Observed Evolution of Galaxy Properties

university of groningen
faculty of science and engineering
kapteyn astronomical institute

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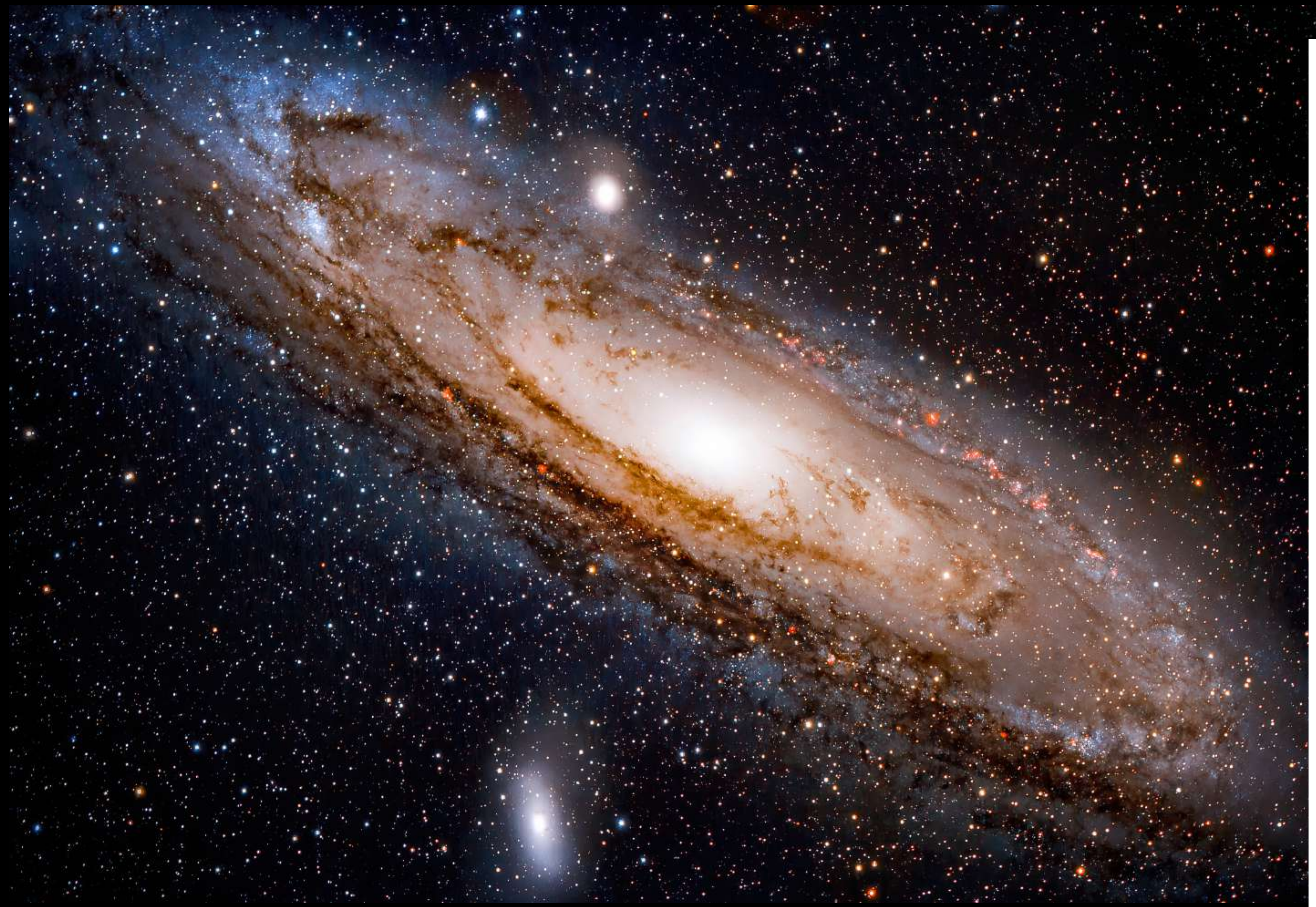
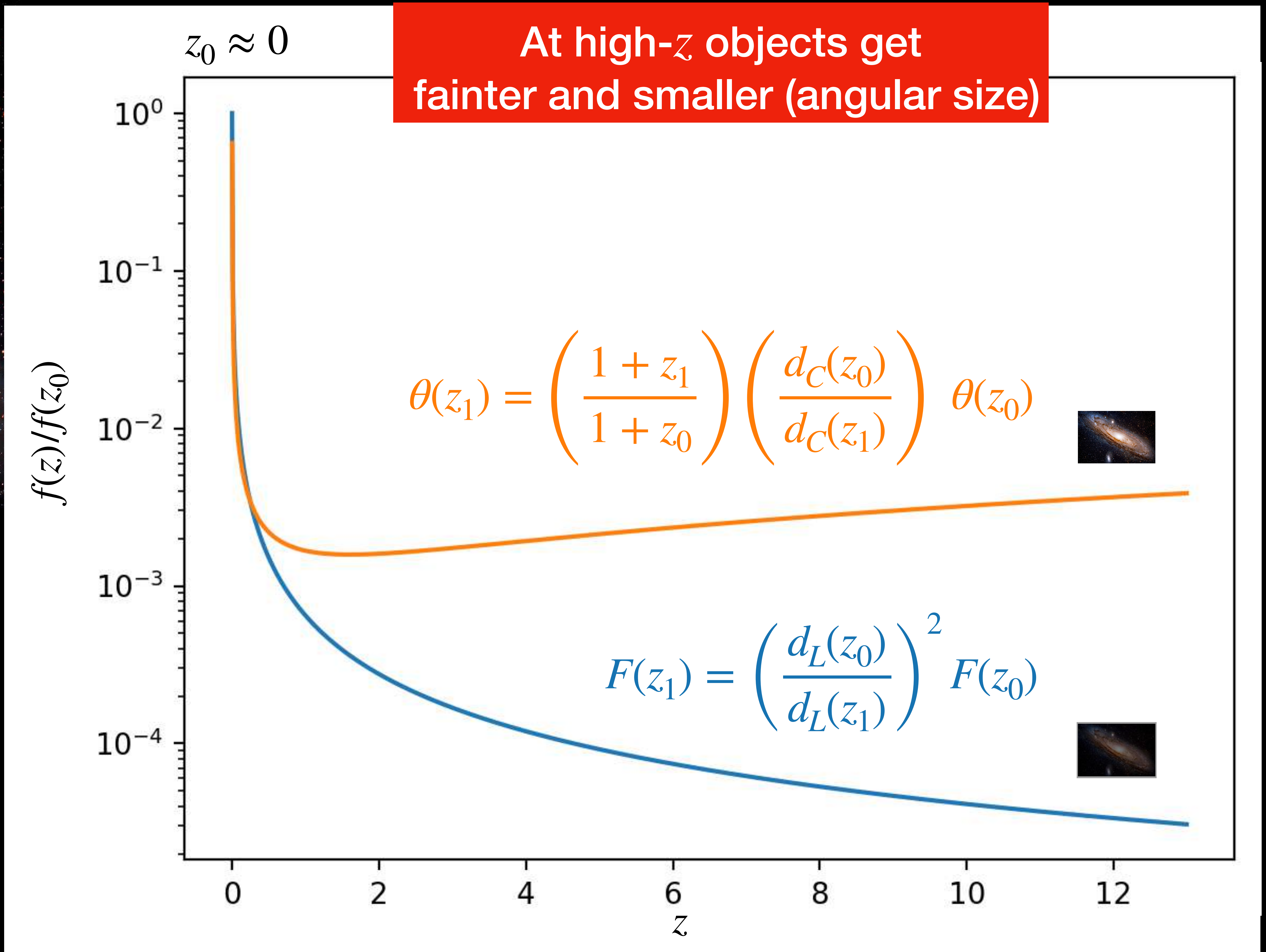
12th October 2023 - Kapteyn Institute - 13:00-15:00

Galaxy Formation and Evolution

ARAA Conselice (2014)
ARAA Madau & Dikinson (2014)
Introduction to galaxy formation and evolution, Chap. 11, Cimatti et al. (2020)

Why such a ‘young’ field?

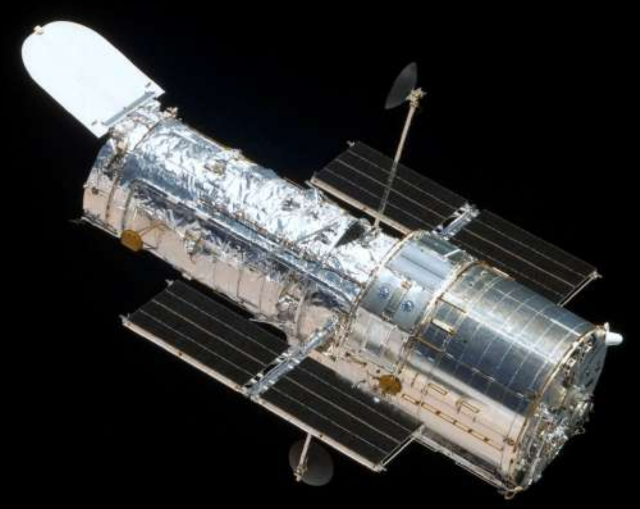




Flat $\Lambda-$CDM cosmology ($\Omega_k = 0$):

- $d_C(z) = \frac{c}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_r(1+z')^4 + \Omega_m(1+z')^3 + \Omega_\Lambda}}$
- $d_L(z) = (1+z)\ d_C(z)$

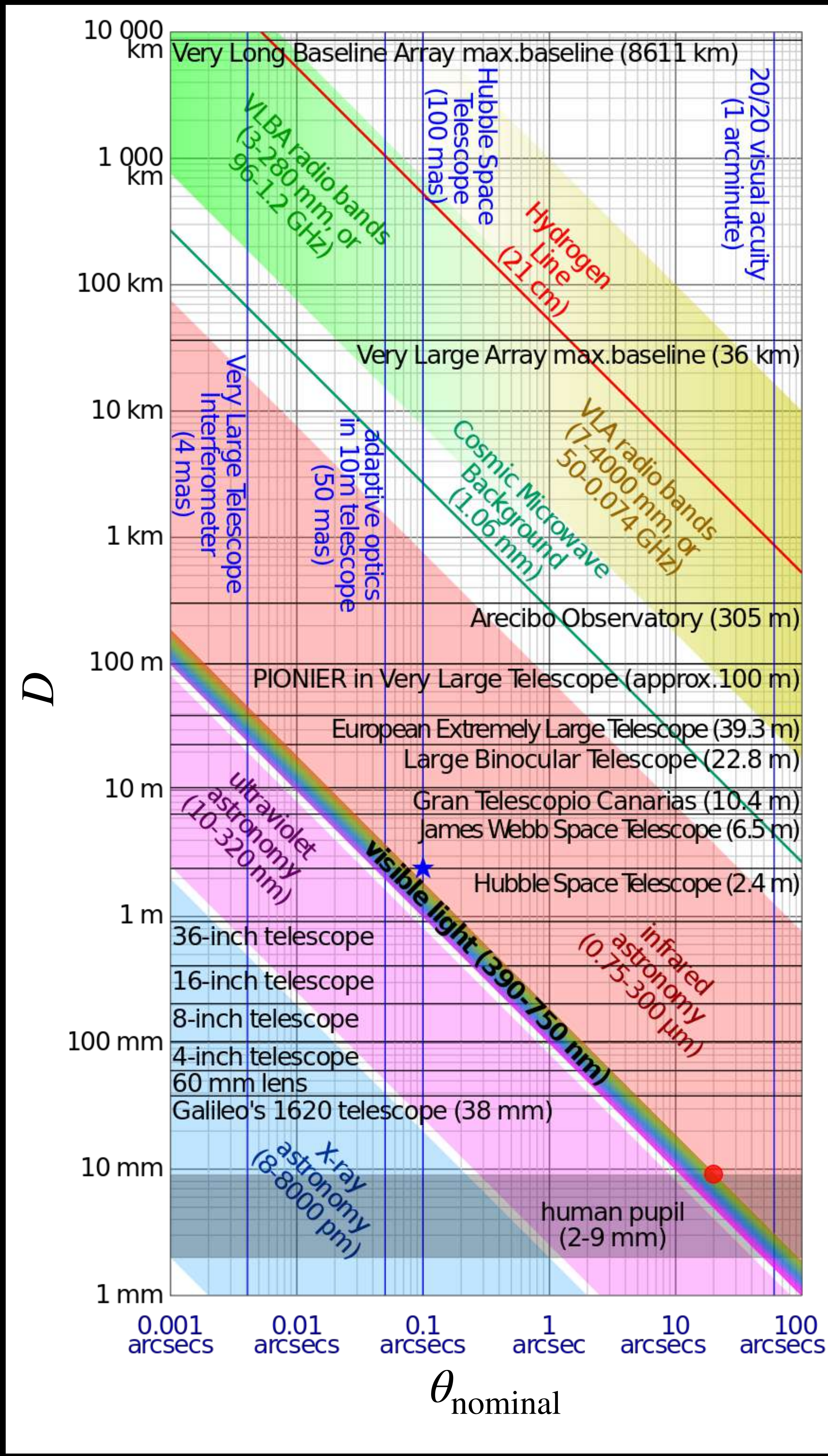
Instrumentation limits



Angular resolution:

$$\theta_{\text{nominal}} \approx 2.44 \frac{\lambda}{D}$$

In the real world, $\theta > \theta_{\text{nominal}}$:
- Misalignments
- Finite quality of the optics
- …



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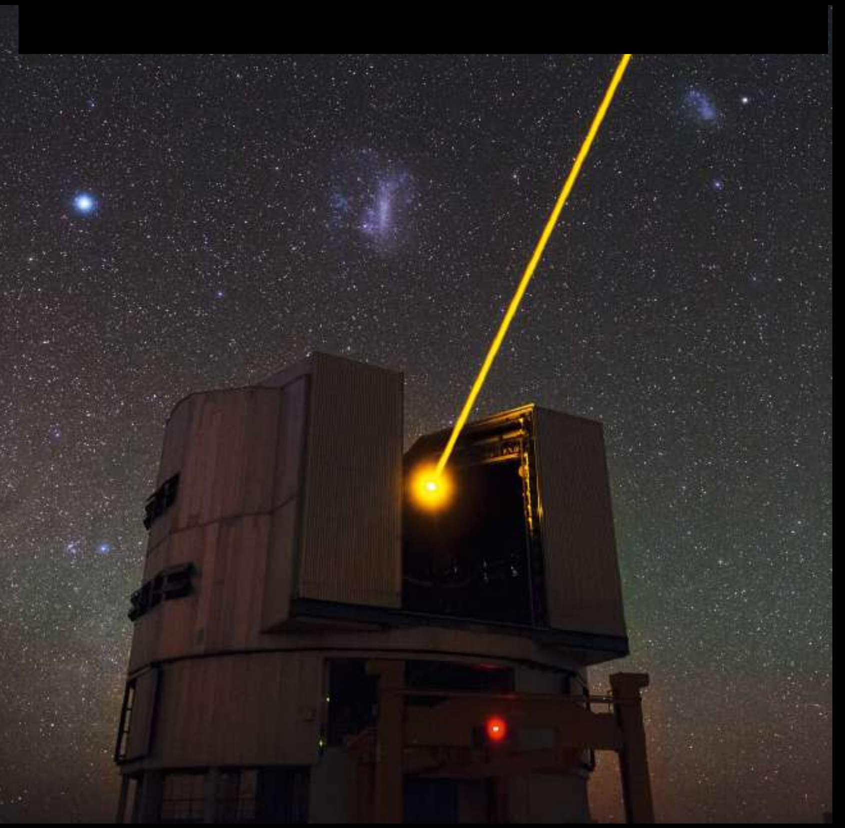

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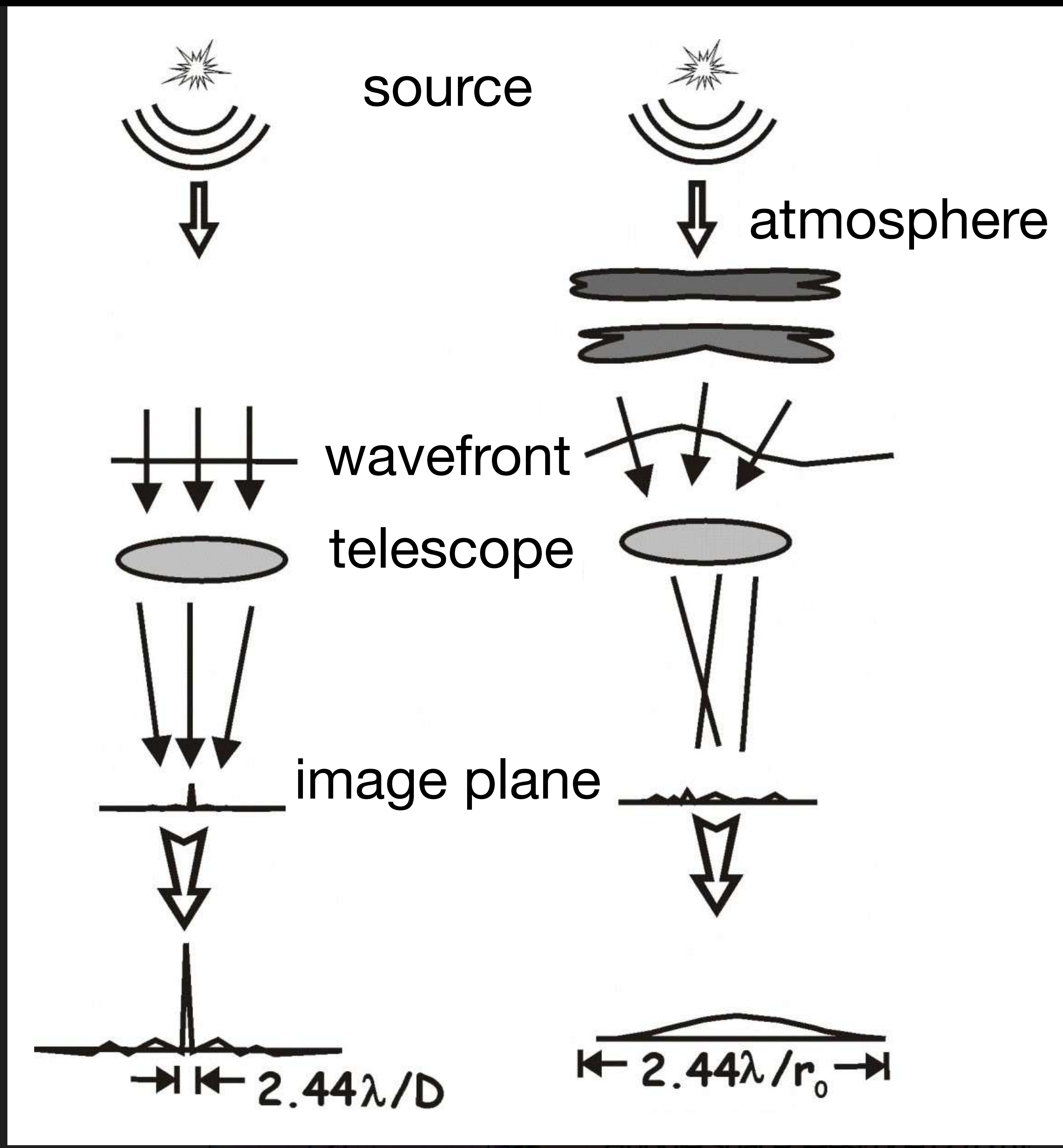
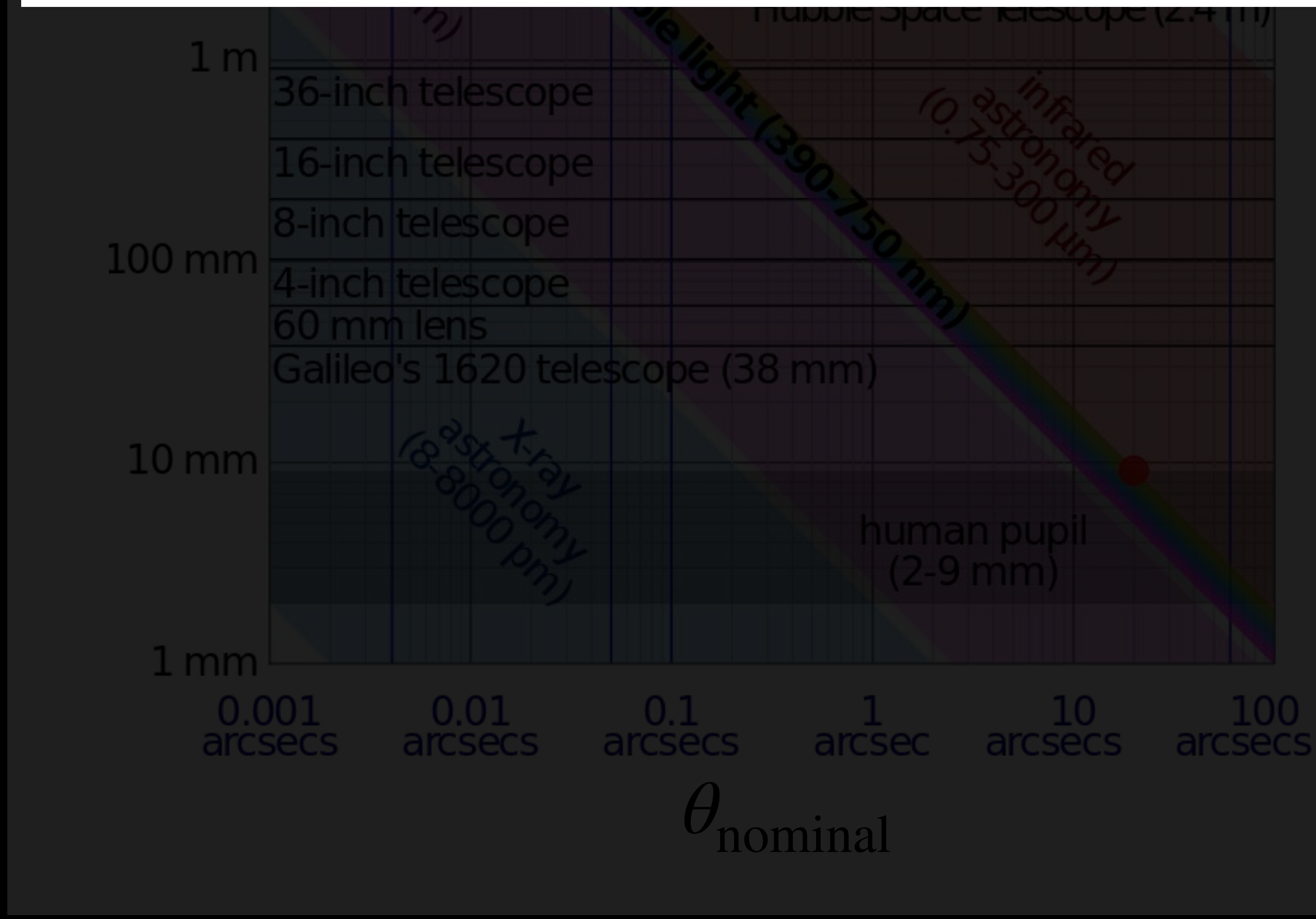
For ground-based telescopes, θ is limited by the **seeing** (no matter what D is):

$$\theta \approx 2.44\frac{\lambda}{r_0}$$

$r_0 = r_0(t, \lambda)$**:** Fried parameter (average size turbulent cell)





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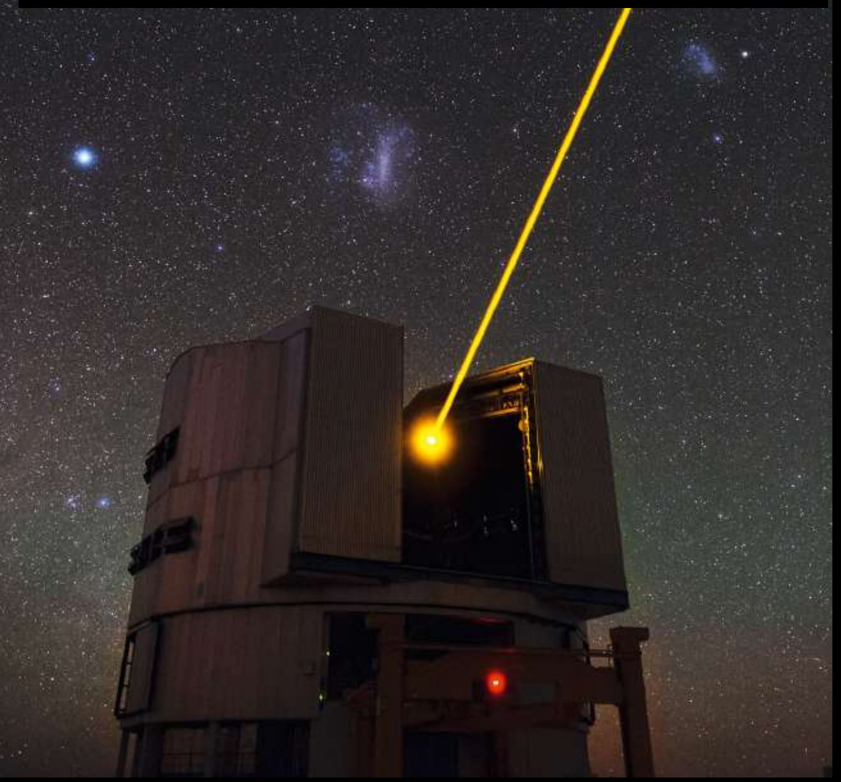

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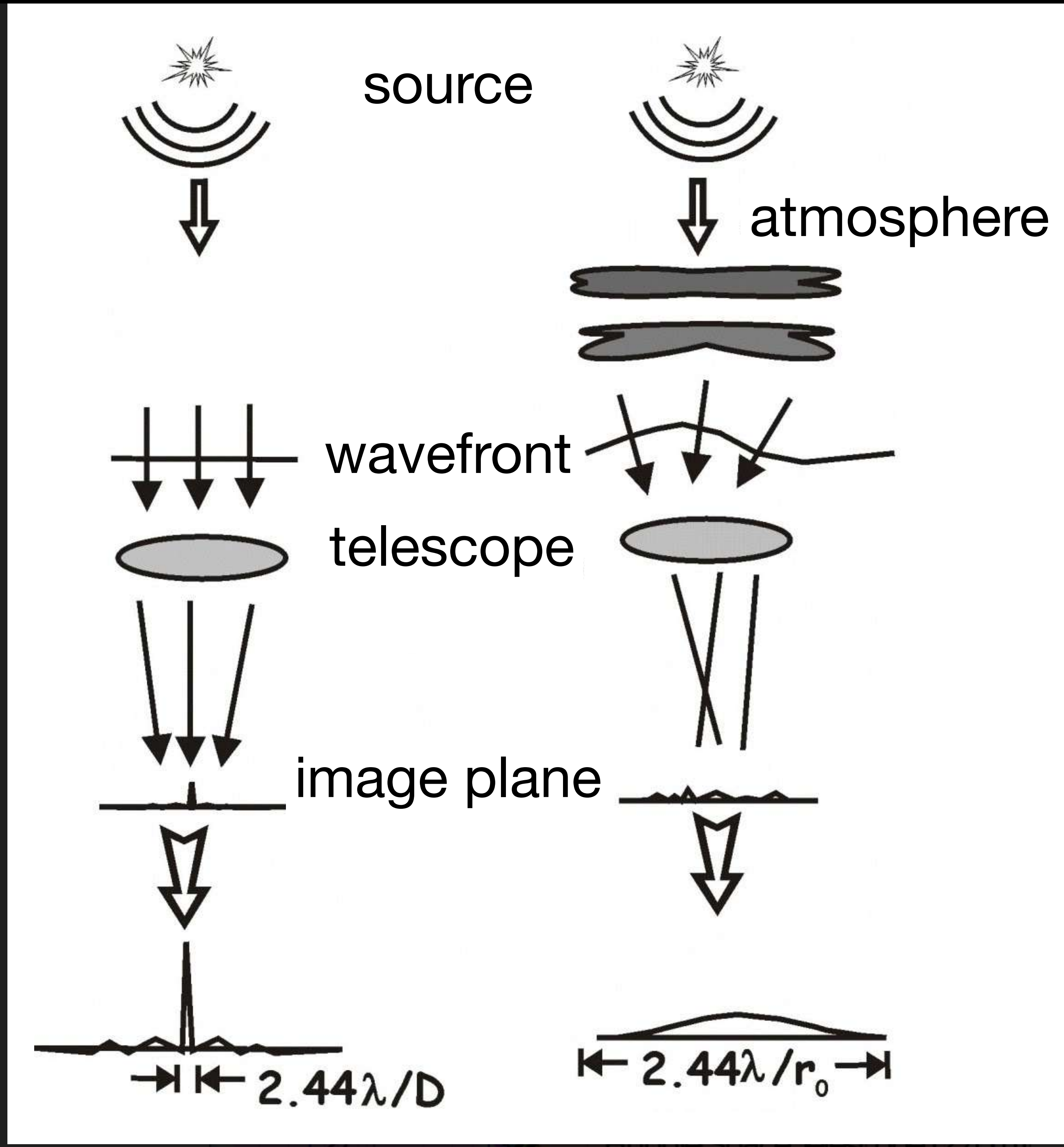
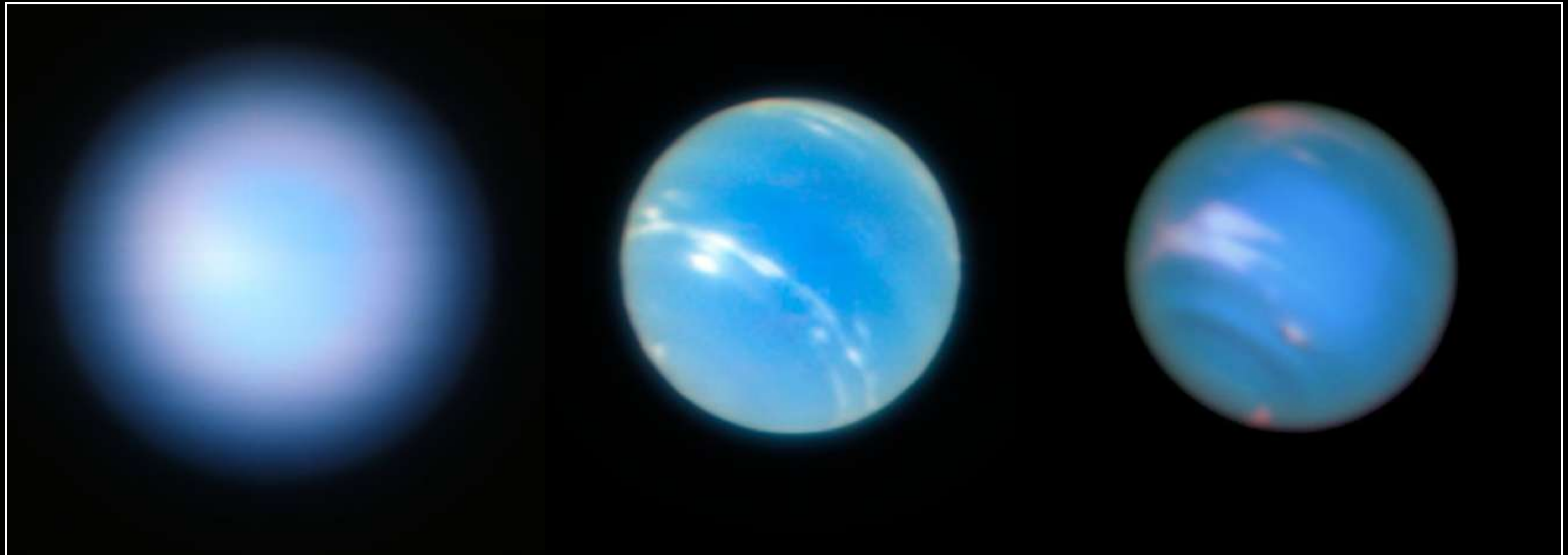
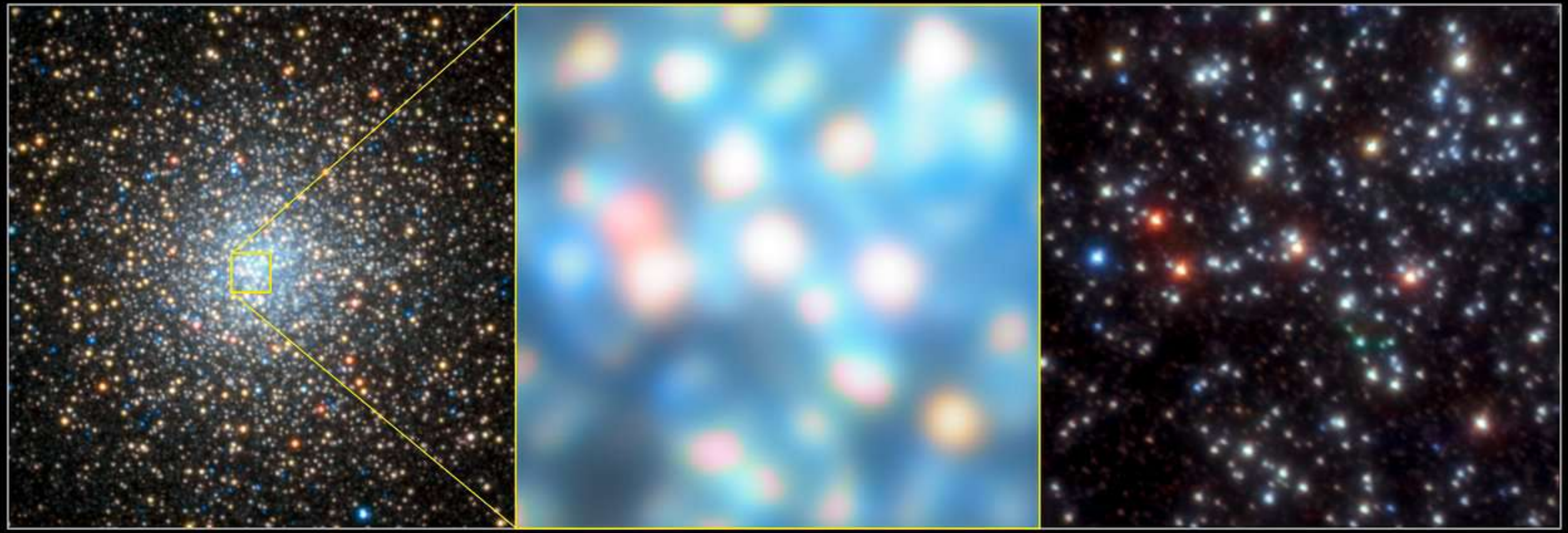


but AO (adaptive optics) can help!



