Event Horizon Telescope

Misaligned AGN jets from formation to dissipation

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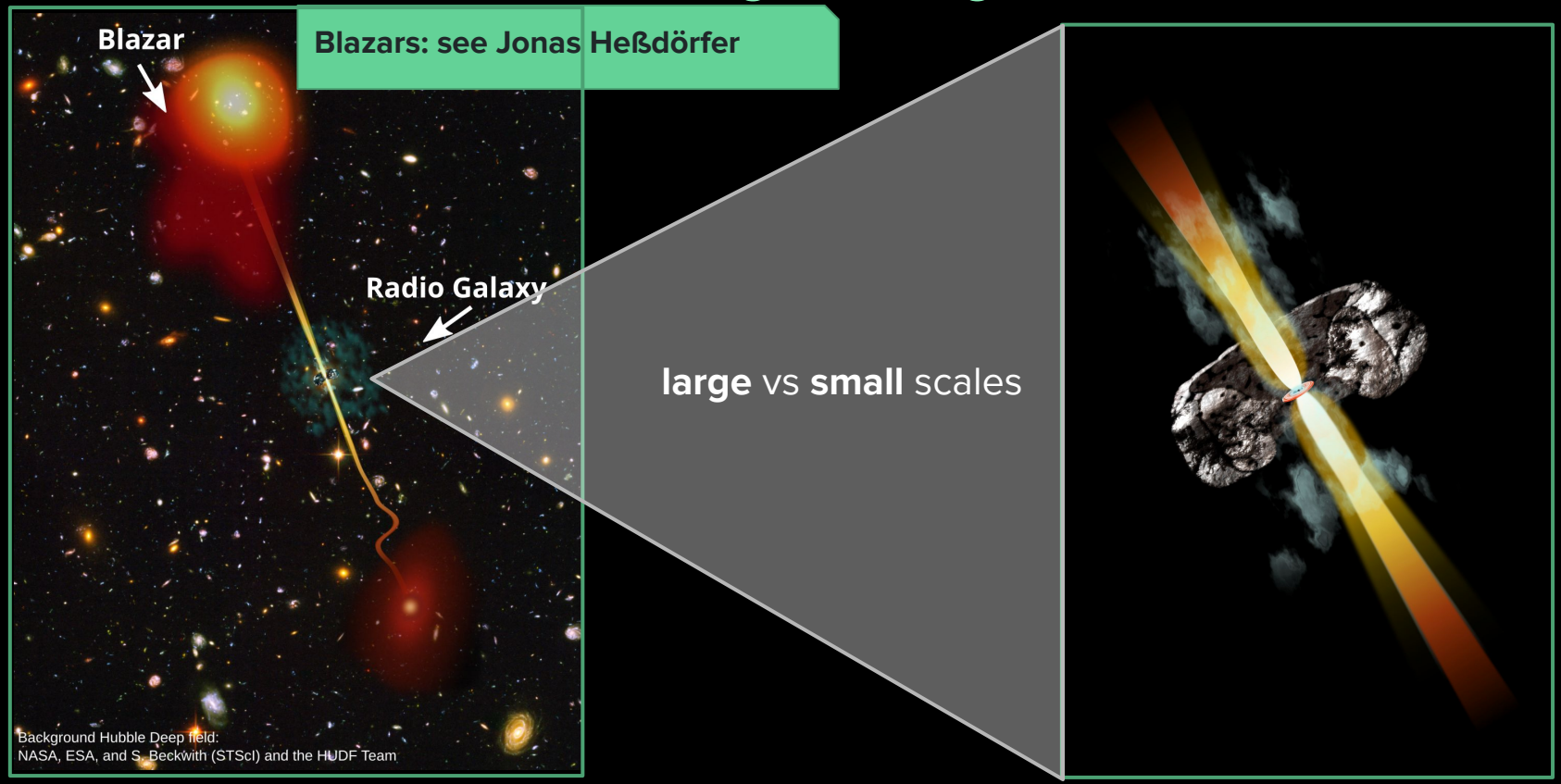
Active Galactic Nuclei - Setting the stage

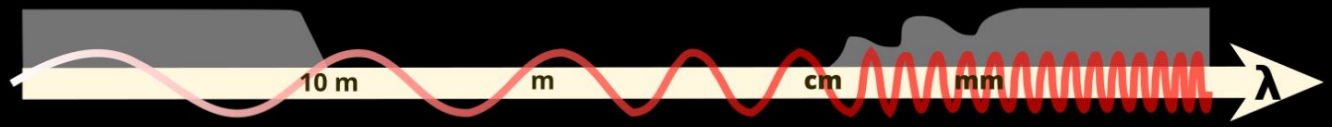


Active Galactic Nuclei - Open questions

The physical description of AGN jets and the interaction with the host galaxy are still incomplete:

- AGN model biased towards bright, strongly Doppler boosted sources
- Physical processes behind jet launching, acceleration, and collimation remains one of the central open questions of extragalactic astronomy
- BH feeding and AGN feedback: interactions between central engine, jets, and host galaxy still poorly understood

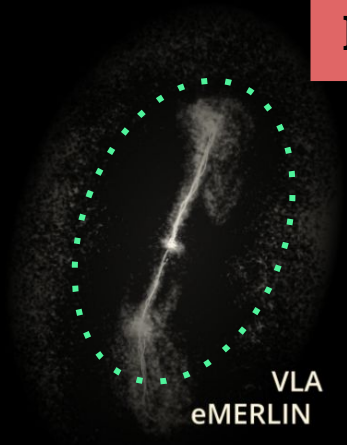
RADIO



RADIO

kpc - Mpc

Large Scale

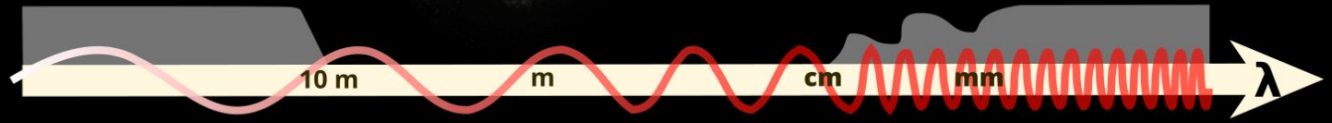


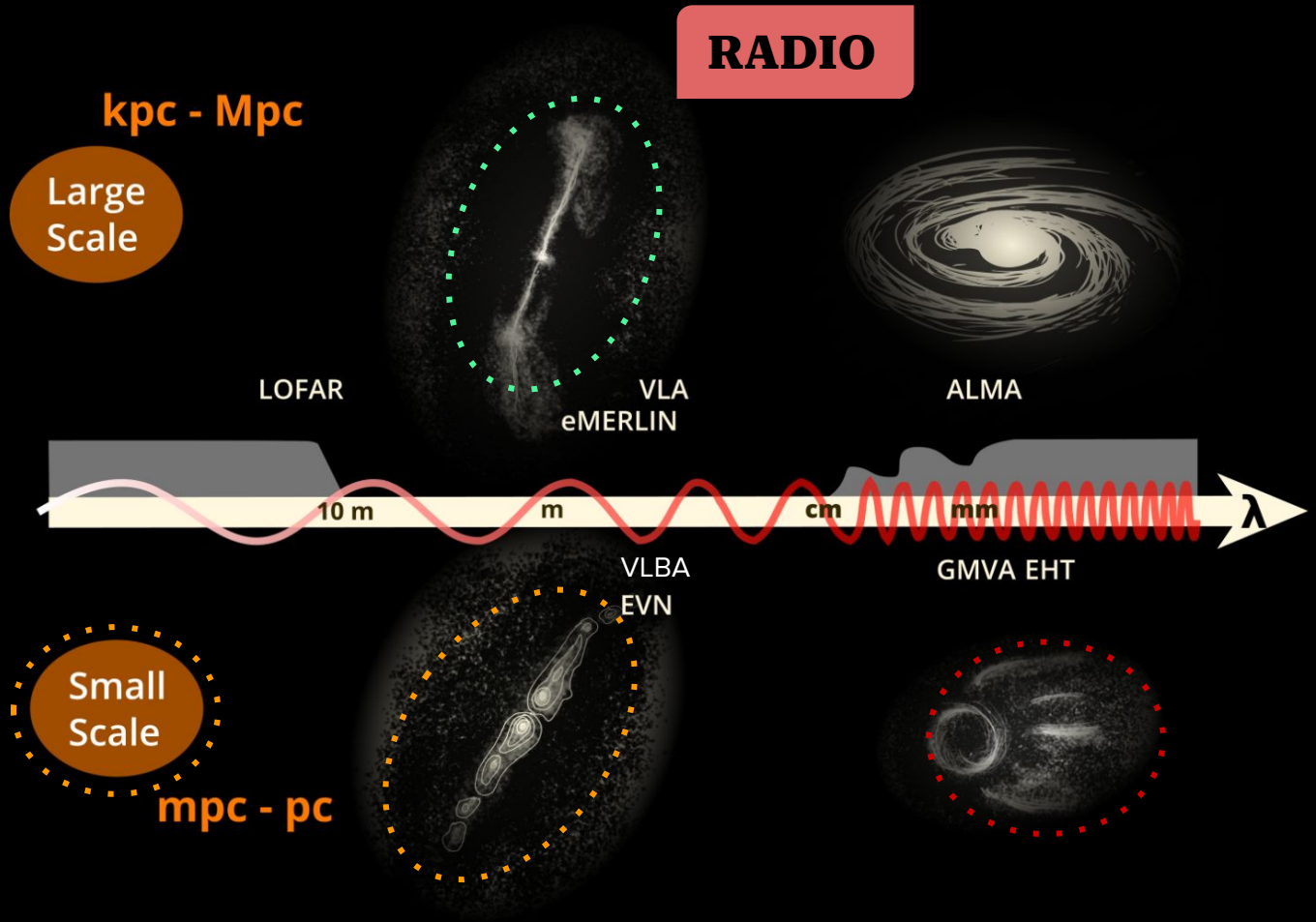
LOFAR

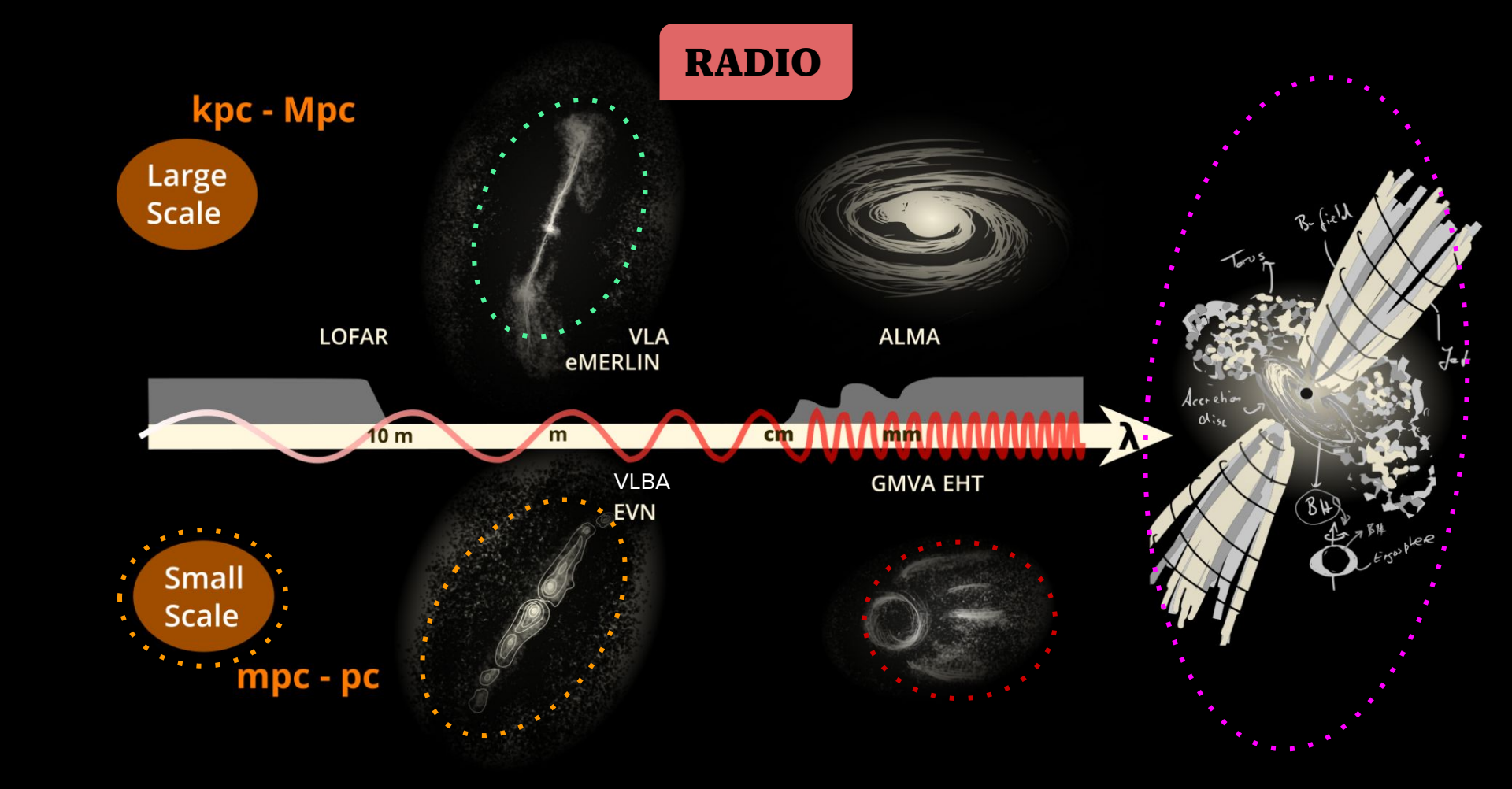
VLA

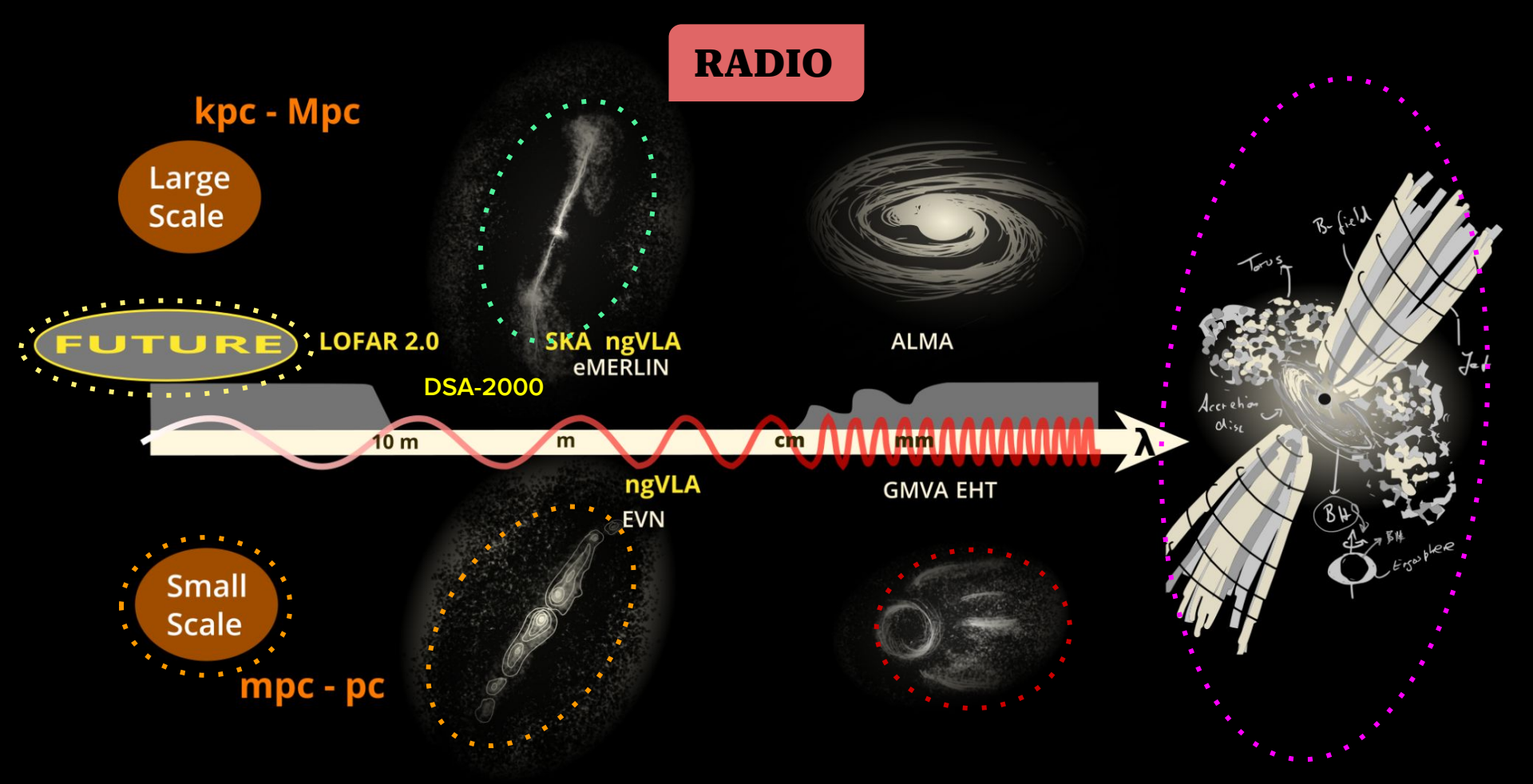
eMERLIN

ALMA




RADIO
kpc - Mpc
Large Scale
LOFAR
VLA
eMERLIN
ALMA
10 m
m
cm
mm
λ
VLBA
EVN
GMVA EHT
Small Scale
mpc - pc


