1982: early days with thanks to Bob Fosbury

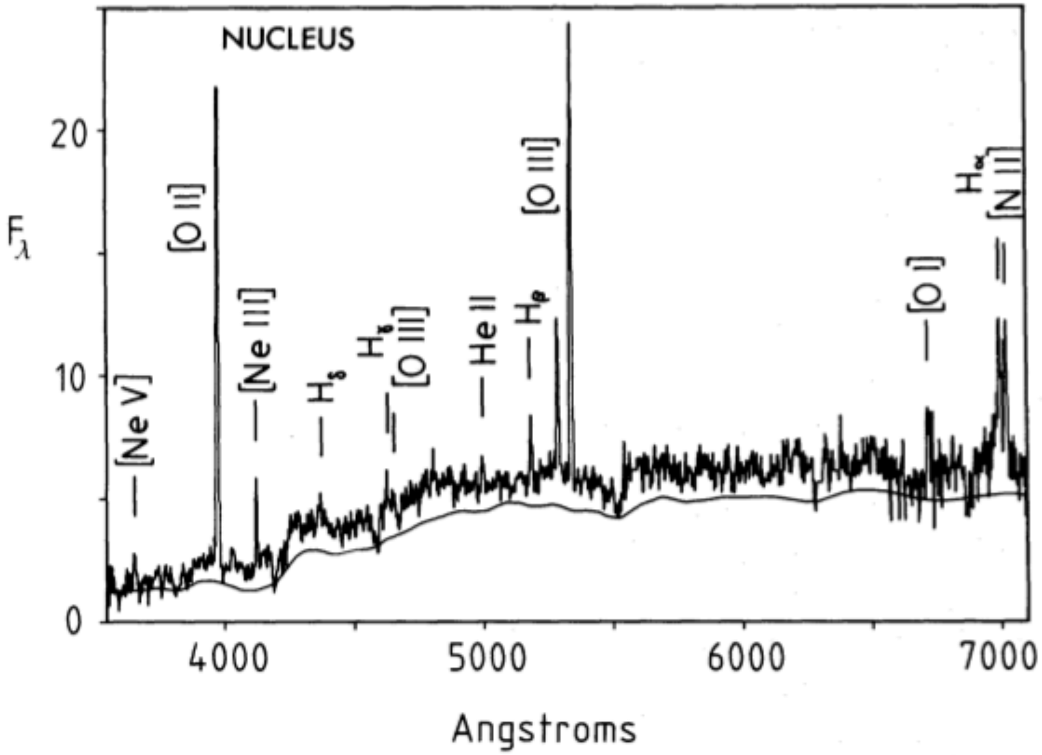

Figure 1. The flux-calibrated spectra of the nuclear region of PKS 0349 – 27 summed from the four different slit-positions. A smoothed standard *E*-galaxy spectrum in the same rest frame is also shown as a solid line.

Pence (1976) first paper on K corrections

3D Mapping of AGN and Starburst Driven Outflows

Rob Sharp, Joss Bland-Hawthorn

ANU / U Sydney

The Astrophysical Journal, 711:818–852, 2010 March 10 doi:10.1088/0004-637X/711/2/818

THREE-DIMENSIONAL INTEGRAL FIELD OBSERVATIONS OF 10 GALACTIC WINDS. I. EXTENDED PHASE ($\gtrsim$10 Myr) OF MASS/ENERGY INJECTION BEFORE THE WIND BLOWS

R. G. Sharp[1] and J. Bland-Hawthorn[2,3,4]
[1] Anglo-Australian Observatory, P.O. Box 296, Epping, NSW 1710, Australia; rgs@aao.gov.au
[2] Sydney Institute for Astronomy, School of Physics A28, University of Sydney, NSW 2006, Australia
[3] Physics Department, University of Oxford, 1 Keble Rd, Oxford, OX1 3RH, UK; jbh@physics.usyd.edu.au
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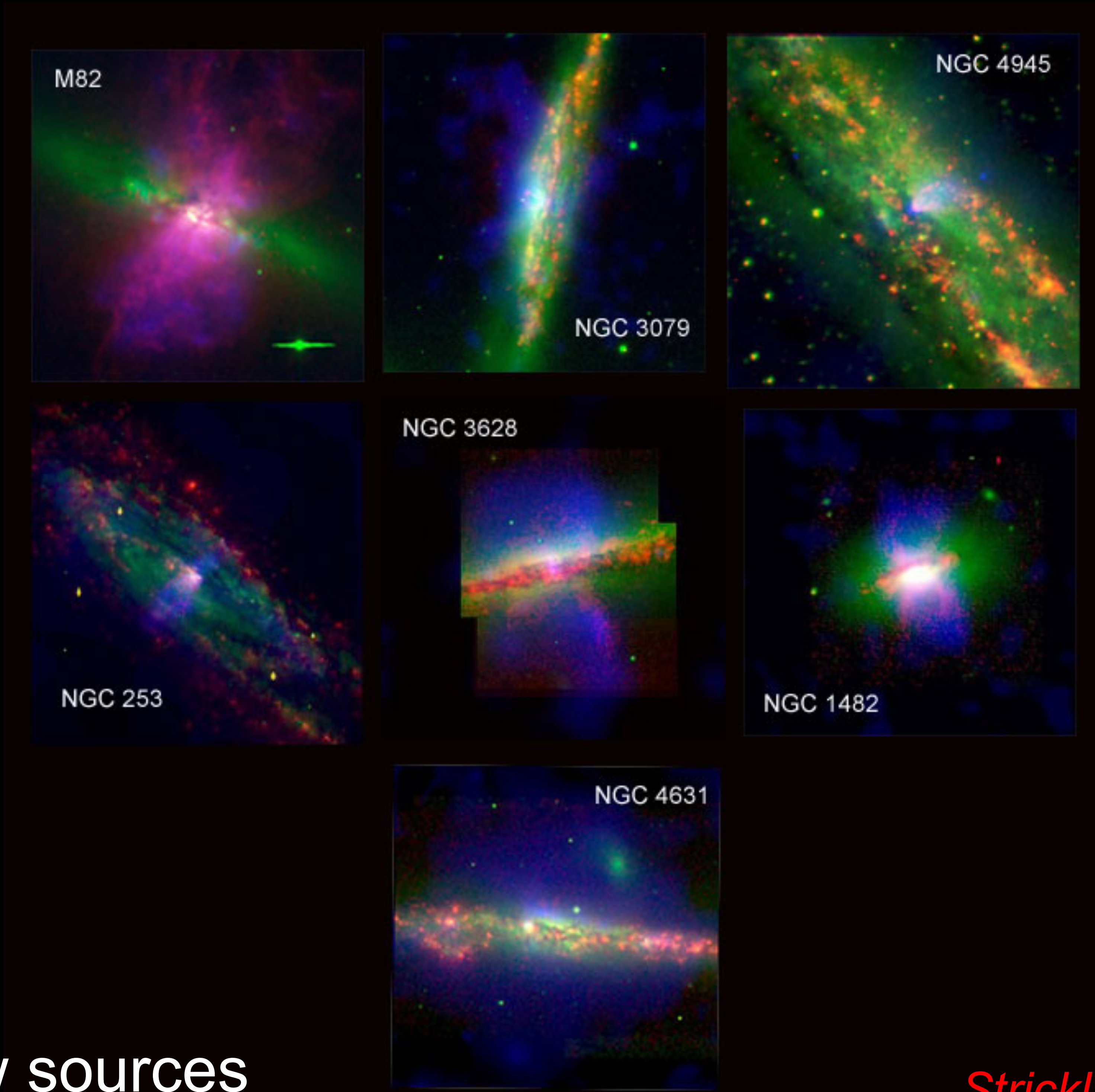
ABSTRACT

In recent years, we have come to recognize the widespread importance of large-scale winds in the life cycle of galaxies. The onset and evolution of a galactic wind is a highly complex process which must be understood if we are to understand how energy and metals are recycled throughout the galaxy and beyond. Here we present three-dimensional spectroscopic observations of a sample of 10 nearby galaxies with the AAOmega-SPIRAL integral-field spectrograph on the 3.9 m Anglo-Australian Telescope, the largest survey of its kind to date. The double-beam spectrograph provides spatial maps in a range of spectral diagnostics: [O III]5007, Hβ, Mg *b*, Na D, [O I]6300, Hα, [N II]6583, [S II]6717, 6731. We demonstrate that these flows can often separate into highly ordered structures through the use of ionization diagnostics and kinematics. All of the objects in our survey show extensive wind-driven filamentation along the minor axis, in addition to large-scale disk rotation. Our sample can be divided into either starburst galaxies or active galactic nuclei (AGNs), although some objects appear to be a combination of these. The total ionizing photon budget available to both classes of galaxies is sufficient to ionize all of the wind-blown filamentation out to large radius. We find, however, that while AGN photoionization always dominates in the wind filaments, this is not the case in starburst galaxies where shock ionization dominates. This clearly indicates that after the onset of star formation, there is a substantial delay ($\gtrsim$10 Myr) before a starburst wind develops. We show why this behavior is expected by deriving "ionization" and dynamical timescales for both AGNs and starbursts. We establish a sequence of events that lead to the onset of a galactic wind. The clear signature provided by the ionization timescale is arguably the strongest evidence yet that the starburst phenomenon is an impulsive event. A well-defined ionization timescale is not expected in galaxies with a protracted history of circumnuclear star formation. Our three-dimensional data provide important templates for comparisons with high-redshift galaxies.

Key words: galaxies: individual (NGC 253, NGC 1365, NGC 1482, NGC 1808, NGC 3628, NGC 5128, Circinus, NGC 6240, NGC 6810, IC 5063)

Online-only material: color figures



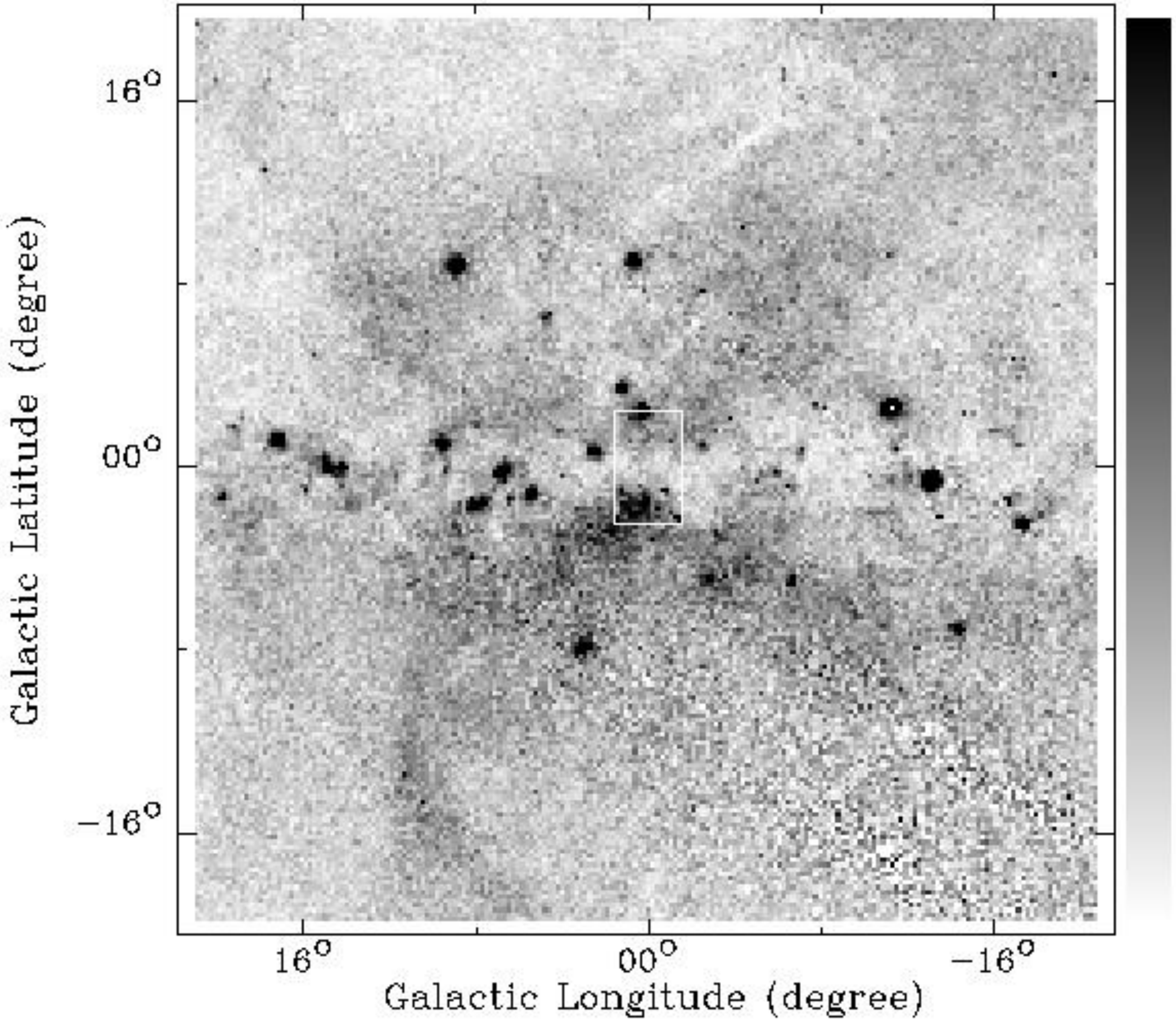
Outflow sources

Strickland 2004

AGNs drive jets, cones, winds

Thanks to Dan Dicken

The Galaxy: bipolar wind seen on 10 kpc scales!



ROSAT 1.5 keV (diffuse)

JBH & Cohen (2003)

The Galaxy: γ-ray bubbles discovered by *Fermi*

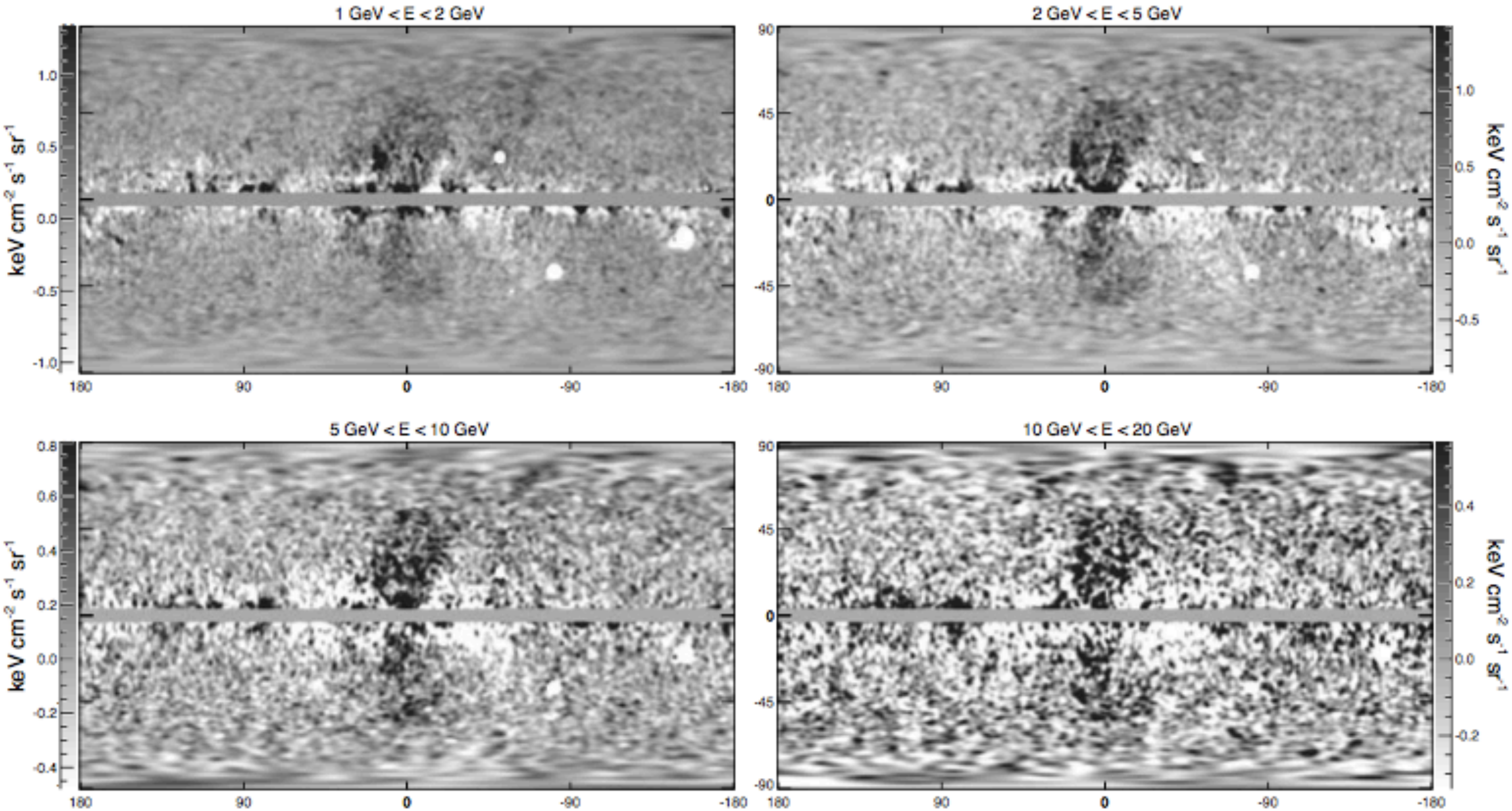


FIG. 2.— All-sky residual maps after subtracting the *Fermi* diffuse Galactic model from the LAT 1.6 year maps in 4 energy bins (see §3.1.1). Two bubble structures extending to $b \pm 50°$ appear above and below the GC, symmetric about the Galactic plane.