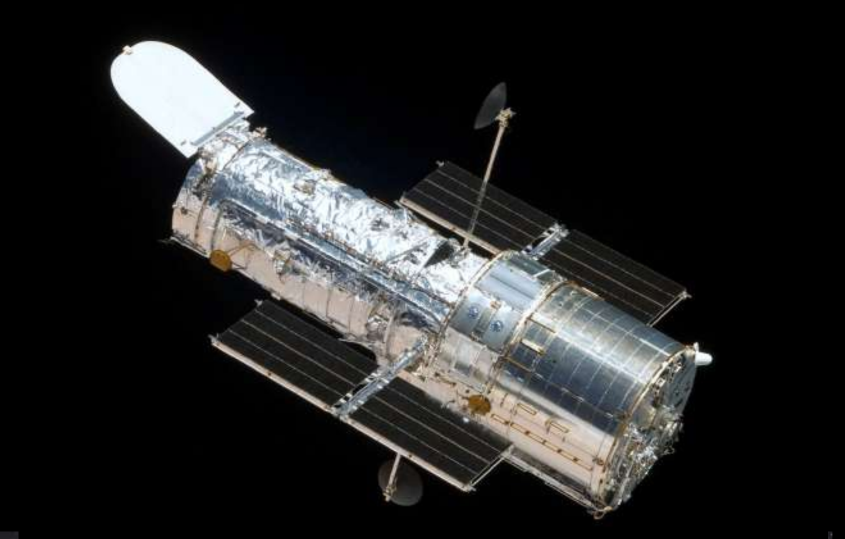
No Adaptive optics | VLT Adaptive Optics | Hubble Space Telescope

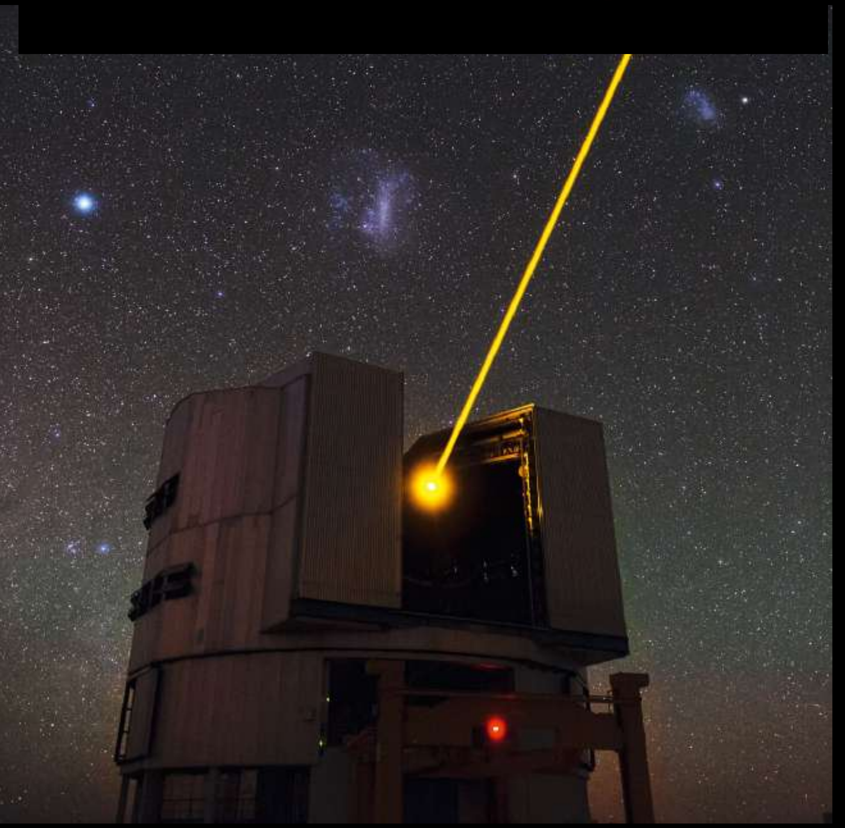


VLT+MUSE Wide Field Mode without Adaptive Optics

VLT+MUSE Narrow Field Mode with Adaptive Optics

Instrumentation limits





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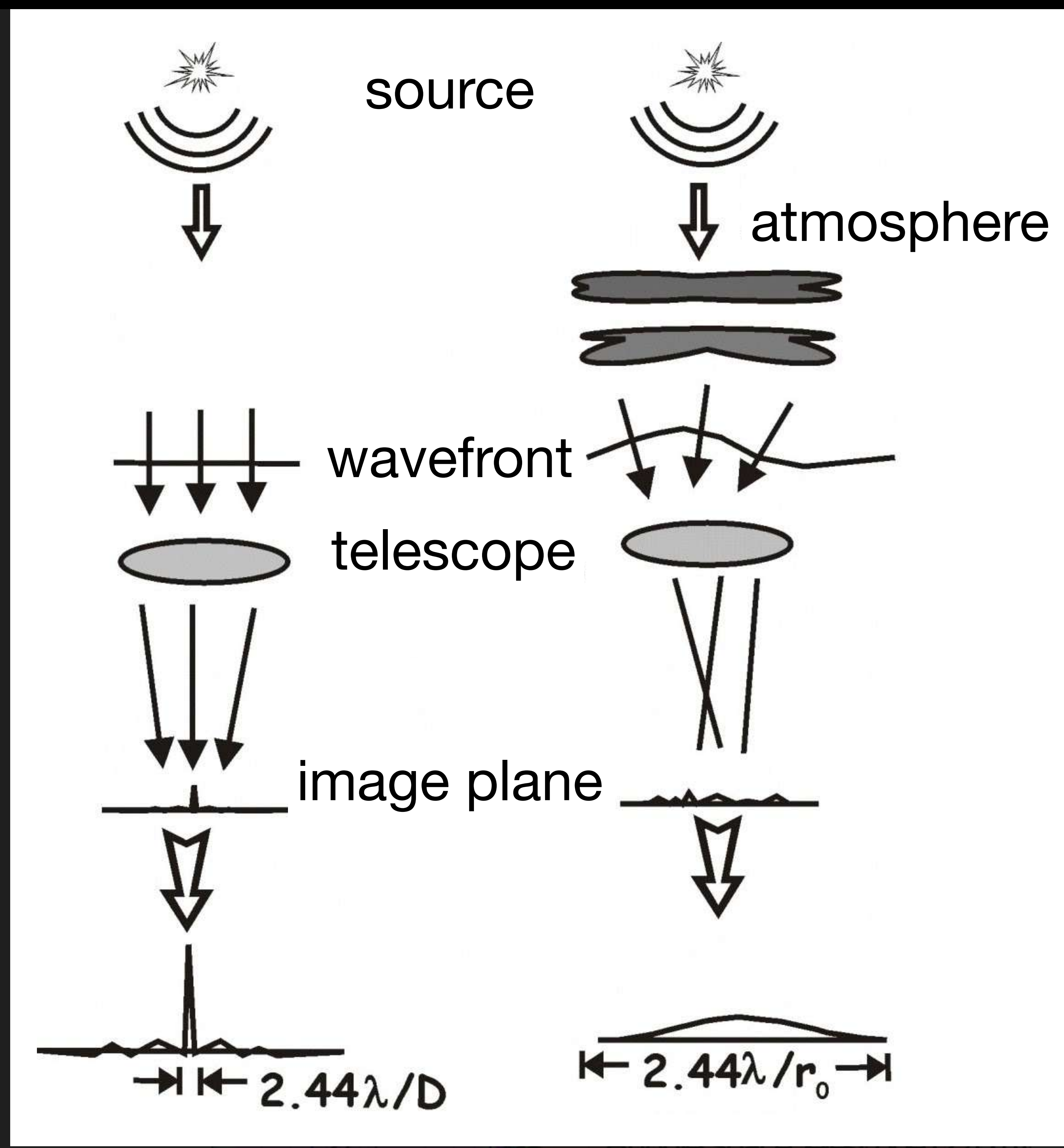
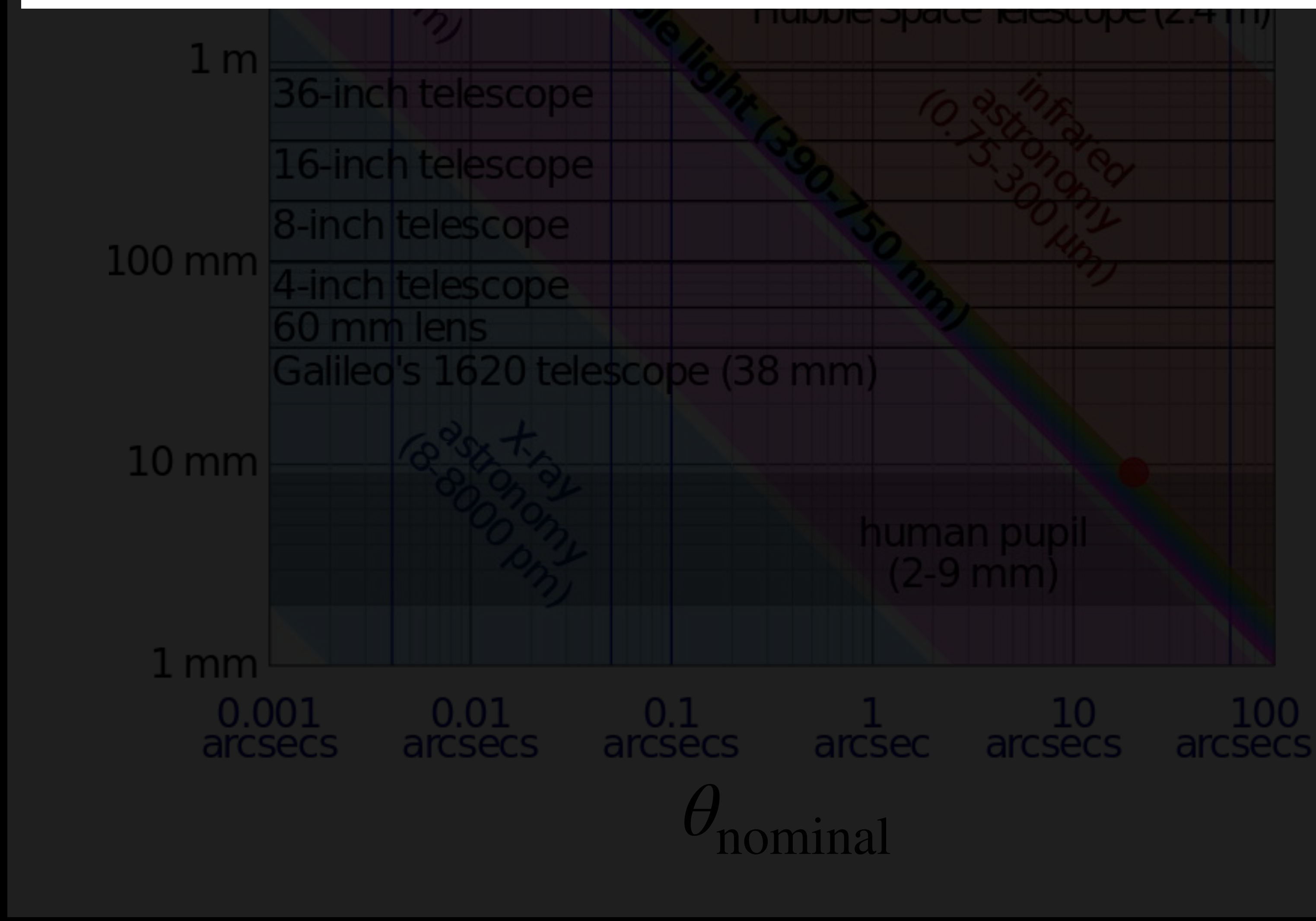


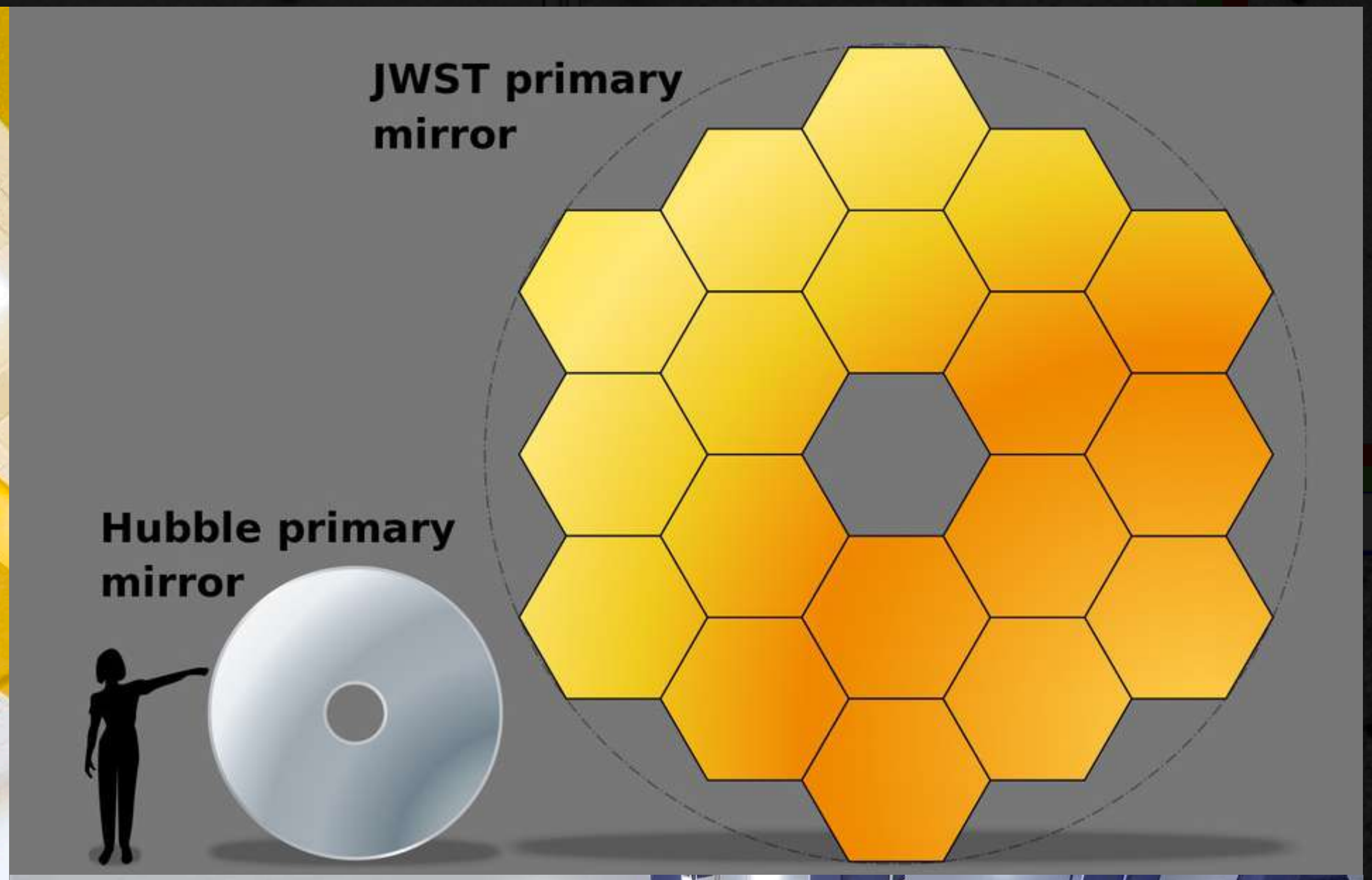


Sensitivity:

- **Aperture** $\propto D^2$
- **Exposure time** $(\mathrm{SNR} \propto \sqrt{t_{\text{exp}}})$
- Detector quantum efficiency (Q.E.)
- Background light (light pollution, airglow, telluric, zodiacal light, …)
- (Atmospheric transmission)

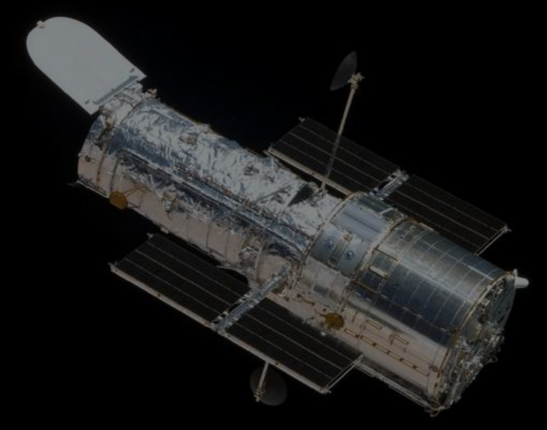

VIMOS U
CTIO U
ACS F435W
Legend:
— space telescopes
— ground-based telescopes
ACS F606W
ACS F775W
ACS F850LP
WFC3 F160W
ISAAC J
HST (Hubble Space Telescope)
1990-2030/40 (estimated)
$D = 2.4$ m
$\lambda = 0.1 - 1.7\ \mu$m
$\theta_{\rm nominal} = 0.01'' - 0.15''$
ISAAC H
ISAAC K
IRAC 3.6
IRAC 4.5
MIPS 24
SST (Spitzer Space Telescope)
2003-2020
$D = 0.85$ m
$\lambda = 3 - 180\ \mu$m
$\theta_{\rm nominal} = 0.74'' - 44.7''$
PACS 100
PACS 160
SPIRE 250
SPIRE 350
SPIRE 500
Herschel Space Observatory
2009-2013
$D = 3.5$ m
$\lambda = 55 - 672\ \mu$m
$\theta_{\rm nominal} = 3.3'' - 40.3''$
5"

Looking forward for JWST!



JWST (James Webb Space Telescope)
Launched on the 25/12/2021

$D = 6.5\ \mathrm{m}$
$\lambda = 0.6 - 28.5\ \mu\mathrm{m}$
$\theta_{\mathrm{nominal}} = 0.02'' - 0.92''$



HST (Hubble Space Telescope)
1990-2030/40 (estimated)

$D = 2.4\ \mathrm{m}$
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$\theta_{\mathrm{nominal}} = 0.01'' - 0.15''$

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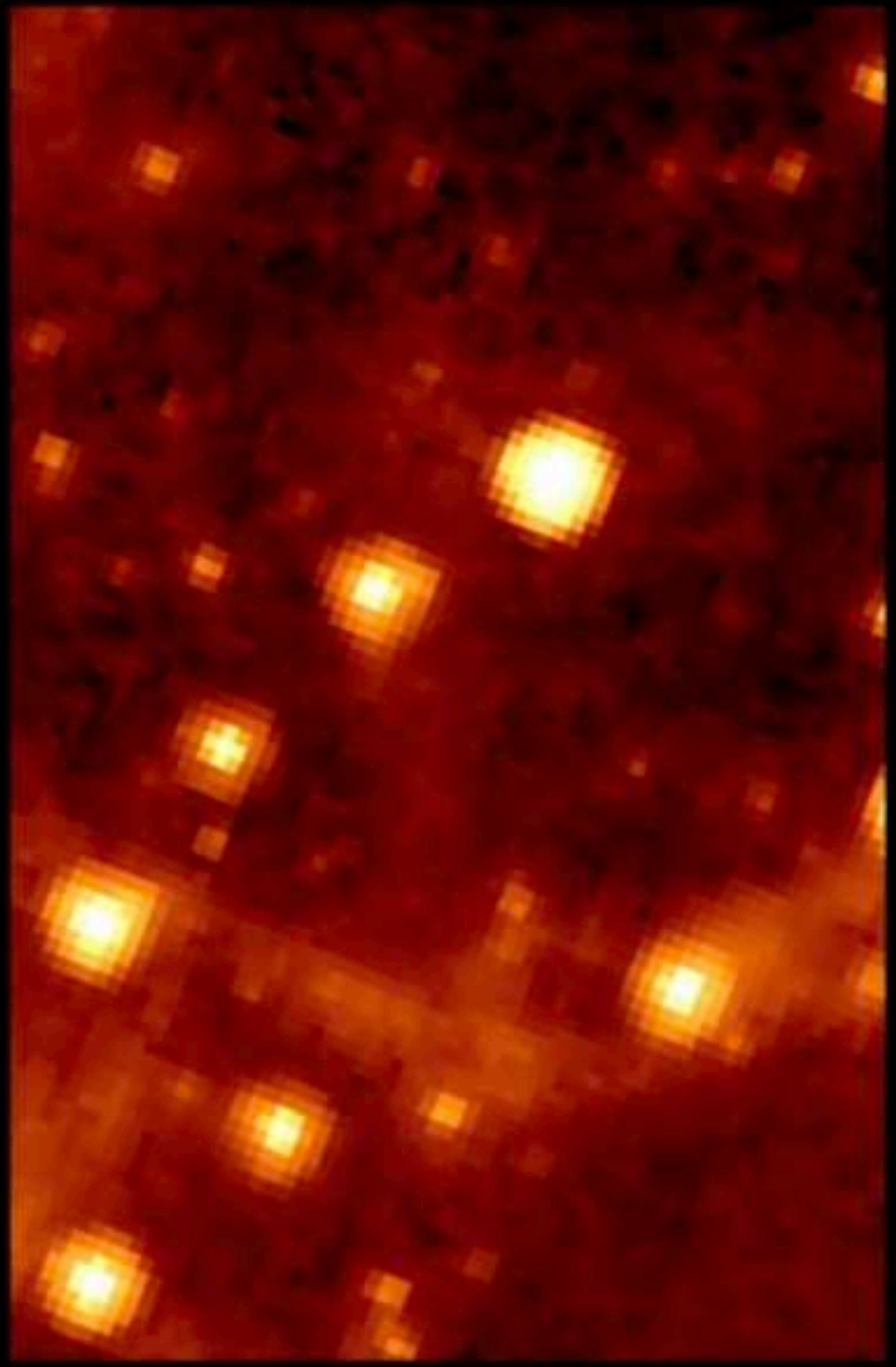


