DARKER
a science case to shed light on dark matter and dark energy with the tri-band receivers

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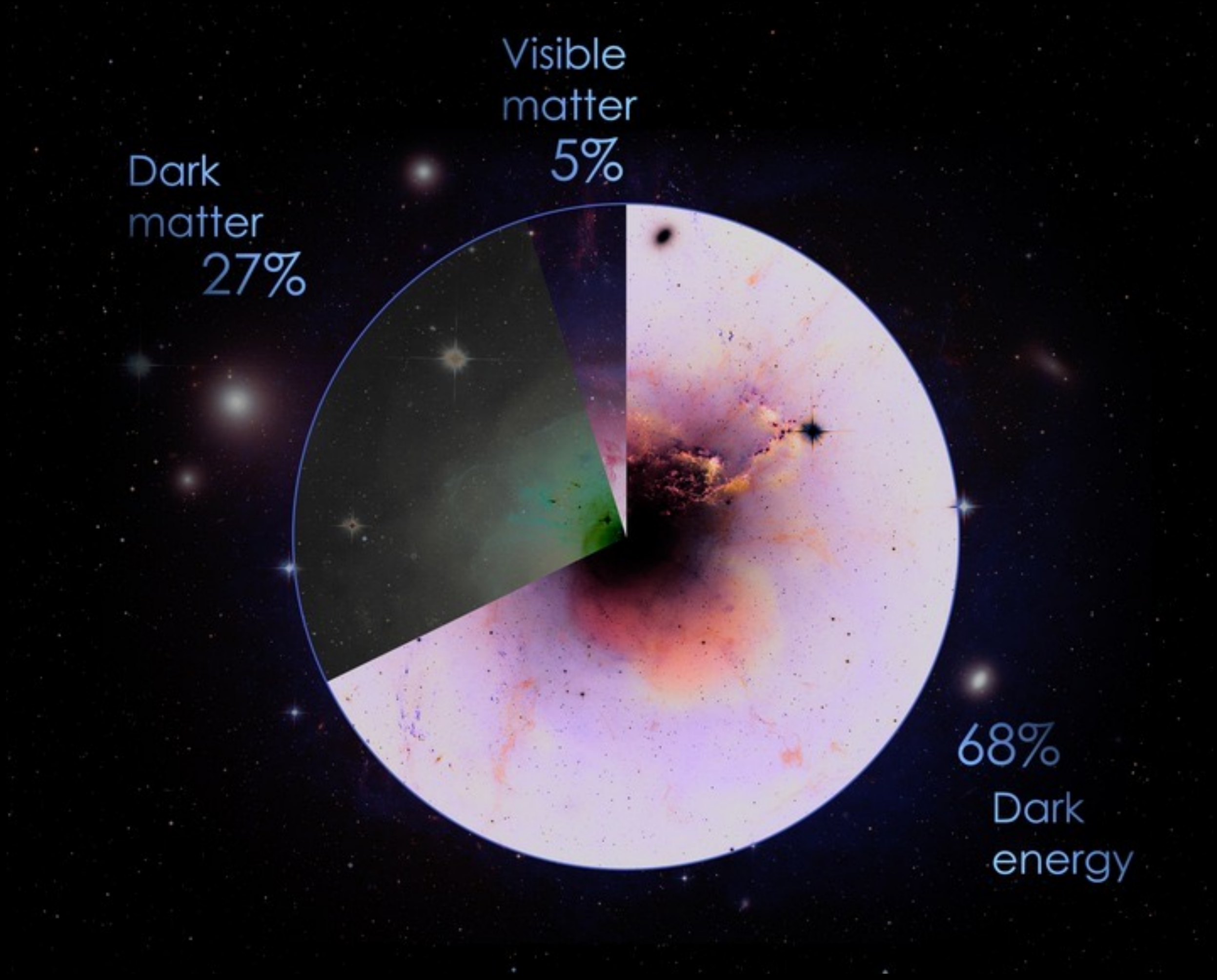
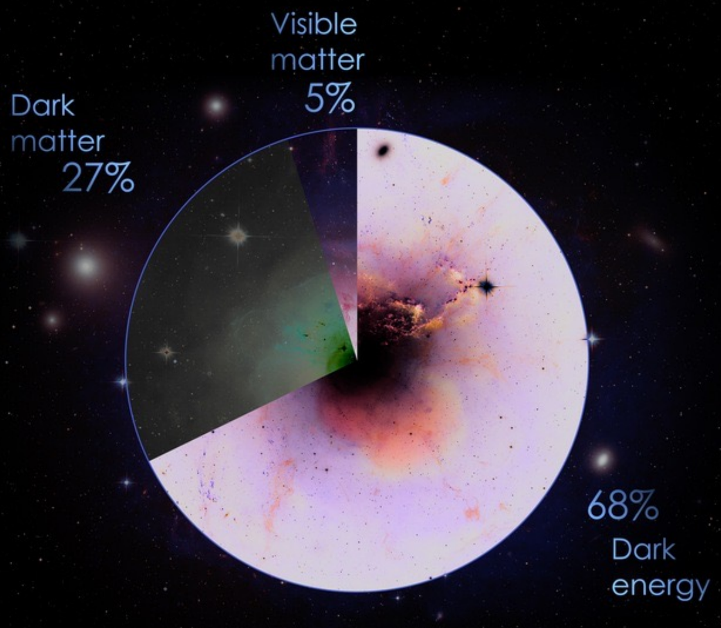
Ministero dell'Università e della Ricerca
FONDO ITALIANO PER LA SCIENZA
INAF ISTITUTO NAZIONALE DI ASTROFISICA
DARKER

Towards high-performance mm-VLBI science operations with multi-band receivers / 28 October 2025, Bologna (Italy)

The ΛCDM model and the dark Universe

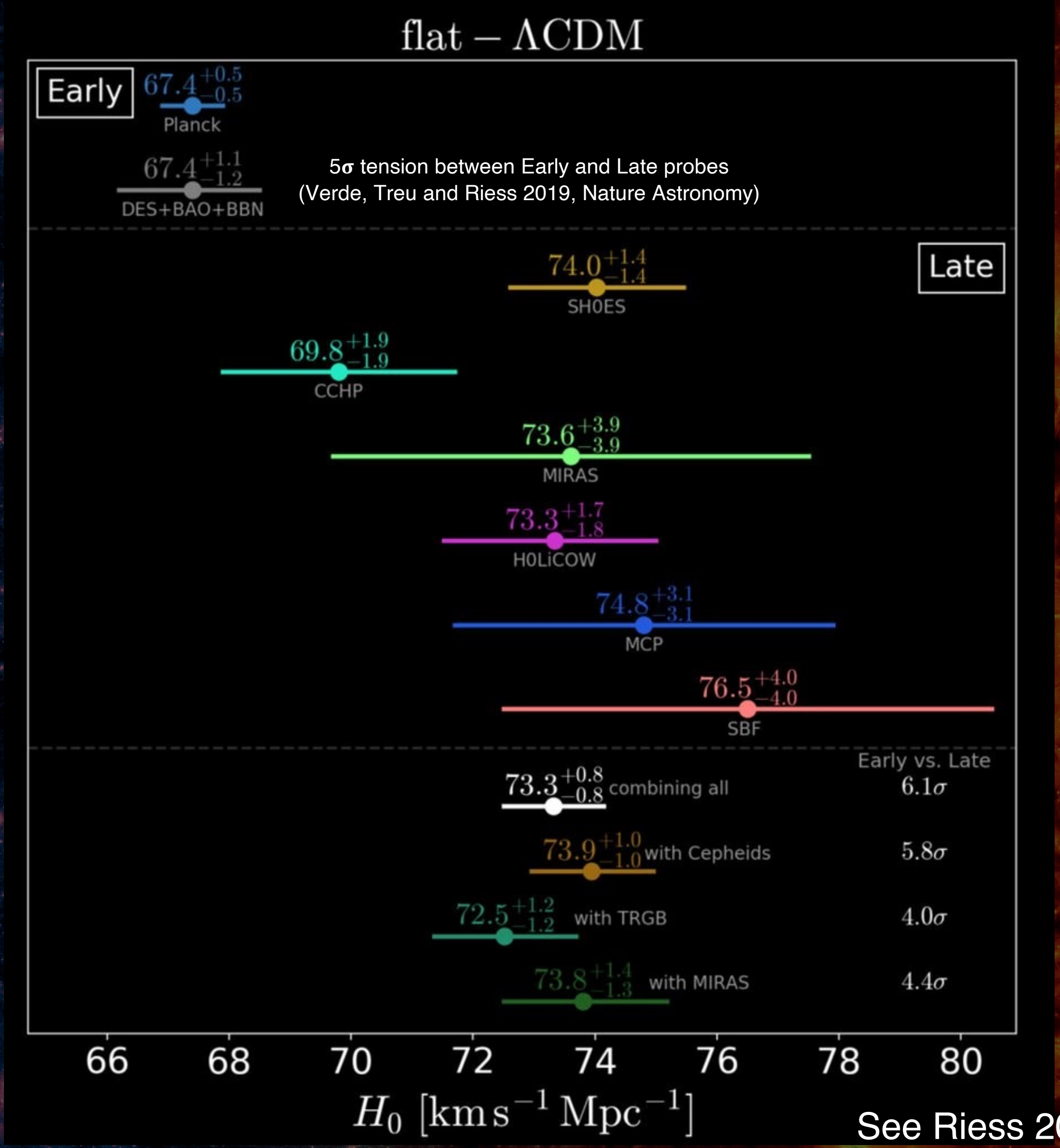


Challenges to the ΛCDM paradigm



The Hubble Tension

Is there the evidence for an Early Dark Energy?

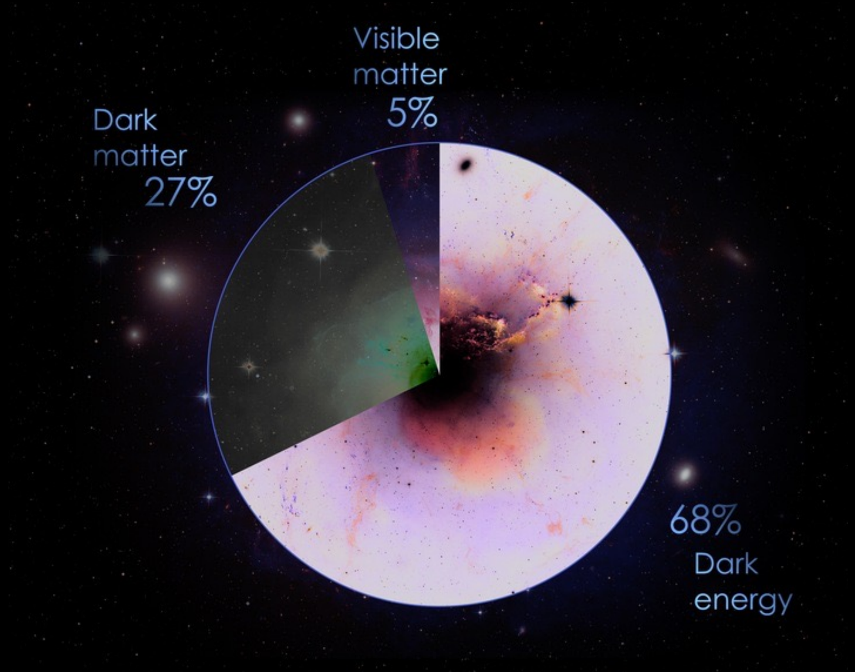


5σ tension between Early and Late probes
(Verde, Treu and Riess 2019, Nature Astronomy)

See Riess 2020
Nature Reviews Physics

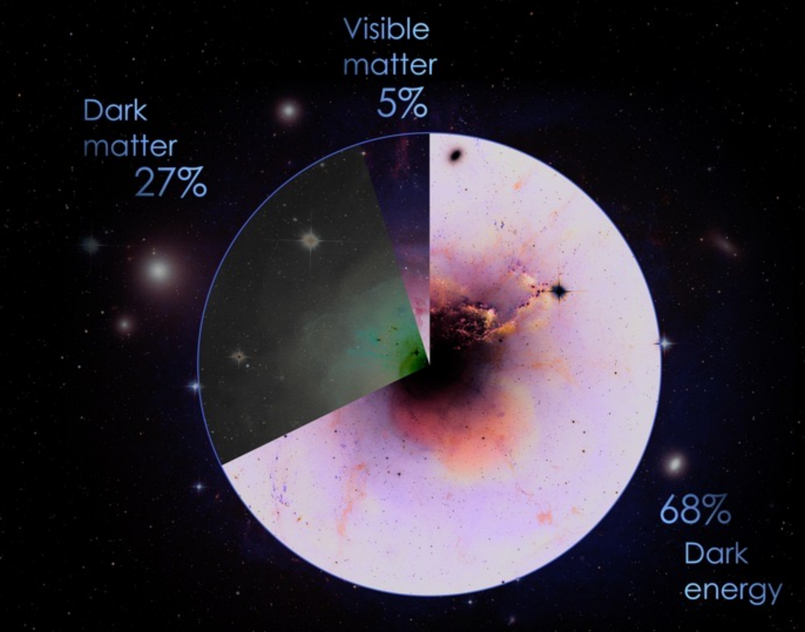
Challenges to the ΛCDM paradigm

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



Challenges to the ΛCDM paradigm

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



- **Missing satellite problem** (Moore et al 1999, Klypin et al. 1999)
- **Cusp-core problem** (Moore et al. 1994, Flores et al. 1994)
- Too-big-to-fail problem (Boylan-Kolchin et al. 2011, 2012; Parry et al. 2012)
- The diversity of rotation curves (Oman et al. 2015 – related to cusp-core problem)
- Plane of satellites problem (Pawlowski et al. 2014)
- Dark matter-free galaxies (e.g., Mancera Pina et al. 2022)
- The «impossibly early galaxies» problem (Steinhardt et al. 2016, Behroozi & Silk 2018, Boylan-Kolchin 2023)

Challenges to the ΛCDM paradigm

Missing satellite problem

A solution is provided by changing the ***mass of the dark matter particle*** *(to lighter particles)*

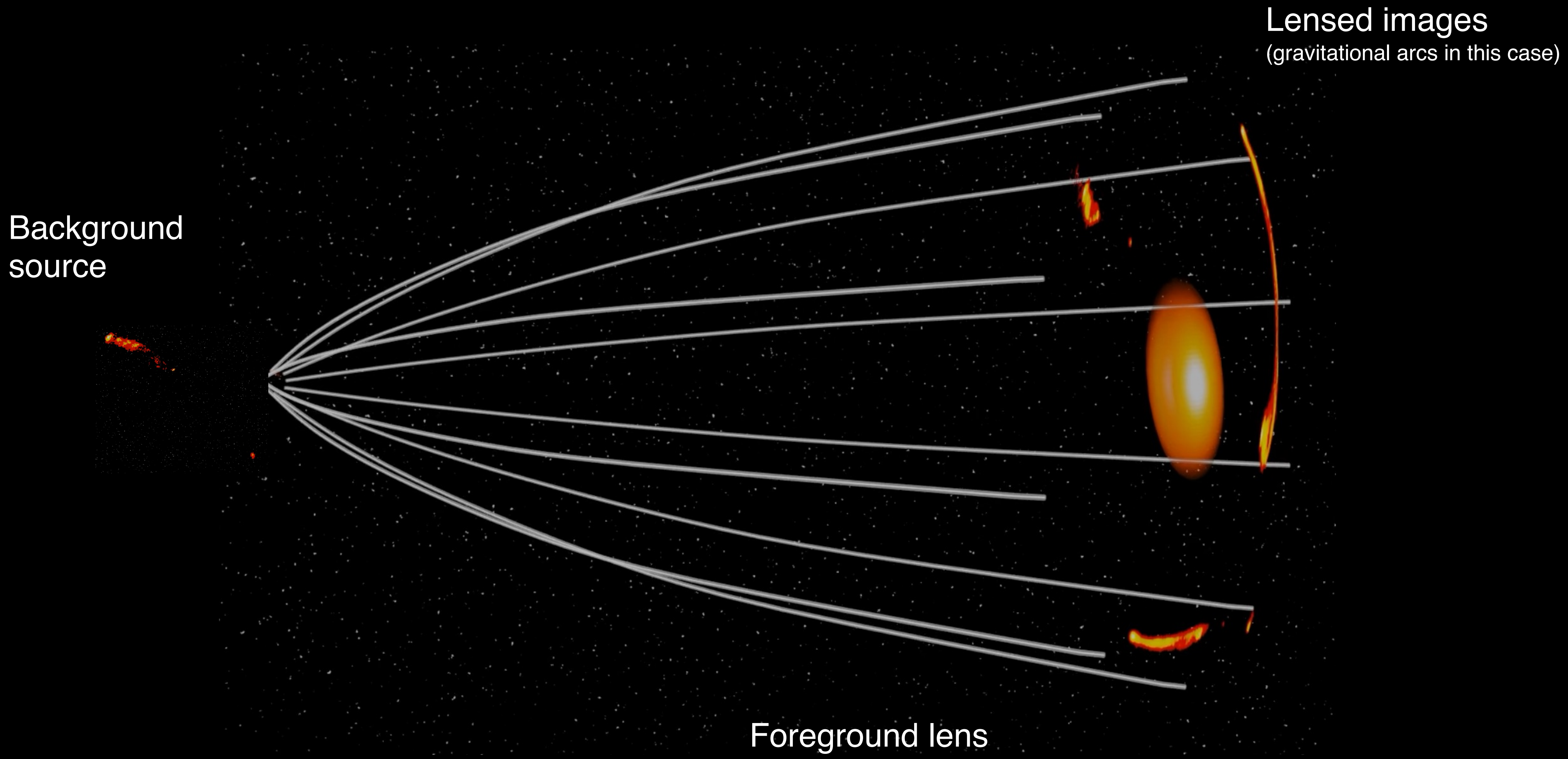
The less concentrated WDM sub-halos get destroyed during the merger process

Cold dark matter

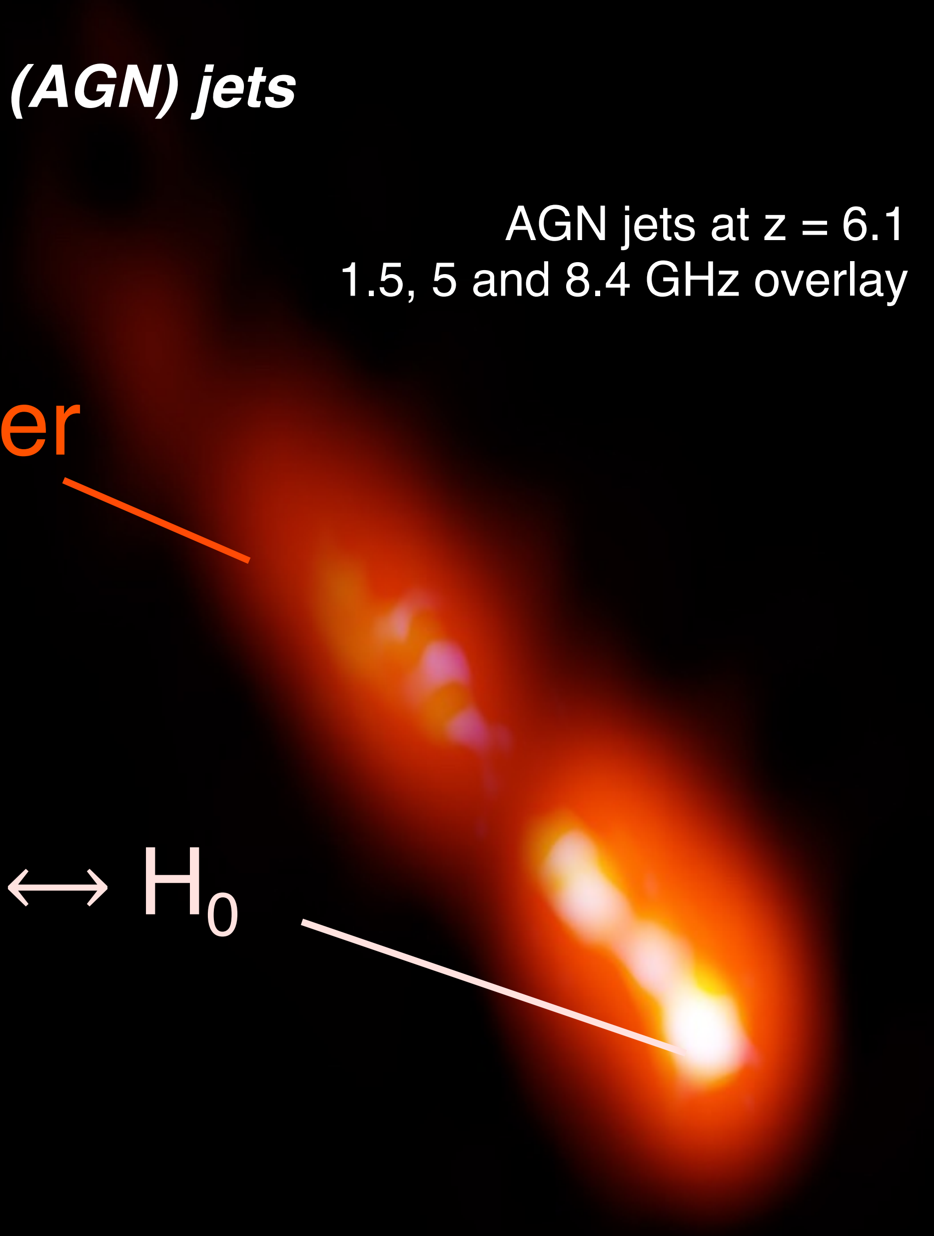
Warm dark matter

Lovell et al. 2012

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



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

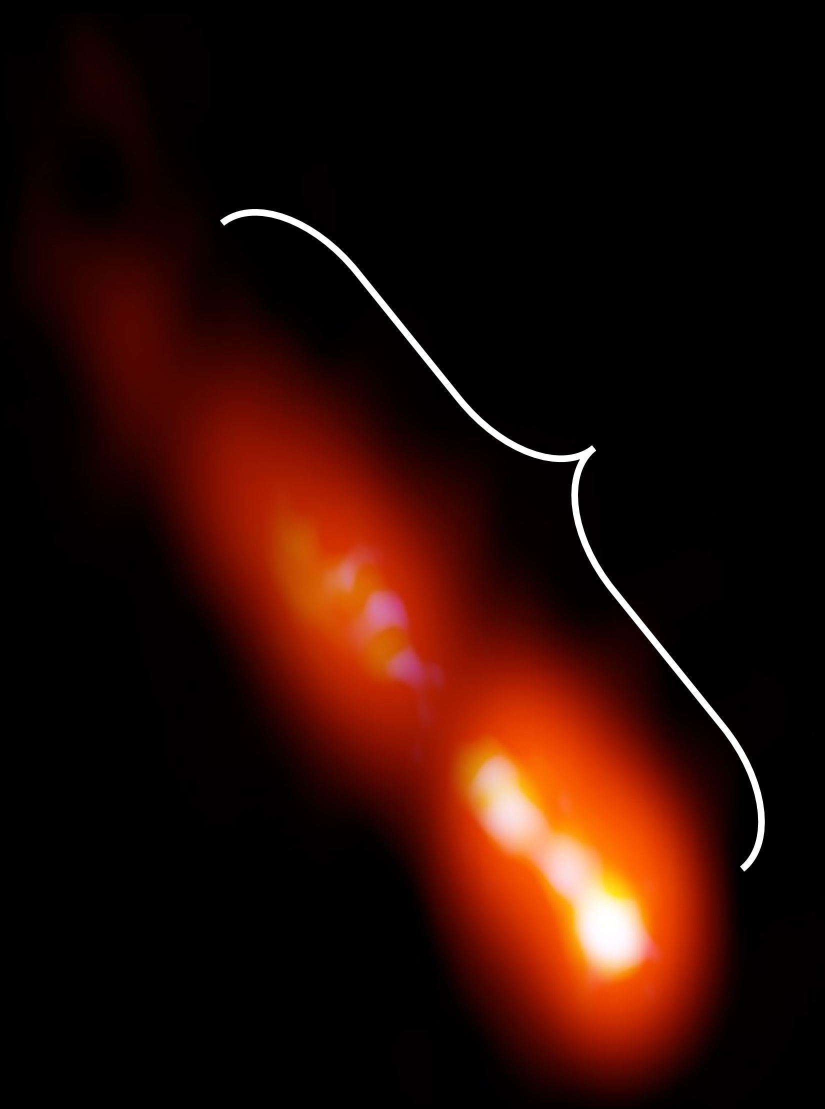


AGN jets at z = 6.1
1.5, 5 and 8.4 GHz overlay

Extended emission ↔ Dark matter

Cores (variable emission) ↔ H_0

(Spingola et al. 2020)

