The sharpest view of blazar jets through space and mm-VLBI observations

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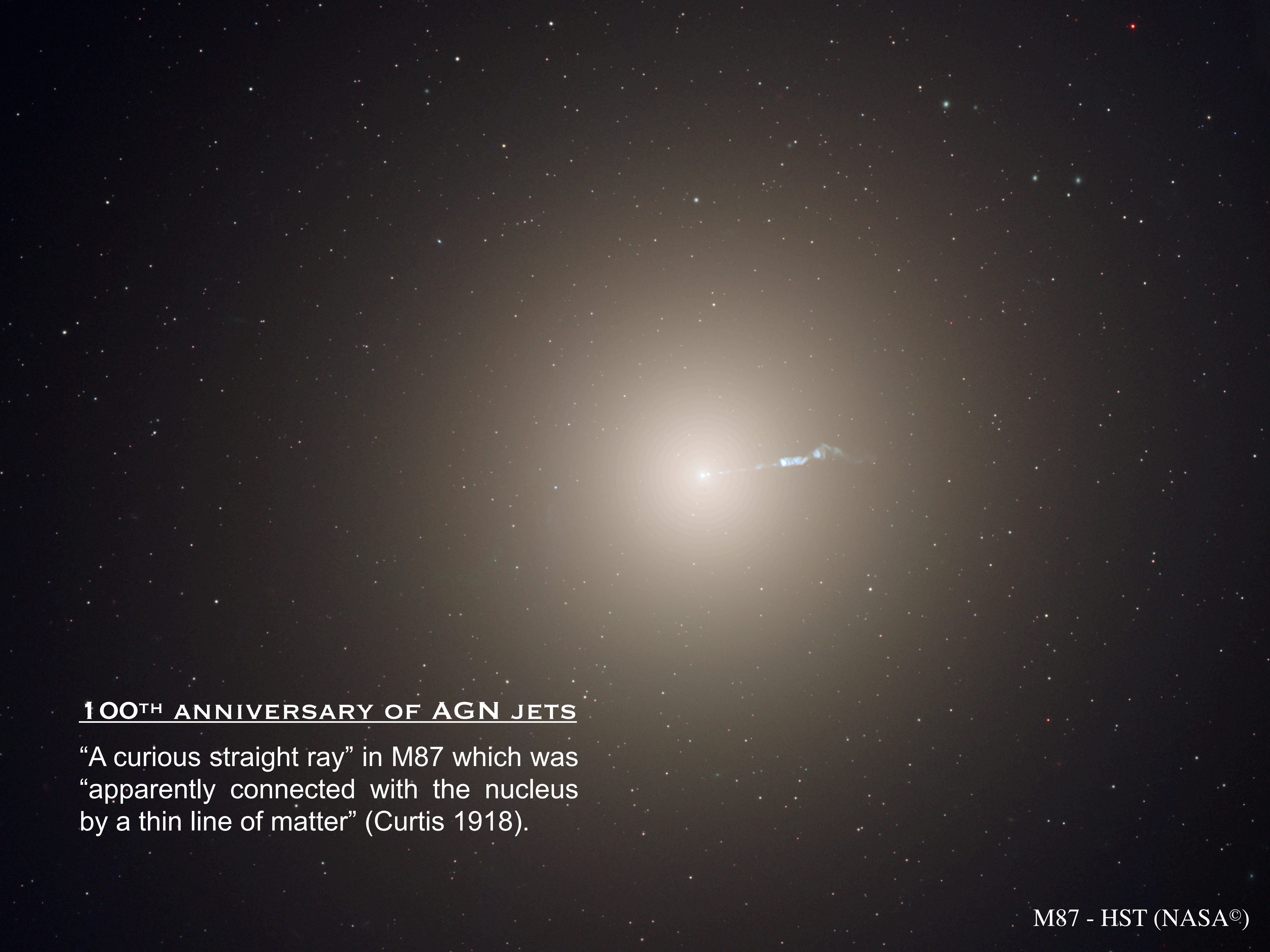
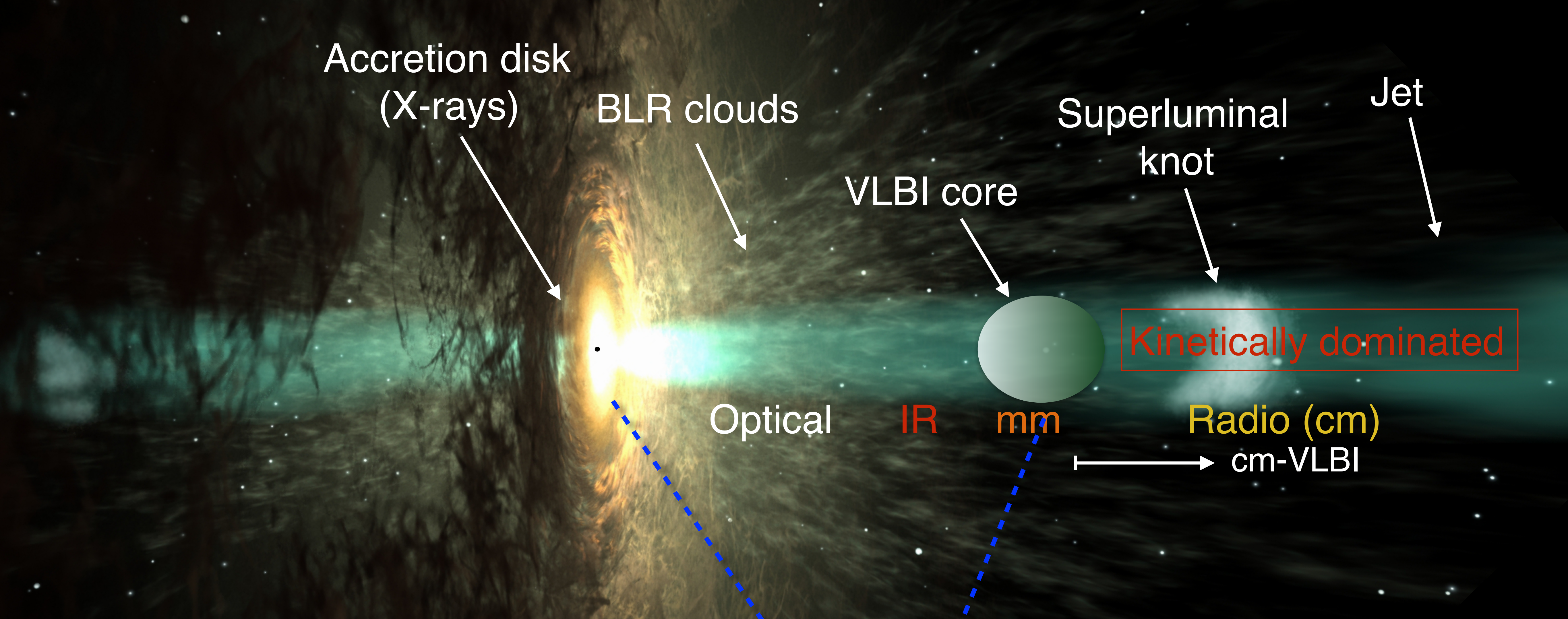
EVN 2018, Granada, October 8-11, 2018



