Dissecting the Red Sequence:

Star Formation Histories & Structural Evolution of Early Type Galaxies

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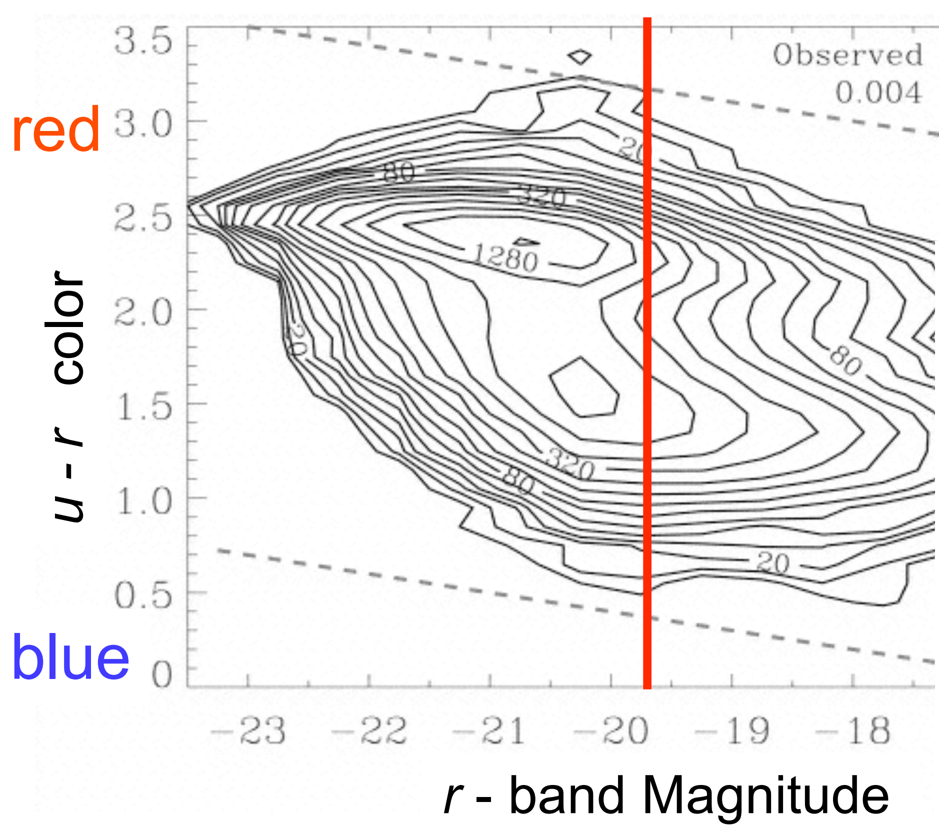
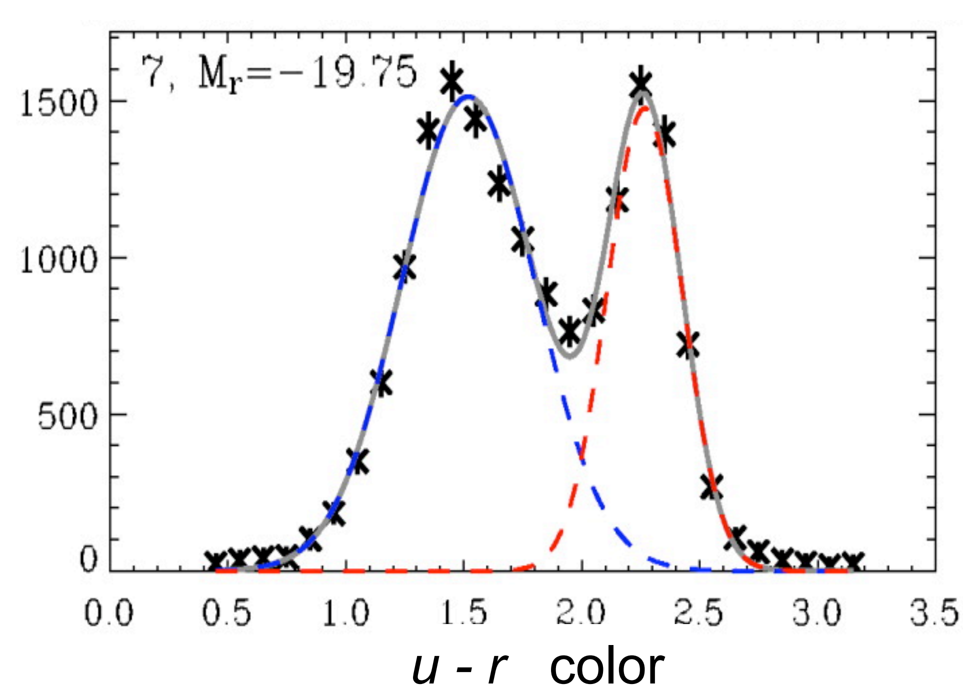
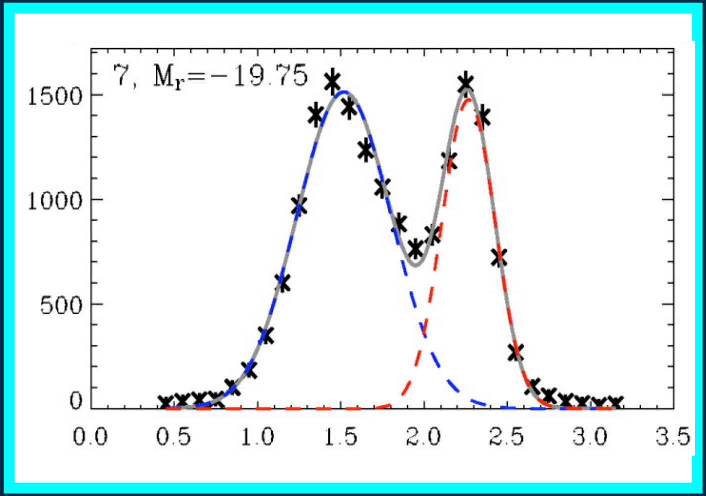
galaxy colors: bimodal

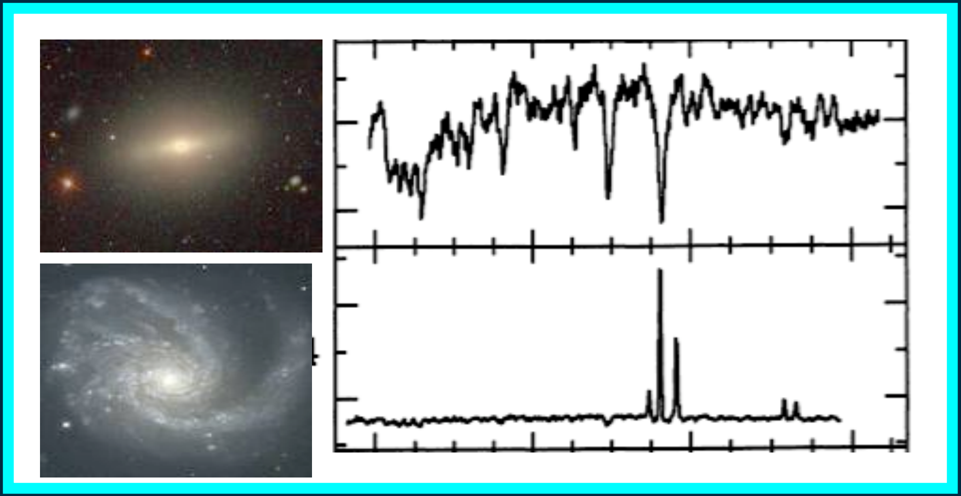


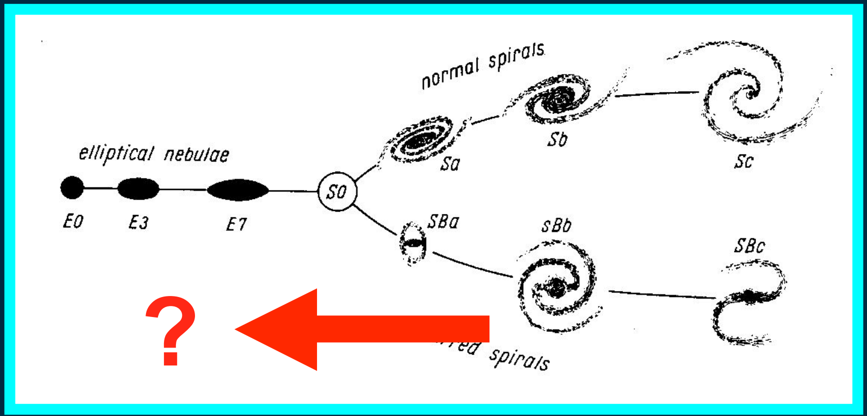


SDSS, Baldry et al. (2004)

galaxy bimodality

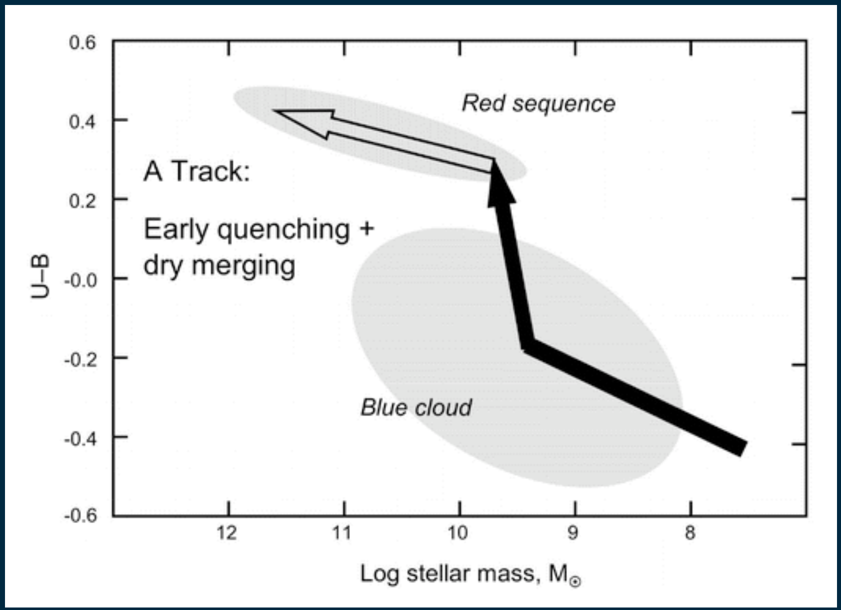




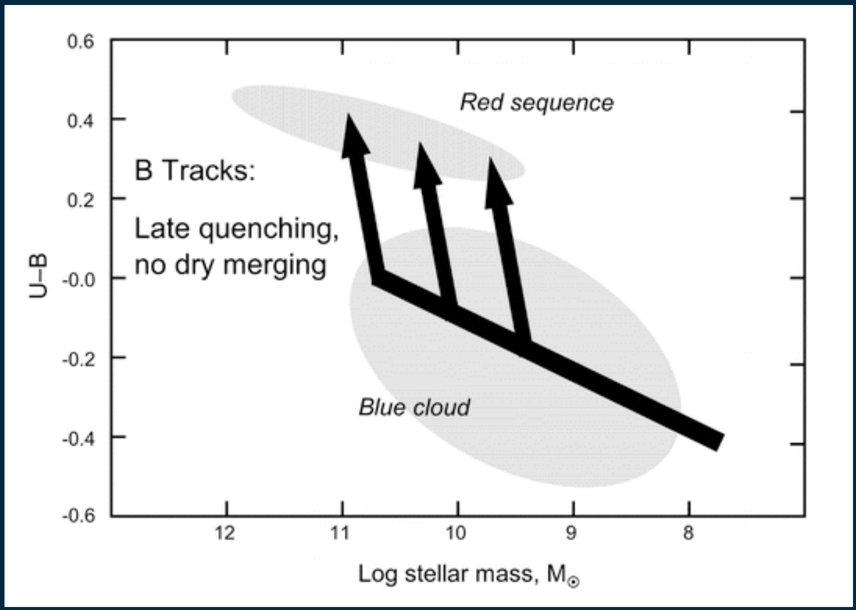


evolution onto the red sequence

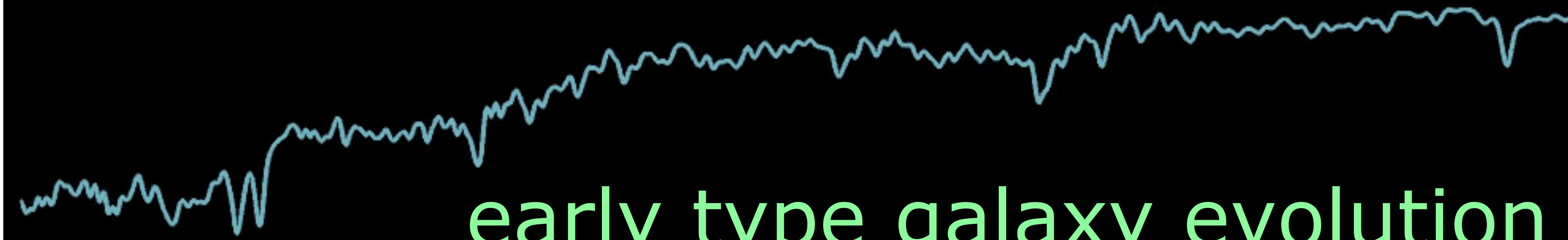
early quenching &
dry merging



late quenching &
no dry merging



Faber et al. 2007



early type galaxy evolution

ΛCDM:

hierarchical formation
(small things form first)