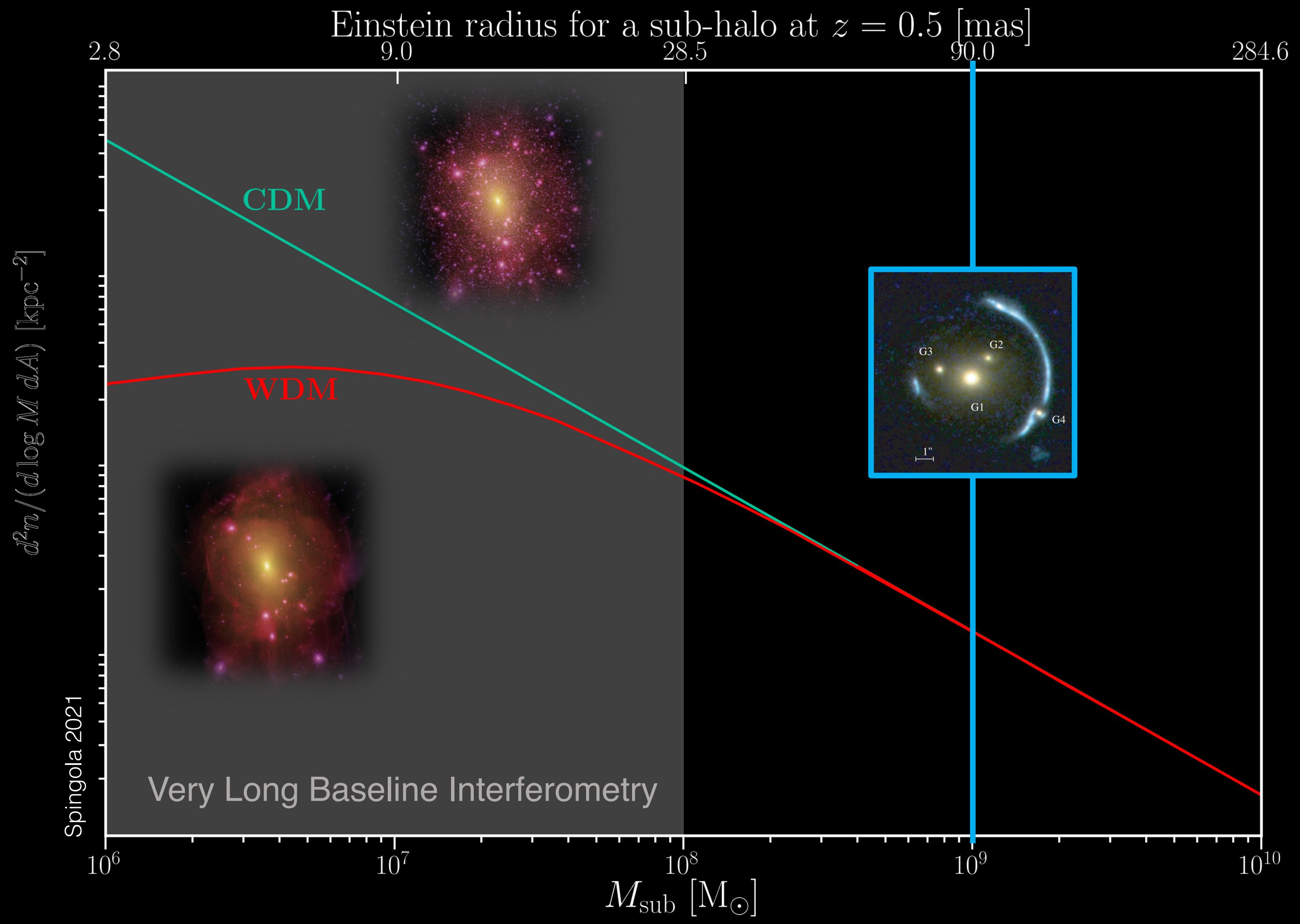


DARK MATTER

Extended emission
in lensed AGN jets

The role of strong gravitational lensing

Dark sub-halos



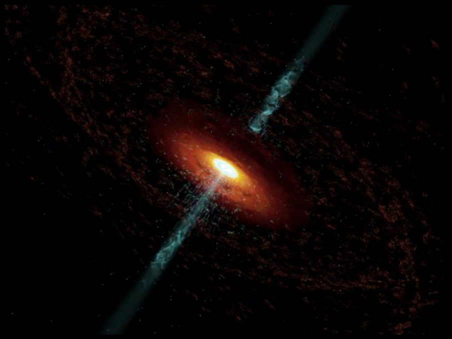
Spingola 2021

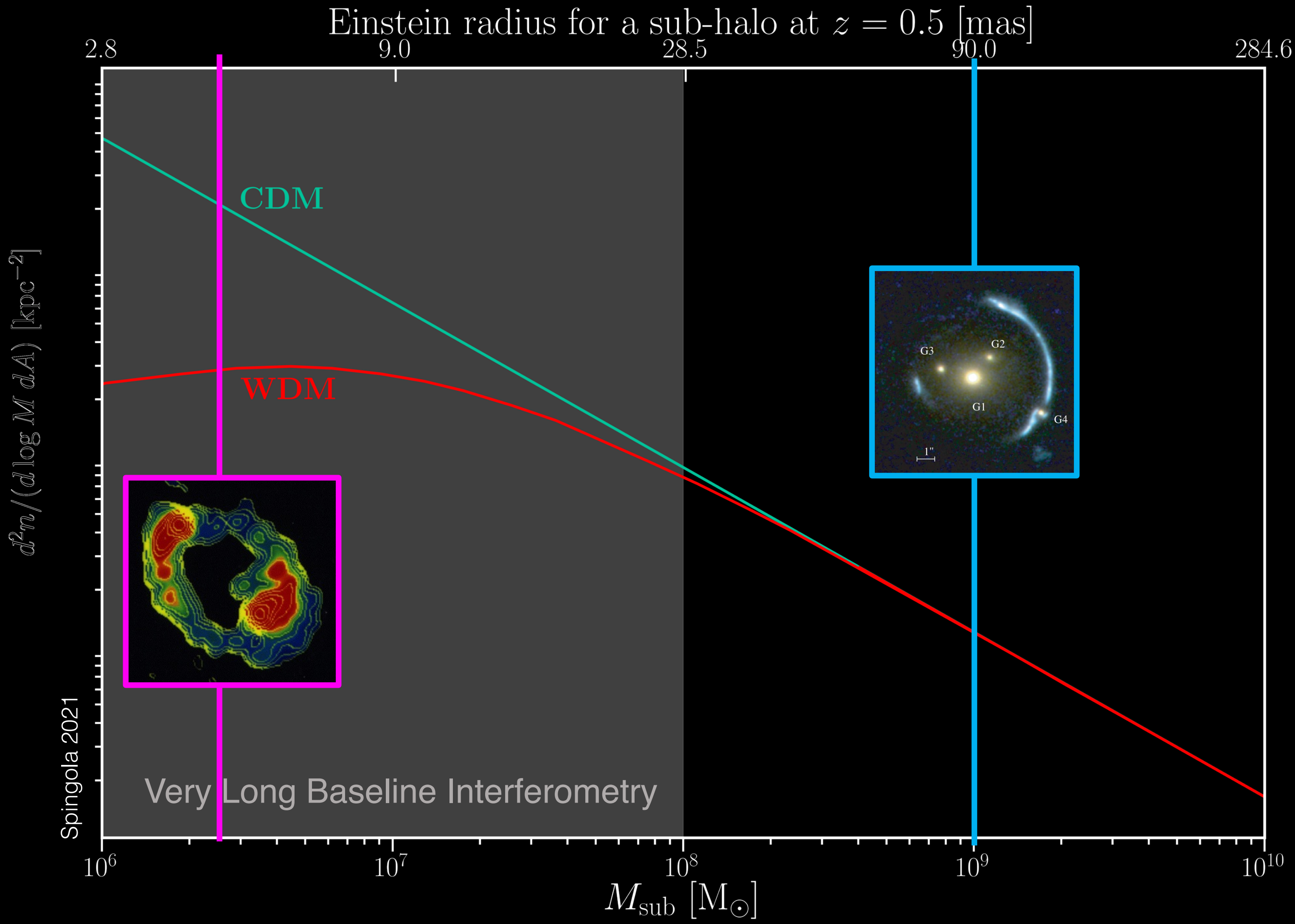
See also Metcalf & Madau 2001, Dalal & Kochanek 2002 , Dye et al. 2005, Koopmans 2005, Chen 2007, Vegetti & Koopmans 2009, Vegetti+ 2012, Hezaveh+2016, Gilman+2020, Despali +2022, Abe+ 2024

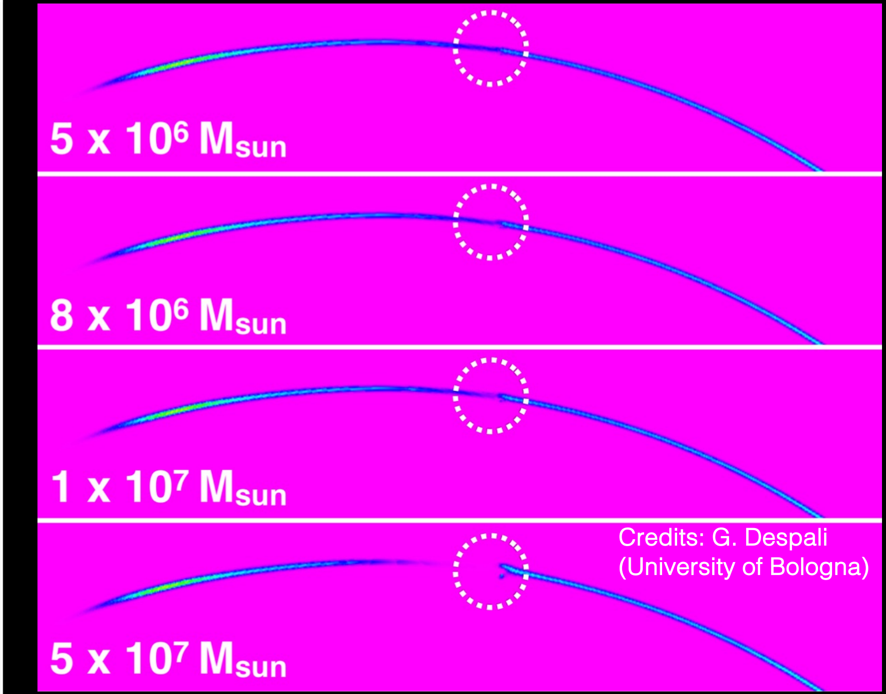
The role of strong gravitational lensing

Dark sub-halos

The background source consists of active galactic nuclei (AGN) jets







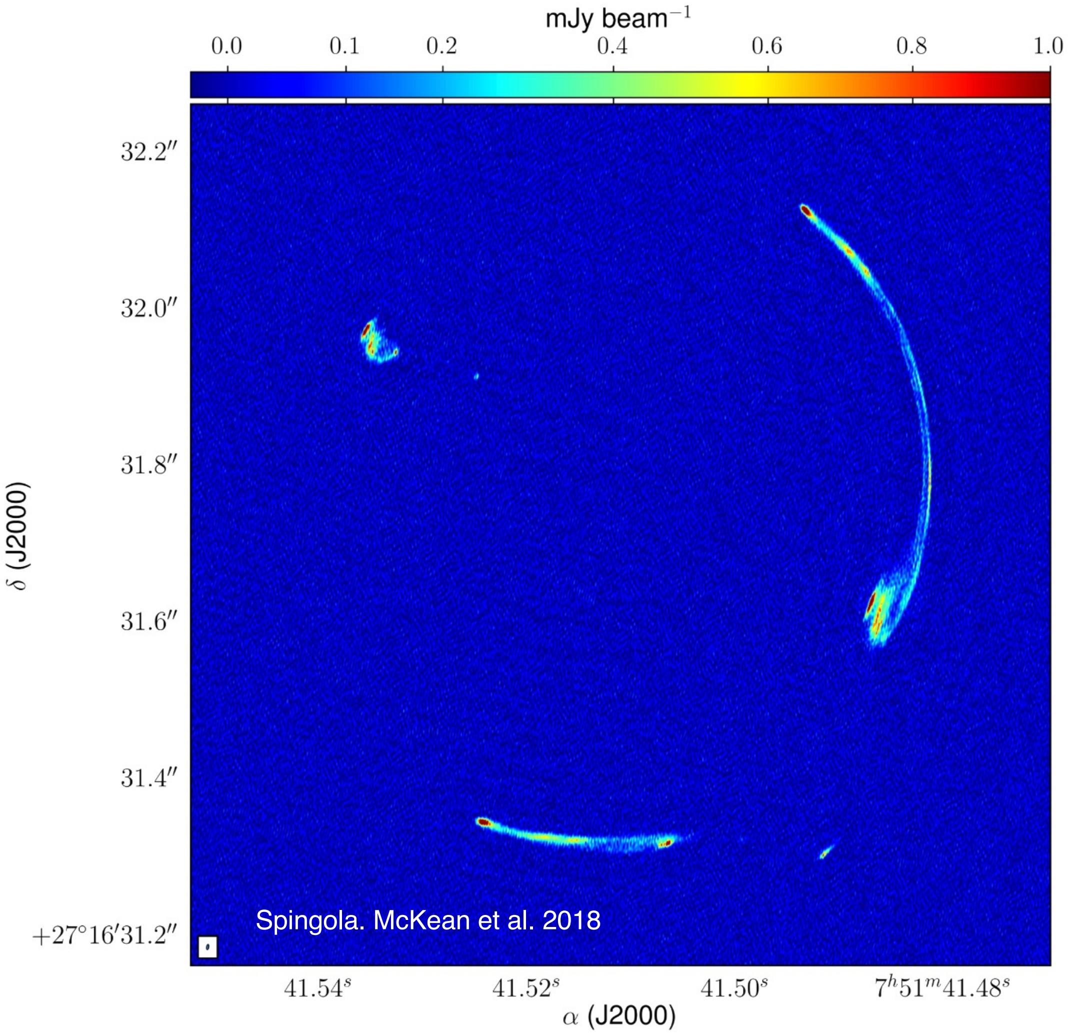
Credits: G. Despali (University of Bologna)

Sub-halos of10^{6-7} M$_{\rm sun}$
can be directly detected only with mas angular resolution

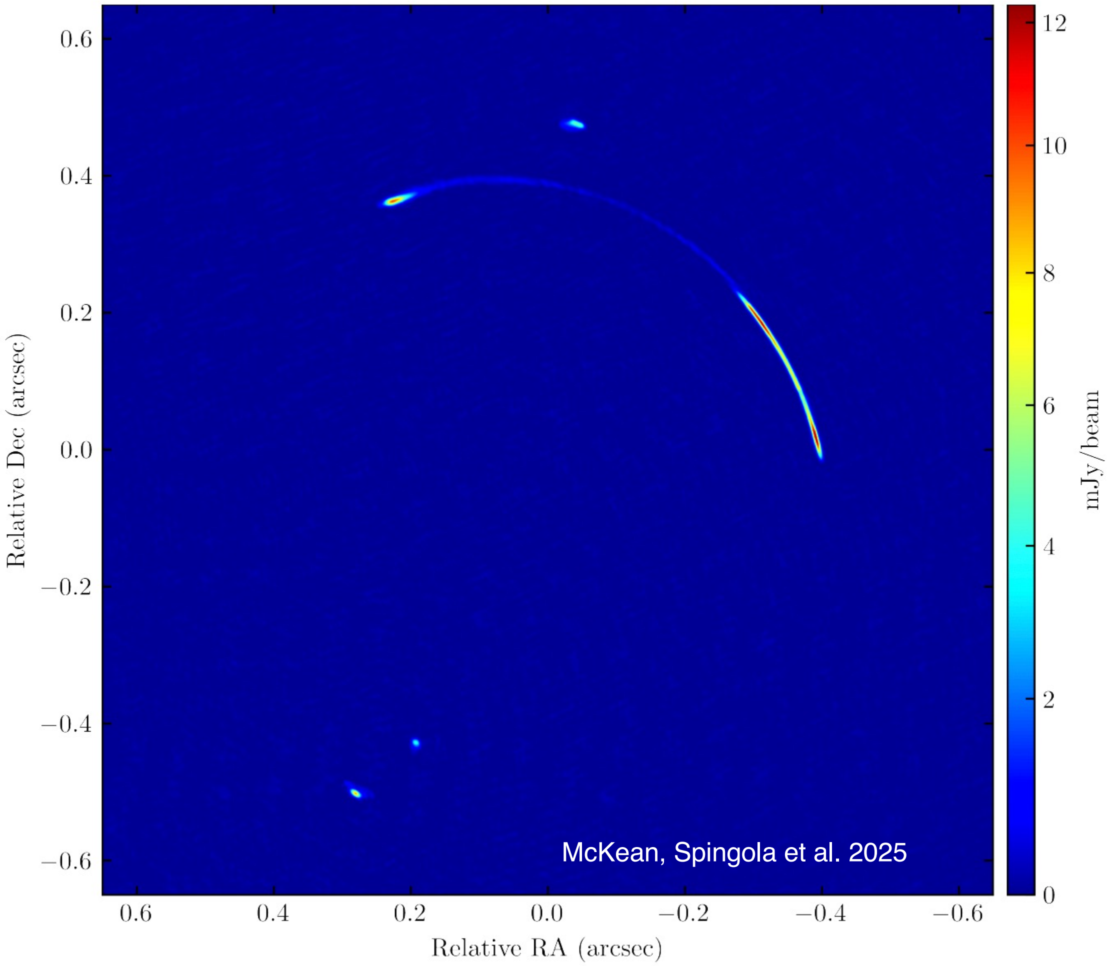
They should be completely dark

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

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



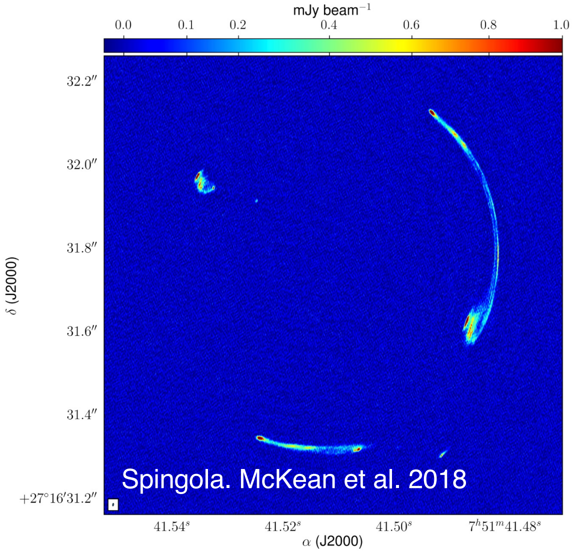
Spingola. McKean et al. 2018



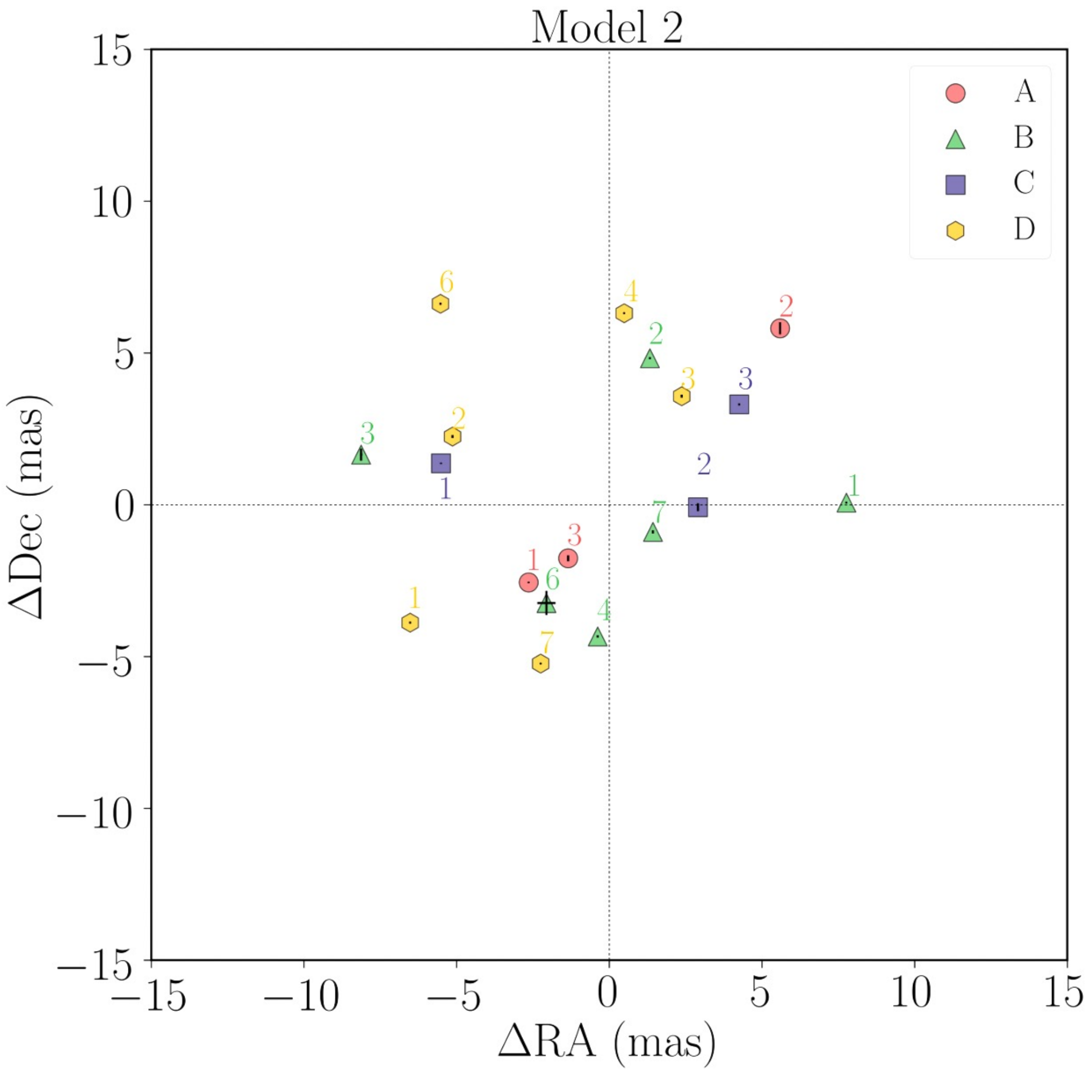
McKean, Spingola et al. 2025

But, to date, there are only these two!

