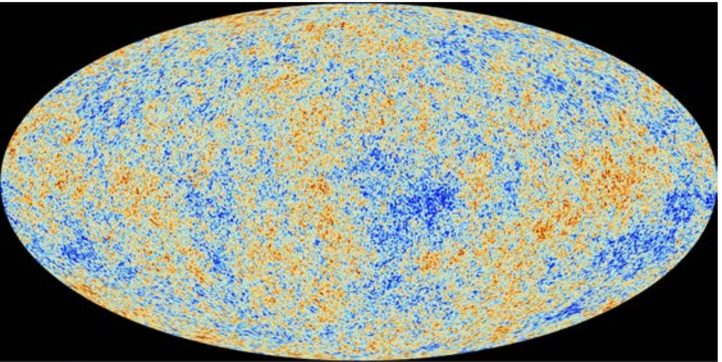
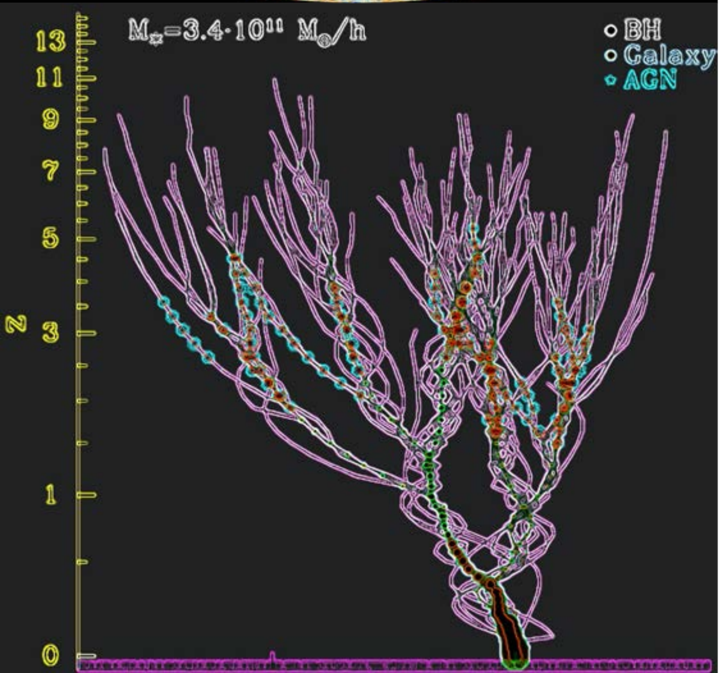
Observational inventory of the ISM of galaxies at the cosmic noon

Image credit: NRAO / AUI / NSF / S. Dagnello

David Elbaz, Benjamin Magnelli, Carlos Gomez Guijarro
CEA Saclay

Galaxy formation: Cosmological context





1902: gravitational instability pressure vs gravitation / James Jeans + 1964: **shear/diff.rotation** Toomre Q parameter

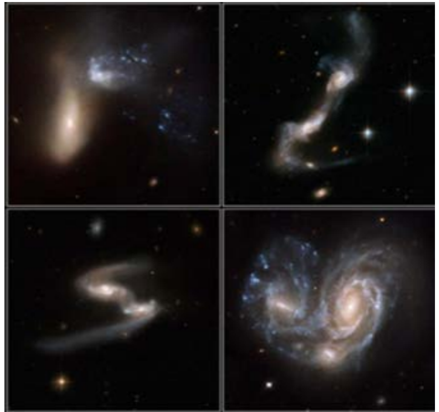
1933: **dark matter** / Zwicky

1981: **inflation → galaxy seeds** / Guth

1982-84: **CDM + seeds → galaxies + mergers**

/ Peebles ; Blumenthal, Faber, Primack, & Rees

Bottom-up hierarchical galaxy formation



Galaxy formation: Open questions

Some tensions with the **Bottom-up hierarchical galaxy formation** model

- galaxy bimodality: nearly 50% mass of stars in dead regions !
- galaxy downsizing: most massive galaxies form first, then died !
- SMBH paradigm: dead regions all possess a SMBH, universal $M_{BH}/M_{\star}$ ~1/1000 !
- Main sequence paradigm: minor role of mergers in hierarchical scenario + not enough infall

Questions:

- **do we understand what causes star-formation ?**

Jeans instability vs multi-phase ISM physics (turbulence, B, stellar and SN feedback, AGN feedback): is star-formation mostly natural, i.e. gravity driven, or triggered, e.g. by mergers ?

- **do we understand what ends star-formation ?**

natural gas exhaustion vs feedback, intergalactic infall vs no infall

- **how did BH grow in mass and how did the affect galaxies ?**

accretion vs early massive seeds, positive vs negative vs null feedback

Questions:

- **do we understand what causes star-formation ?**
- **do we understand what ends star-formation ?**
- **how did BH grow in mass and how did the affect galaxies ?**

We do not understand the nature of dark energy and dark matter, but we believe that we understand how they affect the dynamics of the Universe.

We understand the nature of baryons, but we still do not understand how galaxies form and form their stars…

Observational inventory of the ISM of galaxies at the cosmic noon

Observational inventory of the ISM of galaxies at the cosmic noon

Part I : A strongly evolving cosmic star formation history

Part II : The main sequence of star-forming galaxies

Part III : The gas properties of galaxies

Part IV : The quenching of star formation

David Elbaz, Benjamin Magnelli, Carlos Gomez Guijarro
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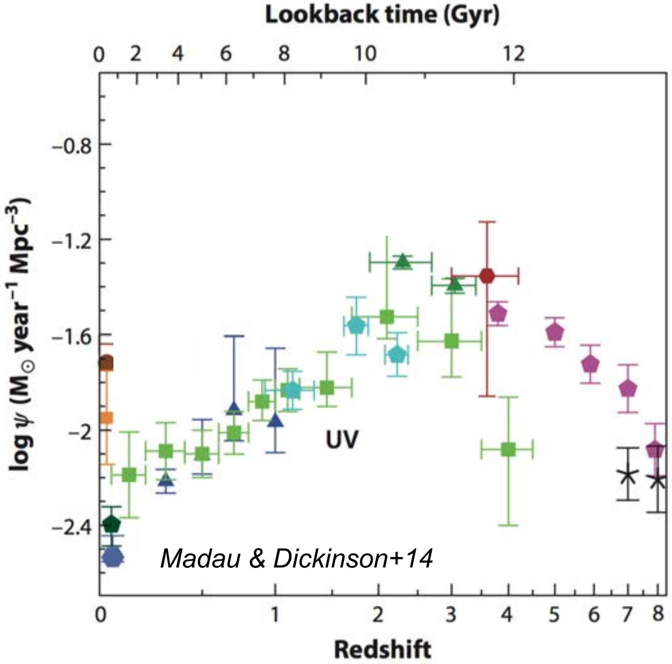
Part I:

The cosmic history of star formation

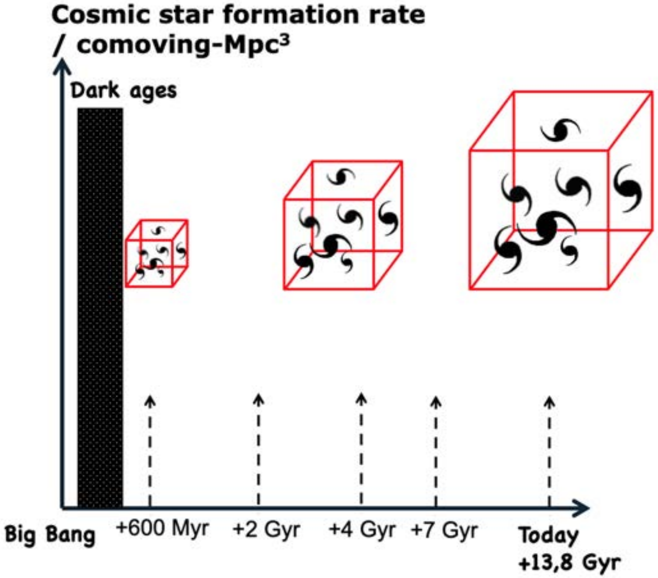
Part I :   A strongly evolving cosmic star formation history

star-forming
region

Star Formation Rate Density
≡ SFR / comoving-Mpc^3



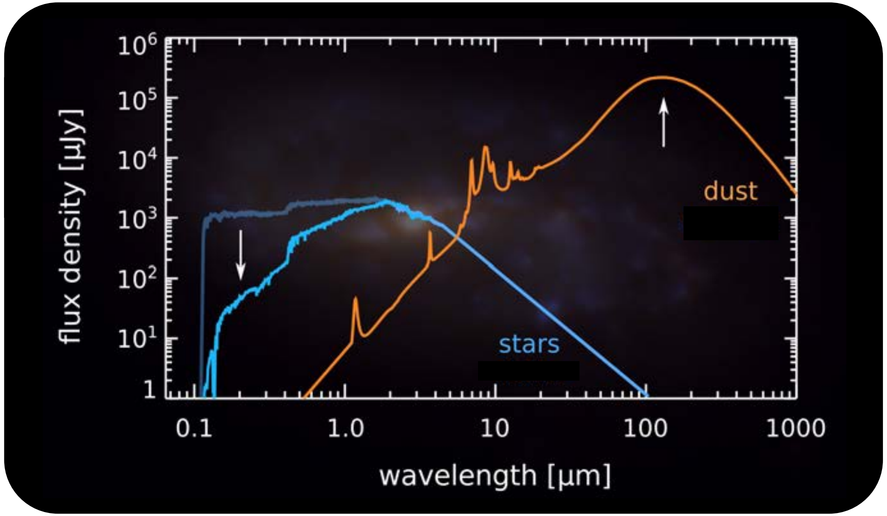
Madau & Dickinson+14



Part I : A strongly evolving cosmic star formation history

star-forming
region

SED of a star-forming galaxy



short-lived high-mass stars radiate mostly in the UV, so

UV $\propto$ birthrate of stars

… BUT …

long-lived low-mass stars which radiate mostly in the NIR, dominate the stellar mass

… most UV light is absorbed by dust which radiates in the far-infrared

Part I : A strongly evolving cosmic star formation history

star-forming
region

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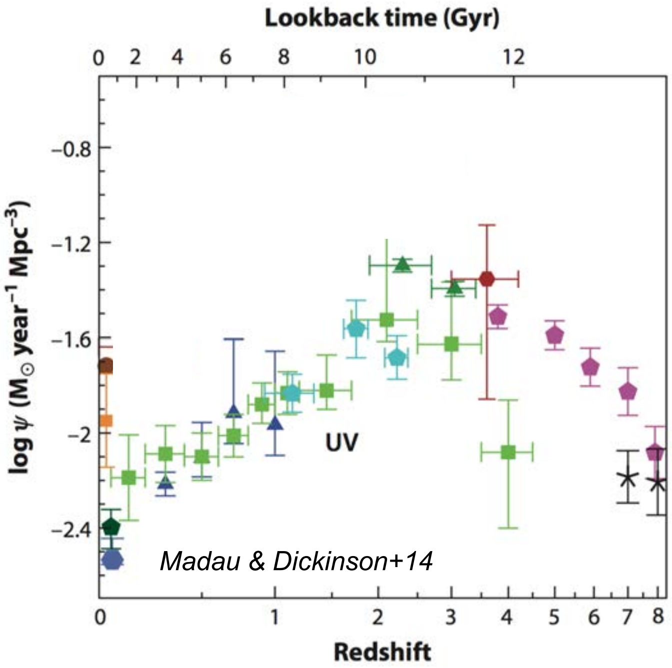

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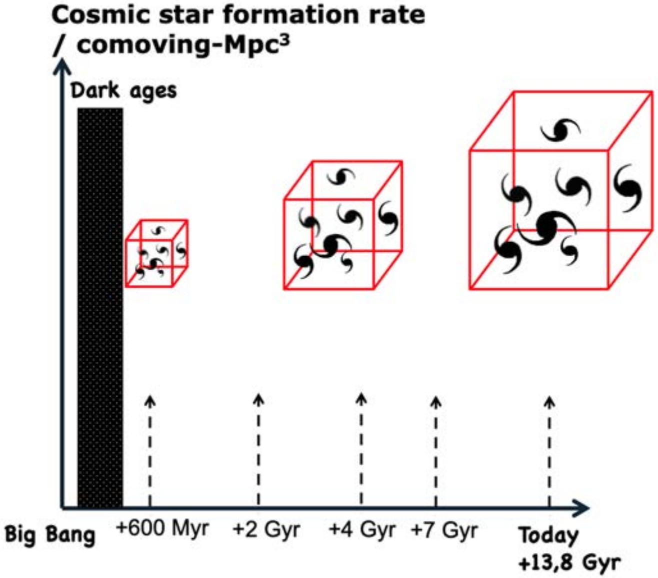

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star-forming
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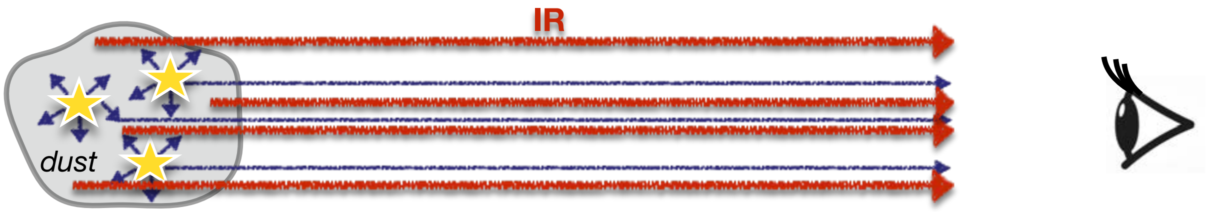

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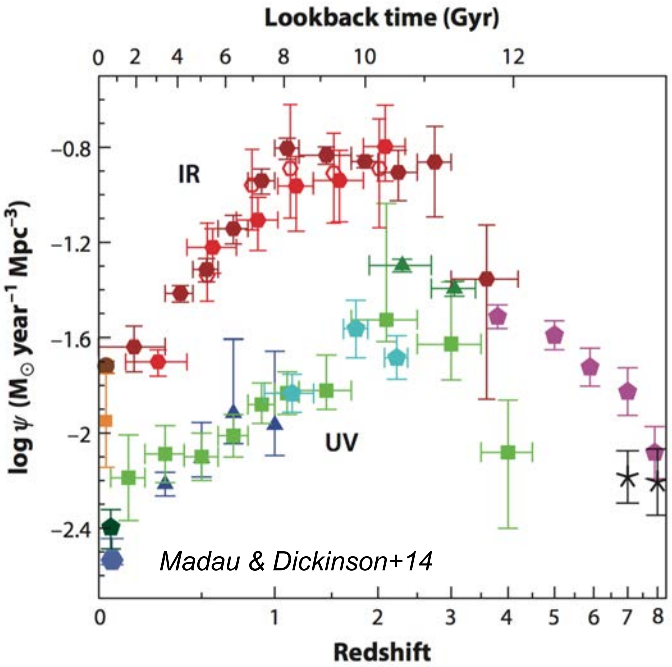

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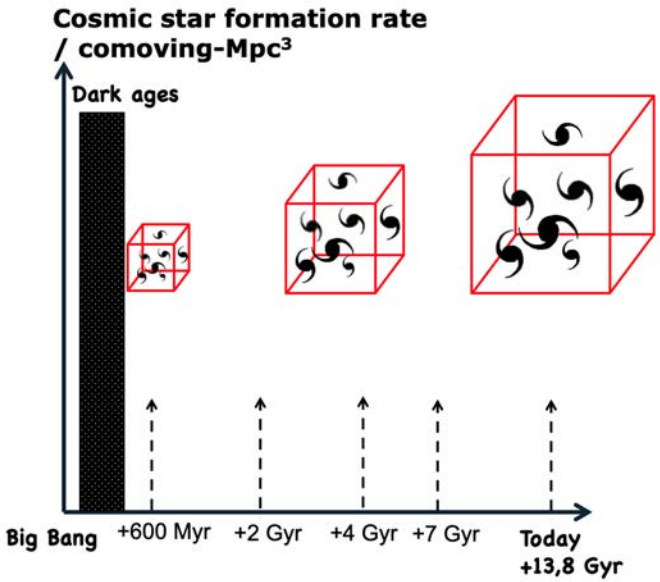

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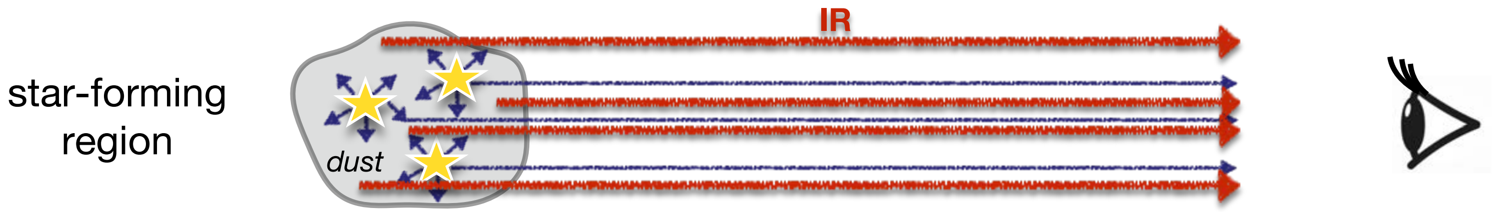

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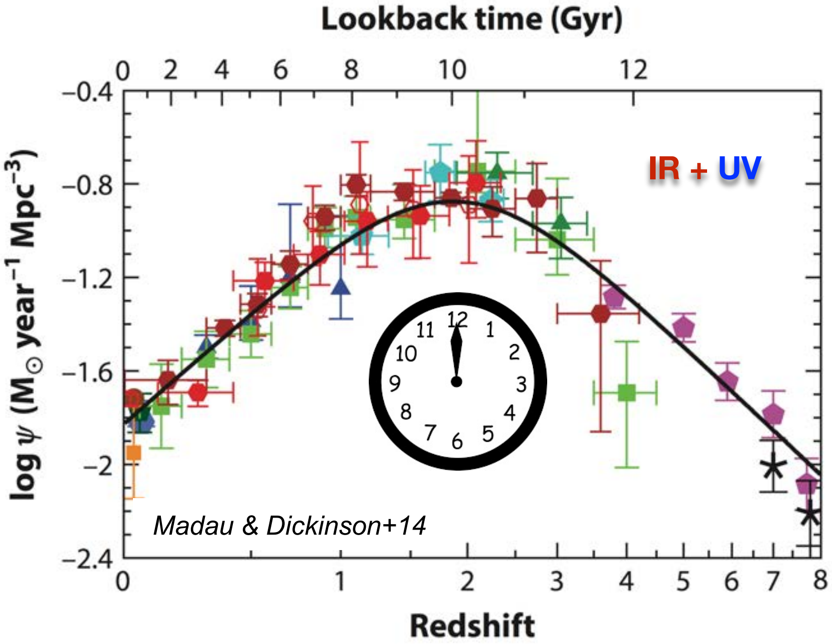
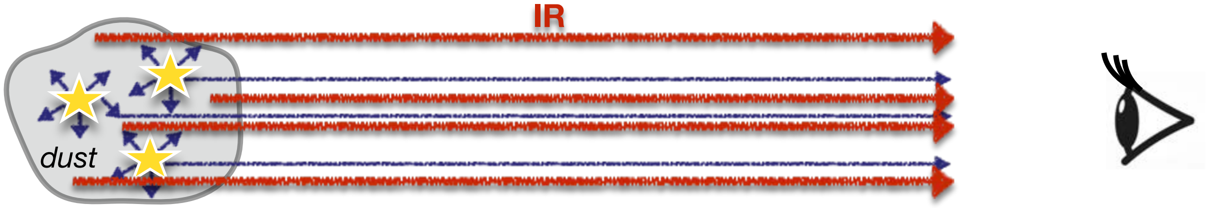


Madau & Dickinson+14

- Significant evolution of the SFRD, peaks at z ~ 2
- at $z \lesssim 3$, ~80% of star formation is dust-enshrouded

Part I : A strongly evolving cosmic star formation history

star-forming
region



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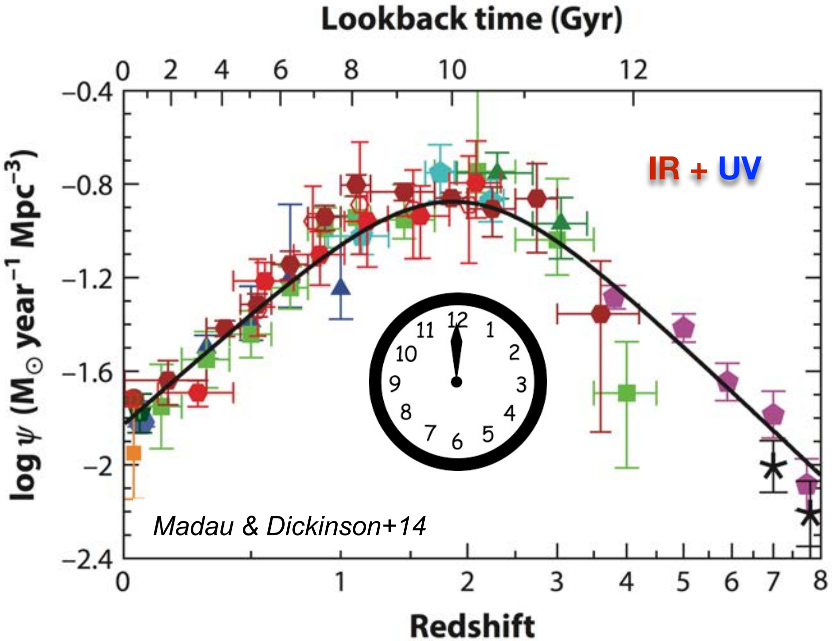

Madau & Dickinson+14

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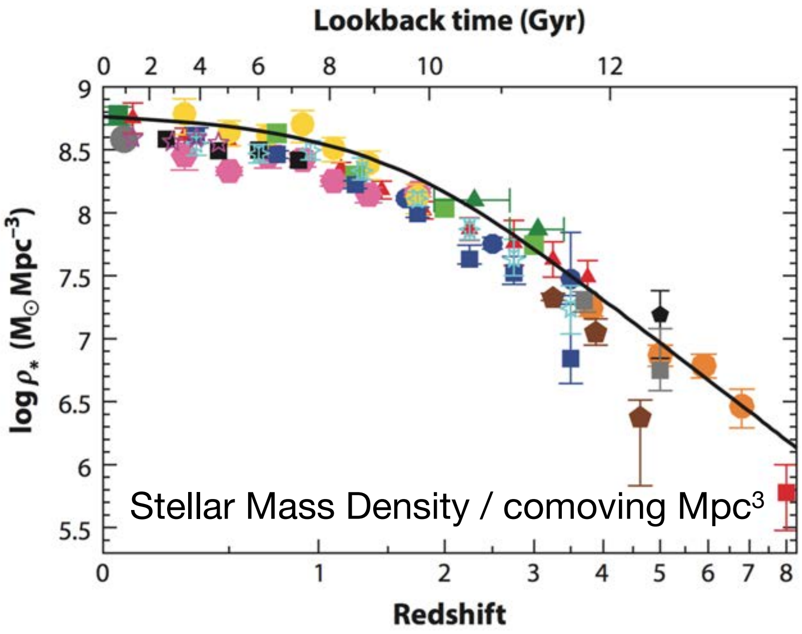
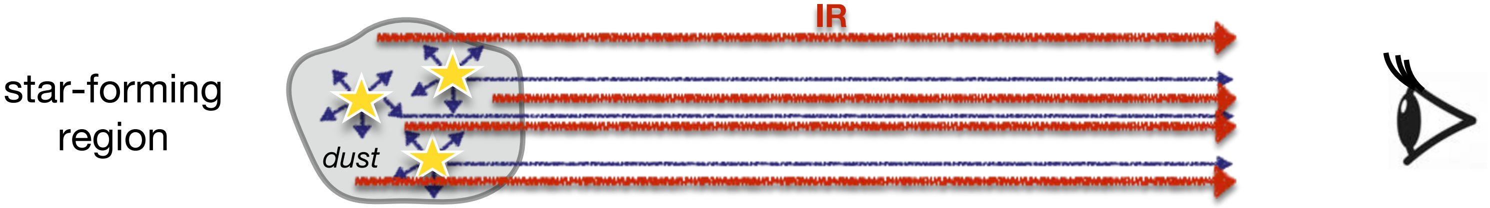
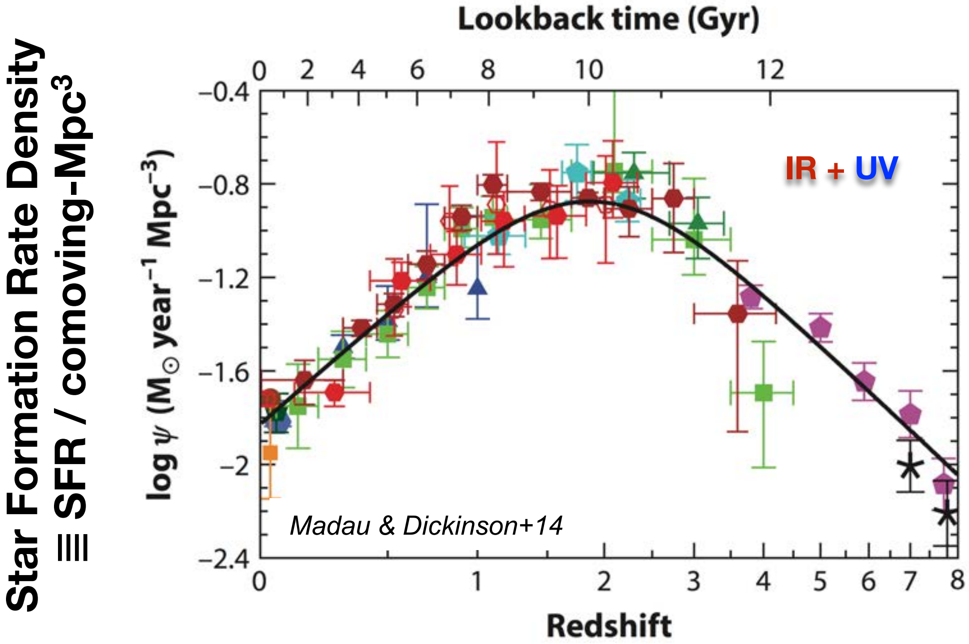


