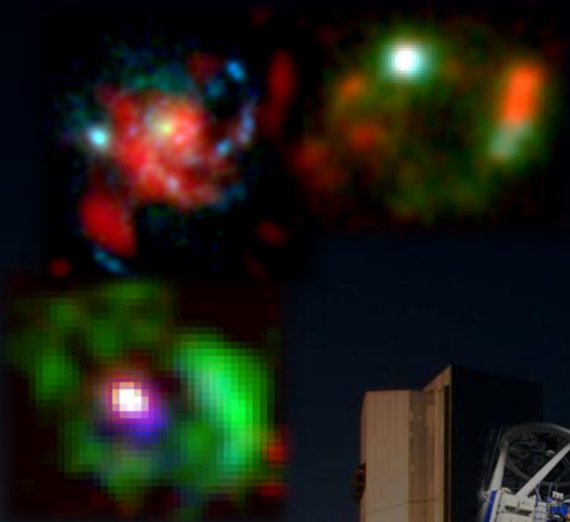
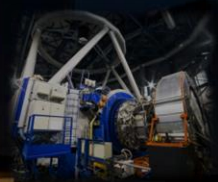


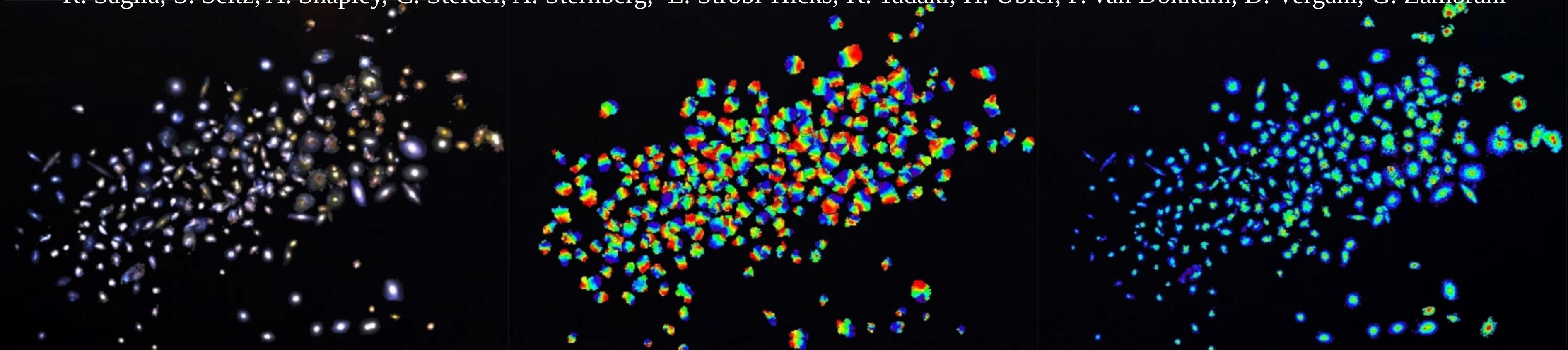
Galaxy Evolution



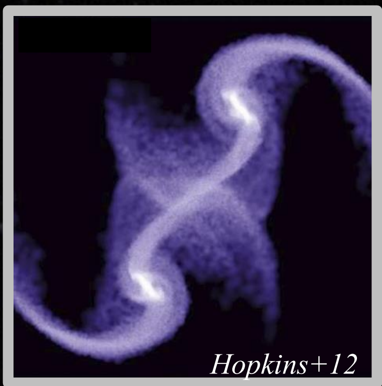
Insights from Spatially & Spectrally Resolved Studies at the Peak Epoch of Cosmic Star Formation

N.M. Förster Schreiber and the KMOS^{3D}, SINS/zC-SINF, 3D-HST, PHIBSS/2 Teams

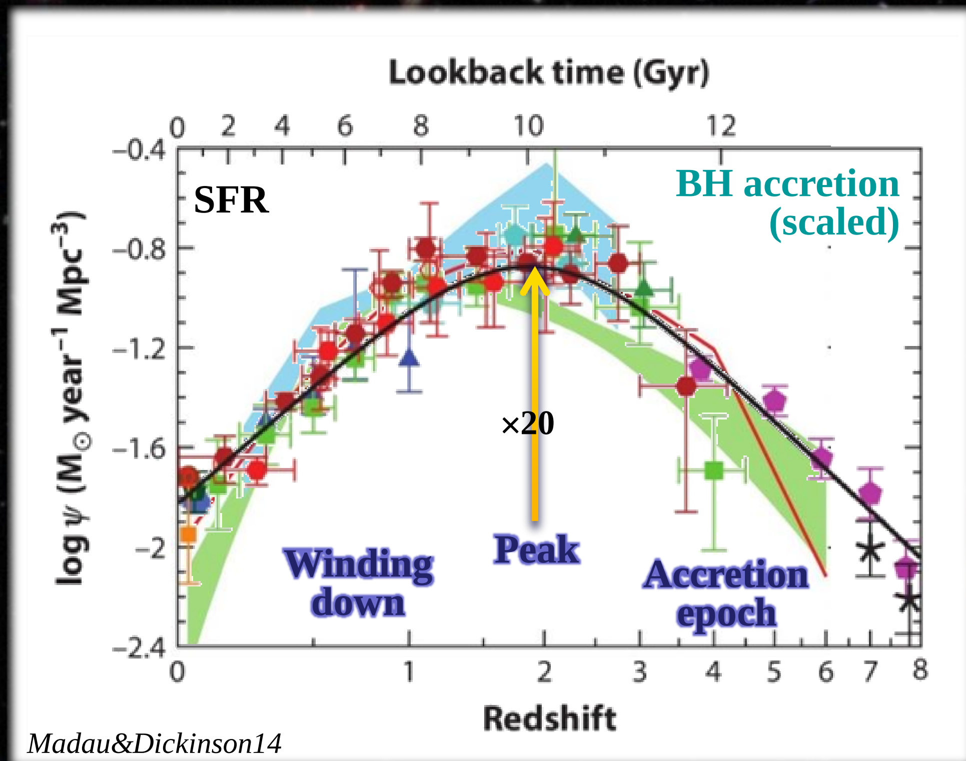
R. Genzel, E. Wisnioski , E. Wuyts, S. Wuyts, P. Lang, L.J. Tacconi, D. Lutz, M. Fossati, D. Wilman, A. Renzini, S. Tacchella, M. Carollo
K. Bandara, A. Beifiori, R. Bender, N. Bouché, G. Brammer, A. Burkert, J. Chan, A. Cimatti, G. Cresci, E. Daddi, R. Davies, D. Erb,
A. Galametz, S. Kulkarni, S. Lilly, C. Mancini, J.T. Mendel, I. Momcheva, T. Naab, E.J. Nelson, S. Newman, Y. Peng, D. Rosario,
R. Saglia, S. Seitz, A. Shapley, C. Steidel, A. Sternberg, E. Strobl-Hicks, K. Tadaki, H. Übler, P. van Dokkum, D. Vergani, G. Zamorani

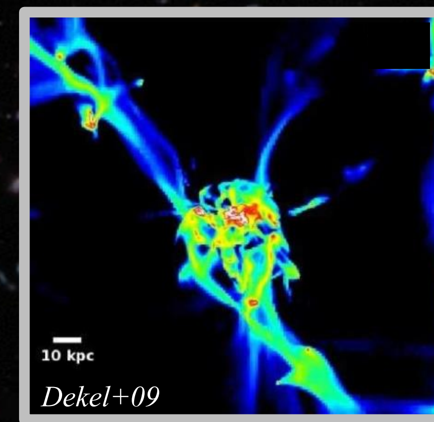


Star Formation across Cosmic Times



(Major) Mergers and Starbursts





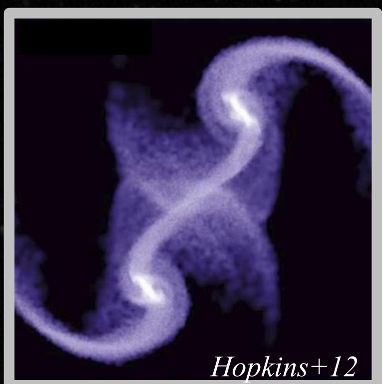
Smoother Accretion from Halo + Minor Mergers and Disk Instabilities

Lilly+96; Madau+96; Steidel+96; Schiminovich+05; Le Floc'h+05; Pérez-Gonzáles+05,08; Hopkins&Beacom06; Caputi+07; Dahlen+07; Reddy+08,09;Soifer+08; Le Borgne+09; Rodighiero+10; Robotham&Driver11; Gruppioni+10;13; Magnelli+11,13; Cucciati+12; Bouwens+12; Schenker+13; delVecchio+14; among others.

And, e.g., Baker+04; Coppin+07; Tacconi08;10,13; Genzel+10,12,13,15; Daddi+10; Geach+11; Saintonge+11,13; Combes+12; Bauermeister+12; Magdis+12; Magnelli+12; Freundlich+13; Santini+13; Baker+04; Walter&Carilli13

Also, Rees&Ostriker77; Silk77; White&Rees78; Kauffmann+93,10; Steinmetz&Navarro03; Dekel&Birnboim03,06;Hopkins+03-14; Springel+05; Kereš+05,09,15; Kitzbichler&White07; Naab+07; Davé+07-14; Robertson&Bullock08; Governato+08; Ocvirk+08; Dekel+09-14; Agertz+09; Guo+09,11; Teyssier+10; Bournaud+10-15; Genel+08,10,14,15; Vogelsberger+13;Ceverino+12-14; Shaye+14; & others.