Constraints on dark matter particle mass



Spingola. McKean et al. 2018



Spingola et al. 2018

Astrometric anomalies

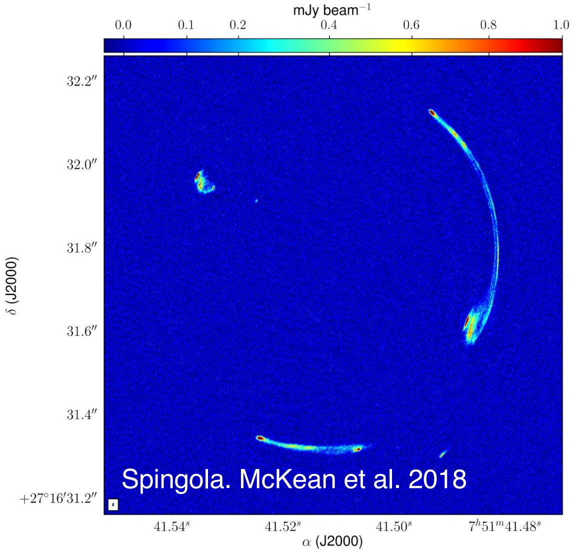
evidence for

GRANULARITY

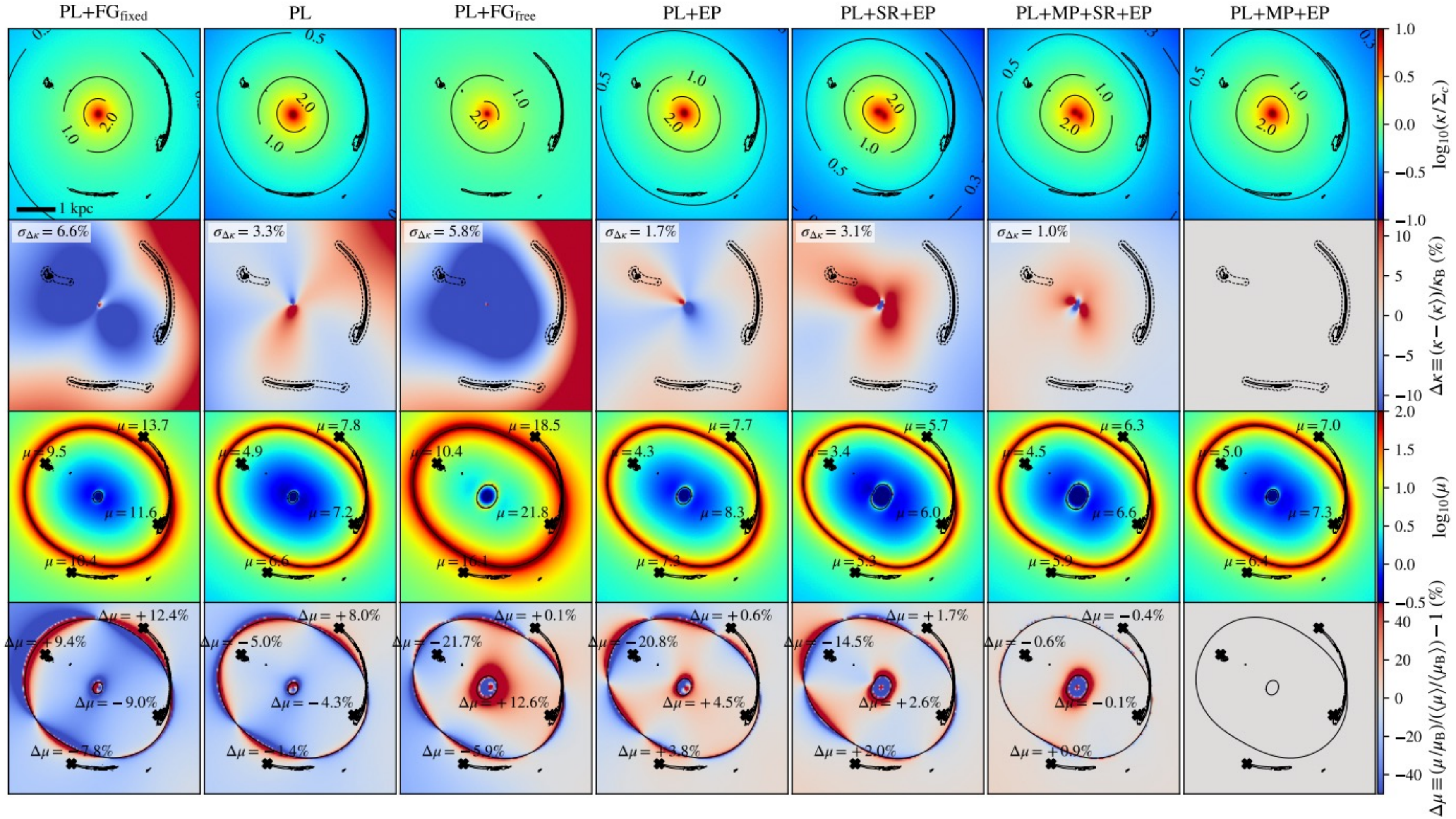
there is no localized offset, but that’s all over the system

Constraints on dark matter particle mass

Powell et al. 2022



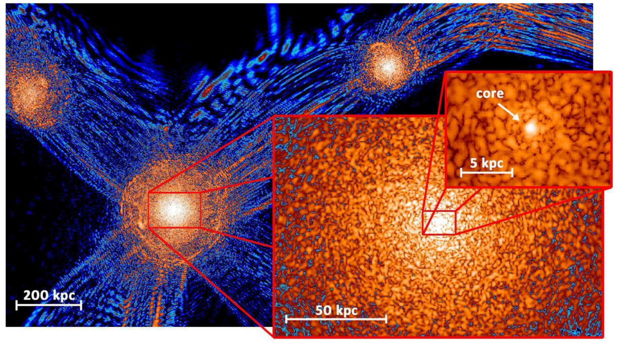
Spingola. McKean et al. 2018



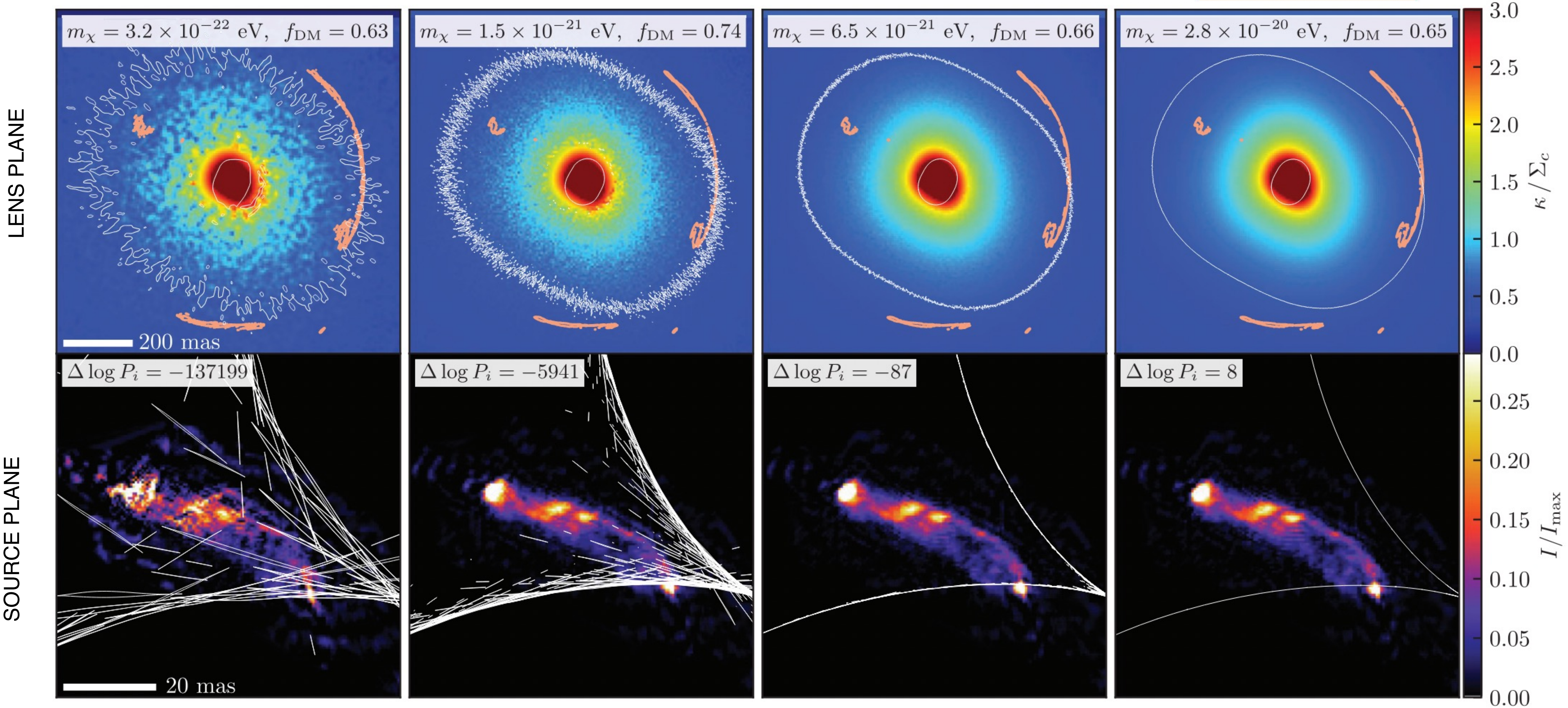
Angular structure is strongly favoured by the data

Constraints on dark matter particle mass

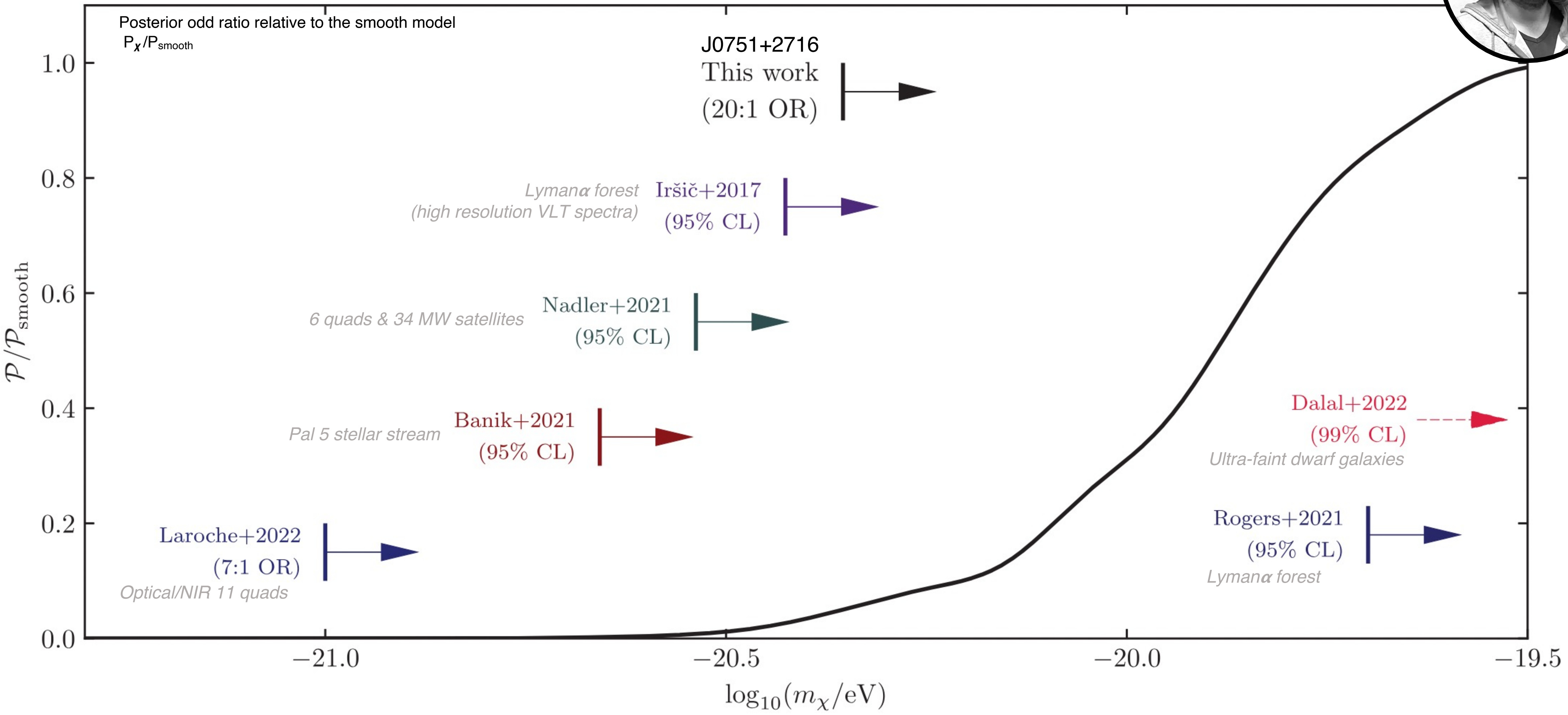
Fuzzy dark matter



Powell et al. 2023

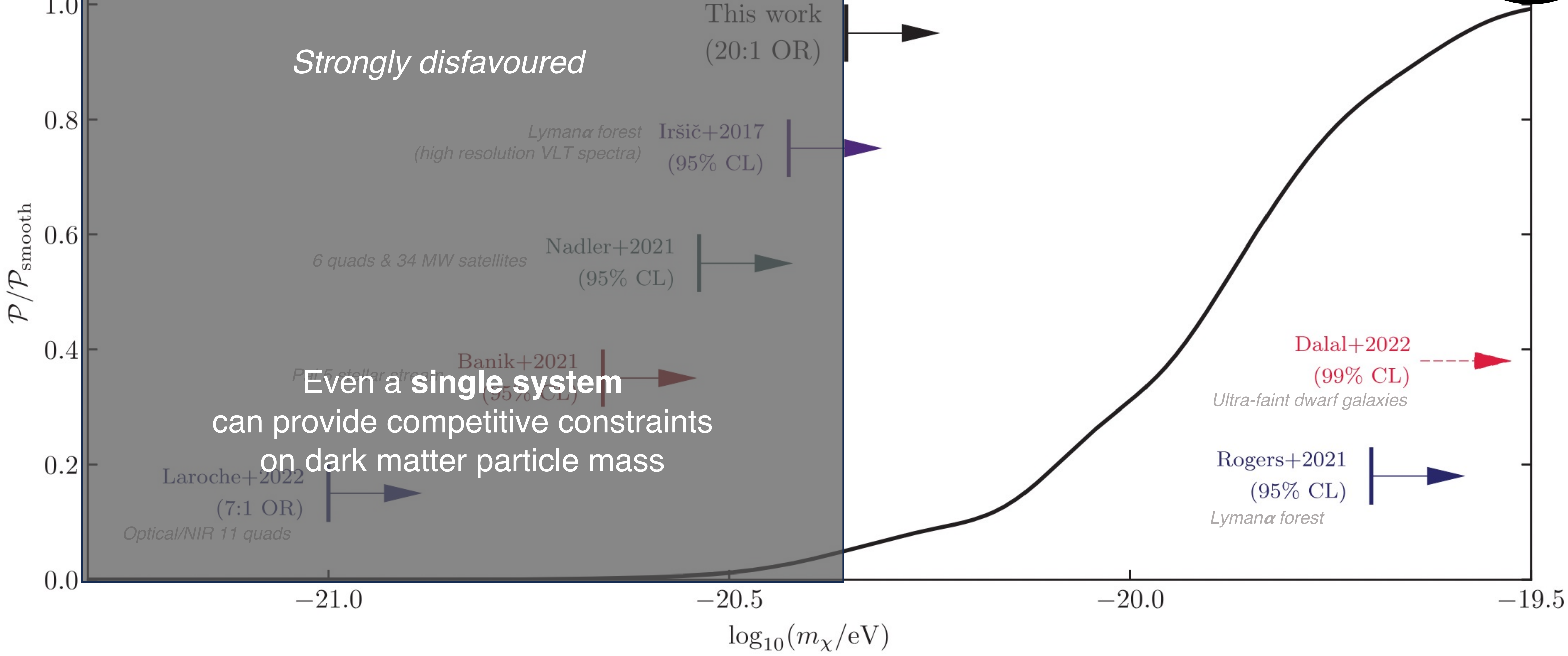


Constraints on dark matter particle mass



Powell et al. 2023
(incl.CS)

Constraints on dark matter particle mass



Posterior odd ratio relative to the smooth model
$P_\chi/P_{\rm smooth}$

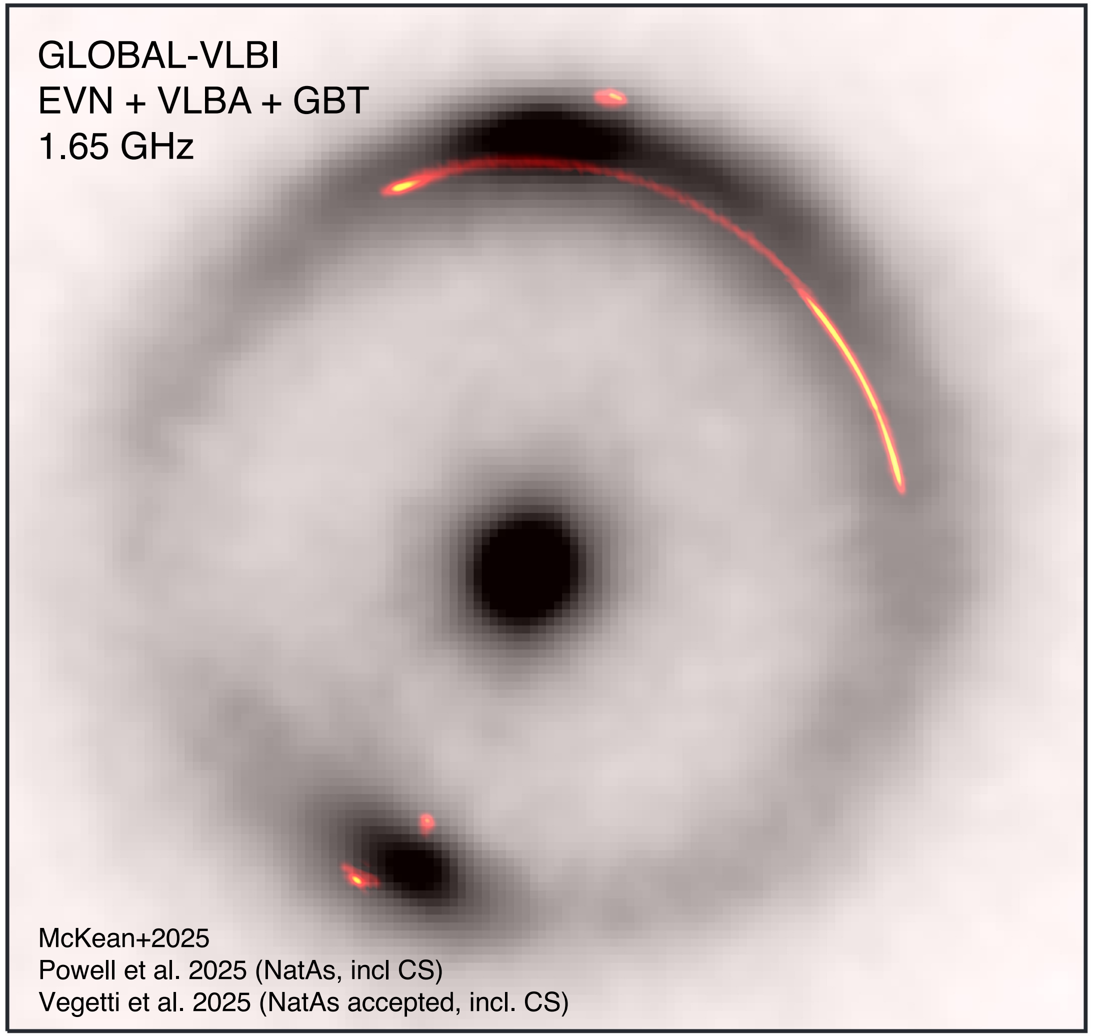
Strongly disfavoured

Even a **single system**
can provide competitive constraints
on dark matter particle mass

Powell et al. 2023
(incl.CS)

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

Credits: J. P. McKean



McKean+2025
Powell et al. 2025 (NatAs, incl CS)
Vegetti et al. 2025 (NatAs accepted, incl. CS)

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

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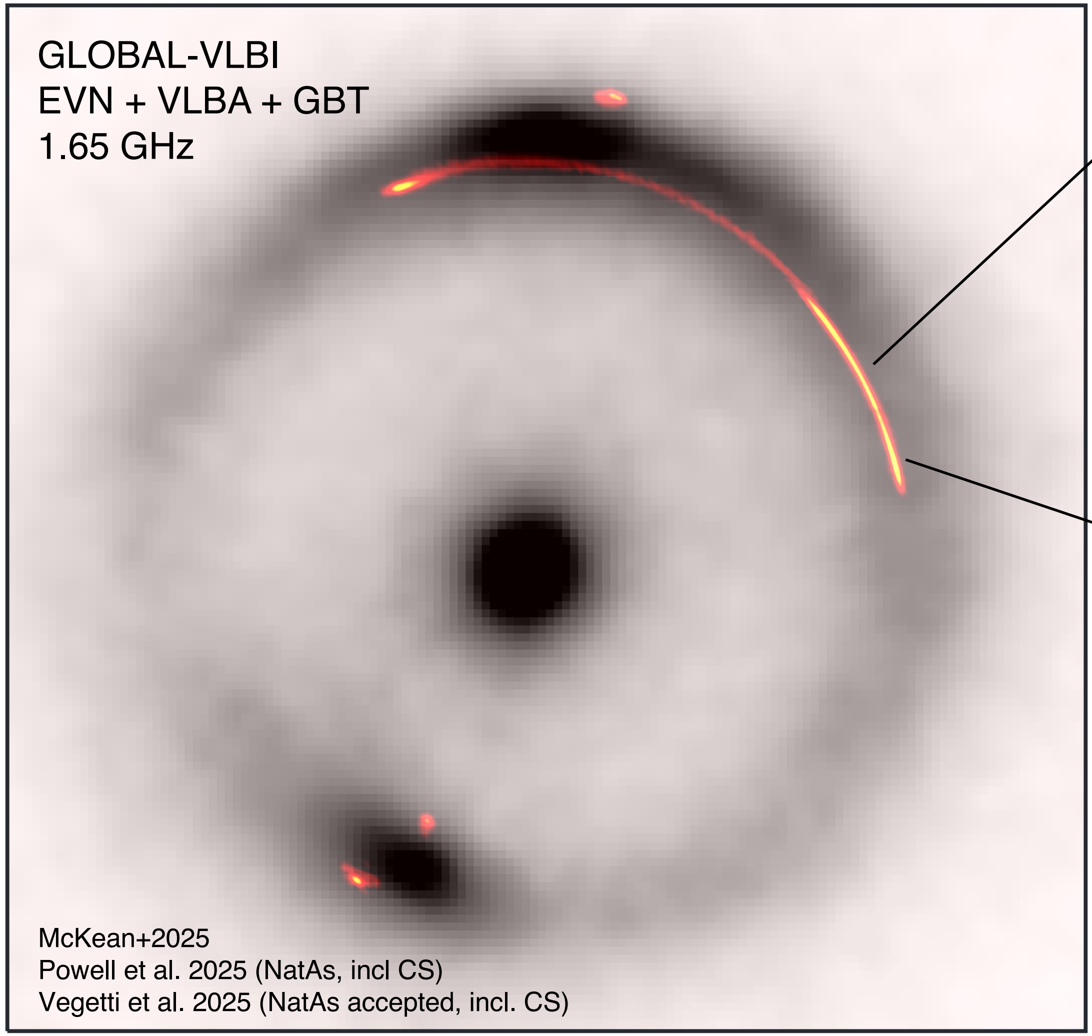

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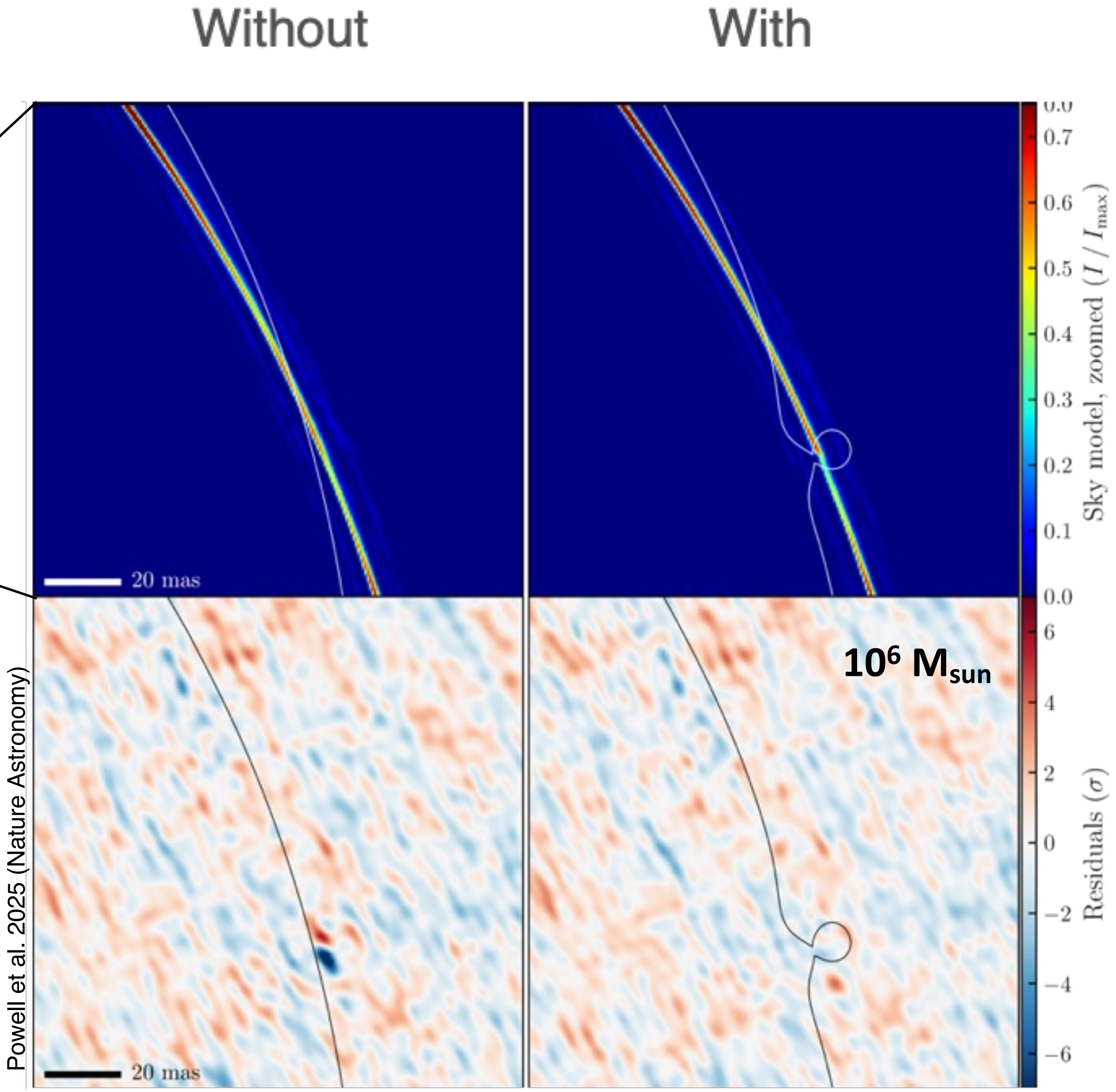

