Effects of cosmic rays on ionized gas in AGN and starburst galaxies

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Collaborators:

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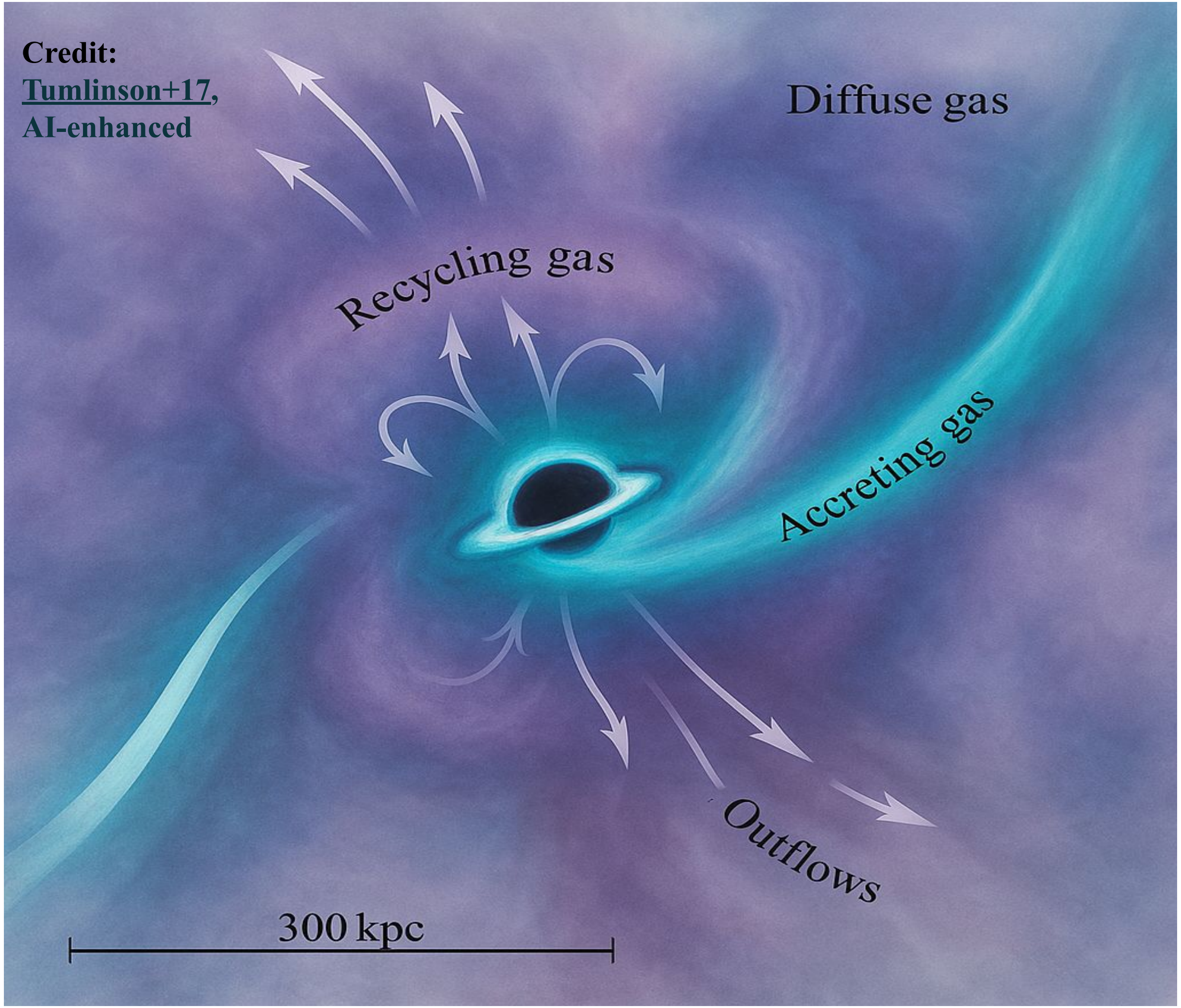
ΙΔΡΥΜΑ ΚΡΑΤΙΚΩΝ ΥΠΟΤΡΟΦΙΩΝ IKY

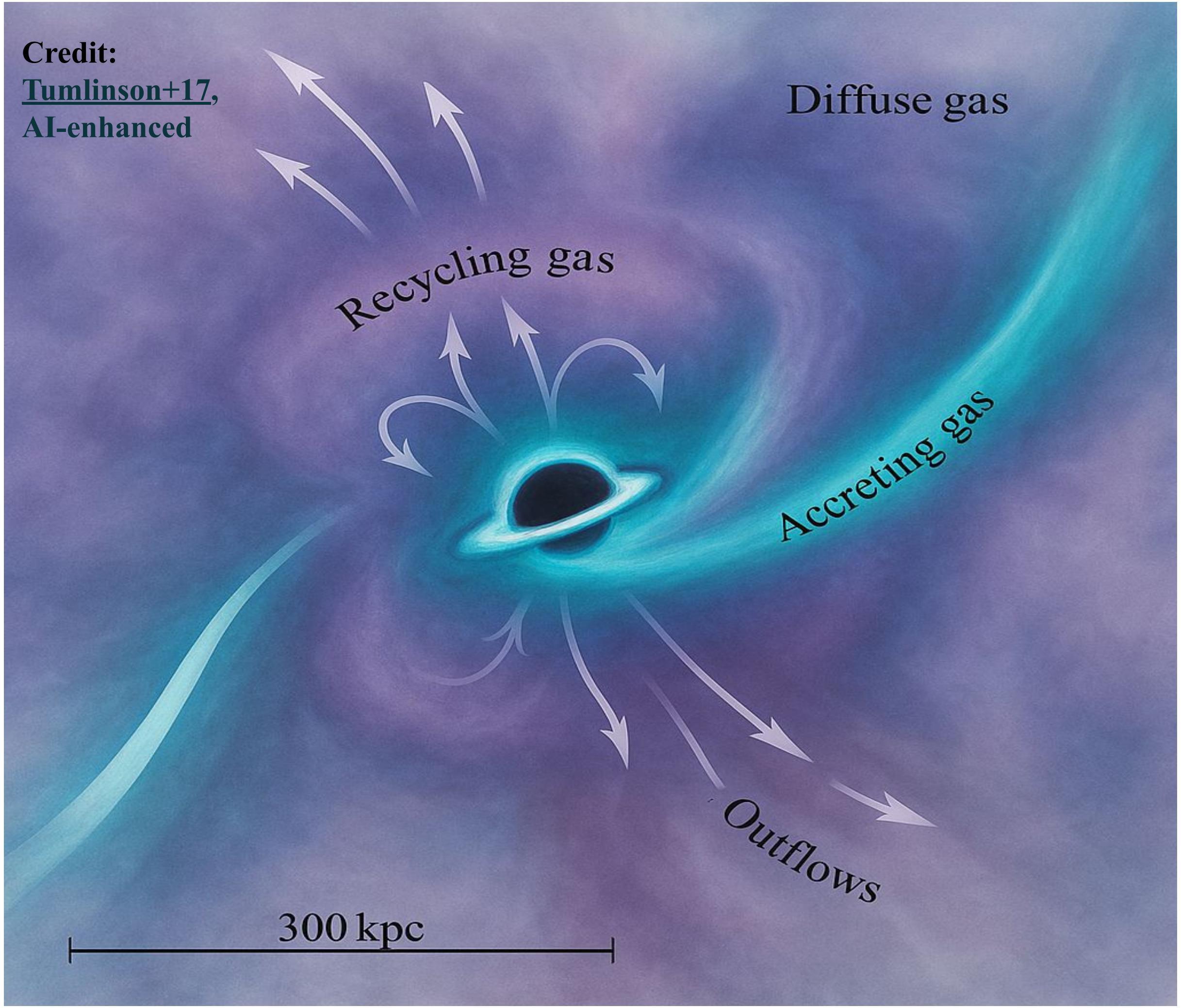
National and Kapodistrian University of Athens

Escape of Lyman radiation from galactic labyrinths, 7-11 April 2025, OAC, Kolymbari, Crete



Feedback Mechanisms

- ⭐ *Photoionization*
- ⭐ *Shocks*
- ⭐ *X-ray Heating*
- ⭐ *Cosmic Rays*



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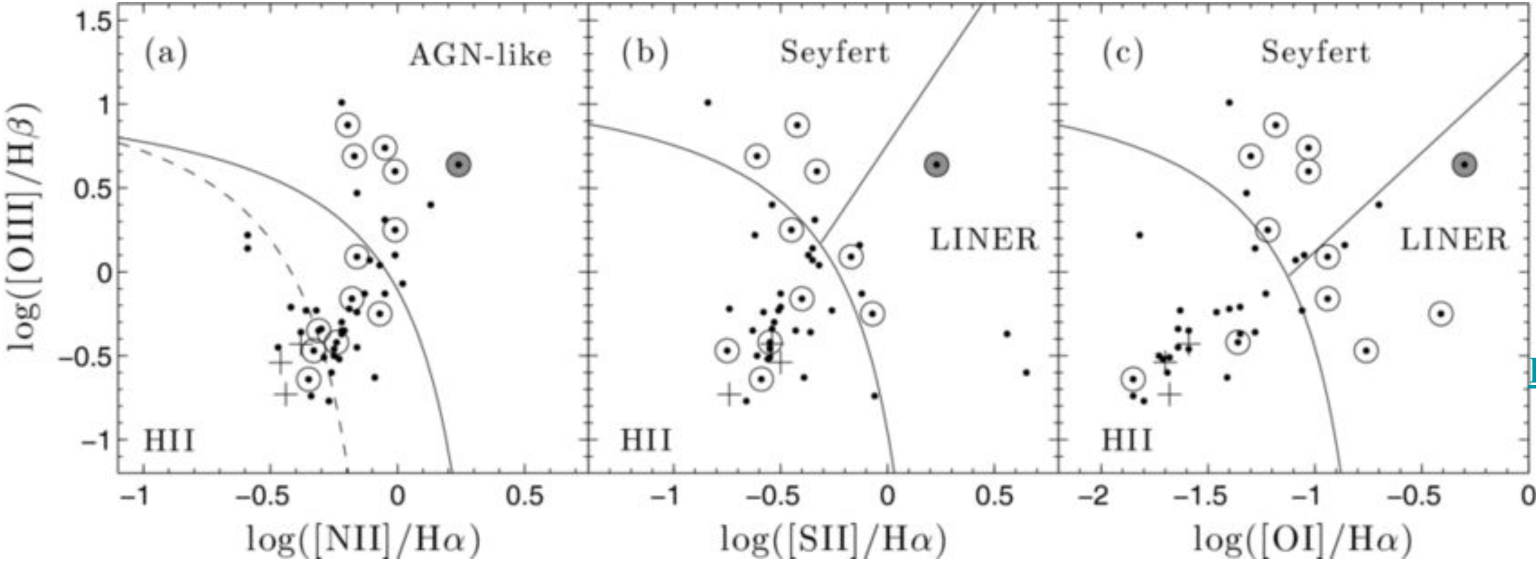
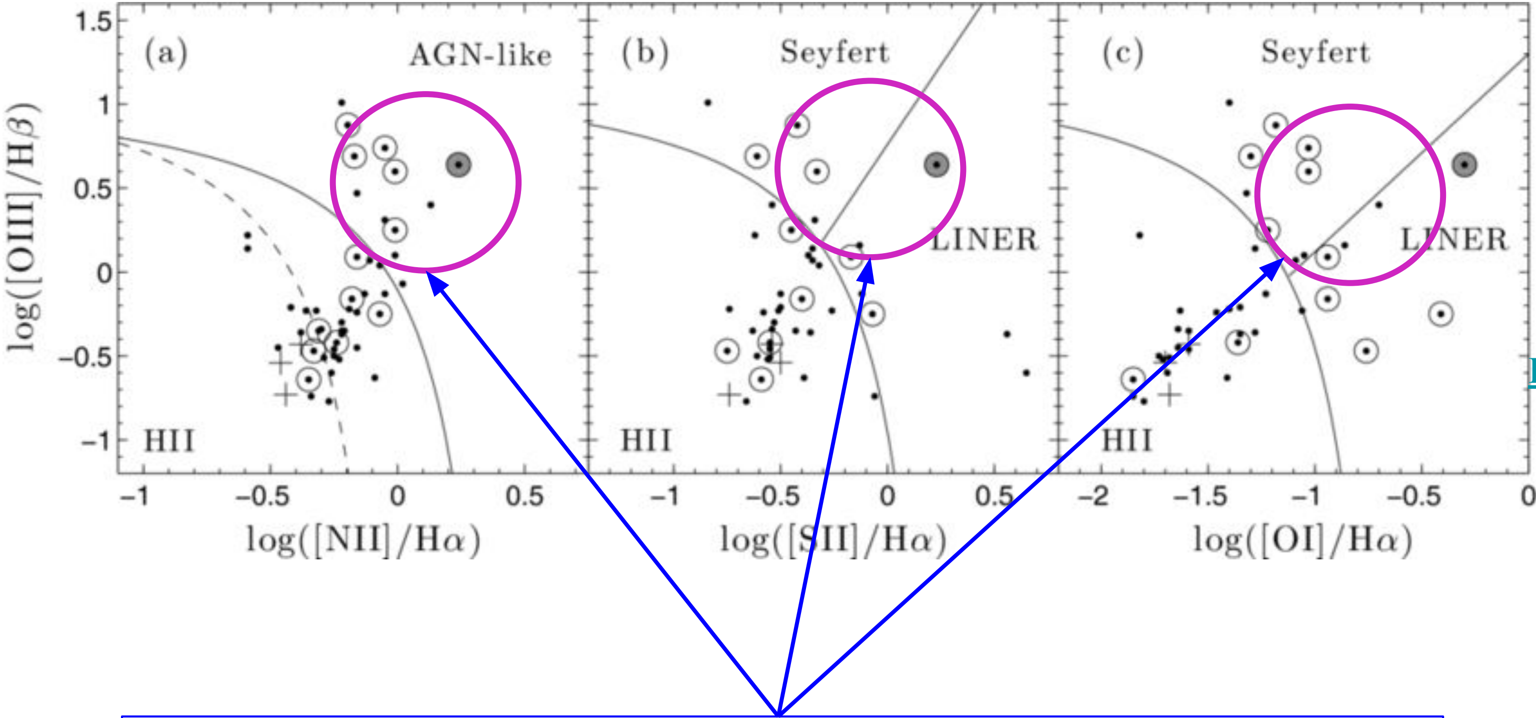
BPT Diagrams



Parra+2010

BPT Diagrams



Parra+2010

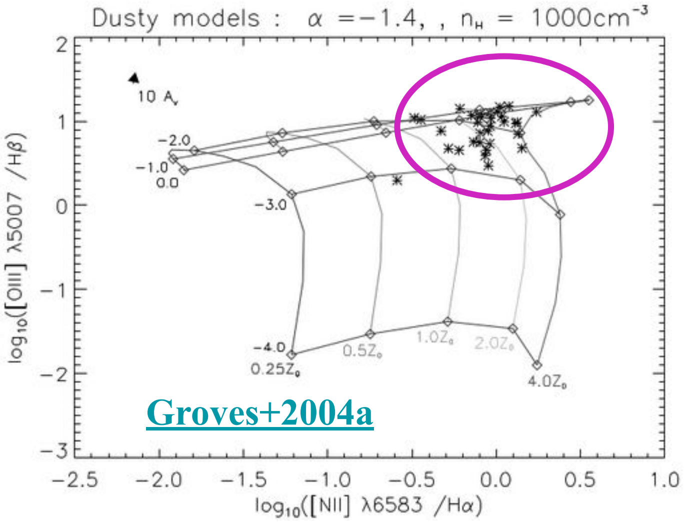
Works on modeling these areas:

Dopita+02, Groves+04a, Feltre+16, Zhu+23

Motivation

Works so far:

- ☆ Focus on photoionization & shocks
- ☆ Do not include CRs
- ☆ Use higher than solar metallicities

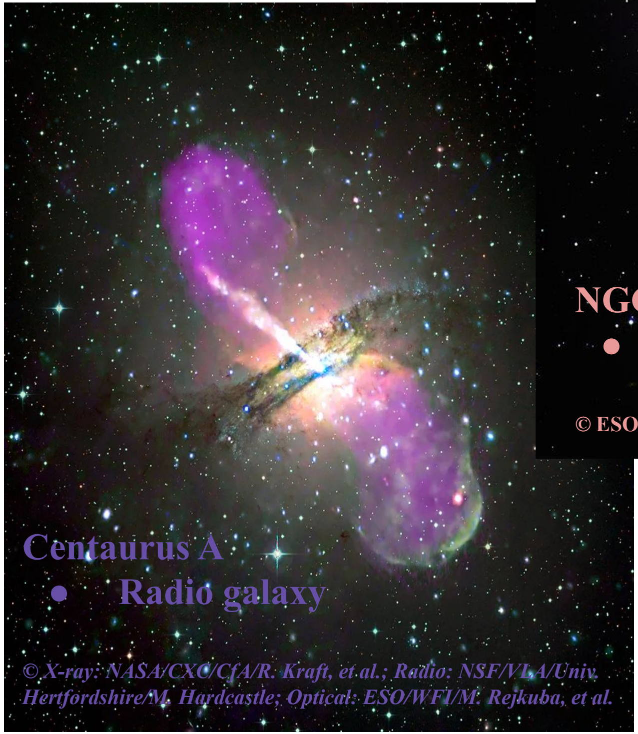


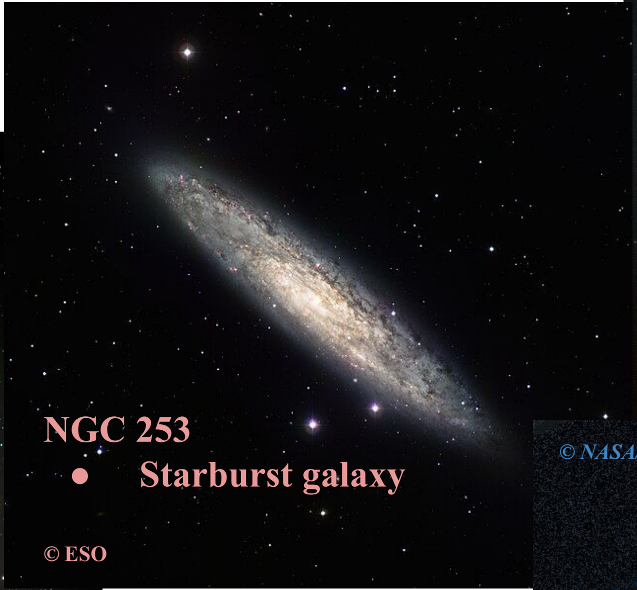
Groves+2004a

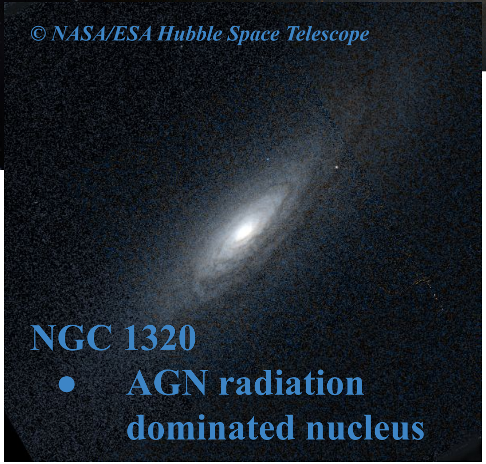
Our models:

- ☆ Study CRs as an ionization mechanism along with photoionization
- ☆ Explore CR impact deep in the clouds
- ☆ Assume solar metallicity

Galaxy Sample

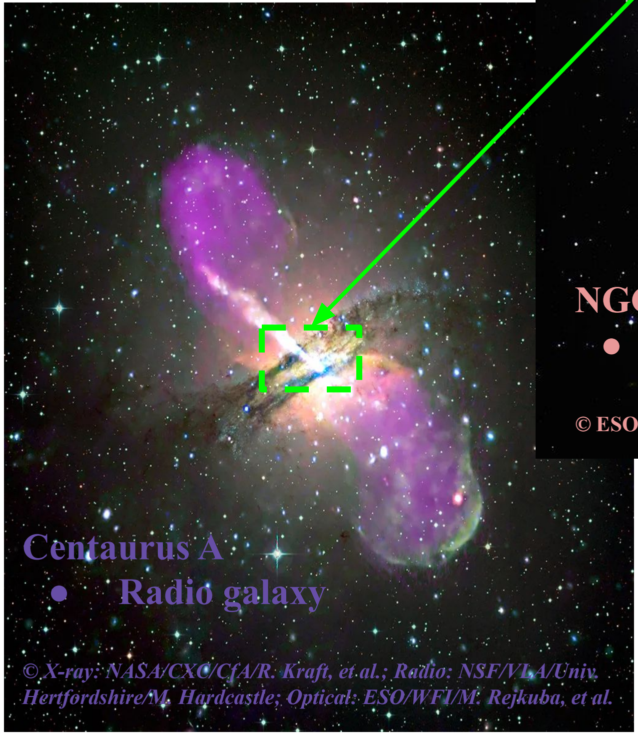


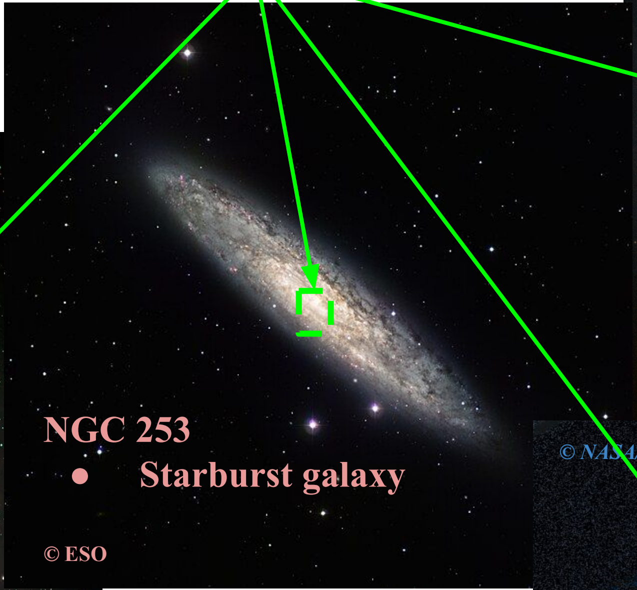


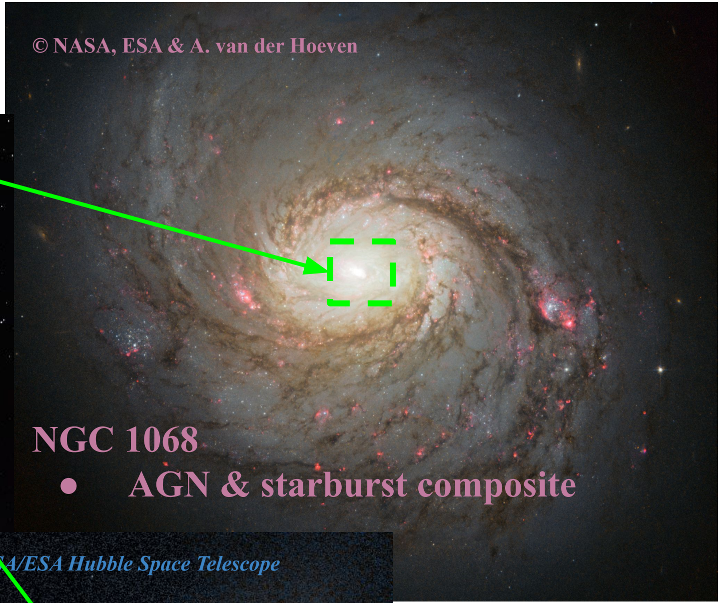


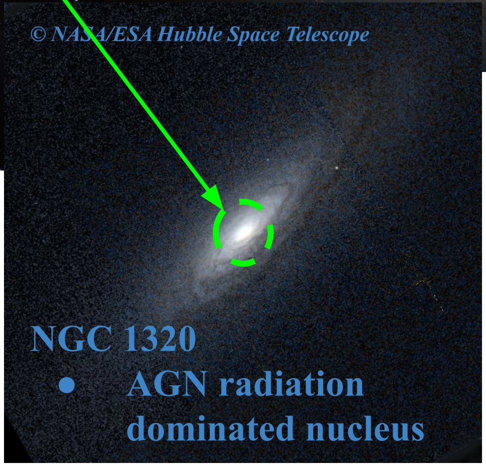
Galaxy Sample

MUSE datacubes





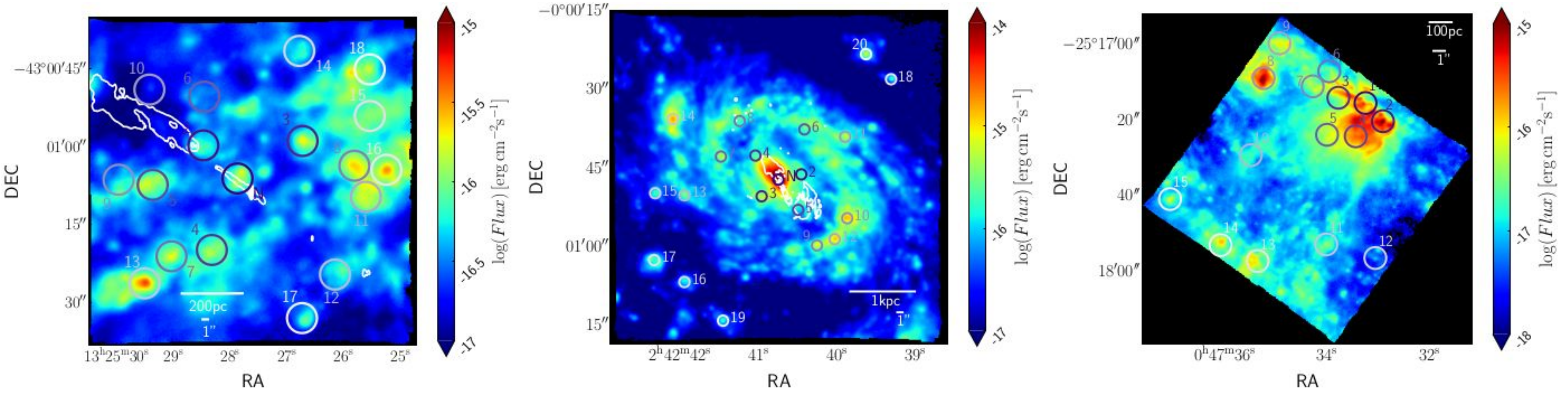




Proposal IDs:

- ★ 094.B-0321(A)
- ★ 102.B-0078(A)
- ★ 108.229J.001

Region Selection - Hα Linemaps - MUSE Data

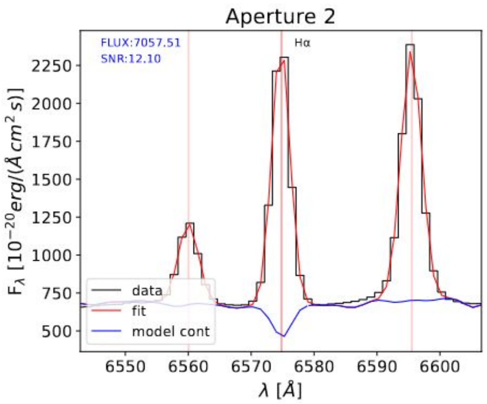


Centaurus A **NGC 1068** **NGC 253**

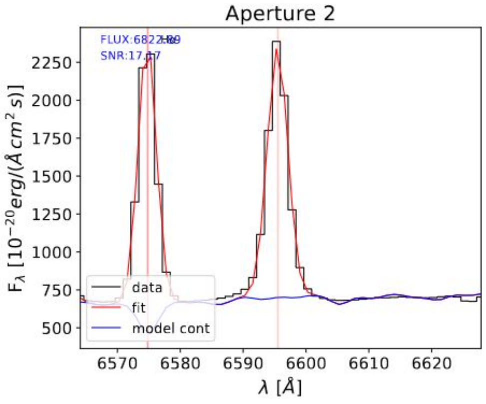
Radio Data for Centaurus A & NGC 1068 provided by

Lenc & Tingay 2009, Mutie+2024

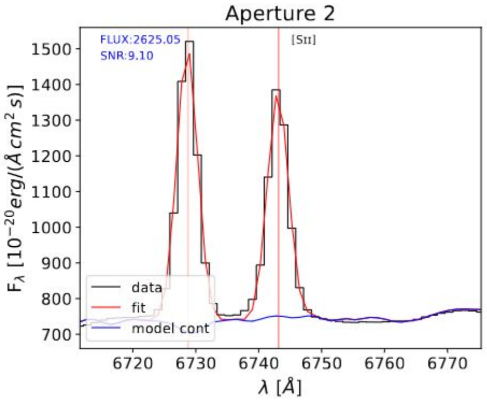
Emission line fitting



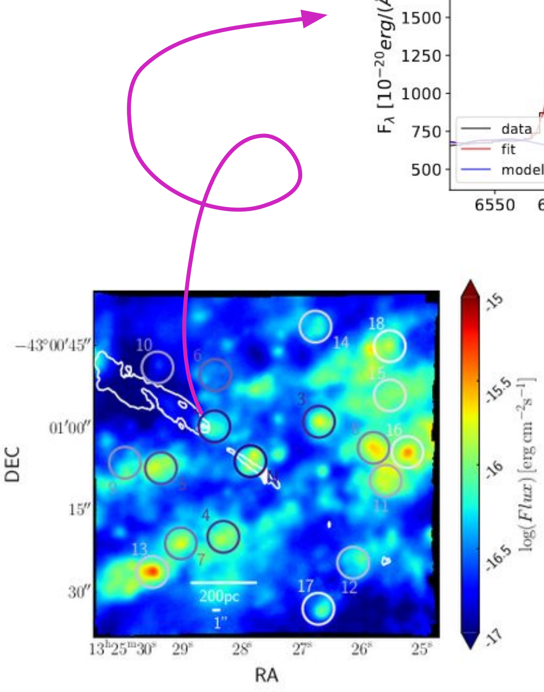
(a) $H\alpha$



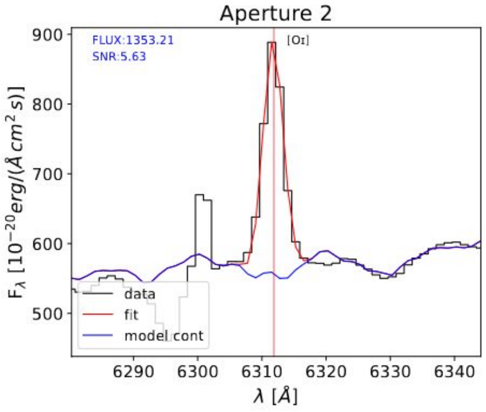
(b) [N II]λ6584Å



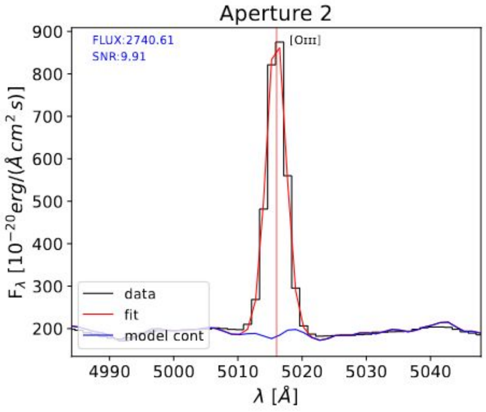
(c) [S II]λλ6717,6731Å



Centaurus A



(d) [O I]6300Å.



(e) [O III]λ5007Å

BPT emission lines' fit in the rest frame of Centaurus A.

CLOUDY (Ferland+17) Modeling Parameters

- AGN and Star-forming models
- $-3.5 \leq \log U \leq -1.5$
- $0 \leq \log n_H \leq 4$
- $-14 \leq \log (\zeta_{CR}/s^{-1}) \leq -12$
- $1\ Z_\odot$

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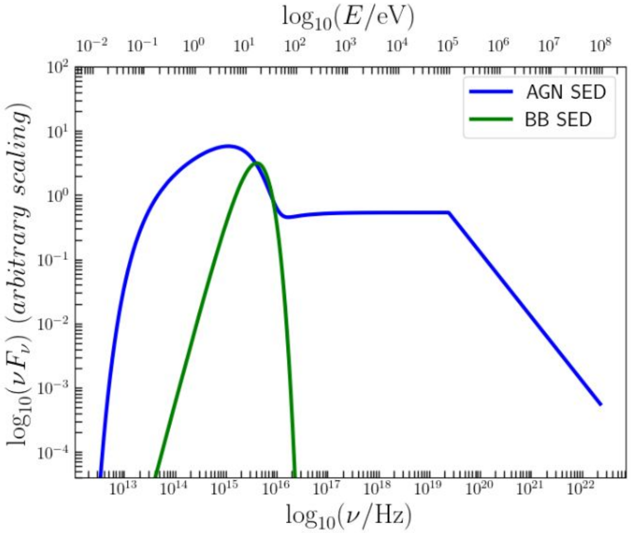

Galaxy	$\log_{10}$ U	$Z/Z_\odot$
Centaurus A	[-3.5, -3.2]	[0.4, 1.2]
NGC 1068	[-3.4,-2.8]	[0.5, 1.1]
NGC 253	[-3.1,-2.6]	[0.4, 0.8]
NGC 1320	[-3.4, -2.9]	[0.6, 1.1]

HCm

Pérez-Montero +14, +19

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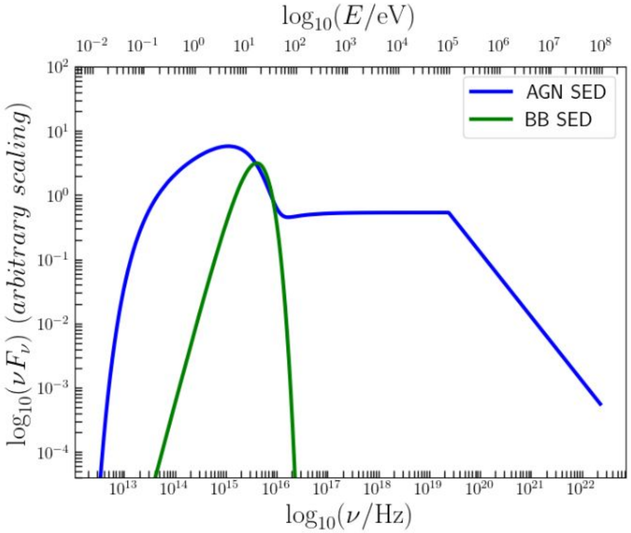

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Motivated by the chosen galaxies

HIICm

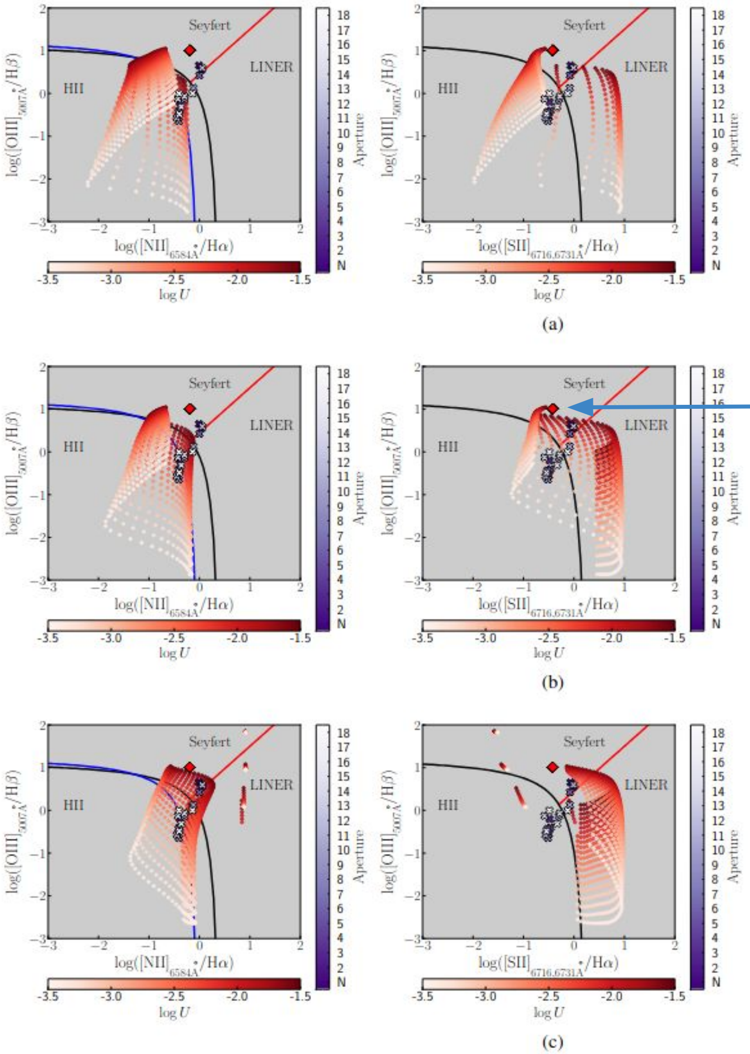
Pérez-Montero +14, +19

BPTs - AGN Models

$\zeta_{CR} = 10^{-14}\ s^{-1}$

$\zeta_{CR} = 10^{-13}\ s^{-1}$

$\zeta_{CR} = 10^{-12}\ s^{-1}$



Centaurus A

NGC 1320

$\log(\zeta_{CR}/s^{-1}) \geq -13$

in agreement with:

★ **Molecular cloud chemistry** (González-Alfonso+13)

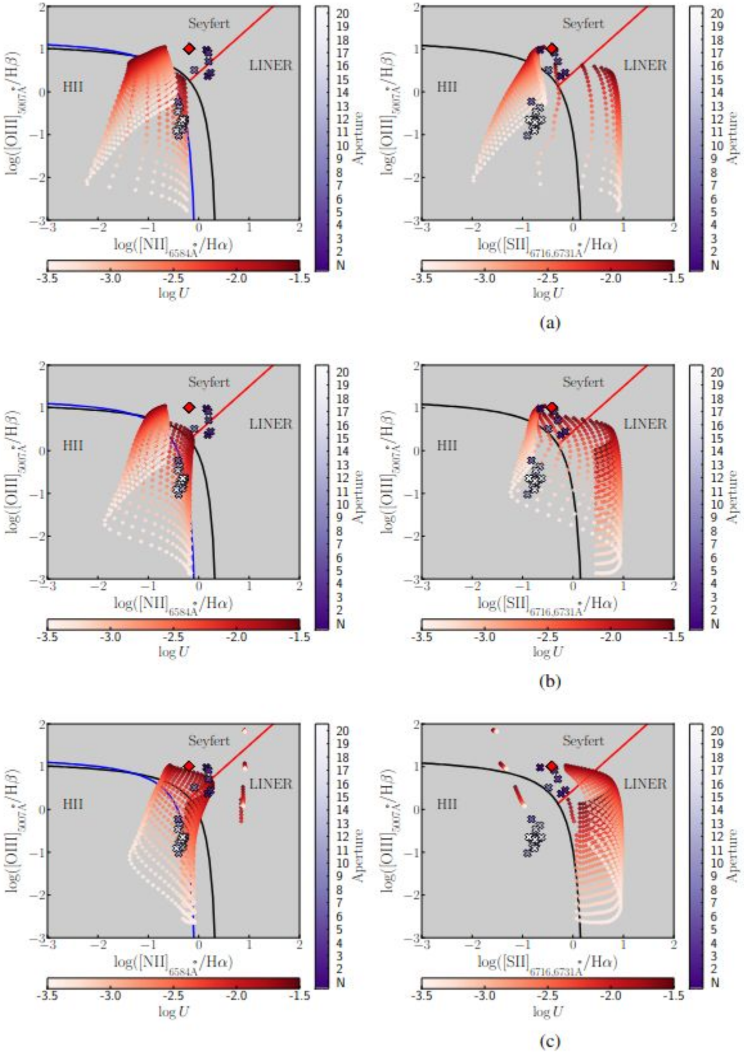
★ **Synchrotron fit** (lower limit)

BPTs - AGN Models

$\zeta_{CR} = 10^{-14}$ s^{-1}

$\zeta_{CR} = 10^{-13}$ s^{-1}

$\zeta_{CR} = 10^{-12}$ s^{-1}



NGC 1068

$\log(\zeta_{CR}/s^{-1}) \geq -13$

in agreement with:

★ **Molecular cloud chemistry** (González-Alfonso+13)

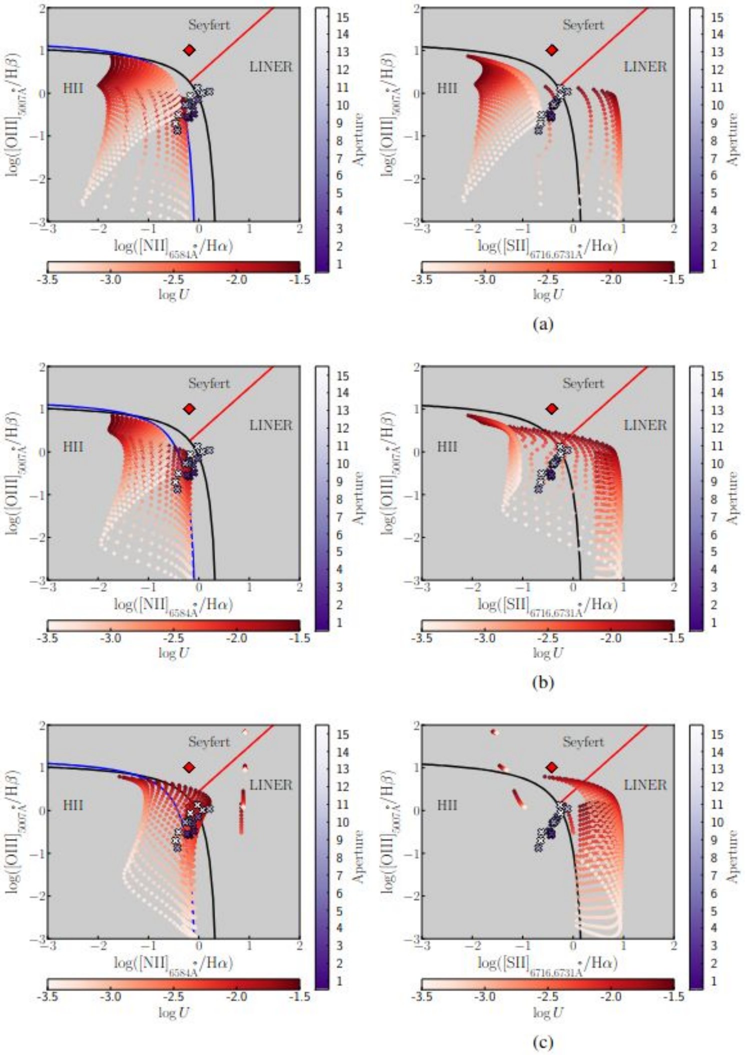
★ **Synchrotron fit** (lower limit)

BPTs - SF Models

$\zeta_{CR} = 10^{-14}\ s^{-1}$

$\zeta_{CR} = 10^{-13}\ s^{-1}$

$\zeta_{CR} = 10^{-12}\ s^{-1}$



NGC 253

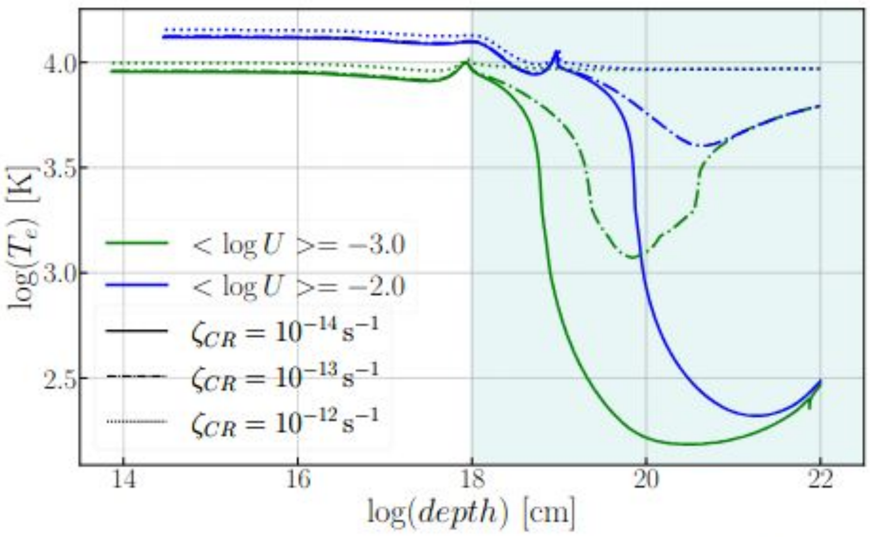
$\log(\zeta_{CR}/s^{-1}) \simeq -12$

According to:

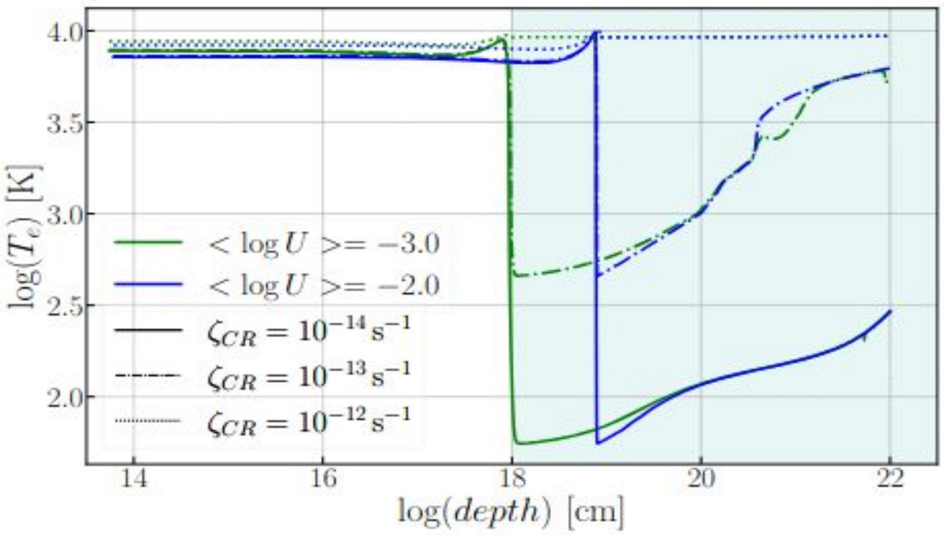
- ★ Behrens+22
- ★ Holdship+22
- ★ Beck+23

Gas Stratification

AGN Models

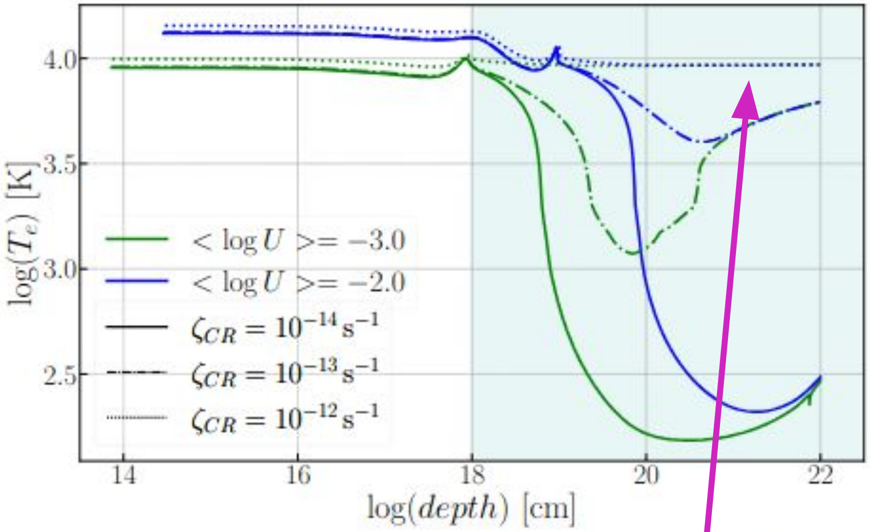


SF Models



Gas Stratification

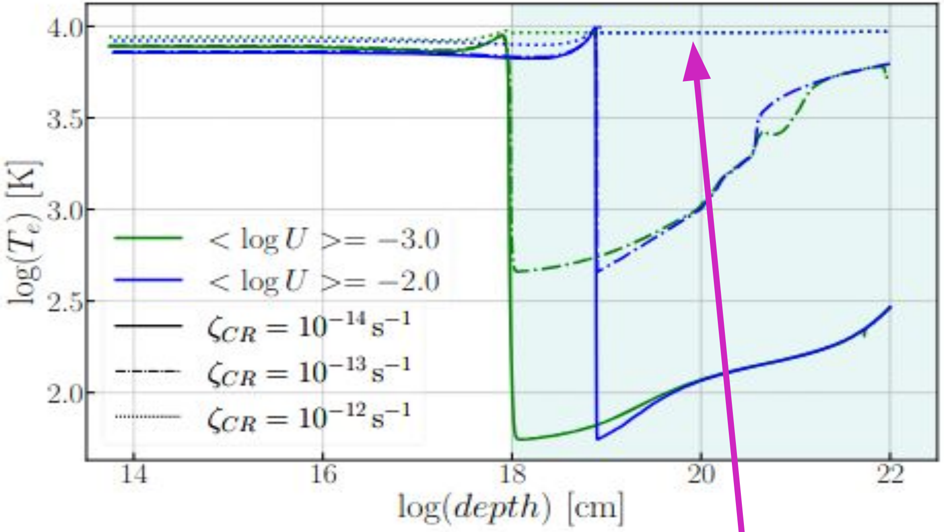
AGN Models



AGN Photoionization

CRs

SF Models



Photoionization

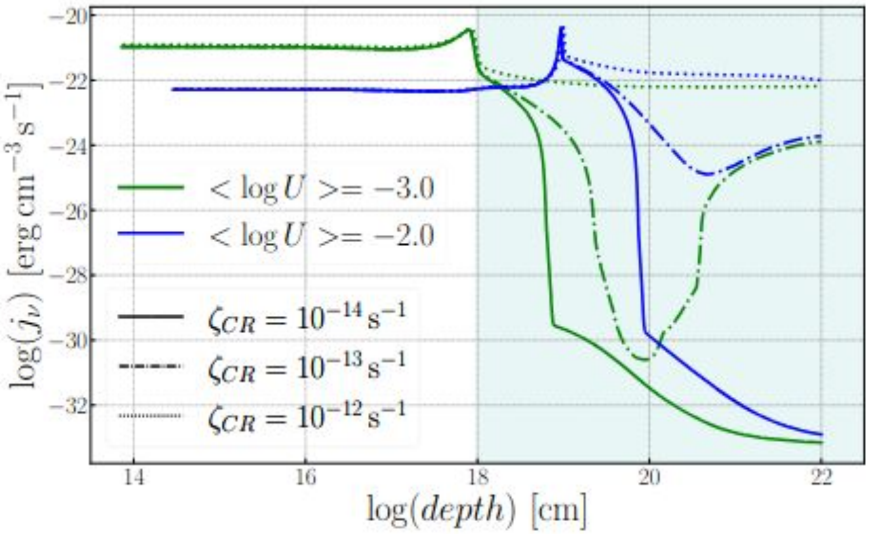
CRs

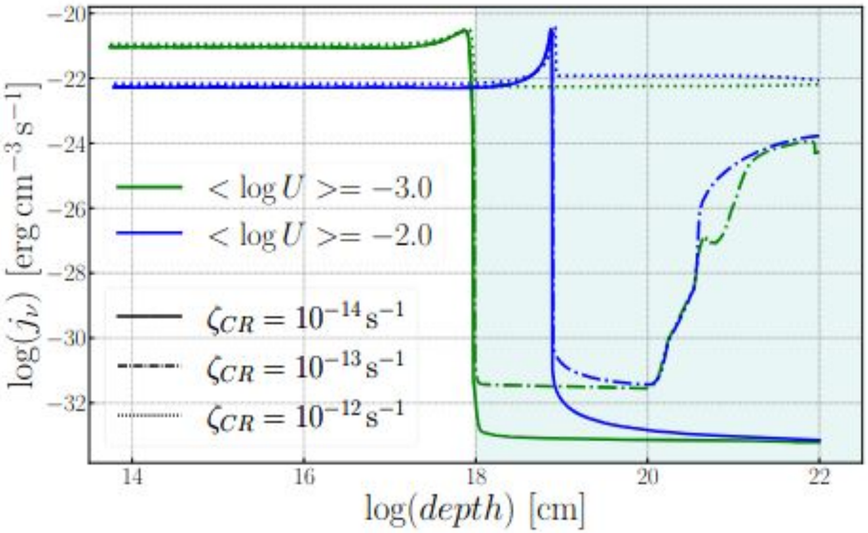
Gas Stratification

AGN Models

SF Models

[NII]