Star Formation across Cosmic Times



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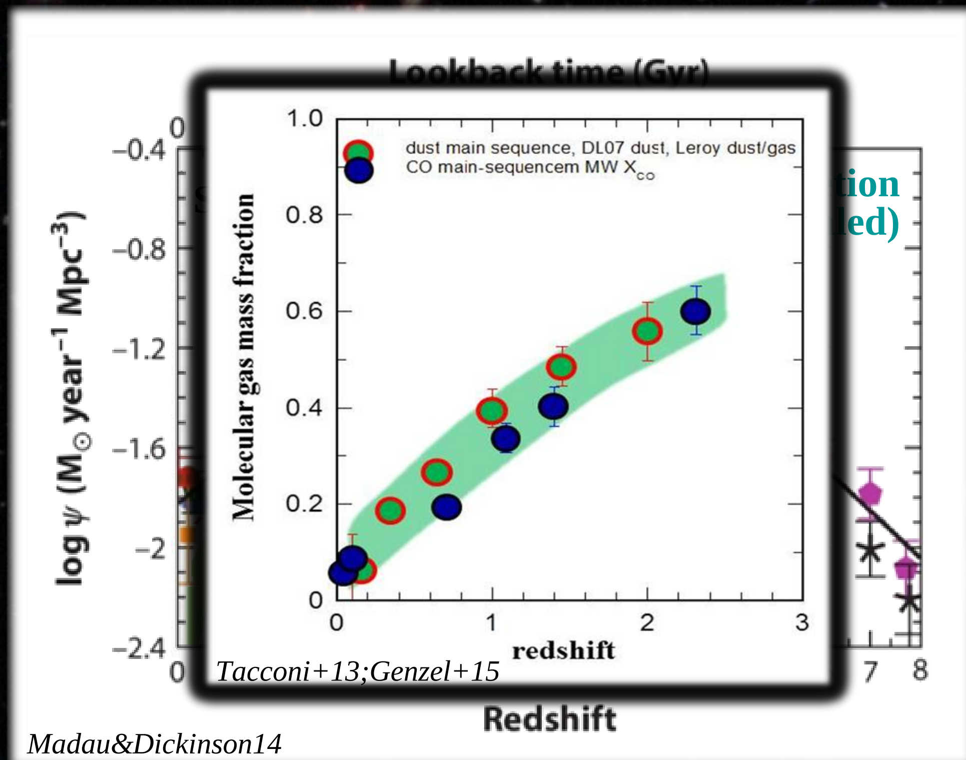

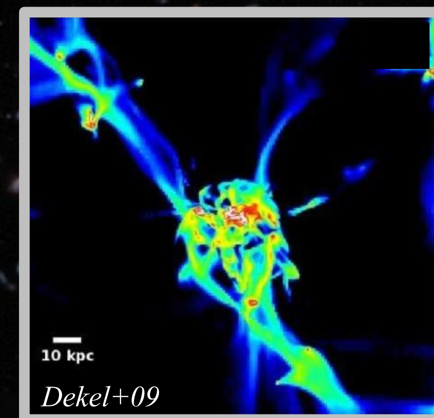

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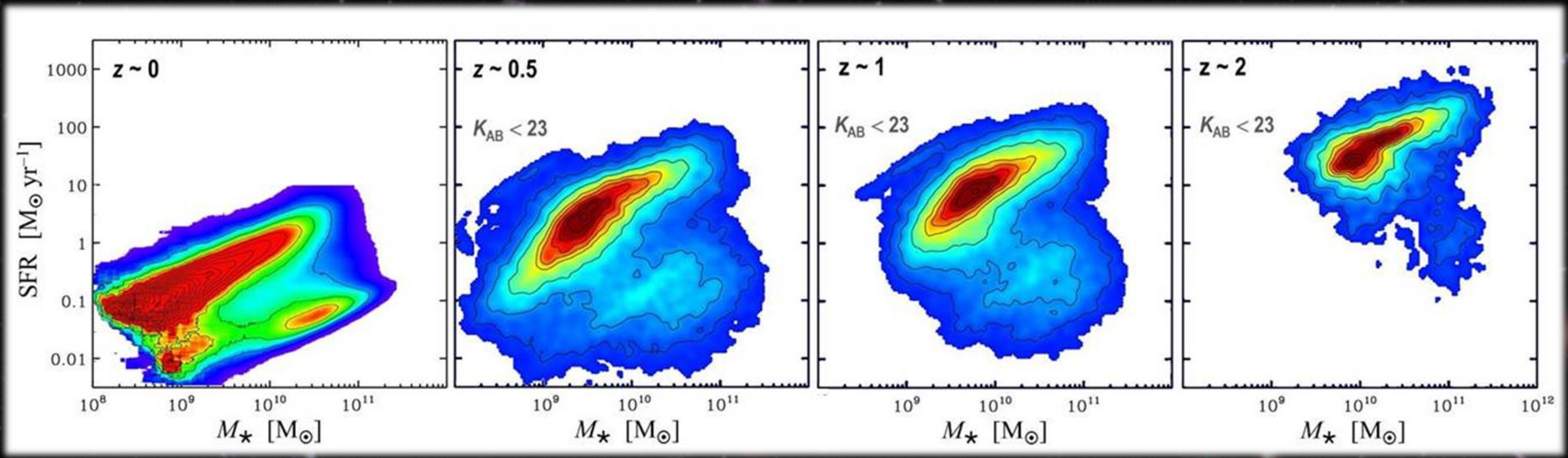
The “Main Sequence” of Star-Forming Galaxies

- SFR ~ M_* on the MS
- ~ 90% of the cosmic SFR occurs on the MS
- MS SFGs have gas depletion times $\lesssim$ 1 Gyr
- Efficient quenching above $\log(M_*/M_\odot)$ ~ 11



E.g., Rudnick+03,06; Noeske+07; Elbaz+07; Daddi+07,10; Marchesini+09; Shankar+09; Ilbert+10,13; Peng+10; Brammer+11; Rodighiero+11,14; Caputi+11; Gonzalez+11; Magnelli+11,12,13; Saintonge+11,13; Whitaker+12,14; Combes+12; Magdis+12; Ilbert+13; Muzzin+13; Stark+13; Steinhardt+14; Koprowski+14,15; Tasca+15; Grazian+15; Renzini&Peng15.
Also Kereš+05,09;Oppenheimer&Davé+06;Genel+08;Guo+09;Dekel+09;Dutton+09;Bouché+10;Davé+10-12;Krumholz+12;Lilly+13;Peng+15; & others

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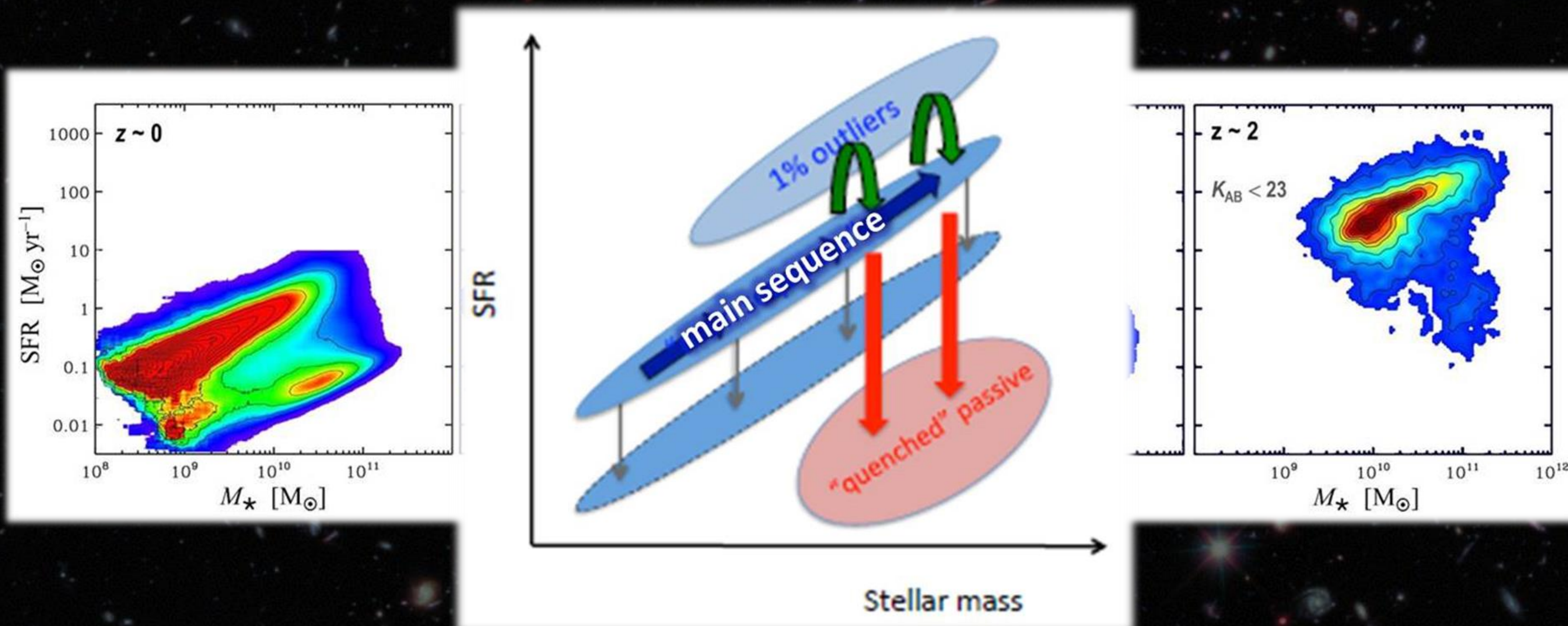

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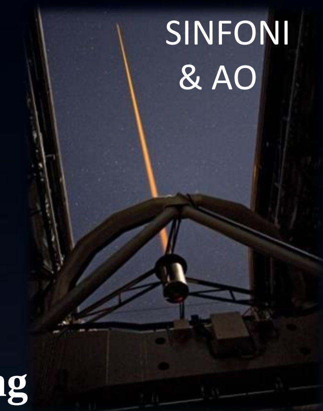
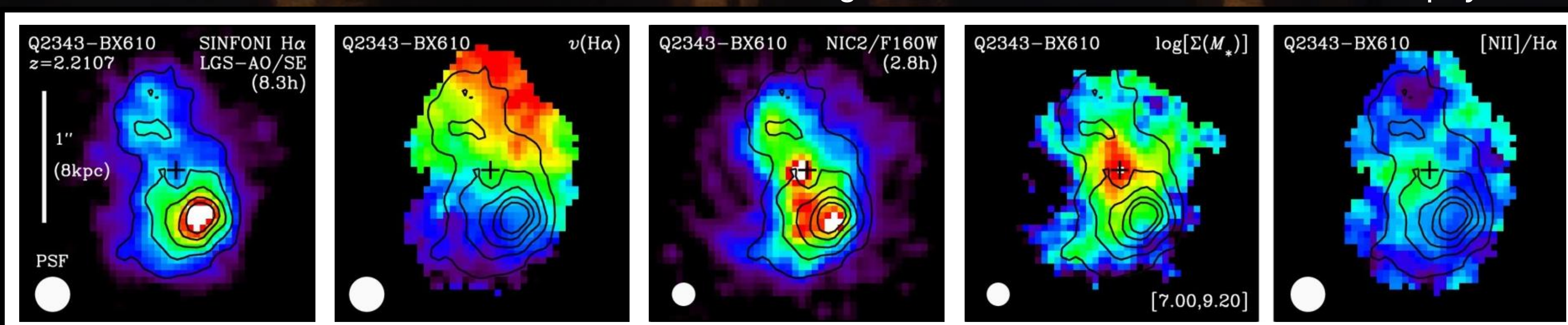