100TH ANNIVERSARY OF AGN JETS

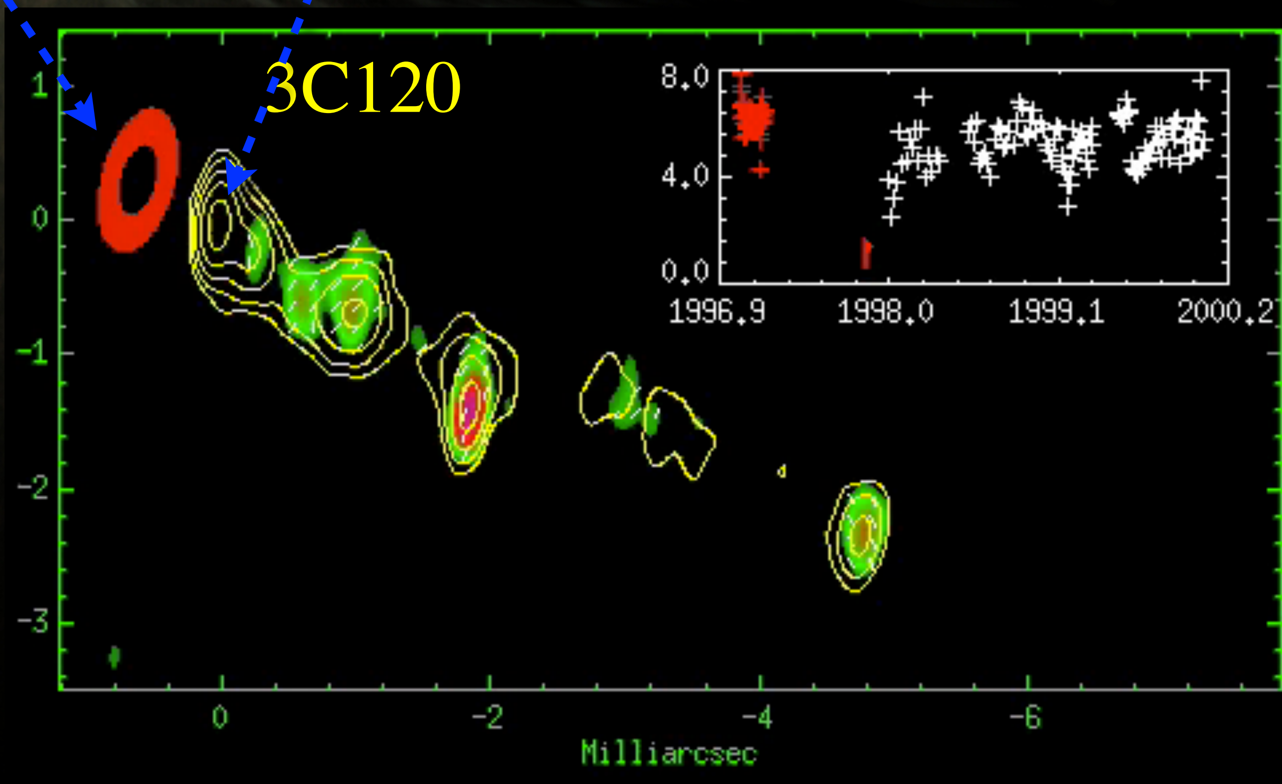
"A curious straight ray" in M87 which was "apparently connected with the nucleus by a thin line of matter" (Curtis 1918).

