AGN13 - Beauty and the Beast

Milano - October 11, 2018

Outflows vs star formation in nearby AGN from the MAGNUM survey

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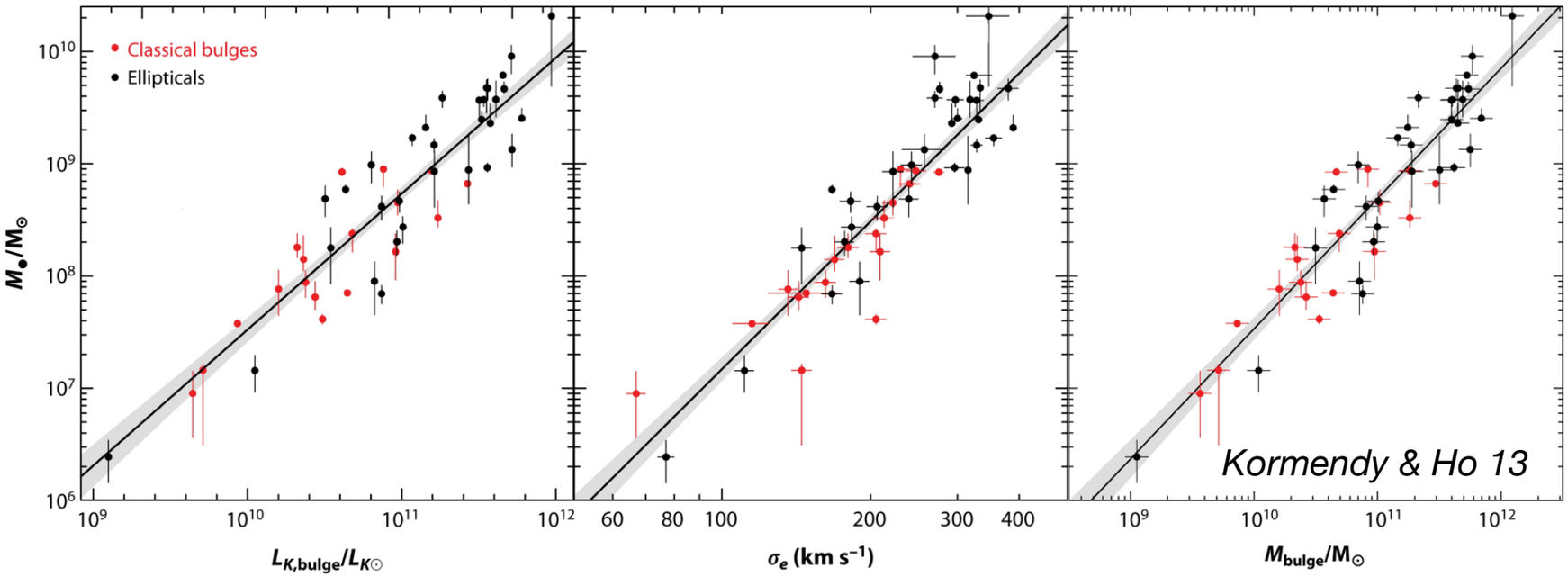
in collaboration with

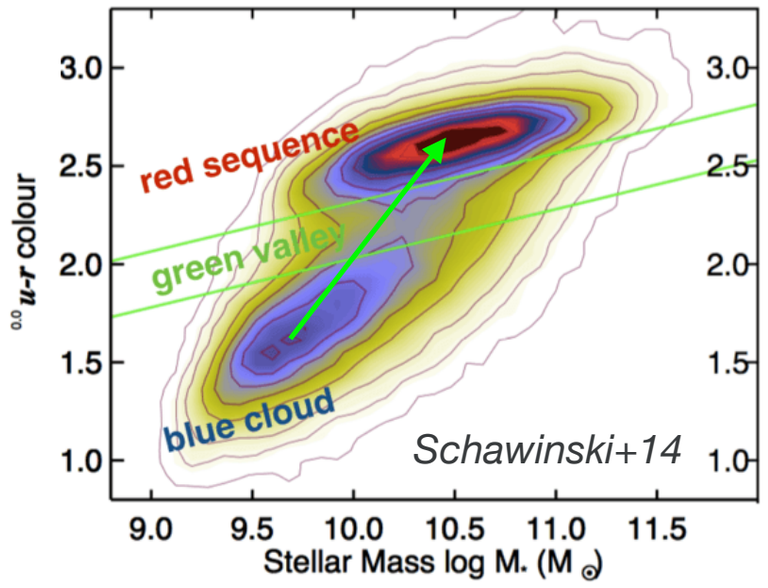
A. Marconi (P.I.), M. Mingozzi, E. Nardini, S. Carniani, R. Maiolino, G. Cresci et al.

Galaxy evolution: the need for feedback

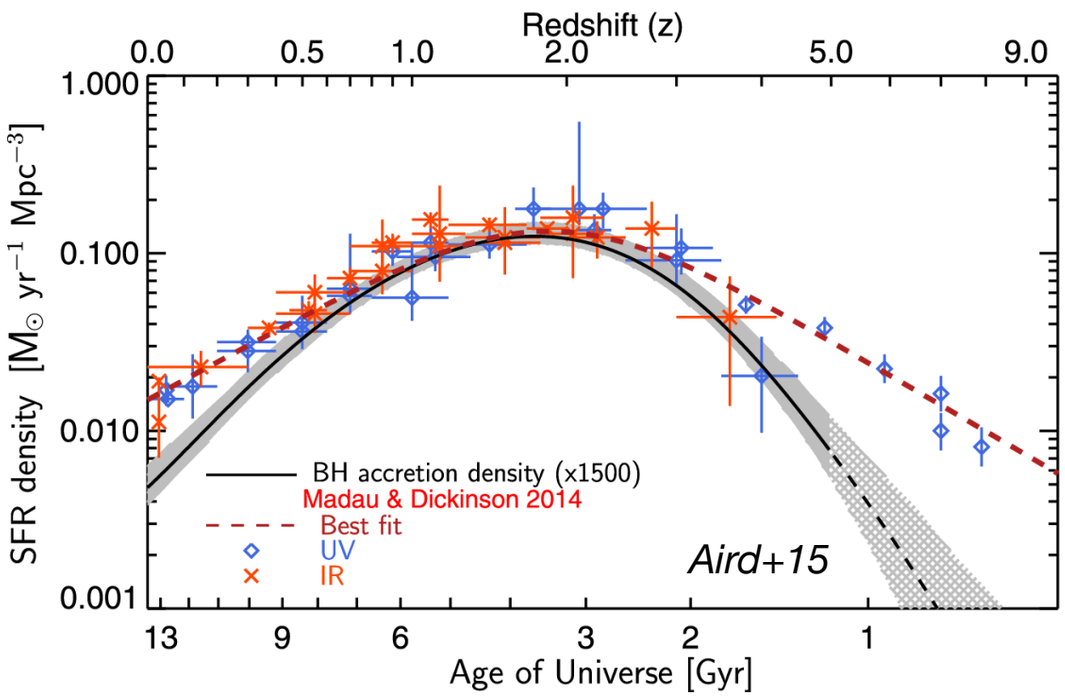
1) M_{BH}-L_{bul}, M_{BH}-σ_{bul}, M_{BH}-M_{bul} scaling relations



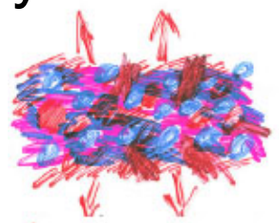
2) Galaxy bimodality



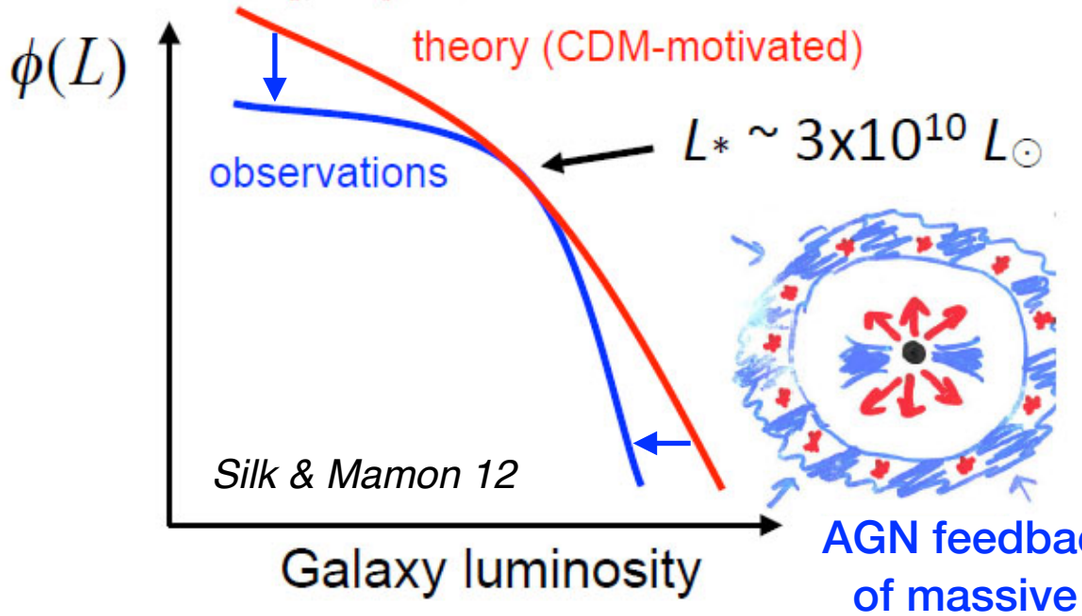
3) SFR similar to BH accretion history



4) Galaxy luminosity function



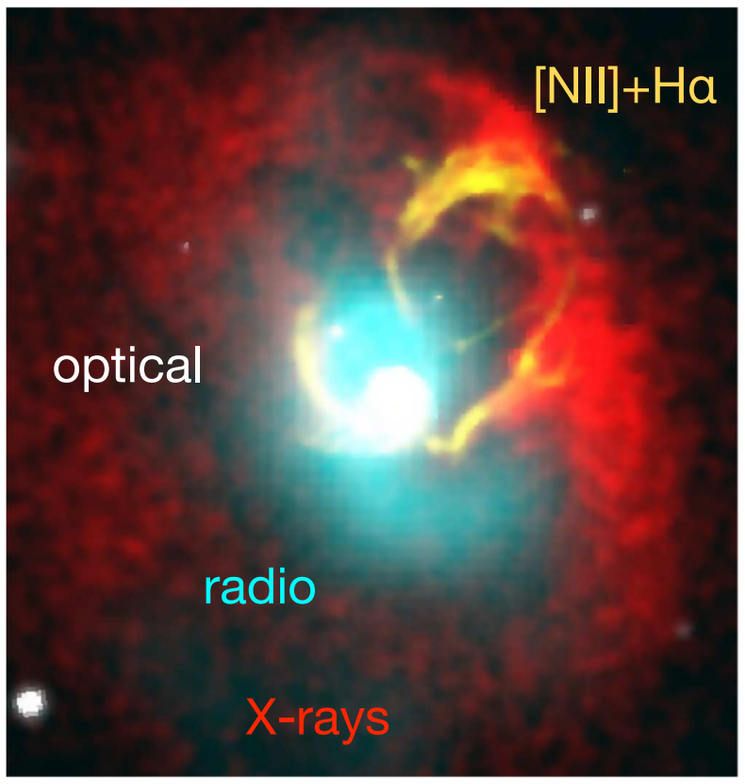
Stellar (SN) feedback accounts for the lack of low-mass galaxies



AGN feedback for lack of massive galaxies

Searching for feedback in action

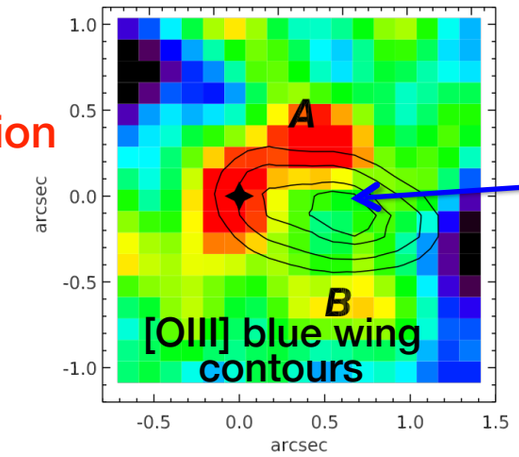
Feedback from radio jets in massive elliptical galaxies

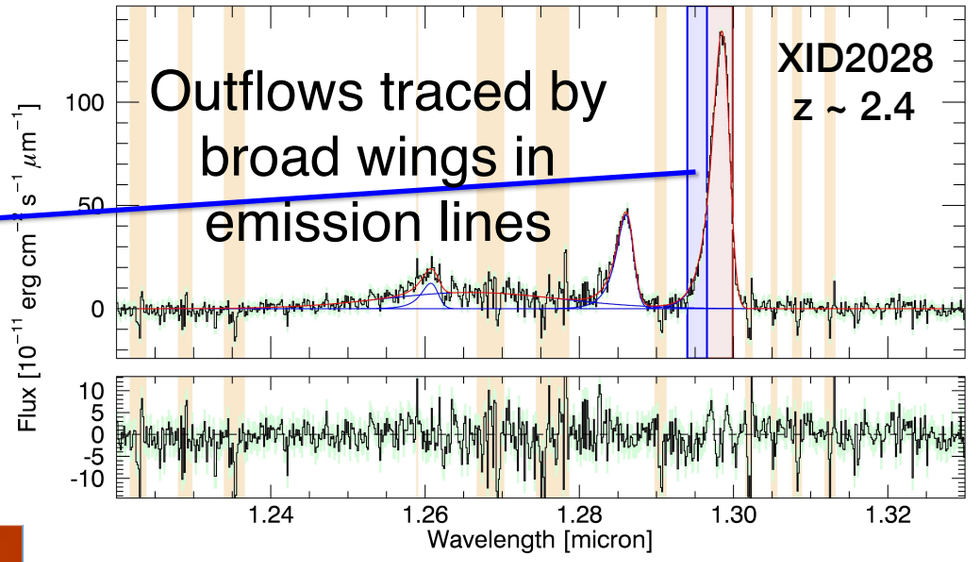


Balmaverde,GV+18

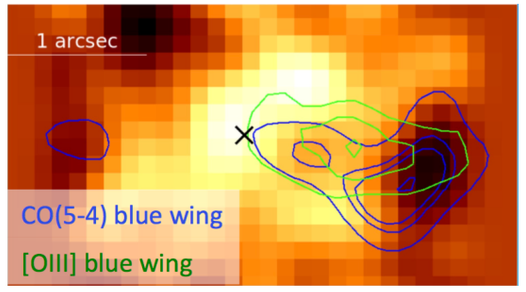
Feedback from outflows in powerful quasars at peak of AGN activity $z \sim 1$-3

Star Formation (Hα)





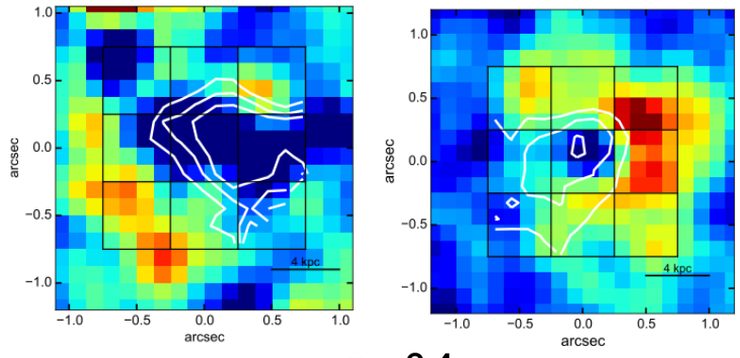
Molecular + ionized outflow



Low gas fraction (<5%) and depletion timescales (<10^8 yr)

Cresci+15a, Brusa+18

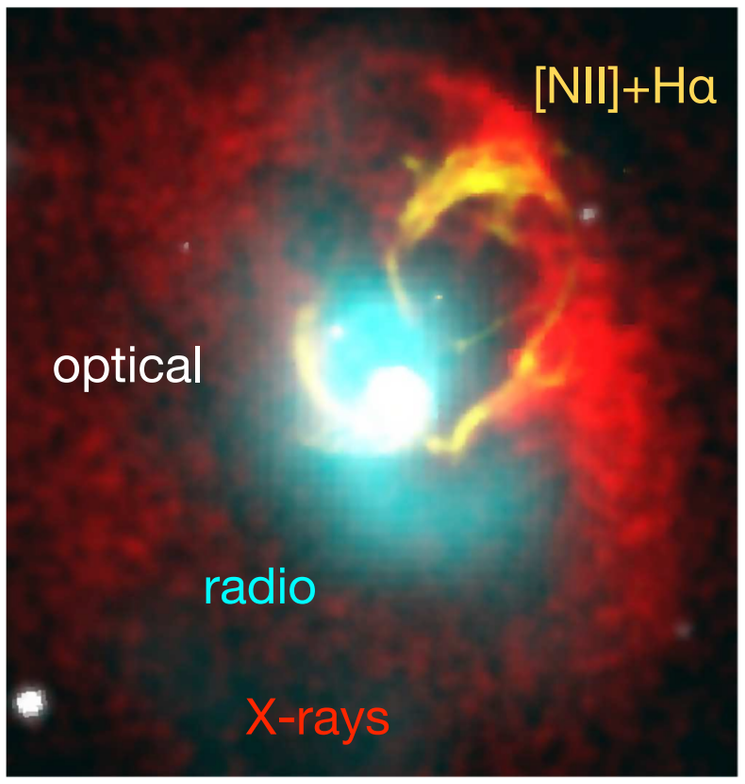
Star Formation (Hα) vs [OIII] blue wing contours



Carniani+15,16 z ~ 2.4

Searching for feedback in action

Feedback from radio jets in massive elliptical galaxies



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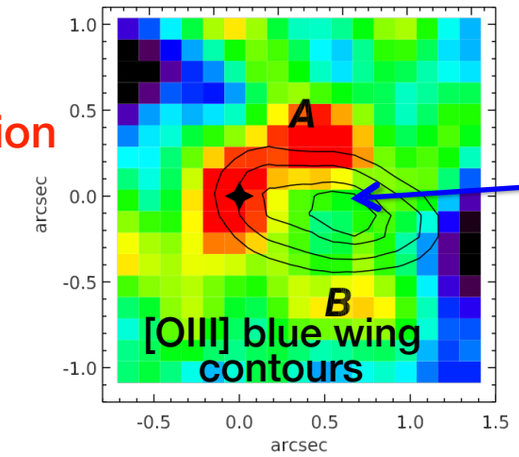

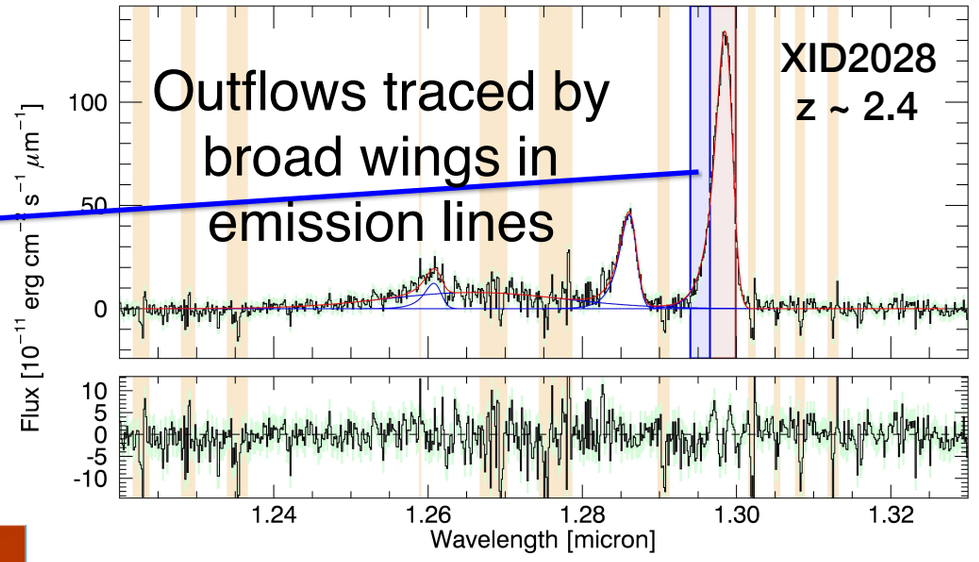

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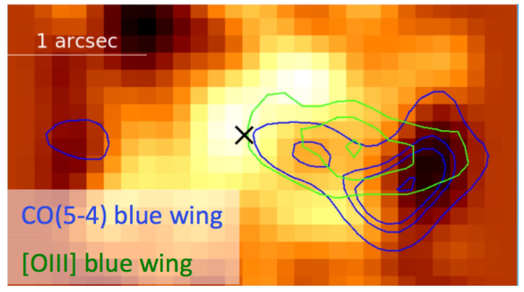

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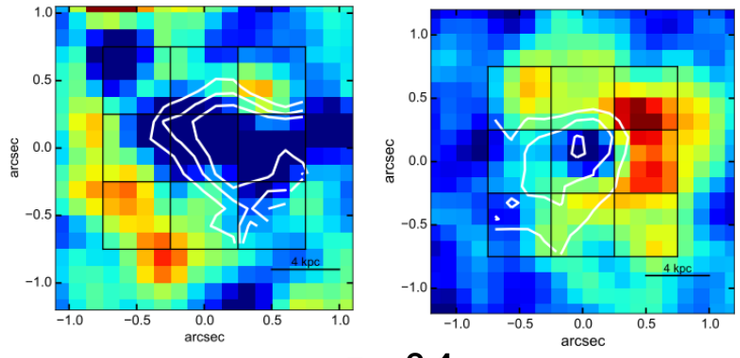


Carniani+15,16 z ~ 2.4

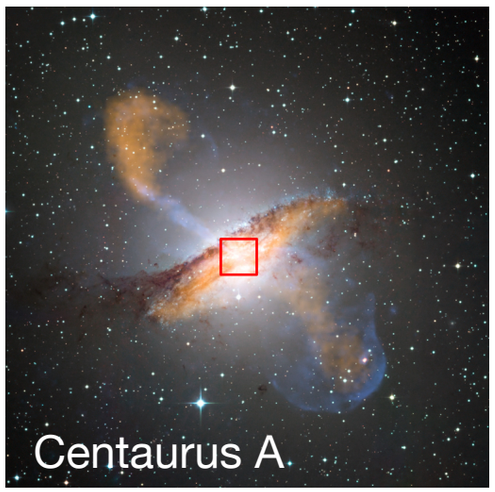
…but low-resolution, difficult to study in detail feedback and outflow physical properties

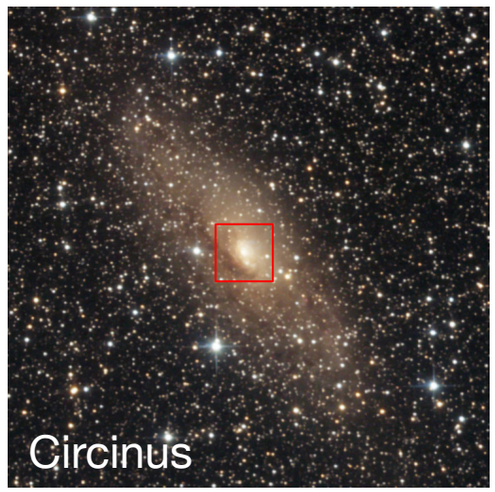
MAGNUM survey

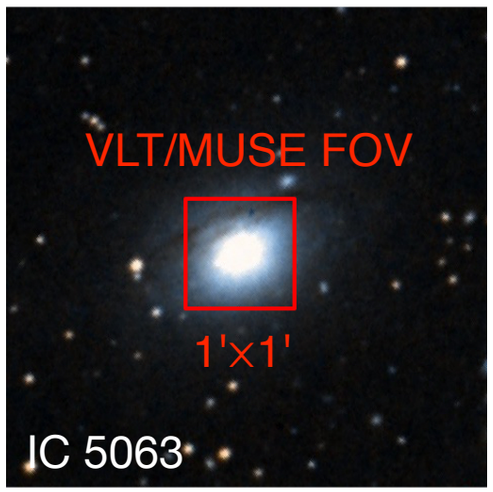
Nearby (*D* < 50 Mpc) **Seyferts** with **VLT/MUSE**

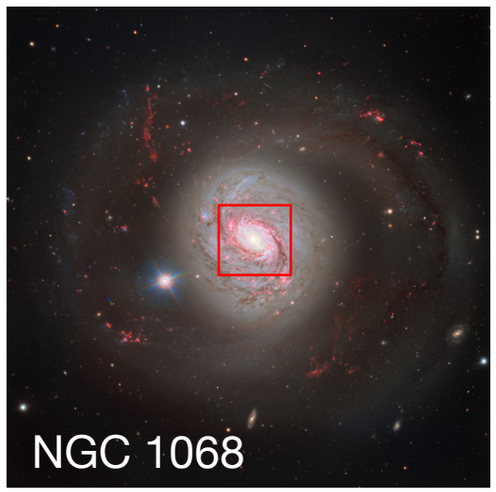
to characterize **feedback** and **outflow properties** in detail

