United Nations | International Day for the Elimination of Violence against Women 25 November

The Fifth National Workshop on the SKA Project
25^{th} Nov 2025 Area della Ricerca del CNR, Bologna (Italy)

Illuminating the dark Universe through strong gravitational lensing in the SKA era

Cristiana Spingola
INAF Istituto di Radioastronomia (Bologna)

INAF ISTITUTO NAZIONALE DI ASTROFISICA | Ministero dell'Università e della Ricerca | FONDO ITALIANO PER LA SCIENZA

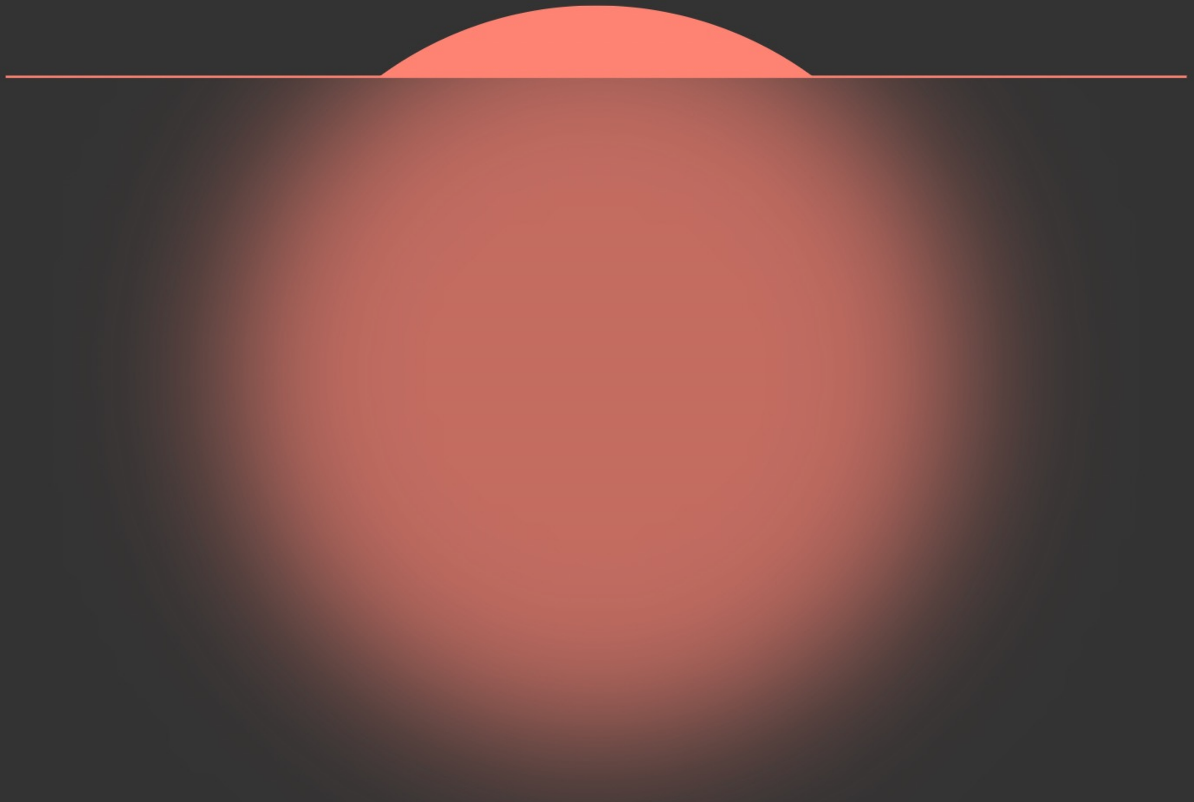
J. P. McKean (Univ. Pretoria / Univ. Groningen), **M. Giroletti** (INAF-IRA),
S. Vegetti (Max Planck Institute for Astrophysics, MPA), D. Powell (MPA), S. D. M. White (MPA), G. Despali (Univ. Bologna), C. Fassnacht (UC Davis), L. Koopmans (Univ. Groningen), D. Massari (INAF-OAS), M. Orienti (INAF-IRA), S. Buson (U. Würzburg), T. Cheung (Naval Research Laboratory), S. Belladitta (MPIA), A. Caccianiga (INAF-OAB), A. Moretti (INAF-OAB), L. Ighina (Harvard-Smithsonian)

Image credits: John McKean

The ΛCDM model and the dark Universe

5%

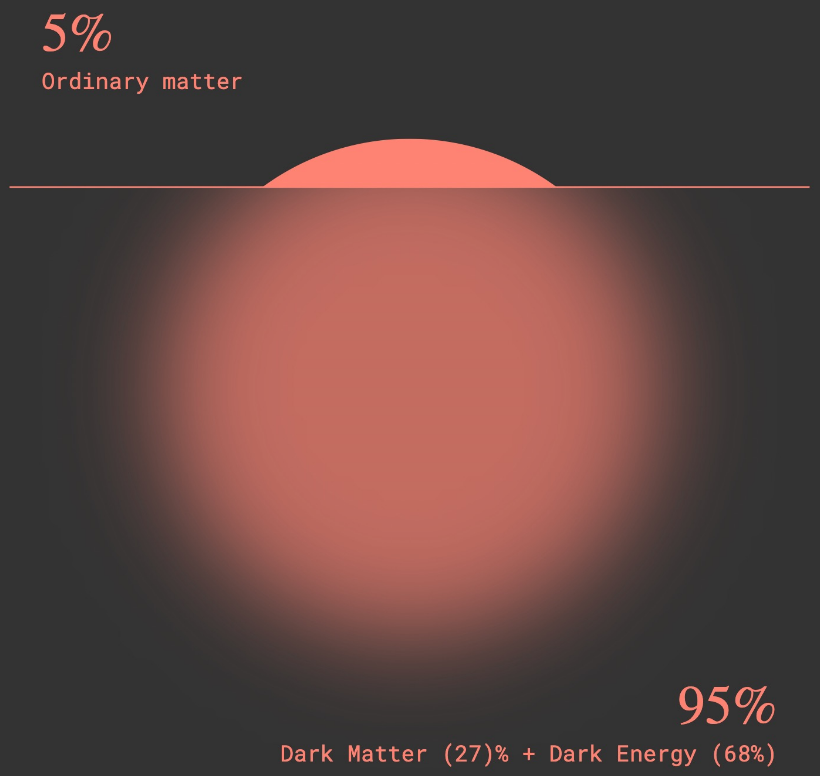
Ordinary matter



95%

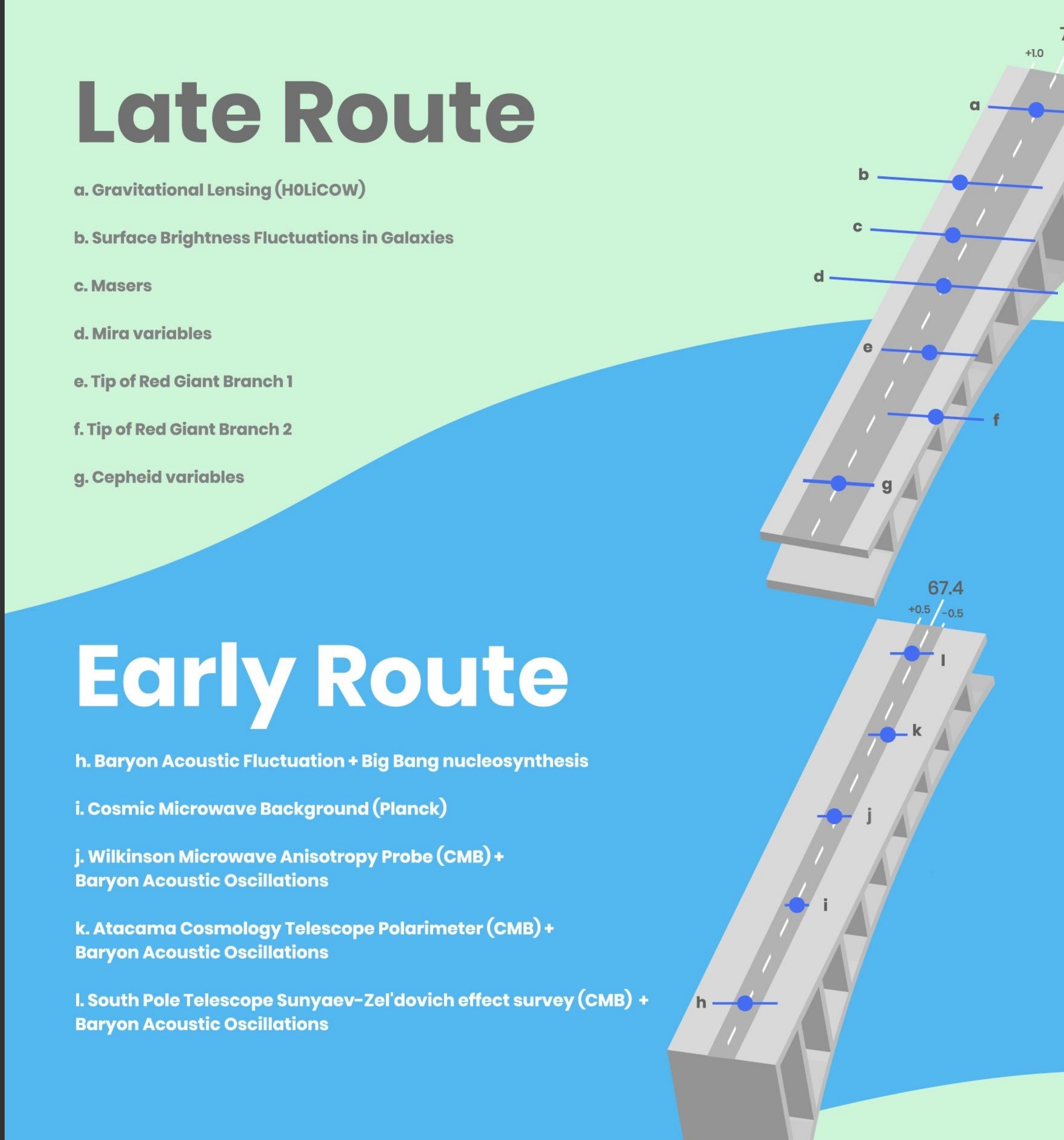
Dark Matter (27)% + Dark Energy (68%)

The ΛCDM model and the dark Universe



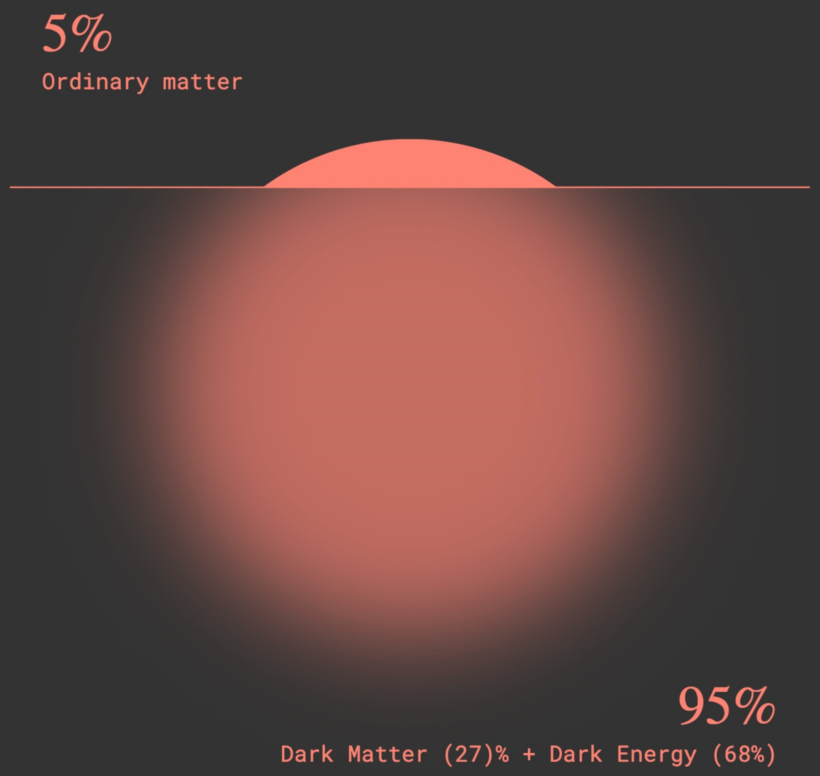
The Hubble Tension
Is there the evidence for an Early Dark Energy?

Riess 2019, Nature Review Physics



5σ tension between Early and Late H_0 probes

The ΛCDM model and the dark Universe



The Cold Dark Matter model is in tension with observations at galactic and sub-galactic scales

Challenges to the ΛCDM paradigm

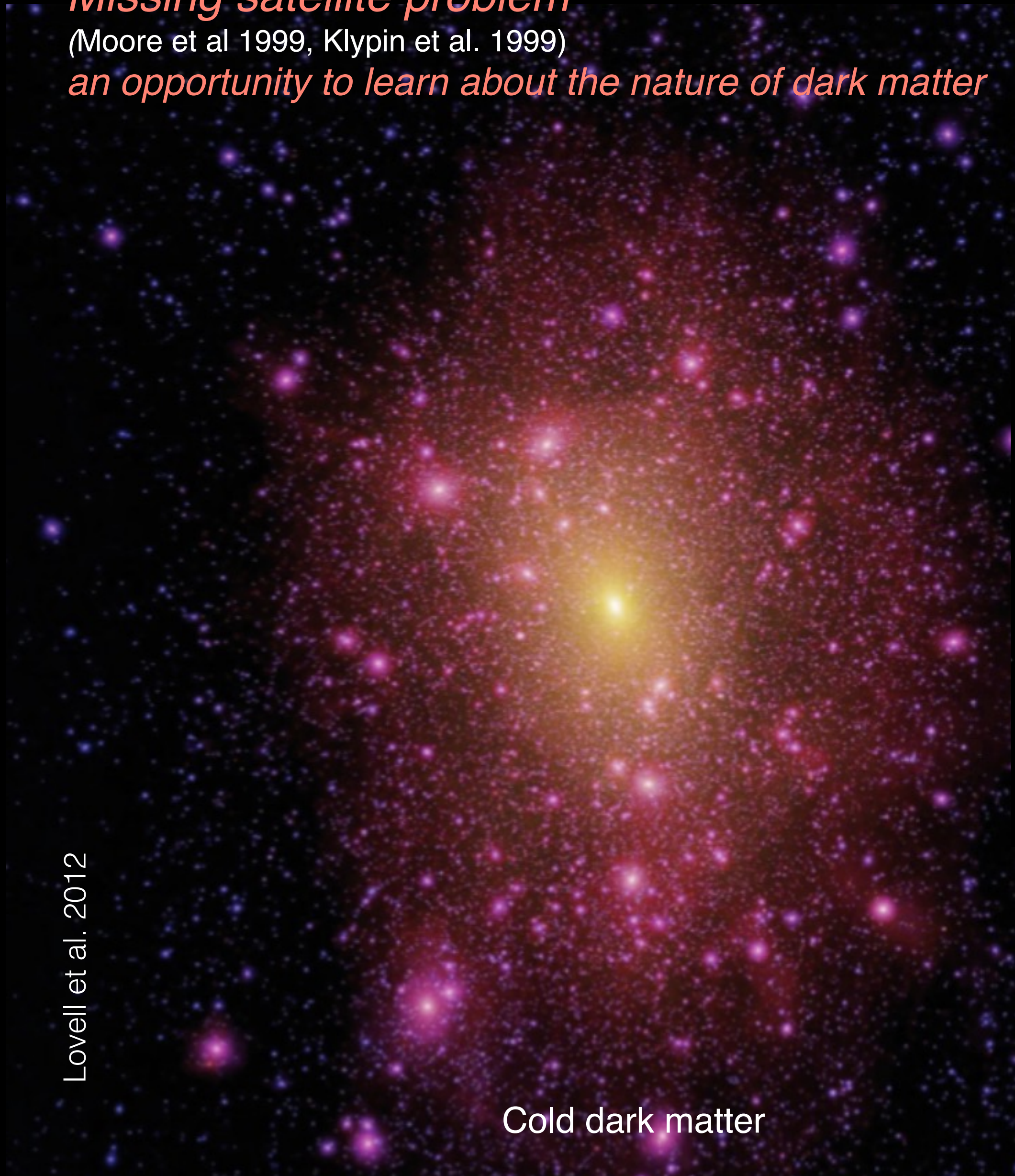
Missing satellite problem

(Moore et al 1999, Klypin et al. 1999)

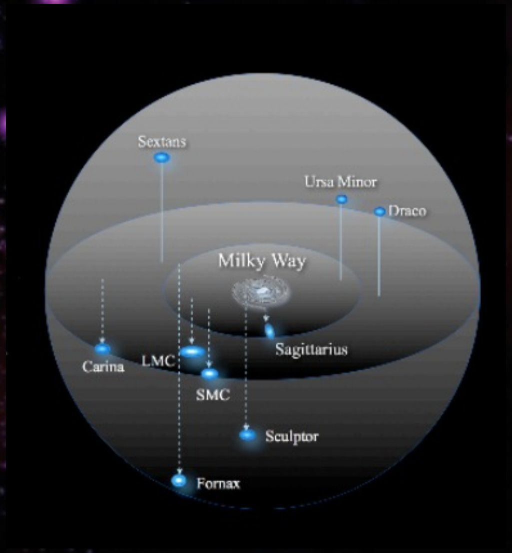
an opportunity to learn about the nature of dark matter

