The Star Formation History of the Universe

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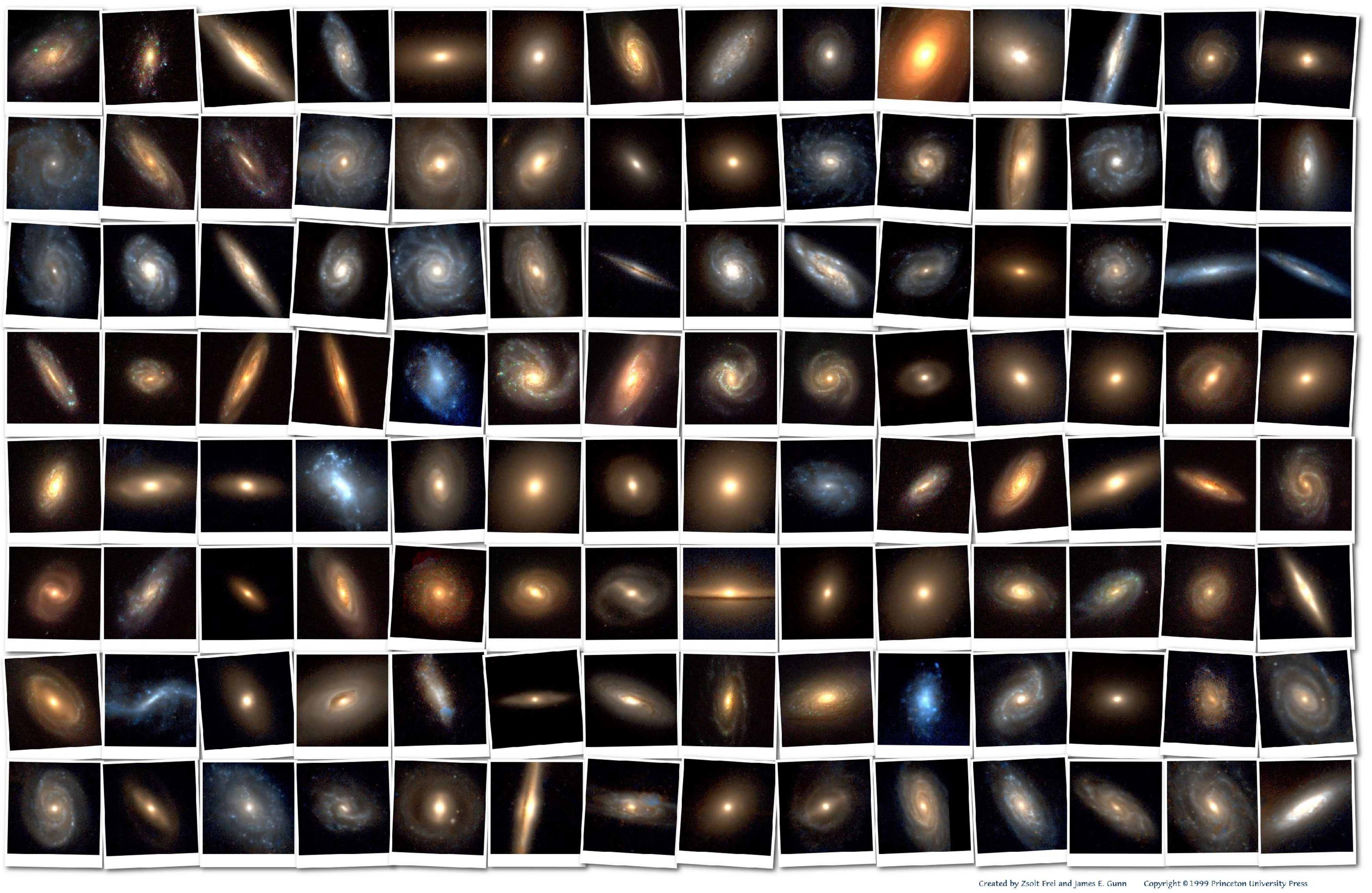

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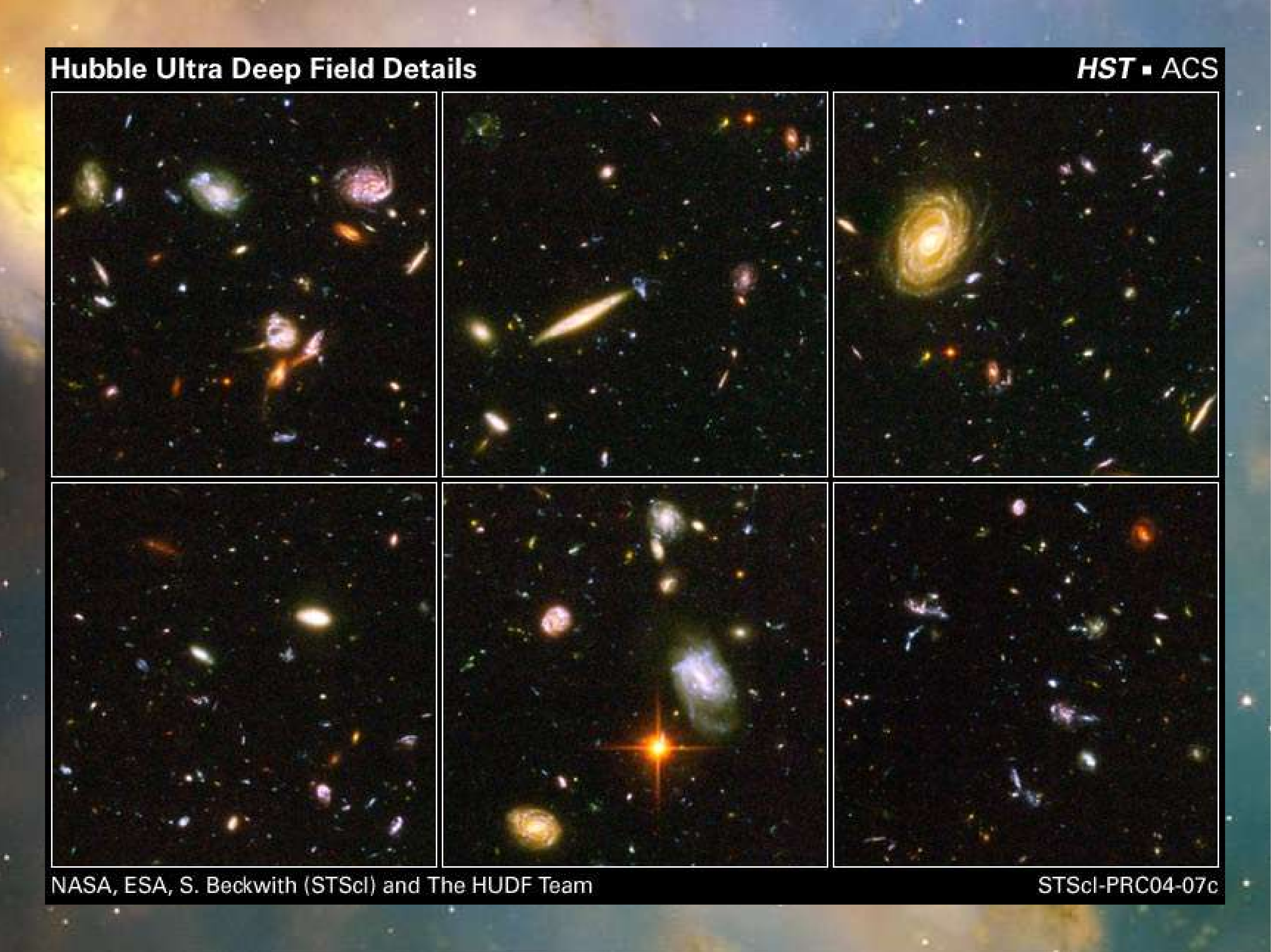

Hubble Ultra Deep Field Details
HST ▪ ACS
NASA, ESA, S. Beckwith (STScI) and The HUDF Team
STScI-PRC04-07c

Star formation in galaxies can be measured using many tracers:

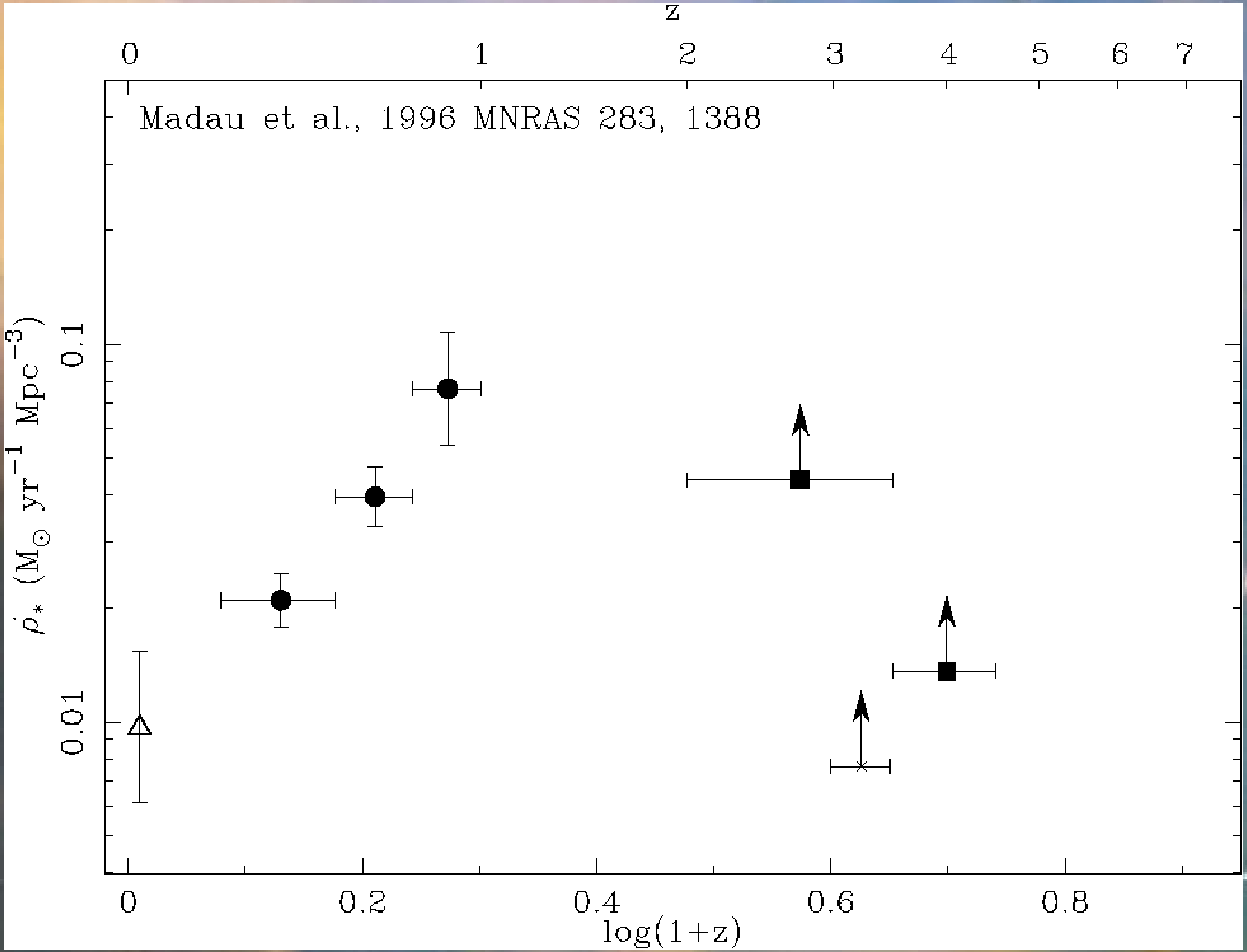
- Ultraviolet (UV) radiation, photons emitted directly by massive, young, short-lived stars
- Balmer recombination line emission (Hα in particular)
- Dust emission (observed at far-infrared, FIR, wavelengths) – this is emission produced by dust grains which absorb UV and re-emit in the FIR.
- Synchrotron emission (at radio wavelengths, empirical connection to SFR through radio-FIR correlation) – associated with star formation processes through supernova ejecta shock-accelerating cosmic ray electron populations to relativistic speeds in an ambient galactic magnetic field.
- Others: Lyman, Paschen series in H, forbidden [OII] transition, X-rays, sub-mm dust emission, mid-infrared, and more.

