Galaxies and their Gas at the Peak Epoch of Star Formation

Dawn Erb | Arizona State University | September 30, 2015

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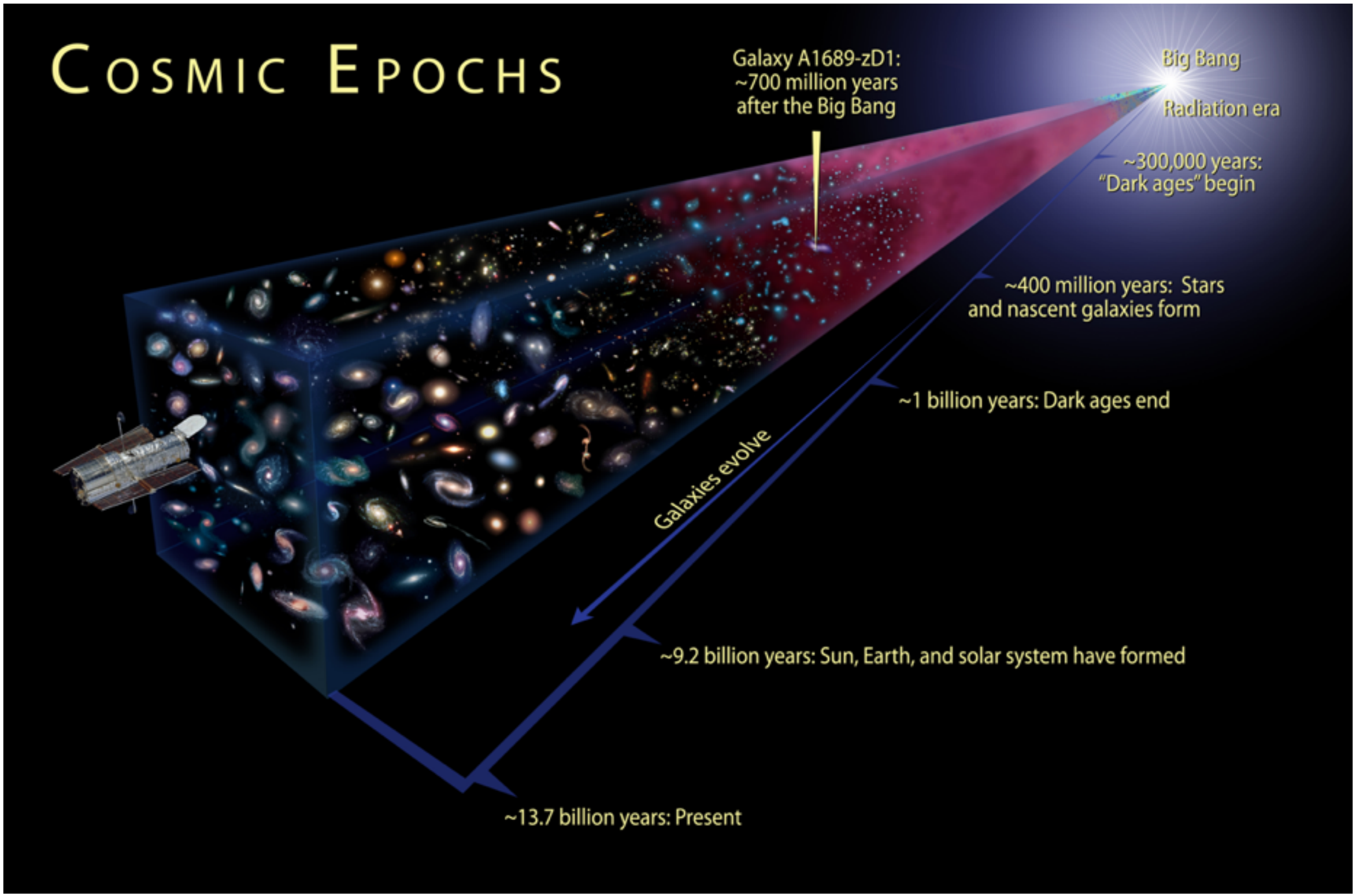
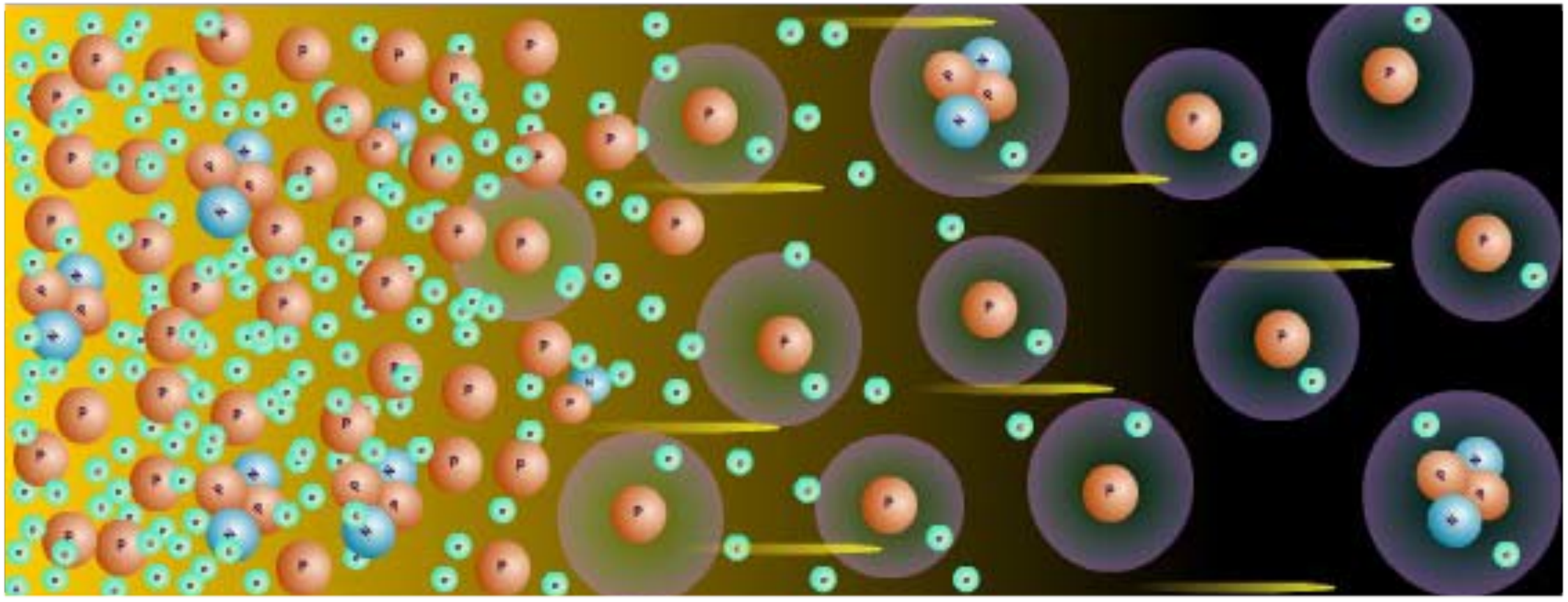
A brief history of the Universe



