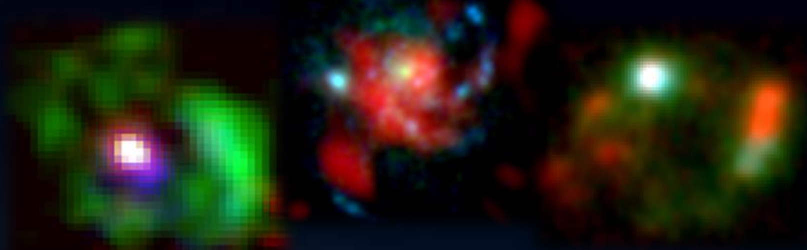
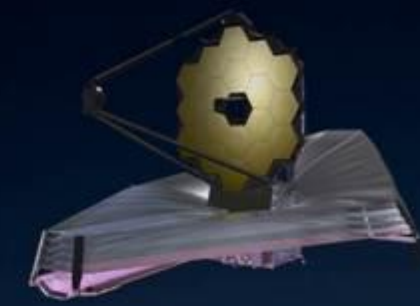


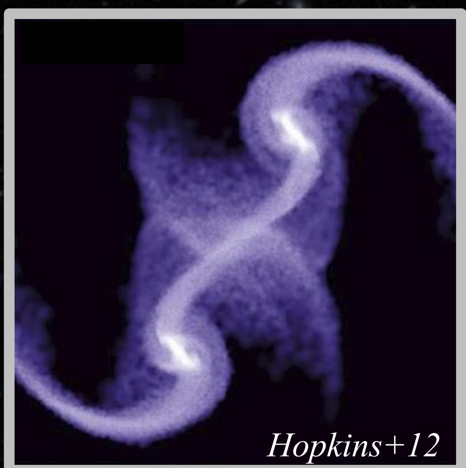


Galaxy Evolution

Highlights from In-Situ Studies
Prospects for the 2020's

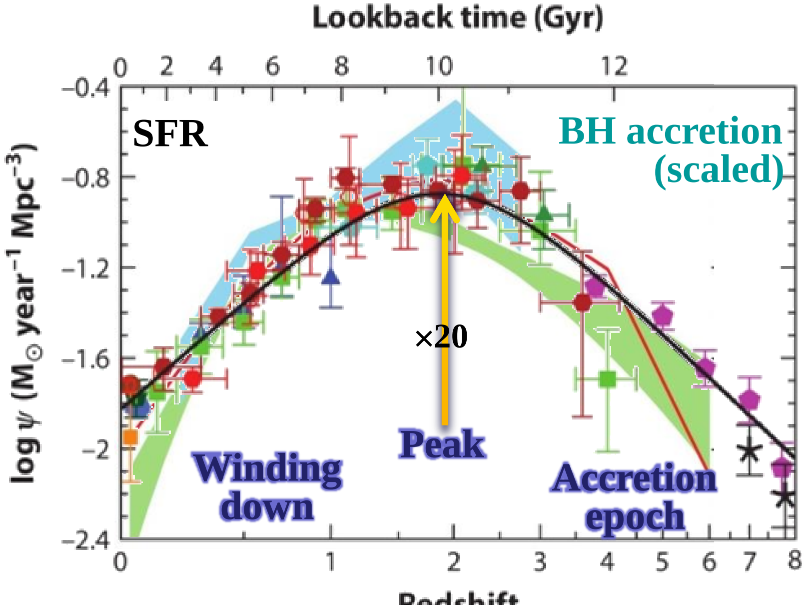
N.M. Förster Schreiber
(MPE)
R. Davies, R. Genzel, D. Lutz, L. J.Tacconi, S. Wuyts
K. Bandara, A. Beifiori, R. Bender, N. Bouché, G. Brammer, A. Burkert, M. Carollo, J. Chan, G. Cresci, M. Fossati, , A. Galametz,, E. Hicks, S. Kulkarni, P. Lang, S. Lilly, C. Mancini, J.T. Mendel, I. Momcheva, T. Naab, E.J. Nelson, S. Newman, Y. Peng, A. Renzini, D. Rosario, R. Saglia, S. Seitz, A. Sternberg, S. Tacchella, K. Tadaki, P. van Dokkum, D. Vergani, D. Wilman, E. Wisnioski, E. Wuyts, G. Zamorani
and the full SINS/zC-SINF, KMOS^{3D}, VIRIAL, and 3D-HST teams

Star Formation across Cosmic Times

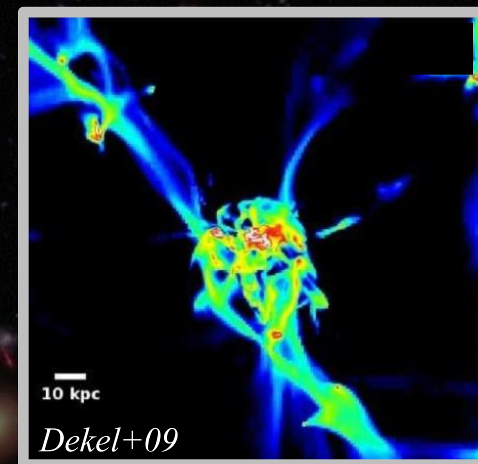


Hopkins+12

(Major) Mergers and Starbursts?



Madau&Dickinson14



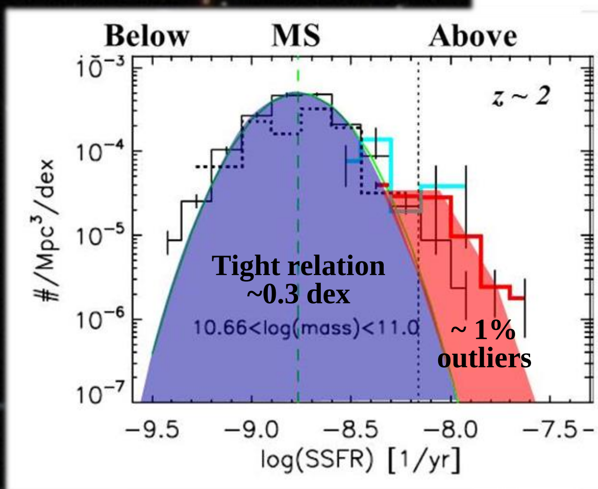
Dekel+09

Continuous Accretion from Halo and Disk Instabilities?

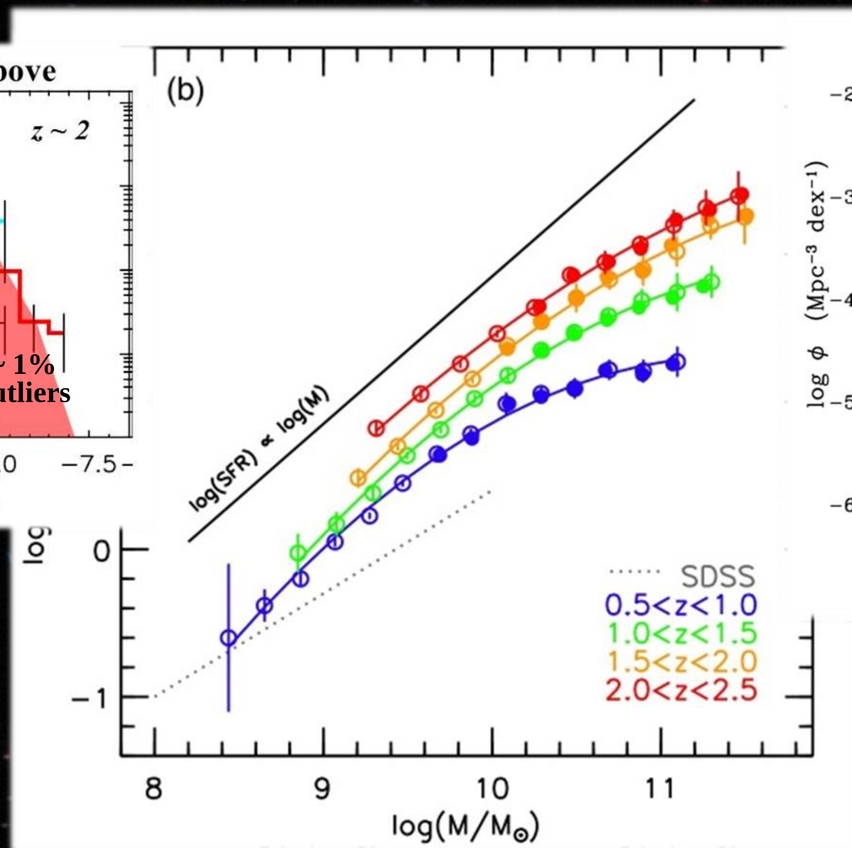
Lilly+96; Madau+96; Steidel+96; Schiminovich+05; Le Floc'h+05; Pérez-Gonzáles+05,08; Hopkins&Beacom06; Caputi+07; Dahlen+07; Reddy+08,09;Soifer+2008; Le Borgne+2009; Rodighiero+10; Robotham&Driver11; Gruppioni+10;13; Magnelli+11,13; Cucciati+12; Bouwens+12; Schenker+13; delVecchio+14; among others.

The "Main Sequence" of Star-Forming Galaxies

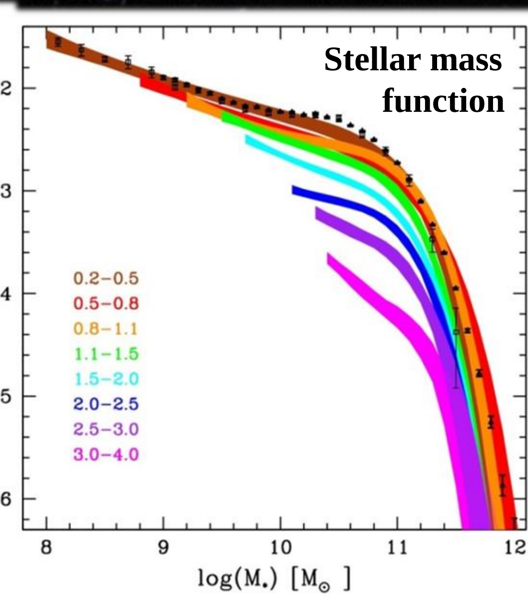
MS SFGs have high duty cycles ~ 30%-70%
~ 90% of the cosmic SFR occurs on the MS
Efficient quenching of star formation above $\mathcal{M}^*$



Rodighiero+11



Whitaker+14



Ilbert+13

E.g., Rudnick+03,06; Adelberger+04; Noeske+07; Elbaz+07; Daddi+07; Marchesini+09; Shankar+09; Ilbert+10,13; Rodighiero+11,14; Caputi+11; Brammer+11; Gonzalez+11; Magnelli+11,13; Whitaker+12,14; Muzzin+13; Stark+13; among others

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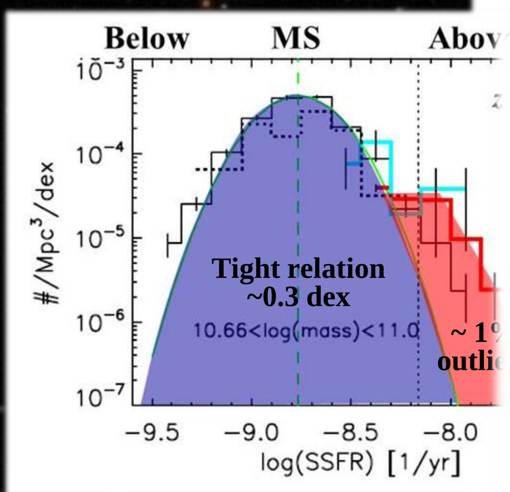
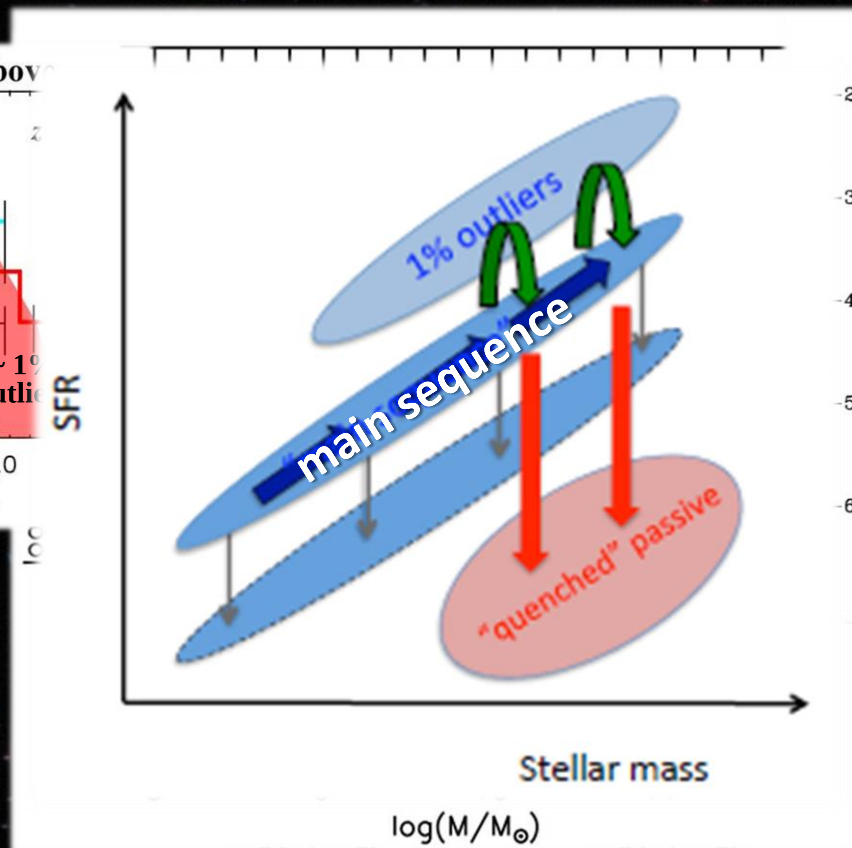