Star Formation Rate Density

- Perform an observational survey, at a star-formation sensitive wavelength.
- Calculate the Luminosity Function (the number of galaxies as a function of luminosity, per unit volume).
- Scale luminosity to SFR using appropriate calibration, correcting as necessary for obscuration effects, incompleteness, instrumental or other systematics, etc. (A lot of recent work in particular has emphasised reliable dust corrections, but the correction factors for other effects can be similar, or even greater.)
- Integrate over the Luminosity (SFR) Function to determine total space density of SFR.
- Repeat for as many redshift slices as possible.

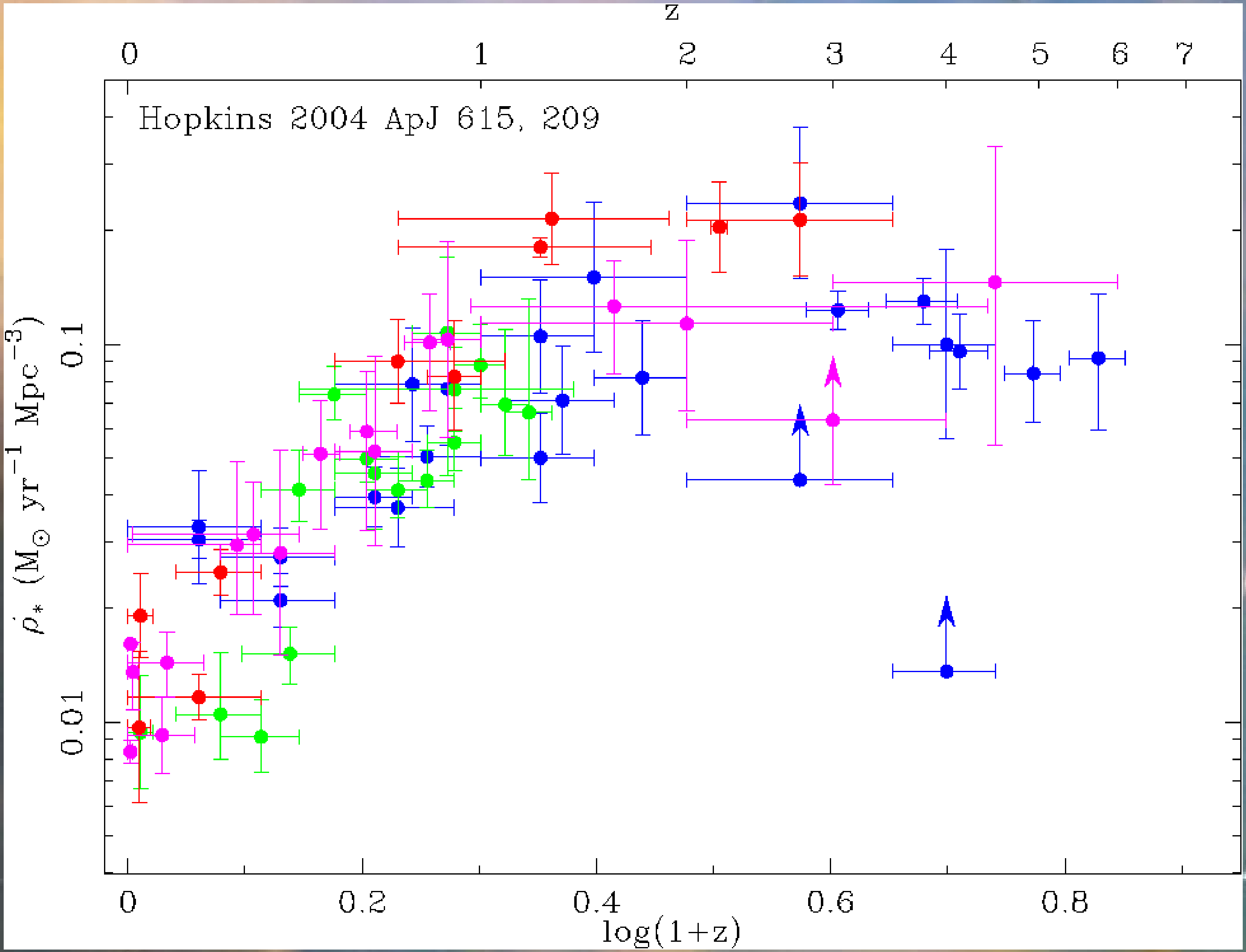
Comoving space density of SFR

SFR density



Redshift

Comoving space density of SFR



SFR density

Redshift

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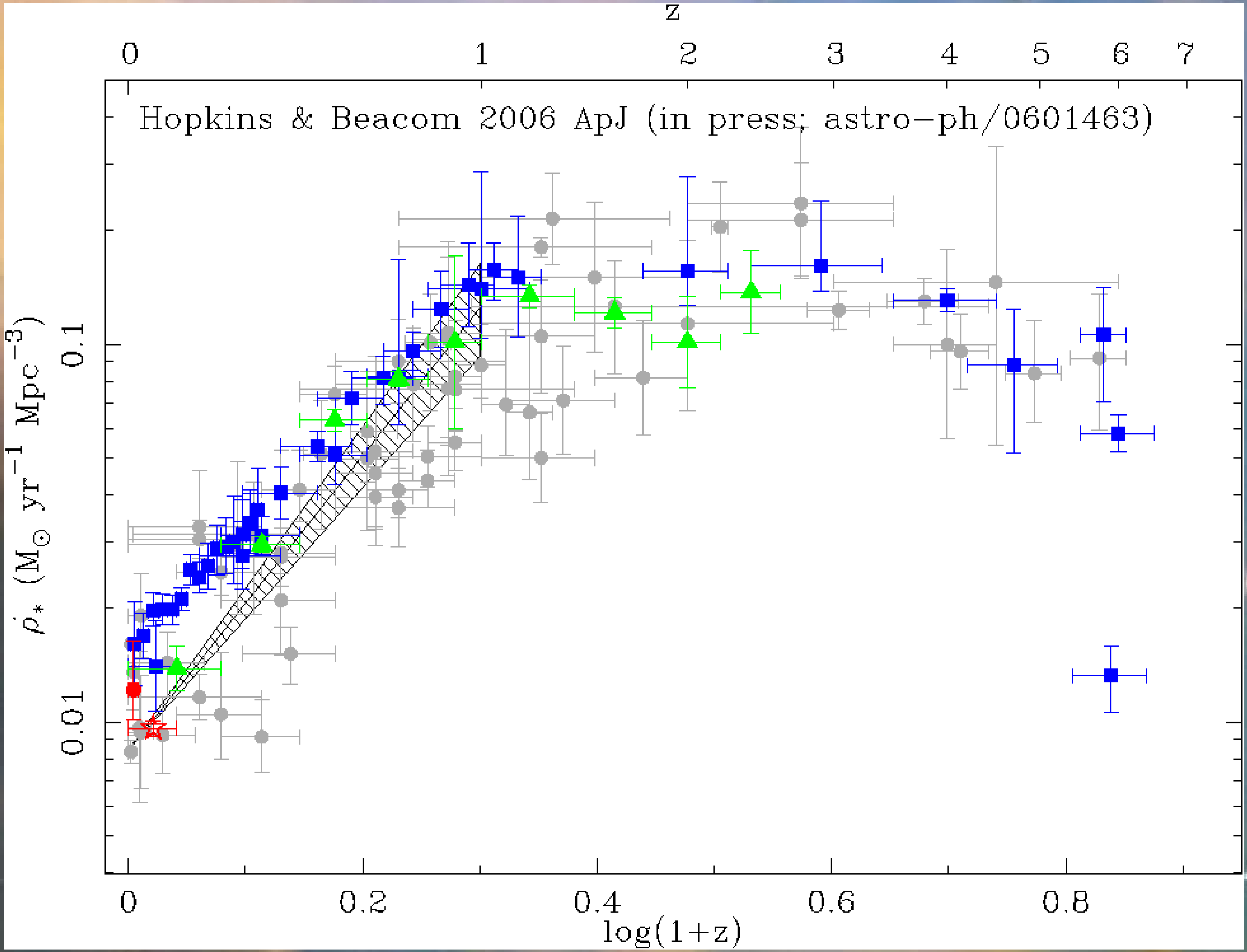
SFR density



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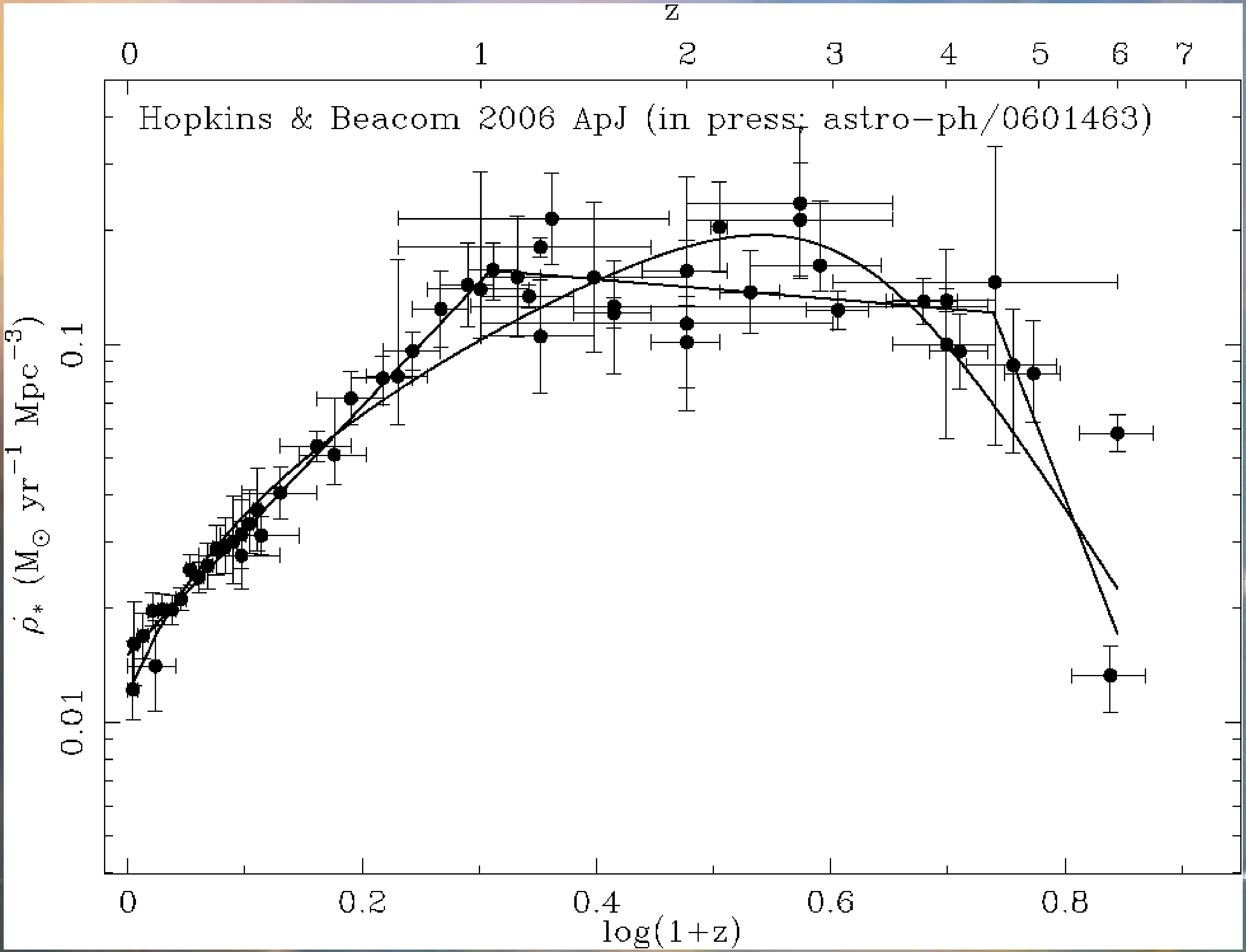
SFR density



