Max-Planck-Institut für Radioastronomie

Alexander von HUMBOLDT STIFTUNG

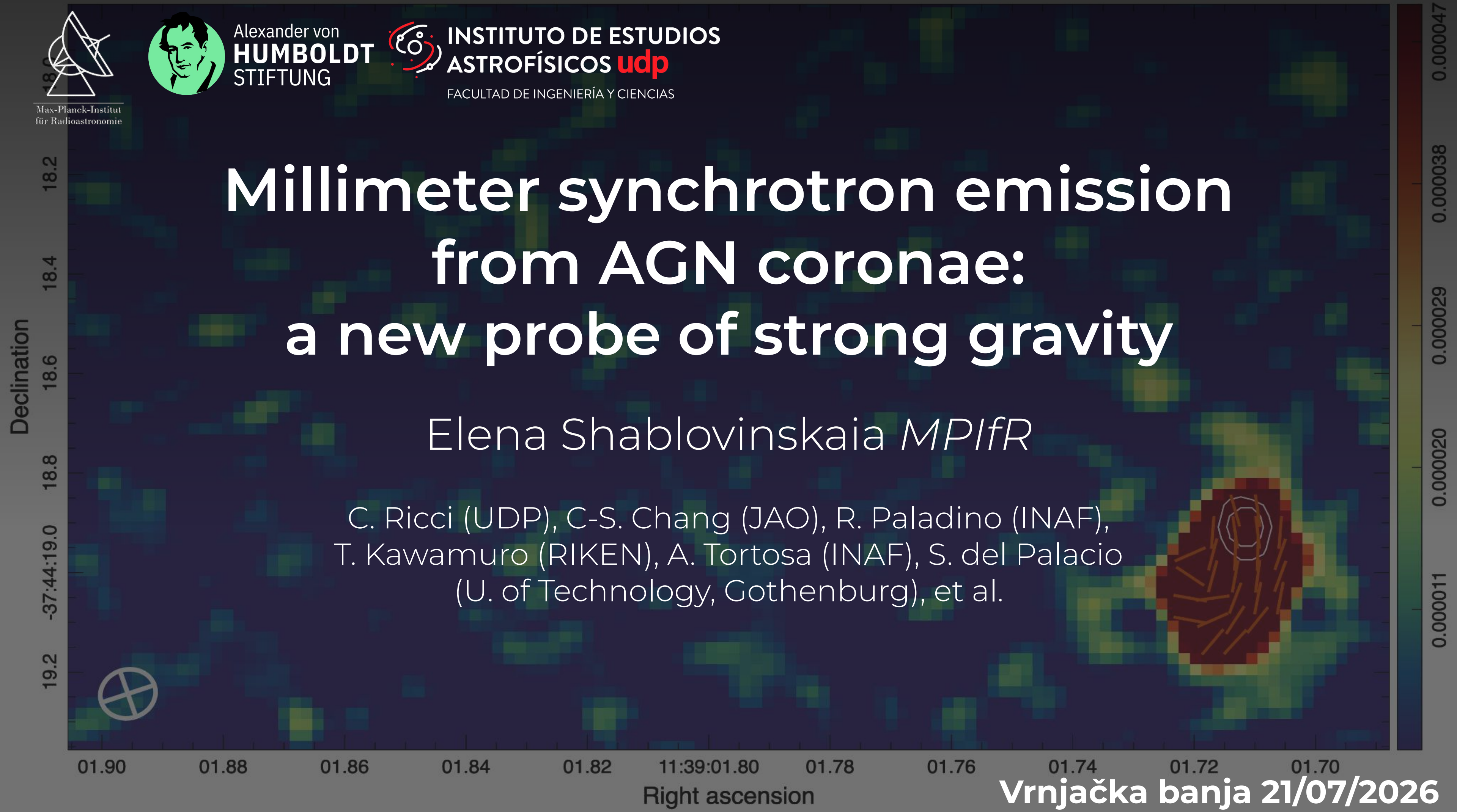
INSTITUTO DE ESTUDIOS ASTROFÍSICOS udp

FACULTAD DE INGENIERÍA Y CIENCIAS

Millimeter synchrotron emission from AGN coronae: a new probe of strong gravity

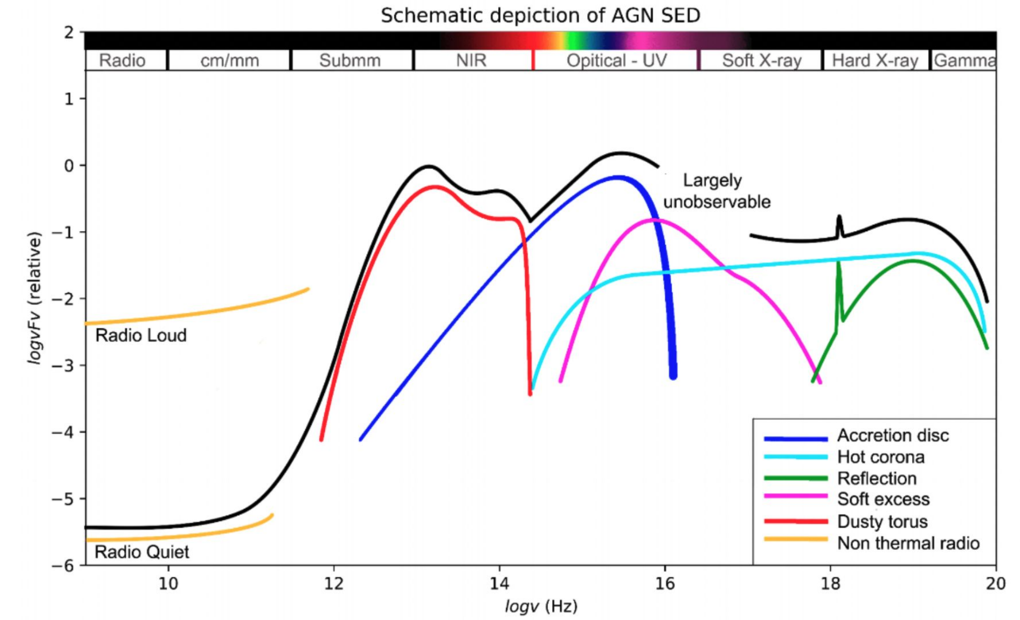
Elena Shablovinskaia *MPIfR*

C. Ricci (UDP), C-S. Chang (JAO), R. Paladino (INAF), T. Kawamuro (RIKEN), A. Tortosa (INAF), S. del Palacio (U. of Technology, Gothenburg), et al.

