Introduction to SSP modelling

We will discuss the basics of:

- ★ Different methods of modelling the universe
- ★ Building SSPs
- ★ Modelling spectral properties of galaxies
- ★ Associated uncertainties
- ★ Understanding star-formation

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With contributions from Prof. Jarle Brichmann, University of Porto, Portugal.

Why it is necessary to model

- Observations only have a single time snapshot and limited physical information
- Can use analytical models but has very large simplifications since the real Universe is very complicated

Hydrodanimical simulations

- Some only simulate dark matter and gravity
  - Advantages:
    - Relatively simple
    - Physics “understood”
    - Large volumes possible
  - Disadvantages
    - No galaxies
    - Ignore effect of baryon physics on dark matter
- Some may include full physics but volumes are smaller, cannot resolve individual star-forming regions

Semi-analytic models

- Galaxies included to dark matter simulation by hand
- Use analytical functions to explore the evolution
- Such simulations are fast to run and easy to explore model variations but are several simplified and doesn’t consider baryon-dark matter interactions and the IGM

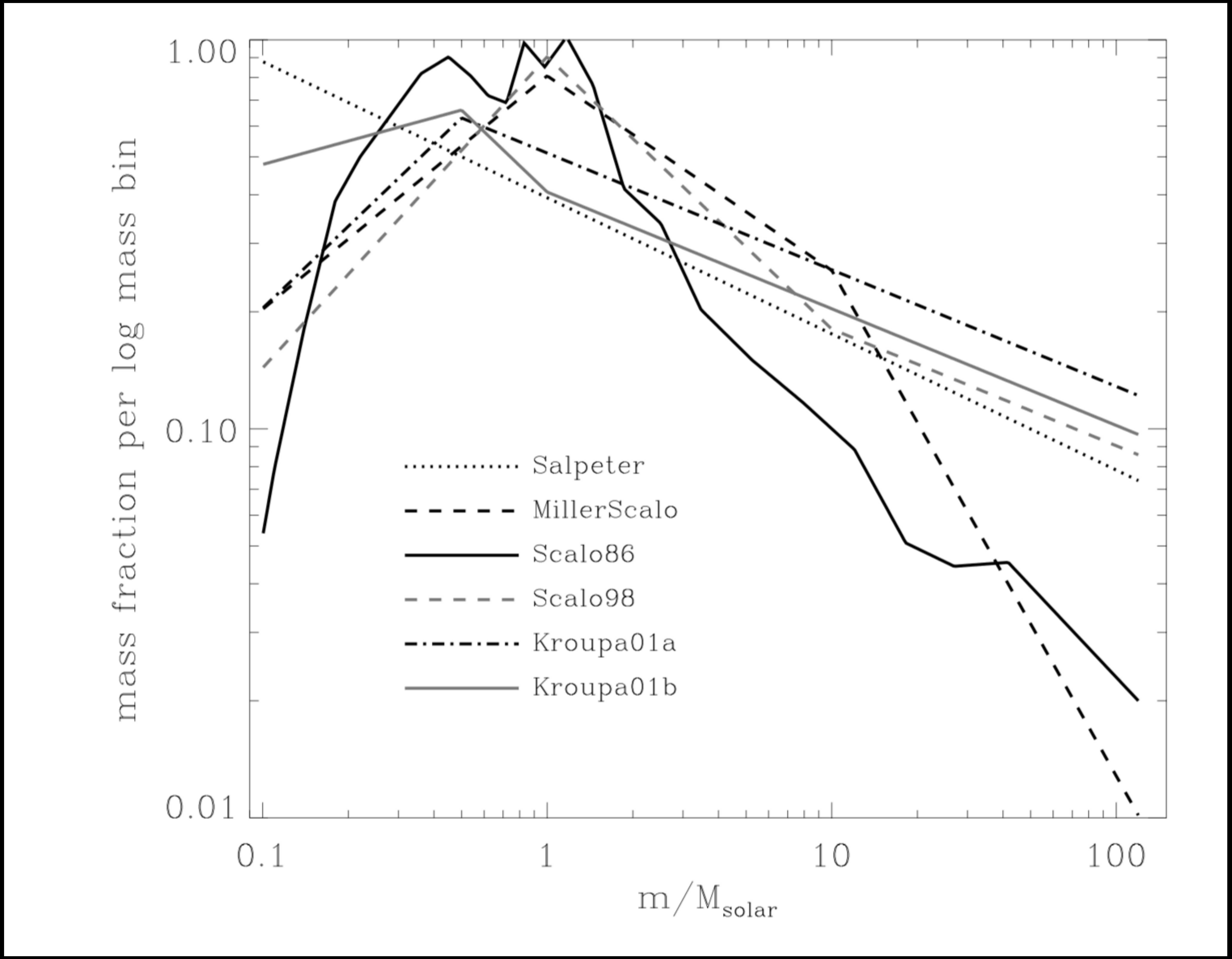
SSPs

Building a SSP

- SSPs require three basic ingredients:
  1. Isochrones
  2. Stellar libraries
  3. IMF

$$f_{\mathrm{SSP}}(t, Z) = \int_{m_{\mathrm{lo}}}^{m_{\mathrm{up}}(t)} f_{\mathrm{star}}[T_{\mathrm{eff}}(M), \log g(M)|t, Z]\, \Phi(M)\, \mathrm{d}M\,,$$

IMF

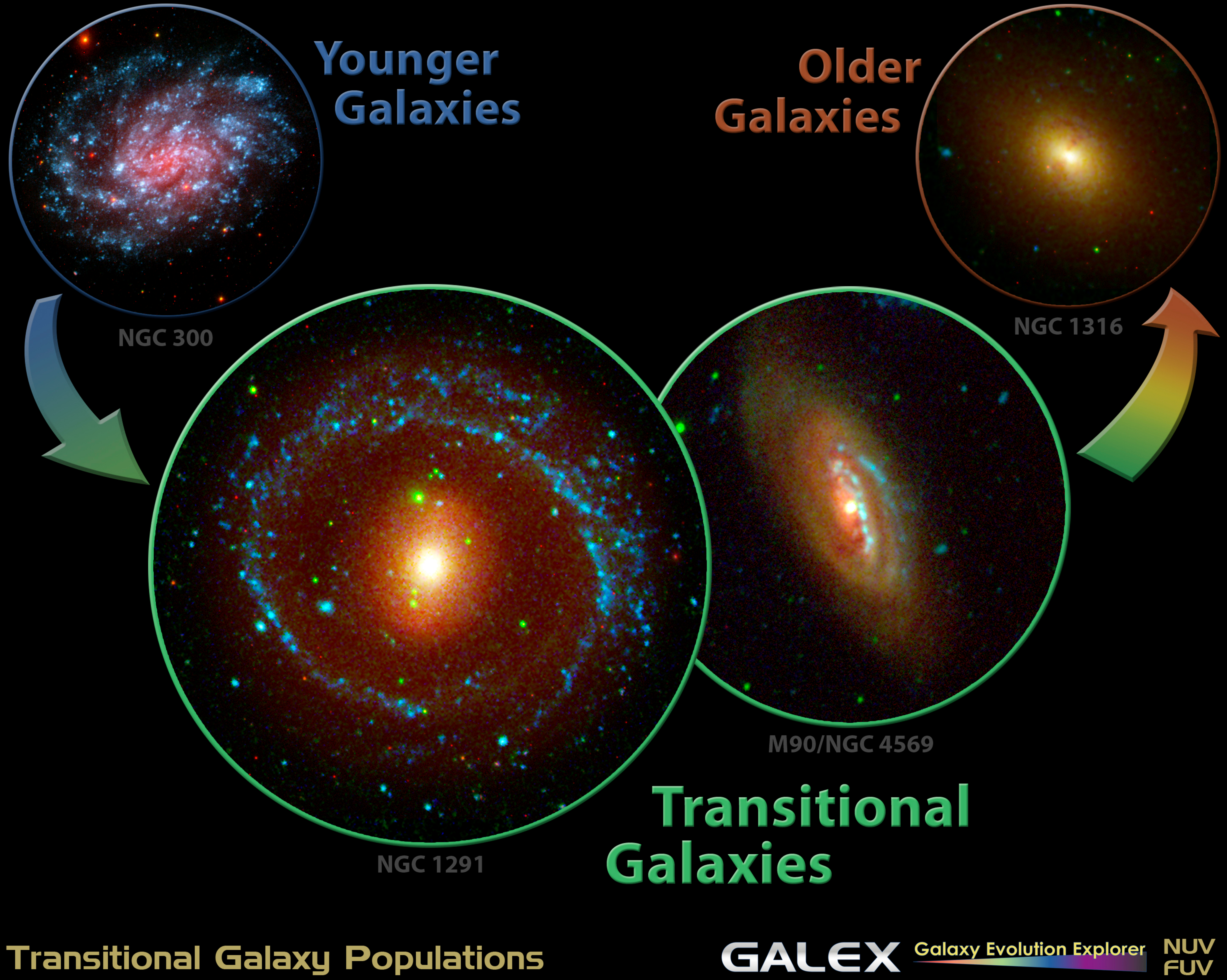


The Initial mass function of a stellar population is the distribution of birth masses of stars at a given time

Video removed due to github file size restrictions
This can be downloaded from here: https://www.astro.ex.ac.uk/people/mbate/Cluster/cluster500RT.html