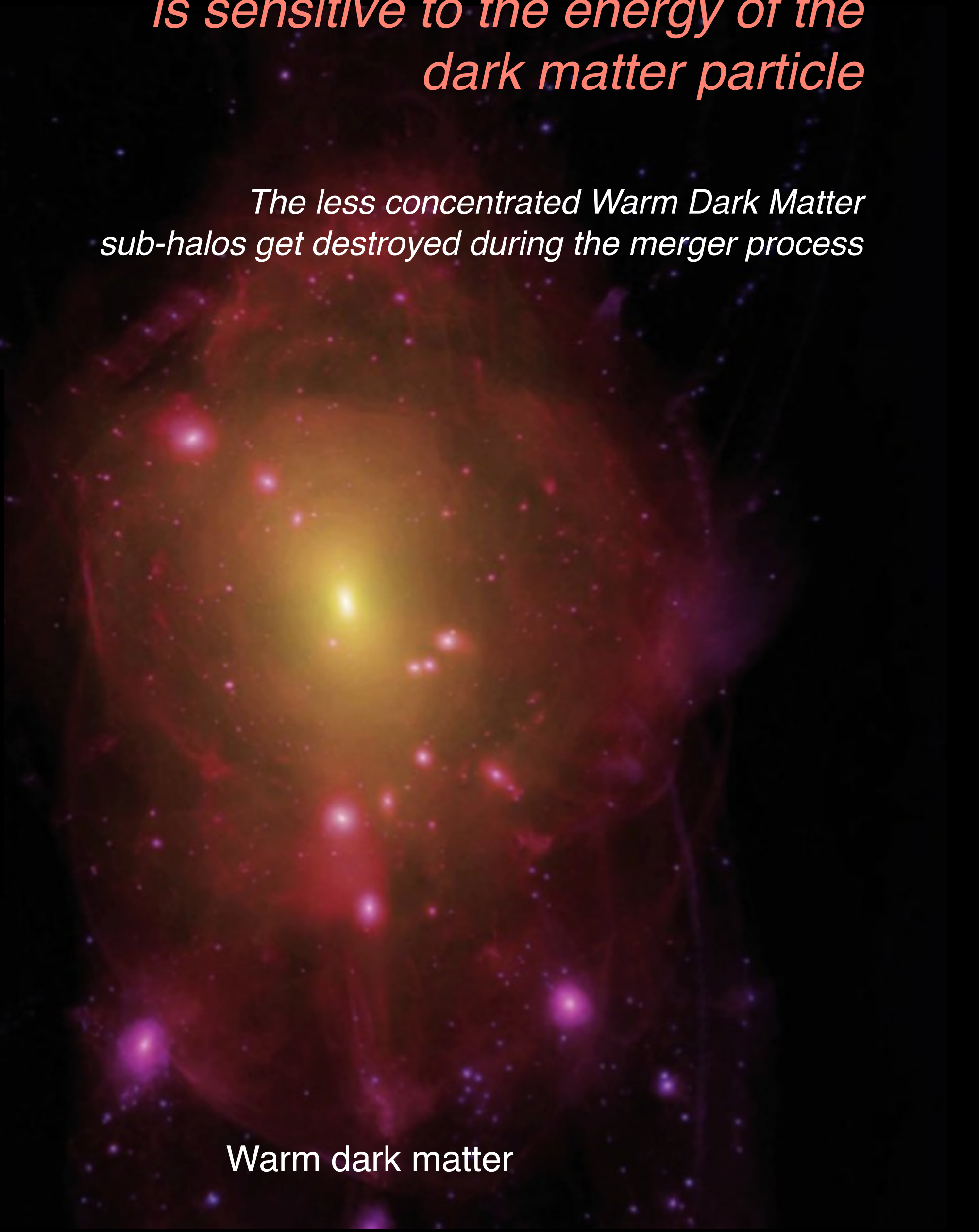
The abundance of low-mass sub-halos is sensitive to the energy of the dark matter particle

The less concentrated Warm Dark Matter sub-halos get destroyed during the merger process



Cold dark matter





Warm dark matter

Lovell et al. 2012

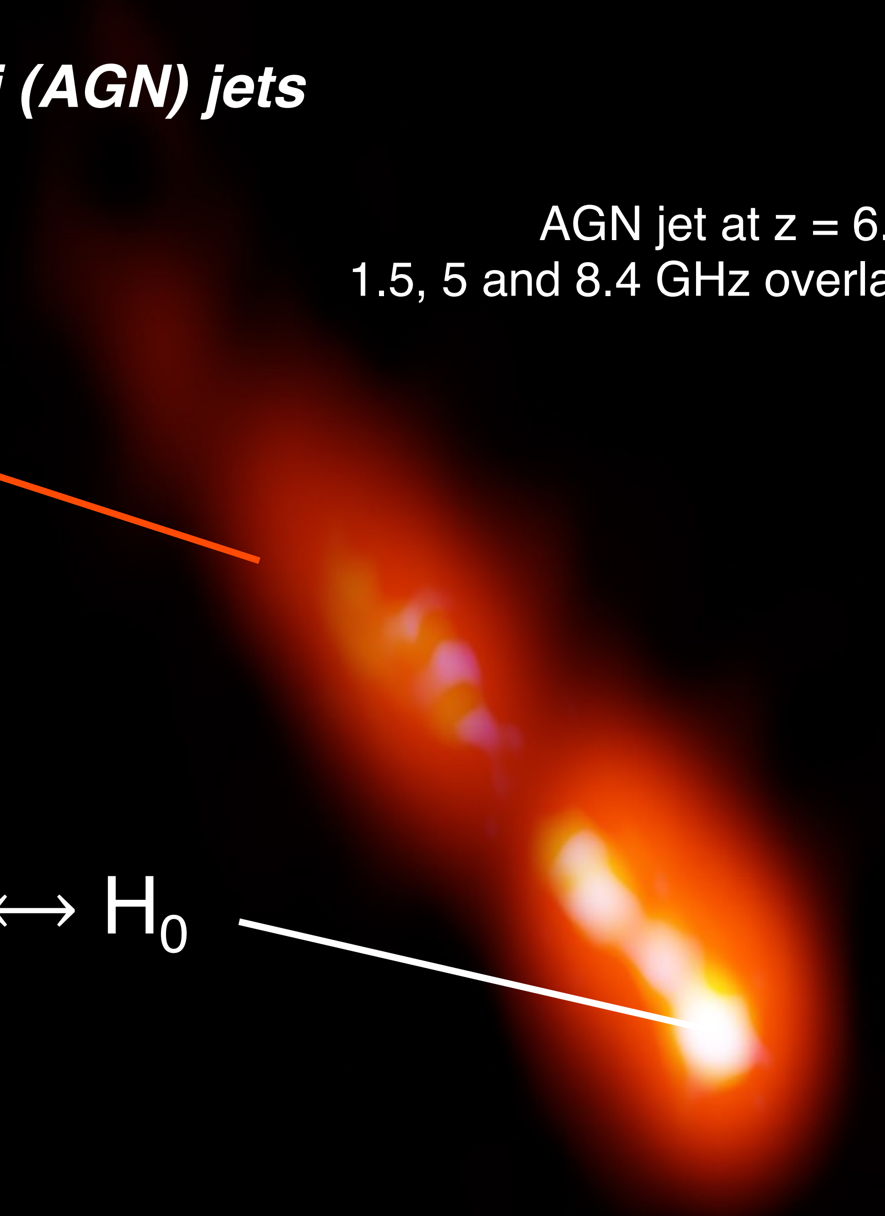
The role of strongly lensed Active Galactic Nuclei (AGN) jets

Credits: Robert Schulz (Leiden University); Data from Spingola et al. 2018, Spingola et al. 2020b

Images position and flux ratios /surface brightness ⟺ lens mass density distribution, gravitational signatures of sub-halos

Time delays ∝ H_0^{-1}

The role of strongly lensed Active Galactic Nuclei (AGN) jets



AGN jet at z = 6.1
1.5, 5 and 8.4 GHz overlay

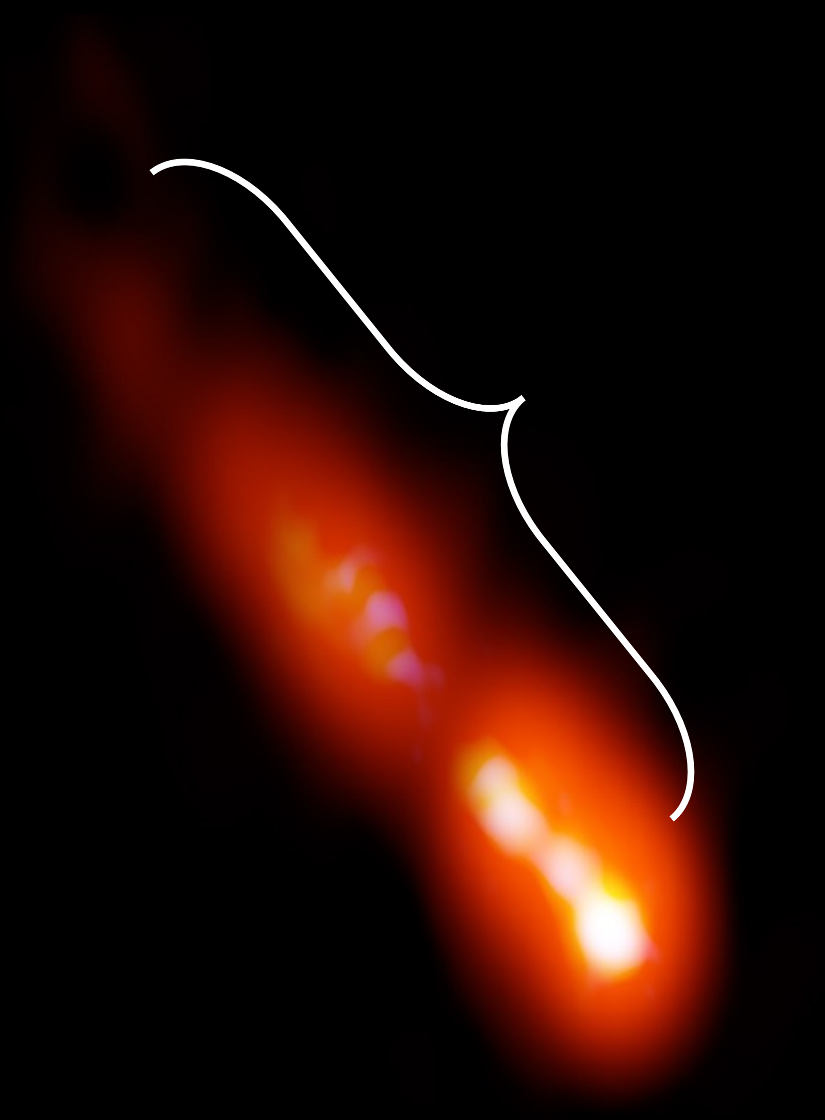
Extended emission ⟷ Dark matter

Cores (variable emission) ⟷ H_0
(and lens searches)

Image credit: NRAO press release
Data from Spingola et al. 2020

Submitted **SKA White Chapter** for Advancing Astrophysics with the SKA – II
«SKA–VLBI view of AGN jets in the early Universe» **Spingola,** Mezcua, Liu, Frey, Belladitta, An et al.

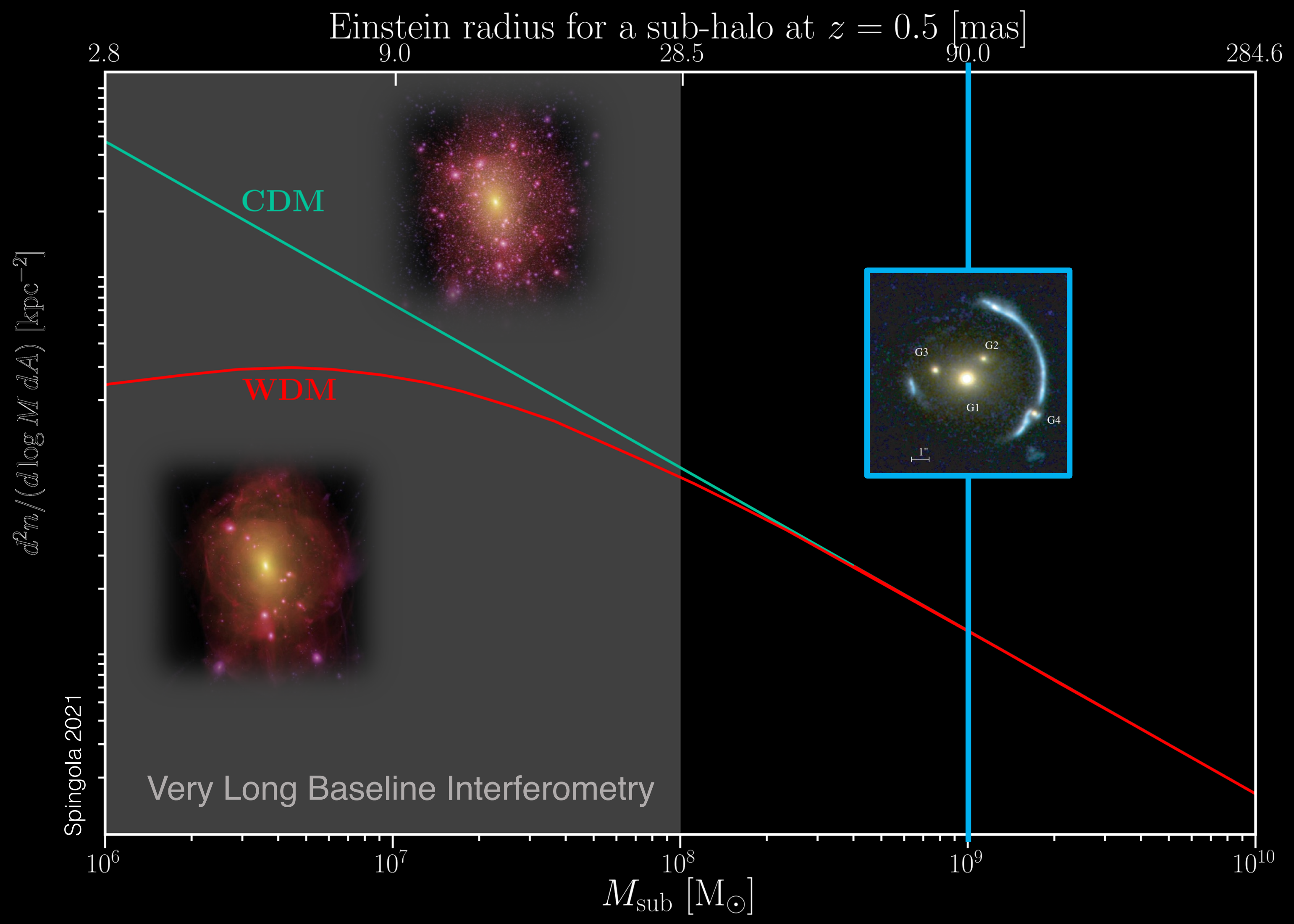
See also Belladitta et al. 2020, Moretti et al. 2021, Ighina et al. 2022, ***Caccianiga et al. al. 2019 and 2024 for population studies***



DARK MATTER

Extended emission
in lensed AGN jets

The role of strong gravitational lensing
Dark sub-halos

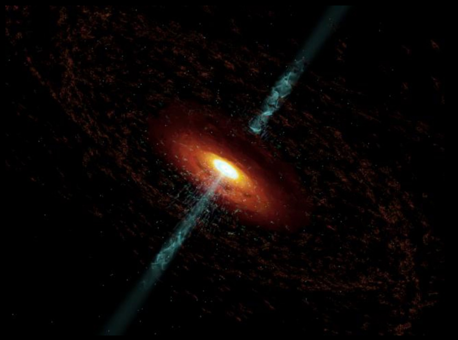


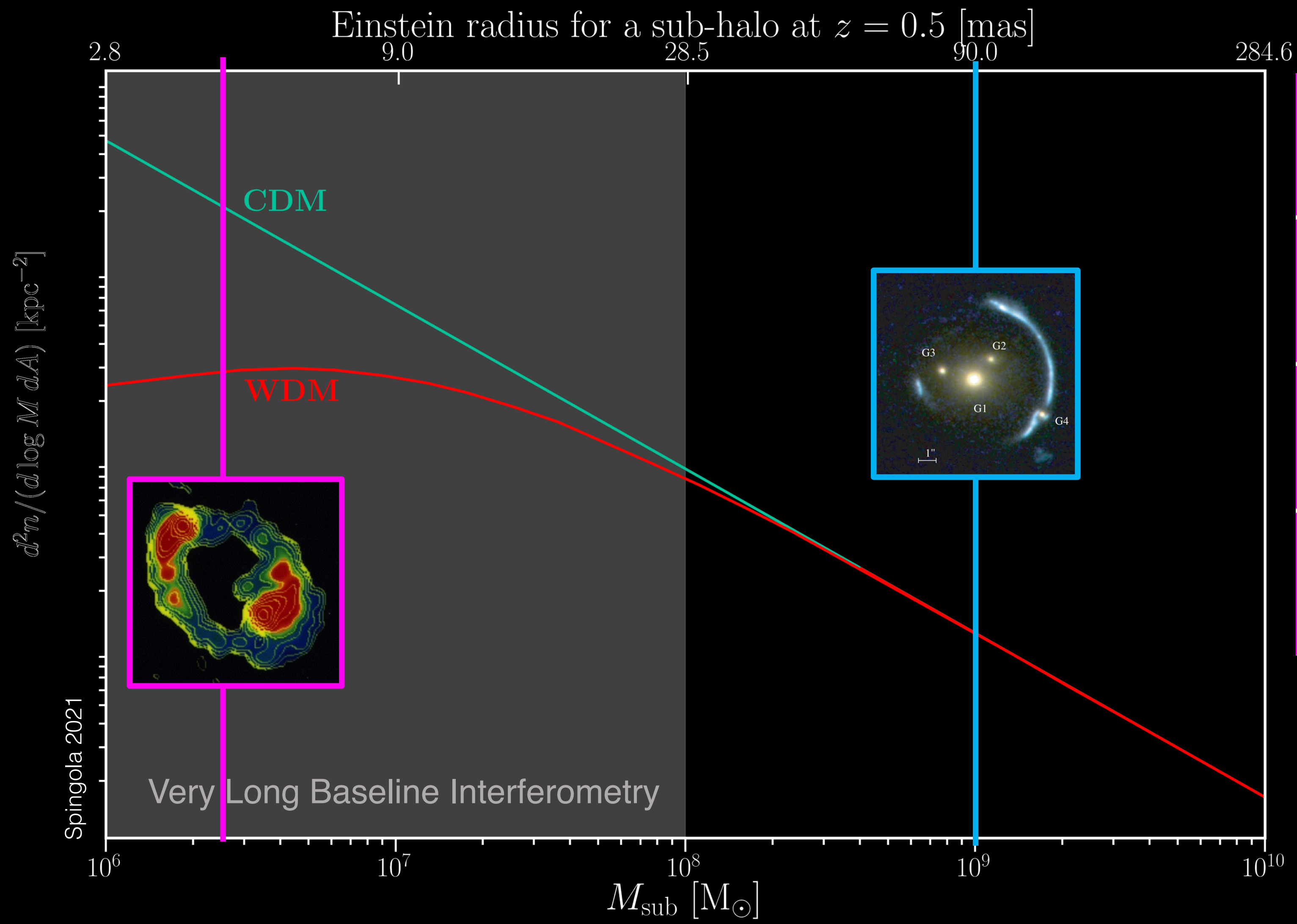
See also Metcalf & Madau 2001, Dalal & Kochanek 2002 , Dye et al. 2005, Koopmans 2005, Chen 2007, Vegetti & Koopmans 2009, Vegetti+ 2012, Hezaveh+2016, Gilman+2020, Despali +2022, Abe+ 2024