Spitzer/IRAC 8.6 µm

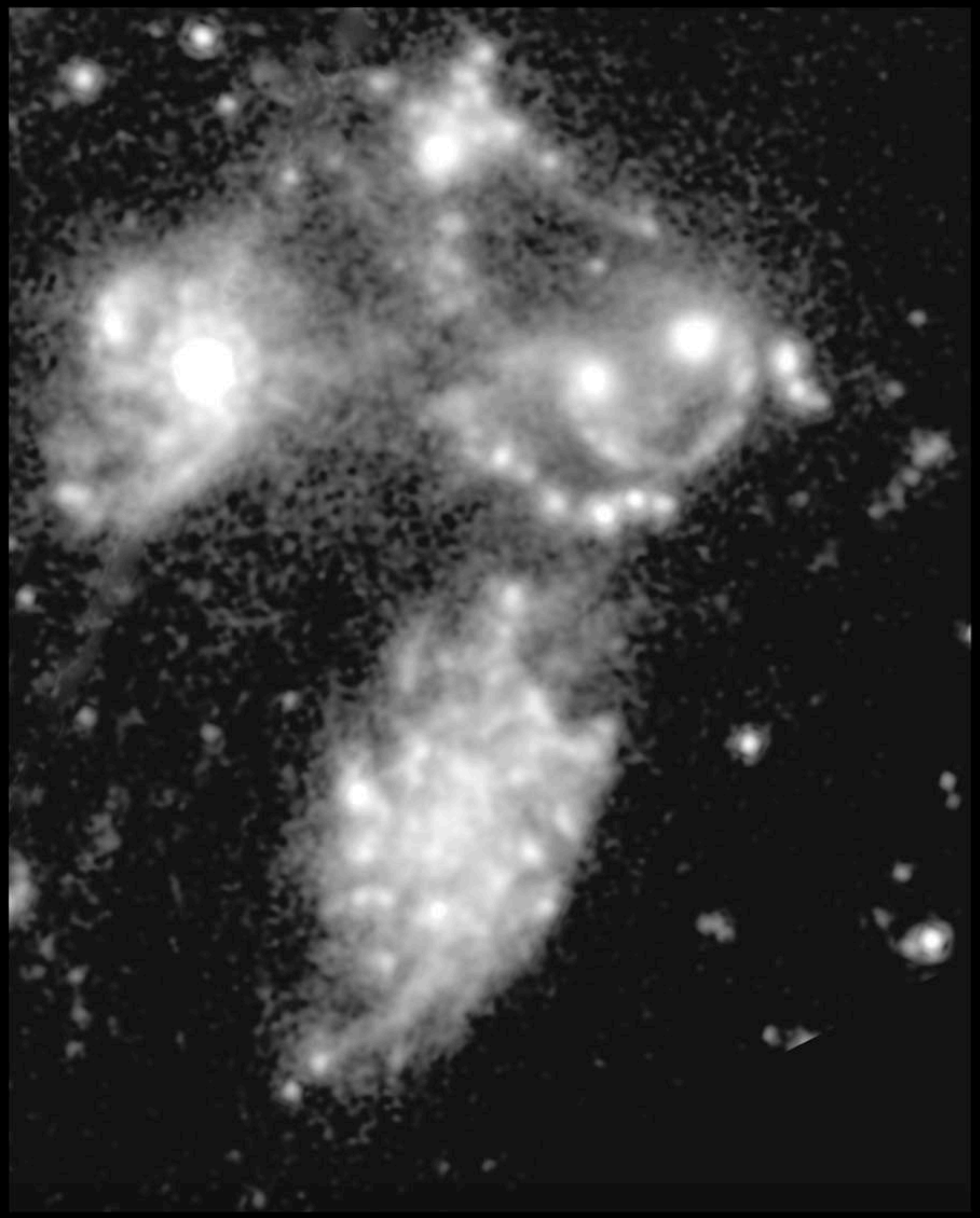
JWST/MIRI 7.7 µm

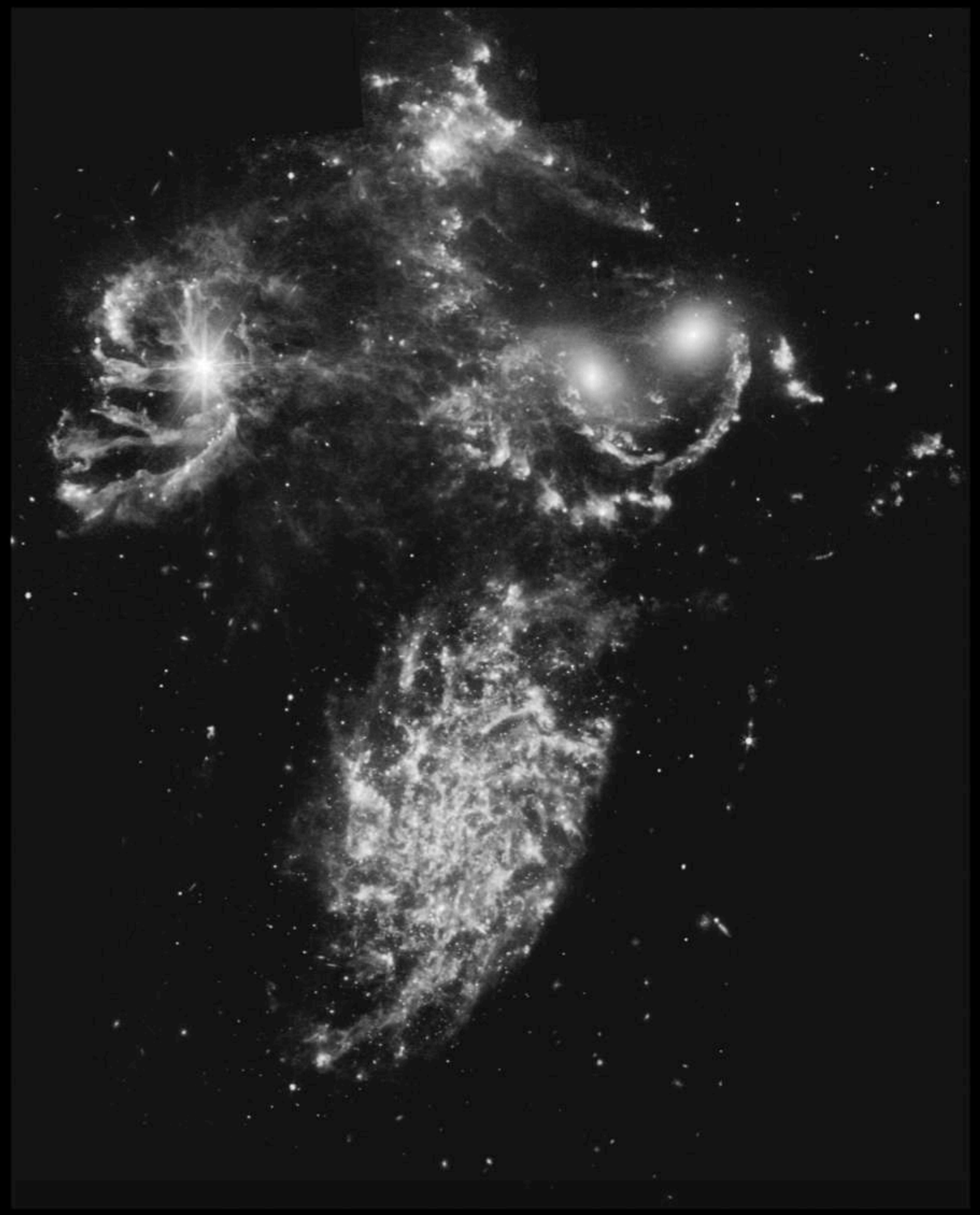
Large Magellanic Cloud

Stephan’s Quintet

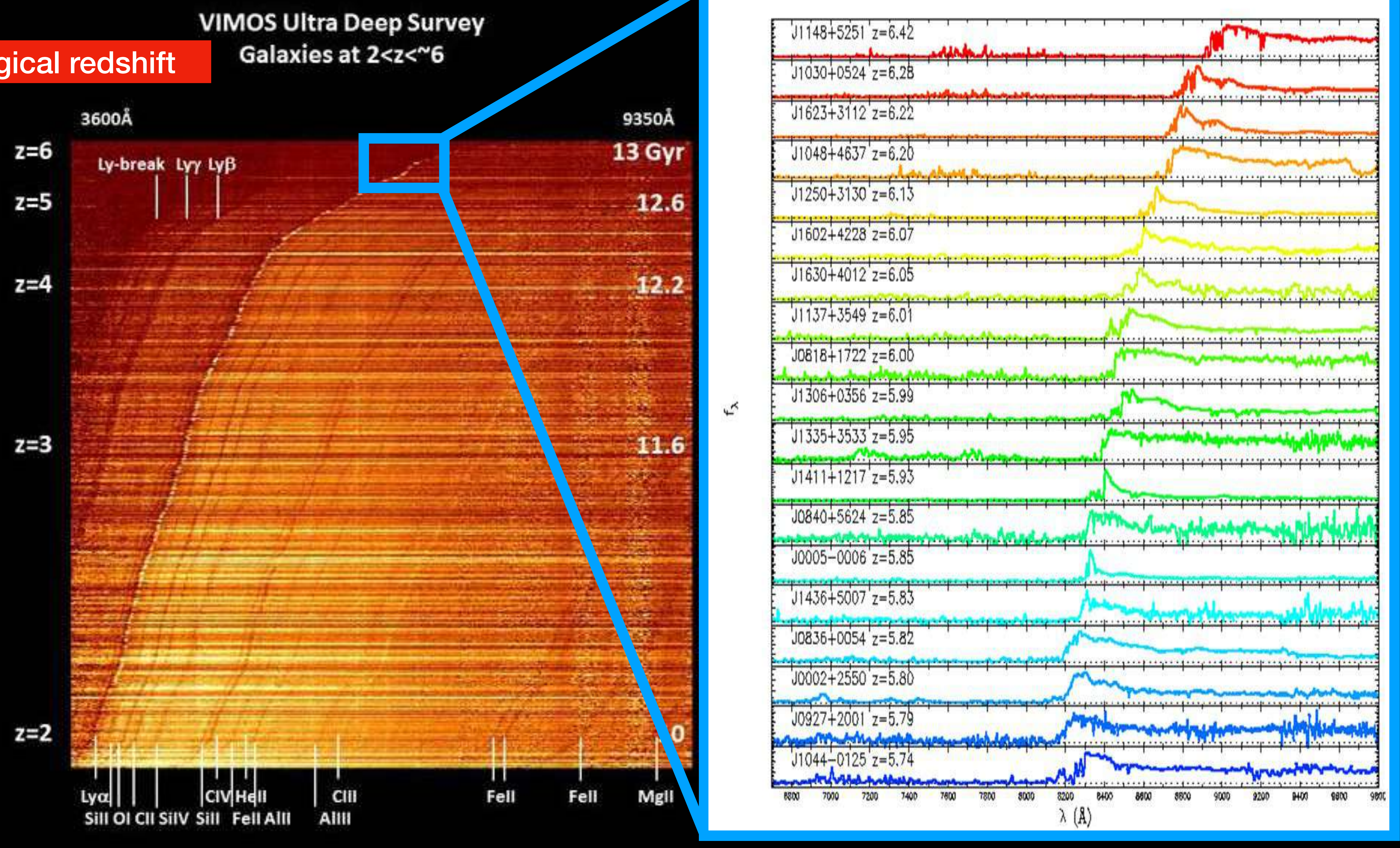
Spitzer 8µm

JWST 7.7µm



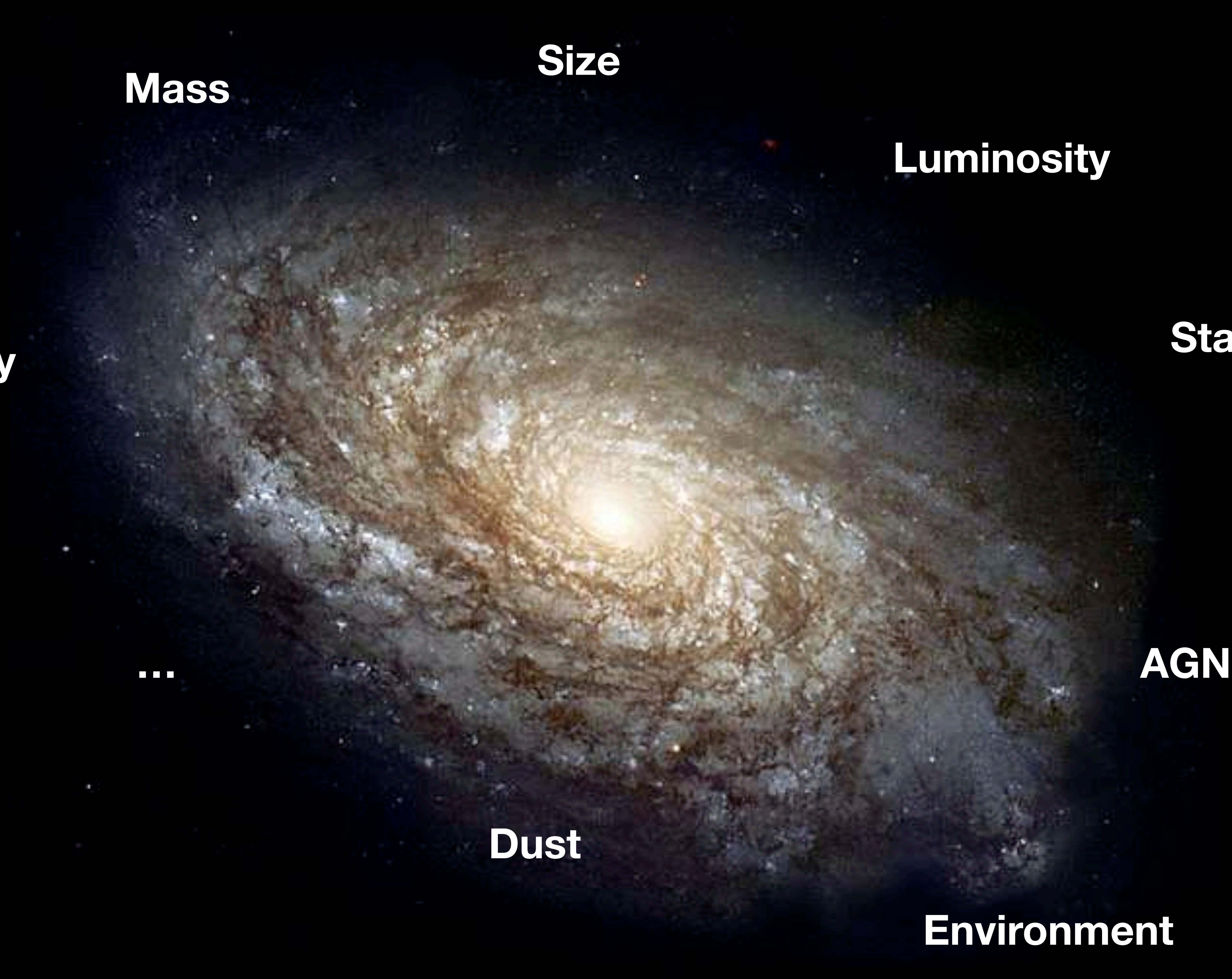


Cosmological redshift



VI
3600Å
z=6
z=5
z=4
z=3
z=2
Ly-break
Lyγ
Lyα
SiII OI CII SiIV SiII
CIV
Elliptical Galaxy at z=0.0
Elliptical Galaxy at z=0.4
Elliptical Galaxy at z=0.7
u
g
r
i
z
F_λ
Wavelength [Ang]
λ (Å)
K-CORRECTION

The observed evolution of galaxies



Mass

Size

Luminosity

Morphology

Star formation

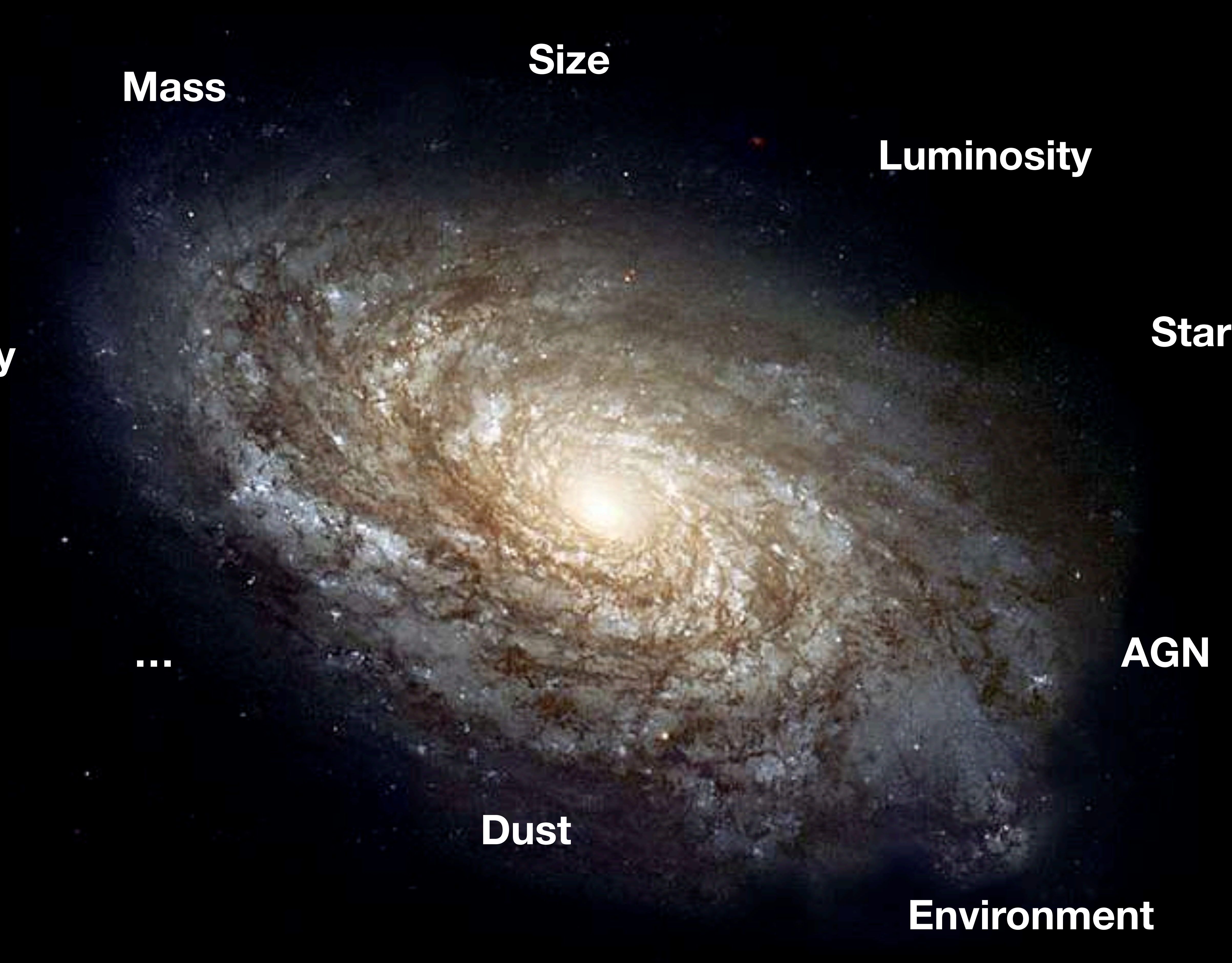
...

AGN

Dust

Environment

The observed evolution of galaxies



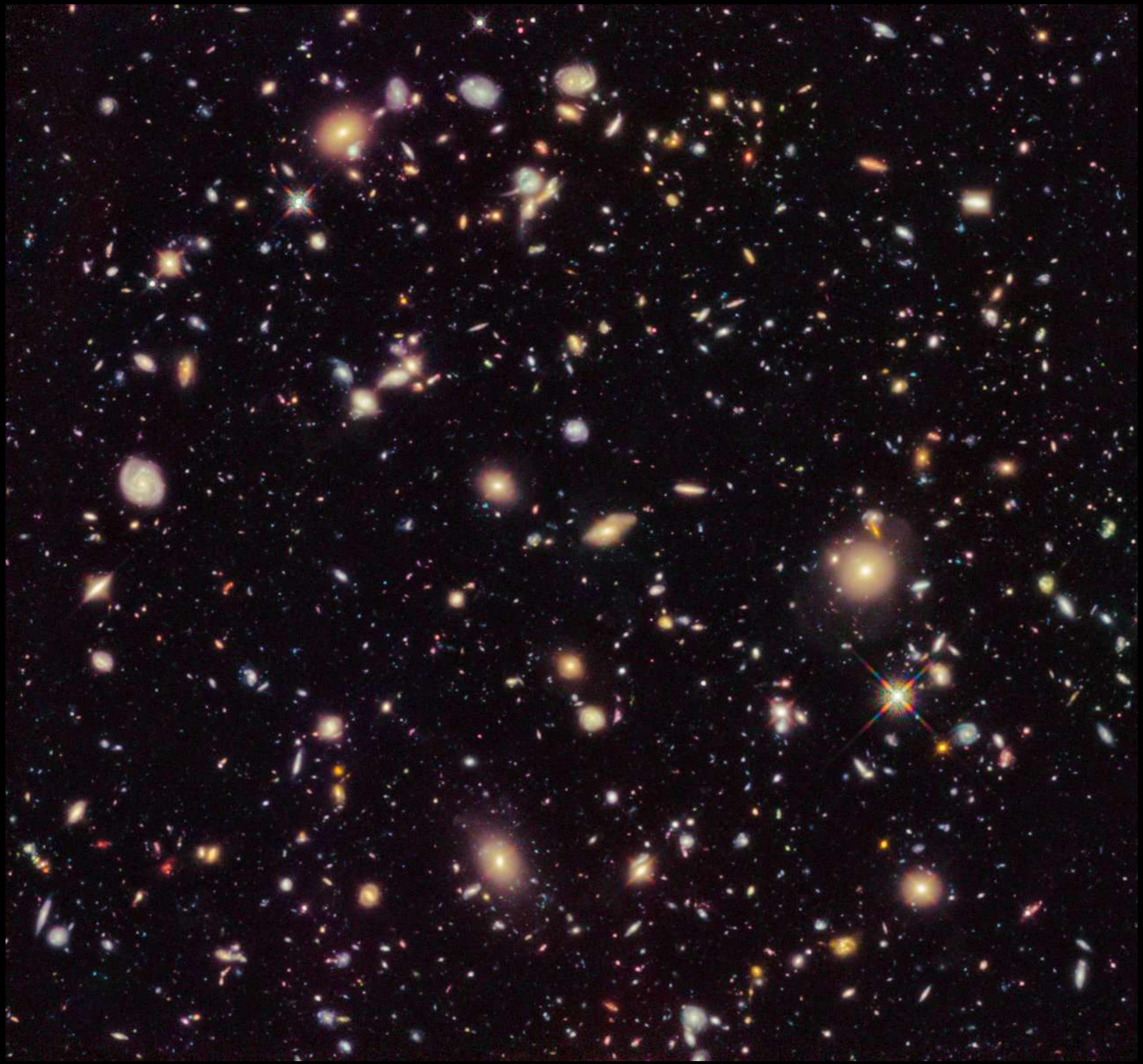
In today's lecture:

- Morphology
- Size
- Colours
- Luminosity
- Star Formation

General Approach

Steps to derive the evolution of galaxy properties (observational approach):

1. Survey (photometric, spectroscopic, mixed);
2. Selection of a sample;
3. Derive the galaxy properties (e.g. z, L, $M_\star$, SFR);
4. Divide galaxies into redshift bins;
5. Correction for biases and selection effects (e.g. incompleteness);
6. Determine how galaxy properties varies with z;
7. Comparison with model predictions.



Main Biases in Galaxy Surveys

What is a Bias? BIAS is a systematic effect that leads to an incorrect interpretation of the observational results. In galaxy surveys we have to take into account:

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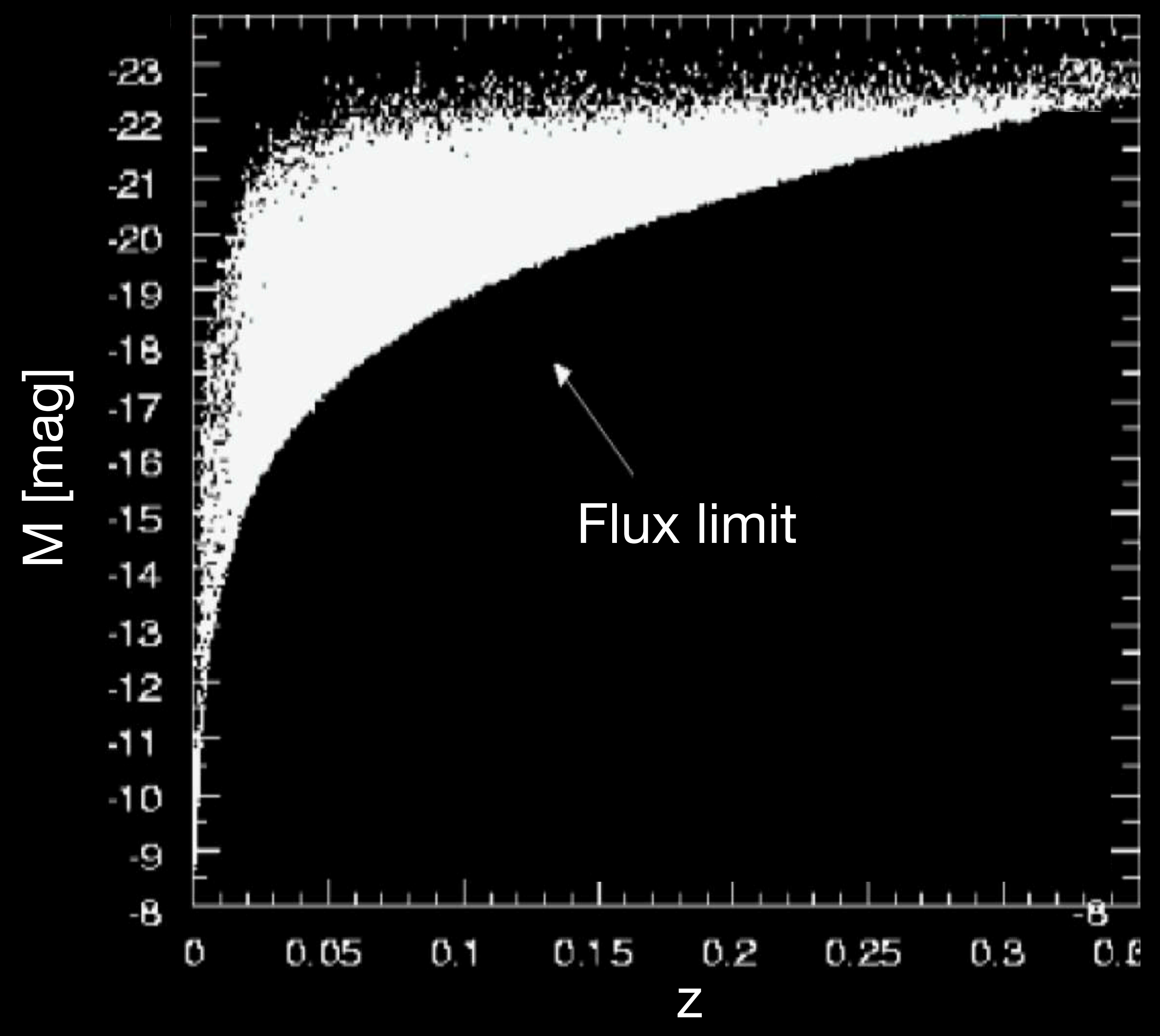
- **Malmquist bias** (Malmquist, 1922): only the galaxies above a given flux threshold can be detected (surveys have a maximum 'depth' that depends, e.g., on the exposure time)

$$L < L_{\rm lim} = 4\pi d_L^2 F_{\rm lim}$$



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Main rveys

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observational res

- Malmquist shold can be
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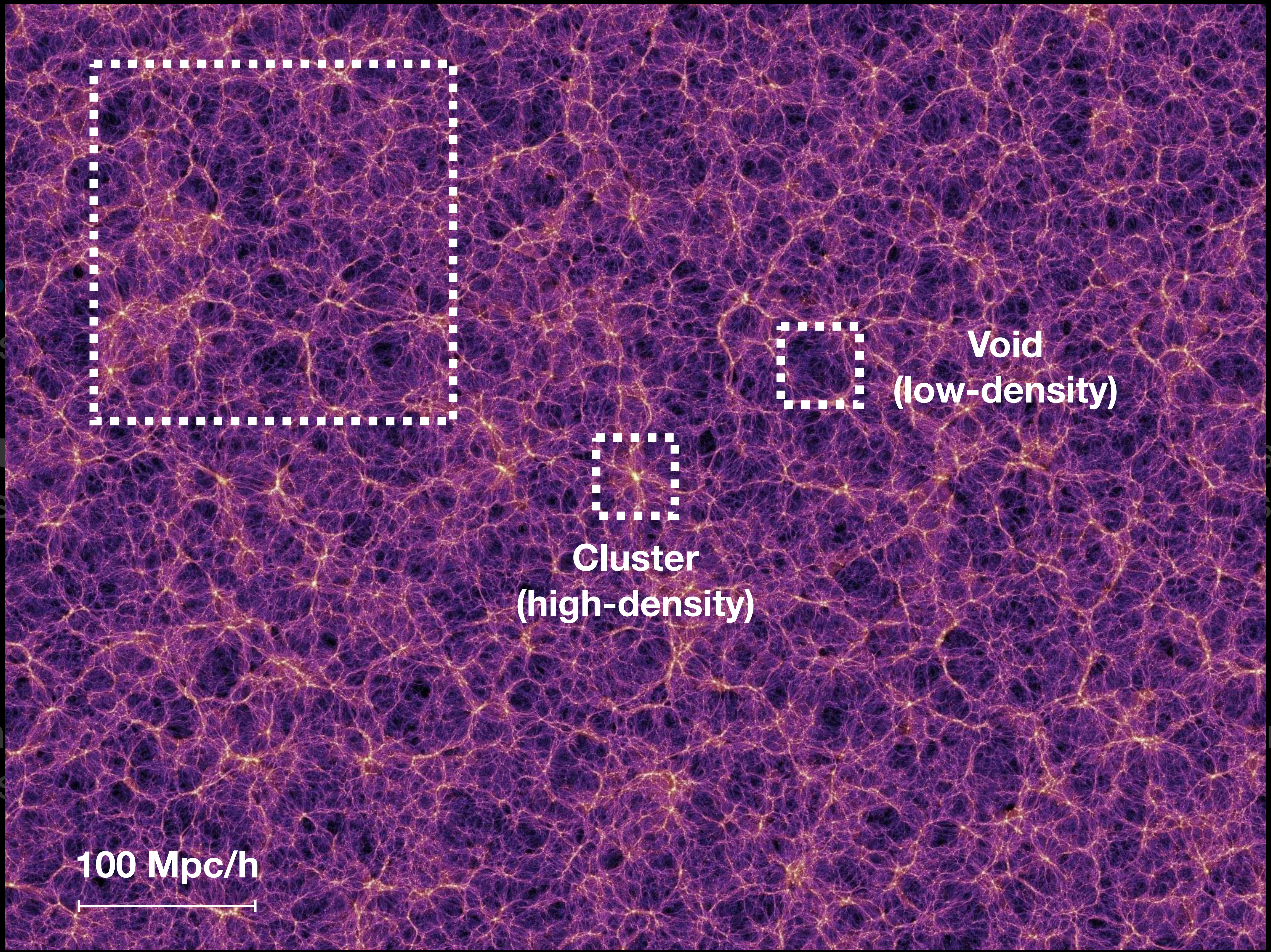

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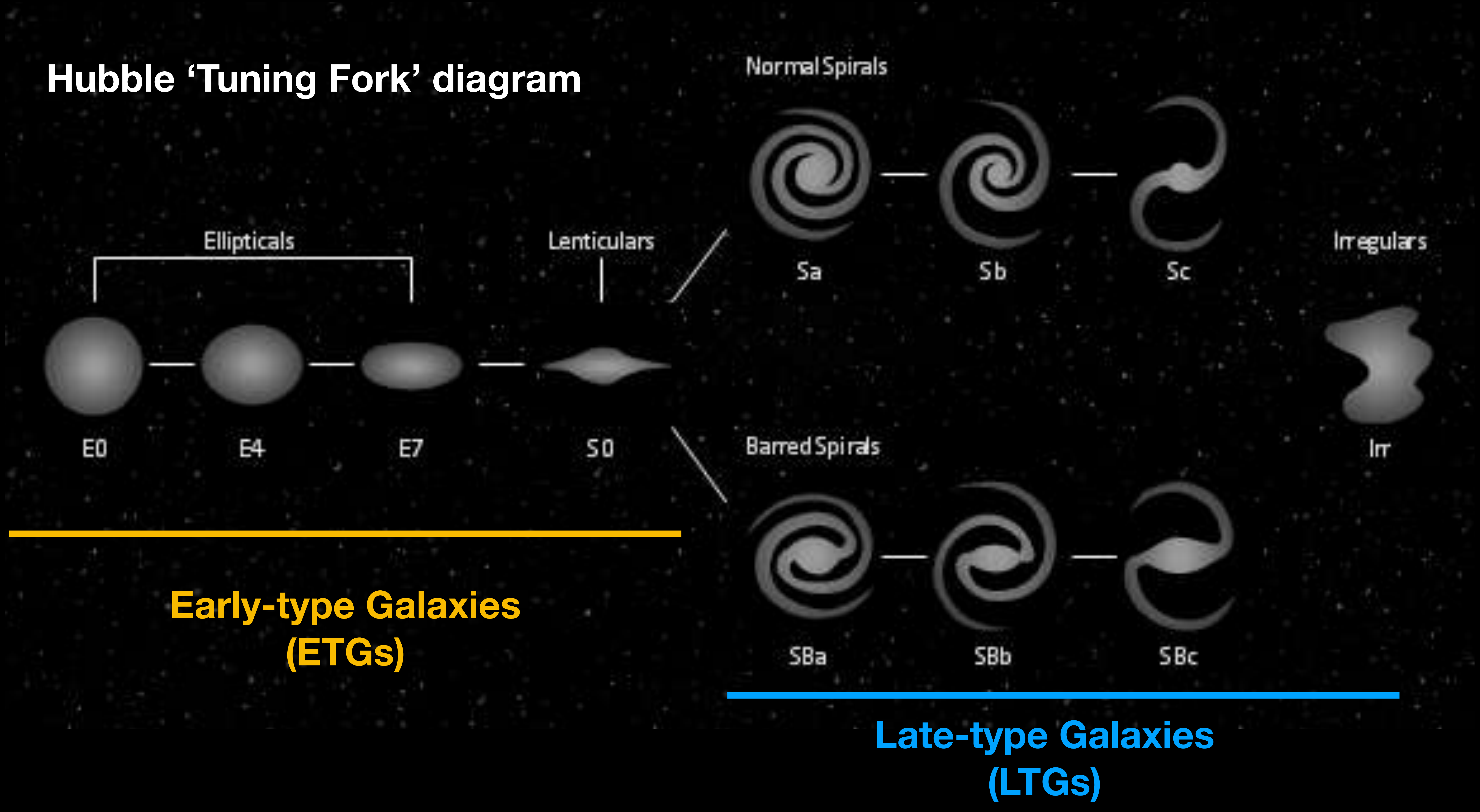
- **Progenitor bias** [when studying the z-evolution of a given galaxy population]: arises from the assumption that the properties of distant objects can be directly compared to their 'local counterparts'.

