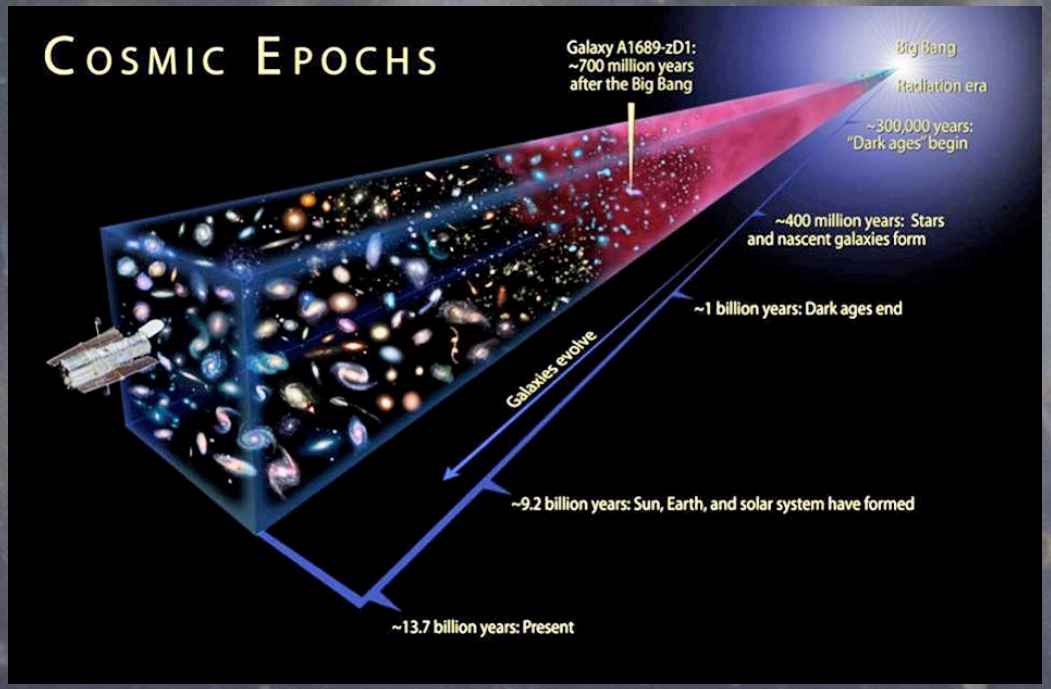
Exploring the distant Universe with AO at the focus of cosmic telescopes



INAF OAS BOLOGNA

Eros Vanzella (INAF - OAS/Bologna)

In collaboration with M. Meneghetti, P. Rosati, P. Bergamini, G.B. Caminha, F. Calura, M. Castellano, A. Mercurio, M. Nonino, G. Cupani, S. Cristiani, E. Sani, A. Fontana, M. Castellano, L. Pentericci, A. Grazian, P. Tozzi, et al.

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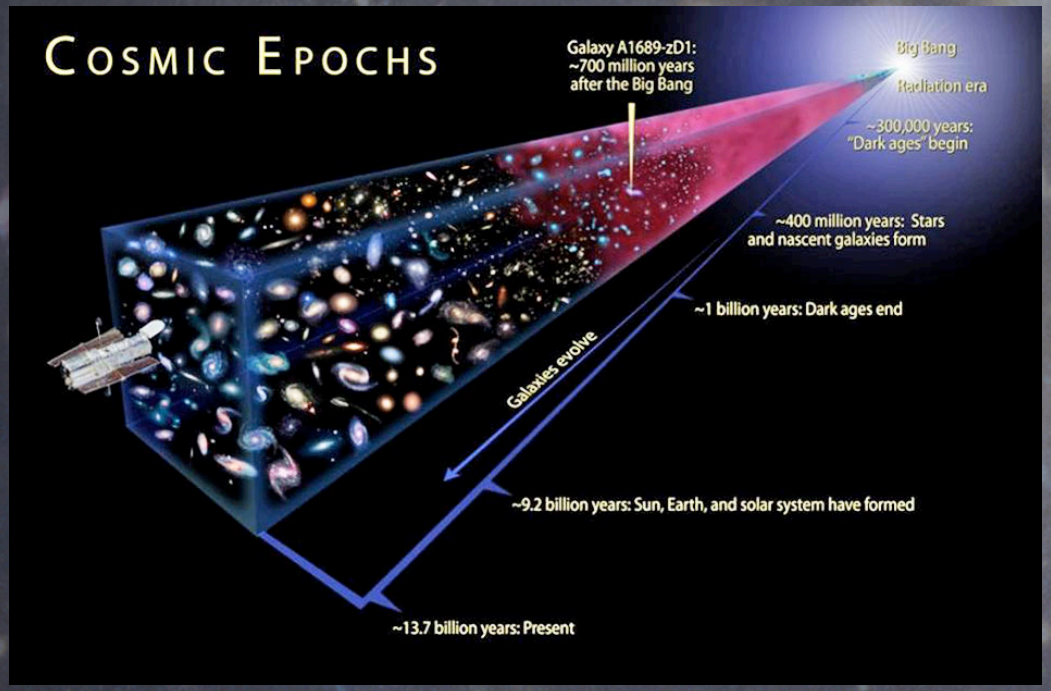
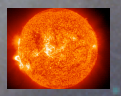


Motivation (I): Reionzation

Dayal & Ferrara 2018

$$\dot{n}_{ion,gal} = \rho_{SFR} \times \xi_{ion} \times f_{esc}$$



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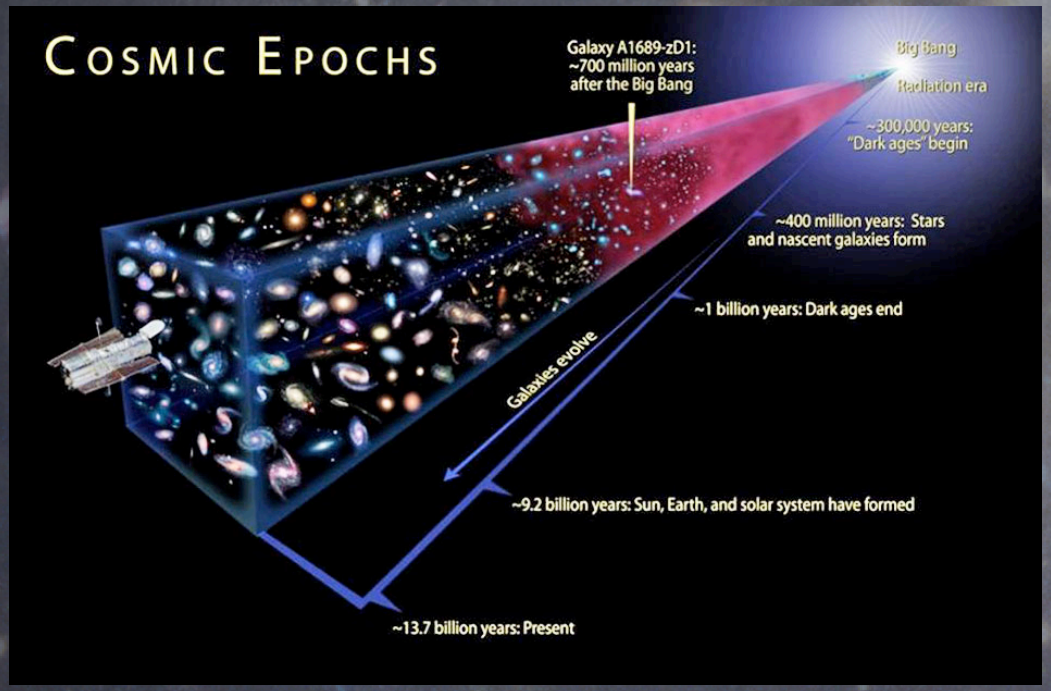

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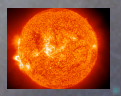

Motivation (II): Search for proto-GCs

SF-complexes size ~60(150) pc -> 10(25) mas at z~3(6)

star-clusters need Re<20 pc, that is < 3mas at z>3 !

INAF OAS BOLOGNA

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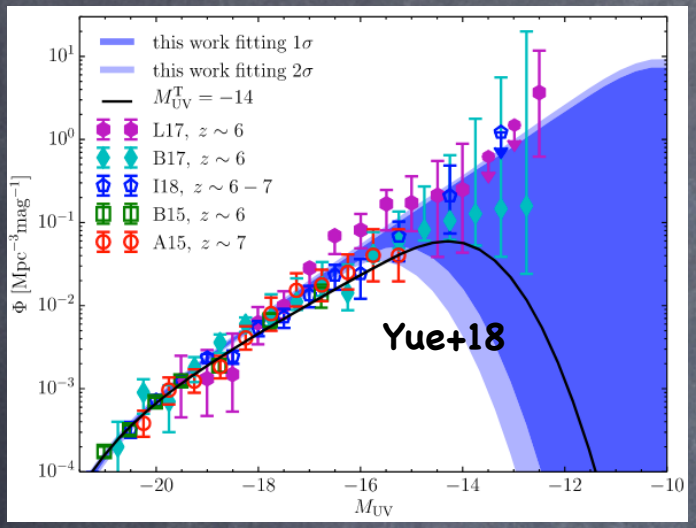
Looking for faint SF galaxies: approaching the globular cluster formation



- Can we detect YMCs at cosmological distance (z>2) ? YES

stellar mass 2x10^6 Msun, 3 Myr, Muv = -17 (29.7)

(e.g., Pozzetti, Maraston & Renzini+19)

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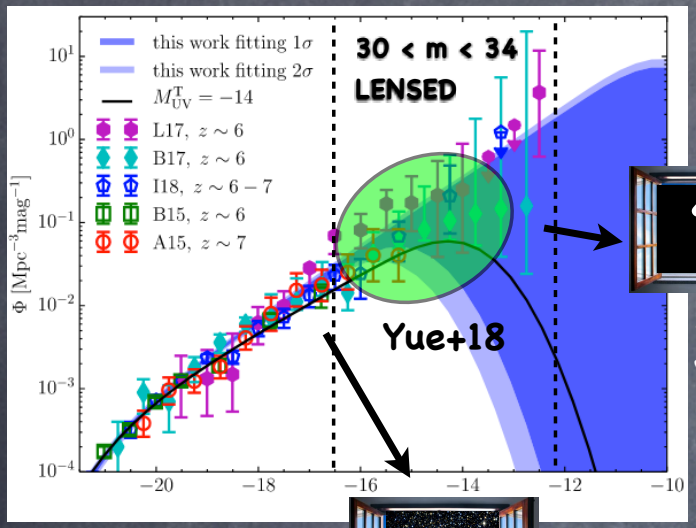

SF-complexes

YMCs ?

dwarfs

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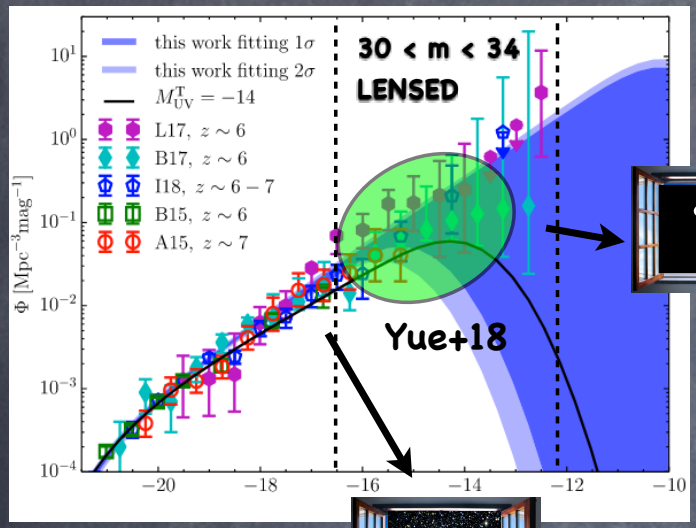
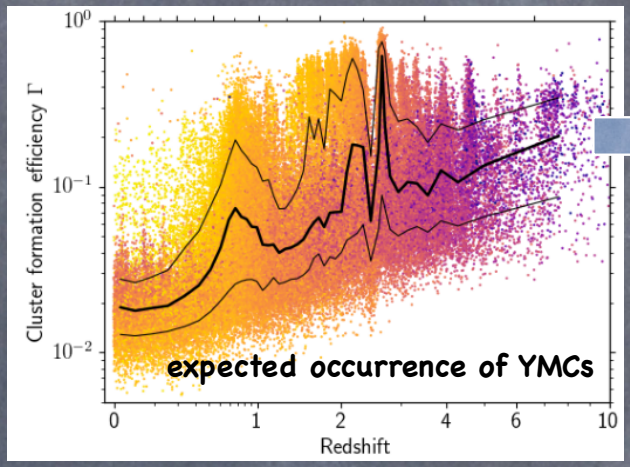


SF-complexes

YMCs ?

dwarfs

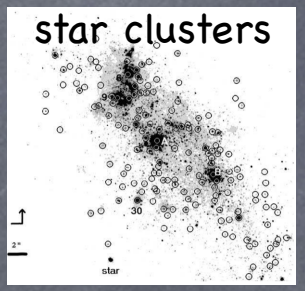
E-MOSAICS simulation (Pfeffer+18)

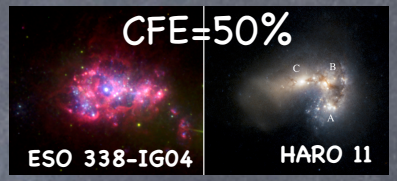


CFE = cluster formation efficiency
= ongoing SF in star clusters

Local examples (e.g., Adamo+11)

CFE=50%





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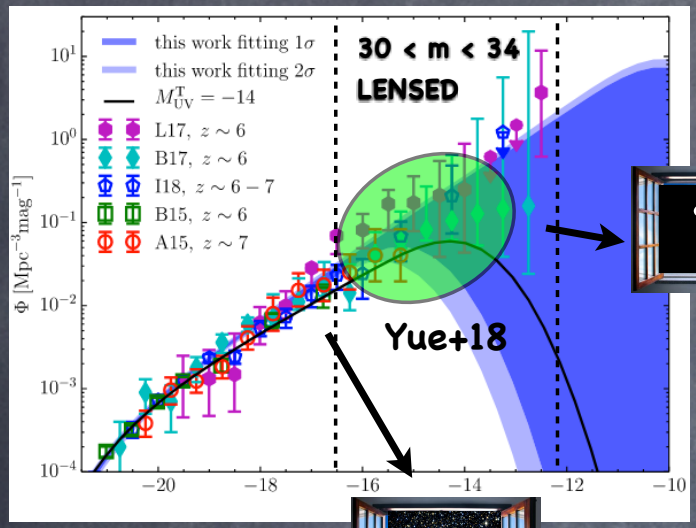
Stellar mass of the Univ. in YMCs at z>5-6
is substantial 30-50% (e.g., Renzini 2017)

O-type stars located mainly in YMCs (Bik15)

YMCs occurrence is high

They can play a role in the ionization & fate of gal.
(modulo $\xi_{\rm ion}$, $f_{\rm esc}$)

Looking for faint SF galaxies: approaching the globular cluster formation



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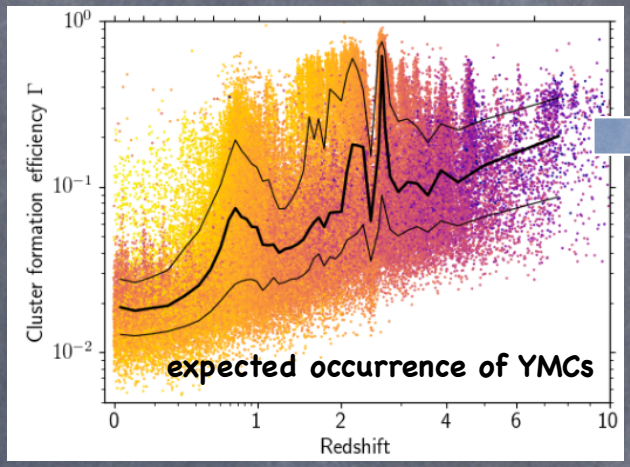

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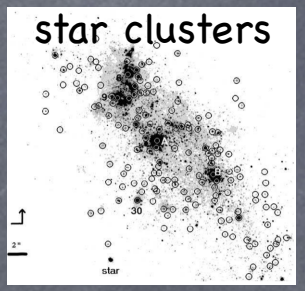

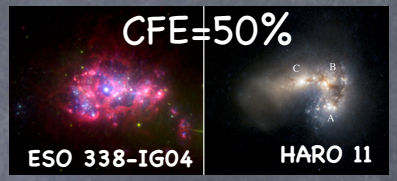

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Stellar mass of the Univ. in YMCs at z>5-6 is substantial 30-50% (e.g., Renzini 2017)

- Can we probe grav. bounded YMCs at high-z ? (almost) NO -> AO is needed

Can we recognize GC Precursors ? (key for the GC-formation scenarios, Renzini+15)

O-type stars located mainly in YMCs (Bik15)

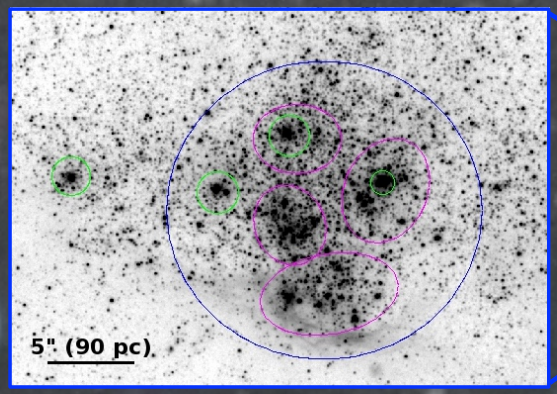
YMCs occurrence is high

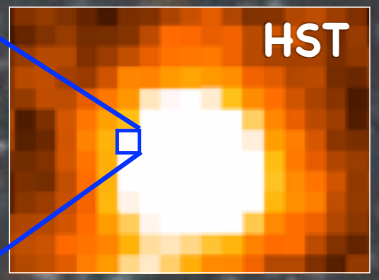
They can play a role in the ionization & fate of gal. (modulo $\xi_{\rm ion}$, $f_{\rm esc}$)

The deepest observation: limitations

Hubble Extreme Deep Field Illingworth+13

- mag > 29 sources have poor S/N (2-5);
- 1 HST pixel (30 mas) ~ 0.2-0.3 kpc at 2<z<7
  (probes SF clumps)





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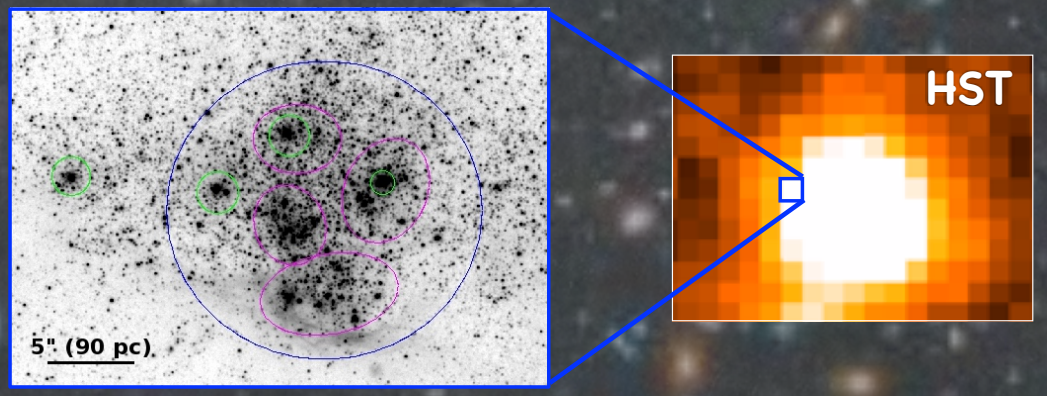