Rodighiero+11



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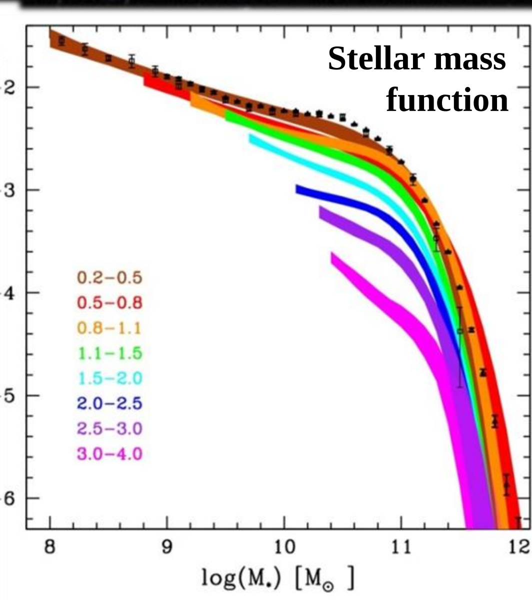

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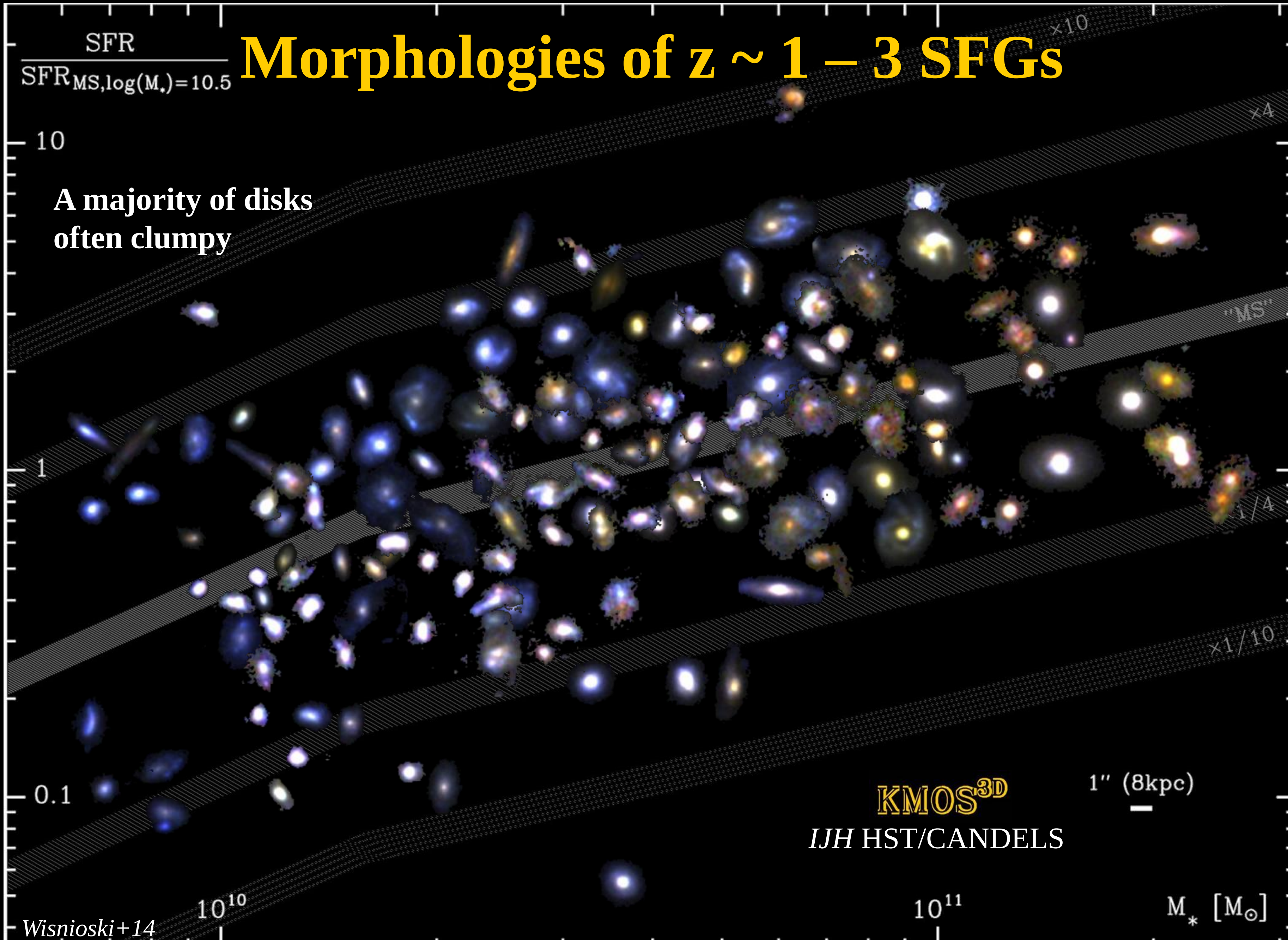
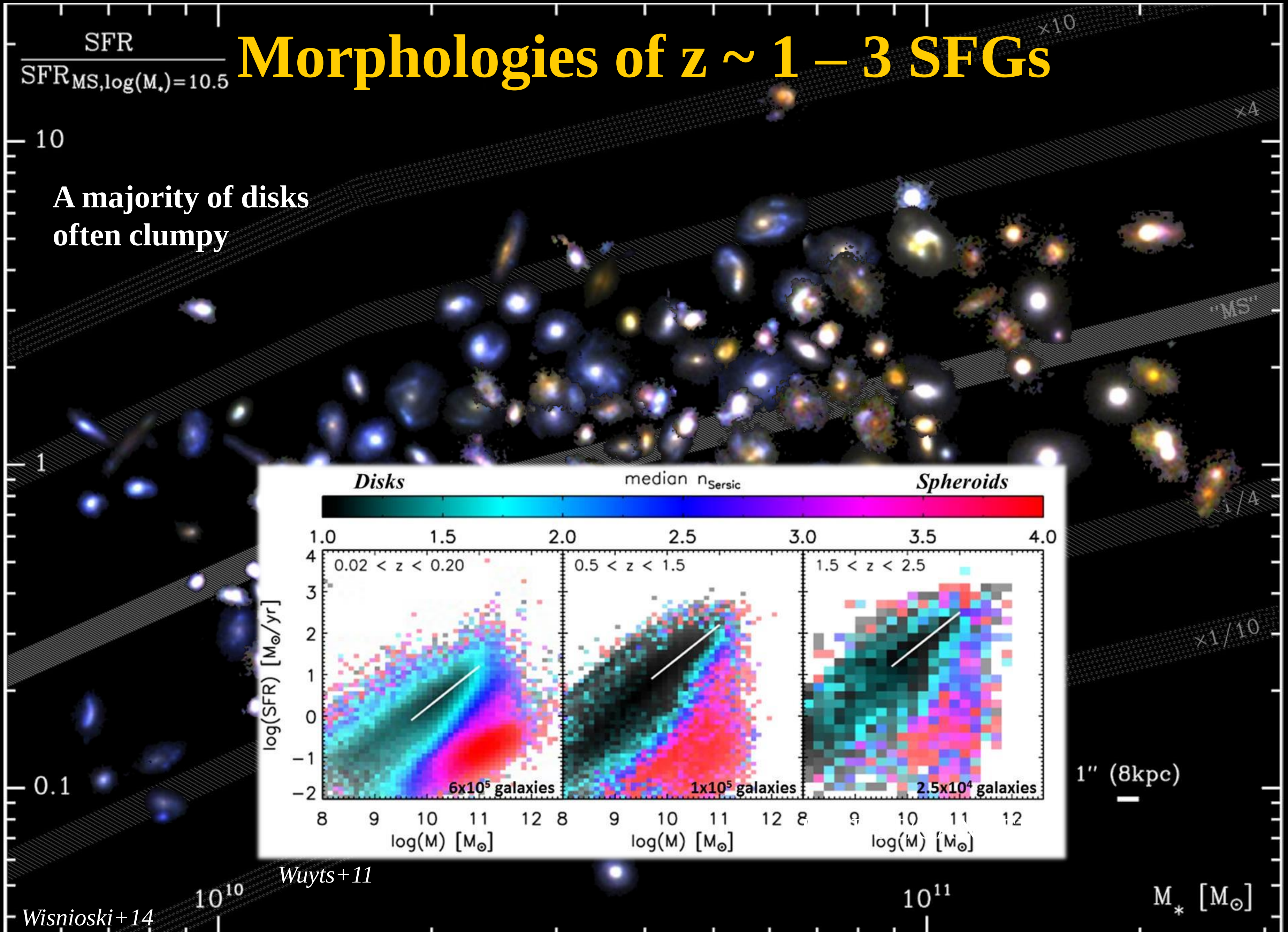
Morphologies of z ~ 1 – 3 SFGs



E.g., Labbé+03; Elmegreen+07-09; Kriek+09;NMFS+11a,b; Guo+12; Lanyon-Foster+12; Szomoru+13; Nelson+13; Tacchella+14

Morphologies of z ~ 1 – 3 SFGs

A majority of disks often clumpy



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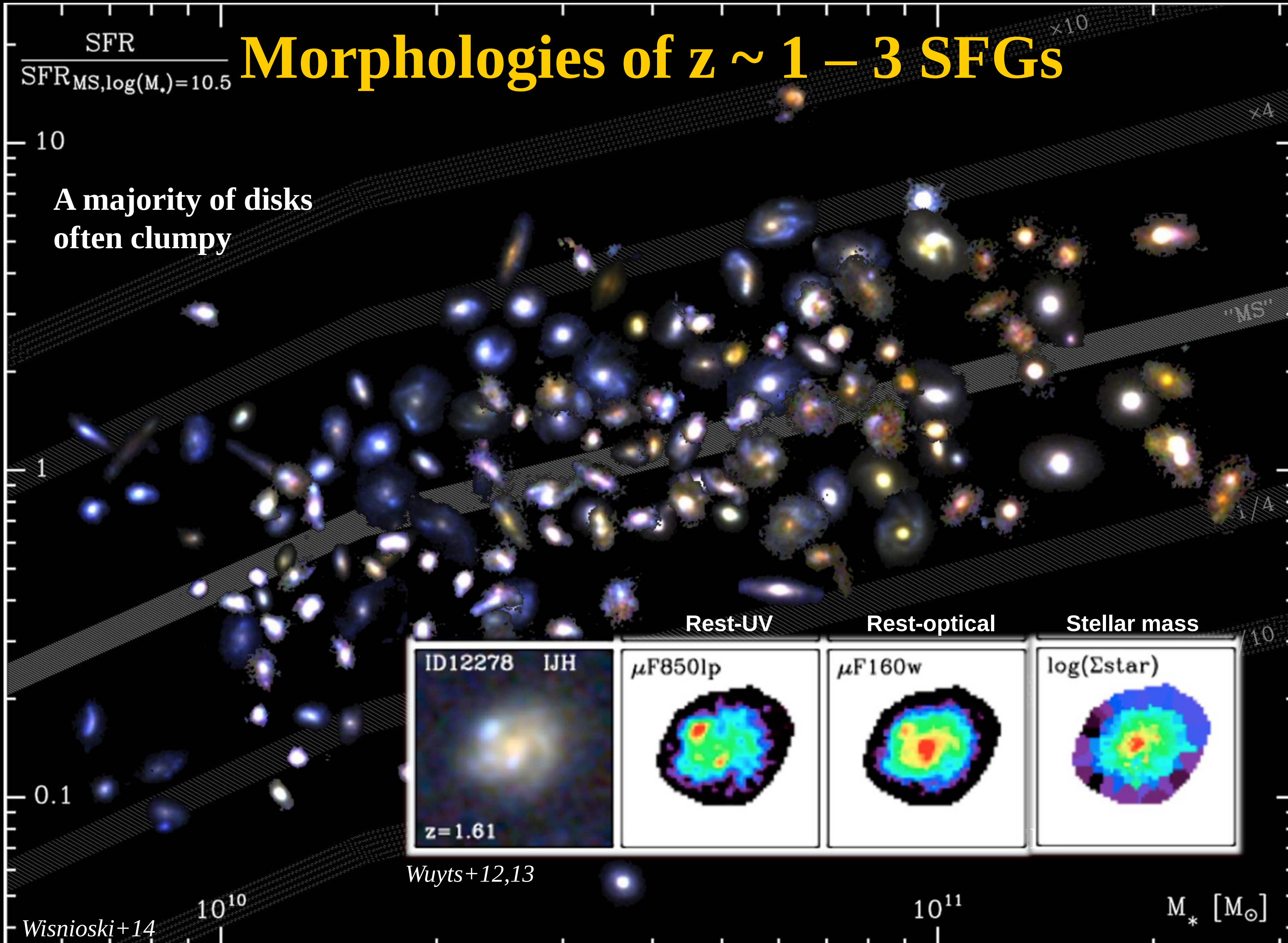