AGN Photoionization

CRs

Photoionization

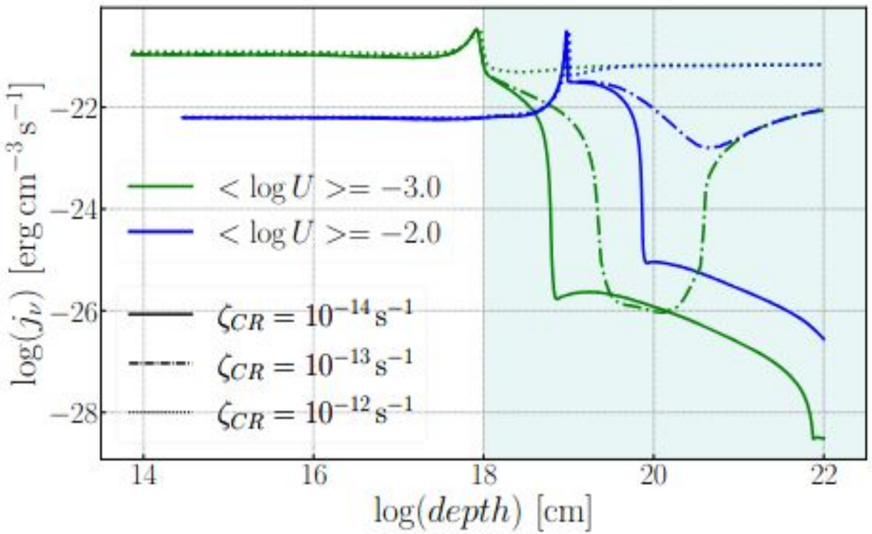
CRs

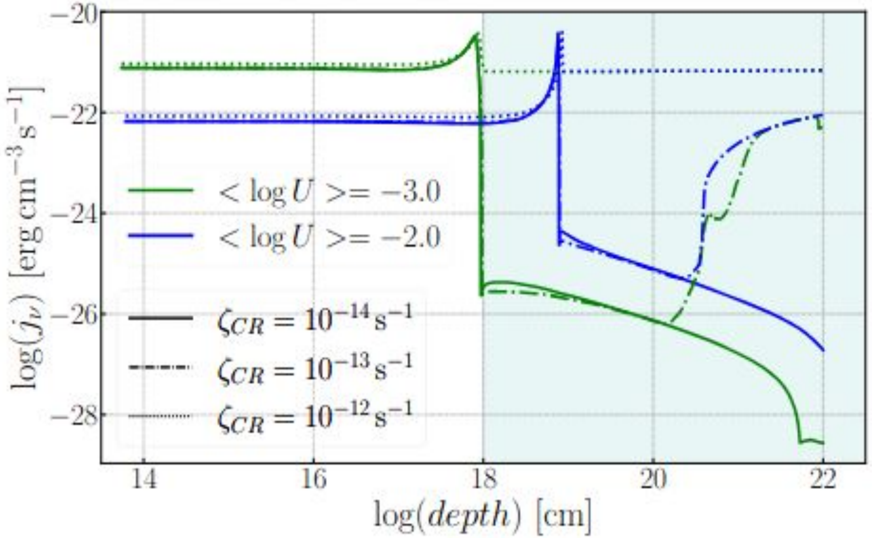
Gas Stratification

AGN Models

SF Models

[SII]





AGN Photoionization

CRs

Photoionization

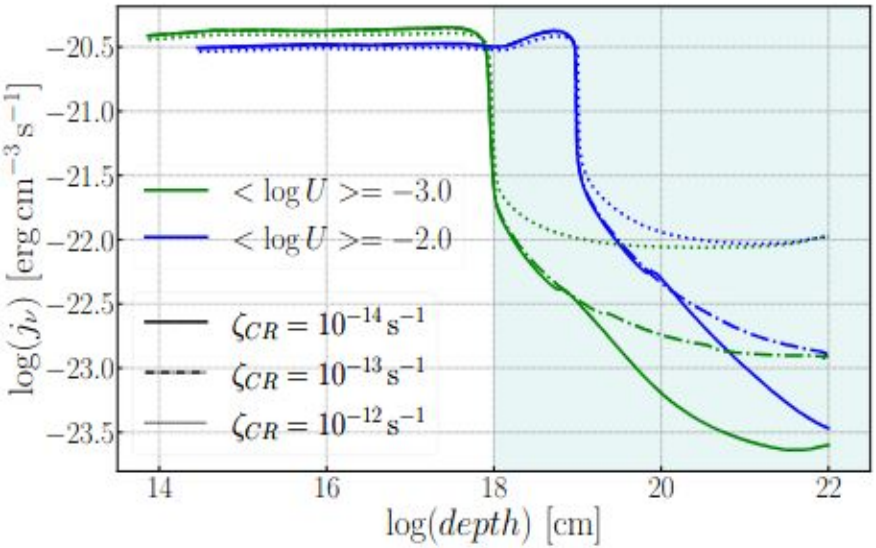
CRs

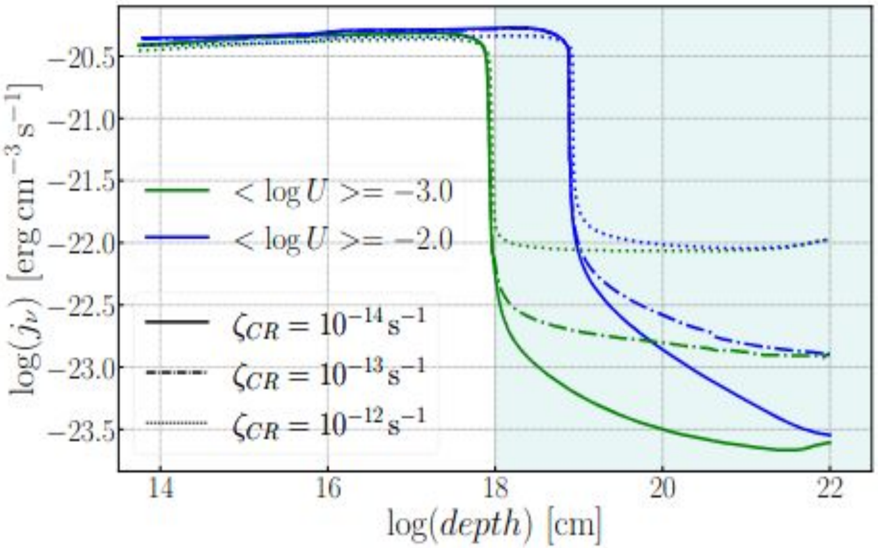
Gas Stratification

AGN Models

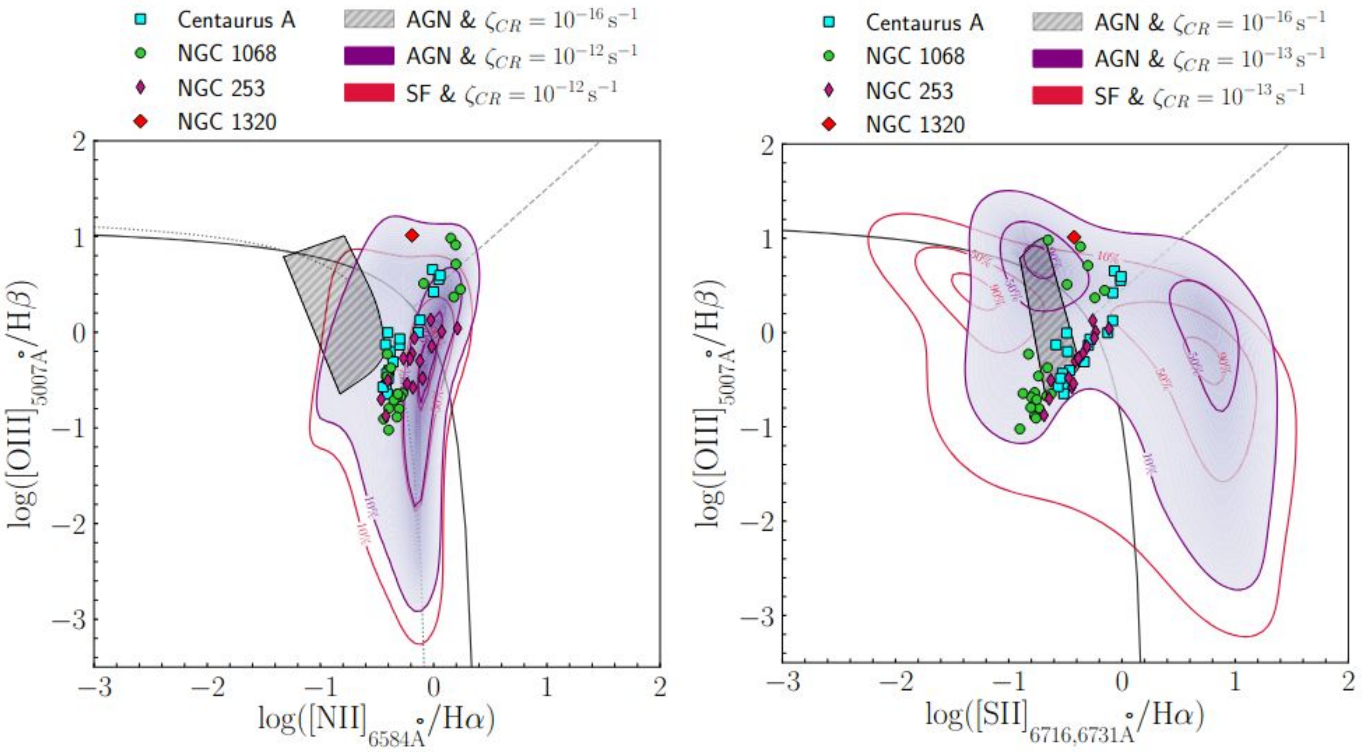
SF Models

Hα





AGN Photoionization **CRs** **Photoionization** **CRs**


Centaurus A
NGC 1068
NGC 253
NGC 1320
AGN & $\zeta_{CR} = 10^{-16}\,\mathrm{s}^{-1}$
AGN & $\zeta_{CR} = 10^{-12}\,\mathrm{s}^{-1}$
SF & $\zeta_{CR} = 10^{-12}\,\mathrm{s}^{-1}$
$\log([\mathrm{OIII}]_{5007\mathrm{\AA}}/\mathrm{H}\beta)$
$\log([\mathrm{NII}]_{6584\mathrm{\AA}}/\mathrm{H}\alpha)$
Centaurus A
NGC 1068
NGC 253
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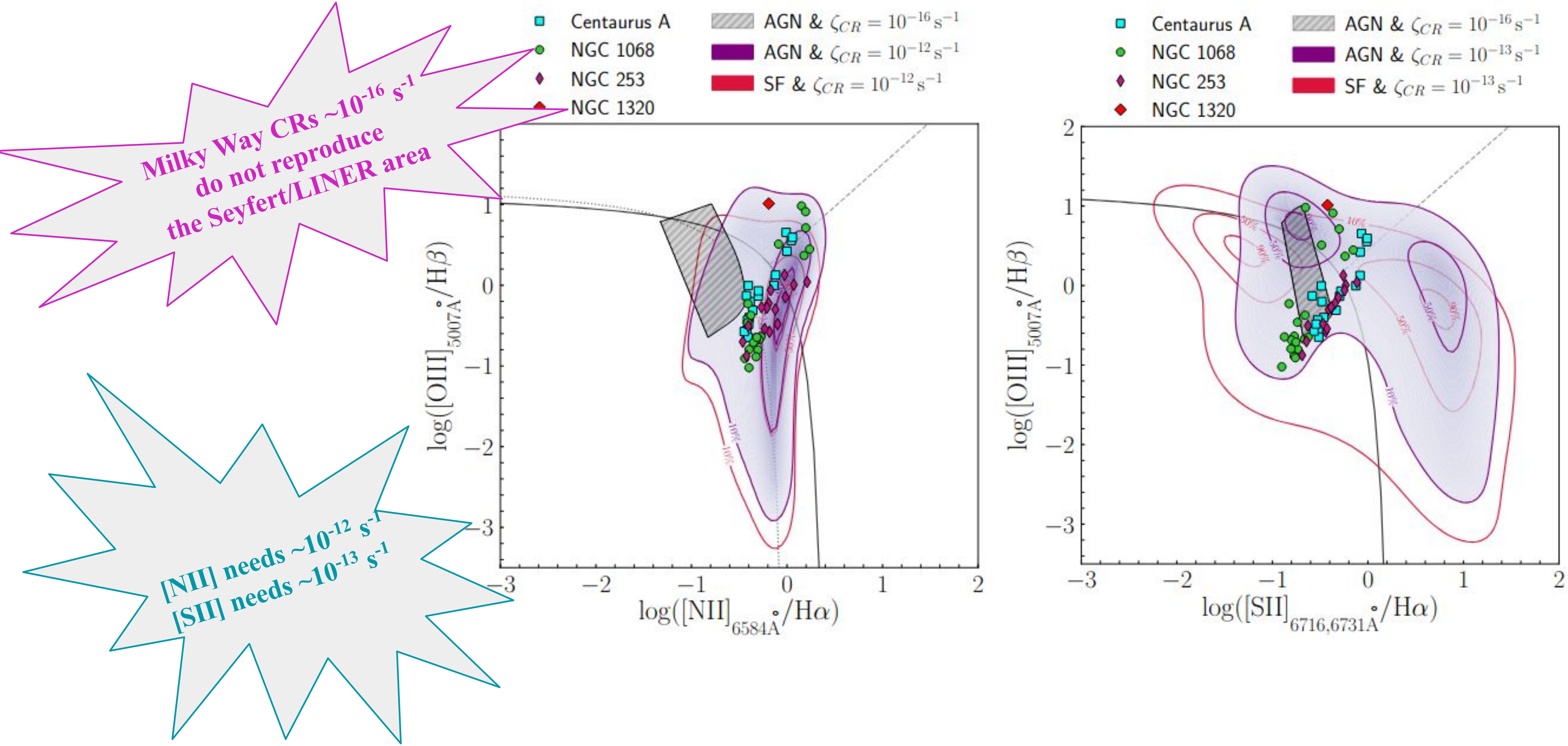
$\log([\mathrm{SII}]_{6716,6731\mathrm{\AA}}/\mathrm{H}\alpha)$


Milky Way CRs ~10^-16 s^-1
do not reproduce
the Seyfert/LINER area
[NII] needs ~10^-12 s^-1
[SII] needs ~10^-13 s^-1
Centaurus A
NGC 1068
NGC 253
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AGN & $\zeta_{CR} = 10^{-16}\,s^{-1}$
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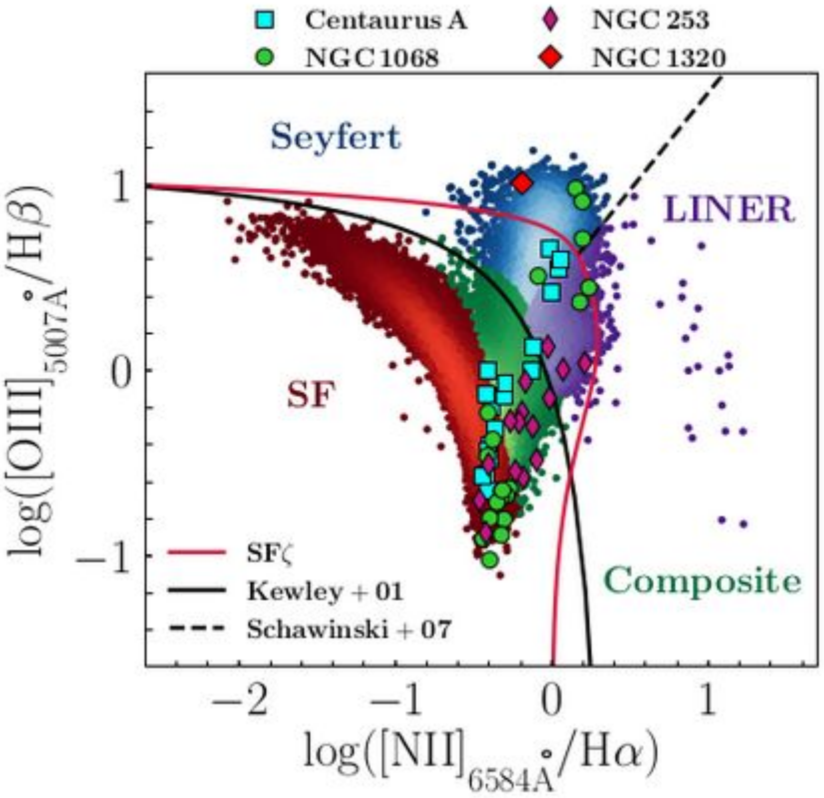
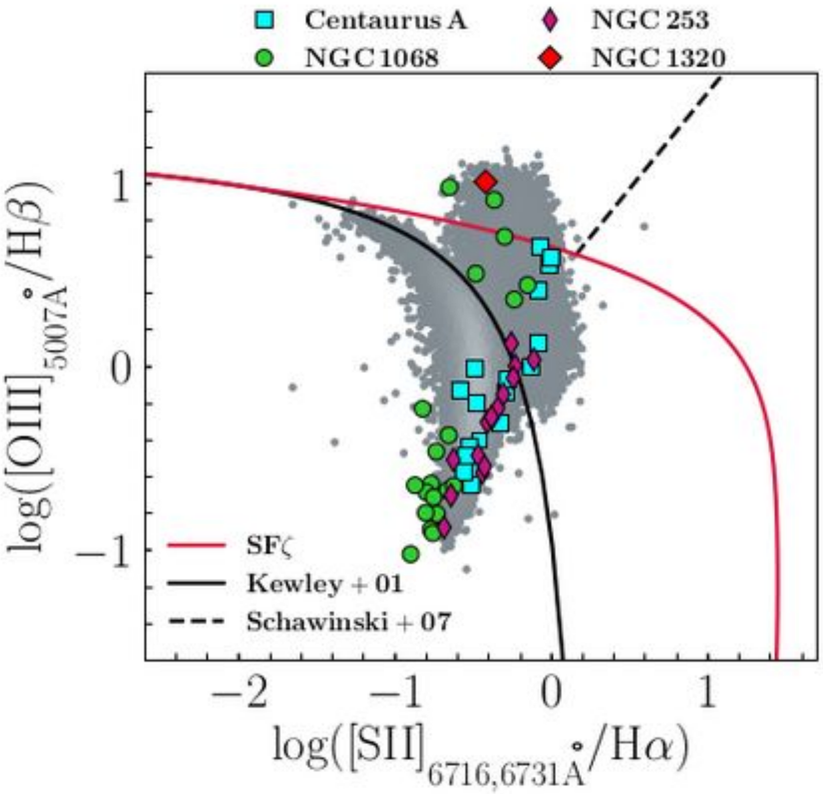
SF & $\zeta_{CR} = 10^{-13}\,s^{-1}$
$\log([OIII]_{5007Å}/H\beta)$
$\log([NII]_{6584Å}/H\alpha)$
$\log([SII]_{6716,6731Å}/H\alpha)$


Centaurus A
NGC 253
NGC 1068
NGC 1320
Seyfert
LINER
SF
Composite
SFζ
Kewley + 01
Schawinski + 07
log([OIII]$_{5007Å}$/Hβ)
log([NII]$_{6584Å}$/Hα)
−2
−1
0
1
(a)


Centaurus A
NGC 253
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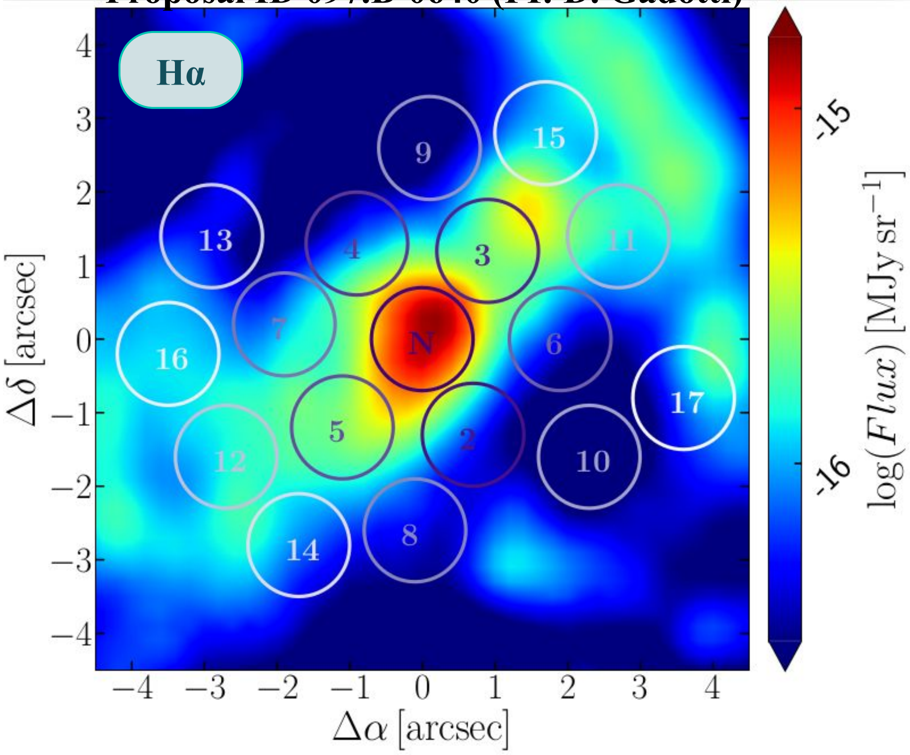
log([OIII]$_{5007Å}$/Hβ)
log([SII]$_{6716,6731Å}$/Hα)
−2
−1
0
1
(b)

NGC 5728 in Optical & Mid-Infrared

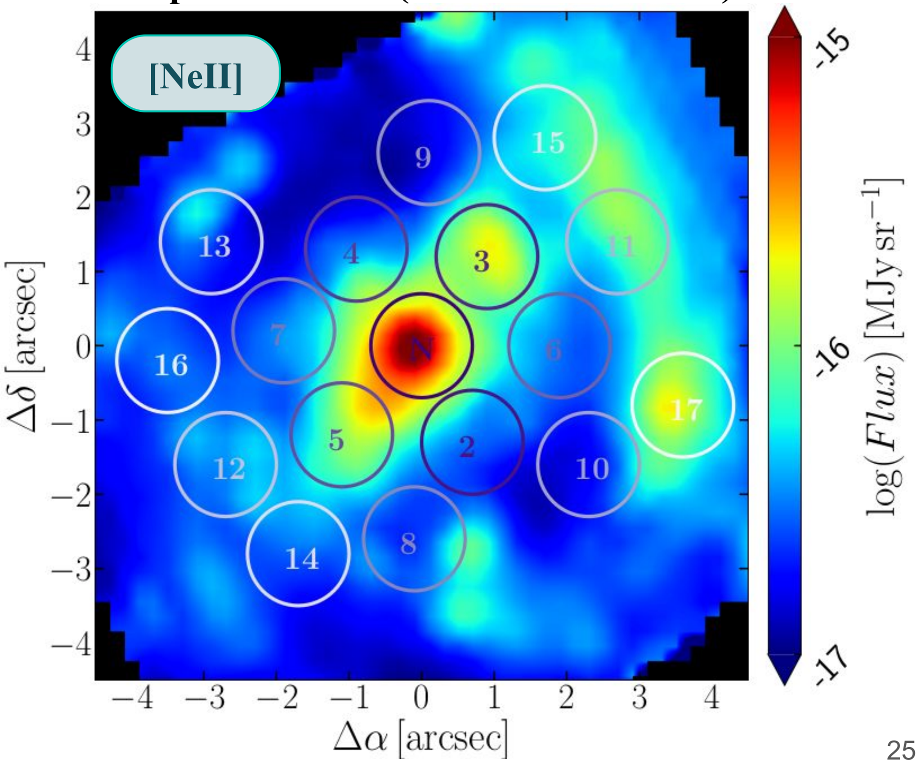
MUSE data

Proposal ID 097.B-0640 (PI: D. Gadotti)



JWST data

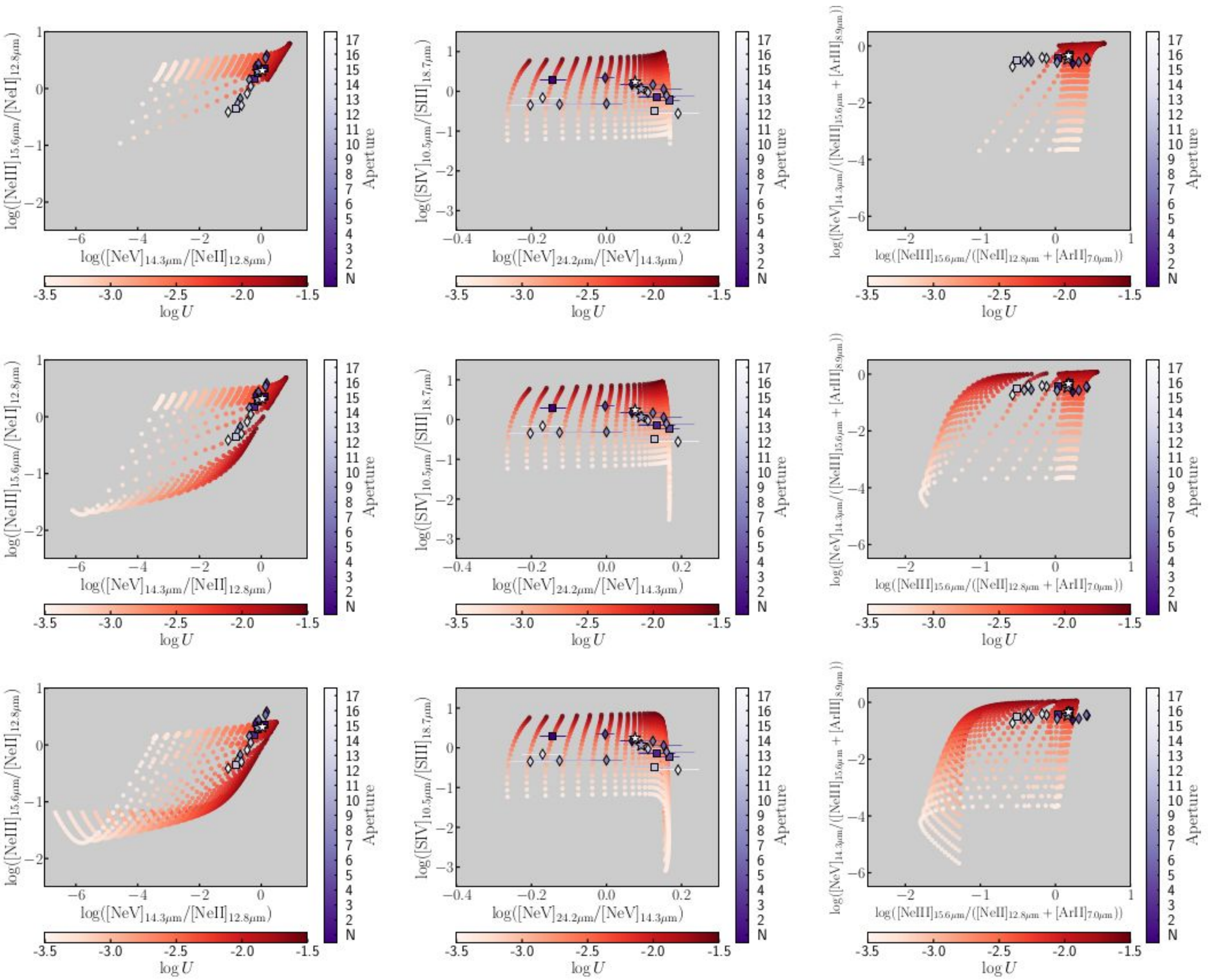
Proposal ID 1670 (PI: T. Taro Shimizu)