Strong lensing + deep fields

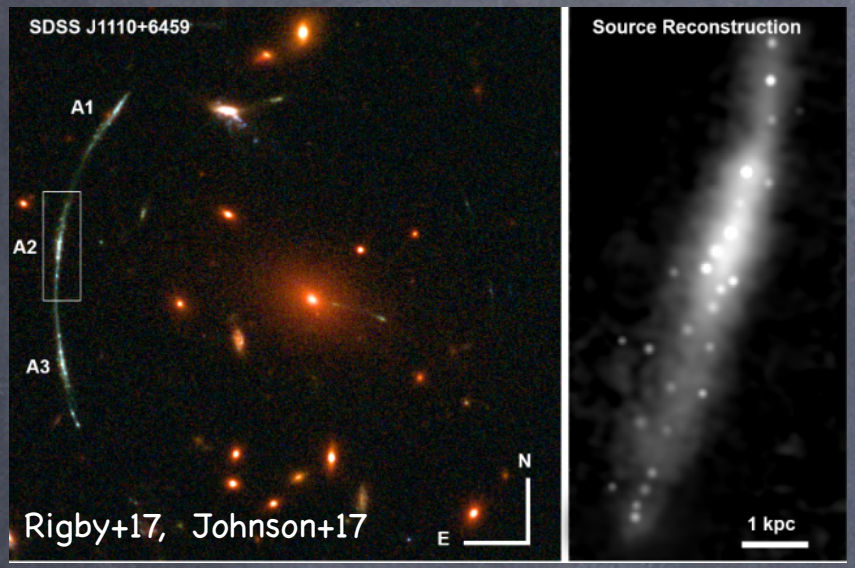
A preview of the - extreme - AO (<30 mas) science

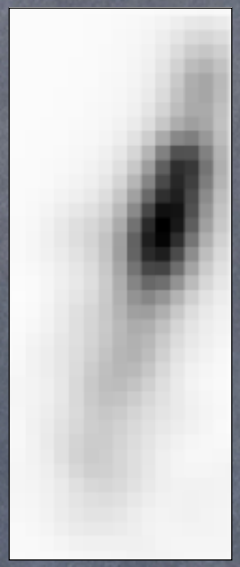
- BOOST in S/N ratio: spectroscopic info !
- BOOST in spatial resolution (10 pc)

HST + Strong lensing
(> 20 pc) AO-preview

AO + Strong lensing
(< 20 pc) ``super-AO"

Strong gravitational lensing reveals "sub-grid" SF-mode





Multi-knot SF seems to be a common property whenever the spatial resolution increases, down to star-clusters level

Observations

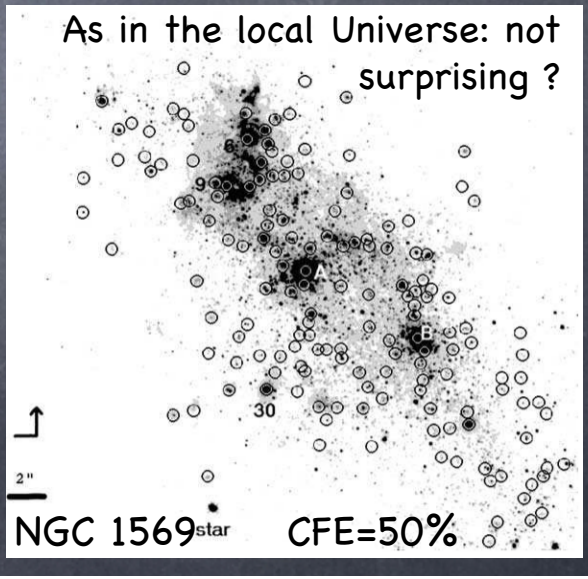
Lensed galaxy
SGAS J111020.0+645950
z=2.481, magnif. x28+/-8

Source plane recostruction
F390W, ~1300A

HST PSF

model

no lensing:
Almost all SF arises from an exponential disk with Re~2kpc, centrally concentrated

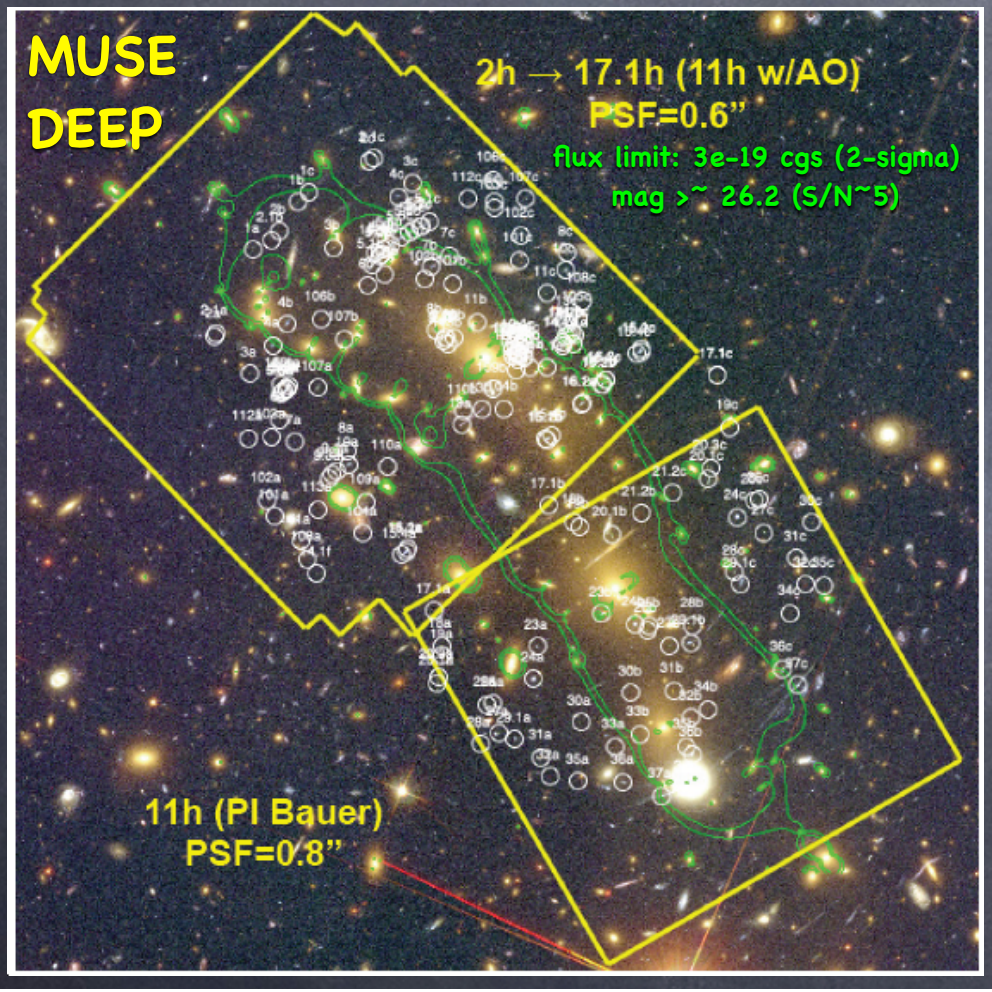


much of the SF arises from more than 20 clumps with sizes of <30-50 pc containing 25% of the total UV light

The MUSE deep lensed field (MDLF) on HFF J0416

Wide Field Mode with Ground Layer Adaptive Optics, GLAO , offered by the GALACSI module

Vanzella et al in prep., Bergamini et al. in prep.



PI Vanzella
Co-I Rosati, Calura
Meneghetti, Mercurio
Sani, Cupani, Balestra
Caminha, Grillo, Caputi,
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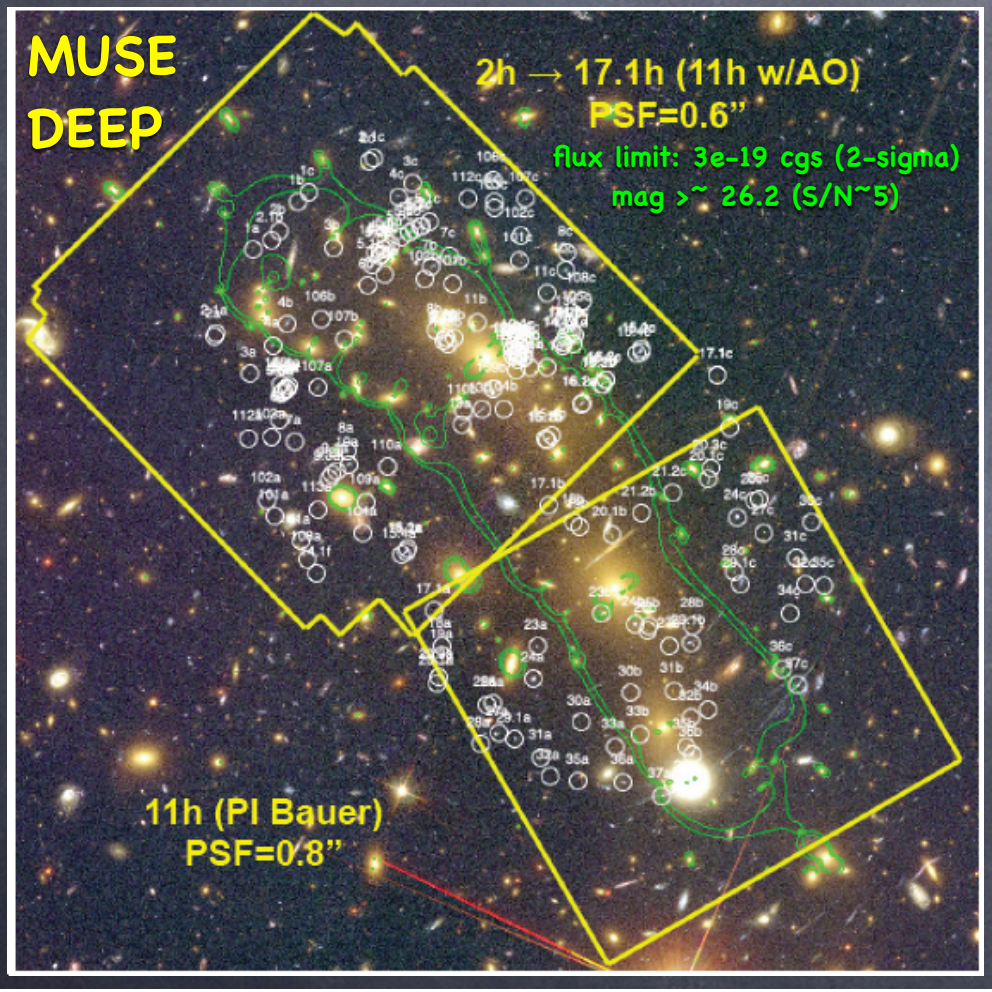
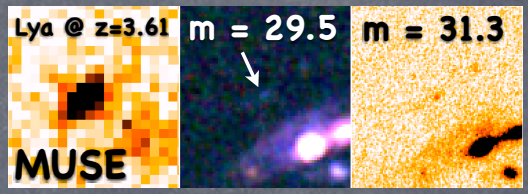


1) No target pre-selection
(boost the discovery space, m>28)



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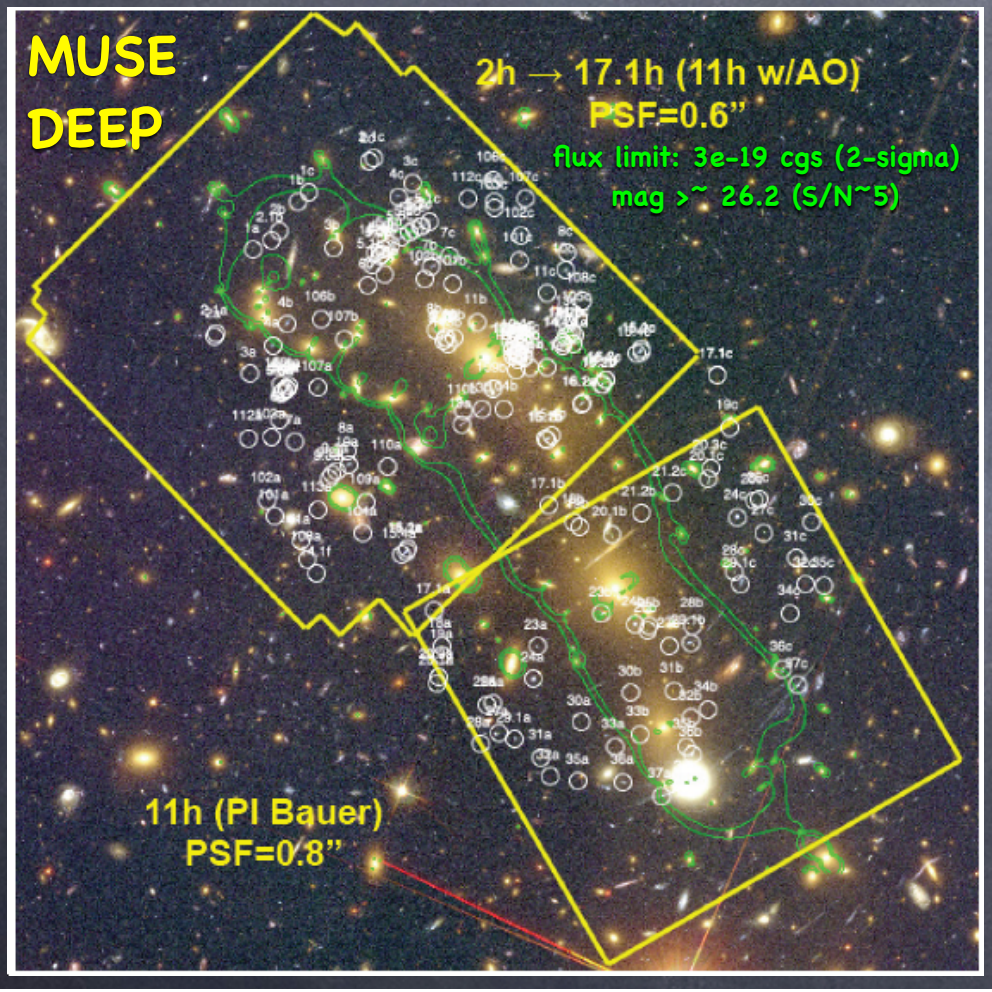

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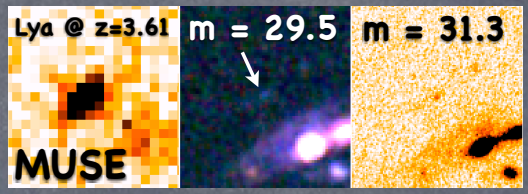

2) Uniform coverage on caustics
(extreme magnified regions)

de-lensed
m > 35
PopIII cand.
(EV20b)

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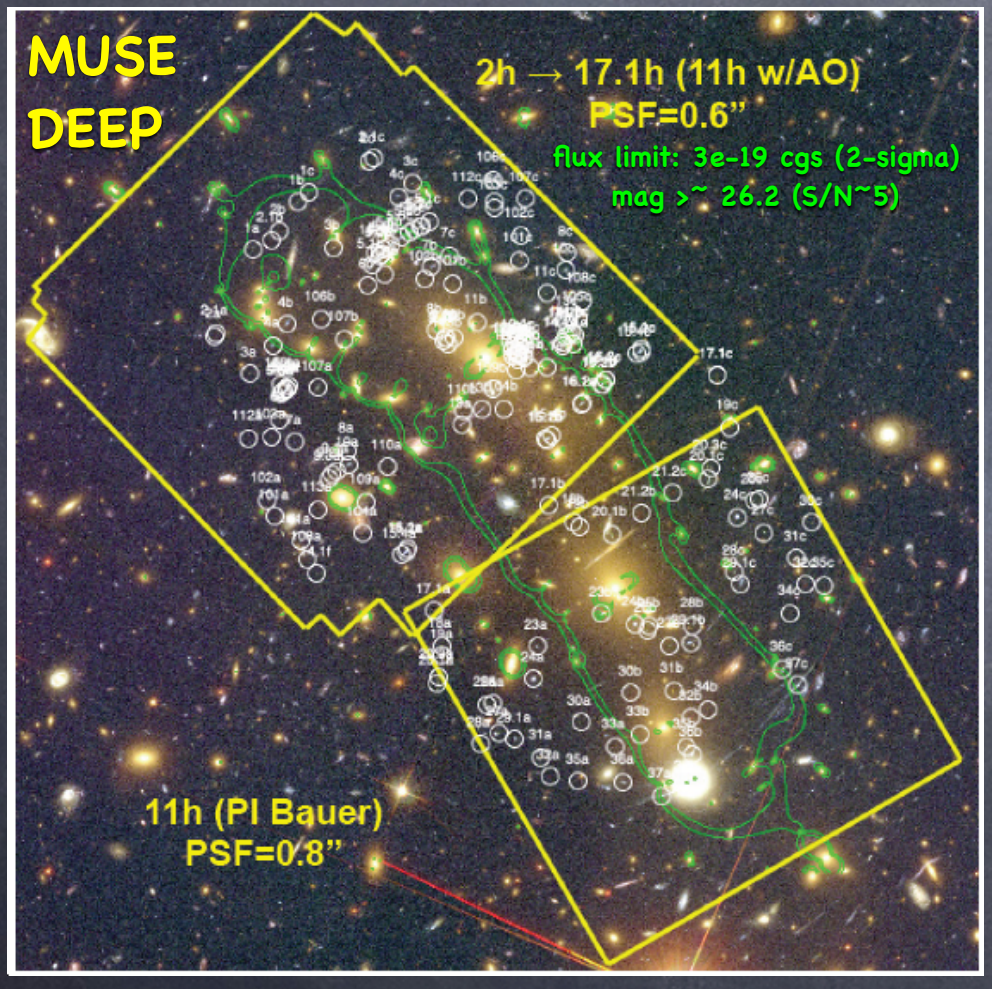

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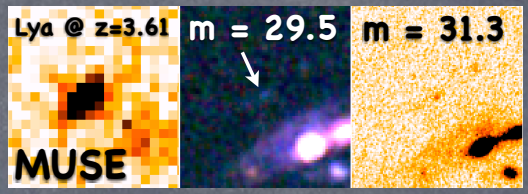

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PopIII cand.
(EV20b)

3) Efficient multiple-image finder
(lens models, errors under control, e.g., Meneghetti+17)

182 spectroscopic multiple images ! RMS = 0.42"

No. of multiple images

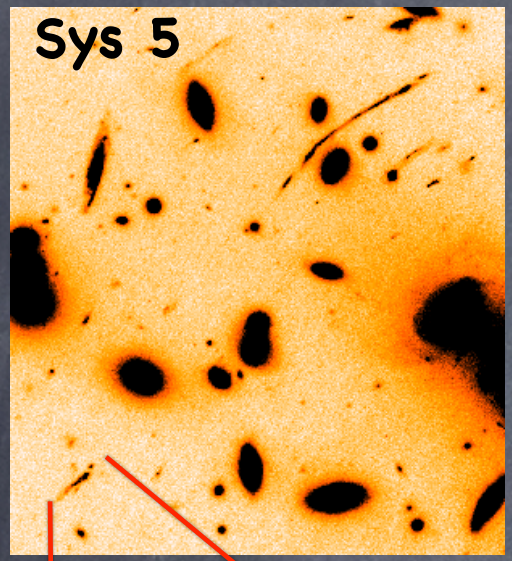
62 (182) — MUSE DEEP

37 (104) — MUSE (Caminha+17)

