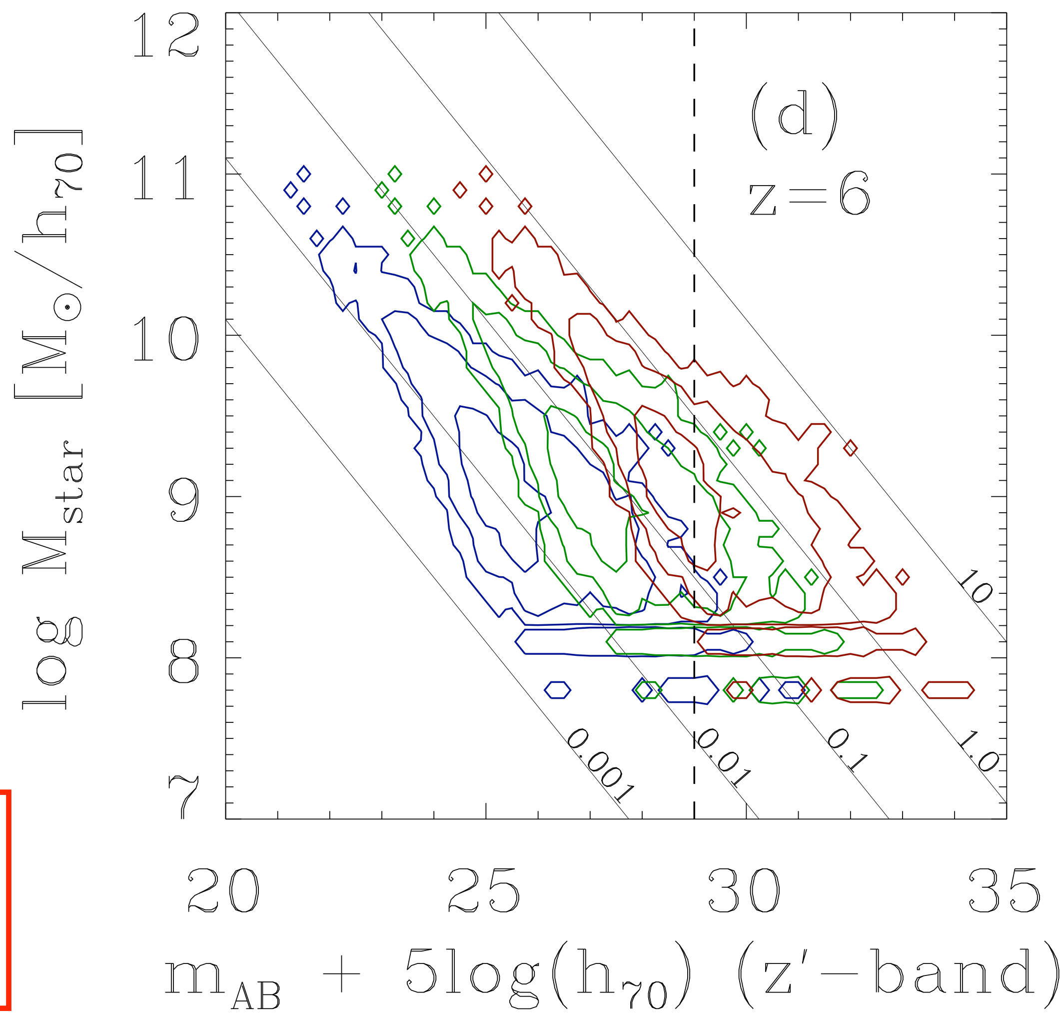
The most massive gal @ z=6 has 10^{11} M⊙

- Eyles et al. (2005)
  - Mstar>10^10M⊙

Not a surprise.

There is no "mass-scale problem" at z=2-6.

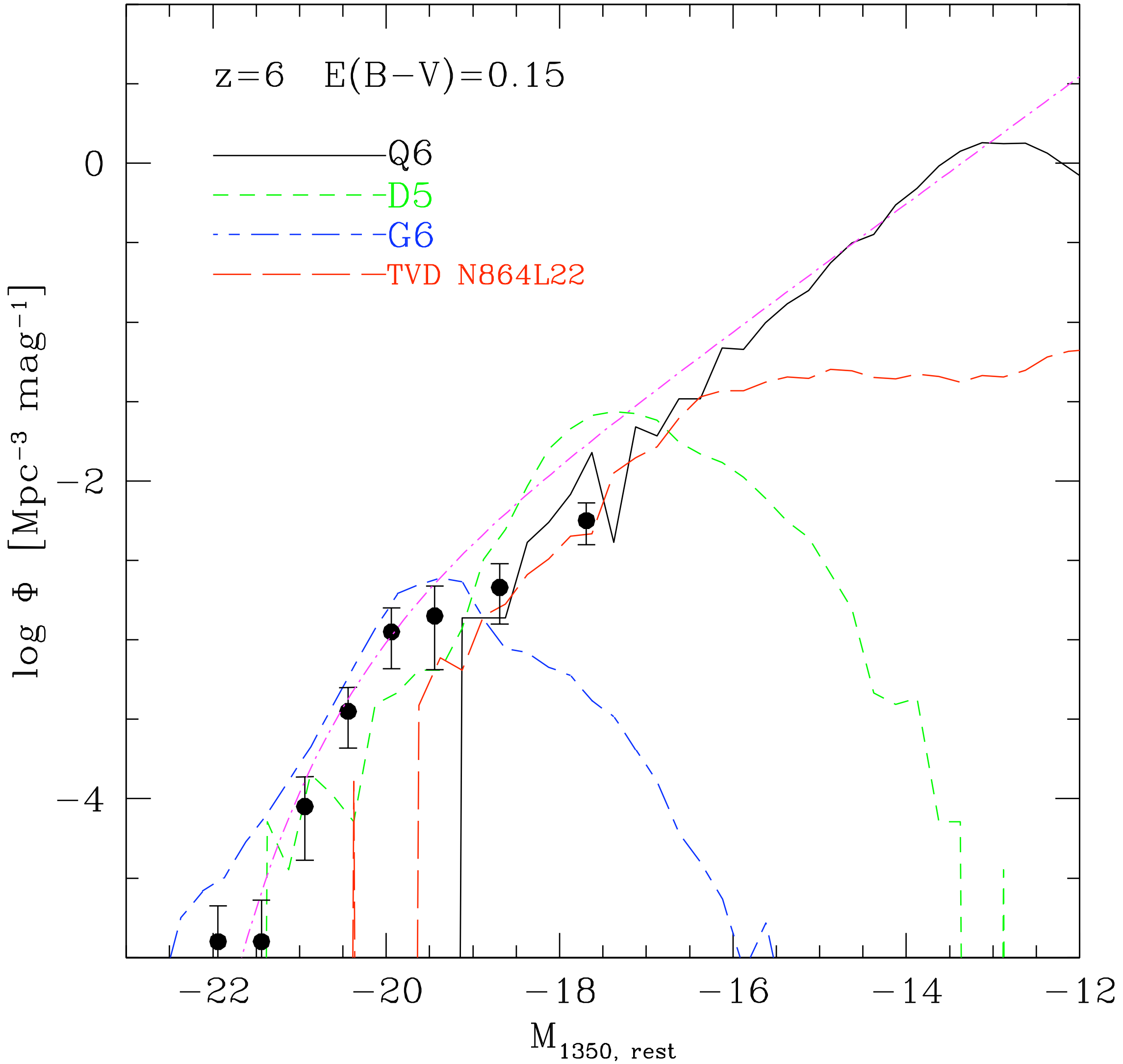
KN et al. 2004, 2005a,b



Night, KN + '06
KN+ '06

Rest-frame UV LF at z=6

- Reasonable agreement with obs at bright-end
- Steep faint-end in sims: $\alpha \sim -2.0$



Updated data points: Bouwens+ '06

Nagamine+ '06

`BzK' = (B-z) - (z-K) galaxies

SPH G6 run:

K<20

$3.6 \times 10^{-4} h^3 \mathrm{Mpc}^{-3}$

K<20 & z-K>2.5

$1.9 \times 10^{-4} h^3 \mathrm{Mpc}^{-3}$

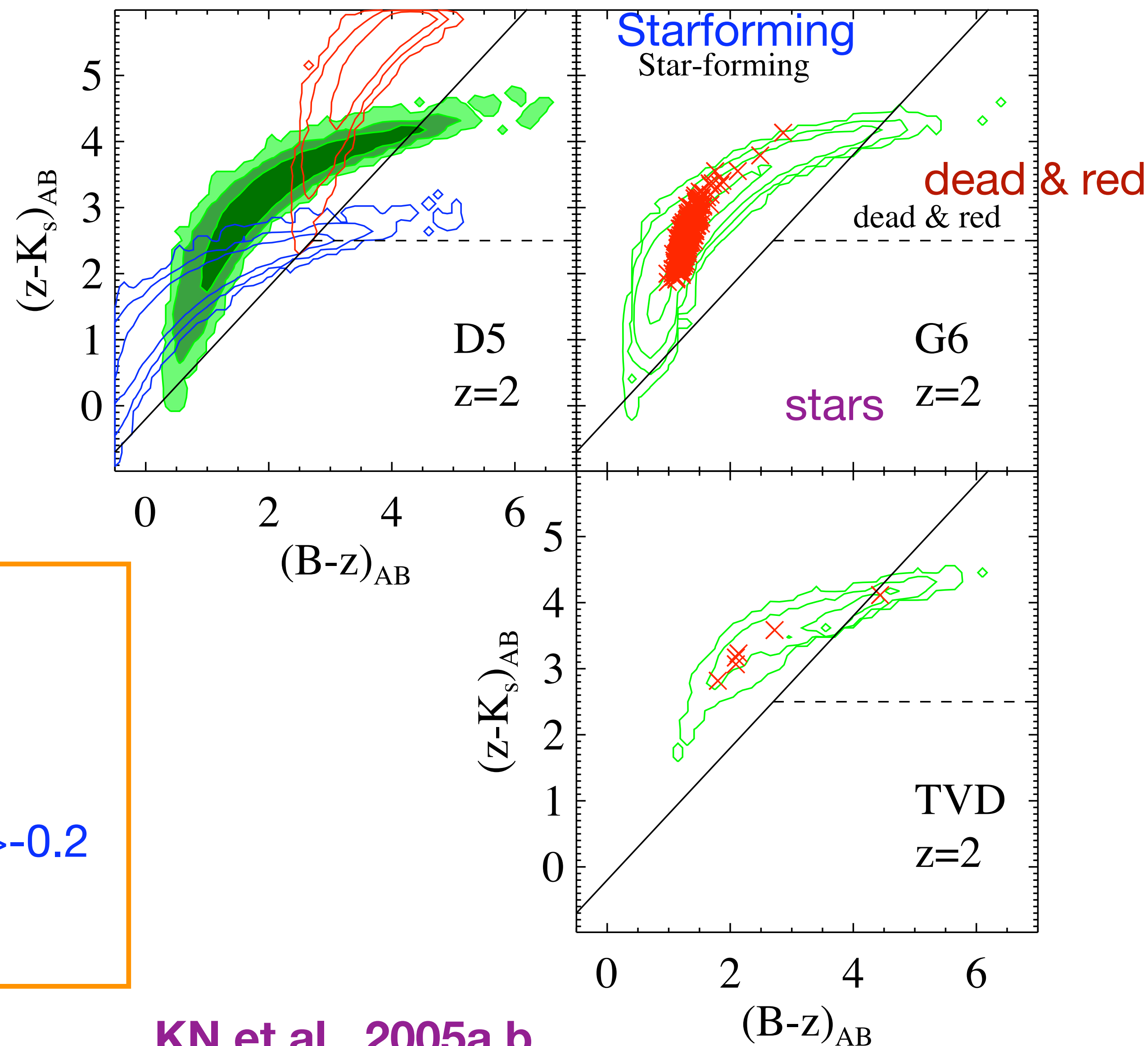
TVD run:

K<20 & z-K>2.5

$5.6 \times 10^{-4} h^3 \mathrm{Mpc}^{-3}$

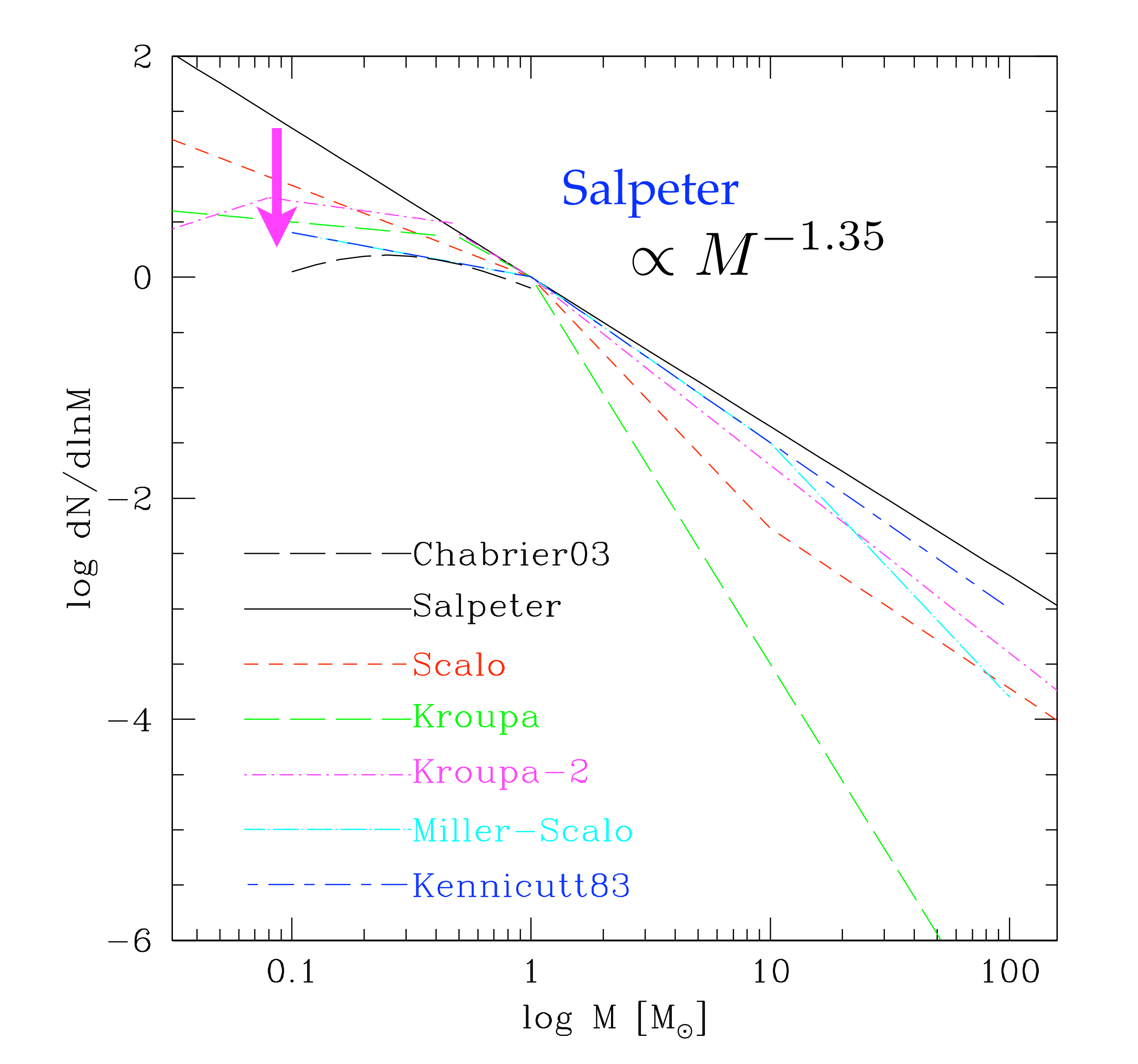
K<20 & z-K>2.5 & BzK>-0.2

$1.0 \times 10^{-4} h^3 \mathrm{Mpc}^{-3}$



KN et al. 2005a,b

Initial Mass Function of Stars (IMF)