“Downsizing”:

massive galaxies are old, star formation moves to smaller galaxies

mass assembly ↔ star formation history

How are these processes related?

present-day structure ↔ current stellar population

outline

1. Stellar Populations along the Fundamental Plane
   - stellar population modelling: a how-to guide
   - the 2-D family of stellar populations
   - mapping this 2-D family onto a X-section through the FP

2. Mass-to-Light ratios on the Fundamental Plane
   - contributions from different physical processes
   - variations in central dark matter fraction or IMF needed
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3. Scenarios for varying *M/L*
   - Different types of “top-heavy” IMF
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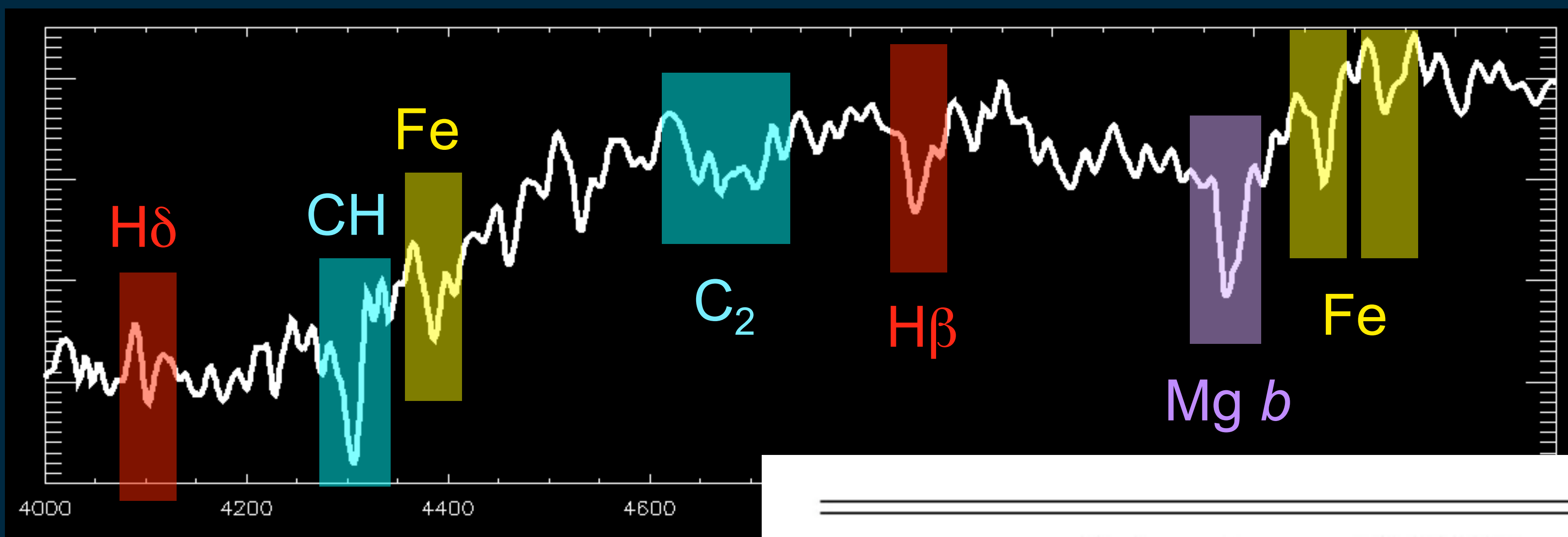
stellar population modelling

Use strong, well-understood absorption lines (low resolution okay)



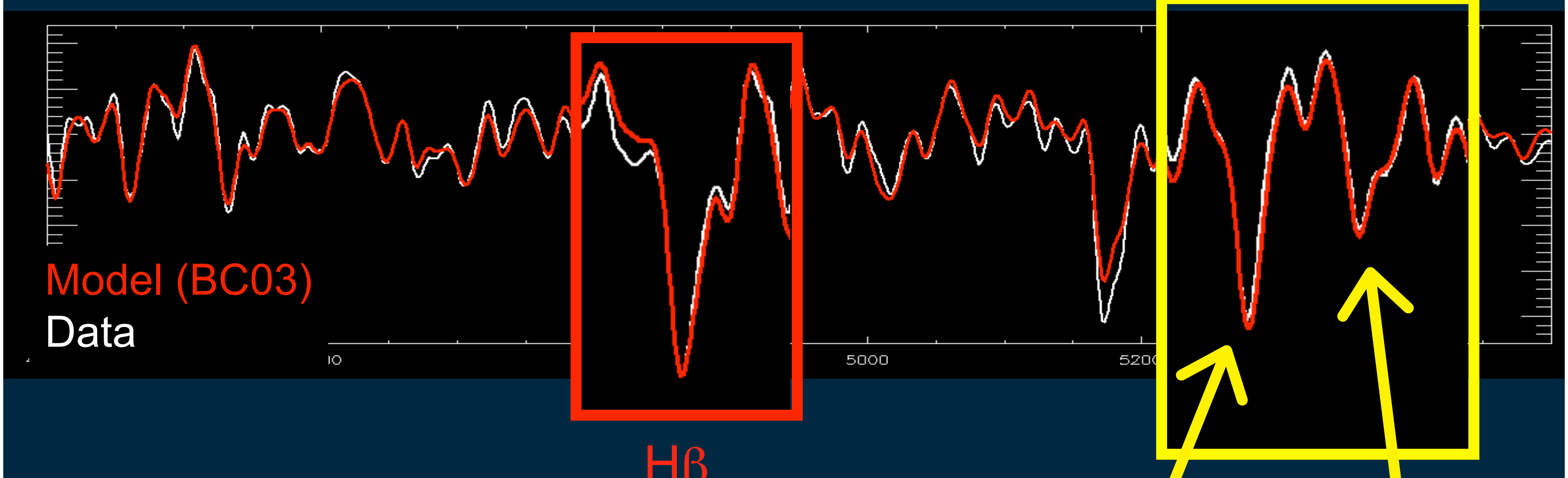
Balmer lines

Fe lines

Other metal lines

	Balmer lines	Metal lines
Age $\Uparrow$	$\Downarrow$	$\Uparrow$
[Fe/H] $\Uparrow$	$\Downarrow$	$\Uparrow$

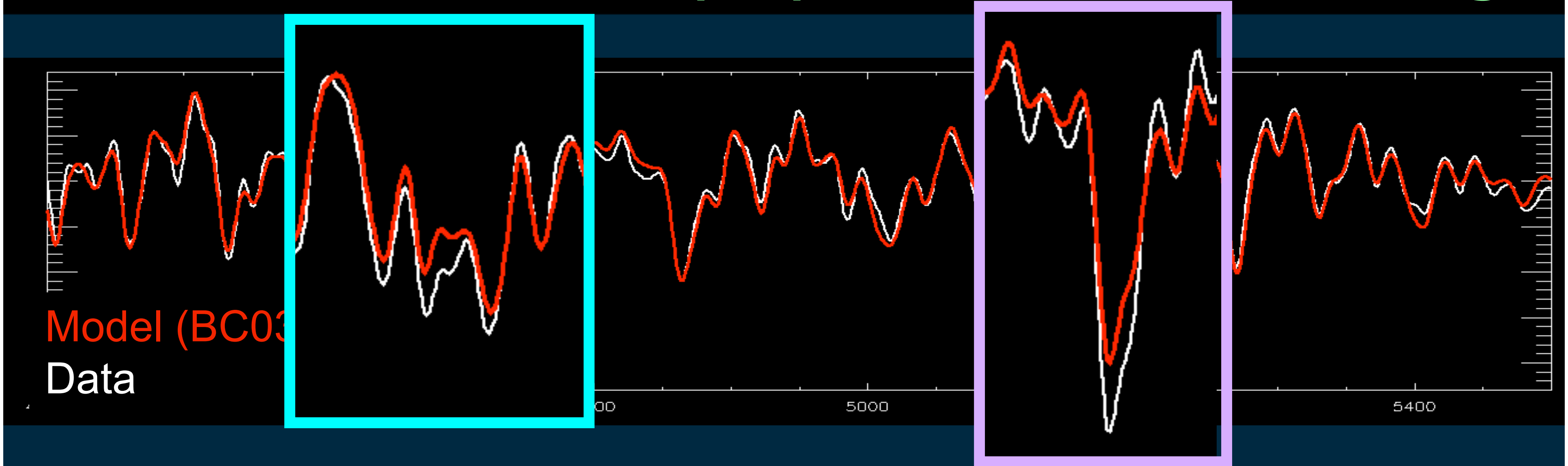
stellar population modelling



Determine mean luminosity-weighted Age, [Fe/H]
from Hβ and (Fe5270+Fe5335)

$\Rightarrow$ start with Solar-abundance model

stellar population modelling



$C_2$4668

Mg *b*

Solar-abundance model is not a good fit to the data - too weak in C and Mg indices

- keep Age and [Fe/H] fixed
- increase [C/Fe] to match $C_2$4668
- increase [Mg/Fe] to match Mg *b*
- iterate fit to get self-consistent solution

stellar pop modelling: results

Index measurements: → stellar pop parameters:

Hβ, <Fe>, Mg *b* → Age, [Fe/H], [Mg/Fe]

Age = “mean luminosity-weighted” age

Mg = SN II product (short timescale for production)