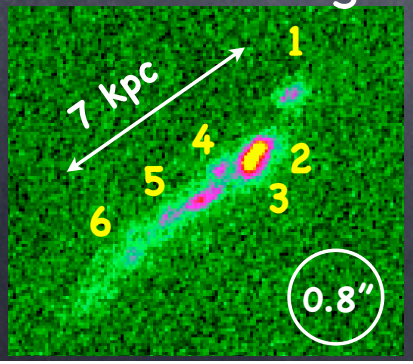
15 — GLASS (Hoag+16)

8 — CLASH-VLT (Grillo+15)

MDLF, example 1

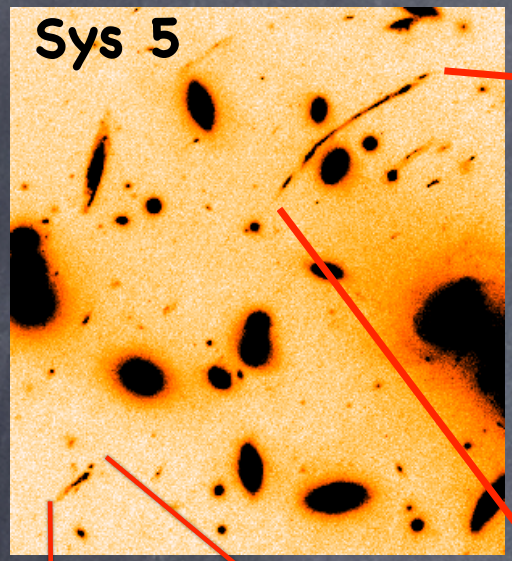


Counter image



MDLF, example 1

Arc at z=1.896, ~50pc/HSTpix => sizes, line emissions, SF complexes, star clusters



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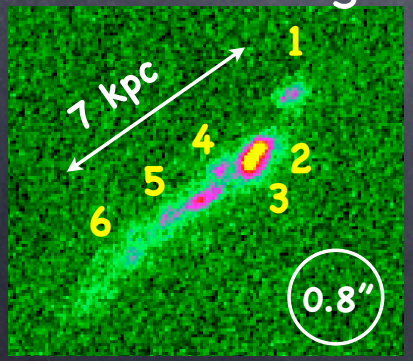

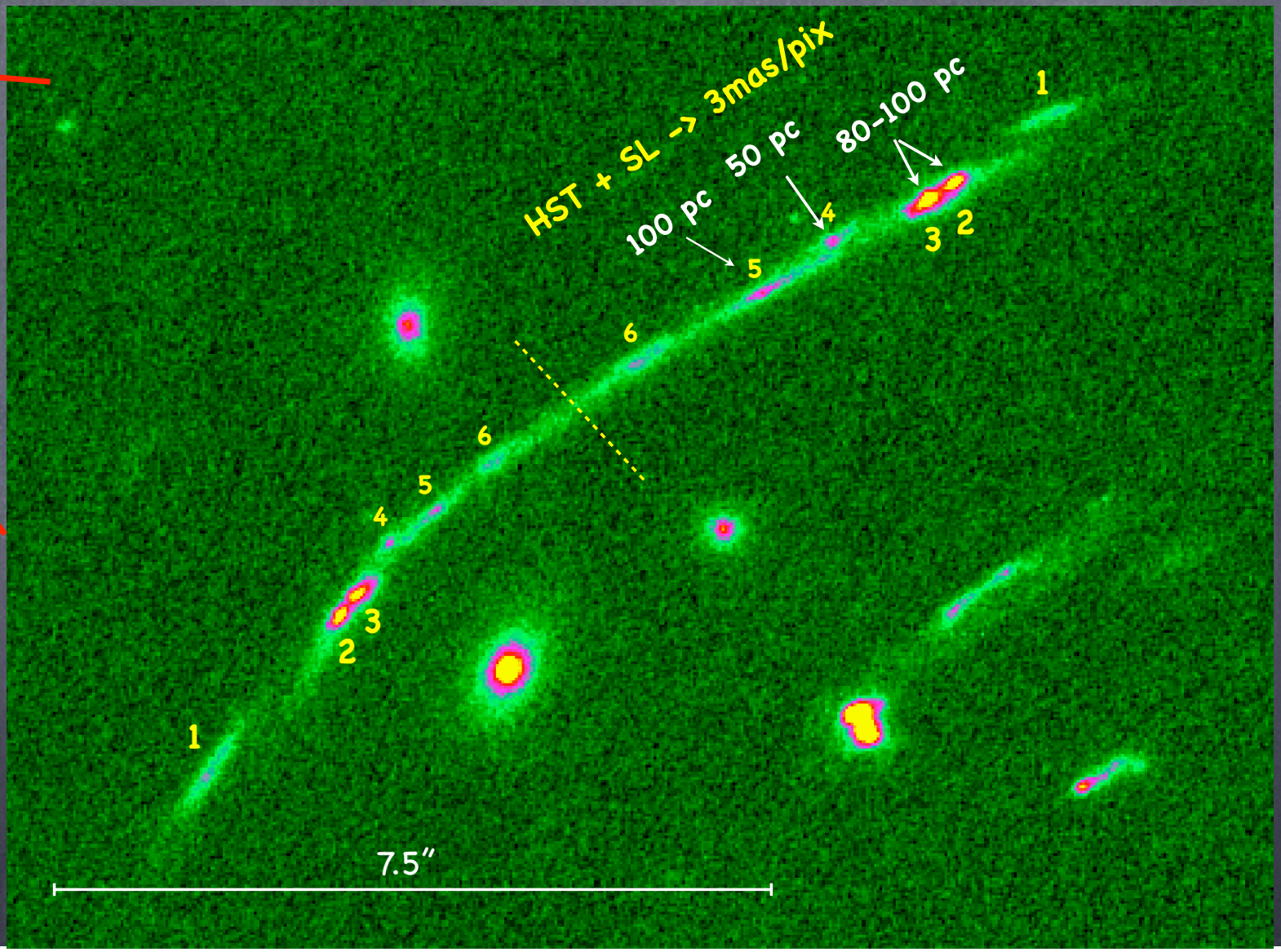

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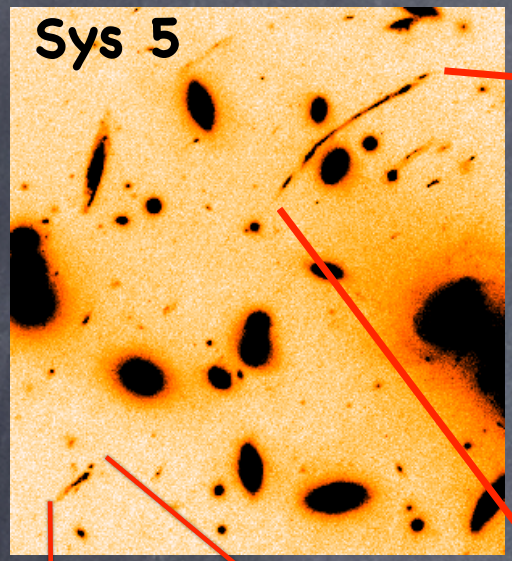

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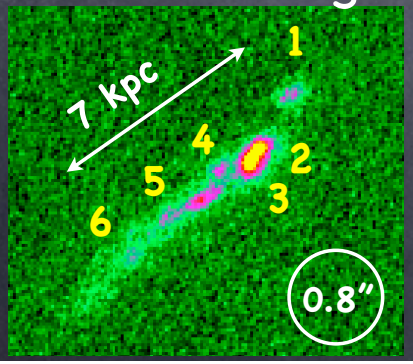
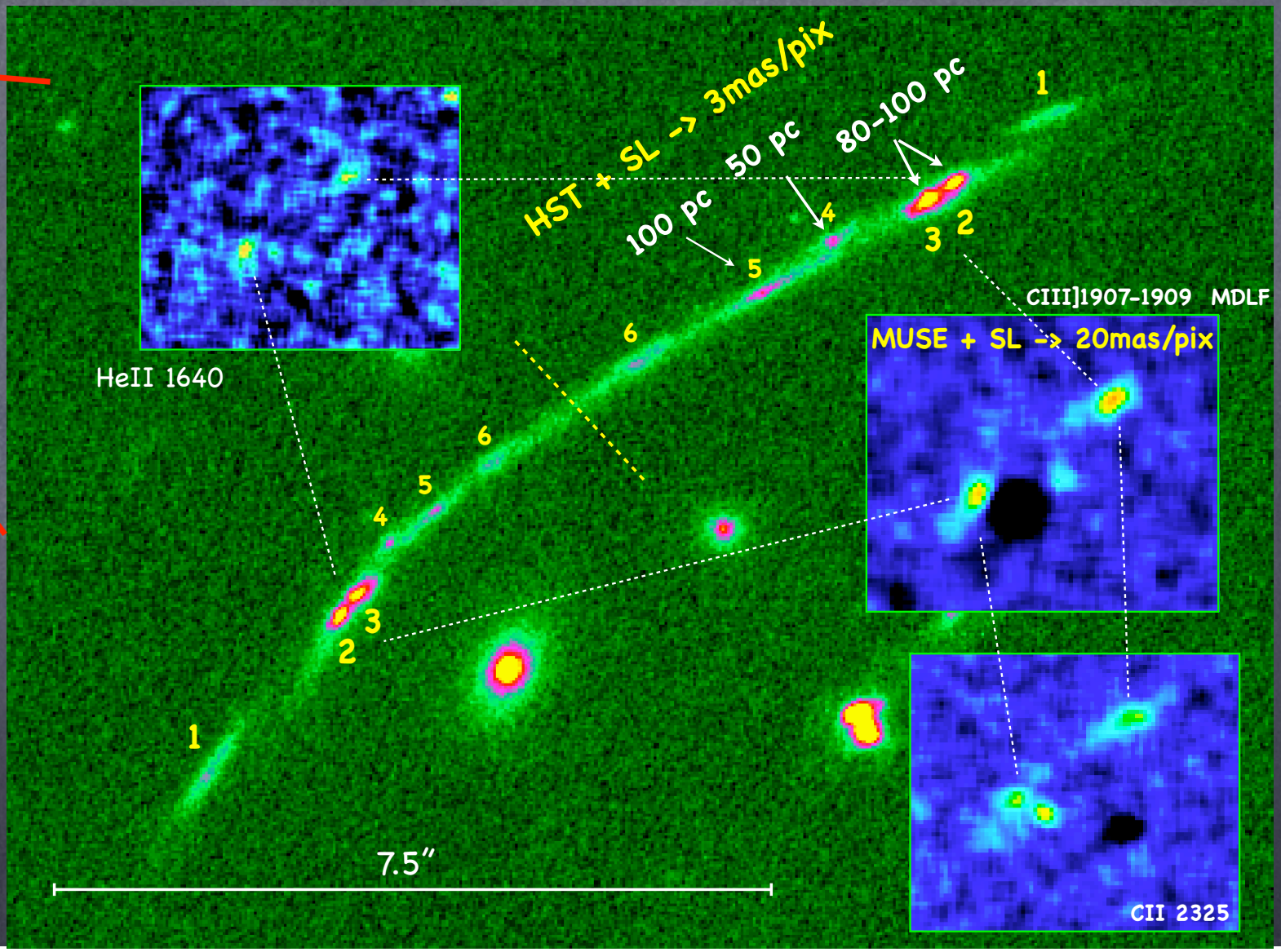
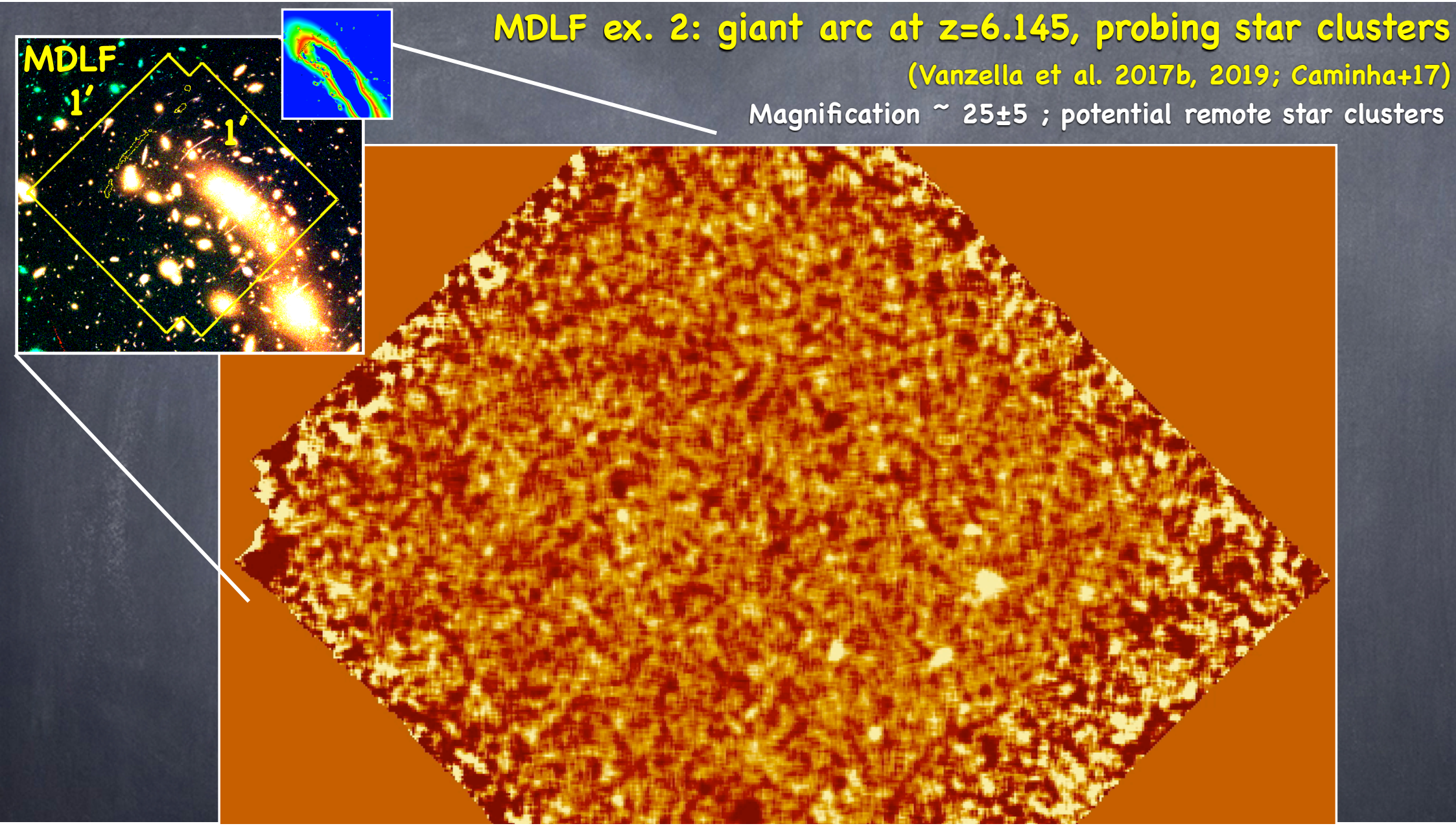