Recombination

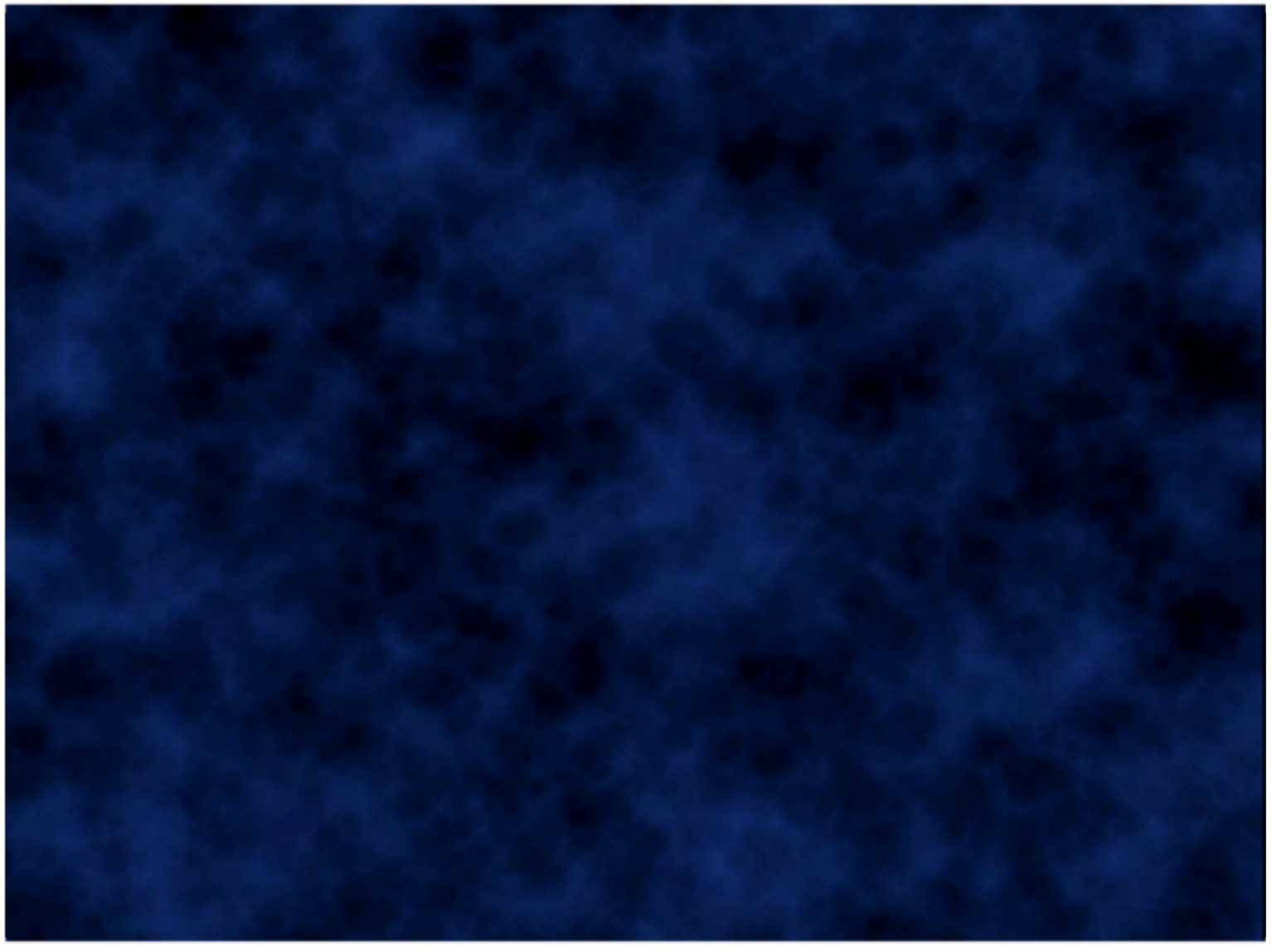


Ionized hydrogen

Neutral hydrogen

Universe expands and cools

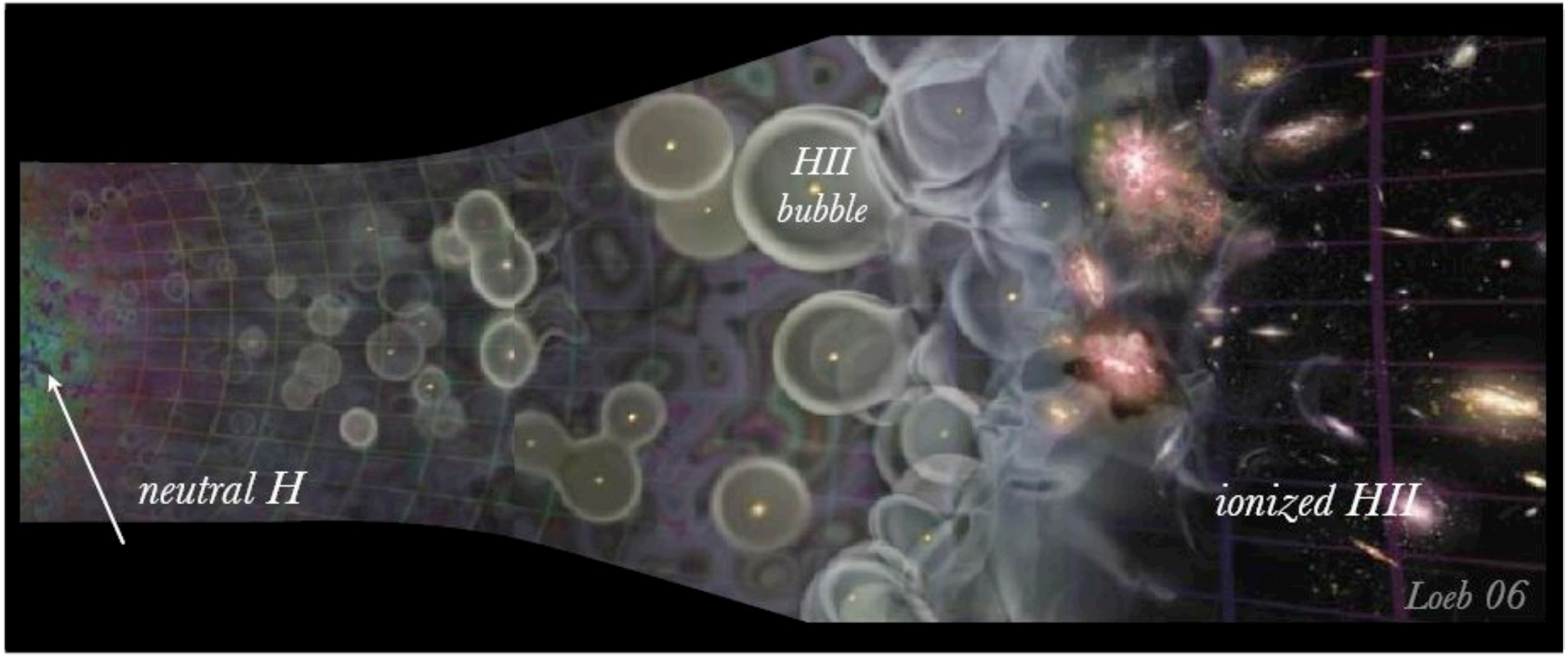
The cosmic dark ages



400 thousand – 400 million years after the Big Bang

Universe contains dark matter, neutral hydrogen and helium gas

Reionization

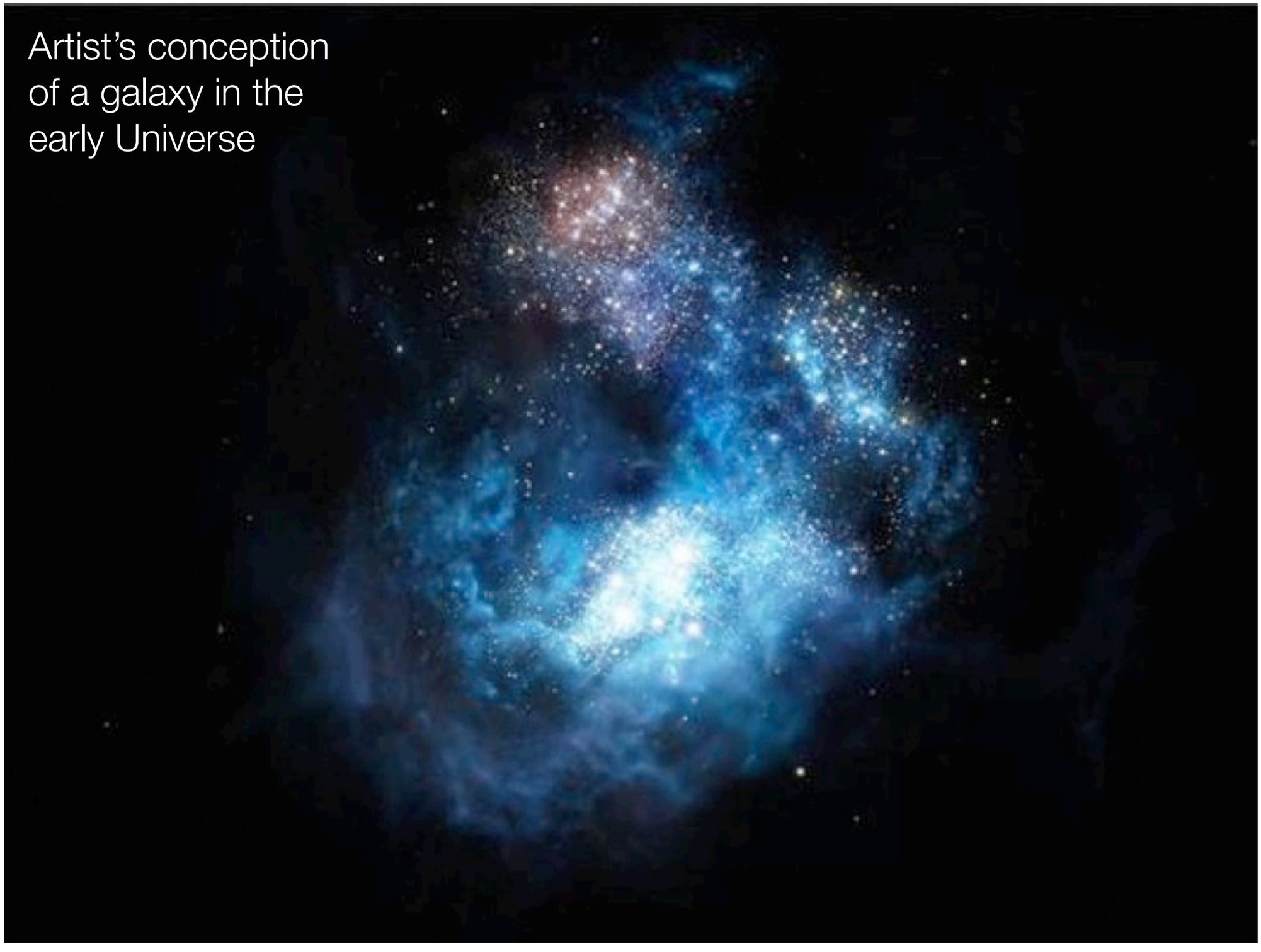


First stars and galaxies emit ionizing radiation

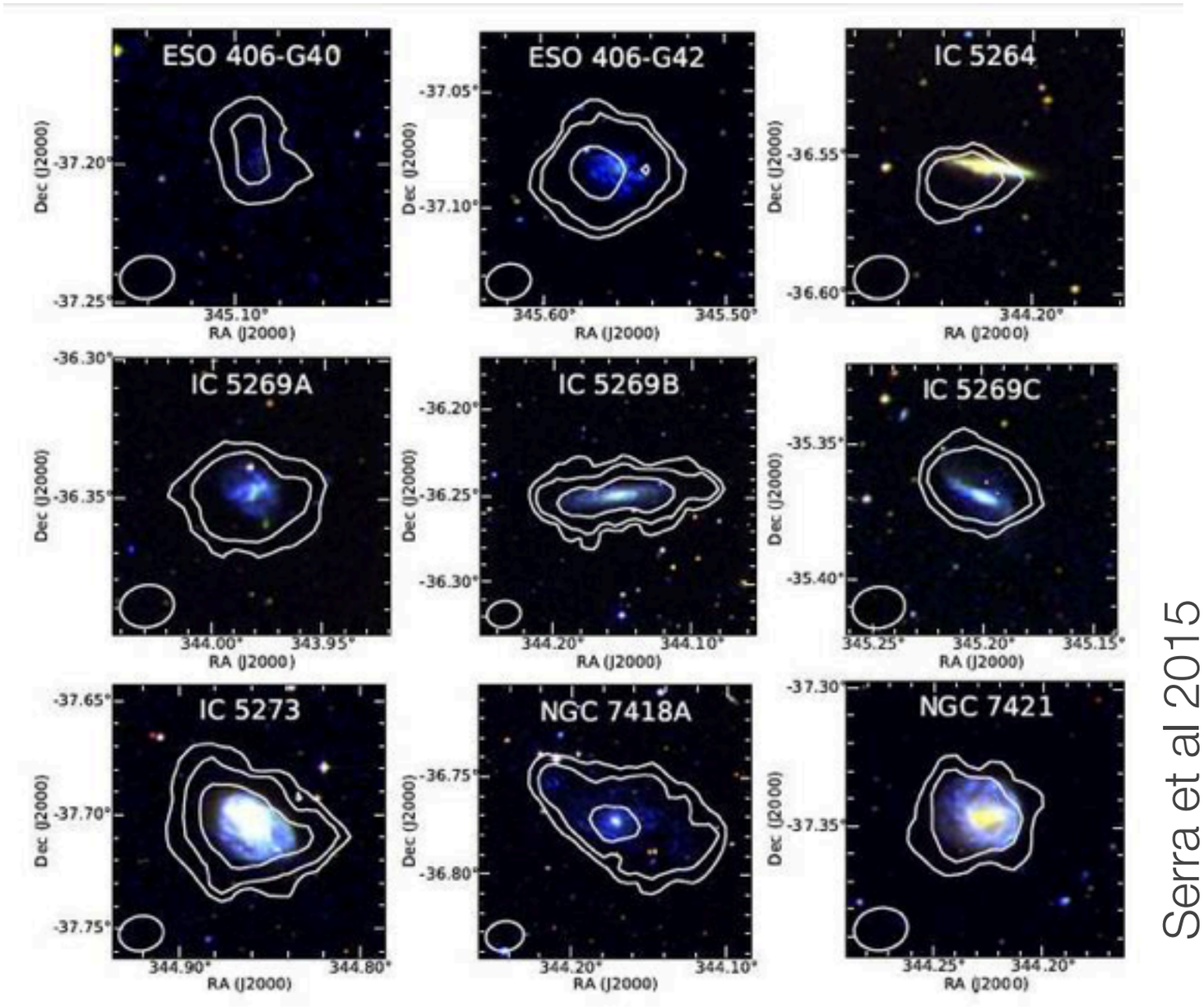
Gas between galaxies becomes ionized

Last major phase change in the universe

How did reionization happen?



Galaxies with radio vision



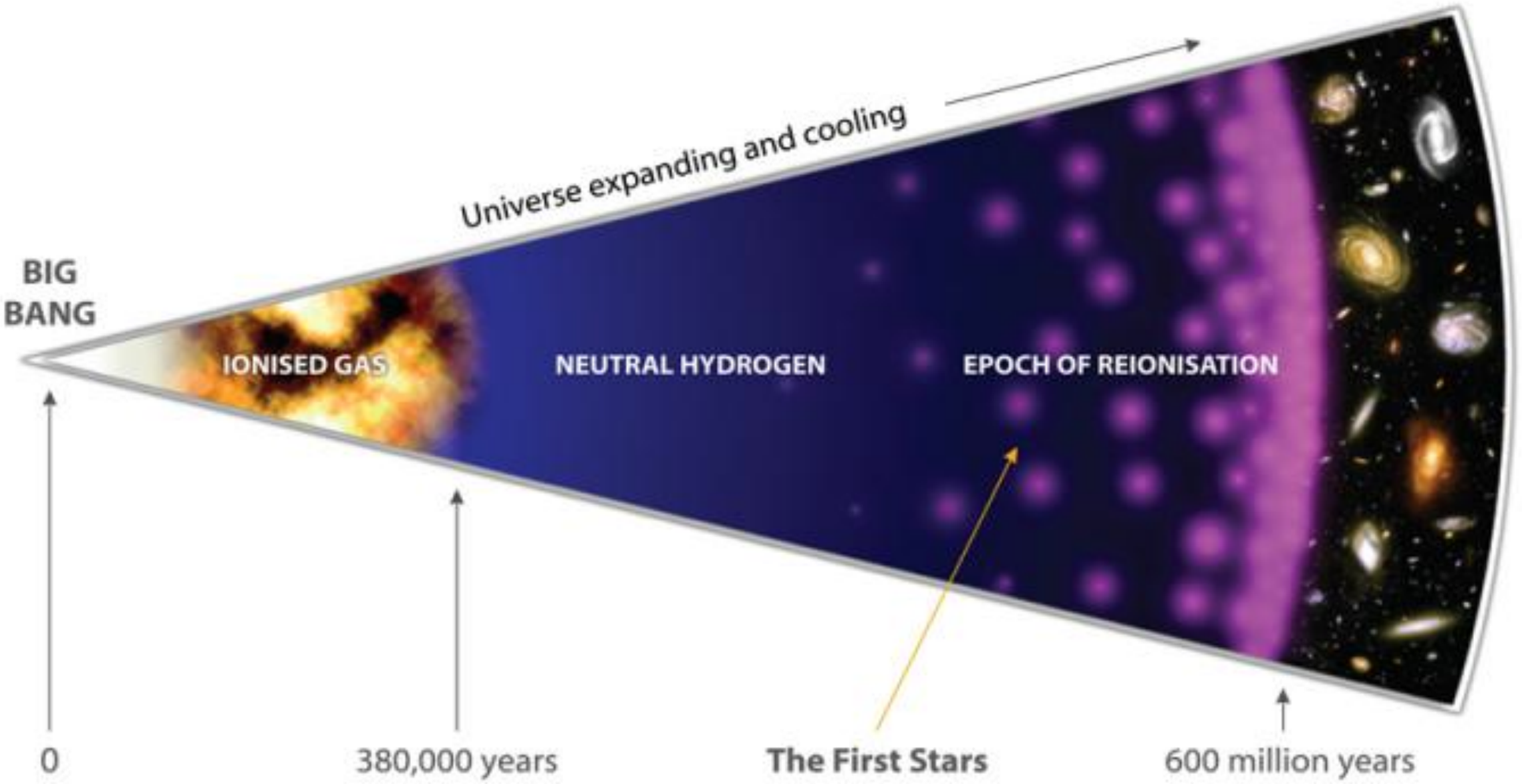
Serra et al 2015

Galaxies are surrounded by neutral hydrogen

Hard for ionizing radiation to get out

How do we get enough photons?

How did reionization happen?

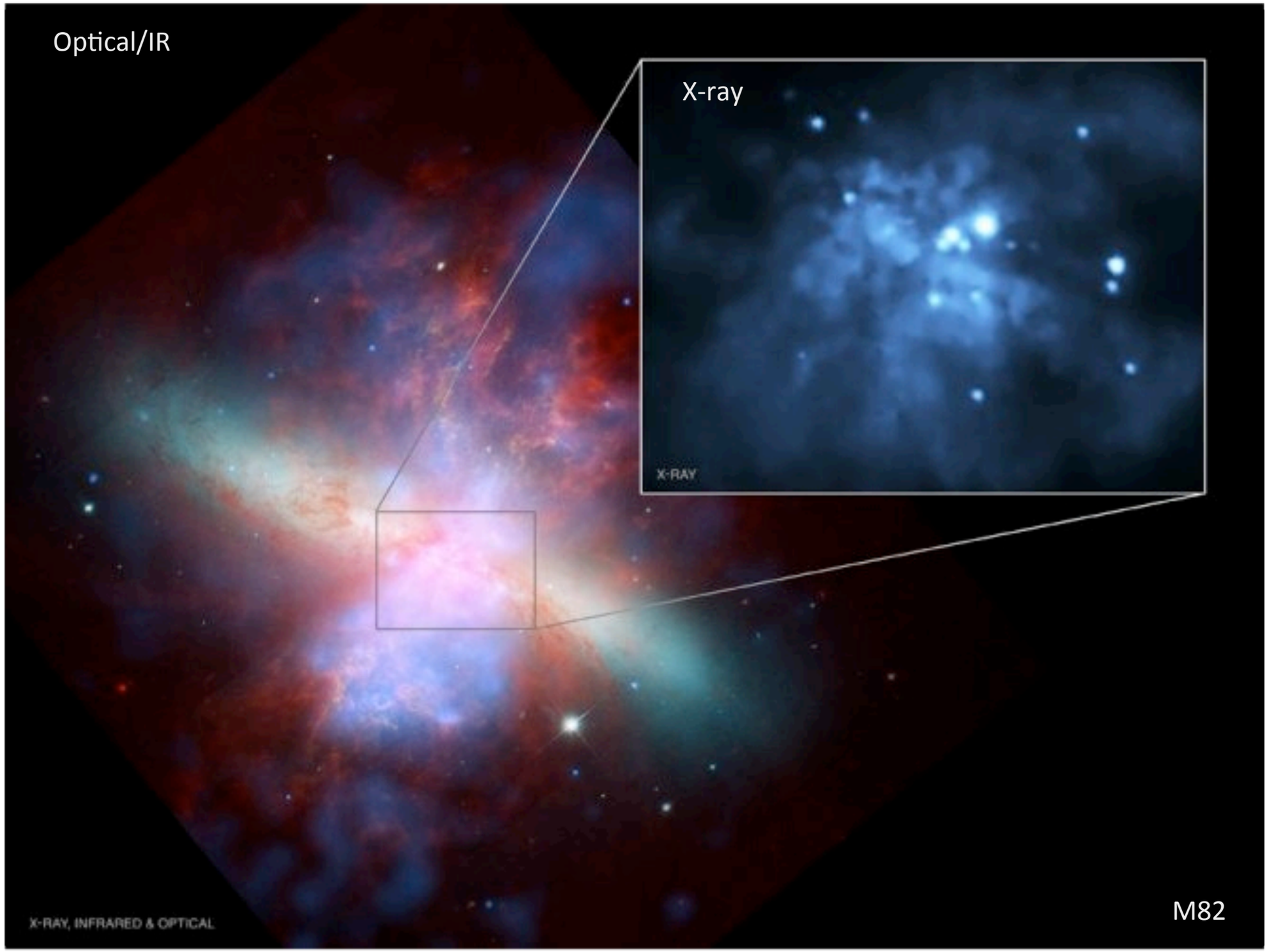


Need many energetic photons escaping from many galaxies

Starburst galaxies

M82

Starburst galaxies: galactic outflows



M82

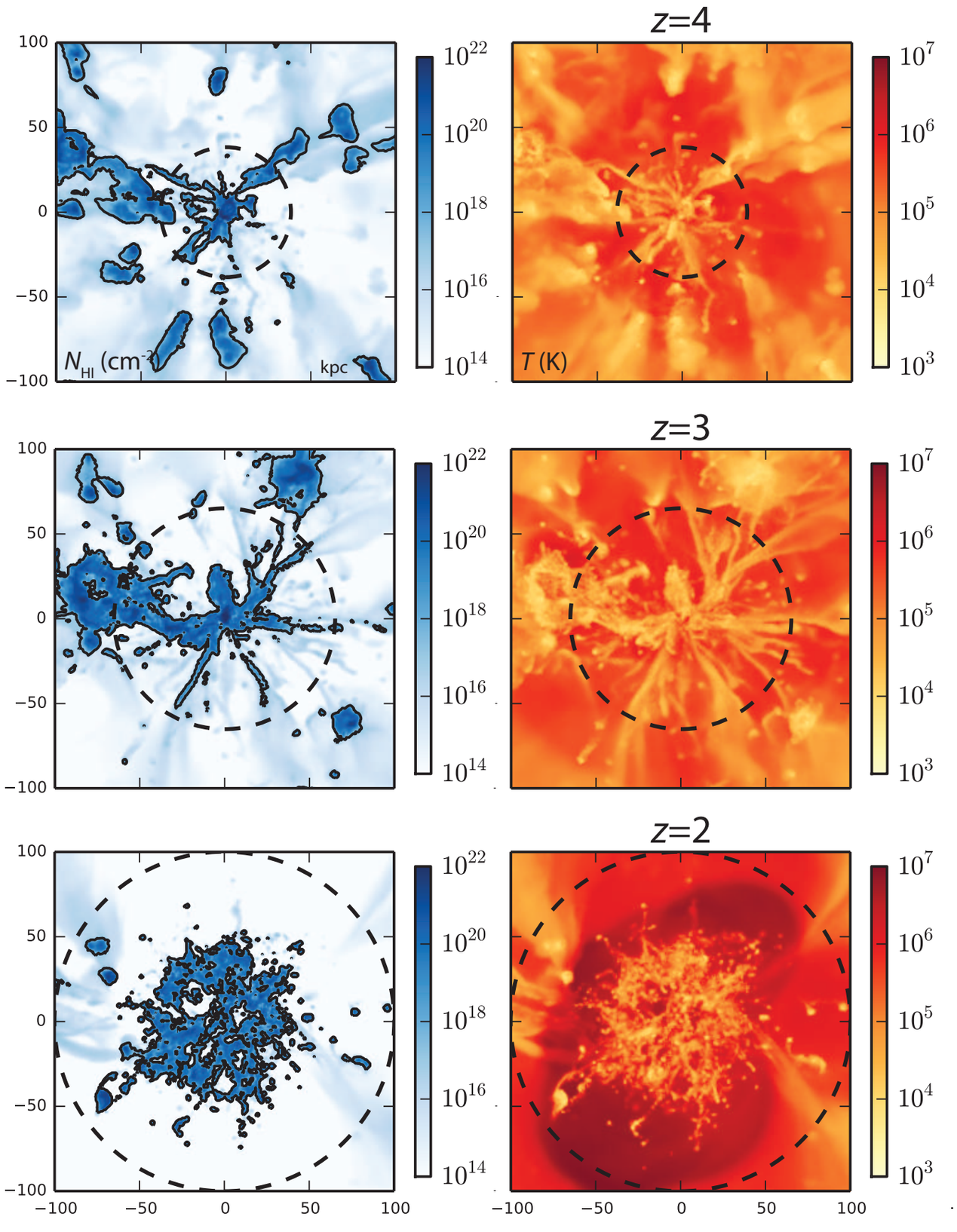
Galactic outflows

Intense star formation in small volume

Energy from supernovae and stellar winds, momentum from radiation pressure drive gas out of galaxies

Complex, not understood in detail

Growing galaxies in boxes



Multiple driving mechanisms for outflows

Dominant mechanism may depend on galaxy type

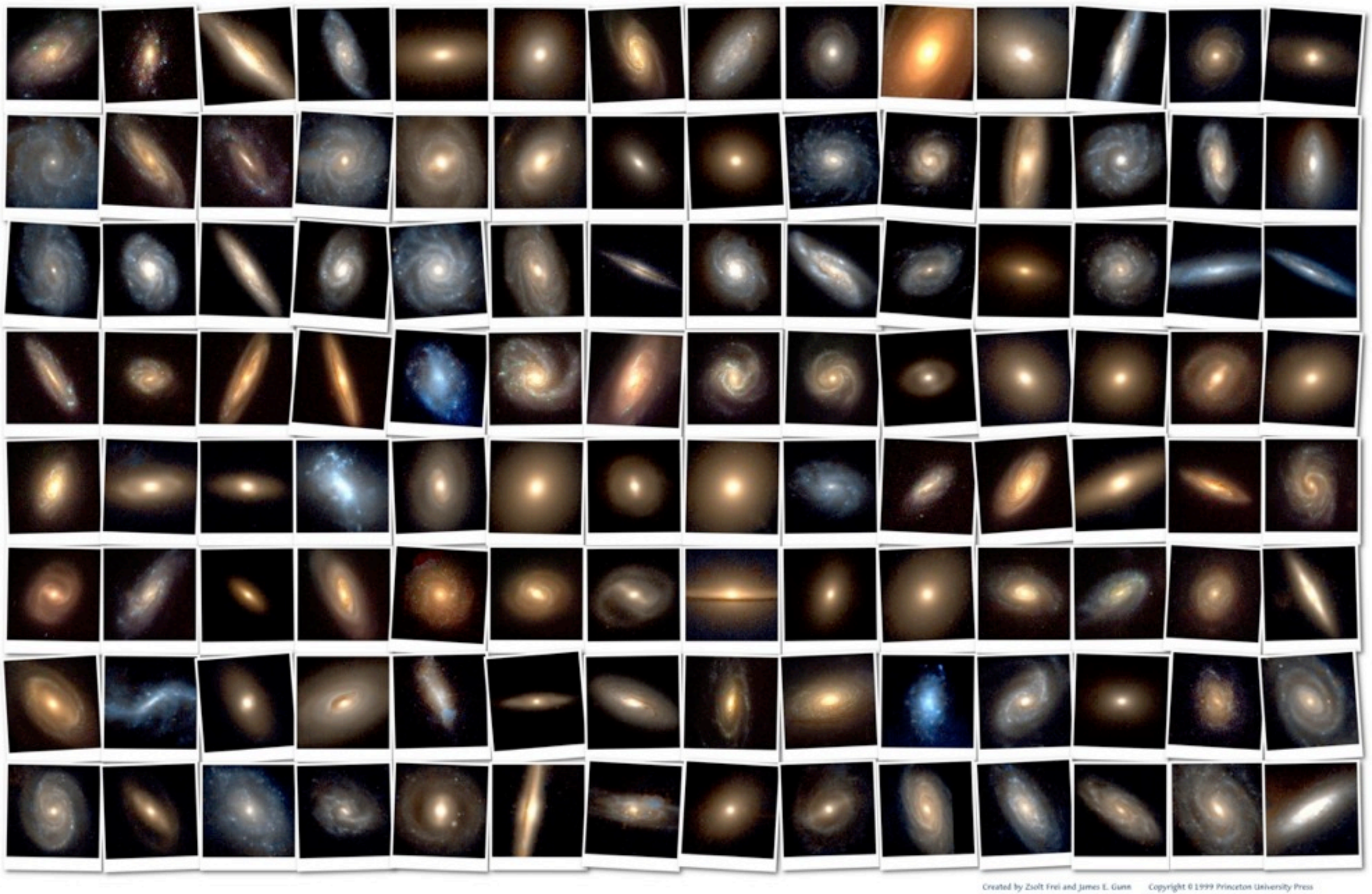
Wide range in temperature, velocity in all galaxies

