Negative and Positive AGN feedback

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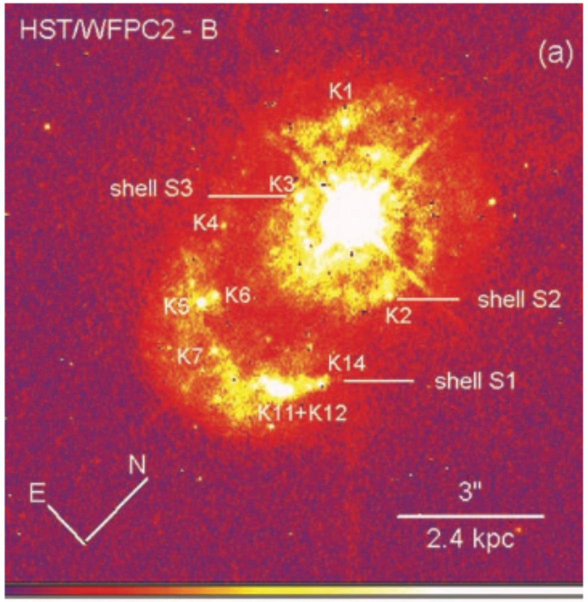
C. Cicone,

AGN-driven outflows & jets invoked to suppress star formation in galaxies

- Gas removal
- Preventing gas accretion ("starvation")

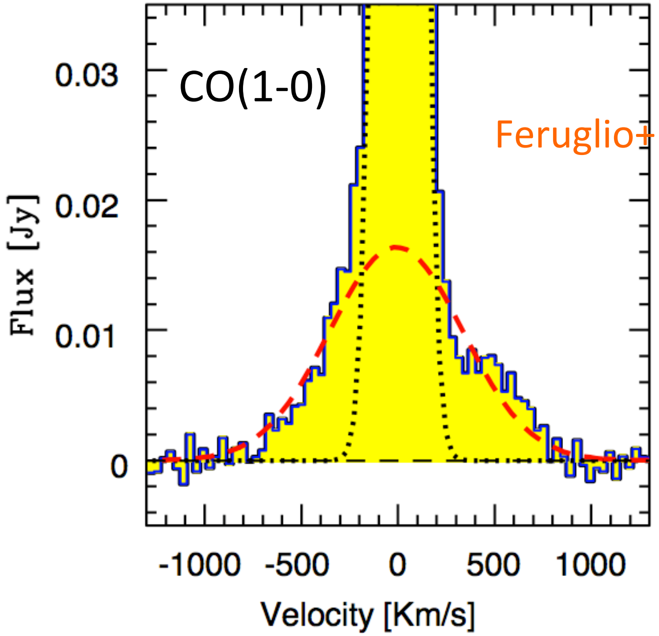
Observational evidences of massive, quasar-driven outflows

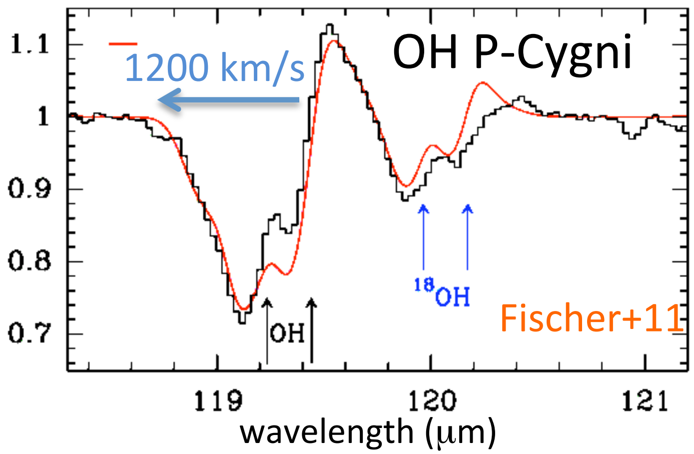
Ionized outflows



Lipari+09

Key discovery of **cold molecular outflows** (generally carrying most of the mass)

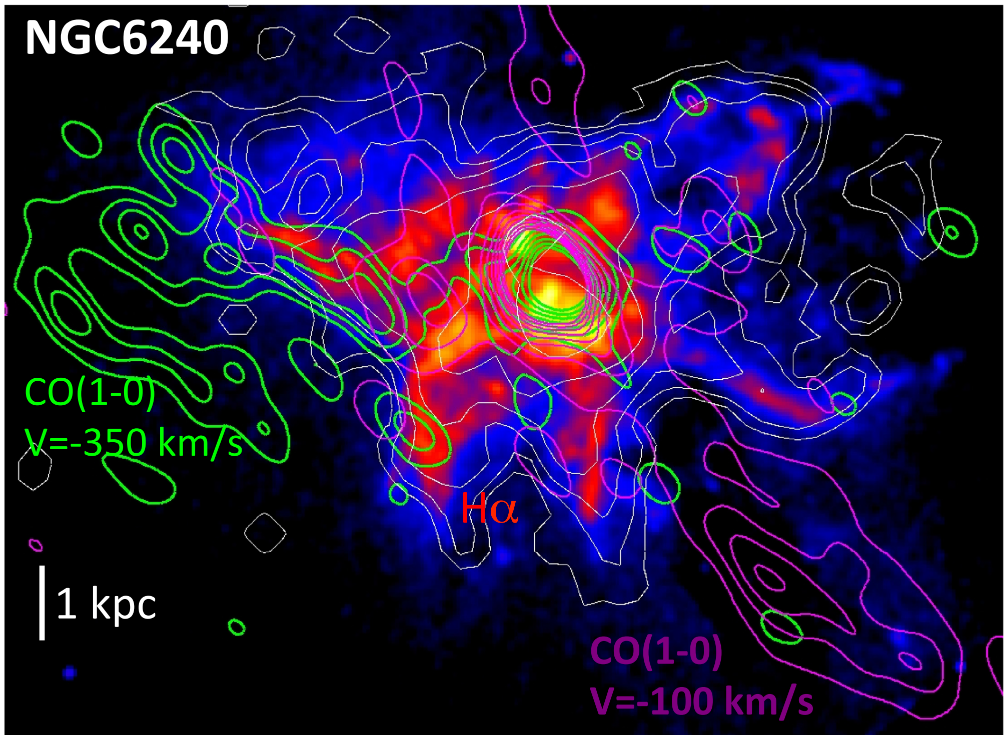




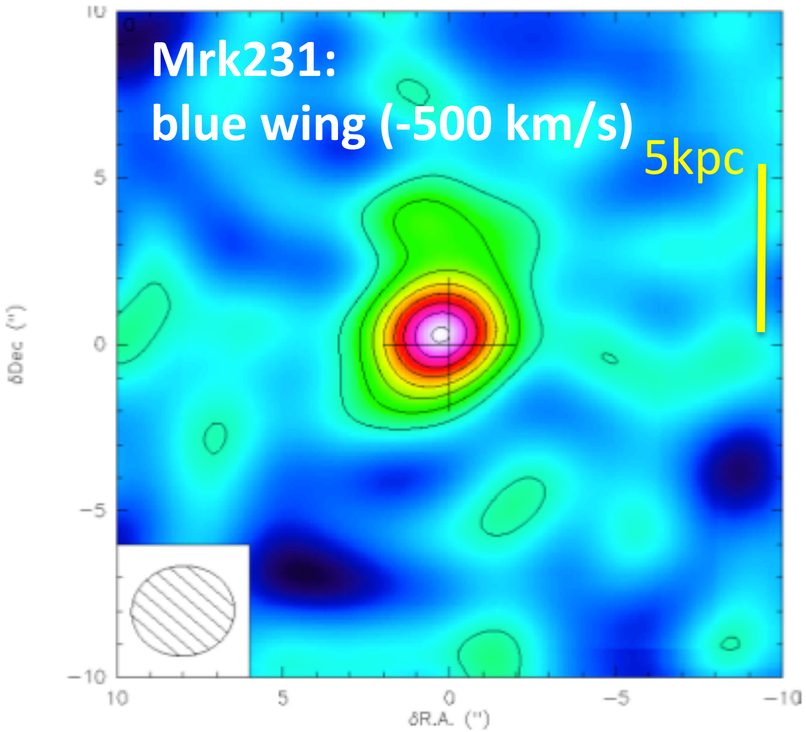
Fischer+10, Sturm+11
Gonzalez-Alfonso+14,17
Feruglio+10,13,15
Aalto+11,15
Cicone+13,14
Gracia-Burillo+15
Veilleux+13
Combes+14
Sakamoto+14

Clear evidence that such fast and massive quasar-driven molecular outflows can seriously "hurt" their host galaxies

Extended on kpc scales
Outflow rates as high as ~1000 $M_{\odot}$/yr
Potentially "depletion" times scales as short as ~ 10 Myr

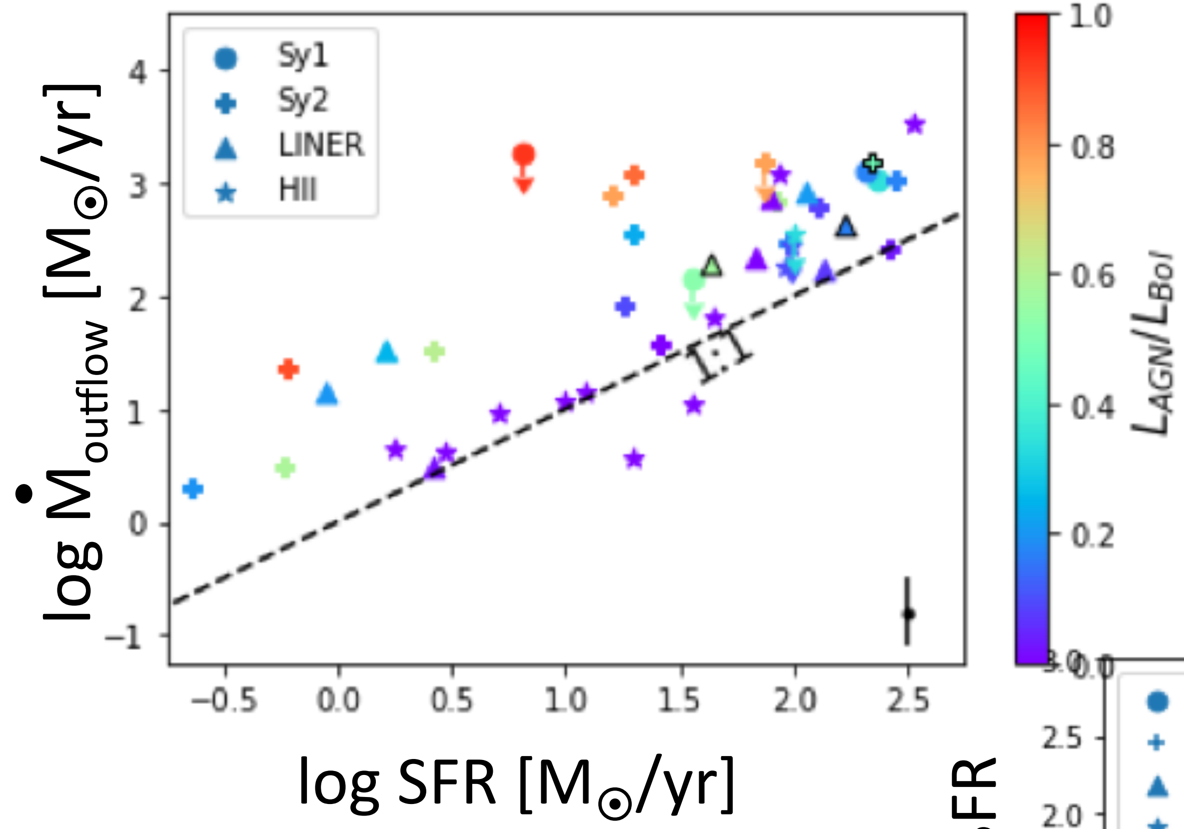


Feruglio+13



Feruglio+10

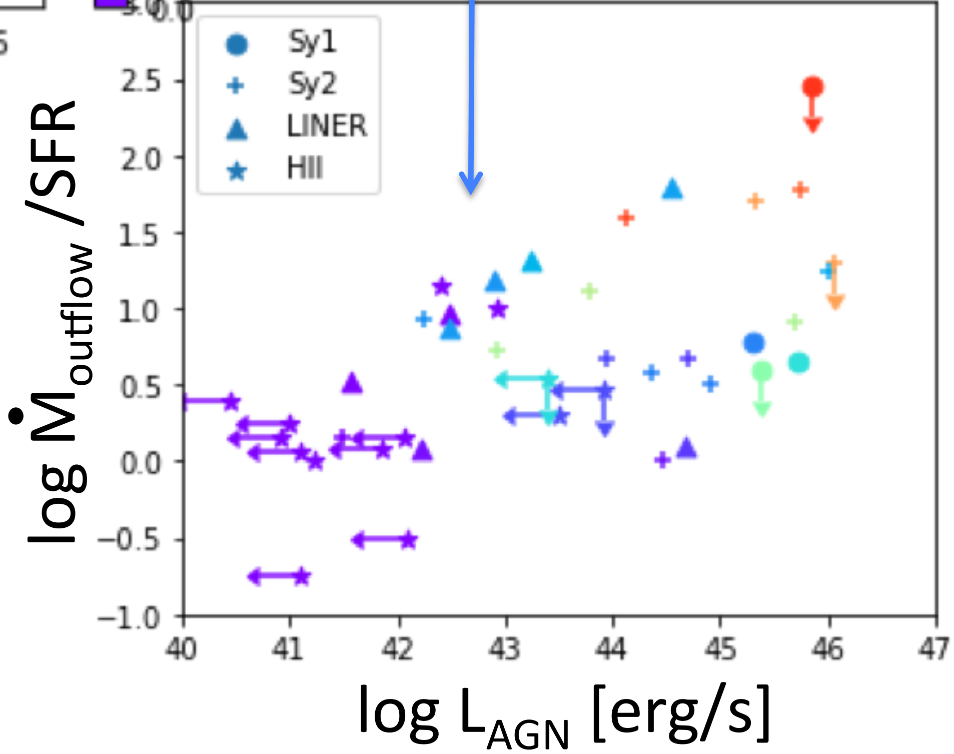
AGNs can boost the outflow rate by a large factor



Also powerful outflows in weak AGNs... remnants of past activity? King+14

~40 galaxies with spatially resolved (CO) molecular outflows

outflow “loading factor”

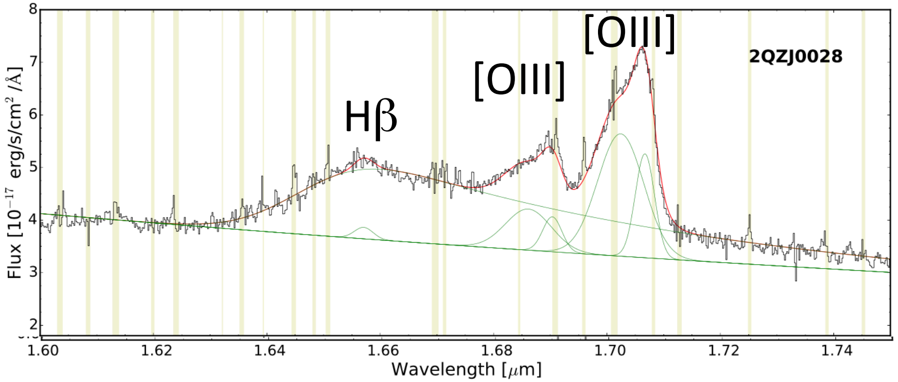


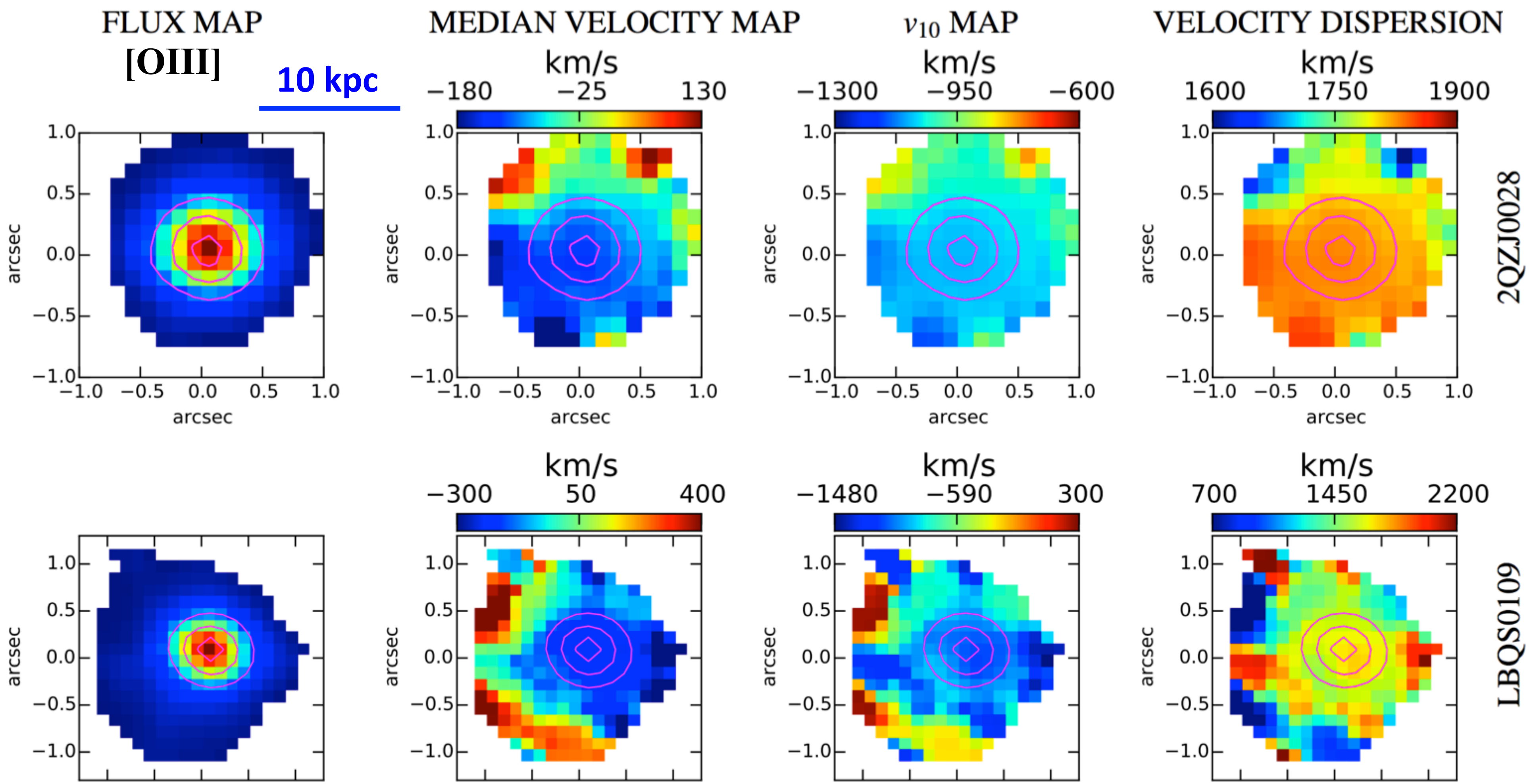
Flutsch+17
Cicone+14

At high-z quasar-driven outflows primarily traced in the ionized phase

Carniani+15,16, Brusa+15
Cresci+15, Harrison+16, ...

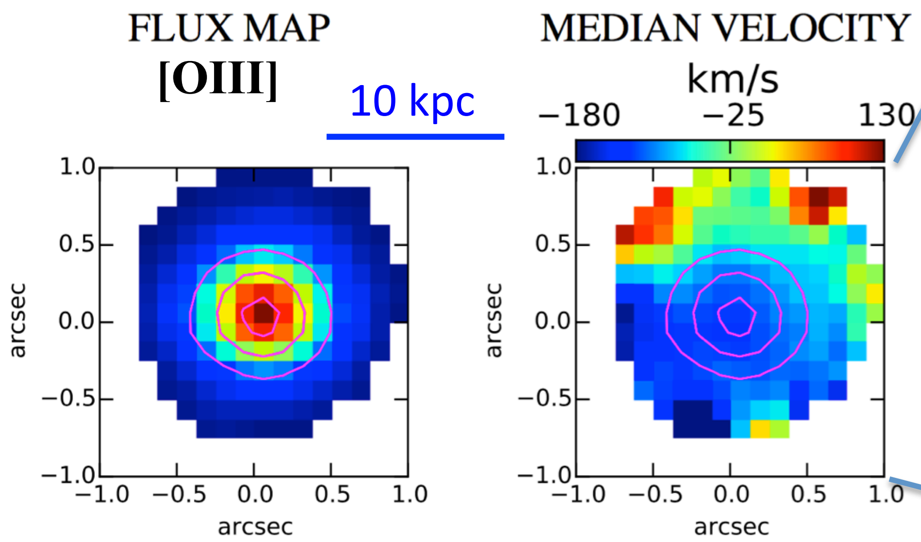
z = 2.3

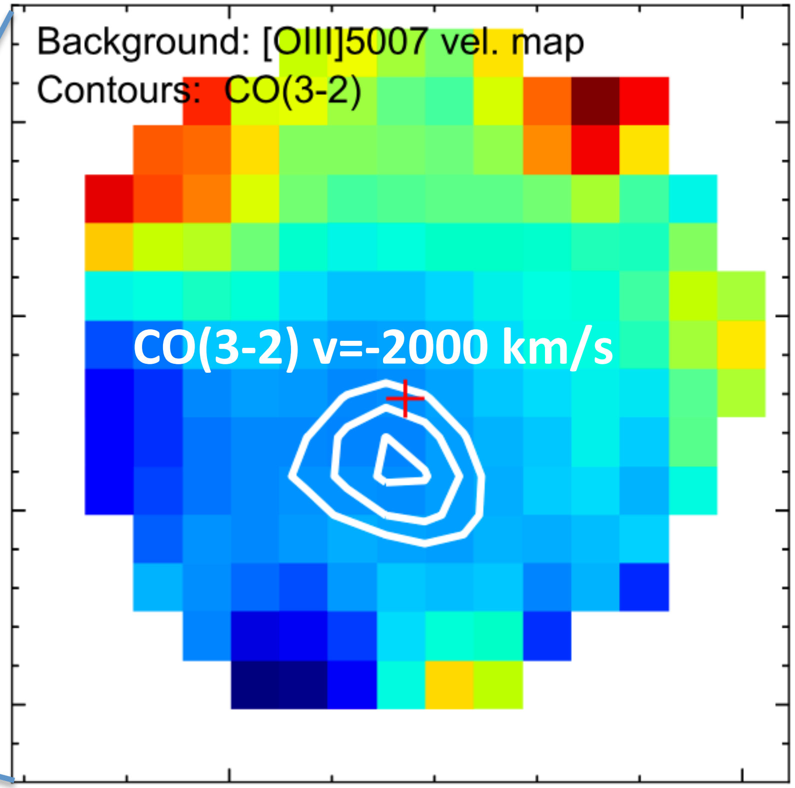


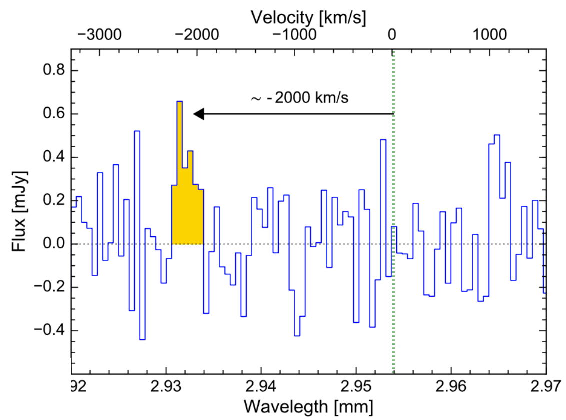


The detection of molecular outflows at high-z is still very difficult (the rising T_{CMB} does not help)

z = 2.3





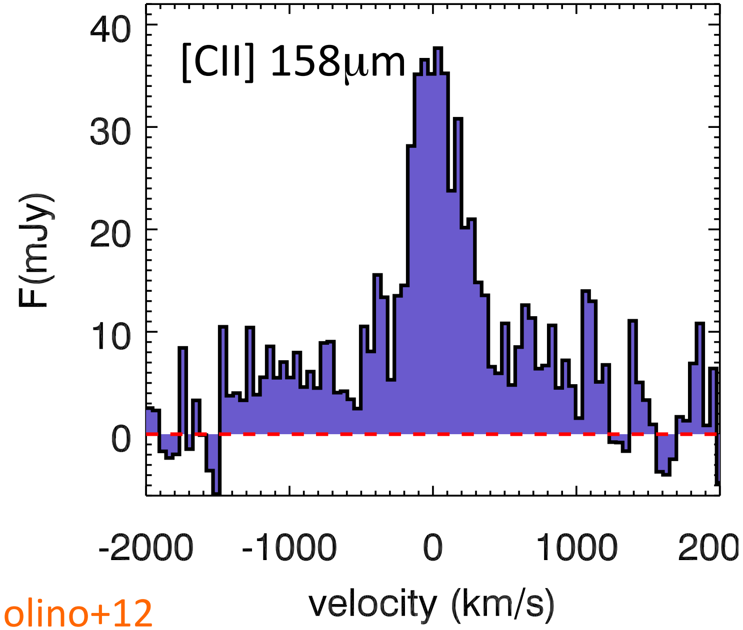


CO(3-2) @ z=3.2
v=-2000 km/s

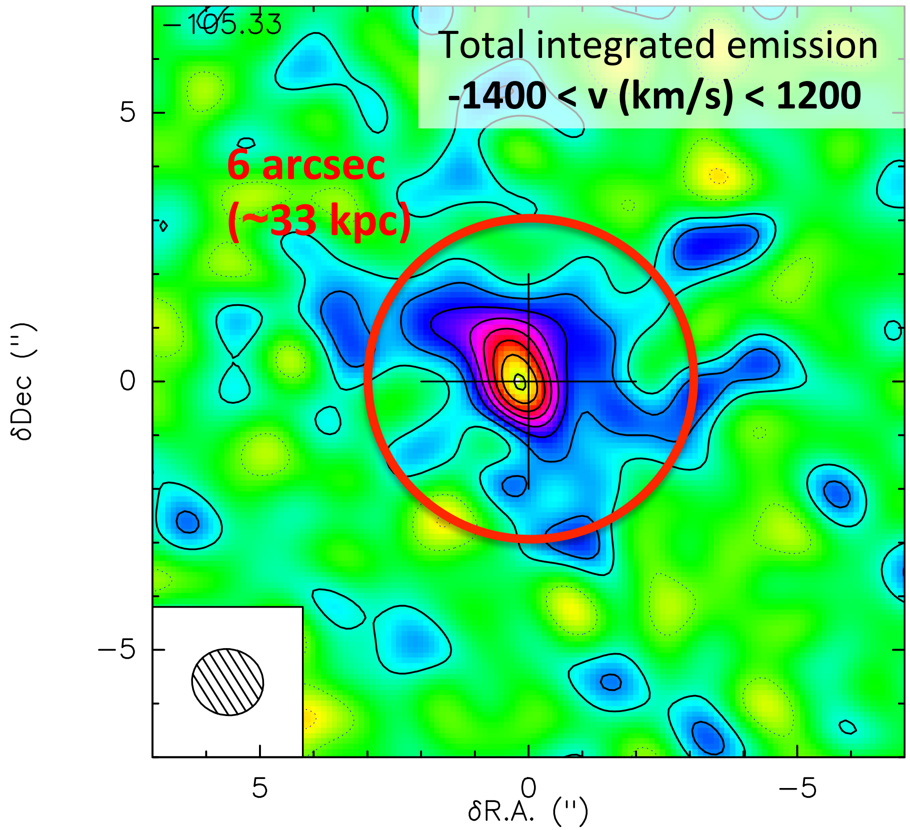
Carniani+17

Even more extreme quasar-driven outflows at high-z

Quasar at z=6.4



Maiolino+12
Cicone+15



Cold gas expelled with velocities in excess of 1,000 km/s!