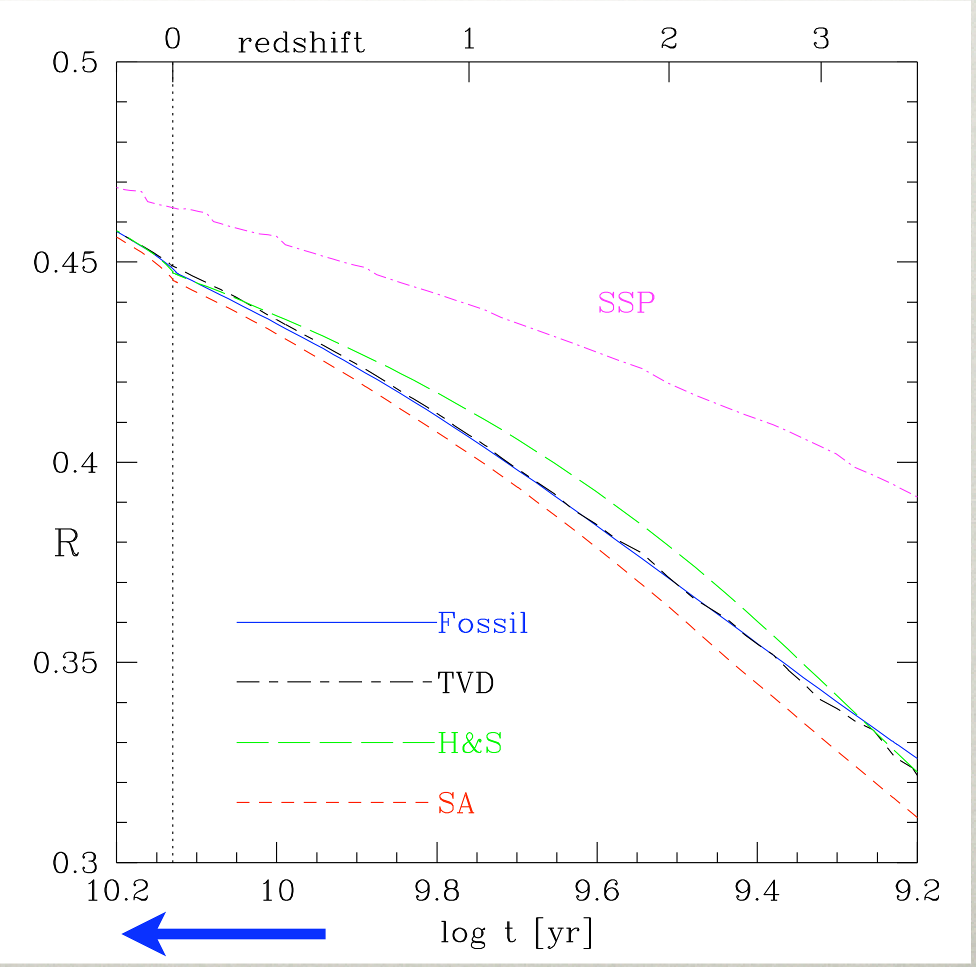


Gas Recycling Fraction

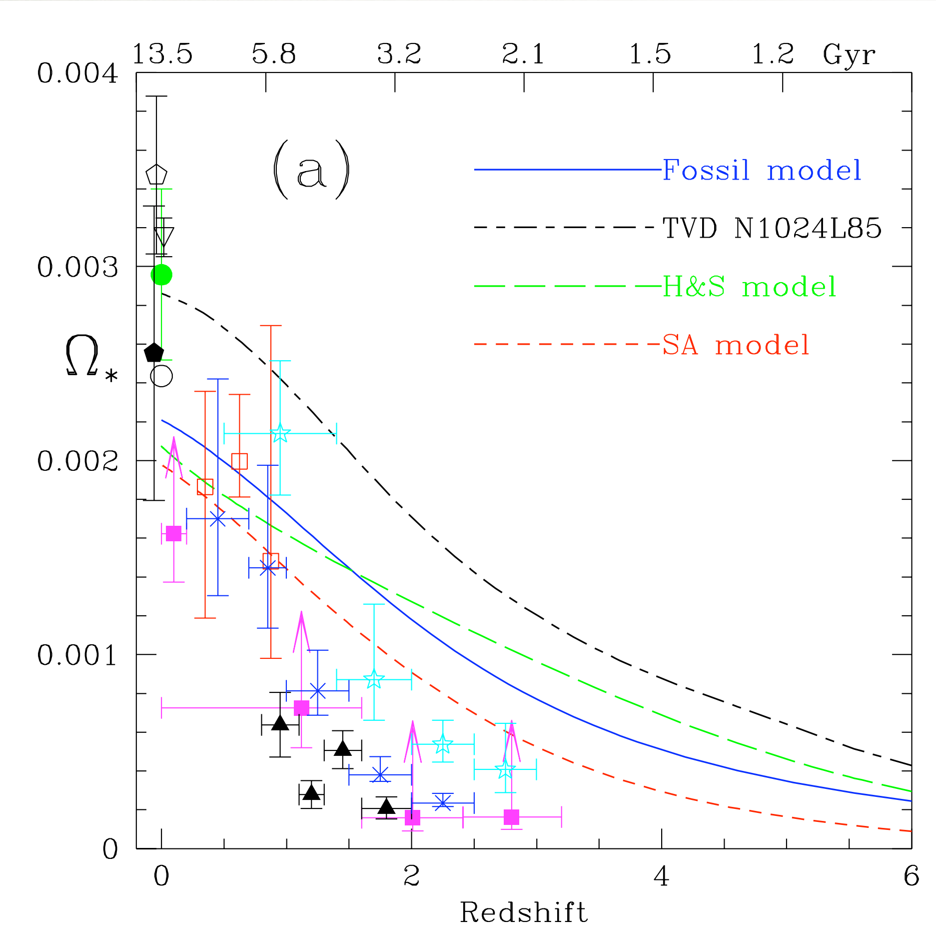
$$R \equiv \frac{\text{Gas returned to ISM}}{\text{Total amount of gas initially converted to stars}}$$

