Galaxy Formation and Evolution in the Big Data Era

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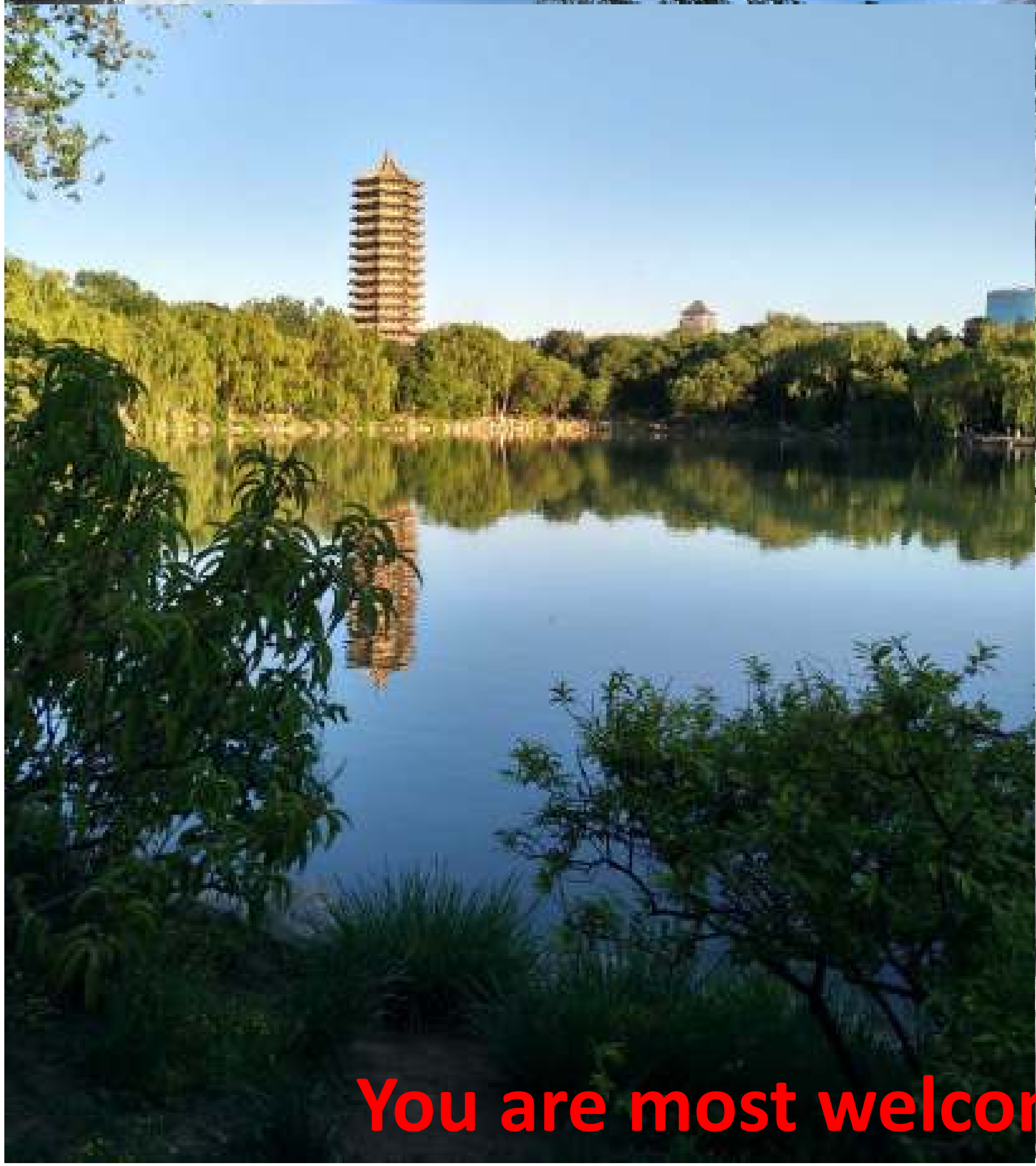
The Kavli Institute for Astronomy and Astrophysics at Peking University

北京大学科维理天文与天体物理研究所



You are most welcomed to visit us!

Galaxy Formation and Evolution Group @ KIAA-PKU

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Gas, star formation,
quenching,
Gas regulation,
chemo-evolution
HI

Chengpeng Zhang

Galaxy surveys (spec/photo-z),
large-scale structure,
environmental effect,
Galaxy properties on DM Halo

Zhongyi Man

Multi-wavelength Modeling of Stellar Population,
Post-starburst Quasars and Their Role in Star-formation Quenching

Petchara Pattarakijwanich, KIAA Fellow

Gas, star formation,
quenching,
Gas regulation, chemo-evolution
CO

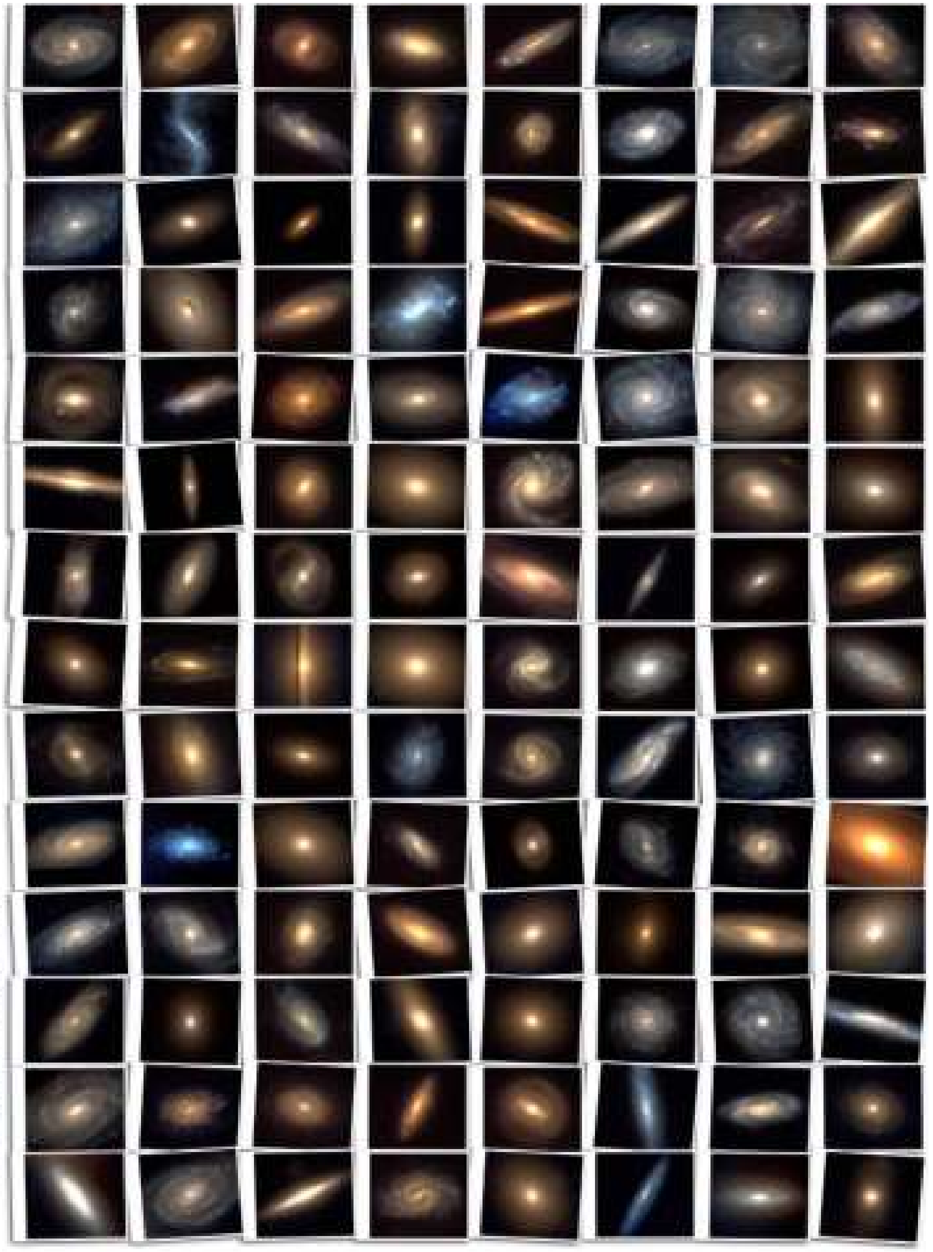
Jing Dou

star formation, quenching,
Structure and morphology,
IFU-MaNGA

Kexin Guo, KIAA Postdoc

Students/Postdocs/Collaborators/Visitors are most welcome!

the many aspects of the evolving galaxy population



- stellar mass: based on models of stellar population (easy) or dynamics (harder)
- star formation rate (SFR)
- gas content (HI and H_2)
- gas phase metallicities (abundance of heavy elements)
- stellar metallicity
- stellar age

Structure and morphology:
- sizes and densities
- Spheroid and disk (e.g. budge-to-disk)
- surface brightness profile (e.g. Sersic profile)

Environment:
- dark matter halo mass (from groups, lensing, abundance matching)
- Local projected surface density
  distance to the Nth nearest neighbor
  number density of nearest galaxies
- central galaxy or satellite?
- distance to the BCG
- Location in the cosmic web of filaments, clusters, sheets and voids.

Galaxy Evolution

Playing God of the Universe

Halo –> Gas –> Stars

Gadget-2 hydro-simulation, credit: Klaus Dolag

Richard Bower:
"We haven't understood galaxy formation, until we have translated the ***simulation results*** in a coupled set of differential equations (to be put in a SAM)"

"Reverse Engineering" of the Universe

Stars –> Gas –> Halo

SDSS (The Sloan Digital Sky Survey)
credit: Dinoj Surendran and Mark Subbarao

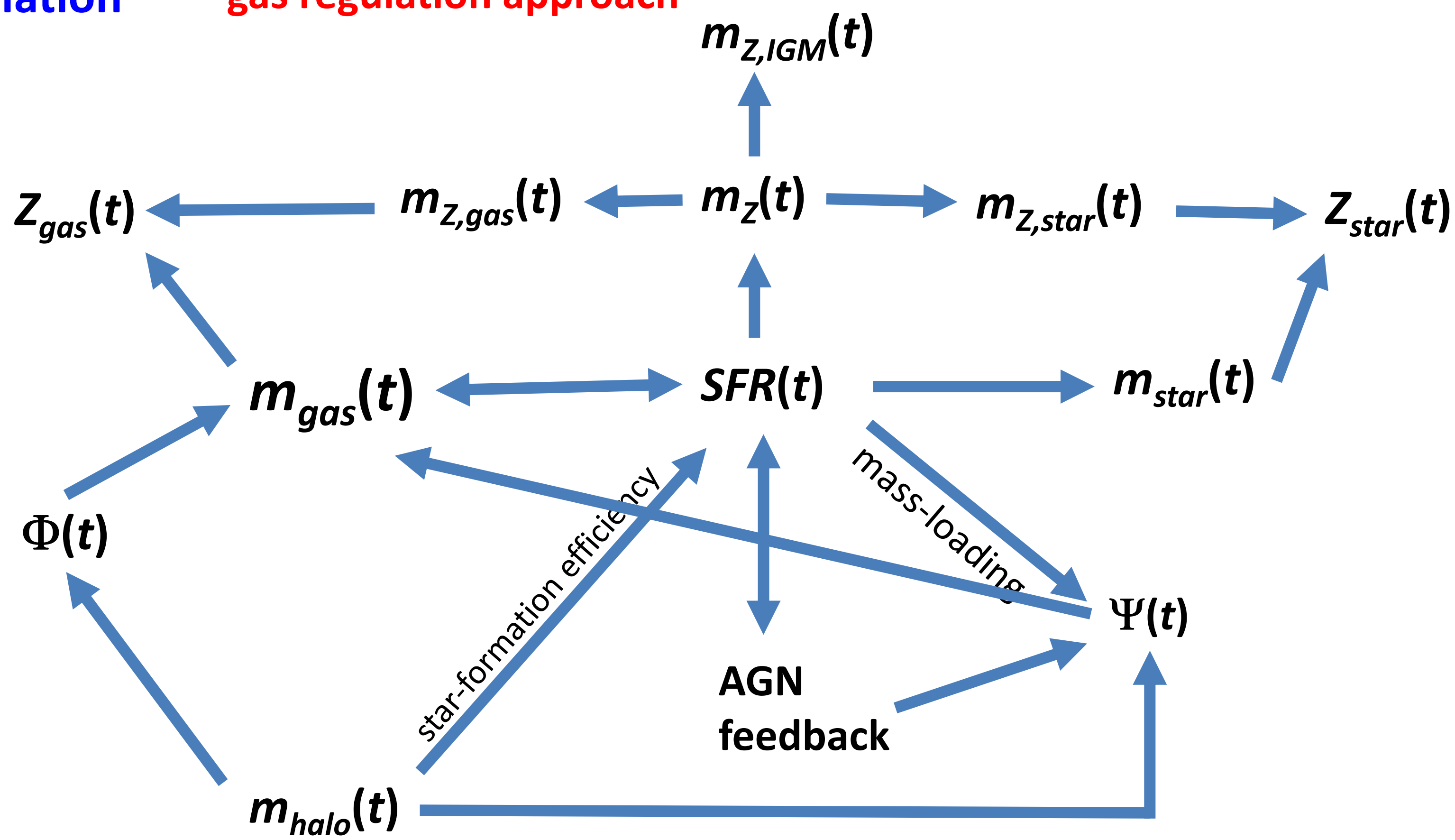
Peng:
We haven't understood galaxy formation, until we have translated the ***data*** in a coupled set of differential equations (to be put in a simulation)"

The Evolving Galaxy Population

The distribution function – continuity approach

$\phi\,(t, SFR, m_{star}, \rho, m_{halo}, morphology, central/satellite, Z, m_{gas} \ldots)$

The scaling relation – gas regulation approach



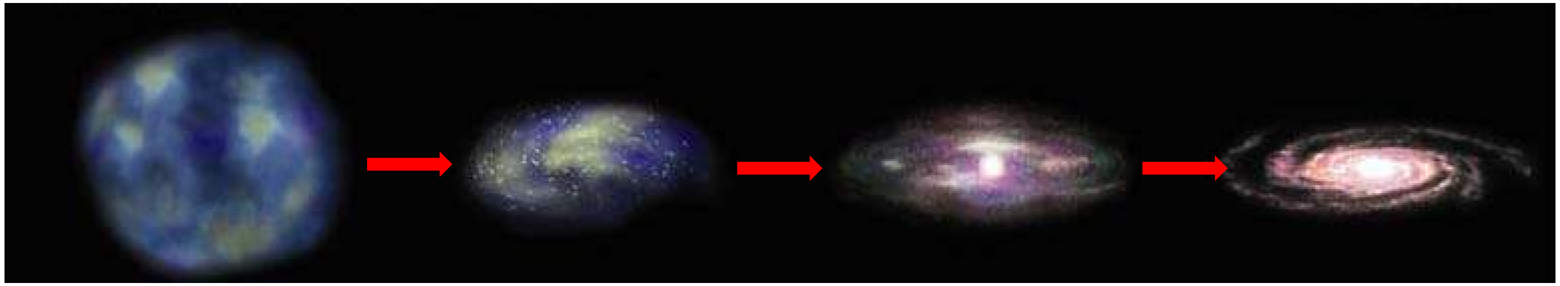
central/satellite, ρ

What's the key processes that regulate galaxy evolution?
What's the physical interrelationship between different parameters?