Powell et al. 2025 (Nature Astronomy)

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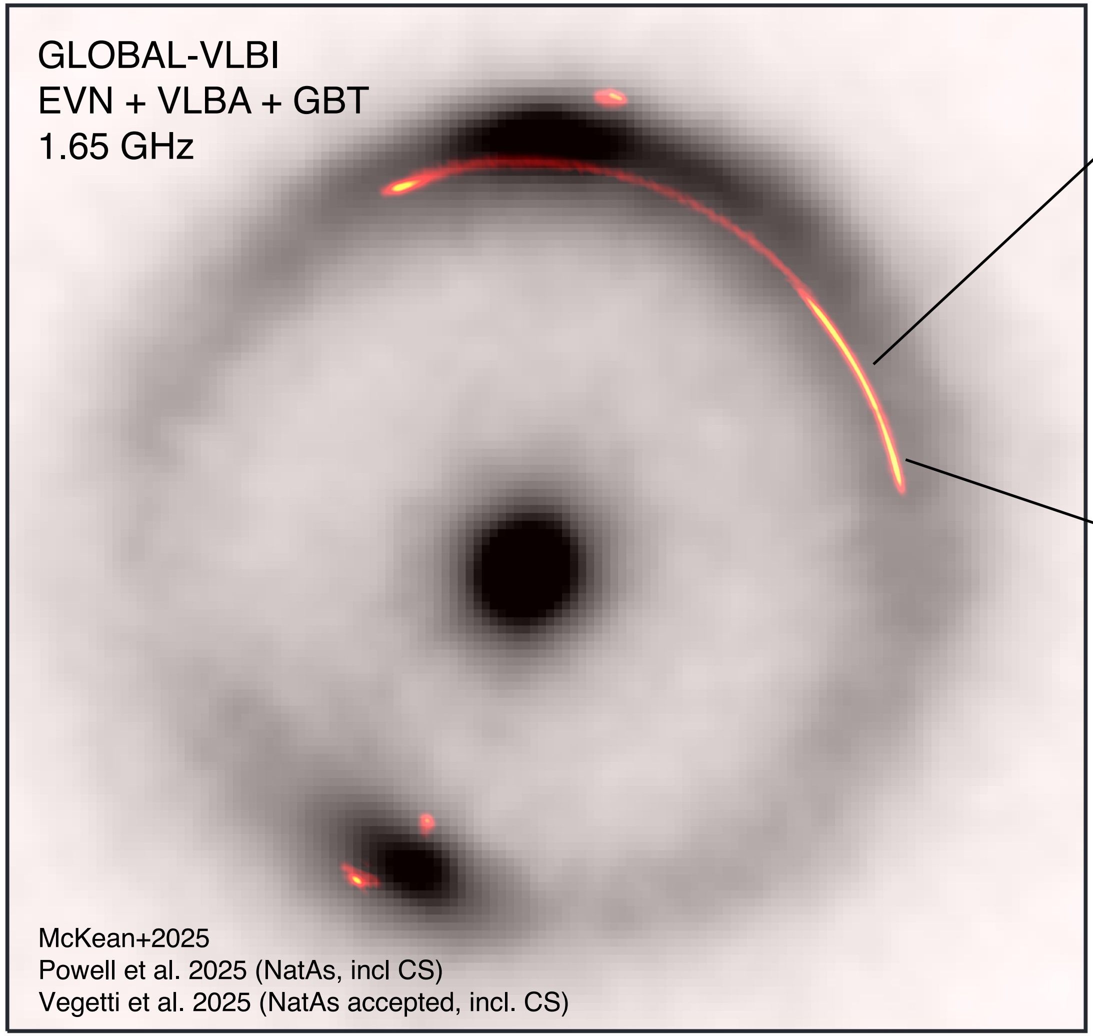
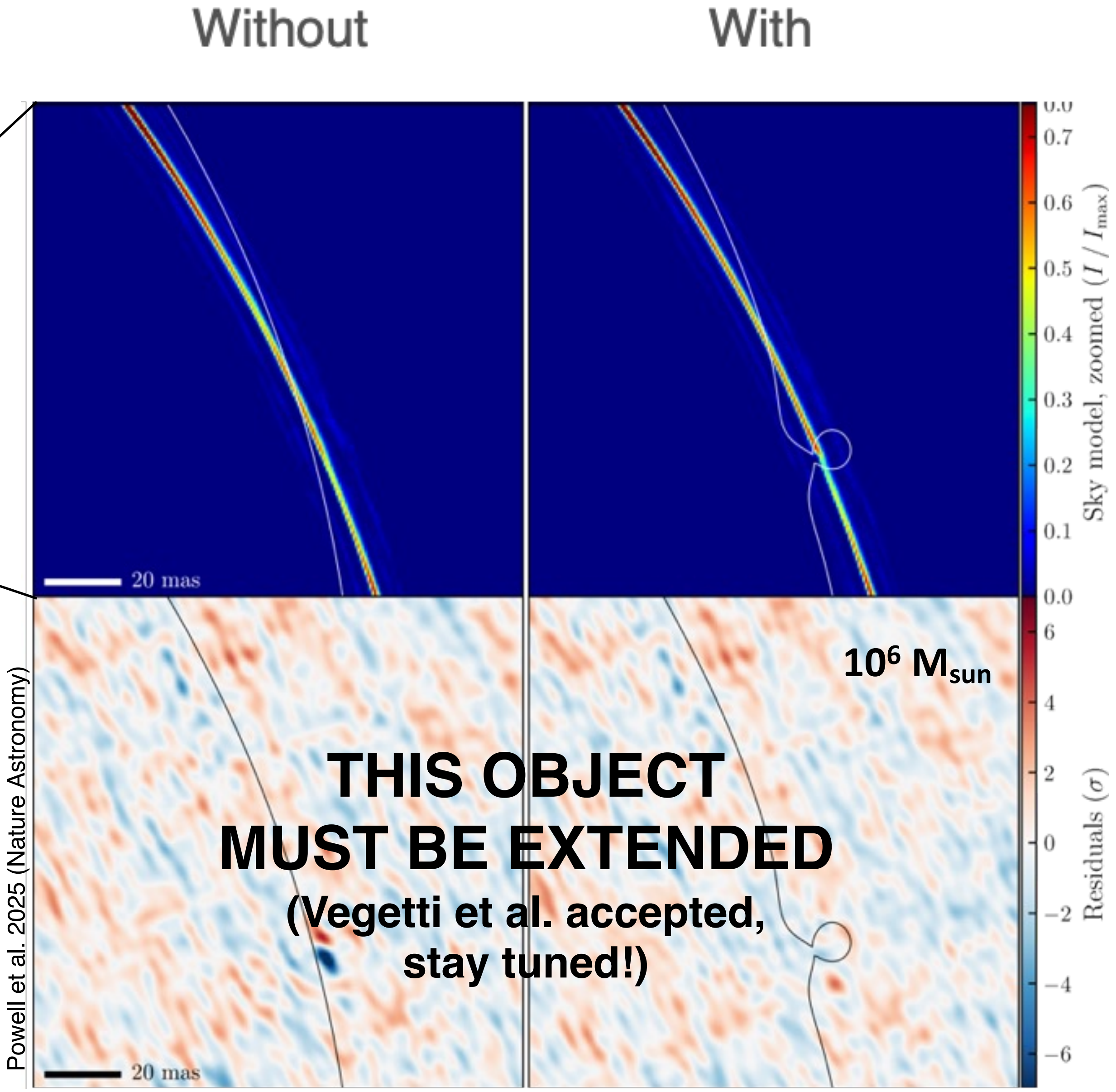


GLOBAL-VLBI
EVN + VLBA + GBT
1.65 GHz

McKean+2025
Powell et al. 2025 (NatAs, incl CS)
Vegetti et al. 2025 (NatAs accepted, incl. CS)



Powell et al. 2025 (Nature Astronomy)

10^6 M_{sun}

THIS OBJECT MUST BE EXTENDED

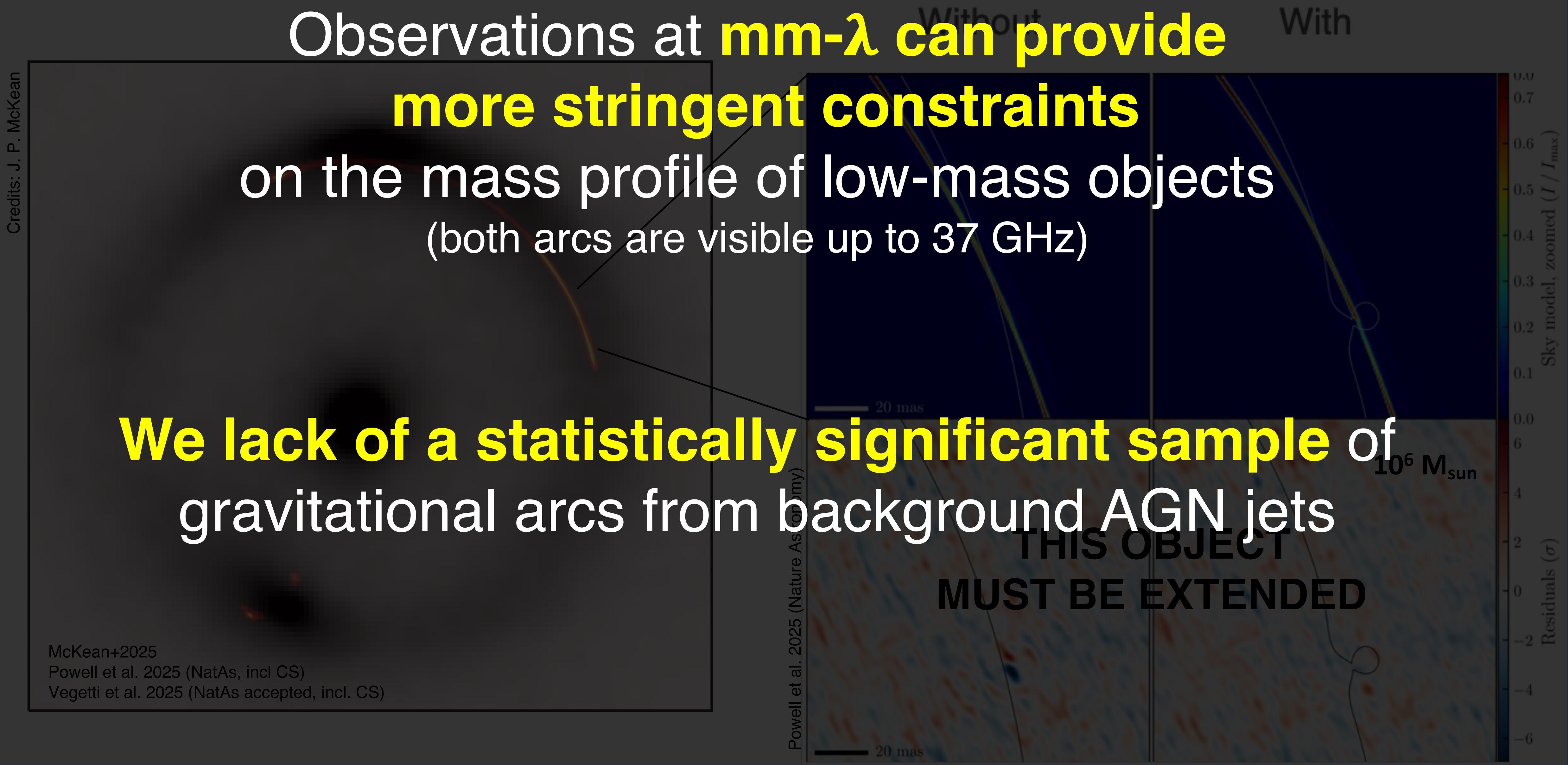
(Vegetti et al. accepted, stay tuned!)

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

Observations at **mm-λ can provide more stringent constraints** on the mass profile of low-mass objects

(both arcs are visible up to 37 GHz)

We lack of a statistically significant sample of gravitational arcs from background AGN jets



Powell et al. 2025 (Nature Astronomy)

McKean+2025
Powell et al. 2025 (NatAs, incl CS)
Vegetti et al. 2025 (NatAs accepted, incl. CS)

DARK ENERGY

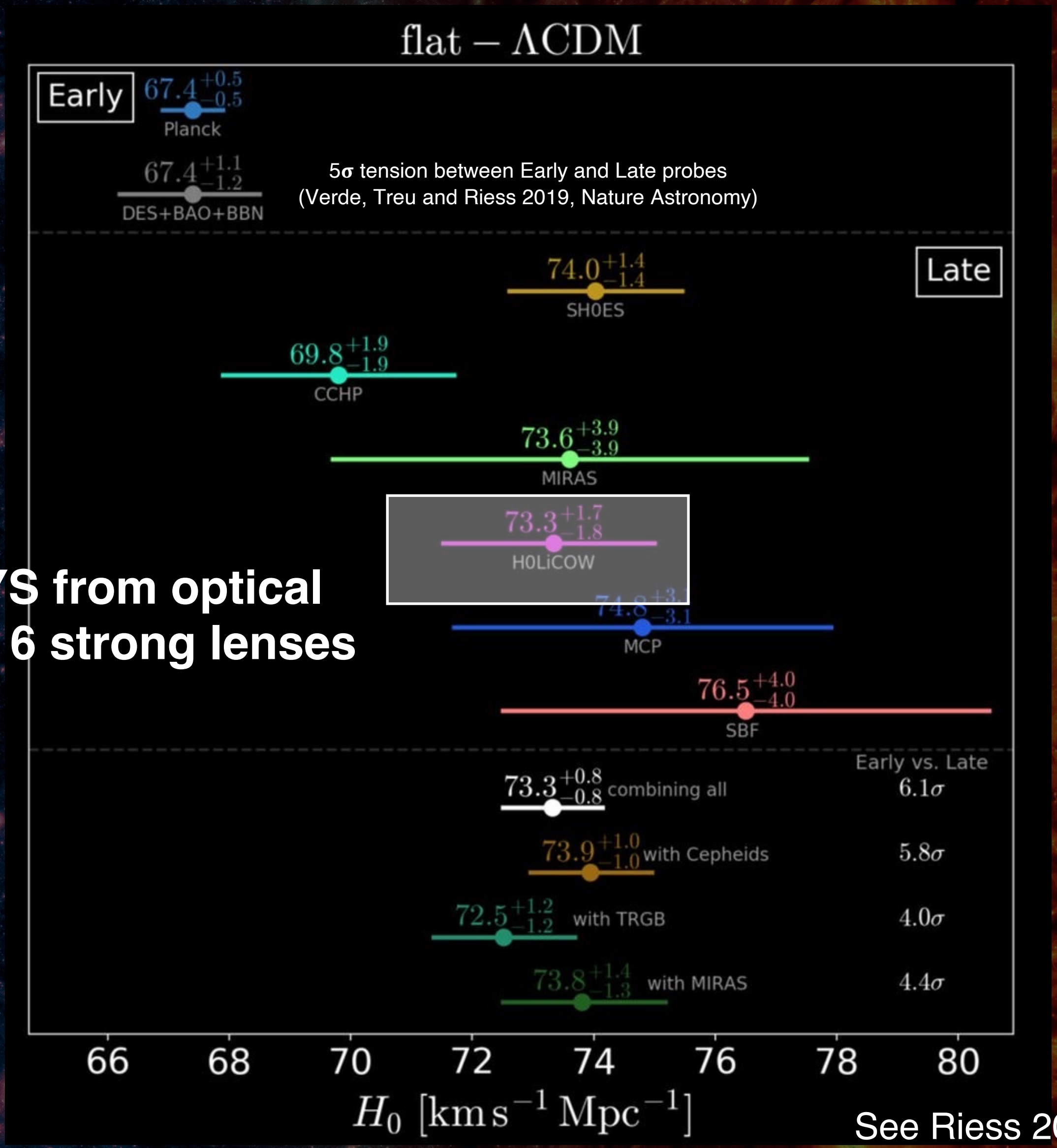
AGN cores

The Hubble tension

Is there an evidence for an Early Dark Energy?

Tension or Systematics?

TIME DELAYS from optical monitoring of 6 strong lenses



5σ tension between Early and Late probes
(Verde, Treu and Riess 2019, Nature Astronomy)

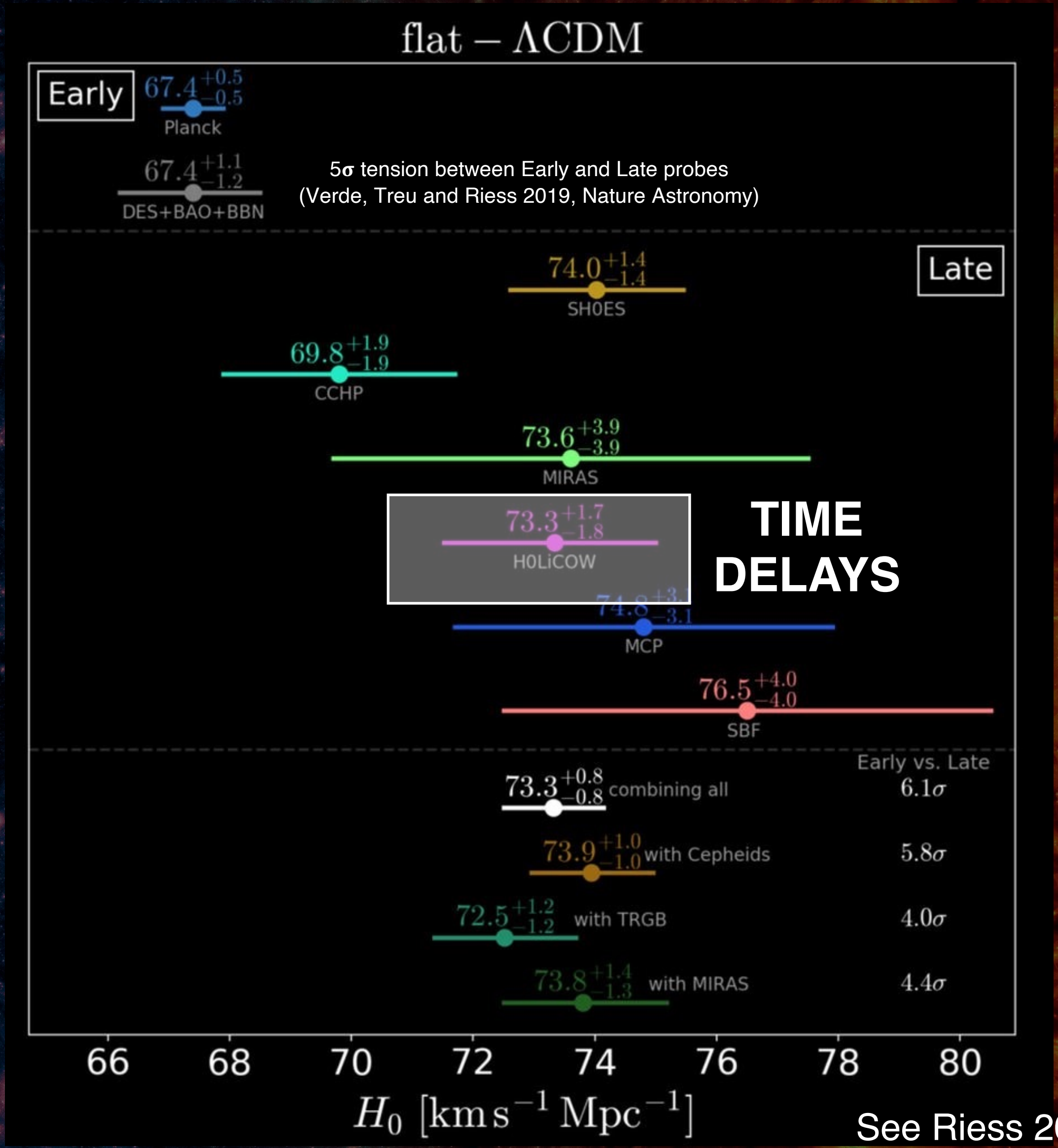
See Millon et al. 2020, Birrer & Treu 2021, Gilman 2021

See Riess 2020
Nature Reviews Physics

The Hubble tension or systematics?

Is there an evidence for an Early Dark Energy?

- mas and sub-mas angular resolution
  Spatially resolving the lensed images and their structure on mas and sub-mas scales
- micro-arcsec astrometric precision on position of lensed images
  Precise lens mass models (sub-percent level precision)
- no dust obscuration due to lensing galaxy
  Reliable measurement of the surface brightness distribution of the lensed images
- no microlensing due to stars
  Sources on VLBI-scales are not point like – surface brightness anomalies cannot be due to microlensing
- monitoring of lensed images possible
  But VLBI monitoring programmes are difficult to schedule
  we need highly variable sources → BLAZARS



See Riess 2020
Nature Reviews Physics

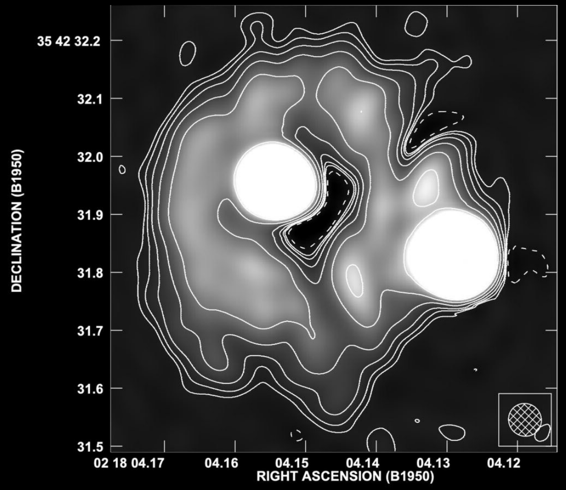
The (only) two strongly lensed **blazars**

…both detected at gamma-rays!

JVAS B0218+357

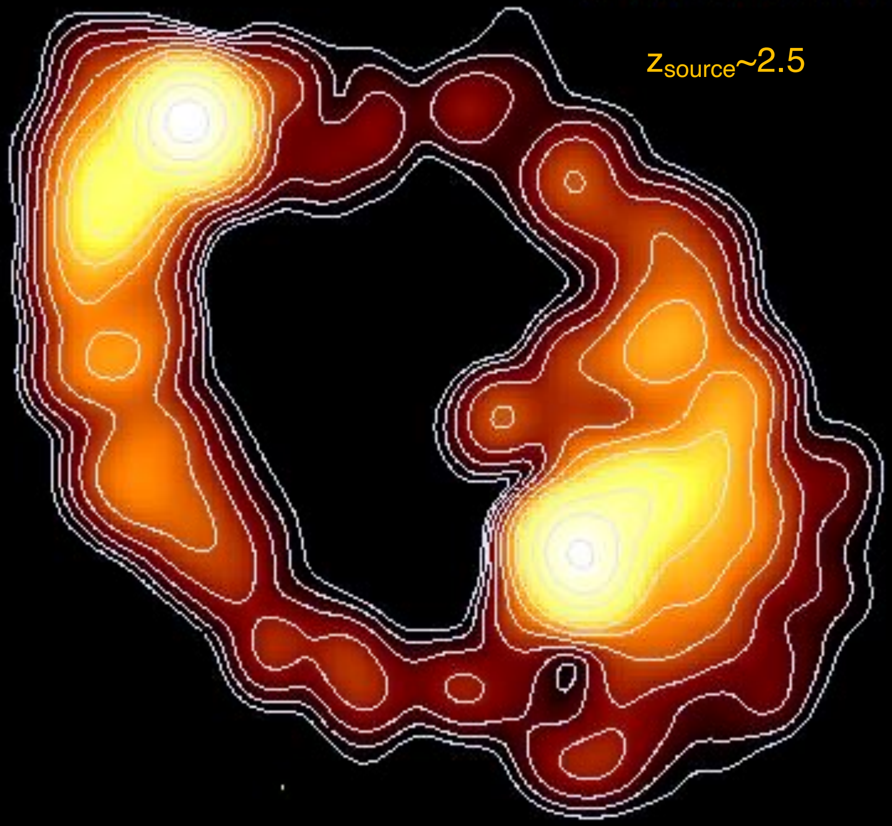
z_{source}~0.94

Biggs+ 2001, 2004



~350 mas

PKS 1830-211

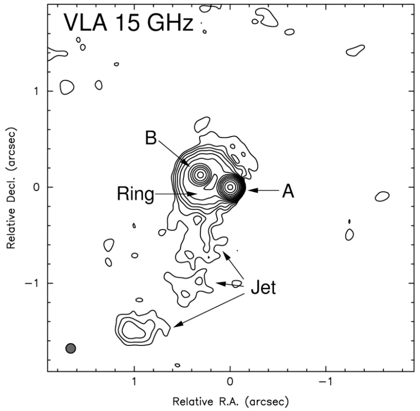


z_{source}~2.5

~1 arcsec

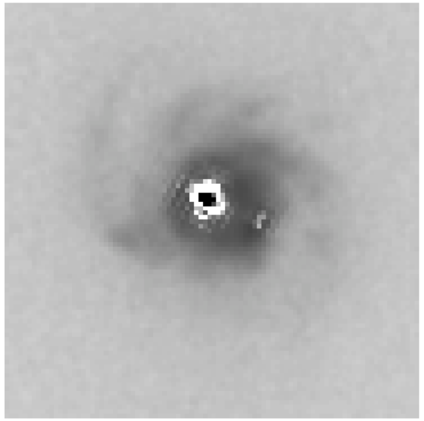
Jauncey+1991, Lovell+1993, Patnaik+1993

JVAS B0218+357

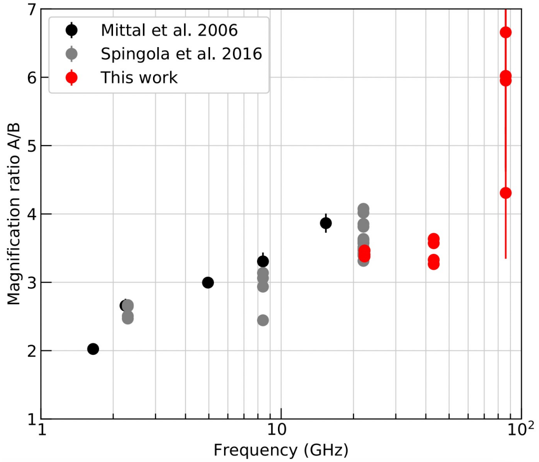


Biggs & Browne 2018

Lens = late-type galaxy!