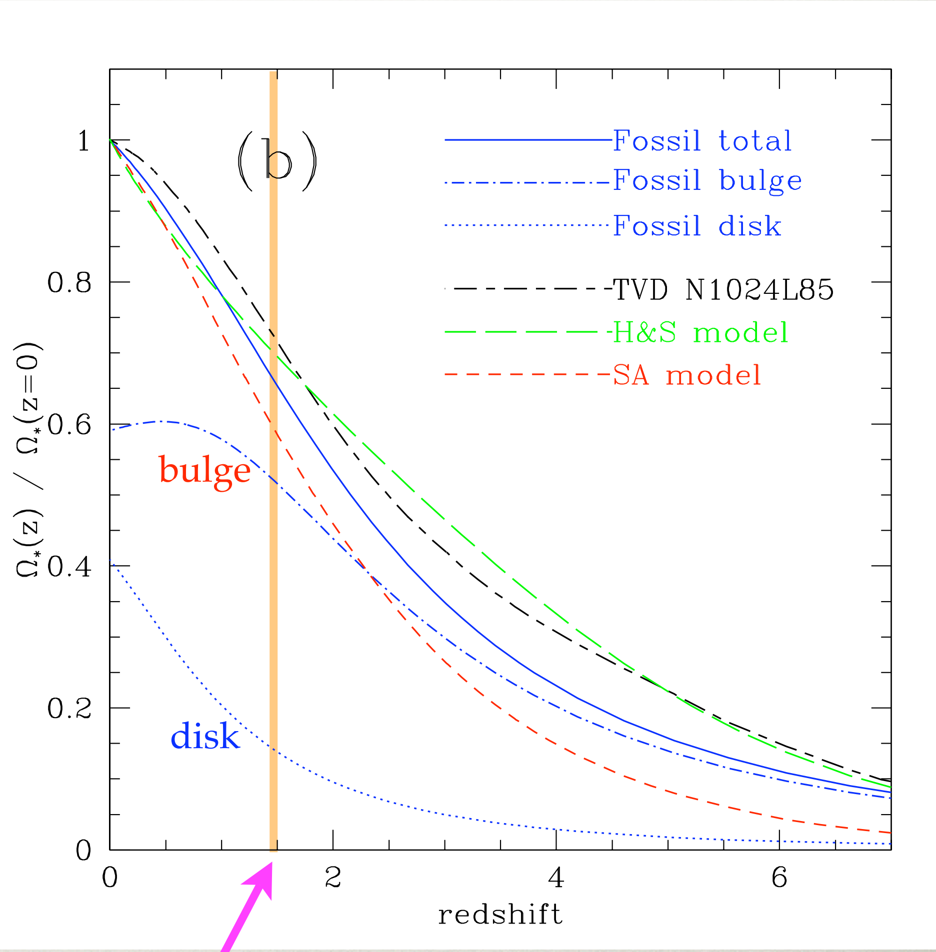
Chabrier IMF $[0.01, 100]\, M_{\odot}$

$$R \sim 0.45$$
$$@\ t = t_0$$



Stellar Mass Density





"Is there a Missing Galaxy Problem at High Redshift?"

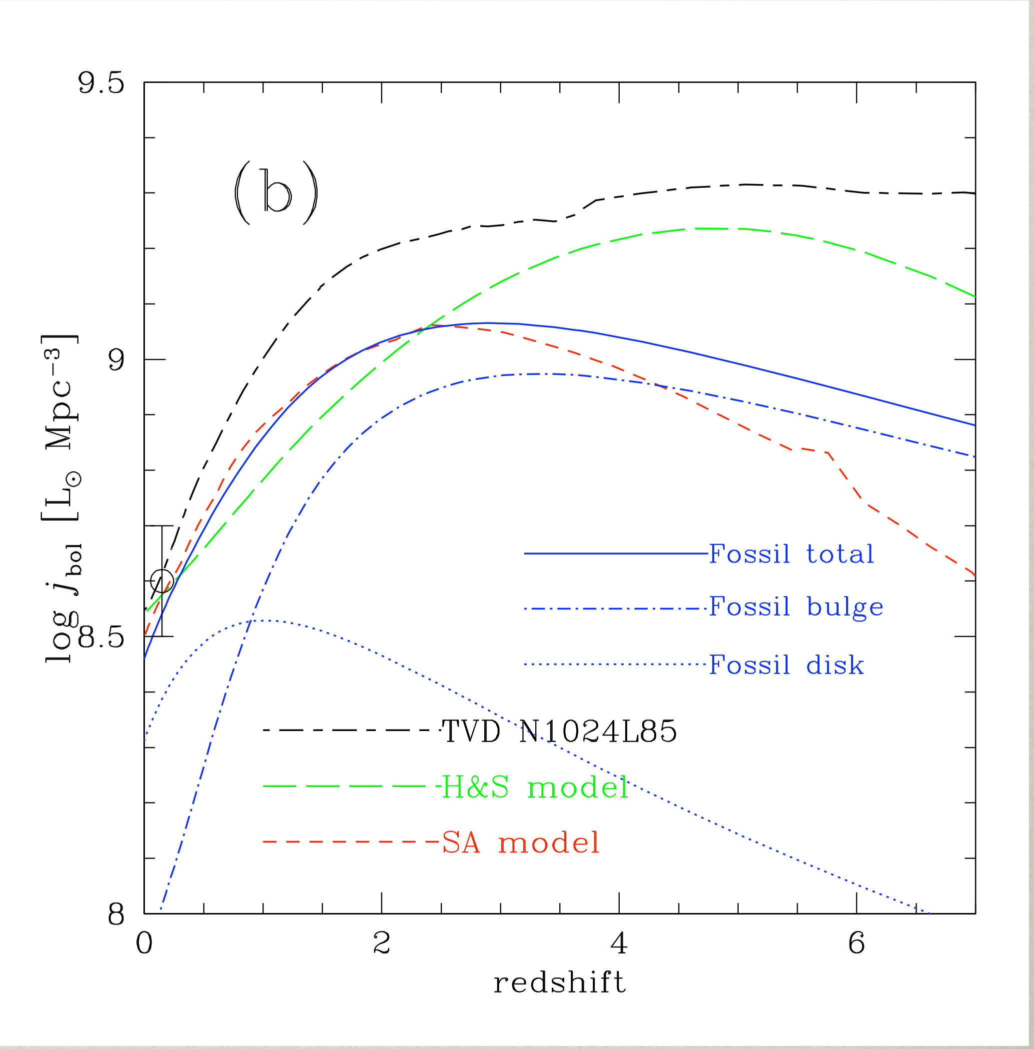
(Nagamine+ '05)