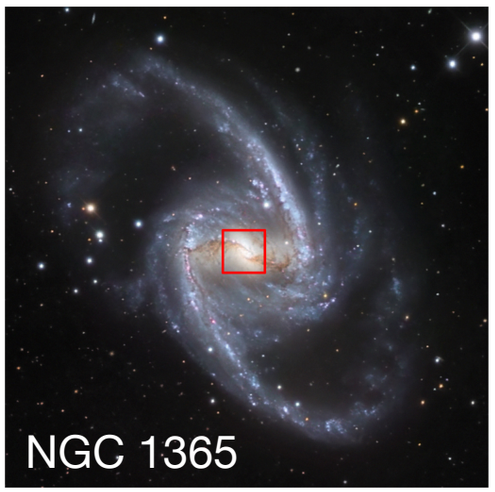
FOV covers **1 to 15 kpc** with **resolution: 15 pc** (@4Mpc) to **115 pc** (@30Mpc)

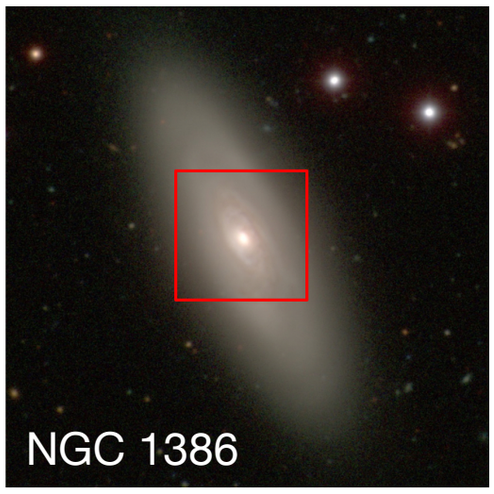


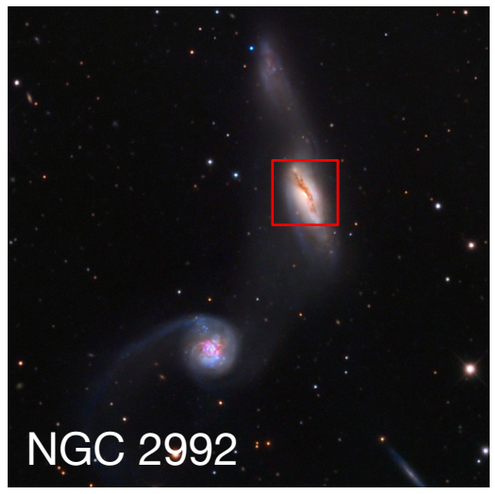


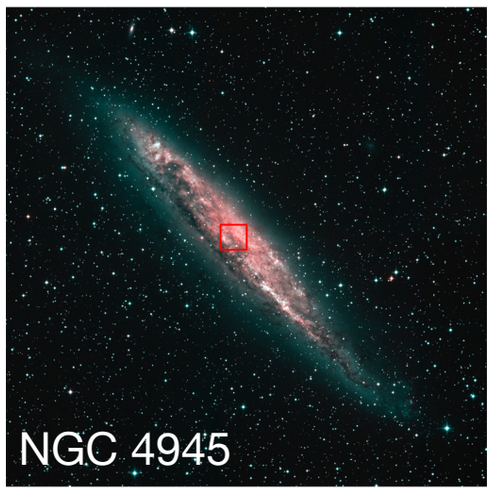


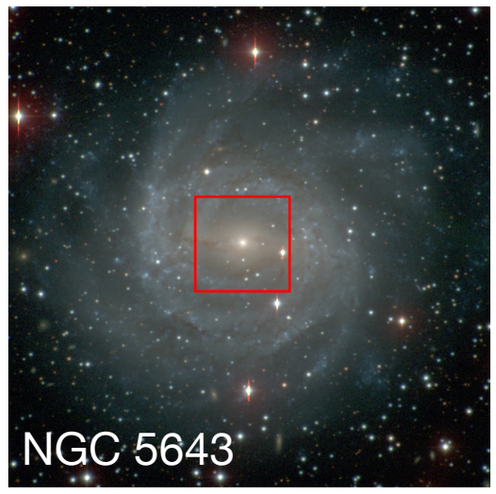


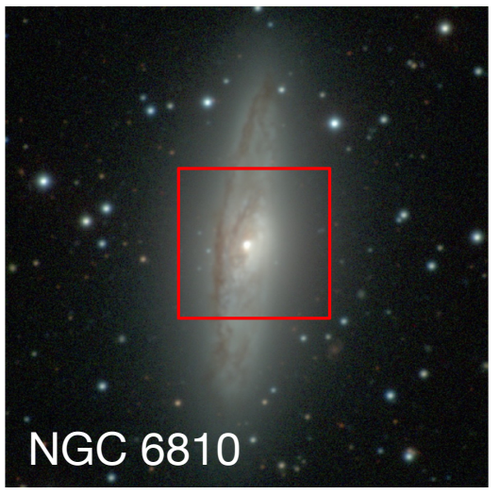












Venturi+17, Mingozzi+subm.

Part 1: NGC 1365

Detailed study of ionized gas in the central kpcs of **NGC 1365**:

AGN vs star formation, mapping the **outflow properties**

from optical (**MUSE**) and X-ray (**Chandra**) data

Venturi et al., 2018

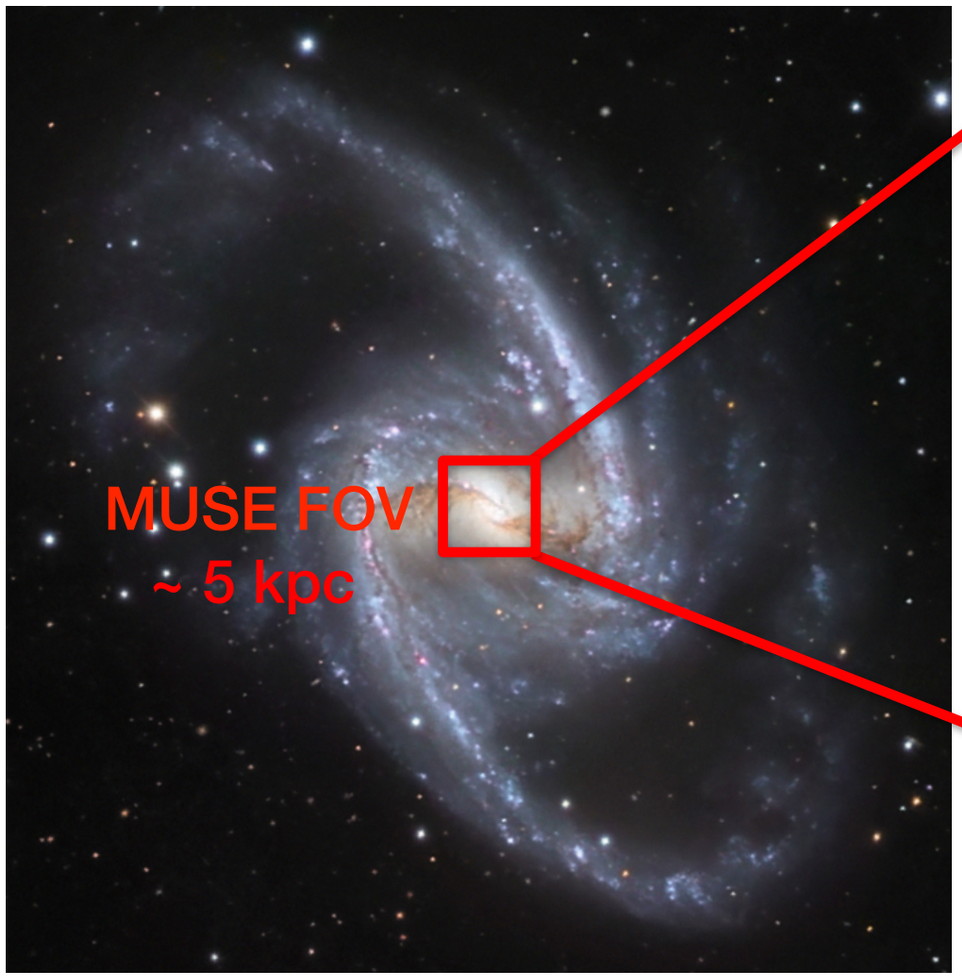
NGC 1365: complex environment in central kpcs

Massive barred galaxy (4×10^{11} $M_\odot$)

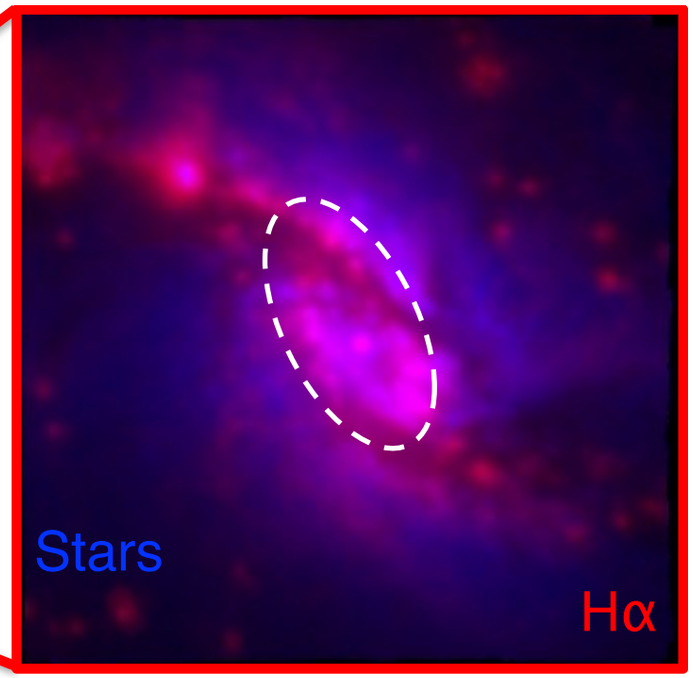
hosting a low-luminosity AGN:

$L_{AGN} \sim 2\times10^{43}$ erg/s

NGC 1365: complex environment in central kpcs



Spatial res. —> ~60 pc



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Star formation (~7 $M_\odot$/yr):

Hα follows dust lanes along

the bar + circumnuclear

ring (~5.6 $M_\odot$/yr)

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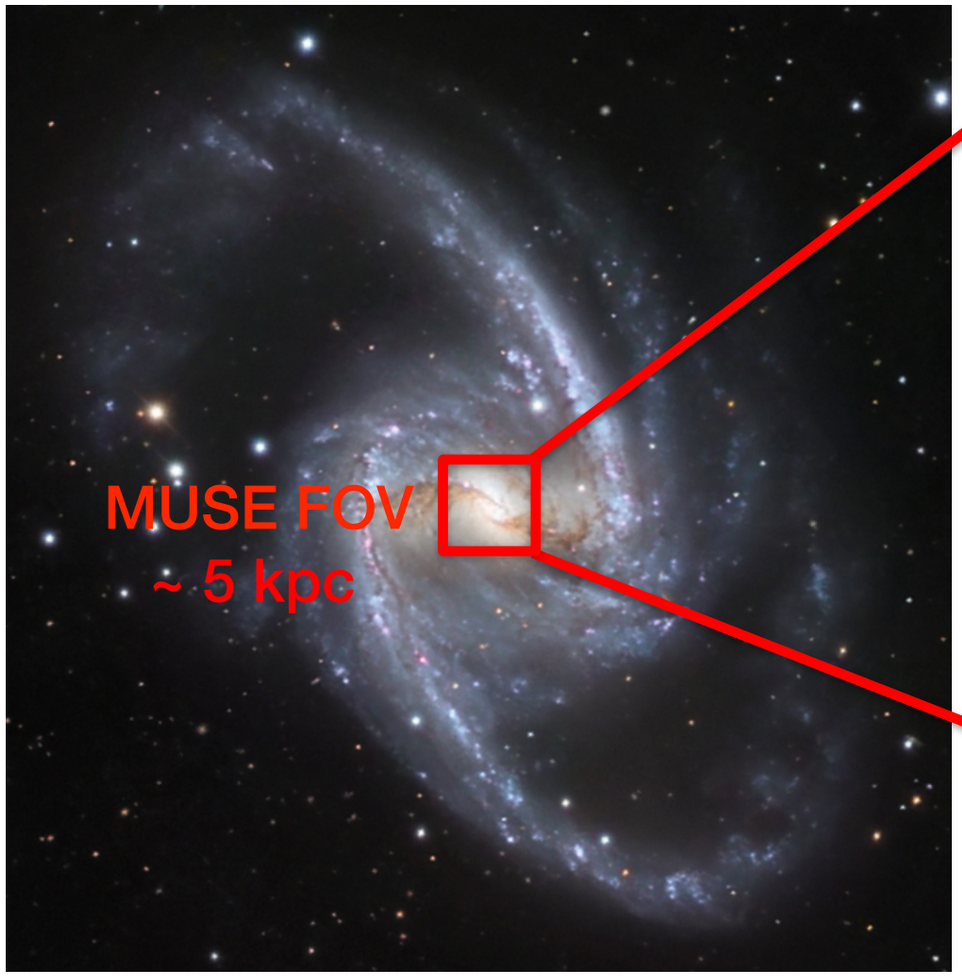

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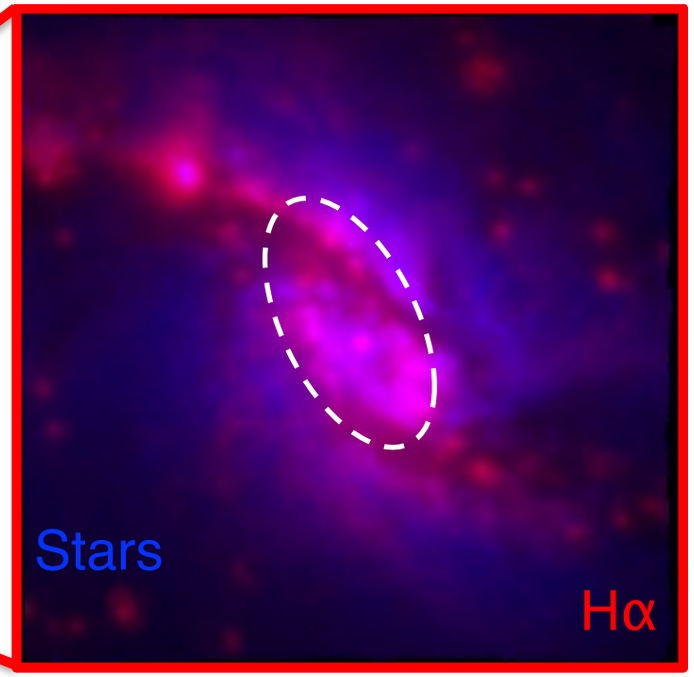

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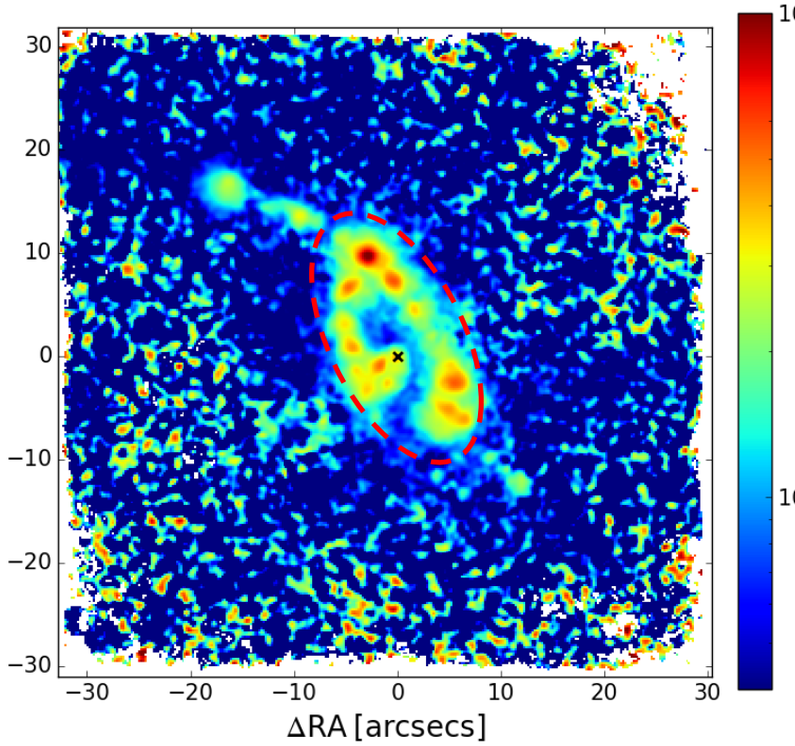
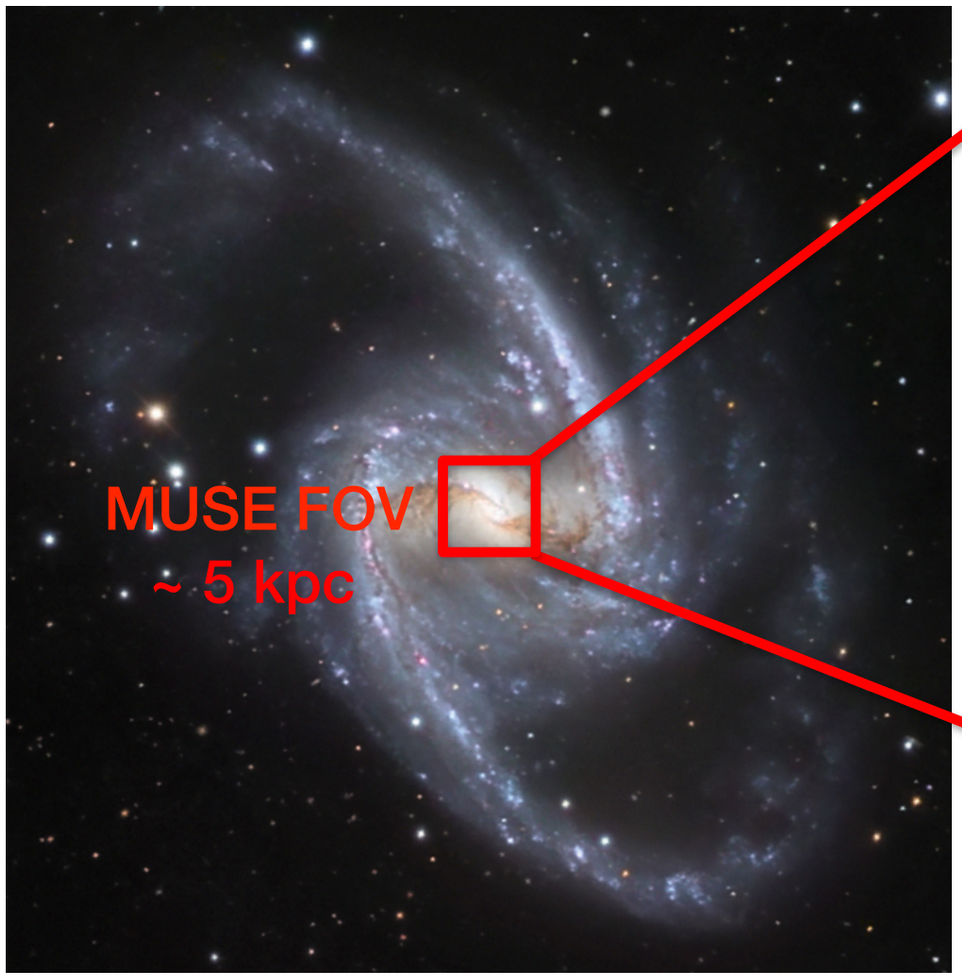


Density from [SII] doublet

up to 10^3 cm^{-3} in the ring

NGC 1365: complex environment in central kpcs



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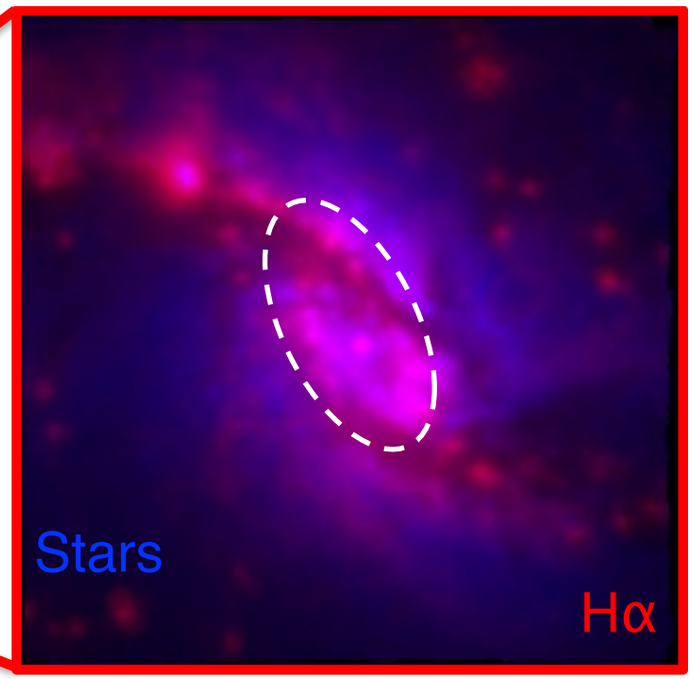

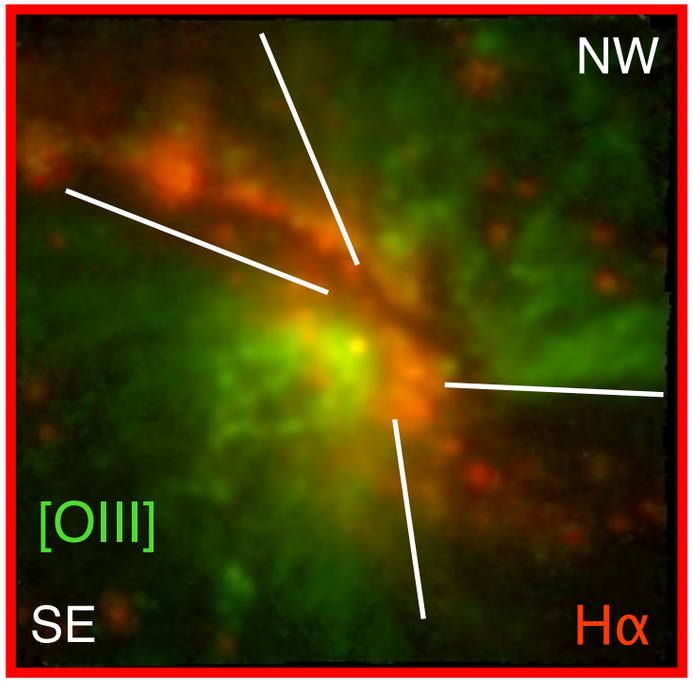

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Hα follows dust lanes along the bar + circumnuclear ring (~5.6 $M_\odot$/yr)