Morphology

Morphological classification:

- Visual inspection (optical):



Can you guess the morphological type?

WARNING

Misleading image display: time exposure

WARNING

Dependence on the wavelength

λ

MORPHOLOGICAL K-CORRECTION

Morphology

Morphological classification:

- Visual inspection (optical)
- **Surface brightness profile**:

Sérsic profile
(Sérsic 1968)

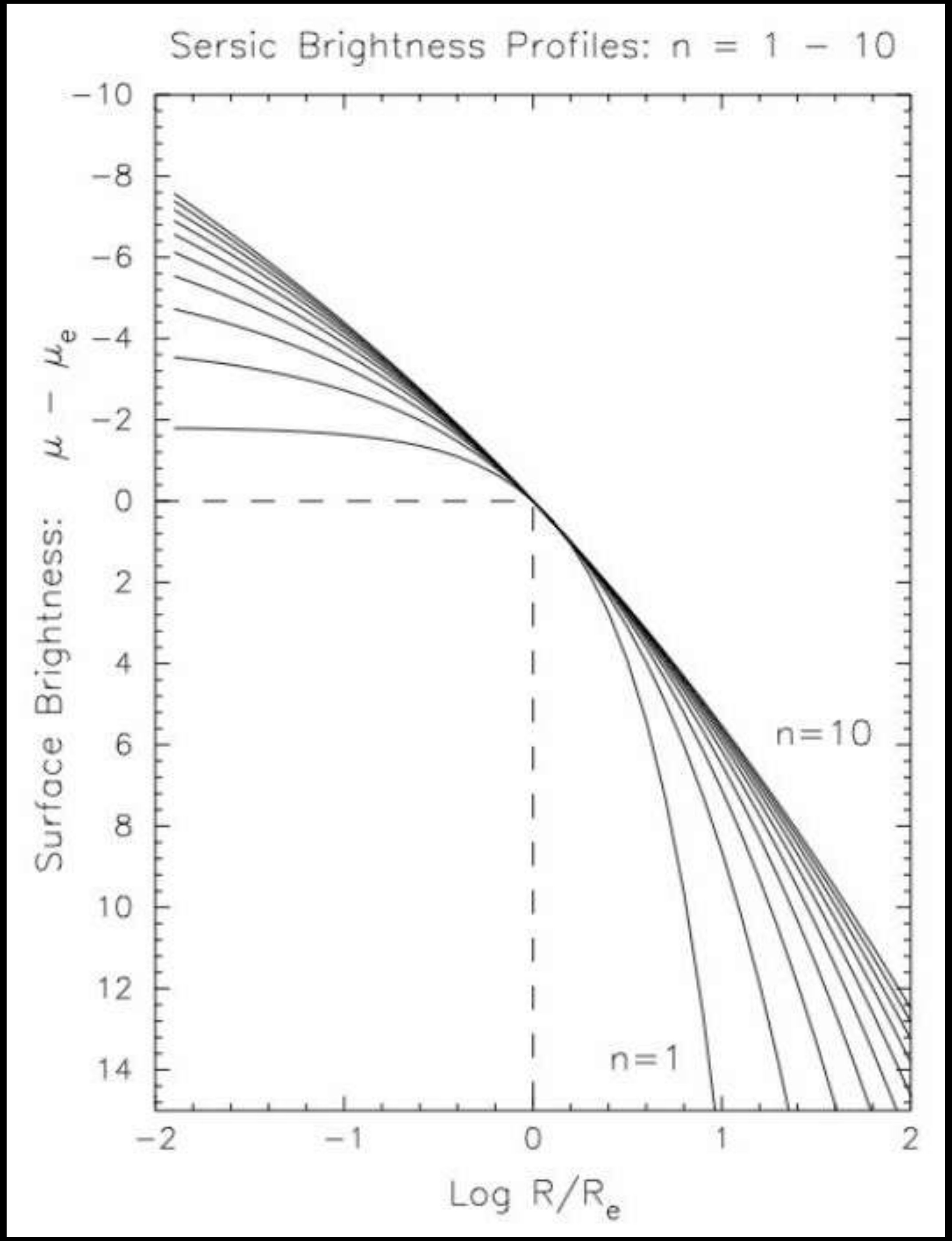
$$I_\lambda(R) = I_{\lambda,e}\exp\left\{-b(n)\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]\right\}$$

$$b(n) = 2n - \frac{1}{3} - \frac{4}{405n}$$

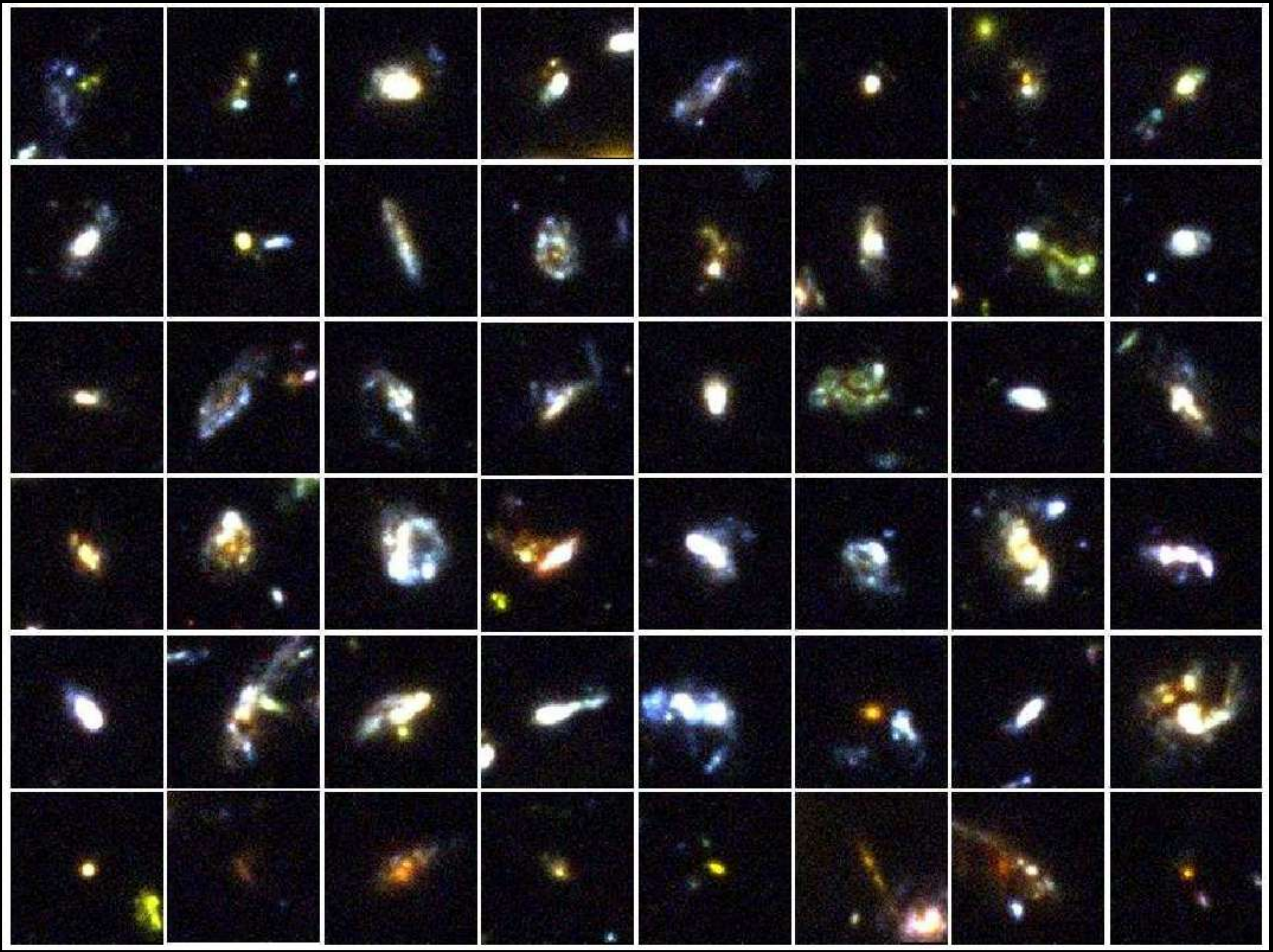
n Sérsic index

$n = 1$ discs

$2 < n < 10$ ellipticals/bulges



From Kong (2008)



Examples of galaxies in the Hubble Ultra Deep Field (HUDF) at $z \simeq 2$

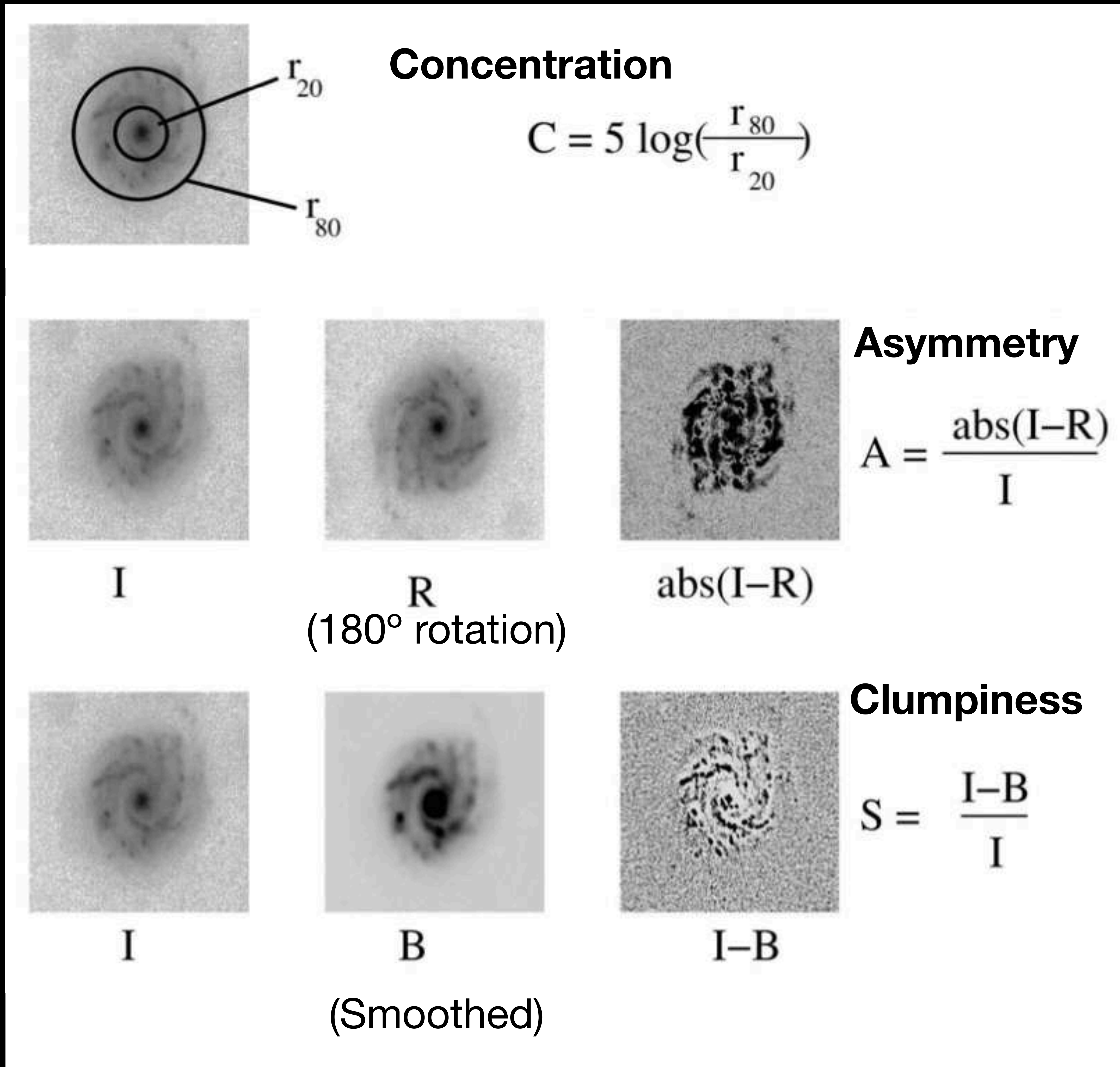
Ellipticals?
Spirals?

Morphology

Morphological classification:

- Visual inspection (optical)
- Surface brightness profile
- **Non-parametric measurement** (structural indices):
  - > CAS (e.g. Conselice et al. 2003)
  - > Gini/M20 (e.g. Abraham et al. 2003, Lotz et al. 2004)
  - > MID (e.g. Freeman et al. 2013)
  - > Fasano et al. 2011 (11 parameters!!)

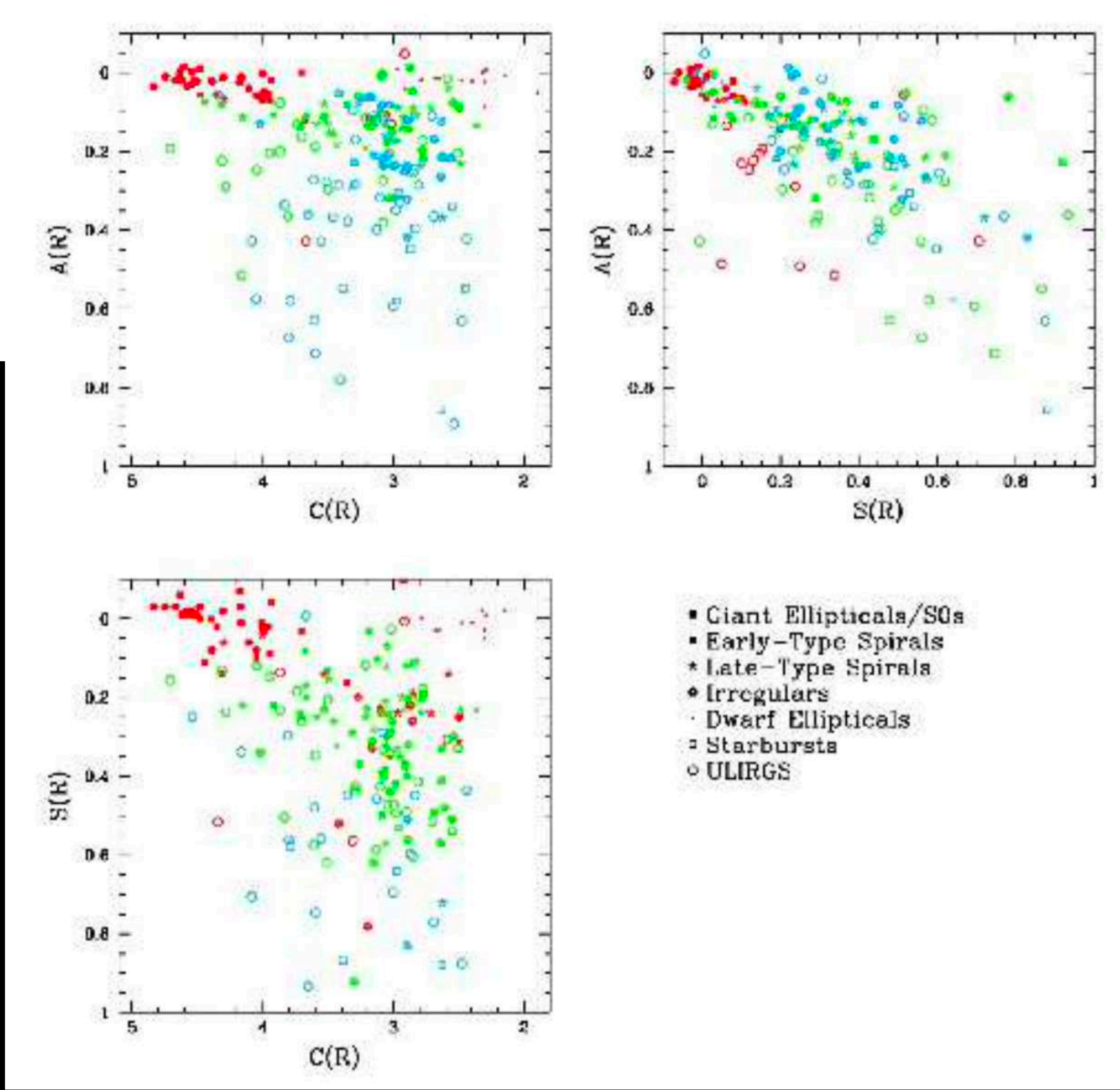
Adapted from Conselice (2014)



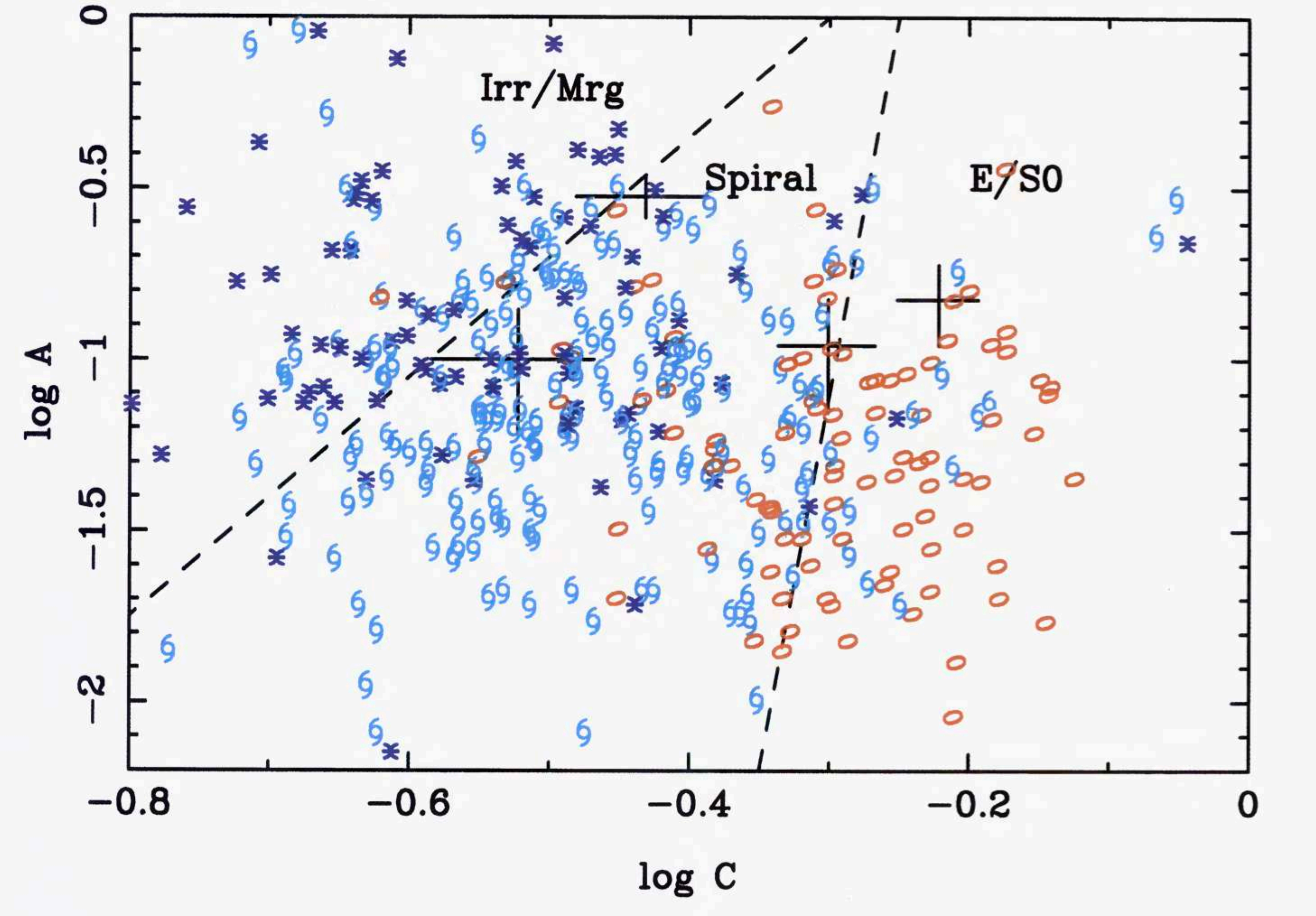
From Conselice (2014)

Table 1: The average concentration (C), asymmetry (A), and clumpiness (SS) parameters for nearby galaxies as measured in the optical R-band (see Conselice 2003).

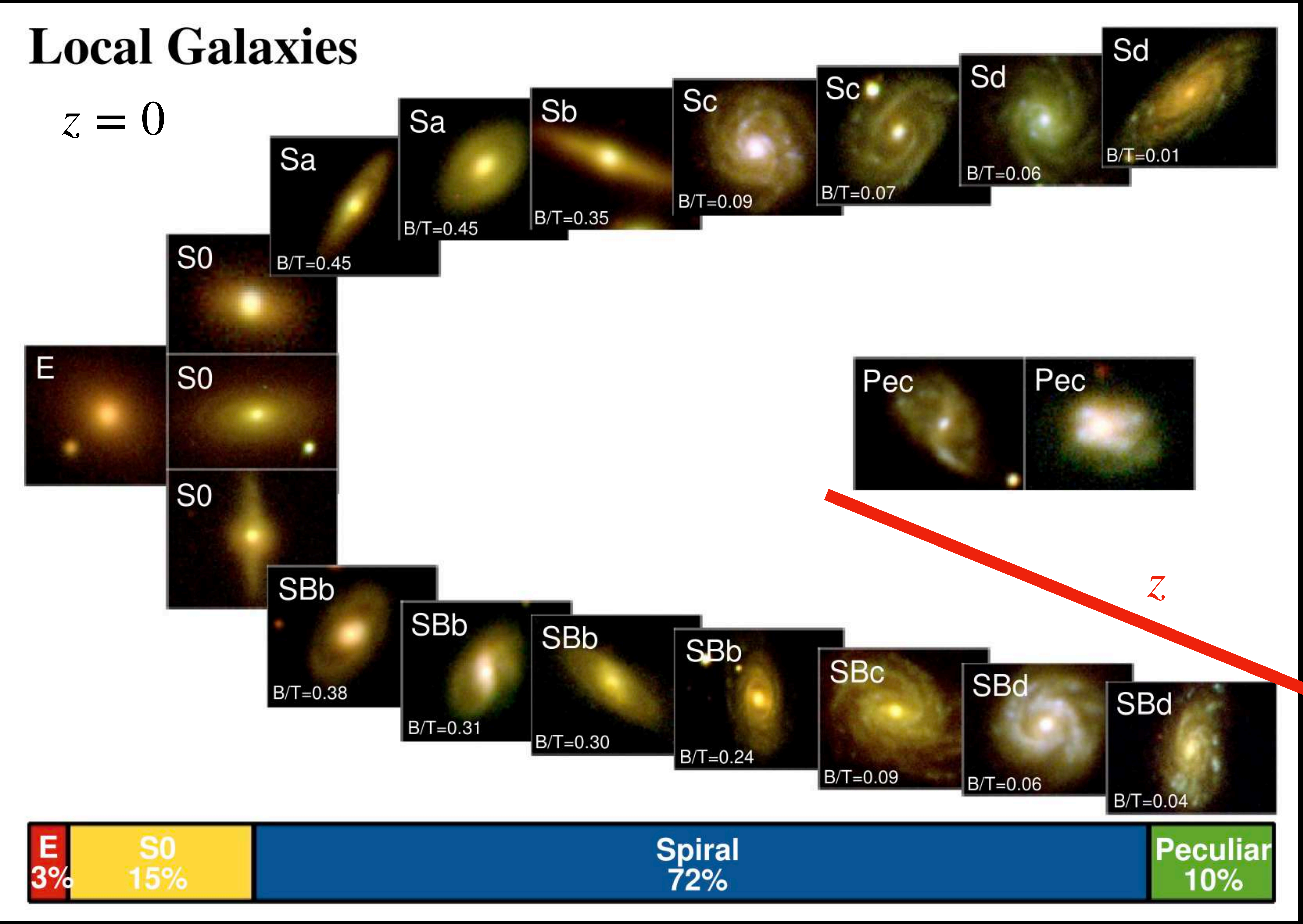
Galaxy Type	Concentration (R)	Asymmetry (R)	clumpiness (R)
Ellipticals	4.4±0.3	0.02±0.02	0.00±0.04
Early-type disks (Sa-Sb)	3.9±0.5	0.07±0.04	0.08±0.08
Late-type disks (Sc-Sd)	3.1±0.4	0.15±0.06	0.29±0.13
Irregulars	2.9±0.3	0.17±0.10	0.40±0.20
Edge-on Disks	3.7±0.6	0.17±0.11	0.45±0.20
ULIRGs	3.5±0.7	0.32±0.19	0.50±0.40
Starbursts	2.7±0.2	0.53±0.22	0.74±0.25
Dwarf Ellipticals	2.5±0.3	0.02±0.03	0.00±0.06

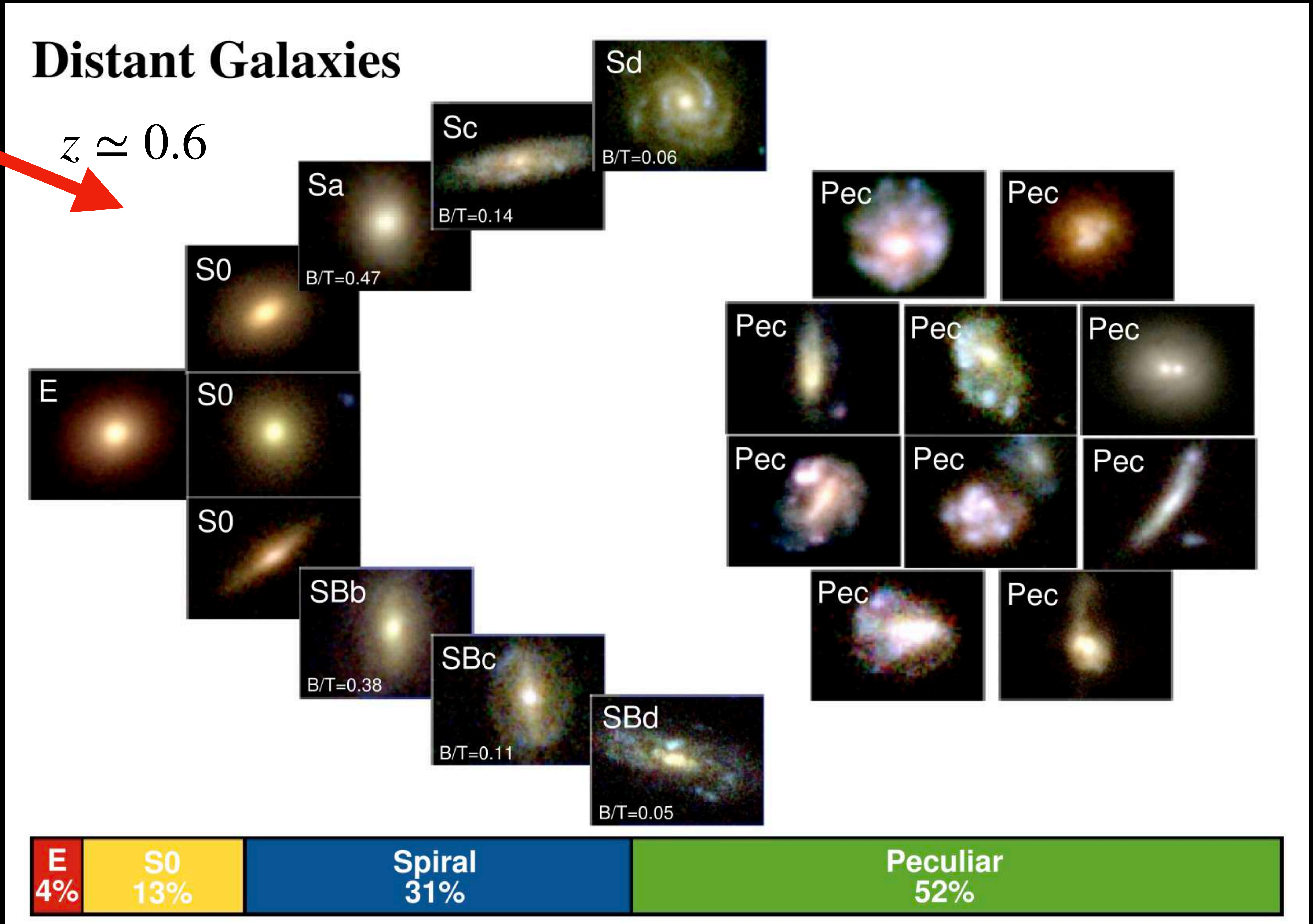


From Abraham (1996)



At $z \simeq 0.6$ (6 Gyr ago) the Hubble sequence was already in place, but much larger number of **Peculiars**

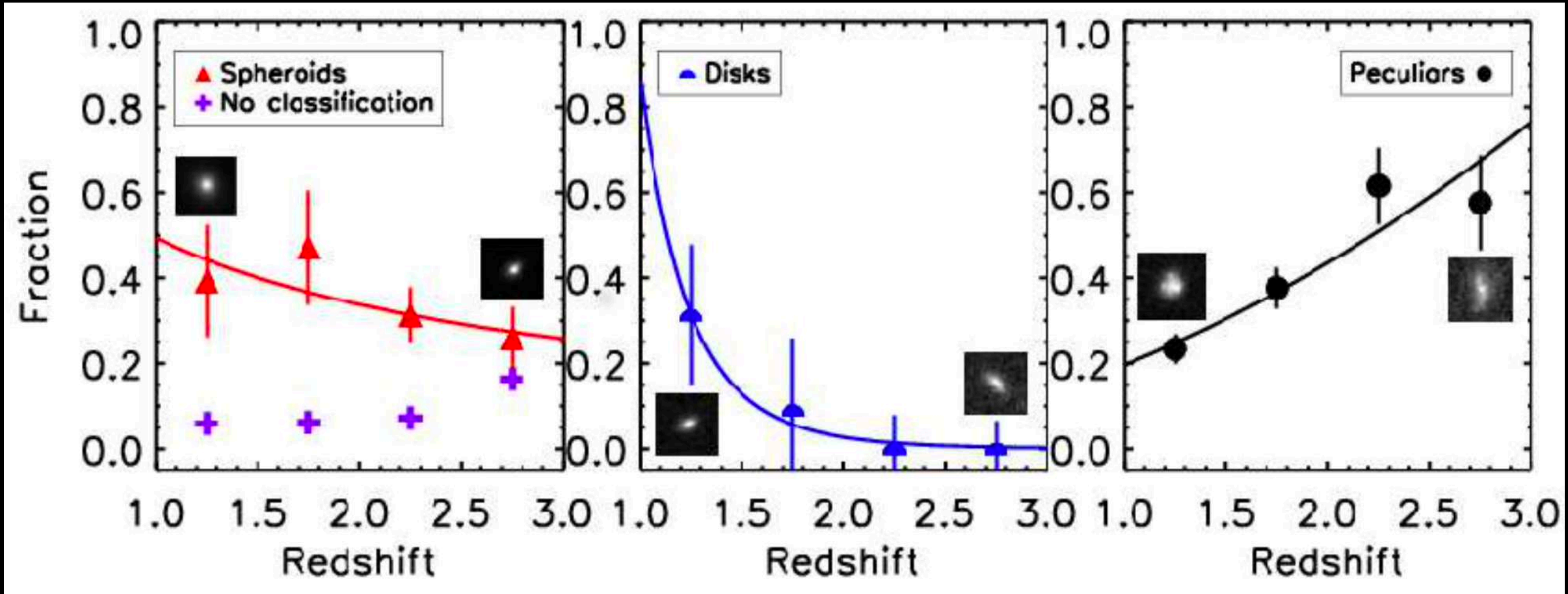




Delgado-Serrano et al. 2010

Evolution at $1 < z < 3$

From Conselice (2014) adapted from Mortlock et al. (2013)