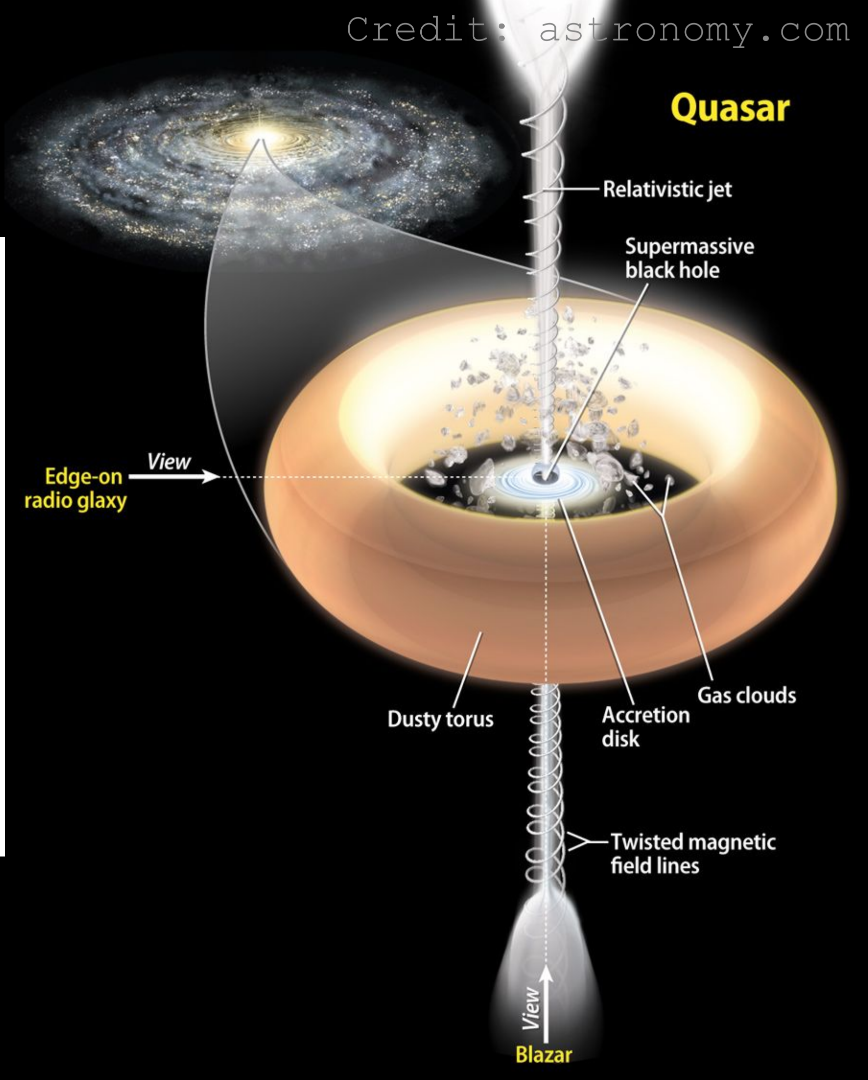


Vrnjačka banja 21/07/2026

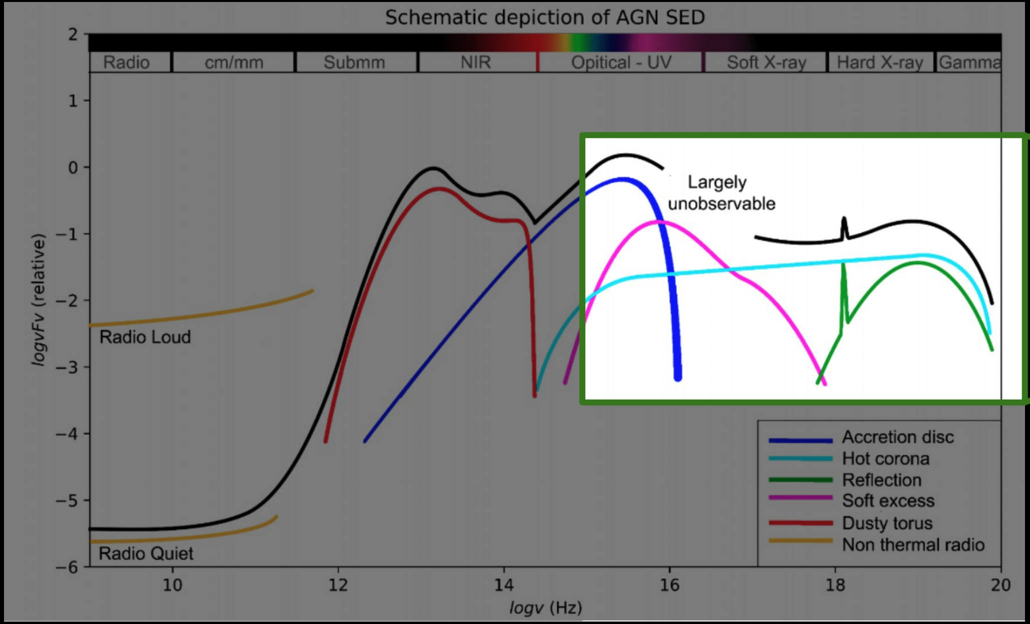
Active Galactic Nuclei

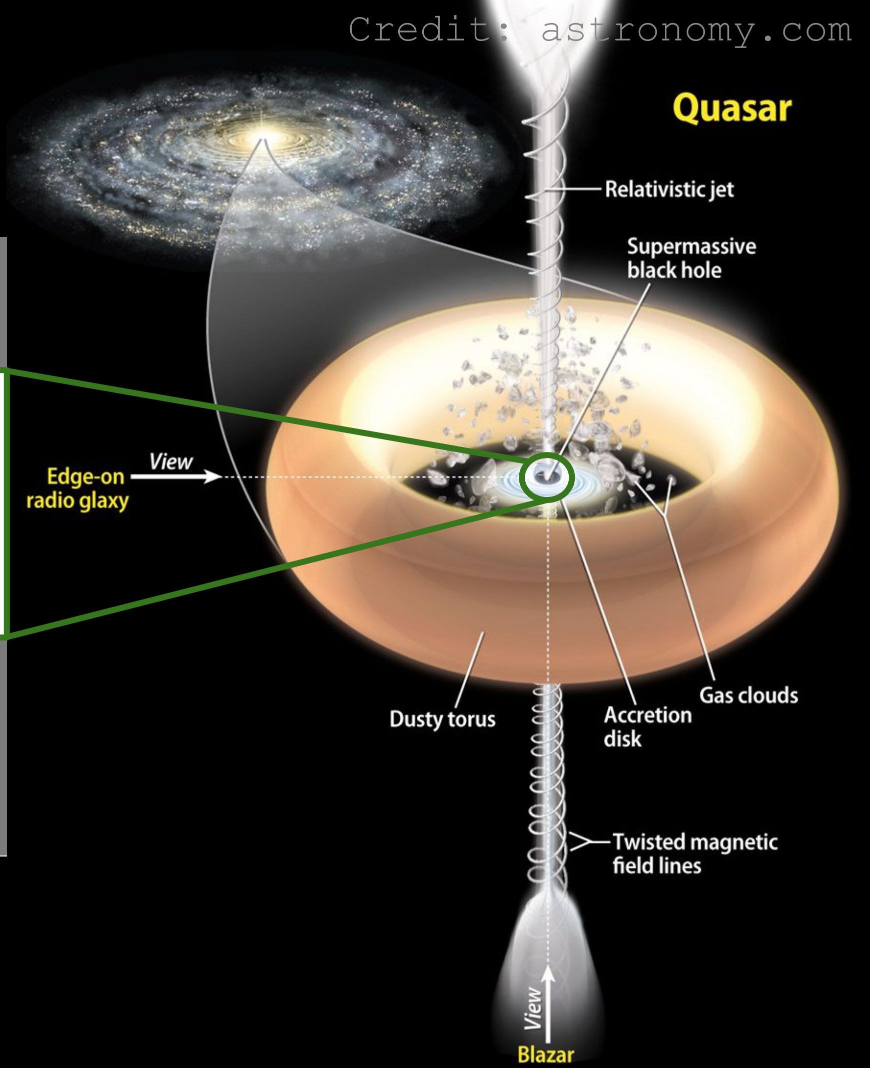


Credit: P. Monaco



Active Galactic Nuclei

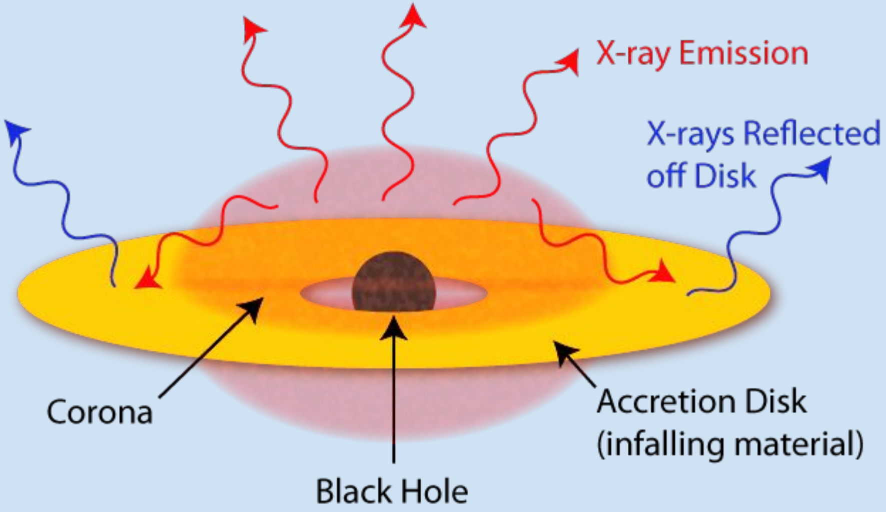




X-ray corona in AGN

- **key AGN feature** – traces energy release and shapes AGN structure
- size of ~tens R_g
- hot (10^8–10^9 K) and dense (10^9 cm^{-3})
- heated via magnetic fields
- inverse Compton scattering on thermal relativistic electrons

Credit: D. wilkins



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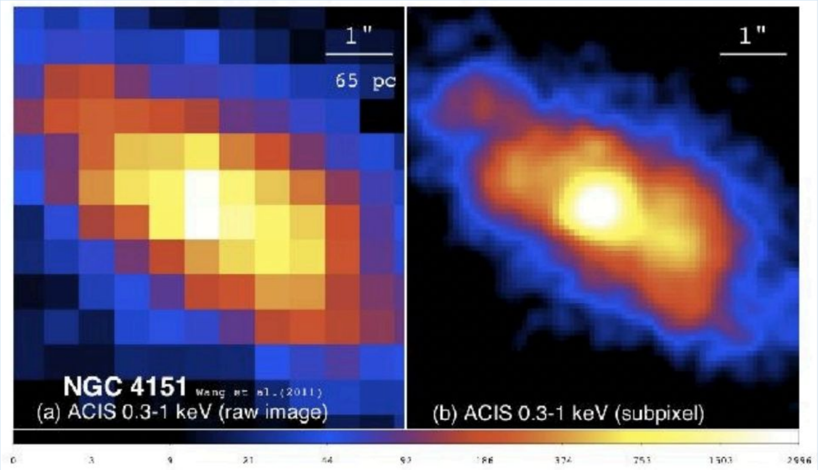
but...

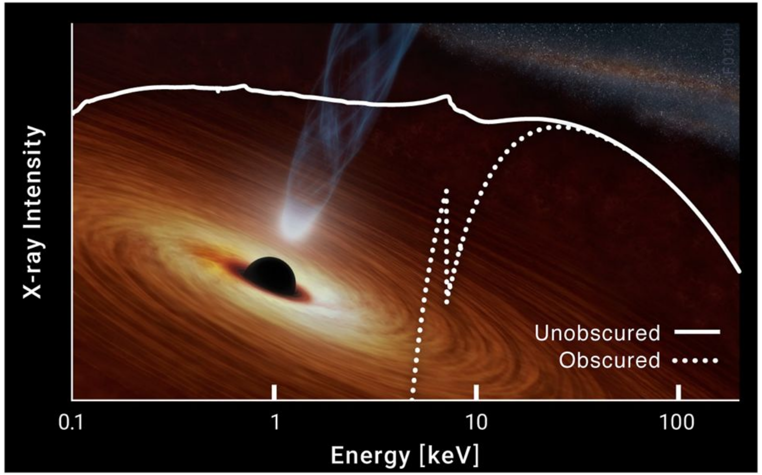


Wang+ 2011, *Chandra*

X-ray corona in AGN: what we <u>don't</u> know

(despite decades of X-ray studies)

- **How compact** is the emitting region?
- How strong and ordered is the **magnetic field**?
- Can we probe the corona through **heavy obscuration**?
- Can the corona **accelerate** non-thermal particles?



García+ 2024

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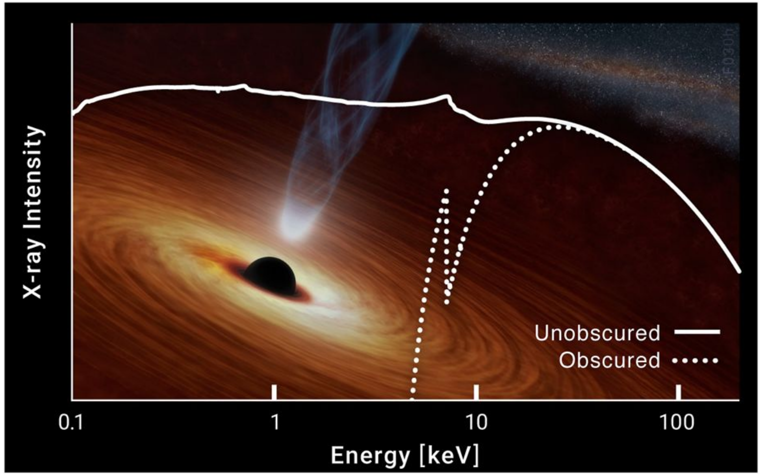
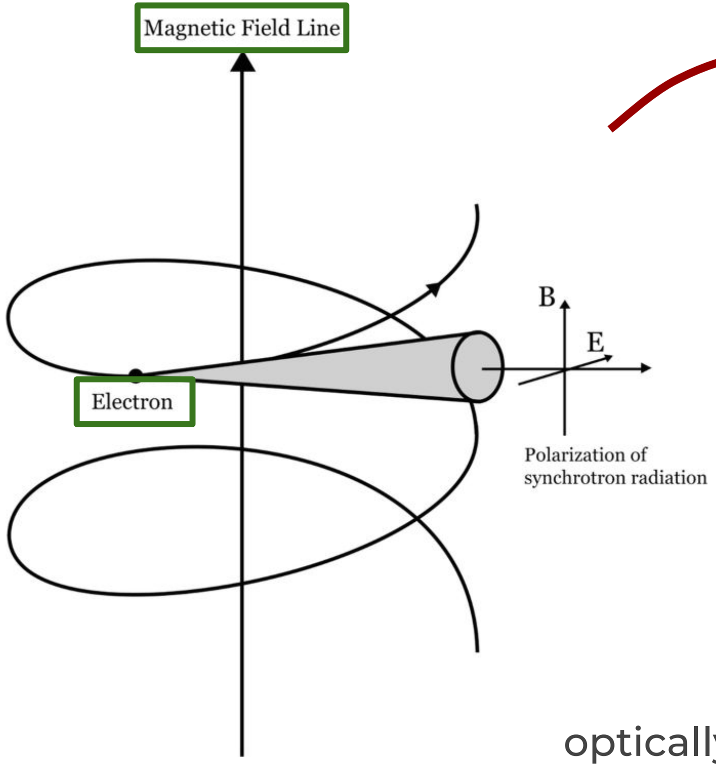
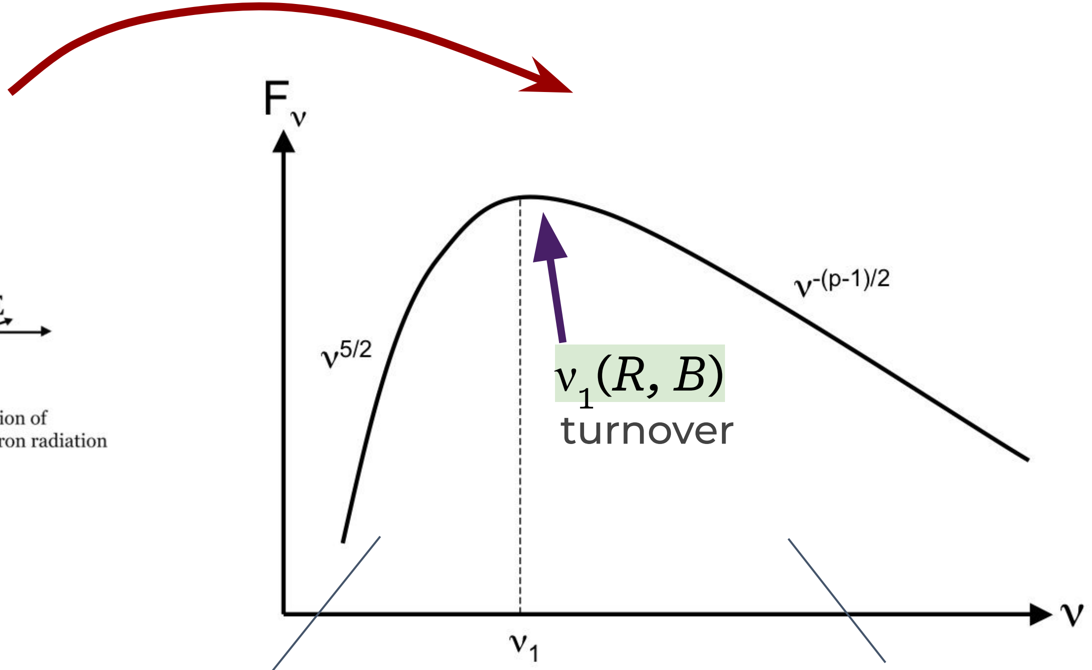
New approach to corona is needed!