[OIII] ⊥ double cone

SE less obscured

→ above disk,

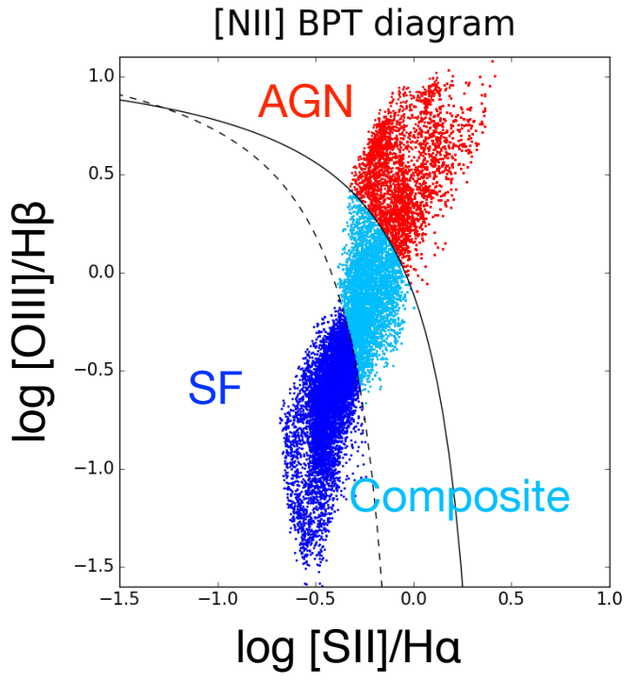
NW → behind disk

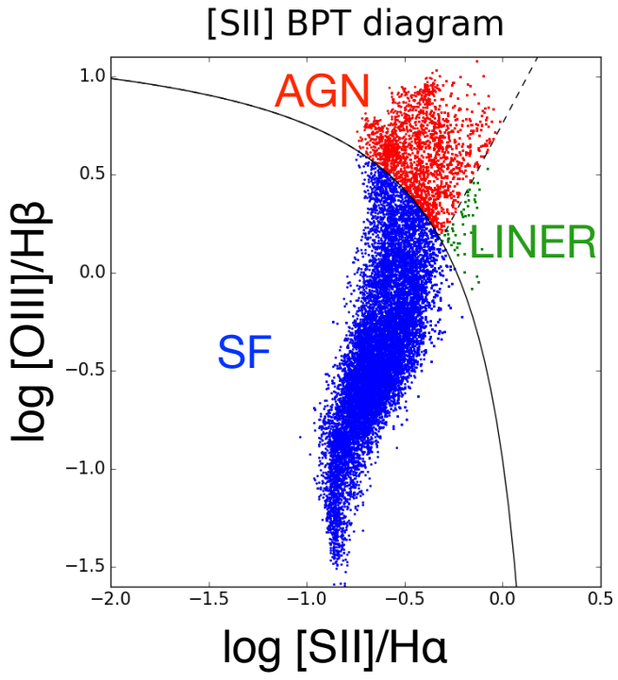
NGC 1365: source of gas ionization

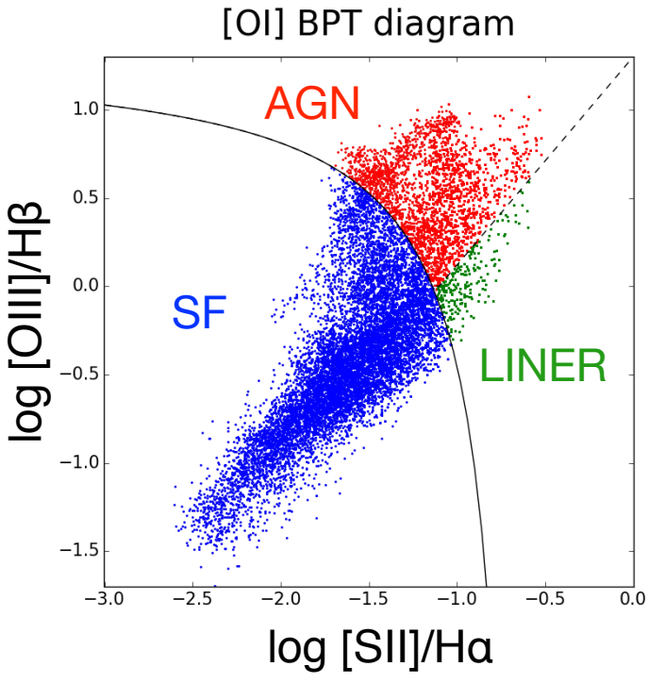
Spatially resolved BPT diagrams

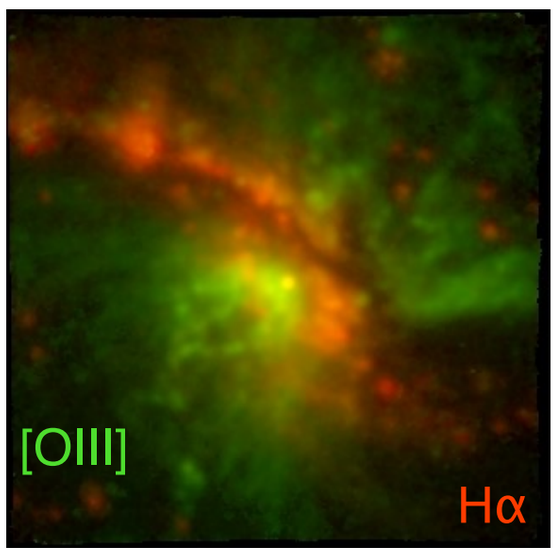
Double cone ionized by AGN

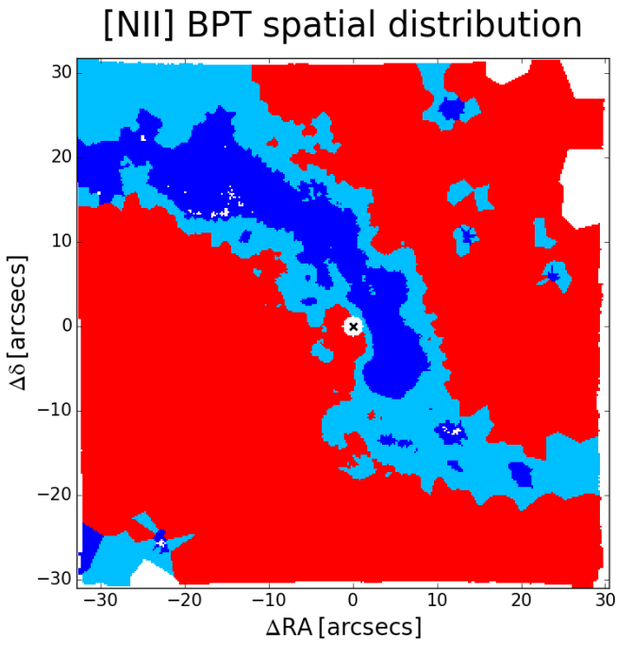
SF dominates along the bar

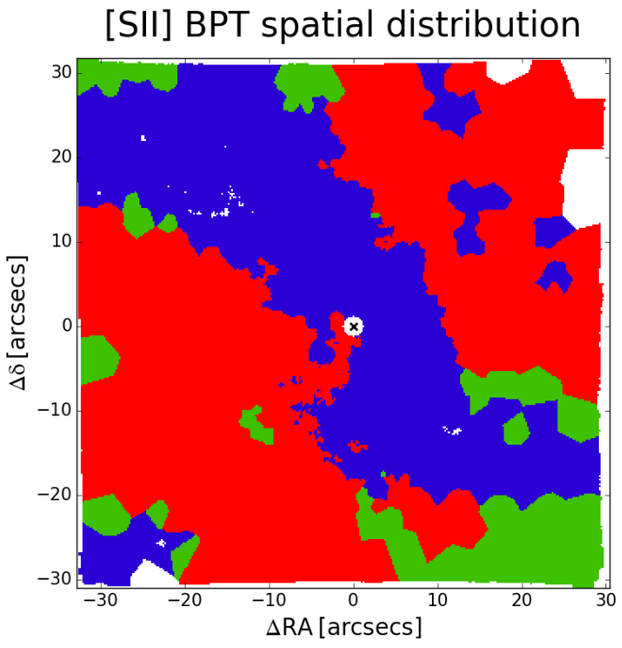


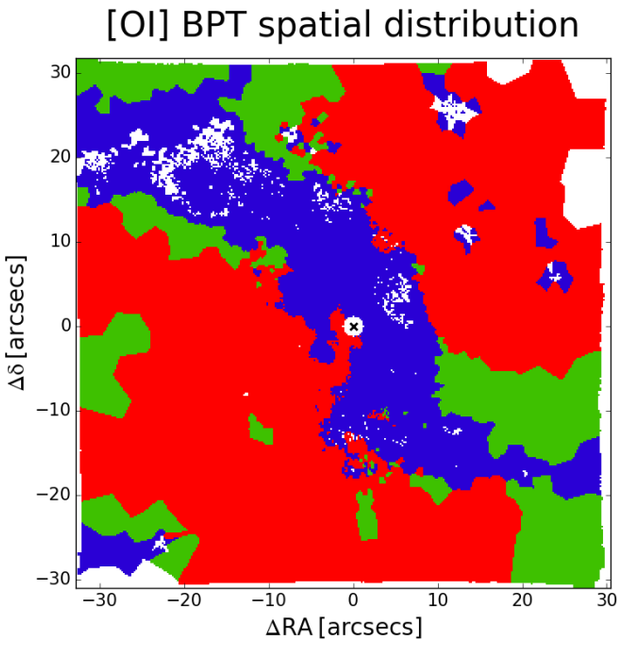








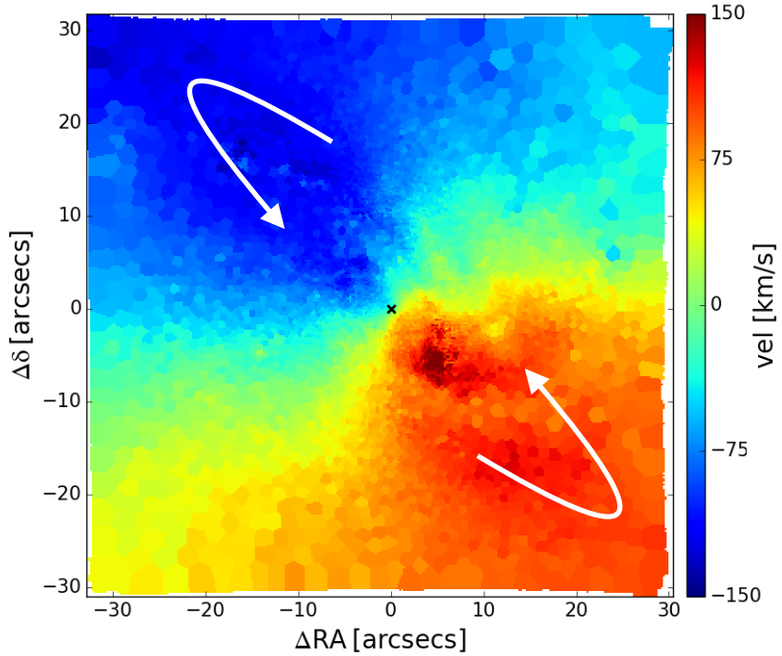




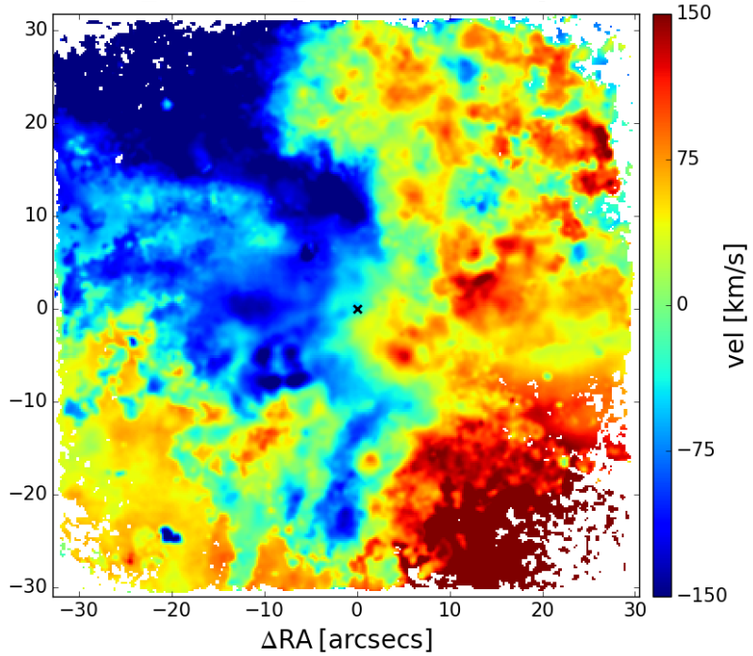
NGC 1365: double-conical outflow

Outflow spatially traced by motions deviating from rotation

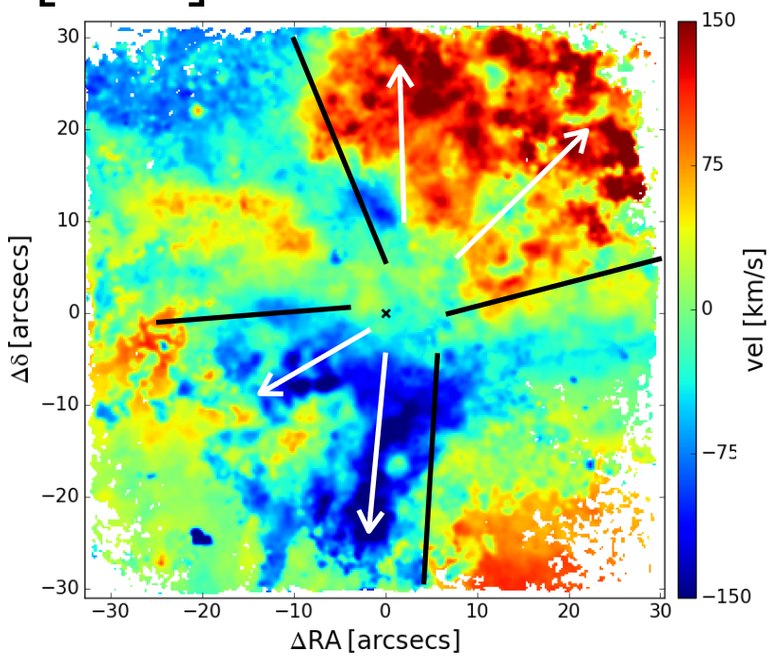
Stellar velocity



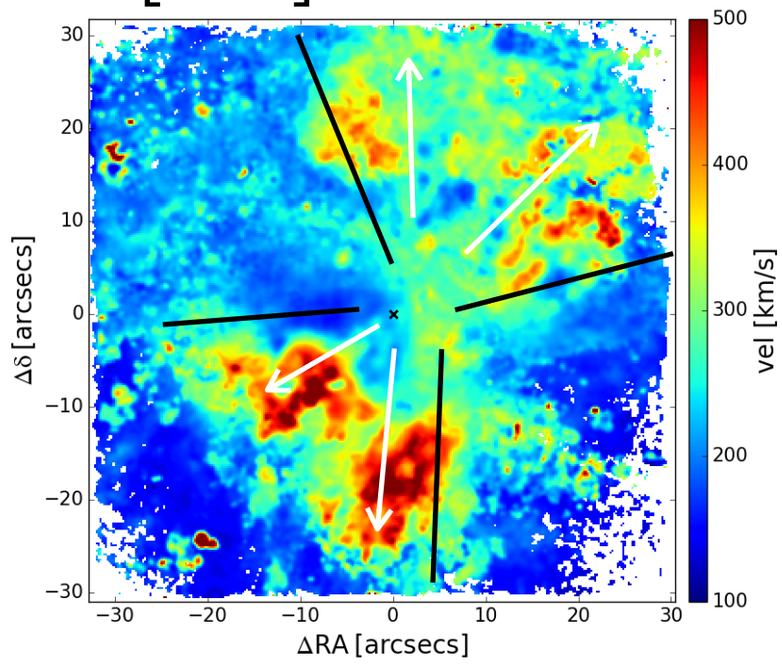
[OIII] velocity



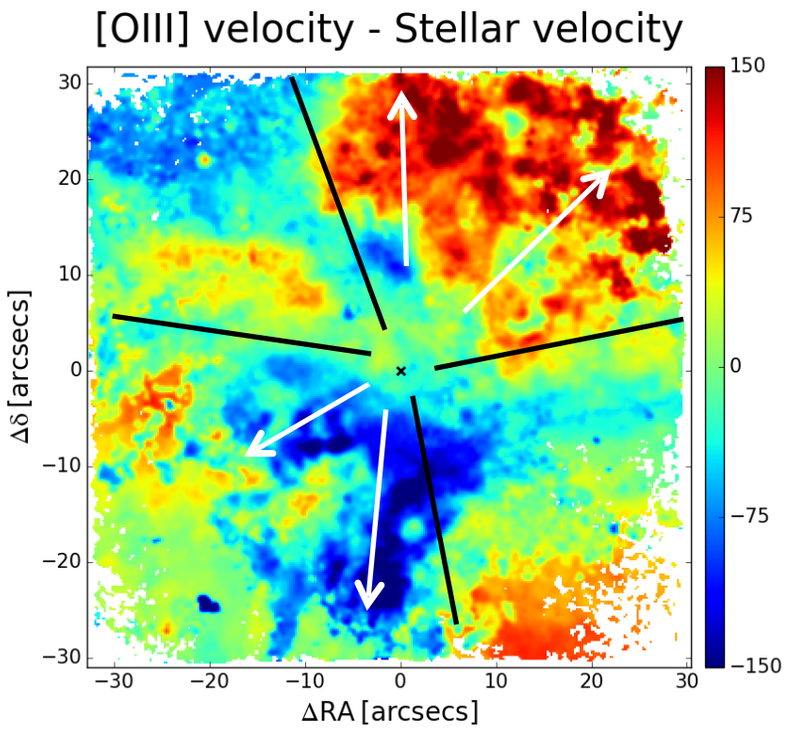
[OIII] vel. - Stellar vel.



[OIII] line width



NGC 1365: mapping the mass outflow rate

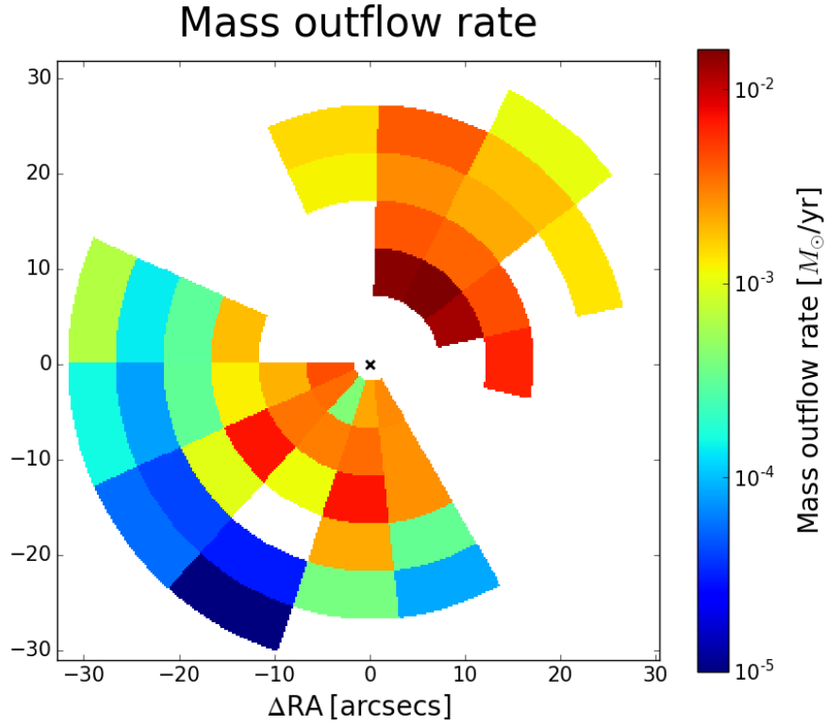


NW cone: positive velocity

→ receding

SE cone: negative velocity

→ approaching



Outflow sliced in a grid to separate outflow from disk component in fitting

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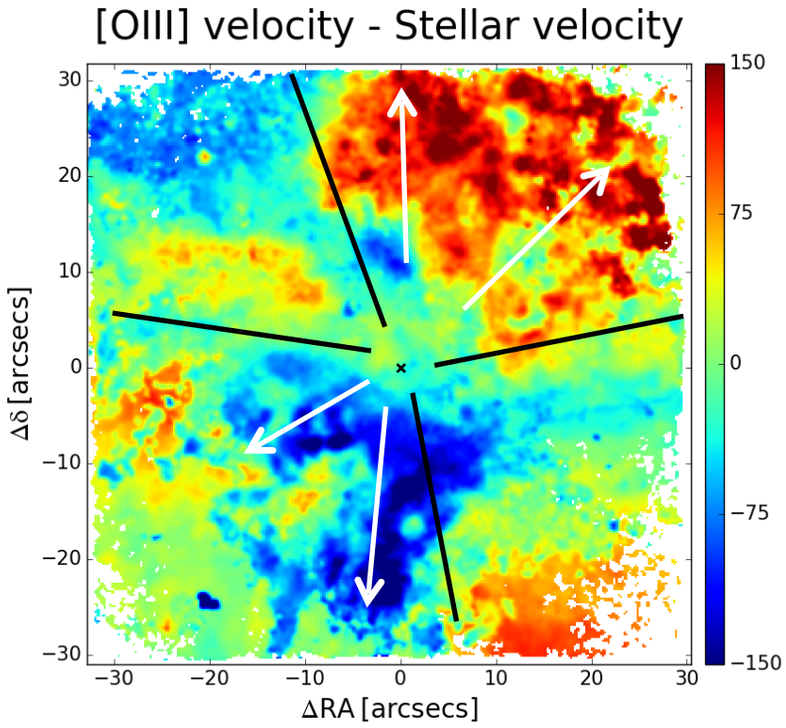

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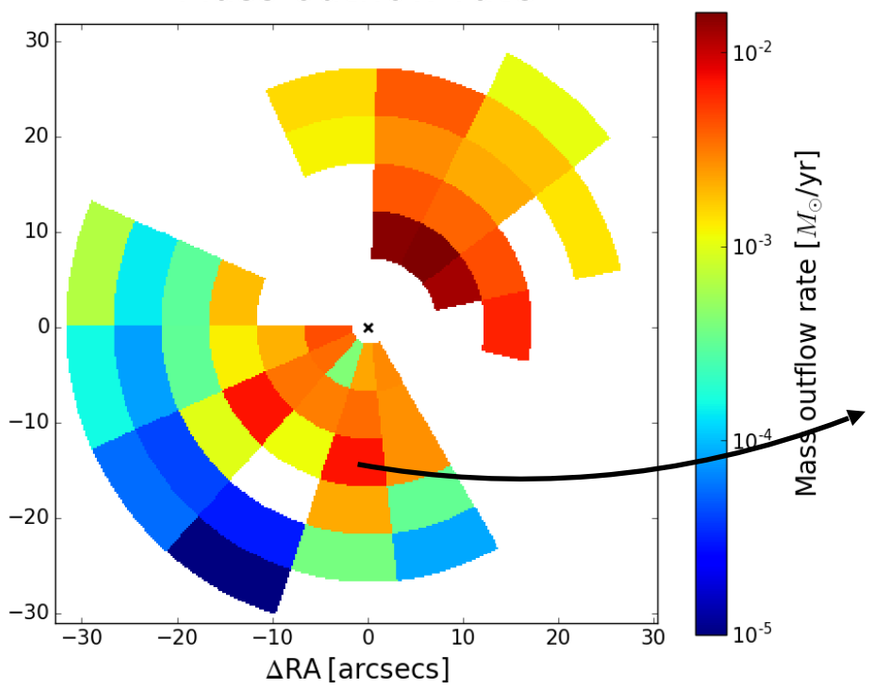
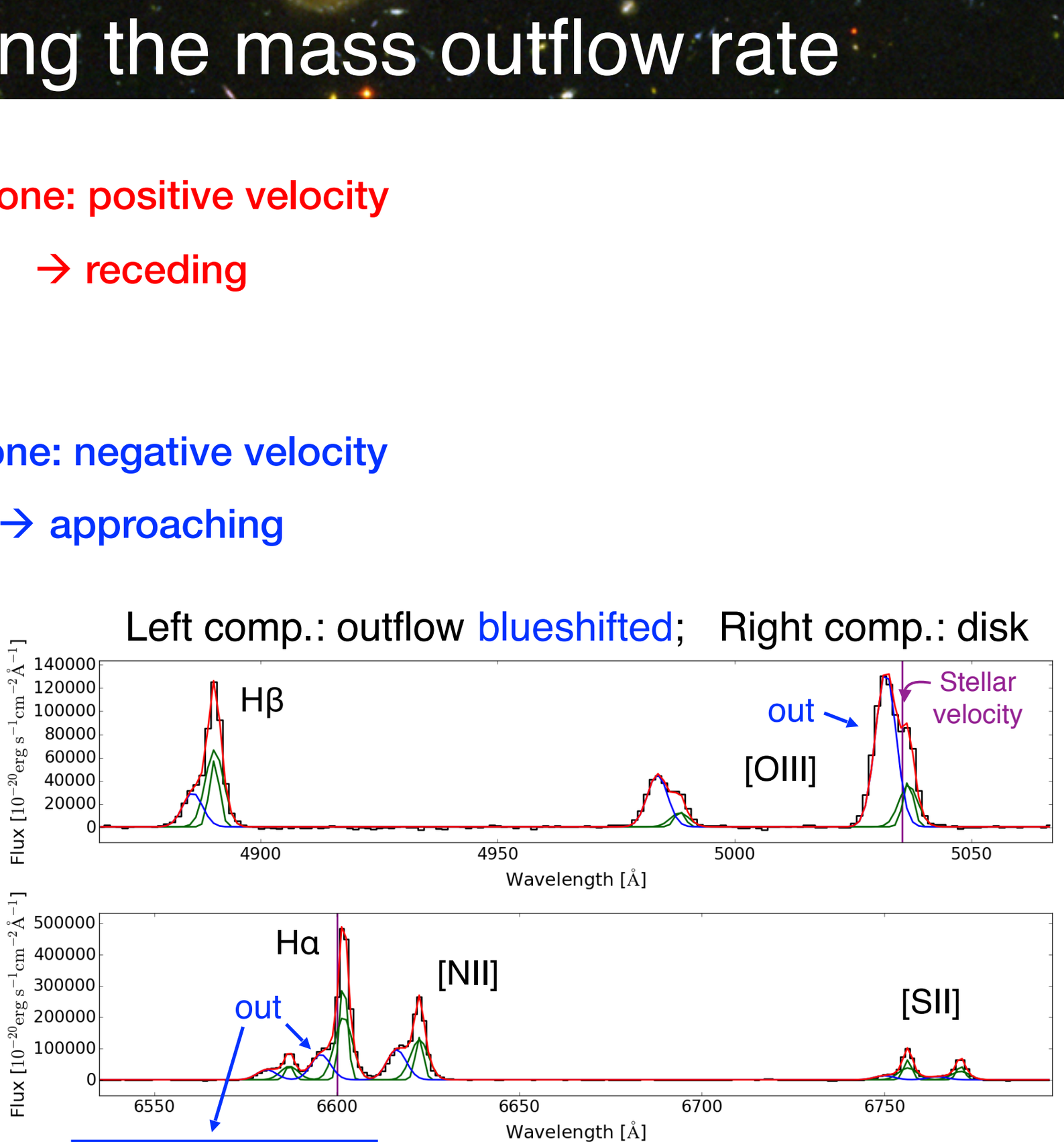
Mass outflow rate