M87 - HST (NASA©)

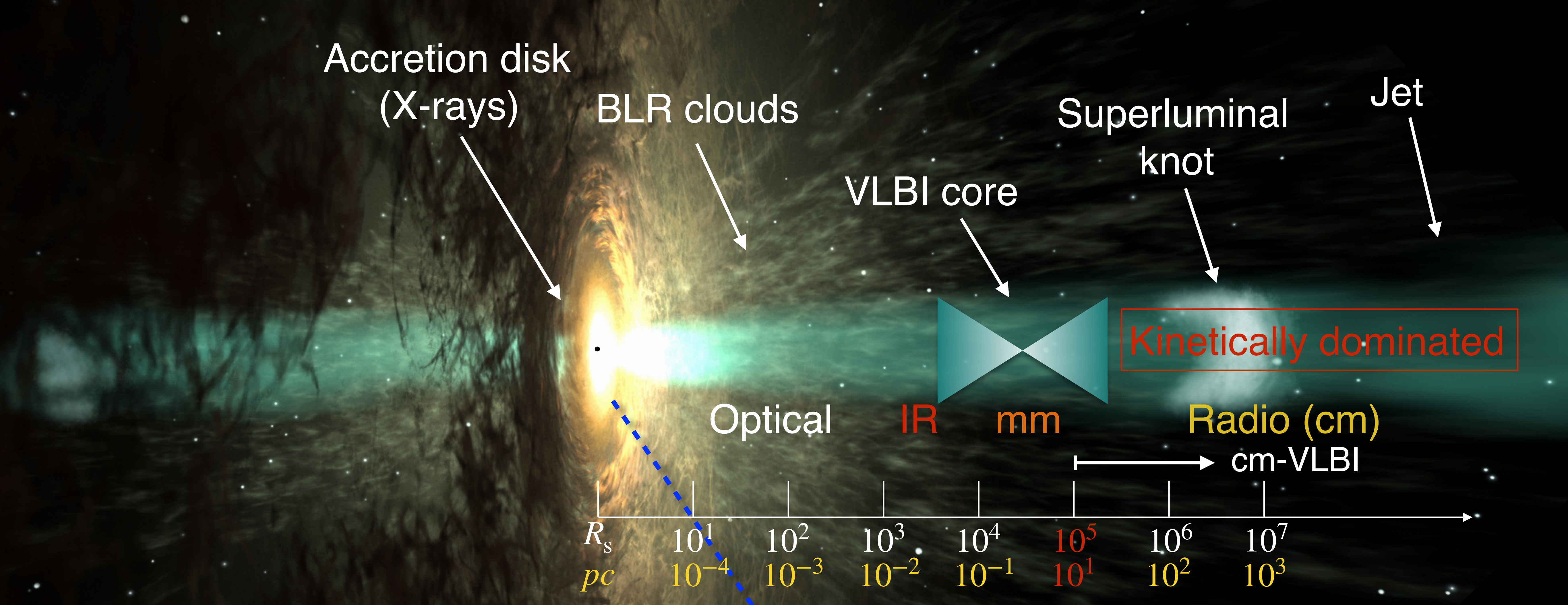


cm-VLBI observations

- Moving shocks (Marscher & Gear 1985)
- MOJAVE & BU monitorings:
  - Collimated conical jets (Pushkarev+ 2017)
  - $\Gamma \sim 10$, $\theta \lesssim 10$
  - Kinetic-flux dominated
- Disk-jet connection. VLBI core may correspond to a recollimation shock located ~pc away from the central BH (Marscher+ 2002, Chatterjee+ 2011, Casadio+2015, Fromm+2015).
- Crossing of components through mm-VLBI core may trigger high energy flares (Marscher+2010)



Marscher, Jorstad, JLG+ (2002, Nature)



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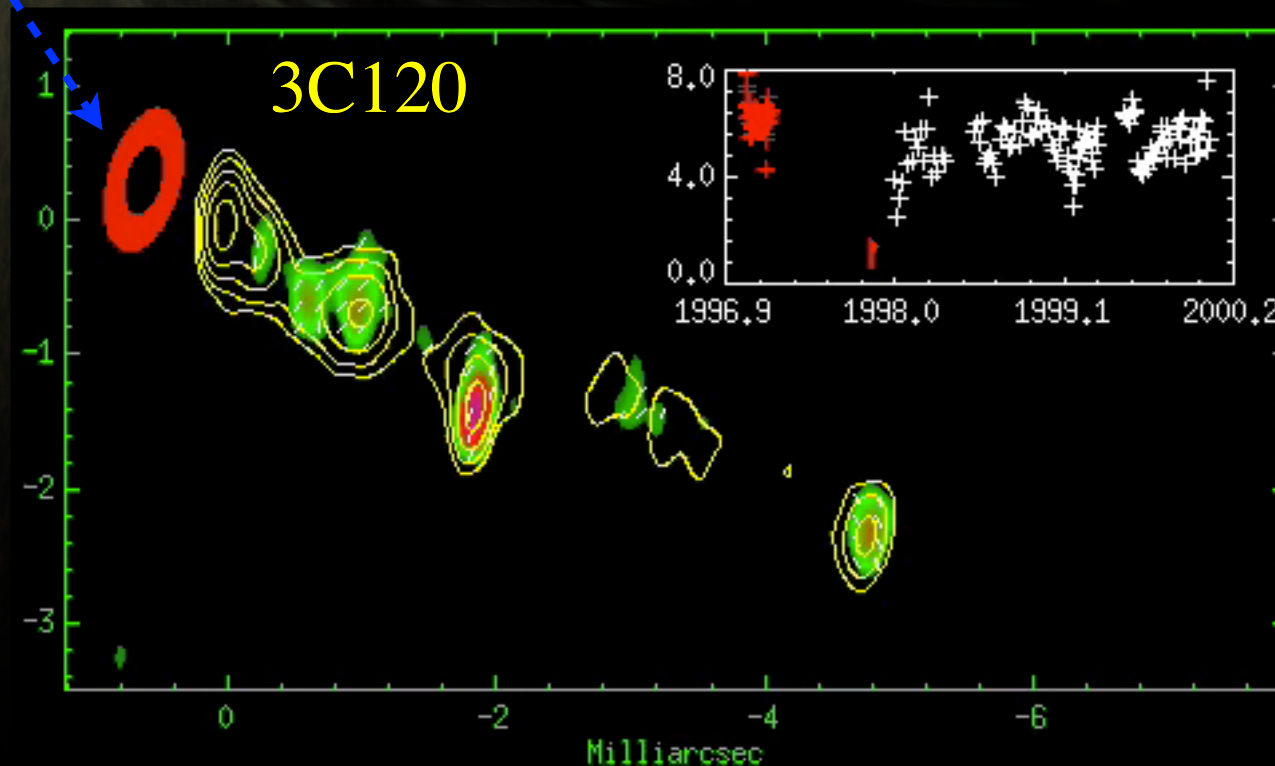

