The effects of Cosmic-ray ionization rate on the nebular gas in nearby AGN and starburst galaxies

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Collaborators:

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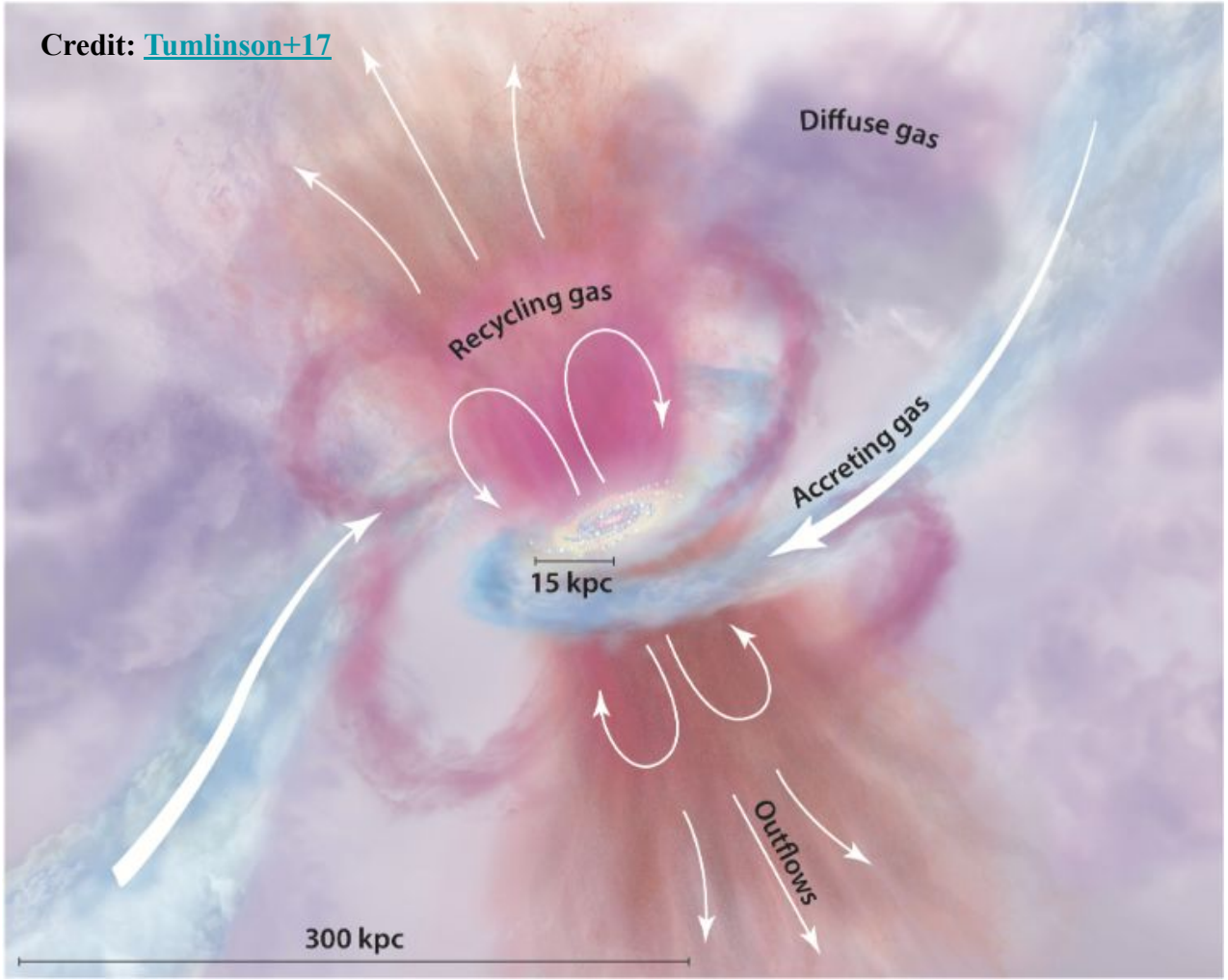
K. M. Dasyra (NKUA)
L. Spinoglio (INAF–IAPS)

22nd-24th October 2024
Arcetri, Florence, Italy



Feedback Mechanisms

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

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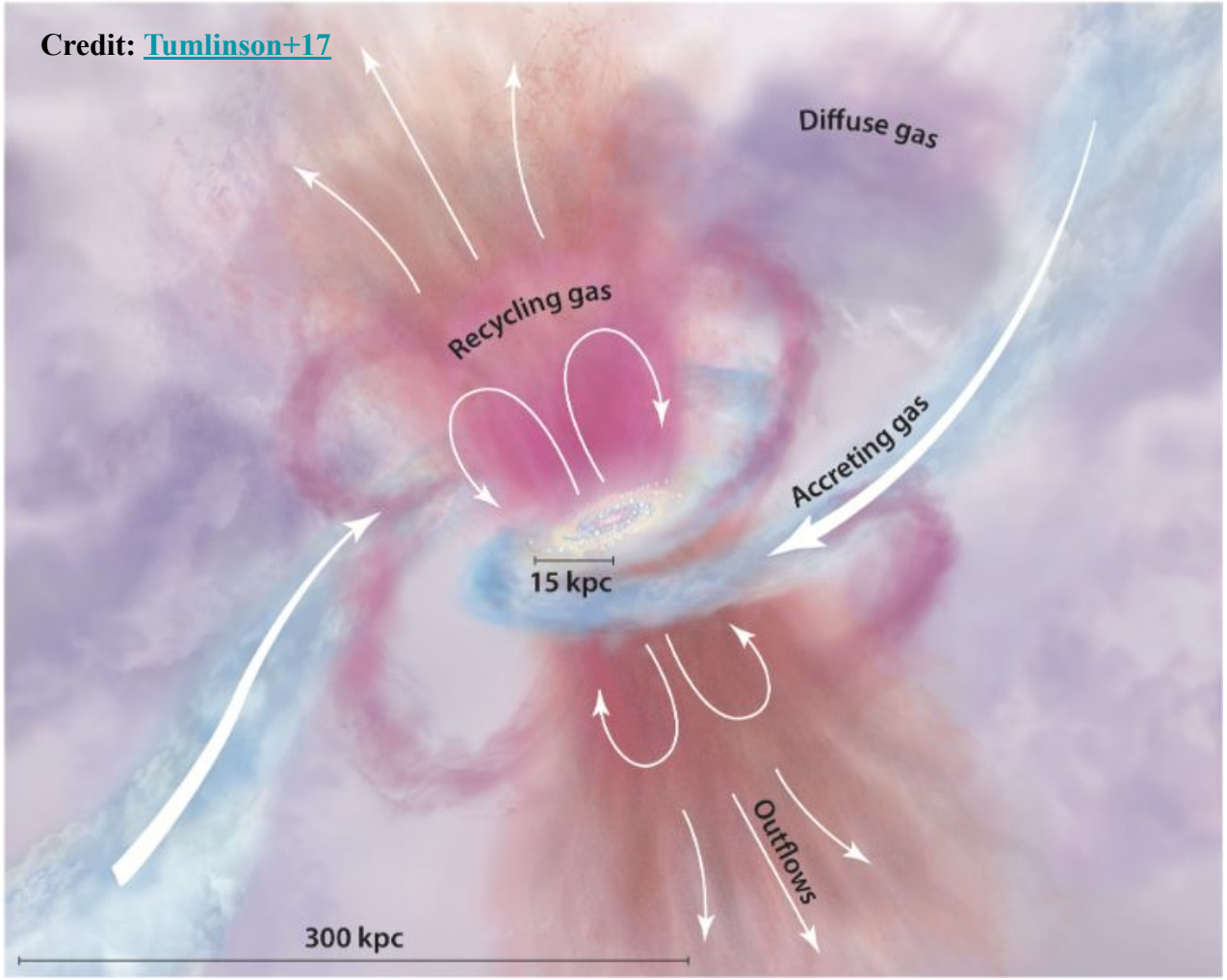

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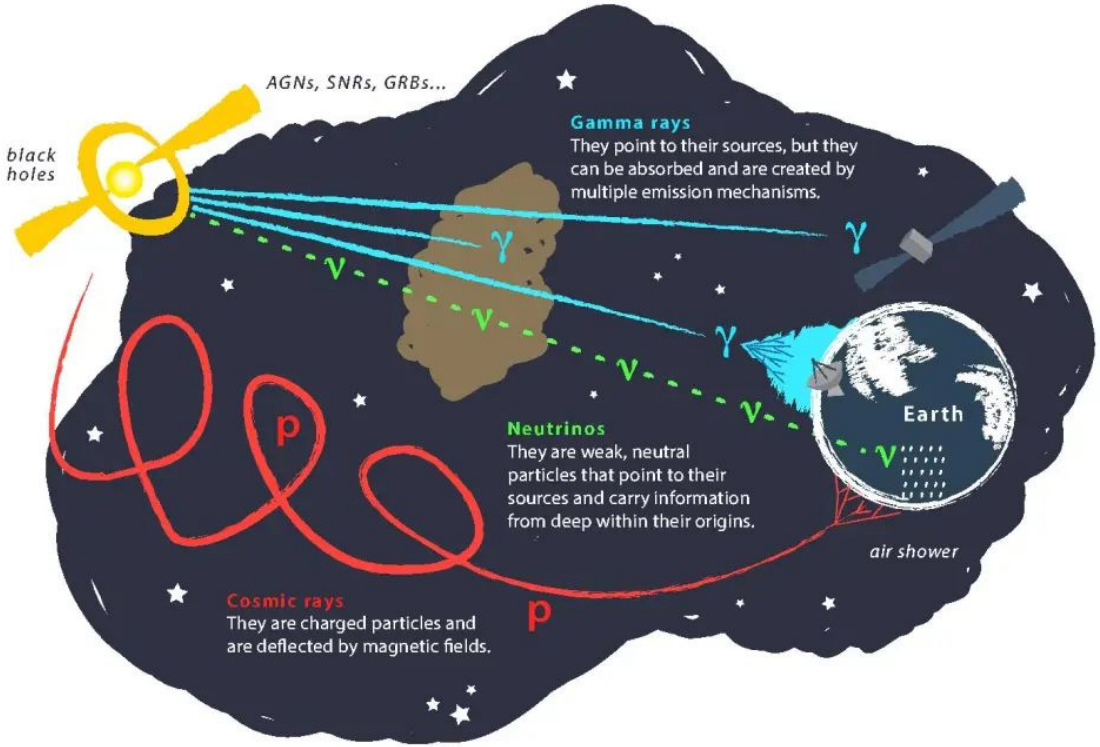
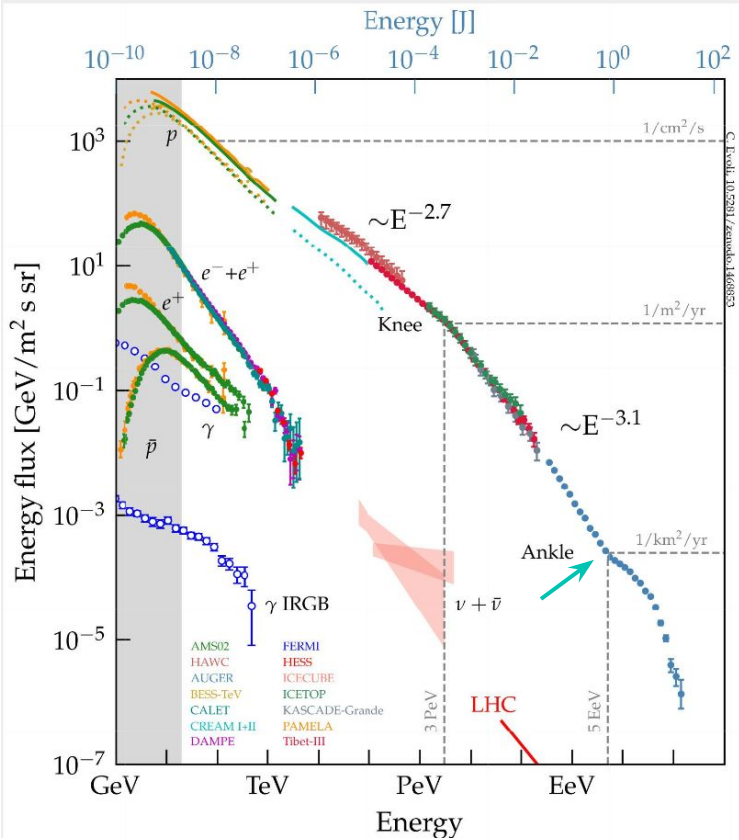
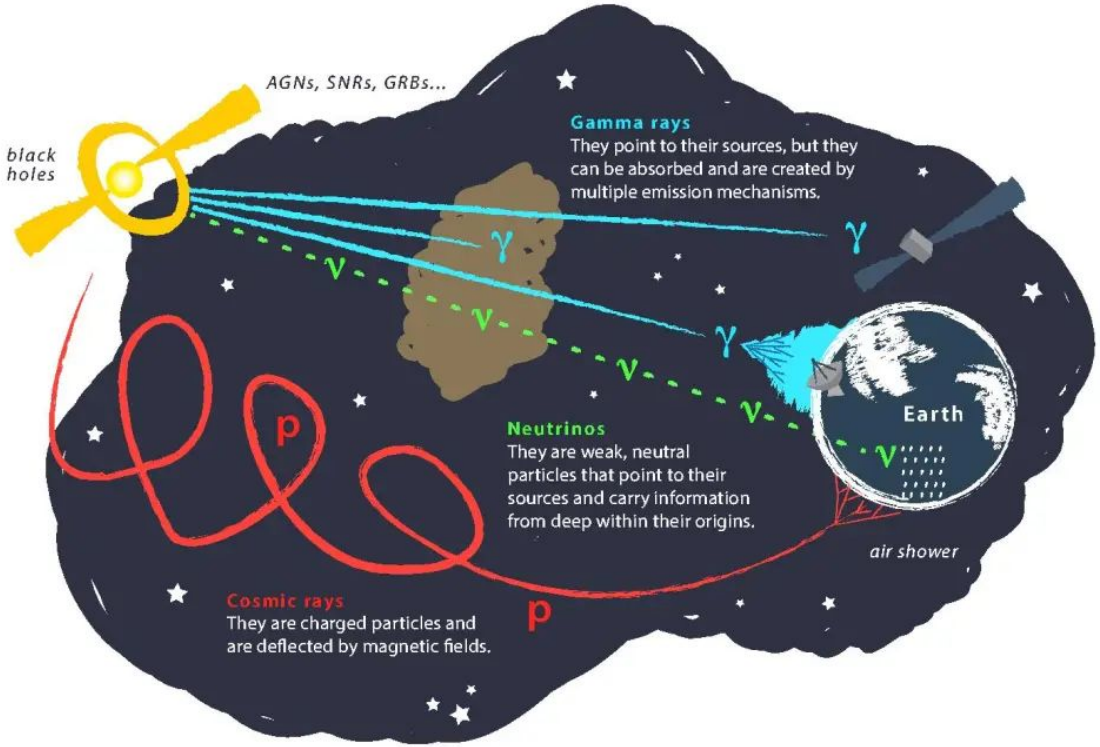


