The evolution of starburst galaxies

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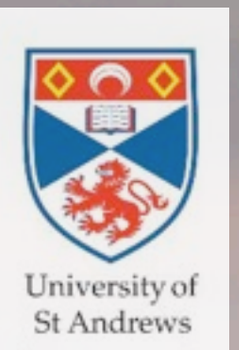
Tim Heckman (JHU), Stephane Charlot (IAP)



Overview

- ✦ Taxonomy
  - What is a starburst galaxy?
  - Post-starburst / E+A / K+A galaxies
- ✦ Defining an evolutionary sequence

- ✦ (post)-starburst - AGN connection
- ✦ Evolution of SFR, gas mass, dust properties
- ✦ Build-up of the red sequence and redshift evolution

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- ✦ Definition/selection varies:
  - IR bright
    - low-z ULIRGS are extreme examples
  - Birth rate or SFR/M* *(specific SFR)*
    - time to build stellar mass at current SFR << t_H
  - Intensity (surface brightness)
    - Maximum close to 20 M_{sol}/yr/kpc^2
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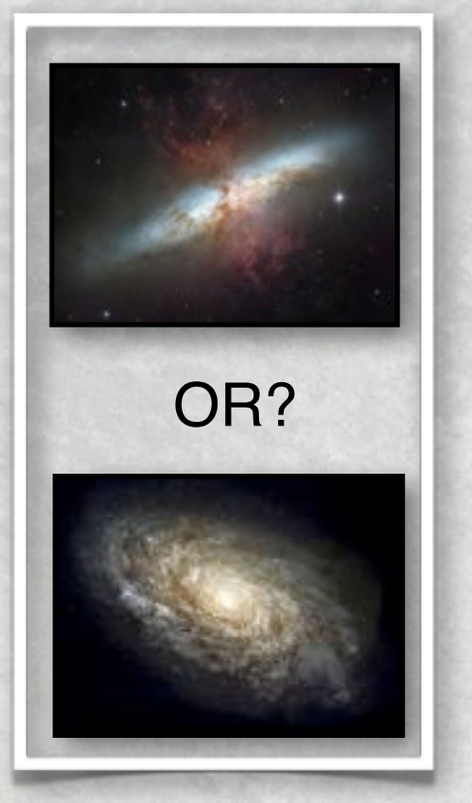
✔ Easy observables
✘ Dependent on mass and redshift

✔ Better physical motivation
✘ Difficult observables

Why are starburst galaxies interesting?



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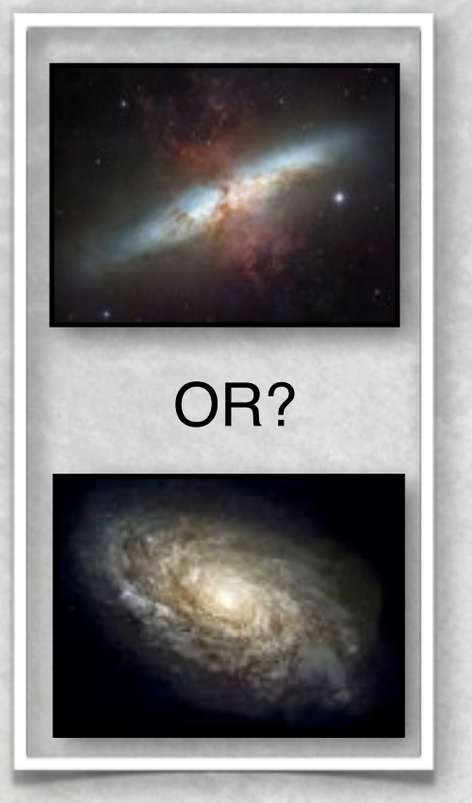

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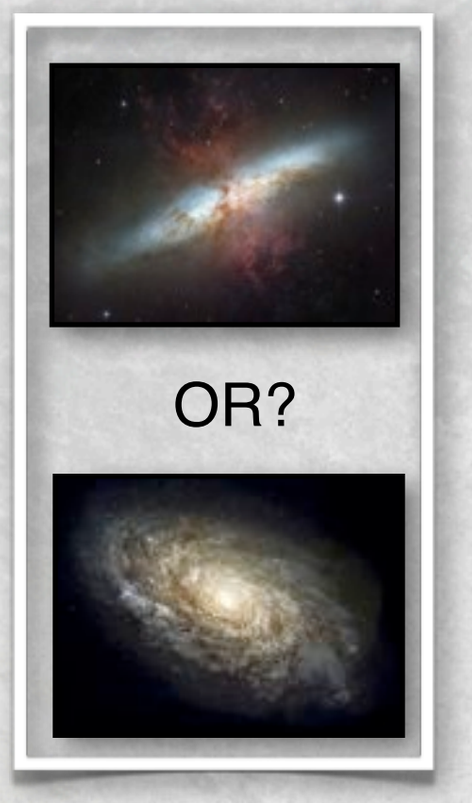

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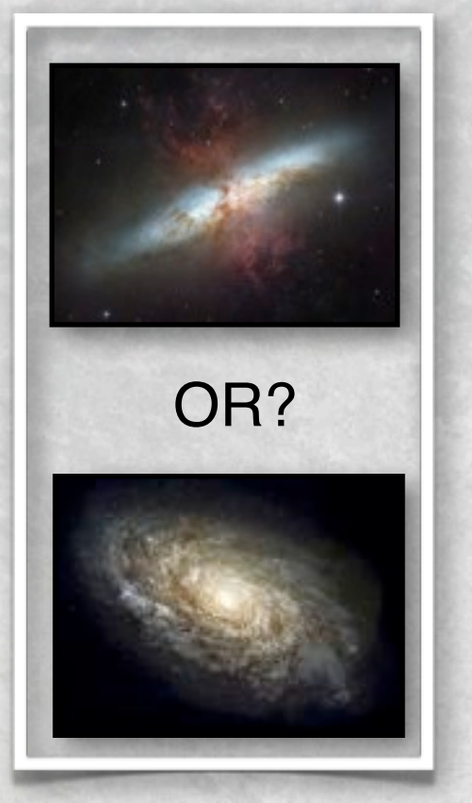
  - How well do galaxies follow Dark Matter's hierarchical growth?



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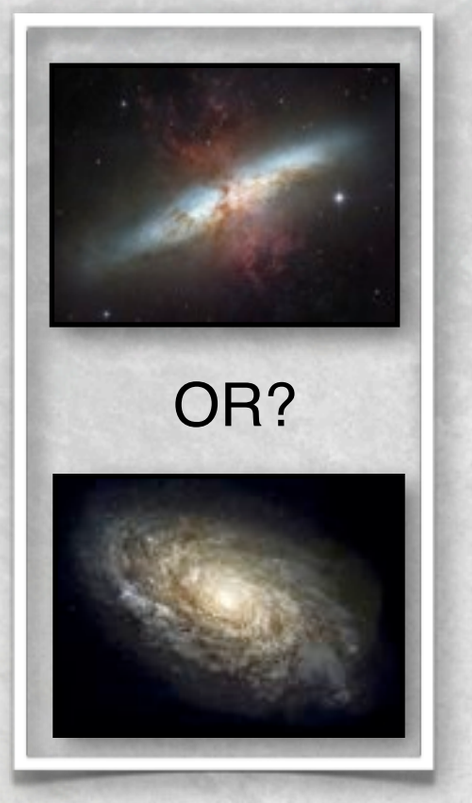
- ✦ Physics of high mass star formation
  - Millions of OB stars
  - Outflows and self-regulation



Defining starbursts

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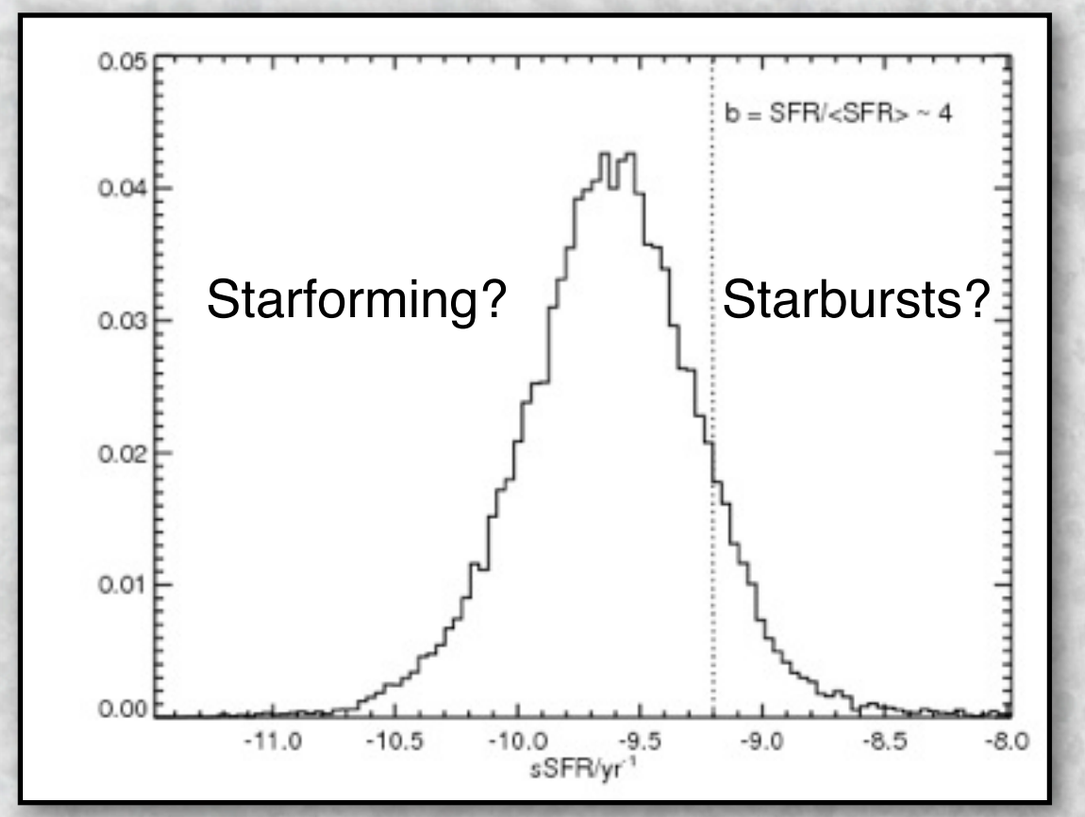
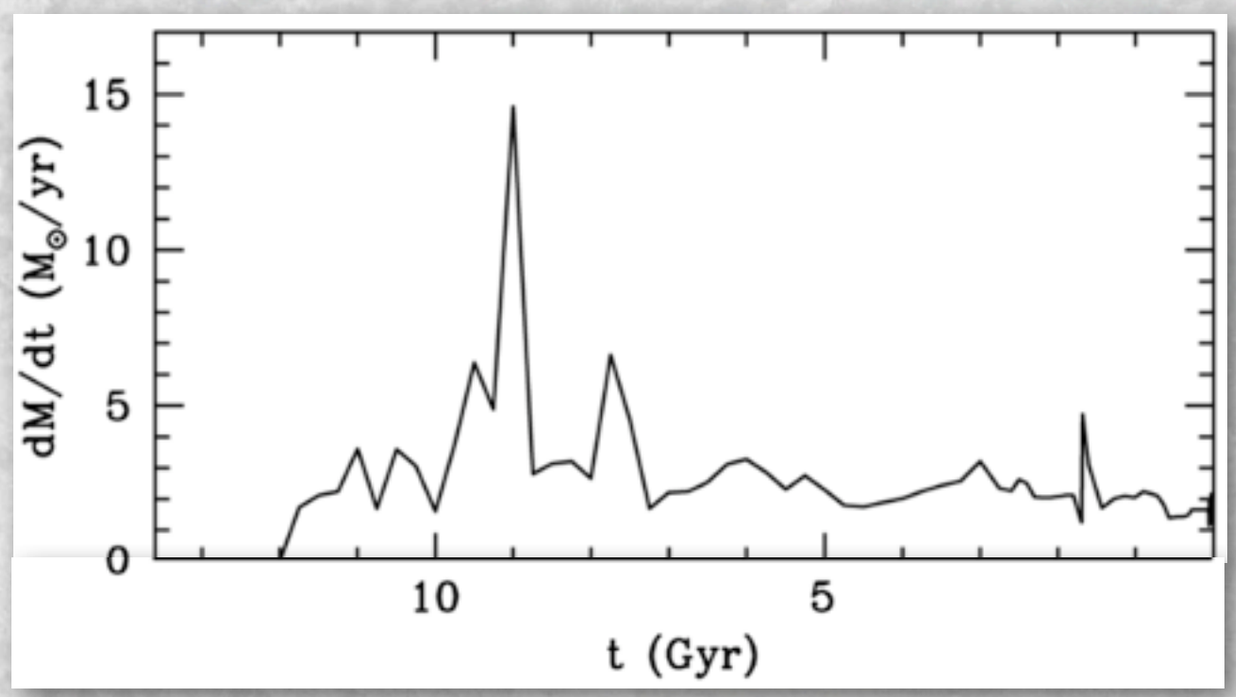


SDSS DR7 Starforming galaxies

2) Threshold detection



De Lucia & Blaizot semi-analytic SFH
(**Pacifici et al. 2011**)

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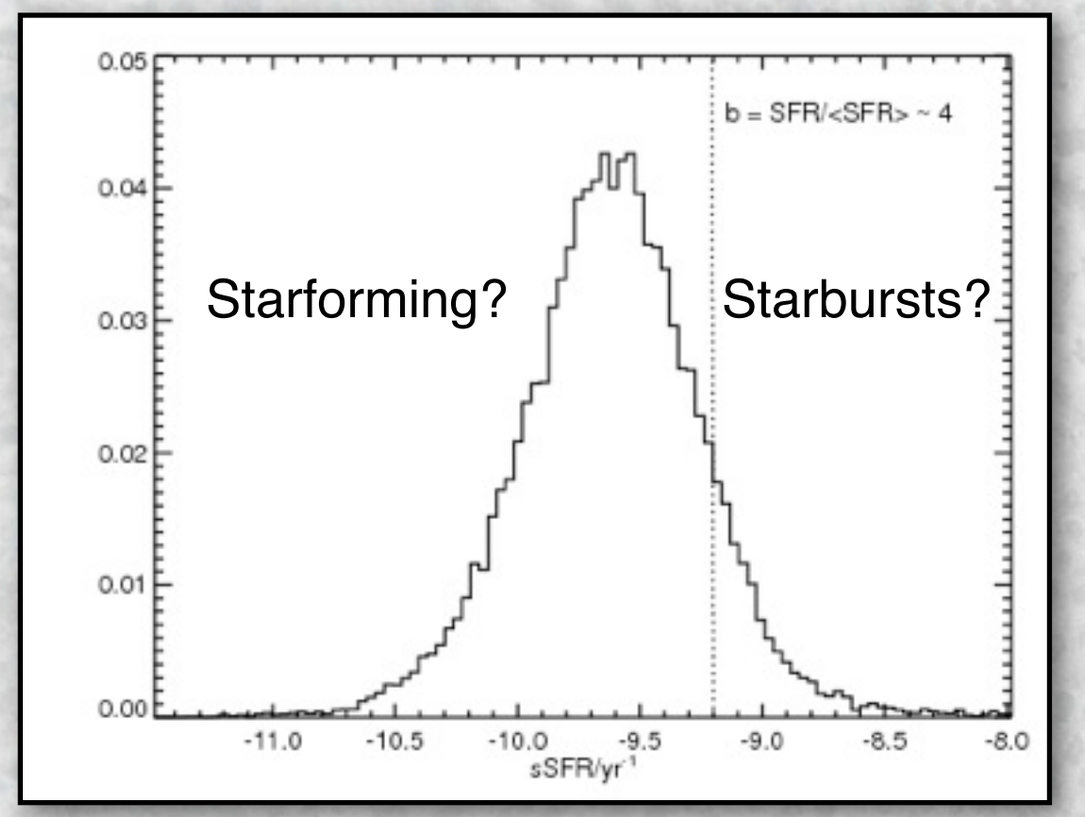

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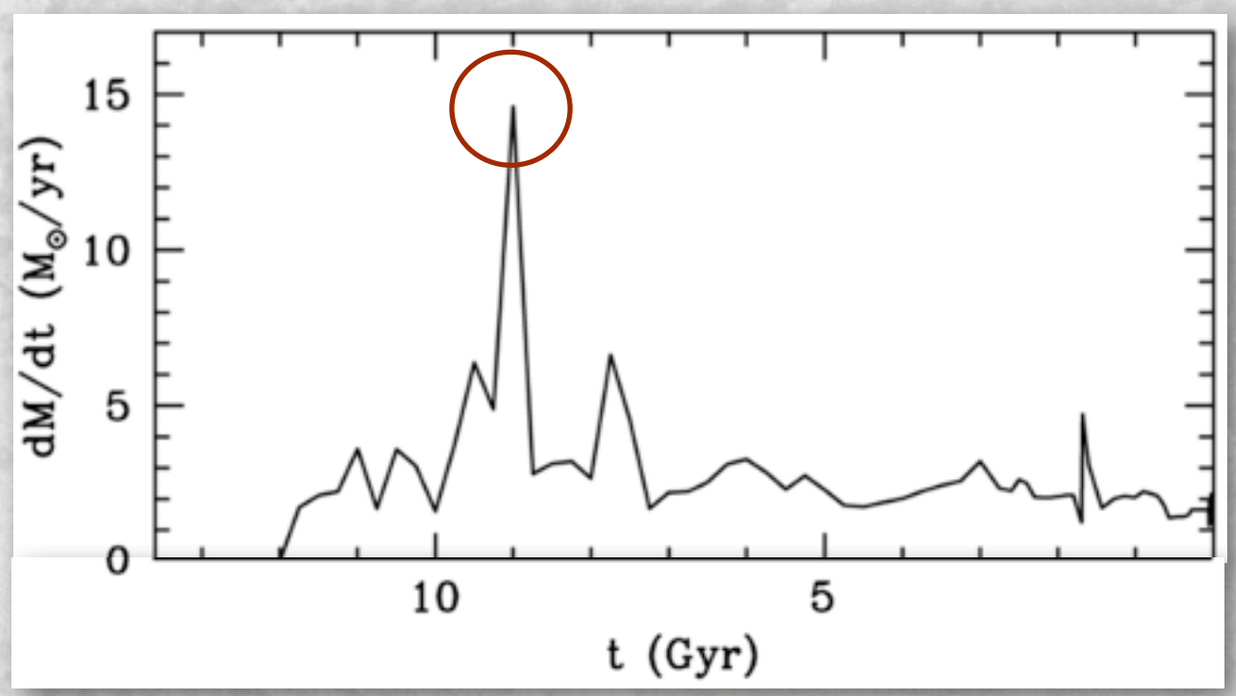

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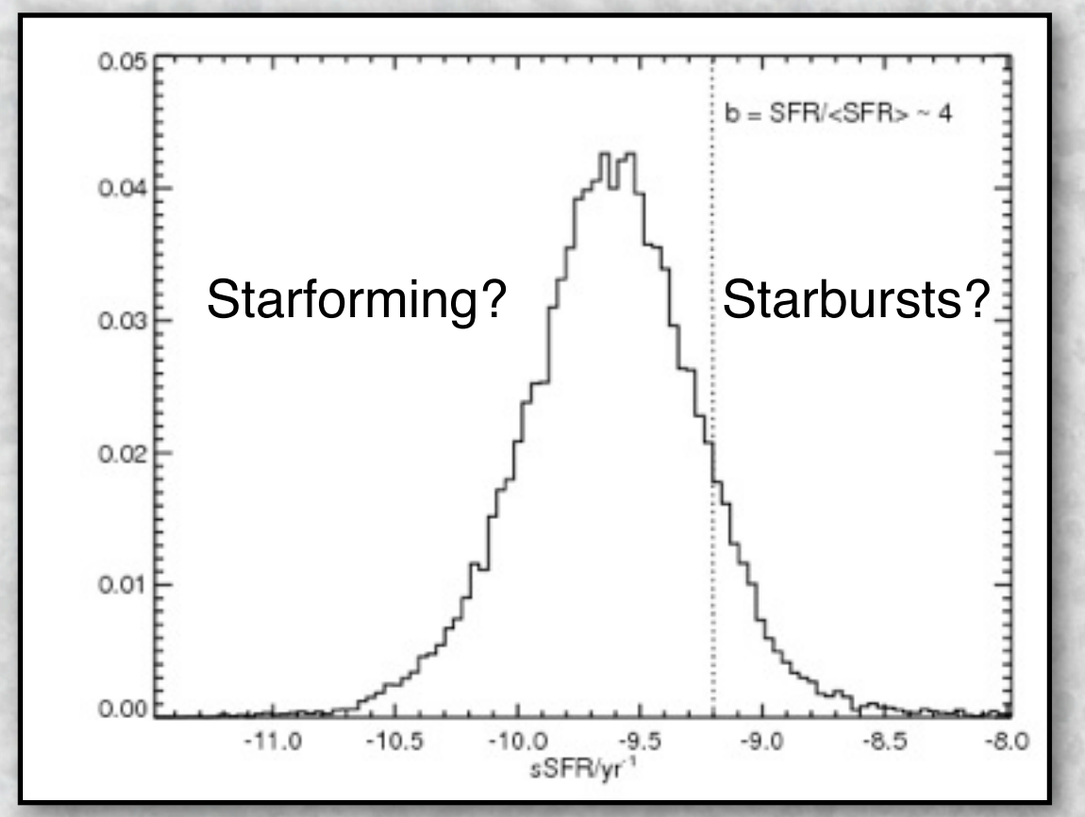

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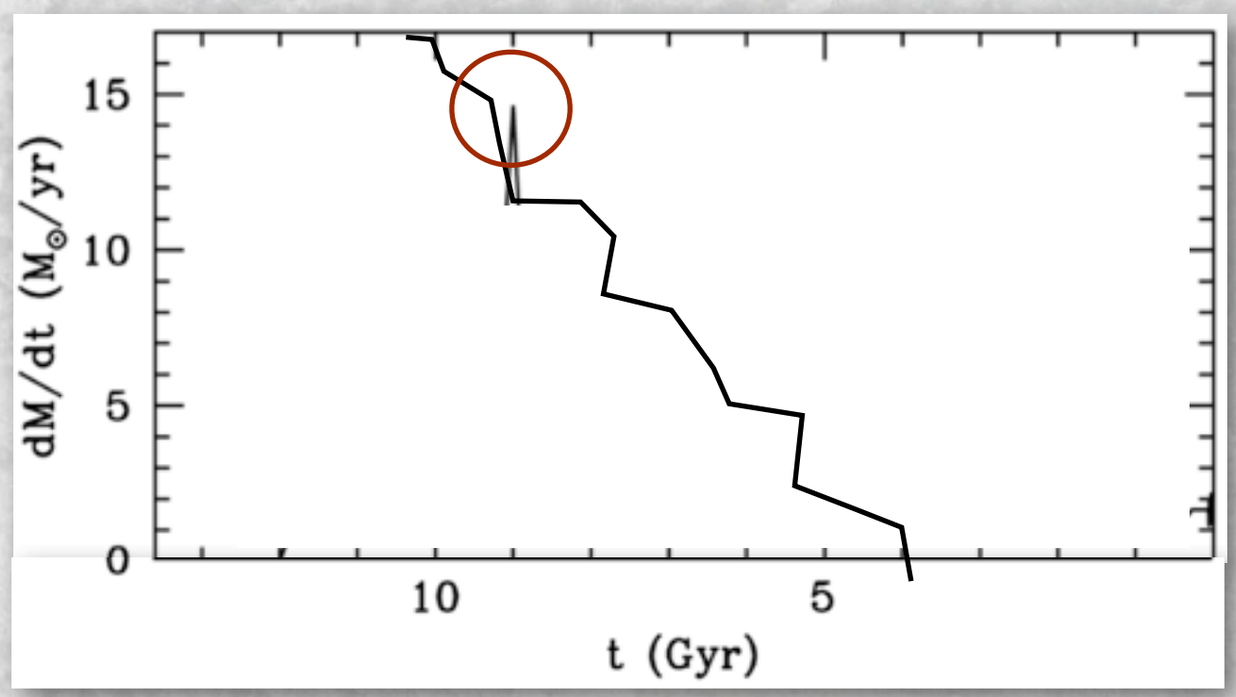

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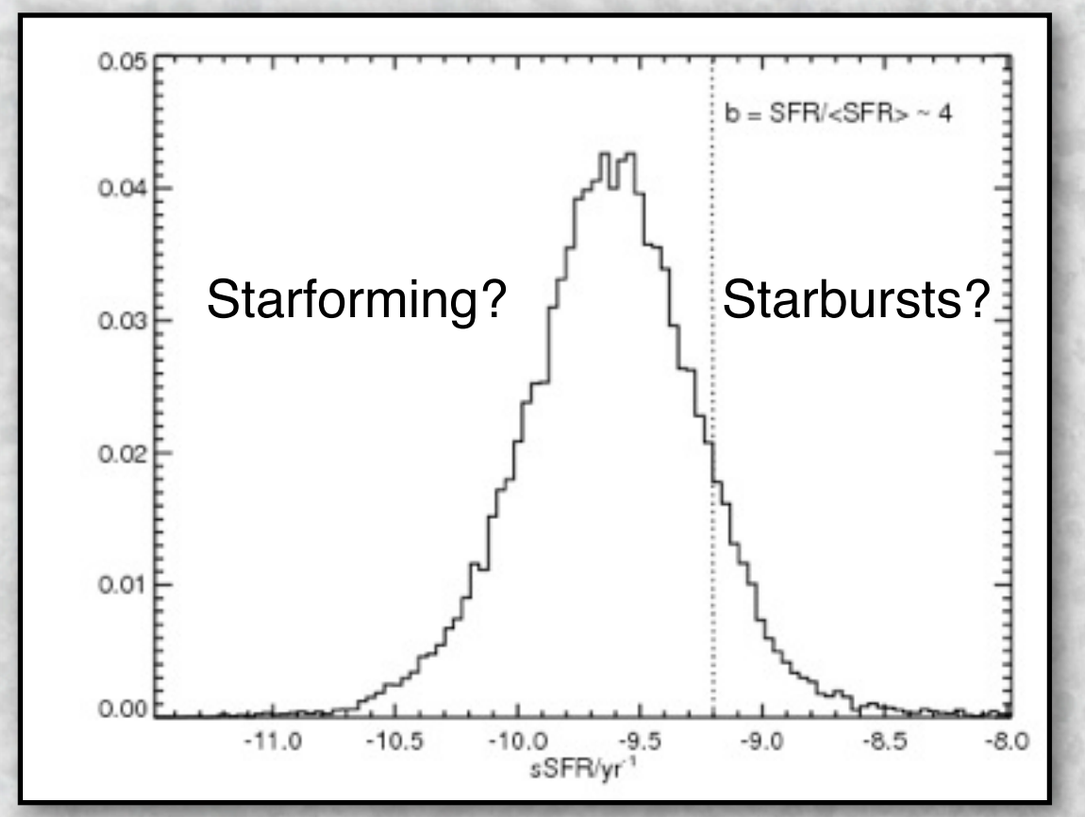

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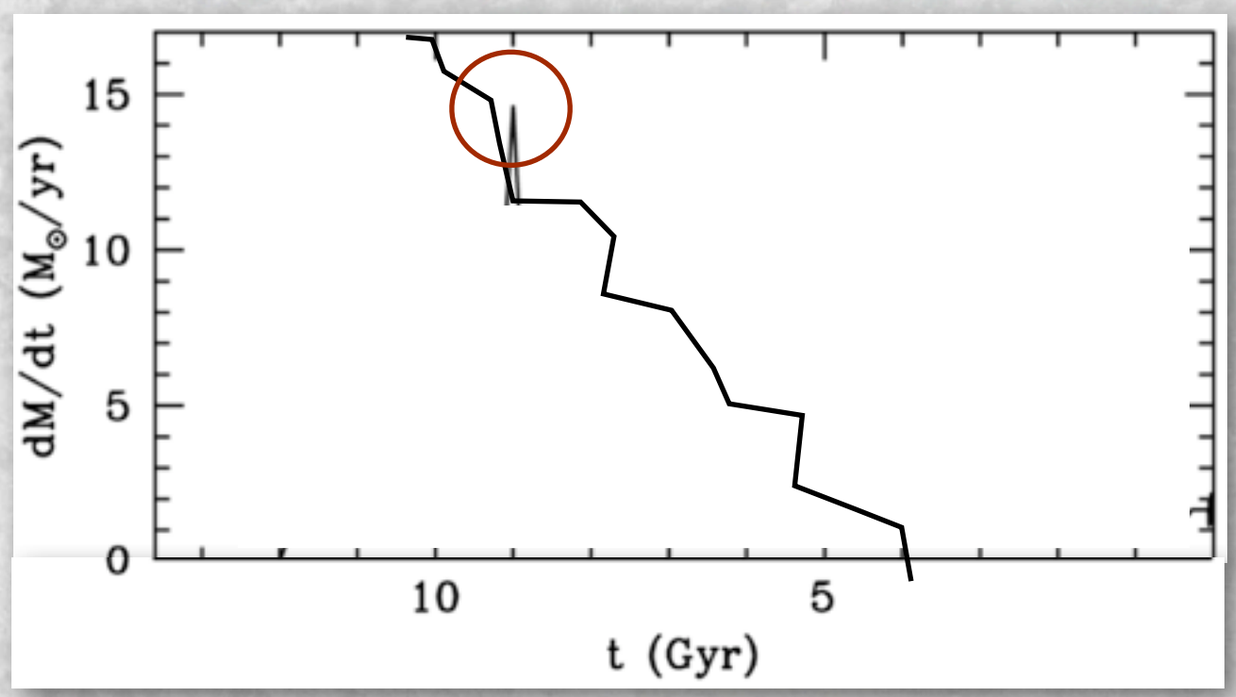

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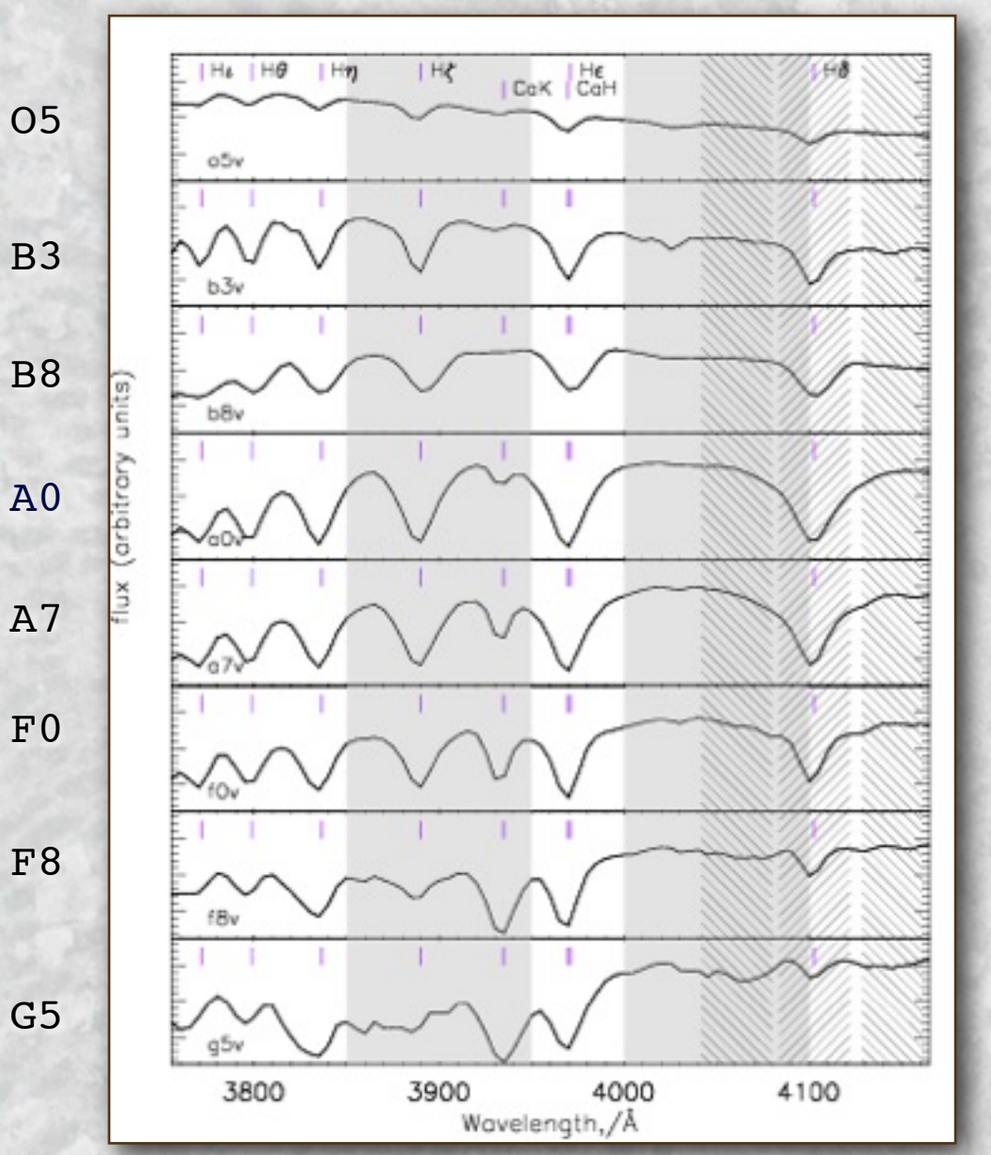
- A starburst (for the purposes of this talk):
  - Is an unsustainable star formation event
    - And therefore decays into a post-starburst phase
  - Occurs “once-in-a-lifetime” of an average galaxy (or a few times)
  - Adds significant (~10%) stellar mass to galaxy

Building stellar populations



	Main Sequence Lifetime	Spectral features	
O star	~10^6	Steep UV continuum He absorption	Strong UV continuum excites nebular emission lines
B star	~10^7	Some Balmer (HI) absorption	
A star	~5x10^8	Strong Balmer lines and Balmer break Ca H&K lines	A trend with temperature within A stars: T↓ Ca↑ break ↓
G star	~8x10^9	Strong metal lines Balmer series weak Strong 4000Å break	

