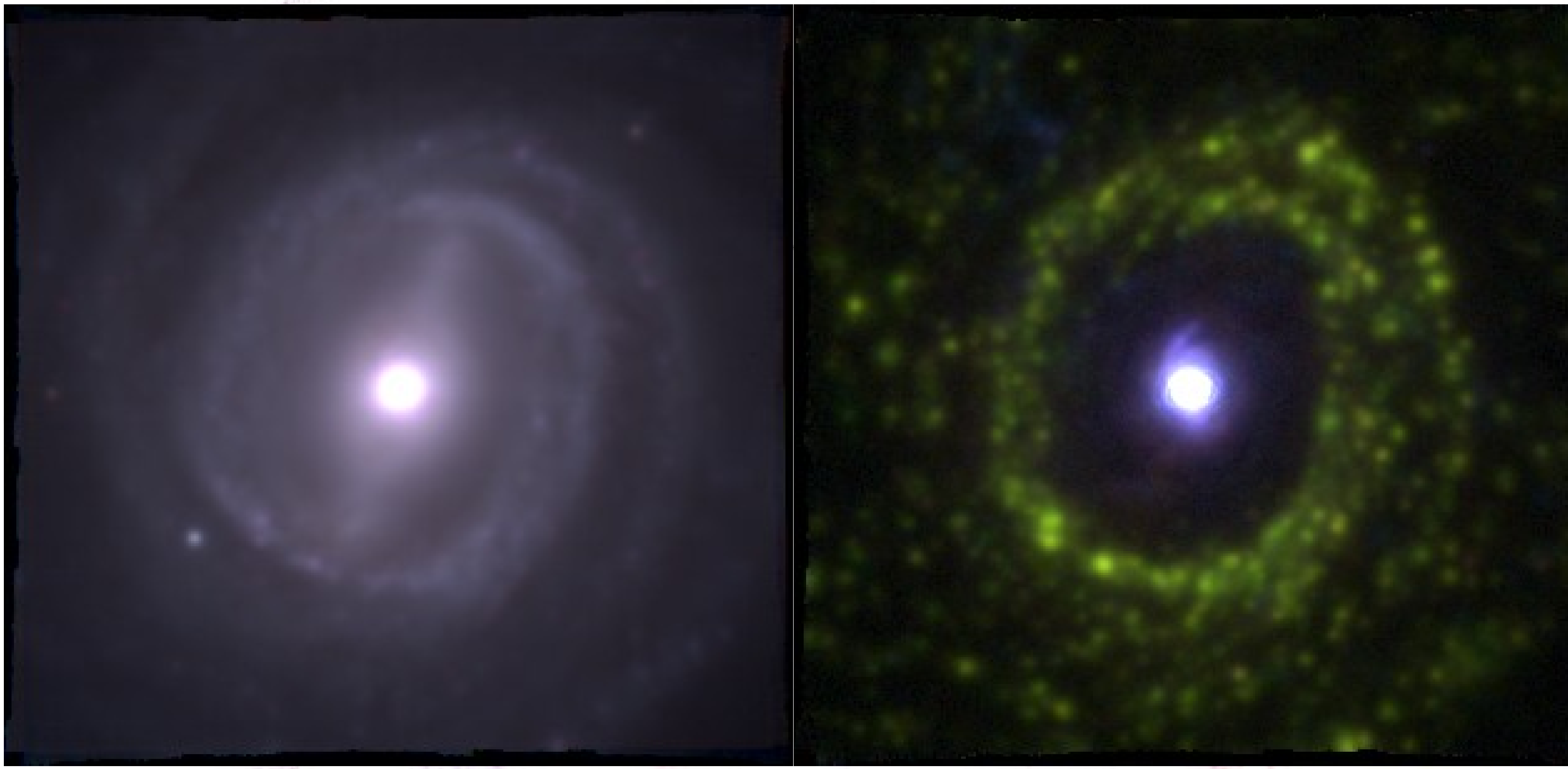
Spatially resolved properties of low z galaxies using Integral Field Spectroscopy data



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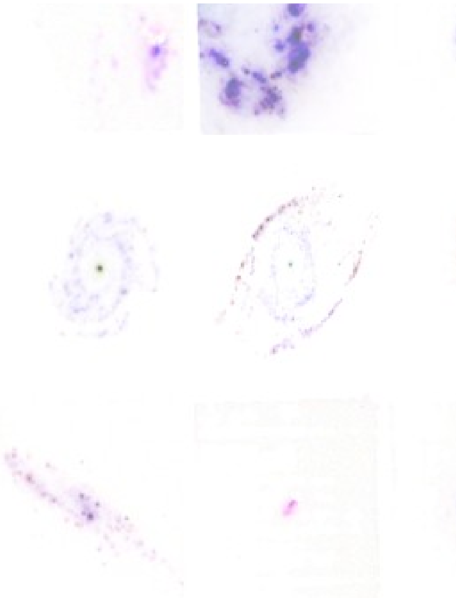
Astronomy 511: Topics in Observational Extra-galactic Astronomy
Spring 2024

Sánchez 2020ARA&A..58...99S



Spatially-Resolved Spectroscopic Properties of Low-Redshift Star-Forming Galaxies

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Keywords

galaxies: evolution, galaxies: star-formation, galaxies: resolved properties, galaxies: fundamental parameters, techniques: imaging spectroscopy

Abstract

I review here the spatially-resolved spectroscopic properties of low-redshift star-forming galaxies (and their retired counter-parts), using results from the most recent optical Integral Field Spectroscopy galaxy surveys. First, I briefly summarise the global spectroscopic properties of these galaxies, discussing the main ionization processes, and the global relations described between the star-formation rates, gas-phase oxygen abundances, and average properties of their stellar populations (age and metallicity) with the stellar mass. Second, I present the local distribution of the ionizing processes, down to kiloparsec scales, and I show how the global scaling relations found between integrated parameters (like the star-formation main sequence, mass-metallicity relation and Schmidt-Kennicutt law) have local/resolved counter-parts, with the global ones being, for the most part, just integrated/average versions of the local ones. I discuss

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FROM GLOBAL TO SPATIALLY RESOLVED IN LOW-REDSHIFT GALAXIES

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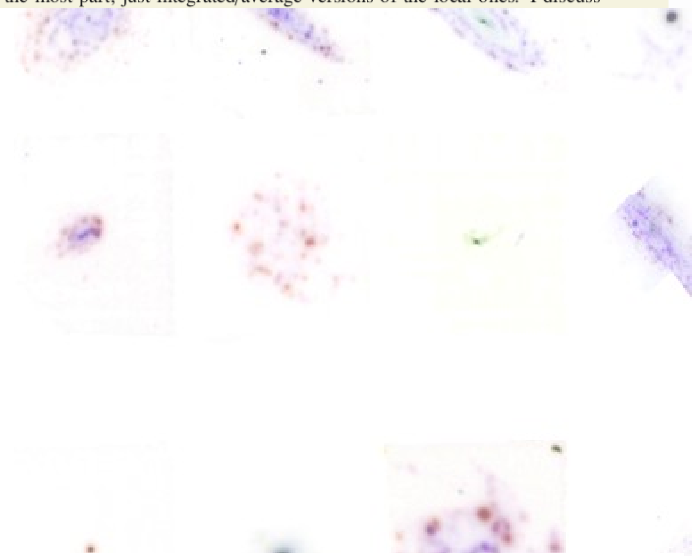
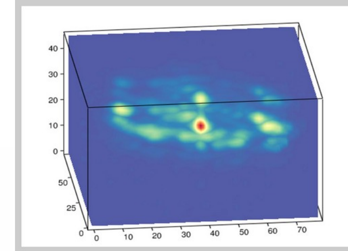
ABSTRACT

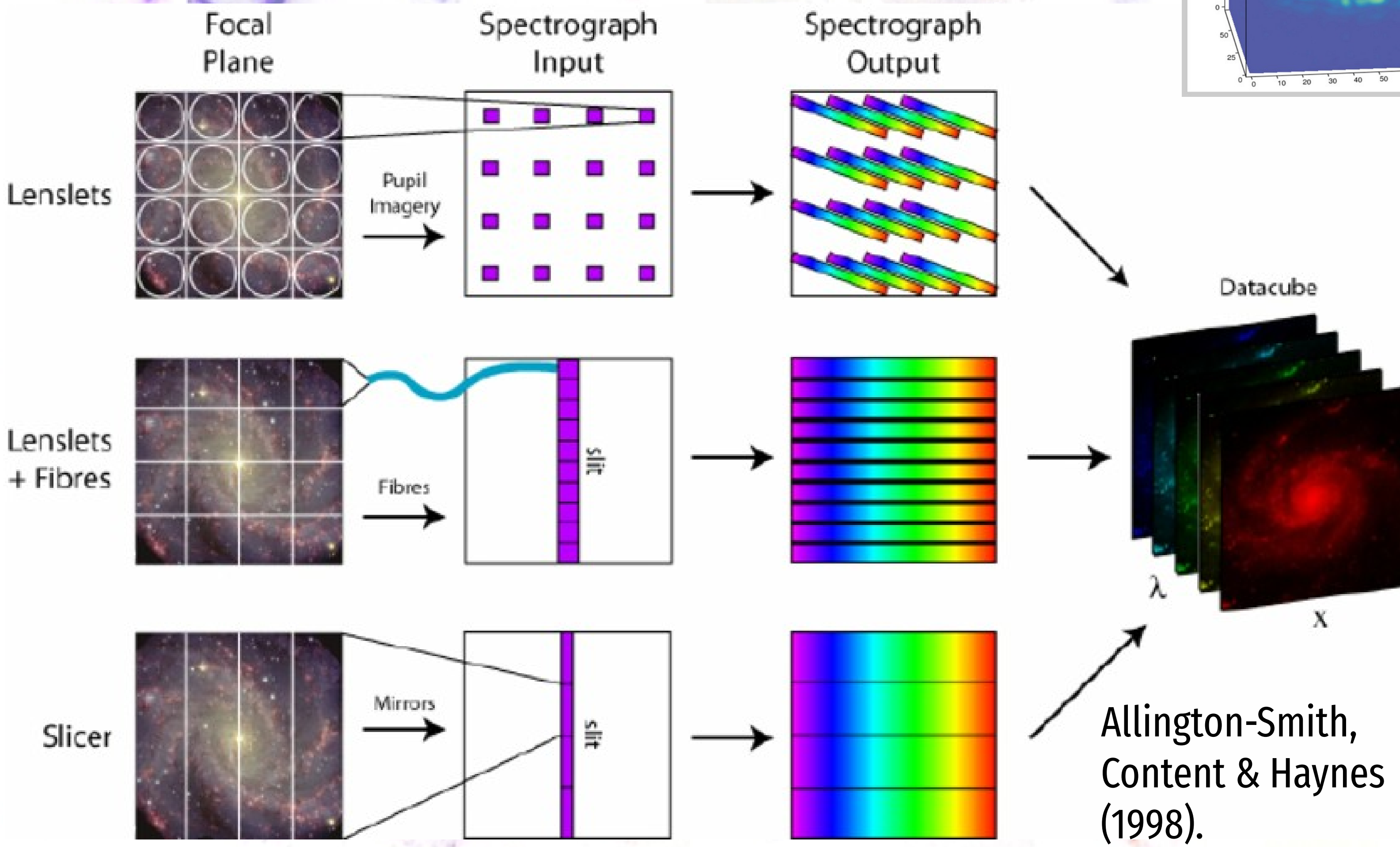
Our understanding of the structure, composition and evolution of galaxies has strongly improved in the last decades, mostly due to new results based on large spectroscopic and imaging surveys. In particular, the nature of ionized gas, its ionization mechanisms, its relation with the stellar properties and chemical composition, the existence of scaling relations that describe the cycle between stars and gas, and the corresponding evolution patterns have been widely explored and described. More recently, the introduction of additional techniques, in particular integral field spectroscopy, and their use in large galaxy surveys, have forced us to re-interpret most of those recent results from a spatially resolved perspective. This review is aimed to complement recent efforts to compile and summarize this change of paradigm in the interpretation of galaxy evolution. To this end we replicate published results, and present novel ones, based on the largest compilation of IFS data of galaxies in the nearby universe to date.



Sánchez et al. 2021, RMxAA, 57, 3

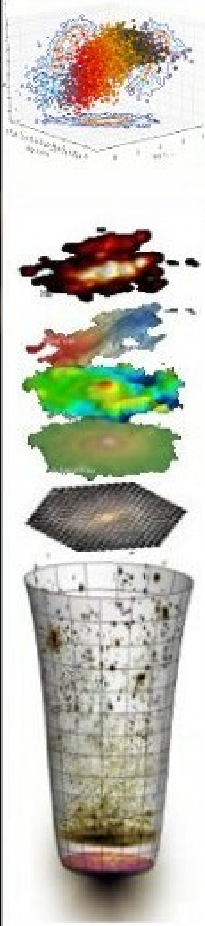
Integral Field Spectroscopy



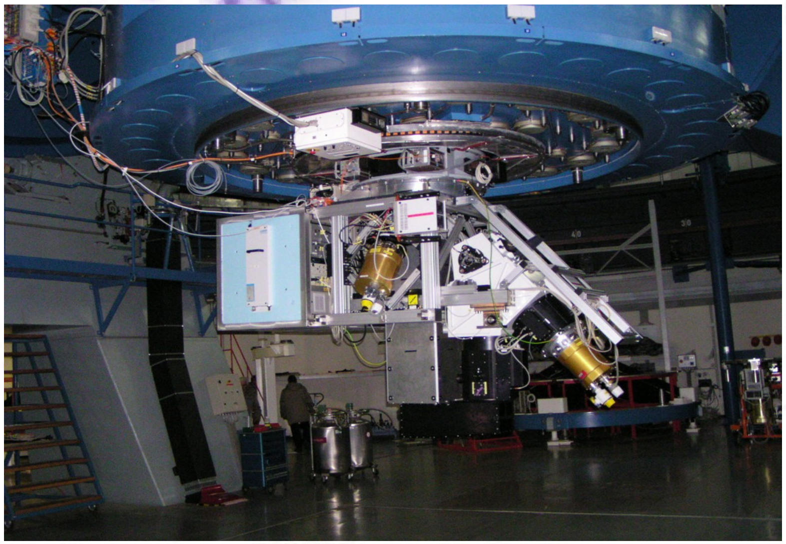


Allington-Smith, Content & Haynes (1998).

Integral field spectroscopy (IFS), is the technique that allows us to obtain simultaneously several spectra (within a defined field-of-view, FoV) of a quasi-continuous region in the sky. The final data, after reduction, consist either of a spatially continuous distribution of spectra (3D cube), or a set of individual spectra arranged across the FoV in certain fixed positions.



Some IFUs in the North

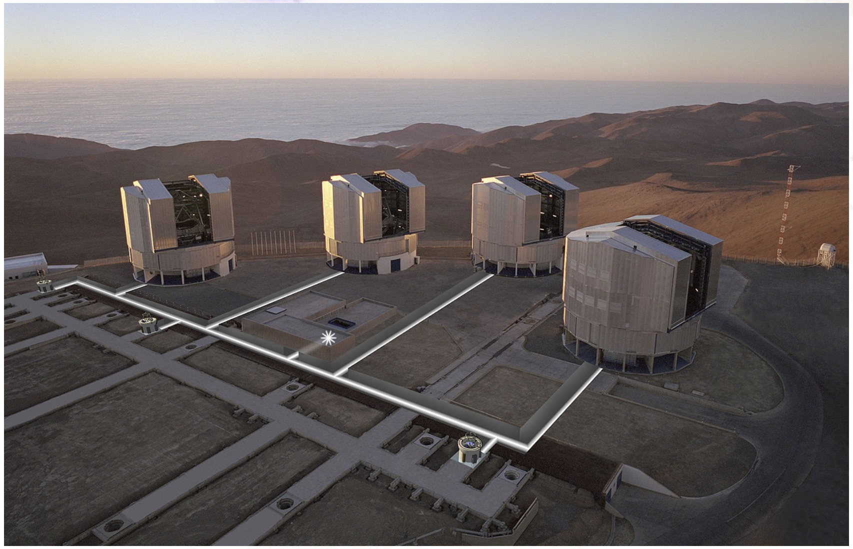


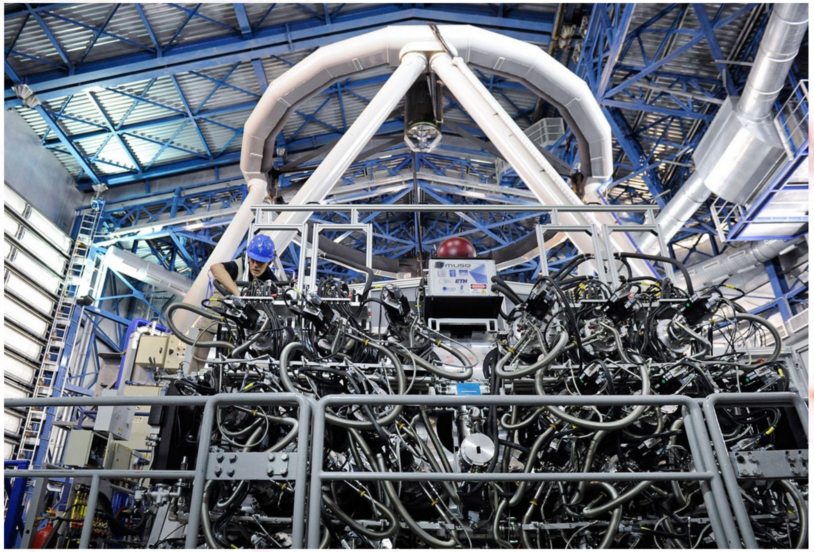
PMAS@CAHA

WEAVE @ WHT

MEGARA @ GTC

Some IFUs in the South



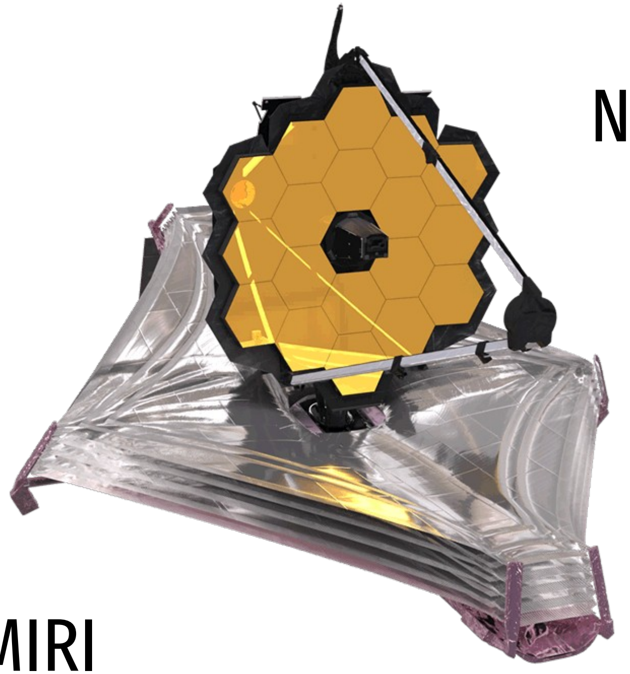


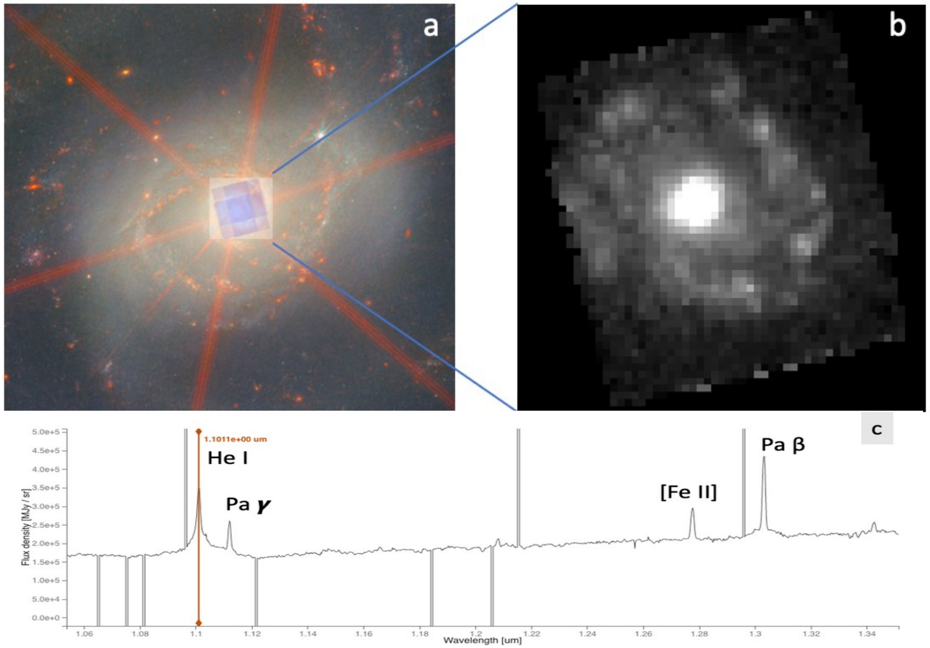
VIMOS, SINFONI... @MUSE

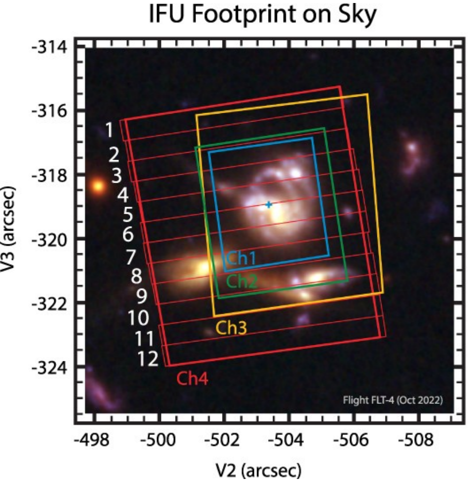
Some IFUs in the Space

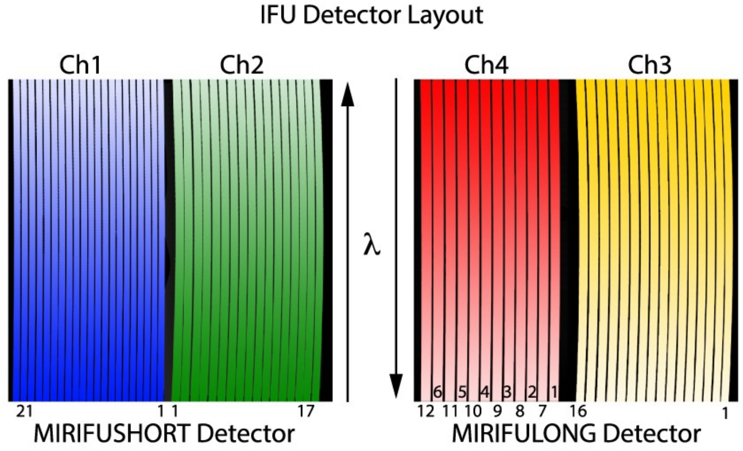
NIRSpec

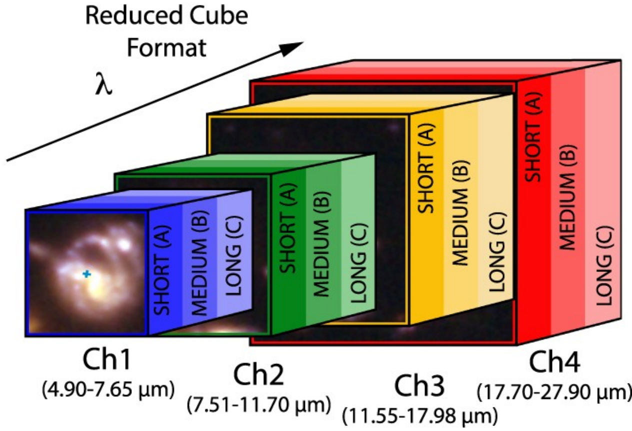
MIRI





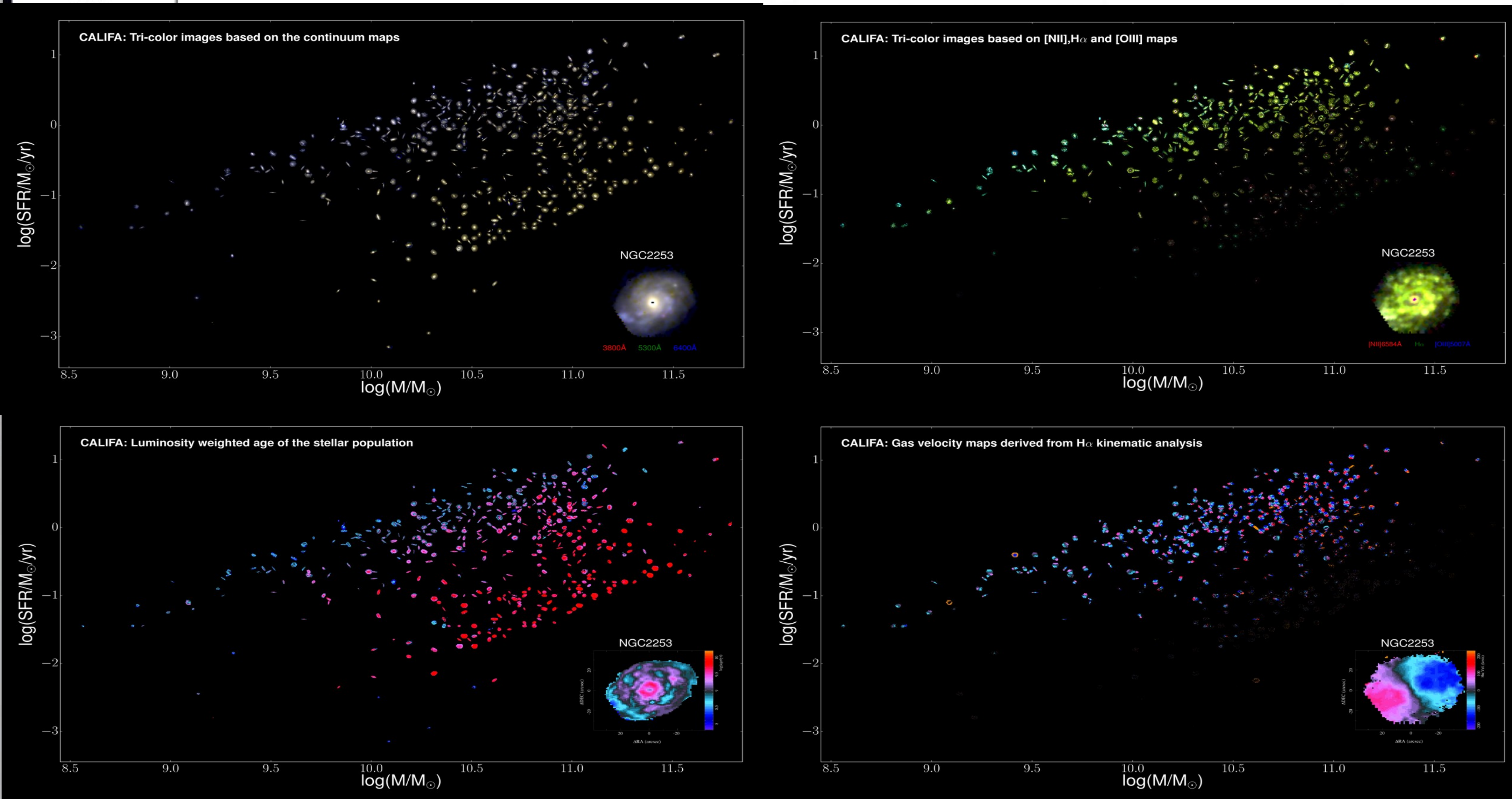






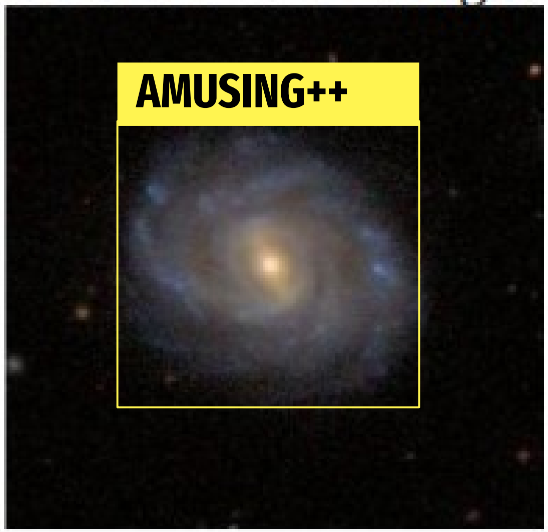
JWST: NIRSpec & MIRI

IFS Galaxy Surveys: (i) cover a large fraction of the optical extension of each galaxy; (ii) large/representative samples, (iii) stellar population analysis, (iv) ionized gas content, (v) kinematics and dynamics.

