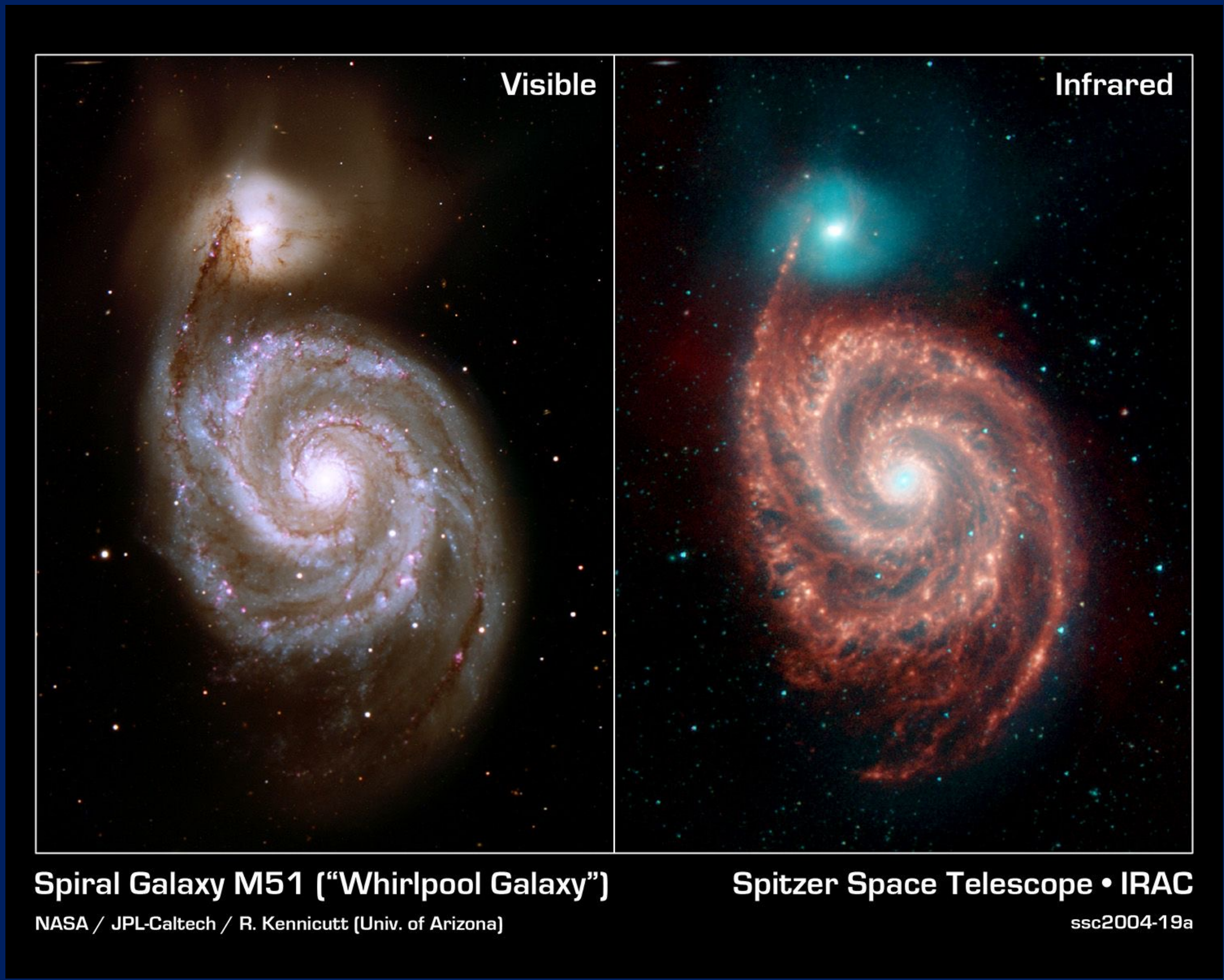
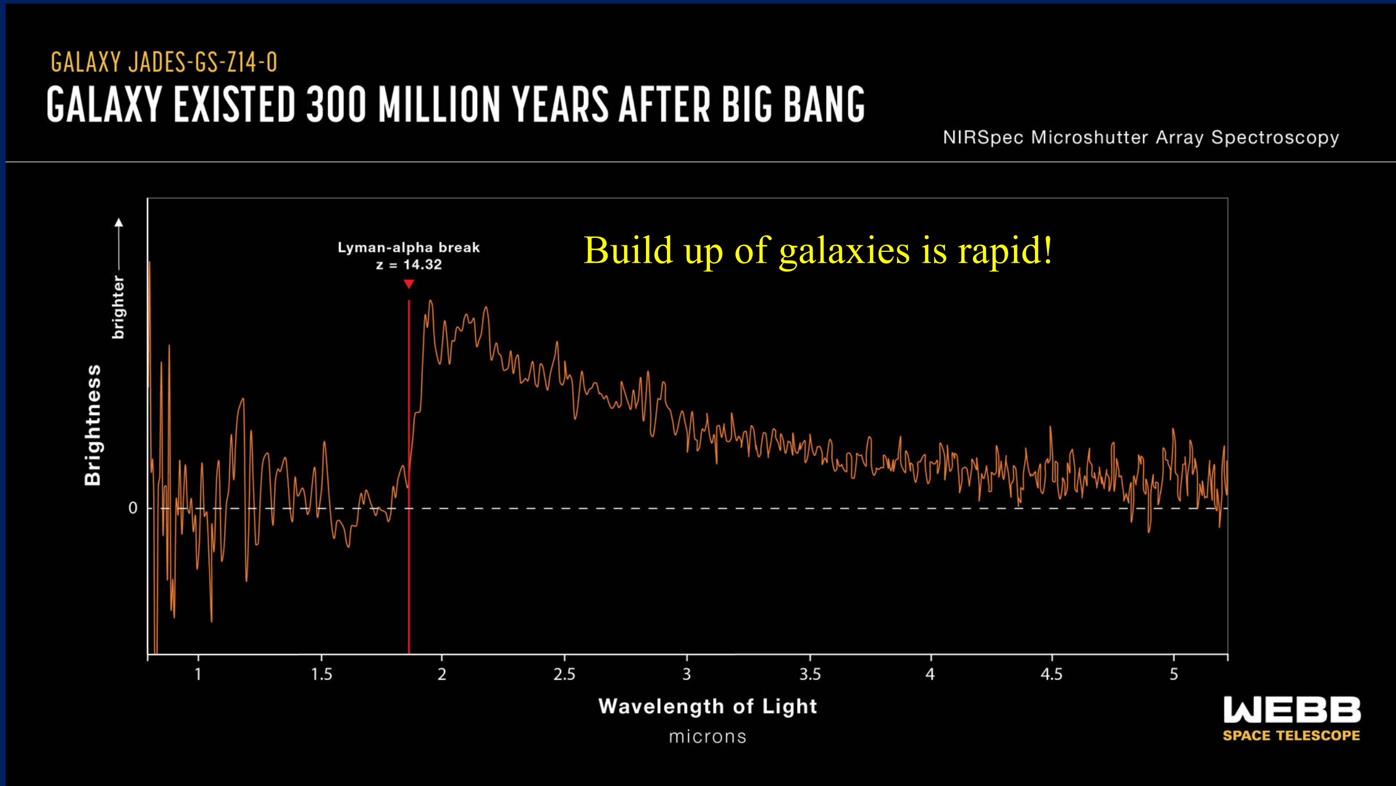
Extragalactic Star Formation