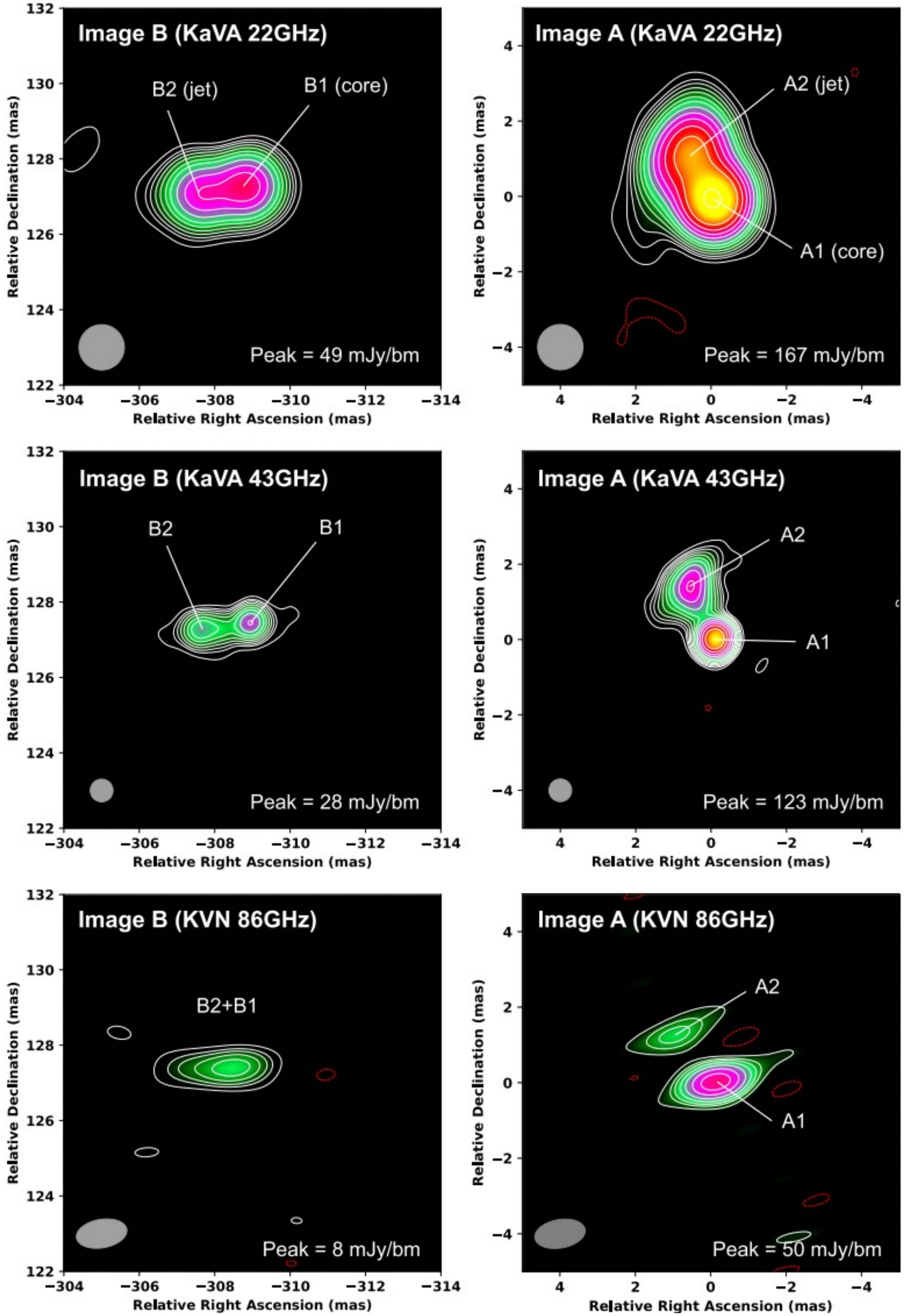


Hada et al. 2020



absorption effects due to the intervening lensing galaxy become negligible at millimeter wavelengths

mm-VLBI observations are a better tool
for inferring intrinsic properties of the lensed images
(⇔ background sources)

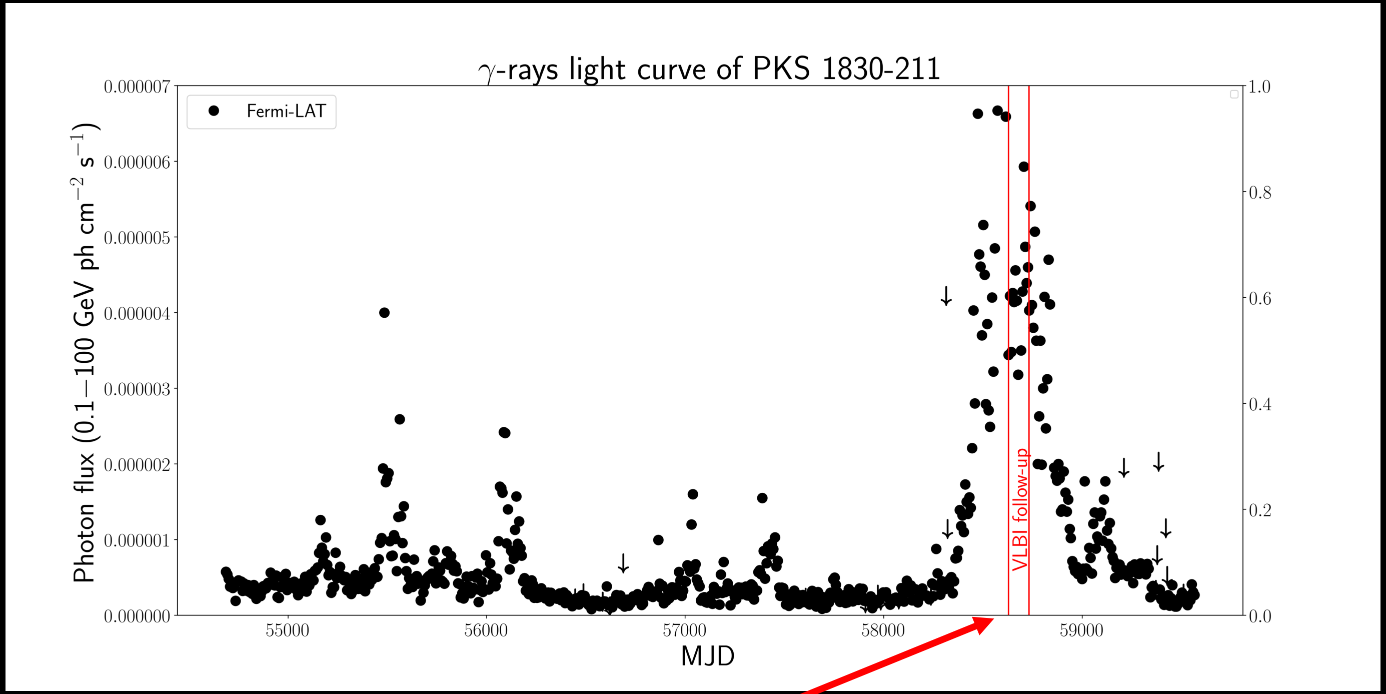


Hada et al. 2020 (incl. CS)

The outstanding γ-ray flare from PKS 1830-211 → variability from hours to years

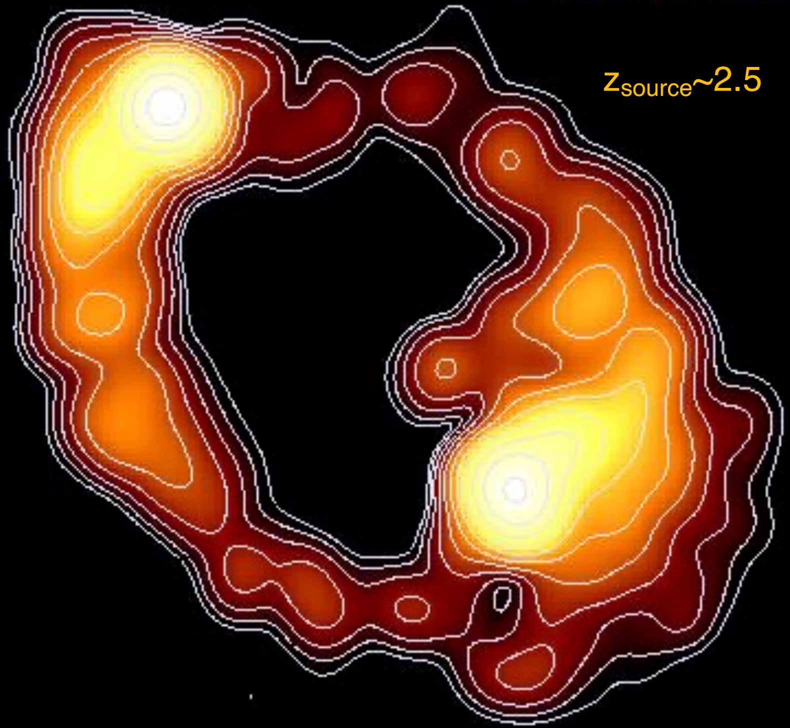
Flare detection from radio to **γ**-rays

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



VLBI follow-up 3 months across the peak of the flare (PI Spingola)

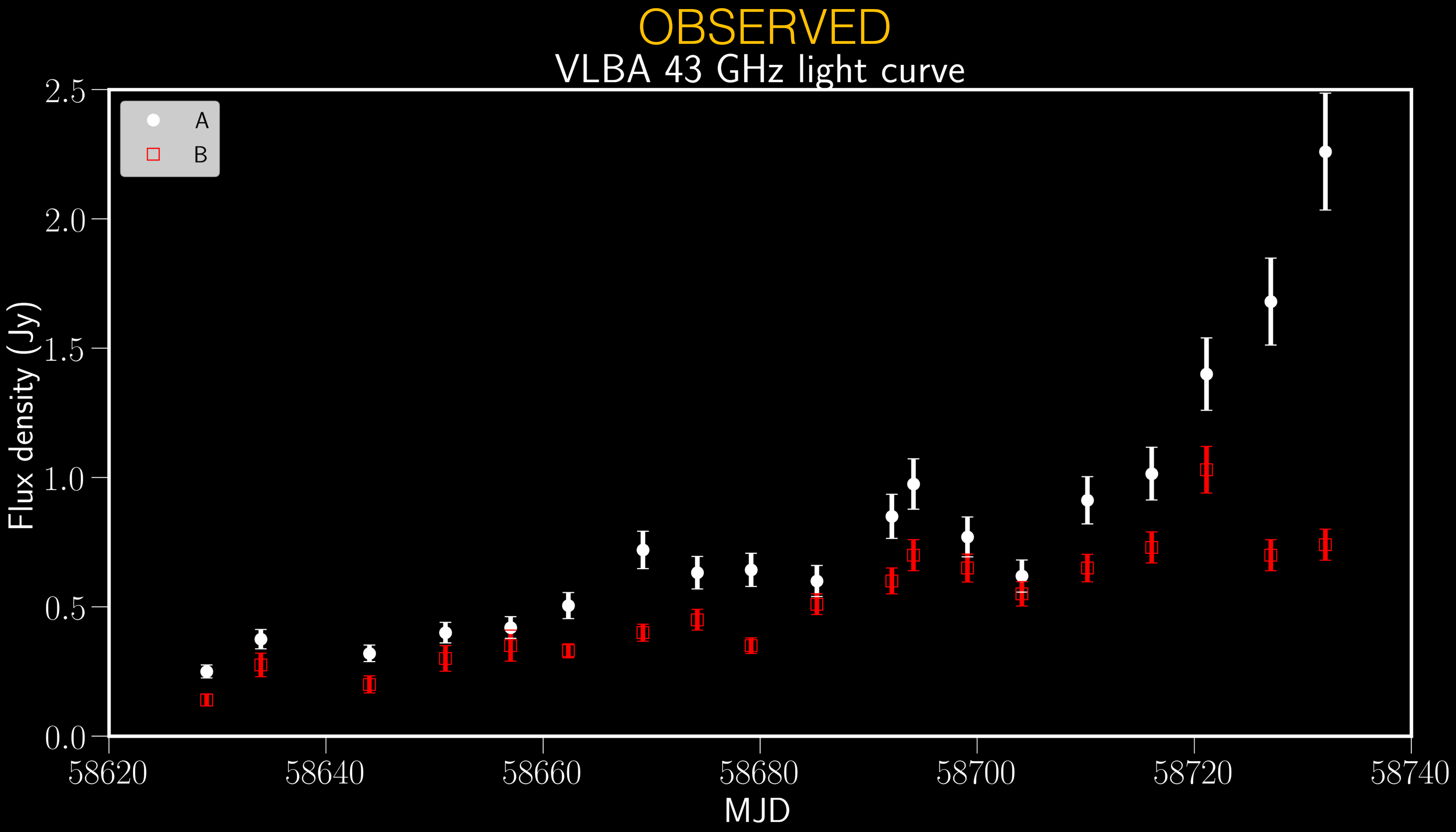
+ several follow-ups across the entire electromagnetic spectrum (PI Buson)

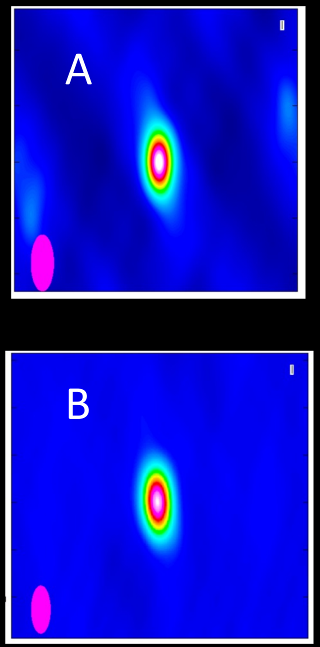


Jauncey+1991, Lovell+1993, Patnaik+1993

Controversial measurement of the time delays at radio and gamma-rays

mm-VLBI follow-up of the outstanding γ-ray flare from PKS 1830-211 at 43 GHz





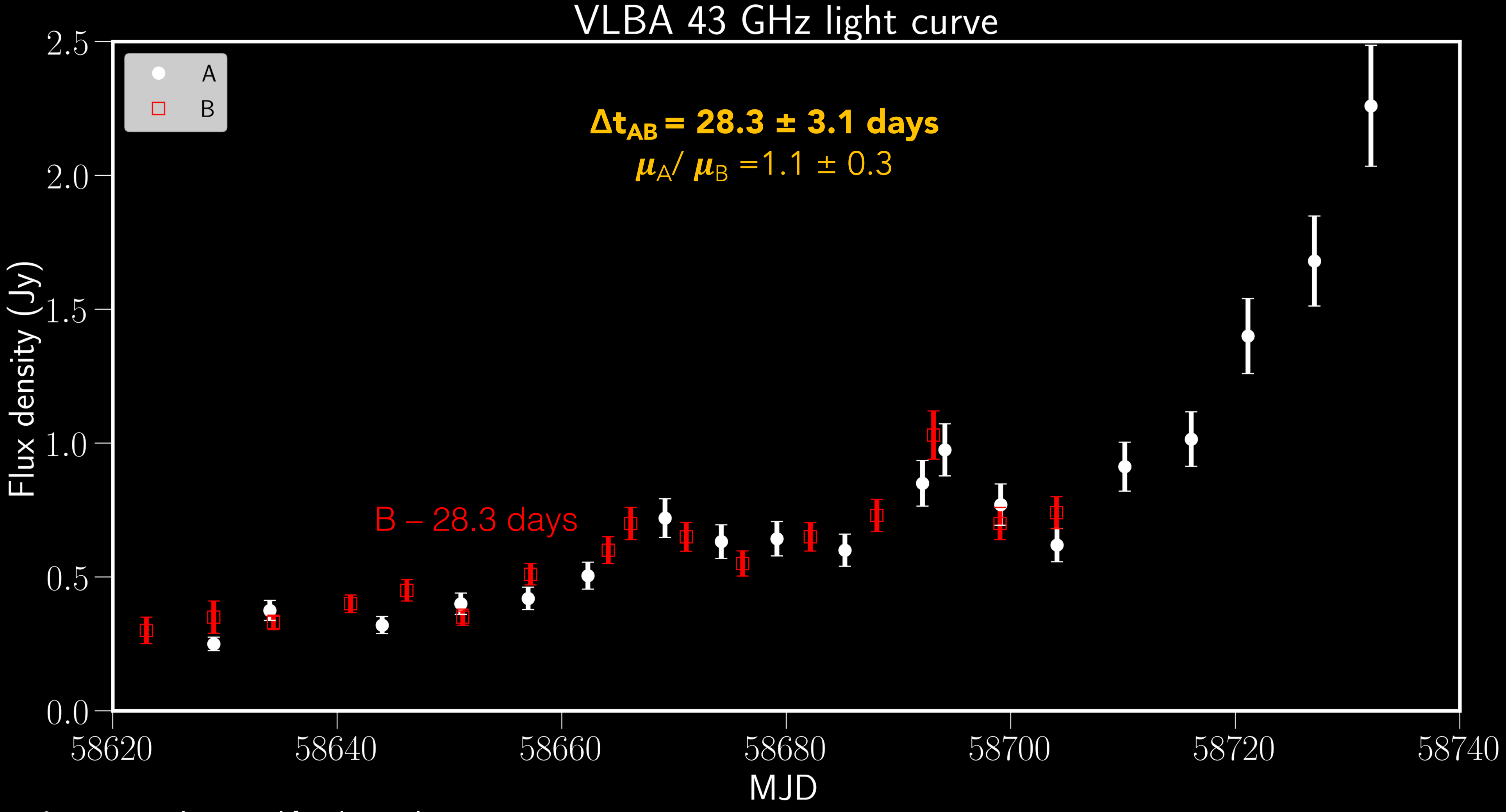
7 mm

Beam 0.5 mas x 0.2 mas,
rms 0.5 - 2 mJy/beam

Spingola, Giroletti et al. in prep

mm-VLBI follow-up of the outstanding γ-ray flare from PKS 1830-211 at 43 GHz

TIME SHIFTED



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

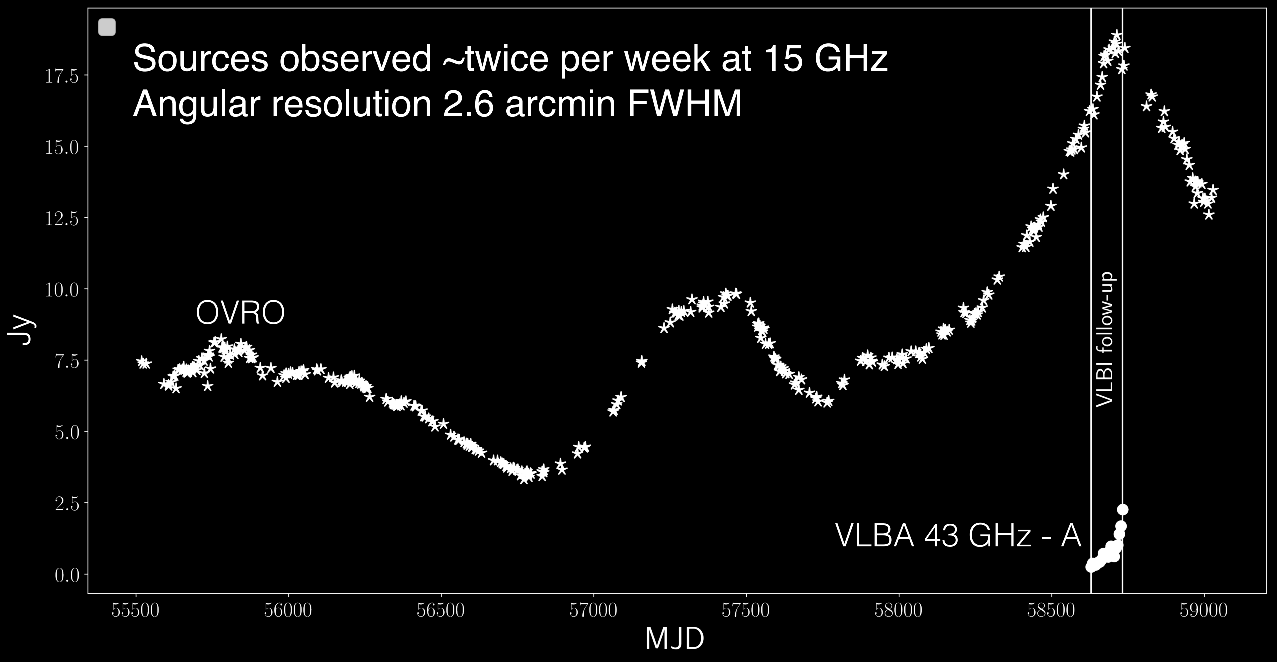
optically thin part of the jet: ideal to detect variability

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

Spingola, Giroletti et al. in prep

Single dish monitoring and time delay

Owens Valley Radio Telescope: 40m antenna in California
Monitoring programme of more than 1500 Fermi-LAT sources



Sources observed ~twice per week at 15 GHz
Angular resolution 2.6 arcmin FWHM

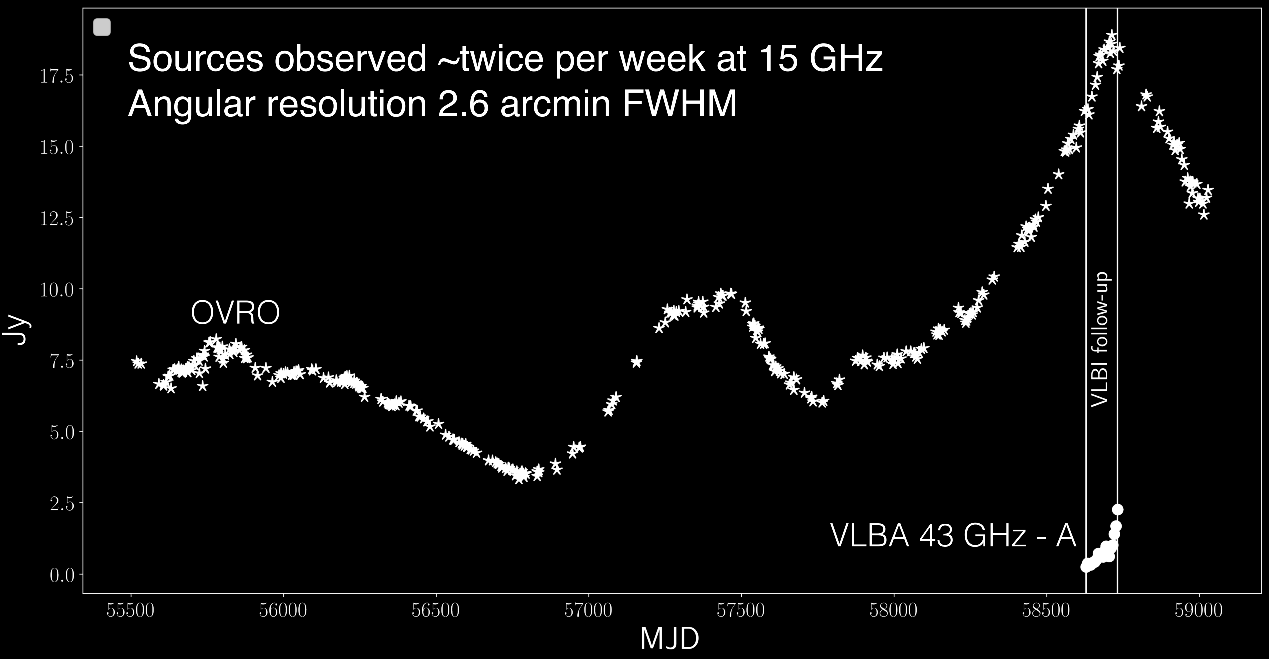
VLBI $\Delta t_{AB} = 28.3 \pm 3.1$ days