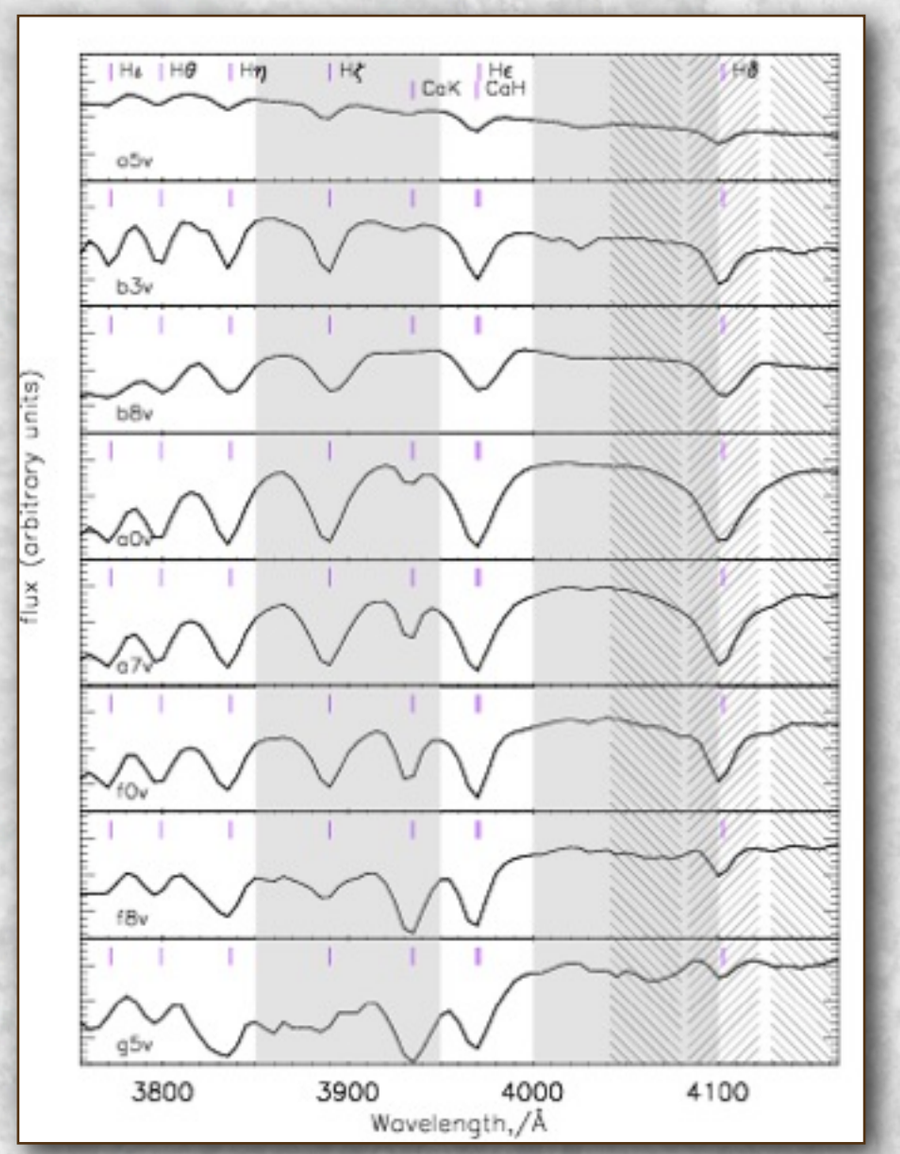
- Galaxy spectrum = stellar spectra+IMF+SFH+ZH (x dust)
  - Invert to recover SFH
  - Light from some galaxies can be dominated by one type of star

Building stellar populations

~starburst galaxy

~post-starburst galaxy

~elliptical galaxy



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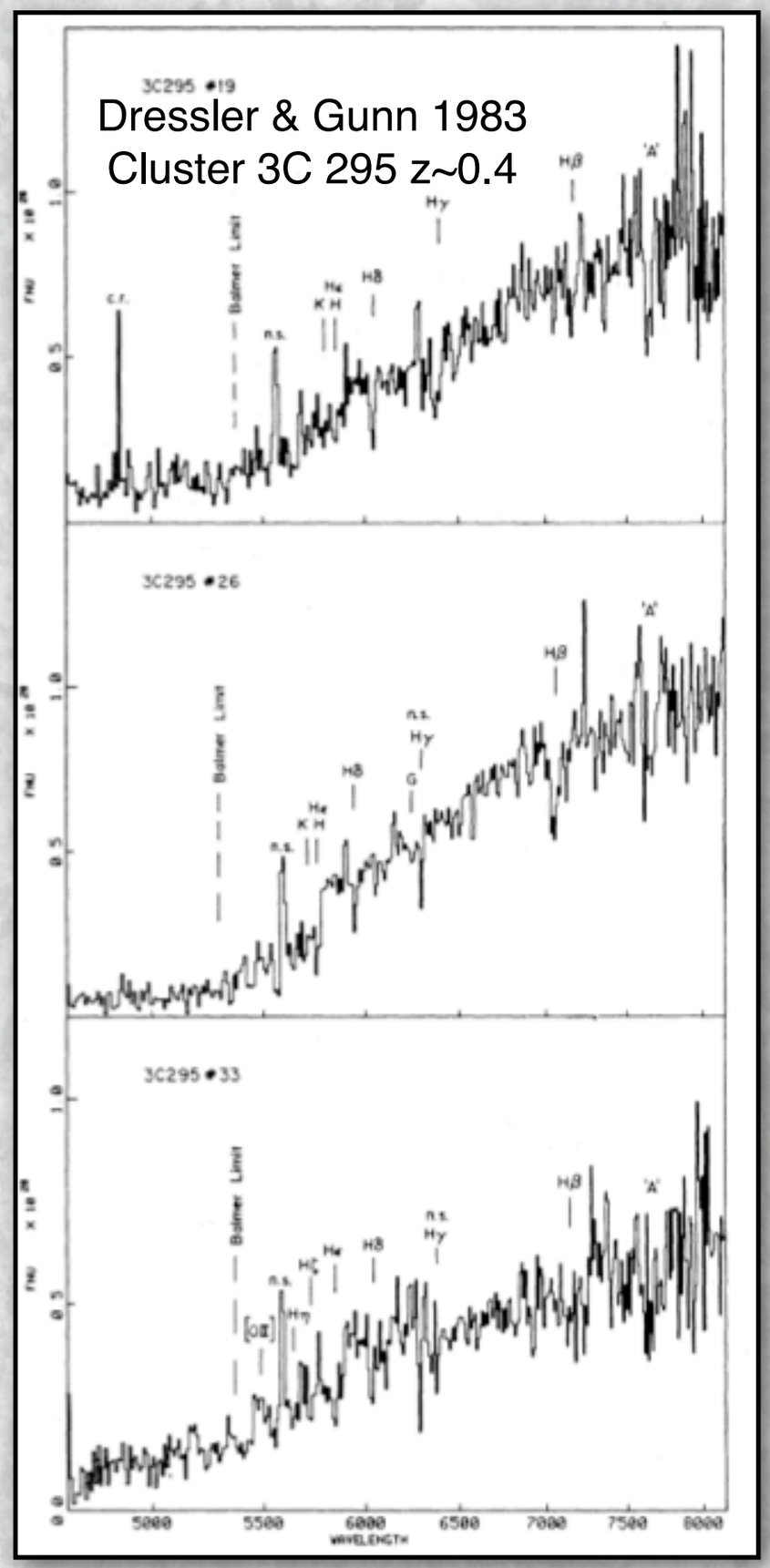
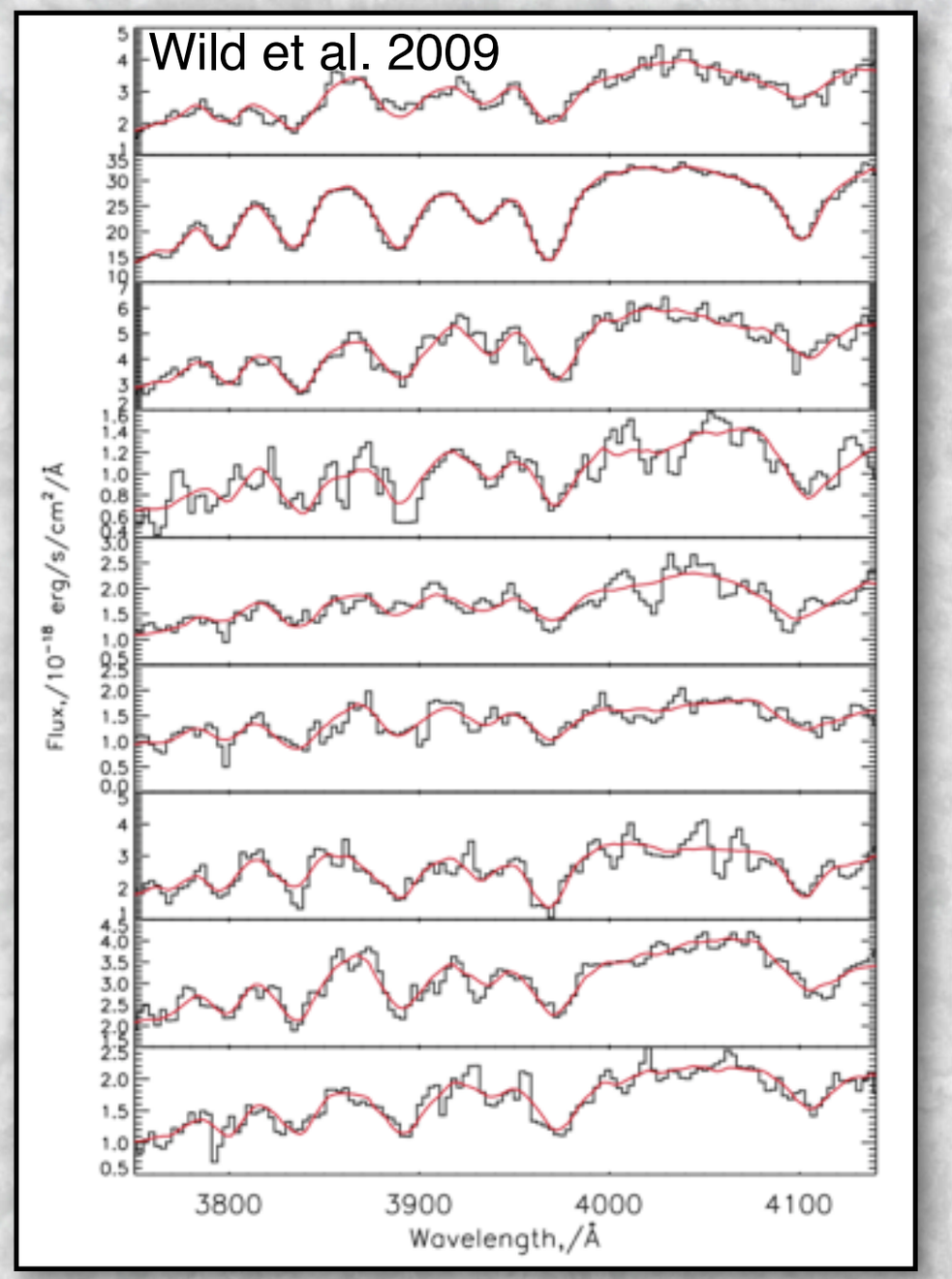


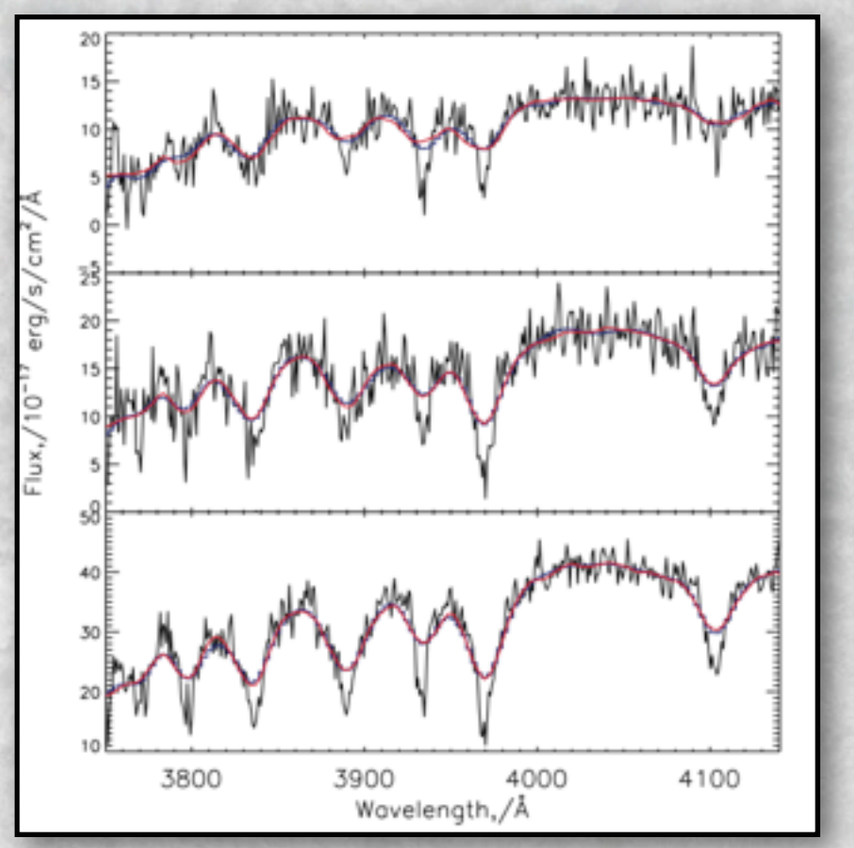
Dressler & Gunn 1983
Cluster 3C 295 z~0.4

“colour is typical of Sb spirals .... but the integrated spectrum of an Sb spiral is completely incompatible with the spectra of the 3 objects”

“...consistent with an old population mixed with an equal blue luminosity of A-stars, which indicates a large burst of star formation 10^9 years before the light left the galaxy”

Post-starburst galaxies



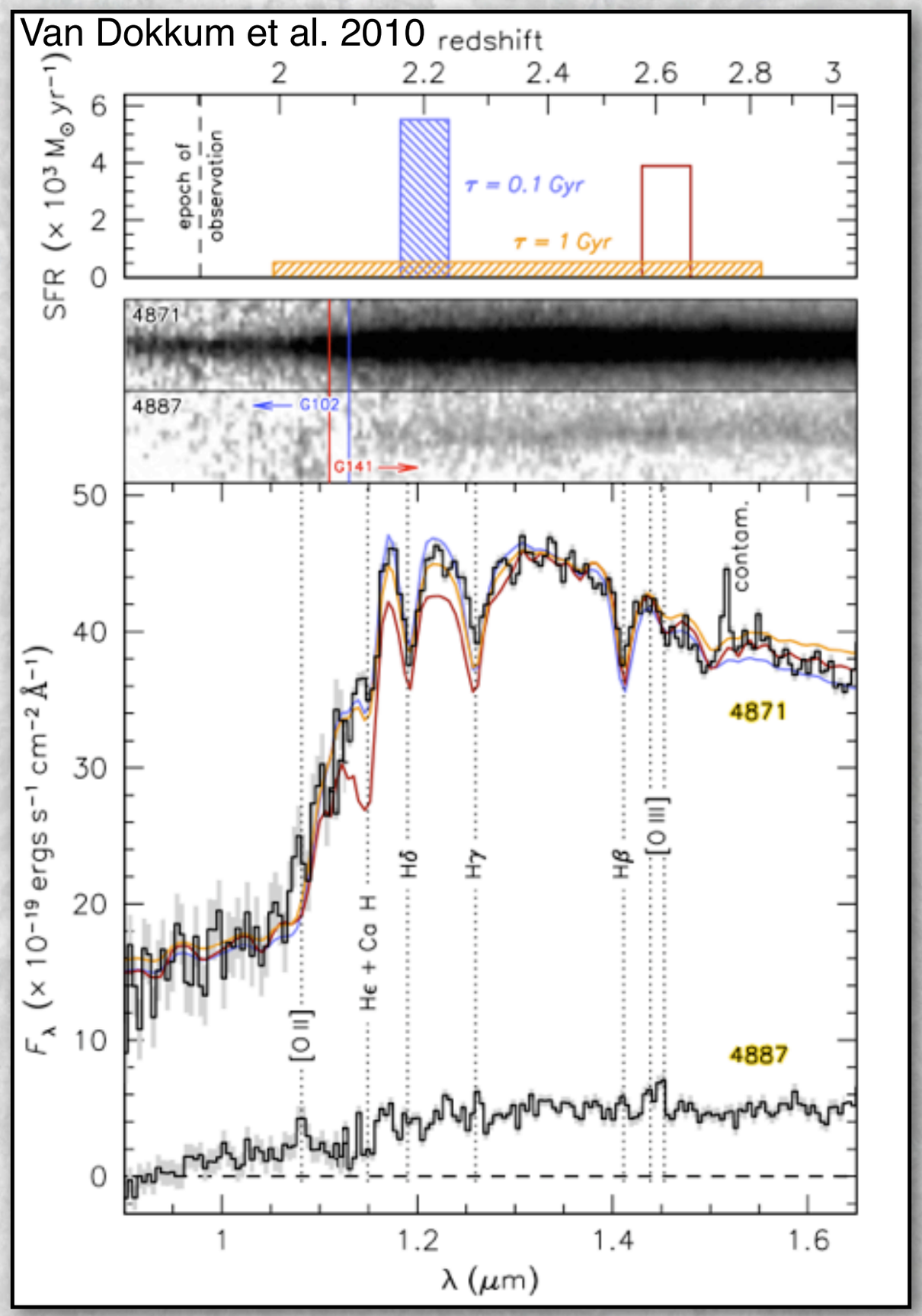


“compare with simulations to show that the galaxies are consistent with being the descendants of gas-rich major mergers”

“post-starburst galaxies could account for ~40% of the growth rate of the red sequence”

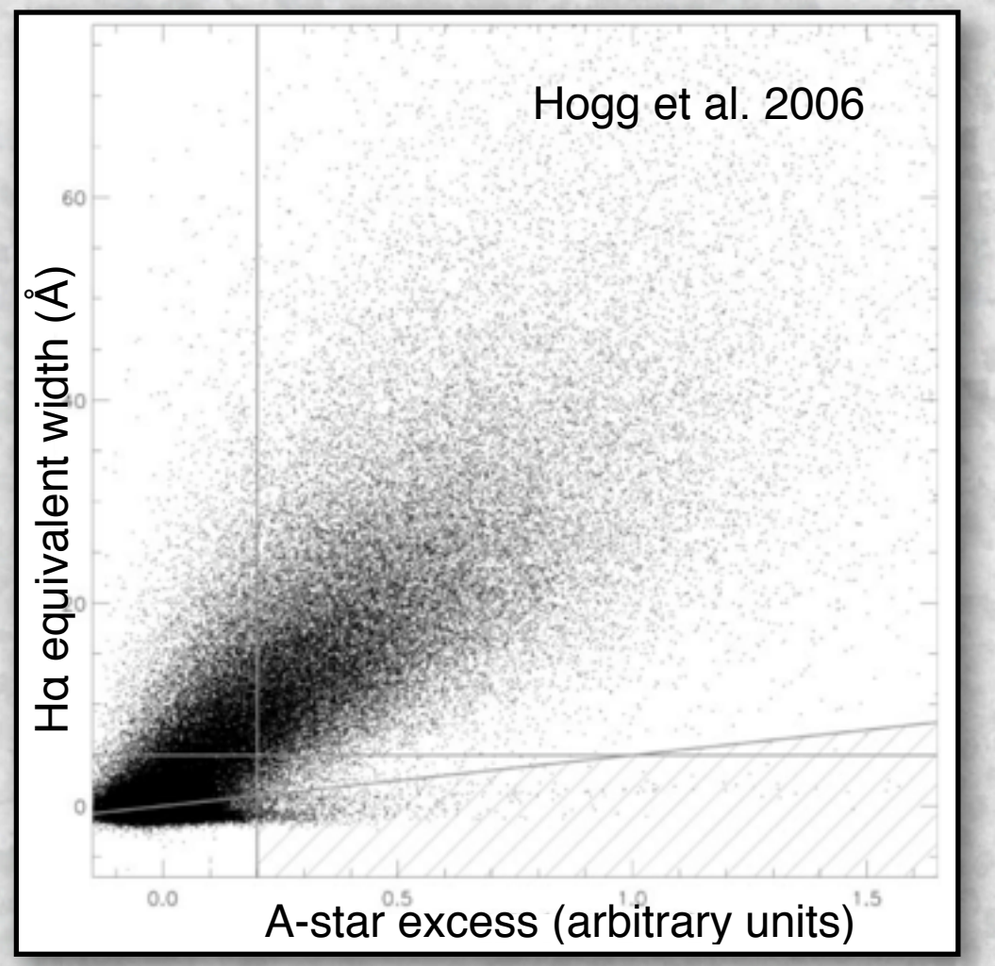
Post-starburst galaxies

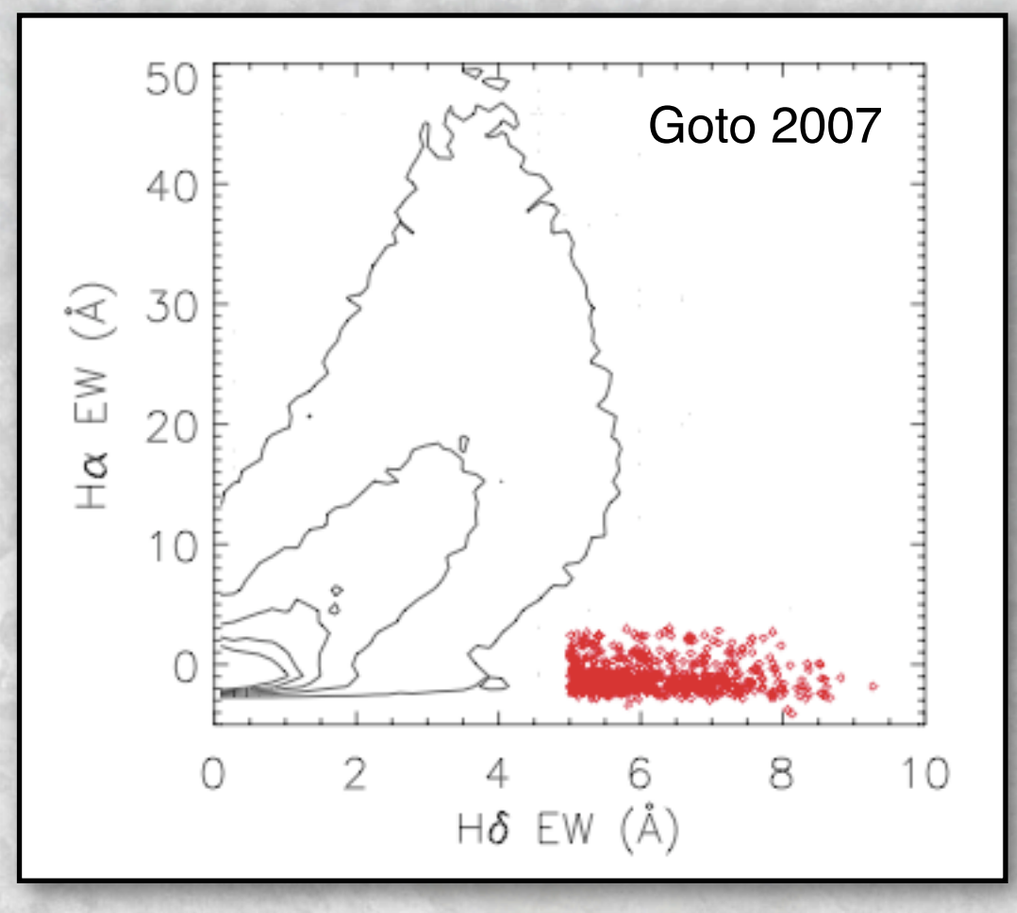
“Similar to other massive galaxies at z~2 the galaxy is compact, with an effective radius of 2.1 ± 0.3kpc”



“the data can be fit with an extreme burst of ~5000 M⊙/yr at z~2.2 (blue), or with a star formation rate of ~500 M⊙/yr sustained over ~1 Gyr (orange)”

Post-starburst selection - traditional





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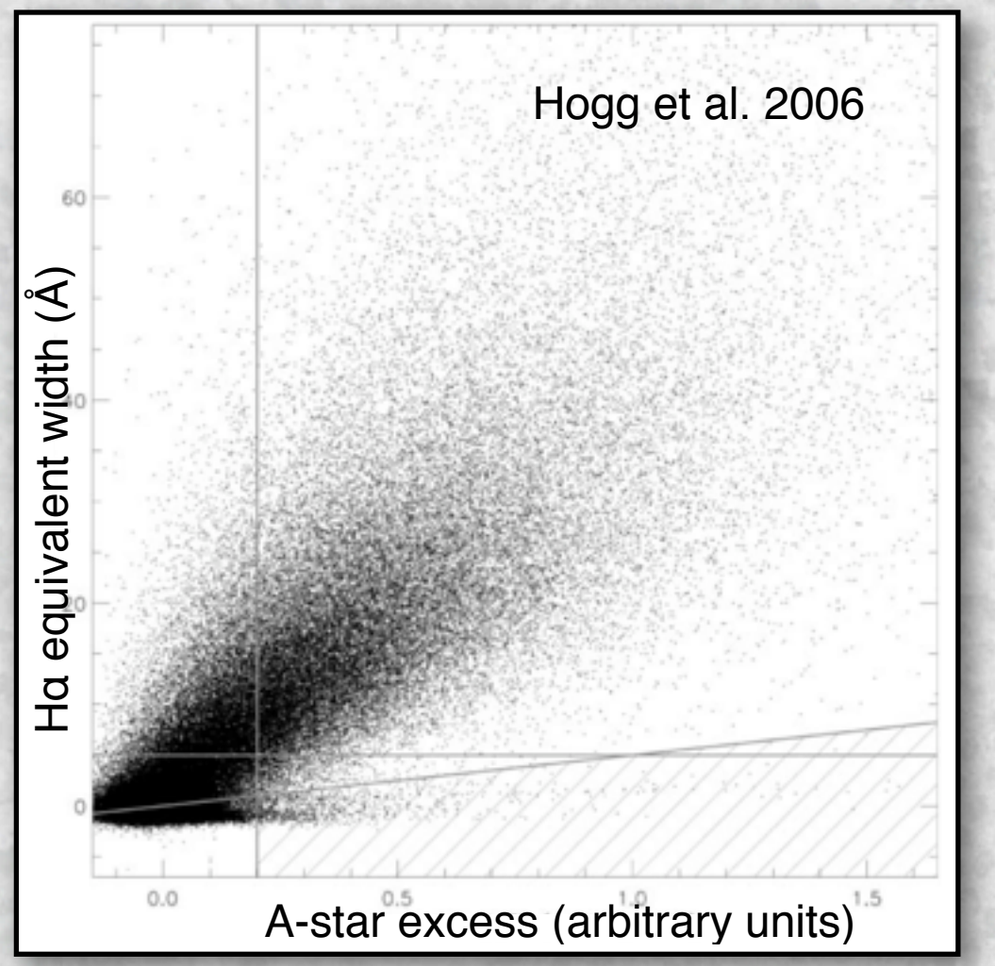
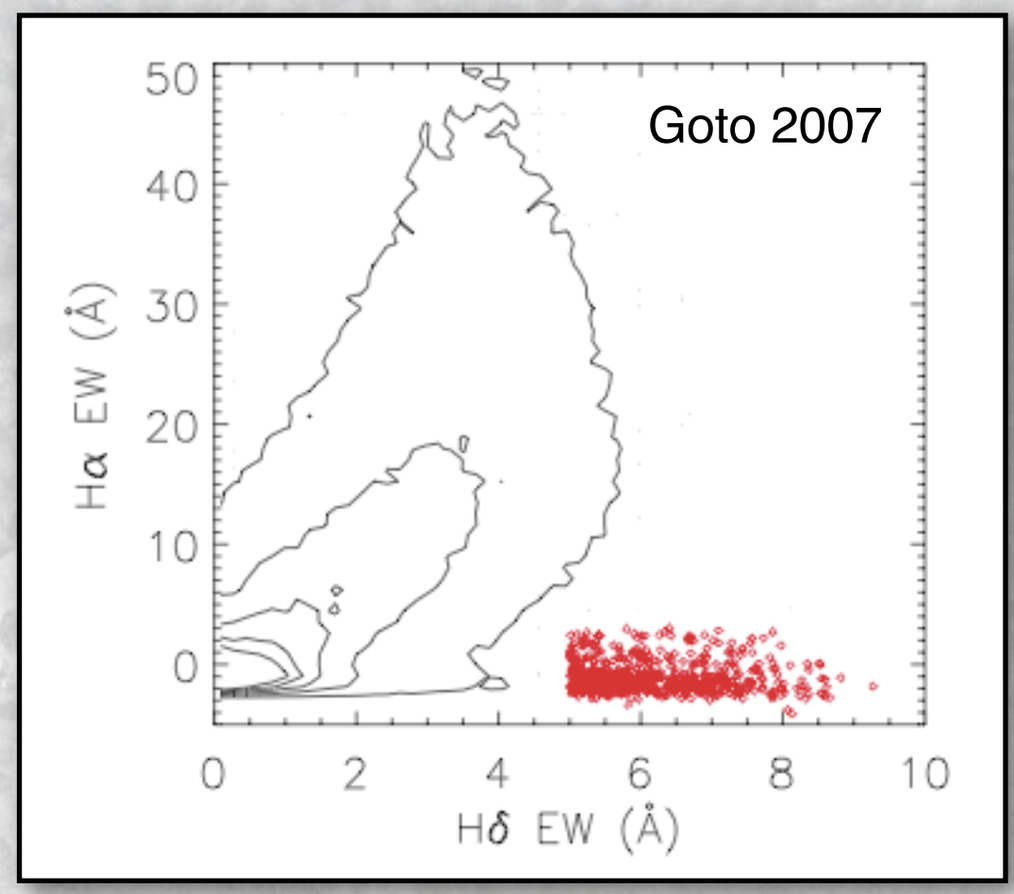


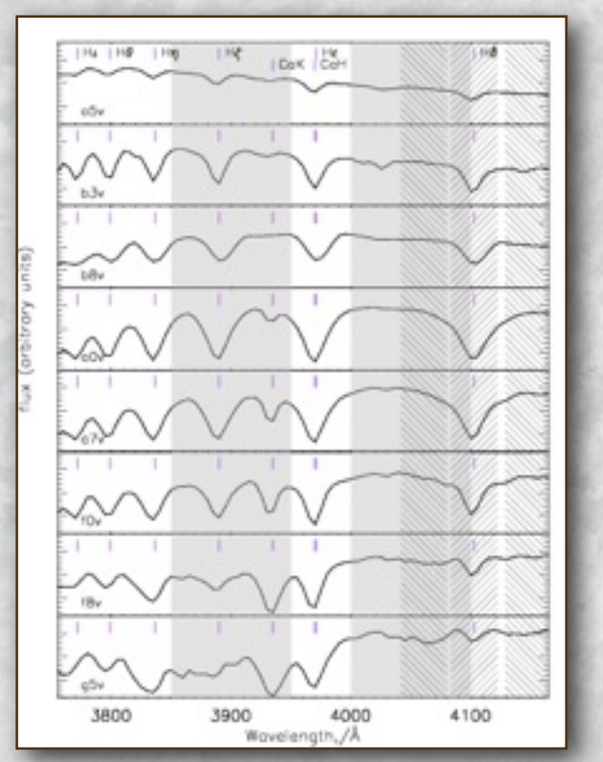


- Problems:
  - EQW emission/absorption combination = complicated physical selection function
  - Ignores possibility for slow decay in SFR after starburst
  - **Impossible to study evolution of starburst -> post-starburst**
  - Excludes objects with AGN
    - and post-starbursts have higher probability of having an AGN (Wild et al. 2007, Yan et al. 2009)

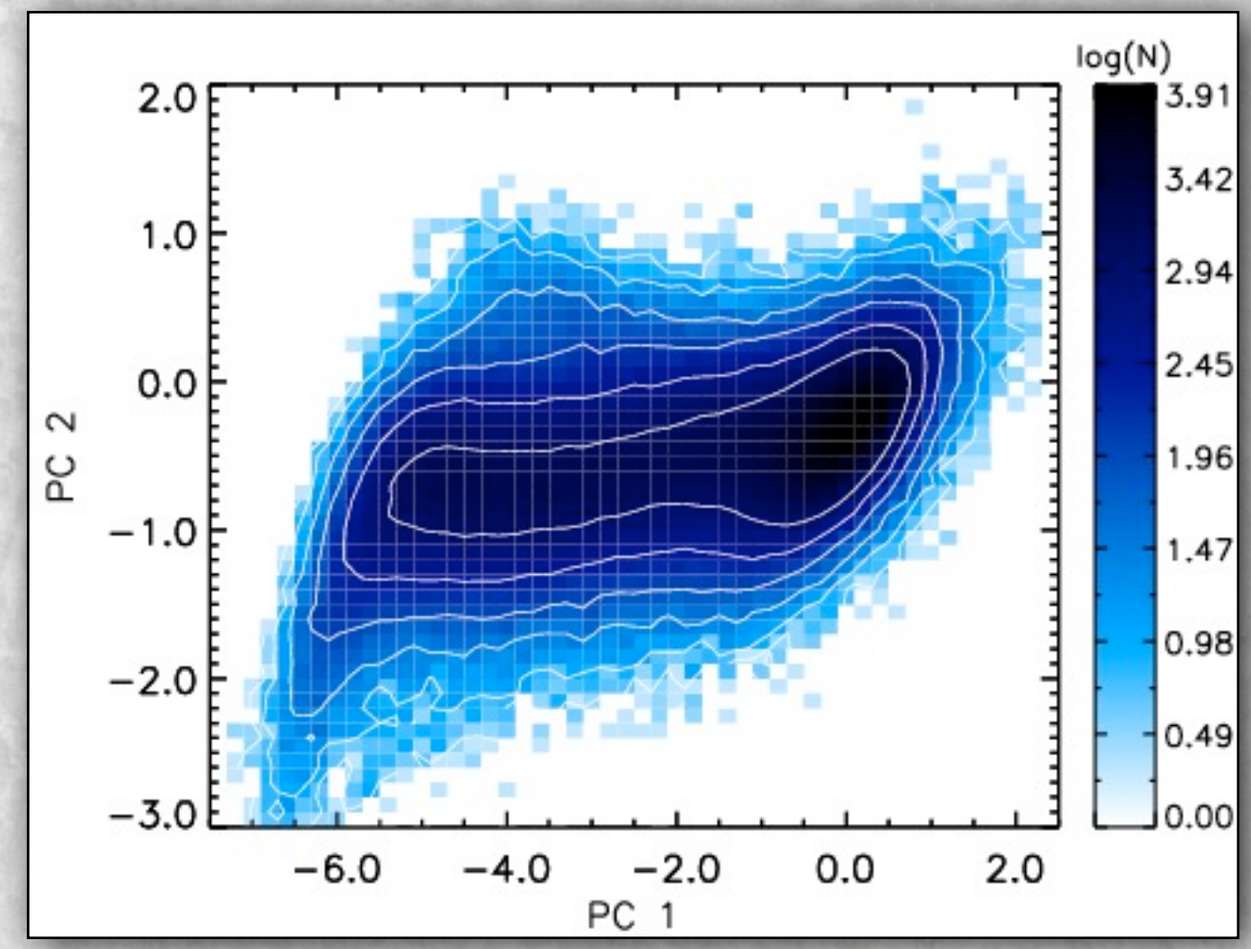
PSB selection with PCA

- ✦ Parameterise shape of spectrum using spectral indices
- ✦ Plot distribution of indices for a *complete sample* of galaxies (e.g. mass limited)
- ✦ Utilise edges of distribution to extract additional “population” information

Reminder:



Stronger Balmer lines



Increasing 4000Å break
(decreasing SSFR)

SDSS DR7
galaxies

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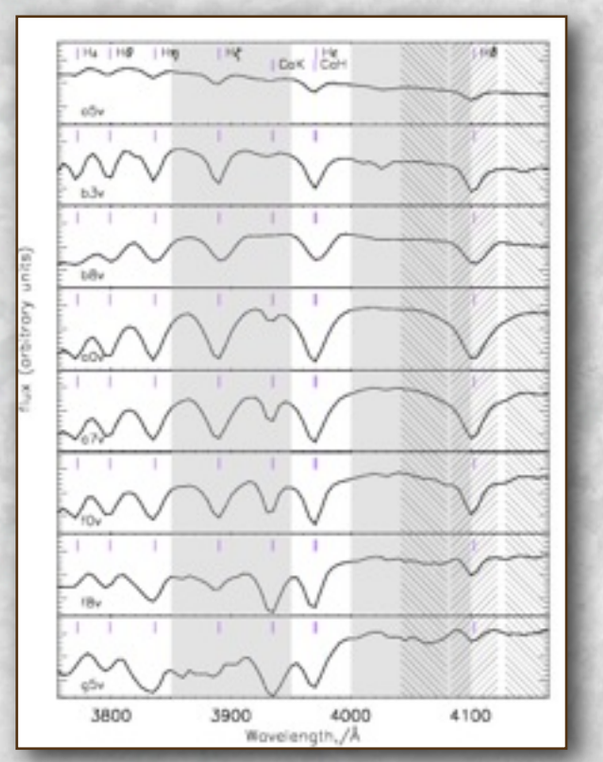