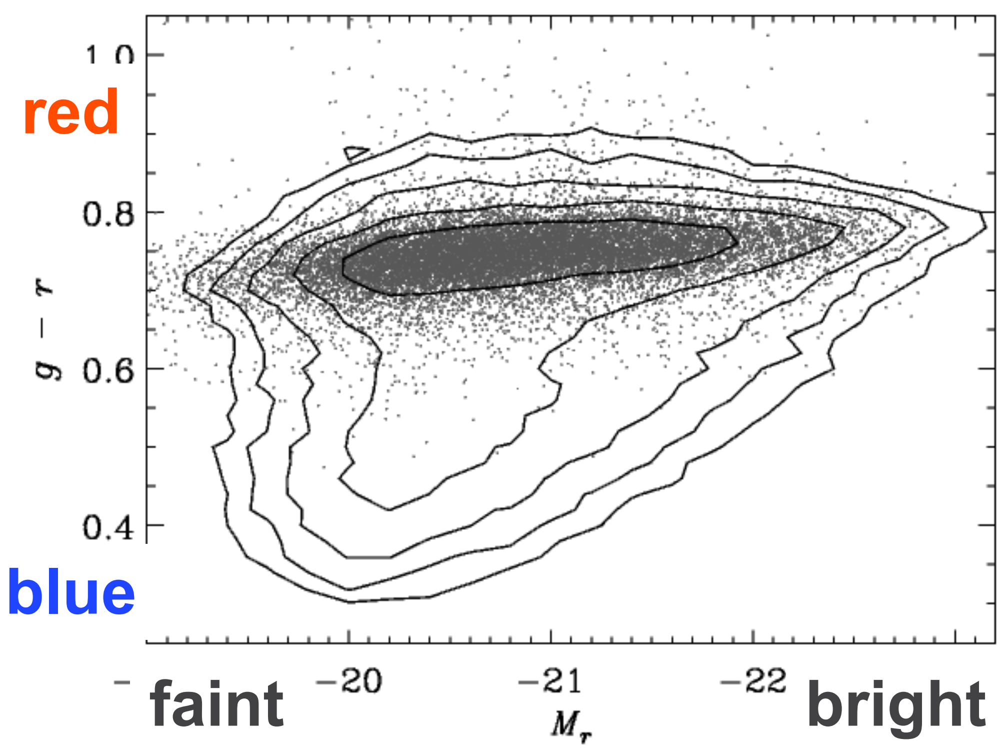
Fe = SN Ia product (longer timescale for production)

$\Longrightarrow$ only metals released in SNe *before or during active star formation* contribute to observed stellar abundances

[Mg/Fe] is related to star formation timescale (or IMF)

ETG stellar populations

Our sample: ~16,000 SDSS early type galaxy spectra



* $0.04 < z < 0.08$

* no emission
  ($< 2\sigma$ in Hα and [OII])

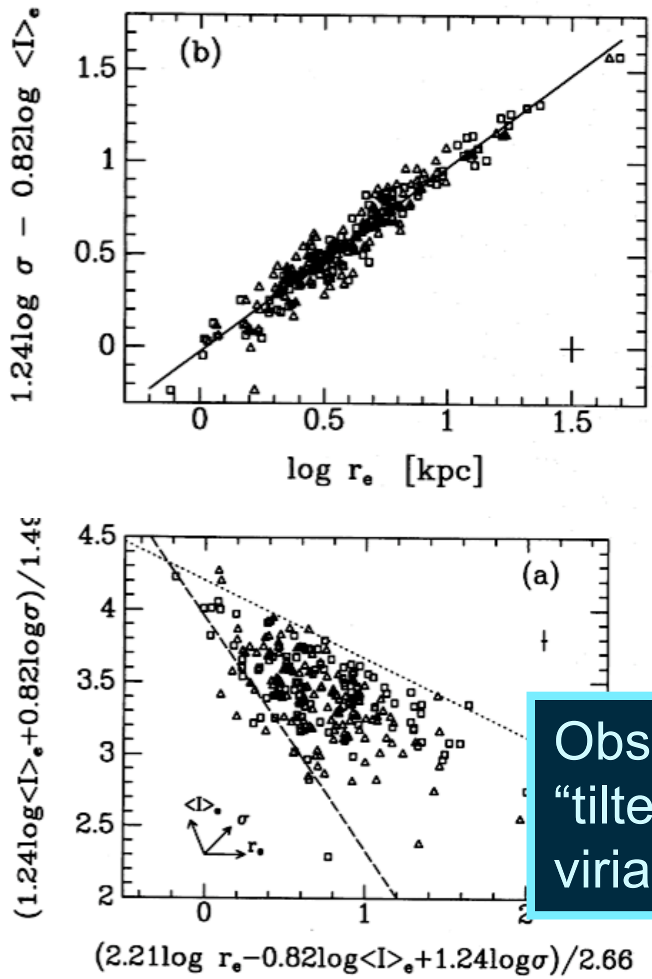
* concentrated light profile
  ($R_{90} / R_{50} > 2.5$)

* no color selection

spectra: $S / N \sim 20$ Å^{-1}

ETG structure: the fundamental plane

Jorgensen et al. (1996)



Observed FP is "tilted" from the virial plane

$$R_e \propto \sigma^{1.24} \; I_e^{\,-0.82}$$

Definition:

$$I_e \propto L / \pi R_e^2$$

$$L \propto R_e^2 \, I_e$$

Virial Th^{m}:

$$GM / R_e \propto \sigma^2$$

$$M_{dyn} \propto \sigma^2 R_e$$

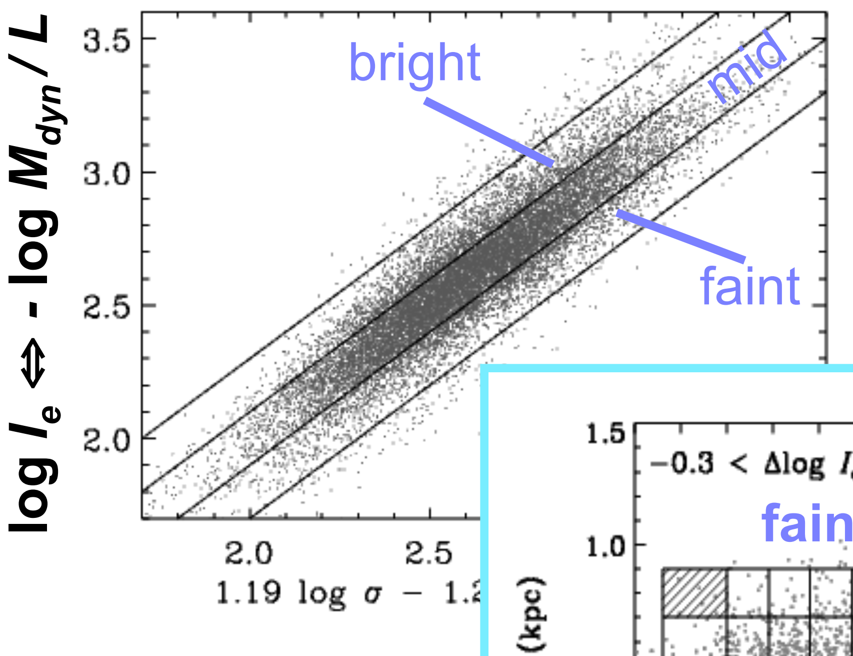
If M / L = const.:

$$L \propto M_{dyn}$$

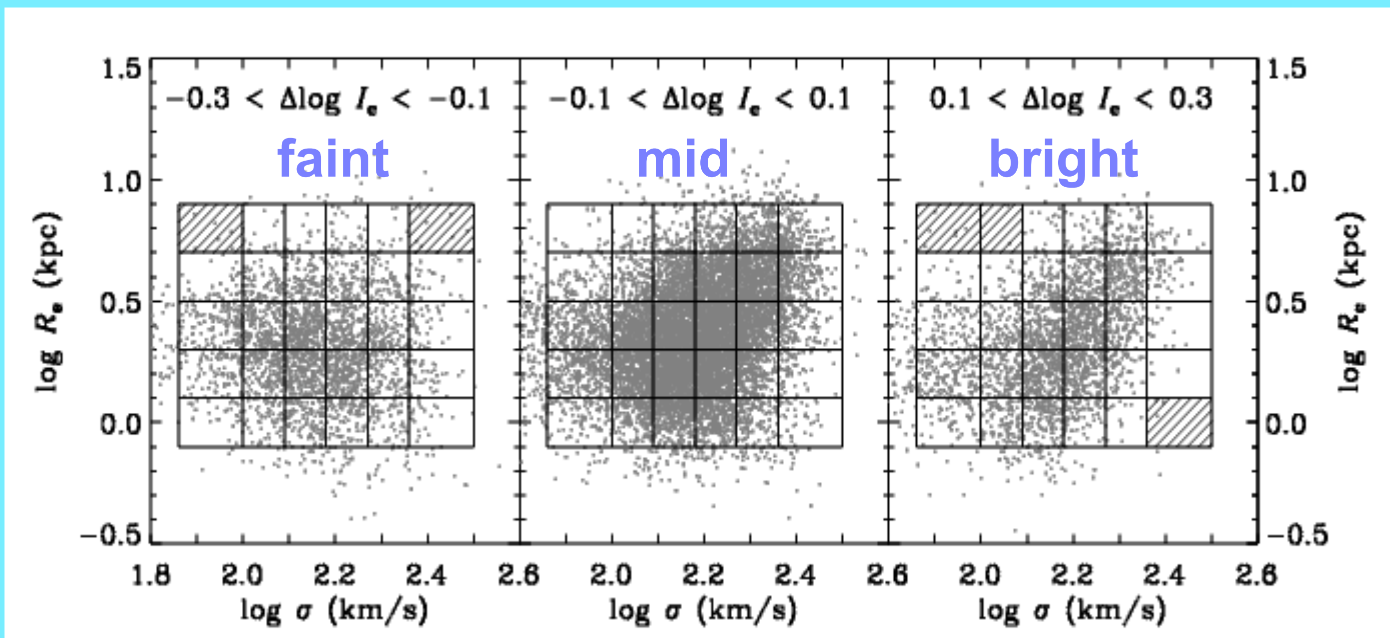
$$R_e^2 \, I_e \propto \sigma^2 R_e$$

$$R_e \propto \sigma^2 \, I_e^{-1}$$

binning galaxies in the fp

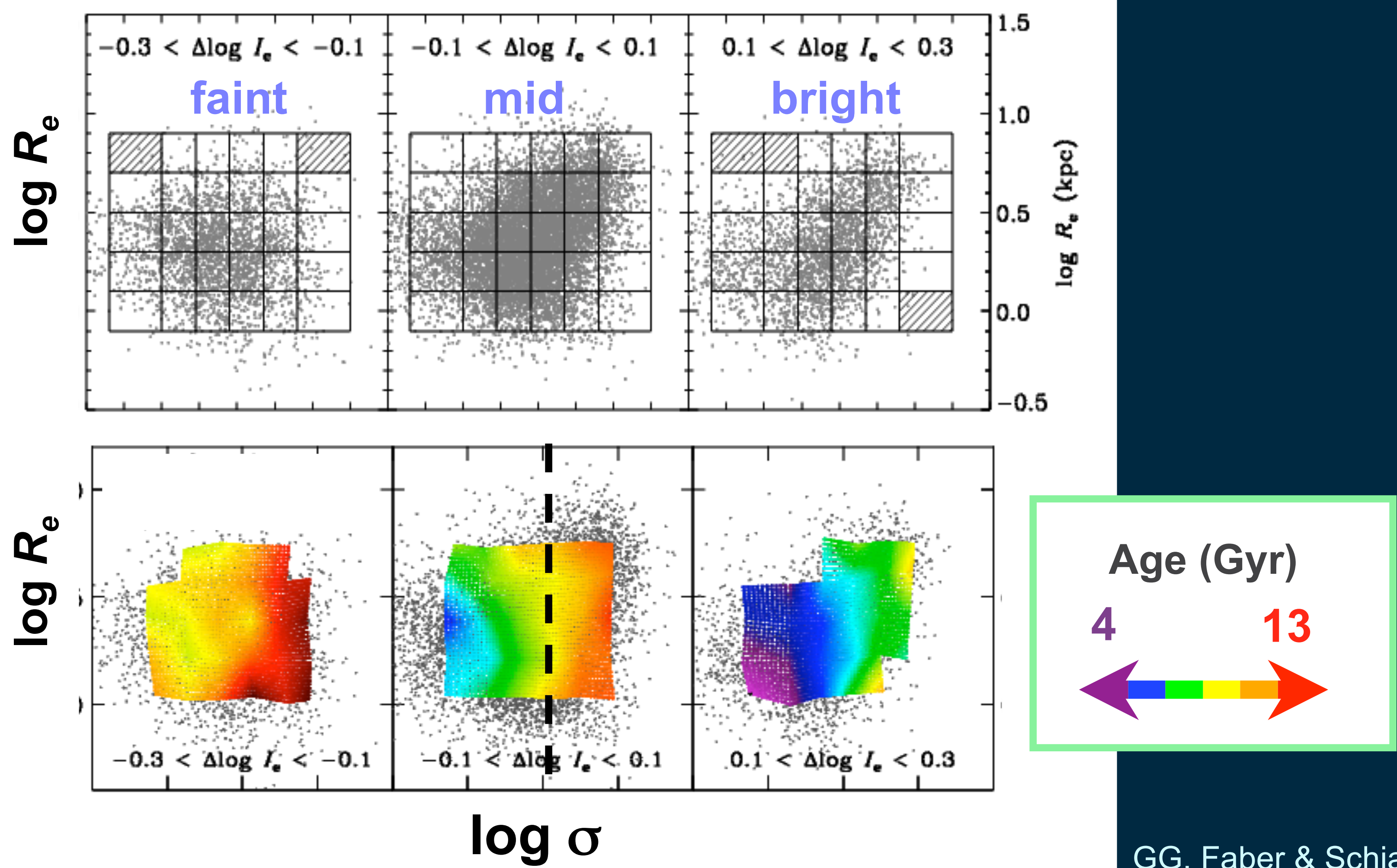


$$\frac{M_{dyn}}{L} \propto \frac{\sigma^2 R_e}{I_e R_e^2} \propto \frac{\sigma^2}{I_e R_e}$$



