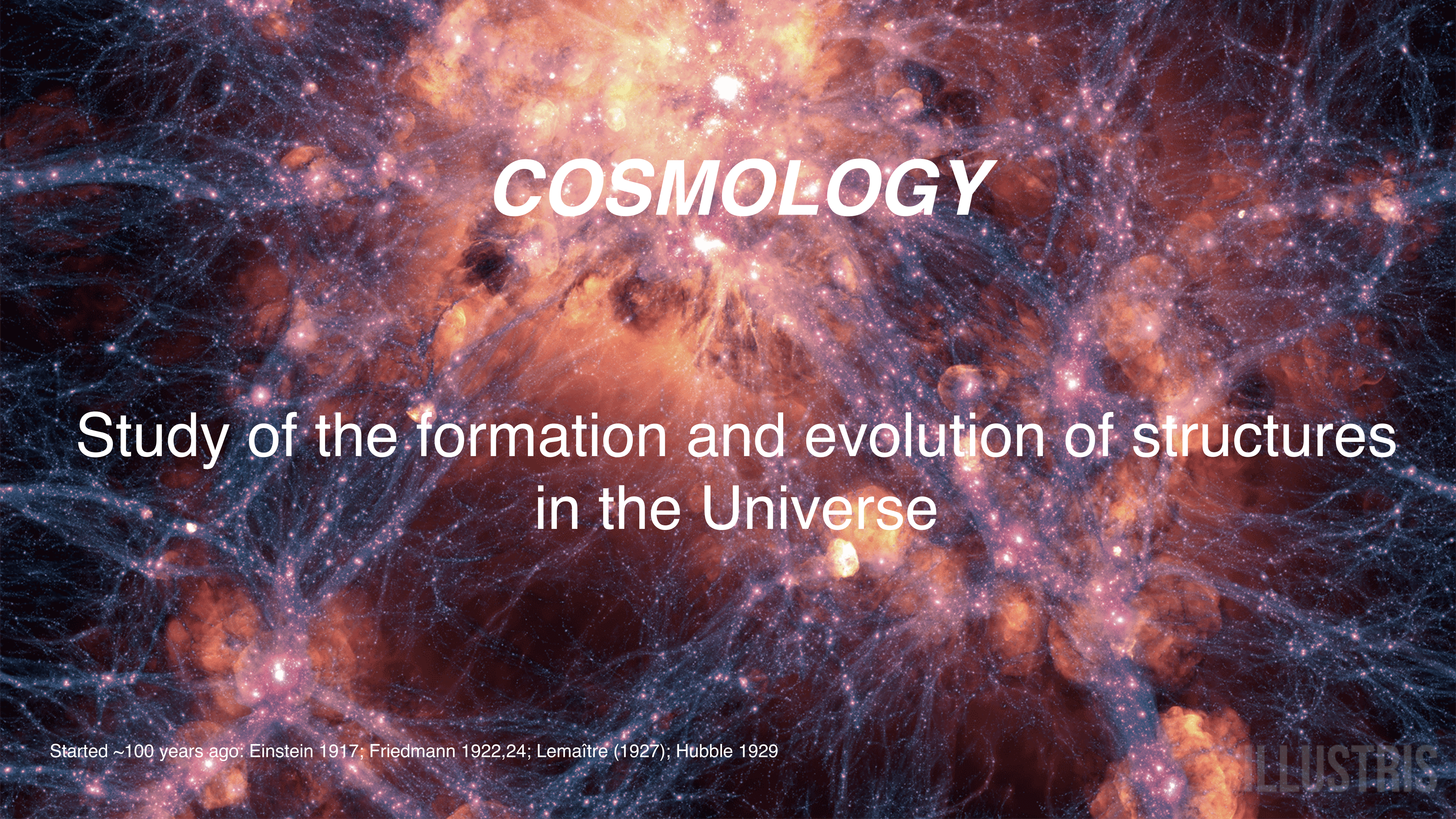
Cosmological studies with VLBI

Cristiana Spingola

INAF – Istituto di radioastronomia (Bologna, Italy)

15th EVN Symposium & Users meeting, University College, Cork (Ireland) July 14th, 2022

Image credits:NRAO/AUI/NSF, data from Spingola+2018, 2020



COSMOLOGY

Study of the formation and evolution of structures in the Universe

Started ~100 years ago: Einstein 1917; Friedmann 1922,24; Lemaître (1927); Hubble 1929

Current cosmological framework - *ΛCDM*

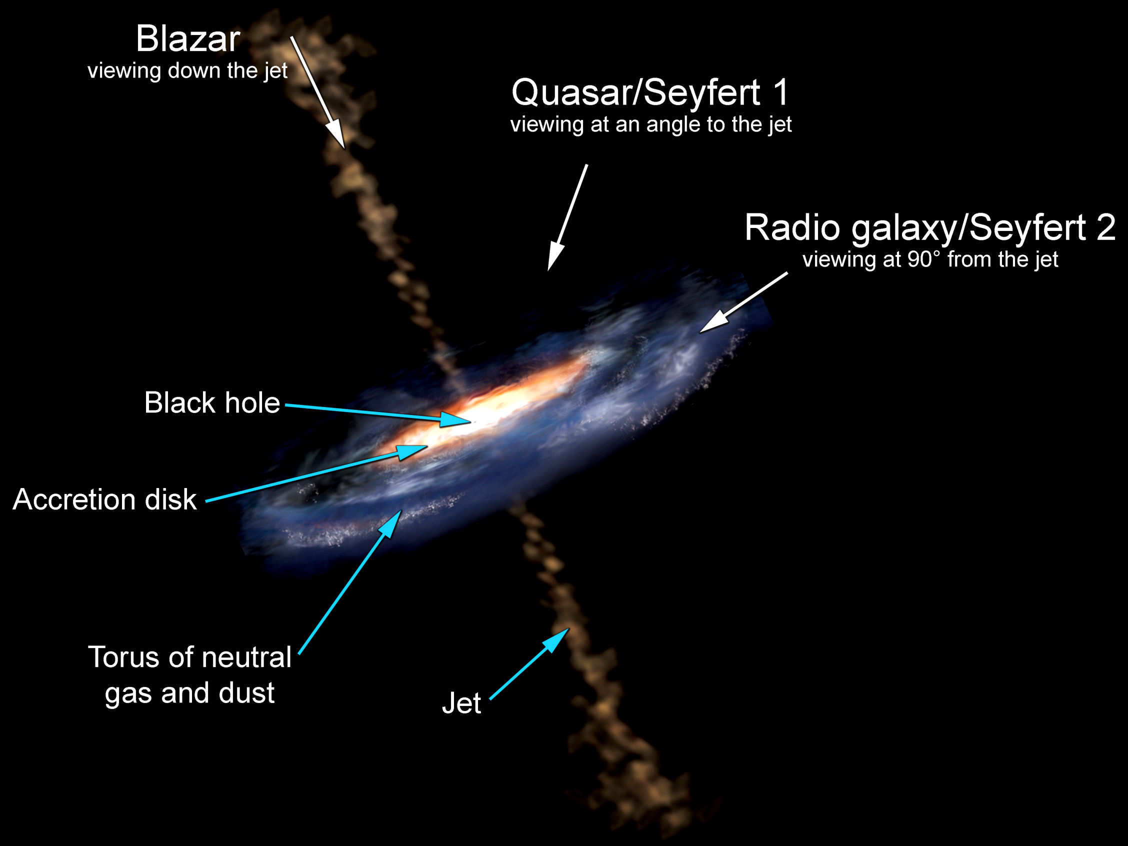
blue: cold gas
green: warm gas
white/red: hot gas

From simple GAS (mostly H and He) to complex GALAXIES (metal enriched gas, stars, dust, supermassive black holes and dark matter)
all in an expanding Universe (dark energy)
OK large scales, issues on small scales (e.g., Bullock & Boylan-Kolchin review 2017)– we need high angular resolution obs. of high-z sources

Cosmological studies with VLBI

Active Galactic Nuclei (AGN)
see Gabuzda's review talk

especially jetted AGN
because of the boosted luminosity
they can be observed up to the highest redshifts



Credit: Gsfc/Nasa

Cosmological studies with VLBI

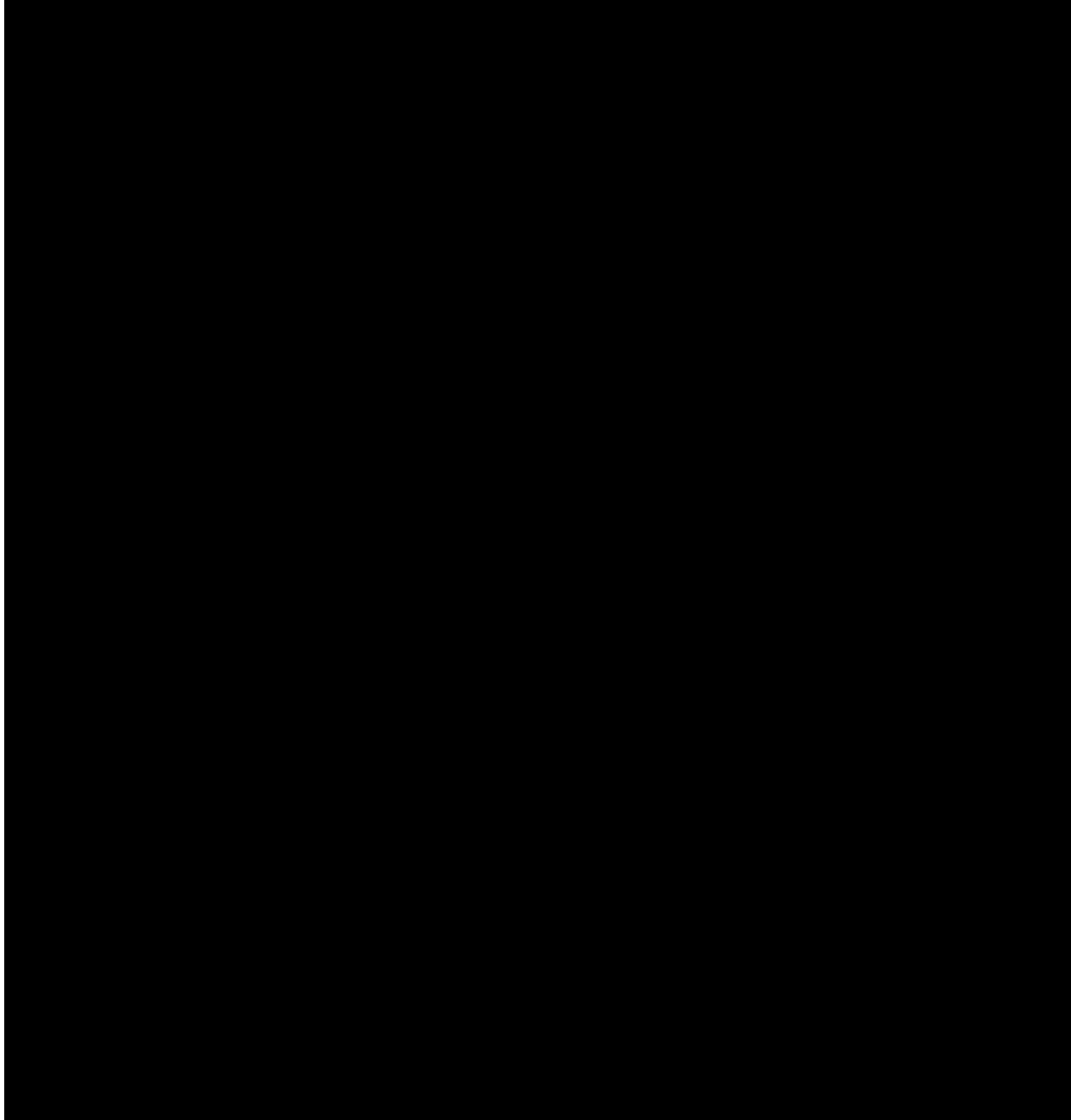
Active Galactic Nuclei (AGN)
see Gabuzda's review talk

especially jetted AGN
because of the boosted luminosity
they can be observed up to the highest redshifts

Strong gravitational lensing

Some of these high-z AGN could be magnified by the gravitational effect of a foreground galaxy/cluster

(see Review by Tommaso Treu 2020)



Credits: R. Schulz, VLBI data from Spingola et al. 2018
source reconstruction from Powell et al. 2021

Outline of the talk

not to scale

Part 1 SMBHs and luminous matter

Outline of the talk

not to scale

Part 1 SMBHs and luminous matter

Part 2 Dark energy

Outline of the talk

not to scale

Part 1 SMBHs and luminous matter

Part 3 Dark matter

Part 2 Dark energy

Outline of the talk

not to scale

Part 1 SMBHs and luminous matter

Part 3 Dark matter

Part 2 Dark energy

Part 4
Wide-field VLBI

*sorry, it didn't fit the stout

Part 1
Supermassive black holes and luminous matter at very high redshift

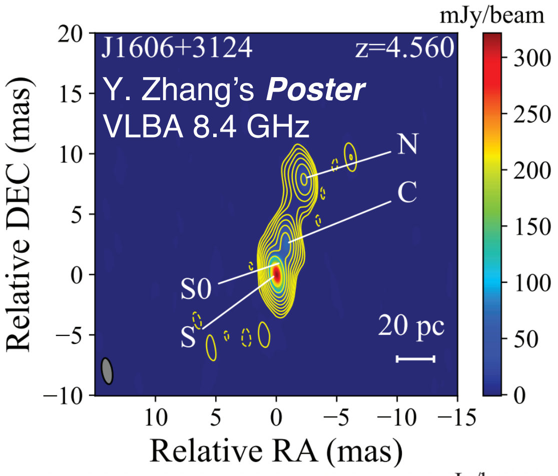
SMBHs in the early Universe

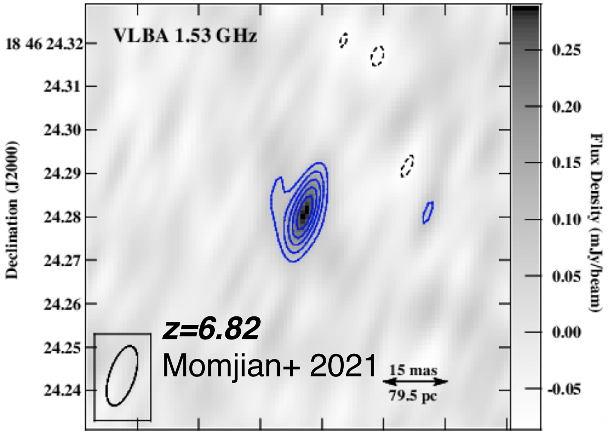
Initial growth phase dominated by BH mergers (z>6) → then **gas accretion from the interstellar medium**
(e.g., Piana+2021 and references therein)

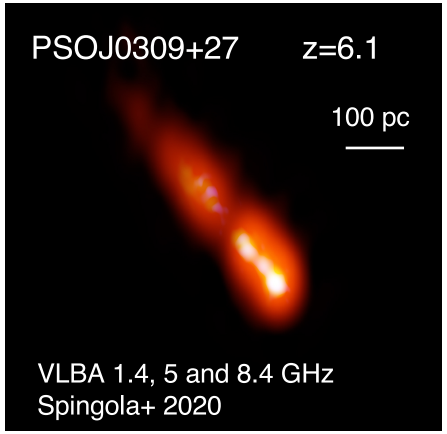
Radio-loud AGN almost always reside in gas-rich mergers environments (e.g., Chiaberge+2015 – also more recent Gao+2020, Garofalo+2020, Romano+2021, Shen+2021, Pierce+2022)

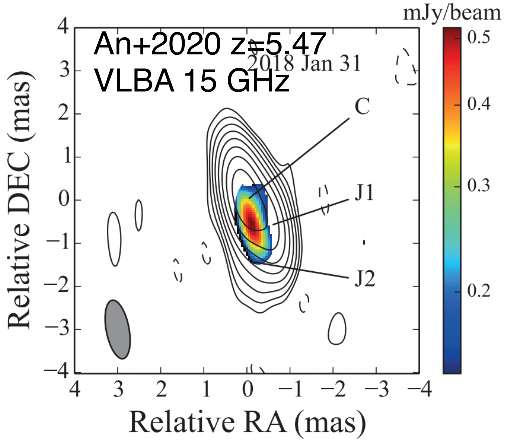
Merging ?=? Activates radio-loudness

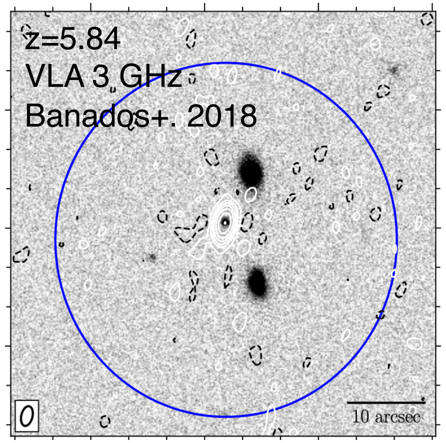
See also
Poster n. 9 by Y. Zhang
Poster n. 10 by K. Perger
S. Frey's talk in this session