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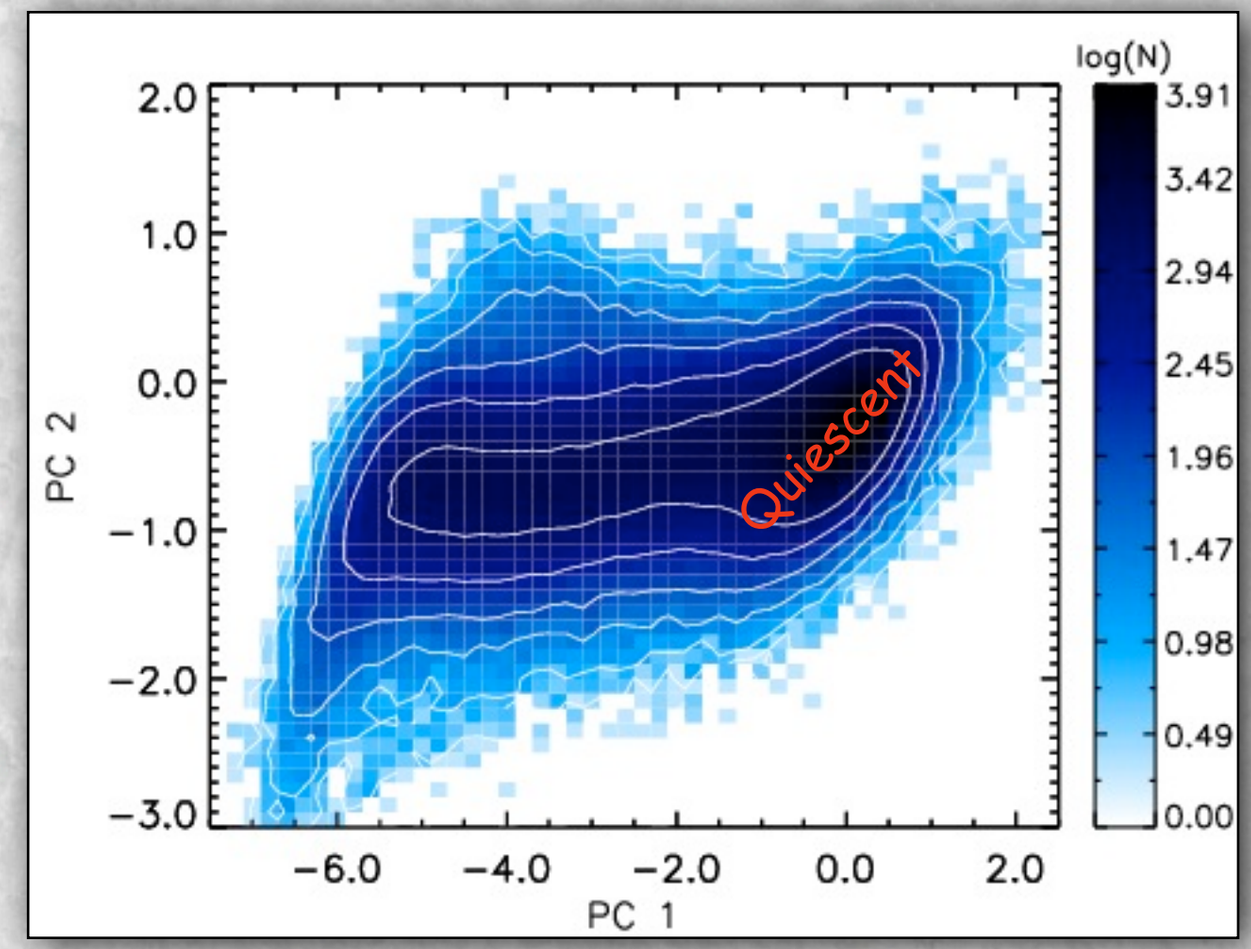

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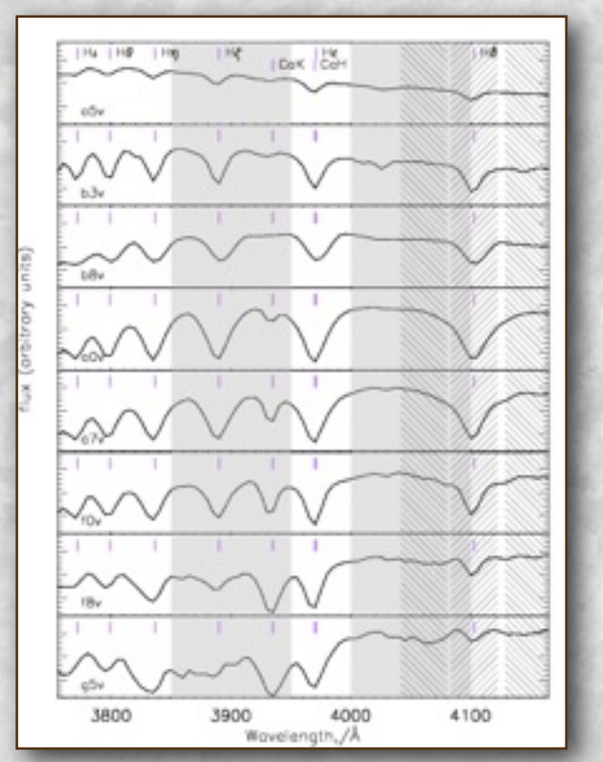

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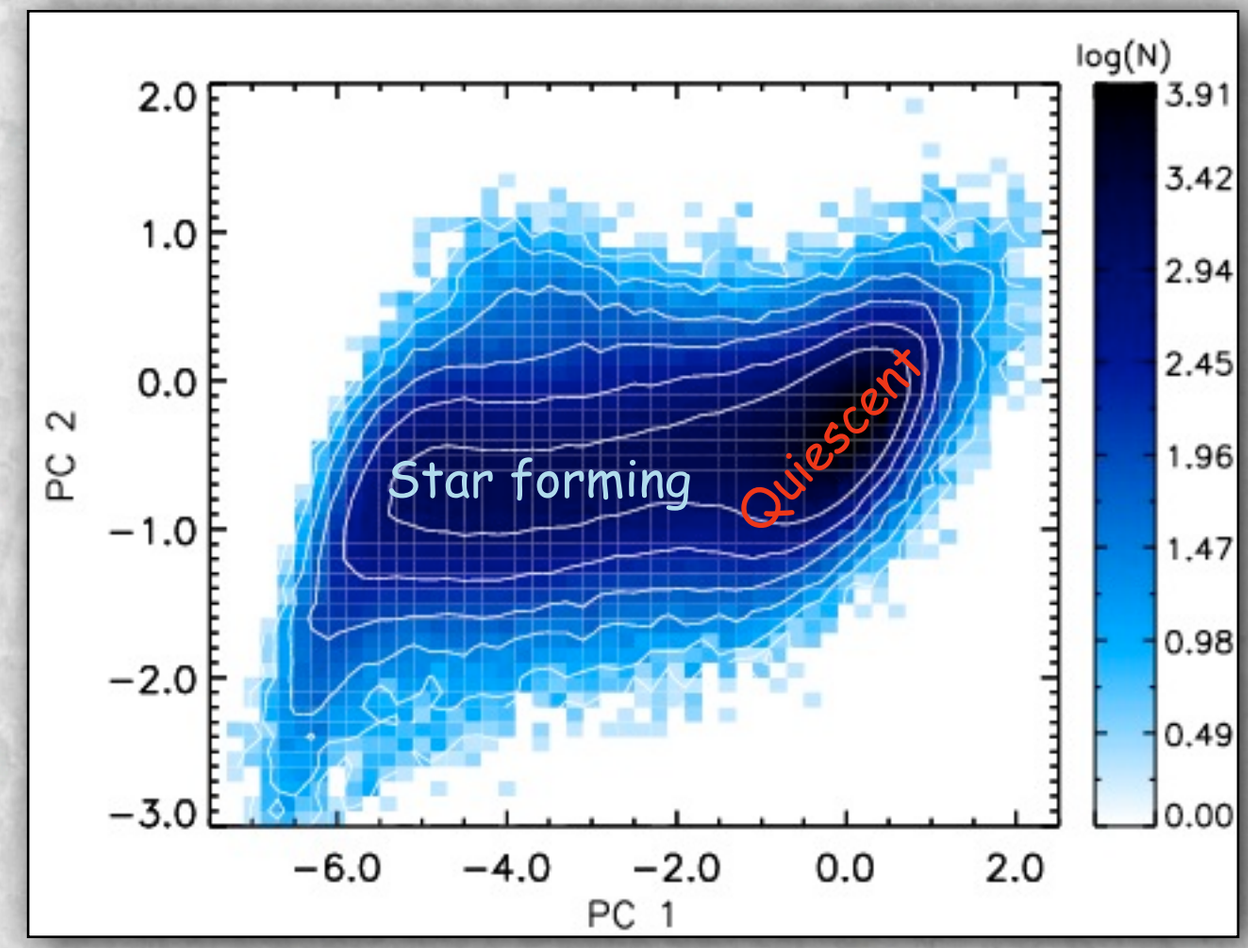

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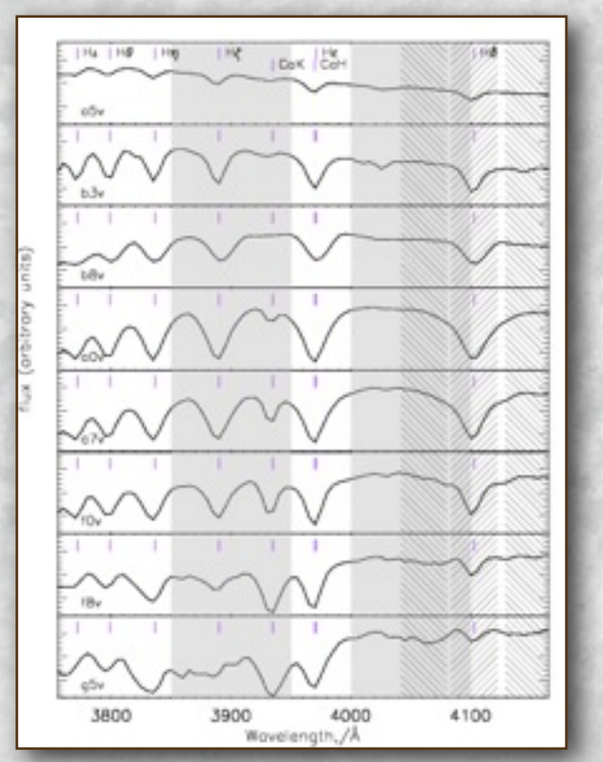

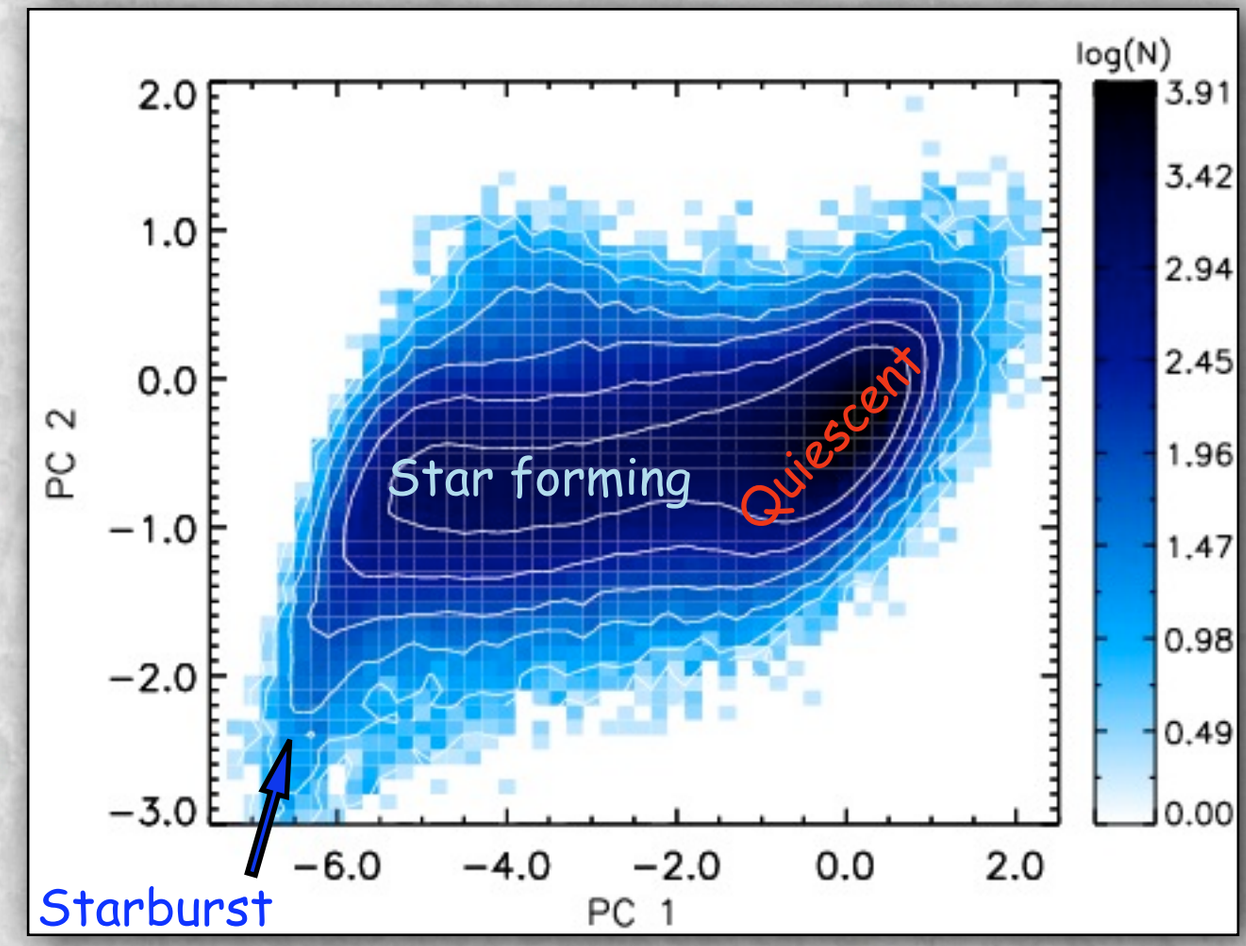

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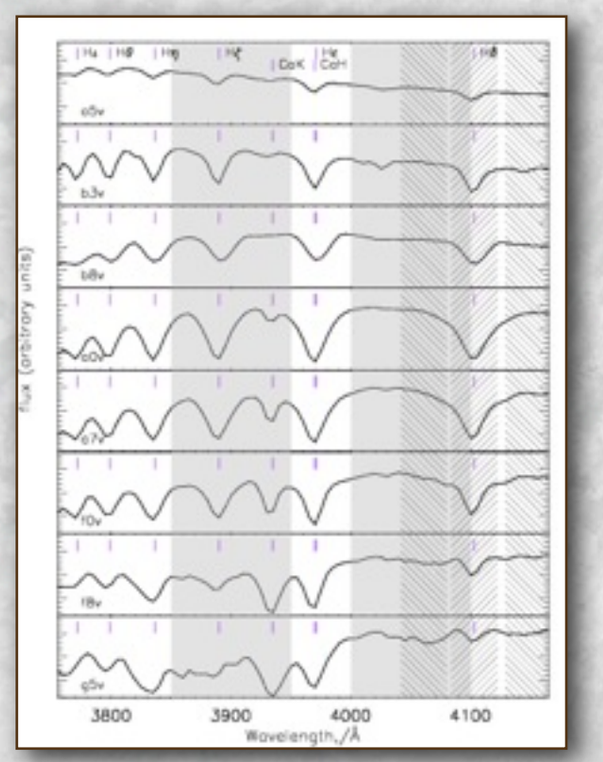

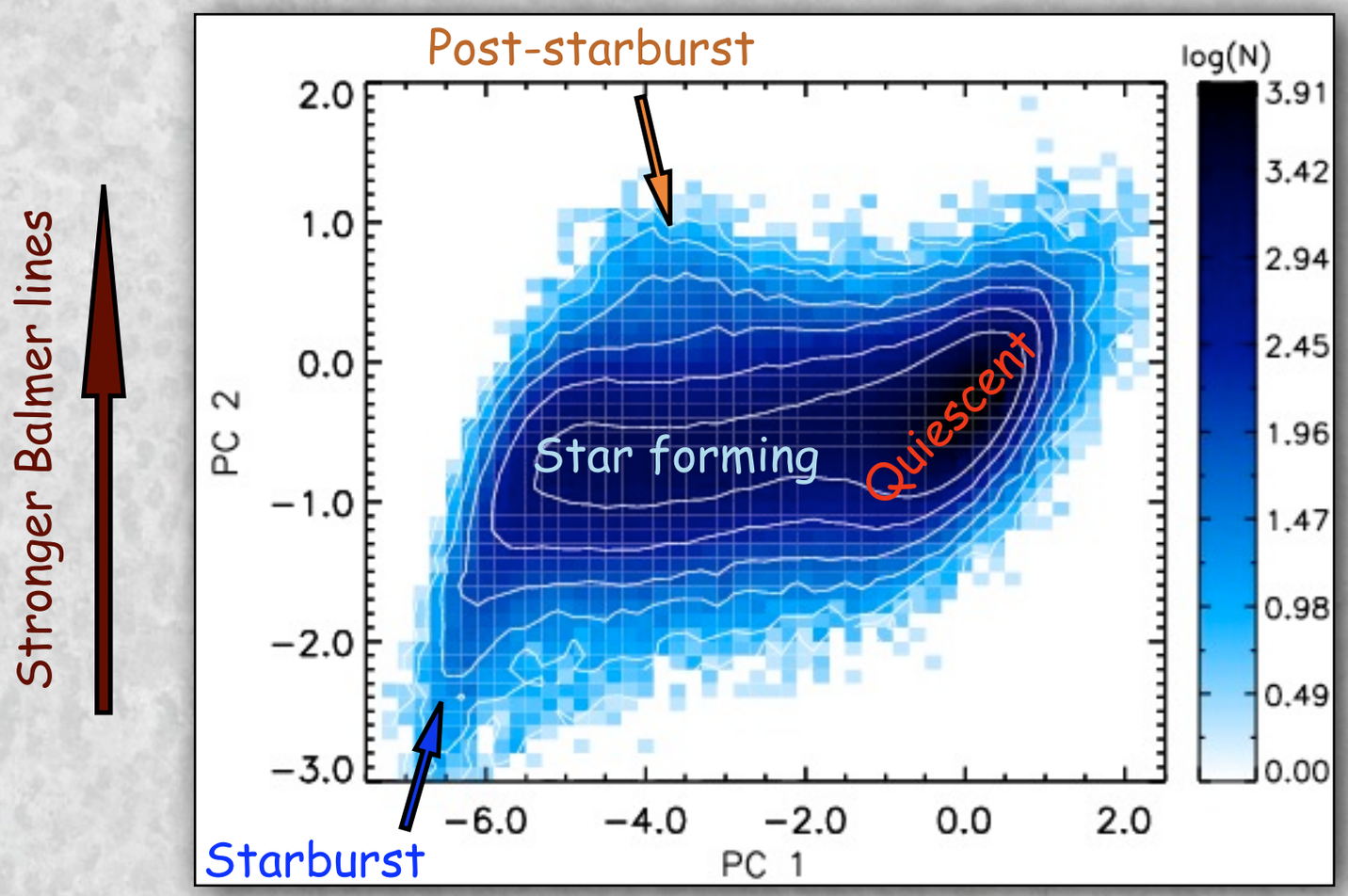

SDSS DR7 galaxies

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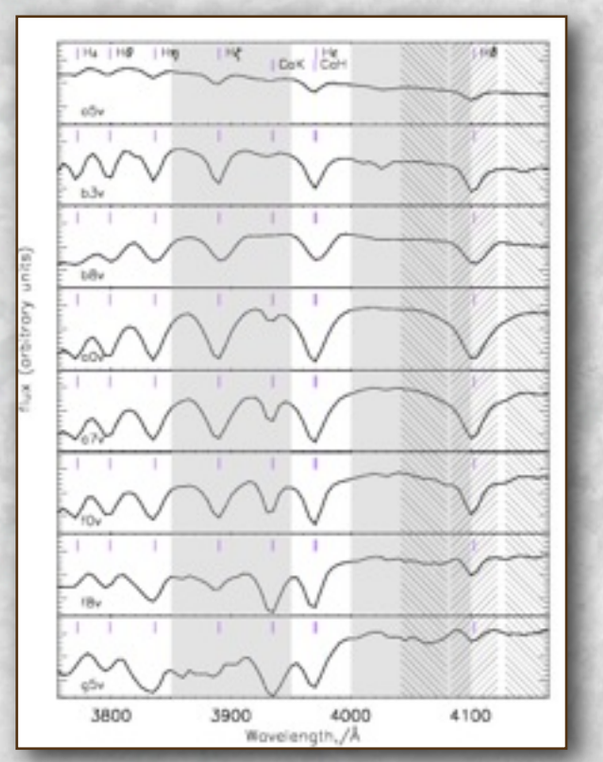
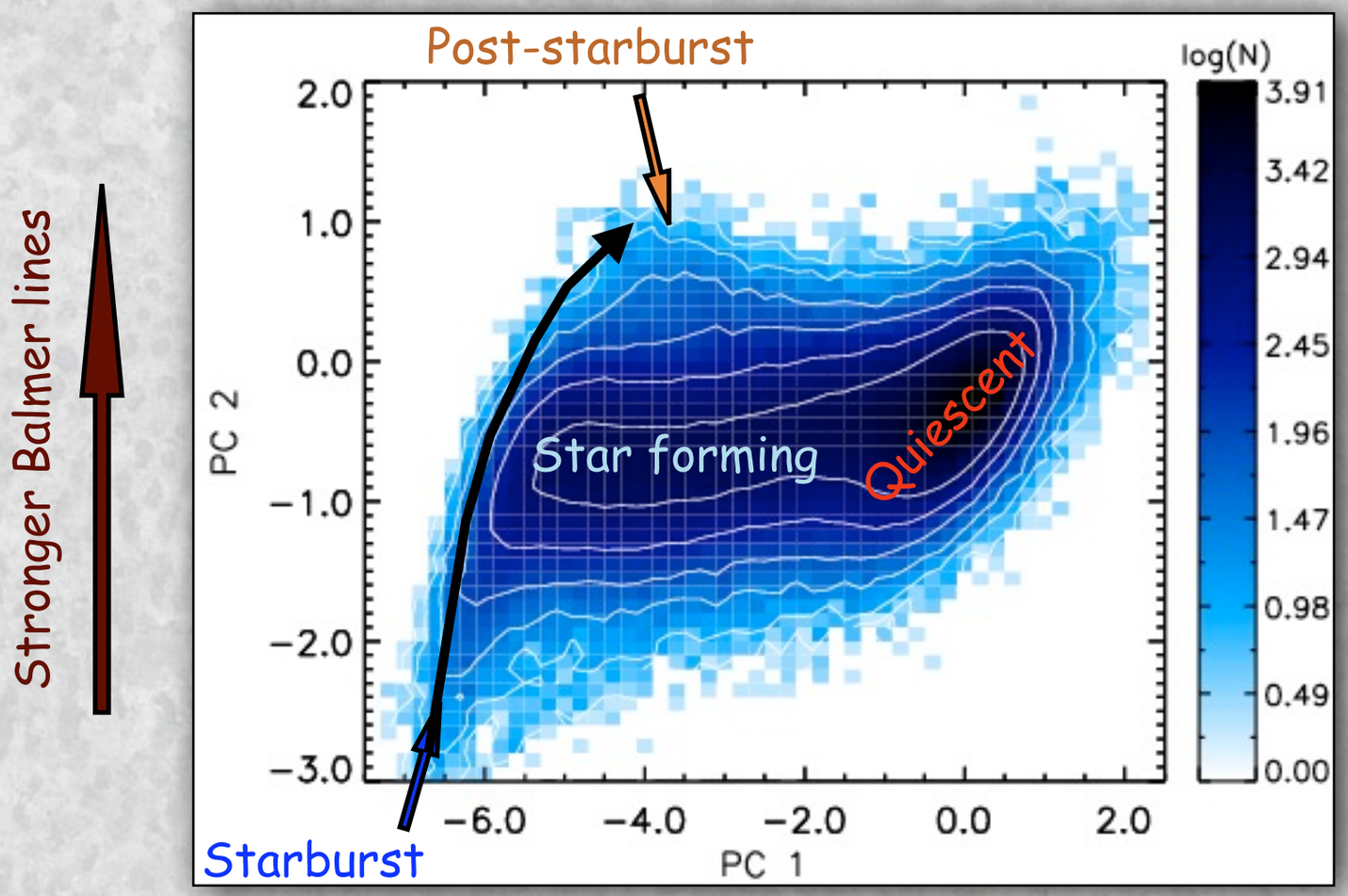
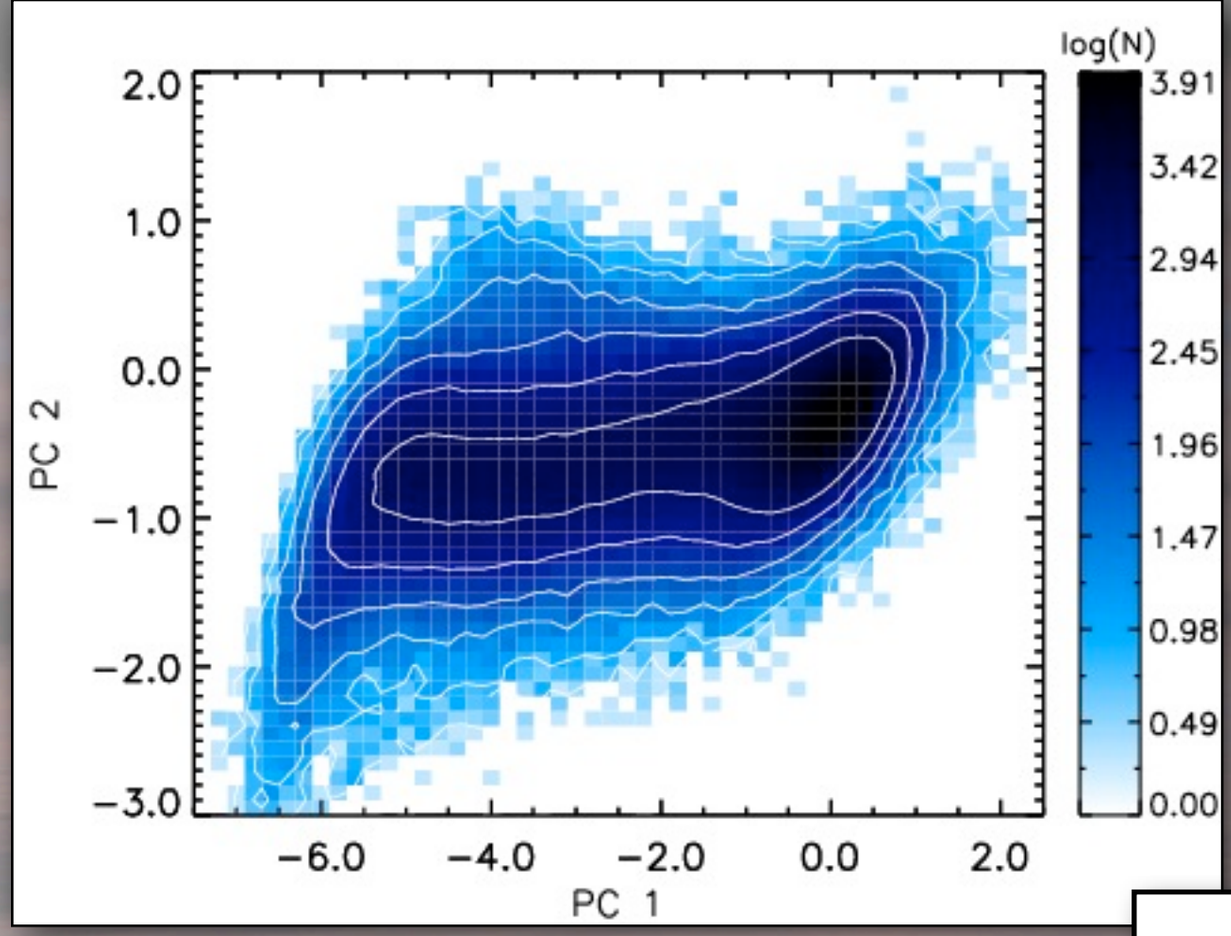




SDSS


log(N)
3.91
3.42
2.94
2.45
1.96
1.47
0.98
0.49
0.00
2.0
1.0
0.0
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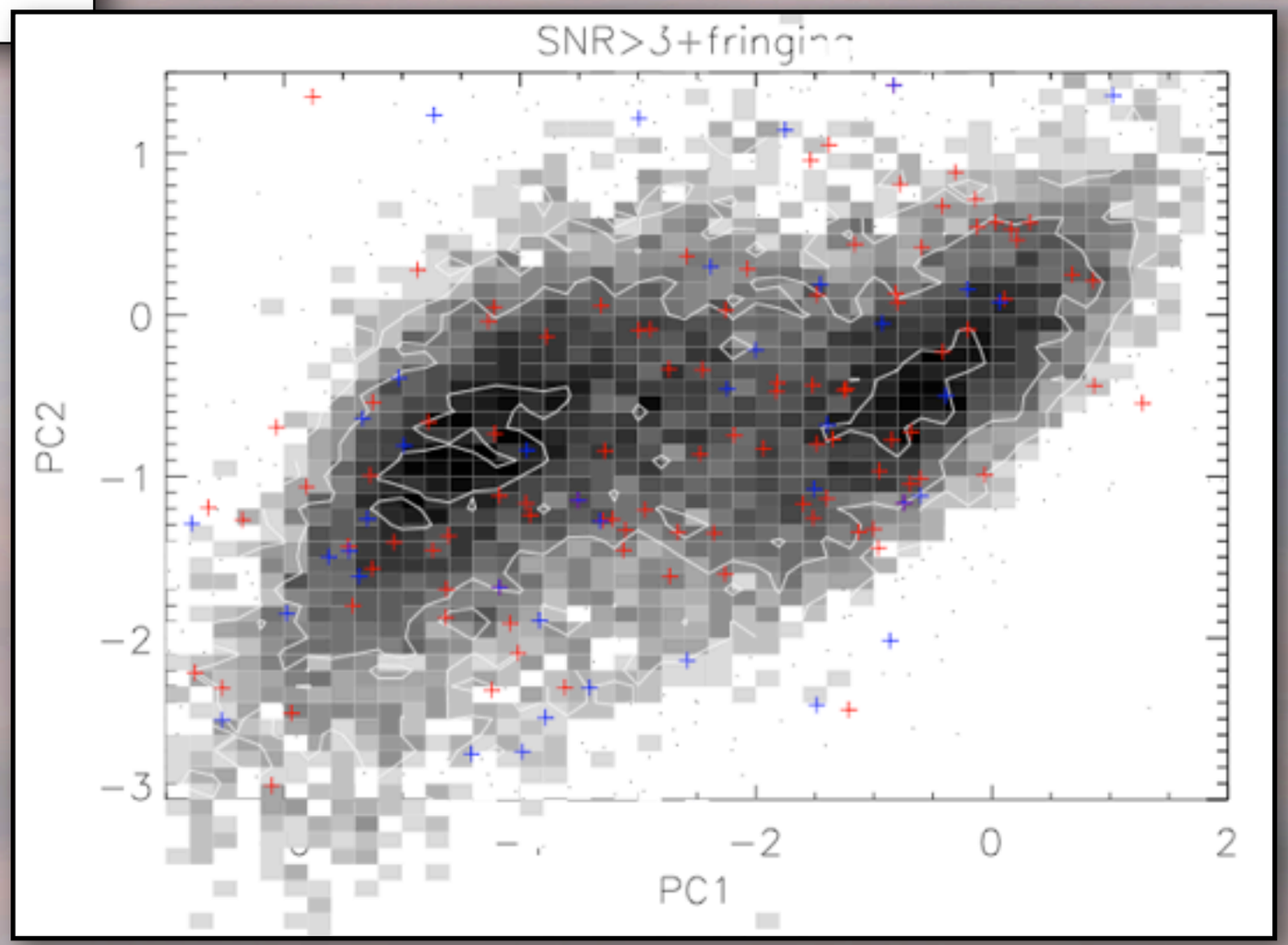
−3.0
PC 2
−6.0
−4.0
−2.0
0.0
2.0
PC 1