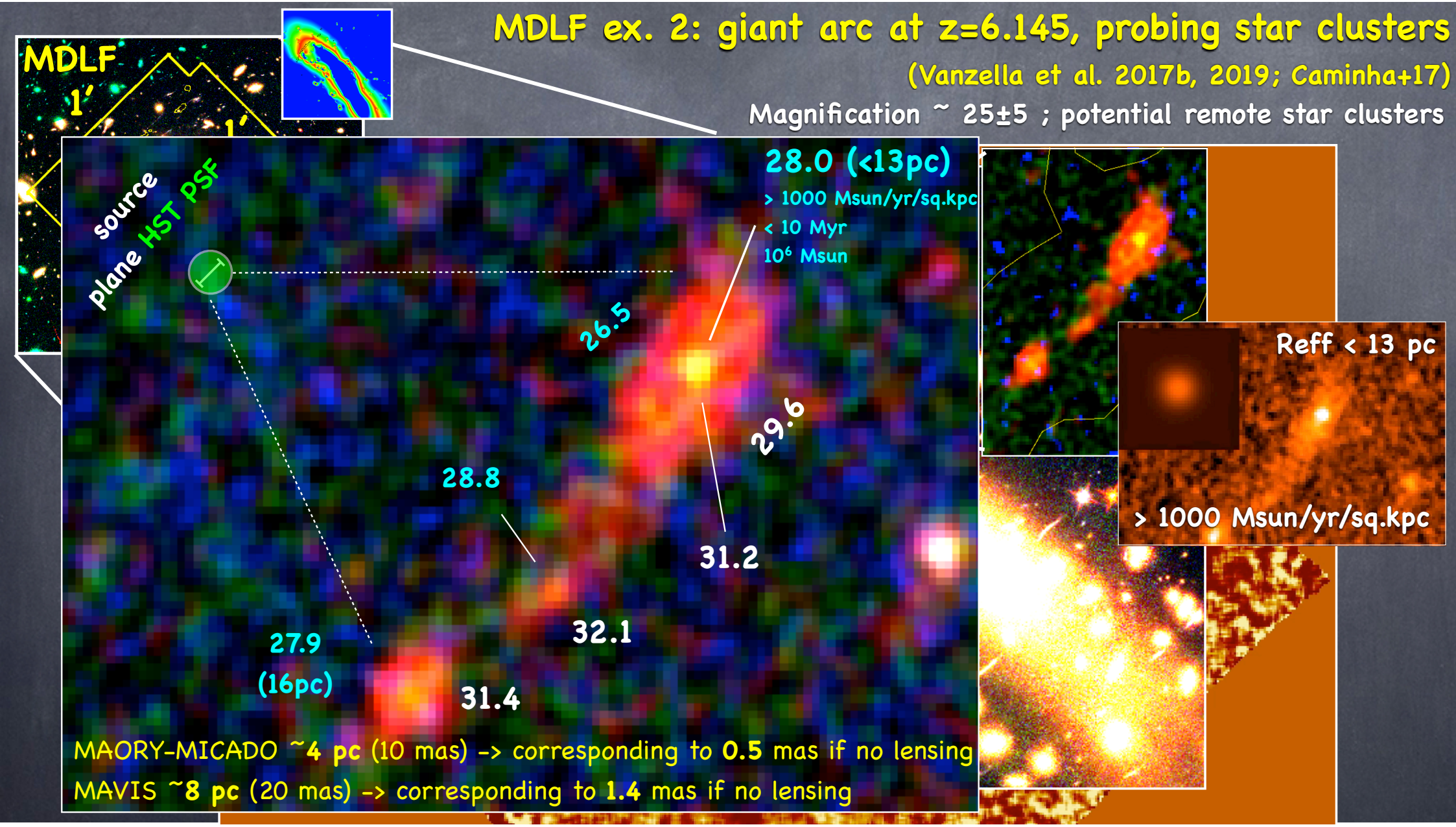


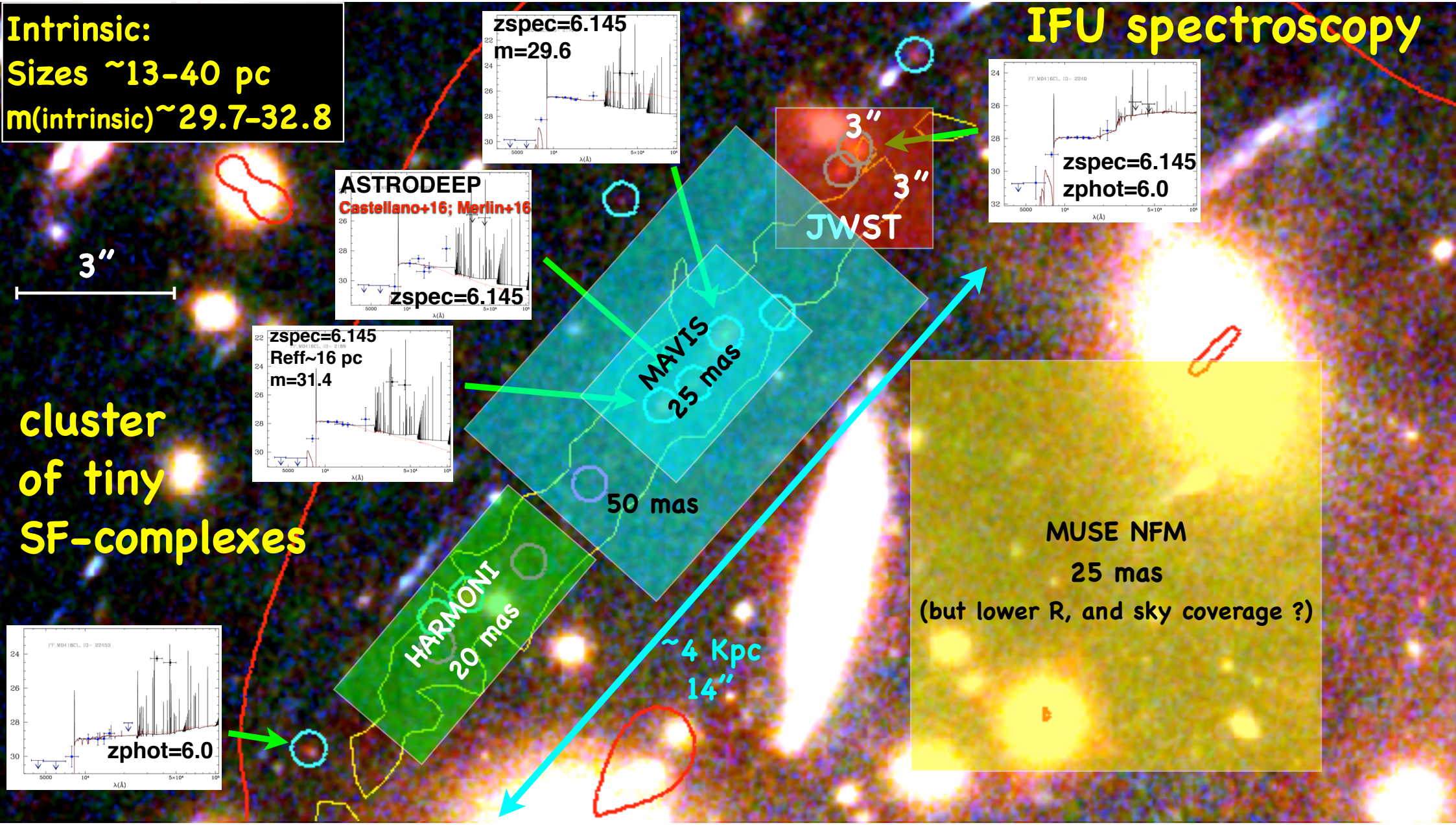


MDLF ex. 2: giant arc at z=6.145, probing star clusters

(Vanzella et al. 2017b, 2019; Caminha+17)

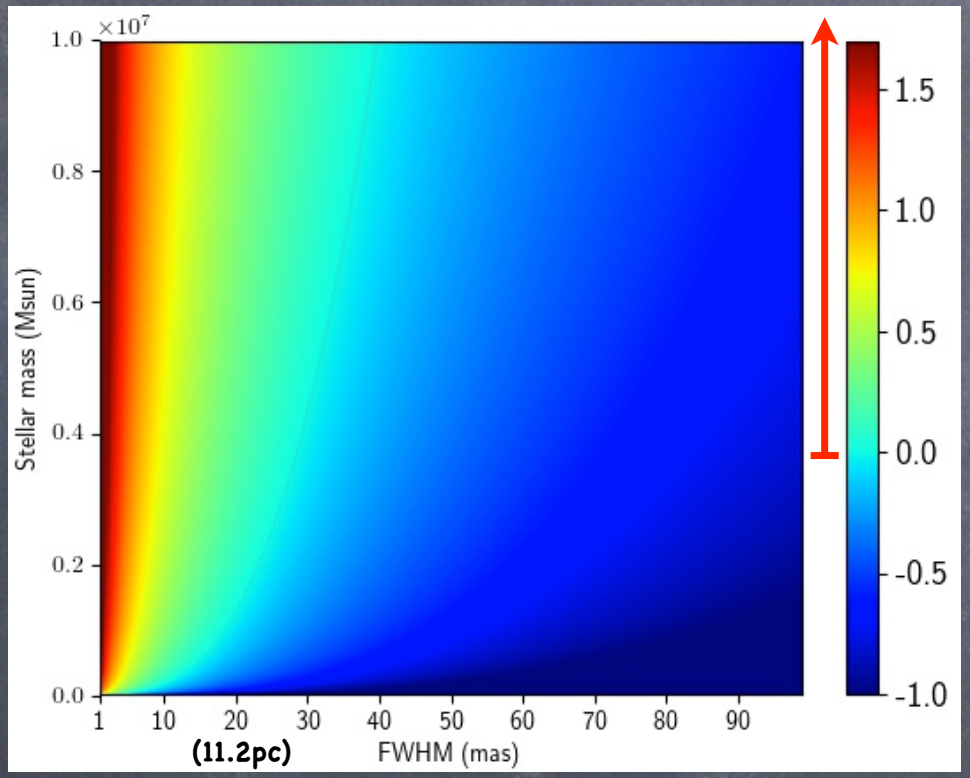
Magnification ~ 25±5 ; potential remote star clusters


MDLF ex. 2: giant arc at z=6.145, probing star clusters
(Vanzella et al. 2017b, 2019; Caminha+17)
Magnification ~ 25±5 ; potential remote star clusters
MDLF
1'
1'
source plane
HST PSF
28.0 (<13pc)
> 1000 Msun/yr/sq.kpc
< 10 Myr
10^6 Msun
26.5
29.6
28.8
31.2
32.1
27.9
(16pc)
31.4
Reff < 13 pc
> 1000 Msun/yr/sq.kpc
MAORY-MICADO ~4 pc (10 mas) -> corresponding to 0.5 mas if no lensing
MAVIS ~8 pc (20 mas) -> corresponding to 1.4 mas if no lensing


Intrinsic:
Sizes ~13-40 pc
m(intrinsic)~29.7-32.8
IFU spectroscopy
zspec=6.145
m=29.6
3″
3″
JWST
zspec=6.145
zphot=6.0
ASTRODEEP
Castellano+16; Merlin+16
zspec=6.145
3″
MAVIS
25 mas
zspec=6.145
Reff~16 pc
m=31.4
cluster
of tiny
SF-complexes
50 mas
HARMONI
20 mas
MUSE NFM
25 mas
(but lower R, and sky coverage ?)
~4 Kpc
14″
zphot=6.0

Probing gravitationally-bound star clusters at cosmological distance (Re < 20 pc)

Assumptions: Age = **5Myr**; z = **6**; μ = **10**



The dynamical age Π

Age/Tcr = Π , if Π>1 grav. bound

$$T_{cr} \equiv 10 \left(\frac{R_{eff}^3}{GM} \right)^{1/2}$$

Stellar agglomerates for which the age of the stars exceeds the crossing time are bound

Gieles+11, Ryon+1, e.g., LEGUS (Calzetti+15)

Future AO will probe gravitationally bound YMCs down to (1-10)e5 Msun at 1 < z < 10 and extreme SFR or stellar mass surface densities ("GC-like")

Probing gravitationally-bound star clusters at cosmological distance (Re < 20 pc)

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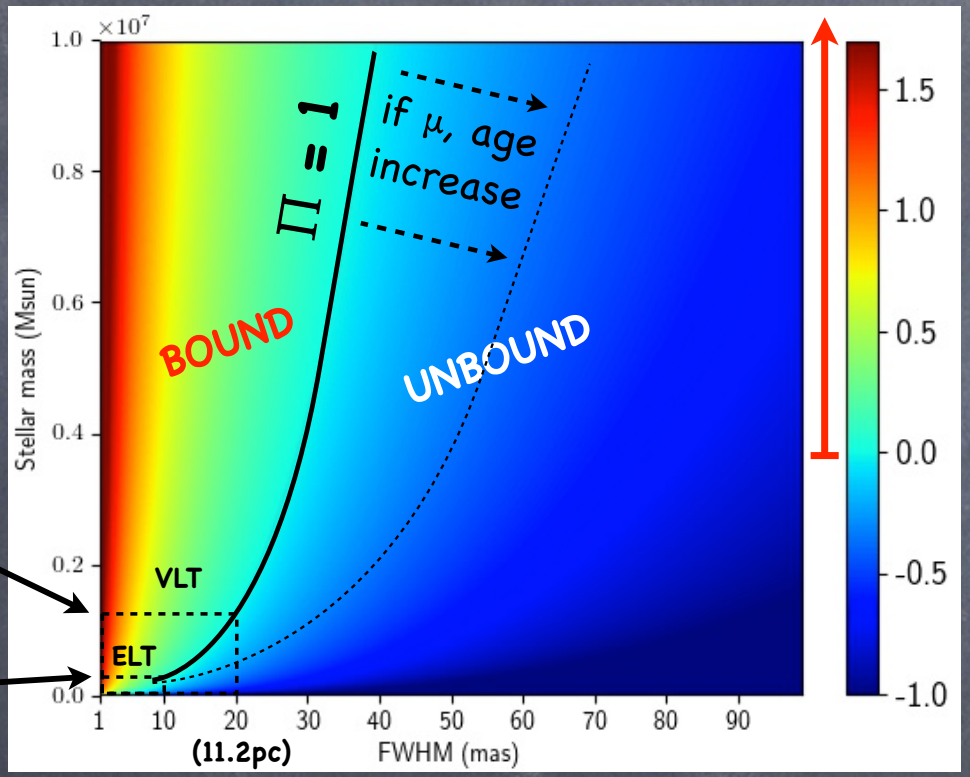

1.3e10⁶M⊙

0.2e10⁶M⊙

The dynamical age Π

Age/Tcr = Π , if Π>1 grav. bound

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Future AO will probe gravitationally bound YMCs down to (1-10)e5 Msun at 1 < z < 10 and extreme SFR or stellar mass surface densities ("GC-like")

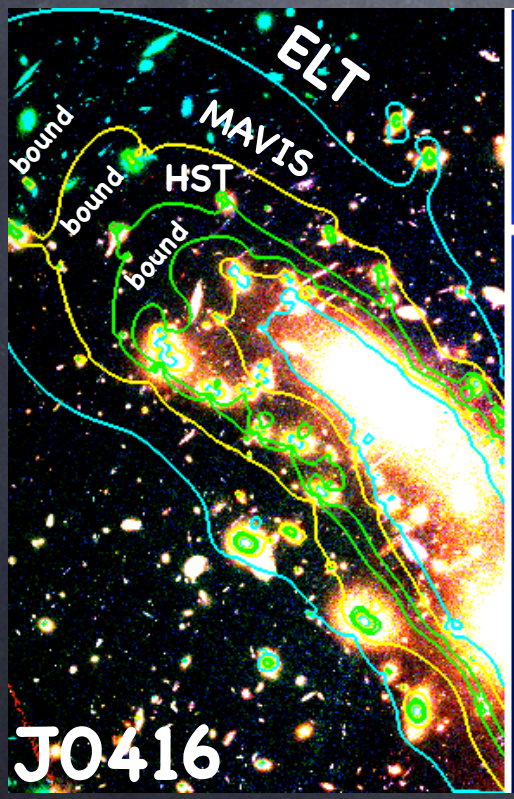
down to what magnitude ? Need proper simulations ...

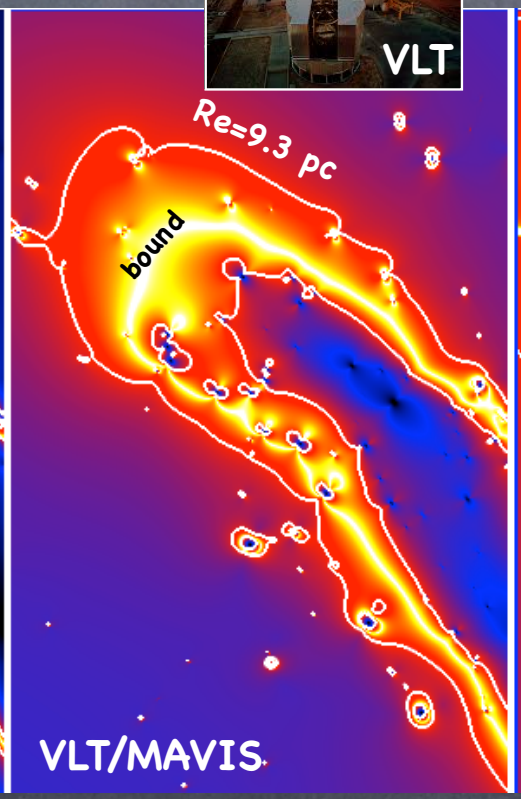
Dynamical-age lensing cross-section (Π)

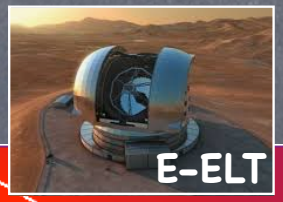
Assumed star cluster properties (YMC):

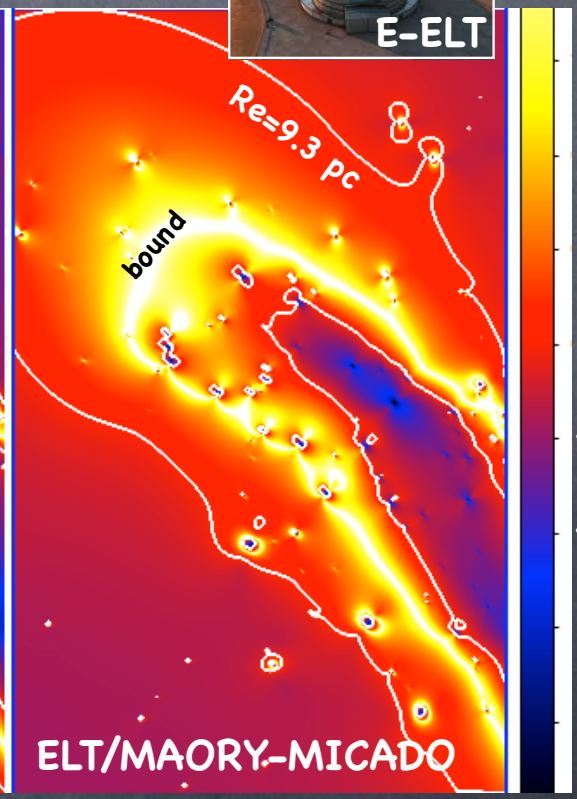
M=2x10^6 Msun
Age=3x10^6 Myr
M_{1500} = -17 (29.7)

Π > 1 requires Re < 9.3 pc



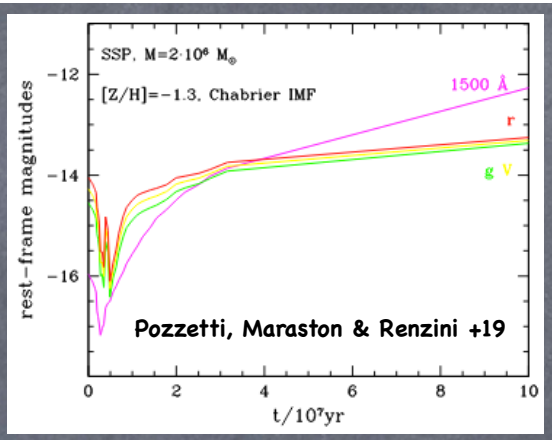


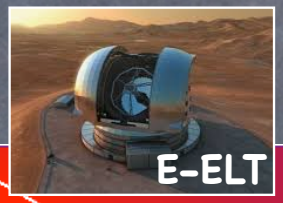


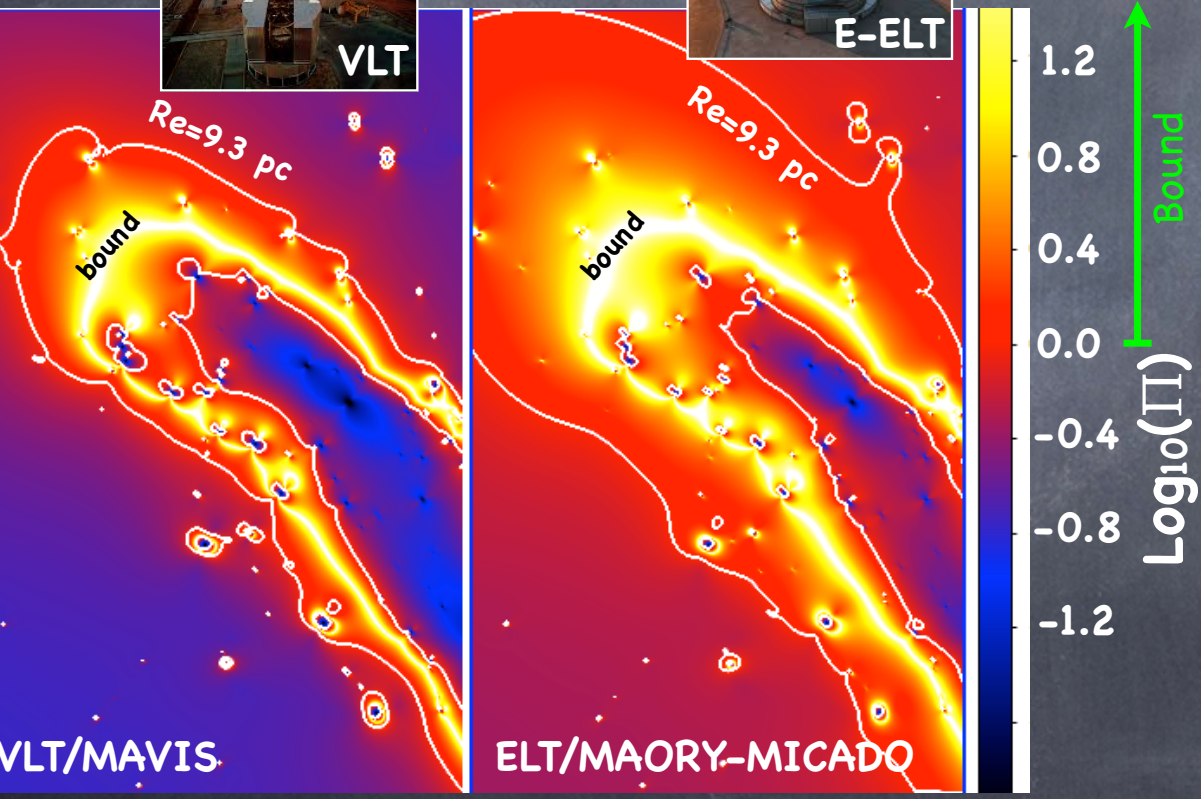


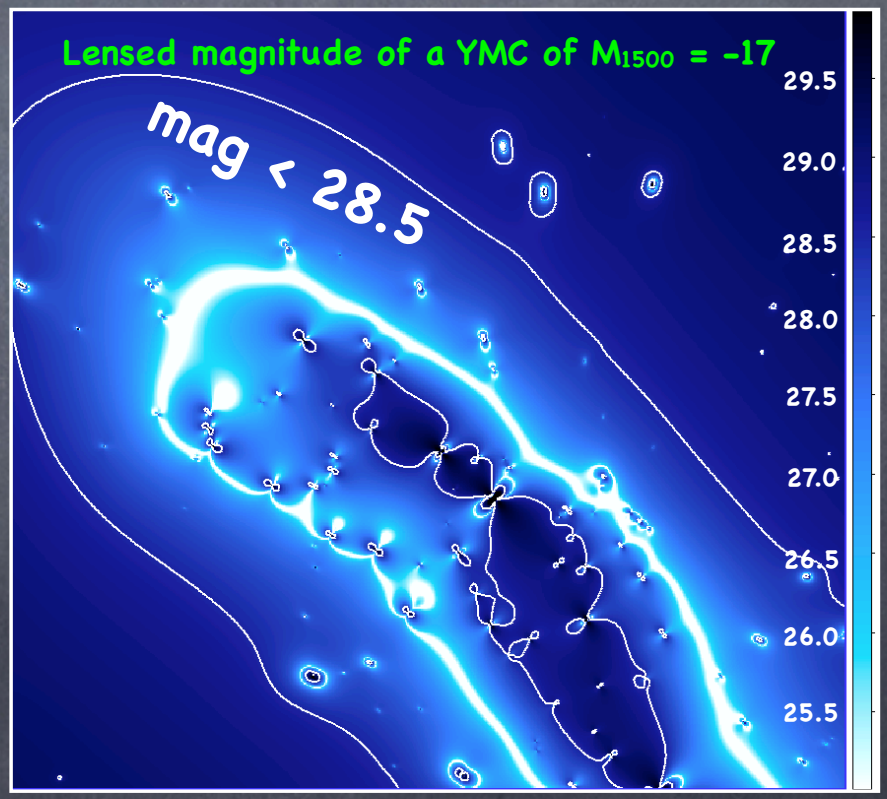
Dynamical-age lensing cross-section (Π)