©APOD

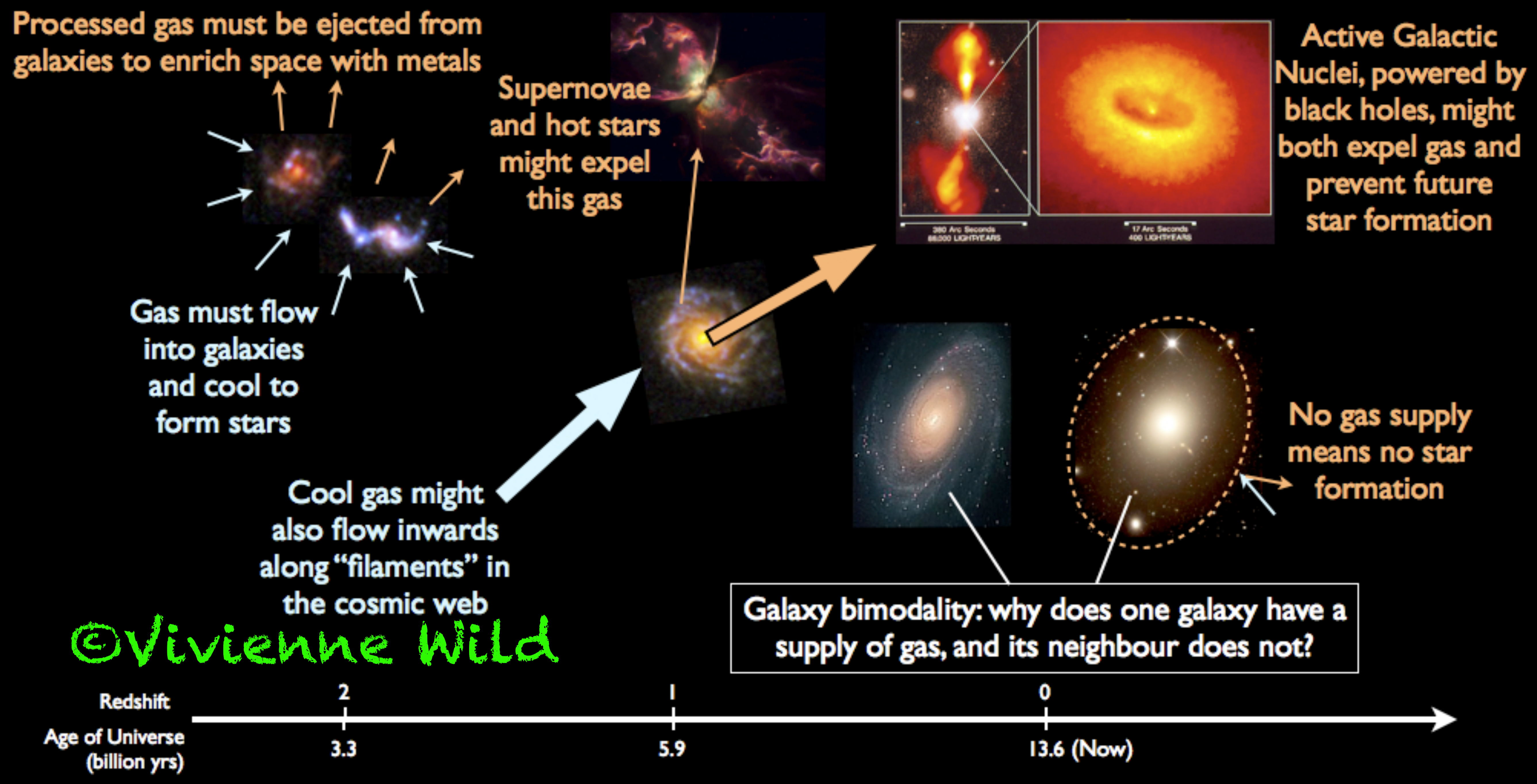
IMF is the number distribution of stars in logarithmic bins in a stellar population



Younger Galaxies
Older Galaxies
NGC 300
NGC 1316
NGC 1291
M90/NGC 4569
Transitional Galaxies
Transitional Galaxy Populations
GALEX
Galaxy Evolution Explorer
NUV
FUV

THE IMF IS FUNDAMENTAL

- ☐ Measuring star-formation in galaxies
- ☐ Measuring the mass of the galaxies
- ☐ Understanding dark matter contents and profiles
- ☐ How the galaxy would evolve
- ☐ Synthetic Stellar Populations
- ☐ High redshift cosmology
- ☐ Energetics and phase balance of the ISM
- ☐ ………………………………………………