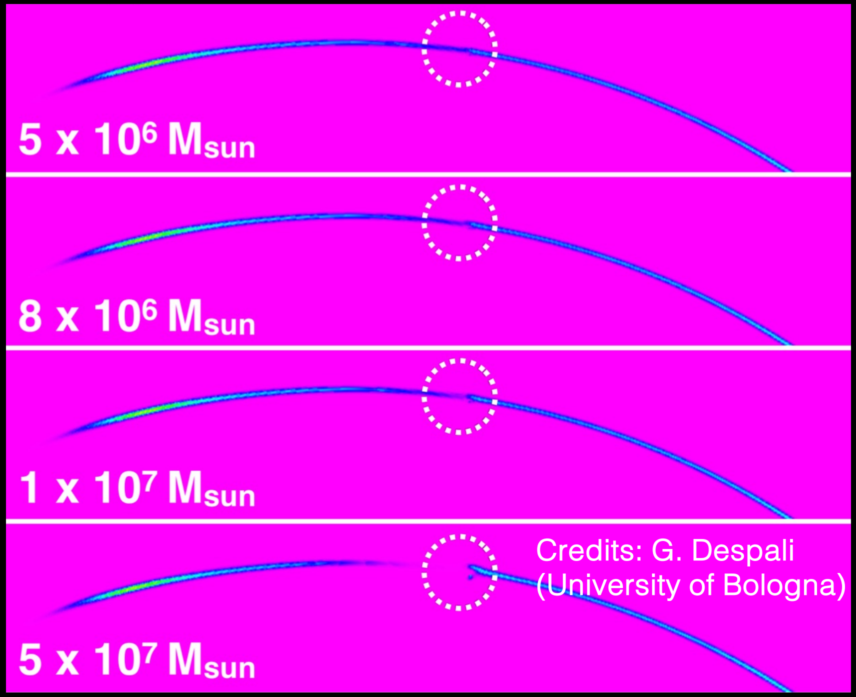
The role of strong gravitational lensing

Dark sub-halos

The ideal background source consists of active galactic nuclei (AGN) jets as they are extended and not resolved out on VLBI scales







Sub-halos of $10^{6\text{-}7}\ M_{sun}$ can be directly detected only with **mas angular resolution**

They are expected to becompletely dark

See also Metcalf & Madau 2001, Dalal & Kochanek 2002 , Dye et al. 2005, Koopmans 2005, Chen 2007, Vegetti & Koopmans 2009, Vegetti+ 2012, Hezaveh+2016, Gilman+2020, Despali +2022, Abe+ 2024

Very Long Baseline Interferometry (VLBI)

JIVE
Joint Institute for VLBI
ERIC

EUROPEAN vlbi NETWORK

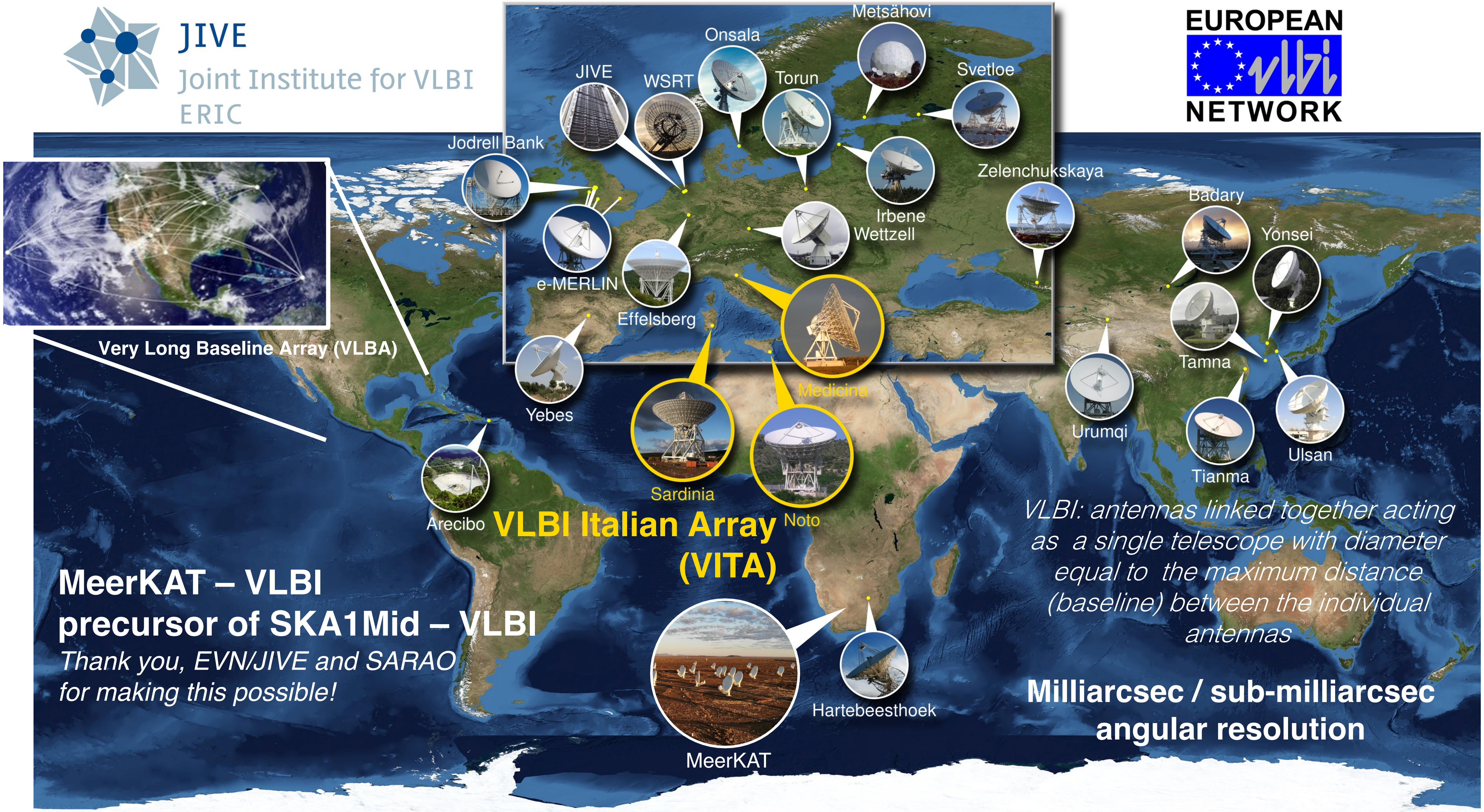
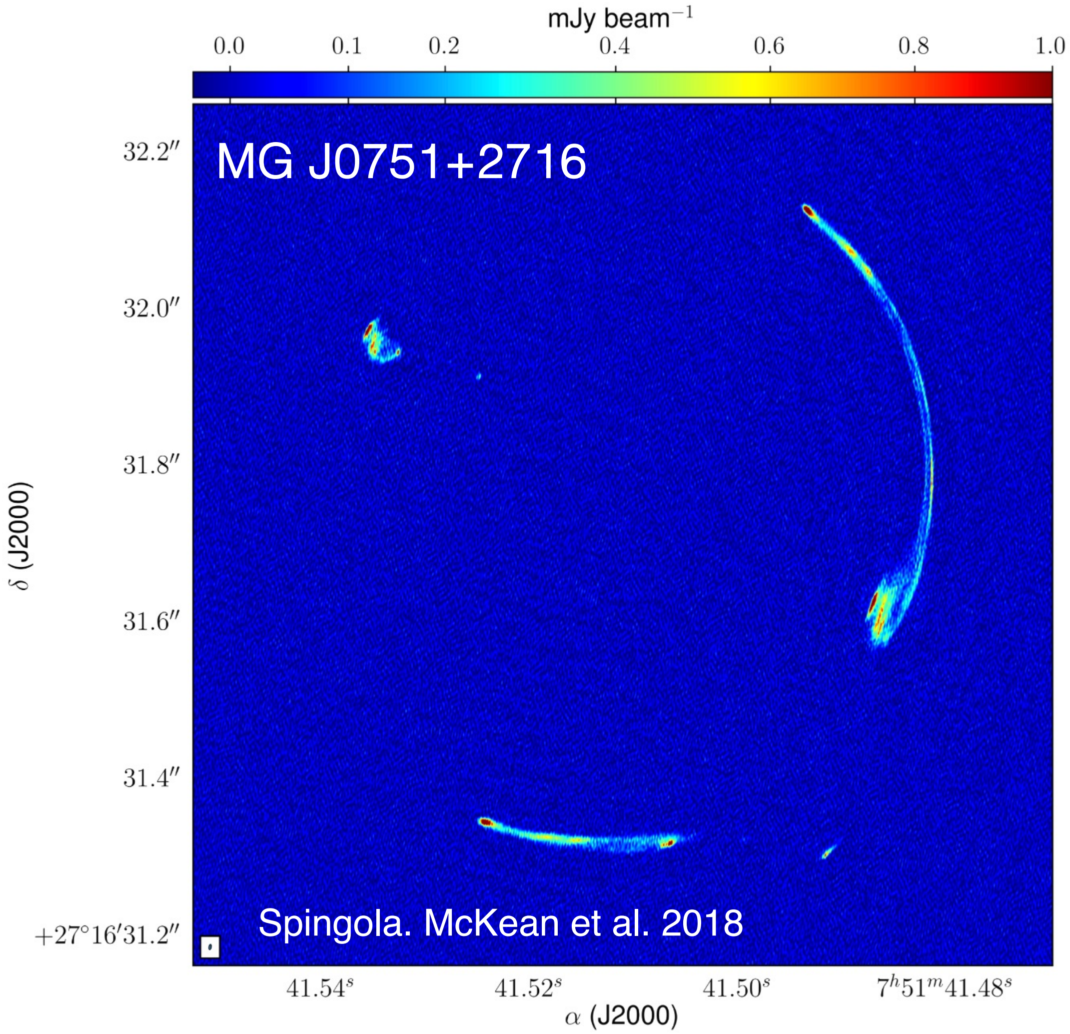


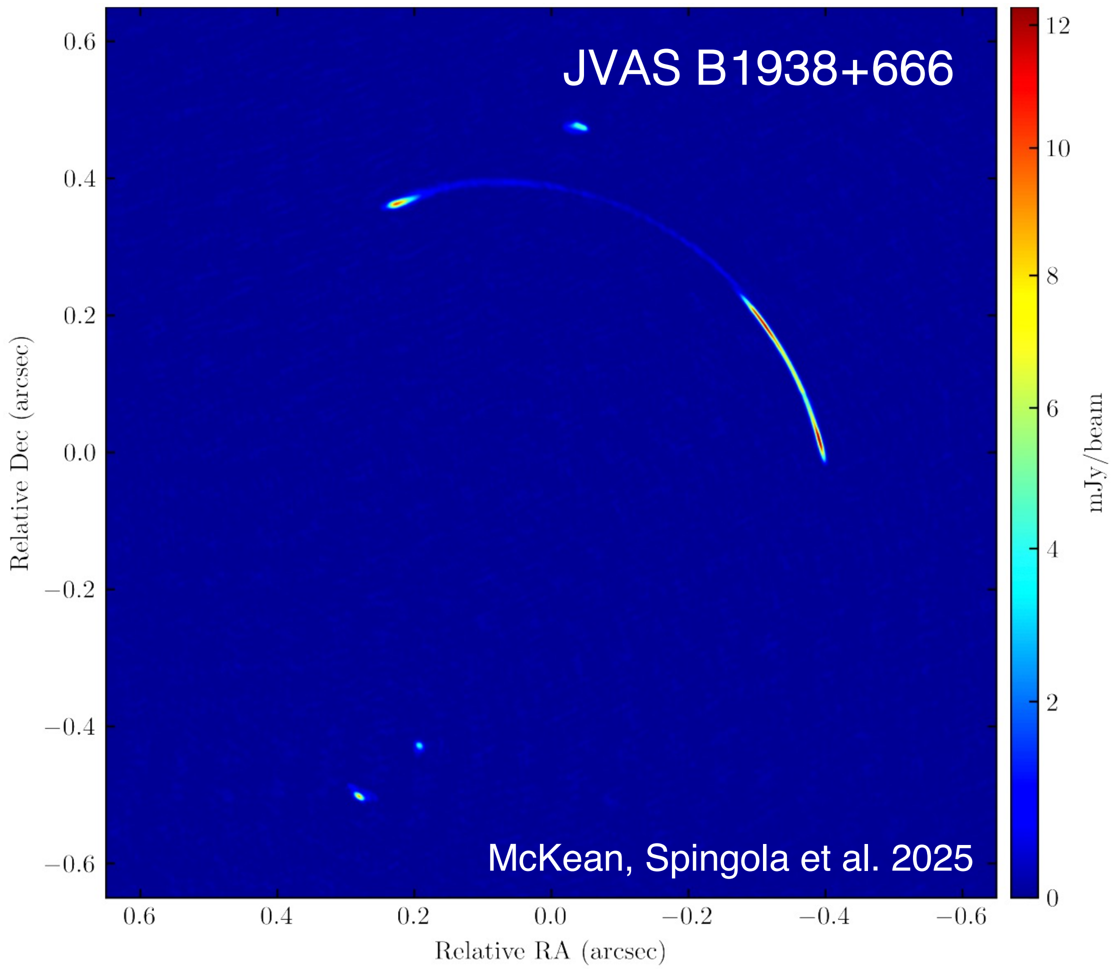
Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).