A key issue in understanding the evolving galaxy population

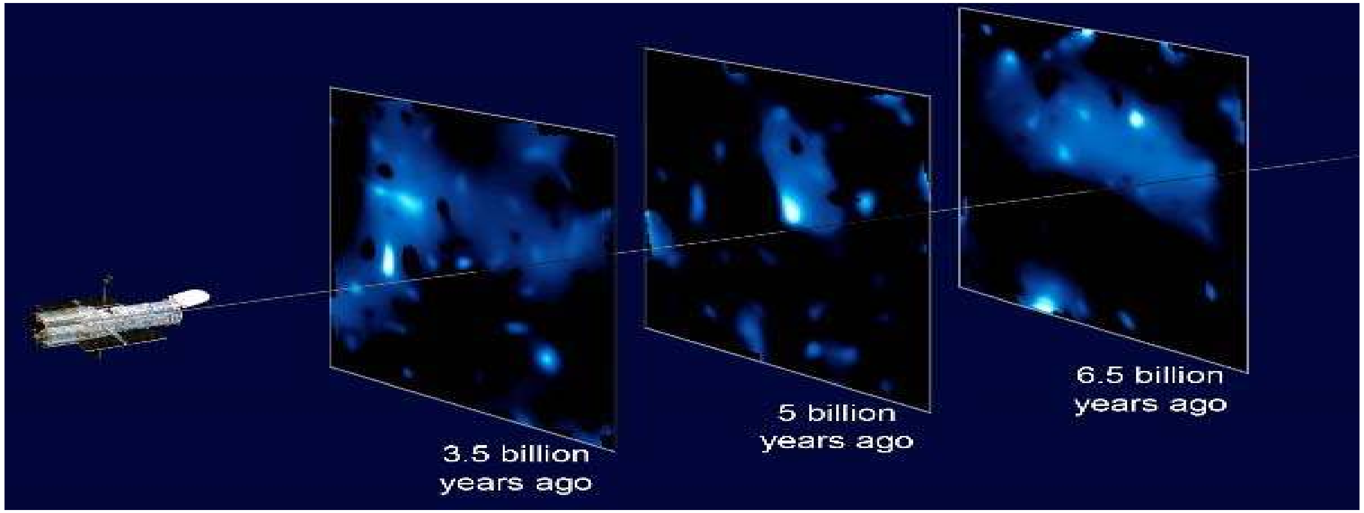
What we want to observe:

continuous evolution of the galaxy population with time, like a movie.



What we observed:

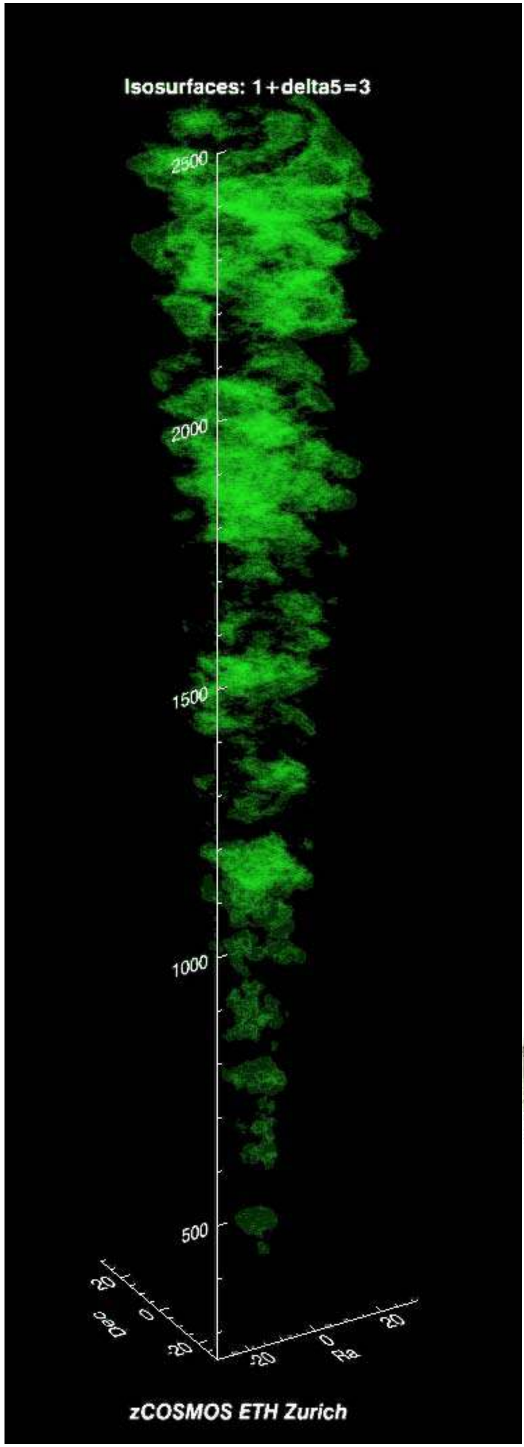
galaxy population at different epoch, like a snapshot of a movie at different time



progenitor problem:

The $10^{11}M_{sun}$ star-forming galaxy at z~2 is very different from the $10^{11}M_{sun}$ star-forming galaxy at z~0

We need to reconstruct the evolutional sequence of the galaxy population as a function of time from observations at different epoch. → **Continuity Approach**



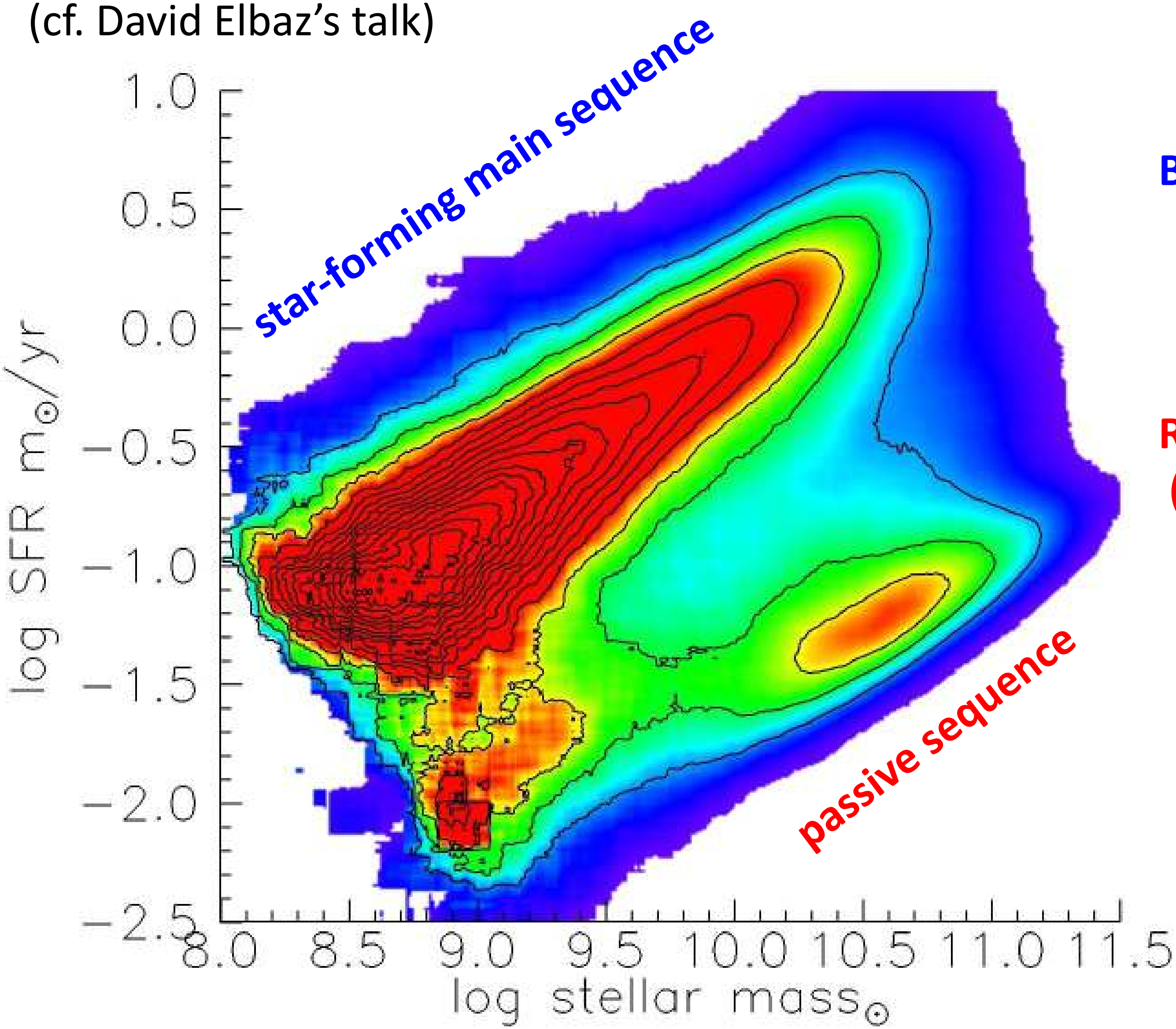
Large surveys enables new approach

(SDSS, COSMOS, GOODS, VVDS, DEEP, GAMA etc.)

zCOSMOS + SDSS DR7 visualized by Yingjie Peng

key observational facts- The Star-forming Main Sequence

There are broadly two populations of galaxies on the basis of their specific star-formation rates (sSFR=SFR/m_{star}):
(cf. David Elbaz's talk)



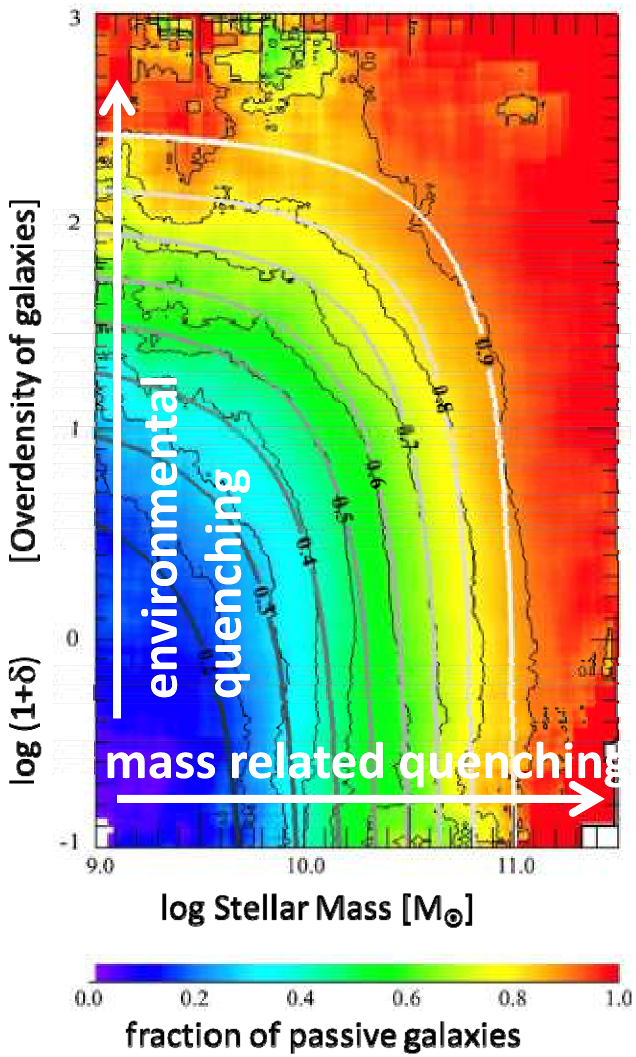
Blue star-forming galaxies
$(sSFR)^{-1} \sim \tau_H$