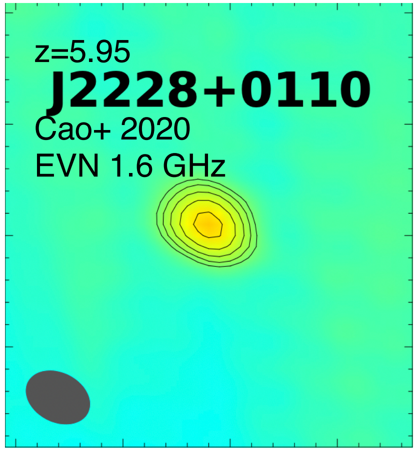


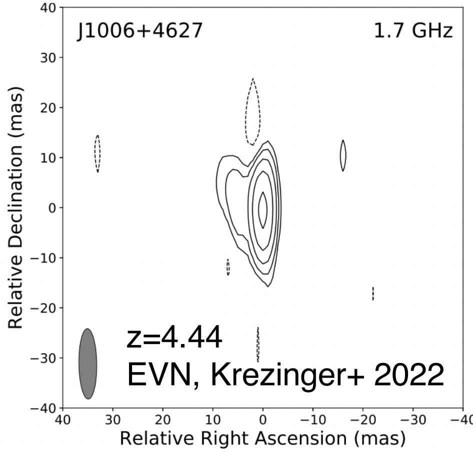


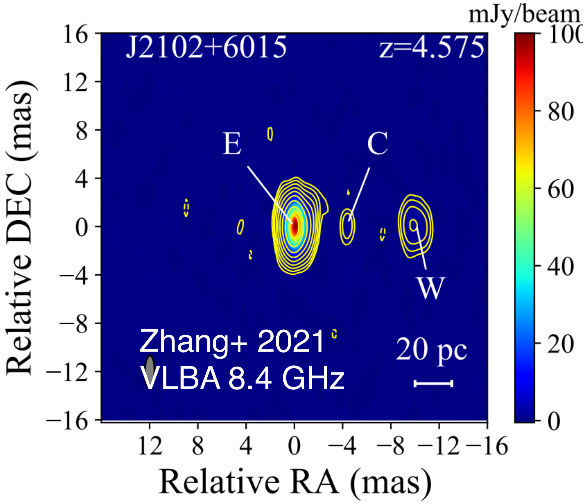


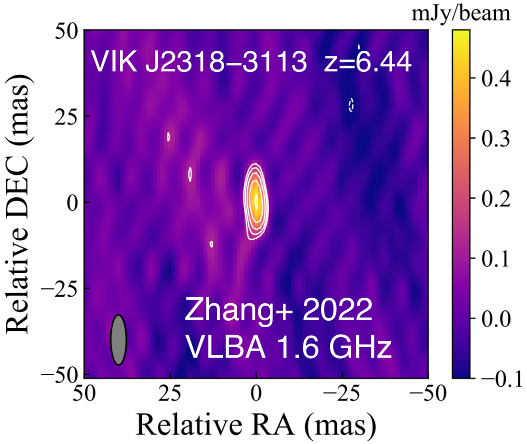








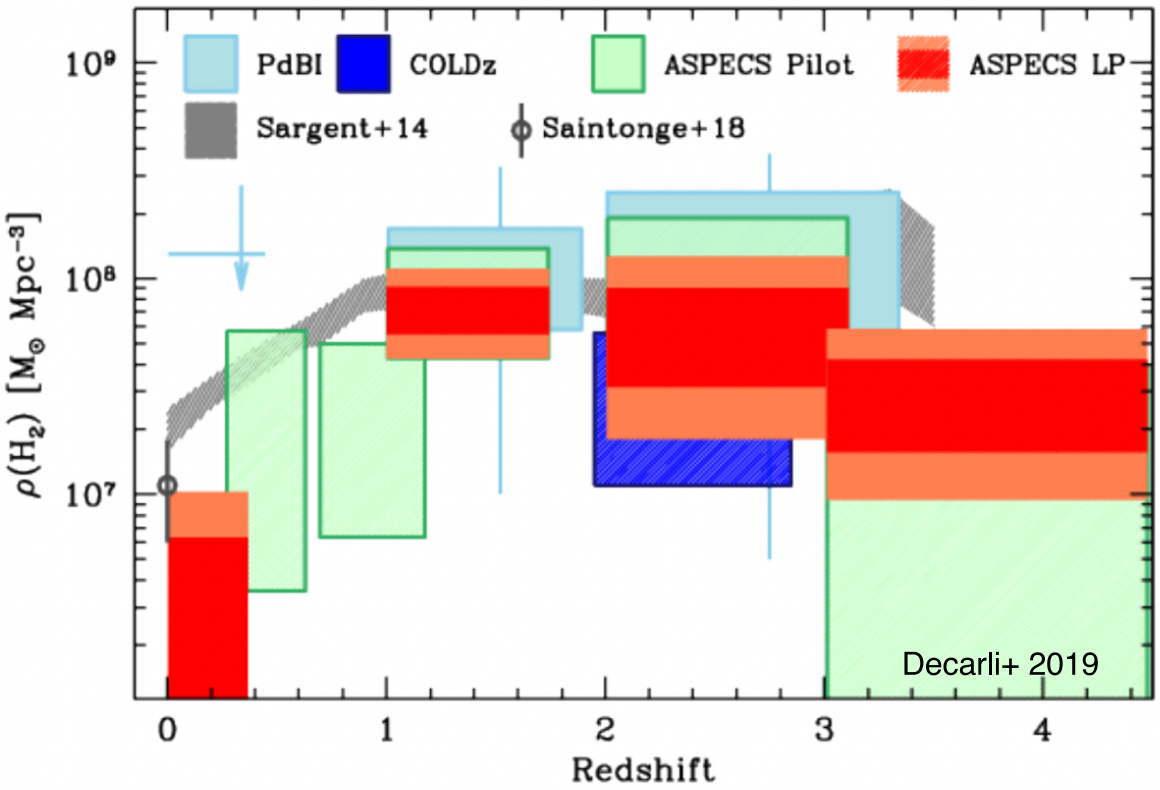




SMBHs in the early Universe – accretion: molecular gas

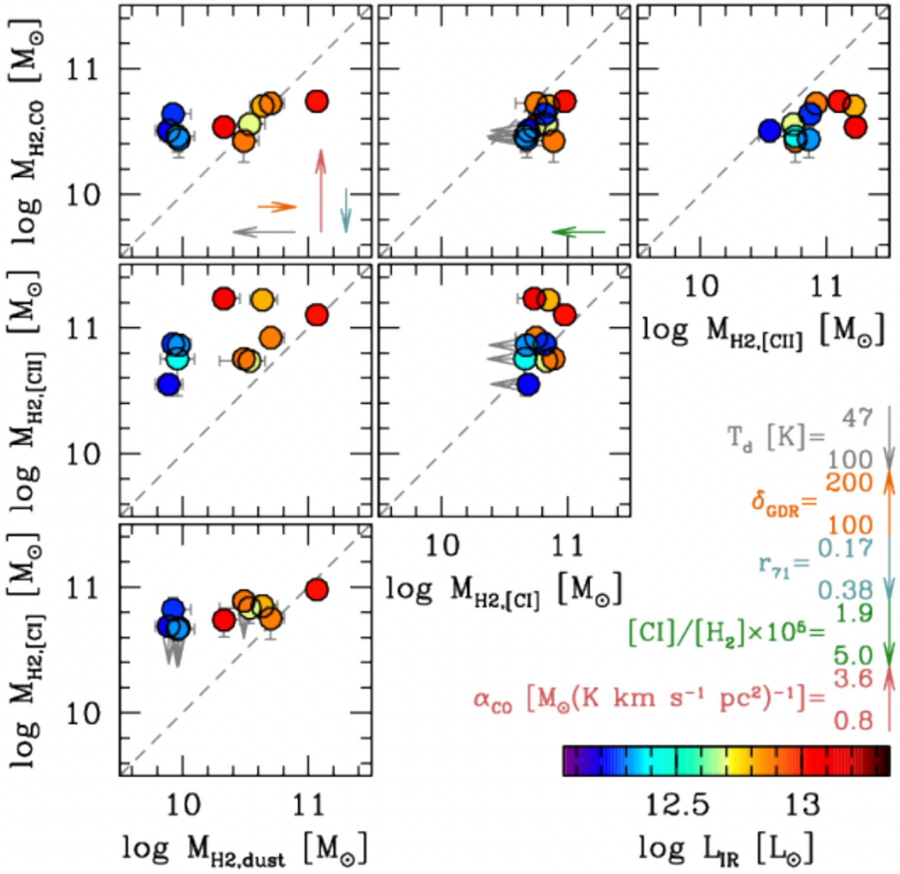
CO emission lines best tracers for H_2: at high-z = radio/mm band (also C^+)
(Carilli & Walter 2013, Walter+ 2014, Aravena+2016, Decarli+2016, Riechers+2019,2020, Bischetti+2020, Spingola+2020, Cicone+2020, Circosta+2021, Liu+2022 Dye+2022)

Cosmic evolution of the cold molecular gas density



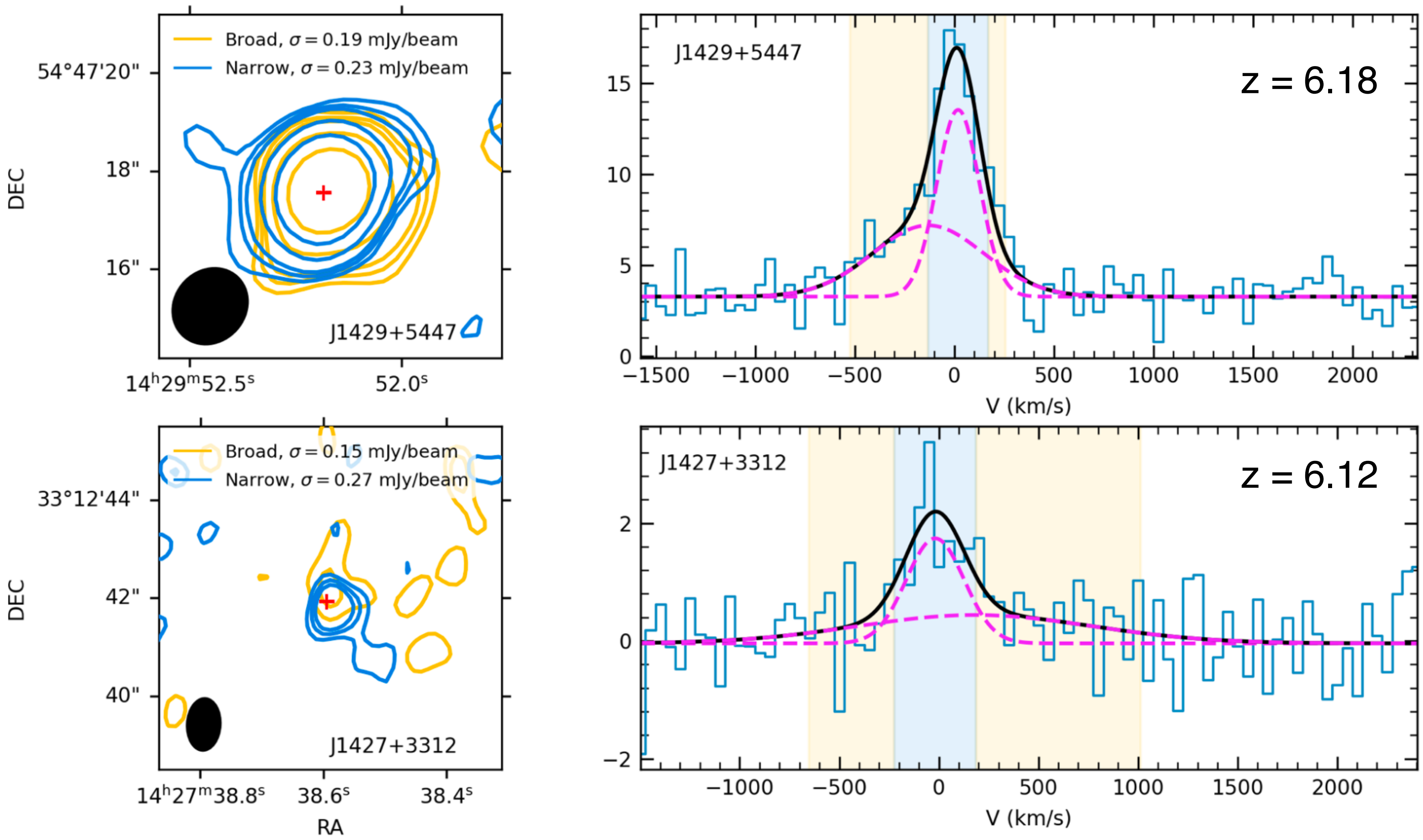
Same trend as AGN and star formation history (e.g., Hopkins+2006)

Decarli+ 2022



Expected large molecular gas reservoirs and mergers from simulations
(Di Matteo+ 2008, Davé+2020)

SMBHs in the early Universe – accretion: molecular gas and mergers



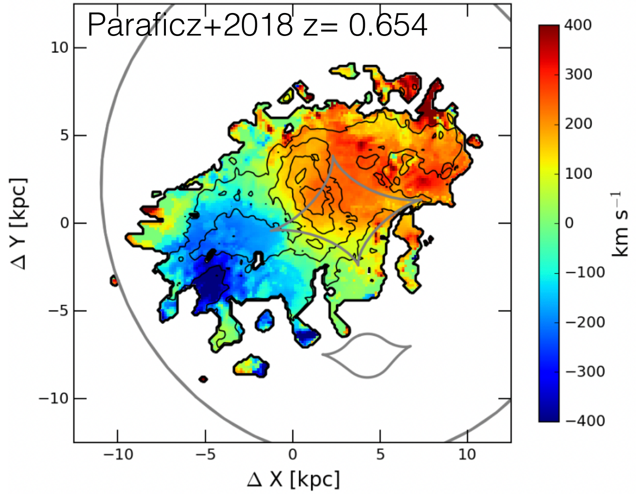
Evidence for mergers in gas-rich radio-loud AGN at z>6 from line profile (Khusanova et al. 2022)

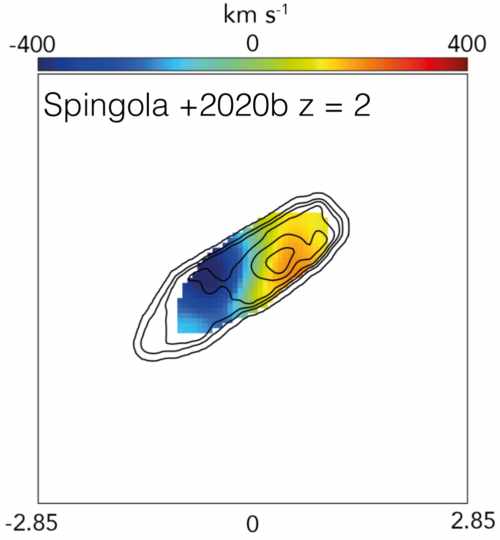
SMBHs in the early Universe – accretion: molecular gas and mergers

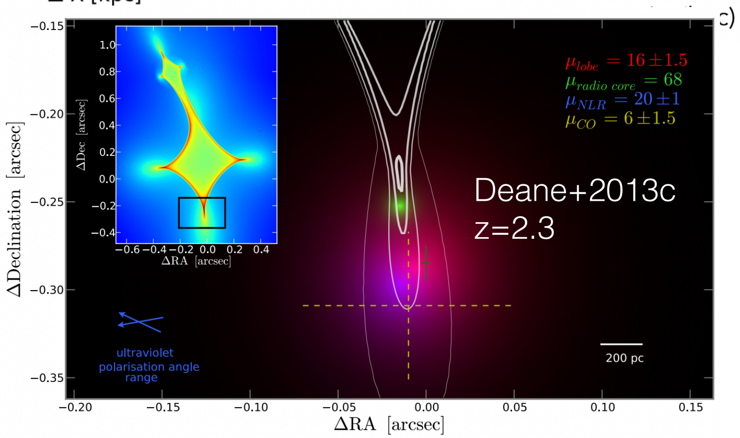
Lensing magnification = **boost in spatial resolution and sensitivity** necessary for CO low-J (low surface brightness)

DISKS

ordered rotation on ~kpc scales

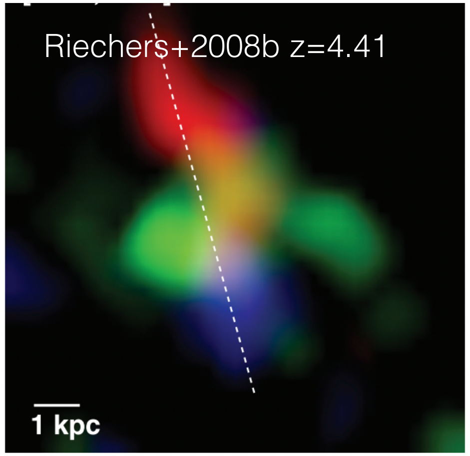


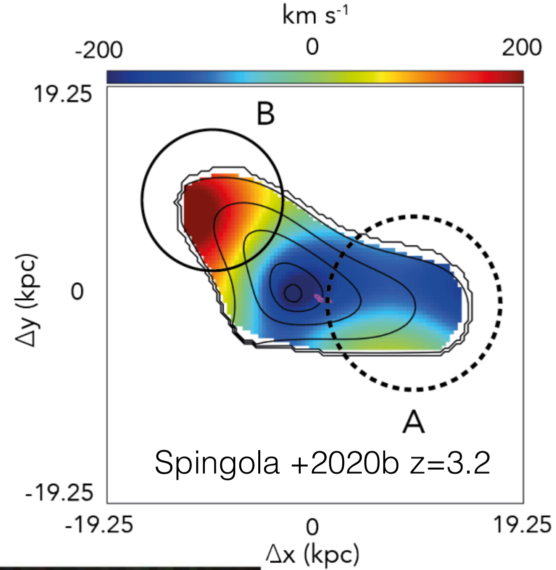




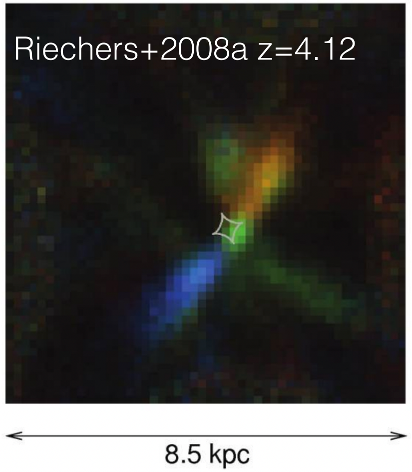
MERGERS

Multiple velocity fields + kinematical modelling





Source reconstruction
of molecular gas in lensed
radio-loud AGN at high-z

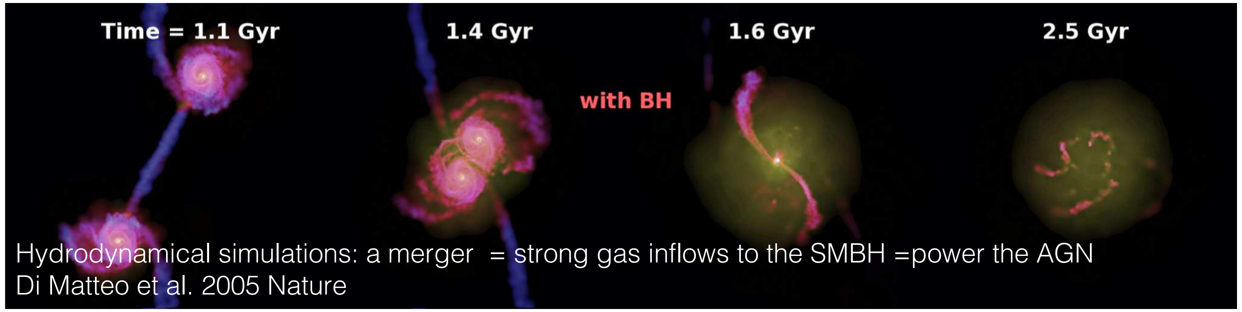


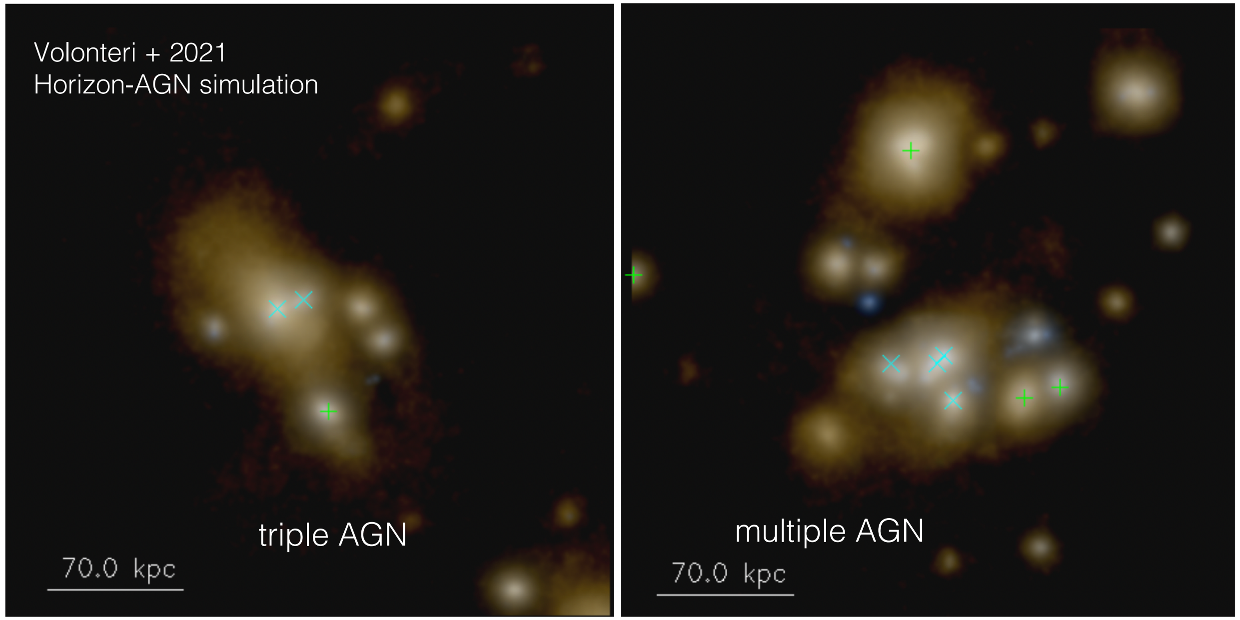
See also Ryback+2015a,b; Neeleman+2020(Nature), Rizzo+2021(Nature) Muñoz-Elgueta+2022;
Rizzo+2022 dynamical characterization up to z~7

SMBHs in the early Universe – binary AGN

Hierarchical scenario = binary AGN (or even multiple SMBH systems)
Begelman+1980, Volonteri 2003, Di Matteo+2005, Volonteri+2010

Dual AGN = separation < 10 kpc, Binary AGN = separation <100 pc (Burke-Spolaor+2011)





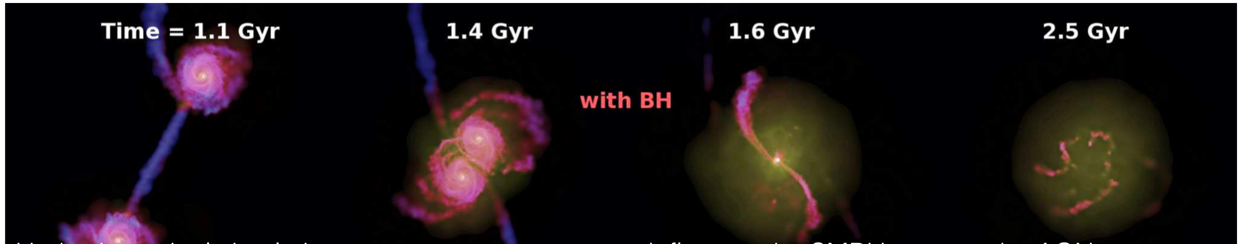
Problem of simulations = resolution → «Final parsec problem»

Binary AGN are in the sub-grid physics in large volume simulations

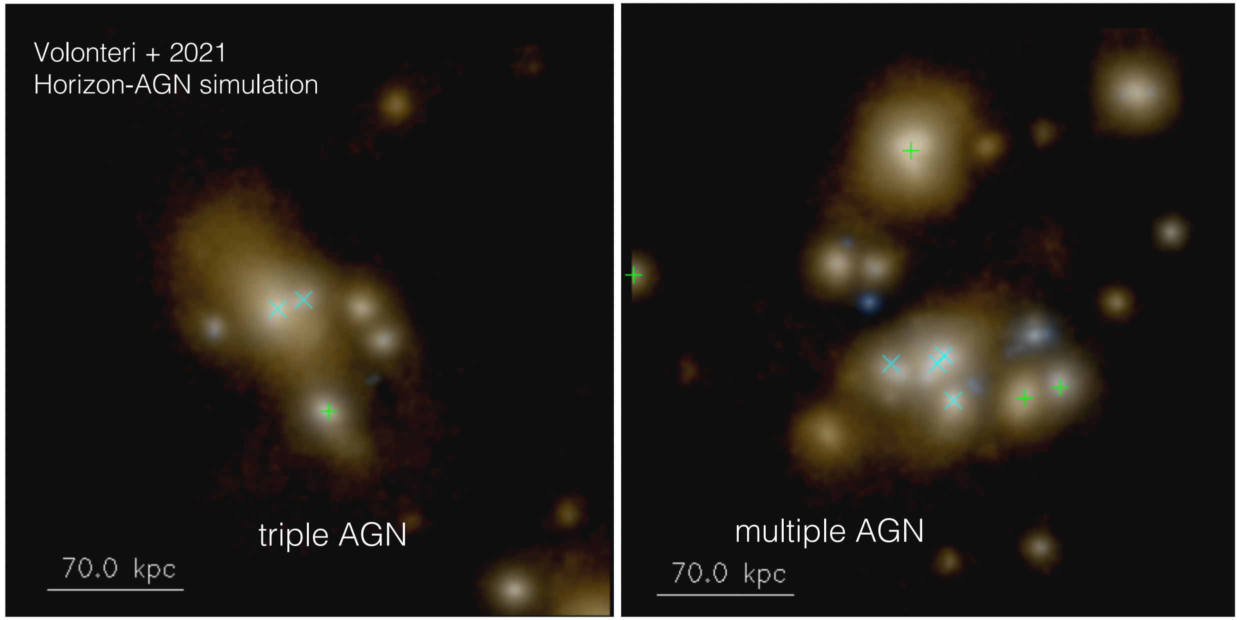
SMBHs in the early Universe – binary AGN