Extended gravitational arcs observed with VLBI are ideal to find low-mass sub-halos

Extended gravitational arcs observed with VLBI are ideal to find low-mass sub-halos

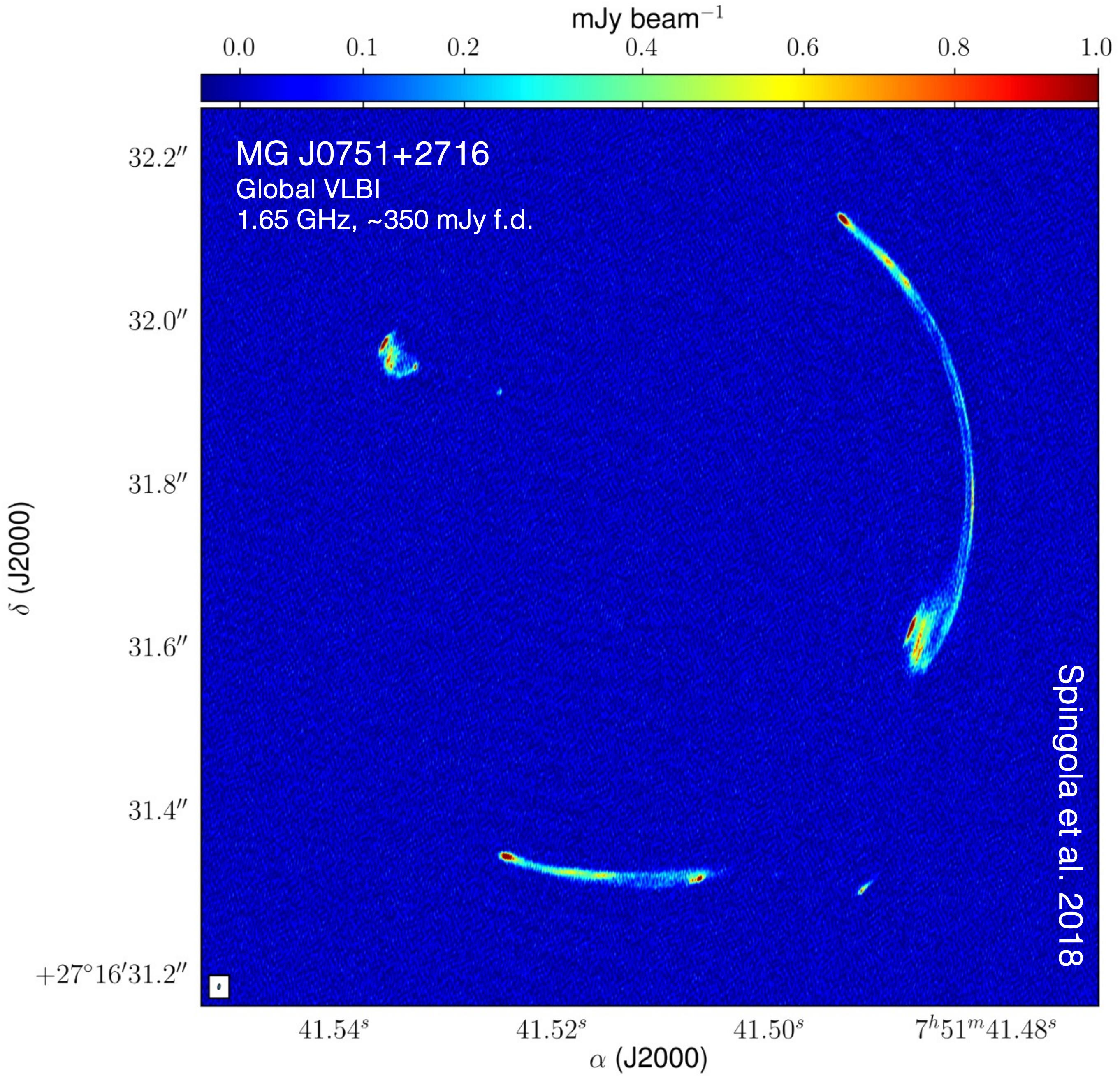
Global VLBI observations EVN + VLBA + eMERLIN (short + long baselines)



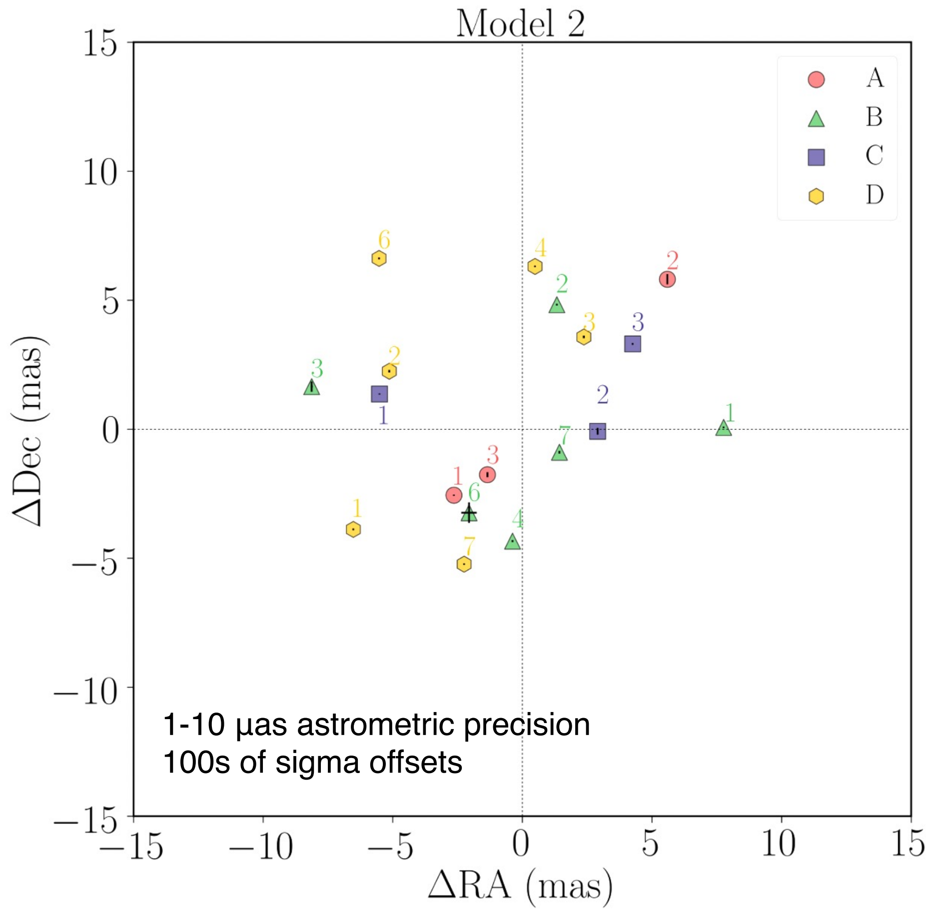


But, to date, there are only these two!

Gravitationally lensed jets to find low-mass sub-halos



Deviation from a smooth mass model



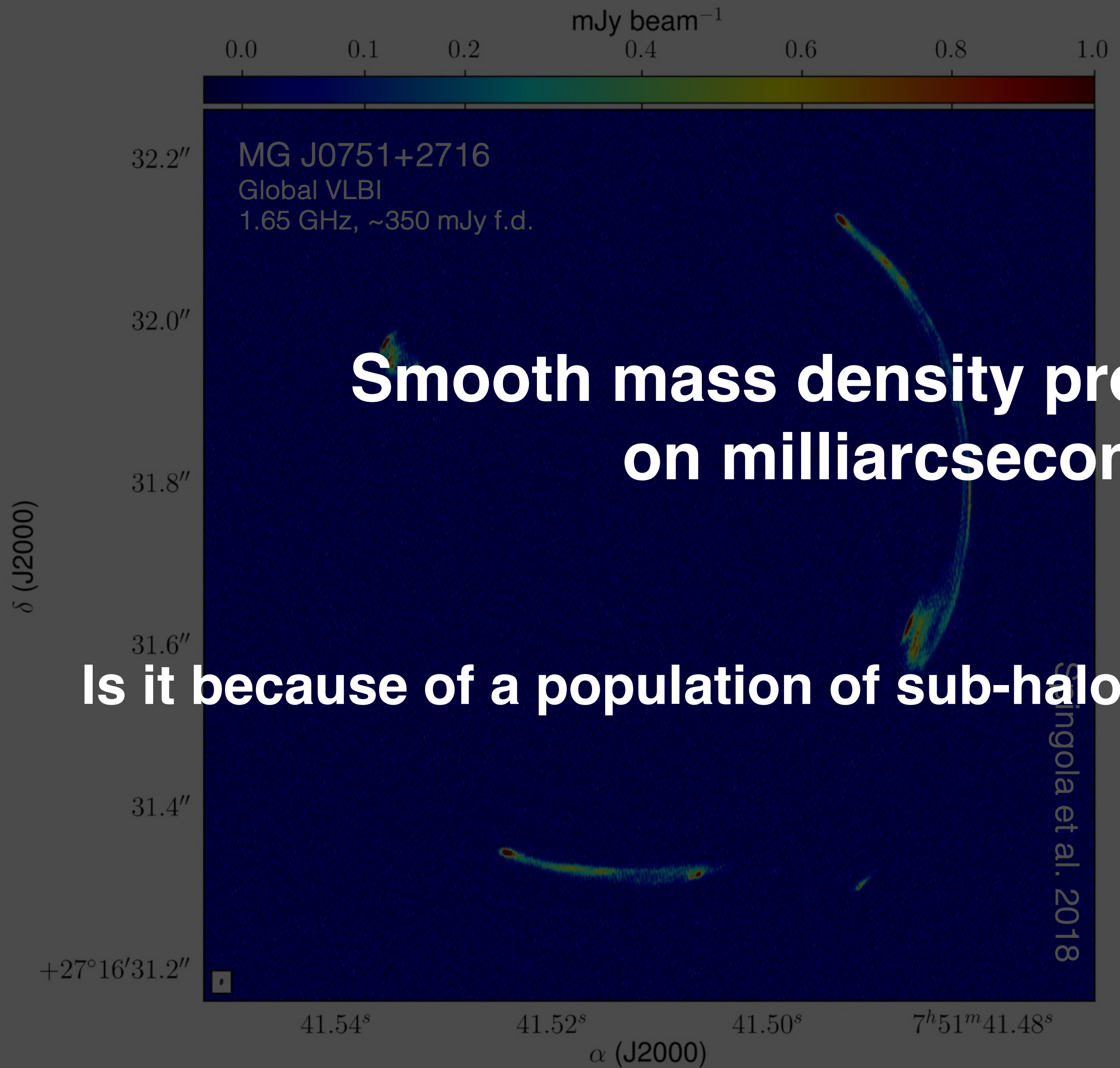
Astrometric anomalies

evidence for **GRANULARITY**

(there is no localized offset, but that's a generalized effect)

See also Hartley et al. 2019

Gravitationally lensed jets to find low-mass sub-halos



Smooth mass density profiles do not work on milliarcsecond scales

Is it because of a population of sub-halos or is the model too «simple» ?

Astrometric anomalies

evidence for **GRANULARITY**

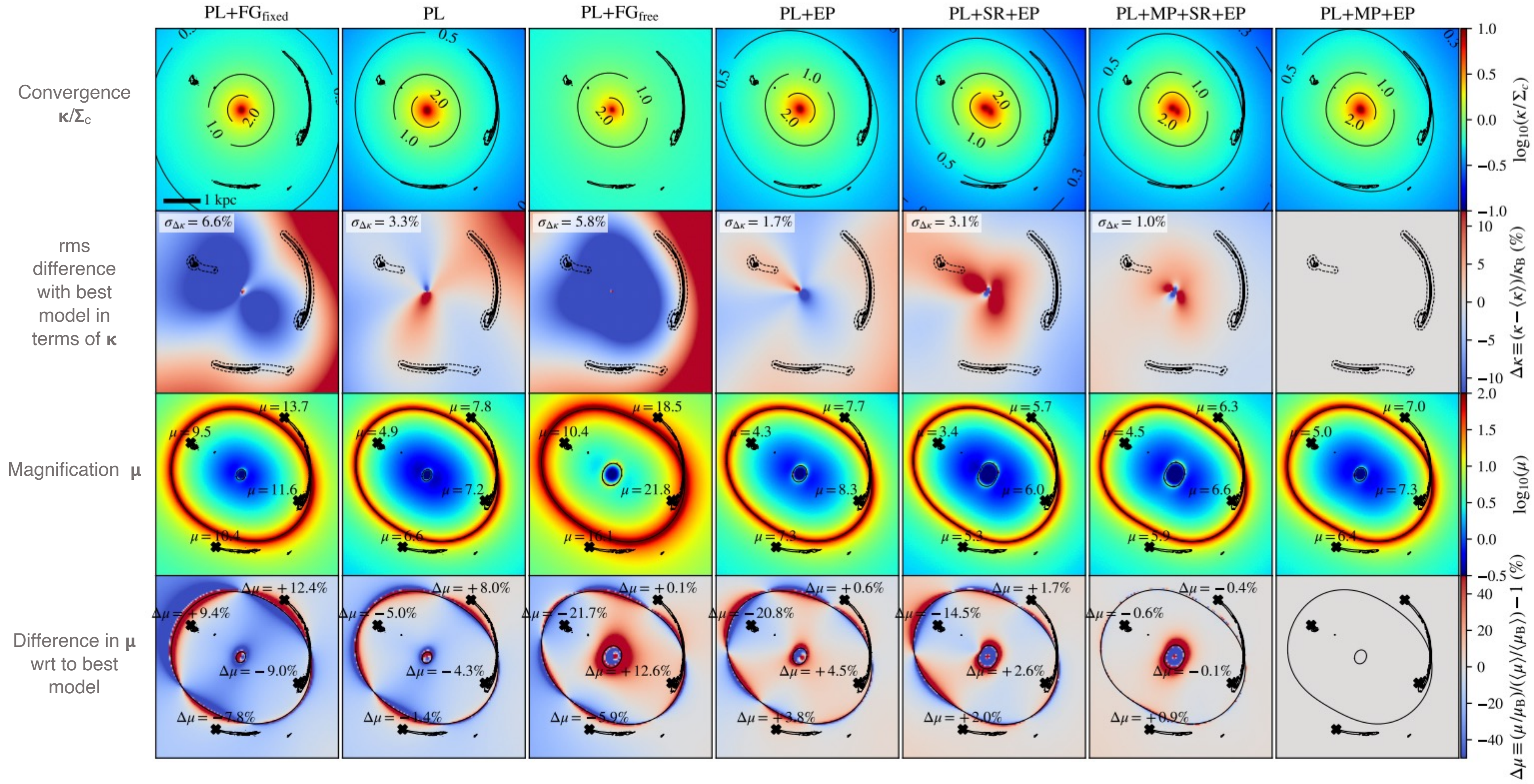
(there is no localized offset, but that's a generalized effect)

See also Hartley et al. 2019

Testing more complex models: angular structure

Powell et al. 2022

Best model



Angular structure is strongly favoured by the data

Potential corrections for CDM sub-halos on-going!

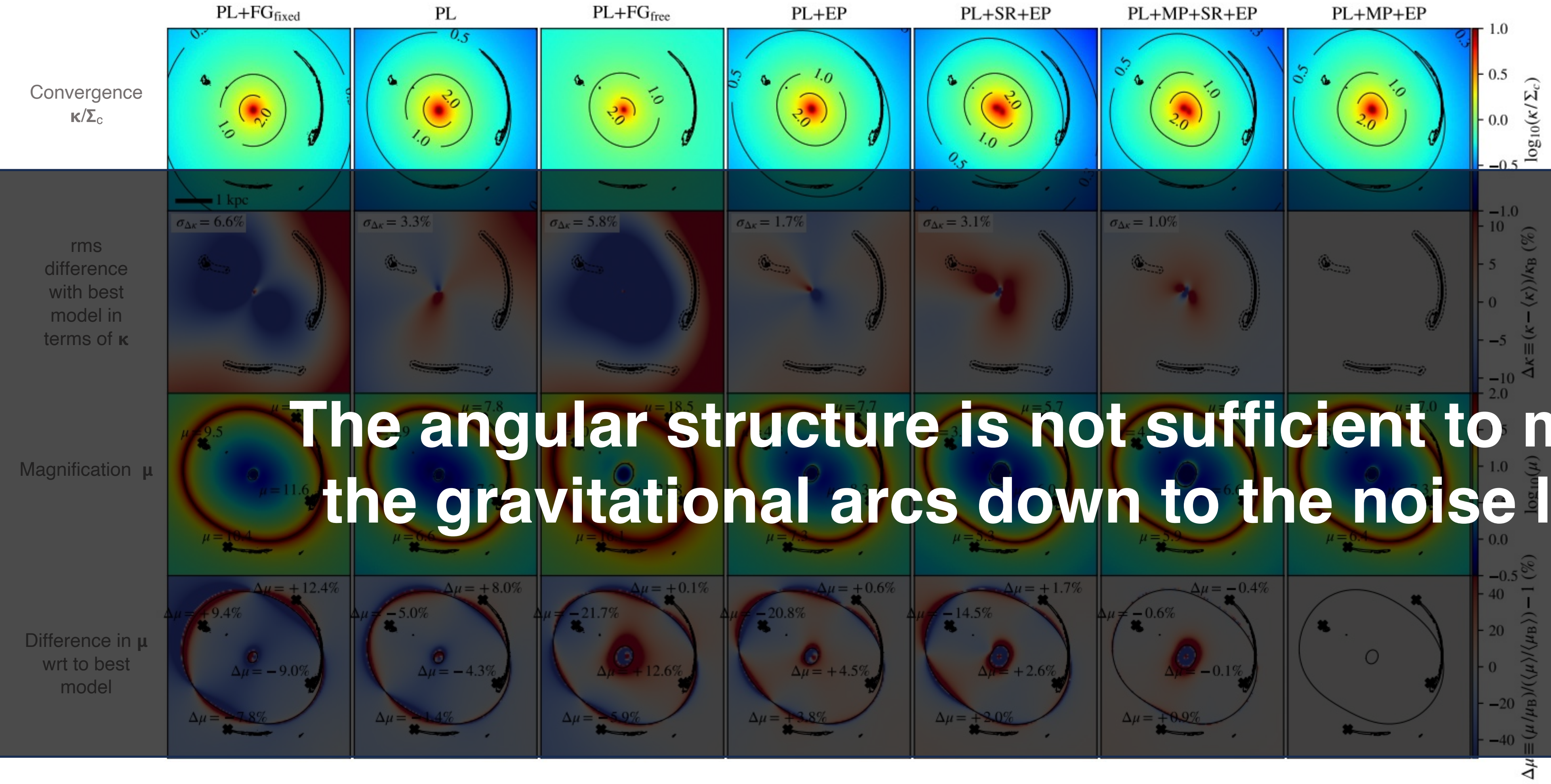
Complex models in a Bayesian framework **in the visibility domain**

See Gilman et al. 2024, Cohen et al. 2024, O'Riordan & Vegetti 2024, Gilman et al. 2023, Galan et al. 2022

Testing more complex models: angular structure

Powell et al. 2022

Best model



Angular structure is strongly favoured by the data

The angular structure is not sufficient to model the gravitational arcs down to the noise level