Outflow rate ~1,500 Msun/yr (comparable to SFR ~1,000 Msun/yr)

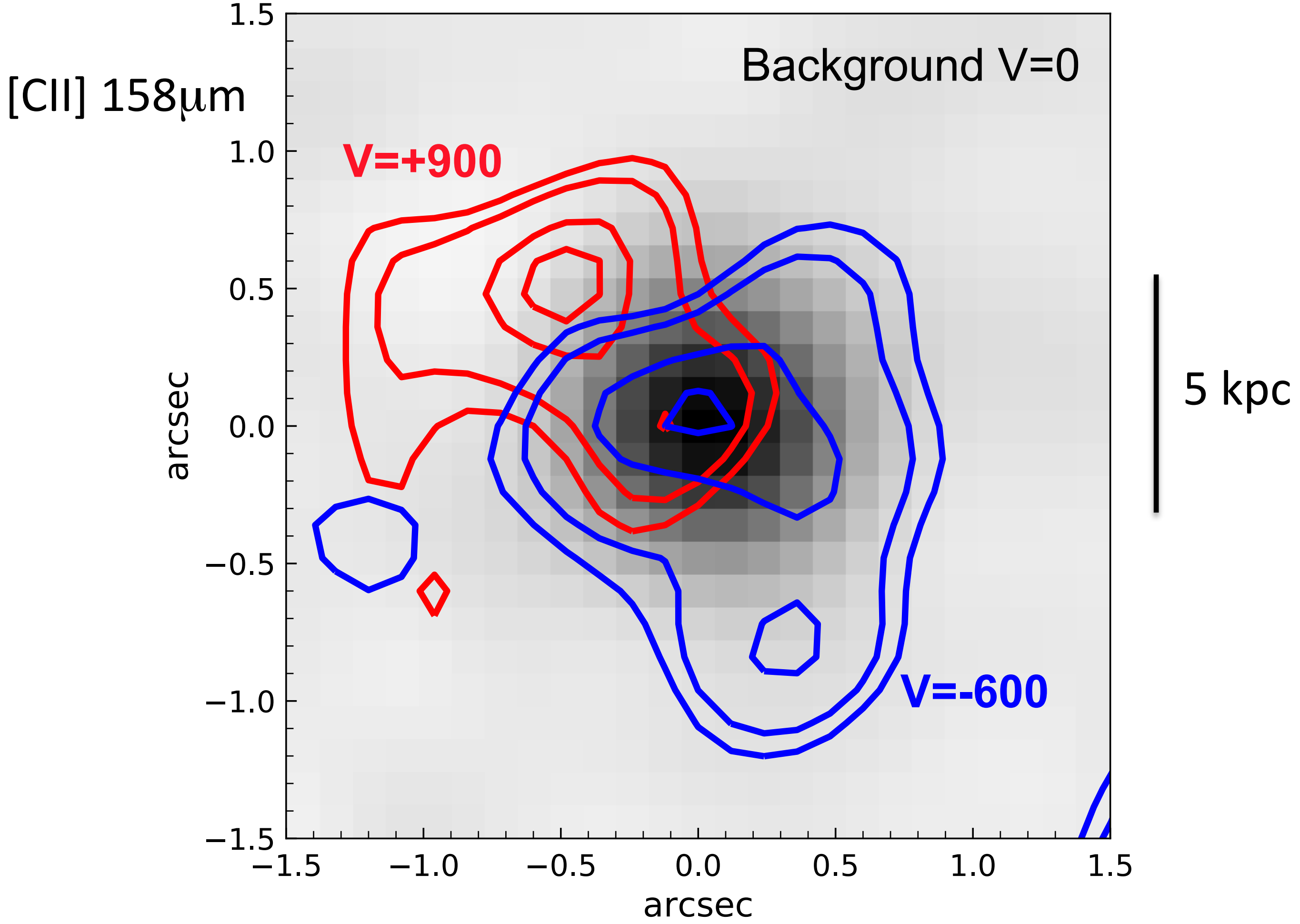
Can potentially clean the whole galaxy of its gas content in only ~10 Myr

Gas expelled out of the galaxy on scales of 30 kpc !

Even more extreme quasar-driven outflows at high-z

Quasar at z=6.03

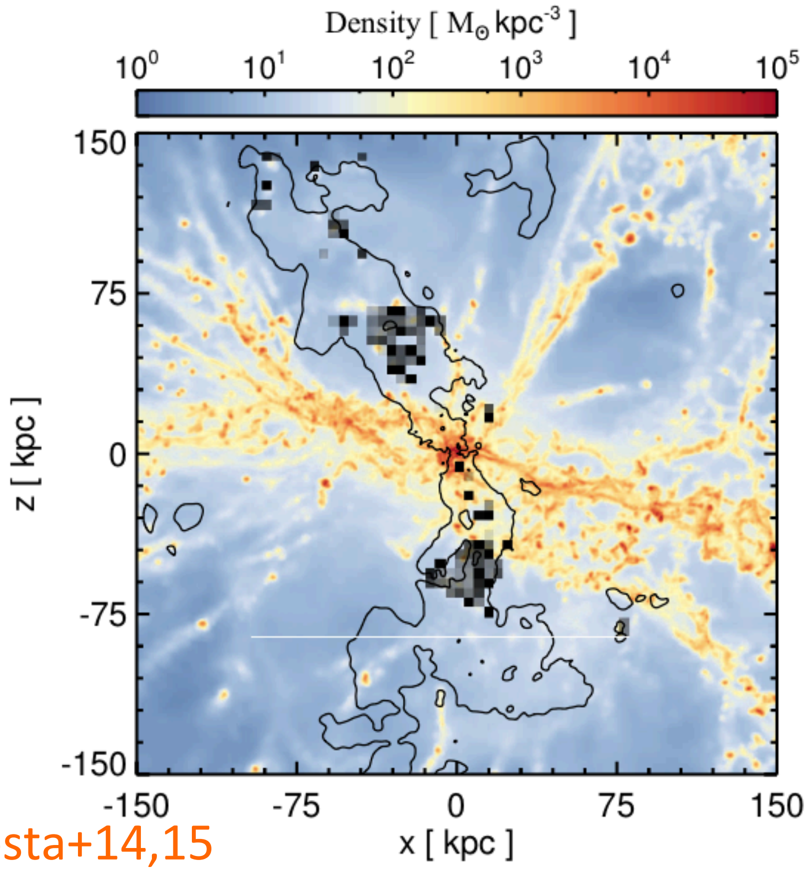
High velocity outflow on ~10-15kpc scales



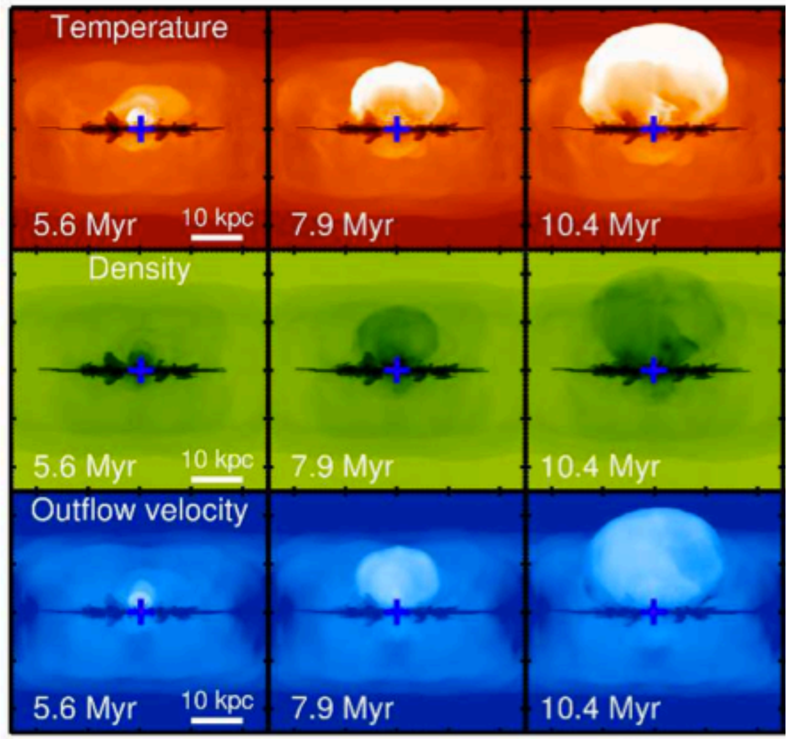
Outflow rate ~ 1000 Msun/yr

Carniani+ 2017

AGN-driven outflows and jets certainly damage their host galaxies… but can they really totally quench star formation?



Costa+14,15



Gabor+14, Roos+15

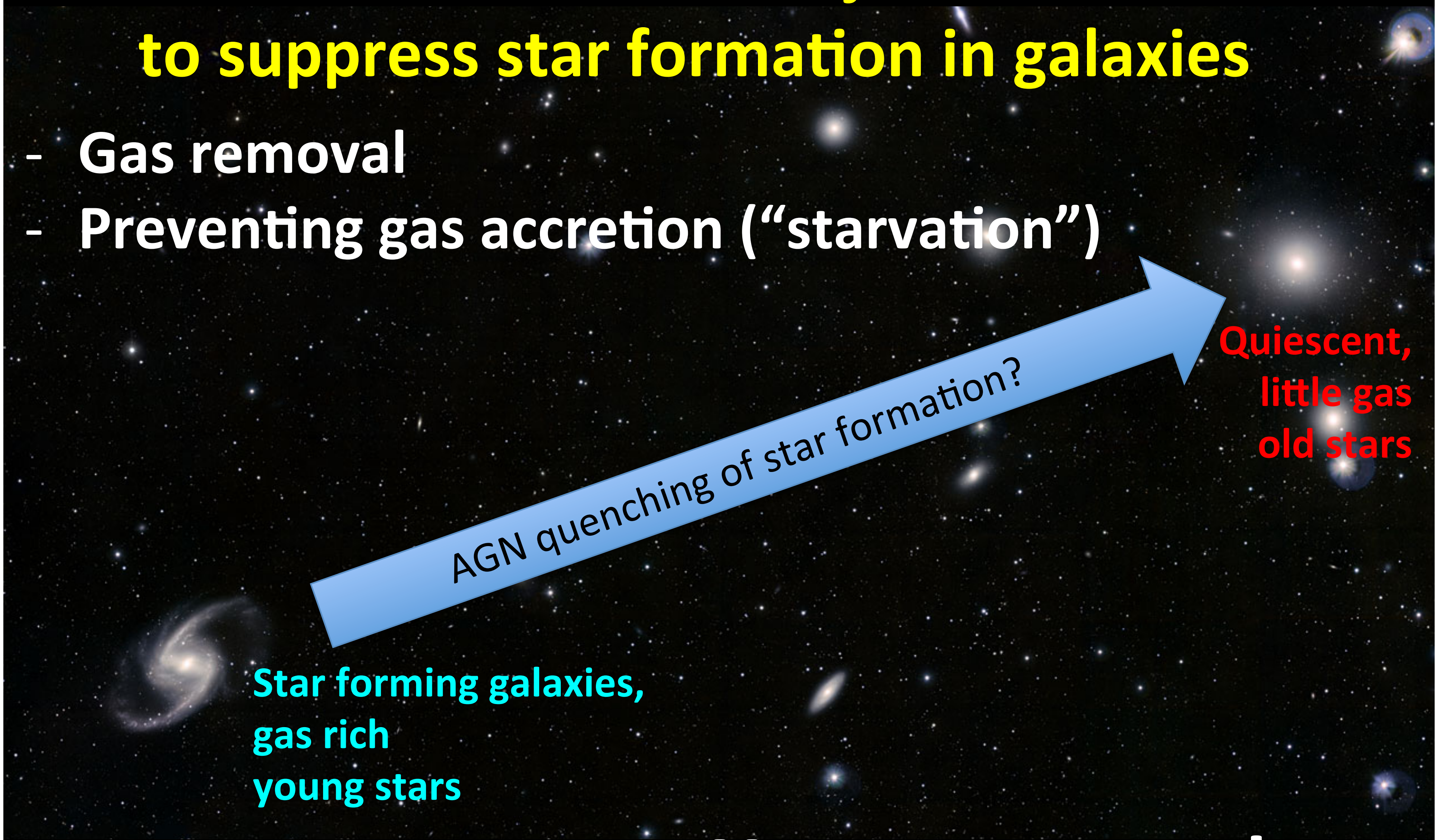
Outflowing gas mostly escapes through low density, least resistance regions

Possibly the primary role of outflows/jets is to prevent further gas accretion -> death by strangulation/starvation

Peng, Maiolino, Cocharne (2015, Nature)
Richard's talk

AGN-driven outflows & jets invoked to suppress star formation in galaxies

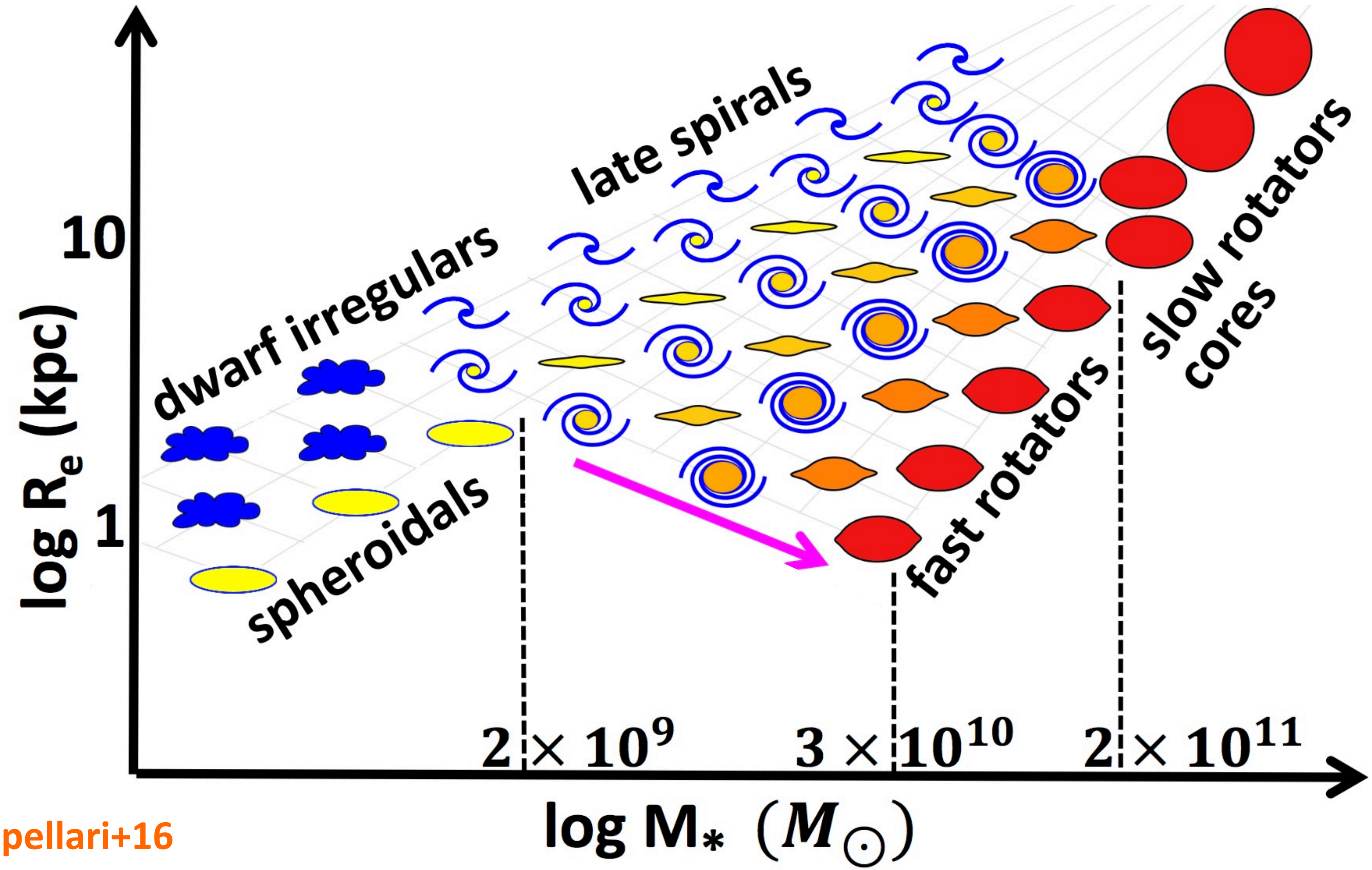
- Gas removal
- Preventing gas accretion ("starvation")



Yet, not enough...

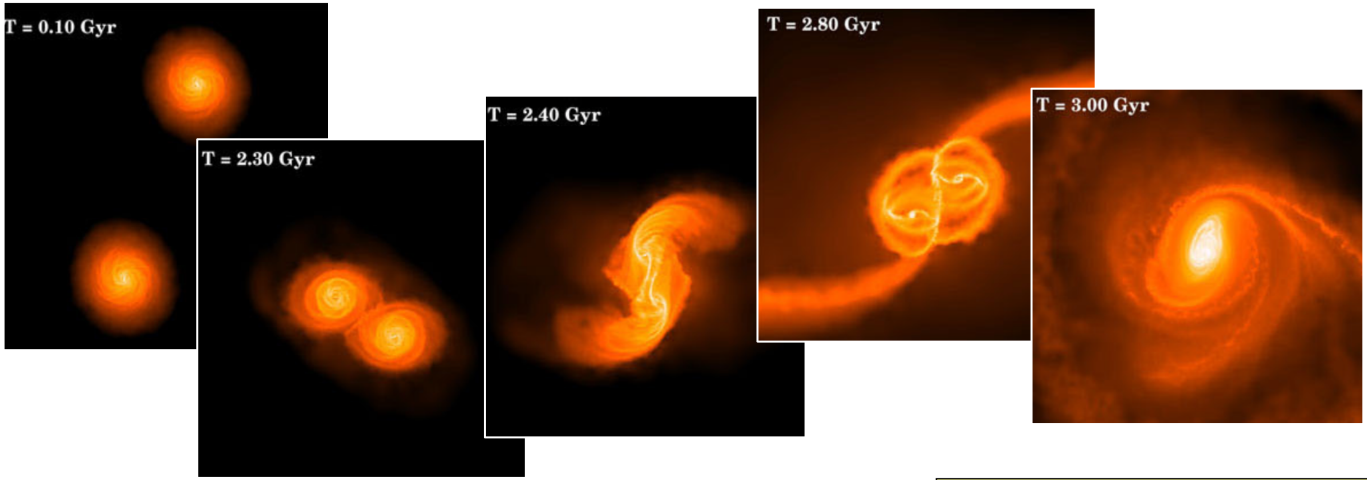
Morphological transformation is also needed!