FIRE simulations
Faucher-Giguere et al 2015
left: neutral hydrogen density
right: temperature

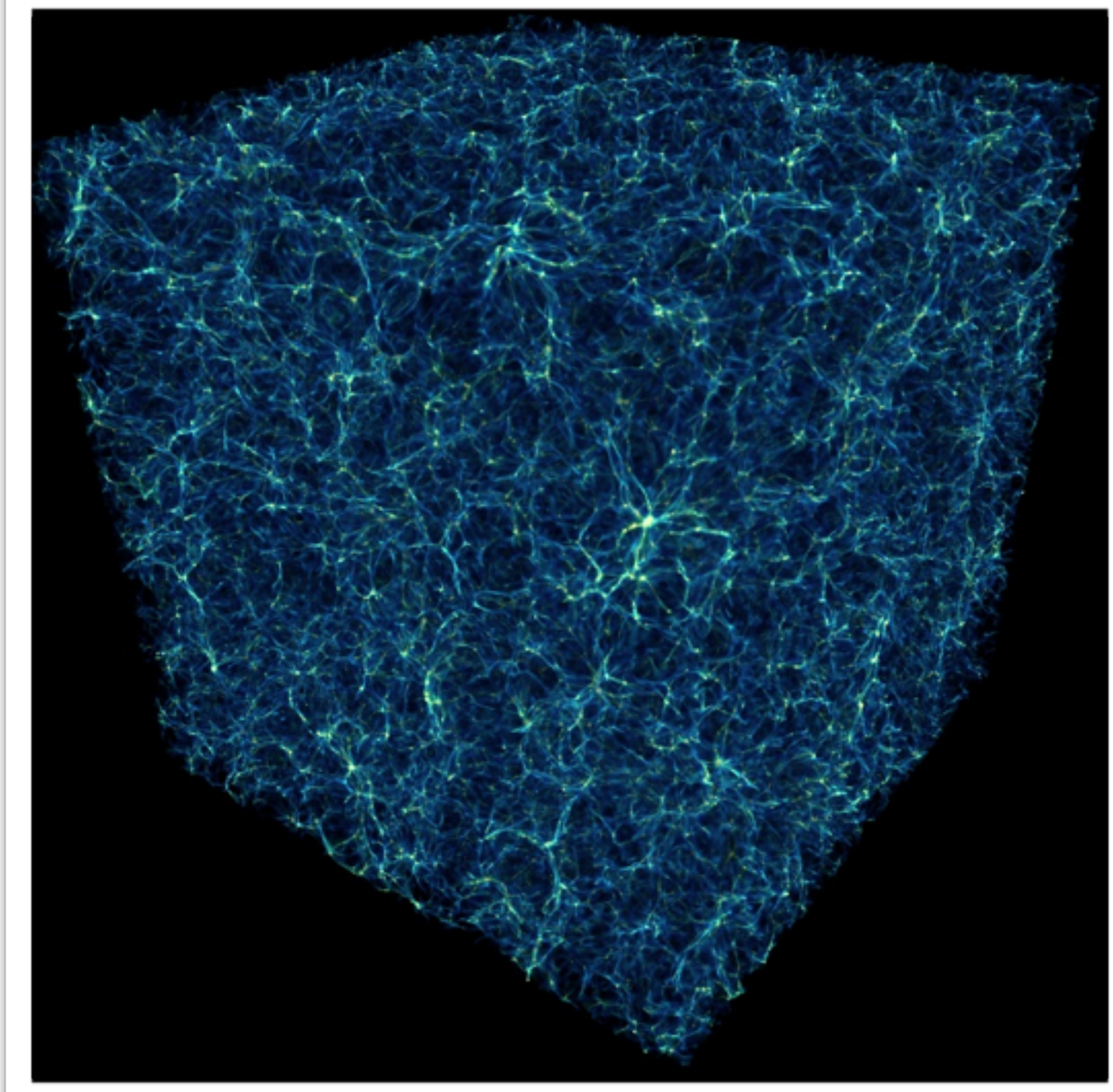
The importance of galactic outflows

Regulate star formation

Do outflows shut off star formation?



Gas between galaxies is chemically enriched



Matt Hall,
National Center for
Supercomputing
Applications

Computer simulation of gas between galaxies:
the intergalactic medium

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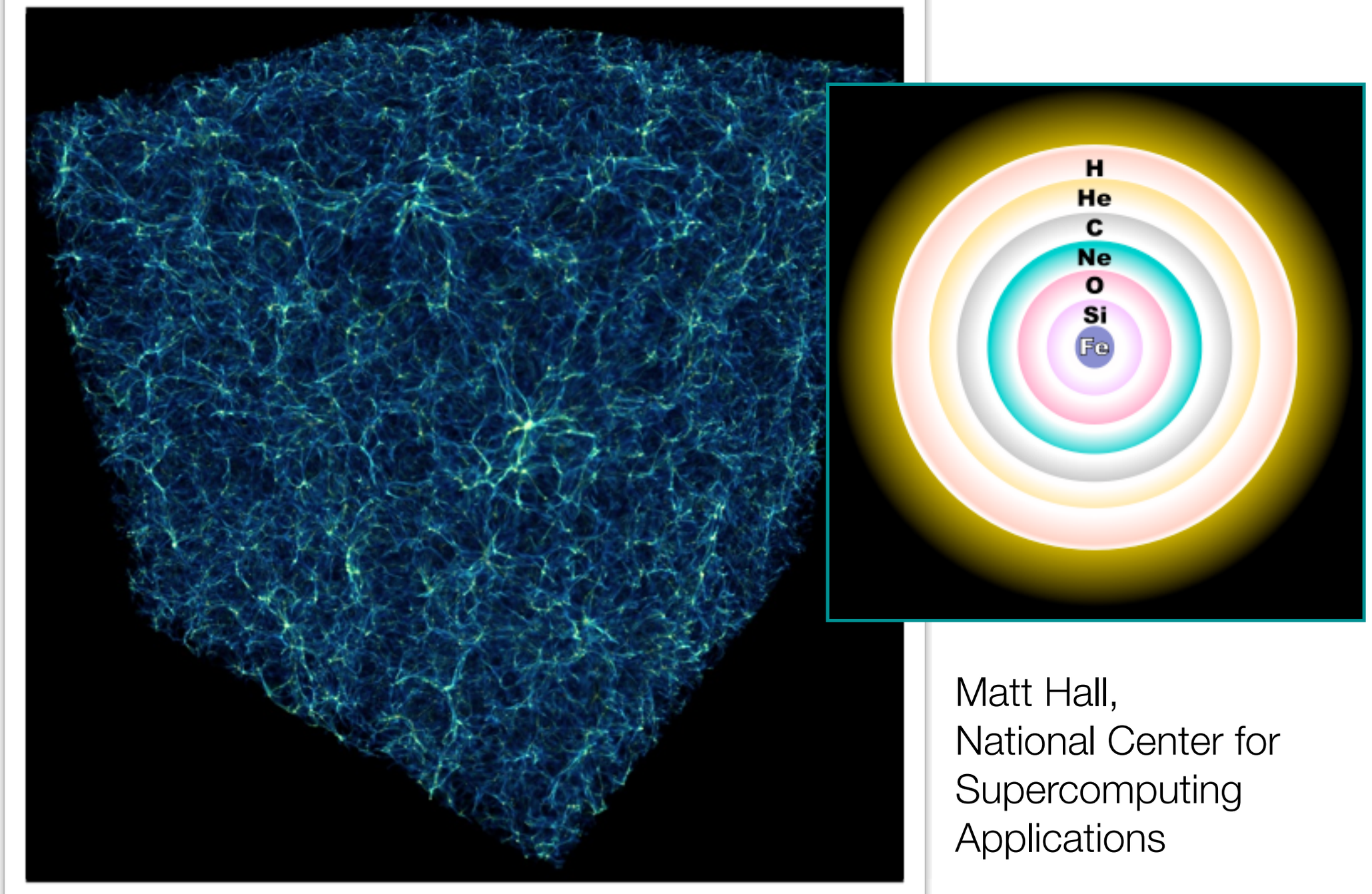

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Computer simulation of gas between galaxies:
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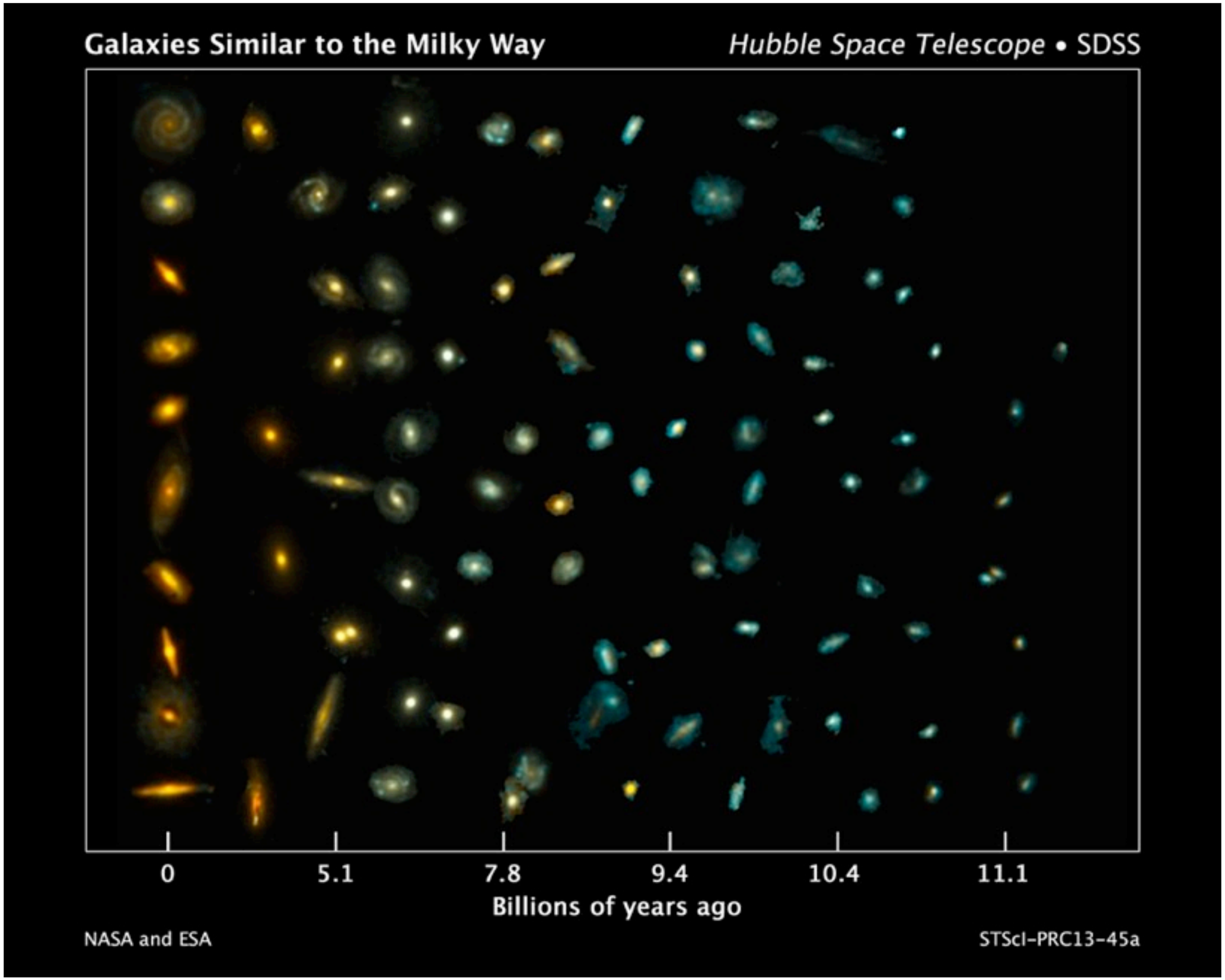
How do galaxies change over time?



Age of the Universe (billions of years)

0 2 4 6 8 10 12

Star Formation Rate / Volume

Madau & Dickinson 2014

0 1 2 3 4 5 6 7 8

redshift

Now

Big Bang →

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Star Formation Rate / Volume

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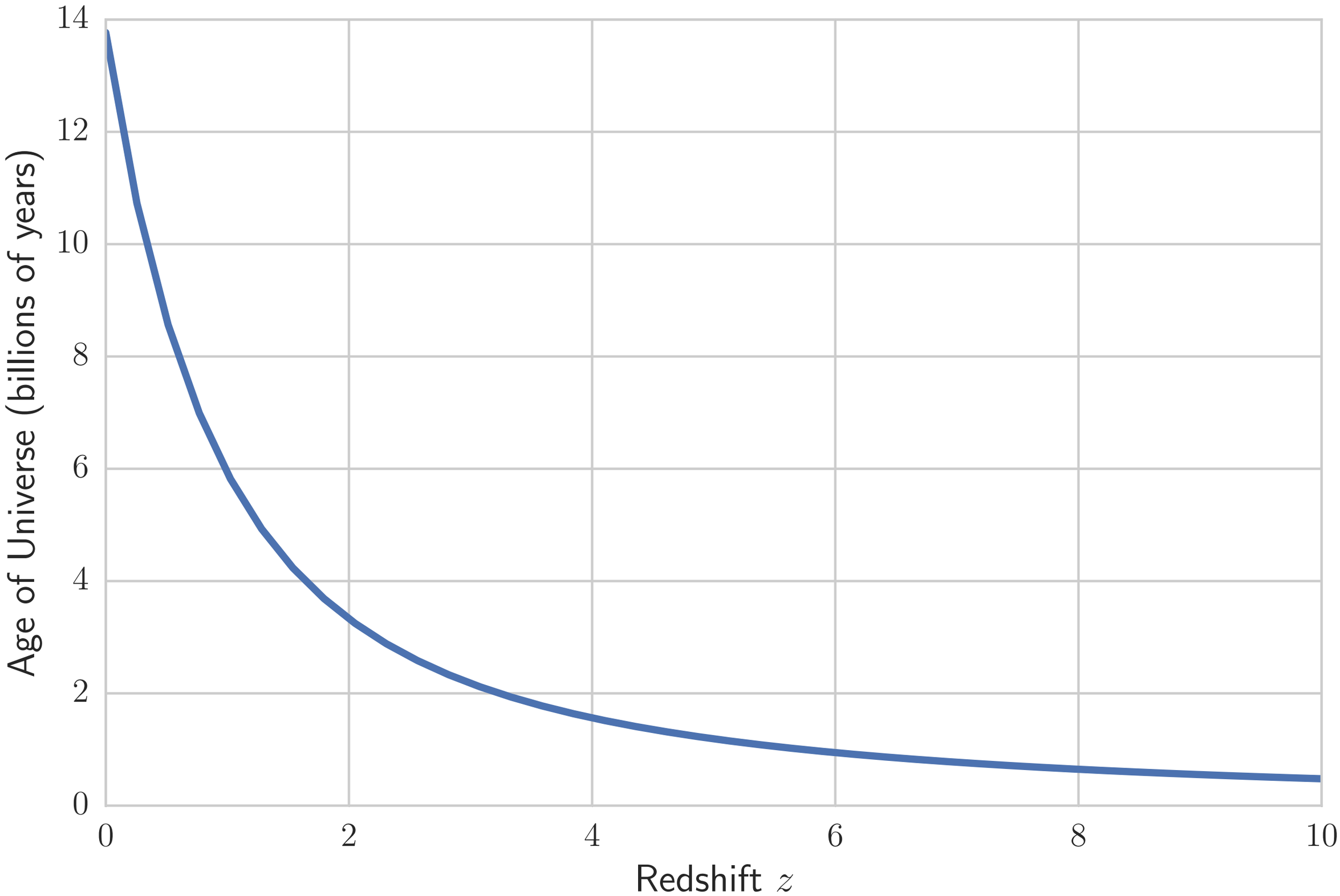
redshift