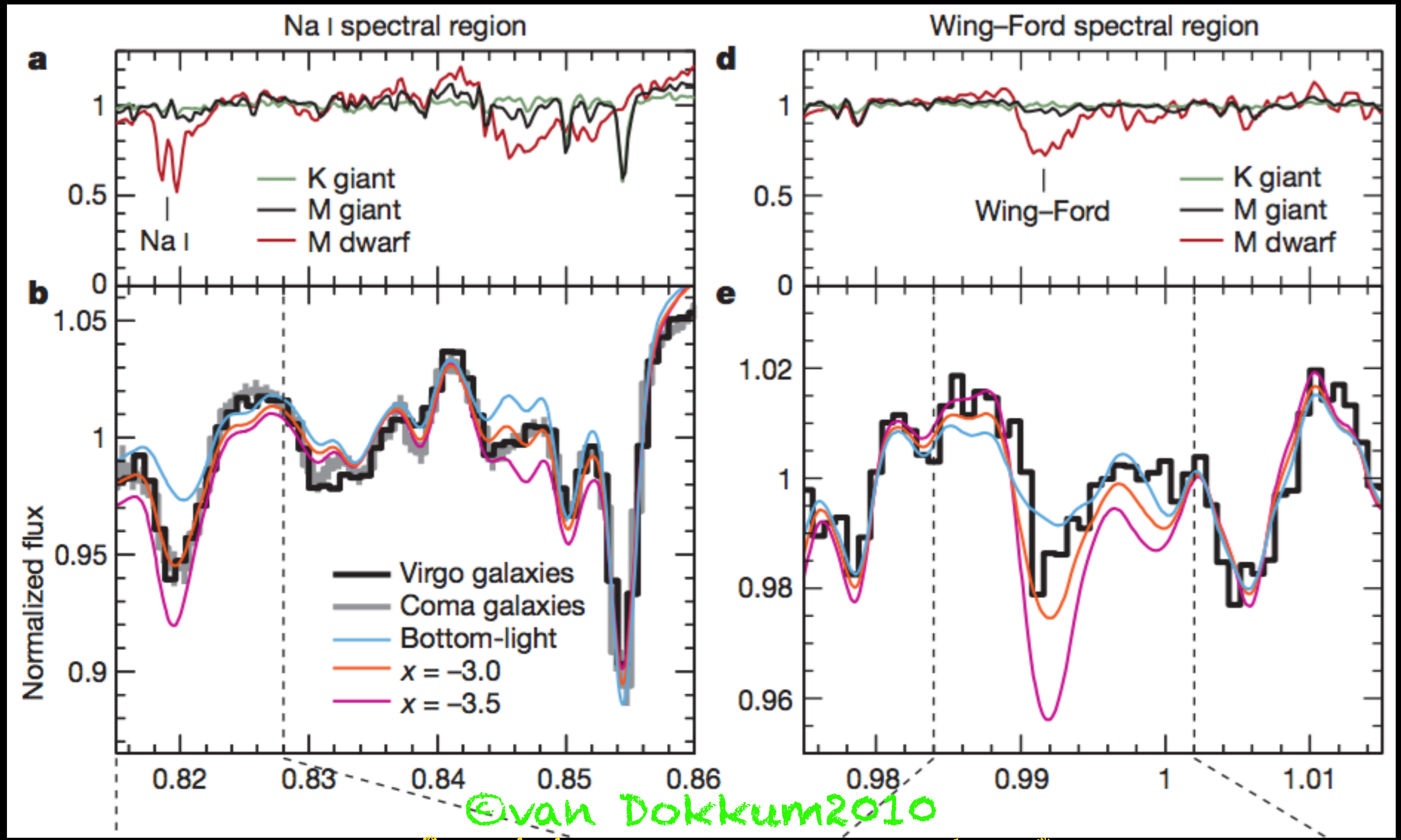


IMF CAN BE PROBED USING DIRECT OR INDIRECT METHODS

- Direct Methods

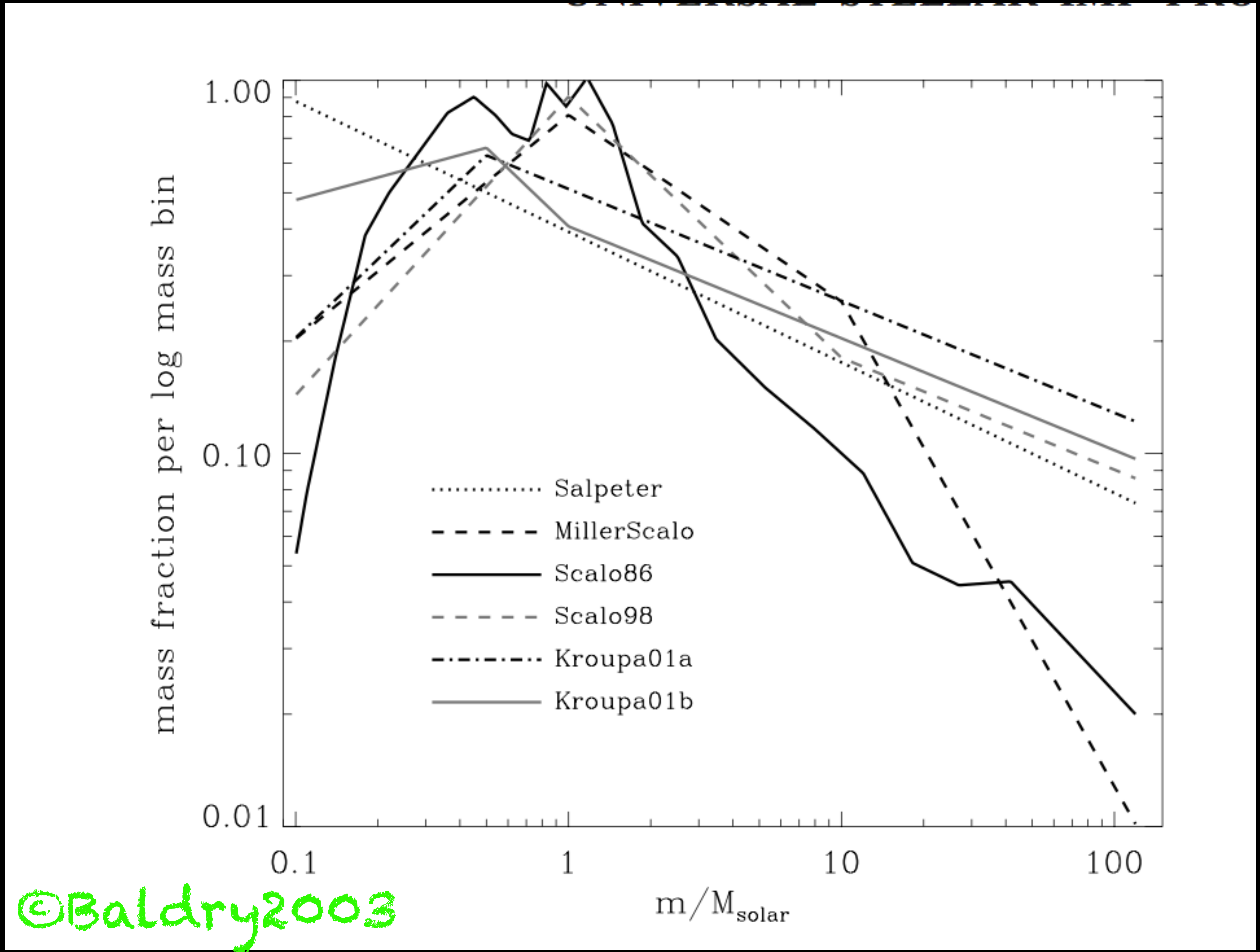
counting individual stars

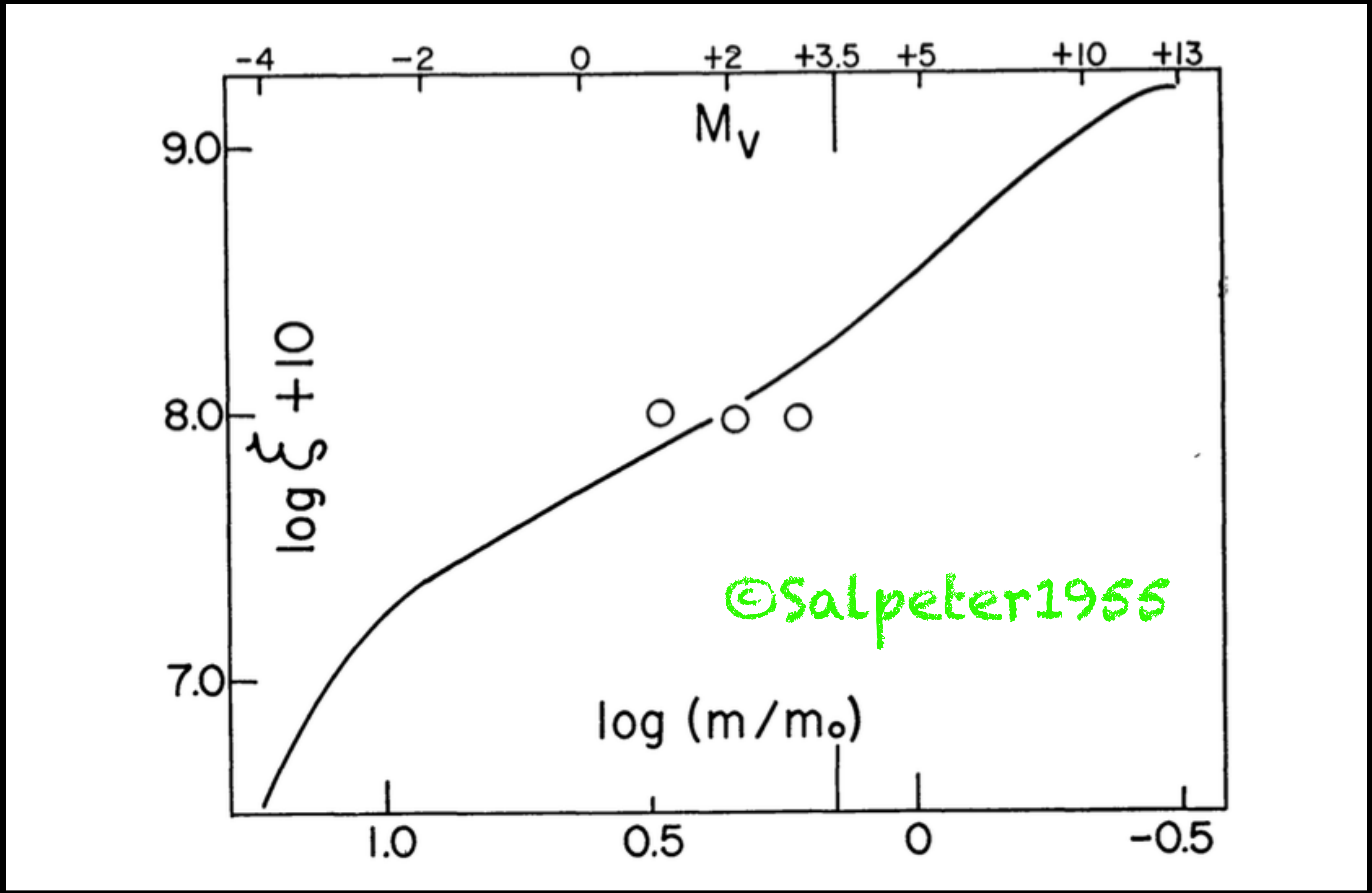
- Indirect Methods



use stellar population properties

Historically we consider the IMF to be universal between Any & all types of galaxies





It is extremely difficult to imagine that the observed complexity of star formation results in a universal IMF (Kennicutt 1998)

environmental variations

©HST

radial variations

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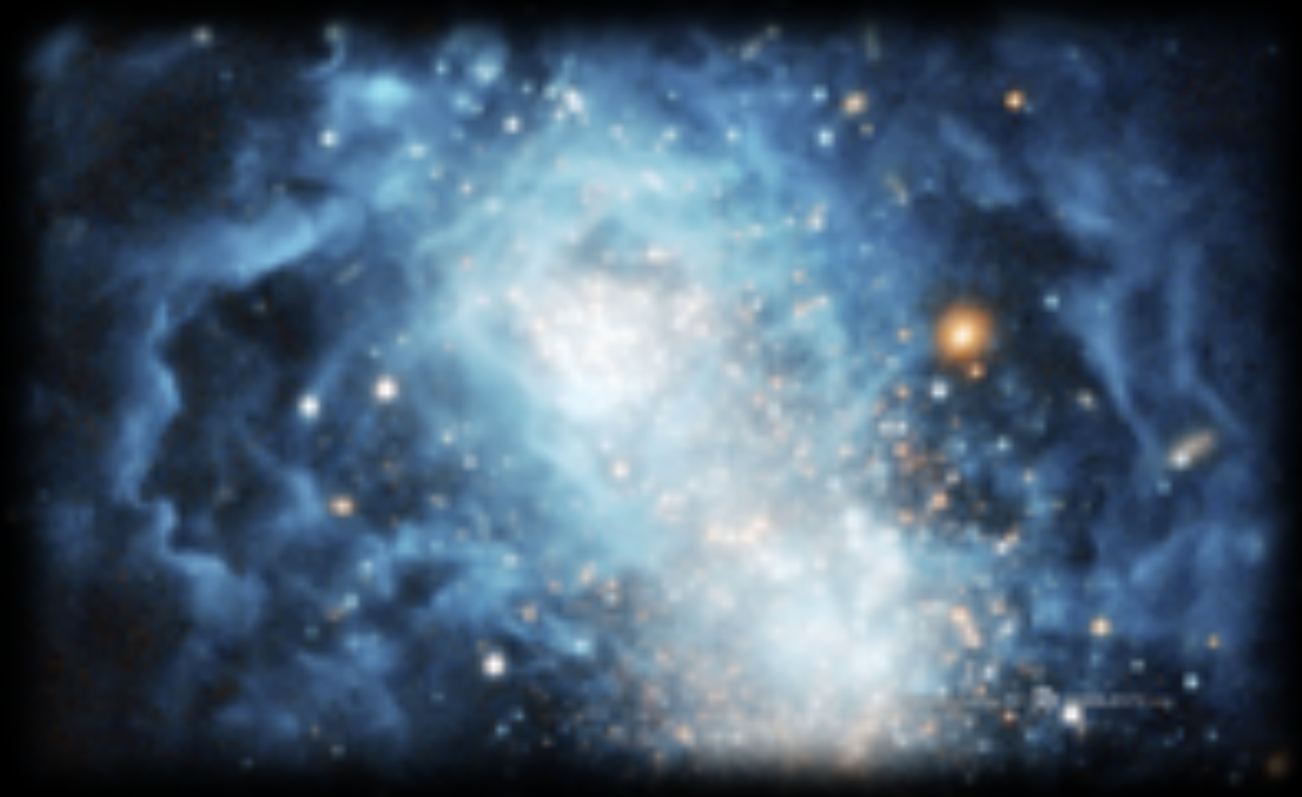
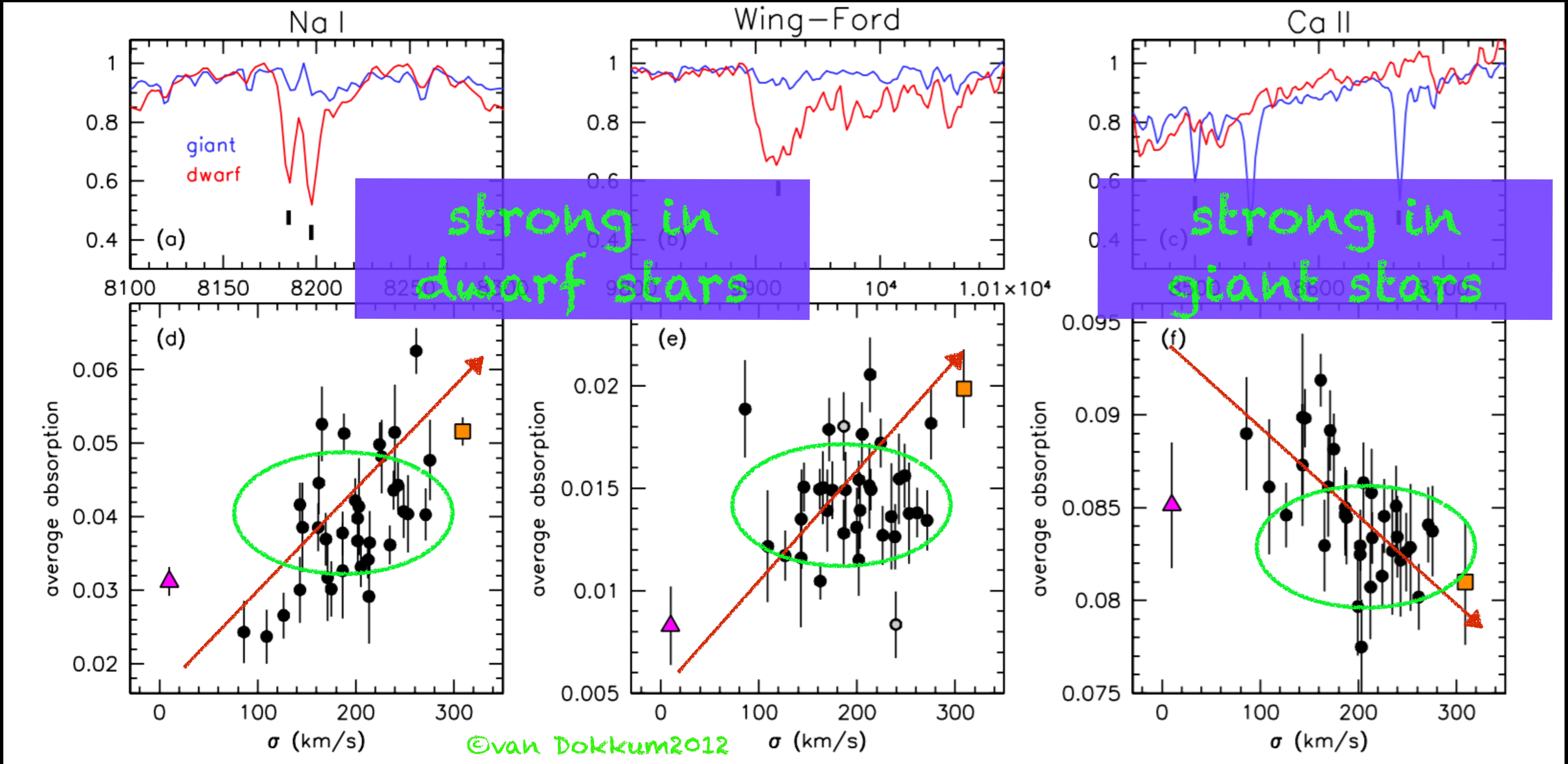
Is there any observational evidence?