Stellar Mass Density / comoving Mpc^3

Part I : A strongly evolving cosmic star formation history



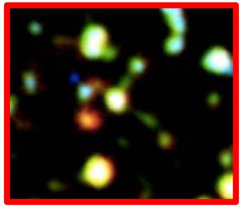


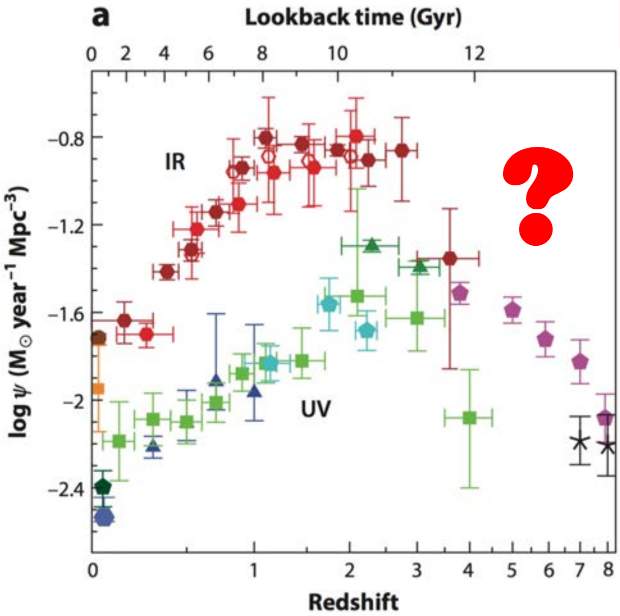
- Significant evolution of the SFRD, peaks at $z \sim 2$
- at $z \lesssim 3$, ~80% of the cosmic SFRD is dust-enshrouded
- ~50% of the present-day stars have formed at $z \gtrsim 1$

Part I :   A strongly evolving cosmic star formation history

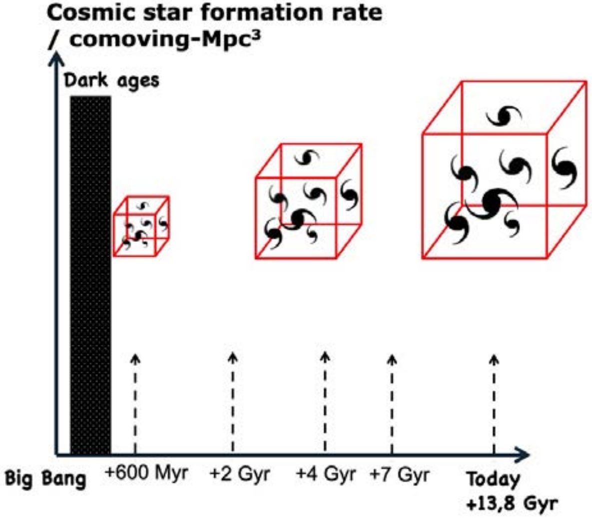
Visible side

Dust-obscured

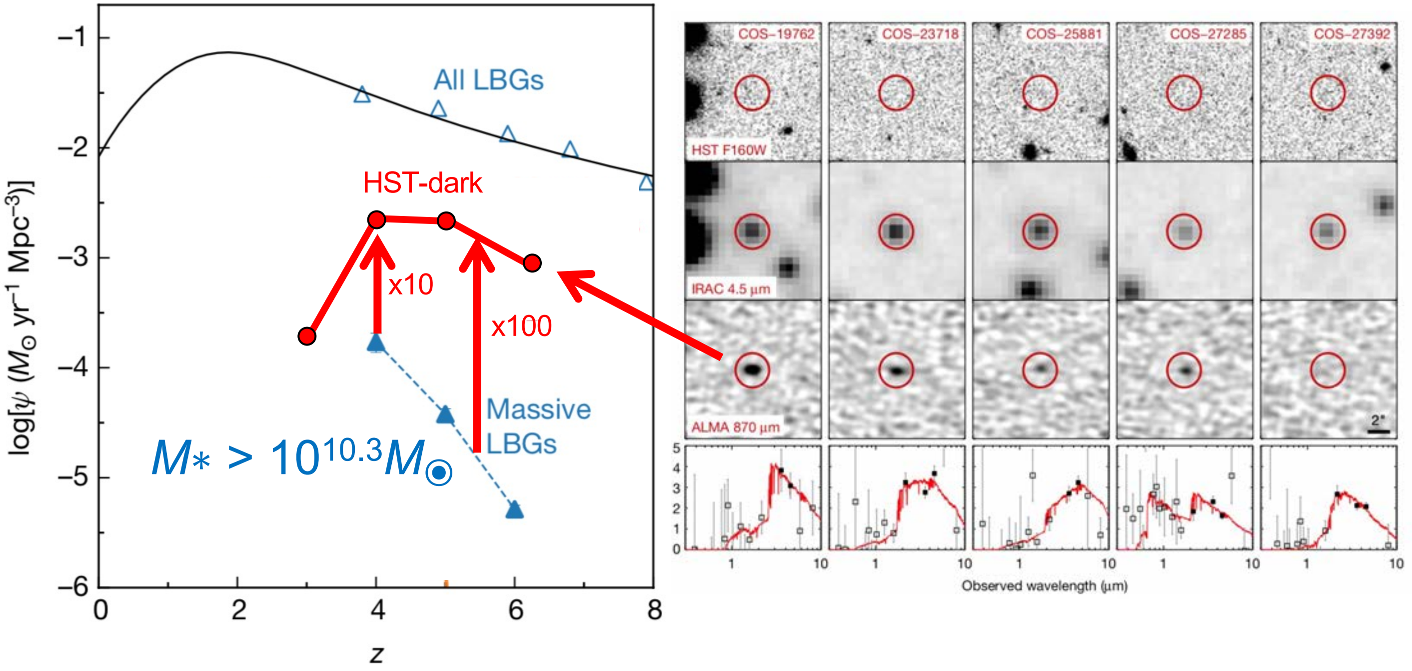




Madau & Dickinson 2014, ARAA



The most massive galaxies in the early universe are optically dark



space density: $n \sim 10^{-5}\ \mathrm{Mpc}^{-3}$, SFR $\sim 200\ M_\odot \mathrm{yr}^{-1}$

Wang, Schreiber, Elbaz +19, Nature

Part I : A strongly evolving cosmic star formation history

- Dust attenuation affects galaxies even at the highest redshifts, in **massive** galaxies
- We have most probably reached a **robust census** of the global star-formation history, but the high-z dust-obscured massive galaxies remain largely unknown

→ deep gravitational potential means metals and dust are locked within galaxies

→ we need a **third dimension : galaxy mass**

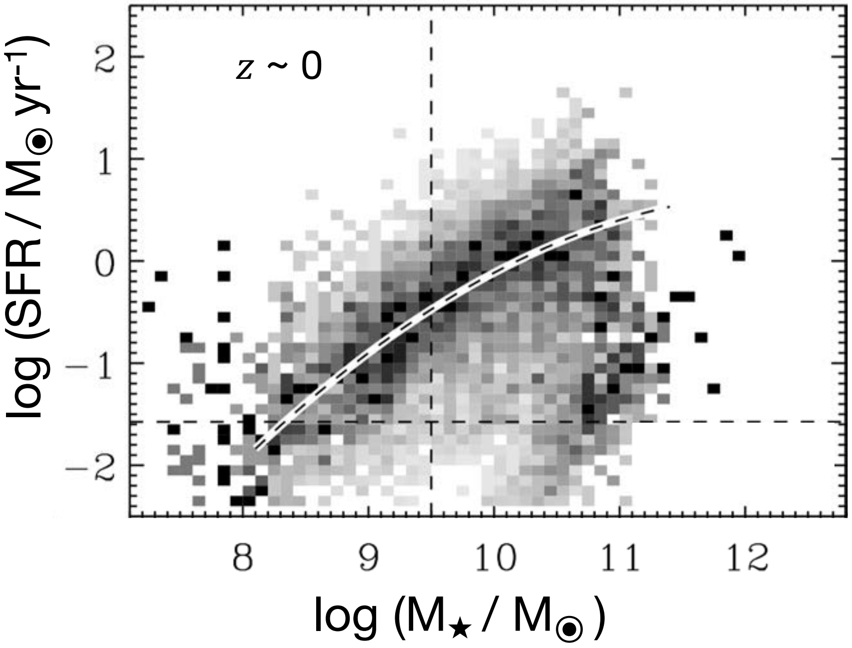
Part II :

Adding the third dimension of galaxy mass

The main sequence framework

Part II : The main sequence of star-forming galaxies

Tight (dispersion ~ 0.3 dex) correlation between the stellar mass and SFR of galaxies, a.k.a. the main sequence (MS) of star-forming galaxies



E.g., Noeske+07; Elbaz+07; Daddi+07; Karim+11; Rodighiero+11; Elbaz+11; Whitaker+12; **Magnelli+14**; Speagle+14; Schreiber+15; Leslie+20

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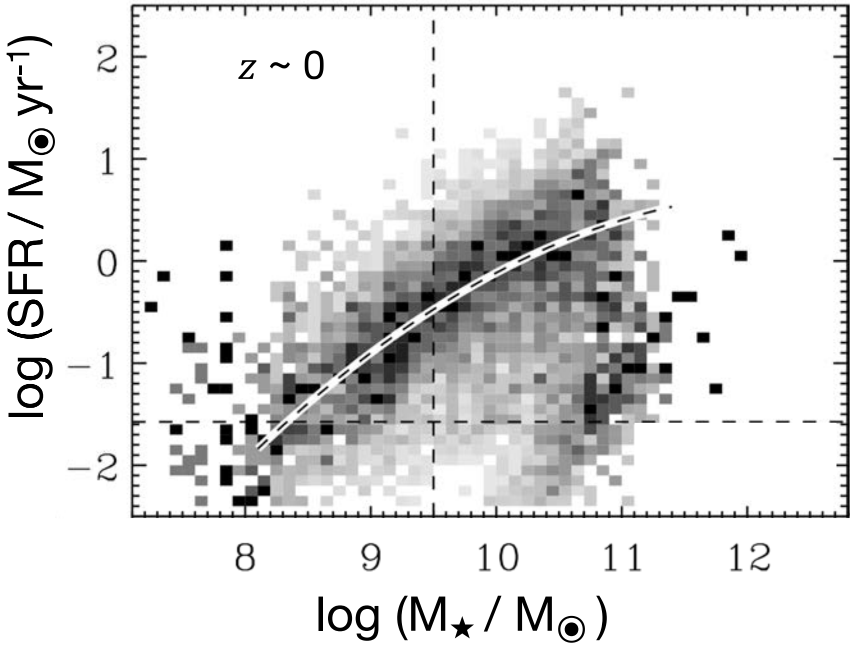

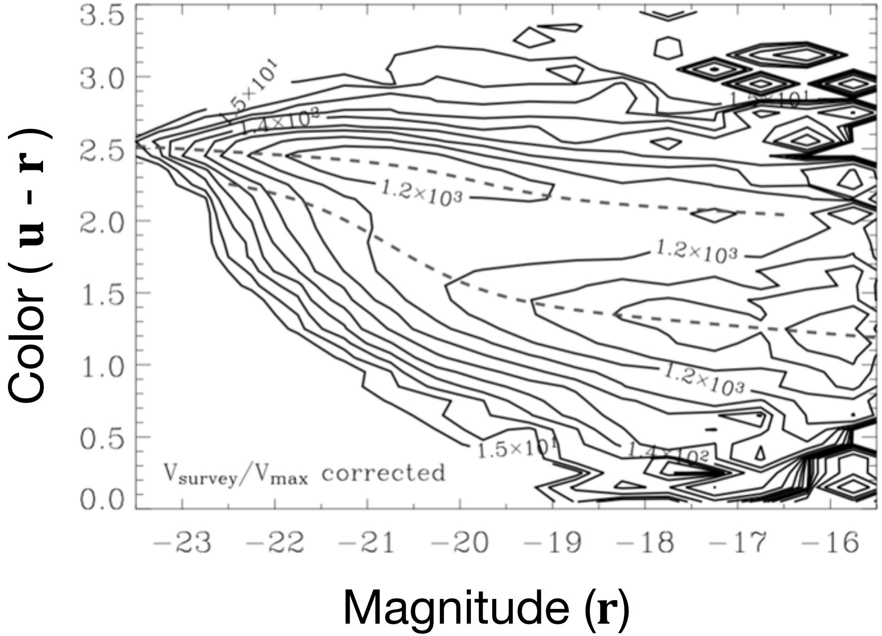

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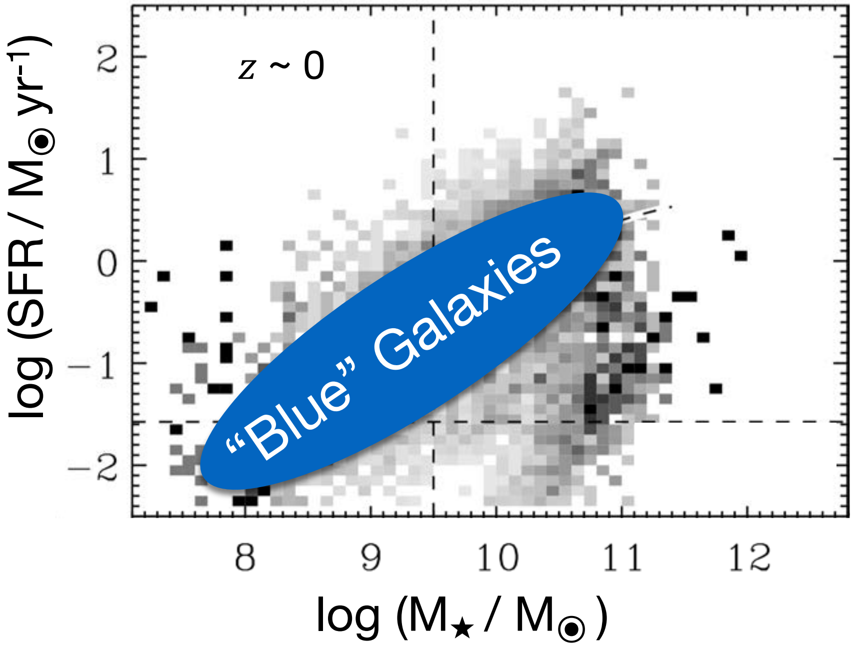

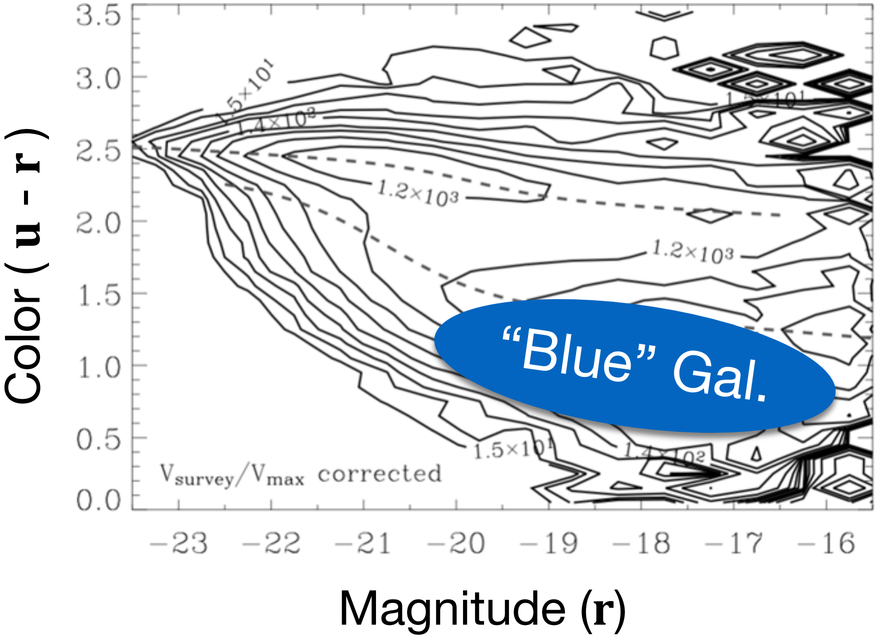

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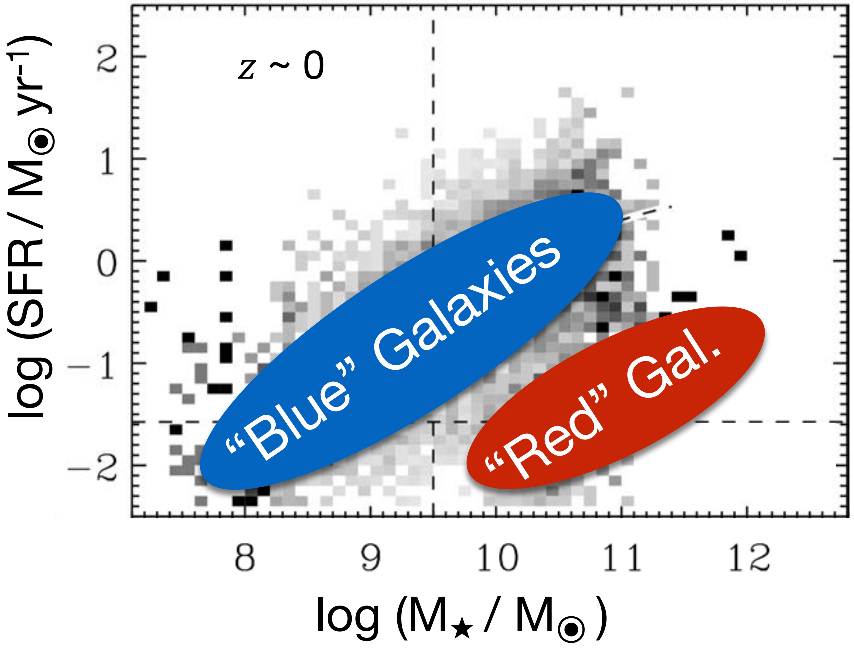

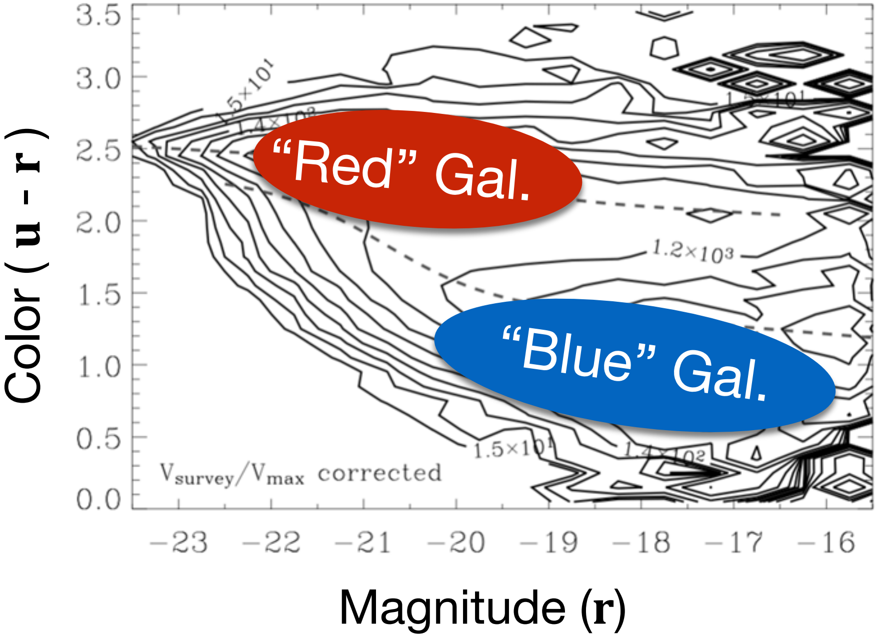

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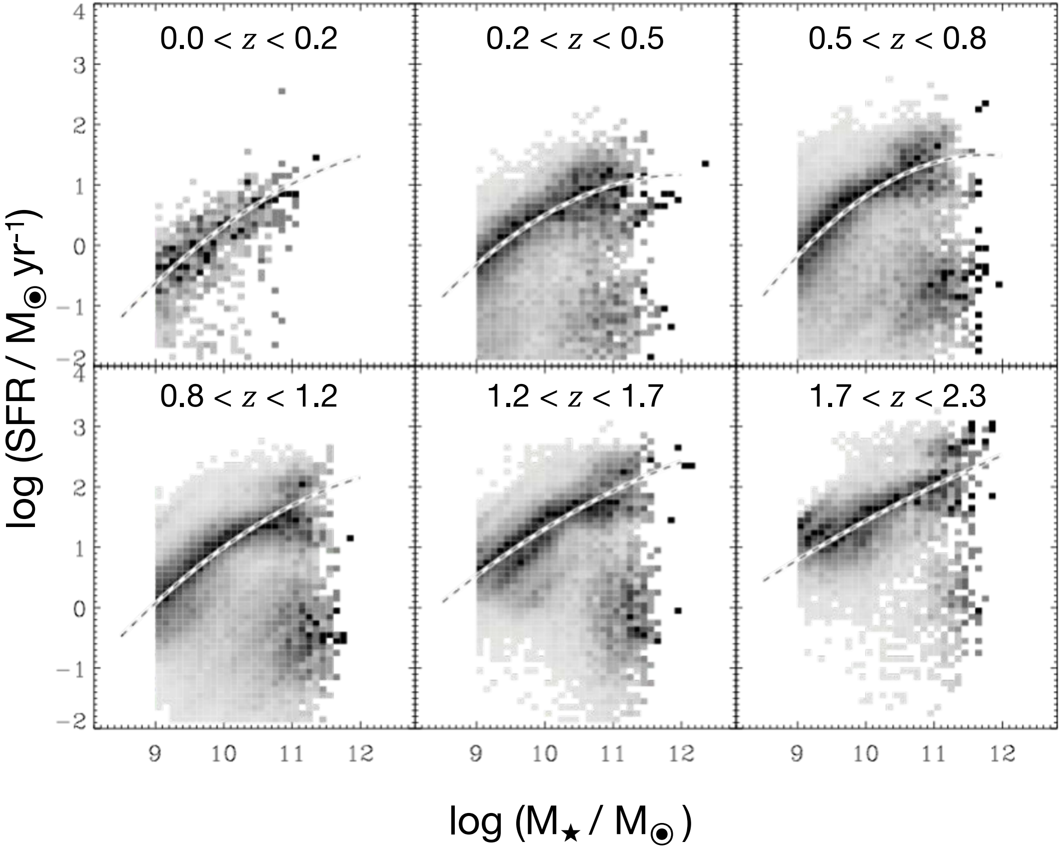

- This tight correlation is observed up to z~2

E.g., Noeske+07; Elbaz+07; Daddi+07; Karim+11; Rodighiero+11; Elbaz+11; Whitaker+12; Magnelli+14; Speagle+14; Schreiber+15; Leslie+20

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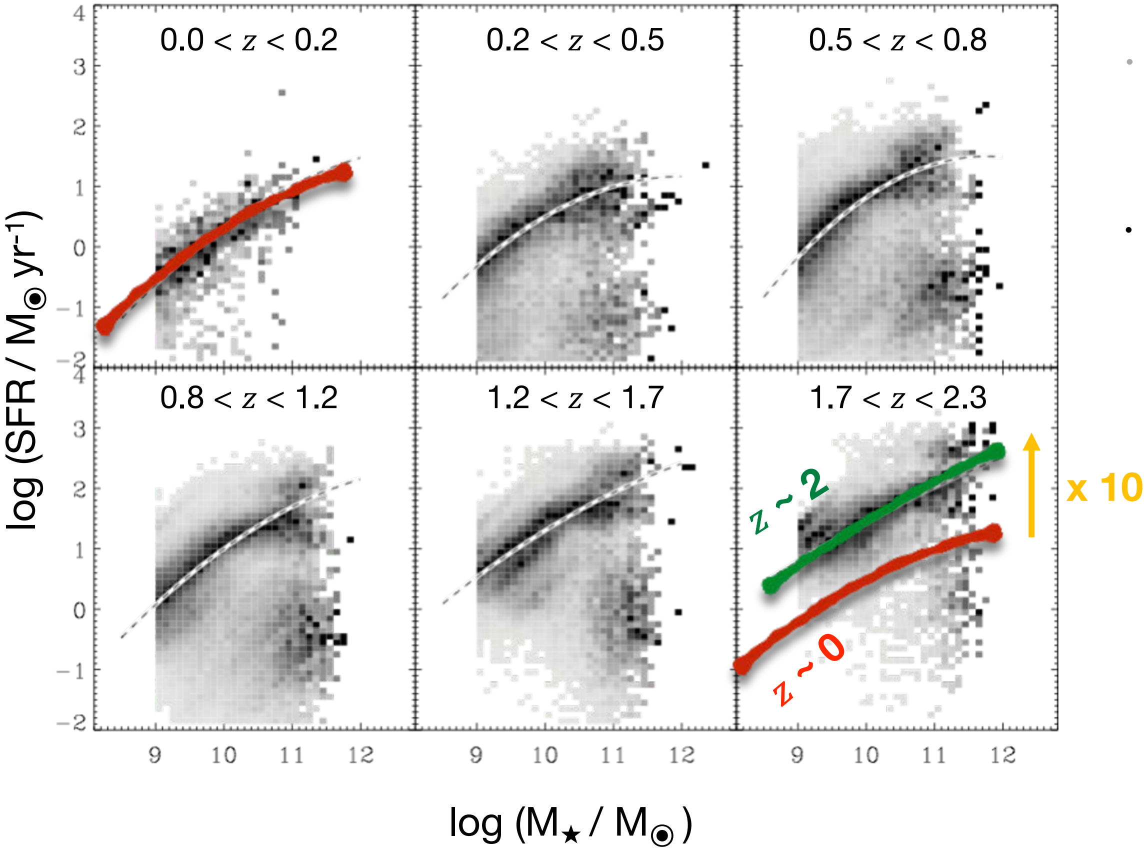

- This tight correlation is observed up to z~2
- The normalisation of the MS increases ×10 between z~0 and z~2
- ~80% of present-day stars have been formed “in” the MS (Schreiber+15)
- Slope flatten at high masses and $z < 2$, sign of an onset of quenching (?)