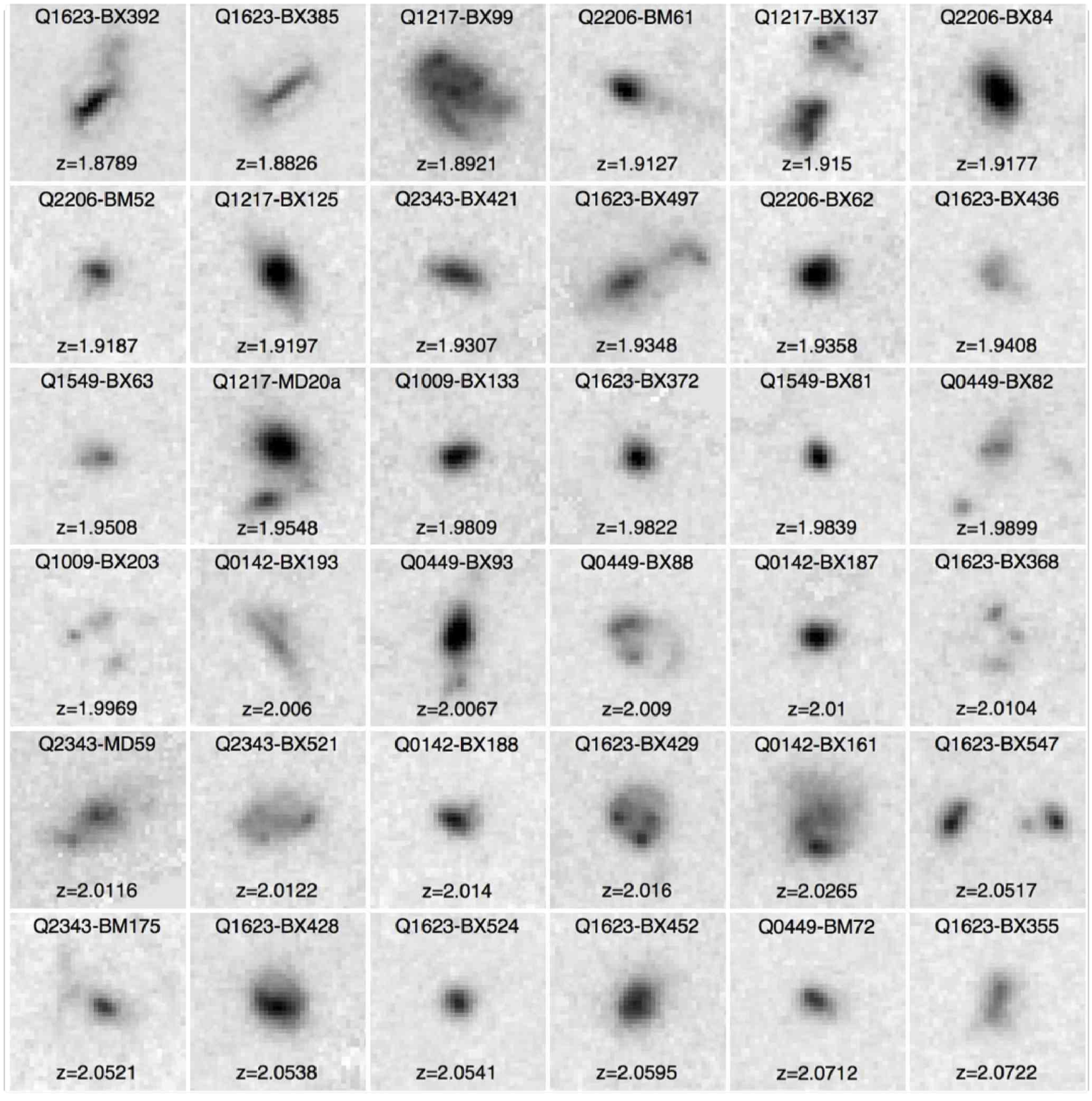
Now

Big Bang →

Looking back in time

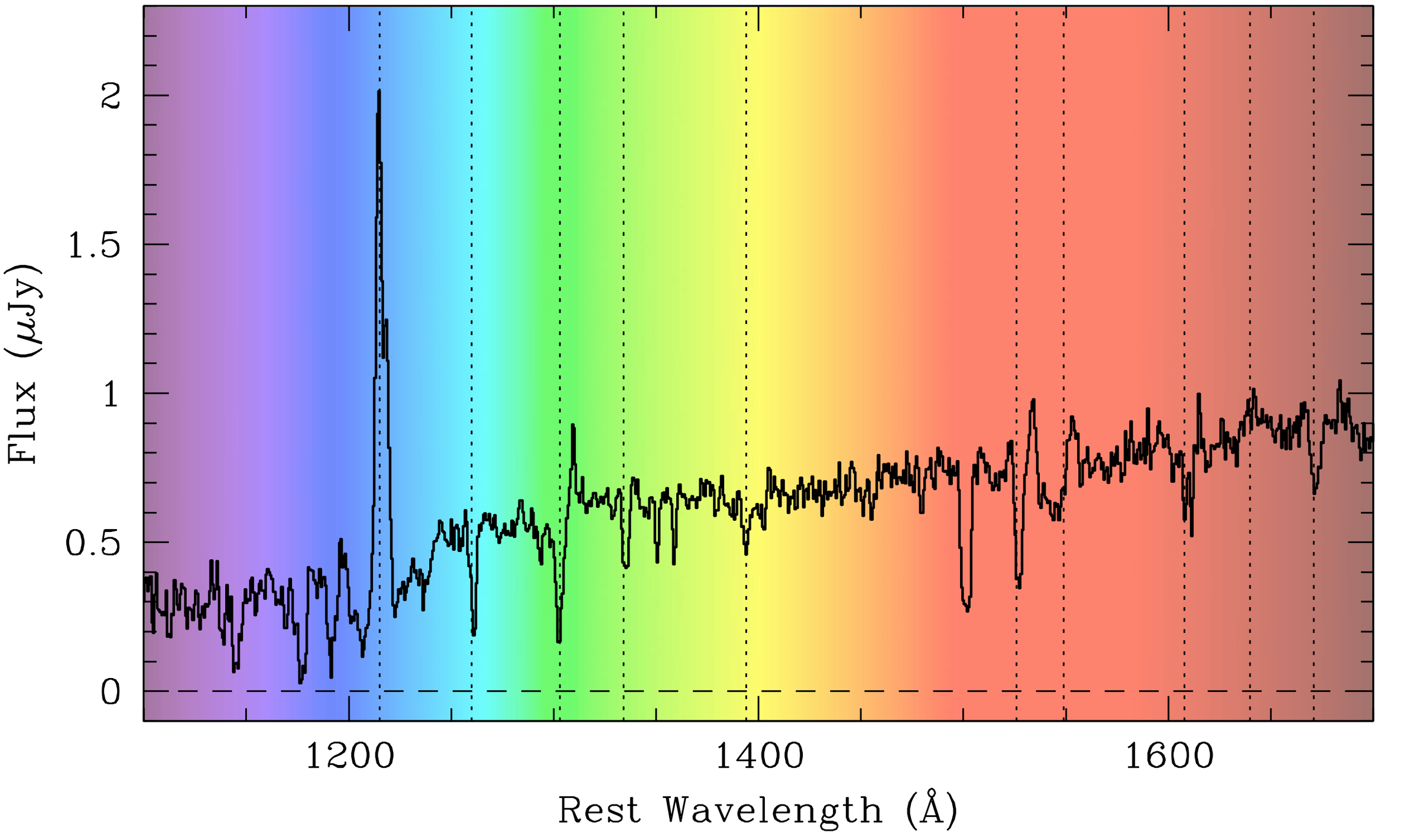


Galaxies at the peak epoch of star formation



Law et al 2012

Rest-frame UV spectrum of galaxy at z~2



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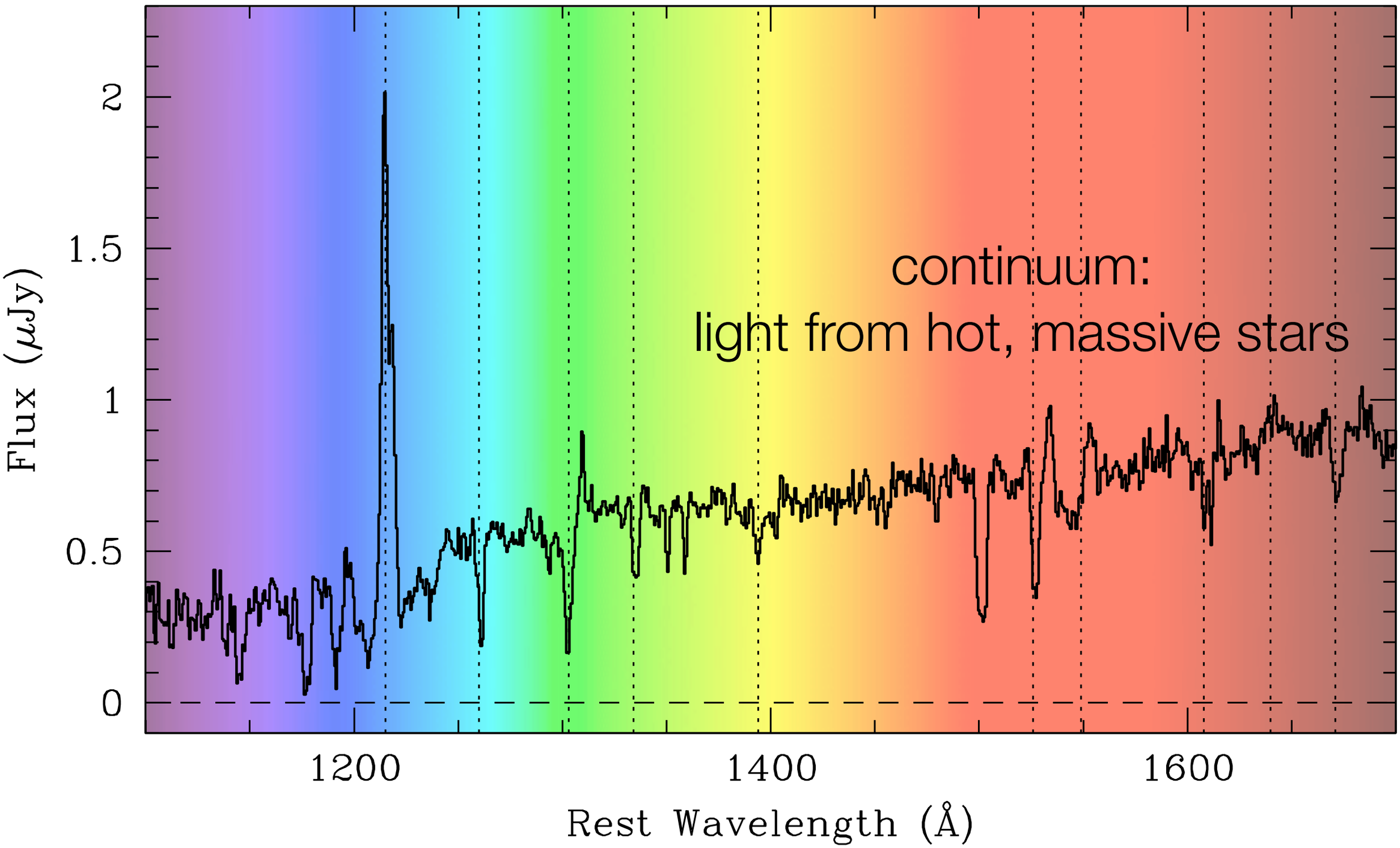

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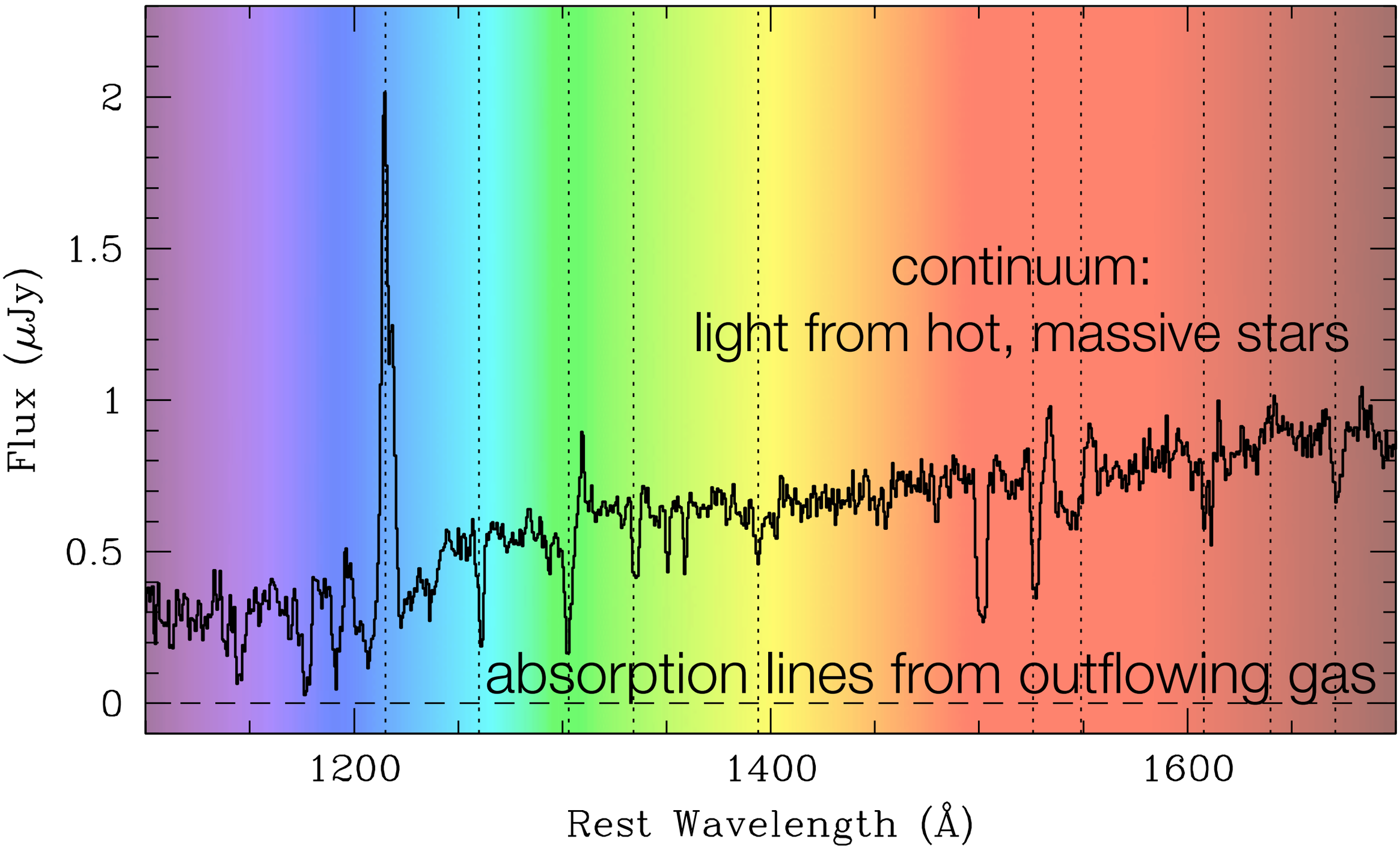

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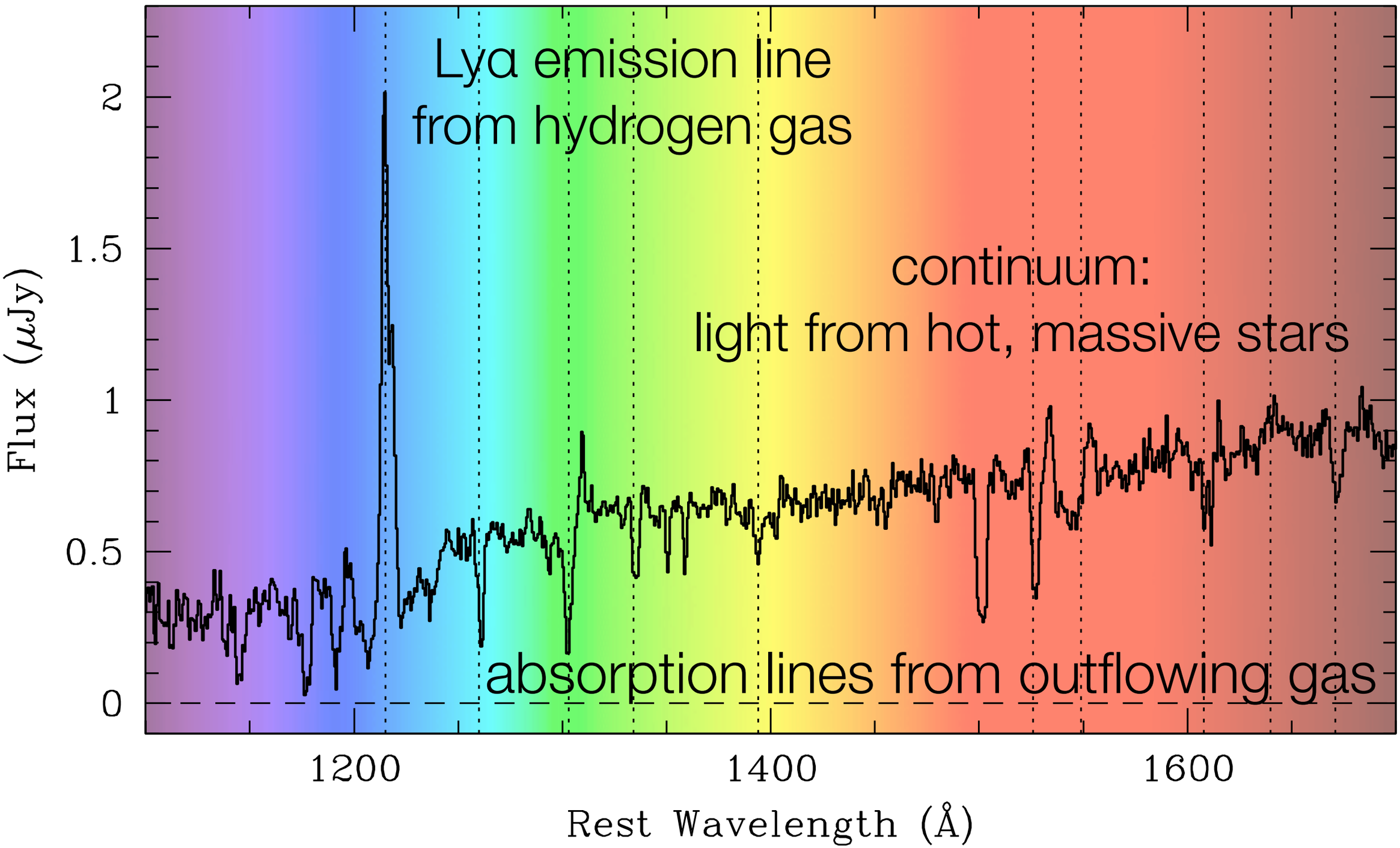
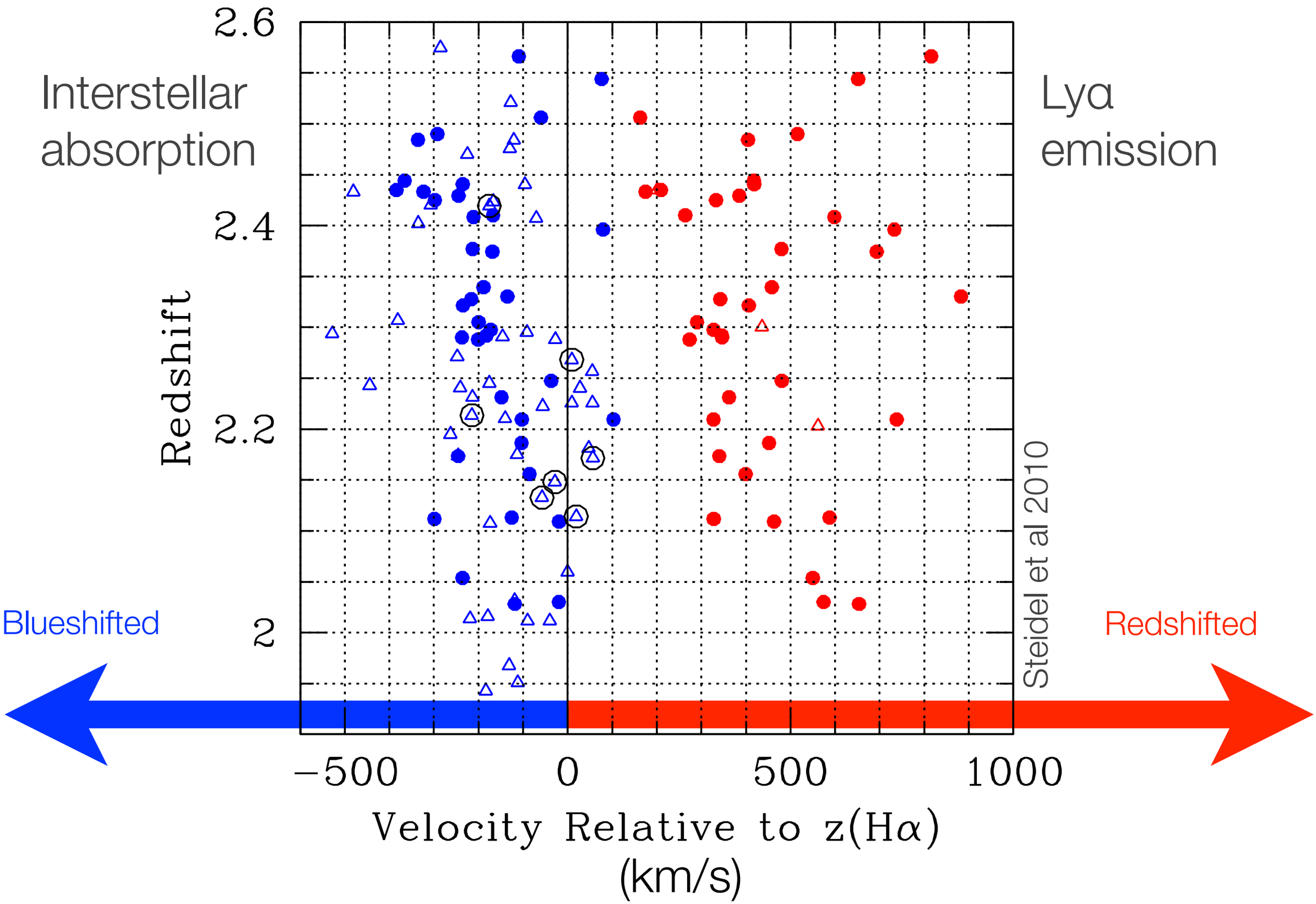
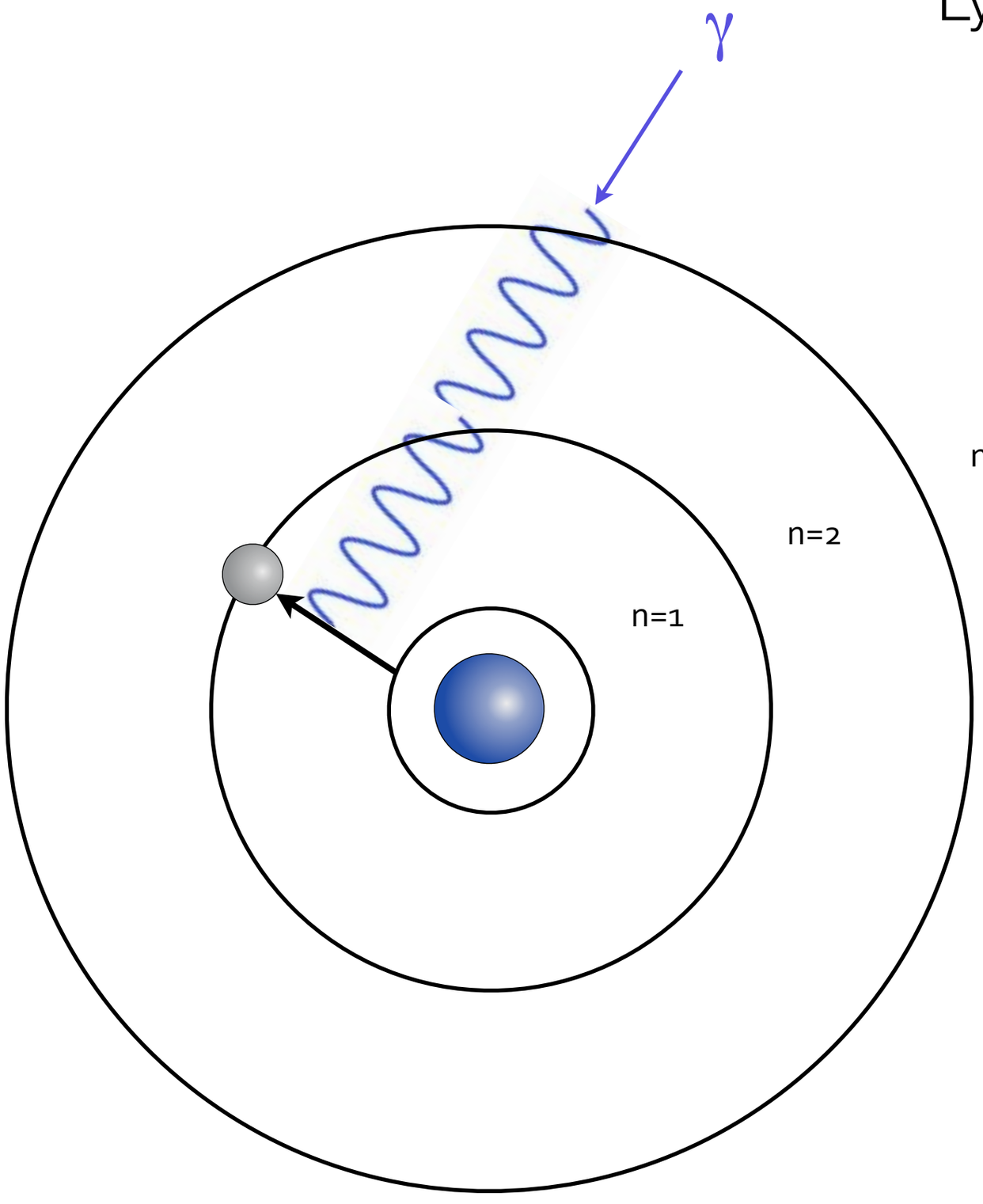