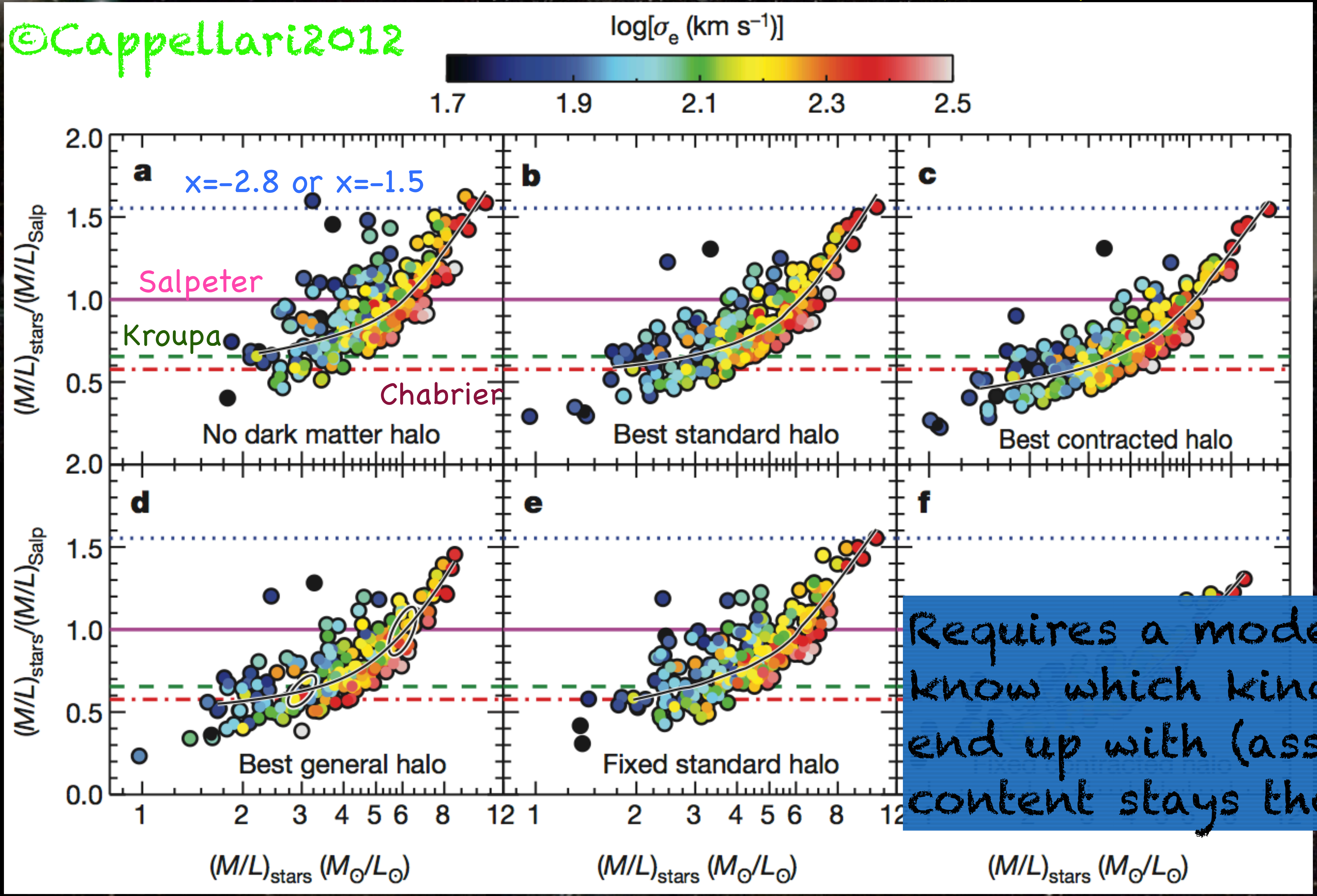
time variations?

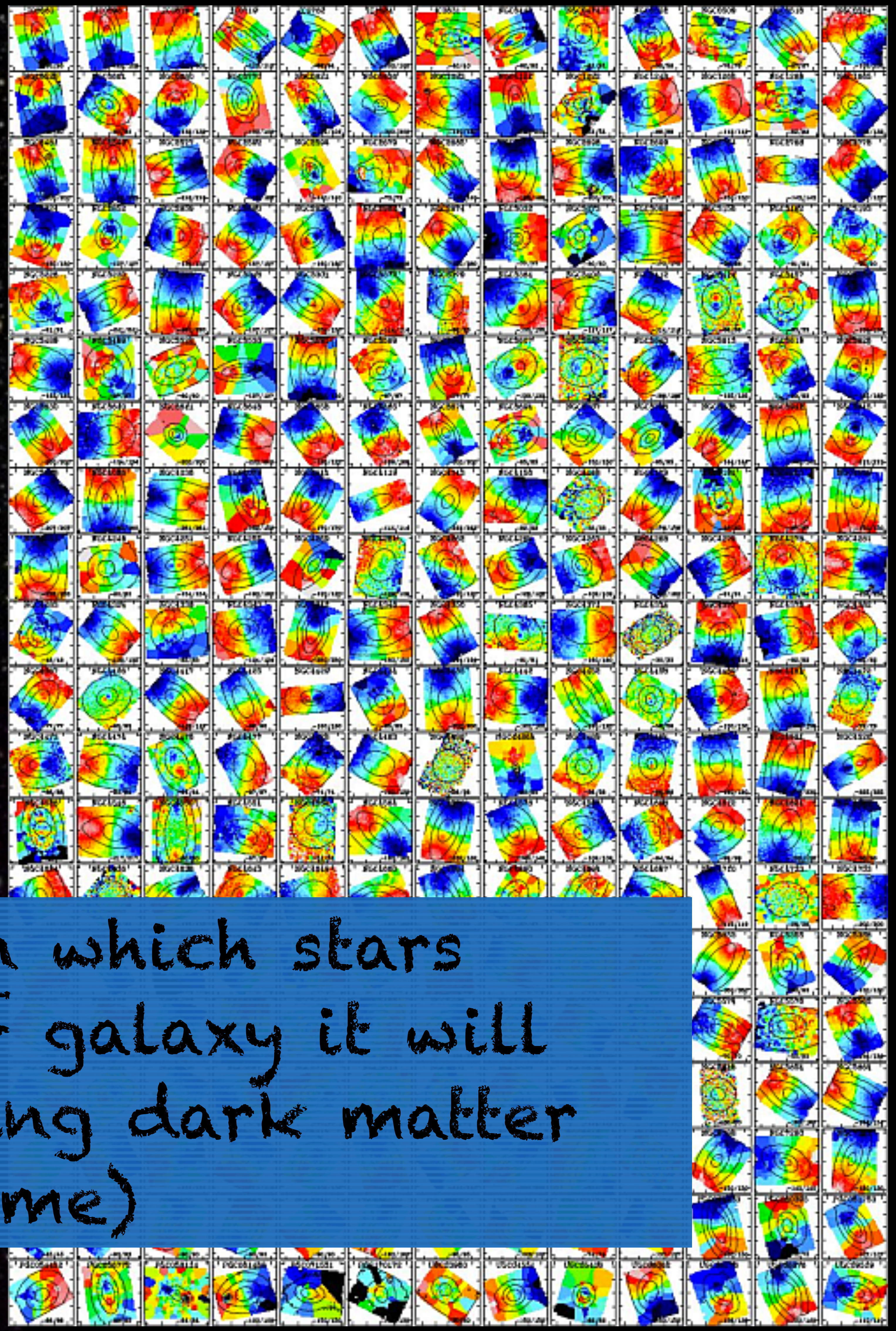
©Hirschauer2016

ETG absorption line/SSP studies show IMF variation with velocity dispersion



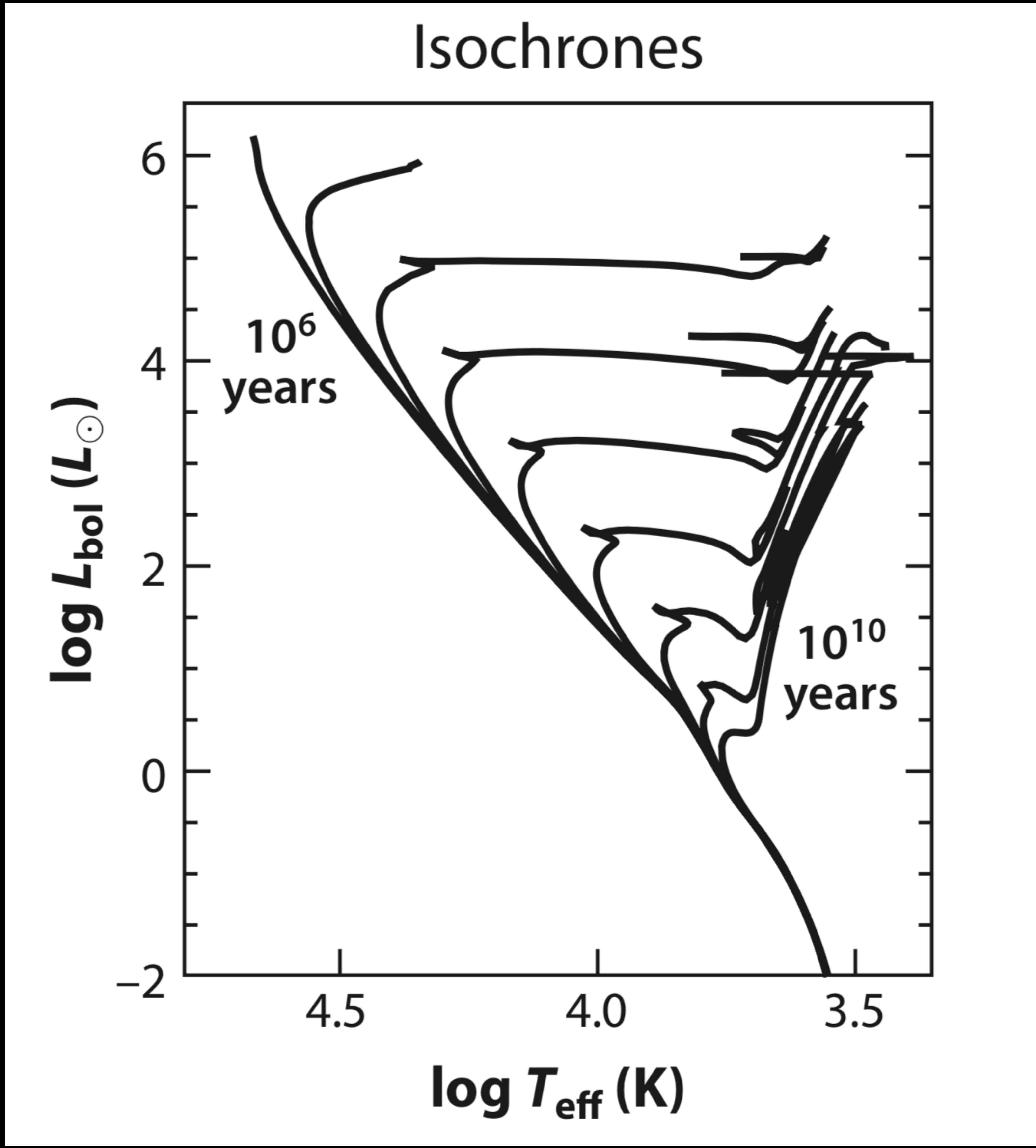
ATLAS3D showed that regardless of the dark matter profile used IMF systematically changes as a function of stellar velocity dispersion