A single dish monitoring is typically used
to **trigger a VLBI follow-up,**
but it can be also used to **measure time delays**

Single dish monitoring and time delay

Autocorrelation function: correlation of a signal with a
delayed version of itself

Owens Valley Radio Telescope: 40m antenna in California
Monitoring programme of more than 1500 Fermi-LAT sources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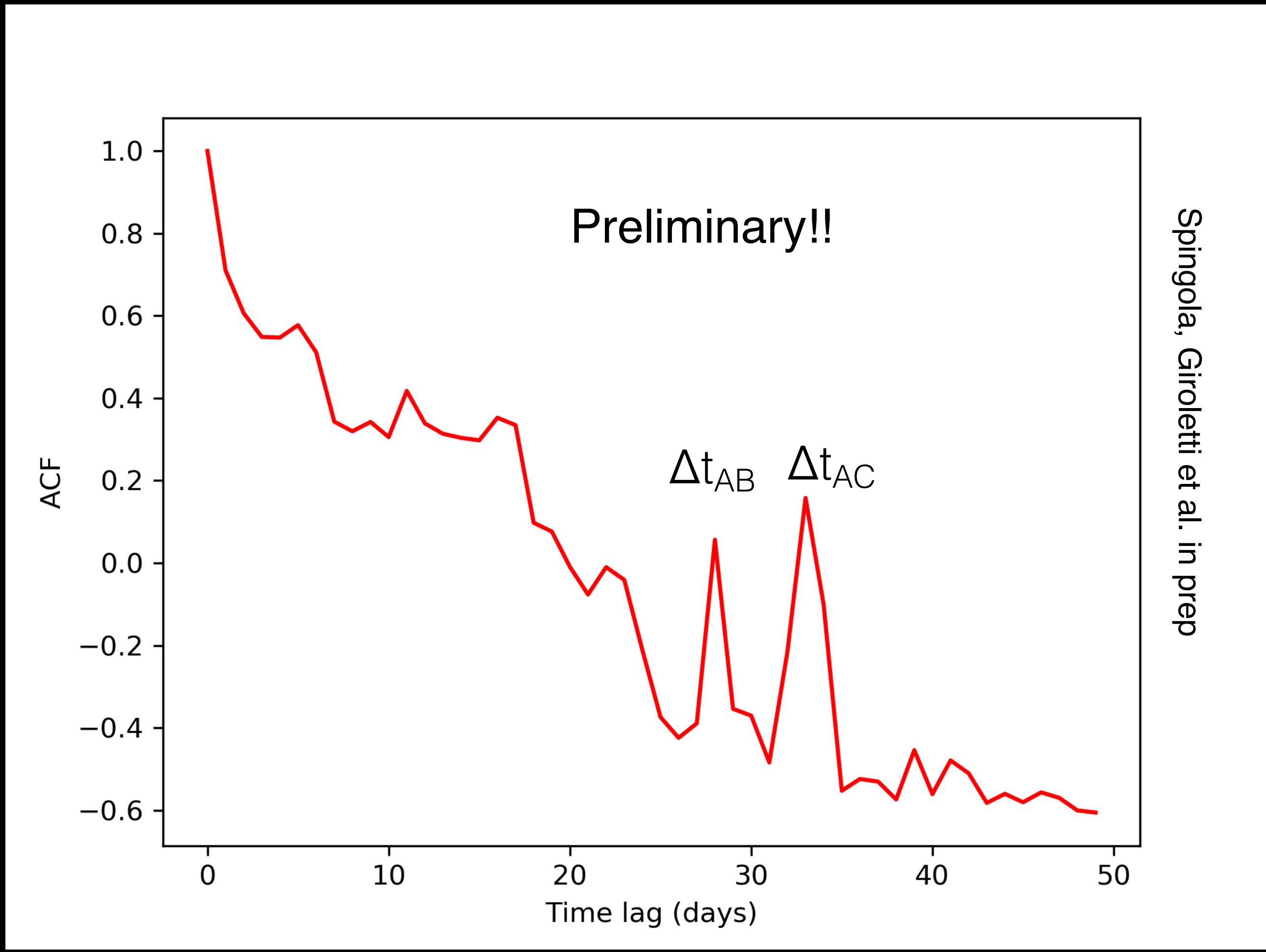


Spingola, Giroletti et al. in prep

A single dish monitoring is typically used
to **trigger a VLBI follow-up,**
but it can be also used to **measure time delays**

ACF on OVRO
Δt_{AB} = 29 ± 3 days
Δt_{AC} = 34 ± 3 days

Predicted by lens model - Muller+2020
Δt_{AB}= 26 – 29 days
Δt_{AC}= 31 – 34 days

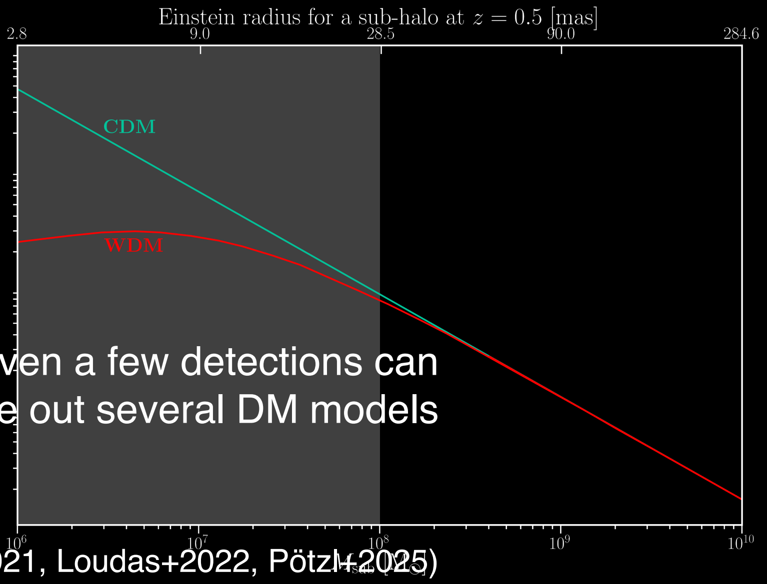
Time delays can be used as a signature to innovatively **search** for strong lenses at **any mass range** in the **time domain**

DARKER: A lens search in the time domain to answer fundamental open questions

What is dark matter?

Gravitational time delays **$\Delta t \propto M$**

for $10^{5\text{-}8}\,M_{sun}$ → **Δt** = tens of hours to days



Even a few detections can rule out several DM models

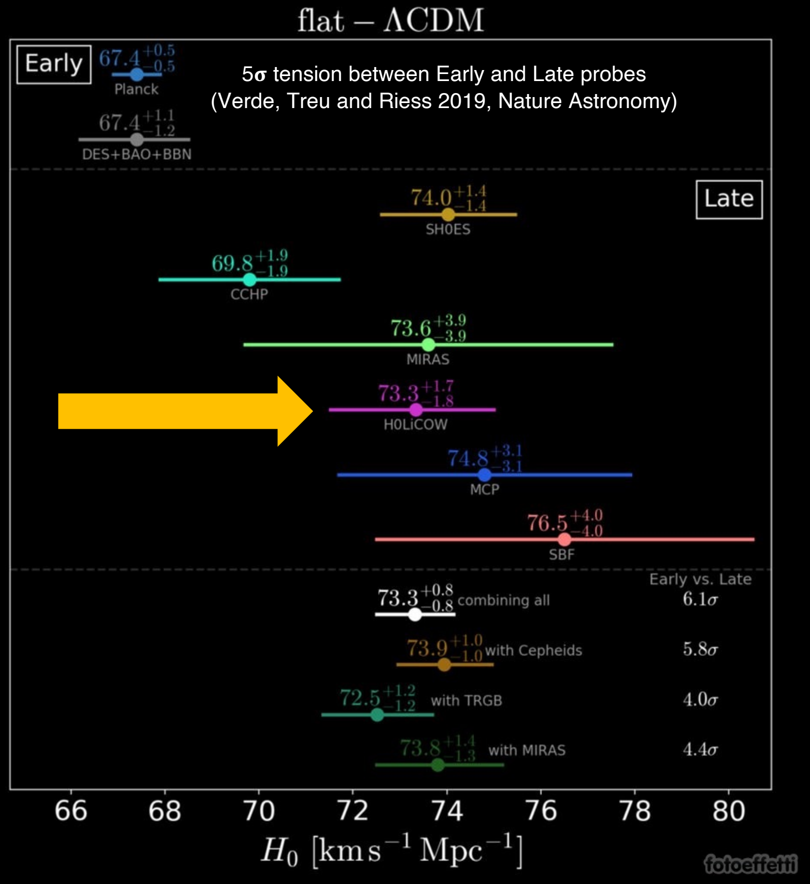
(Casadio+2021, Loudas+2022, Pötzl+2025)

DARKER will be able to find in the time domain those **critical low-mass lenses** that are missed in current «standard» image-domain lens searches

(Fermi-LAT, autocorrelation fct method)

1) Is there an Hubble tension?

Gravitational time delays **$\Delta t \propto H_0^{-1}$**



5σ tension between Early and Late probes
(Verde, Treu and Riess 2019, Nature Astronomy)

To solve this tension we need ~40 gravitational lensing systems with precise time delays

(Birrer & Treu 2021, Gilman+ 2021)

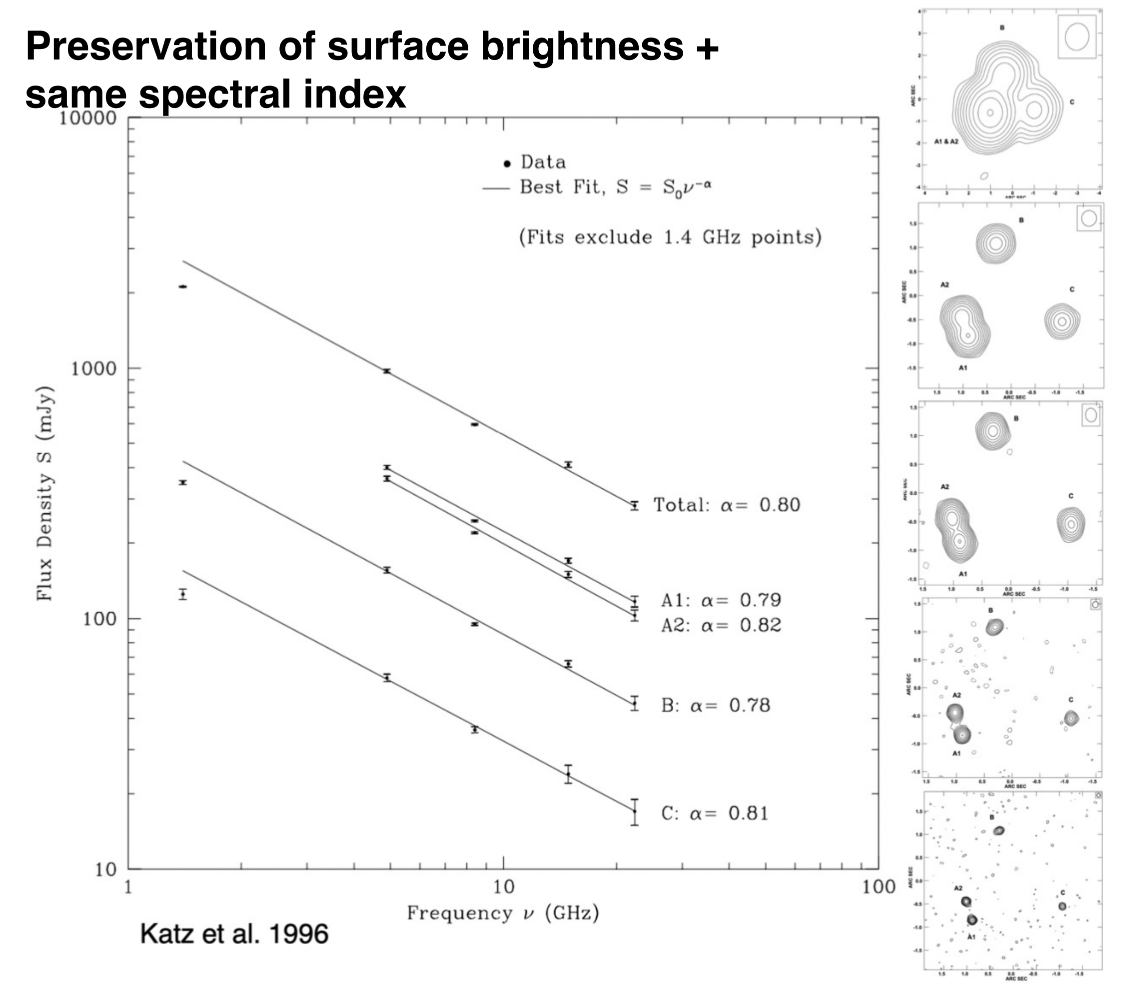
DARKER will find **hundreds** of variable lensing systems in the time domain (GAIA) + low-mass lenses
→ shed light on this tension

DARKER: A lens search in the time domain to answer fundamental open questions

What is dark matter?

Gravitational time delays **$\Delta t \propto M$**

for $10^{5\text{-}8}\,M_{sun}$ → **Δt** **=** tens of hours to days



Preservation of surface brightness + same spectral index

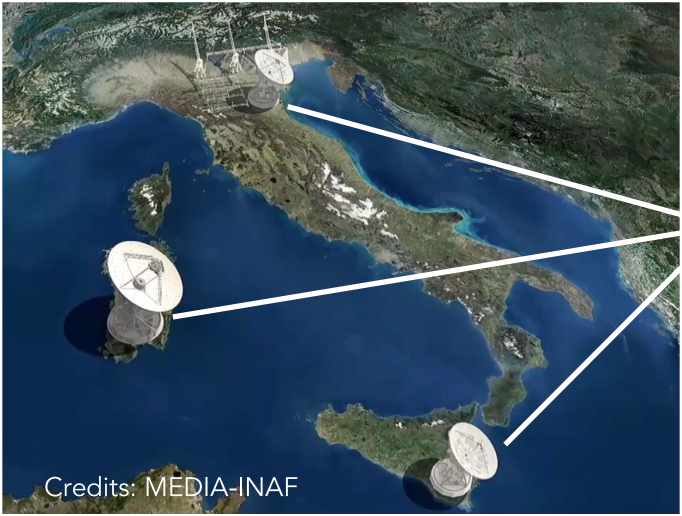
Katz et al. 1996

Follow-up of **γ**-ray-discovered systems in the North with

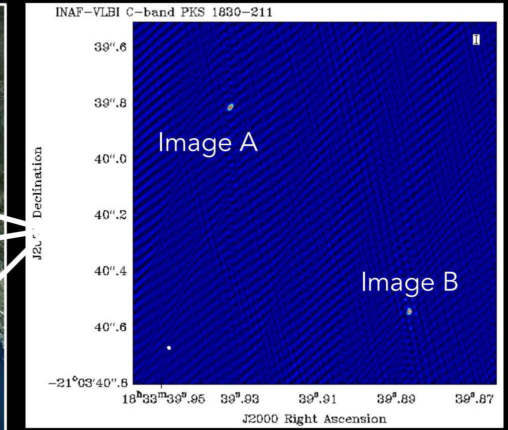
INAF-VLBI array

1.4 **to 116 GHz coverage thanks to new tri-band receivers**

Baldini 2023 and Bolli 2024



Credits: MEDIA-INAF



INAF-VLBI observations
of the lensed blazar PKS 1830-211
(Spingola et al. in prep.)

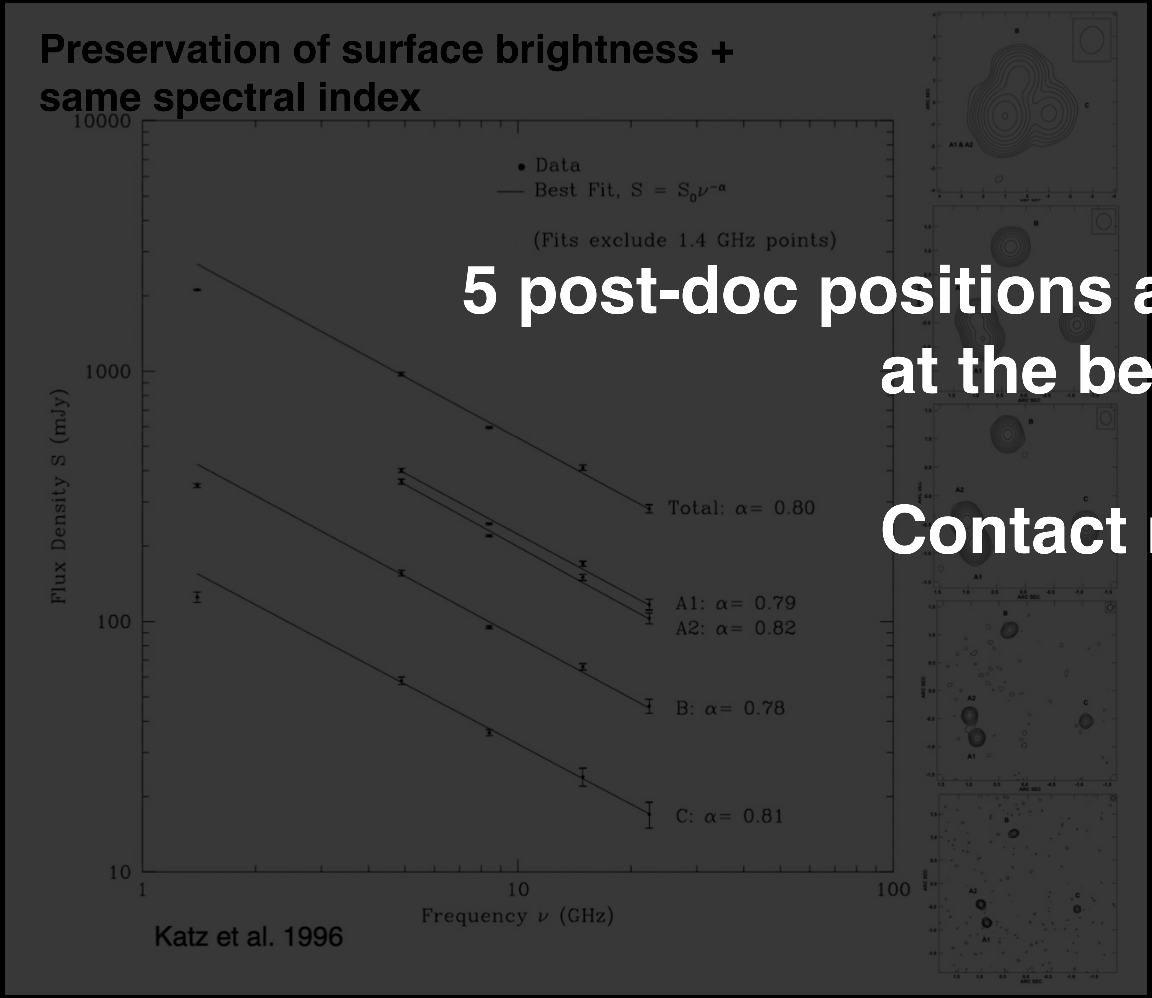
+ **single dish monitoring of candidates at mm-λ**

confirm the time delay

study the physics of the high-z background sources

(see also Marchili et al. 2025)

DARKER: A lens search in the time domain to answer fundamental open questions



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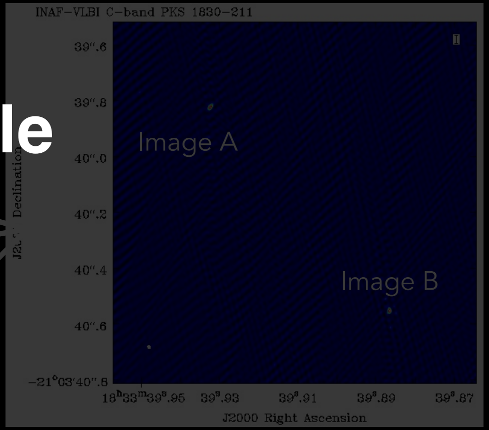

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5 post-doc positions at INAF - IRA will be available at the beginning of 2026

Contact me if interested!

Summary

- **Highly complex models** can be tested precisely with VLBI observations of gravitational arcs (e.g. multipoles of many orders)
- Even a single lensing system showing **gravitational arcs** can put **competitive constraints** on the dark matter particle mass
- We can detect **direct signatures of low-mass objects** with VLBI observations and test several mass density profiles
- **Only VLBI can image the crucial angular scales** to directly test **the nature of dark matter** -- **mm-wavelengths would be ideal to better resolve the perturbations**

We lack of a statistically significant sample of strong lensing systems:

- Time delays can innovatively be used to search for lenses
  DARKER will provide the first search for lenses at all masses in the time domain, **simultaneously testing the nature of dark matter** and **H_0 tension**
- At gamma-rays we will search for low-mass lensing systems, which will show VLBI emission → blazars, **visible up to mm-wavelengths**

Tri-band observations with
the Italian VLBI Network
\+ **all the antennas with tri-band receivers**
\+ **the African mm Telescope**
can be used to **confirm** low-mass lens candidates

determine the nature of dark matter
test the Hubble tension with a new class of lenses

Thank you!

cristiana.spingola@inaf.it

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

Ministero dell'Università e della Ricerca

FONDO ITALIANO PER LA SCIENZA

DARK ENERGY

AGN cores

100 years ago!