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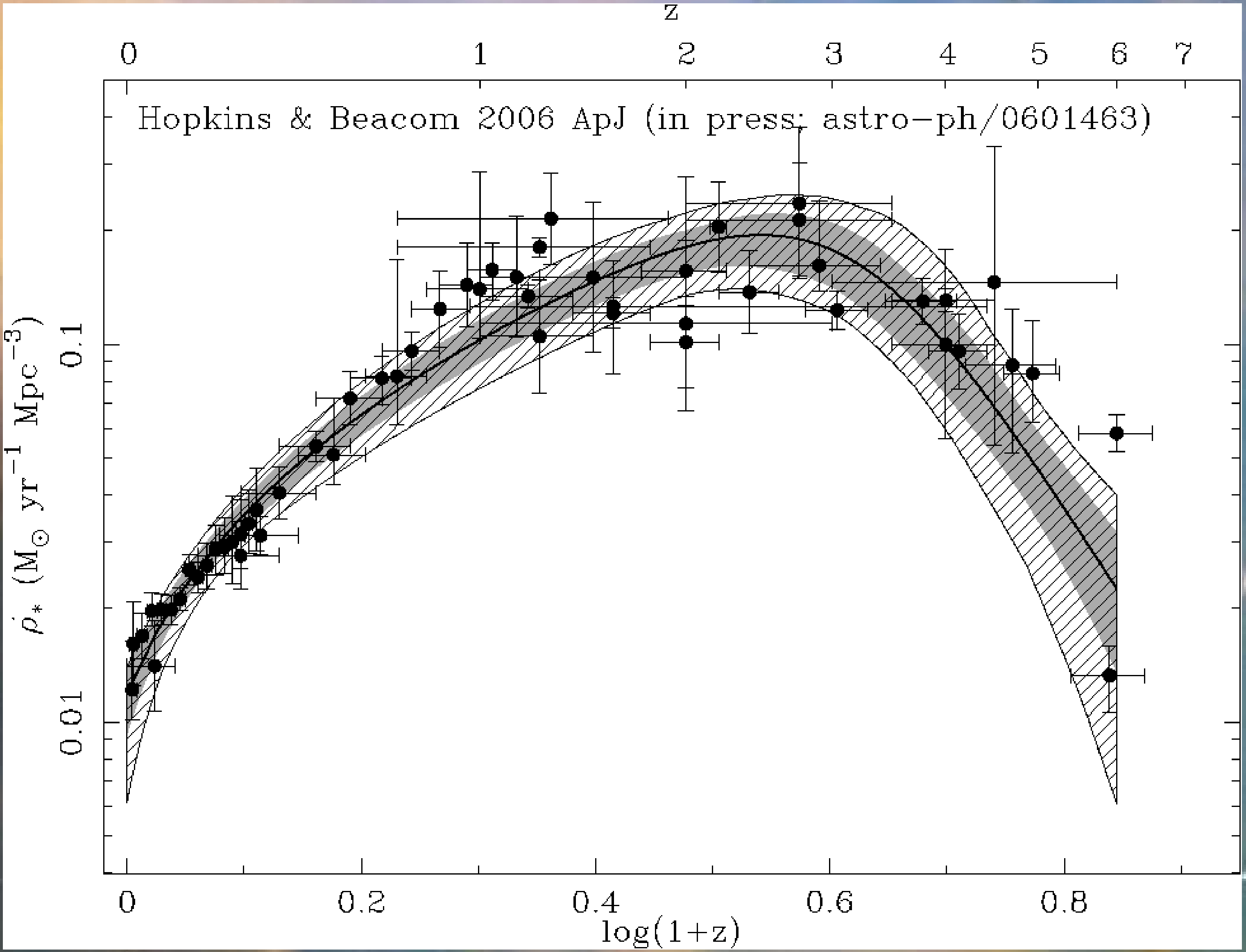

SFR density

Redshift

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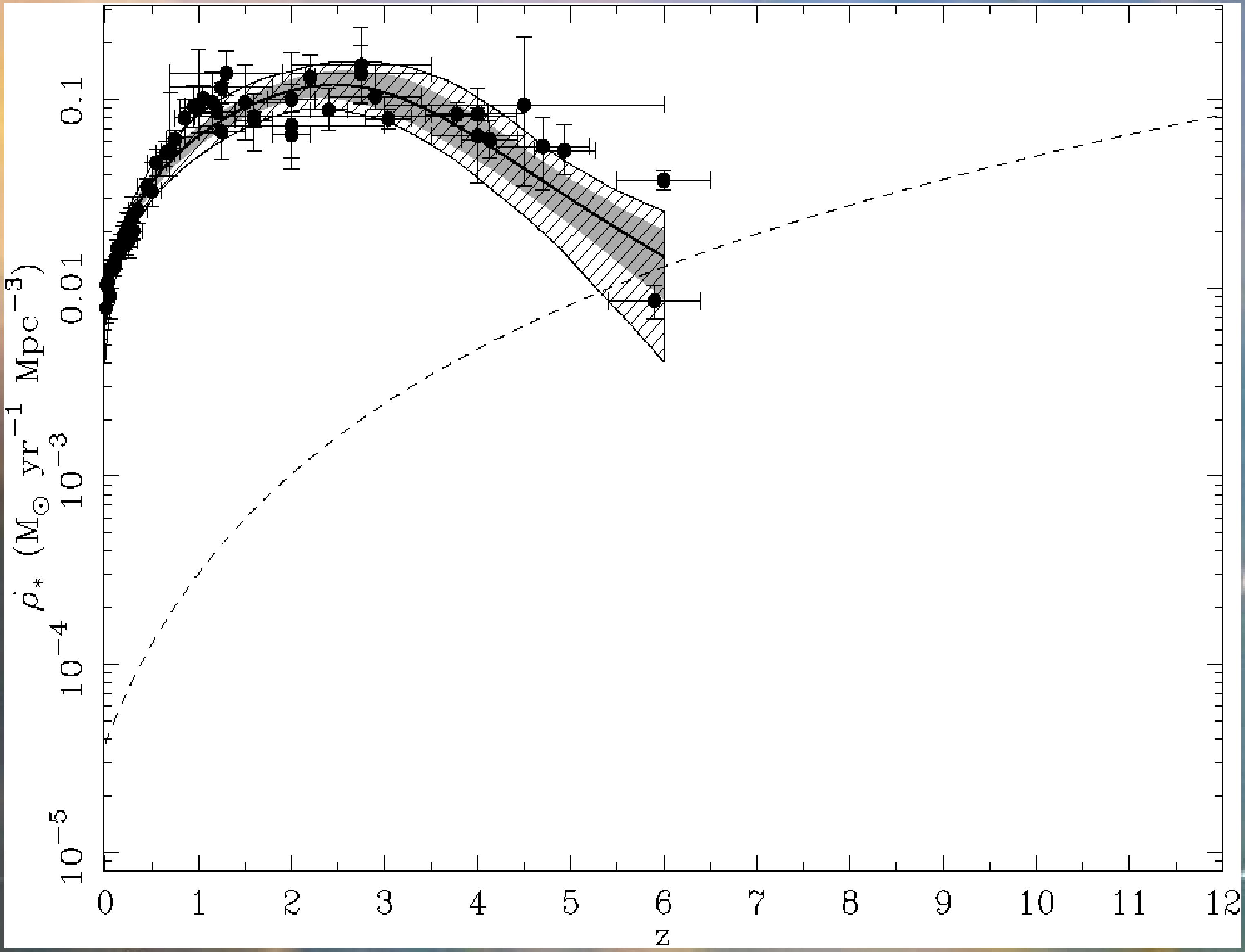

SFR density

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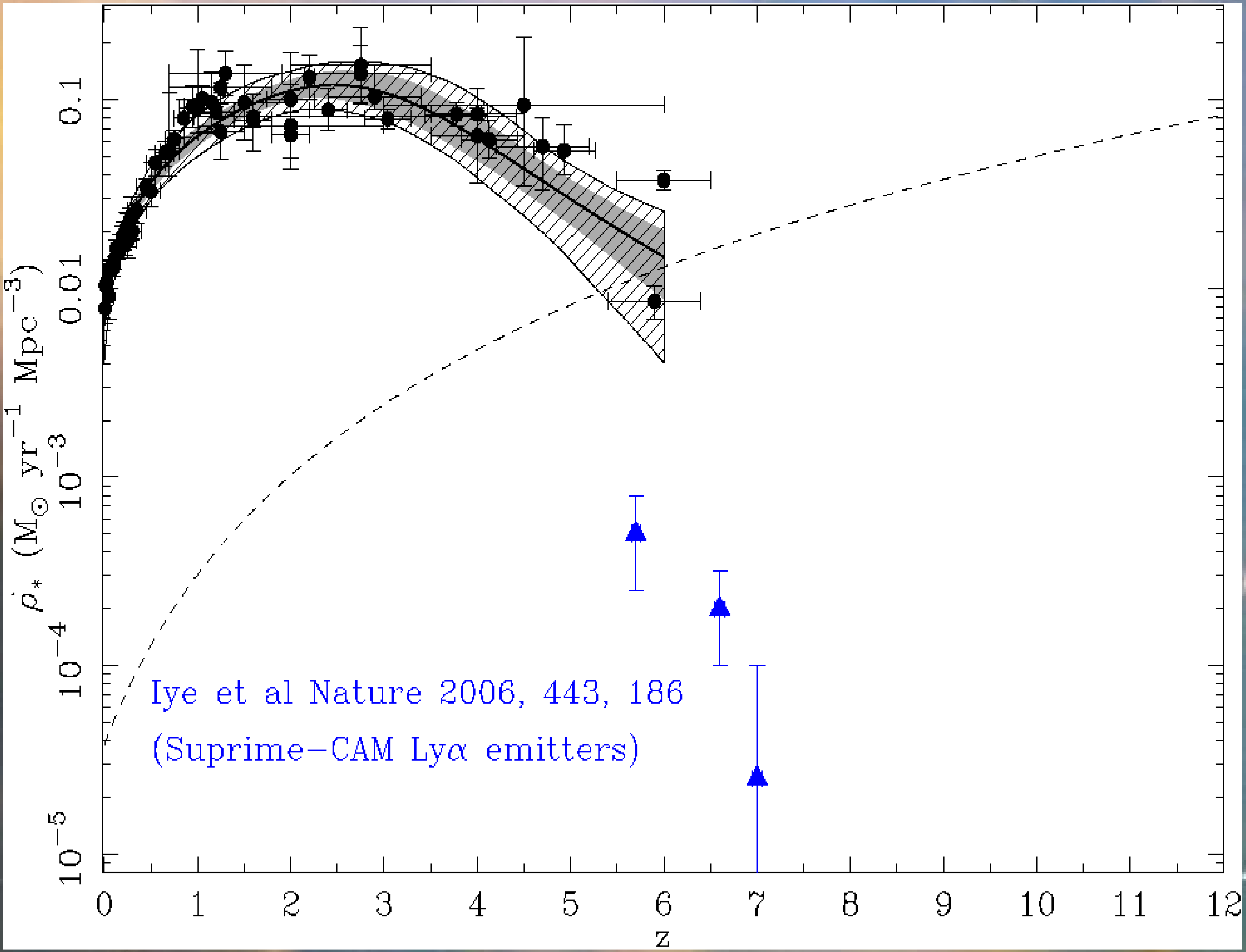