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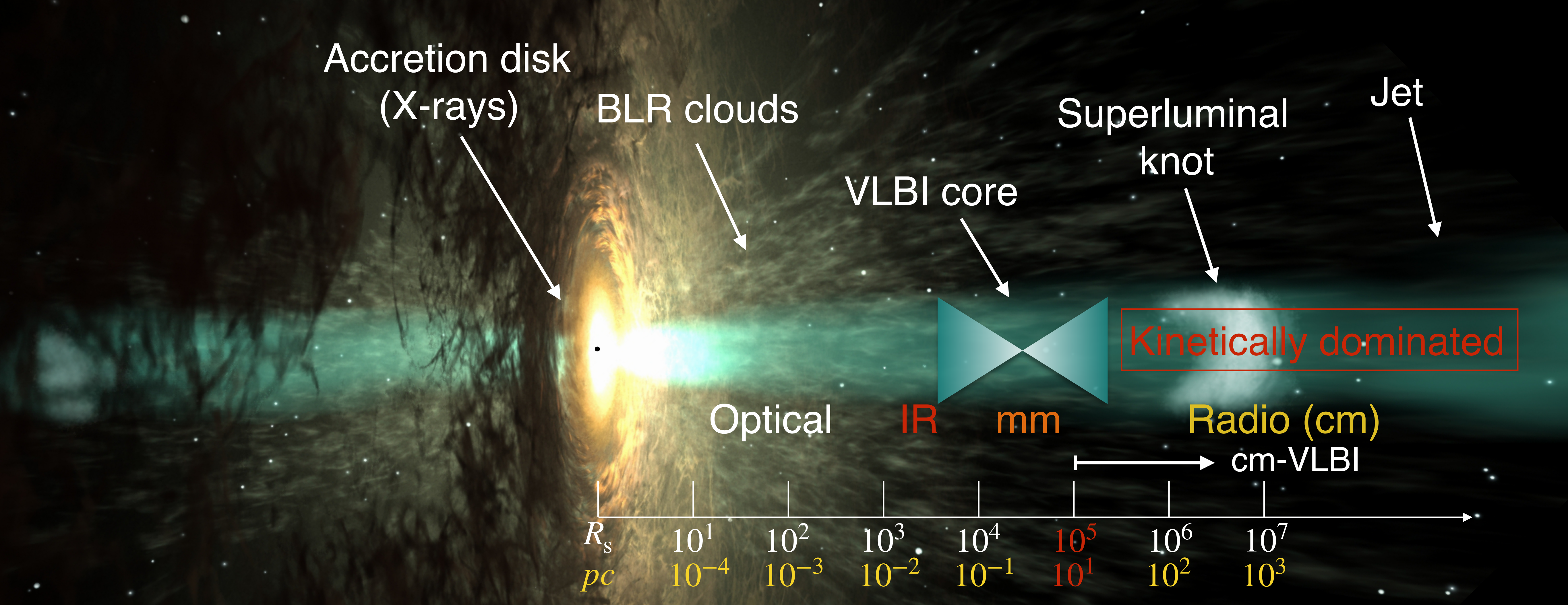