Credit: [IceCube Neutrino Observatory]

Galactic Origin ← *Extragalactic Origin* →



Credit: [E.Carmelo]



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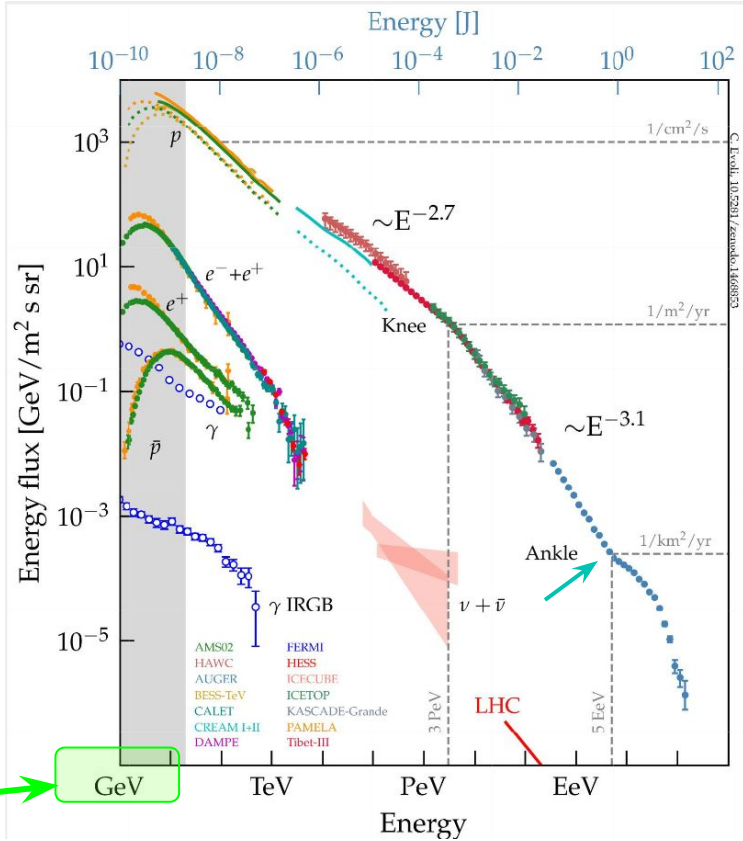
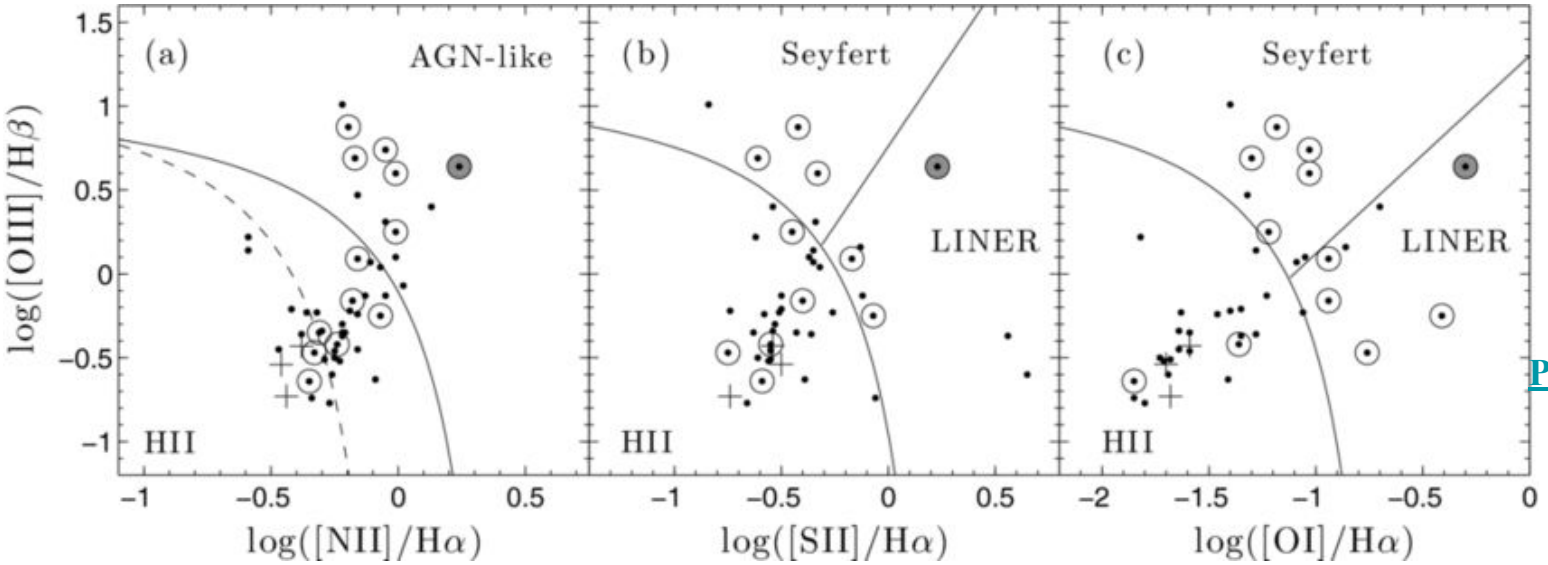


Credit: [E.Carmelo]

BPT Diagnostic Diagrams

BPT Diagrams



Parra+2010

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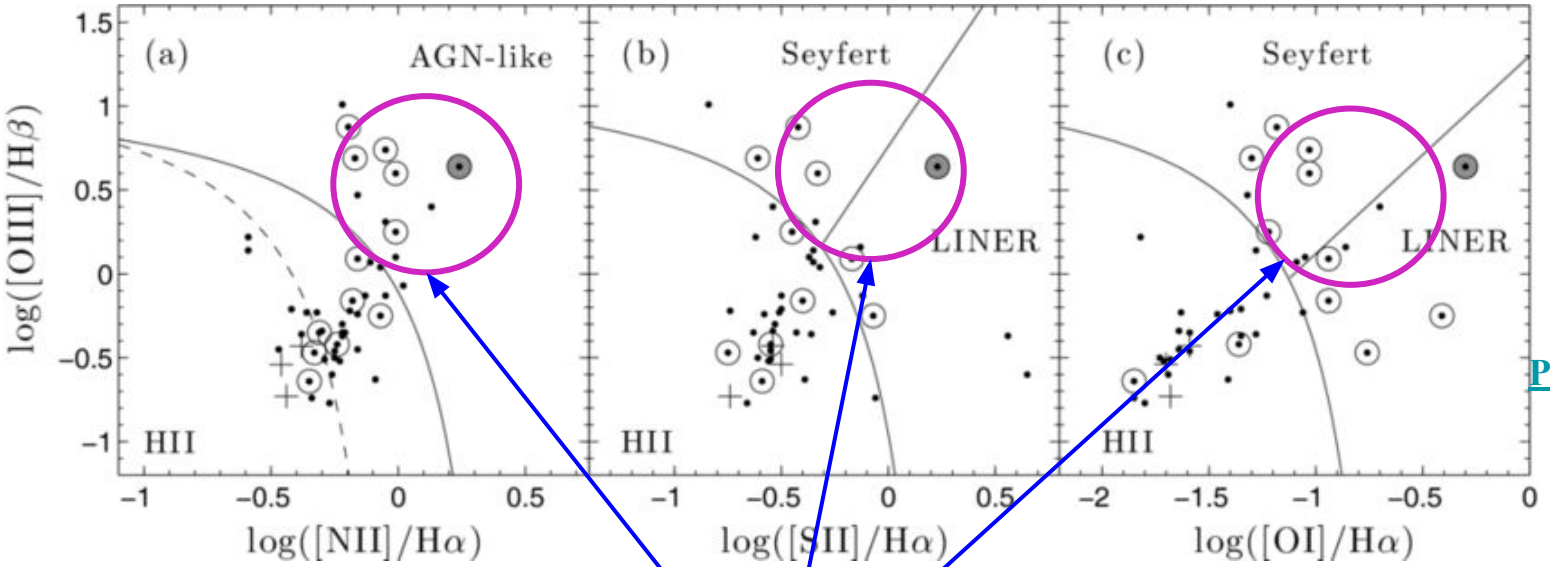
BPT Diagrams



Parra+2010

Works on modeling these areas:

Dopita+2002, Groves+2004a, Feltre+2016, Zhu+2023

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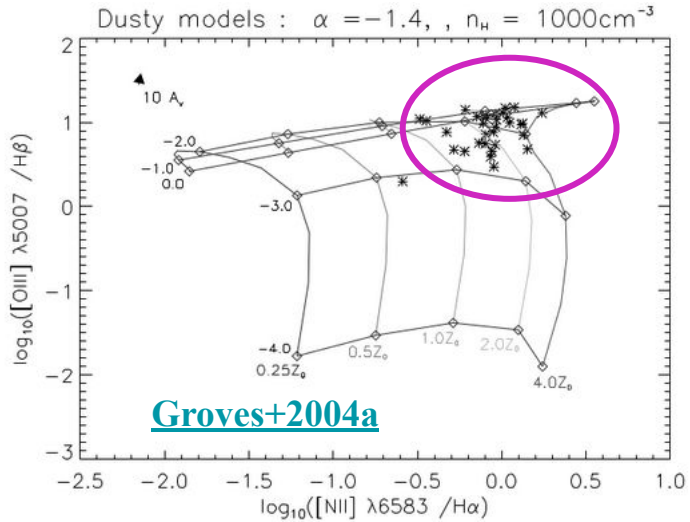
Motivation

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

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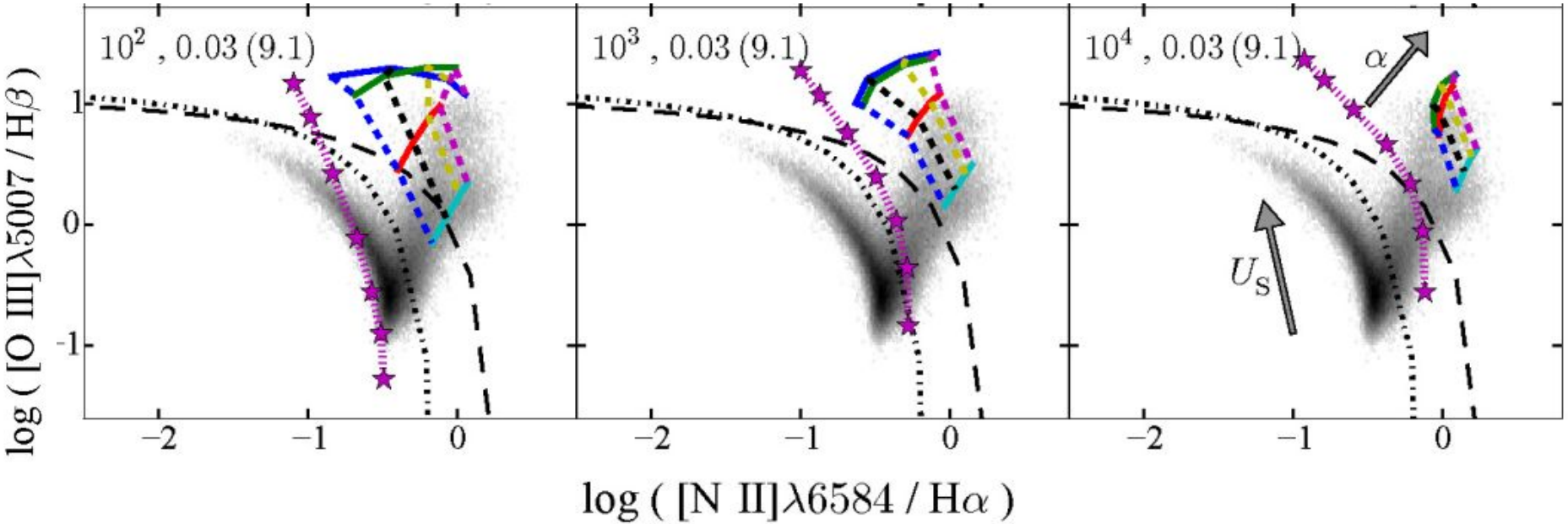

[Feltre+2016]

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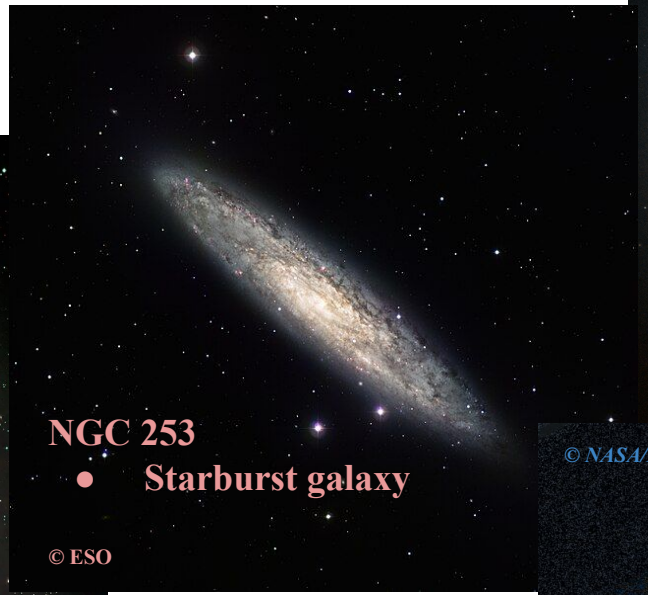
Galaxy Sample

Centaurus A
- Radio galaxy

© X-ray: NASA/CXC/CfA/R. Kraft, et.al.; Radio: NSF/VLA/Univ. Hertfordshire/M. Hardcastle; Optical: ESO/WFI/M. Rejkuba, et al.