García+ 2024

Synchrotron emission



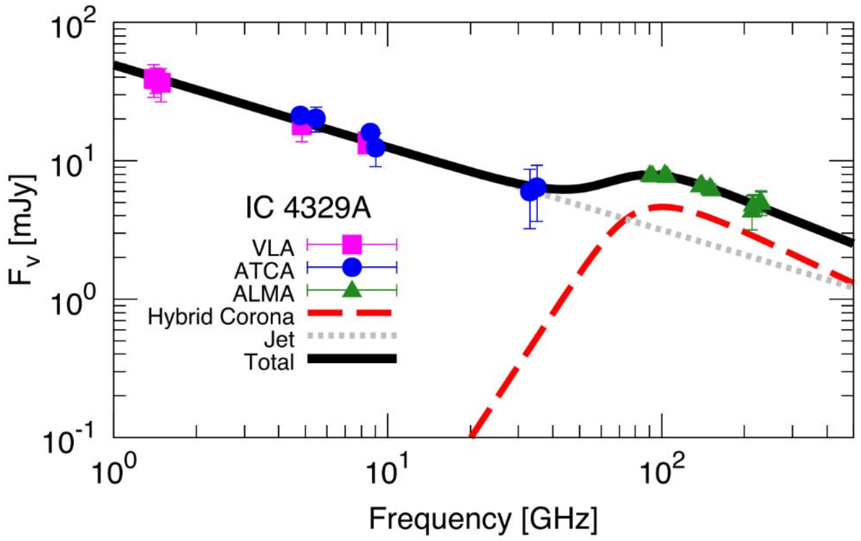


optically thick regime =
synchrotron
self-absorption

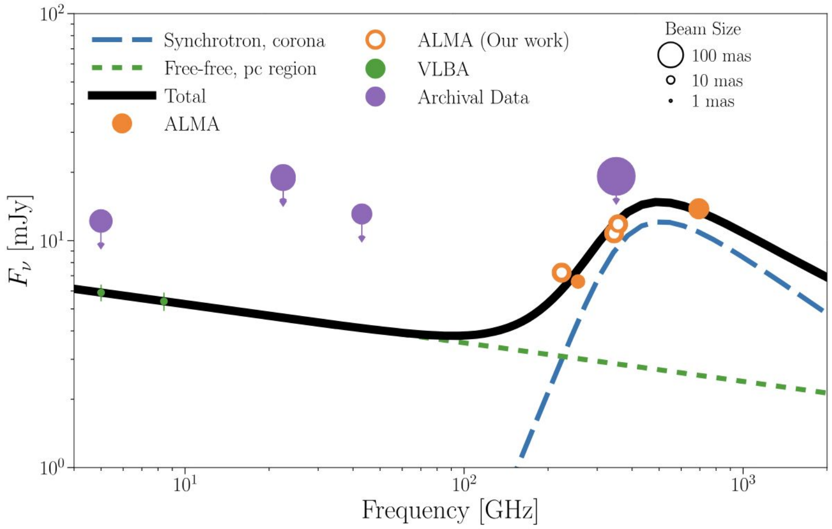
optically thin regime

(1) Spectral turnover ➡ compact magnetized source

Non-jetted AGNs showed mm-excess:



Inoue+Doi 2018: Sy1 IC 4329A & Sy1 NGC 985

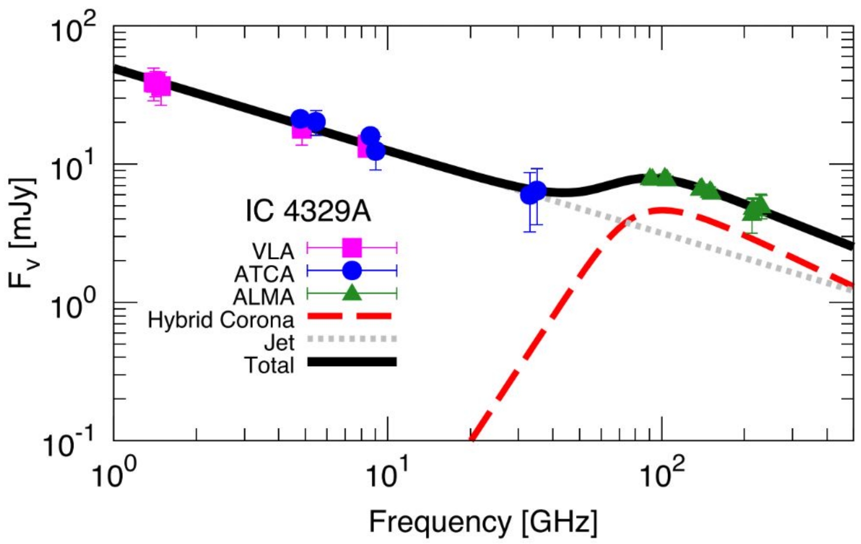


Inoue+ 2020: Sy2 NGC 1068

(1) Spectral turnover ➡ compact magnetized source

Non-jetted AGNs showed mm-excess:

$B \approx 1\text{–}10$ G and $R \approx$ few $\cdot\ 10\ R_g$ ← resembles corona!



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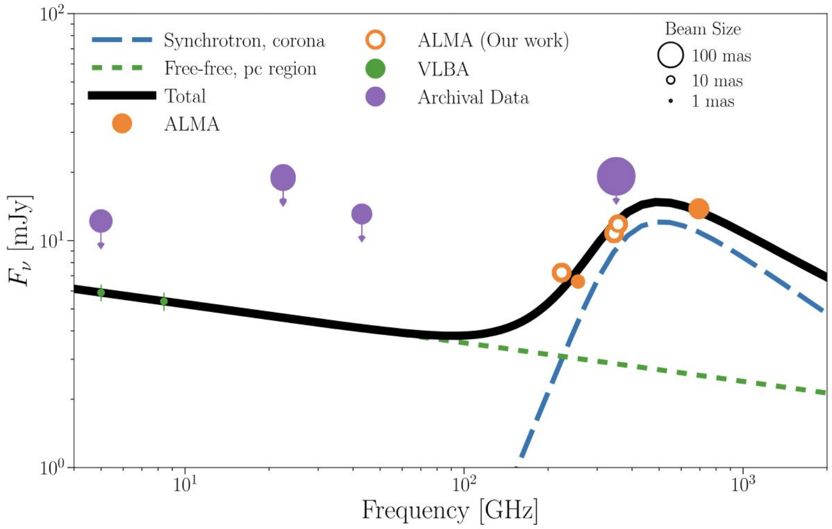
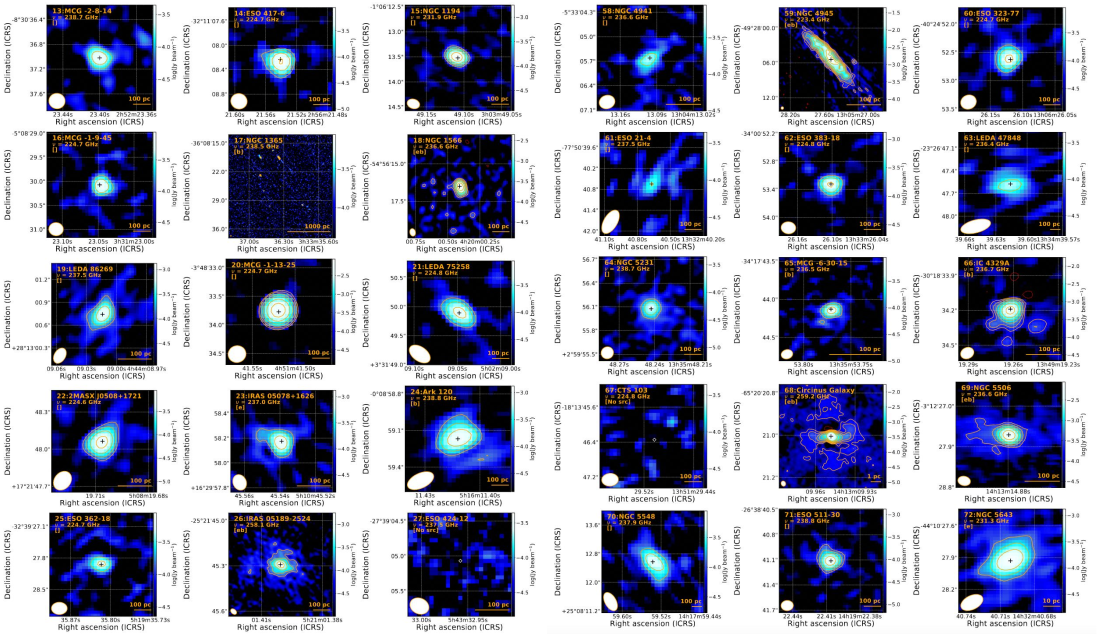


Inoue+ 2020: Sy2 NGC 1068

(2) Compact mm cores are ubiquitous in AGN



Kawamuro+ 2022,2023

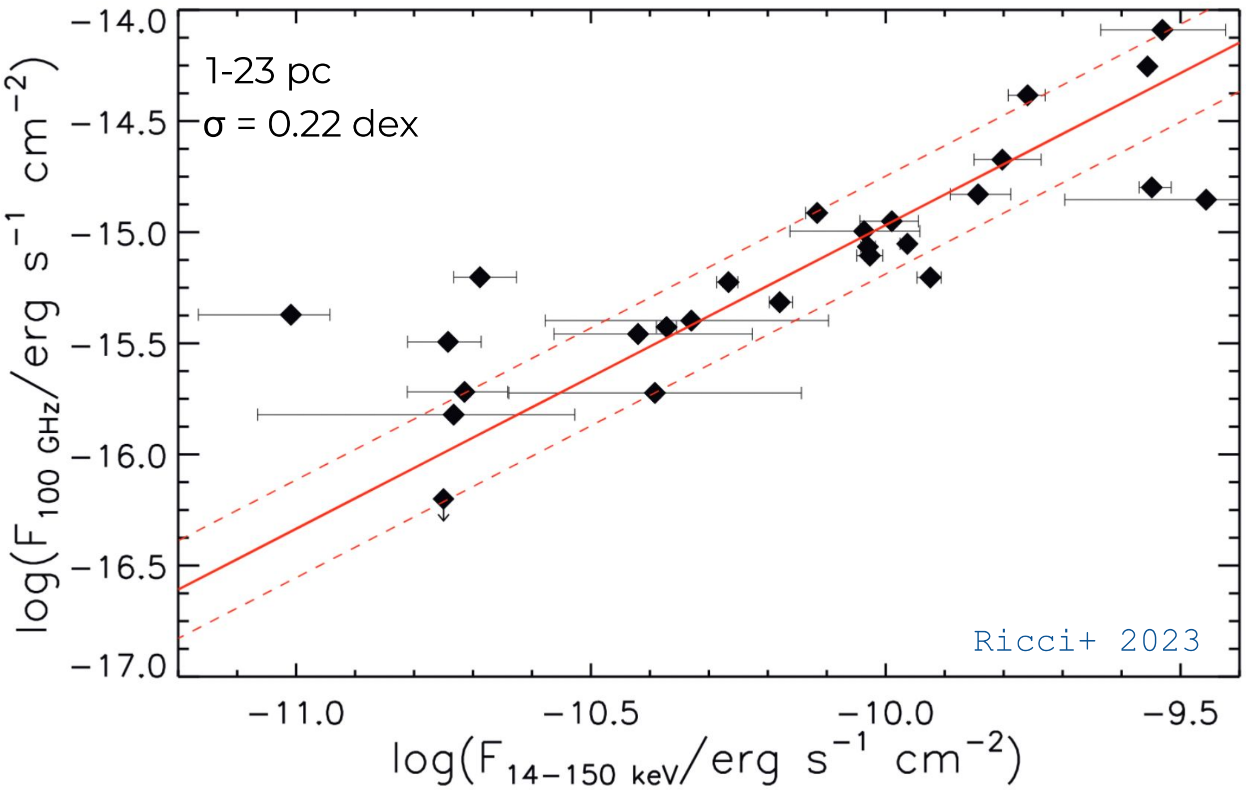
ALMA survey @ 230 GHz:

92% (90/98) of X-ray selected BASS AGNs show compact mm emission

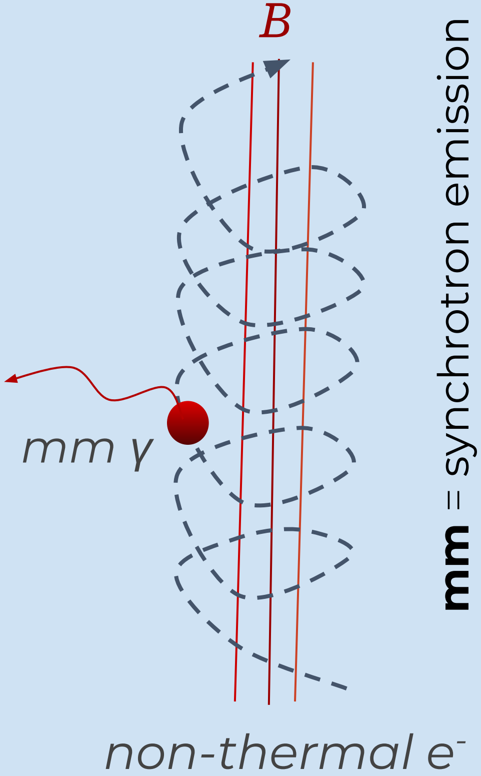
The BAT AGN Spectroscopic Survey
Koss+ 2022

(3) mm and X-ray emission follow a tight relation

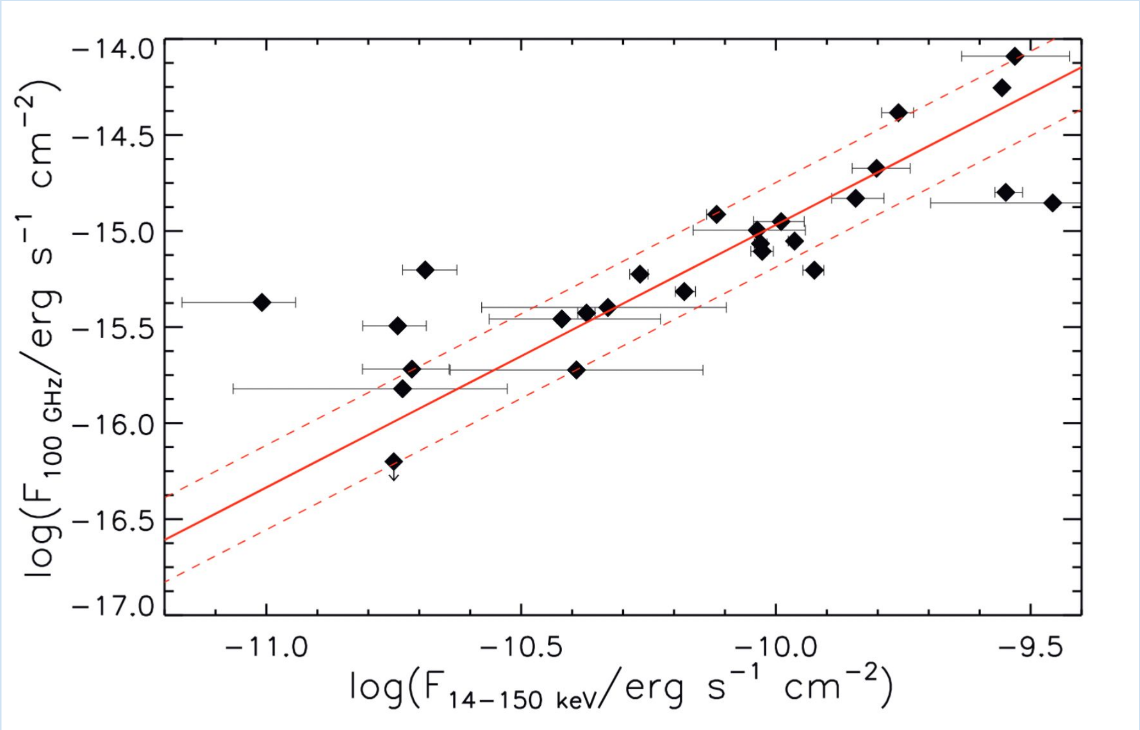
mm emission scales with the accretion powered X-ray engine:



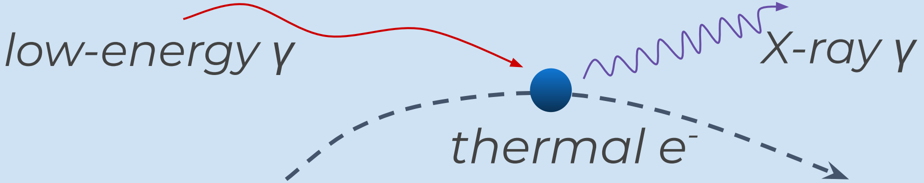
also: Laor+Behar 2008, Behar+ 2015…



mm = synchrotron emission

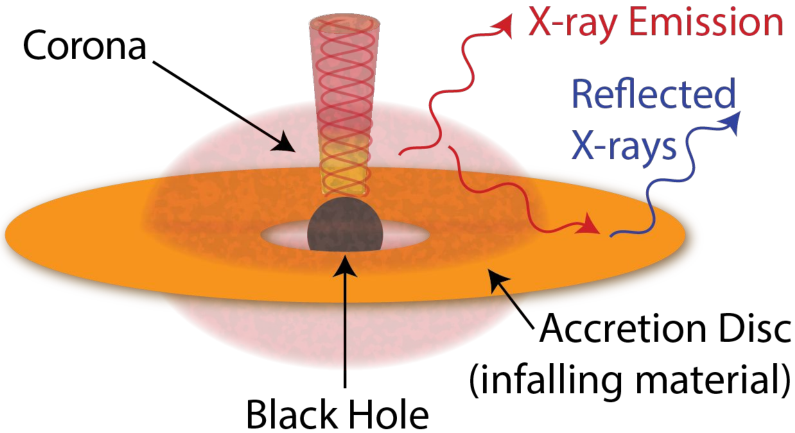


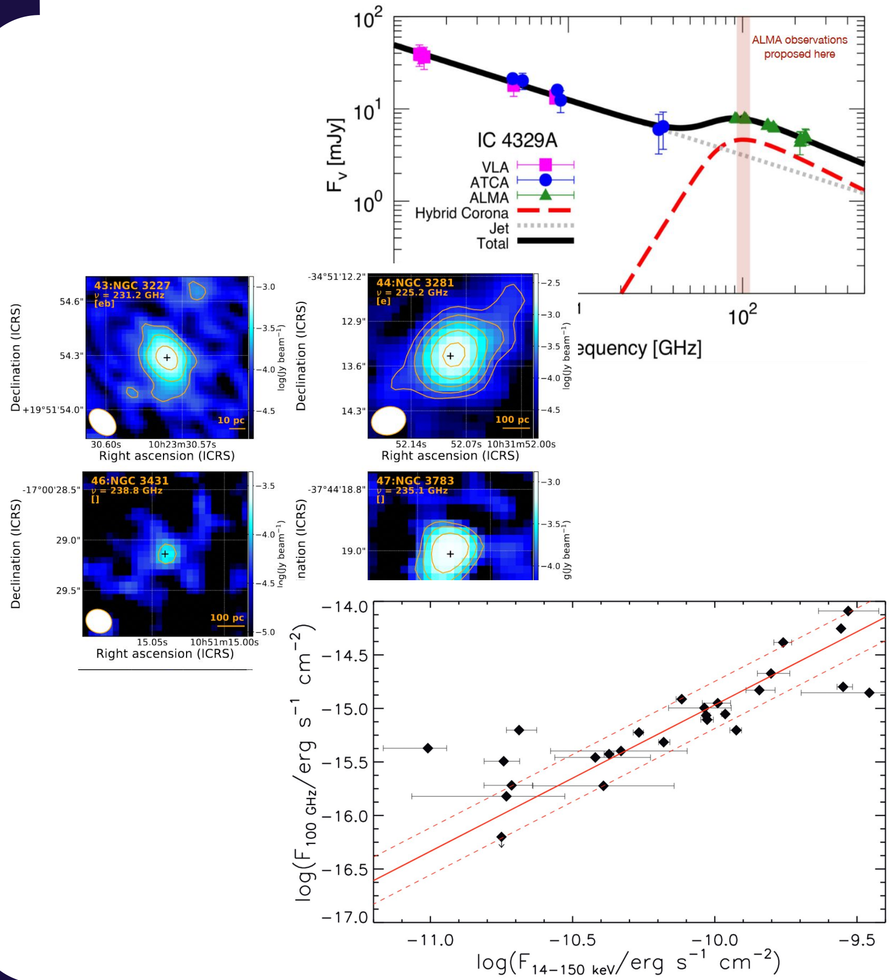
X-ray = inverse Compton scattering



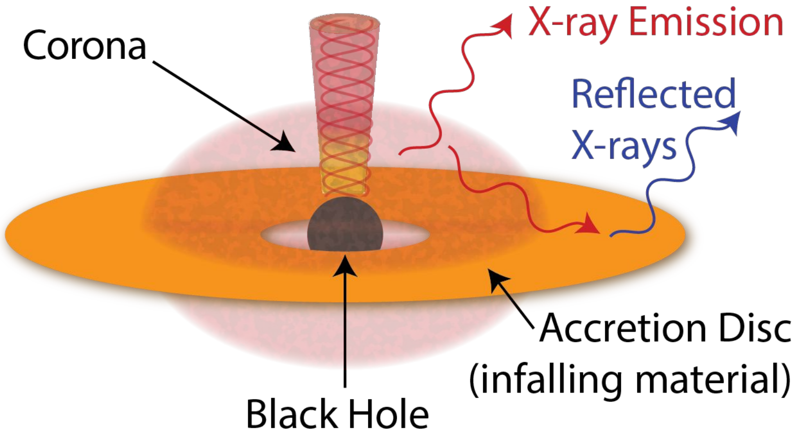
Ricci+ 2023

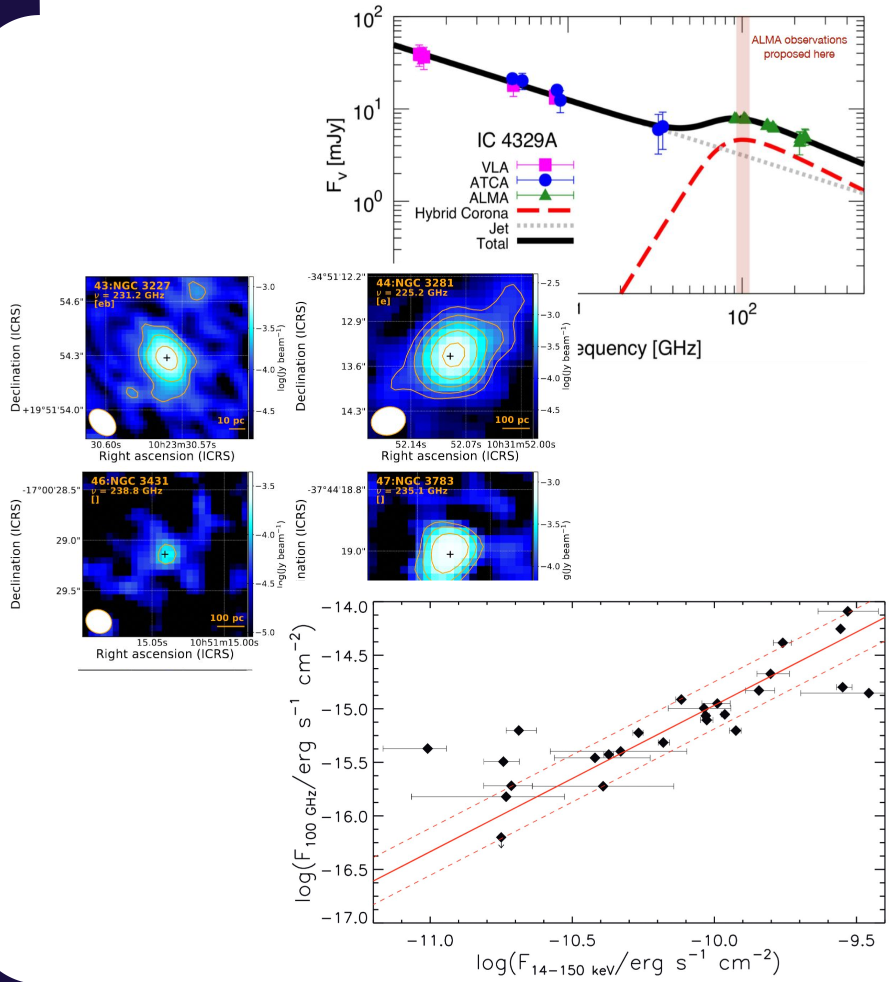
All roads lead to...