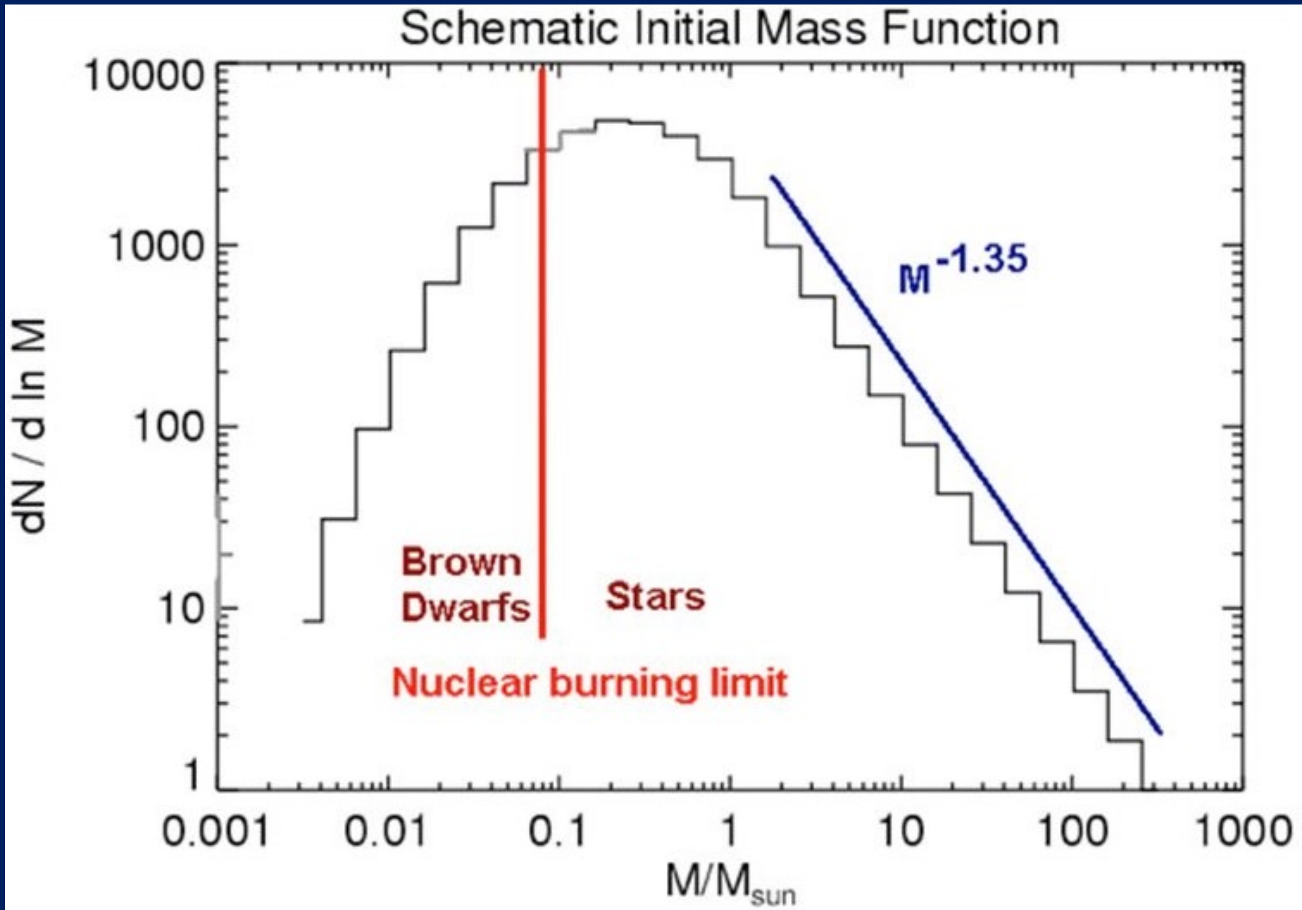
A Galaxy at z=14.2 Forming Massive Stars



- Stars dominate UV luminosity.
- Oxygen observed with ALMA facility.

Jades Collaboration (2024)

Differences between high-z Star Formation and MW Star Formation



MW: 0.01 – 100 M_{sun}
Characteristic Mass: 0.7 M_{sun}

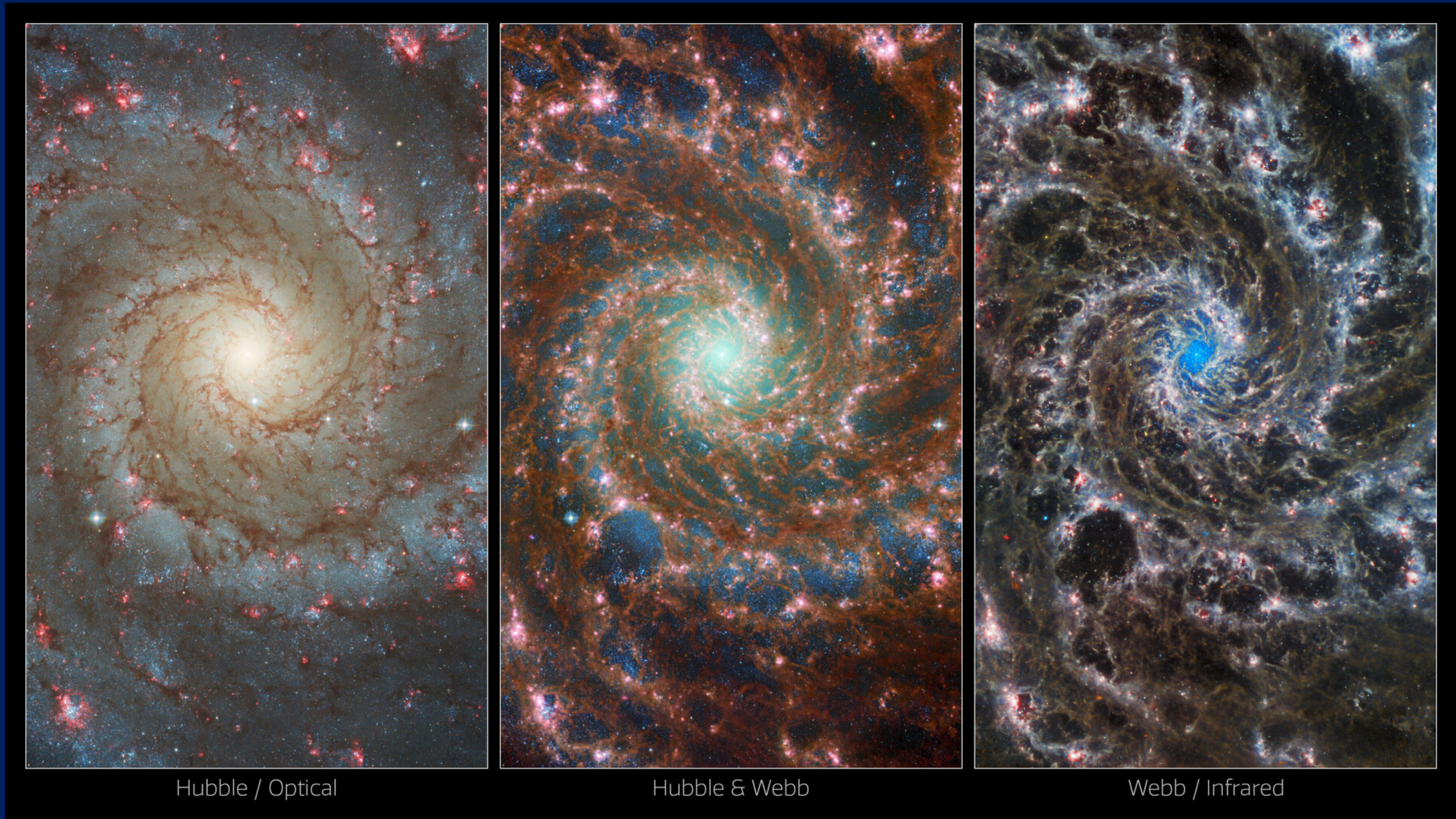
Early Universe:

20 – 600 M_{sun}
Characteristic Mass: 100 M_{sun}

Values are highly uncertain (fragmentation)

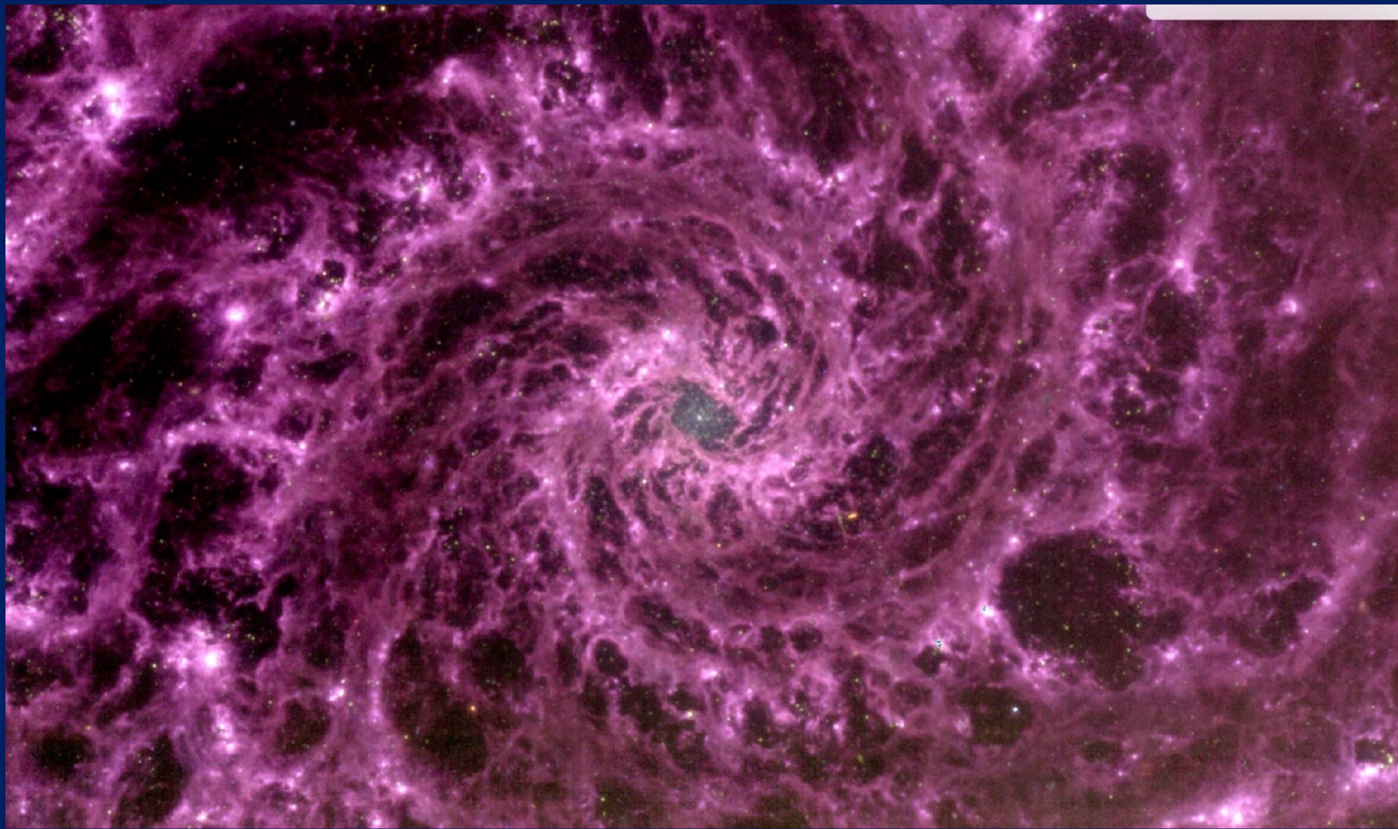
Argument: Less cooling, Higher Temperatures, Higher Jeans Mass

Extragalactic Star Formation



M74 – Phantom Galaxy (PHANGS program) – Grand Design Galaxy

MIRI/JWST Image of NGC 628 - M 74



Bubbles & Hierarchical Filament Structure – Stellar Clusterin Centre
19 galaxies with star formation: HST/JWST - PHANGS Collaboration
(ApJL 944, 2023); Hoyer et al. (2023)

Extragalactic Star Formation Quantities

- We only „see“ short-lived massive star formation (duration different for diff. measures)
- SFR – Rate (Mass per year, often also per area- SFR density)
- SFR/Mstar – Specific star formation rate
- SFH - History of SF (continuous/steady state; instantaneous)
- SFE - Efficiency of conversion of gas mass in stars

- How to measure SFR and to determine the SF history?
- Where is SF taking place in a galaxy?
- What triggers star formation?

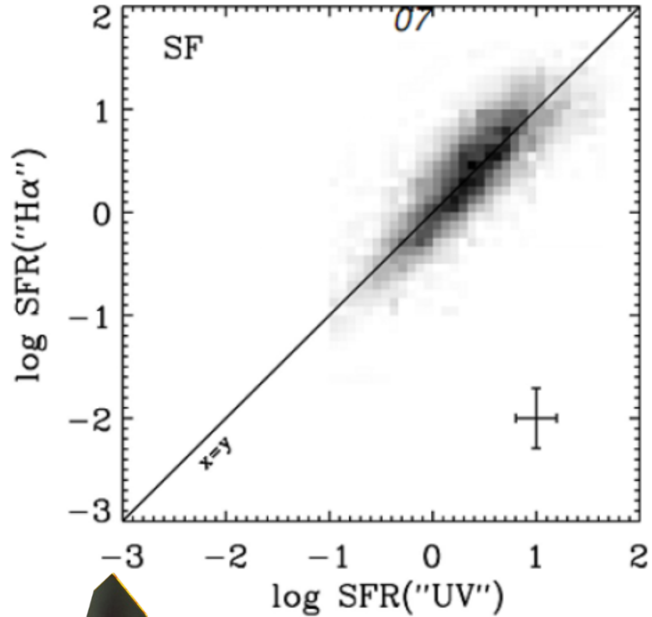
Bottom-up ΛCDM structure formation model: Primordial density fluctuations grow by gravitational instability driven by cold (collisionless) dark matter. Merger events.