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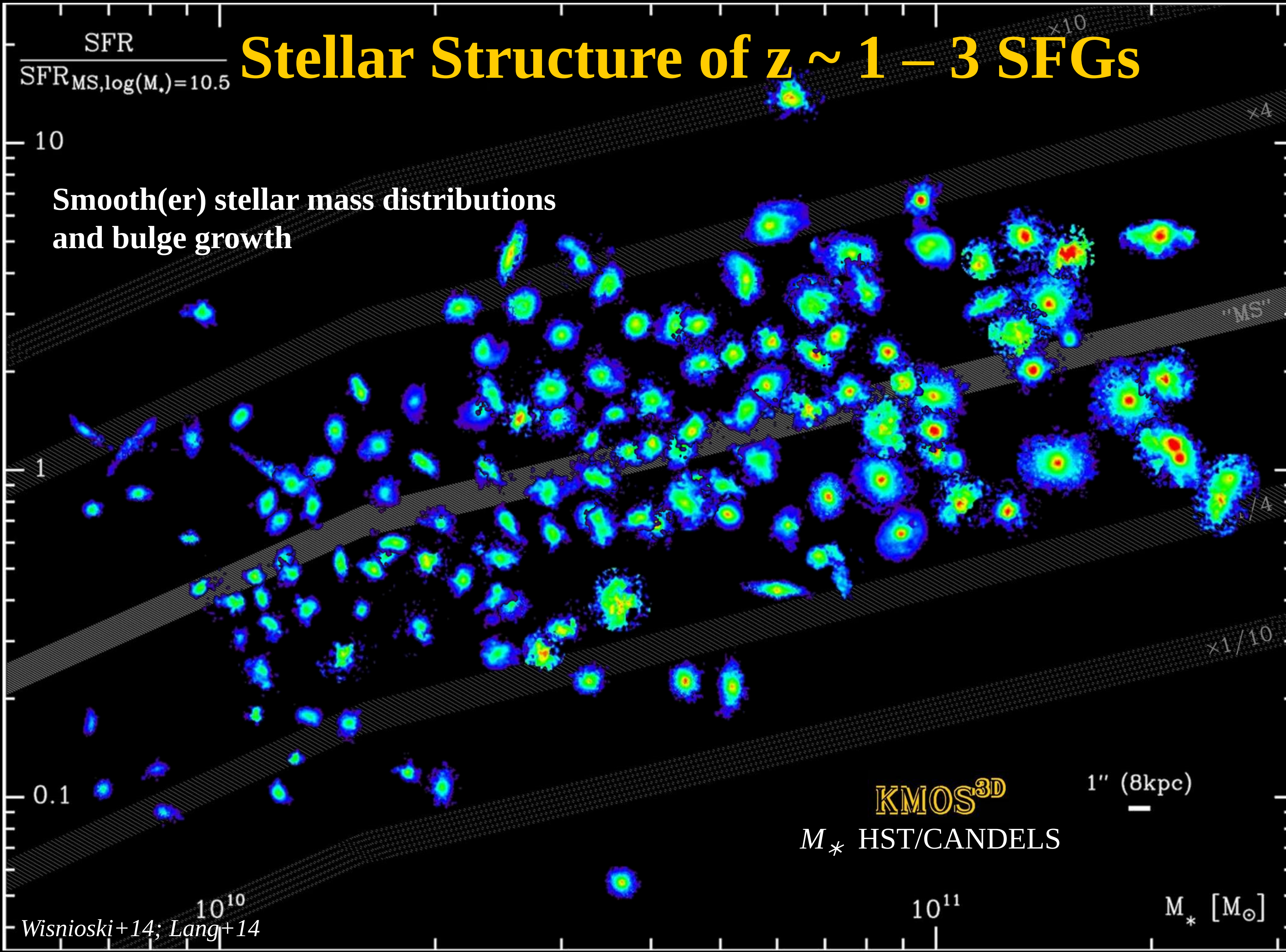
Stellar Structure of z ~ 1 – 3 SFGs

Smooth(er) stellar mass distributions and bulge growth



Wisnioski+14; Lang+14

Also, e.g., Kauffmann+03,06; Schiminovich+07; Bell08; Bell+12; Cheung+12; Fang+13; Bluck+14; Tacchella+15

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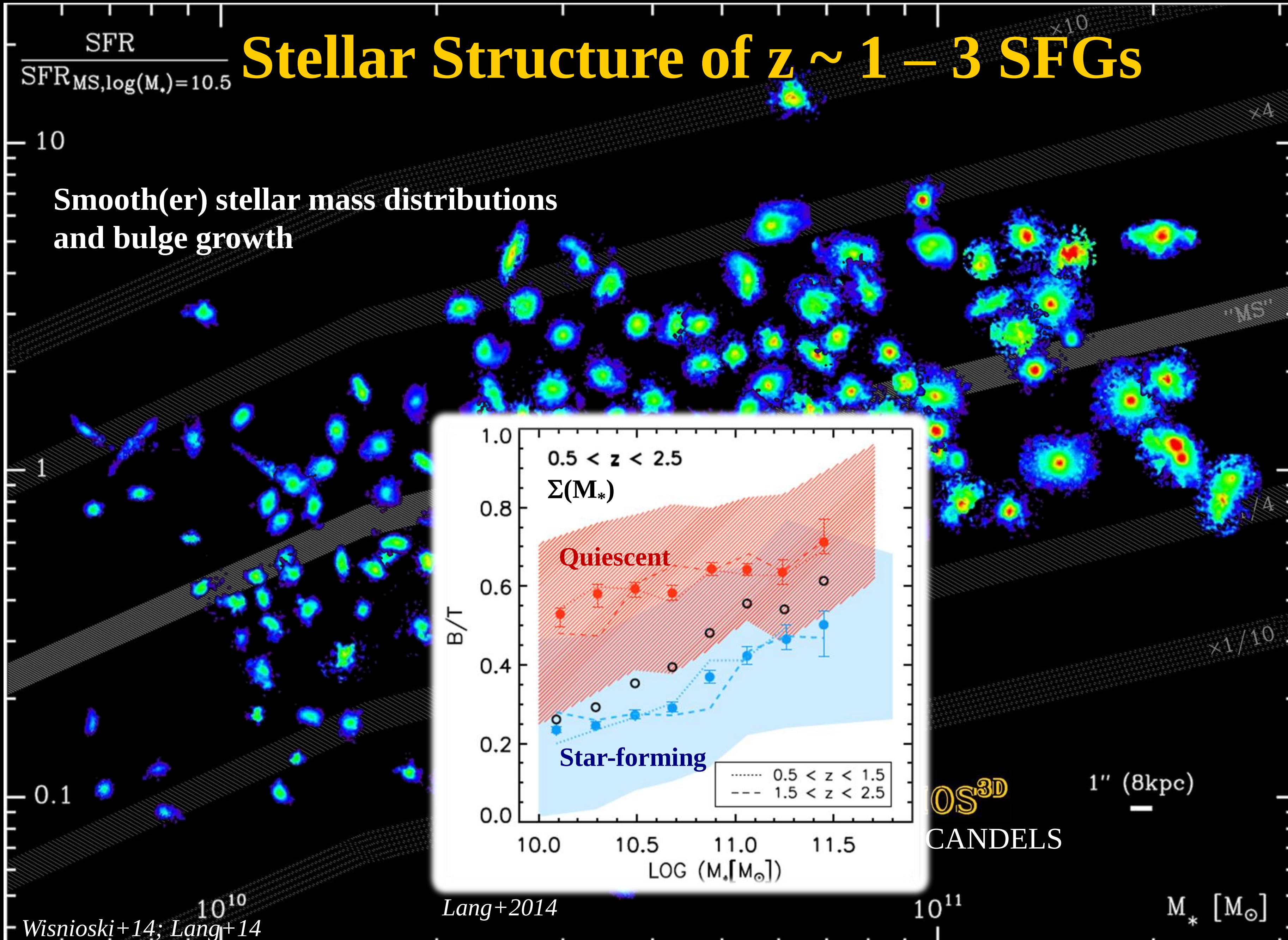

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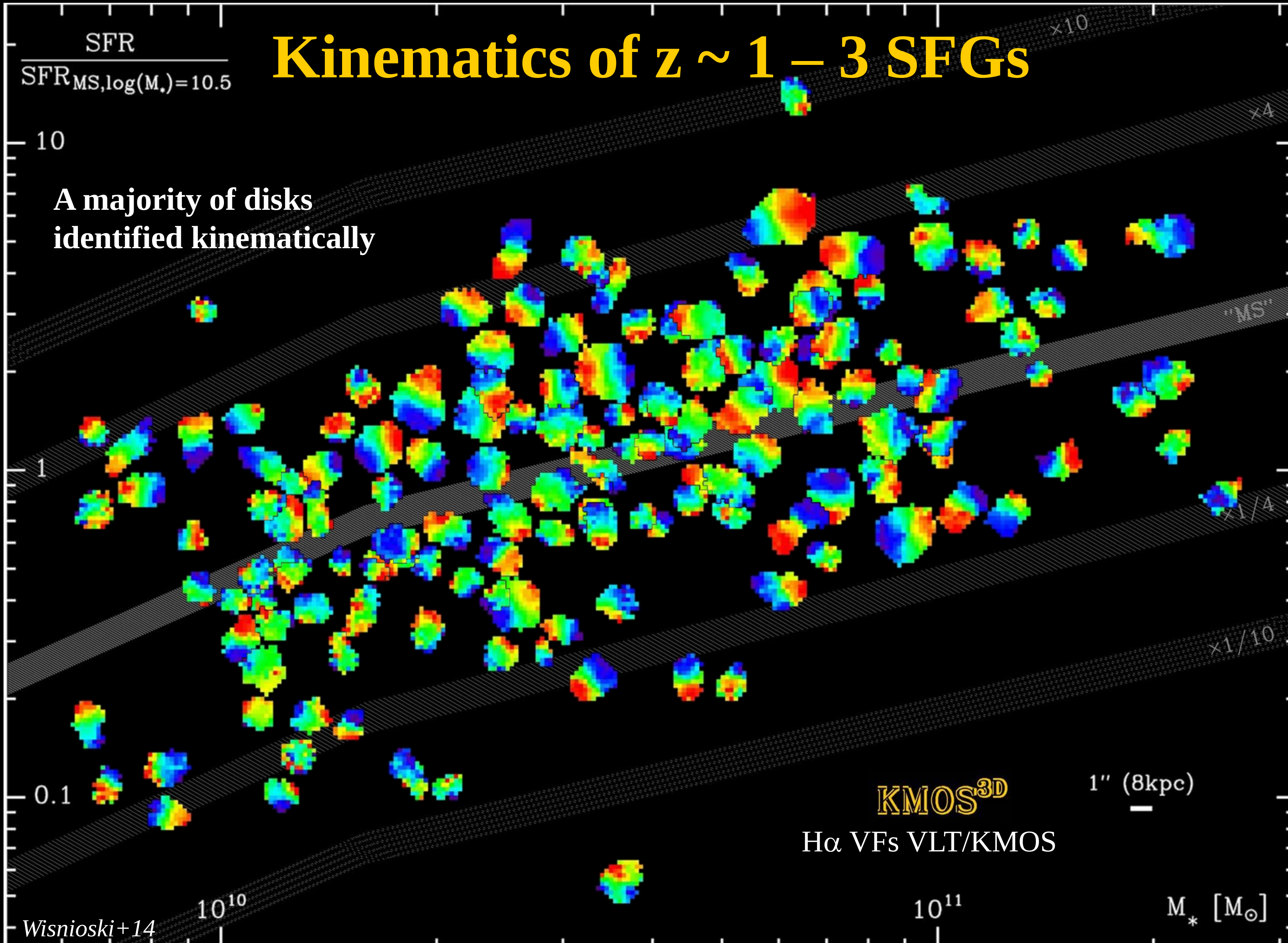
Kinematics of z ~ 1 – 3 SFGs