All roads lead to...





What new have we recently found?

ALMA turns the corona into...

- **a clock:** variability → size and dynamics
- **a window:** low opacity → obscured accretion
- **a magnetometer:** polarization → magnetic field

mJy sensitivity · 40–950 GHz · down to a few mas · full-Stokes

1. ALMA as a clock: **the corona is violently variable**

mm flux <u>tripled</u> in four days:

$$F_{\mathrm{var}}^{\mathrm{mm}} = 37\%$$

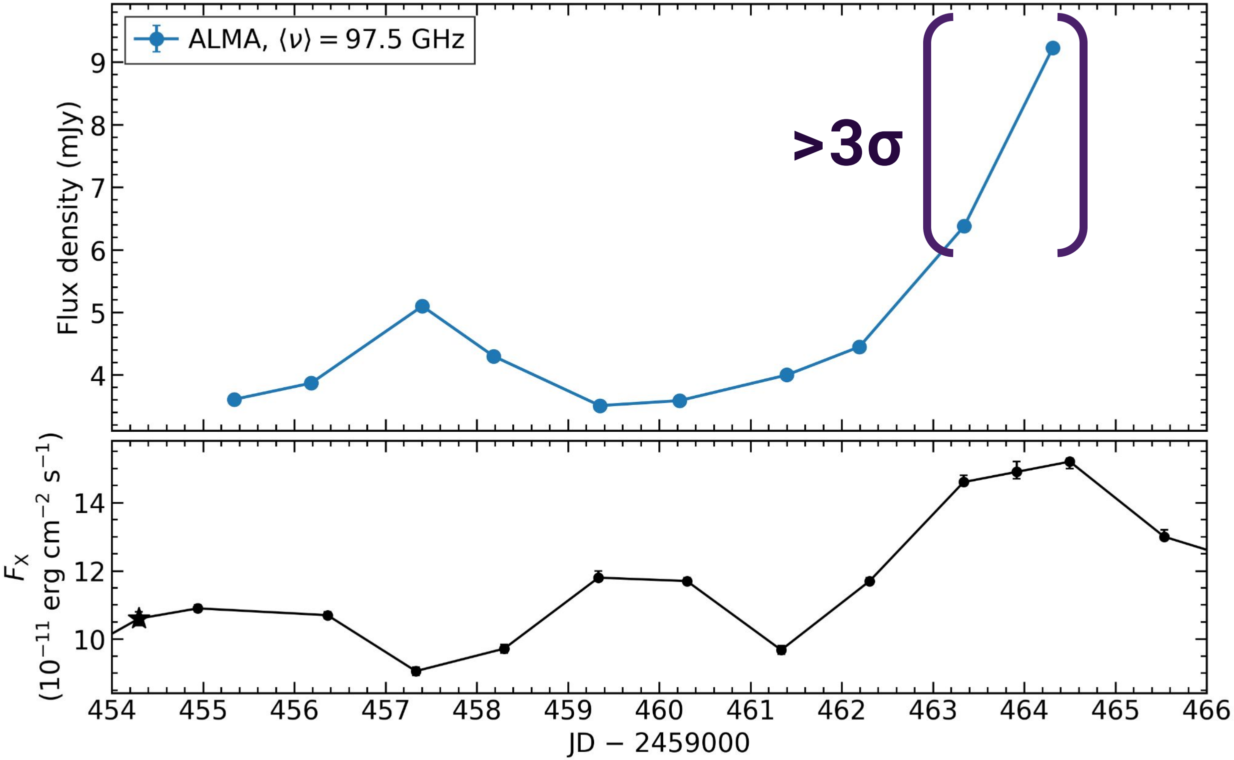
vs

$$F_{\mathrm{var}}^{\mathrm{X}} = 18\%$$

Day-scale variability proves compactness:

$$R \lesssim c\Delta t \lesssim 300\, R_g$$

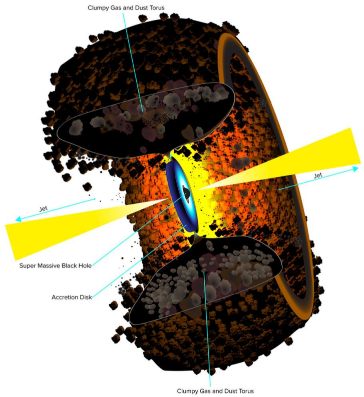
Sy1 IC 4329A

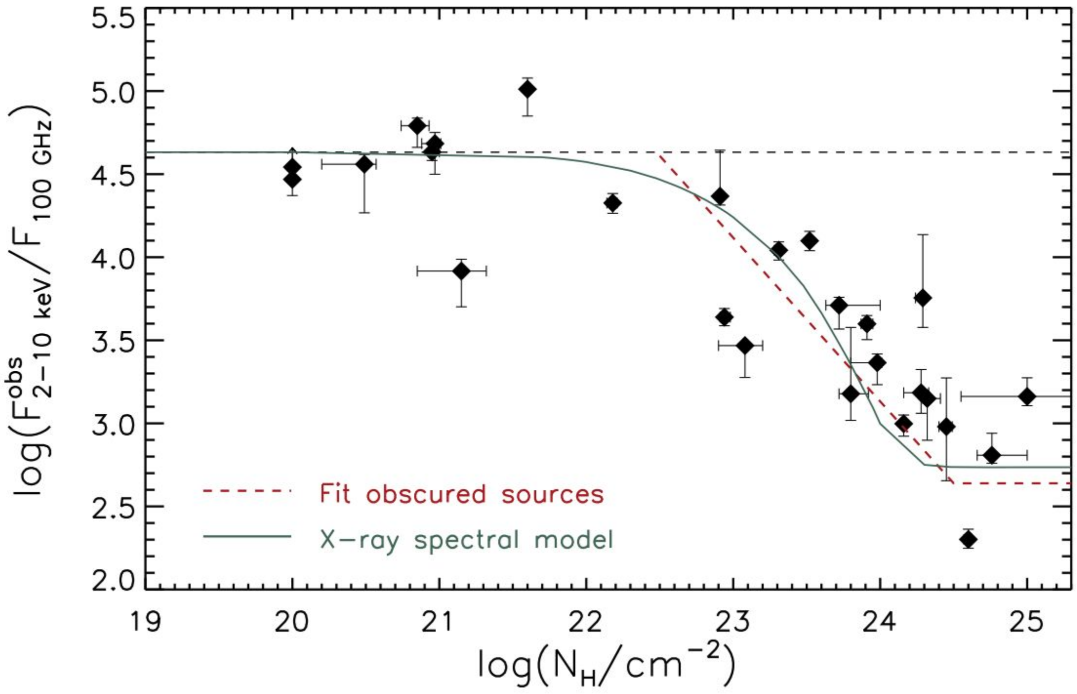


2. ALMA as a window: **access to (hidden) accretion**

At 100 GHz, the torus becomes almost transparent:

up to ~10^3 larger column density



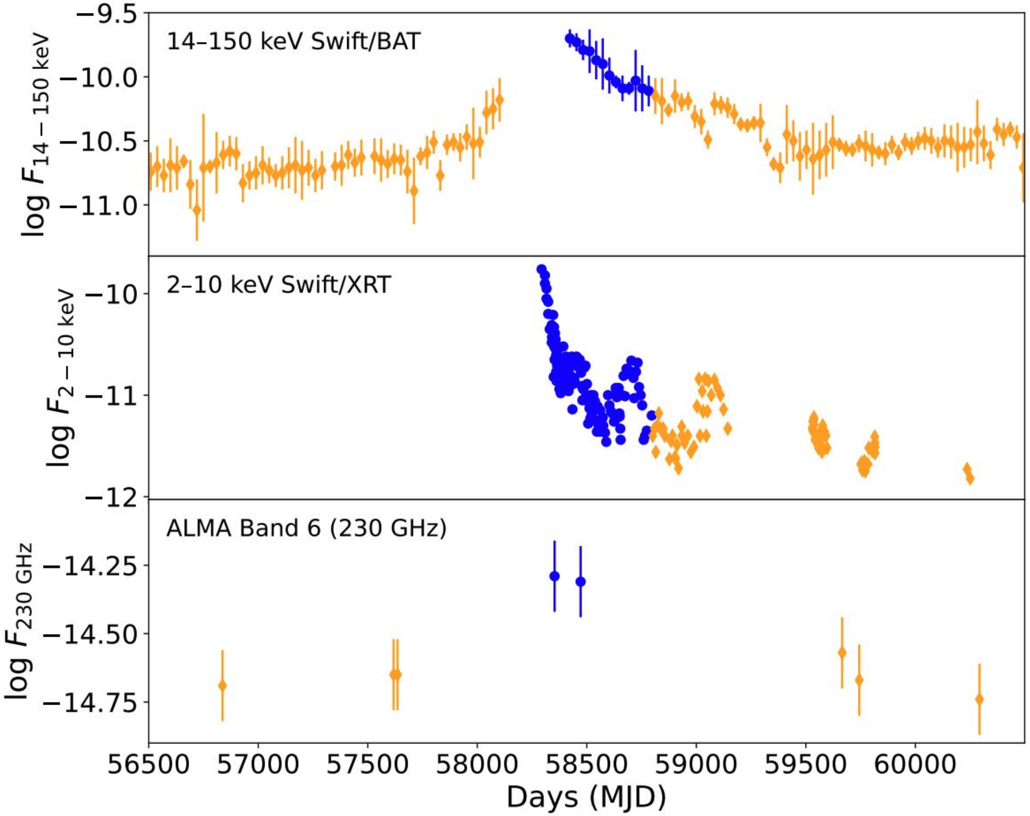


$$\tau_{100\,\mathrm{GHz}} \sim \frac{N_{\mathrm{H}}}{7\times10^{26}\ \mathrm{cm}^{-2}}, \qquad \tau_{10\,\mathrm{keV}} \sim \frac{N_{\mathrm{H}}}{8\times10^{23}\ \mathrm{cm}^{-2}}$$

Ricci+ 2023

2.1 The mm core follows a changing-look transition

NGC 1566:
● type 1, ◆ type 2



Jana+ 2023

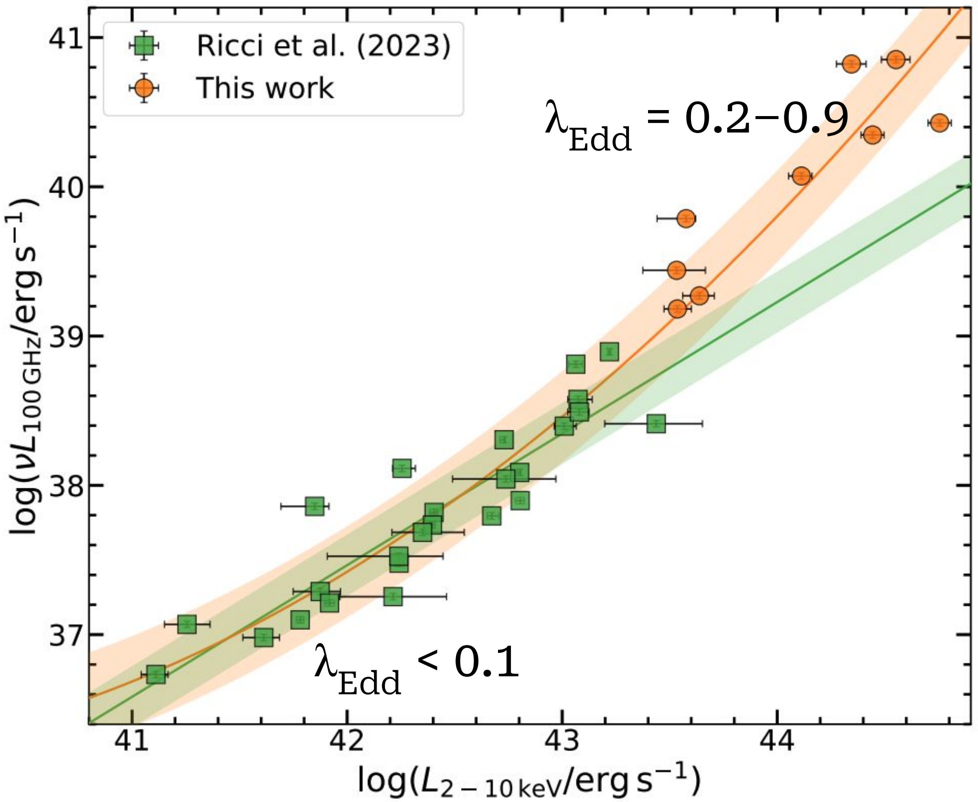
2.2 High-Eddington AGNs deviate

mm are too bright for their X-rays:

Enhanced non-thermal emission?