Doppler shifts of emission and absorption lines



Lyα and Resonant Scattering



Lyα : n=2 to n=1 transition of neutral H, 121.5 nm

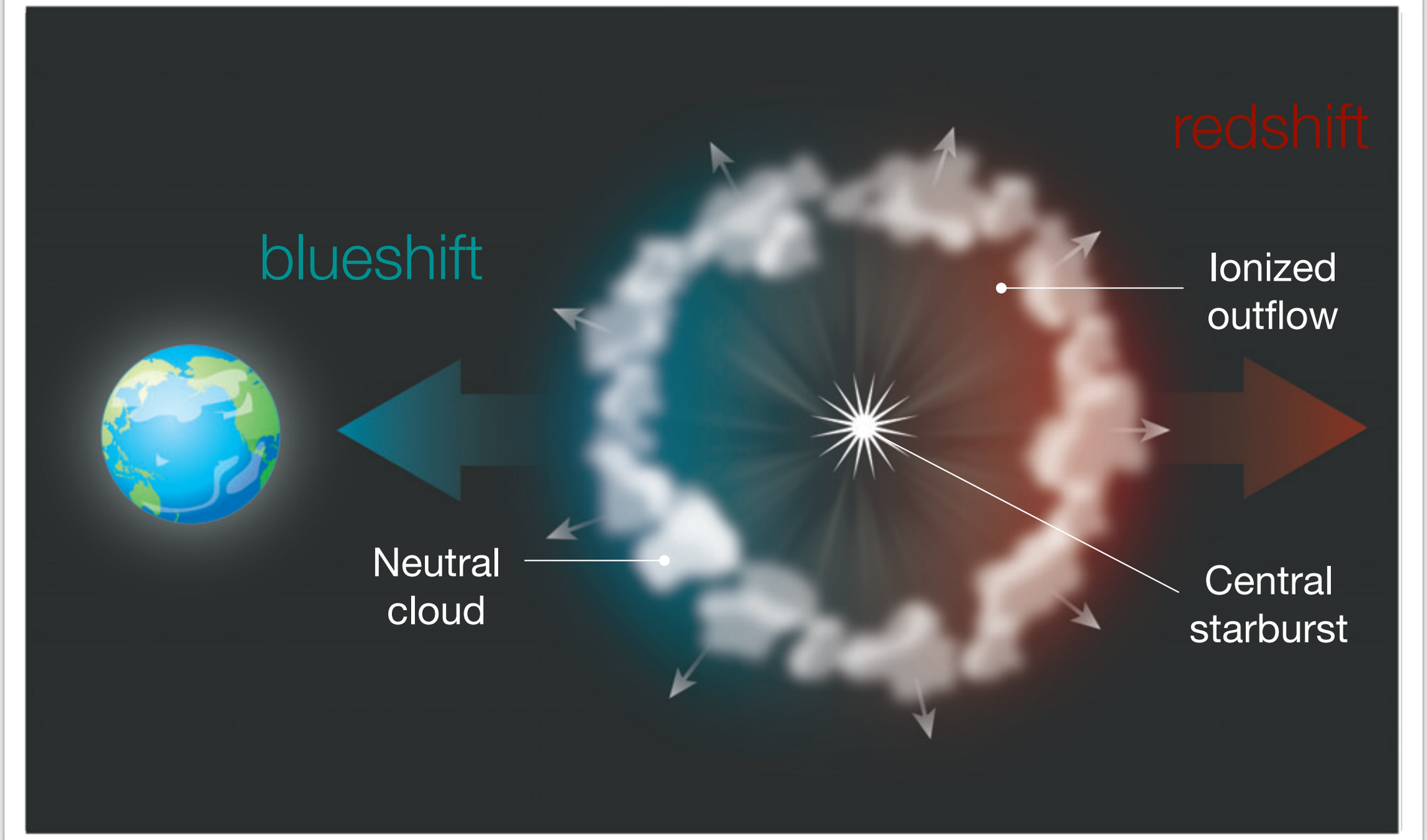
Neutral hydrogen in or near galaxies absorbs and re-emits Lyα photons

Re-emitted photons have Doppler shift due to the velocity of the atom

Result is scattering of the photon, in both space and wavelength: resonant scattering

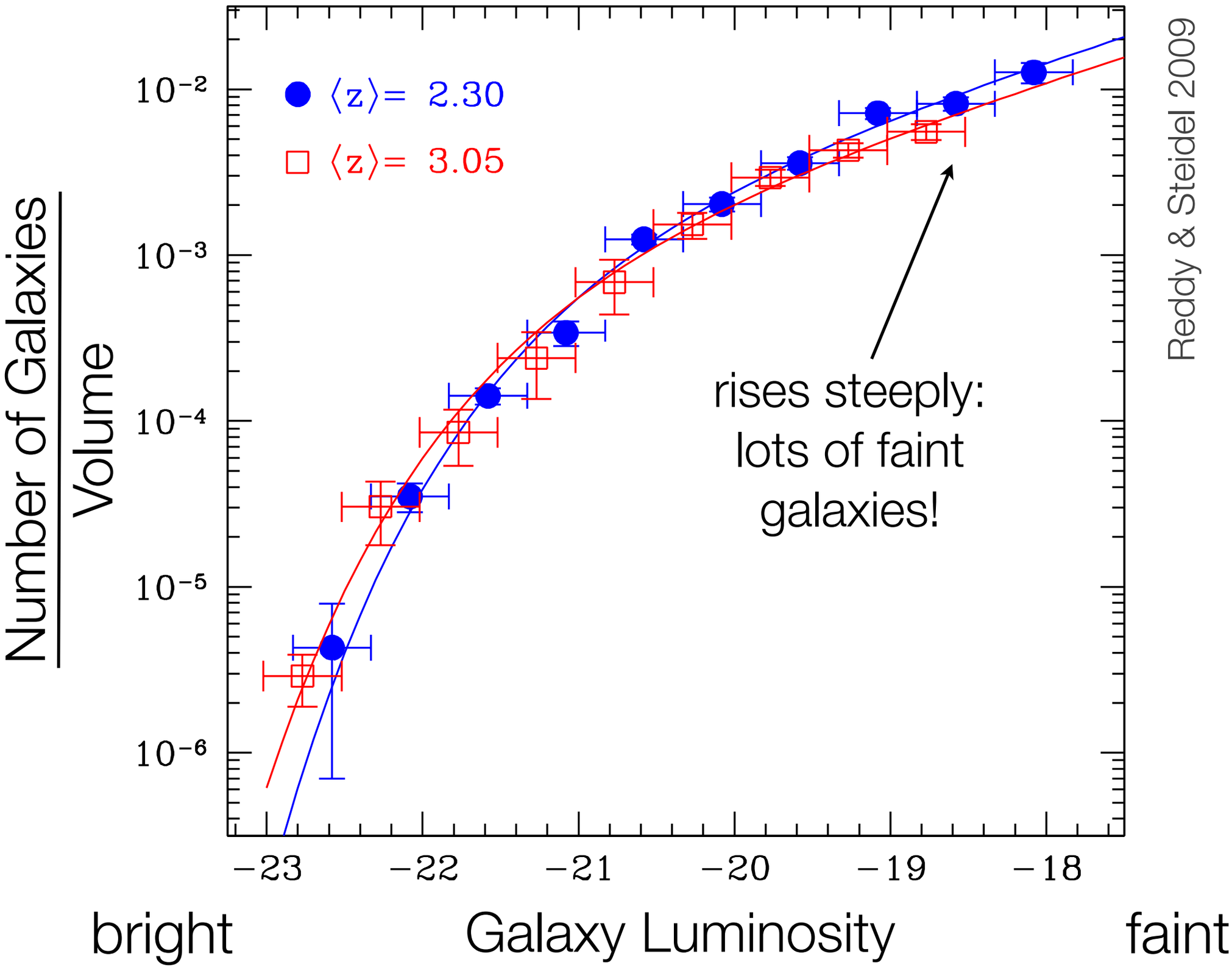
Measuring Doppler shifts of photons then reveals velocity structure in the absorbing gas

Most galaxies are starburst galaxies



Erb 2015

The importance of faint galaxies



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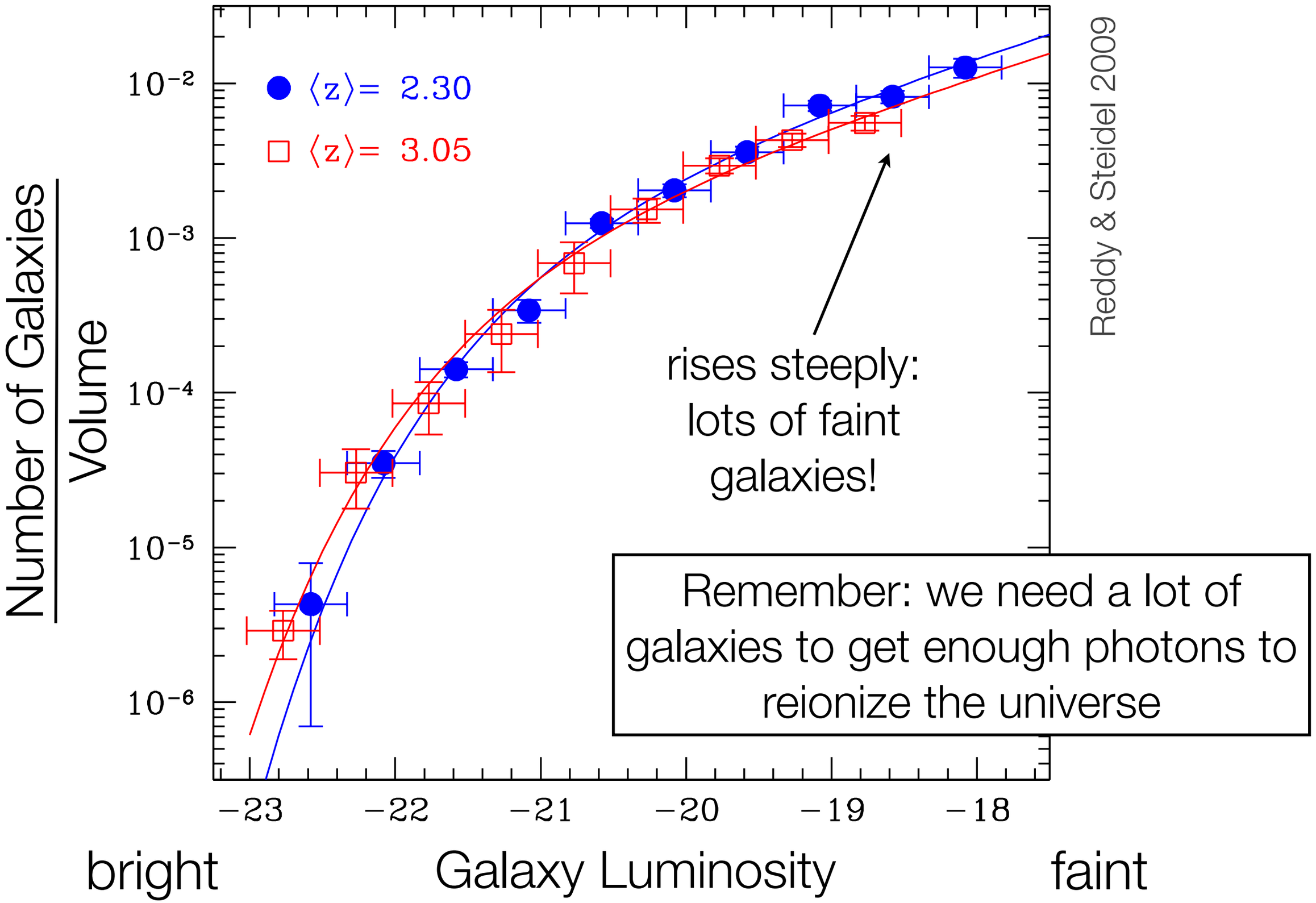
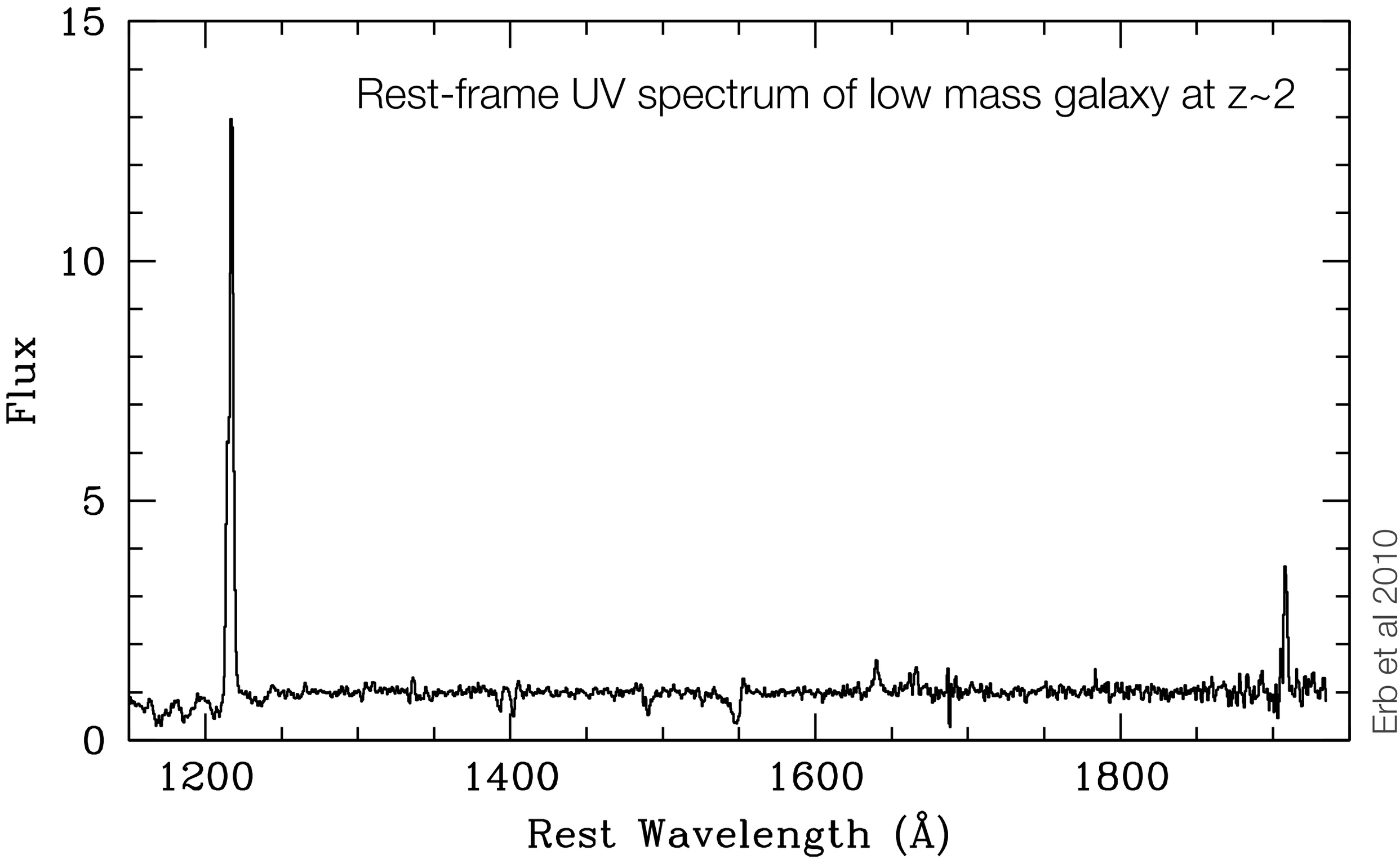