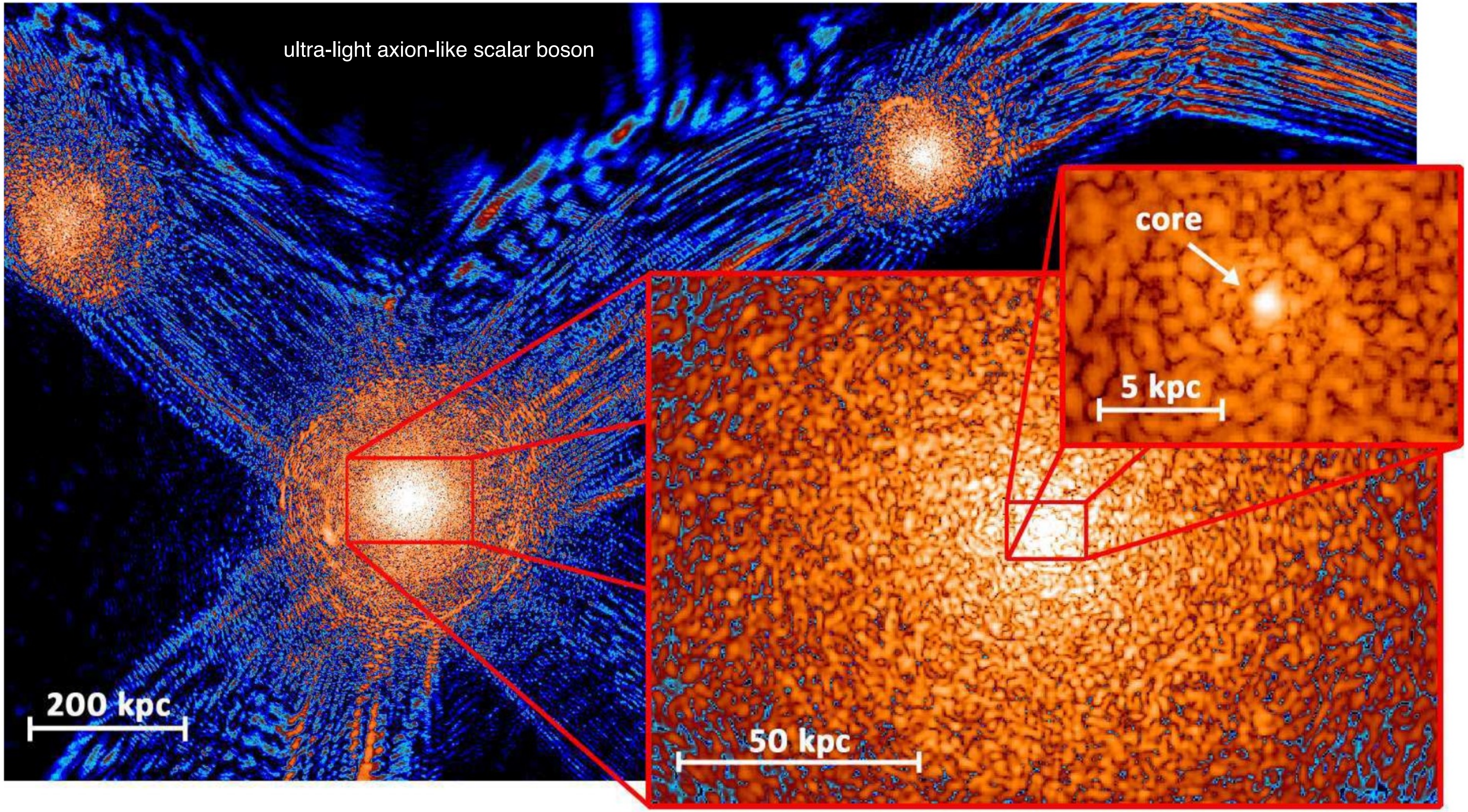
Potential corrections for CDM sub-halos on-going!

Complex models in a Bayesian framework **in the visibility domain**

See Gilman et al. 2024, Cohen et al. 2024, O'Riordan & Vegetti 2024, Gilman et al. 2023, Galan et al. 2022

Testing alternative dark matter models: fuzzy dark matter

Large scale structure extremely simlar to CDM

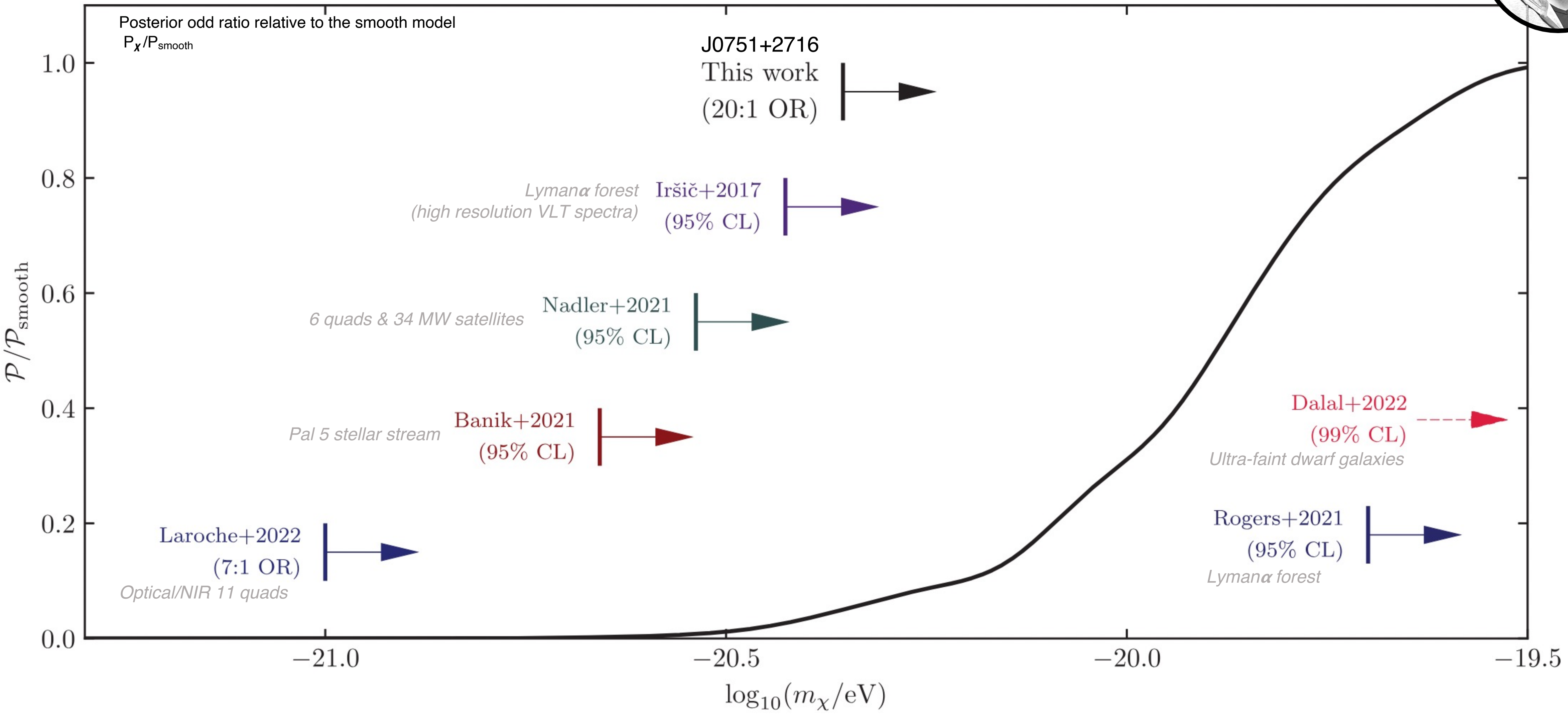


Schive et al. 2014, Nature Physics

The presence of thin, extended lensed radio arcs and the milli-arcsecond resolution of the observation provide direct sensitivity to the presence of FDM granules in the halo of the lens galaxy

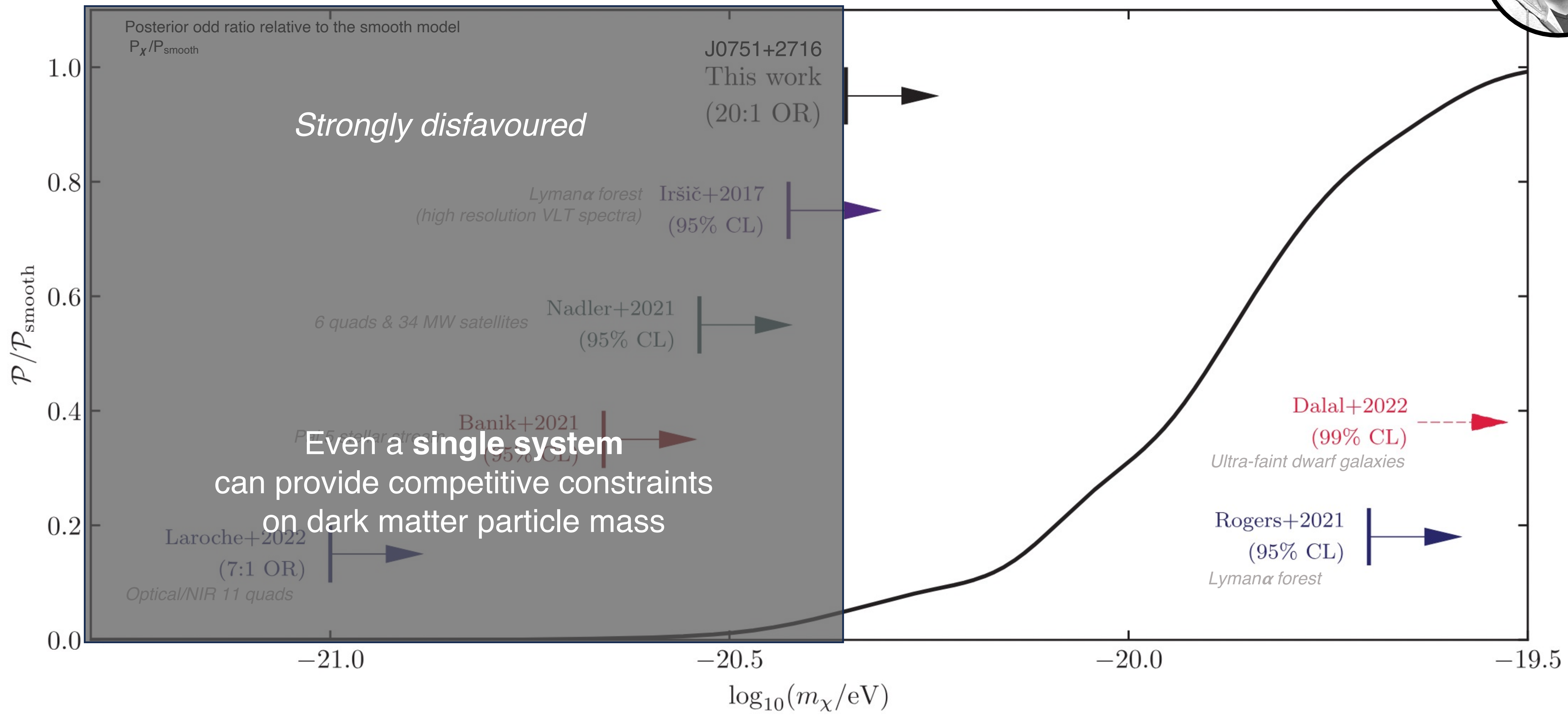
Granularity on sub-galactic scales (by construction)

Testing alternative dark matter models: fuzzy dark matter



Powell et al. 2023
(incl.CS)

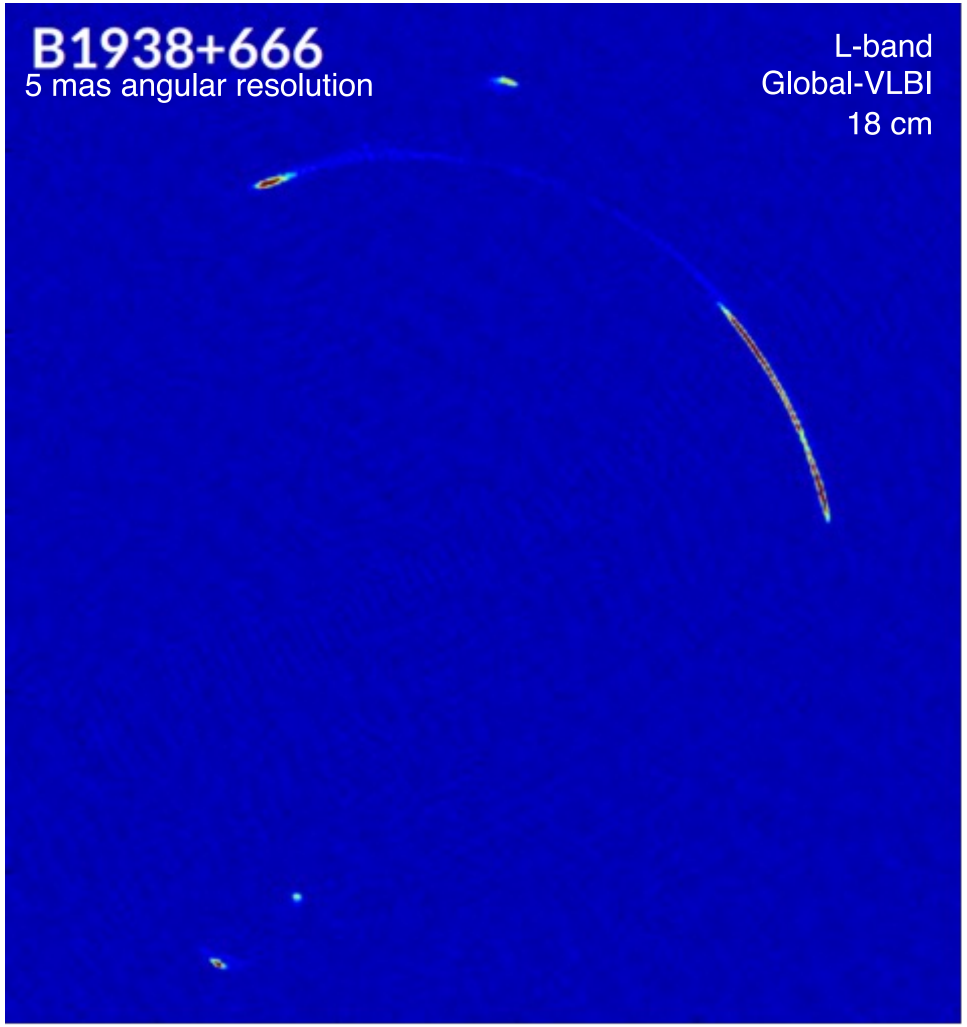
Testing alternative dark matter models: fuzzy dark matter



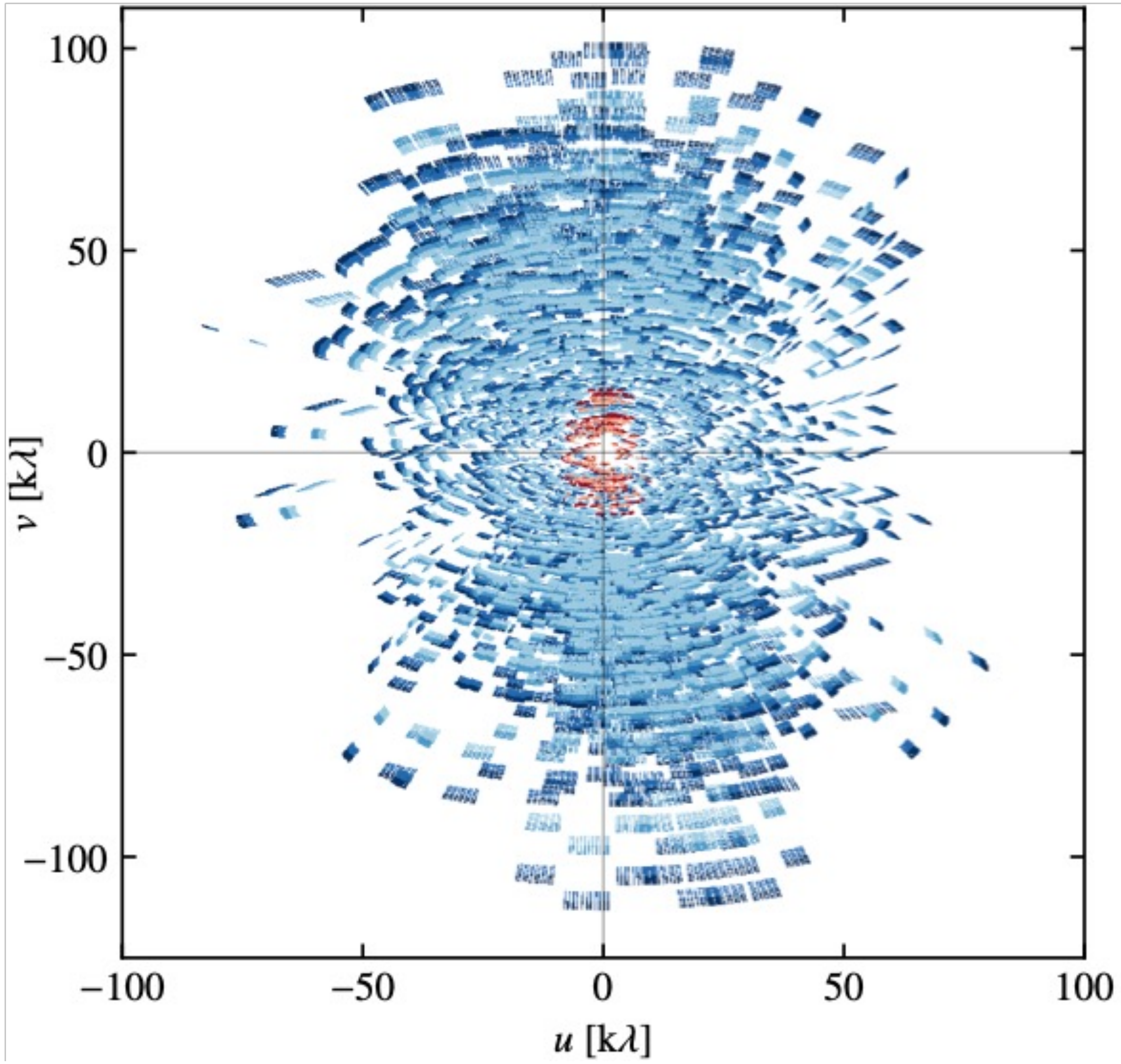
Powell et al. 2023
(incl.CS)