RADIO
kpc - Mpc
Large Scale
LOFAR
VLA
eMERLIN
ALMA
10 m
m
cm
mm
λ
VLBA
EVN
GMVA EHT
Small Scale
mpc - pc
B-field
Torus
Jet
Accretion disc
BH
Ergosphere


RADIO
kpc - Mpc
Large Scale
FUTURE
LOFAR 2.0
SKA ngVLA
eMERLIN
DSA-2000
ALMA
10 m
m
cm
mm
λ
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GMVA EHT
Small Scale
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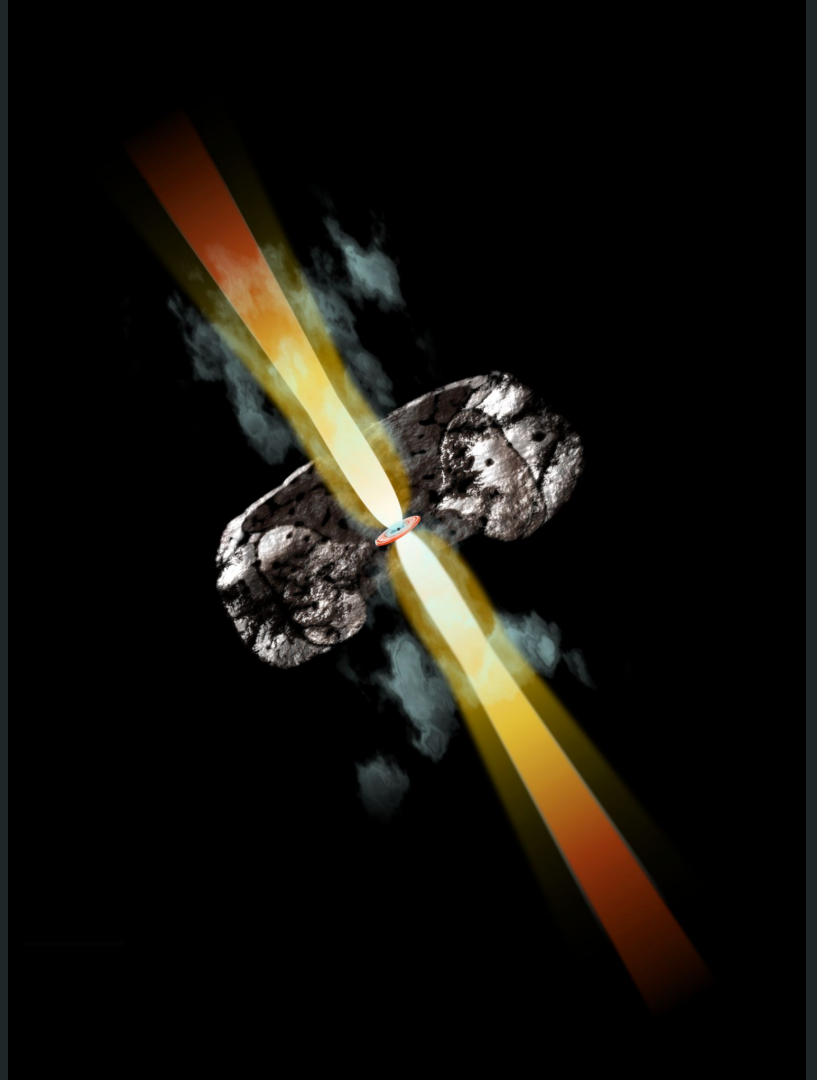
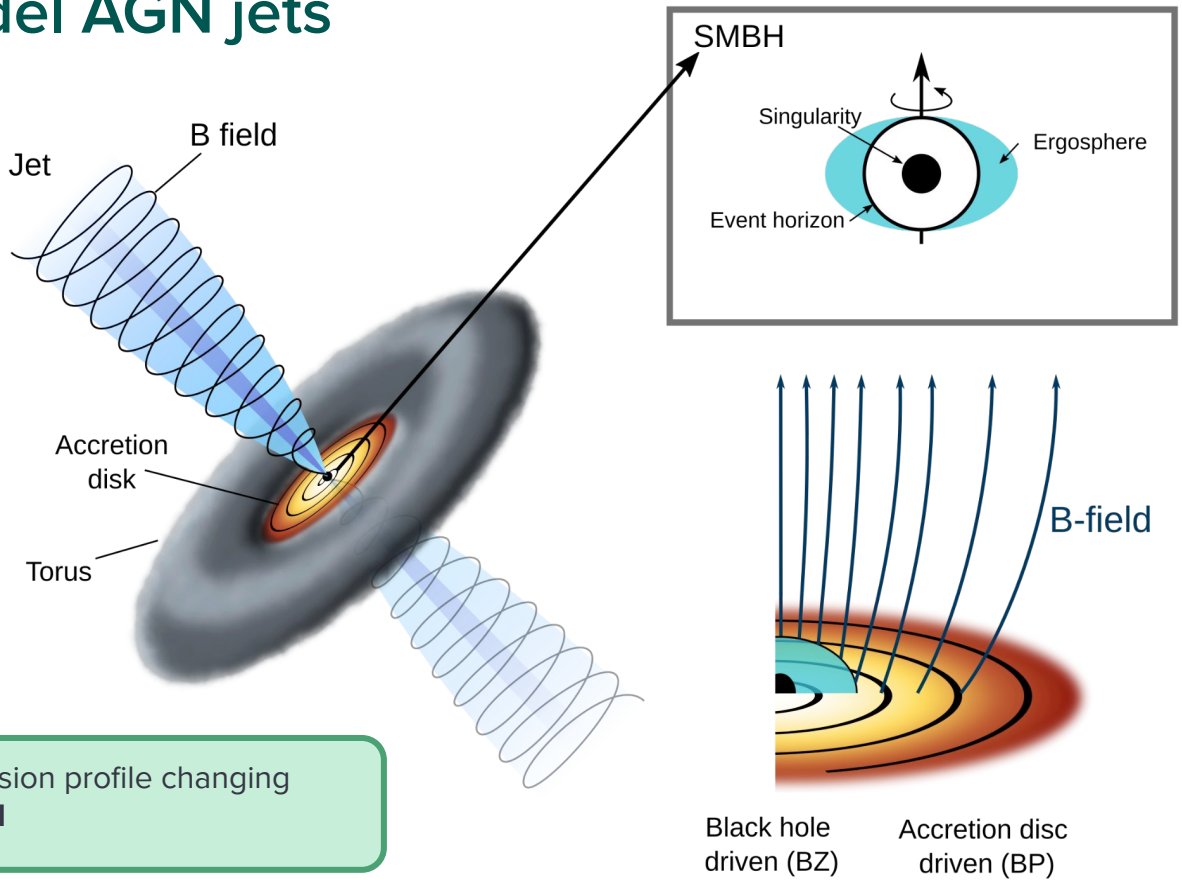
AGN jets at small scales

linking observations and Physics



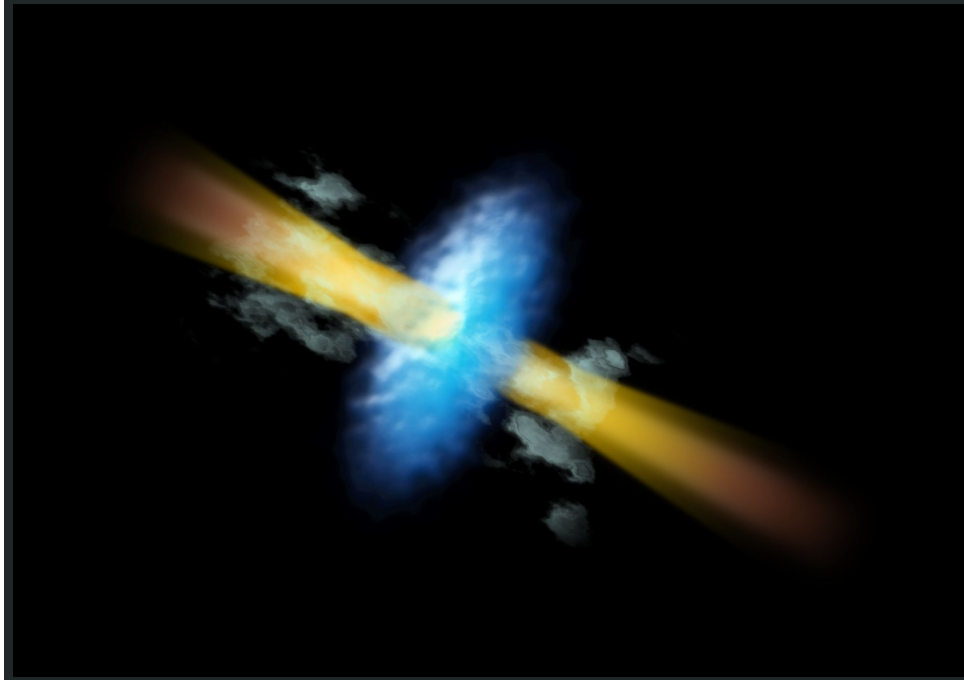
How to model AGN jets



Most jets show an expansion profile changing from **parabolic to conical**

NGC 1052: Jet collimation scales

Linking observations and Physics

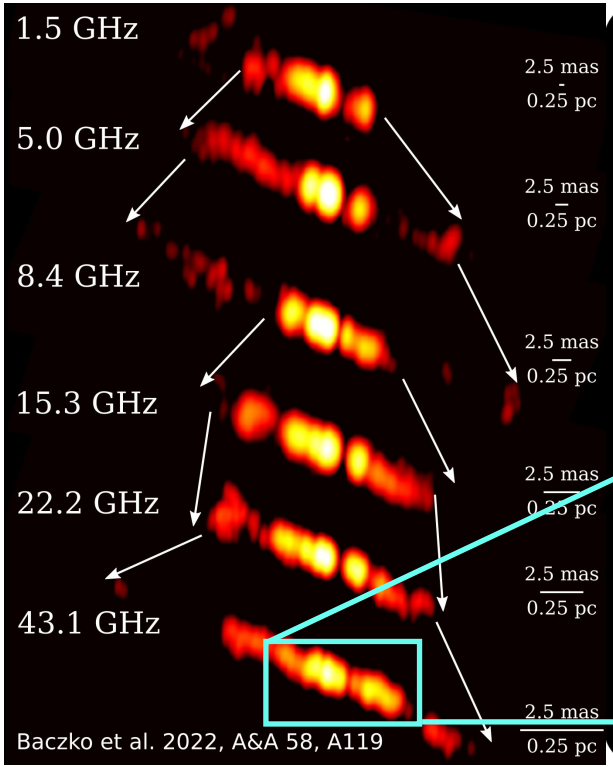


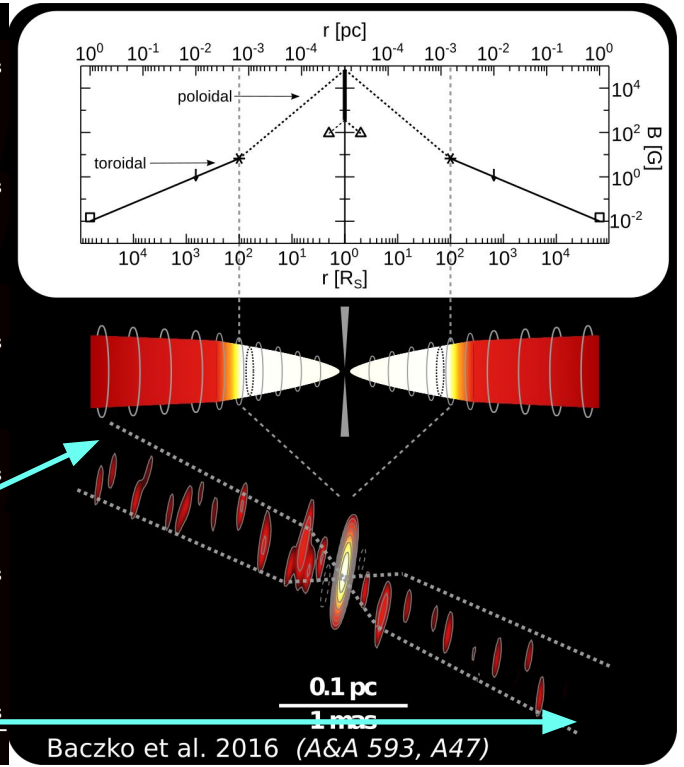
NGC 1052: A Twin-jet in the plane of the sky

Distance: 20 Mpc
BH mass: $10^{8.2} M_\odot$
Scale: 1 mas ~ 0.1 pc
20 μas ~ 140 R_S
Inclination: nearly 90°

Classified as LINER galaxy

At 1 R_S: 200 G < *B* < 8x10^4 G
(Baczko et al. 2016 A&A 593 A47)
Asymmetric twin jet
(Baczko et al. 2019 A&A 623 A27)
Non-parabolic Collimation
(Baczko et al. 2022 A&A 658 A119)