Properties of faint, low mass galaxies



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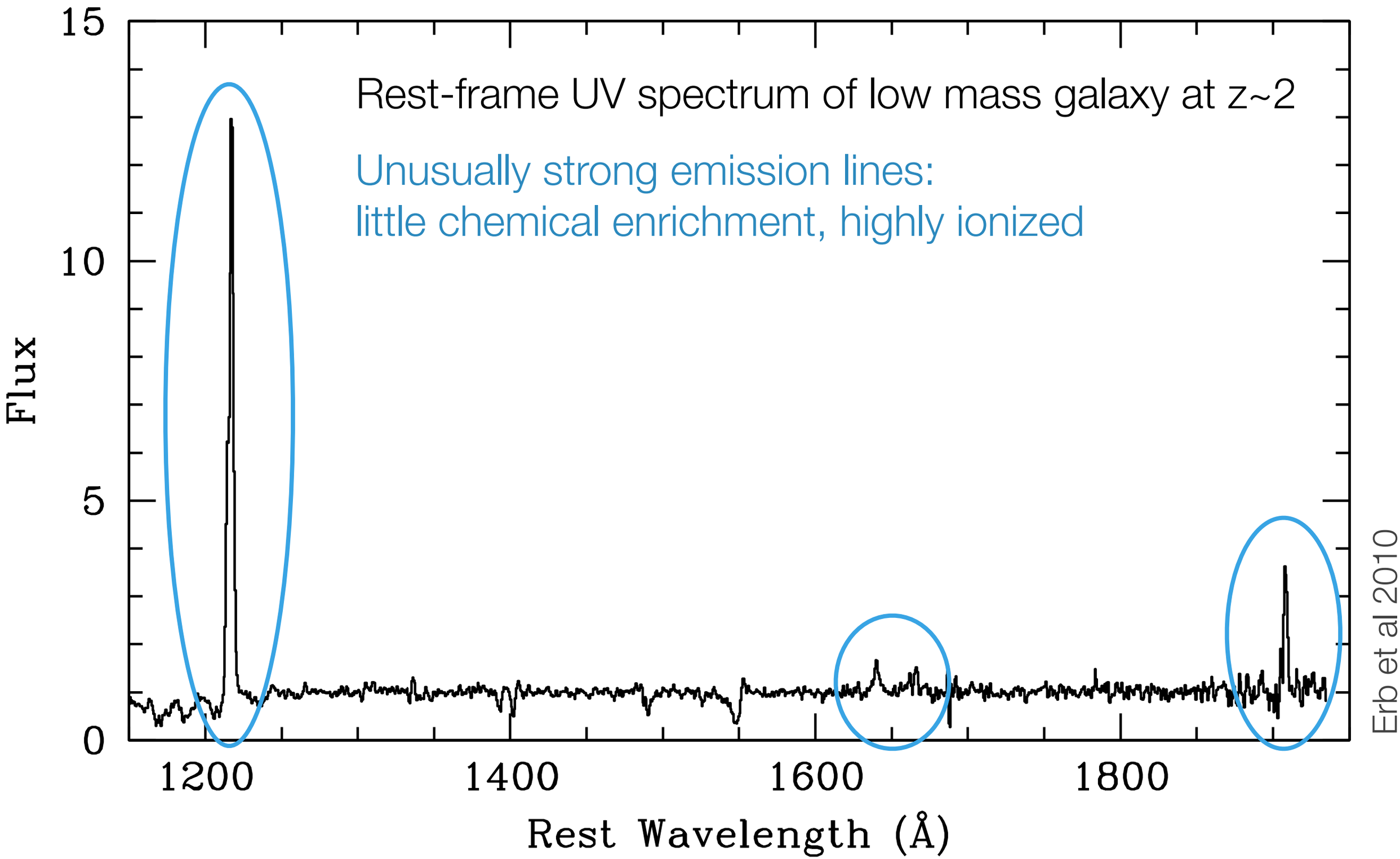

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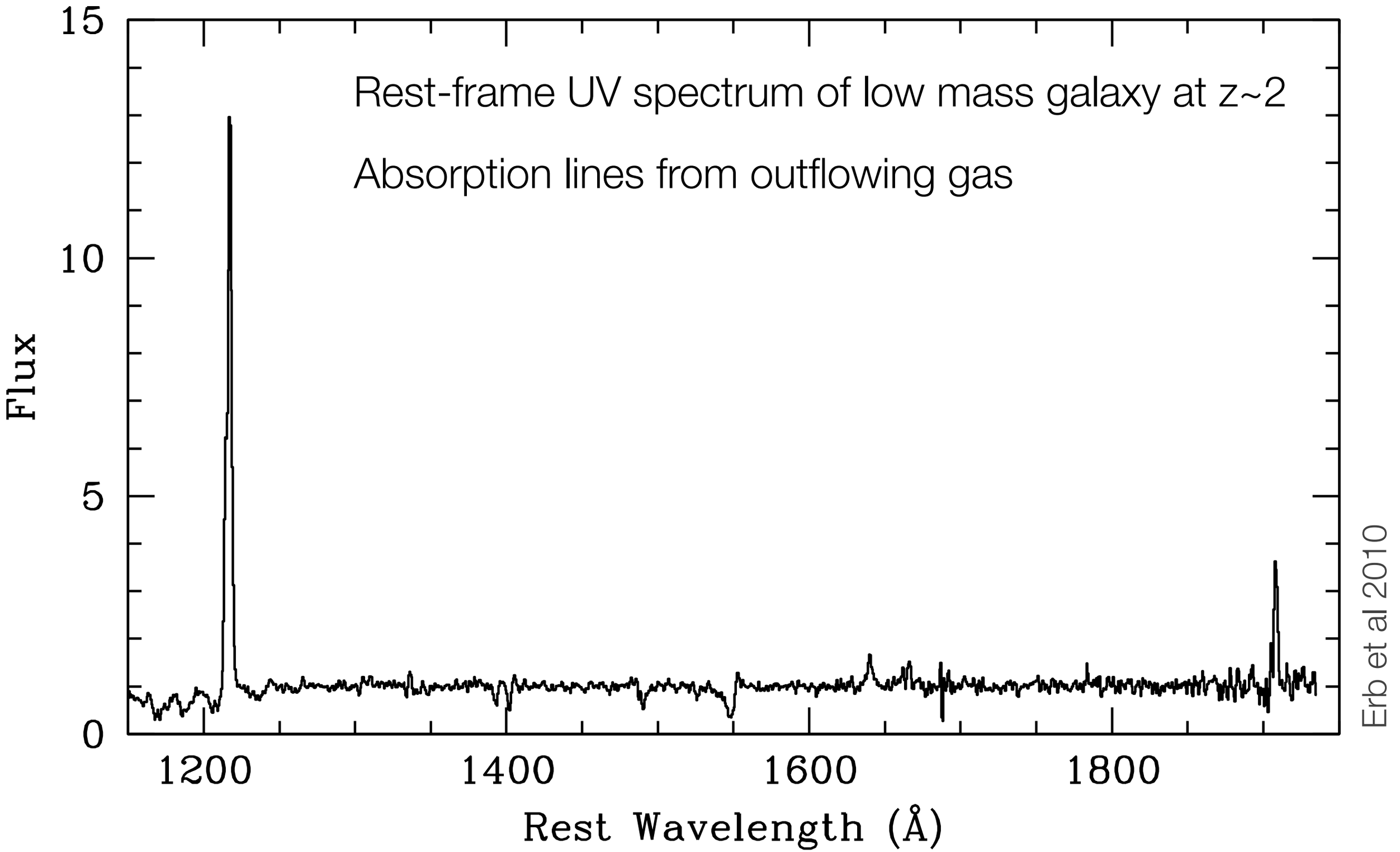

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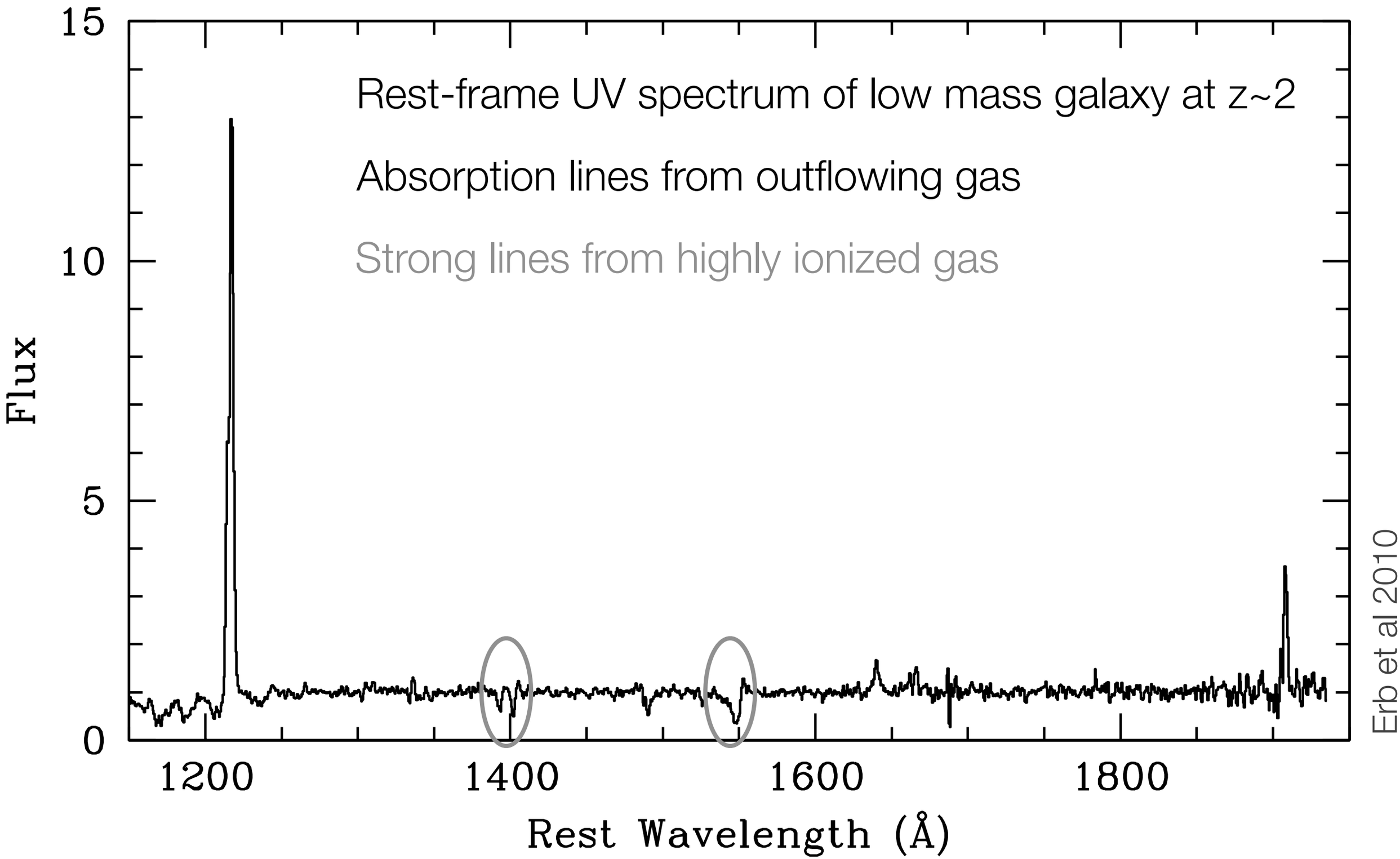

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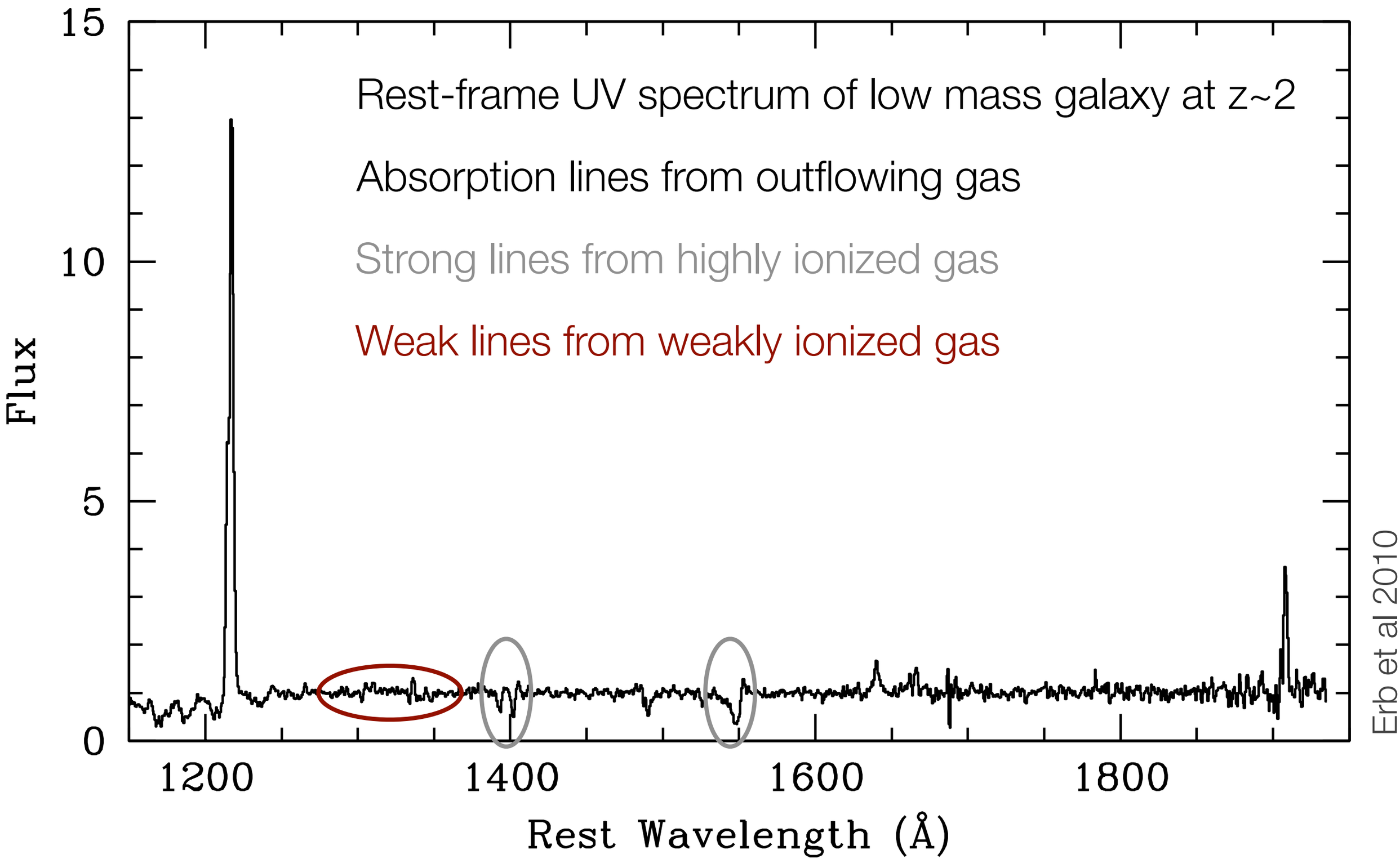
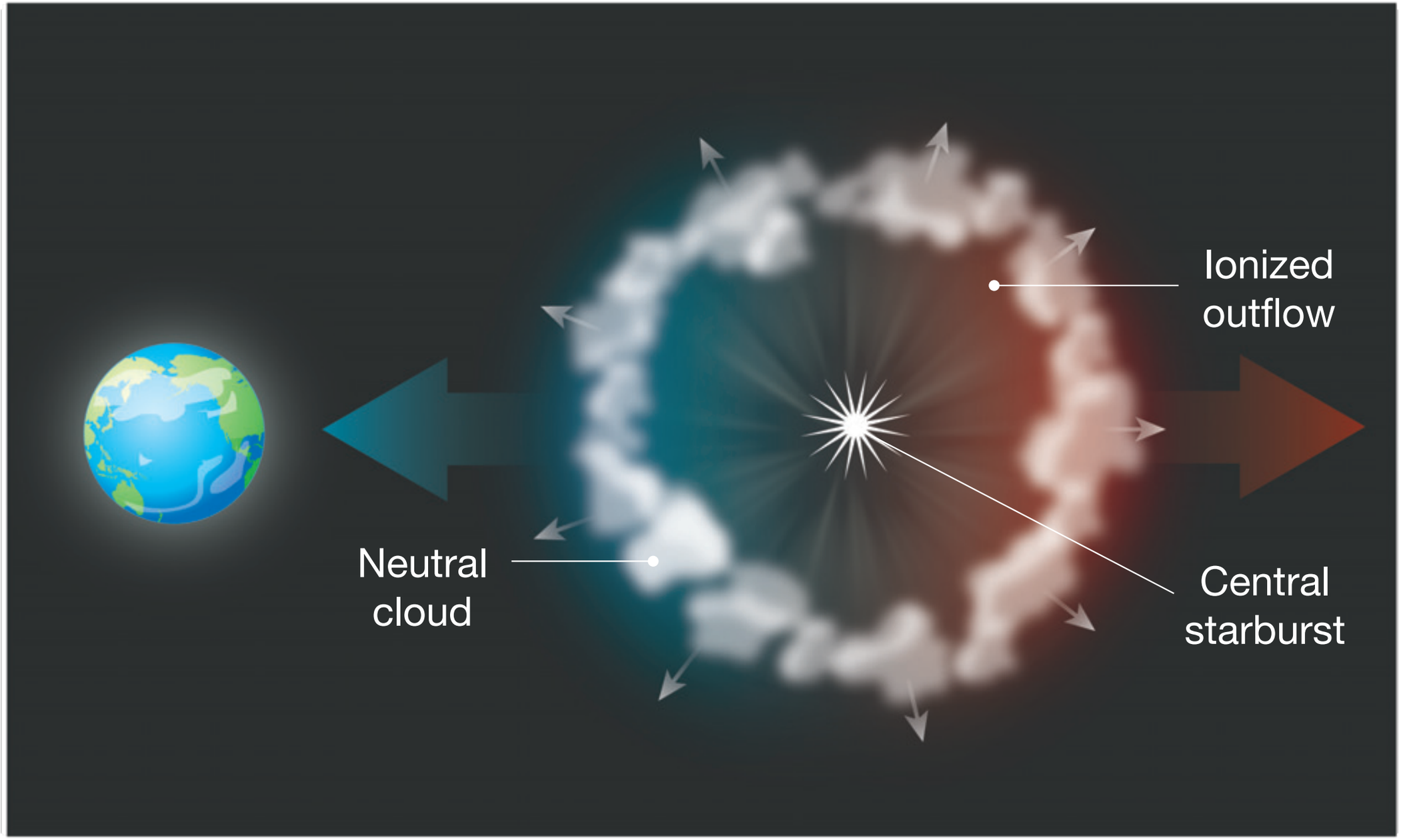
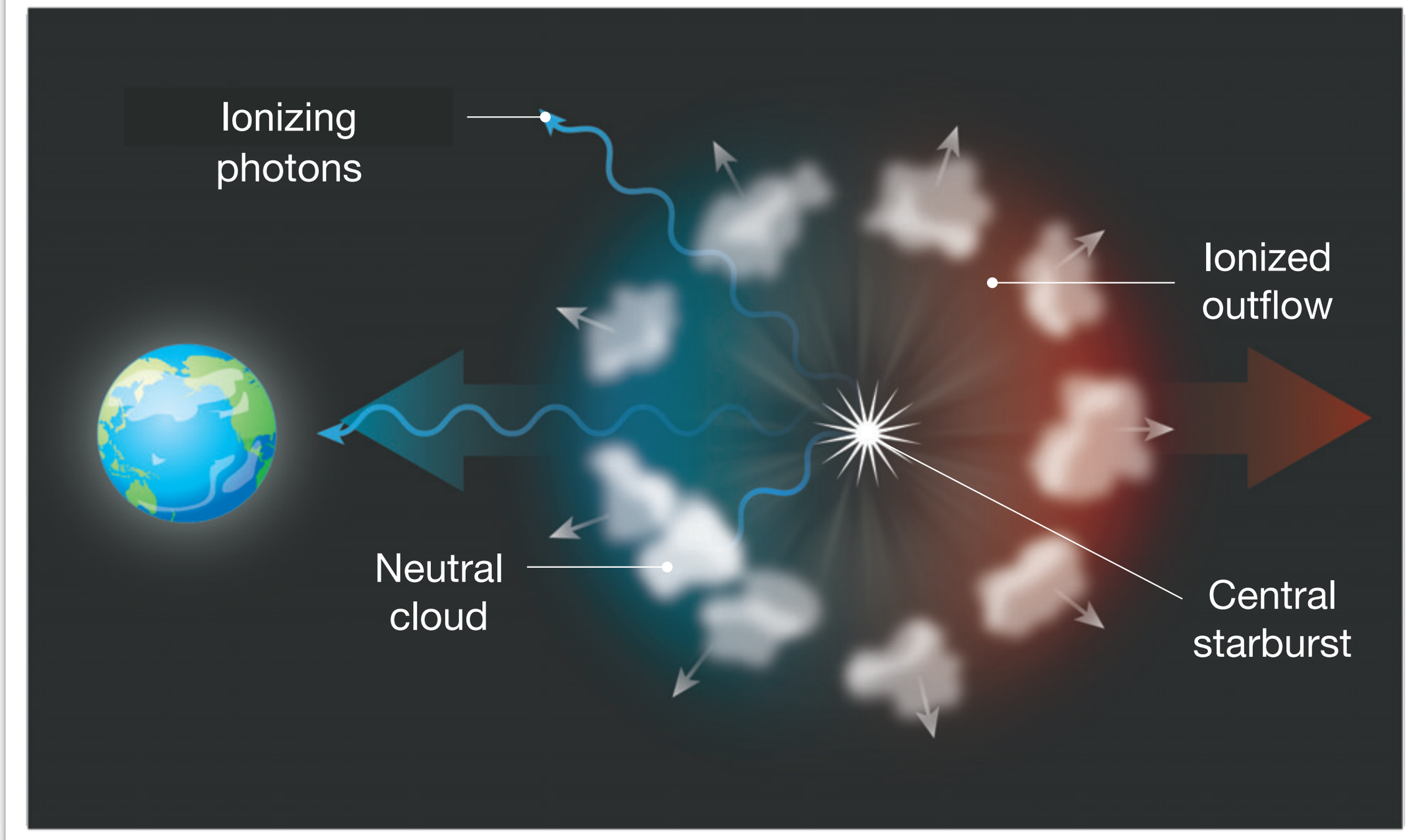