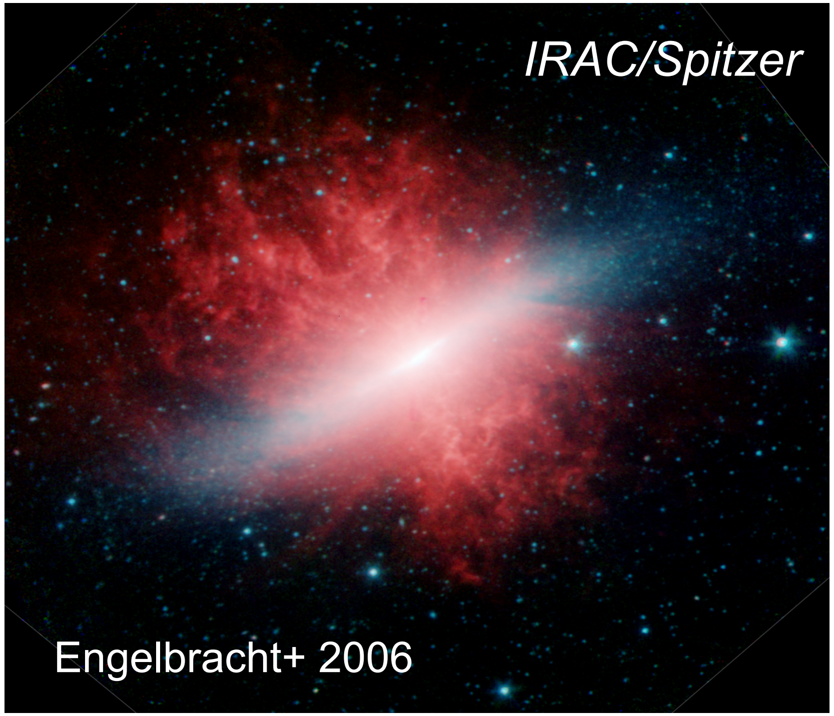
Su, Slayter, Finkbeiner (2010)

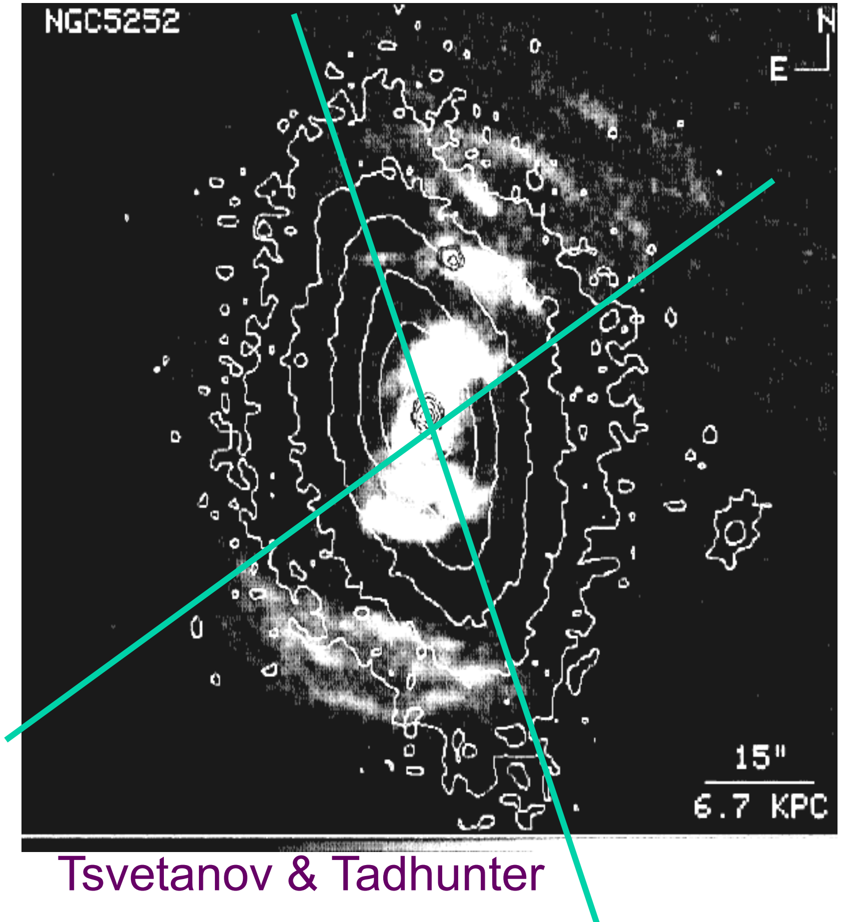
A question to the audience:

What timescale is associated with AGN or nuclear ★B activity?

How well can we distinguish them?

Is there a co-dependence?





Tsvetanov & Tadhunter

This calls for a differential study:

Ionization vs. dynamical times in starburst vs. AGN winds

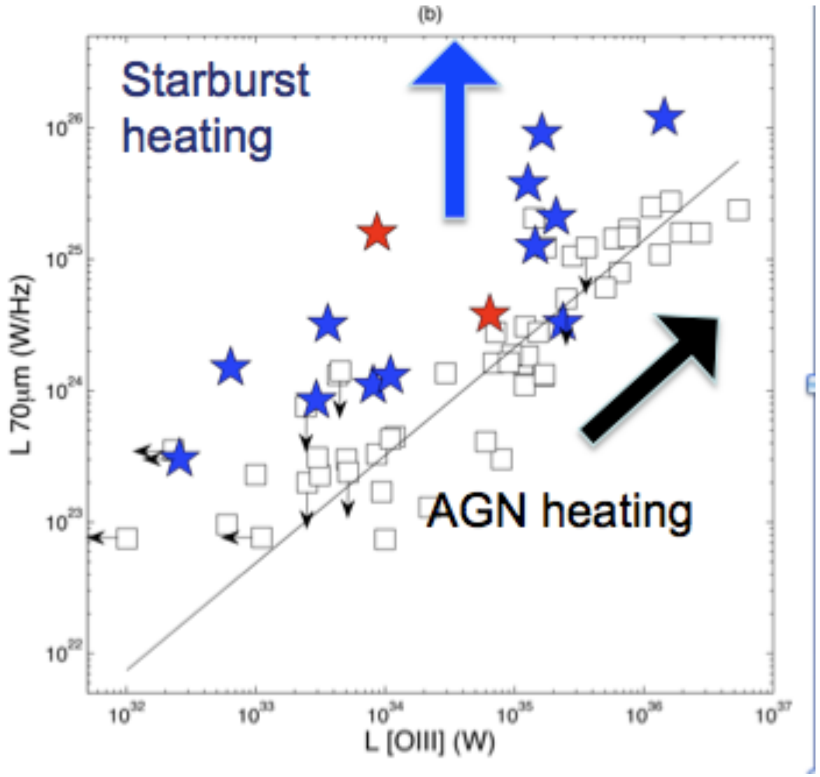
It is surprisingly difficult to distinguish the large-scale energetic influence of an AGN vs. ★B:

1. Both operate on similar timescales?

2. Both have similar photon budgets scaled to L_{BOL}

3. Both generate powerful outflows

4. Both heat dust (AM, DD talks)



With thanks to Dan Dicken

Ionizing photon budget from AGN

$$L_A = \epsilon \dot{m} c^2 \quad (1)$$

$$= 7 \times 10^{11} \left(\frac{\epsilon}{0.05}\right) \left(\frac{\dot{m}}{M_\odot \, \mathrm{yr}^{-1}}\right) L_\odot \quad (2)$$

$$L_E = \frac{4\pi G m_{\mathrm{BH}} m_p c}{\sigma_T}$$

$$= 2 \times 10^{11} \left(\frac{m_{\mathrm{BH}}}{10^7 \, M_\odot}\right) L_\odot$$

$$\mathcal{N}_{\mathrm{LyC,A}} \sim 10^{54} \xi_A \left(\frac{L_{\mathrm{bol,A}}}{10^{11} L_\odot}\right) \ \mathrm{phot\ s^{-1}}$$

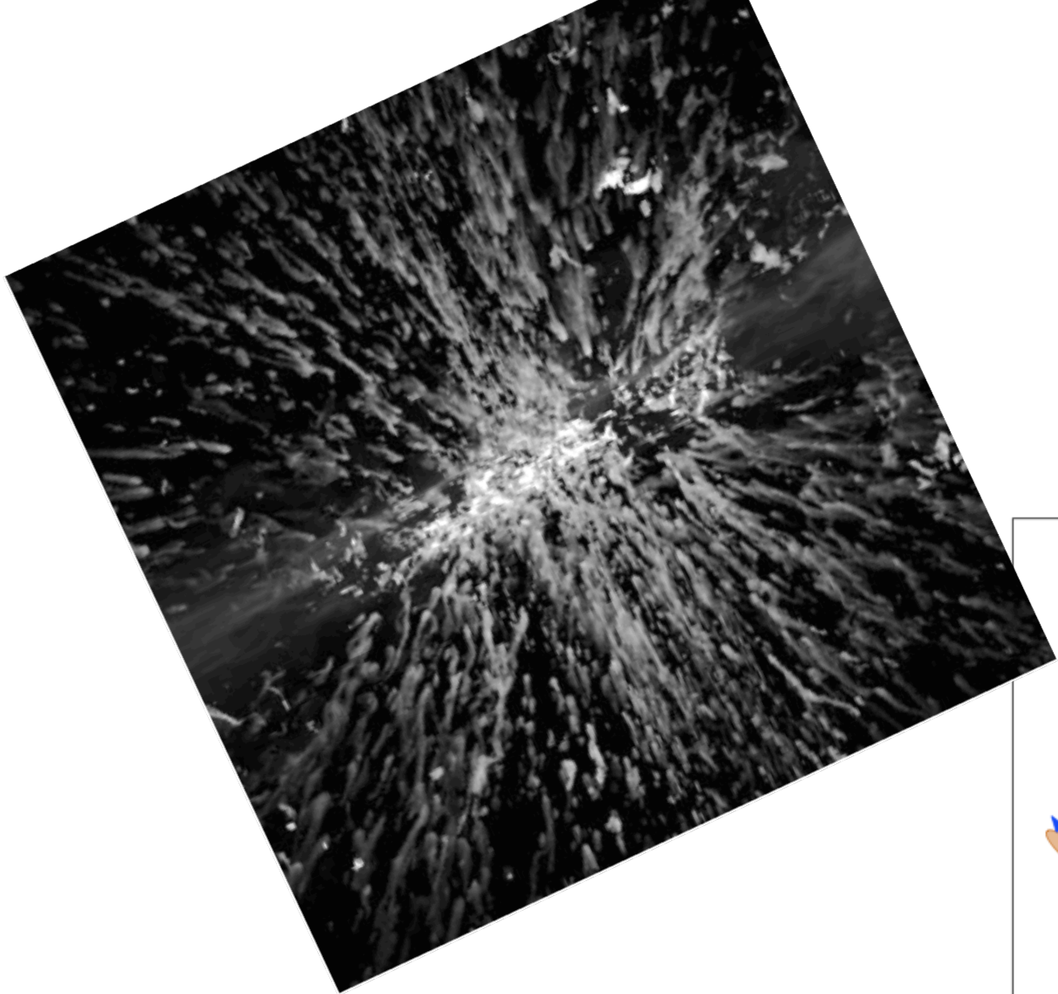
Ionizing photon budget from nuclear ★B

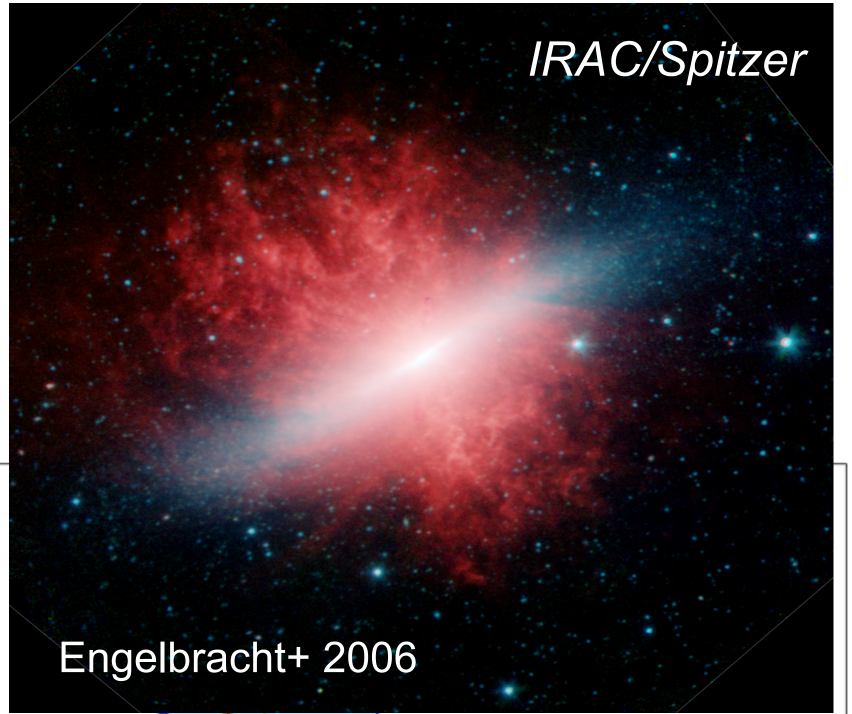
$$L_S \sim 10^{11} \left(\frac{\dot{s}}{5\ M_\odot\ \mathrm{yr}^{-1}}\right)\left(\frac{\Delta t}{10^8\ \mathrm{yr}}\right)^{0.67} \times \left(\frac{m_L}{1\ M_\odot}\right)^{0.23}\left(\frac{m_U}{100\ M_\odot}\right)^{0.37} L_\odot$$

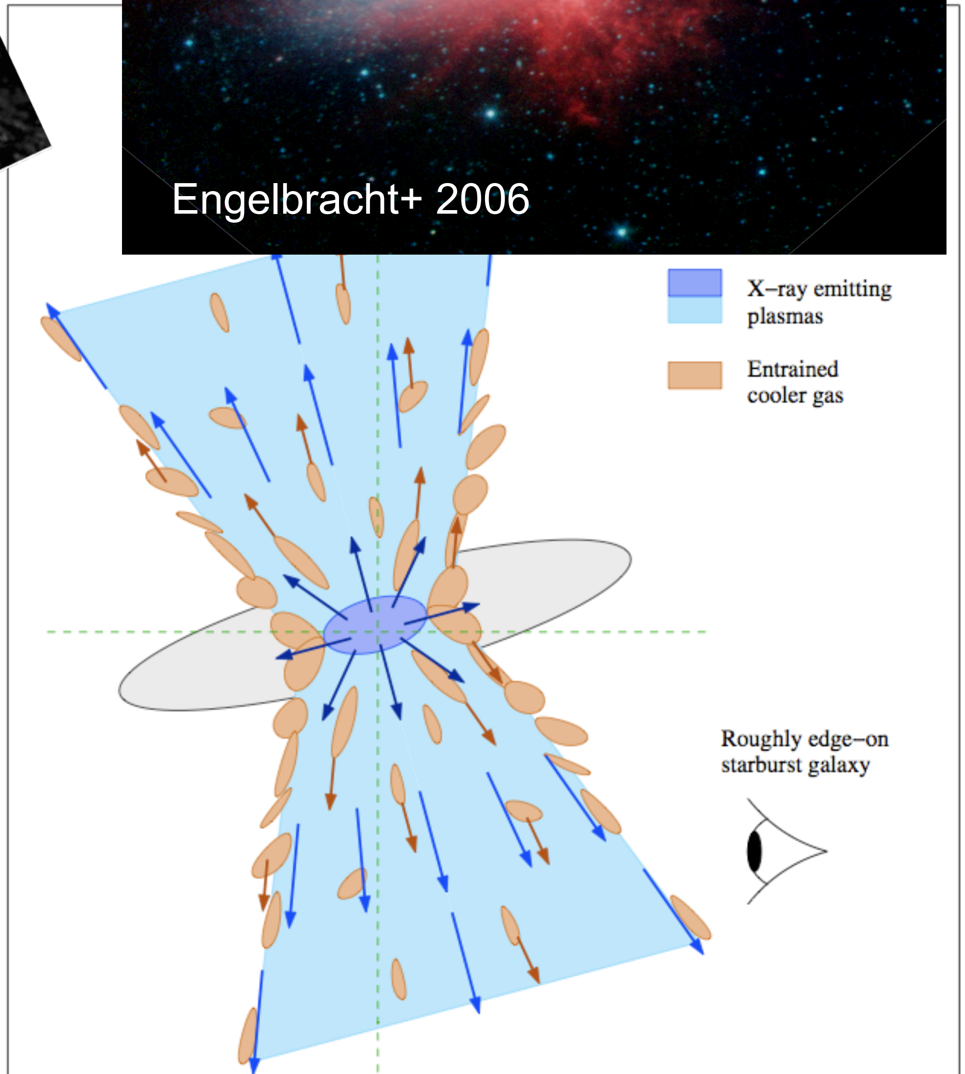
$$\dot{s} \sim 5 \left(\frac{L_S}{10^{11}\ L_\odot}\right)\left(\frac{\Delta t}{10^8\ \mathrm{yr}}\right)^{-0.67} M_\odot\ \mathrm{yr}^{-1}.$$

$$\mathcal{N}_{\mathrm{LyC,S}} \sim 10^{54} \left(\frac{\dot{s}}{5\ M_\odot\ \mathrm{yr}^{-1}}\right)\left(\frac{m_L}{1\ M_\odot}\right)^{0.23}\left(\frac{m_U}{100\ M_\odot}\right)^{0.37}$$

$$\sim 10^{54} \xi_S \left(\frac{L_{\mathrm{bol}}}{10^{11} L_\odot}\right)\ \mathrm{phot\ s^{-1}}$$





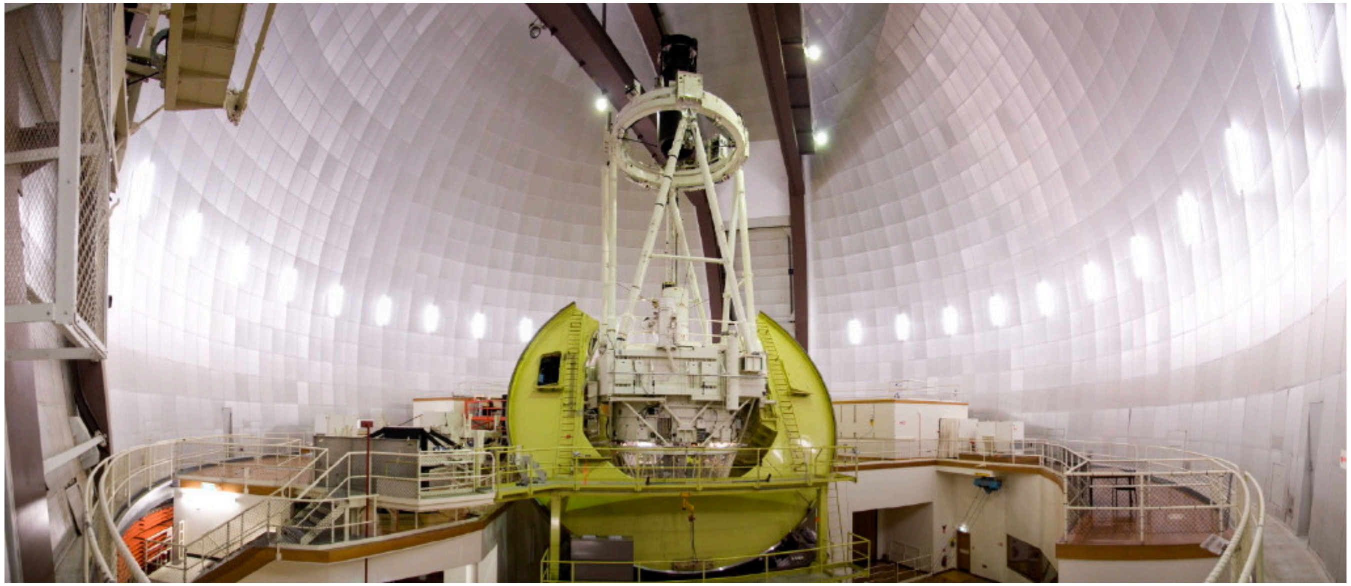


Origin & physics of filaments:
Cooper+ 2008, 2009

Rotation in the filament system tells you all the gas you see is entrained from the disk.