A majority of disks identified kinematically

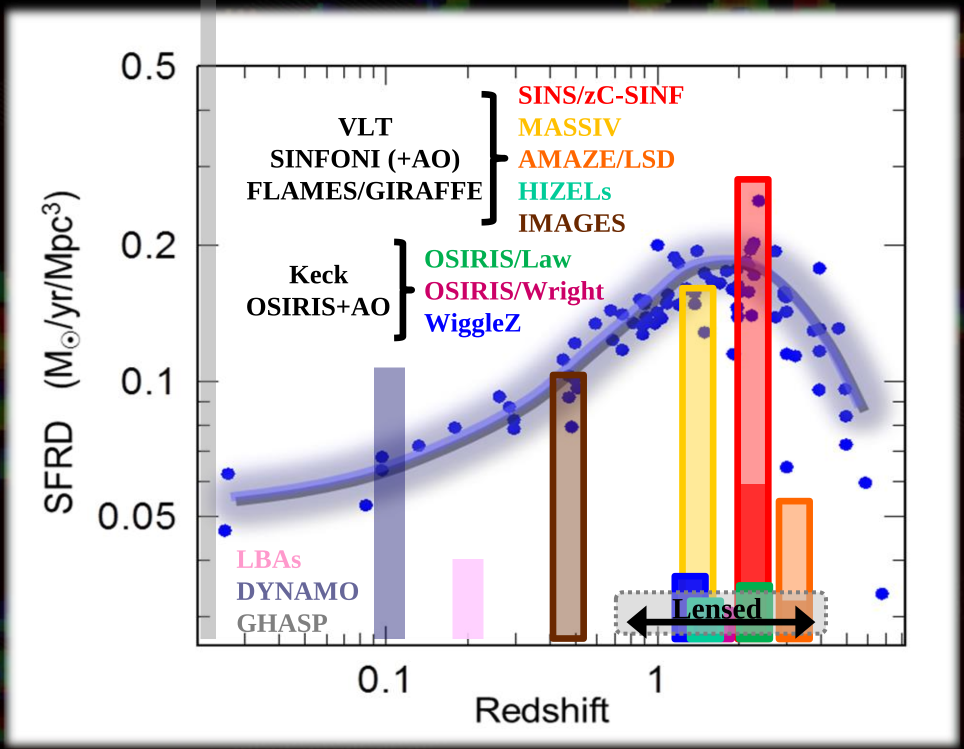


Hα VFs VLT/KMOS

Wisnioski+14

Other first results from KMOS: Sobral+13; E.Wuyts+14; Genzel+14; Stott+14

Kinematics of z ~ 1 – 3 SFGs



➡ **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, Bandara+13
KMOS: Wisnioski+14, Genzel+14, E.Wuyts+14, Sobral+13, Stott+14

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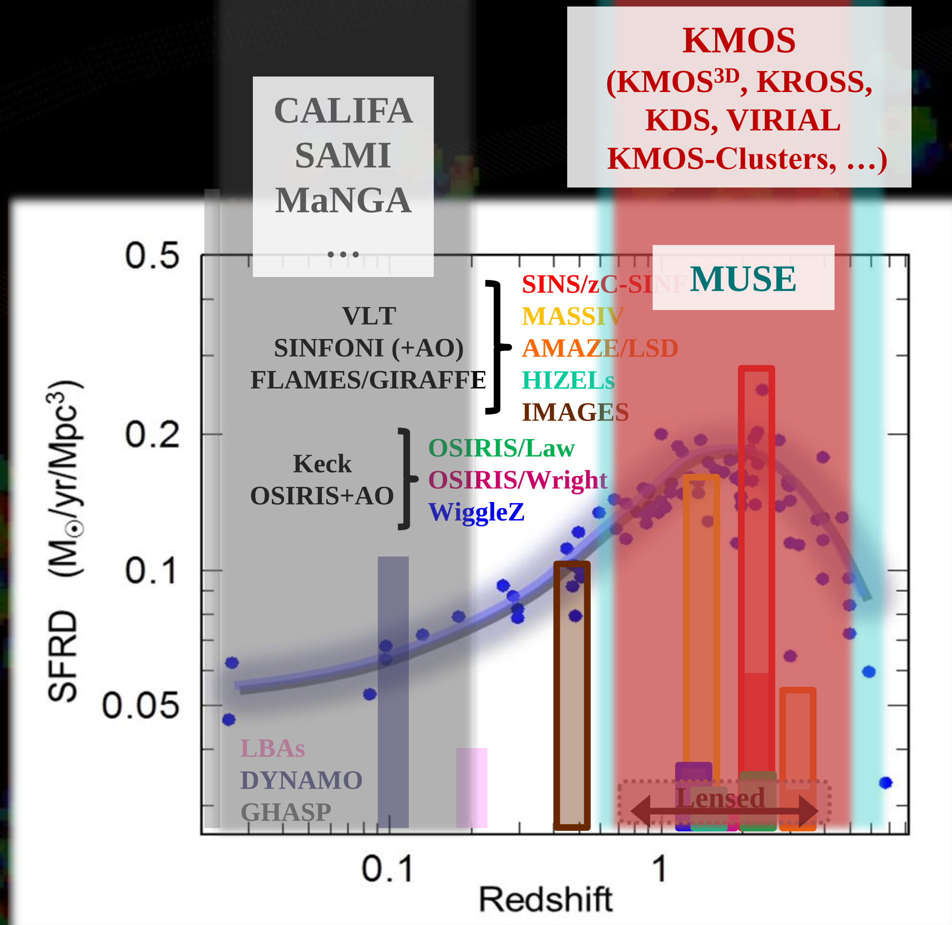

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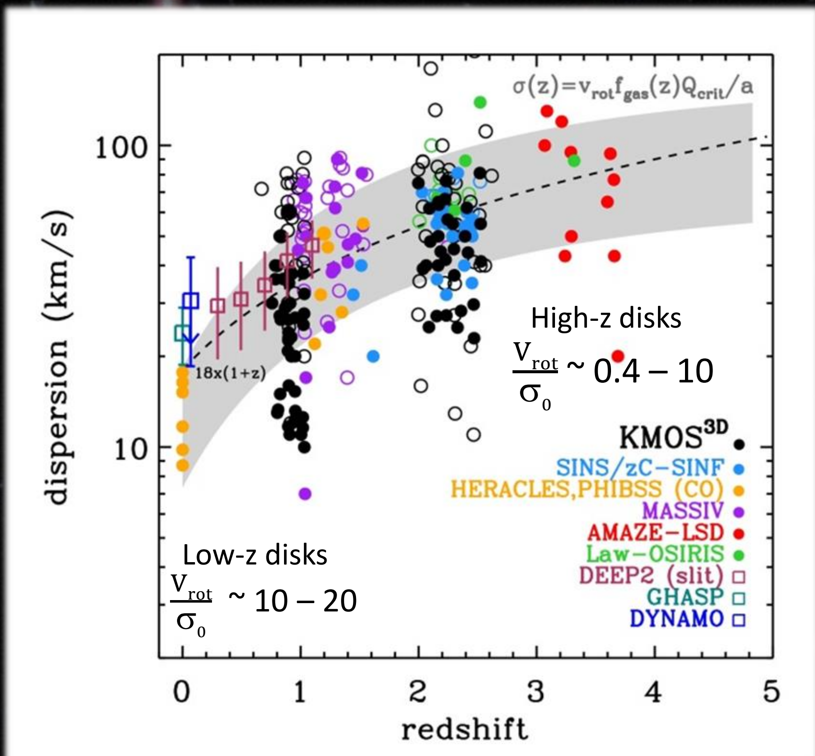
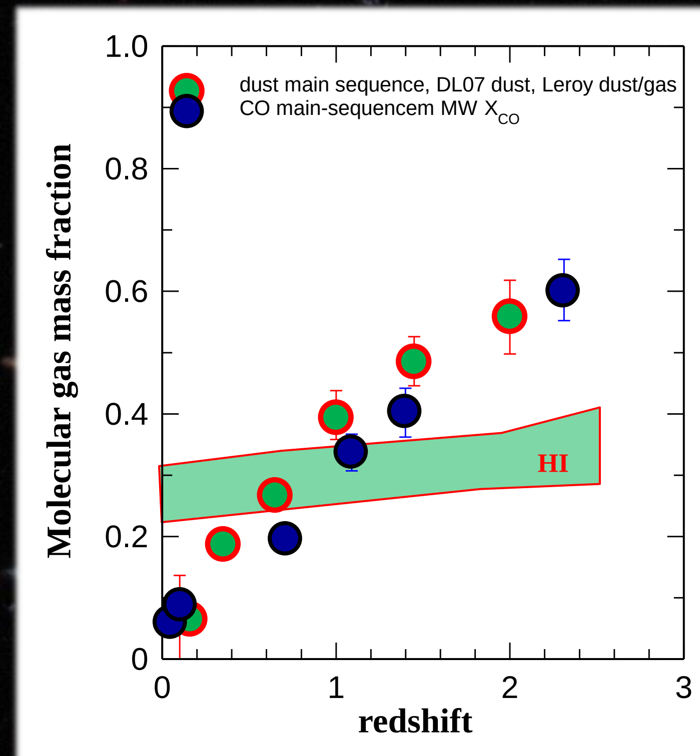
High-z Disks are Turbulent and Gas-Rich

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



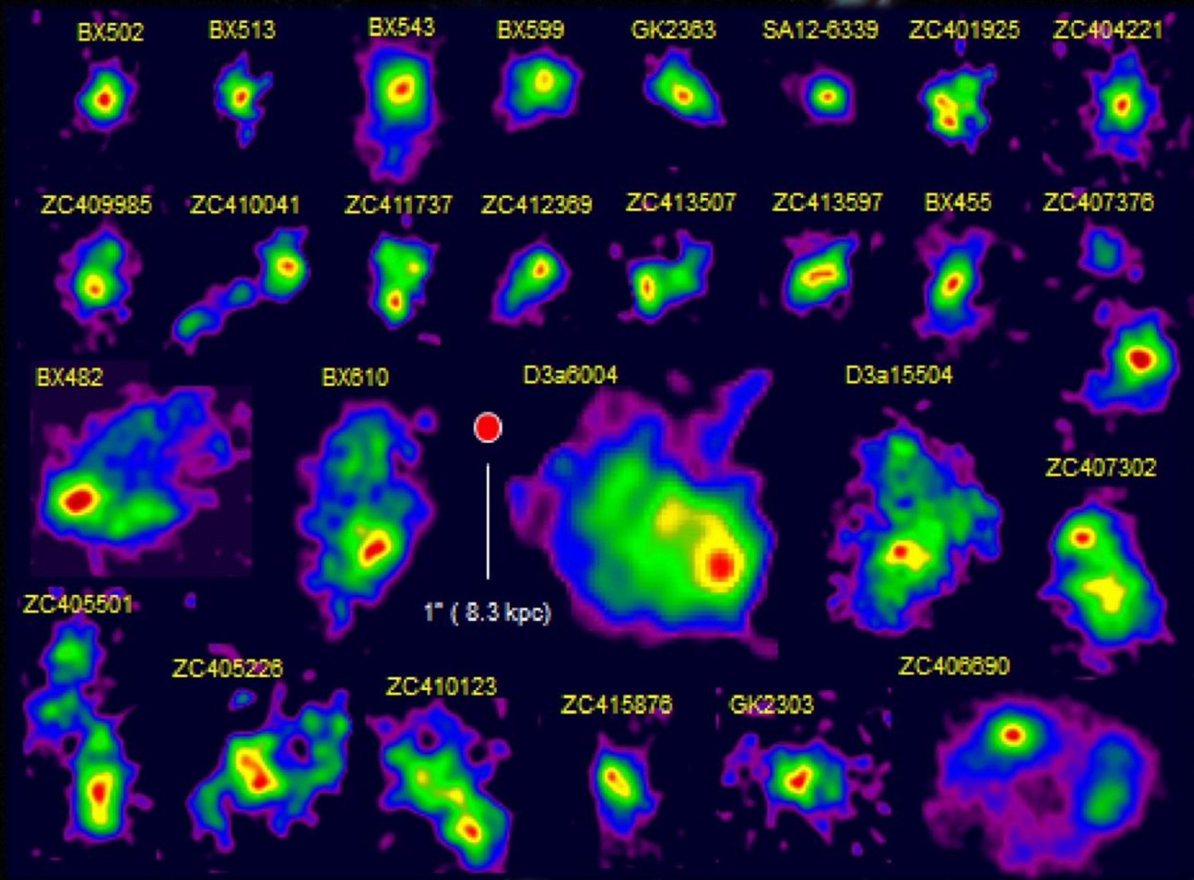


Dib+06; NMFS+06,09,14; Genzel+06,08,13; Stark+08; Cresci+09; Law+09,12; Wright+09; Épinat+09a,09b,12; Lehnert+09,13; Jones+10; Green+10; Gnerucci+10; Yuan+11,12; Swinbank+12; Kassin+12; Lemoine-Busserolle+12; Newman+13; Tacconi+13; Sobral+13,14; Wisnioski+14