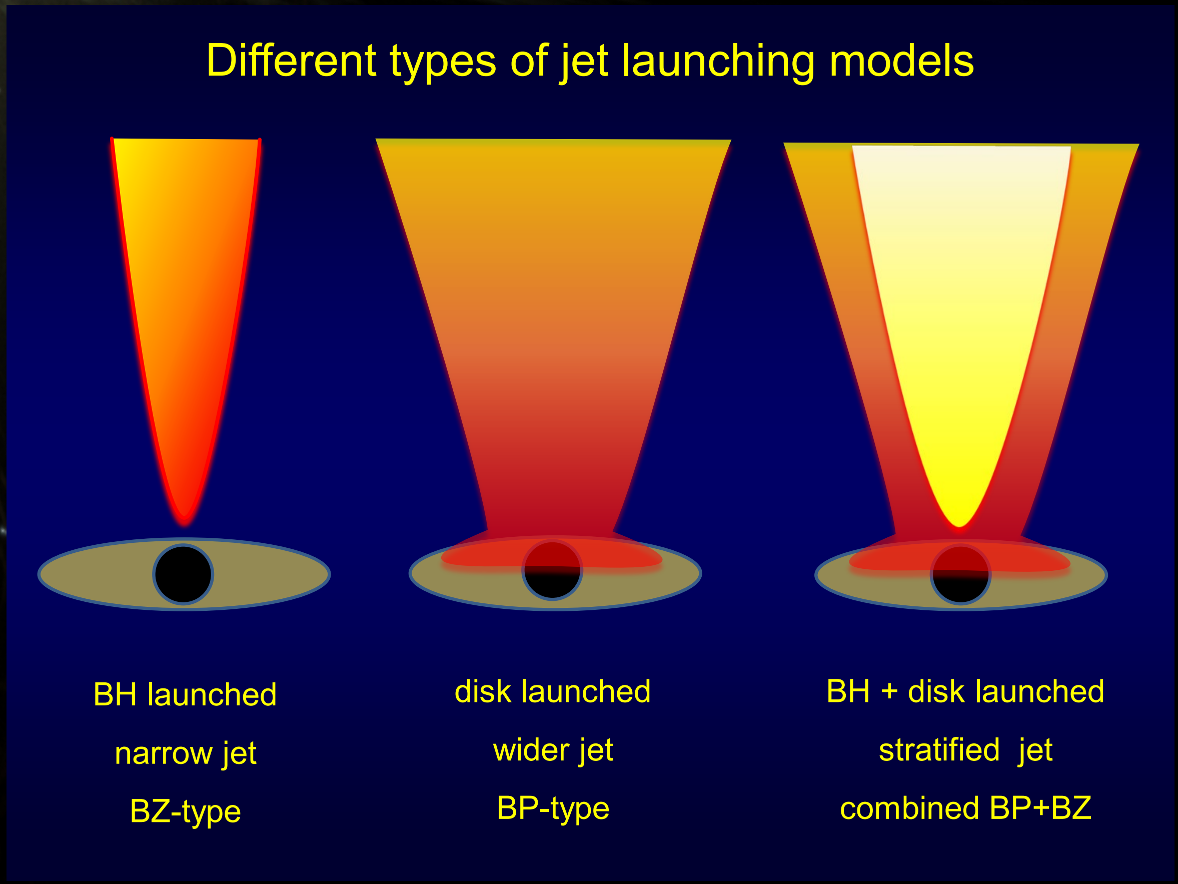
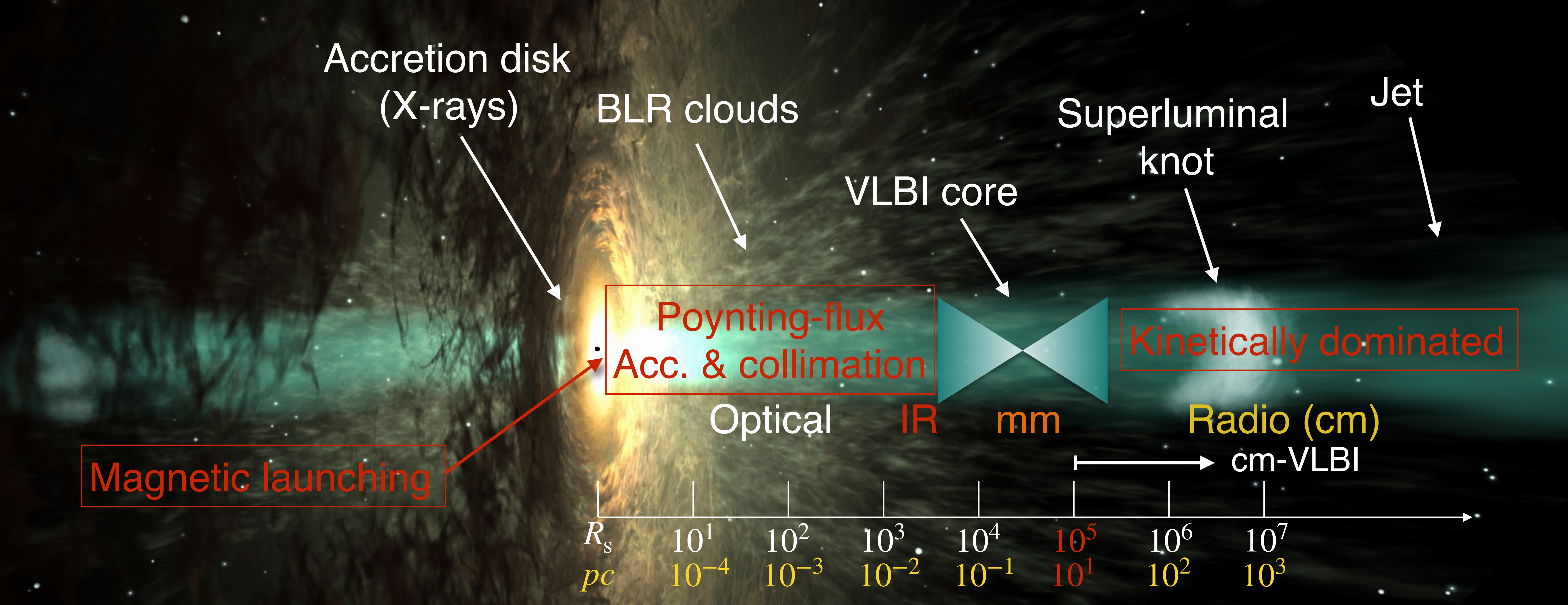