Red passive galaxies
$(sSFR)^{-1} >> \tau_H$

Renzini & Peng 2015

Two independent quenching processes

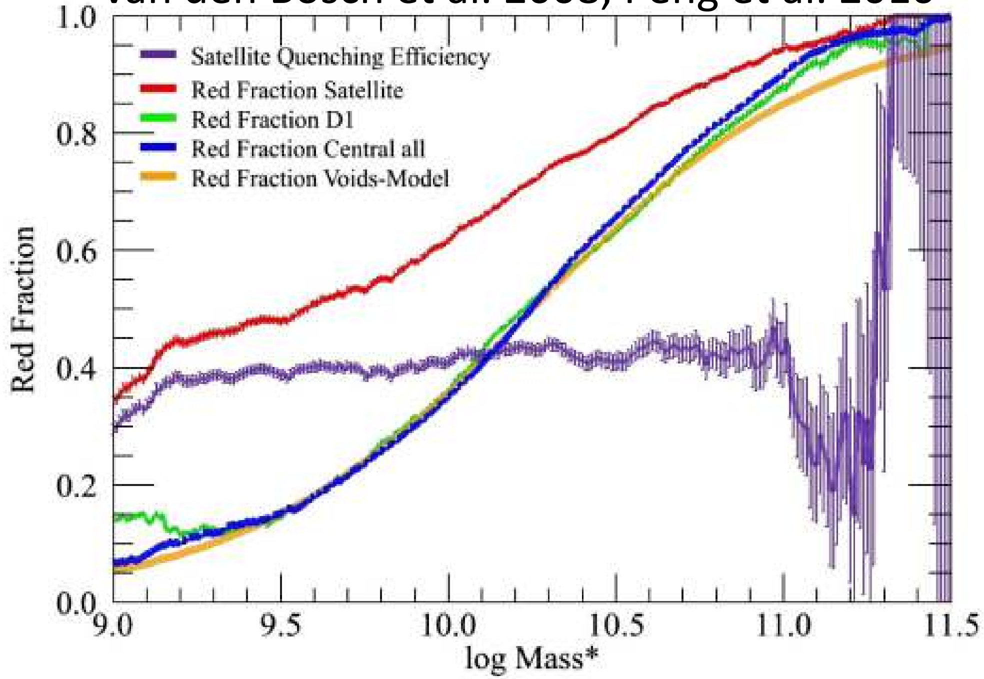
Peng et al. 2010



Central/Satellite Dichotomy

using Yang et al. group catalogue

van den Bosch et al. 2008, Peng et al. 2010



$\phi_{passive,cen}(m, \rho, t)$ $\phi_{passive,sat}(m, \rho, t)$

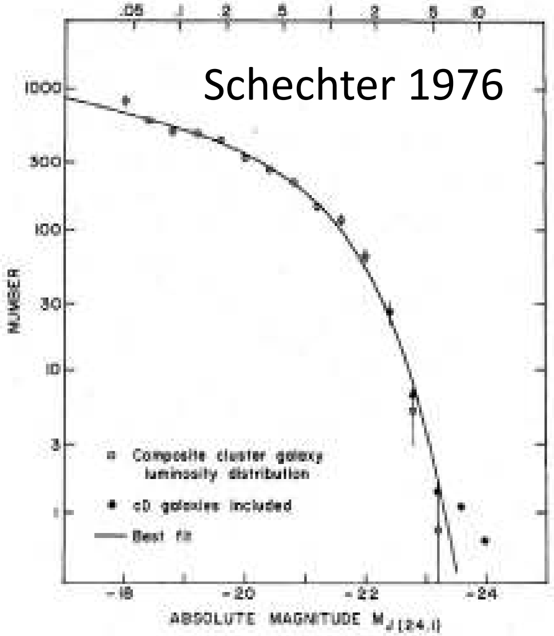
$\phi_{SF,cen}(m, \rho, t)$ $\phi_{SF,sat}(m, \rho, t)$

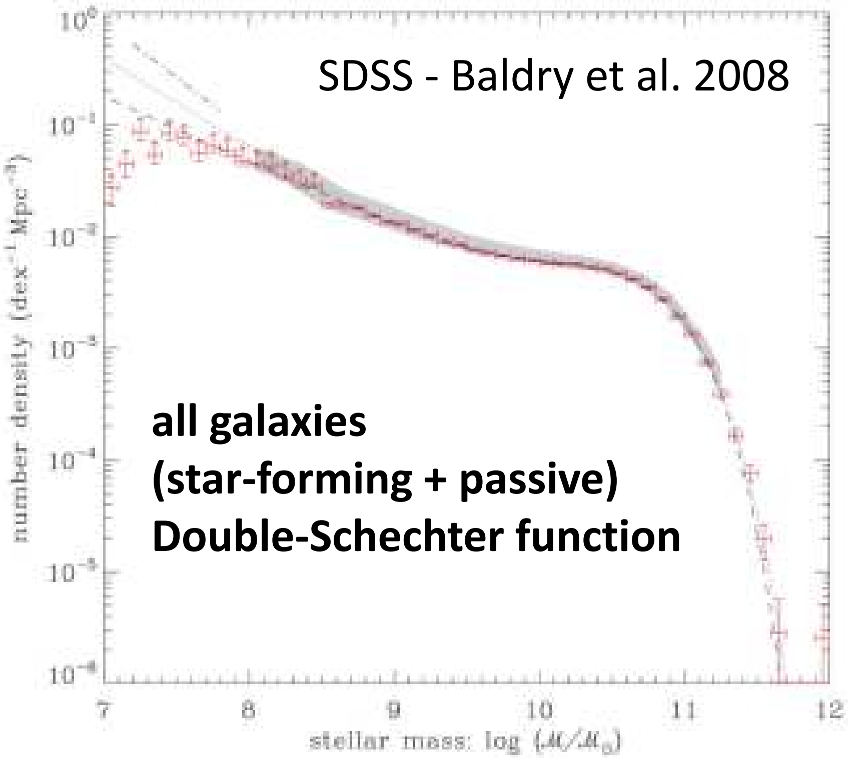
Reconstruct the evolutional sequence of the galaxy population via continuity equations

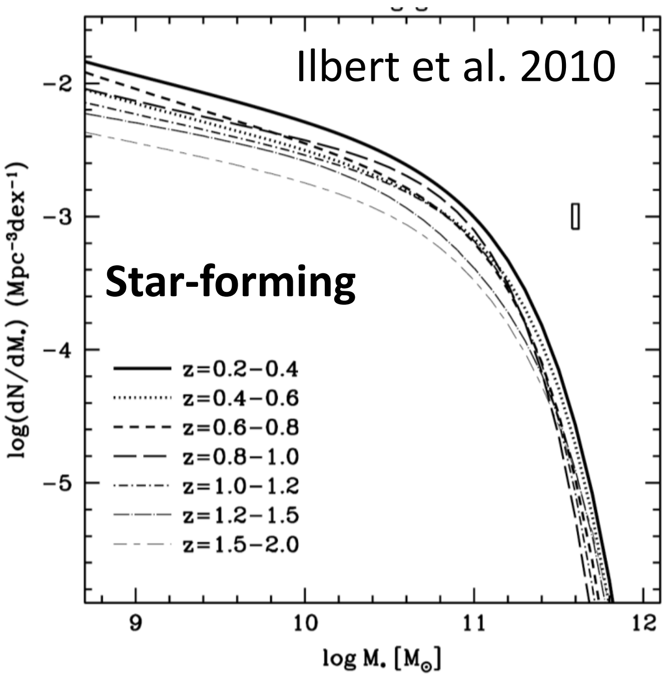
Peng et al. 2010, 2012, 2014, 2017 in prep.

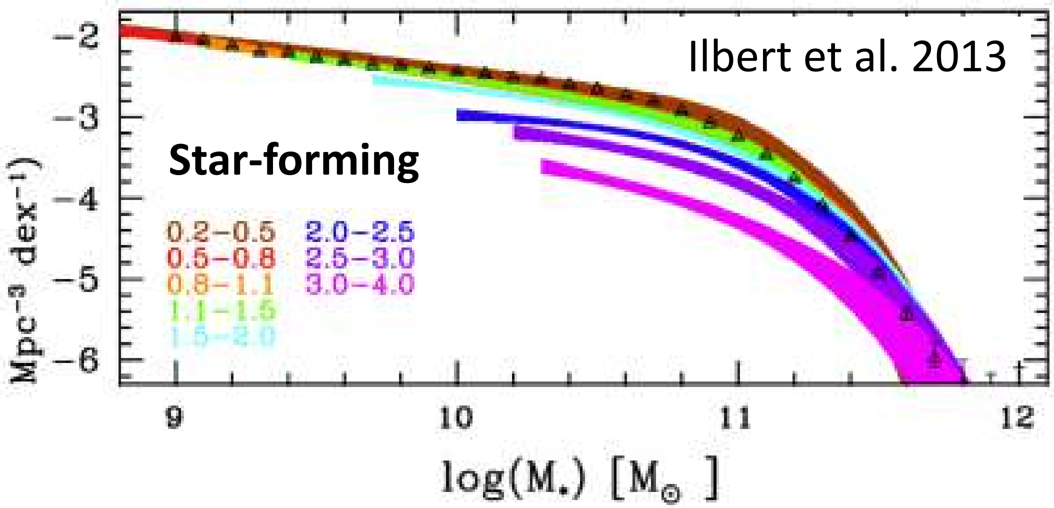
$$\frac{\partial \phi(m,\rho,t)}{\partial t} + \left(\frac{\partial}{\partial \log m}\hat{m} + \frac{\partial}{\partial \log \rho}\hat{\rho}\right) \bullet \left[\phi(m,\rho,t)\left(\frac{\partial \log m}{\partial t}\hat{m} + \frac{\partial \log \rho}{\partial t}\hat{\rho}\right)\right] = -\eta\phi(m,\rho,t)$$

Galaxy Stellar Mass Functions









The required form of the mass quenching rate

$$\frac{\partial N}{\partial t} + \nabla \bullet (N v) = \sigma$$

basic continuity equation

at fixed mass and environment:

$$\frac{\partial \phi_{blue}(t)}{\partial t} + \frac{\partial}{\partial \log m} \bullet [\phi_{blue}(t) \frac{\partial \log m}{\partial t}] = -[\lambda_m(t) + \kappa_{\_}(t)] \phi_{blue}(t)$$

λ_m is the mass-quenching rate to be derived

$$\frac{1}{\phi_{blue}(t)} \frac{\partial}{\partial \log m} \bullet [\phi_{blue}(t) \frac{\partial \log m}{\partial t}] = sSFR(t)(\alpha + \beta)$$

the merging term $\kappa_{\_}$, is either independent of stellar mass or that it is negligible in under-dense regions.

$$\alpha = \frac{\partial \log \phi_{blue}(t)}{\partial \log m} = (1 + \alpha_s) - \frac{m}{M^*} \qquad \beta = \frac{\partial \log sSFR(t)}{\partial \log m}$$

$$\frac{1}{\phi_{blue}(t)} \frac{\partial \phi_{blue}(t)}{\partial t} = -sSFR(t)(\alpha + \beta) - \lambda_m(t) - \kappa_{\_}(t)$$

$$= -sSFR(t)(1 + \alpha_s + \beta) + \frac{SFR(t)}{M^*} - \lambda_m(t) - \kappa_{\_}(t)$$

To keep a constant shape (in terms of α_s and M*) of the star-forming mass function with time, requires $d\log\phi_{blue}/dt$ to be independent of mass.

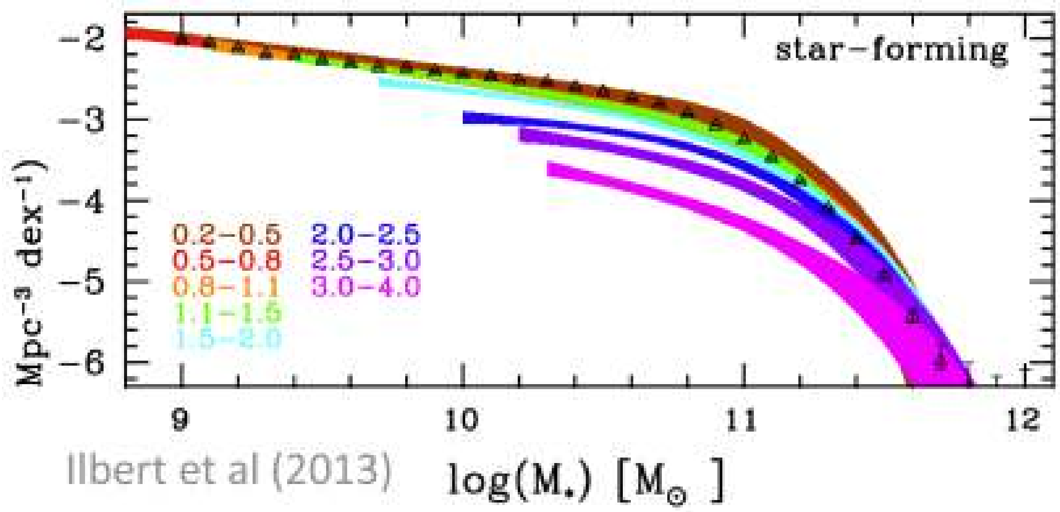
$\lambda_m(t) = SFR(t)/M^* + C(t)$

low mass galaxies in low density environments are still all blue

$\lambda_m(t) = SFR(t)/M^*$

The required form of the mass quenching rate

Observations



Ilbert et al (2013)

Continuity Equation

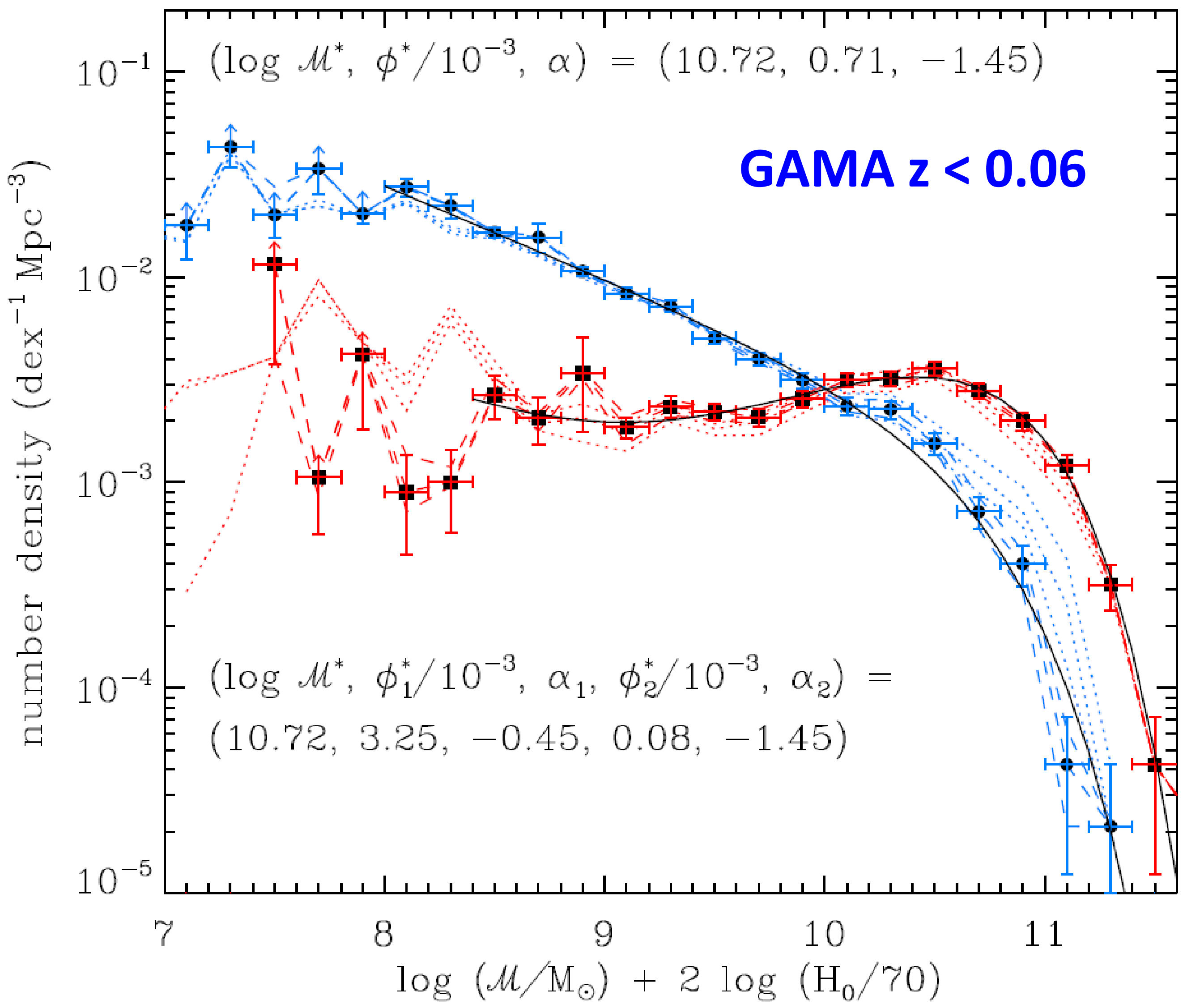
Mass-Quenching Rate:

$\lambda_m(t) = SFR(t)/\mathrm{M}^*$

survival probability:

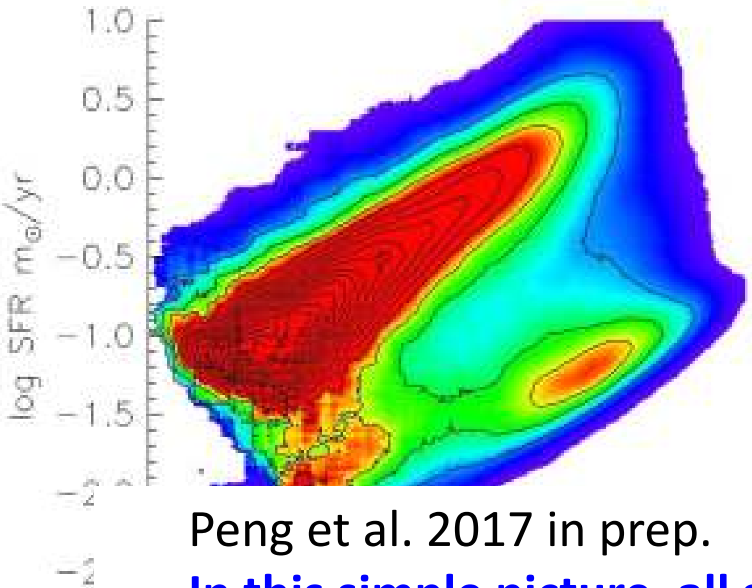
$P = exp\ (-\ m/\mathrm{M}^*)$

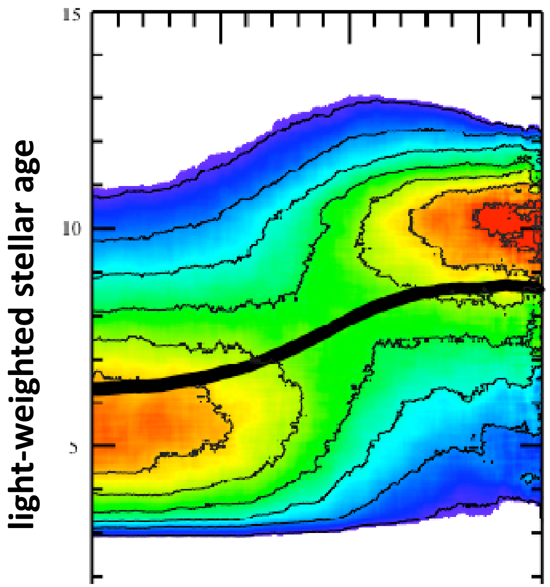
Quenching occurs, statistically, when a galaxy has formed M* of stars.

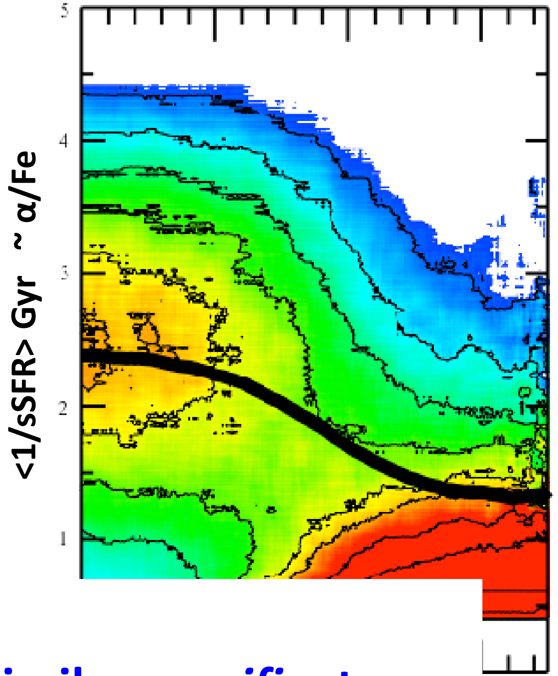


Baldry et al 2012:
"This supports the empirical picture, quenching model, for the origin of the Schechter function by Peng et al. (2010)"

Star-formation and Quenching



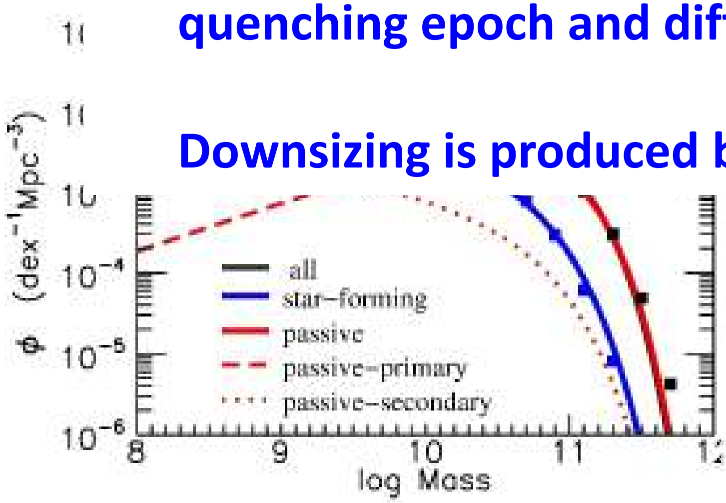


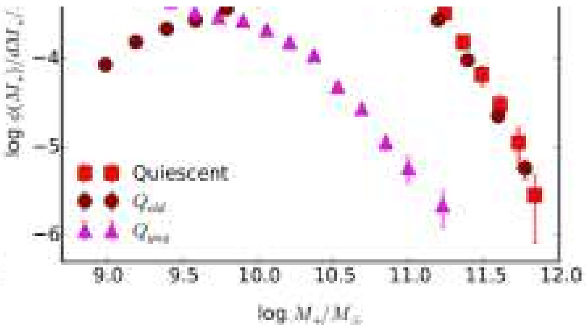


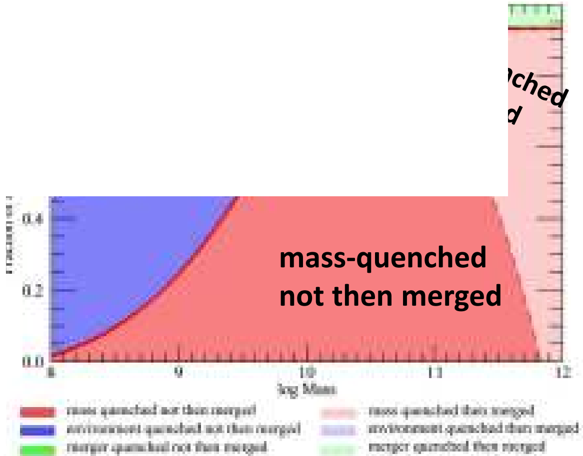
Peng et al. 2017 in prep.

In this simple picture, all star-forming galaxies have similar *specific* star-formation history. What makes the differences are the different quenching epoch and different quenching channel.

Downsizing is produced by quenching.





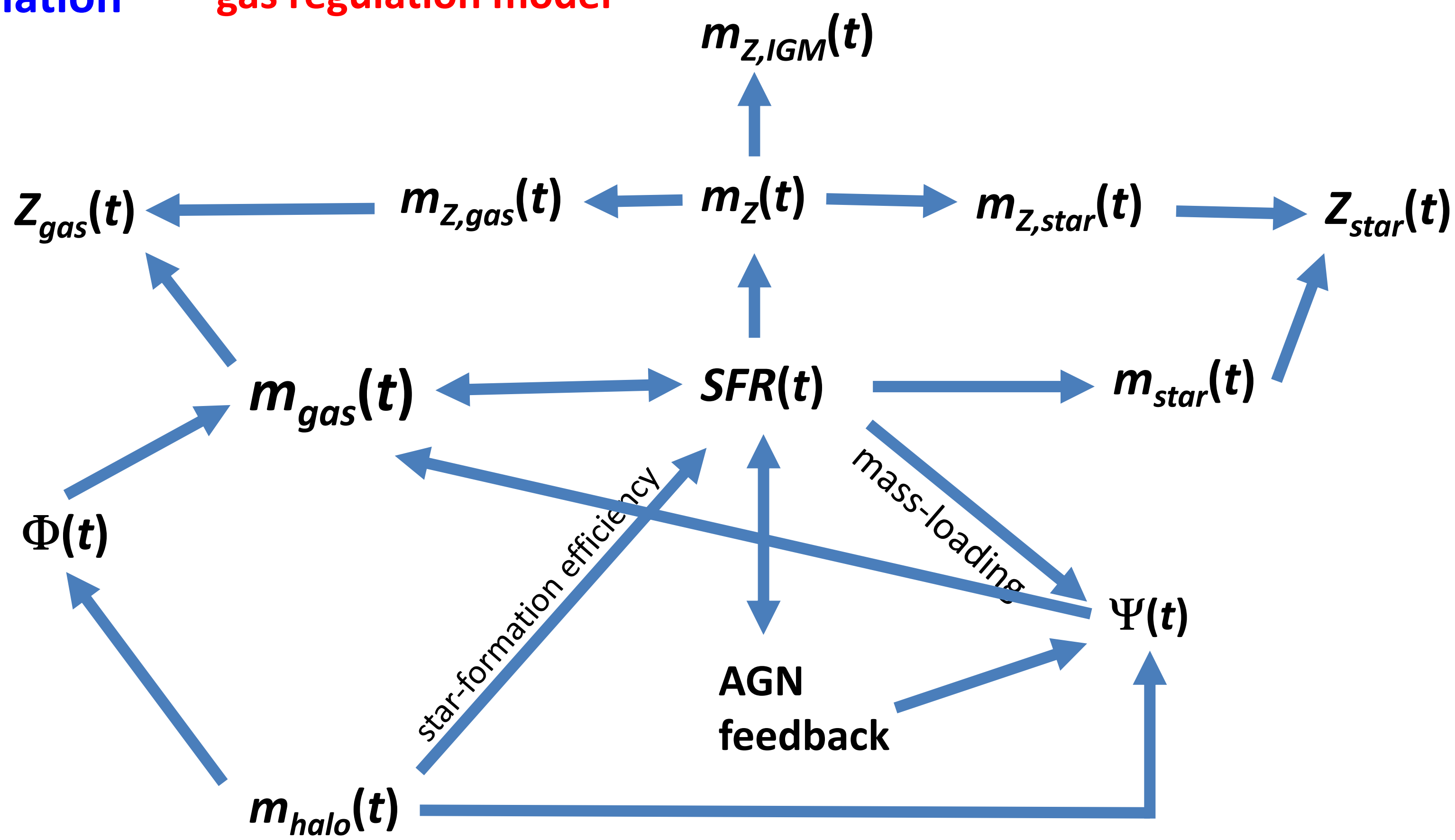


The Evolving Galaxy Population

The distribution function – continuity approach

$\phi\,(t, SFR, m_{star}, \rho, m_{halo}, morphology, central/satellite, Z, m_{gas} \ldots)$

The scaling relation –gas regulation model

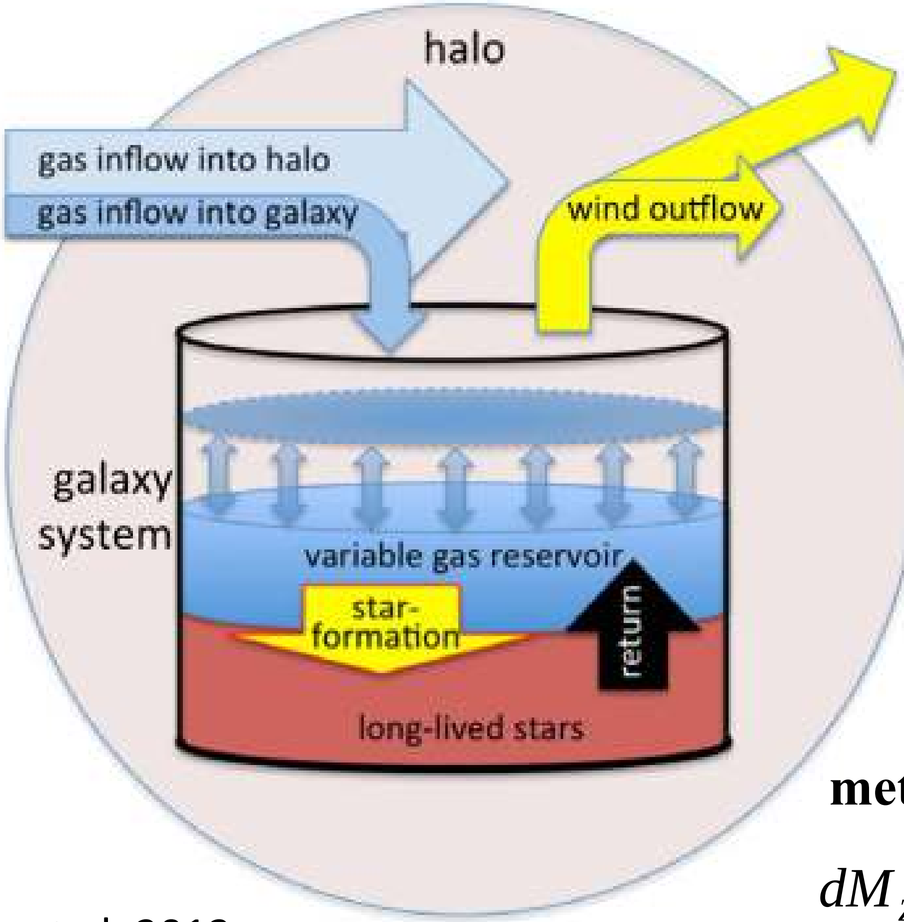


central/satellite, ρ

What's the key processes that regulate galaxy evolution?
What's the physical interrelationship between different parameters?