Hierarchical scenario = binary AGN (or even multiple SMBH systems)
Begelman+1980, Volonteri 2003, Di Matteo+2005, Volonteri+2010

Dual AGN = separation < 10 kpc, Binary AGN = separation <100 pc (Burke-Spolaor+2011)

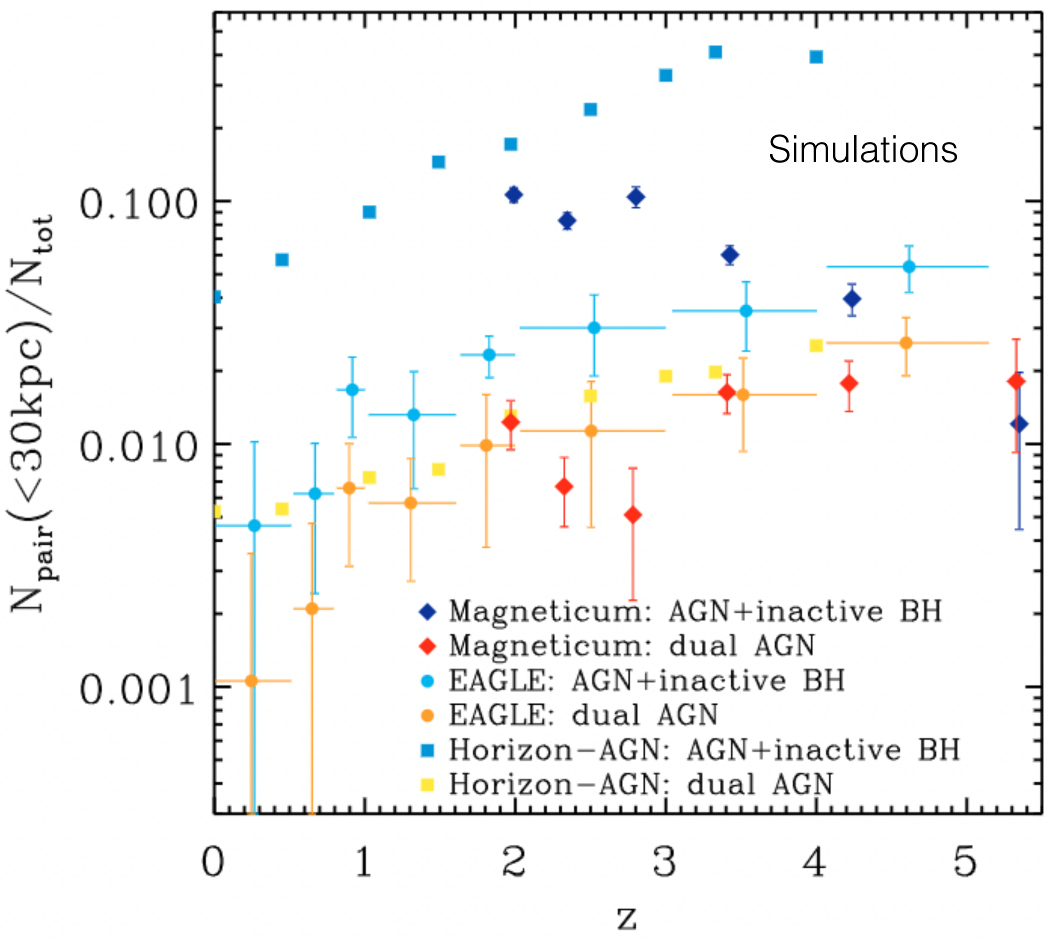


Hydrodynamical simulations: a merger = strong gas inflows to the SMBH =power the AGN
Di Matteo et al. 2005 Nature



Problem of simulations = resolution → «Final parsec problem»
Binary AGN are in the sub-grid physics in large volume simulations

De Rosa et al. 2019 Review

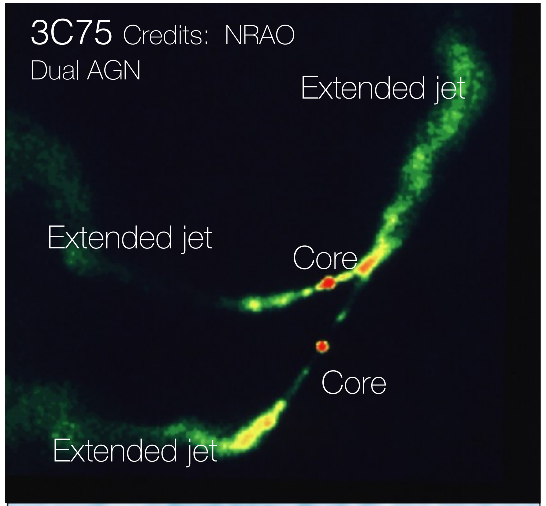


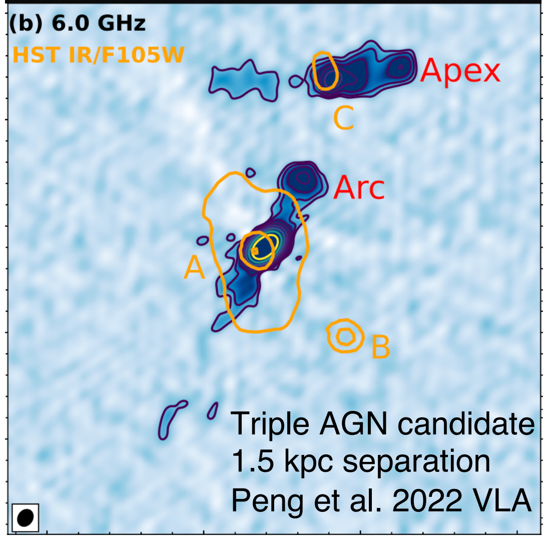
Fraction of dual AGN wrt the total number of AGN in different simulations

Number increases at high redshift

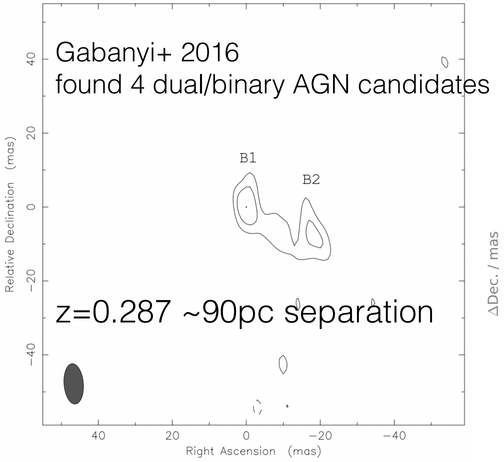
SMBHs in the early Universe – binary AGN with VLBI

VLBI can spatially resolve pc-scale systems even at high-z





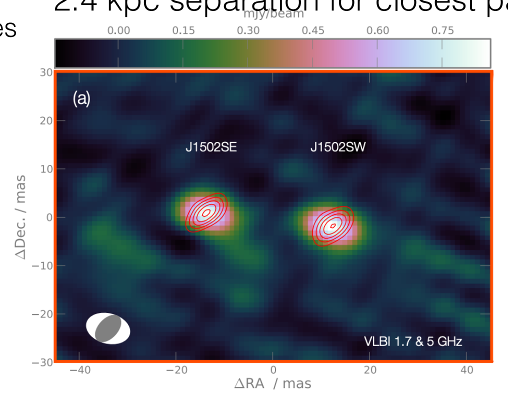
Triple AGN candidate
1.5 kpc separation
Peng et al. 2022 VLA



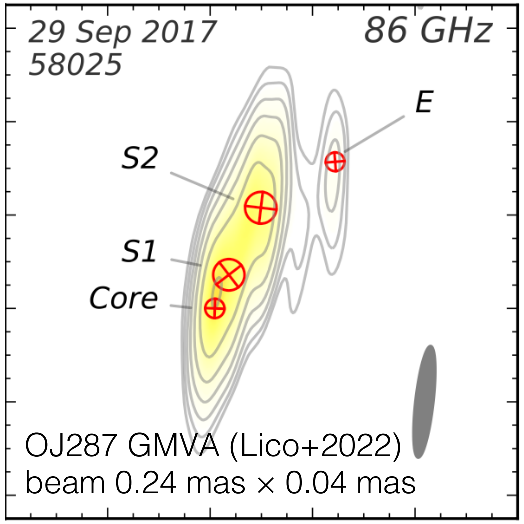
Gabanyi+ 2016
found 4 dual/binary AGN candidates

z=0.287 ~90pc separation

Triple AGN z= 0.39 Deane+ 2014, Nature
2.4 kpc separation for closest pair

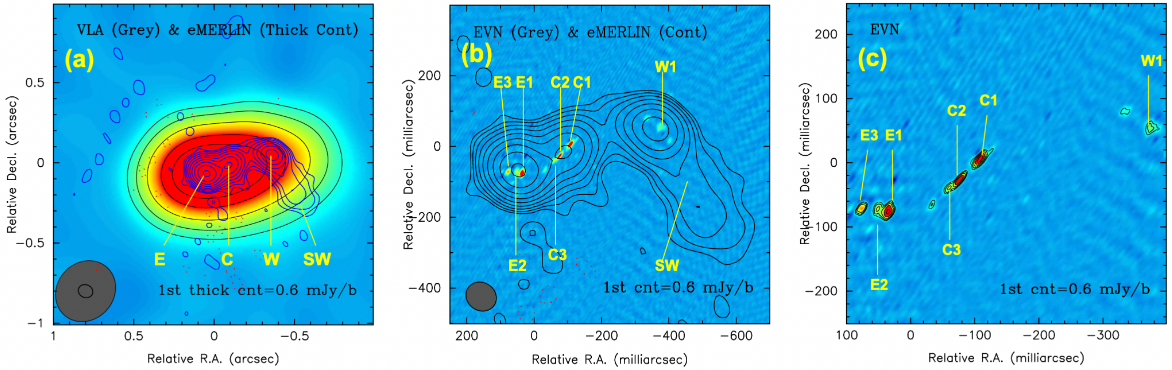


Sup-pc binary AGN candidate from monitoring (periodicity)

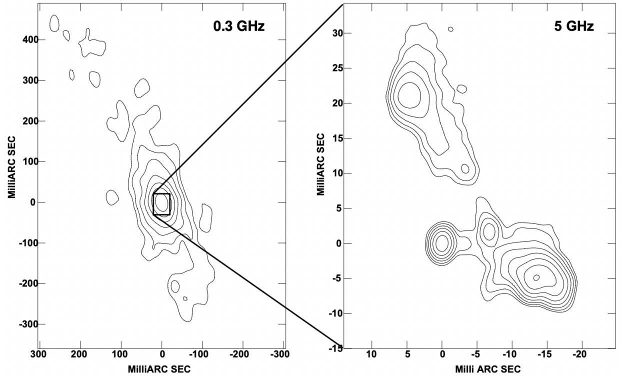


OJ287 GMVA (Lico+2022)
beam 0.24 mas × 0.04 mas

Bondi & Perez-Torres 2010
EVN 50 pc separation
z~0.4 (candidate)



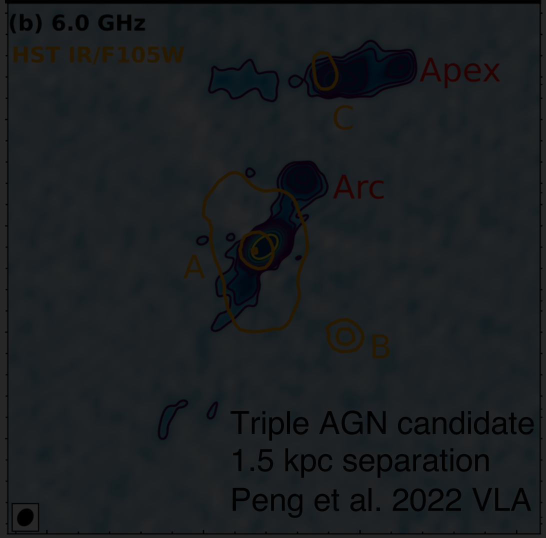
Dual AGN candidate but very complex structure (An+ 2013)
z=0.578, total extent 3 kpc



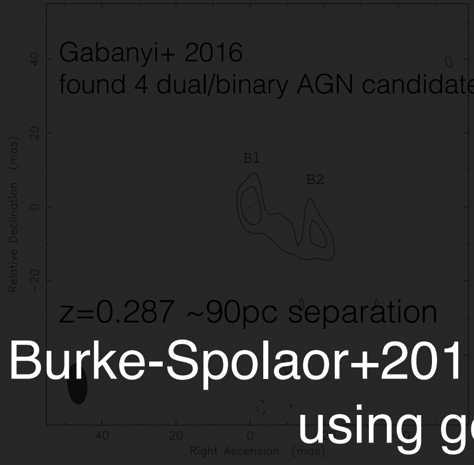
Rodriguez+2006 7.3pc separation
z=0.055 confirmed binary AGN

SMBHs in the early Universe – binary AGN with VLBI

VLBI can spatially resolve pc-scale systems even at high-z



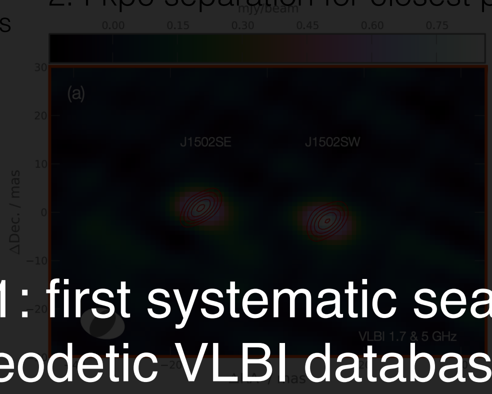
Triple AGN candidate
1.5 kpc separation
Peng et al. 2022 VLA



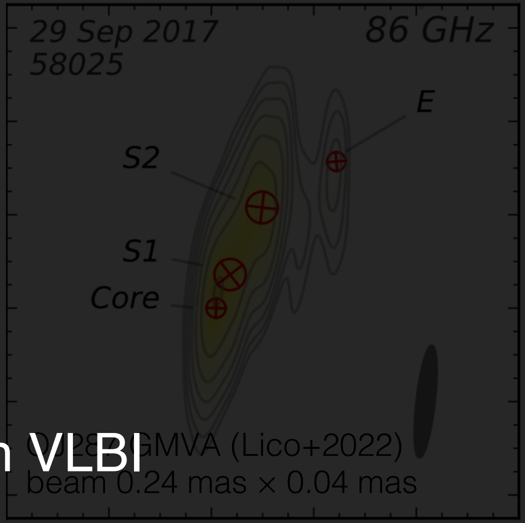
Gabanyi+ 2016
found 4 dual/binary AGN candidates

z=0.287 ~90pc separation

Triple AGN z= 0.39 Deane+ 2014, Nature
2.4 kpc separation for closest pair



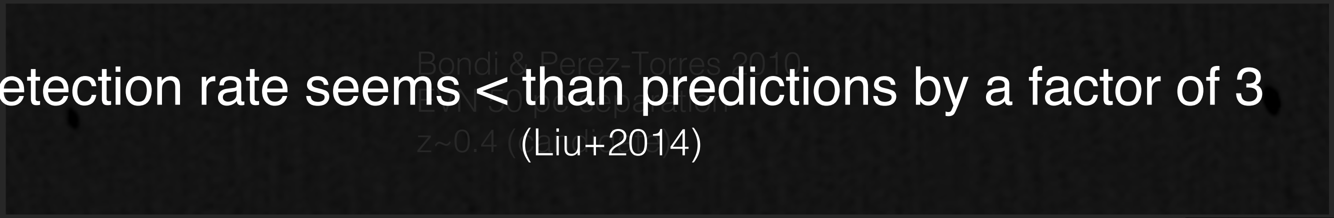
Sup-pc binary AGN candidate from monitoring (periodicity)

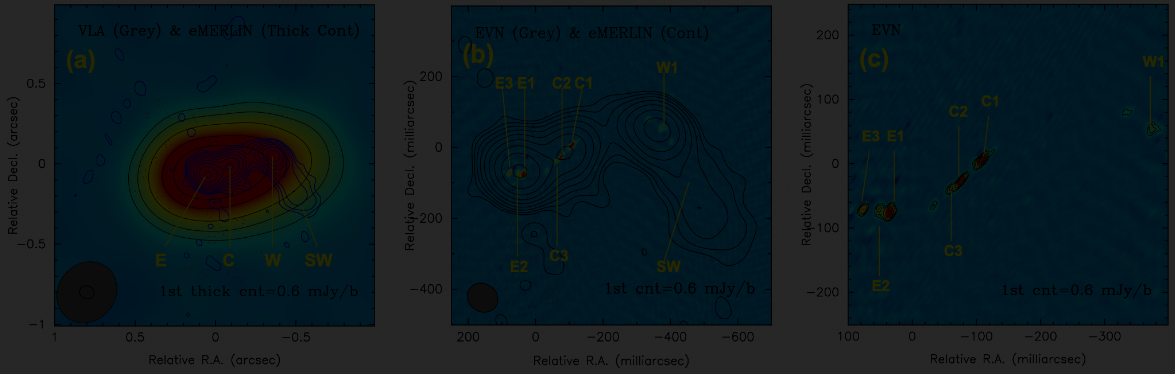


OJ287 GMVA (Lico+2022)
beam 0.24 mas × 0.04 mas

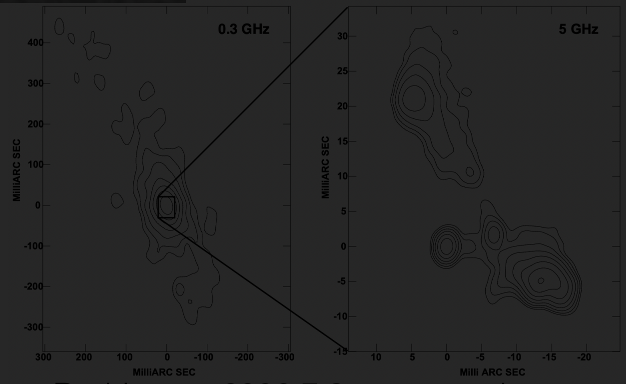
Burke-Spolaor+2011: first systematic search with VLBI using geodetic VLBI database

Detection rate seems < than predictions by a factor of 3 (Liu+2014)





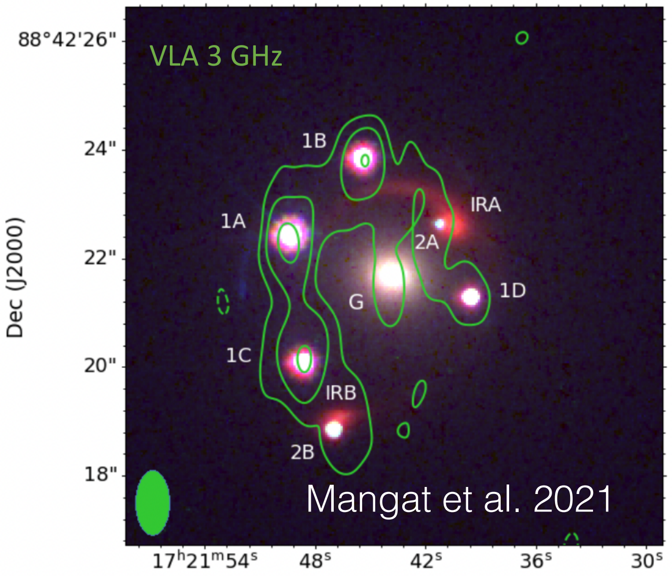
Dual AGN candidate but very complex structure (An+ 2013)
z=0.578, total extent 3 kpc