- The Universe at $z > 2$ is dominated by peculiar morphologies ($\geq 70\ \%$ at $z > 2.5$)
- The Universe becomes dominated by **today's morphology types at** $z_{\text{trans}} < 1.9\ (\pm 0.6)$
- The number densities of disc galaxies equals that of peculiars at $z \sim 1.4$

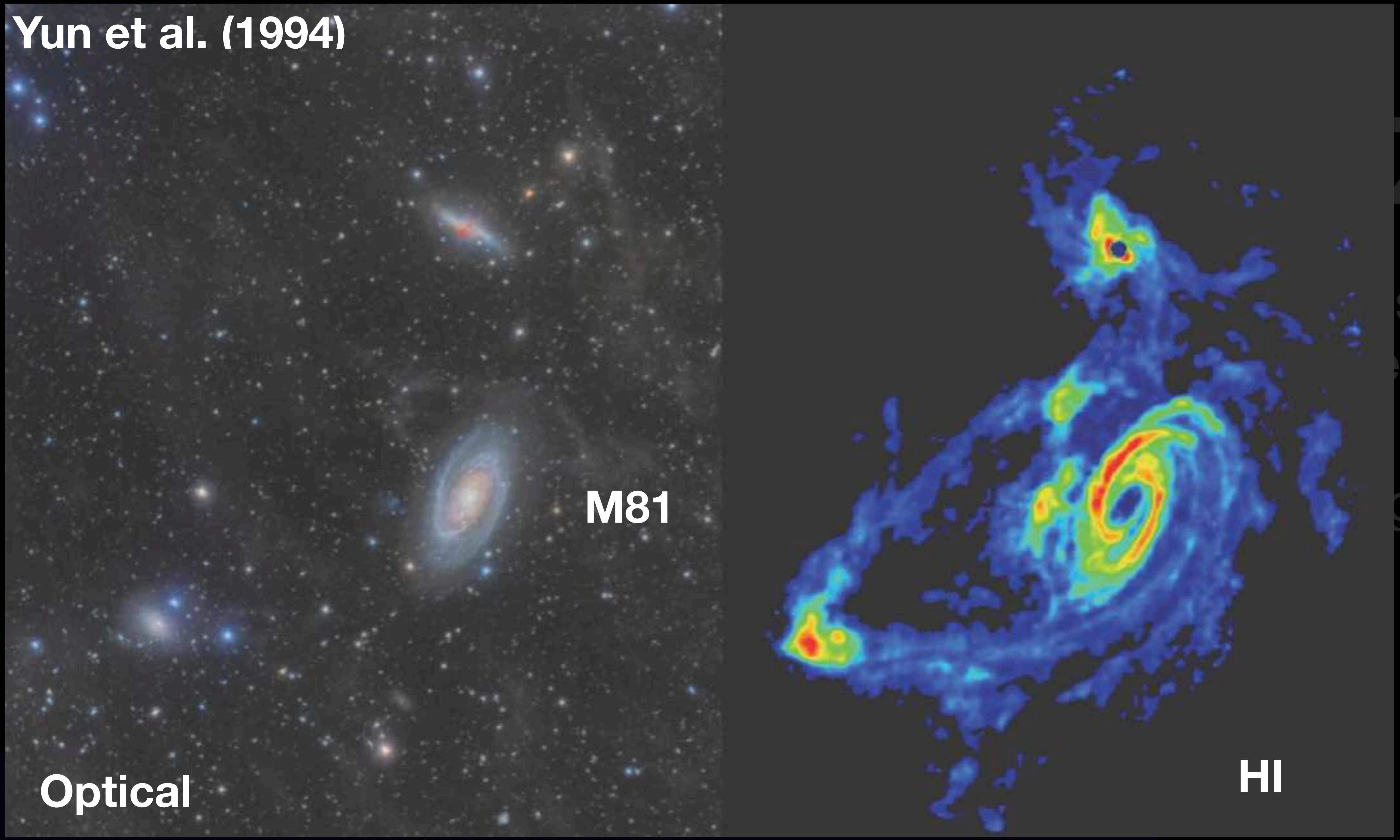
Size

How to estimate the size? The surface brightness profile can be used to quantify the size of a galaxy within a given limiting threshold of surface brightness.

R_e (effective or half-light radius): radius containing 50% of the galaxy light.

In general,

$$R_e \propto M_\star^\alpha \qquad \begin{array}{ll} \alpha \leq 0.4 & \text{LTGs} \\ \alpha \approx 0.5 - 0.6 & \text{ETGs} \end{array}$$



ze

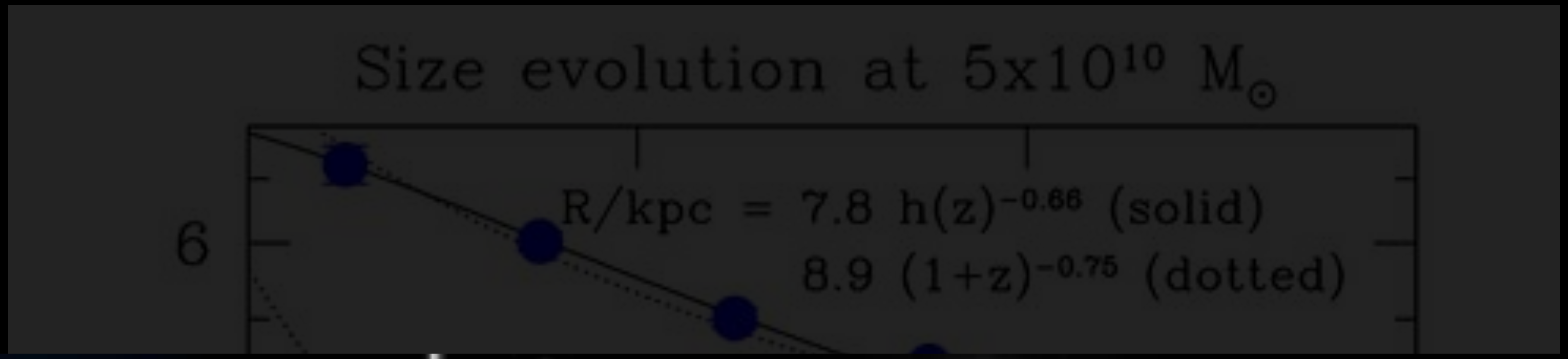
WARNING

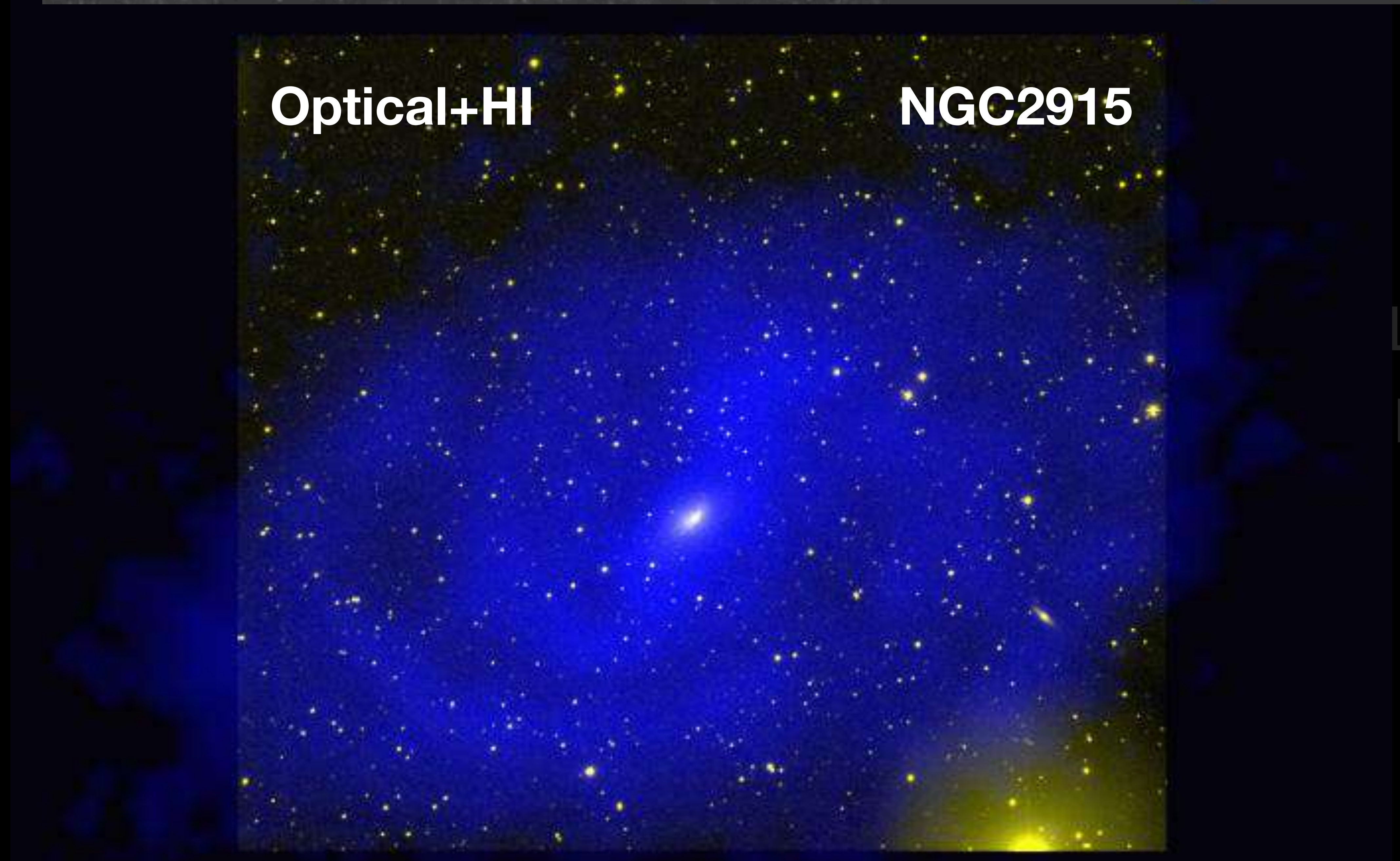
Size depends on wavelength!

ss profile can be used to quantify the size of a
brightness.

g 50% of the galaxy light.

Adapted from van der Wel et al. (2014)





LTGs
ETGs

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$R_e \propto M_\star^\alpha$ $\qquad \alpha \leq 0.4$ LTGs

$\qquad \alpha \approx 0.5 - 0.6$ ETGs

$R_e \propto (1+z)^\alpha$ $\qquad \alpha \approx -0.7$ LTGs

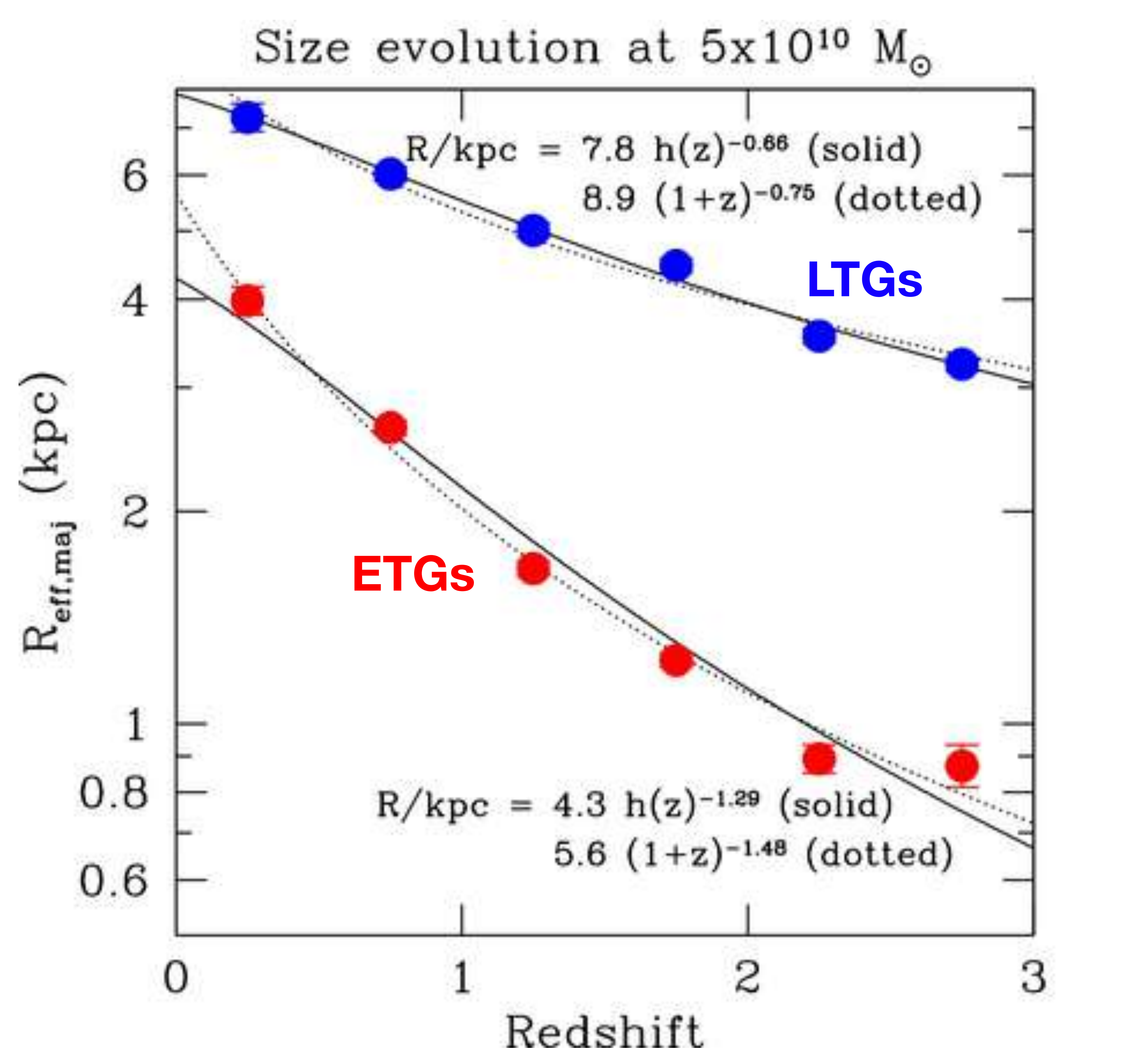
$\qquad \alpha \approx -1.5$ ETGs

Strong evolution with redshift:

- Minor and major mergers
- Inside-out star formation
- Gas accretion

NB. The details and relative importance of the single processes are still unclear!

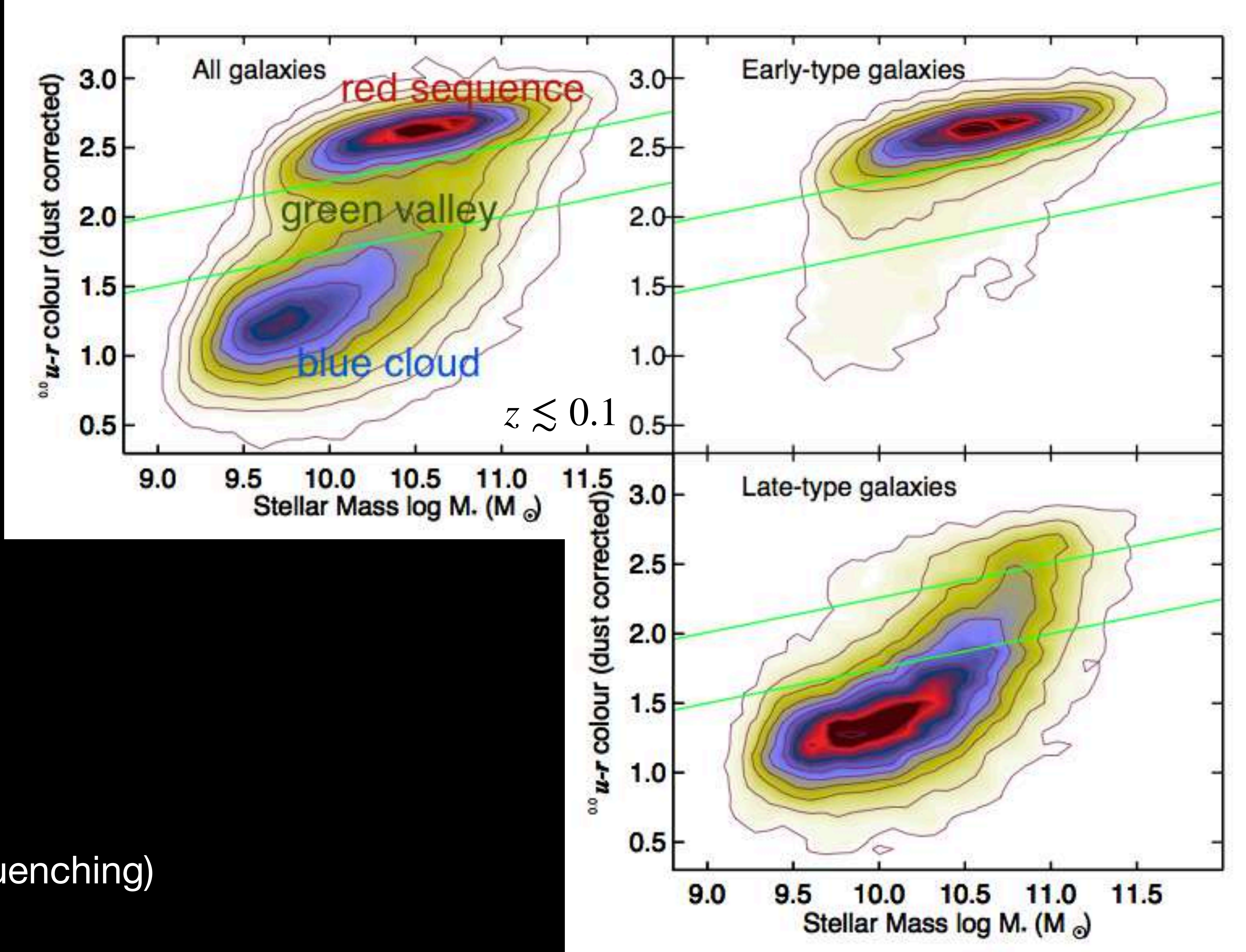
Adapted from van der Wel et al. (2014)



Colours

Adapted from Schawinski et al. (2014)

Colours are easy to estimate and enclose important information on the age of stellar population, the metallicity and dust extinction (degeneracy!).



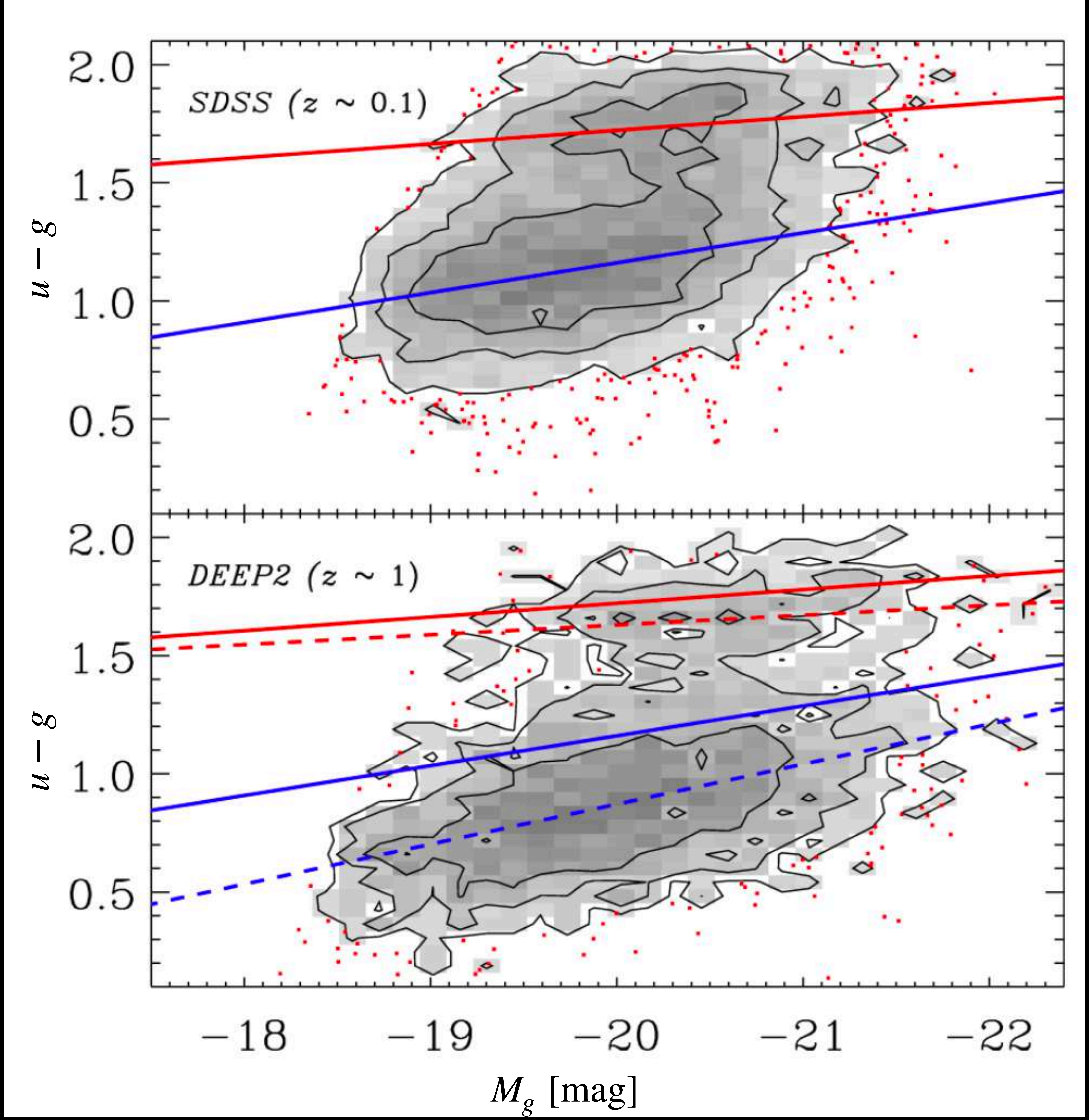
Bimodal distribution in the colour-magnitude (or colour-luminosity, or colour-mass) plane.

Red sequence: mostly ETGs (~15-30% are SFGs - due to dust extinction or large bulge)

Blue cloud: mostly SFGs

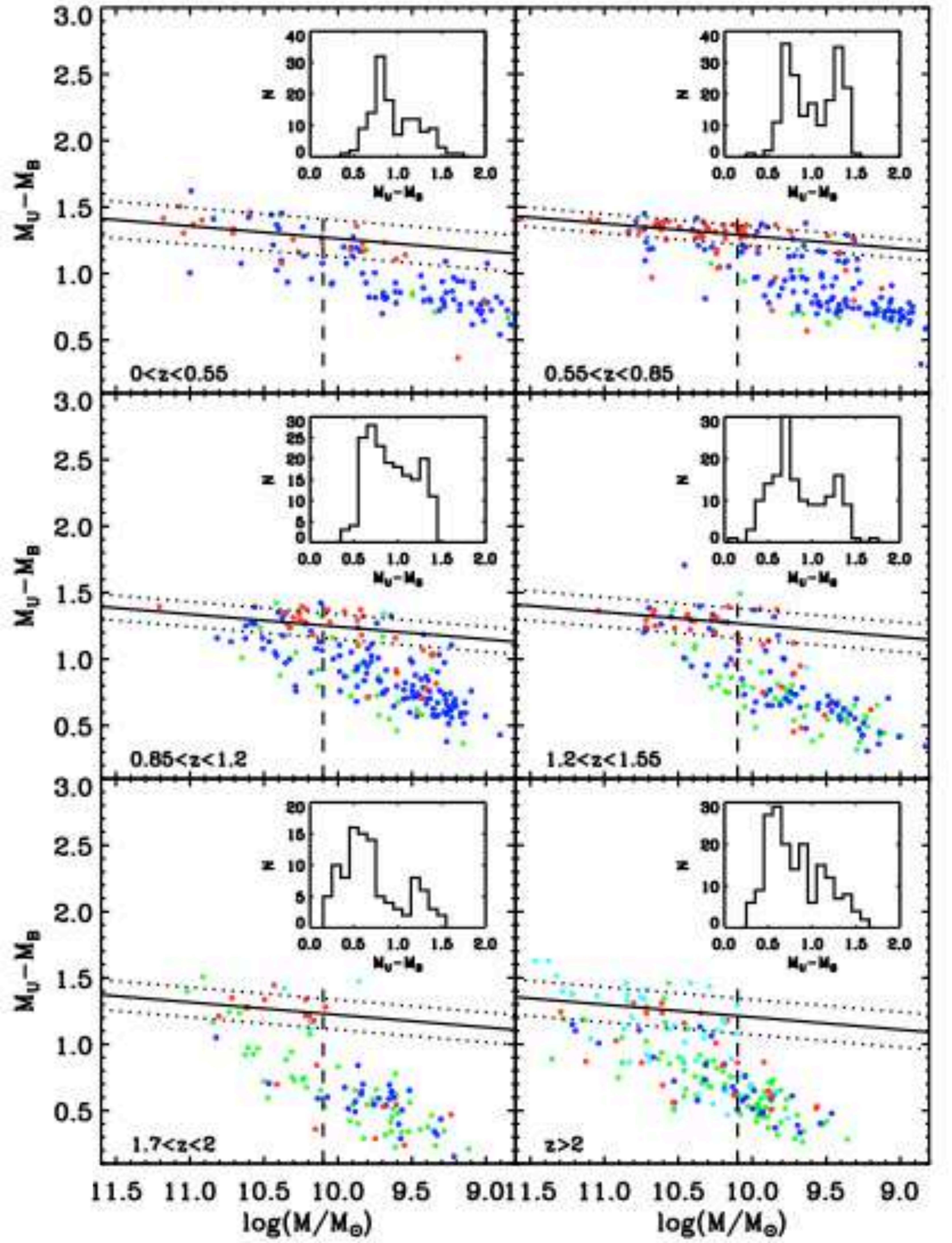
Green valley: transitioning galaxies (quenching)

Blanton et al. (2006)



Both the blue cloud and the red sequence are **BLUER** at higher redshifts

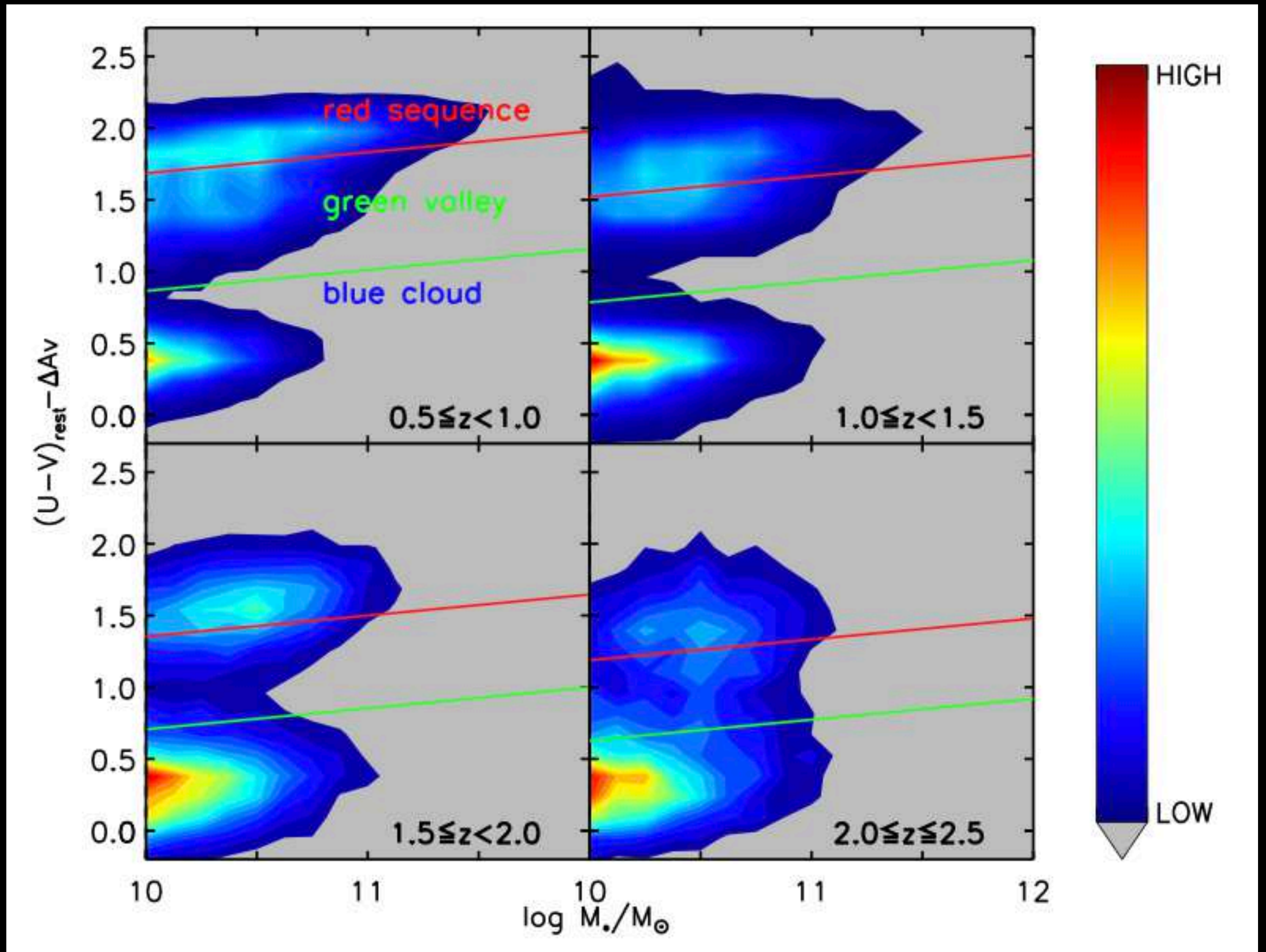
At high-z, the blue cloud is more populated than the red sequence