Π > 1 requires Re < 9.3 pc



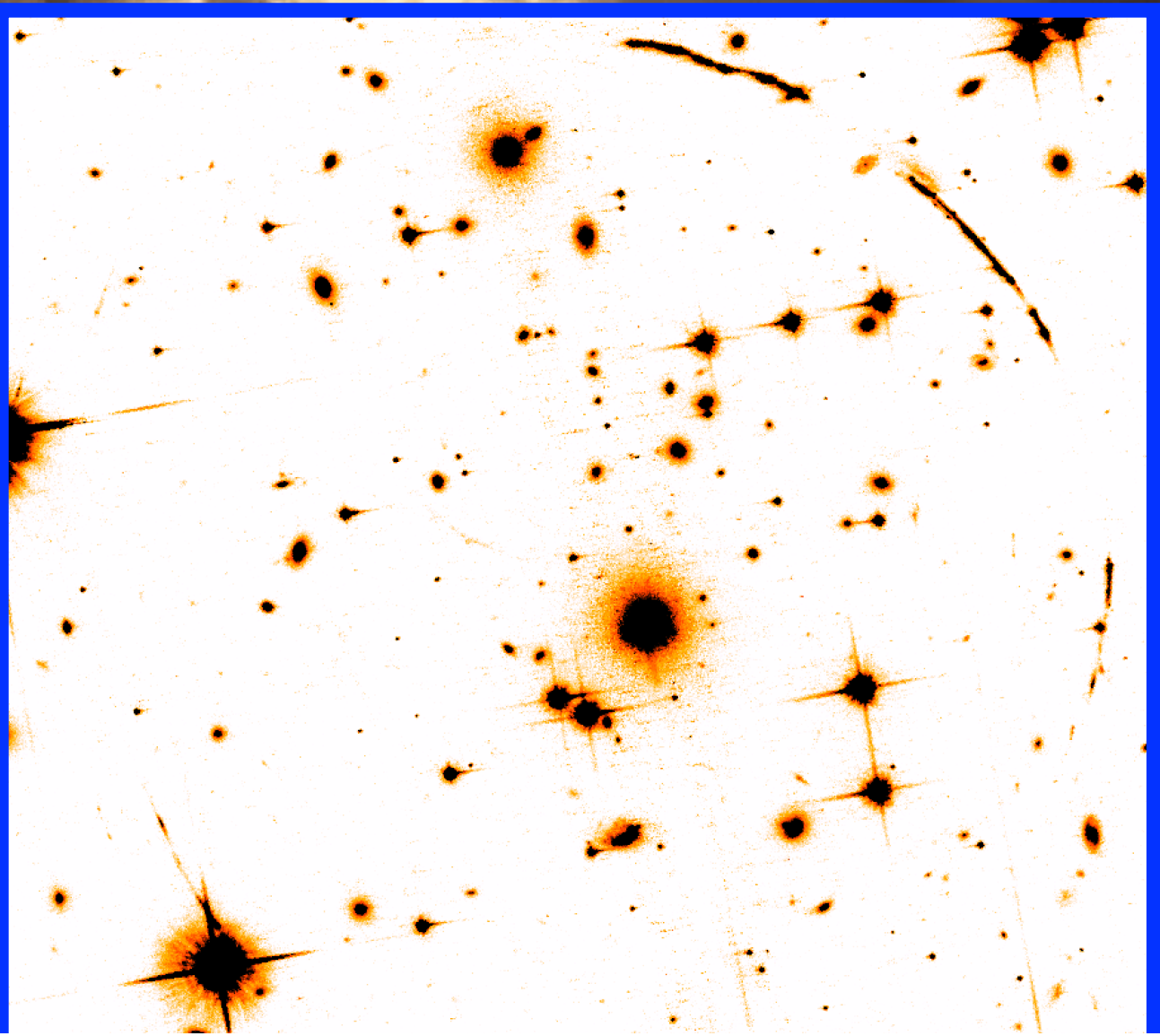






Superlensed (and bright) systems

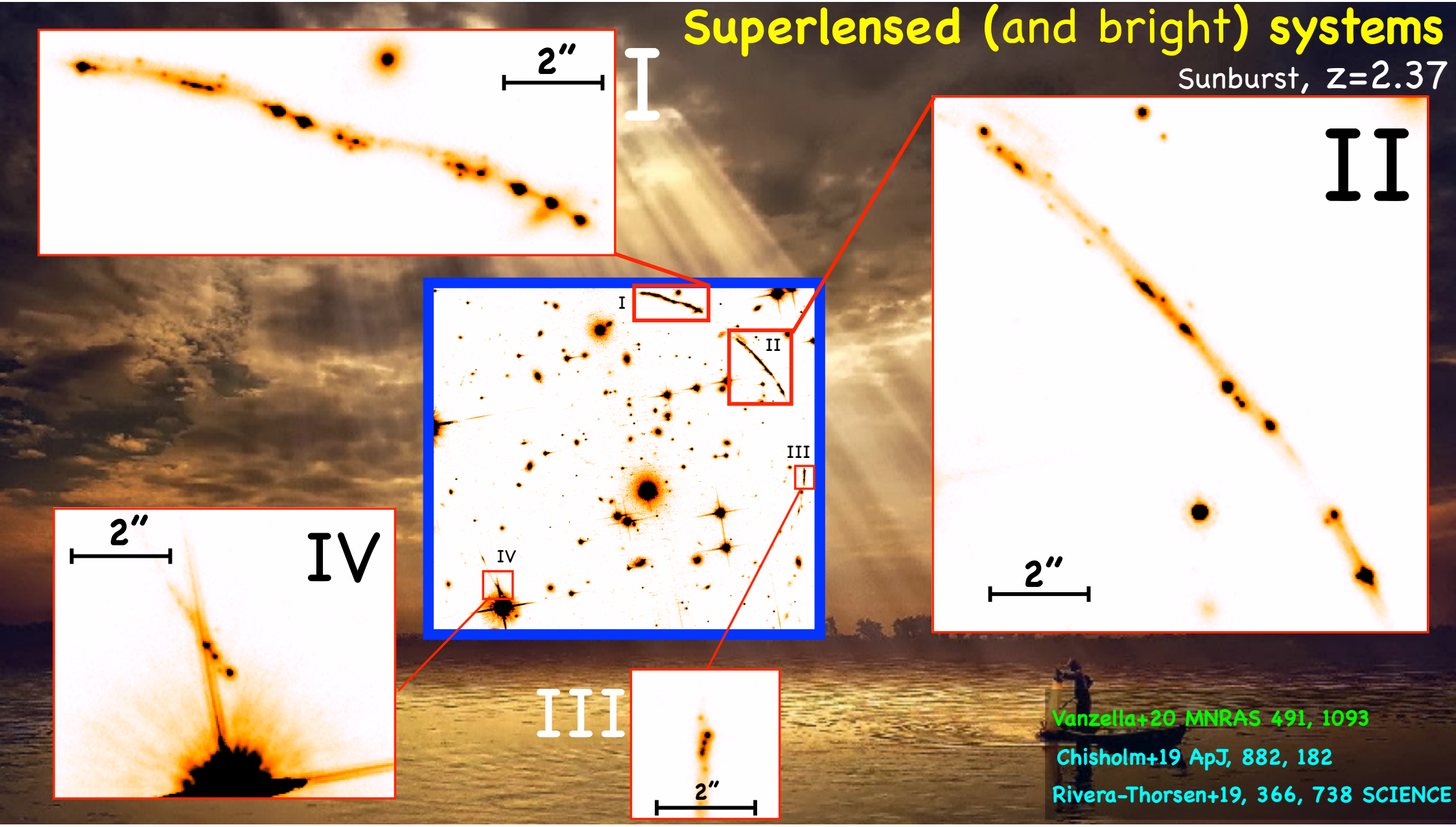
Sunburst, z=2.37



Vanzella+20 MNRAS 491, 1093

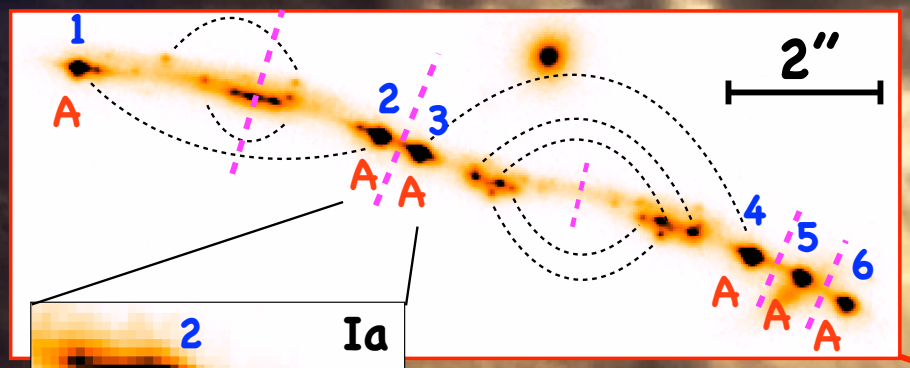
Chisholm+19 ApJ, 882, 182

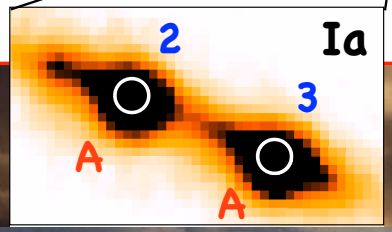
Rivera-Thorsen+19, 366, 738 SCIENCE


Superlensed (and bright) systems
Sunburst, z=2.37
I
2″
II
2″
III
2″
IV
2″
I
II
III
IV
Vanzella+20 MNRAS 491, 1093
Chisholm+19 ApJ, 882, 182
Rivera-Thorsen+19, 366, 738 SCIENCE

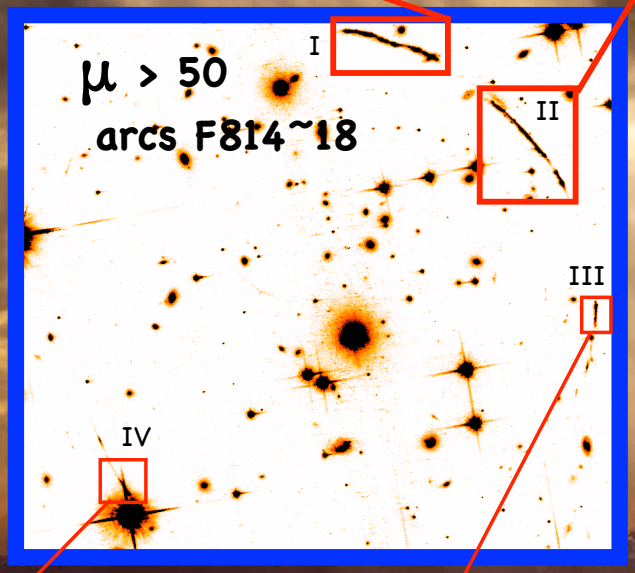
Superlensed (and bright) systems

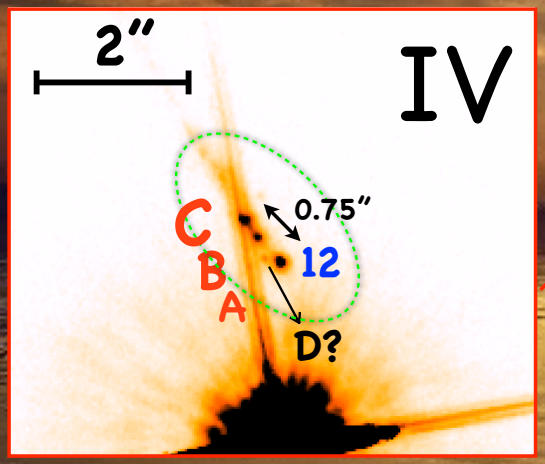
Sunburst, z=2.37

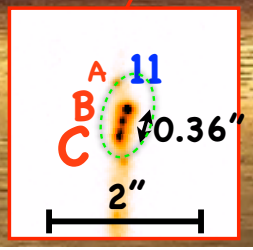


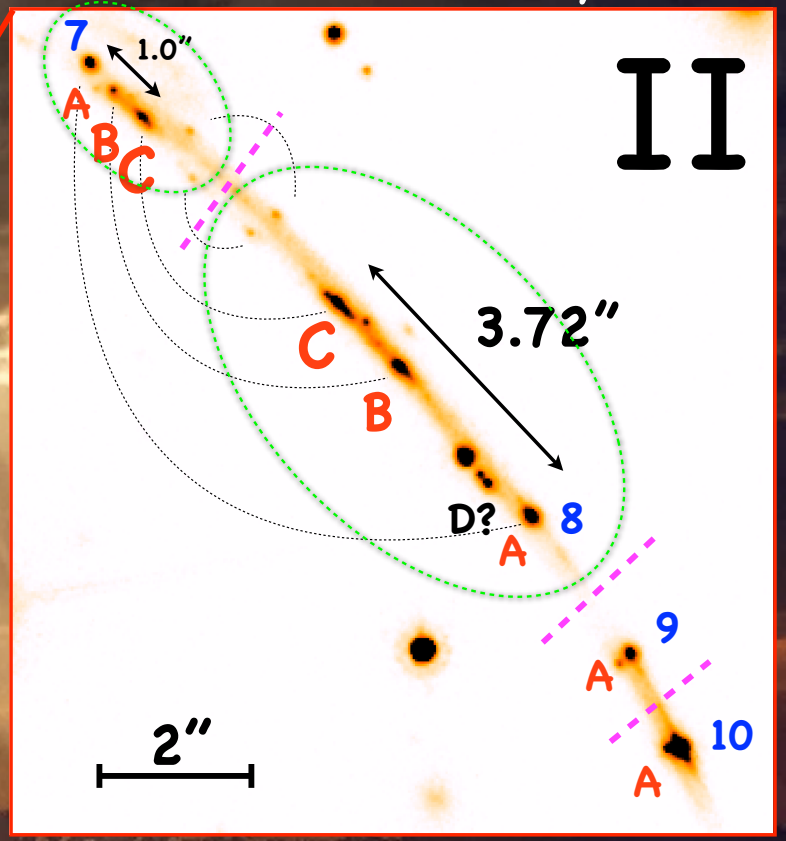


'A' is also a Lyman continuum emitter, $\lambda < 912$A photons escape $N_{HI}<10^{17.2}$ cm^{-2} : ionizer !