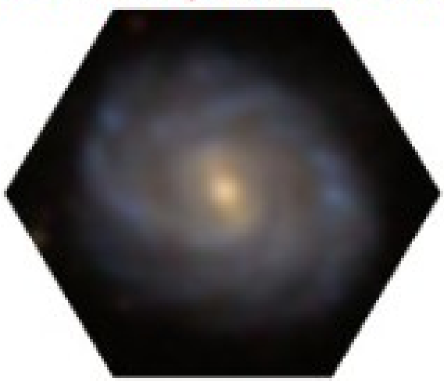


Only possible with dedicated pipelines: Pipe3D (CALIFA, MaNGA, SAMI and AMUSING++), DAP (MaNGA), Firefly (MaNGA), PyCASSO (CALIFA), LZIFU (SAMI)...

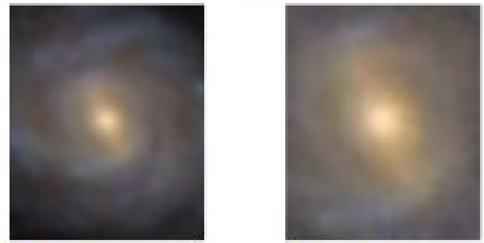
SDSS 90"x90" image



CALIFA (V500/V1200)



Atlas3D



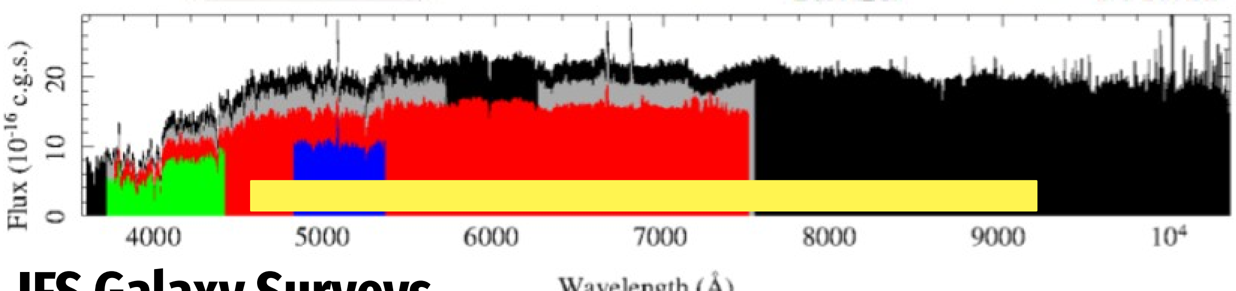
Z~Z califa   Z~Z Atlas3D

MaNGA largest FoV

FoV~1.5Re   ~2.5Re

SAMI

Z~Z califa   Z~Z SAMI



eCALIFA
2x3x331 spaxels; 2.7"/spaxel
974 galaxies of any type
~1.200.000 spec.; 3700-7500 Å

AMUSING ++

MUSE: 90000 spaxels, 0.2"/spax
Compilation of ~900 galaxies
~40M spec. 4650-9300 AA

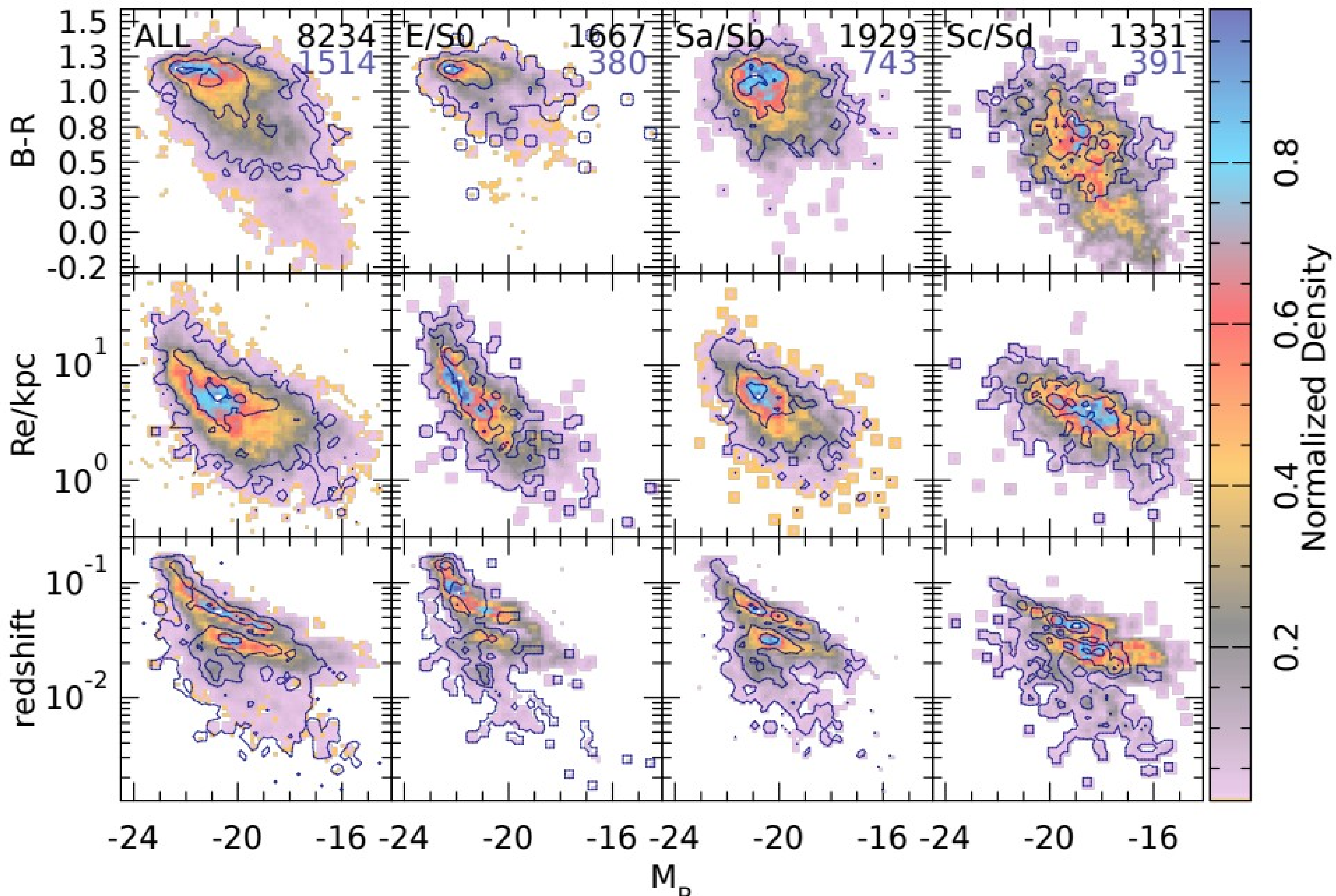
(AMUSING,MAD, TIMER,GASP...)

MaNGA
3x(19-127) spaxels; 2"/spaxel
7000 gal. of any type (~1.5Re)
2000 gal. of any type (~2.5Re)
1000 gal. of any type (any Re)
~800.000 spec.; 3550-10000 Å

SAMI
9x61 spaxels; 1.6"/spaxel
3400 galaxies of any type
~1.900.000 spec.; 3700-9500 Å

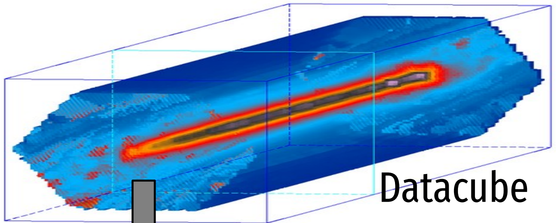
IFS Galaxy Surveys

IFS-GS Compilation

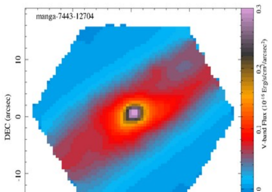


We compiled a total of ~8000 galaxies in the nearby Universe (~100Mpc), observed using IFS (MaNGA, CALIFA, MUSE and SAMI public data). Of them ~ 1500 are "well resolved" and sampled, i.e., Re>2 $FWHM_{psf}$ and they are sampled up to 2.5 Re. We analyze all them using Pipe3D, and homogenize the resolution and sampling differences (details in Sánchez et al. 2021).

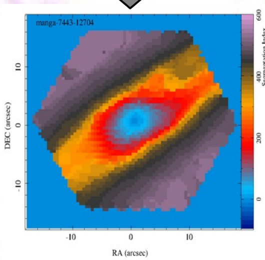
Pipe3D: An IFS analysis pipeline for MaNGA, CALIFA, SAMI and AMUSING.



Datacube

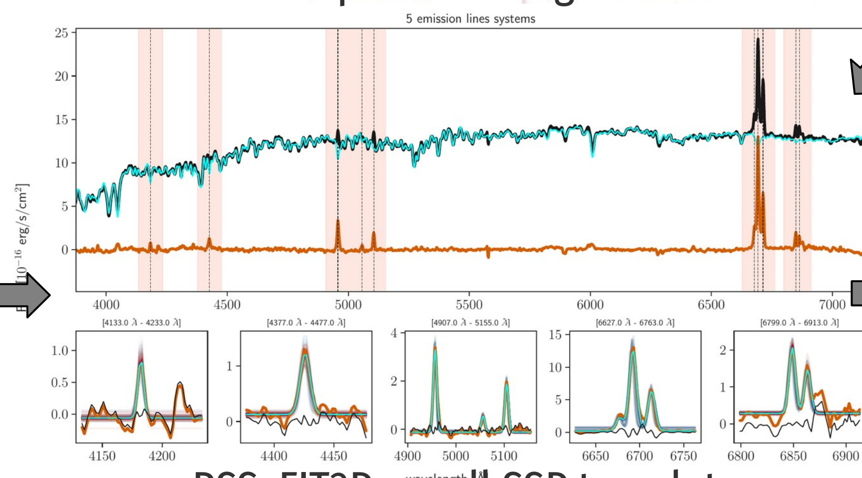


Broad-band + S/N



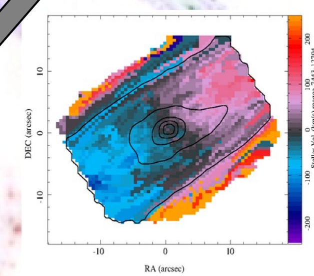
Central Aperture+FIT3D
+small SSP template +Strong Em. lines

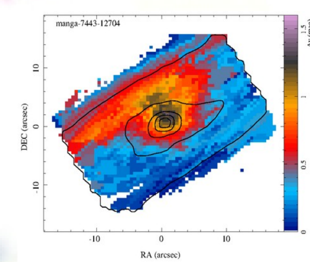
- Sys. Velocity
- σ_{cen} vel. dispersion
- Range of parameters

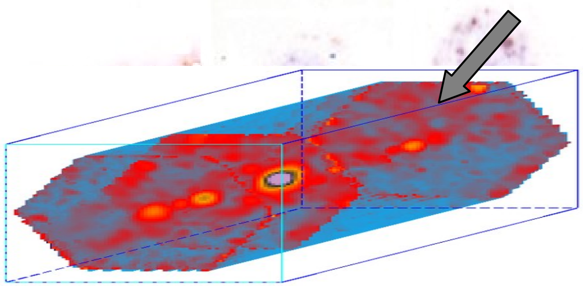


RSS+FIT3D+small SSP template
+Strong Emission Lines

- Stellar Vel. map.
- Stellar σ map.
- Stellar Av map.





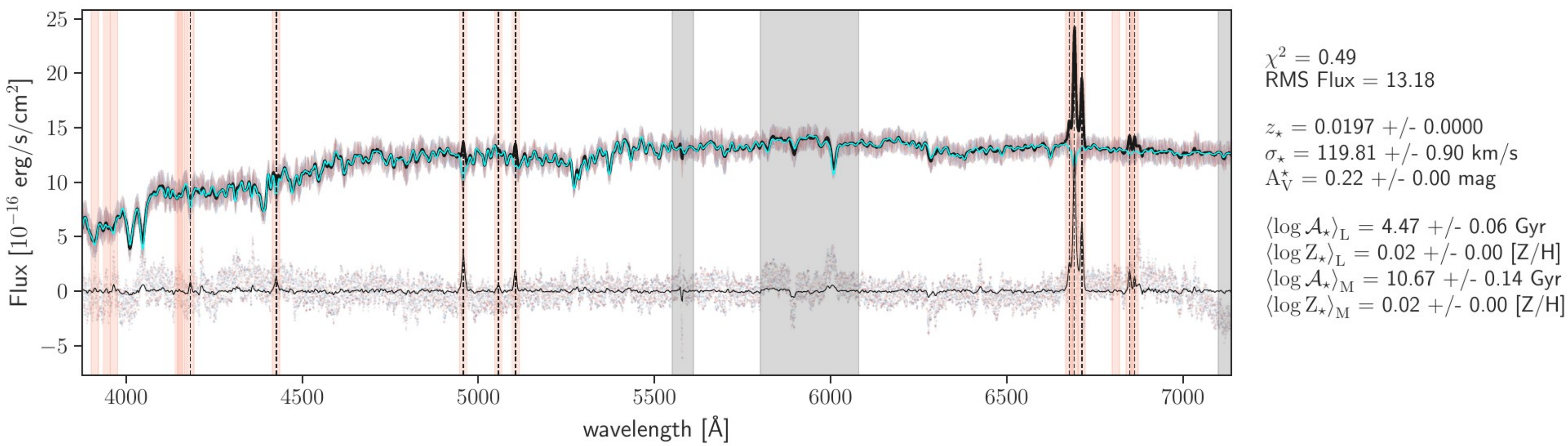


Gas pure Datacube →
Analysis of the strong and weak emission lines

Gas "cleaned" datacube
RSS-segmented
FIT3D+large SSP template
SFH, Age, [Z/H], St. Mass

Sánchez et al., 2016, RMxAA, 52, 171

Archaeological approach: Model the spectra to recover the SF and ChE histories



$\log Z_\star$ [Z/Z$_\odot$] \ $\log t_\star$ [yr]	6.00	6.48	6.60	6.75	6.95	7.00	7.10	7.15	7.25	7.30	7.40	7.50	7.60	7.75	7.80	7.80	7.85	8.00	8.05	8.10
0.22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.00	0.0	0.3	0.0	0.0	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
−0.40	0.0	0.8	0.1	0.0	0.5	0.8	0.6	0.2	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
−0.71	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

$\log Z_\star$ [Z/Z$_\odot$] \ $\log t_\star$ [yr]	8.20	8.30	8.45	8.55	8.70	8.85	8.95	9.05	9.10	9.15	9.30	9.40	9.55	9.65	9.80	9.90	10.00	10.10	10.15
0.22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	3.3	4.5	0.0	3.0	0.0	10.4	0.0	0.0	0.0	0.0
0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.7	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	47.7	3.7
−0.40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.7
−0.71	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	2.4	0.0	0.0

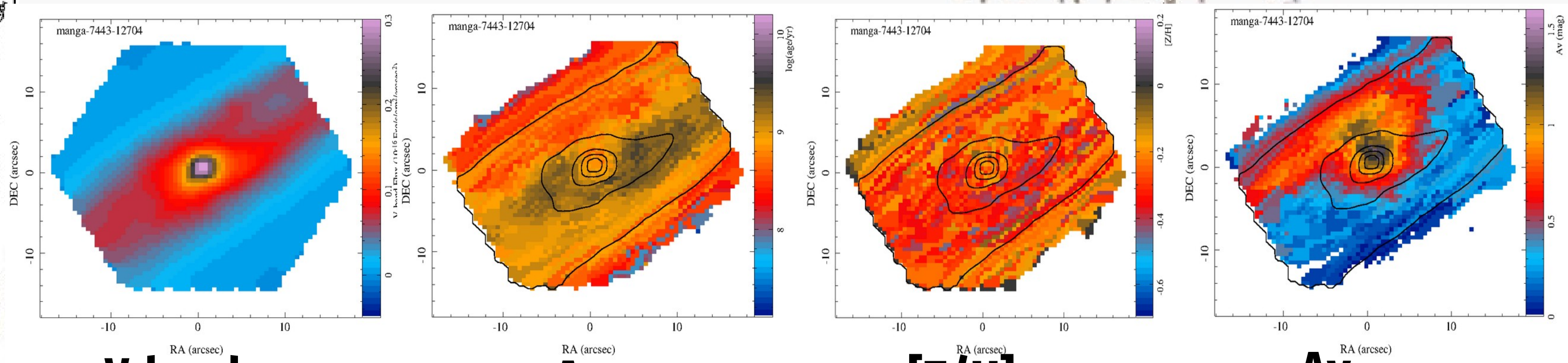
Sánchez et al. 2016; Lacerda et al. in prep.

$$S_{obs}(\lambda) \approx S_{mod}(\lambda) =$$

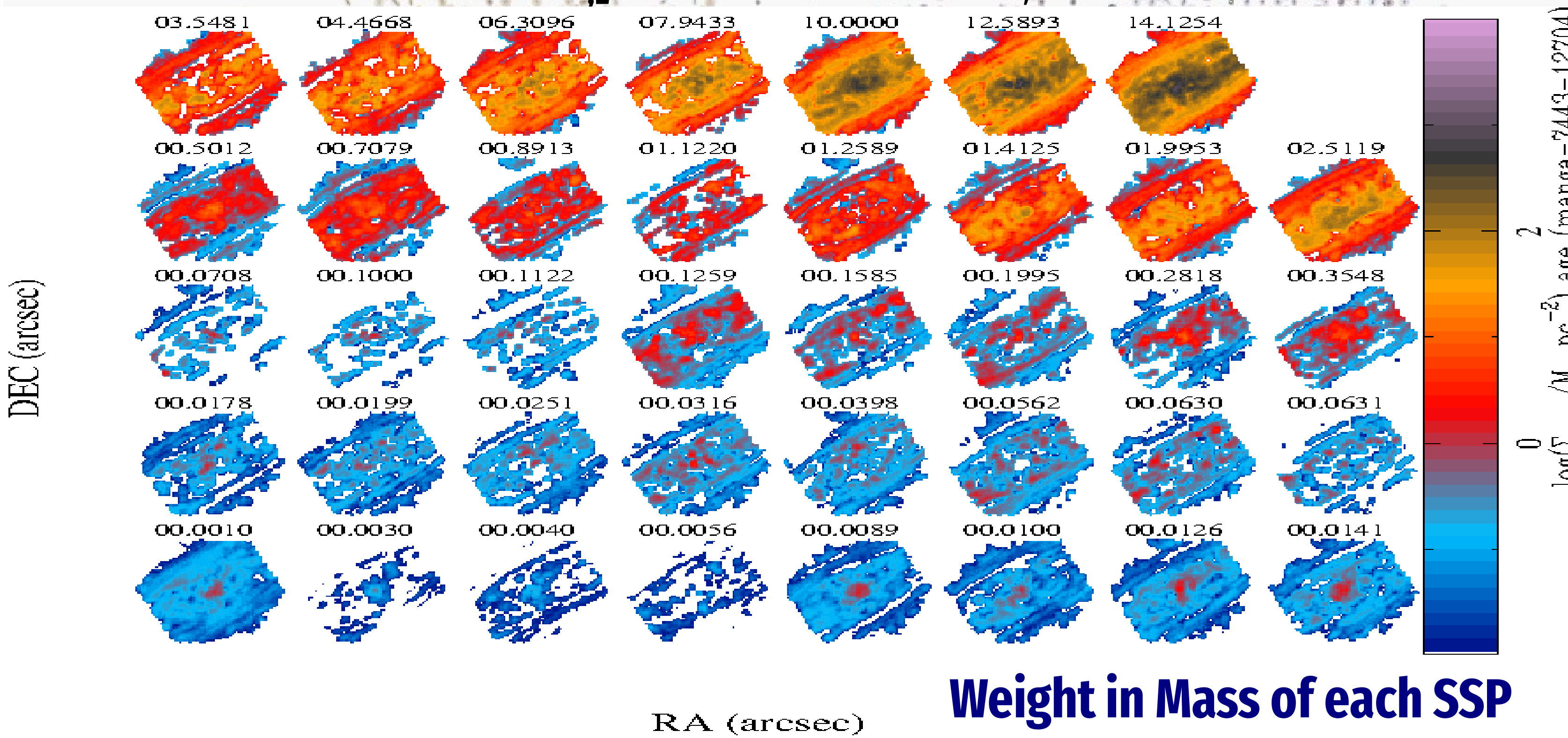
$$\left[\Sigma_{ssp} w_{ssp} S_{ssp}(\lambda)\right] 10^{-0.4\, A_V\, E(\lambda)} * G(v, \sigma)$$

Tinsley et al. 1972-80
Conroy 2013

Pipe3D: Stellar Data products

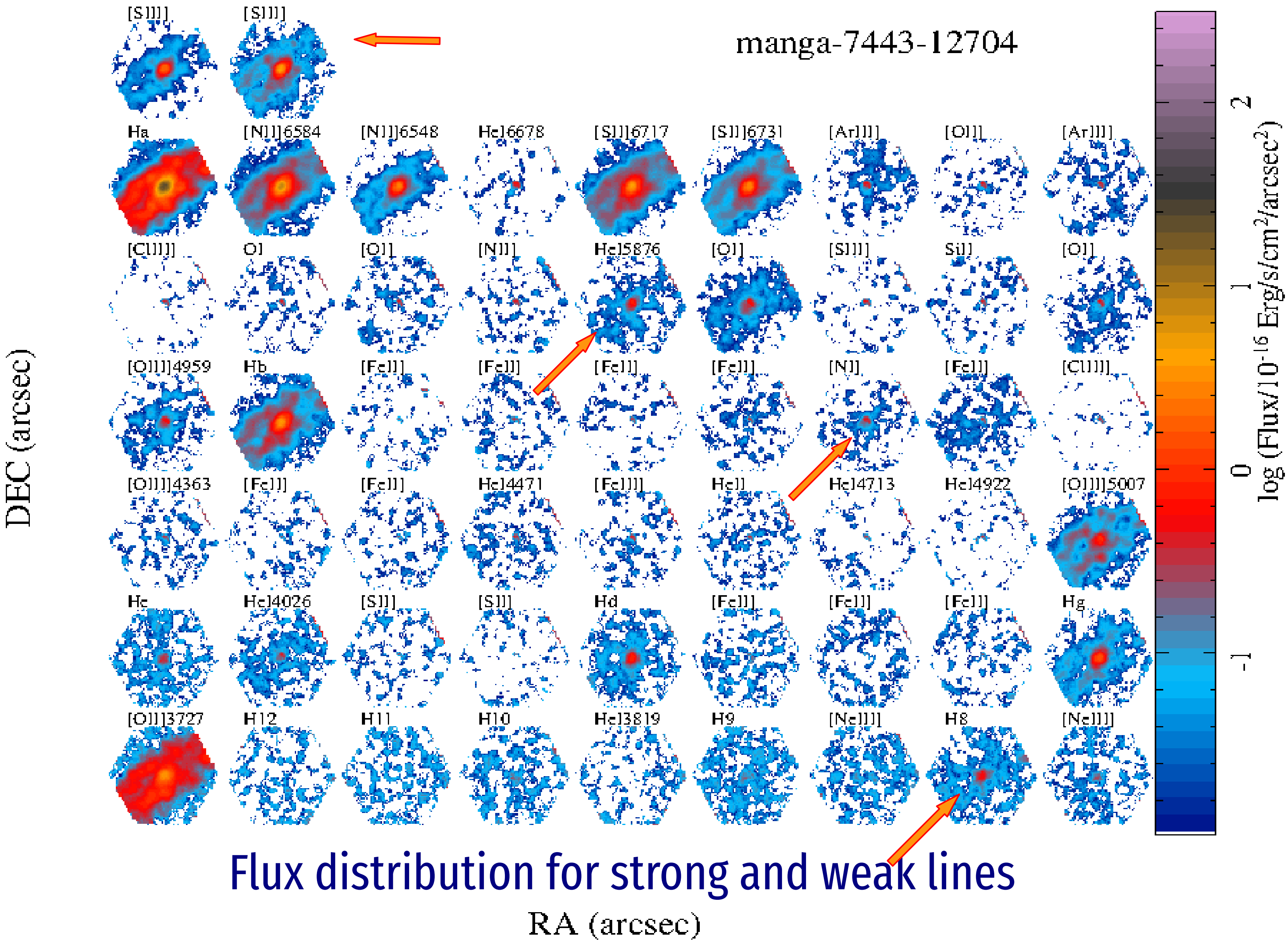


V-band $A_{*,L}$ $[Z/H]_{*,L}$ $Av_{*,L}$



Weight in Mass of each SSP

Pipe3D: Gas Data products

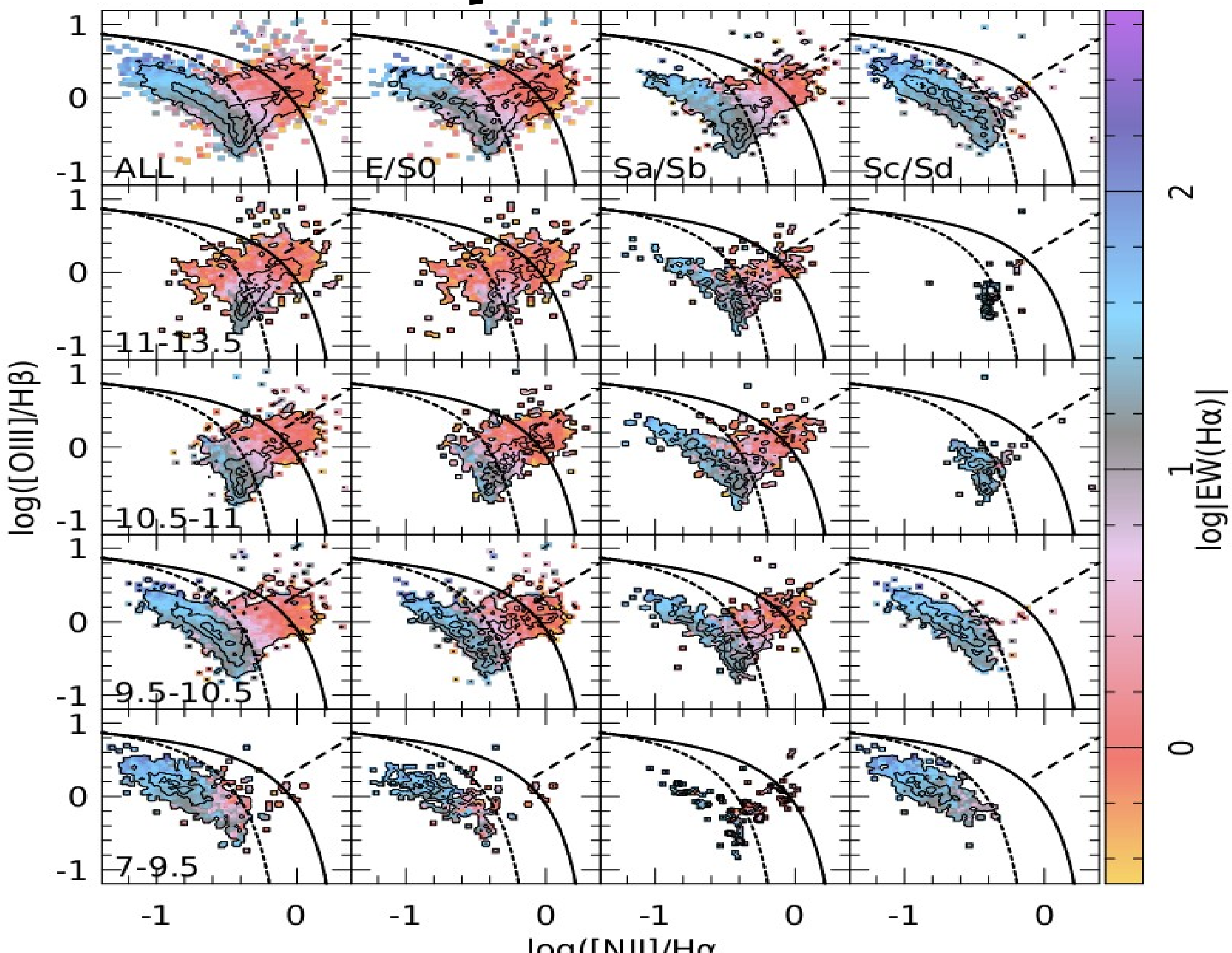


Flux distribution for strong and weak lines

Global Properties of Galaxies

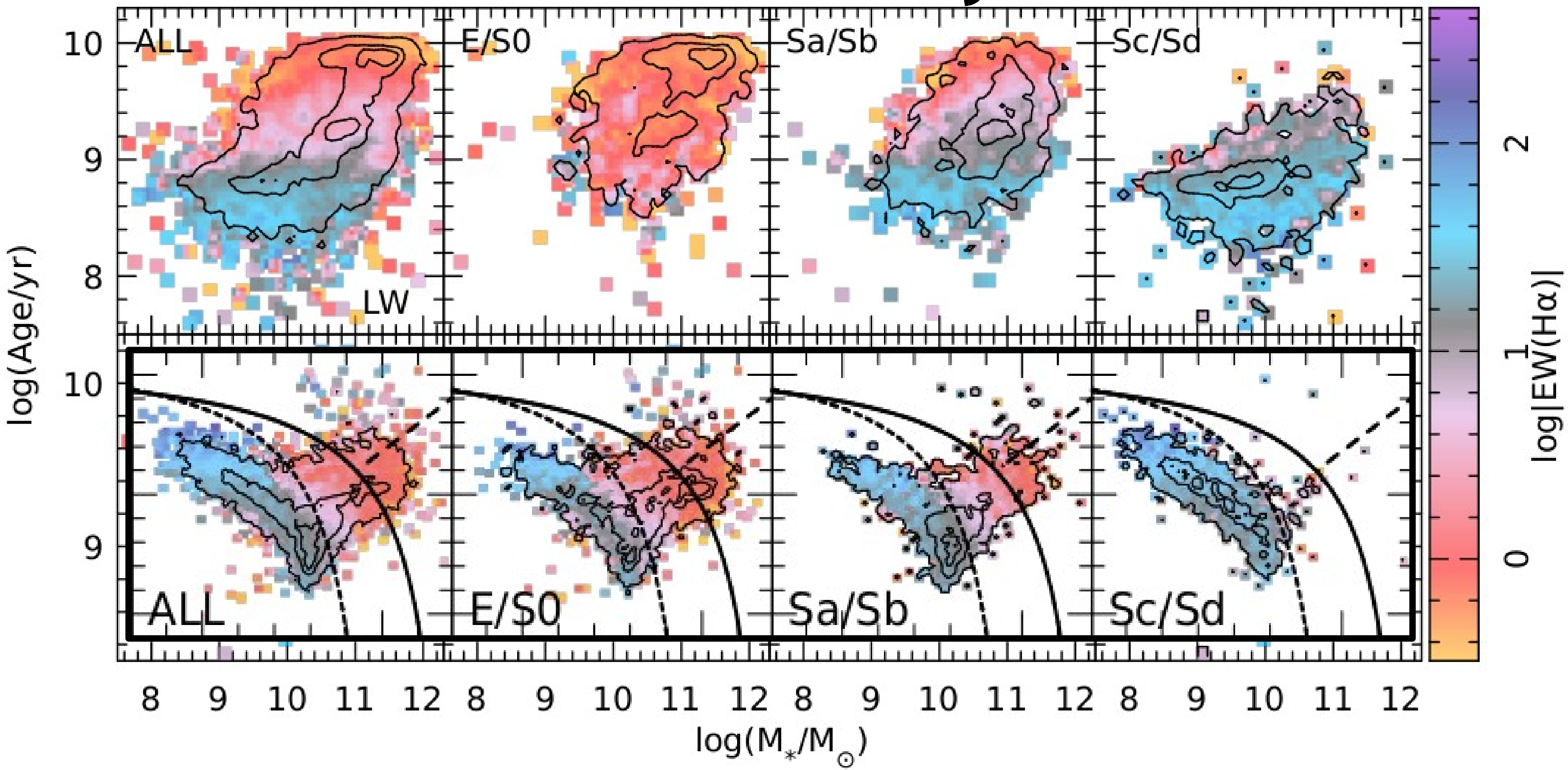
What we knew before IFS-GS?