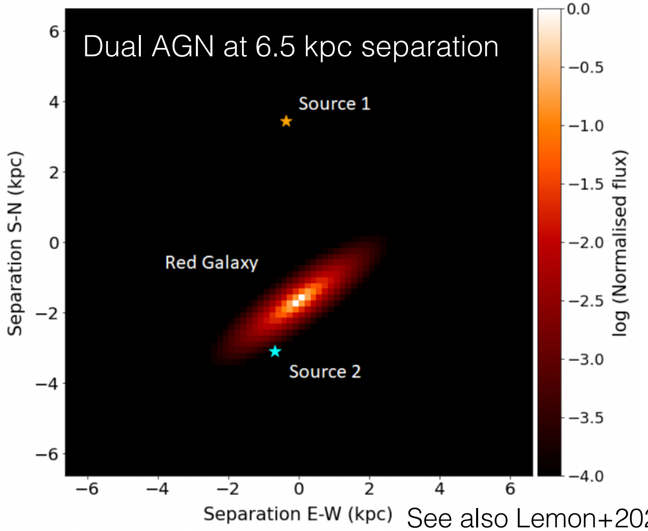


Rodriguez+2006 7.3pc separation
z=0.055 confirmed binary AGN

SMBHs in the early Universe – binary AGN with VLBI and strong lensing

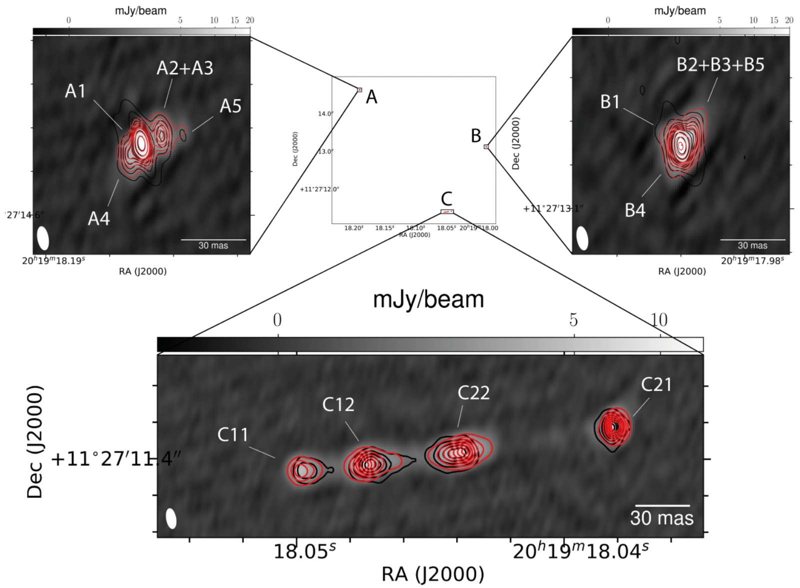
PS J1721+8842 z=2.37





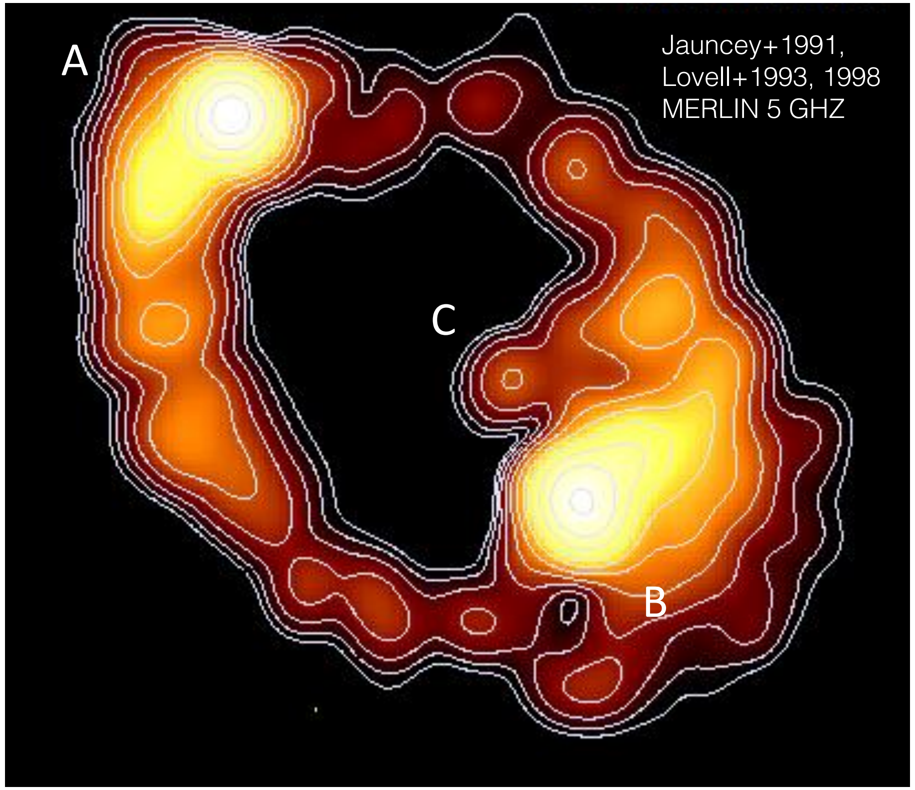
See also Lemon+2021
for independent optical identification

MG 2016+112 z=3.2



Binary AGN with separation ~200pc
Two flat spectrum components + proper motions
Complex narrow emission lines
(Spingola et al. 2019b)
+ Two X-ray compact sources (Schwartz+2021)

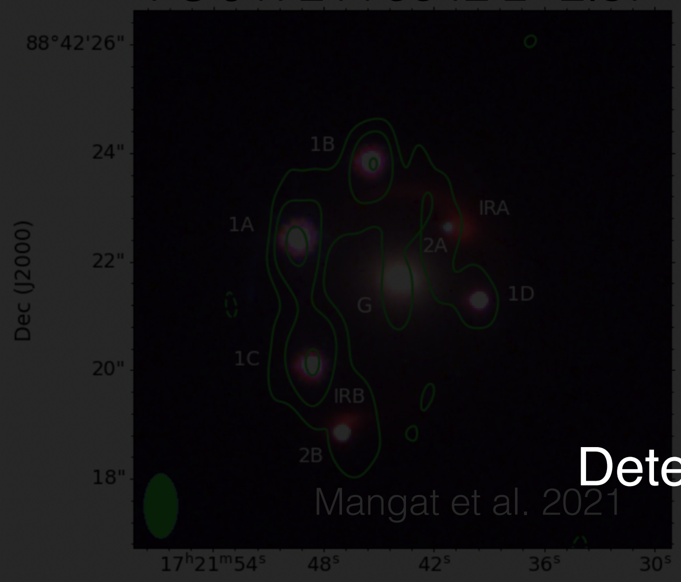
PKS 1830-211 z=2.5

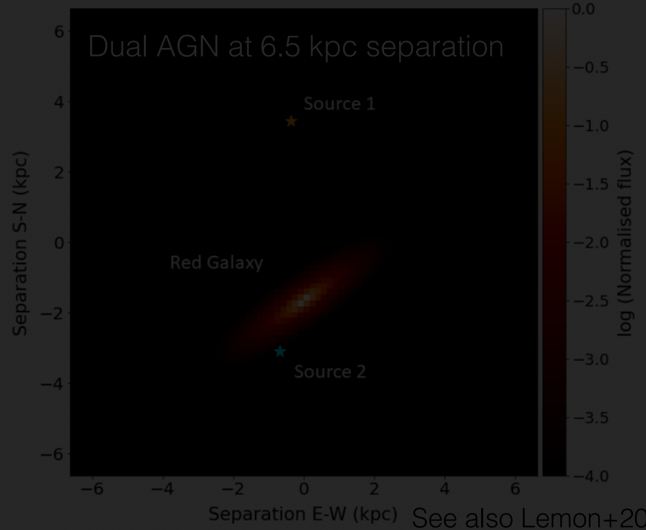


HELICAL JET using VLBI observations at 43 GHz as evidence for sub-pc binary AGN (Nair et al. 2005)

SMBHs in the early Universe – binary AGN with VLBI and strong lensing

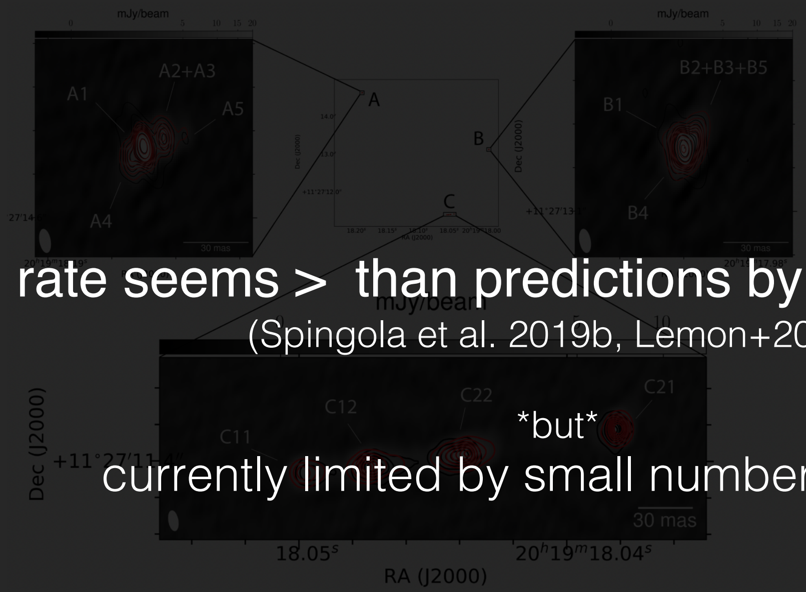
PS J1721+8842 z=2.37





See also Lemon+2021
for independent GAIA identification

MG 2016+112 z=3.2



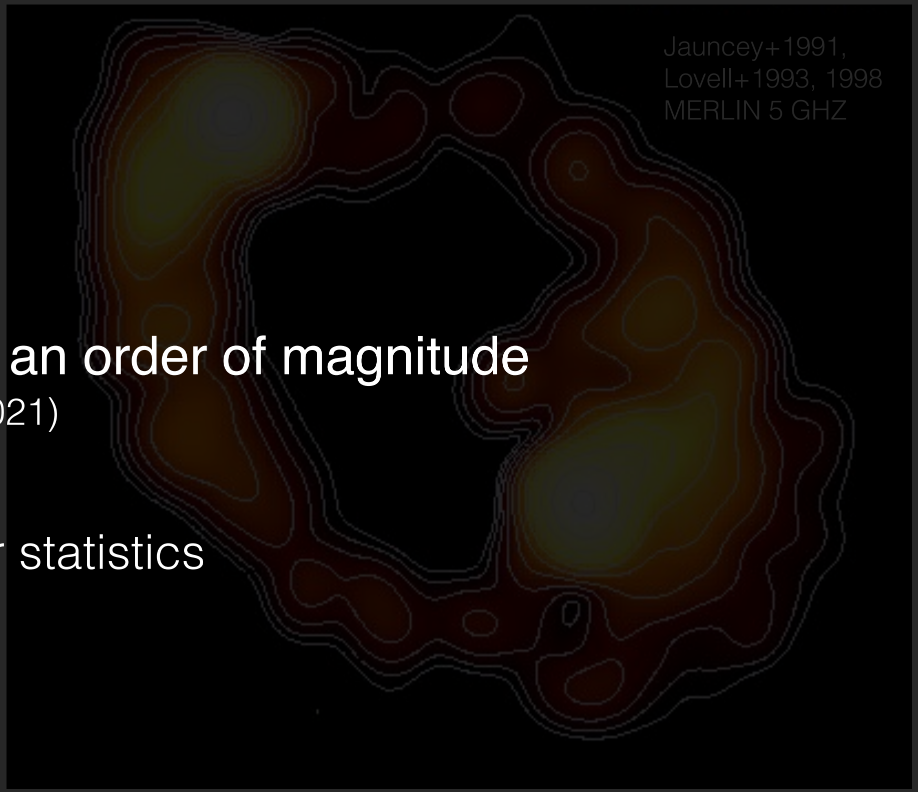
Detection rate seems > than predictions by an order of magnitude
(Spingola et al. 2019b, Lemon+2021)

but

currently limited by small number statistics

Binary AGN with separation ~200pc
Two flat spectrum components + proper motions
Complex narrow emission lines
(Spingola et al. 2019b)

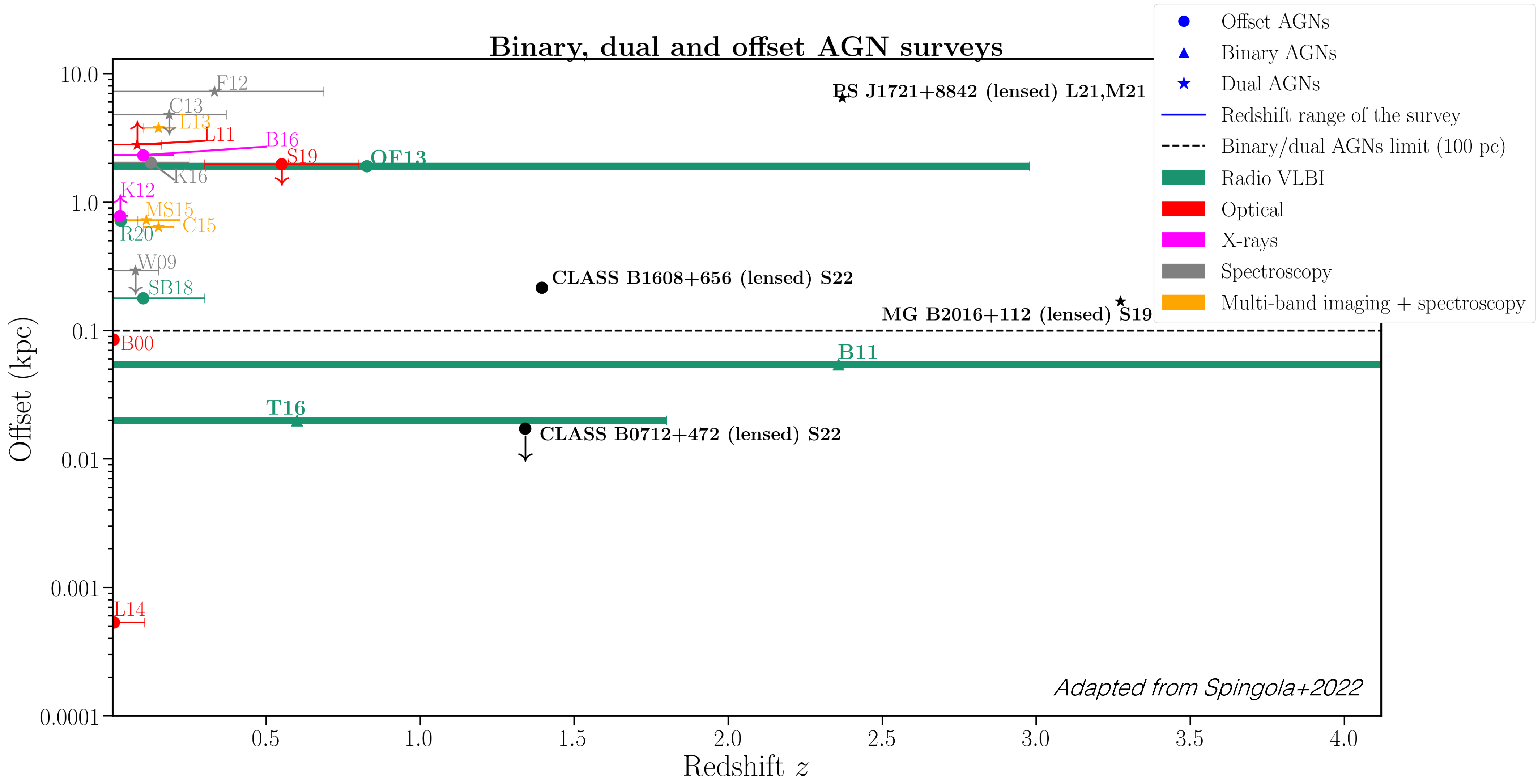
PKS 1830-211 z=2.5



HELICAL JET using VLBI observations as evidence for sub-pc binary AGN (Nair et al. 2005)

SMBHs in the early Universe – binary AGN with VLBI and strong lensing

(Binggeli et al. 2000, B00; Koss et al. 2012, K12; Orosz & Frey 2013, OF13; Lena et al. 2014, L14; Kim et al. 2016, K16; Barrows et al. 2016, B16; Skipper & Browne 2018, SB18; Shen et al. 2019, S19; Reines et al. 2020, R20; Wang et al. 2009, W09; Burke-Spolaor 2011, B11; Liu et al. 2011, L11; Fu et al. 2012, F12; Comerford et al. 2013, C13; Comerford et al. 2015, C15; Muller-Sanchez et al. 2015, MS15; Tremblay et al. 2016, T16; S22 Spingola et al. 2022; S19 Spingola et al. 2019; L21 Lemon et al. 2021; M21 Mangat et al. 2021)



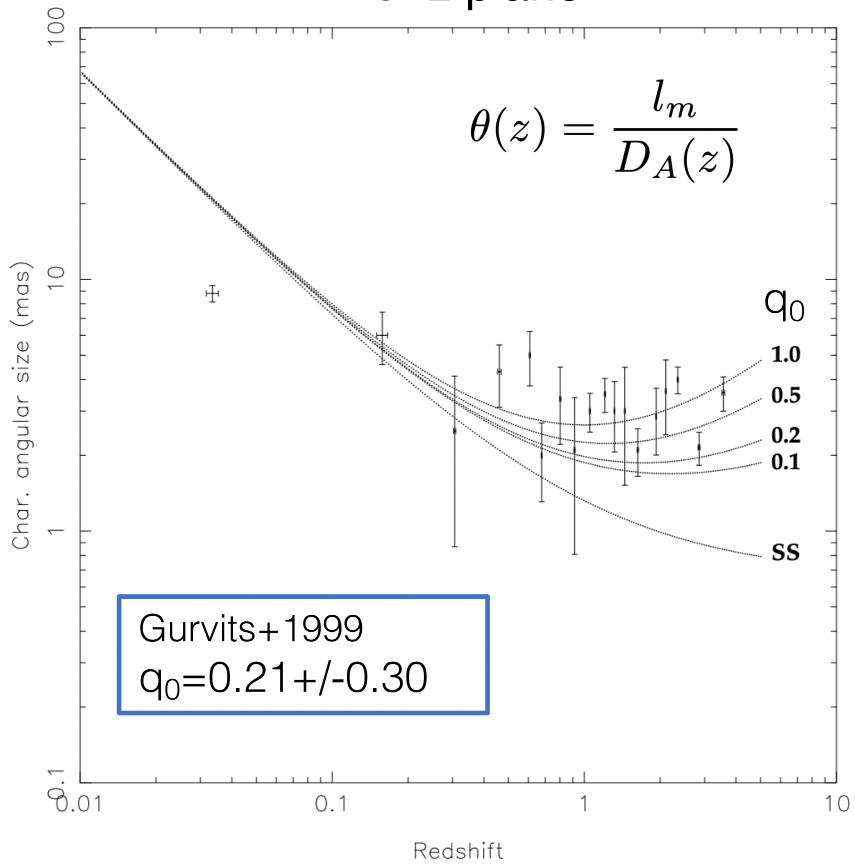
Dual AGN will spend most of the time at large scales but only VLBI can probe the bound systems and final stages

Part 2
Dark energy
cosmological parameters from VLBI sources

VLBI observations of high-z AGN for cosmological parameters

An, Zhang & Frey 2020: innovative way to use μ -z plane for estimating z in future radio surveys

ϑ–z plane

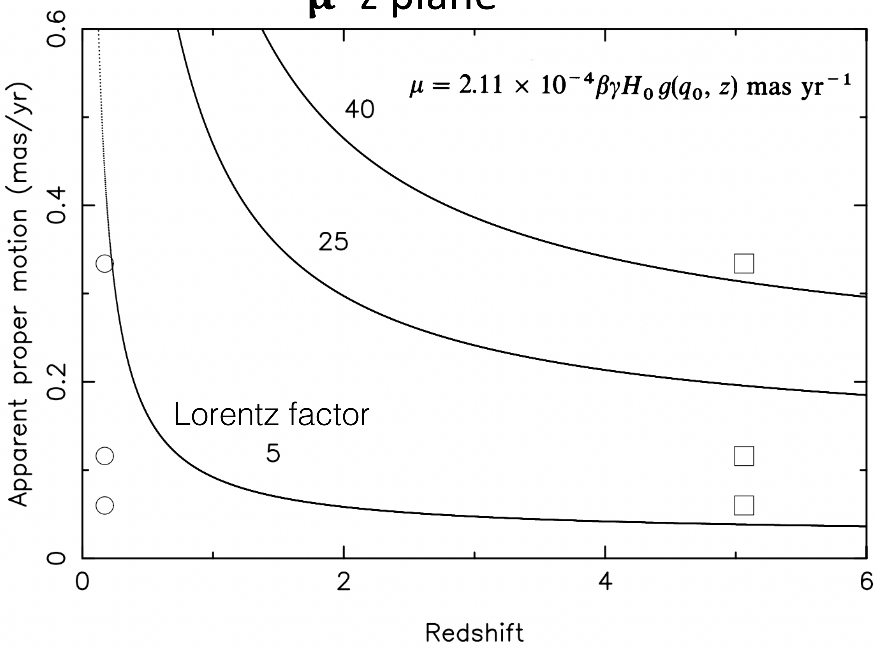


Gurvits+1999
q_0=0.21+/-0.30

Pioneering work of Gurvits, Kellermann & Frey 1999
using radio-loud AGN as standard rulers
compact radio quasars with flat spectral index (Cao et al. 2018)

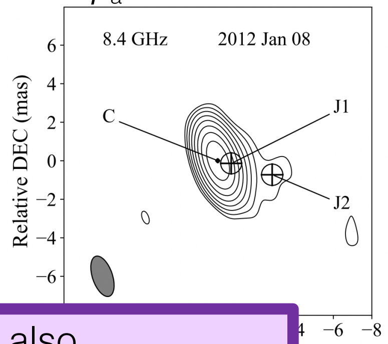
Details on methodology:
Kellermann 1972, Gurvits+1999, Wiik 2001, Wiik & Valtaoja2001,Gurvits 2003

μ–z plane

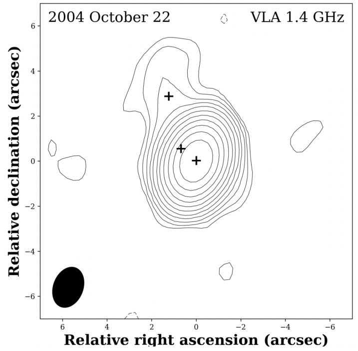


Cohen+1988
Kovalev 1995
Kellermann+ 2004
Britzen+ 2008
Jorstad+2017

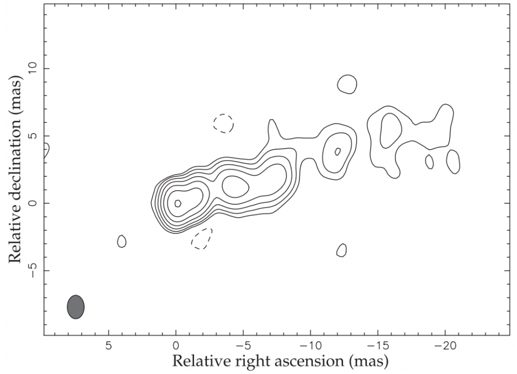
z=4.72 Zhang+2020
$1\beta_a$ = 9.5 c



z=4.3 Perger+2018
β_a = 4.1c



z=5.3 Frey+2015 β_a >10c



These measurements are challenging to obtain!