NGC 253
- Starburst galaxy

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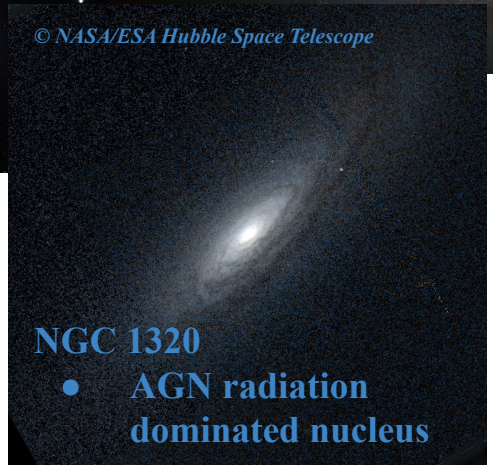
NGC 1068
- AGN & starburst composite



© NASA/ESA Hubble Space Telescope

NGC 1320
- AGN radiation dominated nucleus

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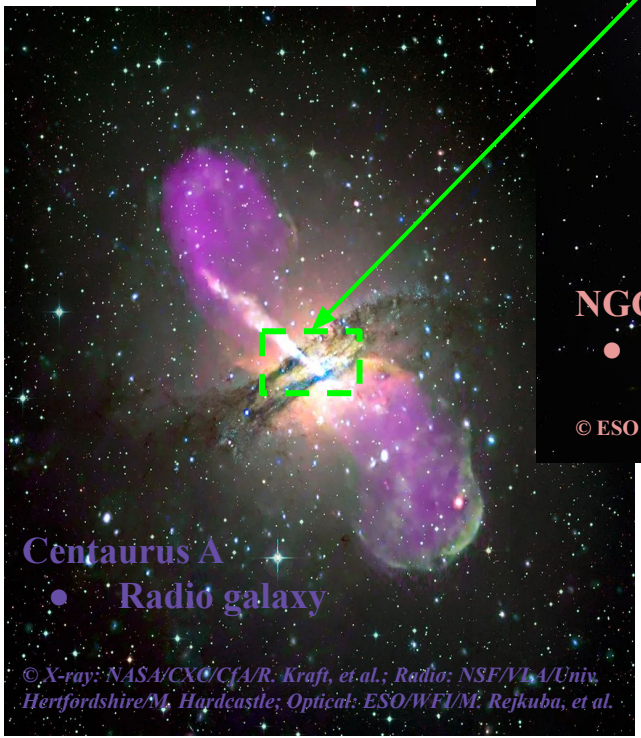
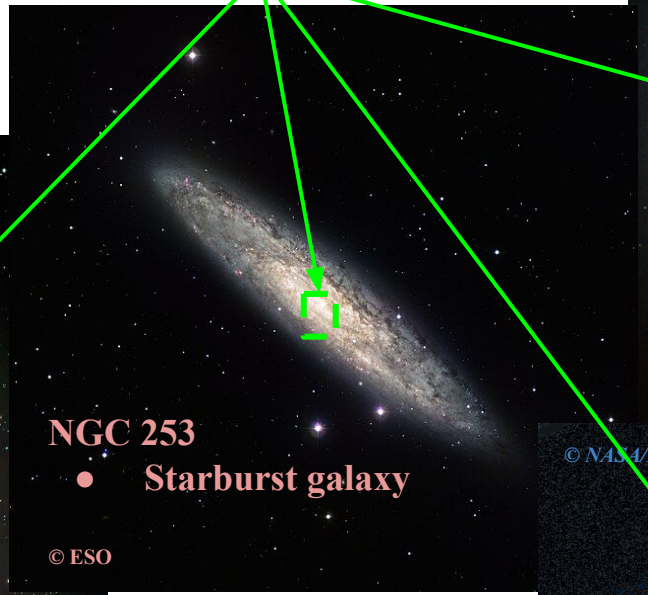
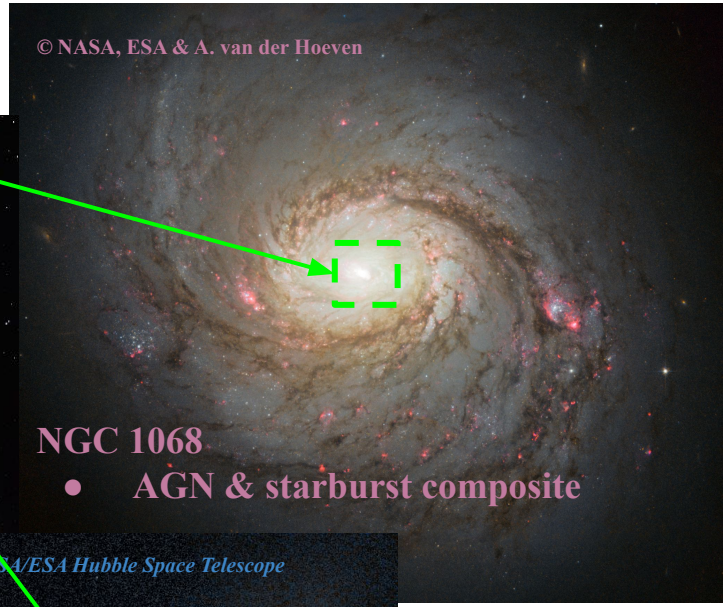
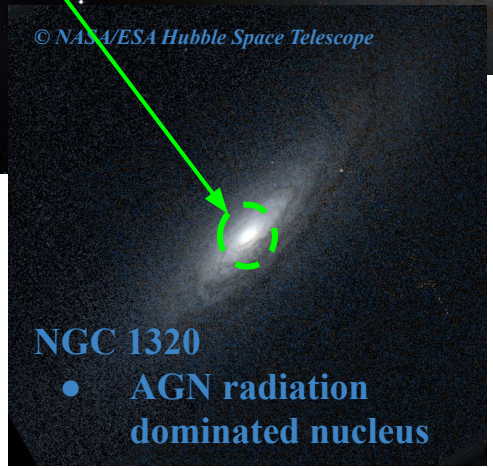
Galaxy Sample

MUSE datacubes









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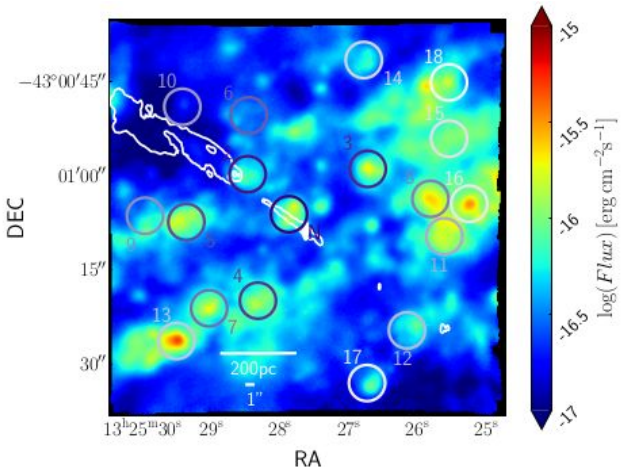
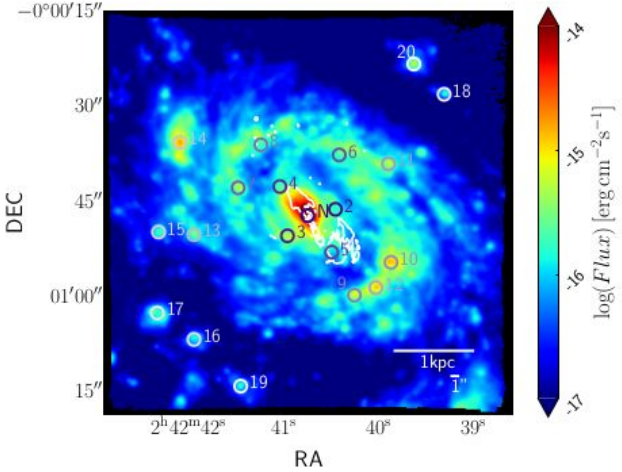
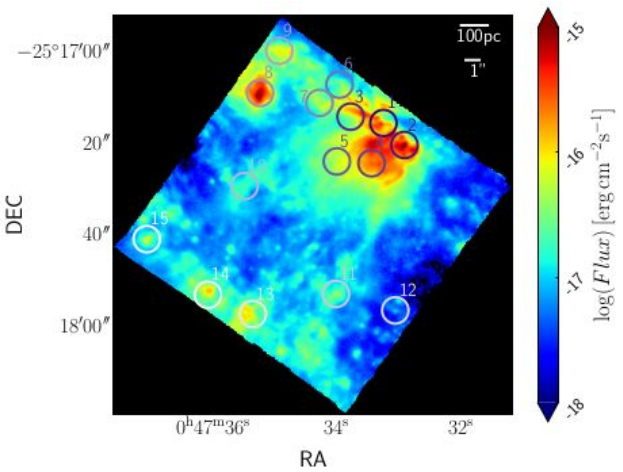
Region Selection - Hα Linemaps - MUSE Data



Centaurus A



NGC 1068



NGC 253

Radio Data for Centaurus A & NGC 1068 provided by

Lenc & Tingay 2009, Mutie+2024

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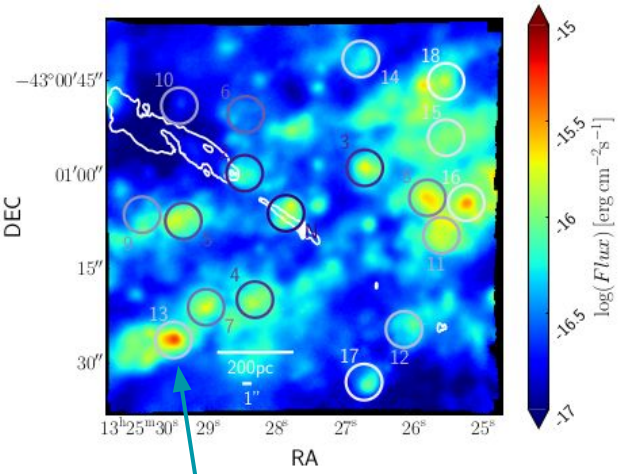
Region Selection - Hα Linemaps - MUSE Data



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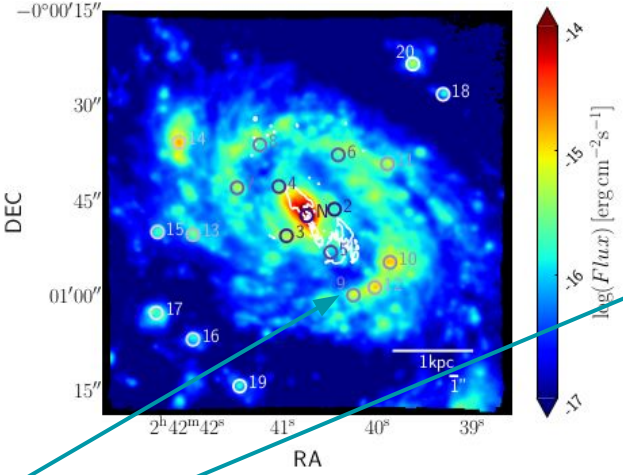
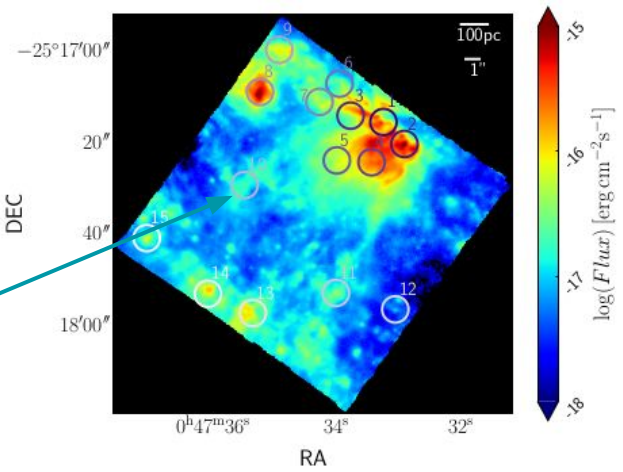