Most galaxies are starburst galaxies



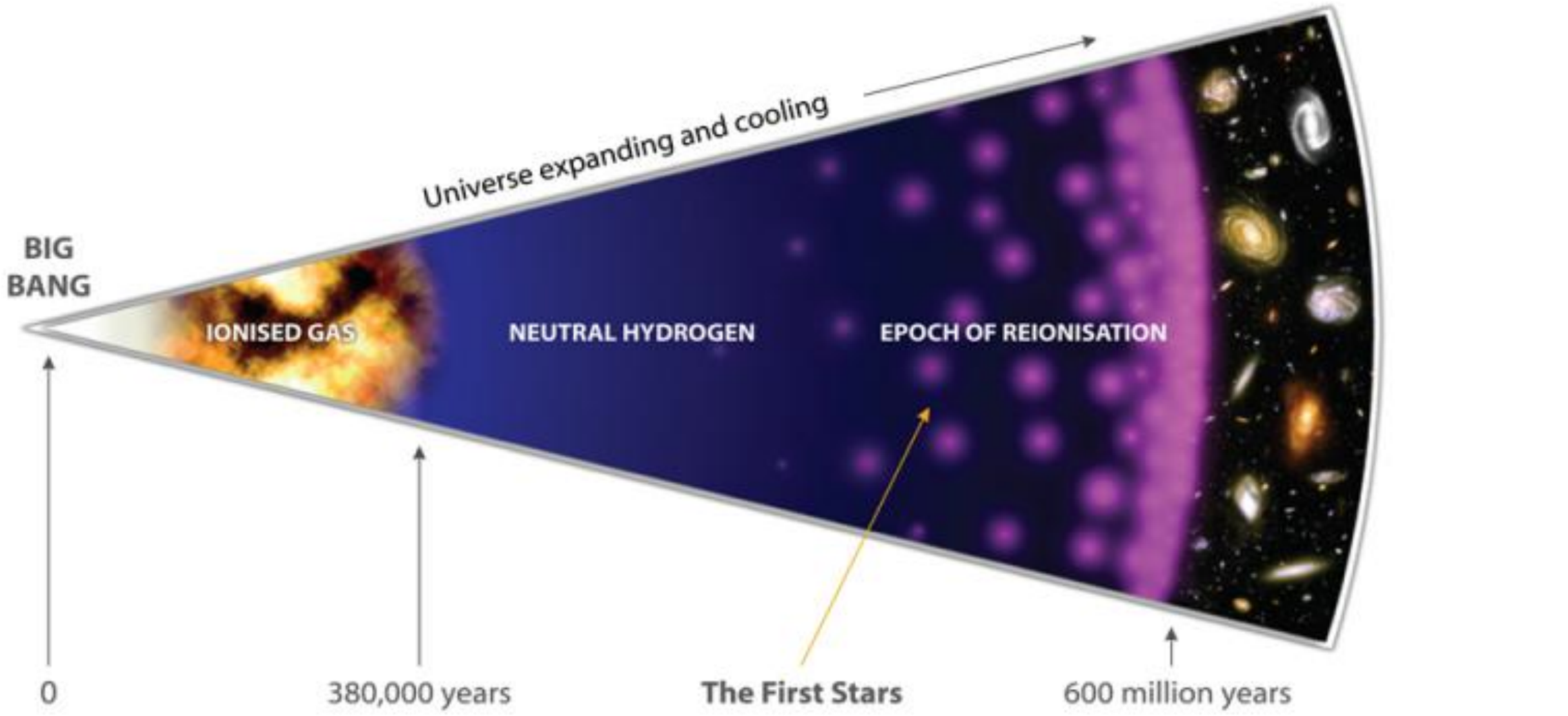
Erb 2015

Outflows in faint galaxies

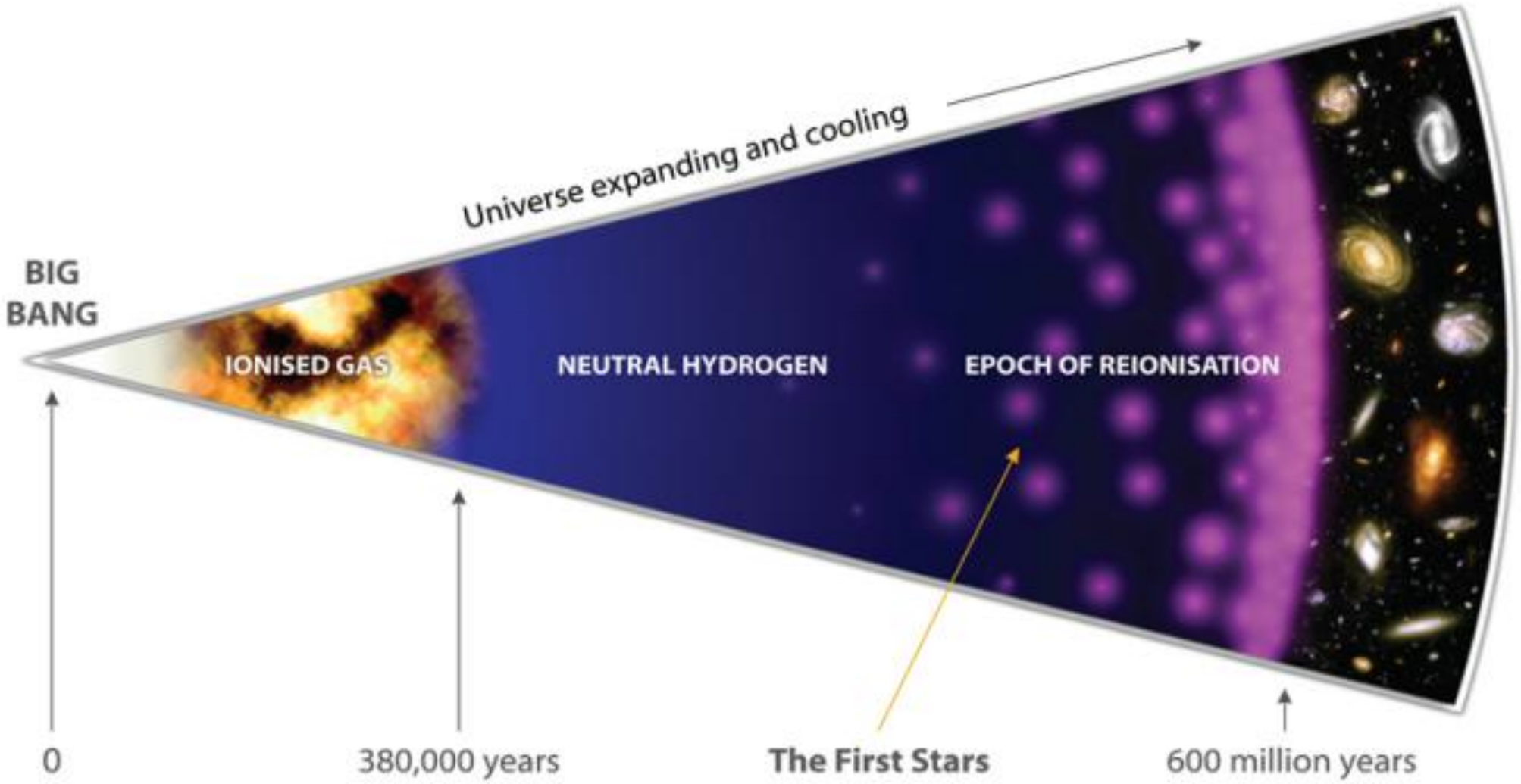


Erb 2015

Summary


Universe expanding and cooling
BIG BANG
IONISED GAS
NEUTRAL HYDROGEN
EPOCH OF REIONISATION
0
380,000 years
The First Stars
600 million years