GAMA


SNR>3+fringi
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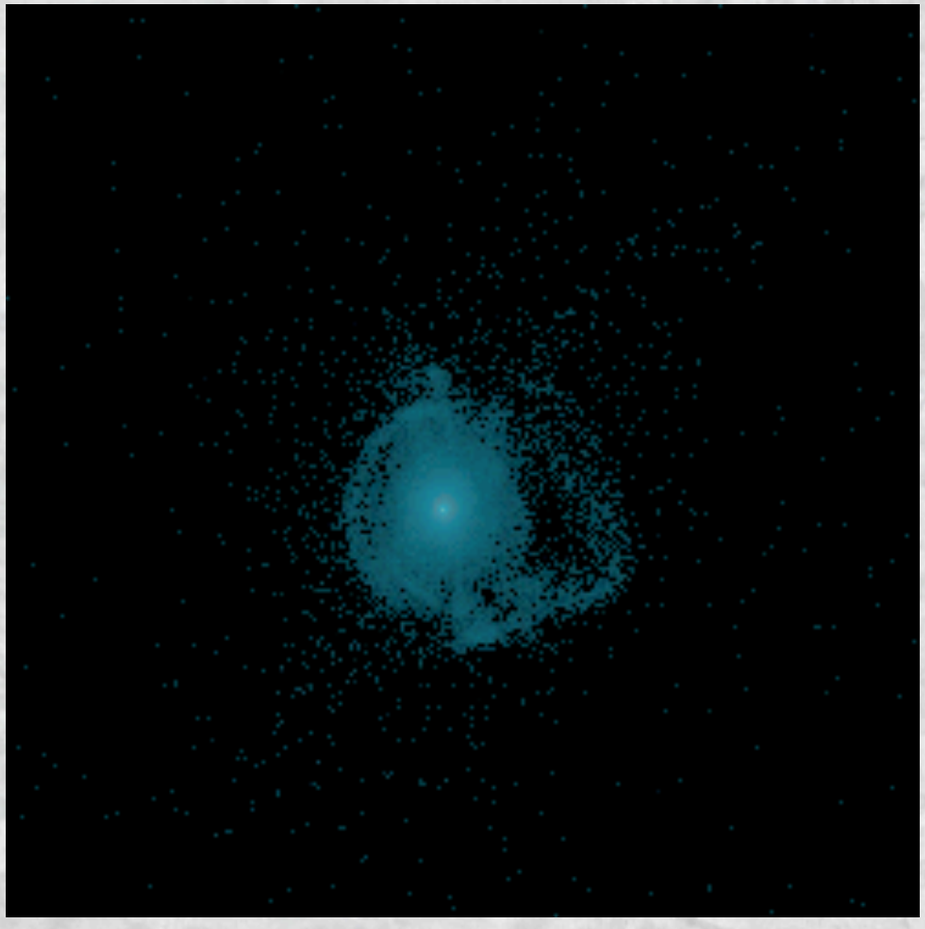
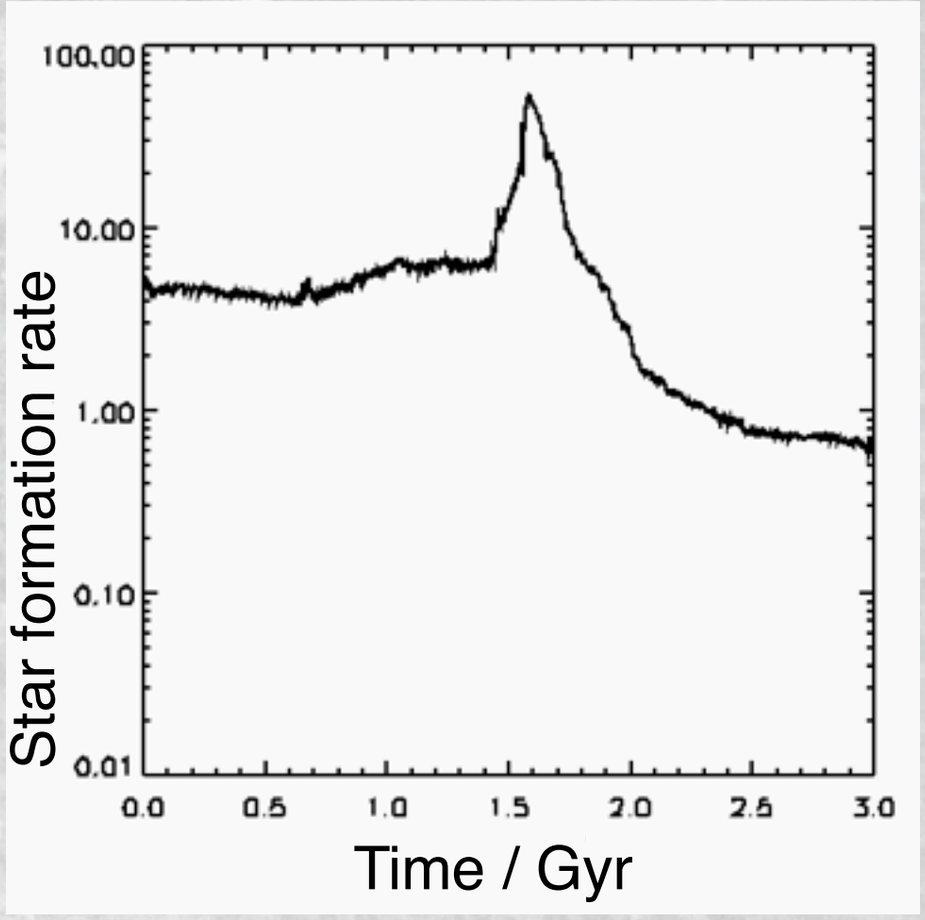
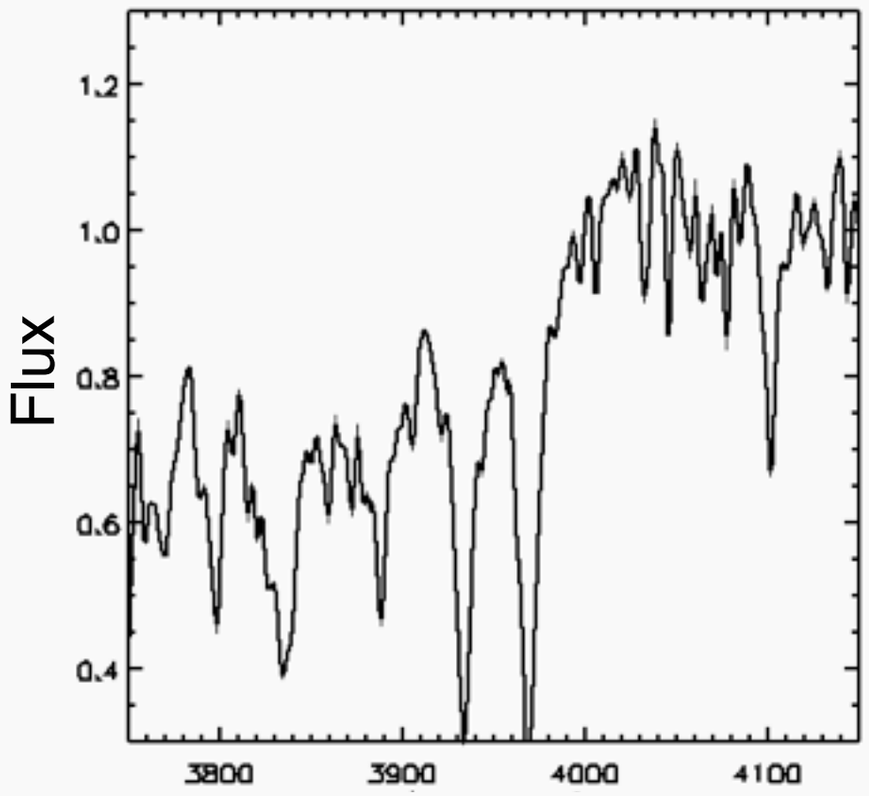
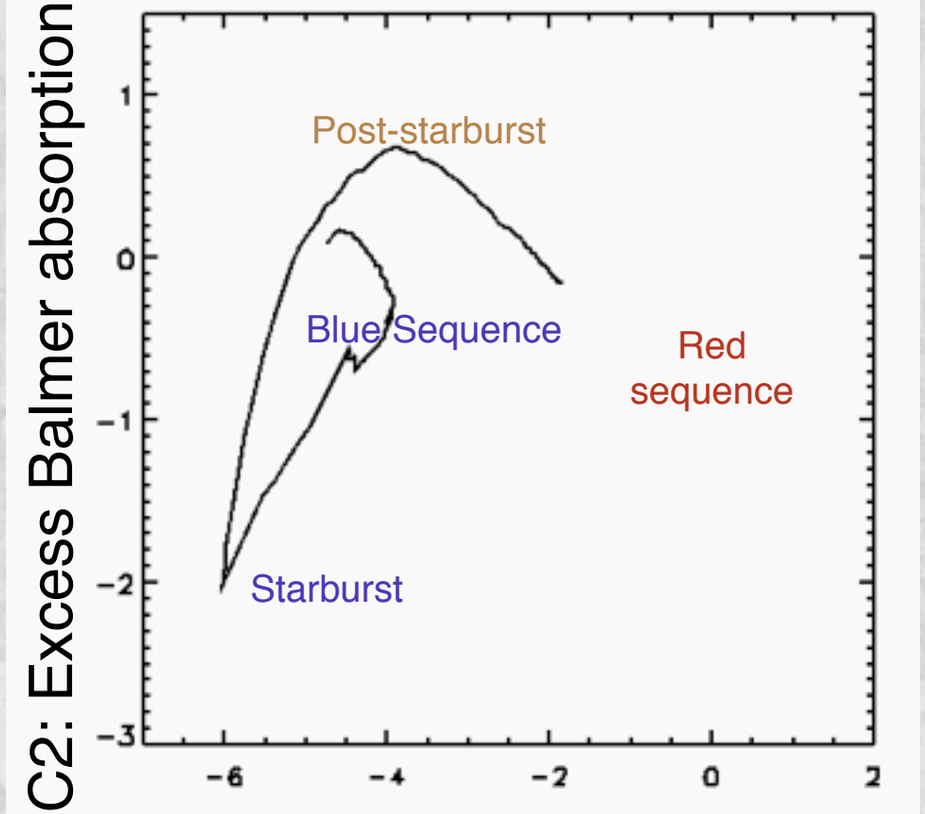




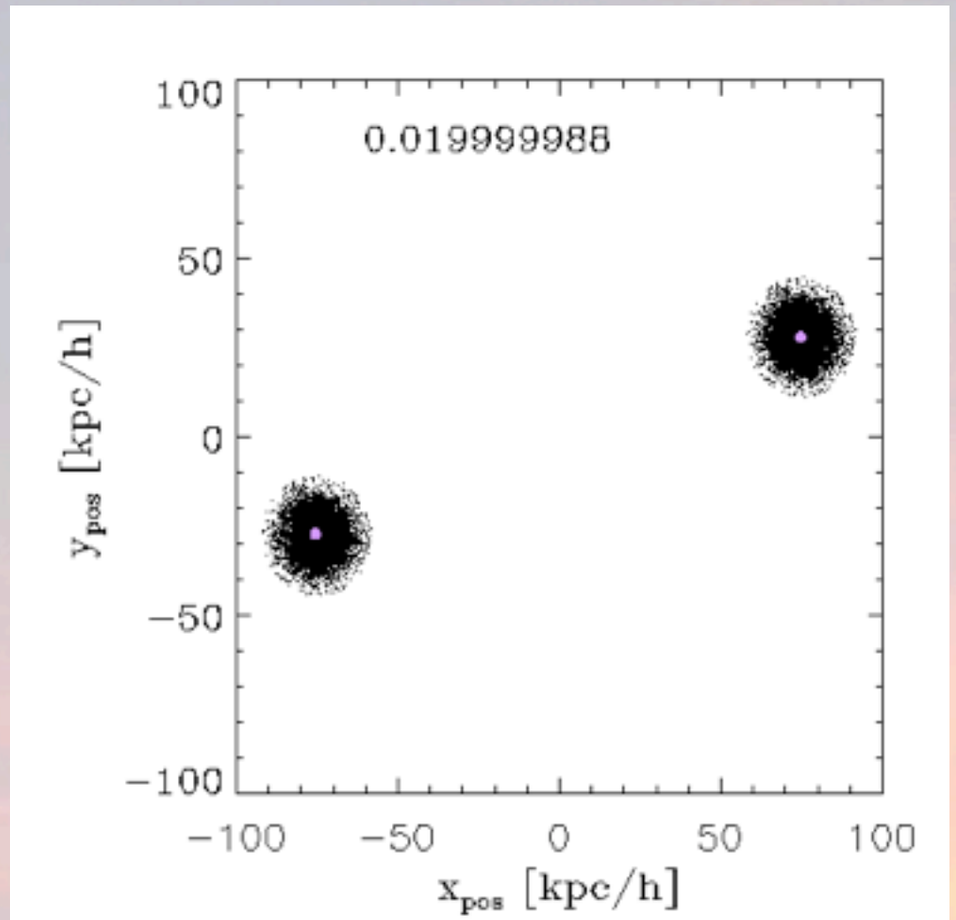
Link to gas-rich mergers?

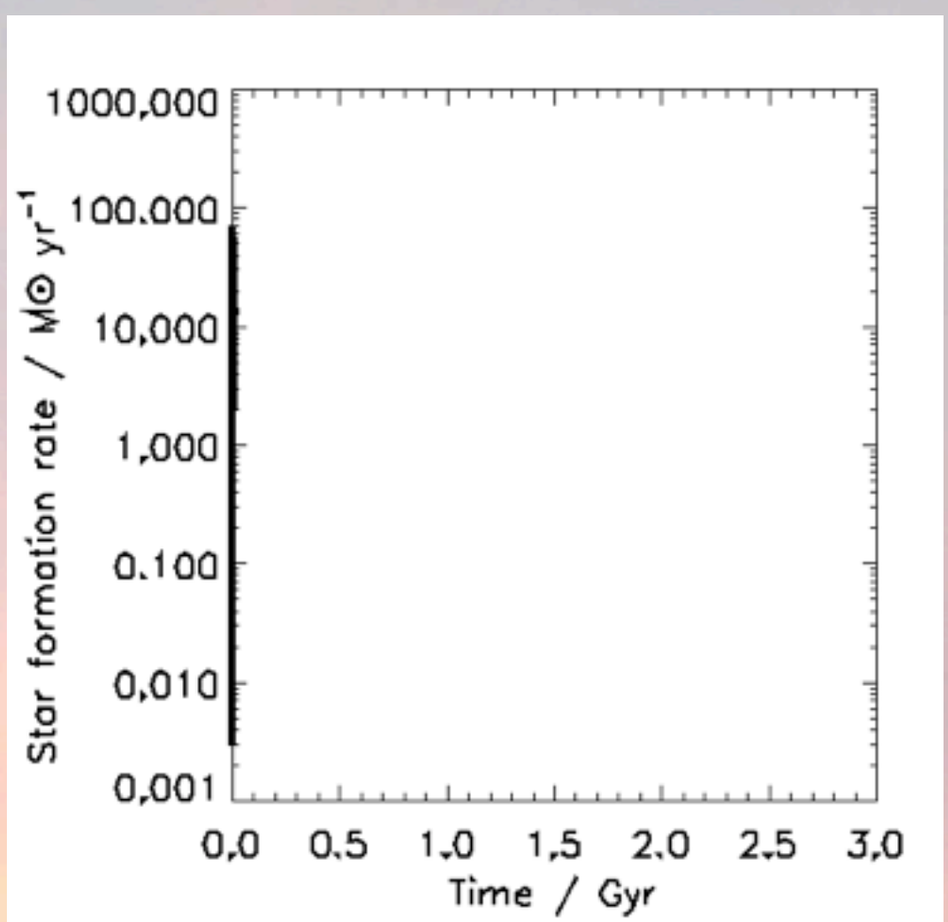




Wild, Walcher, Johansson et al. 2009

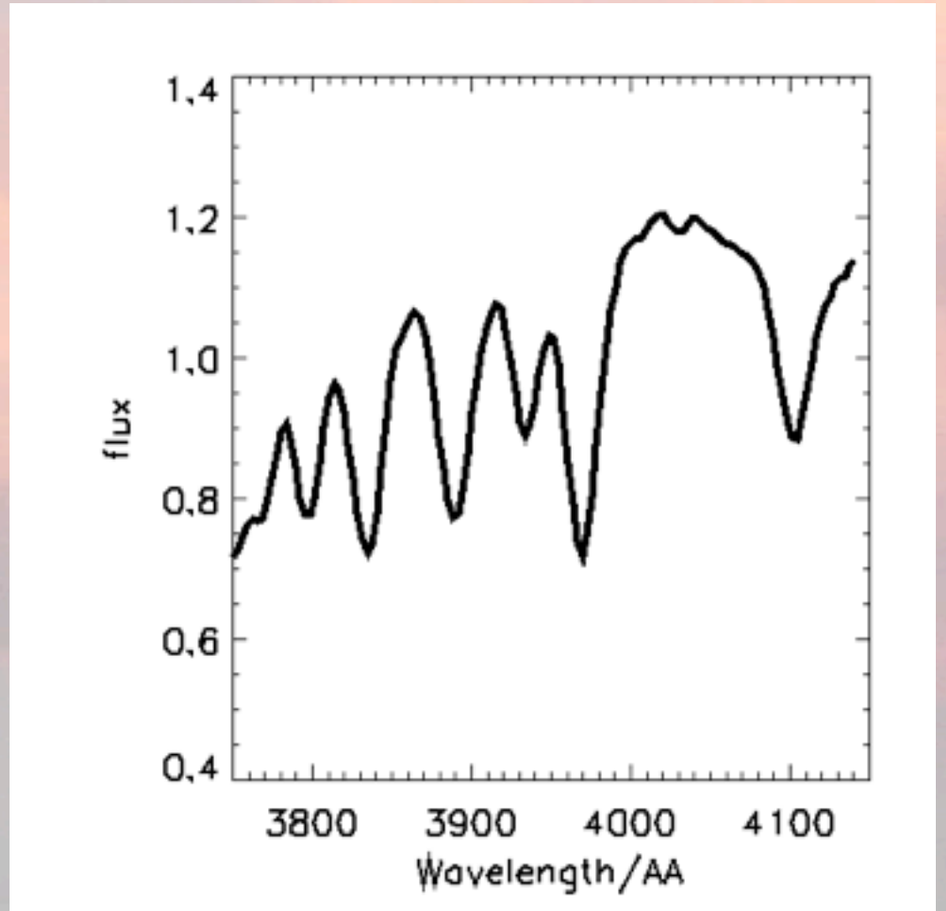
Johansson et al. 2009

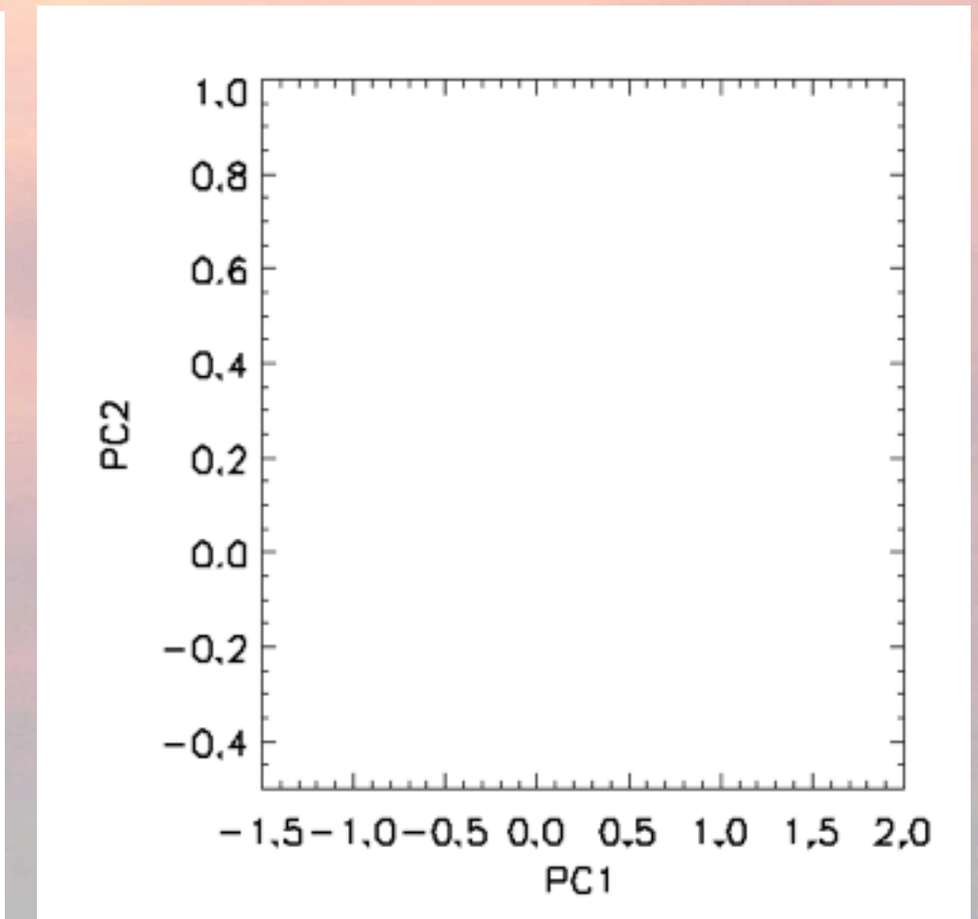




Link to "feedback"?

Wild, Walcher,





(Post-) starbursts in merger simulations

Wild, Walcher, Johannson et al. 2009, MNRAS

(Post-) starbursts in merger simulations

- ✦ Conclusion 1: Gas rich spiral merger leads to remnants with strong Balmer absorption, before galaxy enters red sequence

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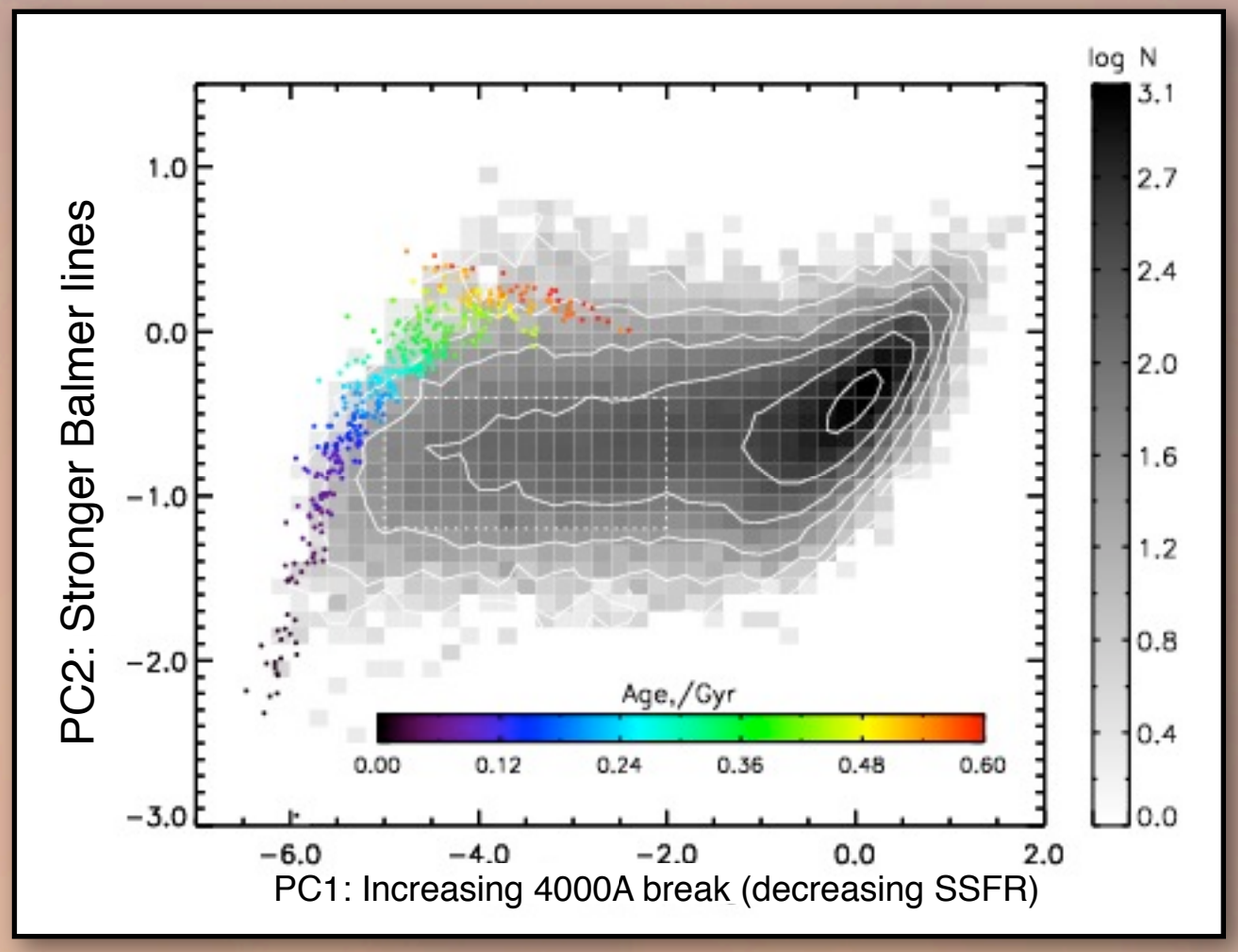
(Post-) starbursts in merger simulations

- Conclusion 1: Gas rich spiral merger leads to remnants with strong Balmer absorption, before galaxy enters red sequence
- Conclusion 2: “AGN feedback” makes little difference to stellar population
  - Decay in SF caused by gas exhaustion + SNe feedback
- To detect PSBs observationally:
  - Initial decay timescale must be short: < 1e8 years
  - Detectable for ~1.5Gyr for strongest bursts
  - Detectable burst mass fraction >~5-10%

Wild, Walcher, Johannson et al. 2009, MNRAS

Starburst-AGN connection



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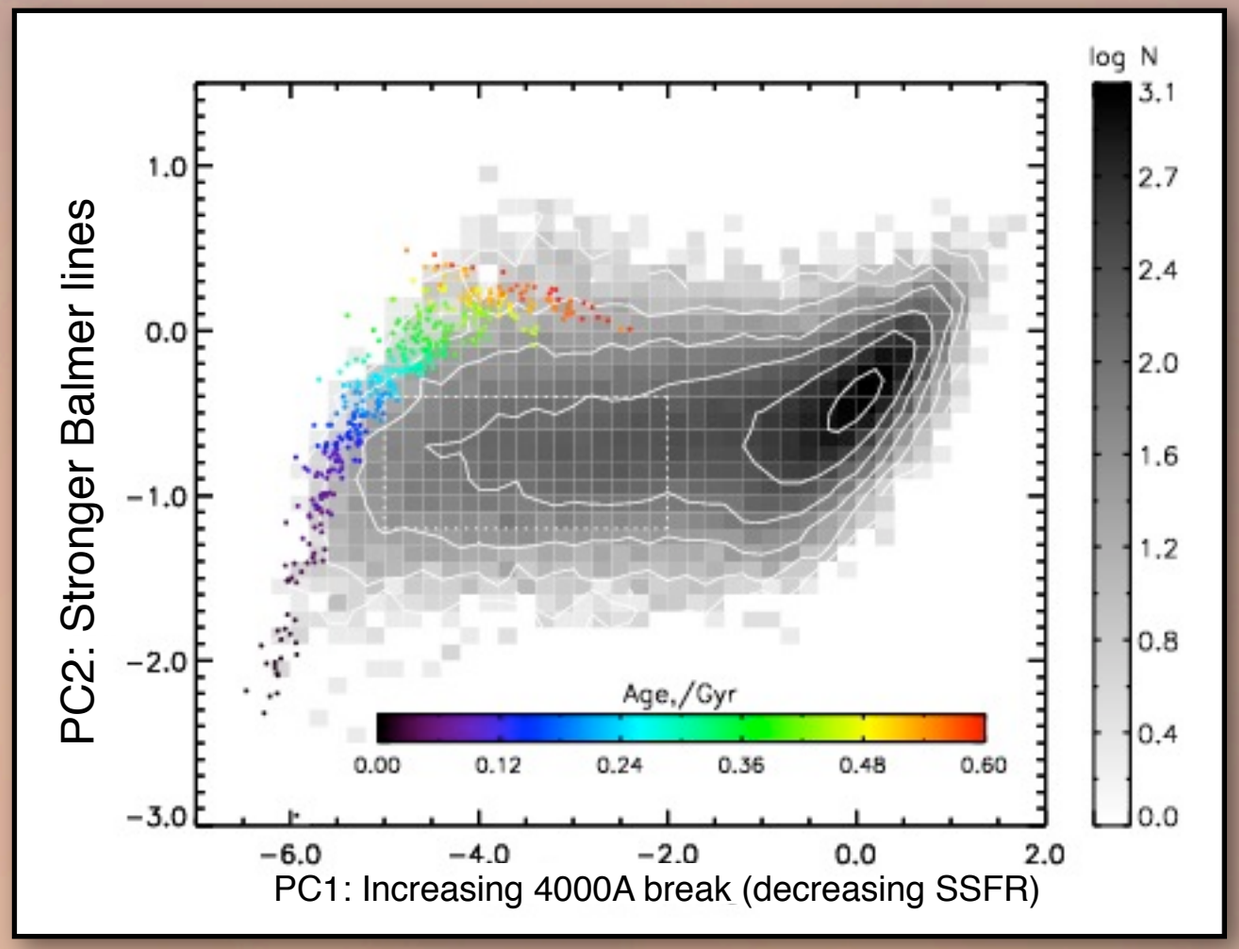

- 400 strongest starburst to post-starburst bulge-galaxies in local Universe
  - $0.01 < z < 0.07$ (3” SDSS fibre => 0.6 - 4 kpc diameter)
  - Stellar surface mass density $> 3 \times 10^8$ $M_\odot$ /kpc^2 (where majority of $L[OIII]_{AGN}$ originates)
  - **Complete sample** to 600Myr: constant number per unit starburst age
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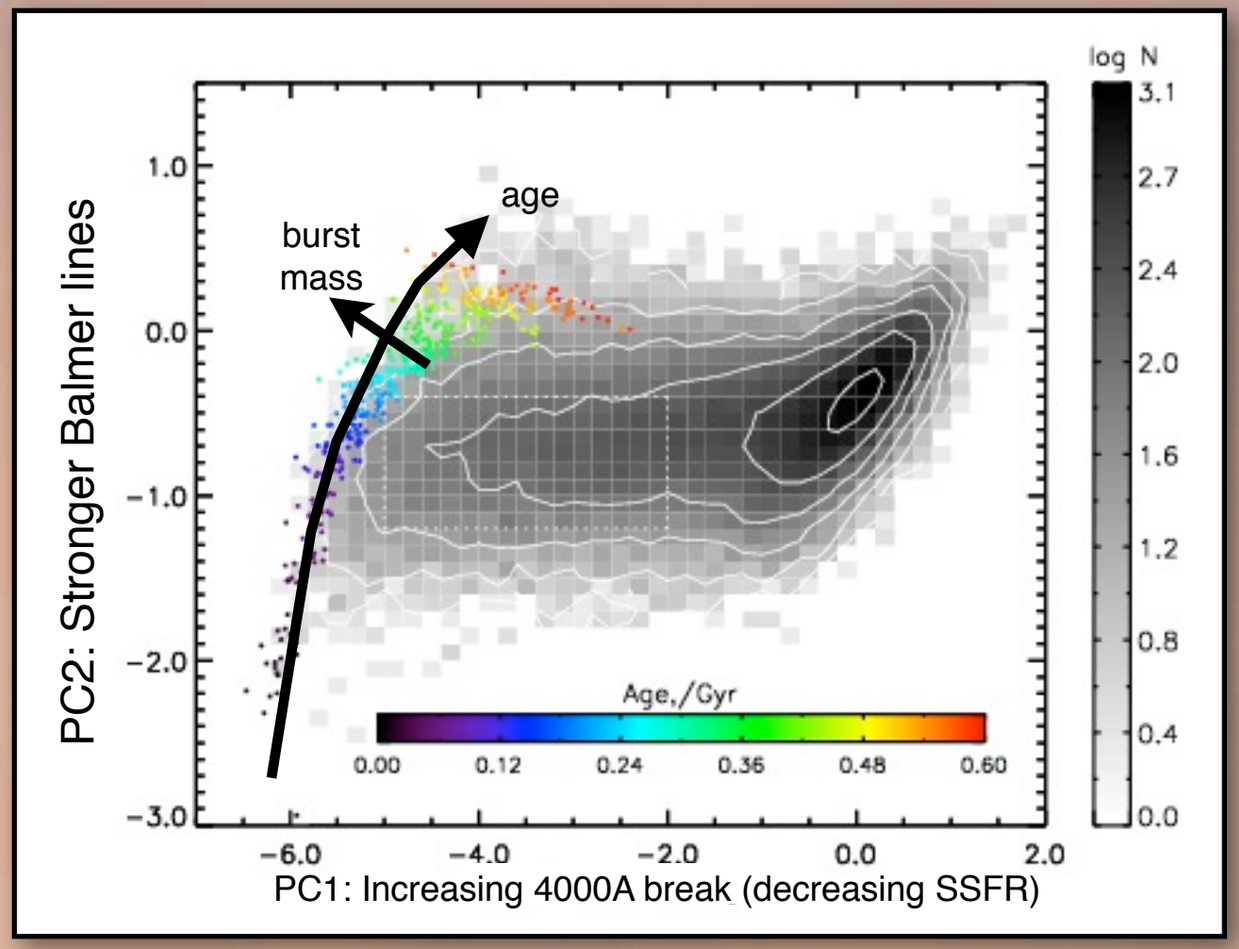

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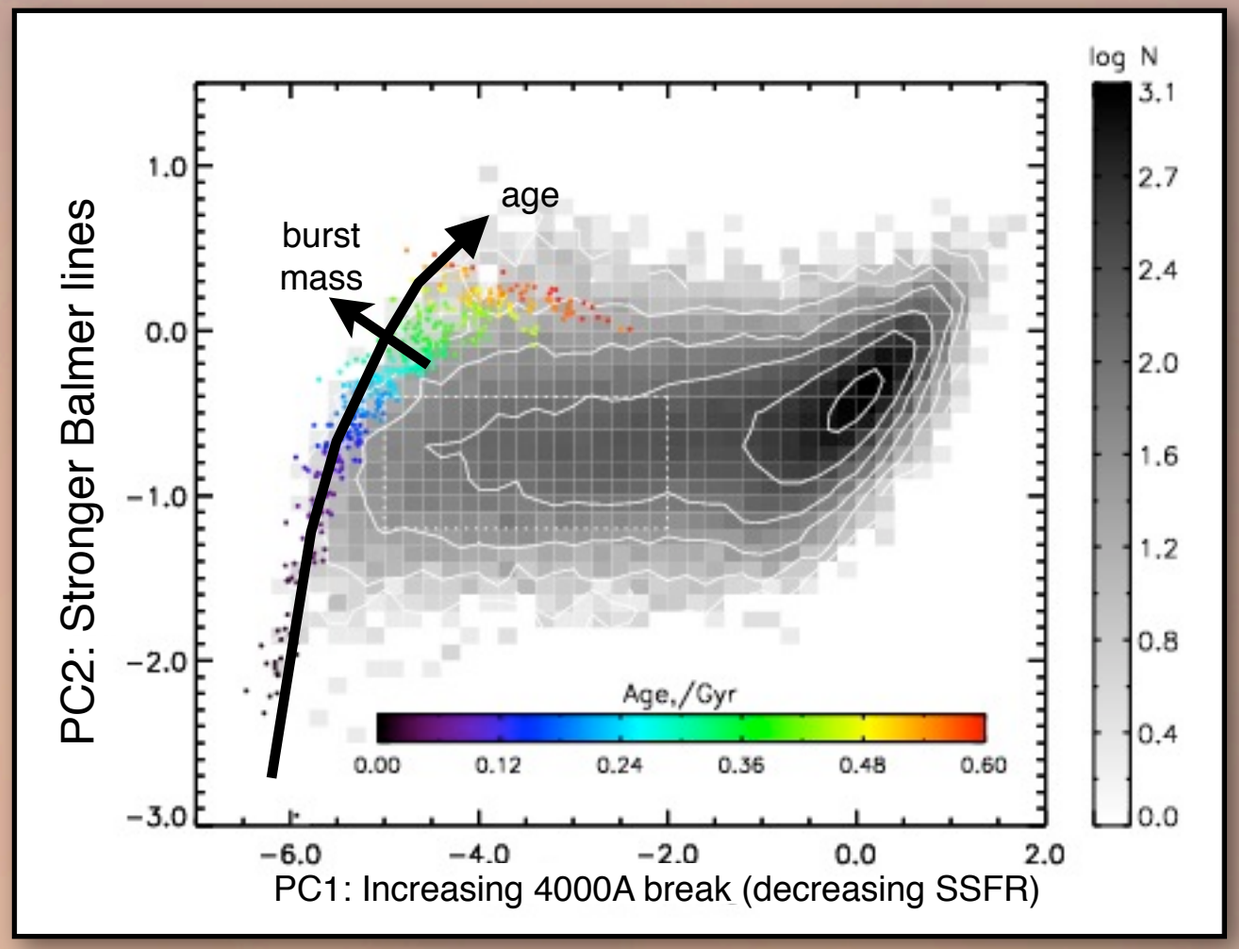
Starburst-AGN connection

Stellar continuum -> age of the starburst

Emission lines -> black hole accretion
(+ instantaneous SFR)