Passive galaxies are more spheroidal and more bulgy...
this cannot be achieved by gas removal and/or starvation



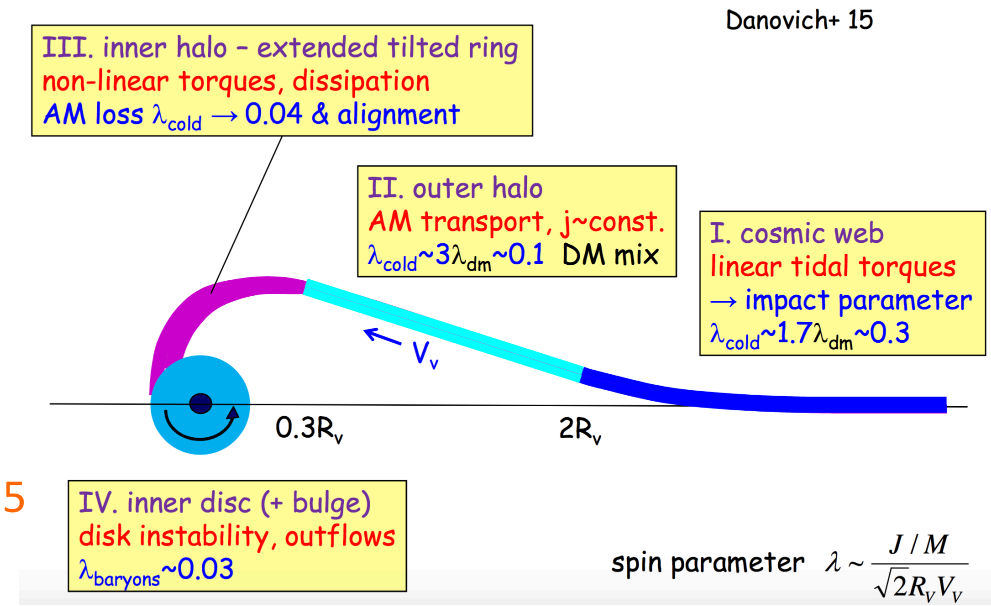
Cappellari+16

Additional mechanisms have to be invoked:
major/minor mergers and/or “compactation”



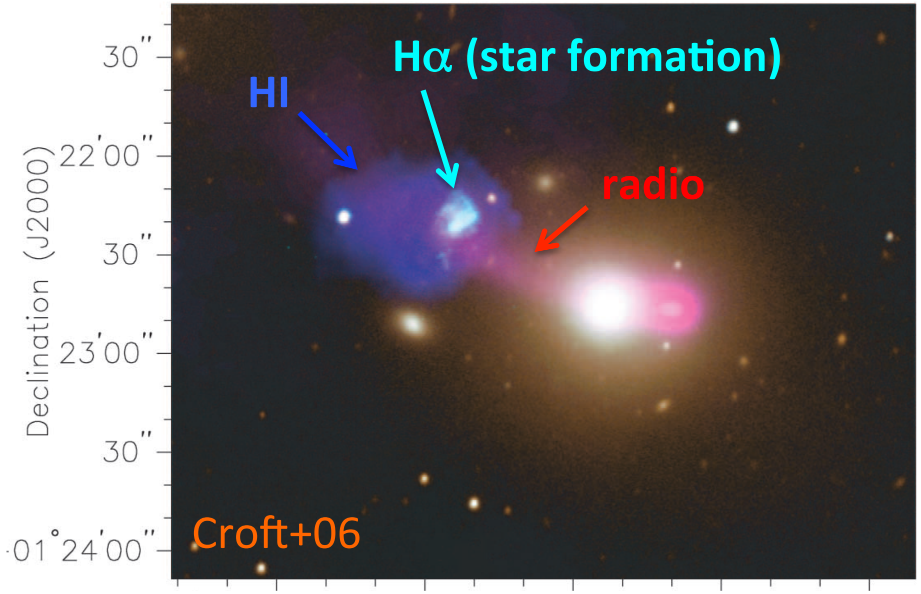
Mihos & Hernquist 1996
Walter+1996
Springel+05,+15
... many others
yet see
Bois+13
Naab+14

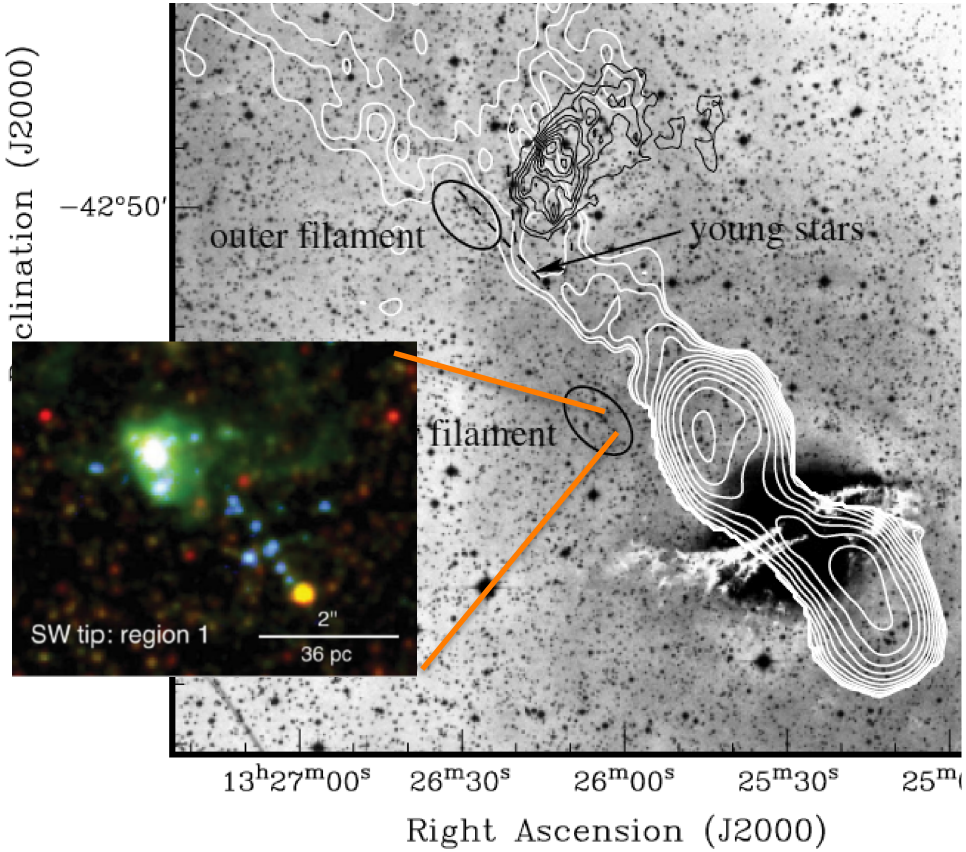
Dekel+16
Danovich+15



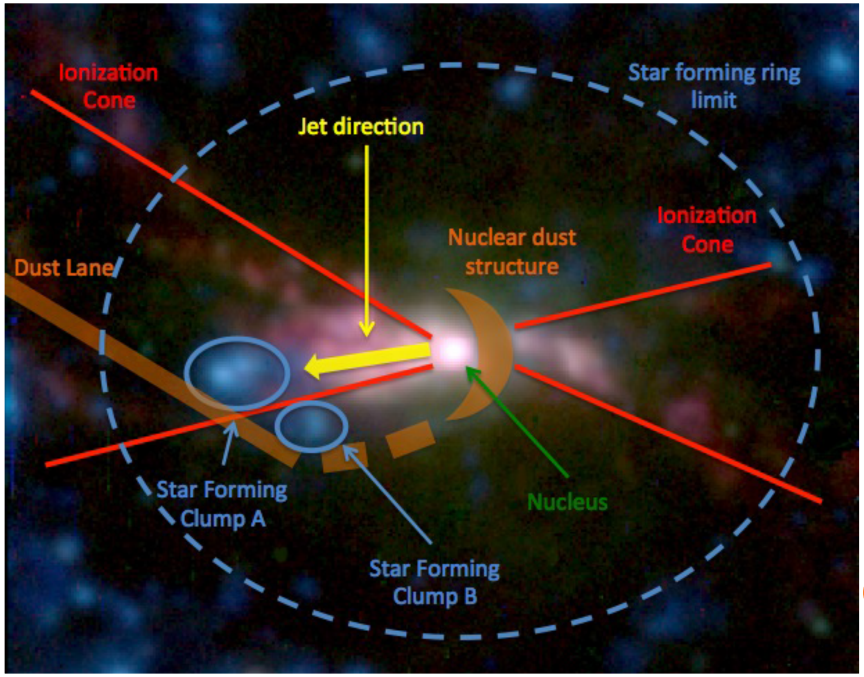
Are these the only possible routes?

AGN ejecta do not have only a negative feedback effect...
they can also trigger star formation in their host galaxy or in the circumgalactic medium





Crockett+12

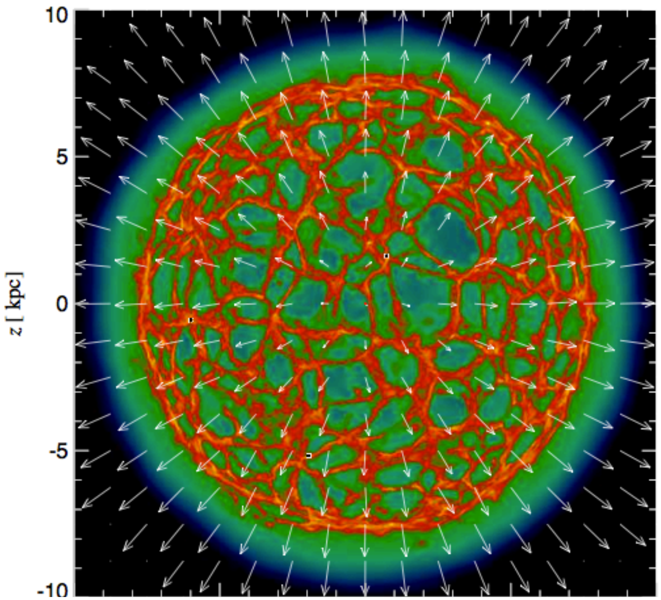


Cresci+15

Yet...
SFR ~ 0.5-0.1 $M_\odot$/yr

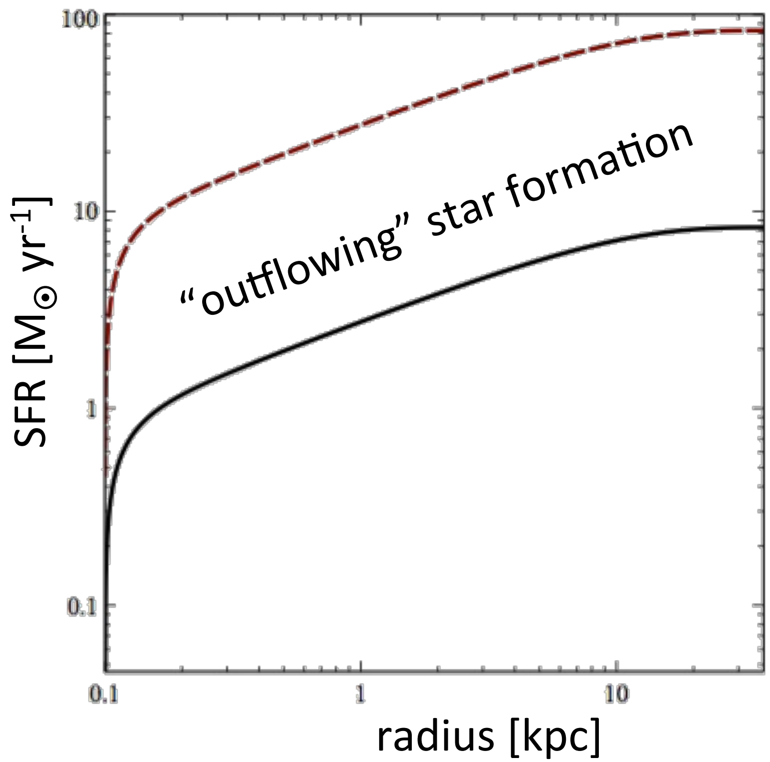
Even more fascinating scenario...

...star formation within outflows!



Expected by several models to resusult from gas cooling, fragmentation and compression

Silk+15, +17
Ishibashi & Fabian +14, +15
Zubovas+13
Zubovas & King '13
Nayakshin+12
Zachary+14
Gaibler+12



Even more fascinating scenario...

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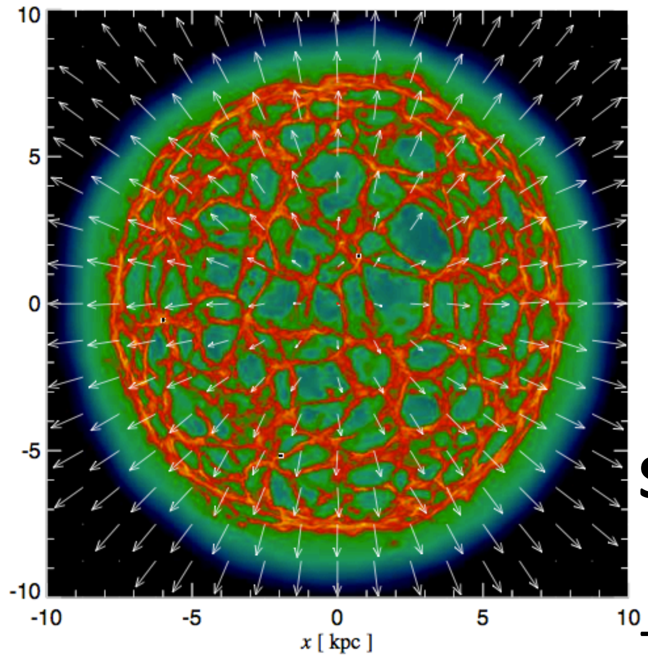


Silk+15, +17
Ishibashi & Fabian +14, +15
Zubovas+13
Zubovas & King '13
Nayakshin+12
Zachary+14
Gaibler+12

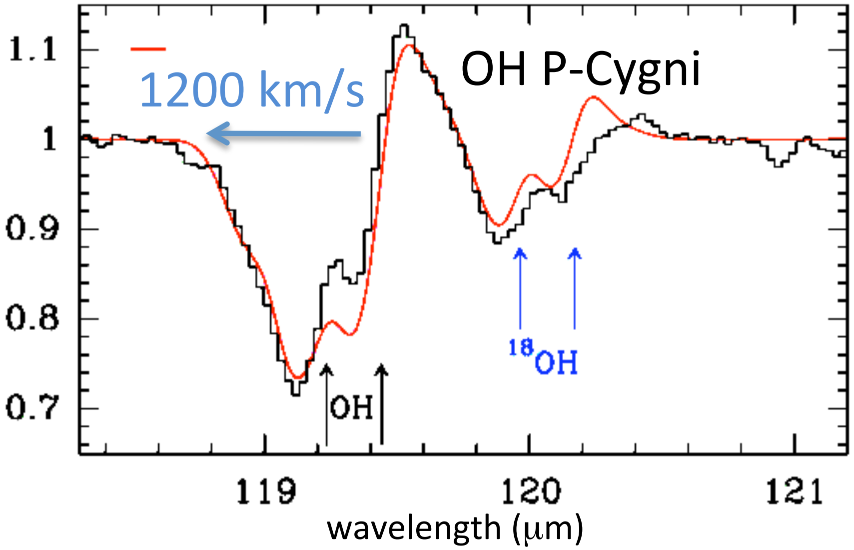
Expected by several models to resusult from gas cooling, fragmentation and compression

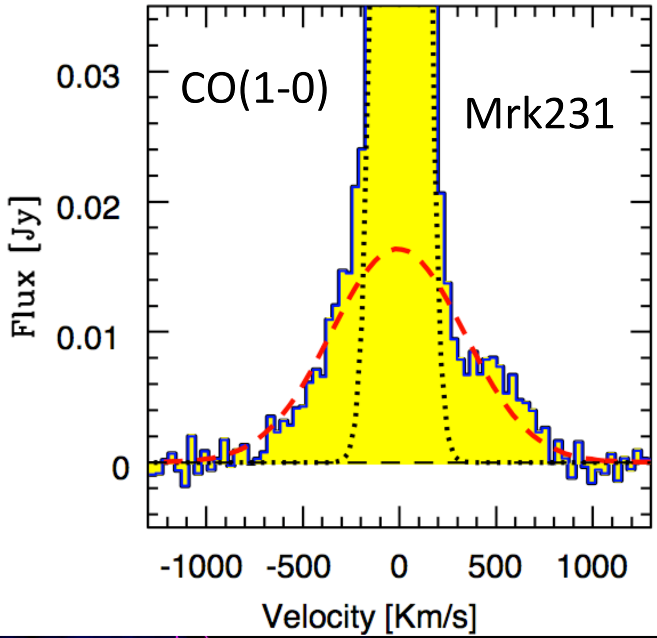
Stars forming at high velocities on radial orbits
➔ would have fantastic potential implications!

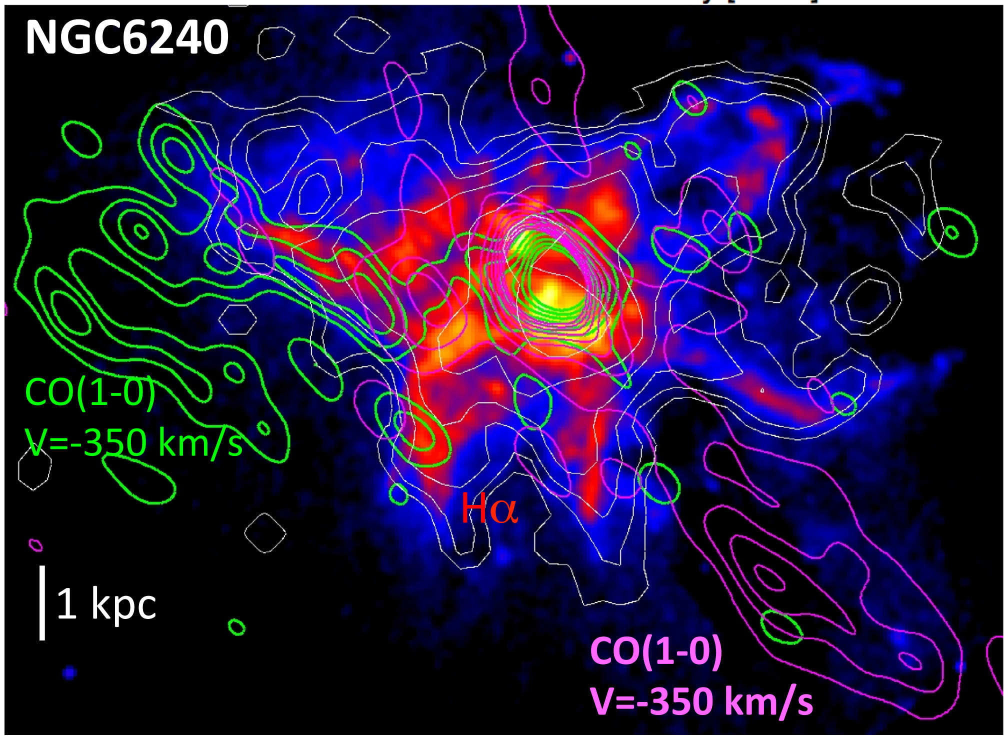
- Palaxy morphology: contribution to the spheroidal component of galaxies
- Stellar kinematics (velocity dispersion)
- Some of the stars can possibly escape into the intergalactic space
- Direct metal enrichment of the circumgalactic and intergalactic medium
- Enhanced escape fraction of ionizing photons -> contribution to reionization of the Universe

Star formation within galactic outflows, is this something reasonable to expect?

Large amount of molecular gas in fast galactic outflows

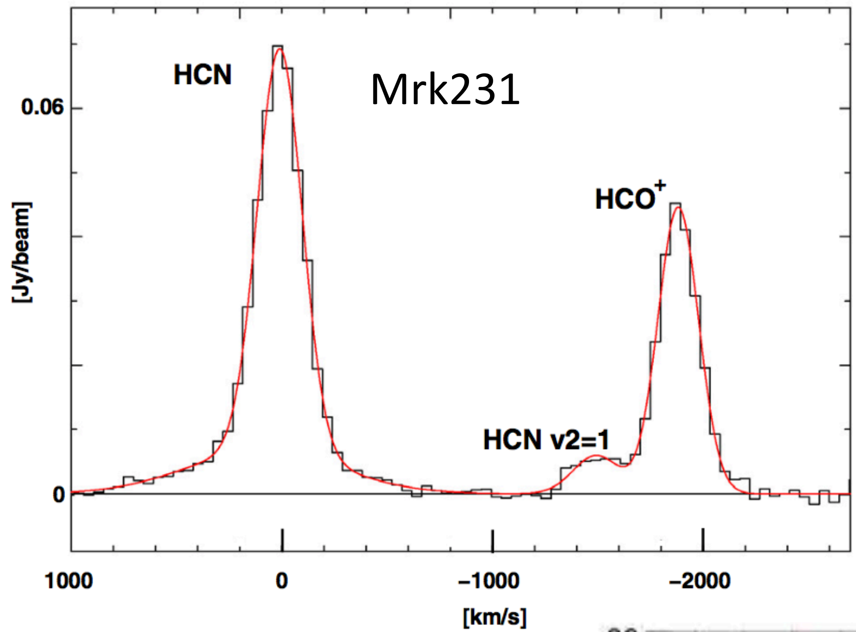


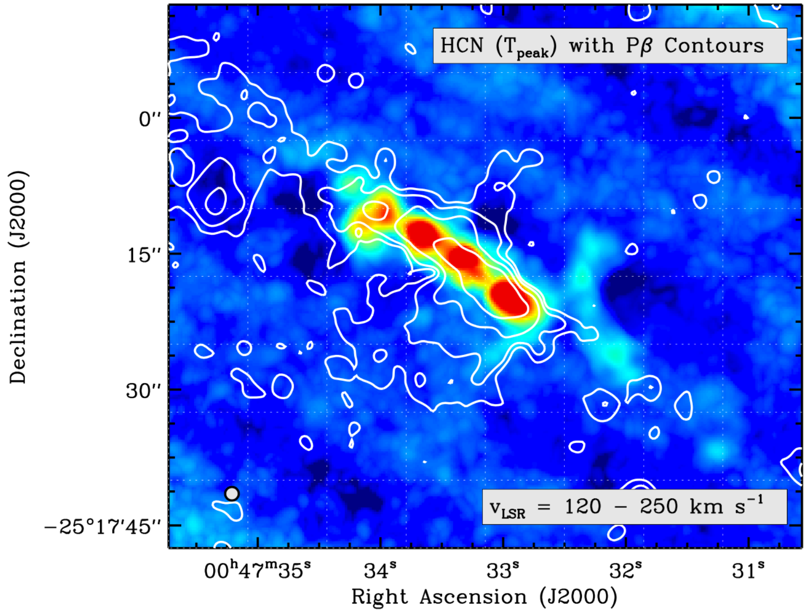




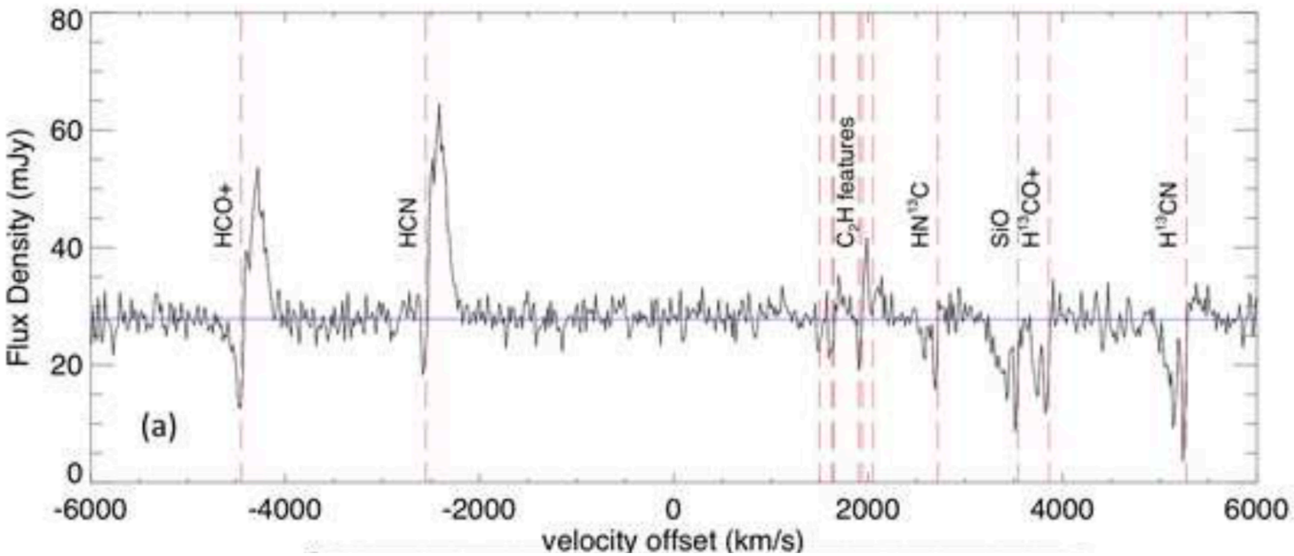
Fischer+10
Sturm+11
Feruglio+10,13,15
Aalto+11,15
Cicone+13,14
Gracia-Burillo+15
Combes+14
Sakamoto+14

A large fraction of the outflowing molecular gas is very dense $\sim 10^5$ cm^{-3} ~similar to the gas in star forming regions



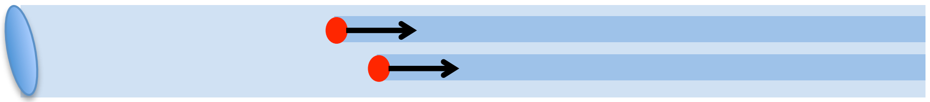


Lin+16
Aalto+15, 16
Walter+17
Gonzalez-Alfonso+17
Zschaechner+15
Tunnard+15
Sakamoto+08



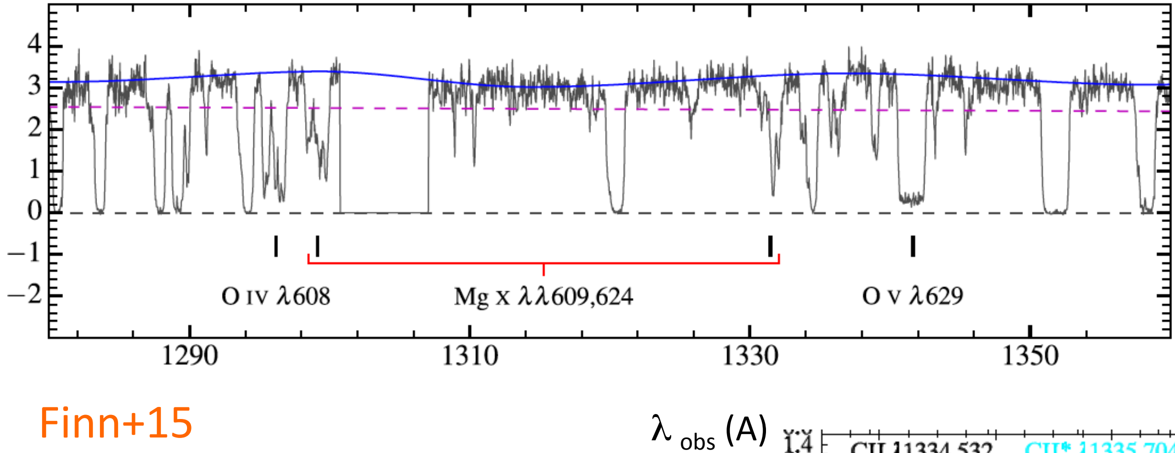
The outflowing gas is extremely clumpy

UV absorption lines in quasars



Velocities ~800-2000 km/s
Density +ionization parameter ➔ distance: D=0.3-20

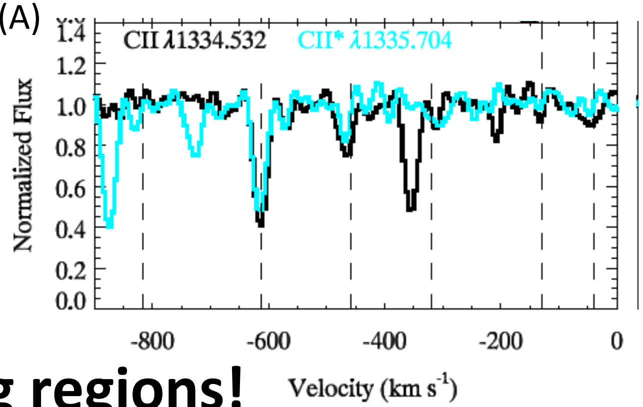
covering factor ~ 0.5-0.8



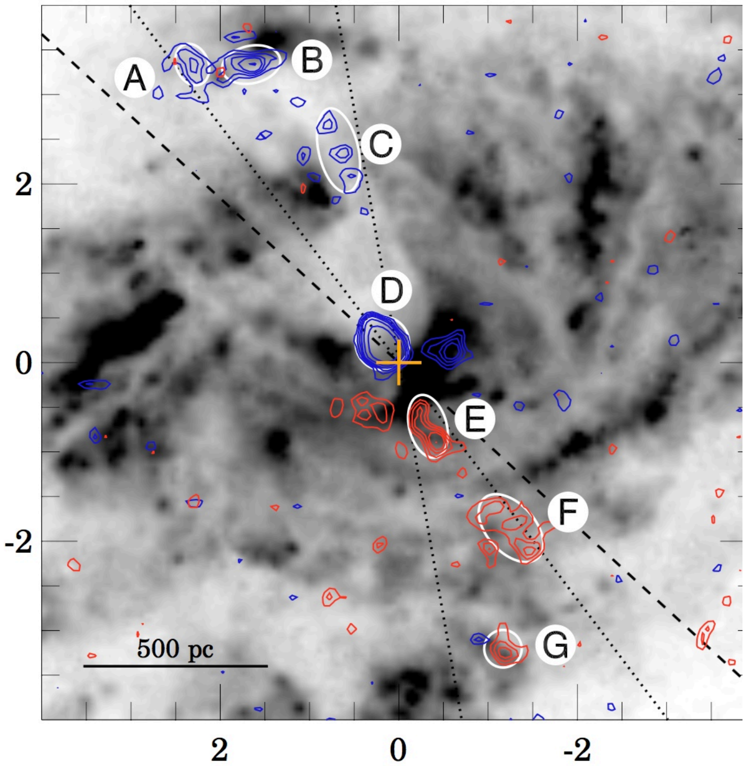
Finn+15

Borguet+12

Implied size of clumps as small as < 1 pc -> comparable with dense cores in star forming regions!