$\zeta_{CR} = 10^{-15}\ s^{-1}$

$\zeta_{CR} = 10^{-14}\ s^{-1}$

$\zeta_{CR} = 10^{-13}\ s^{-1}$



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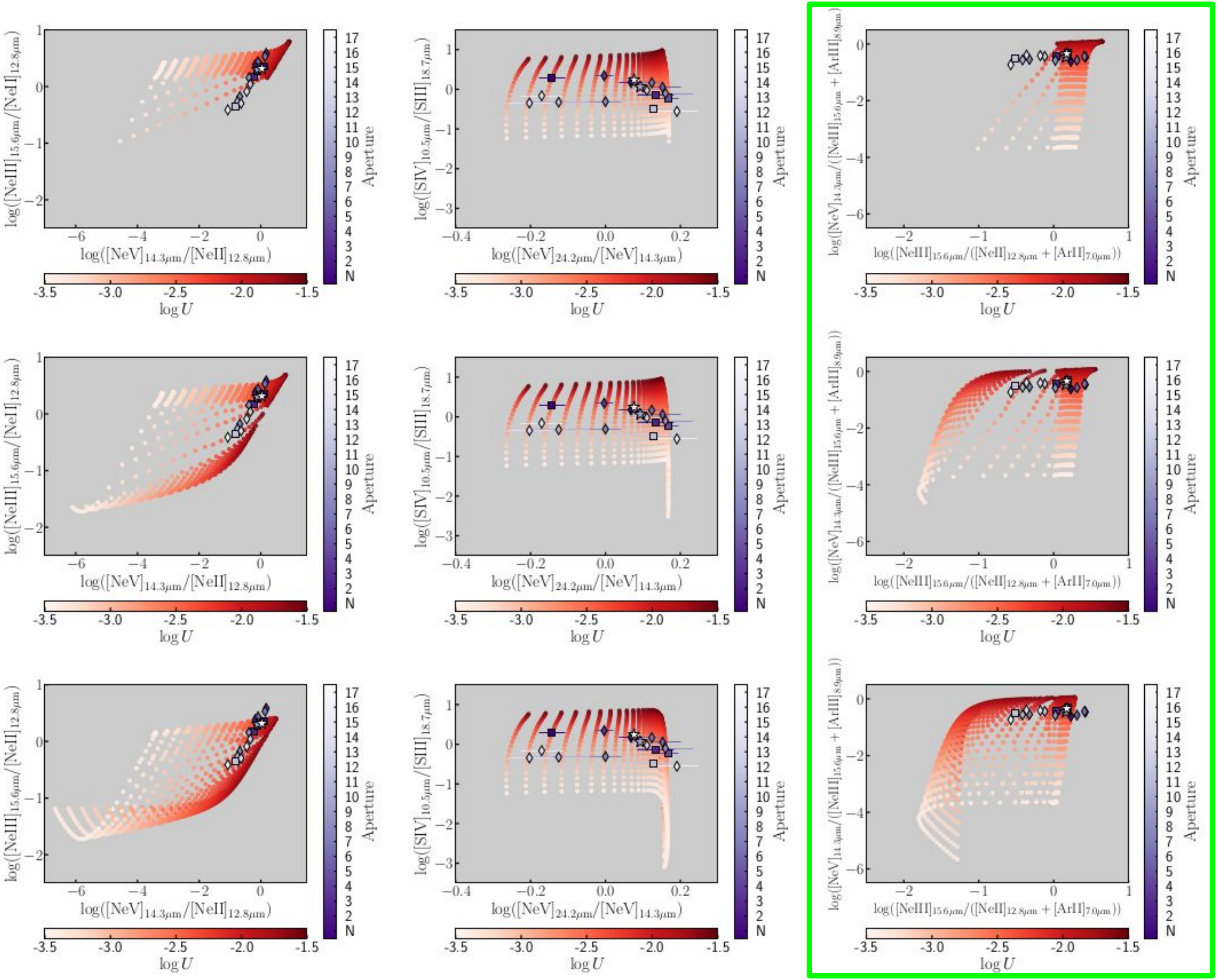

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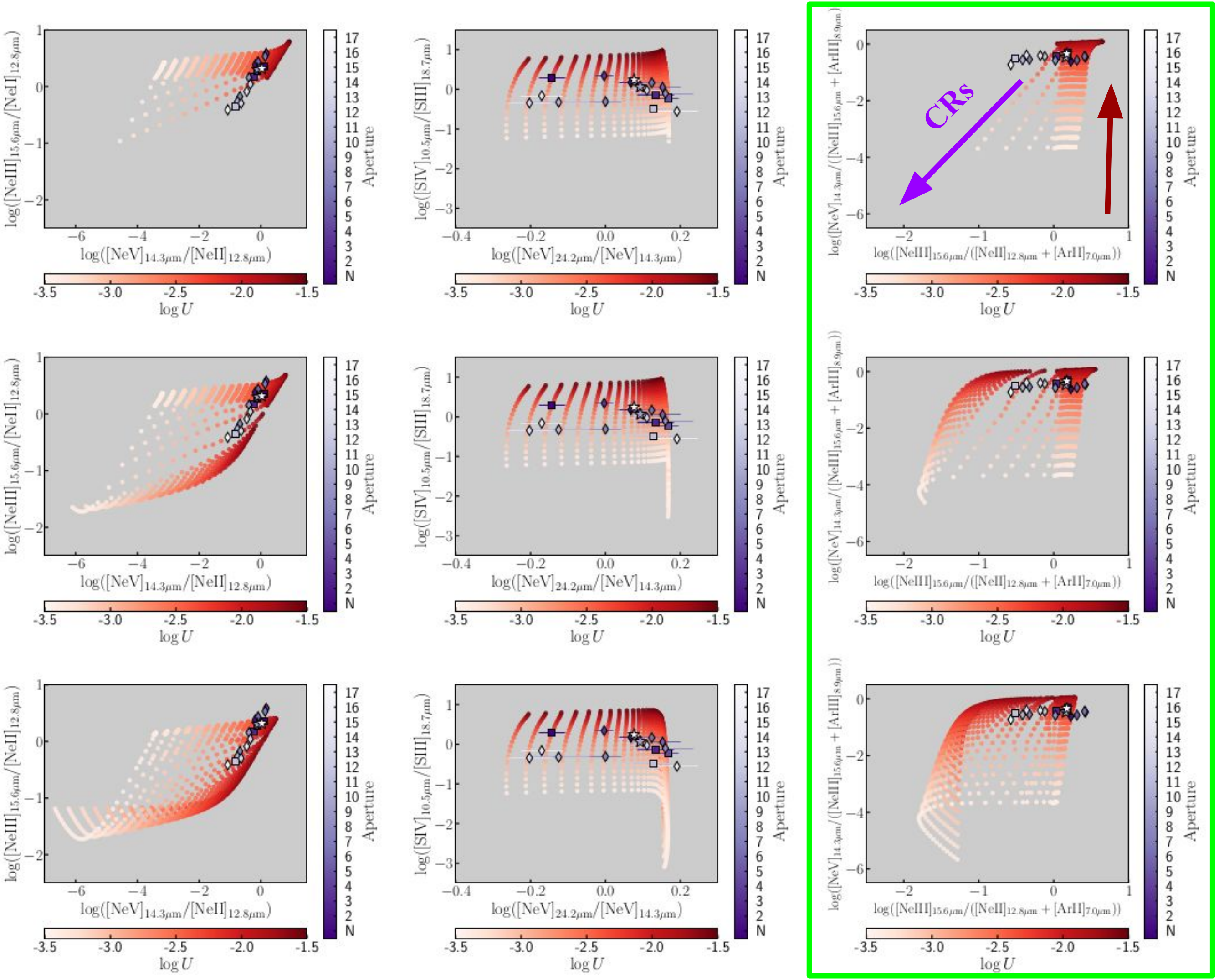

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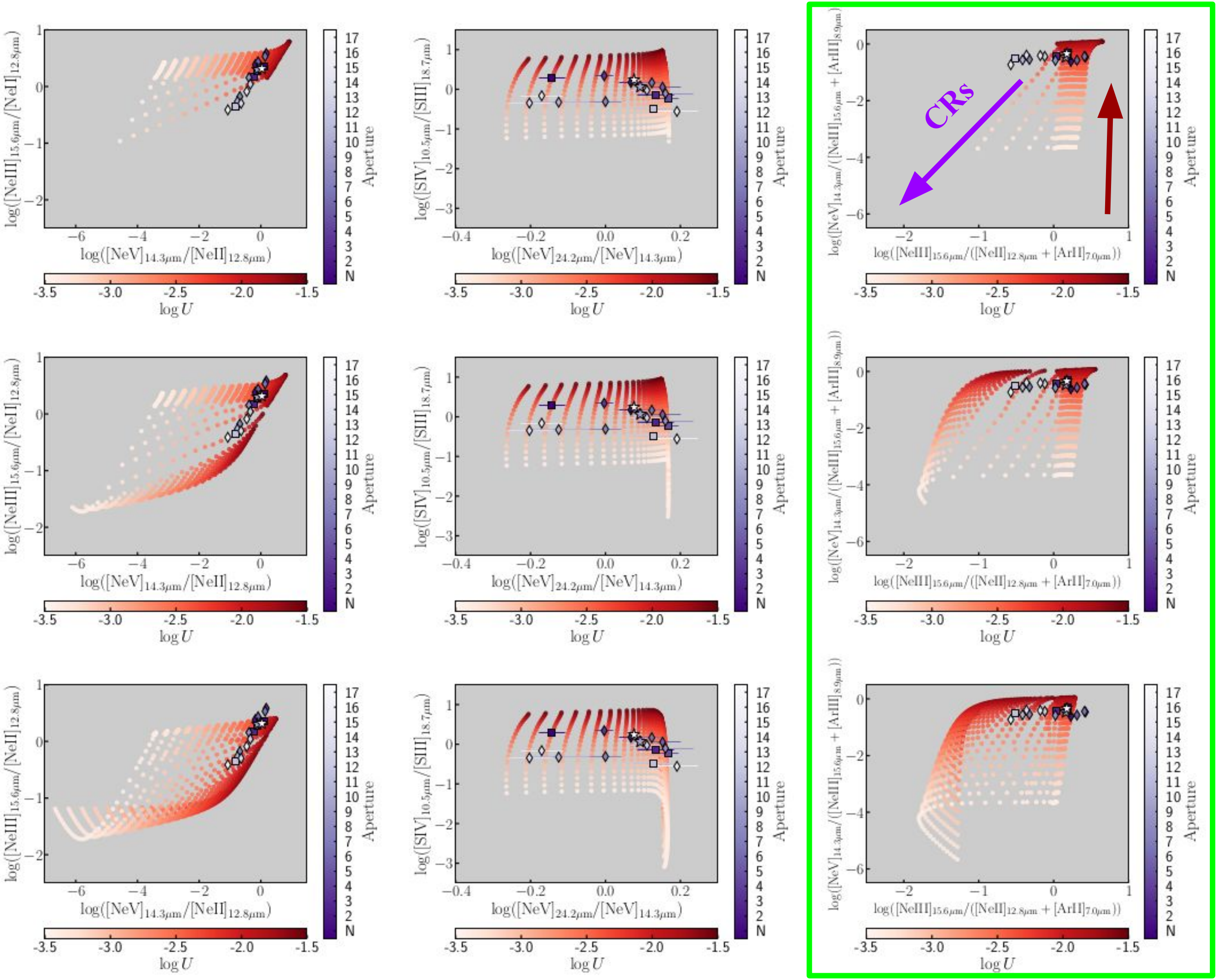

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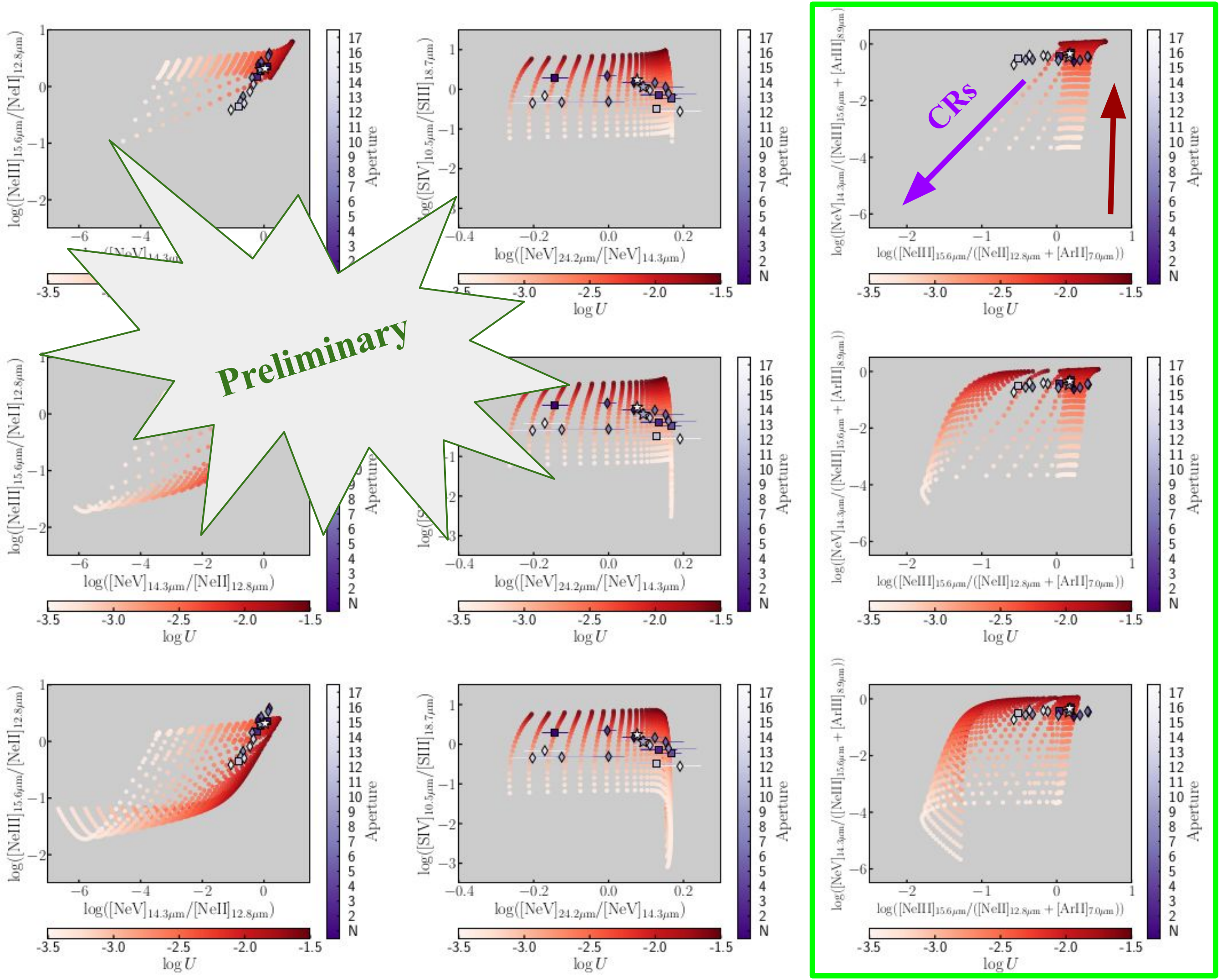

Conclusions

- ★ CRs ($\gtrsim 10^{-13}$ s^{-1}) an important source of feedback in AGN and starbursts.
- ★ CRs penetrate deep within the clouds → UV and secondary ionization.
- ★ 'Warm' secondary ionized layer (~10^4 K) → Te enhances emissivity of low ionisation lines ([NII], [SII]).
- ★ Emissivity of [NII], [SII] ↑ + Emissivity of Hα, Hβ, [OIII] ~fairly constant→AGN & SF models ↝.
- ★ Photoionization + CR ionization do not require supersolar metallicities to reproduce Seyfert/LINER loci in the BPT diagrams → New limits on BPTs.

Koutsoumpou, E., Fernández-Ontiveros, J. A., Dasyra, K. M., & Spinoglio, L. 2025, A&A, 693, A215

SCAN ME

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Koutsoumpou, E., Fernández-Ontiveros, J. A., Dasyra, K. M., & Spinoglio, L. 2025, A&A, 693, A215

SCAN ME

In Preparation

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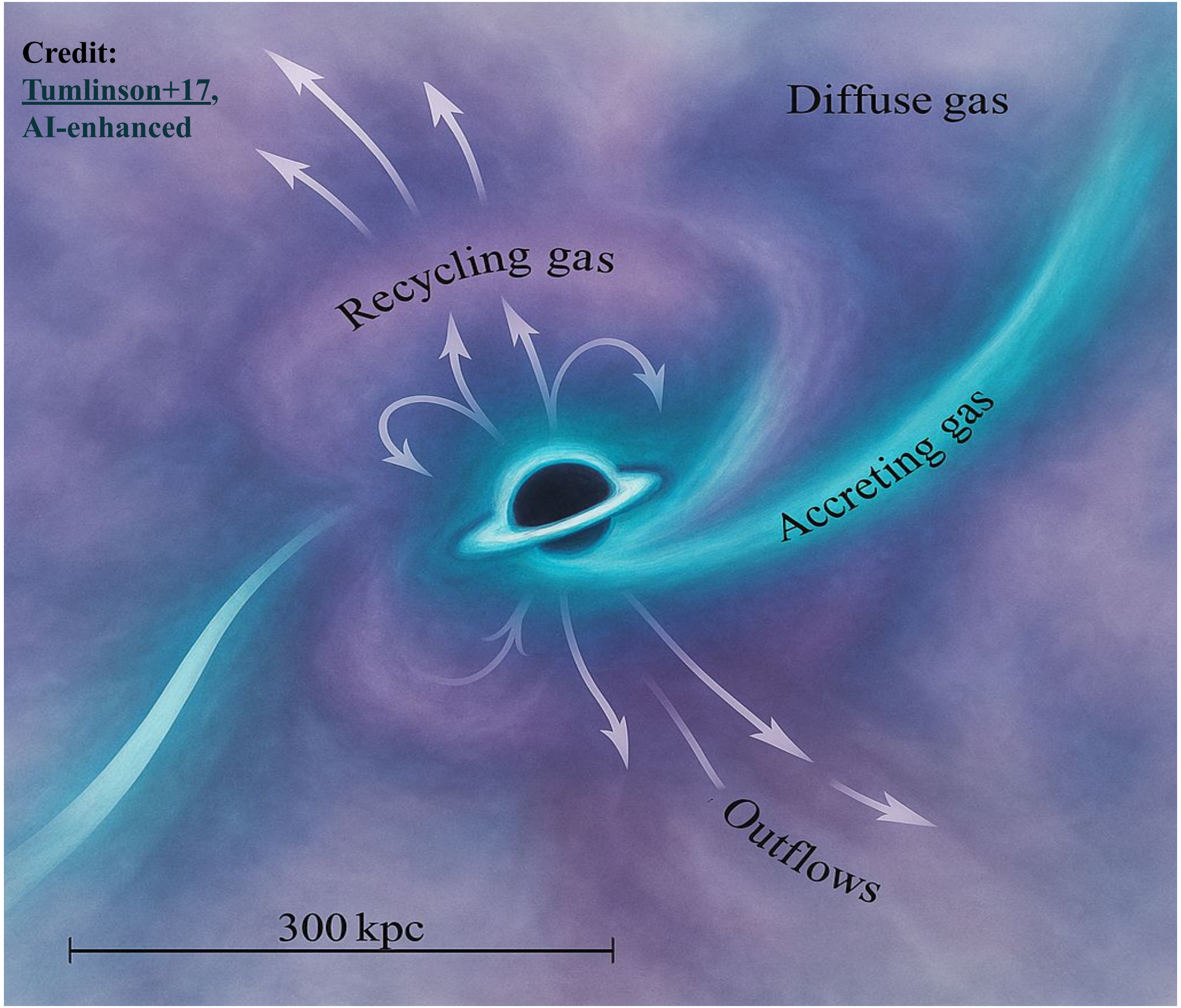
SCAN ME

In Preparation

Thank you!

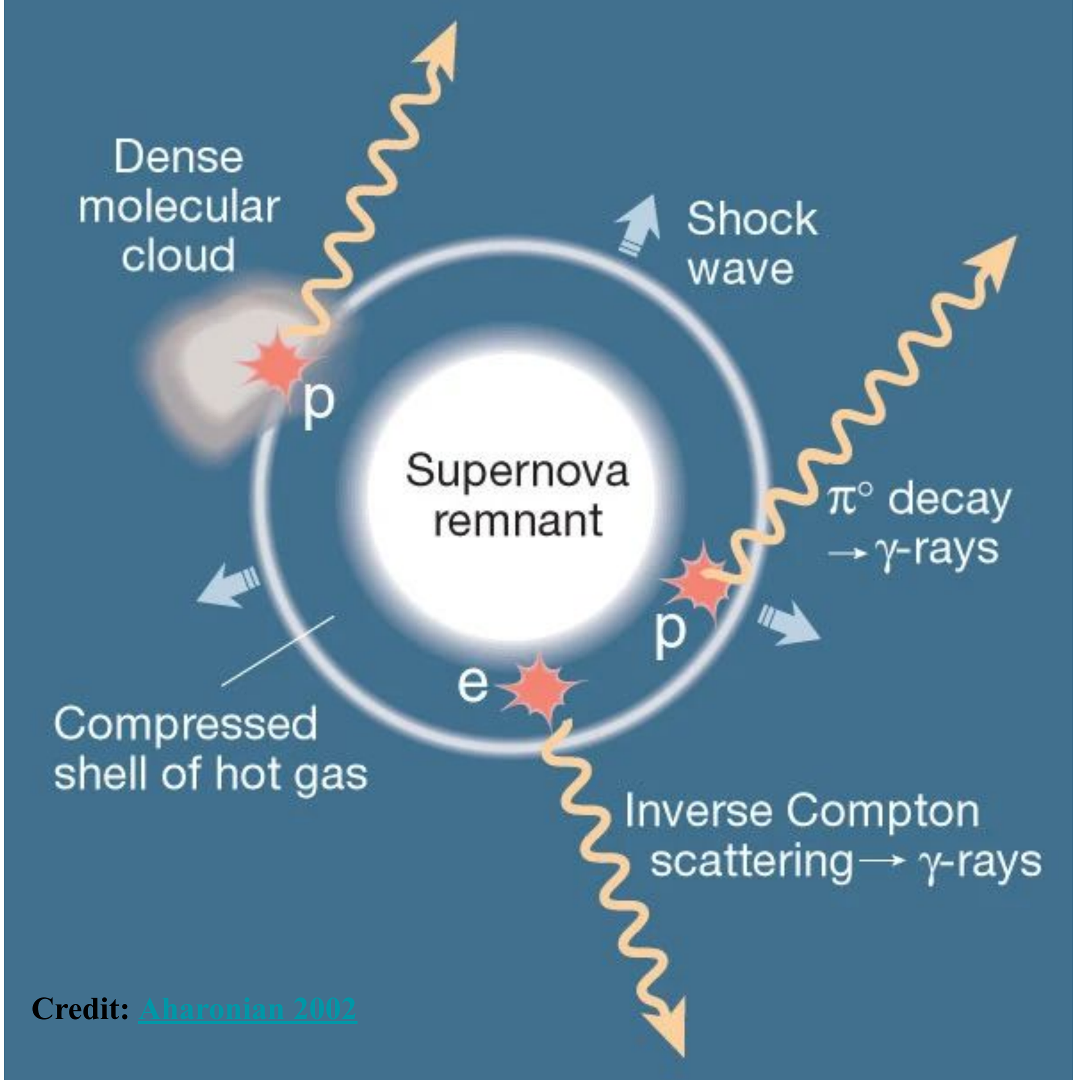
Extra slides



Feedback Mechanisms

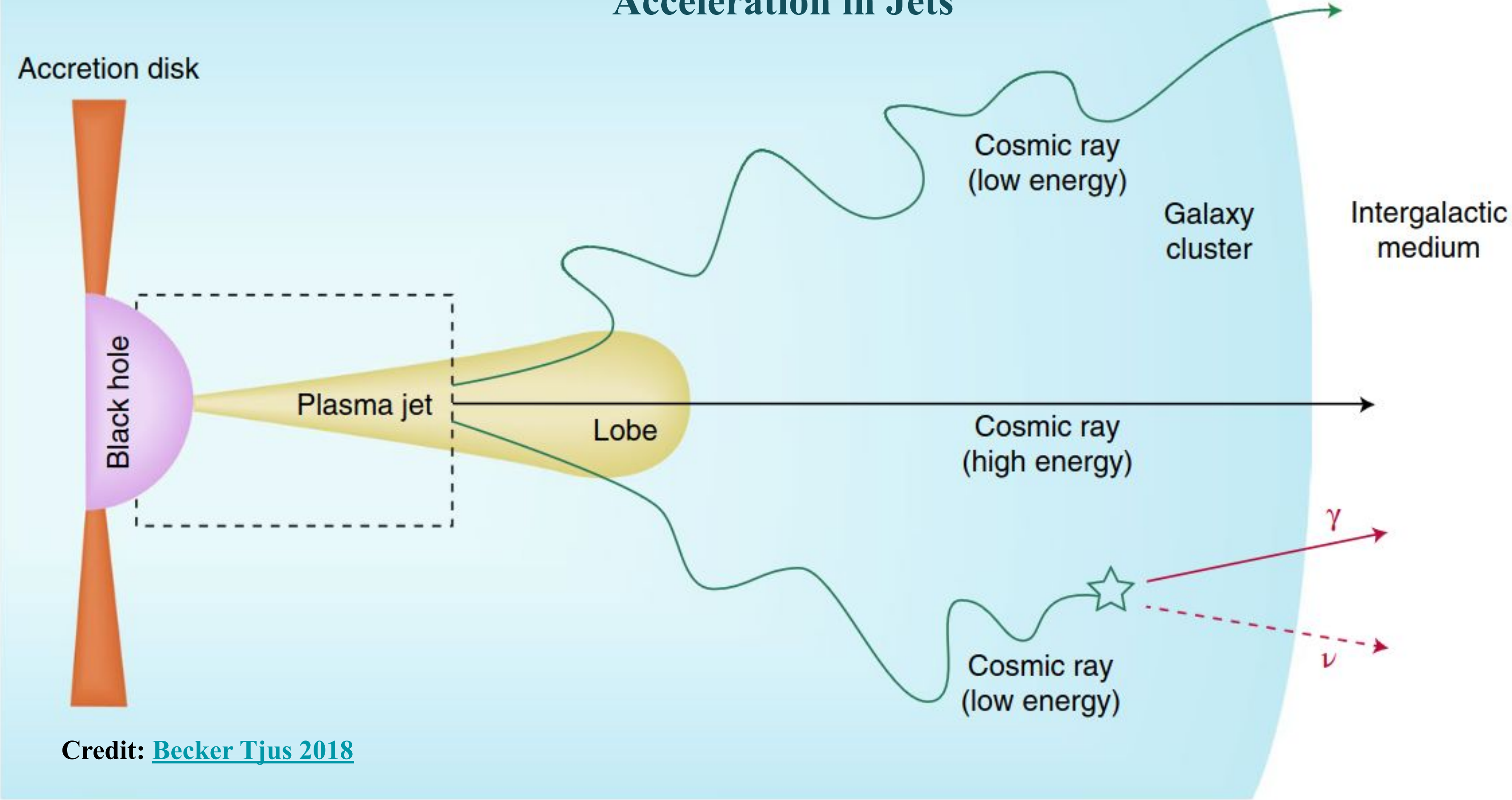
- ★ *Photoionization*
- ★ *Shocks*
- ★ *X-ray Heating*
- ★ *Cosmic Rays*