Cassata et al. 2008

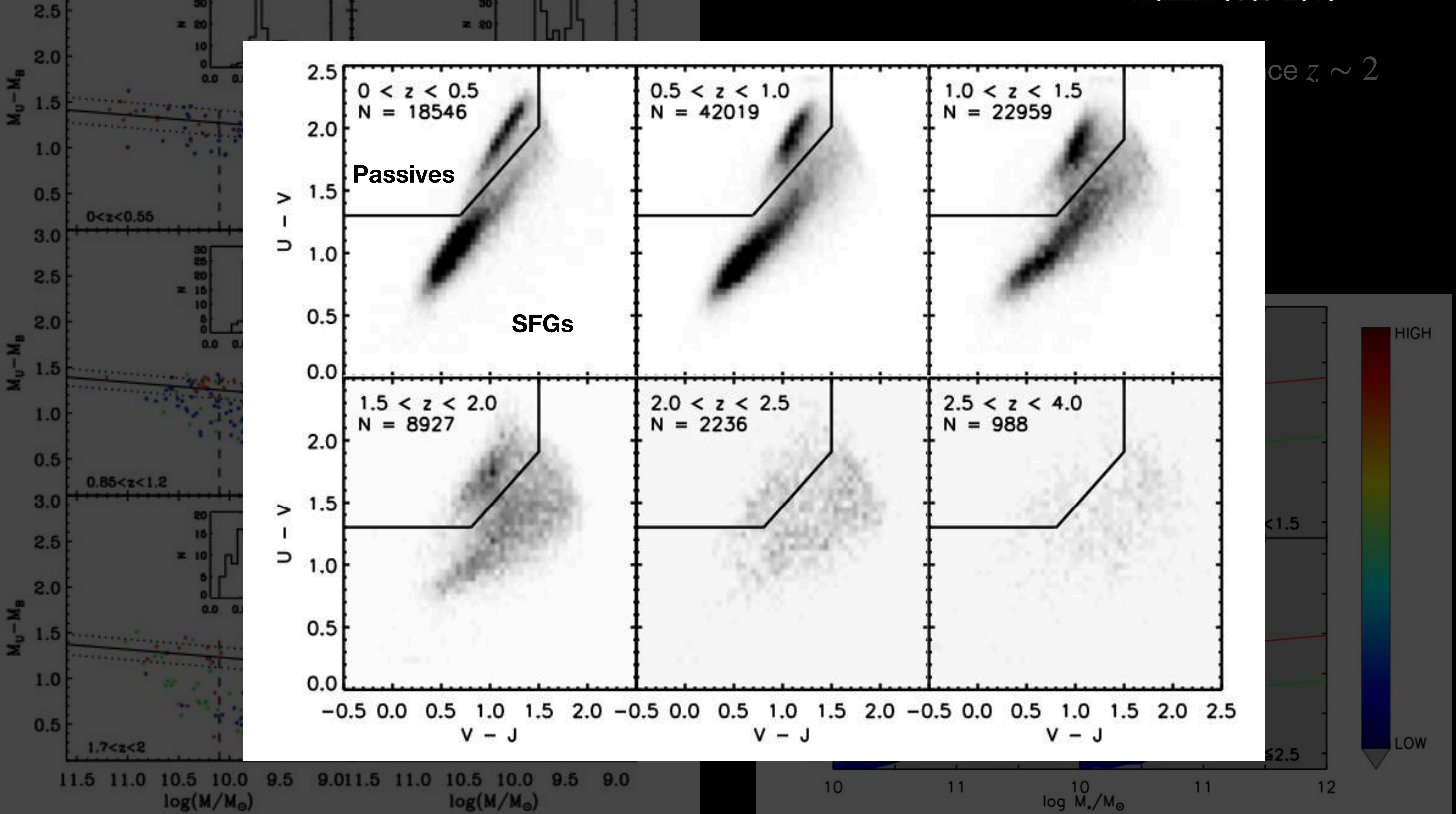
The red sequence is in place since $z \sim 2$

Lin et al. 2019



Cassata et al. 2008

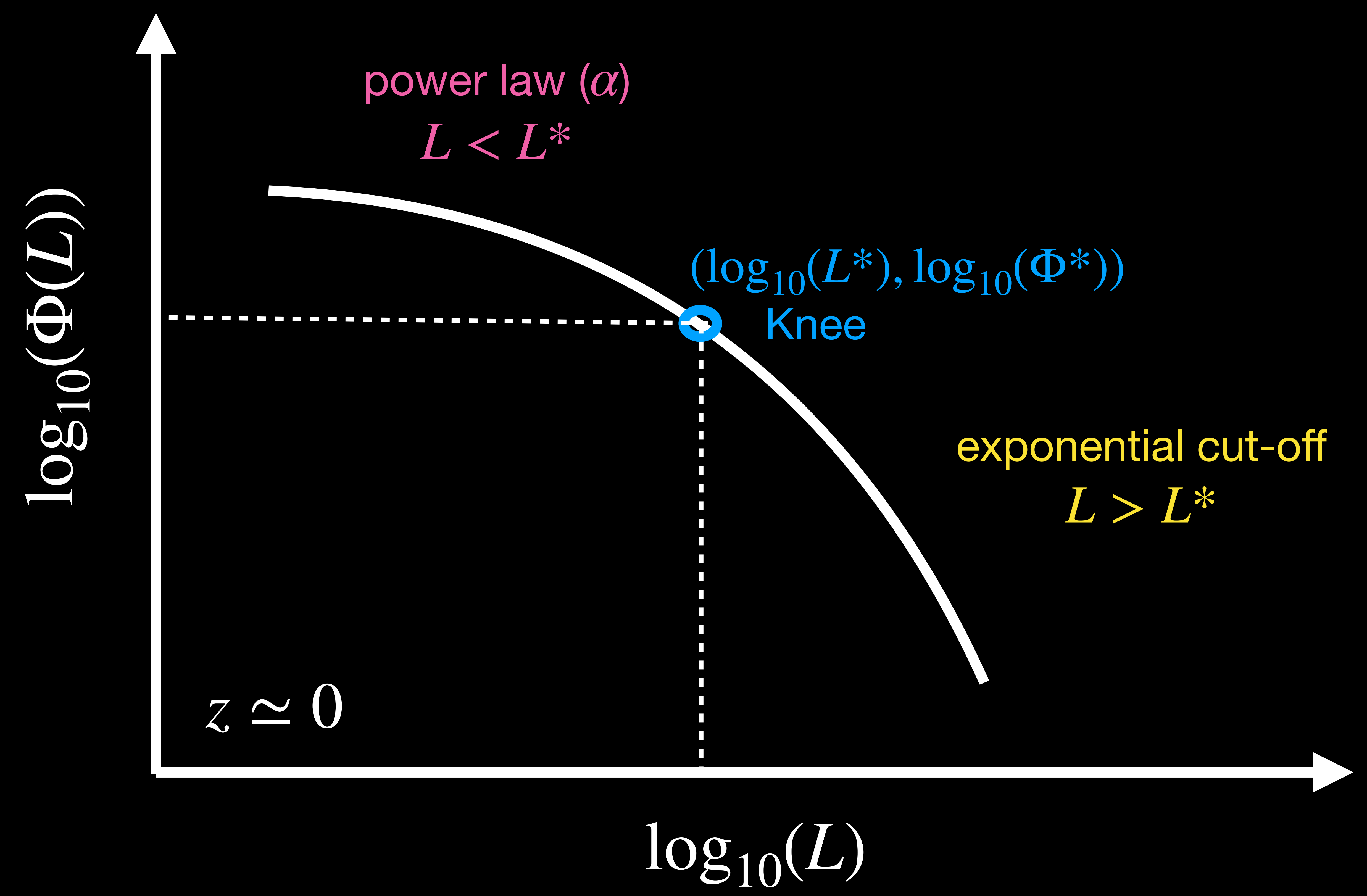
Muzzin et al. 2013



Luminosity Function & Cosmic SFR density

The LF tells us how galaxy luminosities are statistically distributed.

- Schechter's law (Schechter 1976): $$\frac{dn}{dL} = \Phi(L) = \left(\frac{\Phi^*}{L^*}\right)\left(\frac{L}{L^*}\right)^{\alpha} e^{-\frac{L}{L^*}}$$

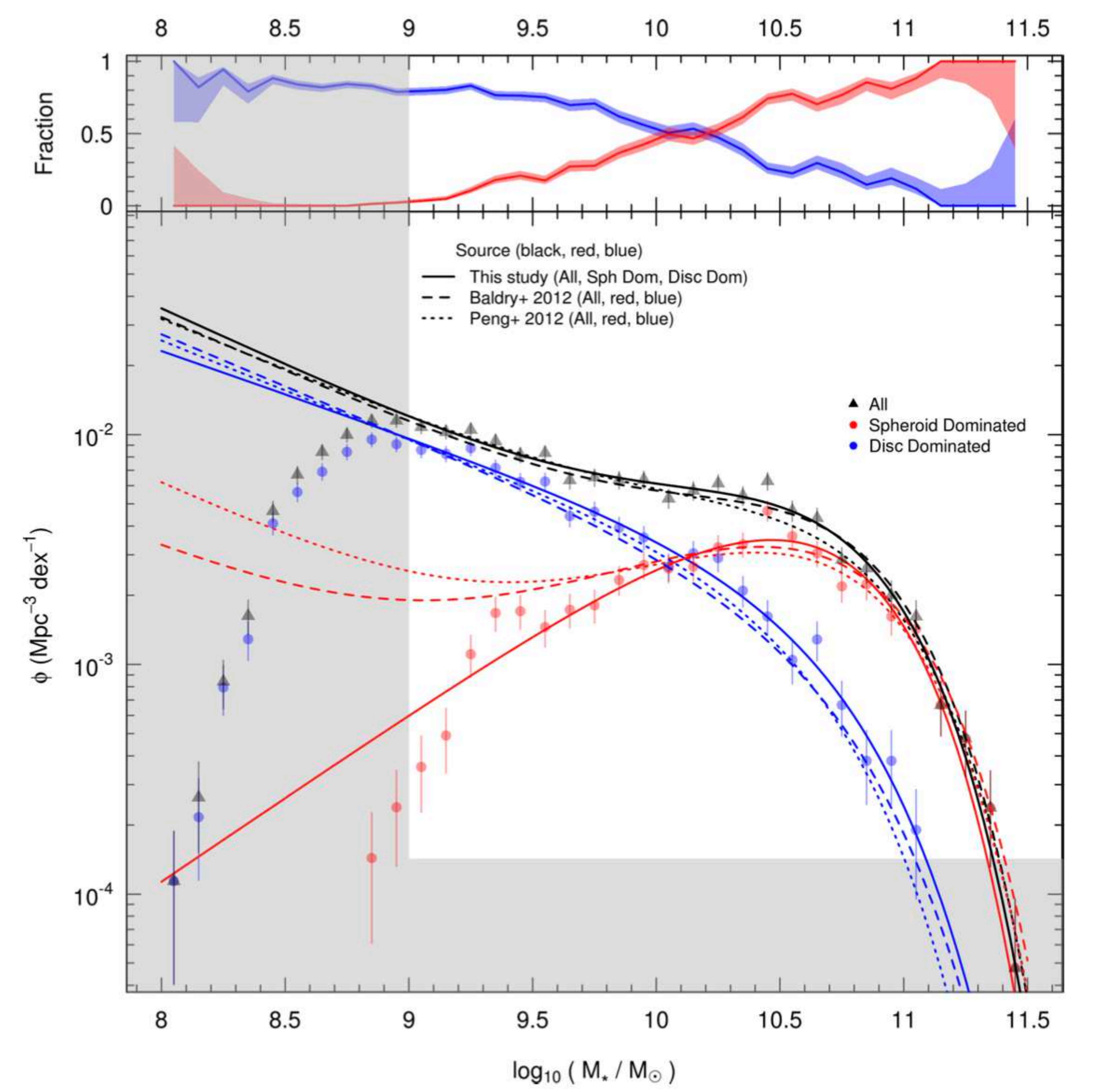


Lumino... density

The LF tells us h...

- Schechte...

From Kelvin et al. (2014)



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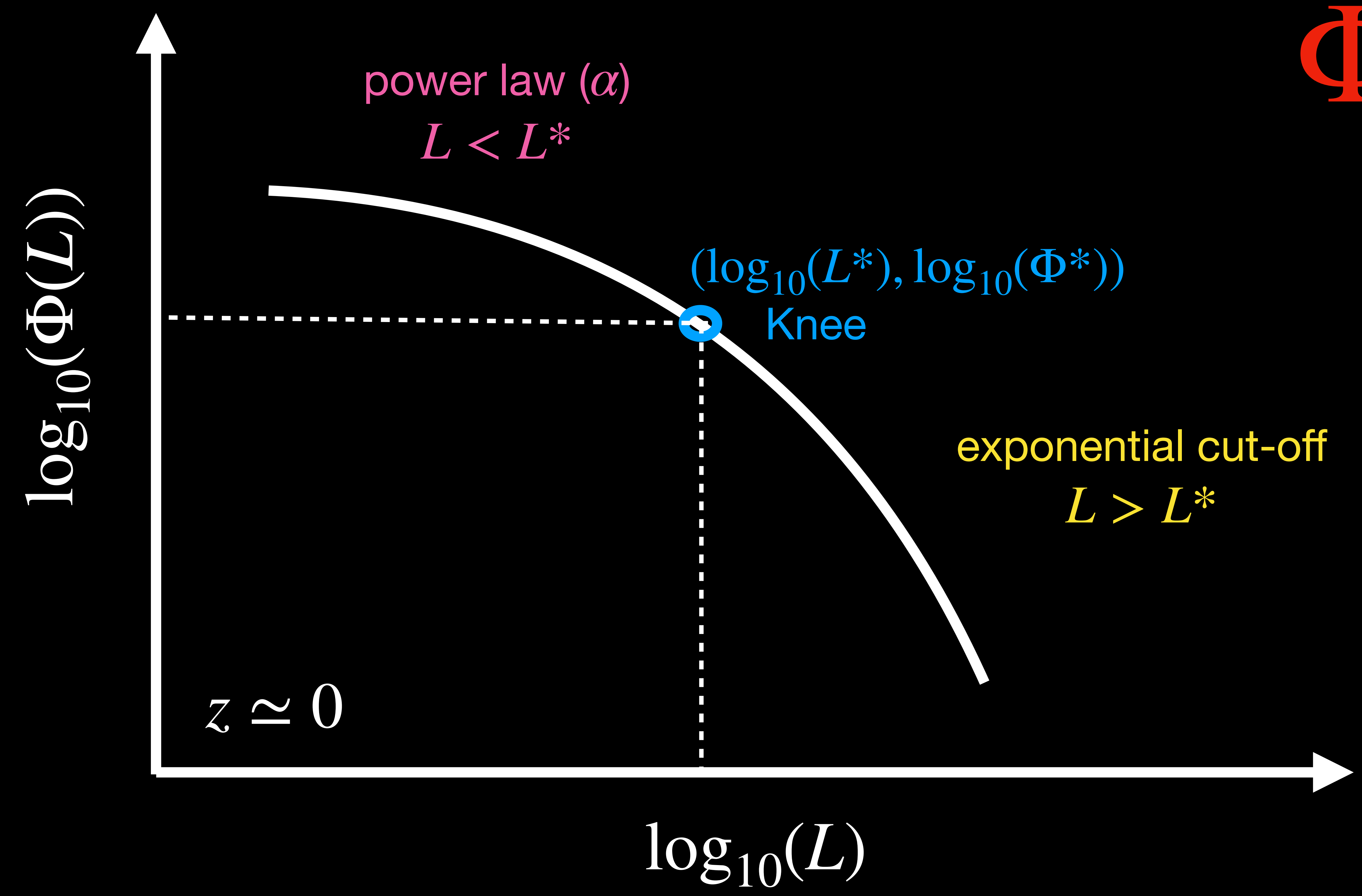

$\Phi(L, z)$?

$\Phi^*(z)$? $L^*(z)$?

$\alpha(z)$?

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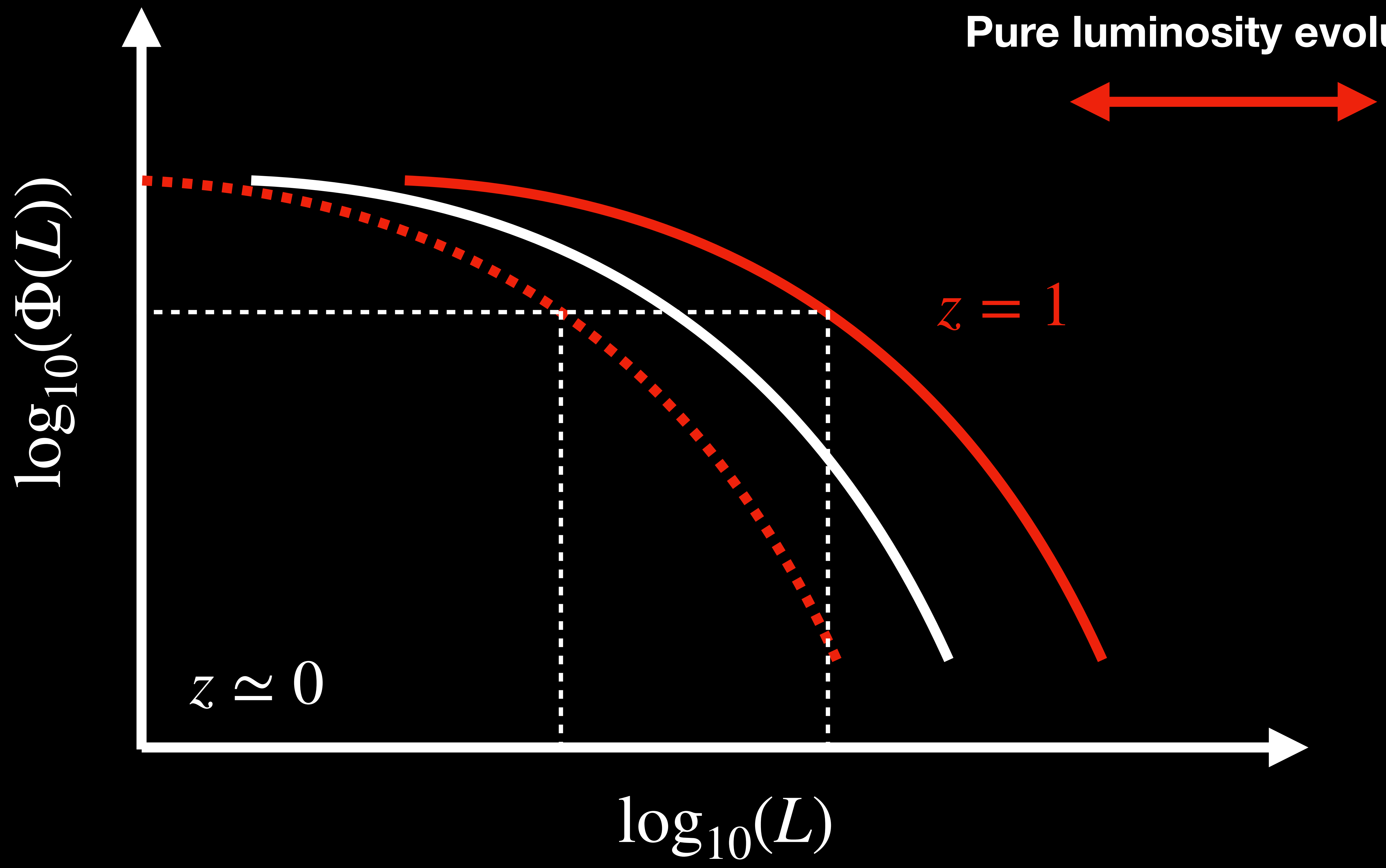

Pure luminosity evolution

$\Phi^*(z) = \text{const}\,.$

$L^*(z) \neq \text{const}\,.$

Luminosity Function & Cosmic SFR density

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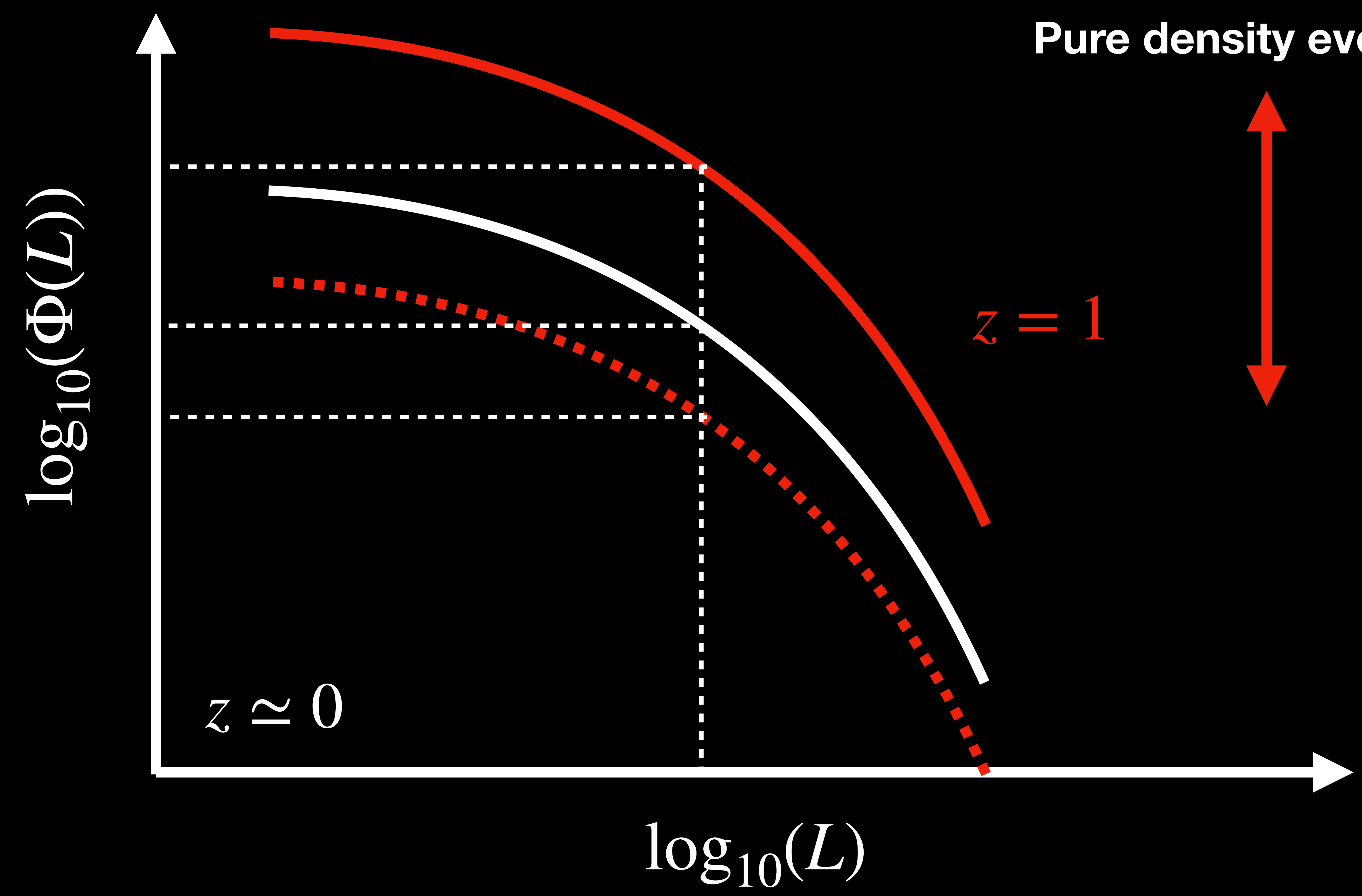
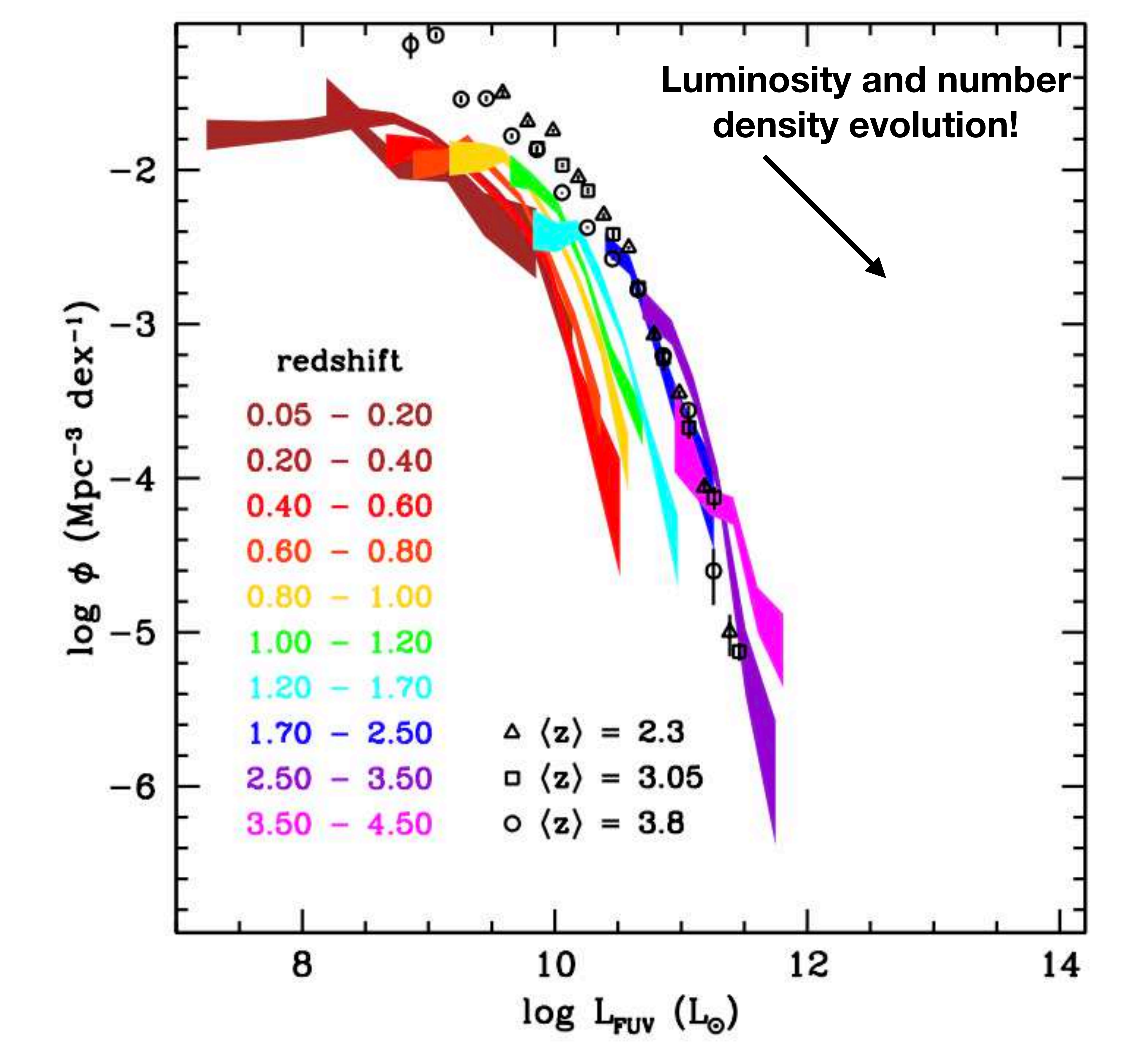