z≥1.5 : epoch of bulge formation

Bolometric Luminosity Density

$$j_{\rm bol}(t) = \int_0^t \dot{\rho}_*(\tau) L_{\rm bol}(t-\tau) d\tau,$$

Bolometric lum density per unit solar mass for age=t-τ

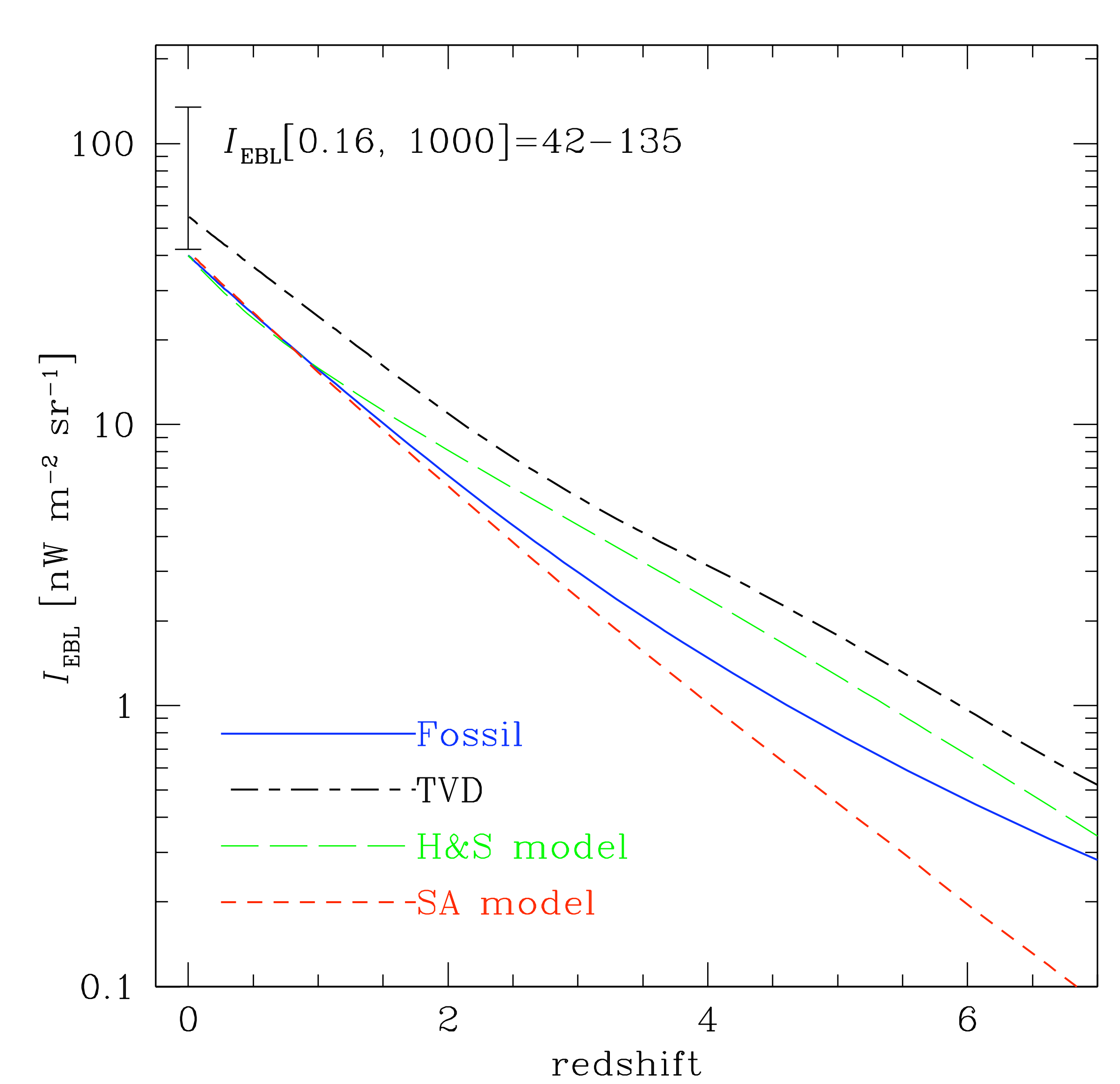


Extra-galactic Background Light (EBL)

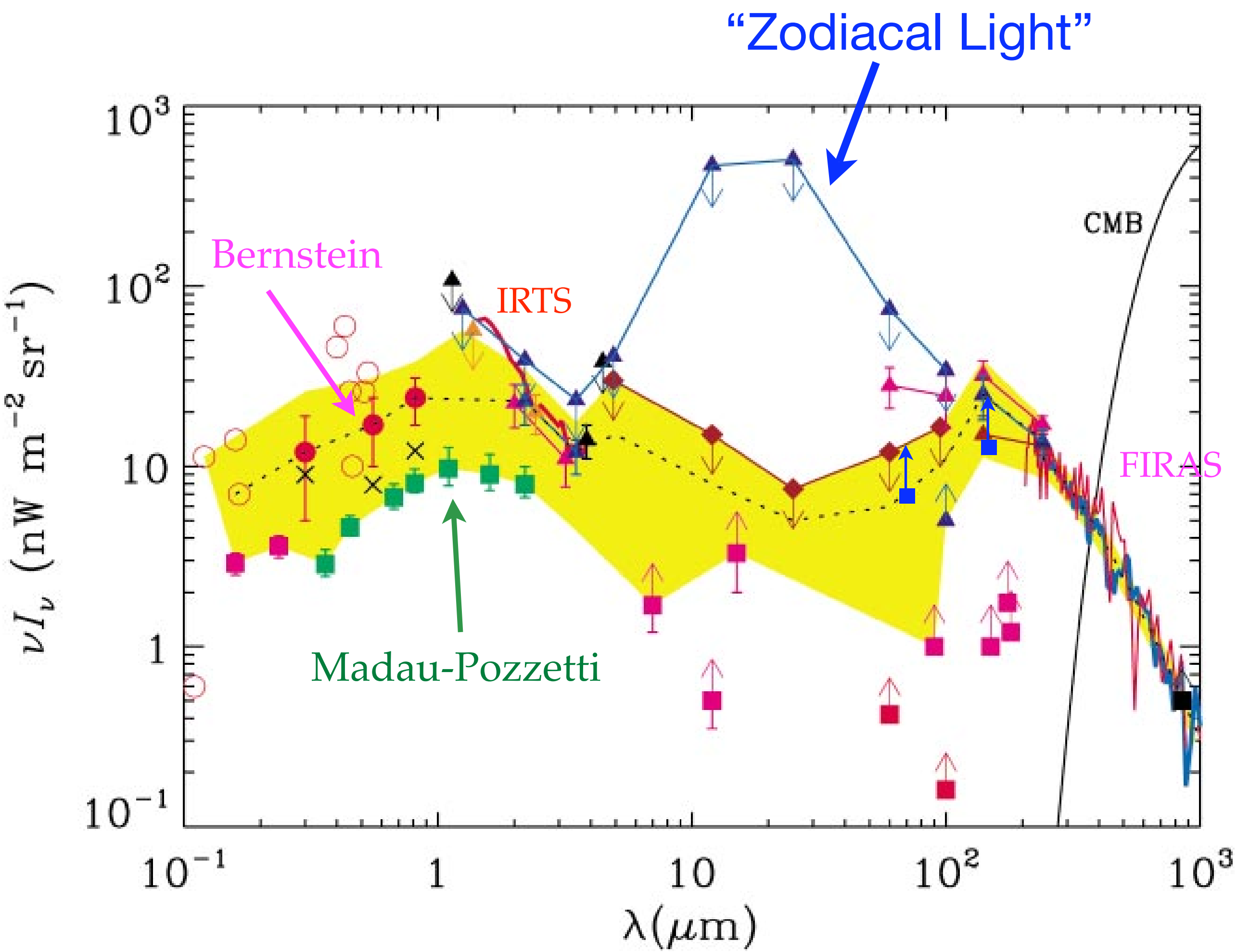
$$I_{EBL}(z) = \left(\frac{c}{4\pi}\right) \int_z^\infty j_{\rm bol}(z') \left|\frac{dt}{dz'}\right| dz'$$

All models give
~ 40-60 nW m^{-1} sr^{-1}

Total energy output available from stars



Observational constraints on EBL



Hauser & Dwek (2001)