NGC 1052: Multi-frequency campaign

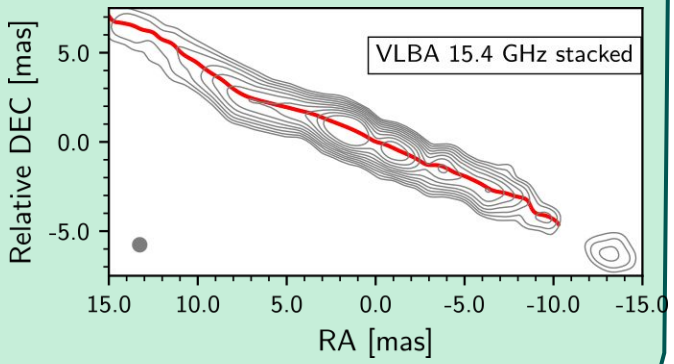
(Baczko et al. 2022 A&A 658 A119)

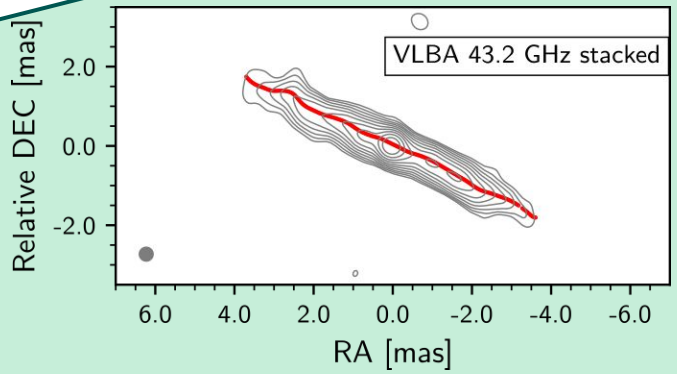
2005-2009 VLBA 22 & 43 GHz
1995-2012 VLBA (MOJAVE) 15 GHz

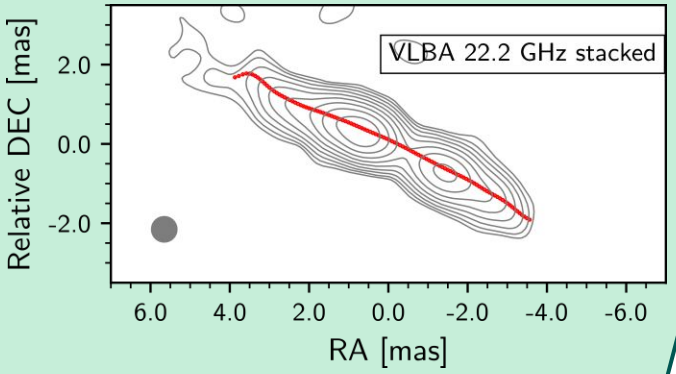
2016 Global RadioAstron 22 GHz

2017
VLBA 1.5 – 43 GHz
GMVA 86 GHz
EHT 230 GHz

VLBA stacked images

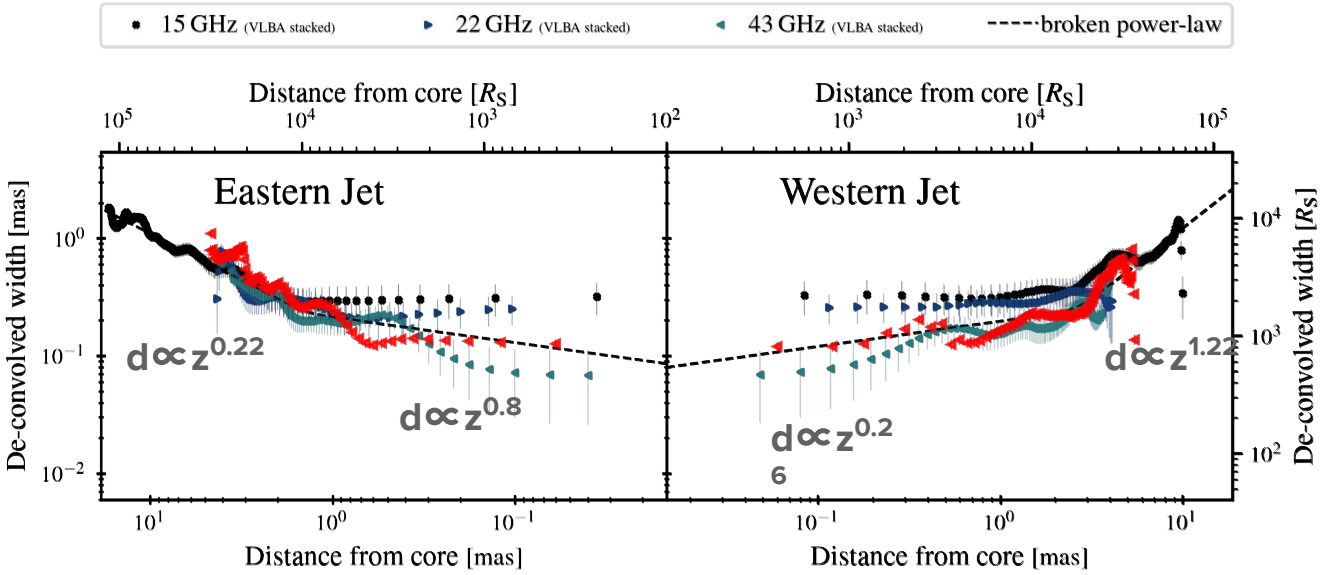






NGC 1052: Jet collimation

(Baczko et al. 2022 A&A 658 A119)



Red: Newest 43 GHz 3 epoch stacked (Luca Ricci+ in prep)

43GHz: Slope steepens spine-sheath?

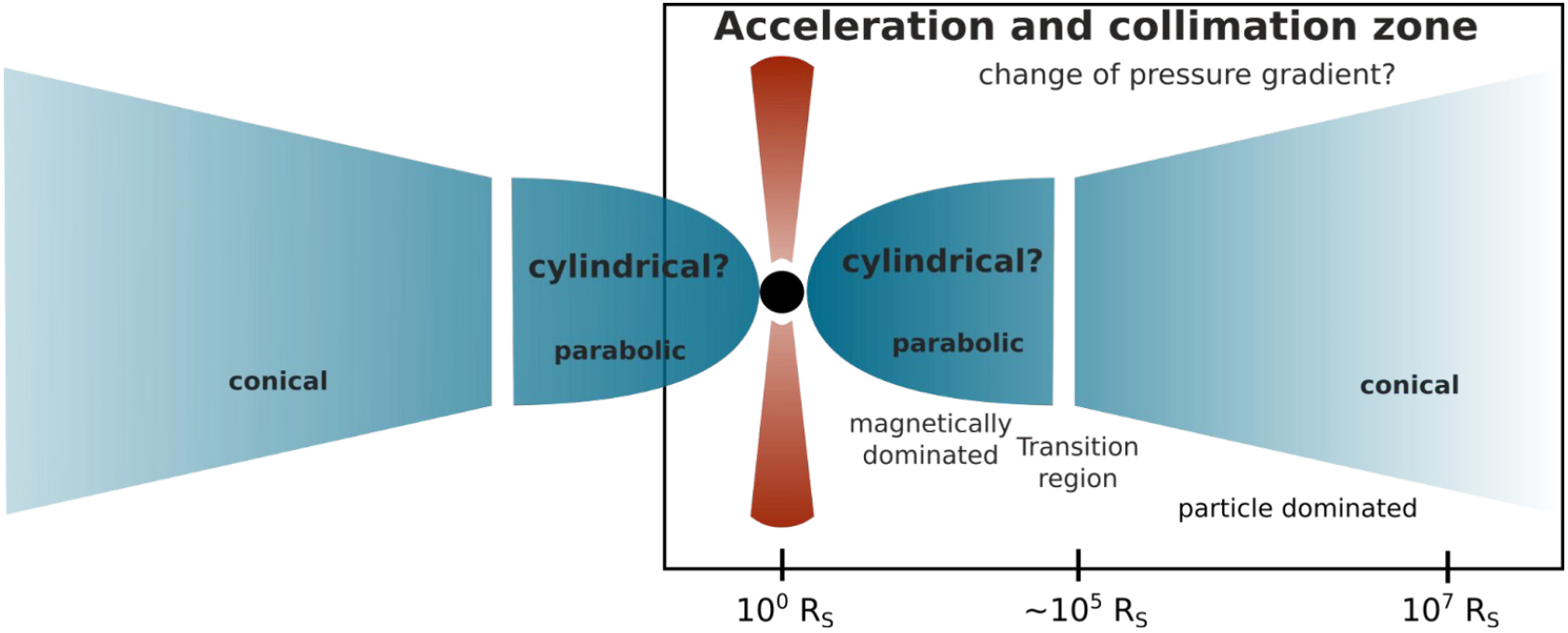
Supporting this scenario:
Inner jet at 43 GHz faster with hints off acceleration

$15\mathrm{GHz}: \ \beta \simeq 0.25$

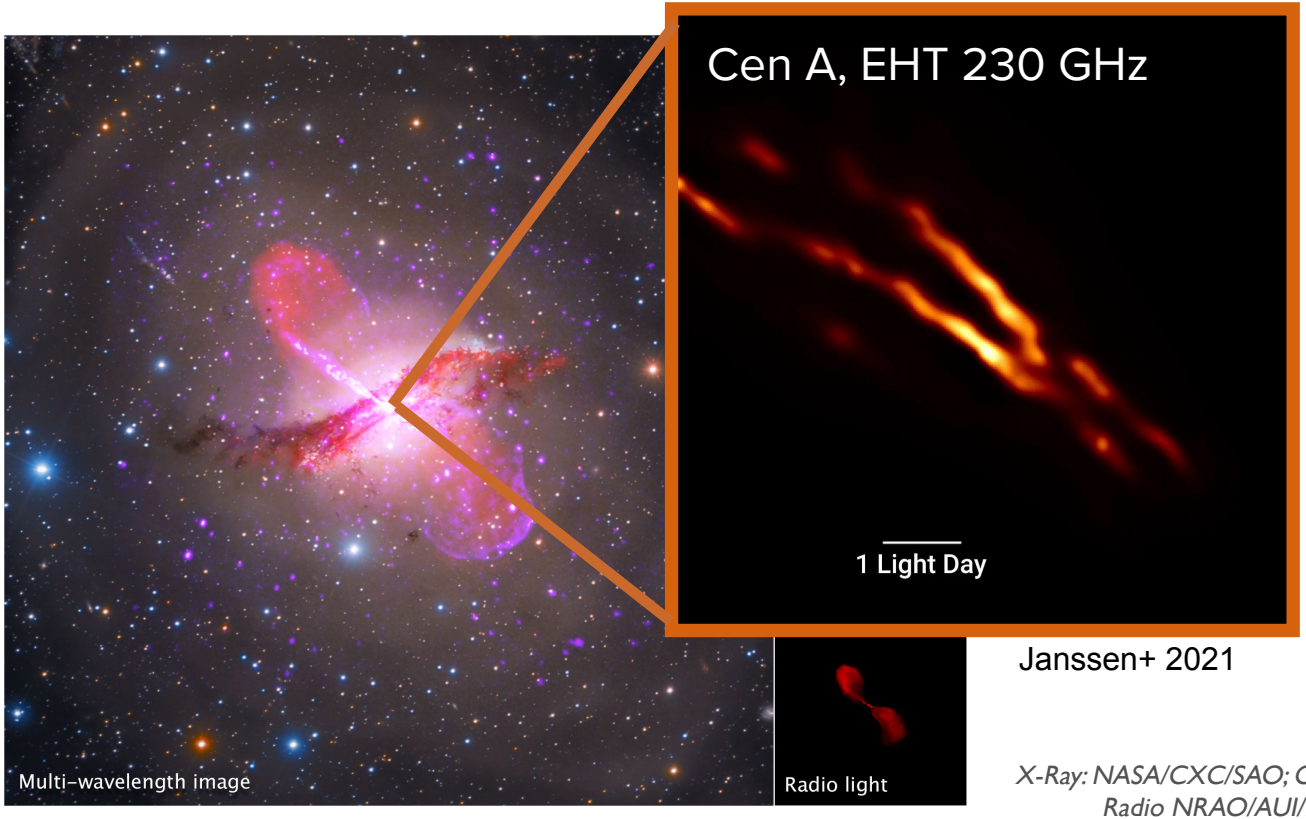
$43\mathrm{GHz}: \ \beta \simeq 0.50$

The acceleration and collimation zone

studied with multi-frequency VLBI



Centaurus A: edge brightened at EHT scales



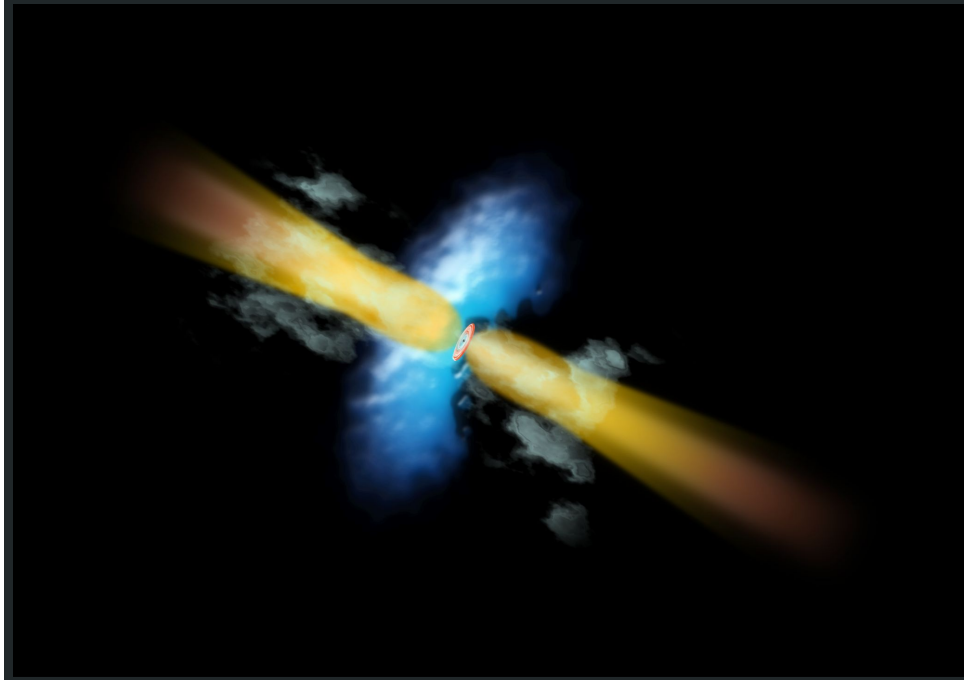
Janssen+ 2021

Do we just not have high enough resolution to resolve an edge-brightening in NGC 1052?