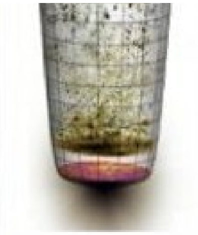
Global Properties of Galaxies



Dominant ionizating source depends on M* and morphology: (I) SF dominates in late-type, less massive galaxies (e.g, Kauffmann et al. 2003; Lacerda et al. 2018), (ii) post-AGB ionization (LINER-like) dominates in early-type (Signh et al. 2013; Gomes et al. 2016), more massive galaxies (Stashinska et al. 2008; Cid Fernandes et al. 2010), (iii) AGN are hosted mostly in early-type spirals (Schawinski et al. 2010; Sánchez et al. 2019).

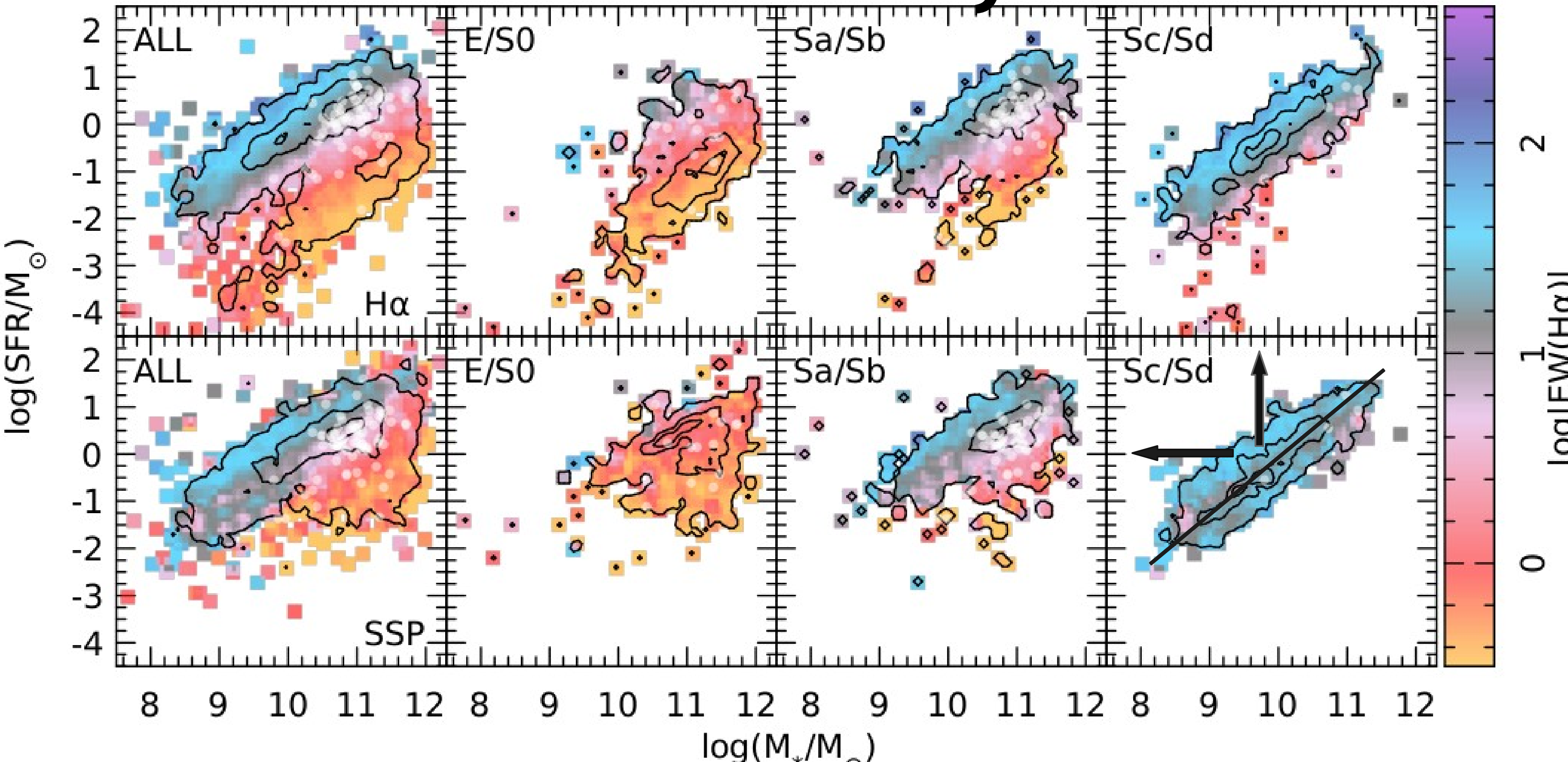
Global Properties of Galaxies
- bimodality -





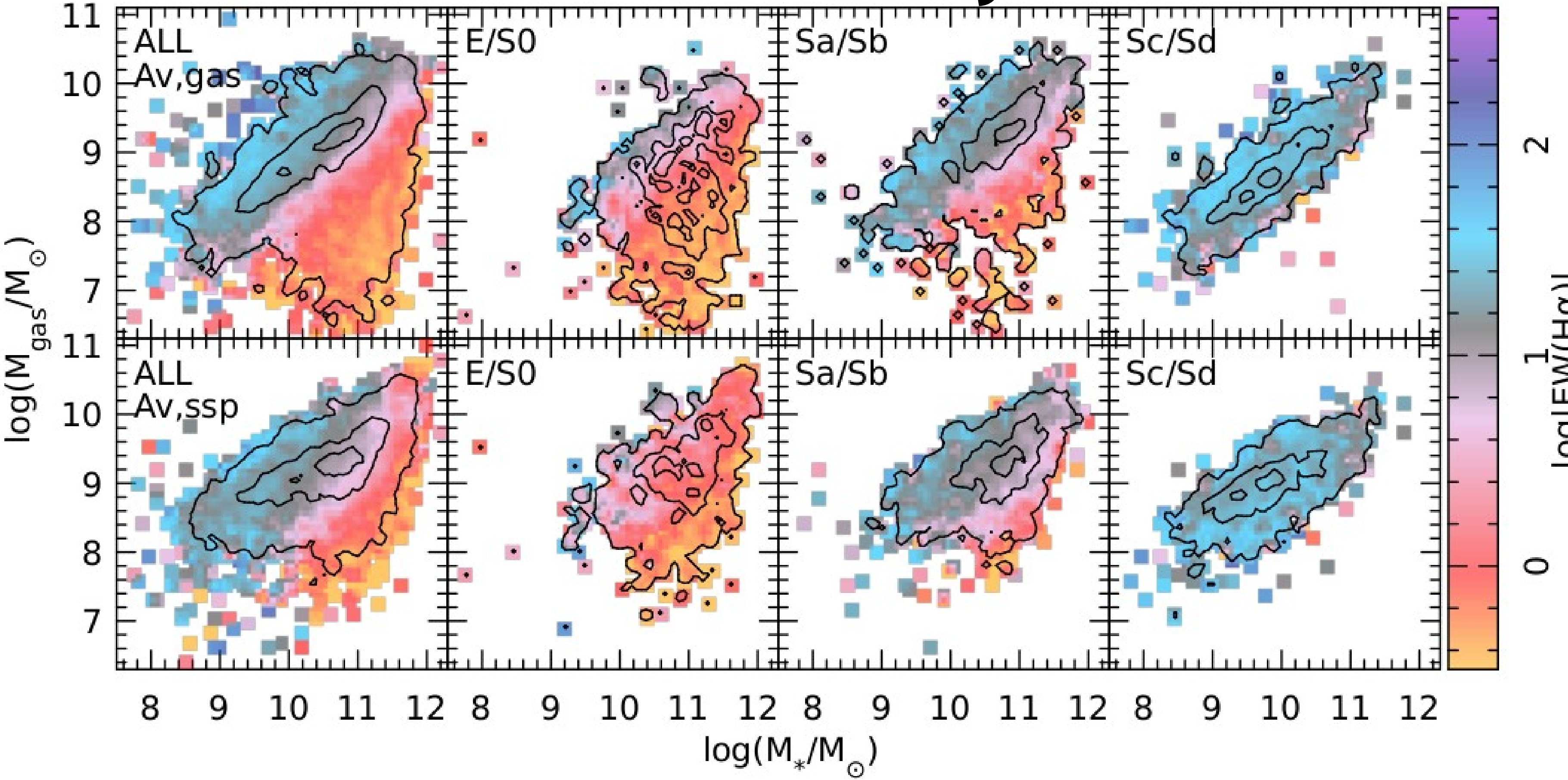
Large (spectroscopic/imaging) surveys have allowed to explore the evolution of galaxies using large samples, statistically well defined (SDSS, York et al. 2000; GAMA, Driver et al. 2009) . Galaxies present a clear bimodality that depends on the morphology and the mass.

Global Properties of Galaxies
- bimodality -



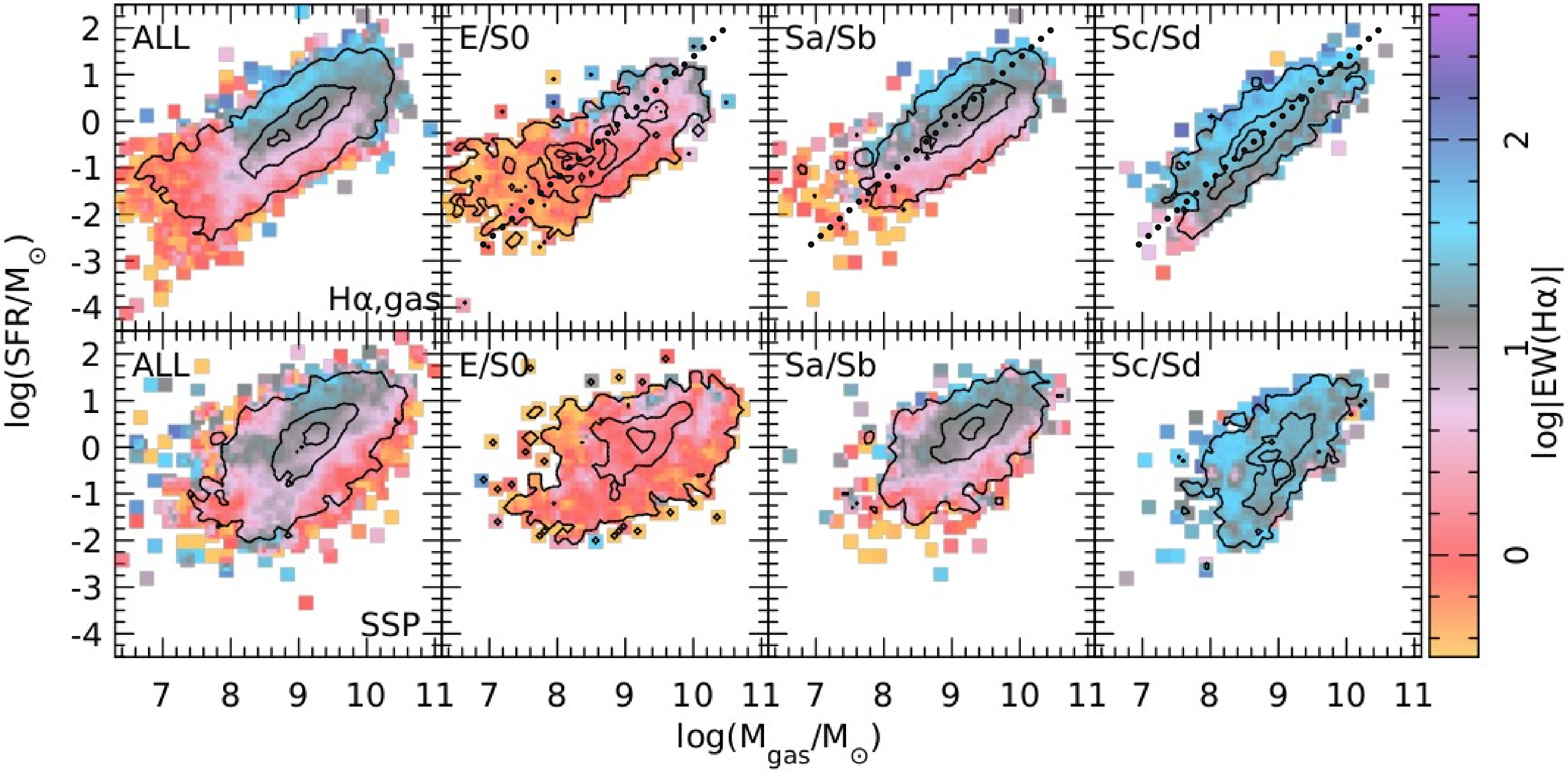
SFGs/RGs segregates pretty well along the SFR-M* diagram. SFGs follow a well defined sequence (SFMS; Renzini & Peng 2015), that evolves with time (Speagle et al. 2014; Sánchez et al. 2019). There should be a fast transition between SFGs and RGs (lack of GVGs). AGNs are mostly in the GV (Kauffman et al., 2003; Schawinski et al. 2010)

Global Properties of Galaxies
- bimodality -



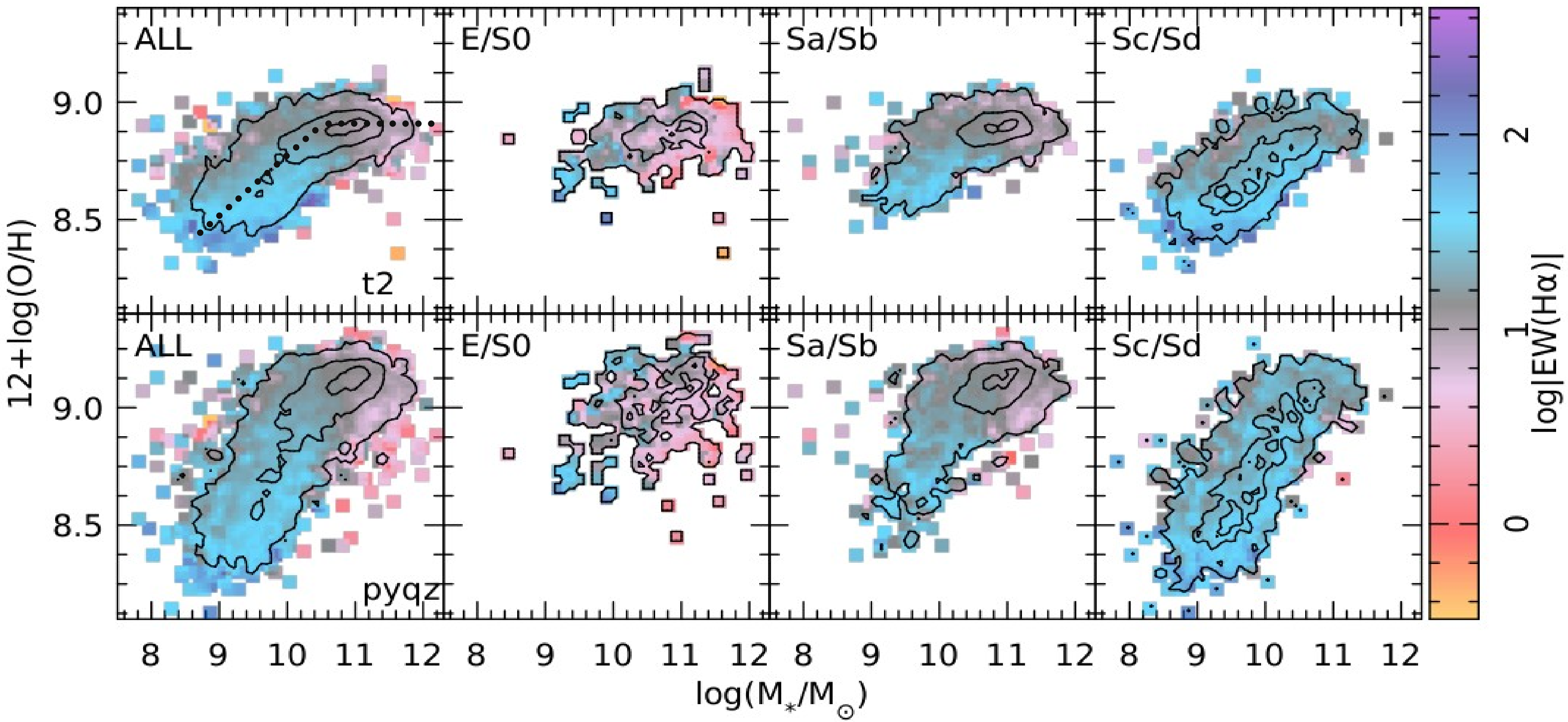
Galaxies halt SF primarily due to a lack of (molecular) gas, that affects mostly to early-type galaxies (e.g. Saintoinge et al. 2011; Calette et al. 2019).

Global Properties of Galaxies
- bimodality -



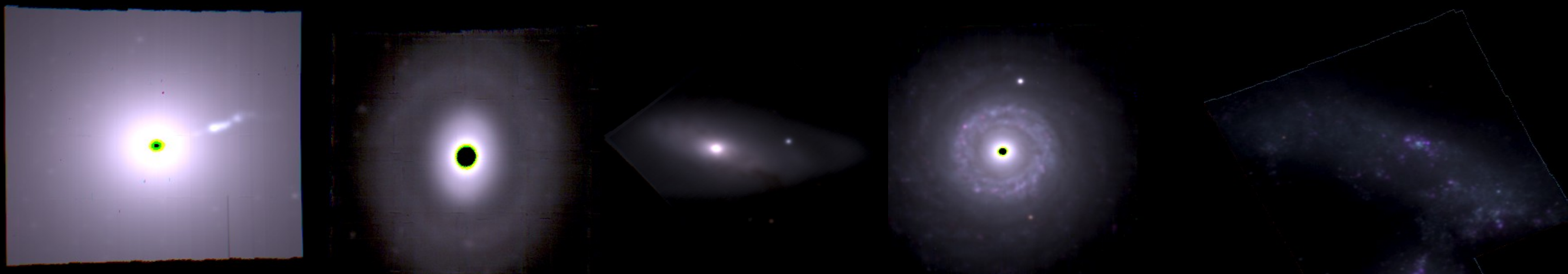
However, depletion time (τ=SFE^{-1}; SFE=SFR/M_{gas}) changes along M* and the morphological type (e.g., Davies et al. 2014; Colombo et al. 2014).

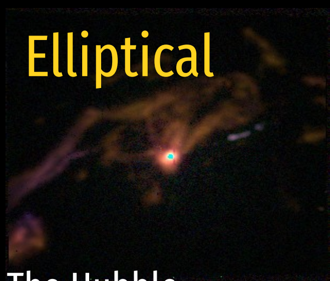
Global Properties of Galaxies
- Scaling relations -



SFGs present different scaling relations: (1) SFMS (SFR-M_*); (2) SK-law (SFR-Mgas); (3) MGMS (Mgas-M_*); and (4) Mass-Metallicity relation (MZR, Tremonti et al. 2004). The MZR is not lineal. It presents two regimes, a lineal one (M_*<$10^{9.5}$ $M_\odot$) and a plateau (M_*~10^{11} $M_\odot$): Outflows/inflows equilibrium?

However, galaxies are resolved objects: SF, ionization, metal enrichment are local processes, not global ones.





The Hubble Sequence Observed By AMUSING (PI: J. Anderson, Galbany et al. 2016)

Top: B,R,I colour image,showing the stelllar populations.

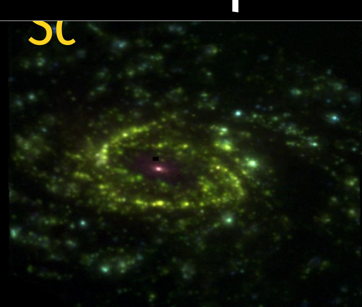
Bottom: [OIII] (B), Ha (G), [NII] (R), showing the ionized gas.

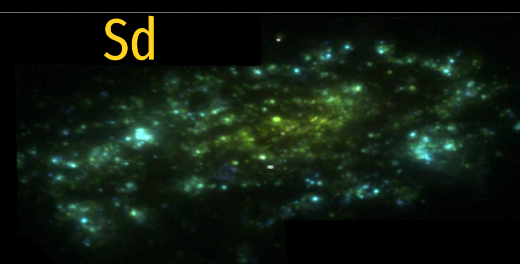
Are the scaling relations local or global?

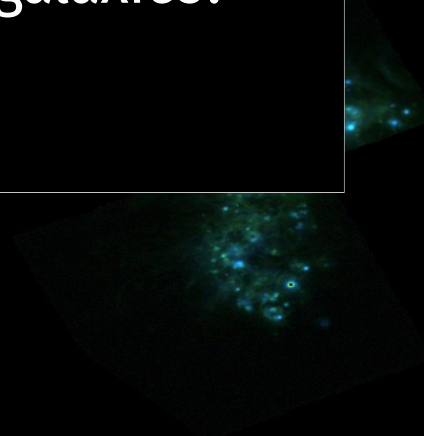
At which scales are still verified?

What they tell us about the evolution in galaxies?

IFS is required!!!

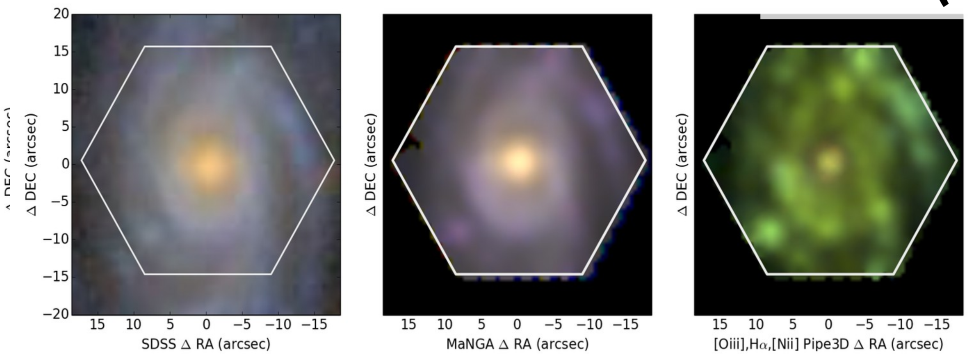


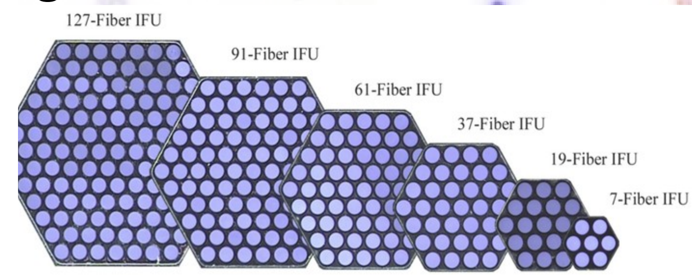




Not all IFS Galaxy Surveys provides the same information!

MaNGA (largest bundle)

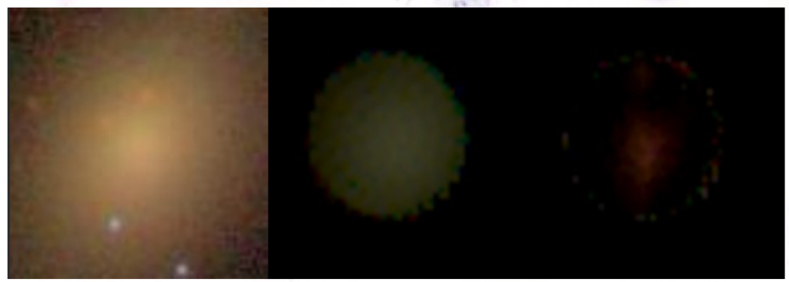




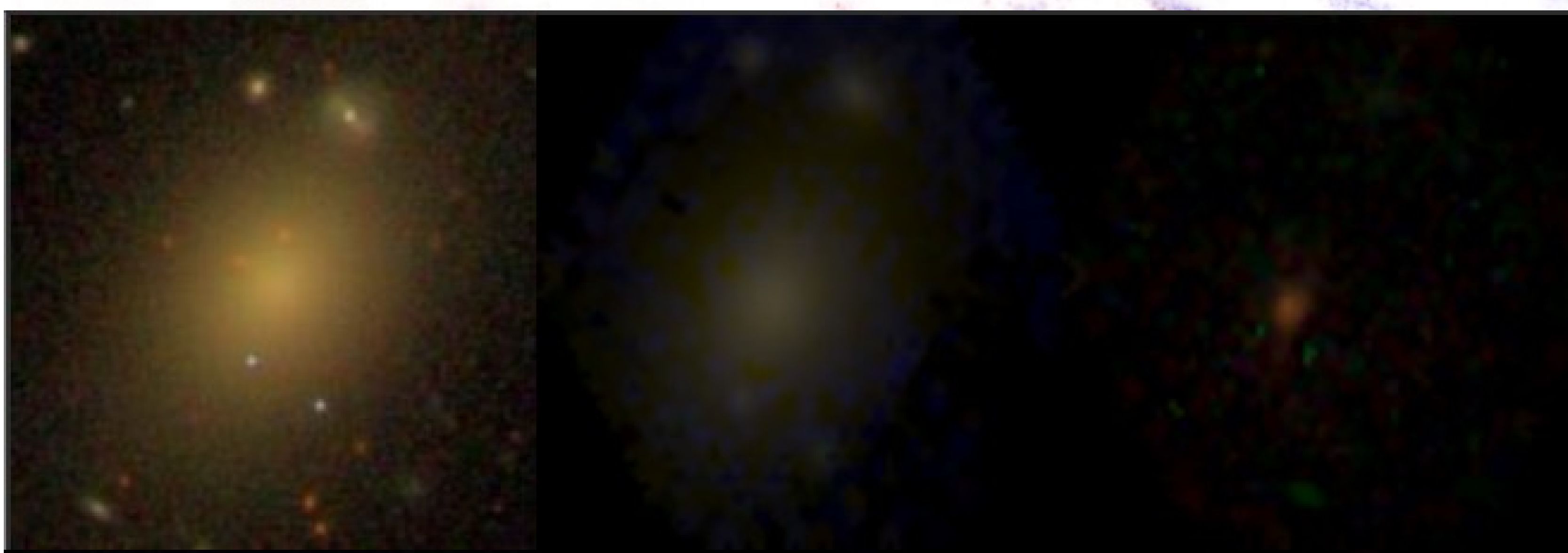
CALIFA

Not all IFS Galaxy Surveys provides the same information!