See also
Poster n. 9 by Y. Zhang

VLBI observations of high-z AGN for cosmological parameters

$$D_A = \frac{c\Delta t}{\theta_{VLBI}(1+z)}$$

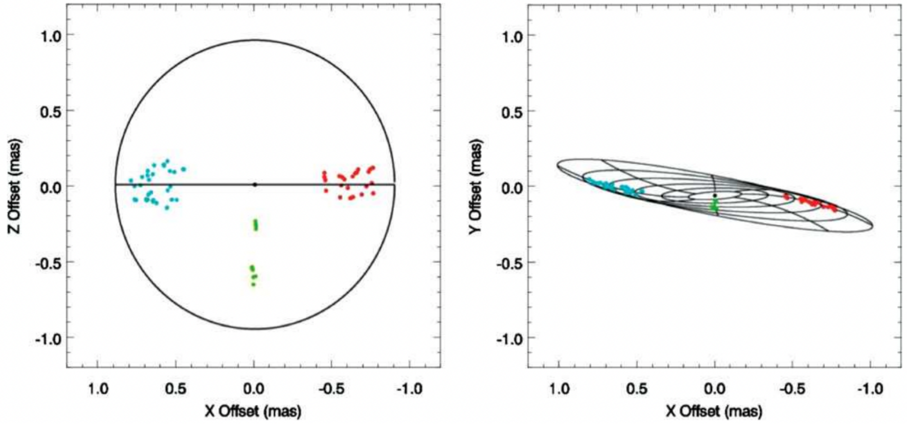
$$H_0 = 73^{+5}_{-6}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

J. Hogdson's talk in this session

Hodgson+ 2020: using variability to determine linear size of AGN, then use this size to compare it with VLBI → constrain $D_{A,}$ hence H0

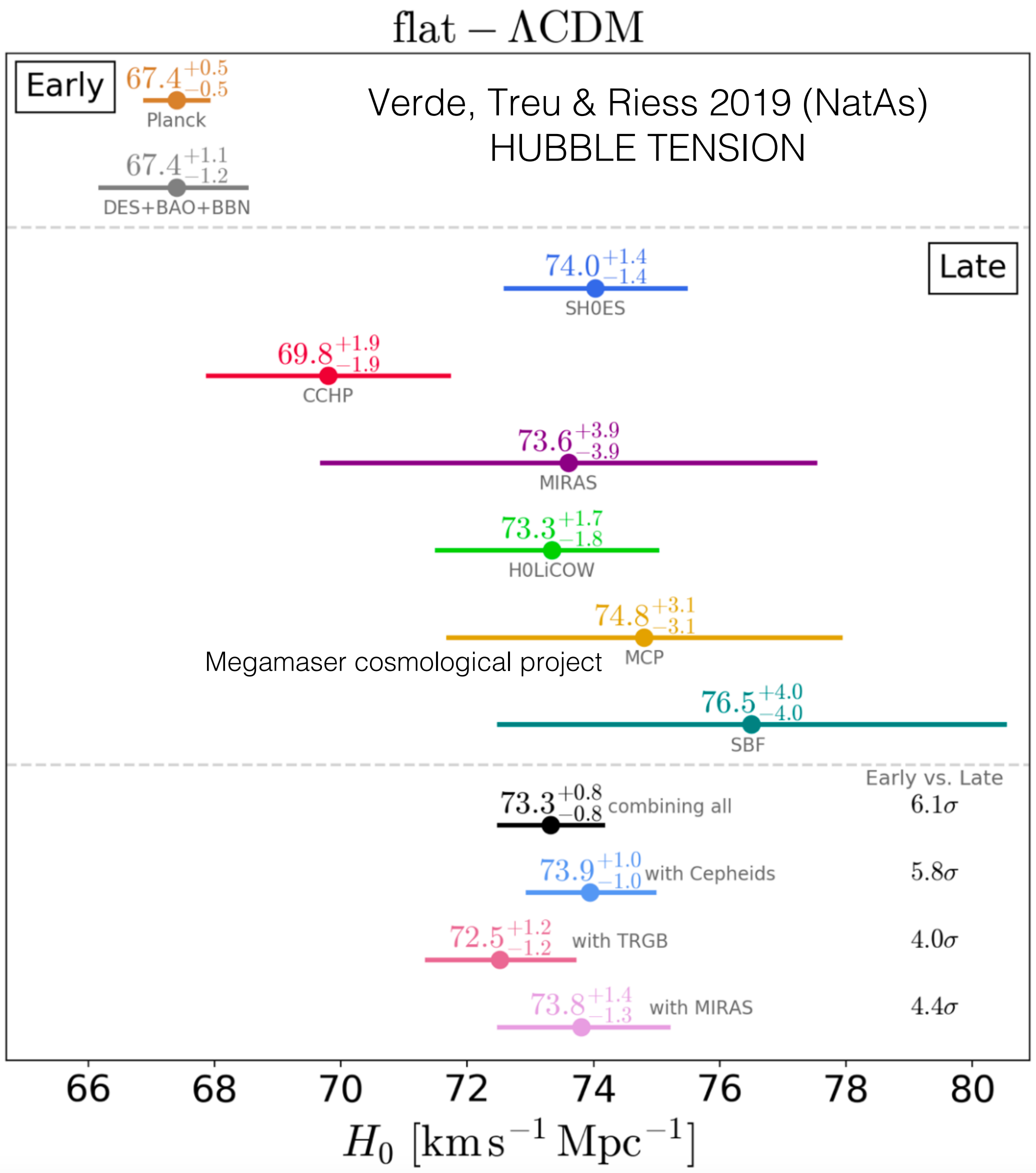
....With a single object!
Similar precision of other «late Universe» methods

Also water masers! VLBI needed for angular radius of a maser orbit
See Review Talk of Humphreys



One gravitationally lensed at z=2.64!

(Impellizzeri+2008, Garsden+2011, Castangia+2012, Stacey+2020)



we want VLBI-AGN to make it to this plot

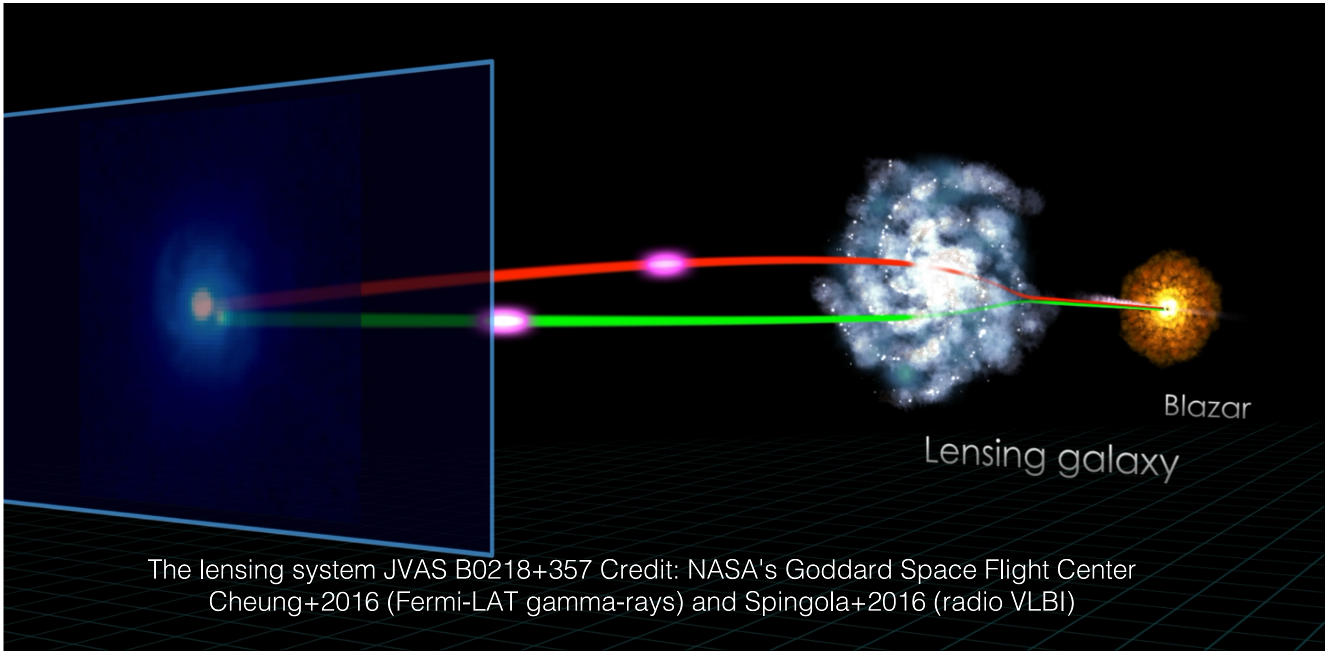
For all methods: N. Jackson (review) 2015

PART 2 – Dark energy

VLBI observations of high-z AGN for cosmological parameters

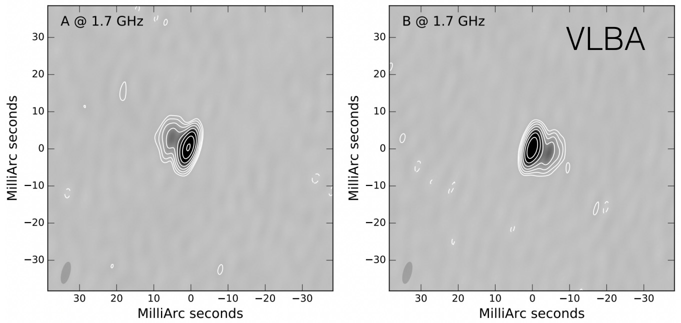
Gravitational time delays provide a one-step measurement for H_0
(e.g., H0liCOW Collaboration, Suyu+ 2017)

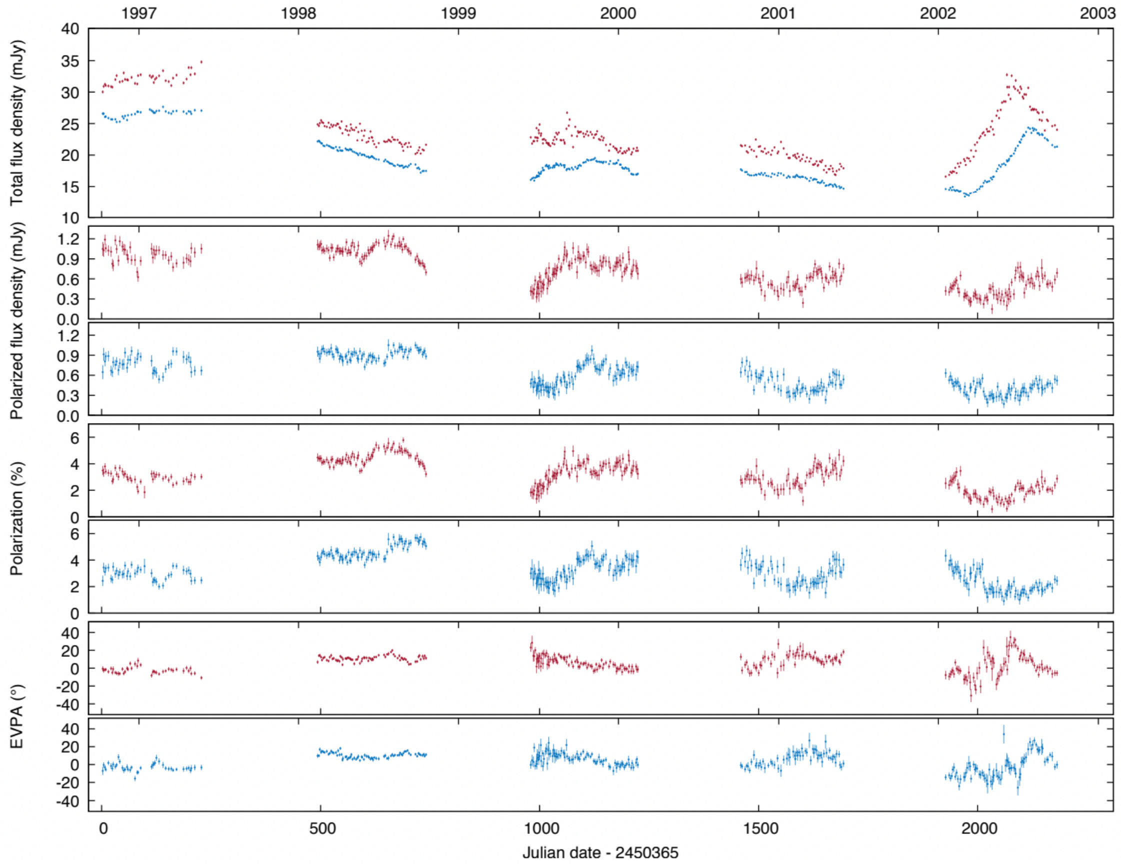
$$D_{\Delta t} \equiv (1+z_d)\frac{D_d D_s}{D_{ds}} \propto H_0^{-1}$$ Time delay distance (Chen+2020)



The lensing system JVAS B0218+357 Credit: NASA's Goddard Space Flight Center
Cheung+2016 (Fermi-LAT gamma-rays) and Spingola+2016 (radio VLBI)

CLASS B1600+434 (Biggs 2021)





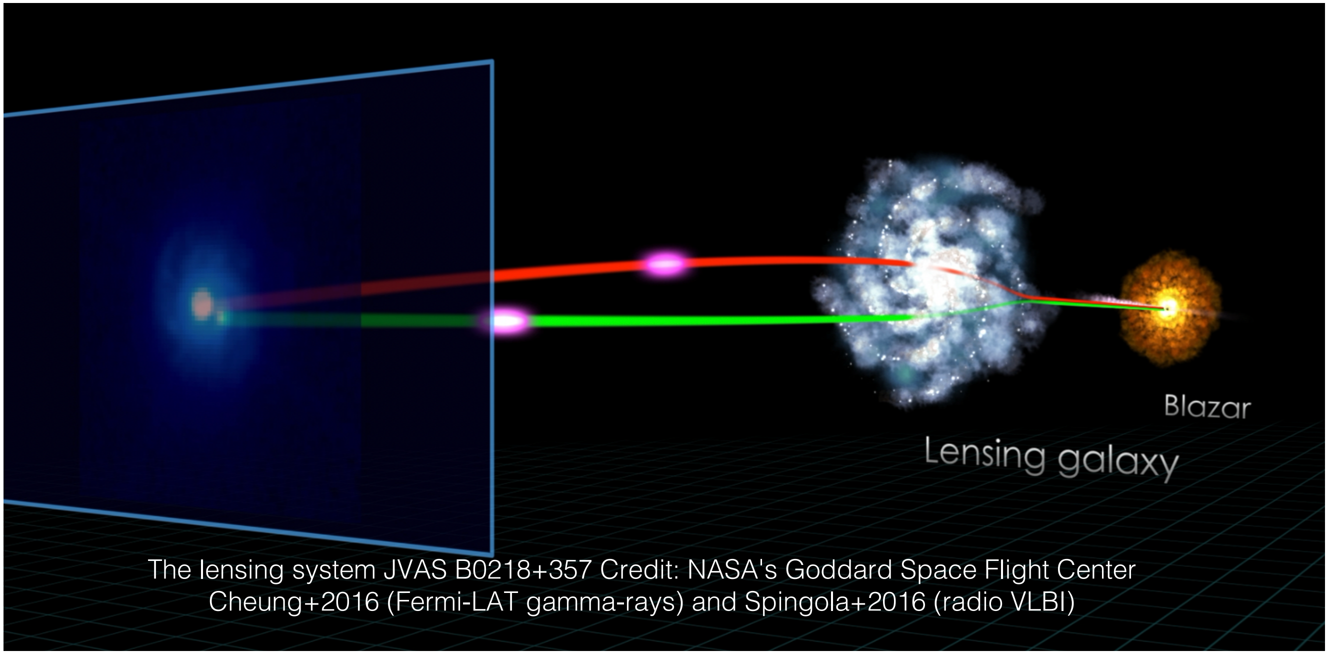
VLA monitoring: total intensity AND POLARIZATION!

VLBI observations of high-z AGN for cosmological parameters

Gravitational time delays provide a one-step measurement for H_0

(e.g., H0liCOW Collaboration, Suyu+ 2017)

$$D_{\Delta t} \equiv (1+z_d)\frac{D_d D_s}{D_{ds}} \propto H_0^{-1}$$ Time delay distance (Chen+2020)

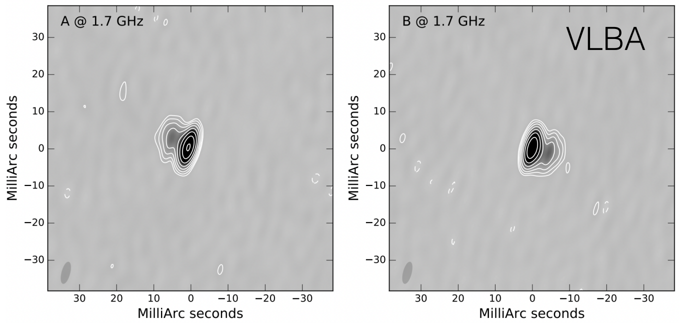


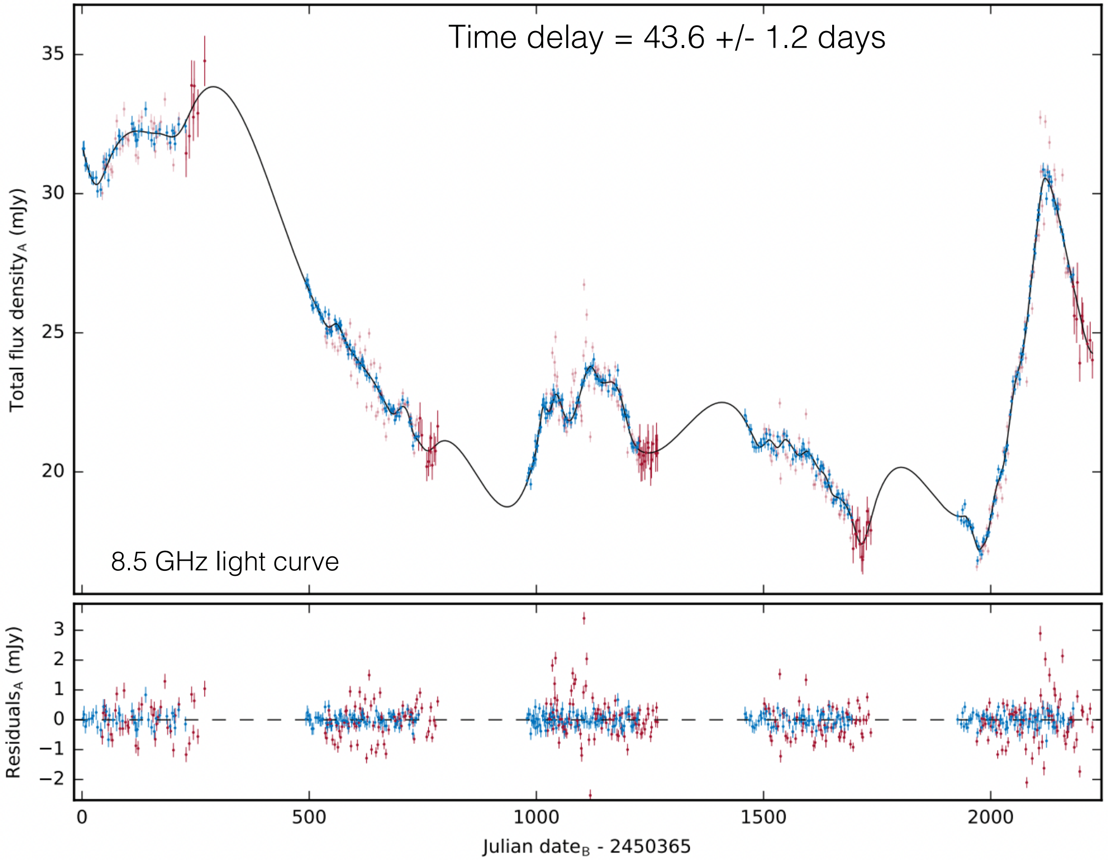
The lensing system JVAS B0218+357 Credit: NASA's Goddard Space Flight Center
Cheung+2016 (Fermi-LAT gamma-rays) and Spingola+2016 (radio VLBI)

problems

1) The unknown gravitational potential of the lens (e.g. Oguri 2007, Holicow collaboration)
2) Need high variabity and long-term monitoring programmes (e.g. Rumbaugh+2015 no variability no time delay)