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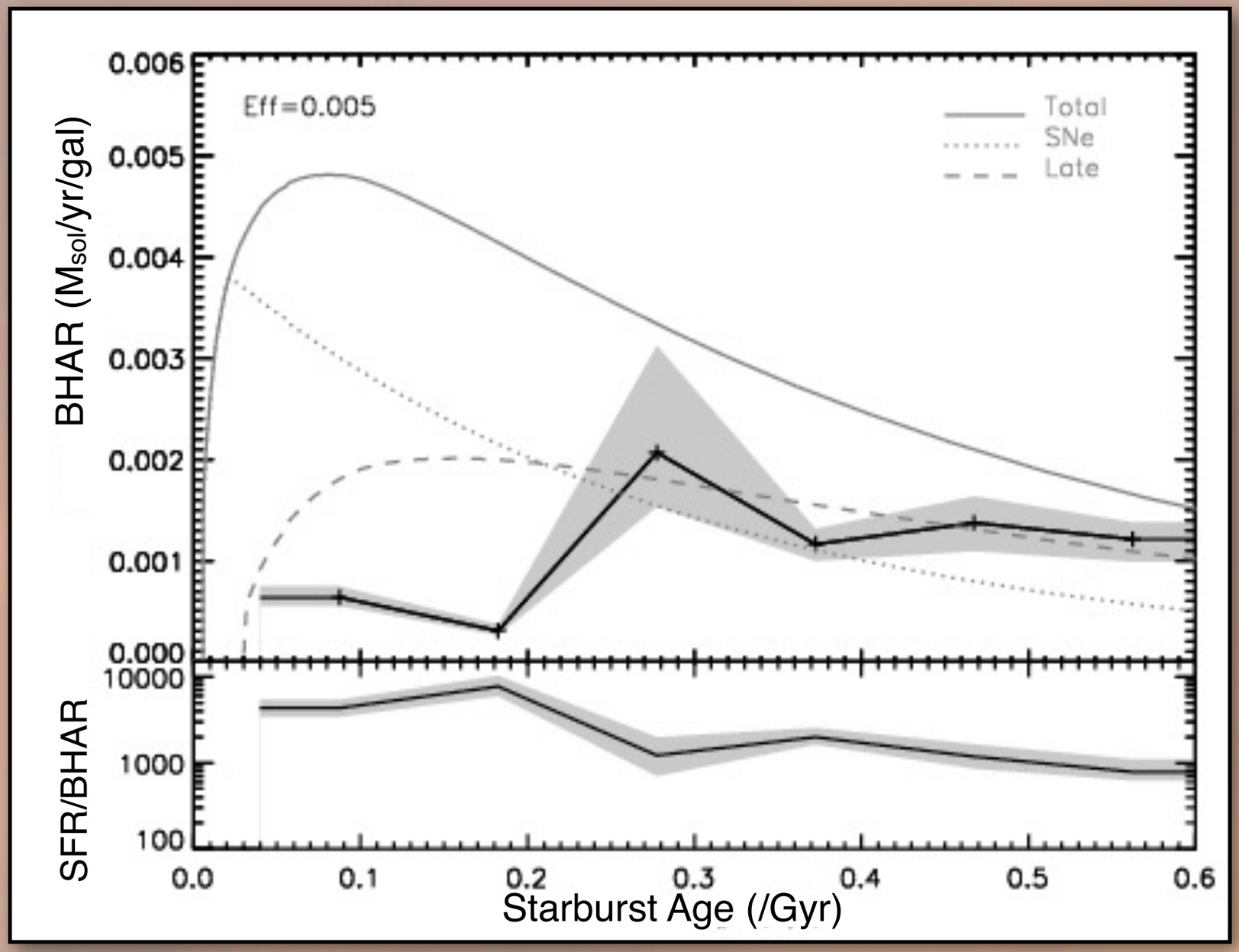
Timing the AGN accretion



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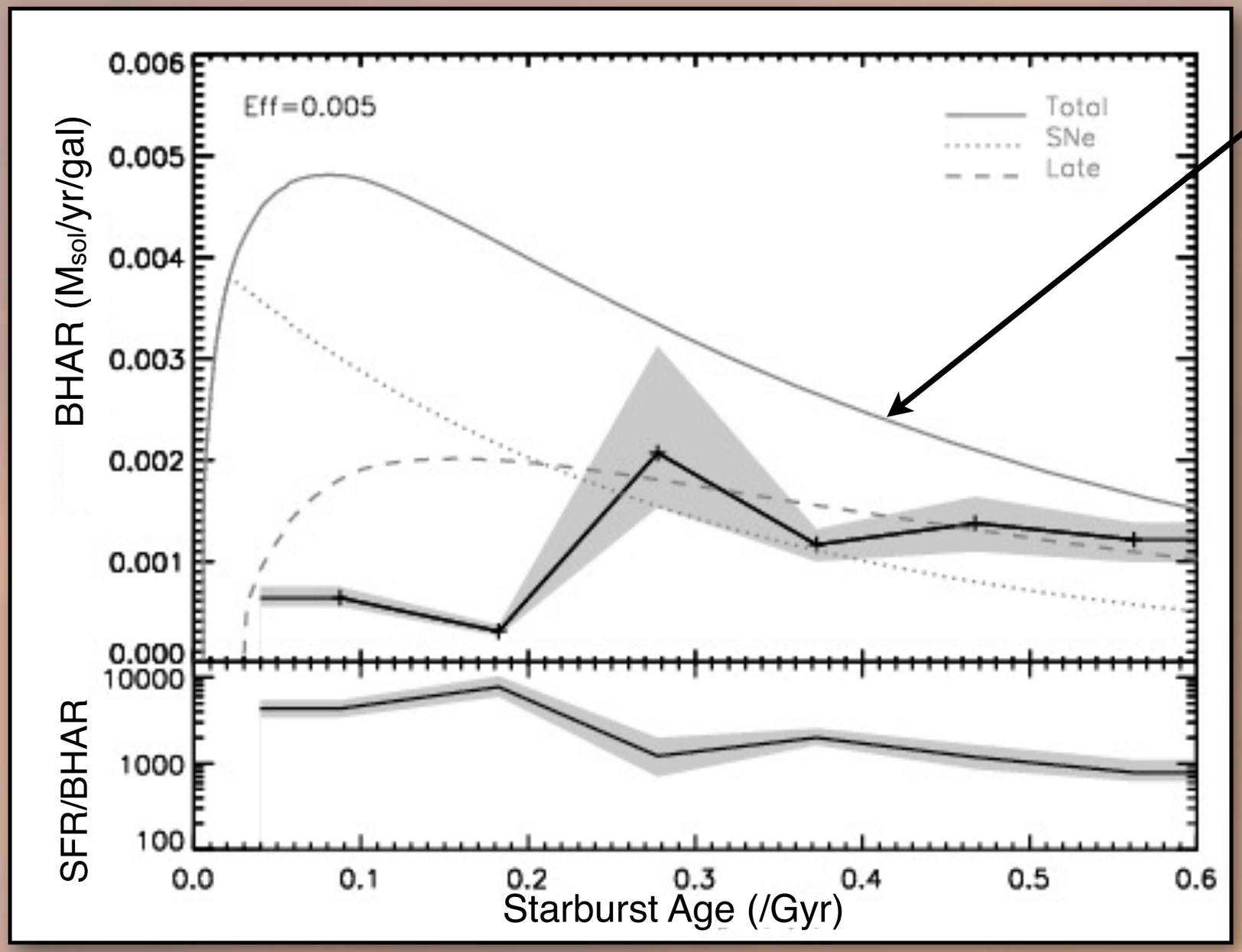
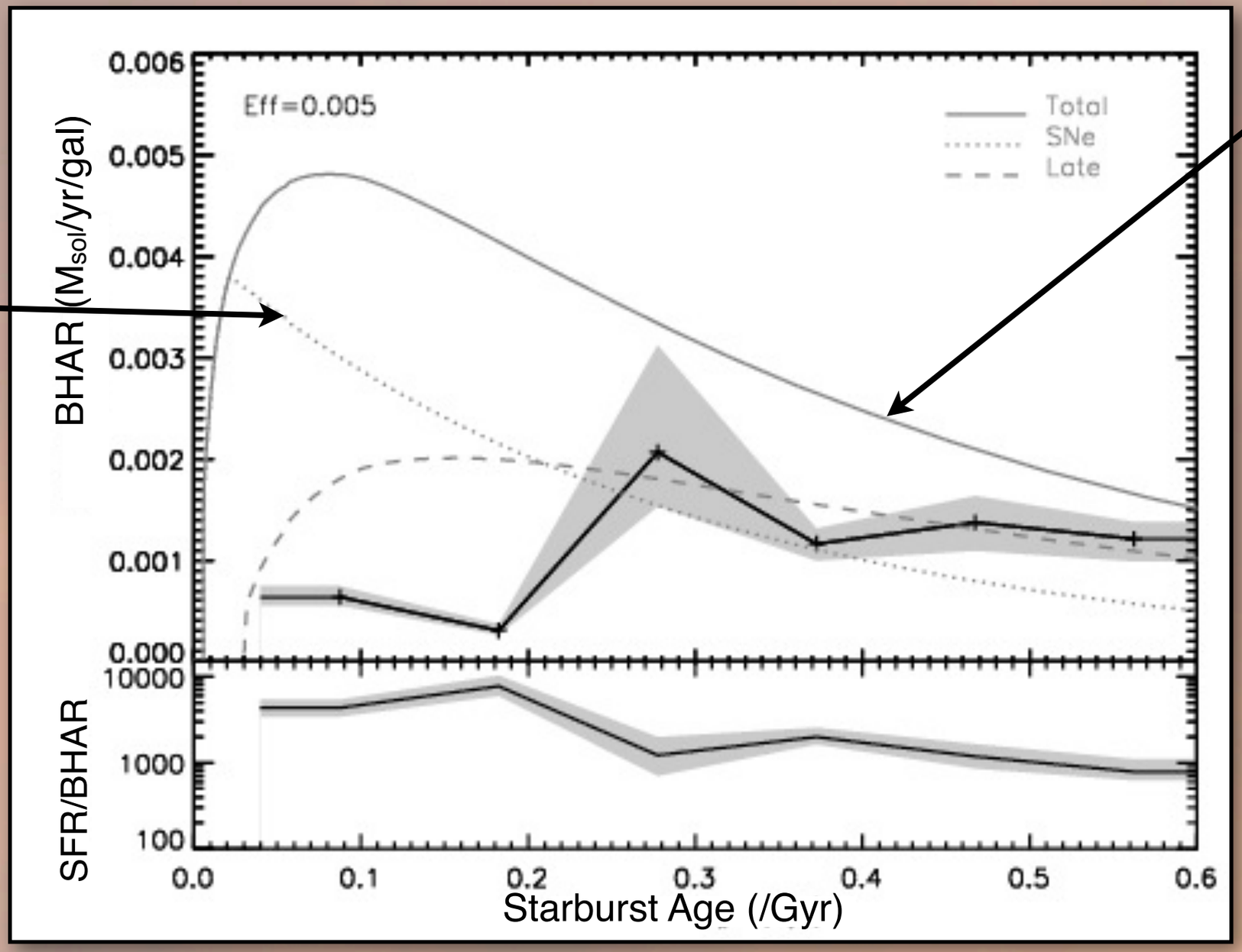


Mass loss rate from stars in starburst

τ_{exp} =0.3Gyr

Timing the AGN accretion

First 200Myr dominated by **fast** ejecta from high mass stars (SNe,O/B)



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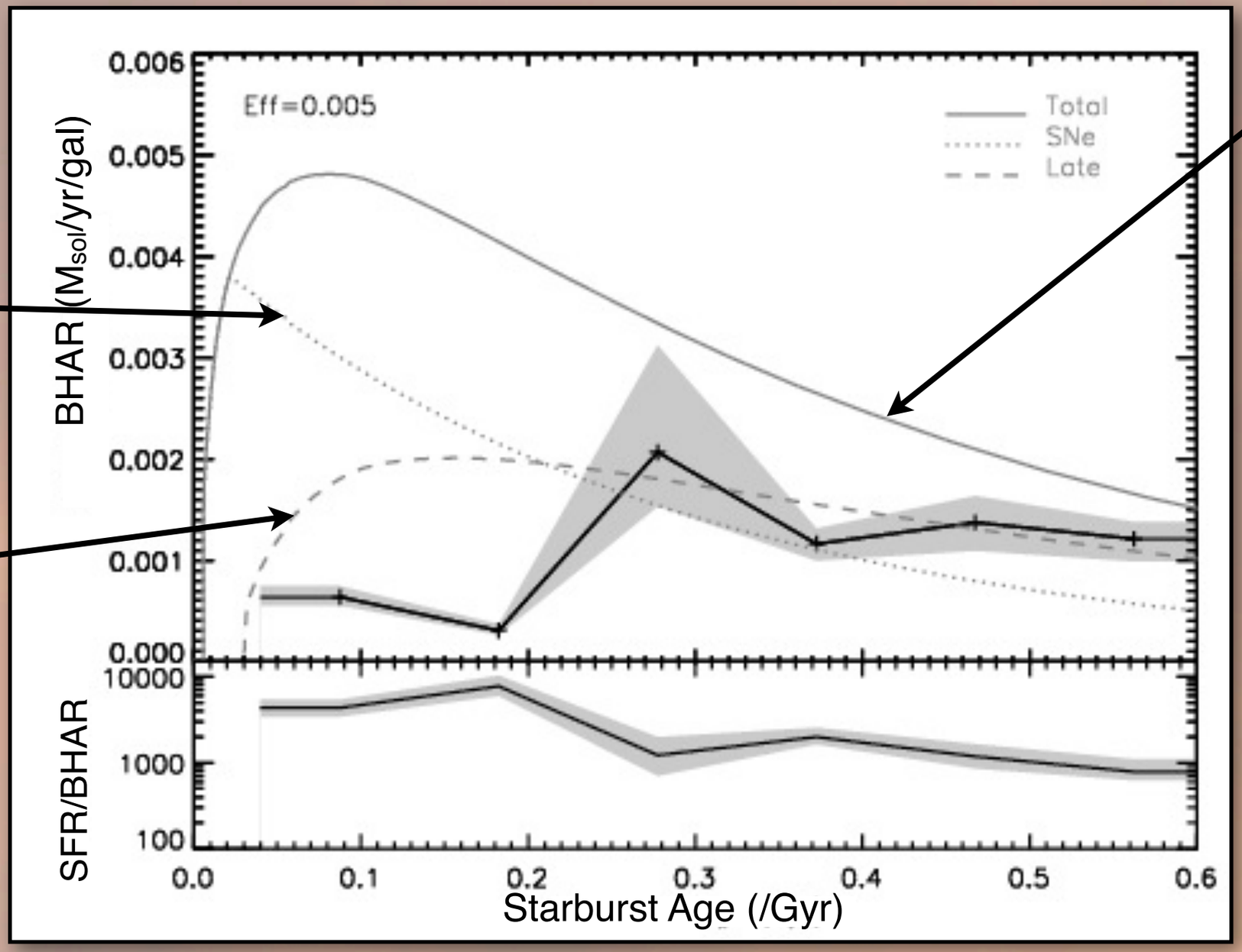

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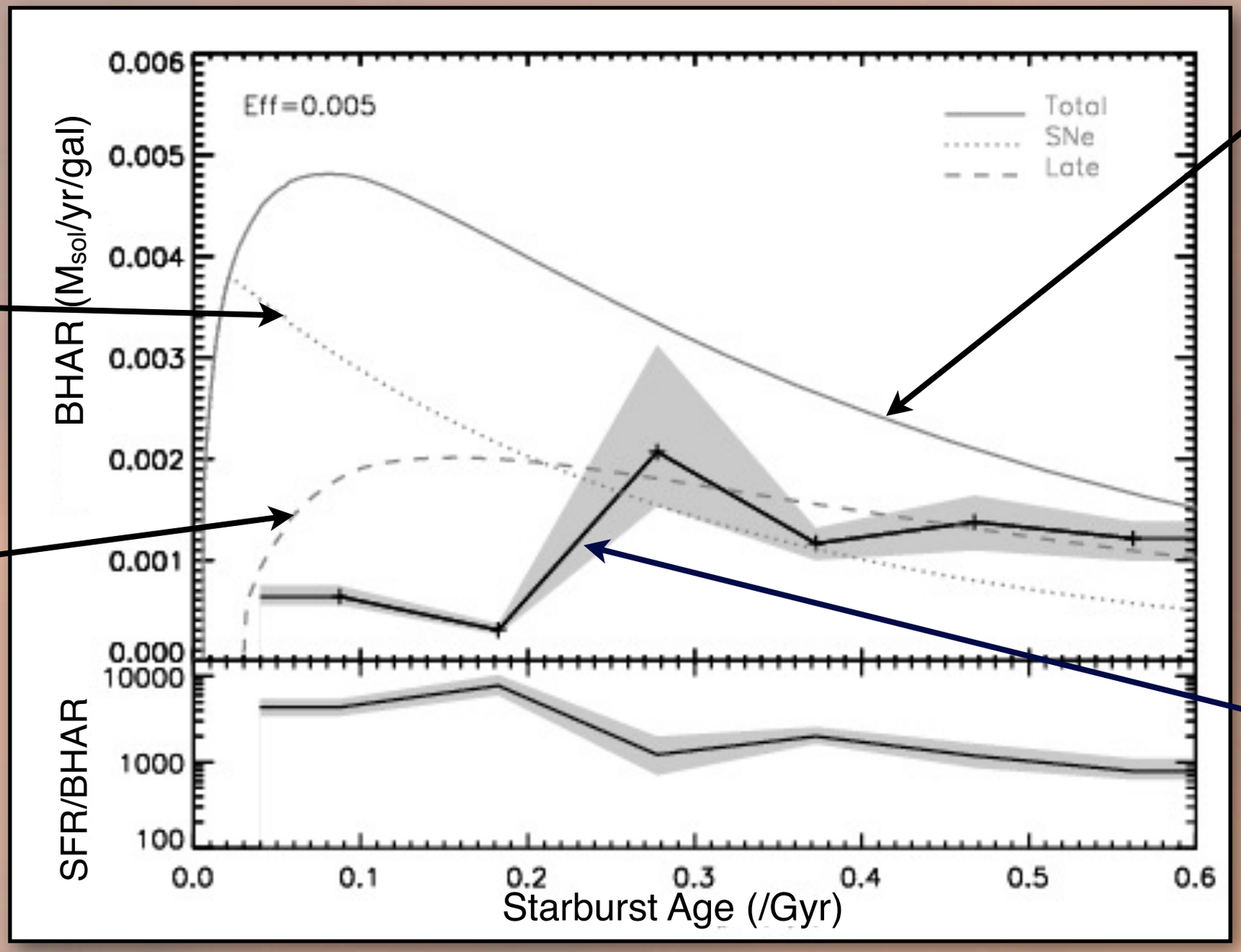

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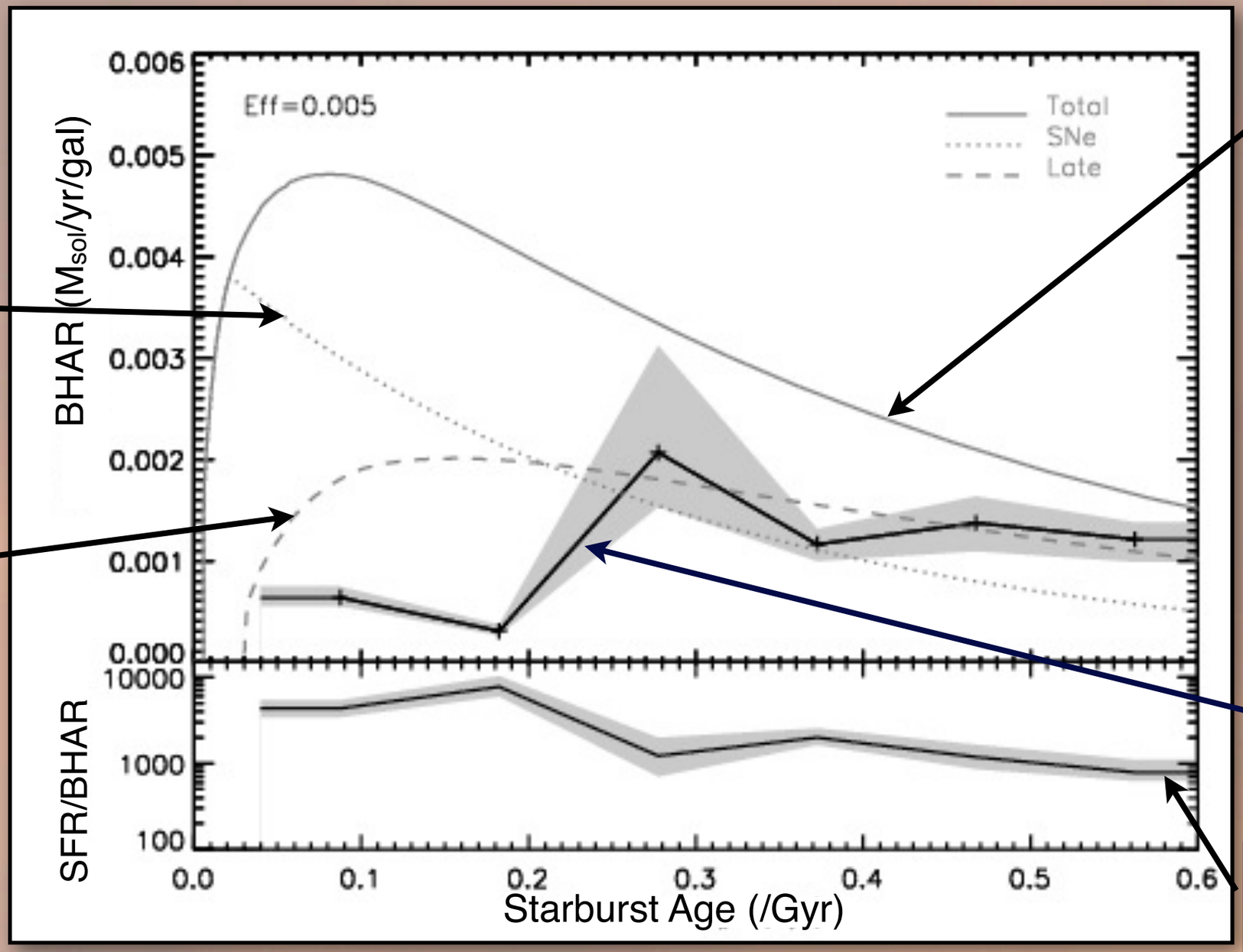

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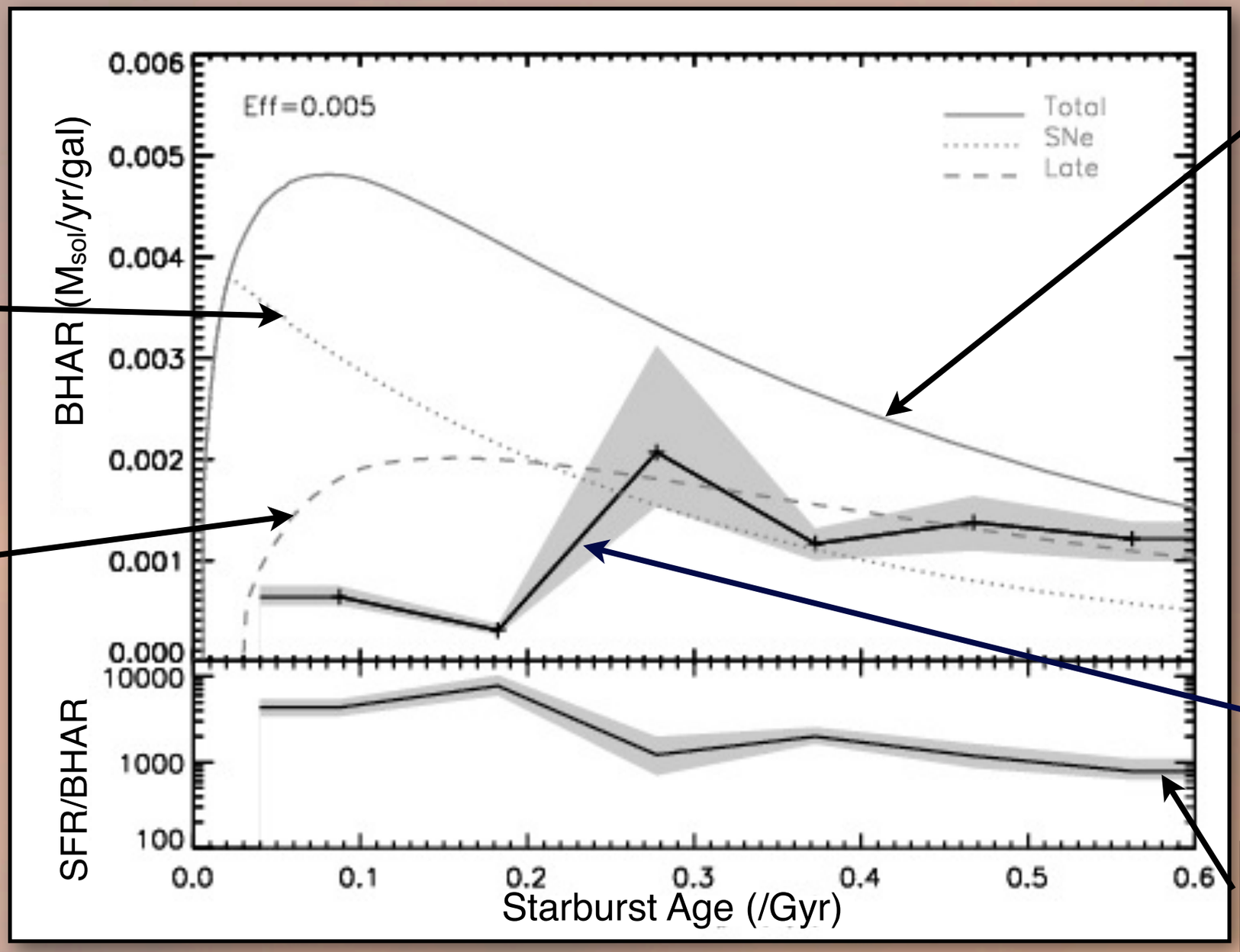

Mass loss rate from stars in starburst τ_{exp} =0.3Gyr

Black Hole starts to accrete after **~200Myr**.

Consistent with M-σ relation after ~10Gyr

- ✦ Accretion commences when fast ejecta have decayed
  - **Feedback from fast stellar ejecta prevents accretion??**
- ✦ Accretion efficiency: ~1% of low mass stellar ejecta
  - (see also Ciotti & Ostriker 07; Kauffmann & Heckman 09)

Post-starburst AGN connection

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✦ Method:

- Stellar continuum: complete sample of starburst -> post-starburst galaxies
- Nebular emission lines: black hole accretion rate

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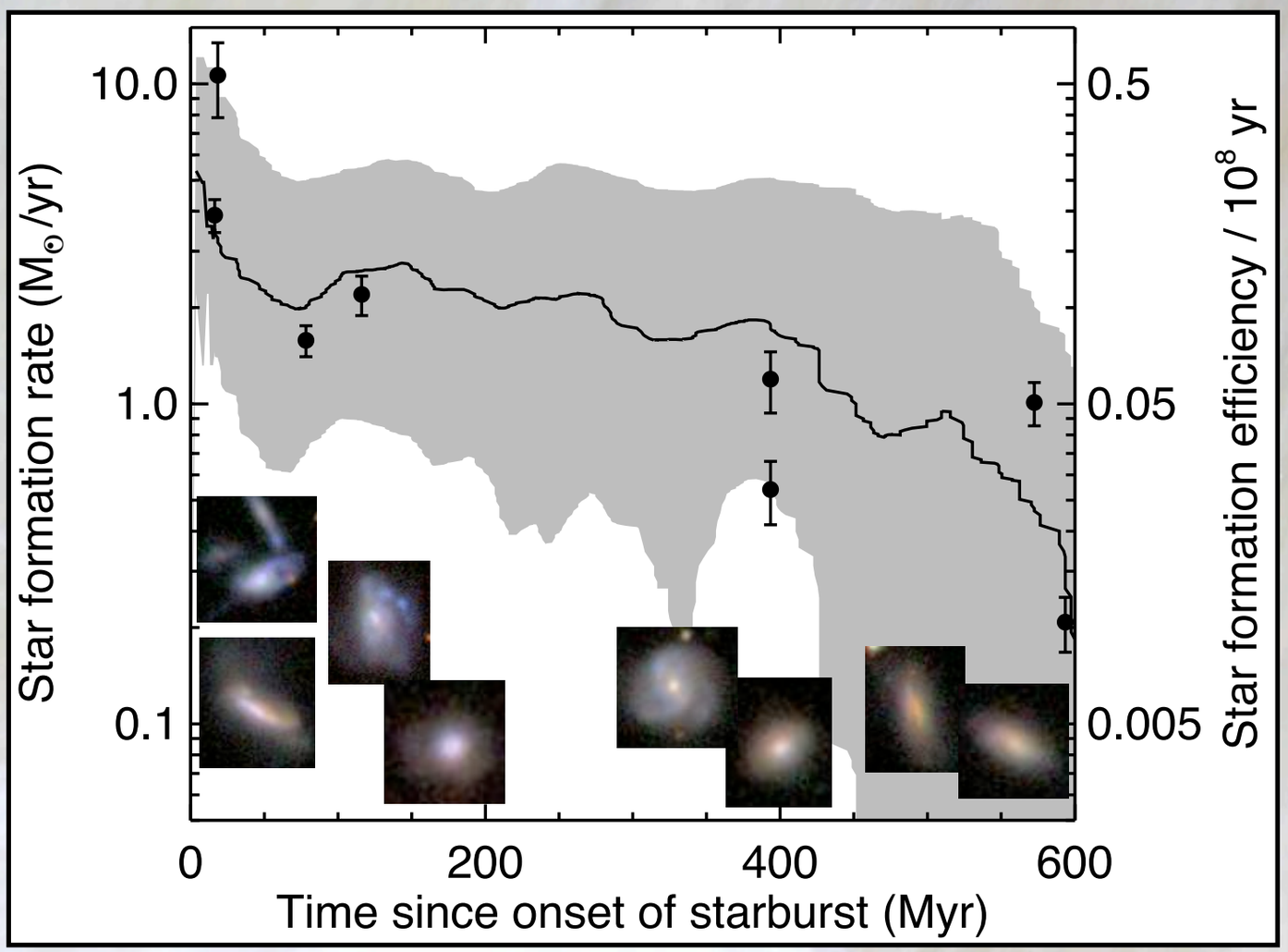
  - Nebular emission lines: black hole accretion rate
- ✦ Results:
  - Delay between onset of starburst and black hole accretion
  - Too long for simple stellar ejecta hypothesis
- ✦ Conclusion??:
  - Black holes grow through accretion of slow stellar ejecta
  - Feedback from SNe prevents accretion early on
  - Or, something to do with dynamical timescale for fueling
    - (Phil Hopkins 2012, MNRAS, 420, 8)

Decline of SFR after starburst

- 3 phases:
  - Peak ~ 50 Myr
  - Slow decline ~ 350 Myr
  - Rapid decline into late post-starburst phase



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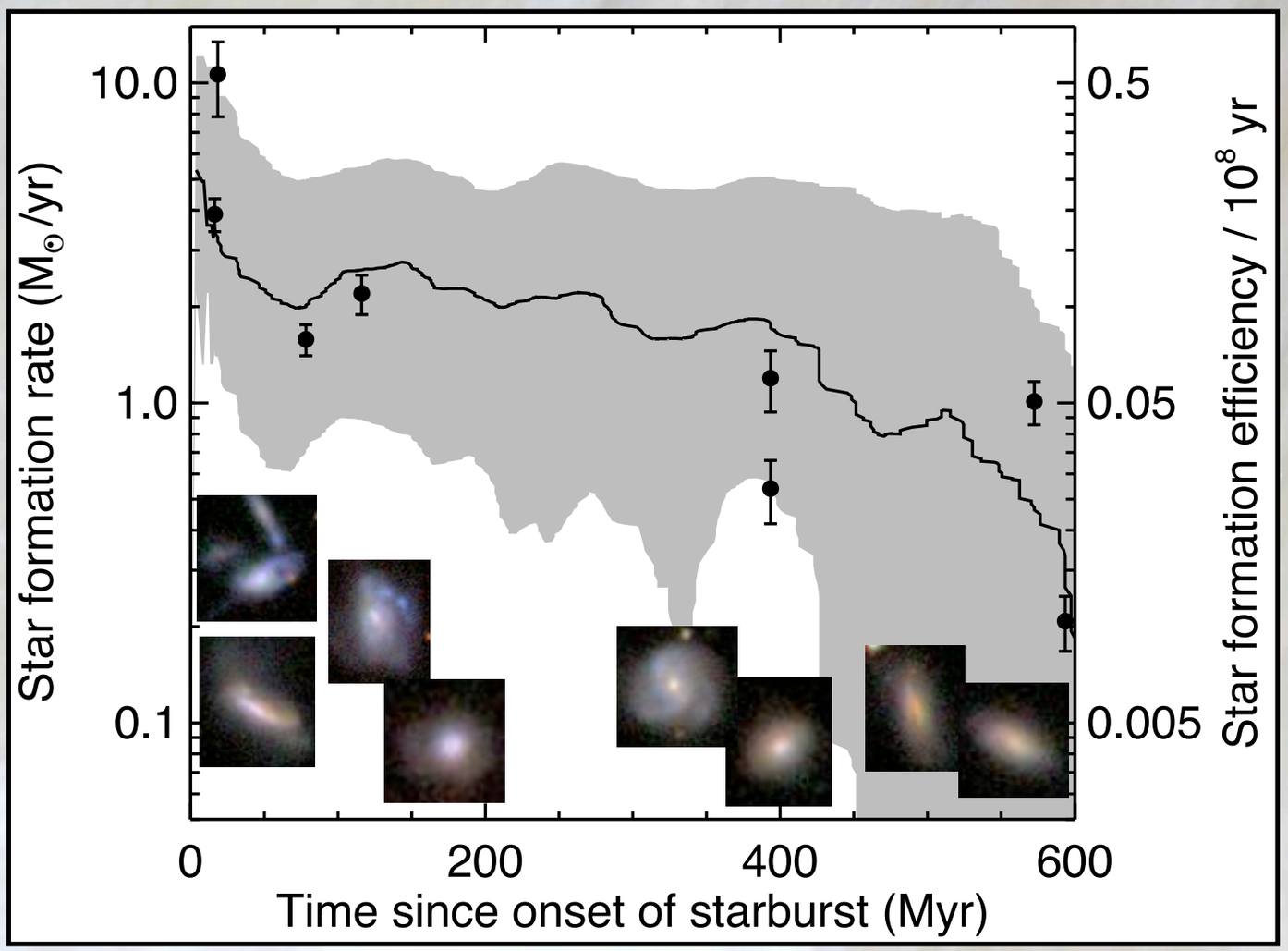


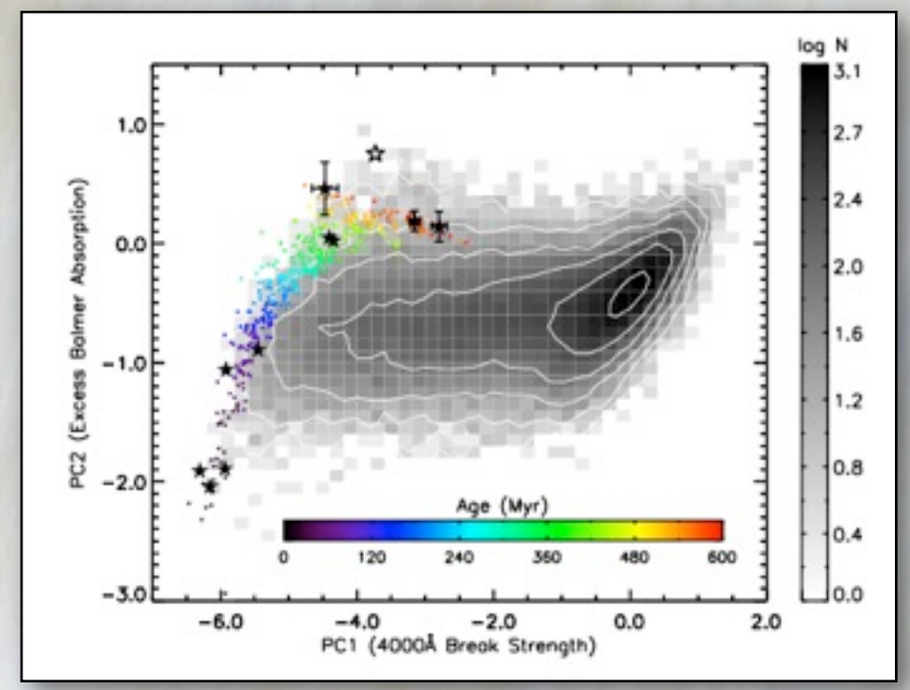
~0.3Gyr decline in agreement with:

✦ Gas consumption times from Kennicutt-Schmidt relation (Kennicutt 1998)