SAMI

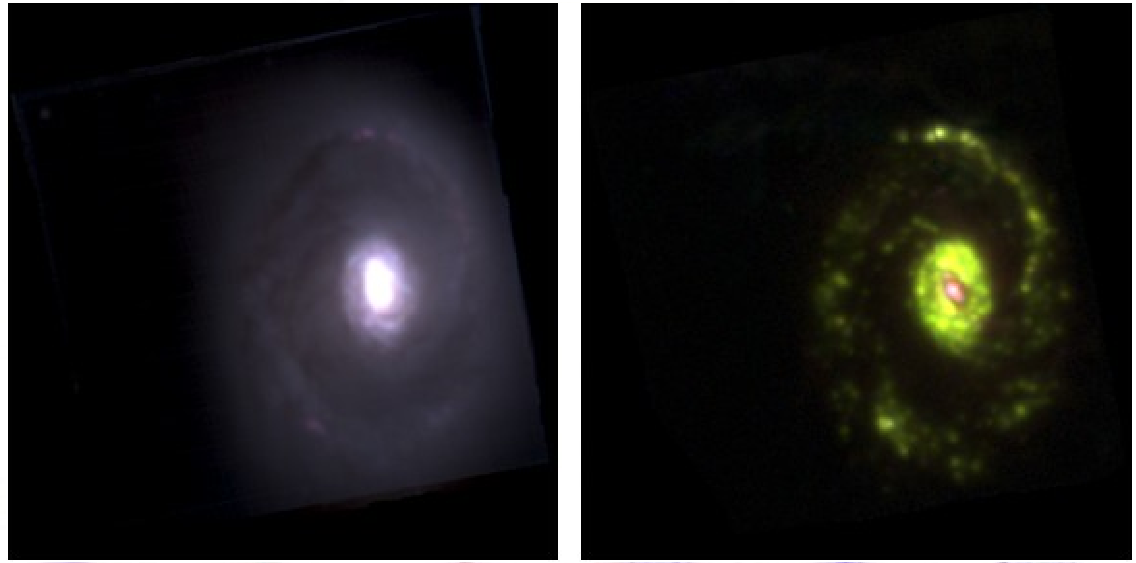


CALIFA



Not all IFS Galaxy Surveys provides the same information!

MUSE



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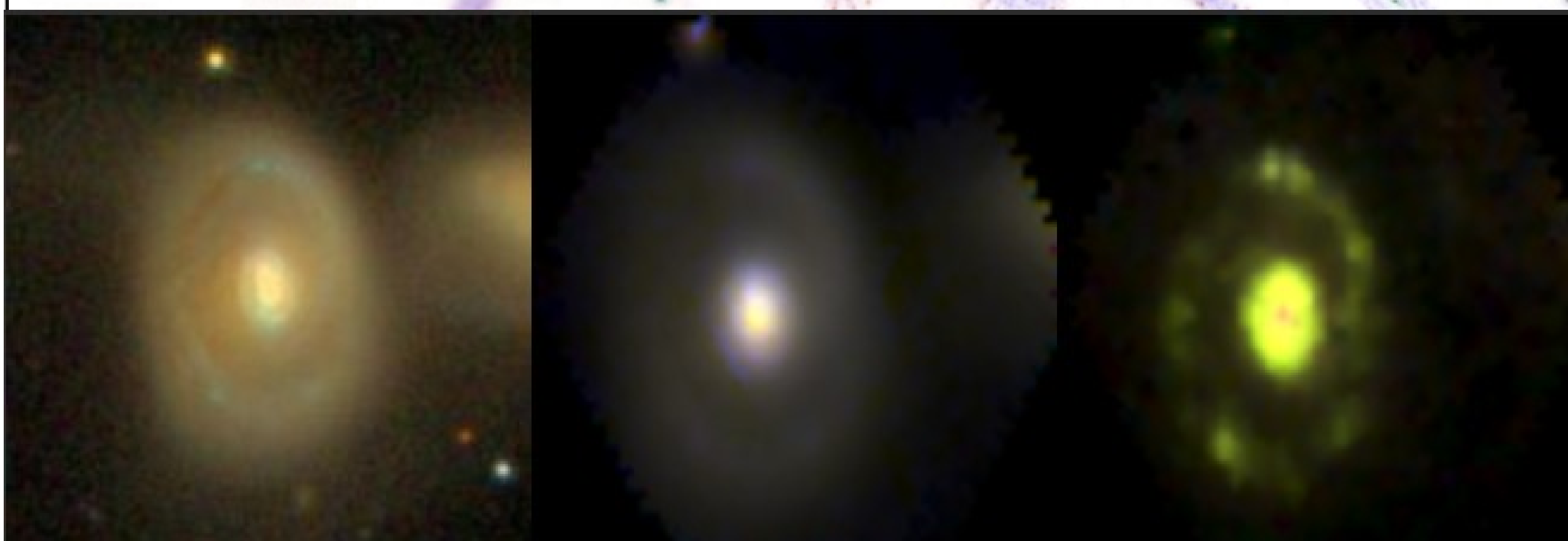
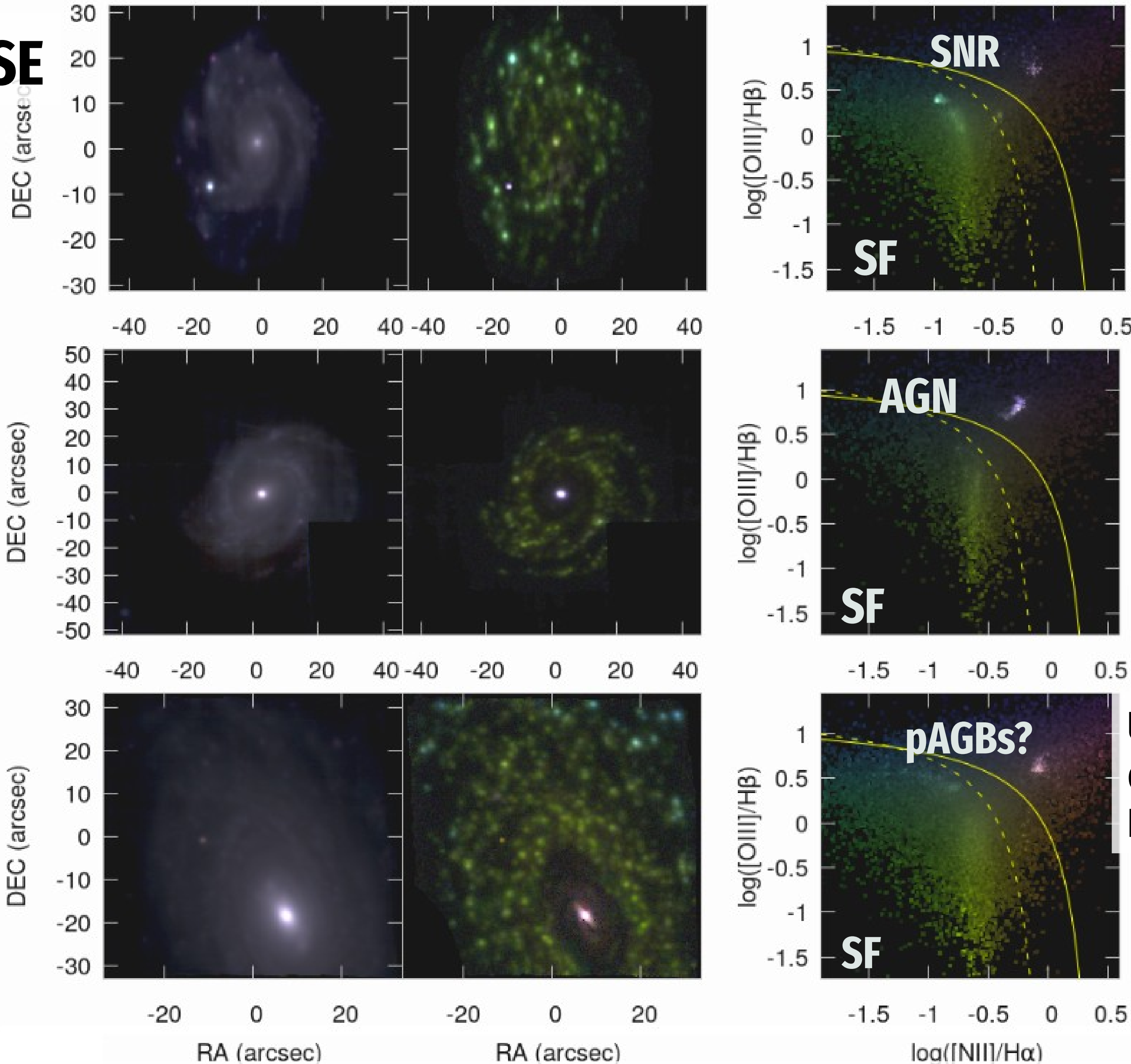


Resolved Properties of Galaxies

Ionizated gas

Gas is ionized by local processes

MUSE



Off-center, point-like, EWα>3Å

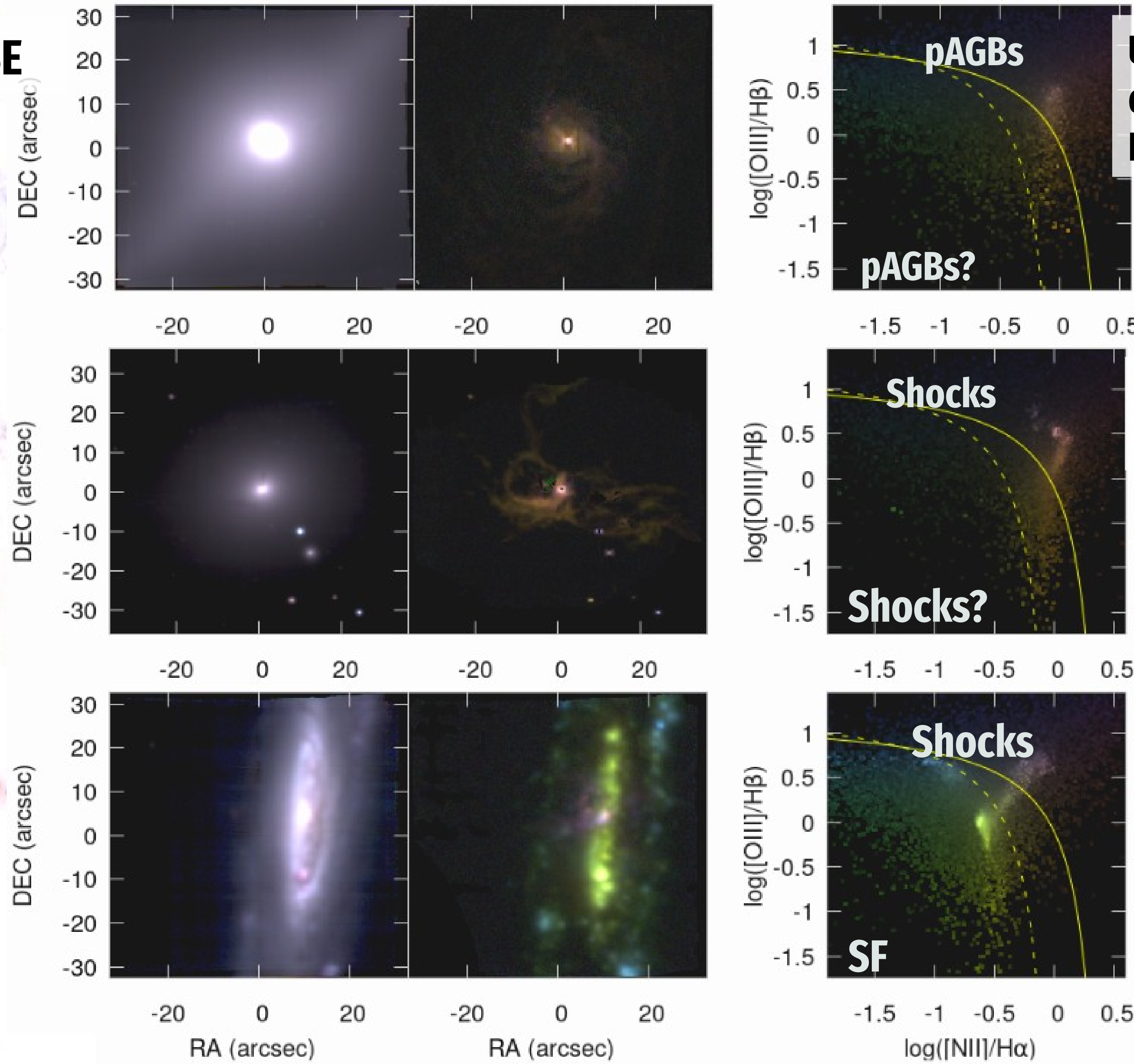
Centred, point-like, EWα>3Å

Ubiquitious, diffuse, EWα<3Å

Ionization associated with SF (OB stars) is always clumpy with EWα>>3A

Gas is ionized by local processes

MUSE



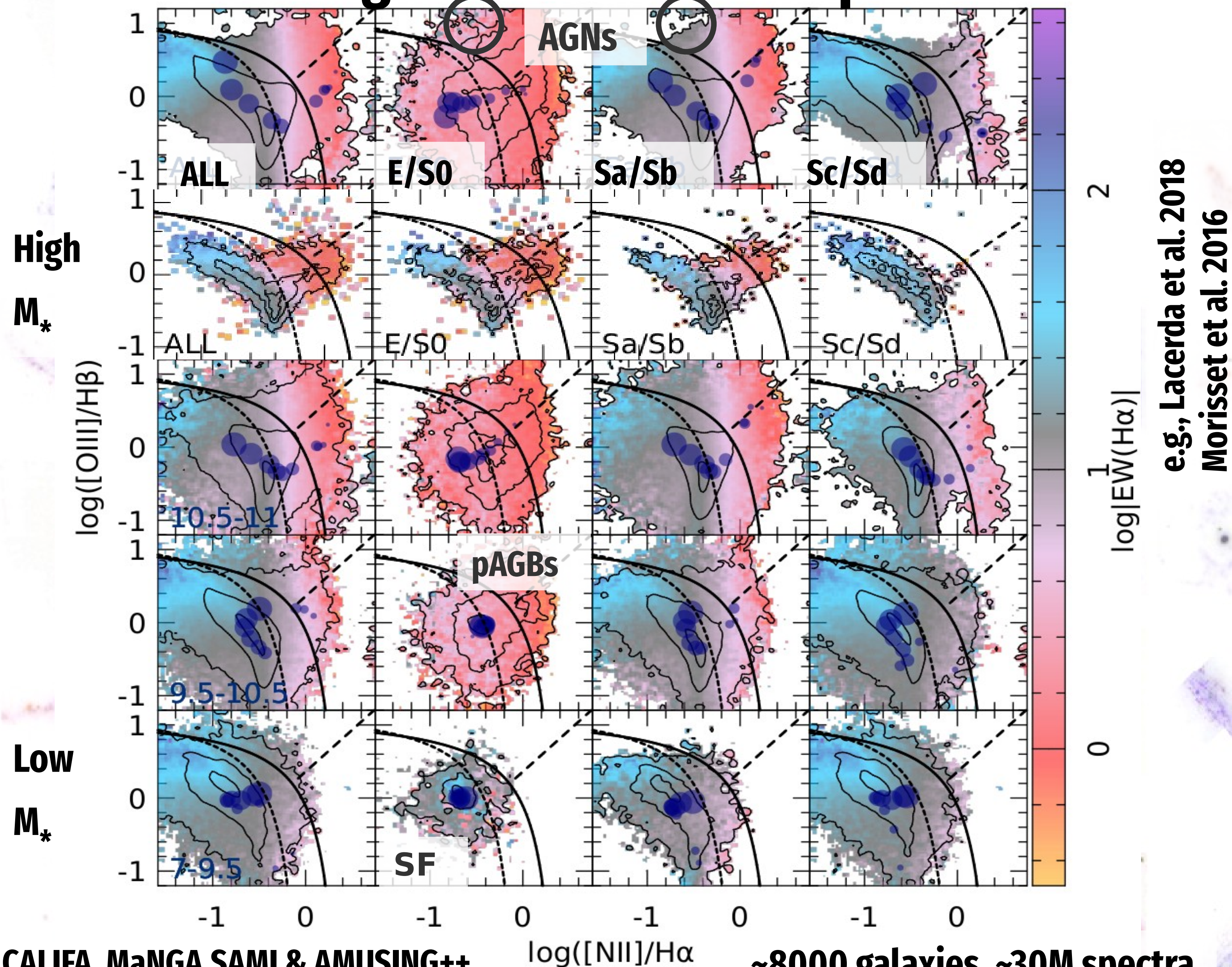
Ubiquitious, diffuse, EWα<3Å

Filaments, Any EWα

Outflow, biconical, EWα>3Å

Ionization associated with SF (OB stars) is always clumpy with EWα>>3Å

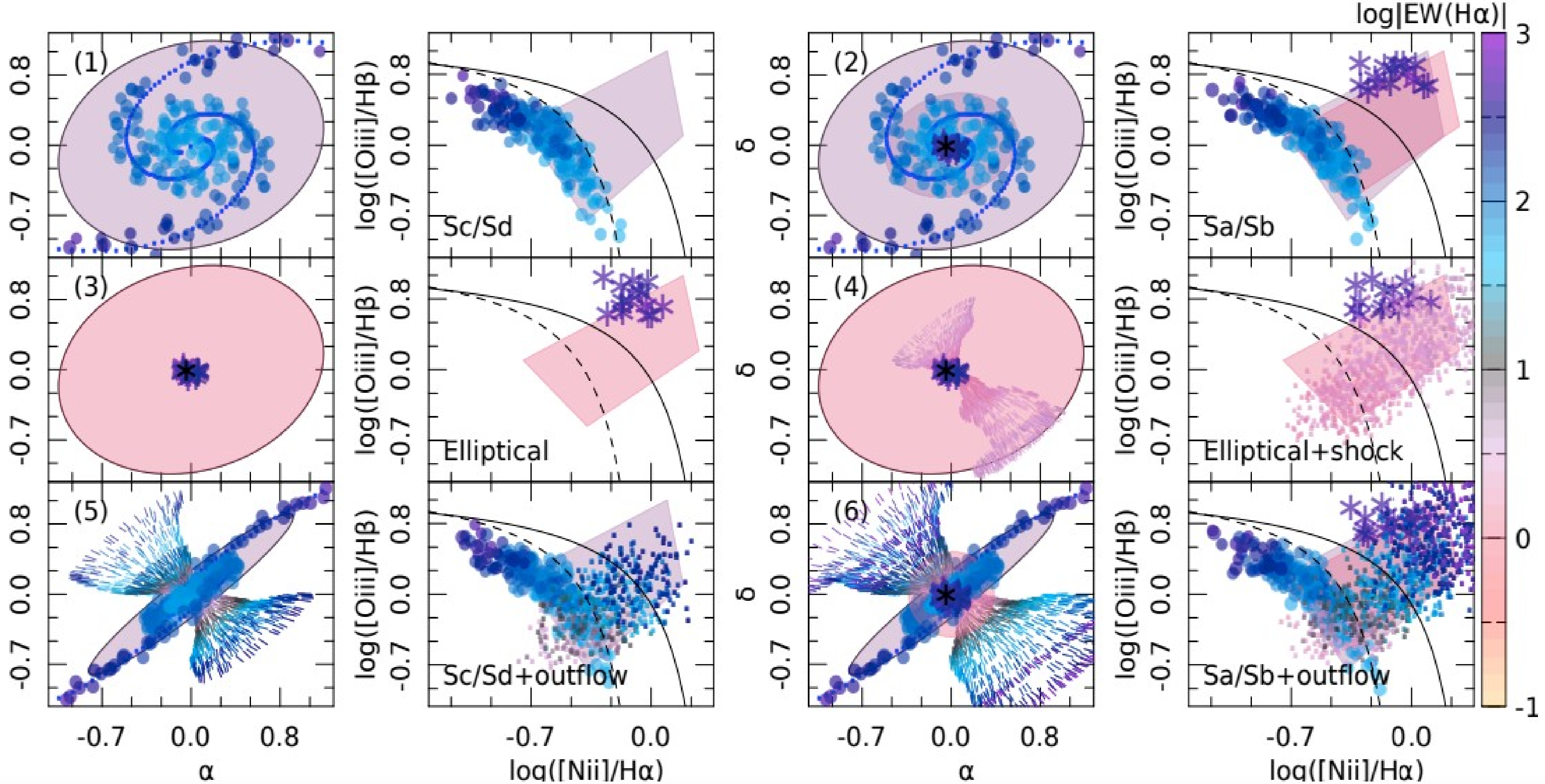
Ionized gas: Local vs Global patterns



CALIFA, MaNGA,SAMI & AMUSING++

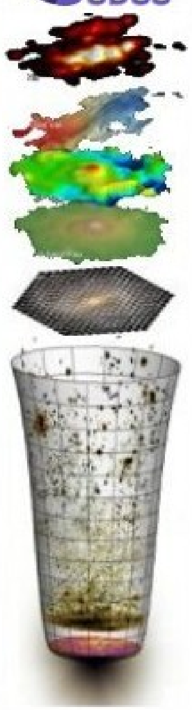
~8000 galaxies, ~30M spectra

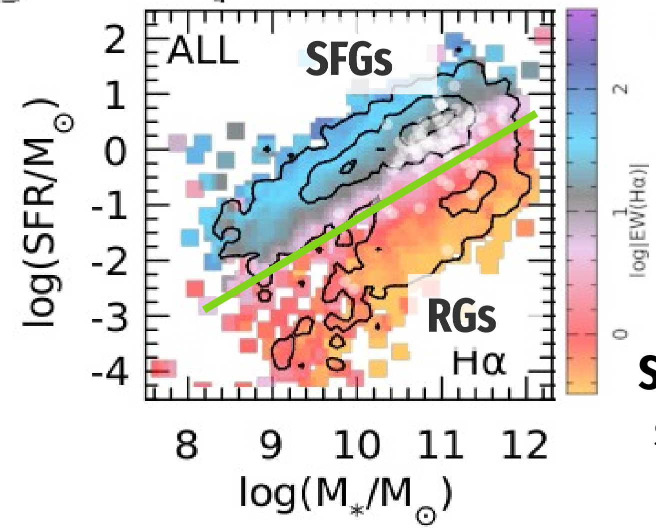
Ionized gas: Patterns depend on Morphology and Stellar Mass



Resolved Properties of Galaxies

Scaling Relations

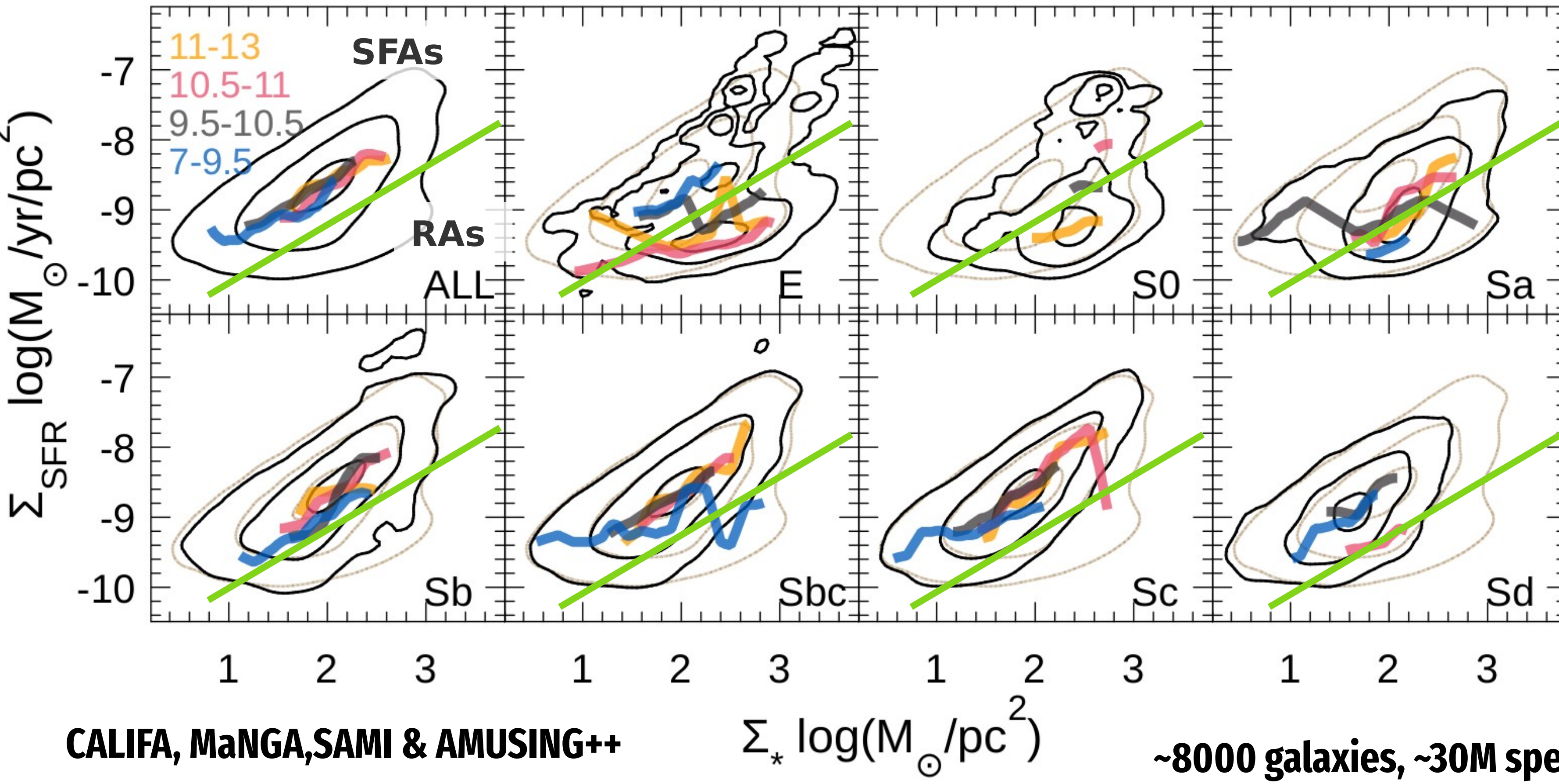




Ionized Gas: SFAs vs RAs rSFMS or Σ_* - Σ_{SFR} relation

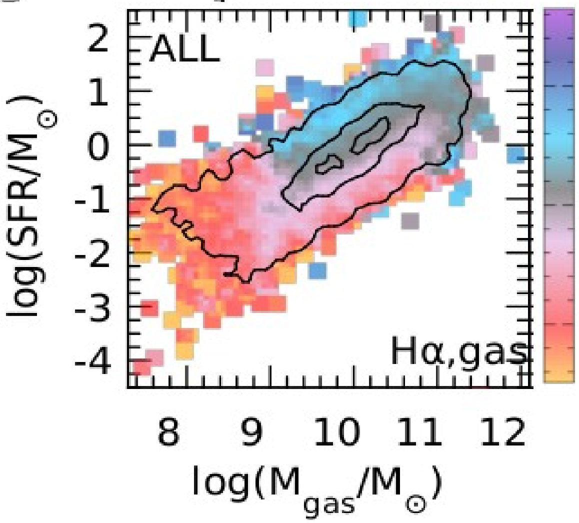
Sánchez et al. 2013 (z=0.01), Wuyts et al al. 2013 (z~0.7)
Cano-Diaz et al. 2016; Hsieh et al. 2017; Ellison et al. 2018; Bulck in prep.