We need more lensed jets detected at VLBI scales

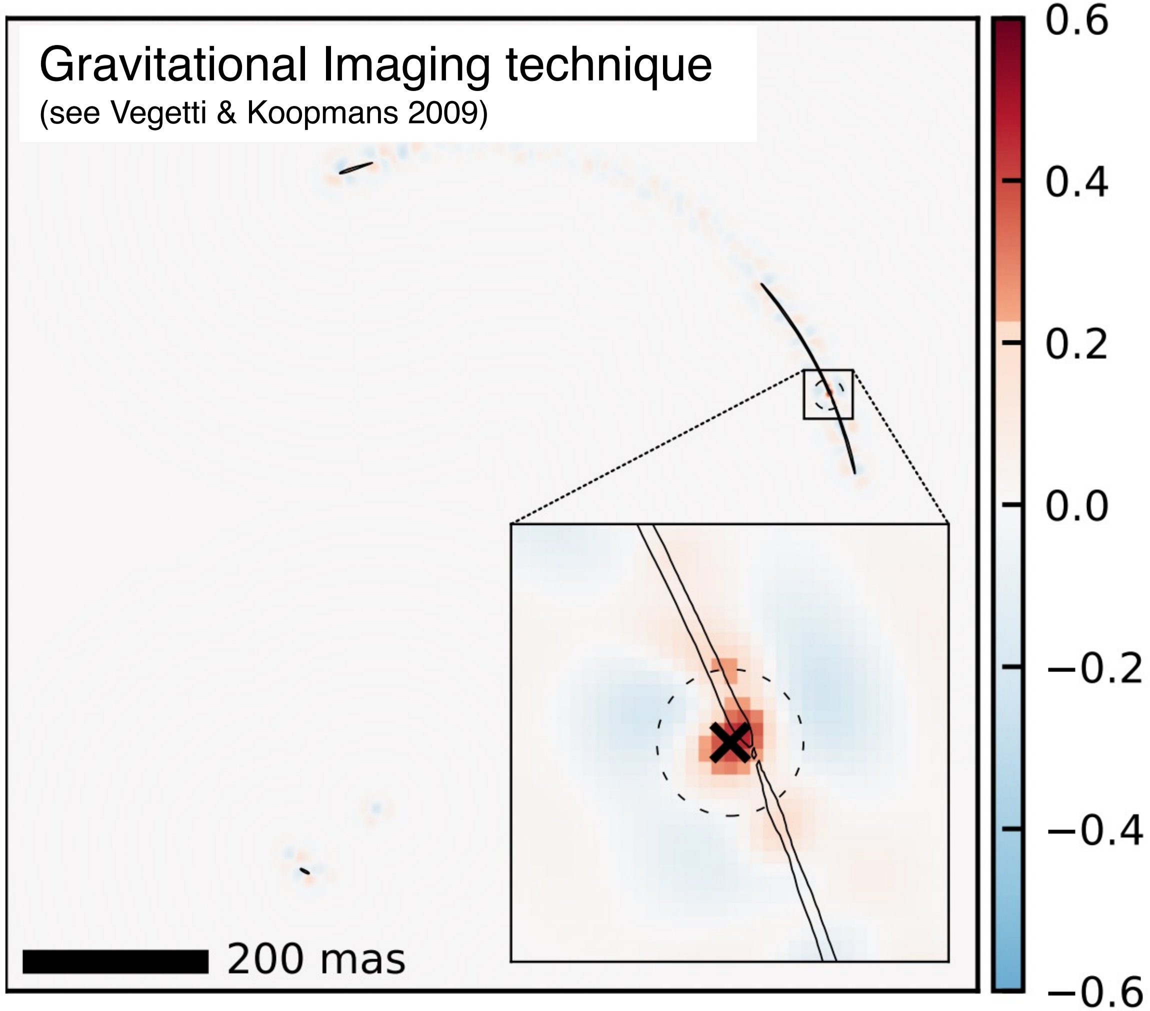
Great *uv*-coverage of Global-VLBI
important to recover the emission at low surface brightness

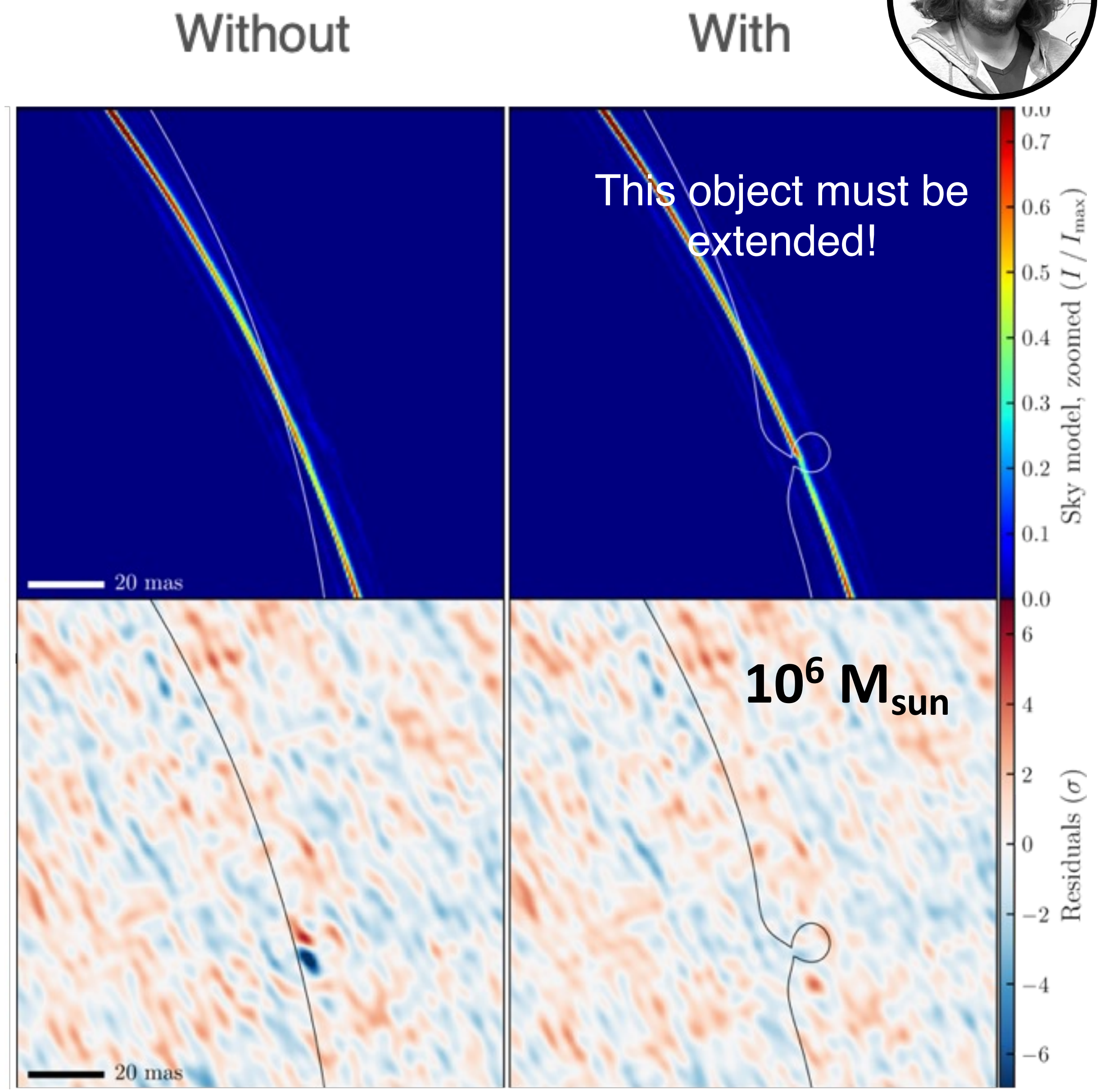


McKean, Spingola et al. 2025



The first low-mass object detected at high-z only via its gravitational effect





Powell et al. 2025 Nature Astronomy (incl. CS)

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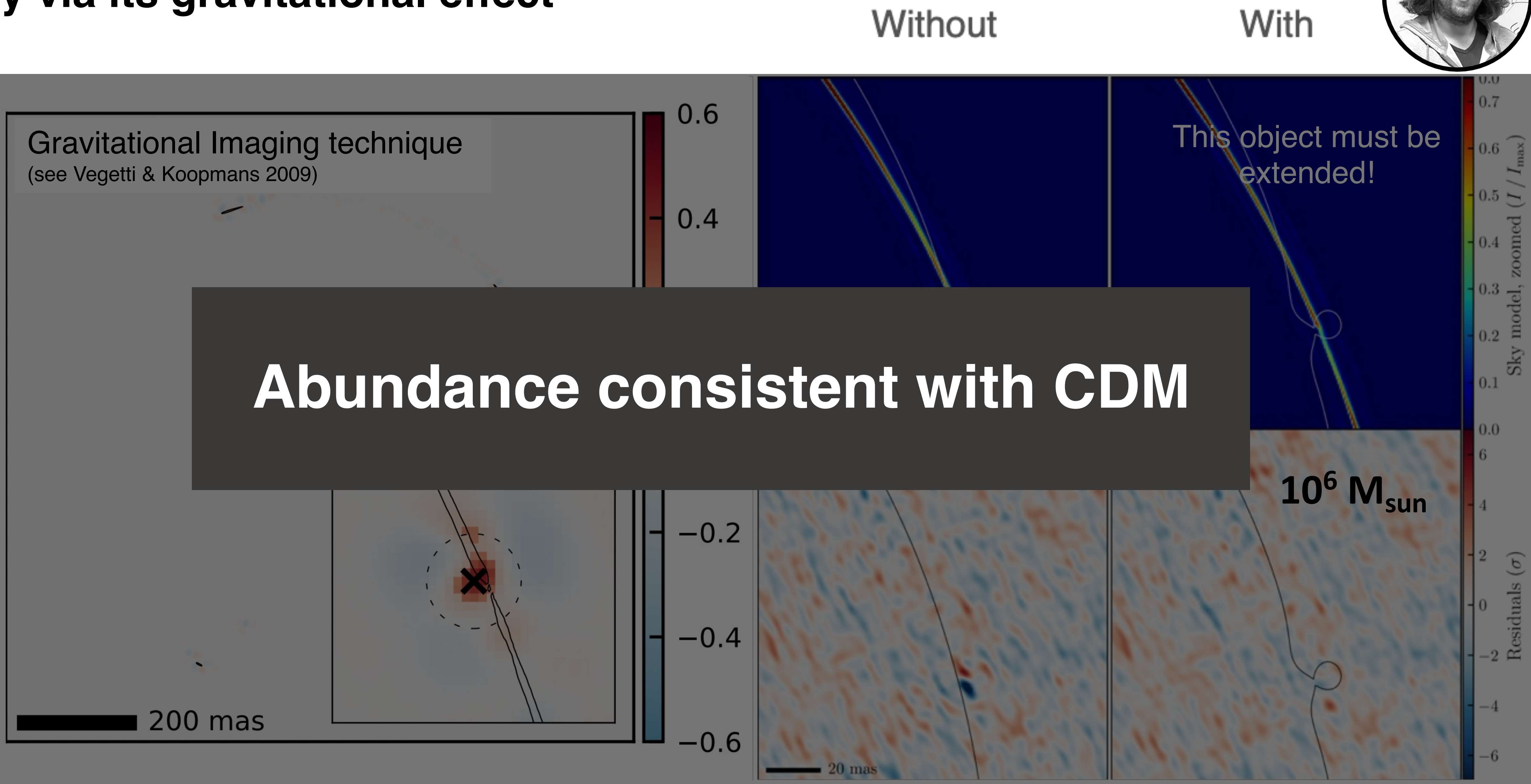
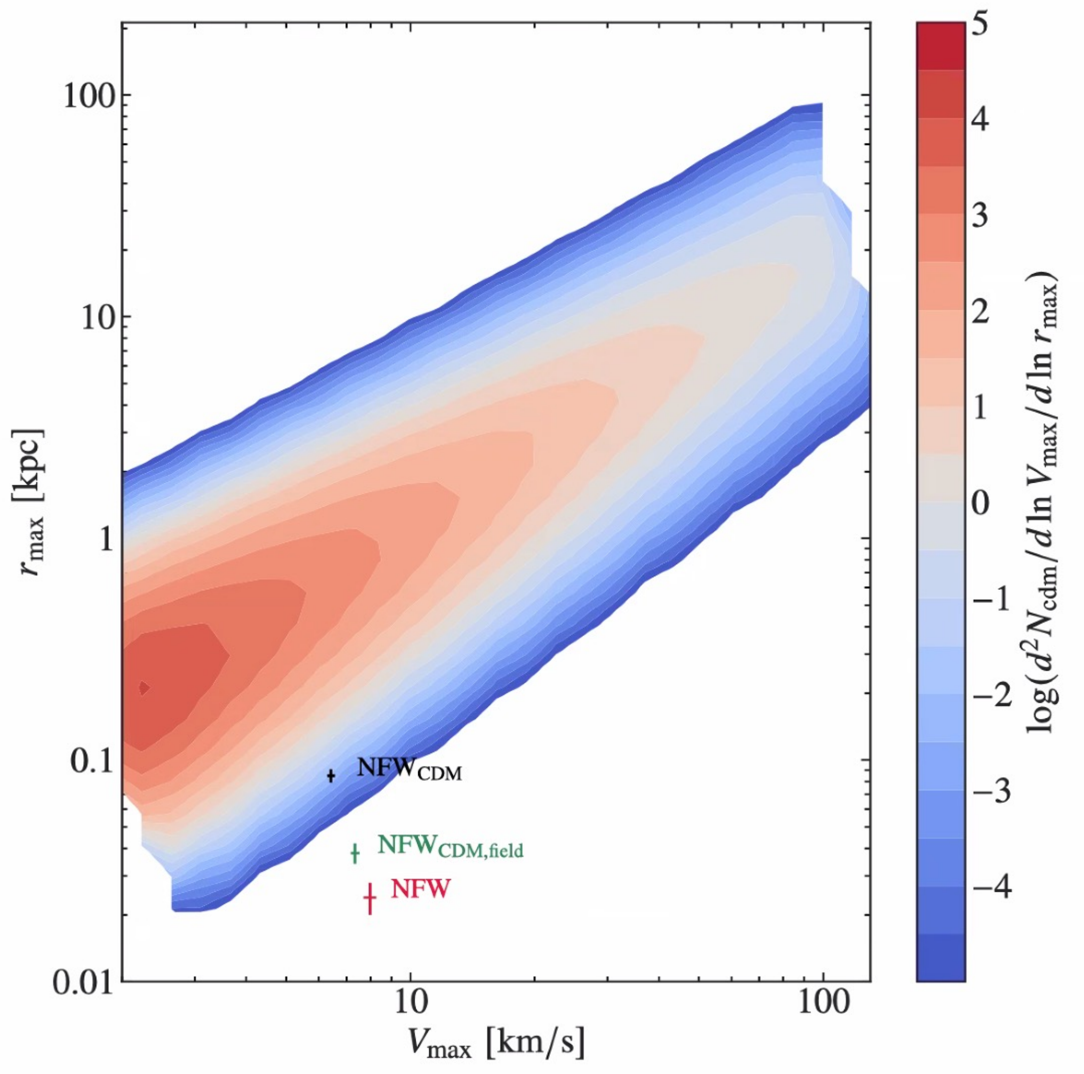