SFR density

Redshift

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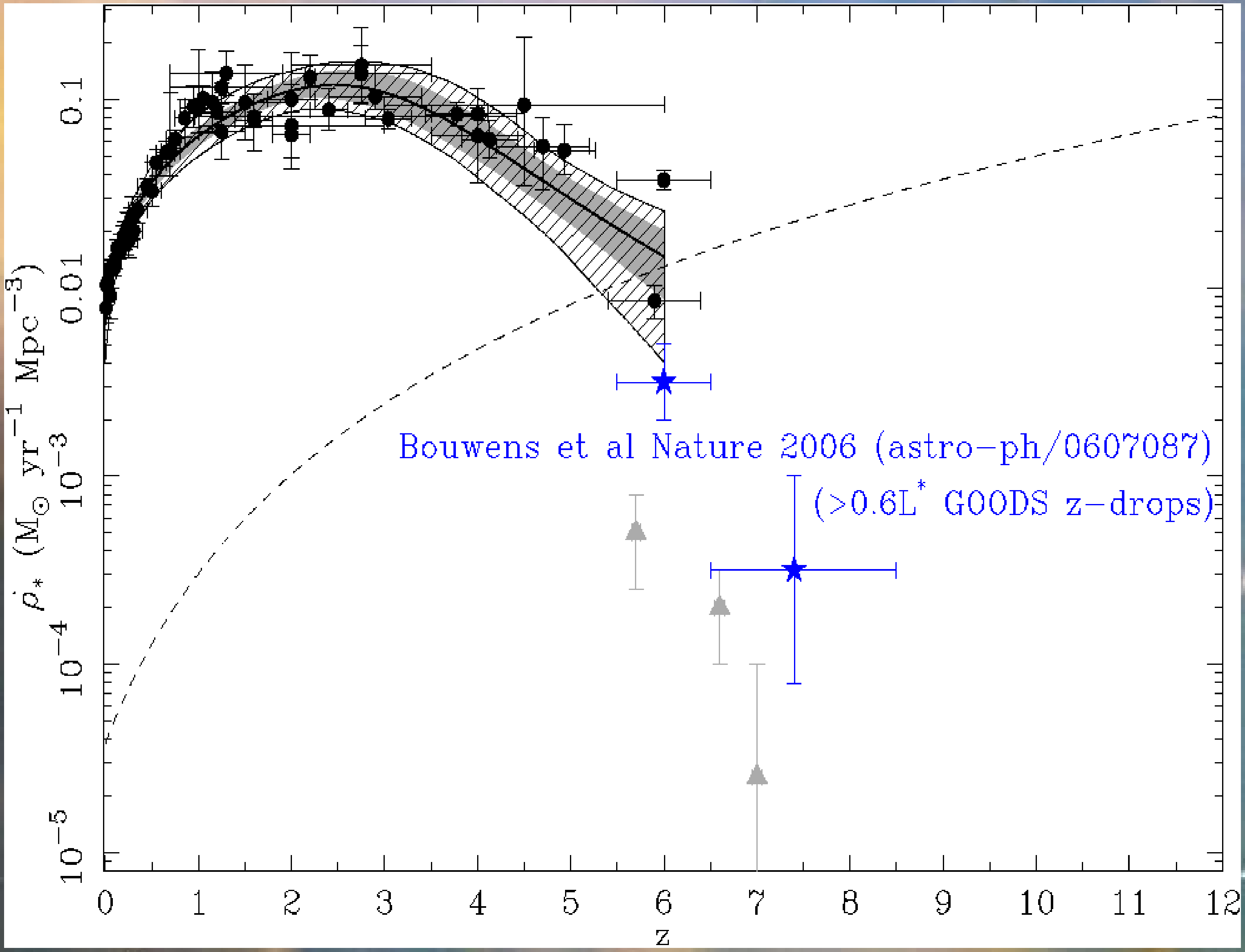
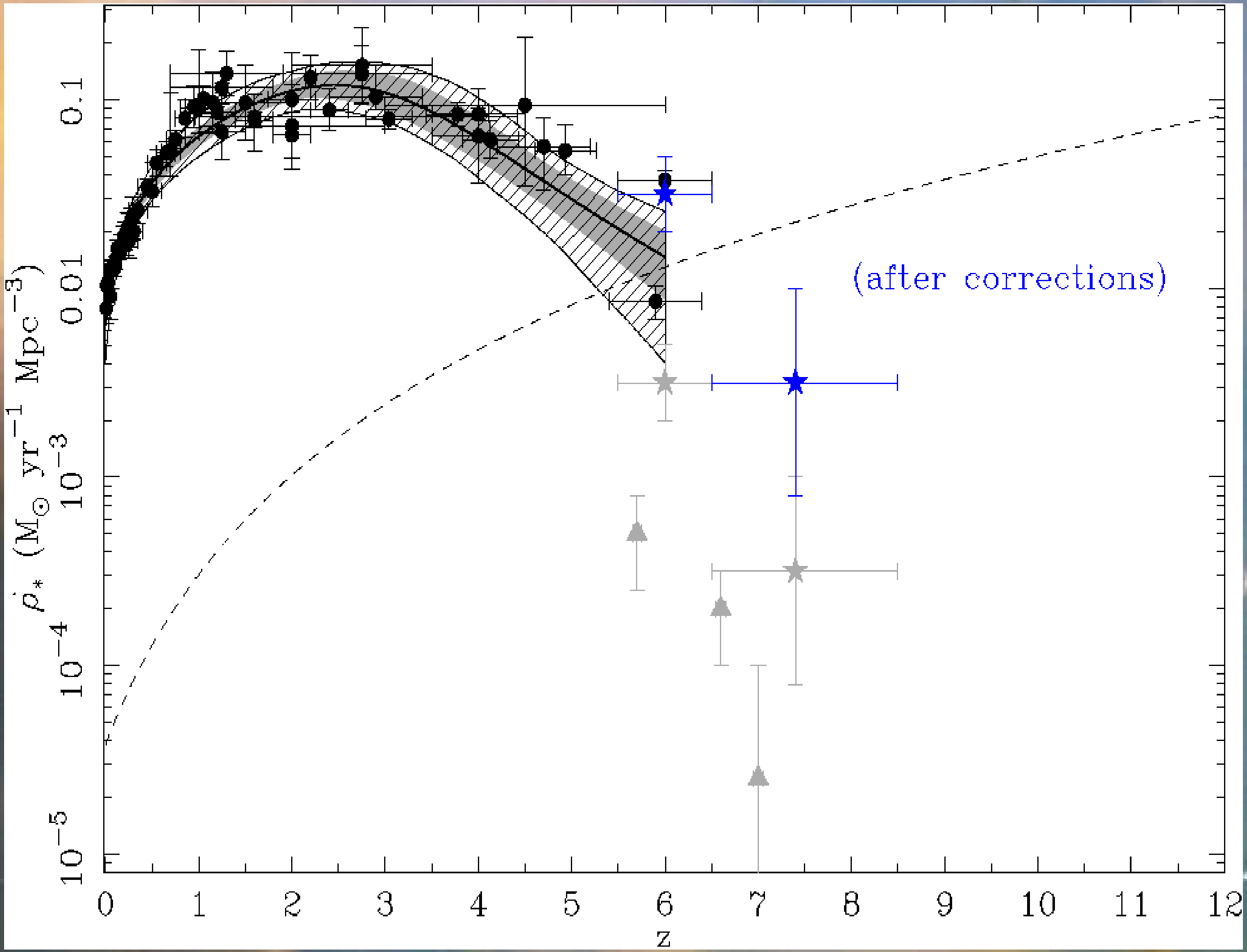