From Censuses to the Physics of Galaxy Evolution

Mass assembly – star formation – structural buildup – – SMBH growth – chemical enrichment – feedback – quenching

- **Kinematics and structure**
- **Mass budget** and angular momentum
- **Outflow and quenching processes**
- ISM conditions and excitation, metallicities

Star formation | Kinematics | Stellar light | Stellar mass | Nebular physics



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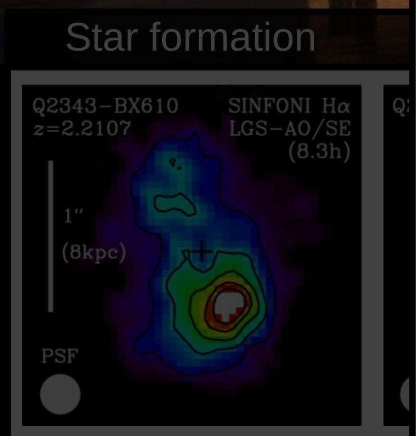
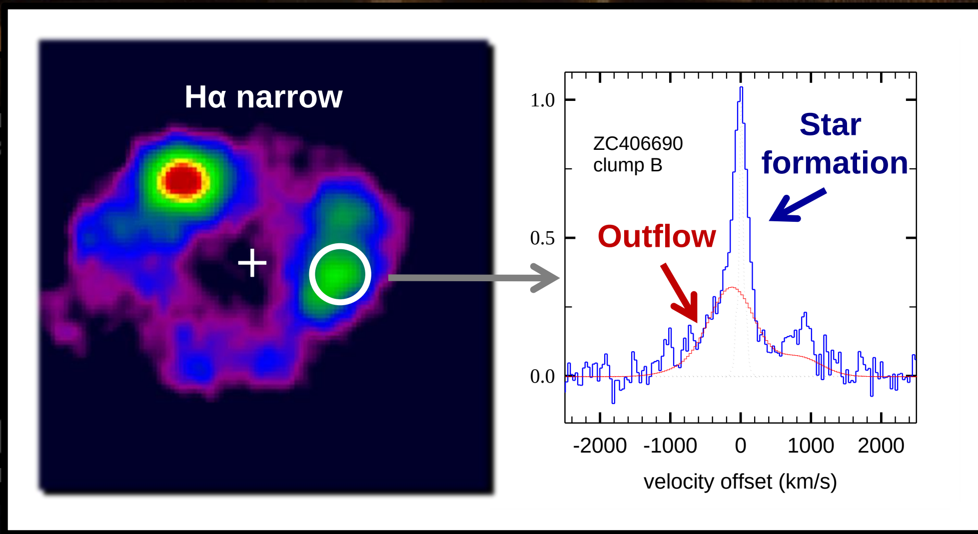
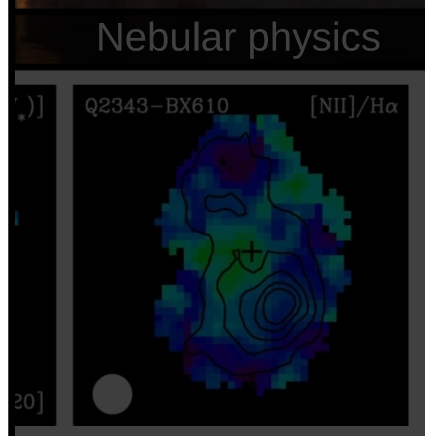
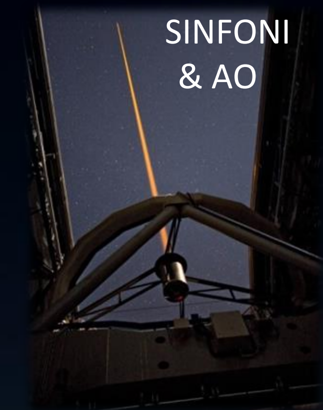
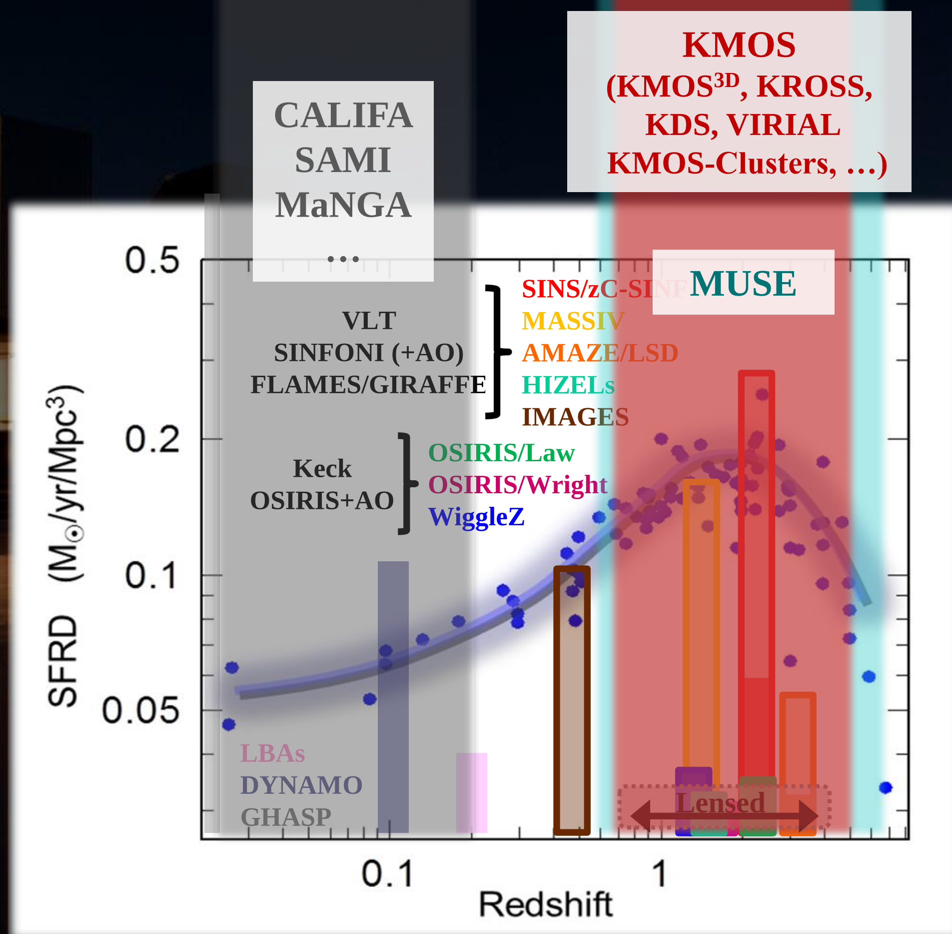






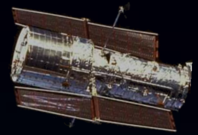
Surveys with Opt/NIR IFUs

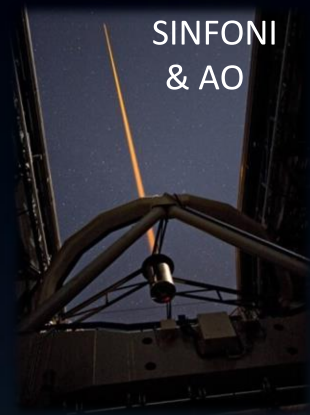




➡ **Review by Glazebrook (2013)**

SINS/zC-SINF: NMFS+09/15,Mancini+11,Newman+13; MASSIV: Épinat+09a/12,Contini+12,Sanchez-Lopez+12; AMAZE/LSD: Gnerucci+10/11; OSIRIS: Law+09/12,Wright+09; WiggleZ: Wisnioski+11,12; HiZELs: Swinbank+12a/12b; IMAGES: Flores+06, Yang+08, Puech+12; LBAs: Basu-Zych+09,Gonçalves+10; DYNAMO: Green+10; GHASP: Épinat+09b/10 Lensed objects: Stark+08, Jones+10/12, Yuan+11/12, E.Wuyts+13, Livermore+15, Leethochawalit+15 KMOS: Wisnioski+15, Genzel+14, E.Wuyts+14, Sobral+13, Stott+14; Mendel+15, Burkert+15, and more in prep.