SPIRAL: optical integral field dual-beam spectroscopy

- A sample of nearby AGN and ★B wind galaxies
- Luminosity range: 1-10 x 10^{10} $L_{\odot}$
- Most AGNs show evidence of circumnuclear SF



AAOmega+SPIRAL

- **Dual beam spectrograph**
- 512 element fibre feed
- 32x16 rectangular array
- **0.7 arcsec square pixels**
- 11.2x22.4 arcsec FoV
- *R* = 5700-6300 over 370-890 nm

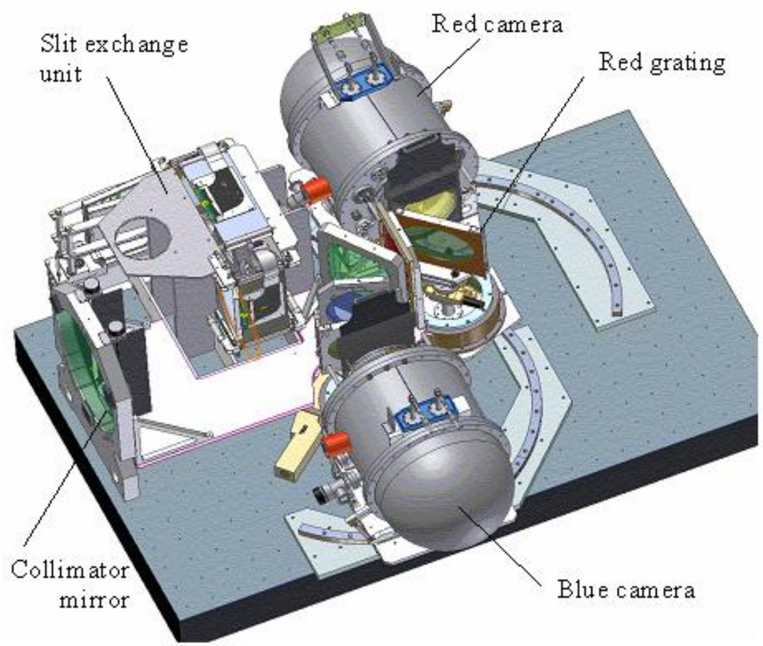
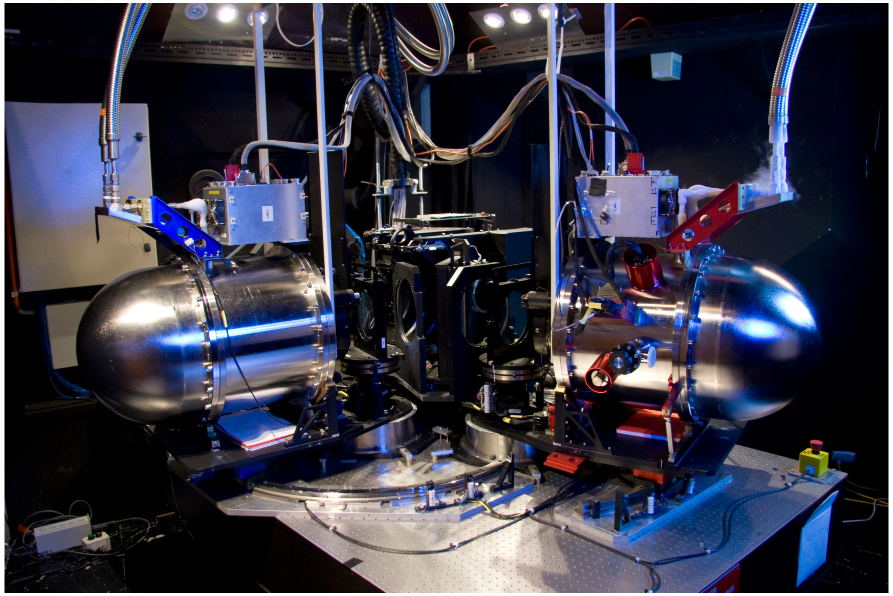
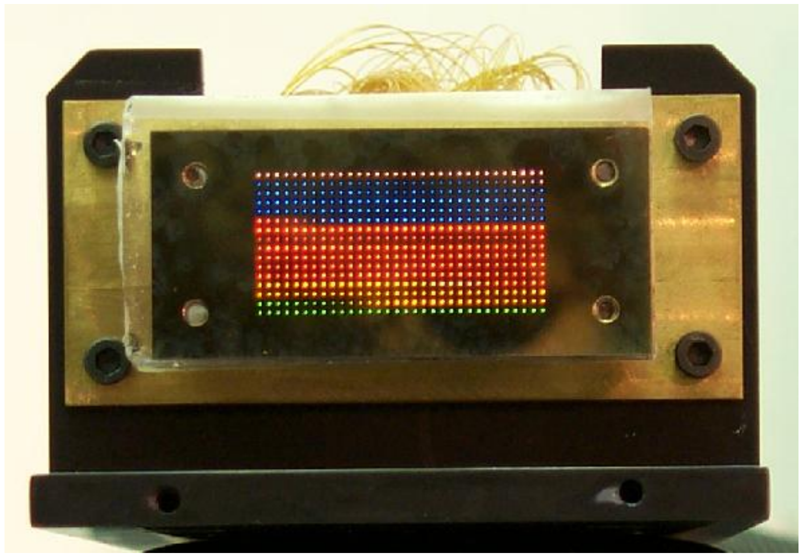


Figure 1. Physical layout of AAOmega, layout, showing the red camera in high dispersion mode, and blue camera in low dispersion mode.



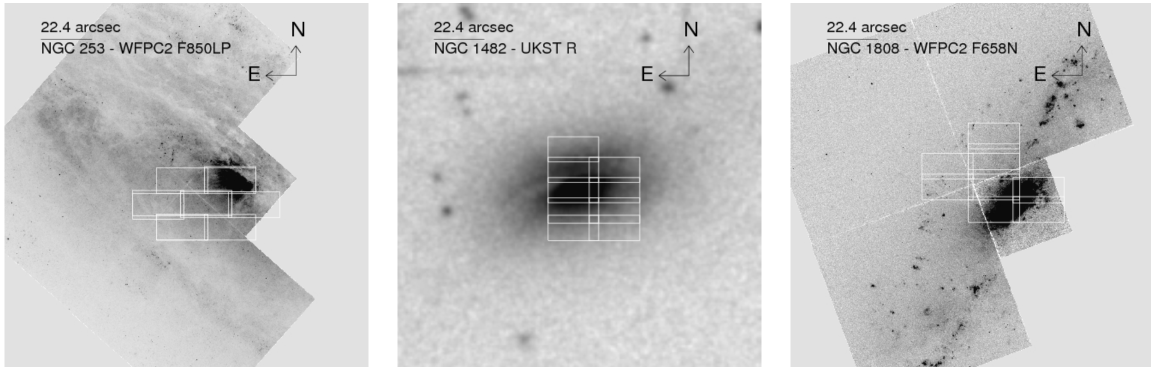


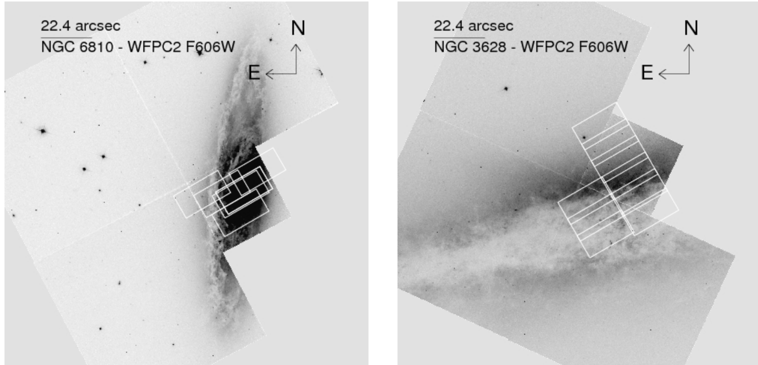
Object	RA/Dec (J2000)	Redshift	Hubble type[1]	Spec class[2]	i	M_B	L_{Bol}[3]
NGC 253	00 47.6 −25 18	0.00081	Sc(X)	HII	86	−20.02	2.8
NGC 1365	03 33.7 −36 08	0.00546	Sb(B)	HII, Sy2	63	−21.26	9.3
NGC 1482	03 54.7 −20 30	0.00639	Sa(P)	HII	58	−18.89	1.1
NGC 1808	05 07.7 −37 31	0.00332	SO/a(X)	HII, Sy2?	50	−19.52	2.2
NGC 3628	11 20.3 +13 37	0.00281	Sb(P)	HII, LINER	87	−19.96	2.8
NGC 5128	13 25.3 −43 01	0.00183	SO, Lenticular	Sy2	43	−20.97	8.5
Circinus	14 13.2 −65 20	0.00145	Sb(A)	Sy2	65	−21.23	9.0
NGC 6240	16 53.0 +02 24	0.02445	I0	LINER, Sy2	—	−21.30	8.2
NGC 6810	19 43.6 −58 40	0.00678	Sa(A)	HII, Sy2?	82	−20.61	5.5
IC 5063	20 52.0 −57 04	0.01135	Sa	Sy2	—	−20.34	4.2

AGNs are 3x more luminous than ★B on average

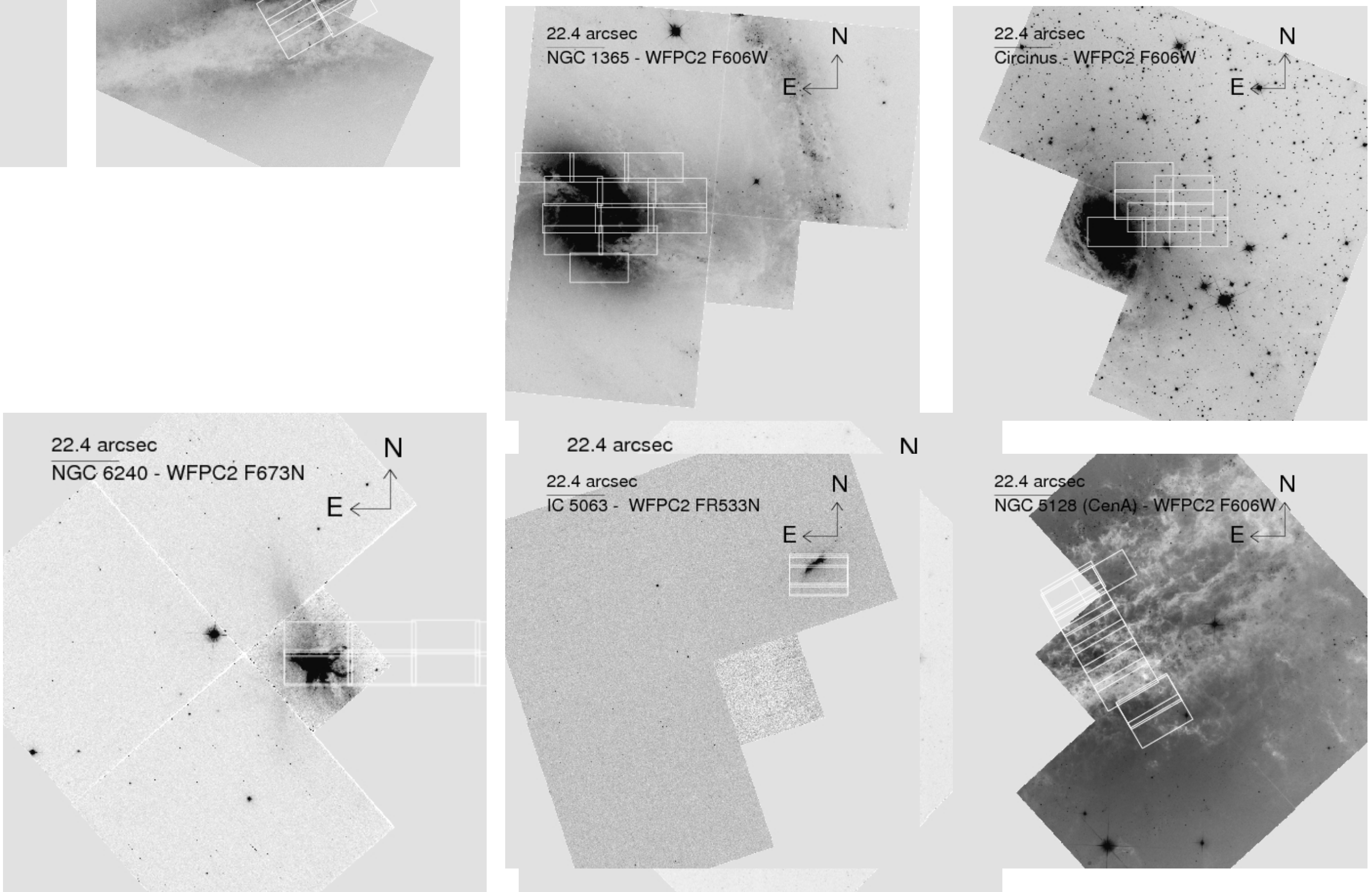
Multi-pointing IFS mosaics

The Starburst sample





The AGN sample



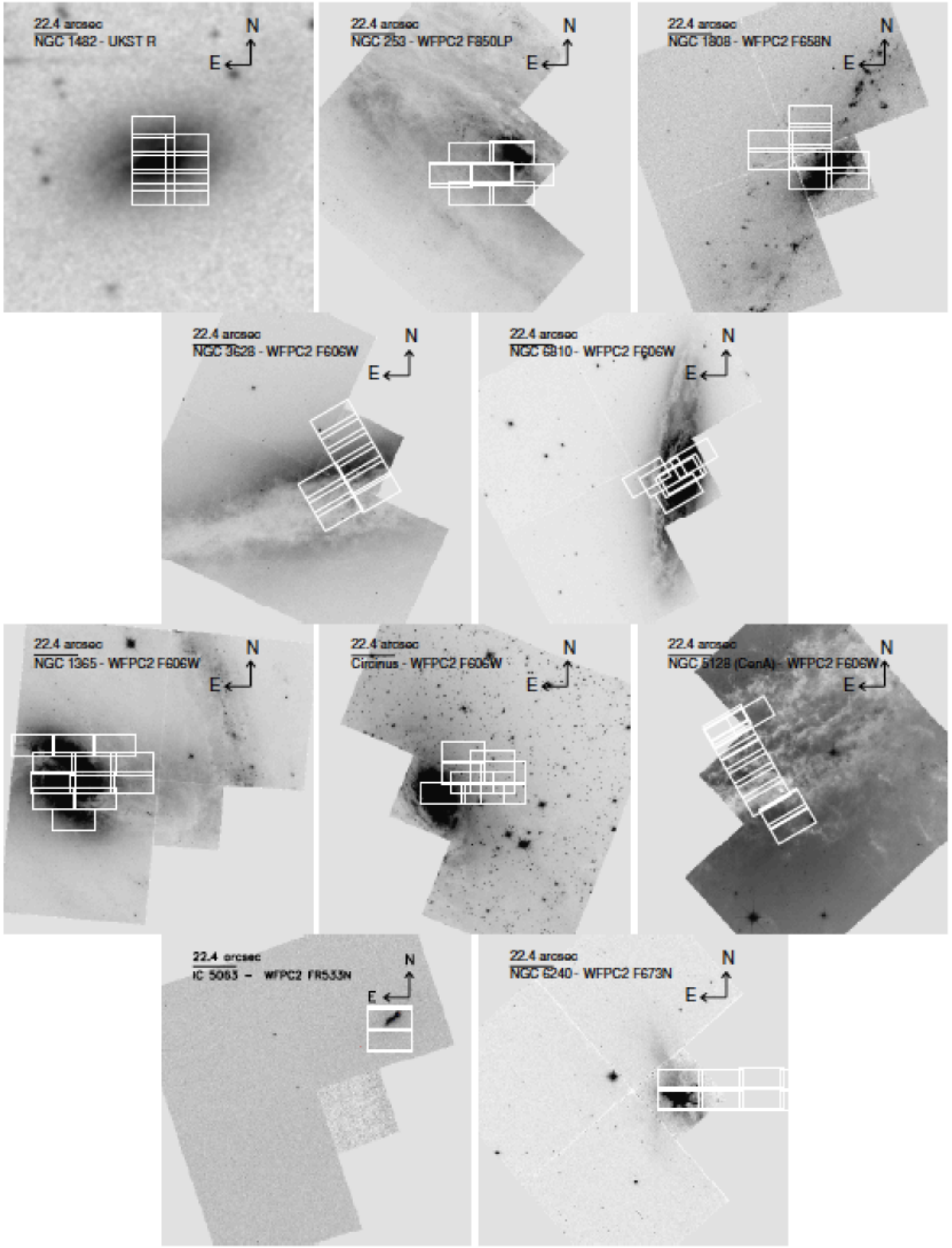
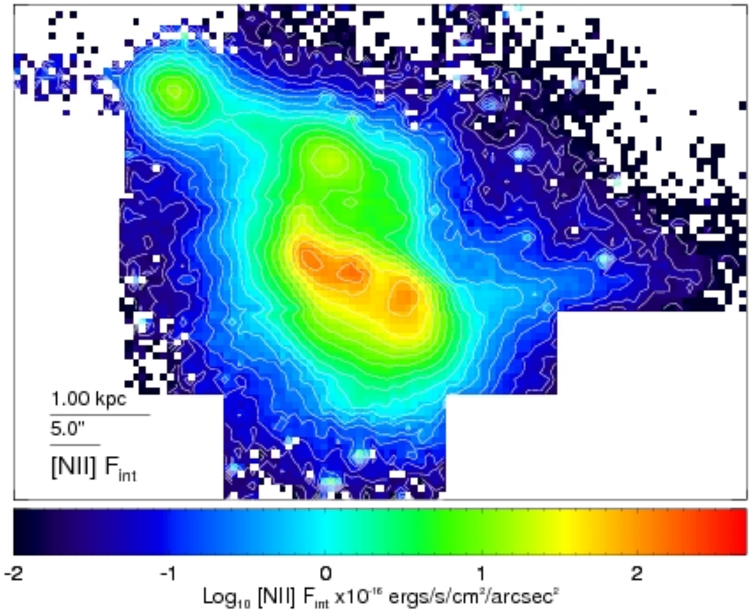
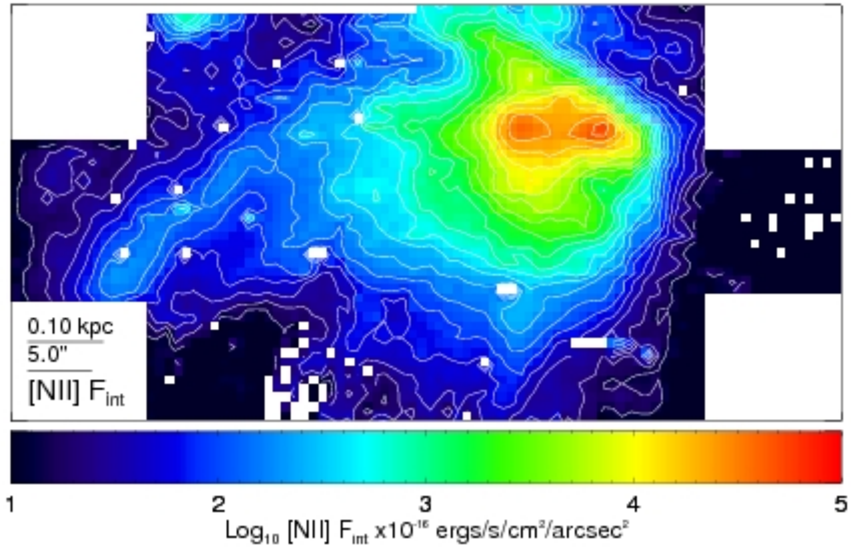
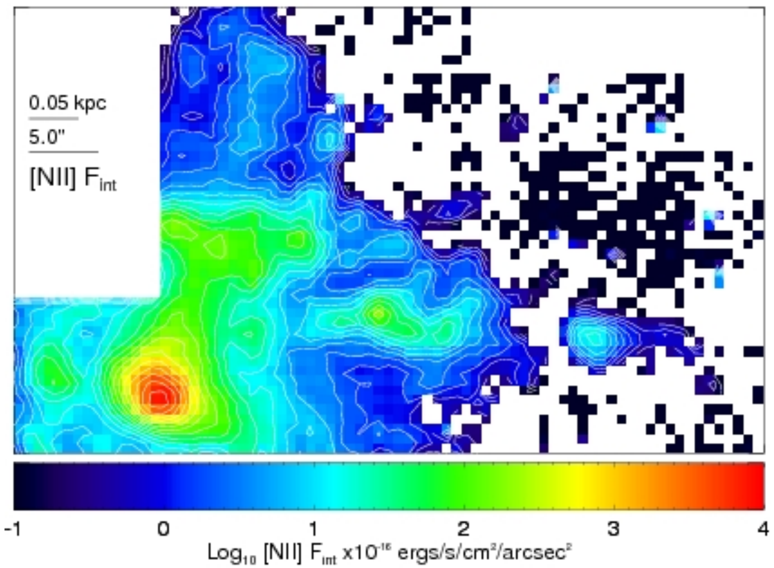