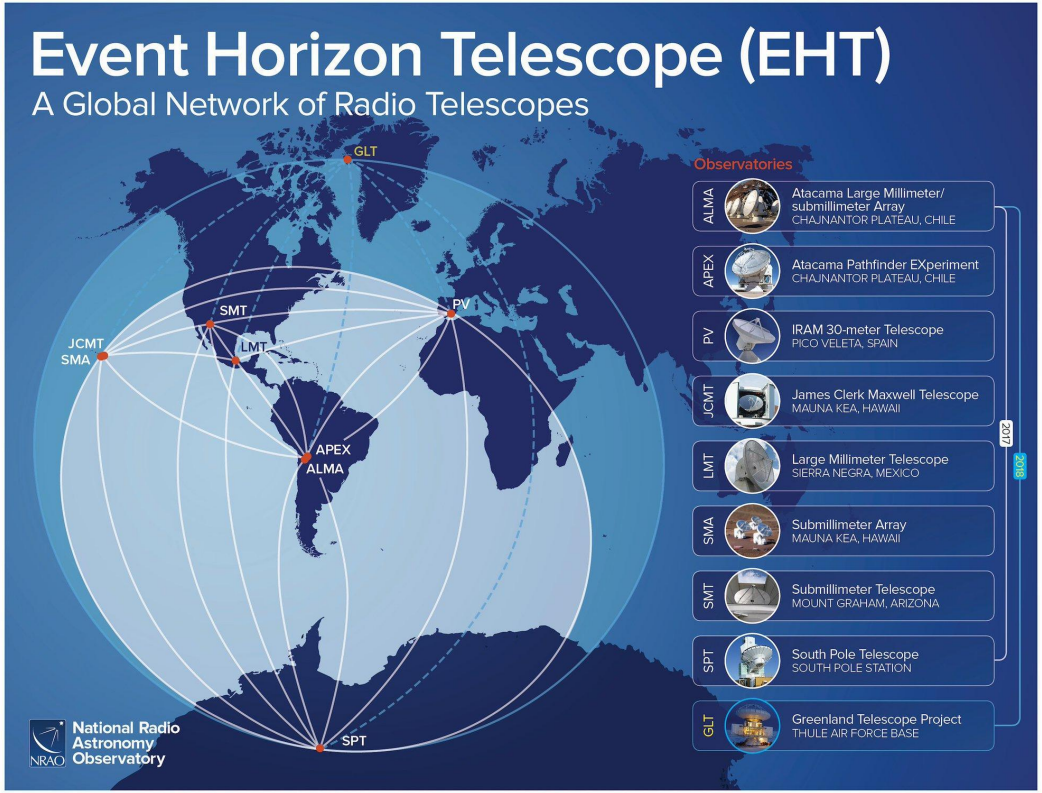
X-Ray: NASA/CXC/SAO; Optical: Rolf Olsen; Infrared: NASA/JRL-Caltech; Radio NRAO/AUI/NSF/Univ. Hertfordshire/ M. Hardcastle

Jet formation scales

Towards
the central engine



The Event Horizon Telescope (EHT) to study SMBHs



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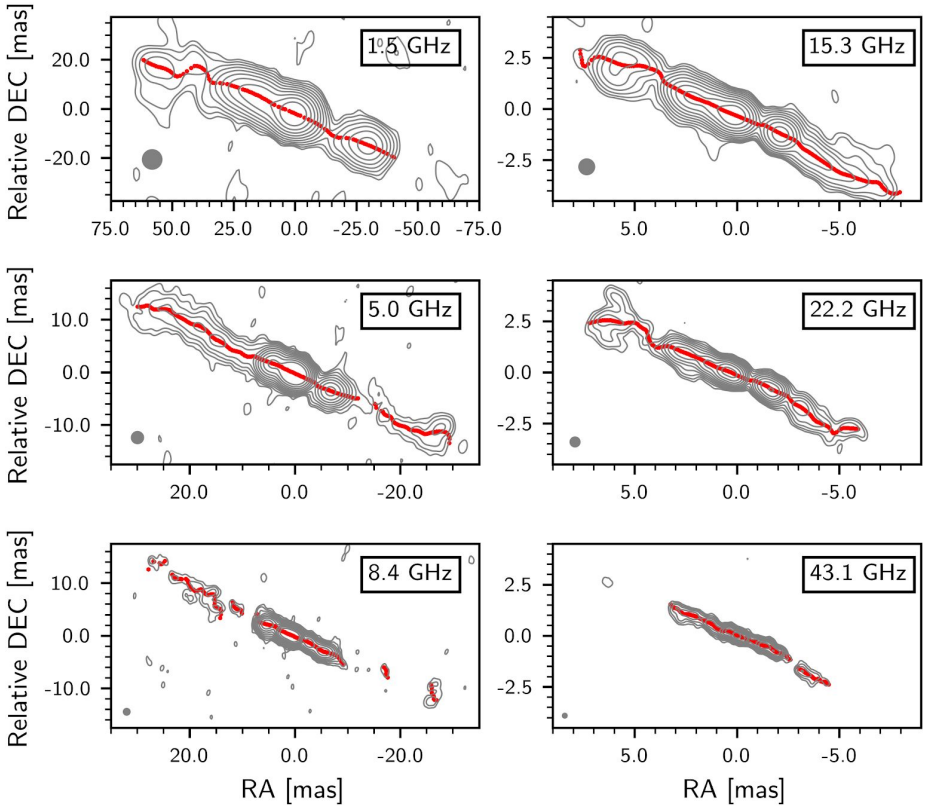

Baczko et al. 2024 A&A, in press

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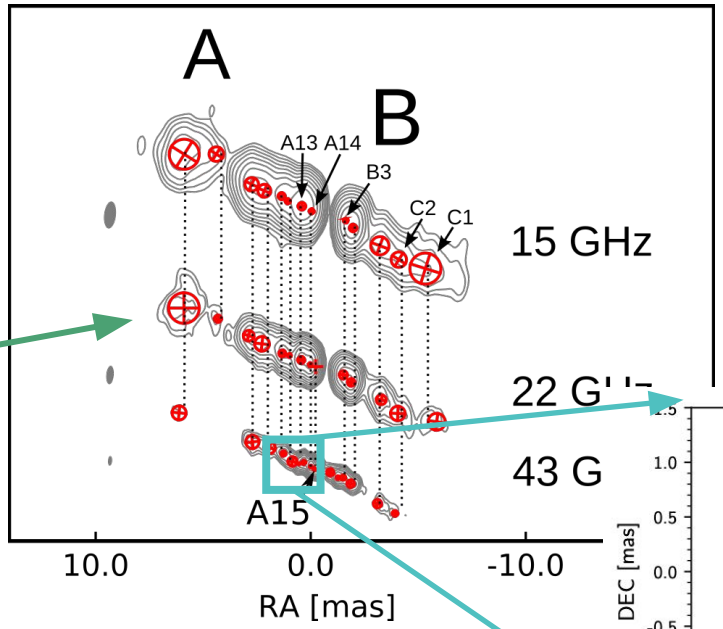
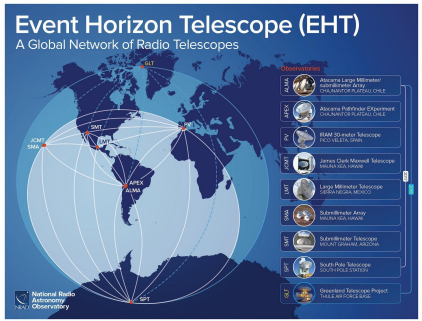
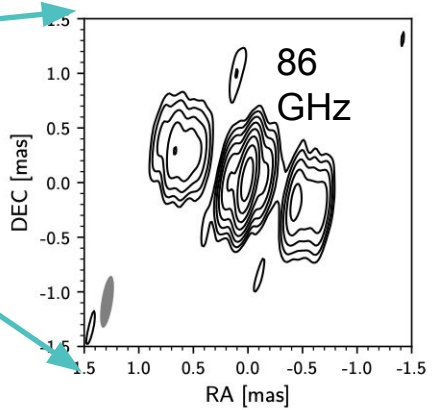
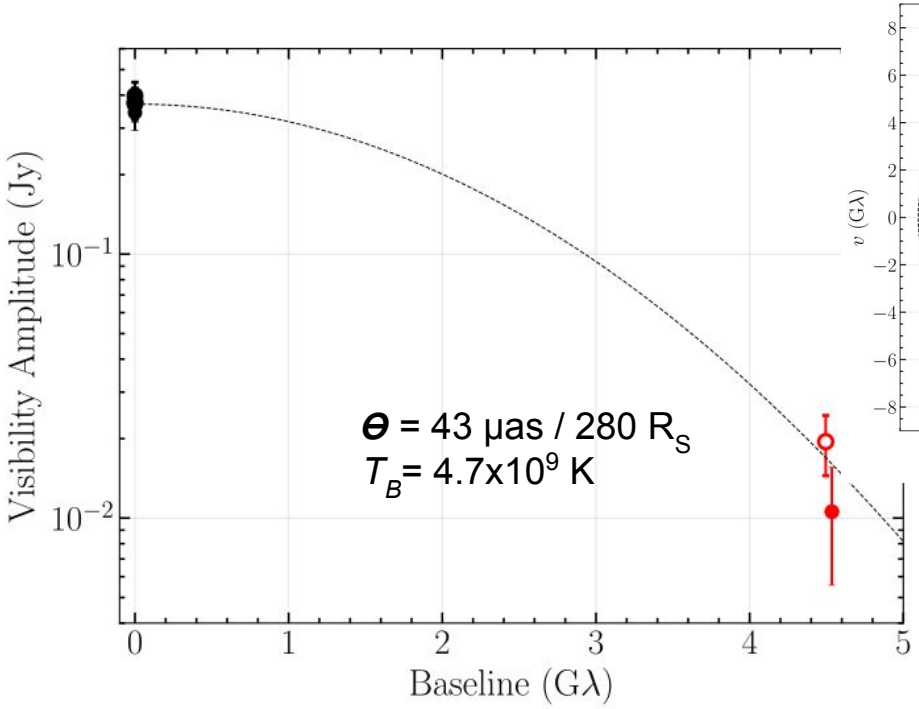


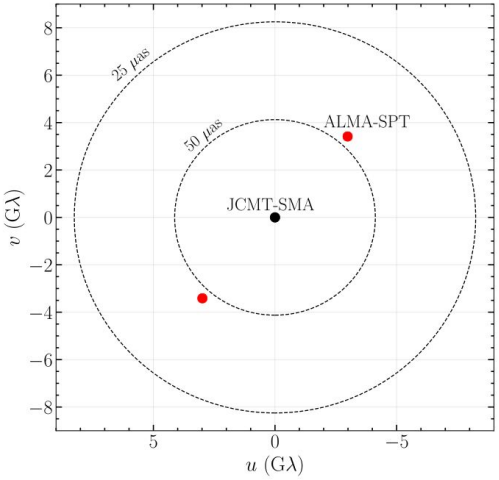




Baczko et al. 2024 A&A, in press

NGC 1052: 230 GHz EHT 2017

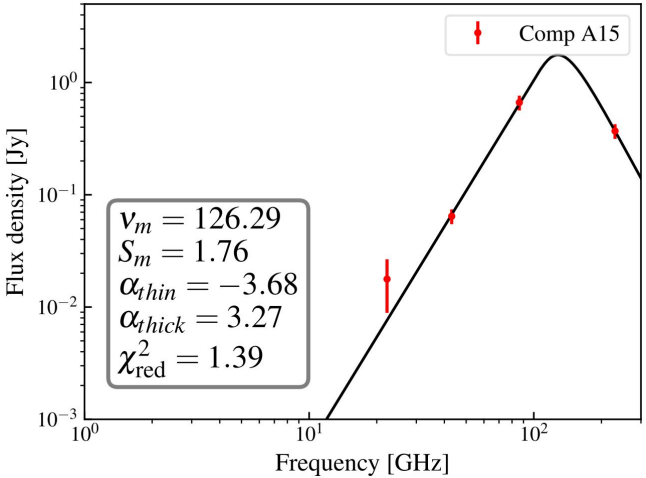




EHT PI: **M. Kadler** (U. Würzburg)

Detection allows estimation of T_b and comparison with models (Fromm et al. 2019 A&A 629 A4)

NGC 1052: at mm-wavelengths



Baczko et al. 2024 A&A in press (17.12.2024)
https://doi.org/10.1051/0004-6361/202450898

Turnover at around 130 GHz: B_{SSA} **= 1.25 G**

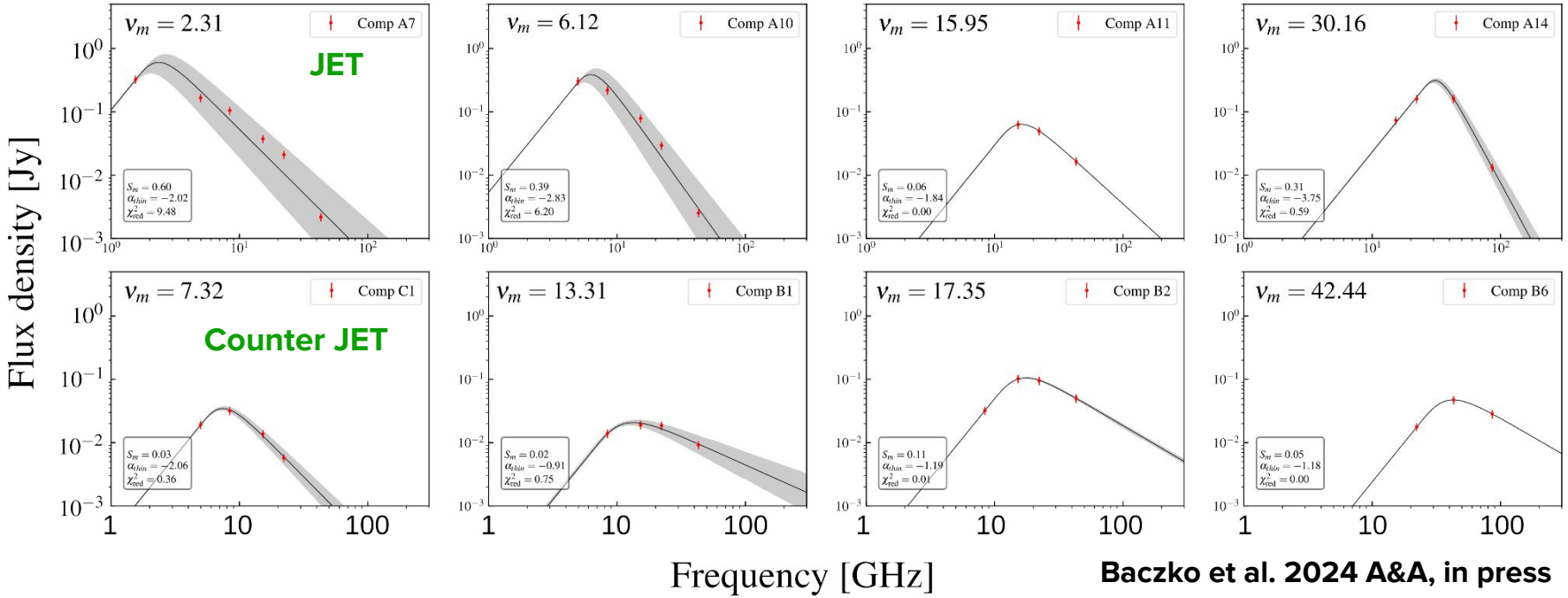
Implies a B-field at 1 R_S **392 G < B < 2.6** 10^4 **G**
depending on the B-field morphology (poloidal/toroidal)

3-epoch 86 GHz GMVA monitoring data reduction in progress (Luca Ricci):

- Time-variability of 43 GHz and 86 GHz structure
- Extent collimation study towards closer distances to the center
- Spectral Index 43 to 86 GHz