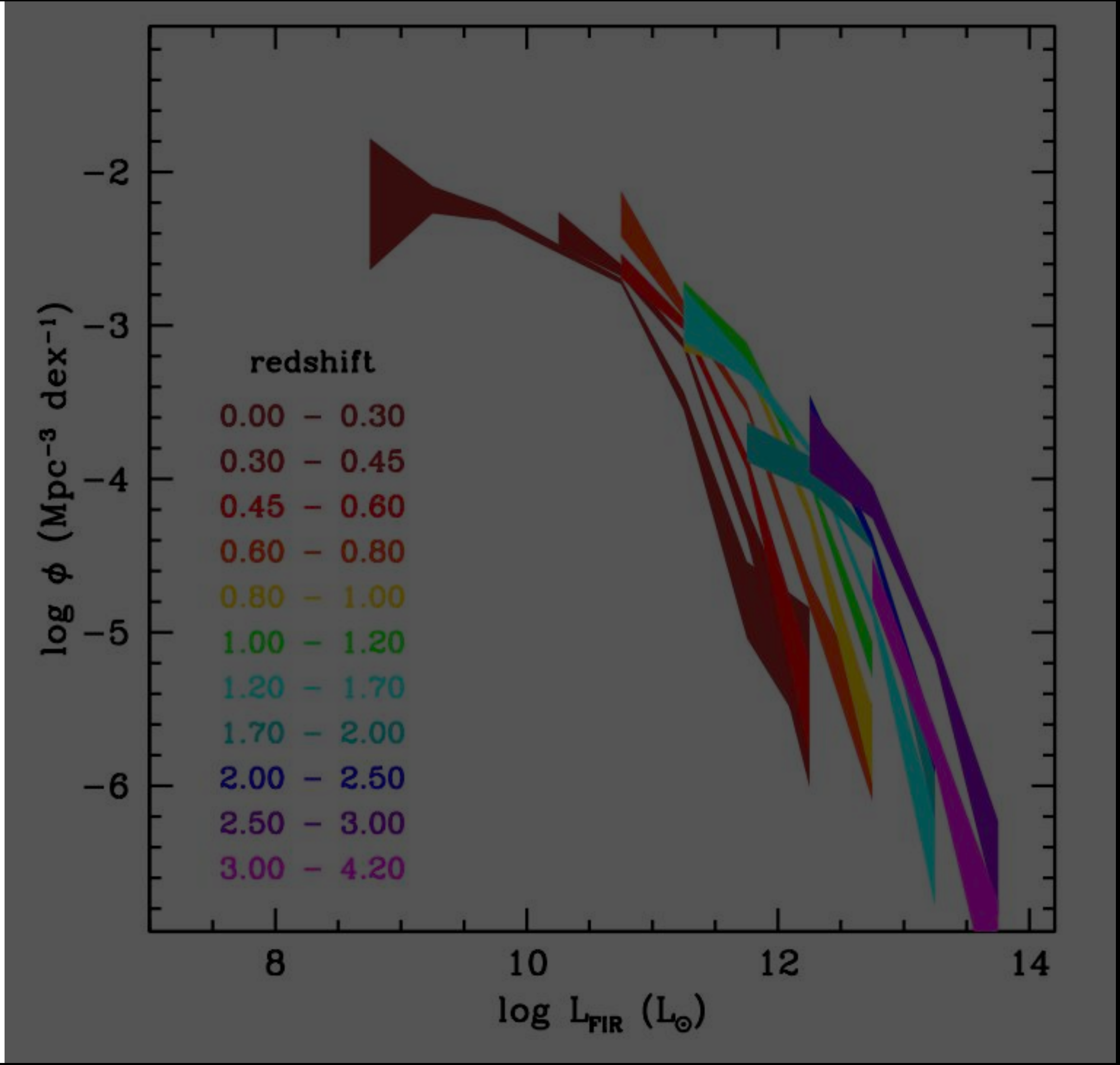
Pure density evolution

$\Phi^*(z) \neq \text{const}.$

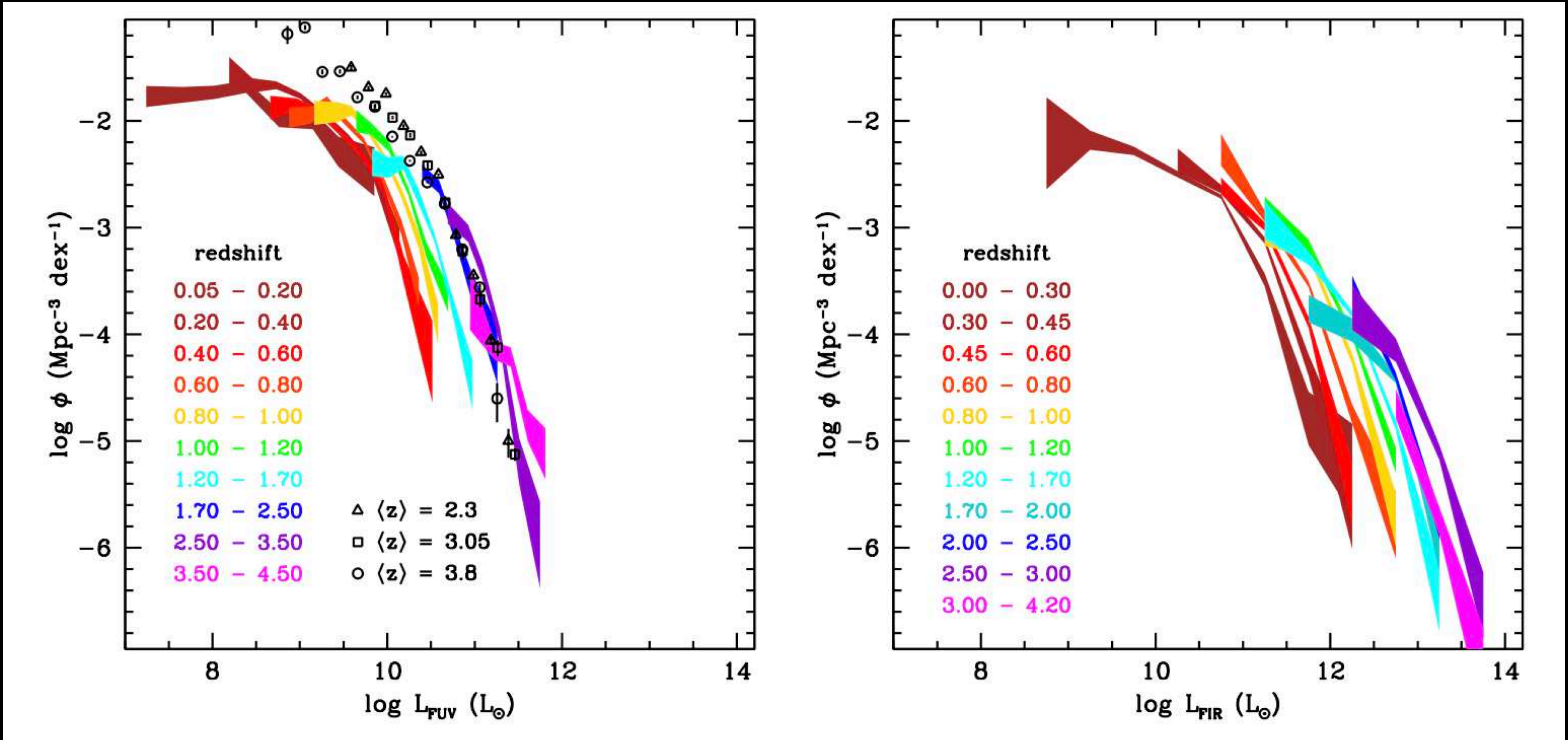
$L^*(z) = \text{const}.$

From Madau & Dickinson (2014)

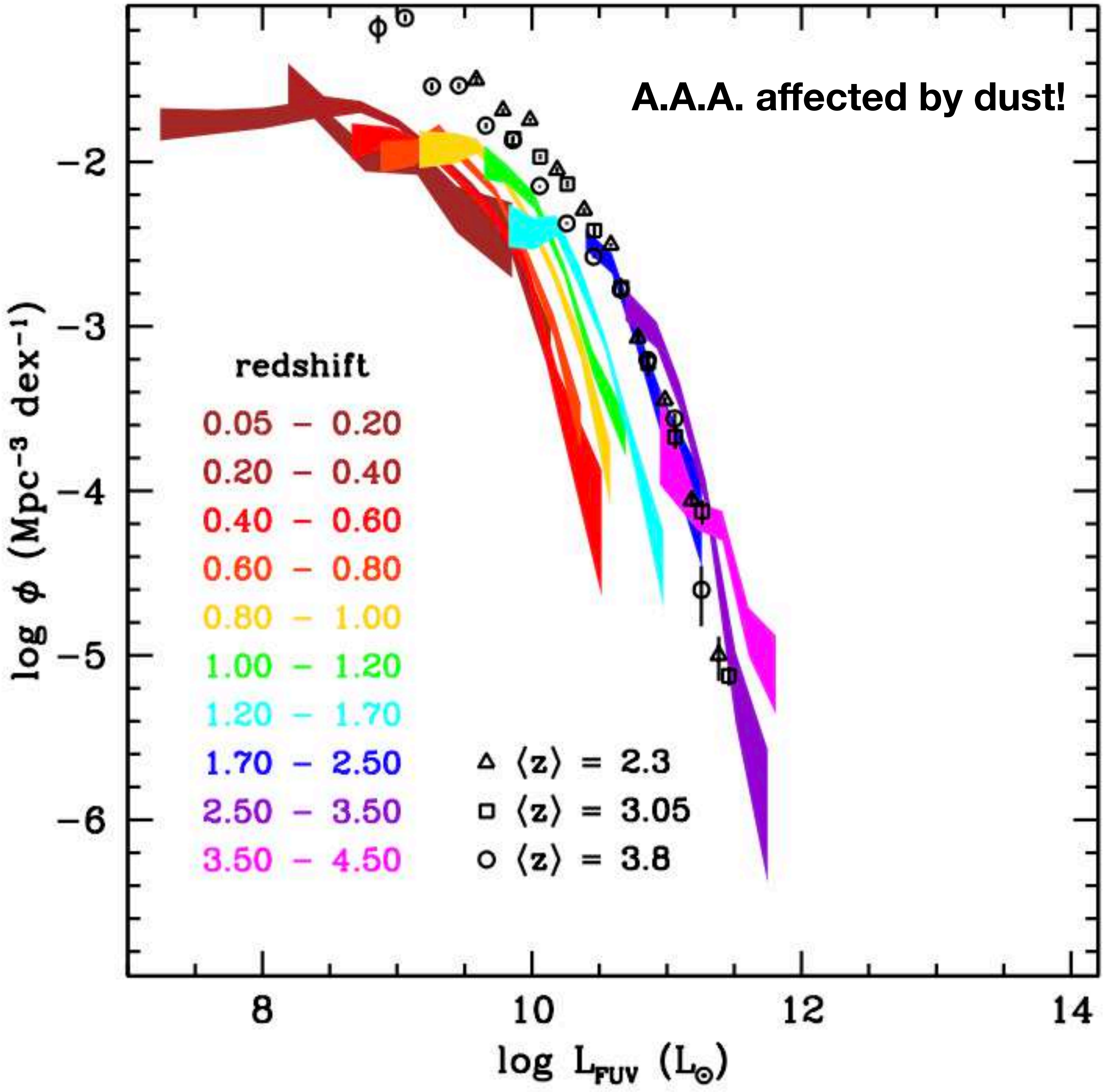


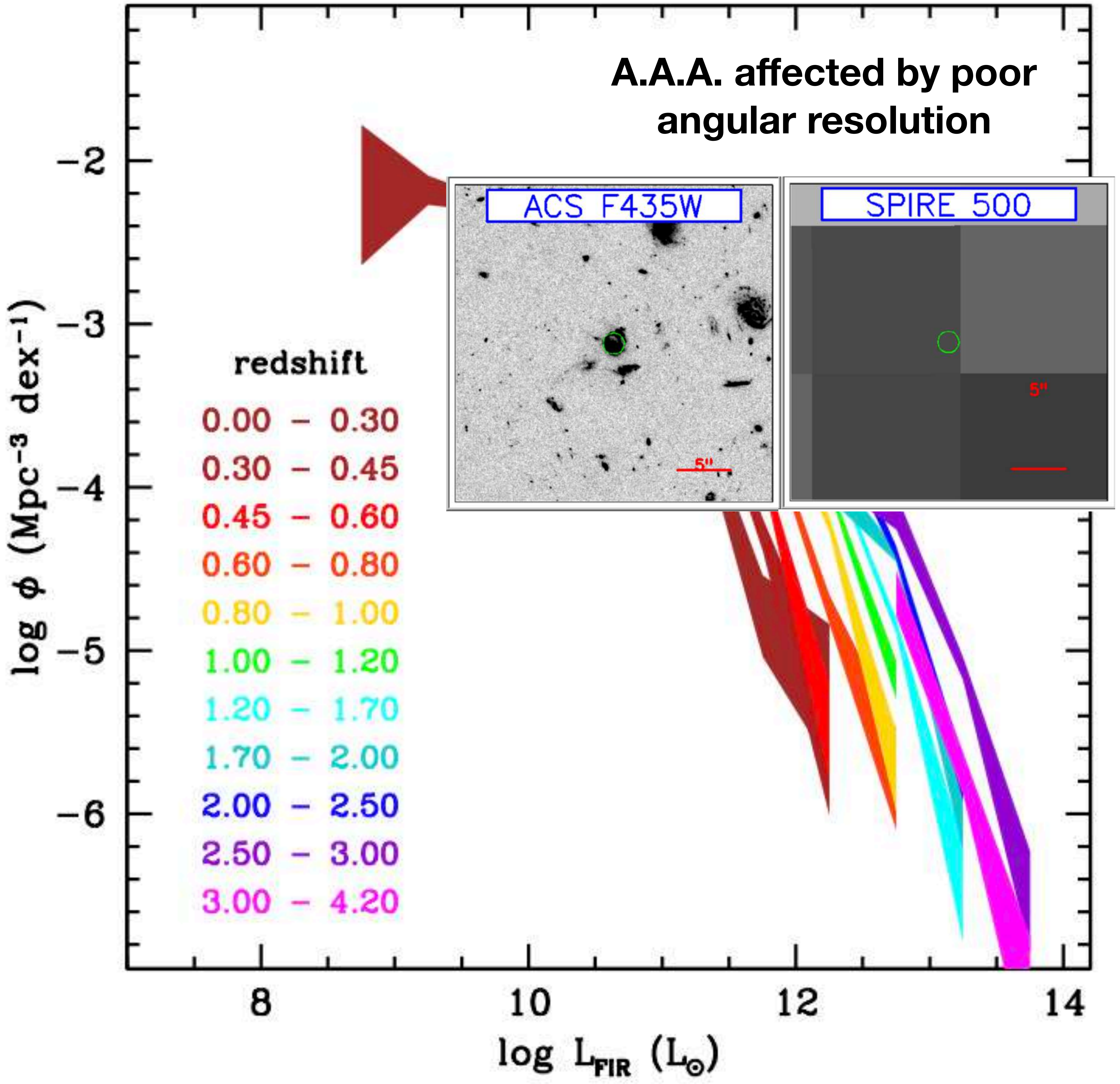


From Madau & Dickinson (2014)



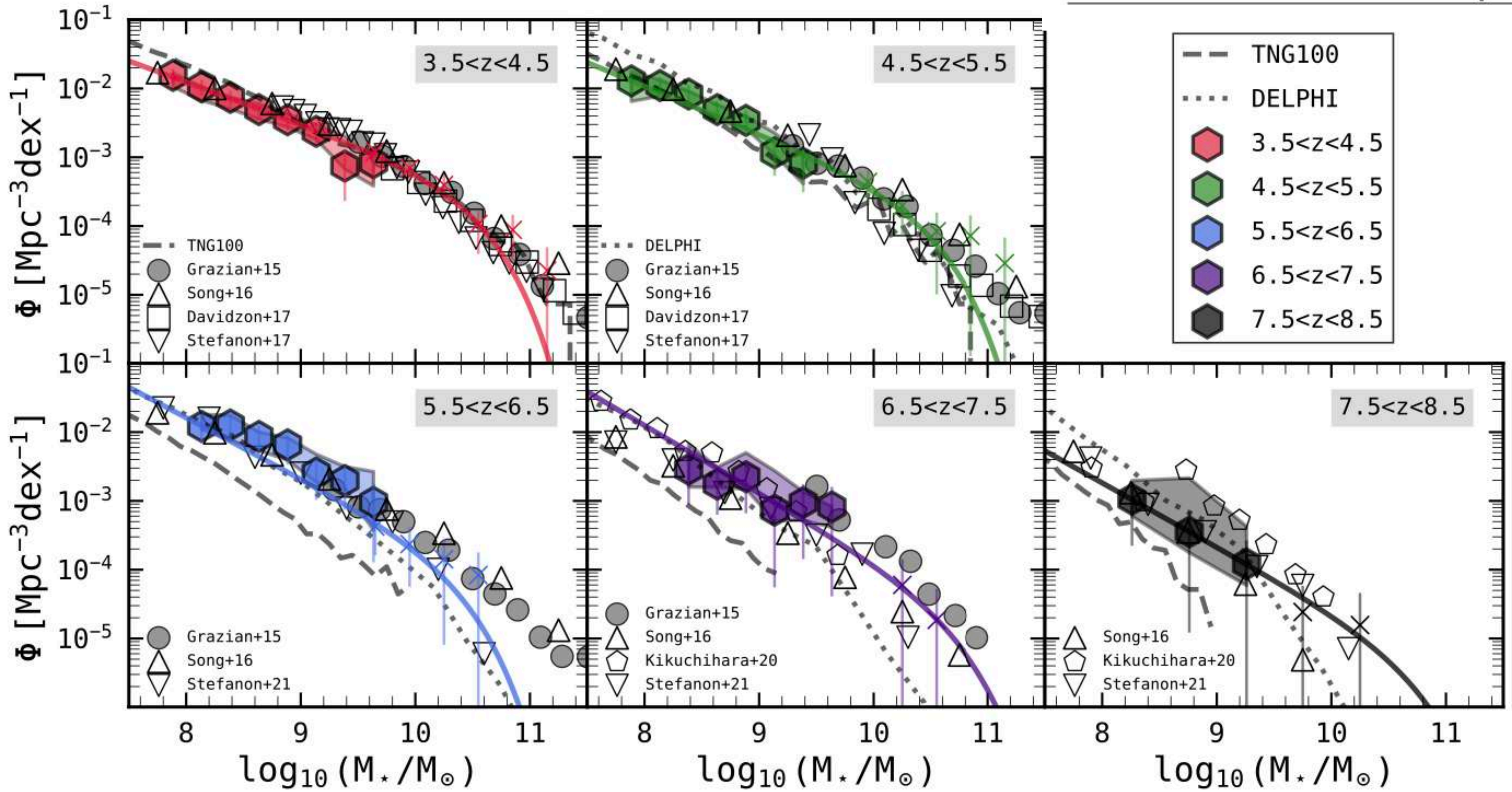
From Madau & Dickinson (2014)



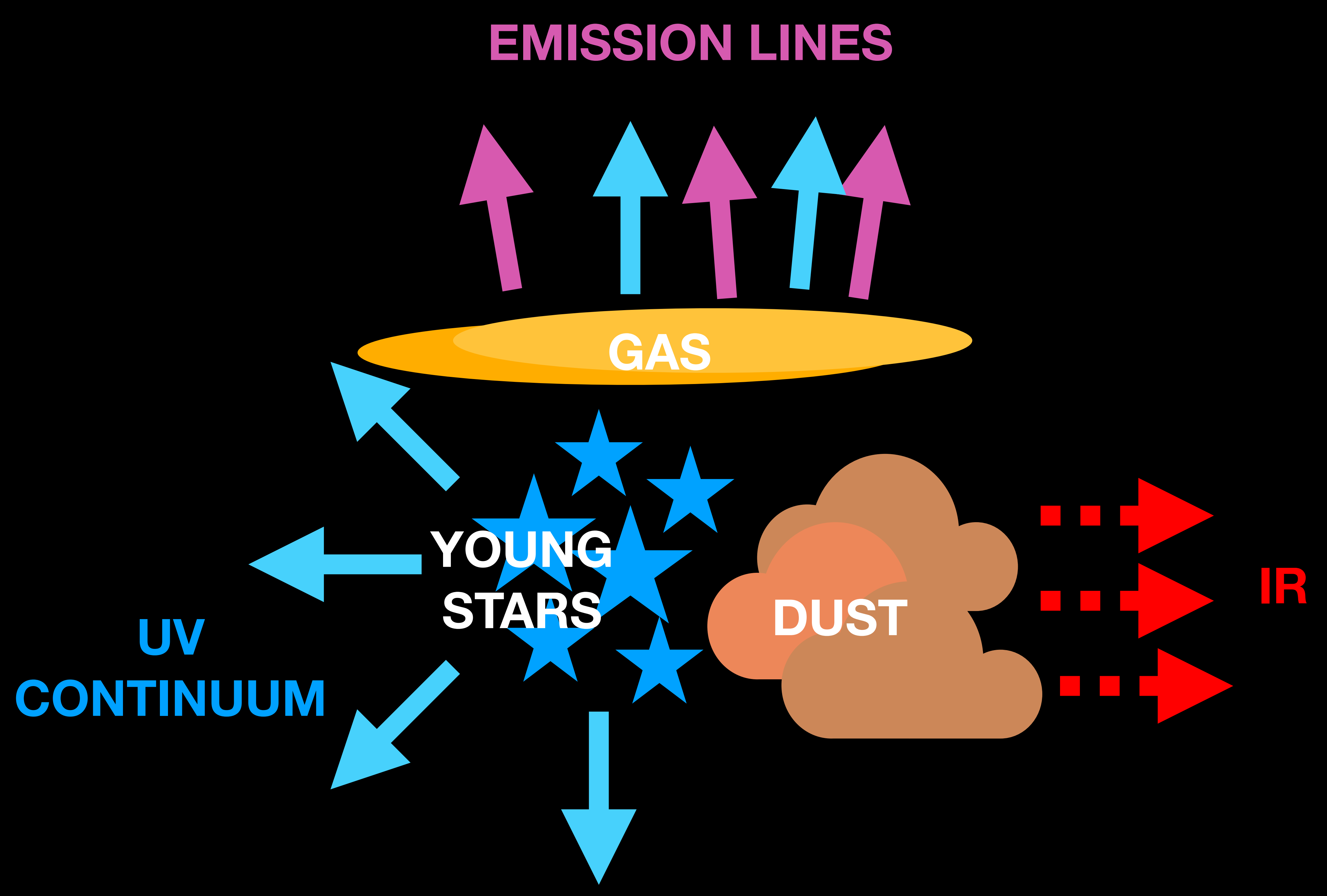


From Navarro-Carrera et al. (2023)

Redshift	N_{gal}	α	$\log_{10}(M^*/M_\odot)$	ϕ_*
3.5-4.5	615	-1.61±0.06	10.48±0.15	$(1.65\pm0.04)\times10^{-4}$
4.5-5.5	467	-1.69±0.07	10.45±0.27	$(9.6\pm0.9)\times10^{-5}$
5.5-6.5	539	-1.88±0.09	10.33±0.36	$(6.3\pm1)\times10^{-5}$
6.5-7.5	147	-1.98±0.14	10.68±0.79	$(1.3\pm1)\times10^{-5}$
7.5-8.5	36	-1.93±0.22	[10.70]	$(2.8\pm2.1)\times10^{-6}$

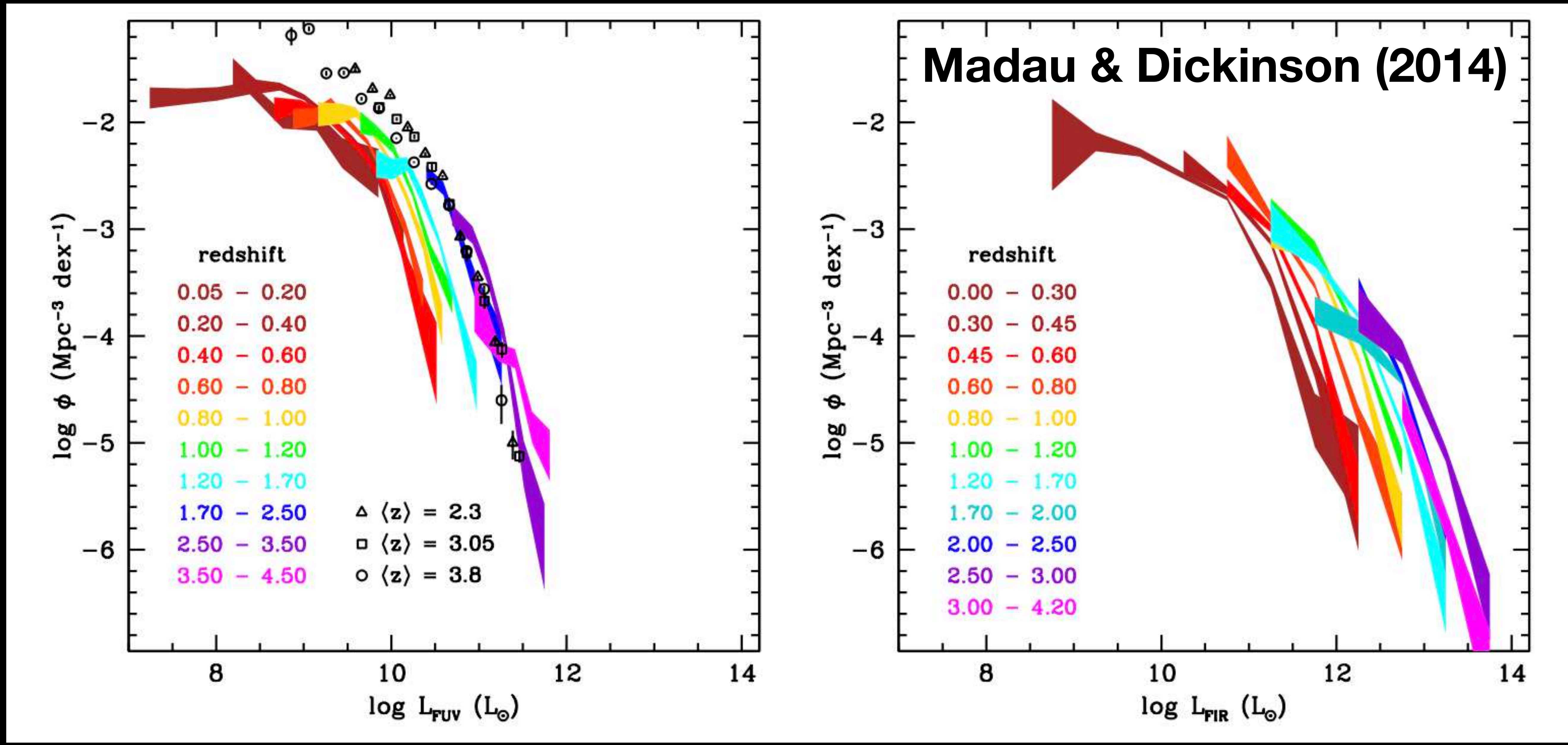


Luminosity Function $\xrightarrow{???}$ Cosmic SFR density



- Emission lines (e.g. Hα, [OII], Lyα);
- UV continuum (e.g. 1500 Å);
- IR emission (e.g. 24 μm, TIR, FIR);
- Radio, sub-mm, X-rays …

ARAA Kennicutt (1998) & Kennicutt (2012)



1. $$\Phi(L, z) = \left(\frac{\Phi^*(z)}{L^*(z)}\right)\left(\frac{L}{L^*(z)}\right)^{\alpha(z)} e^{-\frac{L}{L^*(z)}}$$

2. $$L_{tot}(z) = \int_0^\infty L'\Phi(L', z)dL'$$

$$= n^*(z)L^*(z)\Gamma(\alpha + 2)$$

$$\Gamma(\alpha + 2) = \int_0^\infty e^{-x}x^{\alpha+1}dx$$

Incomplete Gamma Function

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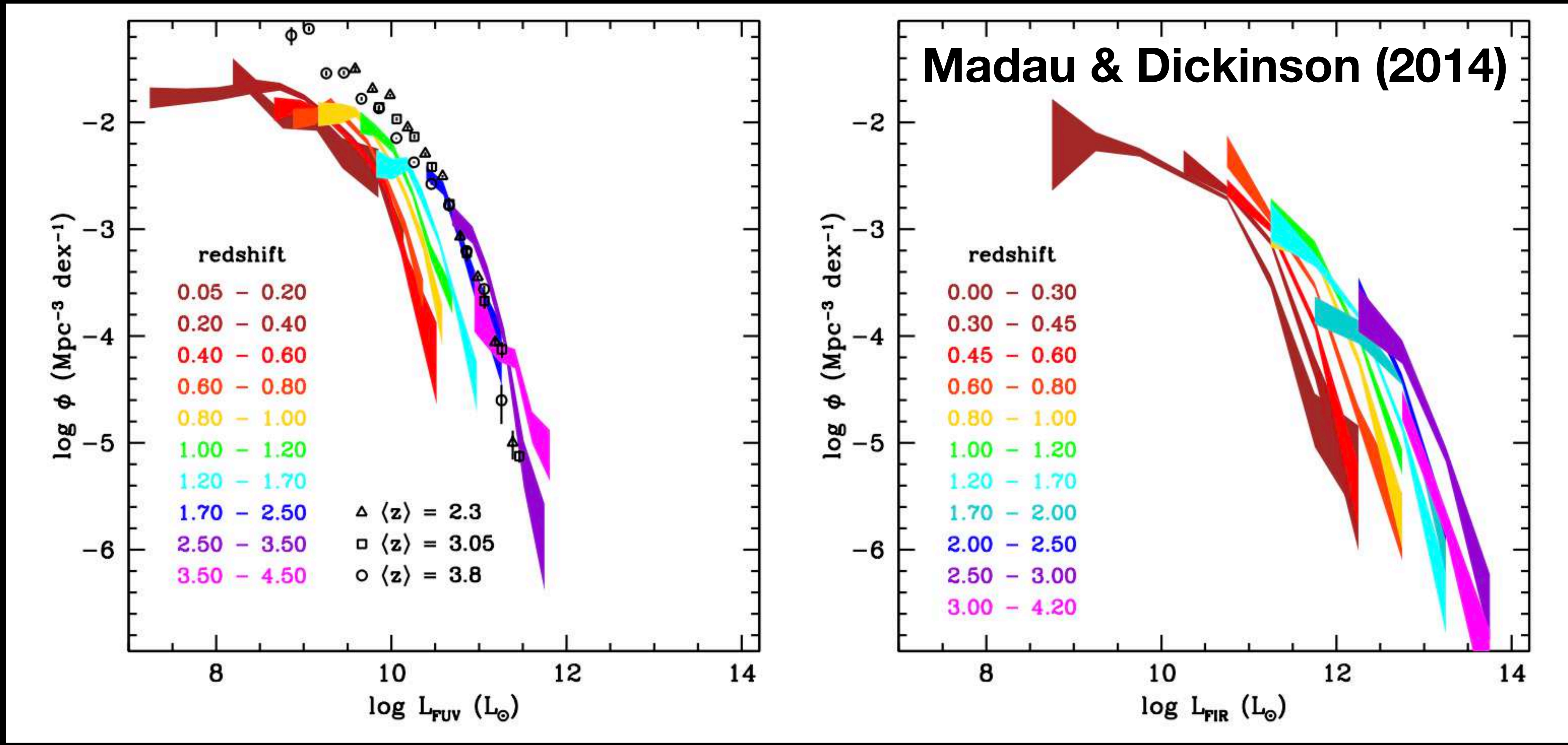
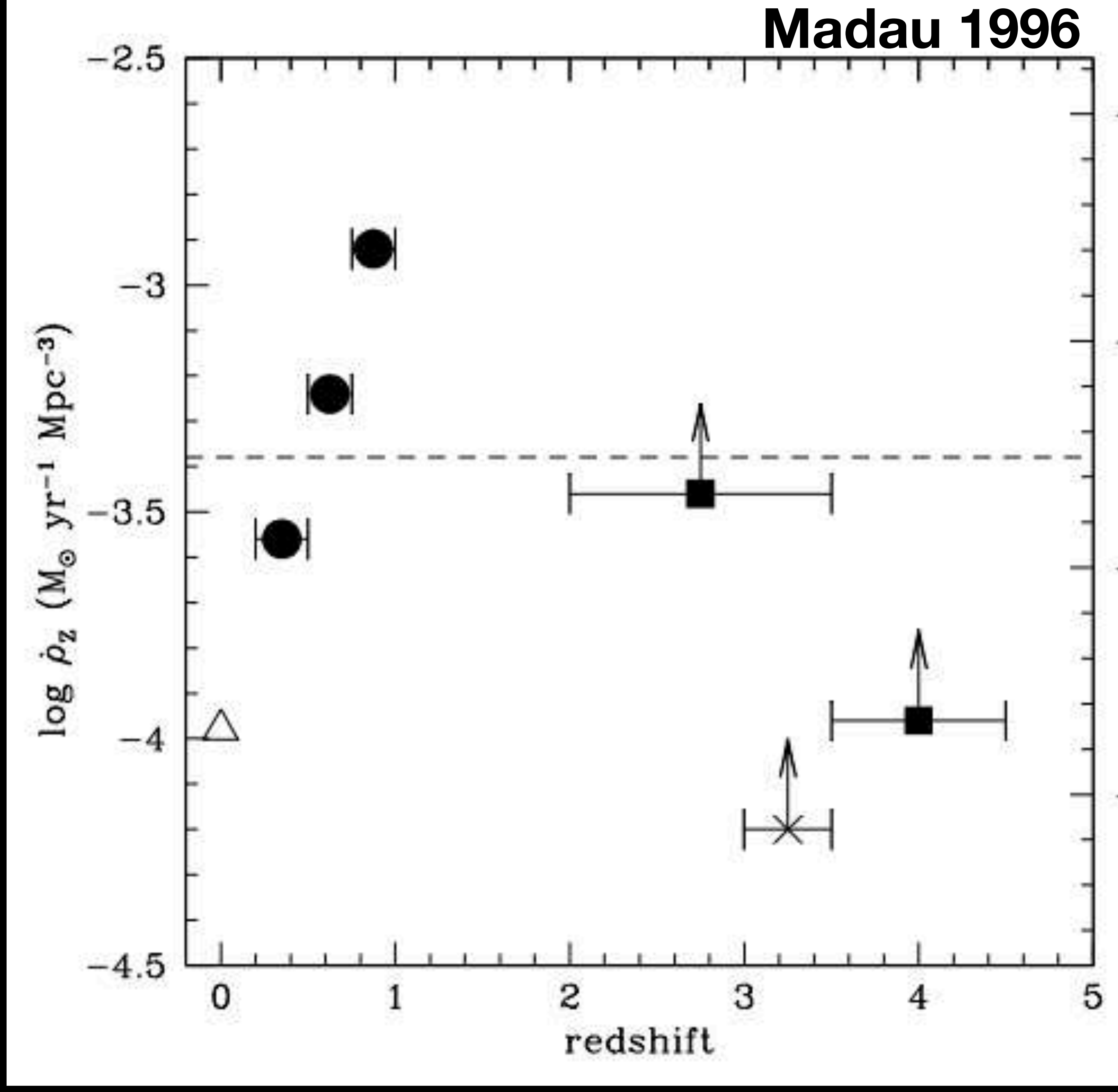
$$\Gamma(\alpha+2) = \int_0^{\infty} e^{-x}x^{\alpha+1}dx$$