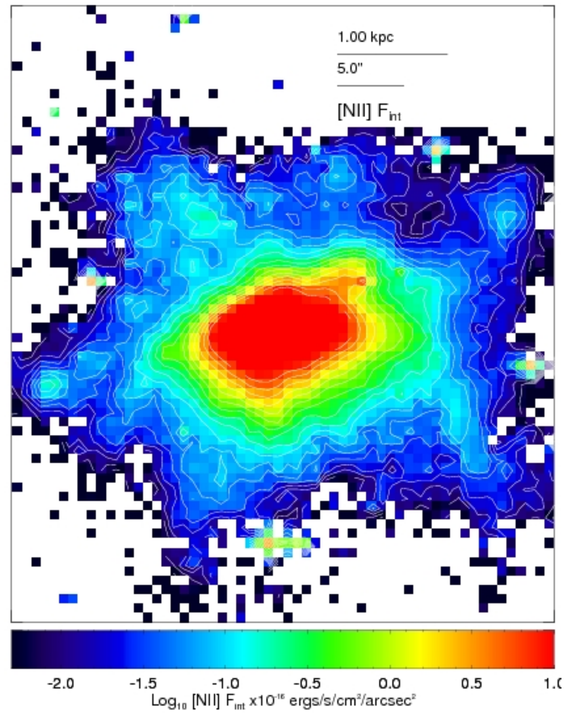
Figure 1. SPIRAL IFU footprints. Images are taken from *HST*/WFPC2 associations where available and from the DSS for NGC 1482. The 22''4 long axis of the SPIRAL IFU is indicated for scale. Note the unusual P.A. for observations of NGC 6810, NGC 3628, and NGC 5128 due to the detailed requirements of the NGC 5128 observing program during the 2007 May run.

~55,000 spectra later…









Spectral data cubes across a range of key diagnostic features

He/Hβ/[OIII]

[OI]/Hα/[NII]/[SII]

Full sample in

Sharp & Bland-Hawthorn (2010)

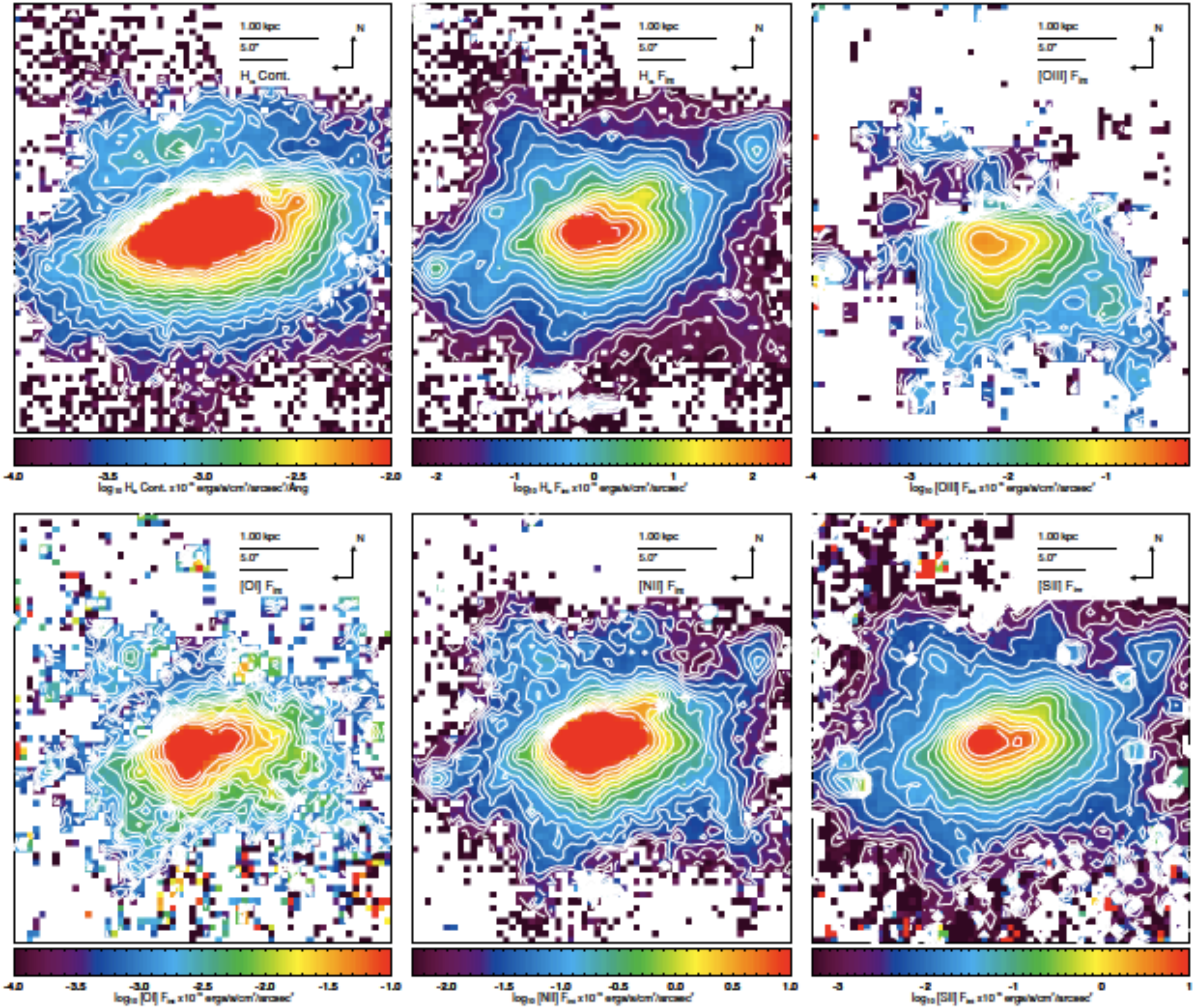


Figure 2. NGC 1482: emission-line integrated flux maps are generated by single Gaussian fitting to individual spectra. The maps shown (left to right, top to bottom) are the continuum at line center for Hα followed by integrated intensity maps ($F_{\rm int}$) for Hα, [O III]λ5007, [O I]λ6300, [N II]λ6583, and [S II]λ6716. Pixels for which no valid fit was obtained are left blank.

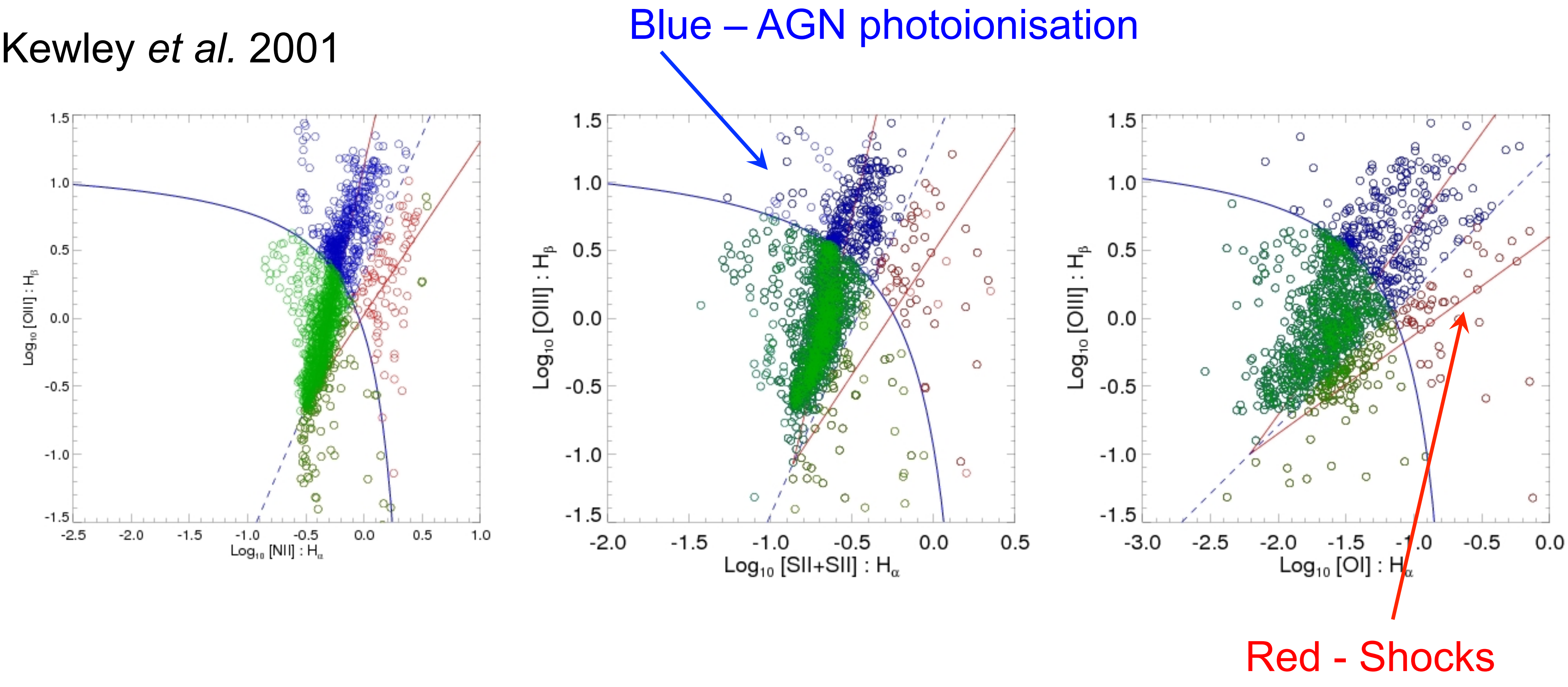
(A color version of this figure is available in the online journal.)

Ionisation Diagnostic Diagrams

Baldwin, Phillips & Terlevich 1981

Veilleux & Osterbrock 1987

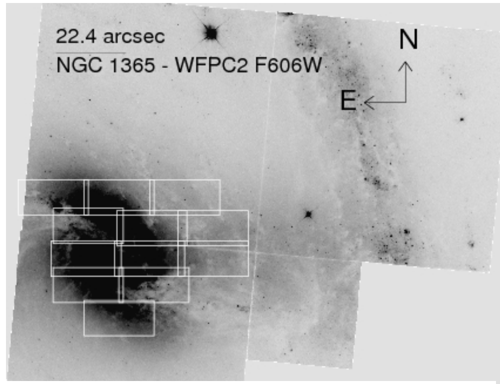
Kewley *et al.* 2001



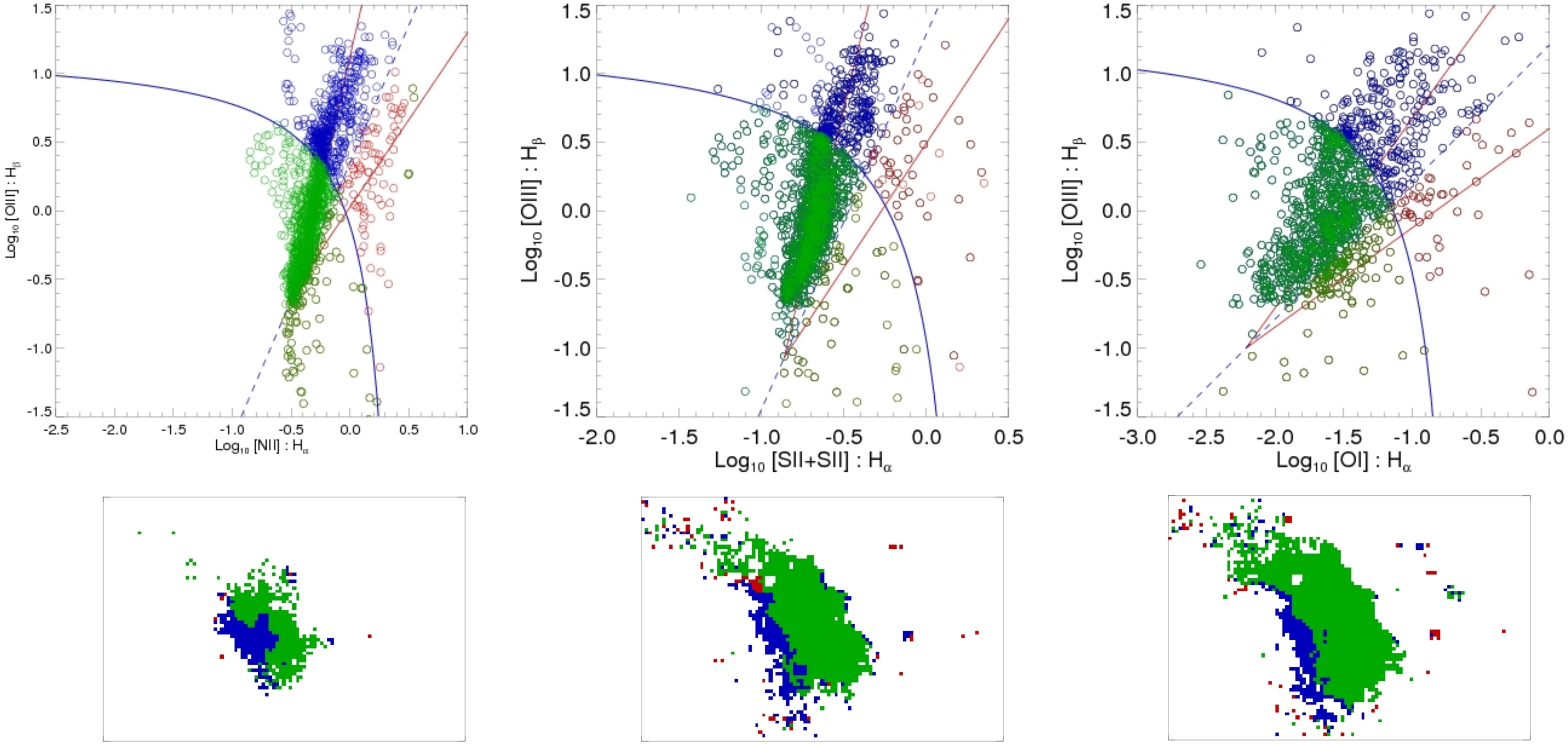
Strong signatures from star formation in disk

Spectral line profile deconvolution is possible when guided by kinematic modelling