Requires a model in which stars know which kind of galaxy it will end up with (assuming dark matter content stays the same)

Isochrones



Specifies the location of stars in same age and metallicity in the HR diagram.

Massive stars are hotter and evolve off the main sequence faster that the less massive stars

Isochrones

- Evolutionary tracks are discretely sampled, so special attention should be given to interpolation.
- Most common tracks span a wide range in age (mass) and chemical composition.
    - ⋆ Padova models
    - ⋆ BaSTI models
- Some models focus specially on certain types of stars
    - ⋆ Geneva models: high mass, rotation, W-R stars but no small mass stars
    - ⋆ Y2 and Victoria Regina models: RGB stars, HB stars
    - ⋆ Lyon models: brown dwarf stars, very low mass stars
- MESA code: highly modular, and sophisticated stellar evolution code that includes the latest stellar interior ingredients, including opacity tables, equations of state, nuclear reaction networks, and surface boundary conditions

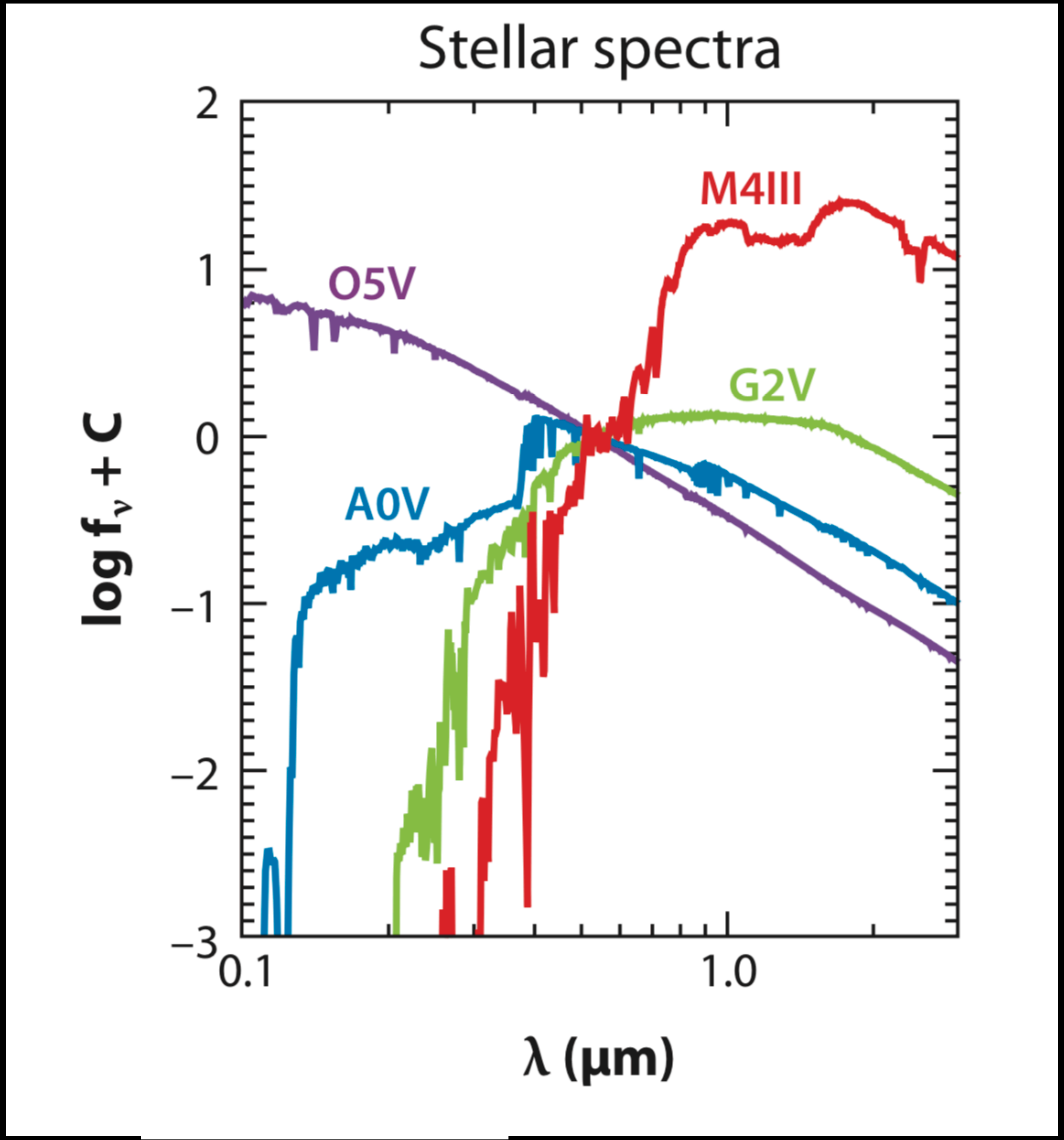
Isochrones

- Effects of rotation
  - ⋆ Only a few SSP codes consider effects of stellar rotation. i.e., Geneva models, MIST models
  - ⋆ Rotation can increase the life time of MS stars by ~25%, lowers the effective surface gravity, lowers the opacity in the radiative envelope, increases the luminosity, and changes the ratio of red to blue supergiants.
  - ⋆ The mixing to the surface of hydrogen burning products caused by rotation will also affect the number and type of WR stars.
  - ⋆ Additionally, rotation can increase the amount of ionising photons by ~1 magnitude and make the colours bluer by 0.1-1 magnitude.

Isochrones

- Effects of binaries
  - So far only BPASS models incorporate effects of binary evolution in stars
  - Binaries will increase the life-time of massive stars, lead to QHE effects giving rise to rapidly rotating stars (contributing to similar effects to rotation).
  - Binaries will decrease the metallicity threshold to produce W-R stars.
  - May also create blue straggler stars and extreme HB stars, which would suggest that binary evolution can affect older stellar populations as well.
  - Currently BPASS models does not consider stellar rotation

Stellar spectra



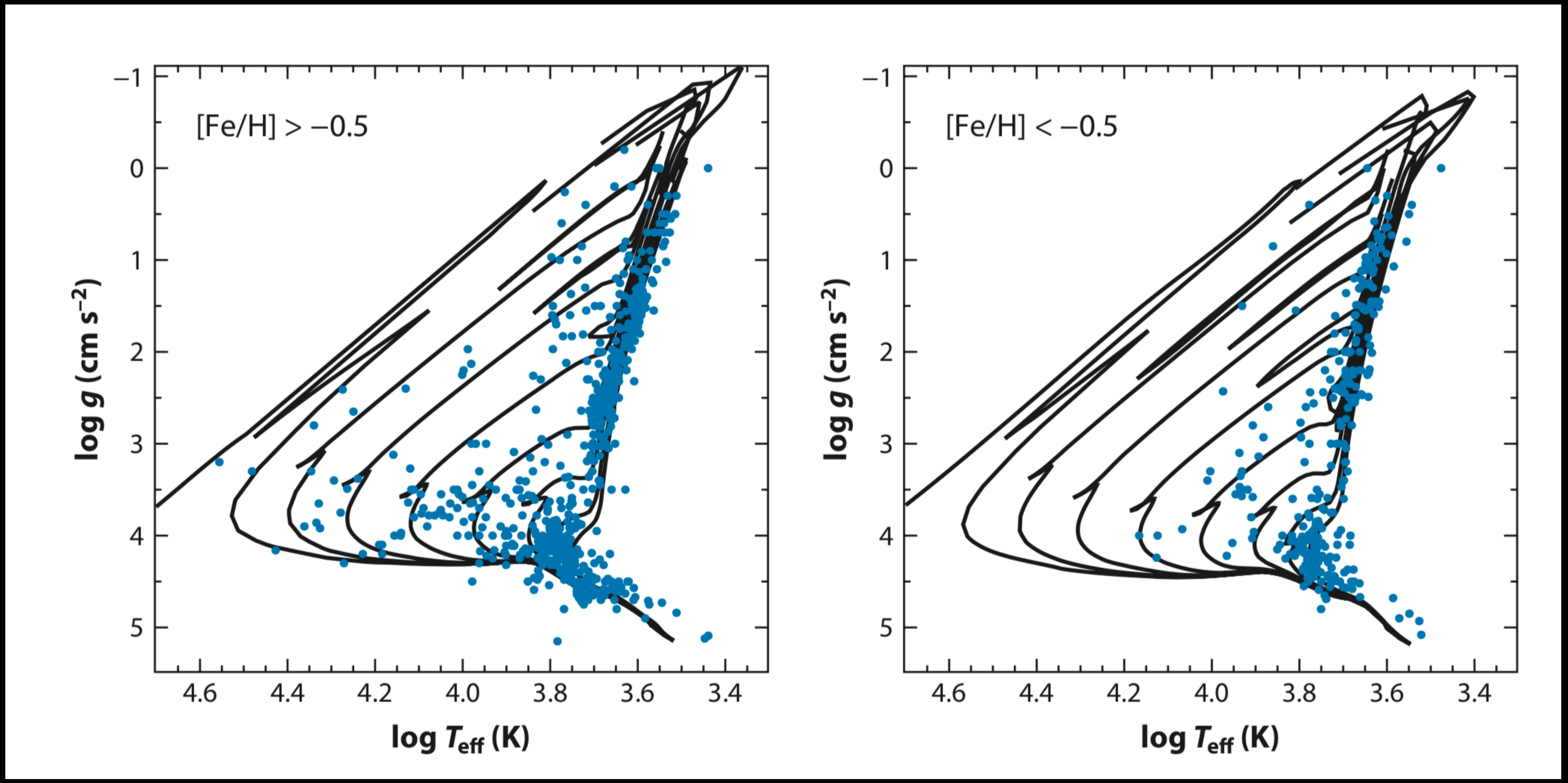
Stellar spectra are necessary to convert the population of stars in to an observed spectral energy distribution (SED)

Stellar spectra

- Severely limited in parameter space due to lack of variety in stars in the solar neighbourhood.