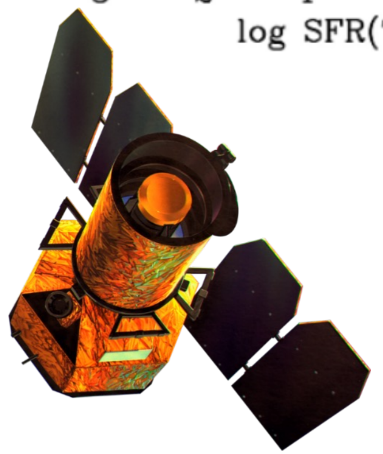
Star Formation Tracers

- Population Synthesis Models to determine colours & spectra (IMF, metallicity, SF history, age)

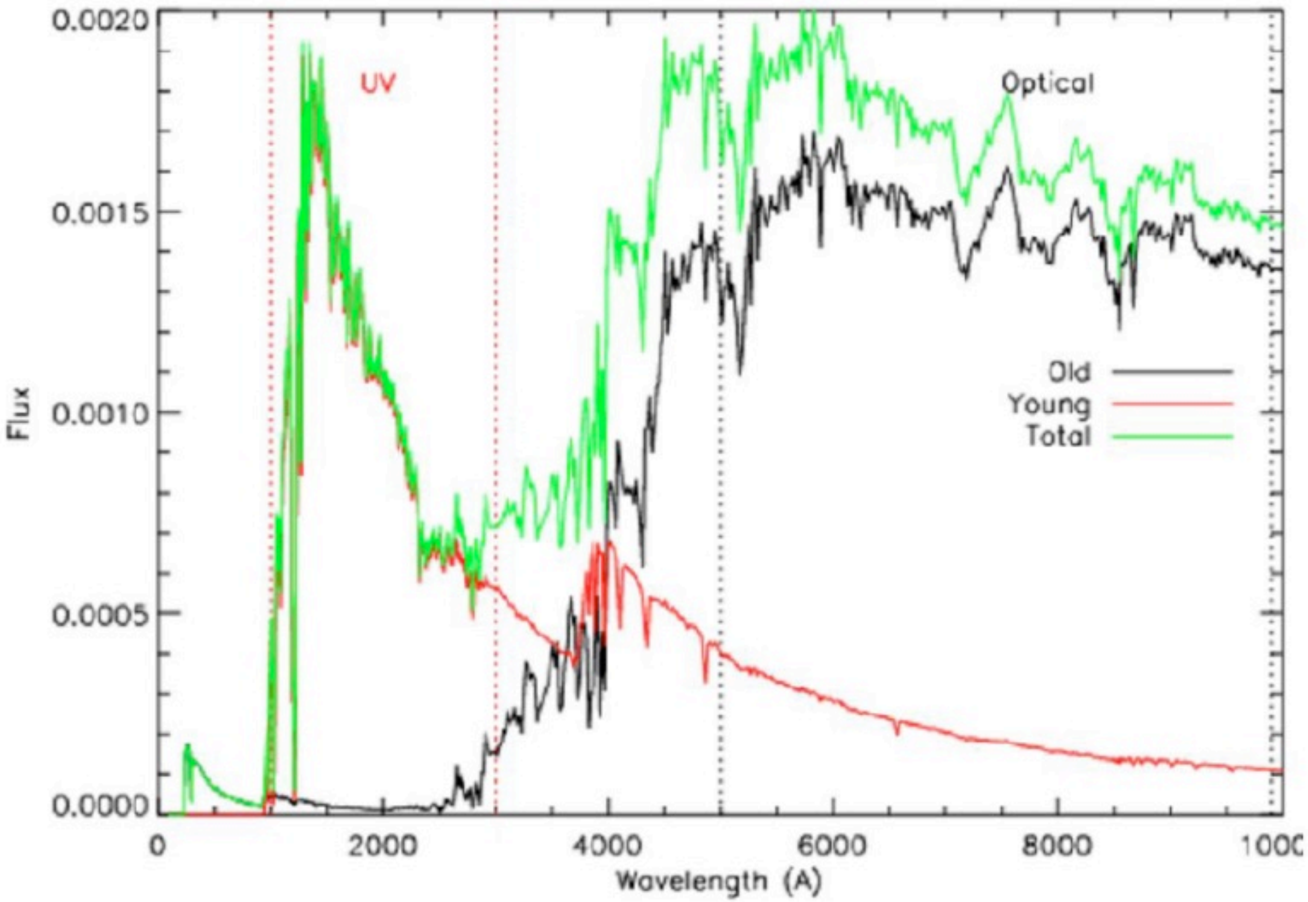
- UV continuum: SFR ~ L(UV) (massive short-lived stars)
  [Extinction + IMF] (GALEX – UV galaxy L function)
- Recombination Lines: SFR ~ L(Hα)
  [Extinction + IMF] (Short-lived O stars – 20 Myr)
- Forbidden lines
- Far-infrared Continuum
  (Dust distribution)
- Radio Continuum [Contributions from AGN and old stars]
  (Thermal vs. Non-thermal radiation)

Salim et al. 07

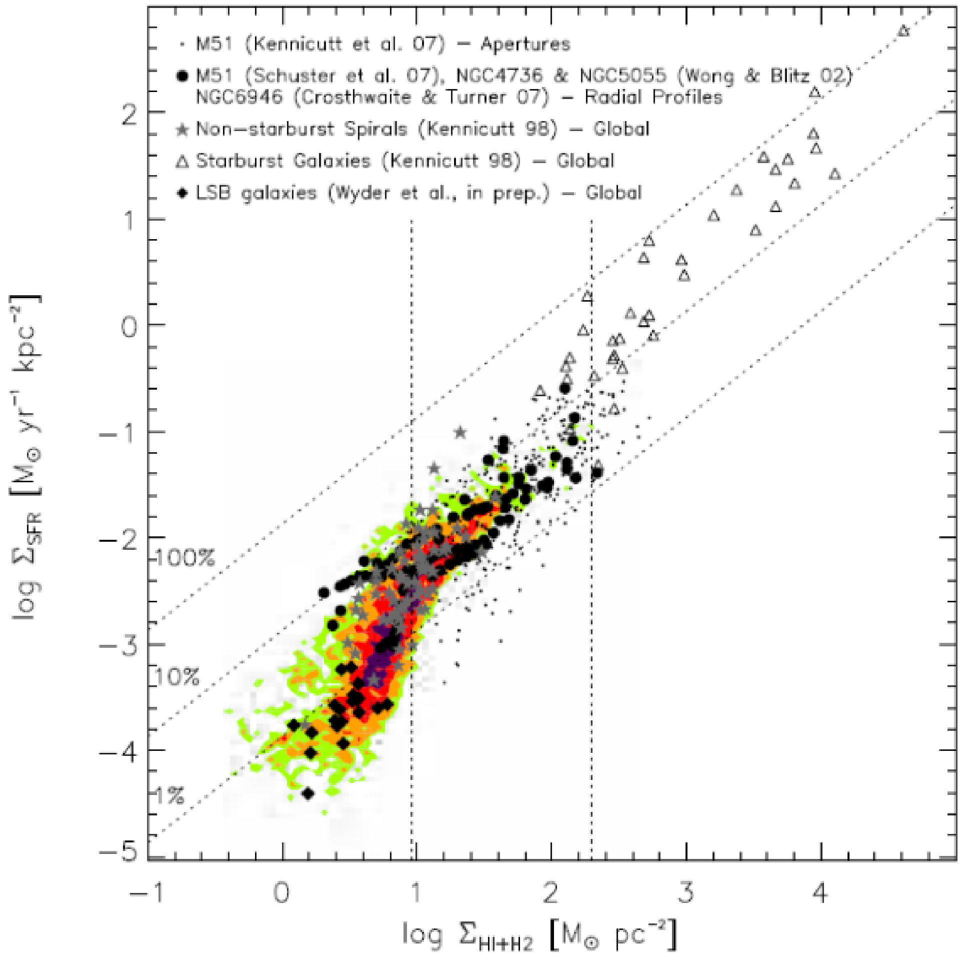




UV as Star Formation Measure



Kennicutt-Schmidt Relation



Bigiel et al. (2009)

Kennicutt-Schmidt Relation

Empirical derived index: Roughly 1.5

How can we understand this?