Example 1. AGN: NGC 1365

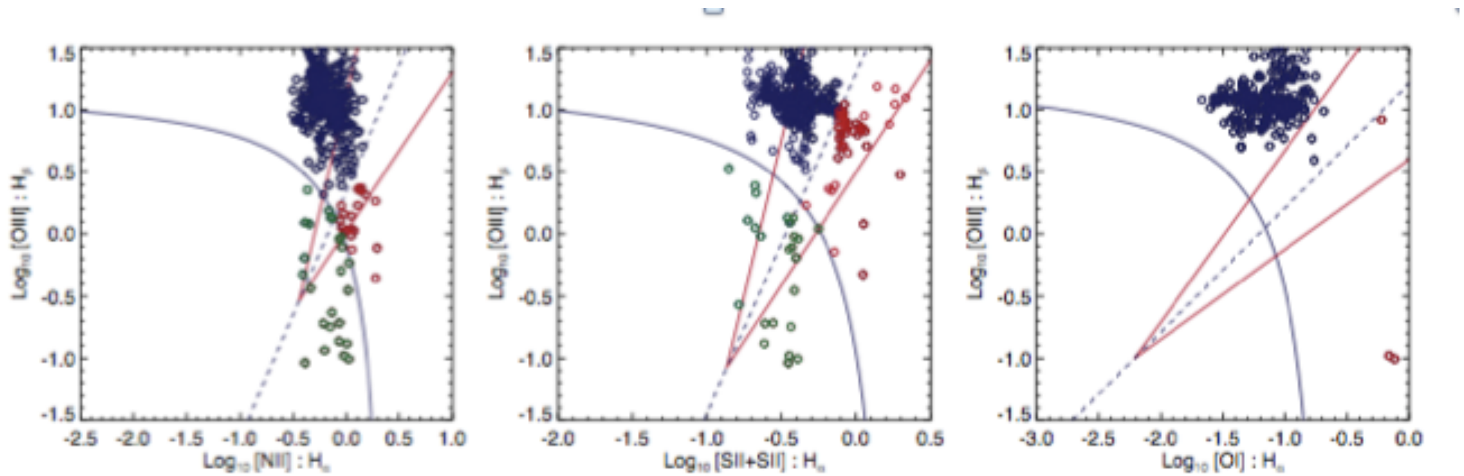


Indicative of the full AGN sample

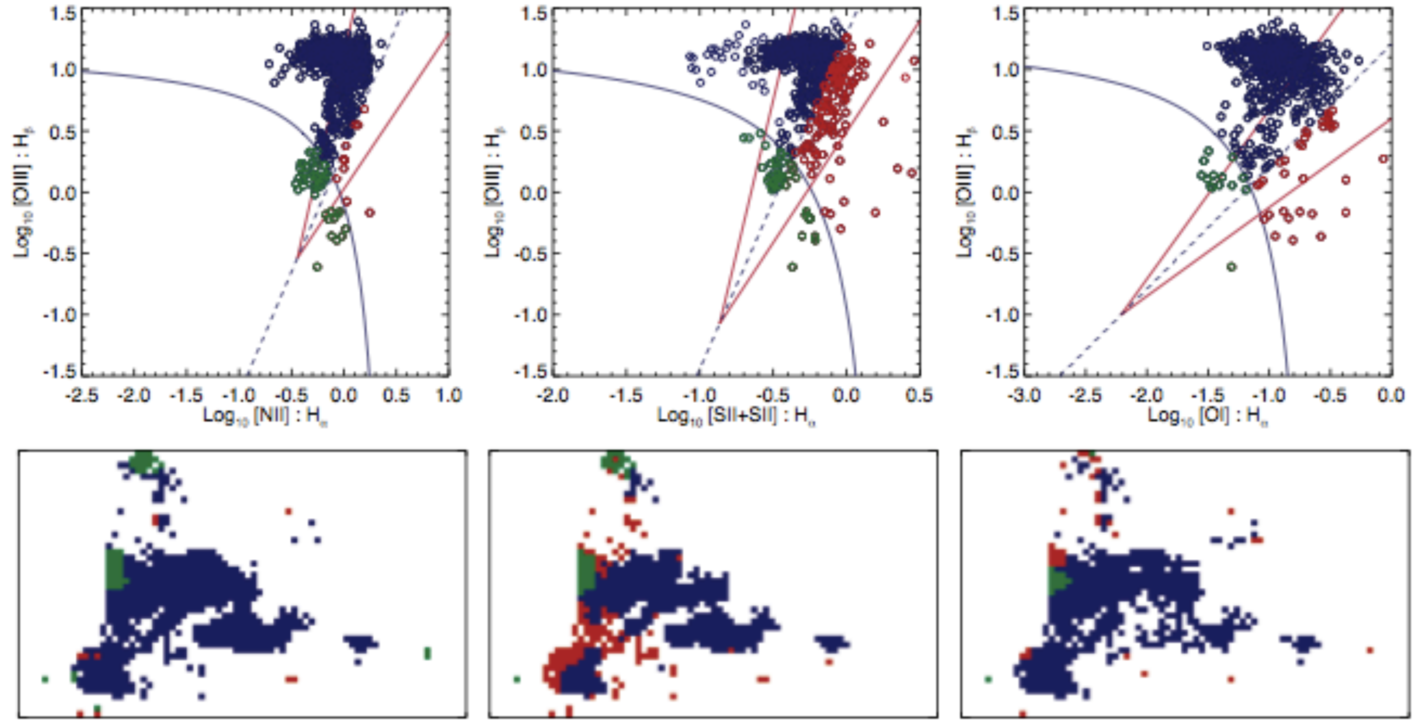


Off planer gas is photoionised by a hard spectrum source (AGN)

AGN: IC 5063



AGN: Circinus



AGN ionisation cones:

several recovered, one new

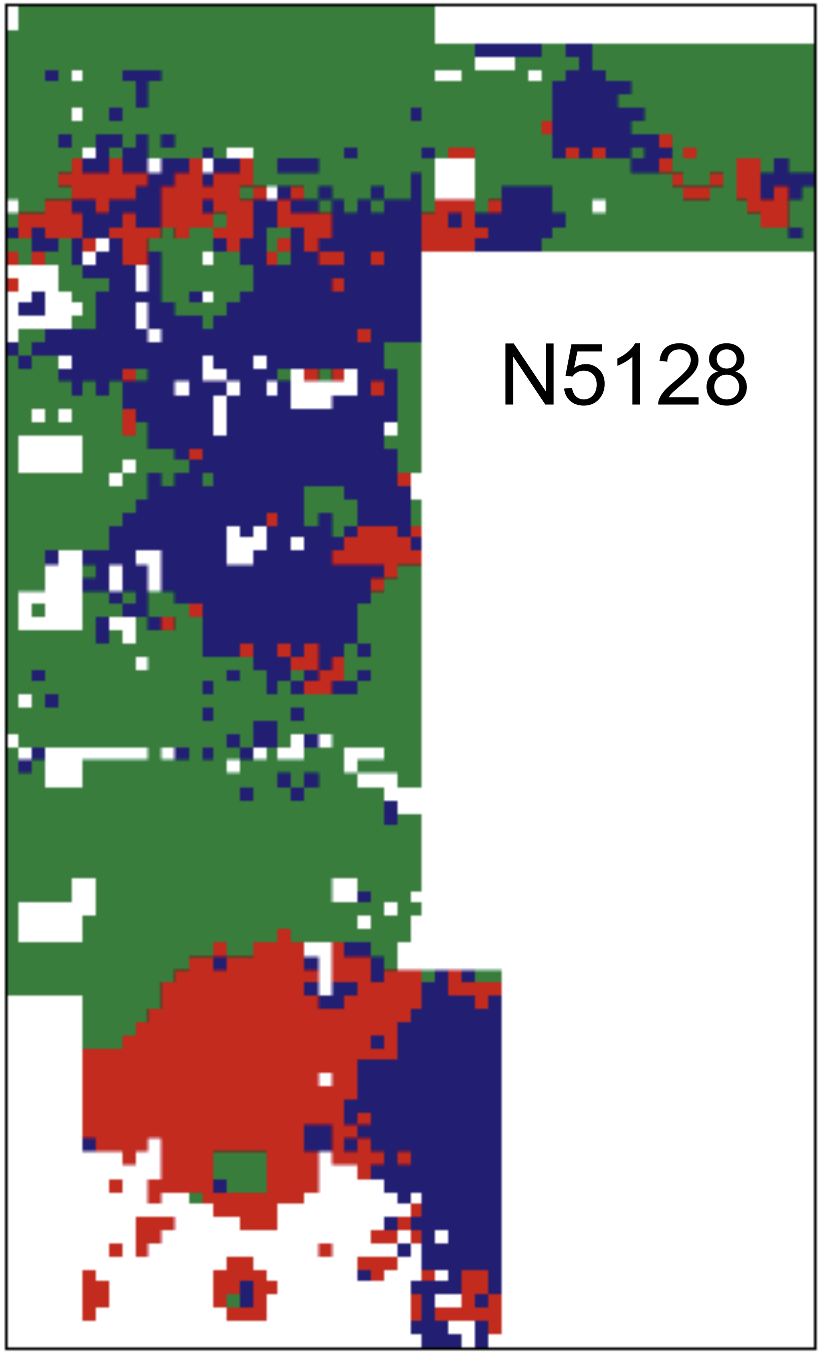
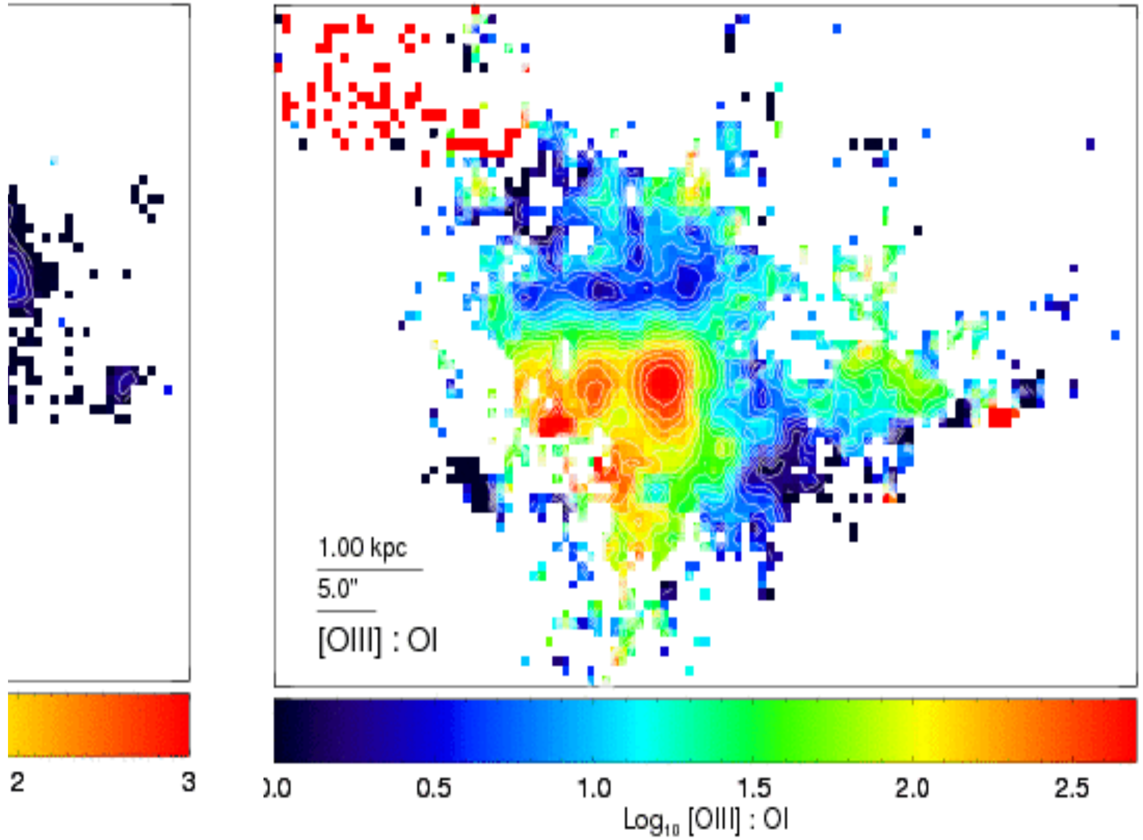


Figure 25. NGC 5128 (CenA): the ionization cone due to the hard AGN spectrum is revealed more clearly in the data after spatially re-binning the spectra 3 × 3. The classification scheme from the [O III]/Hβ vs. [N II]/Hα IDD (Figure 24) is repeated here.

(A color version of this figure is available in the online journal.)