Tacconi10,13; Genzel+10,12,13,14; Daddi+10; Combes+12; Magdis+12; Freundlich+13; Baker+04; Coppin+07; Geach+11; Saintonge+11,13; Bauermeister+12; Magnelli+12; Santini+13; Walter&Carilli13

Clumpy SF in Turbulent Gas-Rich Disks

SINFONI+AO



Newman+13

$z \sim 2$ disks:

$$L_{Toomre} \sim f_{gas} R_{disk} \sim 1 \text{ kpc}$$

$$M_{Toomre} \sim f_{gas}^2 M_{disk} \sim 10^9 \, M_\odot$$

Genzel+08,11; NMFS+11b; Newman+12a; Wisnioski+12; Wuyts+13
See also, e.g., Cowie+95; Colley+96; Giavalisco+96; Elmegreen+04–09; Lotz+04; Conselice+04; Law+07; Swinbank+10-12; Jones+10; Guo+12; Tadaki+14

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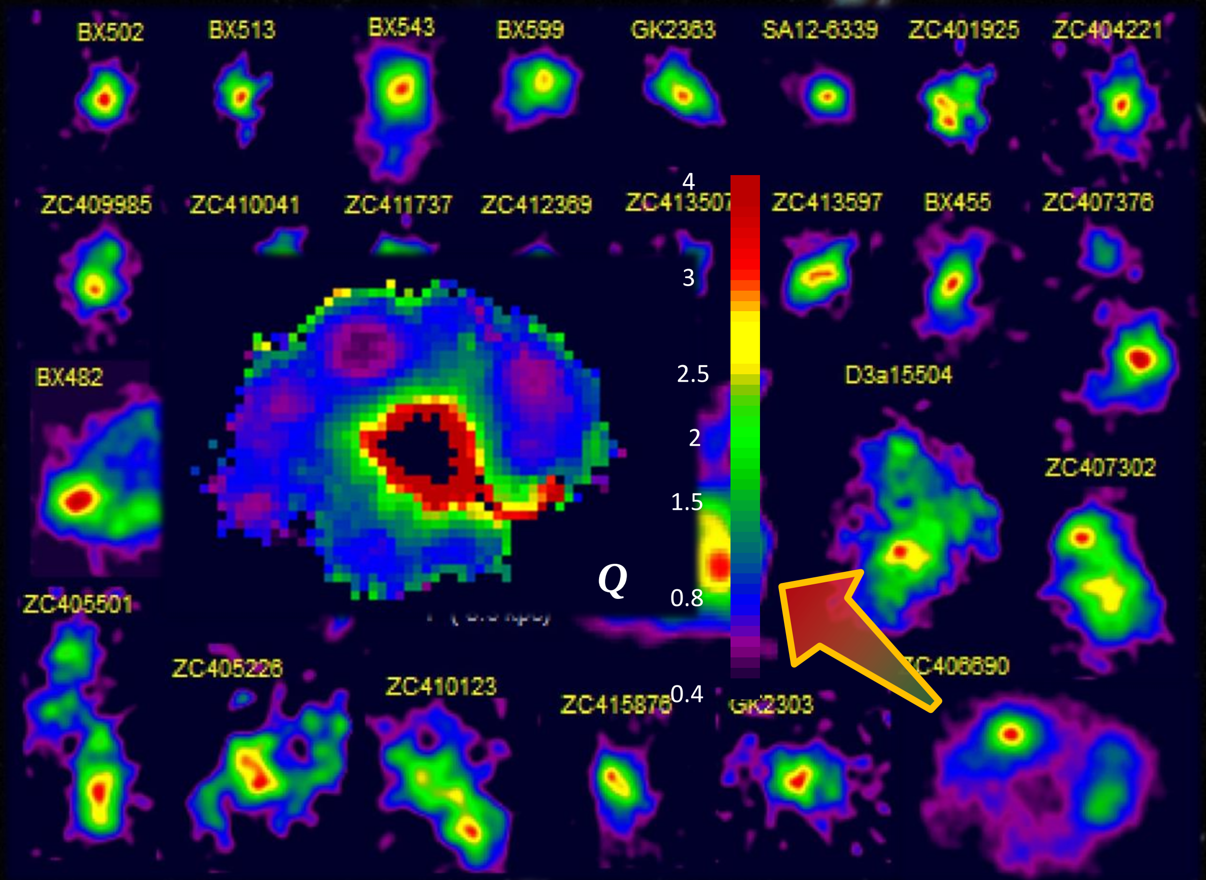

Newman+13

$$Q = \frac{\sigma\kappa}{\pi G \Sigma}$$

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Also, e.g., Noguchi+99; Immeli+04; Carollo+07; Genzel+08; Dekel+09,13; Agertz+09; Ceverino+10,12; Genel+12; Hopkins+12; Dekel&Burkert14

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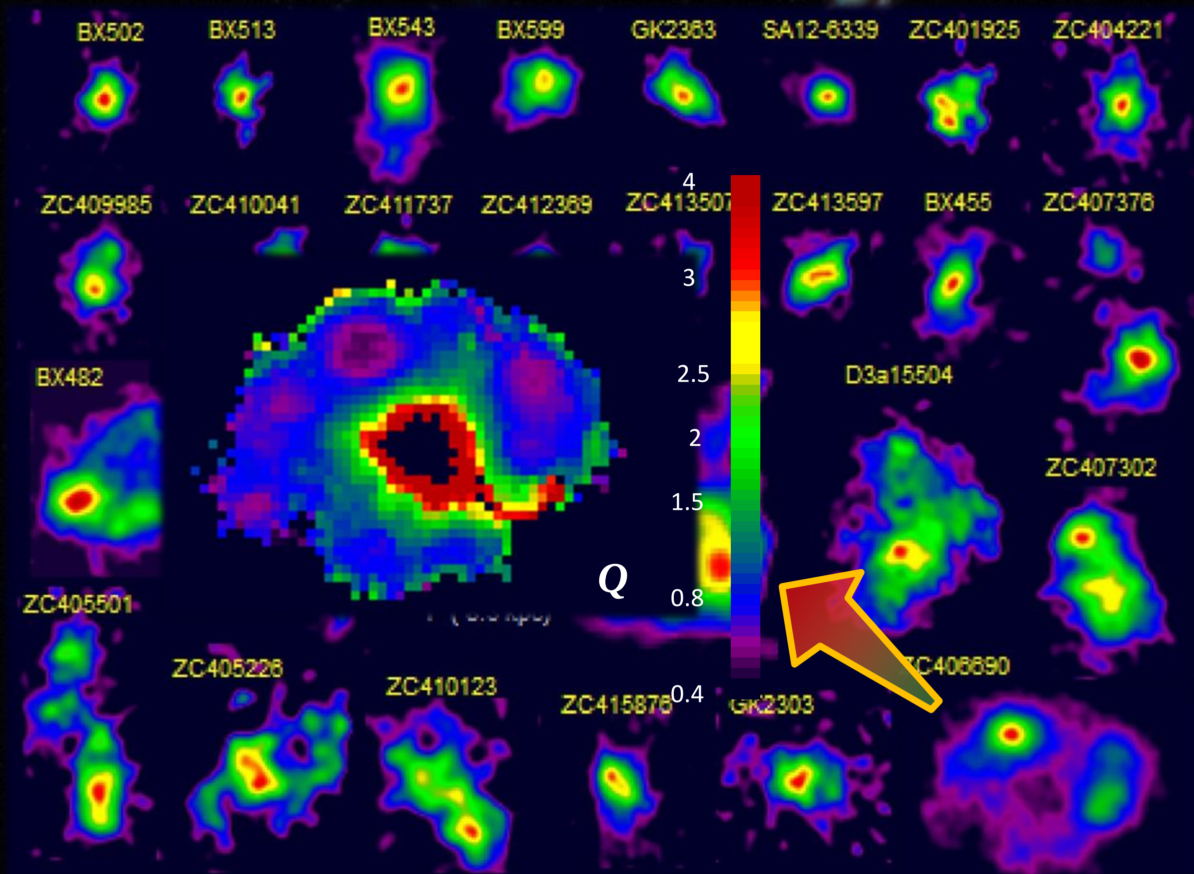
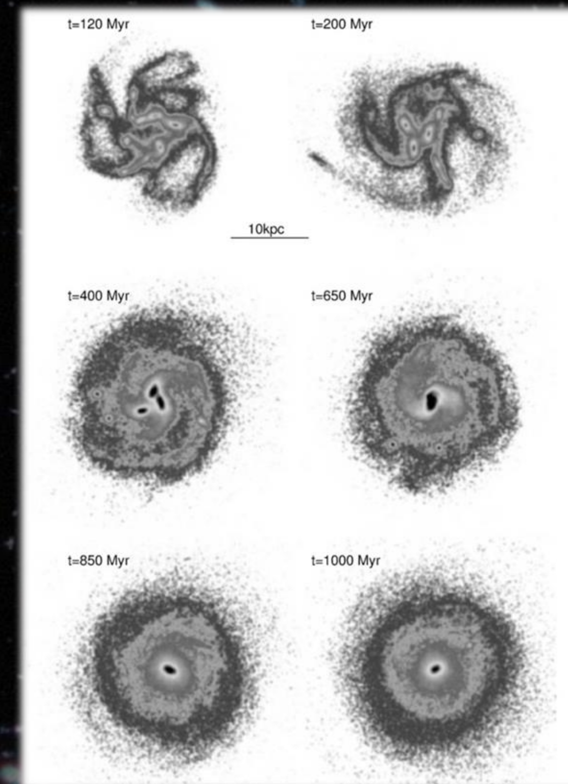


Newman+13

Rapid bulge formation on < 1 Gyr



Bournaud et al.+07–13

Genzel+08,11; NMFS+11b; Newman+12a; Wisnioski+12; Wuyts+13
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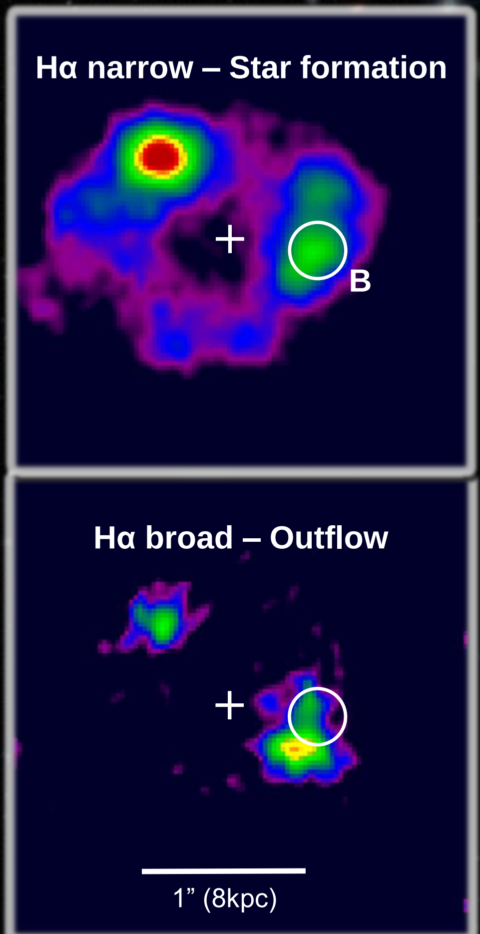
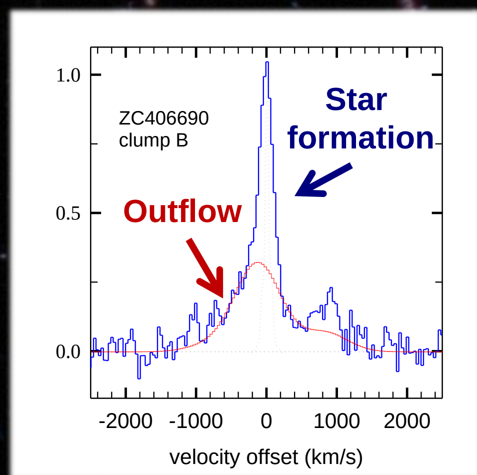
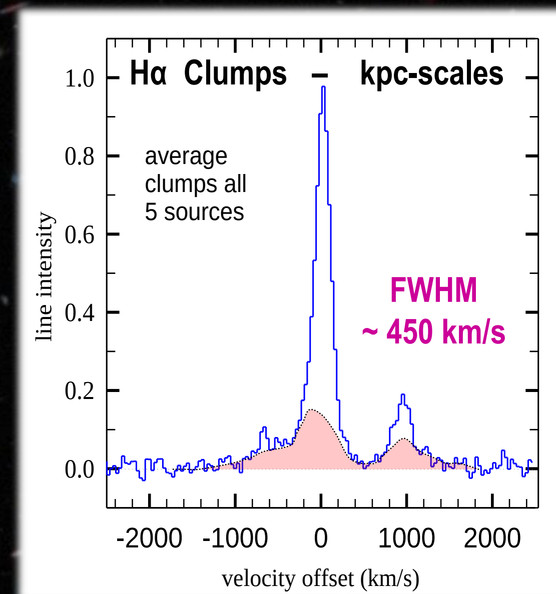
Vigorous Feedback from Star Formation at z ~ 2