From Censuses to the Physics of Galaxy Evolution

Spatially-resolved near-IR IFU
Exploiting VLT and HST opt/NIR, and Herschel far-IR surveys

zCOSMOS → GMASS → K20 →

SINS/zC-SINF

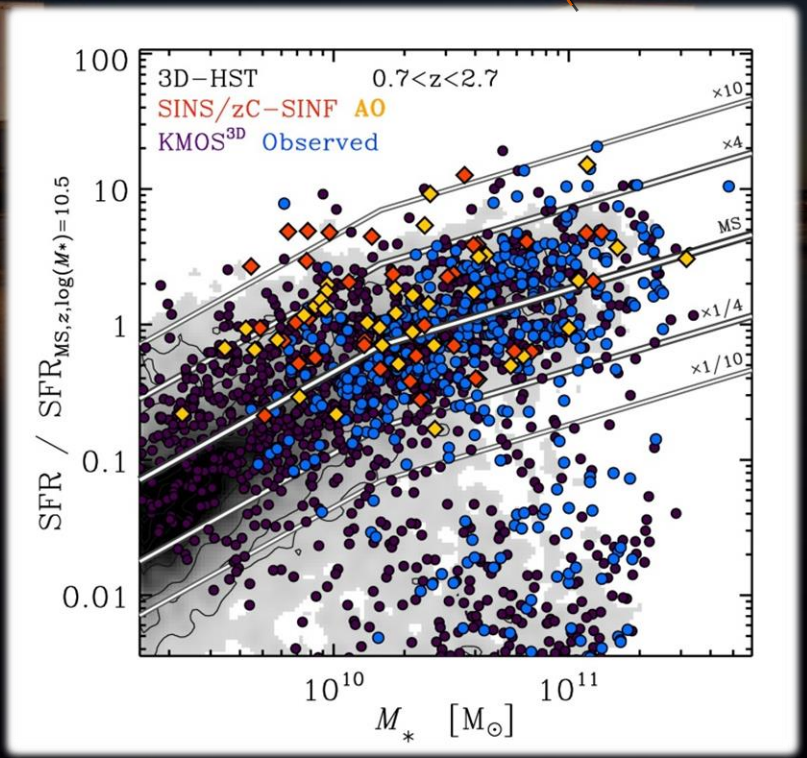
- 110 SFGs at z ~ 1–3
- 35 w/ deep AO follow-up

EIS/DPS
ESO/GOODS
K20
zCOSMOS
GMASS
VVDS
UDSz

3D-HST → CANDELS → PEP →

KMOS[3D]

- 600+ M_*-selected z~0.7-2.7 SFGs
- Deep+wide coverage in M_*-SFR-*UVJ*



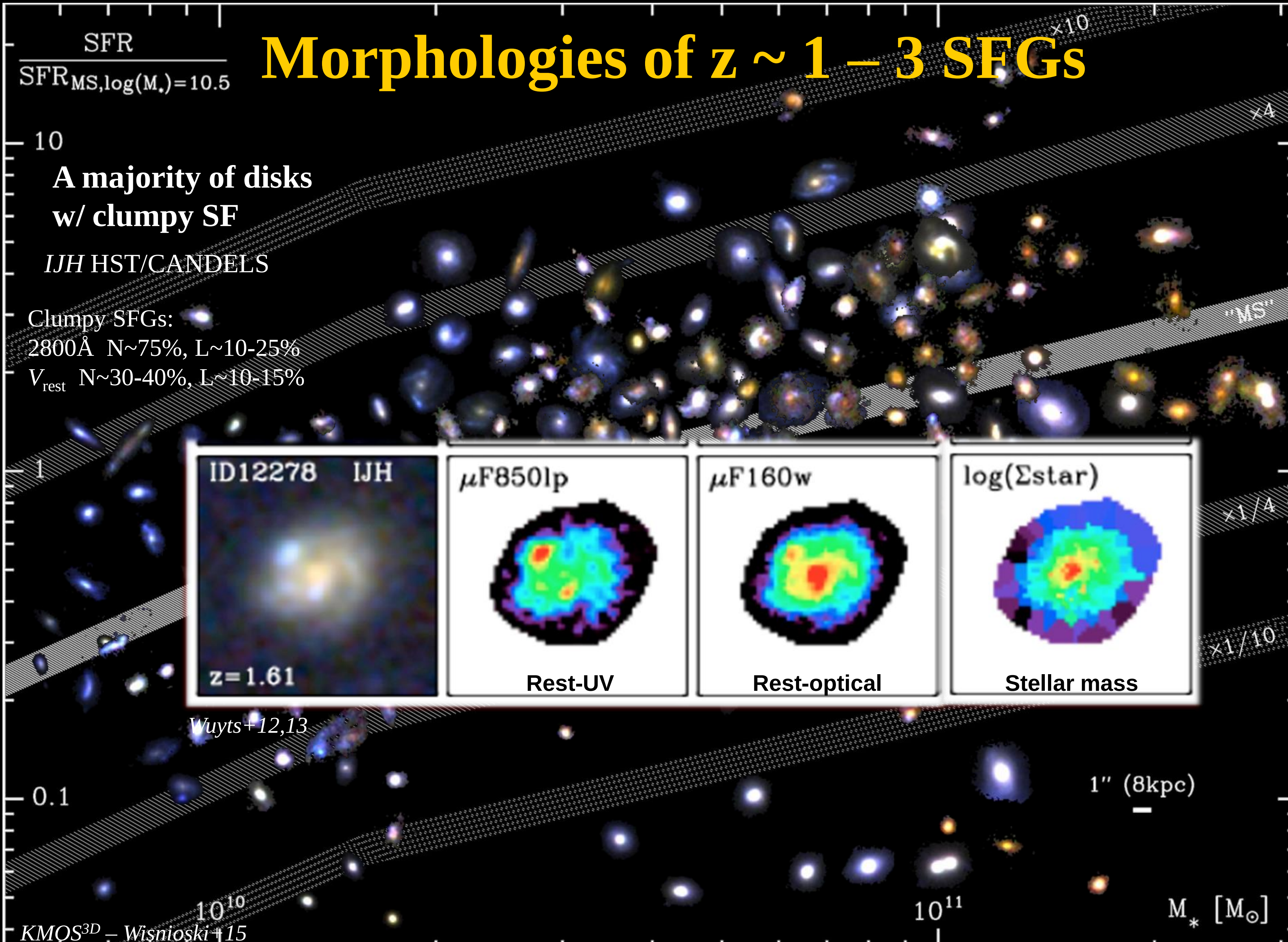
NMFS+09,15; Mancini+11; Wisnioski+15

Morphologies of z ~ 1 – 3 SFGs

A majority of disks w/ clumpy SF

IJH HST/CANDELS

Clumpy SFGs:
2800Å N~75%, L~10-25%
V_{rest} N~30-40%, L~10-15%



Wuyts+12,13

KMOS^{3D} – Wisnioski+15

E.g., Labbé+03;Lotz+06,08,10; Elmegreen+07-09;Kriek+09;NMFS+11a,b;Guo+12,15;Szomoru+13;Nelson+13;Tacchella+15a,b;Tadaki+14a;Cibinel+15

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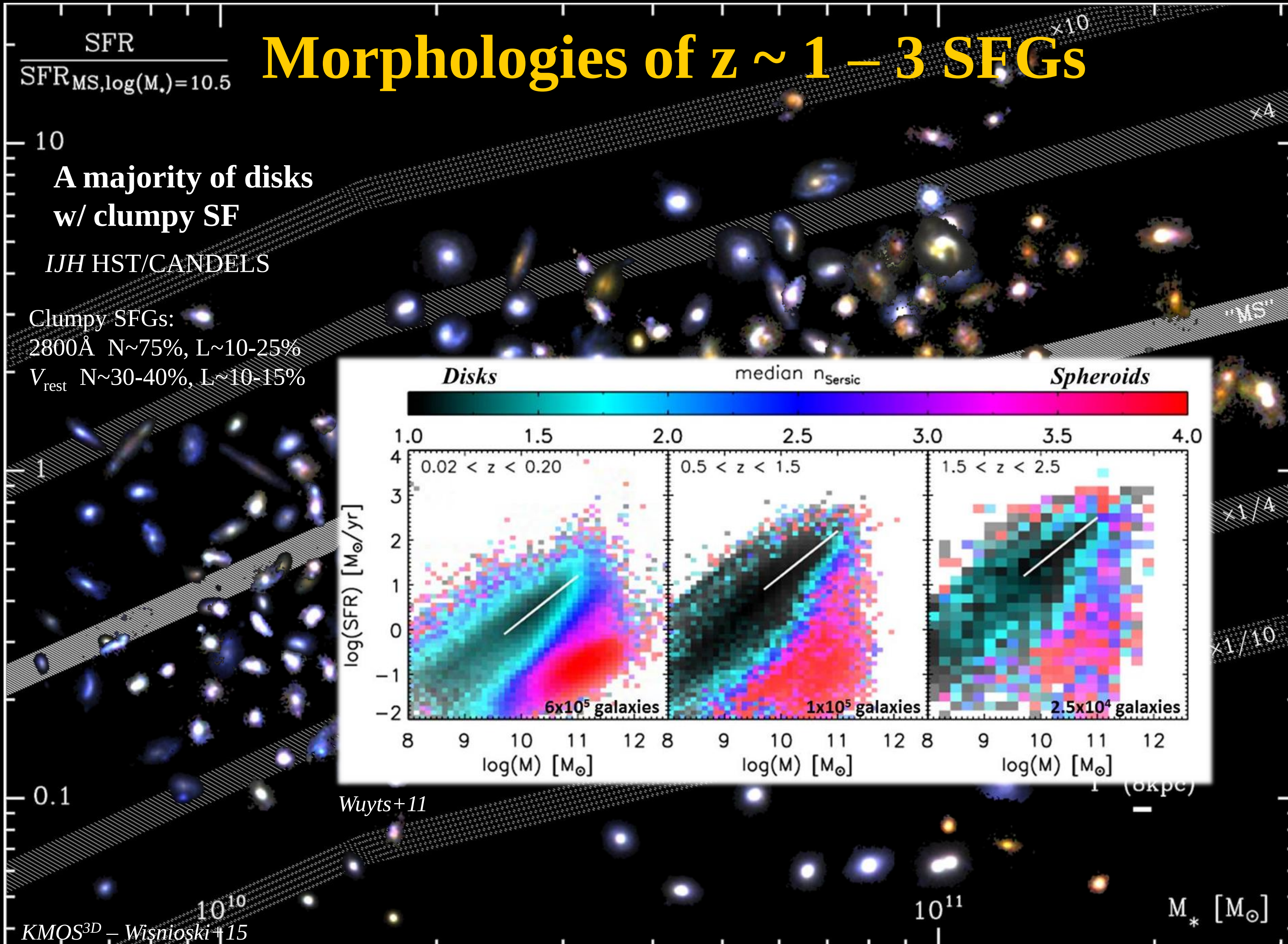