GG, Faber, & Schiavon (2008a, submitted to ApJ)

stellar populations across the fp



GG, Faber & Schiavon (2008a)

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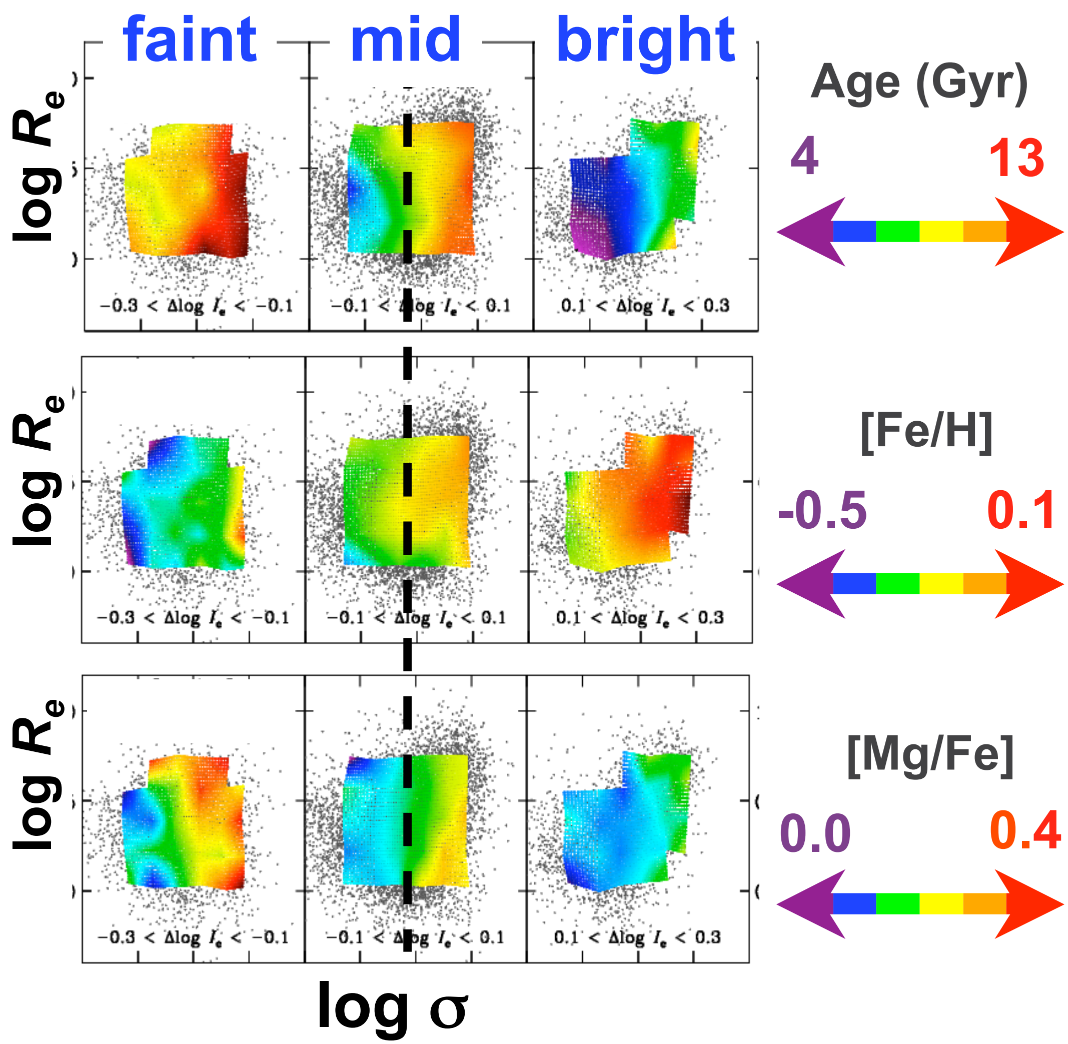


Hβ, <Fe>, Mg *b*

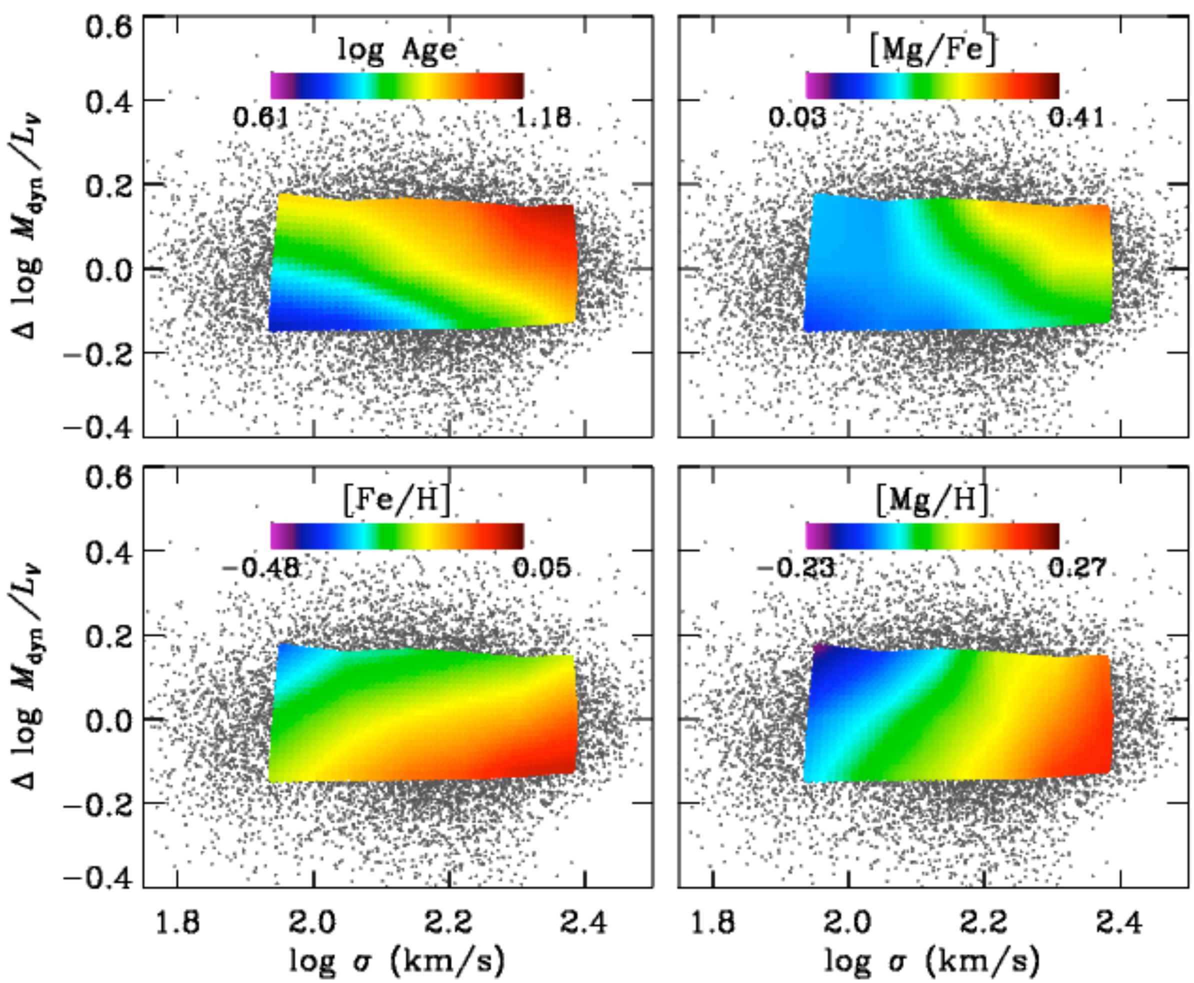
↓

Age, [Fe/H], [Mg/Fe]

stellar populations are independent of R_e

GG, Faber & Schiavon (2008a)

stellar populations across the fp



@ fixed σ, galaxies with lower M_{dyn}/L have:

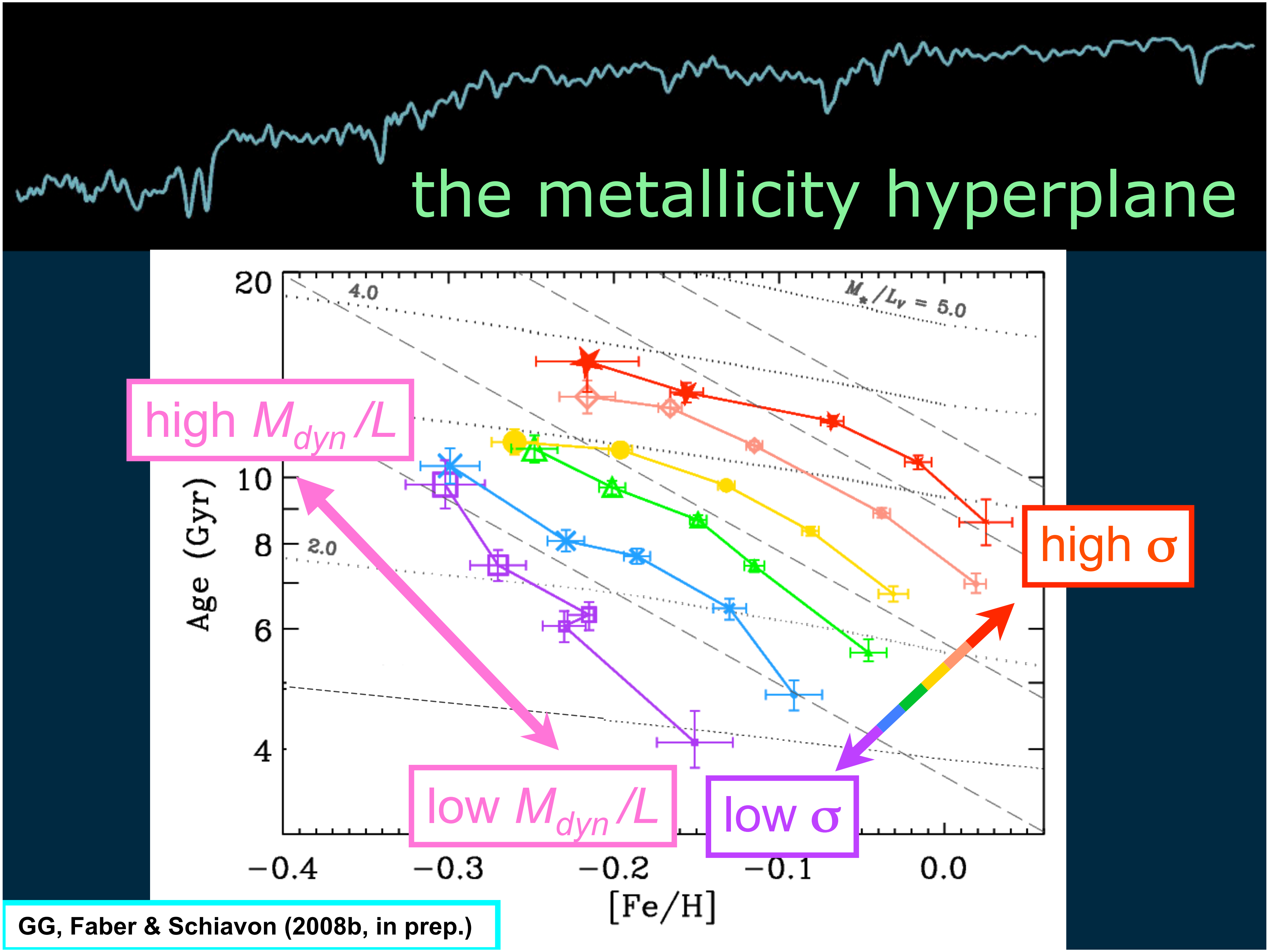
- younger ages
- higher [Fe/H]
- lower [Mg/Fe]