Left comp.: outflow blueshifted; Right comp.: disk



Outflow sliced in a grid to separate outflow from disk component in fitting

$$\dot{M}_{\rm out} = \frac{M_{\rm out} v_{\rm out}}{\Delta R}$$

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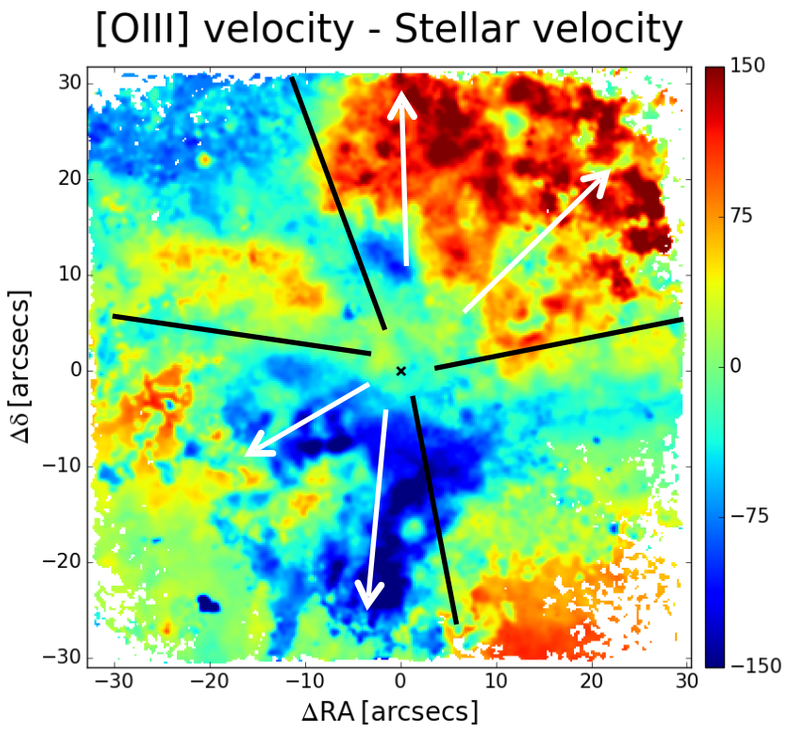

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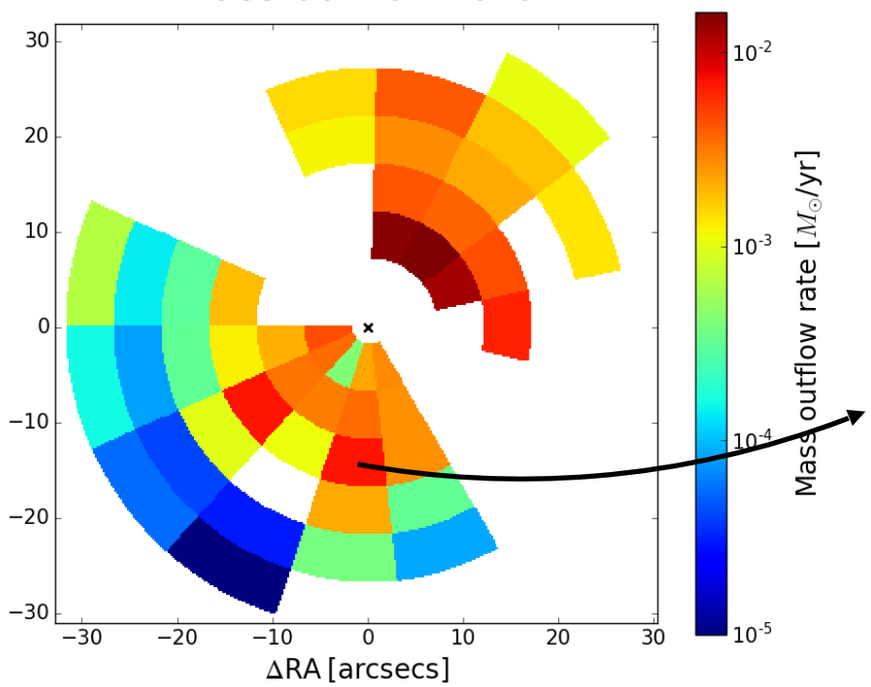
[OIII] dominated by outflow,

Hα dominated by disk

Mass outflow rate



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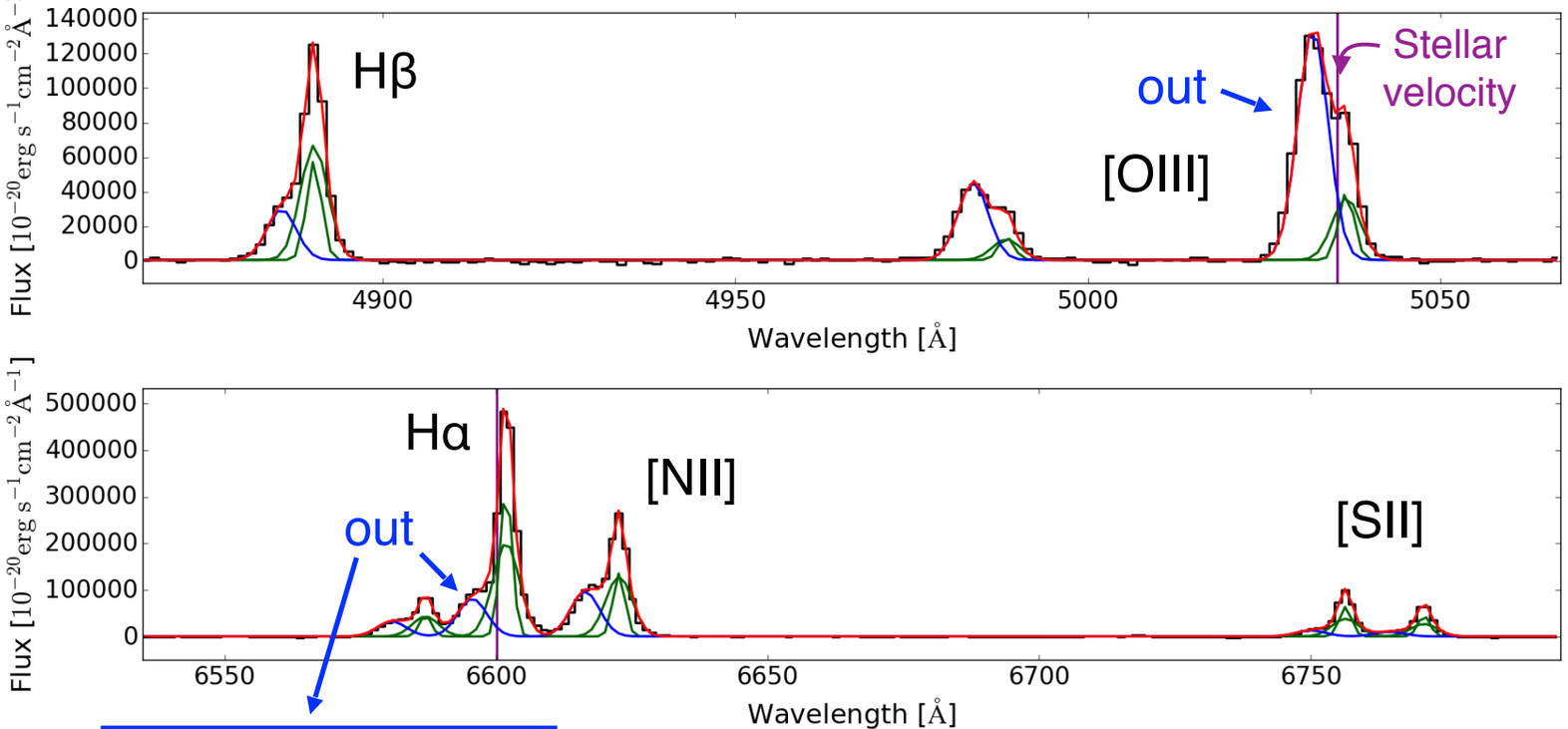
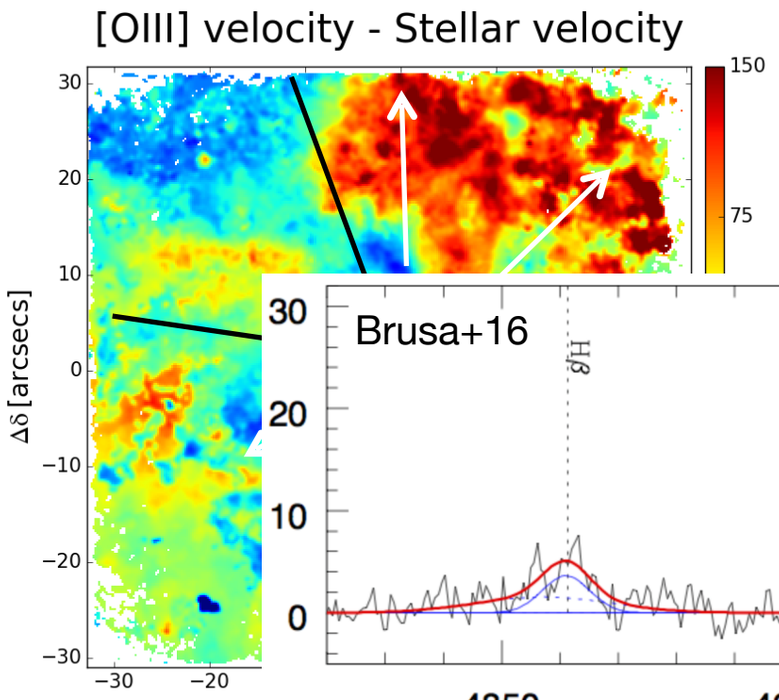


Outflow sliced in a grid to separate outflow from disk component in fitting

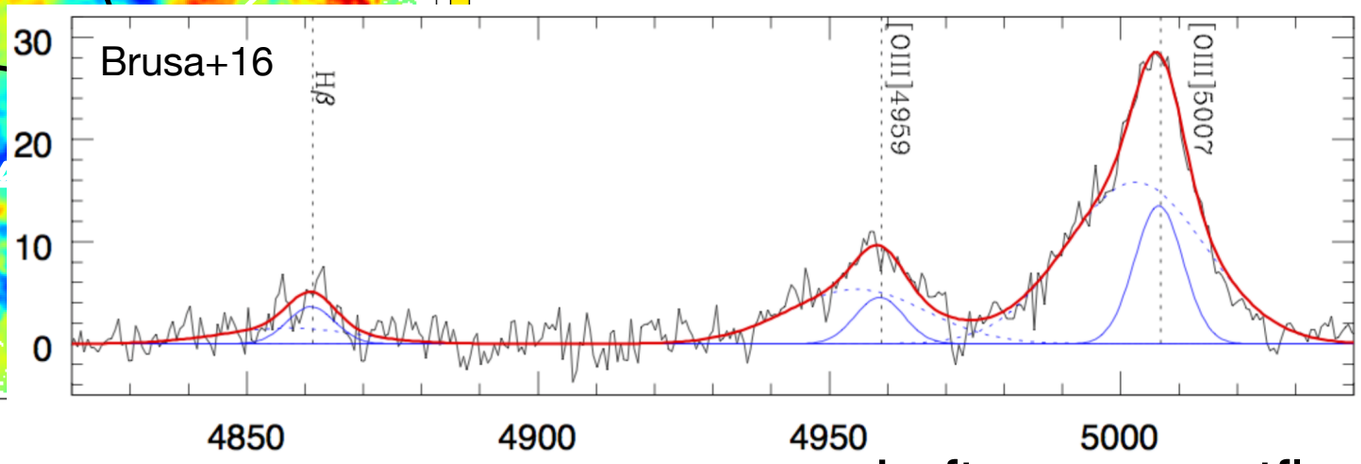
$$\dot{M}_{\rm out} = \frac{M_{\rm out} v_{\rm out}}{\Delta R}$$

NGC 1365: mapping the mass outflow rate



NW cone: positive velocity

→ receding



[OIII] dominated by outflow,

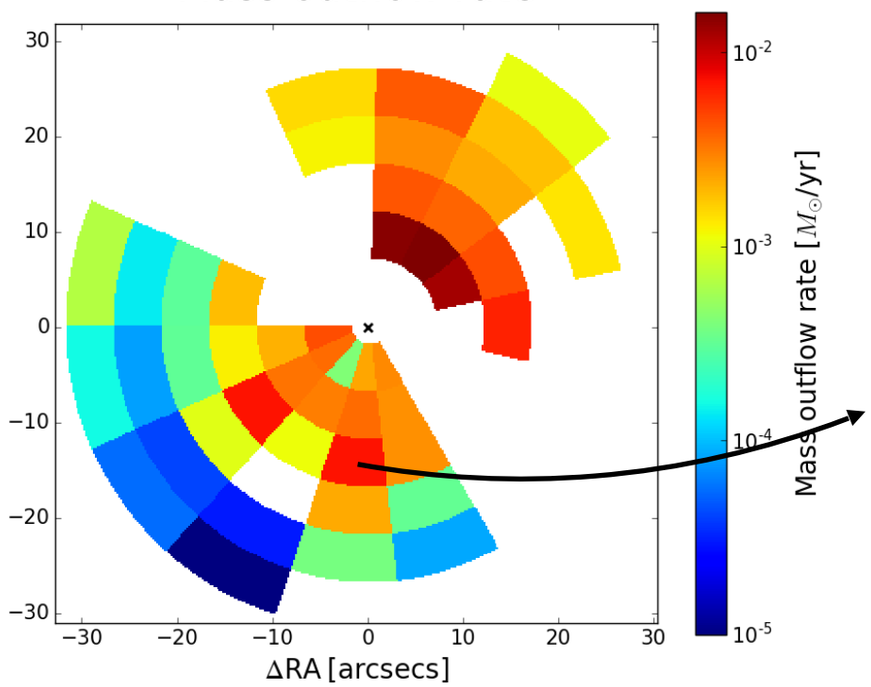
Hα dominated by disk

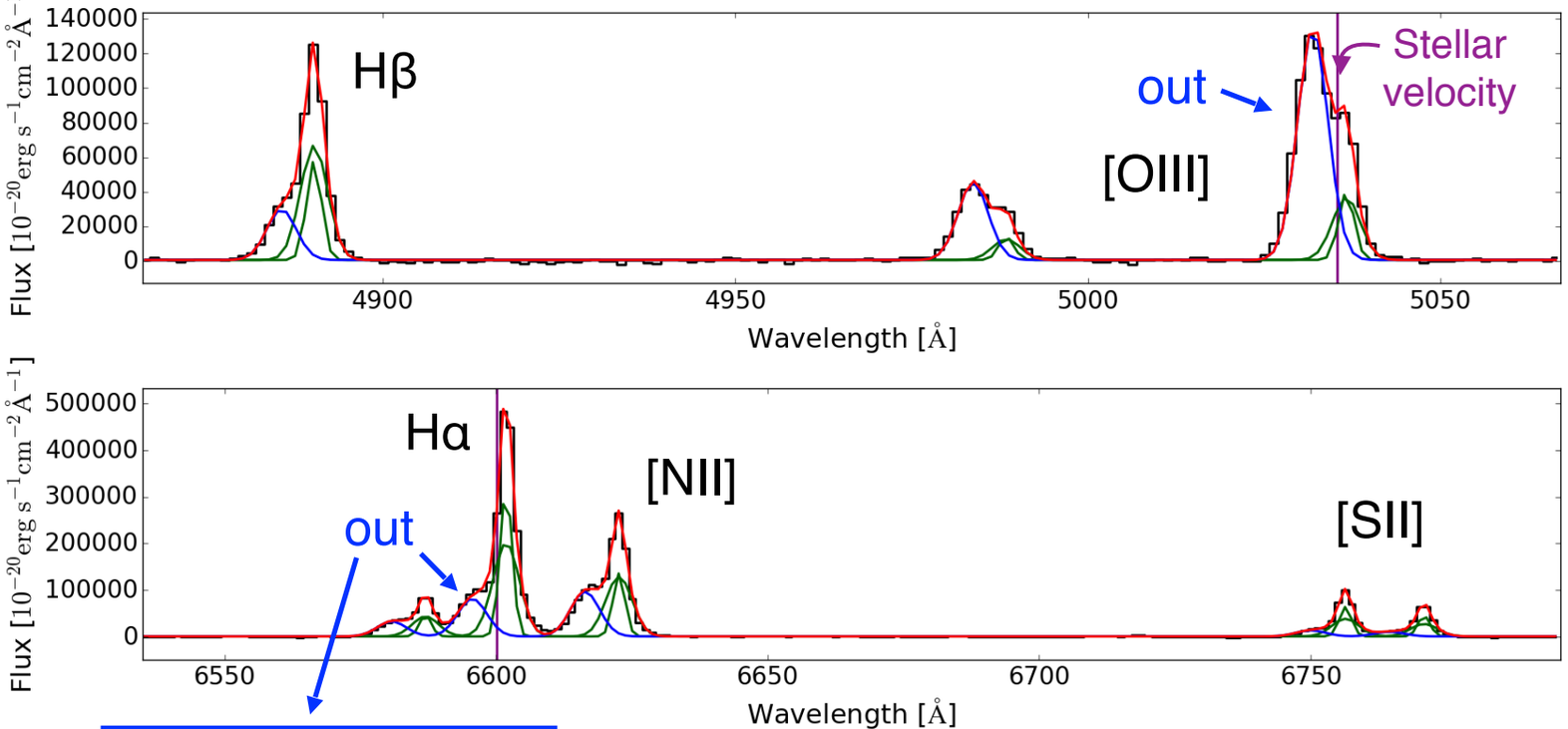
Outflow is not a broad wing

as at low resolution

in more powerful AGN

Left comp.: outflow blueshifted; Right comp.: disk



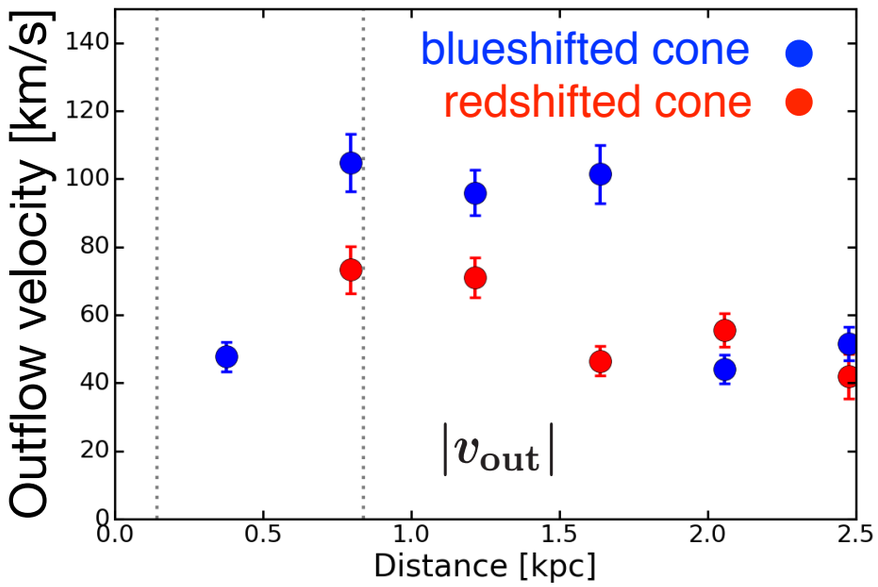


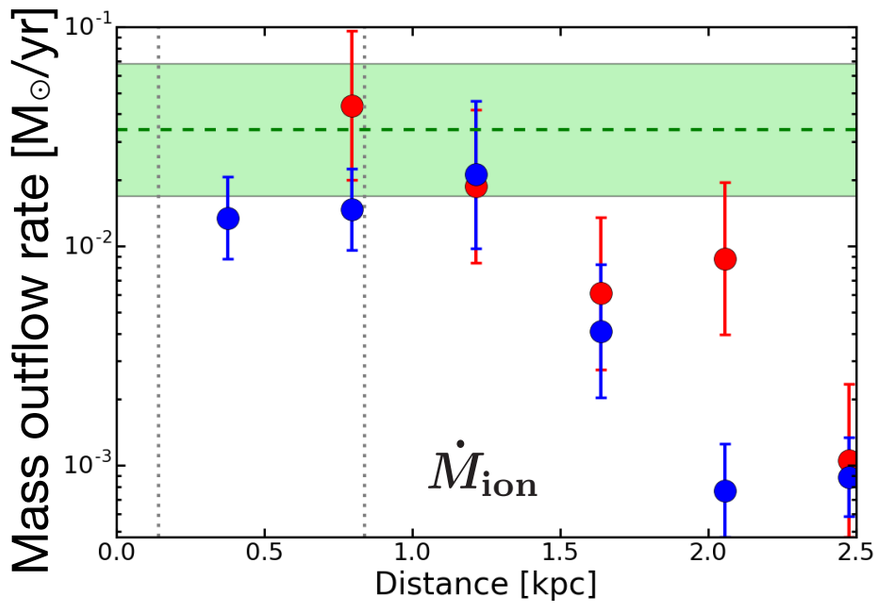
Outflow sliced in a grid to separate outflow from disk component in fitting

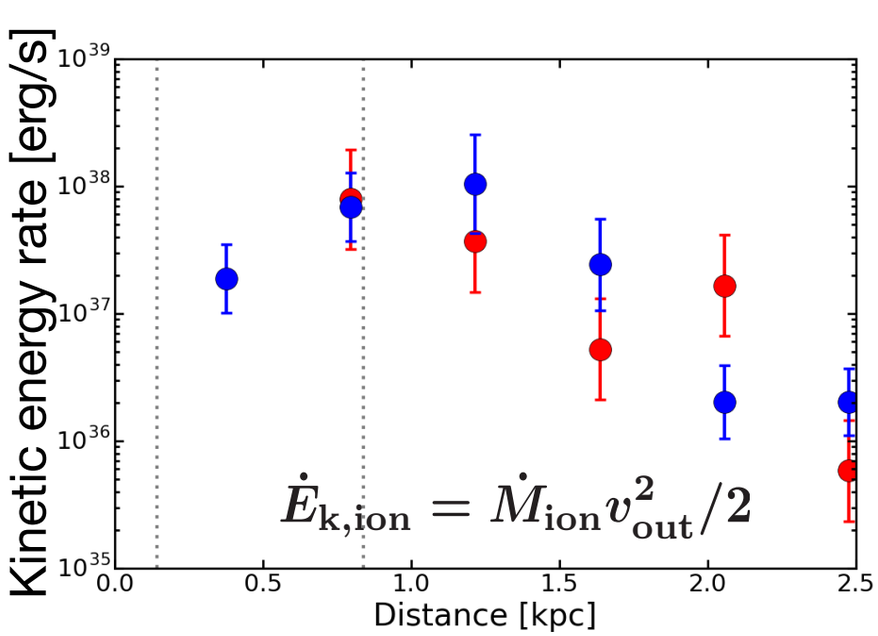
$$\dot{M}_{\rm out} = \frac{M_{\rm out} v_{\rm out}}{\Delta R}$$