Acceleration in SNe



Credit: Aharonian 2002

Acceleration in Jets

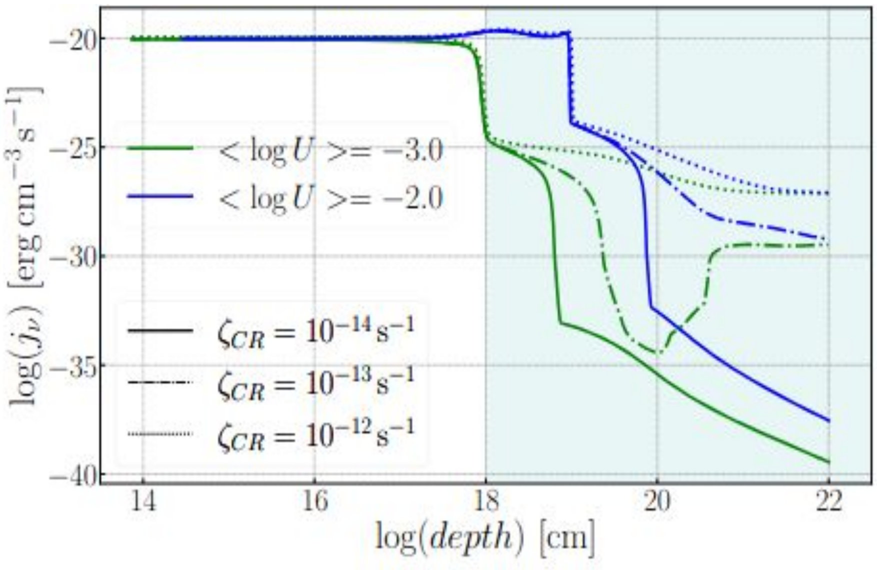


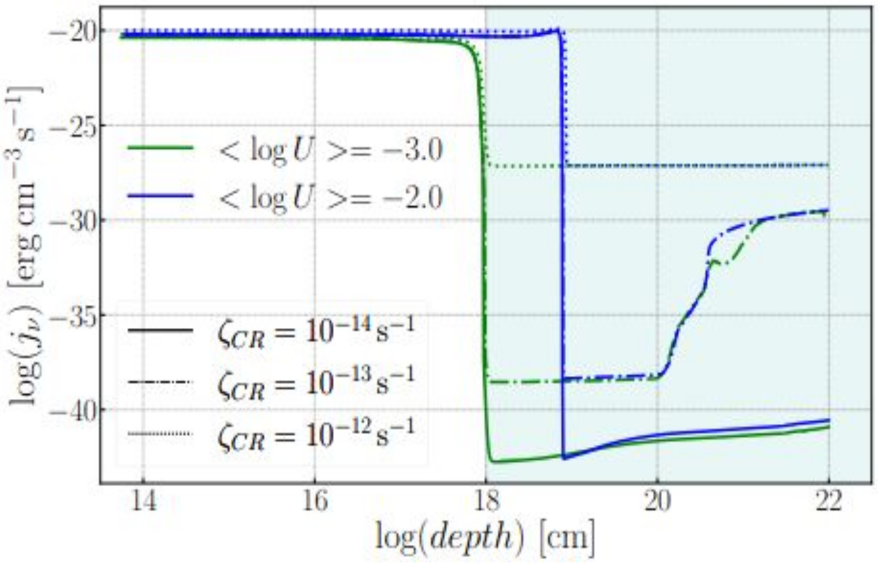
Credit: Becker Tjus 2018

AGN Models

SF Models

[OIII]