$$I_{\rm upper} = 170$$

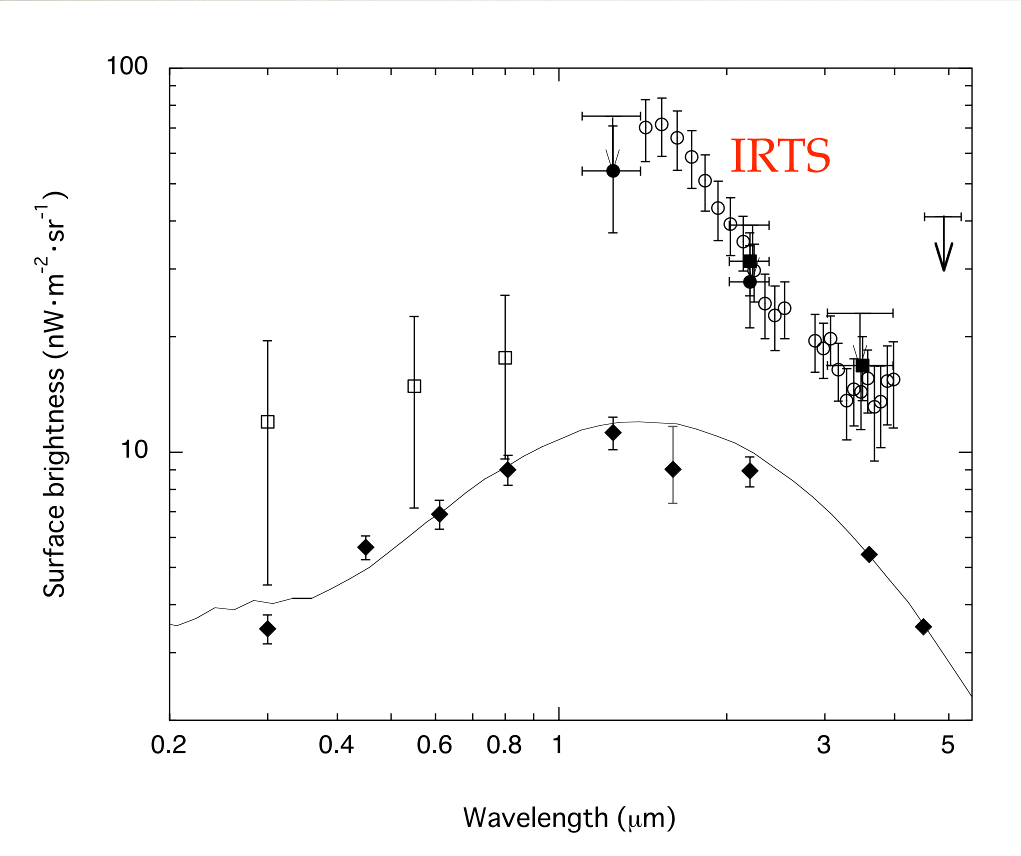
$$I_{\rm middle} = 100$$

$$I_{\rm lower} = 45$$

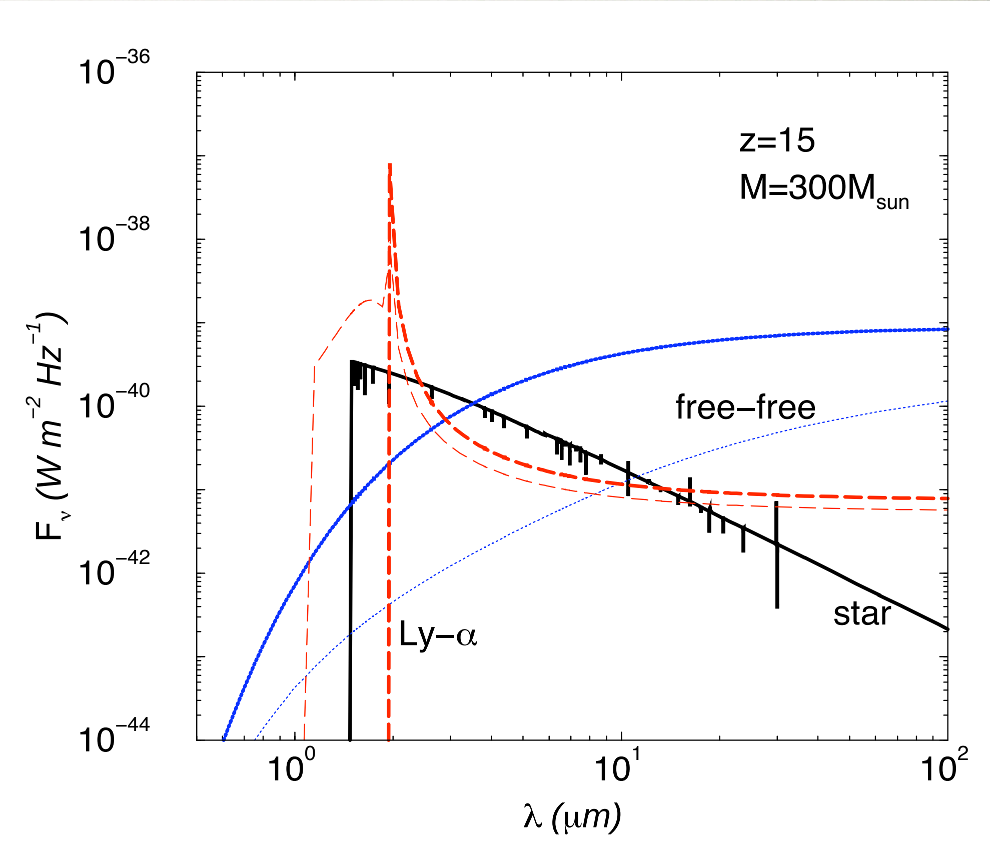
$$\rm nW\ m^{-2}\ sr^{-1}$$

Challenge: Subtraction of Zodiacal light
(emission by interplanetary dust)

NIRB Excess??



(Matsumoto+ '05)



First Star??

(Cooray+ '05)

Physical Quantities at z=0

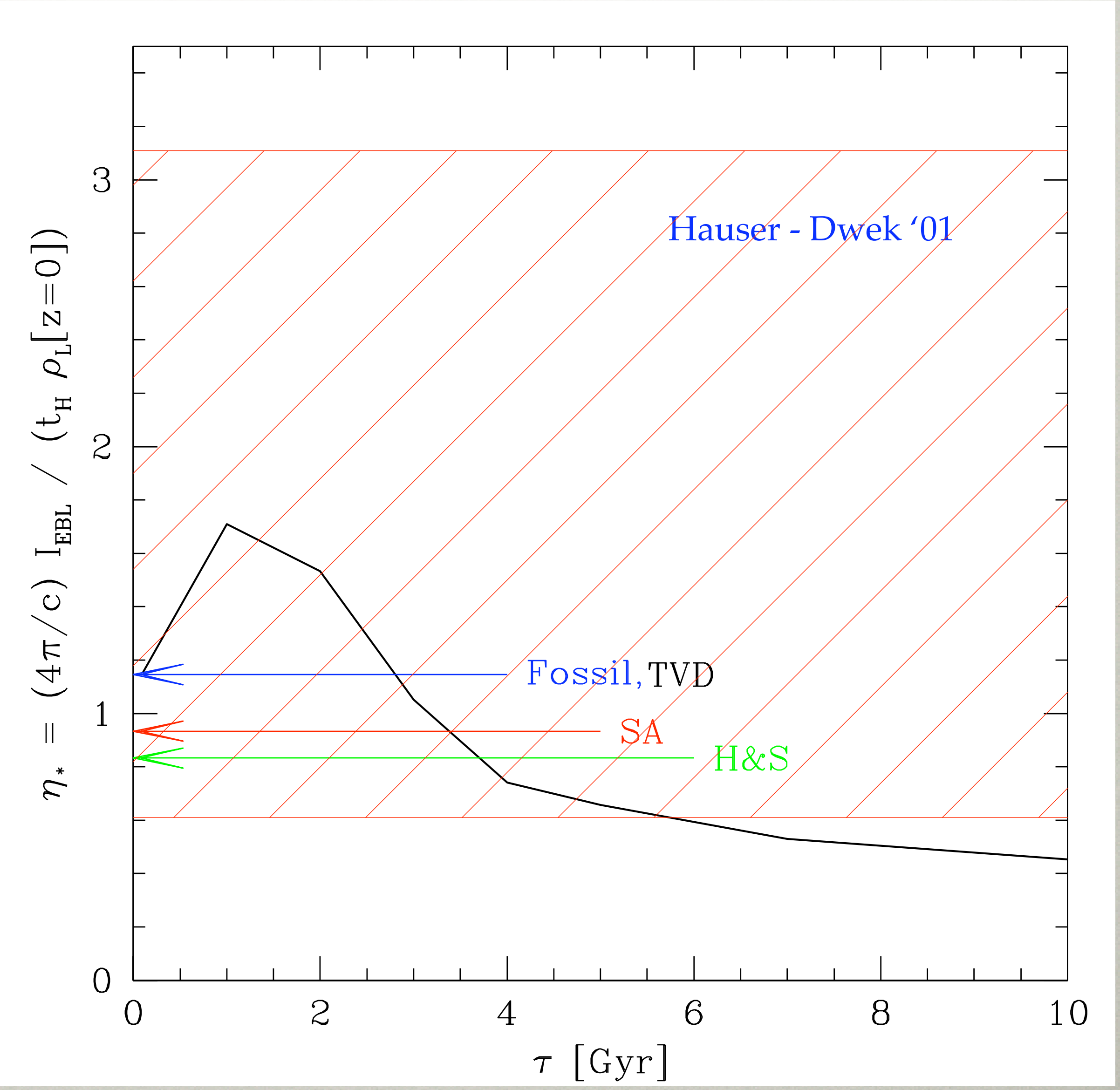
Model	$\Omega_\star$[†]	$M_\star$[♮]	$M_{\rm rem}$[∀]	I_{EBL}[‡]	$\dot{\rho}_\star$[§]	$j_{\rm bol}$[a]	j_U[b]	j_B[c]	j_r[d]	j_K[e]	$u-g$	$g-r$
Fossil	0.0020	2.11	0.59	40	0.86	2.8	1.4	1.3	1.5	4.1	1.54	0.67
..... bulge	0.00115	1.21	0.36	20	0.022	0.7	0.2	0.3	0.5	1.9	1.78	0.84
..... disk	0.00083	0.91	0.22	20	0.837	2.1	1.2	1.0	1.0	2.2	0.94	0.43
TVD	0.0029	3.04	0.85	55	1.02	3.5	1.6	1.6	2.0	5.4	1.20	0.61
H&S	0.0021	2.22	0.60	40	1.30	3.5	1.8	1.6	1.8	4.4	1.00	0.50
SA	0.0020	2.13	0.56	41	1.05	3.2	1.6	1.4	1.7	4.3	1.06	0.53
Consensus	0.0023	2.46	0.68	45	1.06	3.3	1.6	1.5	1.8	4.6	1.25	0.59
Model[¶]	±0.0005	±0.51	±0.15	±9	±0.22	±0.4	±0.2	±0.2	±0.3	±0.7	±0.27	±0.09
Observed	0.0018	—	—	42–	0.5	3.2	1.4	1.2	1.27	3.4	—	—
range	−0.0039	—	—	135	−1.6	−5.0	−1.8	−2.0	−1.33	−5.5	—	—