X-ray suppression?

A different coronal state?



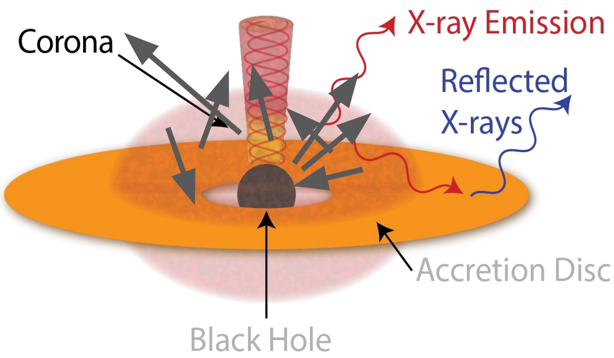
Venselaar+ 2026

3. ALMA as a magnetometer: **the missing polarization**

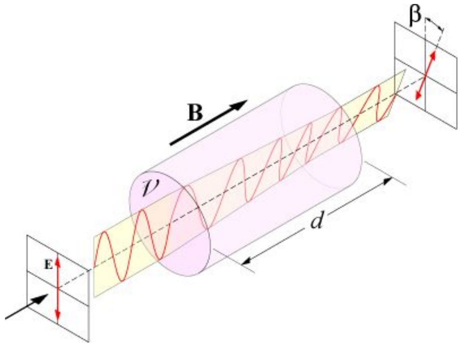
Textbook synchrotron polarization: $\mathrm{PD} = 70\% \perp B$

In real life, we never have it:

- disordered MF



- Faraday effect



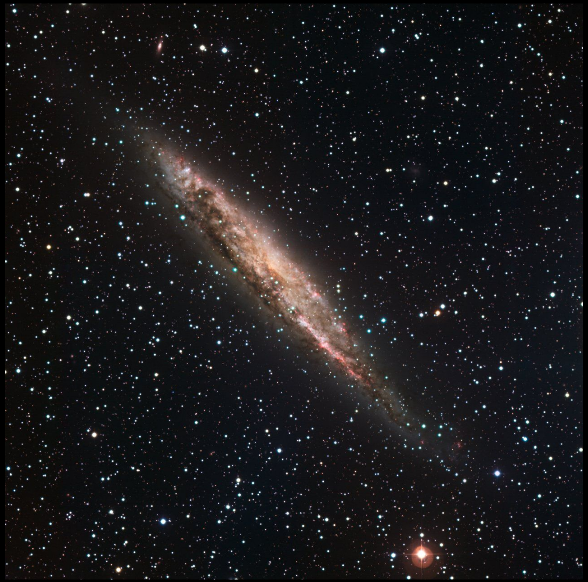
$$\mathrm{RM} = \mathrm{const} \cdot n_e B\, d$$
$$\mathrm{PD_{obs}} \downarrow = \mathrm{RM} \uparrow$$

NGC 3783
type 1

2021:
2.2 mJy

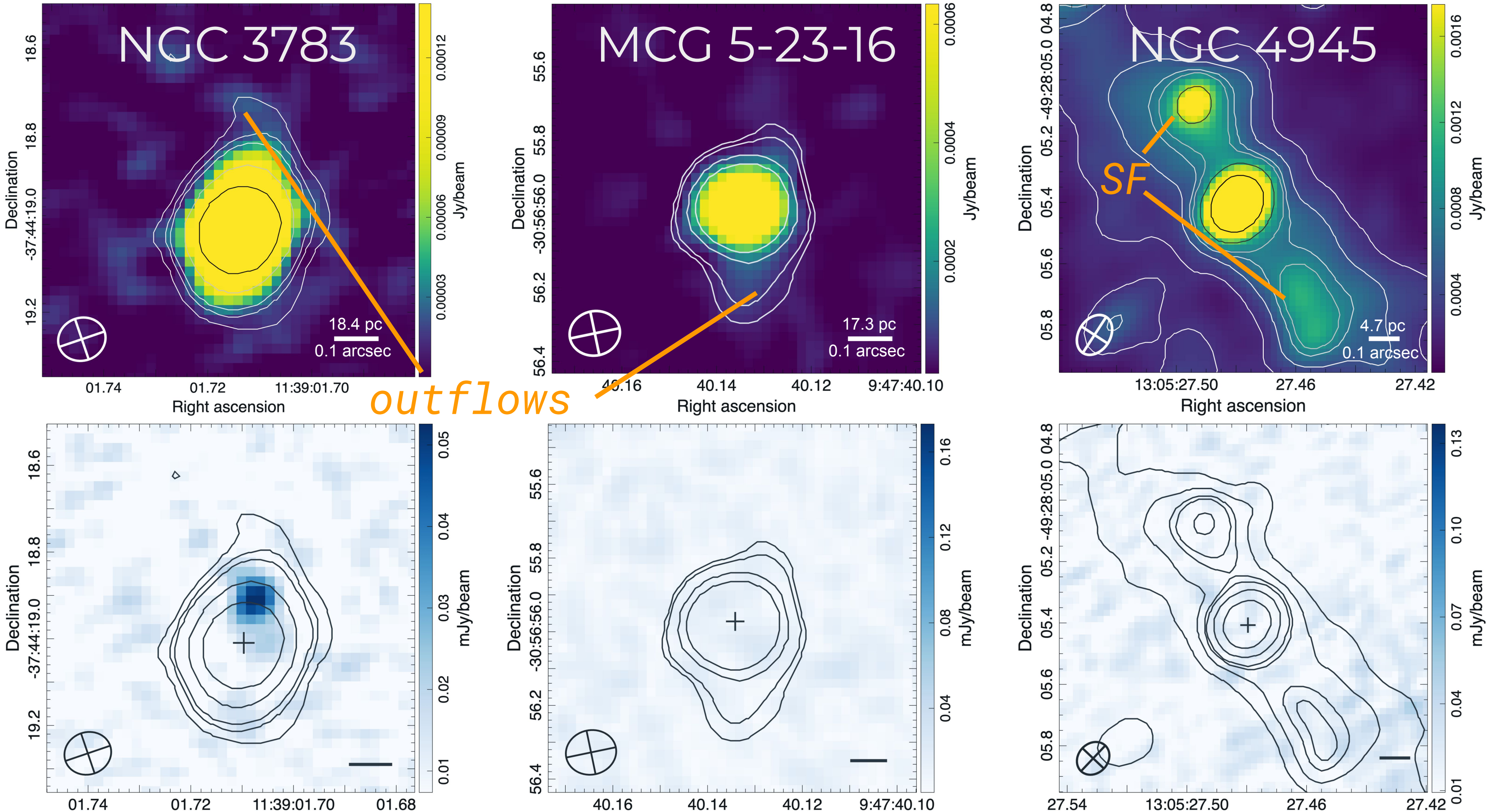
MCG 5-23-16
type 1.9

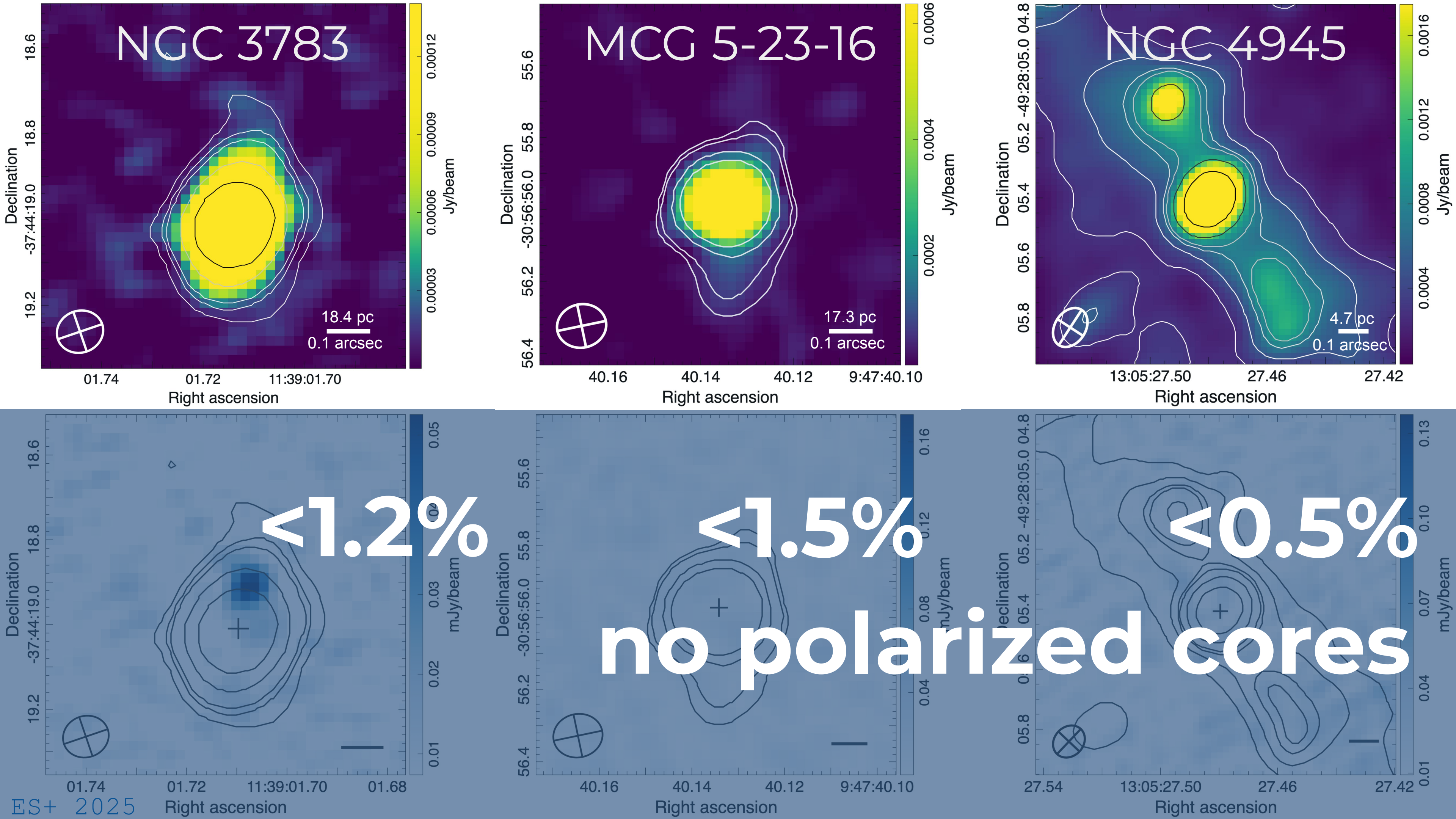
2021:
4.1 mJy



NGC 4945
type 2

2021:
8.1 mJy


NGC 3783
MCG 5-23-16
NGC 4945
outflows
SF
18.4 pc
0.1 arcsec
17.3 pc
0.1 arcsec
4.7 pc
0.1 arcsec
Declination
Right ascension
Jy/beam
mJy/beam
-37:44:19.0
-30:56:56.0
-49:28:05.0
11:39:01.70
9:47:40.10
13:05:27.50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4.7 pc
-37:44:19.0
-30:56:56.0
-49:28:05.0
11:39:01.70
9:47:40.10
13:05:27.50
<1.2%
<1.5%
<0.5%
no polarized cores
ES+ 2025

3. ALMA as a magnetometer: **the missing polarization**

How $\mathrm{PD}_{\mathrm{int}} = 70\% \rightarrow \mathrm{PD}_{\mathrm{obs}} < 1\%$?