CLASS B1600+434 (Biggs 2021)

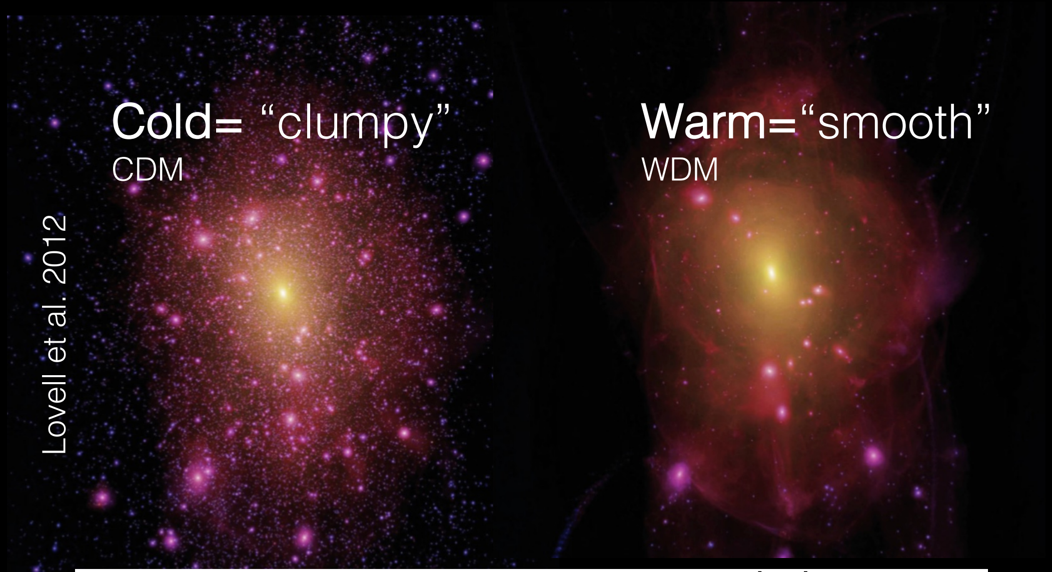


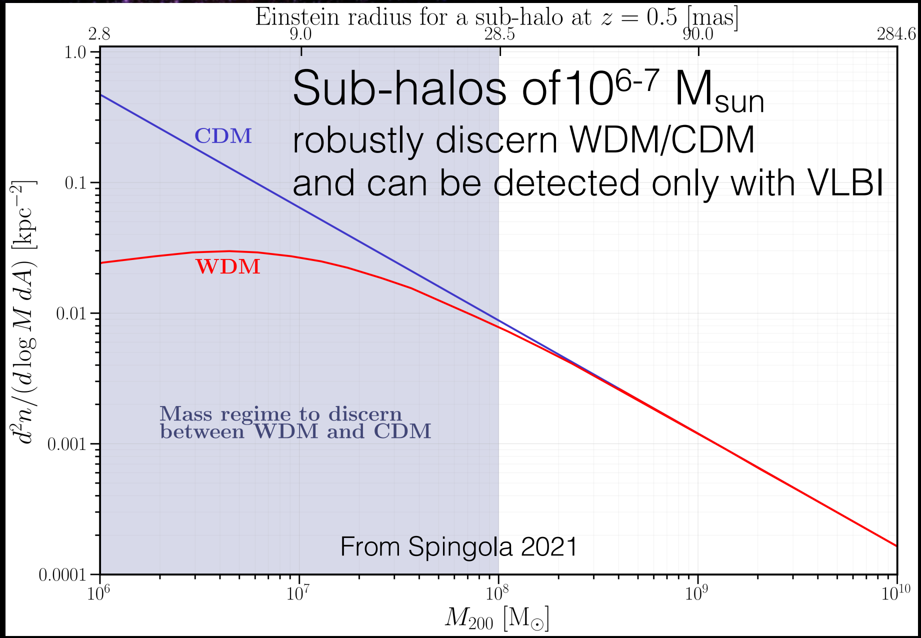


See also Fassnacht+2008, Biggs 2018, Biggs&Browne 2018

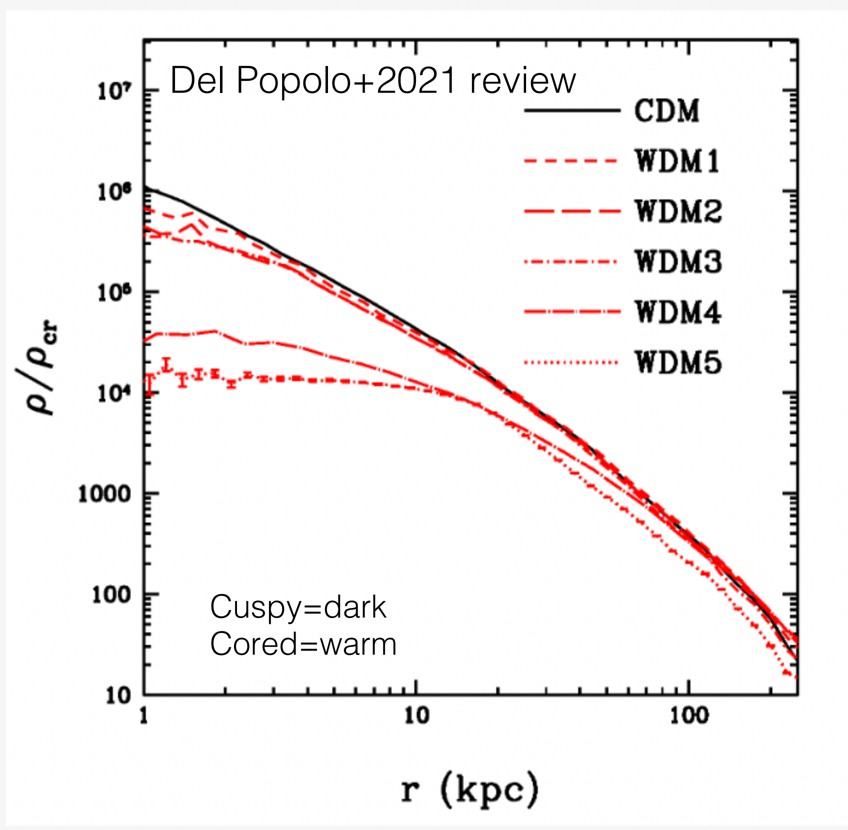
Part 3
Dark matter distribution in high-z galaxies

VLBI observations of lensed AGN to constrain dark matter





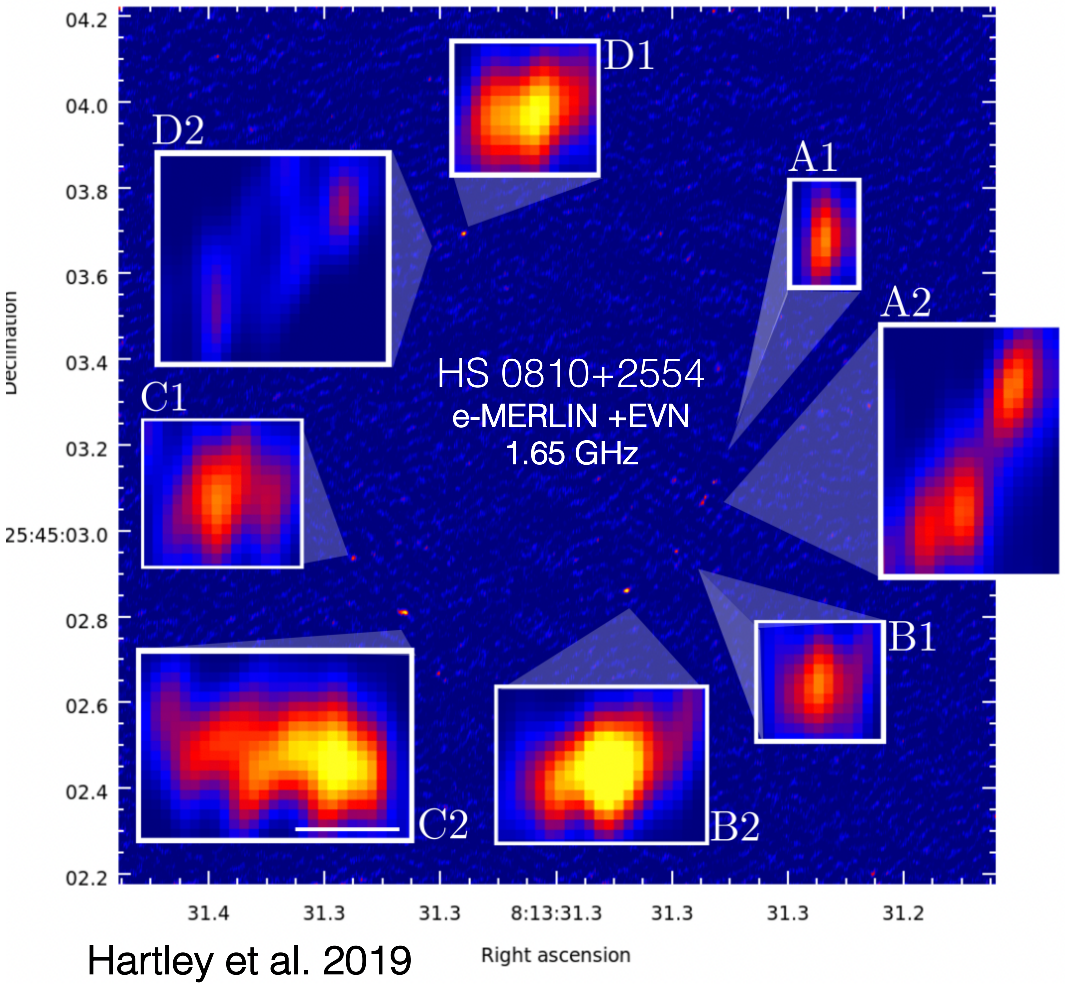
See also
Metcalf & Madau 2001
Dalal & Kochanek 2002
Dye et al. 2005
Koopmans 2005
Vegetti & Koopmans 2009
Vegetti+ 2012 Nature
Hezaveh+2016
Gilman+2020
Despali +2022

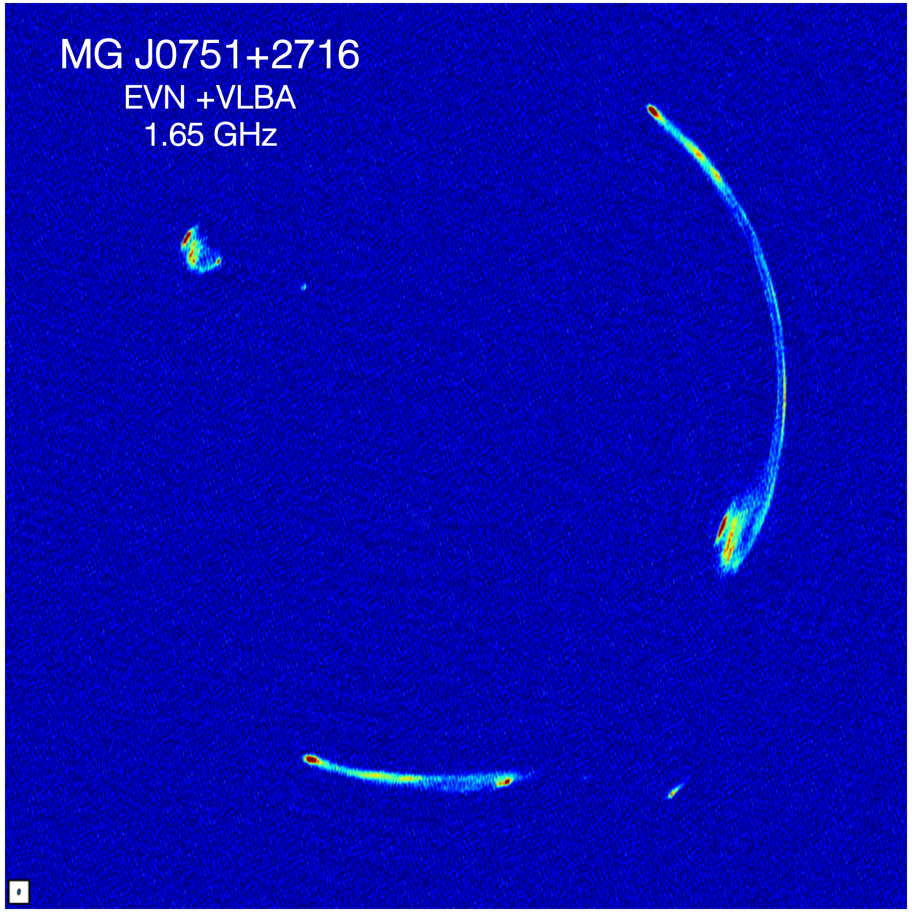


Cuspy-Core problem
One solution could be WARM dark matter

VLBI observations of lensed AGN to constrain dark matter

Best systems = extended images in radial and tangential direction





Hartley et al. 2019

Astrometric and flux ratio anomalies

Spingola et al. 2018

Inner density profile steeper than isothermal $\boldsymbol{\gamma}$=2.08 ±0.02

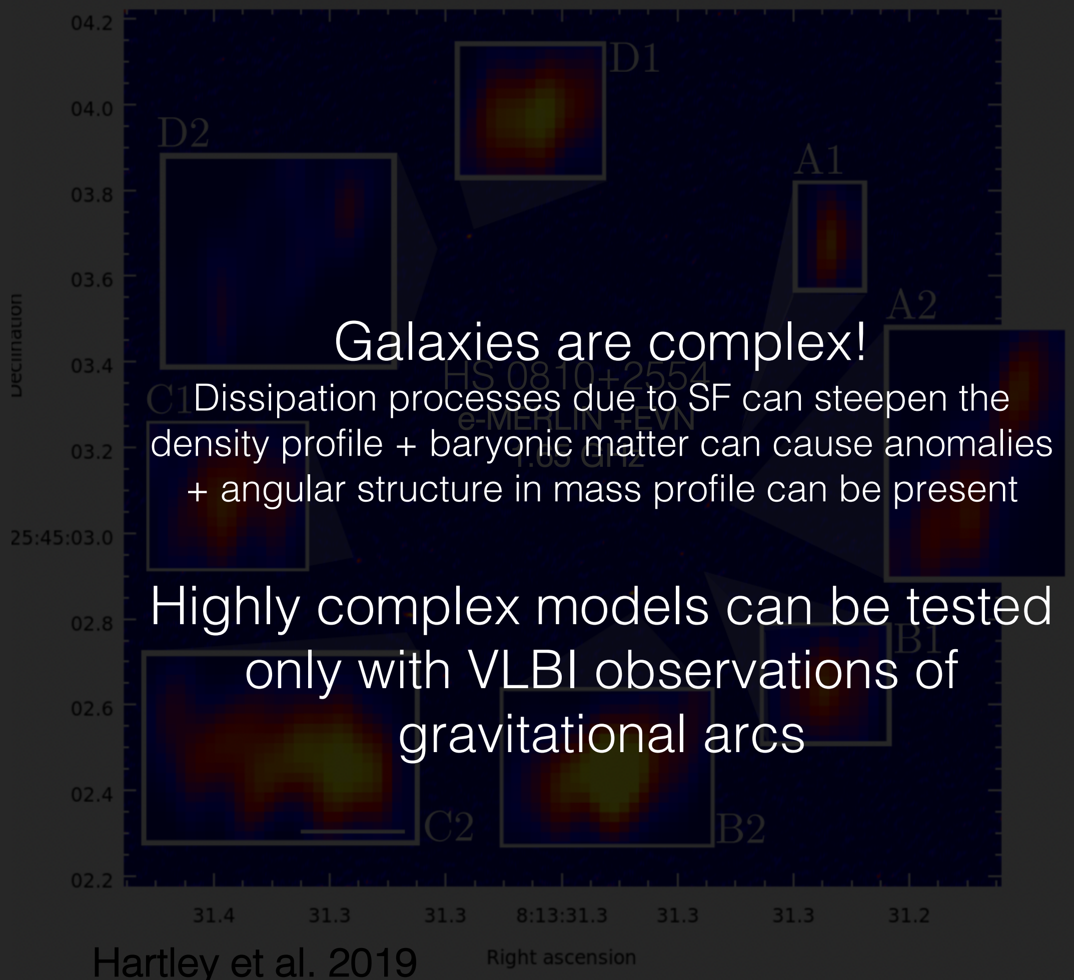
Astrometric anomalies

Note that this is an extremely faint AGN with intrinsic flux density of 880 nJy!!

See also Biggs+2004, Mckean+2007, More+2009, Hsueh+2016,2017;Badole+2020; Stacey+2020

VLBI observations of lensed AGN to constrain dark matter

Best systems = extended images in radial and tangential direction



Galaxies are complex!

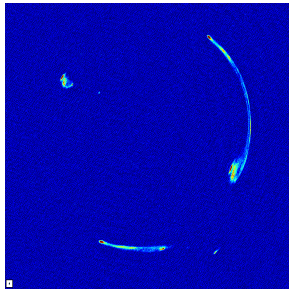
Dissipation processes due to SF can steepen the density profile + baryonic matter can cause anomalies + angular structure in mass profile can be present

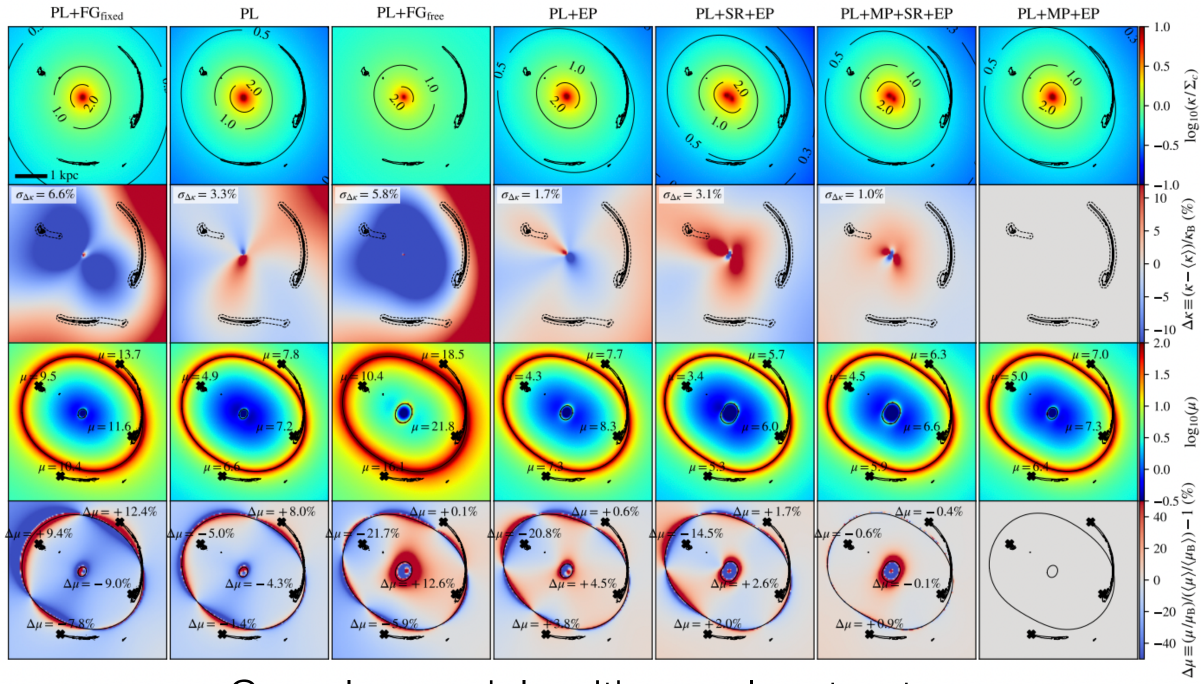
Highly complex models can be tested only with VLBI observations of gravitational arcs

Hartley et al. 2019

Astrometric and flux ratio anomalies

Note that this is an extremely faint AGN with intrinsic flux density of 880 nJy!!