SFR density

Redshift

Comoving space density of SFR

SFR density



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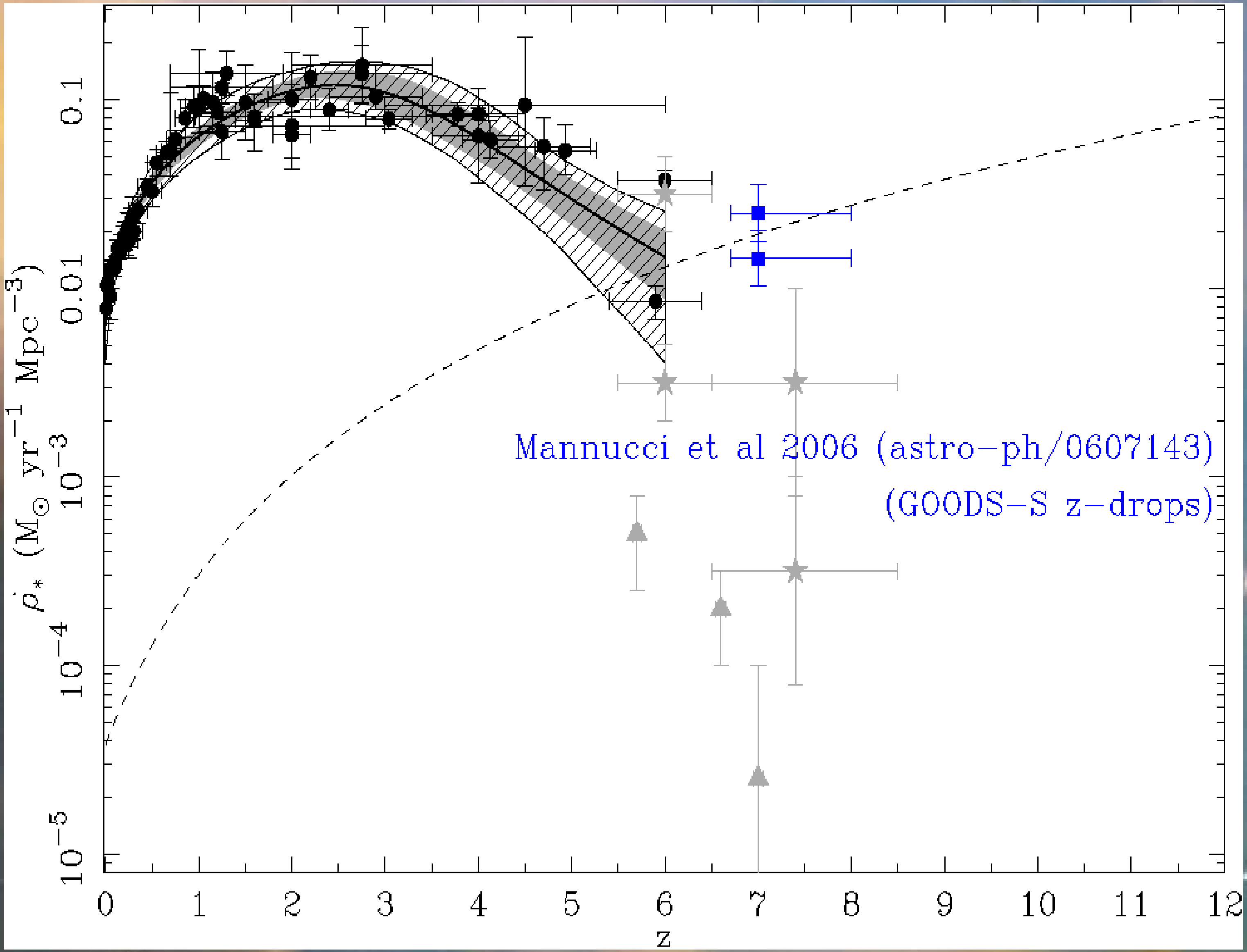
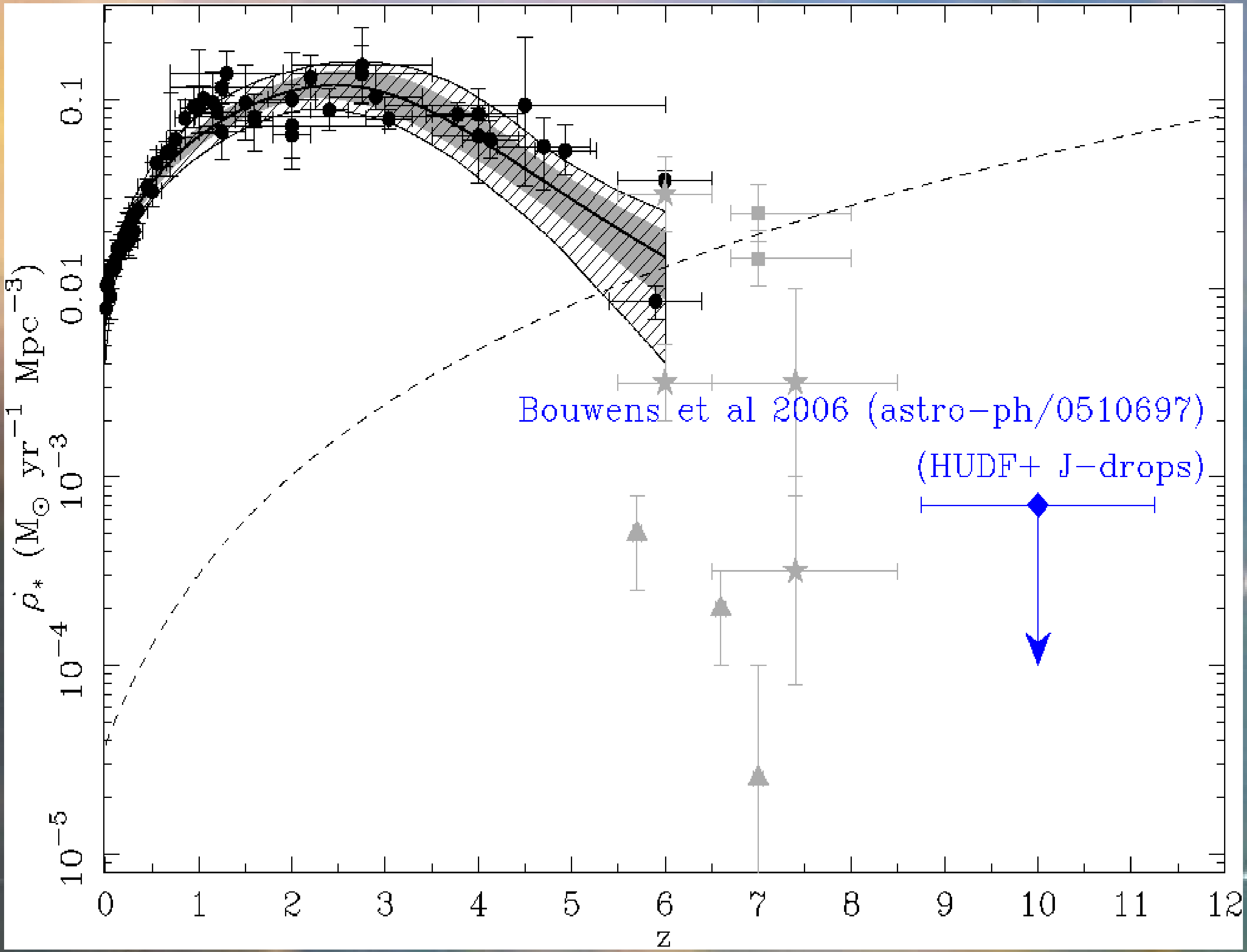


SFR density

Redshift

Comoving space density of SFR

SFR density



Redshift

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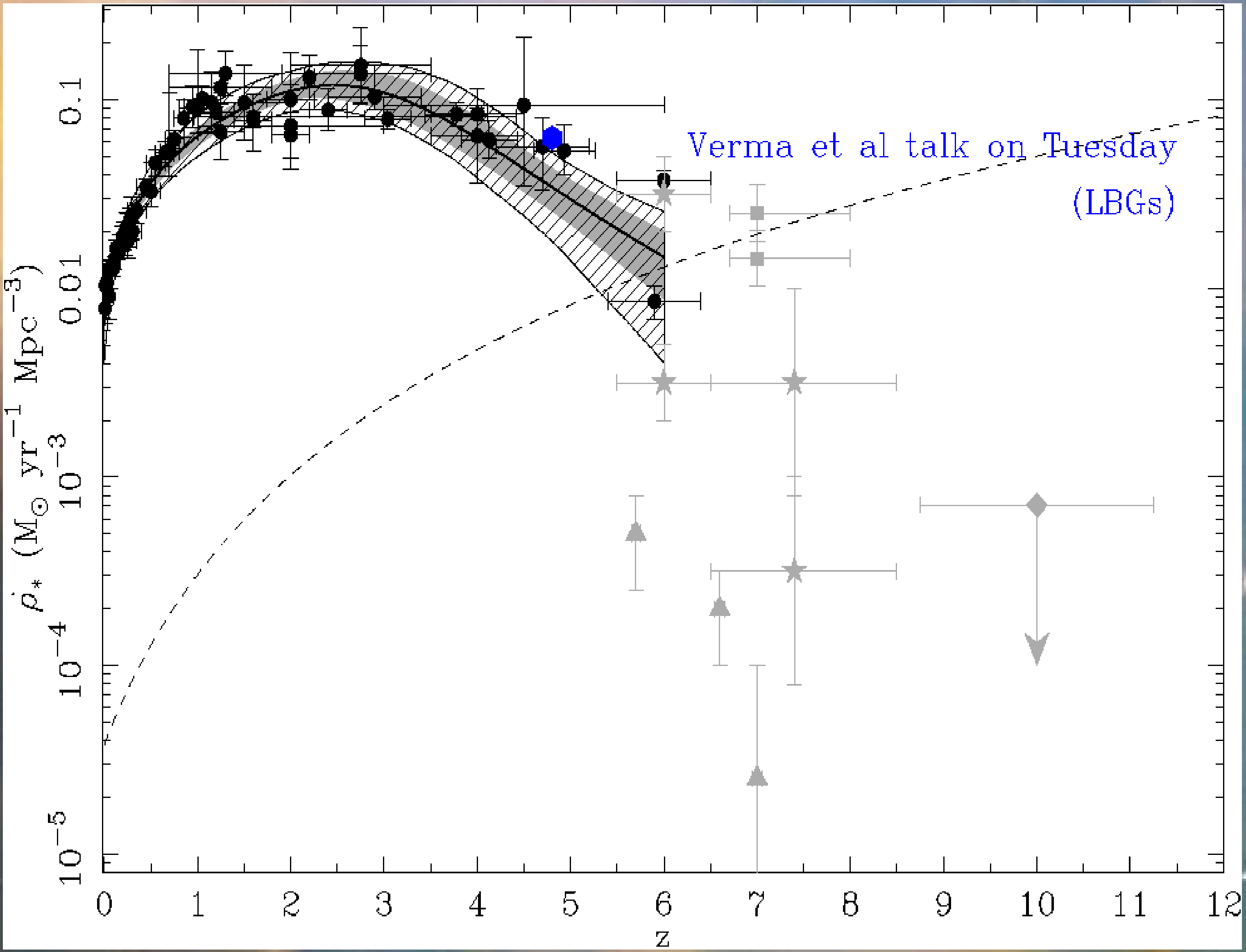
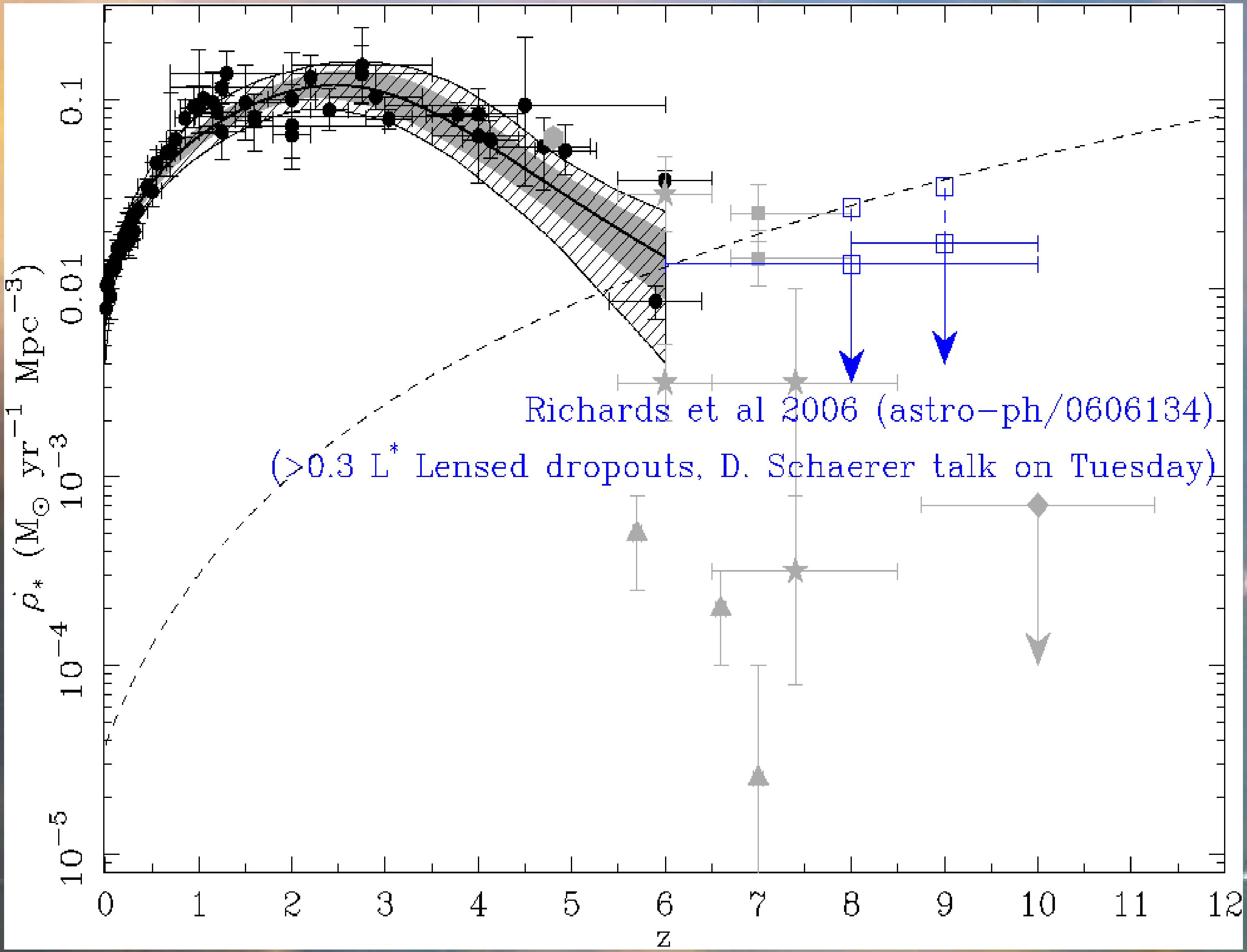