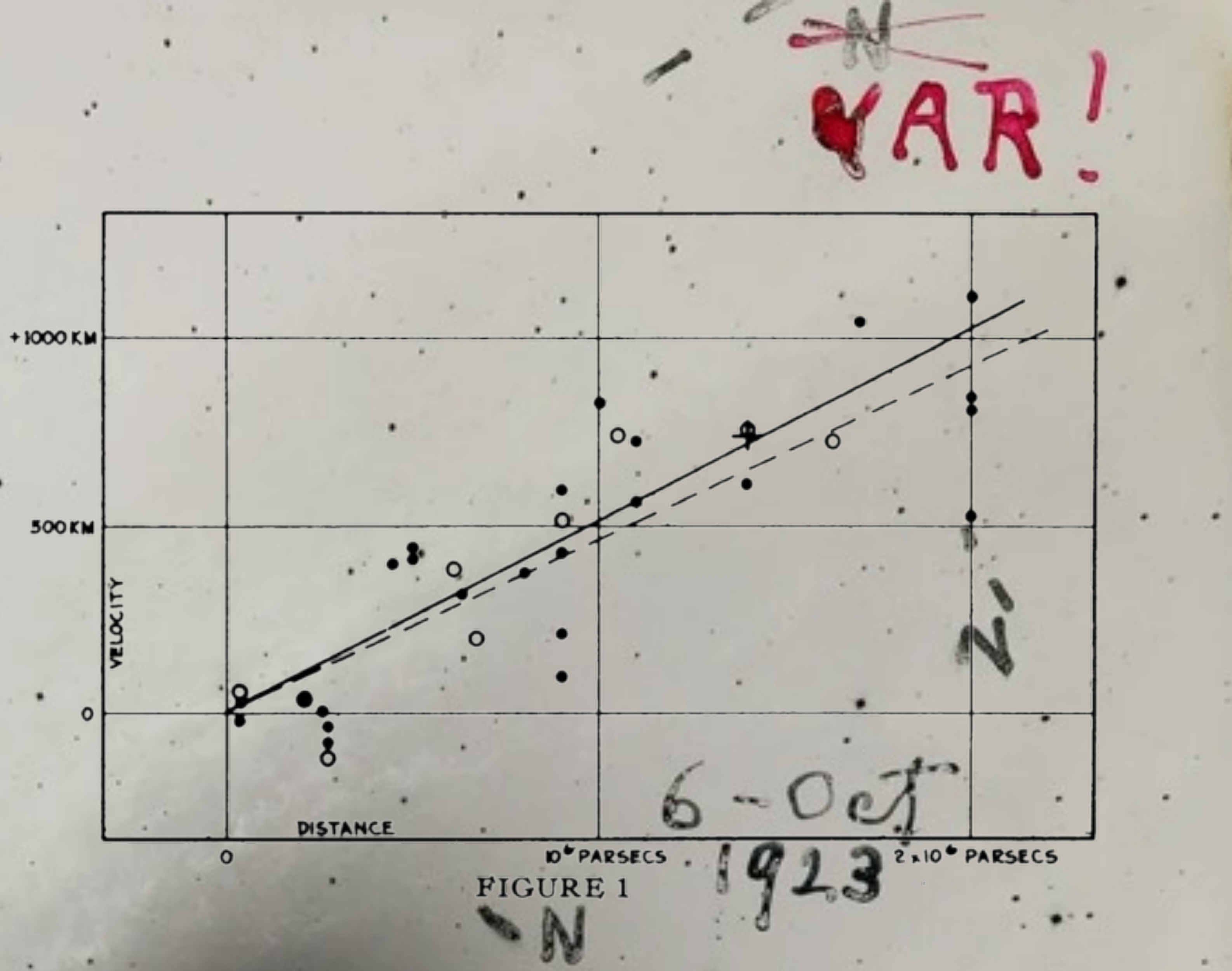
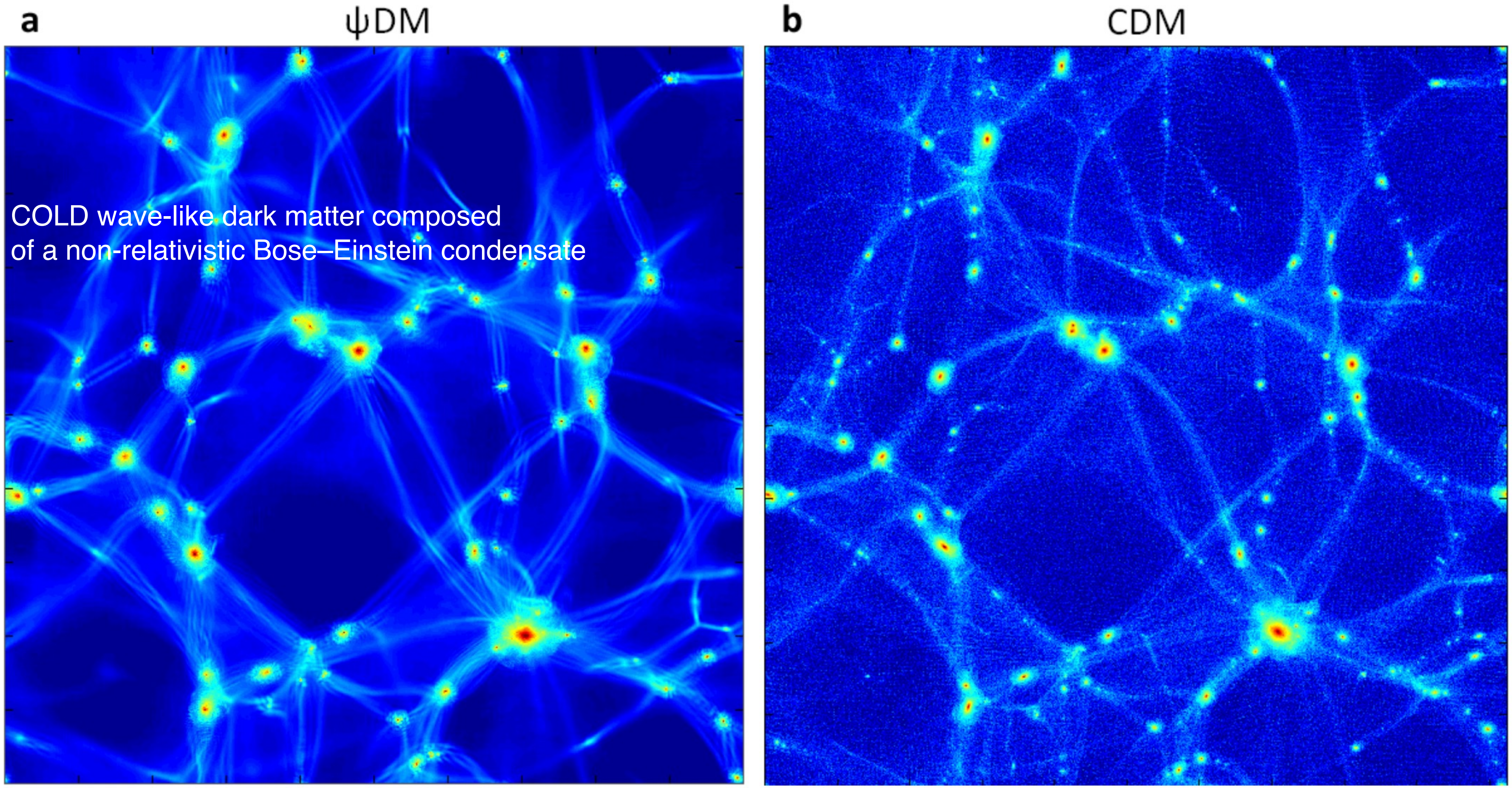


FIGURE 1

Photometric plate of Andromeda galaxy with Hubble’s notes (1923) / Plot from Hubble 1929

Testing alternative dark matter models: fuzzy dark matter



COLD wave-like dark matter composed of a non-relativistic Bose–Einstein condensate

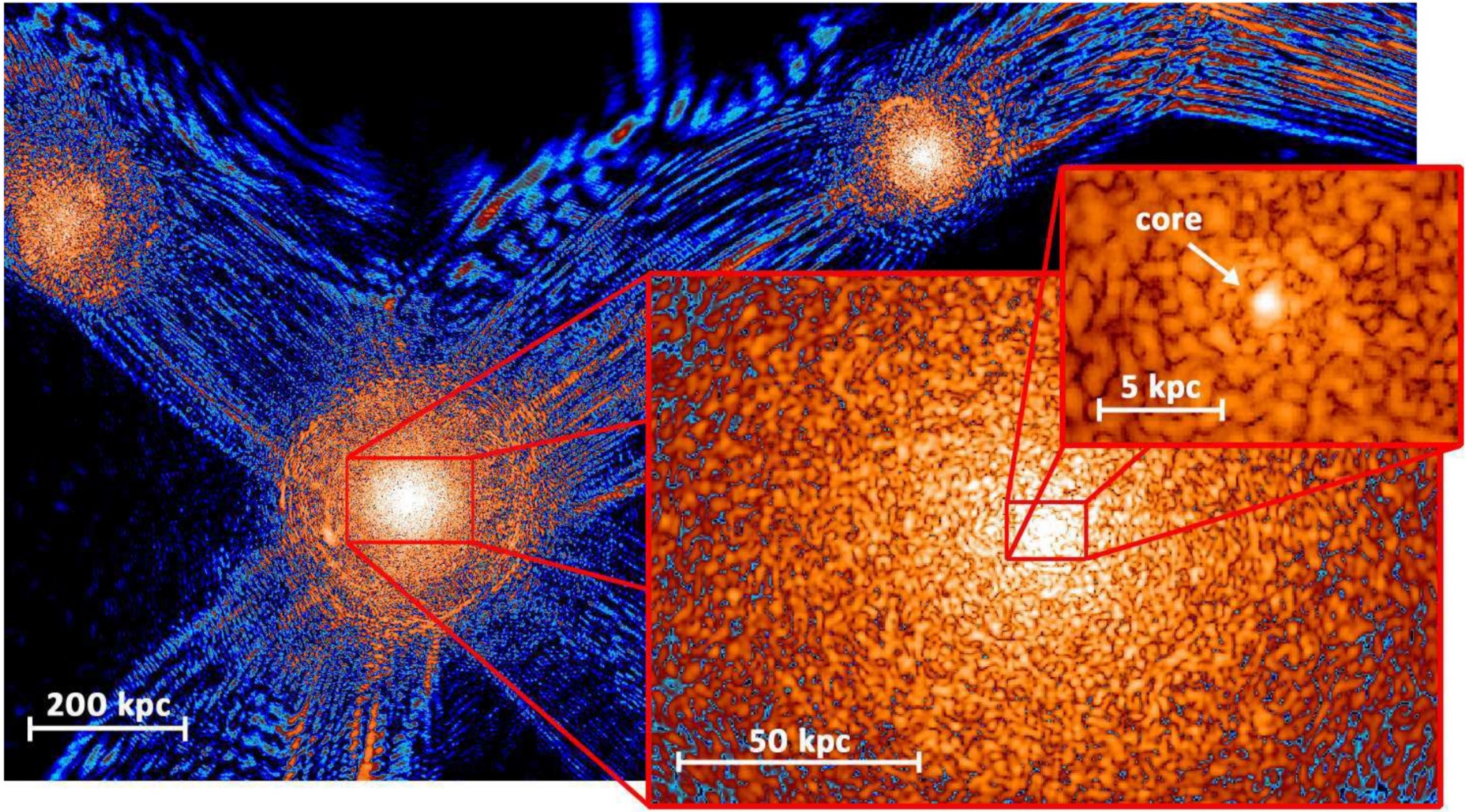
ultra-light axion-like scalar boson

massive electromagnetically non-interacting component

Schive et al. 2014, Nature Physics

Large scale structure indistinguishable from CDM

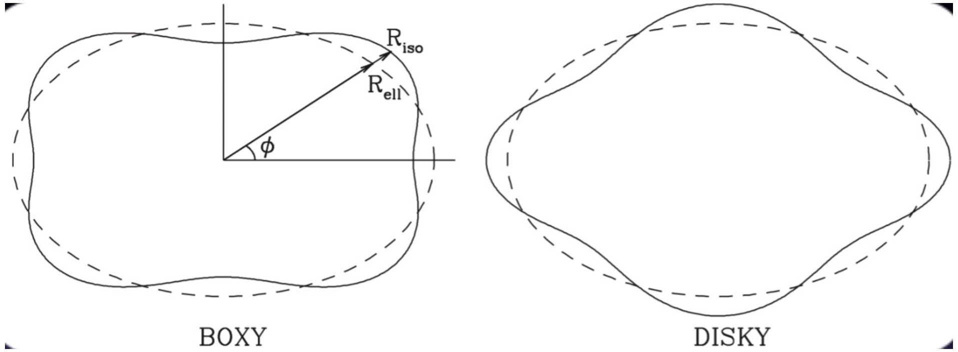
Testing alternative dark matter models: fuzzy dark matter



Schive et al. 2014, Nature Physics

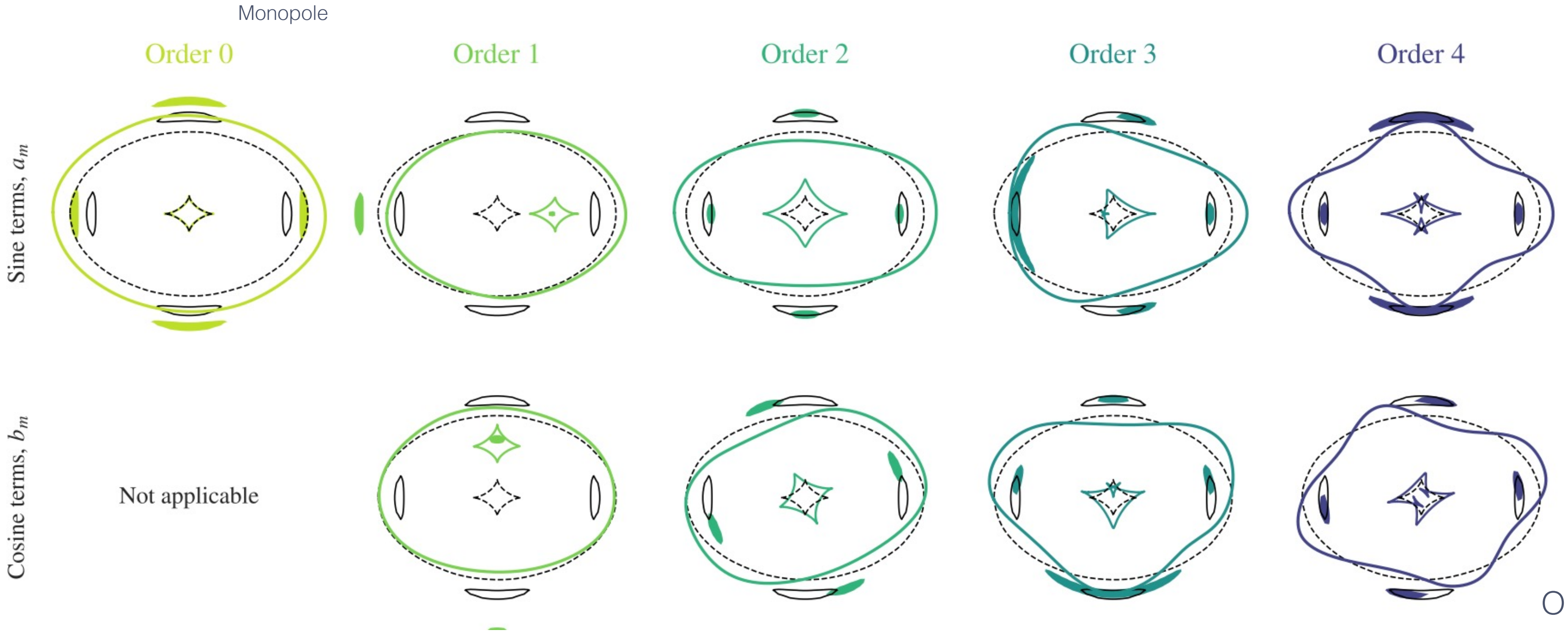
Granularity on sub-galactic scales

Galaxies are complex: let’s include angular structure



The angular structure is a natural consequence of the merging process (e.g., Nieto & Bender 1989)

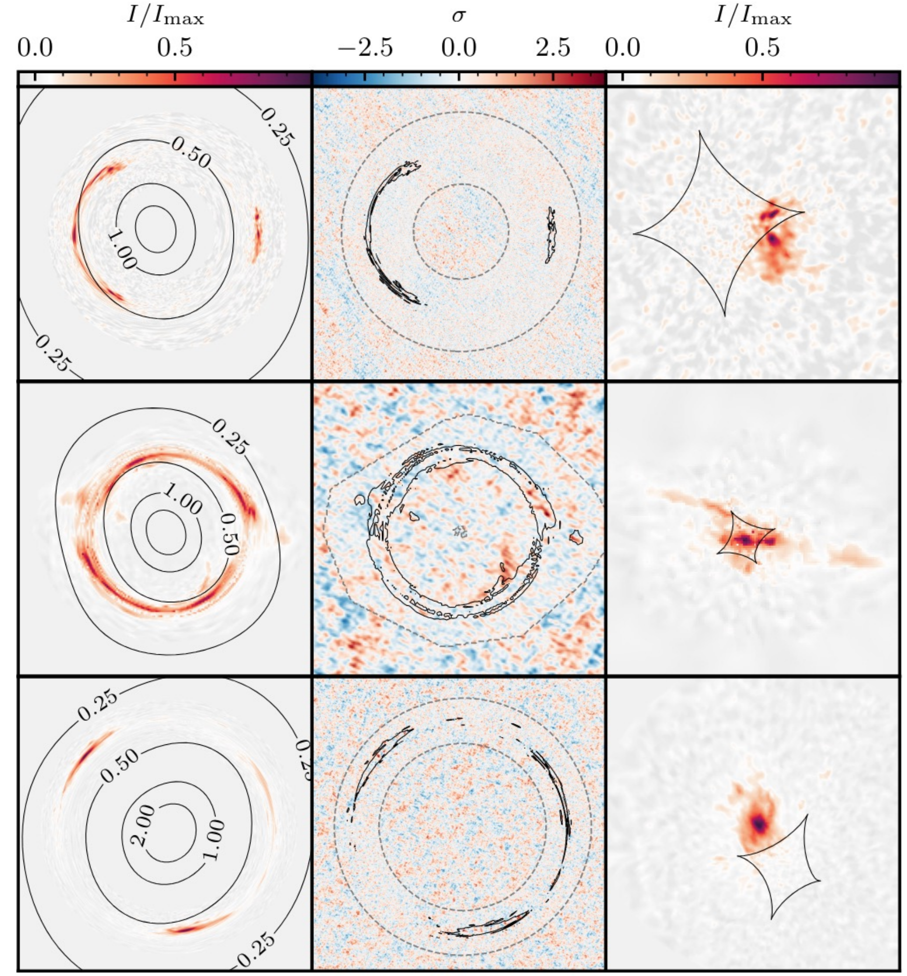
Brighter ellipticals are more likely boxy (disky fraction decreases with luminosity e.g., Pasquali et al. 2007)



O’Riordan & Vegetti 2024

Galaxies are complex: let's include angular structure

Angular structure strongly favoured by the (ALMA) data

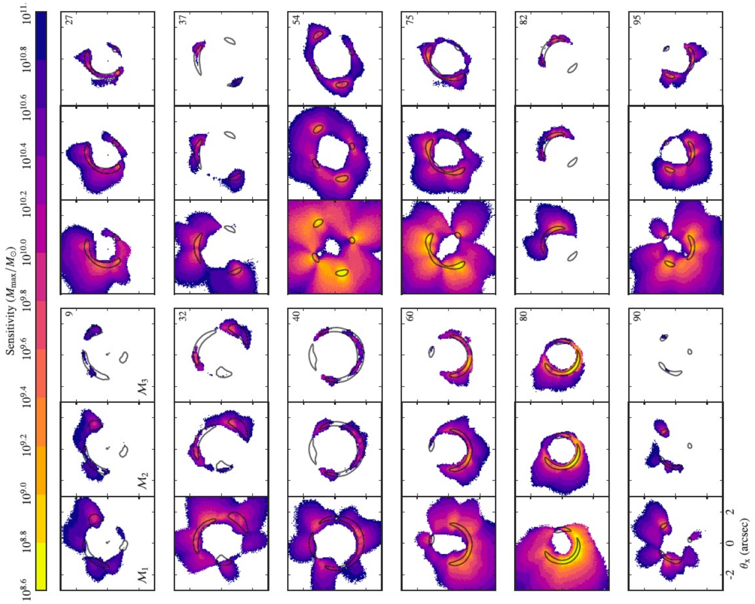


Stacey et al. 2024

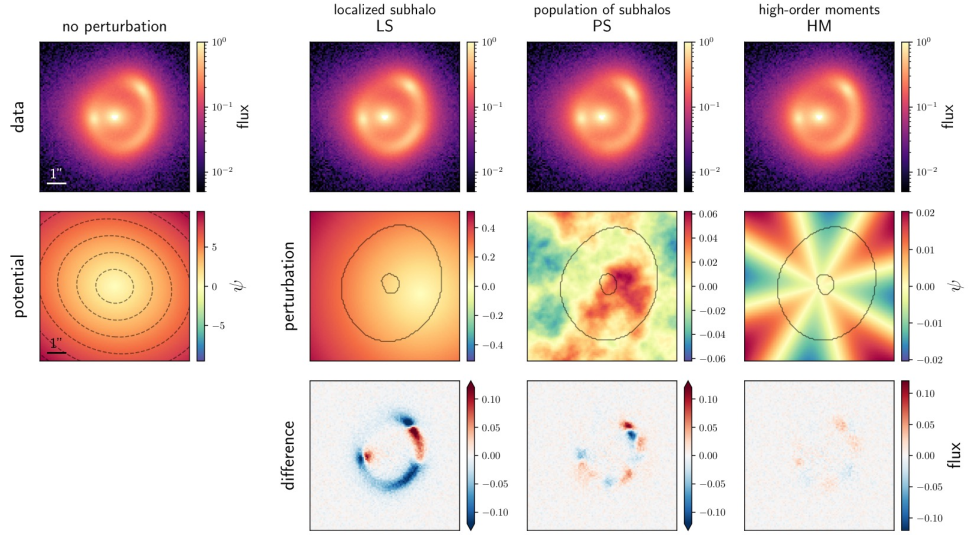
HST mock

Multipoles of 1 per cent = area in the observation where a subhalo could be detected drops by a factor of 3.

Sub-halos are detectable only close (or over) the lensed images



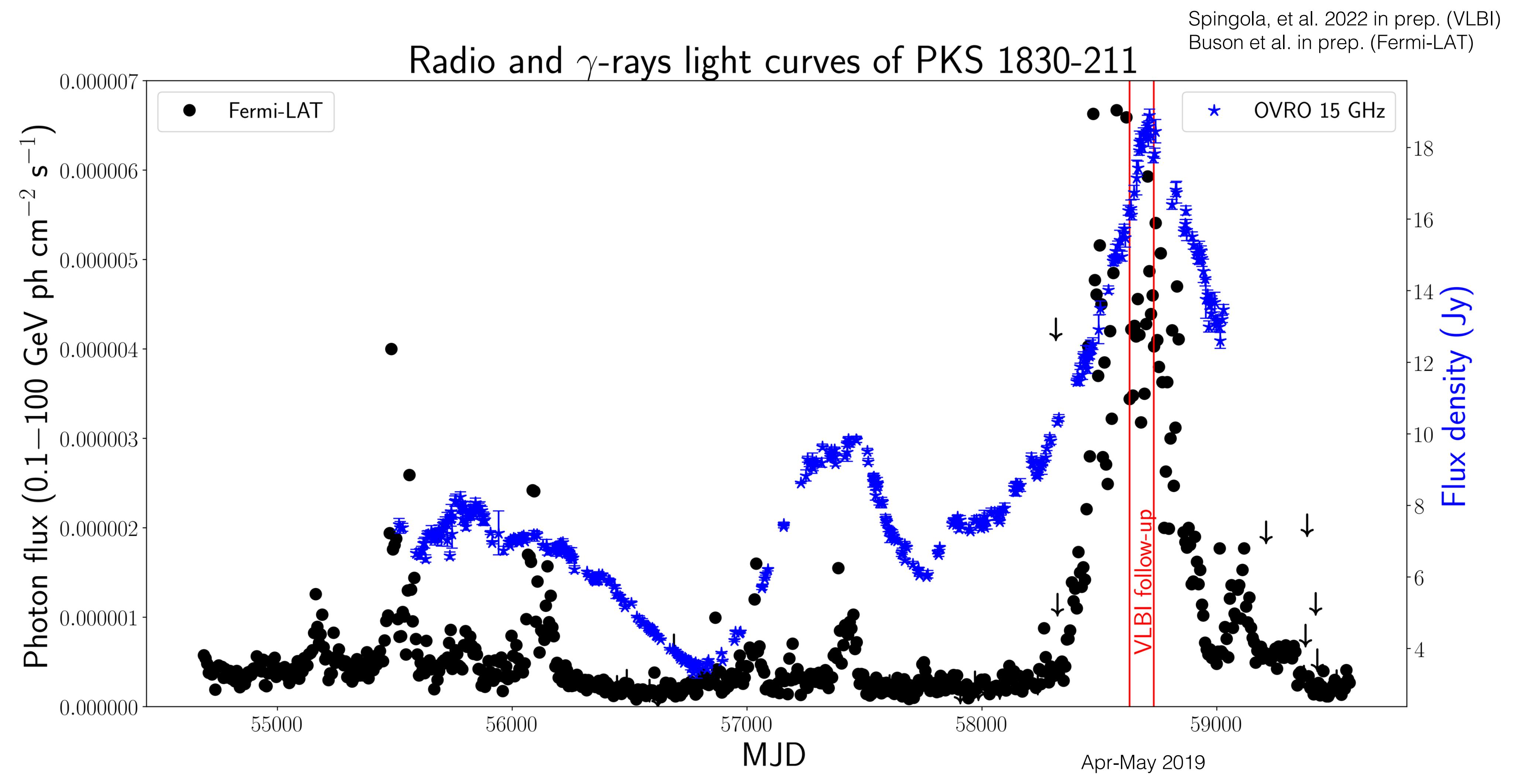
O'Riordan & Vegetti 2024



Galan et al. 2022

It is possible to discern between a population of low-mass halos and intrinsic multipole structure

The outstanding γ-ray flare from PKS 1830-211



Flare detection from radio to γ-rays

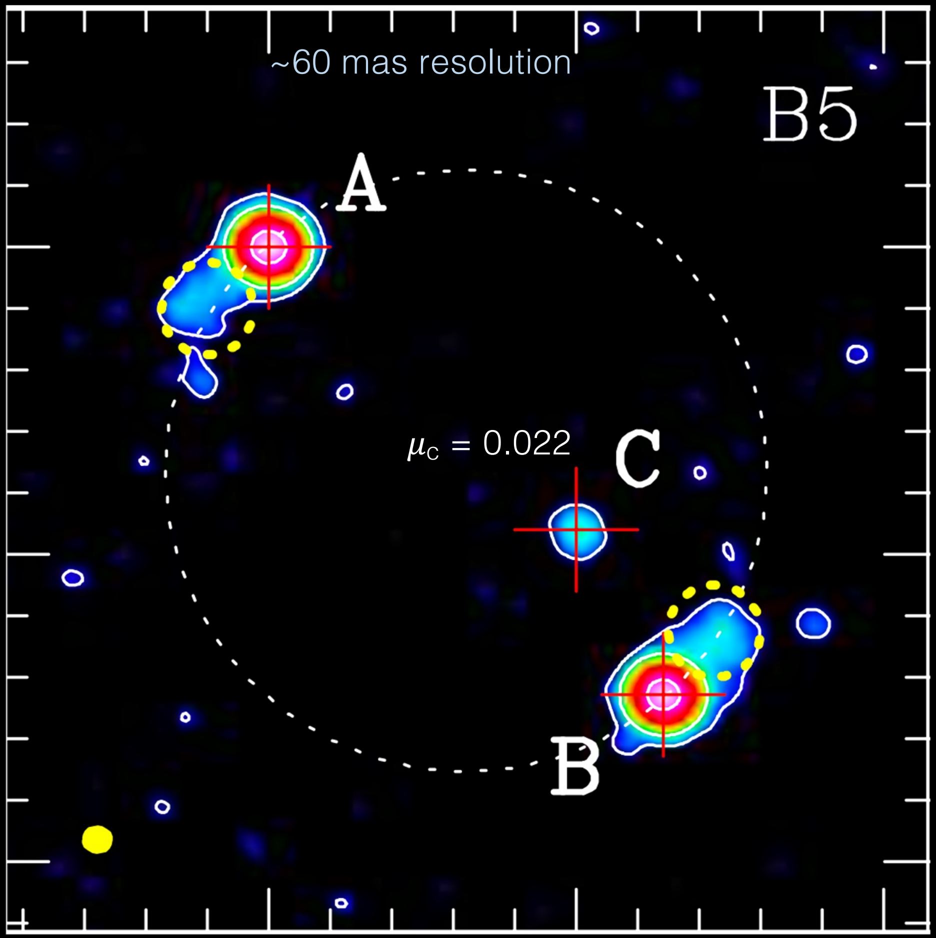
(Buson+2019, Angioni+2019, Cardillo+2019, Carrasco+2019, Ciprini+2019)