Gas regulation in galaxies

(e.g. Finlator et al. 2008, Recchi et al. 2008, Bouche et al. 2010, Davé et al. 2012, Dayal et al. 2013, Lilly et al. 2013, Dekel et al. 2014, Peng et al. 2014)



Lilly et al. 2013
Peng & Maiolino 2014

$$\mathrm{SFR} = \varepsilon\, \mathrm{M}_{\mathrm{gas}}$$

$$\Psi = \lambda \cdot SFR$$

The change of mass in…

stars $$\frac{dM_{star}}{dt} = (1-R)SFR$$

gas $$\frac{dM_{gas}}{dt} = \Phi - (1-R)SFR - \Psi$$

metals

$$\frac{dM_{Z,\mathrm{gas}}}{dt} = y \bullet SFR - Z(1-R)SFR - Z\Psi + Z_0 \bullet \Phi$$

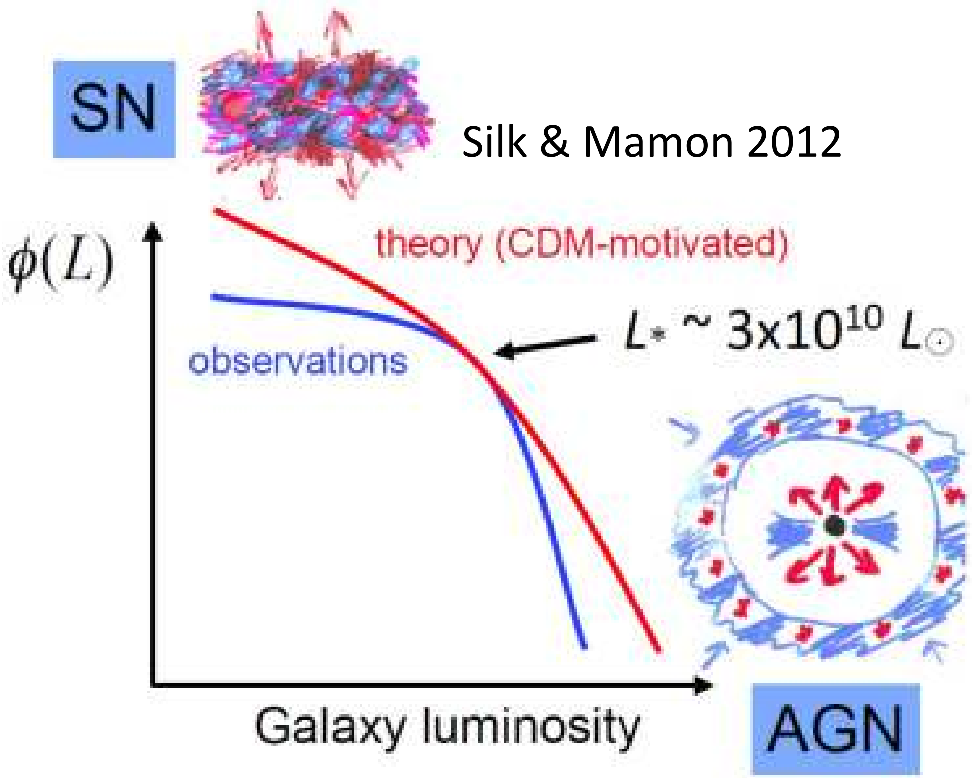
The dynamics of the gas regulator model (Peng & Maiolino 2014)

gas inflow rate of the galaxy Φ, star-formation efficiency ε, mass-loading factor λ

equilibrium timescale $$\tau_{eq} = \frac{1}{\varepsilon(1-R+\lambda)} = \frac{1}{sSFR\cdot(1-R+\lambda)}\frac{f_{gas}}{1-f_{gas}}$$

	General Solution	**Equilibrium Solution ($t >> \tau_{eq}$)**
$M_{\rm gas}(t)$	$\Phi\tau_{\rm eq}(1-{\rm e}^{-\frac{t}{\tau_{\rm eq}}})$	$\Phi\tau_{\rm eq}$
${\rm SFR}(t)$	$\Phi\tau_{\rm eq}\varepsilon(1-{\rm e}^{-\frac{t}{\tau_{\rm eq}}})$	$\Phi\tau_{\rm eq}\varepsilon = \frac{\Phi}{1-R+\lambda}$
$M_{\rm star,int}(t)$	$\Phi\tau_{\rm eq}\varepsilon[t-\tau_{\rm eq}(1-{\rm e}^{-\frac{t}{\tau_{\rm eq}}})]$	$\Phi\tau_{\rm eq}\varepsilon(t-\tau_{\rm eq}) \sim \Phi\tau_{\rm eq}\varepsilon t$
$M_{\rm star}(t)$	$(1-R)\times M_{\rm star,int}(t)$	$(1-R)\times M_{\rm star,int,eq}(t)$
${\rm sSFR}_{\rm int}(t)$	$\frac{1-{\rm e}^{-\frac{t}{\tau_{\rm eq}}}}{t-\tau_{\rm eq}(1-{\rm e}^{-\frac{t}{\tau_{\rm eq}}})}$	$\frac{1}{t-\tau_{\rm eq}} \sim \frac{1}{t}$
${\rm sSFR}(t)$	${\rm sSFR}_{\rm int}(t)/(1-R)$	${\rm sSFR}_{\rm int,eq}(t)/(1-R)$
$f_{\rm gas}(t)$	$\frac{1}{1+\varepsilon(1-R)\left(\frac{t}{1-{\rm e}^{-\frac{t}{\tau_{\rm eq}}}}-\tau_{\rm eq}\right)}$	$\frac{1}{1+\varepsilon(1-R)(t-\tau_{\rm eq})} \sim \frac{1}{1+\varepsilon(1-R)t}$
$\Psi(t)$	$\Phi\tau_{\rm eq}\varepsilon\lambda(1-{\rm e}^{-\frac{t}{\tau_{\rm eq}}}) = \Phi\frac{\lambda}{1-R+\lambda}(1-{\rm e}^{-\frac{t}{\tau_{\rm eq}}})$	$\Phi\tau_{\rm eq}\varepsilon\lambda = \Phi\frac{\lambda}{1-R+\lambda}$
${\rm Z}_{\rm gas}(t)$	$[{\rm Z}_0+y\tau_{\rm eq}\varepsilon(1-e^{-\frac{t}{\tau_{\rm eq}}})][1-e^{-\frac{t}{\tau_{\rm eq}(1-e^{-t/\tau_{\rm eq}})}}]$	${\rm Z}_0+y\tau_{\rm eq}\varepsilon = {\rm Z}_0+\frac{y}{1-R+\lambda}$
${\rm Z}_{\rm star}(t)$	${\rm Z}_{\rm gas}[1-{\rm e}^{-{\rm sSFR}\cdot(1-R)t}]$	${\rm Z}_{\rm gas}$ (2)

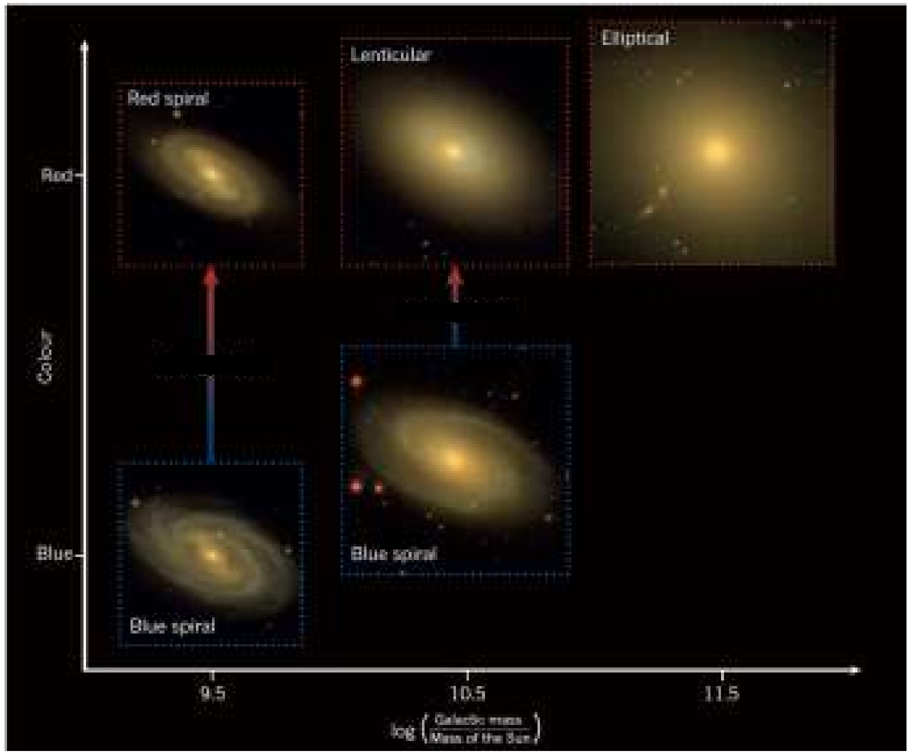
Quenching/ Star Formation Suppression



Silk & Mamon 2012

Morphological Transformation

Cattaneo 2016



Quenching

Mass-quenching (internal-quenching):

- Strongly mass-dependent
- independent of local density
- M* independent of epoch (to z > 4)
- applies equally to all galaxies
  centrals and satellites

Obvious possibilities:

- Limit to halo mass sustaining star-formation
- AGN feedback
- SF feedback
- Other processes linked to mass of galaxy….

Main difficulty:

For centrals M_{star} M_{BH} & M_{halo} tightly correlated

Environment-quenching (external-quenching):

- independent of stellar mass
- dependent on local density and/or
  halo-centric radius
- Independent of halo mass at same
  density
- only for satellites
- might not associate with
  morphological transformation

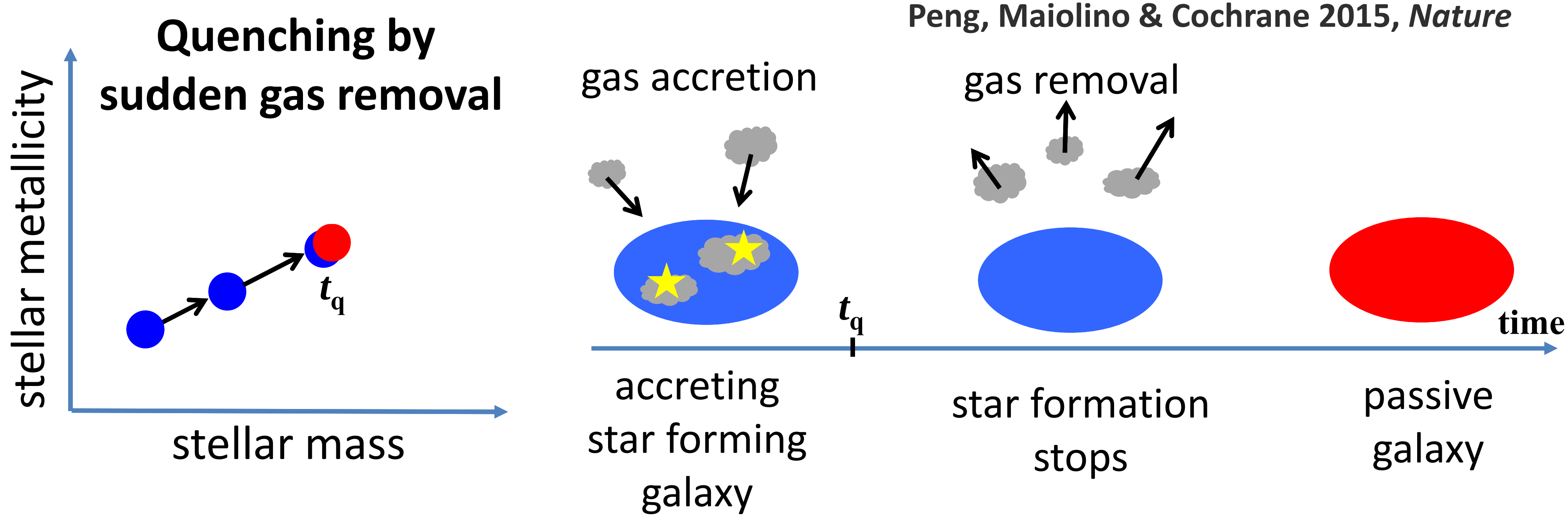
Obvious possibilities:

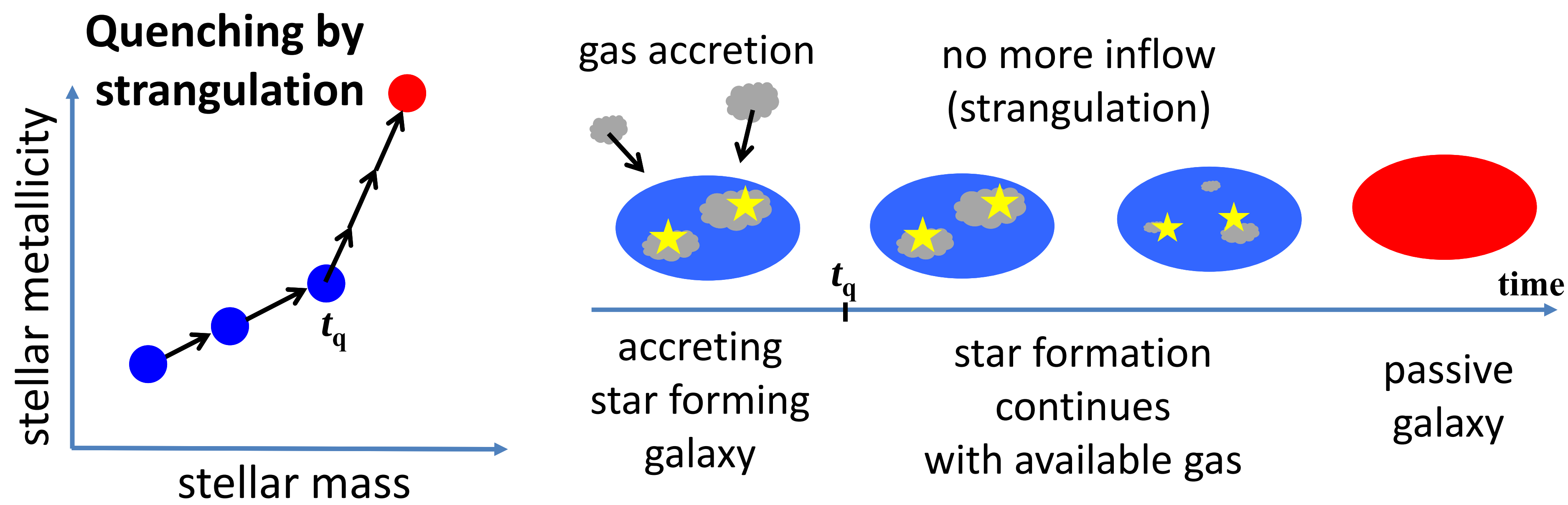
- Strangulation
- Ram pressure stripping
- Tidal effects
- Harassment
- Mergers