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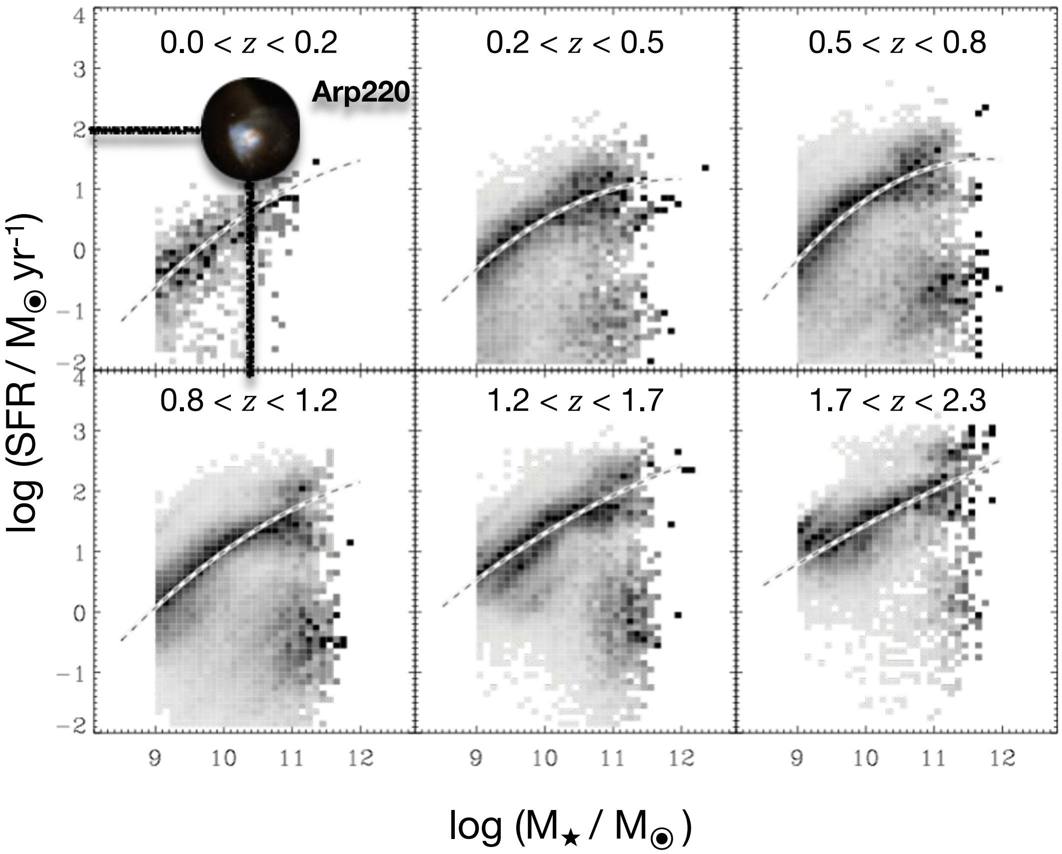

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Part II : … but anyhow what is a starburst ?

t(gas consumption) = Mgas / SFR = 1 / SFE (SF efficiency)

Definition #1: t(gas consumption) « t(Hubble) => starburst

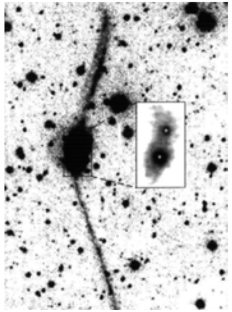
local LIRGs: t(gas consumption) ~ 1 Gyr !

- The Antennae:

  $L_{IR} = 1.1 \times 10^{11} L_\odot \rightarrow$ SFR = 19 $M_\odot yr^{-1}$

  $M(H_2) = 3.9 \times 10^9 M_\odot$

  Molecular gas exhausted in ~200 Myr



- The Super-Antennae:

  $L_{IR} = 1.1 \times 10^{12} L_\odot$ --> SFR = 190 $M_\odot yr^{-1}$

  $M(H_2) = 3 \times 10^{10} M_\odot$

  Molecular gas exhausted in ~160 Myr

Part II : … but anyhow what is a starburst ?

Definition #2: exceptional event, i.e., $b > 3$

$b = \mathrm{SFR}/\langle\mathrm{SFR}\rangle$ = birth-rate parameter

Good proxy = specific SFR (sSFR) when one assumes the same age, i.e.,

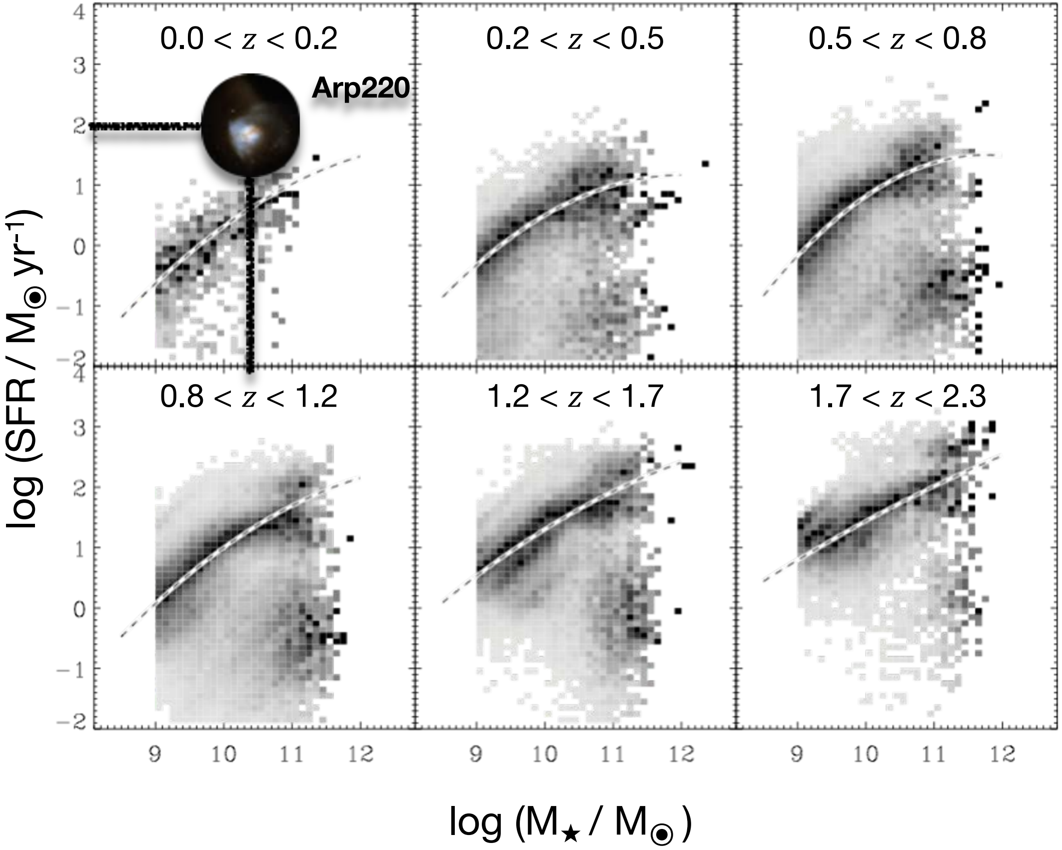
$$\mathrm{sSFR} = \mathrm{SFR}/M_\star = \mathrm{SFR} / \langle\mathrm{SFR}\rangle \times 1 / \mathrm{age}$$

MW → $\mathrm{SFR} / M_\star \sim 0.06\ \mathrm{Gyr}^{-1}$ $\tau \approx 20$ Gyr (time to double $M_\star$)

M82 → $\mathrm{SFR} / M_\star \sim 0.5\ \mathrm{Gyr}^{-1}$ $\tau \approx 2$ Gyr

Arp220 → $\mathrm{SFR} / M_\star \sim 10\ \mathrm{Gyr}^{-1}$ $\tau \approx 0.1$ Gyr

Part II : The main sequence of star-forming galaxies



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- ~80% of present-day stars have been formed "in" the MS (Schreiber+15)
- Slope flatten at high masses and $z < 2$, sign of an onset of quenching (?)
- Starbursts (SBs) are outliers of the MS, i.e., distance(MS) ~ SFR(t) / ⟨SFR⟩

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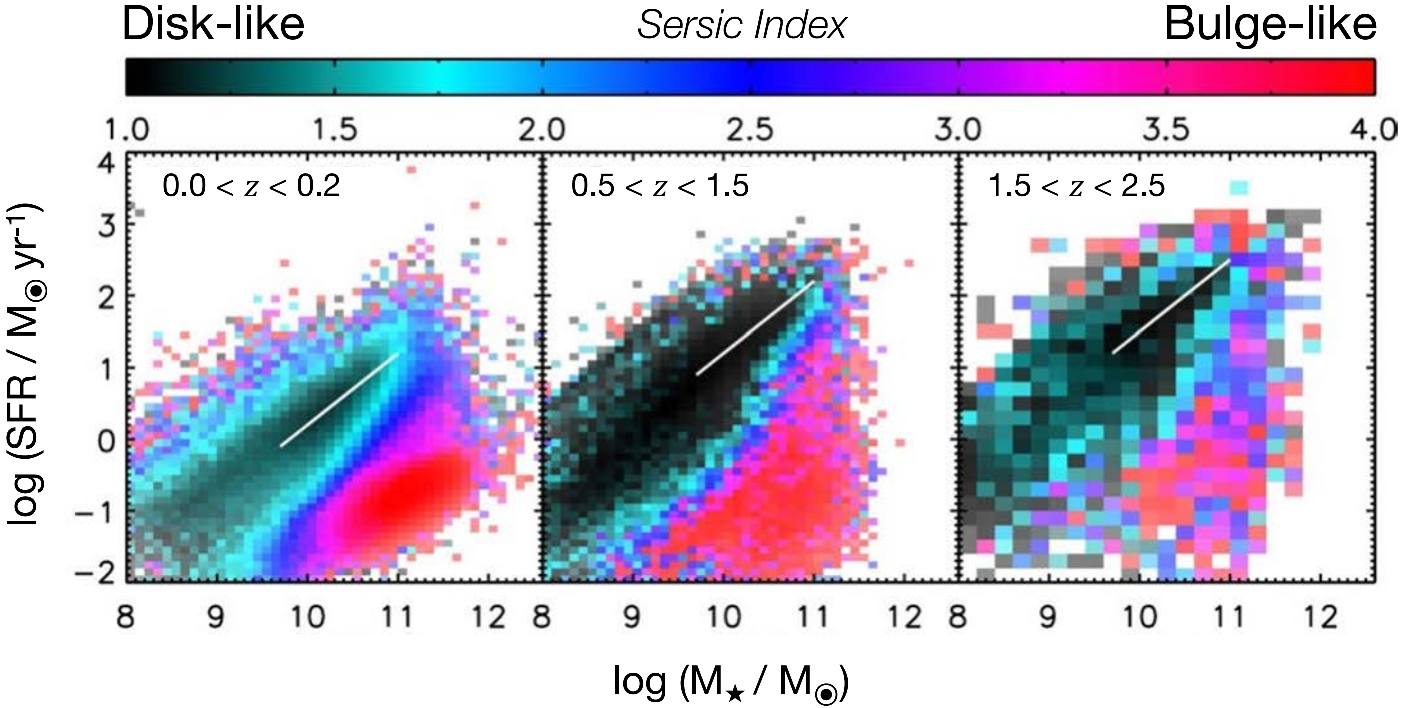
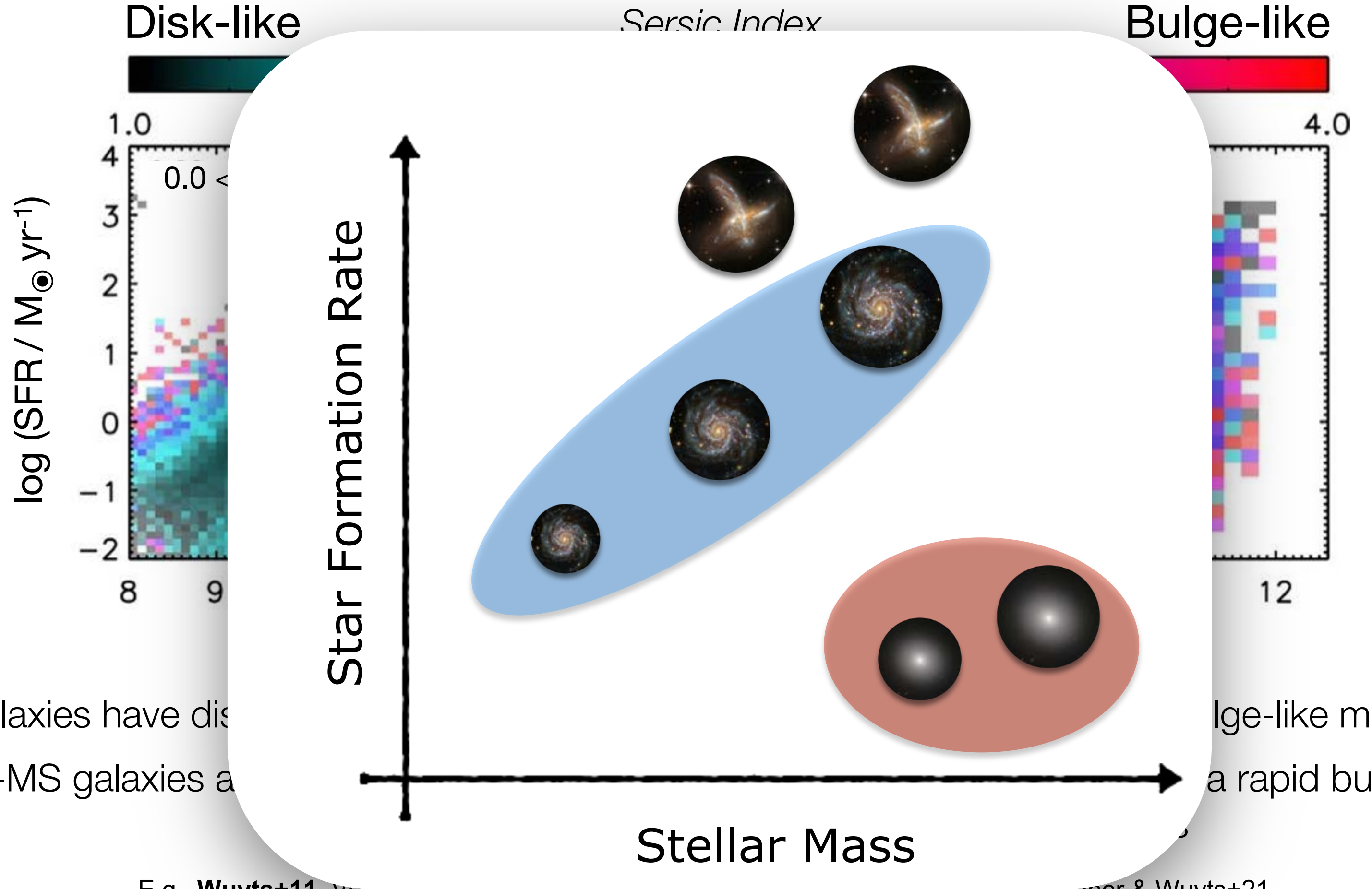
Part II : The main sequence of star-forming galaxies -- Morphology



- MS galaxies have disk-like morphologies while quiescent galaxies (QGs) have bulge-like morphologies
- Above-MS galaxies are better described by de Vaucouleurs profiles, suggesting a rapid build-up of the central mass concentration in these starbursting outliers

E.g., **Wuyts+11**, Van der Wel+14, Shibuya+15, Barro+17, Suess+19, Förster-Schreiber & Wuyts+21

Part II : The main sequence of star-forming galaxies -- Morphology



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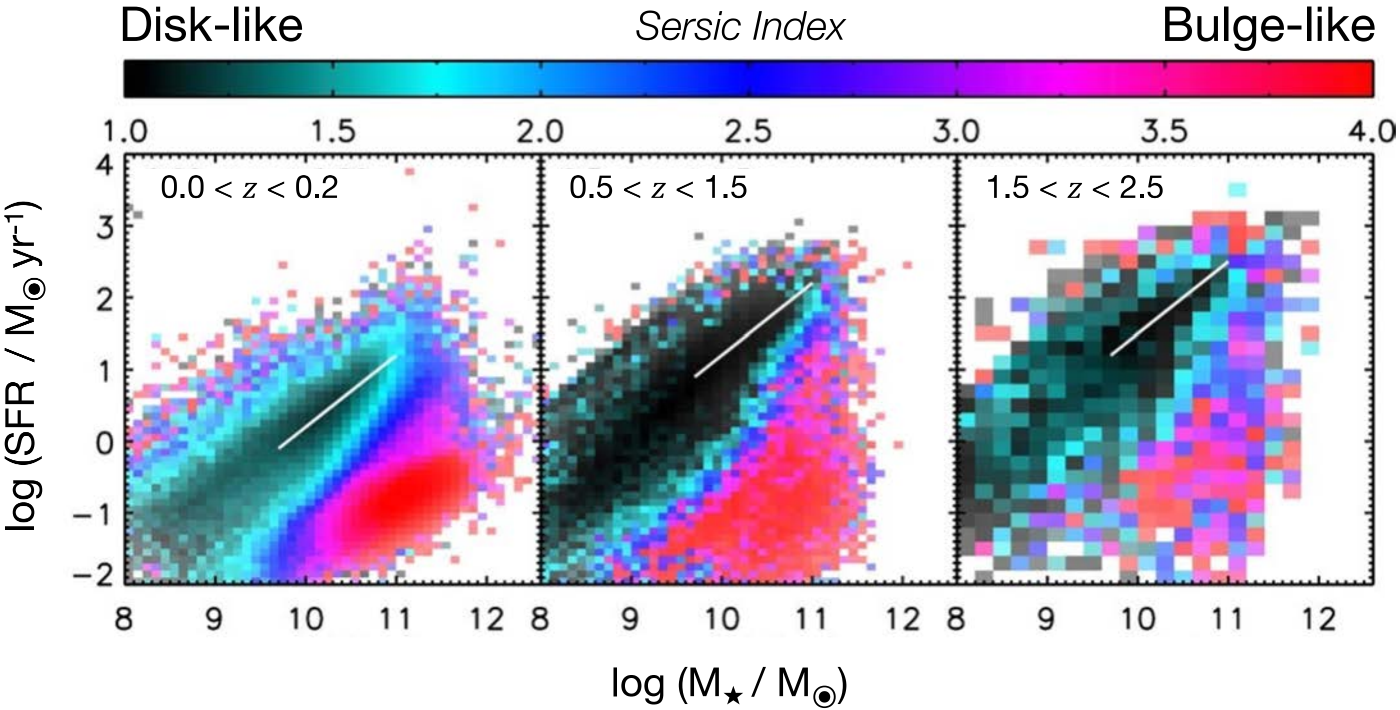

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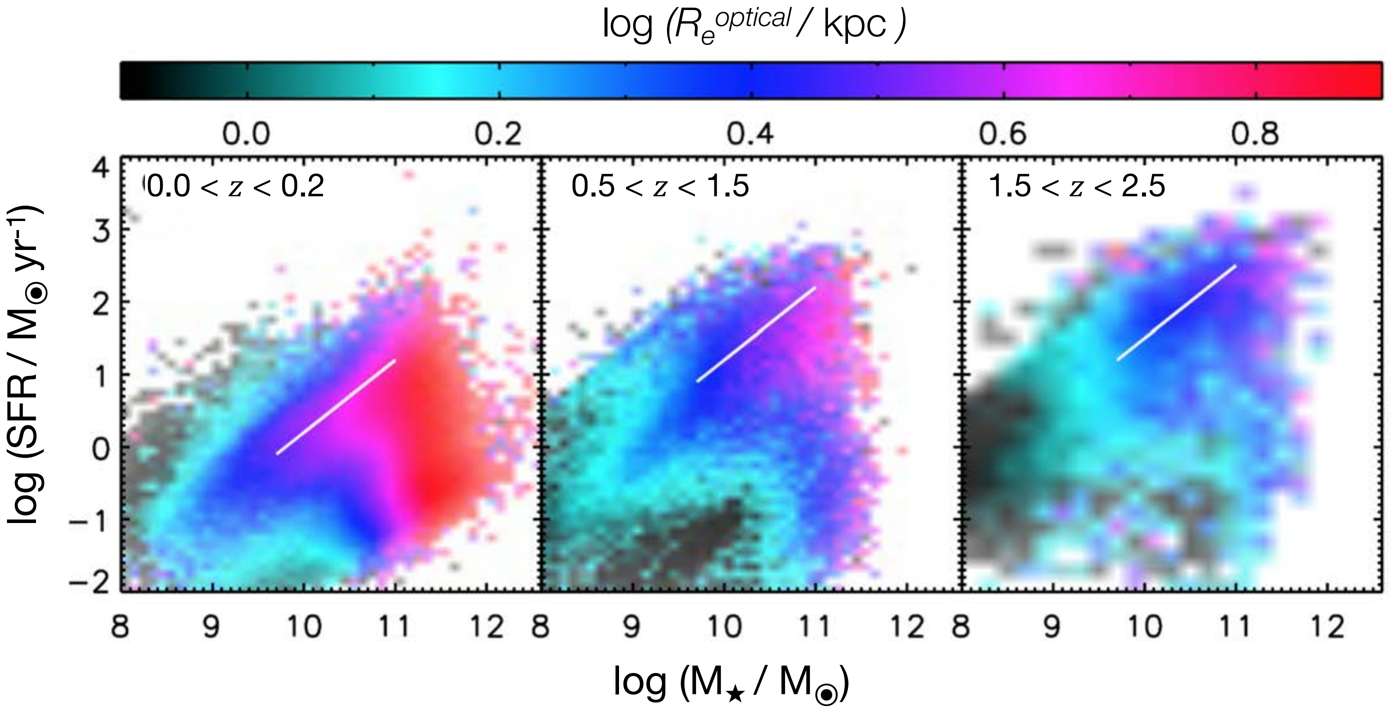