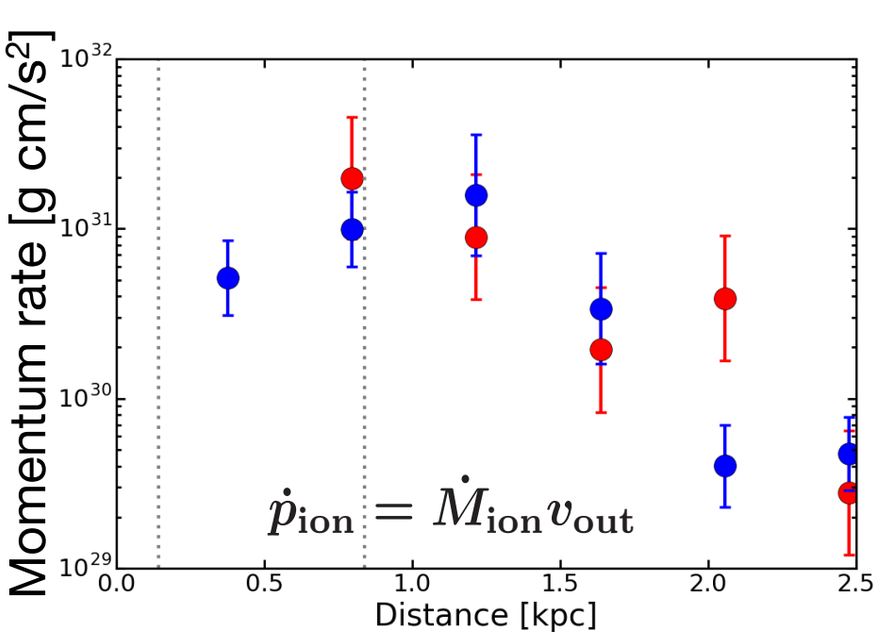
NGC 1365: outflow radial profiles

Radial profiles as a function of distance from the AGN









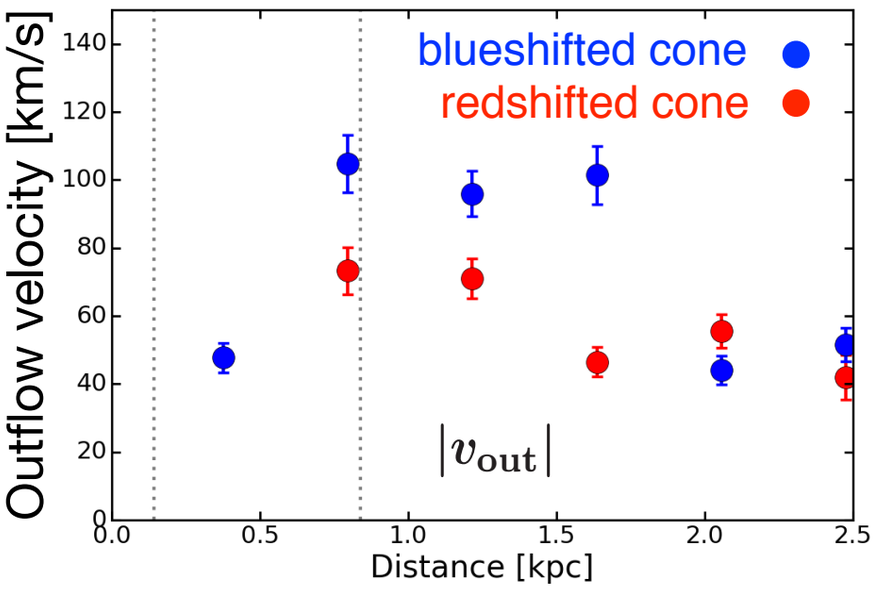
Decreasing trend with distance

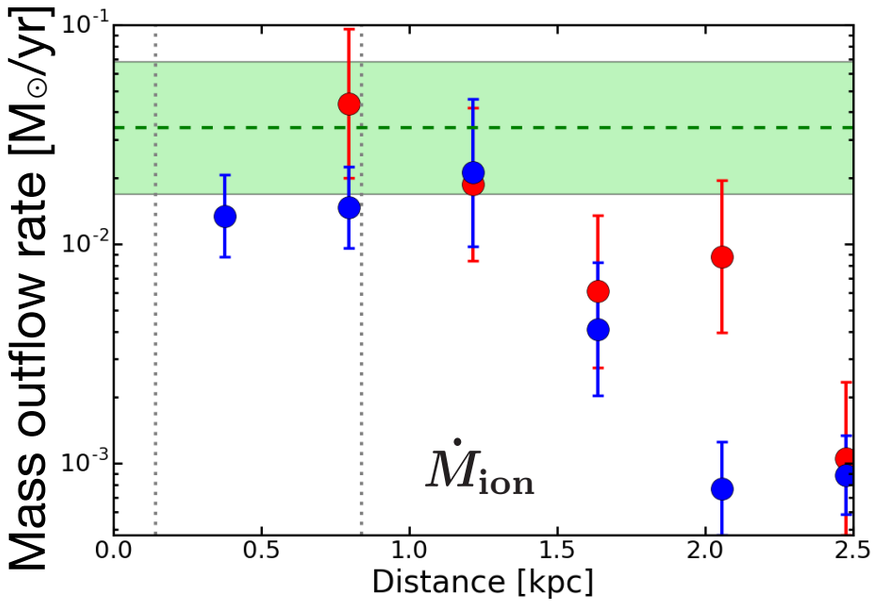
(see also Karouzos+16a,16b, Bae +17, Crenshaw+15, Revalski+18)

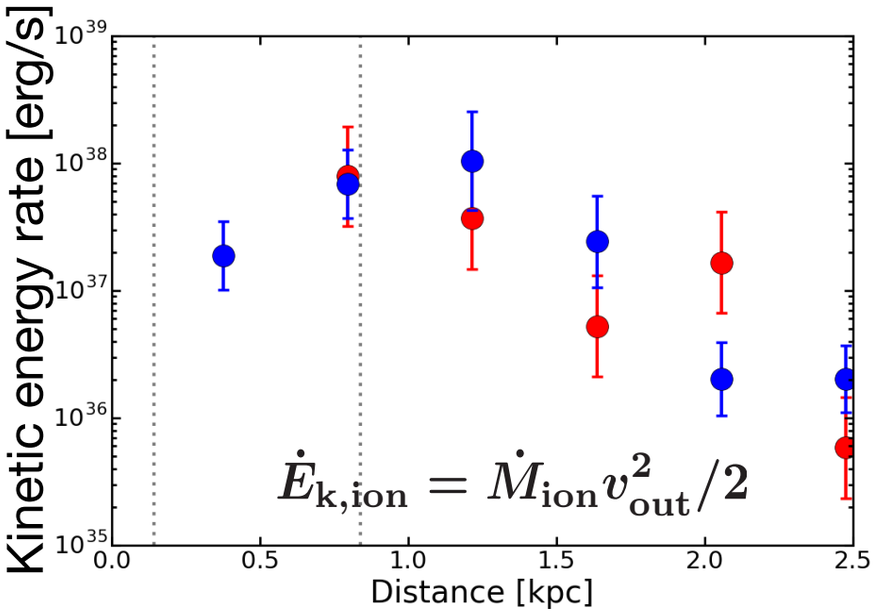
- AGN more powerful recently than in the past
- Outflow does mass loading and slows down (but we don't see mass radially increasing)
- We sample only ionized gas (lacking neutral atomic + molecular), which depends on ionizing flux $\propto r^{-2}$

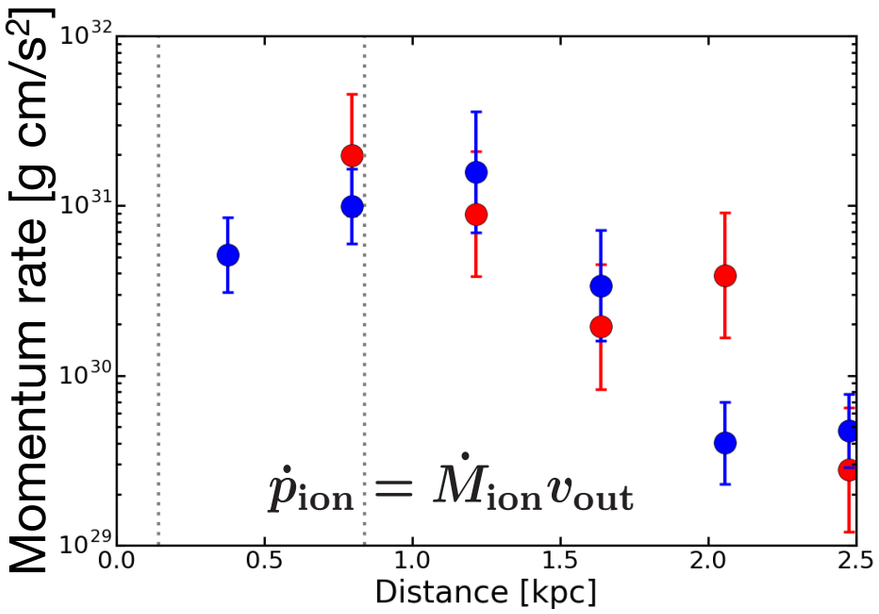
NGC 1365: outflow radial profiles

Radial profiles as a function of distance from the AGN





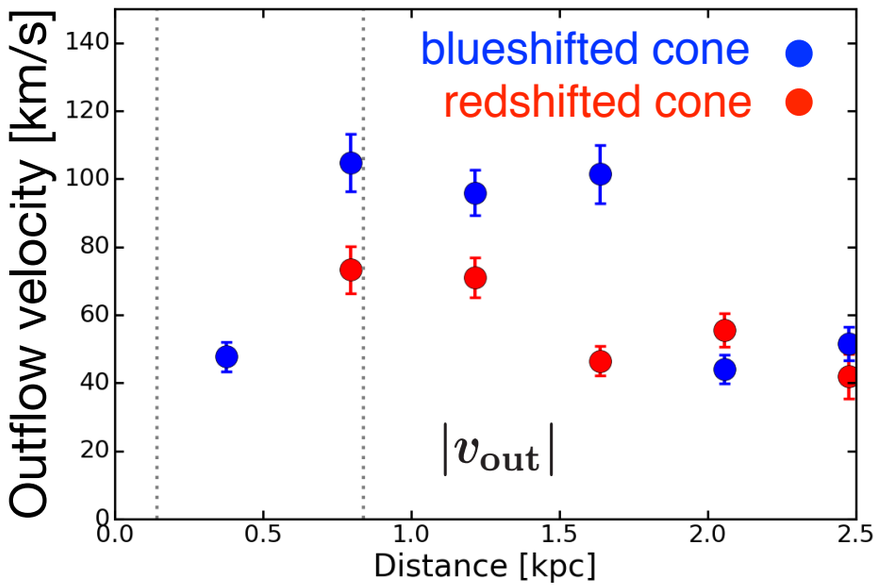


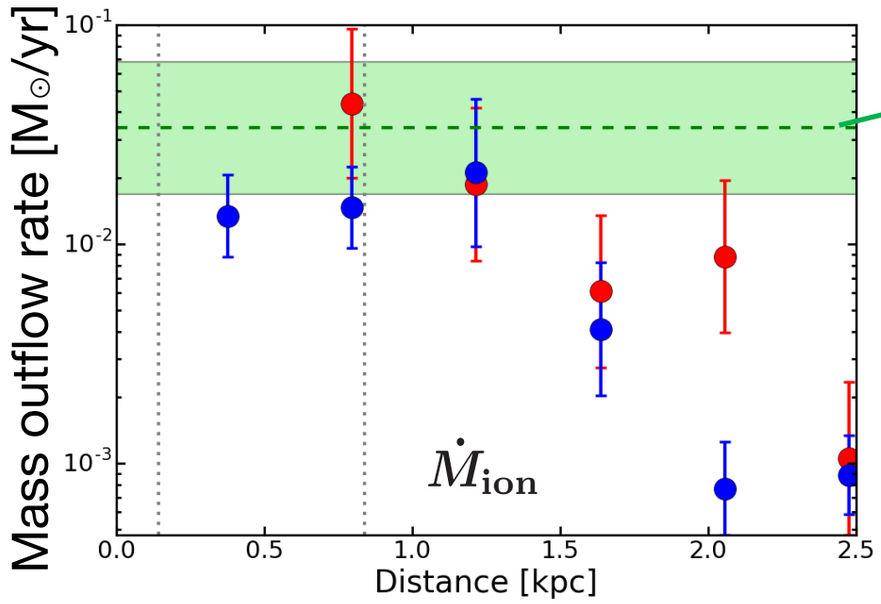


$\dot{M}_{\rm ion} \ll$ SFR (7 M$_\odot$/yr)
—> outflow unable
to affect SF
(at least in the ionized
phase only)

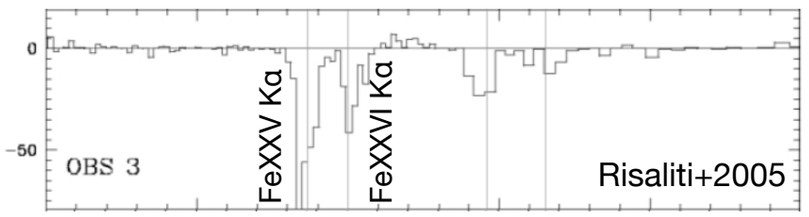
NGC 1365: outflow radial profiles

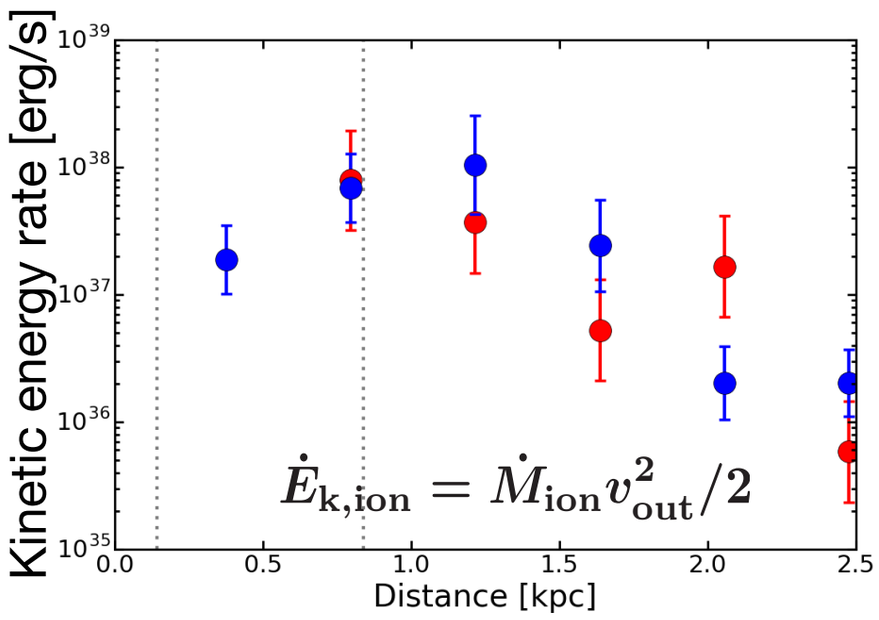
Radial profiles as a function of distance from the AGN

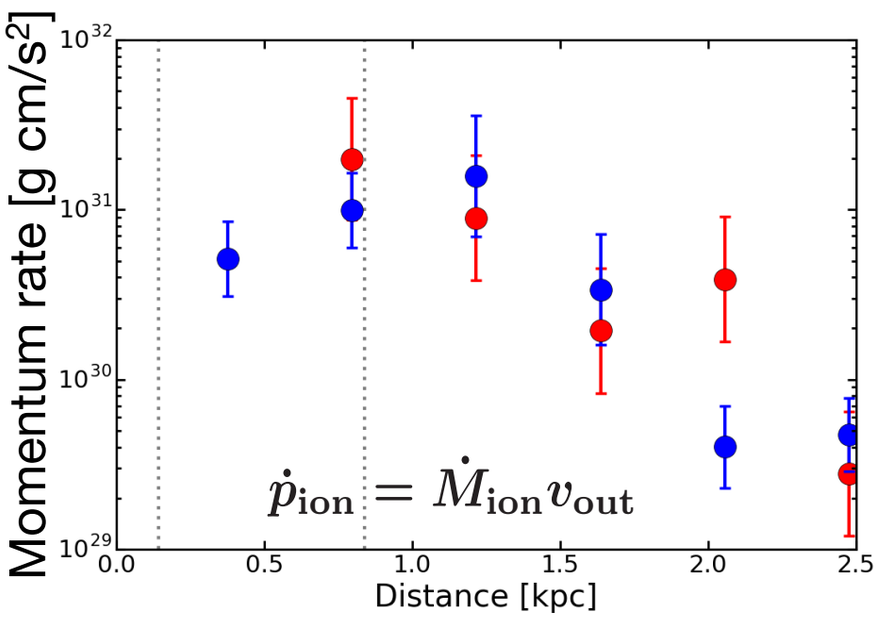


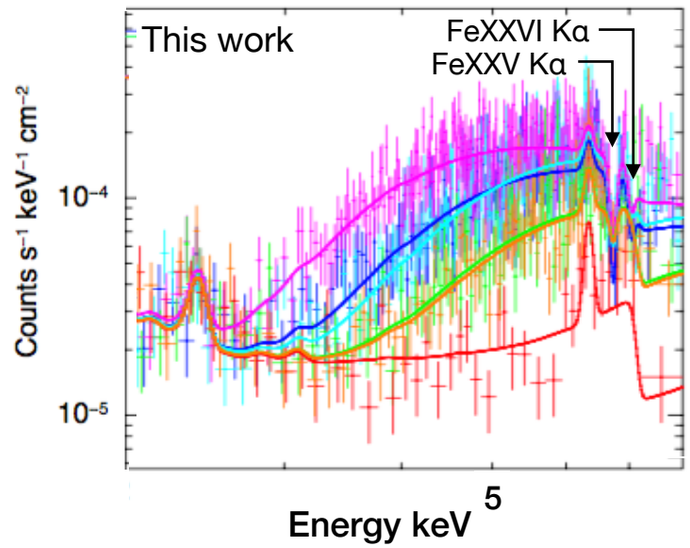


Mass outflow rate of nuclear X-ray wind ($v_{\rm out,X} \sim 3000$ km/s) from FeXXV and FeXXVI abs. lines



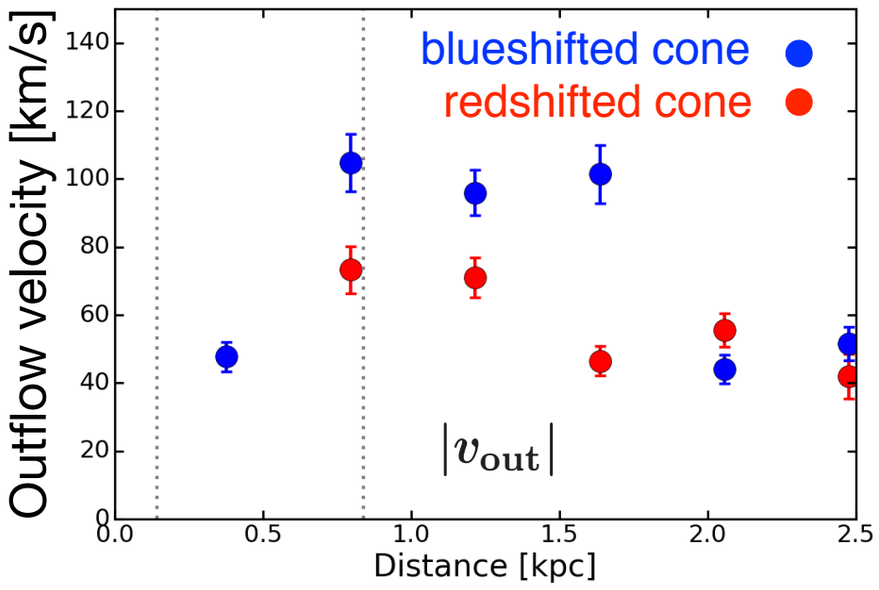


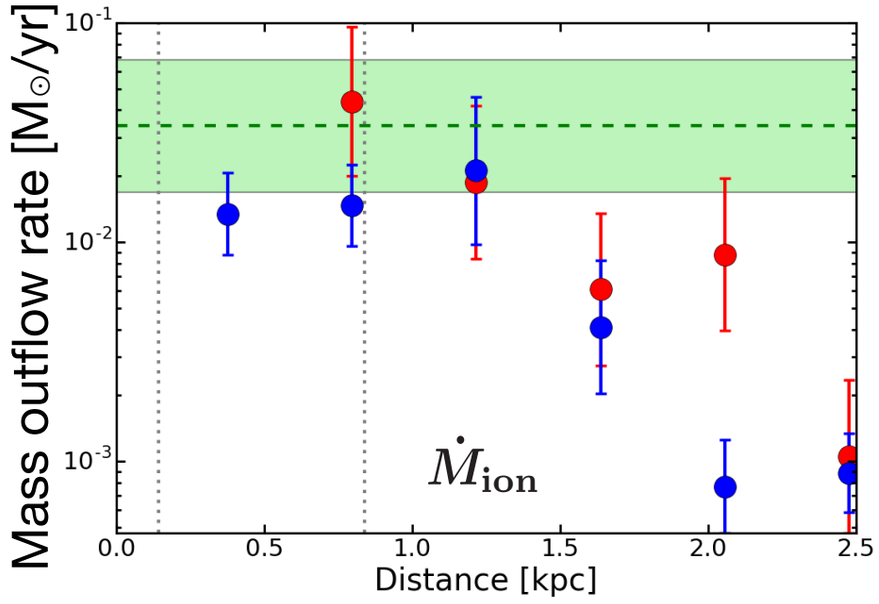


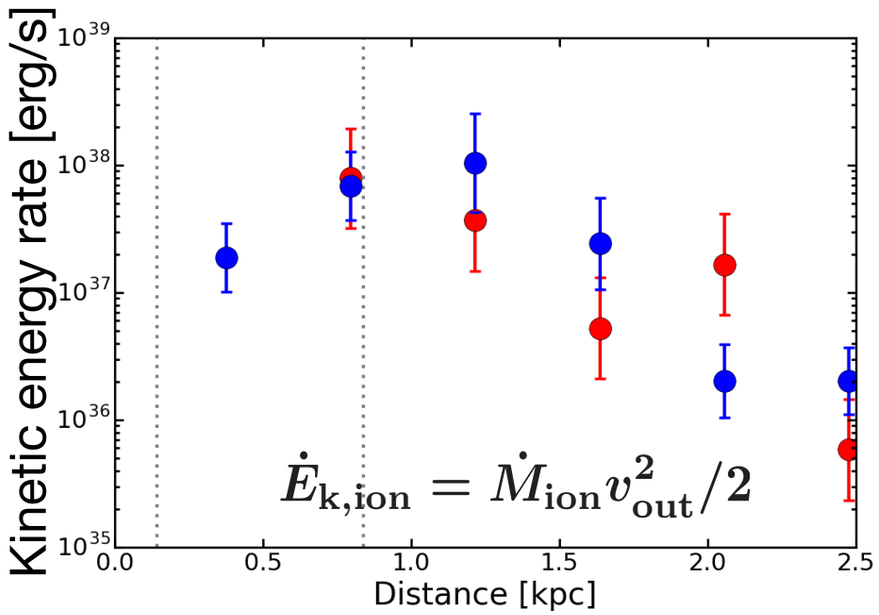


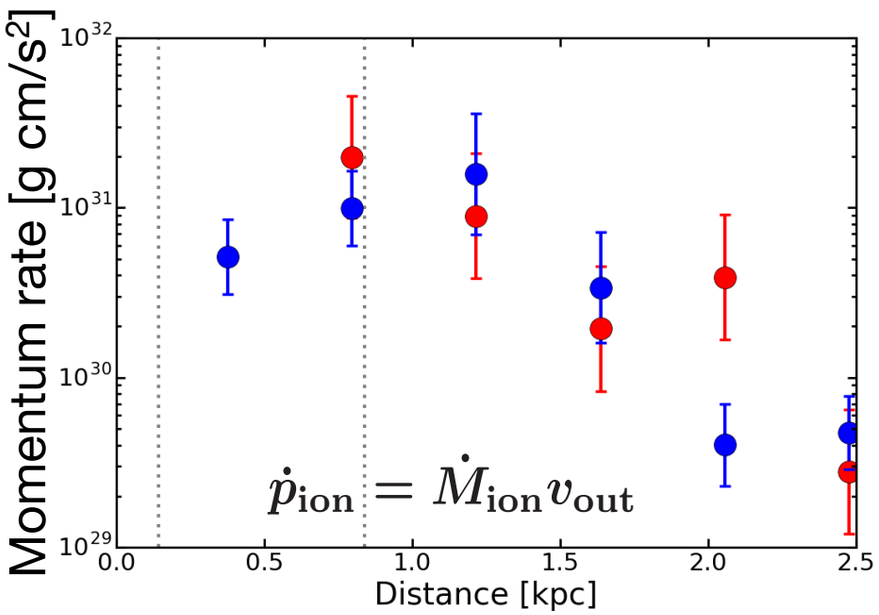
NGC 1365: outflow radial profiles

Radial profiles as a function of distance from the AGN









- **Energy-driven**:
  $\dot{E}_{\rm k,ion} \lesssim 10^{-3}\ \dot{E}_{\rm k,X}$
  —> would need too much neutral atomic + molecular for $\dot{E}_{\rm k,tot} \sim \dot{E}_{\rm k,X}$ (see Carniani+15, Fiore +17, Fluetsch+18)
- **Direct** AGN **radiation pressure** on dusty clouds (e.g. Thomson +15, Ishibashi+18):
  $\dot{p}_{\rm ion} \lesssim 1/20\ L_{\rm AGN}/c$
  (models: $\dot{p}_{\rm tot} \sim$1-5 $L_{\rm AGN}/c$)
  —> in principle could be the driver

Part 2: NGC 6810

Star formation *within* the outflow

in star-forming galaxy NGC 6810

(Venturi et al., in prep.)