↓

longer duration star formation

GG, Faber & Schiavon (2008a)

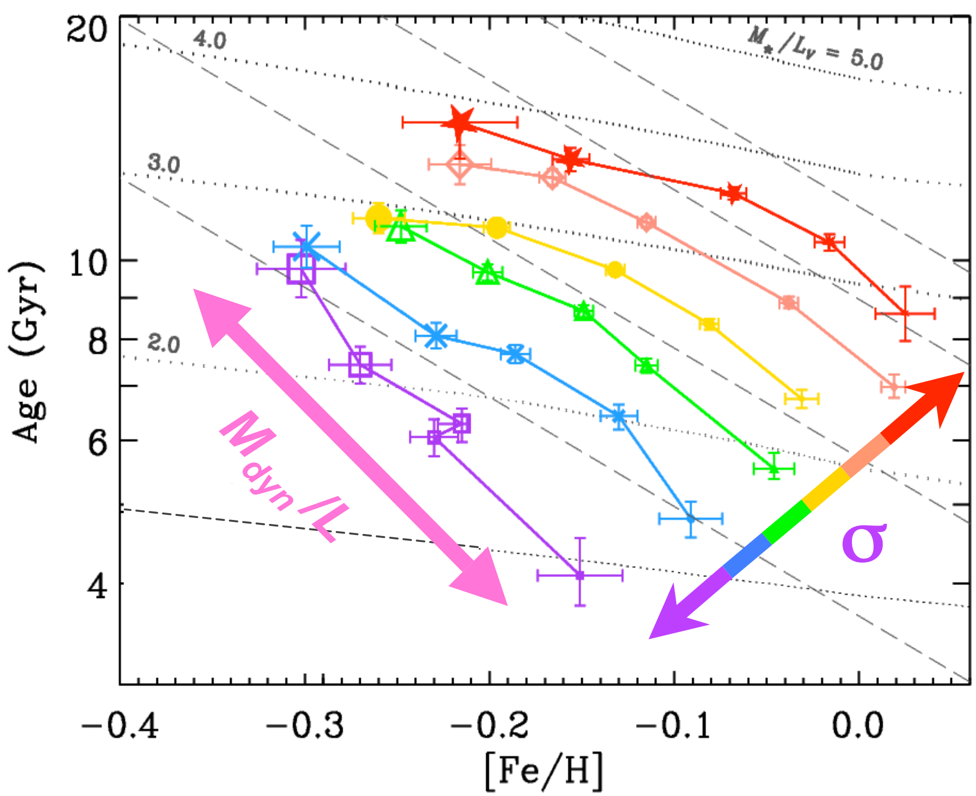
the metallicity hyperplane

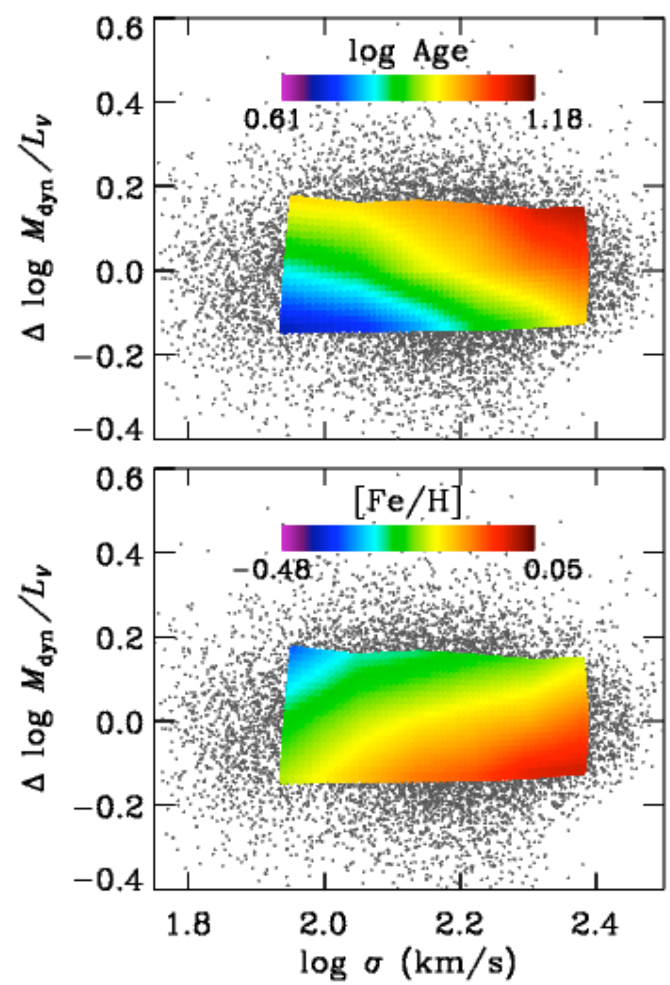


GG, Faber & Schiavon (2008b, in prep.)

MHP maps onto FP X-section

(Age, [Fe/H]) ⟷ (σ, $\Delta M_{dyn}/L$)





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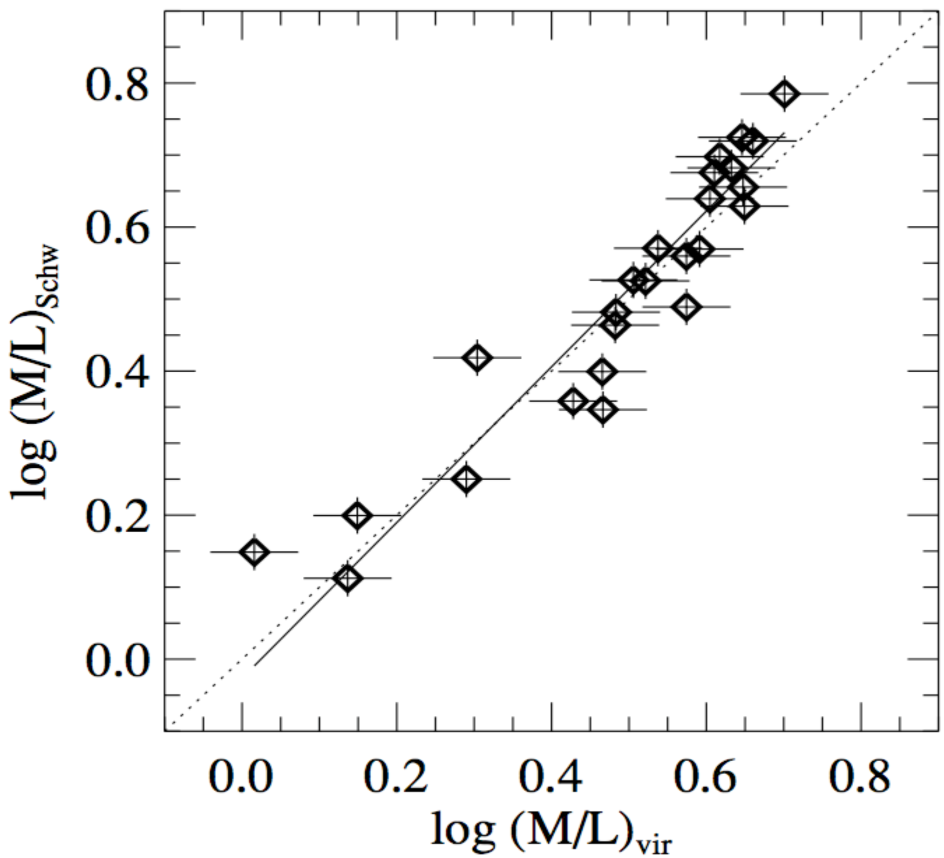
variations in M_{dyn}/L within R_e

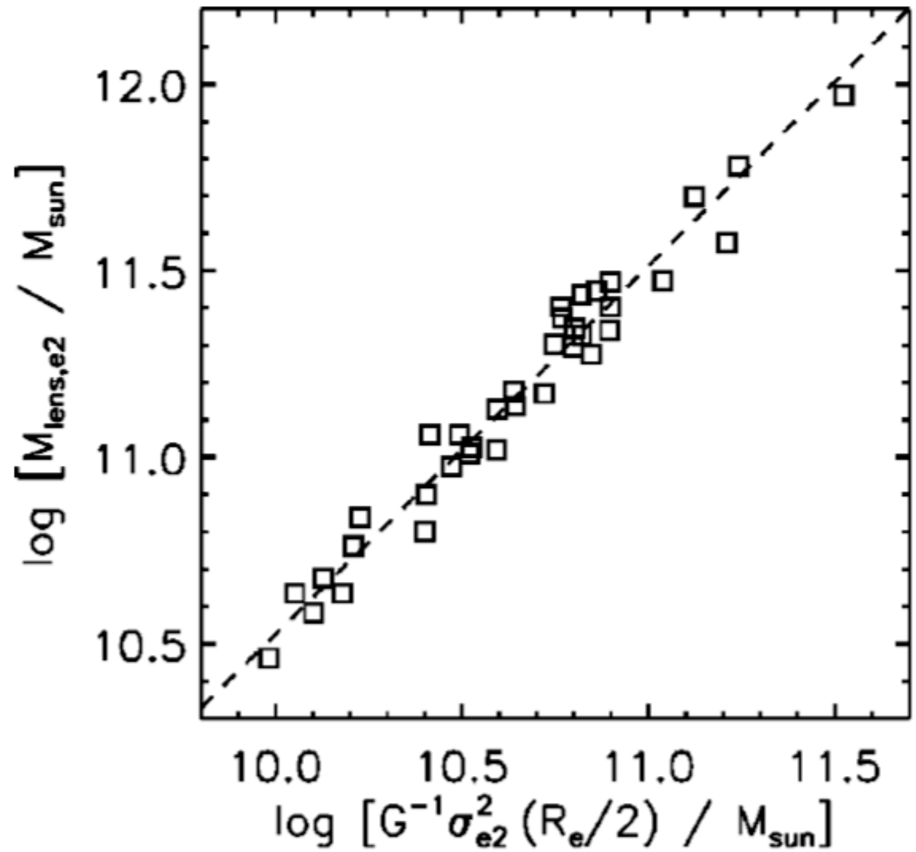
$$\frac{M_{dyn}}{L} = \underbrace{\frac{M_{dyn}}{M_{tot}}}_{\text{dynamical mass estimator}} \times \underbrace{\frac{M_{tot}}{M_{\star,\mathrm{real}}}}_{\text{DM fraction}} \times \underbrace{\frac{M_{\star,\mathrm{real}}}{M_{\star,\mathrm{IMF}}}}_{\text{IMF}} \times \underbrace{\frac{M_{\star,\mathrm{IMF}}}{L}}_{\text{stellar population (age, } Z\text{)}}$$