Vanzella+20 MNRAS 491, 1093

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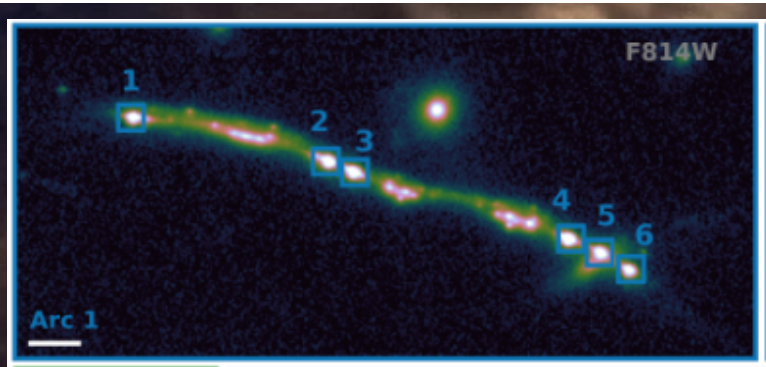
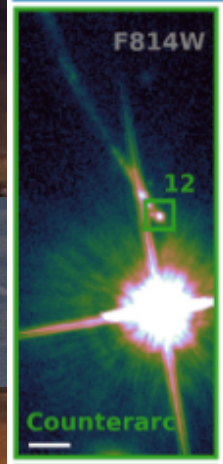
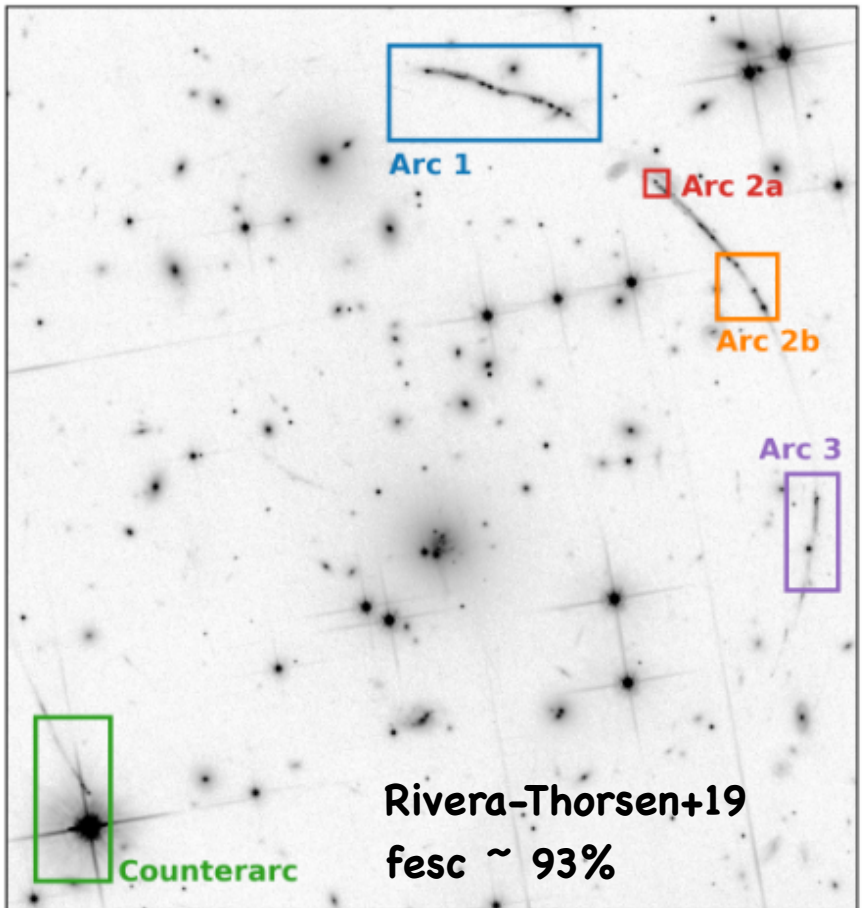
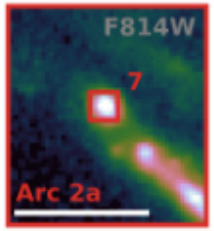
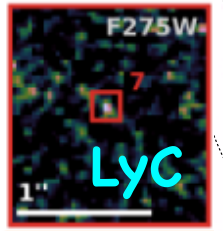
Superlensed (and bright) systems

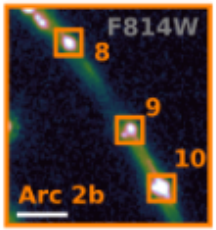


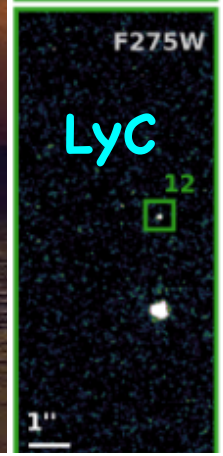


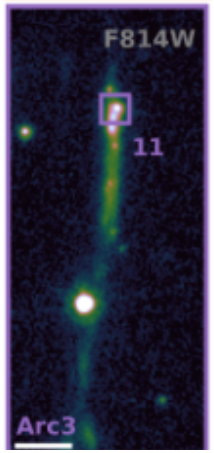




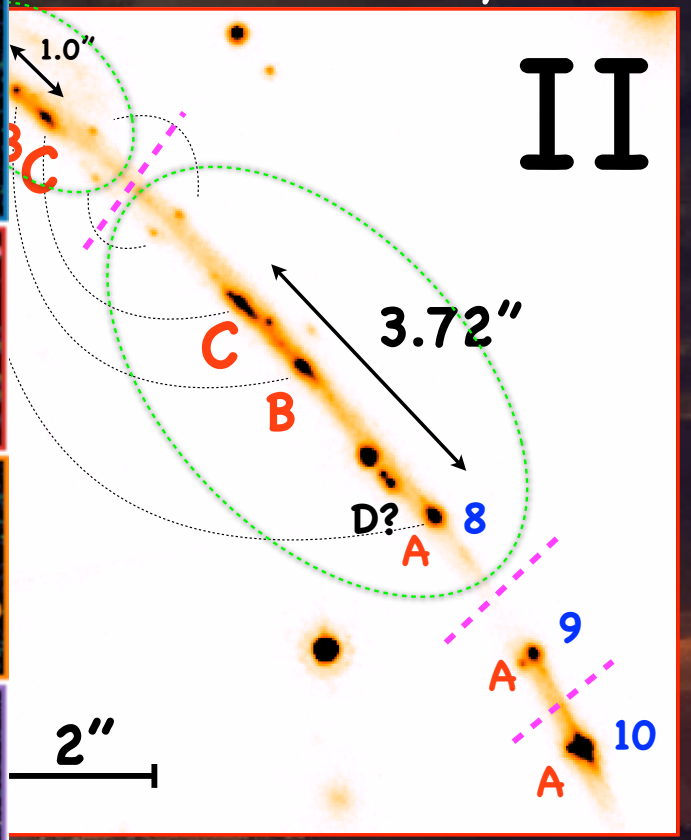


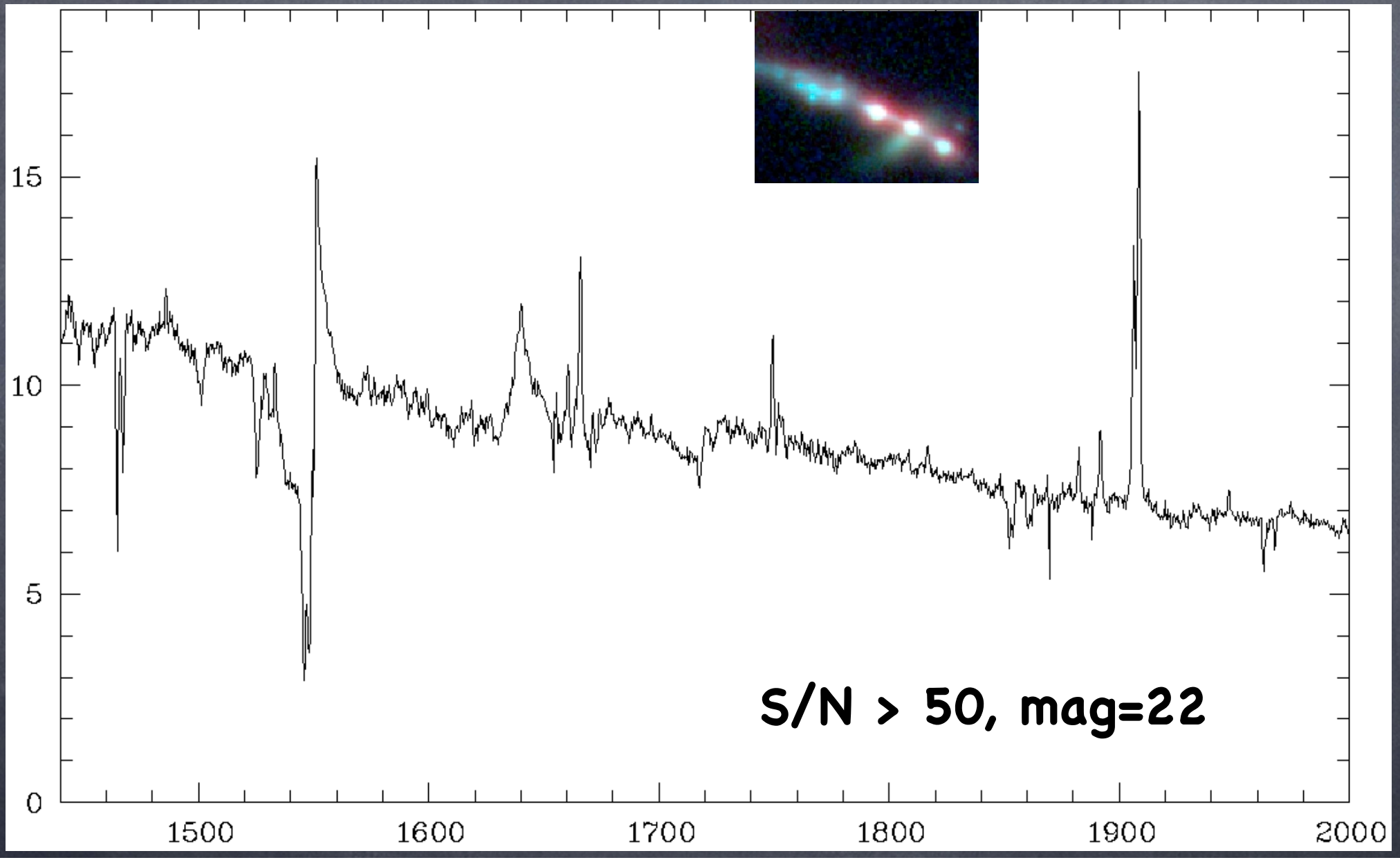


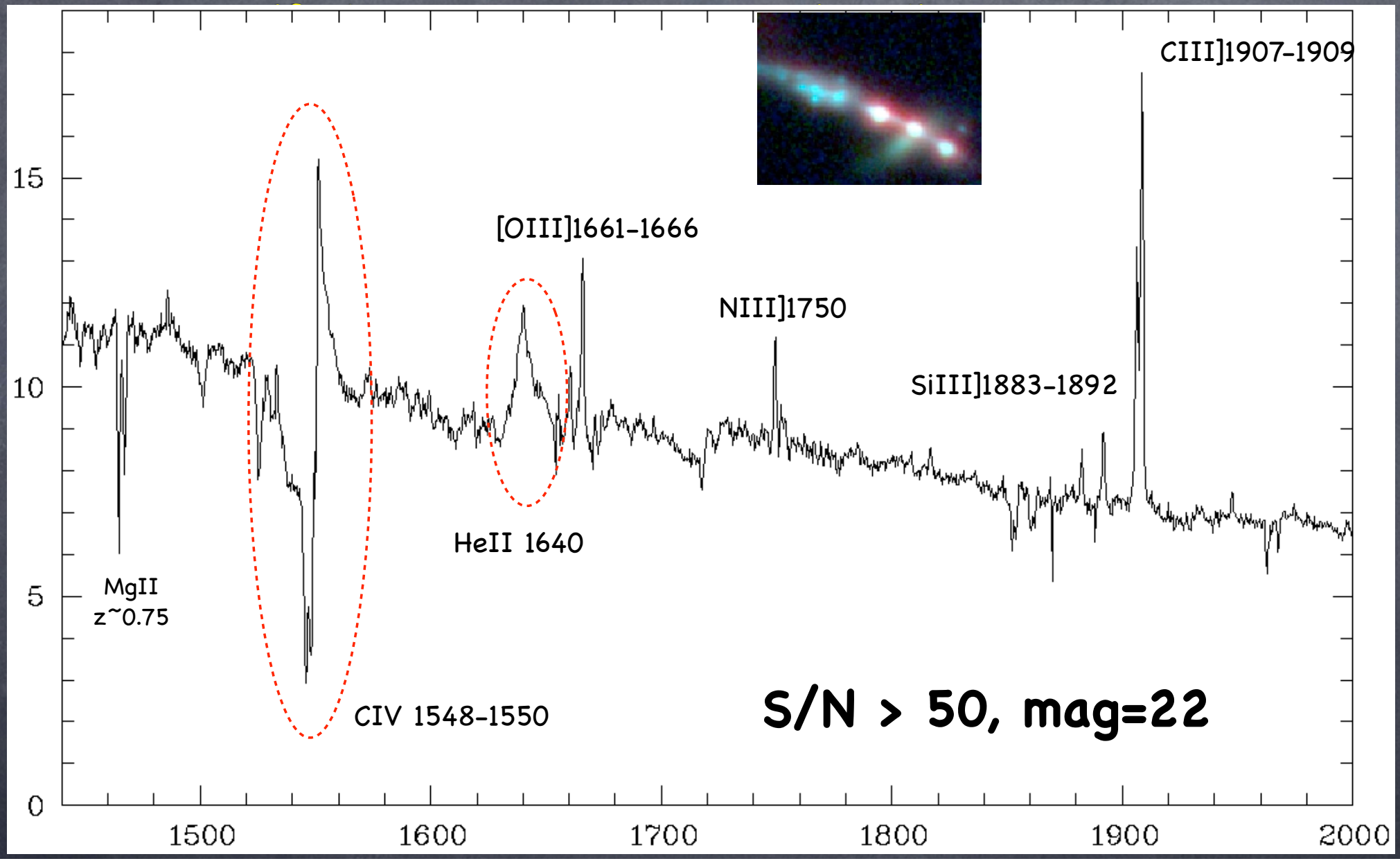




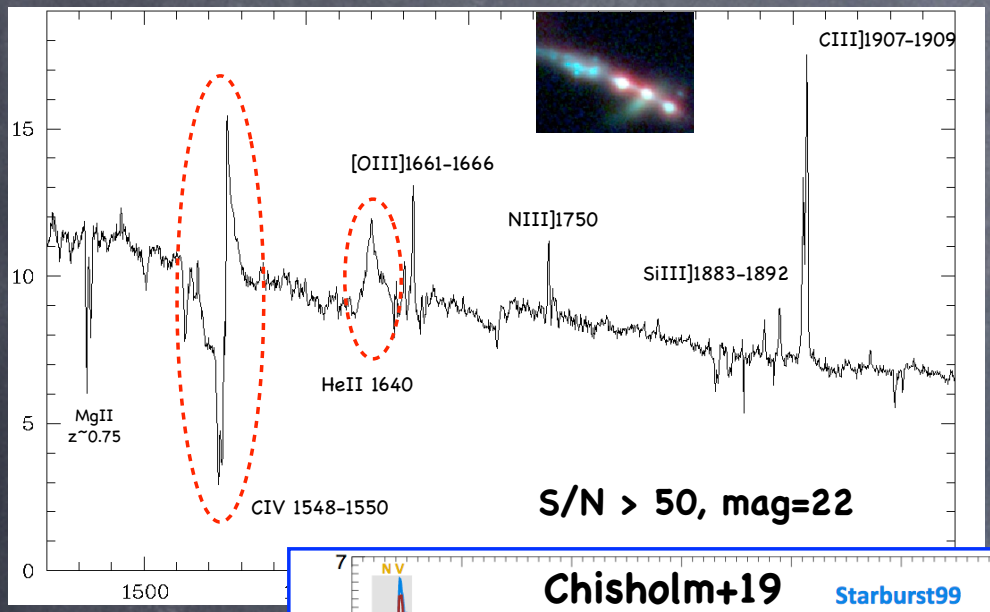
Sunburst, z=2.37

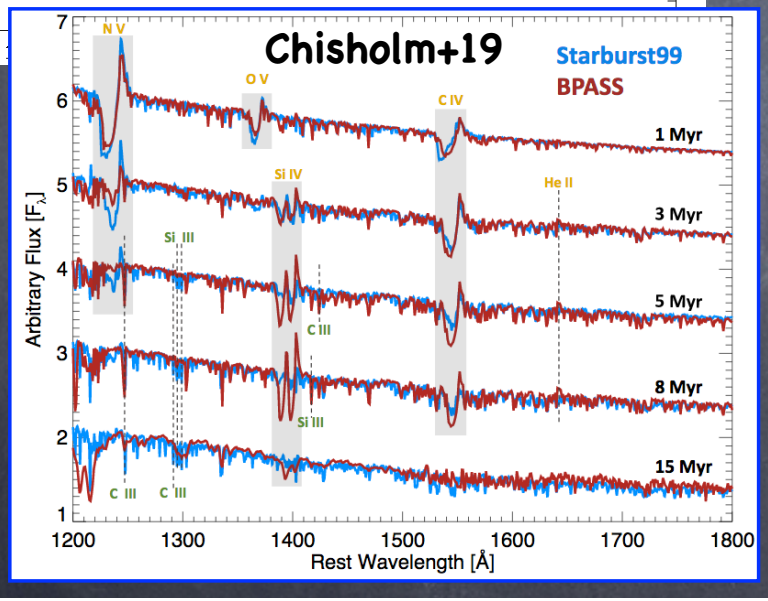


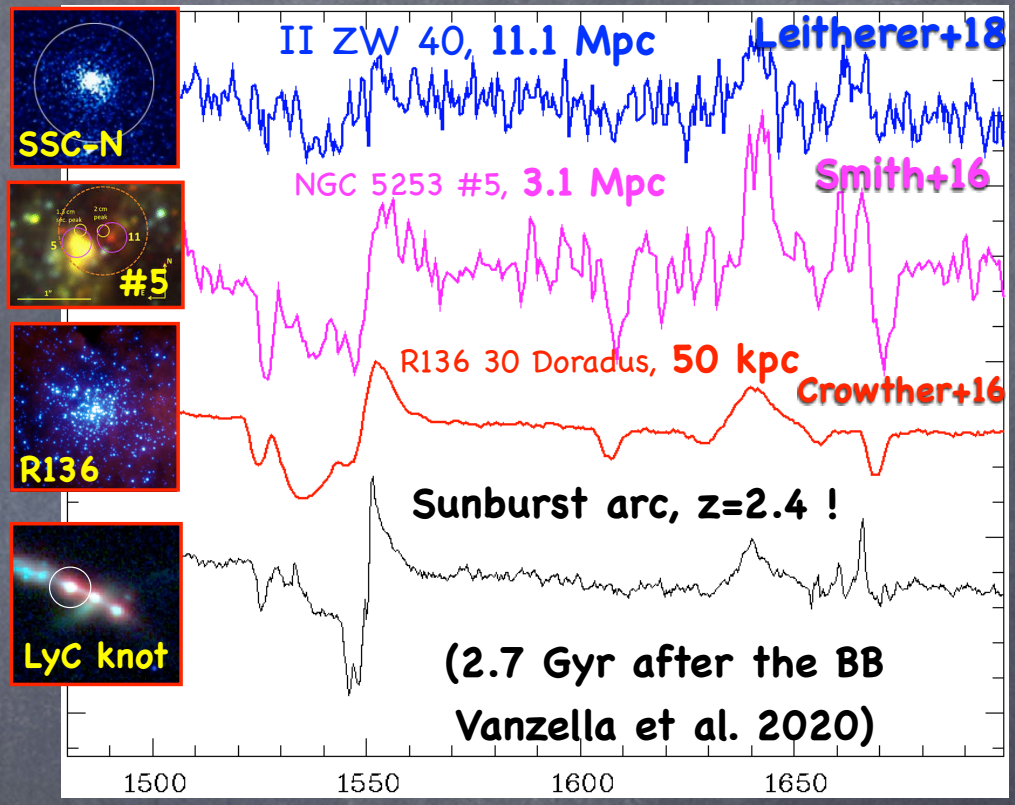

15
10
5
0
1500
1600
1700
1800
1900
2000
S/N > 50, mag=22


CIII]1907-1909
[OIII]1661-1666
NIII]1750
SiIII]1883-1892
HeII 1640
MgII
z~0.75
CIV 1548-1550
S/N > 50, mag=22
15
10
5
0
1500
1600
1700
1800
1900
2000

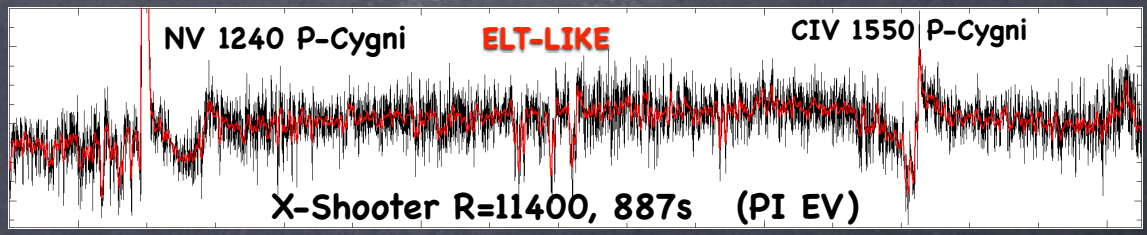
A super-magnified star cluster at cosmological distance: Sunburst arc