SFR density

Redshift

Comoving space density of SFR



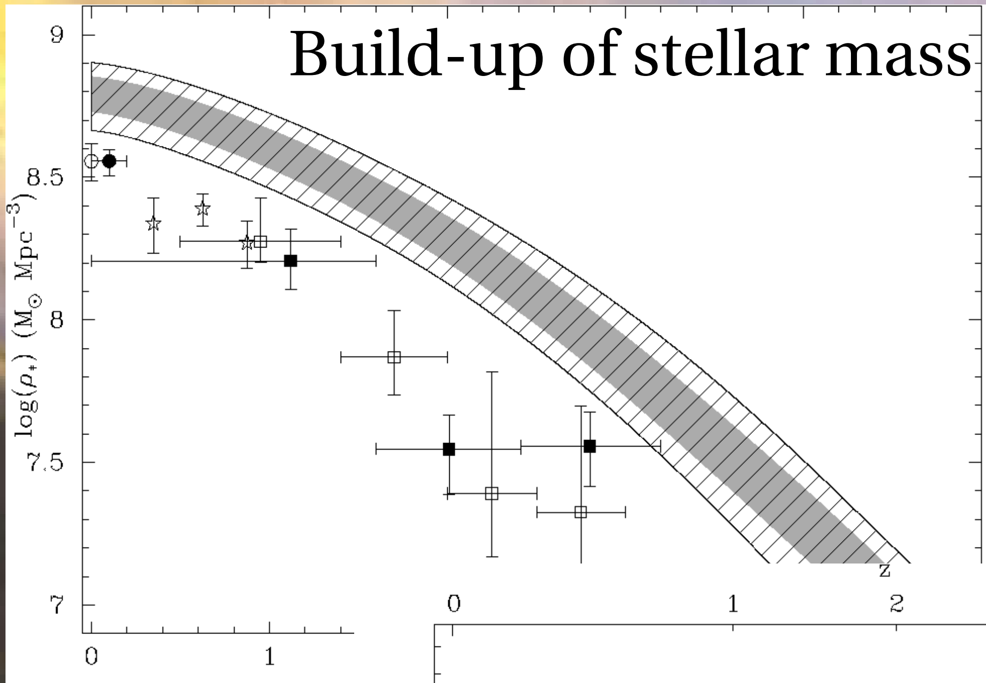
SFR density

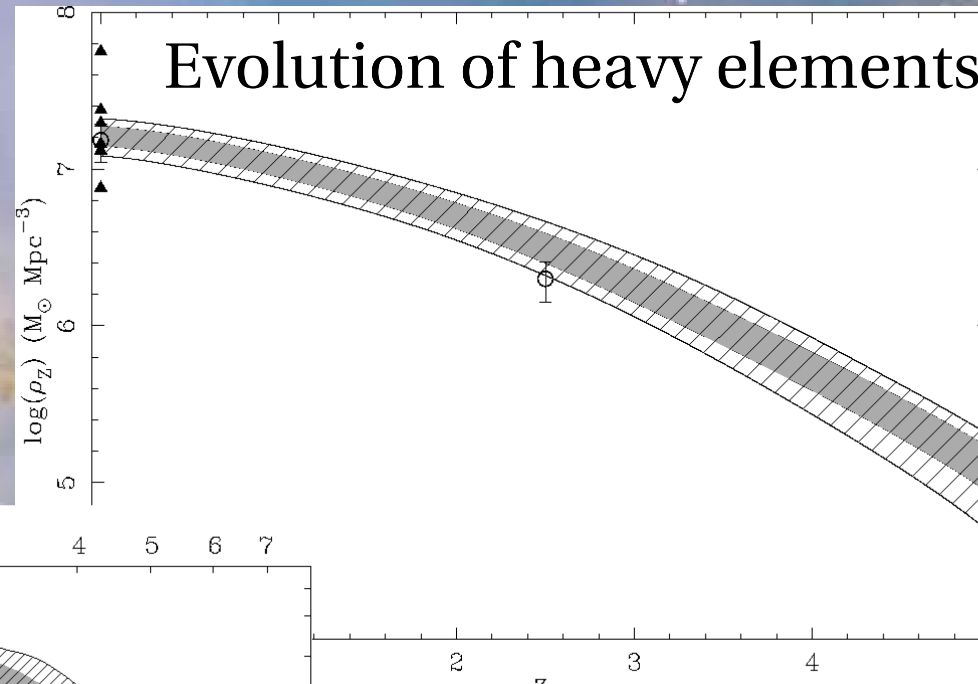
Redshift

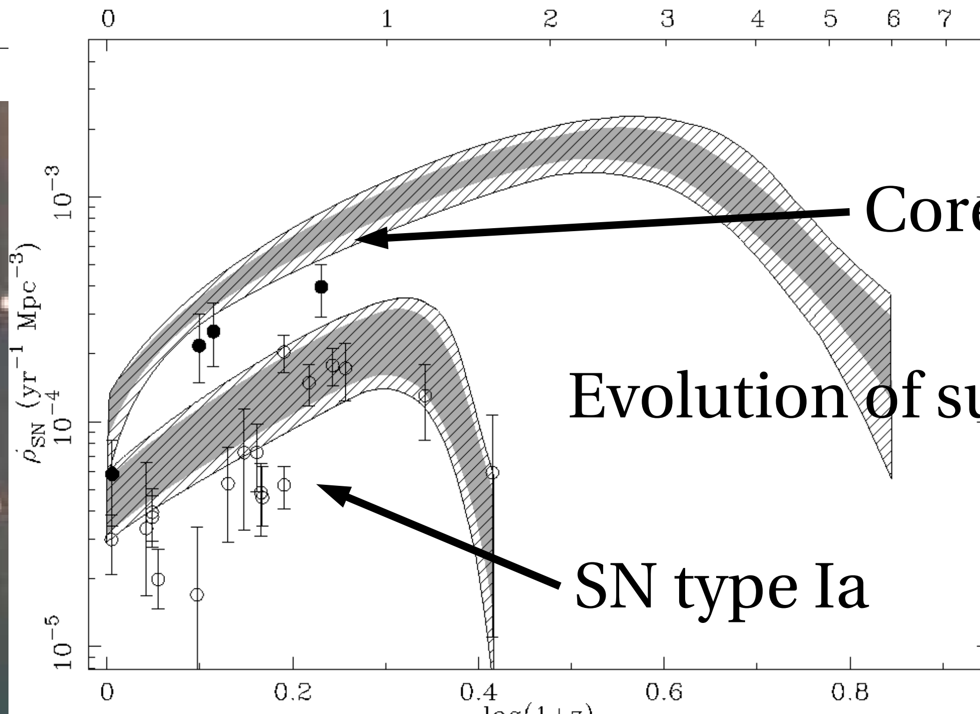
Obscuration at high redshift

- LBGs might be heavily obscured (lack of Lyα emission from z~5 UV-bright LBGs, Ando et al, astro-ph/0510830).
- Lyα emitters might be heavily obscured (A_V~1 mag in a lensed z=6.56 source, Chary et al, 2005, ApJ, 635, L5).
- z~6 LBGs might be less-obscured than at lower redshift (bluer UV-continuum slope compared to z~3, Bouwens et al 2005, astro-ph/0509641).

Predictions from the SFH







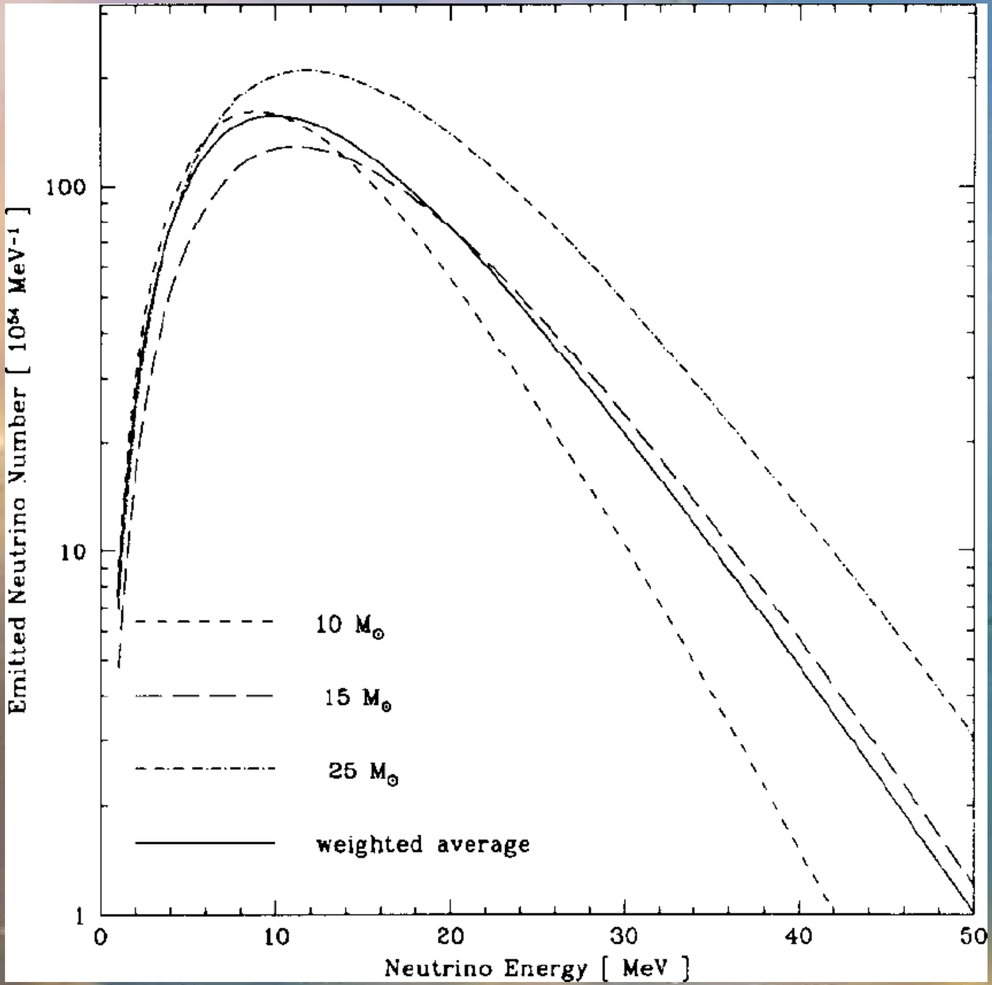
Assumptions about $\bar{\nu}_e$ emission from SNe

- All core-collapse supernovae (types II, Ib, Ic) have similar properties regarding neutrino production
- Neutrinos emitted with Fermi-Dirac energy spectrum
- Total energy of 3×10^{53} erg = 3×10^{46} J
- Total energy mostly shared among neutrino flavours (after mixing in the SN)