dynamical mass estimator

Cappellari et al. (2006) - IFU data, dynamical models



Bolton et al. (2007) - strong lensing

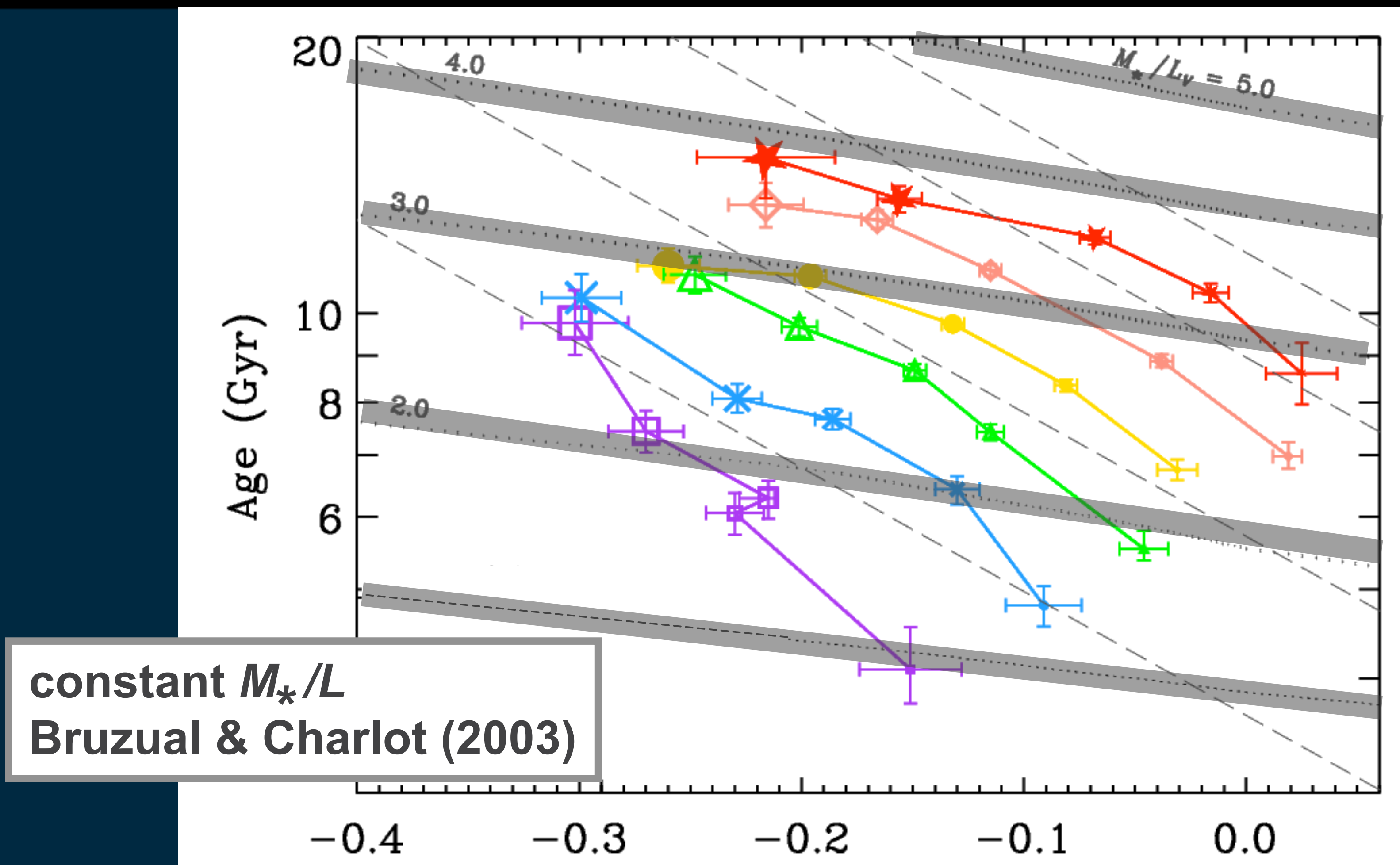


variations in M_{dyn}/L within R_e

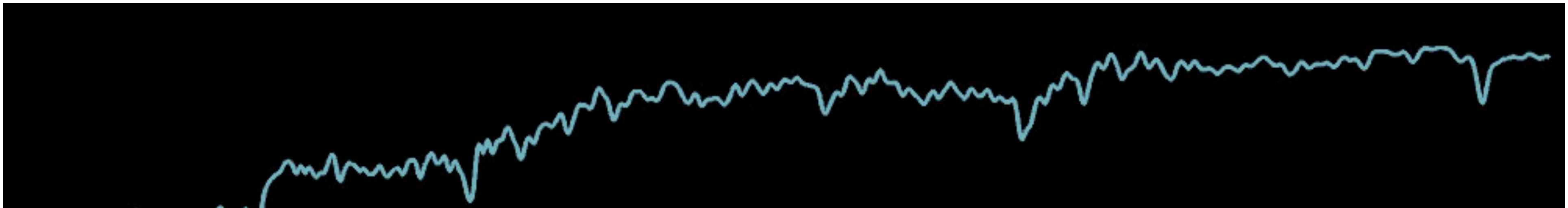
SLACS, SAURON

$$\frac{M_{dyn}}{L} = \underbrace{\cancel{\frac{M_{dyn}}{M_{tot}}}}_{\cancel{\text{dynamical mass estimator}}} \times \underbrace{\frac{M_{tot}}{M_{\star,\mathrm{real}}}}_{\text{DM fraction}} \times \underbrace{\frac{M_{\star,\mathrm{real}}}{M_{\star,\mathrm{IMF}}}}_{\text{IMF}} \times \underbrace{\frac{M_{\star,\mathrm{IMF}}}{L}}_{\text{stellar population (age, } Z\text{)}}$$

the metallicity hyperplane

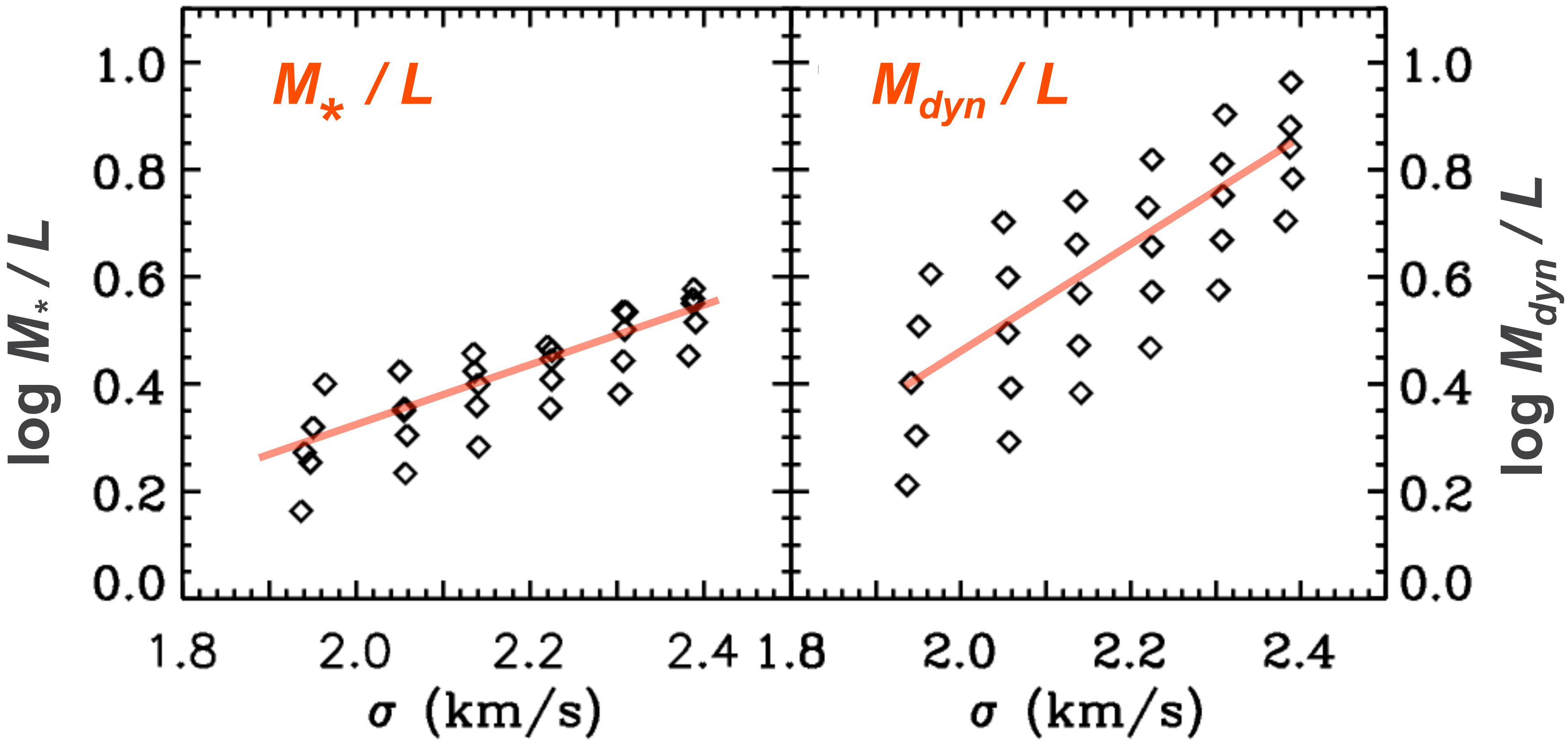


GG, Faber & Schiavon (2008b)



$M_\star/L$ vs. M_{dyn}/L

GG, Faber, & Schiavon (2008b)



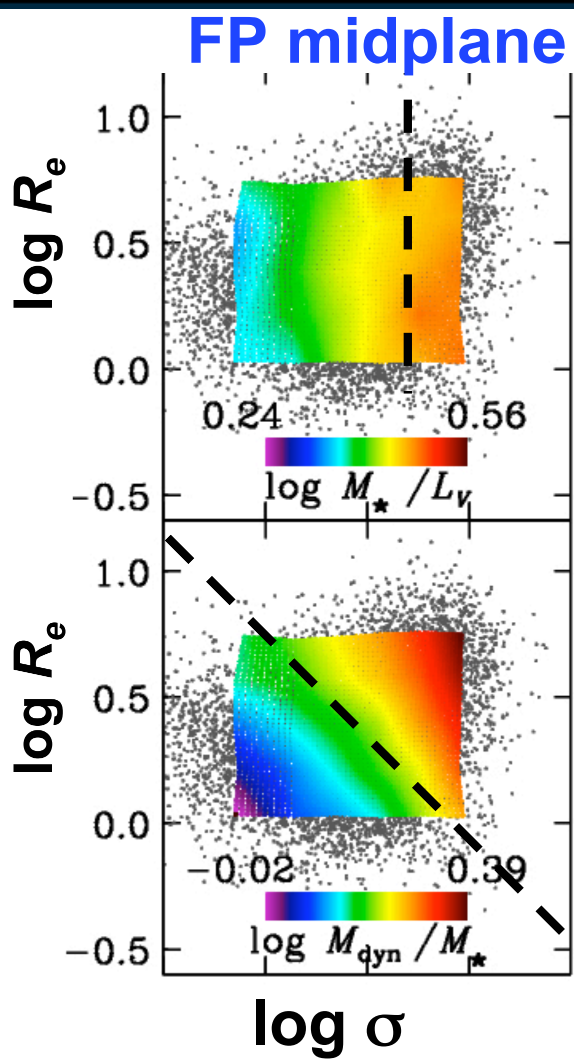
variations in M_{dyn}/L within R_e

SLACS, SAURON

not enough

$$\frac{M_{dyn}}{L} = \underbrace{\cancel{\frac{M_{dyn}}{M_{tot}}}}_{\text{dynamical mass estimator}} \times \underbrace{\frac{M_{tot}}{M_{\star,\mathrm{real}}}}_{\text{DM fraction}} \times \underbrace{\frac{M_{\star,\mathrm{real}}}{M_{\star,\mathrm{IMF}}}}_{\text{IMF}} \times \underbrace{\frac{M_{\star,\mathrm{IMF}}}{L}}_{\text{stellar population (age, } Z\text{)}}$$