- Size of MS galaxies growth with cosmic time, in line with an inside out disk growth (?)
- Above-MS galaxies are slightly more compact.
- QGs are more compact and their size have a much steeper stellar mass dependency

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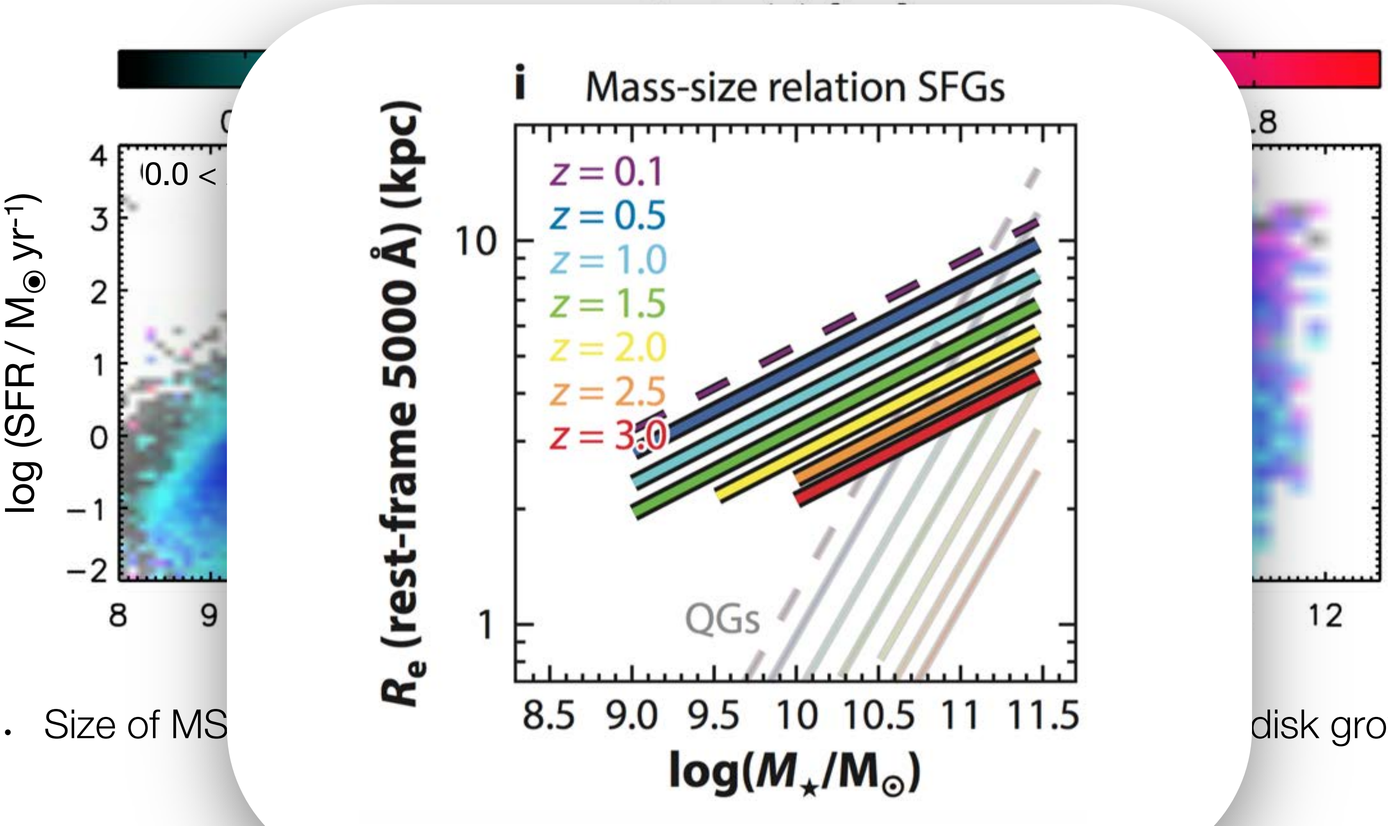

Förster-Schreiber & Wuyts+20

- Size of MS … disk growth (?)
- QGs are more co … mass dependency

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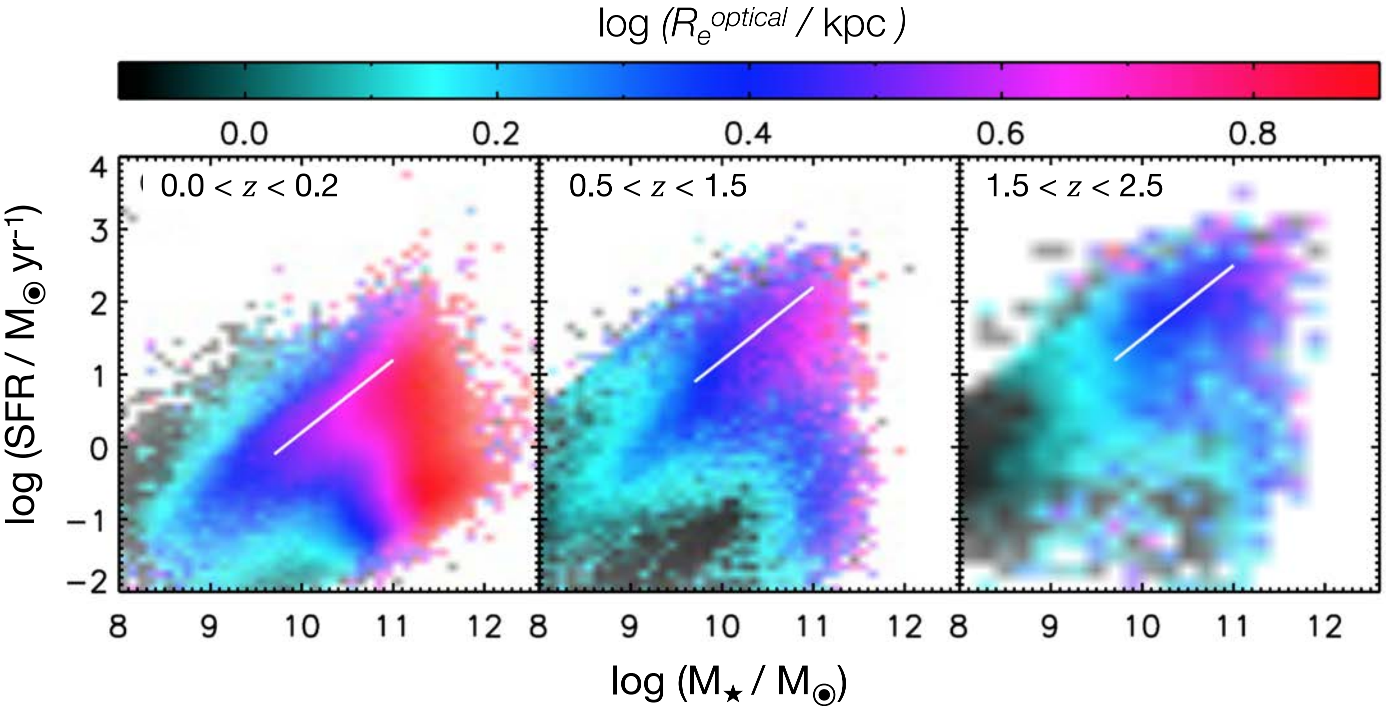

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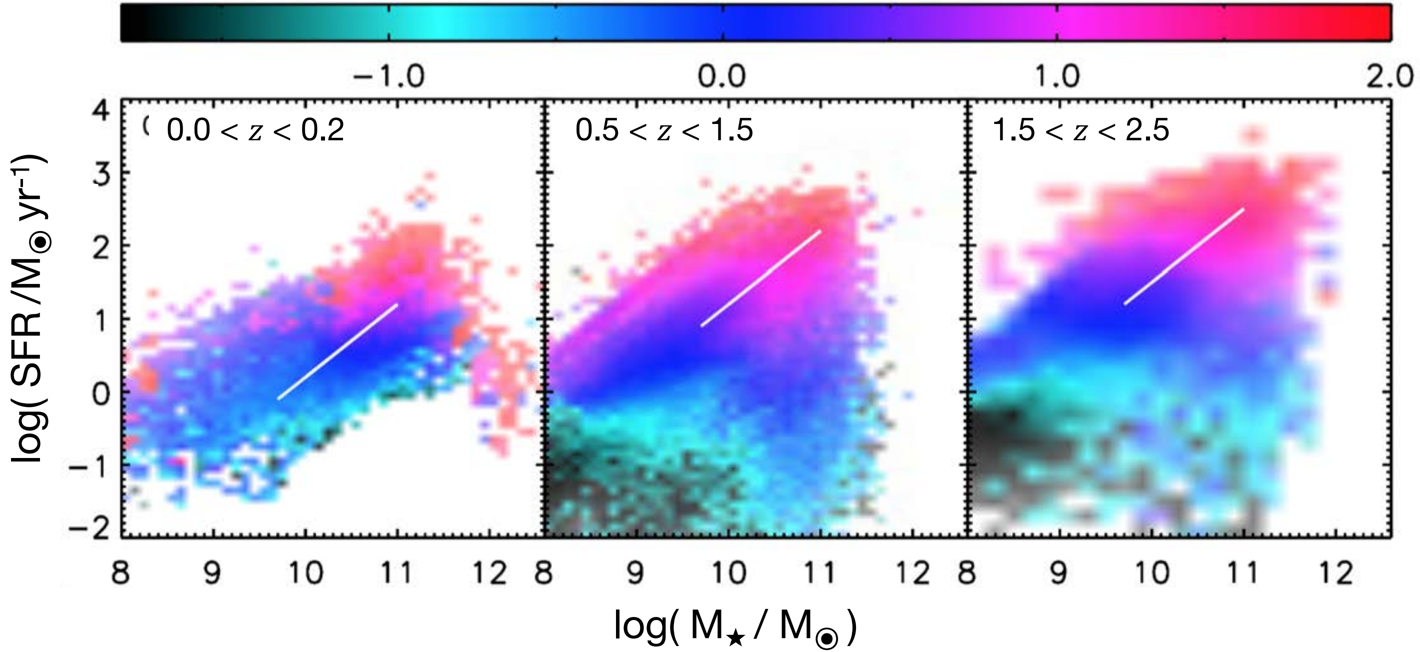
Part II : The main sequence of star-forming galaxies -- Dust opacity

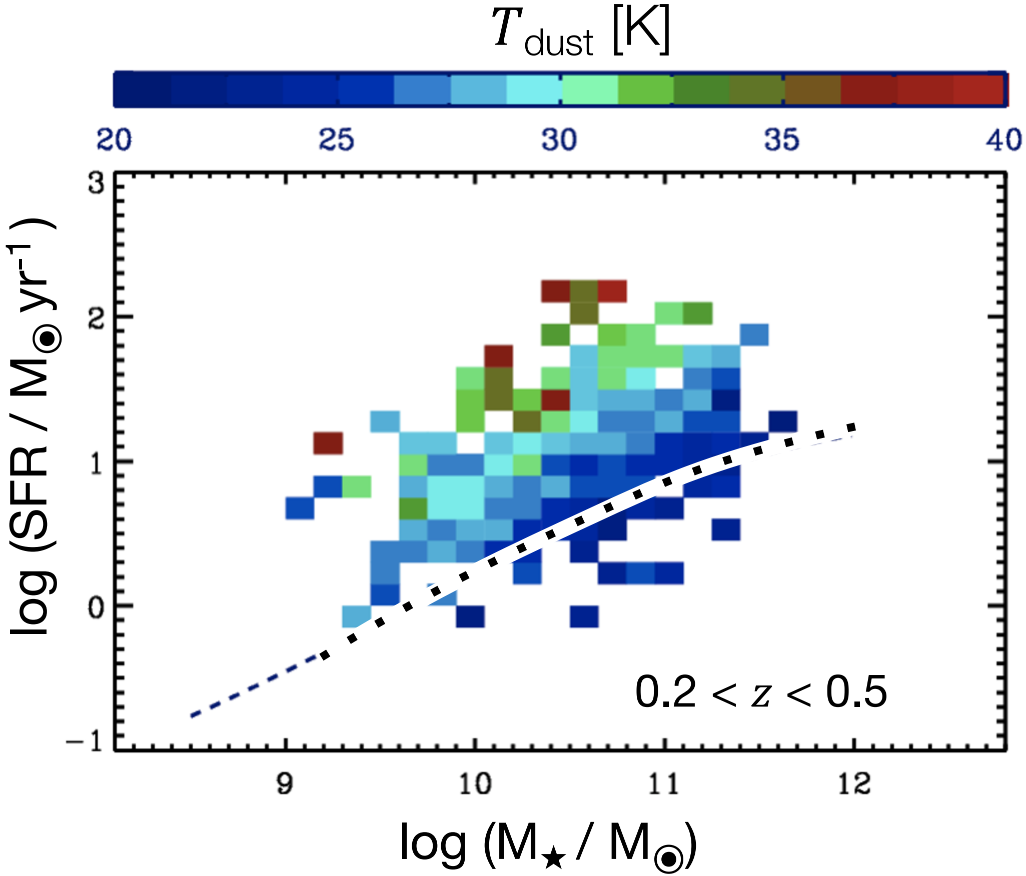
Lightly obscured $\log(SFR_{IR} / SFR_{UV}) \equiv$ *level of dust extinction* Heavily obscured



- Dust obscuration increase with ΔMS and stellar masses but remains relatively constant with redshift
  → Considering the strong decrease of metallicity with redshift, this suggest that high-z MS galaxies have ISM conditions moving closer to those of local starbursts.

E.g., **Wuyts+11**, Whitaker+12, Pannella+15, Förster-Schreiber & Wuyts+21

Part II : The main sequence of star-forming galaxies -- Dust temperature



- MS galaxies with vastly different SFR exhibit similar dust temperature. This temperature increases only slightly with redshift

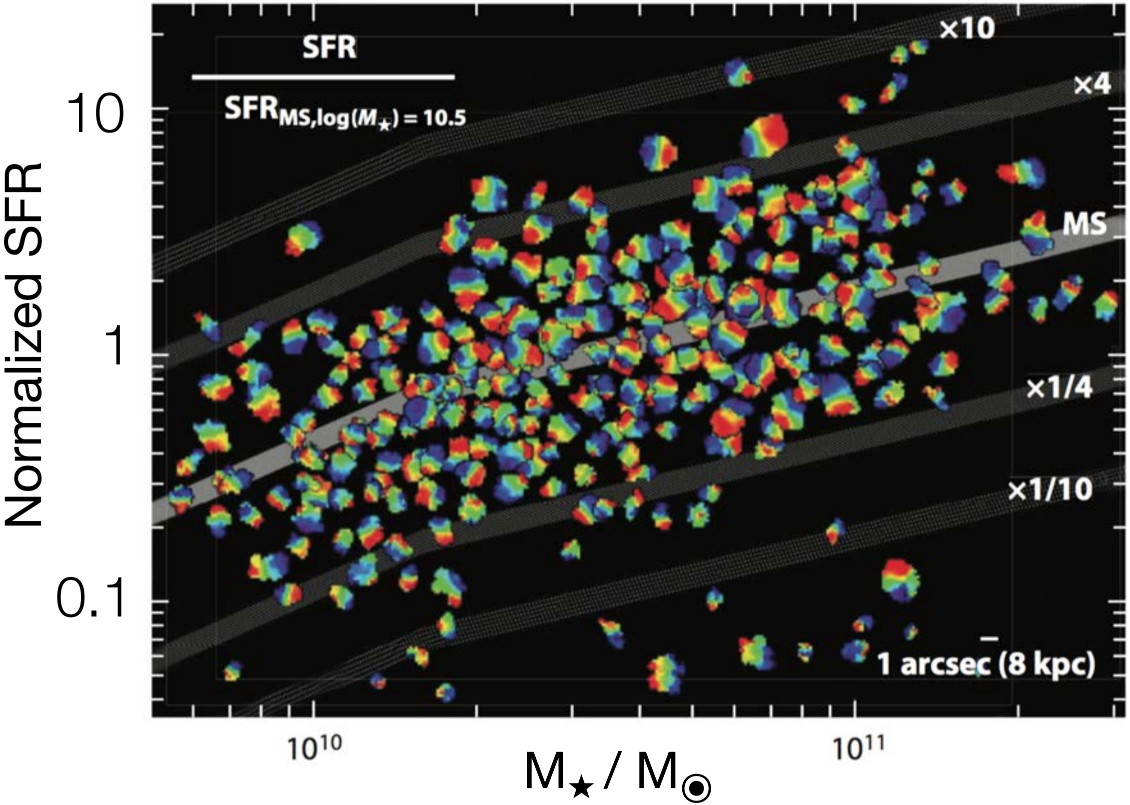
- SBs have higher dust temperatures, (suggesting higher SF efficiencies compared to MS) with little redshift evolution

$T_{\rm dust}$ and IR/UV suggest that on global scales, the properties of (massive) MS galaxies does not evolve significantly with SFR and redshift (~filling factor of relatively similar star-forming regions)

E.g., Magdis+12, **Magnelli+14**, Béthermin+15, Schreiber+18; Franco+20

Part II : The main sequence of star-forming galaxies -- Dynamics

Hα velocity fields (VLT-KMOS, near-IR, Hα at 2µm at z=2)



E.g., Genzel+11, Wisnioski+15+19, Förster-Schreiber+18, **Förster-Schreiber & Wuyts+21**

- Rotational support (v/σ) increases with mass and decreases with redshift

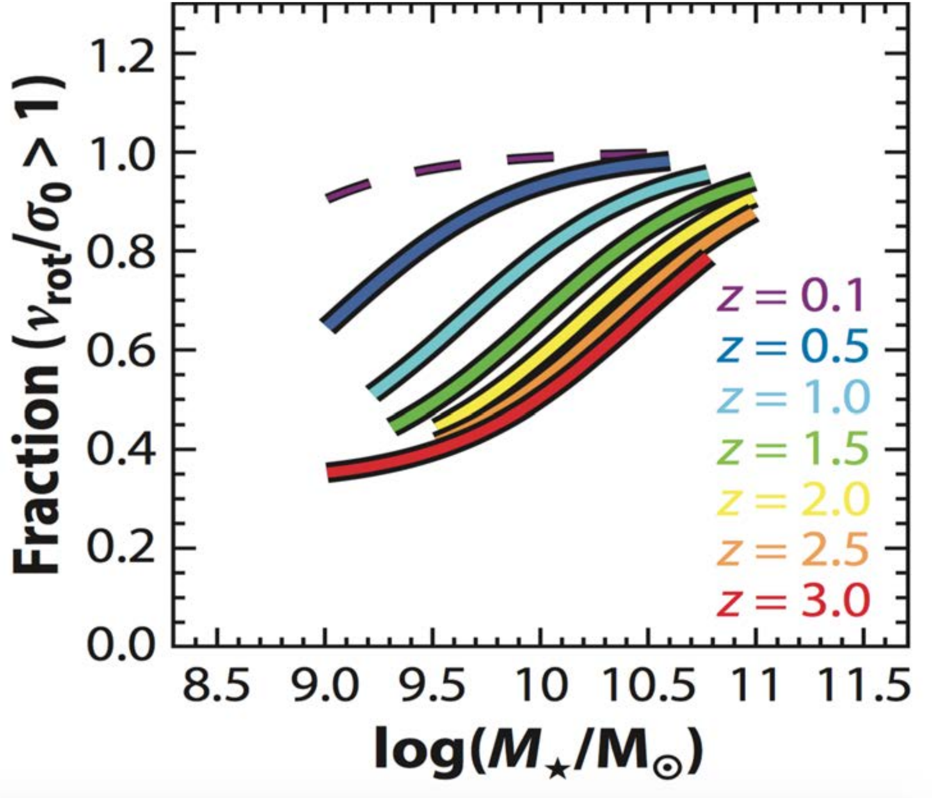
For Q ~ 1 disks (Toomre)

$$v \,/\, \sigma \sim 1 \,/\, f_{\text{gas}}$$

→ high-redshift MS galaxies are gas-rich (see later) and thus have a more turbulent ISM

Part II : The main sequence of star-forming galaxies -- Dynamics

Kinematics



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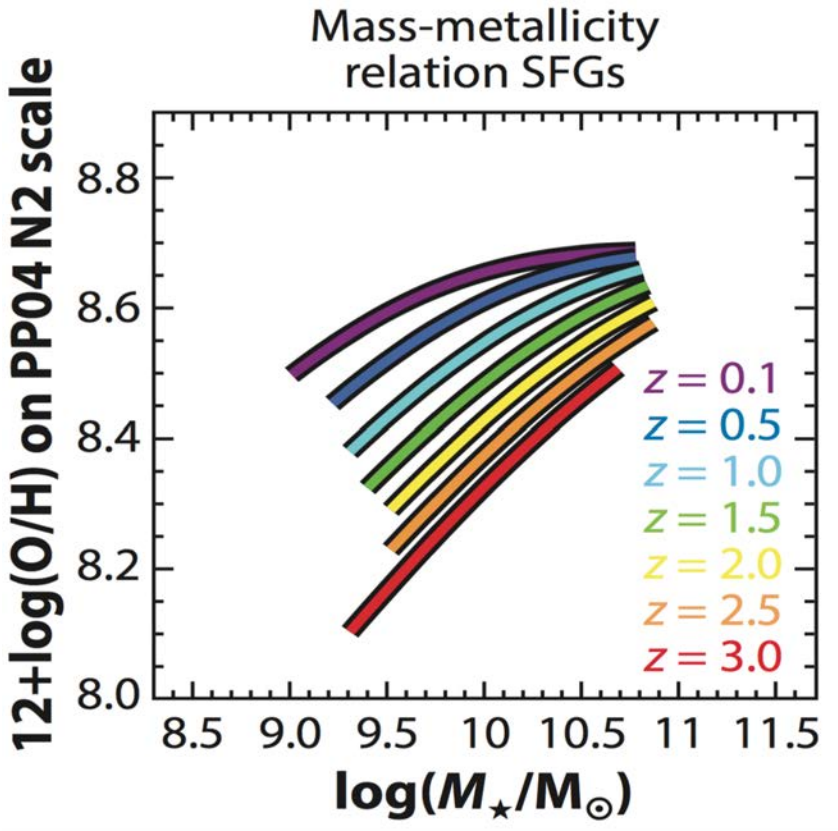
Part II : The main sequence of star-forming galaxies -- Mass vs. metallicity relation



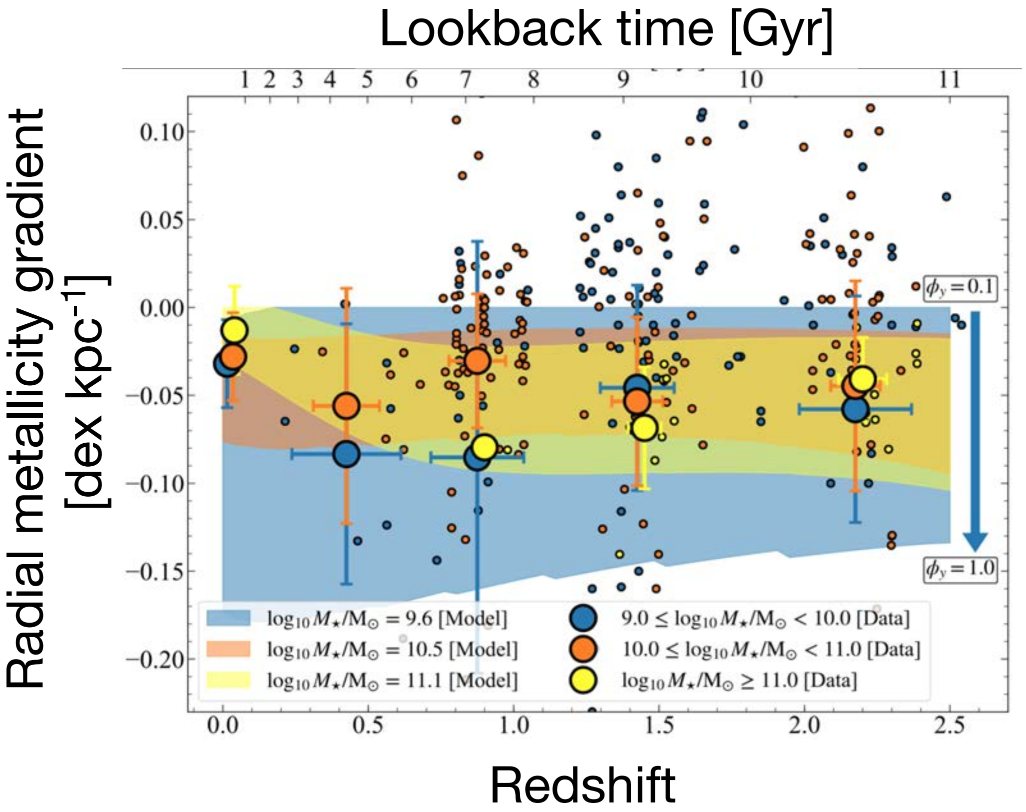
- Metallicity of MS galaxies increases with mass and decreases with redshift
(→ Metal enrichment by newly formed stars)

- SBs show lower metallicity than MS galaxies of similar mass and redshift
(→ inflow of pristine gas/HI (?))