Chabrier IMF $[0.01, 100]\,M_\odot$

THE $\eta_\star$ PARAMETER

$$\eta_\star \equiv \left(\frac{4\pi}{ct_H}\right)\frac{I_{EBL}}{\dot{j}_{\rm bol}}$$

A test independent of IMF



BH Formation Rate
&
Hard X-ray Background
(XRB)

Obtaining the BH Formation Rate

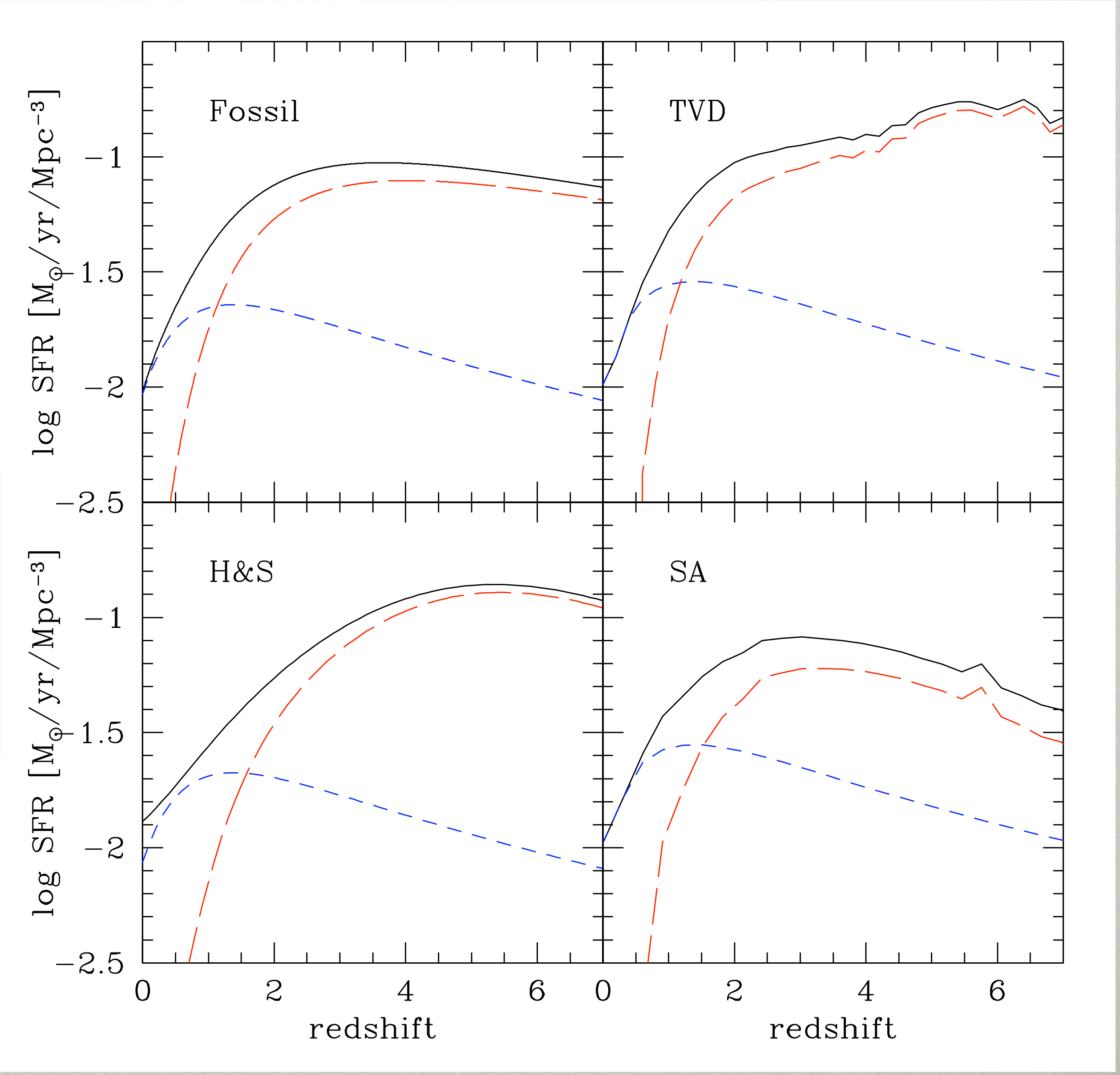
$$\dot{\rho}_\star^{\rm bulge} = \dot{\rho}_\star^{\rm tot} - \dot{\rho}_\star^{\rm disk}$$

Co-evolution of Bulge and BHs

$$\dot{\rho}_{\rm BH} = f_{\rm BH}\,\dot{\rho}_\star^{\rm bulge}$$

$$f_{\rm BH} \equiv \frac{M_{\rm BH}}{M_{\rm bulge}} \sim 10^{-3}$$

e.g. Kormendy & Richstone '95
Ferrarese & Merritt '00
Kormendy & Gebhardt '01
Heckman+ '04



AGN Emissivity

Average spectral emissivity per unit comoving volume

$$j(\nu, z) = \epsilon_{BH} \langle F_\nu \rangle \dot{\rho}_{\rm BH}\, c^2$$

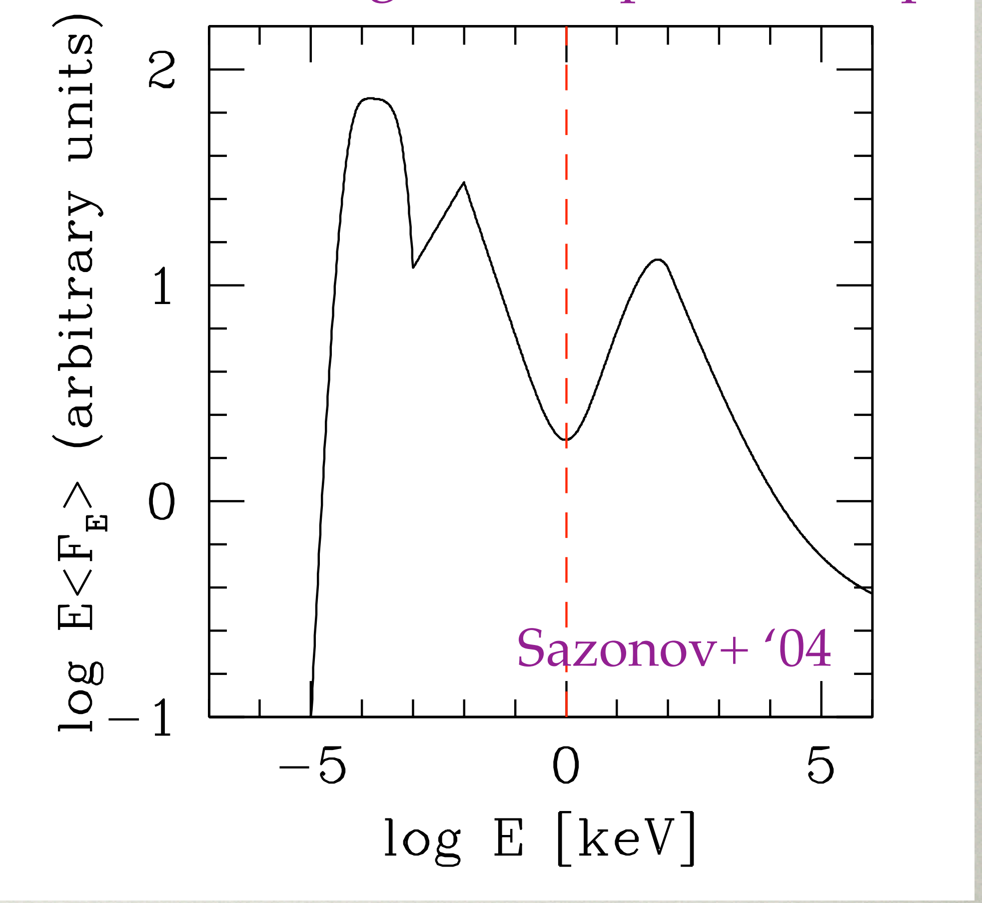
$$= \epsilon_{BH} \langle F_\nu \rangle f_{\rm BH}\, \dot{\rho}_\star^{\rm bulge}(z)\, c^2$$