$\Sigma_{SFR} \sim \varepsilon\, \Sigma_{gas}\ (G\, \rho_{gas})^{1/2}$ (timescale of the conversion of gas = free-fall time scale)

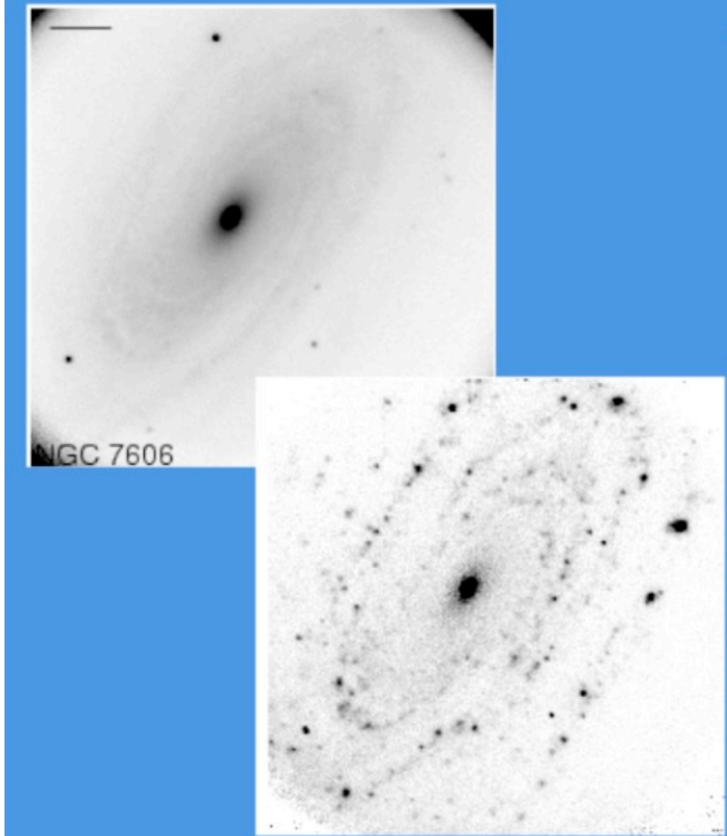
With constant gas scale height:

$\Sigma_{gas} \sim \rho_{gas}$ → This results in $\Sigma_{SFR} \sim \Sigma_{gas}^{1.5}$

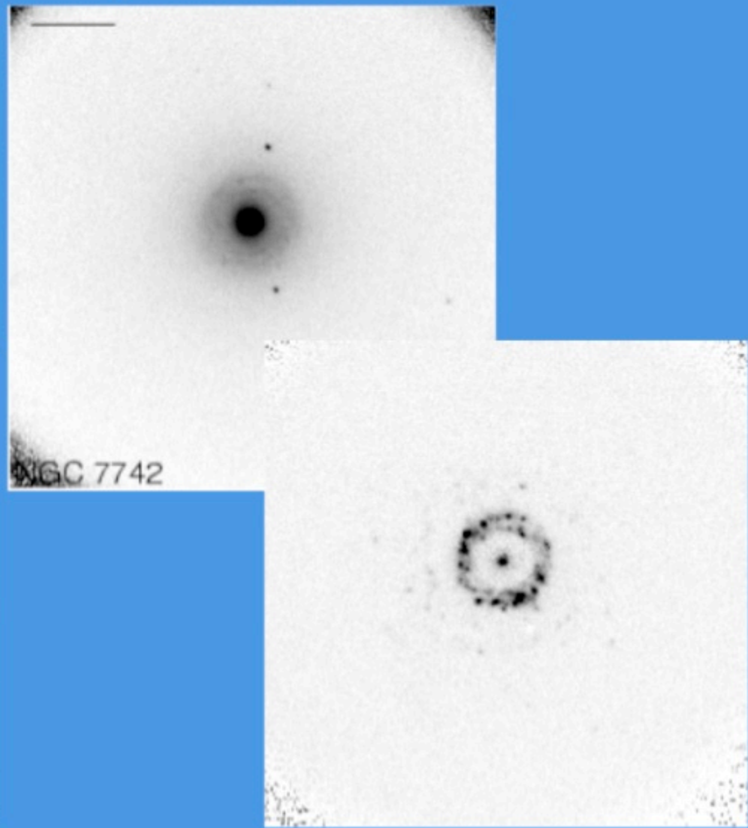
If SF is dominated by gravitational instability in disk, then only valid in this region.

Where - Global

Galactic Disks

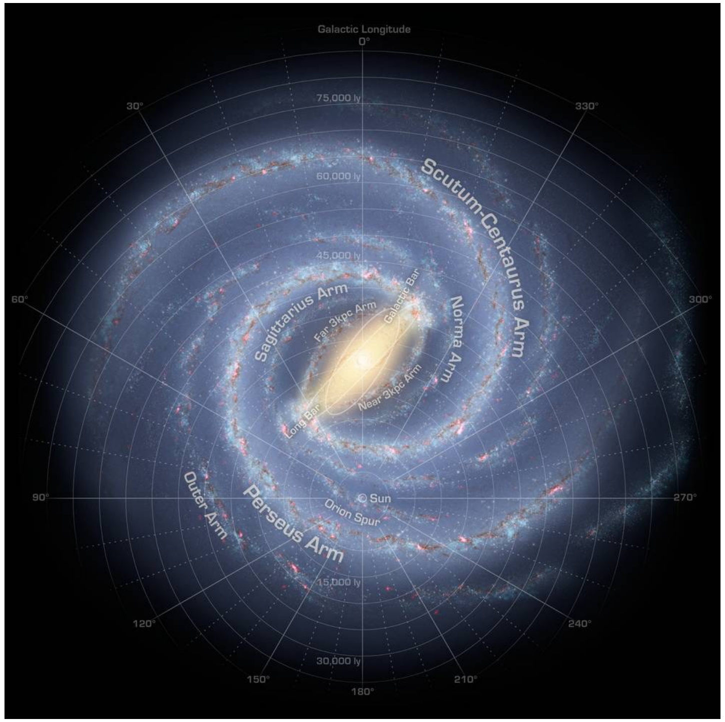


(Circum)nuclear



Star Formation in Disk Galaxies

- Star formation in spiral arms (giant molecular clouds, OB associations)
- Star formation efficiency only few percent (supersonic streaming motions)
- Star formation in circumnuclear regions globally not important
- Interactions influence SF history – in general: Gas supply