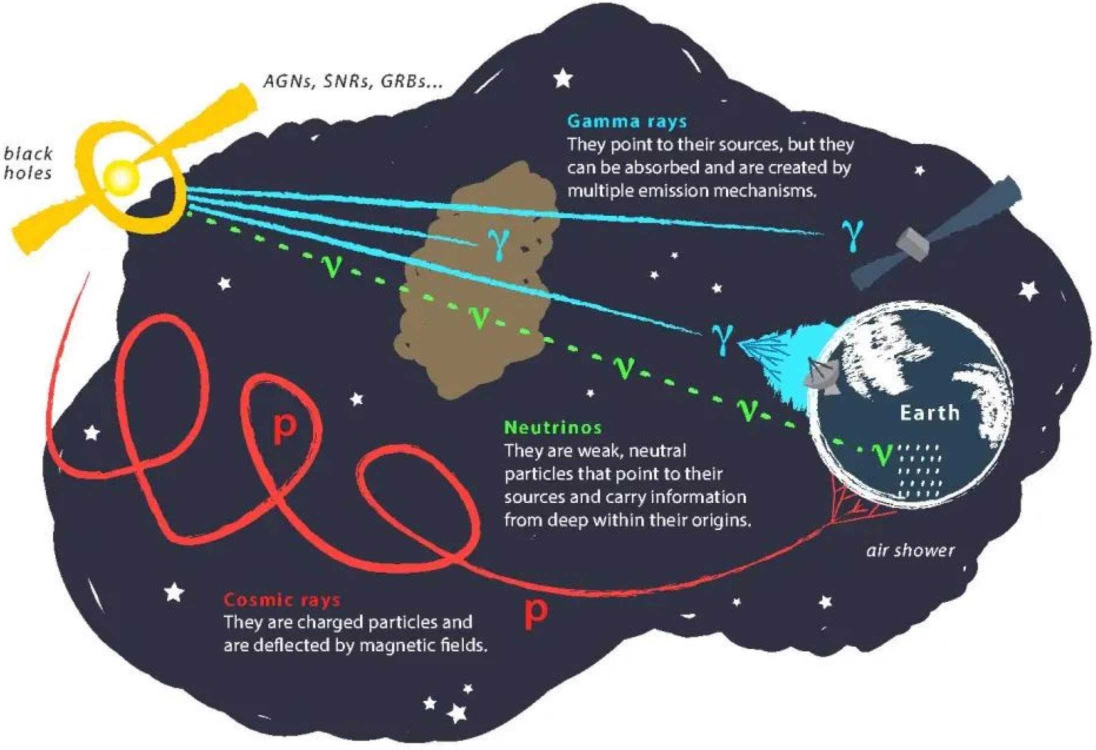


AGN Photoionization

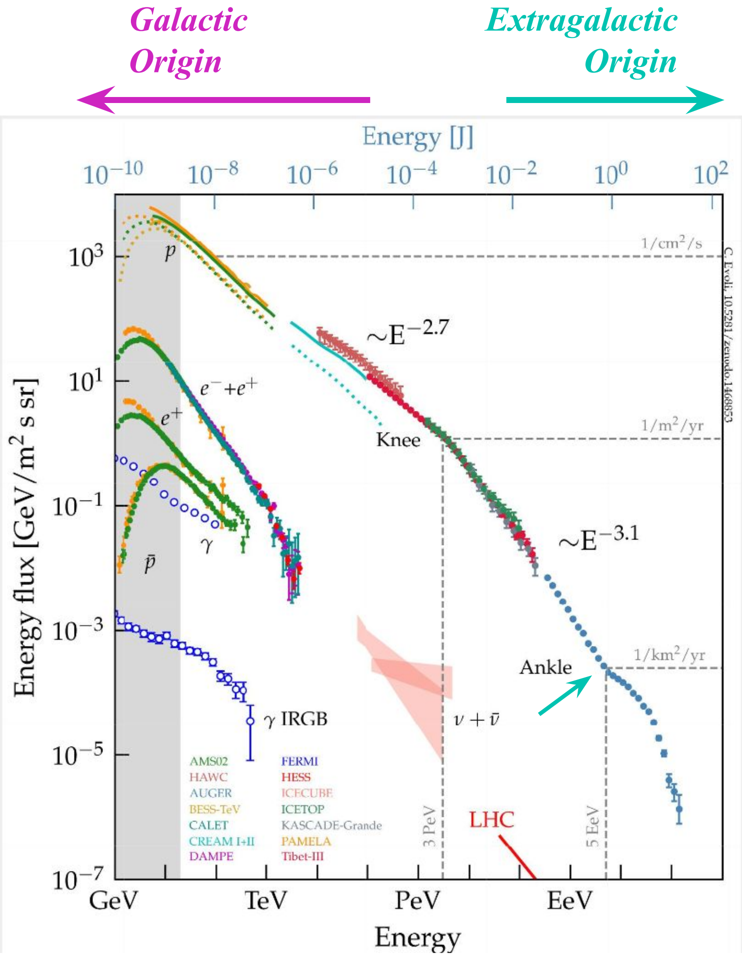
CRs

Photoionization

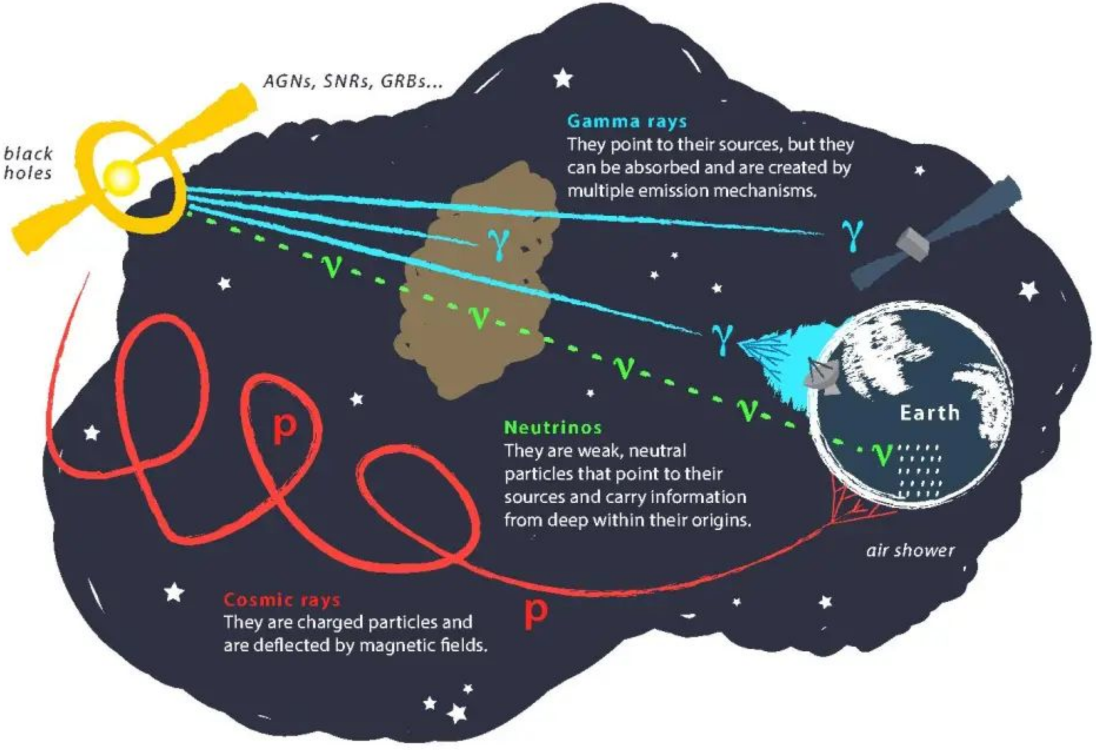
CRs



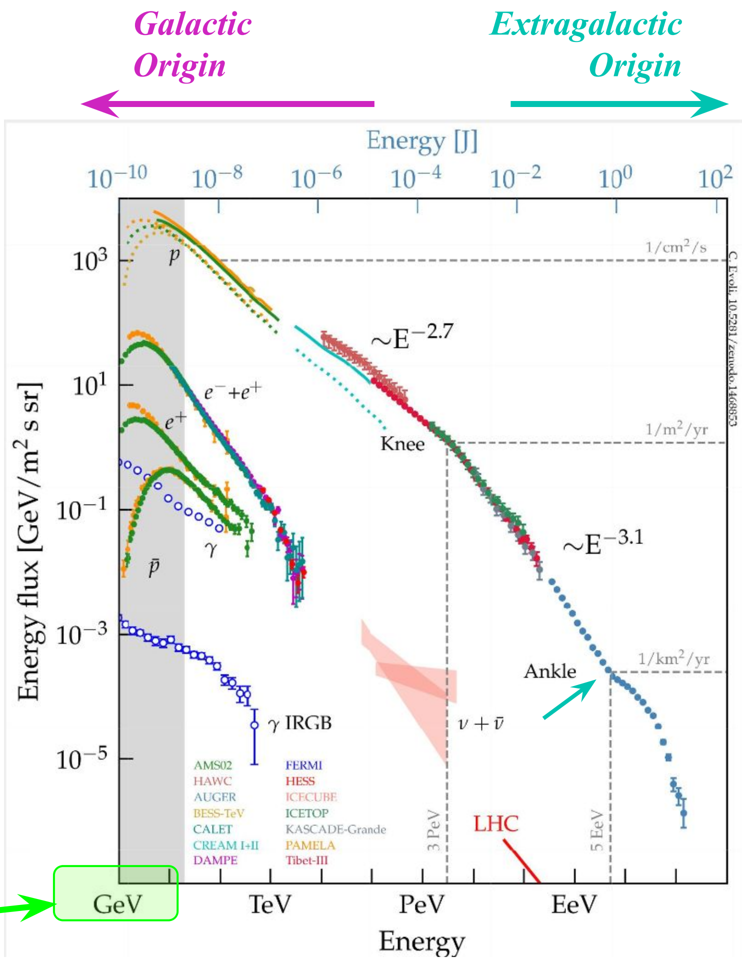
Credit: IceCube Neutrino Observatory



Credit: E.Carmelo



Credit: IceCube Neutrino Observatory

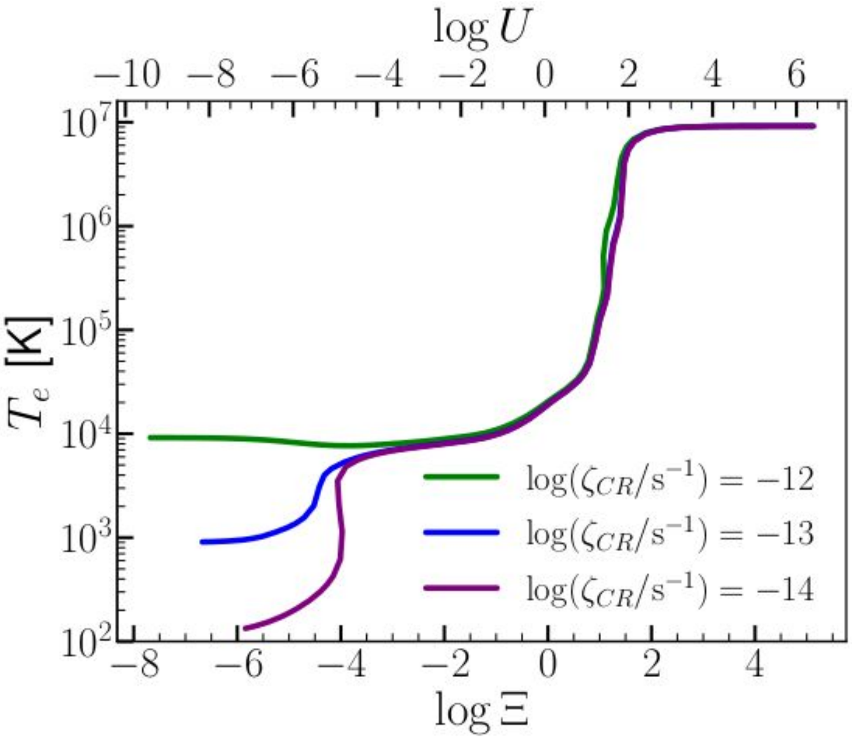


Credit: E.Carmelo

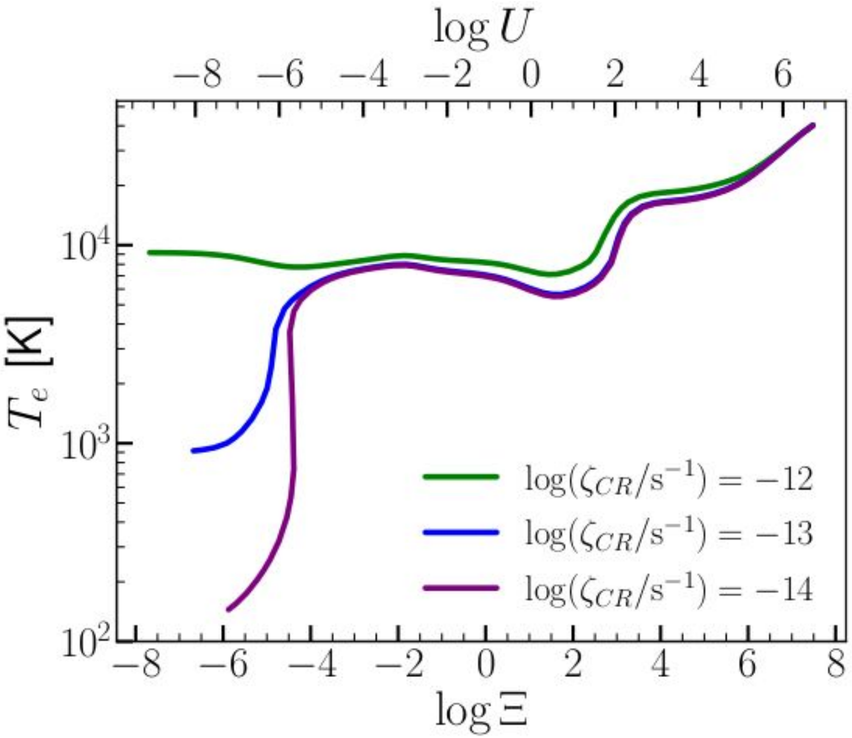
Thermal Stability

- ***How do CRs affect Te along photoinization?***

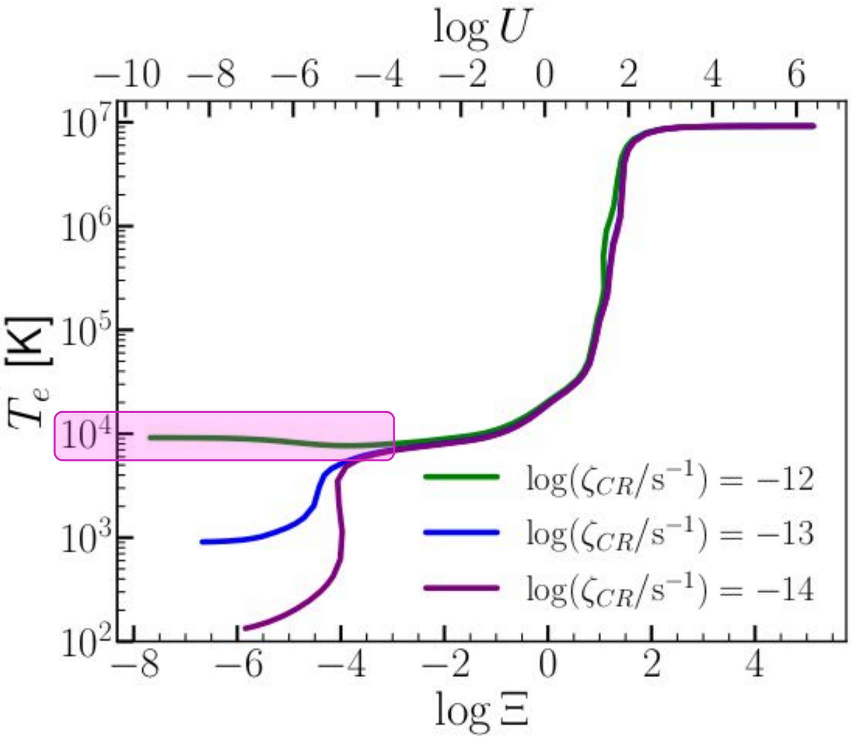
AGN Models



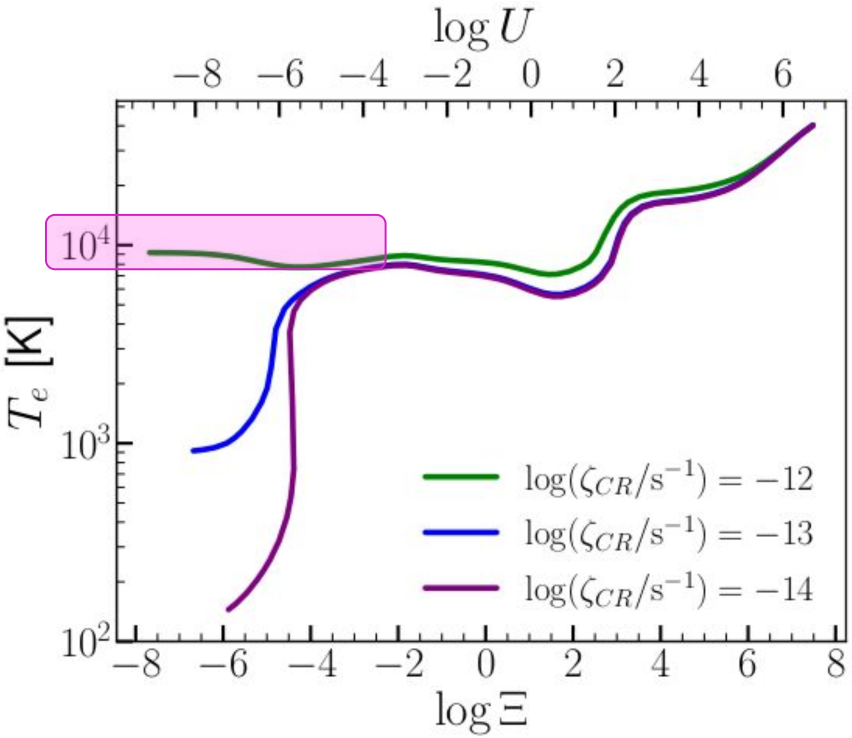
SF Models



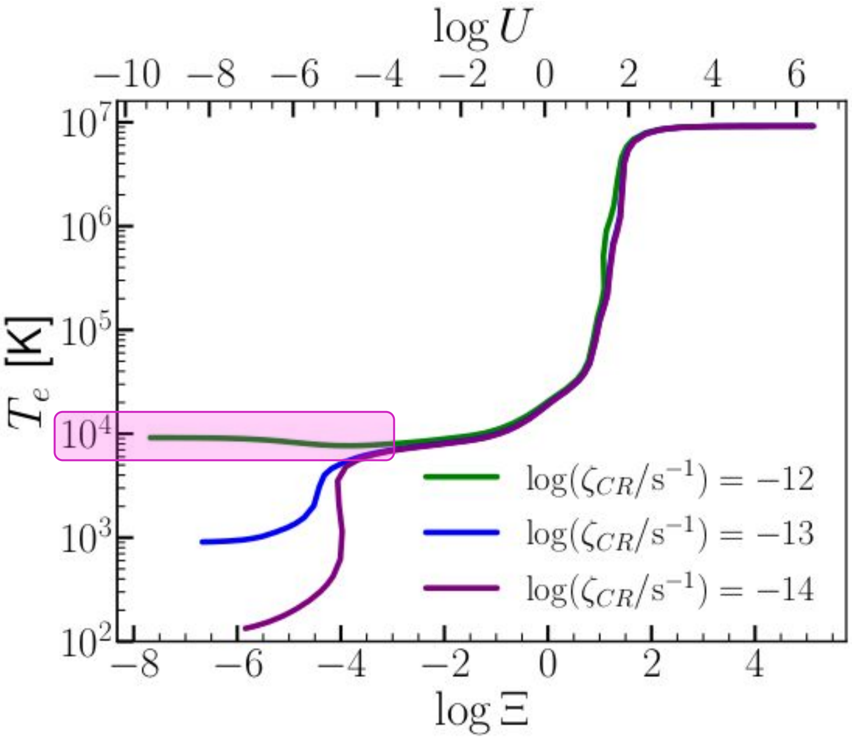
AGN Models



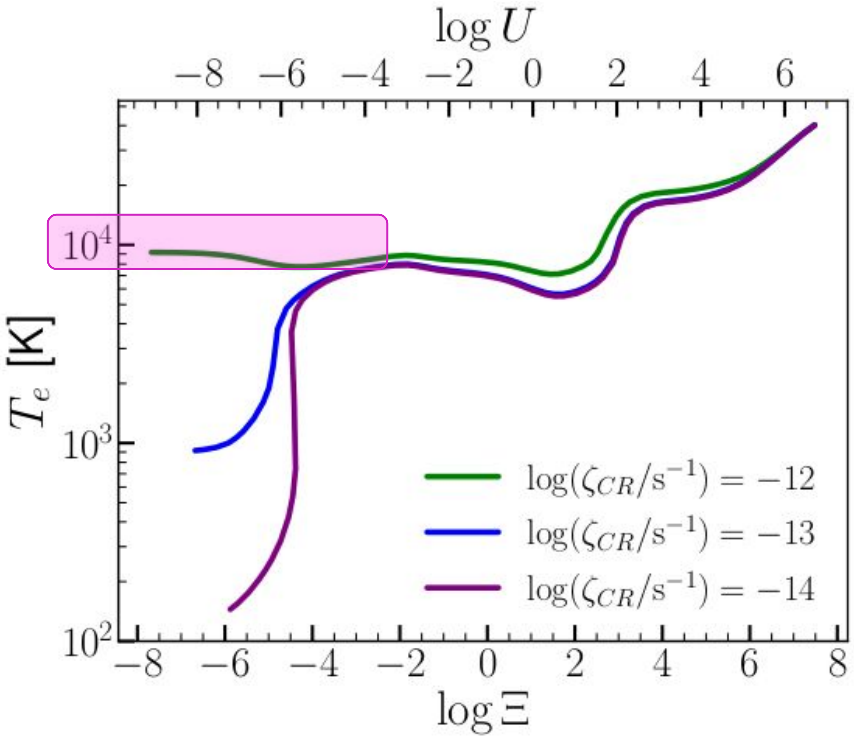
SF Models

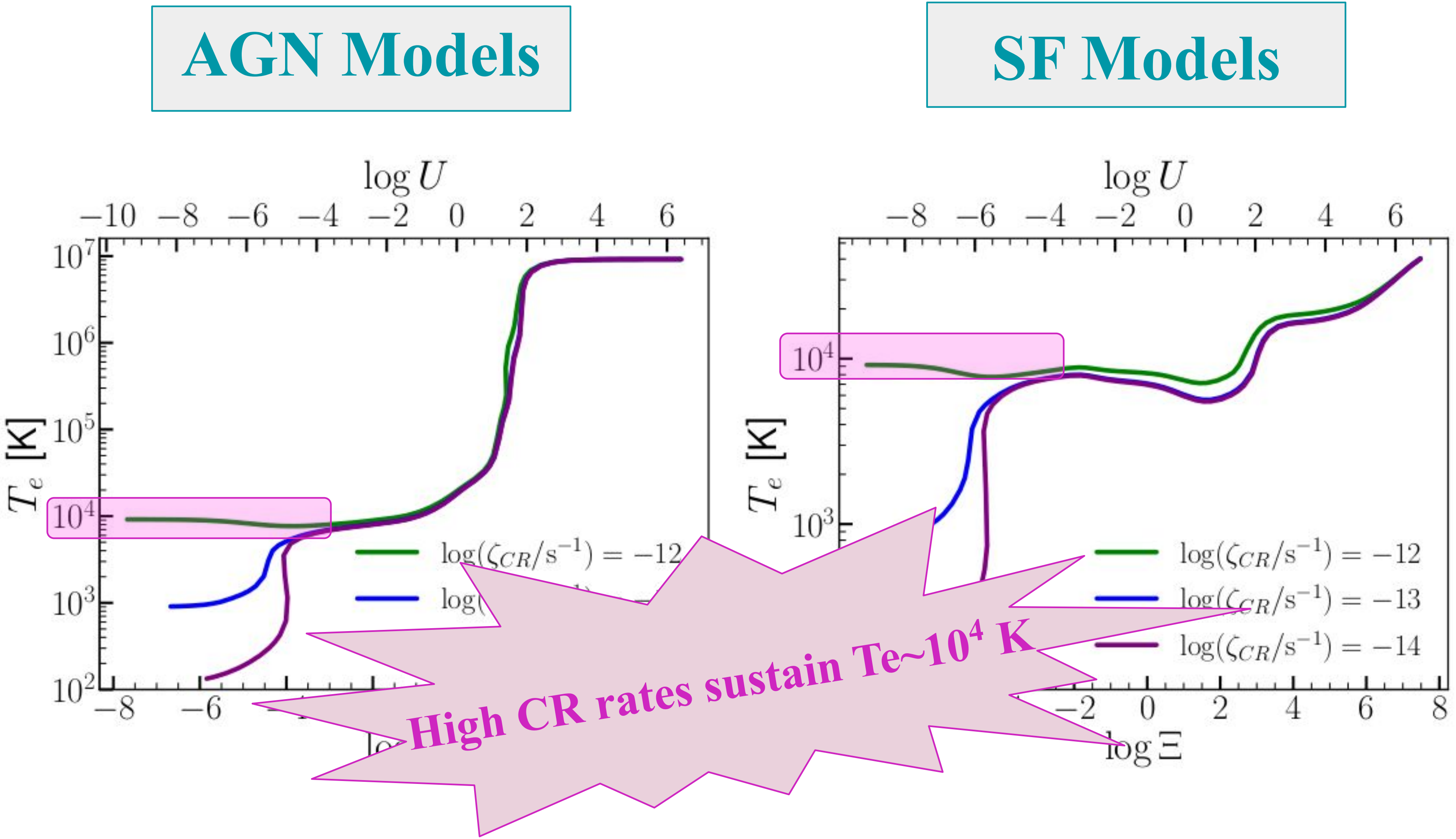


AGN Models

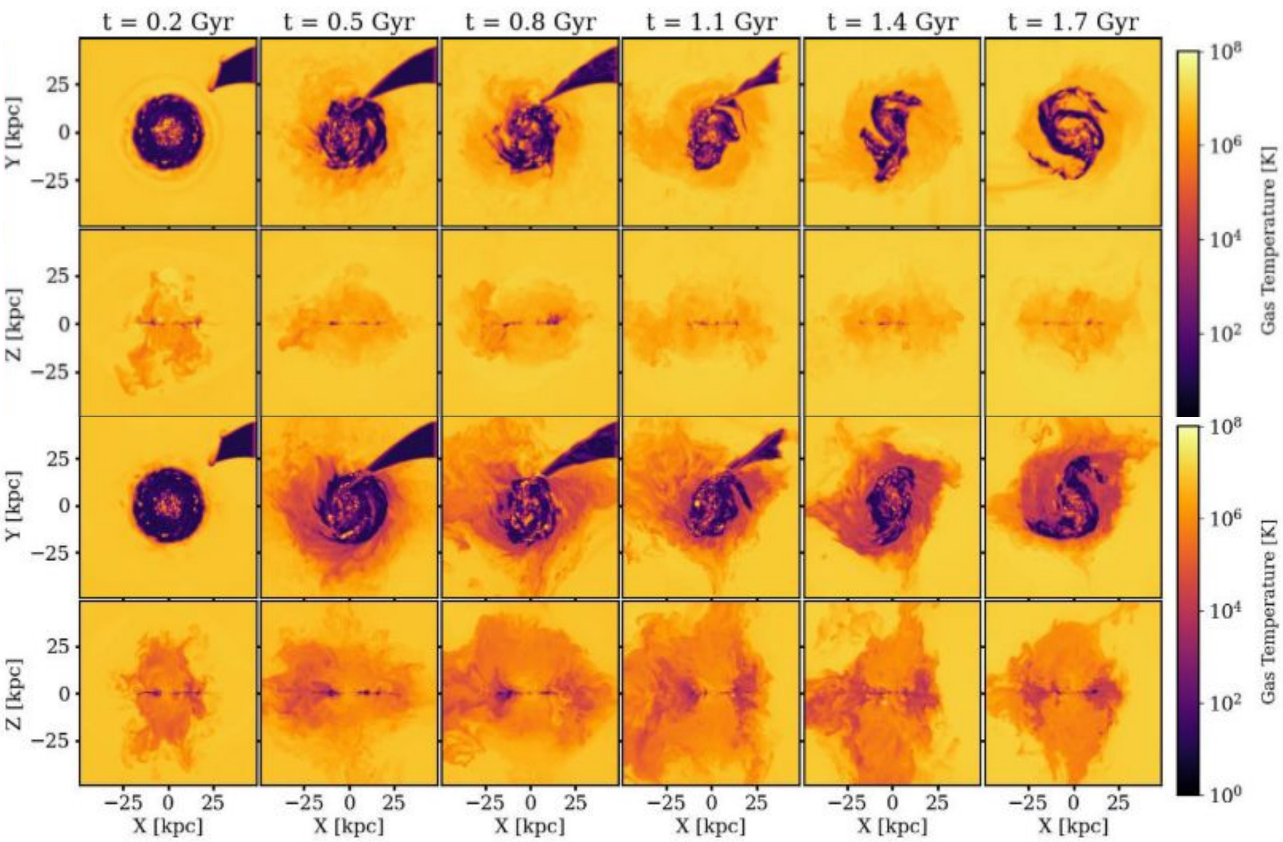


SF Models




AGN Models
SF Models
log U
−10 −8 −6 −4 −2 0 2 4 6
−8 −6 −4 −2 0 2 4 6
T_e [K]
10^7
10^6
10^5
10^4
10^3
10^2
$\log(\zeta_{CR}/s^{-1}) = -12$
$\log(\zeta_{CR}/s^{-1}) = -13$
$\log(\zeta_{CR}/s^{-1}) = -14$
−8 −6
−2 0 2 4 6 8
log Ξ
High CR rates sustain Te~10^4 K

MHD + CRs Simulations

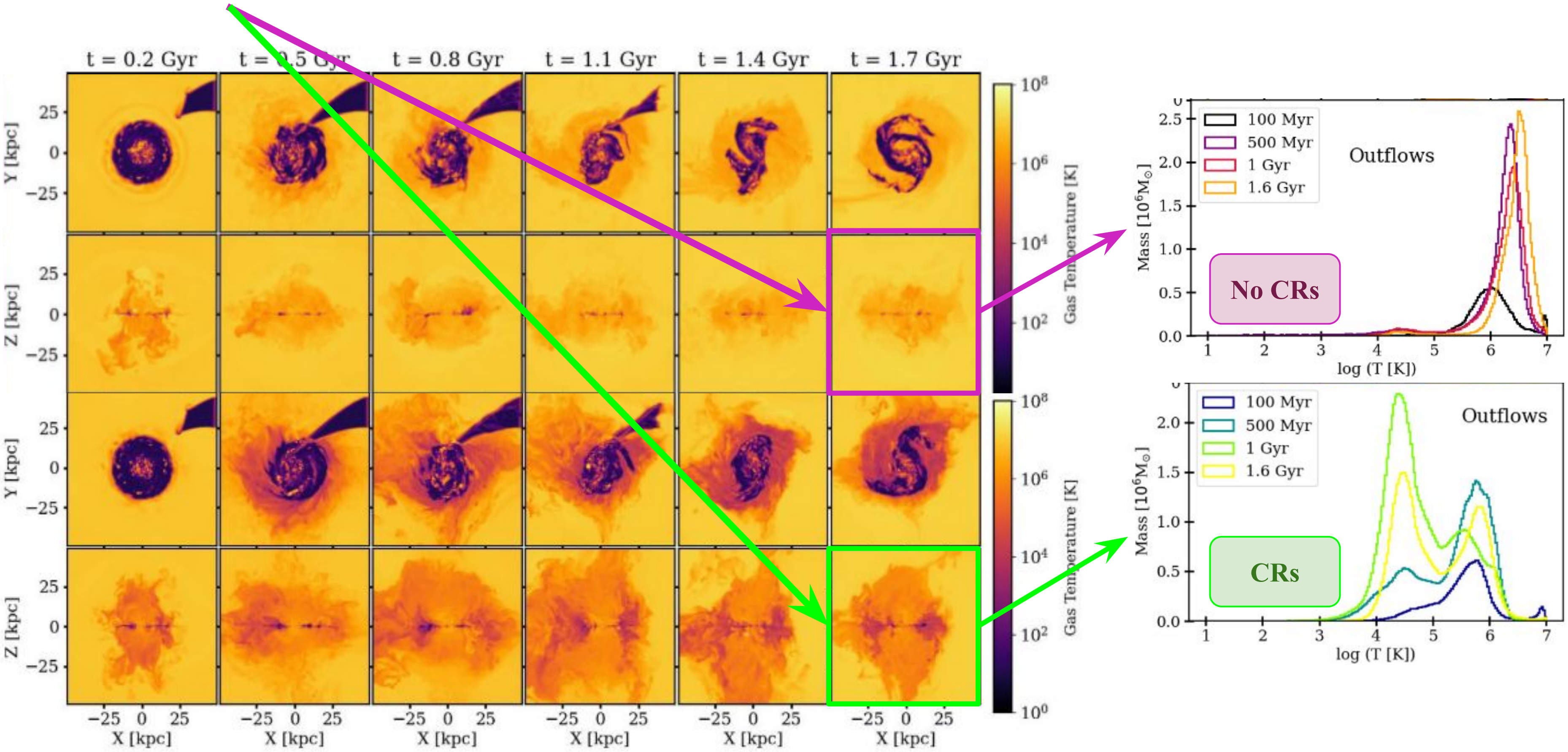


No CRs

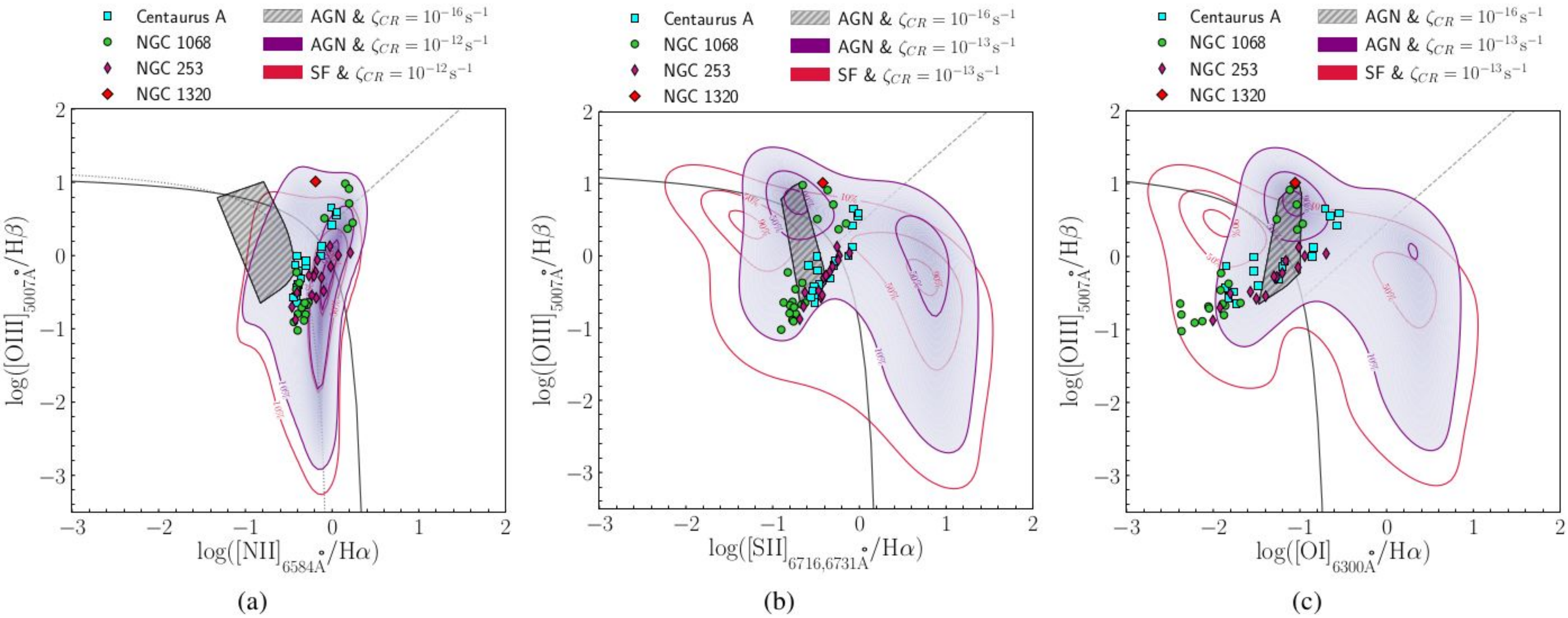
CRs

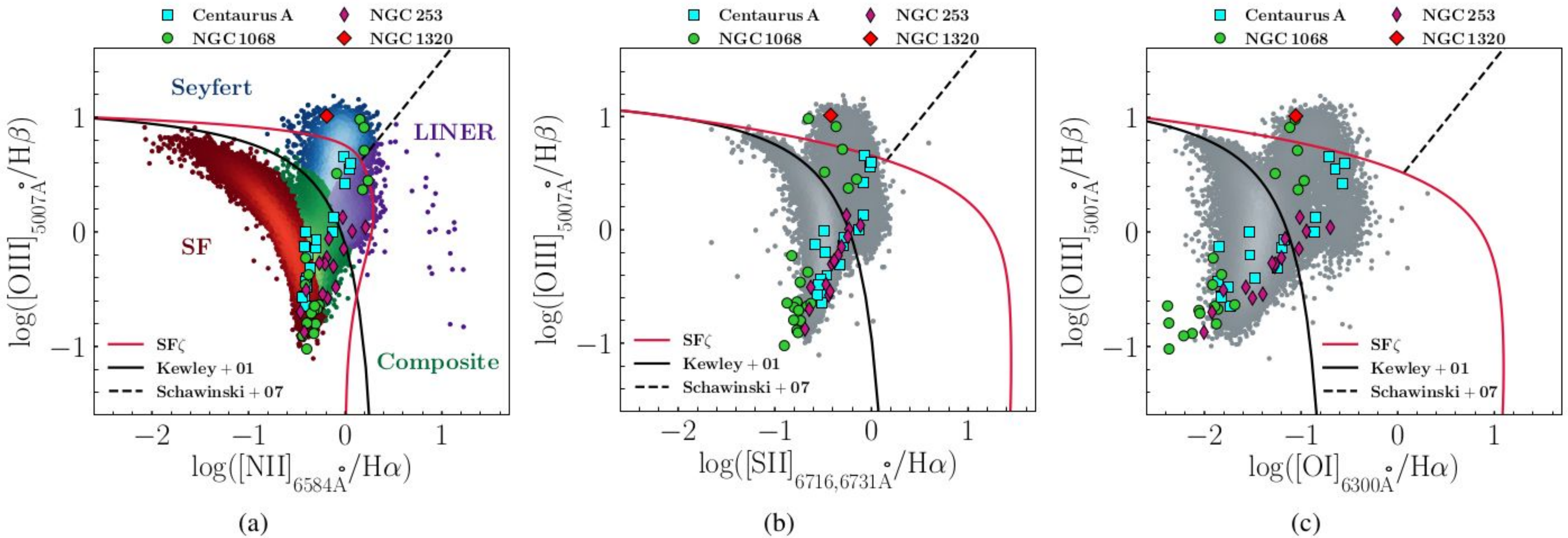
Peschken+2023

MHD + CRs Simulations



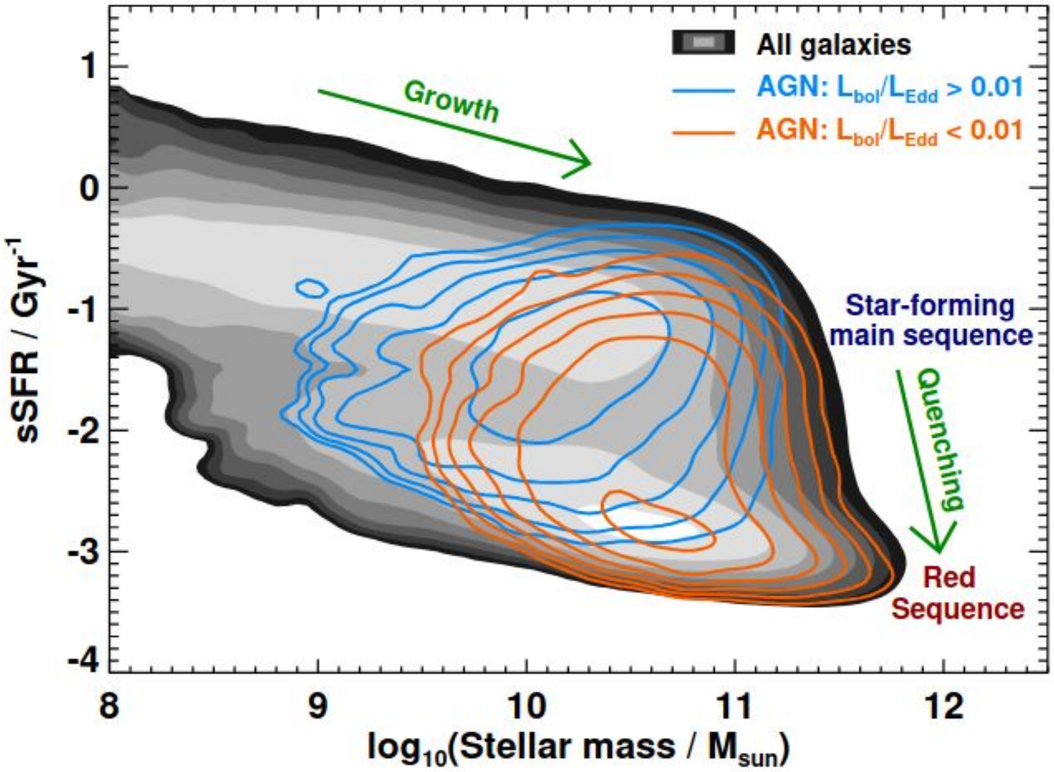
[Peschken+2023]


Centaurus A
NGC 1068
NGC 253
NGC 1320
AGN & $\zeta_{CR} = 10^{-16}\mathrm{s}^{-1}$
AGN & $\zeta_{CR} = 10^{-12}\mathrm{s}^{-1}$
SF & $\zeta_{CR} = 10^{-12}\mathrm{s}^{-1}$
$\log([\mathrm{OIII}]_{5007\mathring{A}}/\mathrm{H}\beta)$
$\log([\mathrm{NII}]_{6584\mathring{A}}/\mathrm{H}\alpha)$
(a)
AGN & $\zeta_{CR} = 10^{-13}\mathrm{s}^{-1}$
SF & $\zeta_{CR} = 10^{-13}\mathrm{s}^{-1}$
$\log([\mathrm{SII}]_{6716,6731\mathring{A}}/\mathrm{H}\alpha)$
(b)
$\log([\mathrm{OI}]_{6300\mathring{A}}/\mathrm{H}\alpha)$
(c)


Centaurus A
NGC 253
NGC 1068
NGC 1320
Seyfert
LINER
SF
Composite
SFζ
Kewley + 01
Schawinski + 07
$\log([OIII]_{5007Å}/H\beta)$
$\log([NII]_{6584Å}/H\alpha)$
$\log([SII]_{6716,6731Å}/H\alpha)$
$\log([OI]_{6300Å}/H\alpha)$
(a)
(b)
(c)

Galaxy Evolution

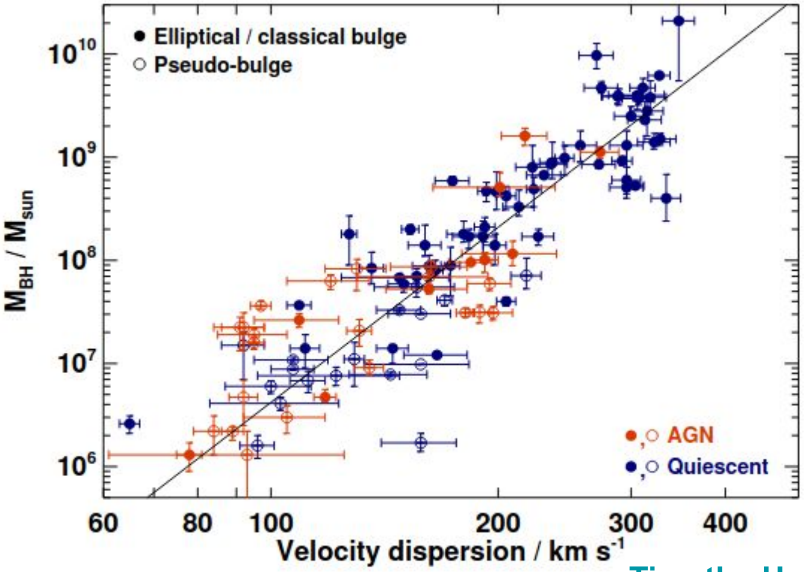
SDSS main galaxy sample

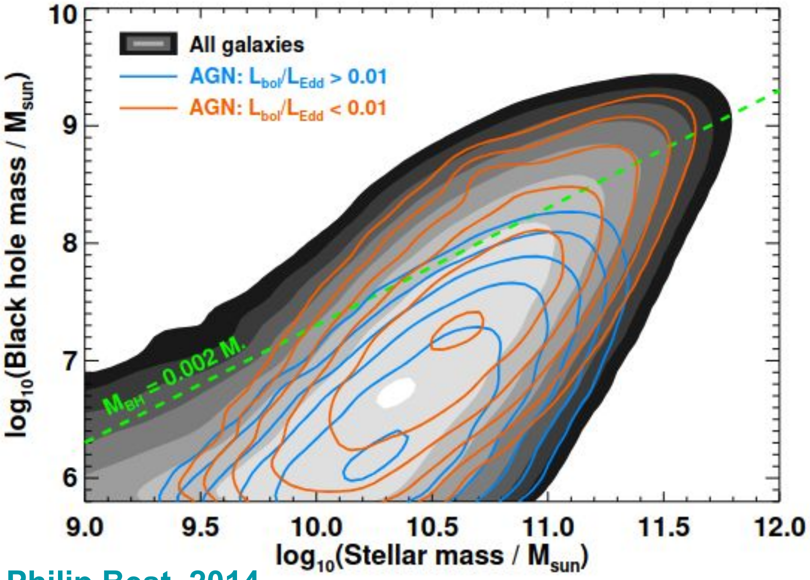


Timothy Heckman & Philip Best, 2014

- Galaxies evolve along the star-forming main sequence, growing in mass via:
  - Accretion of cold gas from the cosmic web.
  - Secondary accretion through mergers with other galaxies.
- Quenching Point:
  - Critical mass where supply of cold gas is cut off.
  - Star formation is quenched, transitioning the galaxy to the red population.
- Post-quenching, galaxies may gain mass through mergers.

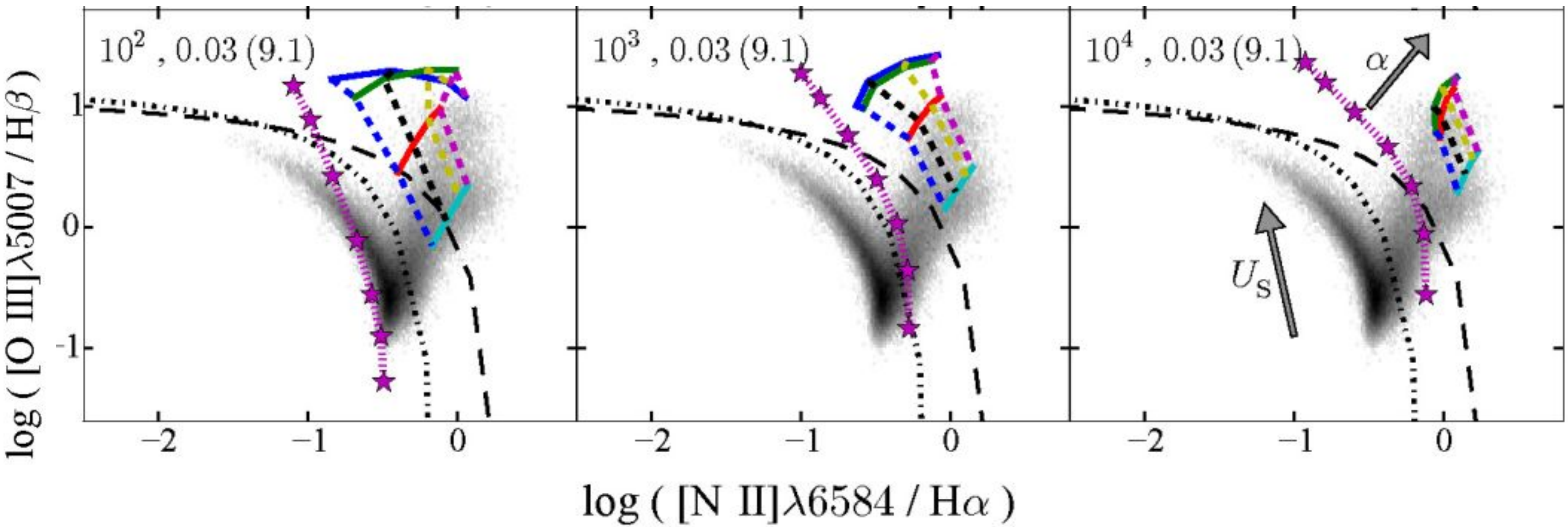
Galaxy Evolution





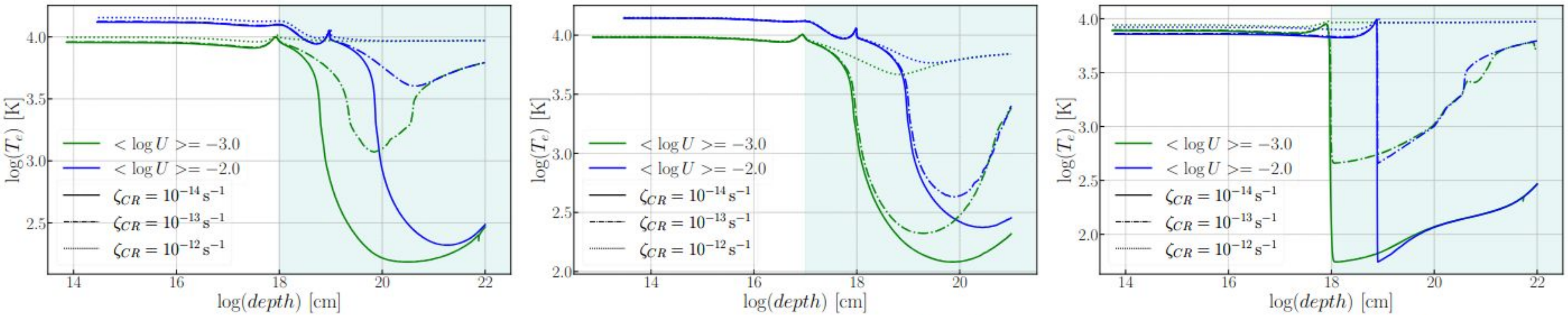
Timothy Heckman & Philip Best, 2014

- MBH−σ relationship of local galaxies → there is a correlation.
- The growth of BH appears to be more significant in hosts with high stellar mass.
- Complex interplay between BH and their host galaxies, → that the mass of the galaxy impacts the growth mechanisms and activity levels of central BH.
- Modes of AGN (radiative/jet) are crucial → feedback mechanisms → galaxy evolution. AGN feedback → regulates star formation and impact on gas.