ALMA high resolution maps of outflows

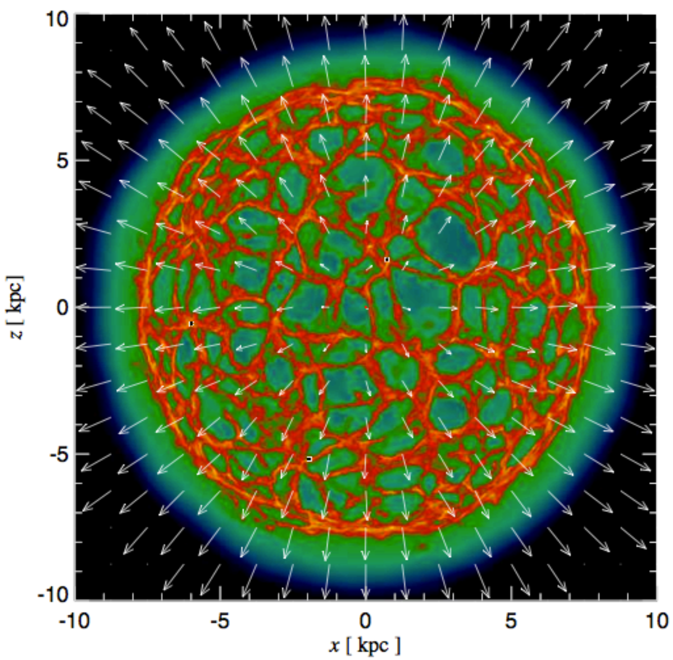


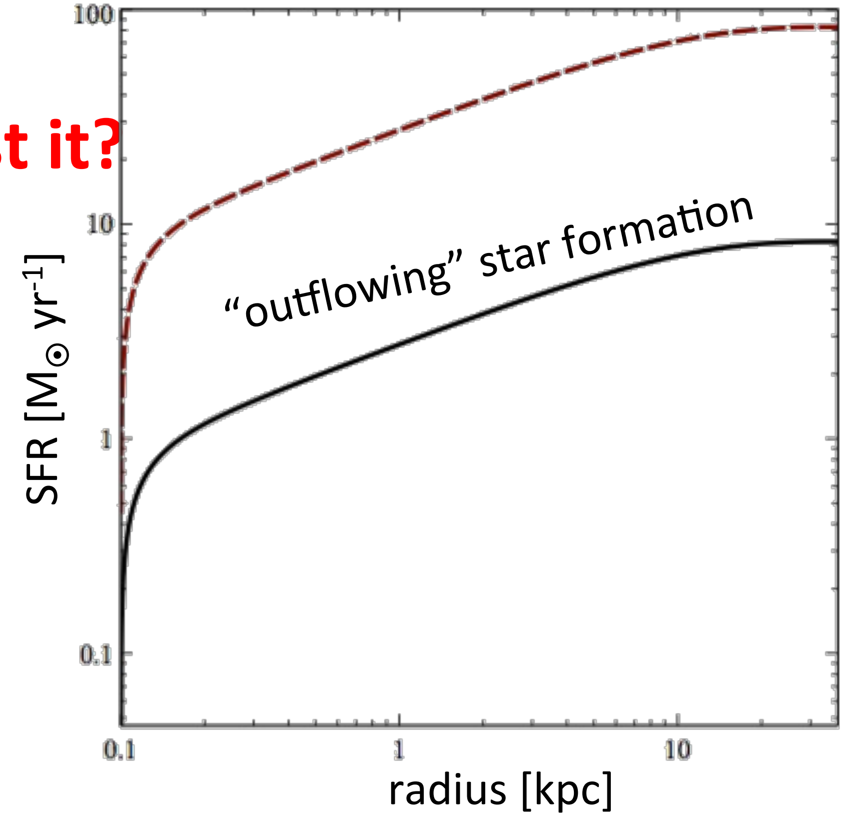
Clump sizes: 60-150 pc

Pereira-Santaella+16

Aalto+15

Star formation in the outflow: how to test it?

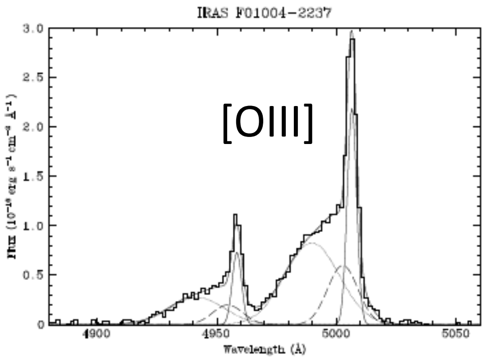




Cannot use many of the tracers:
e.g. IR dust thermal emission and UV imaging cannot disentangle putative SF in the outflow from SF in the host galaxy

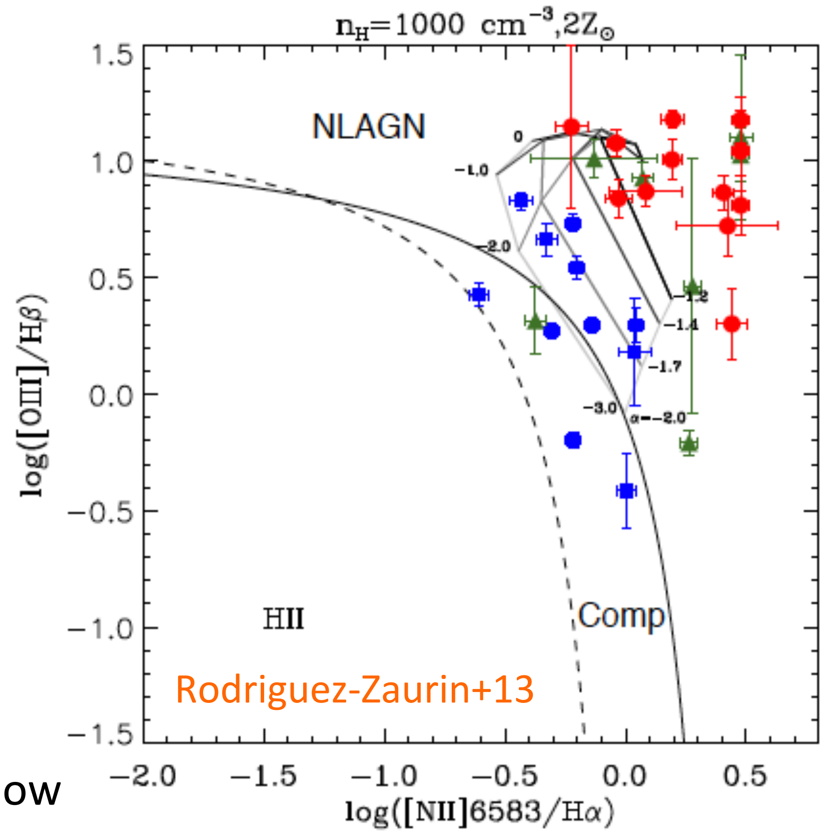
-> Need to use spectroscopic tracers of SF, which bear information of the kinematics of the star forming region...

Optical nebular lines



Decomposition
of broad/intermediate (=outflow)
and narrow component

Sample of ULIRGs with optical Seyfert nuclei



Blue = Narrow

Green = Intermediate
Red = Broad

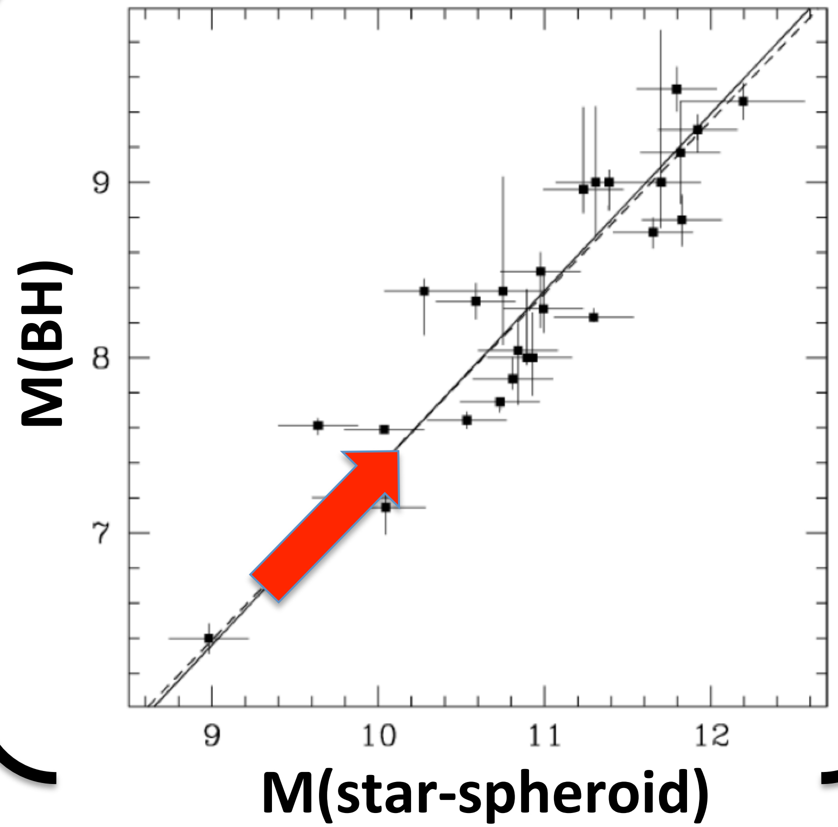
outflow

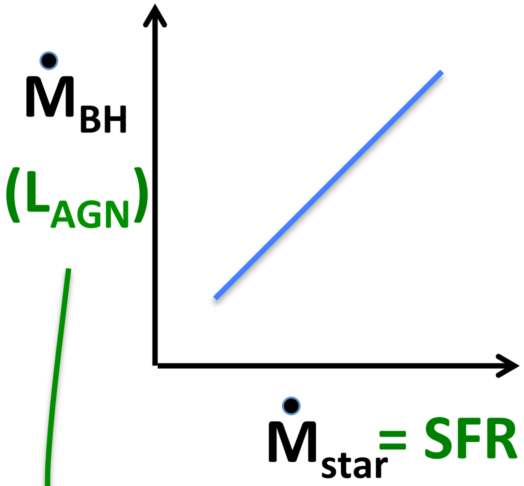
Generally broad/blueshifted component tracing the outflow
is associated with AGN-ionization
and/or shocks (LINERs)...

However, even if substantial SFR is occurs in the outflow,
AGN photoionization likely dominates...

Assume the extreme case that that the stellar spheroid is all formed in the AGN driven outflow,
and that the two evolve along the M(BH)-M(star-sph) relation

$$\frac{d}{dt}$$





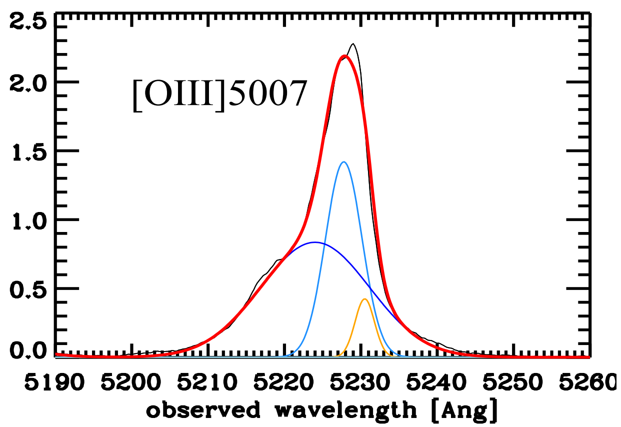
$$L_{AGN}(H\alpha) \approx L_{SF}(H\alpha)$$

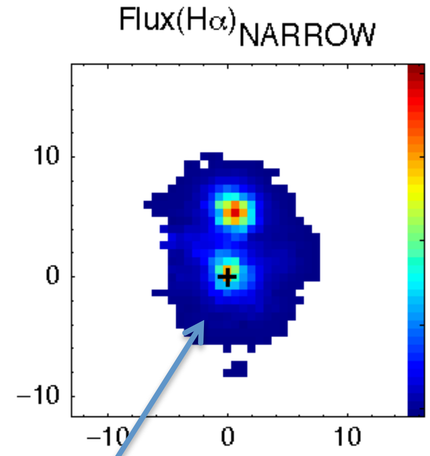
$$L_{AGN}([OIII]) \approx 10\ L_{SF}([OIII])$$

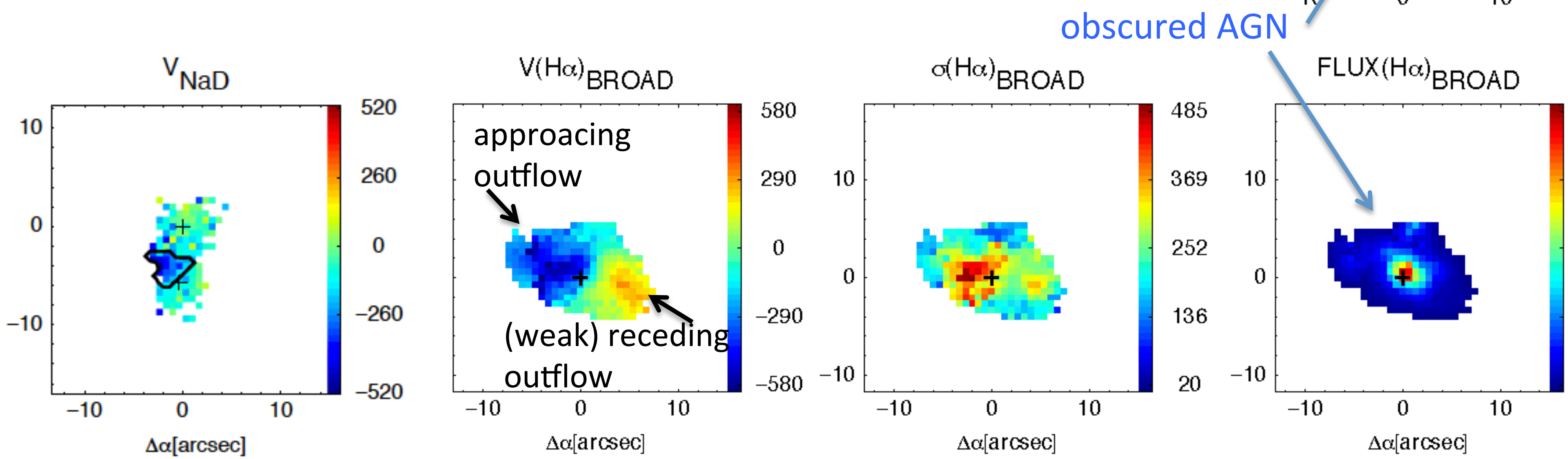
Even if whole spheroid formed in AGN-driven outflows
BPT diagnostics would mostly appear AGN-like.
Shocks makes the BPT deviate even further

→ VERY DIFFICULT!
Needs very detailed observations

IRAS2312-59 hosting obscured AGN and driving prominent outflow

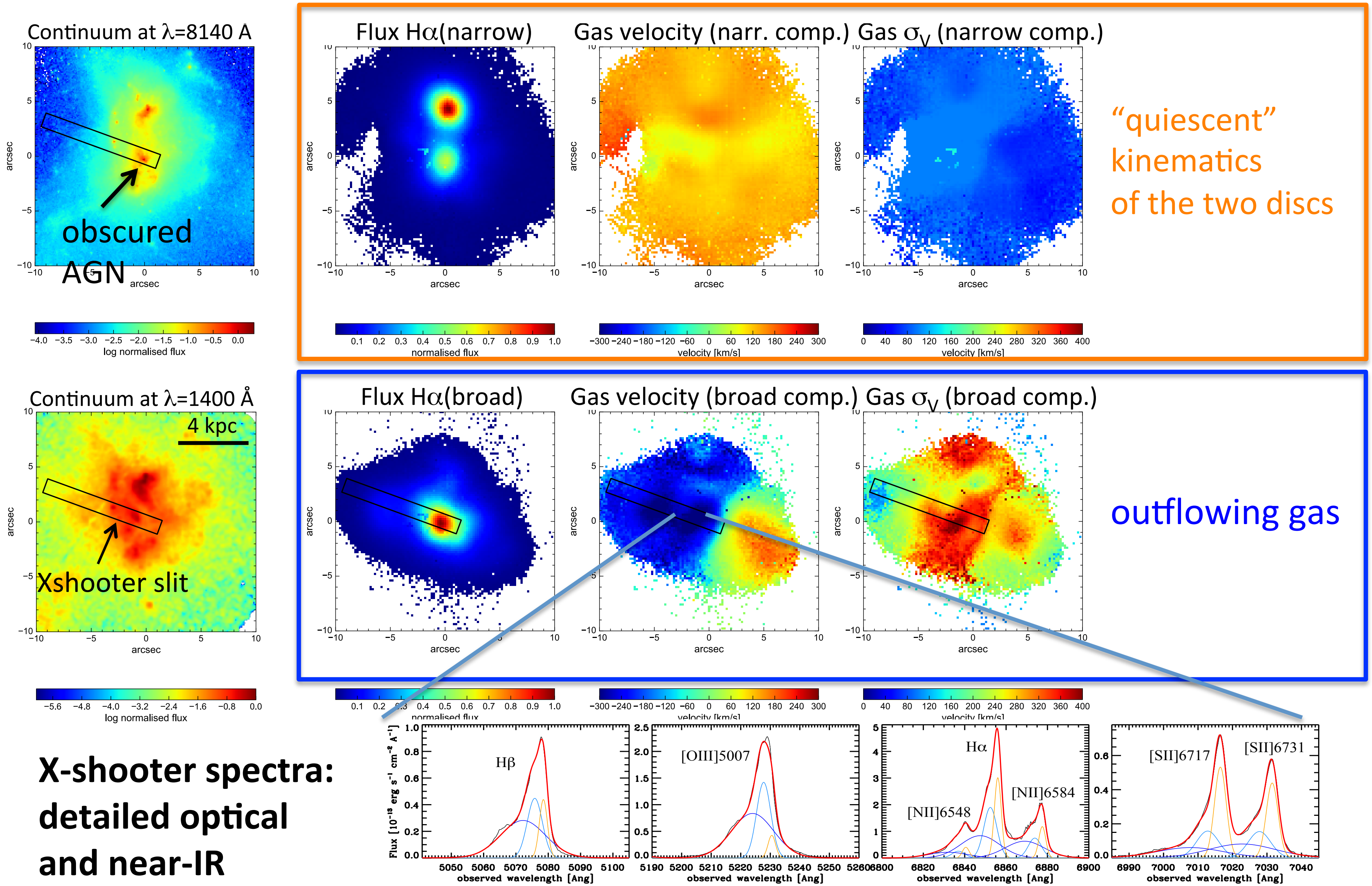






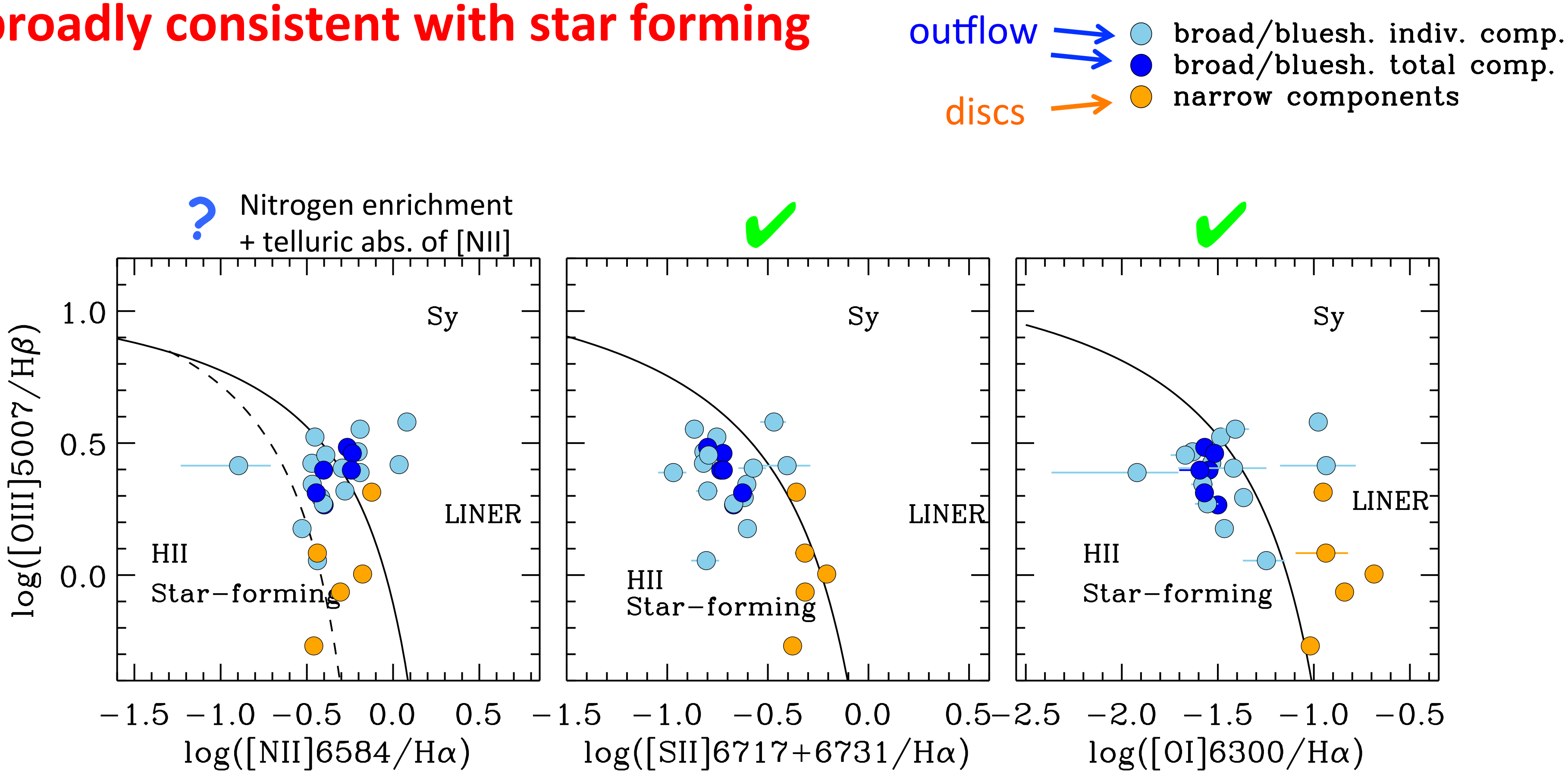
Outflow known from several
previous studies with various tracers:
nebular optical lines, near-IR lines, NaID absorption, 6282Å IB absorption
(Arribas+14, Bellocchi+13, Cazzoli+15, Leslie+15, Piqueras-Lopez+12)