NGC 1052: Peak frequency shifts

Towards the central engine



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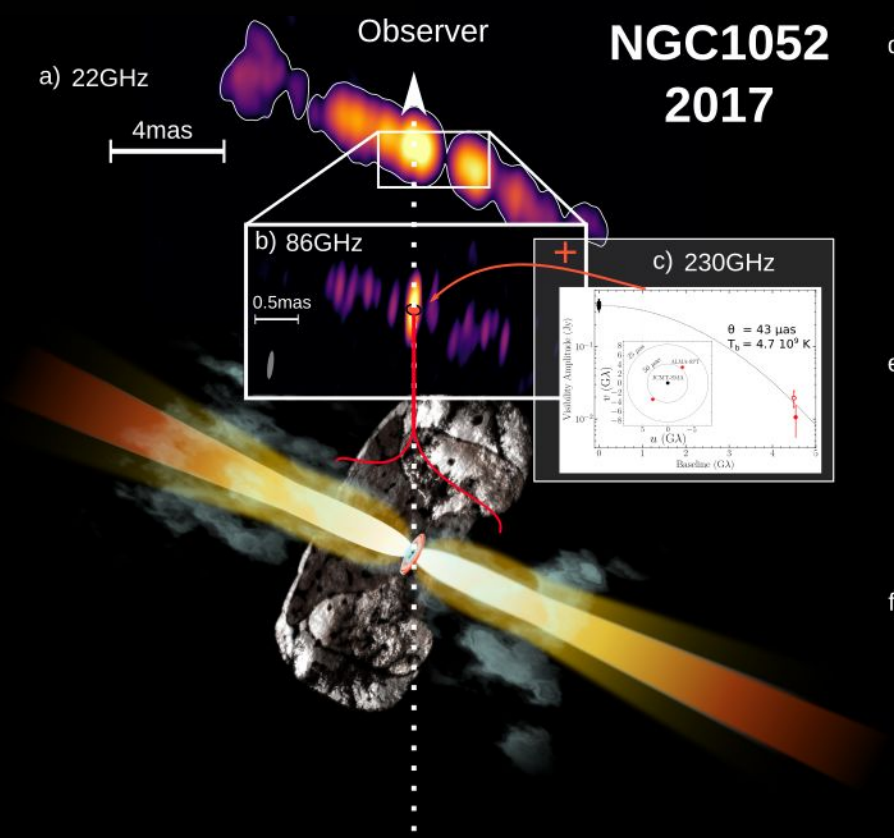

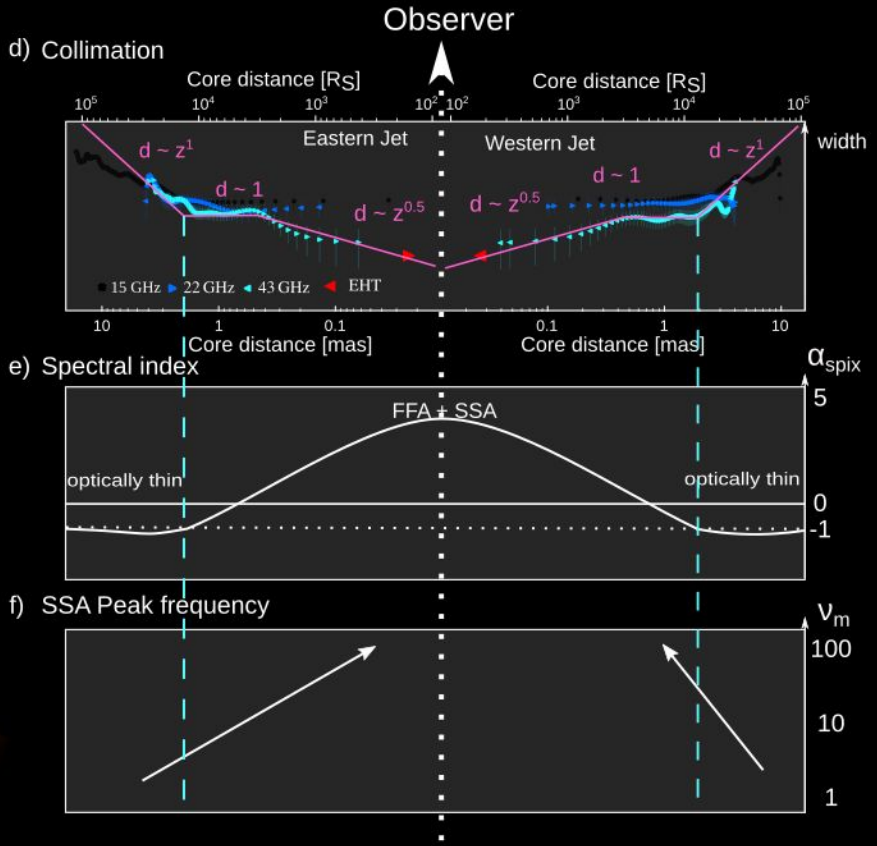

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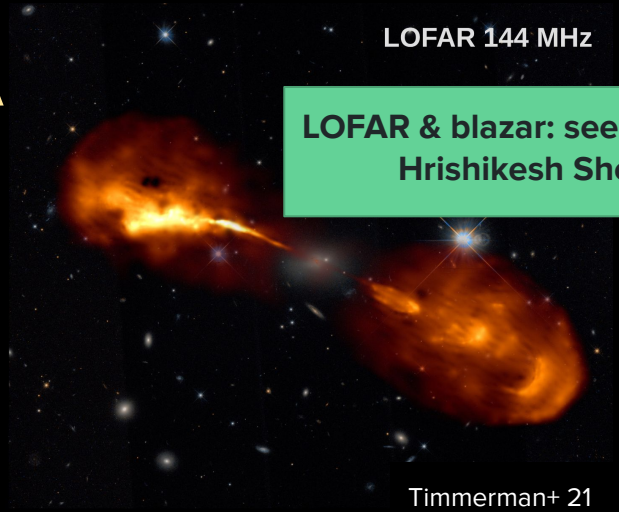
AGN jets at large scales

AGN as seen by VLA and LOFAR

AGN at large scales with LOFAR

Hercules A



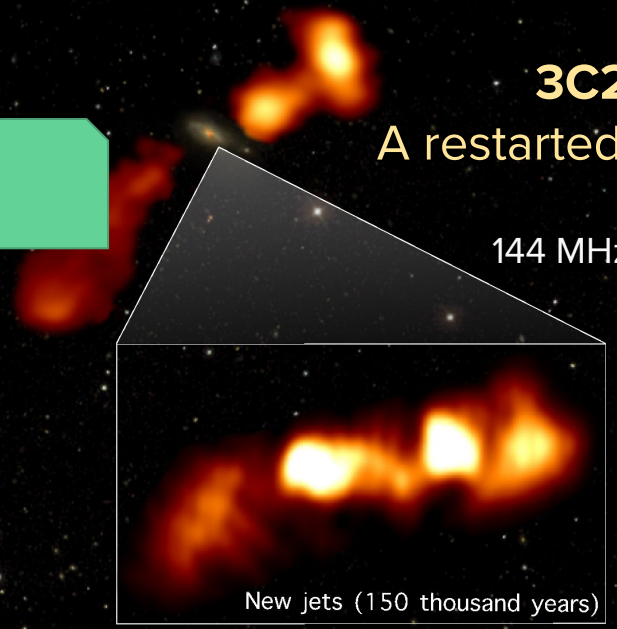
Timmerman+ 21

Saxton, Cotton and Perley (NRAO/AUI/NSF)

LOFAR & blazar: see Hrishikesh Shetgaonkar

jet grows stronger and weaker every few hundred thousand years

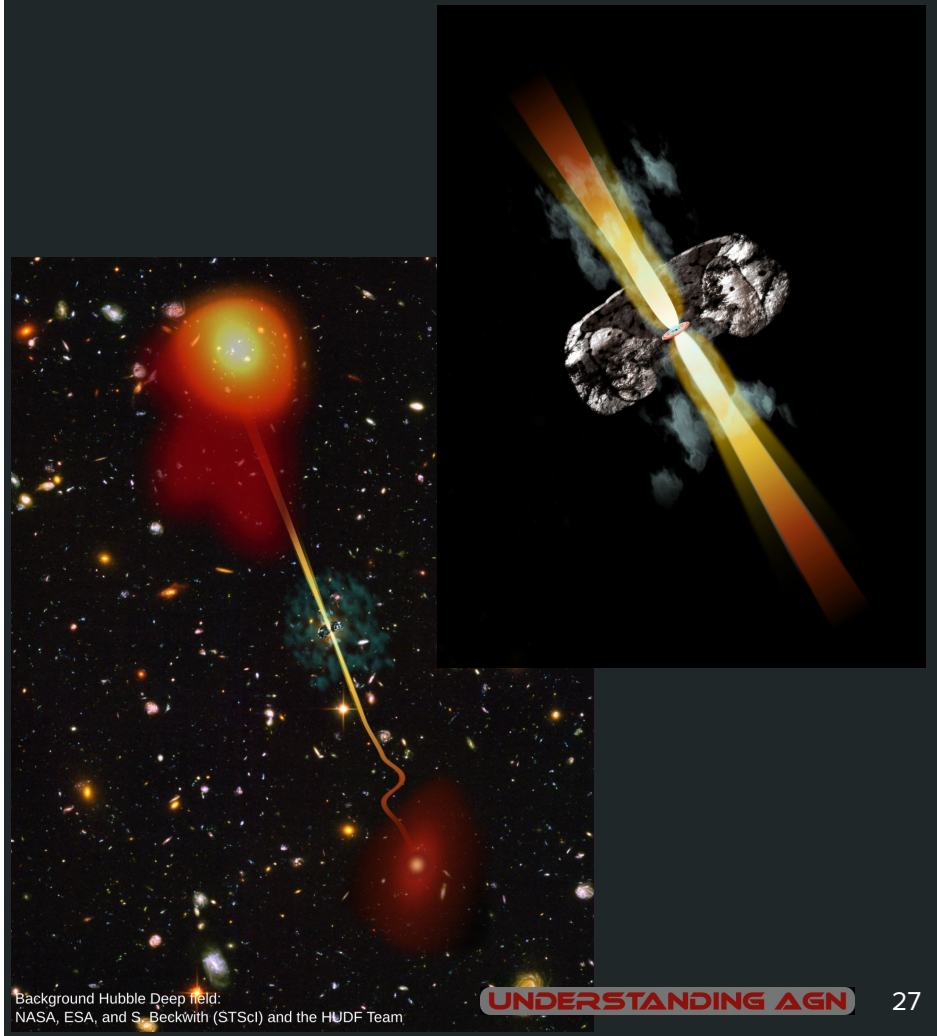
3C293
A restarted jet



Credit:P. Kukreti; LOFAR & Sloan Digital Sky Survey

The bigger picture

Connecting small VLBI scales with large radio scales **today**

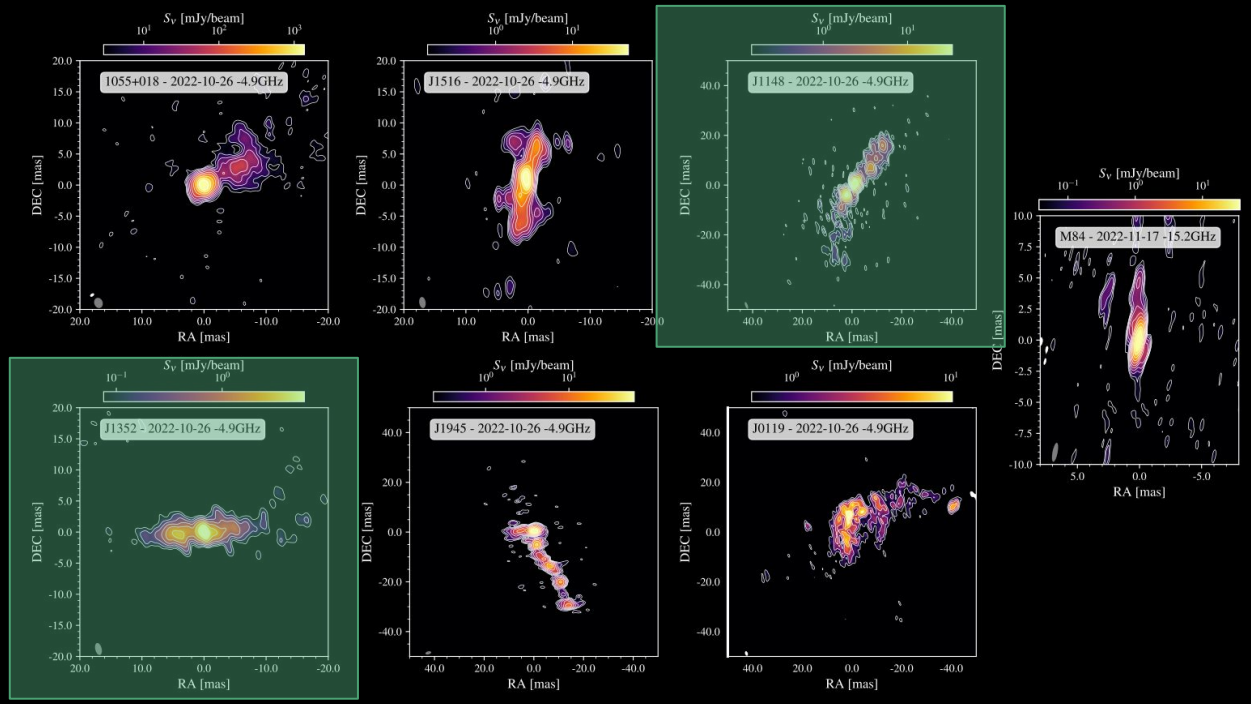


Background Hubble Deep field:
NASA, ESA, and S. Beckwith (STScI) and the HUDF Team

Part of a pilot study including HSA and EVN

Candidate double-sided jets at z<0.1 at 5 GHz (EVN)

M 84
NGC 3894
3C 293
3C 317
4C 31.04
1946+708



44 RG Fermi-LAT

A restarted jet **3C 293:** large (200 kpc) to small (17 pc) scales

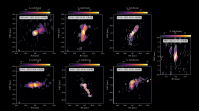
Background:

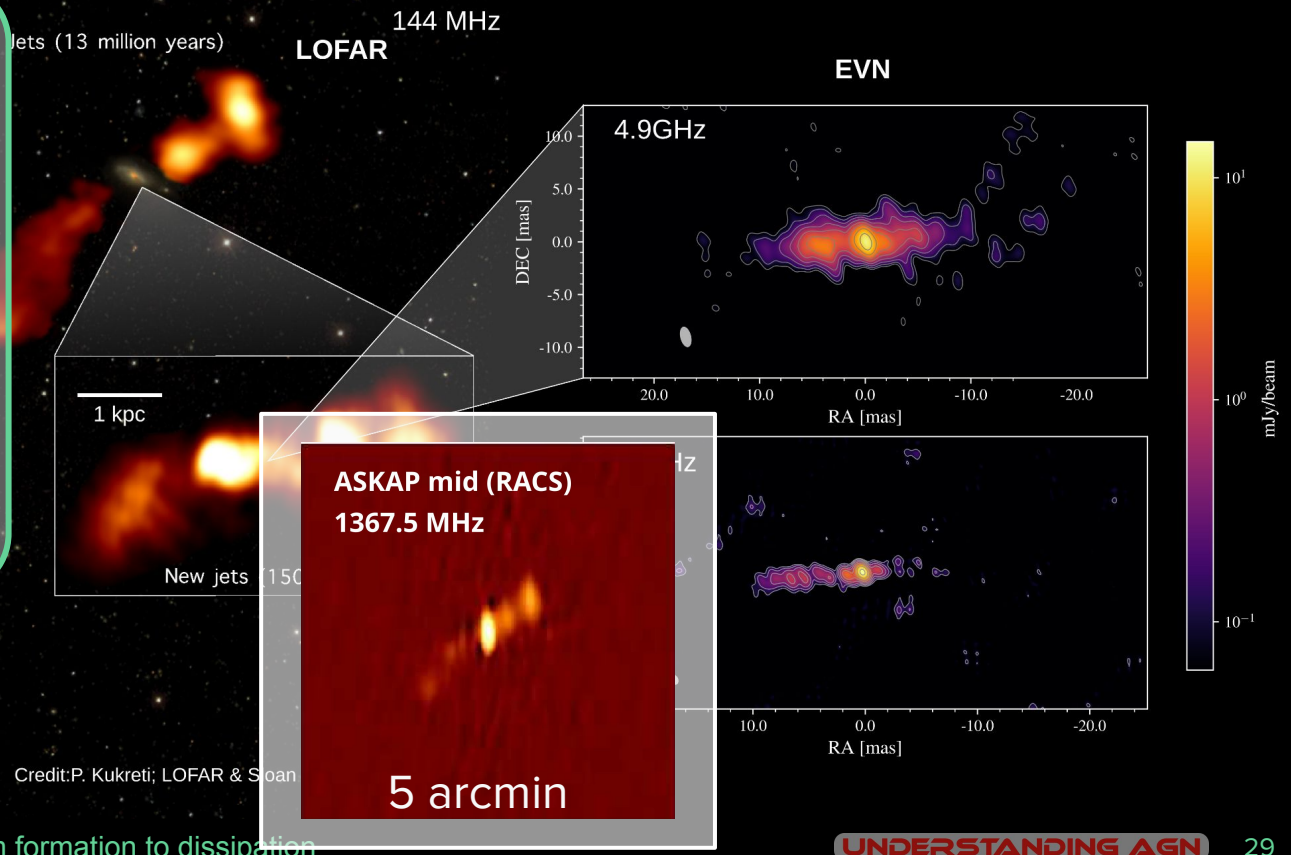
z = 0.0452

Observed with **LOFAR**
at 144 MHz
with 0.3 asec resolution *(Kukreti+ 2021, Astronomische Nachrichten)*