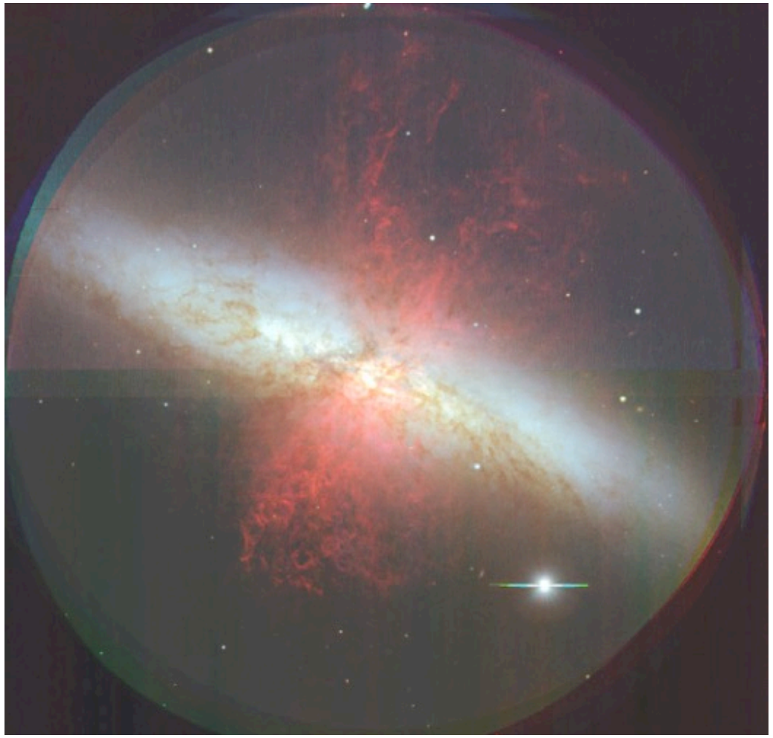
NASA/JPL

Where - Global Properties

Table 1. Star formation in disks and nuclei of galaxies

Property	Spiral disks	Circumnuclear regions
Radius	1-30 kpc	0.2-2 kpc
Star formation rate (SFR)	0-20 $M_\odot$ year^{-1}	0-1000 $M_\odot$ year^{-1}
Bolometric luminosity	10^6-10^{11} $L_\odot$	10^6-10^{13} $L_\odot$
Gas mass	10^8-10^{11} $M_\odot$	10^6-10^{11} $M_\odot$
Star formation time scale	1-50 Gyr	0.1-1 Gyr
Gas density	1-100 $M_\odot$ pc^{-2}	10^2-10^5 $M_\odot$ pc^{-2}
Optical depth (0.5 µm)	0-2	1-1000
SFR density	0-0.1 $M_\odot$ year^{-1} kpc^{-2}	1-1000 $M_\odot$ year^{-1} kpc^{-2}
Dominant mode	steady state	steady state + burst
Type dependence?	strong	weak/none
Bar dependence?	weak/none	strong
Spiral structure dependence?	weak/none	weak/none
Interactions dependence?	moderate	strong
Cluster dependence?	moderate/weak	?
Redshift dependence?	strong	?

Starburst Galaxies

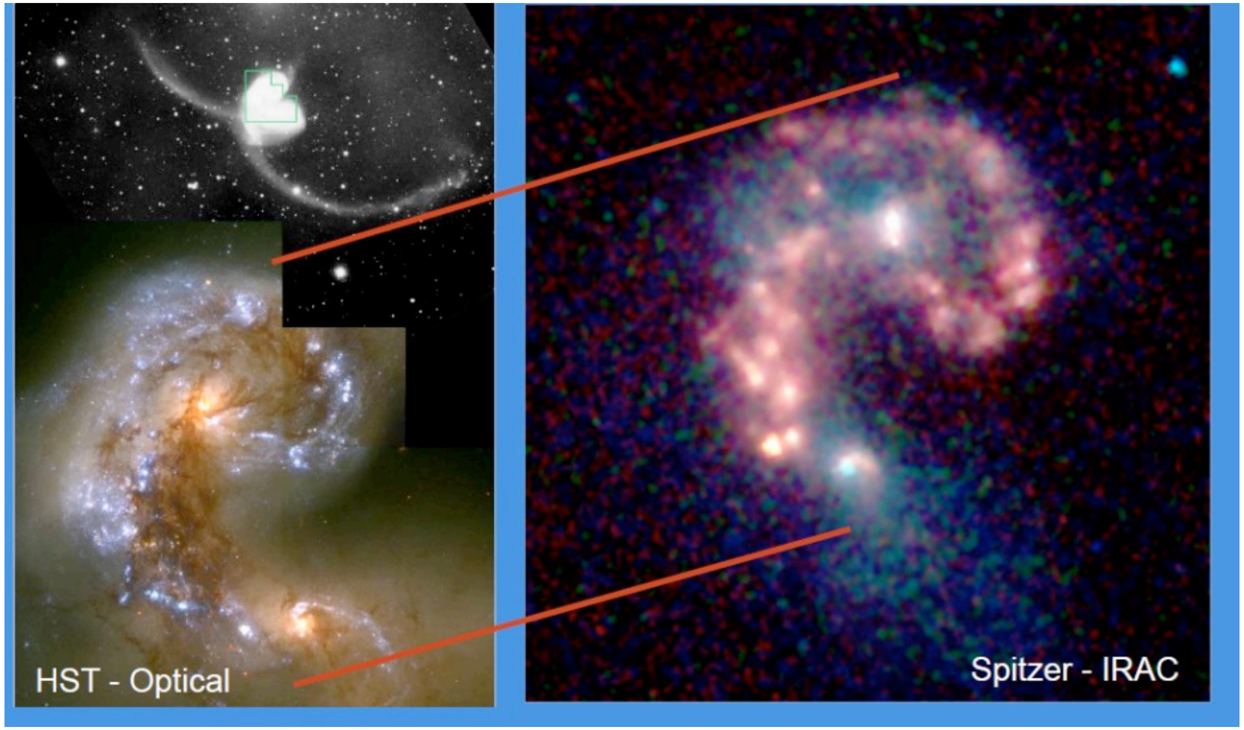


M 82 – nearest starburst
(Hubble Image)

- Short-lived circumnuclear burst – High gas and stellar density density in center
- High star formation efficiency
- Starburst dominates luminosity
- IR starbursts up to 1000 Mo/yr

ULIRG - Mergers

Antennae
(NGC 4038/
NGC 4039)



- Dust heated by AGN and star formation with L > 10^{12} Lsun

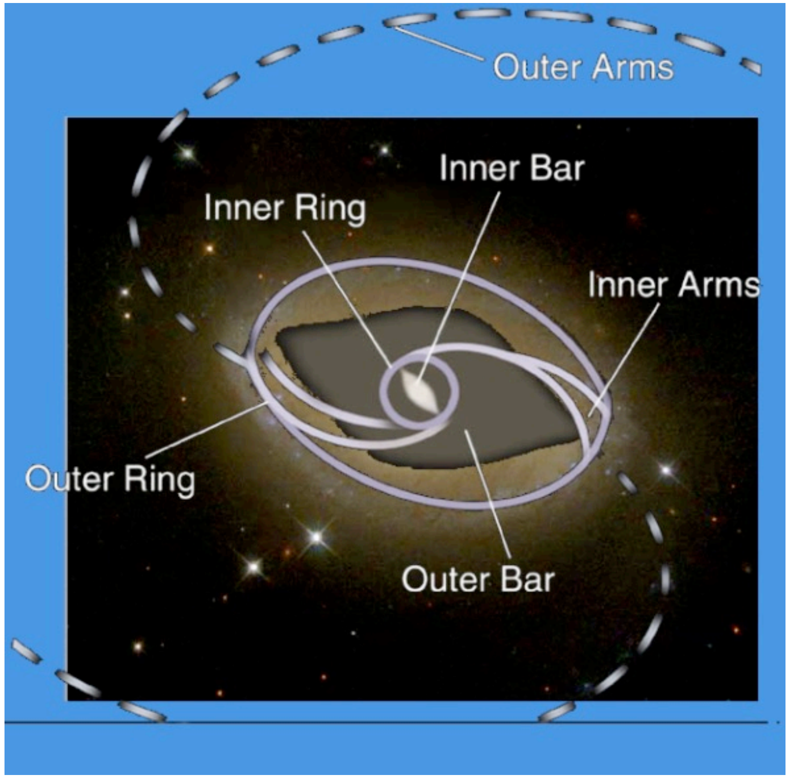
Star Formation Triggers

Galactic Scale Gravity:

Density Waves (Spiral arms, bars, instabilities)
Tidal Interactions (Mergers)
Ram Pressure stripping