SINFONI+AO



- $dM_{out}/dt \sim 1 - 5\times$ SFRs
- Clump lifetimes < a few 100 Myrs



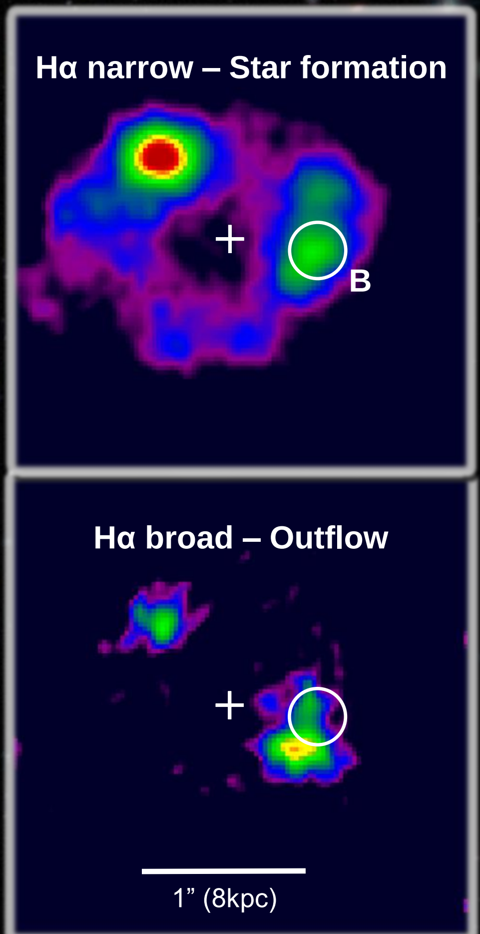


Genzel+11; Newman+12a,b; Shapiro+09

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

Vigorous Feedback from Star Formation at z ~ 2

SINFONI+AO



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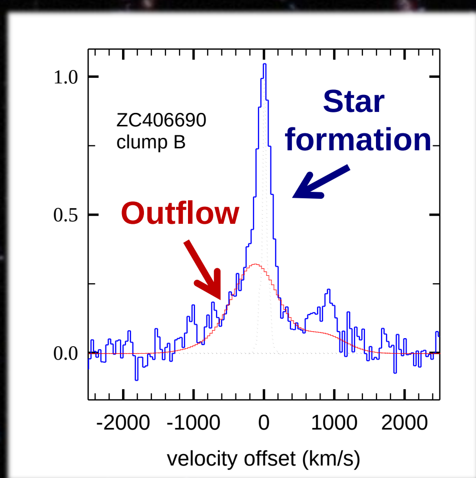

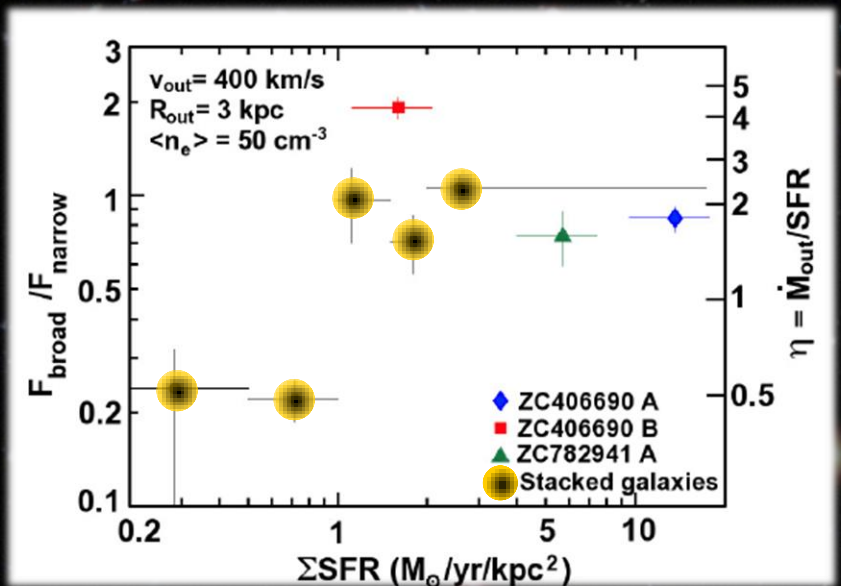

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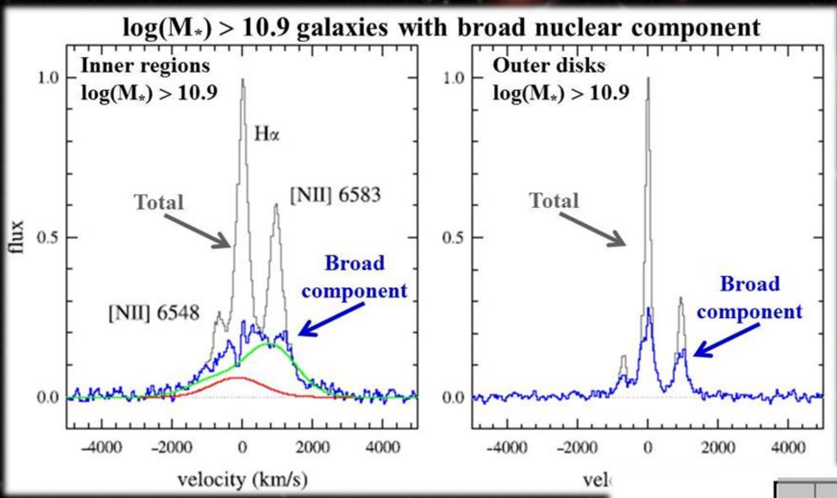
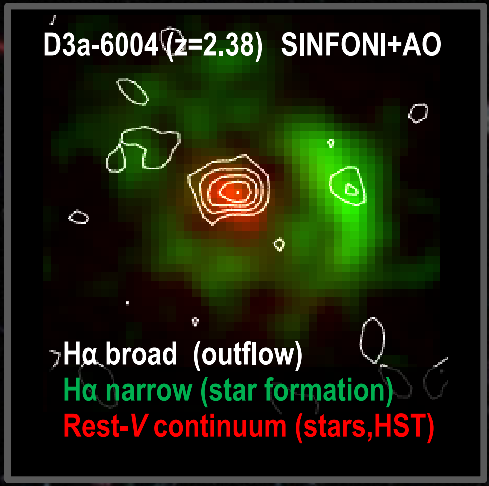
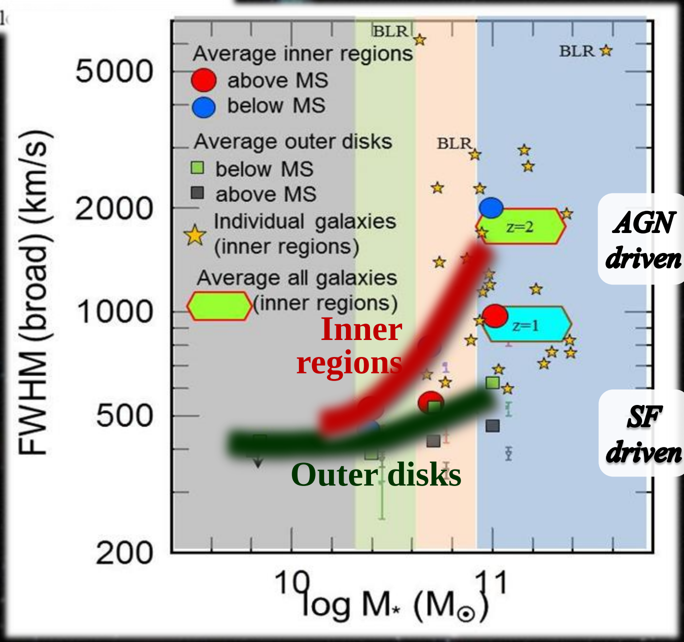
Common Nuclear AGN-driven Outflows at z~1–2



Central regions of
log(M*) ≳ 10.9 galaxies:
- FWHM ~ 500 – 2000 km/s
- In Hα, [NII], [SII]
- 2–3 kpc extent





110 mostly MS z ~ 1 – 2.5 SFGs
(mostly SINFONI+KMOS, 30 w/ AO)

NMFS+14; Genzel+14b.
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;Perna+14;Brusa+15;Cresci+15

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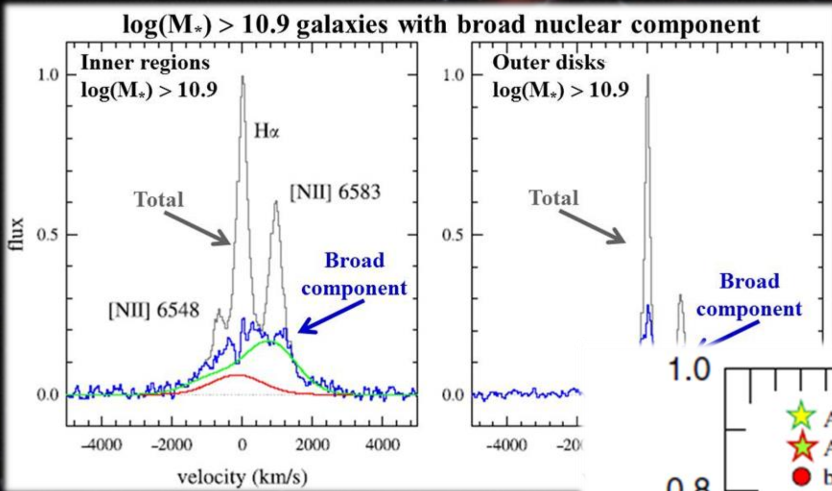

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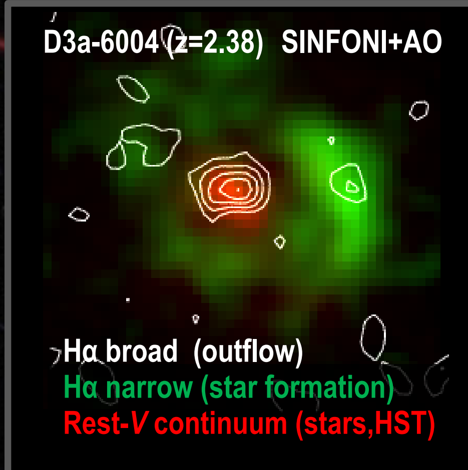
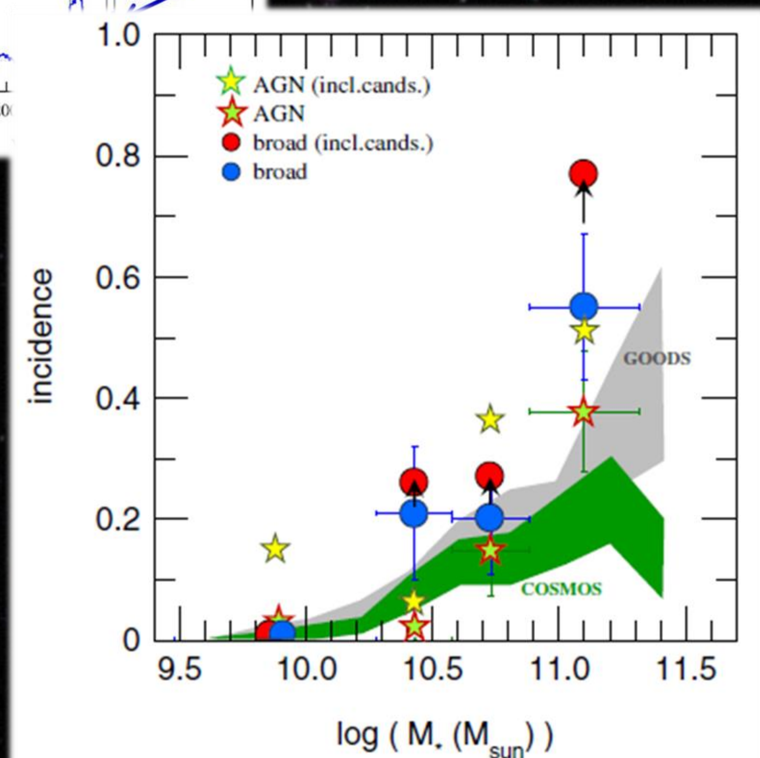