Jet formation

- **Helical magnetic fields**, either anchored in the black hole (Blandford & Znajek 1977) or accretion disk (Blandford & Payne 1982), launch, accelerate, and collimate the jets.





Jet formation

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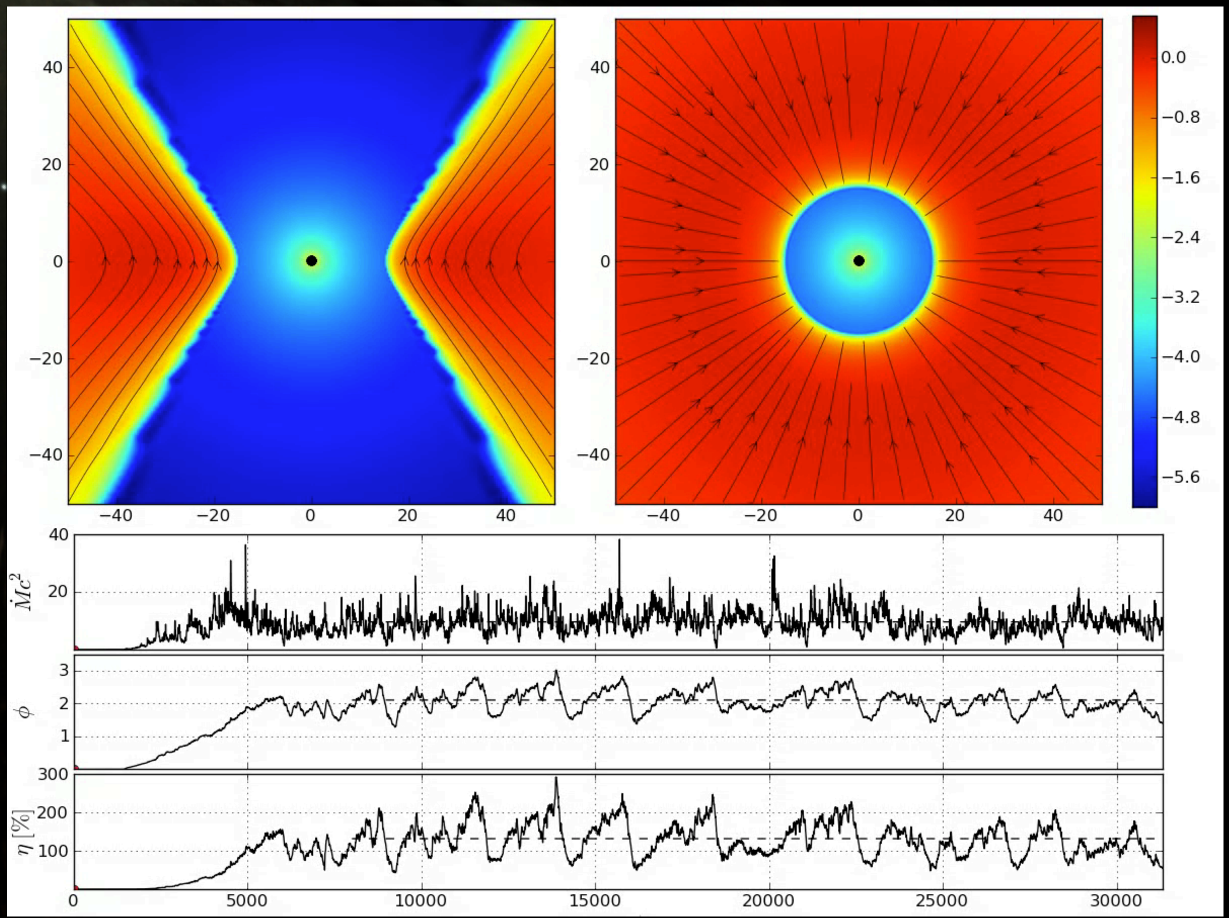
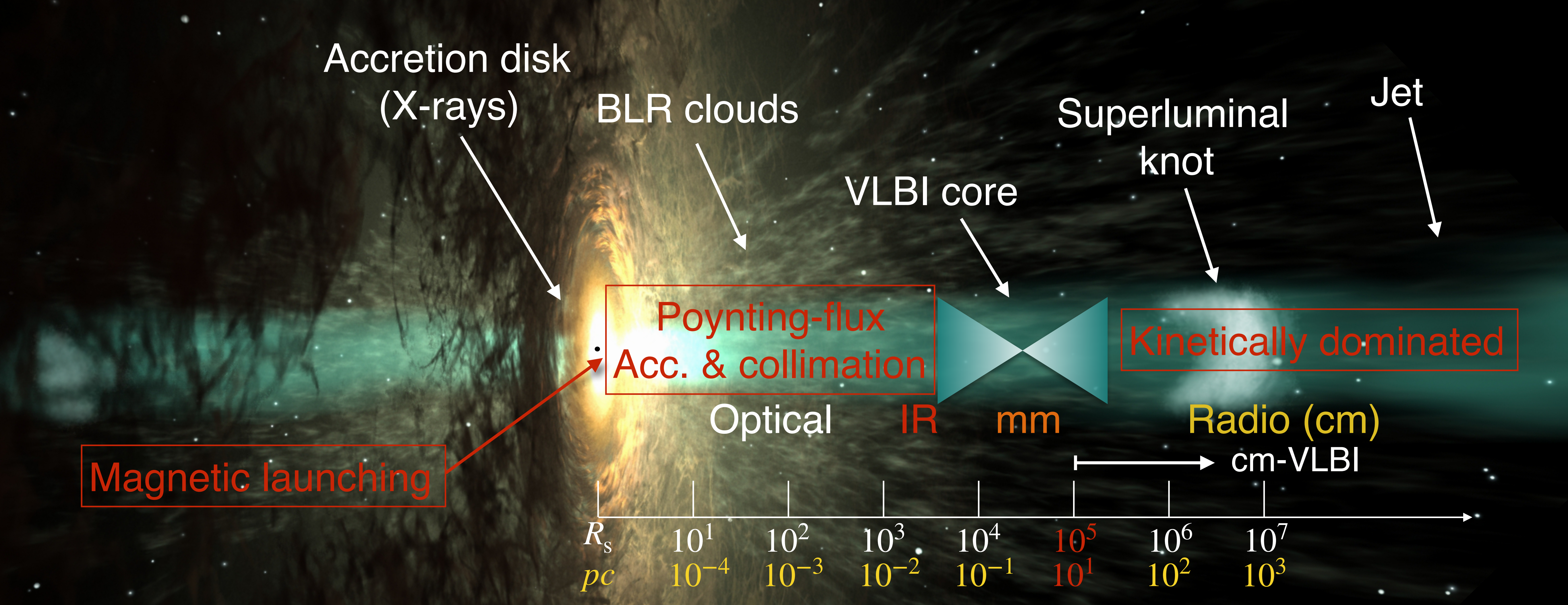
- GRMHD simulations of a fast spinning black hole (a=0.99) are now capable of reproducing the jet launching in magnetically arrested disks (MAD) with an efficiency > 100% (extracting spin energy from the black hole).