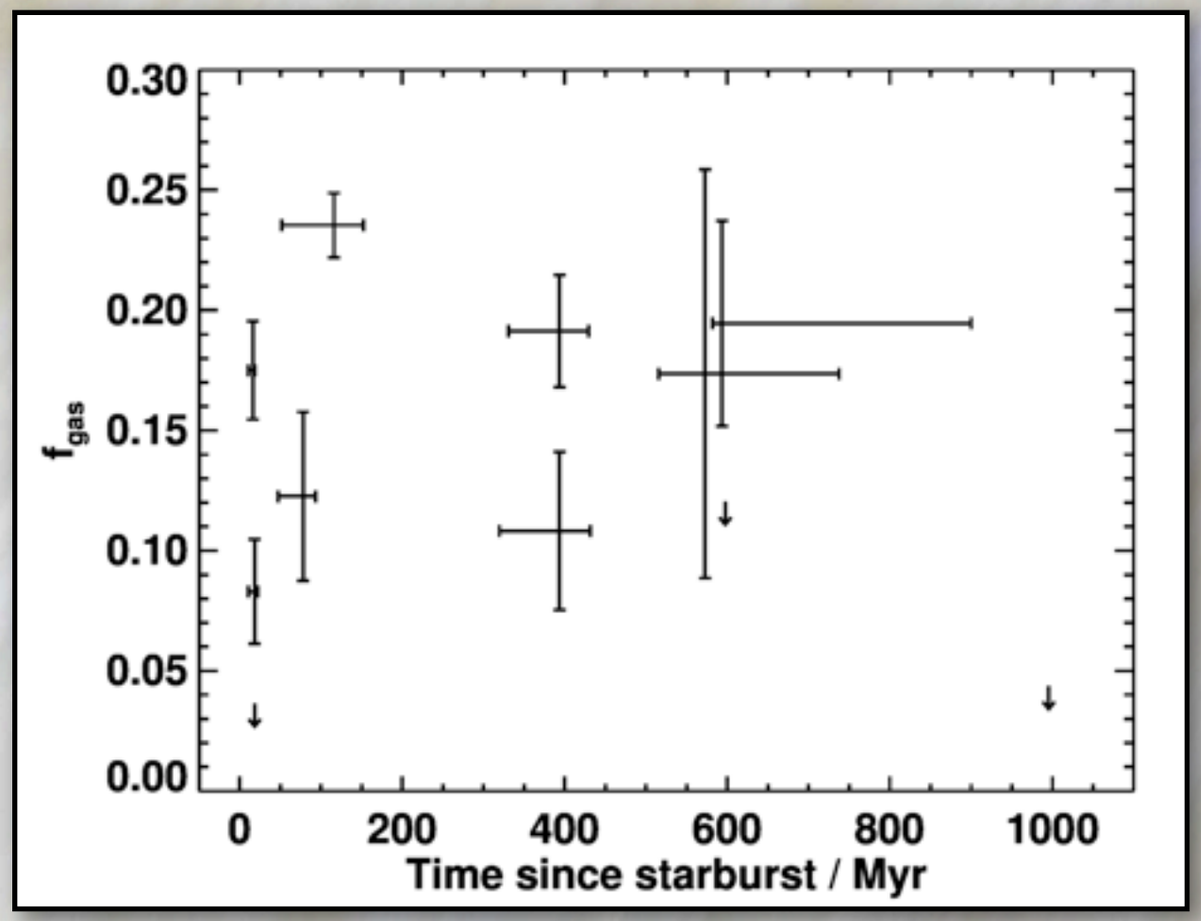
✦ Resolved stellar populations of local dwarfs (McQuinn et al 2010)

✦ Starbursts in close-pairs (Barton et al. 2000; Freedman Woods et al. 2010)

✦ Stellar surface mass densities of elliptical galaxies (Hopkins & Hernquist 2010)



Residual gas supplies



- ✦ No clear decline in global gas mass fraction
  - youngest starbursts slight enhancement in CO(2-1)/CO(1-0) : ISM heating
- ✦ SFR intensity decreases with time
  - Consistent with Schmidt law
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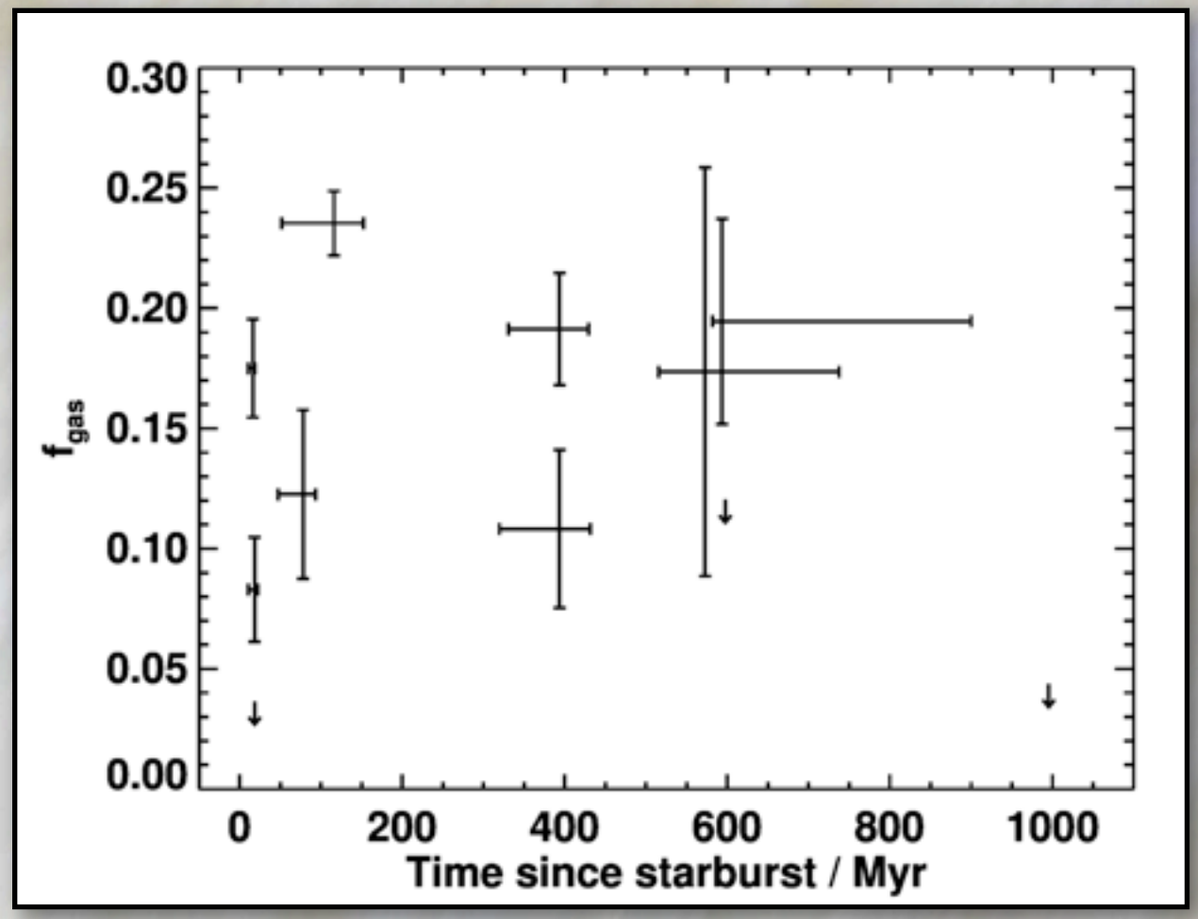

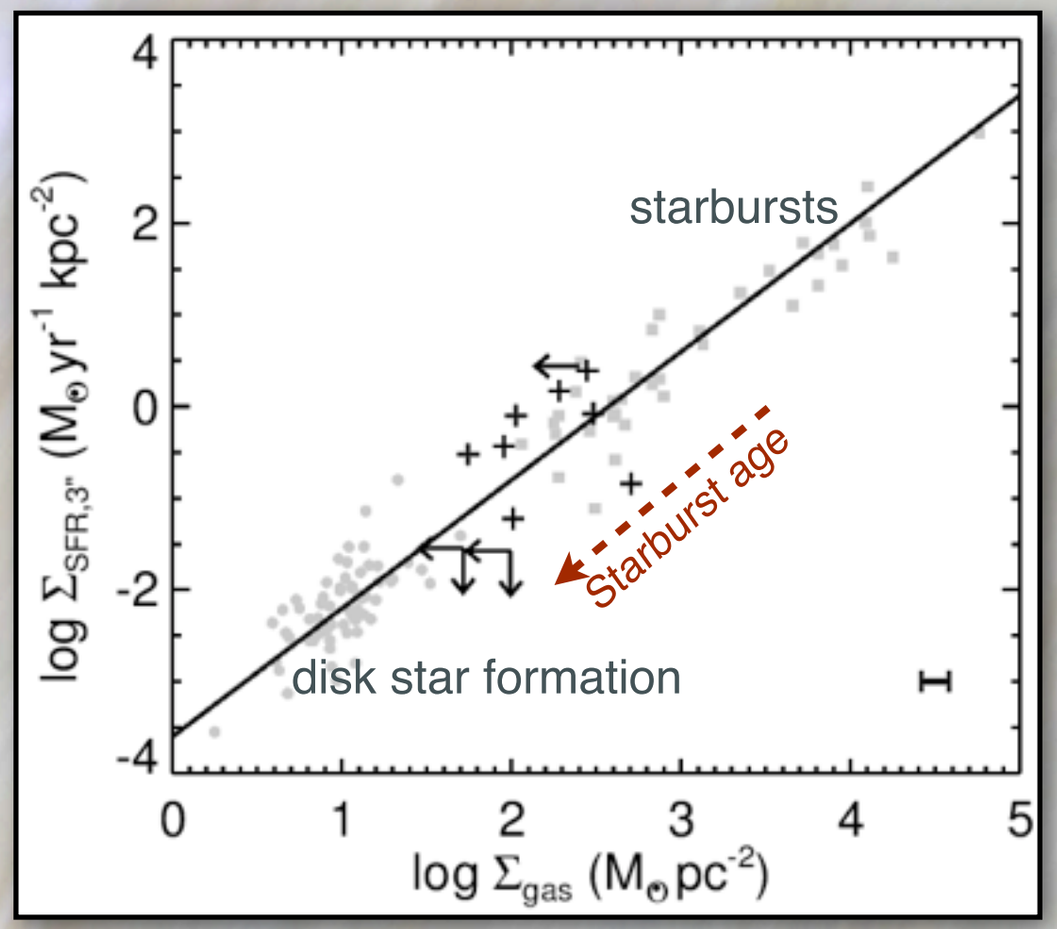

Work-in-progress!!

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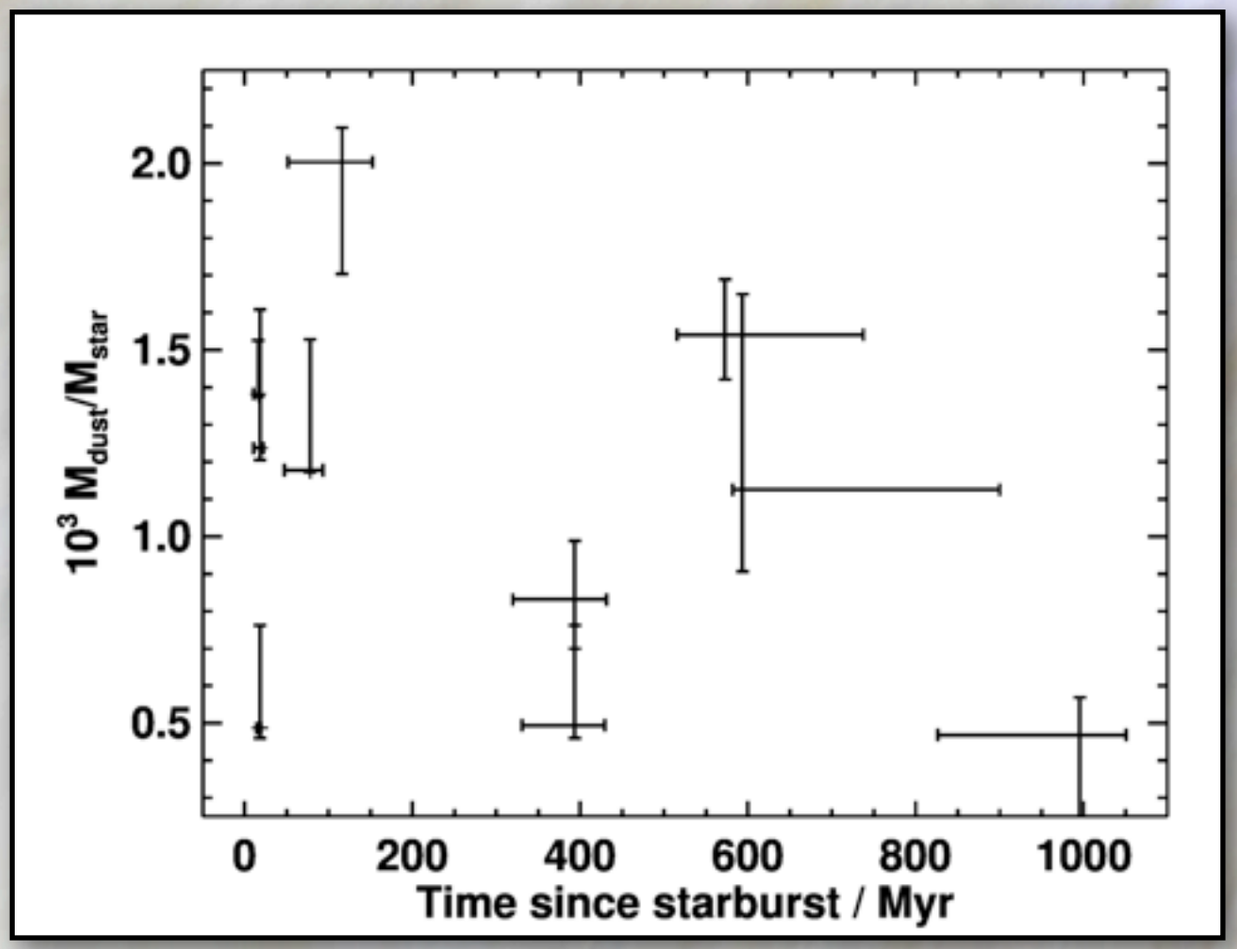

- No clear decline in dust mass fraction
  - Matches CO results: Dust mass determined by gas mass
- Steady decline in dust temperature
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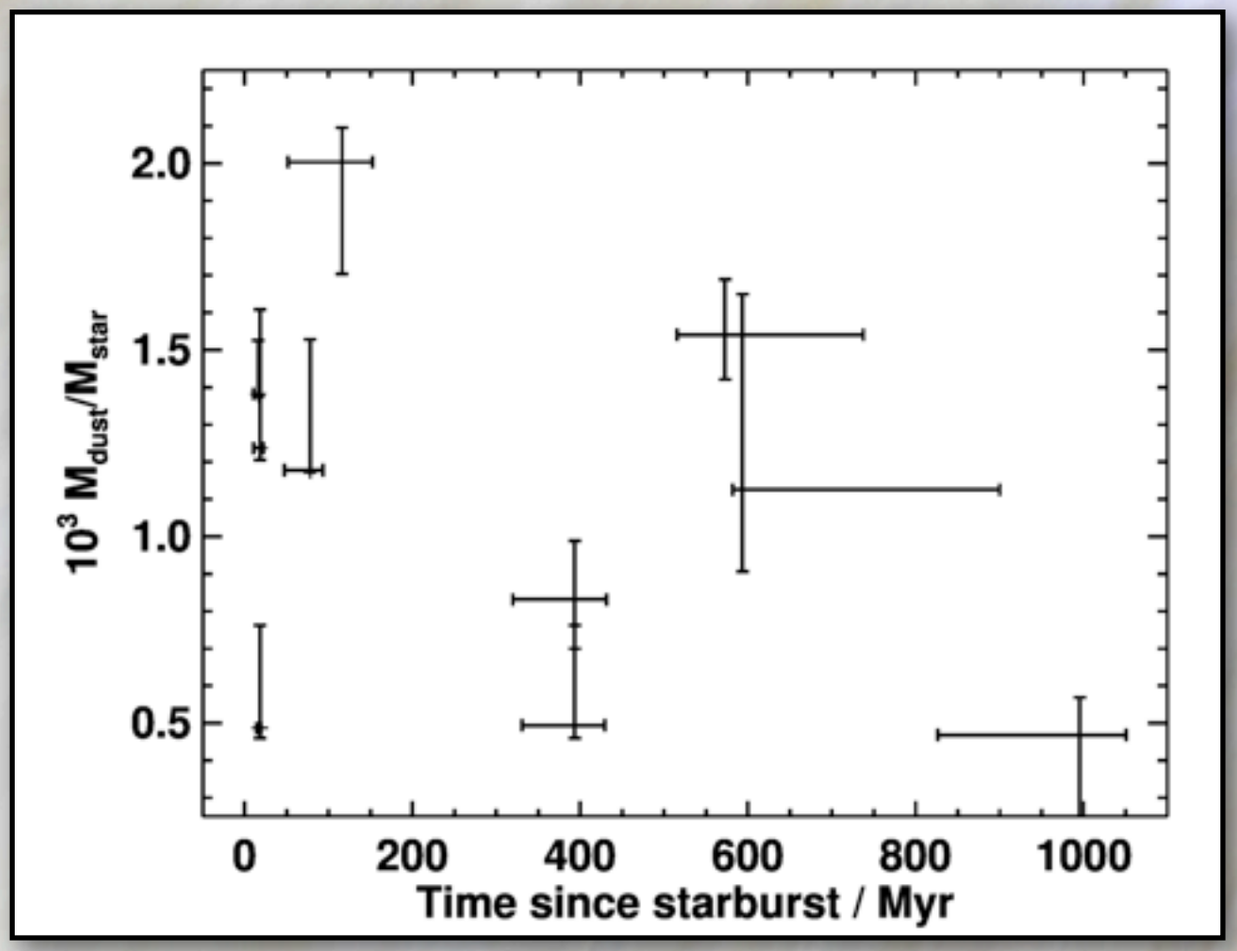
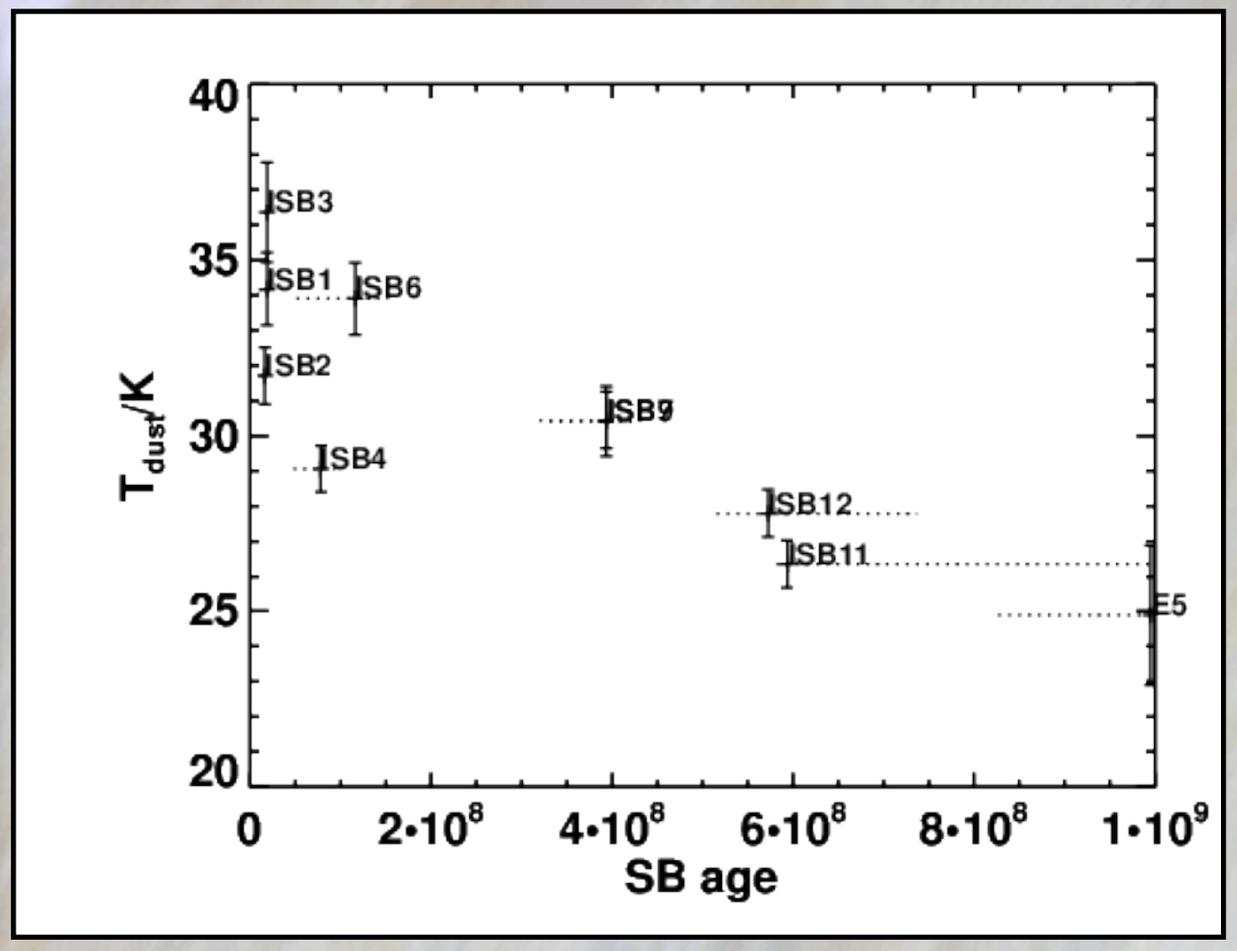
Dust content





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Gas consumption

✦ Method:

- Stellar continuum + sample: time since starburst
- Dust attenuation corrected Hα : instantaneous SFR
- Follow-up IRAM + Herschel of subsample

✦ Results:

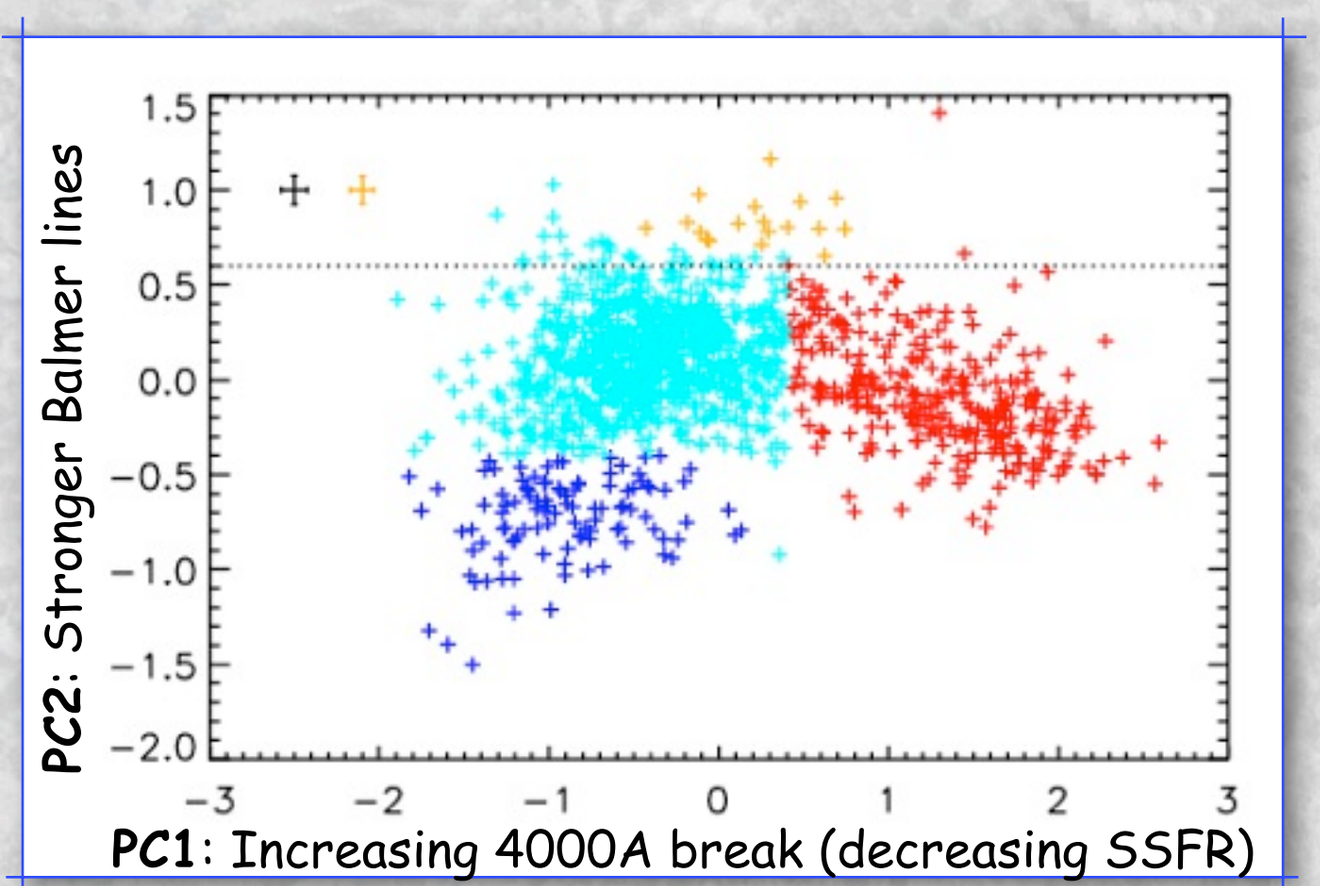
- Nuclear star formation declines in 3 stages
- Global gas and dust mass fraction remain constant
- SFR intensity / dust temperature decline: follow Schmidt law

✦ Conclusions

- No global gas expulsion episode
- Steady decline in SF efficiency = steady evolution of ISM

Starburst evolution: spectroscopic data

0.5 < z < 1.0 : VVDS



Wild, Walcher, Johansson et al. 2009

- VVDS spectra are not great, but good enough....

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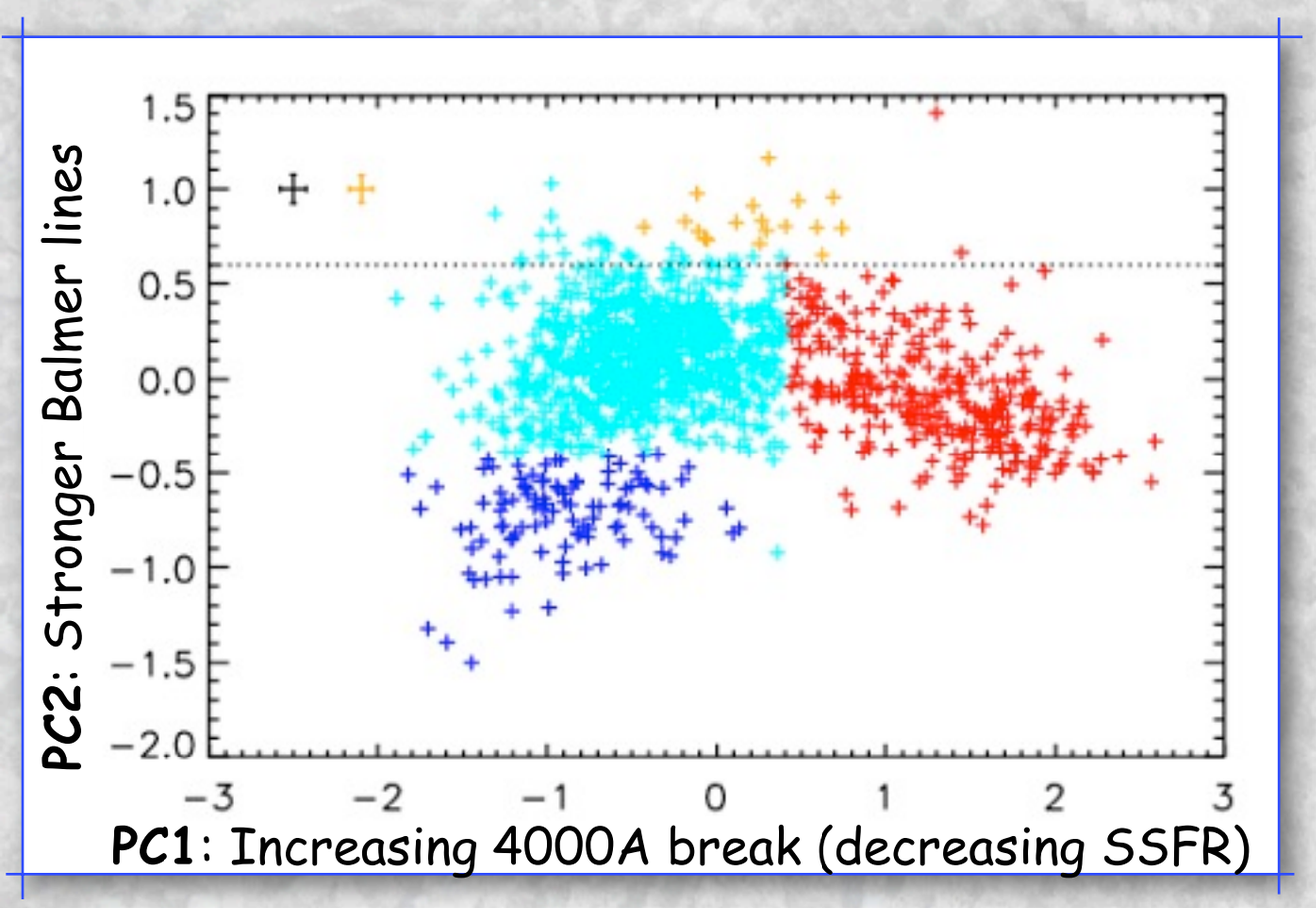
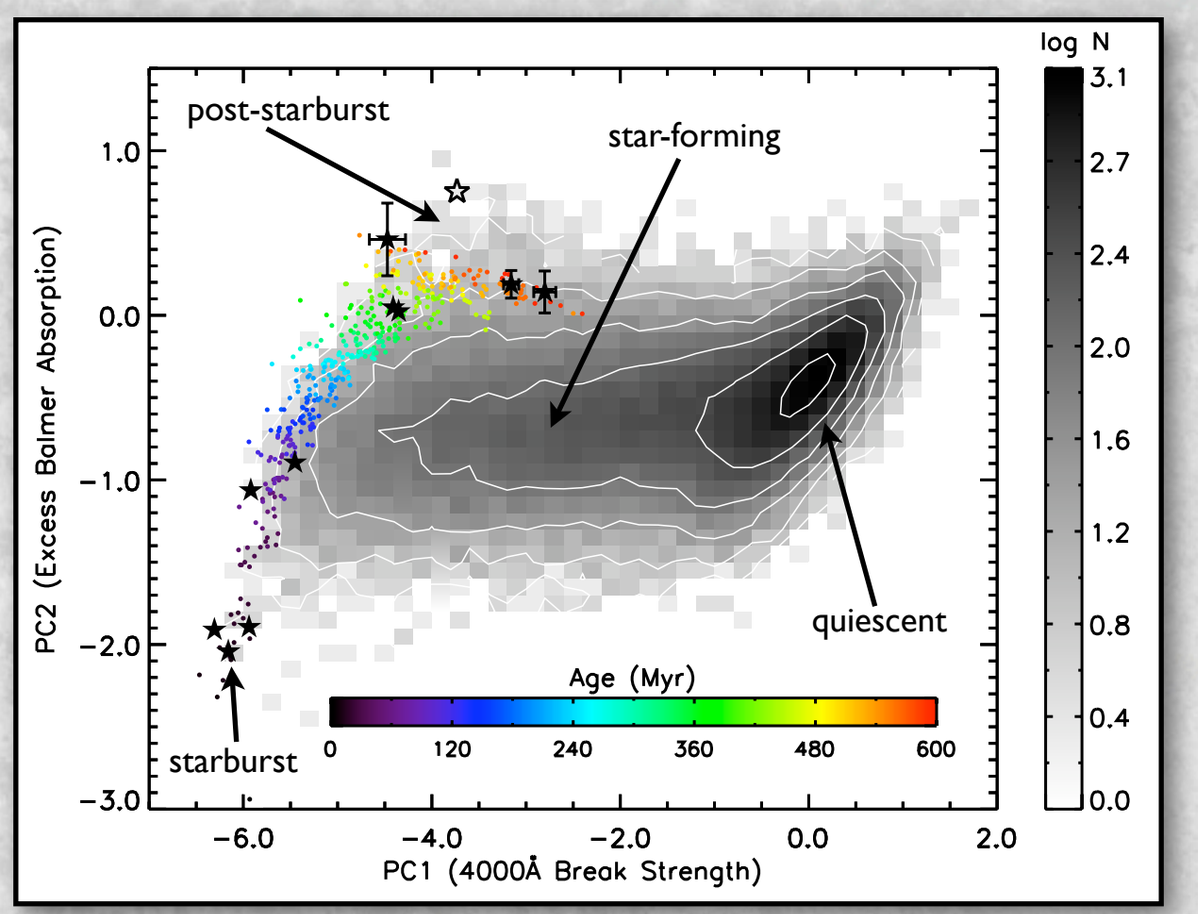


Wild, Walcher, Johansson et al. 2009

z~0 : SDSS



Wild, Heckman, Charlot 2010

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Post-starburst galaxies: not just an interesting curiosity

Fraction of new red sequence mass accounted for by post-starburst galaxies at $0.5 < z < 1.0$

(compared to Arnouts et al. 2007):