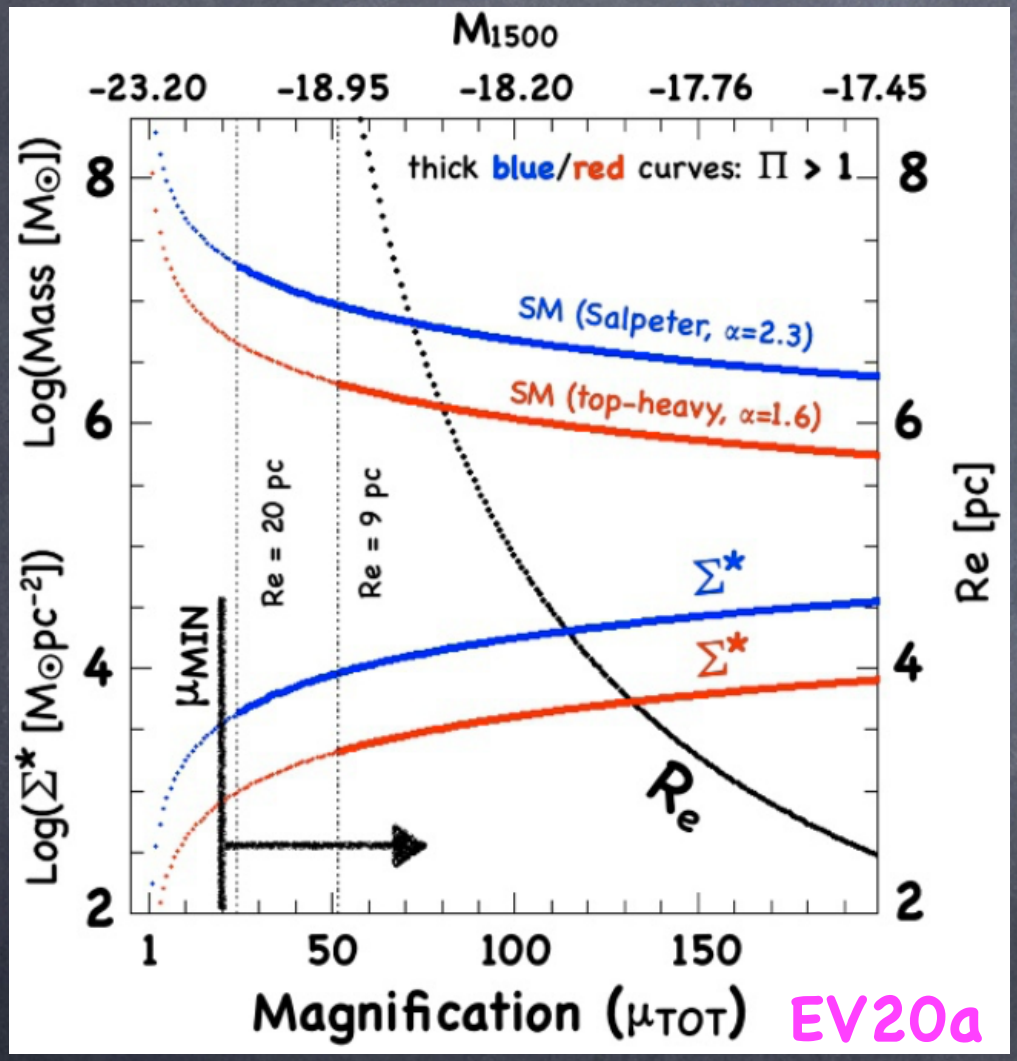




Age: 2.9 ± 0.1 Myr ; Z = 0.5 Zsun (Chisholm+19)



The first grav. bound YMC at high-z leaking LyC



Age: 2.9+/- 0.1 Myr ; Z: 0.5 Zsun — Chisholm+19

Stellar mass: a few 10^6 Msun [< 3e7 Msun]

Reff: 5-10 pc [< 20 pc]

Stellar Mass surf. density: (5-10)x10^3 Msun pc^{-2}

Σ_{SFR} > 1000 Msun/yr/kpc2

Gravitationally bound ? YES? — EV20a

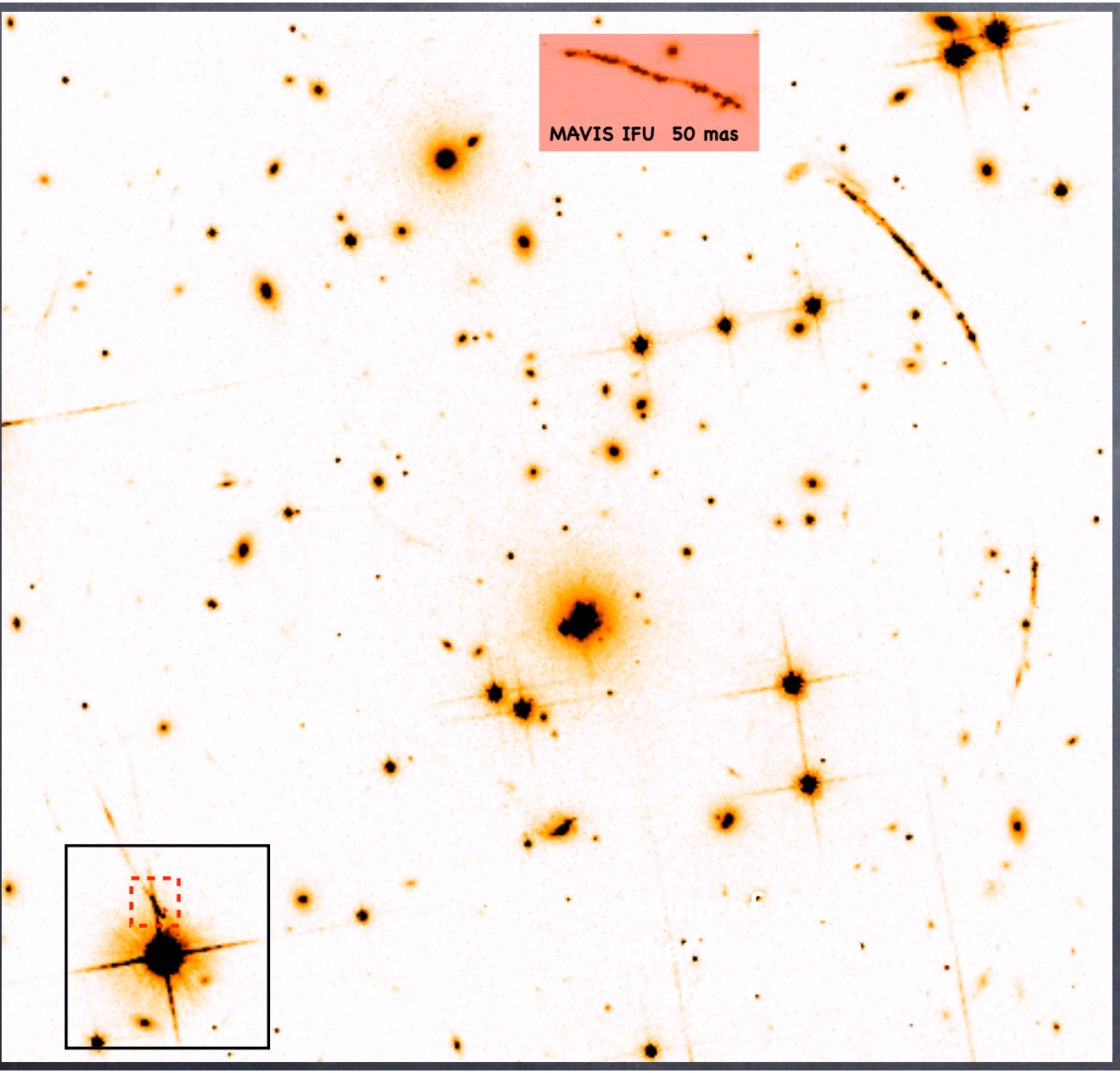
LyC emission ? YES, fesc~93% — Rivera-Thorsen+19

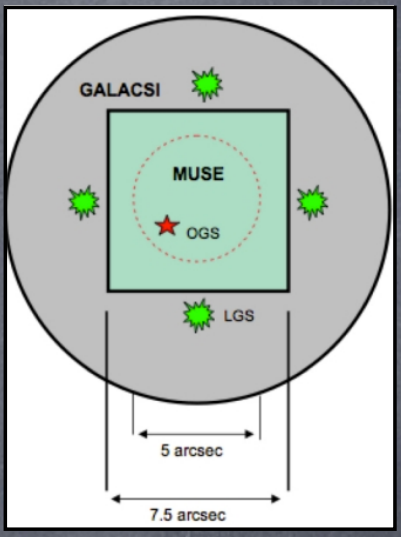
→ fesc(hosting galaxy) ~ 10-20% EV in prep.

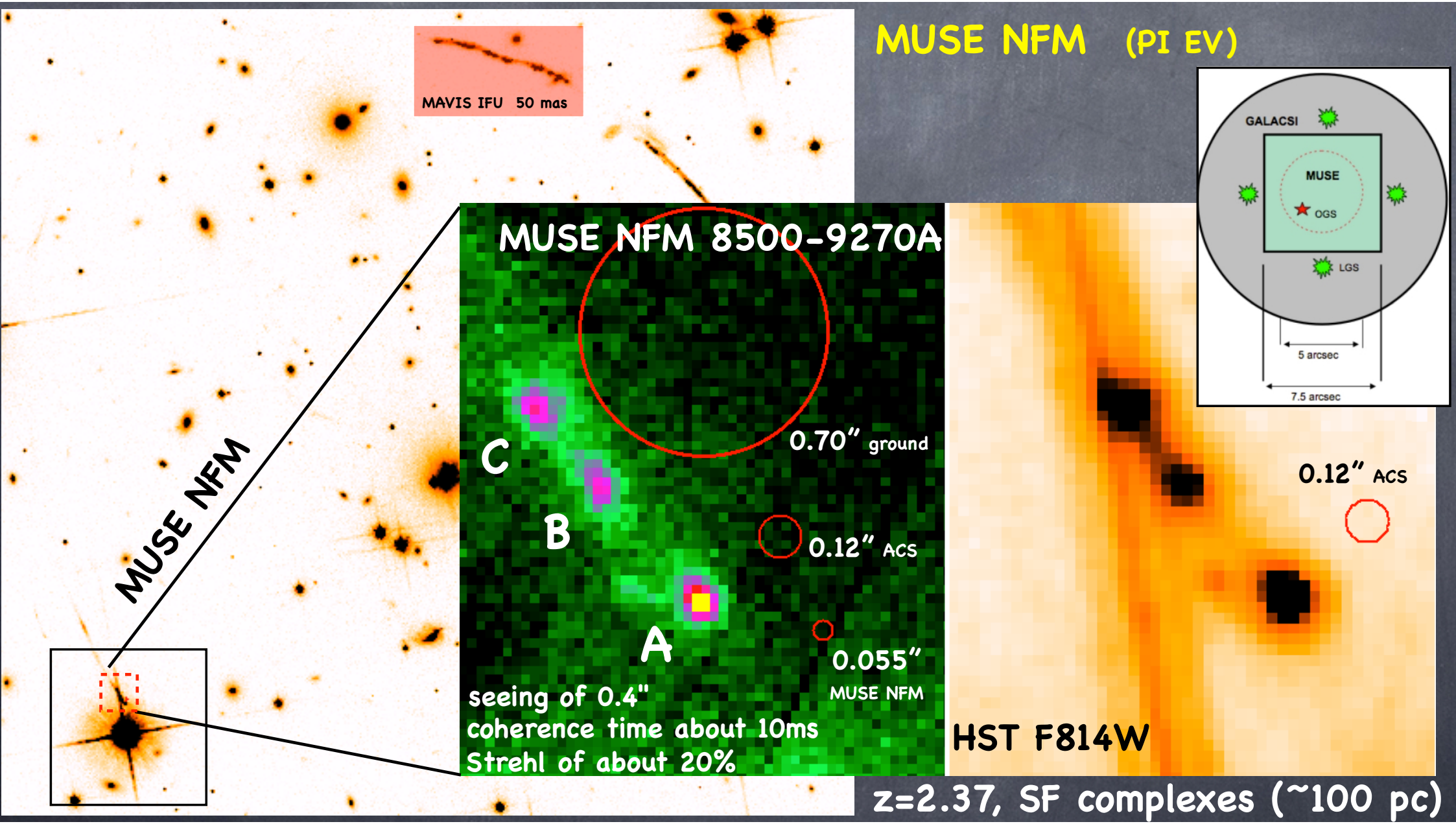
Is it a GCP ? (z=2.37, 2.7 Gyrs after the BB)

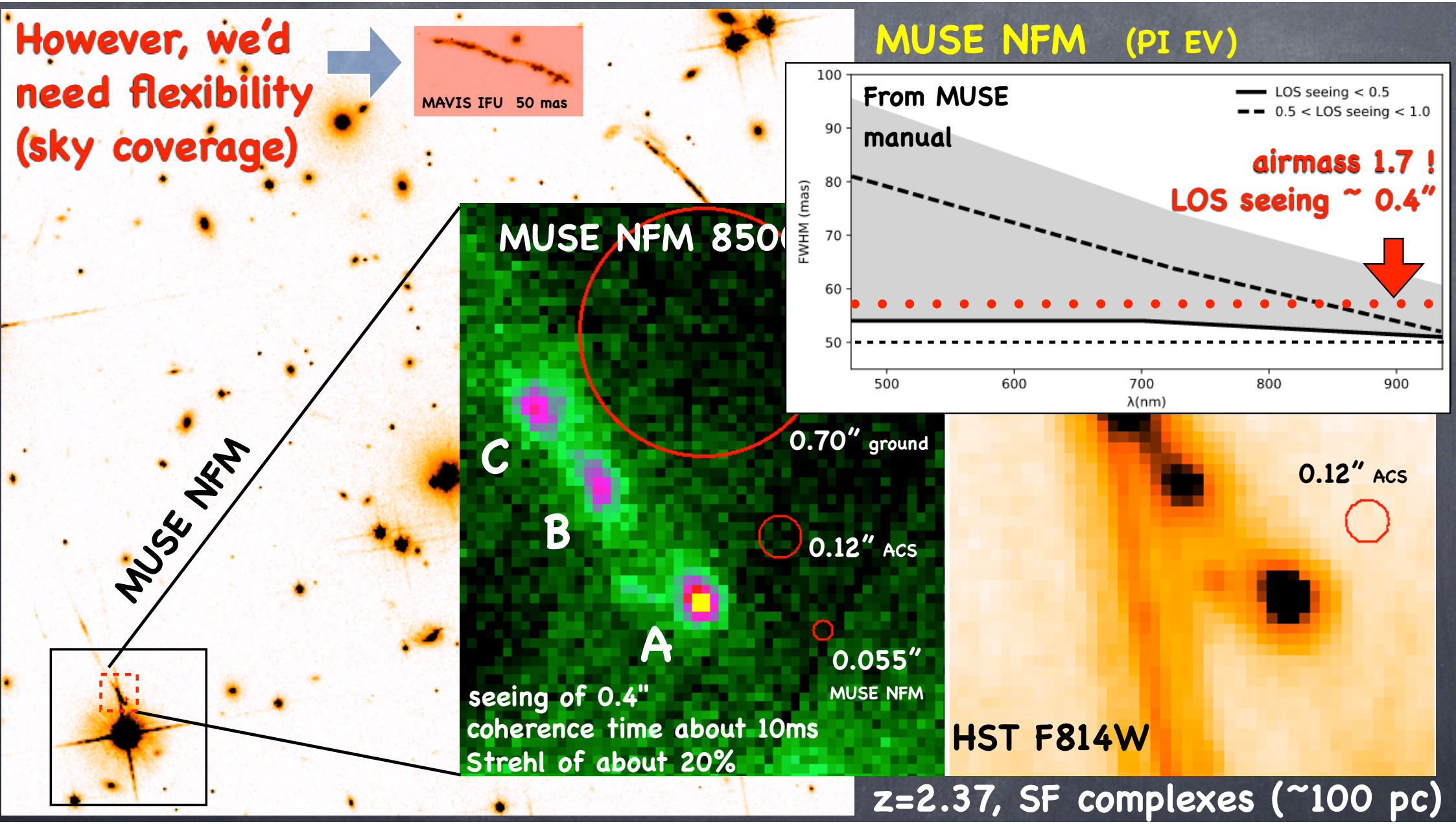
What's next ?? (AO ...)

MUSE NFM (PI EV)



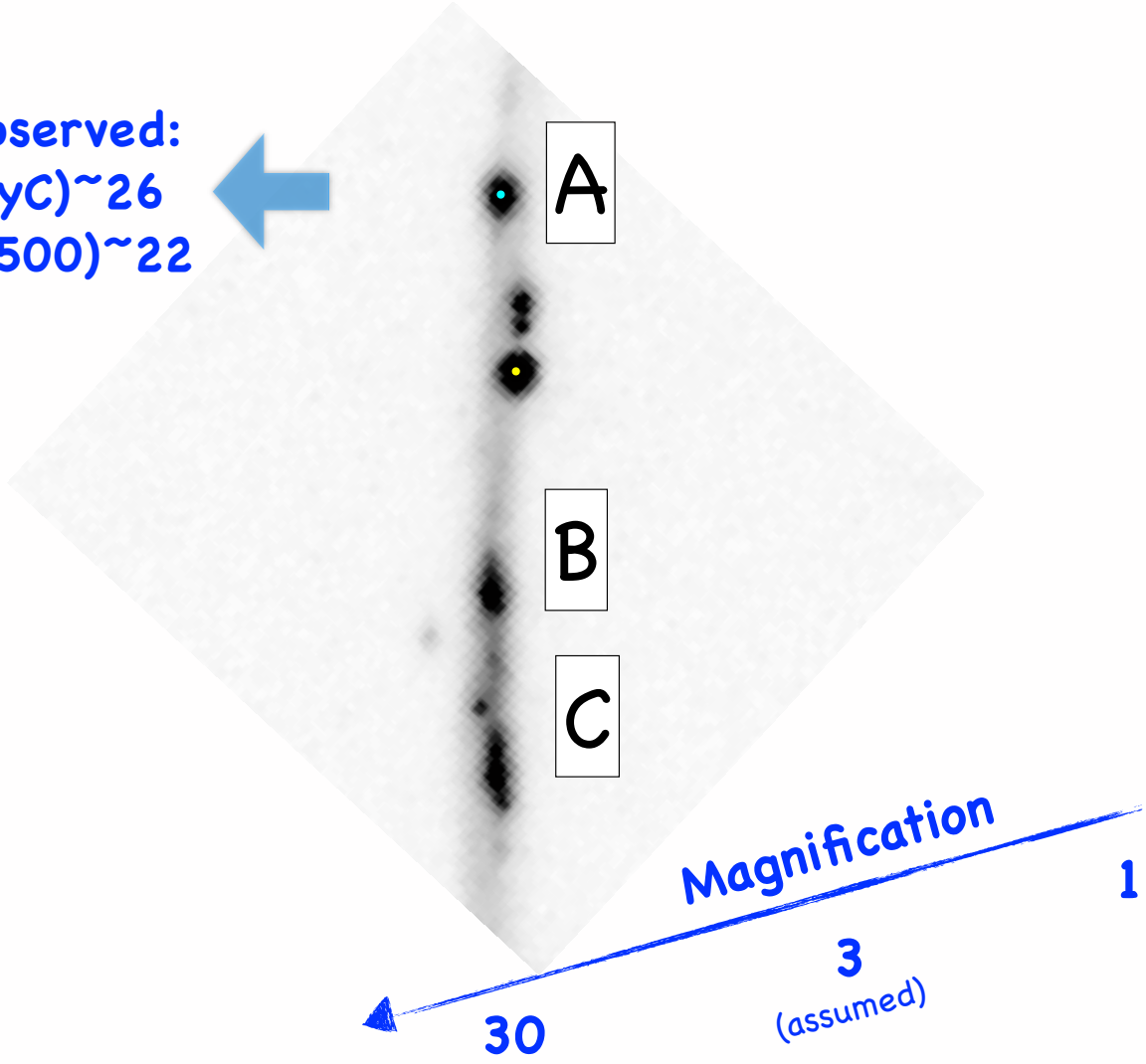



MUSE NFM (PI EV)
MAVIS IFU 50 mas
MUSE NFM
MUSE NFM 8500-9270A
C
B
A
0.70" ground
0.12" ACS
0.055"
MUSE NFM
seeing of 0.4"
coherence time about 10ms
Strehl of about 20%
GALACSI
MUSE
OGS
LGS
5 arcsec
7.5 arcsec
0.12" ACS
HST F814W
z=2.37, SF complexes (~100 pc)