10^2 , 0.03 (9.1)
10^3 , 0.03 (9.1)
10^4 , 0.03 (9.1)
α
U_S
log ([O III]λ5007 / Hβ)
log ([N II]λ6584 / Hα)
1
0
-1
−2
−1
0

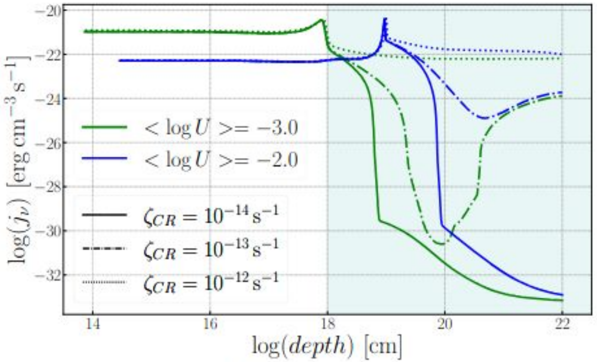
[Feltre+2016]



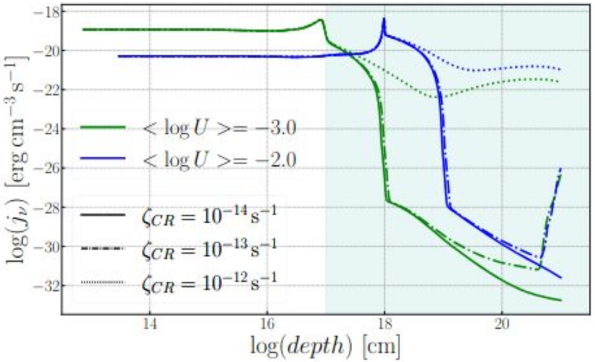
(a) Temperature, AGN, n_H = $100\,cm^{-3}$.

(b) Temperature, AGN, n_H = $10^3\,cm^{-3}$.

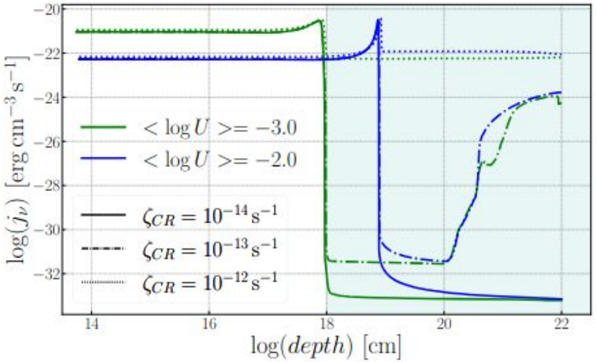
(c) Temperature, SF, n_H = $100\,cm^{-3}$.



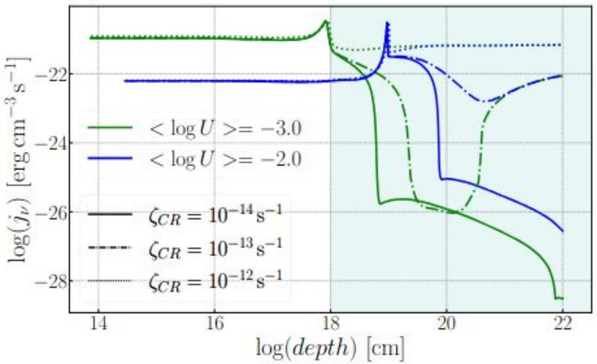
(a) [N II]λ6584Å, AGN, $n_{\mathrm{H}} = 100\,\mathrm{cm}^{-3}$.



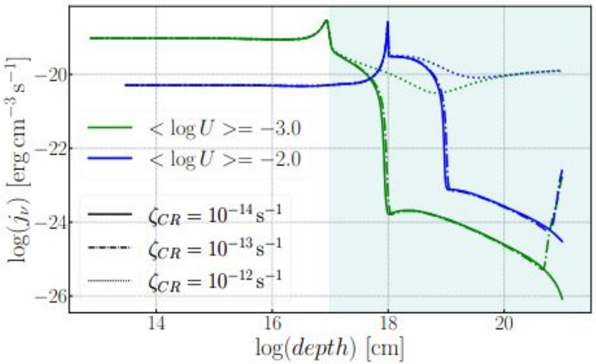
(b) [N II]λ6584Å, AGN, $n_{\mathrm{H}} = 10^3\,\mathrm{cm}^{-3}$.



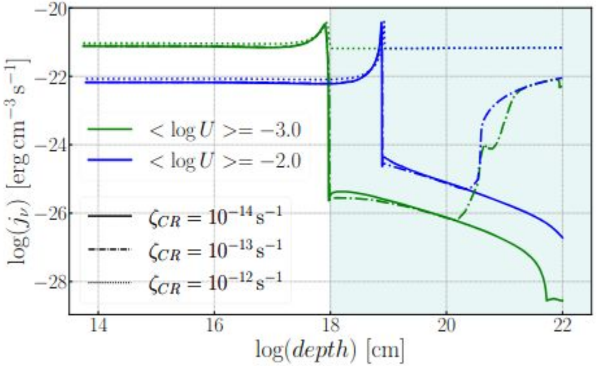
(c) [N II]λ6584Å, SF, $n_{\mathrm{H}} = 100\,\mathrm{cm}^{-3}$.



(d) [S II]$\lambda\lambda$6716,6731Å, AGN, $n_{\mathrm{H}} = 100\,\mathrm{cm}^{-3}$.



(e) [S II]$\lambda\lambda$6716,6731Å, AGN, $n_{\mathrm{H}} = 10^3\,\mathrm{cm}^{-3}$.

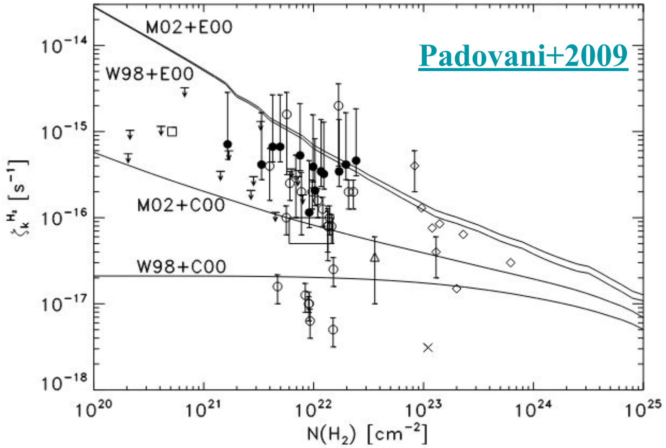


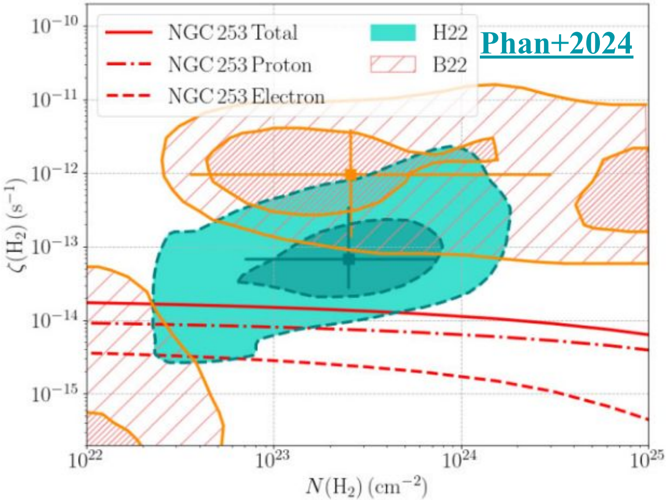
(f) [S II]$\lambda\lambda$6716,6731Å, SF, $n_{\mathrm{H}} = 100\,\mathrm{cm}^{-3}$.

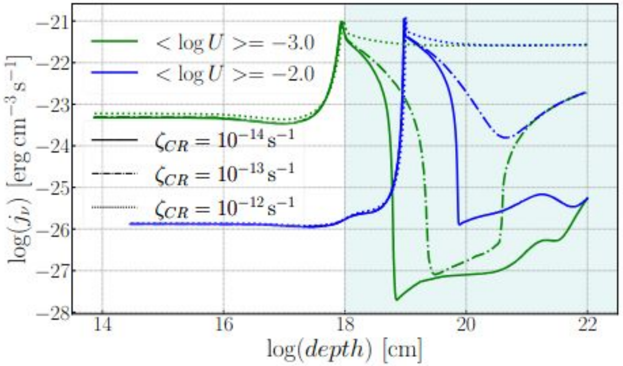
CRs on Different Gas Phases - CR rate Estimations

CRs:

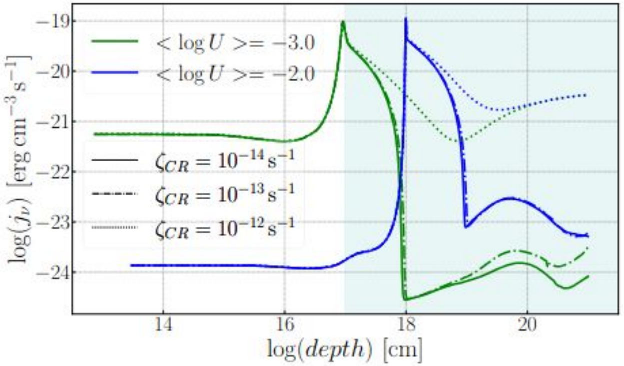
- ☆ **Penetrate molecular clouds, impacting their chemistry and physics (Padovani+2009).**
- ☆ **Heat ionized gas and trigger secondary ionizations (Spitzer & Tomasko 1968).**
- ☆ **Heat the warm ionized medium (WIM) & maintain it against radiative cooling (Walker 2016).**
- ☆ **Can explain filament emissions in galaxy clusters. Also, CRs with ionization rates ≳ 10^{-13} s^{-1}, mainly contribute to heating rather than H2 dissociation (Ferland+2009).**
- ☆ **Influence nebular emission lines, particularly in galaxies with strong star formation or near AGN jets (Ferland & Mushotzky 1984).**



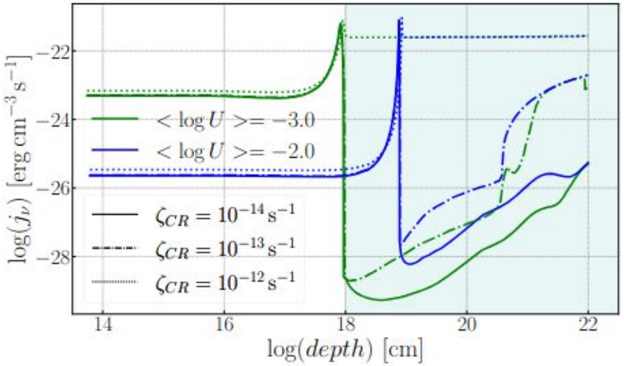




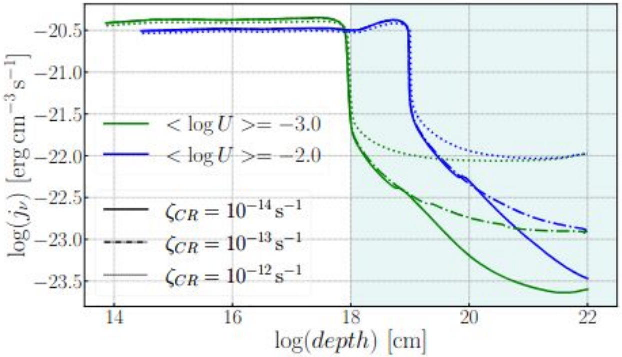
(g) [O I]λ6300Å, AGN, n_H = 100 cm^{-3}.



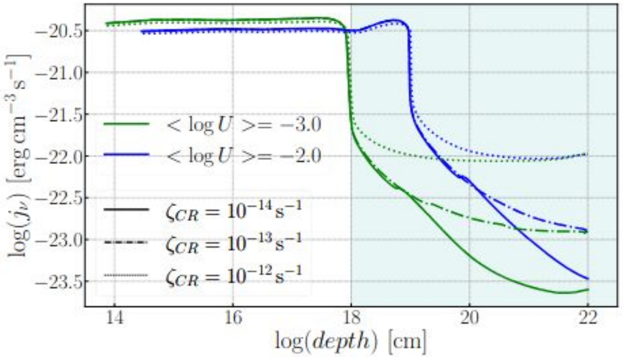
(h) [O I]λ6300Å, AGN, n_H = 10^3 cm^{-3}.



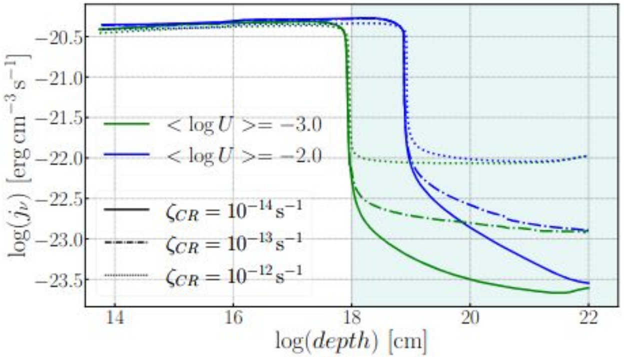
(i) [O I]λ6300Å, SF, n_H = 100 cm^{-3}.



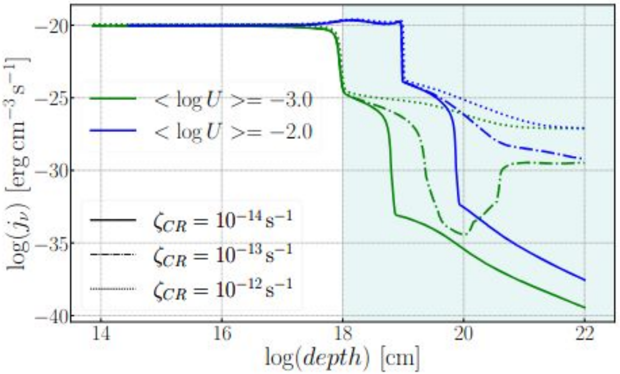
(j) Hα, AGN, n_H = 100 cm^{-3}.



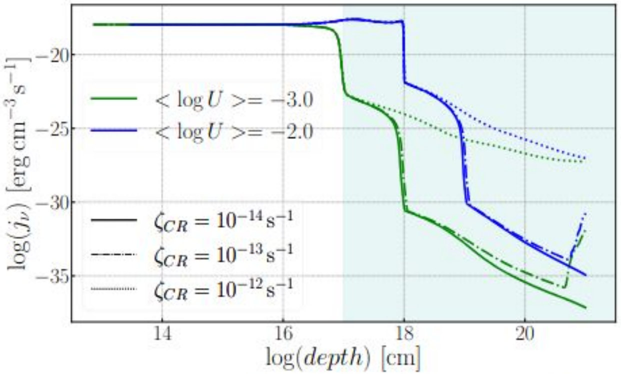
(k) Hα, AGN, n_H = 10^3 cm^{-3}.



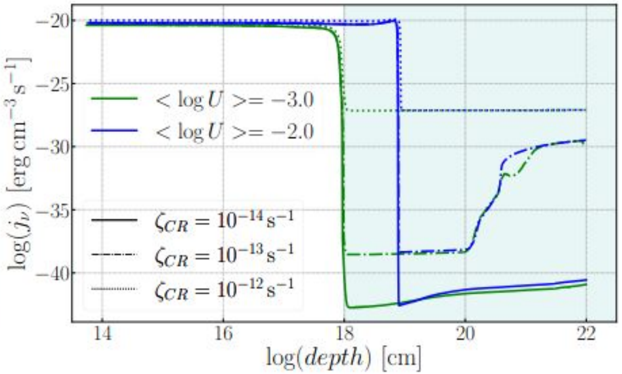
(l) Hα, SF, n_H = 100 cm^{-3}.



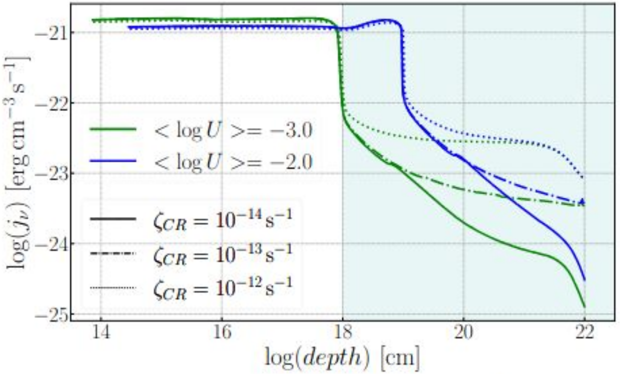
(a) [O III]λ5007Å, AGN, $n_H = 100\,\mathrm{cm}^{-3}$.



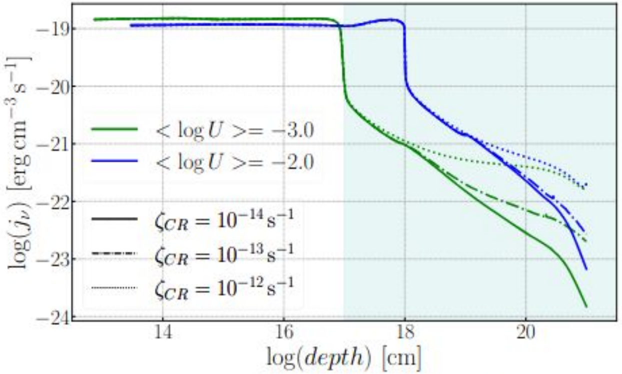
(b) [O III]λ5007Å, AGN, $n_H = 10^3\,\mathrm{cm}^{-3}$.



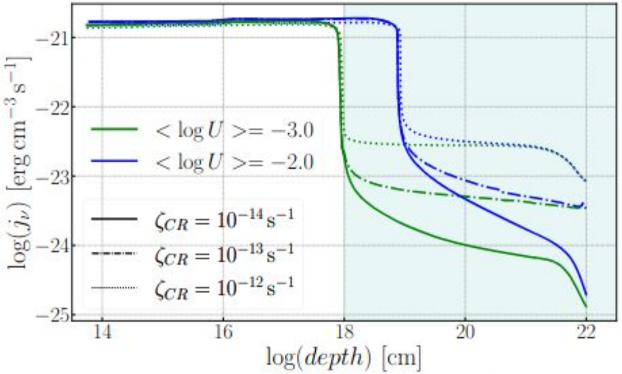
(c) [O III]λ5007Å, SF, $n_H = 100\,\mathrm{cm}^{-3}$.



(d) Hβ, AGN, $n_H = 100\,\mathrm{cm}^{-3}$.



(e) Hβ, AGN, $n_H = 10^3\,\mathrm{cm}^{-3}$.



(f) Hβ, SF, $n_H = 100\,\mathrm{cm}^{-3}$.

CR Acceleration

Synchrotron Fit

$$E_{\min} = 0.1\,\mathrm{MeV}$$

secondary electrons

$$\zeta_{CR}^{H} \simeq 1.3\pi \int_{E_{\min}}^{E_{\max}} dE\, j_e(E)\, \sigma_{H_2-e}^{ion}(E)\, [1 + \phi_{e,H_2}(E)],$$

Gabici 2022

$$N_e dE \propto E^{-p}\, dE,$$

Radio data

$$\sigma_{H_2-e}^{ion}(E).$$

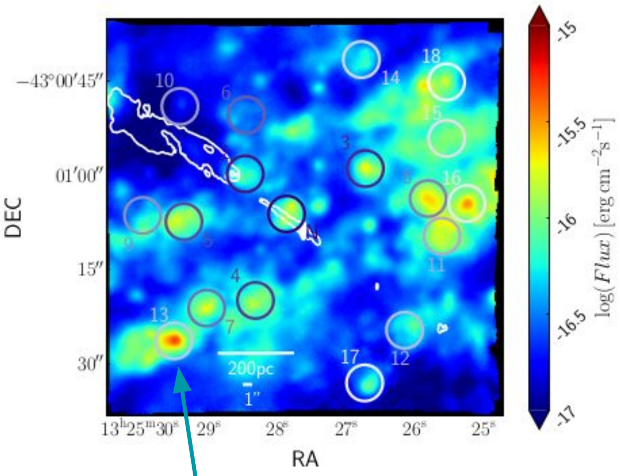
Padovani+2018

$$j_e(E) = cN_e/(4\pi),$$

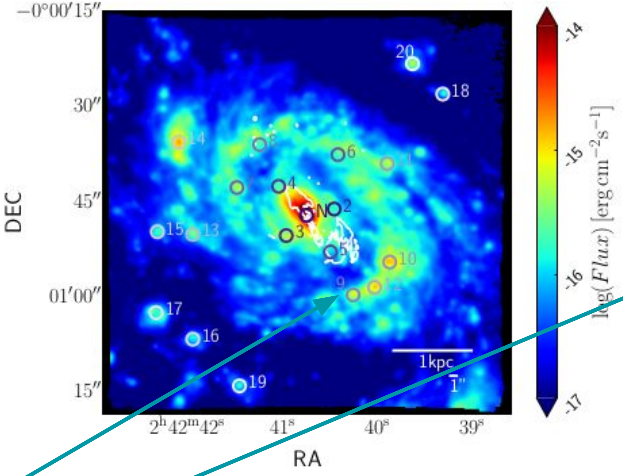
$$1.5\,\zeta_{CR}^{H_2} \simeq 2.3\,\zeta_{CR}^{H}$$

Glassgold & Langer 1974

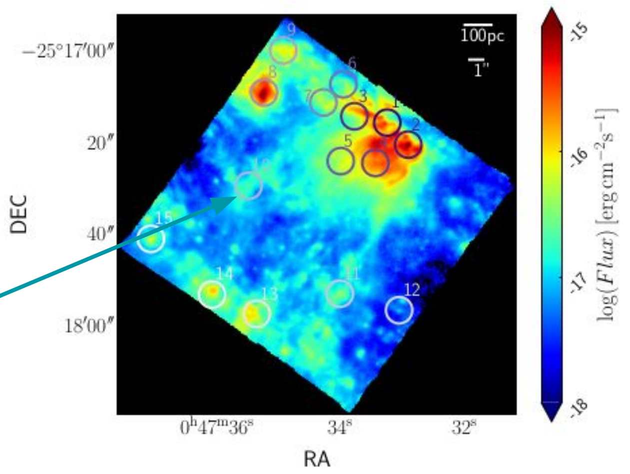
Region Selection - Hα Linemaps - MUSE Data