SFAs (EWα>6Å) at kpcs scales follow a tight relation that depends slightly on the morphology, and less on the mass, and segregate them clearly from RAs (EWα<6Å). *The SFMS is local!*



CALIFA, MaNGA,SAMI & AMUSING++

~8000 galaxies, ~30M spectra

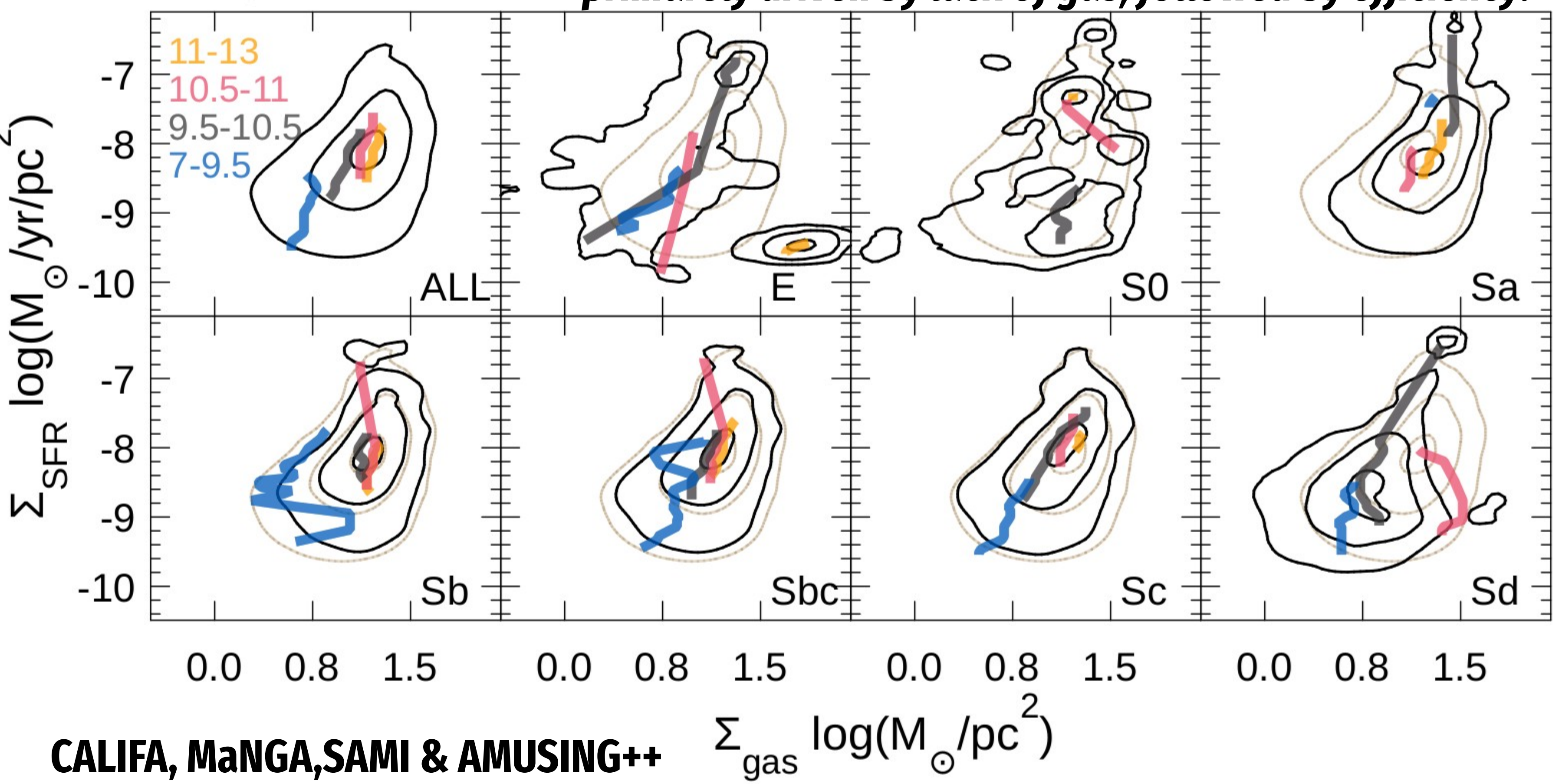


Ionized Gas: SK-law

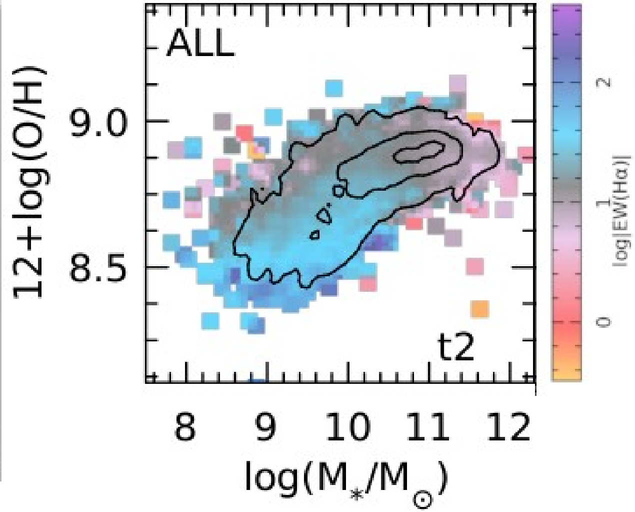
Kennicutt et al. 1998

Bolatto et al. 2017; Utomo et al. 2017; Colombo et al. 2018

The SK-law is verified at a kpc scales for the SFAs. RAs depart only slightly from the SK-law. They present a lower amount of (molecular) gas, but only a slightly lower SFE. *Quenching is primarely driven by lack of gas, followed by efficiency!*



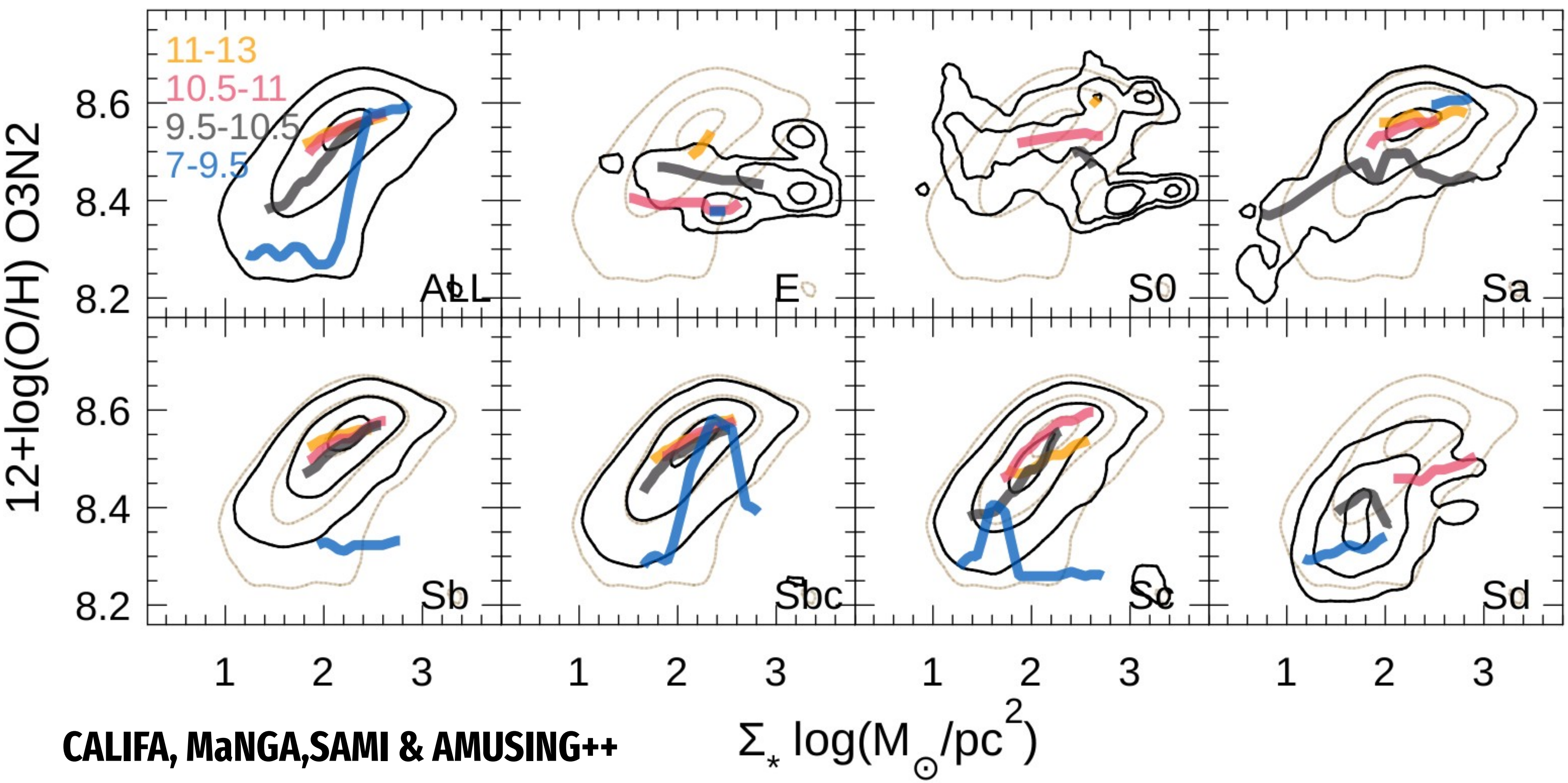
CALIFA, MaNGA,SAMI & AMUSING++



Ionized Gas: local enrichment rMZR or Σ_*- O/H relation

Rosales-Ortega et al. 2012, Moran et al. 2012; Sánchez et al. 2013; Barrera-Ballesteros et al. 2016

SF Areas at kpcs scales follow a tight relation with the oxygen abundance, with a similar shape to that of the global MZR. *The MZR is local!*

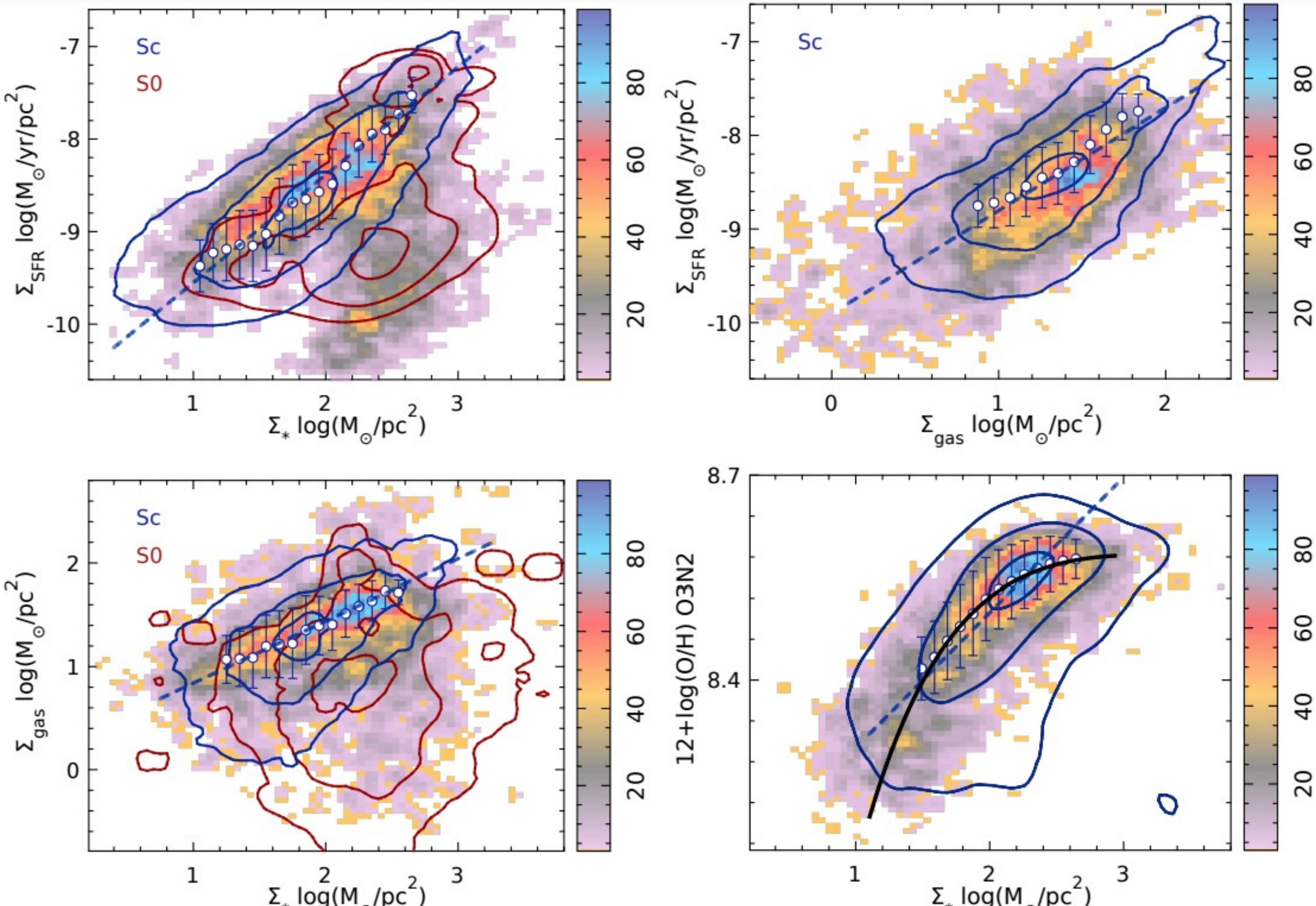


CALIFA, MaNGA,SAMI & AMUSING++

Global vs Local relations

Pan et al. 2018; Cano-Diaz et al. 2019; Sánchez et al. 2020; Sánchez et al. 2021

Global relations between integrated properties of SFGs as the same as local/resolved realtions for SFAs when expressed in their intensive form.



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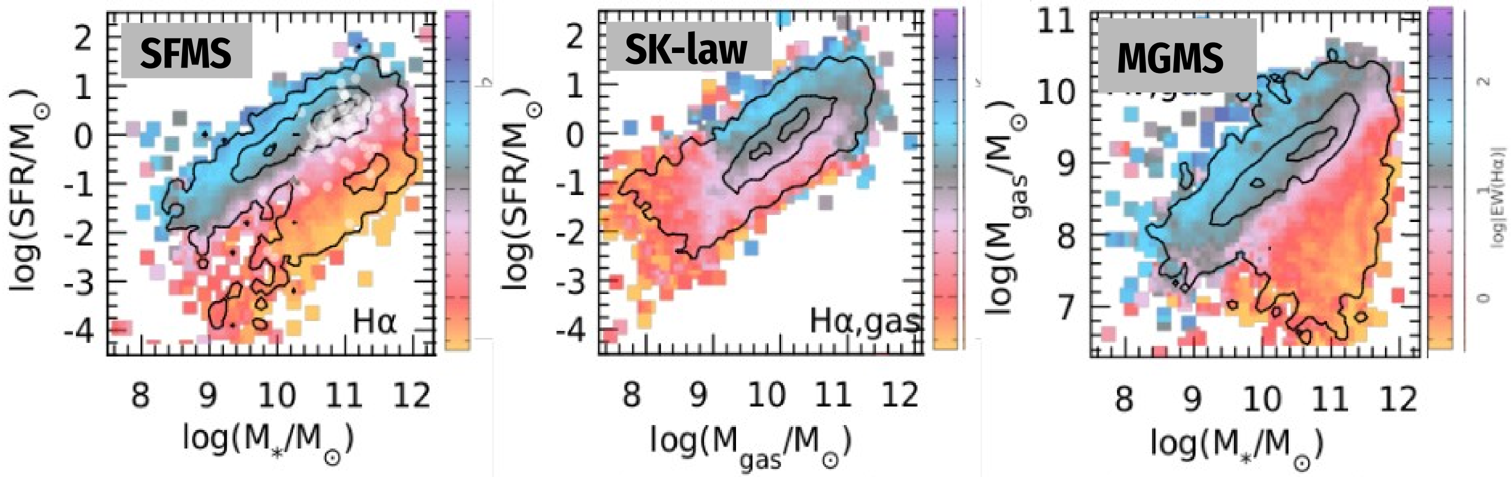
Global vs Local relations

Lin et al. 2019; Cano-Diaz et al. 2019; Ellison et al. 2021; Sánchez et al. 2021



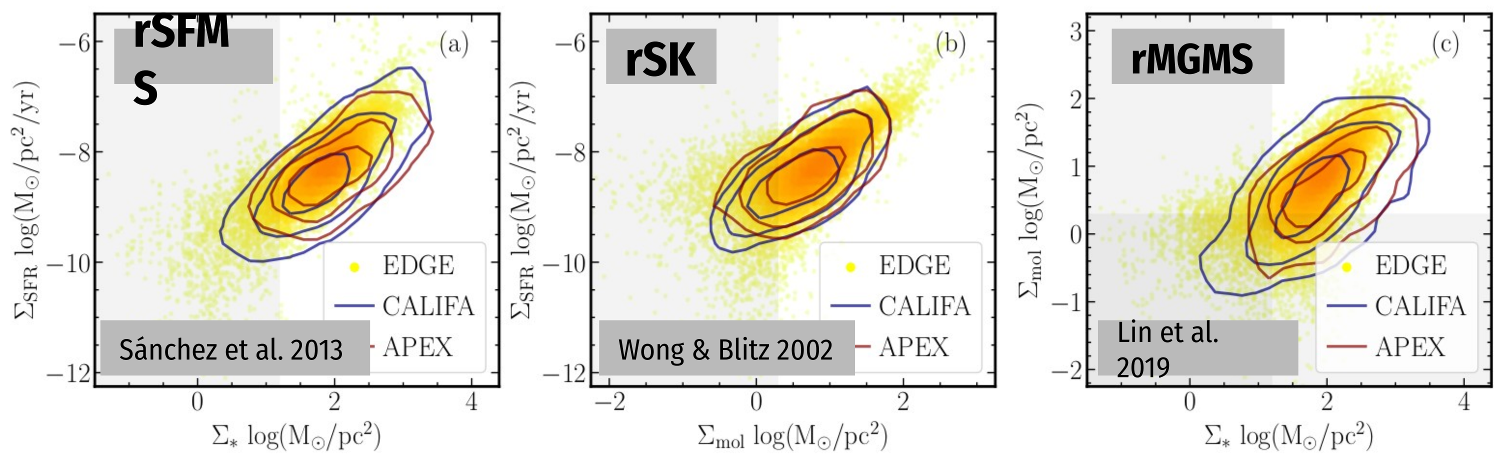
Star-formation galaxy-wide is ruled by global extensive relations:

SFR-M_* => SFMS

SFR-M_{mol} => SK

M_{mol}-M_* => MGMS

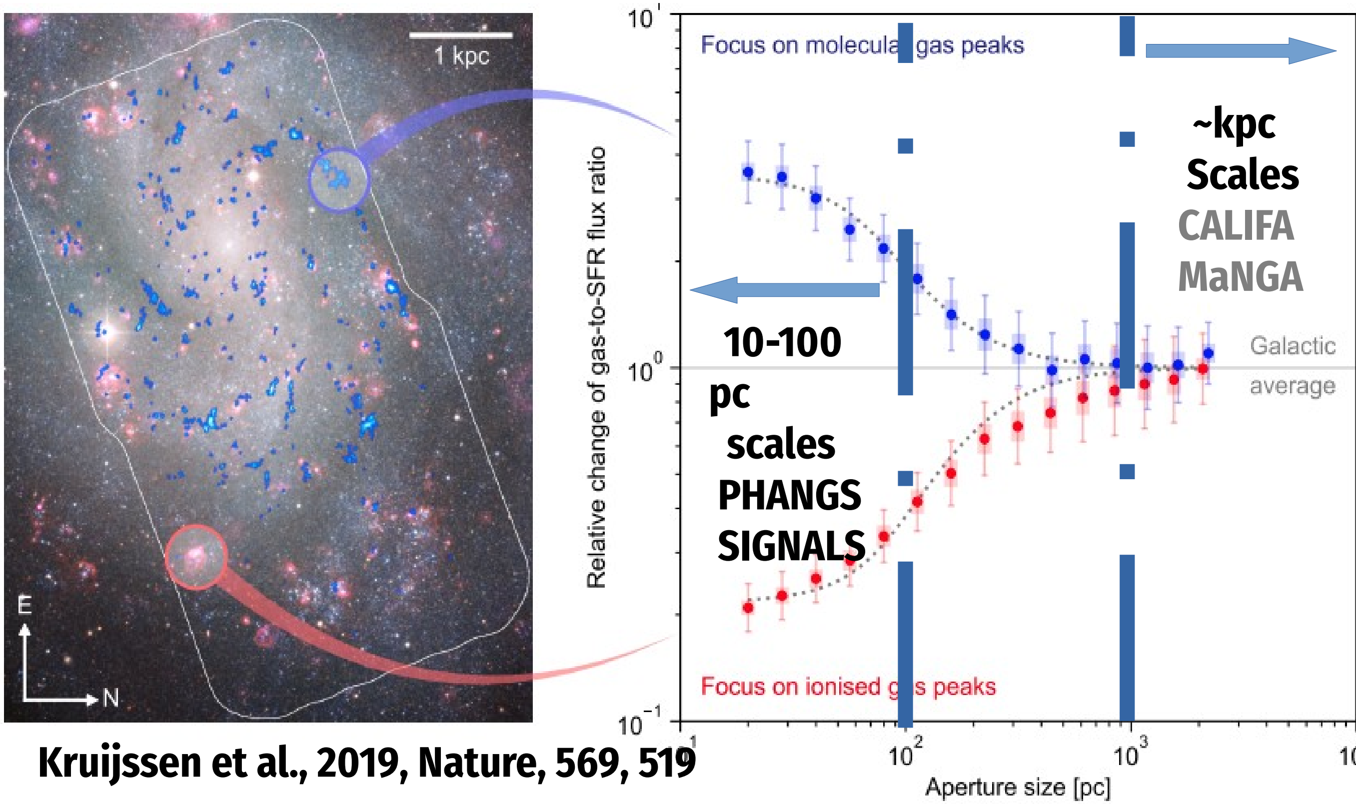
IFS Galaxy surveys uncovered/confirm local/resolved relations verified down to ~1kpc: rSFMS, rSK, rMGMS Do they rule the SF process really?



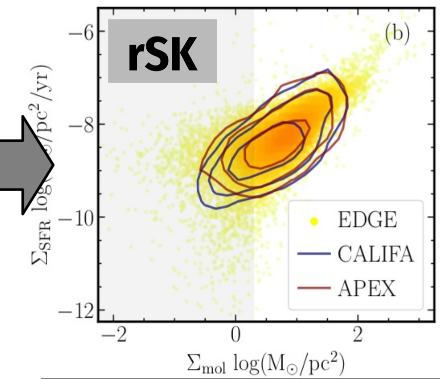
Although global and local (resolved) relations seem to be universal at a first look, there are differences galaxies by galaxies, in particular when they are at different evolutionary stages (e.g., Ellison et al. 2021). Furthermore, we know that they are not fulfilled at scales <500 pc.

Global vs Local relations

Kruijseen et al. 2019; Barrera-Ballesteros et al. 2022; Ellison et al. 2023



Kruijseen et al., 2019, Nature, 569, 519

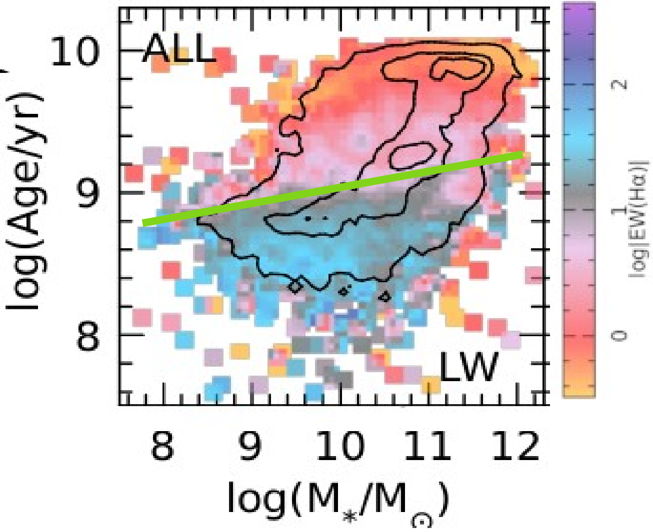


Intensive/resolved relation are fulfilled from ~1kpc to galaxy wide. But, they are not verified below kpc-scales. Why?

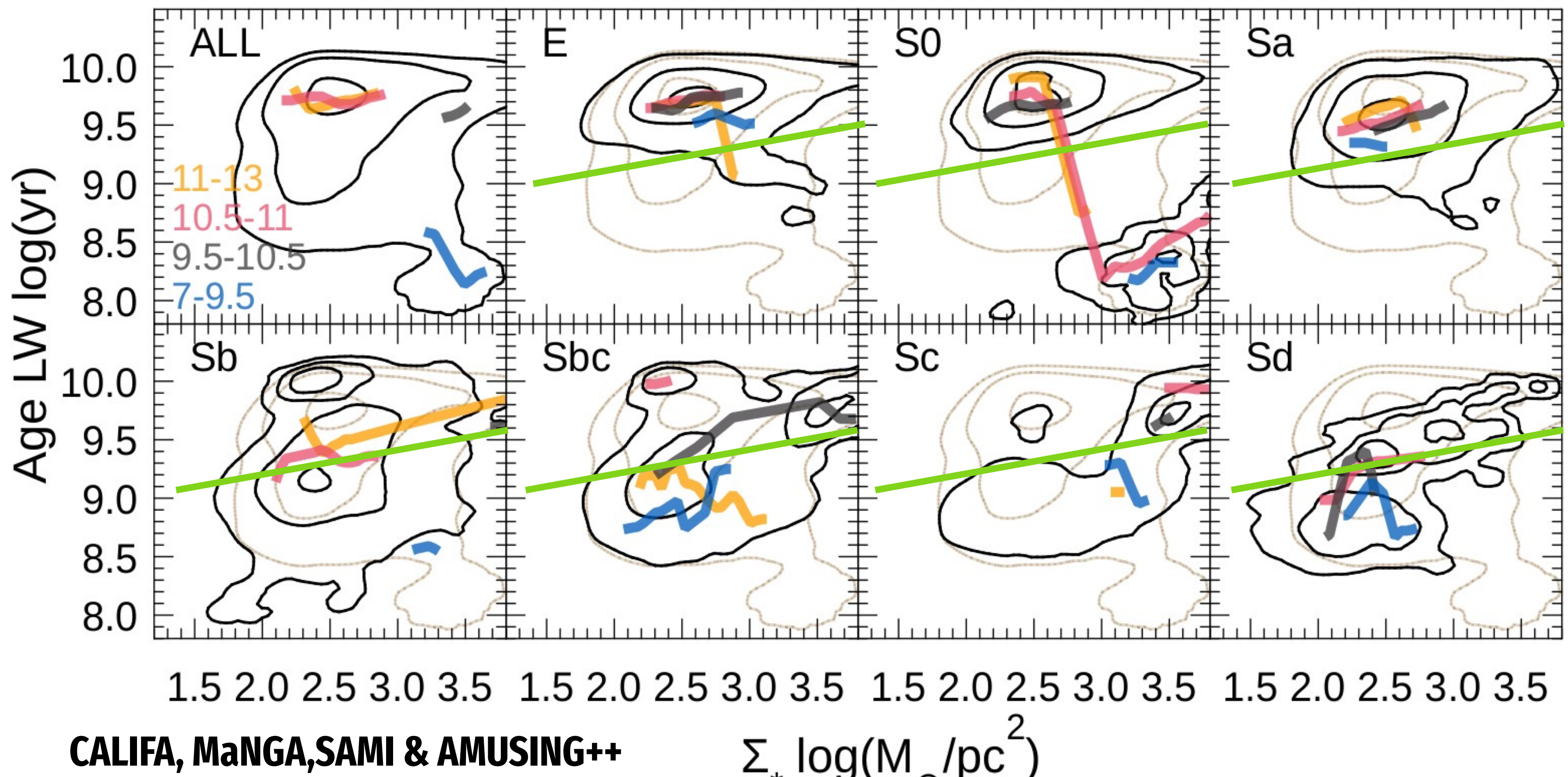
The spatial scales at which these relations are fulfilled tell us about their physical origin: an equilibrium between the energy injected by the SF process itself and the weight /pressure of the environment. Thus, SF-feedback is of a key importance.

Stellar populations: local Age-M* bimodality

Blanton et al. 2009; Zibetti et al. 2017; Sanchez et al. In prep.



RAs in any galaxy is dominated by old stellar populations, while SFAs are dominated by young ones, irrespectively of the global properties of galaxies. *Bimodality is local, thus SF and Quenching are local proccesses!*



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Resolved Properties of Galaxies

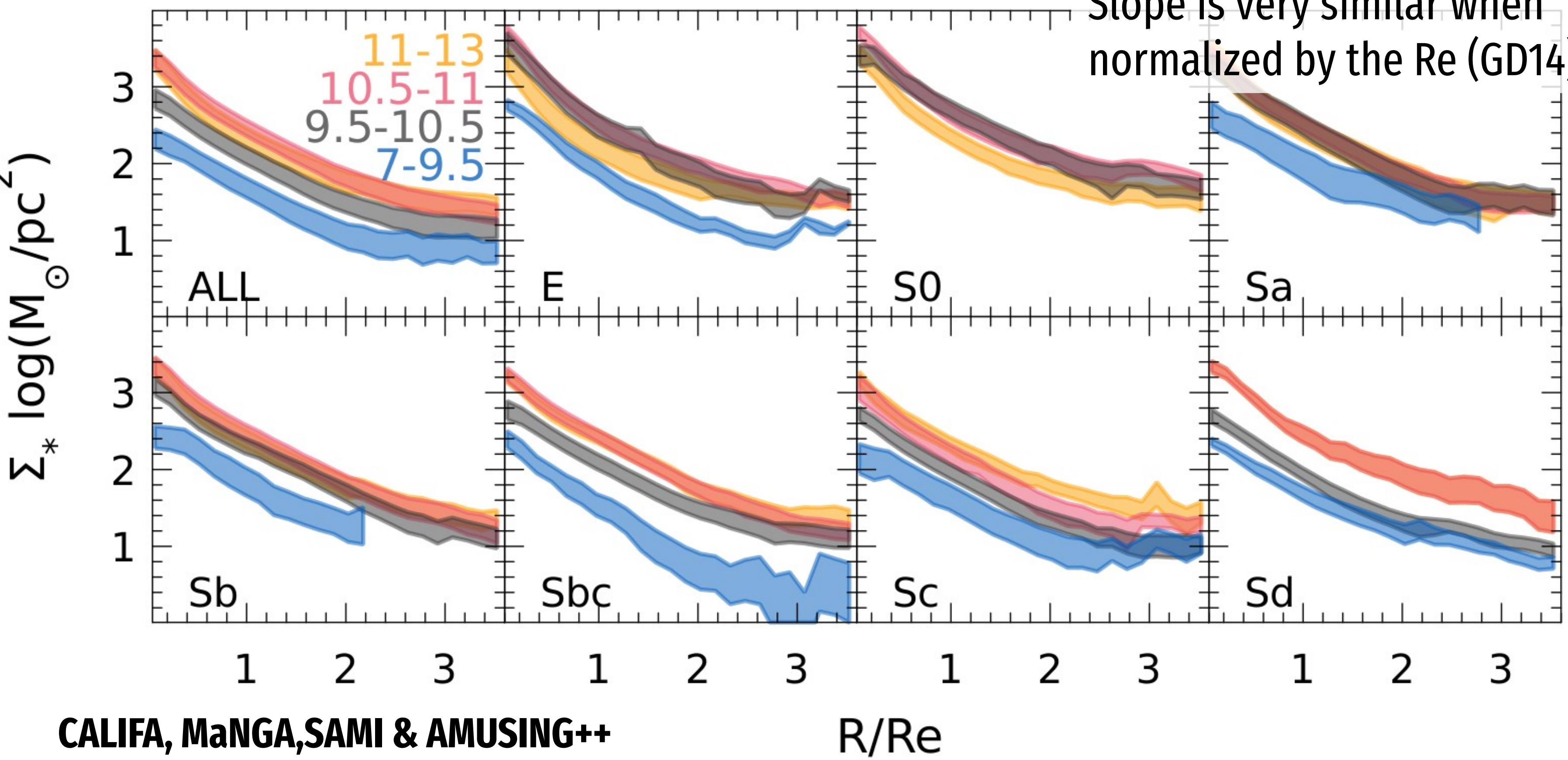
Radial Gradients: Inside-out growth and quenching

Stellar populations: Σ_* gradients

Bell et al. 2000; Kauffmann et al. 2003; Bakos et al. 2009
Gonzalez-Delgado et al. 2014; Sanchez et al. 2018

Σ_* is a fundamental parameter to understand the local evolution in galaxies. In all galaxies it presents a negative gradient that it is steeper in the inner (bulge-dominated) region. In essence it follows the gravitational potential.