- As shown by the figure, even MILES, the largest empirical spectral library only sparsely covers the upper main sequence and supergiants.

- Assigning physical parameters to stars also leads to considerable uncertainties.



Stellar Spectra

- To overcome limitations in empirical stellar libraries theoretical stellar libraries can be used.
- Libraries are only as good as the input atomic and molecular parameters and the approximations made in the computation of the models

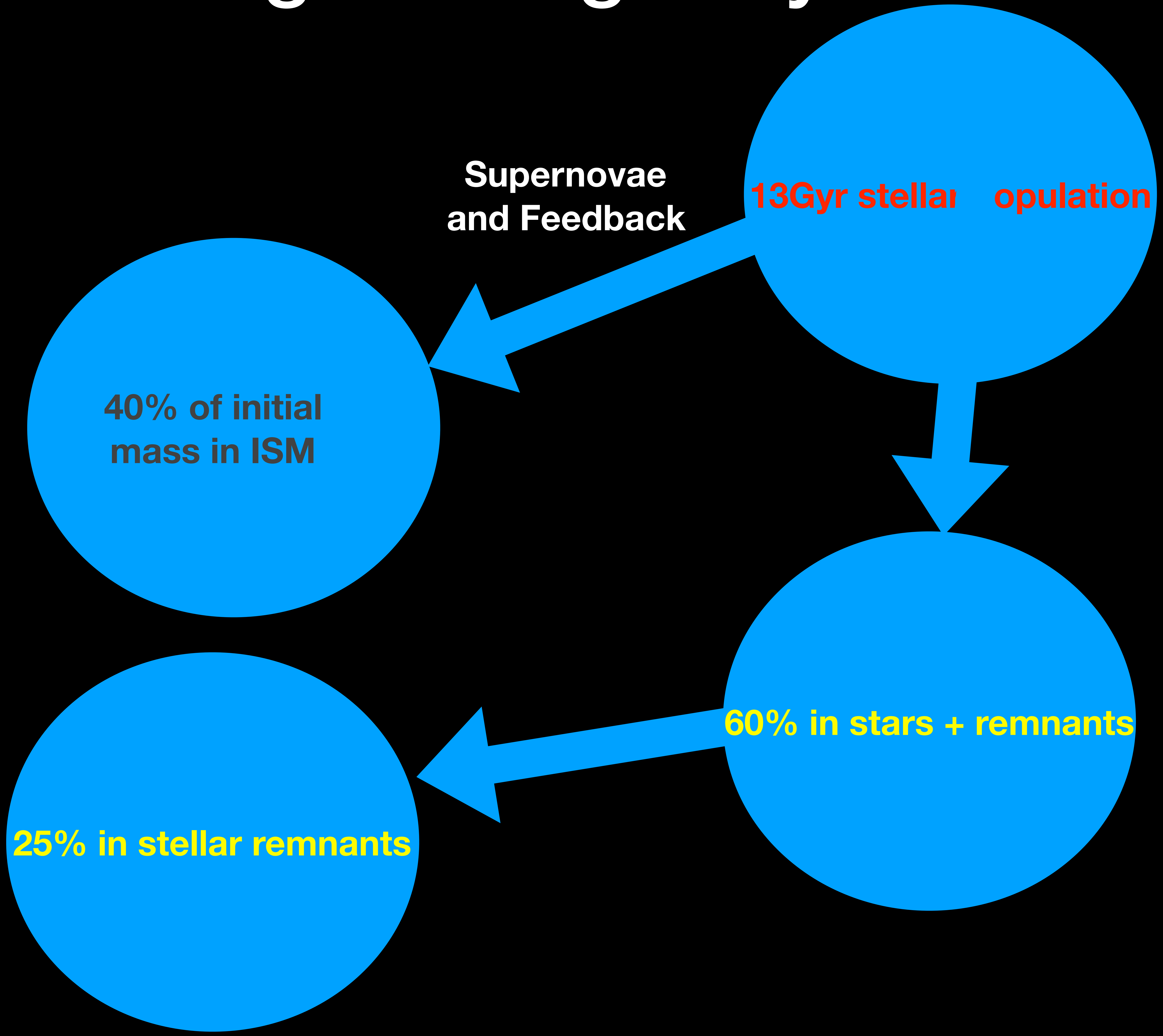
Stellar remnants are also necessary to account for the total mass budget of a galaxy

- The relationship between initial ZAMS stellar mass and the final remnant stellar mass is not well constrained

- More vital at later ages:

  - ★ e.g., 13 Gyr stellar population

    - 7% neutron stars
    - 73% white dwarfs
    - 20% black holes



Composite stellar populations

- Stars with a range of ages
- Stars with a range of metallicities
- Dust

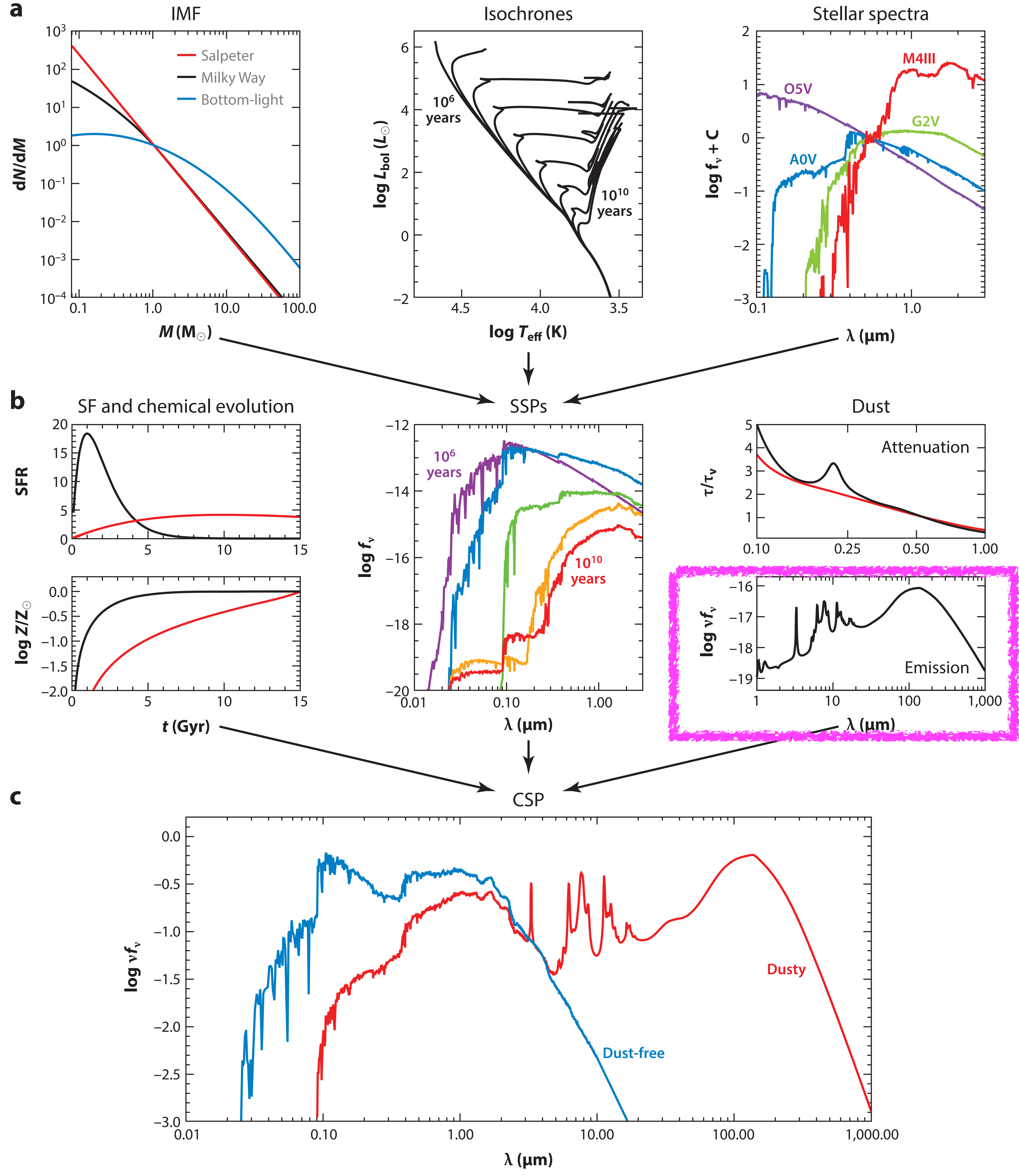
$$f_{\mathrm{CSP}}(t) = \int_{t'=0}^{t'=t} \int_{Z=0}^{Z_{\max}} \left(\mathrm{SFR}(t - t') P(Z, t - t') f_{\mathrm{SSP}}(t', Z) e^{-\tau_d(t')} + A\, f_{\mathrm{dust}}(t', Z) \right) \mathrm{d}t'\, \mathrm{d}Z,$$

Composite stellar populations

- Composite stellar populations may resemble close to reality spectral energy distributions