- Probably **young CSS**
- FFA absorption in inner lobes
- At least 2 cycles of activity

New EVN+eMERLIN
at 5/8.5/22 GHz in 2022





NGC 3894: A young radio galaxy on large scales (16 kpc)

Background:

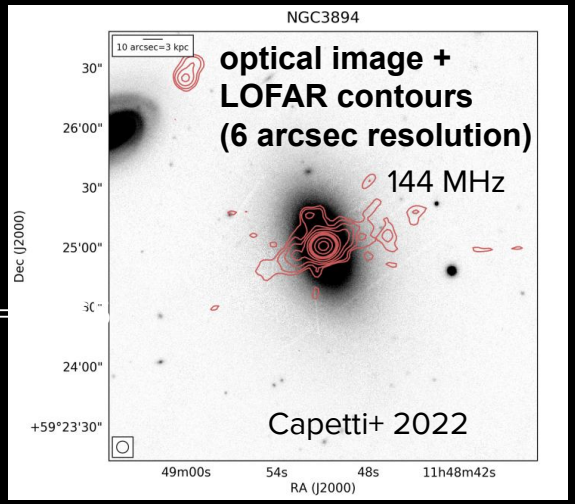
CSO at **z = 0.0108**

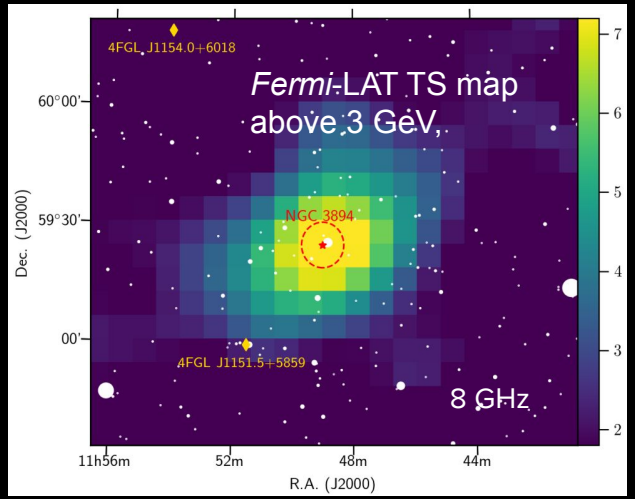
Principe+ 2020:

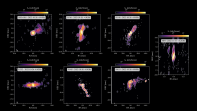
- ***γ*-rays detected** by Fermi-LAT
- **X-Ray detections**
- **VLBA** (8 epochs at 8GHz) $\beta_{app,NW} = 0.132 \pm 0.004\ \beta_{app,SE} \pm 0.003$

➡ suggesting a **young radio source of 59 ± 5 years.**

=

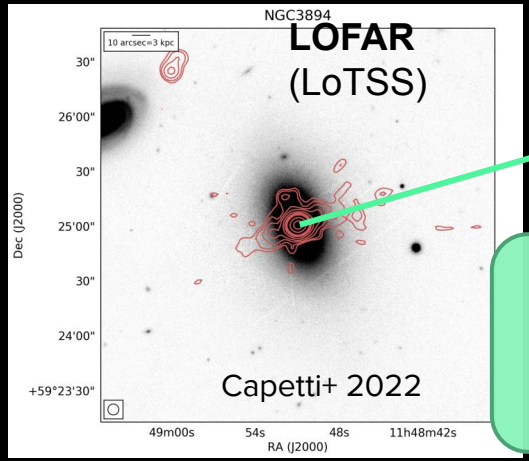




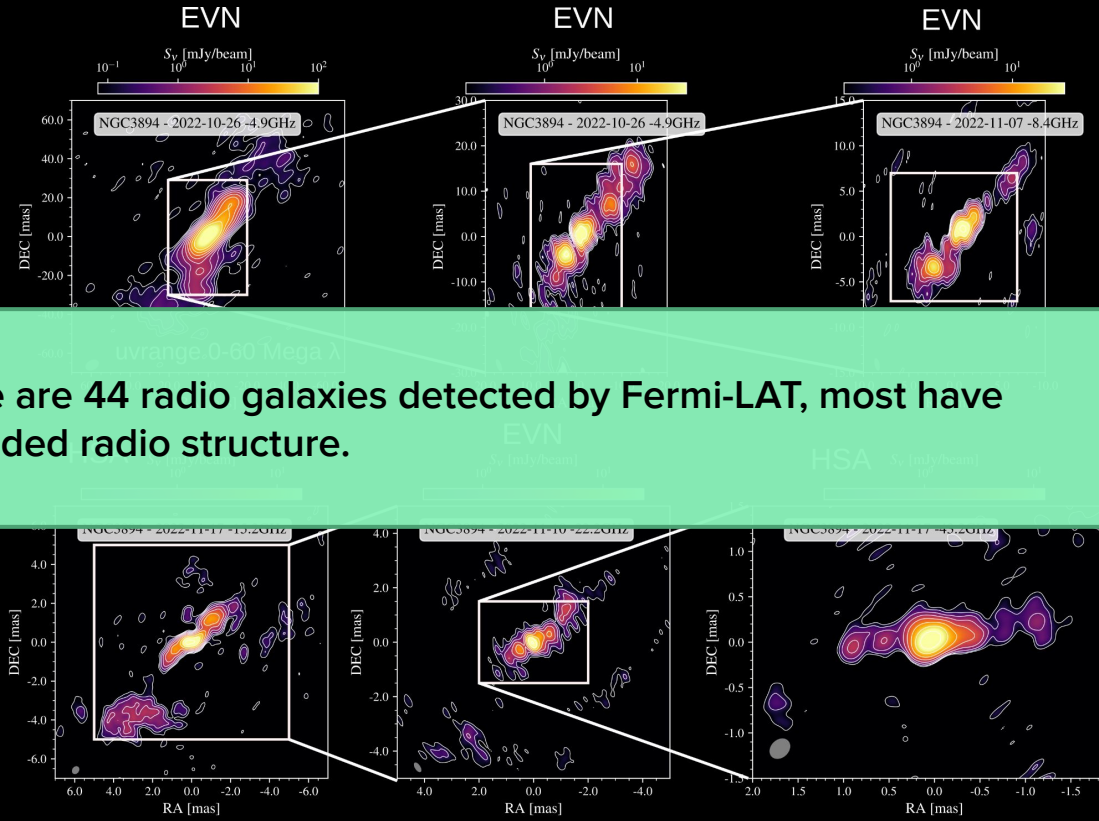


NGC 3894: large (16 kpc) to small (<25 pc) scales

LOFAR resolution: 6 arcsec

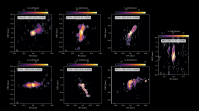


EVN



There are 44 radio galaxies detected by Fermi-LAT, most have extended radio structure.

New EVN+eMERLIN & HSA at 5/8.5/15/22/43 GHz in 2022



The bigger picture case: 3C 120

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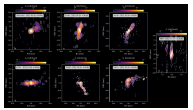

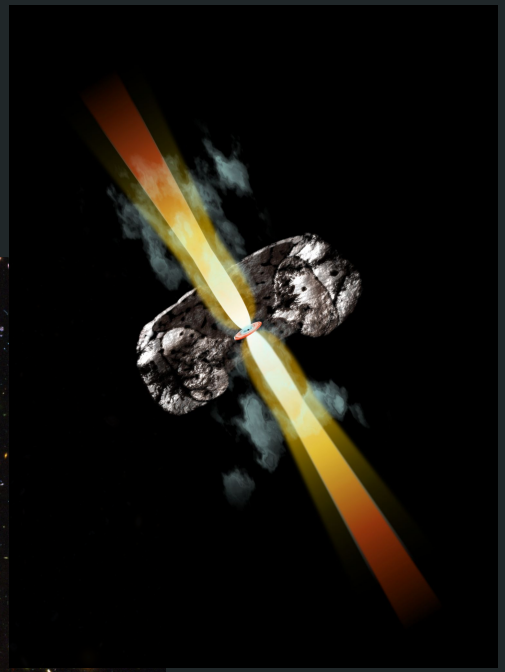

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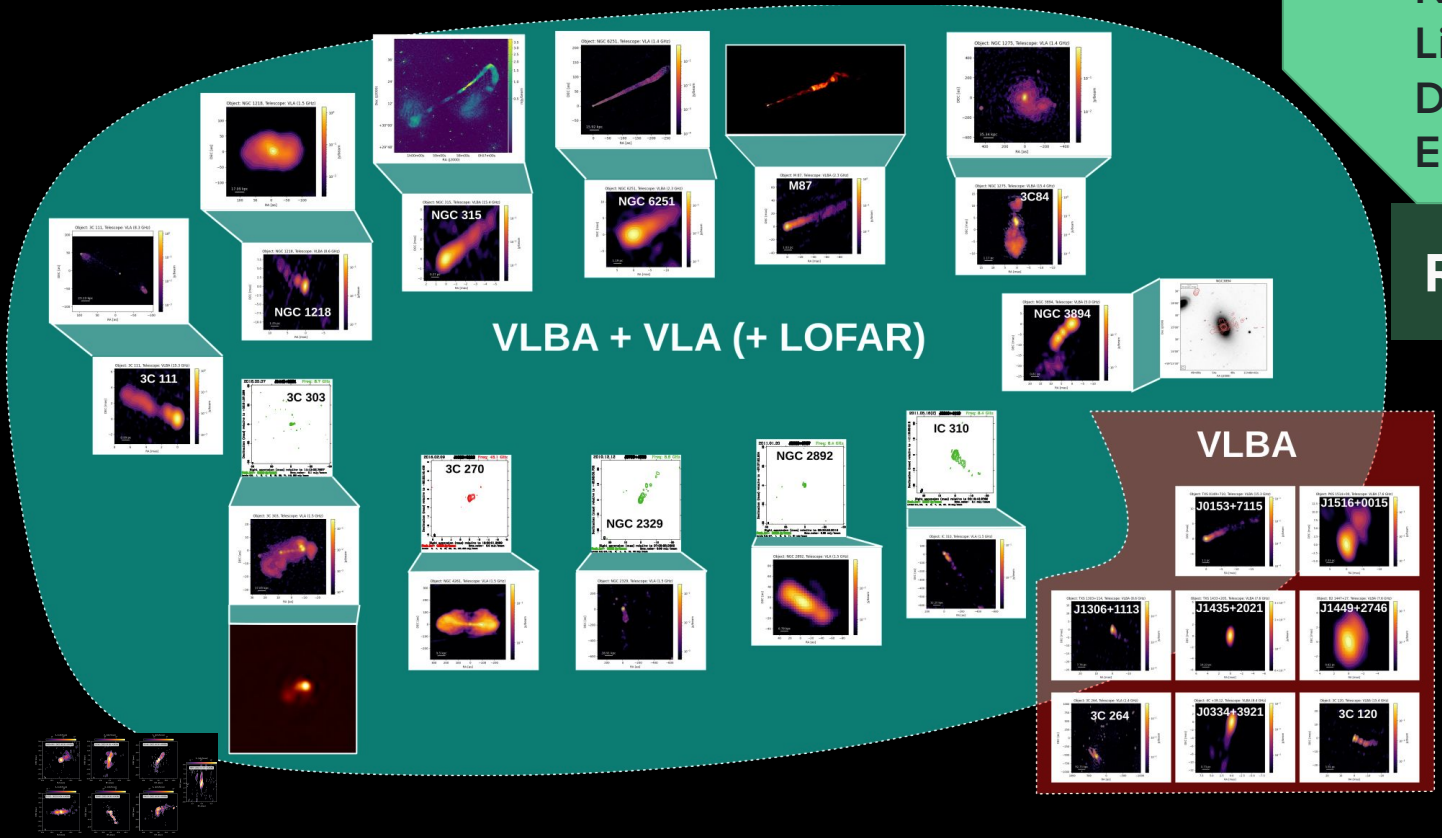
Radio Galaxies detected by Fermi-LAT



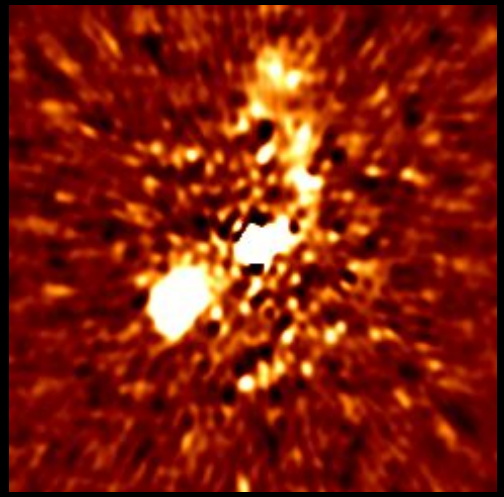
BSc Project:

Nicklas Brodin
Linnea Lövenholm
Daniel Larsson
Emma El-Helou

Radio VLBA - VLA

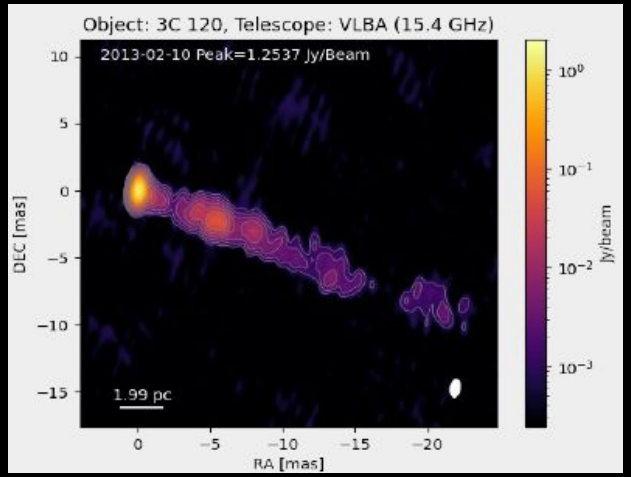
compare large and small scales

Radio Galaxies detected by Fermi - 3C 120



ASKAP 1.4 GHz 8 x 8 arcsec

VLBA 15 GHz 25 x 25 mas

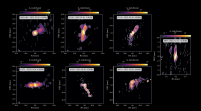


BSc Project:

Nicklas Brodin
Linnea Lövenholm
Daniel Larsson
Emma El-Helou

Scale comparison

Comparing **ASKAP 1.4 GHz** (top)
and **VLBA (MOJAVE) 15 GHz** (bottom)



Radio Galaxies detected by Fermi - 3C 120

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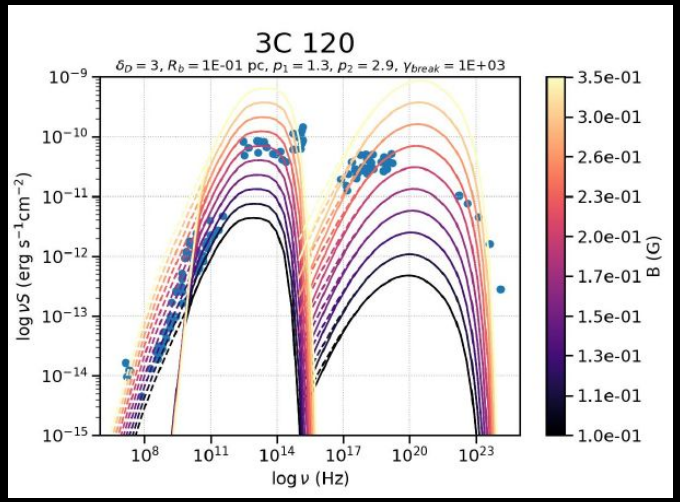
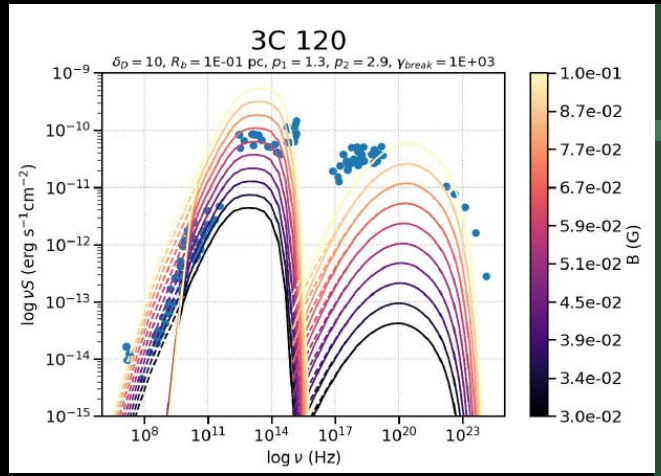


B = 201 mG
Blob radius r = 0.1 pc

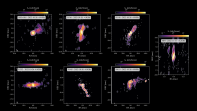


B = 58 mG
Blob radius r = 0.1 pc

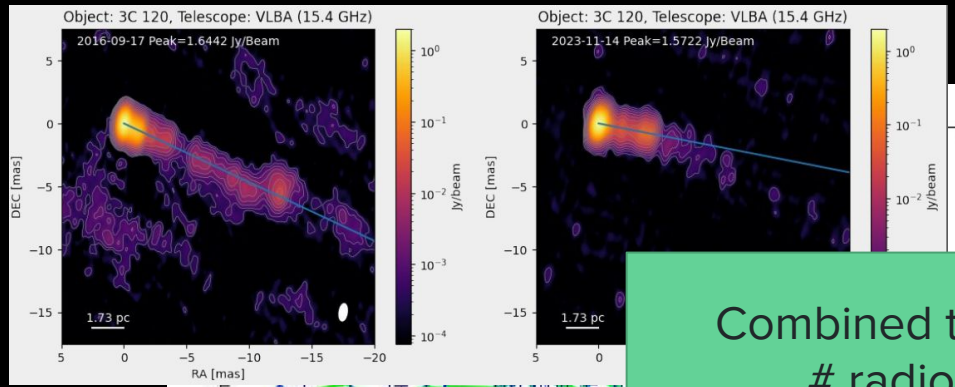
SED - modelling

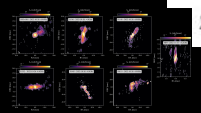
Fit SSA & SSC model using:
AGNpy

(https://github.com/cosimoNigro/agnpy)



Radio Galaxies detected by Fermi - 3C 120





Combined this increases
radio galaxies
in mas jet studies to at least

67

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Emma El-Helou

Lightcurves

Compare Gamma to Radio

Delay about 390 days

Challenge:

Still low number statistics for misaligned jets,
even more so for double sided ones

Challenge:
Still low number statistics for misaligned jets

The way to go: Using big surveys with high sensitivity

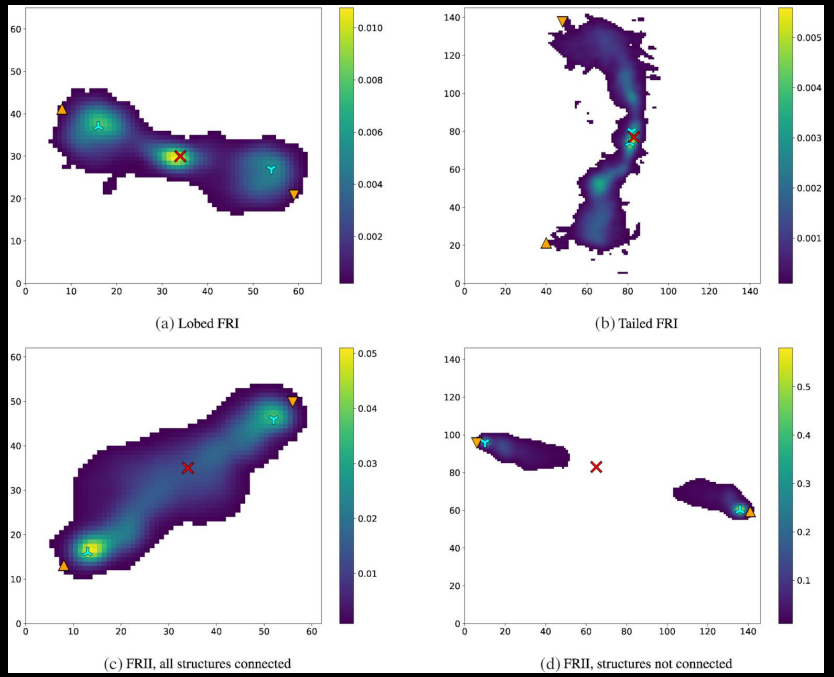
Example: LoTSS (DR1 5805 extended radio-loud sources)

Collaboration with Judith Croston (Open University)
Mingo+ 2019: Classification using LoMorph python code into FR I, FR II and hybrid morphology

Now happening: Filter out compact, misaligned jet structures, observable with EVN+eMERLIN

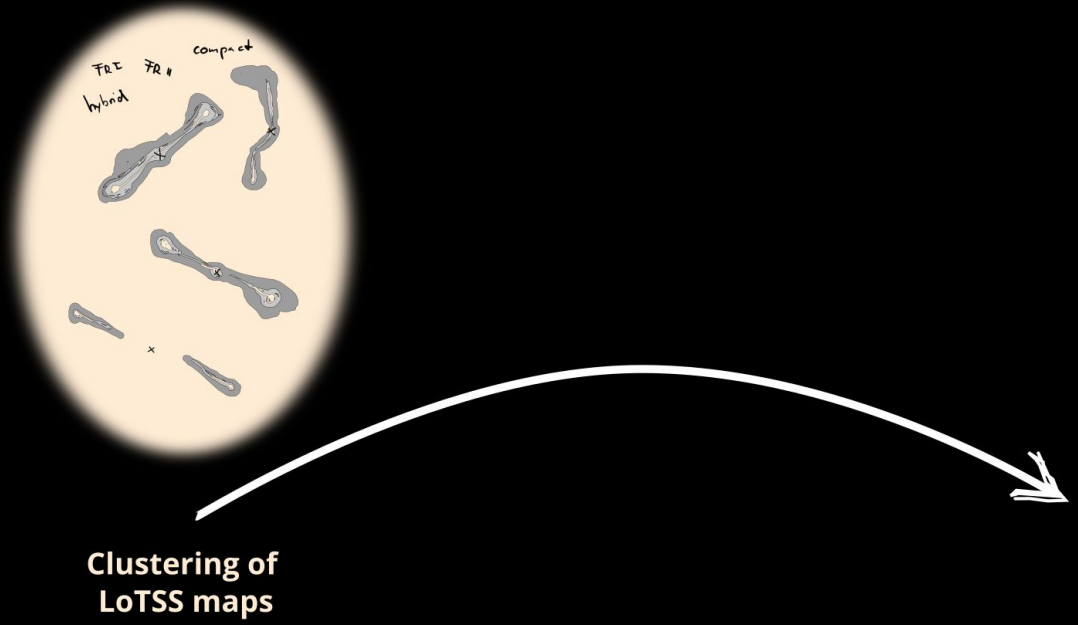
→ compile a more complete sample of misaligned jets.

Other approaches: Astronomaly *(Lochner and Bassett 2021)*

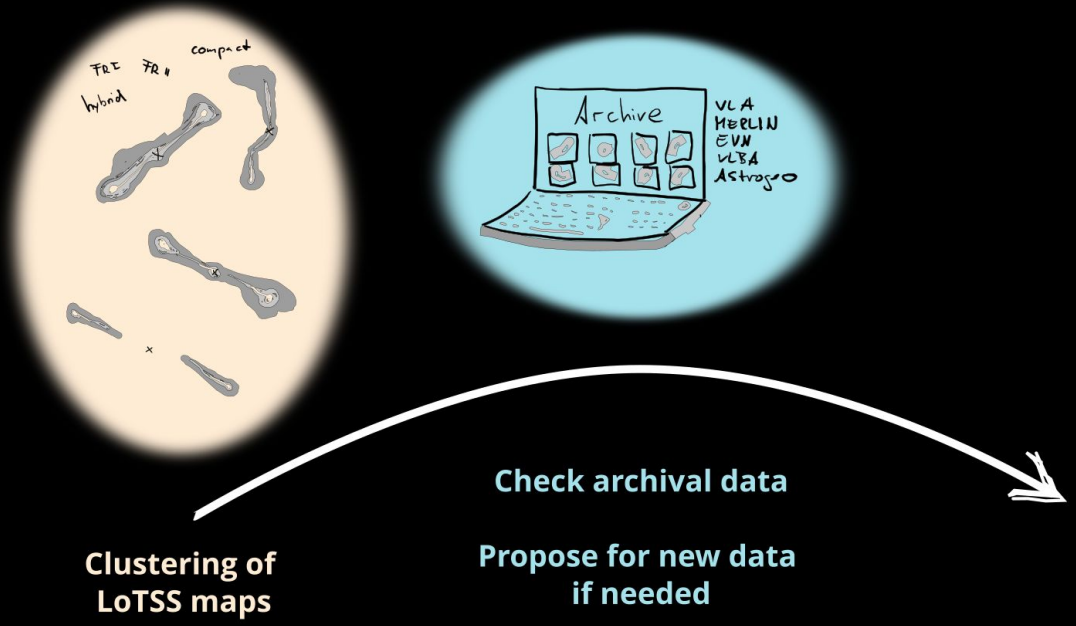


Mingo+ 2019

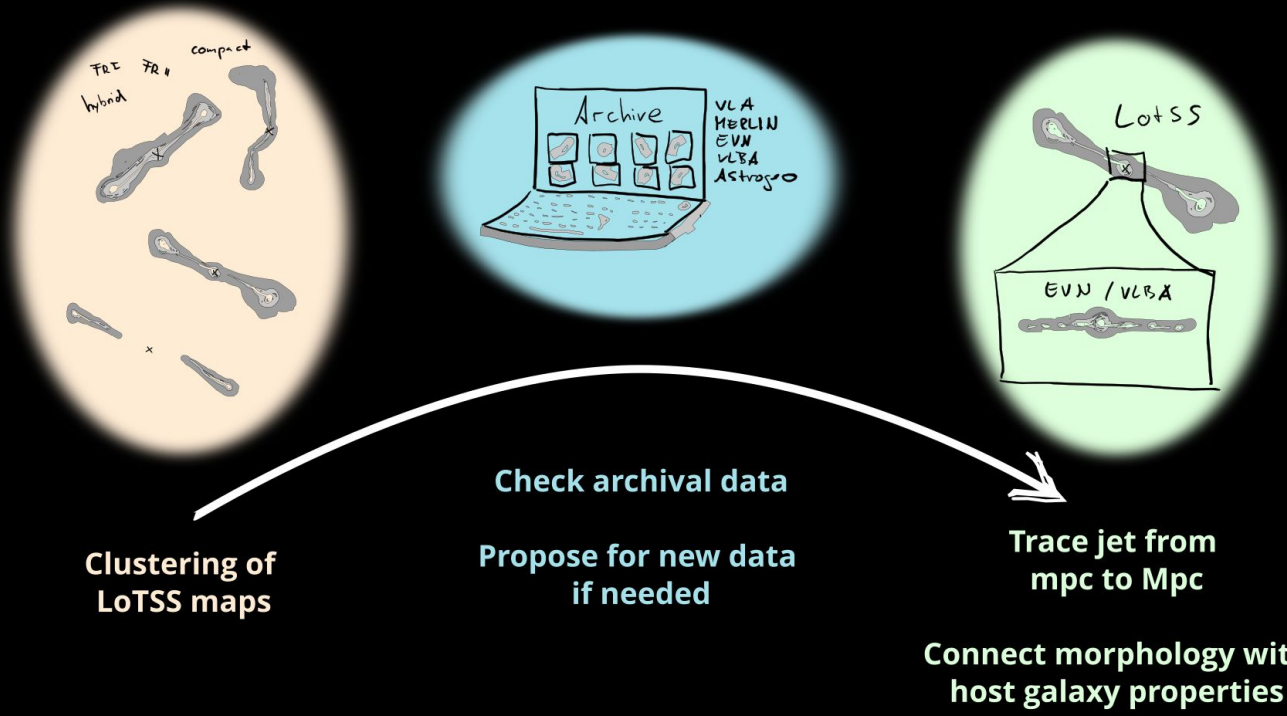
Obtain higher number statistics: start with low frequency



Obtain higher number statistics: start with low frequency



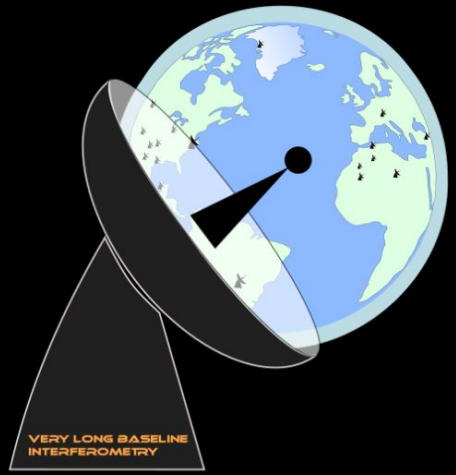
Obtain higher number statistics: start with low frequency