Slope is very similar when normalized by the Re (GD14)



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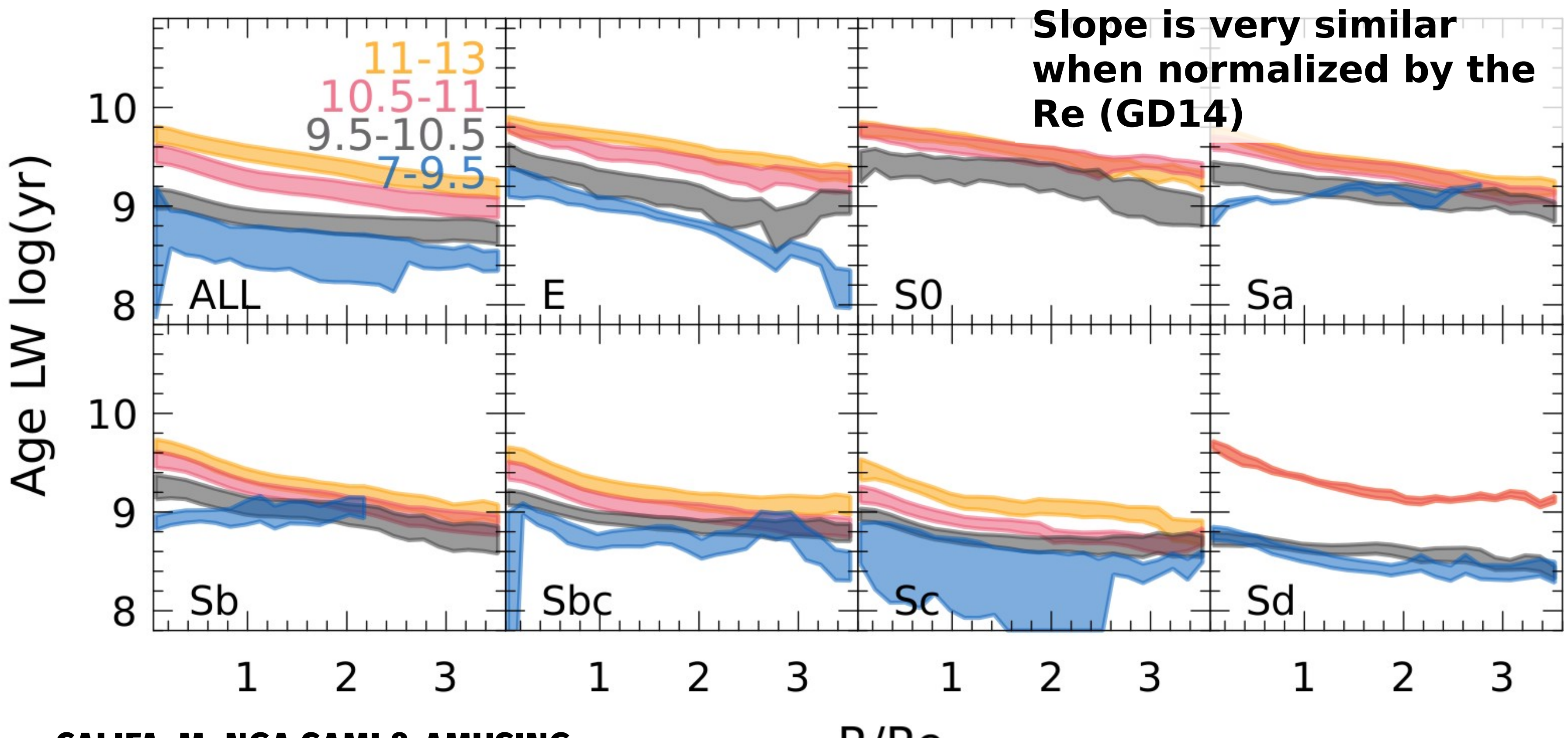
Stellar populations: Age gradients

Gonzalez-Delgado et al. 2014; Sánchez-Blazquez et al. 2014; Li et al. 2015; Goddard et al. 2015

All galaxies present a negative Age gradient, with older stellar populations in the central regions and younger in the outer ones (Goddard et al found somehow different results). ***Evidence for an inside-out growth***



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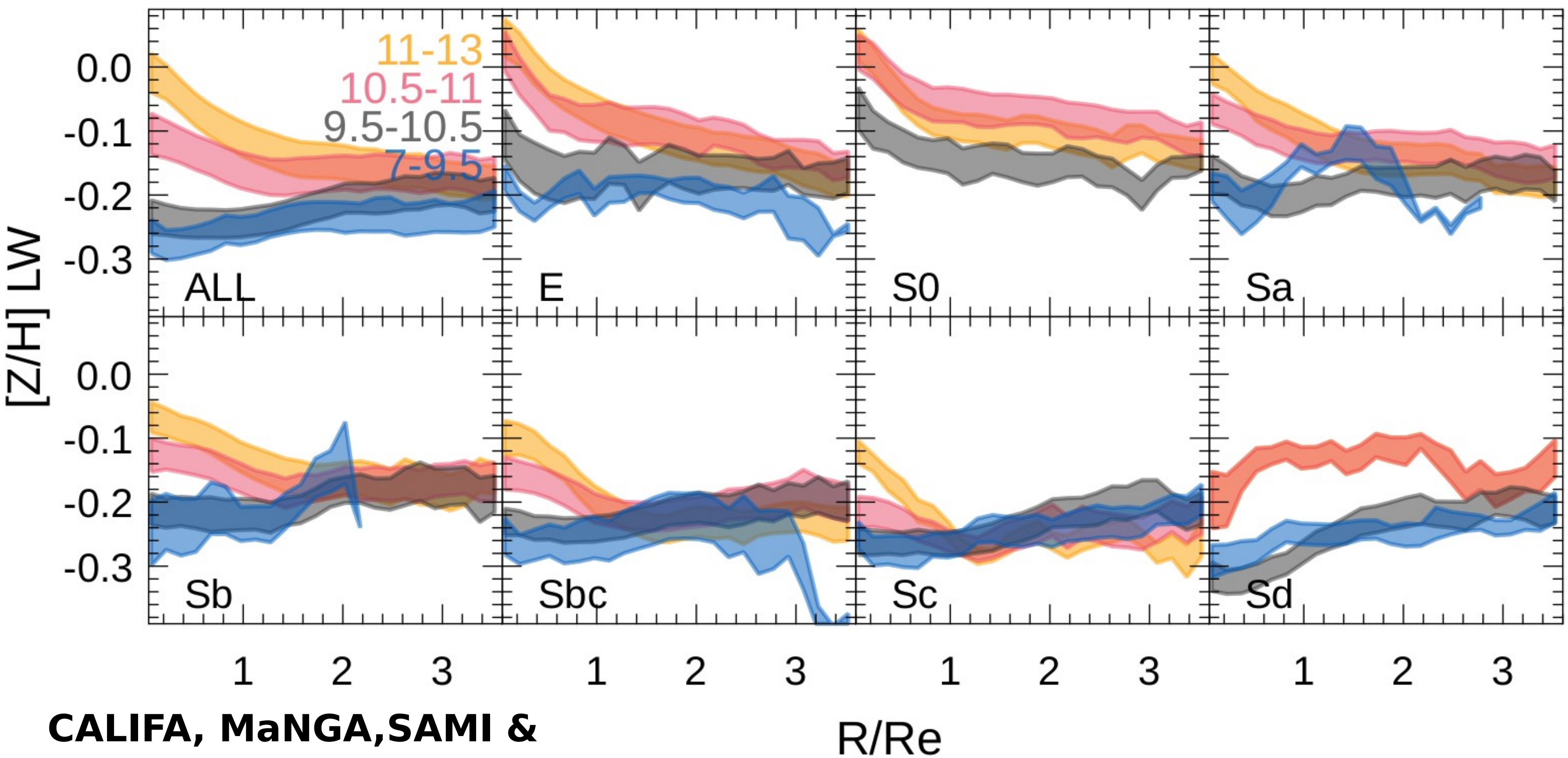
Stellar populations: [Z/H] gradients

Gonzalez-Delgado et al. 2014; Sánchez-Blazquez et al. 2014; Goddard et al. 2015

Massive/earlier-type galaxies present a negative [Z/H] gradient, with more metal rich populations in the ceentral regions (Goddard et al found somehow different results). Less massive/later-type galaxies present an inversion in the gradient.

Despite of inside-out, ChEs and SFHs change with M_* and morphology.



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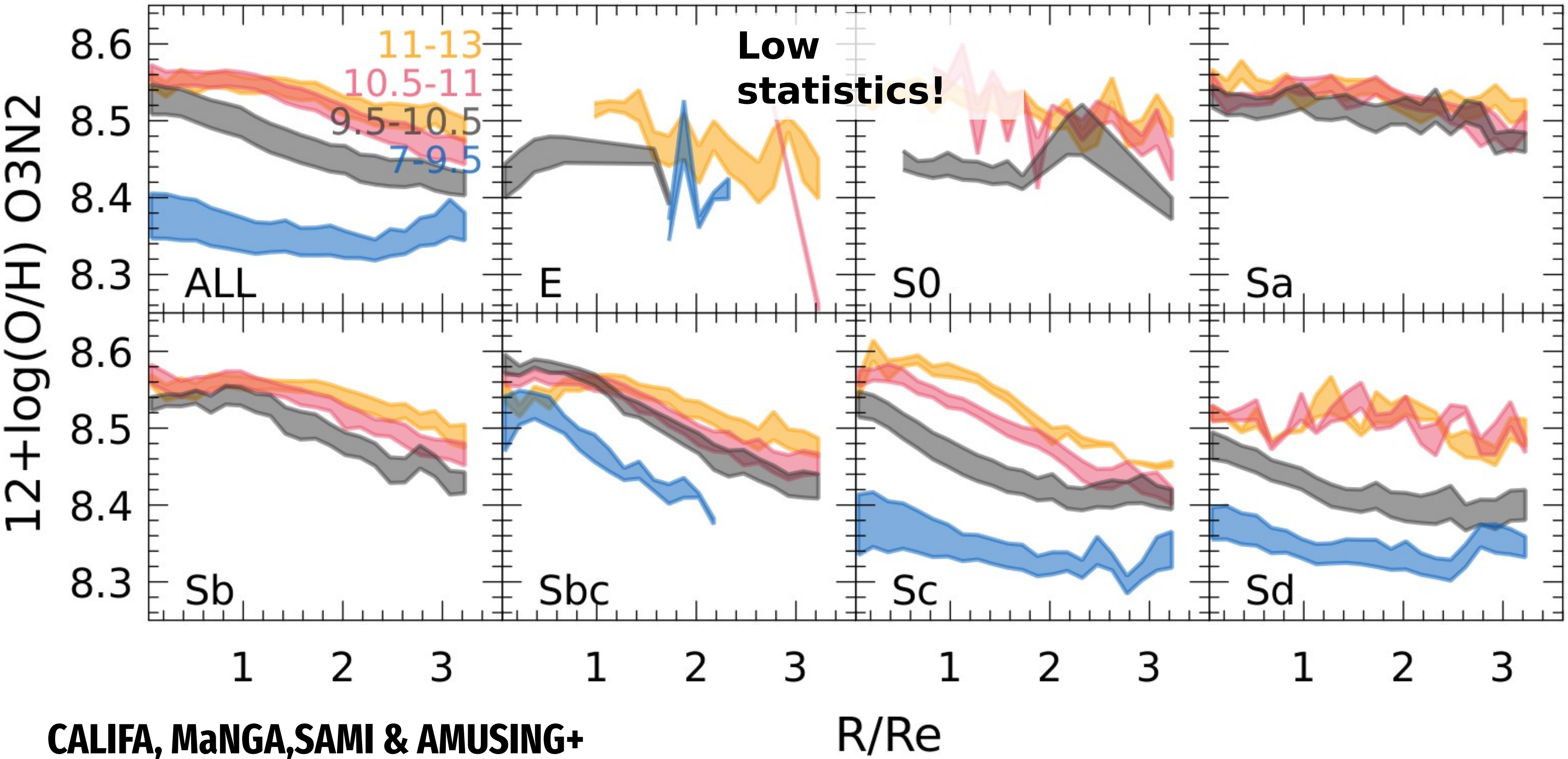
Ionized gas by OB-stars: O/H gradients

Searly et al. 1973; Peimbert et al. 1978; Vila Costas et al. 1992; Sánchez et al. 2014; Sánchez-Menguiano et al. 2016; Belfiore et al. 2017; Sánchez-Menguiano et al. 2018;

Galaxies more massive than $10^{9.5}$ $M_\odot$ present a similar oxygen abundance gradient between 0.5-2.0 Re.

Along the disk the oxygen is following the mass growth through the rMZR.

Inside-out differential [α/Fe] changing by M_* and morphology.

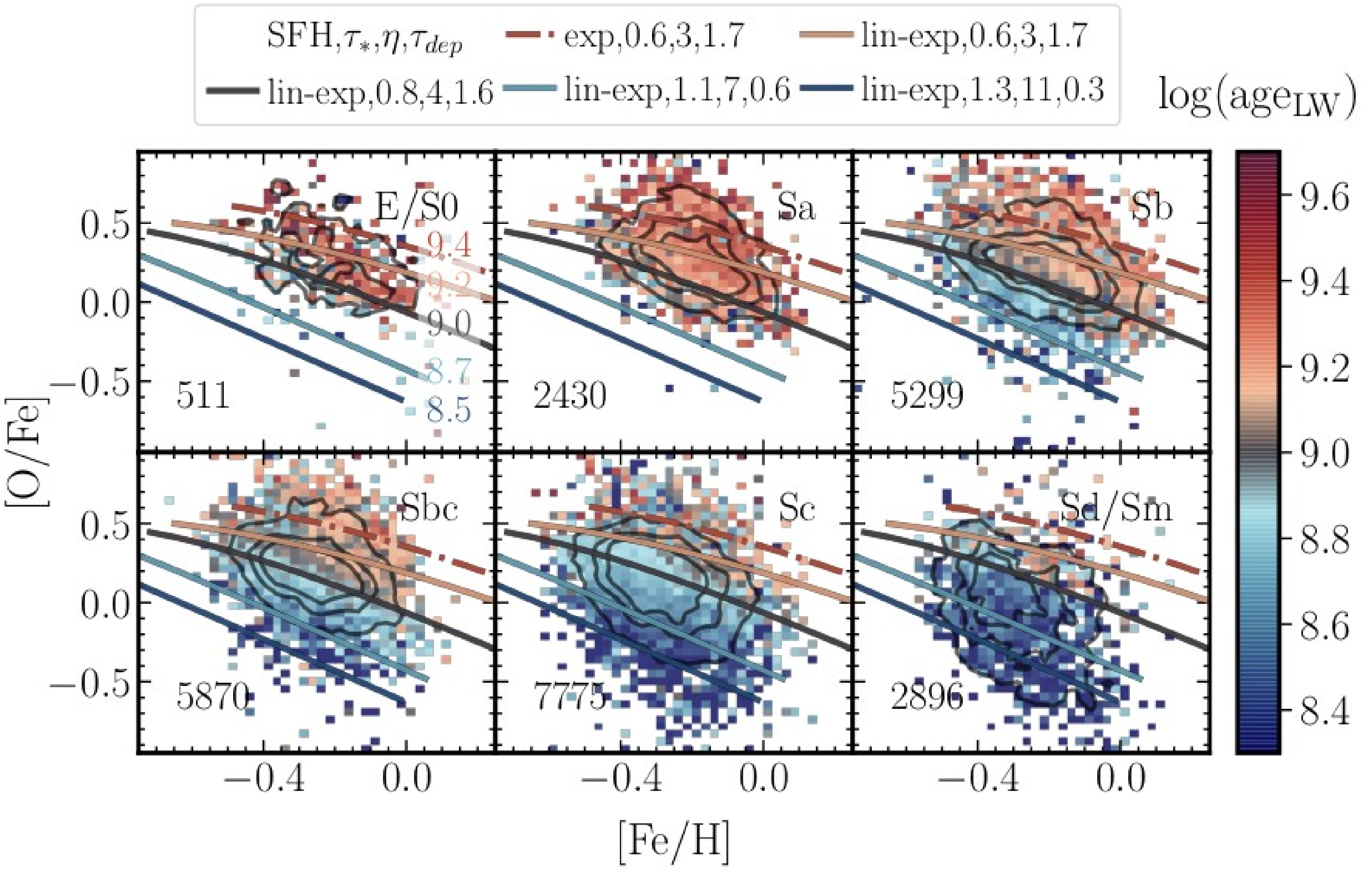


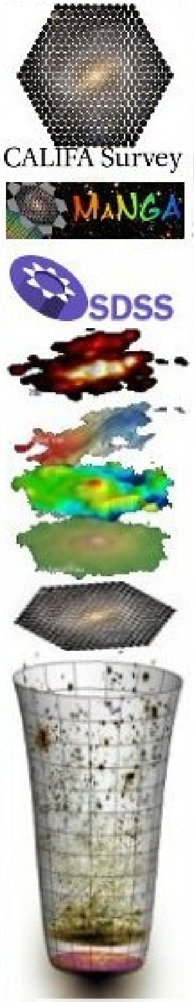
CALIFA, MaNGA,SAMI & AMUSING+

α-enhancement depends on M* and Morphology

Matteucci et al. 2008; Watson et al. 2021; Sánchez et al. 2021

[O/Fe] distribution is a direct consequence of the SFH and ChEH histories at different locations within galaxies



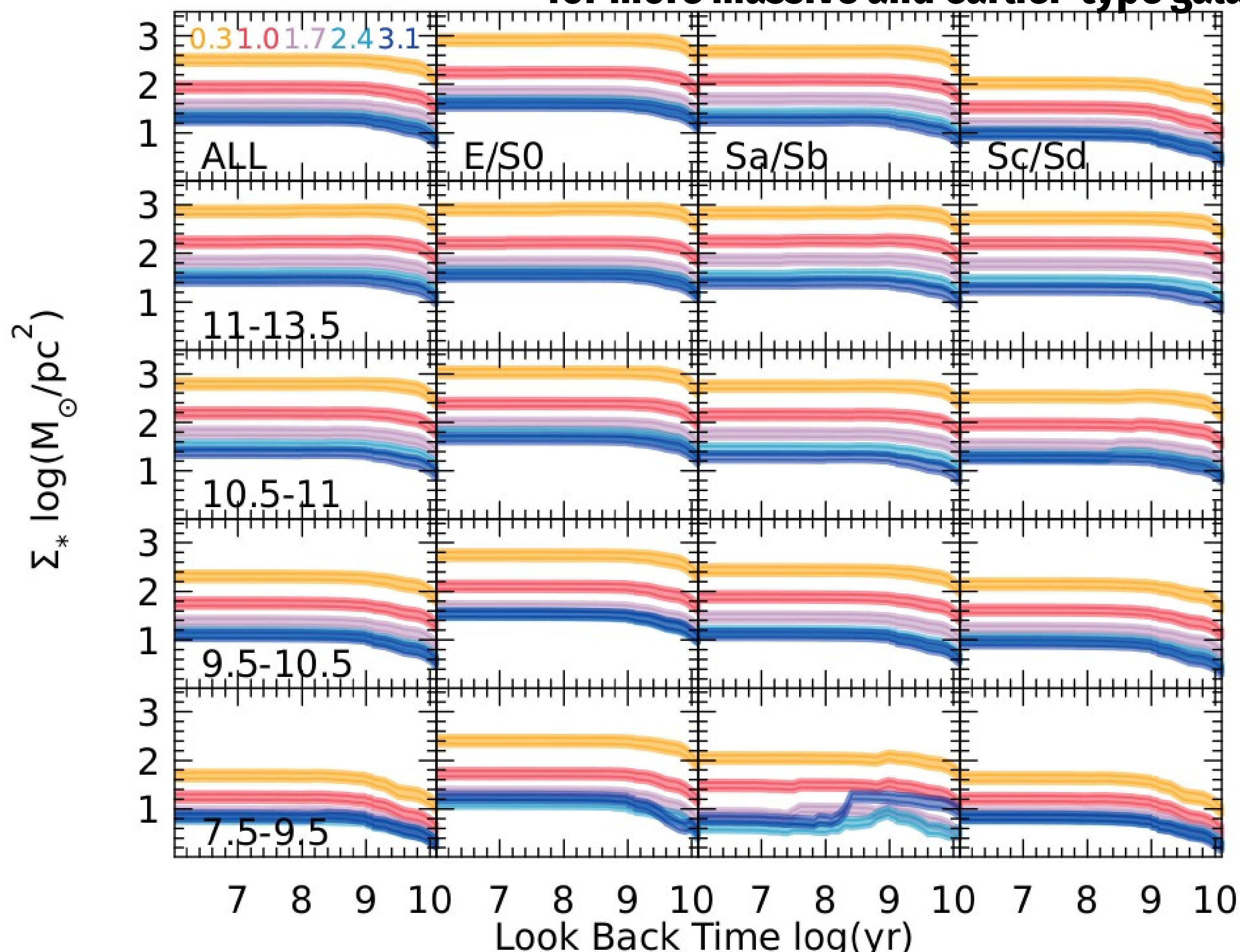


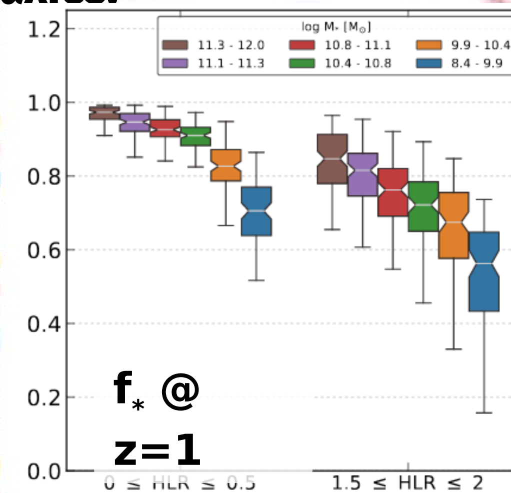
CALIFA

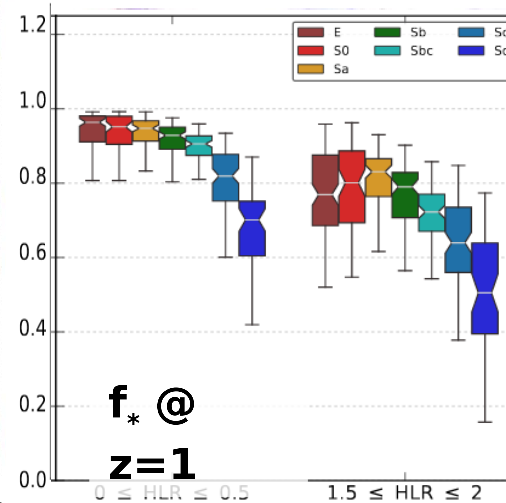
Stellar populations: Inside-out mass growth

Panther et al. 2007; Perez et al. 2013; Ibarra-Medel et al. 2016; Garcia-Benito et al. 2017; López-Fernández et al. 2018; Sánchez et al. 2019

Galaxies with $M_* > 10^{9.5}$ $M_\odot$ present a clear inside-out growth, that it is stronger for more massive and earlier-type galaxies.



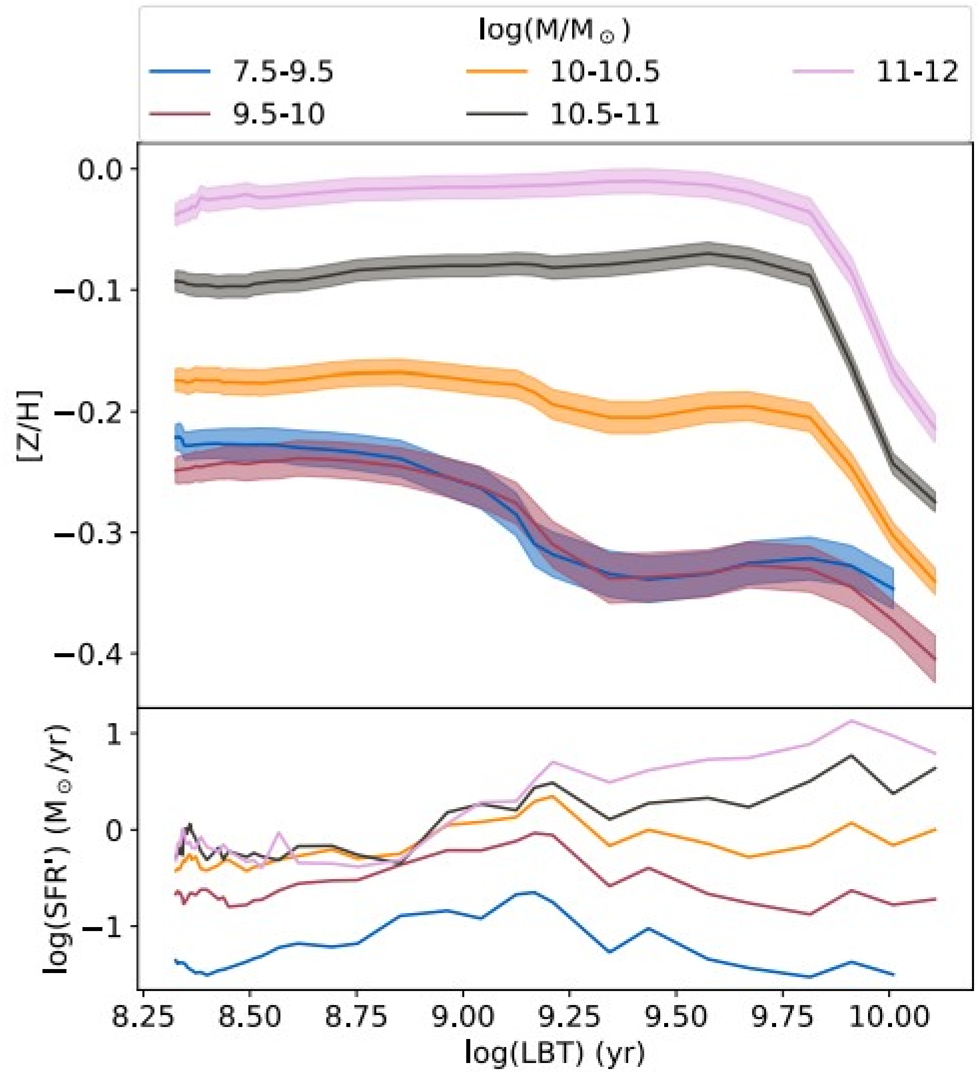


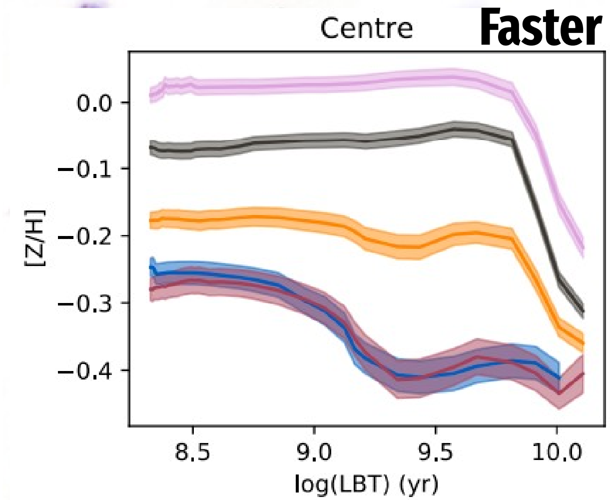


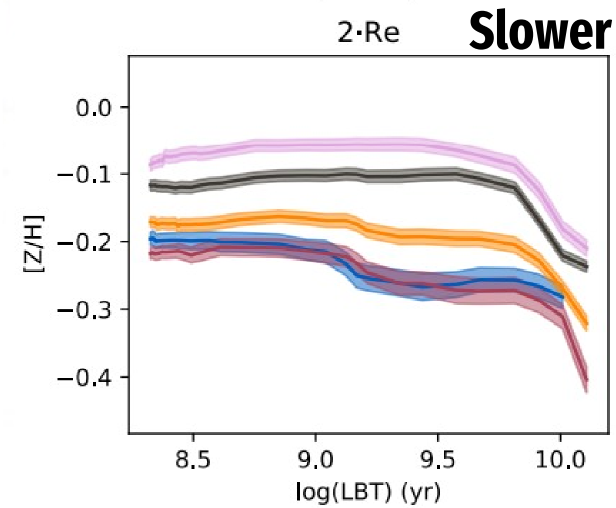
Stellar populations: Chemical Enrichment