High incidence among
"normal" massive galaxies

High duty cycle
$dM_{out}/dt \sim SFR$
$v_{out} > v_{escape}$

110 mostly MS z ~ 1 – 2.5 SFGs
(mostly SINFONI+KMOS, 30 w/ AO)

NMFS+14; Genzel+14b.
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;Perna+14;Brusa+15;Cresci+15

Looking Onwards: 2015 – 2020+

Resolved information

AO
Telescope/Baseline size

Stellar, gas, and kinematic substructure

Compact galaxies (low-M, z > 3, QGs)

Sensitive information

Collecting area
AO

Stellar, gas, and kinematic substructure

Faint sources (low-M, z > 3, QGs)

KMOS *MUSE* *ALMA* *+VLT/VST* *ERIS* *JWST* *MOONS* *4MOST* *MICADO* *HARMONI* *MOS/M-IFU+AO*

Bigger samples

Wide-field
Multiplexing

Population properties
Environment
Evolutionary links

"Framework" (and targets) for detailed studies

Wavelength coverage

Synergies instruments+facilities

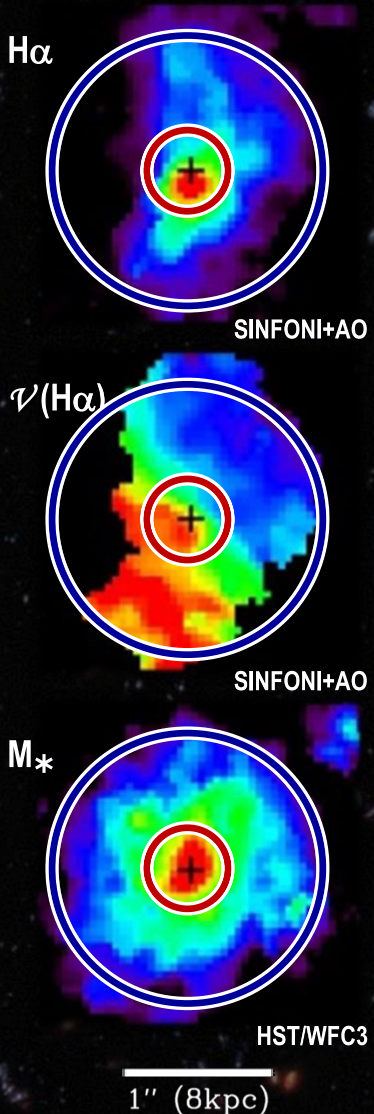
Comprehensive picture (stars, gas, kinematics)

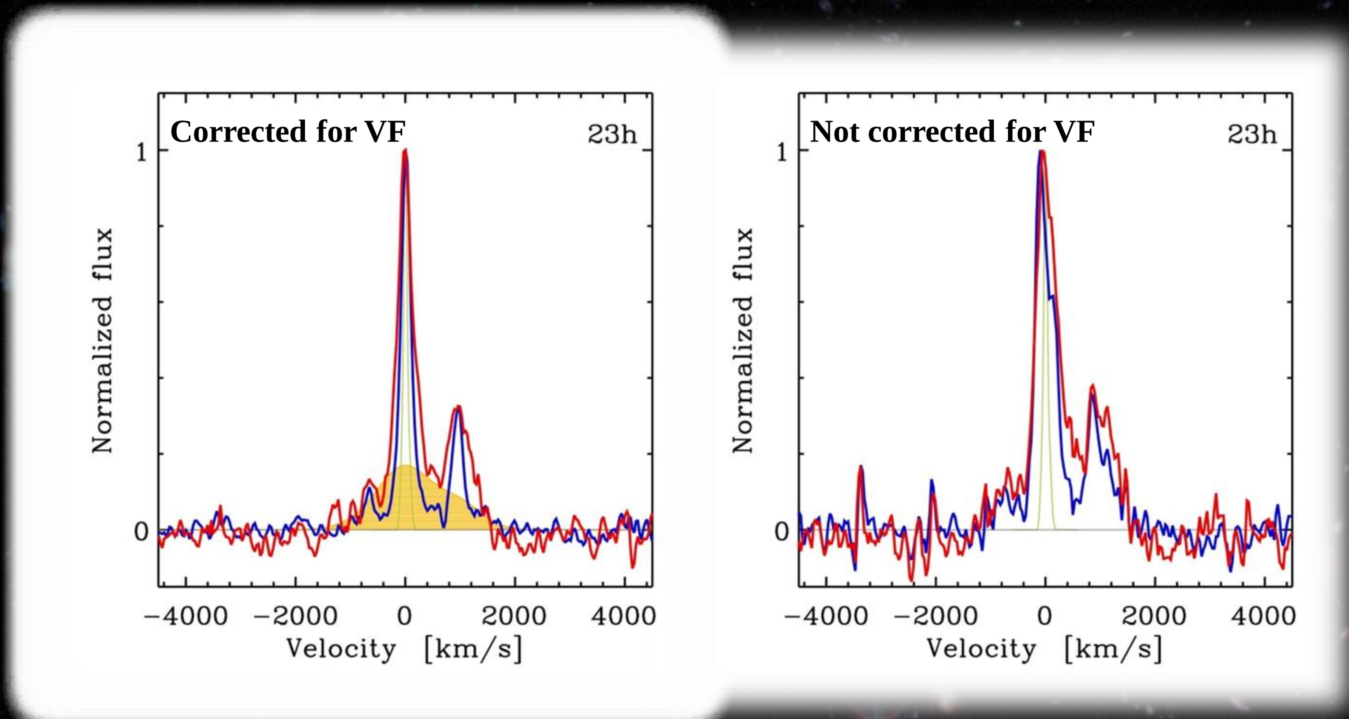
Physics of gas and stars

Redshift coverage (z "desert", z > 3, …)

The Need for Sensitive $\lesssim$ 1kpc-scale Observations

D3a15504 z = 2.4





M_* = 1.1 × 10^{11} $M_\odot$

SFR = 150 $M_\odot$ / yr

F(Ha) = 2 × 10^{-16} cgs

$FWFM_{broad}$ (nucl.) = 1000 km/s

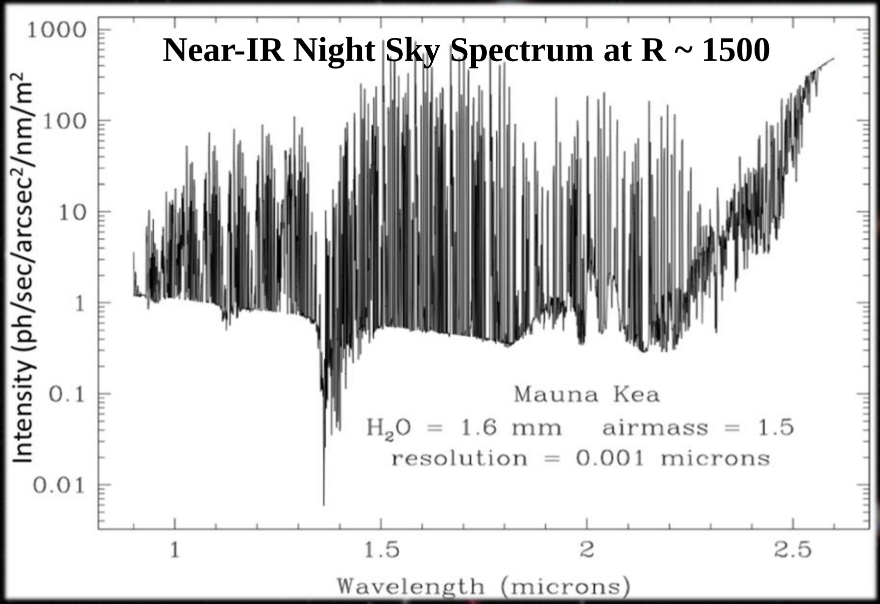
F_{broad}/F_{total} (nucl.) = 0.4

Genzel+06,08,11,14; NMFS+09,14

The Need for R ~ 10000 Spectral Resolution

Sky Lines Avoidance

Sky lines effectively suppressed at R ≳ 10000



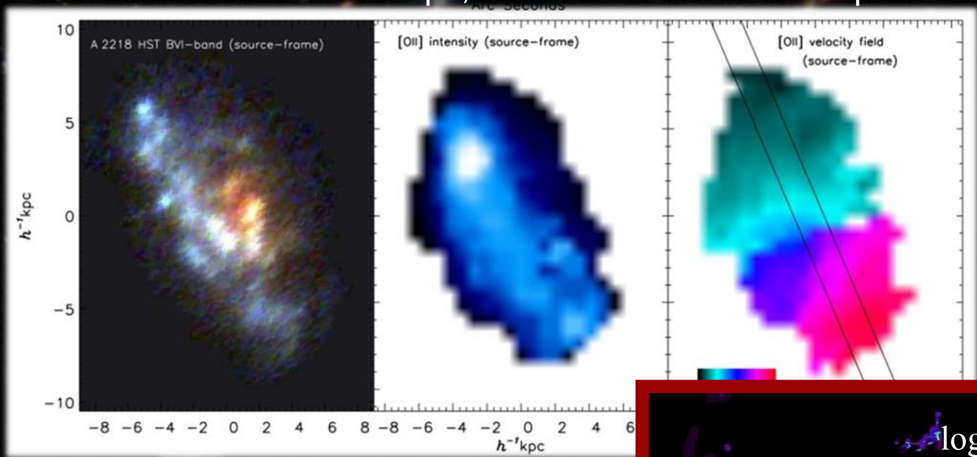
Physics of Galaxies

- Emission line diagnostics of the gas
- Stellar continuum features
- Line profiles
- Kinematics of low-mass objects
- Dynamically cold disks
- …

R ~ 10000 ⟺ σ ~ 10 km/s

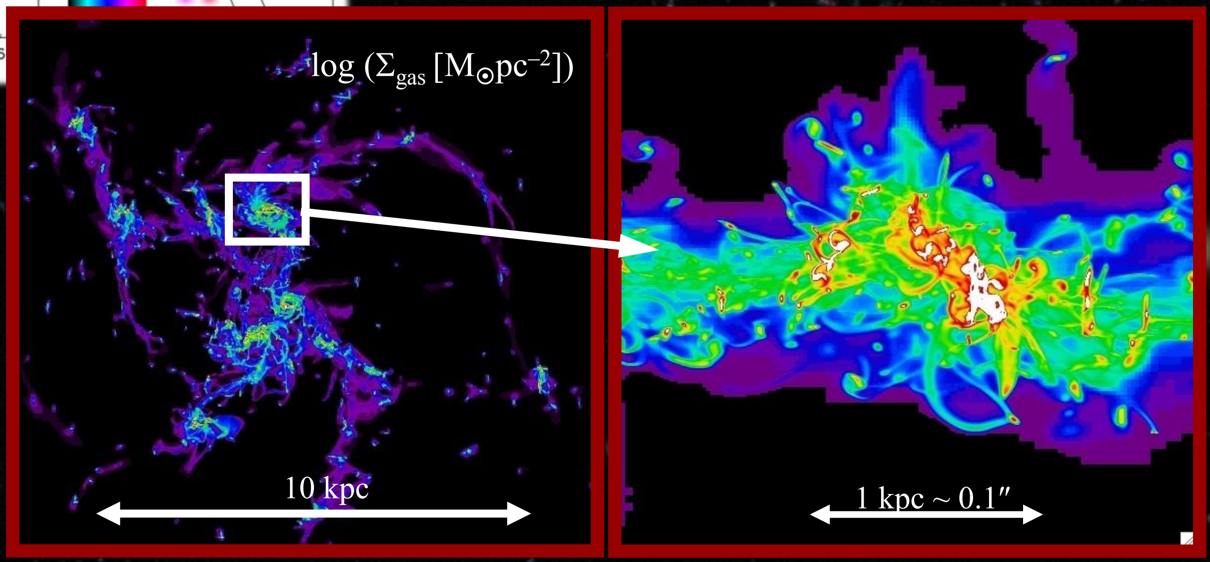
Towards Resolving Distant Galaxies on 100pc Scales

Lensed galaxy at $z \sim 1$, $\mu \sim 10$;
HST resolution ~ 150 pc; GMOS resolution ~ 500 pc



Empirical evidence for sub-kpc structure from strongly lensed z ~ 1 – 3

Hydro-AMR cosmological simulation;
Resolution down to 2 pc ≈ 0.2 mas at $z \sim 2$