→ The slope of the mass-metallicity relation can only be reproduced by models with efficient outflows in low mass galaxies (e.g., Davé+11)

E.g., Zahid+14, Wuyts+14, Kaasinen+17, Shapley+15+19, Maiolino & Mannucci+19, **Förster-Schreiber & Wuyts+21**

Part II : The main sequence of star-forming galaxies -- Radial metallicity gradient

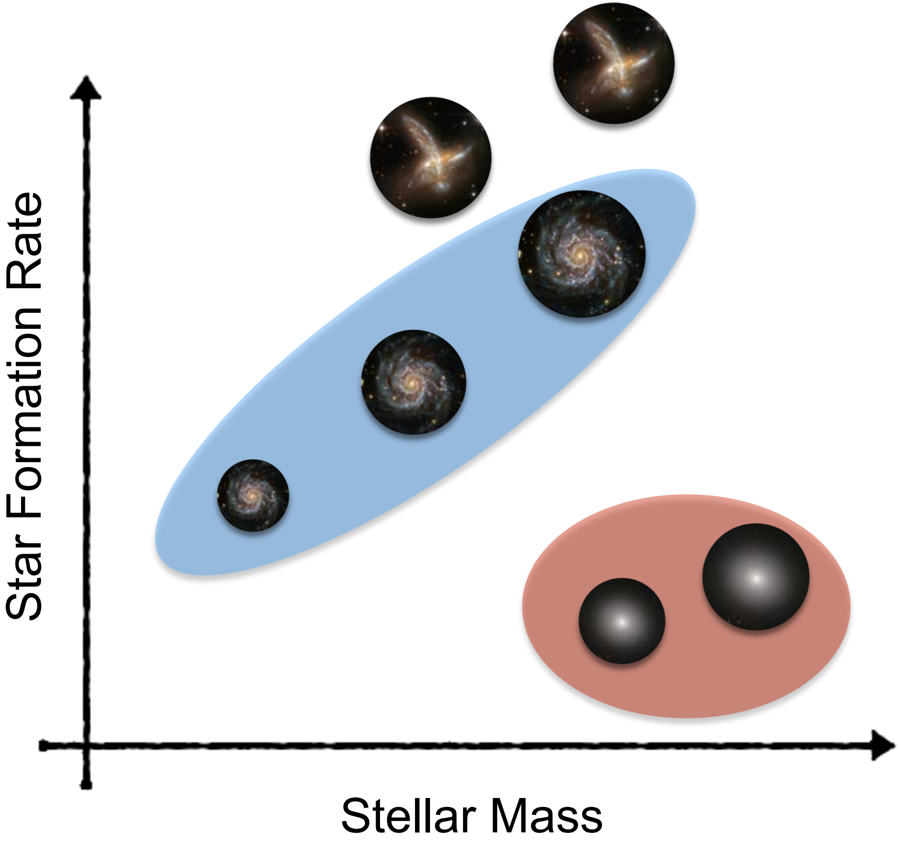


- Radial metallicity gradient are typically flat but with wide spread

→ Metal redistribution via outflows and turbulence/gas transport is important

E.g., **Shraba+21**

Part II : The main sequence of star-forming galaxies



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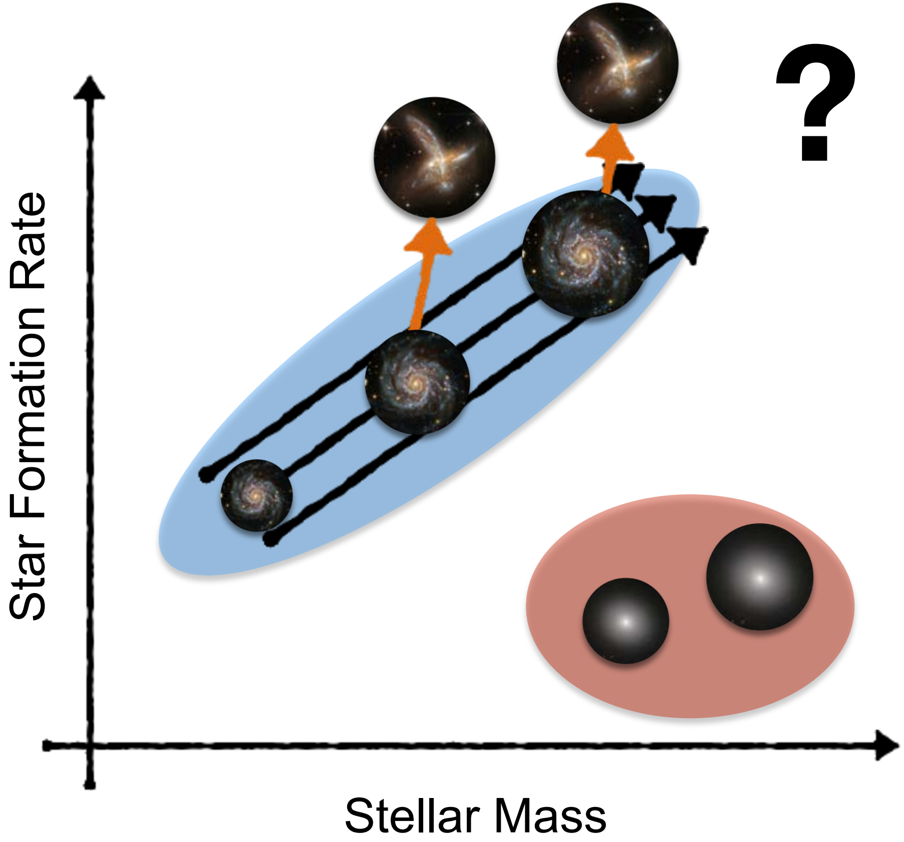
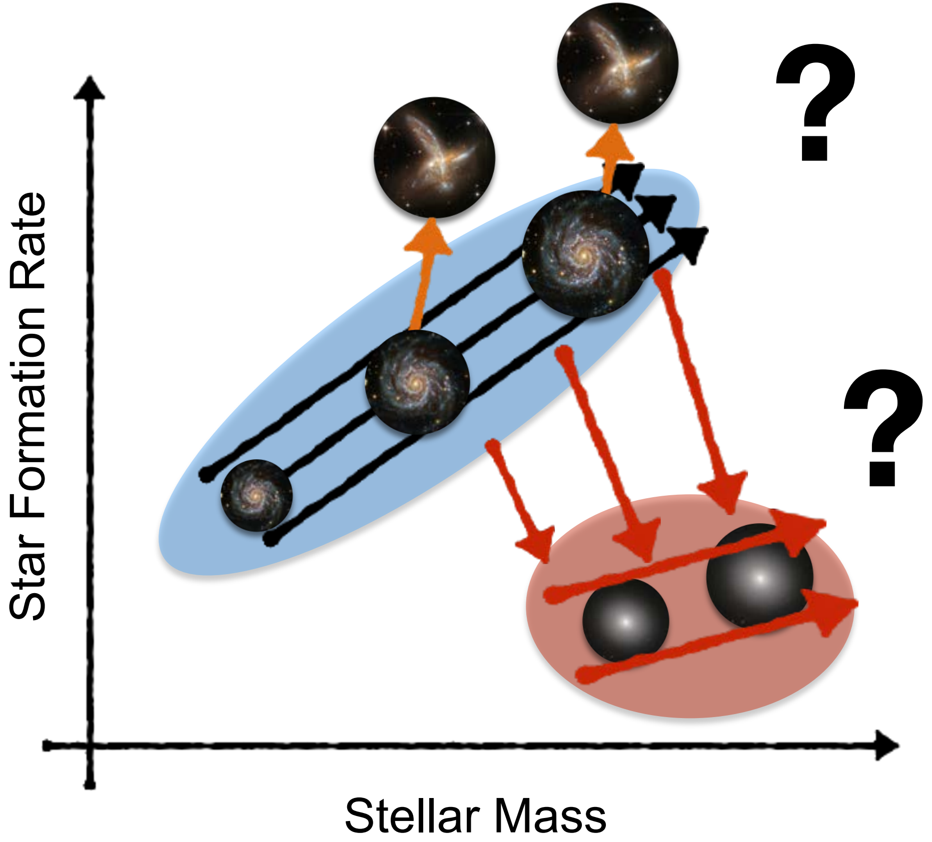


- What is the main driver regulating/triggering star formation in MS and SB galaxies ?
(Part III)

Part II : The main sequence of star-forming galaxies



- What is the main driver regulating/triggering star formation in MS and SB galaxies ?

(Part III)

- Which mechanism(s) quenches star formation and yields to the build up of the "red sequence" ?

(Part IV)

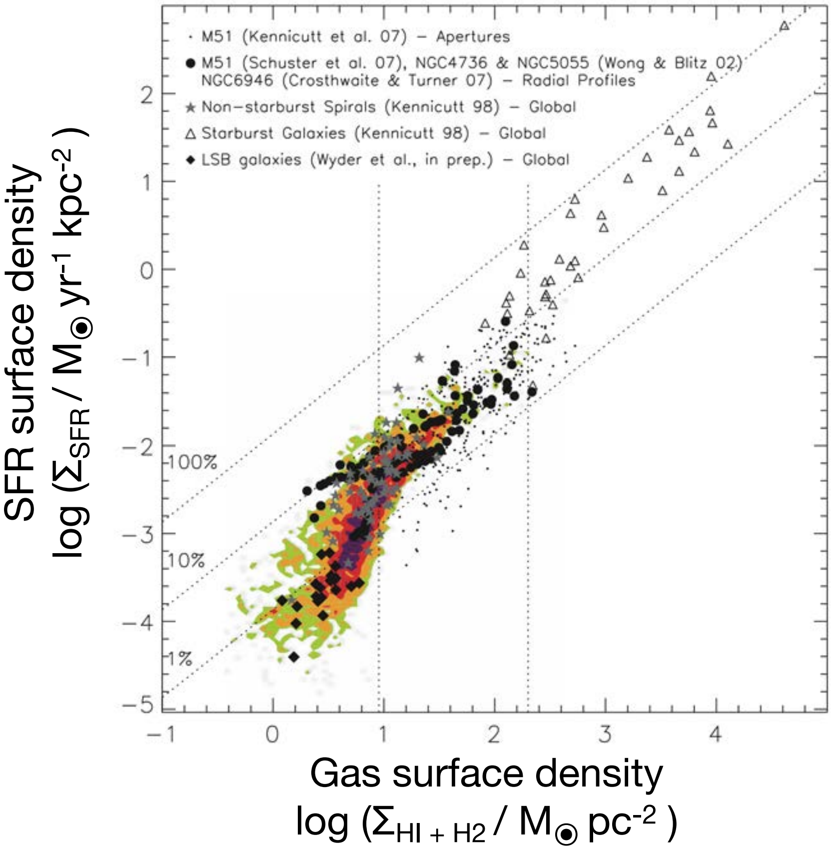
Part III :

gas is the main driver of galaxy formation & evolution

→*adding the fourth dimension of the gas content & state*

Gas scaling relations

Part III : The gas properties of MS galaxies -- The Schmidt-Kennicutt relation

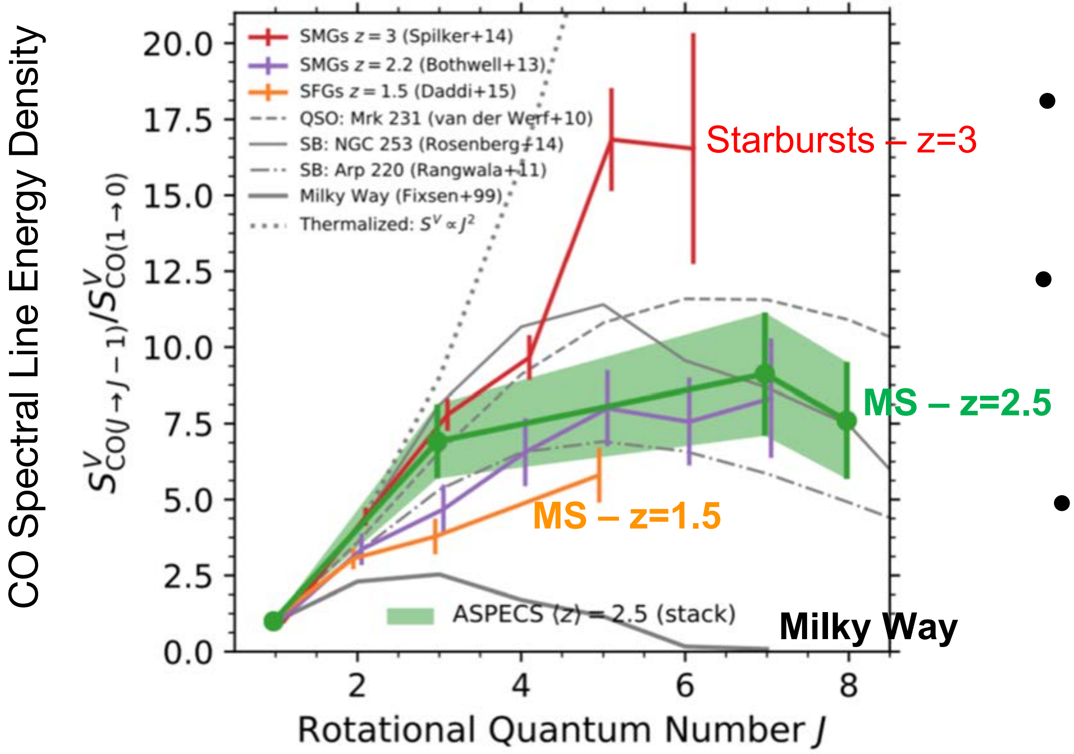


The tight correlation between Σ_{SFR} and Σ_{H2} (the so-called Schmidt-Kennicutt relation) suggests that the molecular gas phase is key to understand star formation

Due to the absence of strong dipole moment the H_2 gas is mostly traced indirectly via CO emission, i.e., the second most abundant molecules in giant molecular clouds

E.g., Kennicutt+98, Wong & Blitz+02, Schuster+07, **Bigiel+08**, Leroy+13, Momose+13, Miura+14, Shetty+14, de los Reyes & Kennicutt+18, Wilson+19, Wang & Hwang+20, Ellison+21, Pessa+21, Sánchez+21

Part III : The gas properties of MS galaxies -- CO SLED



Starbursts – z=3

MS – z=2.5

MS – z=1.5

Milky Way

- ALMA provides detailed constraints on the molecular gas properties ($T_{\rm ex}$, n) via (complete) CO spectral line energy density.
- MS galaxies exhibit somewhat warmer and denser molecular gas properties than the MW, more consistent with that observed in local starbursts
- high-z SBs exhibit highly-excited, nearly-thermalized up to J = 6 CO SLEDs

E.g., Weiss+05, Carilli & Walter+13, Daddi+15, Harrington+18, Cañameras+18, **Boogaard+20,** Valentino+20, Puglisi+21

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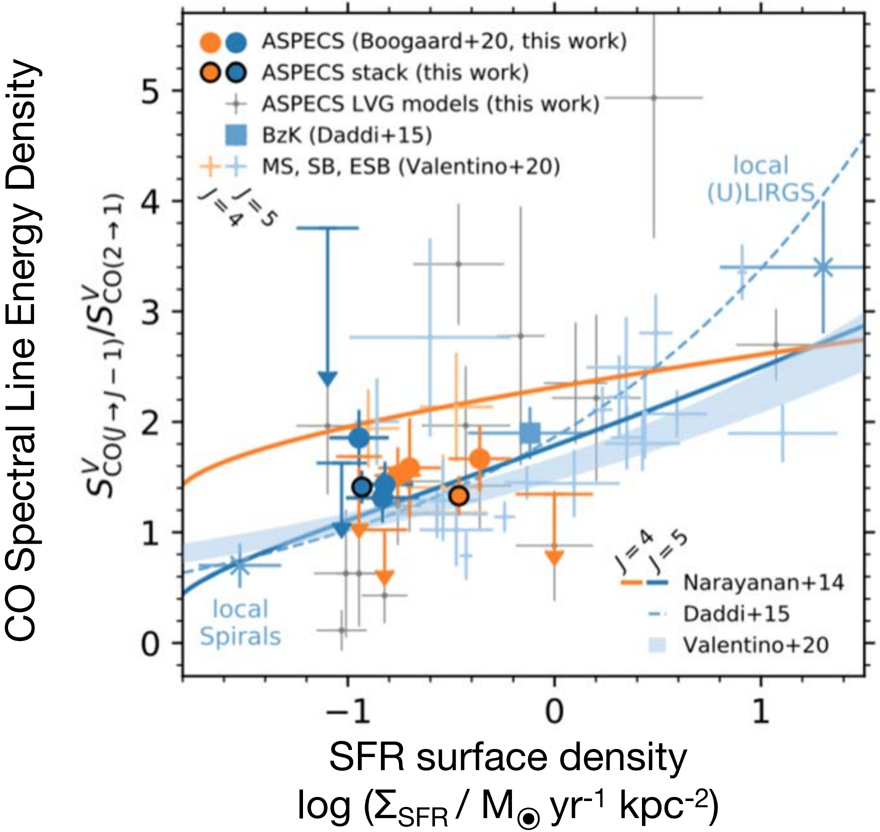

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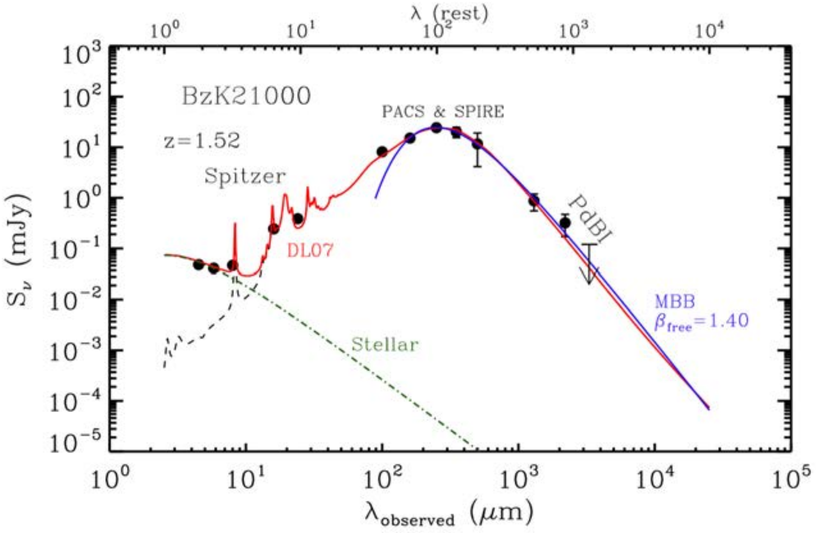
→ high-z MS galaxies have more excited CO SLEDs consistent with their high SFR surface densities

E.g., Weiss+05, Carilli & Walter+13, Daddi+15, Harrington+18, Cañameras+18, **Boogaard+20,** Valentino+20, Puglisi+21

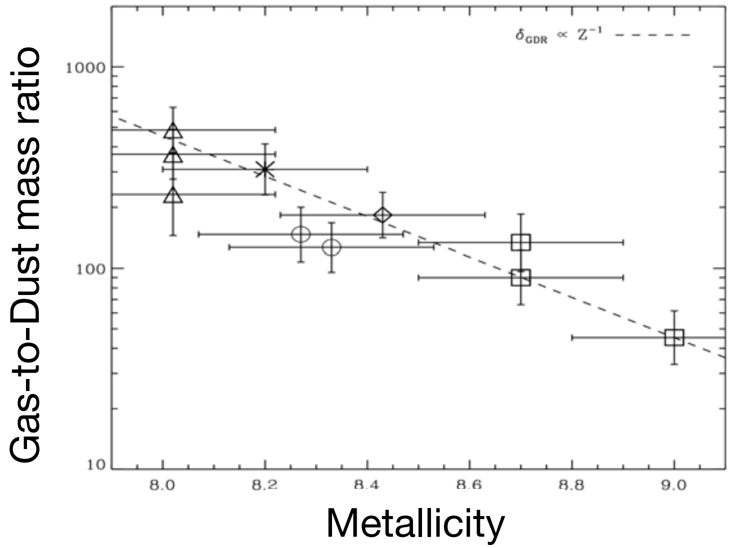
Part III :   The gas properties of MS galaxies -- Dust-based molecular gas masses

Unfortunately, CO observations of high-z MS galaxies still require hour(s) of observing time with ALMA.
→ Alternative proxy of the (molecular) gas: the dust-based approach (~mins with ALMA, albeit T_{dust})



$$M_{dust} = \frac{L_\nu}{4\pi\kappa_\nu B_\nu(T_d)} \qquad \kappa_\nu = \kappa_0\left(\frac{\nu}{\nu_0}\right)^\beta$$

+

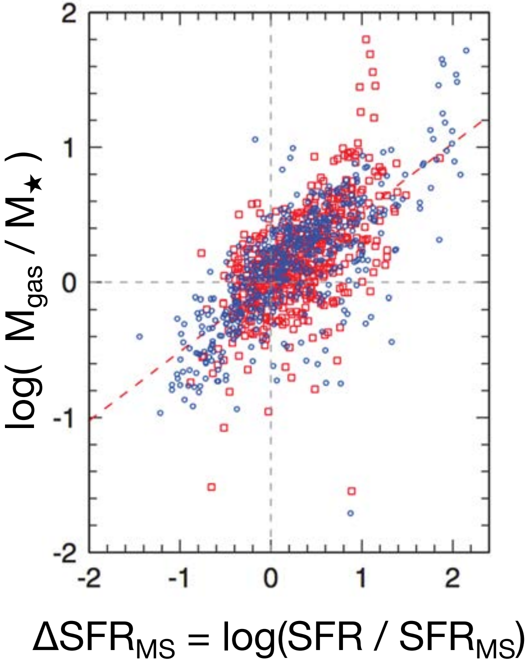


$$= M_{\mathbf{gas}}$$

E.g., **Leroy+11**, **Magdis+11+12**, Magnelli+12, Scoville+14+16, Schinnerer+16, Liu+19, T.M. Wang in prep.

Part III : The gas properties of MS galaxies -- (Molecular) Gas scaling relation

SBs have high
SF efficiencies and gas
fractions



E.g., Daddi+08+10, Tacconi+10+16+18+20, **Genzel+10+15**, Magdis+12, Saintonge+13, Magnelli+14+20, Bethermin+15, Schinnerer+16, Scoville+16+17, Liu+19, T.M. Wang in prep.