two tilts of the FP

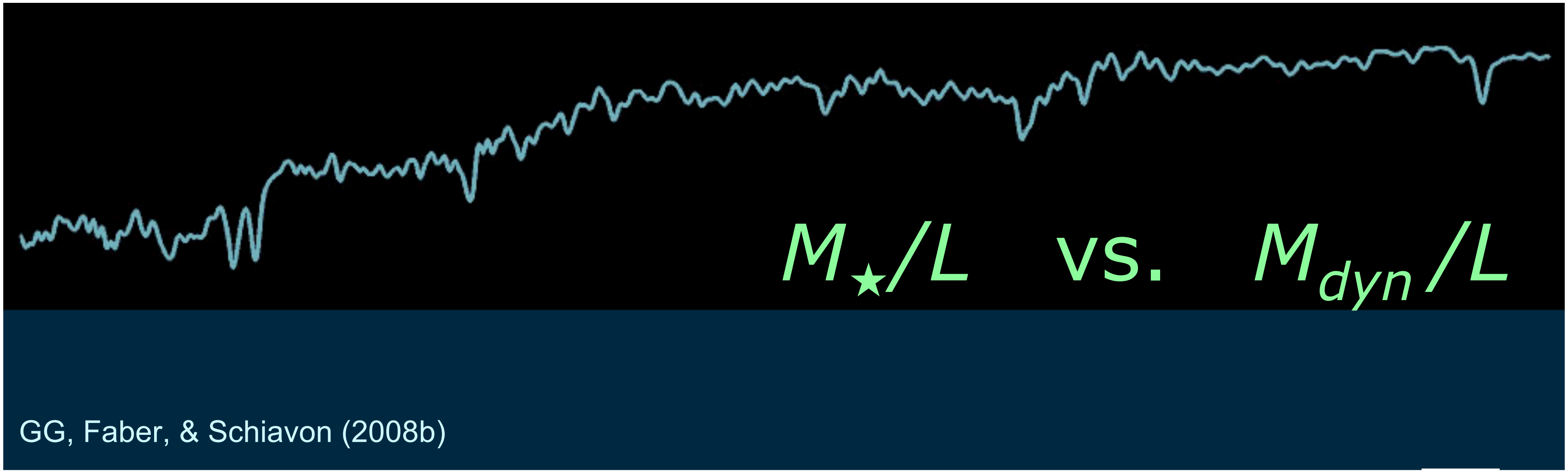


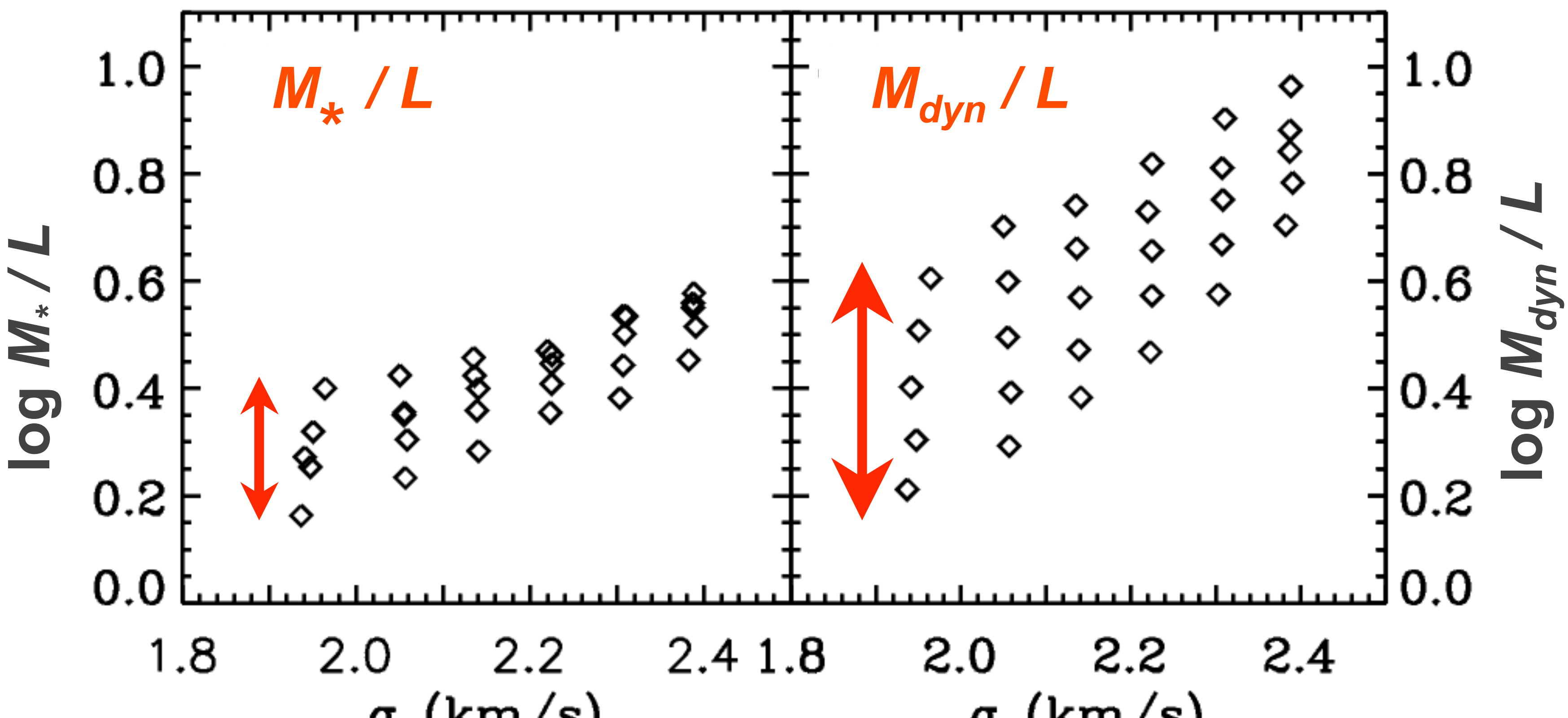
Stellar Population: $M_\star/L \propto \sigma$
$M_\star/L$

residual tilt: $M_{dyn} / M_\star$

Dark Matter, IMF: $M_{dyn} / M_\star \propto \sigma^2 R_e$
$\propto M_{dyn}$

GG & Faber (2008, in prep)


M★/L vs. Mdyn/L
GG, Faber, & Schiavon (2008b)


M* / L
Mdyn / L
log M* / L
log Mdyn / L
1.0
0.8
0.6
0.4
0.2
0.0
1.8
2.0
2.2
2.4
σ (km/s)

observational conclusions

- We have mapped stellar population properties in 3-D FP space
- ETG star formation histories = 2-D parameter space
  (variations with σ and with $\Delta M_{dyn}/L$)
- 2-D family of star formation histories = X-section of FP
- Stellar population effects cannot account for observed tilt of the FP, or the observed thickness of the FP

  → variations in the IMF or central DM fraction required
- The two tilts of the FP:
  Stellar population effects ($M_\star/L$) and variable IMF or DM fraction ($M_{dyn}/M_\star$) tilts rotate the FP around different axes

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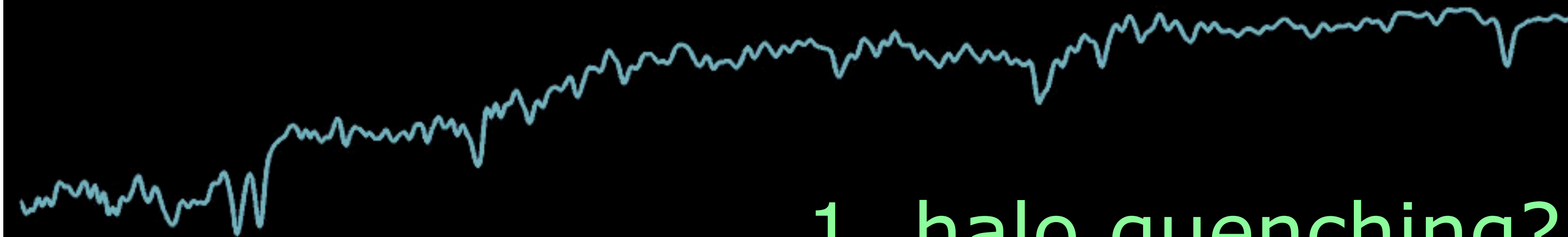
variations in M_{dyn}/L

$\Longrightarrow$ M_{dyn}/L is measured within R_e

1. variations in DM fraction: genuine lack of stellar mass for given halo mass (low star formation efficiency)
   - early truncation of star formation through quenching? (by AGN or massive halo)

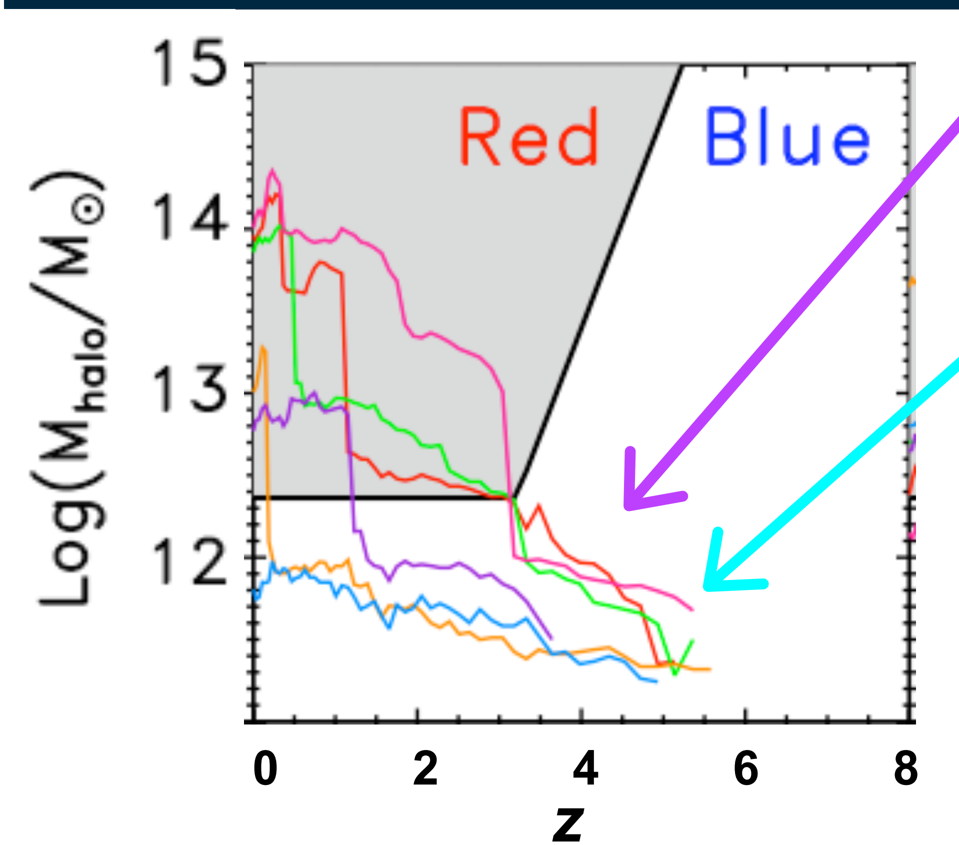
2. variations in DM fraction: redistribution of stellar and dark matter inside/outside R_e
   - gas-rich vs. dry mergers?

3. variations in the IMF:
   - more low-mass stars or more compact remnants



1. halo quenching?