N1365



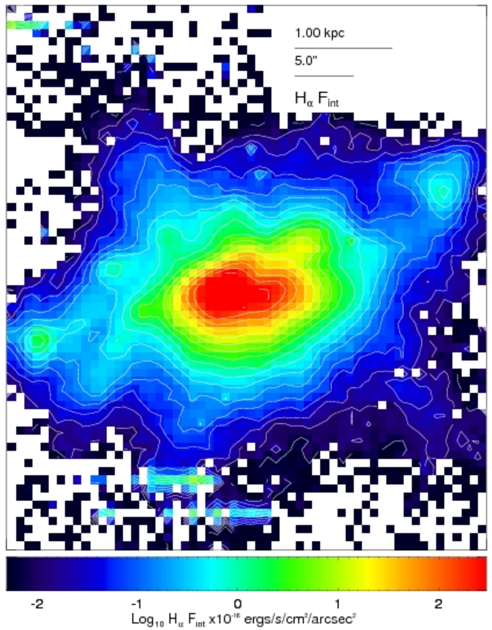
Example 2. ★B: NGC 1482

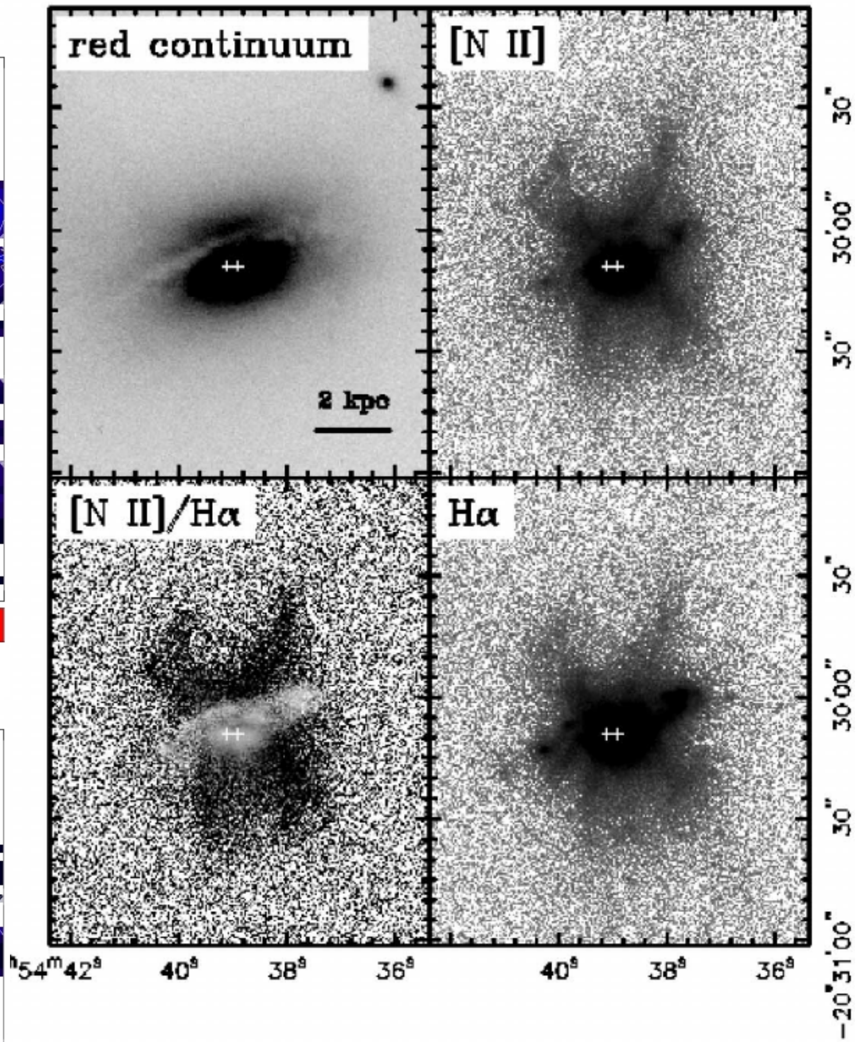
No evidence for an AGN

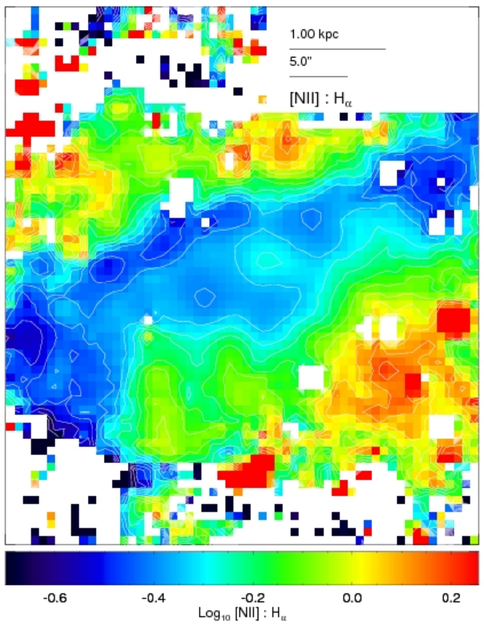
across multiple frequencies

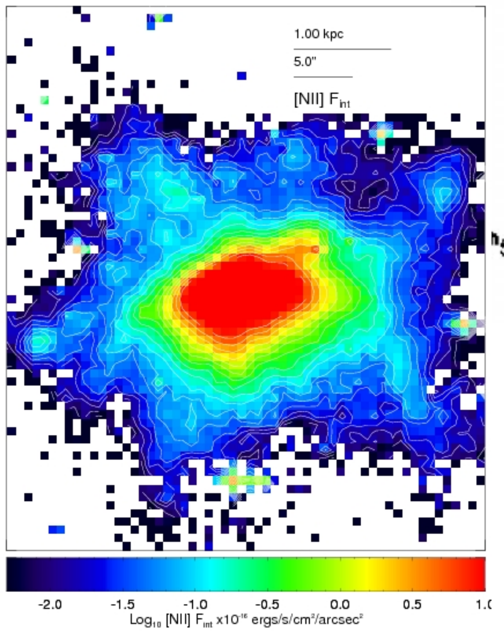
Indicative of full

starburst sample





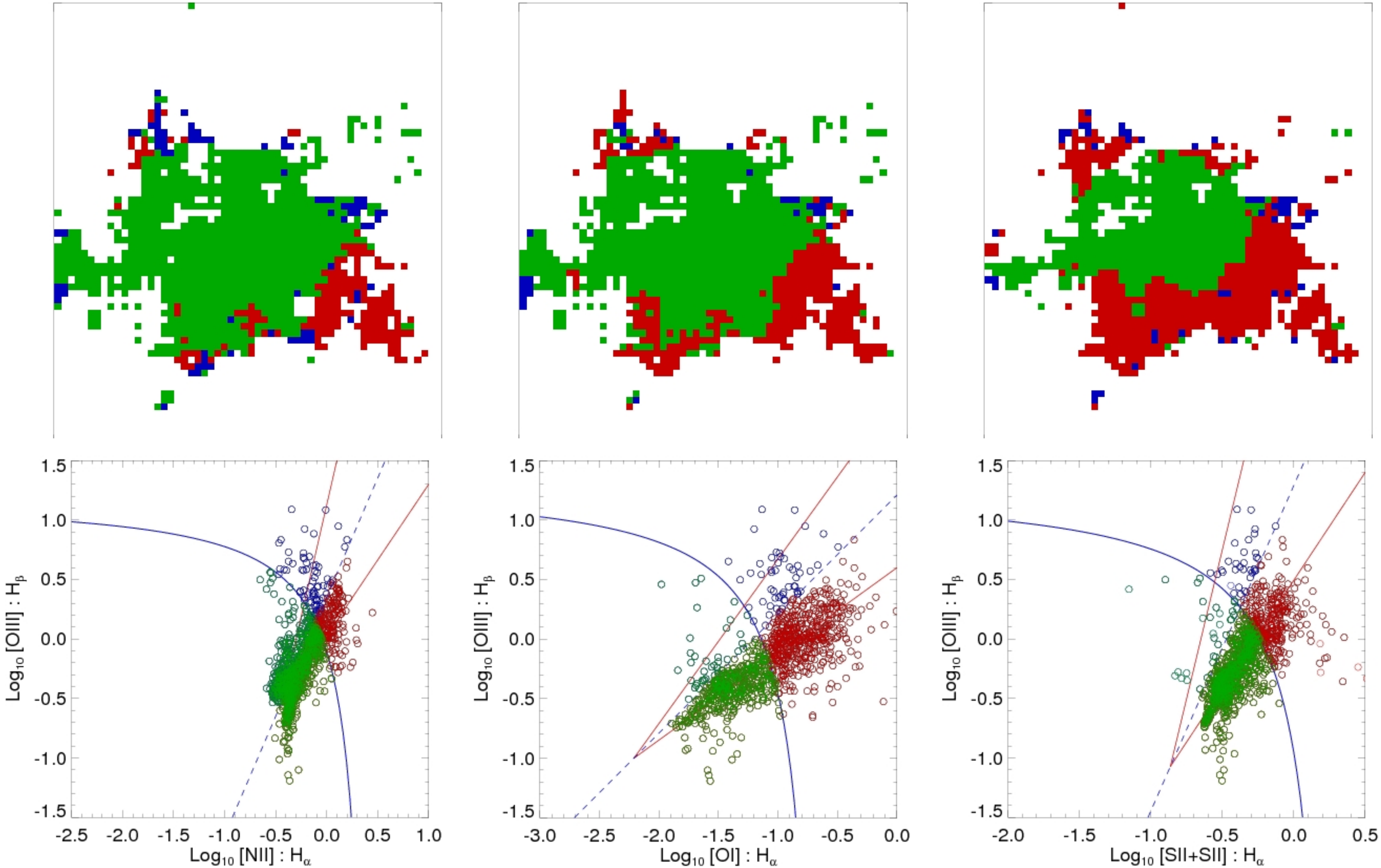




AAT/TTF Veilleux & Rupke 2002

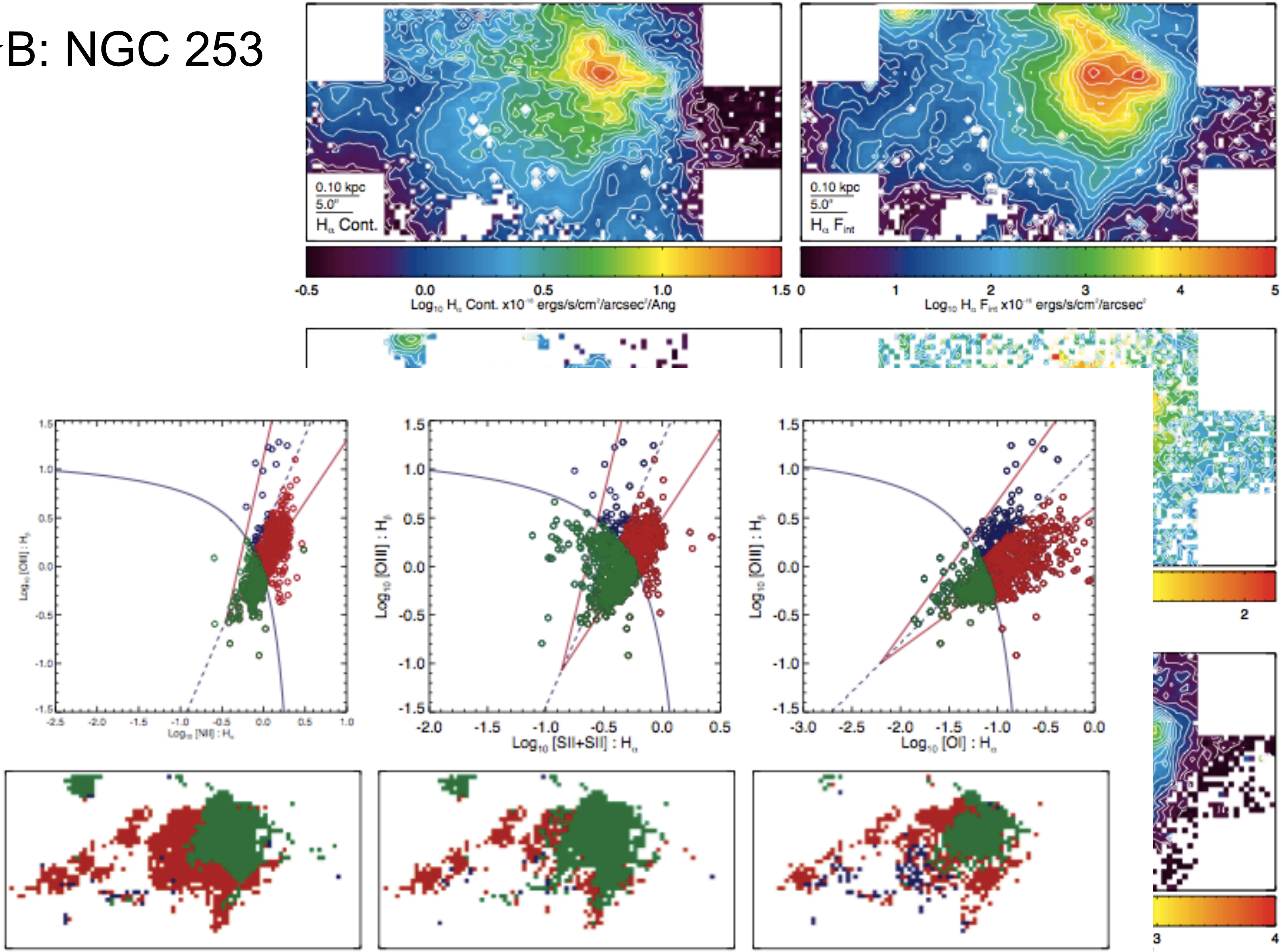
Shocked gas excitation?

Ionisation Diagnostic Diagrams



Confirming **shocks** as the most likely excitation mechanism above the disk plane

★B: NGC 253



0.10 kpc
5.0"
Hα Cont.
-0.5
0.0
0.5
1.0
1.5
Log10 Hα Cont. x10^-16 ergs/s/cm²/arcsec²/Ang
0.10 kpc
5.0"
Hα Fint
0
1
2
3
4
5
Log10 Hα Fint x10^-16 ergs/s/cm²/arcsec²
Log10 [OIII] : Hβ
Log10 [NII] : Hα
Log10 [SII+SII] : Hα
Log10 [OI] : Hα

AGN:shocks

Object	[O III] & [N II]	[O III] & [S II]	[O III] & [O I]
Starbursts			
NGC 253	10:90	10:90	10:90
NGC 1482	10:90	10:90	10:90
NGC 1808	20:80	0:0	0:0
NGC 3628	0:0[1]	—	—
NGC 6810	0:0[1]	0:0	—
AGNs			
NGC 1365	90:10	90:10	100:0
NGC 5128	50:50	0:100	60:40
Circinus	100:0	60:40	100:0
NGC 6240	—	—	—
IC 5063	100:0	90:10	100:0

Far off the plane:

AGN winds are **photo-**ionized

★B winds are **shock**-ionized

Object	L_{Bol} (10^{10} $L_\odot$)	Extent (arcsec)	Deprojected (kpc)	$\mu(H\alpha)$ @ 1 kpc
NGC 253	2.8	30.5	0.5	3.8e-16 ± 4.6e-16
NGC 1365	9.3	16.4	1.8	2.6e-16 ± 1.2e-16
NGC 1482	1.1	15.5	2.2	8.9e-16 ± 4.4e-16
NGC 1808	2.2	22.5	1.7	1.6e-16 ± 5.1e-17
NGC 3628	2.8	28.0	0.4	5.2e-17 ± 2.2e-17
NGC 5128	8.5	36.0	2.8	4.7e-16 ± 2.2e-16
Circinus	9.0	24.6	0.4	1.9e-16 ± 8.5e-17
NGC 6810	5.5	12.0	16.4	5.5e-16 ± 2.4e-16
IC 5063	4.2	6.0	1.4	1.3e-15 ± 5.3e-16

This holds for either AGN or ★B ionization

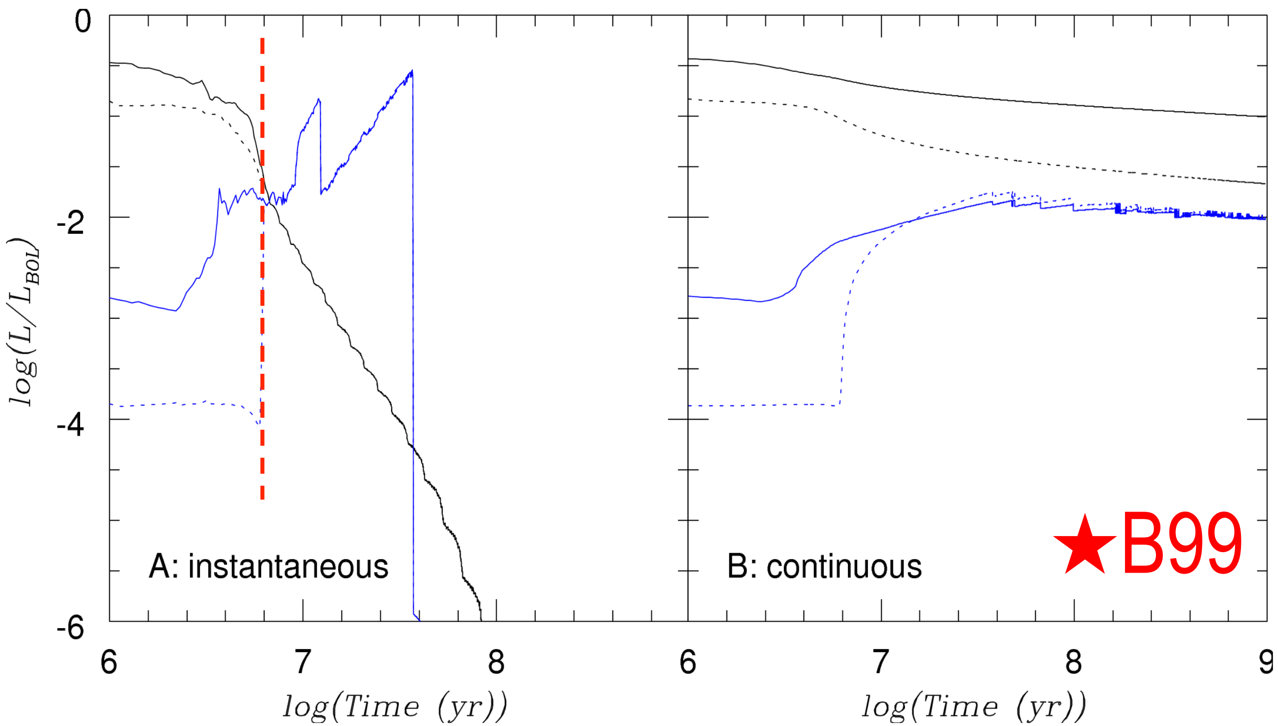
$$\mu(\mathrm{H}\alpha) = 1 \times 10^{-14} \left(\frac{r}{1\ \mathrm{kpc}}\right)^{-2} \left(\frac{L_{\mathrm{bol}}}{10^{11} L_\odot}\right) \quad \mathrm{cgs}$$

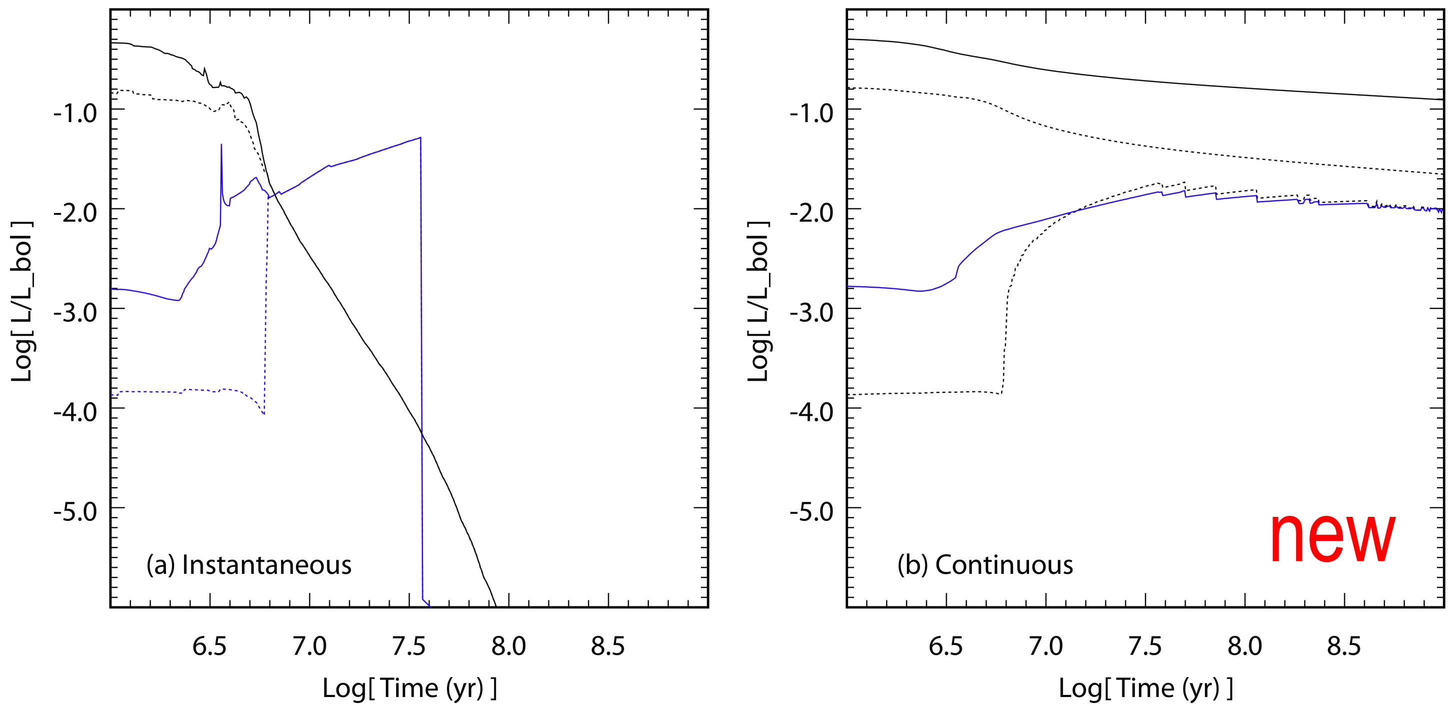
Shock ionization

$$\mu_{\mathrm{shock}}(\mathrm{H}\alpha) \approx 5 \times 10^{-16} \left(\frac{V_{\mathrm{shock}}}{100\ \mathrm{km\ s^{-1}}}\right)^{2.4} \left(\frac{n_o}{10\ \mathrm{cm^{-3}}}\right) \quad \mathrm{cgs} \qquad (25)$$

★B phenomenon is impulsive

★B wind blows after initial delay > 10 Myr

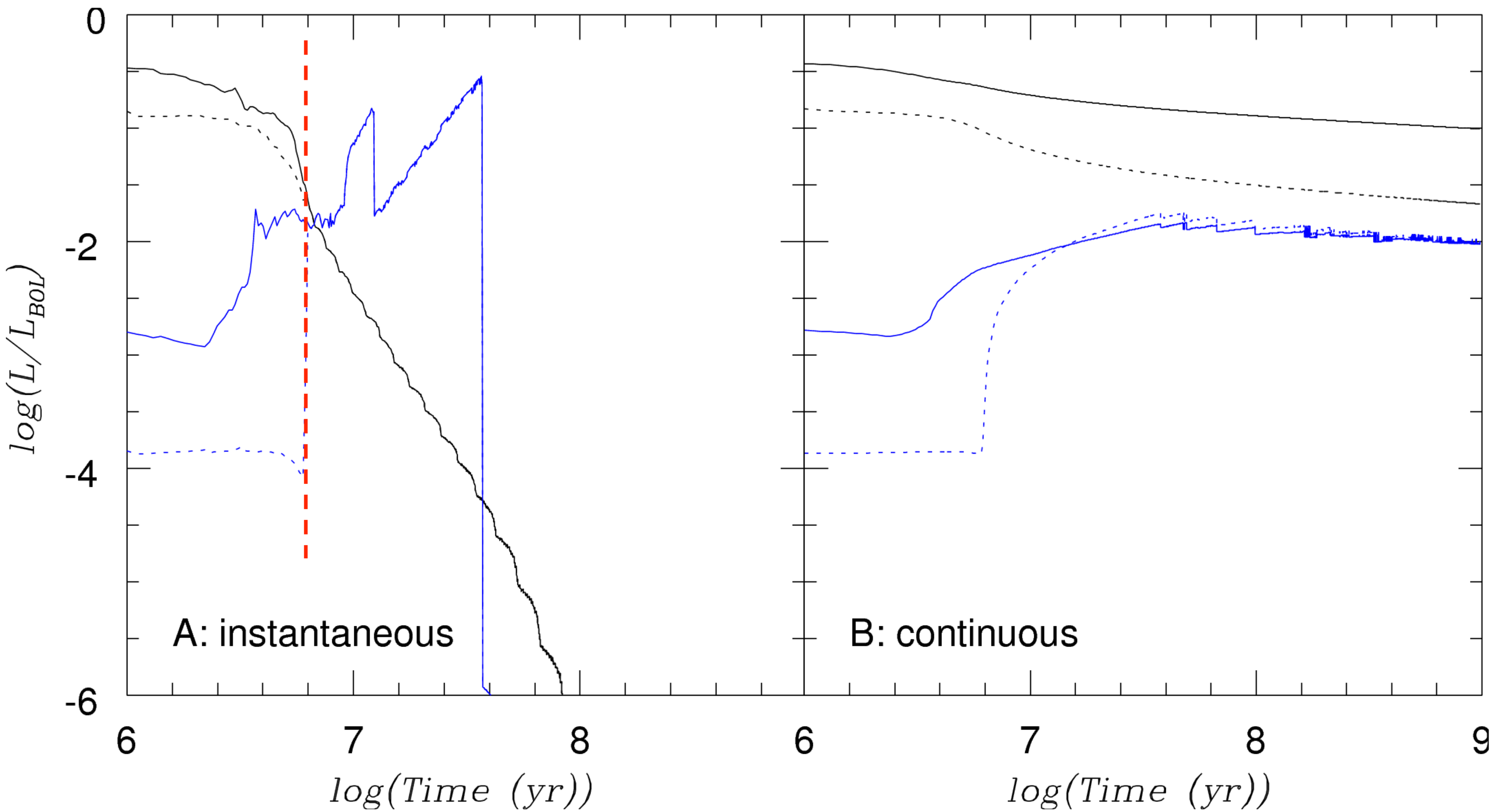




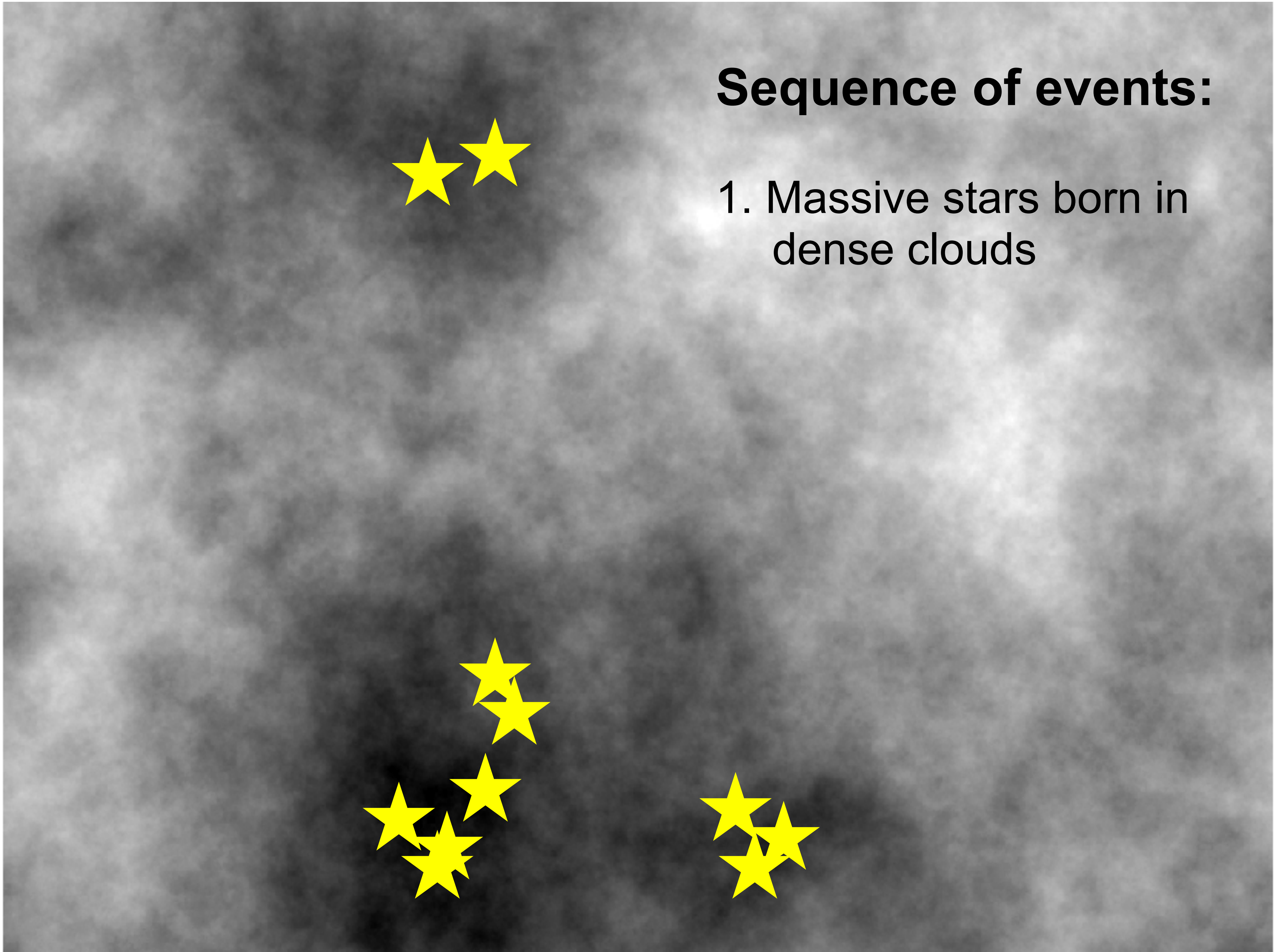
Conclude:

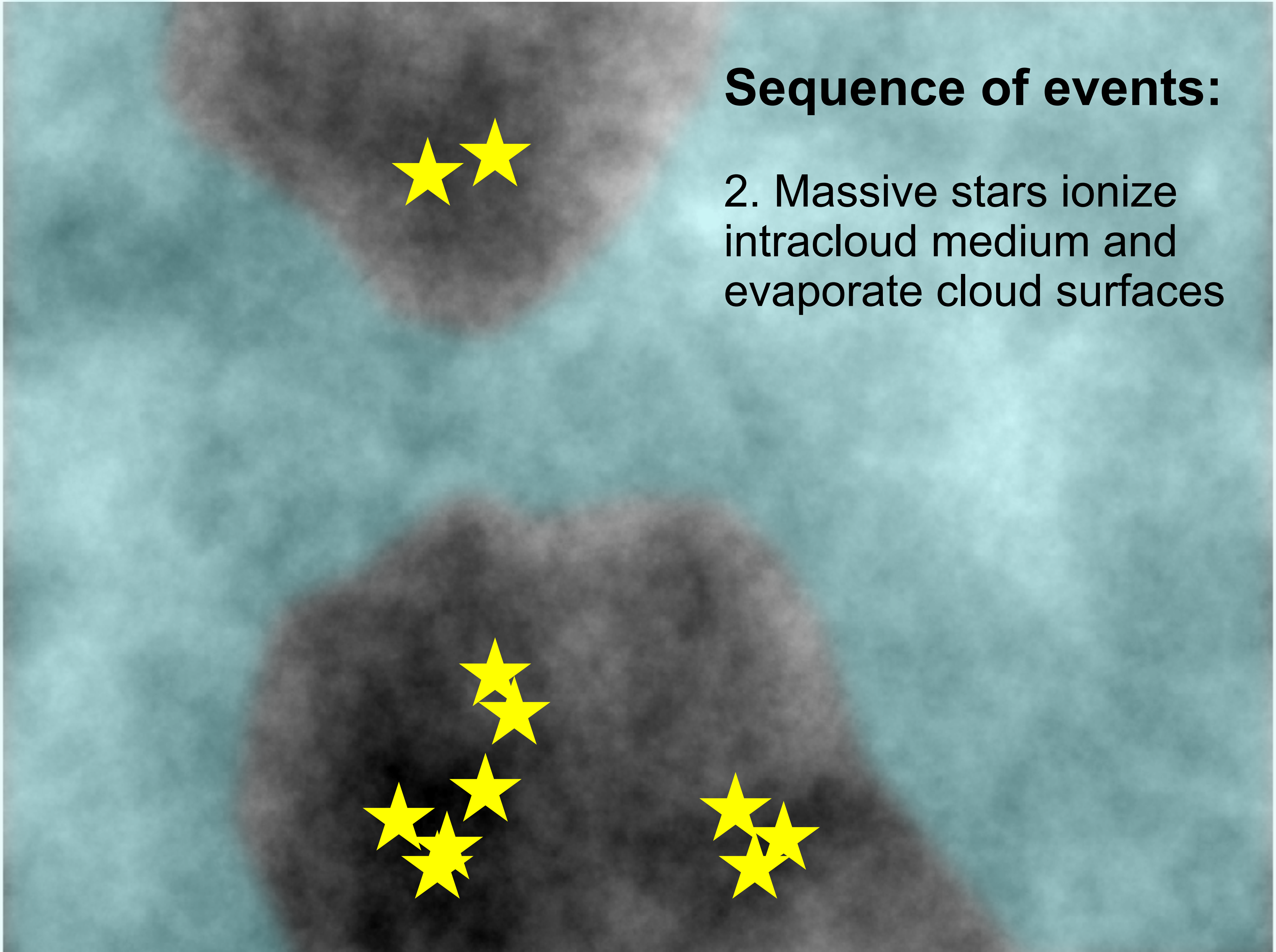
Starbursts are an impulsive phenomenon; continuous SF unlikely

Long delay (>10 Myr) after ★B initiates before wind launch



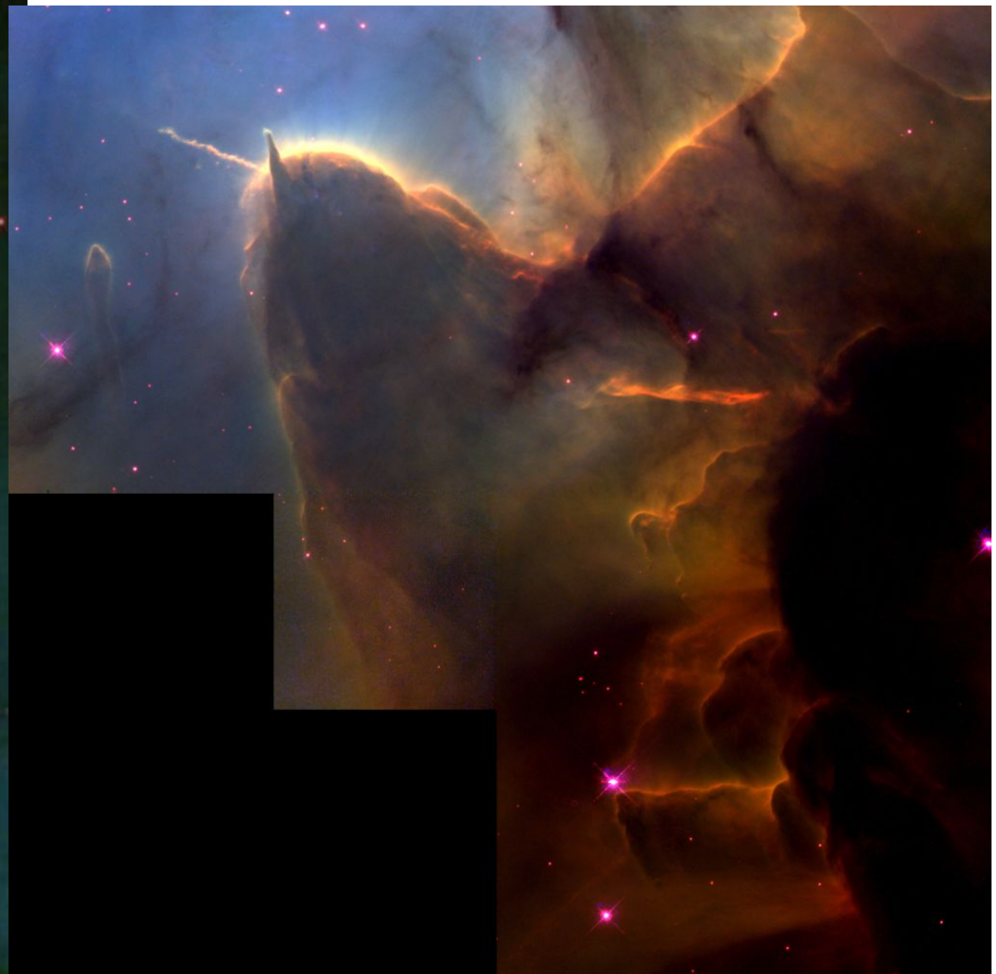
(SB99 model, upper mass cut-offs of 30 and 100 M_{sun})

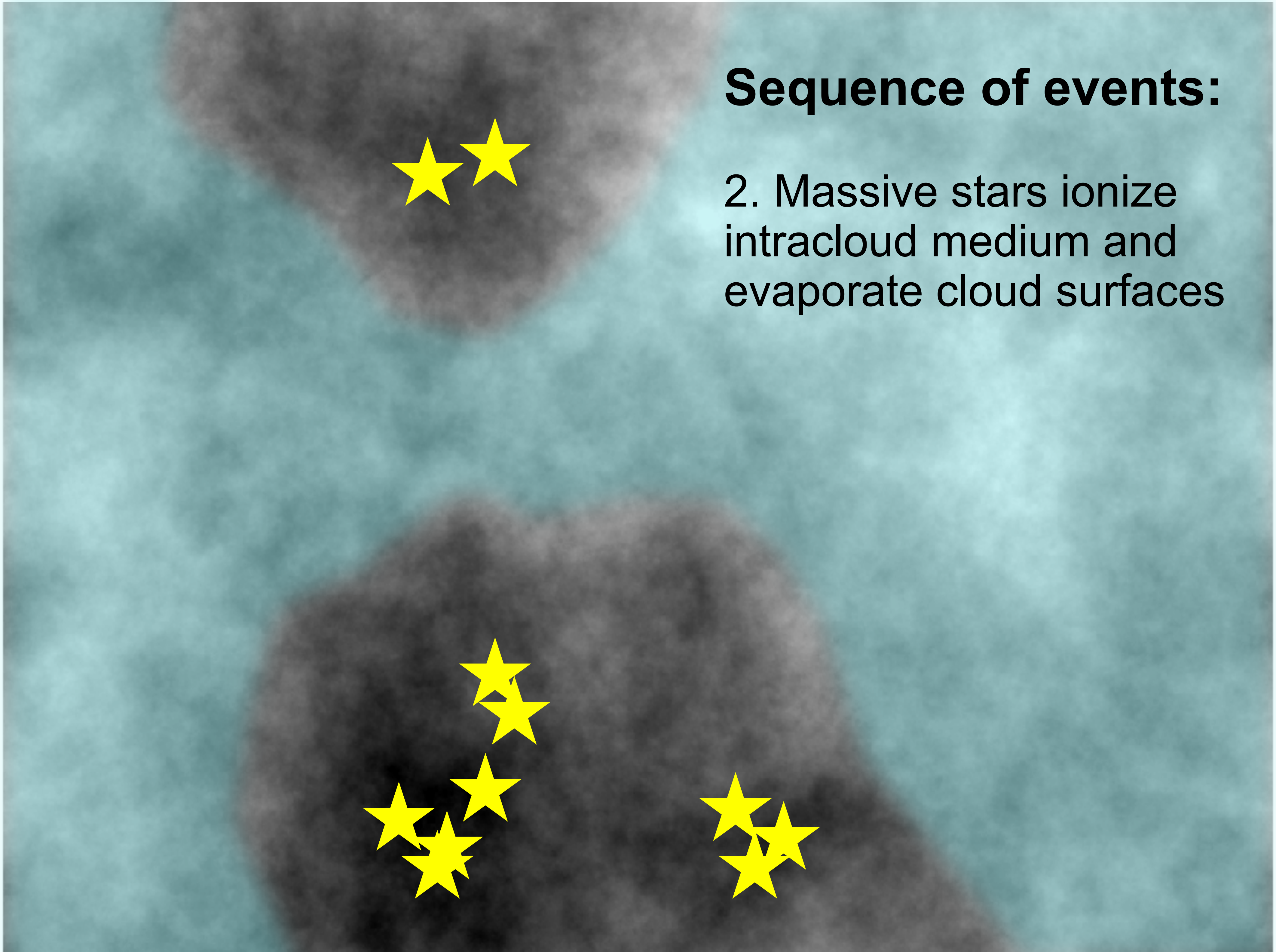

Sequence of events:
1. Massive stars born in dense clouds


Sequence of events:
2. Massive stars ionize intracloud medium and evaporate cloud surfaces

Hot young stars ionize the skins of dense clouds:

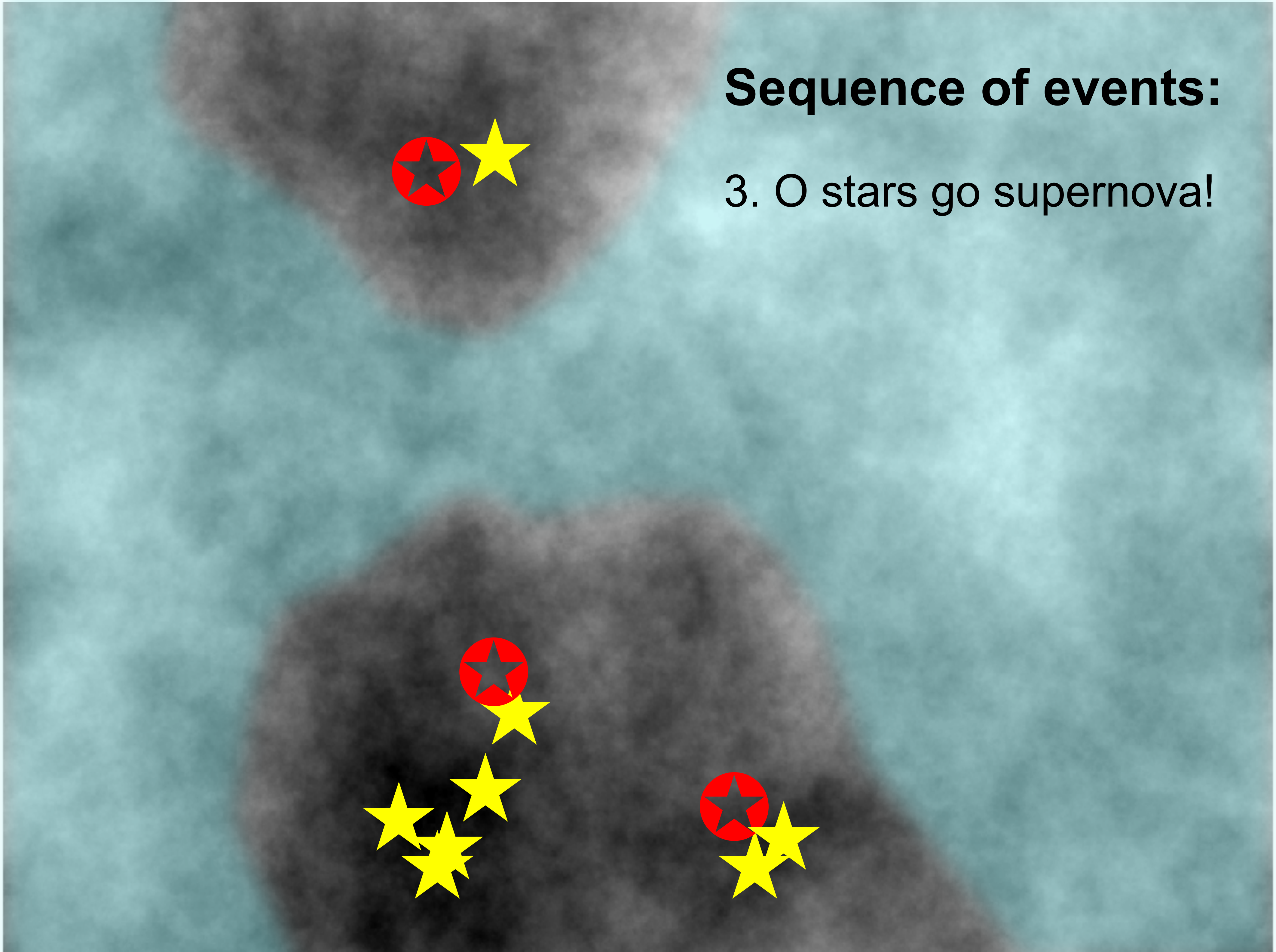
We need the evaporated material before the onset of a large-scale wind.