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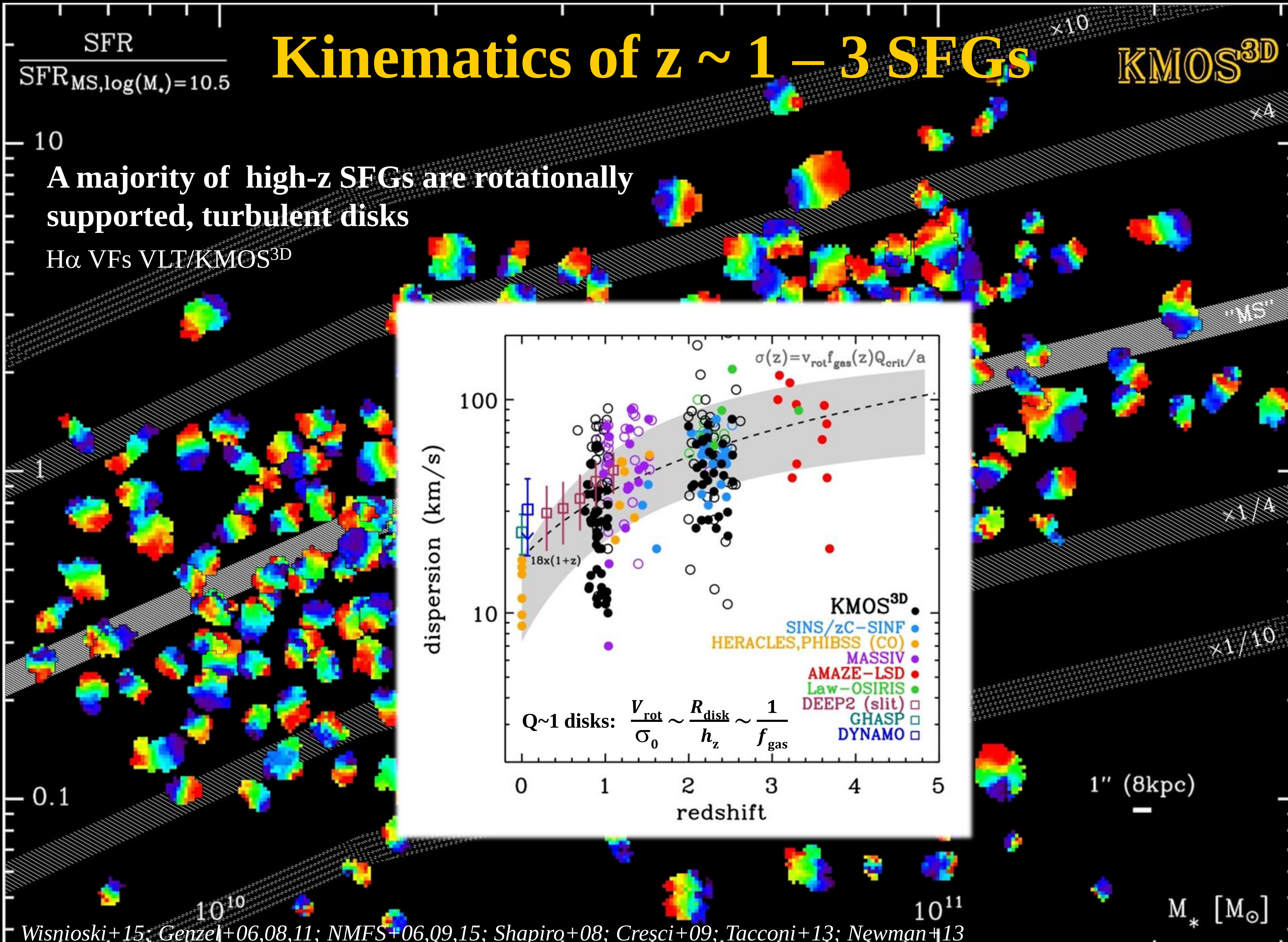
Kinematics of z ~ 1 – 3 SFGs

A majority of high-z SFGs are rotationally supported, turbulent disks

Hα VFs VLT/KMOS[3D]



Q~1 disks: $\frac{V_{rot}}{\sigma_0} \sim \frac{R_{disk}}{h_z} \sim \frac{1}{f_{gas}}$

Wisnioski+15; Genzel+06,08,11; NMFS+06,09,15; Shapiro+08; Cresci+09; Tacconi+13; Newman+13

Also, e.g., Law+09,12;Epinat+09-12;Jones+10;Green+10; Wisnioski+11,12; Yuan+11,12;Kassin+12; Sobral+13;Stott+14; Livermore+15; Leethochawalit+15

Kinematics of z ~ 1 – 3 SFGs

KMOS^{3D}

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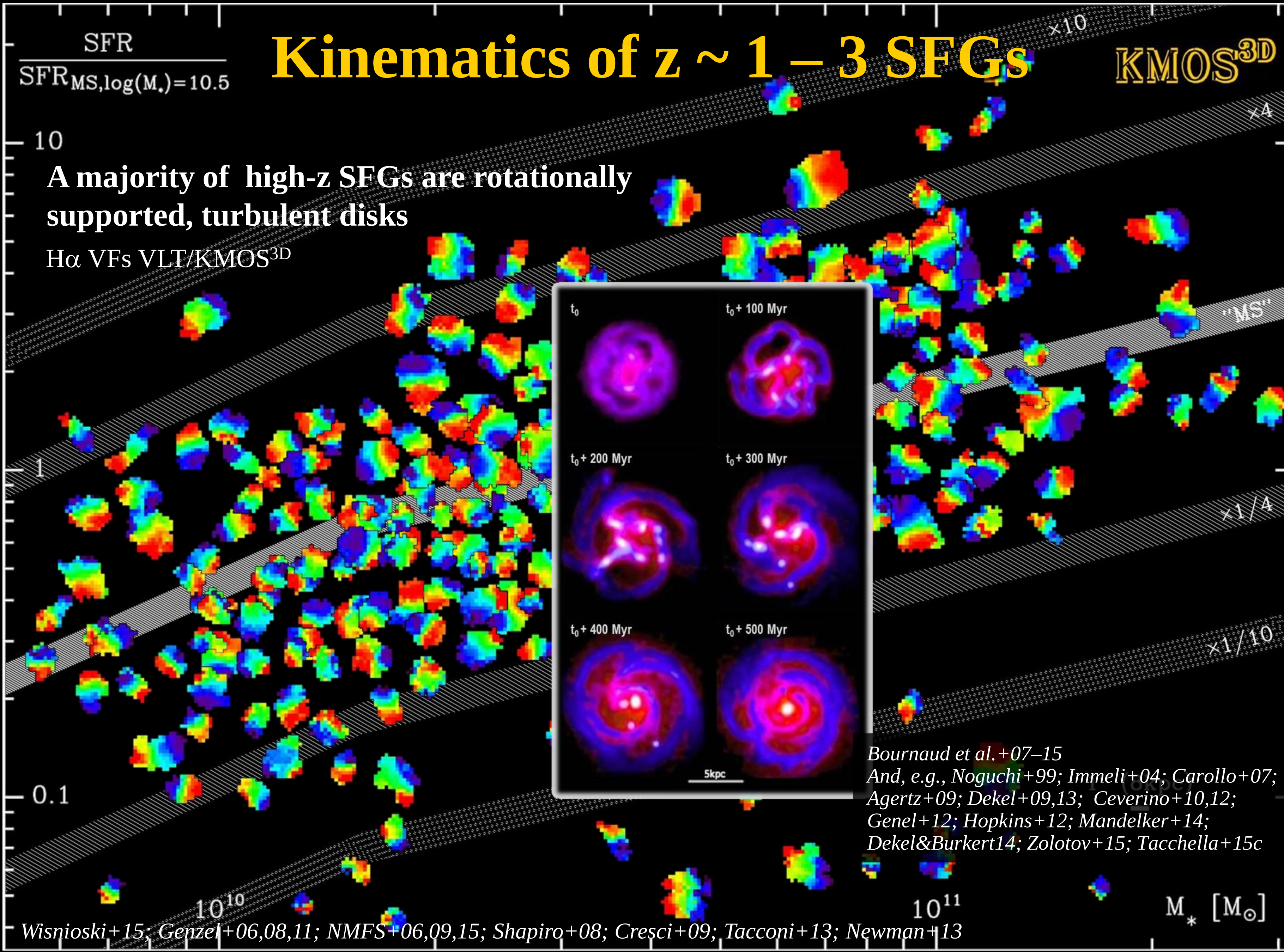
Hα VFs VLT/KMOS^{3D}



Bournaud et al.+07–15
And, e.g., Noguchi+99; Immeli+04; Carollo+07; Agertz+09; Dekel+09,13; Ceverino+10,12; Genel+12; Hopkins+12; Mandelker+14; Dekel&Burkert14; Zolotov+15; Tacchella+15c

Wisnioski+15; Genzel+06,08,11; NMFS+06,09,15; Shapiro+08; Cresci+09; Tacconi+13; Newman+13