NGC 1068



NGC 253

Apertures

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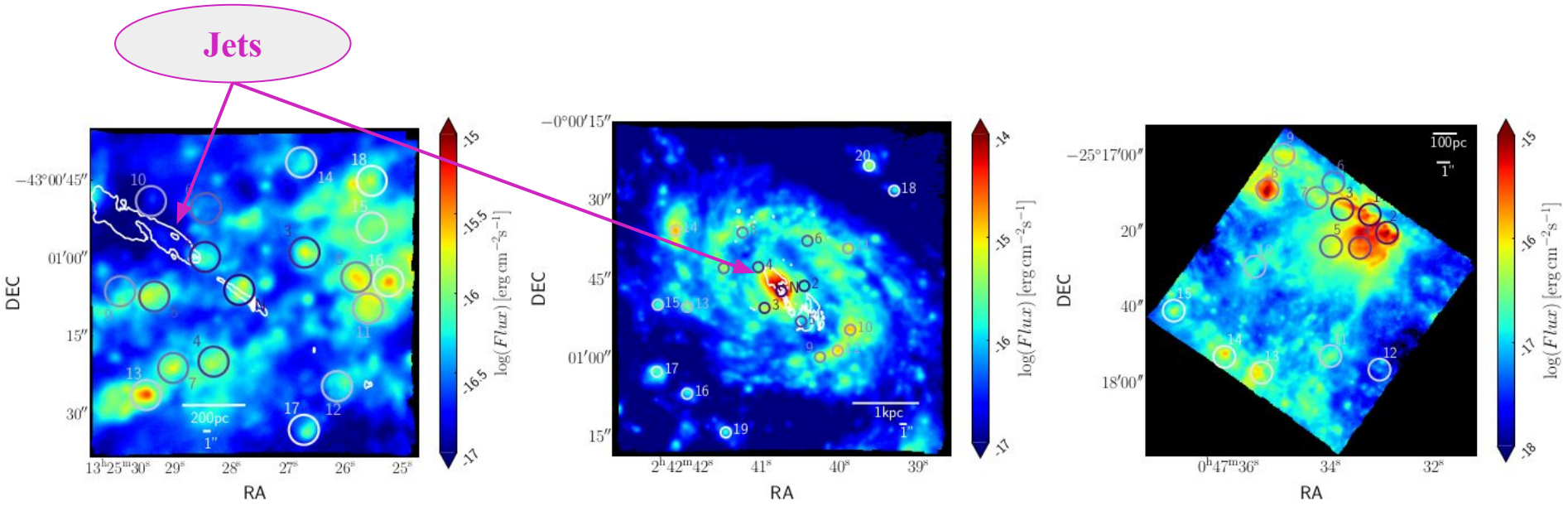
Region Selection - Hα Linemaps - MUSE Data



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

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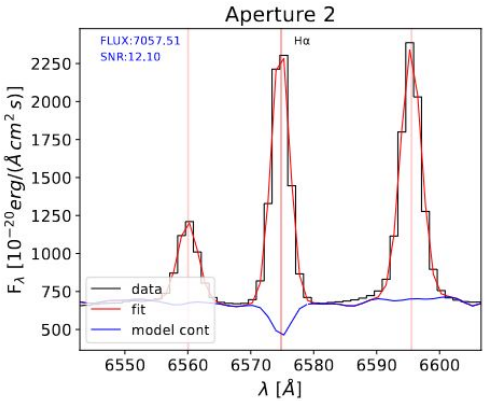
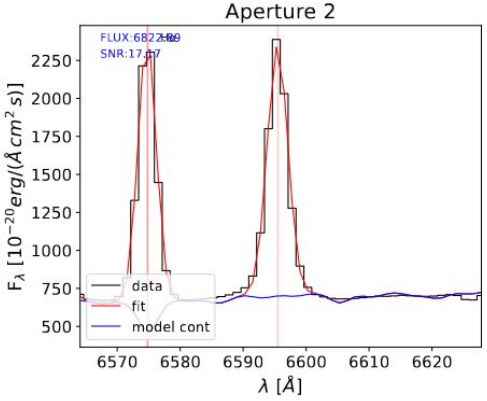
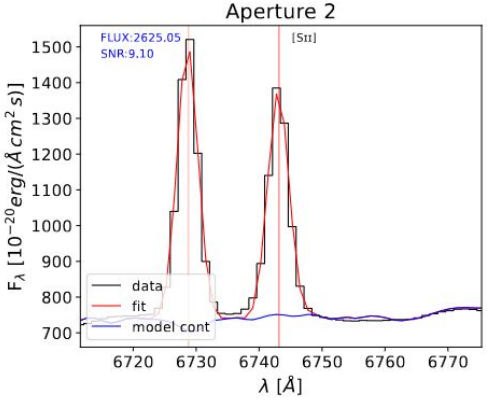
Emission line fitting



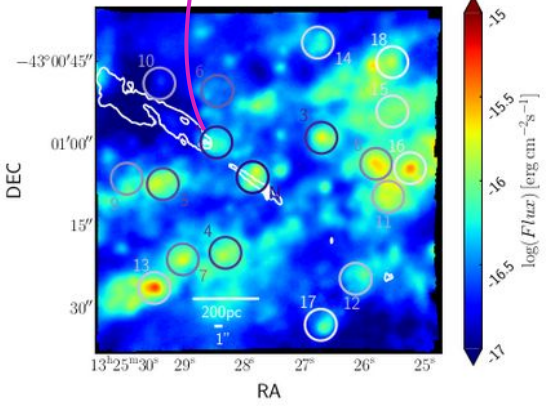
(a) $H\alpha$



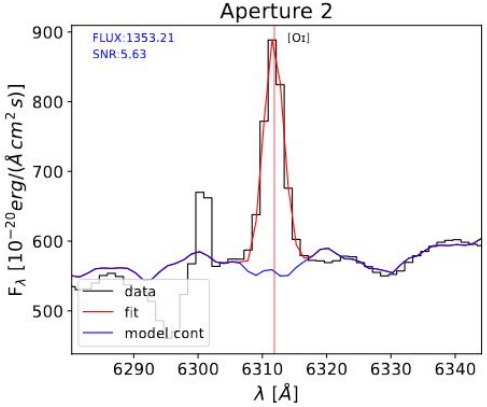
(b) [N II]λ6584Å



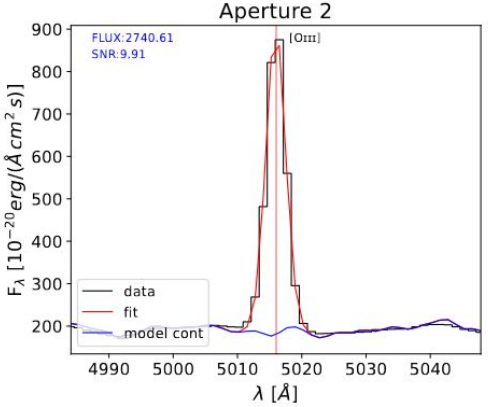
(c) [S II]$\lambda\lambda$6717,6731Å



Centaurus A



(d) [O I]6300Å.



(e) [O III]λ5007Å

Fig. 2: BPT emission lines' fit in the rest frame of Centaurus A.

CLOUDY (Ferland+2017) 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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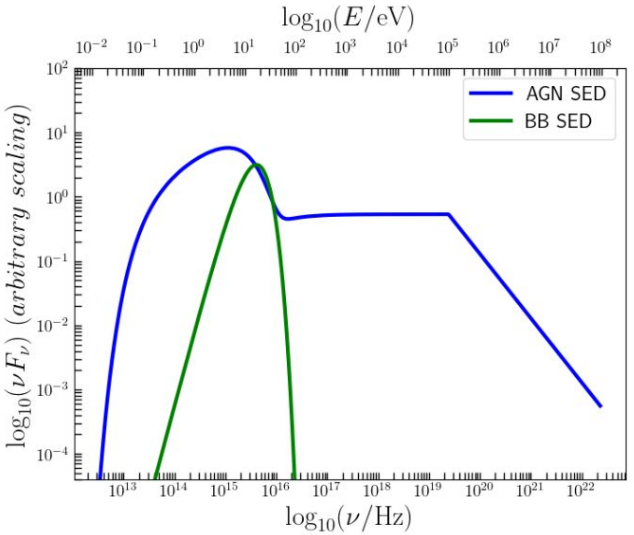

Galaxy	$\log_{10} U$	$Z/Z_\odot$
Centaurus A	[-3.5, -3.2]	[0.4, 1.2]
NGC 1068	[-3.4,-2.8]	[0.5, 1.1]
NGC 253	[-3.1,-2.6]	[0.4, 0.8]
NGC 1320	[-3.4, -2.9]	[0.6, 1.1]

Pérez-Montero +2014, +2019

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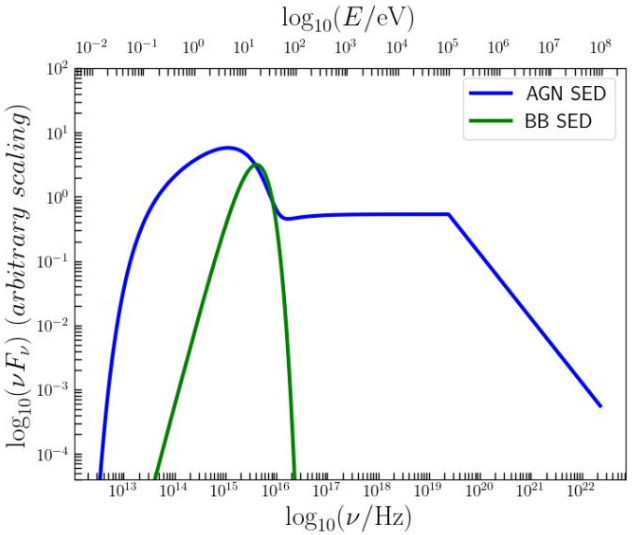

Motivated by the chosen galaxies

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Pérez-Montero +2014, +2019

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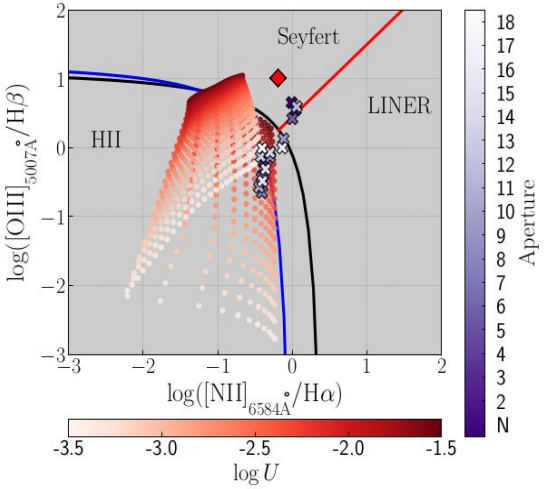
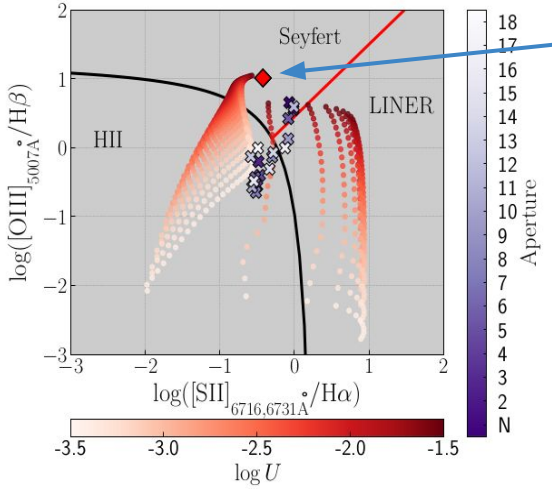
BPTs - AGN Models

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

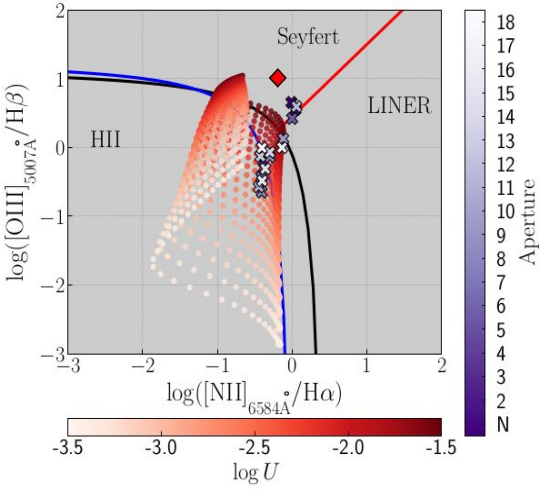


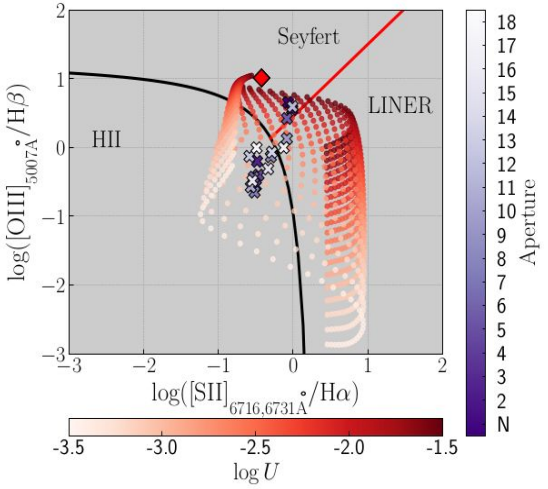


NGC 1320

Centaurus A

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





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

in agreement with:

★ **Molecular cloud chemistry** (González-Alfonso+2013)

★ **Synchrotron fit** (lower limit)