Outflows can also form stars

Models predict new mode of star formation: stars are created with high velocities on ~radial orbits, contributing to bulge of galaxies and enriching CGM/IGM

(Silk+12,17, Ishibashi&Fabian14,15, Zubovas+13, Zubovas&King13, Nayakshin&Zubovas 12, Gaibler+12)

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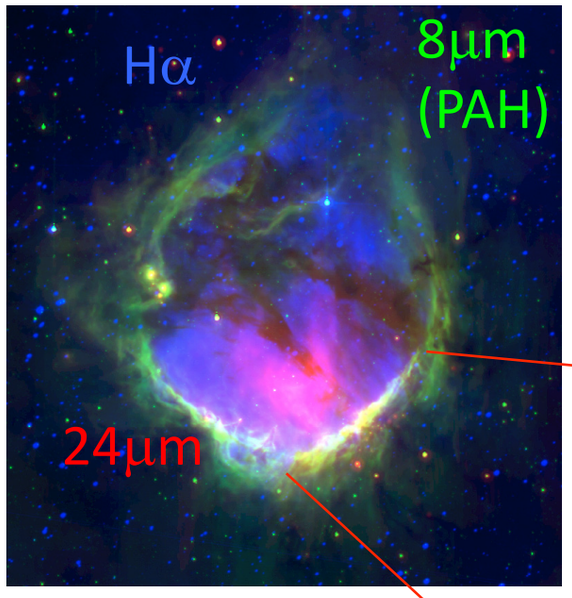
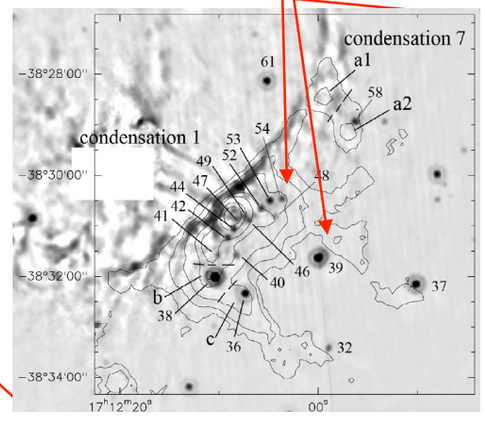
Widespread evidence in our galaxy



Zavagno+10, Lim+18, Dwarkadas+17, Duronea+17, Deharveng+15, Dewangan+12, Thompson+12, Brand+11

Stars form in the shocked front



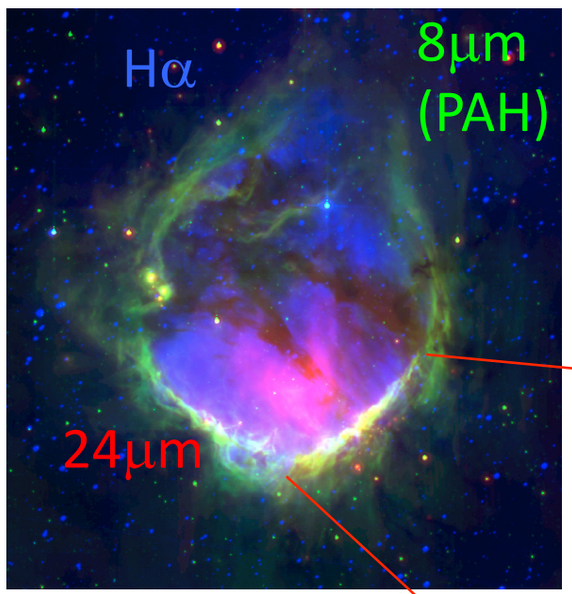
So why not also in galactic outflows?

Outflows can also form stars

Models predict new mode of star formation: stars are created with high velocities on ~radial orbits, contributing to bulge of galaxies and enriching CGM/IGM

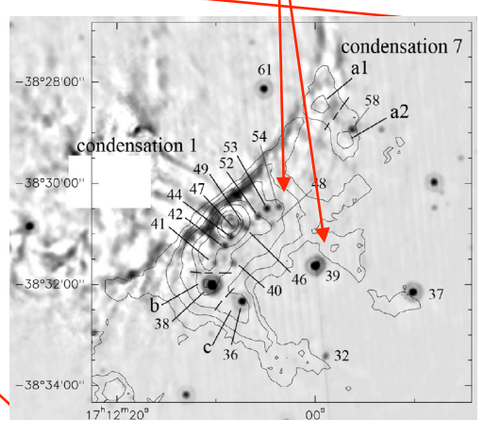
(Silk+12,17, Ishibashi&Fabian14,15, Zubovas+13, Zubovas&King13, Nayakshin&Zubovas 12, Gaibler+12)

Widespread evidence in our galaxy



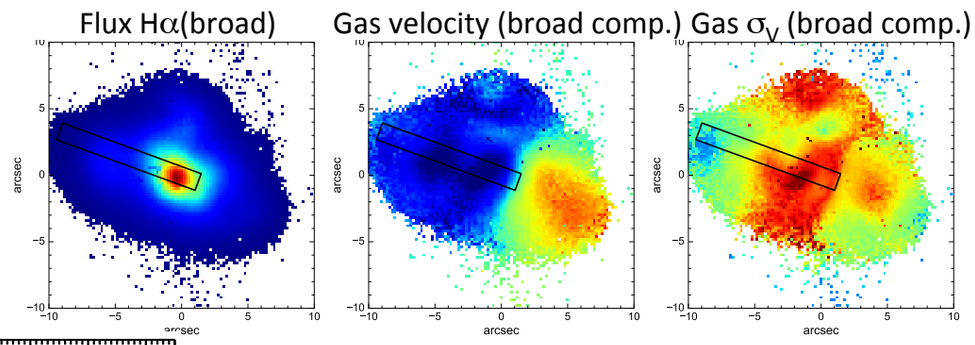
Zavagno+10, Lim+18, Dwarkadas+17, Duronea+17, Deharveng+15, Dewangan+12, Thompson+12, Brand+11

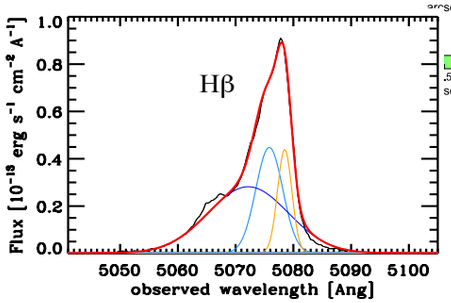
Stars form in the shocked front

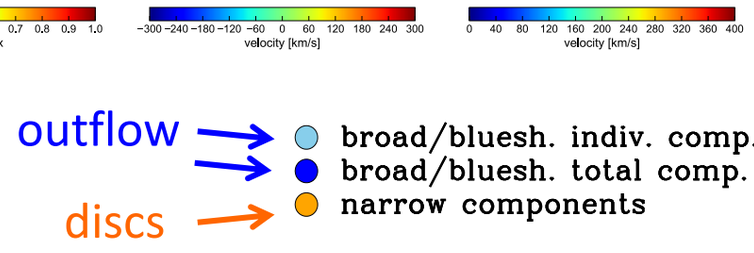


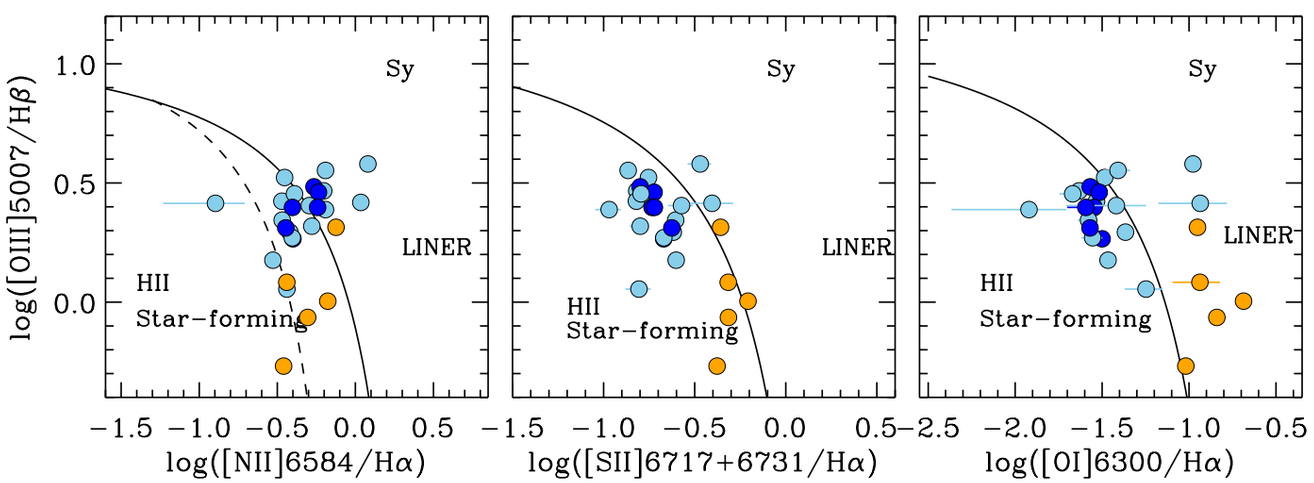
First observational evidence of star formation inside an AGN-driven outflow

IRAS 2312-59
Maiolino+17
(also Gallagher+18)





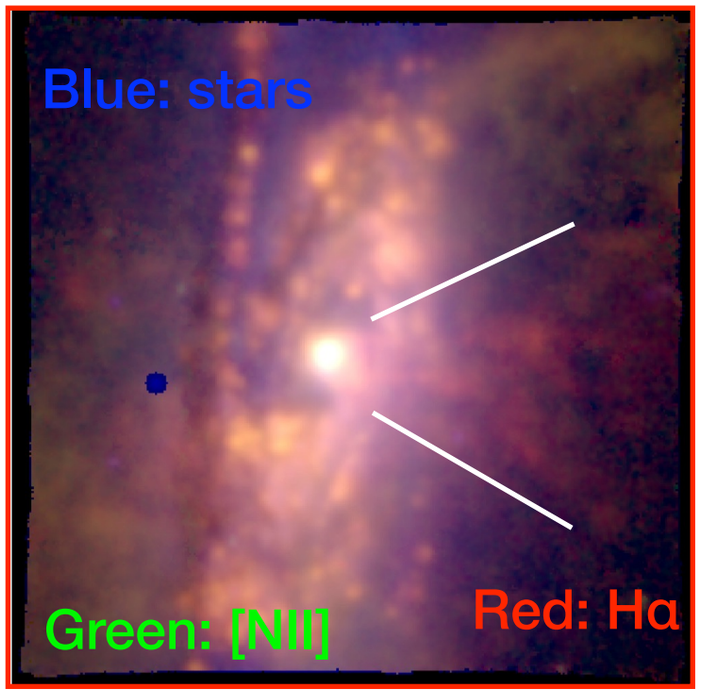


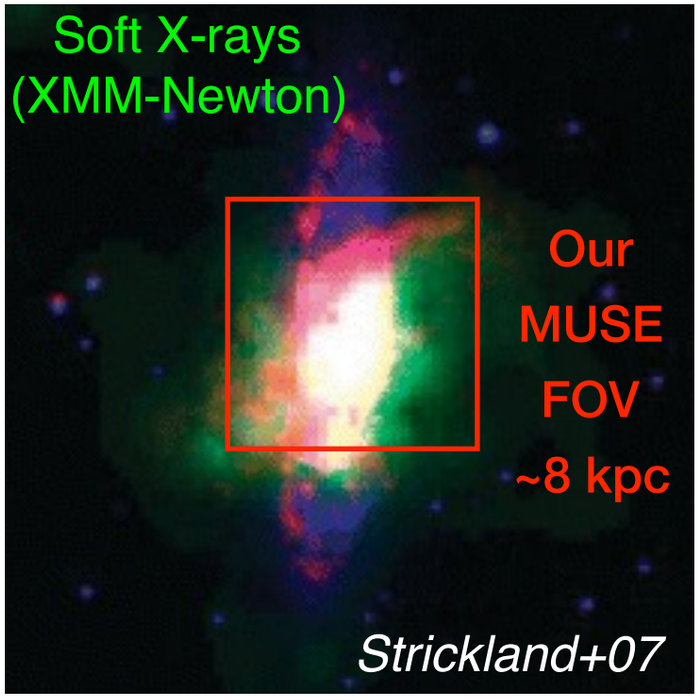


So why not also in galactic outflows?

NGC 6810

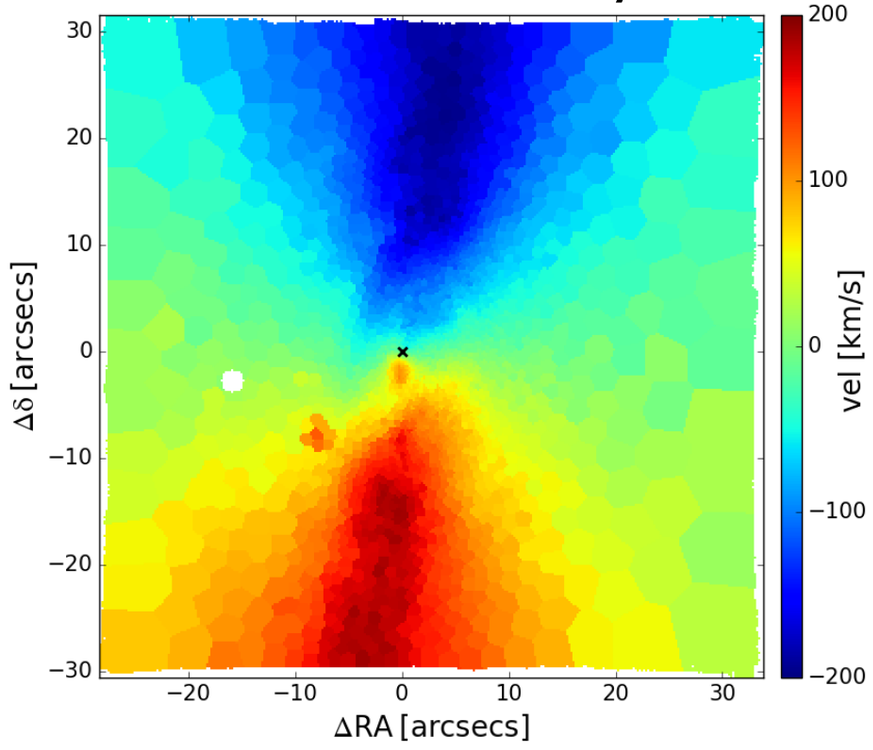
Star-forming galaxy: no trace of AGN from optical diagnostics, hard X-rays, MIR or radio



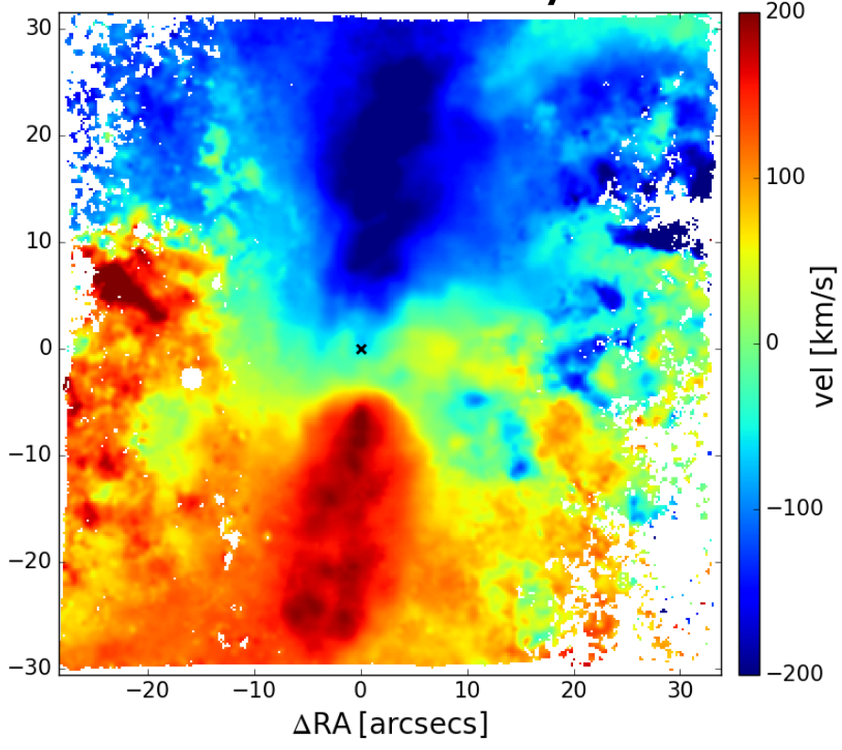


Bipolar starburst outflow

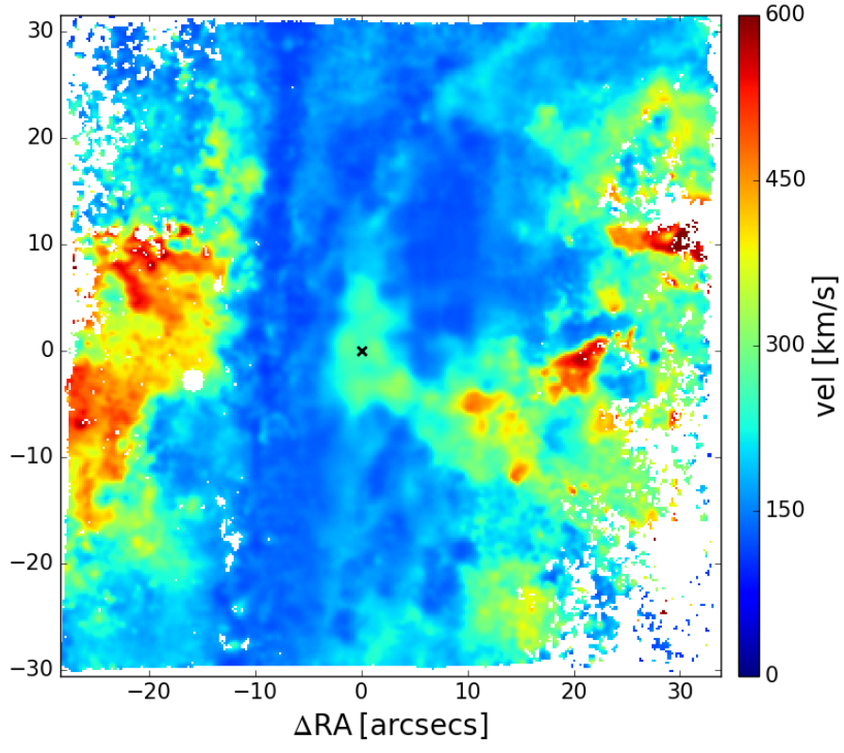
Stellar velocity



Hα velocity



Hα linewidth



NGC 6810

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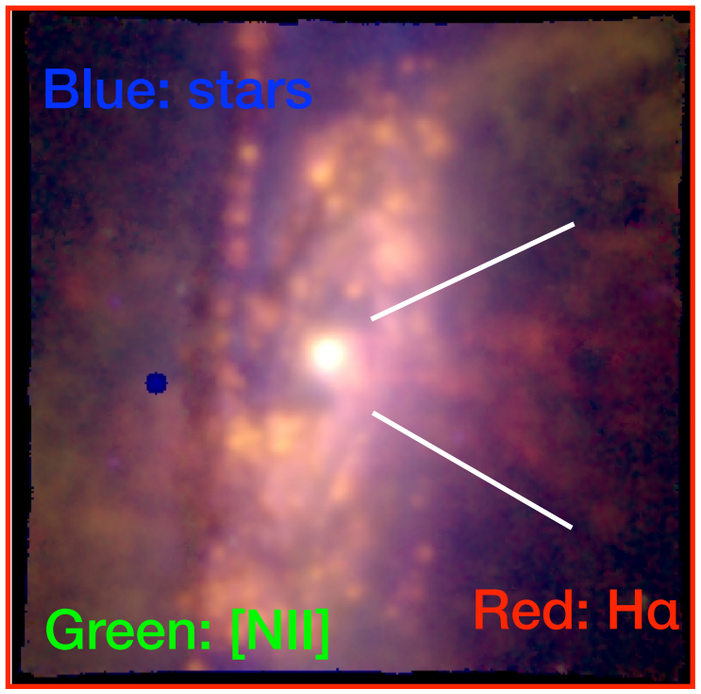
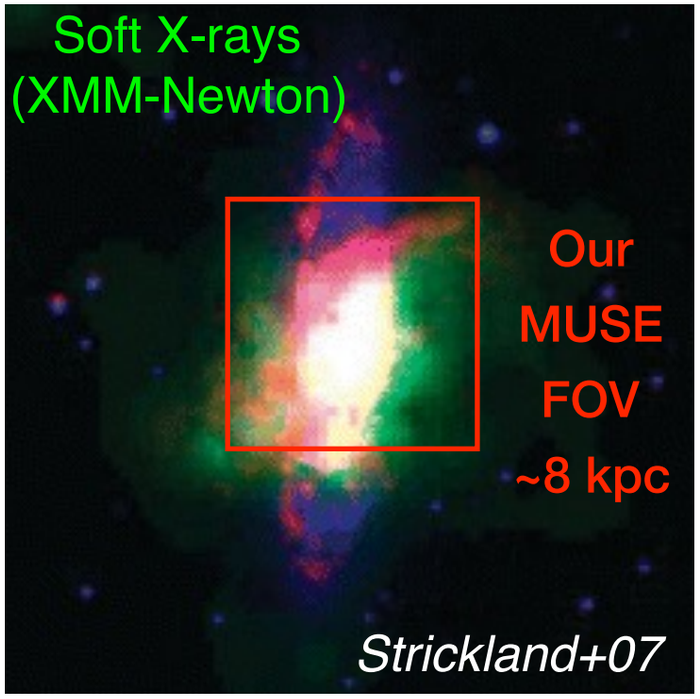
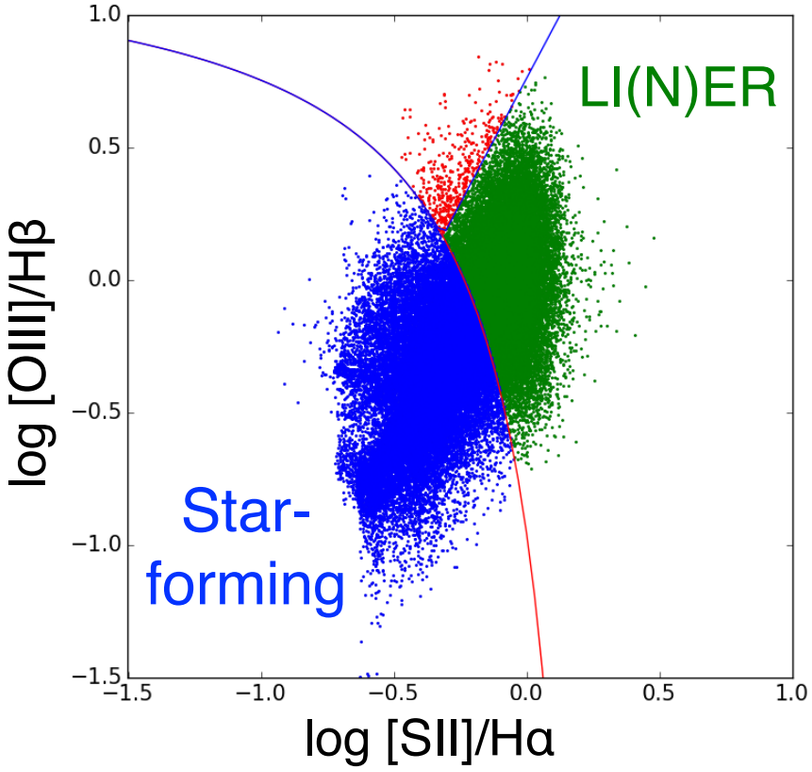