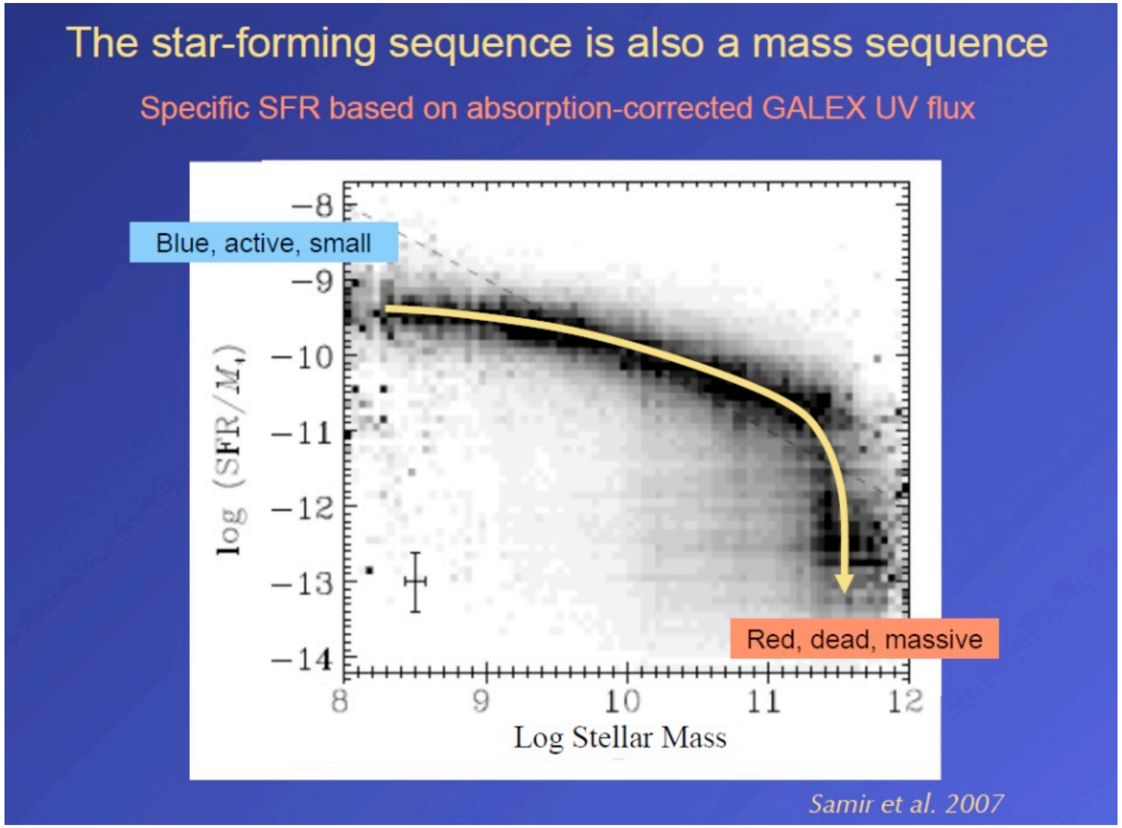
Local Effects

Expanding SN shells
Winds and radiation pressure from massive stars



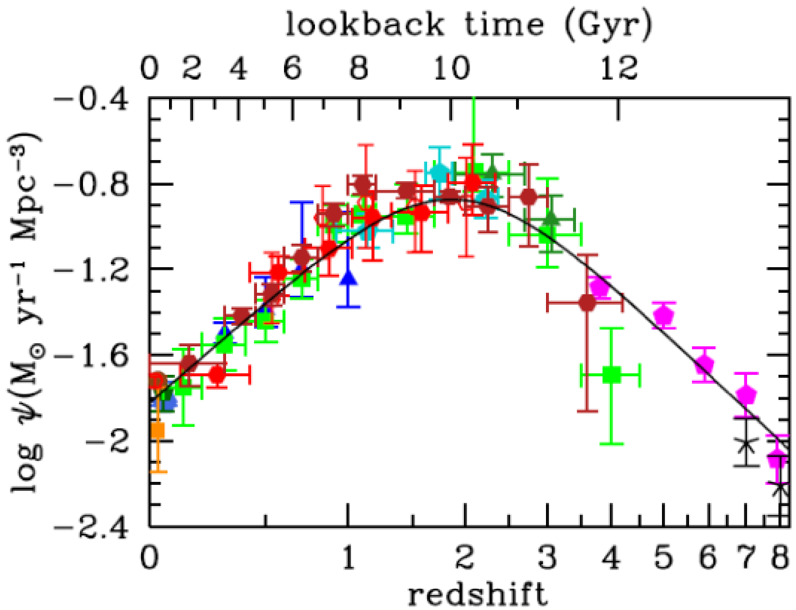
Global rates of galaxy gas accretion determine the cold molecular gas content and SFR.

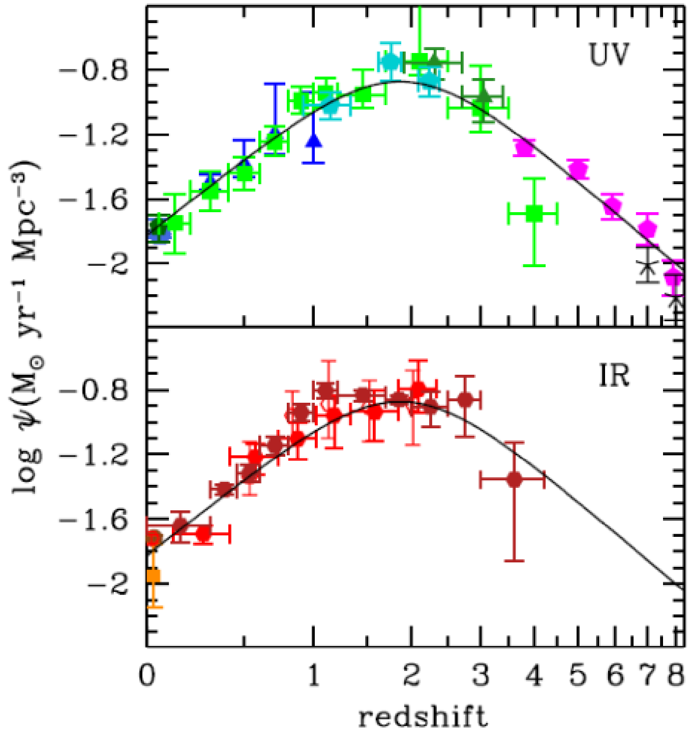
SFR is correlated with M_{star} for main-sequence star-forming galaxies (disky galaxies)
Quiescent galaxies which do not form stars (dead, red, massive): elliptical galaxies, S0 galaxies



- Number of blue galaxies fairly constant; Number of red galaxies rising
- Gas-rich spirals: 20Msun/yr, Ellipticals: 0
- Transition stellar mass is about 10^{11} Msun
- Starburst galaxies have elevated SFR

Cosmic SFRD as a Function of Redshift (Madau Plot)