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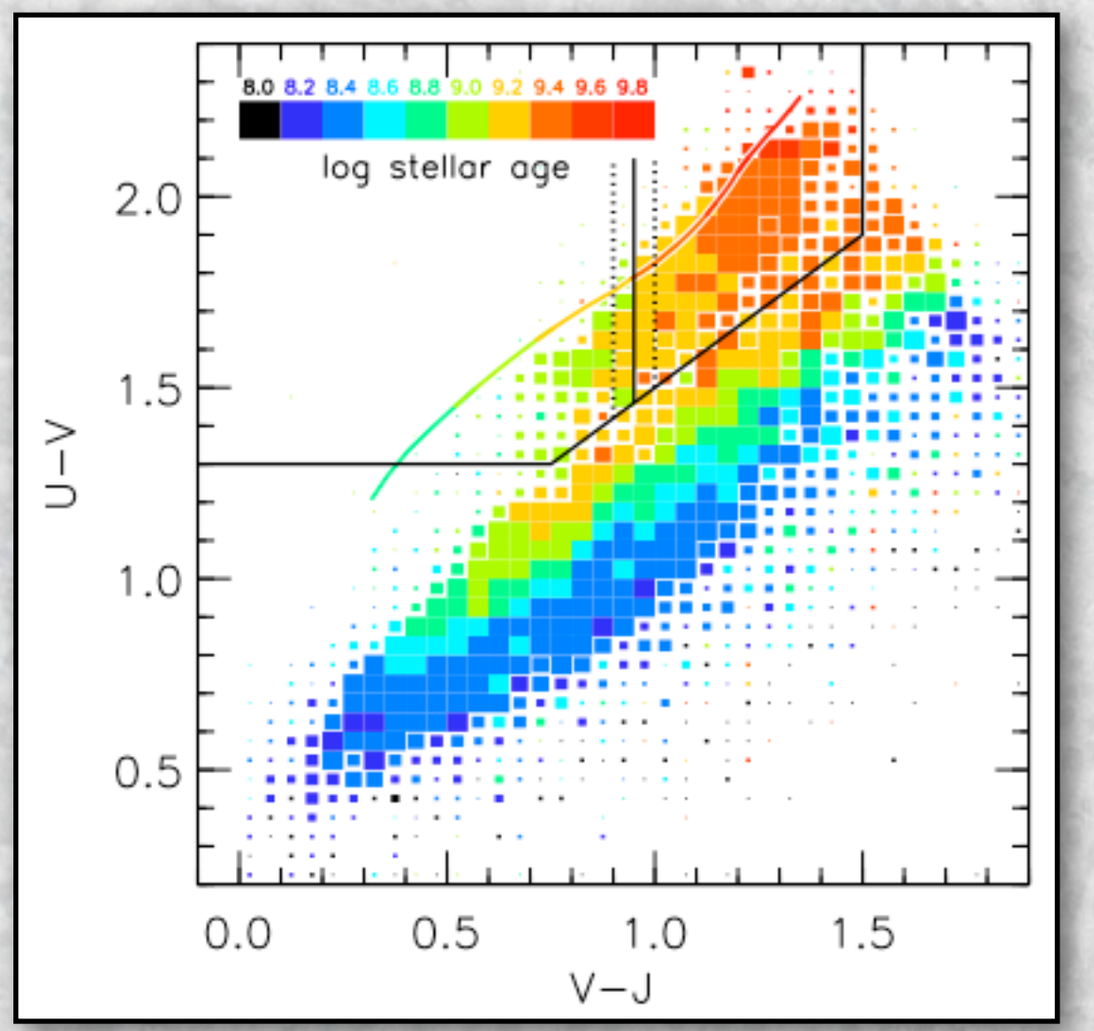
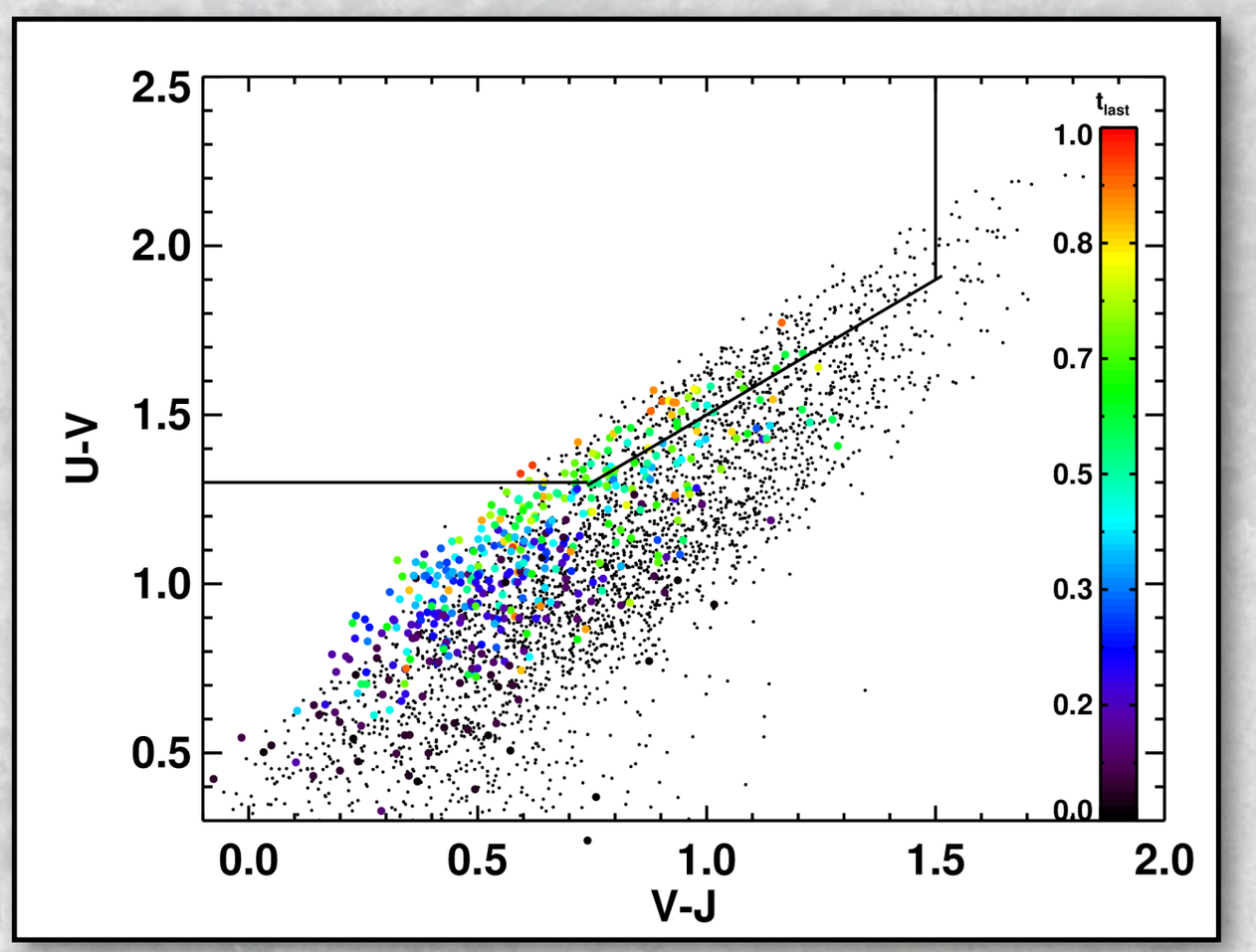
- Potentially a significant blue ⇒ red growth channel
- Also S ⇒ E if we believe simulations
- But only 5 (16) galaxies...
- PSBs are rare and spectroscopy is expensive

Wild, Walcher, Johansson et al. 2009

Post-starbursts from photometry?

Current state-of-the art: Whitaker et al. 2012

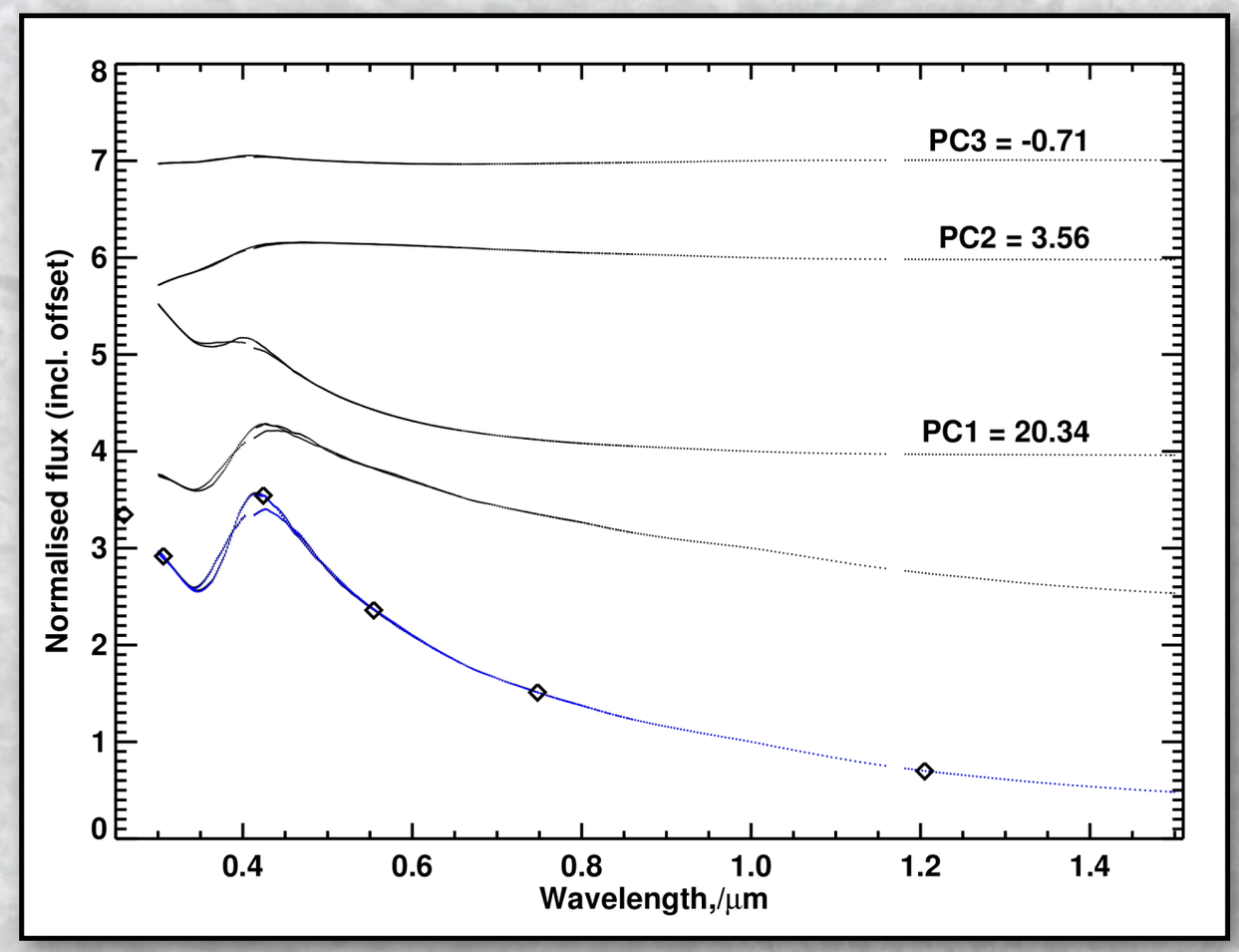




- Rest-frame 4000Å break strength vs. optical slope gives first order measure of age in old populations
- Can we do better with modern statistical methods?

Super-colours

How to build a galaxy SED using PCA:



- ✦ Optimally defined linear combinations of filters
  - uses a Principal Component Analysis and sparse sampling (Connolly & Szalay 1999)
- ✦ Find that almost no information is lost by “sparse sampling”
  - So long as you have FULL, GOOD QUALITY optical-NIR coverage
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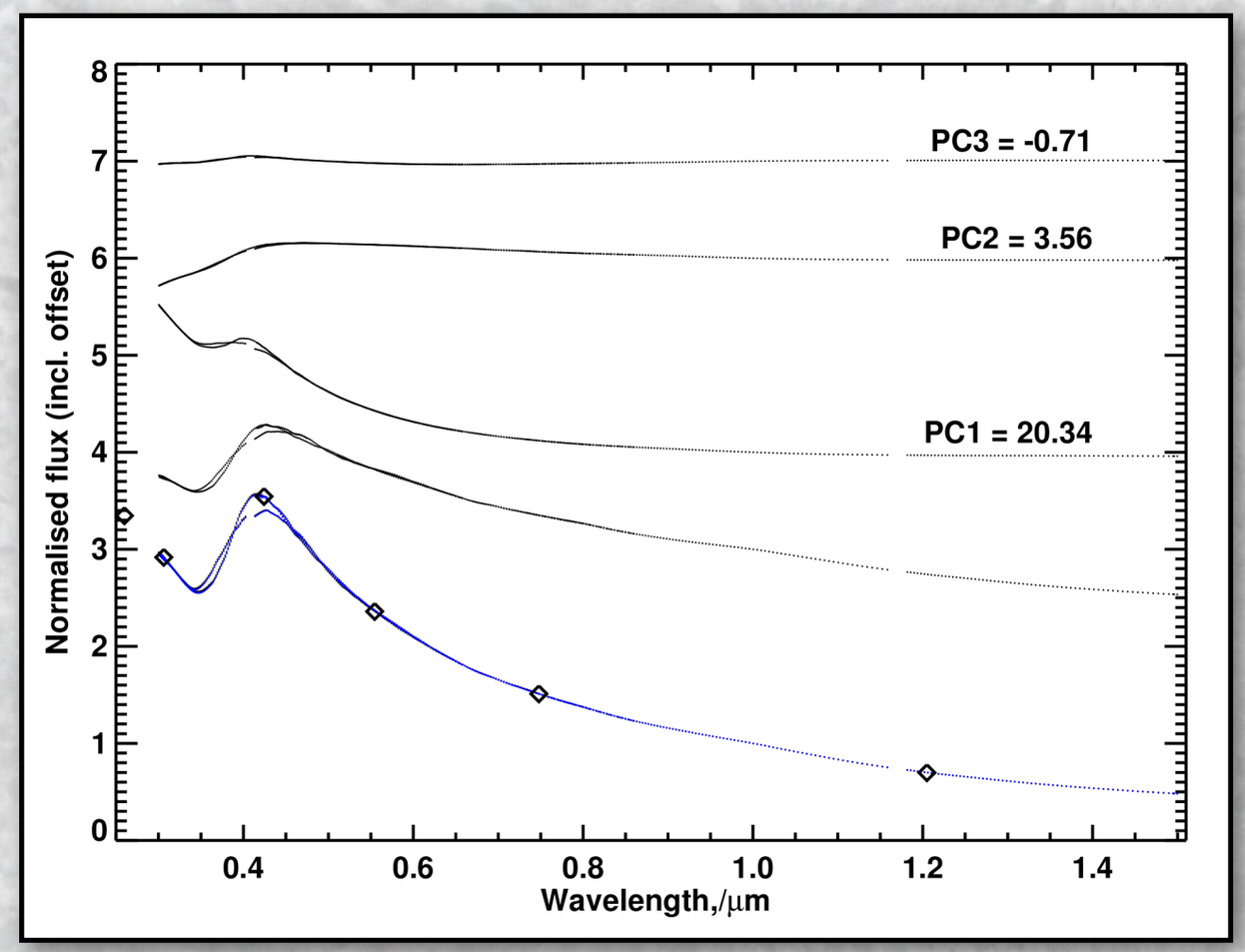
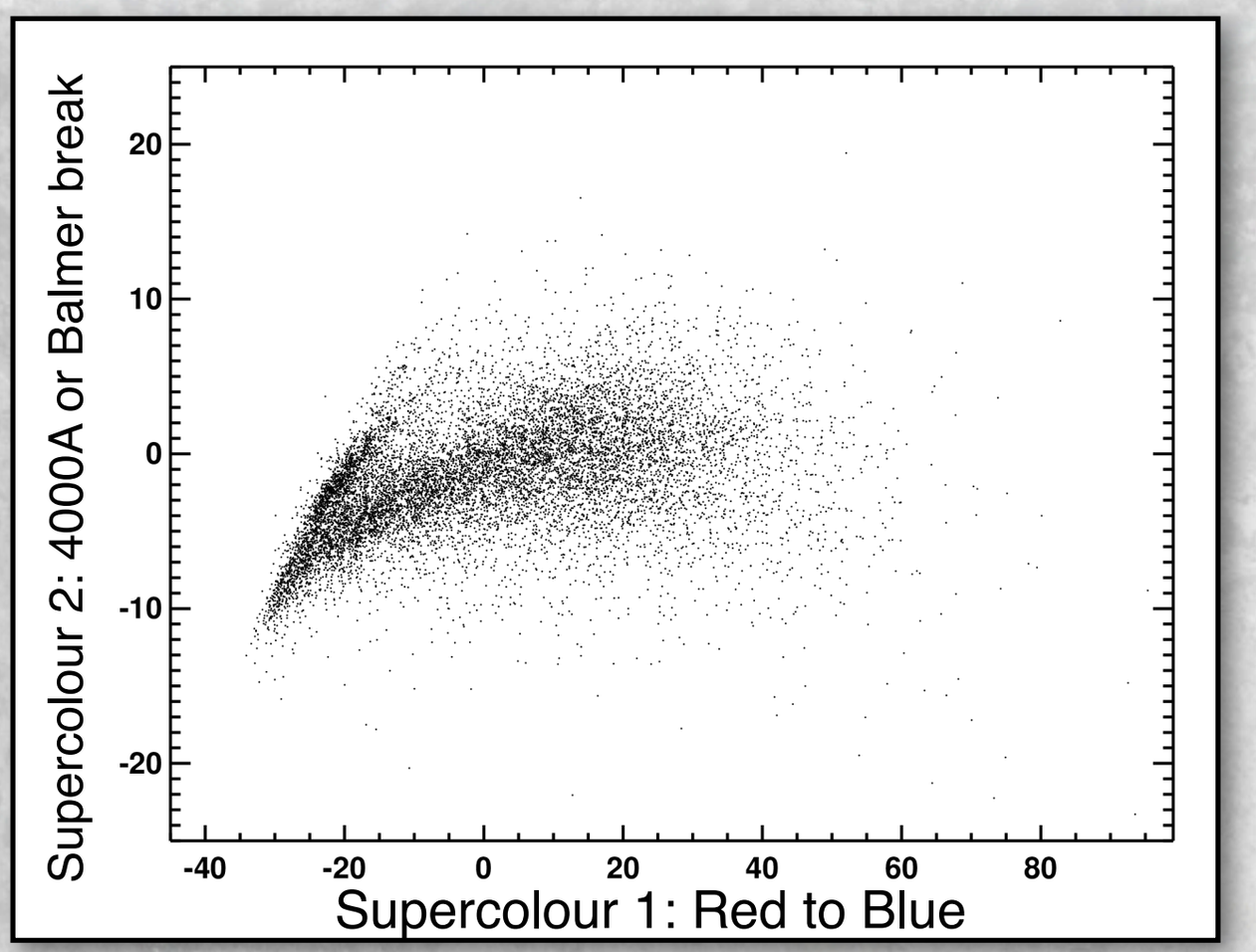


SED shape of 24,000 galaxies $0.9 < z_{phot} < 2.0$



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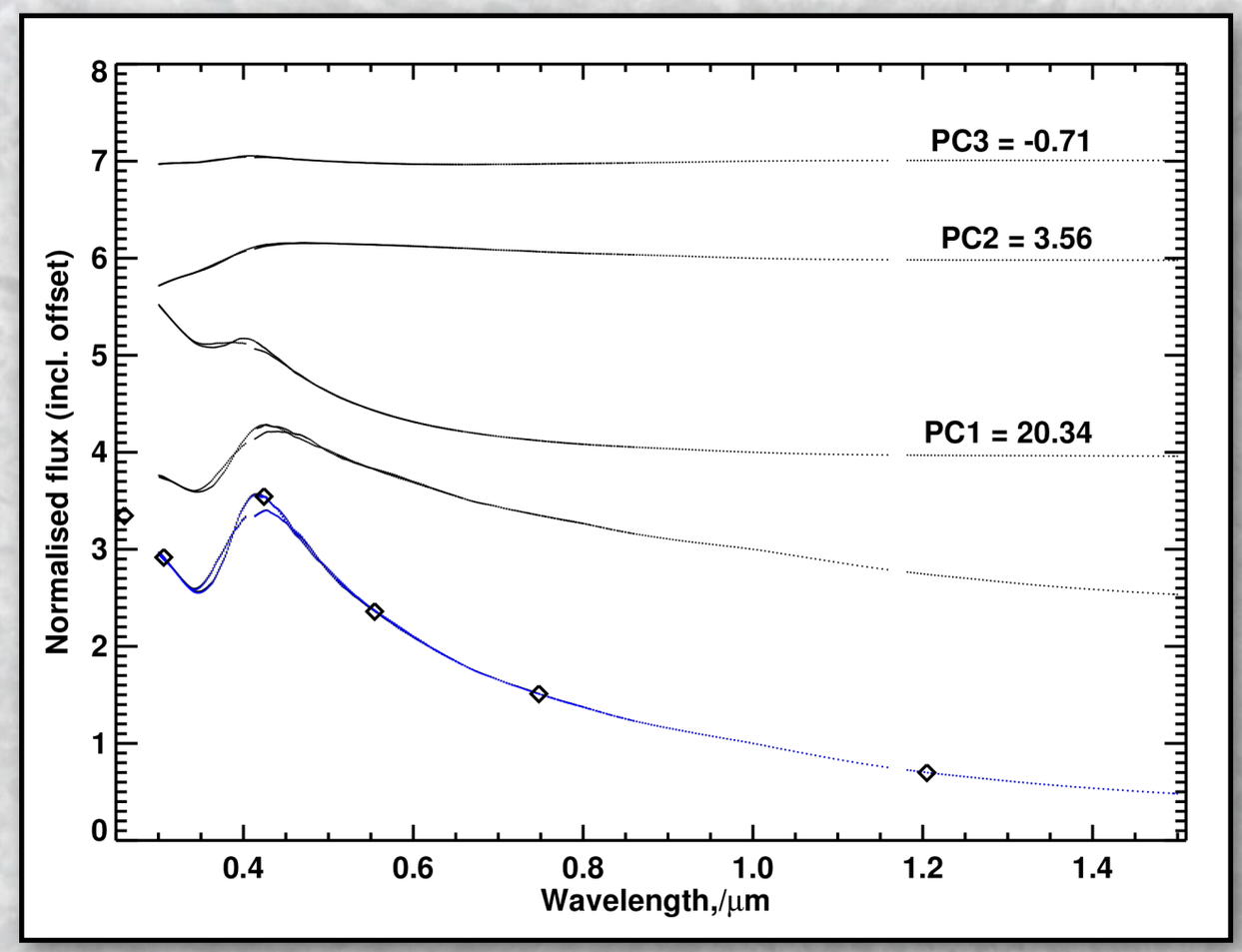

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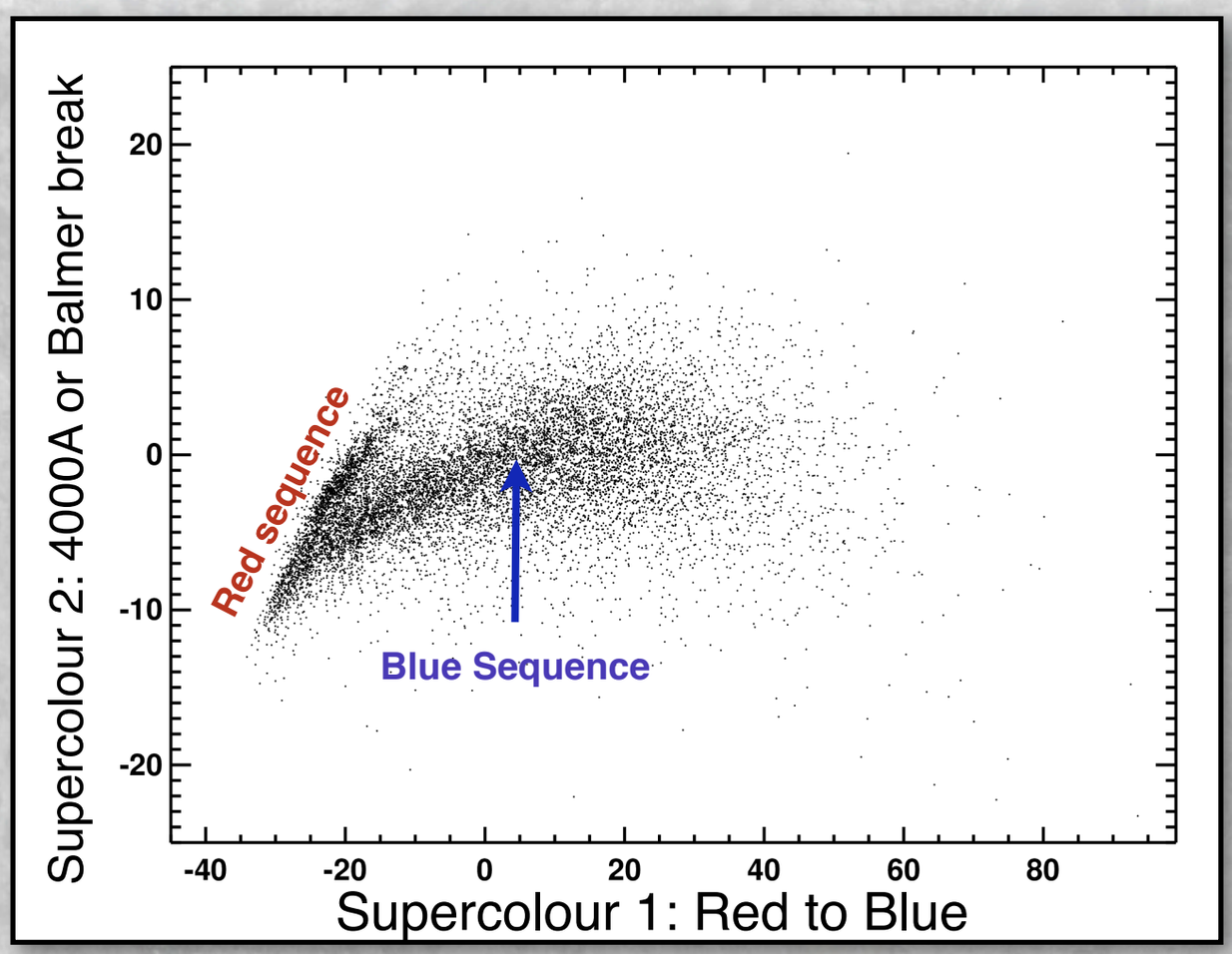

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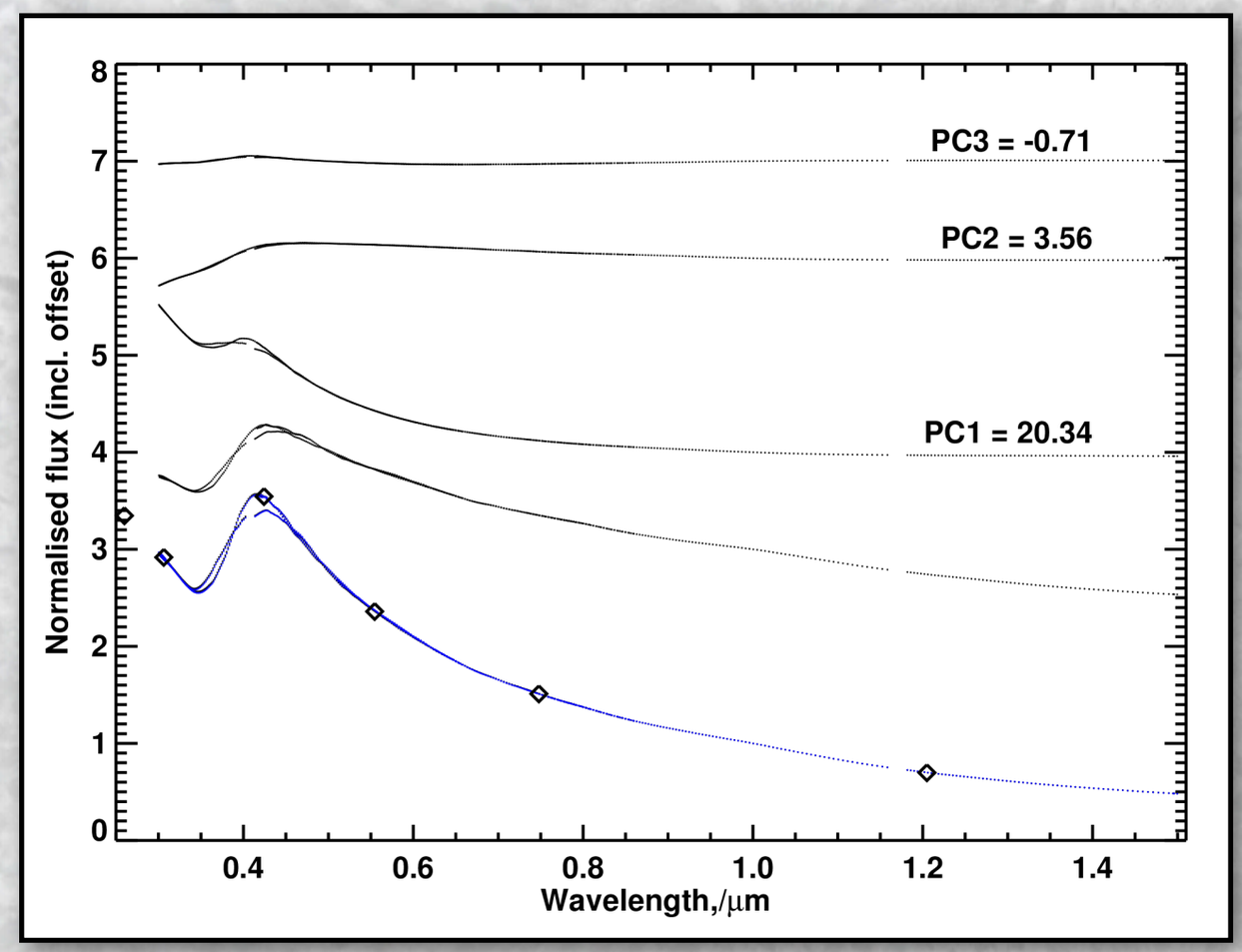

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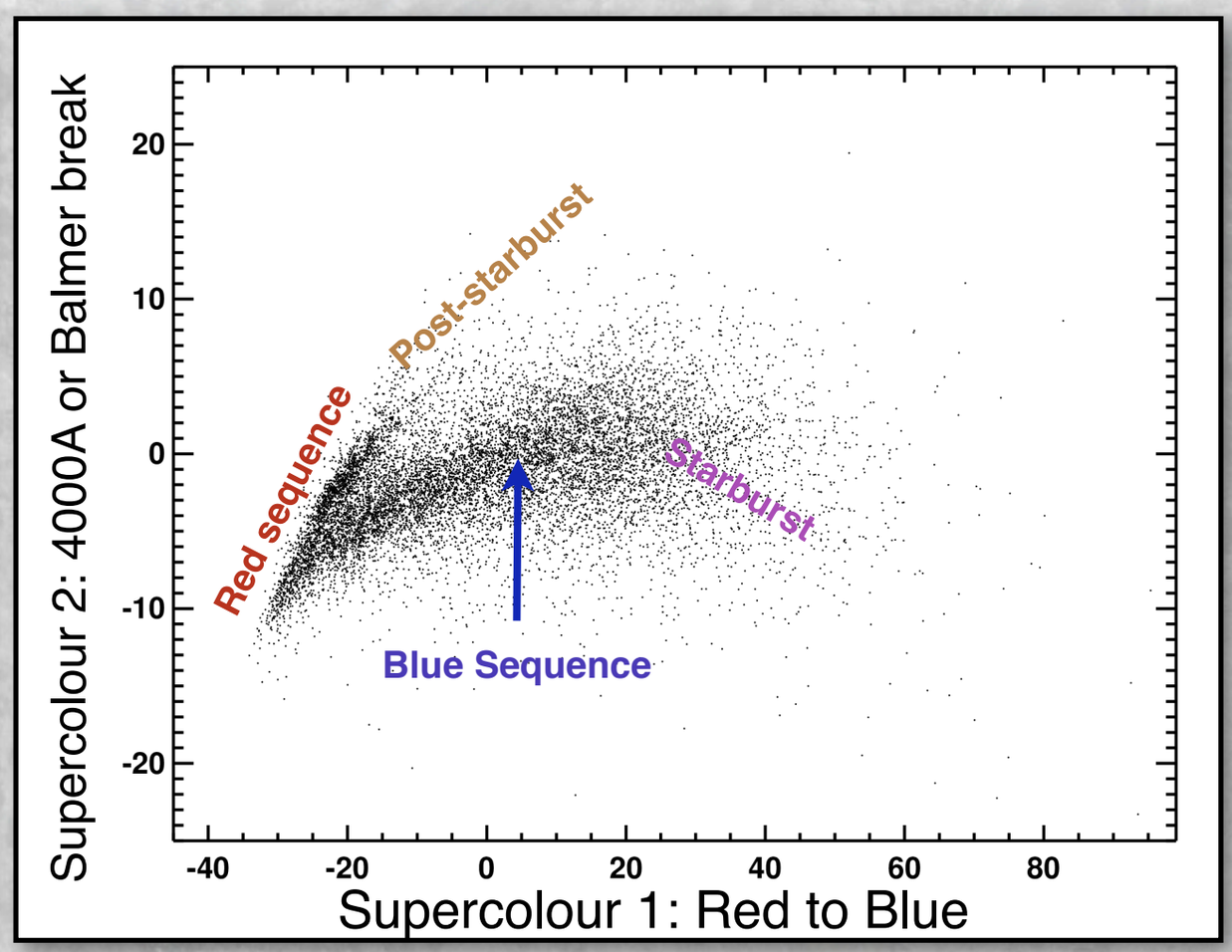

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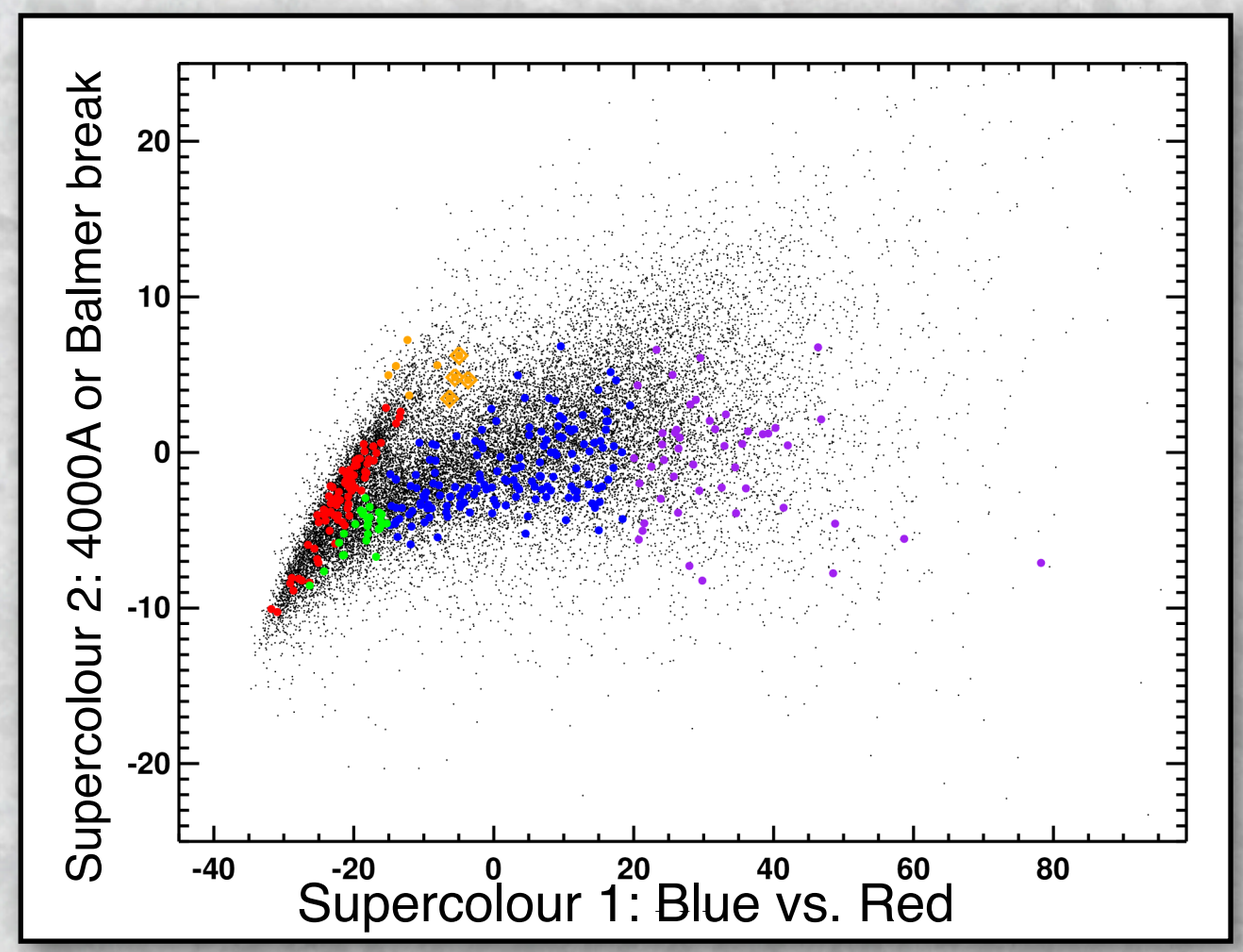
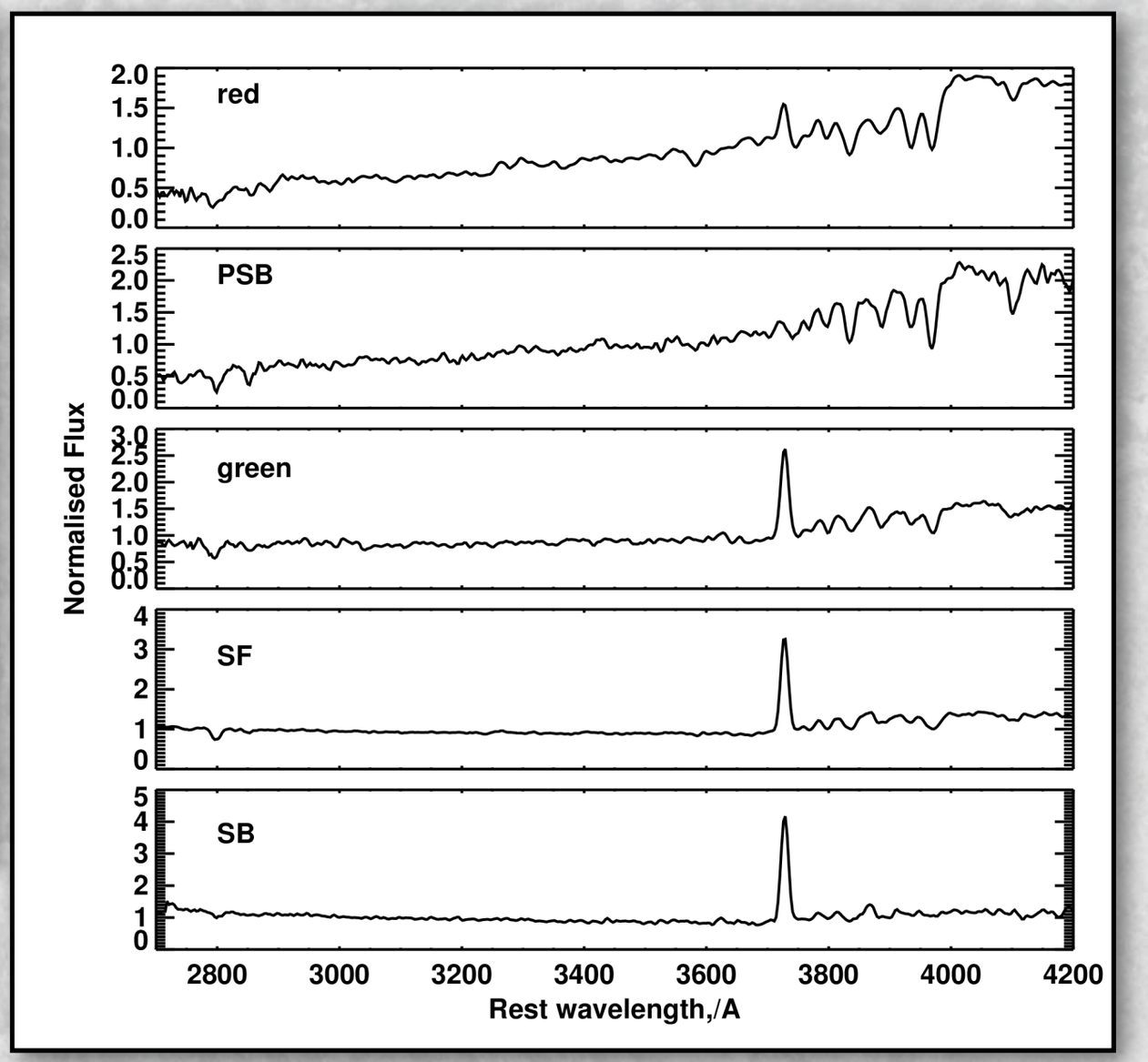
Spectroscopic confirmation