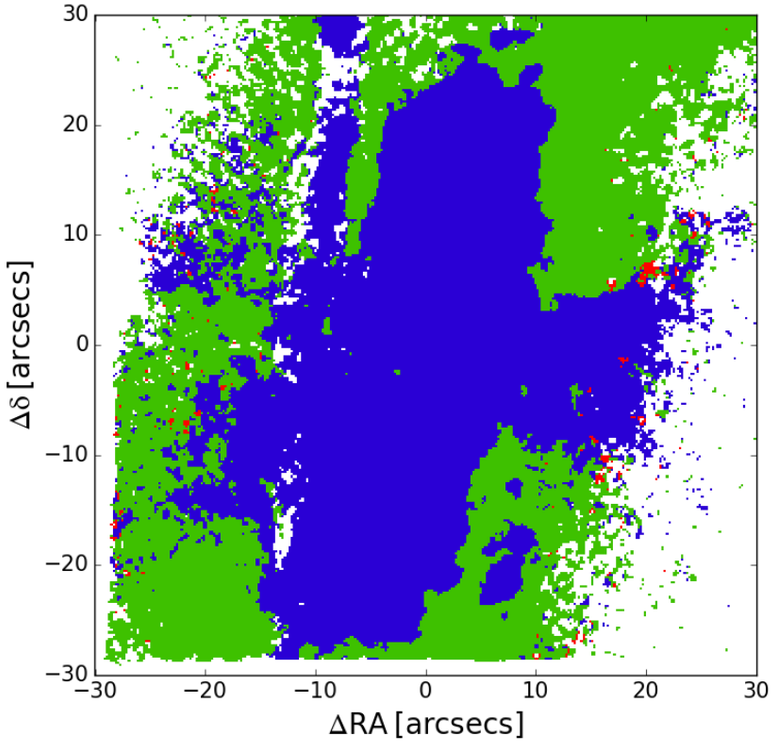


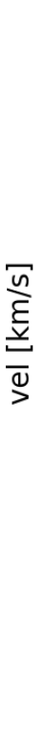
Bipolar starburst outflow

[SII] BPT diagram



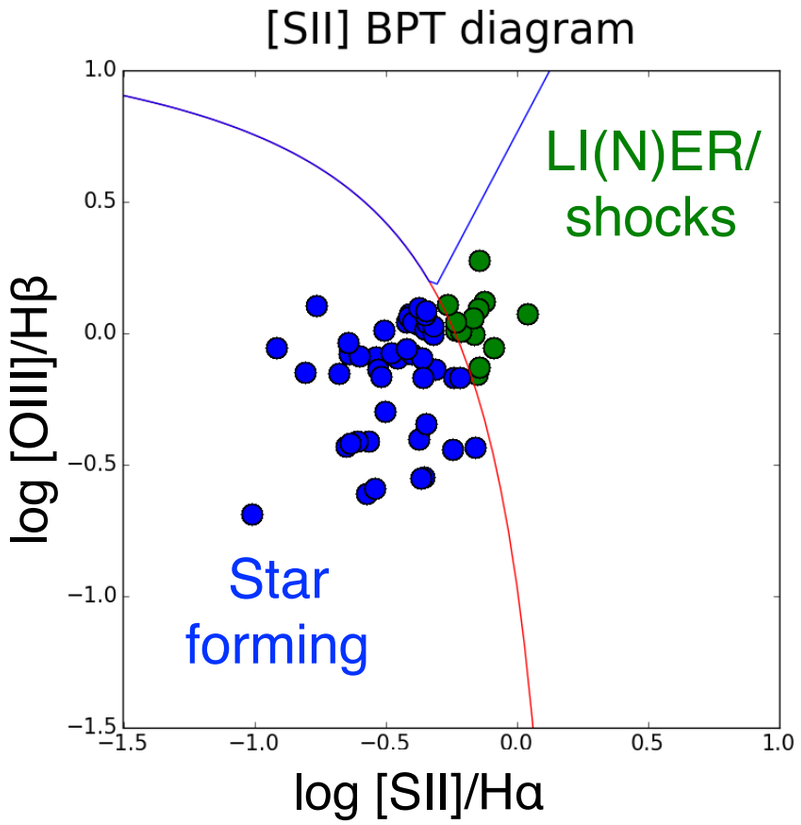
[SII] BPT spatial distribution

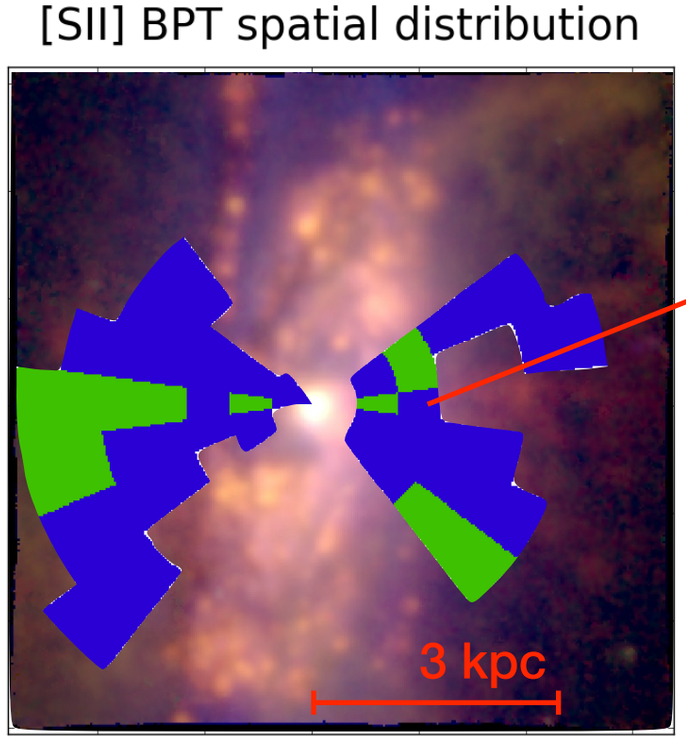


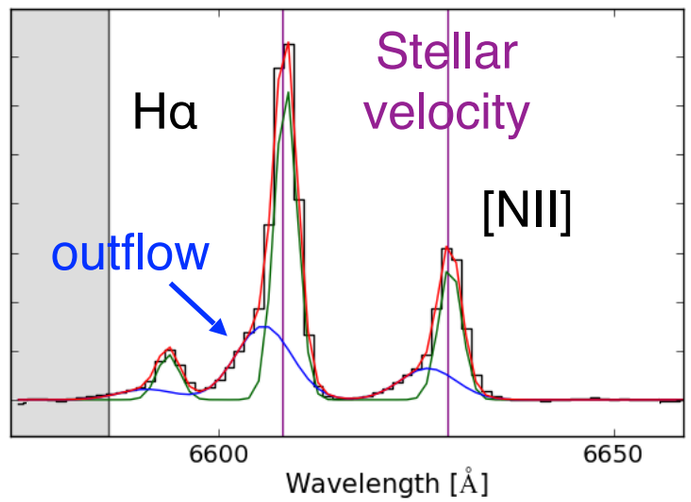


Cone has SF-like ionization

NGC 6810: stars forming *within* the outflow!





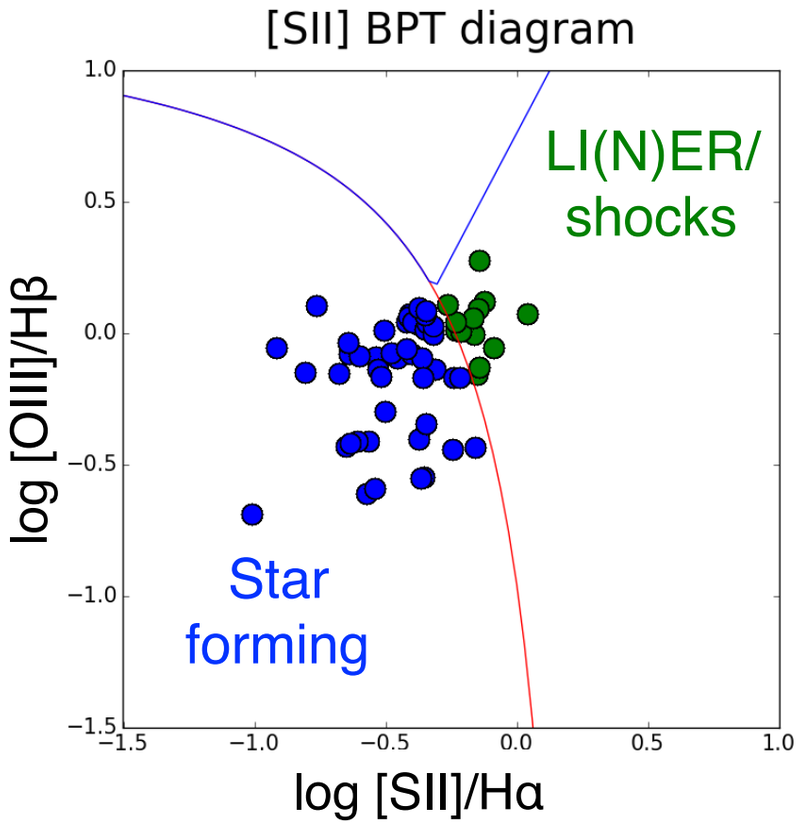


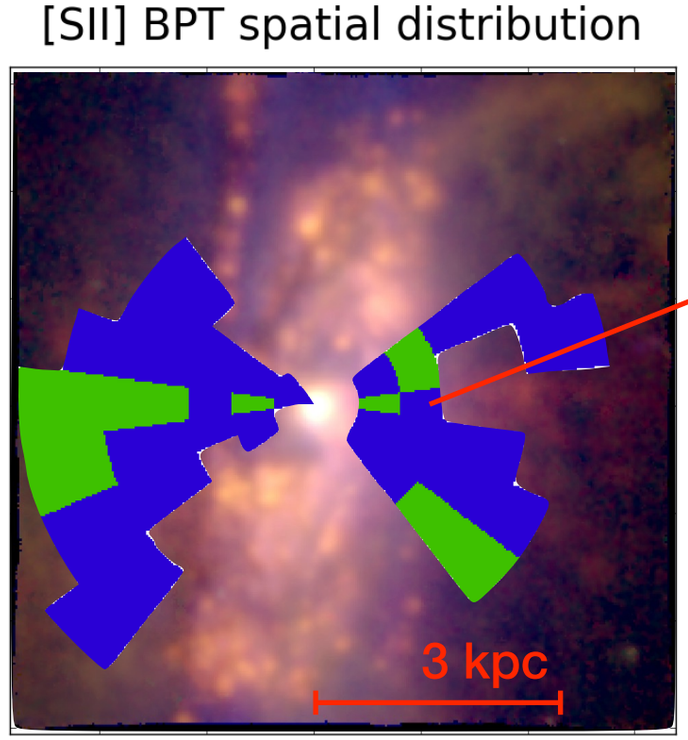
Grid to separate outflow from disk in fitting

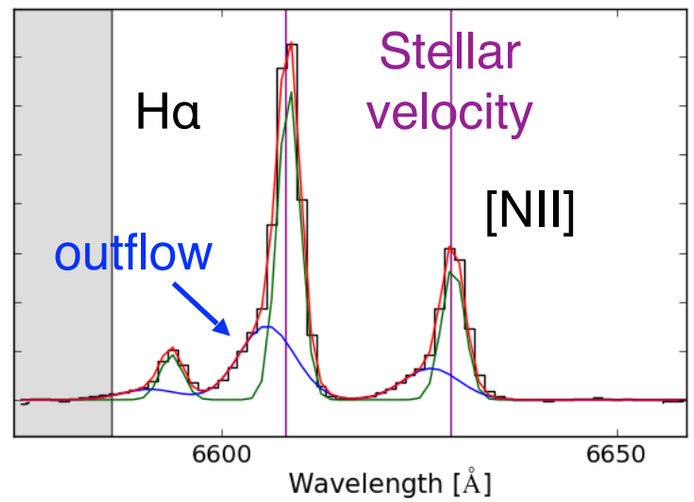
BPT diagram only for

outflow component

NGC 6810: stars forming *within* the outflow!





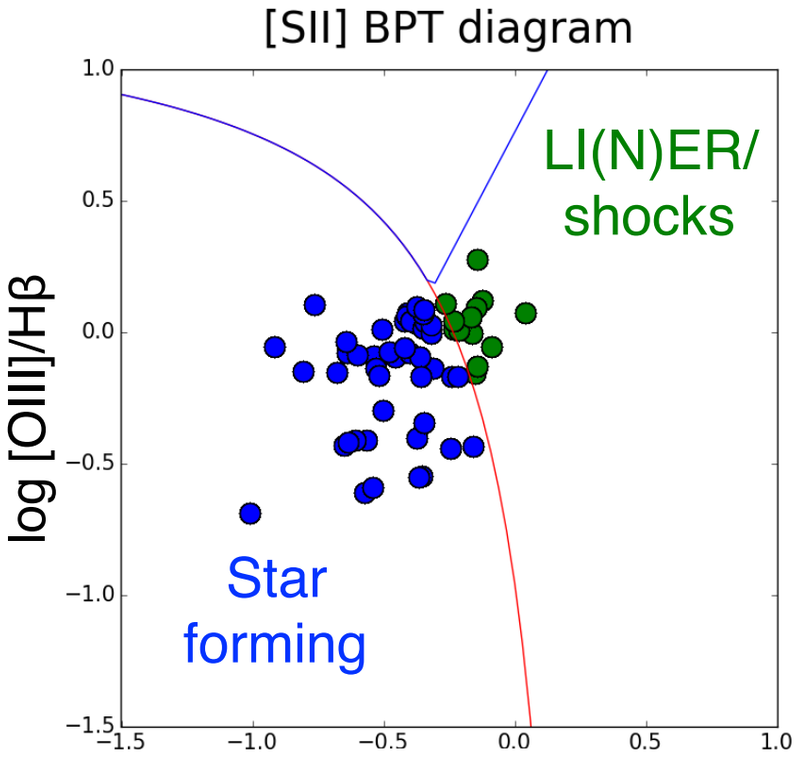


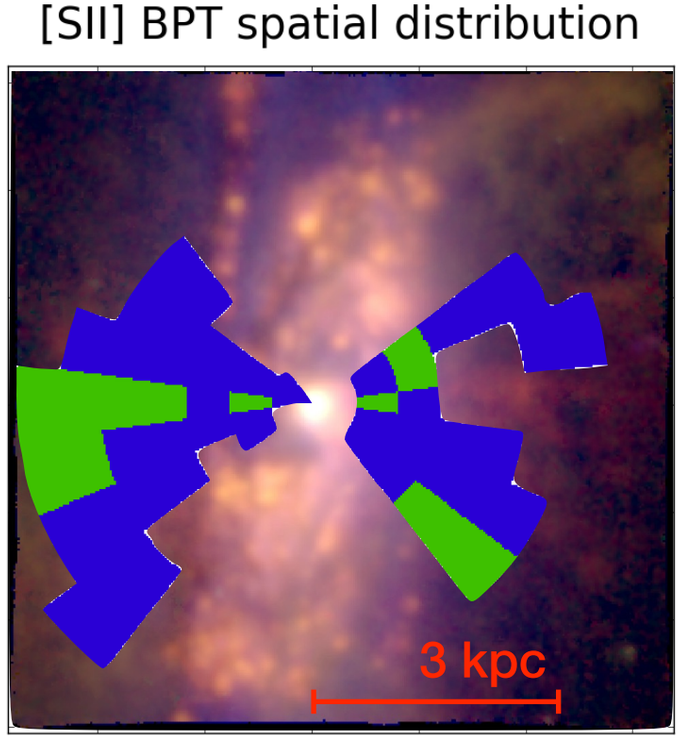
Grid to separate outflow from disk in fitting

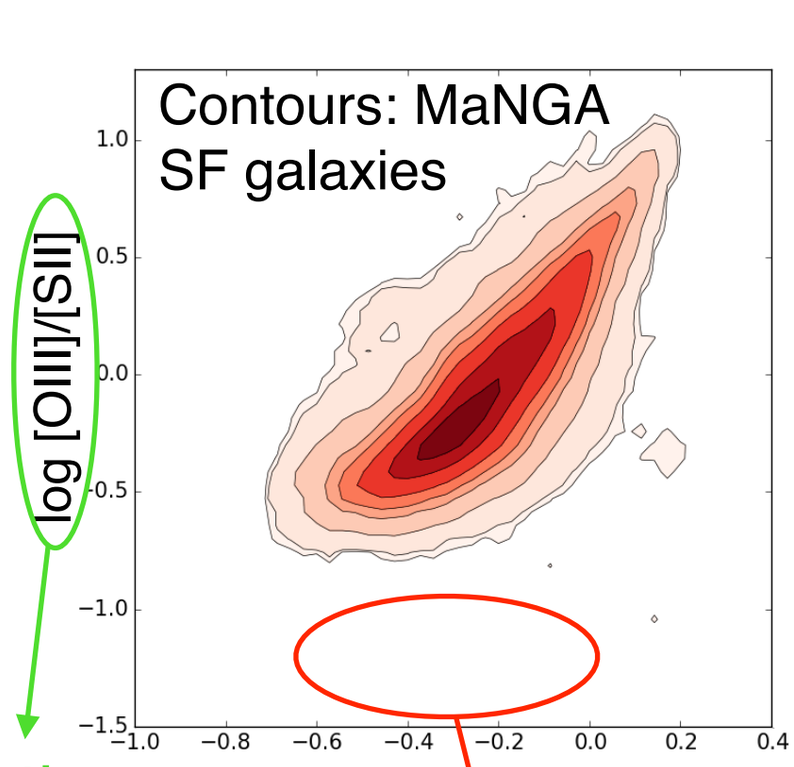
Outflowing cones have SF-like ionization

1. Star formation within outflow!
2. Ionizing photons simply come from SF in the disk…

NGC 6810: stars forming *within* the outflow!







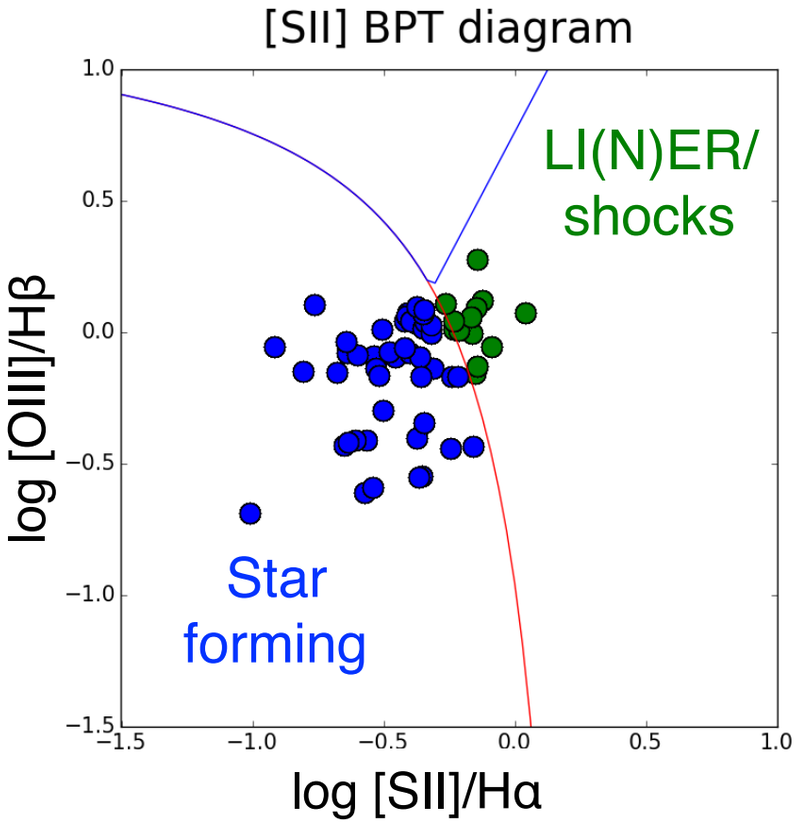
Traces ionization parameter

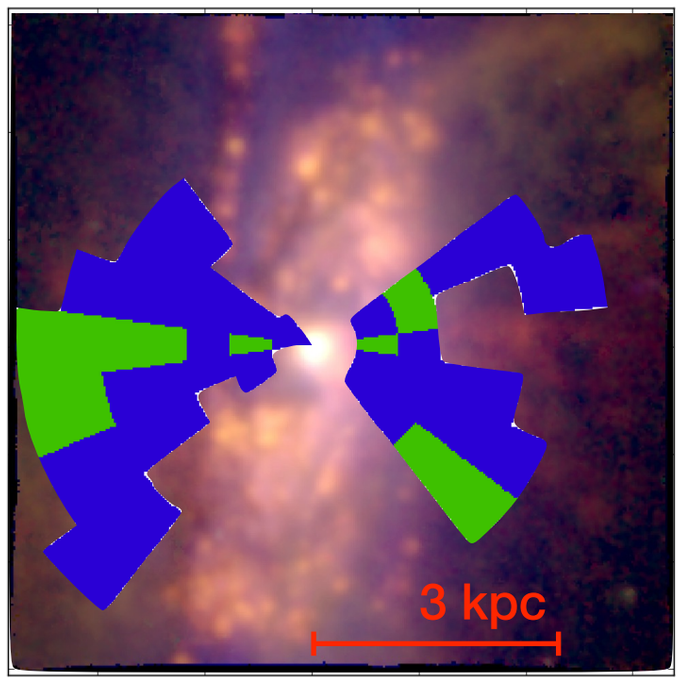
Low ionization parameter expected, if ionization comes from disk (d > 1 kpc)

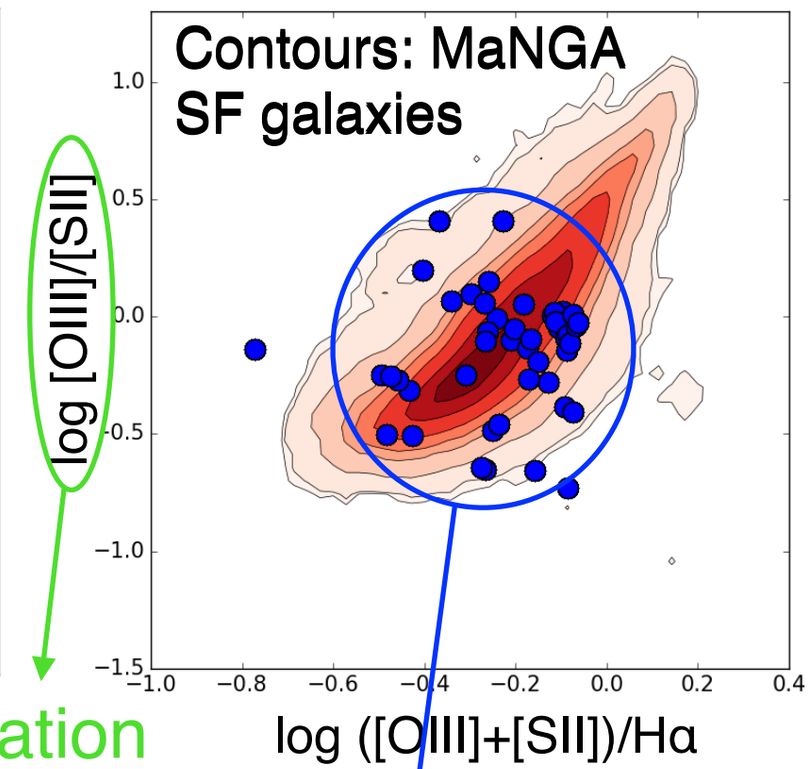
Outflowing cones have SF-like ionization

1. Star formation within outflow!
2. Ionizing photons simply come from SF in the disk…

NGC 6810: stars forming *within* the outflow!







Traces ionization parameter

Outflowing cones have SF-like ionization

1. Star formation within outflow!
2. Ionizing photons simply come from SF in the disk…

Our points are consistent with normal SF regions: ionization from young stars is in situ!

Star formation within the outflow!