However, we'd need flexibility (sky coverage)
MAVIS IFU 50 mas
MUSE NFM
MUSE NFM 850
C
B
A
0.70" ground
0.12" ACS
0.055" MUSE NFM
seeing of 0.4"
coherence time about 10ms
Strehl of about 20%
MUSE NFM (PI EV)
From MUSE
manual
LOS seeing < 0.5
0.5 < LOS seeing < 1.0
airmass 1.7 !
LOS seeing ~ 0.4"
FWHM (mas)
λ(nm)
0.12" ACS
HST F814W
z=2.37, SF complexes (~100 pc)

Ionization by a massive star cluster;
HST+Sunburst outperforms E-ELT in the field

"A" observed:
- m(LyC)~26
- m(1500)~22



Ionization by a massive star cluster;
HST+Sunburst outperforms E-ELT in the field

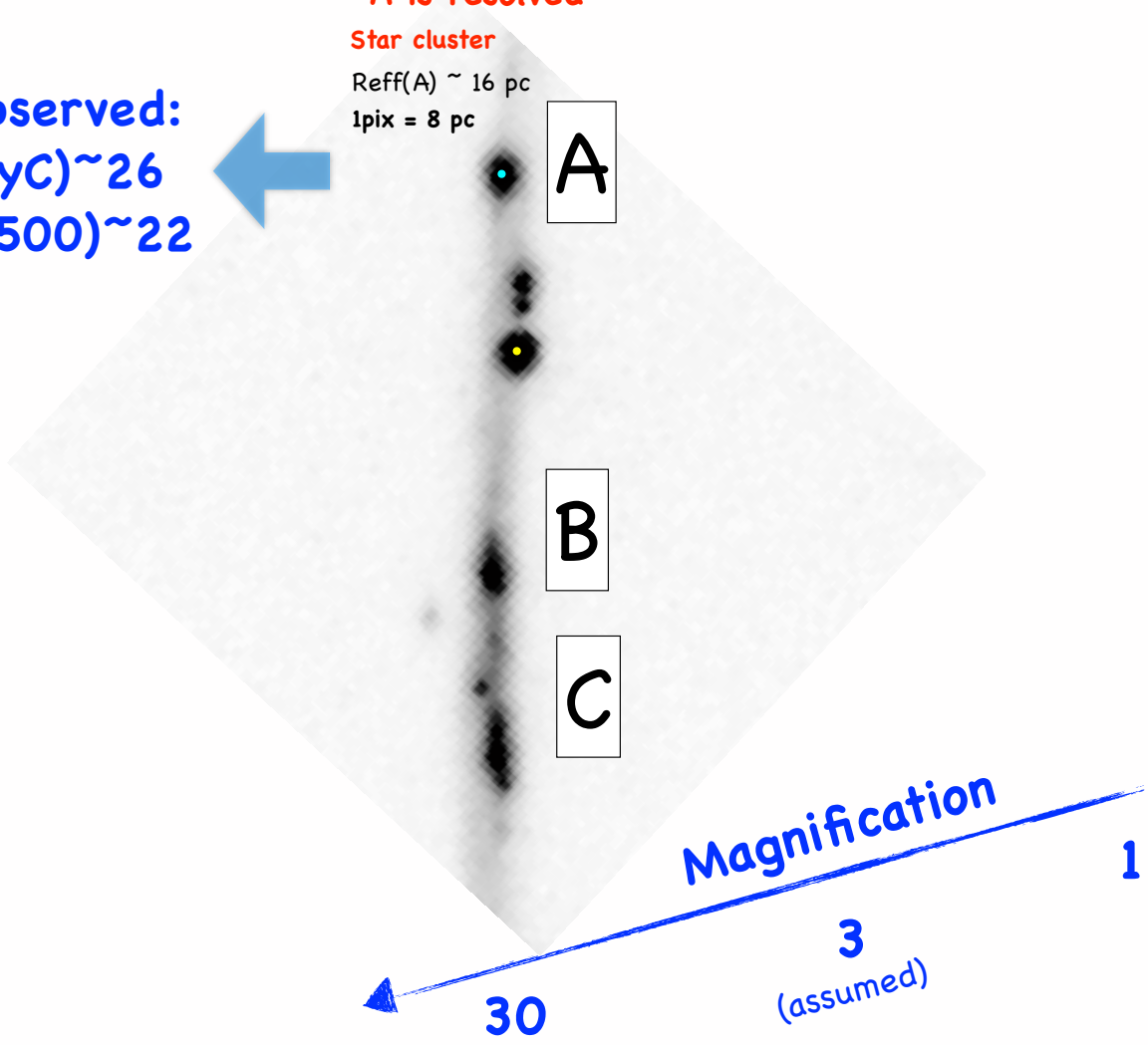
"A is resolved"

Star cluster

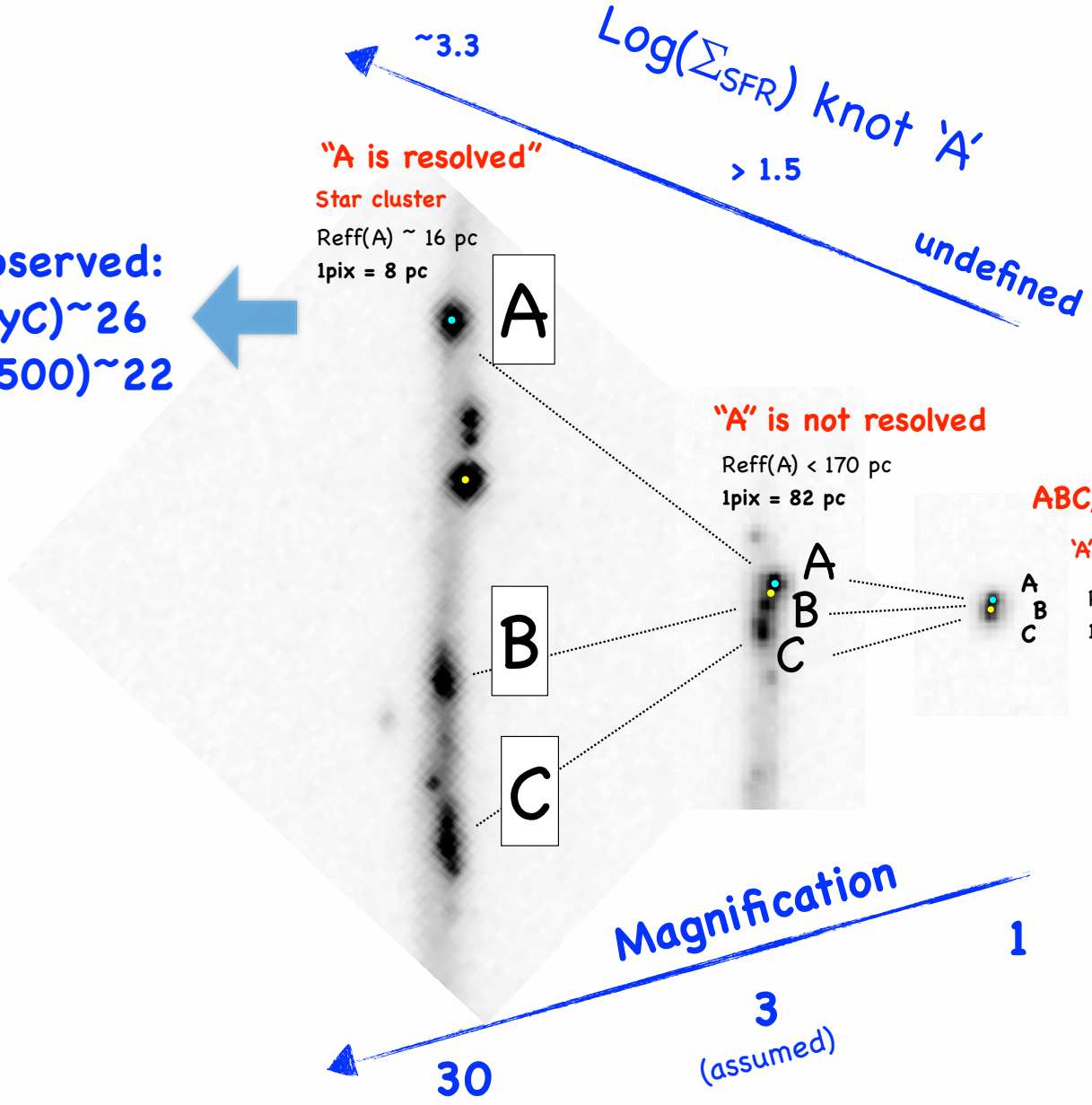
Reff(A) ~ 16 pc

1pix = 8 pc

"A" observed:
- m(LyC)~26
- m(1500)~22



Ionization by a massive star cluster; HST+Sunburst outperforms E-ELT in the field

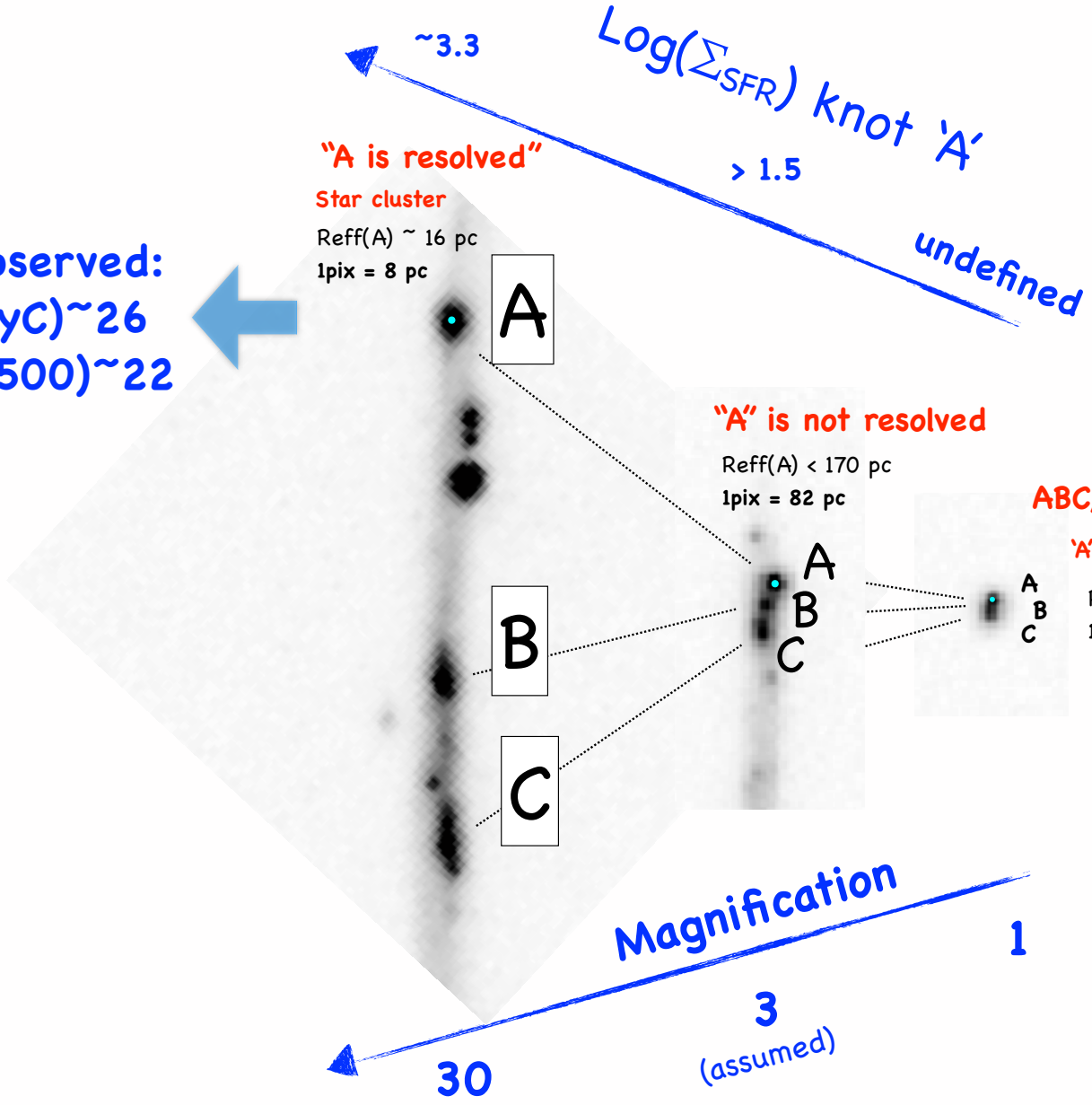


"A" observed:
- m(LyC)~26
- m(1500)~22

No Lensing (HST)
- m(LyC)>30
- m(1500)~26
- "A" unresolved

Lyman continuum
fesc(A)~93%
fesc(blob)~10-20%

Ionization by a massive star cluster; HST+Sunburst outperforms E-ELT in the field



"A" observed:
- m(LyC)~26
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No Lensing (HST)
- m(LyC)>30
- m(1500)~26
- "A" unresolved

Lyman continuum
fesc(A)~93%
fesc(blob)~10-20%

Future: AO+SL will provide super-resolution

MAORY+MICADO

mag =22

?

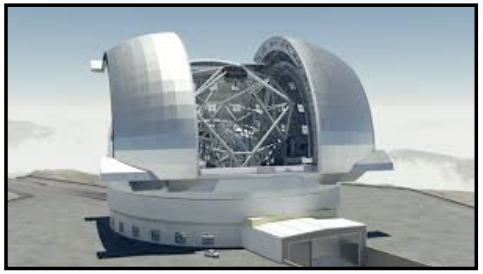
1pix ~ 1 pc (equivalent to **0.2** mas!)

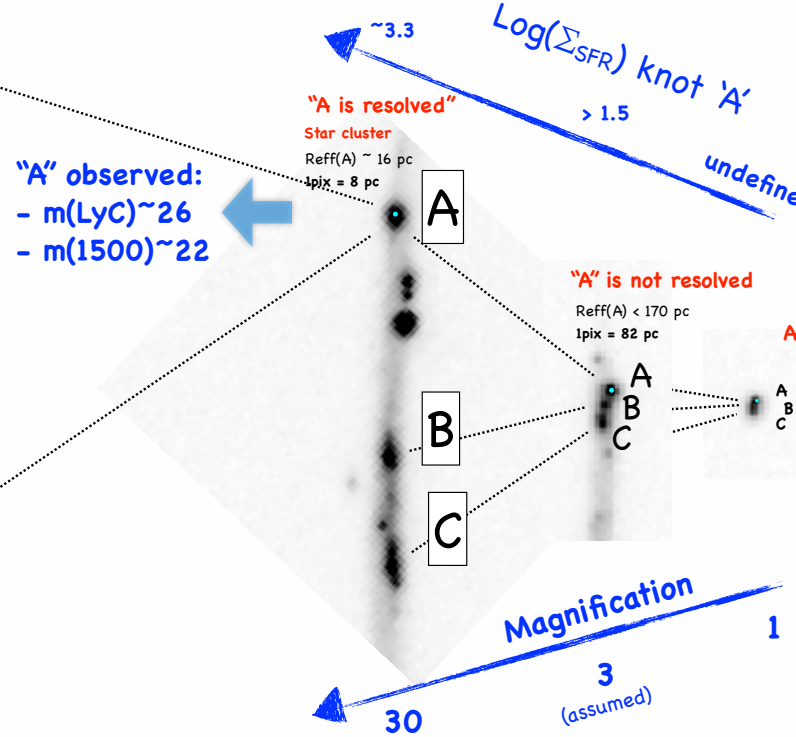
S/N > 30 in 5-10 minutes !

Thanks to Matteo on-the-fly calculations

HARMONI 2d map, dynamical mass, UV lines

MAVIS will complement ELT in the optical





Ionization by a massive star cluster; HST+Sunburst outperforms E-ELT in the field

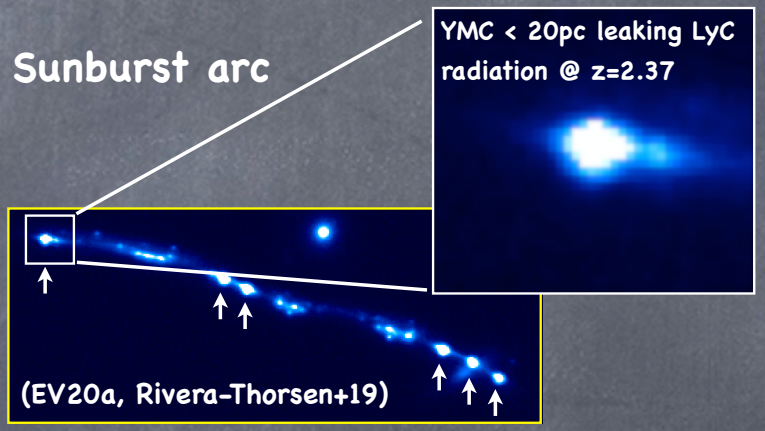
No Lensing (HST)

- m(LyC)>30
- m(1500)~26
- "A" unresolved

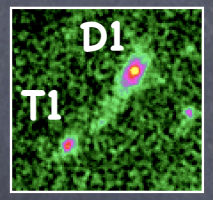
Lyman continuum
fesc(A)~93%
fesc(blob)~10-20%

Take home message: ``unpacking" high-z galaxies along cosmic epochs

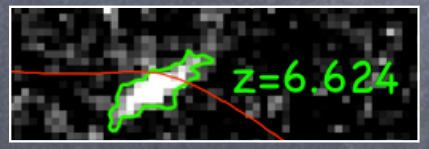
Is reionization driven by massive and hot stars mainly embedded in forming YMCs that might represent a significant fraction of the SF mode at high-z ? How GC formation enters in this game ? feedback, carving ionized channels ?



- MUSE IFU (WFM/NFM) + Strong Lensing + HST:
  preview of the AO science **(MAVIS or ELT)** doable without lensing;
  - produces key targets for extreme AO;
  - start thinking about pc-scale SF complexity at high-z;



Reff<13pc, z=6.145
(EV19)



HST-dark MUSE objs, m>35
extreme SPs ? PopIII ?
(EV+20b)

- AO facilities (e.g., MAVIS, MAORY-MICADO, HARMONI ...) coupled with strong lensing
  will "**routinely**" identify star clusters at high-z, isolating those grav. bounded (proto-GC);
  - The same facilities on superlensed systems will probe 1pc at z>3 (like 0.2mas if no lensing, e.g., "Sunburst);
  - Exotic (?) sources will be recognized as well (e.g., laser action, transients, CSM ?) ...