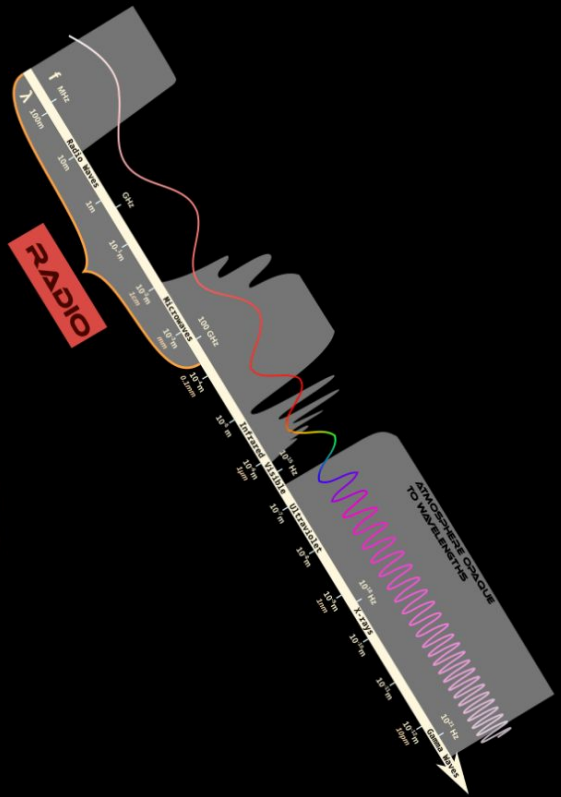


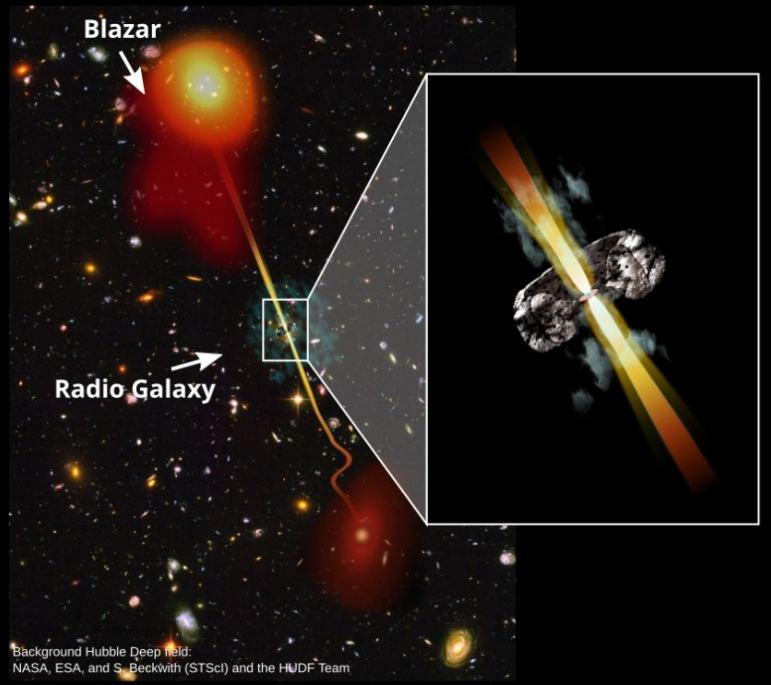
UNDERSTANDING AGN

TELESCOPES

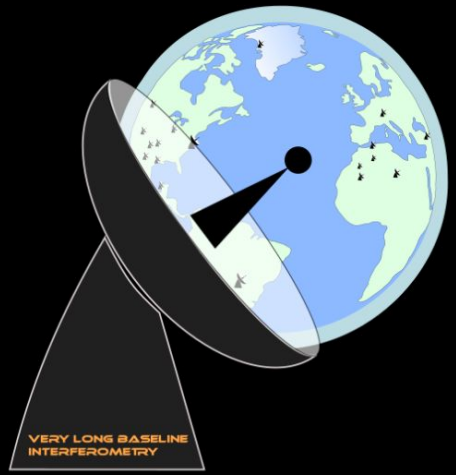
SKAO · GMVA · EUROPEAN VLBI NETWORK · LOFAR · NRAO · CSIRO · NRF National Research Foundation · SARAO South African Radio Astronomy Observatory · THE EAST-ASIA VLBI NETWORK · Event Horizon Telescope



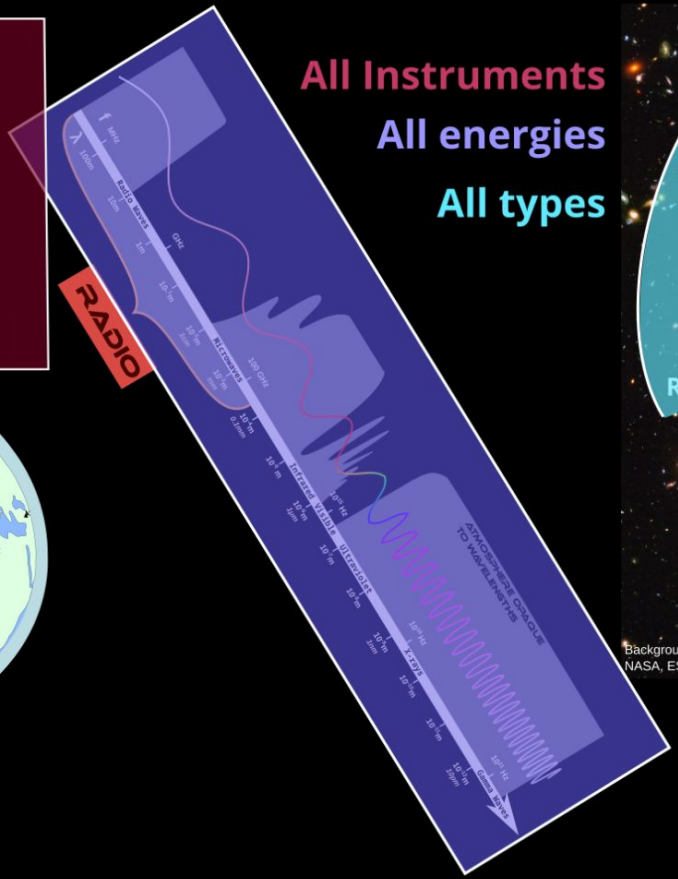


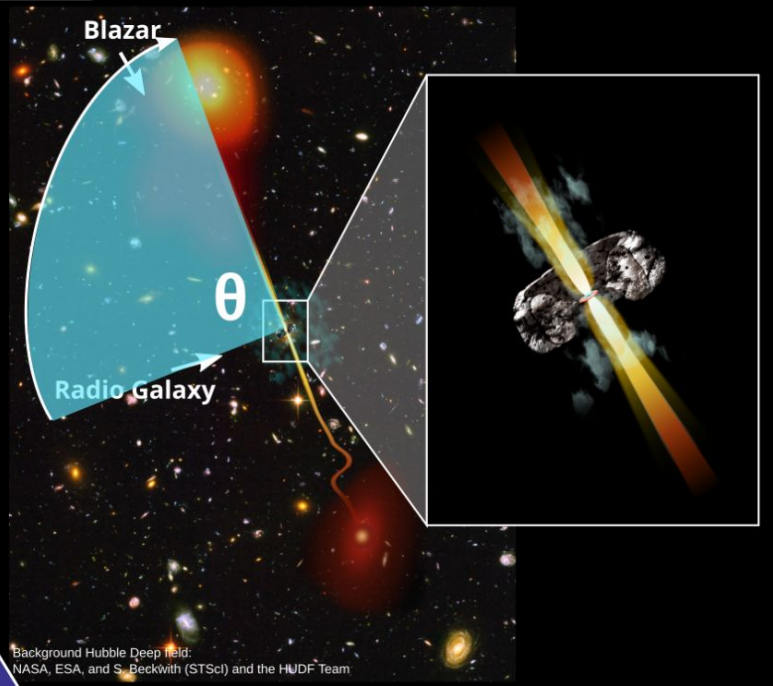


UNDERSTANDING AGN

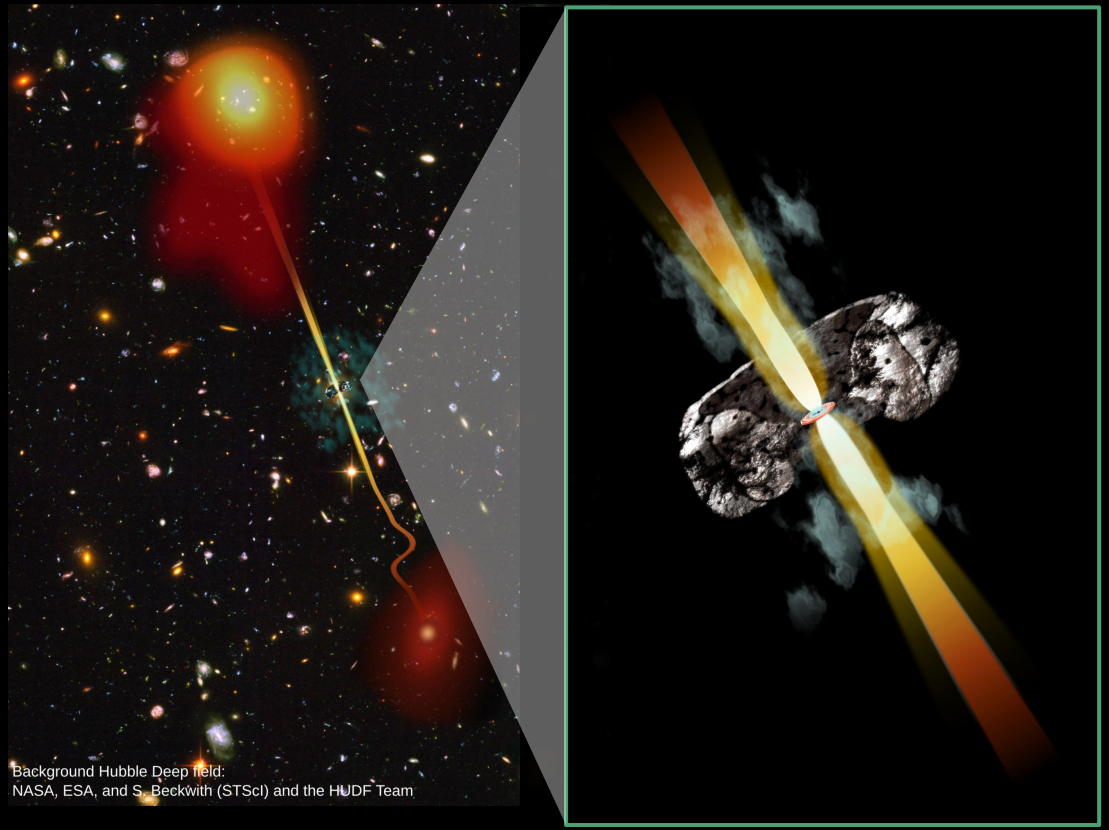


All Instruments
All energies
All types





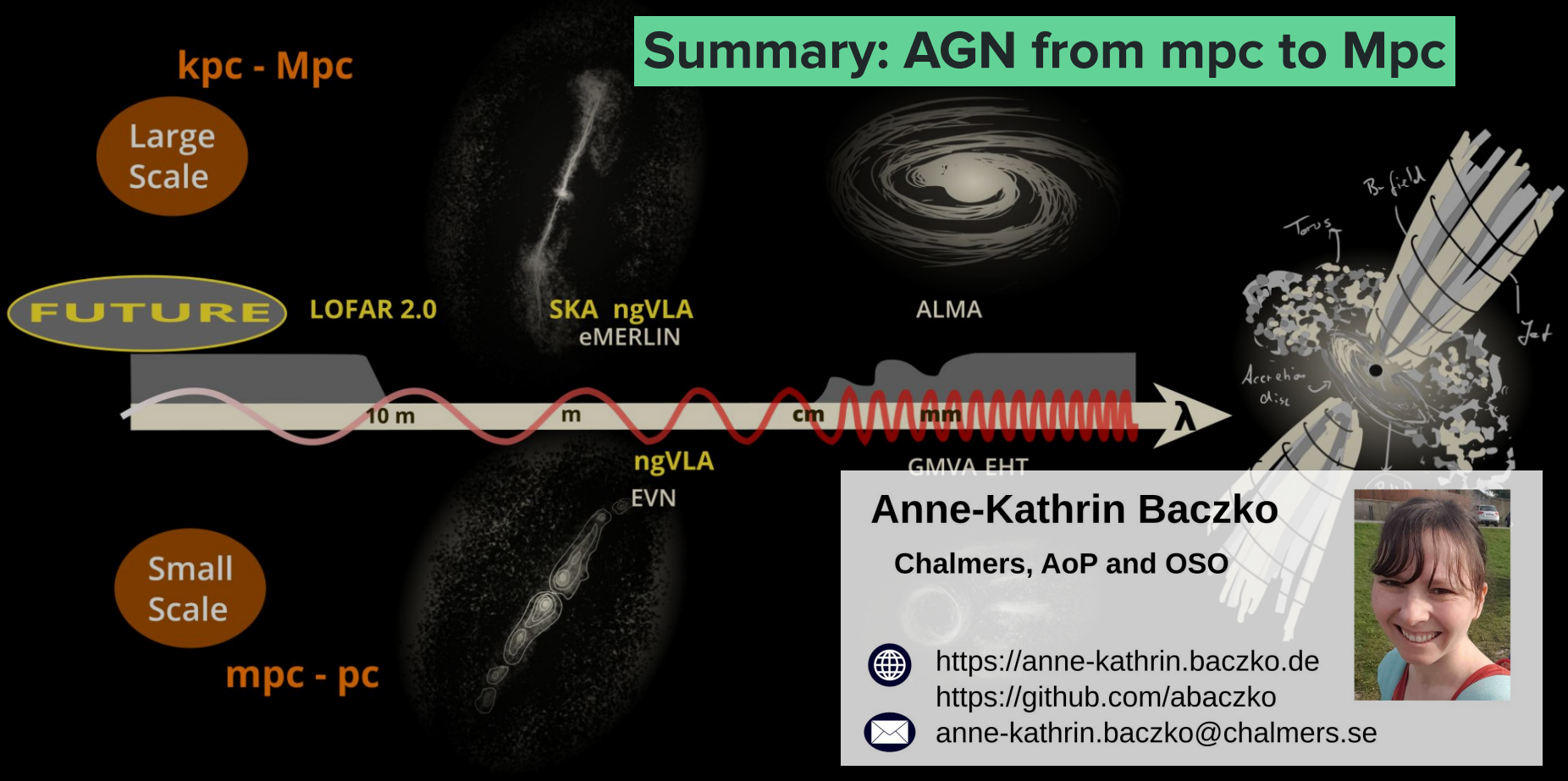
AGN at all scales - The future towards SKA and ngVLA



Combining present VLBI arrays with **SKA and ngVLA** will allow us to study the interplay between AGN jets and their hosts better than ever before.

- Synergies with other radio observatories (ngEHT, LOFAR, MeerKAT, global VLBI, LEVERAGE)
- SKA-VLBI: bridging between low LOFAR frequencies and high ngVLA/GMVA/(ng)EHT
- High sensitivity and large FOV of ngVLA will allow to observe a larger number of double-sided jets to reform the AGN unification scheme

Summary: AGN from mpc to Mpc



Anne-Kathrin Baczko

Chalmers, AoP and OSO

https://anne-kathrin.baczko.de
https://github.com/abaczko
anne-kathrin.baczko@chalmers.se

Part of a pilot study including HSA and EVN

Candidate double-sided jets at z<0.1 at 5 GHz (EVN)

M 84
NGC 3894
3C 293
3C 317
4C 31.04
1946+708

Candidates in the southern hemisphere
Thanks to the addition of ALMA to VLBI arrays