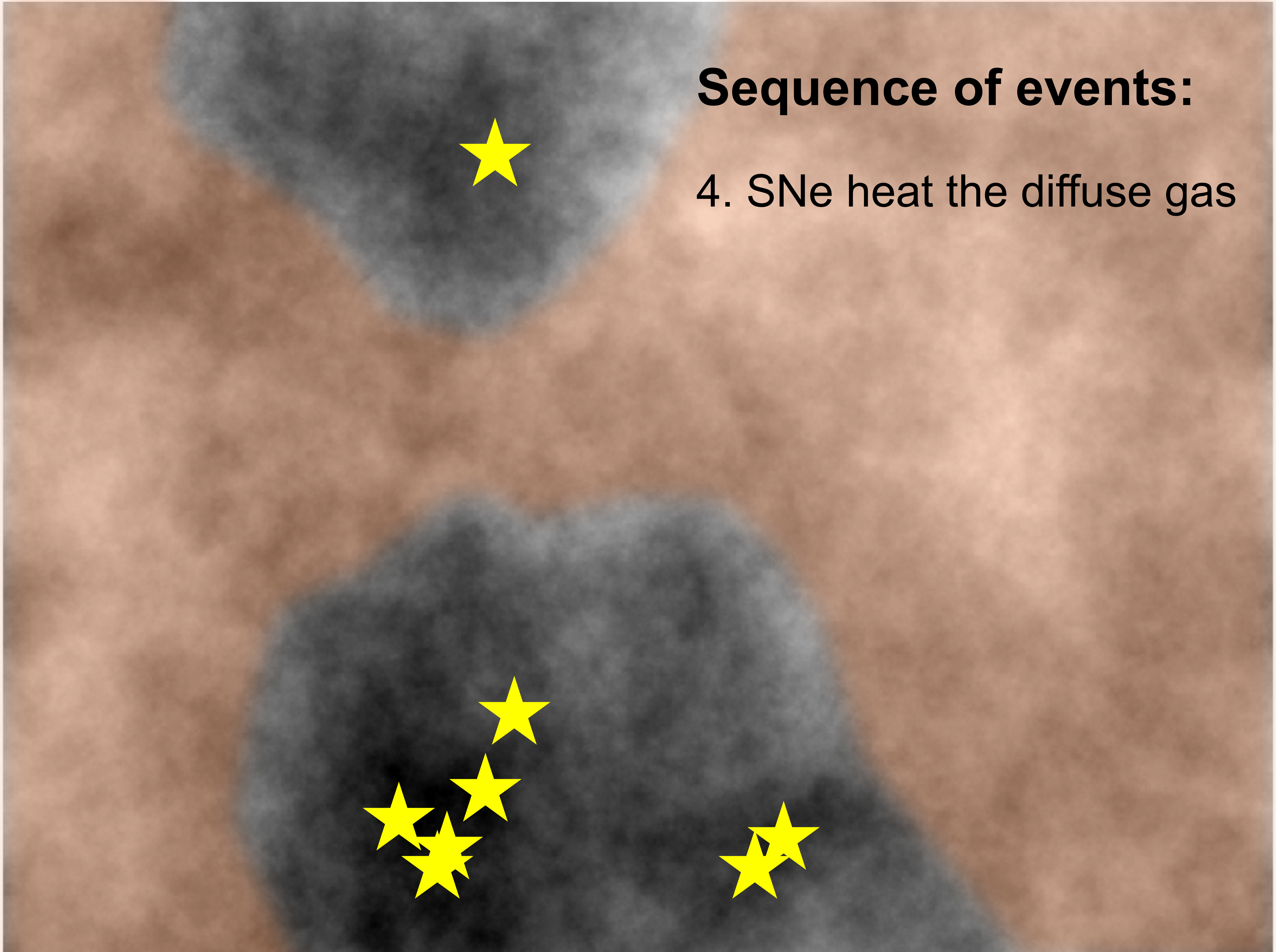


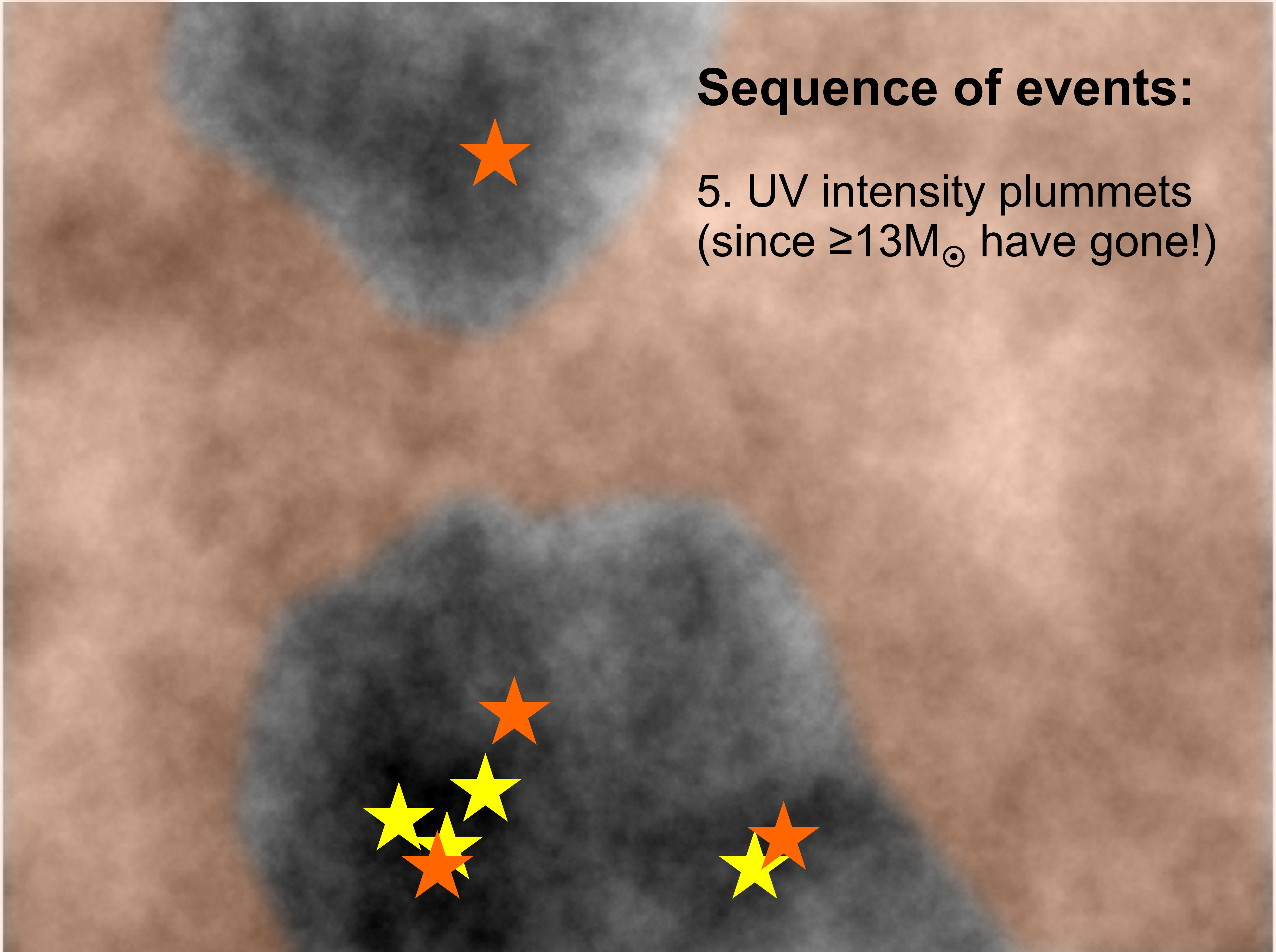

Sequence of events:
2. Massive stars ionize intracloud medium and evaporate cloud surfaces

Sequence of events:

3. O stars go supernova!

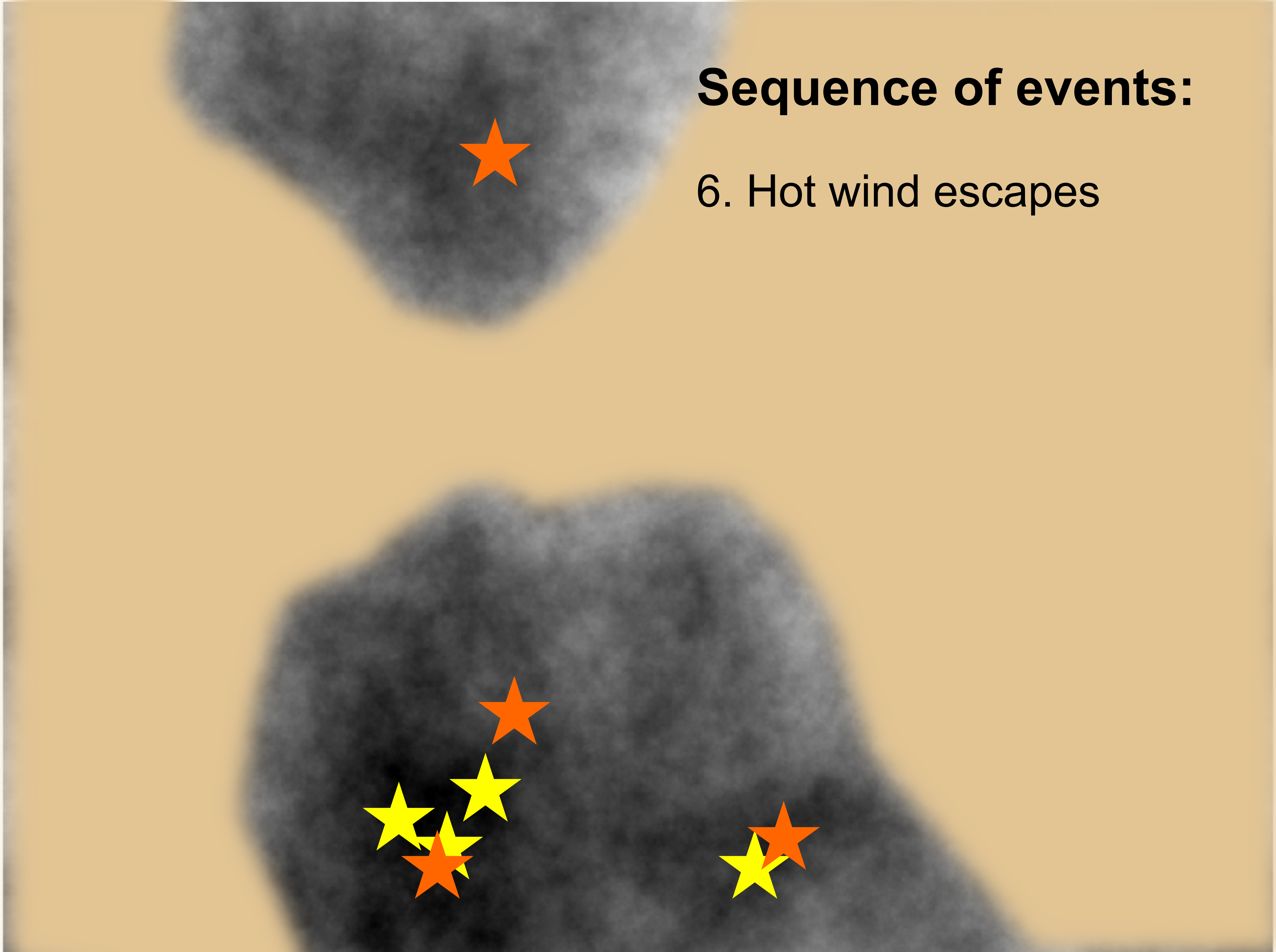



Sequence of events:
4. SNe heat the diffuse gas

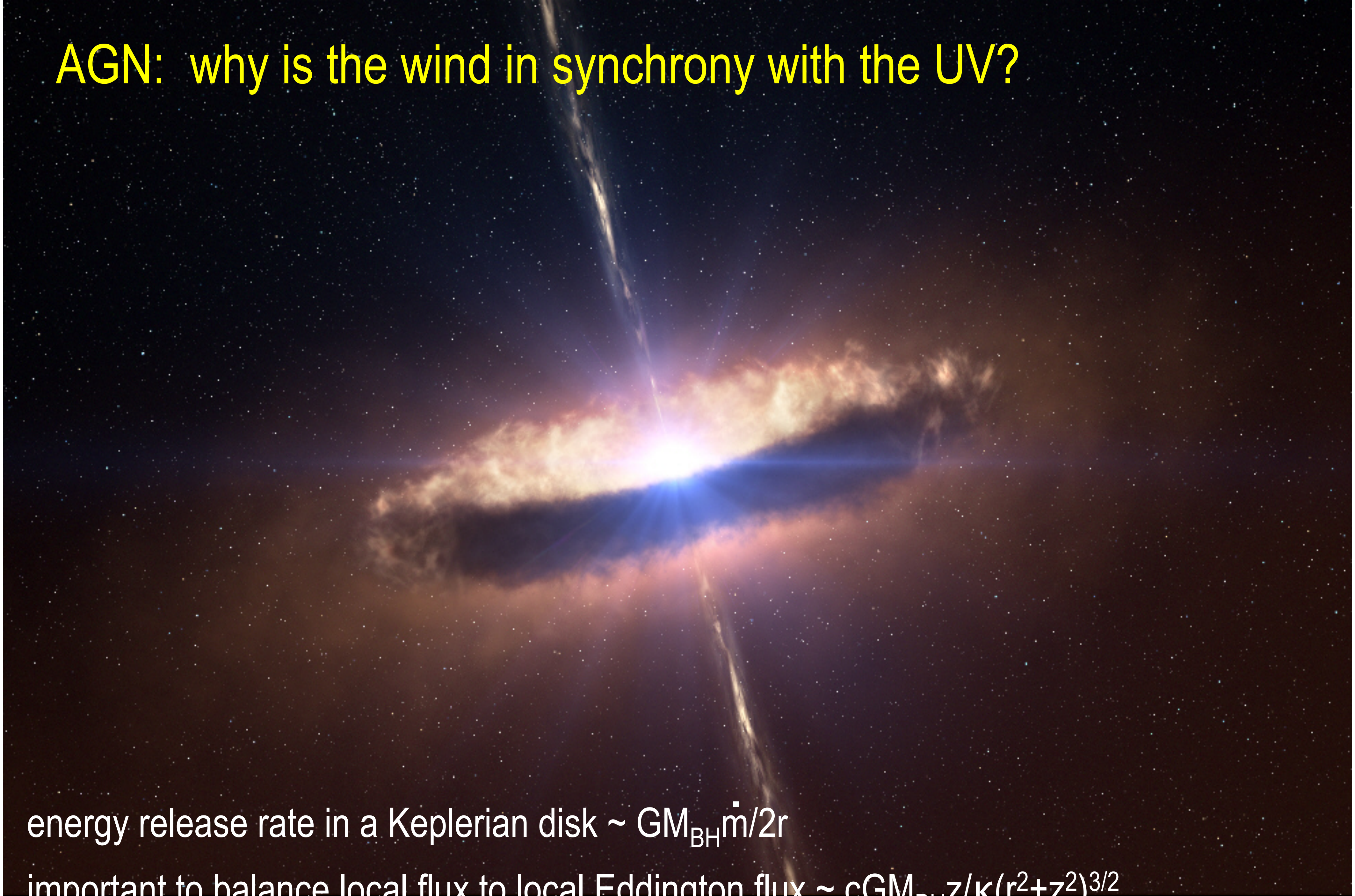

Sequence of events:
5. UV intensity plummets
(since ≥13M$_\odot$ have gone!)

Sequence of events:

6. Hot wind escapes



AGN: why is the wind in synchrony with the UV?



energy release rate in a Keplerian disk ~ $GM_{BH}\dot{m}/2r$

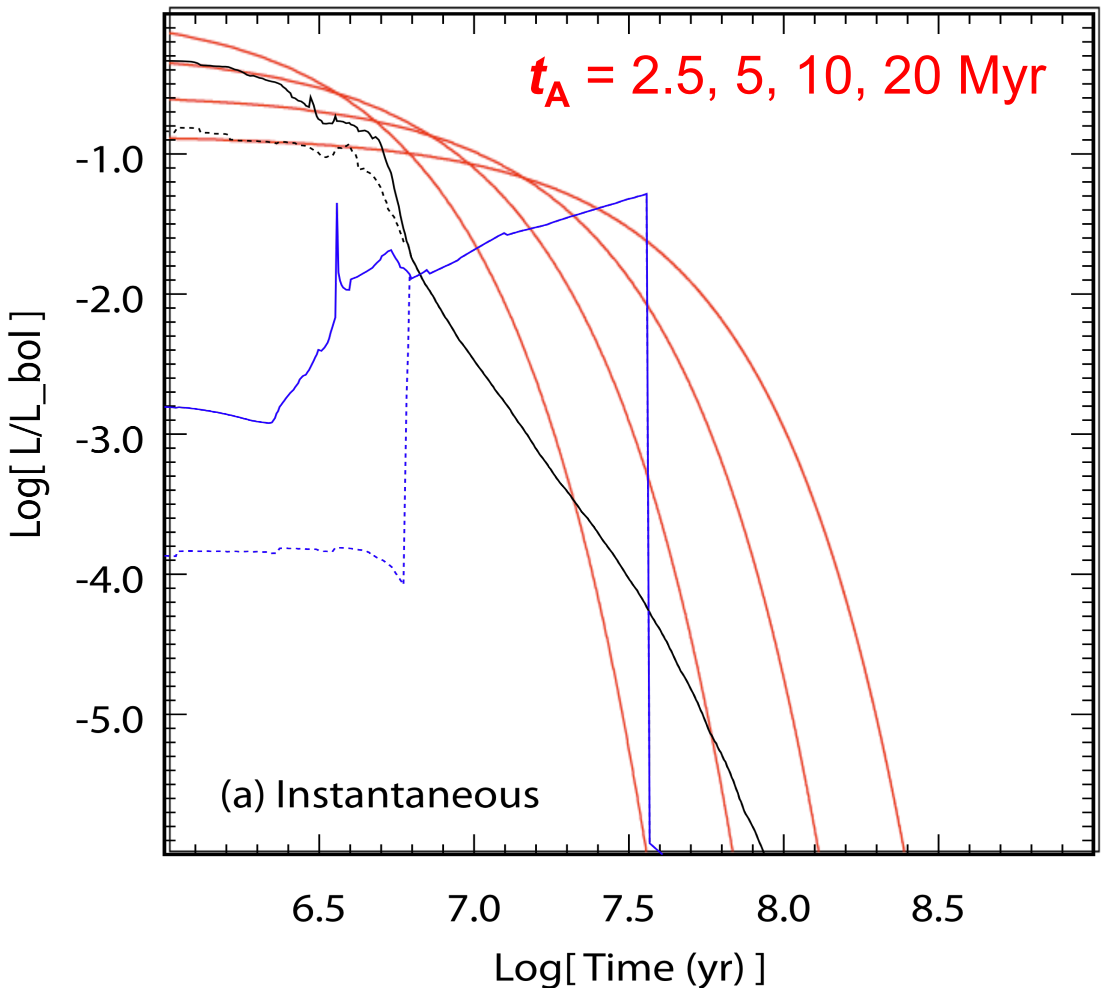
important to balance local flux to local Eddington flux ~ $cGM_{BH}z/\kappa(r^2+z^2)^{3/2}$

accrete gas inwards until local super-Eddington emissivity reached

AGN result:

There are **no** accretion disk predictions yet, steady state or otherwise, on the simultaneous presence of jets, winds, cones.

AGN timescale t_A is **long** if wind evolution is much like ★B to avoid dominance of shock ionization.



Colour code:

★B photoionization
★B mechanical
AGN photoionization

AGN normalization:

$$L_A/L_{\rm bol} = C_{\rm A,max} \exp(-t/t_A)$$

$$\int_{\rm LL}^{\infty} \frac{L_A}{h\nu}\, d\nu = \mathcal{N}_{\rm LyC,A}$$

Final thoughts

Can we say that AGN winds are photoionized unlike nuclear ★B?
Is this how to distinguish ★B vs. AGN?

The importance of high resolution and broad wavelength range (e.g. AM's talk on ISO). A broader sample is close to completion.

Even in the domain of complexity, ratio plots can be very clean (i.e. a differential measure).