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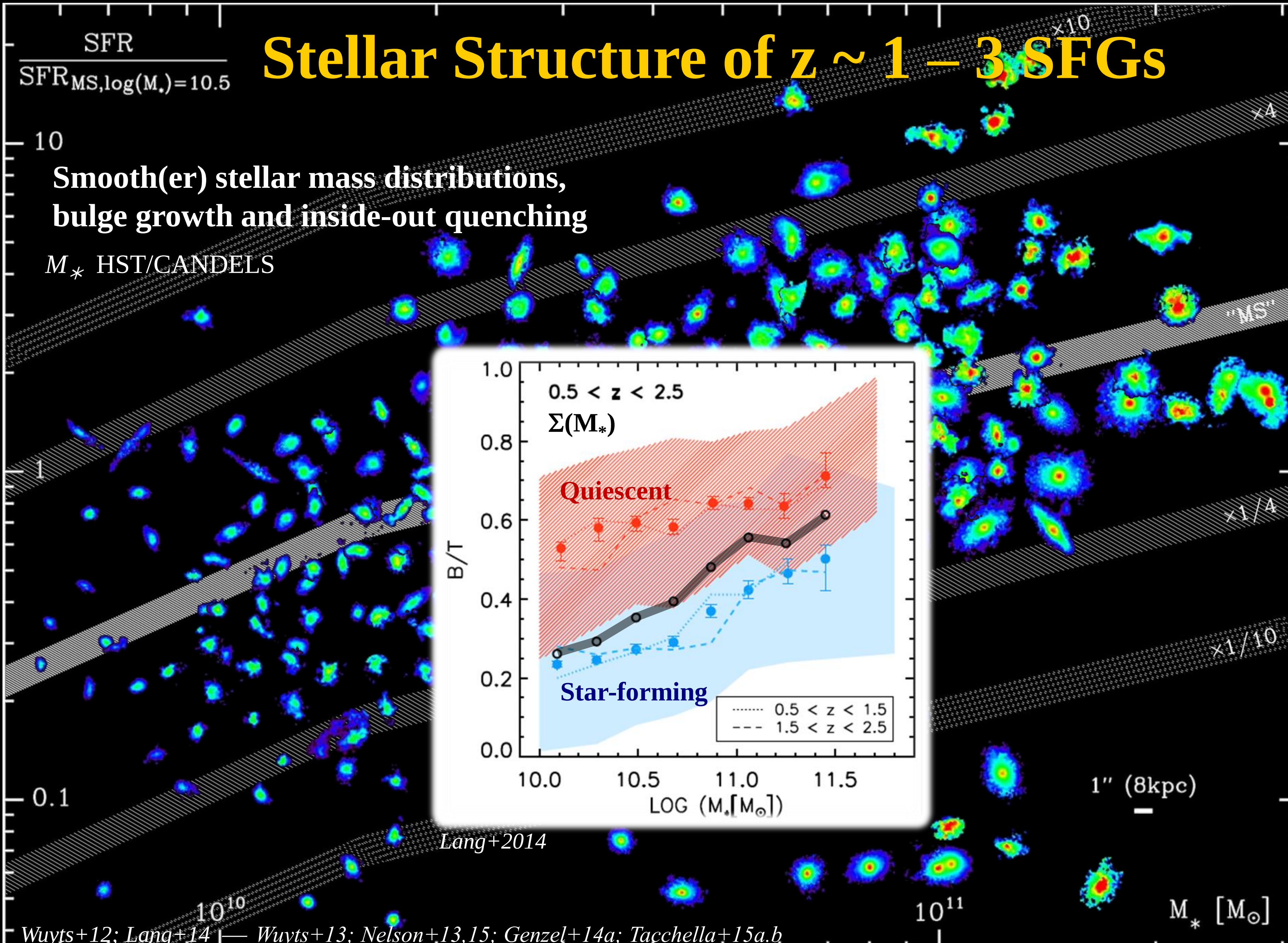
Stellar Structure of z ~ 1 – 3 SFGs

Smooth(er) stellar mass distributions, bulge growth and inside-out quenching



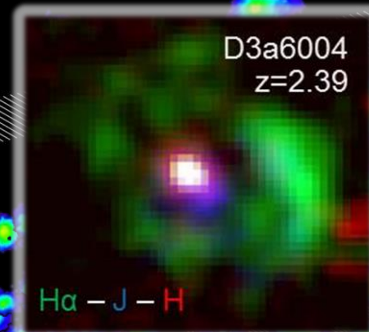
Wuyts+12; Lang+14 — Wuyts+13; Nelson+13,15; Genzel+14a; Tacchella+15a.b

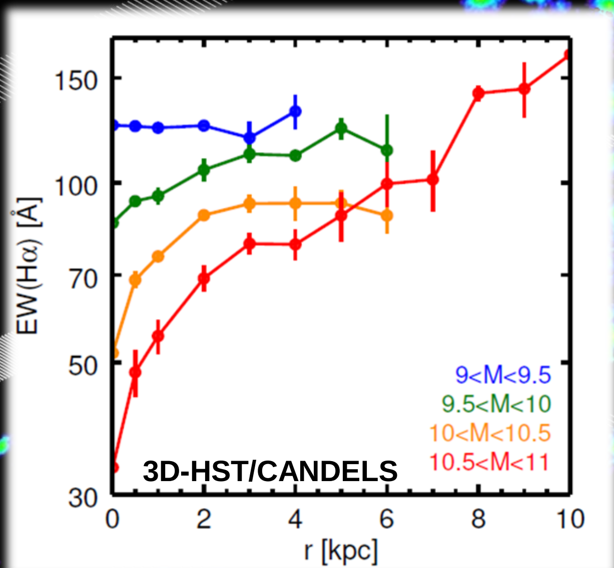
And e.g. Kauffmann+03,06;Schiminovich+07;Bell+08,12;Cheung+12;Bruce+12,14;Fang+13;Bluck+14 ; Hunter+98;Martig+09,13;Saintonge+12;Crocker+12

Stellar Structure of z ~ 1 – 3 SFGs

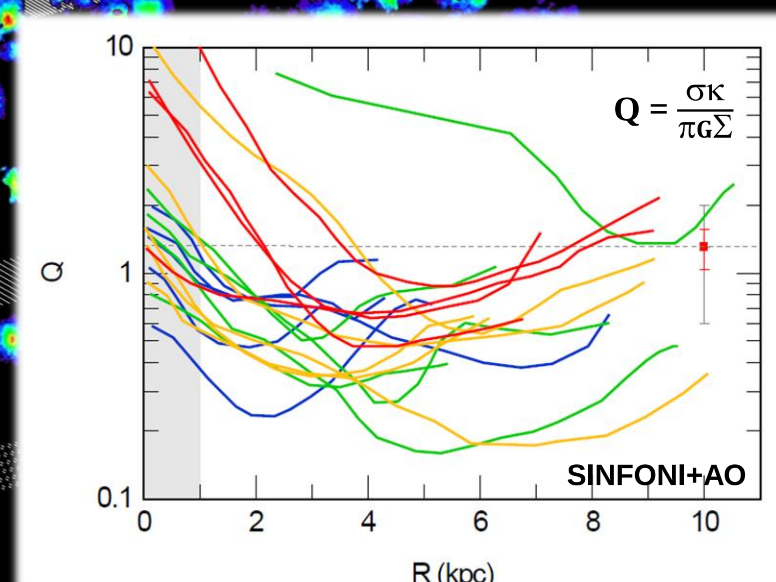
Smooth(er) stellar mass distributions, bulge growth and inside-out quenching

M_* HST/CANDELS





Nelson+15



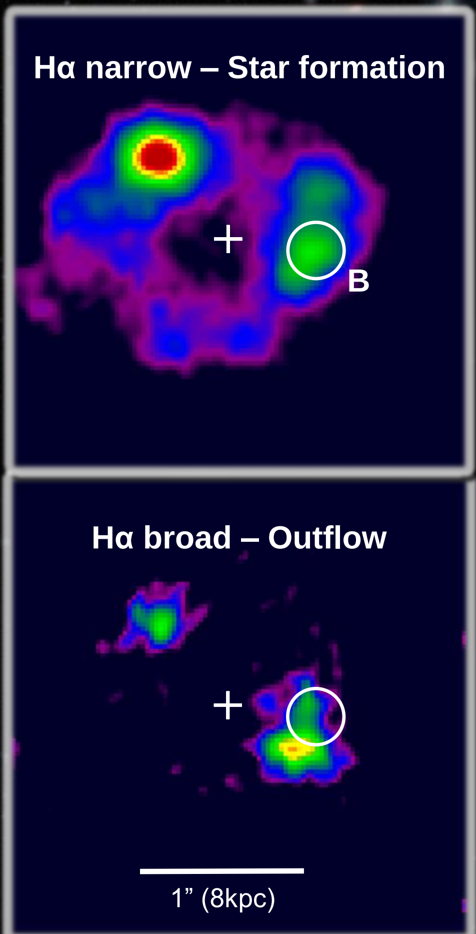
Genzel+14a

Wuyts+12; Lang+14 — Wuyts+13; Nelson+13,15; Genzel+14a; Tacchella+15a.b

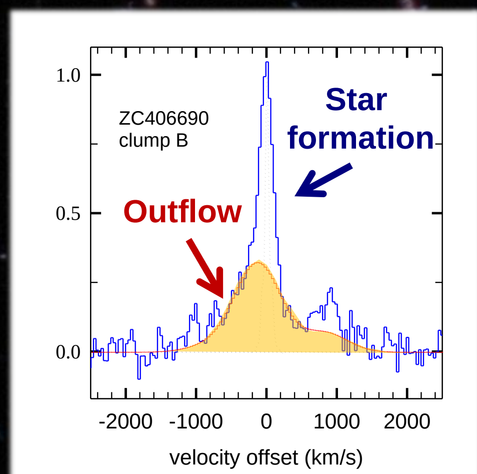
And e.g. Kauffmann+03,06;Schiminovich+07;Bell+08,12;Cheung+12;Bruce+12,14;Fang+13;Bluck+14 ; Hunter+98;Martig+09,13;Saintonge+12;Crocker+12

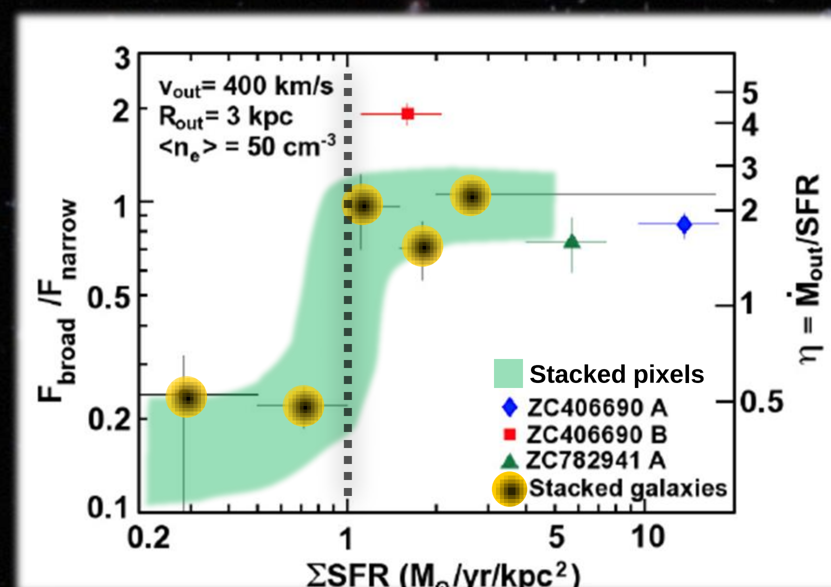
Vigorous Feedback from Star Formation

SINFONI+AO



- FWHM ~ 450 km/s
- dM_{out}/dt (ionized gas) ~ 1 – 5× SFRs
- Breakout at $\Sigma(SFR) \gtrsim 1\ M_{\odot}/yr/kpc^2$