752 UDSz spectra: $0.9 < z_{spec} < 2.0$

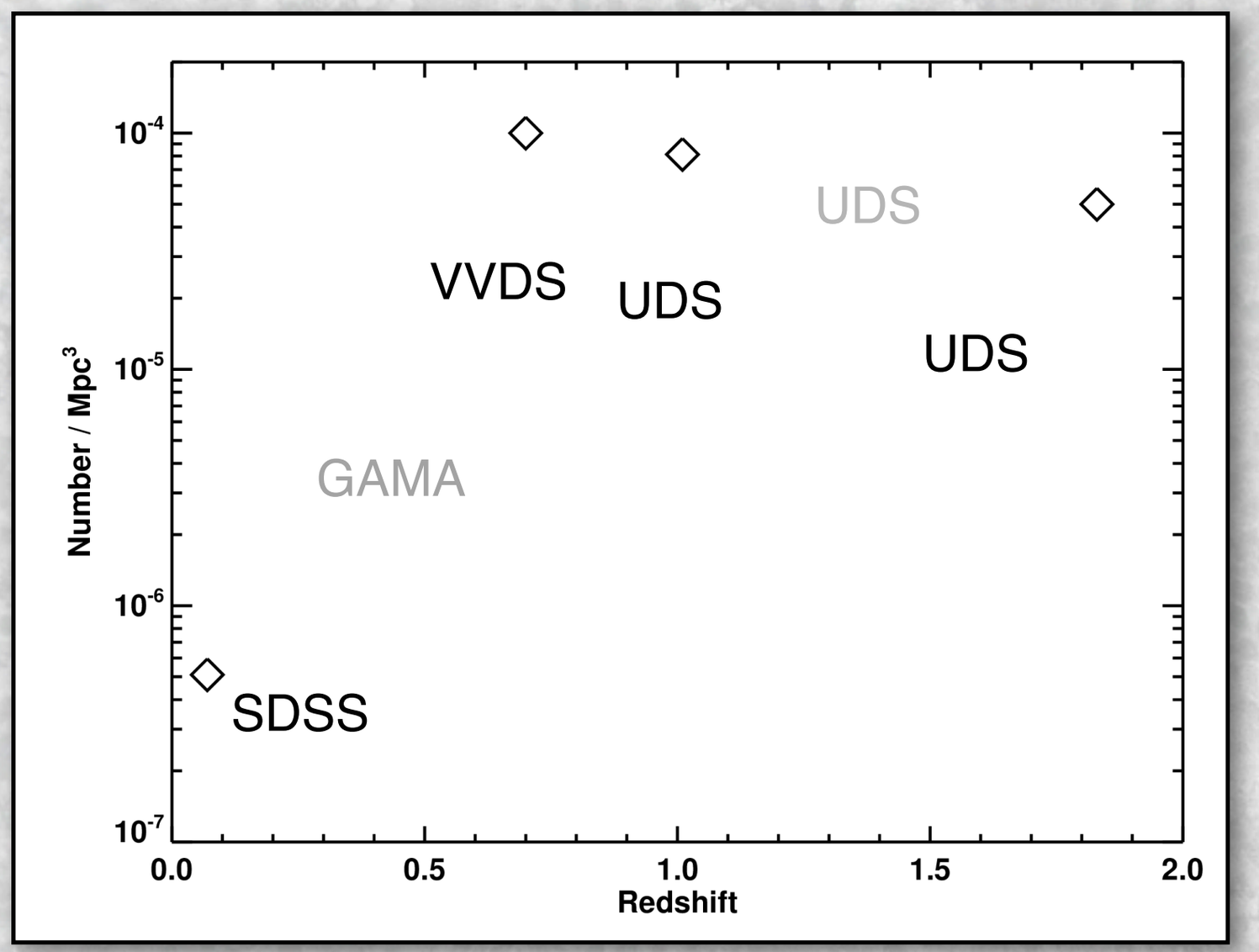


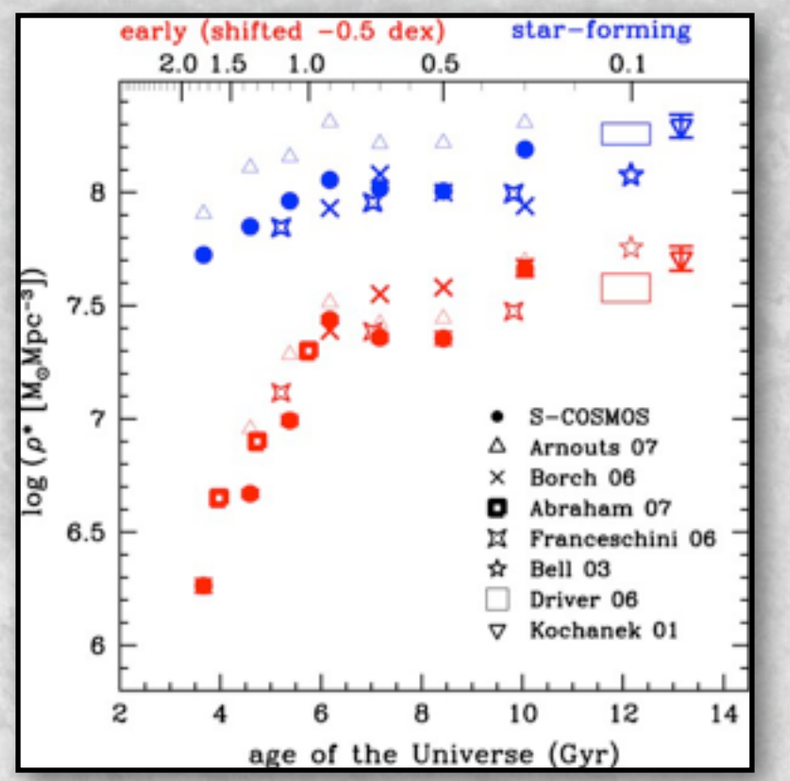
Stacked spectra from different regions



- SNR of most spectra too low to study recent SFH
- Stack based on position on super-colour diagrams

Number density evolution





- Far greater than decline in major merger rates ~$(1+z)^{2.2}$ e.g. Xu+2012
- ~z at which mass transfer to RS stops (e.g. Ilbert et al. 2010)
- In principle: strong constraint on galaxy evolution models
  - Work-in-progress : significant work to make models match at all

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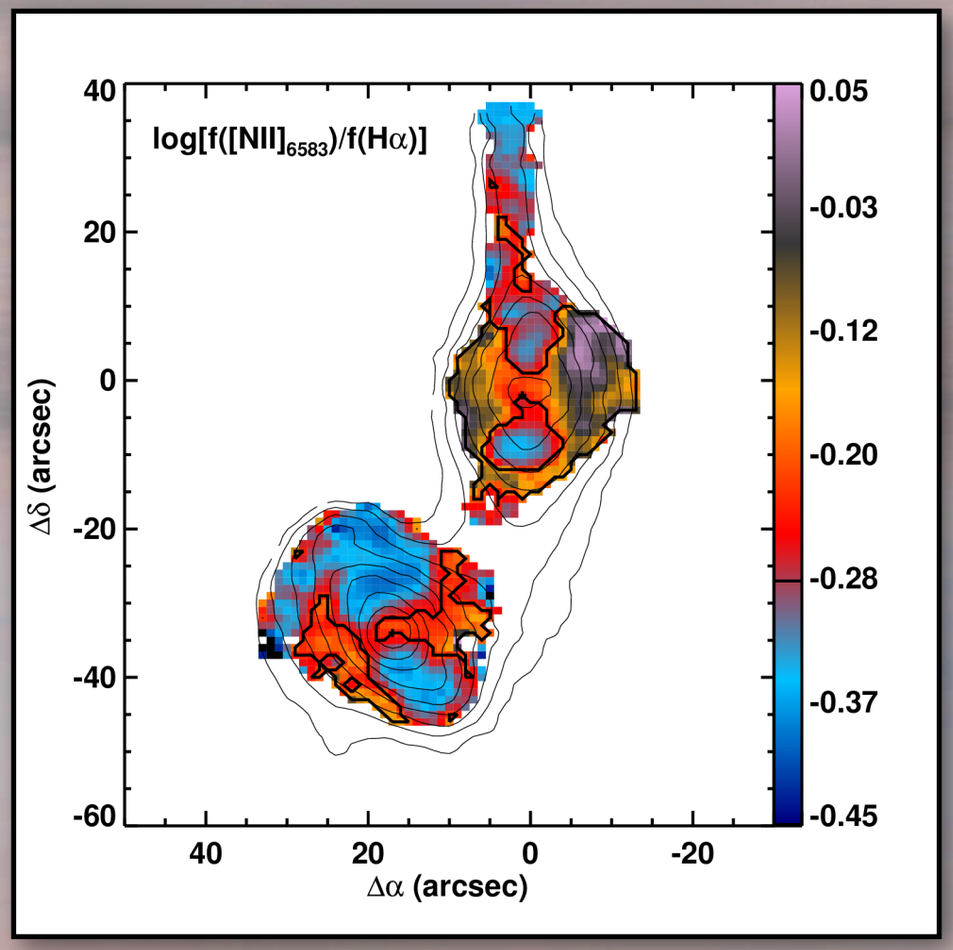

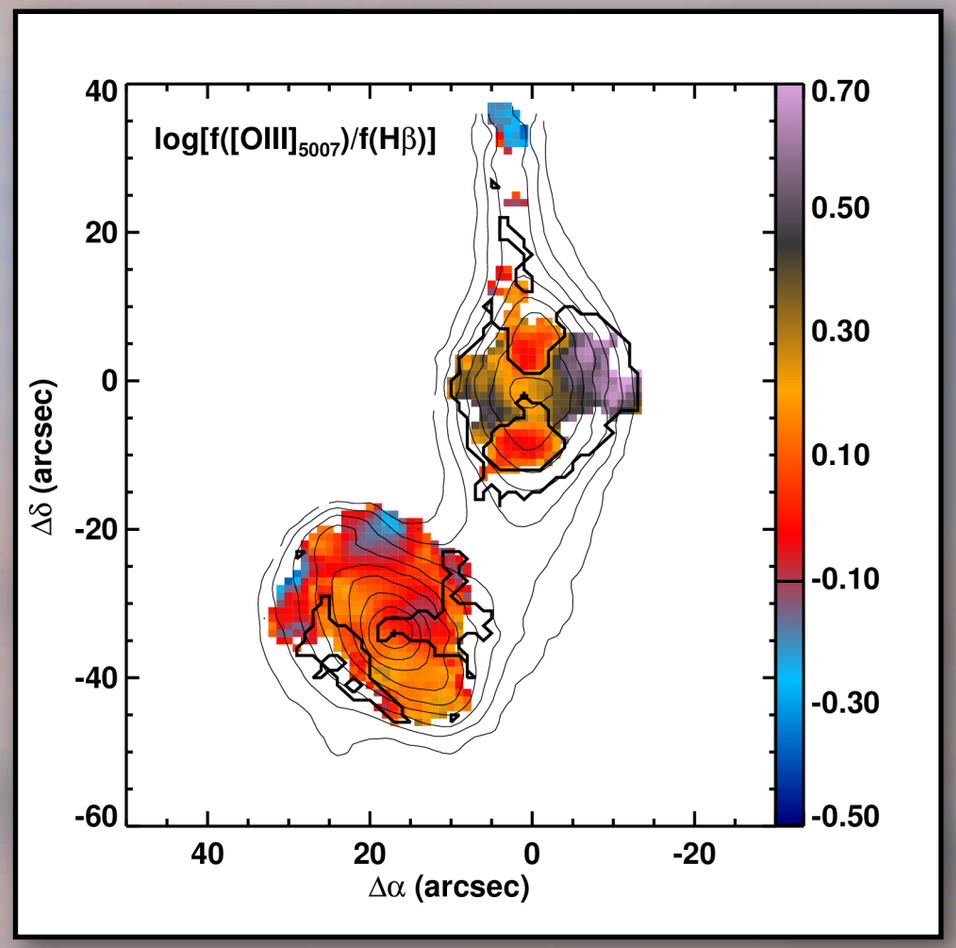

Wild et al. in prep.

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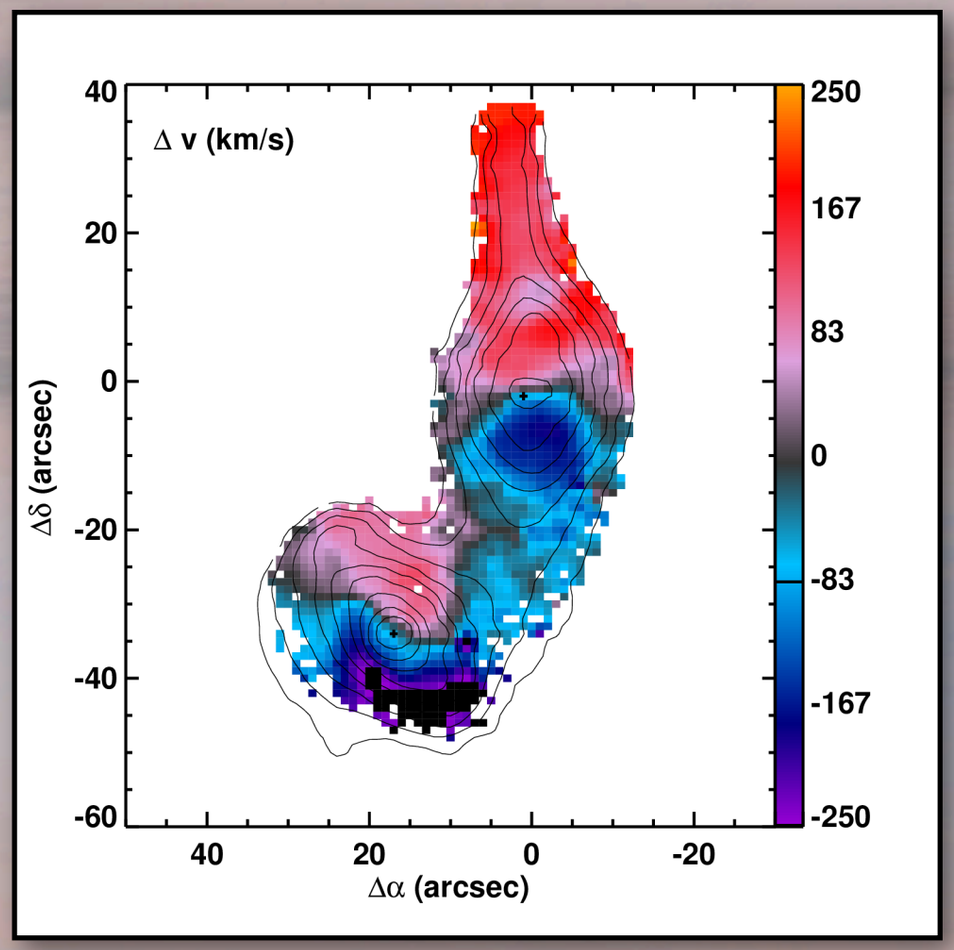

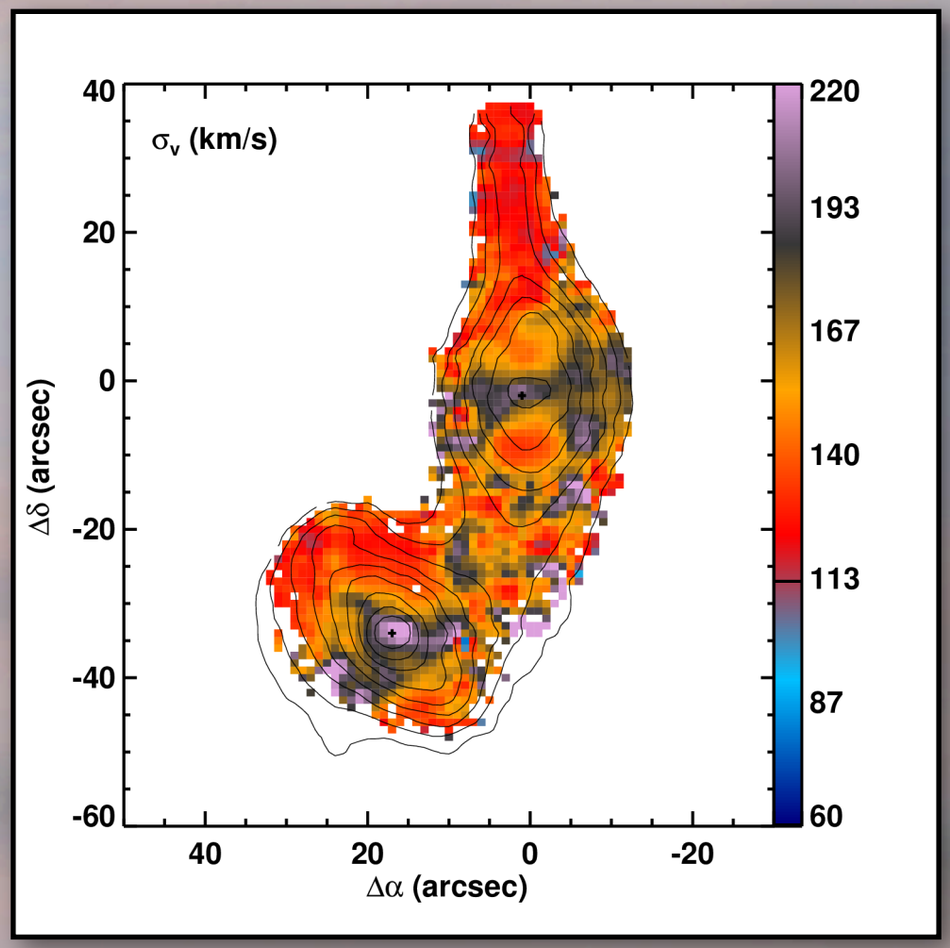

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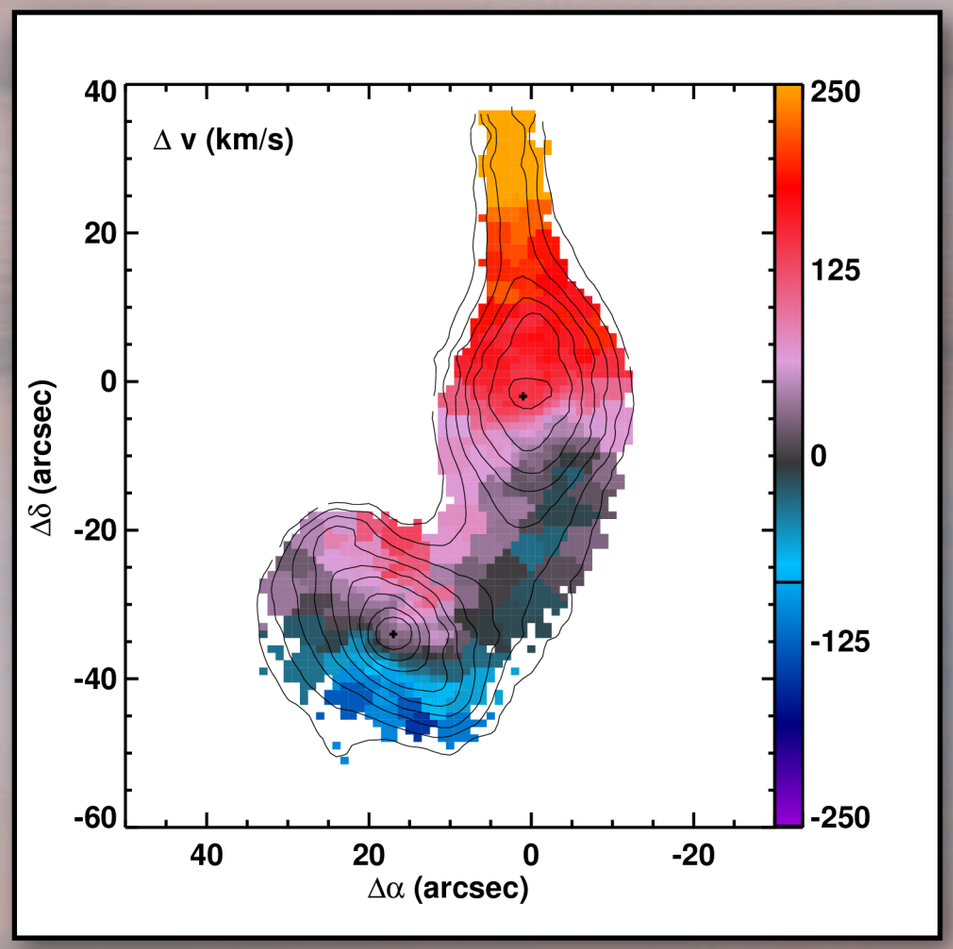

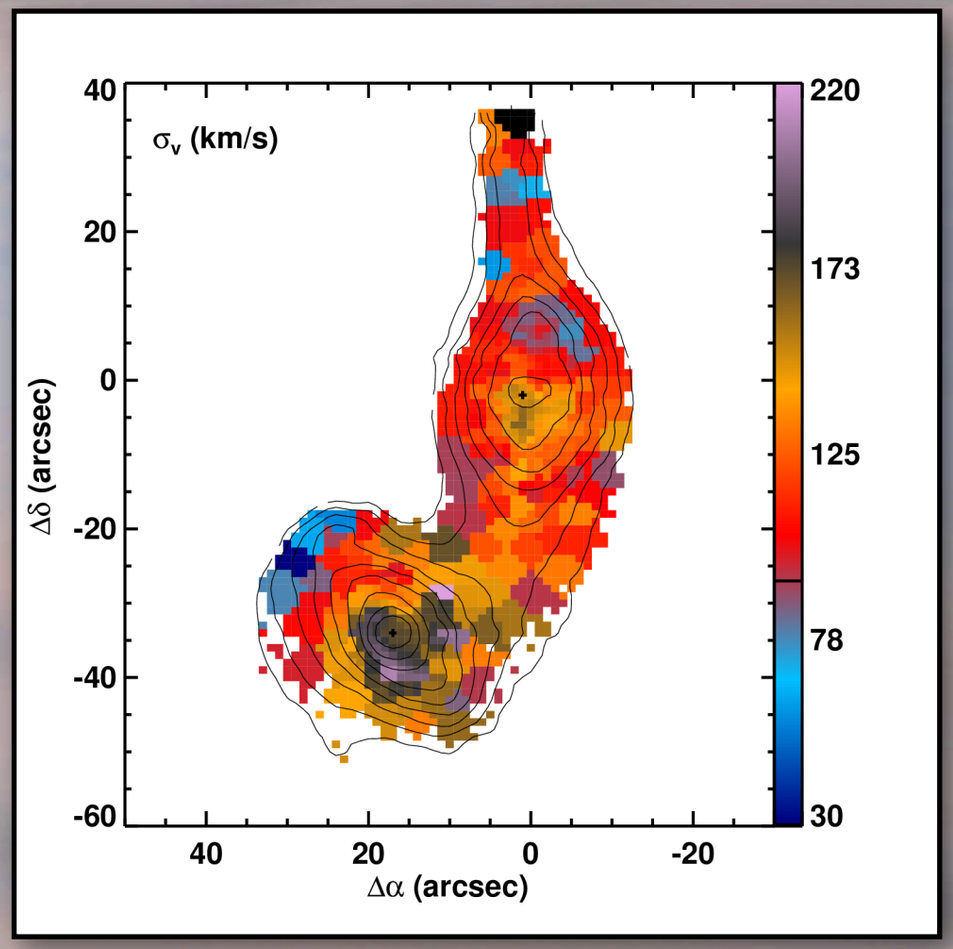

Van der Ven et al. in prep.

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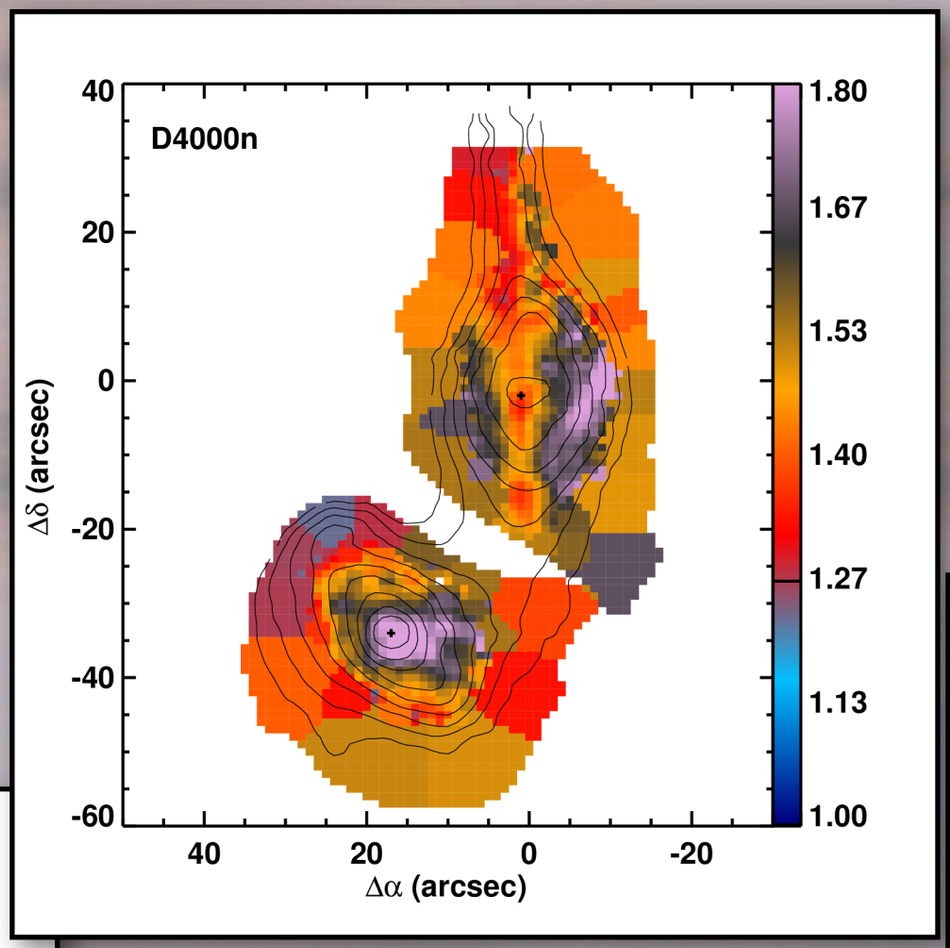

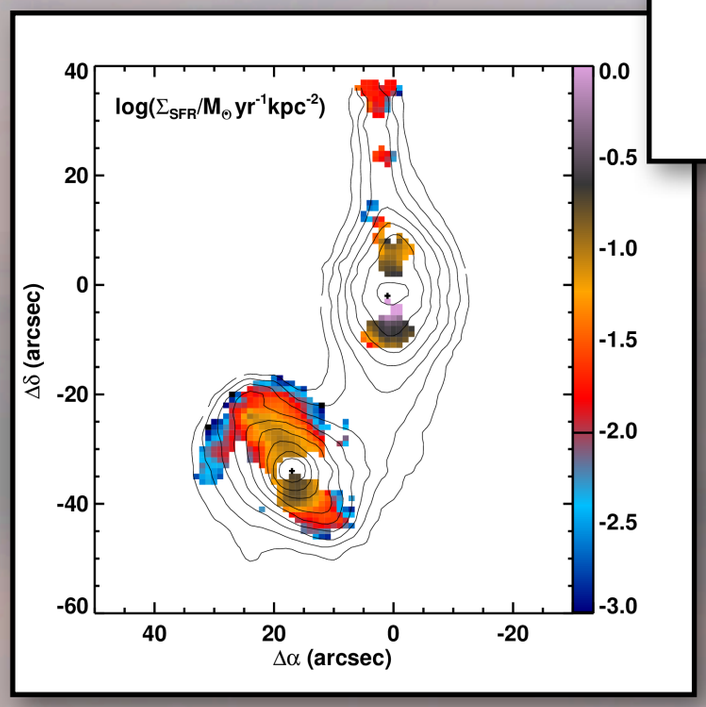

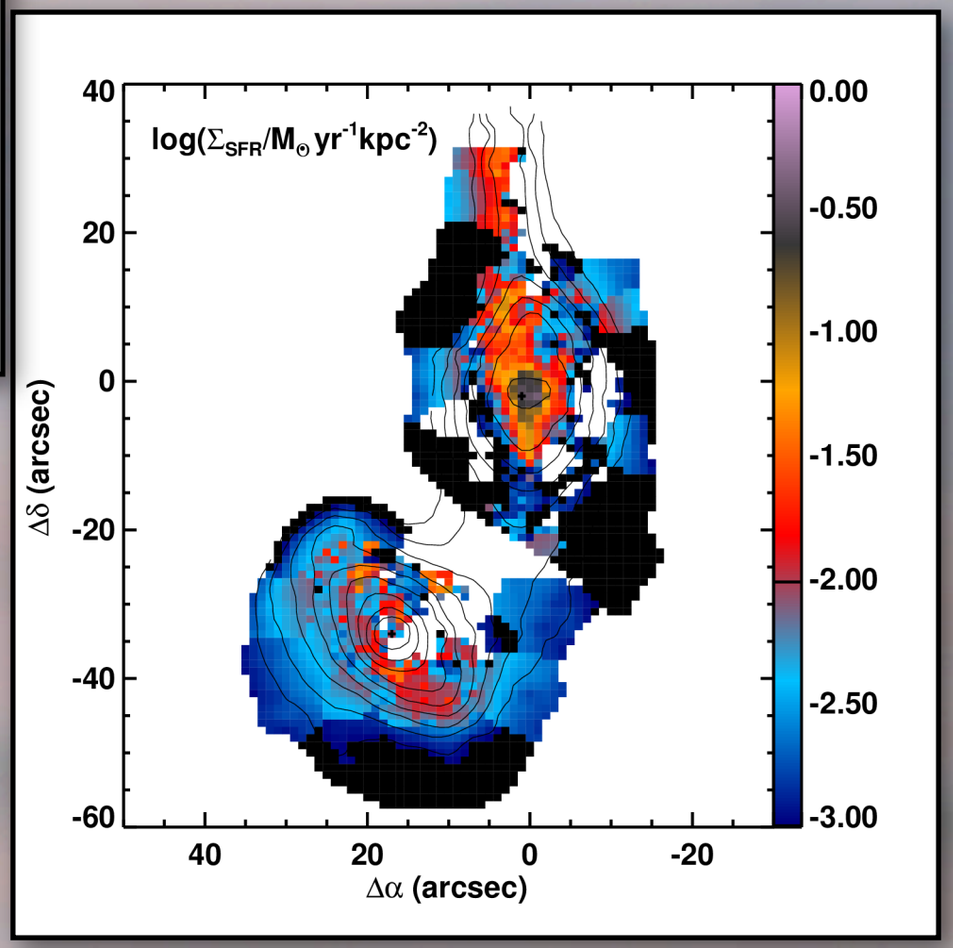

Summary

- ✦ Currently favoured scenario: starbursts/gas-rich mergers do not significantly impact SFR density
  - Most SF occurs in “quiescent” mode
- ✦ But, wet-mergers **are** leading **candidate** for morphological transformation and shut off in SF
  - 40-80% of blue -> red mass flow at 0.5<z<2.0
  - compact, gas-rich merger remnant-like morphologies
- ✦ The rate of wet-mergers leading to massive RS galaxies declines very rapidly at z≲0.7
  - To first order, matches red sequence mass function evn.
    - Fewer very high gas fraction galaxies around to collide?
    - Morphologically defined merger rates not relevant here

Why are (post-)starburst galaxies interesting?

- ✦ Build up of red sequence (Wild et al. 2009):
  - Gas-rich major-merger + starburst could account for 40-80% of growth of red-sequence at z~0.7
- ✦ Post-starburst - AGN connection (Wild et al. 2010):
  - Enhanced AGN activity in all starbursts
  - More enhanced in older starbursts
- ✦ Study ISM changes following starburst:
  - Gradual decline in SF efficiency as gas relaxes
- ✦ Cluster galaxies die slowly (Von den Linden et al. 2010):
  - Slow transition from star forming to quiescent galaxies
  - No evidence for enhanced post-starburst population