Tchekhovskoy et al. (2011)

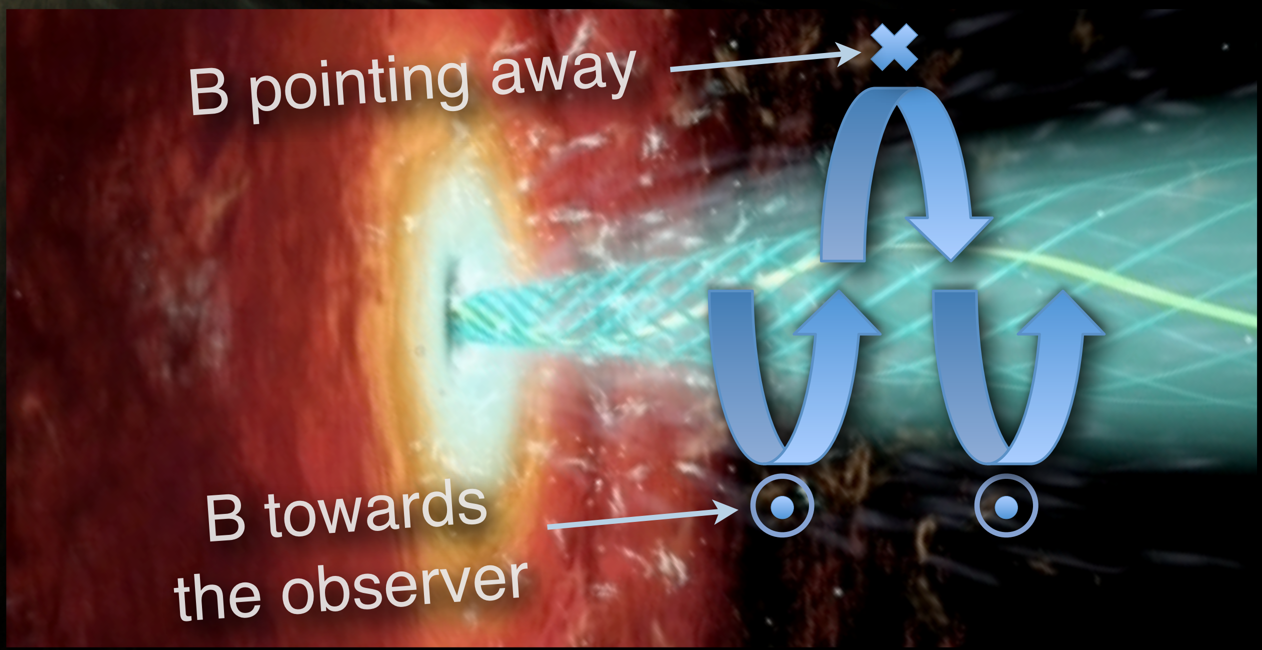


Magnetic field structure at pc-scales

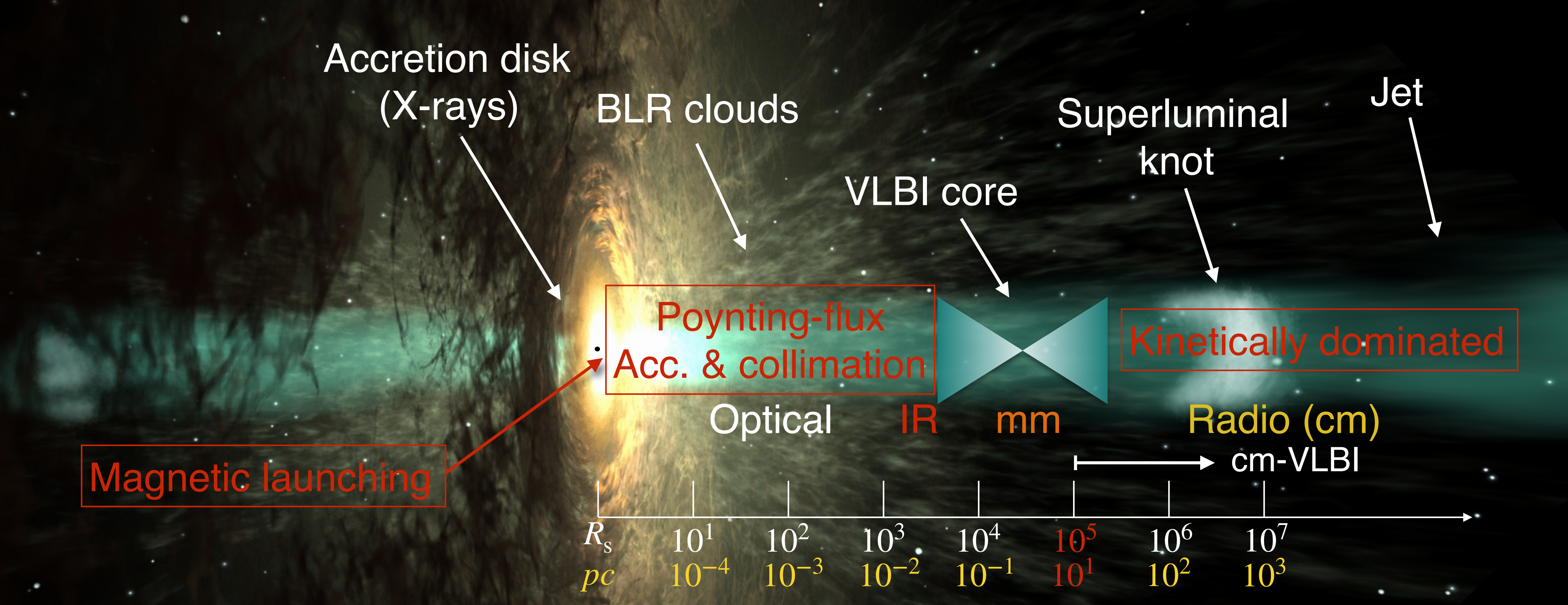
- Low lineal polarization (m≲15%) suggests partially tangled field. But, there are some indications of large scale ordered (helical) field.
- Faraday rotation produces a rotation of the observed polarization $\chi = \chi_0 + \mathrm{RM}\lambda^2$, where