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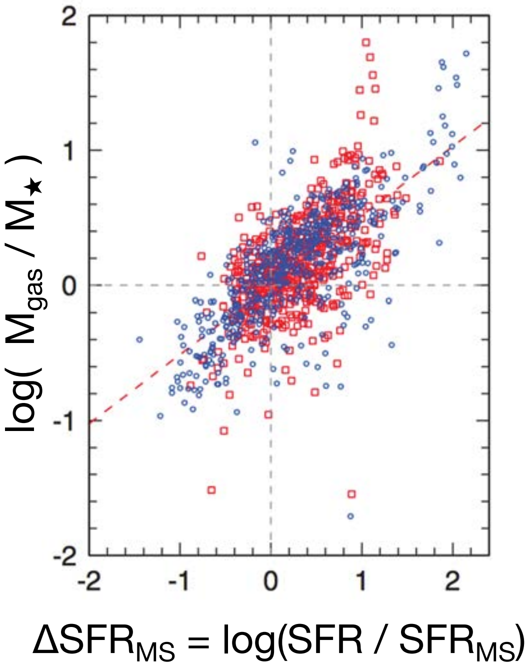
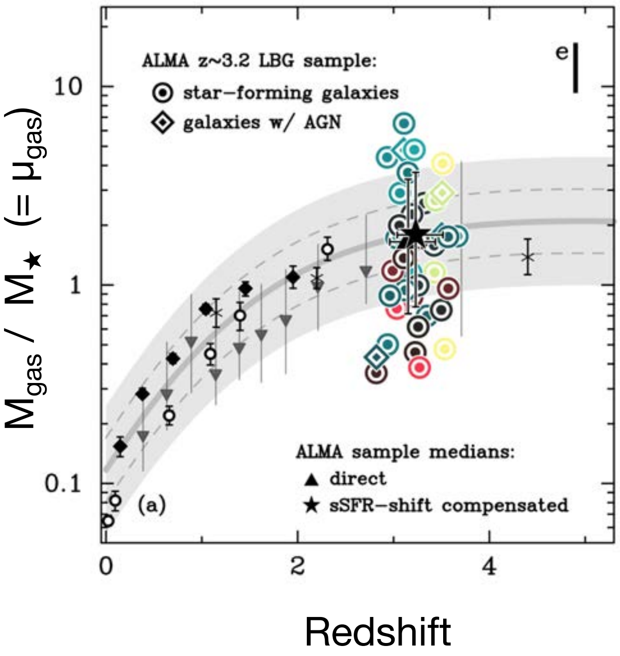


Higher gas fraction in high-redshift MS galaxies (milder SF efficiency evolution)



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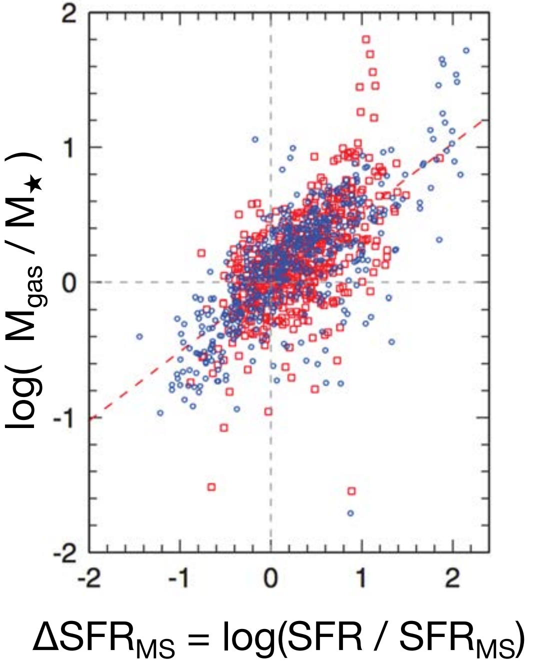

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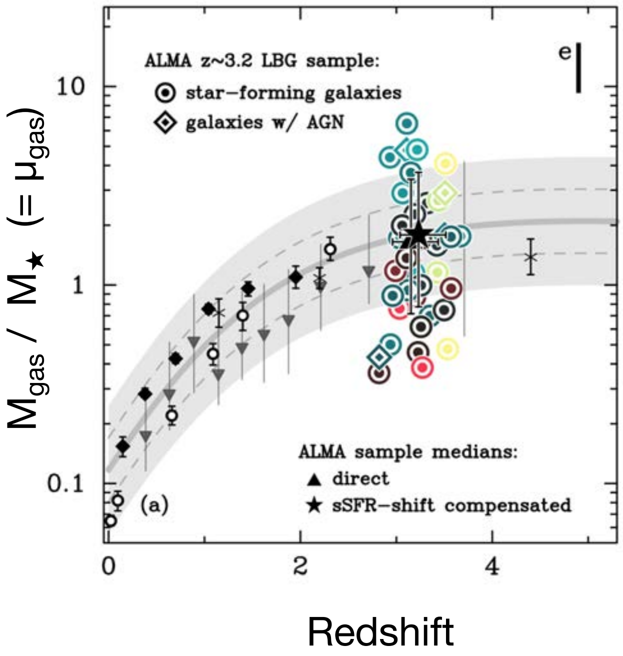
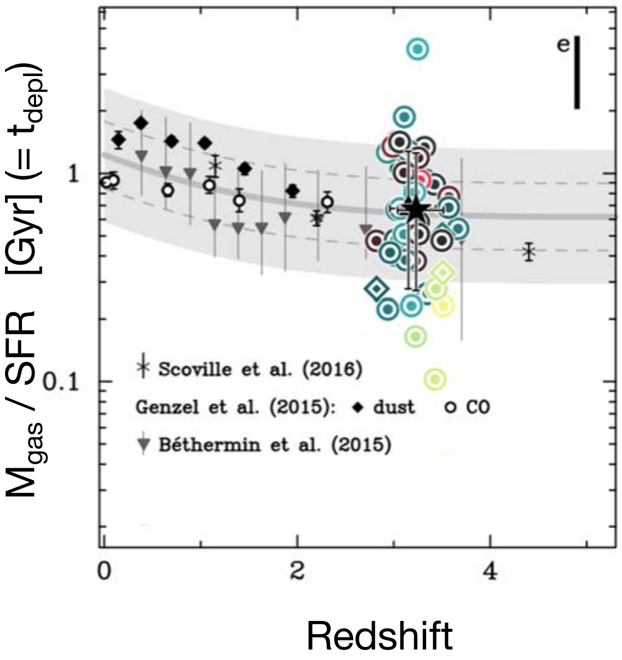


Small gas reservoir
—> Accretion of fresh gas
from the IGM



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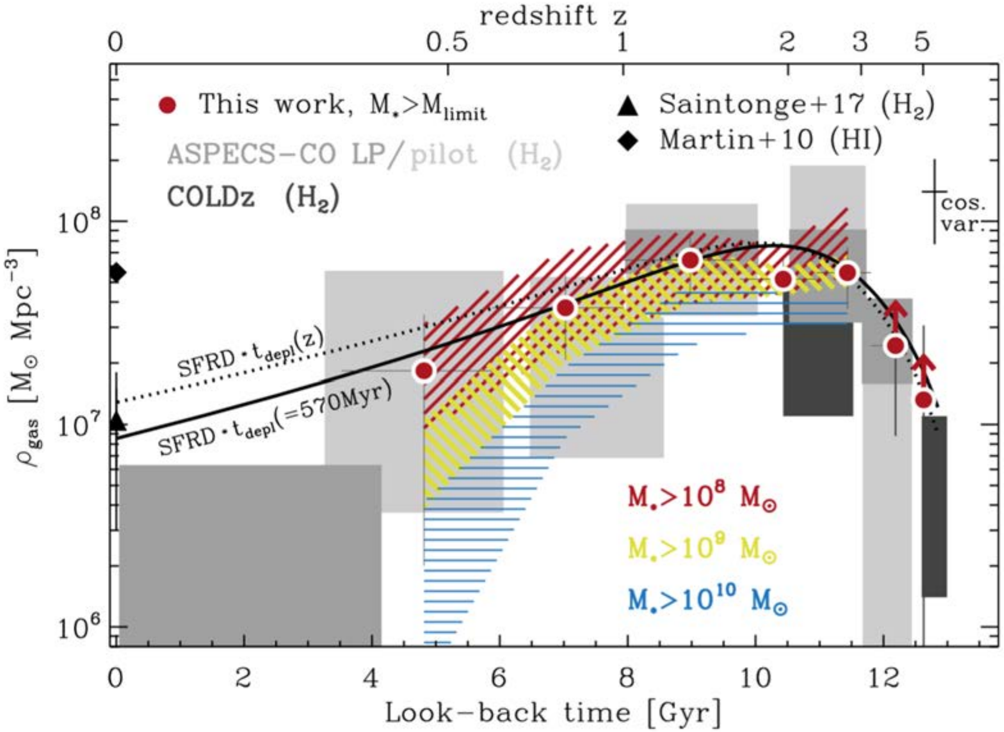
Part III : The gas properties of MS galaxies -- Cosmic Molecular Gas Mass Density

Molecular Gas Mass Density
≡ M$_\odot$ / comoving-Mpc^3



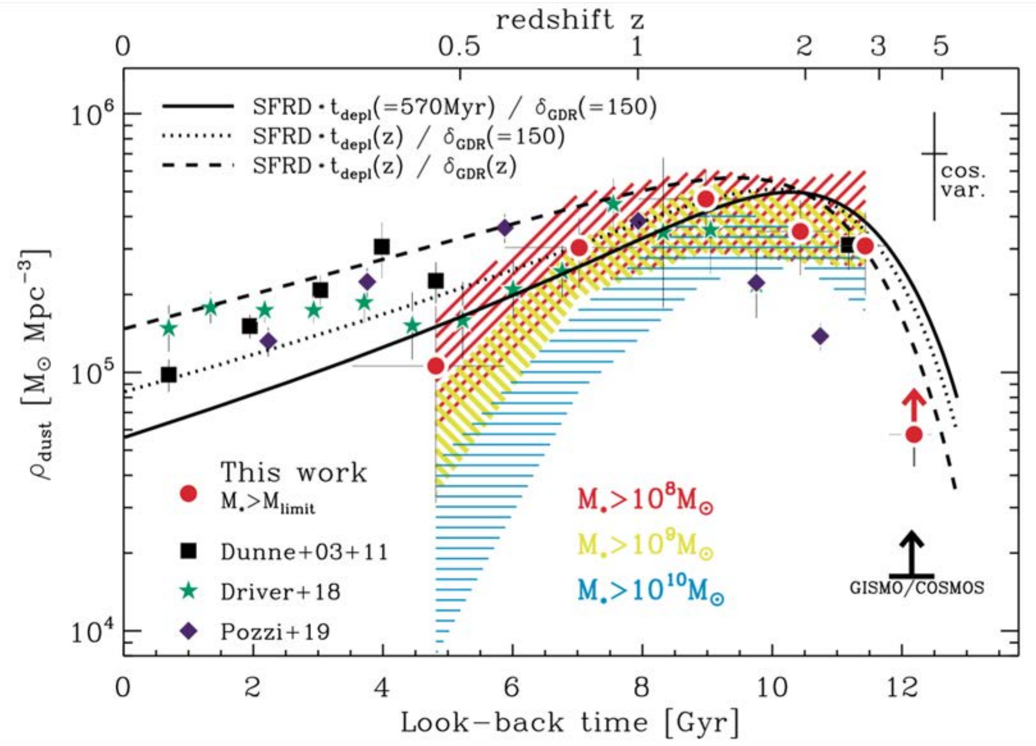
Also on global, cosmic-average scales, the evolution of the SFR density of the Universe seems driven by the availability of gas

At any given epoch, the average depletion time of the molecular gas reservoir of galaxies is ~600 Myr

E.g., Decarli+16,19, **Magnelli+20**, Walter+21

Part III : The gas properties of MS galaxies -- Cosmic Dust Mass Density

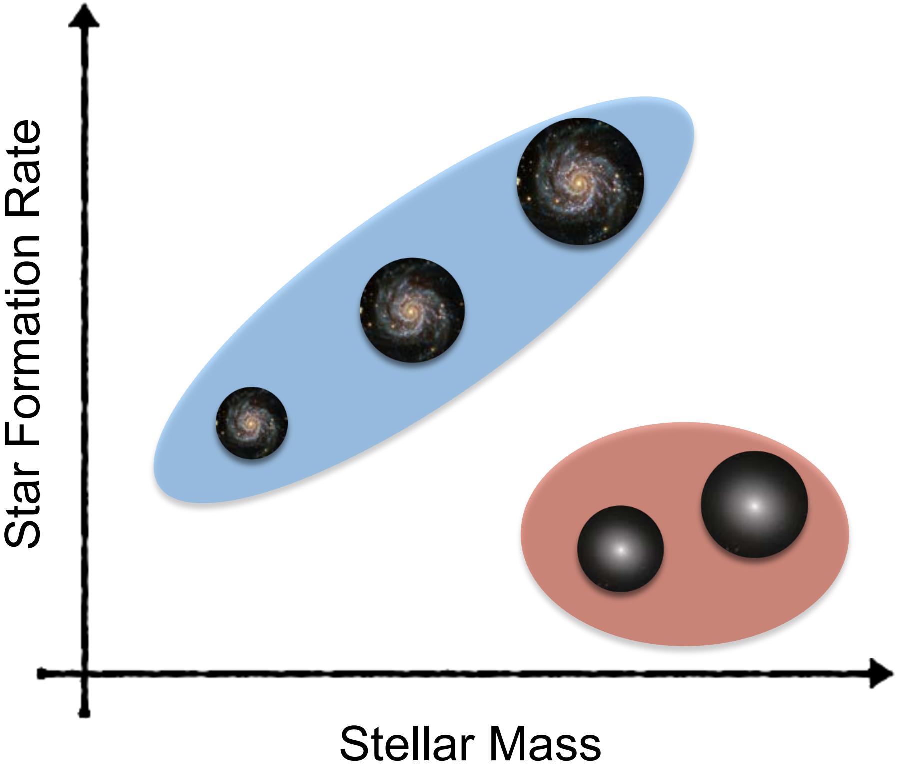
Dust Mass Density
≡ $M_\odot$ / comoving-Mpc^3



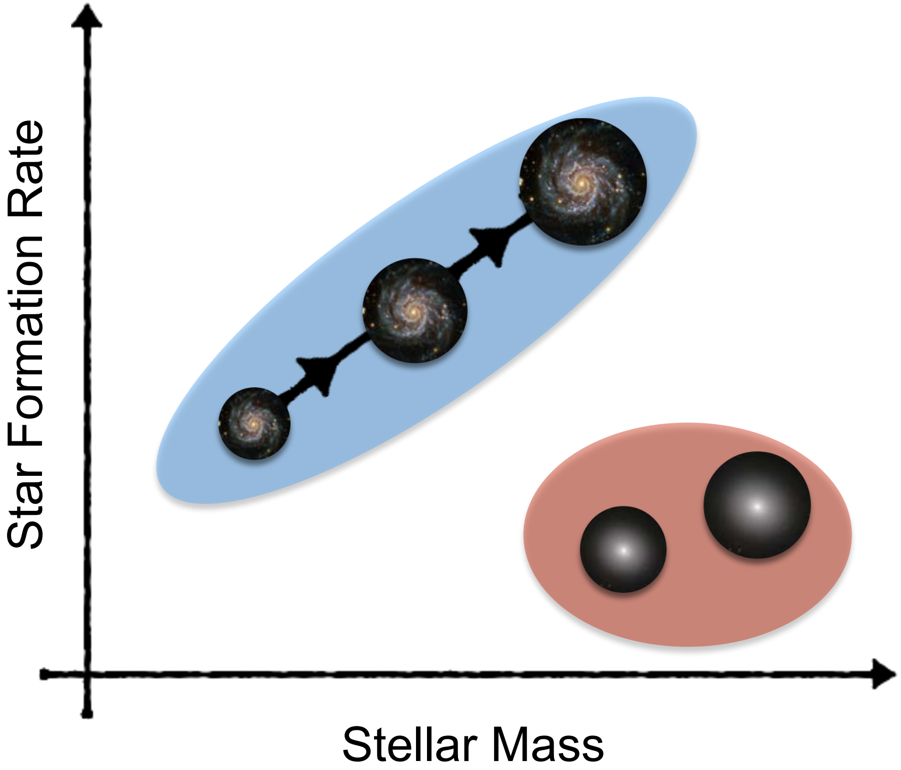
Very rapid build up of the cosmic dust mass density, suggesting very efficient dust yield at early time (SNe, AGB and ISM growth)

E.g., Driver+18, **Magnelli+20**, Pozzi+21

Part III : Galaxy evolution : a new paradigm

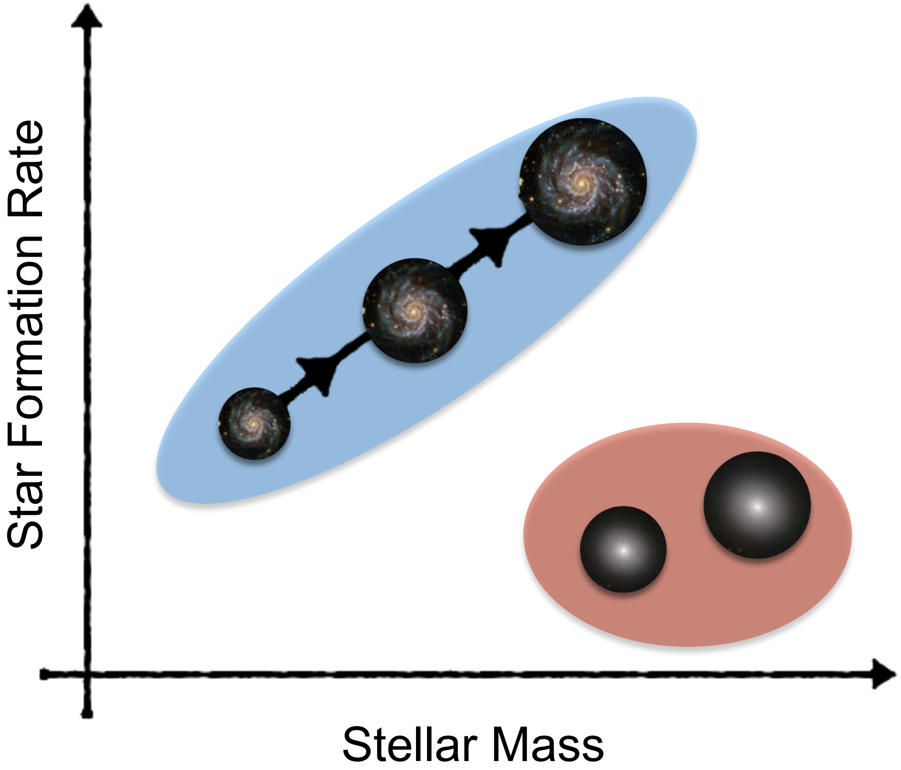


Part III : Galaxy evolution : a new paradigm



- The tightness and time-independent shape of the MS suggests long star formation duty cycles (>few Gyrs)

Part III : Galaxy evolution : a new paradigm



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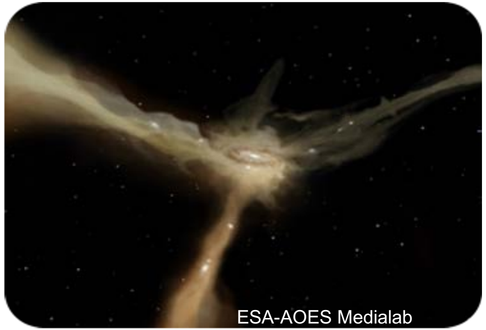
ESA-AOES Medialab

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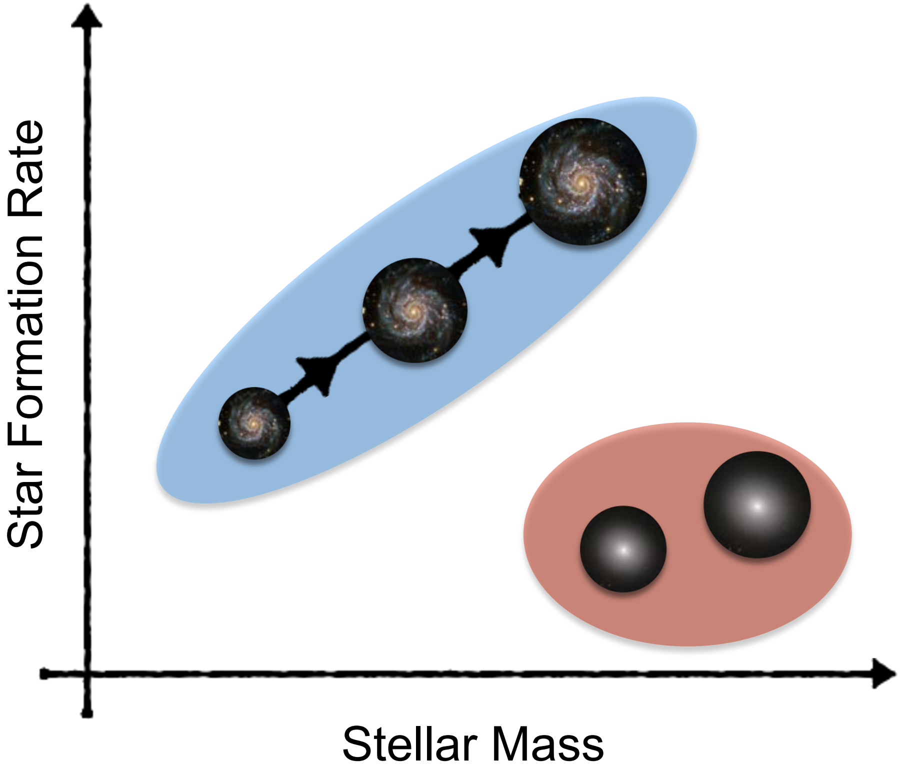

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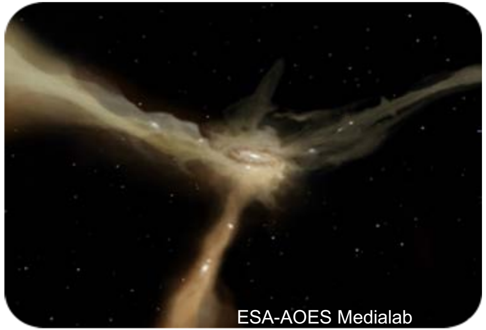
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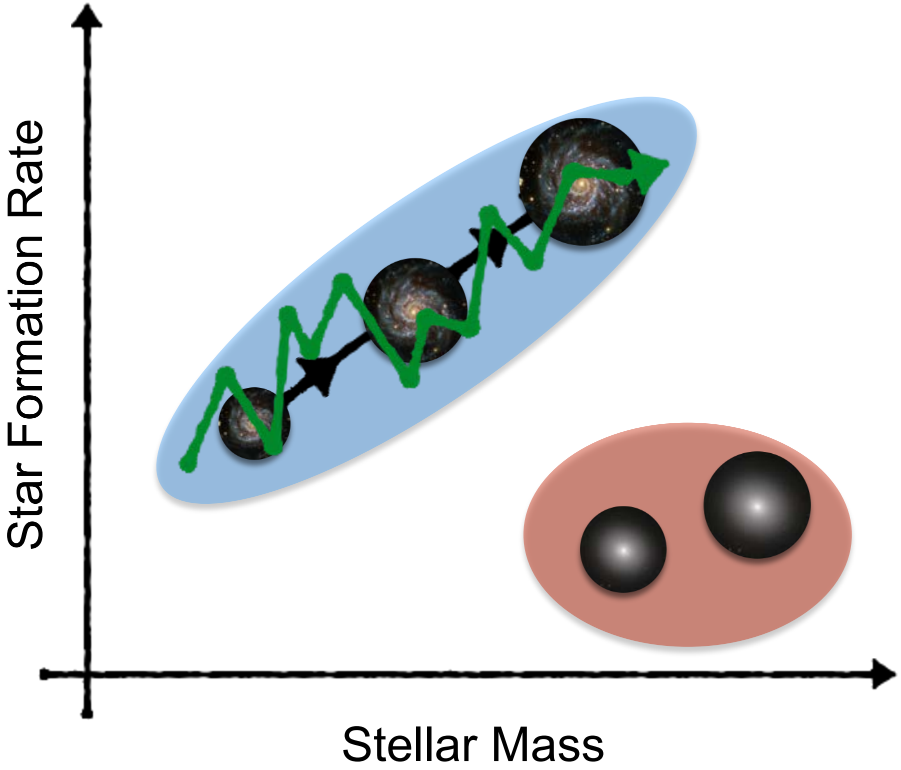