Incomplete Gamma Function

3. $L \rightarrow SFR$ i.e. $L_{tot}(z) \rightarrow \psi(z)$

Lilly-Madau plot
(Lilly et al. 1996, Madau et al. 1996)

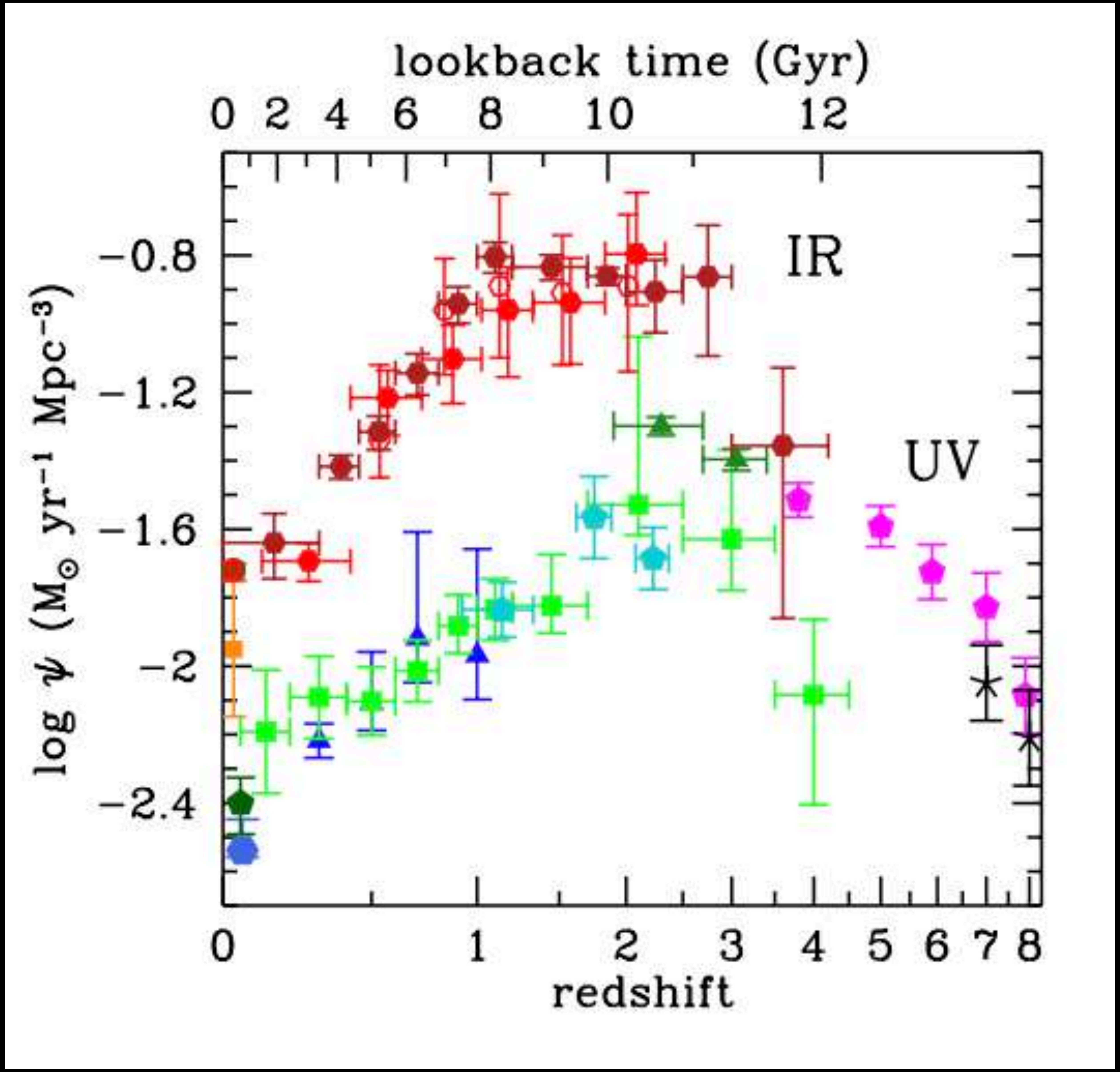




From Madau & Dickinson (2014)

Lilly-Madau plot:

(Madau et al. 1996, Lilly et al. 1996)



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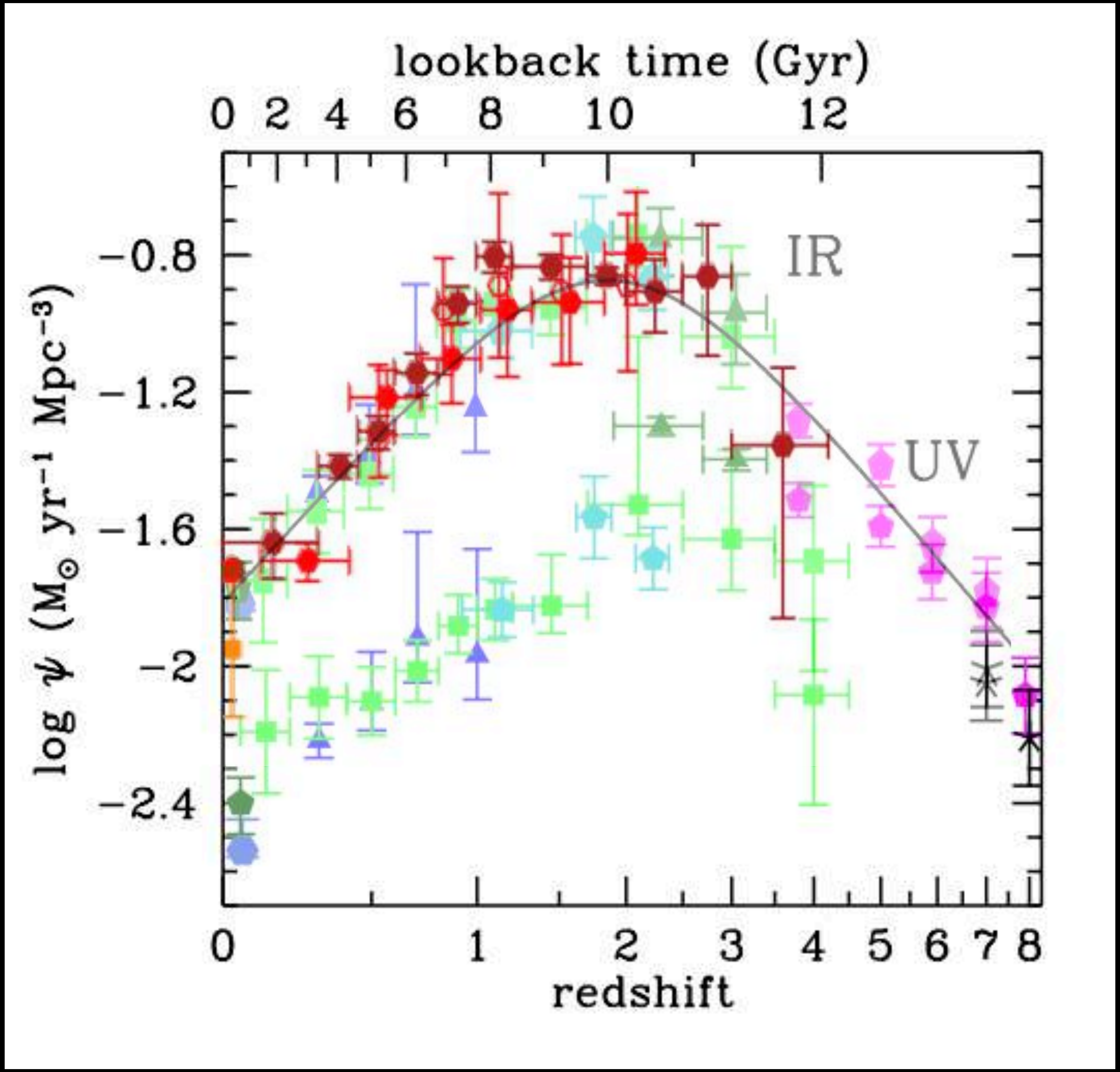

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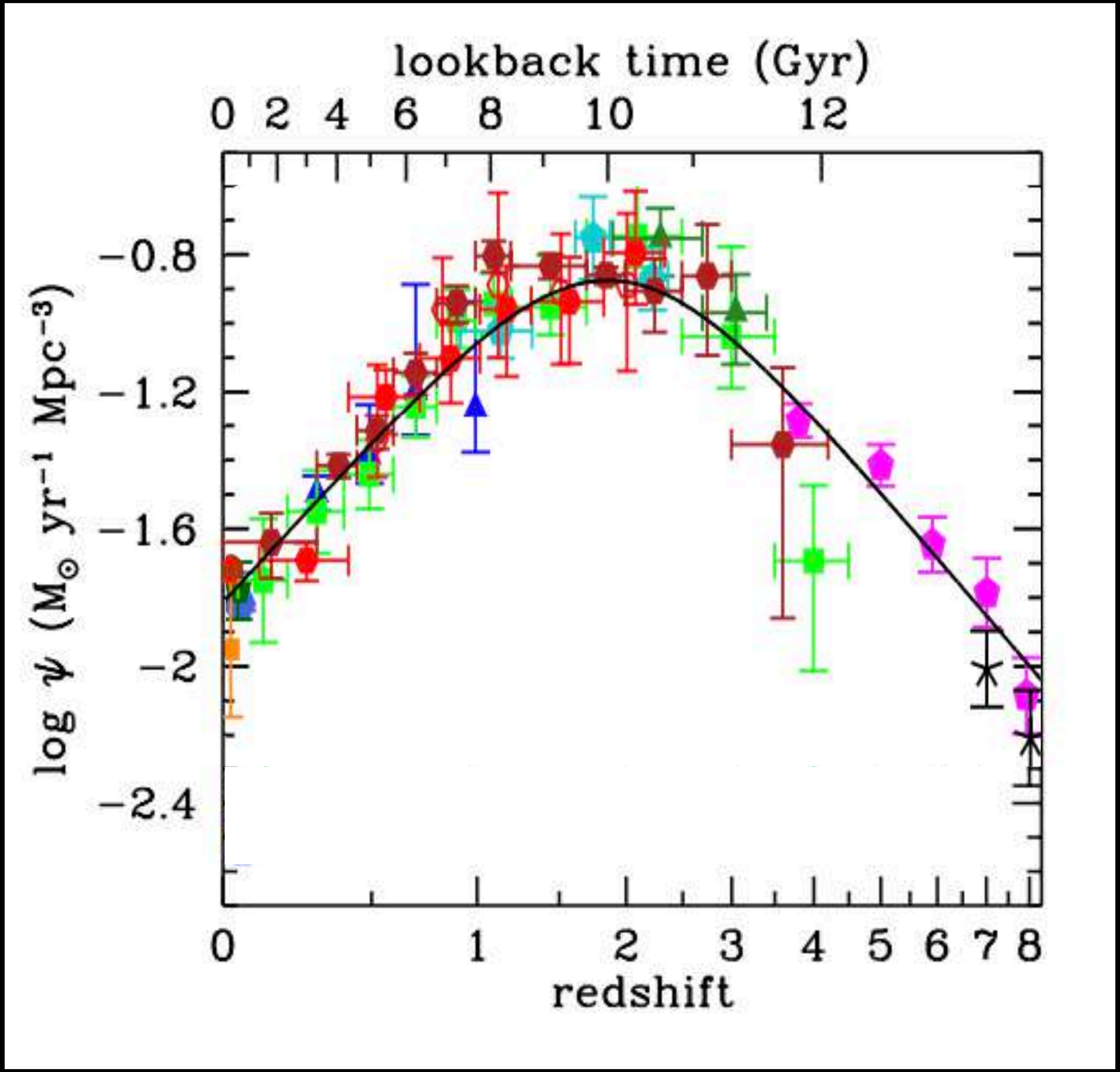

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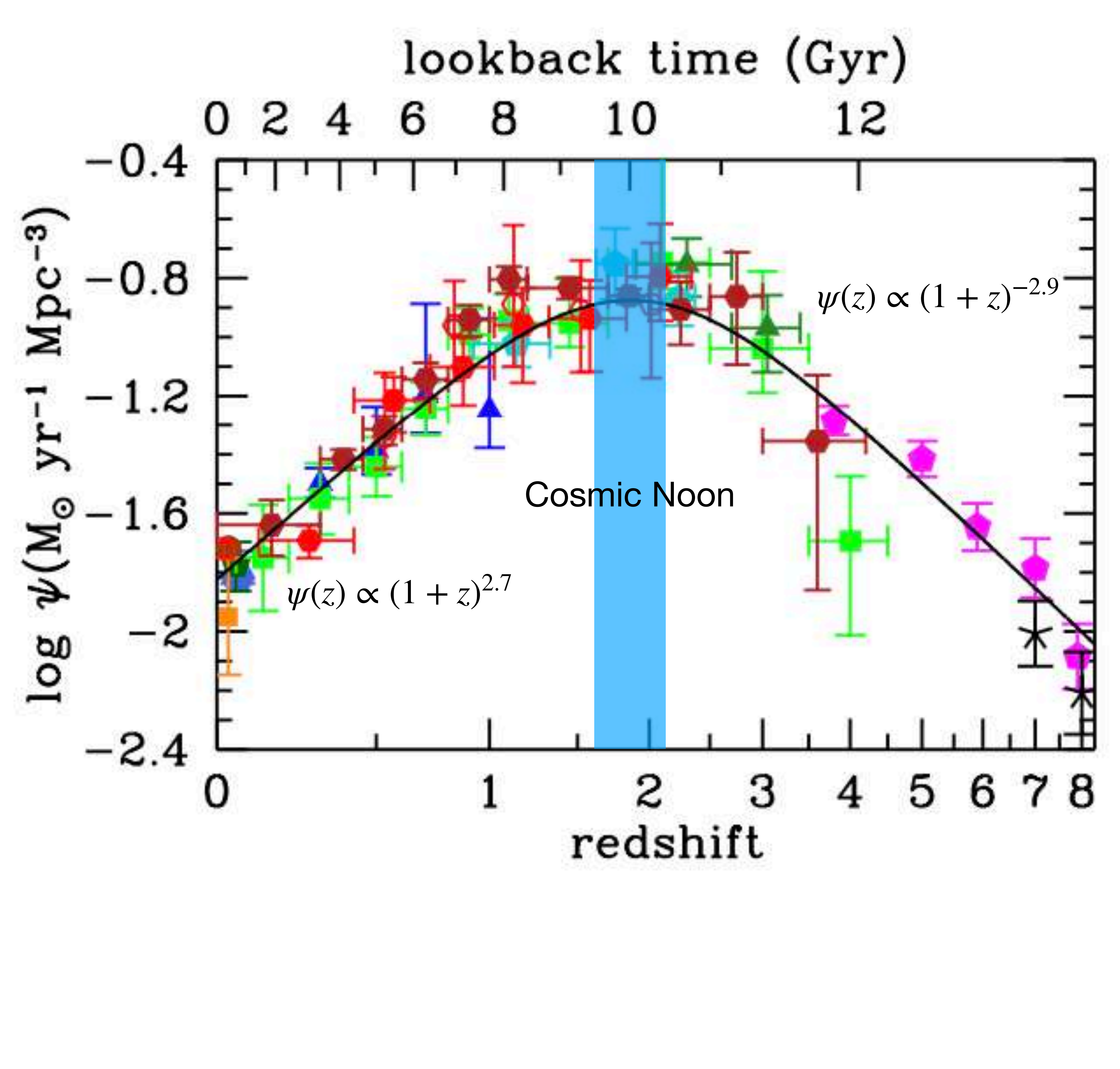


The cosmic SFH is characterised by:

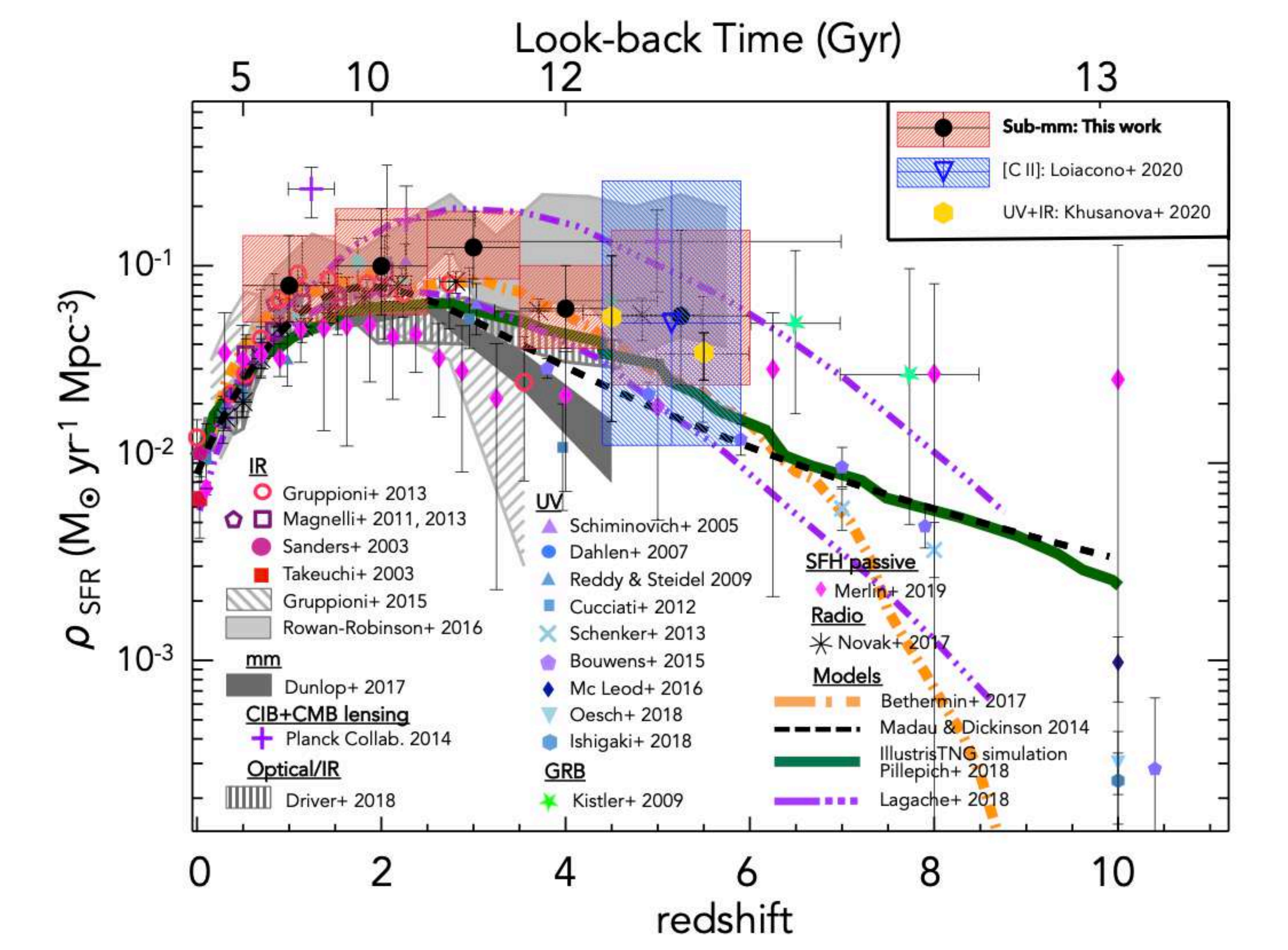
- a rising phase slowing and peaking between $z = 1.5 - 2$

$$\psi(z) \propto (1+z)^{-2.9}$$

- a gradual decline to the present day

$$\psi(z) \propto (1+z)^{2.7}$$

From Gruppioni et al. (2020)



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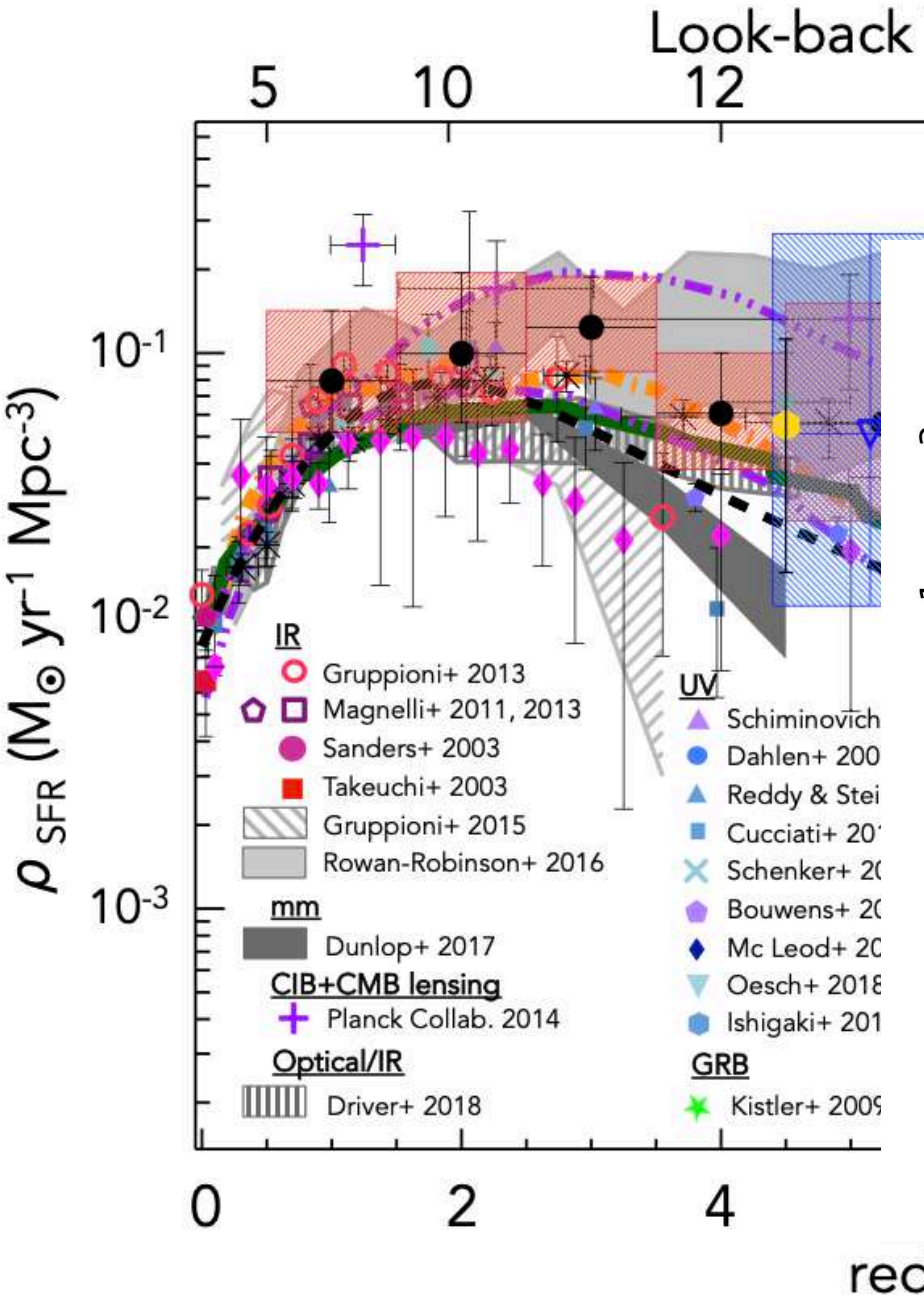
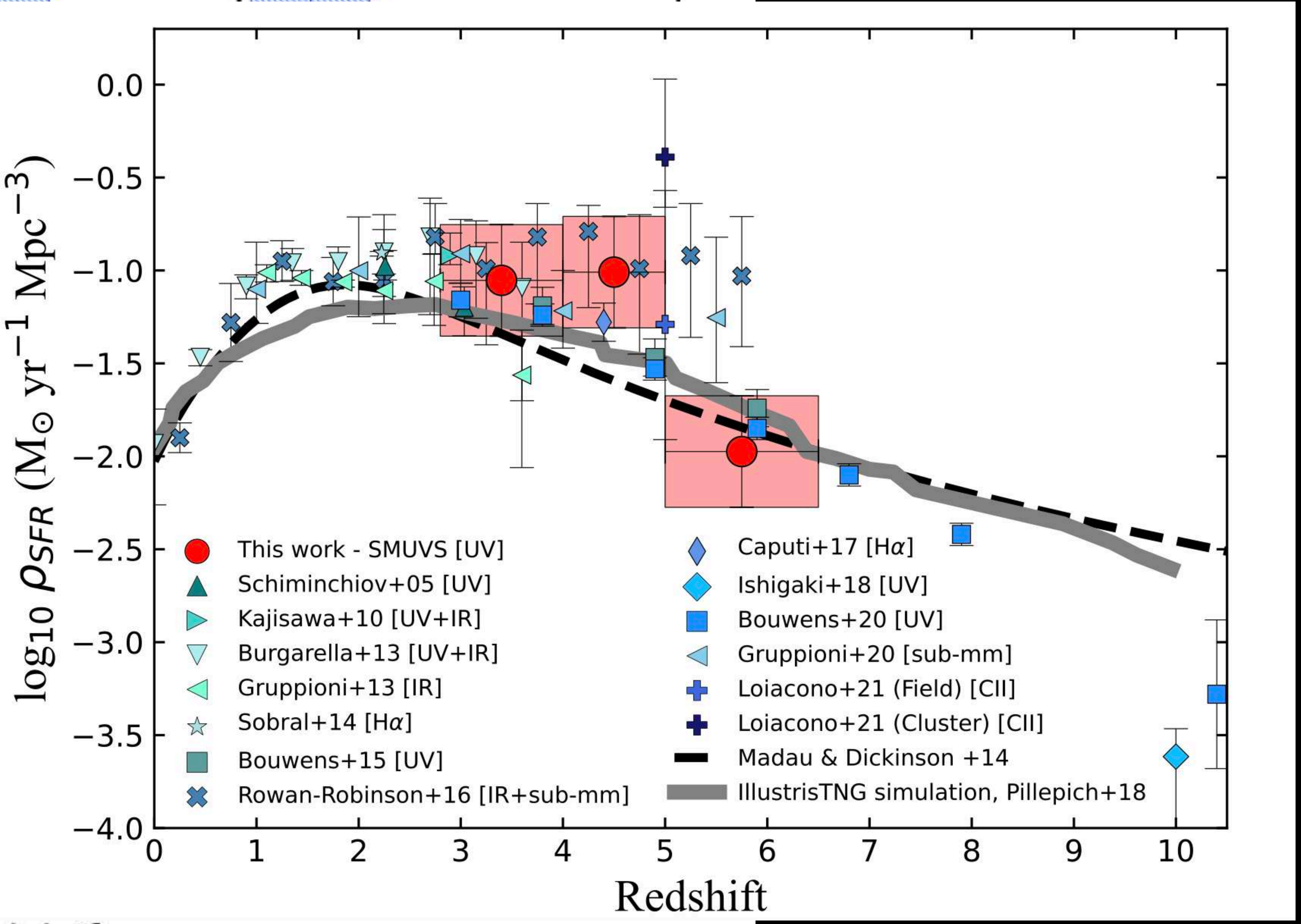


From Rinaldi et al. (2022)



Summary

- Peculiar galaxies are predominant at $z \sim 2.5 - 3$ ($> 70\%$);
- Ellipticals and spirals become progressively more common at lower z;
- The number density of ellipticals + spirals equals that of peculiars at $z \sim 1.4$;

- The size of ellipticals and spirals evolve with redshift (at least up to $z \sim 3$) towards smaller values;
- The evolution in size of ellipticals is significantly steeper than for discs;

- The bimodal distribution of galaxy colours is already in place at $z \sim 2 - 2.5$;
- Both the red sequence and the blue cloud move towards bluer colours with increasing z;
- The red sequence is less and less populated at high-z;

- The luminosity of galaxies (e.g. FUV, FIR) evolves with z, as well as the number density.
- The observed cosmic SFR density seemed to have steadily increased up to $z \simeq 2$ (unclear behaviour at high-z) and decreased since then (expansion and slow depletion of gas).