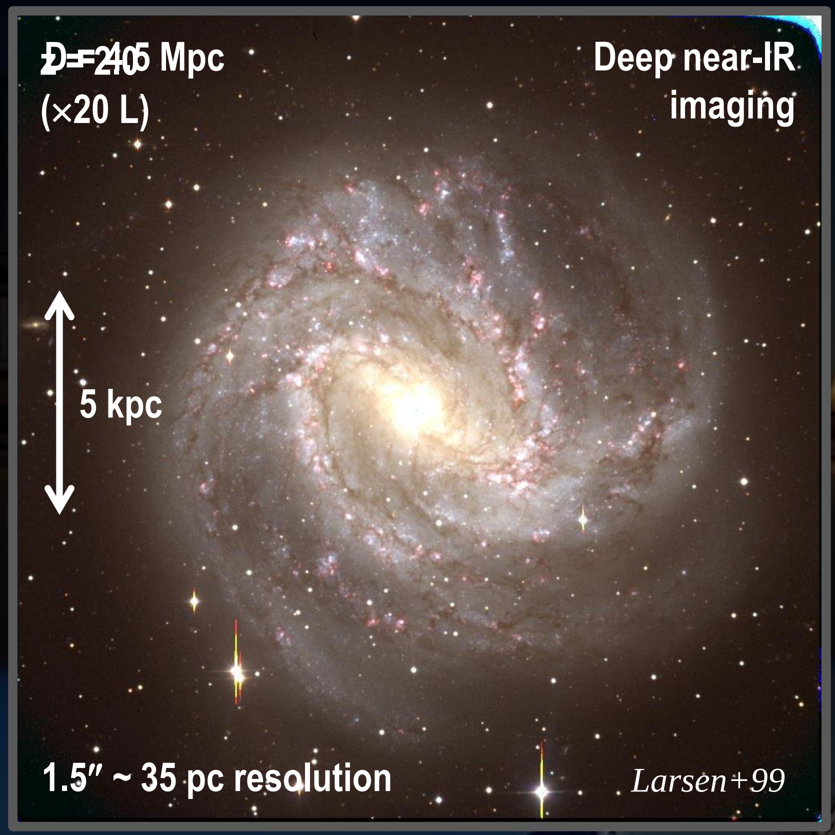


Theory and simulations predict rich structure at z ~ 1 – 3 down to ~ 1 pc scale at z ~ 1 – 3

E.g., Swinbank+03,06,10; Nesvadba+06; Stark+08; Jones+10,12; Yuan+11,12; E.Wuyts+13
E.g., Bournaud+10-14; Genel+10; Ceverino+12; Hopkins+10-12; Gabor+13-14; Mandelker+14

Towards Resolving Distant Galaxies on 100pc Scales

M83
log(M_*) ~ 10.6
SFR ~ 4 $M_\odot$/yr
f_{gas} ~ 10-15%



Towards Resolving Distant Galaxies on 100pc Scales

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SFR ~ 4 $M_{\odot}$/yr
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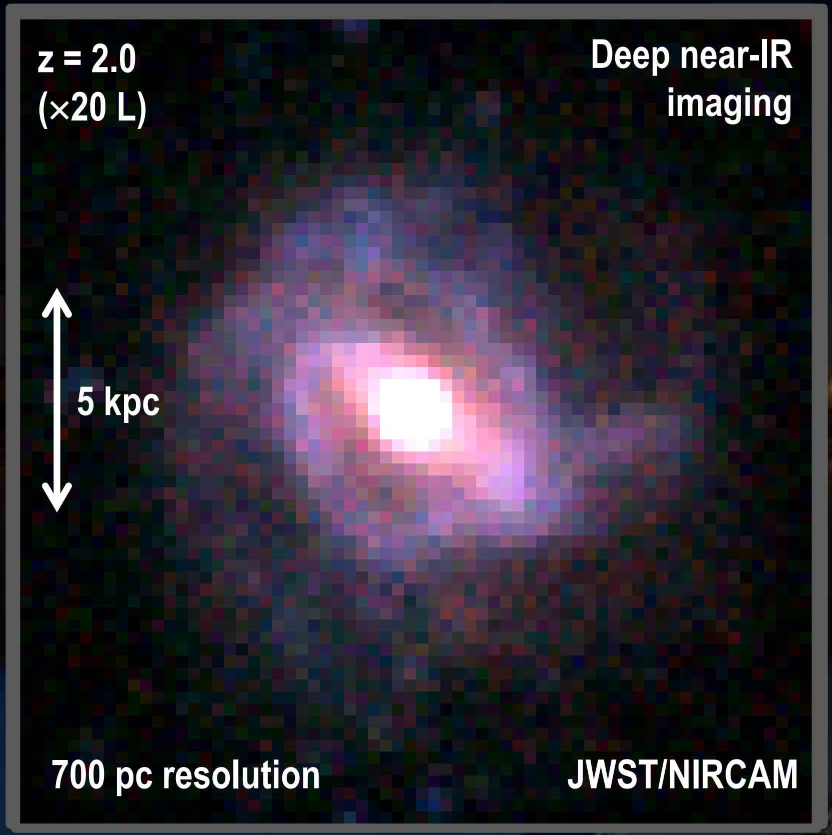

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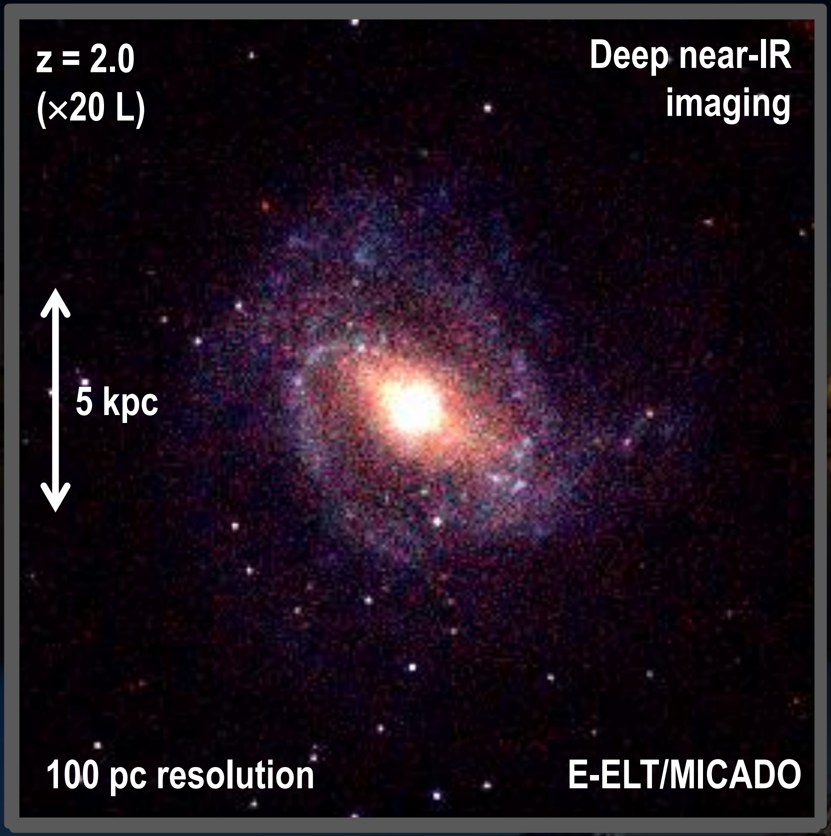
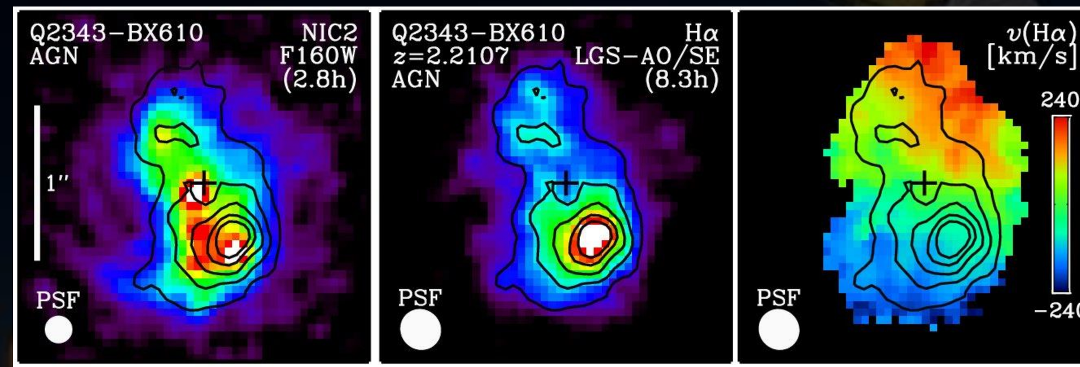
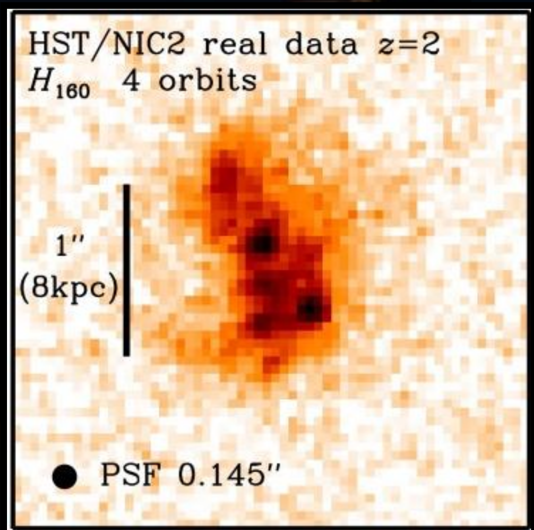
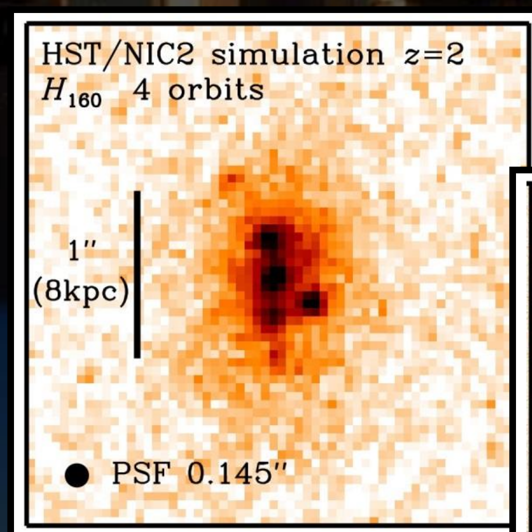


Towards Resolving Distant Galaxies on 100pc Scales

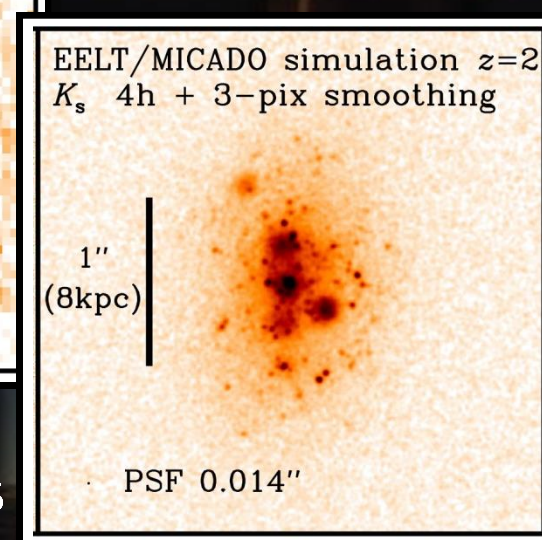


Real disk galaxy at z = 2.3
$R_{1/2}$ = 5 kpc, K_{AB} = 21.3





Mock disk galaxy at z = 2.3
$R_{1/2}$ = 5 kpc, K_{AB} = 21.3



Resolution of ~ 100 pc at z ~ 2
Compact clusters detected to K_{AB} ~ 28.5
($M_{R,AB}$ ~ –16)

Trippe et al. (2010)

Galaxy Evolution and ESO in the 2020's

Topics of Galaxy Evolution

- Mapping the cold gas, the stars, the kinematics
- Sub-galactic structure <~ 1 kpc and evolution
- Complete censuses and evolutionary connections
- Accretion and outflows
- Galaxy and AGN co-evolution
- The role of environment
- Chemical enrichment history of galaxies and IGM
- Connecting the ISM/CGM/IGM
- The first galaxies, the first SMBHs, the first stars, reionization

Requirements

- < 1 kpc resolution
- R ~ 10000
- Sensitivity
- Multiplexing
- Wavelength coverage

KMOS *MUSE* *ALMA* *+VLT/VST* *ERIS* *JWST* *MOONS* *4MOST* *MICADO* *HARMONI* *MOS/M-IFU+AO*