Panther et al. 2007; Vale-Assari et al. 2009; Camps-Fariña et al. 2020

More massive and earlier-type galaxies present a faster and stronger enrichement along cosmological times fully connected with their SFHs



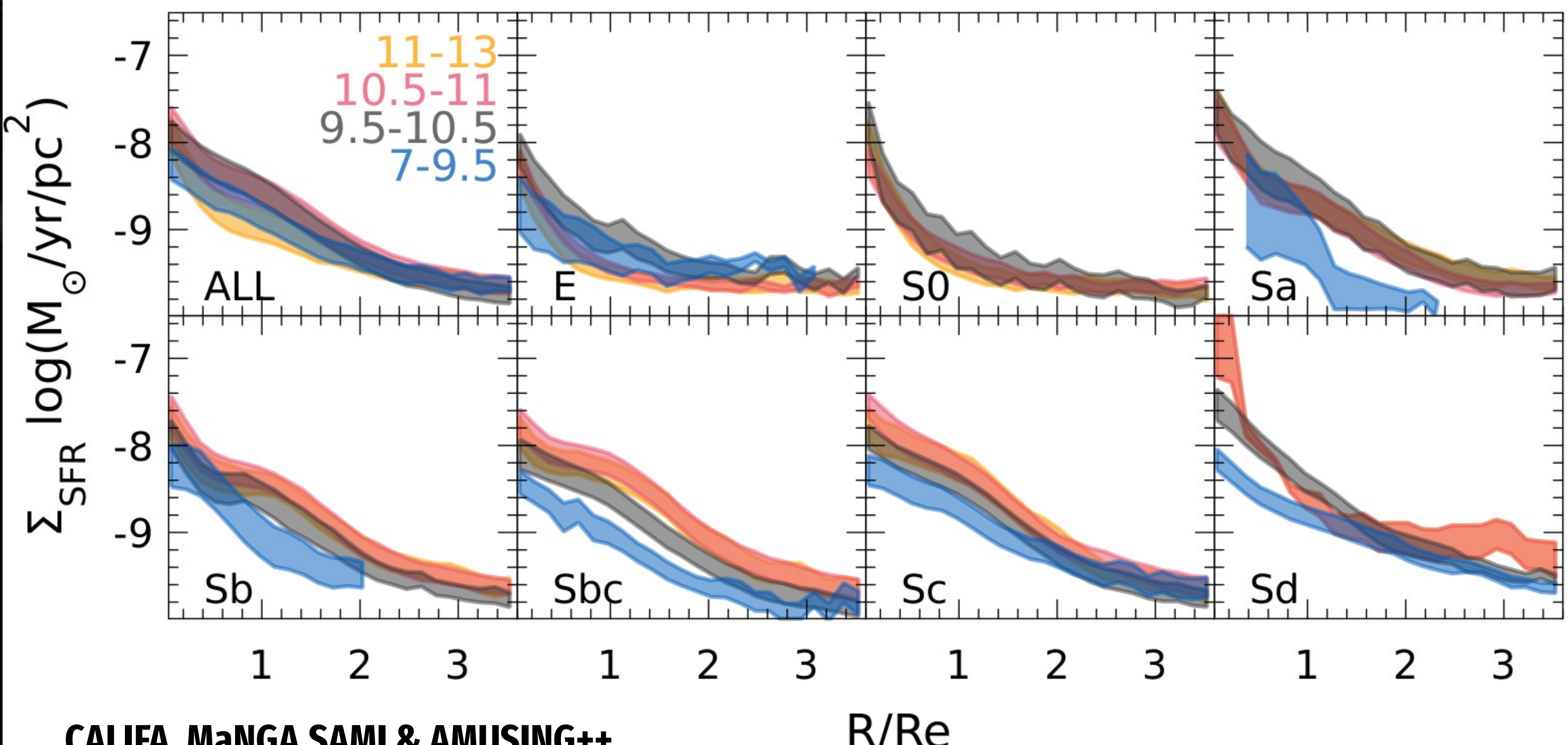




Stellar populations and ionized gas: Σ_{SFR} gradients

Gonzalez-Delgado et al. 2016; Belfiore et al. 2017; Ellison et al. 2018; Sanchez et al. 2018

Σ_{SFR} follows primarely Σ_* in all galaxies (rSFMS), showing a peak in the central regions and a steady decrease towards the outer regions.



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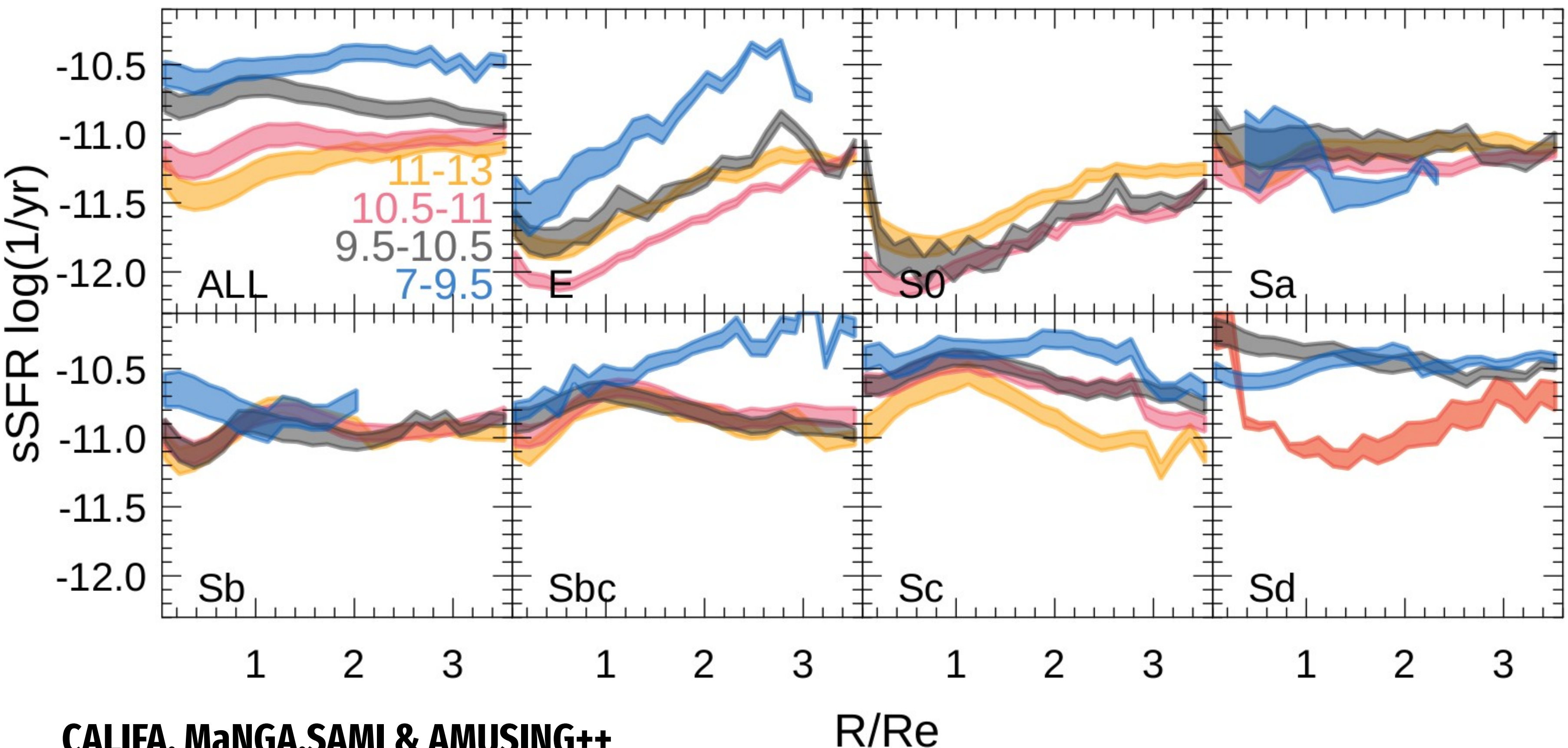
Stellar populations and ionized gas: sSFR gradients

Gonzalez-Delgado et al. 2016; Belfiore et al. 2017b; Ellison et al. 2018; Sanchez et al. 2018; Cano-Diaz et al., submitted.

sSFR presents a decline with M* and mophology. In addition, there is a decline in the central regions, associated with the bulge, where SF has stoped.

Qhenching evolves from the inside-out!

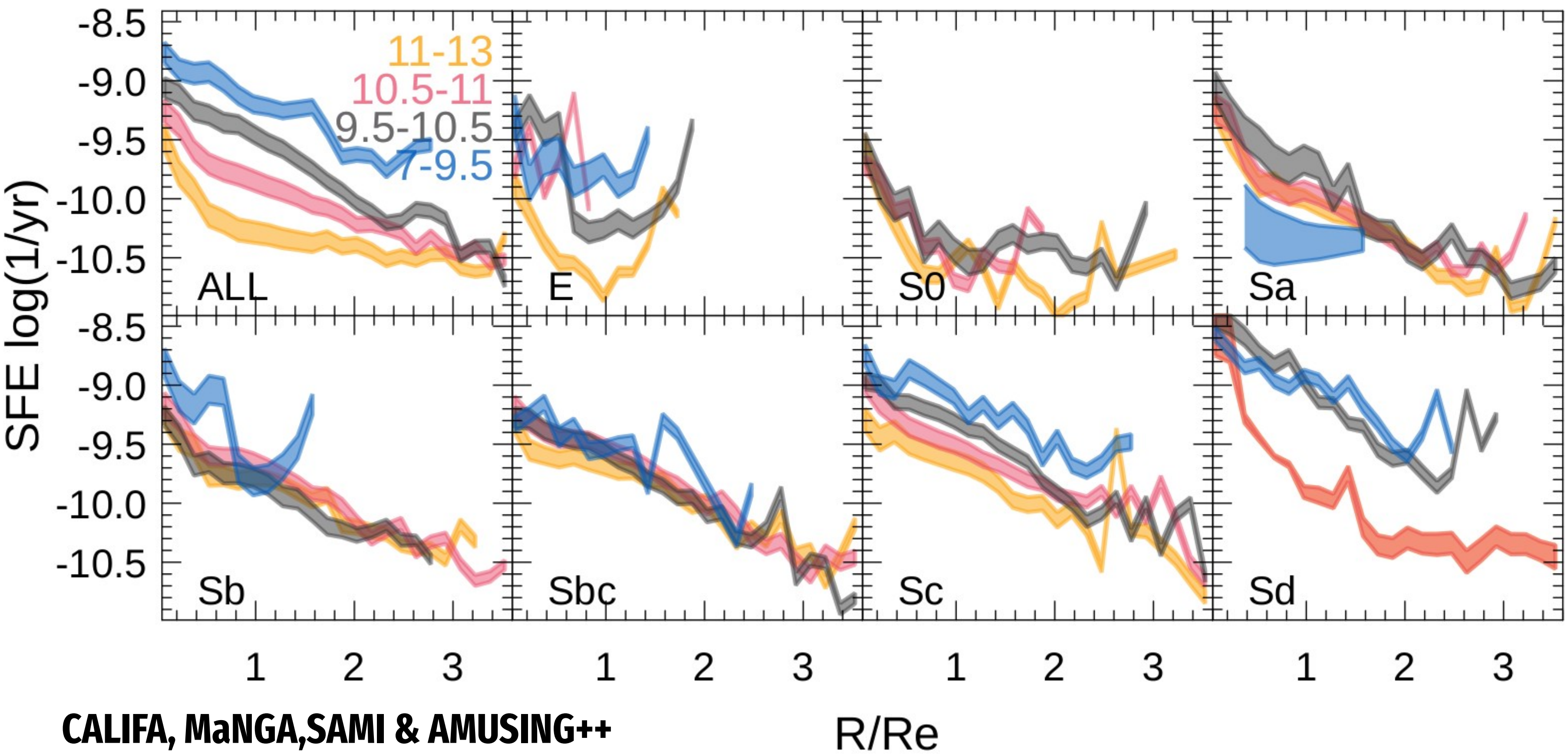


CALIFA, MaNGA,SAMI & AMUSING++

Stellar populations and ionized gas: SFE gradients

Utomo et al. 17; Colombo et al. 2018; Sanchez et al. 2018b

Central quenching is due primarily by a lack of (molecular) gas. However, there is also a decrease (increase) of the SFE (deplection time).



CALIFA, MaNGA,SAMI & AMUSING++

Conclusions

- IFS-GS have improved our understanding of the physical processes that shaped galaxies along their cosmological evolution.

- Ionization is a local process, and the nature and properties of ionized gas can only be derived exploring not only line ratios, but the nature of the underlying stellar population and the morphology of the ionized structures.

- The evolution of galaxies is ruled by local (resolved) relations that link many observed properties with the Σ^* (Σ_{SFR}, Σ_{gas},O/H, Z/H, Age,), that (1) generate most of the radial gradients observed in galaxies, and (2) induce global (integrated) relations, like the SFMS, MZR, SK-law...

Conclusions

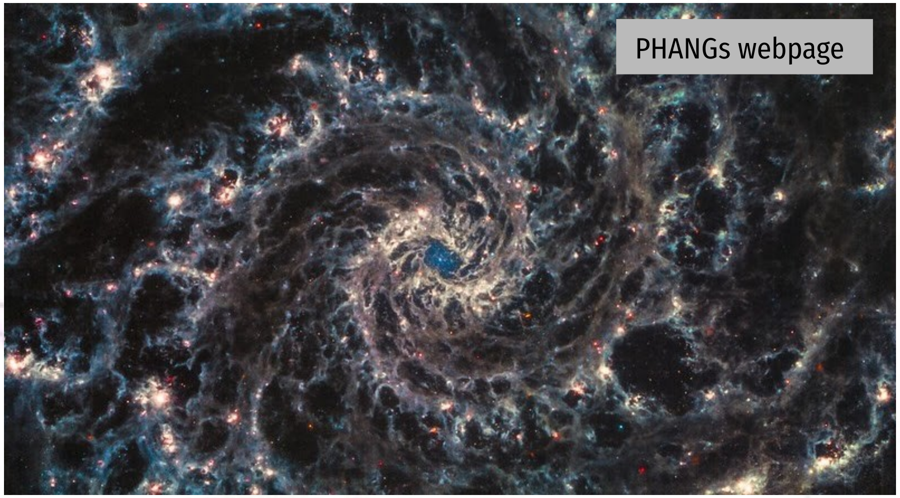
- The local relations are modified by global properties, like the M* and the Morphology (Dynamical effects?).

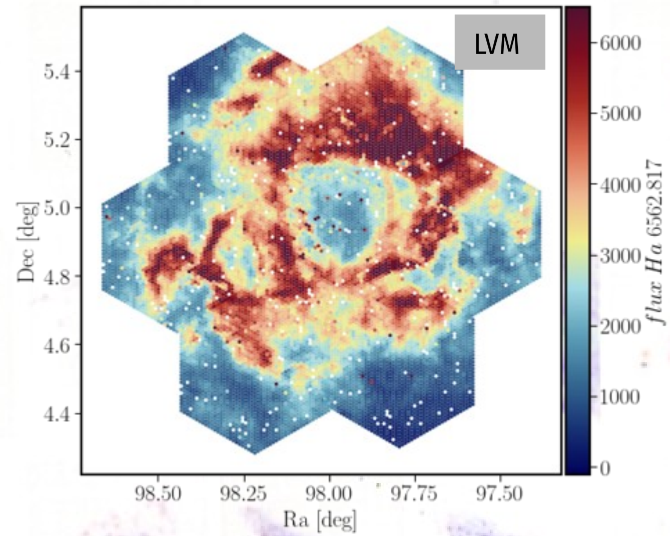
- Galaxies growth from the inside-out, with SFHs and ChEHs that are sharper in the central regions (of more massive and earlier type galaxies).

- Quenching happens from the inside-out, driven by a lack of (molecular) gas, but with a secondary effect induced by a change in the SFE (which strength depends on M* and morph.)

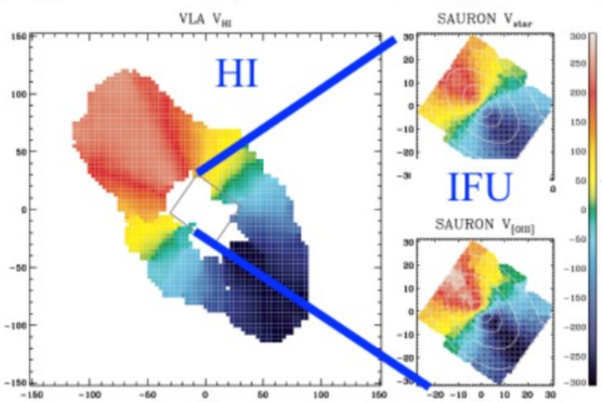
The Future: My guess

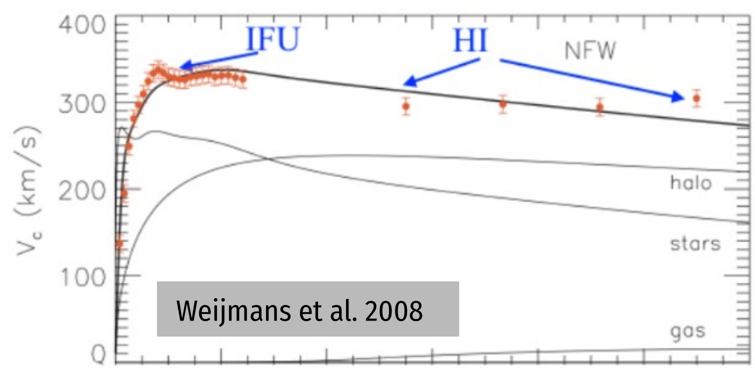
- Going to smaller physical scales: PHANGS, SIGNAL, LVM





-Multiwavelength information: UV?, NIR?, FIR? Radio? Millimetric



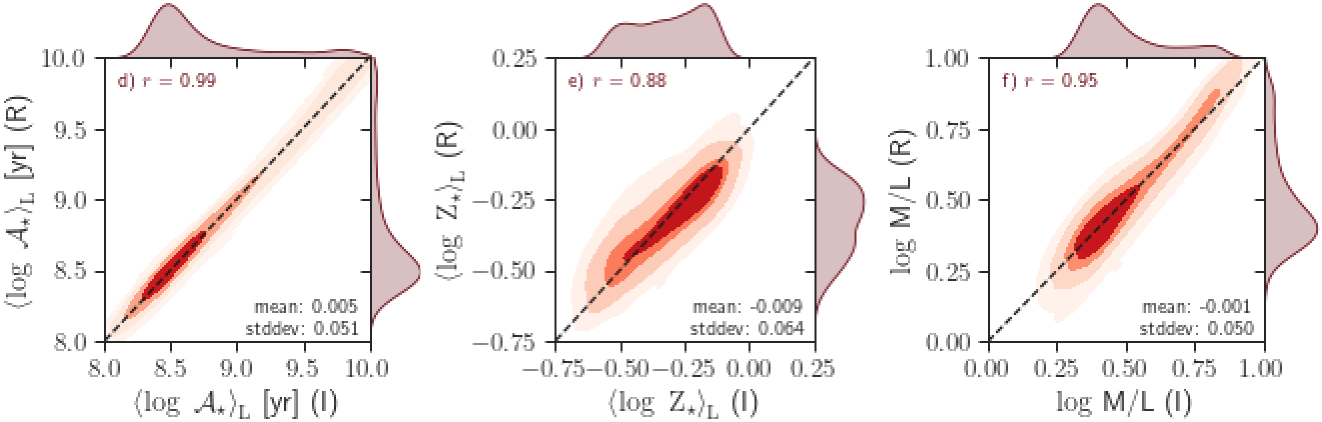


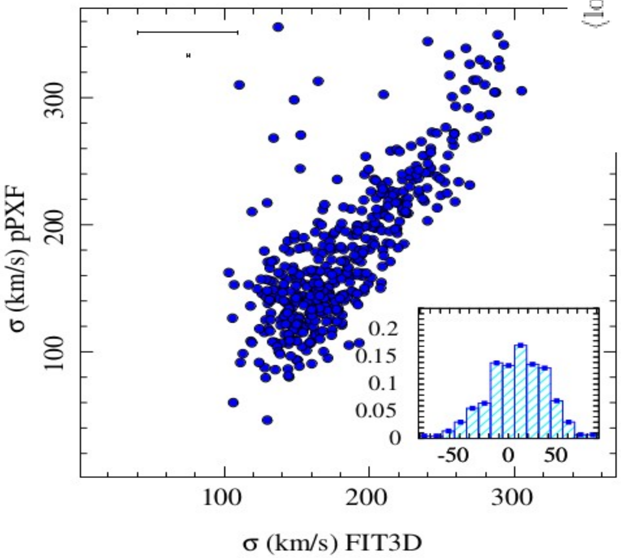
- Going to higher redshift: JWST

Resolved Properties of Galaxies

Some extra slices on how Pipe3D and Stellar decomposition in general works

Pipe3D vs. others



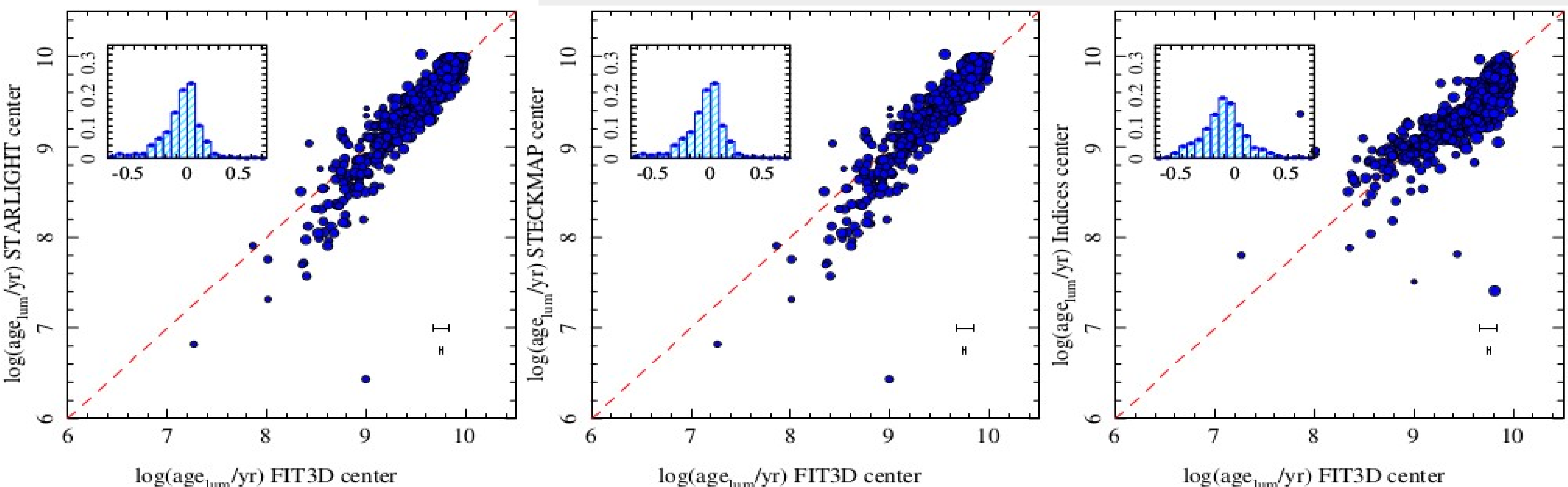


Tested against simulations

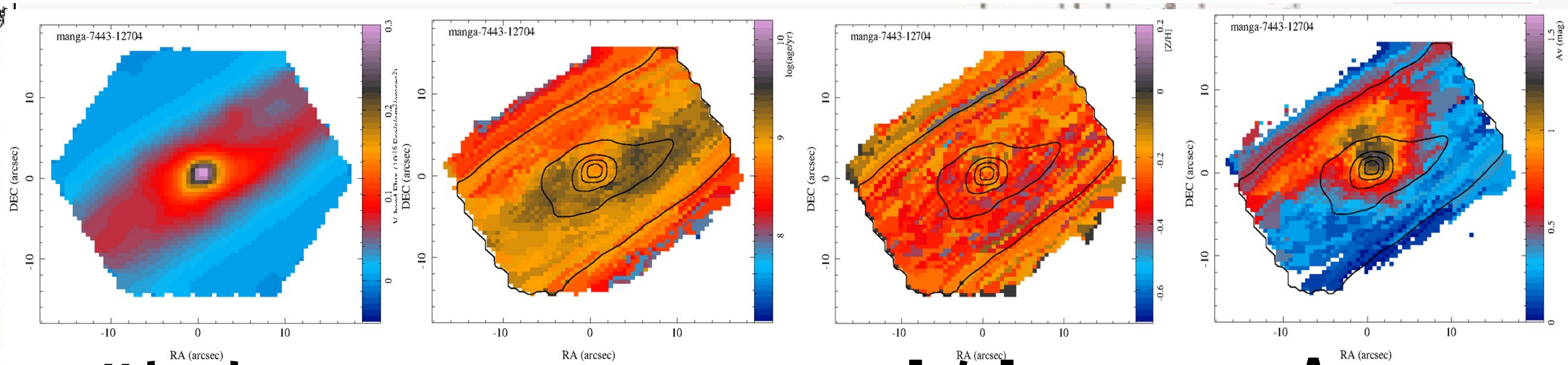
(Sanchez et al. 2016; Lacerda et al. In prep)

Compared with other tools, including MaNGA-DAP

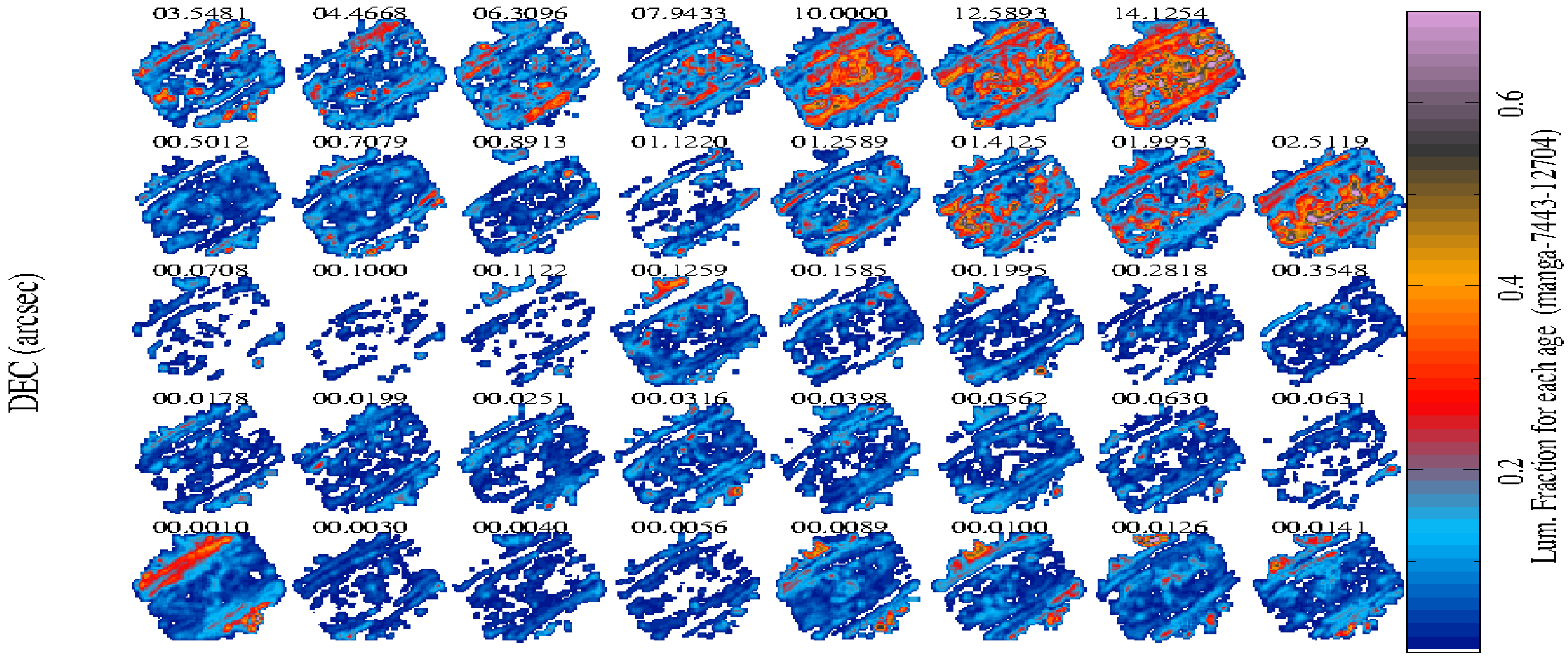
(Sanchez et al. 2016; Belfiore et al. 2019)