Complex models with angular structure

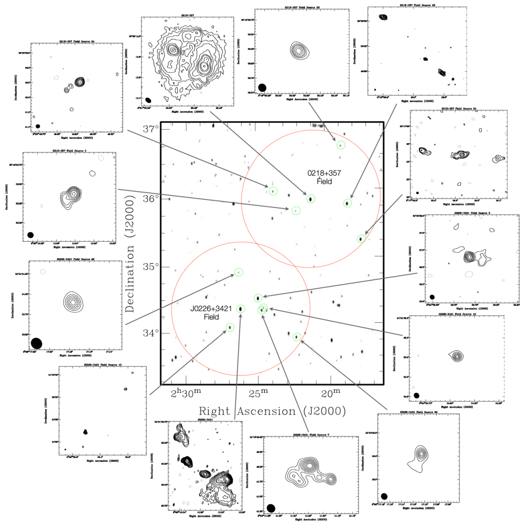
Powell+2022 on arXiv last week, see also Powell+2021 (method for VLBI data)
Potential corrections are on-going: stay tuned!
+ also baryonic structures can cause anomalies, e.g., Hsueh+2016,2017

Part 4
Wide-field VLBI for cosmological probes

The bright future of wide-field VLBI surveys

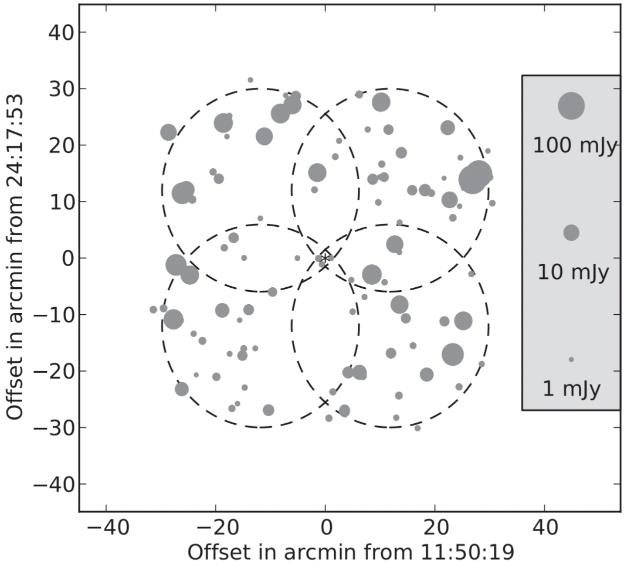
Multi-phase centre correlation = primary beam of VLBI experiment to be imaged (Deller+2011; Morgan+2011)

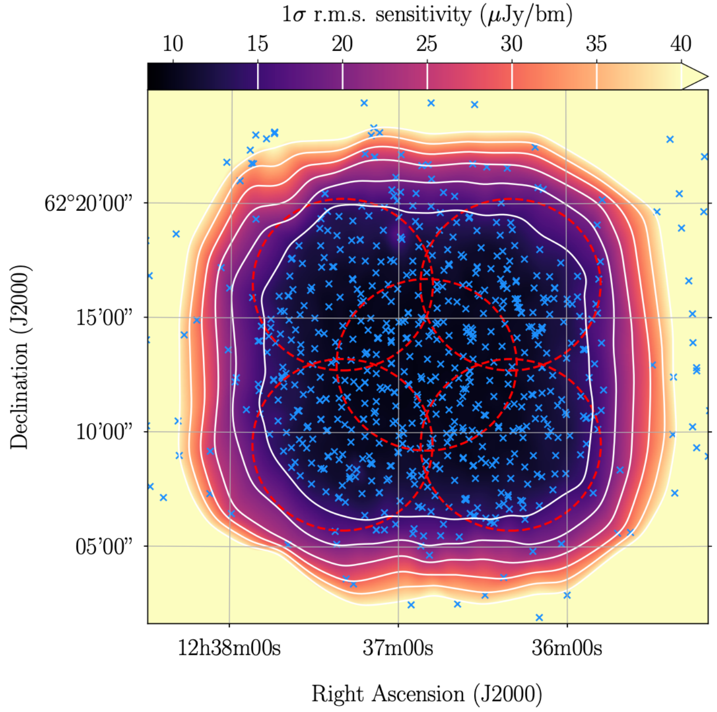
Multi-source self-calibration = reaching the thermal noise w/o suitable calibrator nearby (Radcliffe+2016)



Lenc et al. 2006
2.3 deg² at 90 cm
~1 mJy beam⁻¹

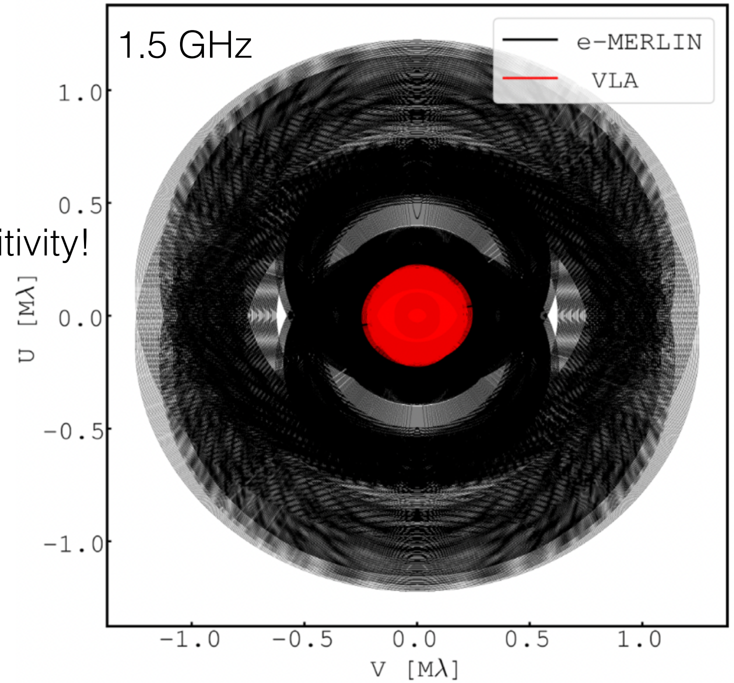
Deller & Middelberg 2014
mJIVE-20
Example of a pointing
1.4 GHz 1 mJy beam⁻¹
Sources pre-selected from FIRST
200+ deg²





Radcliffe et al. 2018
GOODS-N field / EVN
25’ at 1.6 GHz
~10 μJy beam⁻¹

Muxlow+ 2021
e-MERGE survey
Multi-scale multi-band
15 × 15 arcmin²
Sub-μJy beam ⁻¹ sensitivity!



See also Garrett et al. 2001 (wide-field EVN), Lenc et al. 2006, Morgan+2011; Middelberg et al. 2011, 2013; Chi+2013; Deller & Middleberg 2014; Petrov 2016 ; Herrera-Ruiz et al. 2017, 2018; Radcliffe et al. 2018, 2021a,b
<u>+ talks of Muxlow, Njeri and Williams on Monday</u>

The bright future of wide-field VLBI surveys

Search for radio-loud AGN in gas-rich mergers

Shabala+2017

Lenc et al

2.3 deg^2 at 90 cm

~1 mJy beam^{-1}

Deller & Middelberg 2014

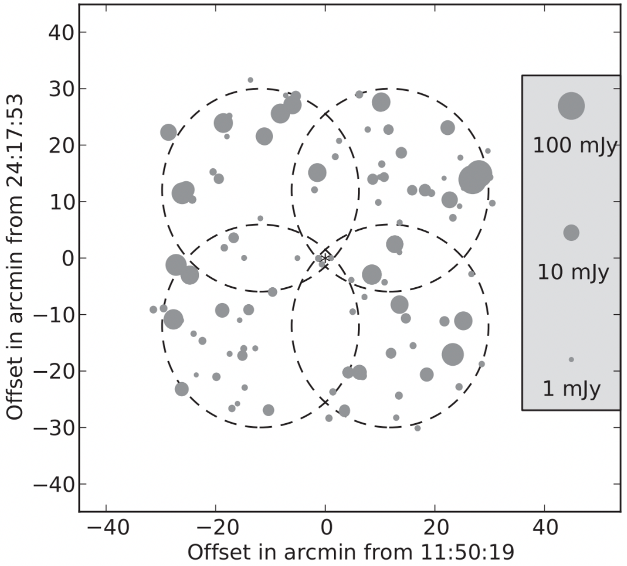
mJIVE-20

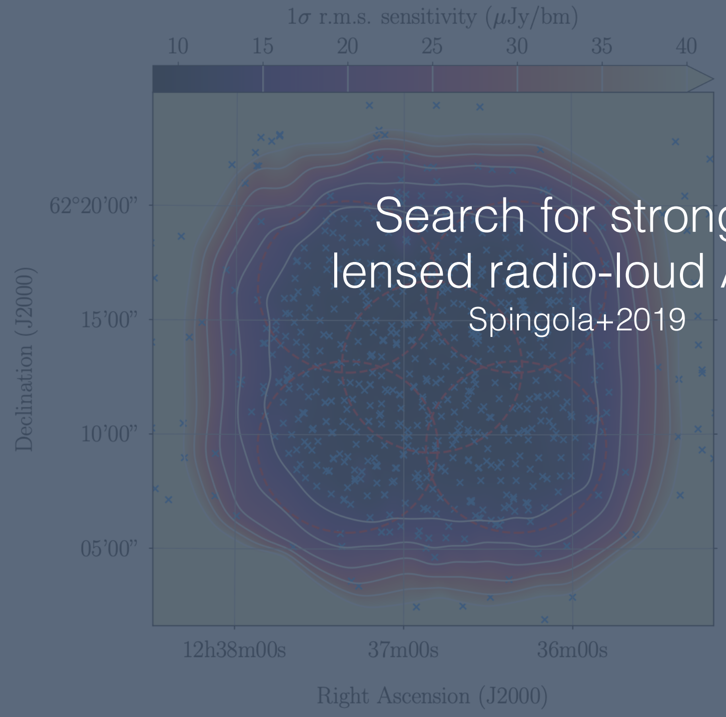
Example of a pointing

1.4 GHz 1 mJy beam^{-1}

Sources pre-selected from FIRST

200+ deg^2





Search for strongly lensed radio-loud AGN

Spingola+2019

Radcliffe et al. 2018

GOODS-N field

at 1.6 GHz

~10 uJy beam^{-1}

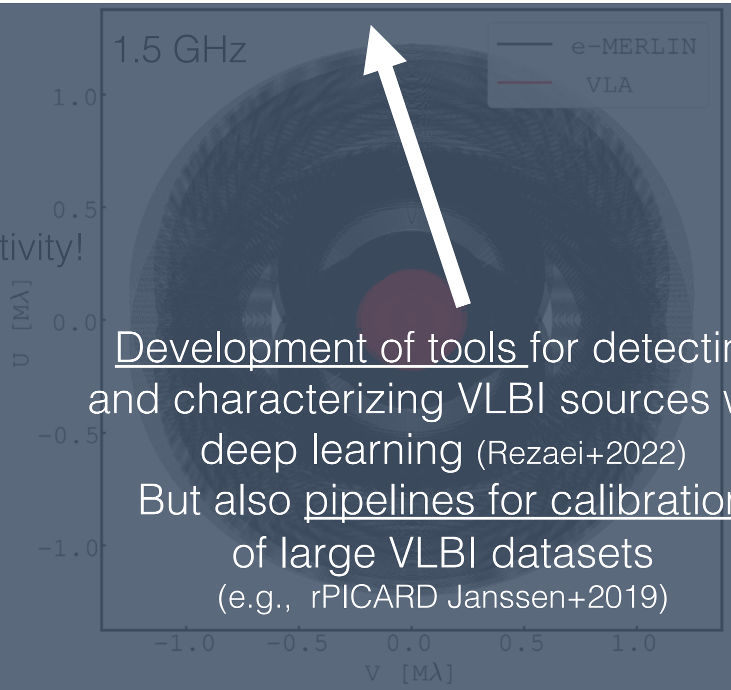
Muxlow+ 2021

e-MERGE survey

Multi-scale multi-band

15 × 15 arcmin^2

Sub-uJy beam^{-1} sensitivity!



Search for dual and binary AGN

Burke-Spolaor 2015

<u>Development of tools</u> for detecting and characterizing VLBI sources with deep learning (Rezaei+2022)

But also <u>pipelines for calibration</u> of large VLBI datasets

(e.g., rPICARD Janssen+2019)

See also Garrett et al. 2001 (wide-field EVN); Morgan+2011; Middelberg et al. 2011, 2013; Chi+2013; Deller & Middleberg 2014; Petrov 2016 ; Herrera-Ruiz et al. 2017, 2018; Radcliffe et al. 2018, 2021a,b + talks about Sparcs and Lemmings surveys

Summary

1) VLBI provides precise and independent cosmological probes

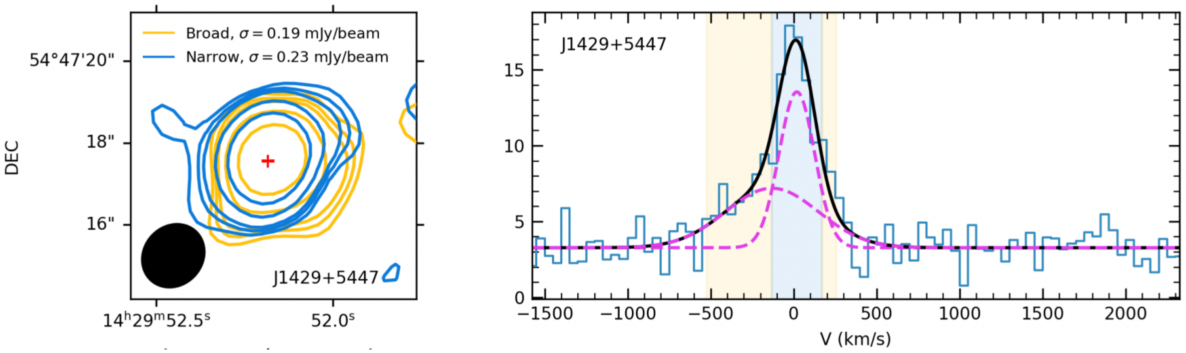
2) Wide-field VLBI surveys are possible NOW and we can use them to:
   - Find AGN at high-z (accretion models, proper motions and angular sizes)
   - Test cosmology with ϑ–z plane (q_0)
   - Search for Binary/multiple AGN systems (stalling time)
   - Find radio lensing systems with arcs (nature of dark matter)
   - Find highly variable lensed and unlensed jetted AGN (H_0)
   - ...and many many more science cases!

3) Future surveys with the SKA and SKA-VLBI will offer significantly improved sensitivity:
   - we will not be limited by the small number statistics anymore
   - + synergy with optical and other λ & monitoring is also important

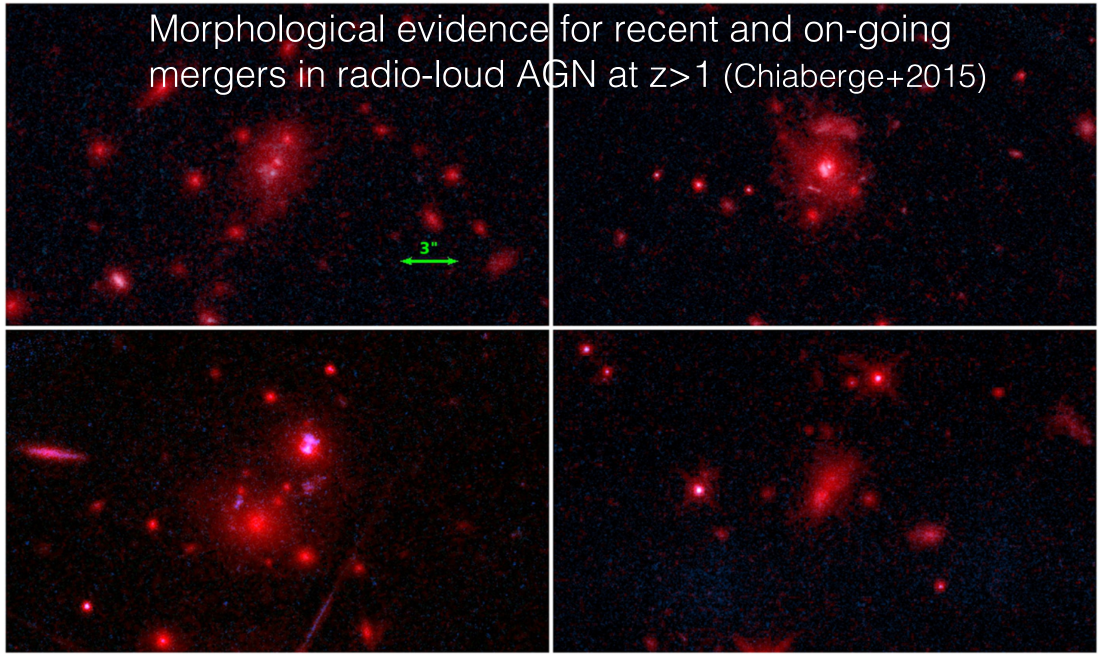
Thank you!

Cristiana Spingola (INAF-IRA) spingola@ira.inaf.it

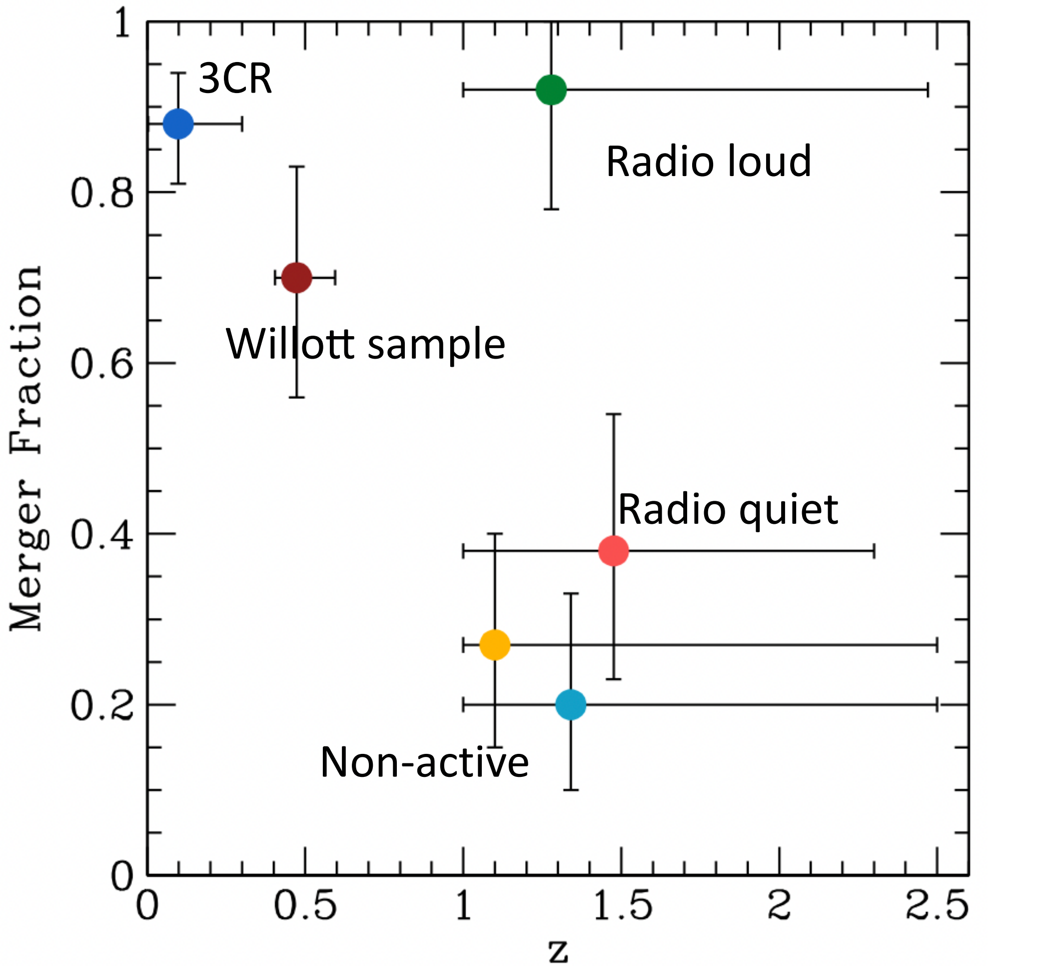
SMBHs in the early Universe – accretion: molecular gas and mergers



Evidence for mergers in gas-rich quasars at z>6 from line profile
Khusanova et al. 2022



Morphological evidence for recent and on-going mergers in radio-loud AGN at z>1 (Chiaberge+2015)

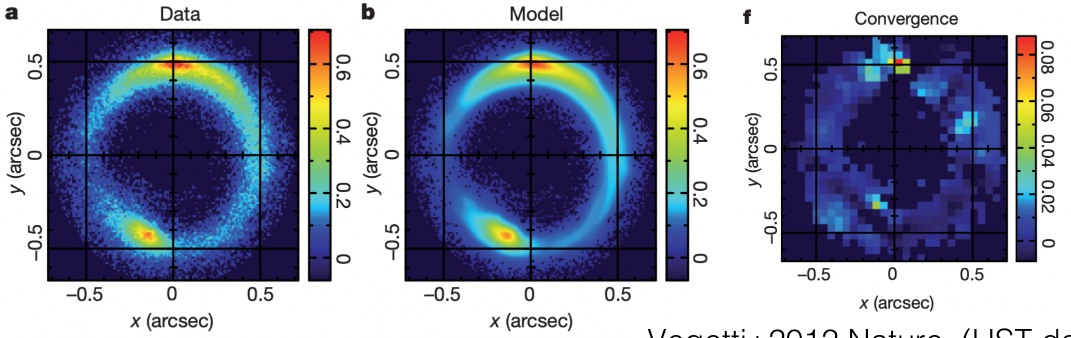


Statistical evidence that the radio-loud AGNs almost always reside in environments where mergers are undergoing, or that recently happened (Chiaberge+2015)