Interacting system with powerful outflow observed with MUSE



X-shooter spectra: detailed optical and near-IR diagnostics

BPT diagrams of gas in the outflow: broadly consistent with star forming

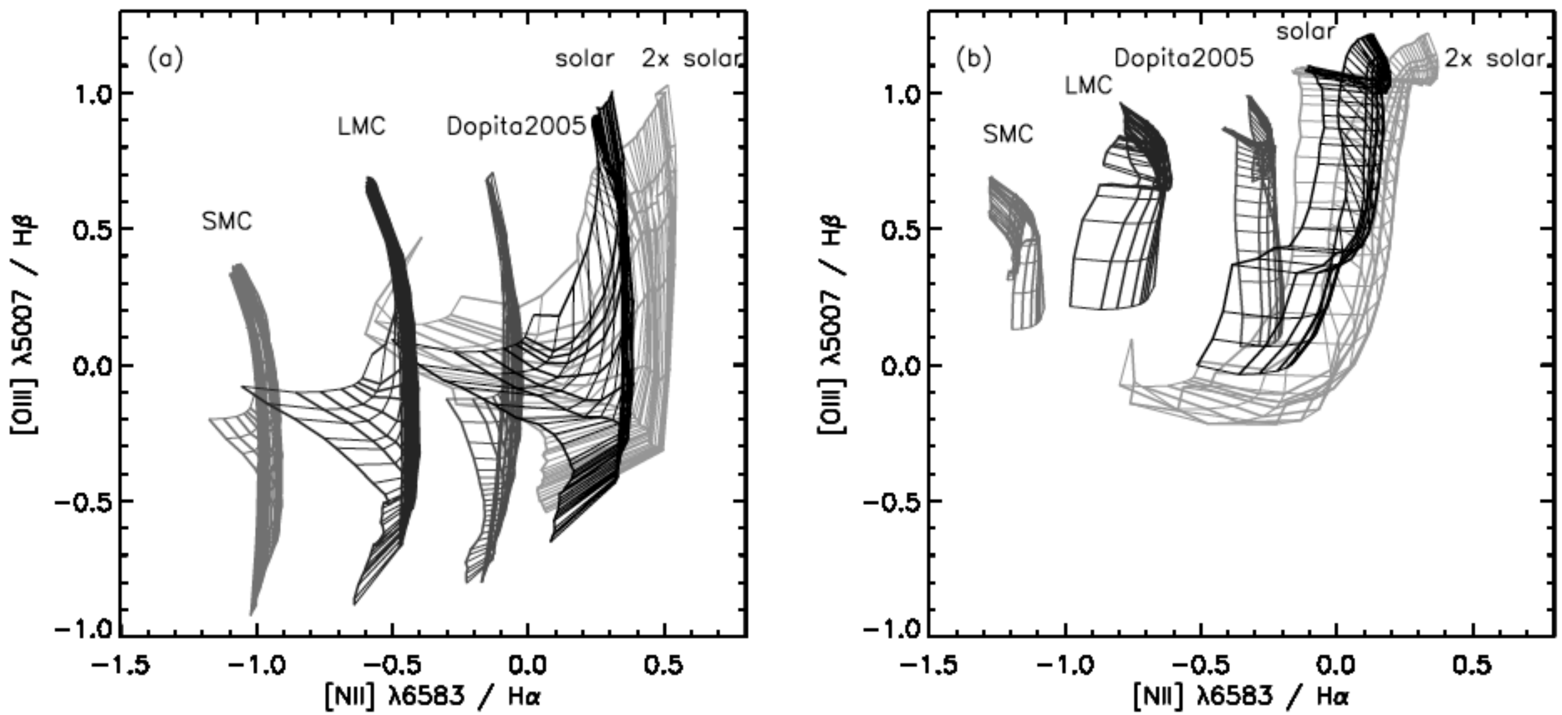


Yet, not enough to exclude other excitation mechanisms

Maiolino+17 (Nature)

Can SF-like BPT
be explained with shocks?

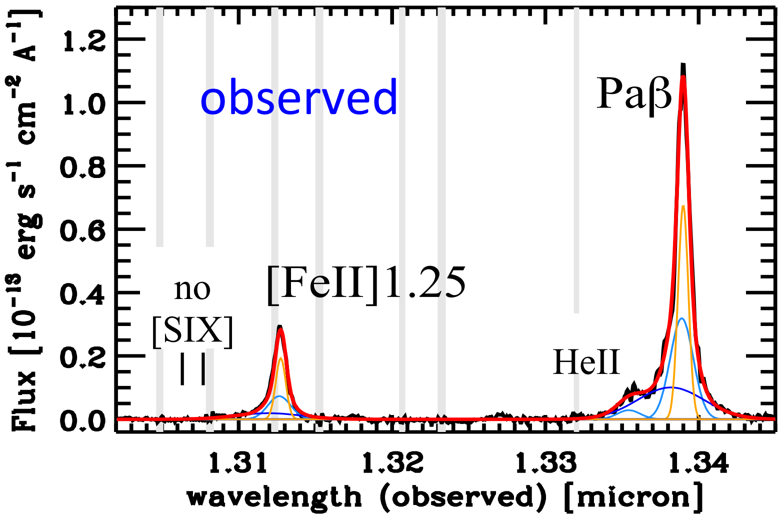
Some combinations of shock parameters can in principle reproduce the observed ratios...



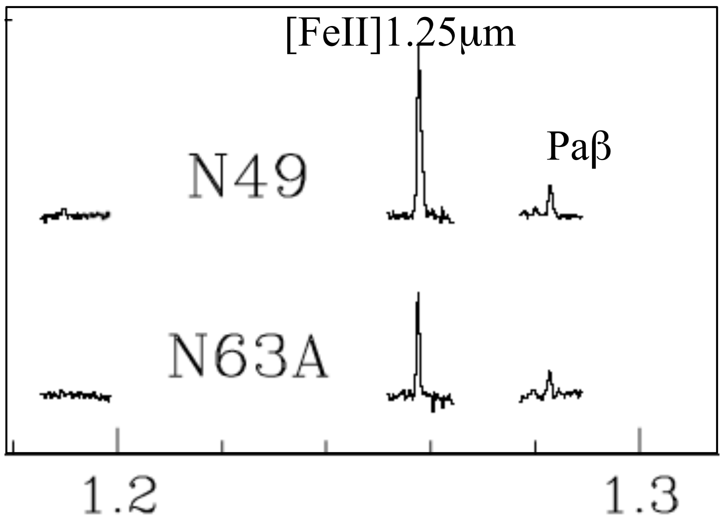
Allen+08

Can SF-like BPTs for this outflow be explained with shocks? NO

[FeII] near-IR transitions excellent tracers of shocked gas



shocked Galactic regions



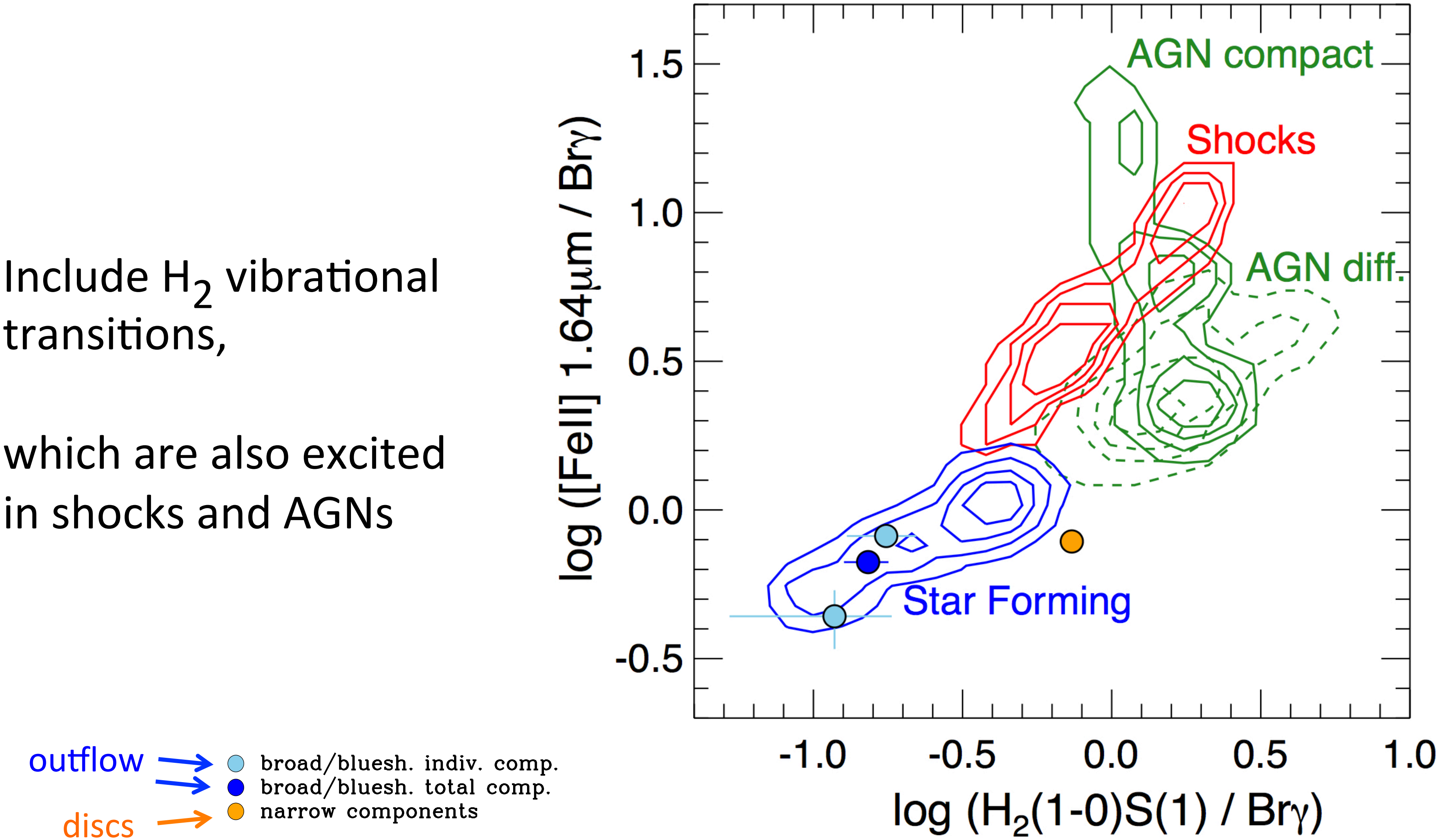
in shocks $\frac{\text{[FeII]}}{\text{Pa}\beta} = 5 - 20$

Can SF-like BPTs for this outflow be explained with shocks? **NO**

[FeII] near-IR transitions excellent tracers of shocked gas

Include H_2 vibrational transitions,

which are also excited in shocks and AGNs

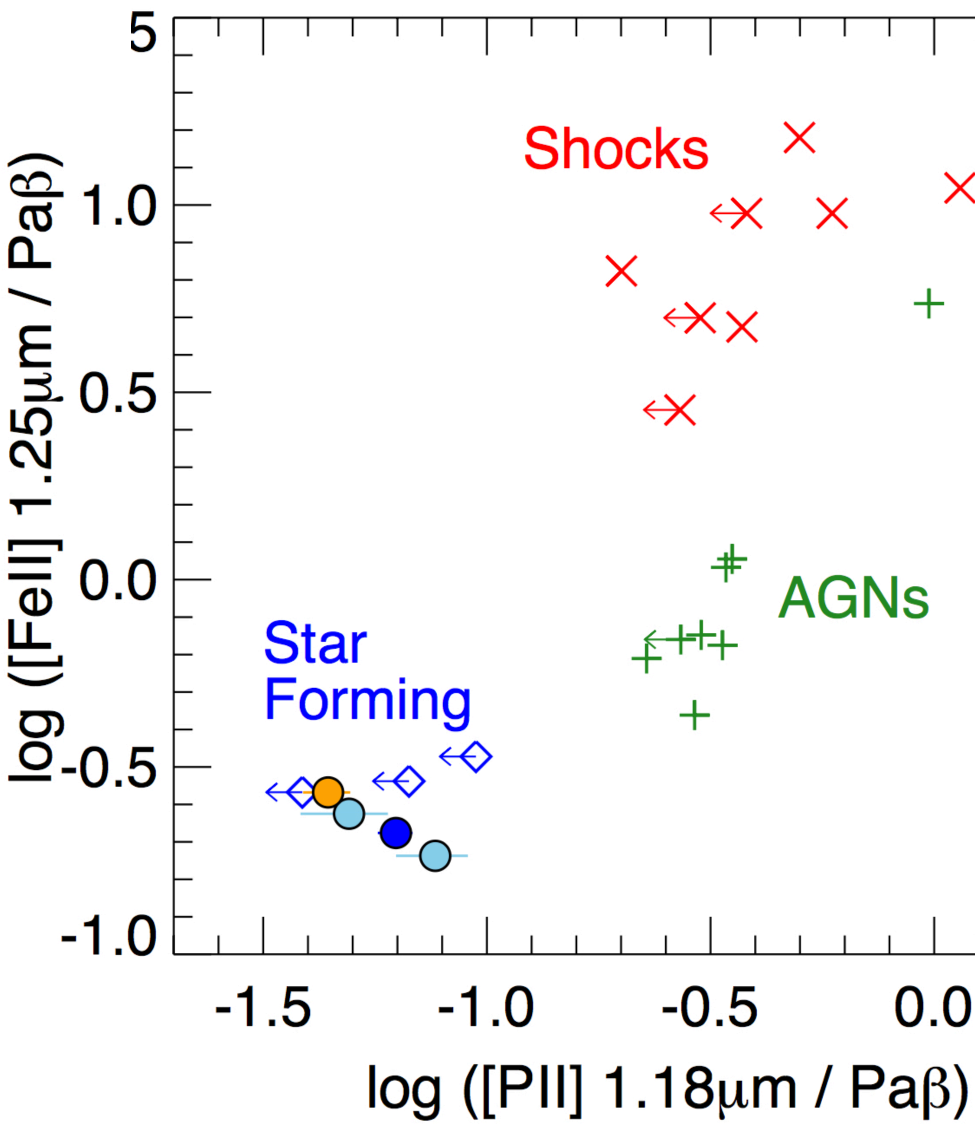


Maiolino+17 (Nature)

Can SF-like BPTs for this outflow be explained with shocks? **NO**

[FeII] near-IR transitions excellent tracers of shocked gas

Include [PII]1.18μm excellent discriminator of excitation by hard X-ray radiation (AGN & shocks)

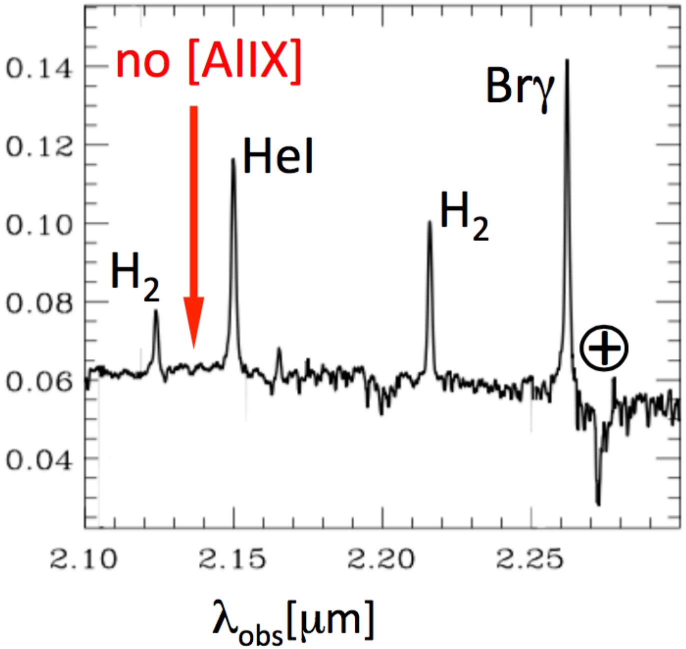


outflow → broad/bluesh. indiv. comp.
outflow → broad/bluesh. total comp.
discs → narrow components

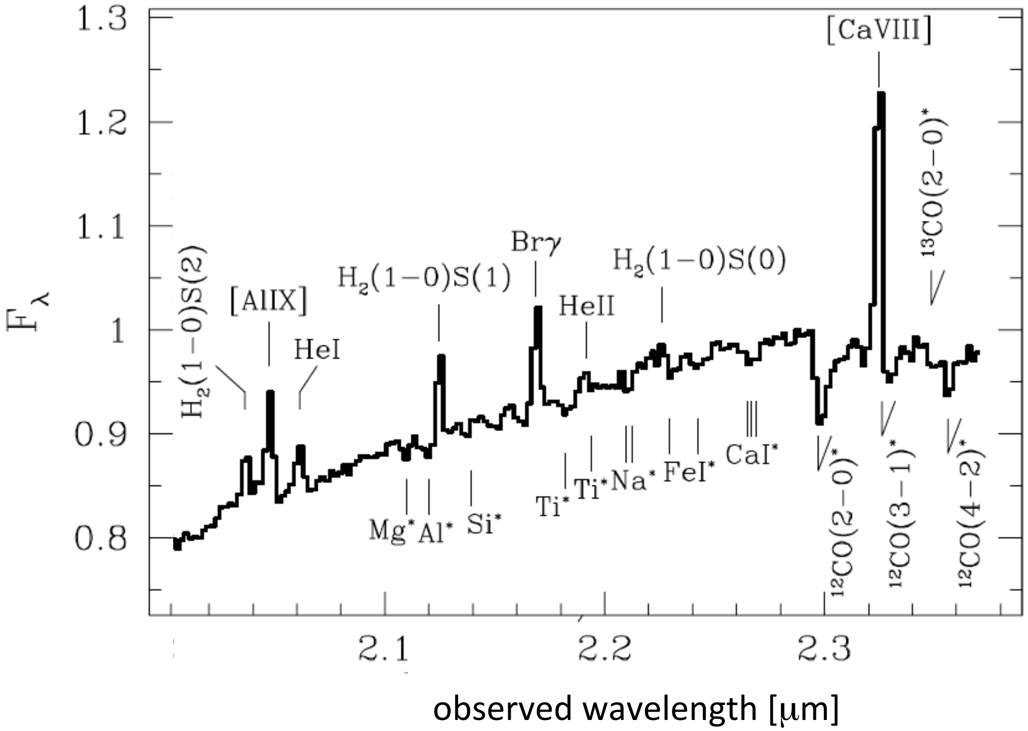
Maiolino+17 (Nature)

Further evidence against any AGN photoionization: AGN-ionized gas often rich of "coronal" (high-ionization) lines

No coronal lines detected



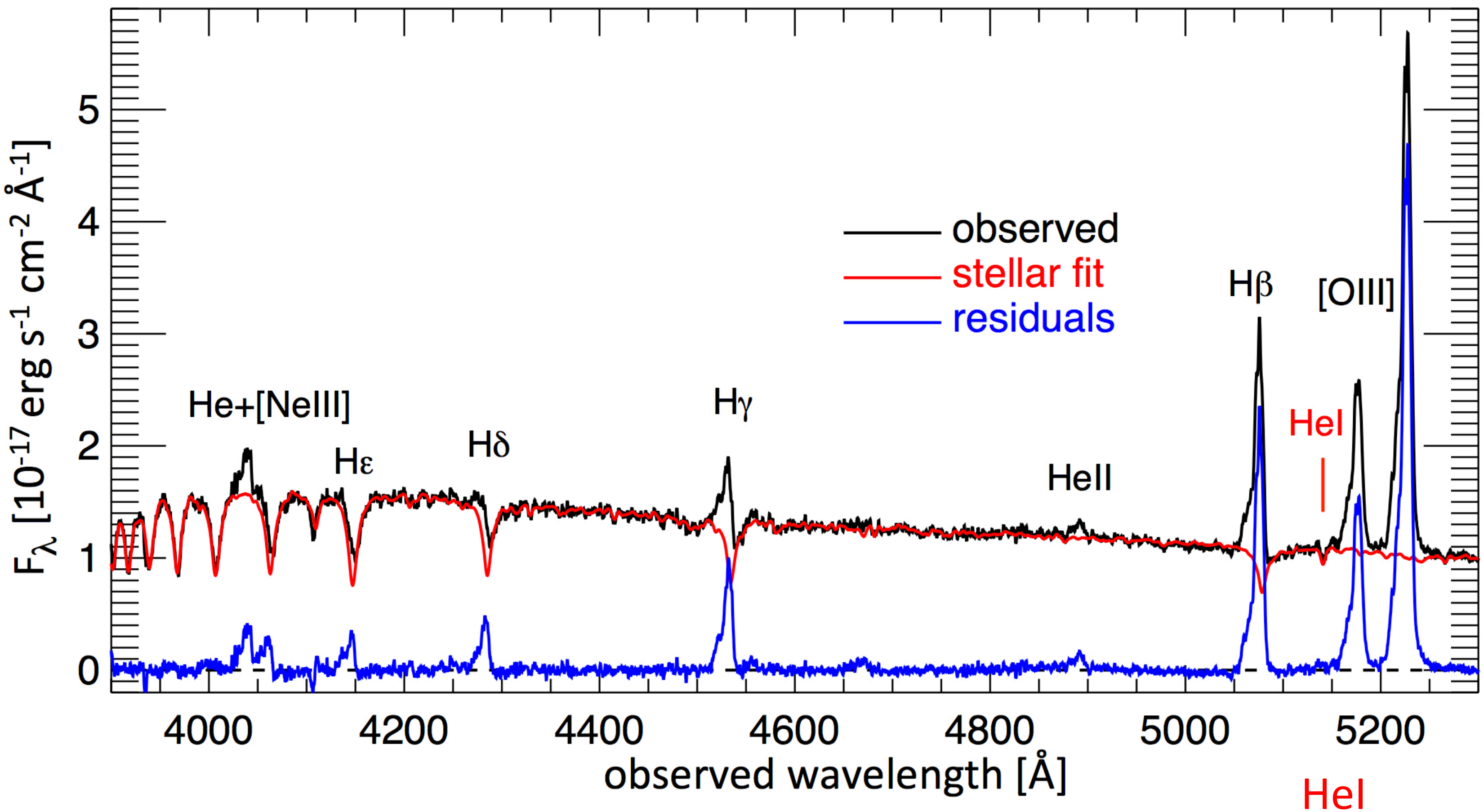
Circinus (prototypical Sy2)



- No shocks
- No AGN

In-situ (in the outflow) star formation is the only viable explanation consistent with all diagnostics

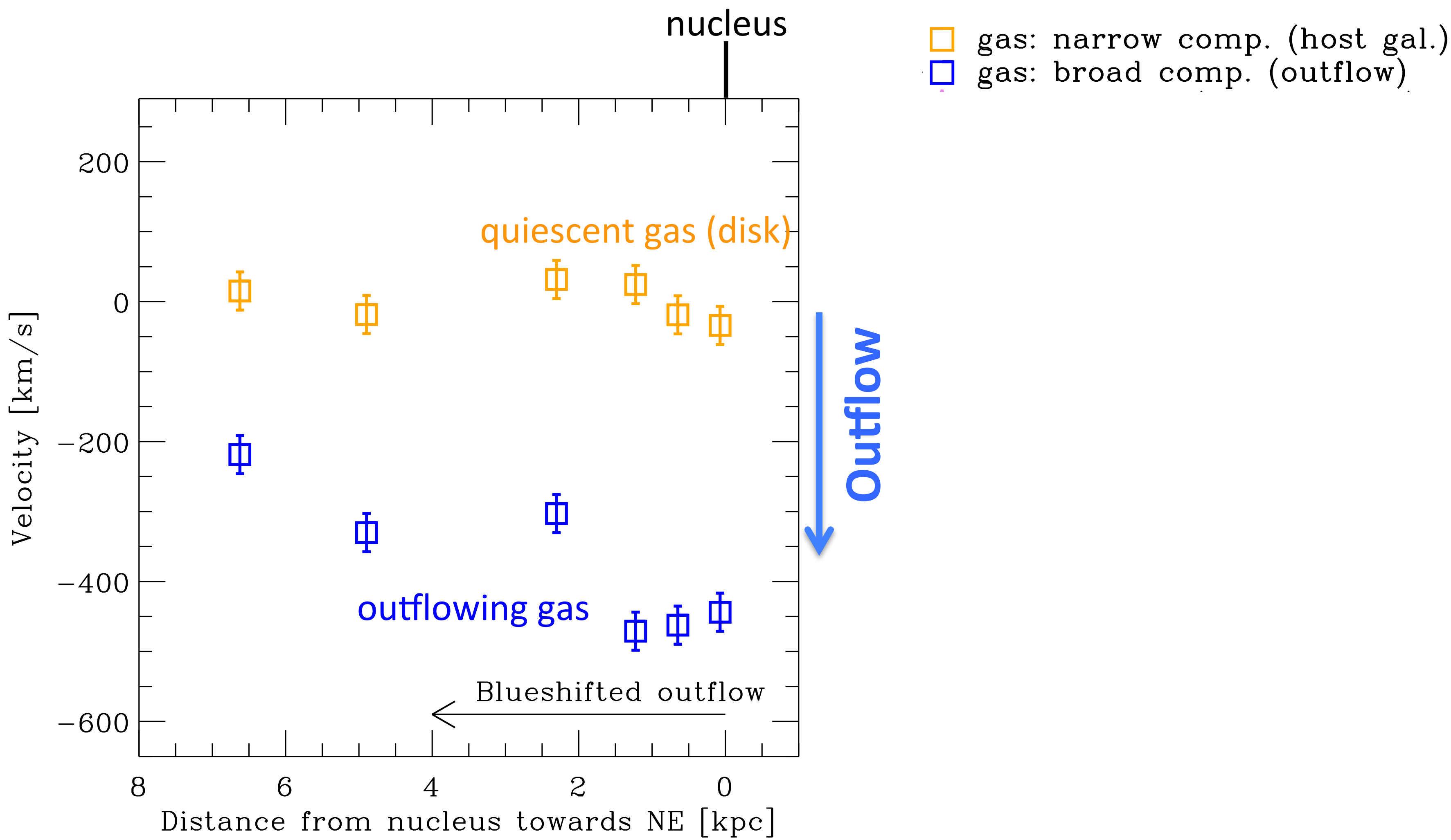
Stellar population with age <30 Myr (very young!)