[erg s^{-1} cm^{-3} Hz^{-1}]

Energy conversion efficiency of BH:

$$\epsilon_{\rm BH} \sim 0.1$$

Average AGN spectral shape

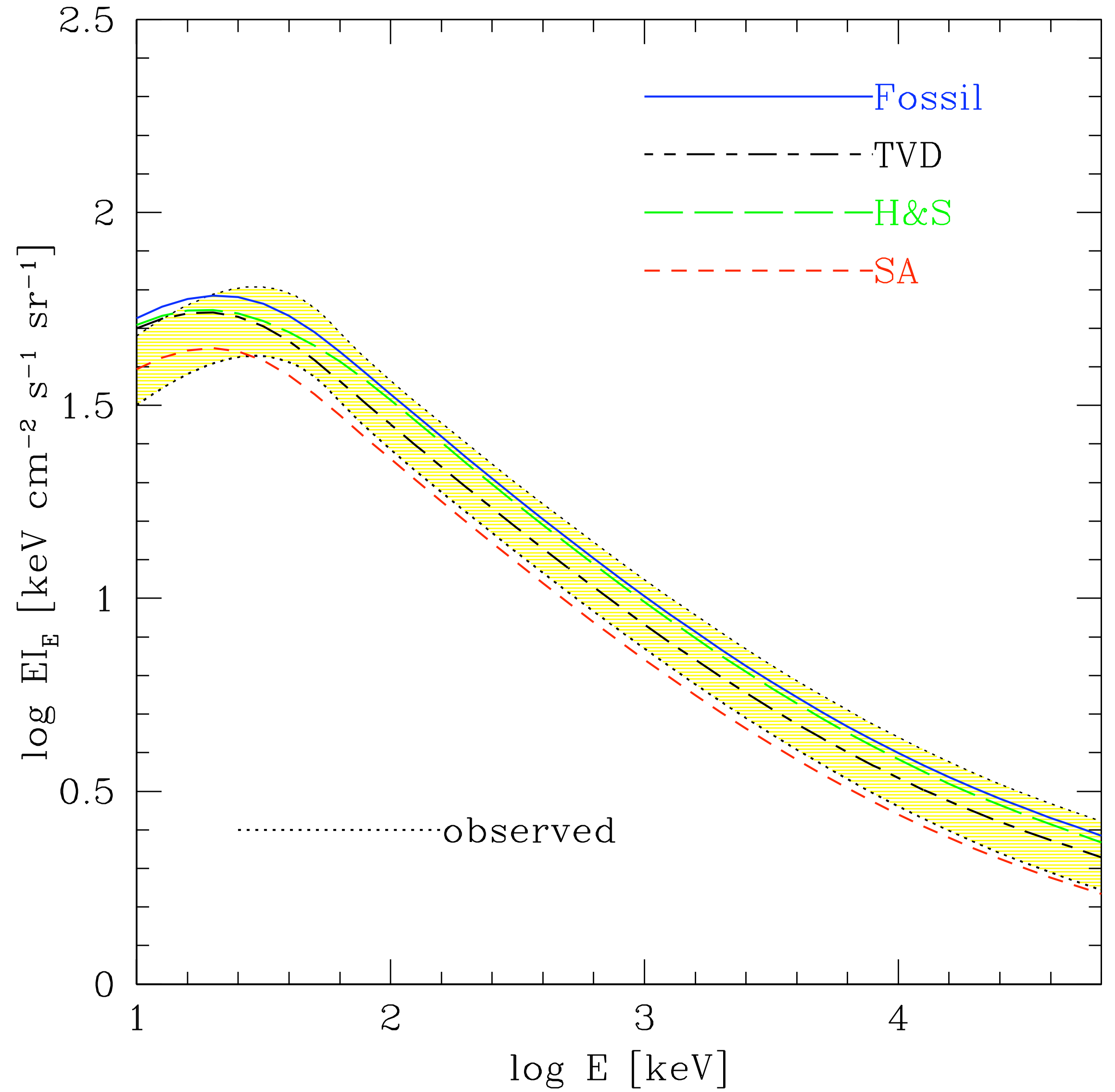


XRB ⟷ $\epsilon_{\rm BH}$ ⟷ $f_{\rm BH}$ ⟷ $\rho_{\rm BH}(0) \sim (2.5 - 3) \times 10^5\, h_{70}^2\, M_\odot\, {\rm Mpc}^{-3}$

(Aller & Richstone '02; Yu-Tremaine '02)

X-ray Background (XRB)

Reducing the ratio of X-rays to total by x1.8 (i.e. increasing the bolometric correction)



Yellow band: observed

Luca & Moledi '04 (upper)

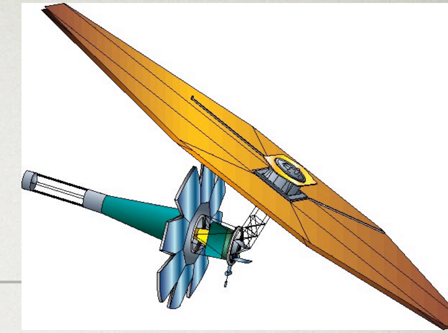
Gruber+ '99 (lower)

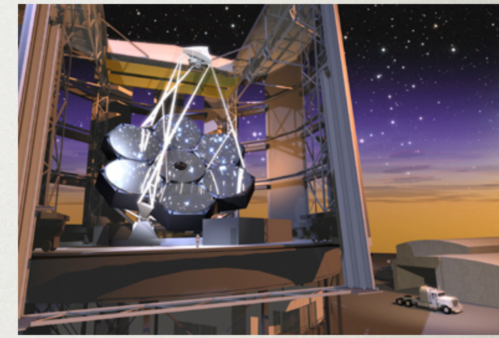
Conclusions

- The Fossil model works well --- simple & clear, matches obs
  - bulge-disk decomposition
  - Epoch of spheroid formation: z>~1.5
  - Madau plot: rise @ z=0->2, ~constant @ z=2-7
- Inconsistent observations:
  - SFR(z) vs. $\Omega_\star(z)$: theory higher @ z≥1 --“Missing galaxies”?
  - j(z=0) vs. EBL(if 100) : theory I ≦60 nW m^{-1} sr^{-1}

astro-ph/0603257

The Future





- Find fainter "Missing Galaxies"@ high-z
  GMT, TMT, NGST, ...
- Understand Star Formation
  IMF(t, environment), efficiency, DLAs, [CII]
- Galaxy -- IGM : SN Feedback
- BH -- Galaxy: AGN Feedback
- Connect

large-scale	⟷	small-scale
high-z	⟷	low-z
Theory	⟷	Observation