~3 months monitoring with the VLBA at 15, 24, 43 GHz

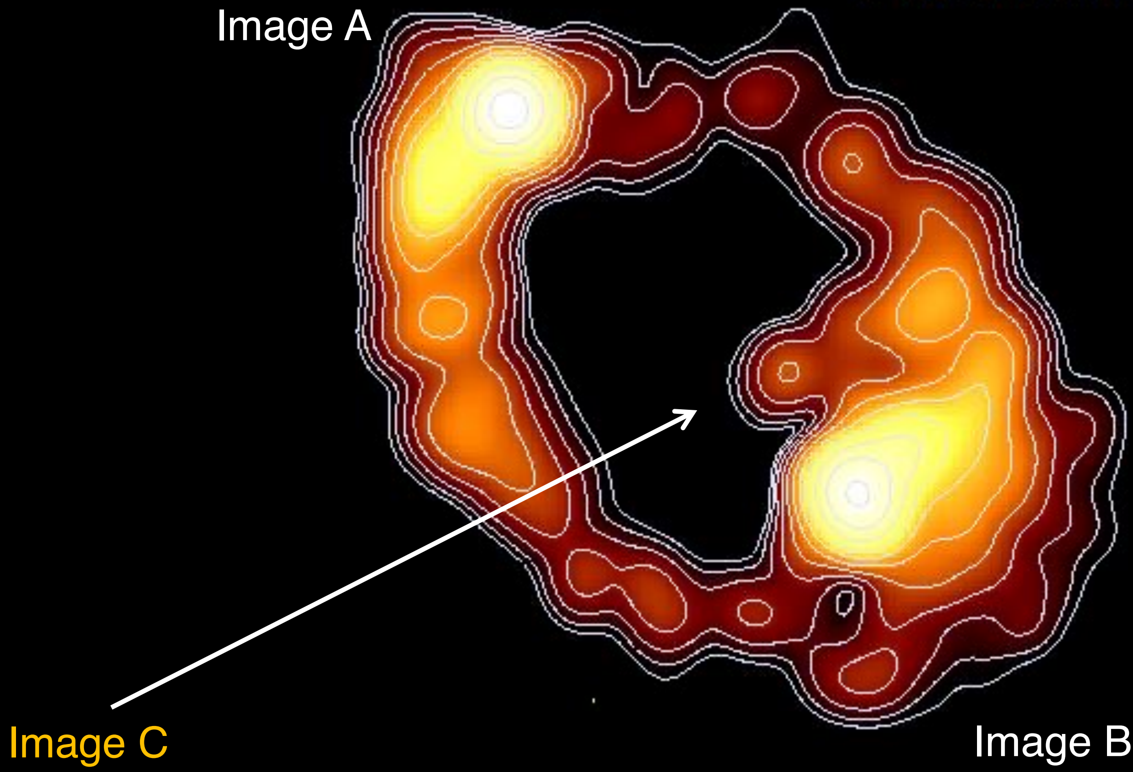
(PI: Spingola)

The central image from PKS 1830-211

ALMA Band 5 (**180 GHz**) during the FLARE



MERLIN 5 GHz (1993!!)



Jauncey+1991, Lovell+1993, Patnaik+1993

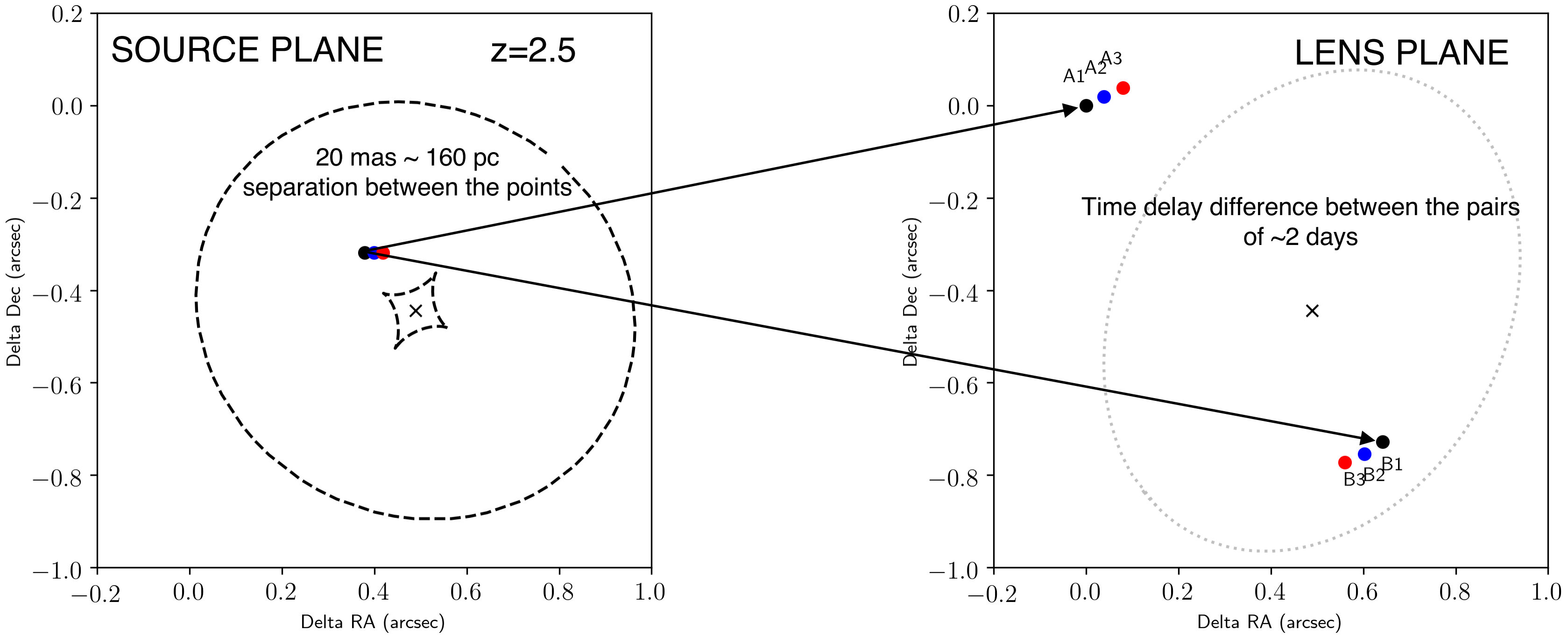
Müller+ 2020

Significantly improved lens model precision

predictions for time delays Δt_{AB}= 26 – 29 days and Δt_{AC}= 31 – 34 days

depending on H_0 value adopted

High angular resolution at gamma-rays: strong gravitational lensing – time delays


SOURCE PLANE z=2.5

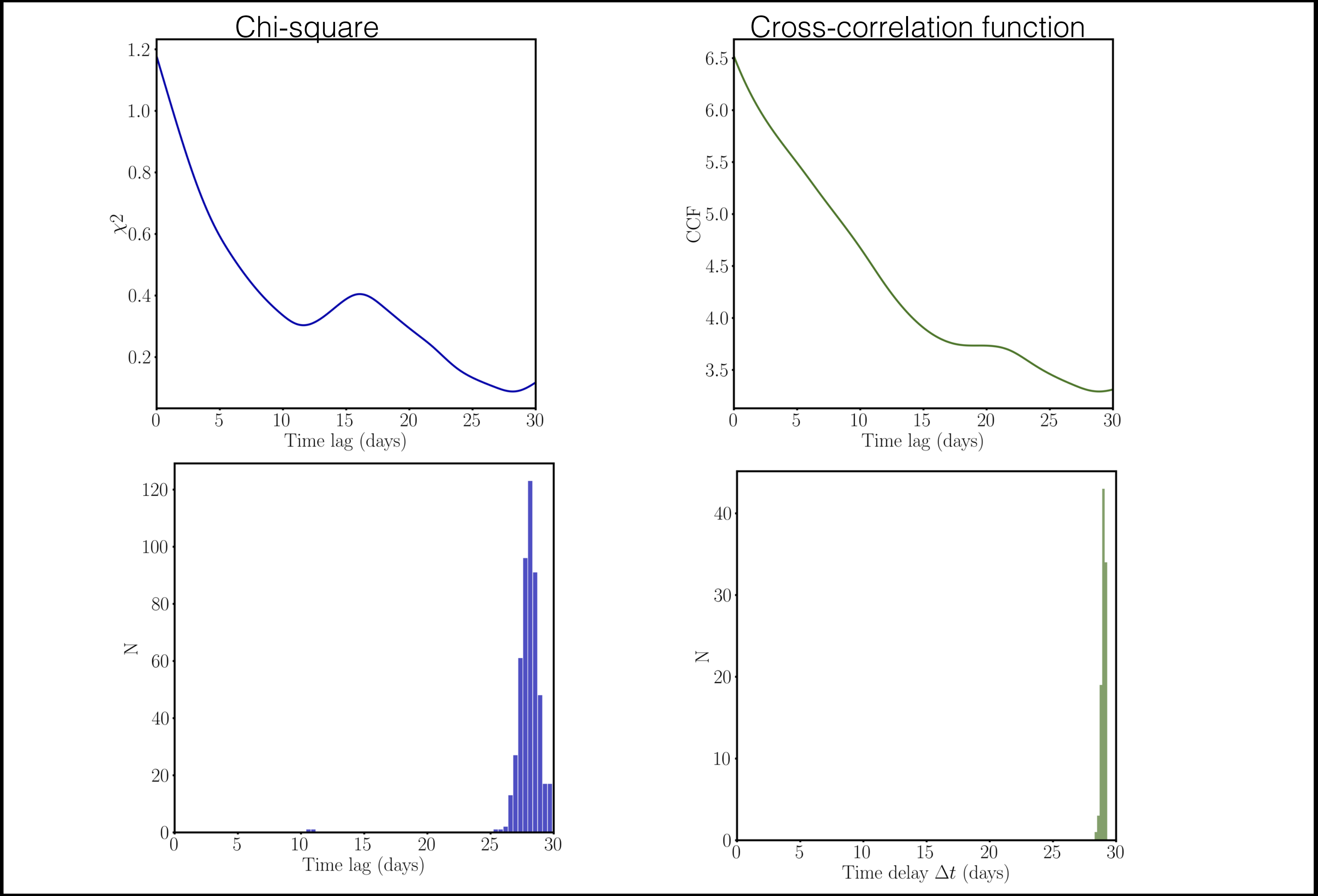
20 mas ~ 160 pc
separation between the points

LENS PLANE

Time delay difference between the pairs
of ~2 days

A1-B1 – time delay = 29 days
A2-B2 – time delay = 27 days
A3-B3 – time delay = 25 days

Time delay estimate with two methods



How many lenses in a given survey?

DARKER

~870 000 extragalactic variable sources
Gaia DR4
~10^2 strong lenses

~1000/2000 sources in Fermi-LAT
~ a few strong lenses

Lensing cross-section

Path length to the background source
(dependent on cosmology)

Lensing probability

$$\tau(z_s) = \int_0^{z_s} n(z)\,\sigma(z)\,\frac{c\,dt}{dz}\,dz$$

$\simeq 10^{-3}$ for lensing <u>galaxies</u>

e.g., Turner, Ostriker & Gott 1984; Spingola+2019a

Mass function of the lens population

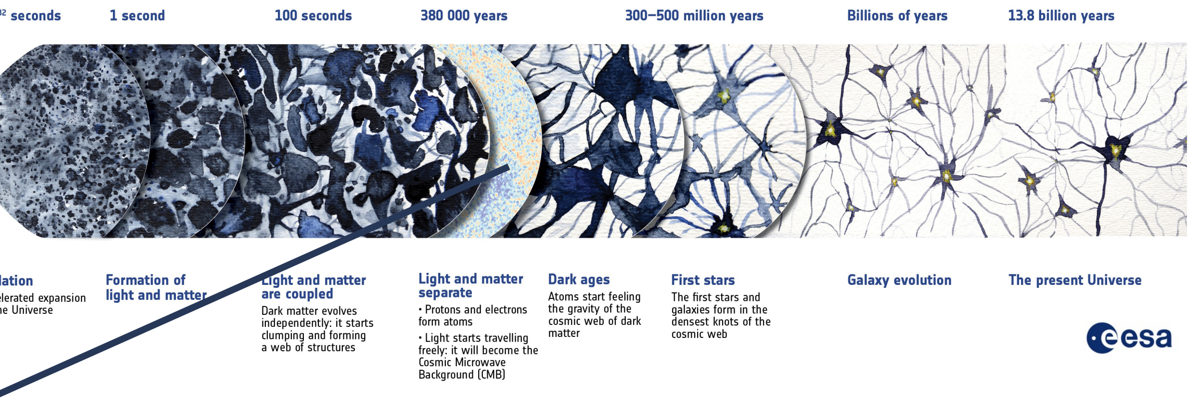
= n(z) and **σ**(z) vary significantly for <u>sub-halos</u> (M<10^8M$_{sun}$)

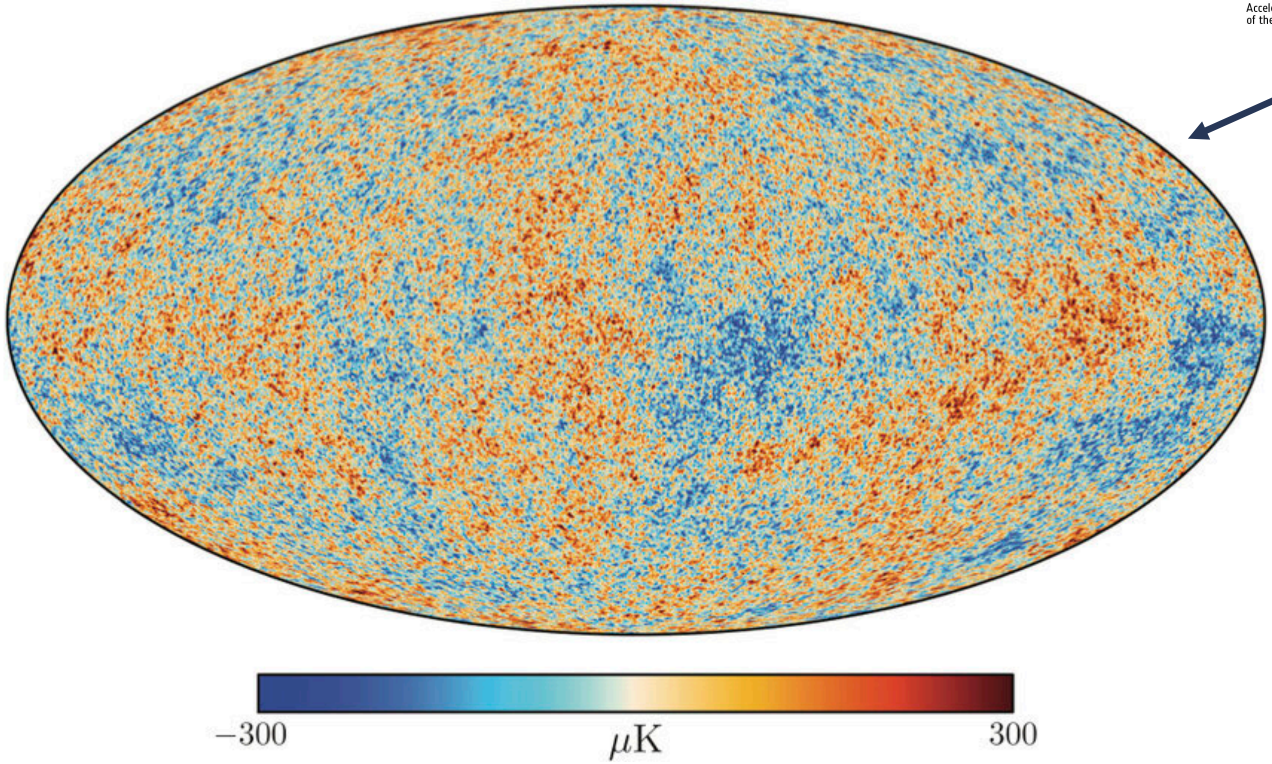
e.g., Press and Gunn+1973, Casadio+2021, Loudas+2022

DARKER (only Fermi-LAT)

~ a few for standard CDM model (<10)
~ none for WDM models

Cosmic Microwave Background





Planck measurement of the temperature fluctuations in the CMB sky

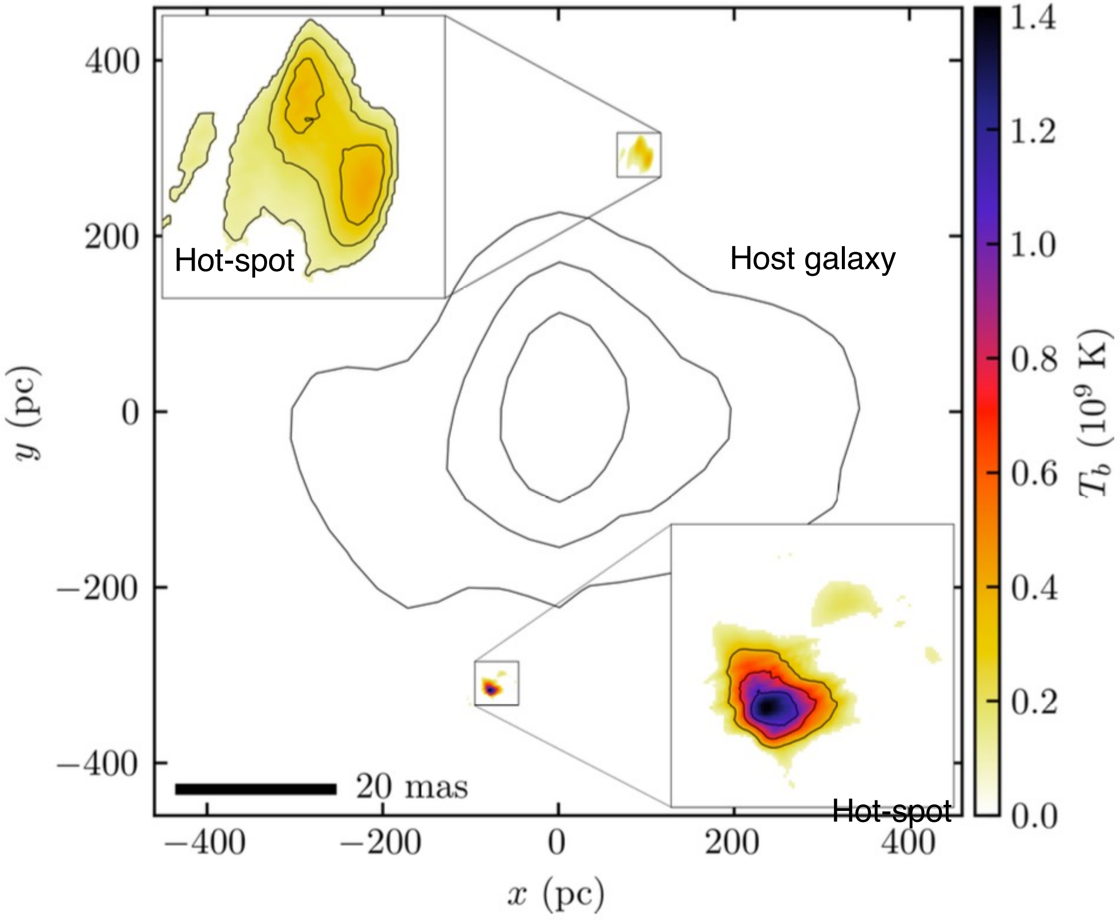
Credits: European Space Agency (ESA)

The temperature of CMB from all directions turns out to be almost the same, except for a tiny fluctuation (of a relative size about 1/100000), implying that the Universe was **highly homogeneous** in the early time

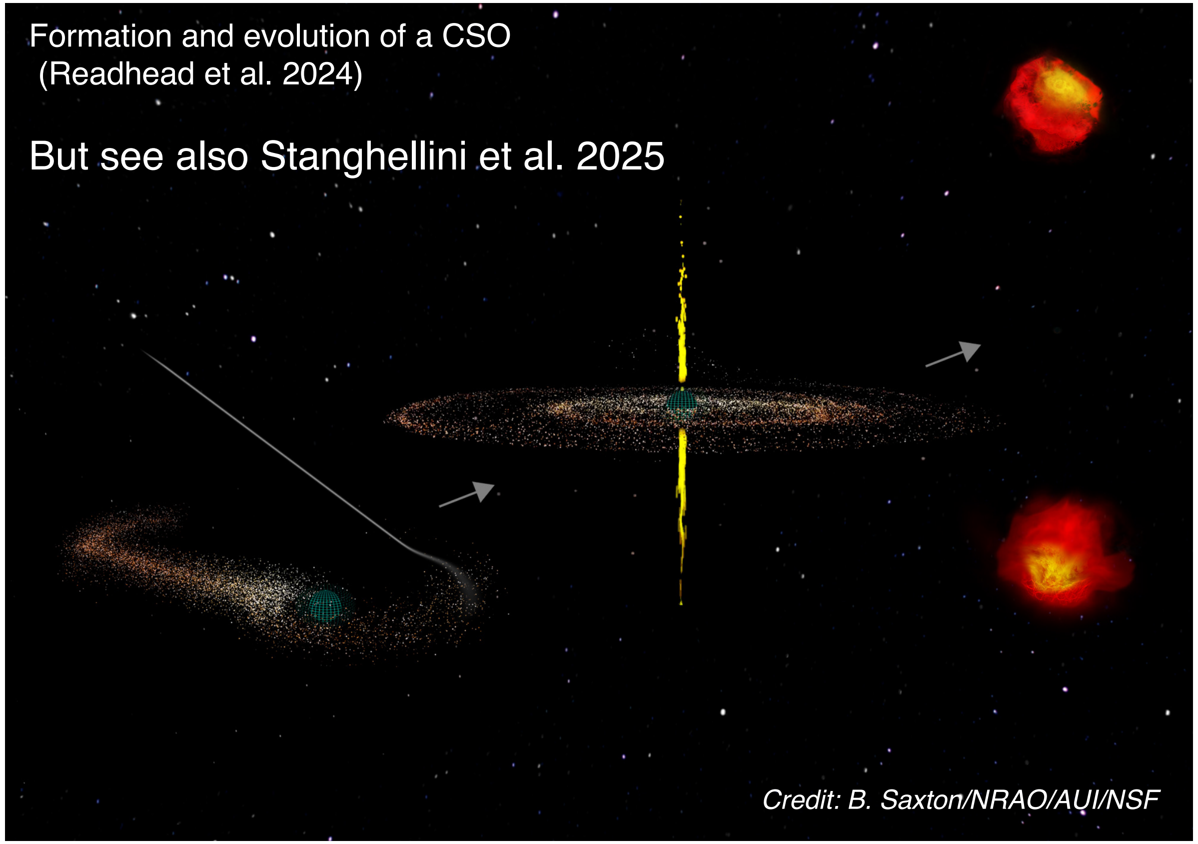
Dark matter cannot be «hot» (v~c) **otherise the small-scale structures would be smoothed out** and we would not be able to form the large scales in the way we observe them

As a by-product we obtain the reconstruction of the background source

a compact symmetric object at $z > 2$



McKean et al. 2025



Formation and evolution of a CSO
(Readhead et al. 2024)

But see also Stanghellini et al. 2025

Credit: B. Saxton/NRAO/AUI/NSF

When a single, massive star wanders too close to a black hole (left), it is devoured and this causes the black hole to shoot out an ultrafast, bipolar jet (center). The jet extends outward and its hot ends glow with radio emissions (right).