HeI
tracer of
young B stars

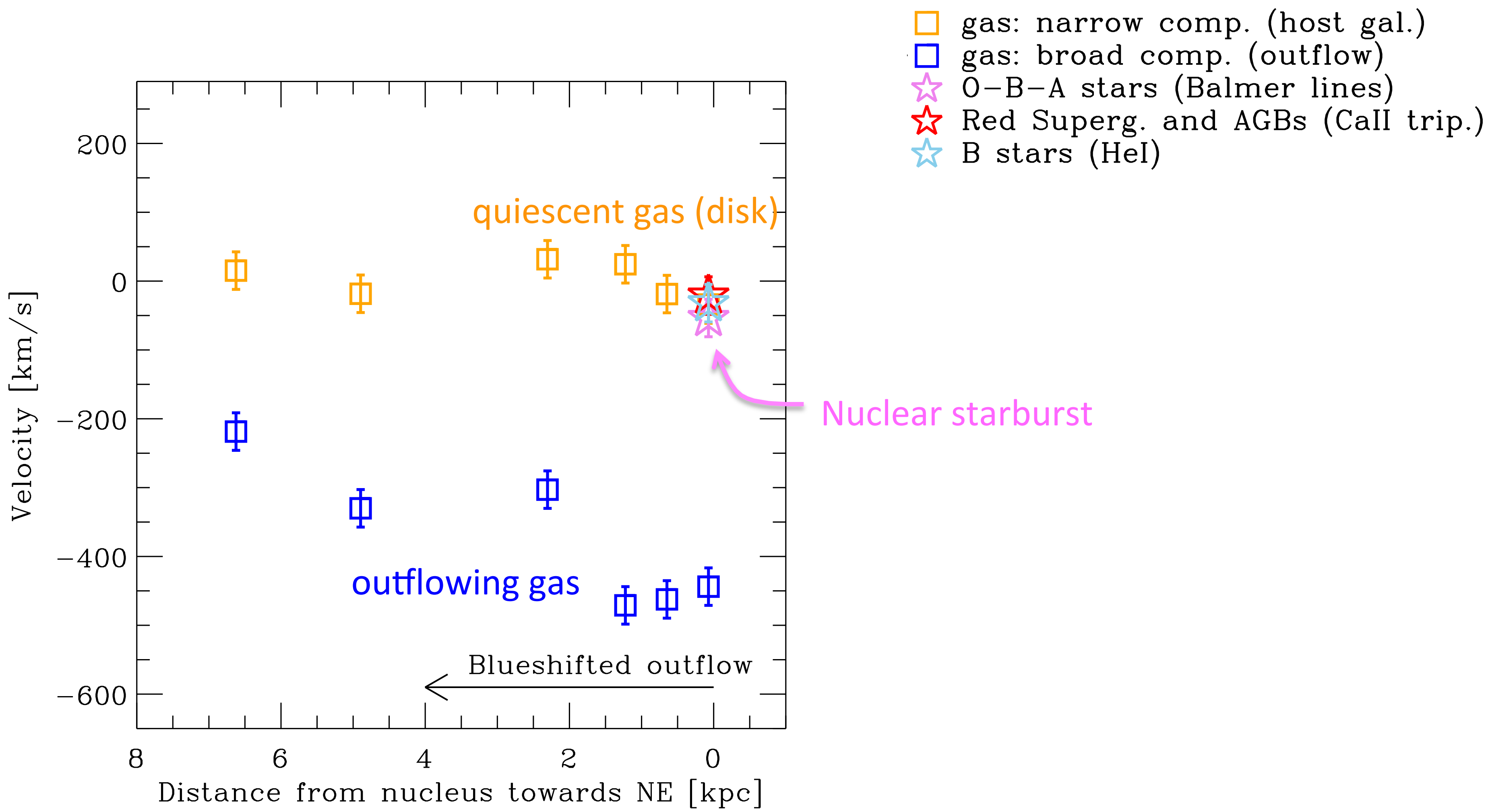
Is the stellar kinematics of the young stellar population **consistent** with the scenario of star formation in the outflow?

Kinematics



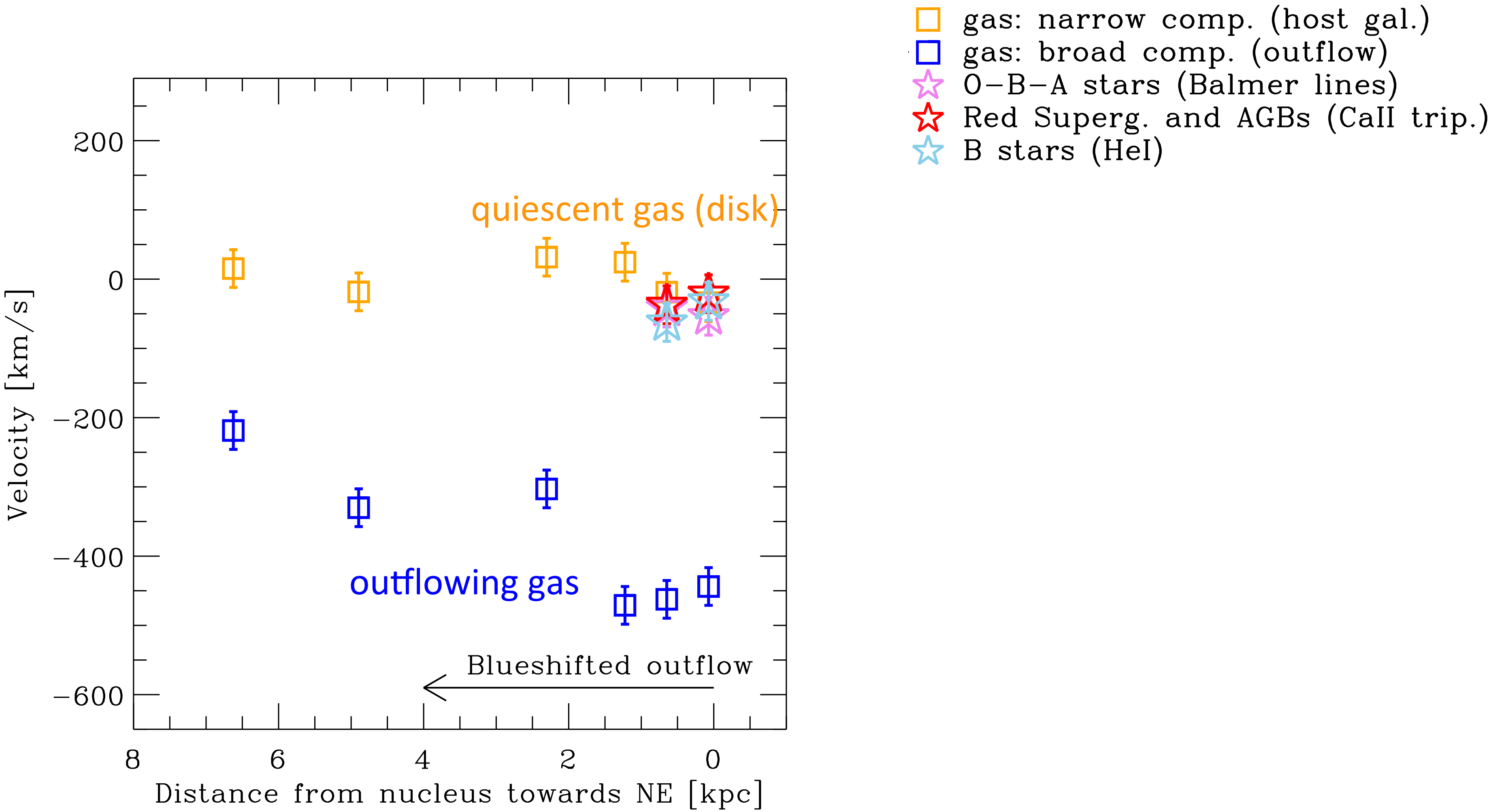
nucleus
gas: narrow comp. (host gal.)
gas: broad comp. (outflow)
200
0
−200
−400
−600
Velocity [km/s]
quiescent gas (disk)
outflowing gas
Outflow
Blueshifted outflow
8
6
4
2
0
Distance from nucleus towards NE [kpc]

Kinematics



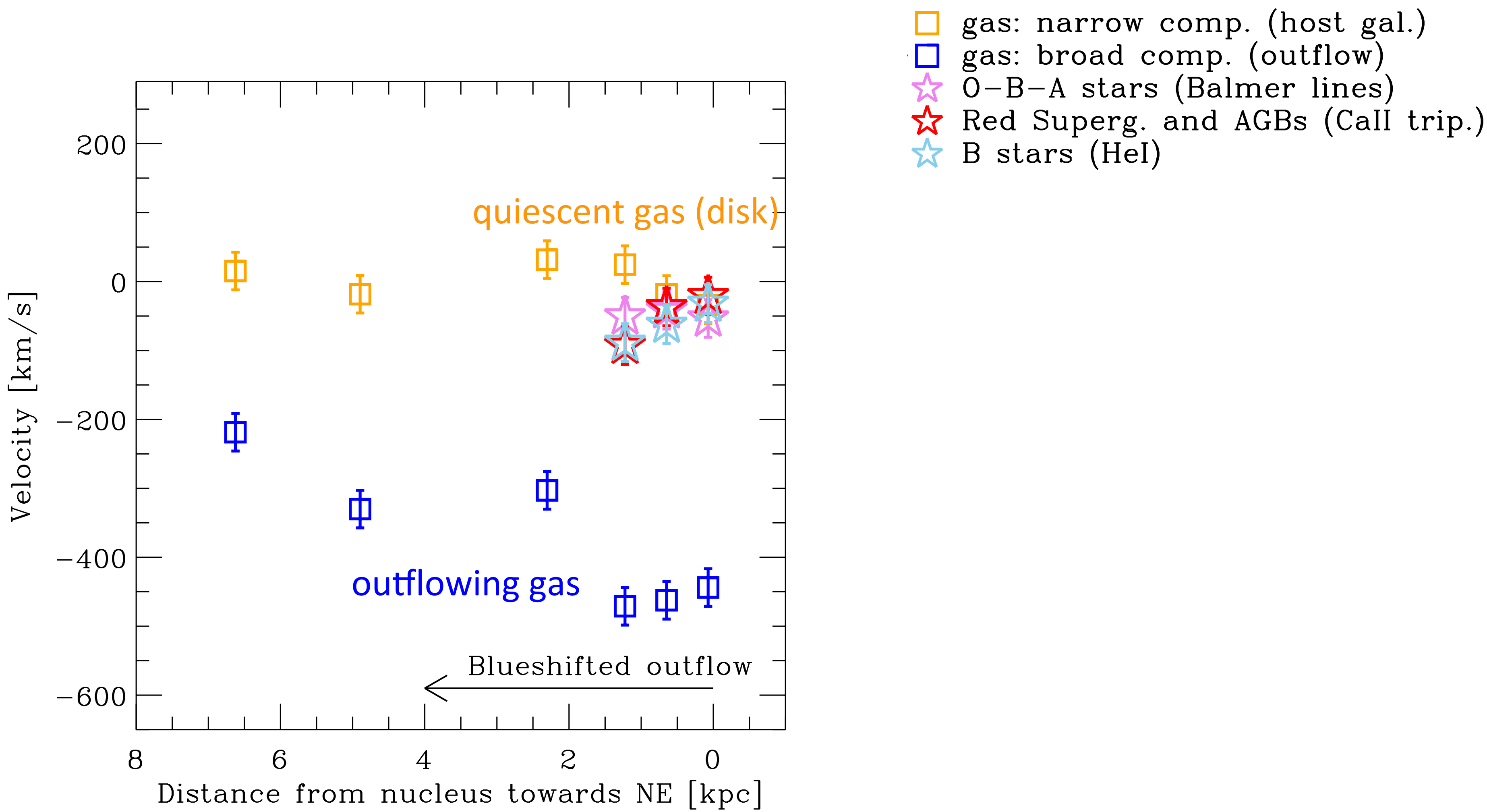
gas: narrow comp. (host gal.)
gas: broad comp. (outflow)
O−B−A stars (Balmer lines)
Red Superg. and AGBs (CaII trip.)
B stars (HeI)
quiescent gas (disk)
outflowing gas
Nuclear starburst
Blueshifted outflow
200
0
−200
−400
−600
8
6
4
2
0
Velocity [km/s]
Distance from nucleus towards NE [kpc]

Kinematics



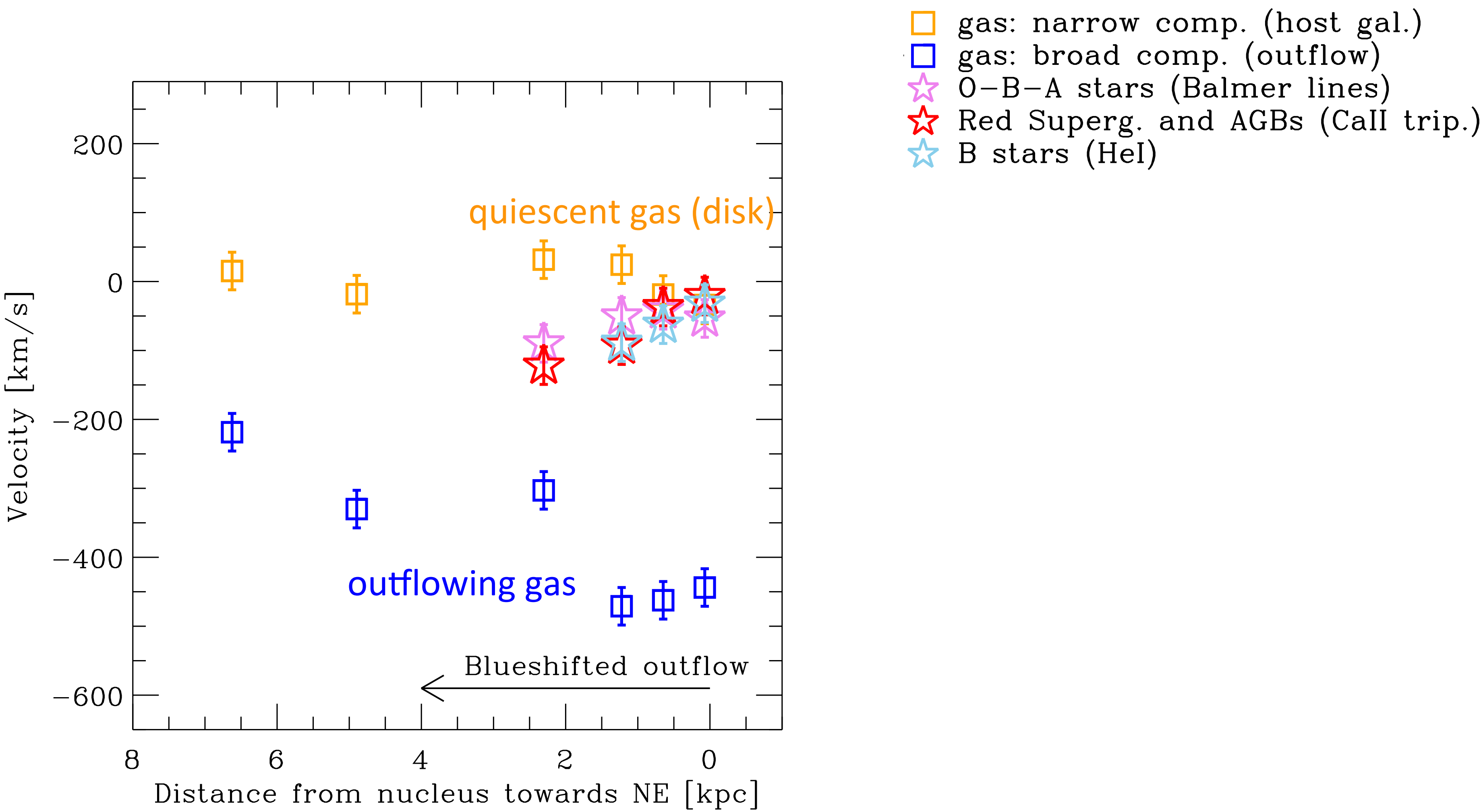
gas: narrow comp. (host gal.)
gas: broad comp. (outflow)
O−B−A stars (Balmer lines)
Red Superg. and AGBs (CaII trip.)
B stars (HeI)
quiescent gas (disk)
outflowing gas
Blueshifted outflow
Velocity [km/s]
200
0
−200
−400
−600
8
6
4
2
0
Distance from nucleus towards NE [kpc]

Kinematics



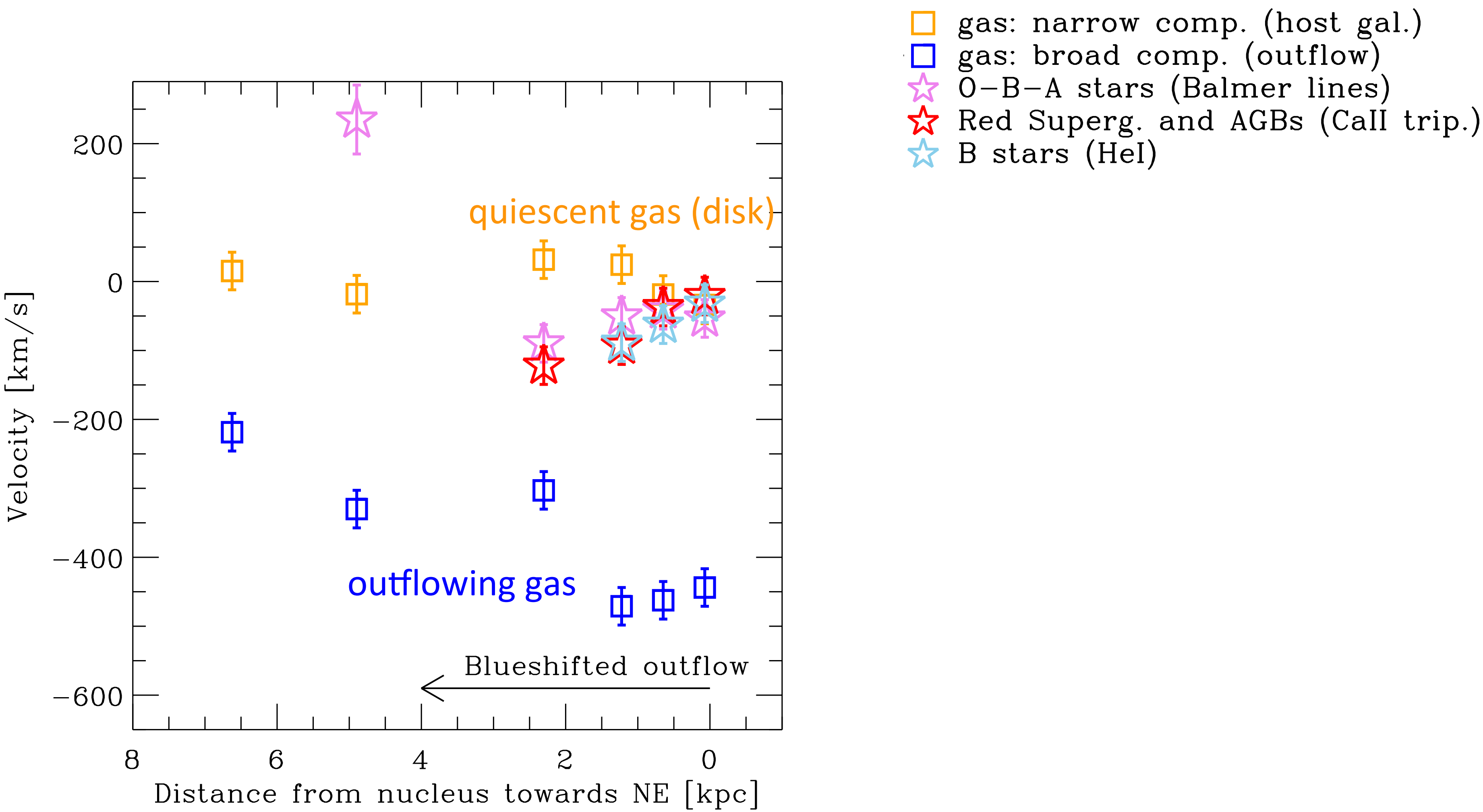
quiescent gas (disk)
outflowing gas
Blueshifted outflow
200
0
−200
−400
−600
Velocity [km/s]
8
6
4
2
0
Distance from nucleus towards NE [kpc]
gas: narrow comp. (host gal.)
gas: broad comp. (outflow)
O−B−A stars (Balmer lines)
Red Superg. and AGBs (CaII trip.)
B stars (HeI)