***Observationally*, the *primary* mechanism responsible for star formation quenching in galaxy *population* is still unclear.**

stellar metallicity is a powerful tool to discriminate between different scenarios

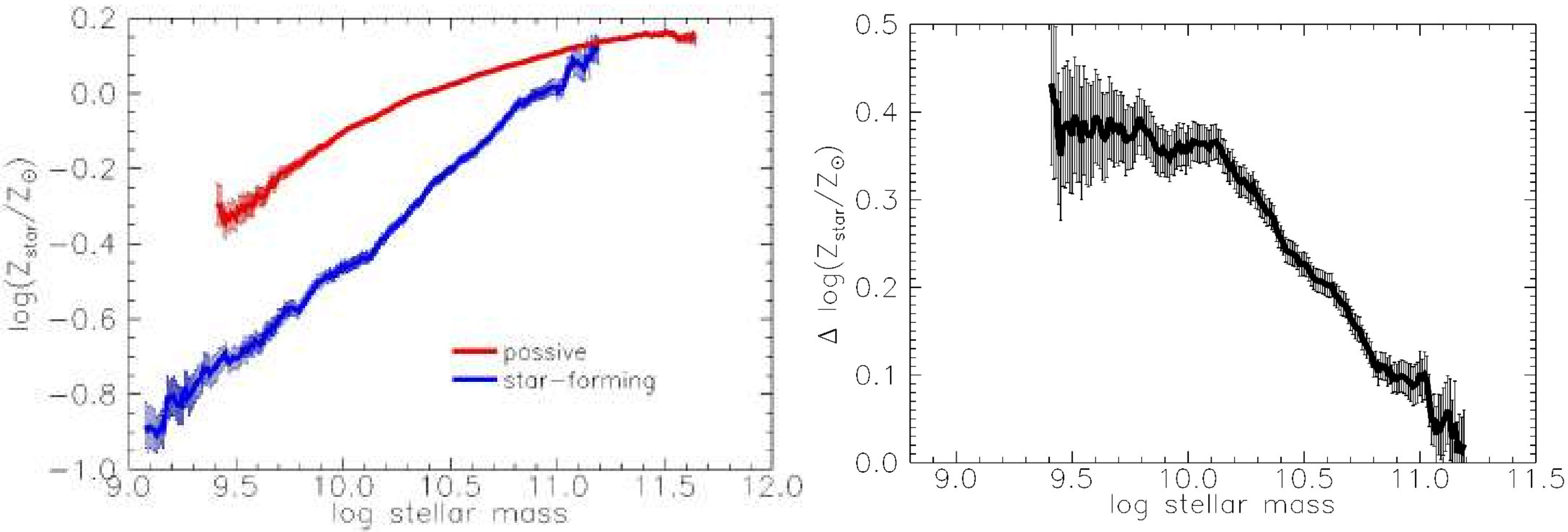
Peng, Maiolino & Cochrane 2015, *Nature*





The stellar metallicities for star-forming and quiescent galaxies

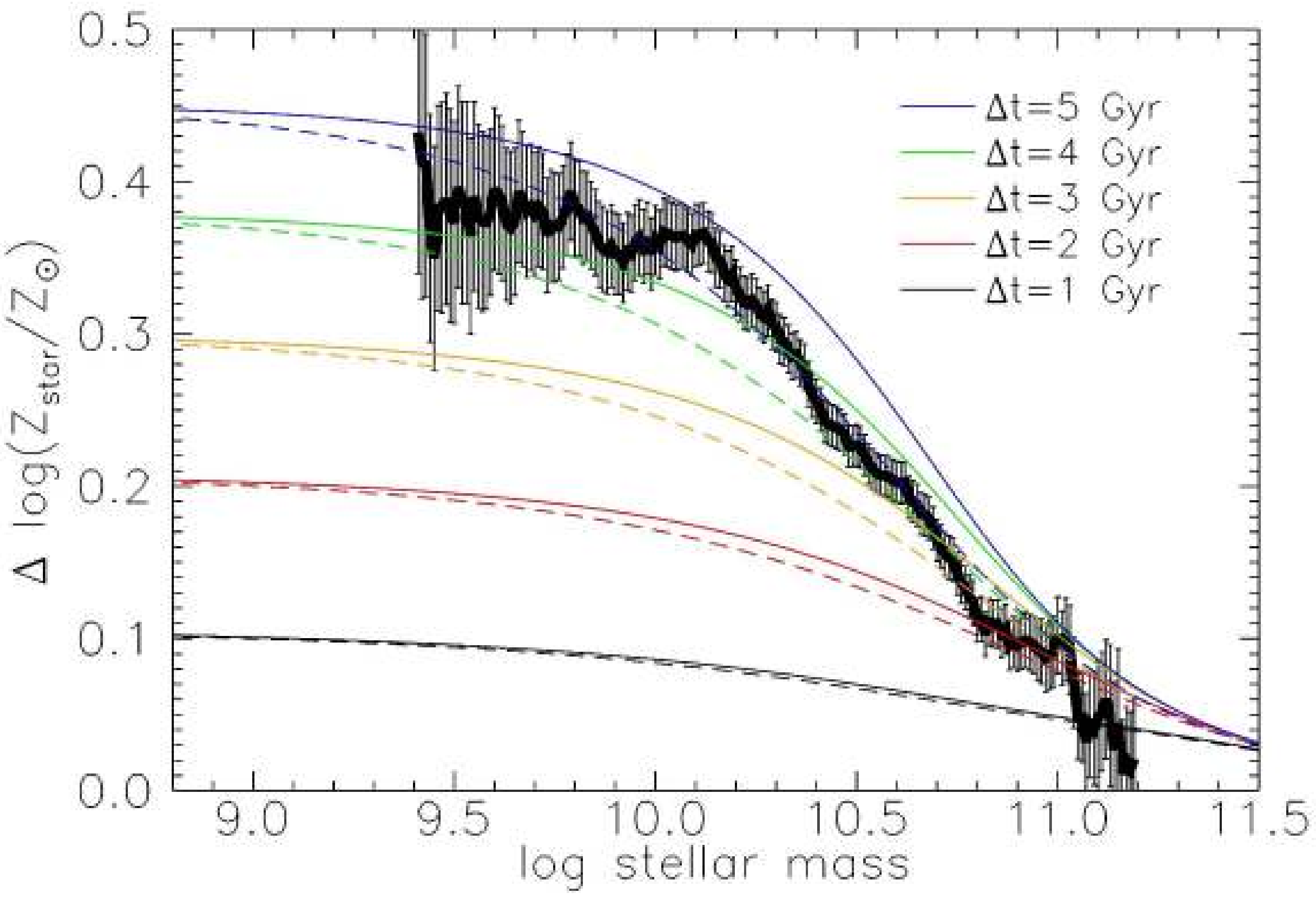
Peng, Maiolino & Cochrane 2015, Nature



The significant ΔZ_{star} in SDSS strongly support that local quiescent galaxies with $M_{star} < 10^{11}\ M_{star}$ are primarily quenched as a consequence of "strangulation" (i.e. cut off the gas inflow).

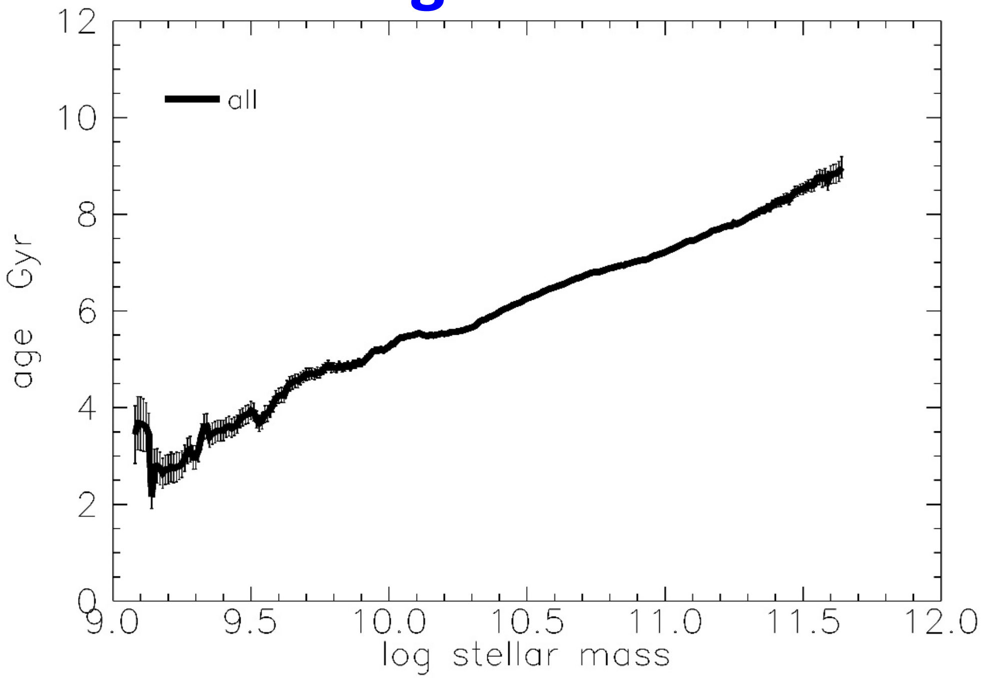
Massive galaxies with $M_{star} < 10^{11}\ M_{star}$ can be explained by both strangulation and fast gas removal.

stellar metallicity enhancement in a "close-box" model



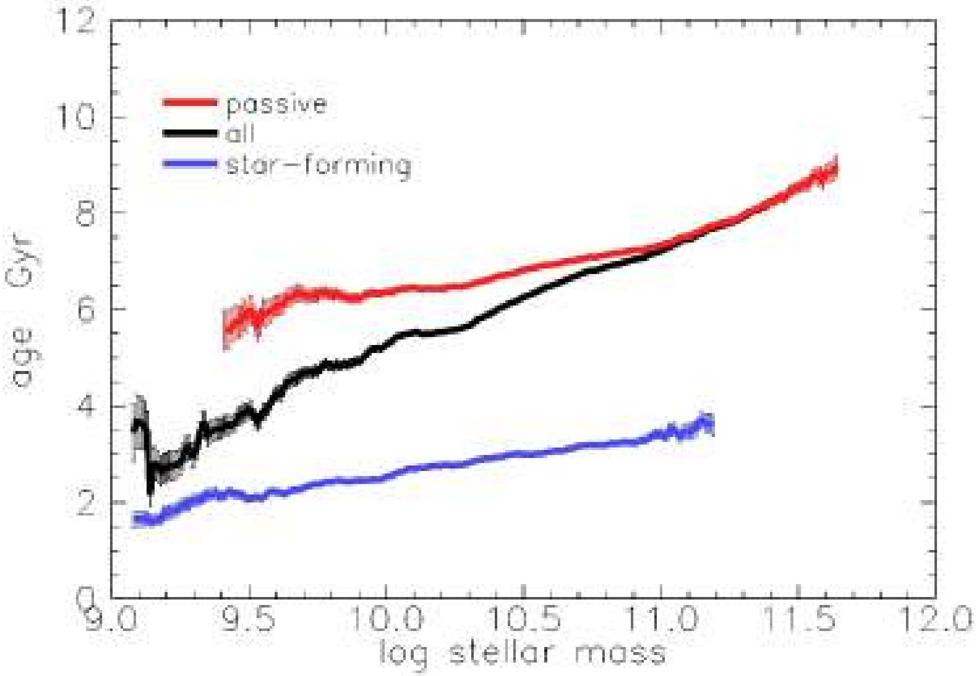
The observed *mass-dependent* ΔZ_{star} is consistent with the strangulation scenario in which quiescent galaxies at $M<10^{11}\ M_{star}$ are on average observed 4 Gyr after quenching due to strangulation, largely *independent of stellar mass*.

Stellar ages for star-forming and quiescent galaxies



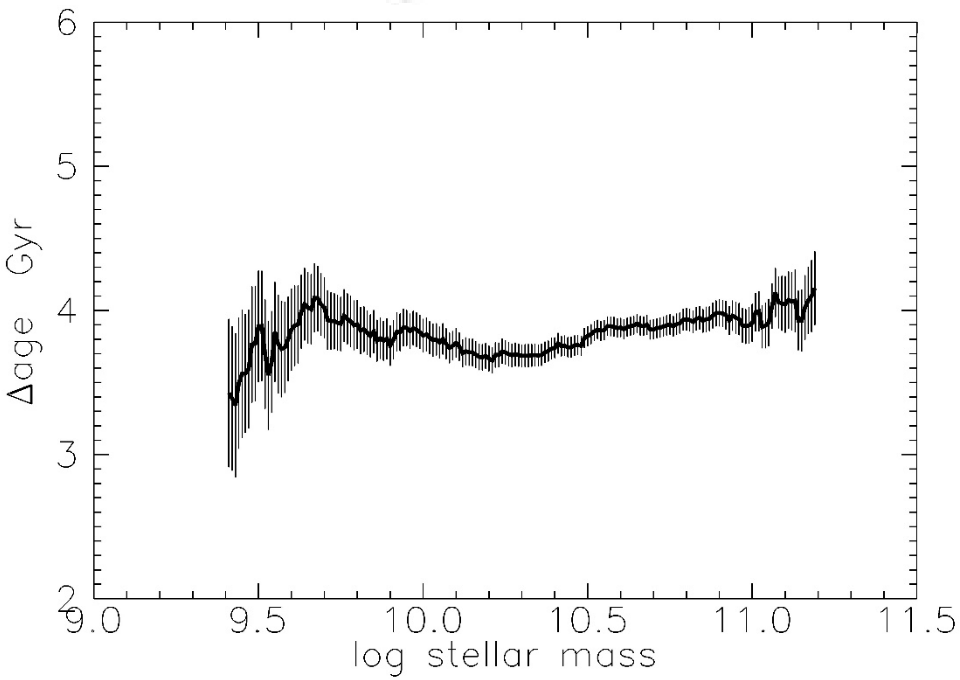
Stellar ages for star-forming and quiescent galaxies

Peng, Maiolino & Cochrane 2015, Nature



The age for *all* galaxies strongly depends on the stellar mass → the red fraction strongly depends on stellar mass.