Pipe3D: Stellar Data products

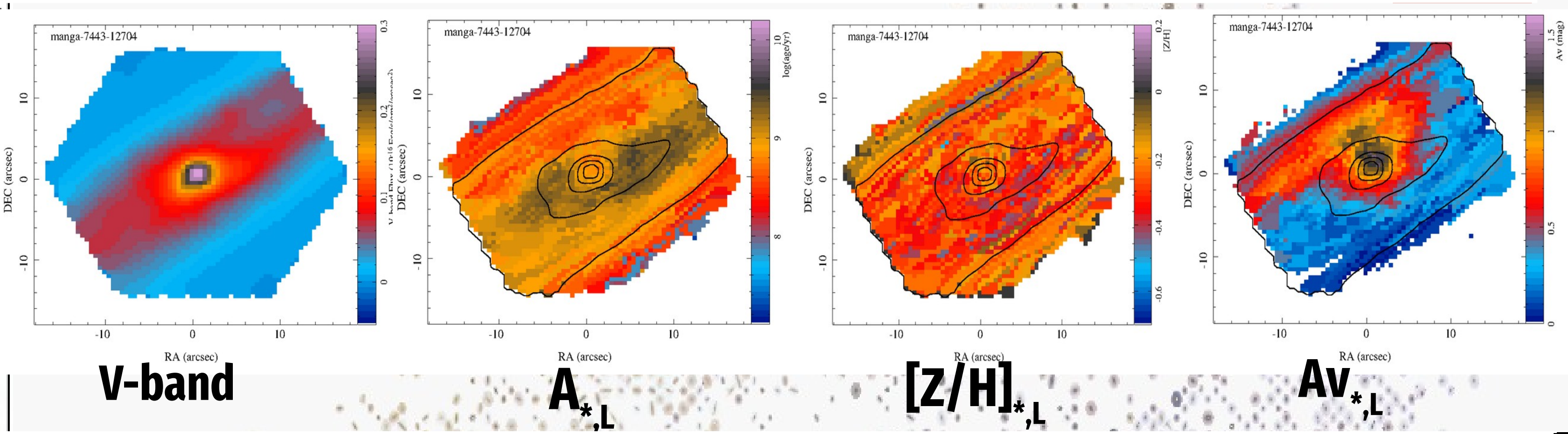


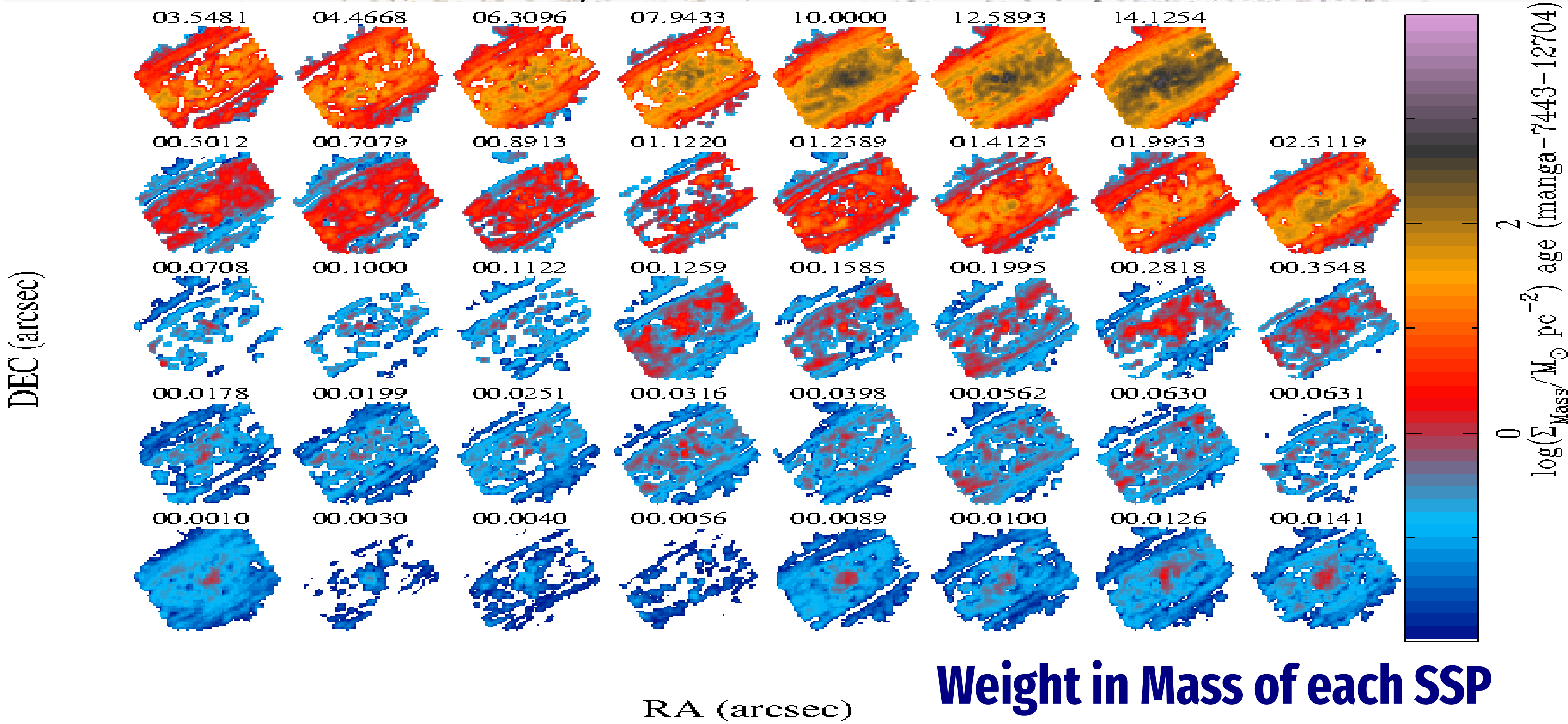
V-band $A_{*,L}$ $[Z/H]_{*,L}$ $Av_{*,L}$



Weight in Light of each SSP

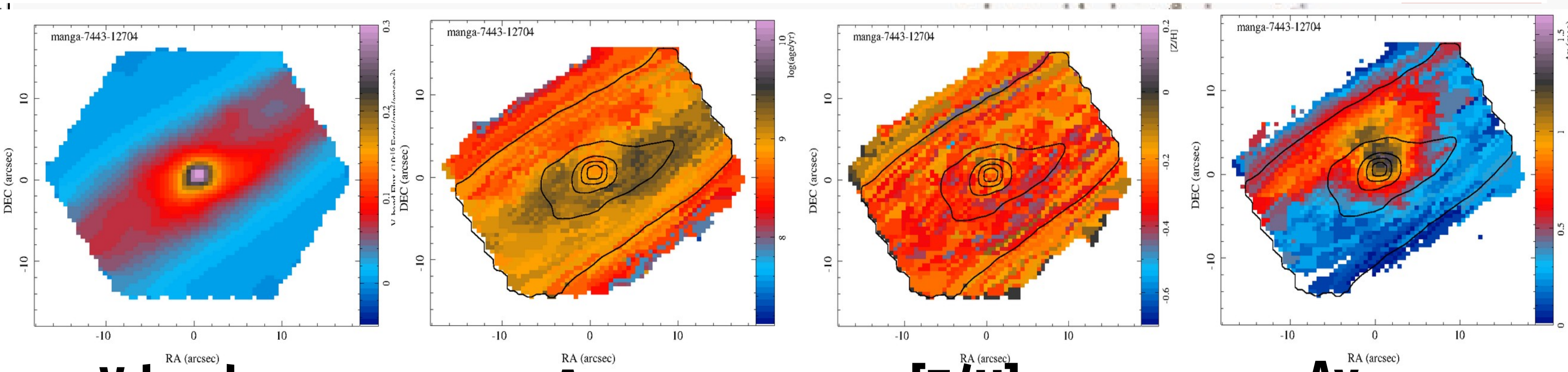
Pipe3D: Stellar Data products



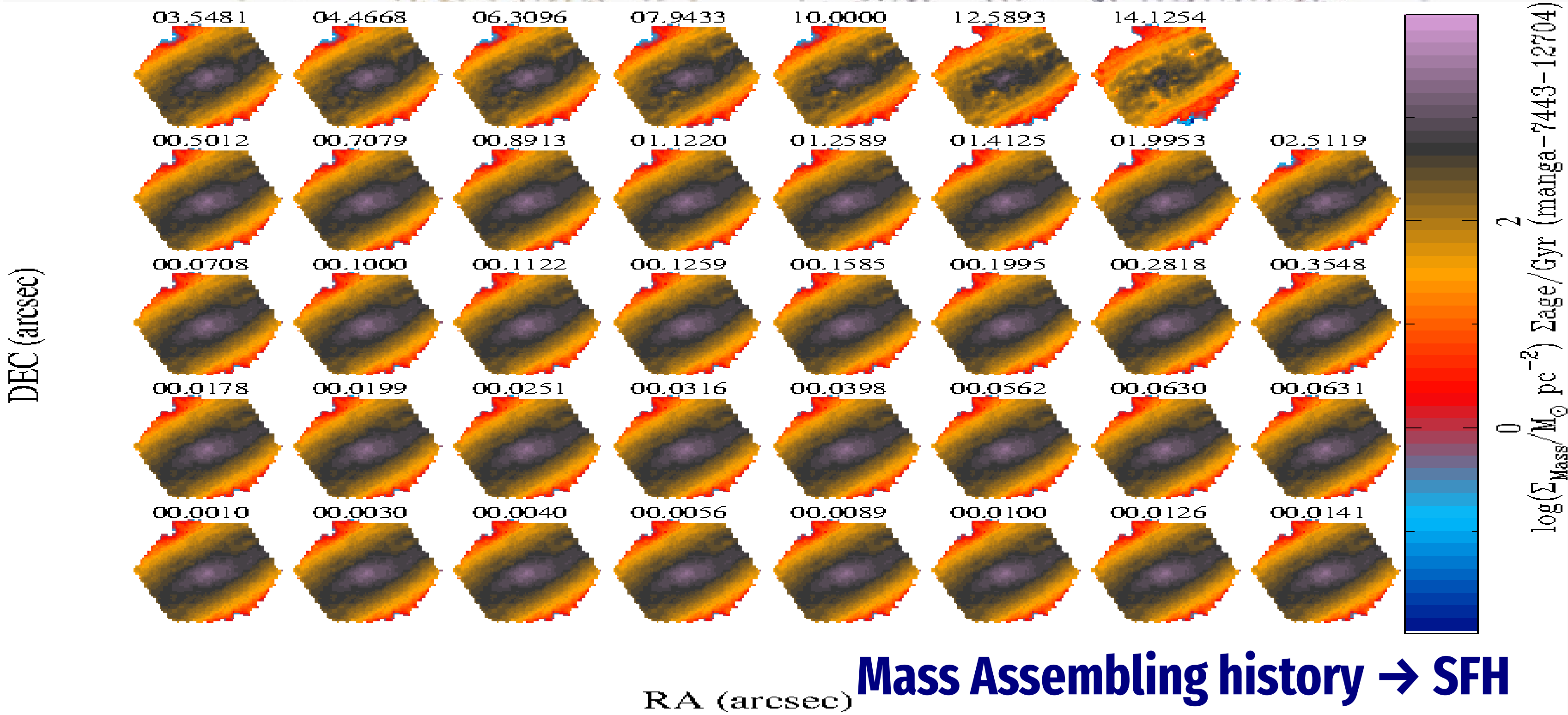


Weight in Mass of each SSP

Pipe3D: Stellar Data products

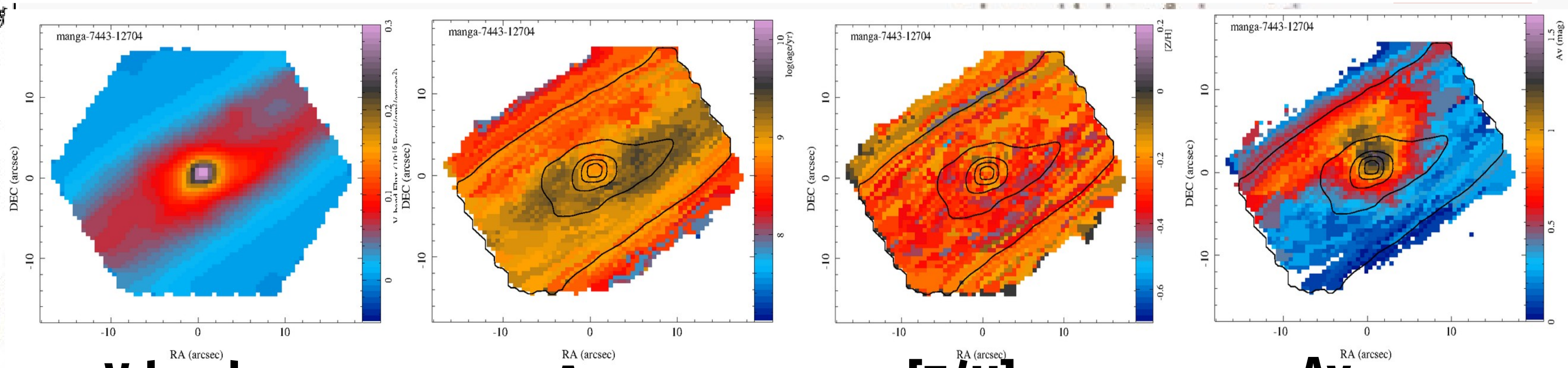


V-band A$_{*,L}$ [Z/H]$_{*,L}$ Av$_{*,L}$

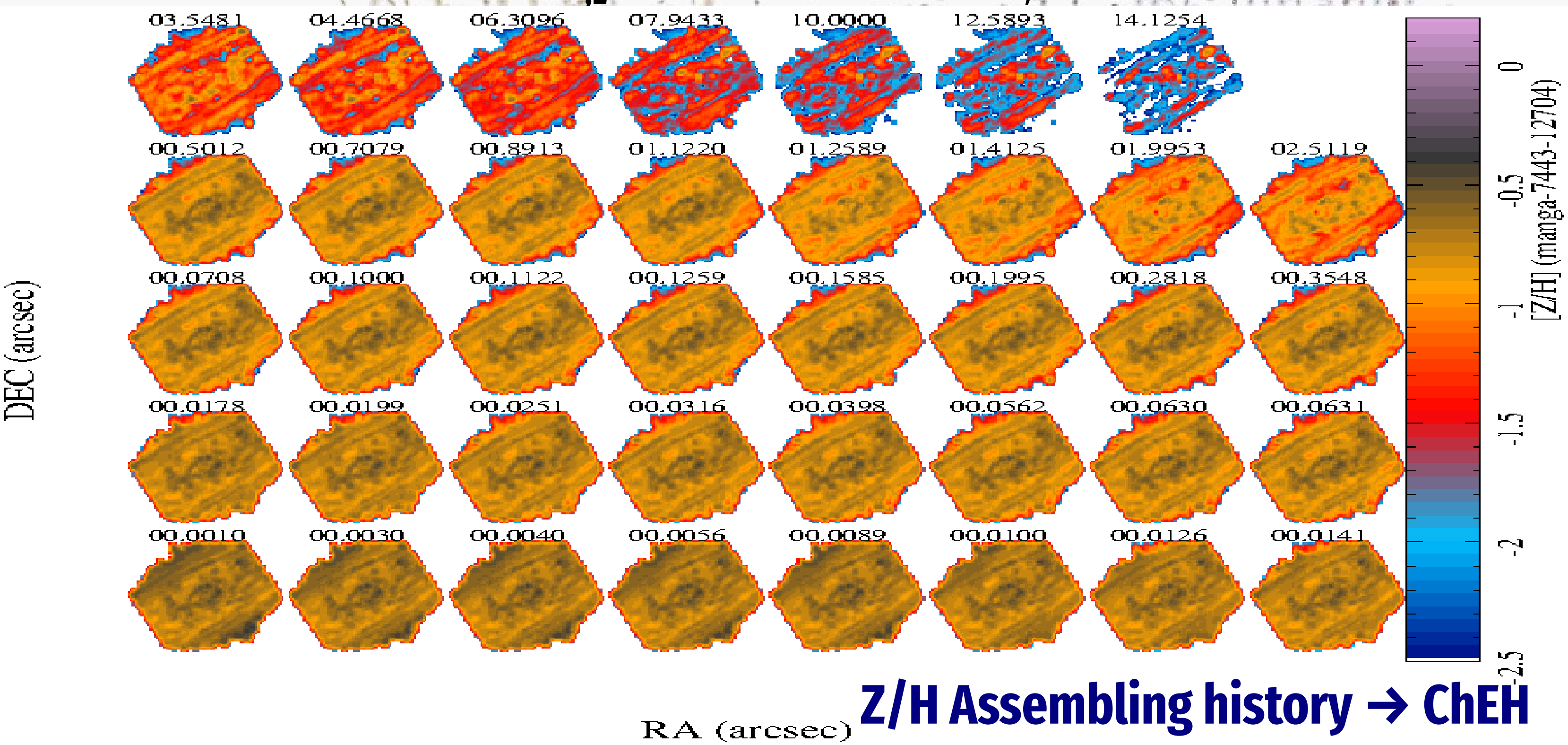


Mass Assembling history → SFH

Pipe3D: Stellar Data products

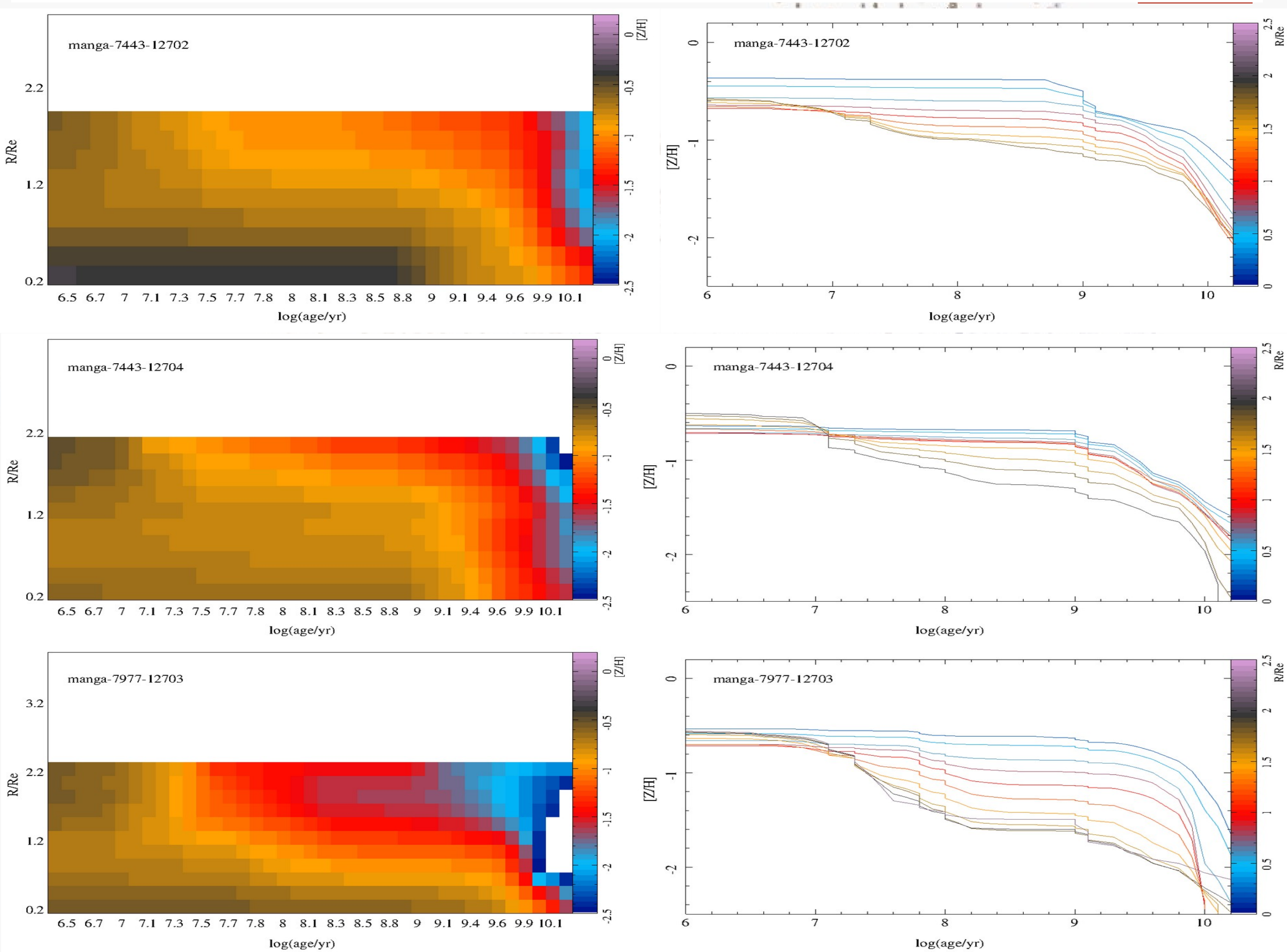


V-band $A_{*,L}$ $[Z/H]_{*,L}$ $Av_{*,L}$

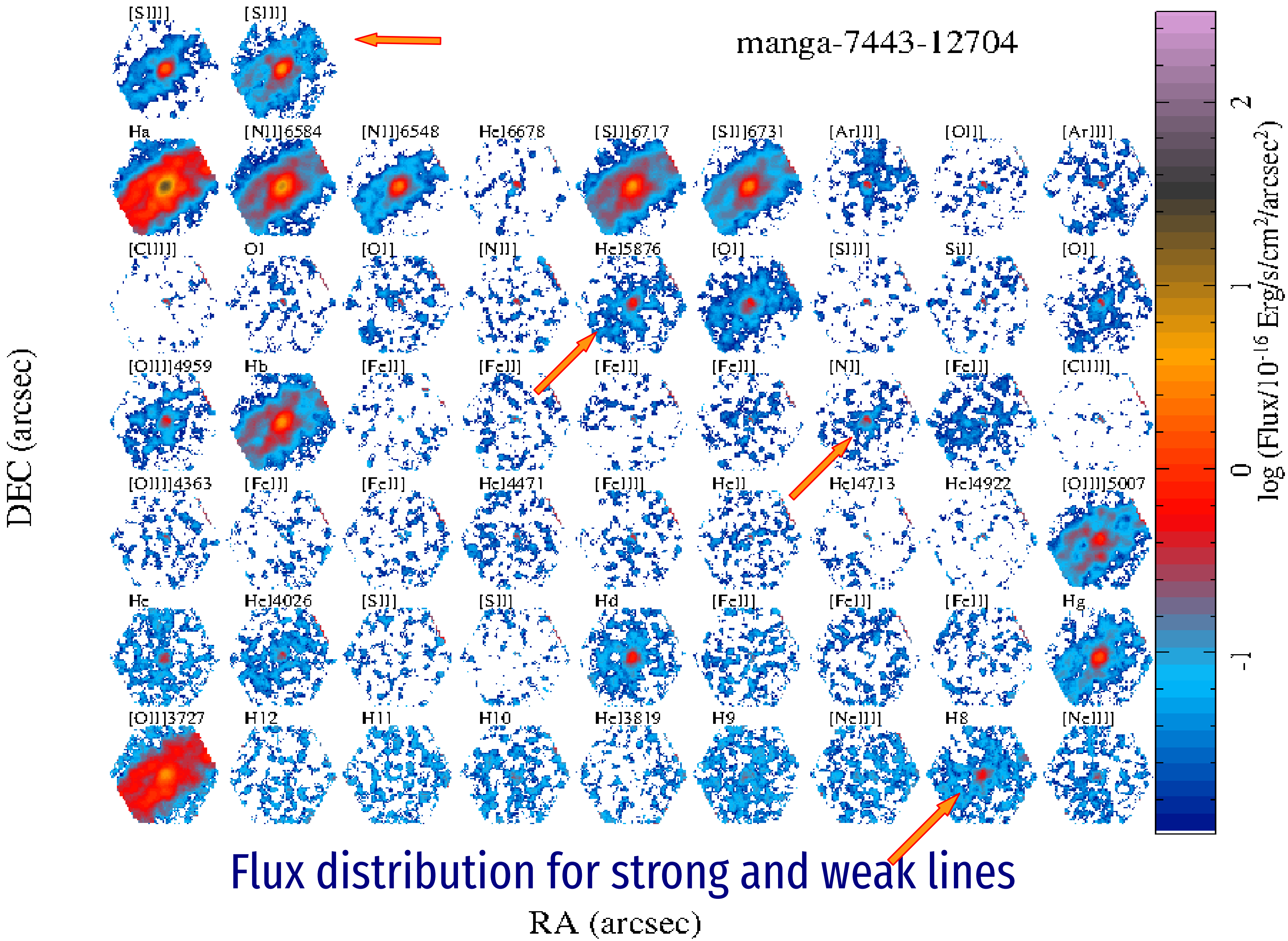


Z/H Assembling history → ChEH

Pipe3D: Radial Chemical Enrichment History (ChEH)

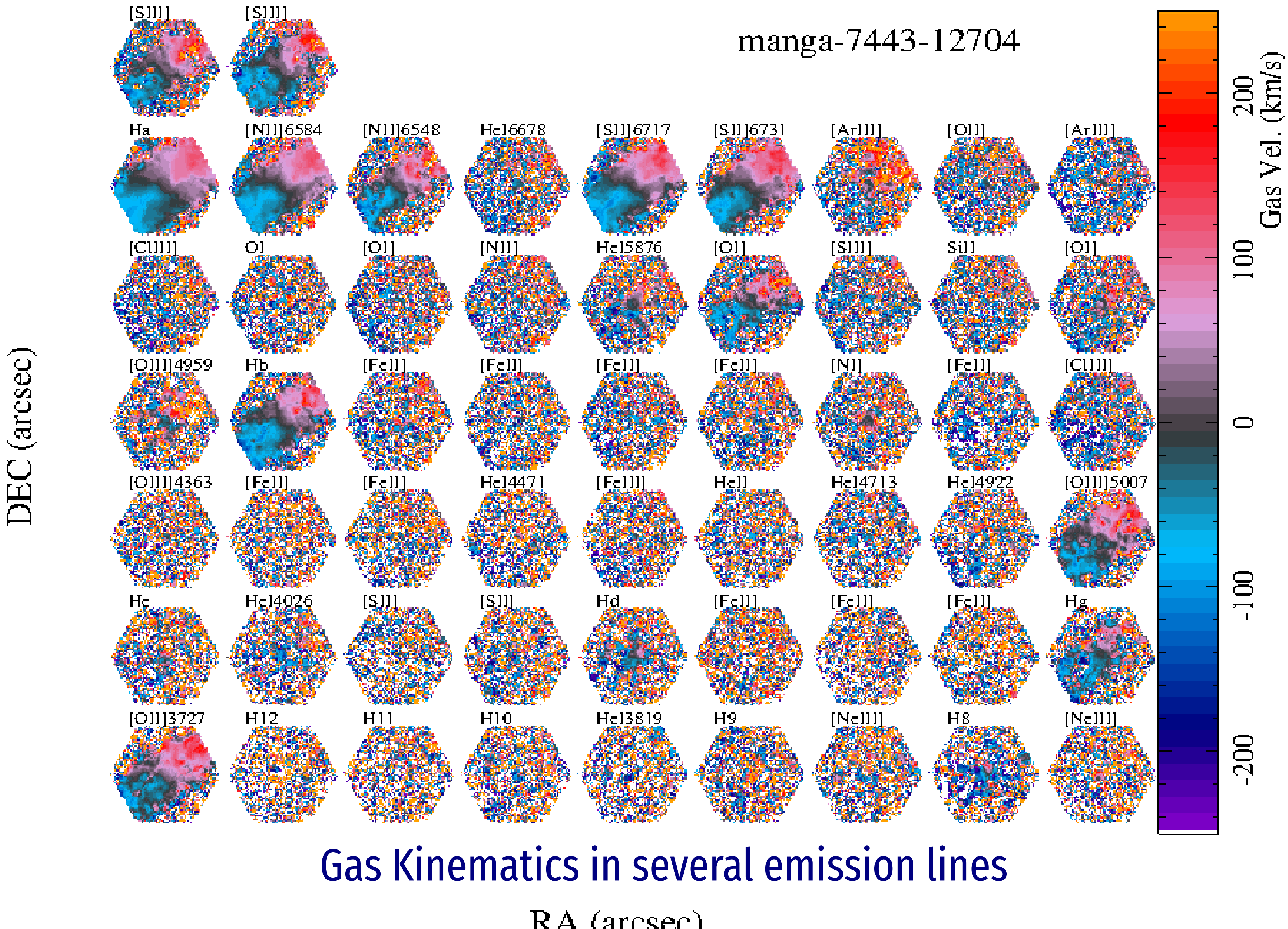


Pipe3D: Gas Data products



Flux distribution for strong and weak lines

Pipe3D: Gas Data products



Gas Kinematics in several emission lines