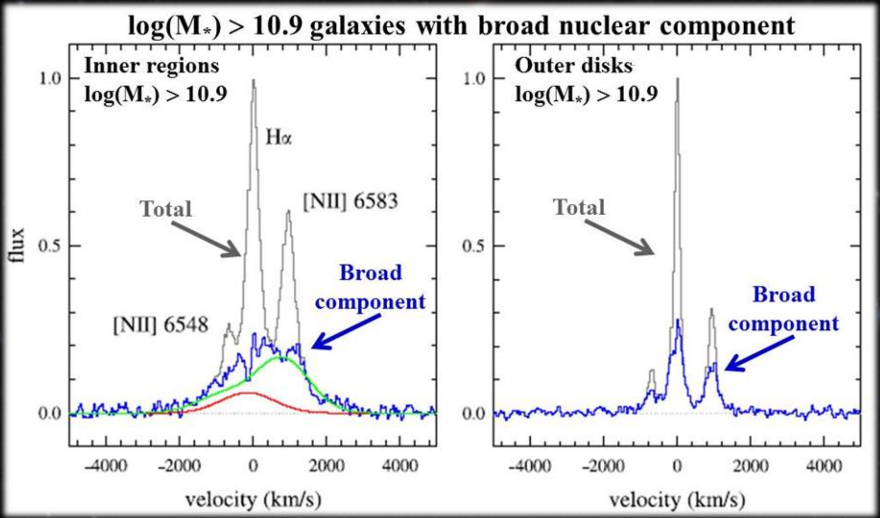


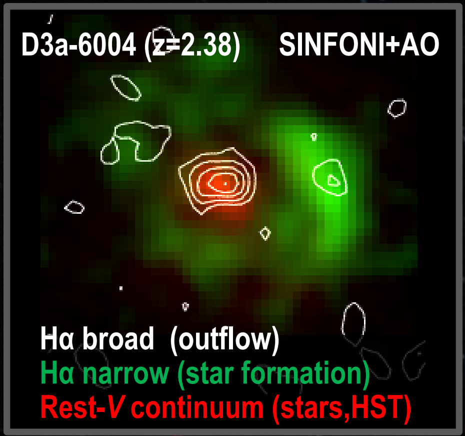
Genzel+11; Newman+12a,b; Shapiro+09

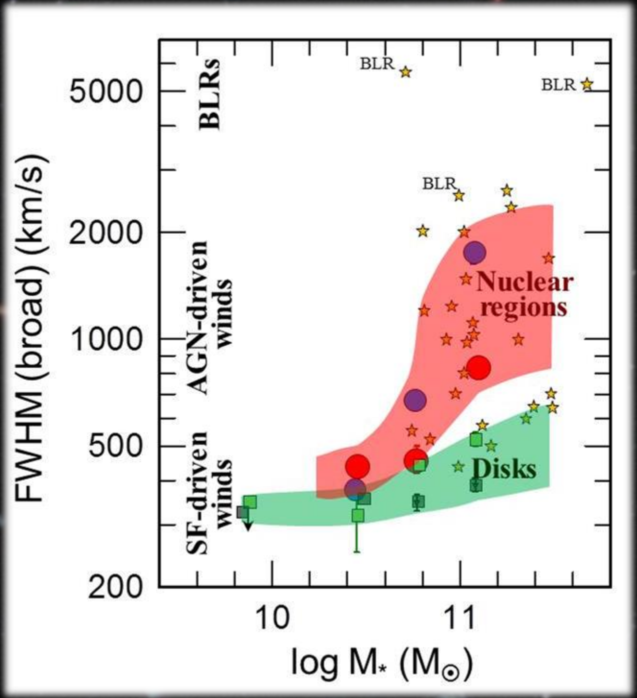
Also, Pettini+00; Heckman+03,15; Shapley+03;Weiner+09; Steidel+10; Coil+11; Kulas+11; Law+12b; Kornei+12; Chen+12; Martin+05; Rupke+02–13; Sharp,Bland-Hawthorn10; Sturm+11; Westmoquette+12,13; Bouché+12,14; RodríguezZaurín+13; Cicone+14; and many others

Widespread Nuclear Outflows Driven by AGN

- Centers of log(M_*) ≳ 10.9 galaxies, FWHM ~ 500–2000 km/s, in Hα+[NII]+[SII], 2 – 3 kpc extent
- High duty cycle among *typical* massive galaxies, dM_{out}/dt (ionized gas) ~ SFR, $v_{out} > v_{esc}$







NMFS+14; Genzel+14b; + in prep.

320 M_*-selected 0.8 < z < 2.6 galaxies; 80 at log(M_*) > 10.8 (KMOS^{3D}, SINS/zC-SINF, LUCI, GNIRS)

.Also, e.g., Rupke+02-13; Sturm+11; Nesvadba+11; Westmoquette+12,13; Harrison+12,14; Maiolino+12; Cano Diaz+12; Fabian12; Diamond-Stanic+12; Mullaney+13; Rodriguez-Zaurin+13; Cicone+12,14,15; Juneau+12,14; Brusa+15; Cresci+15; Perna+15

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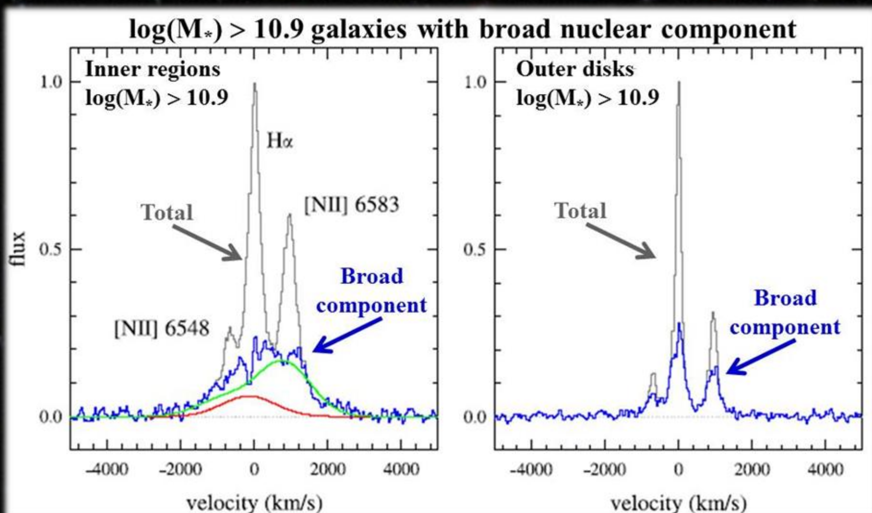
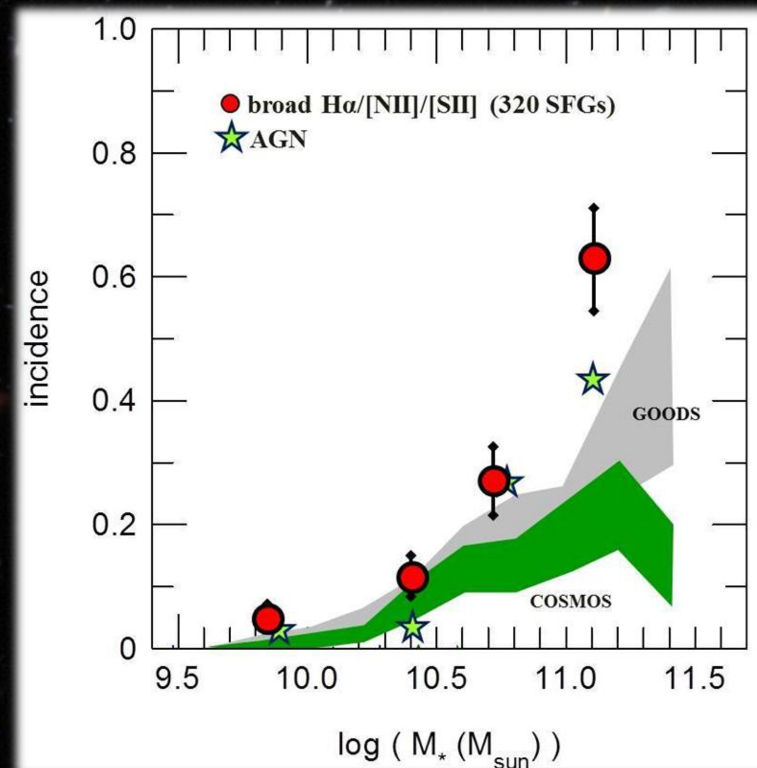
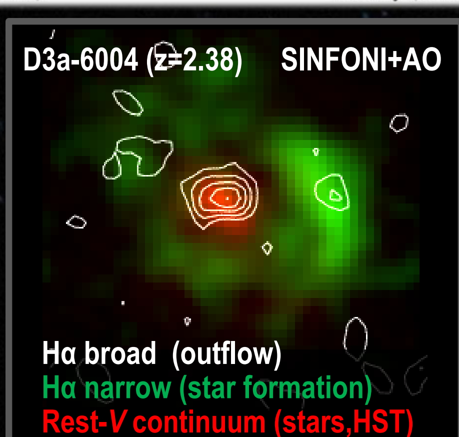






NMFS+14;
Genzel+14b;
+ in prep.