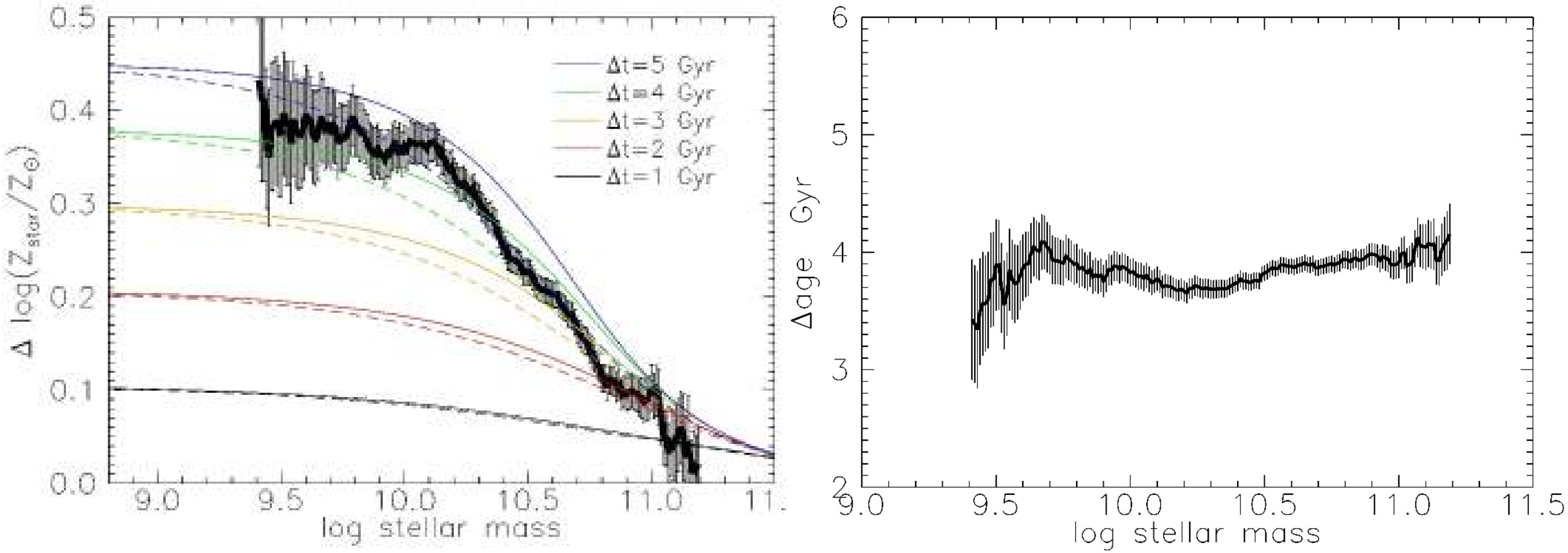
The dependence on stellar mass becomes much weaker once the whole sample is split into star-forming and quiescent galaxies.



the age difference is largely independent of mass, ~**4 Gyr**

Remarkably consistent with the mass-independent time Δt from strangulation required to explain the difference of stellar metallicities.

Peng, Maiolino & Cochrane 2015, Nature



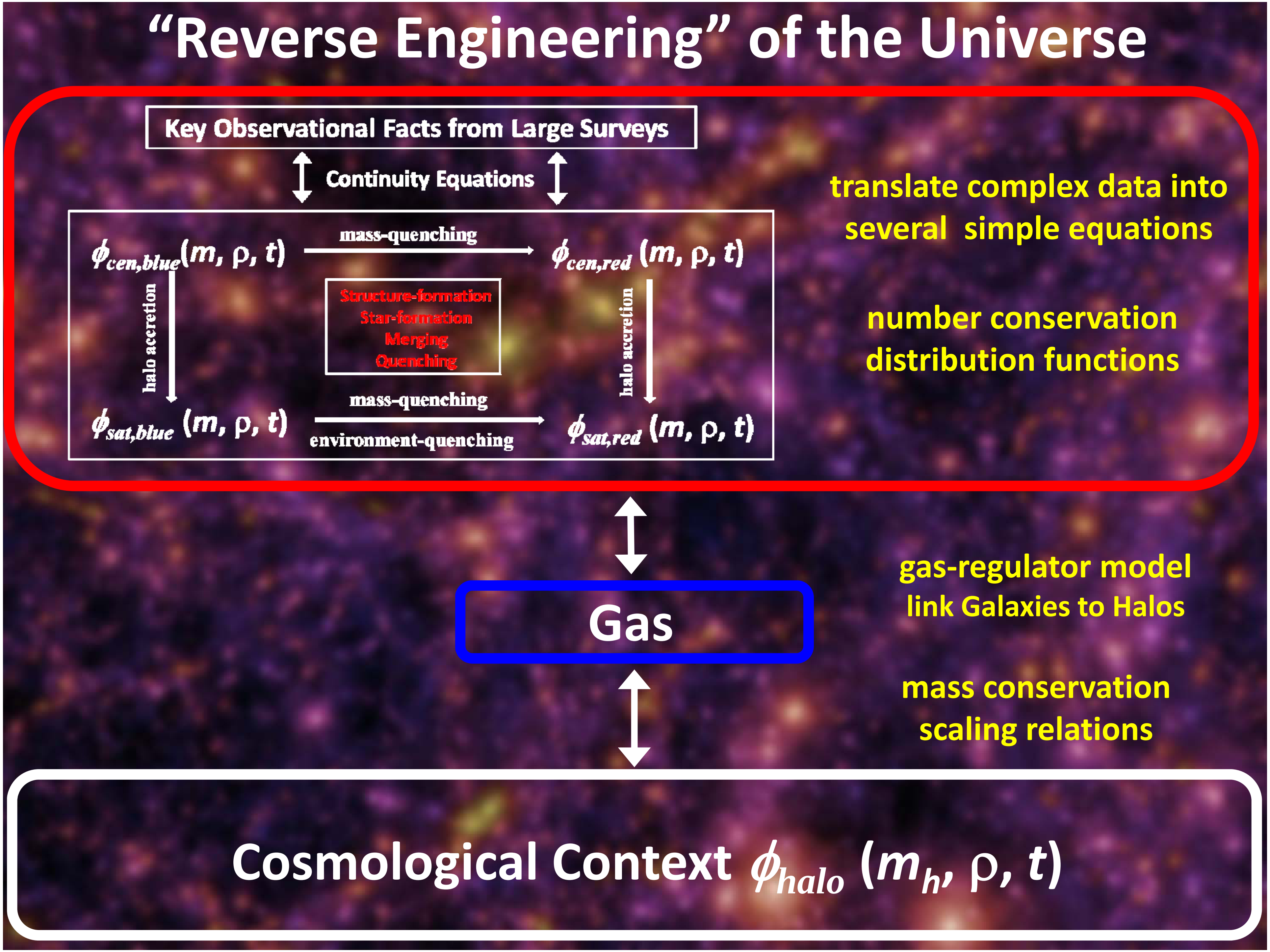
our results are mainly based on metallicity *differences* and age *differences* between star-forming and passive galaxies → uncertainties are much less critical

- strongly support that local quiescent galaxies with $M_{star} < 10^{11}$ M_{star} (i.e. the vast majority of galaxies) are primarily quenched as a consequence of "strangulation".

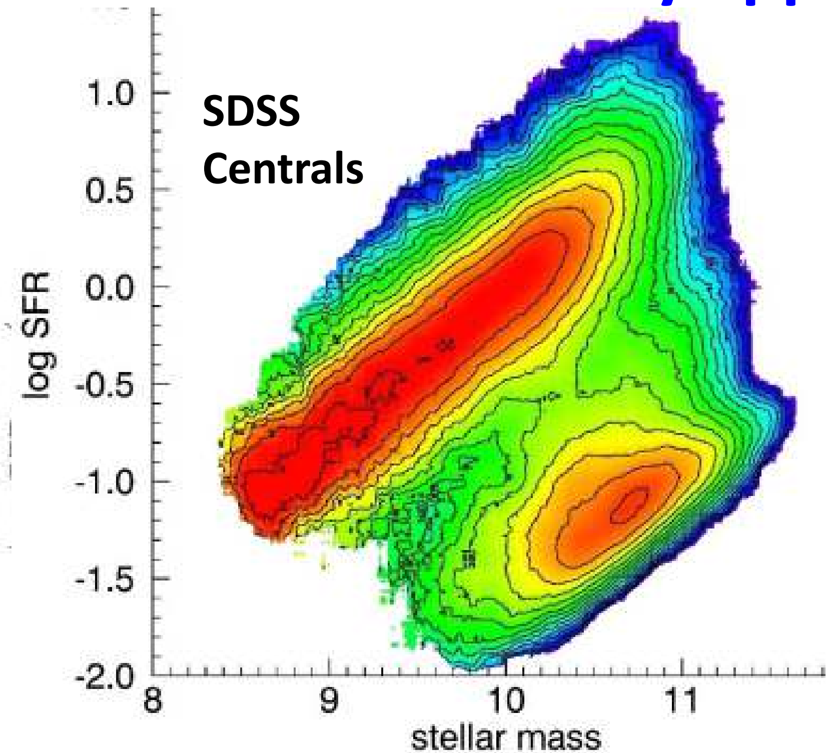
- gas removal by outflows (at low redshifts) plays a minor role in quenching galaxies

- cannot shed light on the quenching mechanism at $M_{star} \geq 10^{11}$ M_{star}

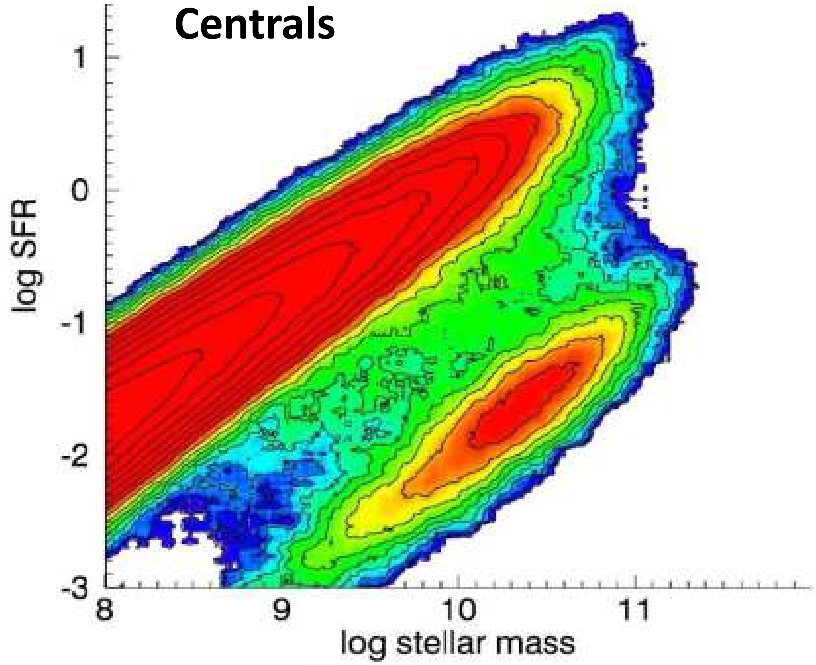
→ *need to perform the same analysis at high redshifts. MOONS/JWST*

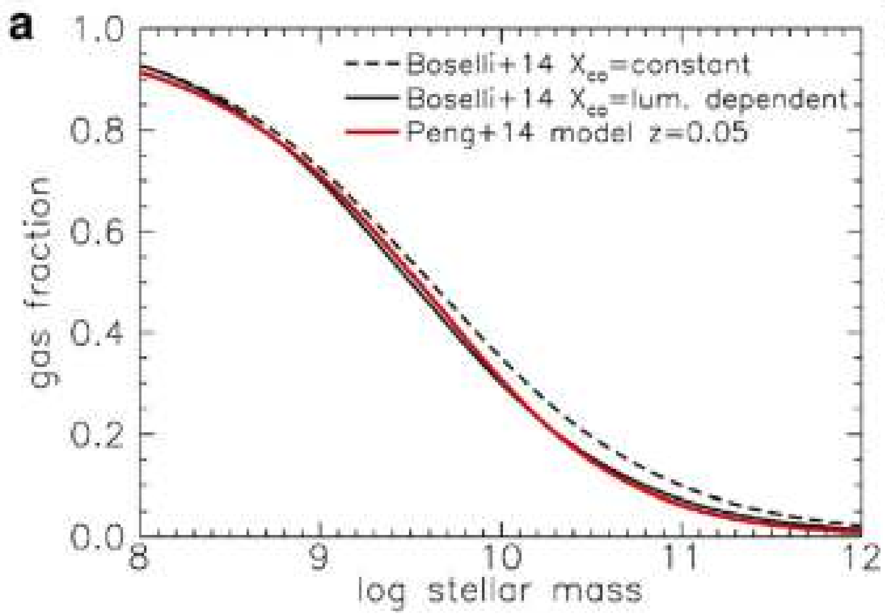

"Reverse Engineering" of the Universe
Key Observational Facts from Large Surveys
Continuity Equations
$\phi_{cen,blue}(m, \rho, t)$
mass-quenching
$\phi_{cen,red}(m, \rho, t)$
halo accretion
Structure-formation
Star-formation
Merging
Quenching
halo accretion
mass-quenching
$\phi_{sat,blue}(m, \rho, t)$
environment-quenching
$\phi_{sat,red}(m, \rho, t)$
translate complex data into
several simple equations
number conservation
distribution functions
Gas
gas-regulator model
link Galaxies to Halos
mass conservation
scaling relations
Cosmological Context $\phi_{halo}(m_h, \rho, t)$

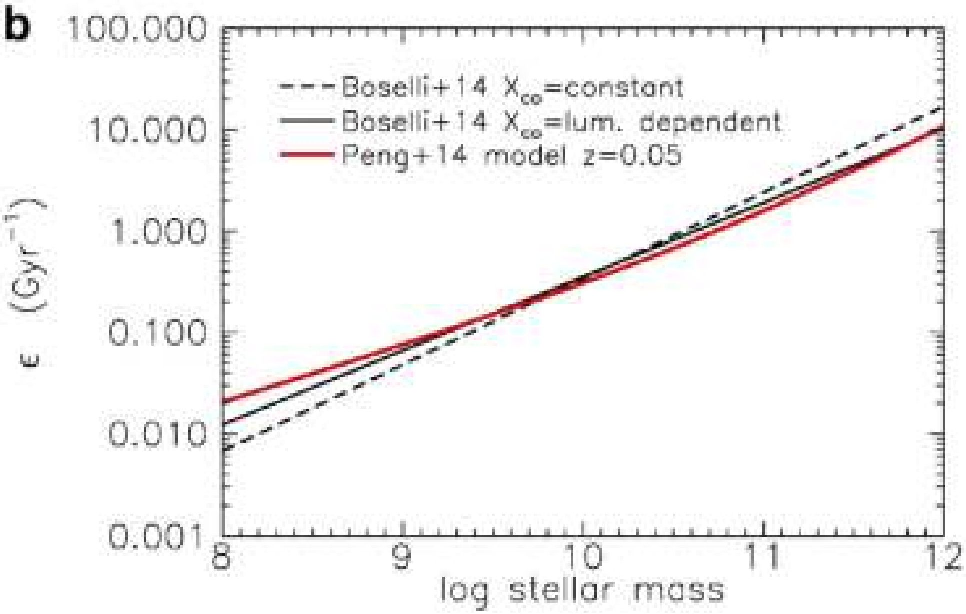
continuity approach + gas regulation



Model - Peng et al. 2017 in prep.