Summary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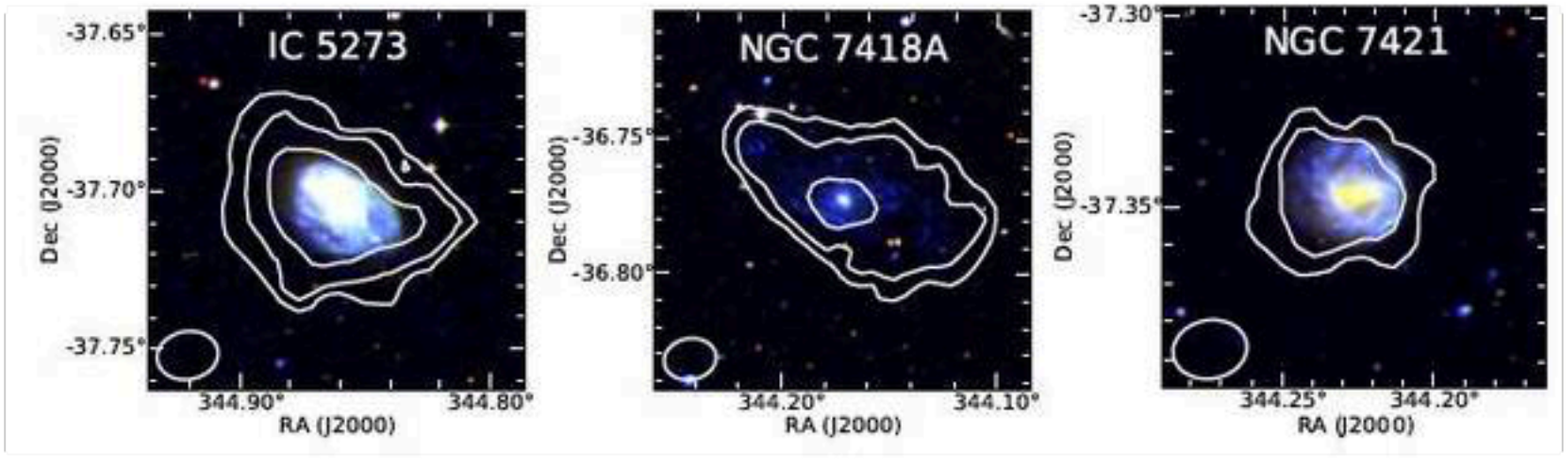
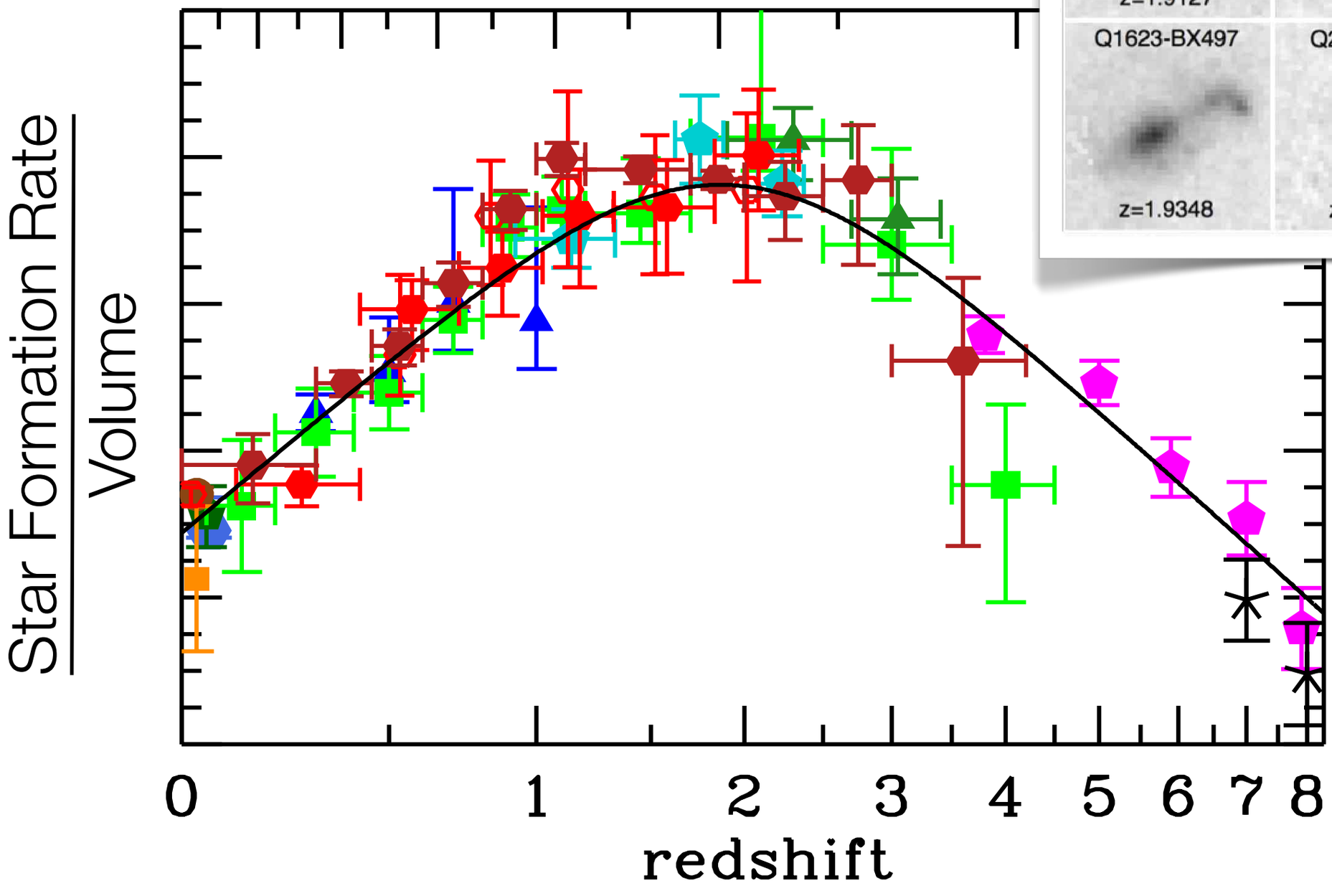
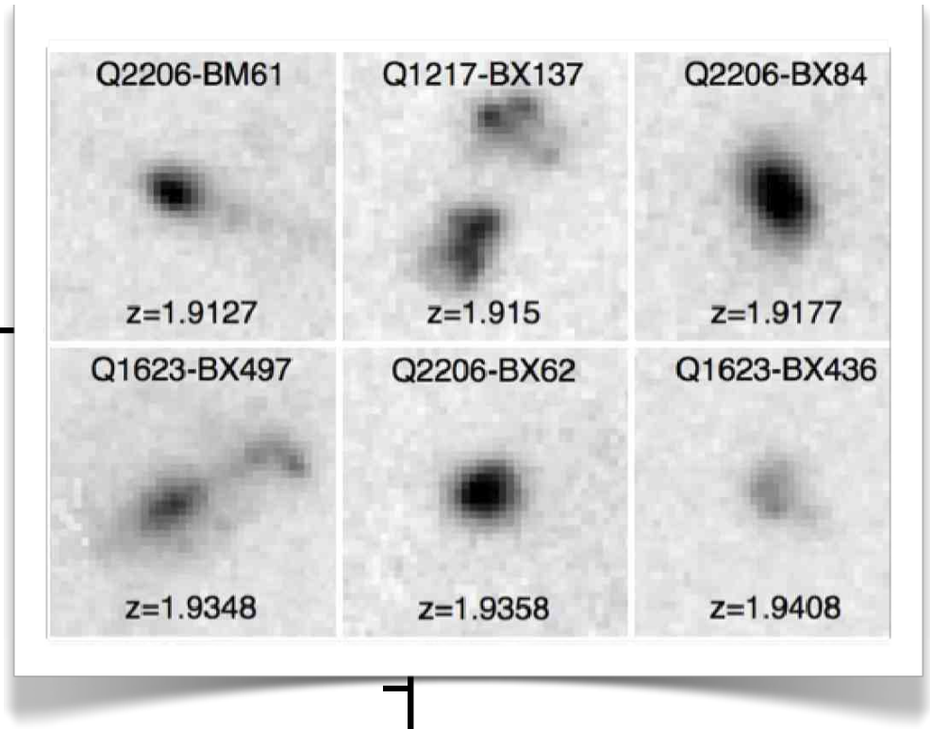
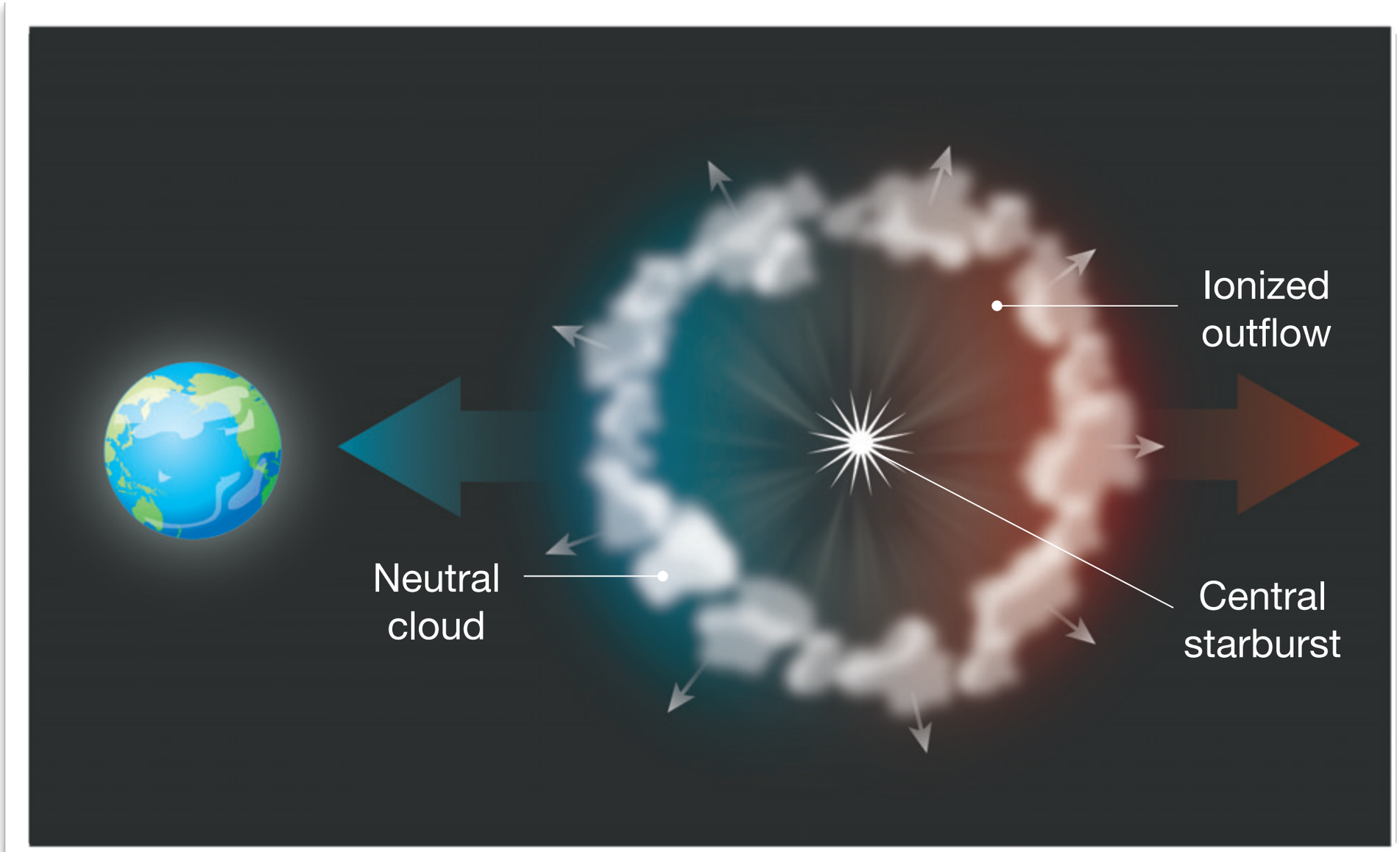

IC 5273
-37.65°
-37.70°
-37.75°
Dec (J2000)
344.90°
344.80°
RA (J2000)
NGC 7418A
-36.75°
-36.80°
Dec (J2000)
344.20°
344.10°
RA (J2000)
NGC 7421
-37.30°
-37.35°
Dec (J2000)
344.25°
344.20°
RA (J2000)

Summary


Star Formation Rate
Volume
0
1
2
3
4
5
6
7
8
redshift


Q2206-BM61
z=1.9127
Q1217-BX137
z=1.915
Q2206-BX84
z=1.9177
Q1623-BX497
z=1.9348
Q2206-BX62
z=1.9358
Q1623-BX436
z=1.9408

Summary



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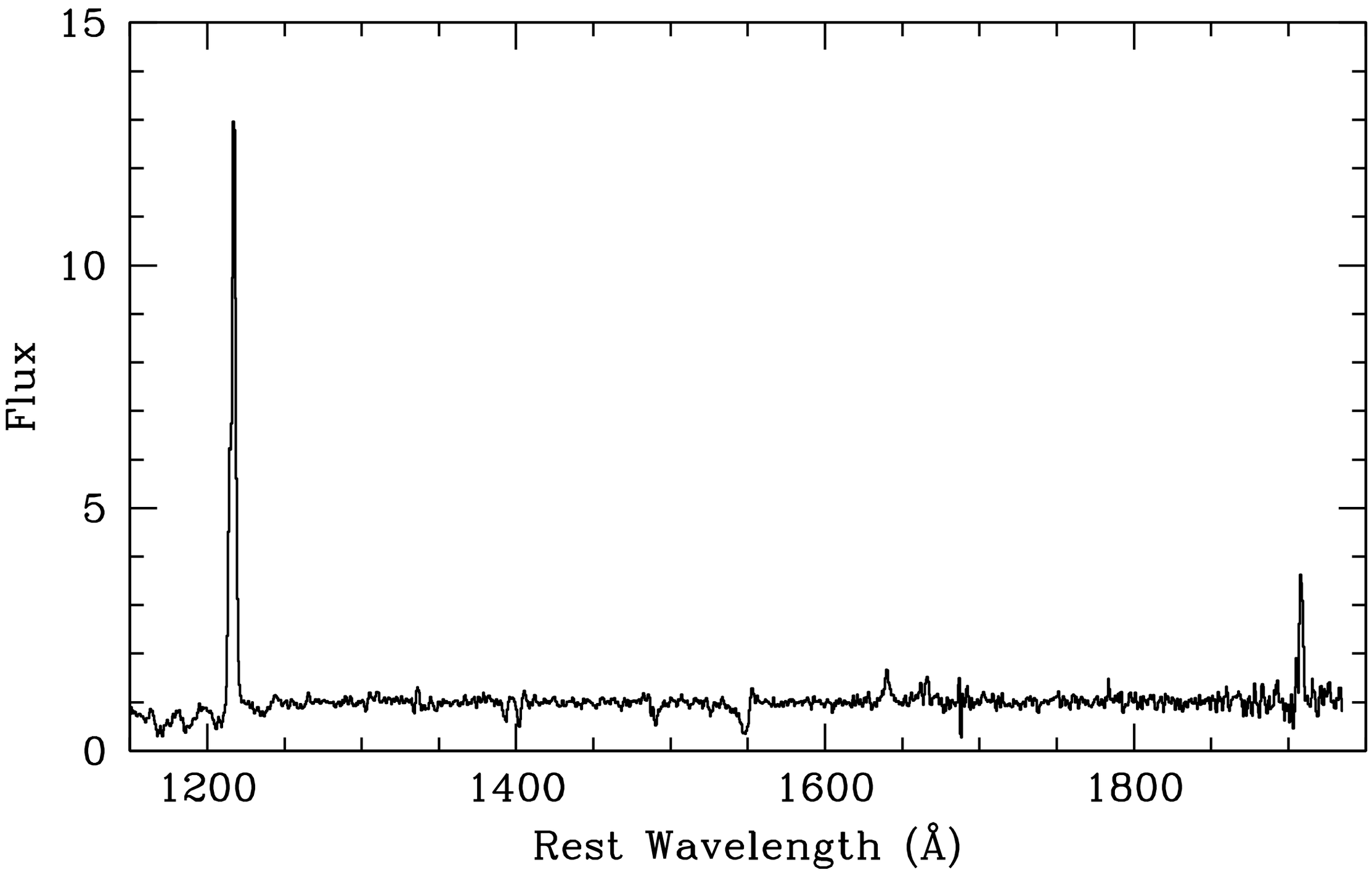

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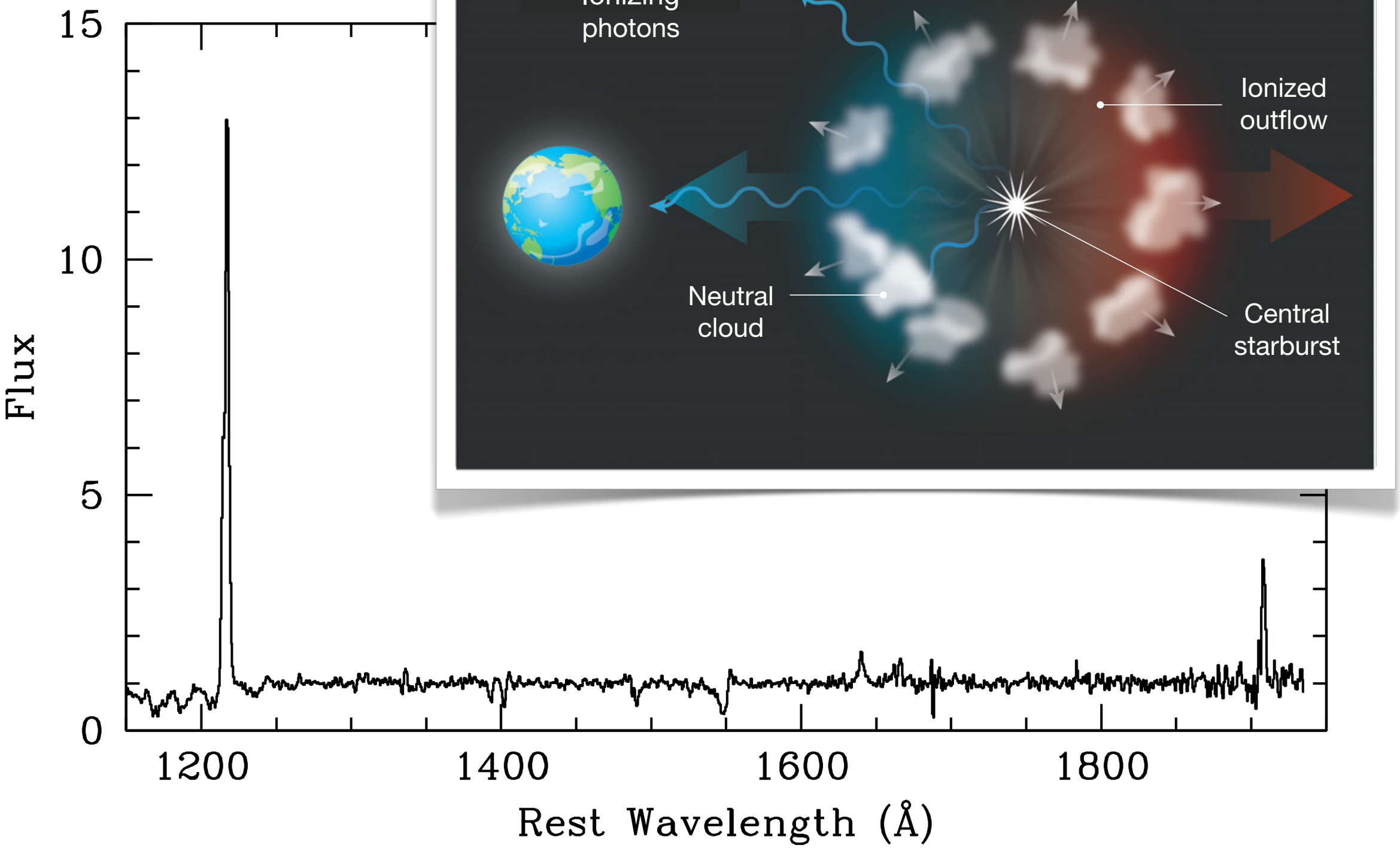
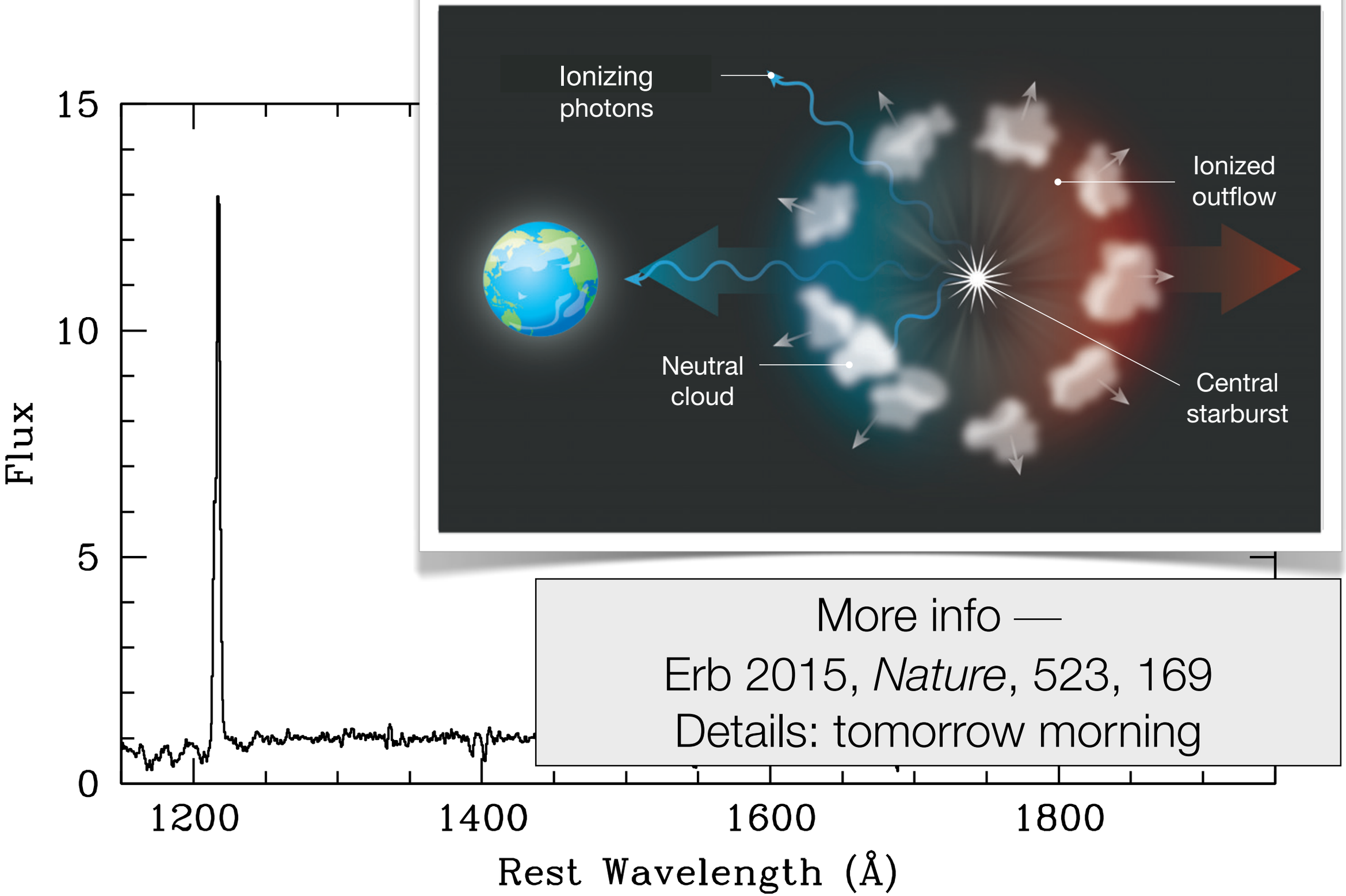

Ionizing photons
Ionized outflow
Neutral cloud
Central starburst
15
10
5
0
Flux
1200
1400
1600
1800
Rest Wavelength (Å)

Summary


15
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More info —
Erb 2015, *Nature*, 523, 169
Details: tomorrow morning