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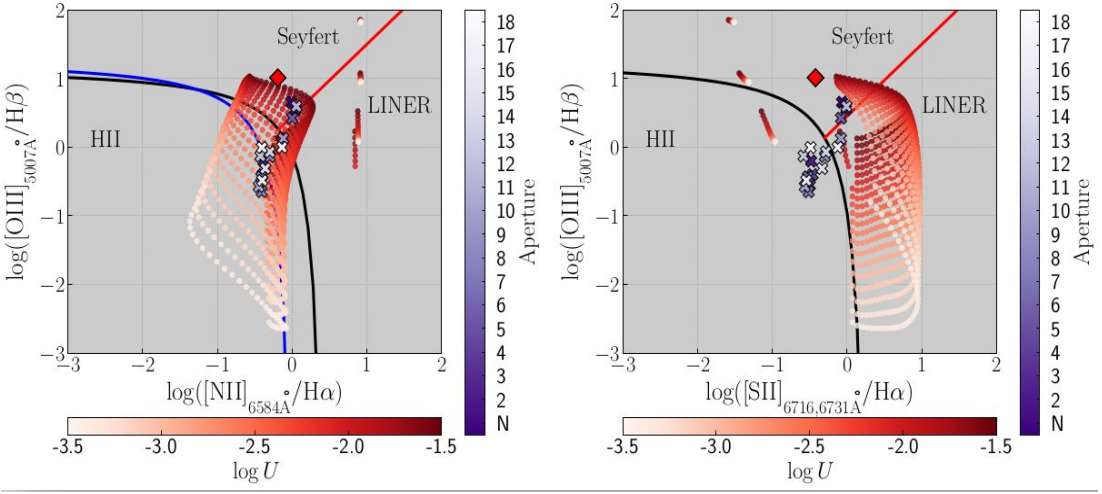
$\zeta_{CR} = 10^{-12}$ s^{-1}



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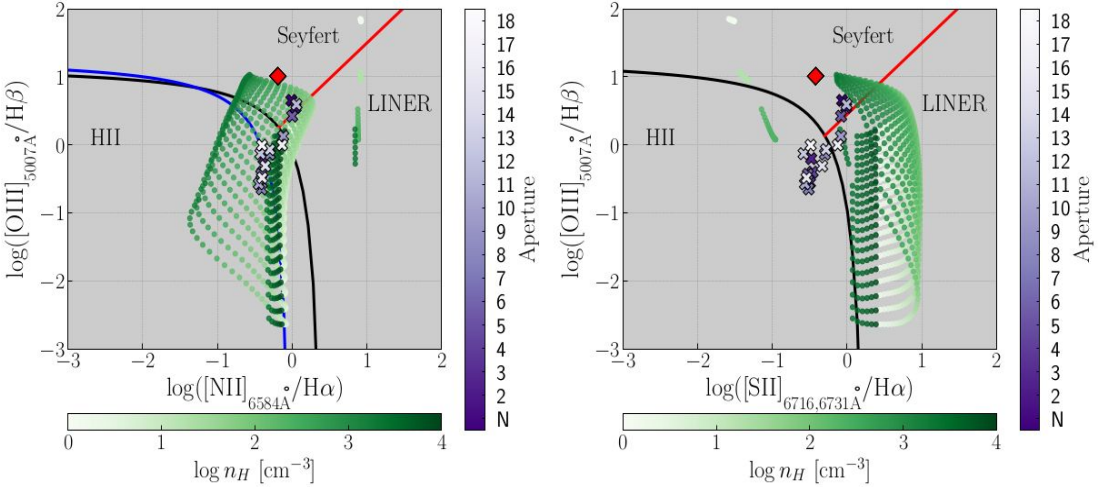

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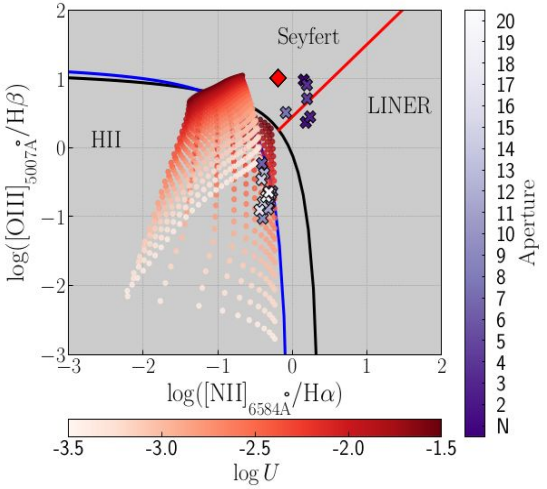
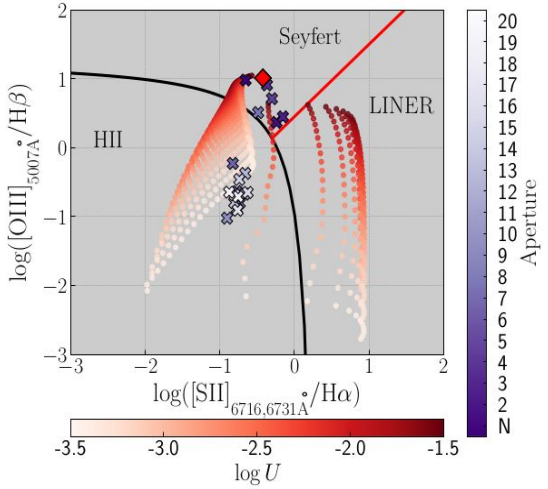
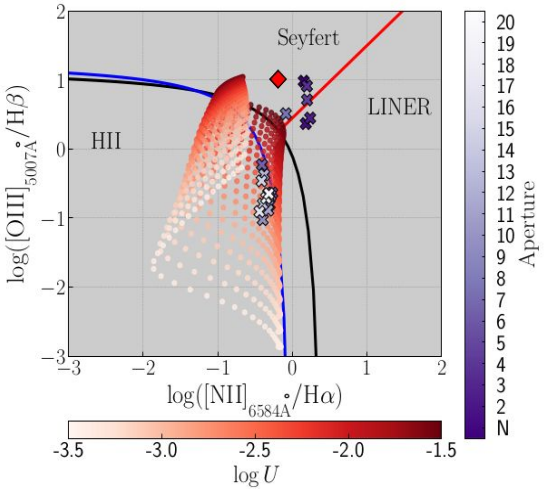
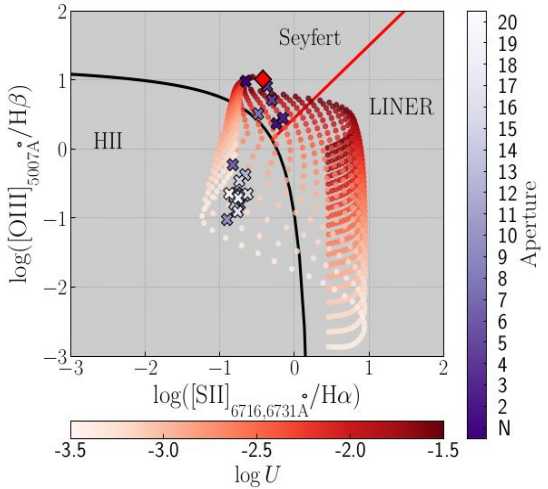




$\zeta_{CR} = 10^{-13}$ s^{-1}





NGC 1068

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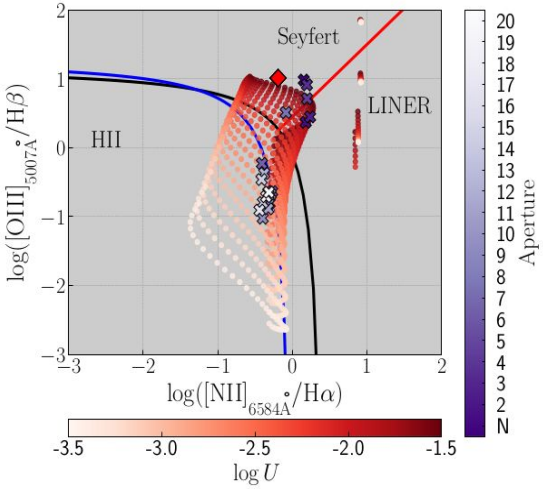

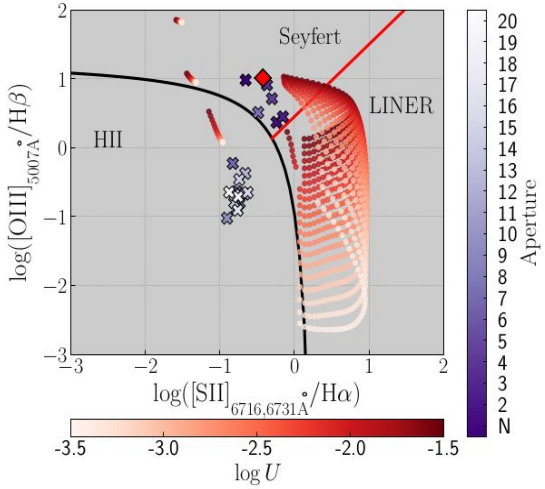

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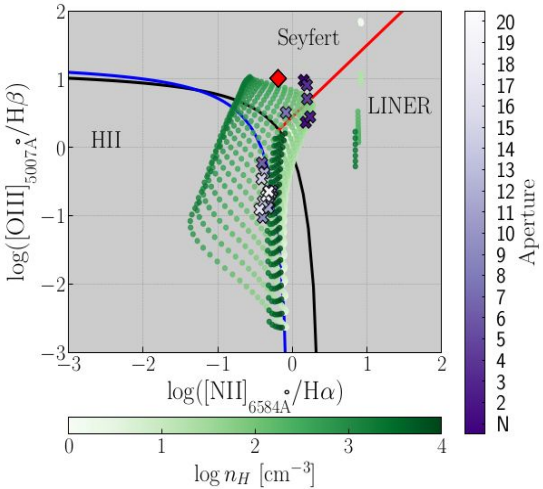

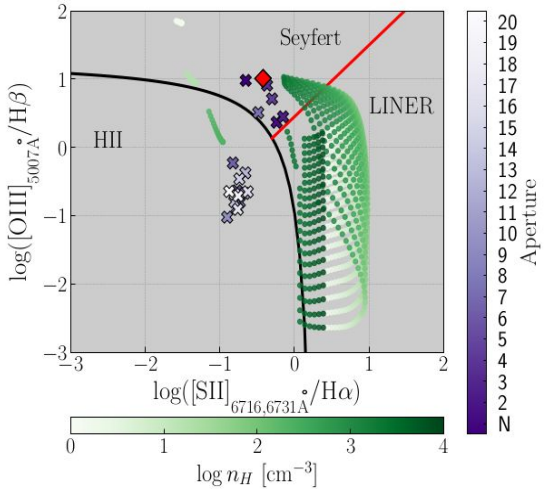

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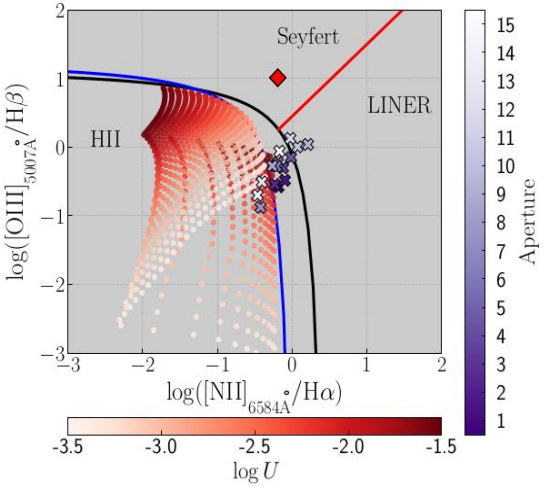
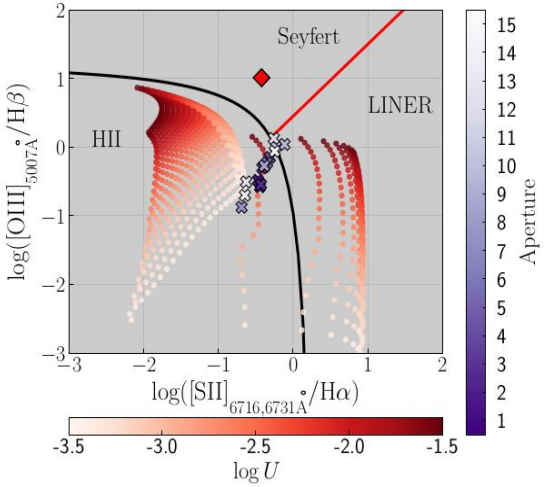
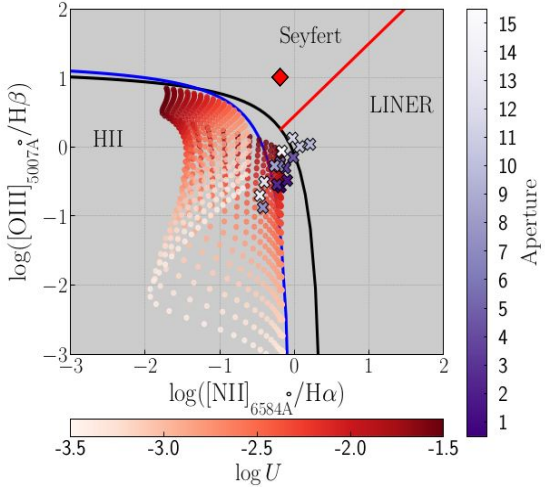
BPTs - Star-Forming Models