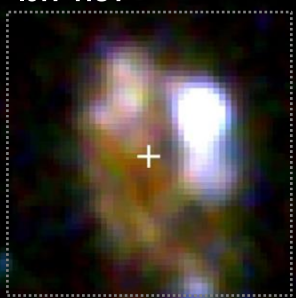
320 M_*-selected 0.8 < z < 2.6 galaxies; 80 at log(M_*) > 10.8
(KMOS^{3D}, SINS/zC-SINF, LUCI, GNIRS)

.Also, e.g., Rupke+02-13; Sturm+11; Nesvadba+11; Westmoquette+12,13; Harrison+12,14; Maiolino+12; Cano Diaz+12; Fabian12; Diamond-Stanic+12; Mullaney+13; Rodriguez-Zaurin+13; Cicone+12,14,15; Juneau+12,14; Brusa+15; Cresci+15; Perna+15

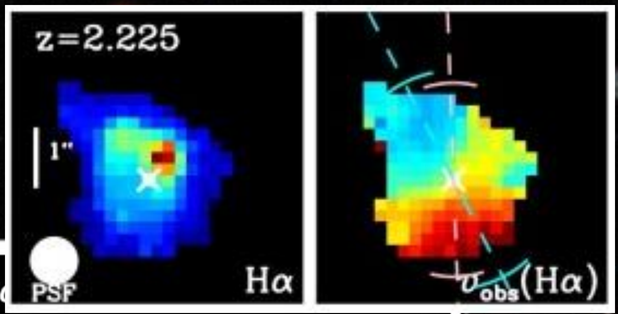
The Need for Sensitive Spatially-Resolved Data

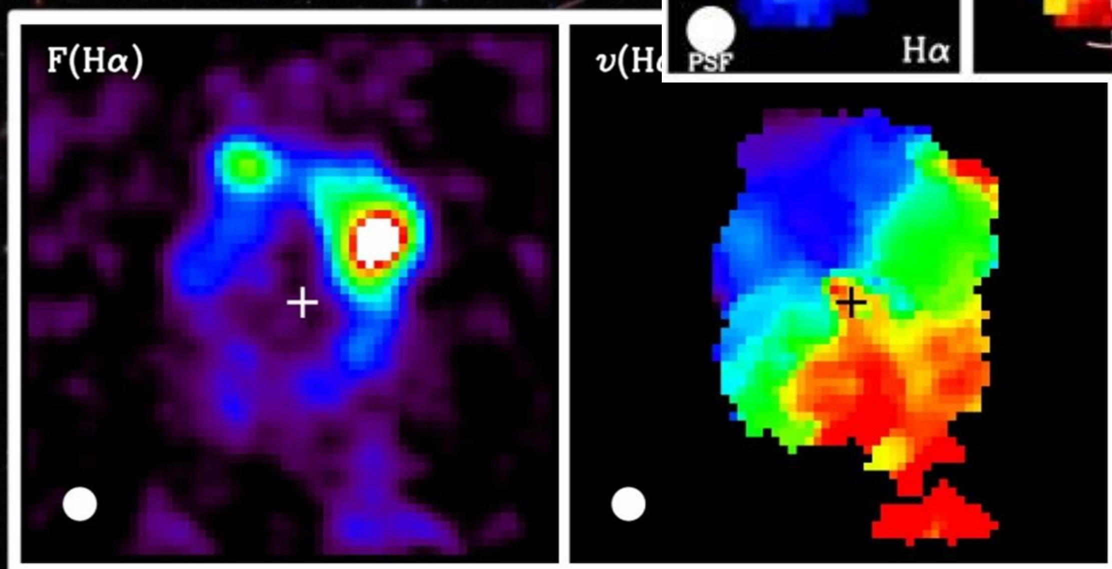
K20-ID7   z = 2.2

IJH HST



KMOS (noAO)





SINFONI+AO

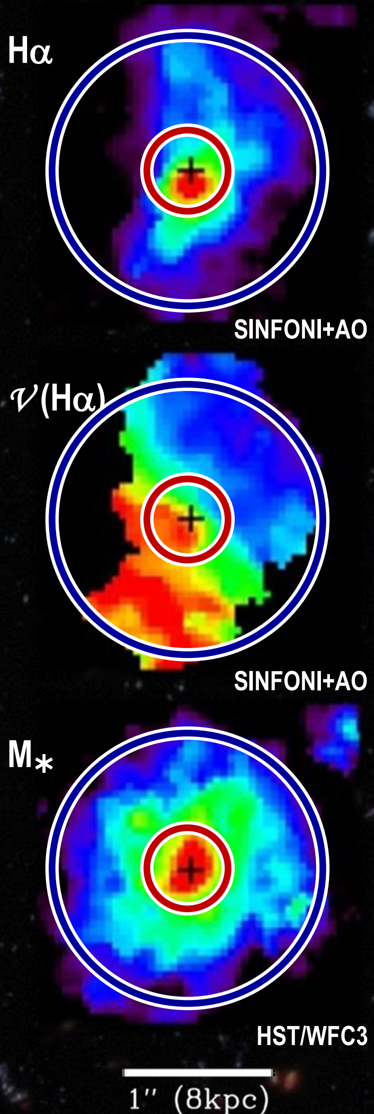
$M_* = 4.0 \times 10^{10}\ M_\odot$
SFR = 210 $M_\odot$ / yr
F(Ha) = 2×10^{-16} cgs

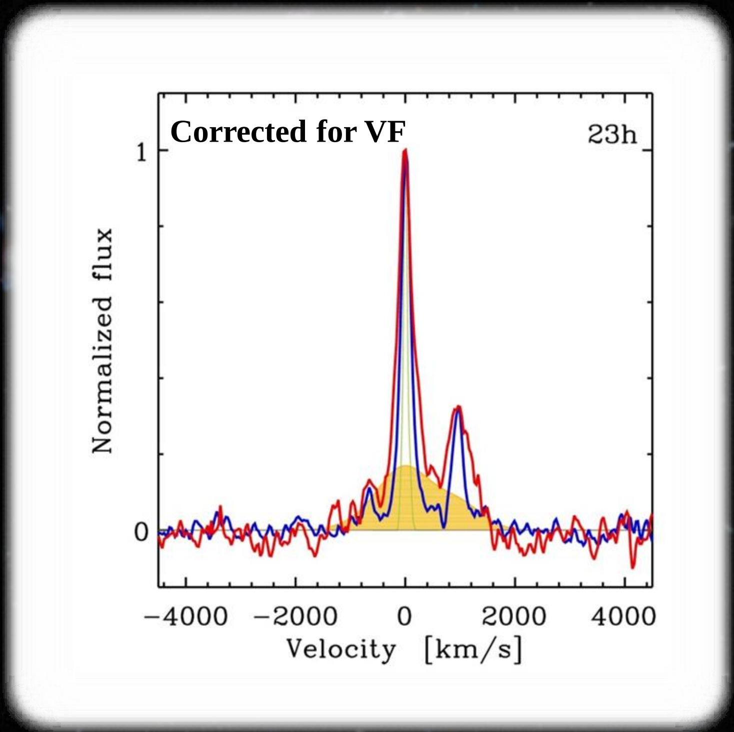
$R_e (H, M_*) \approx 8$ kpc
$n\ (H, M_*) \approx 0.2$

NMFS+09,15; Tacchella+15a; Lang+14

The Need for Sensitive Spatially-Resolved Data

D3a15504   z = 2.4

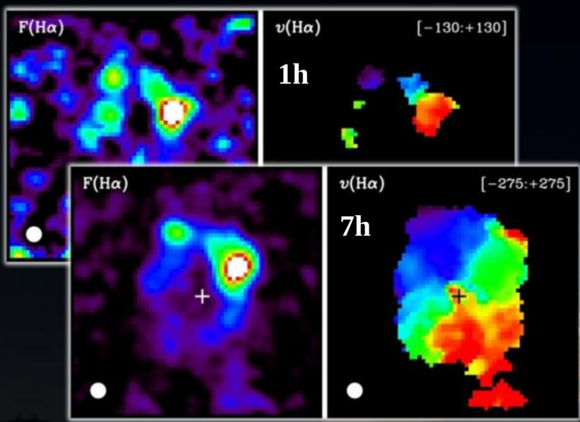




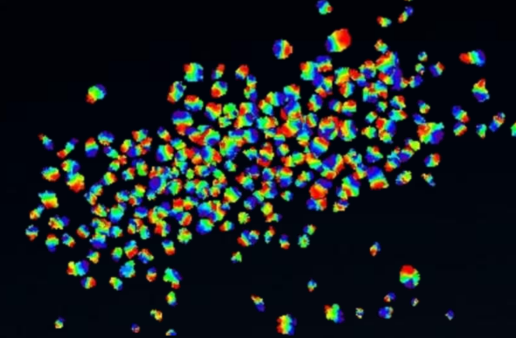
$M_* = 1.1 \times 10^{11}\ M_\odot$
SFR = 150 $M_\odot$ / yr
F(Ha) = 2×10^{-16} cgs
$FWFM_{broad}$ (nucl.) = 1000 km/s
F_{broad}/F_{total} (nucl.) = 0.7

Genzel+06,14; NMFS+14

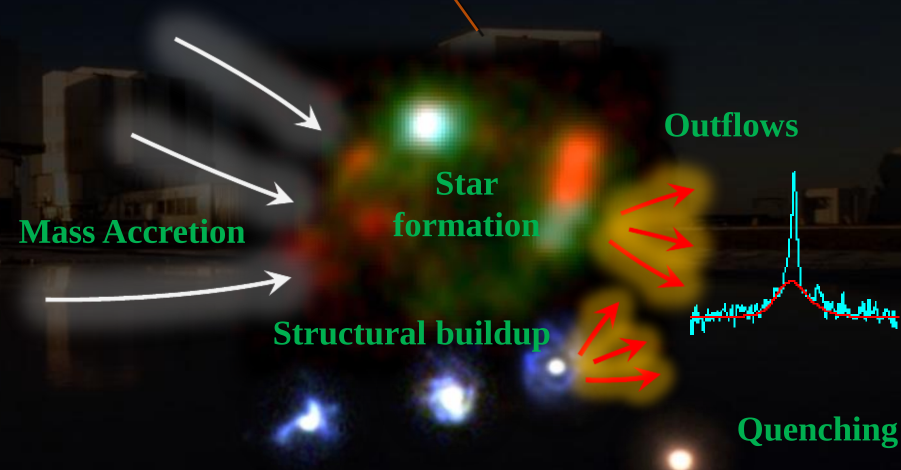
Summary



Sensitivity & resolution
Comprehensive approach
➔ LPs



Physics of lifecycle of massive galaxies from resolved in-situ studies



Cold gas/dust on par with Opt/NIR