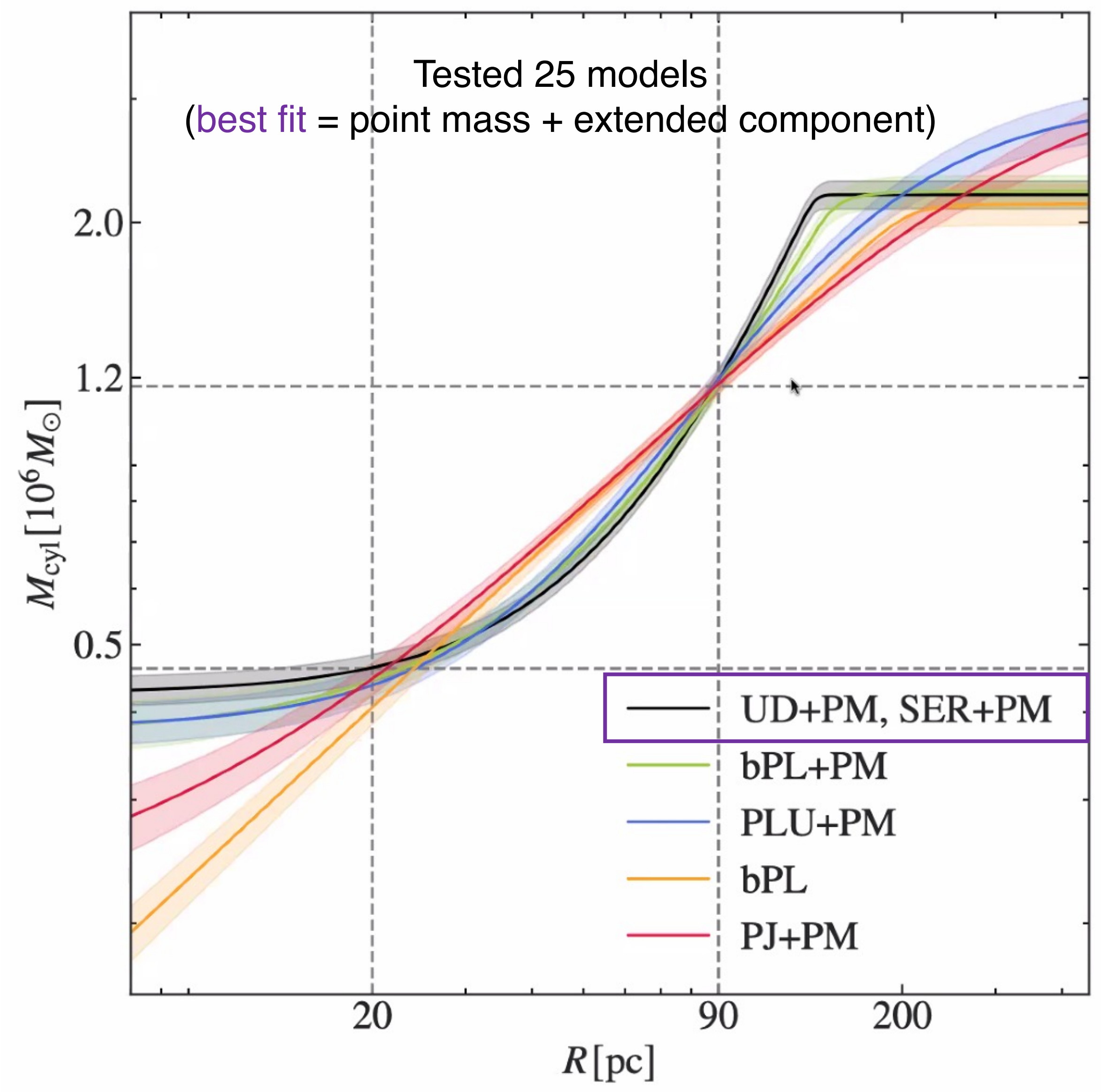
Abundance consistent with CDM

Powell et al. 2025 Nature Astronomy (incl. CS)

However, the profile is not consistent with CDM nor WDM

But such an object is more common in SIDM models





Vegetti et al. 2025, Nature Astronomy (incl. CS), in press

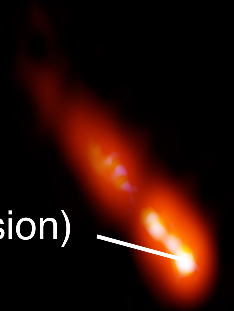
We lack of a statistically significant sample of low-mass lensing objects.

We can take advantage of time delays
to search for low-mass lenses in the time domain,

overcoming the observational difficulties of
a wide-field VLBI «all-sky» survey

(VLBI-based lens searches: Spingola et al. 2019, Casadio et al. 2021, Pötzl et al. 2025)

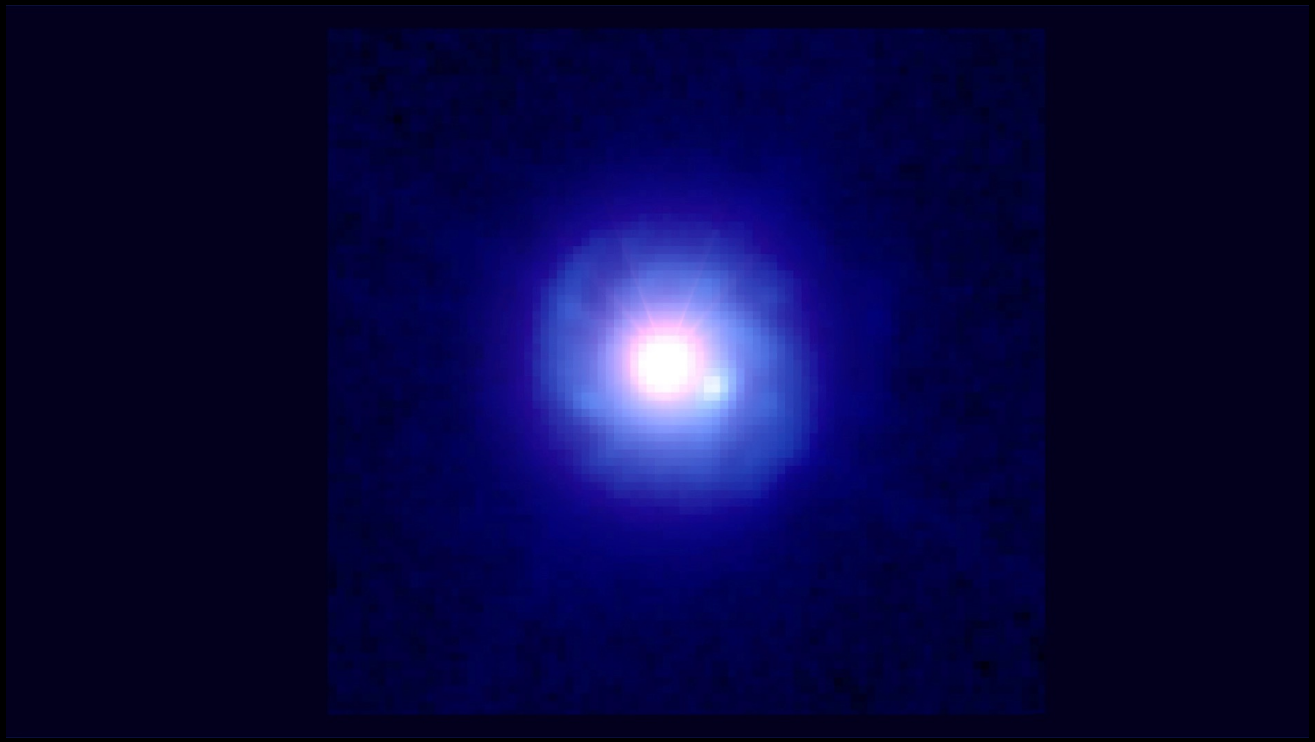
The role of strongly lensed blazars in the time domain



Time delays can be used to estimate H_0
(Refsdal 1964)

To shed light on the Hubble tension we need at least 40 time delays at percent/sub-percent level: we need more systems!
(Birrer & Treu 2021, Gilman et al. 2021, Birrer et al. 2024)

Time delays can be exploited as a signature to find strong lensing systems
(Geiger & Schneider 1996, Bag et al. 2021, Shu et al. 2021)

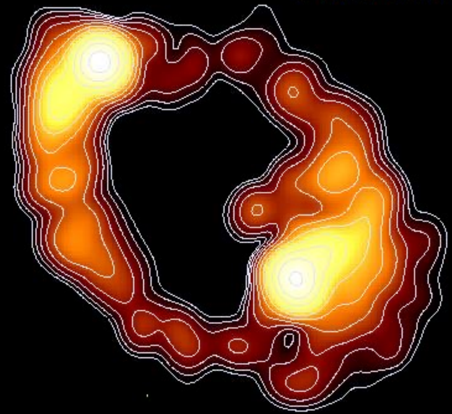


Gamma-rays = spatially unresolved light curves / autocorrelation function
Radio = spatially resolved light curves / cross-corr + several other methods

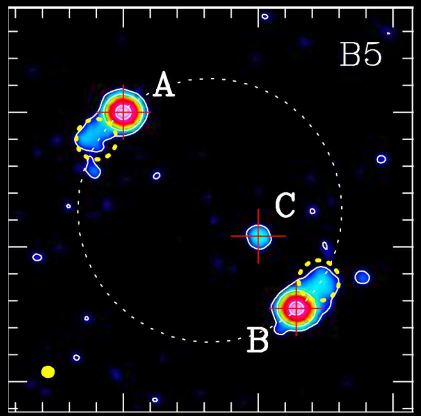
PKS 1830-211: strongly lensed blazar

An outstanding flare detected from radio to γ-rays

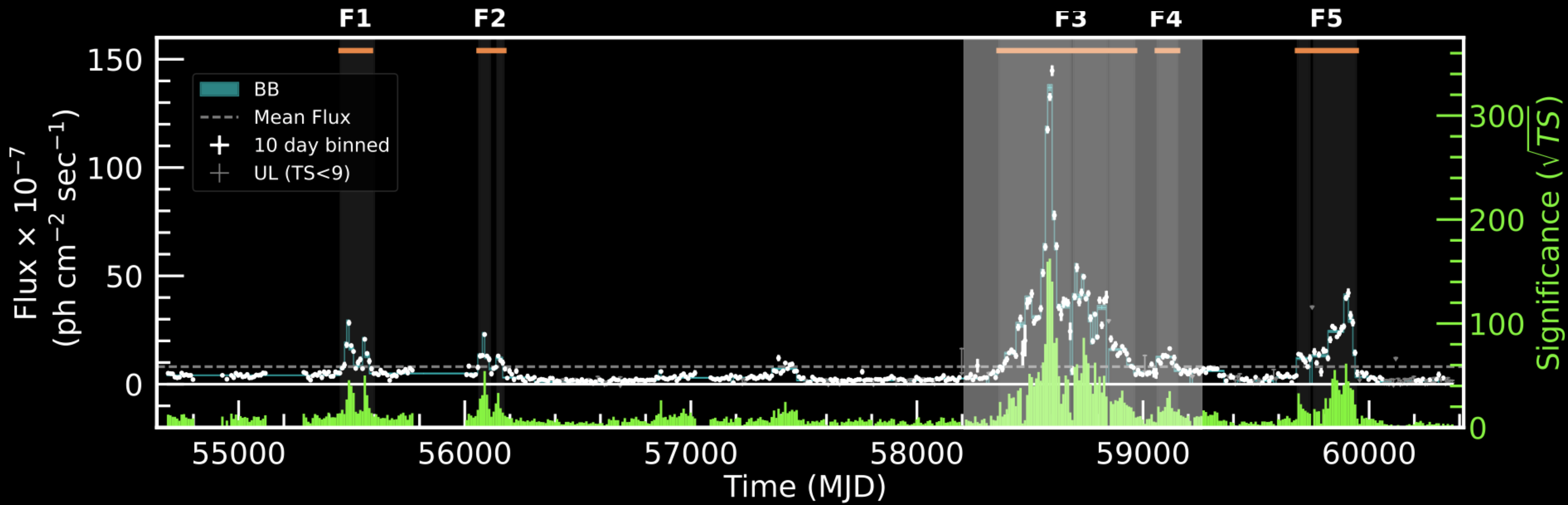
(Buson+2019, Angioni+2019, Cardillo+2019, Carrasco+2019, Ciprini+2019)



MERLIN 5 GHz
Jaunce et al. 1991



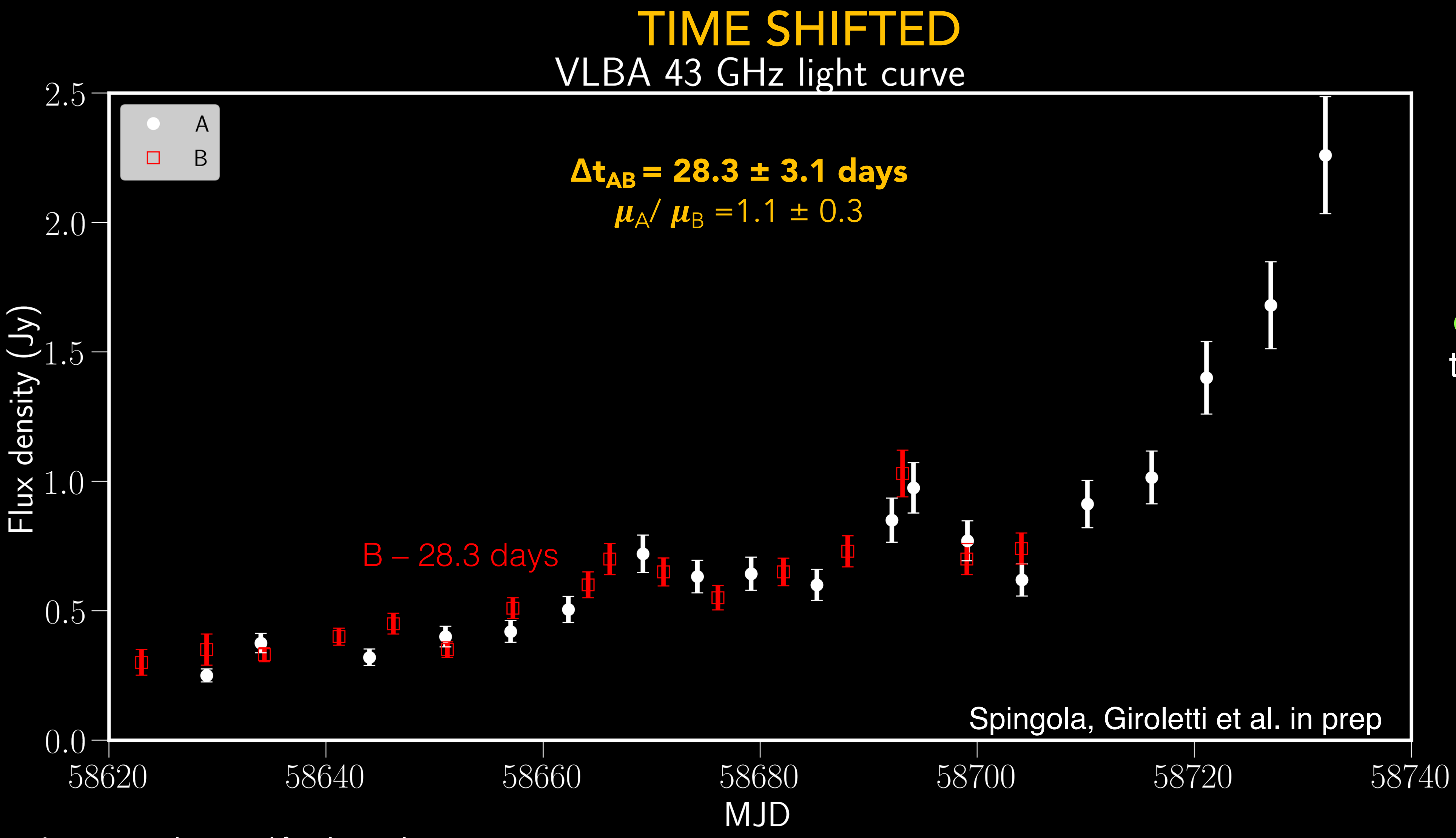
ALMA 180 GHz
Muller et al 2020



Agarwal et al. 2025

A new opportunity to measure its **time delay** at **radio and gamma-rays**

PKS 1830-211 (VLBI)



Using χ^2, cross-correlation and free-knot spline (PyCS3, Millon et al. 2020, 2022) methods / First time delay measured with VLBI

Mm-λ enabled the very first measurement of gravitational time delays with VLBI

optically thin part of the jet: ideal to detect variability!