Totani & Sato 1995

Neutrino spectrum per supernova

Emitted Neutrino Number

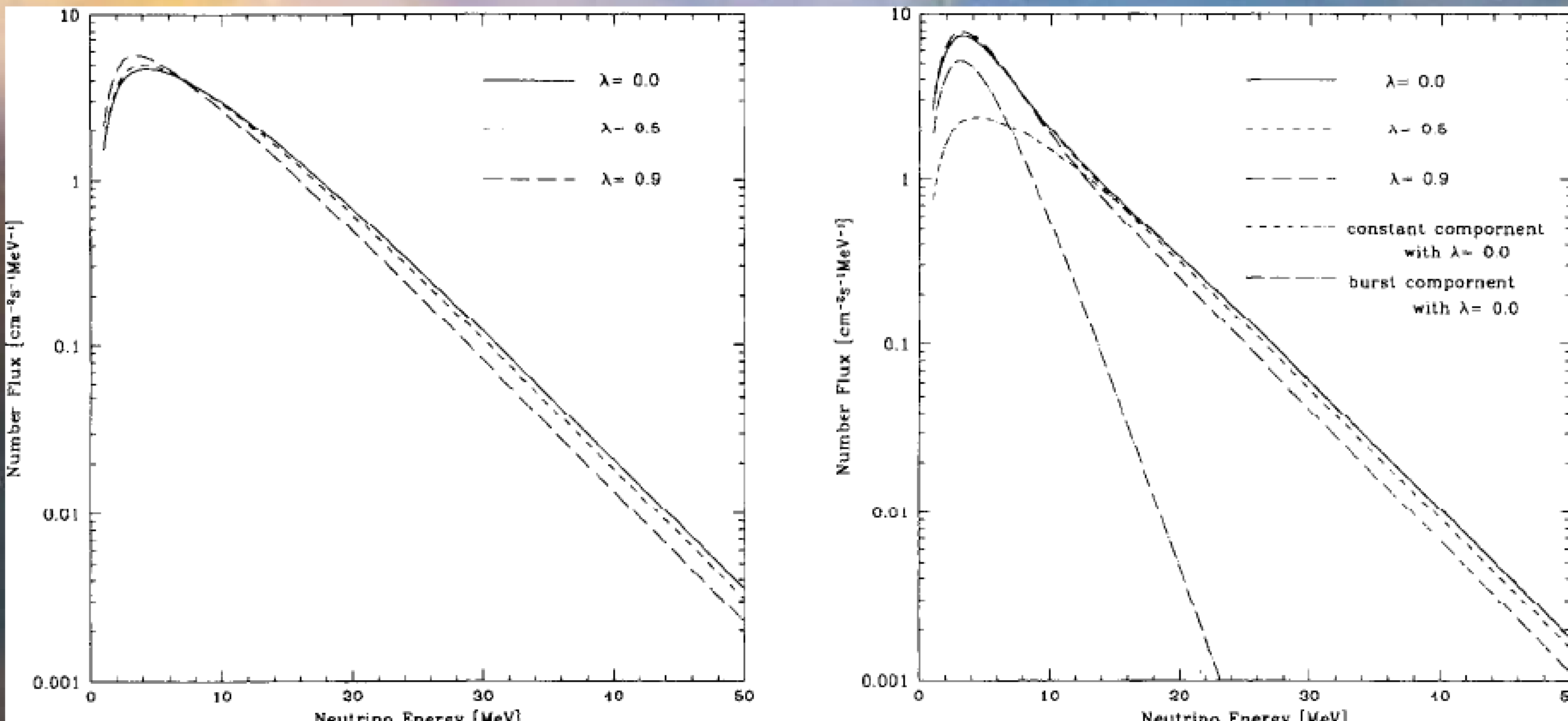


Neutrino Energy (MeV)

Totani & Sato 1995

Predicted DSNB energy spectrum

Number flux (cm^{-2} s^{-1} MeV^{-1})



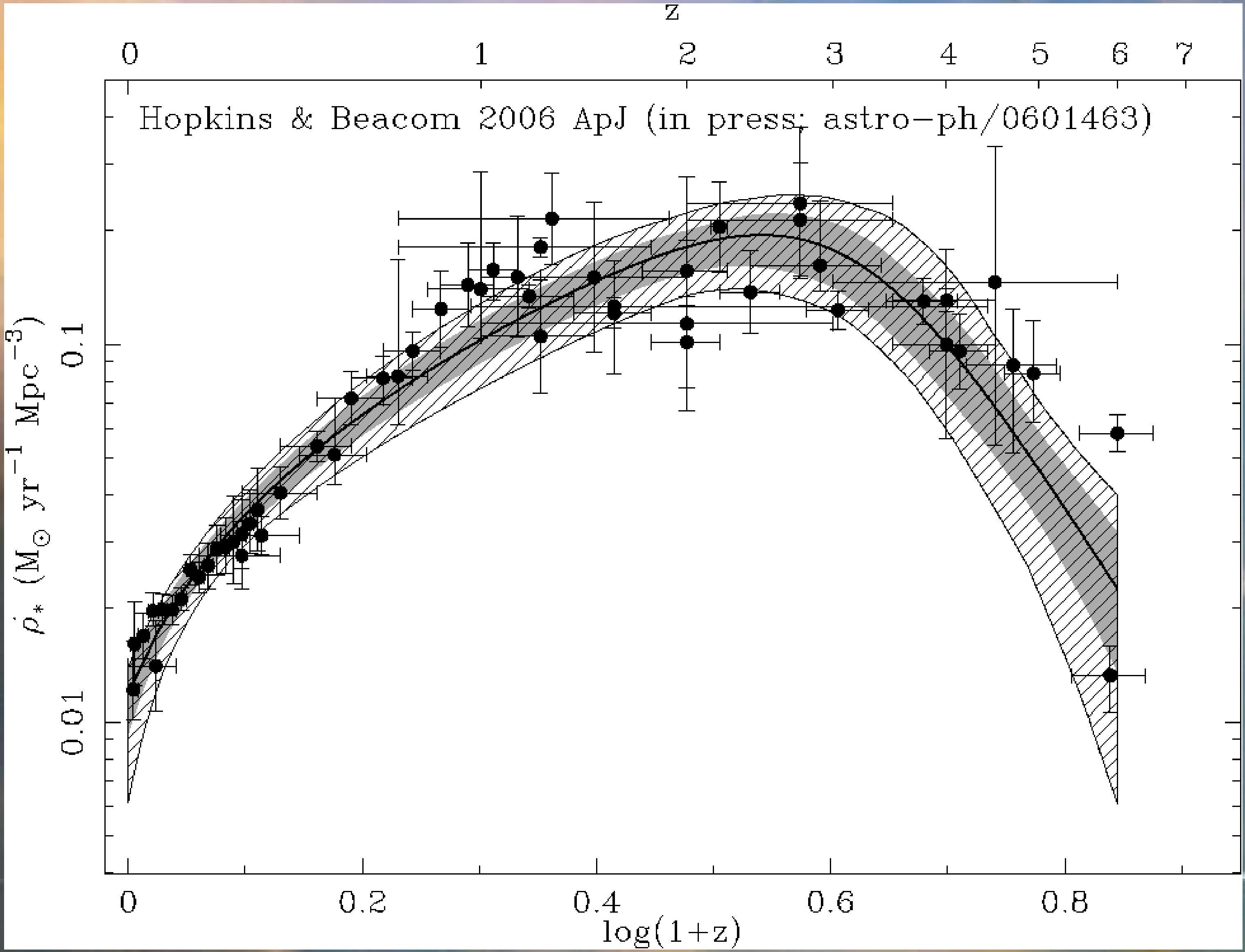
Neutrino Energy (MeV)

Brief summary of the DSNB

- Mid-1980s: Several researchers qualitatively explore neutrino emission from supernovae and the DSNB (e.g., Krauss, Glashow & Schramm, Nature 1984, 310, 191)
- 1995: Totani & Sato (Astropart. Phys. 3, 376) calculate the neutrino spectrum for a supernova, and estimate the flux of electron antineutrinos from all supernovae, the "relic supernova neutrino" flux.
- 1997-2003: Various estimates for the level of the DSNB (e.g., Malaney 1997, Kaplinghat et al 2000, Ando et al 2003, Fukugita & Kawasaki 2003)
- **2003: Malek et al (Phys. Rev. Lett. 90, 061101) measure an upper limit on the DSNB $\bar{\nu}_e$ flux with SK, of 1.2 cm^{-2} s^{-1}.**
- 2004: Beacom & Vagins (Phys. Rev. Lett. 93 171101) suggest loading SK with $GdCl_3$ to improve DSNB detection (and coin the new term).
- 2003-2006: Many and various combinations of cosmic SFH and DSNB limit to infer average $\bar{\nu}_e$ temperature and other parameters.
- 2005: Lunardini (astro-ph/0509233) uses SN1987A to estimate DSNB.
- 2006: Hopkins & Beacom (astro-ph/0601463; ApJ in press) use SK DSNB limit to constrain the normalisation of the cosmic star formation history.