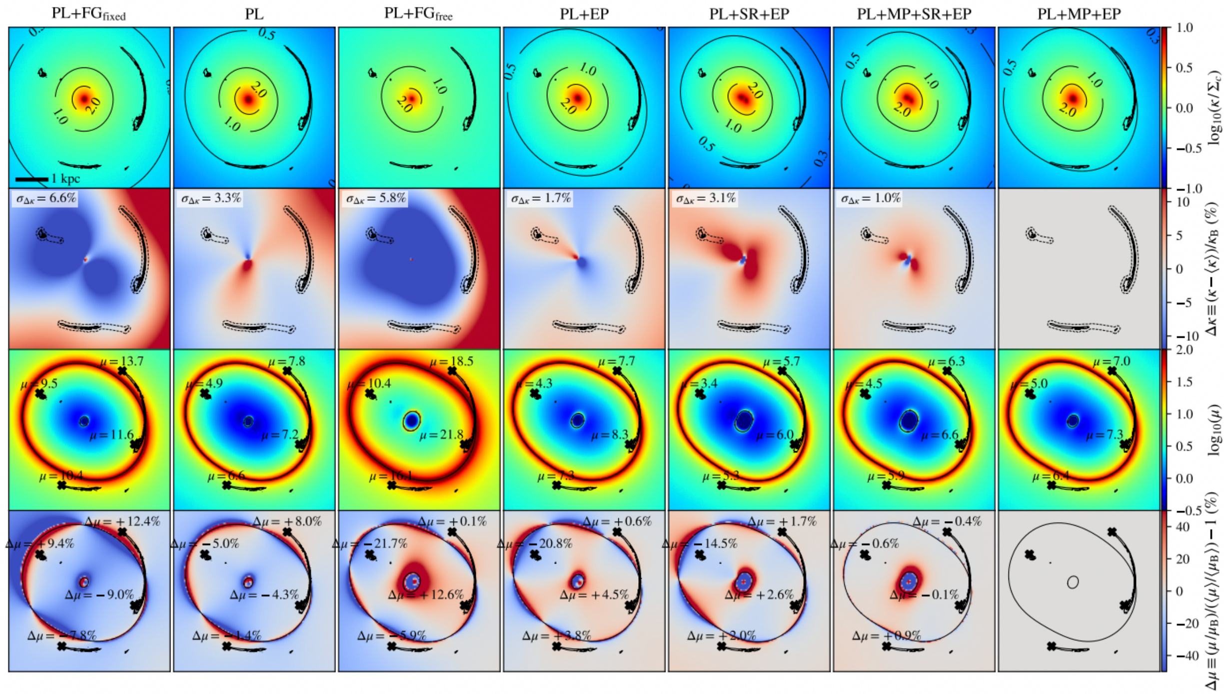
VLBI observations of lensed AGN to constrain dark matter

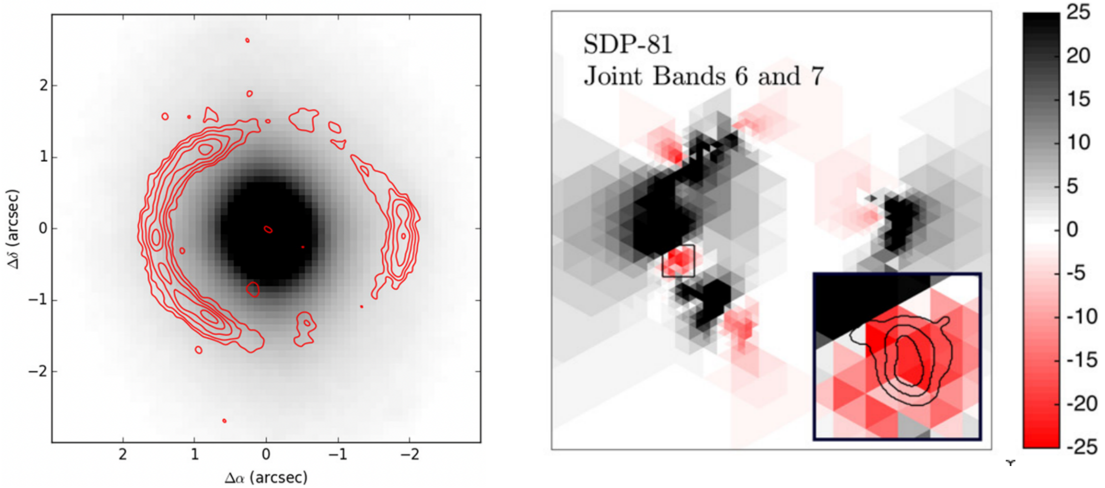
Potential corrections

Not that easy!
Complex models with angular structure can also reproduce the data – but only with VLBI arcs we can test such models



Vegetti+2012 Nature (HST data)
Mass of sub-halo of 10^8 M_{sun}





Heaveh+2013 (ALMA data)
Mass of sub-halo of $10^9 M_{sunc}$

Powell+2022 on arXiv this week
see also Powell+2021 (method for VLBI data)
Potential correcitons are on-going: stay tuned!

+ also baryonic structures can cause anomalies, e.g., Hsueh+2016,2017

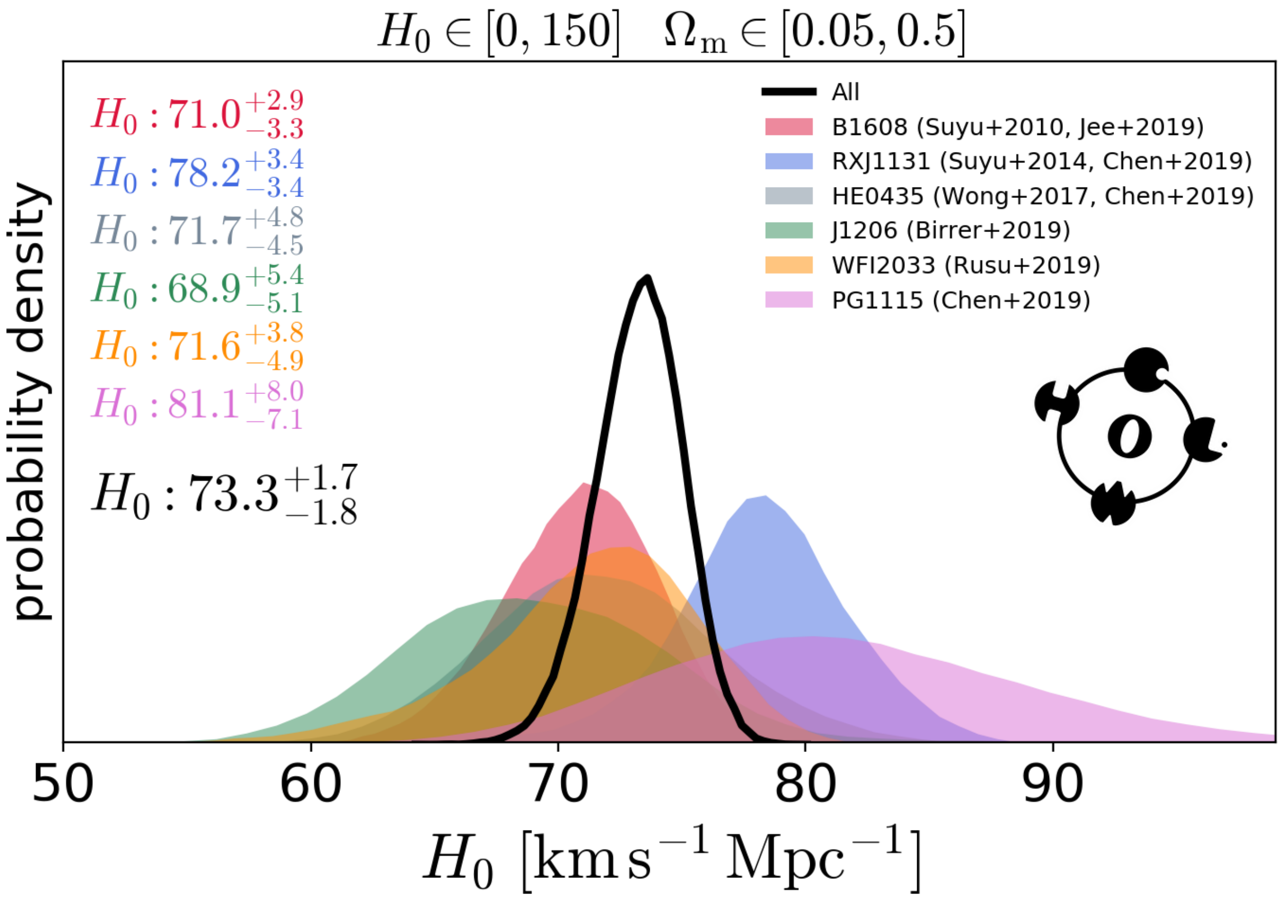
VLBI observations of high-z AGN for cosmological parameters

Gravitational time delays provide a one-step measurement for H_0
(e.g., H0liCOW Collaboration, Suyu+ 2017)

problems

1) The unknown gravitational potential of the lens
(e.g. Biggs 2021, Oguri 2007)
2) Need high variability and long-term monitoring programmes
(e.g. Rumbaugh+2015 no variability no time delay)

We need at least ~40 lensing systems with sub-percent time delay estimates for a 1 % precision in H_0
(Shajib et al. 2018; Birrer & Treu 2021)

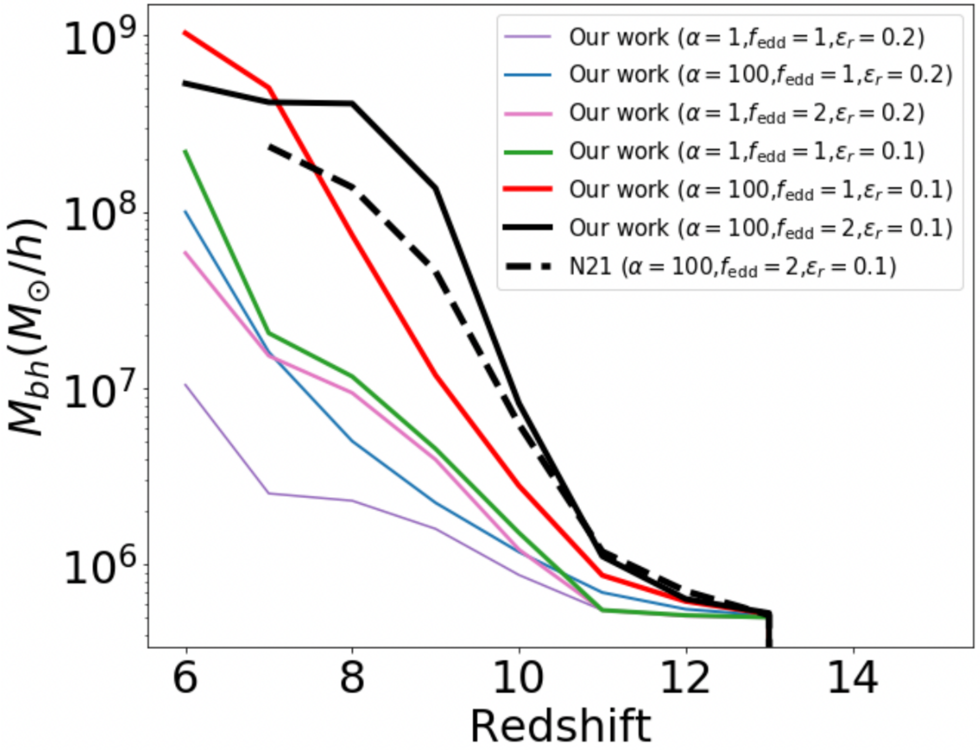


HOLiCOW collaboration, 2.4% precision
(Suyu+2017, Wong+2020,Chen+ 2022
but see also Treu+2018, Millon+2020)

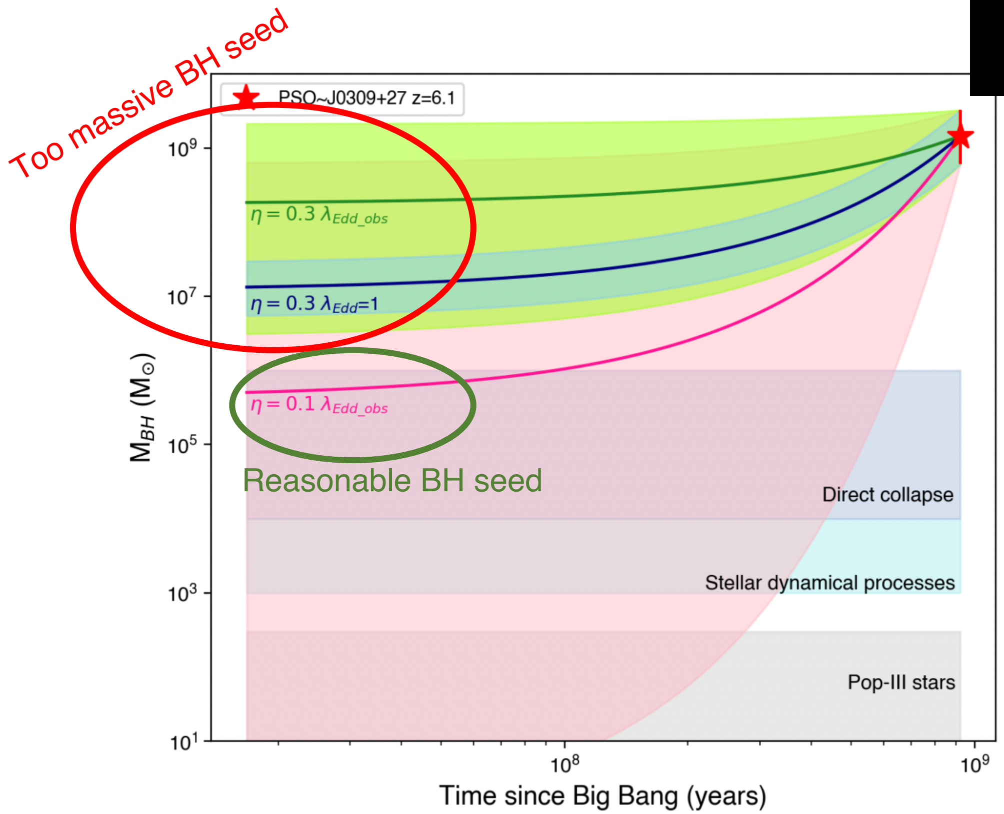
SMBHs in the early Universe – accretion modes

Possible episodic **super-Eddington accretion**
(Begelman 2002, Shapiro 2005, Madau+2014, Pezzulli+2016, Li+2019, Onoue+2019, Sbarrato+2021, Bhowmick+2022 – but see also Sijacki 2009)

Heavy black hole seeds, but somehow difficult to form
(Volonteri+2010, Pacucci+2017,2018; Boco+2020, Volonteri+2021)



ILLUSTRIS TNG z > 6
Episodic super-Eddington accretion
Bhowmick+2022

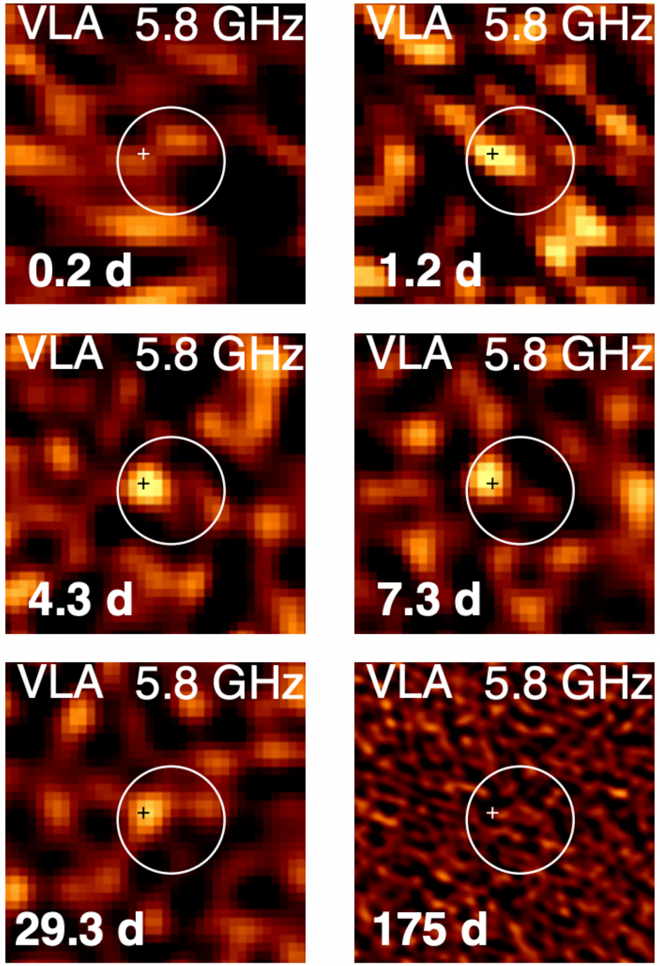


PSO J0309+27 z= 6.1
Assuming constant accretion at L_{edd}
Belladitta+ 2022

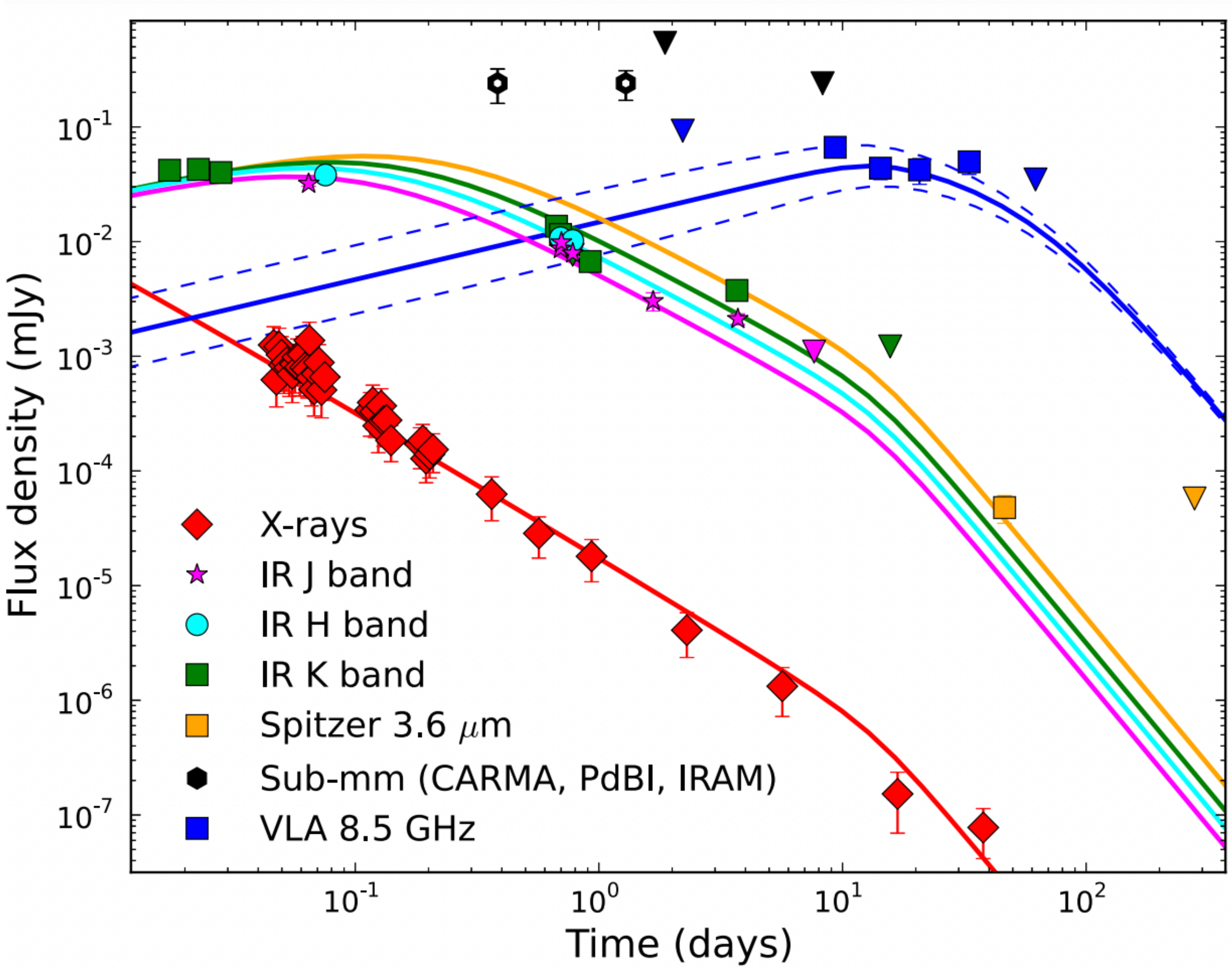
GRB 120521C, 050904 and 090423 with radio detection at z > 6 (Salvaterra 2015 Review)

Cosmological probes for the formation of first stars but also as alternative to quasars for H_2 absorption (Inoue+2007)

Very recent: study GRB host galaxy using multi-scale VLBI (Giarratana, Giroletti et al. 2022)



GRB120521C z= 6.0 (Lascar+2014)



GRB 09423 z=8.2 (Laskar+2014)