- Magnetic field disorder

- Faraday rotation

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$$\mathrm{PD}_{\mathrm{obs}} \simeq \mathrm{PD}_{\mathrm{int}} / \sqrt{N}$$
$$\rightarrow N > 2000 \text{ cells}$$
$$\rightarrow F_{\mathrm{var}} < 2\%$$

This will erase the variability.

not enough!

- Faraday rotation

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This will erase the variability.

not enough!

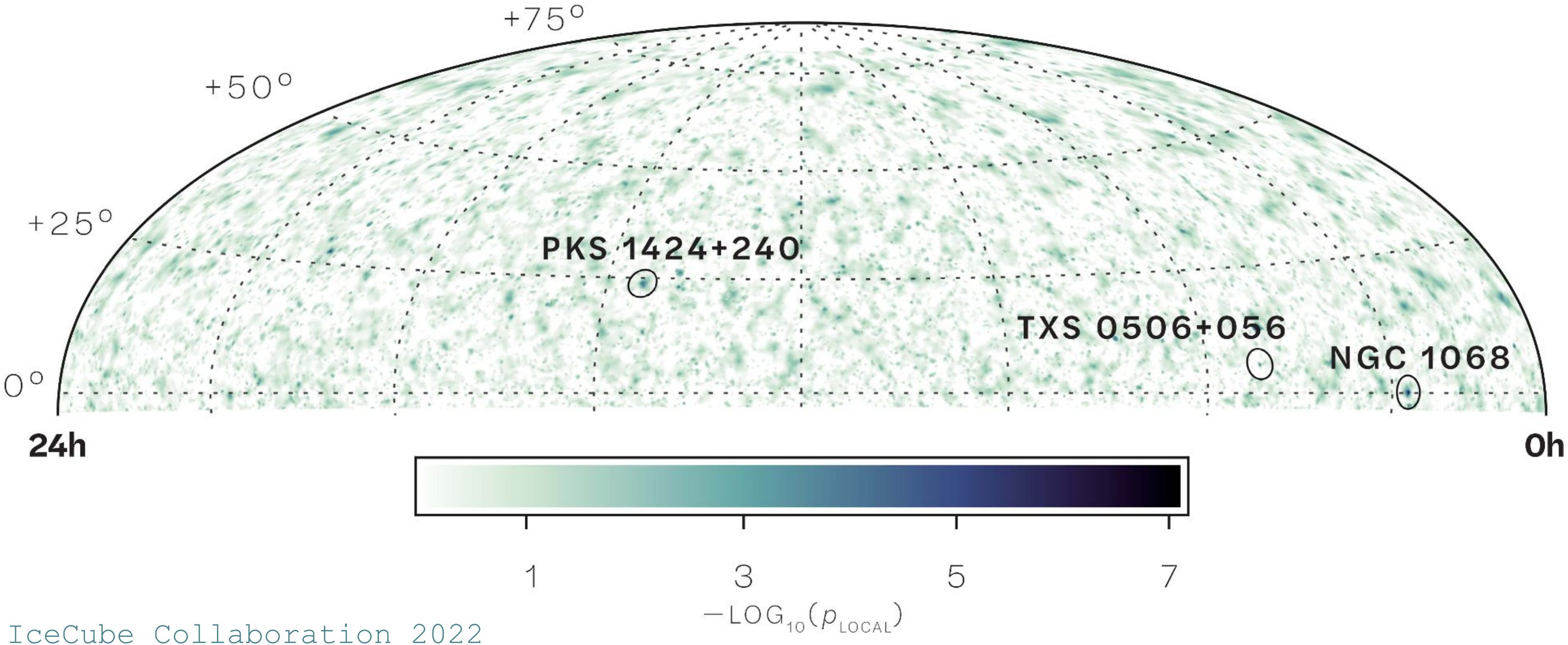
- Faraday rotation

$$R = 10^{-4} - 10^{-6}\ \mathrm{pc}$$
$$B = 1 - 10\ \mathrm{G}$$
$$n_e = 10^{9} - 10^{11}\ \mathrm{cm}^{-3}$$
$$\rightarrow \mathrm{RM} \simeq 10^{\mathbf{11}}\ \mathrm{rad\ m}^{-2}$$
$$\rightarrow \mathrm{PD}_{\mathrm{obs}} \sim 10^{-8}\ \%$$

Zero polarization is exactly what a corona predicts!*

*unless you find the right AGN

4. A radio-quiet AGN is seen in neutrinos



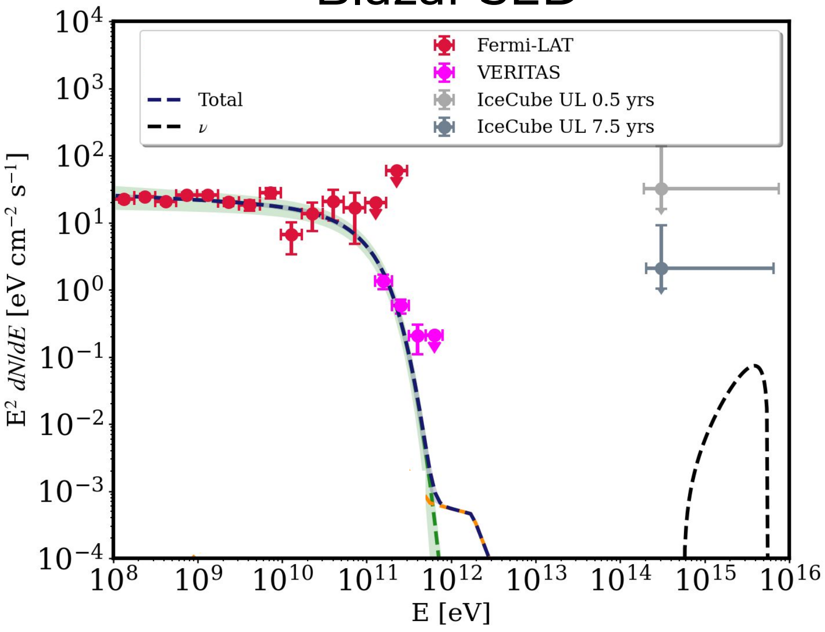
IceCube Collaboration 2022

4. A radio-quiet AGN is seen in neutrinos

Why were we surprised?

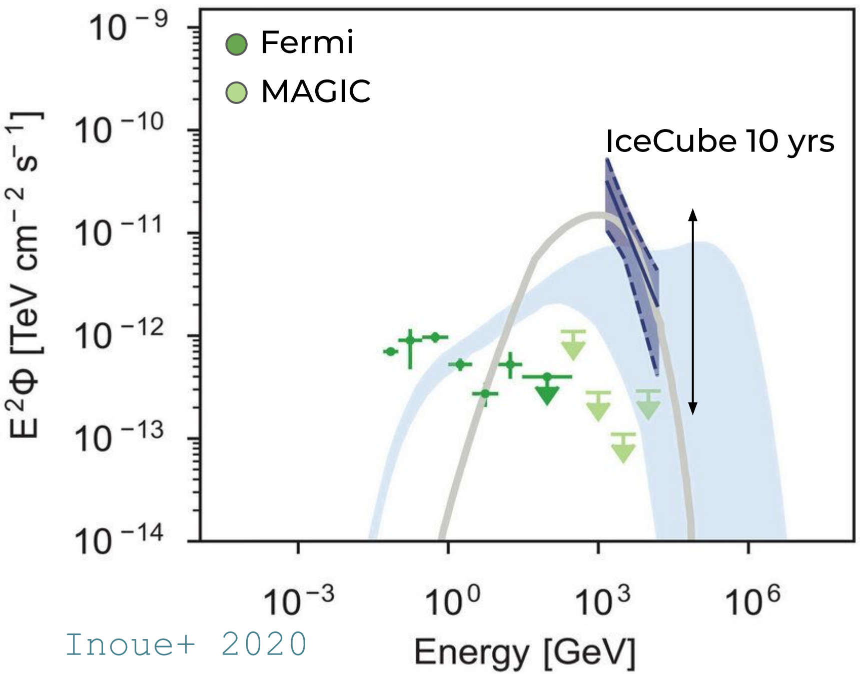
TeV neutrino are produced by hadron processes: pp or $p\gamma \rightarrow \nu + \gamma(\mathrm{GeV})$

Blazar SED



Acharyya+ 2025

NGC 1068 SED



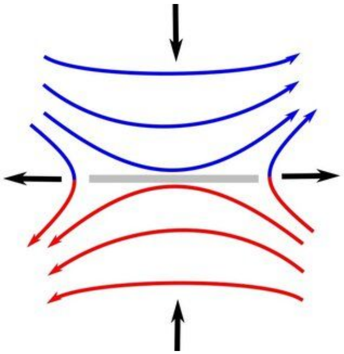
Inoue+ 2020

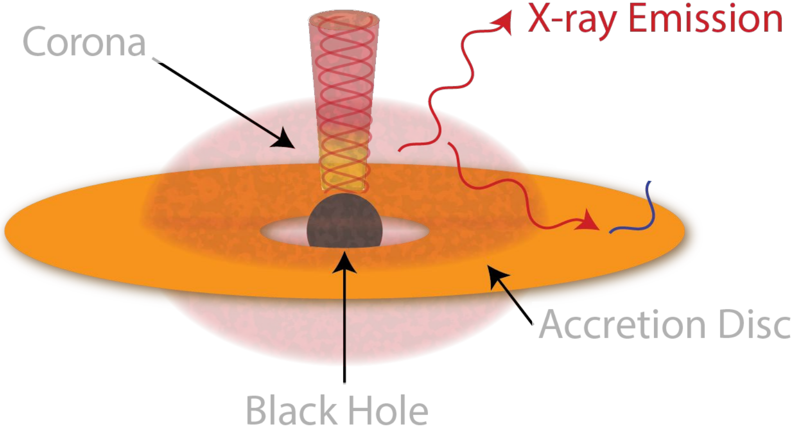
4. The corona is a natural hidden accelerator