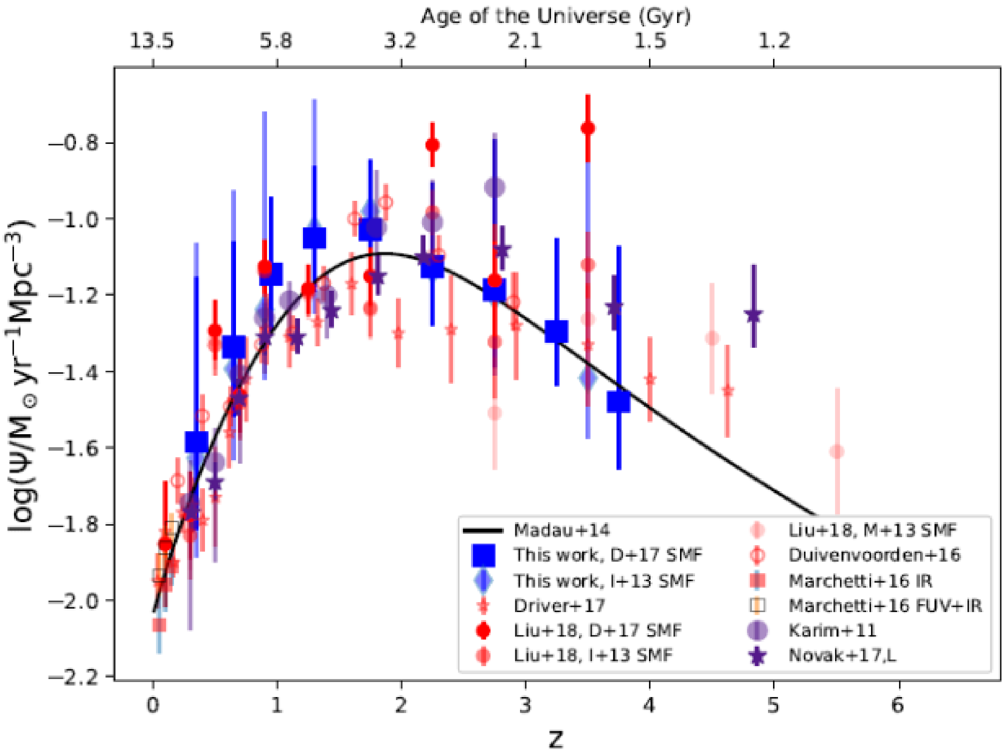


Madau & Dickinson (2014)

Balance between gas accretion and feedback
(stellar, SN, AGN) (both closely related to stellar mass)

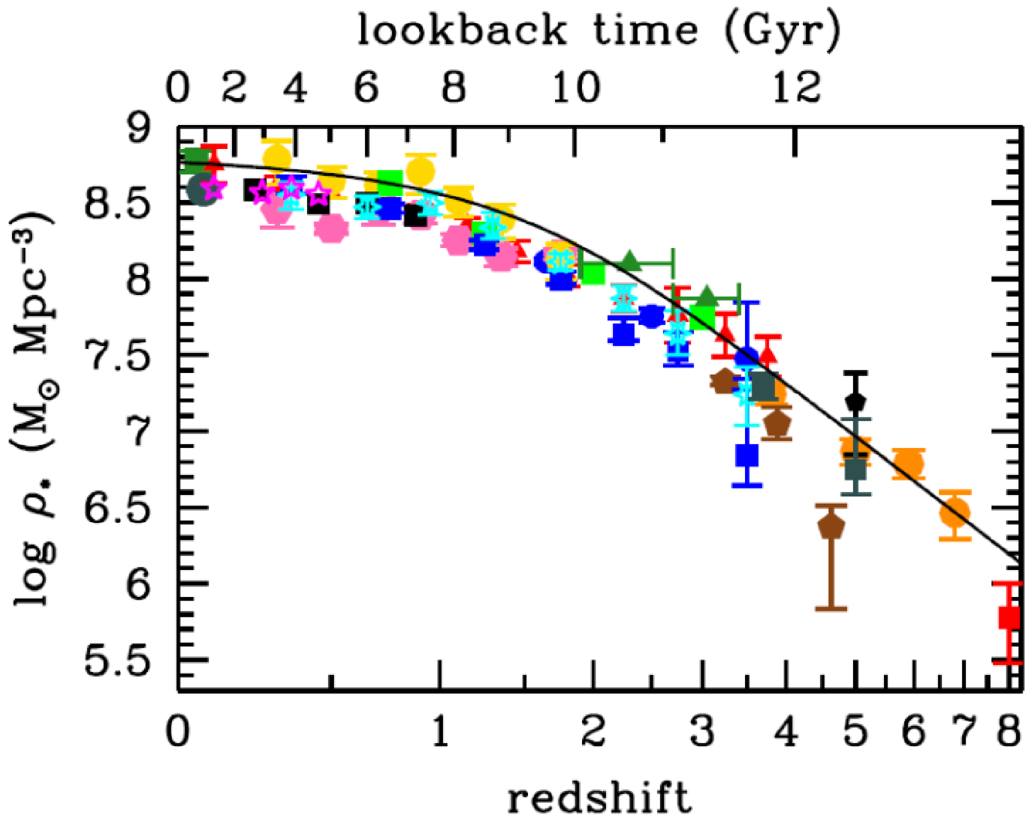
Madau Plot – Cosmic SFRD as a Function of Redshift

Rapid decline over the last 8 billion years after having peaked at redshift 2
- Approximately 3.5 Gyr after the Big Bang (feedback, less mergers)
SFRD declines rapidly for z>4



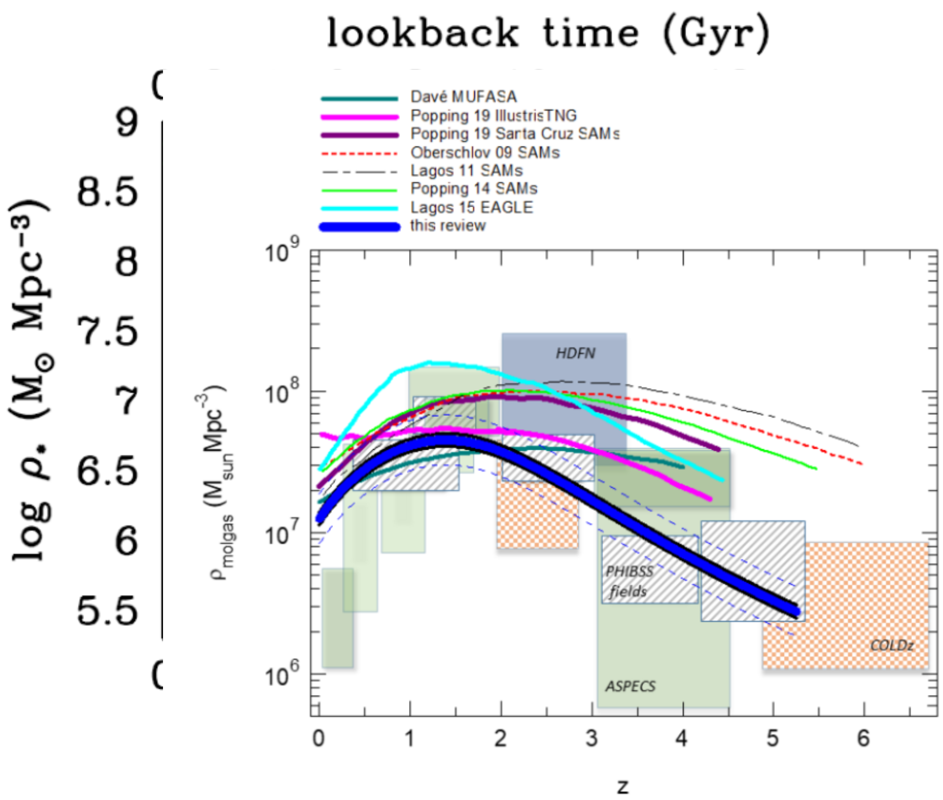
Leslie et al. (2020)

Evolution of Stellar Density



Madau & Dickinson (2014)

Evolution of the Molecular Gas Density



Tacconi et al. (2019)

- Star-forming galaxies contained much more molecular gas at earlier times
- Galaxy integrated depletion time depends on z (or Hubble time)