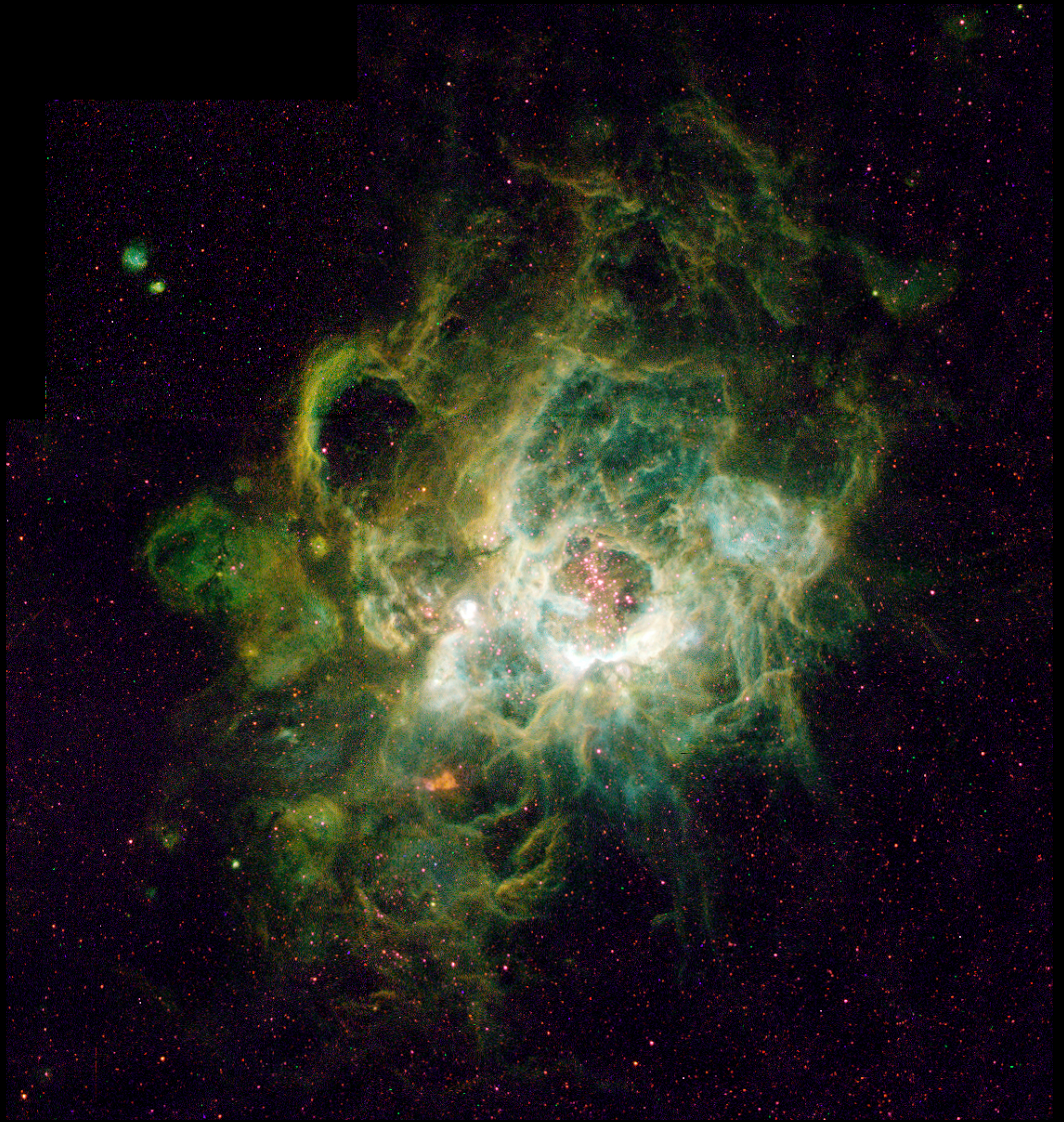
- However, there are a lot of free parameters and uncertainties, which can be tuned to match data with models: we don't know what is correct and what is not

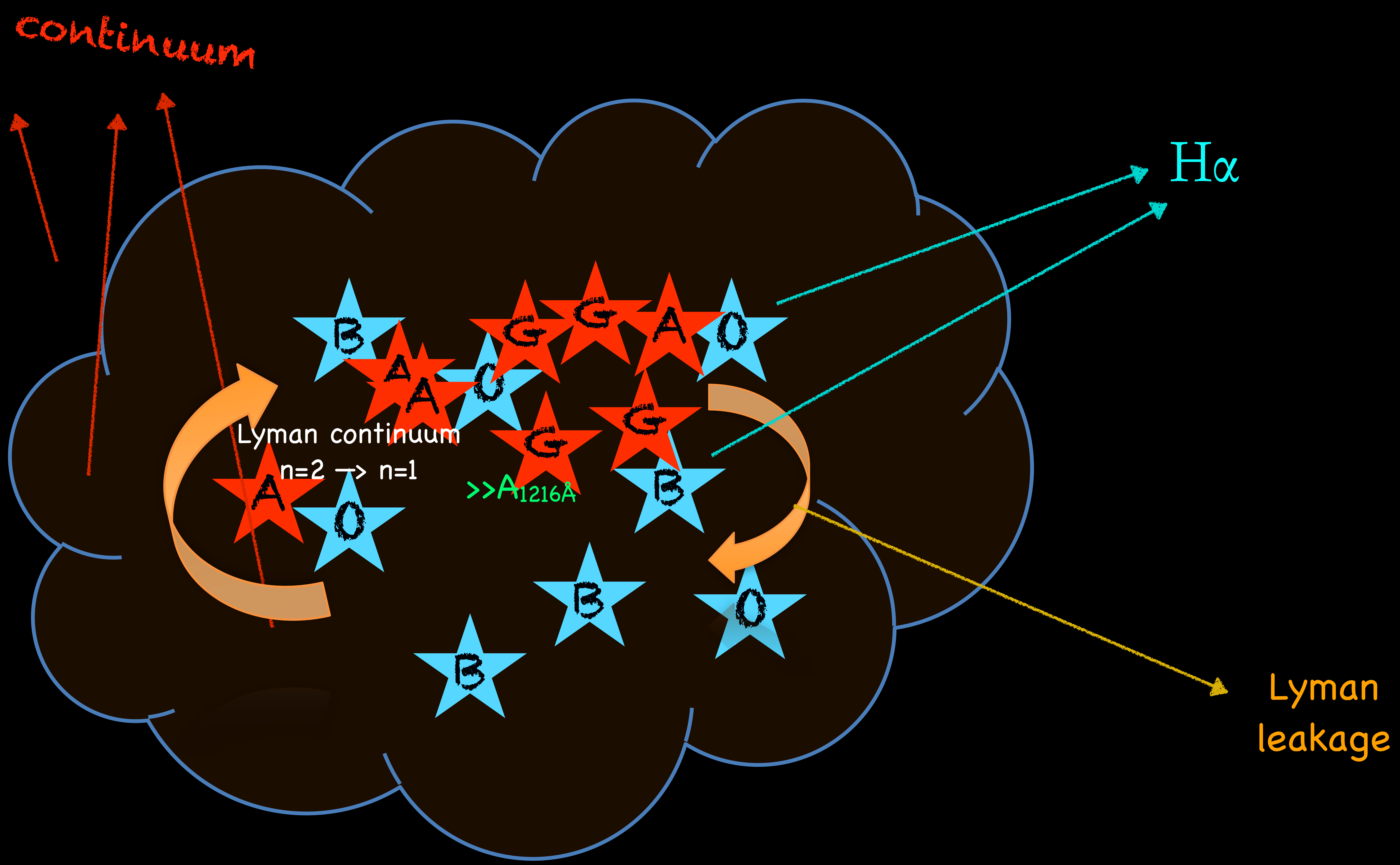
- So use observational data in galaxy populations to get some constraints



Nebular emission

- Adding nebular emission introduces further complexities
- Photoionisation codes such as CLOUDY or MAPPINGS is generally used on top of SSPs to generate nebular emission
- A lot of assumptions go into deriving nebular lines, thus is generally SSPs do not produce emission lines (have to do this separately)

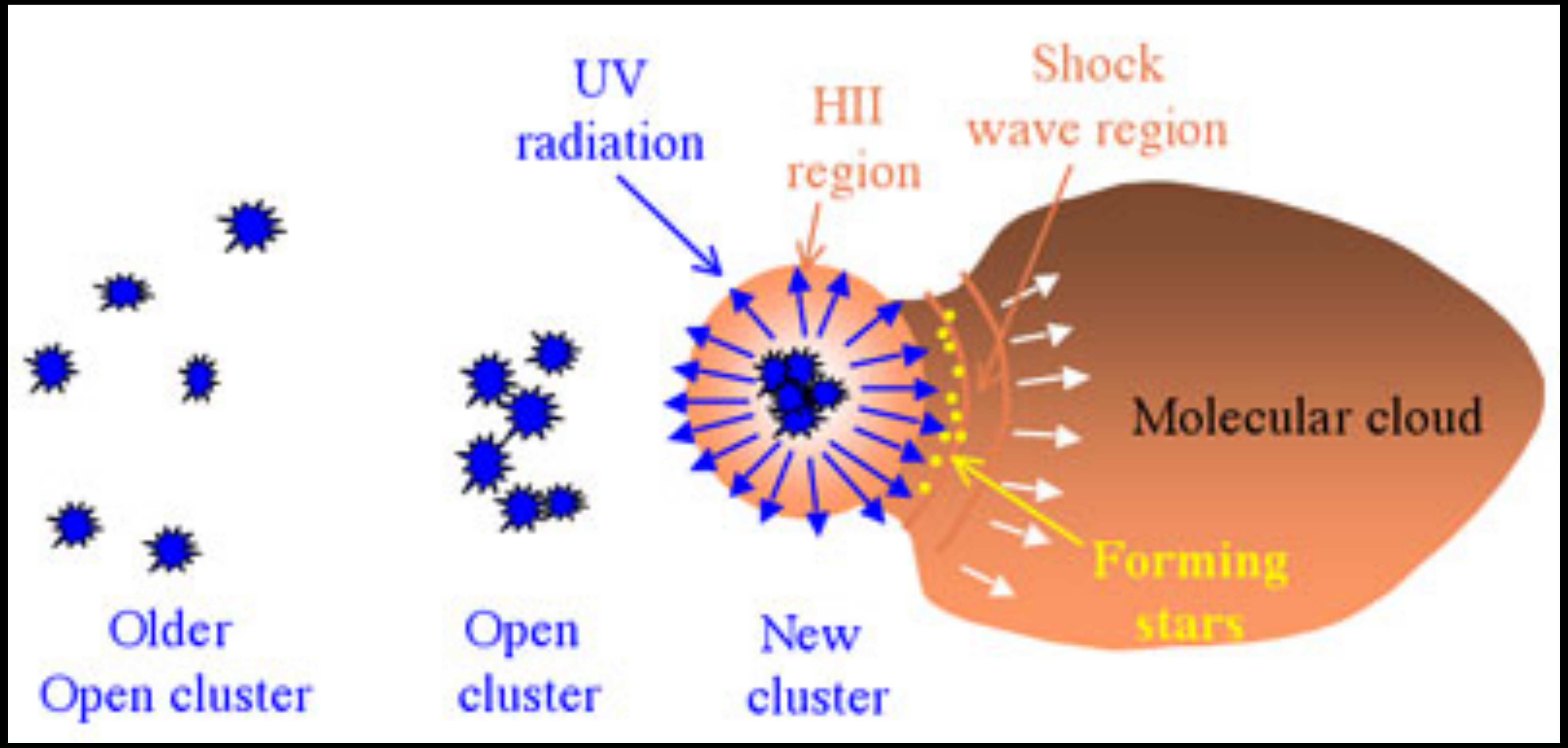



continuum
Hα
Lyman continuum
n=2 —> n=1
>>λ1216Å
Lyman
leakage
B
A
A
G
G
A
O
G
G
B
A
O
B
O
B

Star formation

- Multiple effects related to star formation, magnetic effects, feedback need to be taken into account.