dense radiation and matter provide **interaction** targets

pp or $p\gamma \dashrightarrow \nu + \gamma(\mathrm{GeV})$

magnetic reconnection **accelerates** particles





GeV photons are **absorbed**

$\gamma(\mathrm{keV}) + \gamma(\mathrm{GeV}) \rightarrow e^- + e^+$

4. What can ALMA tell us about corona acceleration?

mm synchrotron

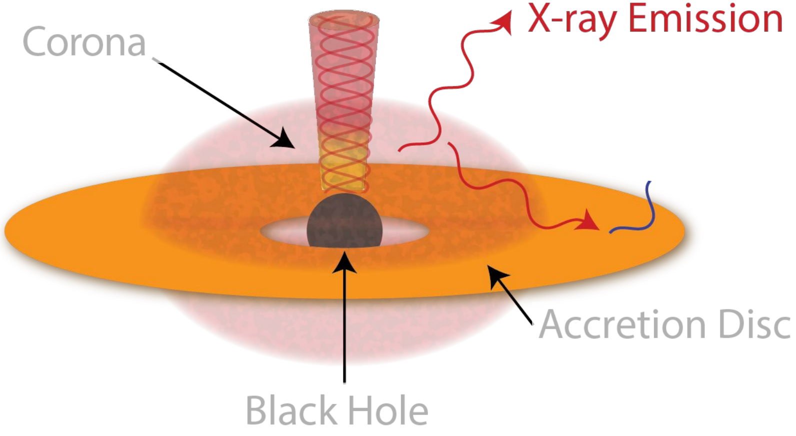
↓

- non-thermal electrons
- magnetic field
- energy dissipation

neutrinos

↓

- non-thermal hadrons
- energy budget



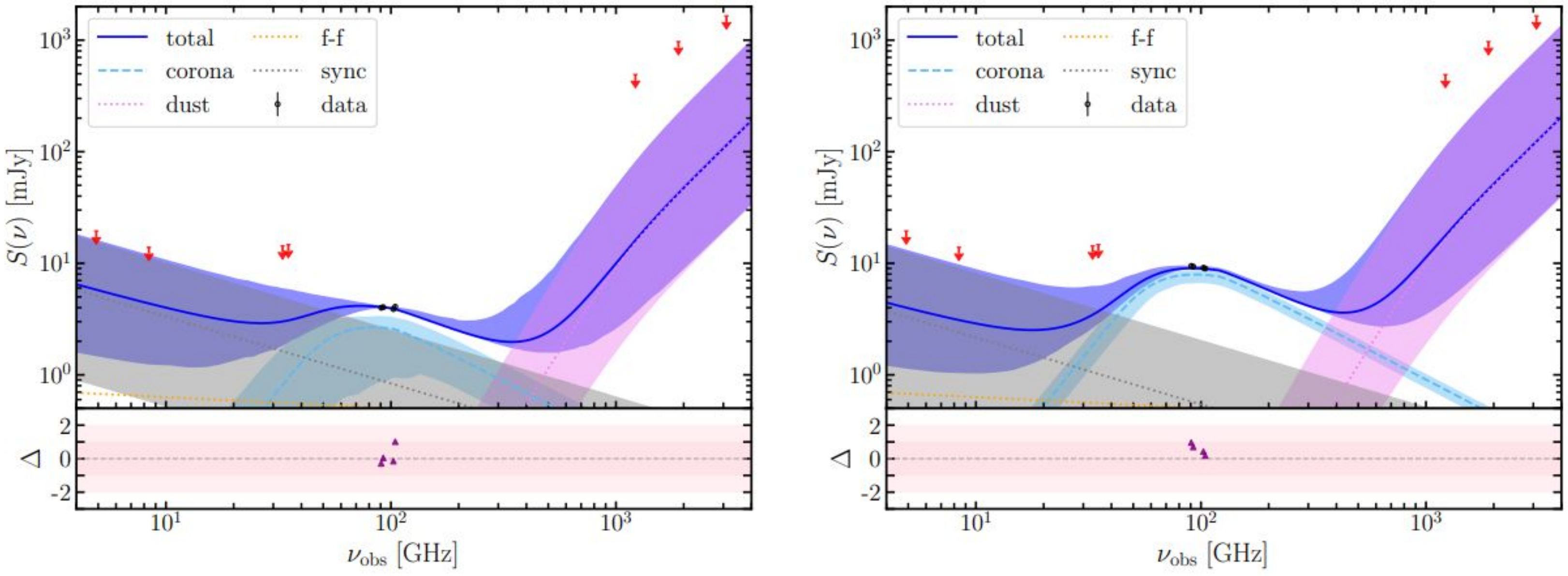
Summary

- compact mm synchrotron is common in RQ AGN
- fast mm variability implies coronal scales
- mm probes much heavier obscuration than X-rays
- missing polarization implies extreme Faraday depolarization
- coronae may host hidden particle acceleration and neutrino production

X-rays discovered the corona.
ALMA starts measuring what X-rays cannot.

Back up

Spectral modelling

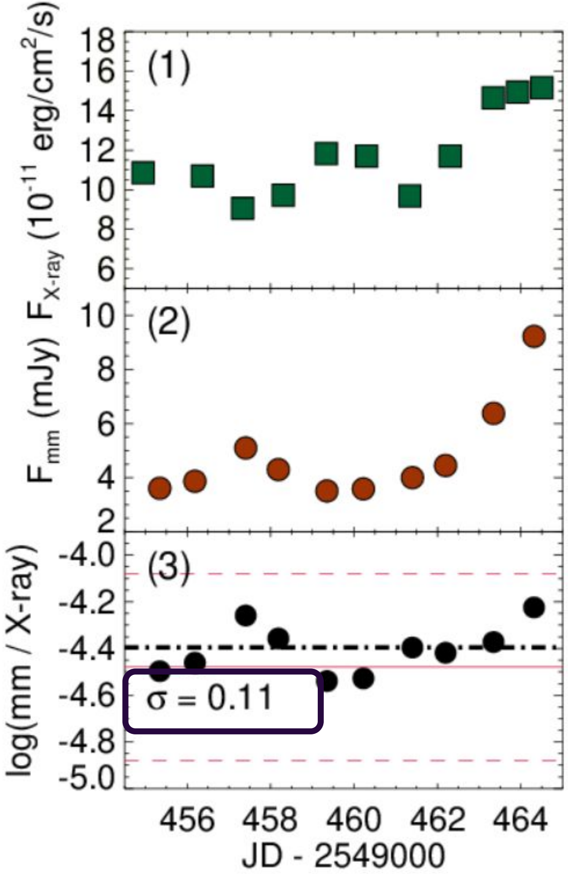


(a) MJD=59461.41

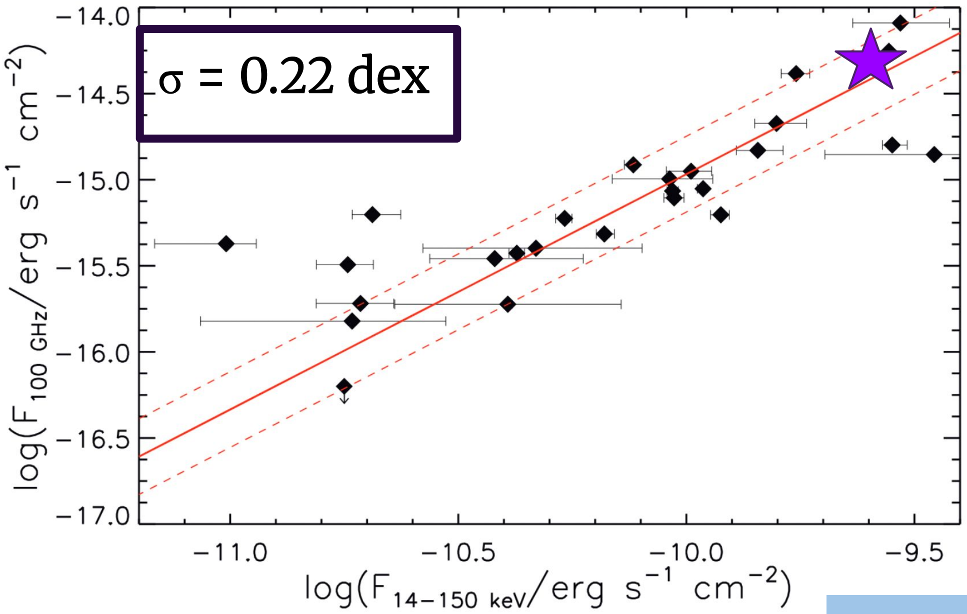
(b) MJD=59464.32

day #7 – R = 179 +-60 Rg (0.70 ld) // B = 10.4 G
day #8 – R = 204 +-70 Rg (0.80 ld) // B = 9.3 G
day #9 – R = 258 +-50 Rg (1.01 ld) // B = 9.6 G
day #10 – R = 368 +-60 Rg (1.44 ld) // B = 7.5 G

Variability of mm/X-ray relation

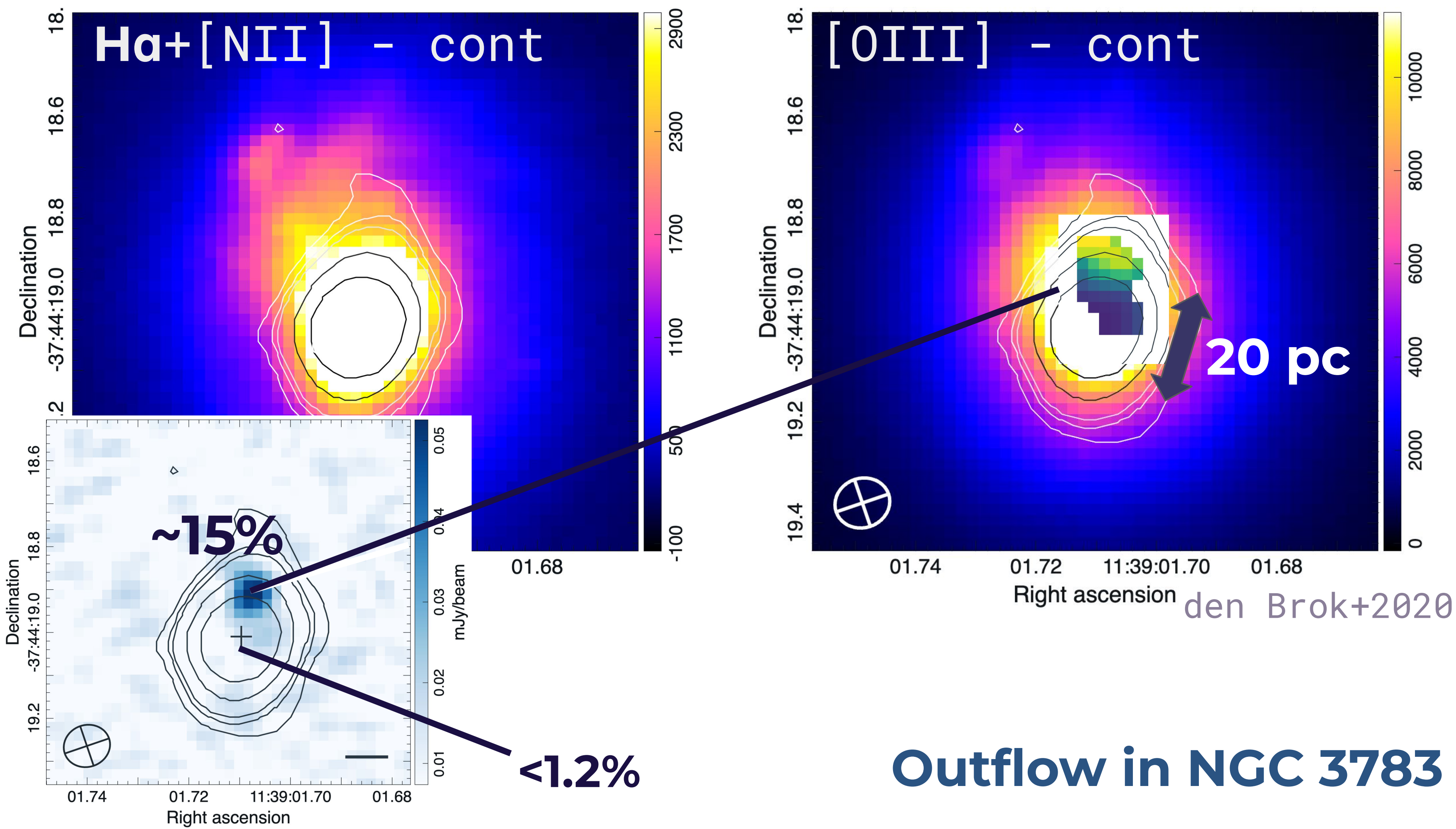


Ricci+2023



$$\sigma = \sqrt{\sigma^2_{int} + \boxed{\sigma^2_{ns}}}$$

75%



Ha+[NII] - cont
[OIII] - cont
20 pc
~15%
<1.2%
Declination
Right ascension
mJy/beam
18.
18.6
18.8
-37:44:19.0
19.2
19.4
01.74
01.72
11:39:01.70
01.68
2900
2300
1700
1100
500
-100
10000
8000
6000
4000
2000
0
0.05
0.04
0.03
0.02
0.01
den Brok+2020
Outflow in NGC 3783

Special NGC 5506

$\tau = 0.02 - 0.09 \sim n_e R$

$\rightarrow \mathrm{RM} = 10^5\text{–}10^7\ \mathrm{rad\ m^{-2}}$