Kinematics



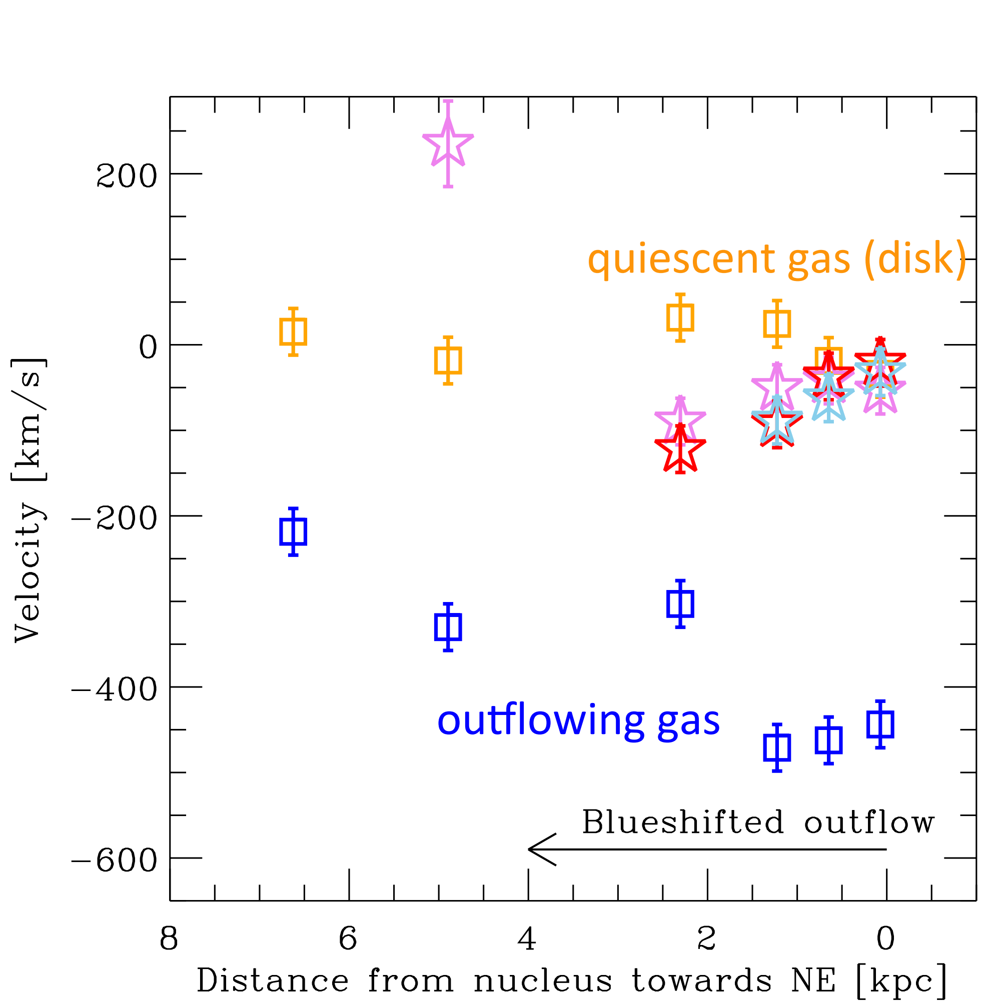
gas: narrow comp. (host gal.)
gas: broad comp. (outflow)
O−B−A stars (Balmer lines)
Red Superg. and AGBs (CaII trip.)
B stars (HeI)
quiescent gas (disk)
outflowing gas
Blueshifted outflow
Velocity [km/s]
200
0
−200
−400
−600
8
6
4
2
0
Distance from nucleus towards NE [kpc]

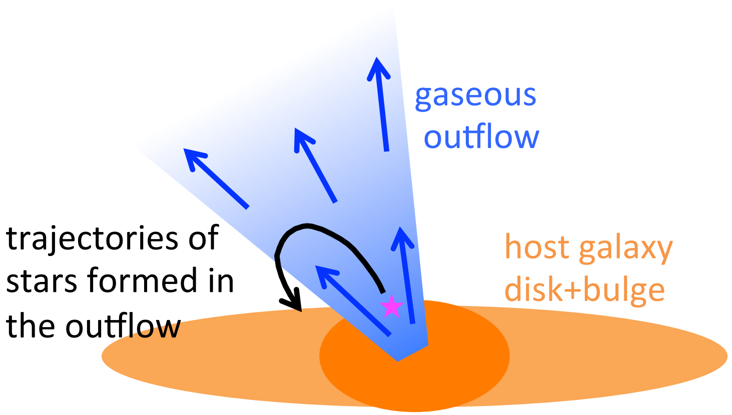
Kinematics



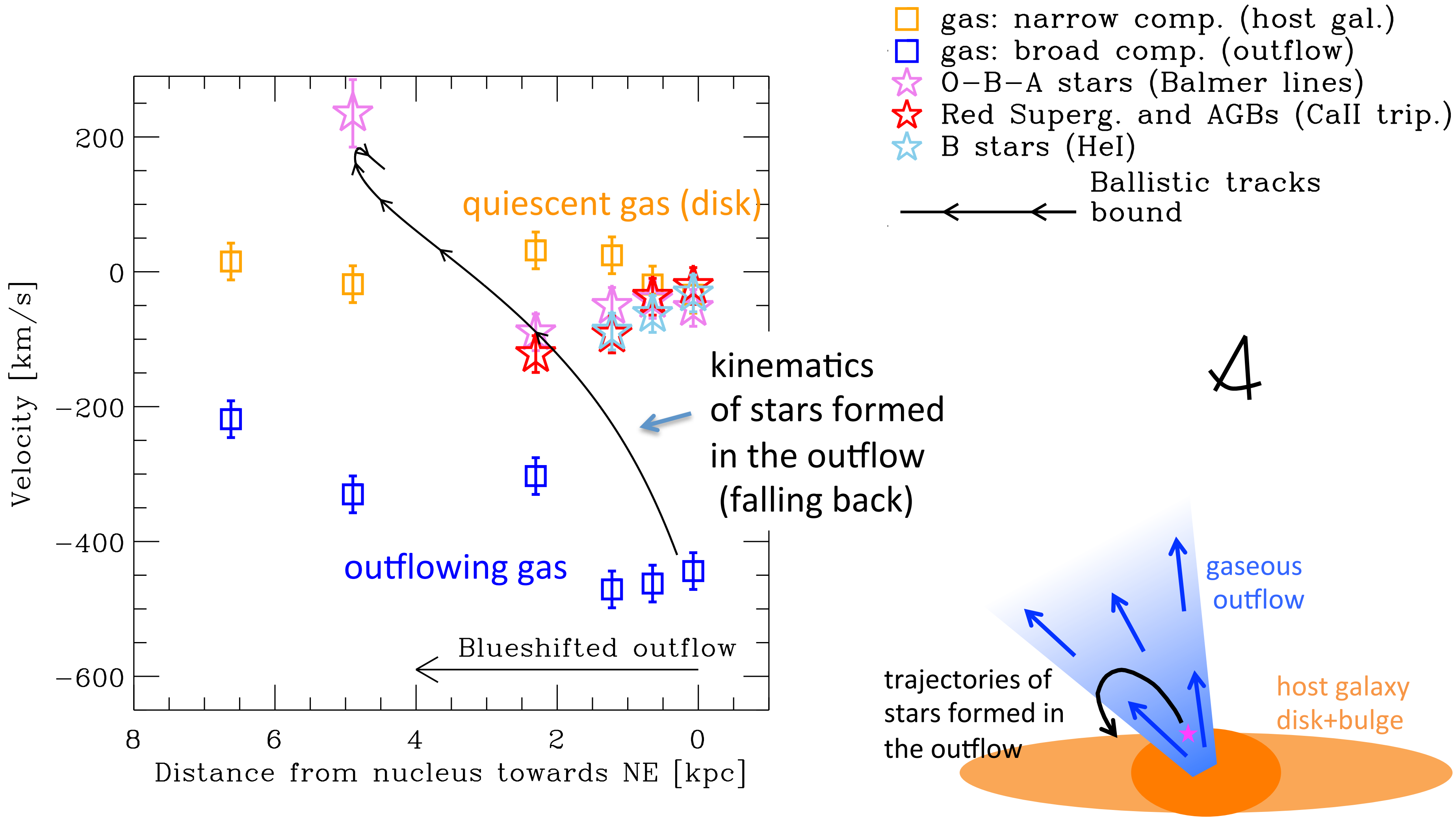
gas: narrow comp. (host gal.)
gas: broad comp. (outflow)
O−B−A stars (Balmer lines)
Red Superg. and AGBs (CaII trip.)
B stars (HeI)
quiescent gas (disk)
outflowing gas
Blueshifted outflow
Velocity [km/s]
Distance from nucleus towards NE [kpc]
200
0
−200
−400
−600
8
6
4
2
0

Kinematics


gas: narrow comp. (host gal.)
gas: broad comp. (outflow)
O−B−A stars (Balmer lines)
Red Superg. and AGBs (CaII trip.)
B stars (HeI)
quiescent gas (disk)
outflowing gas
Blueshifted outflow
Velocity [km/s]
Distance from nucleus towards NE [kpc]
200
0
−200
−400
−600
8
6
4
2
0

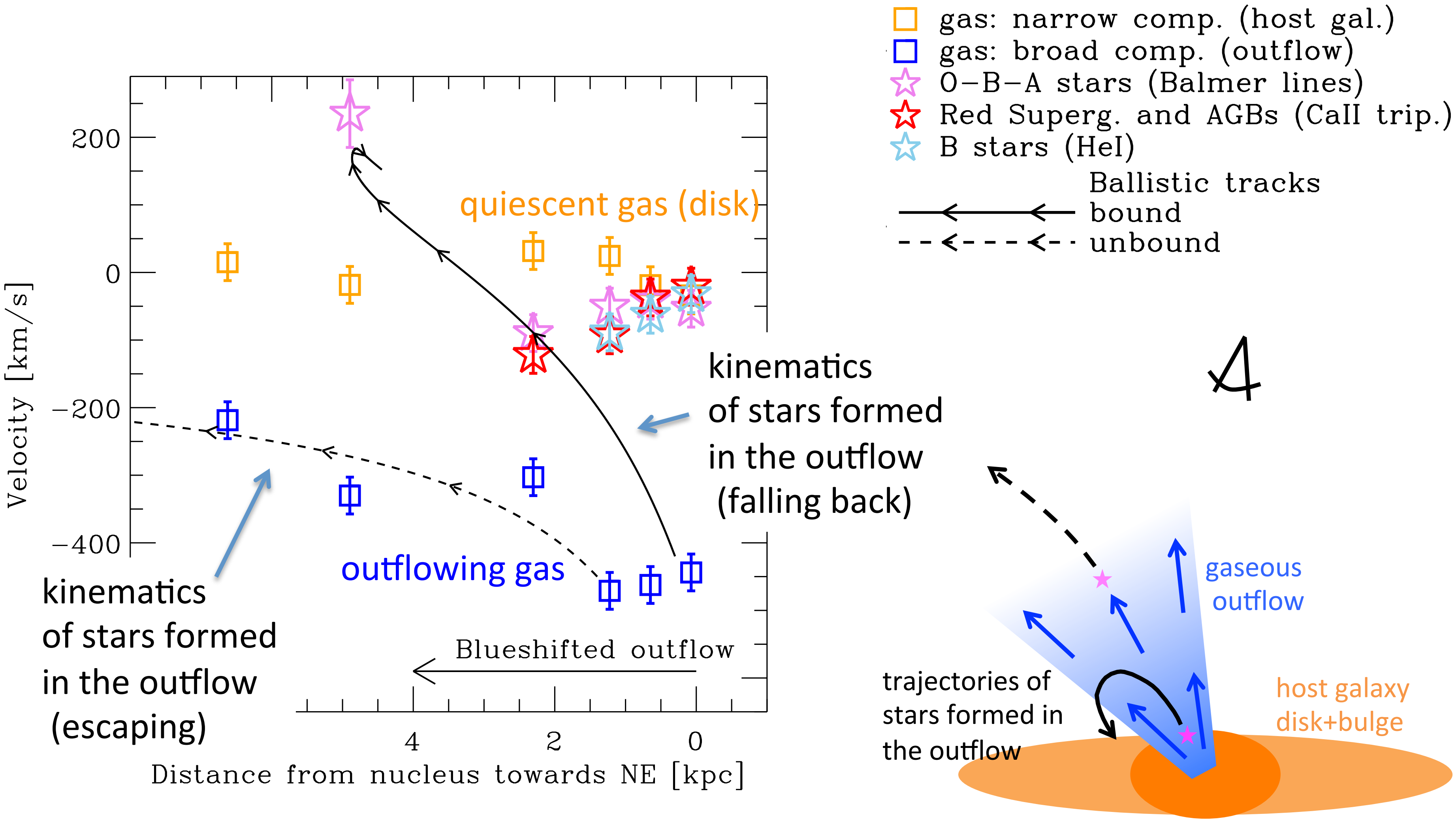

gaseous outflow
trajectories of stars formed in the outflow
host galaxy disk+bulge

Kinematics



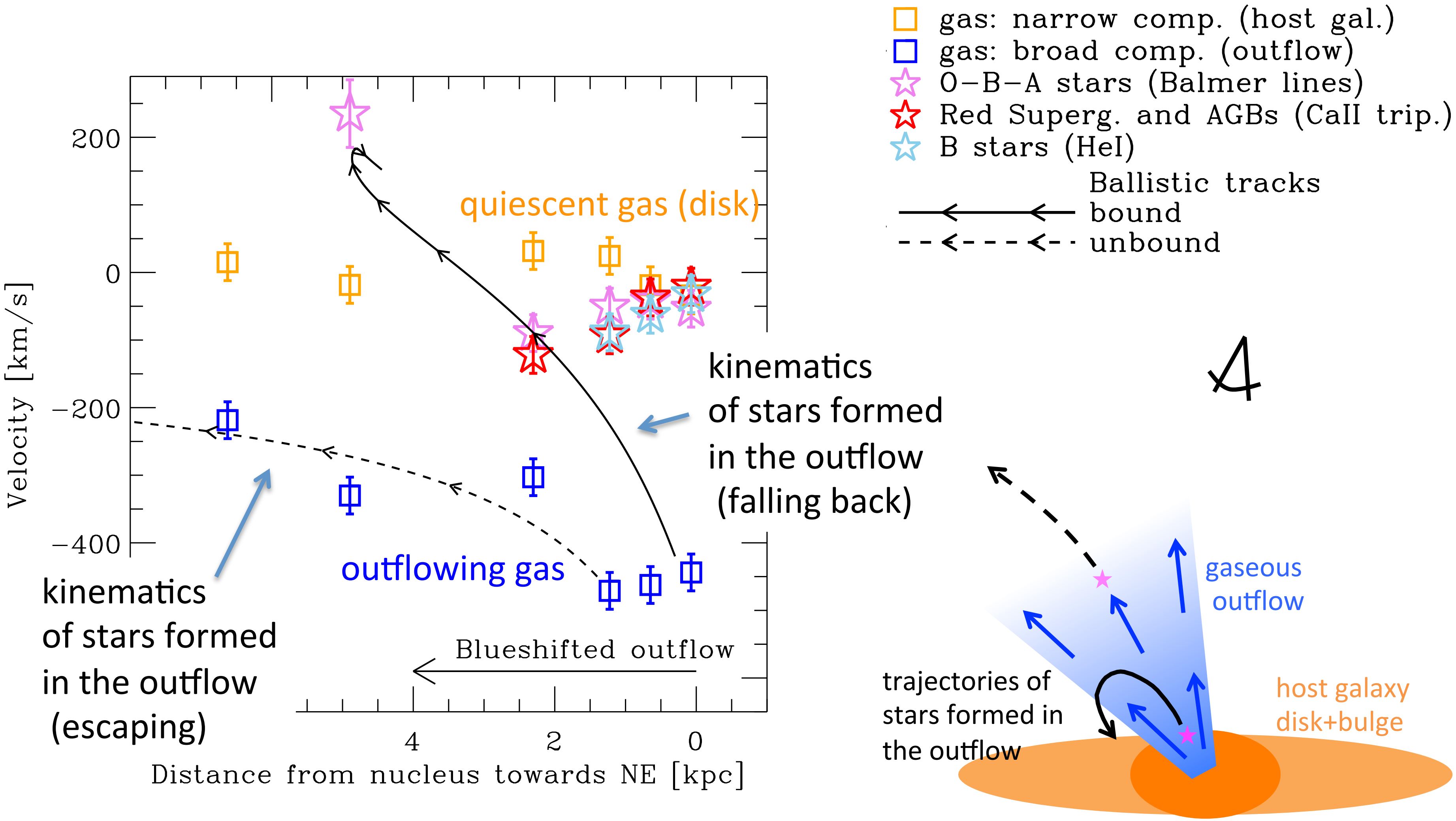
4

Kinematics



gas: narrow comp. (host gal.)
gas: broad comp. (outflow)
O−B−A stars (Balmer lines)
Red Superg. and AGBs (CaII trip.)
B stars (HeI)
Ballistic tracks
bound
unbound
200
0
−200
−400
Velocity [km/s]
4
2
0
Distance from nucleus towards NE [kpc]
quiescent gas (disk)
outflowing gas
Blueshifted outflow
kinematics of stars formed in the outflow (falling back)
kinematics of stars formed in the outflow (escaping)
gaseous outflow
host galaxy disk+bulge
trajectories of stars formed in the outflow

Kinematics



Together with the nebular diagnostics provide further evidence to the scenario of SF in outflows

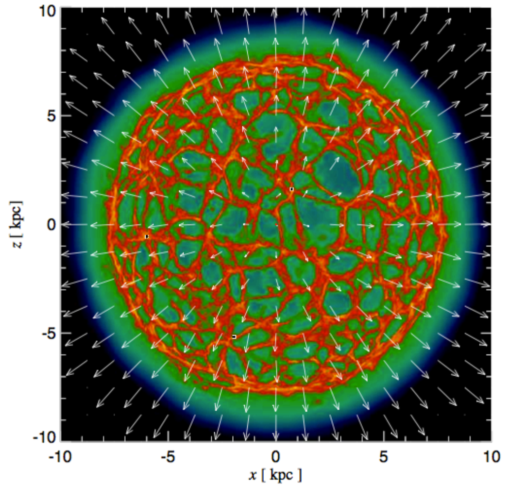
- No shocks
- No AGN

In-situ (in the outflow)
star formation is the
only viable explanation
consistent with all diagnostics

Young stellar kinematics consistent with stars formed in the outflow

Inferred star formation rate in the outflow:

~ 15-30 $M_{\odot}$/yr (i.e. ~15-30% of total)

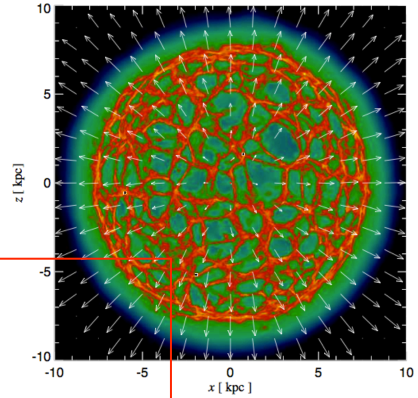


This is a
new mode of star formation
which may have been
overlooked in other outflows

- No shocks
- No AGN

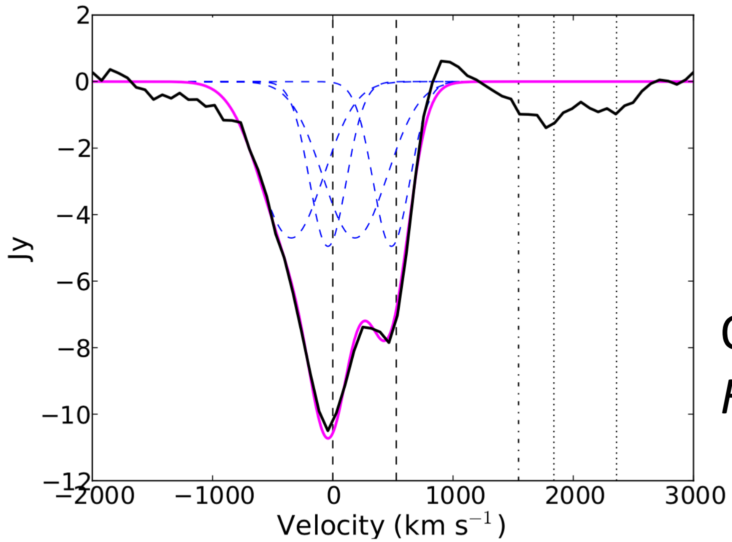
In-situ (in the outflow) star formation is the only viable explanation consistent with all diagnostics

Young stellar kinematics consistent with stars formed in the outflow

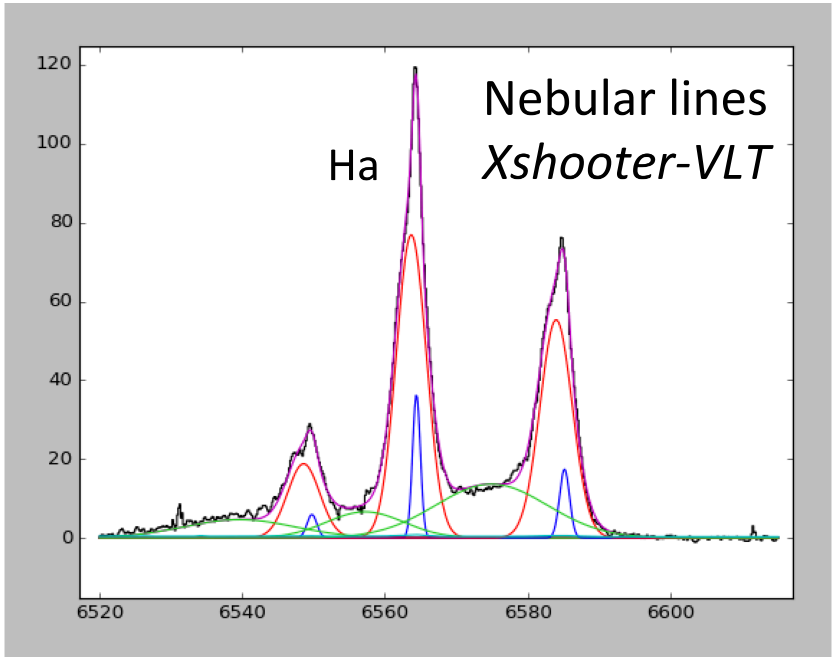


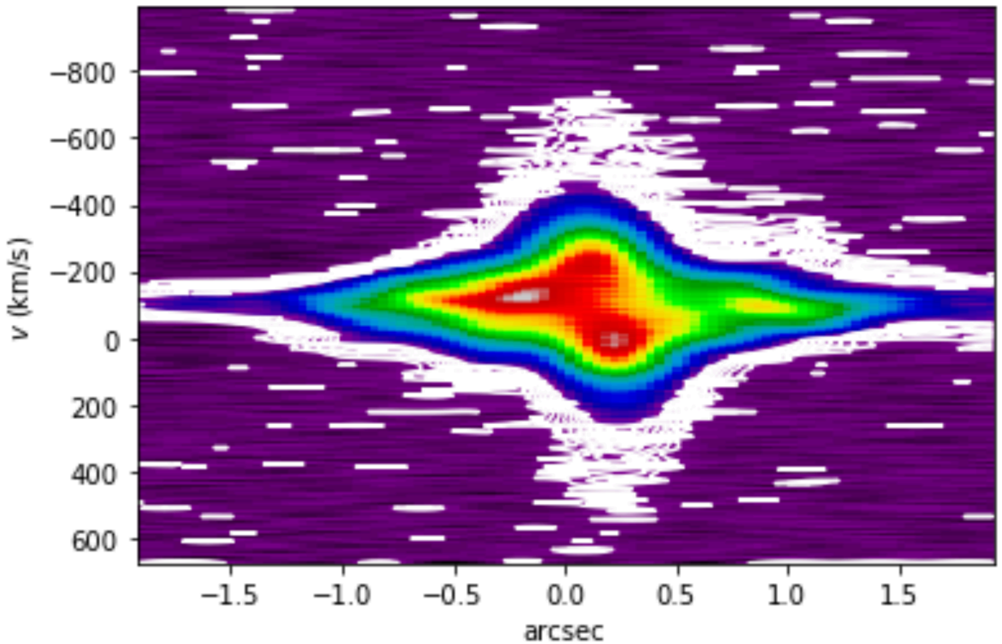
- How common it star formation in outflows?
  - Can it explain wind-SFR correlation? Woo+17
  - Can explain centrally concentrated SF in some AGNs? Mushotzky+14, Alonso-Herrero+15
- What's the efficiency of star formation in the outflow?