Centaurus A



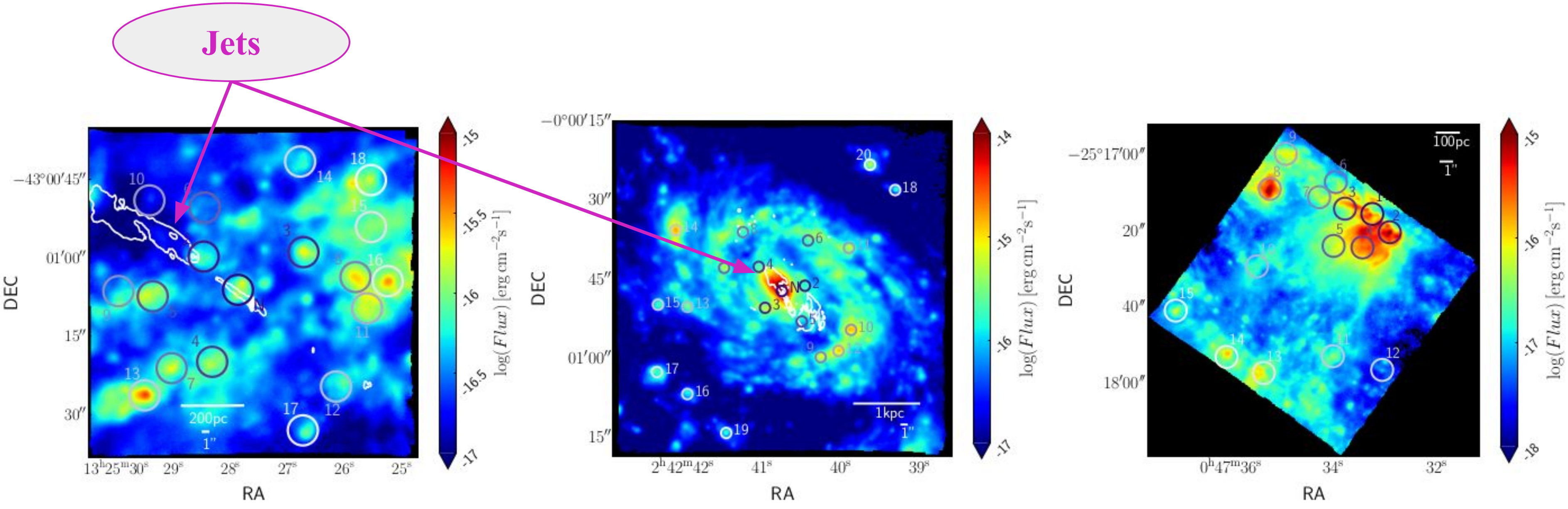
NGC 1068



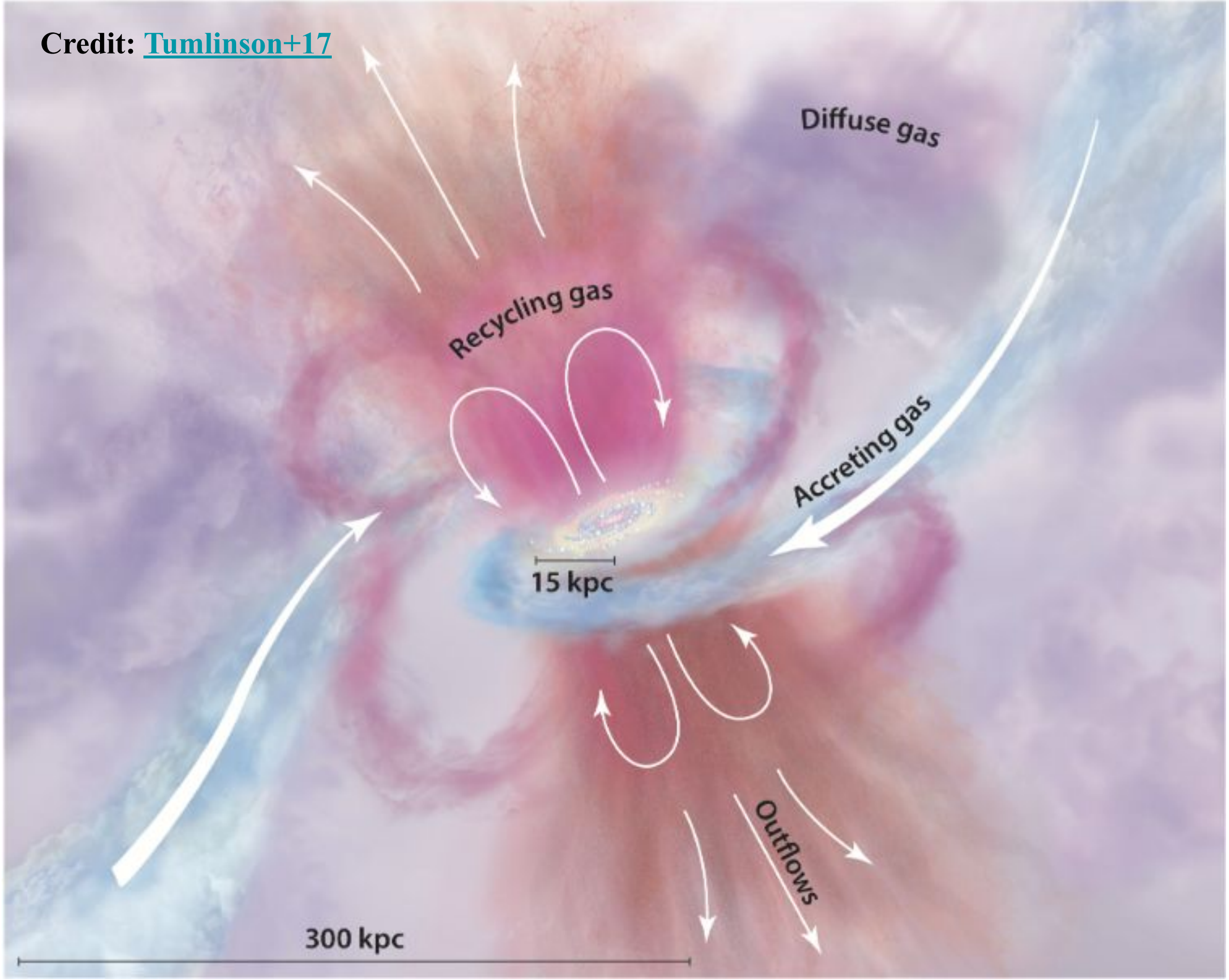
NGC 253

Apertures

Region Selection - Hα Linemaps - MUSE Data



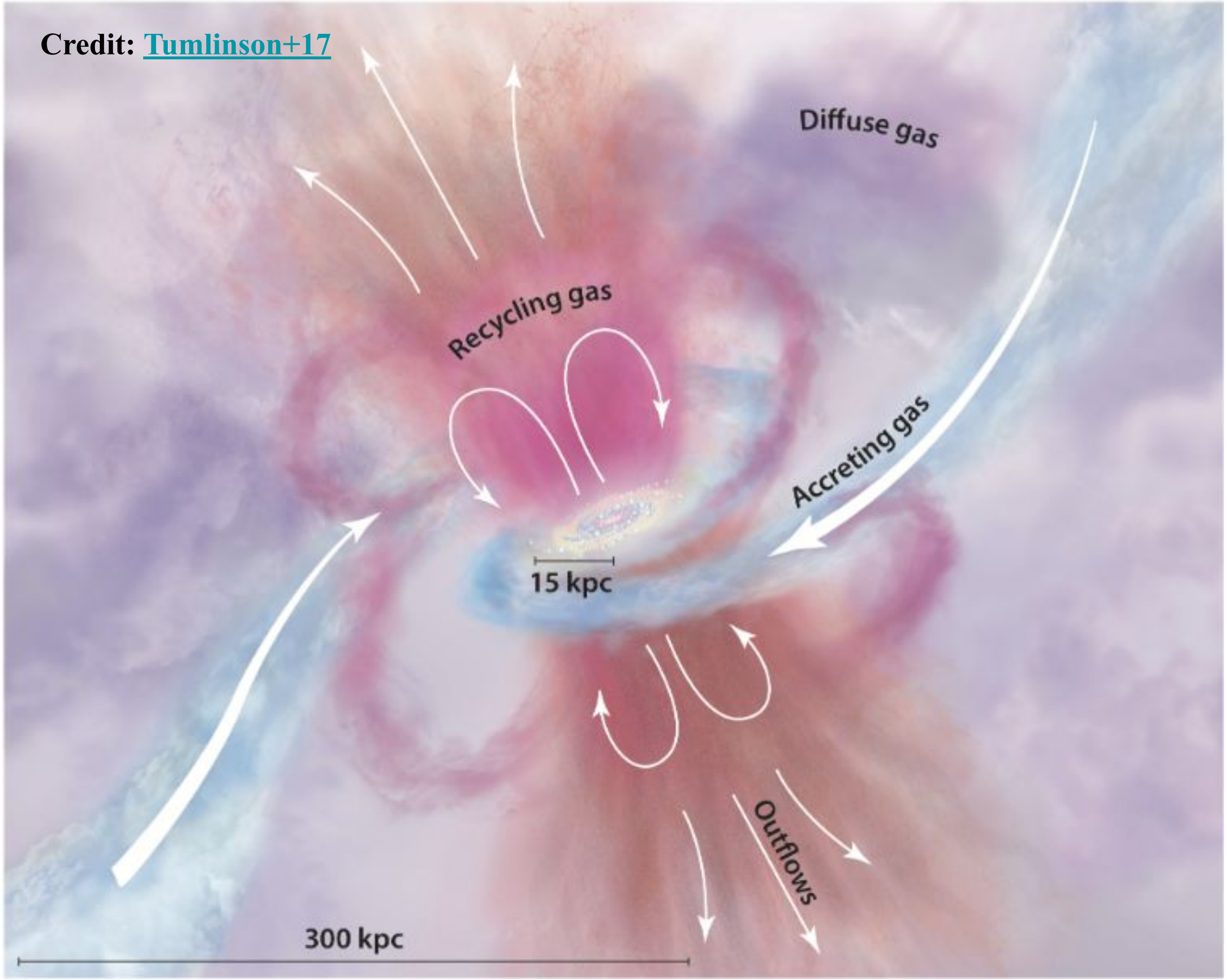
Centaurus A **NGC 1068** **NGC 253**



Feedback Mechanisms

★ ***Photoionization***

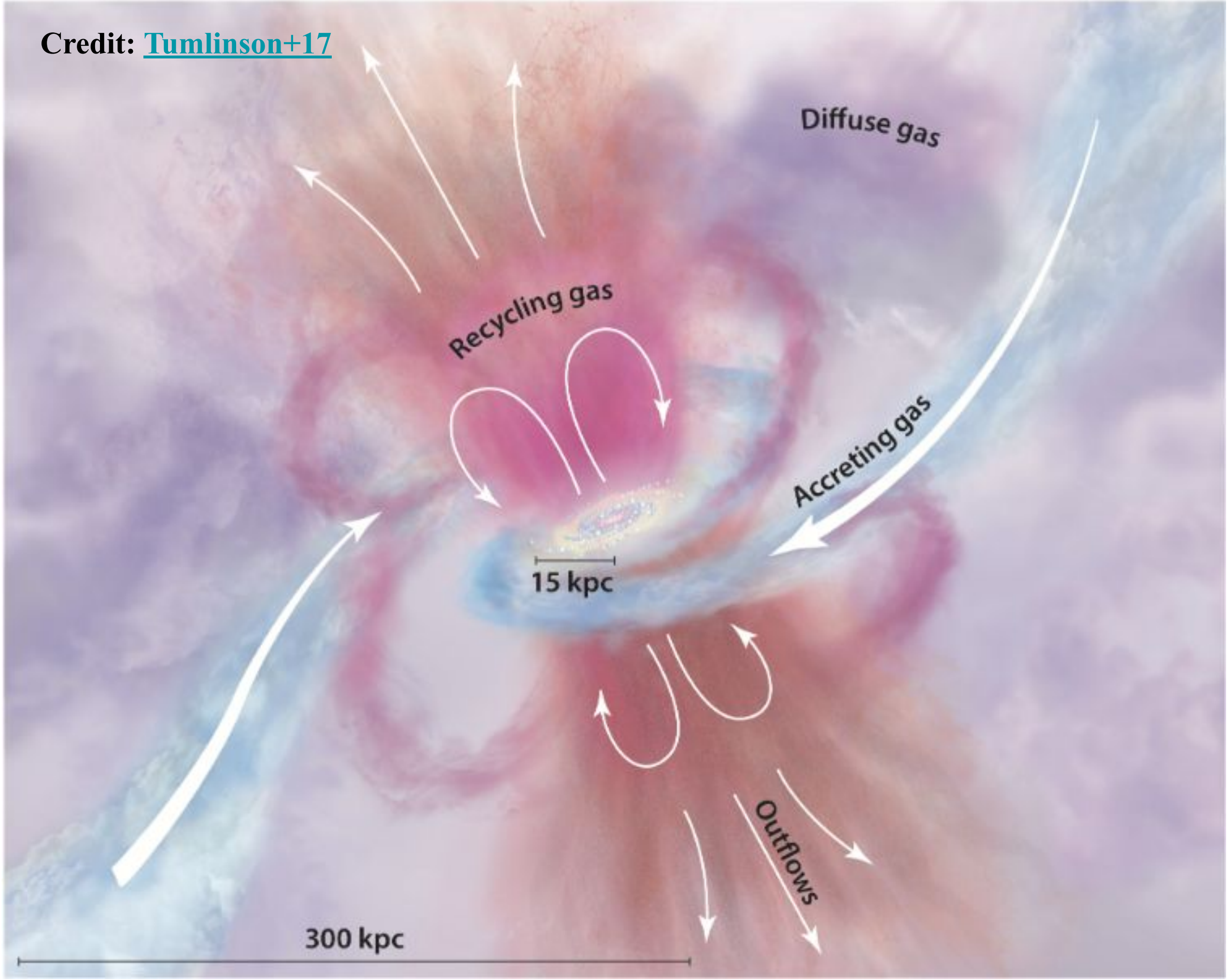
UV and X-ray photons, primarily from the accretion disk around the black hole or the AGN-driven outflows, ionize the atoms and molecules in the gas.



Feedback Mechanisms

★ ***Shocks***

Jets and outflows can generate powerful shock waves as they propagate through the interstellar or intergalactic medium. These shocks can heat and compress the gas.

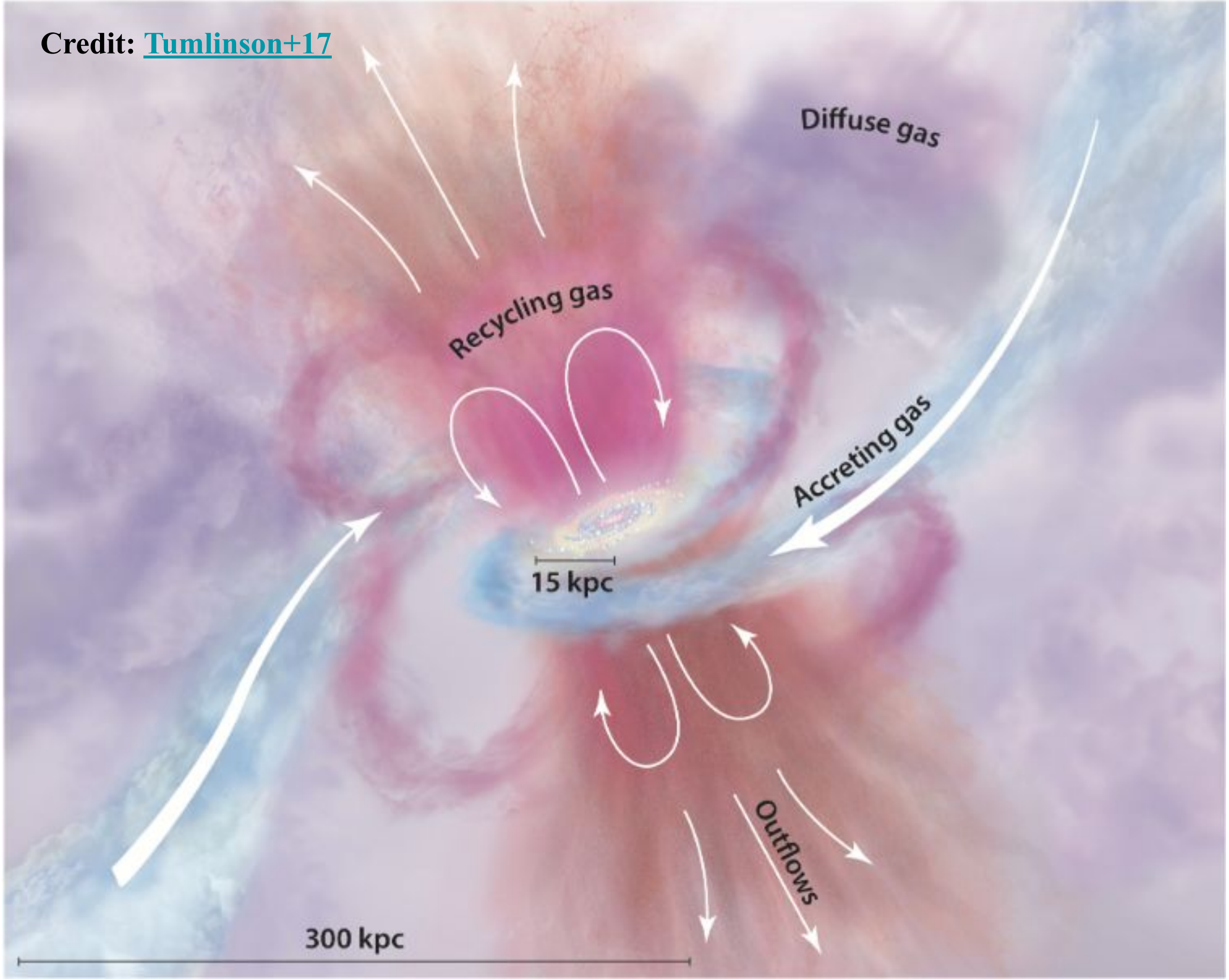


Feedback Mechanisms

★ *Collisions and Heating*

Gas in the vicinity of an AGN may experience collisions with electrons and protons.

Credit: Tumlinson+17

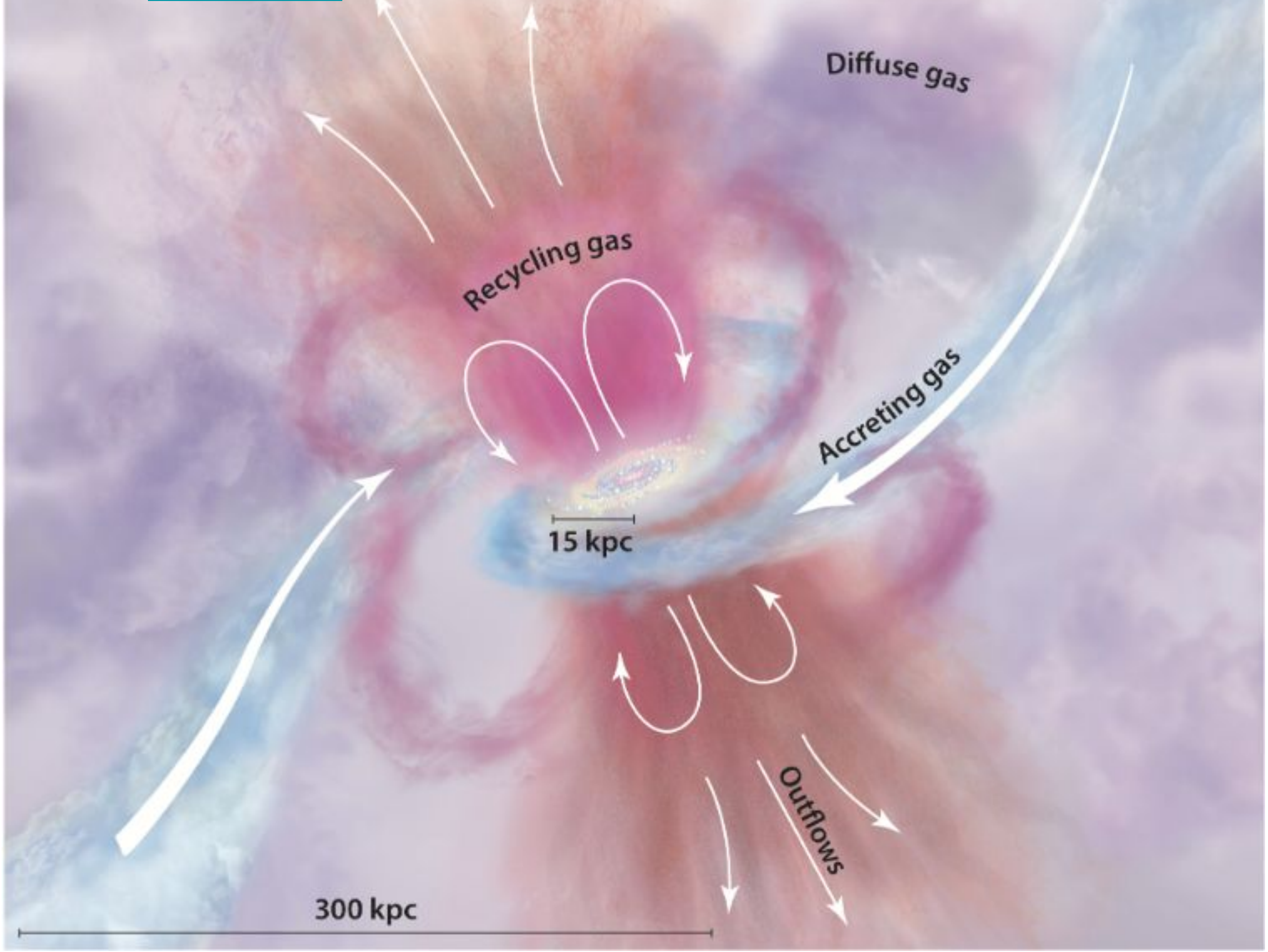


Feedback Mechanisms

★ *X-ray Heating*

X-rays emitted by the AGN can penetrate deep into the surrounding gas and heat it through photoelectric absorption and Compton scattering processes.

Credit: Tumlinson+17

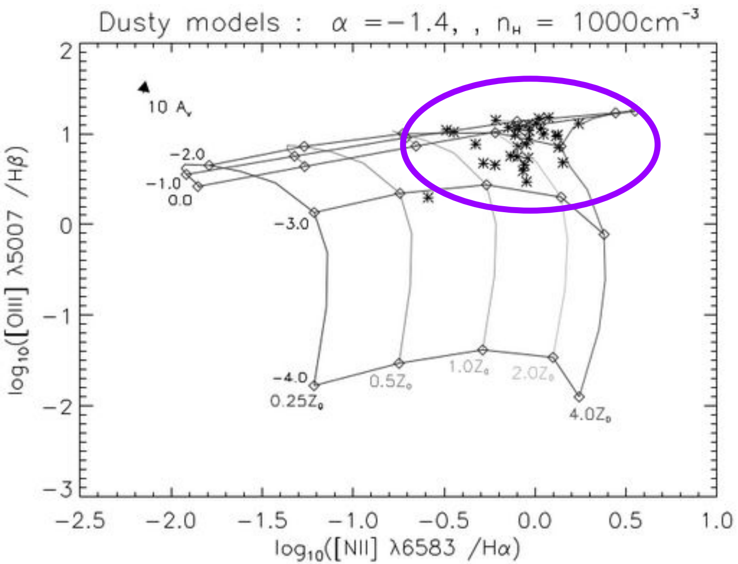


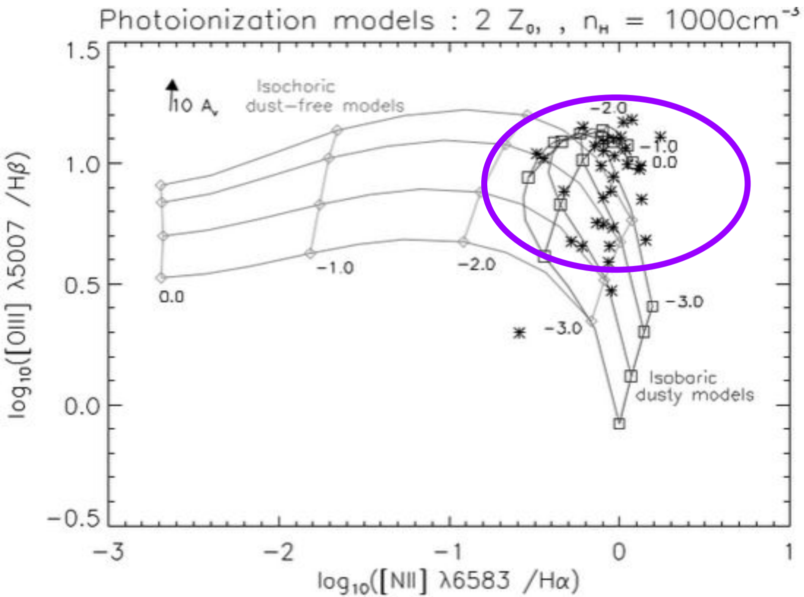
Feedback Mechanisms

★ *Cosmic Rays*

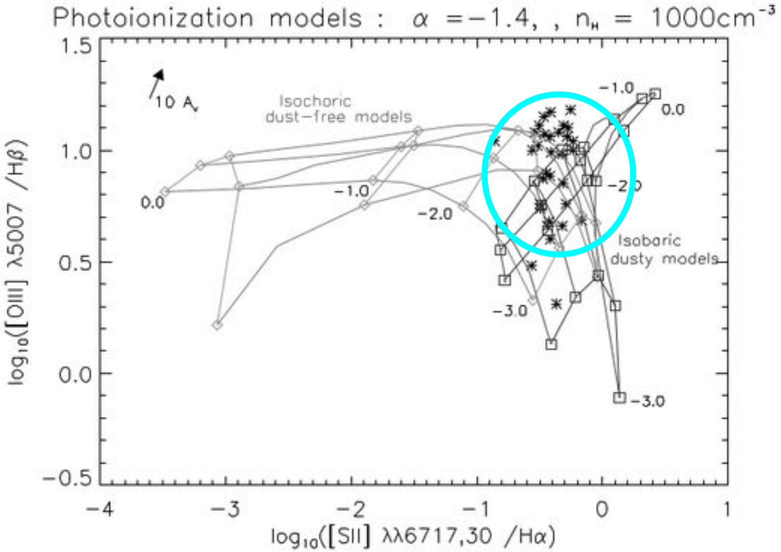
High-energy charged particles, can ionize and excite the gas and also influence the chemistry, dynamics and thermodynamics of the gas.

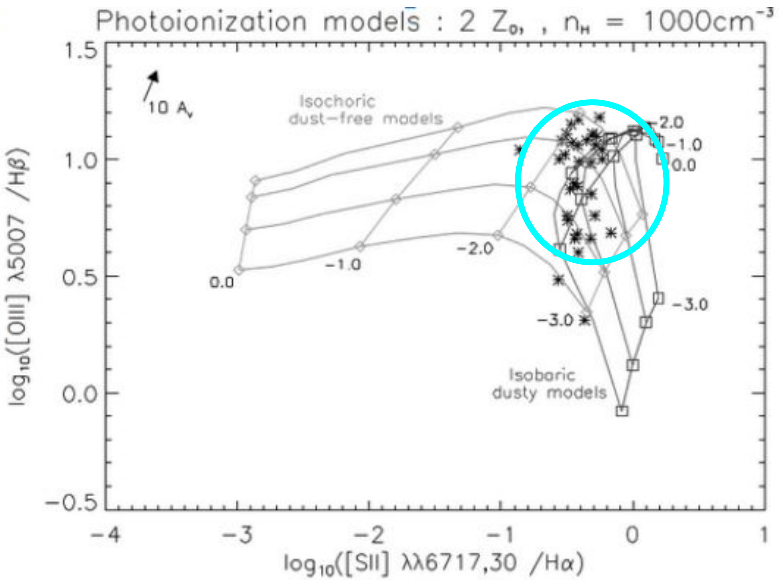
Groves et al. (2004a)





Groves et al. (2004a)





ISM Interaction Mechanisms

Photoionization: UV and X-ray radiation can ionize the surrounding gas. High-energy photons, primarily from the accretion disk around the black hole or the AGN-driven outflows, ionize the atoms and molecules in the gas, leading to the emission of characteristic spectral lines. This process is known as photoionization.

Shock Excitation: Jets and outflows can generate powerful shock waves as they propagate through the interstellar or intergalactic medium. These shocks can heat and compress the gas, leading to excitation and ionization of the atoms and molecules. Shock excitation can produce broad spectral line profiles and signatures of high-velocity gas.

Collisions and Heating: Gas in the vicinity of an AGN may experience collisions with high-speed particles, such as electrons and protons, present in the jet or outflow. These collisions can excite the gas, causing it to emit characteristic spectral lines. Furthermore, the energy deposited by these collisions can heat the gas, resulting in thermal emission.

X-ray Heating: X-rays emitted by the AGN can penetrate deep into the surrounding gas and heat it through photoelectric absorption and Compton scattering processes. This X-ray heating can increase the gas temperature, impacting its ionization state and emission properties.

Cosmic Rays: Cosmic rays, which are high-energy charged particles, can ionize and excite the gas and also influence the dynamics and thermodynamics of the gas.