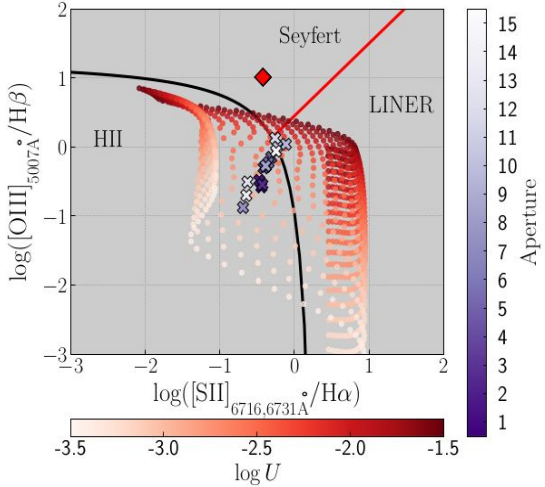
$\zeta_{CR} = 10^{-14}$ s^{-1}





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





NGC 253

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

According to:

- ★ Behrens+2022
- ★ Holdship+2022
- ★ Beck+2023

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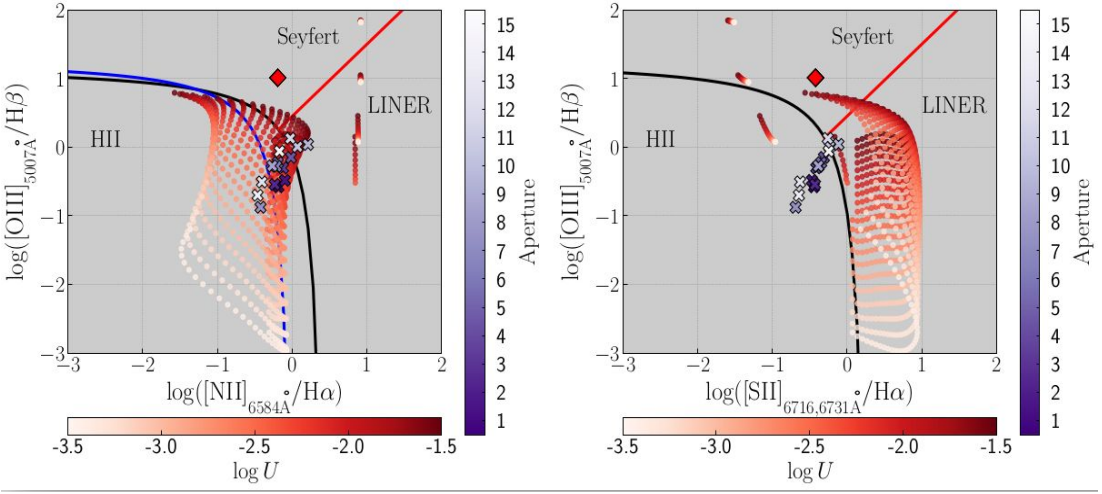
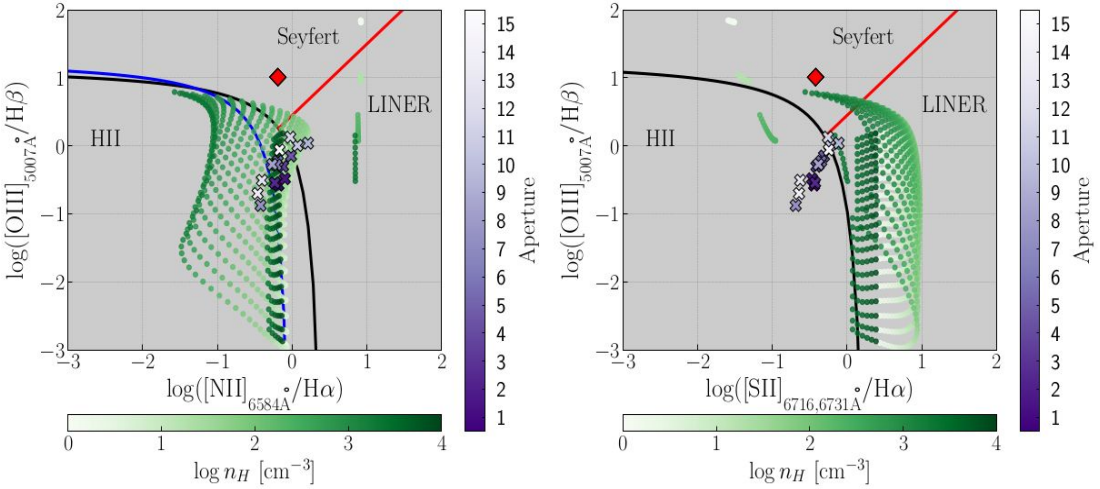
$\zeta_{CR} = 10^{-12}$ s^{-1}



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



NGC 253

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- ★ Behrens+2022
- ★ Holdship+2022
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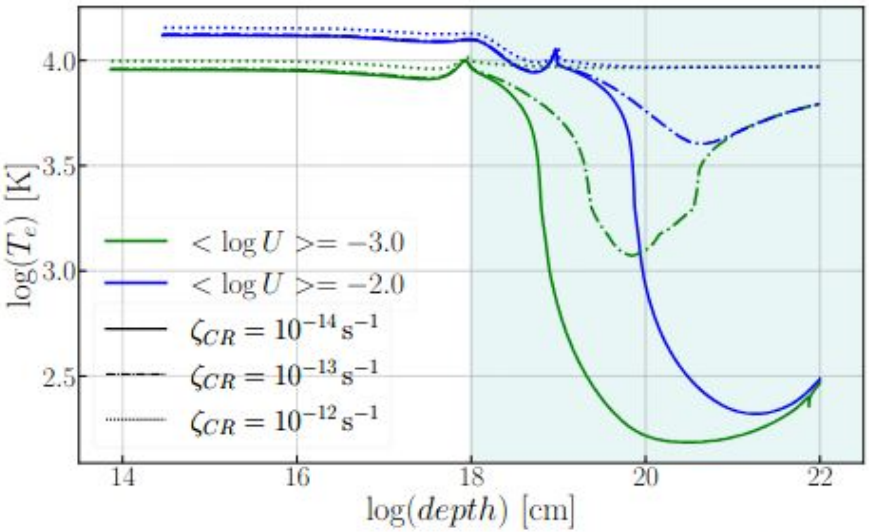
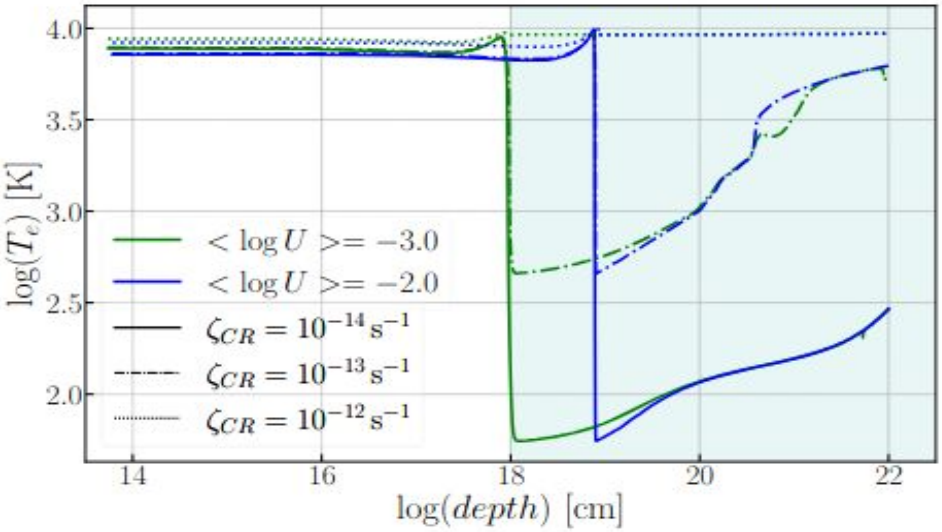
Gas Stratification

- ***What happens within the gas clouds?***
- ***Is the emission of [SII] and [NII] boosted?***

AGN Models



SF Models



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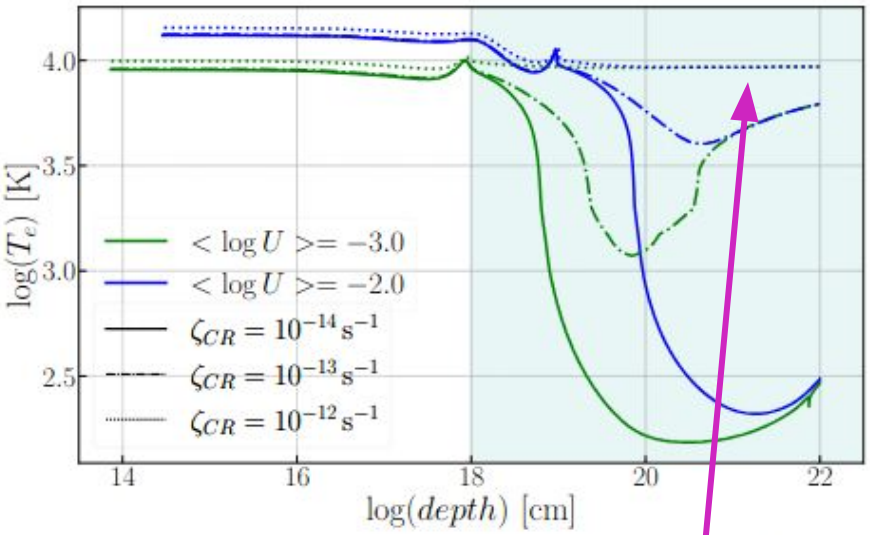
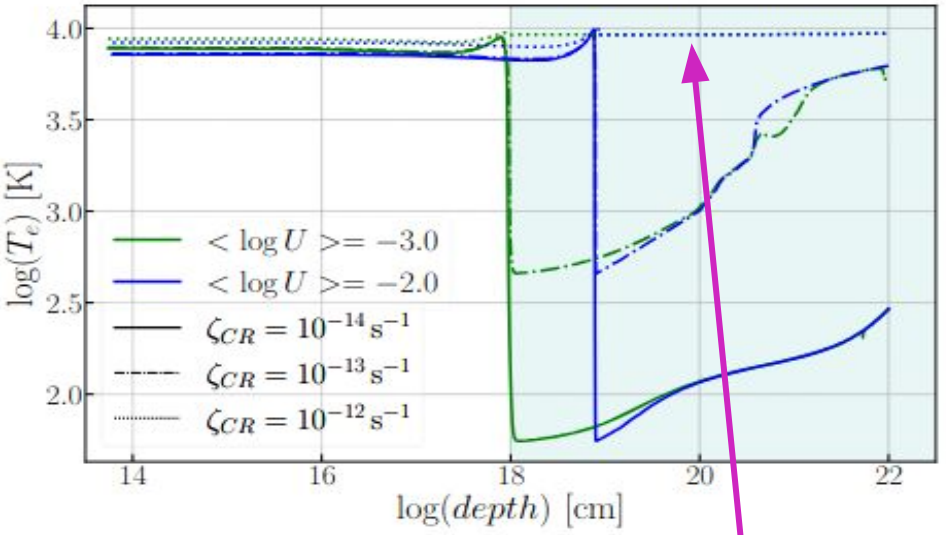
AGN Models



AGN Photoionization

CRs

SF Models



Photoionization

CRs

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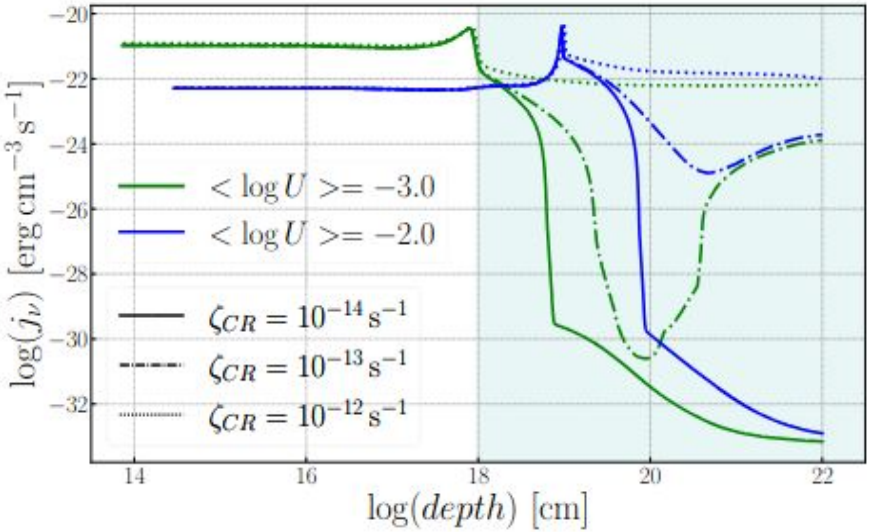
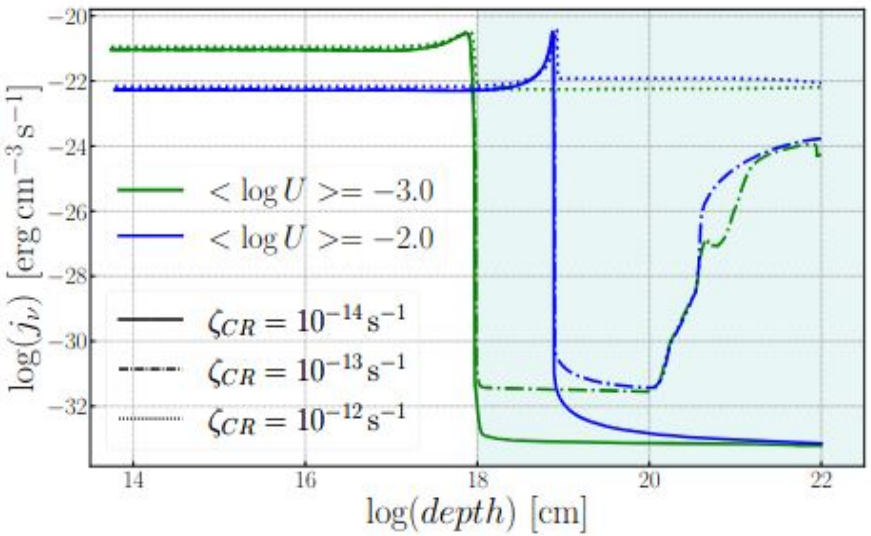
AGN Models