Additional observations of a few additional galaxies with powerful massive molecular winds (Herschel sample, Sturm+11, Veilleux+13)



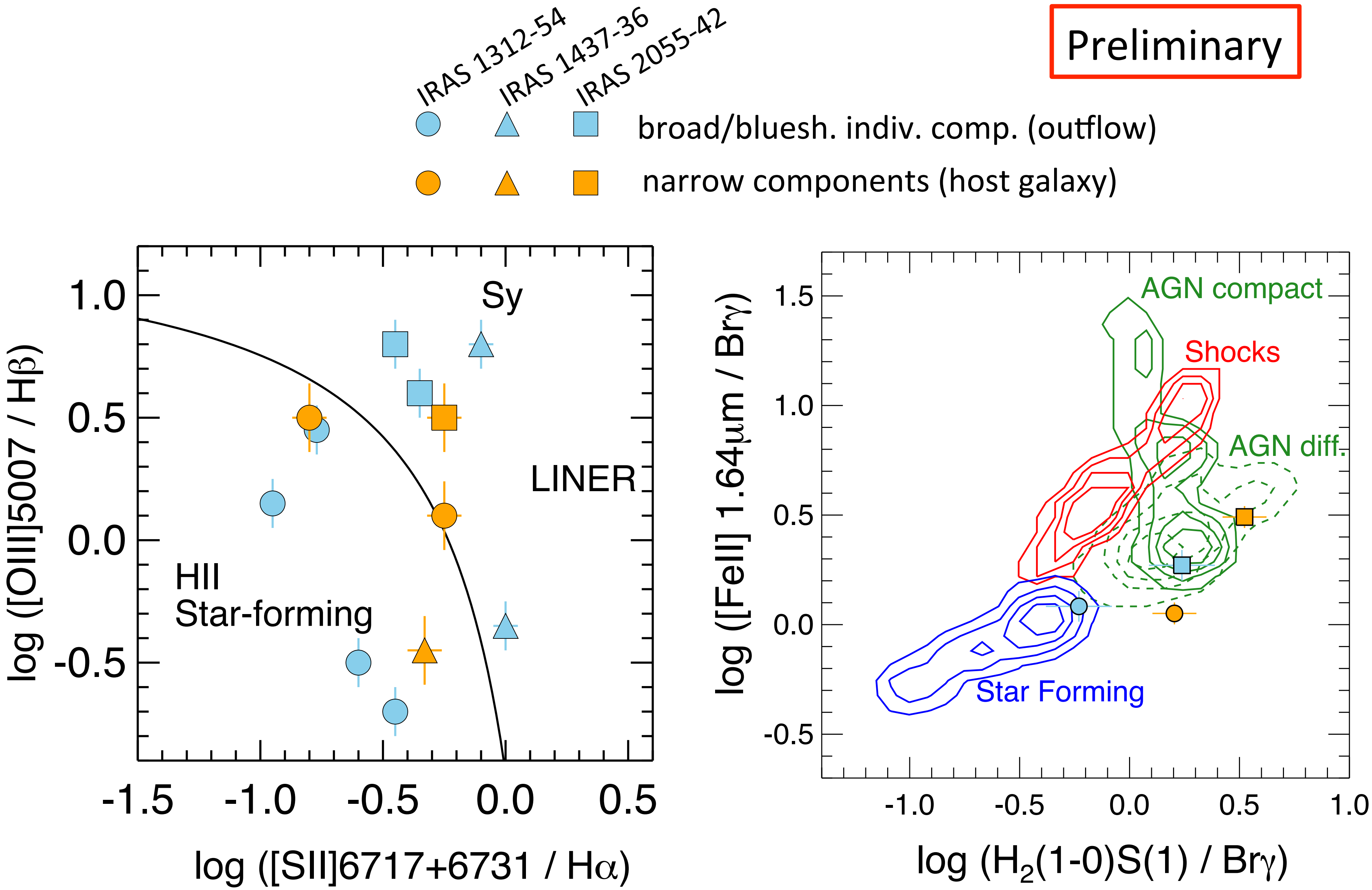
OH
Herschel





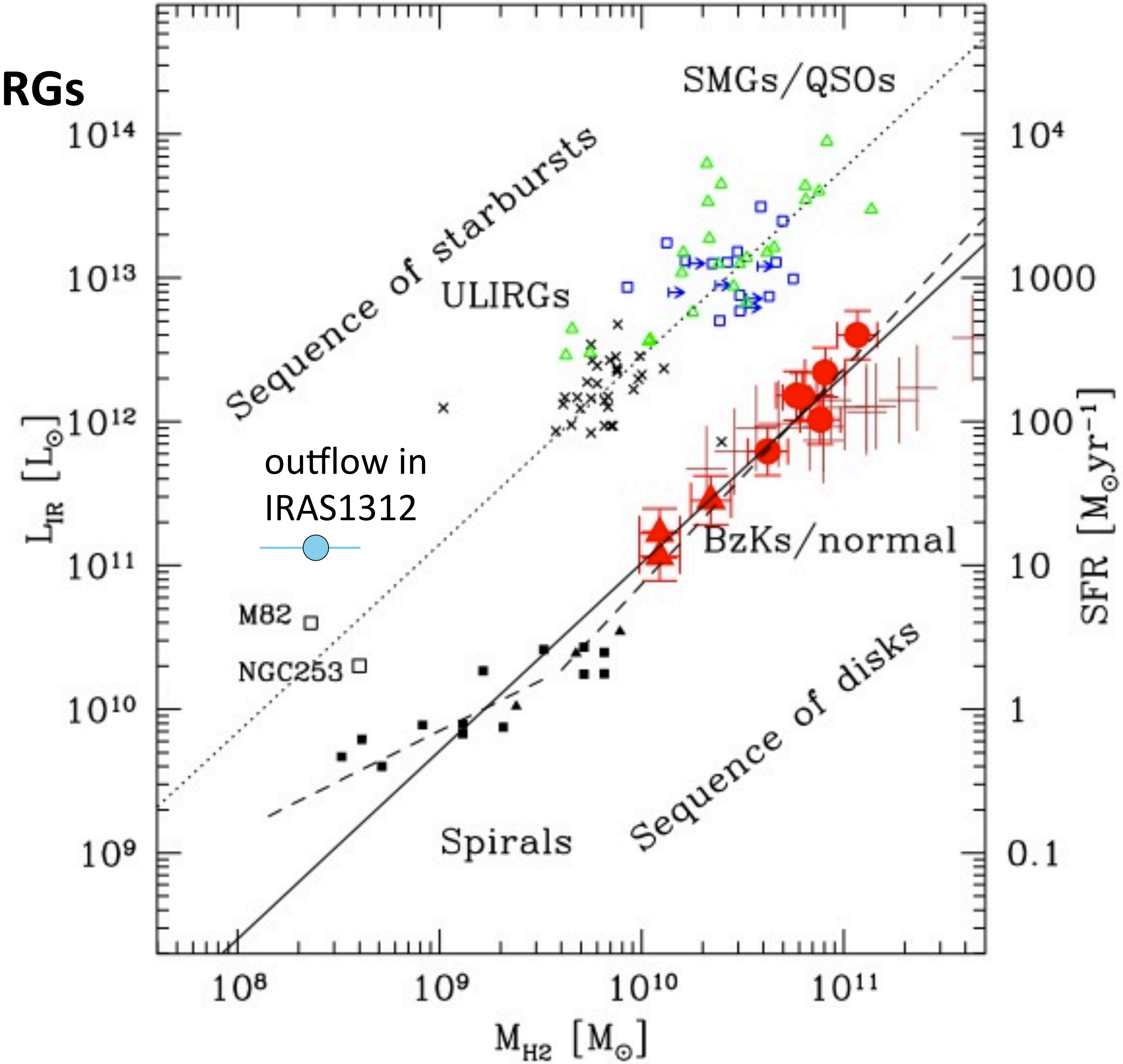
CO(1-0)
ALMA

One of the targets show similar results as in IRAS2312-59 (in progress)

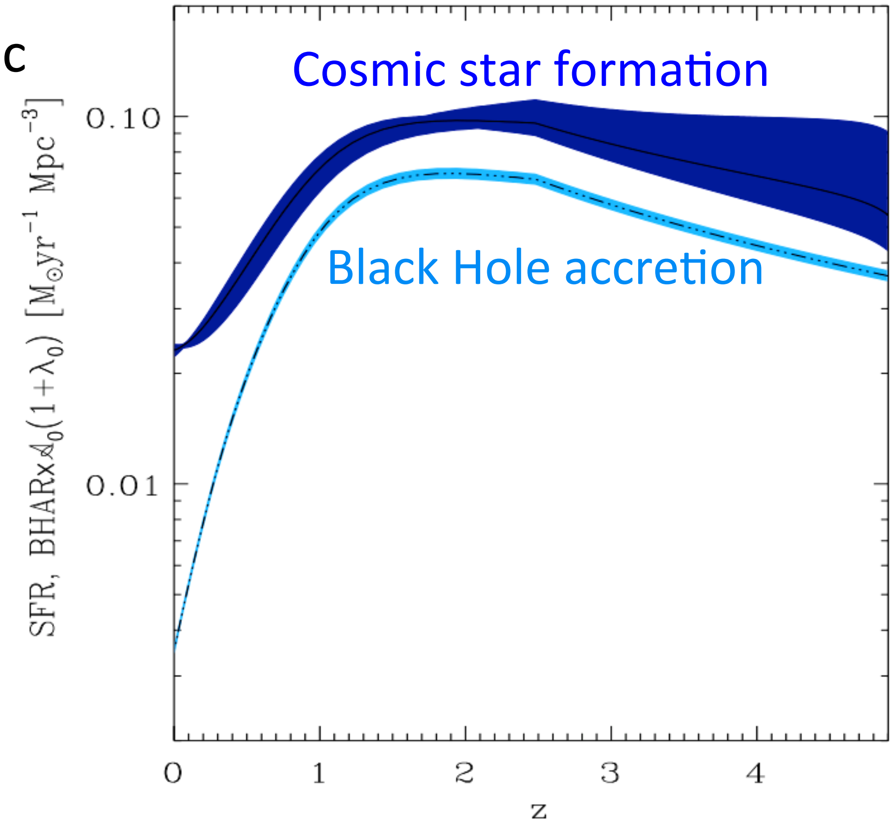

Preliminary
IRAS 1312-54
IRAS 1437-36
IRAS 2055-42
broad/bluesh. indiv. comp. (outflow)
narrow components (host galaxy)
Sy
LINER
HII
Star-forming
1.0
0.5
0.0
-0.5
-1.5
-1.0
-0.5
0.0
0.5
log ([OIII]5007 / Hβ)
log ([SII]6717+6731 / Hα)
AGN compact
Shocks
AGN diff.
Star Forming
1.5
1.0
0.5
0.0
-0.5
-1.0
-0.5
0.0
0.5
1.0
log ([FeII] 1.64μm / Brγ)
log (H2(1-0)S(1) / Brγ)

Star formation ``efficiency'' in the outflow comparable to ULIRGs

Preliminary

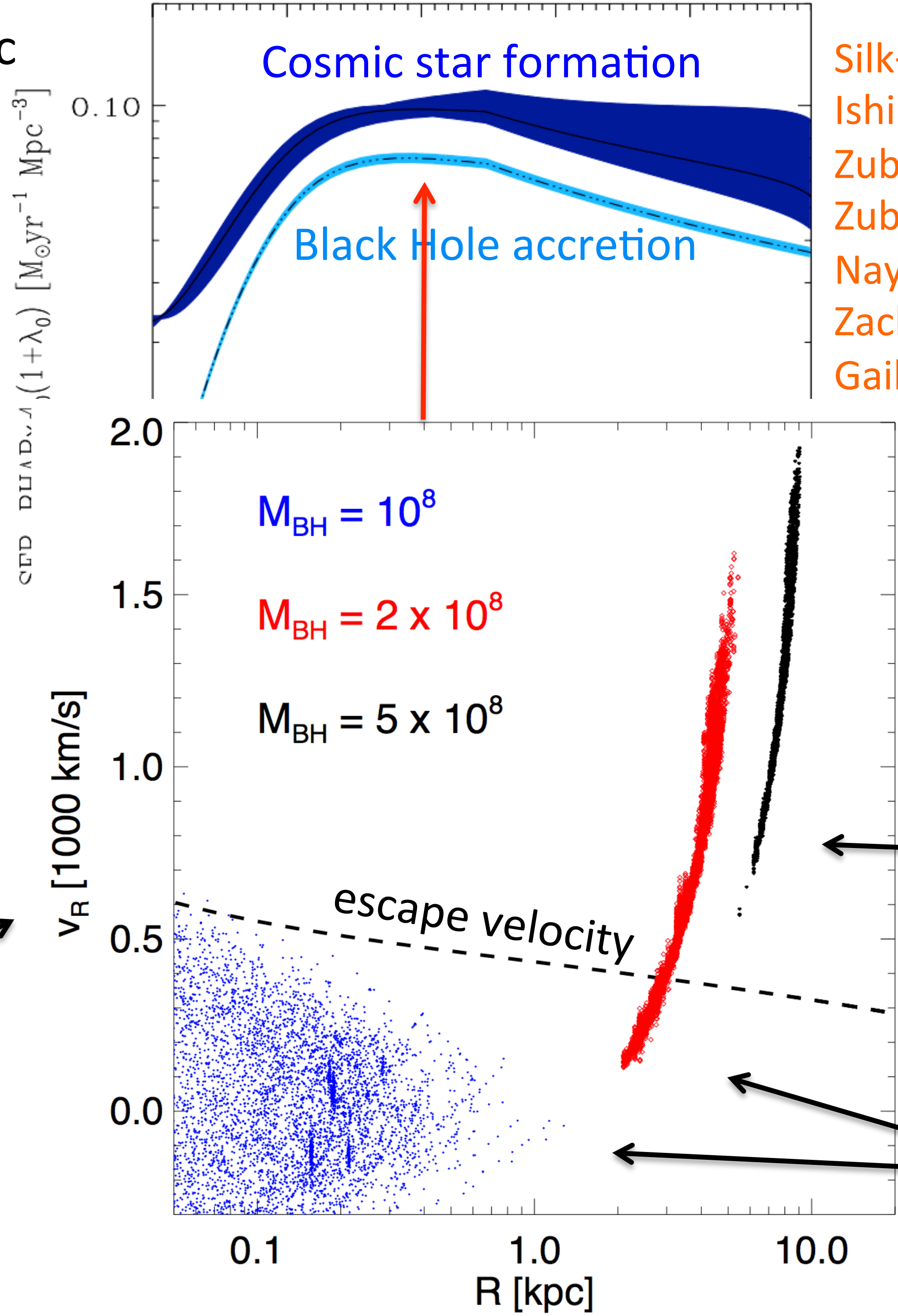


The peak of cosmic BH accretion can potentially contribute significantly to the formation of spheroids (bulges & ellipticals)



Silk+15, +17
Ishibashi & Fabian +14, +15
Zubovas+13
Zubovas & King '13
Nayakshin+12
Zachary+14
Gaibler+12

The peak of cosmic BH accretion can potentially contribute significantly to the formation of spheroids (bulges & ellipticals)



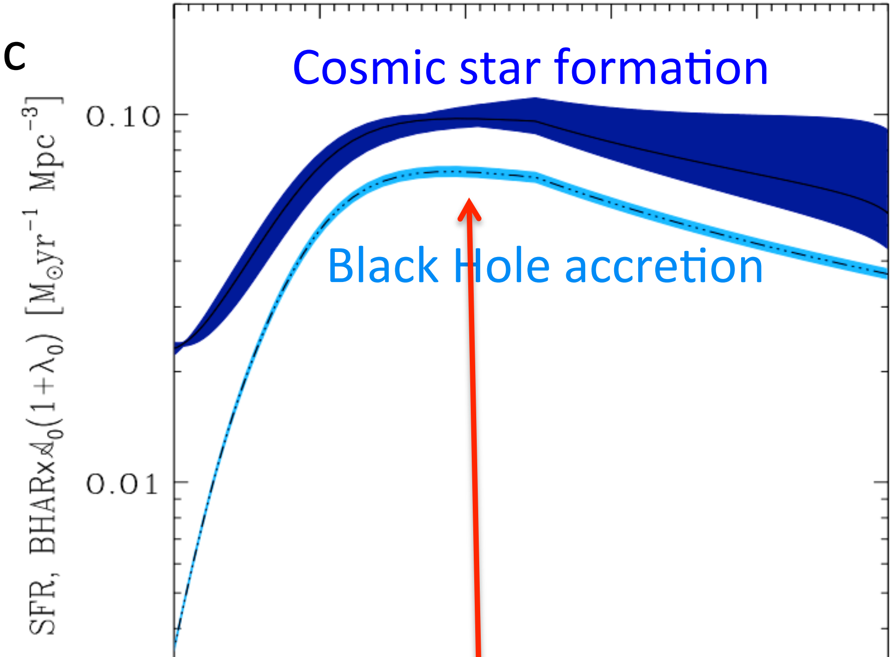
Silk+15, +17
Ishibashi & Fabian +14, +15
Zubovas+13
Zubovas & King '13
Nayakshin+12
Zachary+14
Gaibler+12

radial velocity of stars formed in outflow

escaping SNe ⇒*in situ* metal enrichment of the IGM/CGM

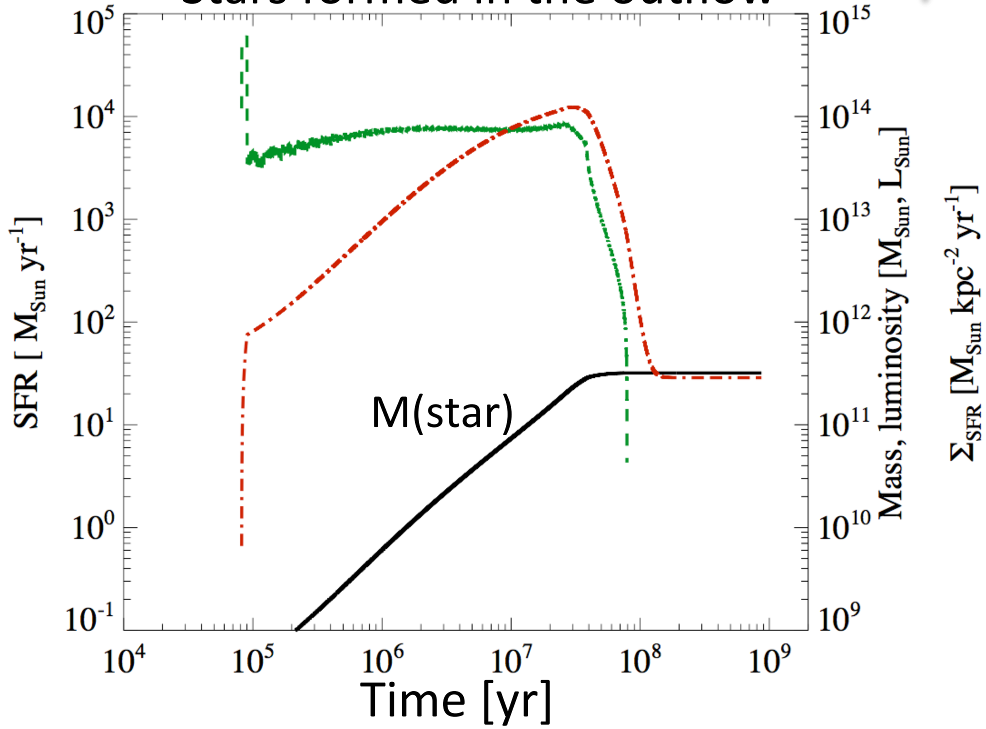
Bulge-Halo stars
Elliptical gal. stars

The peak of cosmic BH accretion can potentially contribute significantly to the formation of spheroids (bulges & ellipticals)

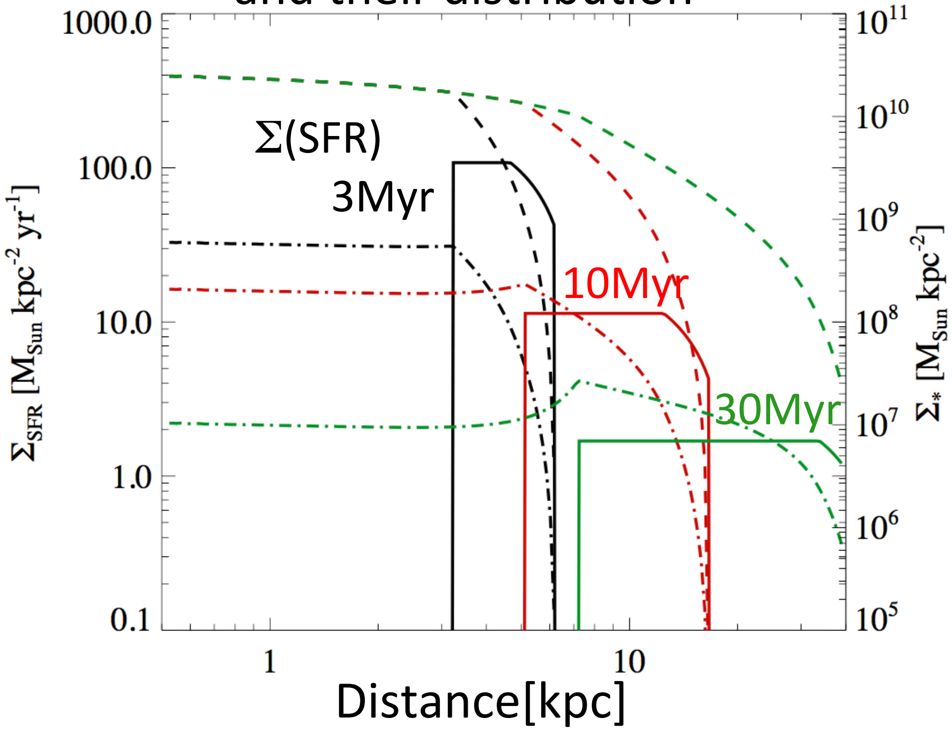


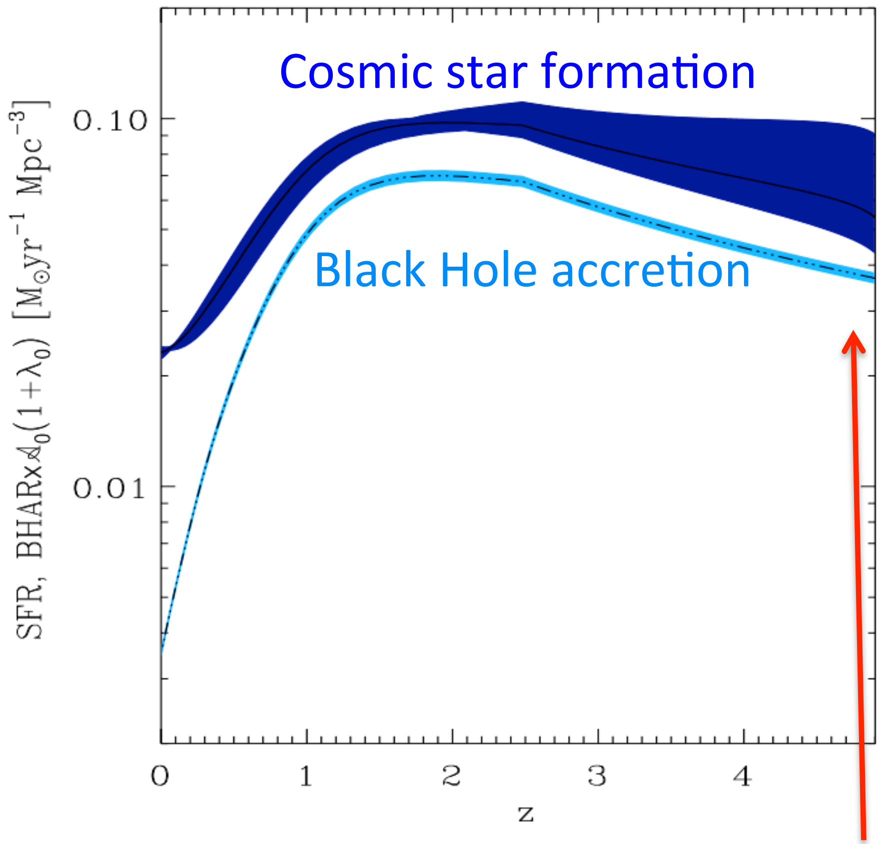
Silk+15, +17
Ishibashi & Fabian +14, +15
Zubovas+13
Zubovas & King '13
Nayakshin+12
Zachary+14
Gaibler+12

Stars formed in the outflow



and their distribution





Silk+15, +17
Ishibashi & Fabian +14, +15
Zubovas+13
Zubovas & King '13
Nayakshin+12
Zachary+14
Gaibler+12

In the early Universe
stars formed in the outflow
can contribute significantly
to the **re-ionization** of the Universe
as they have **high escape fraction**
of ionizing photons

Summary

- AGN-driven winds certainly make a lot of damage to their host galaxy

- Unclear whether AGN-driven winds can really totally quench star formation
  -> possibly help to halt gas inflow
  -> strangulation/starvation

- Star formation can take place within AGN-driven outflows
  -> potential major implications for galaxy evolution