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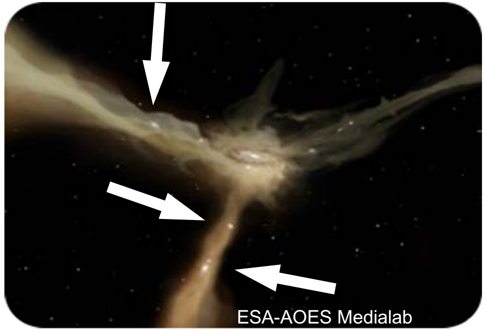
- The MS dispersion could be due to short timescale variation (e.g. minor mergers) of the gas supply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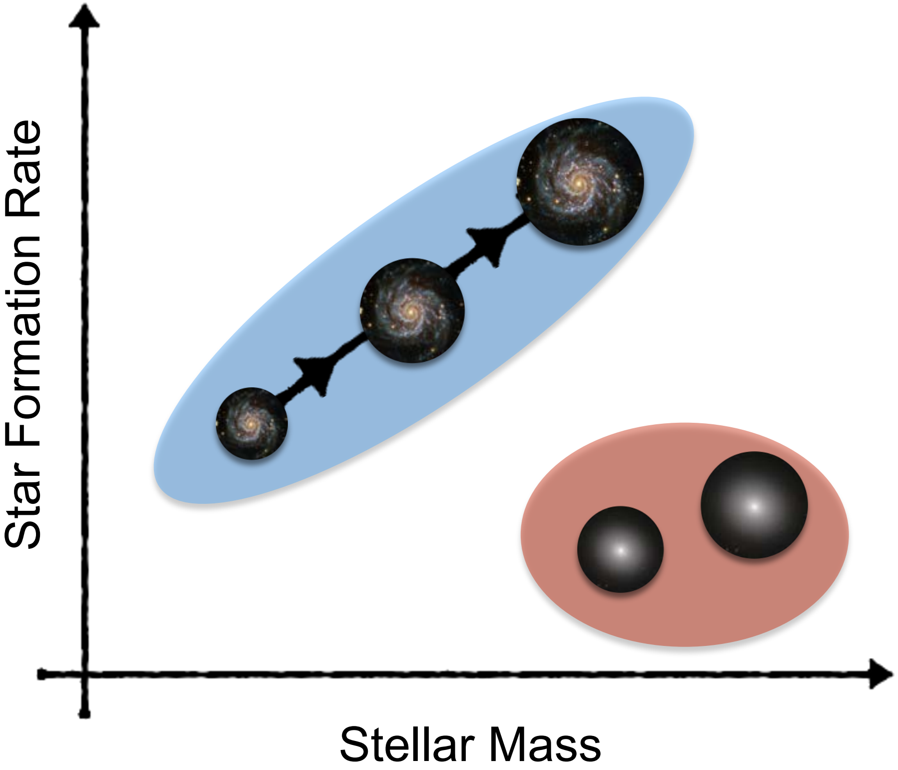
Part III : Galaxy evolution : a new paradigm

The bulk of the SFG population seems to grow along the MS in an equilibrium of gas accretion, star formation, and gas outflows : the "gas regulator models"



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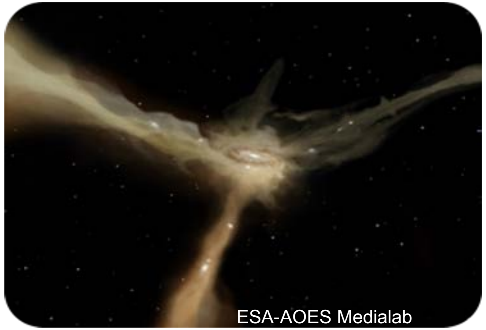
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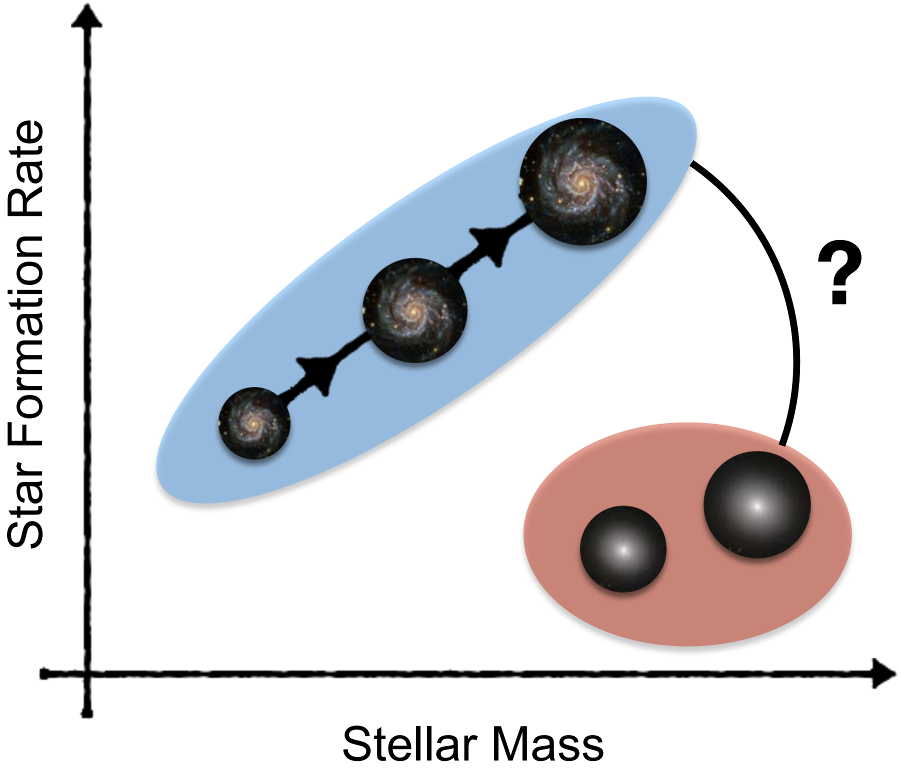
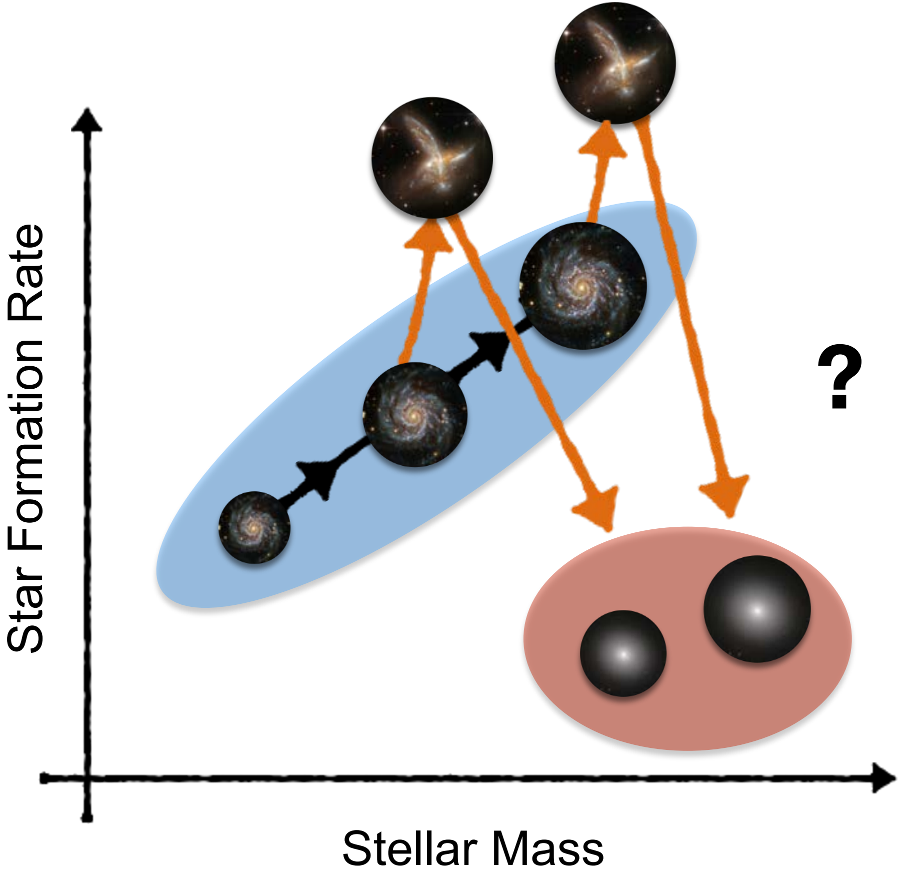
Part III : Galaxy evolution : a new paradigm



The origin of local "red" and "dead" ellipticals still remains unknown…

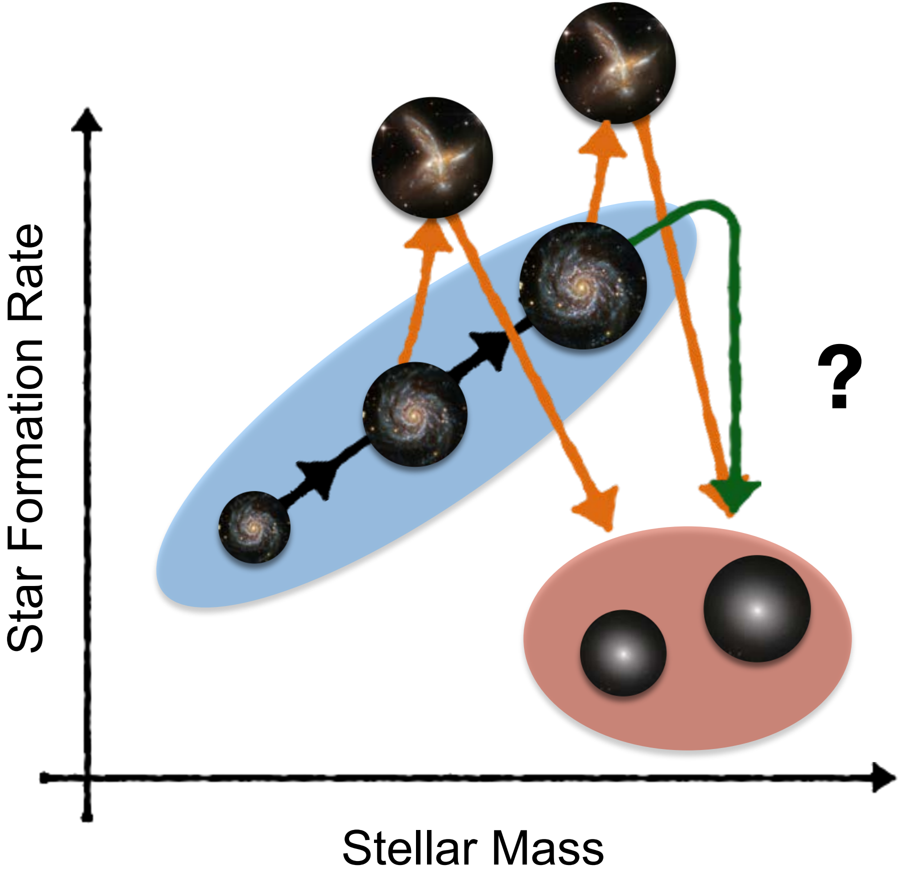
Part III :   Galaxy evolution : a new paradigm



The origin of local "red" and "dead" ellipticals still remains unknown…

… major mergers, triggering short-live SBs

Part III : Galaxy evolution : a new paradigm



The origin of local "red" and "dead" ellipticals still remains unknown…

… major mergers, triggering short-live SBs

… or more secular quenching mechanisms

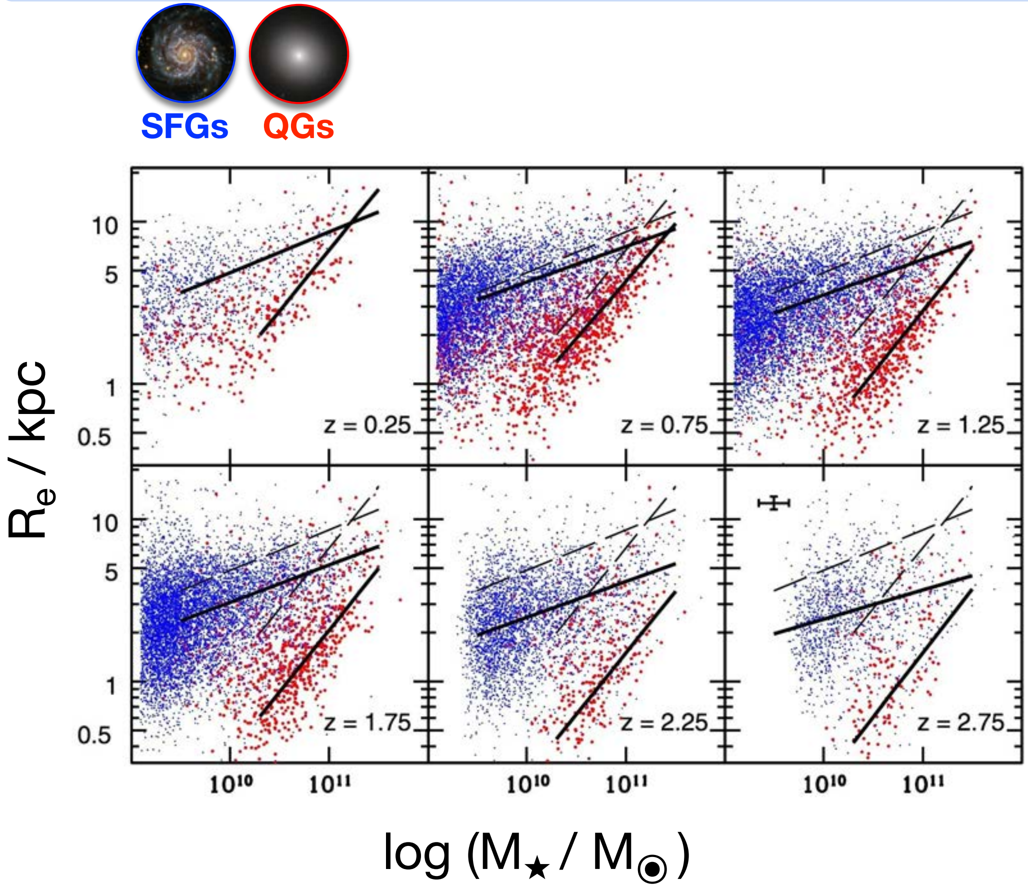
Part IV :

gas infall is the main driver of galaxy evolution

→*why do galaxies become passive?…*

The quenching of star formation

Part IV : The quenching of star formation -- Size evolution



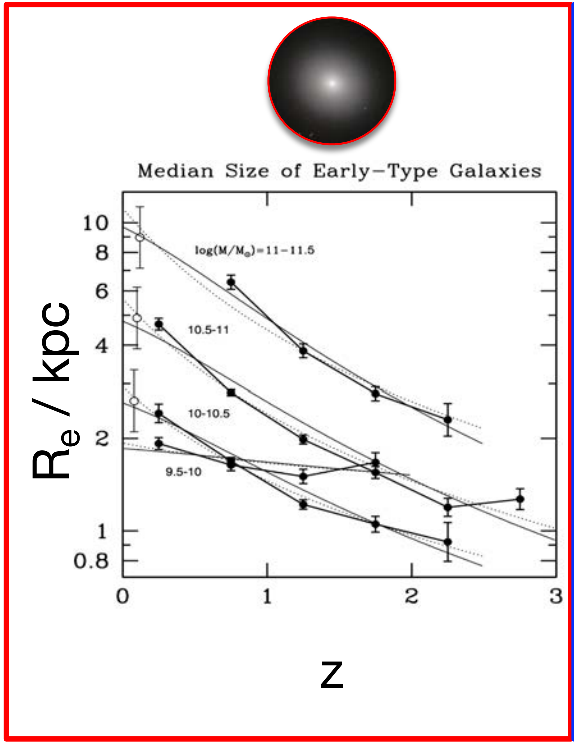
- Stellar sizes increase with stellar mass

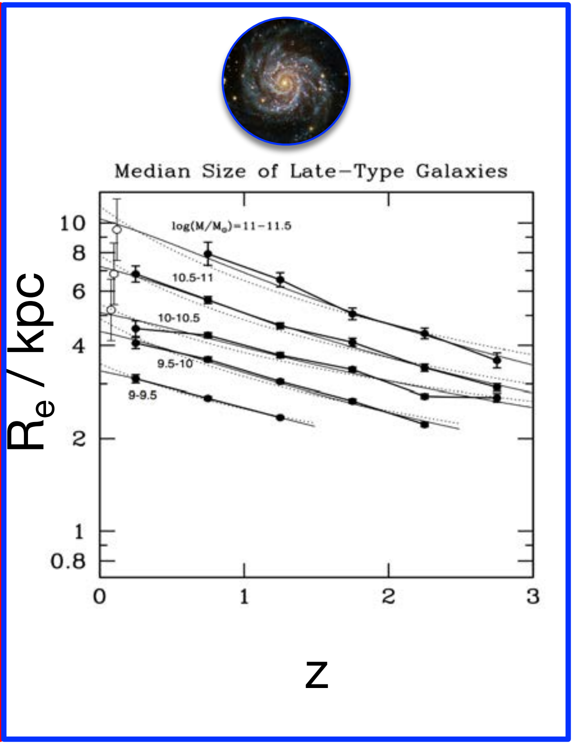
SFGs: $R_e \propto M_*^{0.22}$

QGs: $R_e \propto M_*^{0.75}$

E.g., Kormendy & Bender+96, Shen+03, Ferguson+04; Trujillo+06+07, Buitrago+08, Cimatti+08, van Dokkum+08, Williams+09; Conselice+11, Barro+13, **van der Wel+12+14**, Mowla+19, Suess+19

Part IV : The quenching of star formation -- Size evolution





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- Stellar sizes decrease with redshift

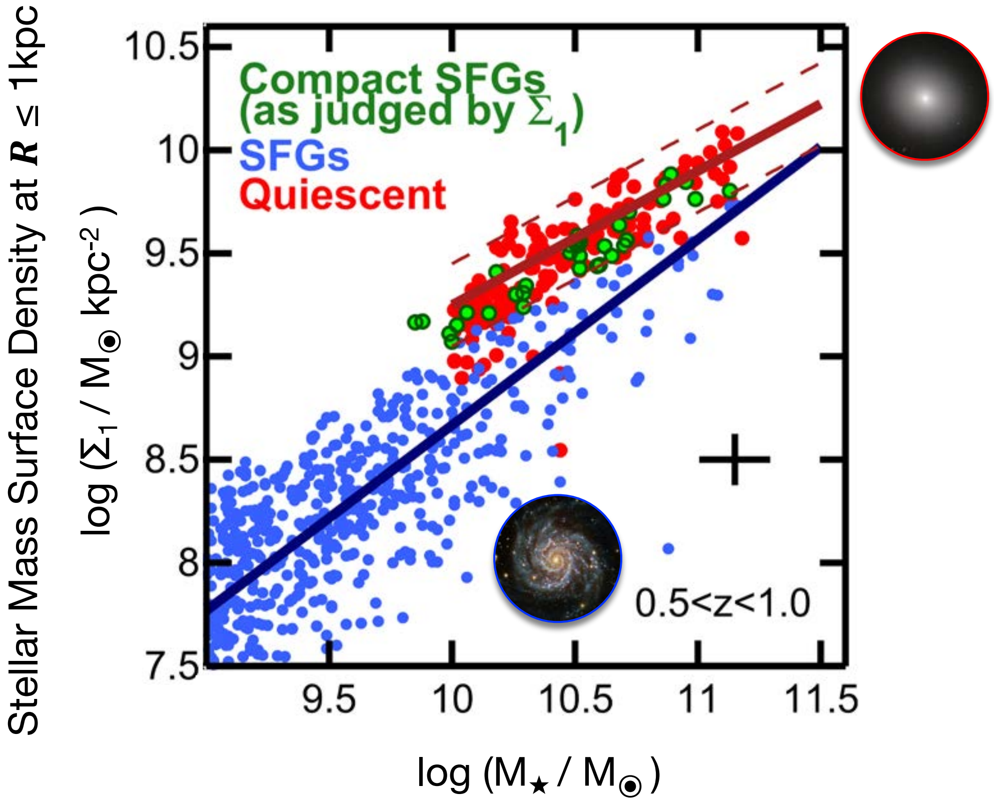
  SFGs: $R_e \propto (1 + z)^{-0.75}$

  QGs: $R_e \propto (1 + z)^{-1.48}$

Stronger size evolution for QGs

E.g., Kormendy & Bender+96, Shen+03, Ferguson+04; Trujillo+06+07, Buitrago+08, Cimatti+08, van Dokkum+08, Williams+09; Conselice+11, Barro+13, **van der Wel+12+14**, Mowla+19, Suess+19

Part IV : The quenching of star formation -- Size evolution



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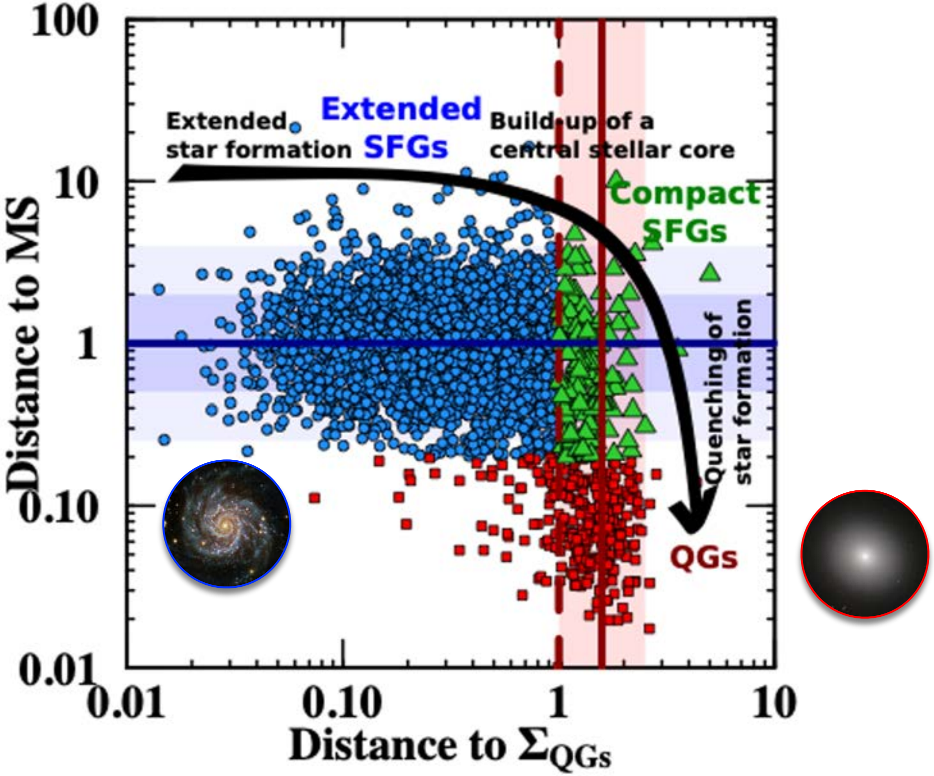
- QGs are denser than SFGs

E.g., Kauffmann+03, Brinchmann+04, Cheung+12, Fang+13, van Dokkum+14, Whitaker+17, **Barro+17**, Lee+18, Gómez-Guijarro+19, Suess+21

Part IV : The quenching of star formation -- Size evolution



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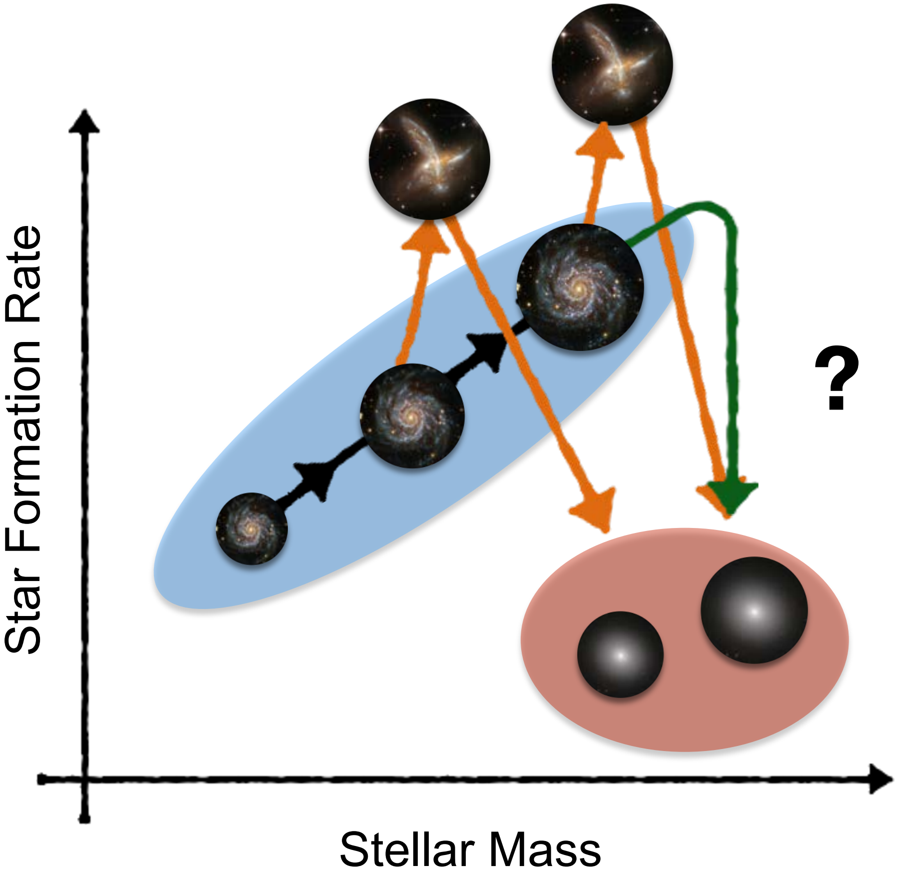
- The build-up of compact stellar cores precedes galaxy quenching