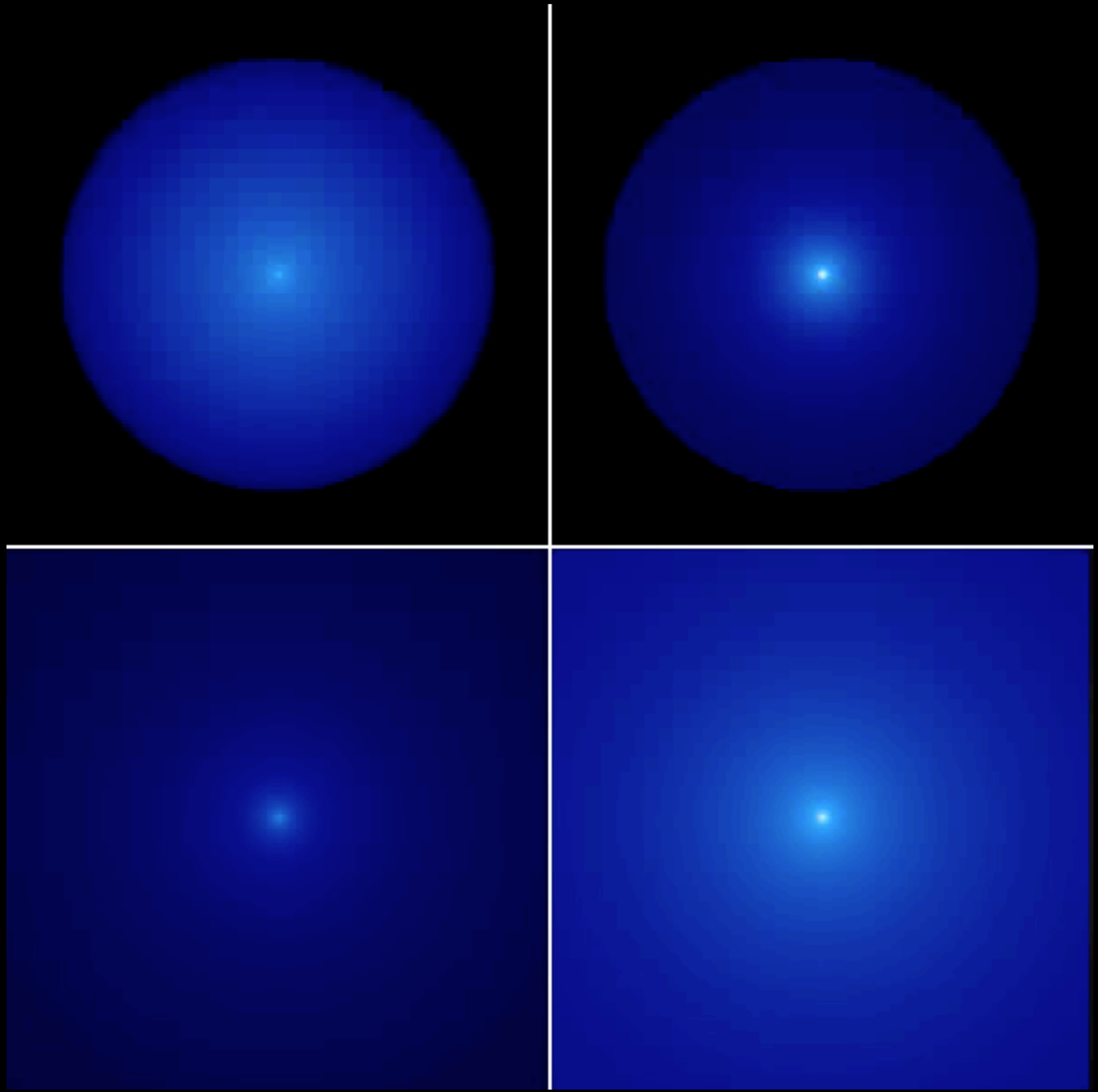
- Simulations show us an insight.



Formation of a massive star cluster by global collapse

http://www.mso.anu.edu.au/~krumholz/movies.html

Formation of a massive star with radiation pressure feedback; left = face-on view, right = edge-on review, top = long view, bottom = zoom view
http://www.mso.anu.edu.au/~krumholz/movies.html



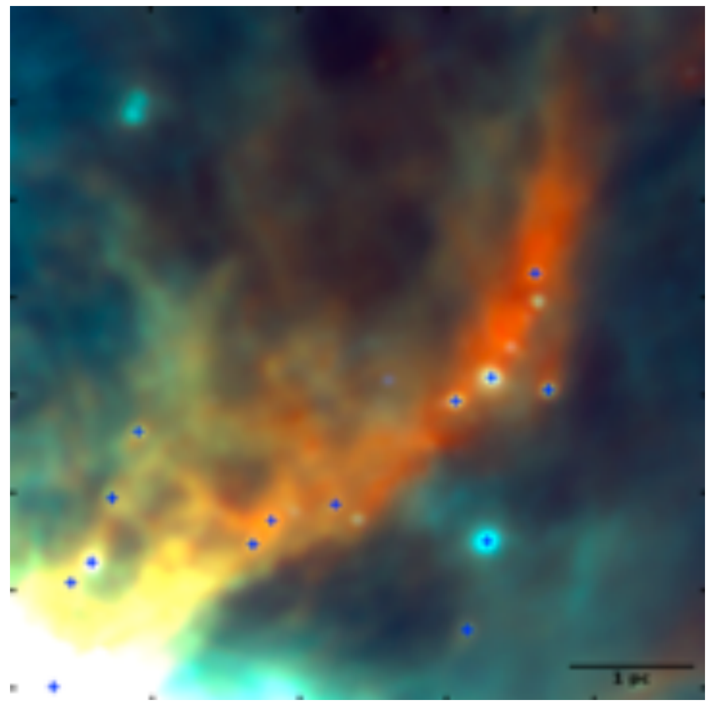
How can we measure star-formation?

What do you need? SFR indicator

Optimal

Less optimal

Proto-stars



Ragan et al (2012)

Trace current star-formation closely. Not (yet) useful for large samples of distant galaxies.

What do you need? **SFR indicator**

Optimal

Proto-stars

Less optimal

Hα

Traces massive stars. Lag up to 10Myr
Best if spectra are available.

What do you need? **SFR indicator**

Optimal

Proto-stars   Hα

Less optimal

UV

Traces massive stars. Lag up to 100Myr

What do you need? **SFR indicator**

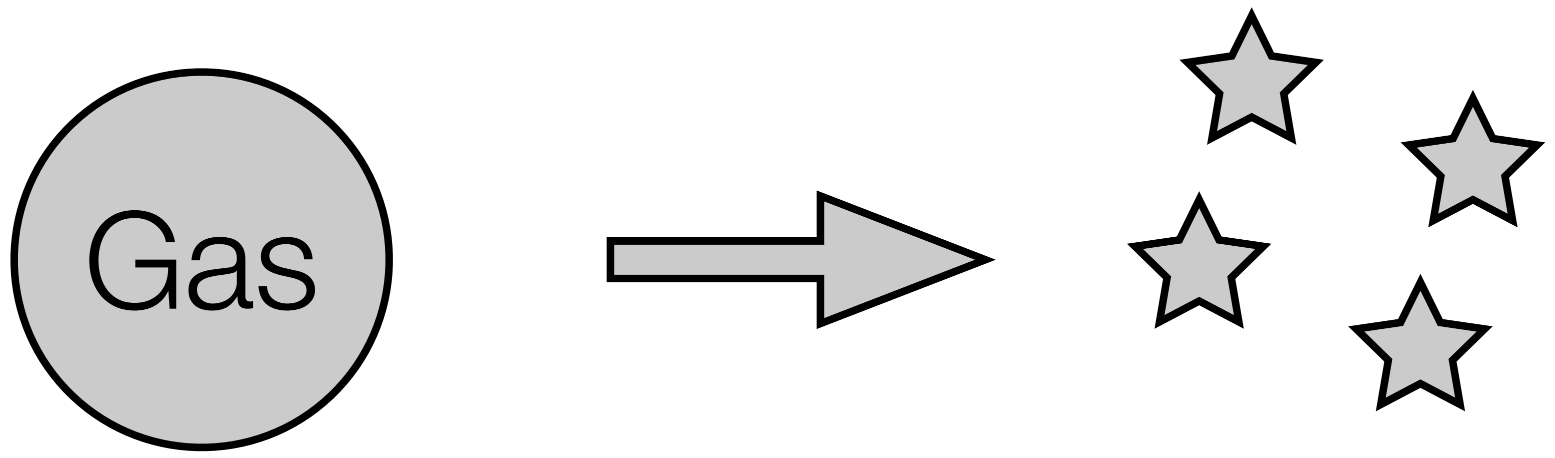
Optimal — Less optimal

Proto-stars, Hα, X-ray binaries, UV, Non-thermal Radio, Far-IR, SN remnants

In general you want a tracer that is close in time to the observed gas.

But it is also important to sample the same spatial scale as the gas (resolution and extent).

SFR indicators & time-lag - why do we care?



Time-scale?

Massive stars formed up to 10 Myrs ago.
The gas they formed from is gone.

On larger scales (kpc?) the mean conditions can be expected to not change too much over ~few Myr.

Longer delay between SF and SFR indicator might affect correlation.

Other physical parameters

- Similarly we can use emission/absorption lines to measure metallicity of galaxies
- SFH, luminosity, or a combination using SED fitting techniques can tell us about stellar mass
- By modelling the observed spectra/SED with different dust laws, using FIR/submm spectra or comparing emission line ratios we can learn about dust
- We will revisit these tomorrow in a more practical way when we use SSP models to match with observations to infer galaxy properties