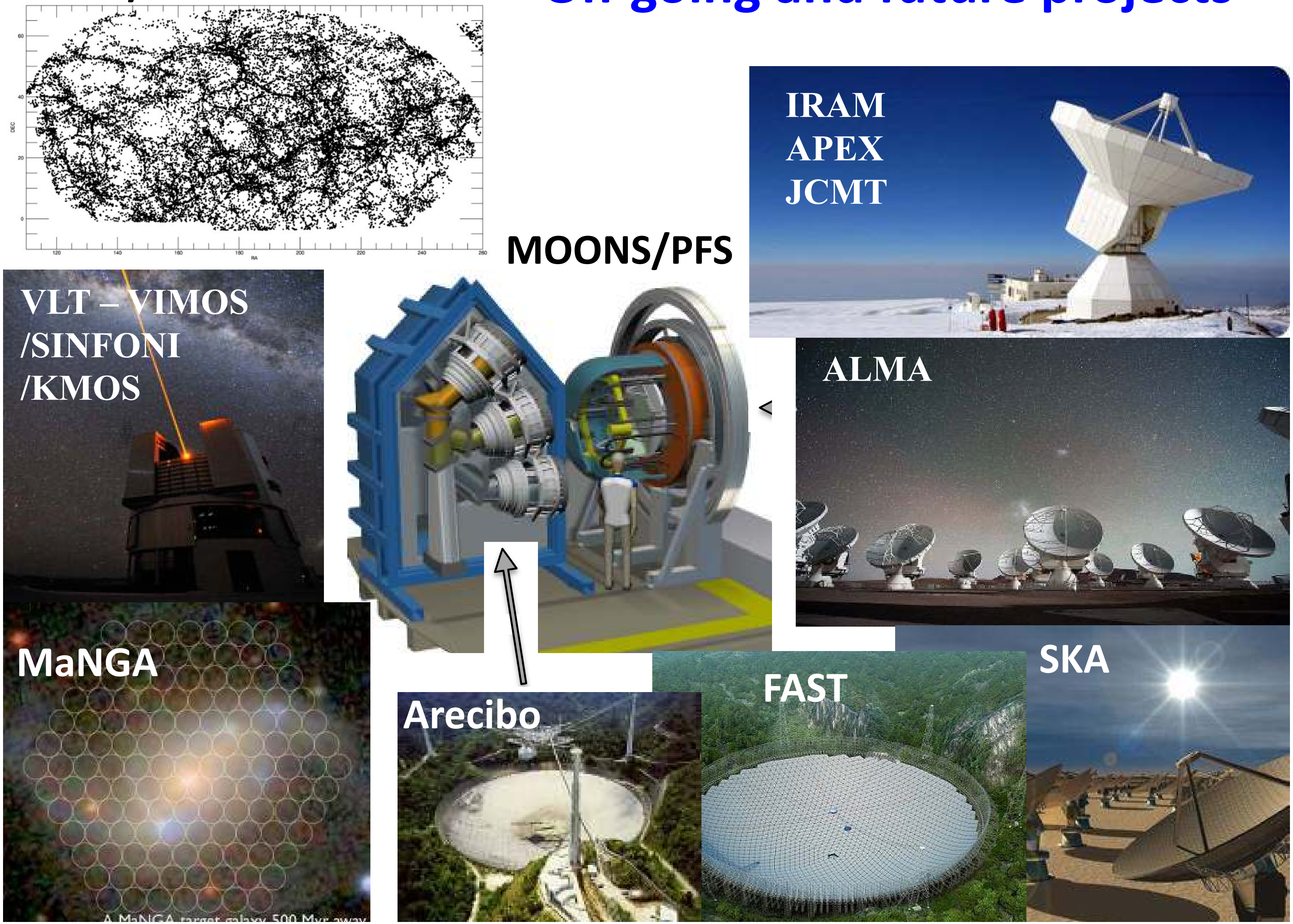






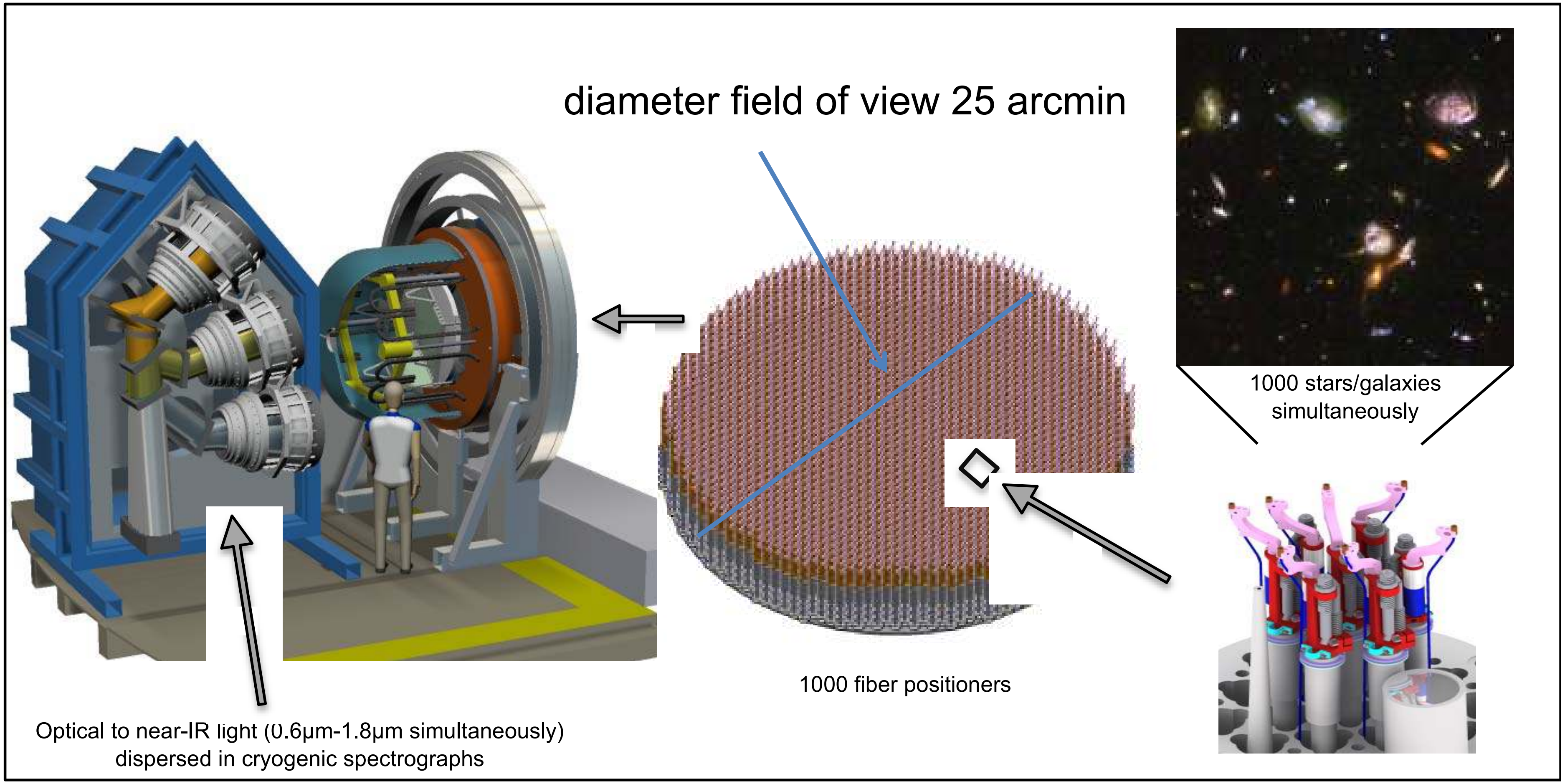
On-going and future projects

SDSS/GAMA



MOONS-(Multi-Object Optical and Near-infrared Spectrograph for VLT)

System Overview



Simultaneously 3 bands:

0.8-0.95µm at R = 8,000

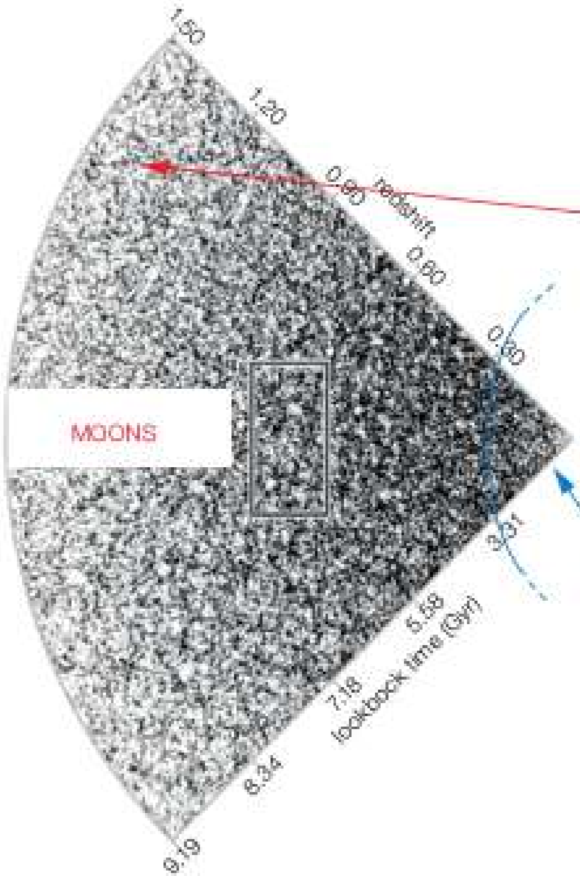
1.17-1.26µm at R=20,000

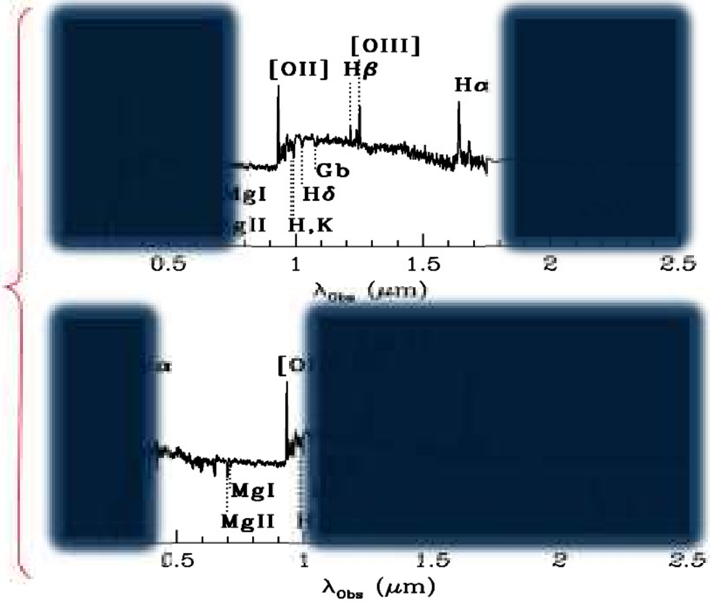
1.52-1.63µm at R=20,000

Property of MOONS team

MOONS - Multi-Object Optical and Near-infrared Spectrograph for VLT

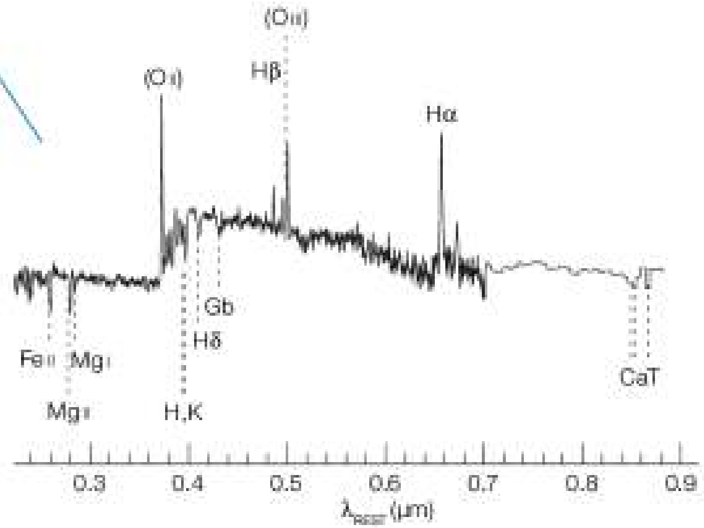
a SDSS-like machine probing the peak of galaxy and black hole formation





MOONS
z = 1.5

Optical spectrographs
z=1.5



SDSS
at z=0.1

Integration 2-16hrs on source
400 nights
~1 Million galaxies at z > 1

Property of MOONS team