E.g., Kauffmann+03, Brinchmann+04, Cheung+12, Fang+13, van Dokkum+14, Whitaker+17, Barro+17, Lee+18, **Gómez-Guijarro+19**, Suess+21

Part IV : The quenching of star formation -- Rapid vs secular evolution

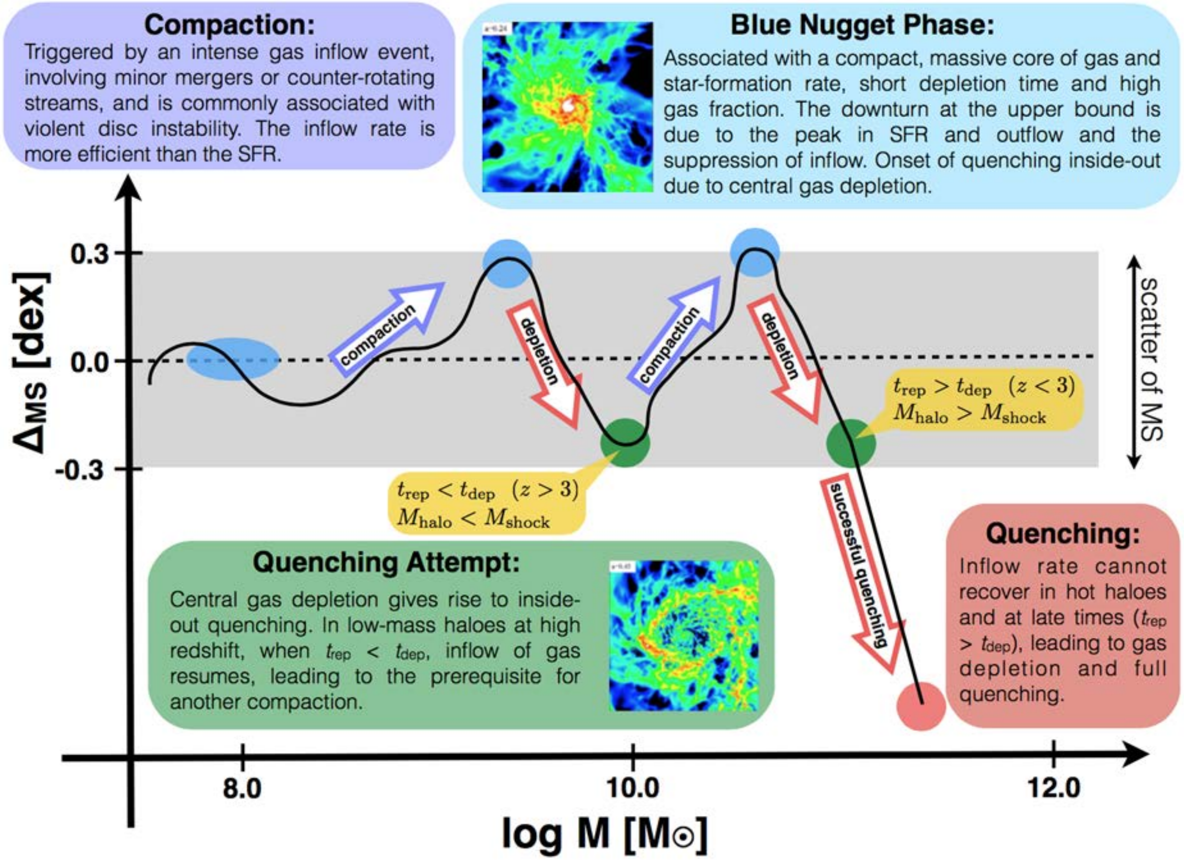


The origin of local “red” and “dead” ellipticals still remains unknown…

… major mergers, triggering short-live SBs

… or more secular quenching mechanisms

Part IV : The quenching of star formation -- Compaction



Compaction:
Triggered by an intense gas inflow event, involving minor mergers or counter-rotating streams, and is commonly associated with violent disc instability. The inflow rate is more efficient than the SFR.

Blue Nugget Phase:
Associated with a compact, massive core of gas and star-formation rate, short depletion time and high gas fraction. The downturn at the upper bound is due to the peak in SFR and outflow and the suppression of inflow. Onset of quenching inside-out due to central gas depletion.

Quenching Attempt:
Central gas depletion gives rise to inside-out quenching. In low-mass haloes at high redshift, when $t_{\rm rep} < t_{\rm dep}$, inflow of gas resumes, leading to the prerequisite for another compaction.

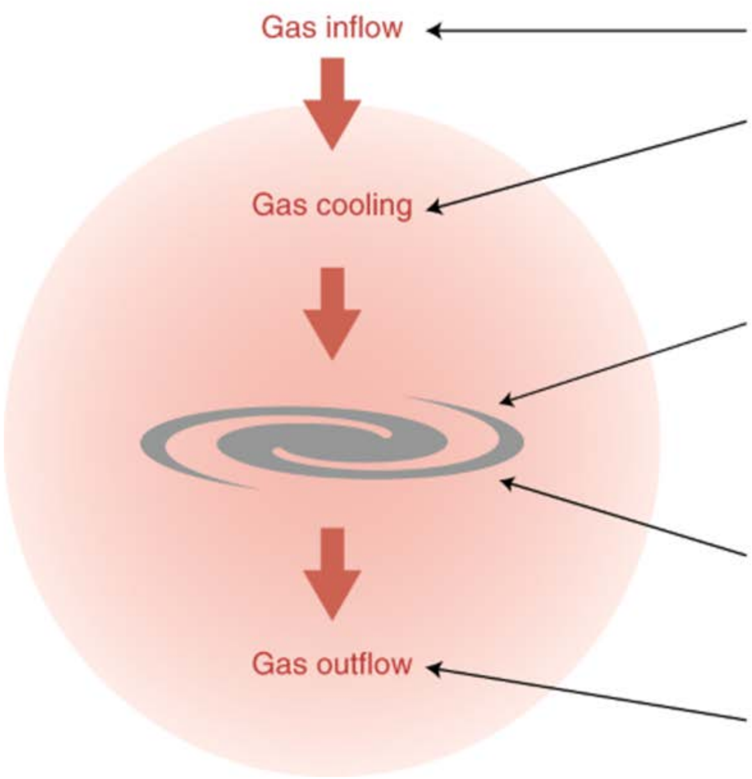
Quenching:
Inflow rate cannot recover in hot haloes and at late times ($t_{\rm rep} > t_{\rm dep}$), leading to gas depletion and full quenching.

- Rapid: Mergers are capable of triggering short-lived starburst episodes of compact star formation
- Secular: Accretion and efficient gas transport inwards builds up compact stellar cores
- Either rapid or secular, quenching could be linked to the halo mass

E.g., Cimatti+08, Fu+13, Ivison+13, Dekel+13, Zolotov+15, **Tacchella+16**, Toft+14, Barro+17, Elbaz+18, Gómez-Guijarro+18+19, Puglisi+19+21, Jiménez-Andrade+19, Franco+20

Part IV : The quenching of star formation -- Mechanisms

What causes quenching in massive galaxies?



(i) **Gas does not accrete**
- Cosmological starvation

(ii) **Gas does not cool**
- Virial shock heating
- AGN feedback
- Gravitational heating
- Stellar feedback

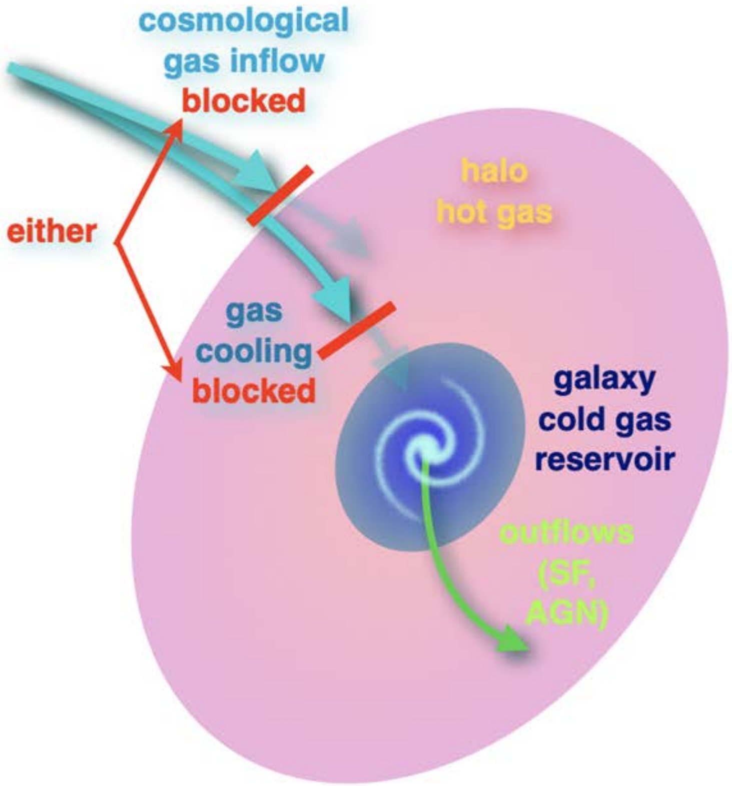
(iii) **Cold gas does not form stars**
- Morphological quenching
- Bar quenching
- AGN feedback
- Magnetic fields

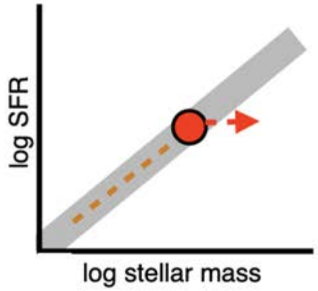
(iv) **Cold gas is rapidly consumed**
- Mergers
- Disk instabilities
- Positive AGN feedback

(v) **Gas is removed**
- AGN feedback

Man & Belli (2018)

Part IV : The quenching of star formation -- Halo mass





Either cosmological inflows or cooling from halo are stopped, galaxy gas reservoir is now no longer replenished

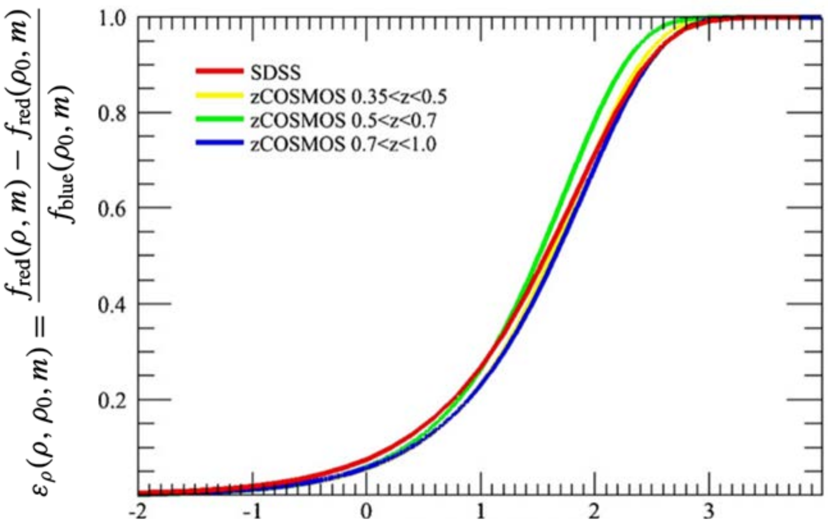
Galaxy leaves main sequence

E.g., Rees+77, Birnboim & Dekel+03, Croton+06, Bower+06, **Schawinski+14**, Feldmann+15

Part IV : The quenching of star formation -- Environment

Differential effects of environment on the fraction of galaxies that are actively forming stars compared with those that are passive

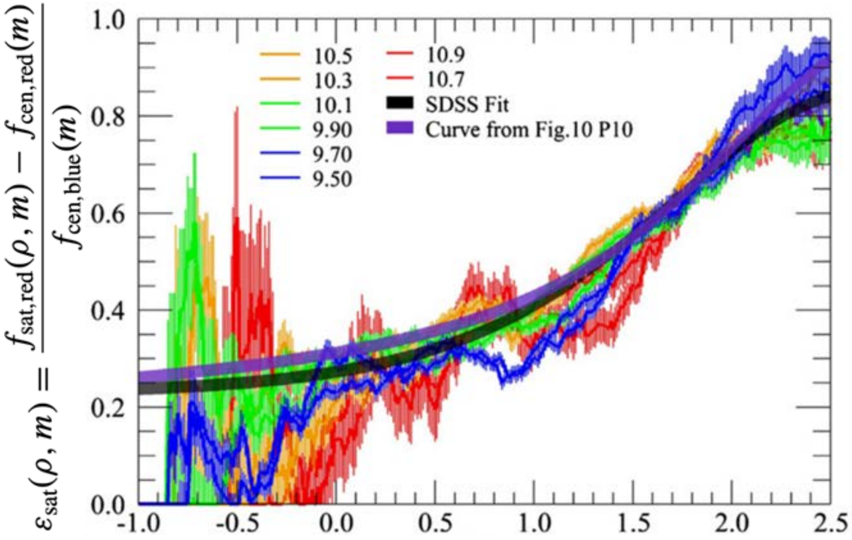
Environmental quenching efficiency



Overdensity log (1 + δ)

Environmental effects important in satellite galaxies

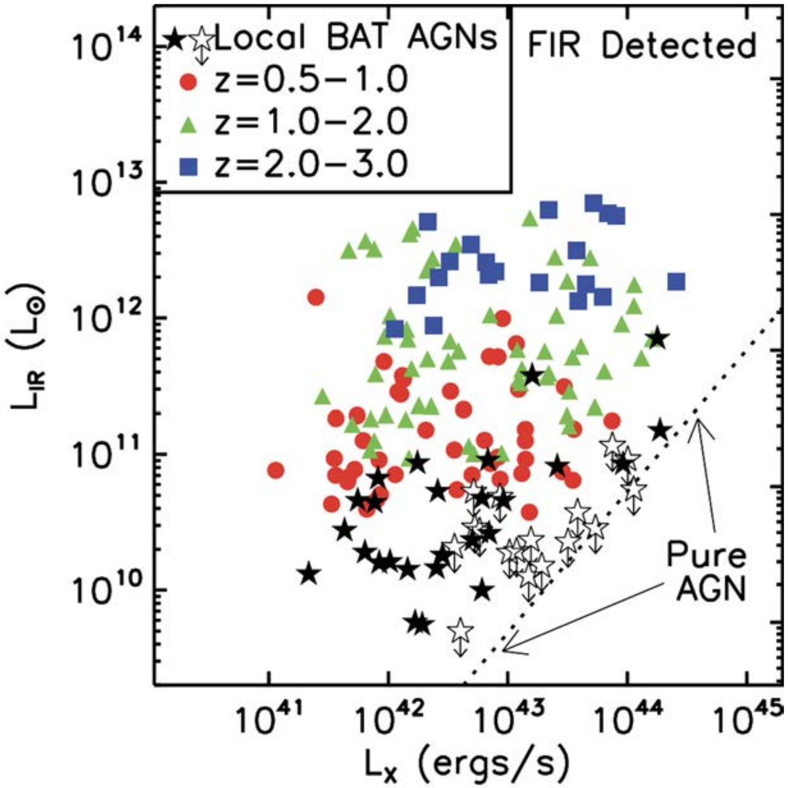
Satellite quenching efficiency



Overdensity log (1 + δ)

E.g., **Peng+10+12**, Lin+12, Fossati+17, Ji+18

Part IV : The quenching of star formation -- AGN and SF



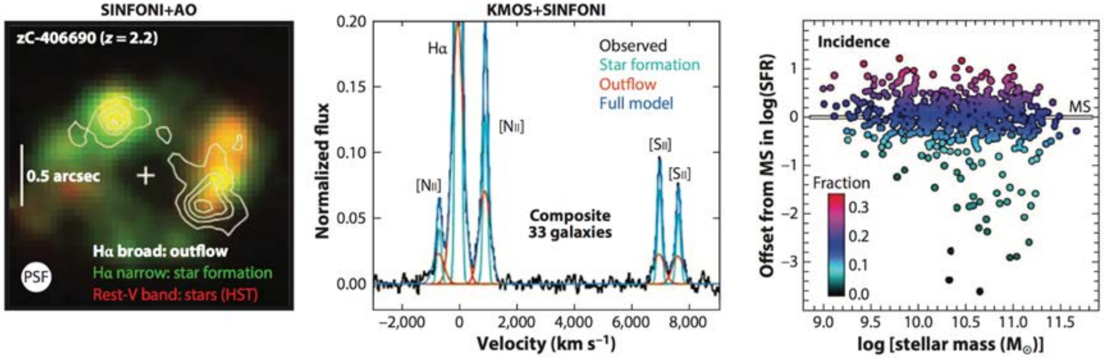
- No apparent link between X-ray and IR luminosities suggests that global star formation is decoupled from nuclear activity (although contradictory literature results)

- AGN-host co-evolution

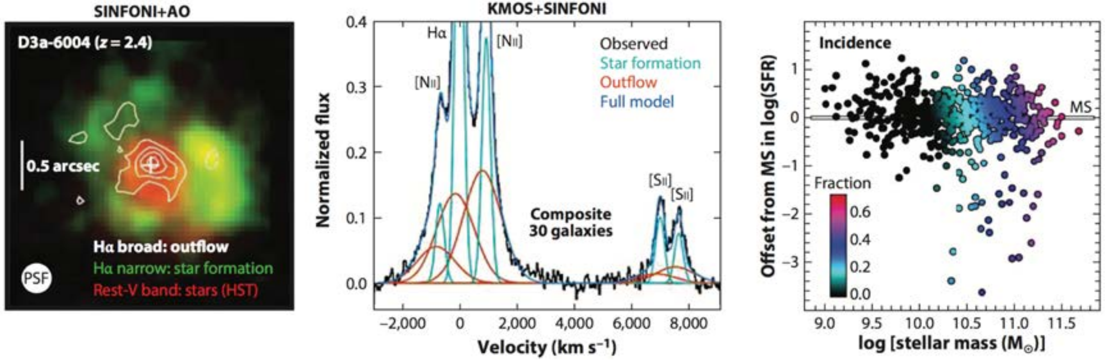
E.g., **Mullaney+12,** Rosario+12, Harrison+12, Hickox+14, Heckman+14, Stanley+15

Part IV : The quenching of star formation -- Outflows

a Star-formation-driven outflows



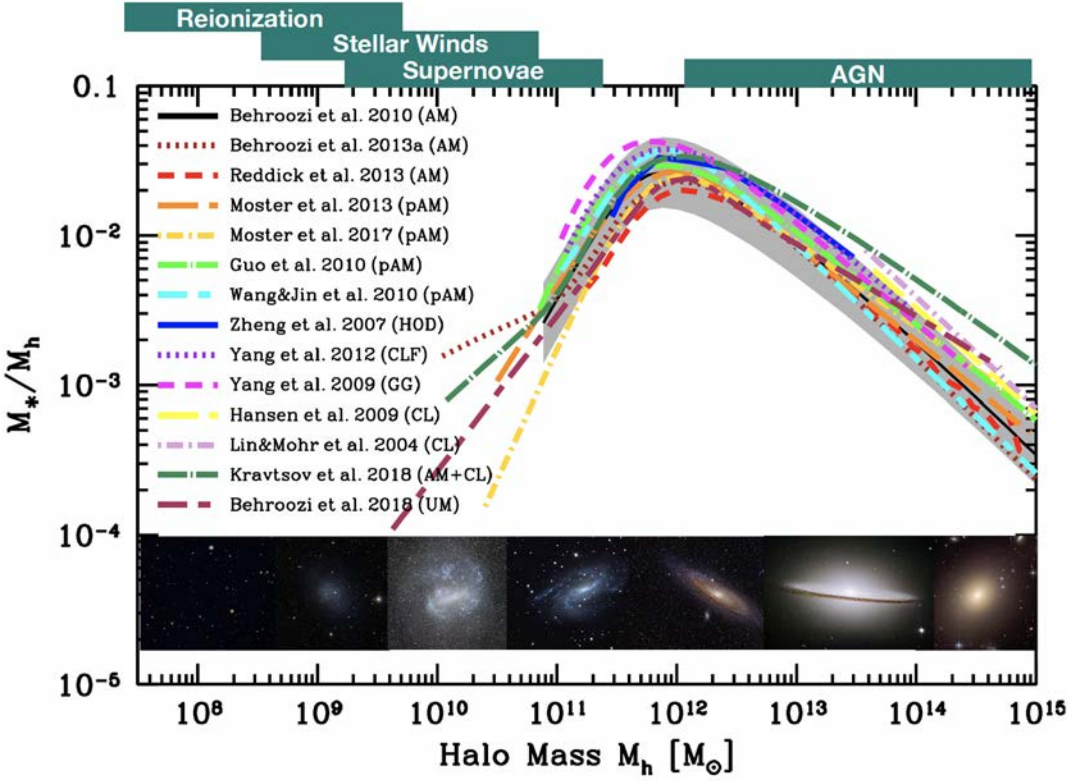
b AGN-driven outflows



- SF-driven outflows correlate with star formation properties (MS offset)
- AGN-driven outflows depend strongly on stellar mass independently of the level of star formation
- Role of feedback in keeping the halo hot, preventing further gas accretion and/or cooling (?)

E.g., Fabian+12, Heckman & Best+14, **Förster-Schreiber & Wuyts+21**

Part IV : The quenching of star formation -- AGN and stellar feedback



- Overall low efficiency in converting baryons into stars
- Efficiency peaks around MW-like galaxies
- Even lower efficiency at the high-mass end (AGN feedback) and low-mass end (stellar feedback)

E.g., Behroozi+10+13+18, Papastergis+12, **Wechsler & Tinker+18**

Observational inventory of the ISM of galaxies at the cosmic noon

David Elbaz, Benjamin Magnelli, Carlos Gomez Guijarro / CEA Saclay

Part I : A strongly evolving **cosmic star formation** history

- Dust attenuation affects galaxies even at the highest redshifts, in **massive** galaxies
- **Global but incomplete census** of the global star-formation history: massive galaxies

Key dimension **: galaxy mass**

Part II : **main sequence of star-forming galaxies** = universal scaling law, **secular evolution**

- Most stars formed / universal star formation efficiency, disk-like, **turbulence** increases with z
- **Hubble sequence** already in place at z~2.5
- **Minor role of merger**-driven starbursts / self-regulation of star-formation

Key dimension : the **gas content controls cosmic star-formation**

Part III : The **gas properties** of galaxies

- Gas in normal MS SF galaxies **analog to local starbursts**: temperature, density, turbulence
- **Duty cycle** = 600 Myr only…

Key dimension : **intergalactic gas infall**

Part IV : The **quenching** of star formation

- high-z galaxies exhibit **more compact SF**, progenitors of **compact ellipticals** identified
- Outflows ubiquitous but don't quench, quenching by **starvation / gravitational heating**

Key dimension : **dark matter halo mass / environment**

FUTURE

Observations:

ALMA → gas properties of high-z galaxies, census on distant massive galaxies, origin of compactness

JWST → high-z obscured galaxies, formation of optically-dark massive galaxies, first galaxies

SKA → HI contribution → key role of circumgalactic gas

Euclid → connexion with structure formation (proto-clusters) and DM halo mass

Simulations :

How to reconcile strong feedback needed / models with high gas content?

Need to simulate galaxies with their circumgalactic HI

If AGNs do not quench star-formation → what is the main cause of starvation?

(I) A strongly evolving **cosmic star formation** history Key: **galaxy mass**

(II) **main sequence of star-forming galaxies** Key: **gas content**

(III) The **gas properties** of galaxies Key: **intergalactic gas infall**

(IV) The **quenching** of star formation Key: **dark matter halo mass, environment**


Image credit: NRAO / AUI / NSF / S. Dagnello

ISM of galaxies at the cosmic noon

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ALMA JWST SKA Euclid + simulations