SF Models

[NII]





AGN Photoionization

CRs

Photoionization

CRs

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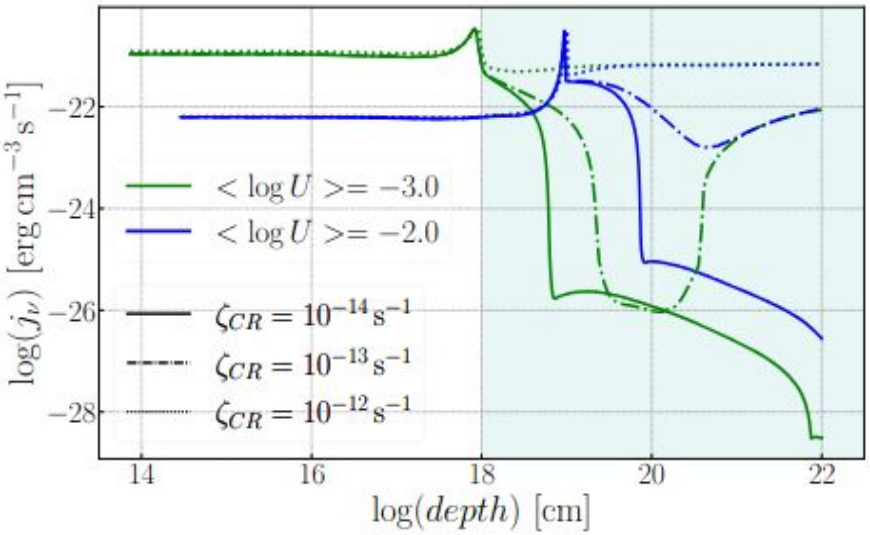
AGN Models

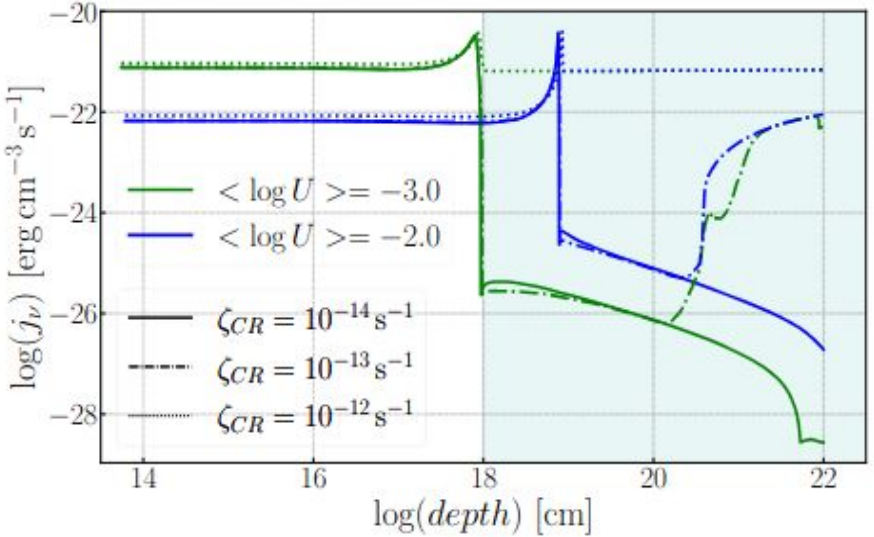
SF Models

[SII]



AGN Photoionization

CRs



Photoionization

CRs

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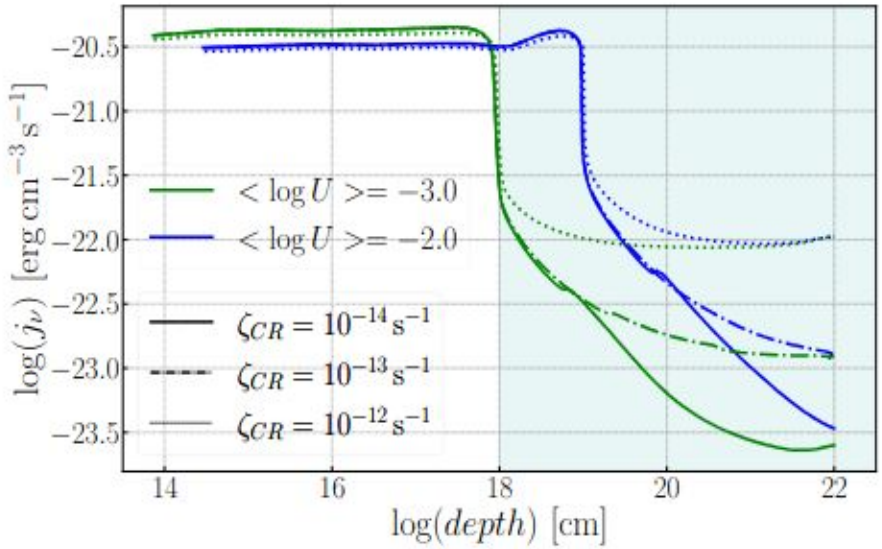
AGN Models

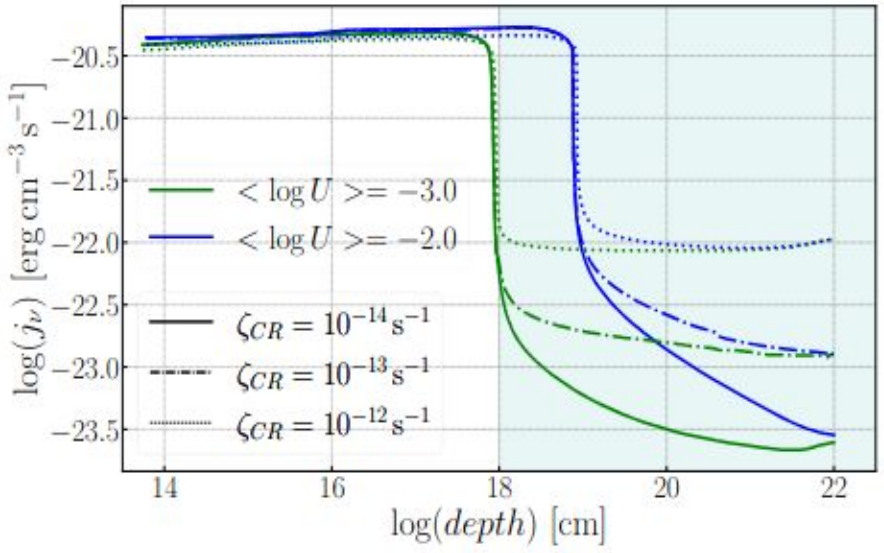
SF Models

Hα



AGN Photoionization

CRs



Photoionization

CRs

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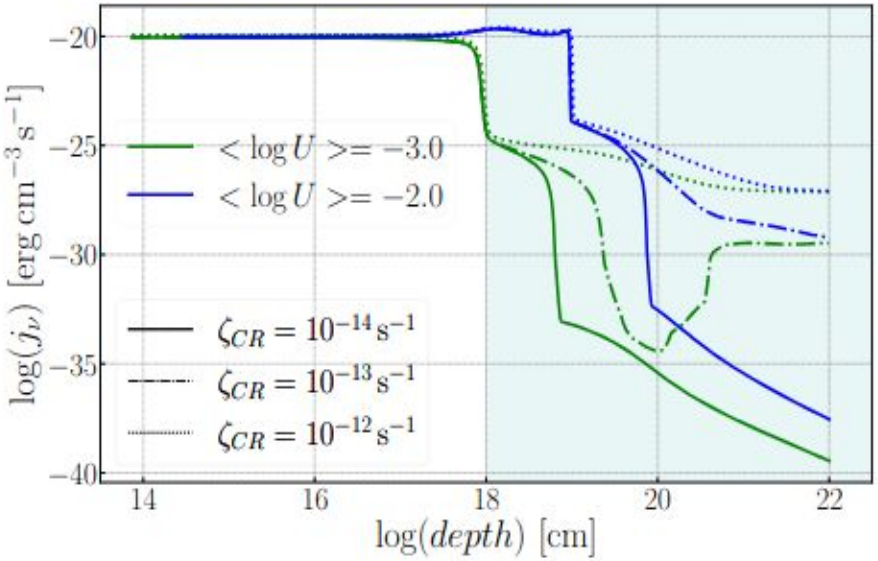
AGN Models

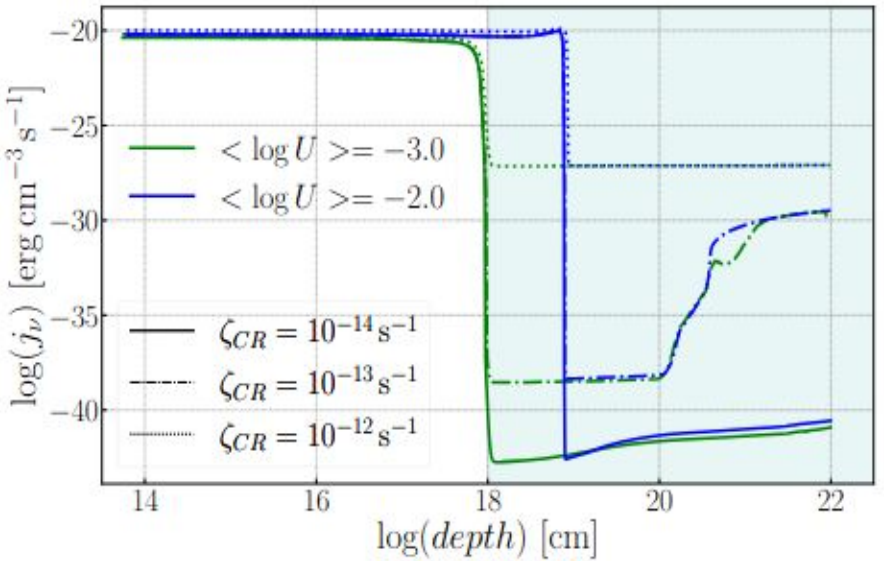
SF Models

[OIII]



AGN
Photoionization

CRs



Photoionization

CRs

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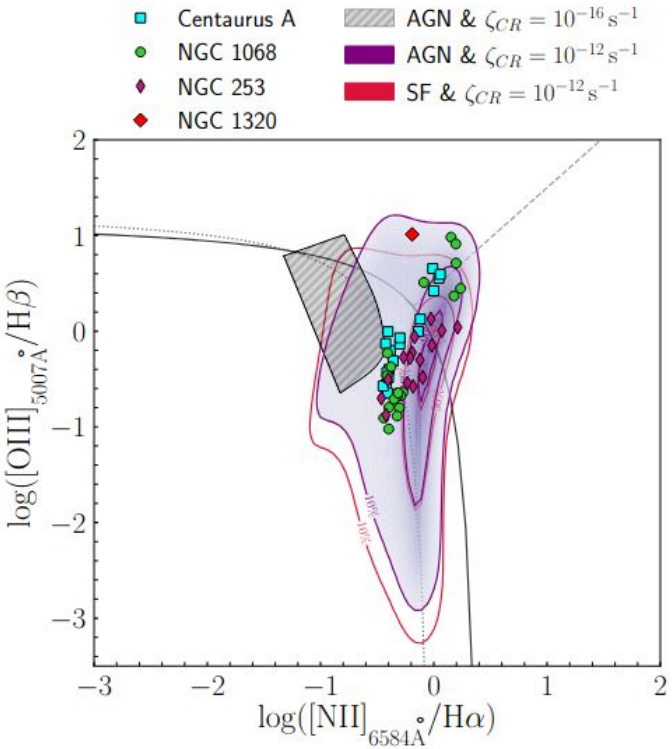