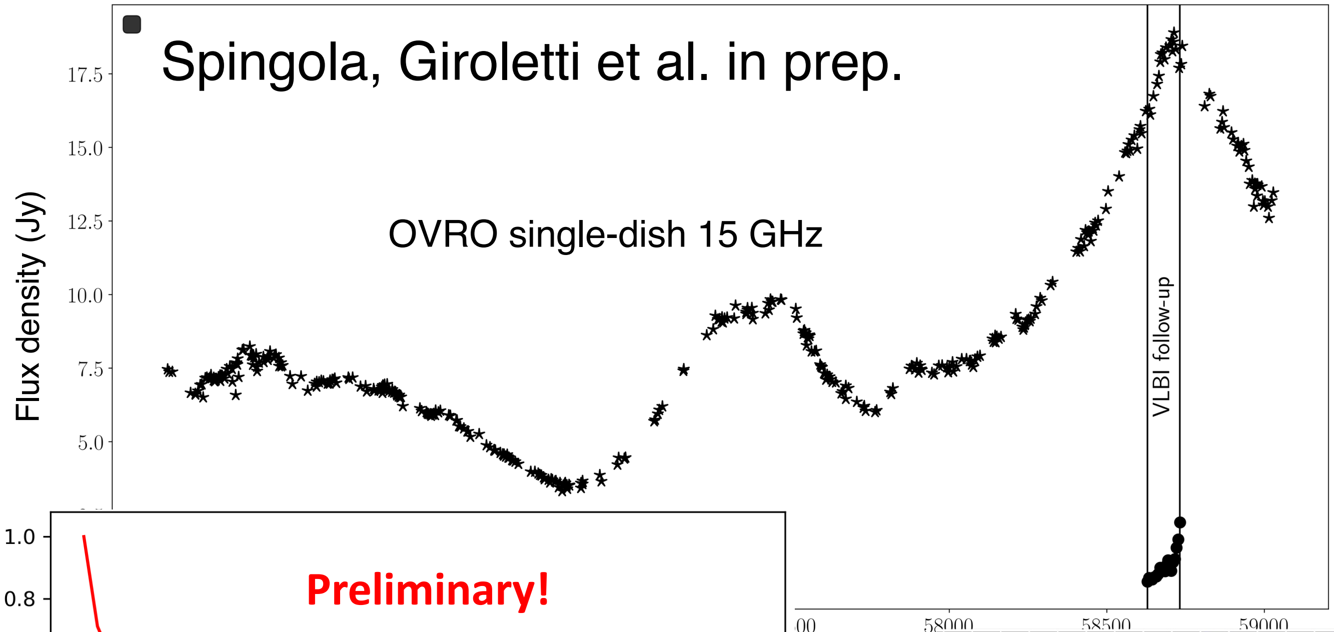
MeerKAT/SKA Band 5 will be important for these studies

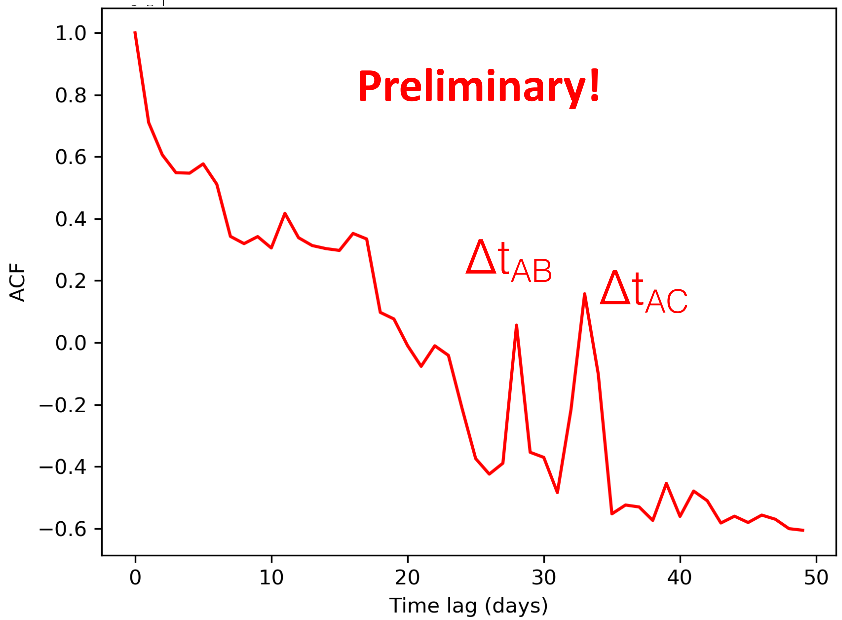
See talks by Umana, Labate, Venturi on Monday

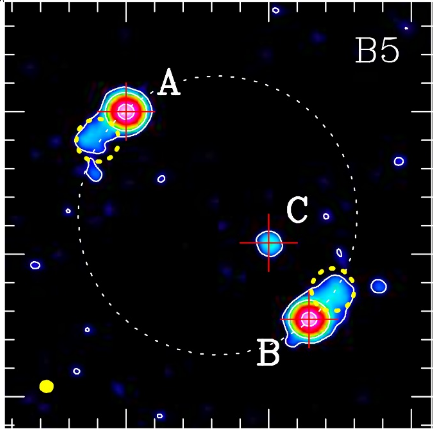
Searching for strong lenses in the time domain

(Geiger & Schneider 1996 first developed the method for radio single-dish observations)

MeerKAT Band 5 freq. range







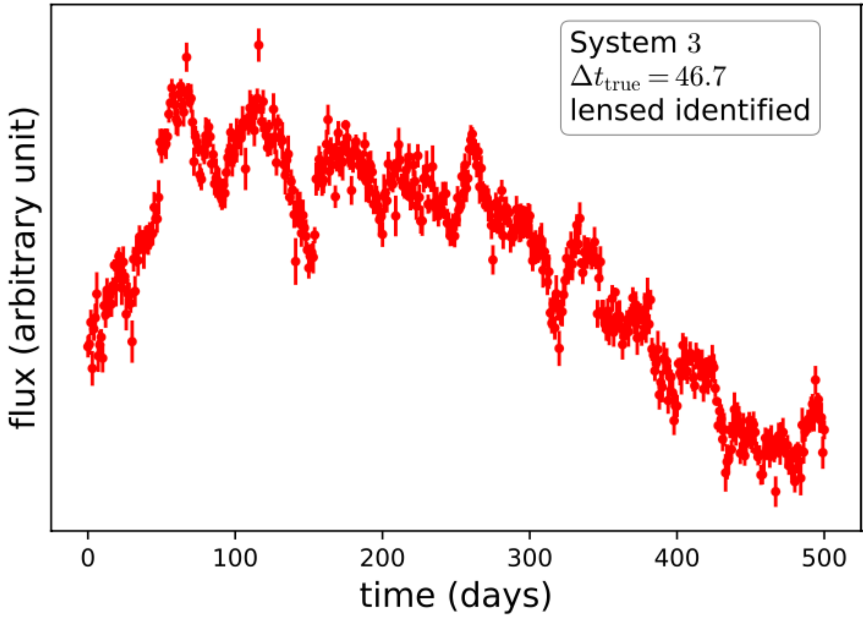
Muller et al. 2020

Searching for strong lenses in the time domain

(Geiger & Schneider 1996 first developed the method for radio single-dish observations)

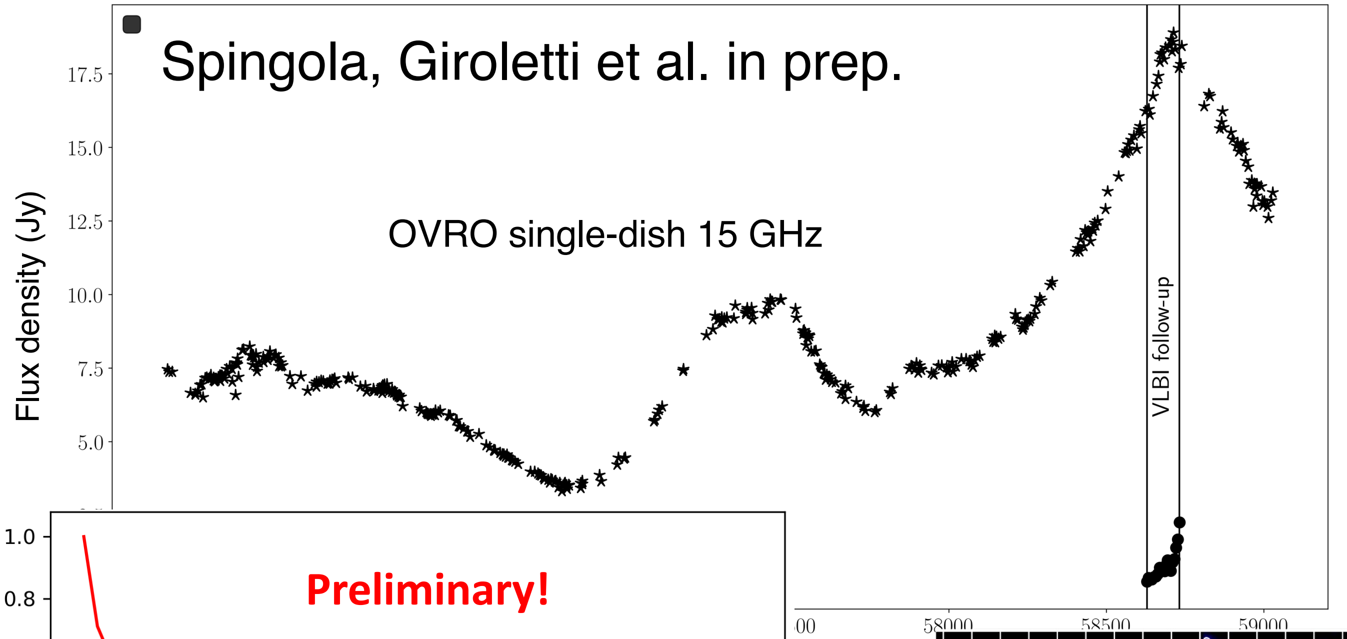
Bag et al. 2021

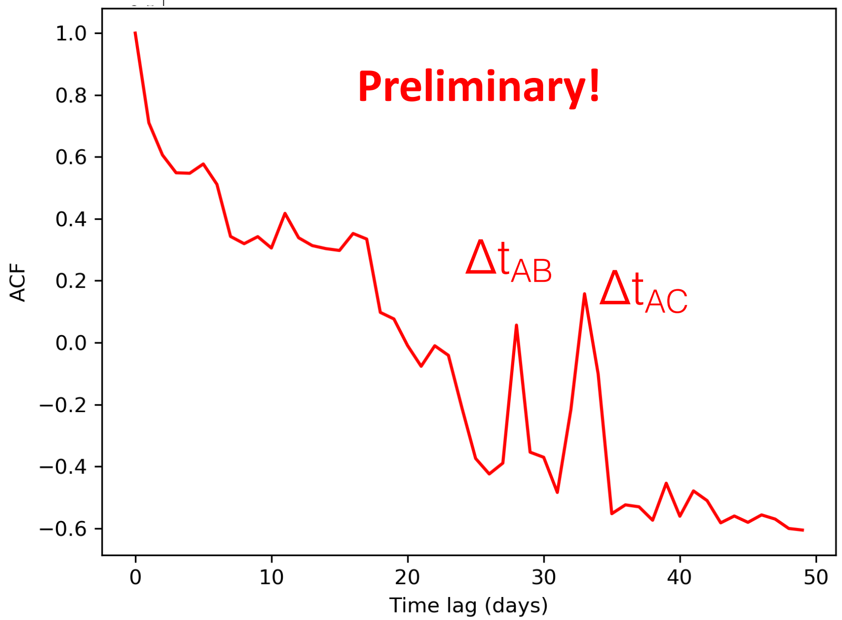
(but see also Liao, Treu et al. 2015, Shu et al. 2021)

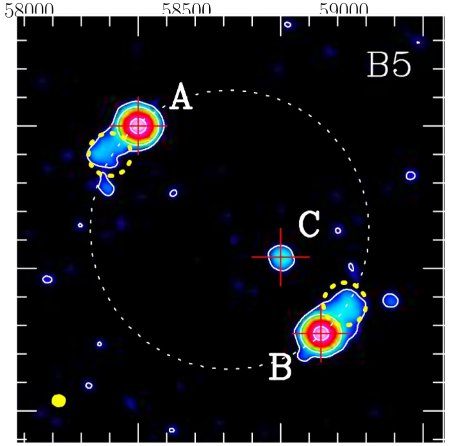


To search lenses in the Zwicky Transient Facility Vera Rubin Observatory data

MeerKAT Band 5 freq. range







Muller et al. 2020

Searching for strong lenses in the time domain

Shedding light on dark matter and the Hubble tension simultaneously (DARKER project)

Ministero dell'Università e della Ricerca

FONDO ITALIANO PER LA SCIENZA

The Fermi-LAT data → 10^5 M_{SUN} smallest lens mass possible by the data

The DARKER project = we will find the critical low-mass lenses that are missed in current «standard» image-domain methods (**follow-up with VLBI** to confirm gamma-ray lens candidates)

→ A **new independent class of low-mass lenses** (testing the systematics of the Hubble tension) **– This can be done now!**

In the future SKA1Mid surveys are expected to find ~10^5 strong lenses

(Koopmans et al. 2004, McKean et al. 2015)

Searching for strong lenses in the time domain

Shedding light on dark matter and the Hubble tension simultaneously (DARKER project)

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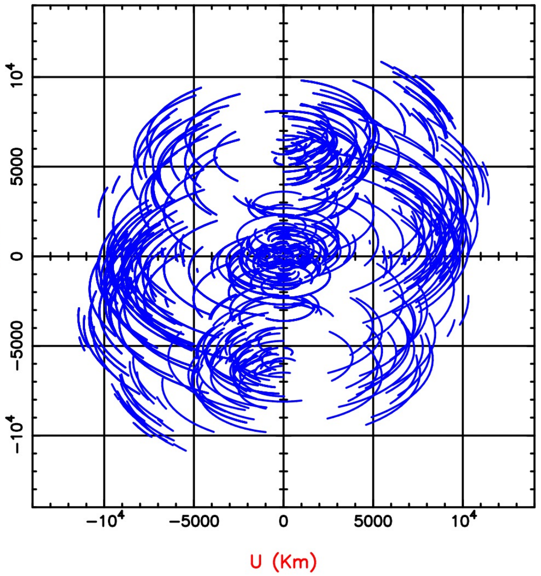
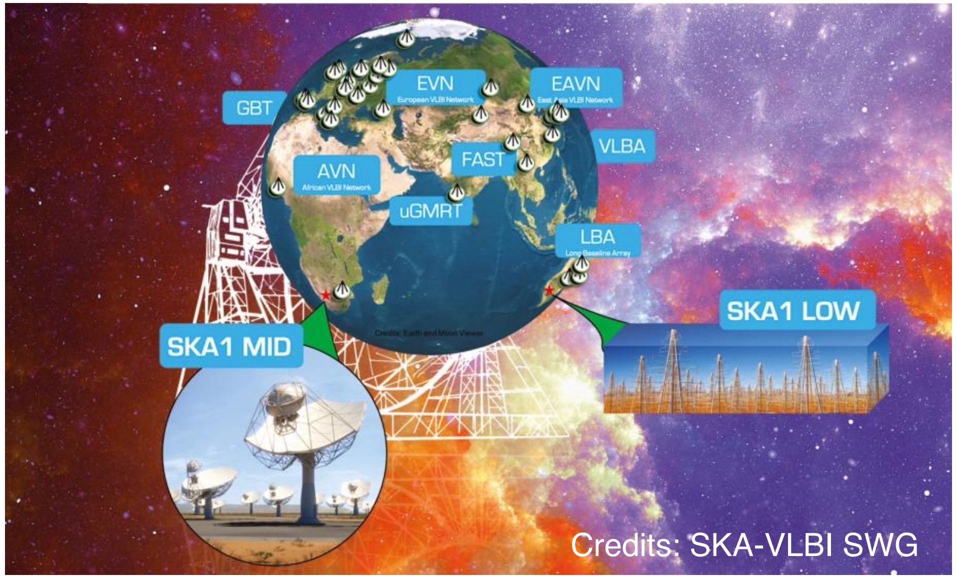
(Koopmans et al. 2004, McKean et al. 2015)

We will need VLBI to reach the mas/sub-mas angular resolution

SKA+EVN+LBA+CVN+AVN, 12h

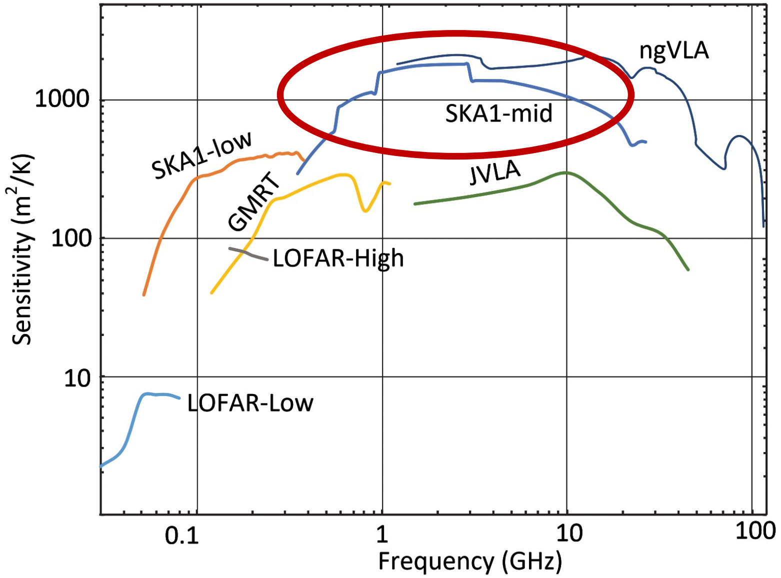


Paragi et al. 2015



Credits: SKA-VLBI SWG

Angular resolution between **0.03 and 4 arcsec without VLBI**
-- phased-up SKA will be a «superstation» in VLBI experiments!



Swart et al. 2022, Revaiew

Summary

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

Even a single lensing system showing **gravitational arcs** can put **competitive constraints** on the dark matter particle mass

We can directly detect low-mass objects with VLBI observations and **quantify their physical properties**

We lack of a statistically significant sample:

At gamma-rays we can search **now** for (low-mass) lensing systems that will show VLBI emission: novel **time domain search** of a new class of lenses to test Hubble tension (systematics or new physics?)

SKA1-MID surveys will be revolutionary
(~10^5 strong lenses, among them ~1000 lensed blazars)
and it is now the moment to develop methods for searching for lenses

Only **SKA-VLBI** will be able to image the **crucial angular scales** to directly test the ΛCDM model at all scales

High-frequency capability is important (**Band 5** and above)

Synergy with multi-wavelengths and time domain facilities
SKA + LSST, for instance, both key projects for INAF

See also **Cecilia Stella's poster** on pre-SKA-VLBI source science!

5 post-doc positions available at the beginning of 2026 at INAF-IRA (Bologna)

Contact me if interested
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Thank you!

Ministero dell'Università e della Ricerca

FONDO ITALIANO PER LA SCIENZA

INAF ISTITUTO NAZIONALE DI ASTROFISICA

United Nations

International Day for the Elimination of Violence against Women
25 November

Background photo credit: John McKean, 1st SARAO-VLBI School, March 2025, Pretoria (South Africa)