Conclusions

- MAGNUM survey: ionized gas kinematics and ionization, outflows and feedback in nearby AGN down to ~10 pc with VLT/MUSE

- NGC 1365 (Venturi et al. 2018)
  - ✦ Hα —> star formation in disk/bar; [OIII] —> AGN-ionized double-conical kpc-scale outflow —> outflow not broad wing like at low-resolution in more powerful objects
  - ✦ Radial profiles of outflow velocity, mass outflow, kinetic and momentum rate —> decrease at larger distance: AGN more powerful recently? mass loading?
  - ✦ Extended vs nuclear X-ray wind —> energy- and momentum-driven scenarios unlikely, radiation pressure-driven feasible. Molecular gas needed

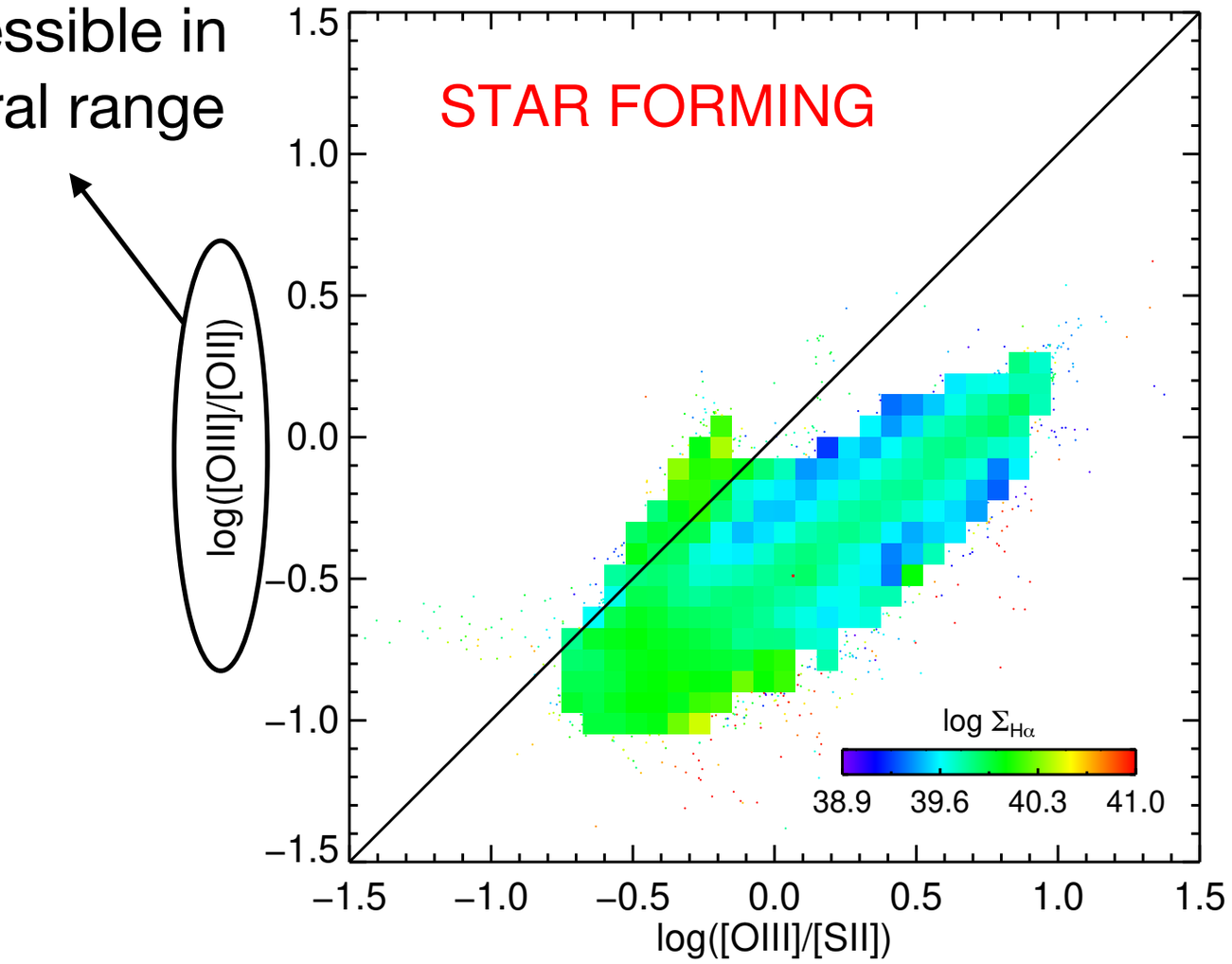
- NGC 6810 (Venturi et al., in prep.)
  - ✦ First detection of star formation within galactic outflow in an unambiguous star-forming galaxy (not AGN)

Far from center of NGC6810 [SIII] is really faint

—> [OIII]∝[SIII] —> use [OIII]/[SII] instead of [SIII]/[SII]

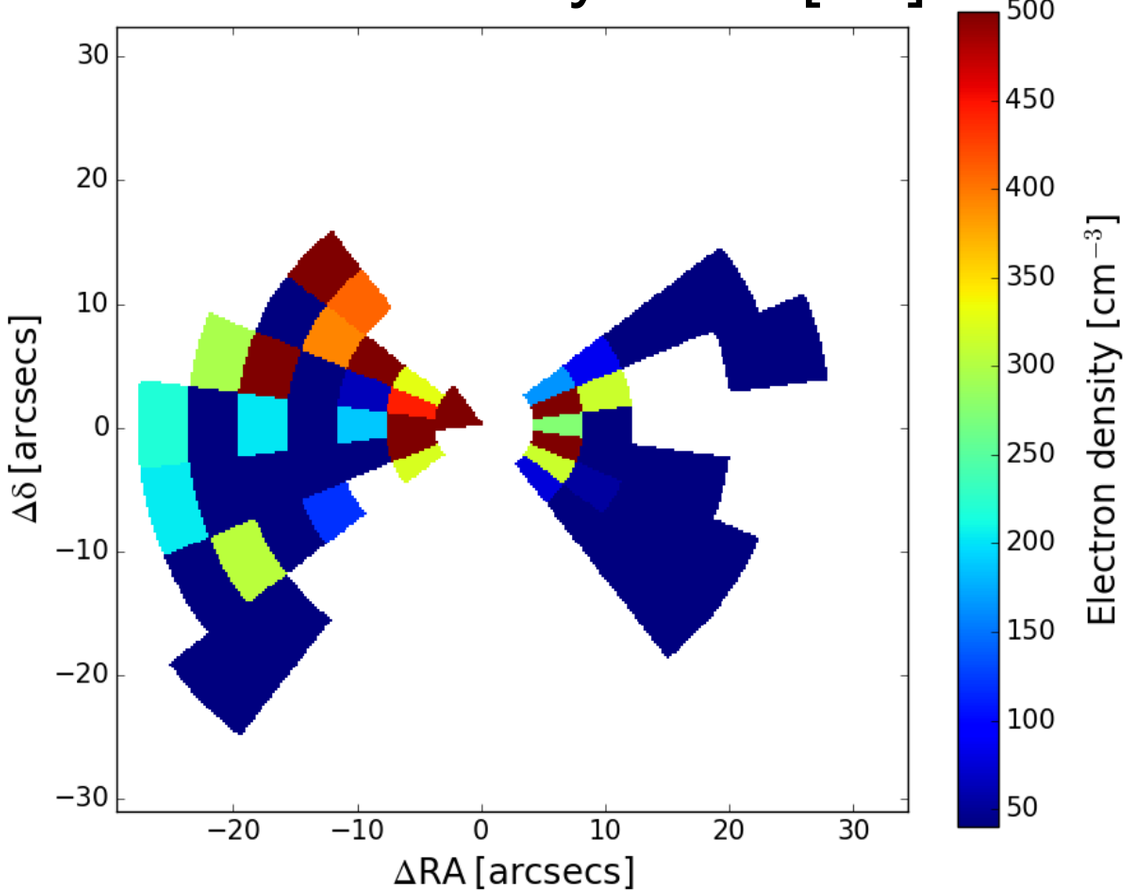
as proxy of ionization parameter

[OII] not accessible in MUSE spectral range



Outflow density in NGC 6810

Outflow density from [SII]



Ionization parameter

$U \propto$ flux/density $\propto r^{-2}\, n_e^{-1}$

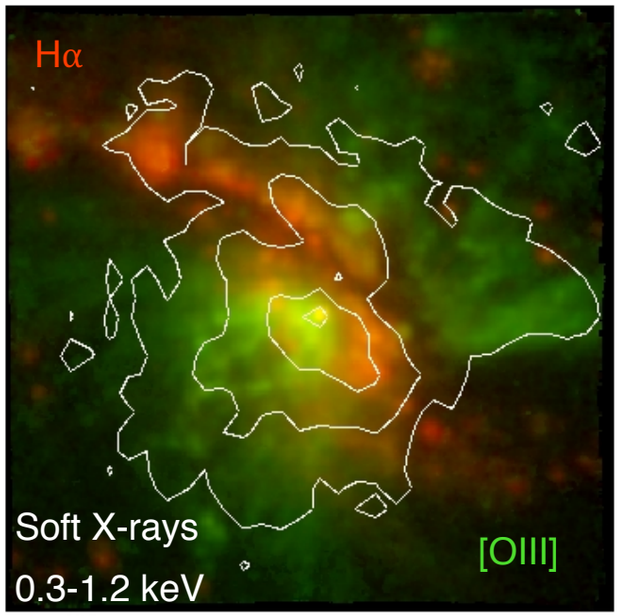
Typical gas densities for local star-forming galaxies:

$n_e \sim$ 20-30 cm^{-3}

(e.g. Sanders+16, Kaasinen+17)

NGC 1365: MUSE-Chandra matching

Compare ionization of warm ionized gas (MUSE) with hot highly-ionized gas from Chandra ACIS-S (X-ray IFU)



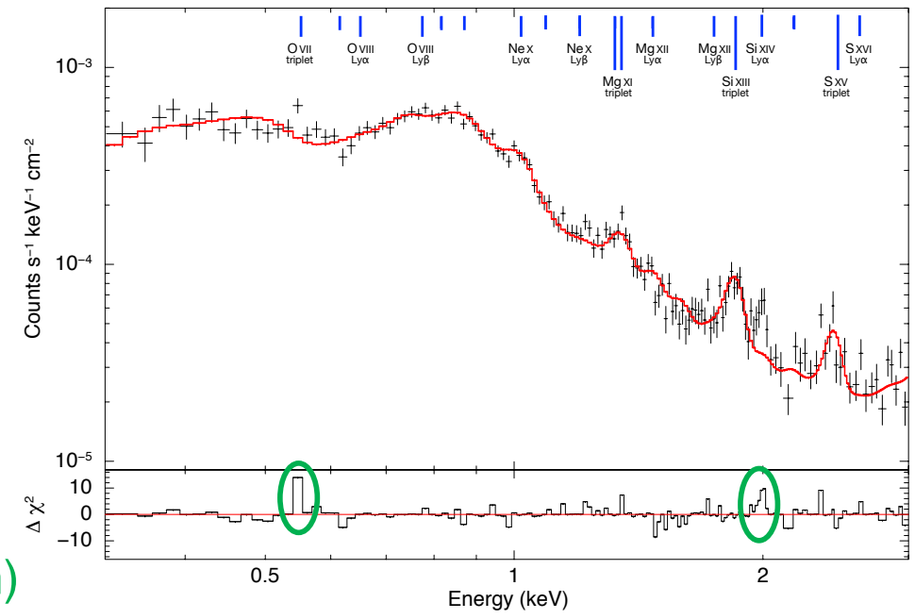
Soft X-rays trace both

[OIII] (AGN) and Hα (SF)

Soft X-ray spectrum:

thermal model (SF) leaves residuals

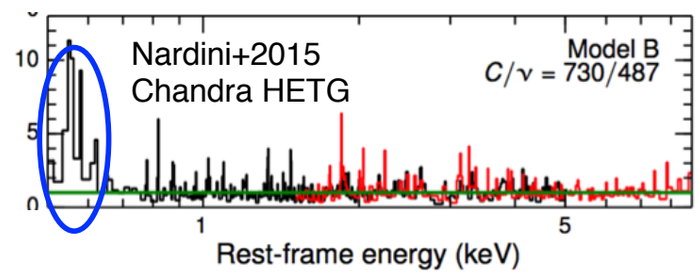
→ emission lines (AGN photoionization)

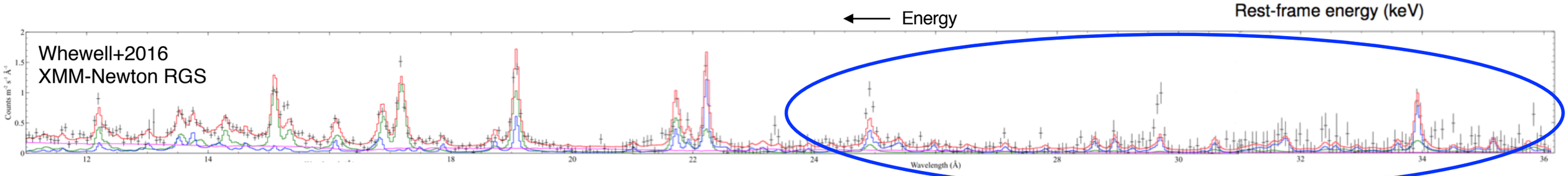


NGC 1365: MUSE-Chandra matching

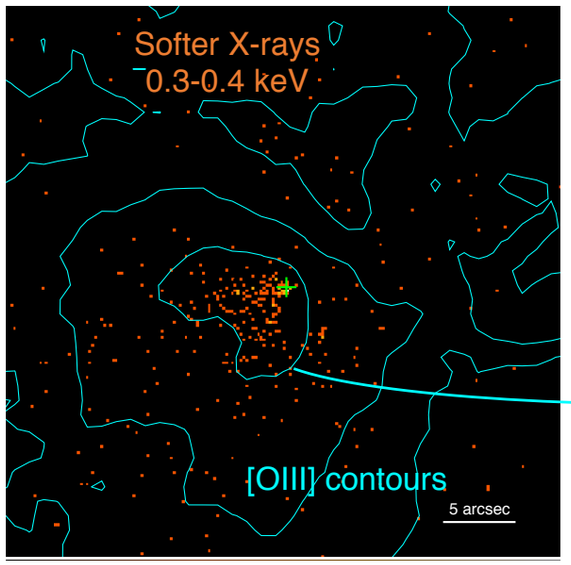
AGN photoionization observed at high spectral resolution with grating data

→ Dominates over SF thermal emission < 0.5 keV

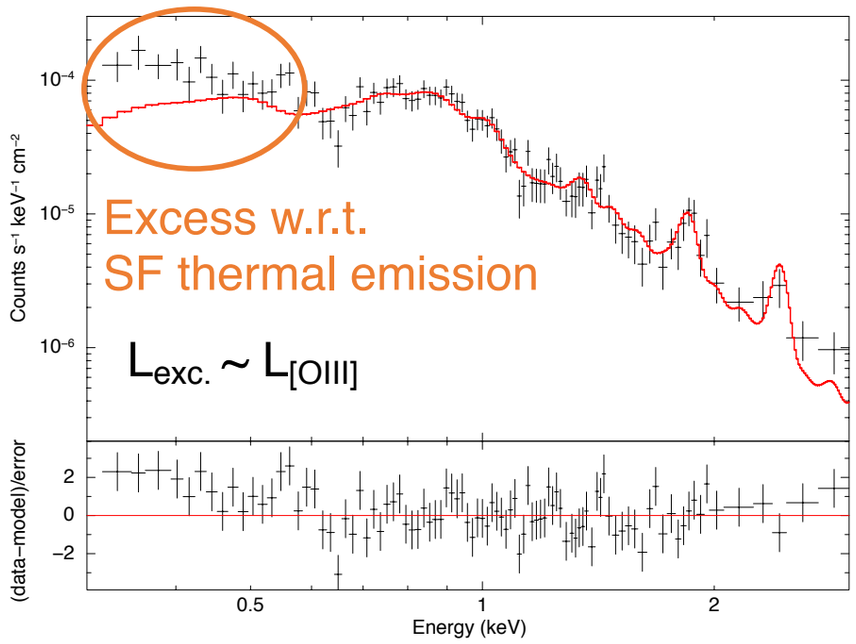




Zoom in central region



0.3-0.4 keV X-rays perfectly trace inner [OIII] emission



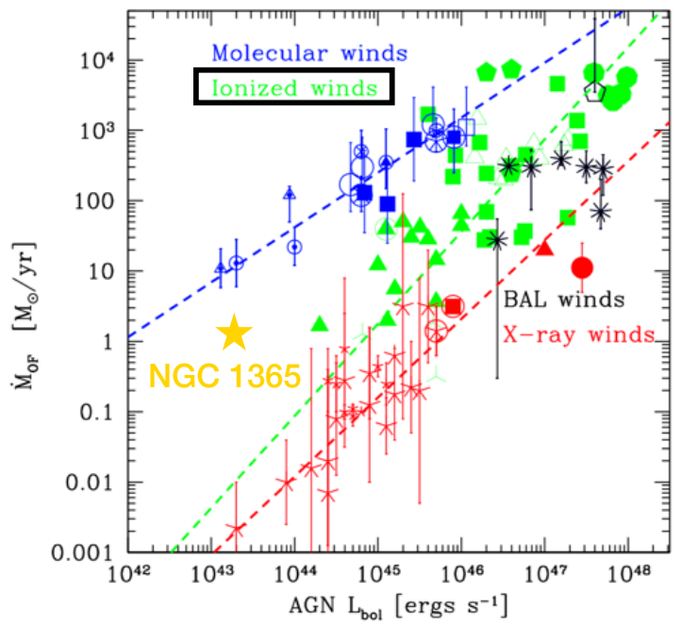
Excess: blend of em. lines

↓

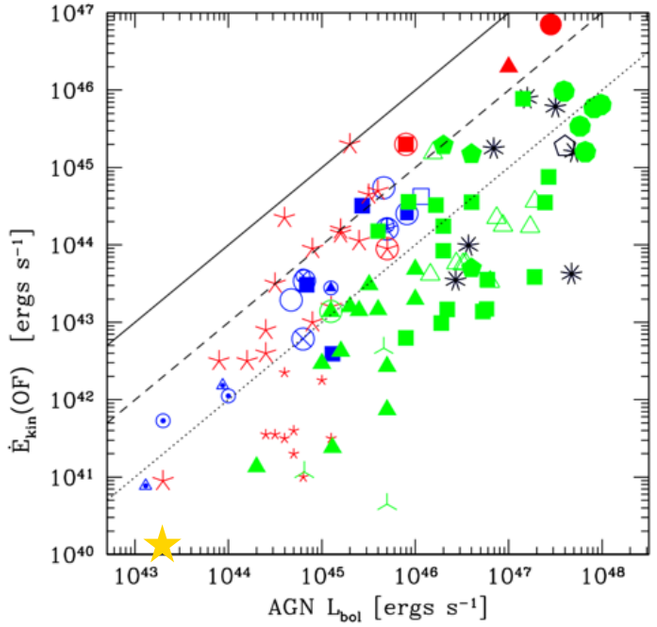
AGN photoionization spatially and spectrally recovered

Comparison with AGN outflow samples

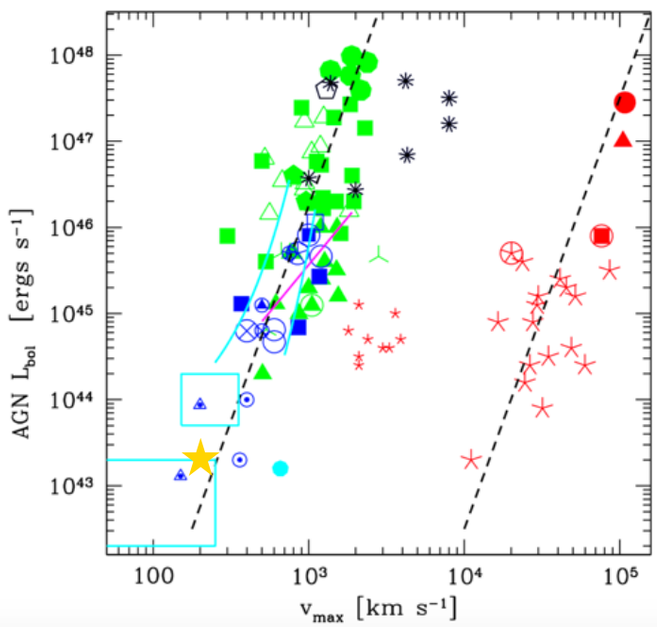
AGN $L_{\rm bol}$ vs $\dot{M}_{\rm out}$



AGN $L_{\rm bol}$ vs $\dot{E}_{\rm kin}$



AGN $L_{\rm bol}$ vs $v_{\rm max}$



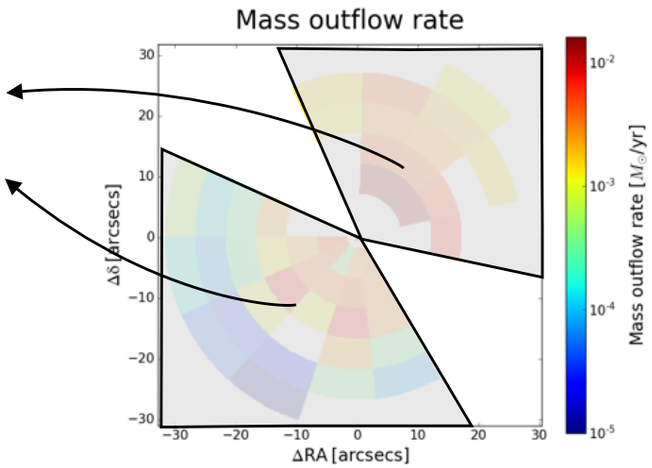
Fiore+2017

$$\dot{M}_{\rm out} = \frac{3 M_{\rm out} v_{\rm max}}{R} \quad (v_{\rm max} = v_{\rm out} + 2\sigma)$$

Instantaneous mass outflow rate

(as in Fiore+2017)

From entire cones

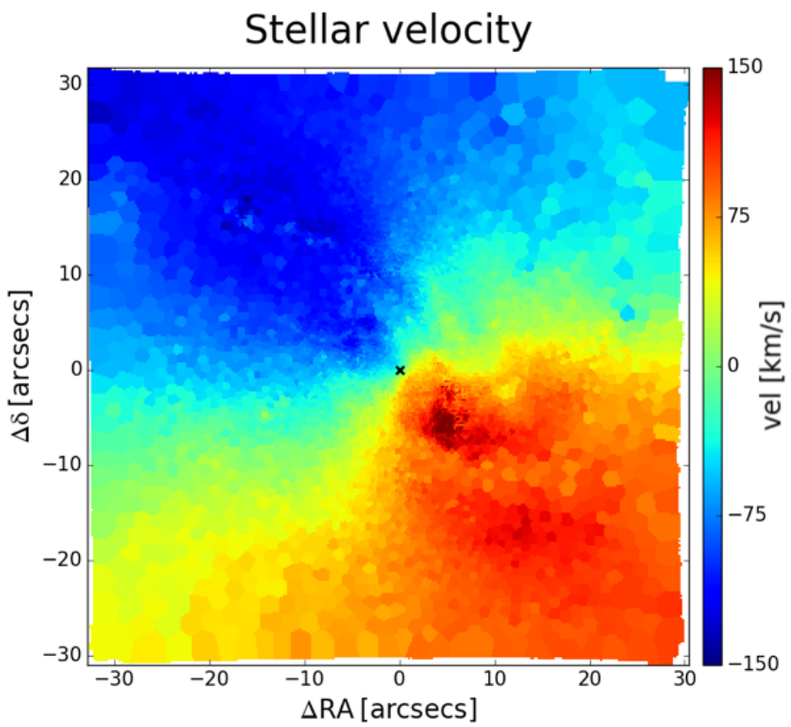


NGC 1365: **AGN $L_{\rm bol} \sim 2 \times 10^{43}$ erg/s**

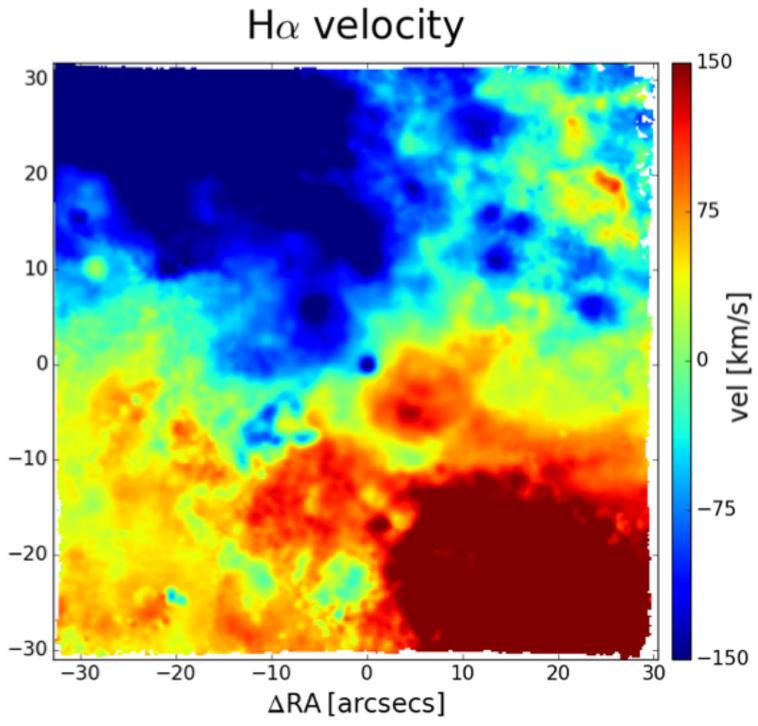
→ $\dot{E}_{\rm kin}, v_{\rm max}$ consistent with extrapolation at low $L_{\rm bol}$ from Fiore+2017 within scatter,

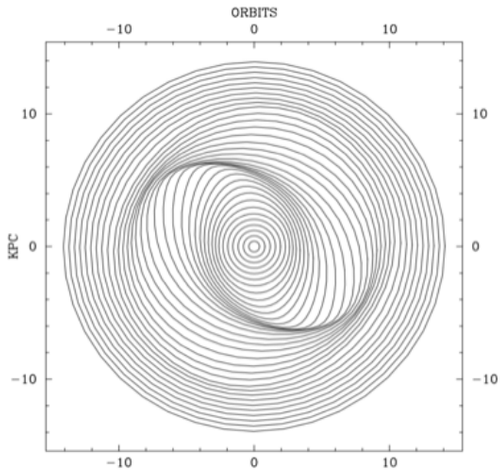
$\dot{M}_{\rm out}$ barely consistent

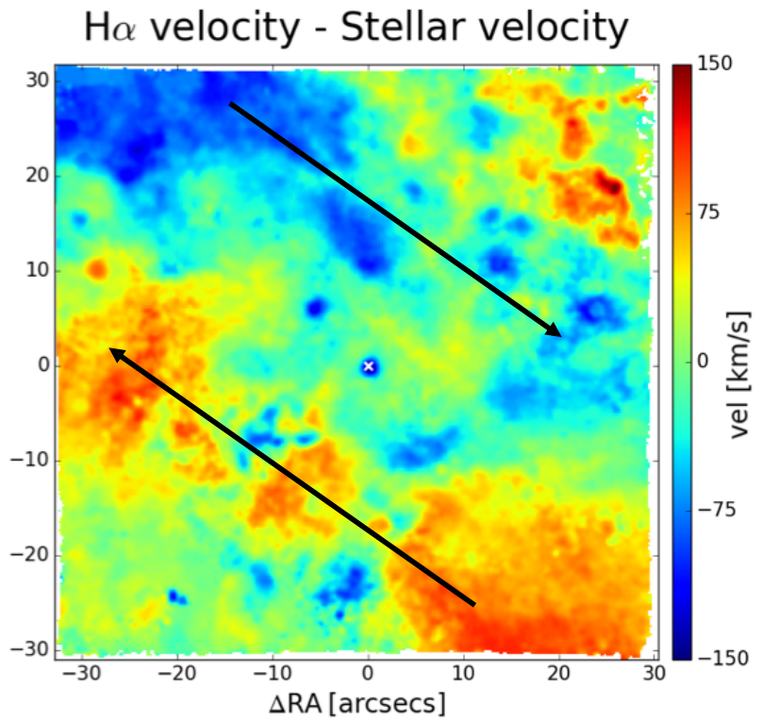
NGC 1365: kinematics of ionised gas



Rotating disk







Non-circular motion

due to the bar

↓

Inflow