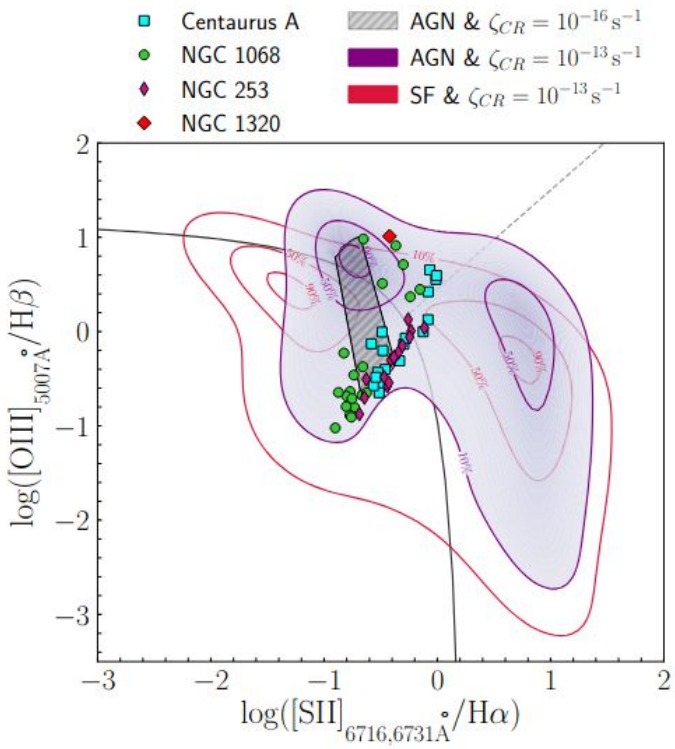

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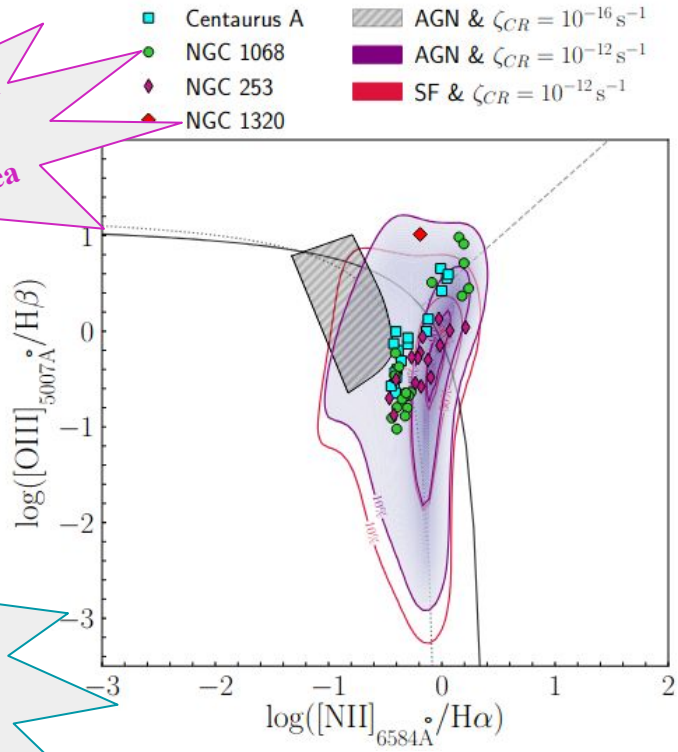
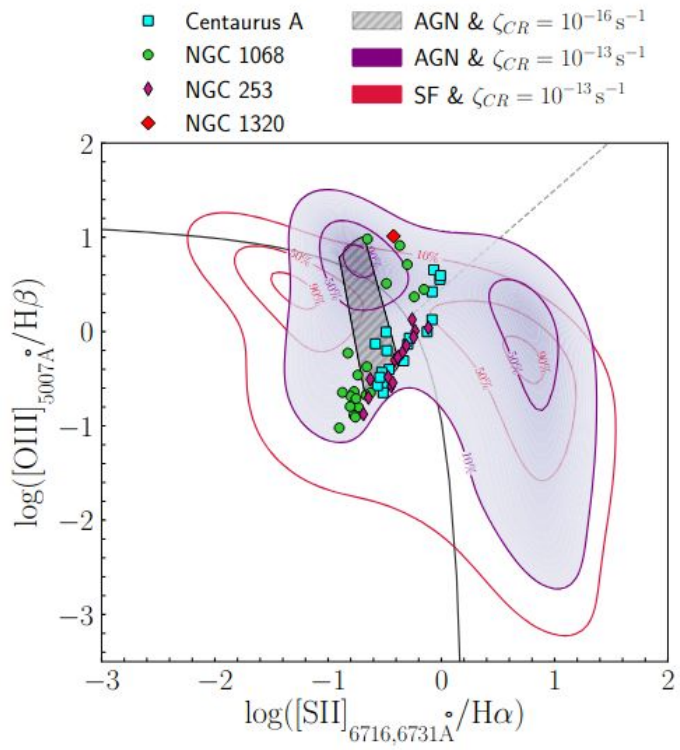
Milky Way CRs ~10^{-16} s^{-1} do not reproduce the Seyfert/LINER area

[NII] needs ~10^{-12} s^{-1}
[SII] needs ~10^{-13} s^{-1}





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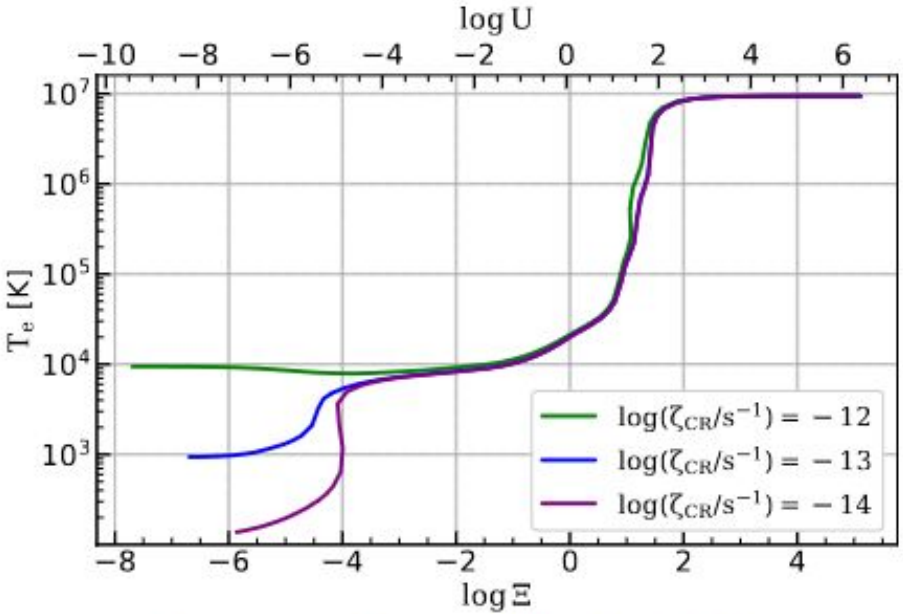
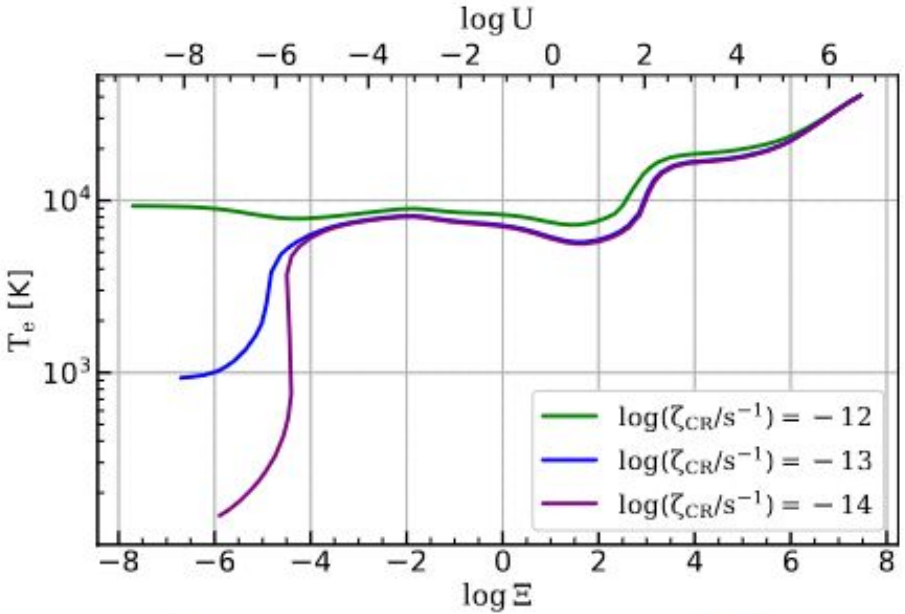
- ***How do CRs affect Te along photoinization?***

AGN Models



(a) Gas temperature for $n_H = 100\,cm^{-3}$, AGN models.

SF Models



(b) Gas temperature for $n_H = 100\,cm^{-3}$, SF models.

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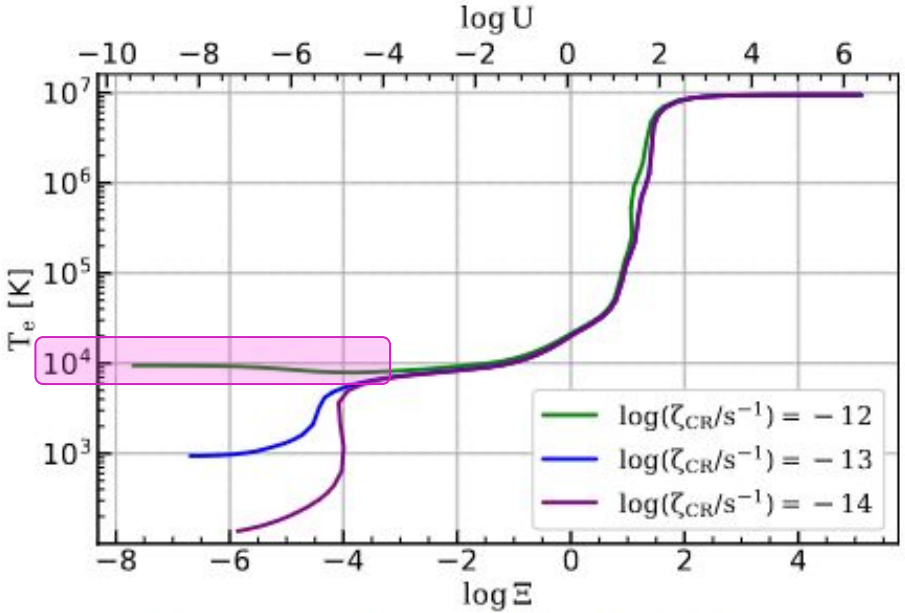
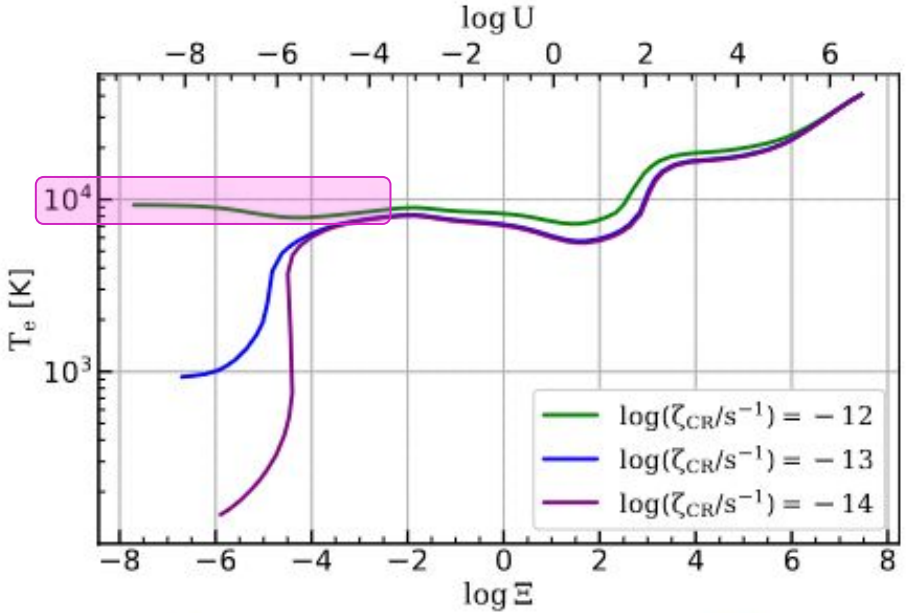
AGN Models



(a) Gas temperature for $n_H = 100\,cm^{-3}$, AGN models.

SF Models



(b) Gas temperature for $n_H = 100\,cm^{-3}$, SF models.

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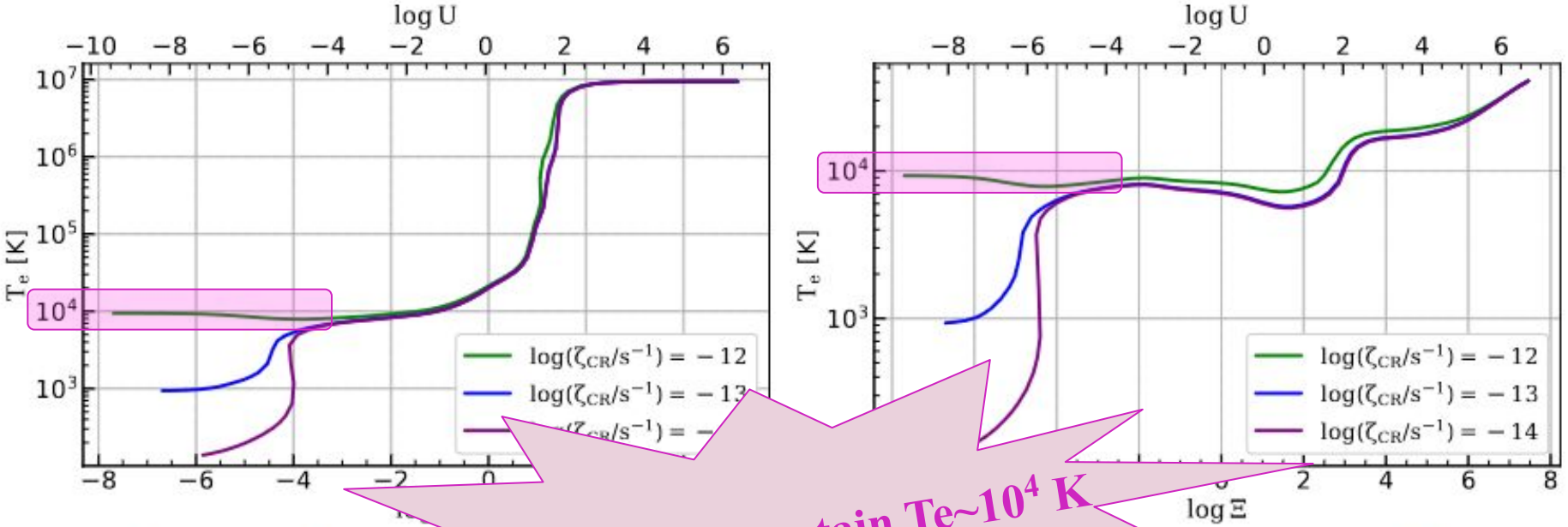
AGN Models

SF Models



(a) Gas temperature fo… …ure for n_H = 100 cm^{-3}, SF models.

High CR rates sustain Te~10^4 K

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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.

Thank you!

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