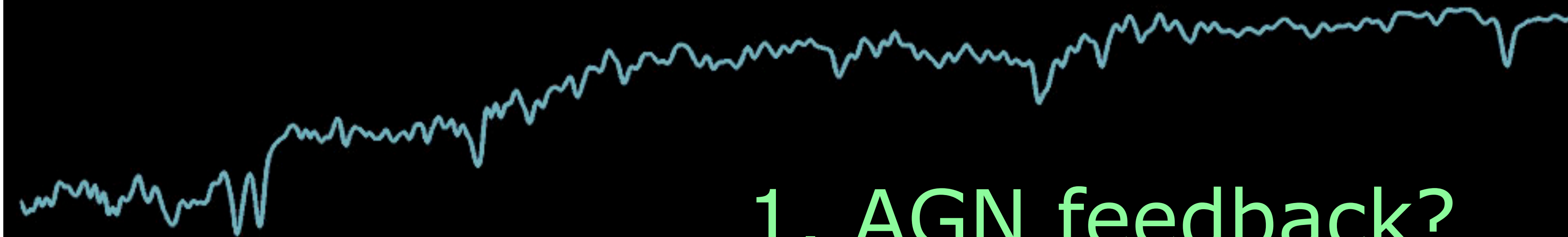
Cattaneo et al. (2008)



early quenching:
low I_e, high M_{dyn}/L

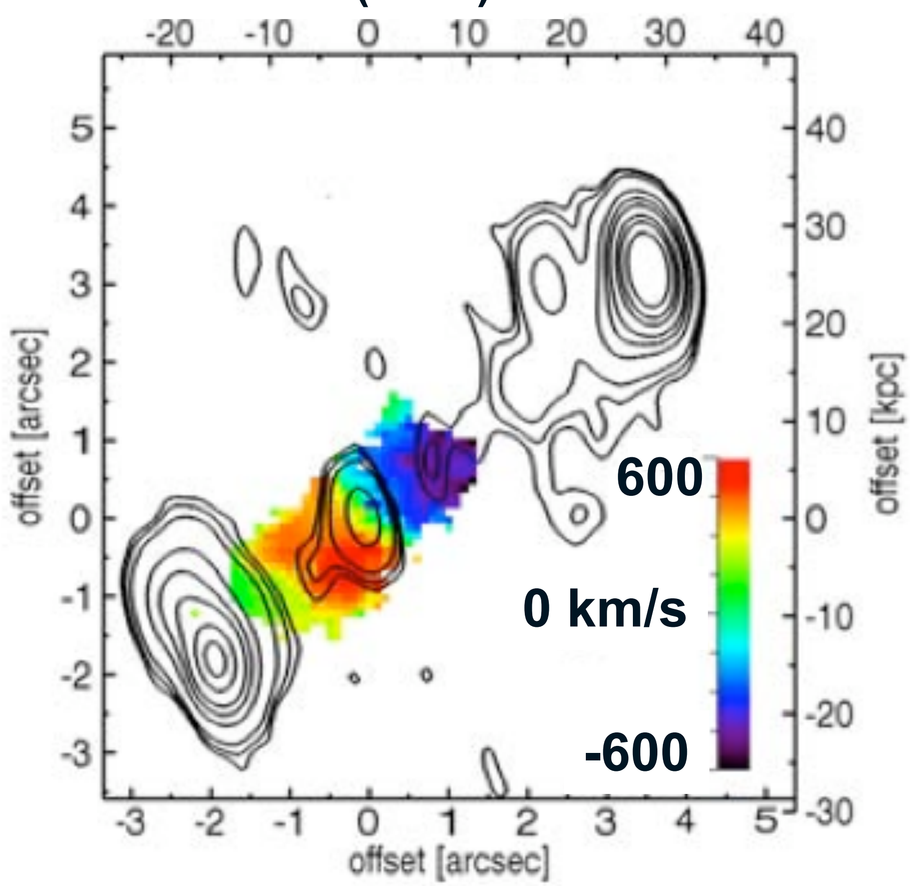
late quenching:
high I_e, low M_{dyn}/L

naturally produces correlation between M_{dyn}/L , short duration star formation @ fixed σ



1. AGN feedback?

Nesvadba et al. (2008)



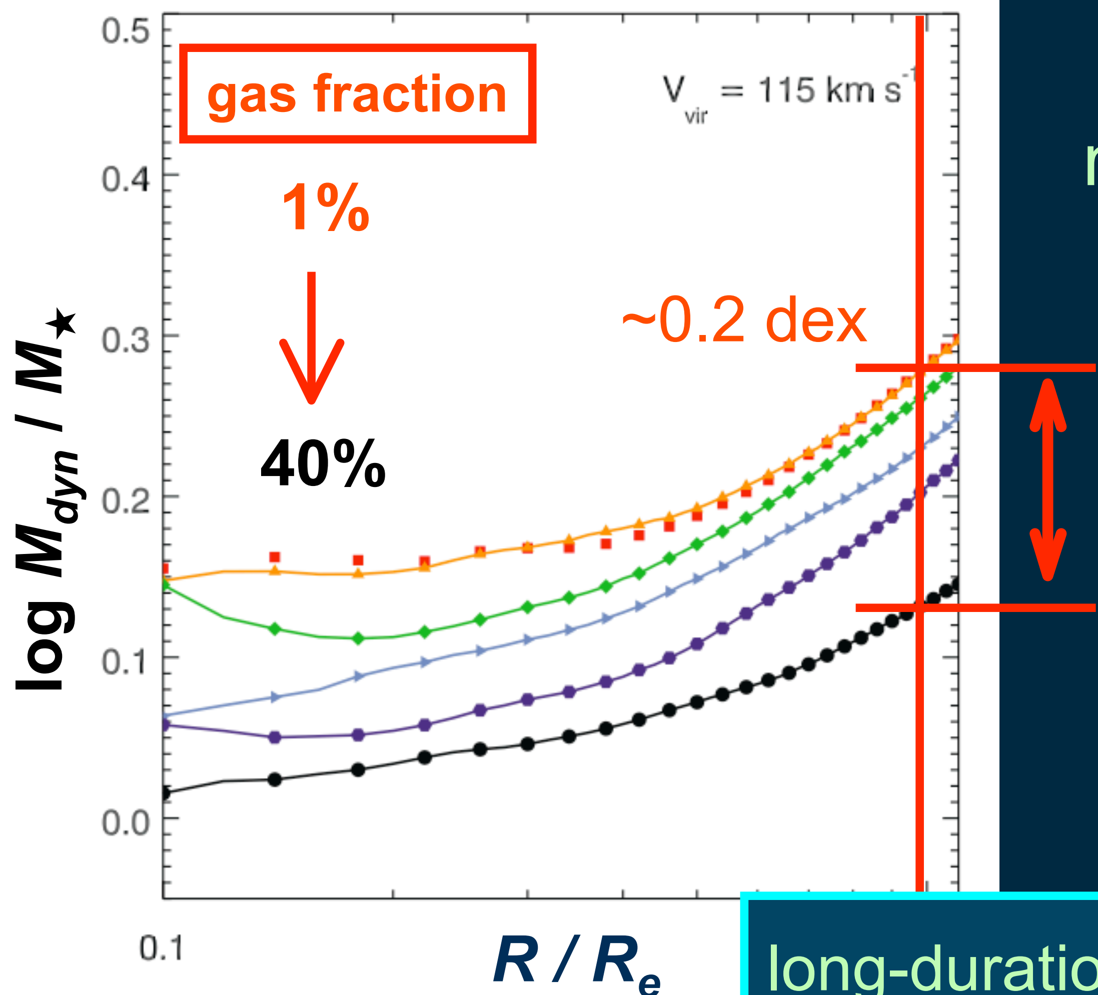
Galaxy w/ Powerful Radio Jets @ z=2.4

[OIII]λ5007 emission:

* aligned w/ radio lobes
* large outflow velocities
* outflow mass-loading and lifetime can carry out ~ few x 10^{10} $M_{\odot}$

→ SF truncated in high M_{dyn}/L objects

2. redistribution of stars?



Robertson et al. (2006)

gas fraction of major-merger changes M_{dyn} / $M_\star$

f_{gas} varies w/ mass

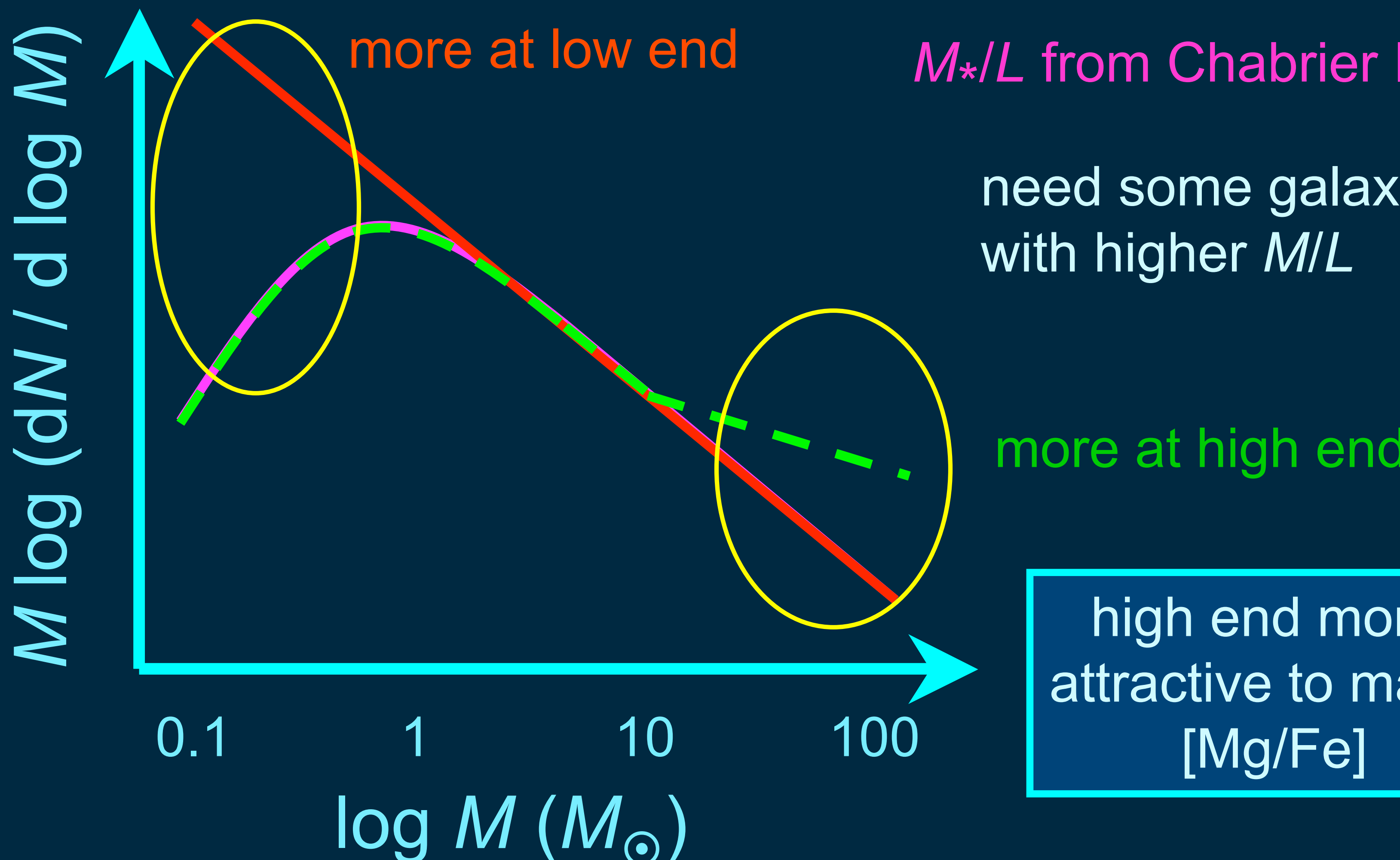
$\Longrightarrow$ contributes to FP tilt

could also have f_{gas} variations @ fixed σ

$\Longrightarrow$ FP thickness

long-duration SF $\Leftrightarrow$ gas-rich mergers

3. variations in the IMF?



M_*/L from Chabrier IMF

need some galaxies with higher M/L

high end more attractive to match [Mg/Fe]

future work

- the role of environment:
  - both merger and massive halo explanations imply environment plays a role
  - relations for central galaxies vs. satellites
- a role for morphology?:
  - dynamical mass estimator only tested *along* FP
- chemical evolution models
  - quantitative modelling of the variation in star formation duration
  - include C, N, Ca abundances