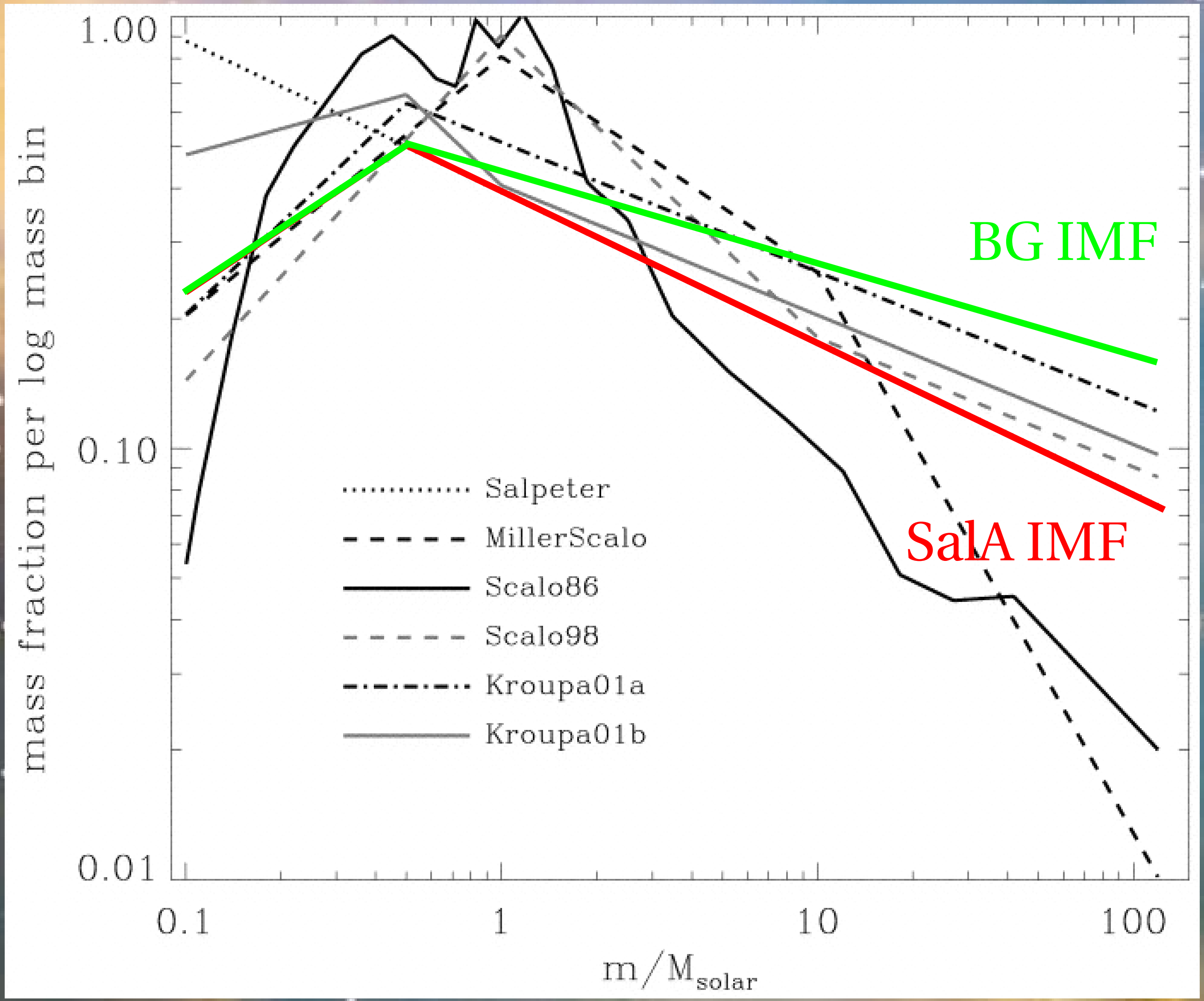
Comoving space density of SFR

SFR density



Redshift

The Initial Mass Function



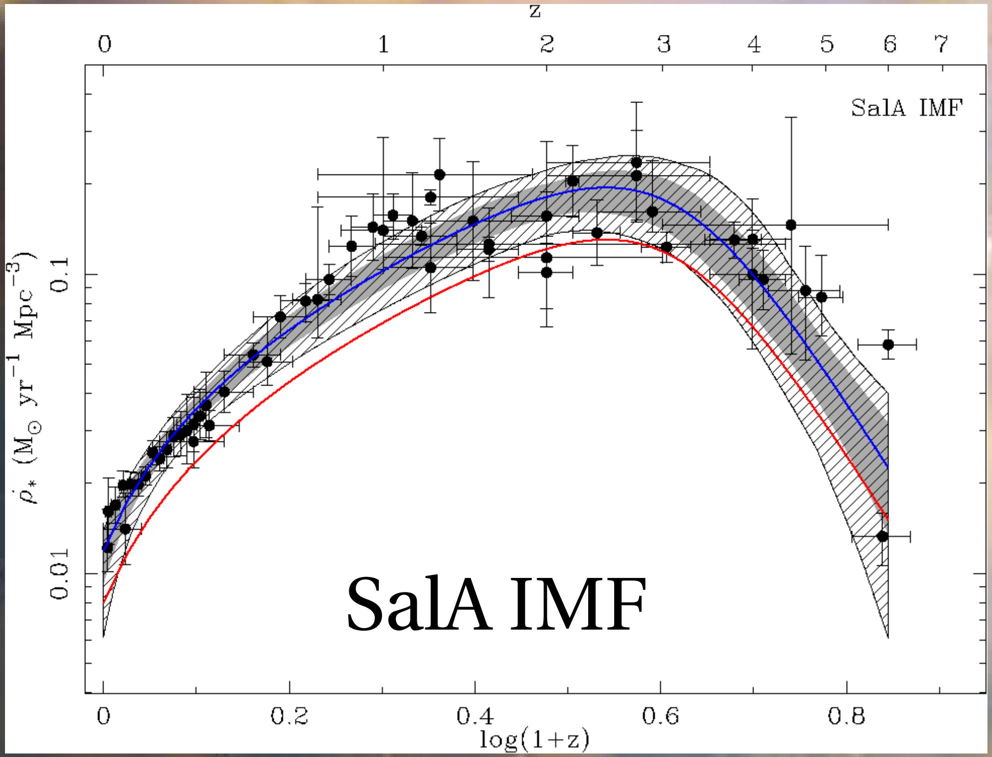
Baldry & Glazebrook 2003 ApJ 593, 258

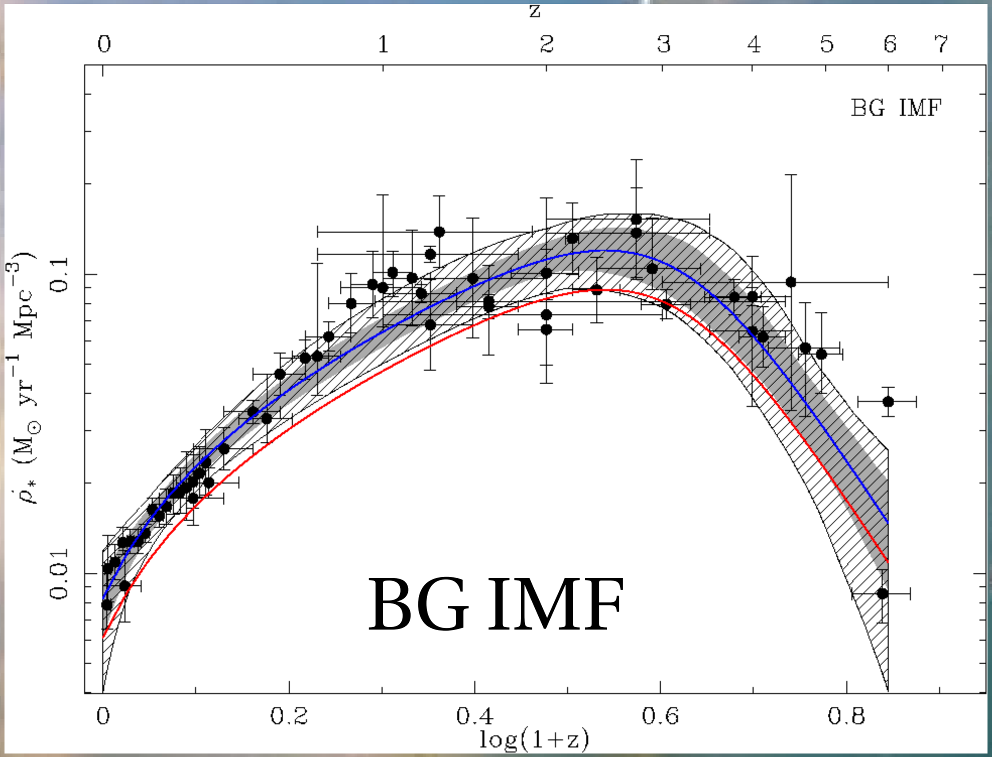
Normalisation of the SFH

Characteristic $\bar{\nu}_e$ temperature:

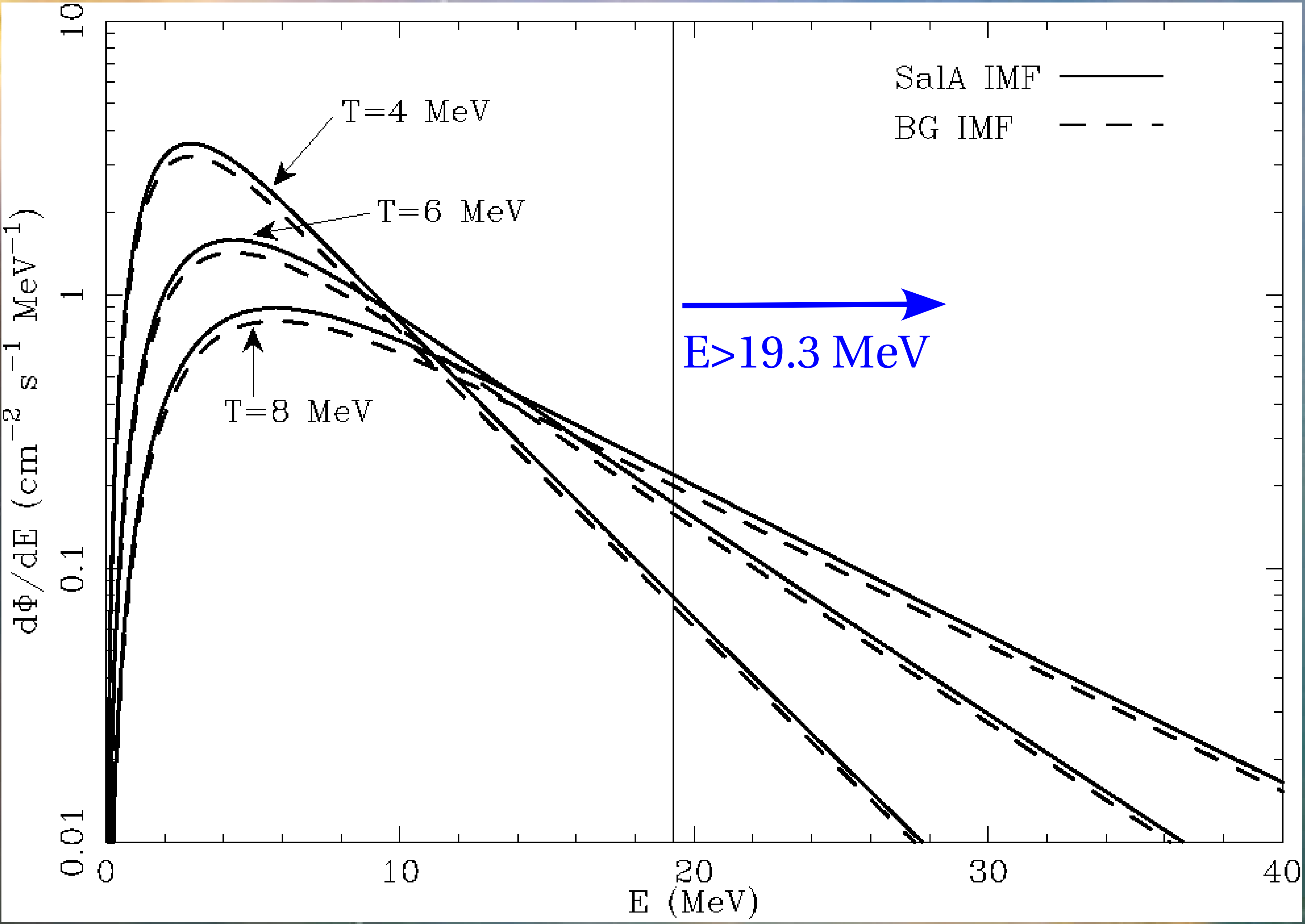
T=4 MeV or 6 MeV

T=8 MeV





Predicted $\bar{\nu}_e$ spectrum given the SFH



The Cosmic SFH: Summary

- The SFH is now robustly determined, up to z~6. The question next becomes how much obscuration is there in galaxies at 6<z<10, and are the SF galaxies alone sufficient to achieve reionisation?
- The SK neutrino limits place an ***upper limit*** on the (z<1) SFH normalisation.
- The space density of SNII rate evolution provides a ***lower limit*** for the normalisation.
- These limits, together with the now quite precise SFH measurements (particularly at z<1), allows the SFH normalisation to be robustly and quantitatively constrained for the first time.
- The resulting allowed cosmic SFH normalisations in turn put constraints on both the stellar IMF and the neutrino temperature.

Comments for further thought

- The SK measurements are limited to energies above about 19 MeV, corresponding to the SFH up to redshifts of z~1. Novel methods for sampling the DSNB spectrum down to ~5 MeV could constrain the SN rate at redshifts z>1 (Malaney 1997).
- The slope of the DSNB spectrum is sensitive to the neutrino temperature. Detecting and resolving the spectrum provides a direct probe of the characteristic SN neutrino temperature (Totani & Sato 1995).
- Loading SK with $GdCl_3$ can improve its sensitivity to the DSNB significantly (Beacom & Vagins 2004).
- Combining the background analysis from SK with the sensitivity to ν_e of SNO can improve the measurement limit to 6 cm^{-2} s^{-1} over 22.5<E<32.5 MeV (Beacom & Strigari 2005).

More comments for further thought

- Detecting and resolving the DSNB spectrum also allows exploration of other neutrino properties, in particular the possibility of an inverted mass hierarchy, and the idea of non-radiative neutrino decay (Ando & Sato 2004).
- Constraining cosmological parameters and Dark Energy independently using the DSNB combined with future SN surveys, as a consistency check on existing measurements (Hall et al 2006, hep-ph/0607109).
- Probing late neutrino mass properties. Depending on the DSNB spectrum, neutrinos could be distinguished between Majorana or Dirac particles, the type of mass hierarchy determined, and possibly even the masses determined (Baker et al 2006, hep-ph/0607281).
- Understanding neutrino emission from SN may also help to probe new physics, like emission of sterile neutrinos or other new particles.