$$\mathrm{RM} = 812 \int n_e B_{||} \mathrm{d}l$$

It is therefore possible to determine the 3D structure of the magnetic field in AGN jets through multi-frequency polarimetric observations.



A helical magnetic field would lead to a gradient in RM across the jet width (Laing 1981) and a point-symmetric structure around the core (Porth+2011).



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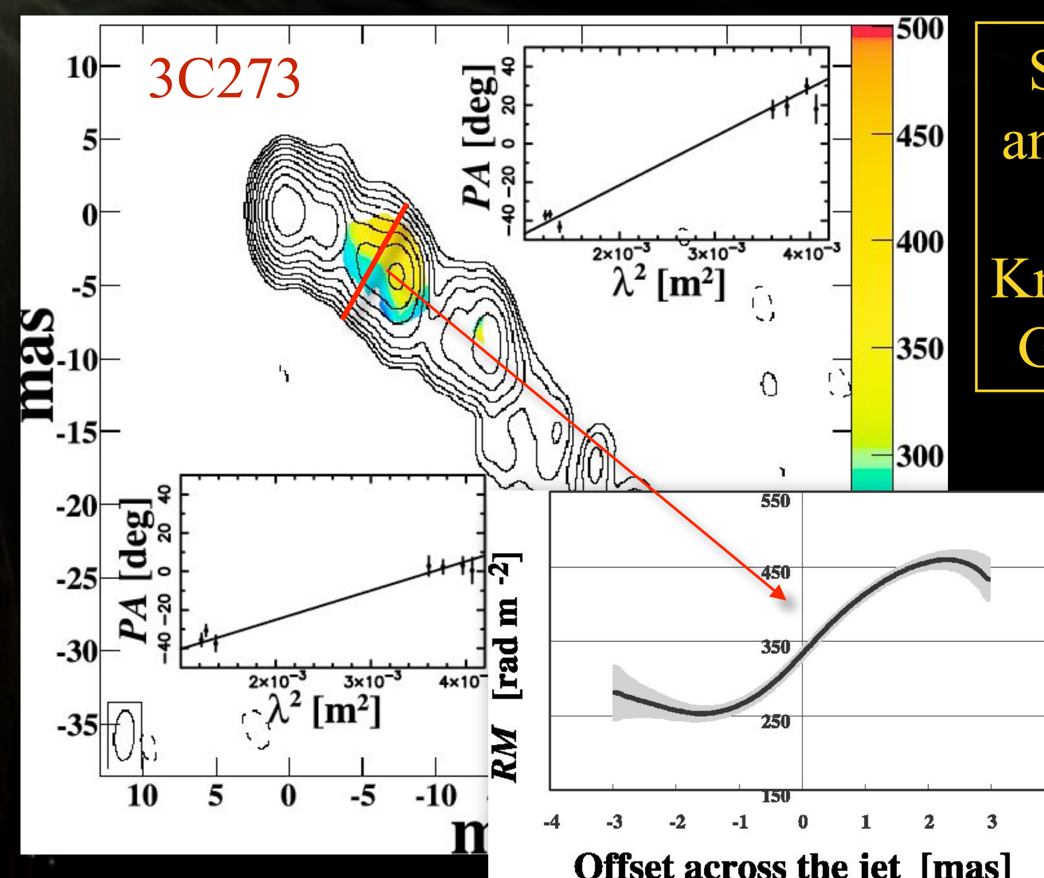
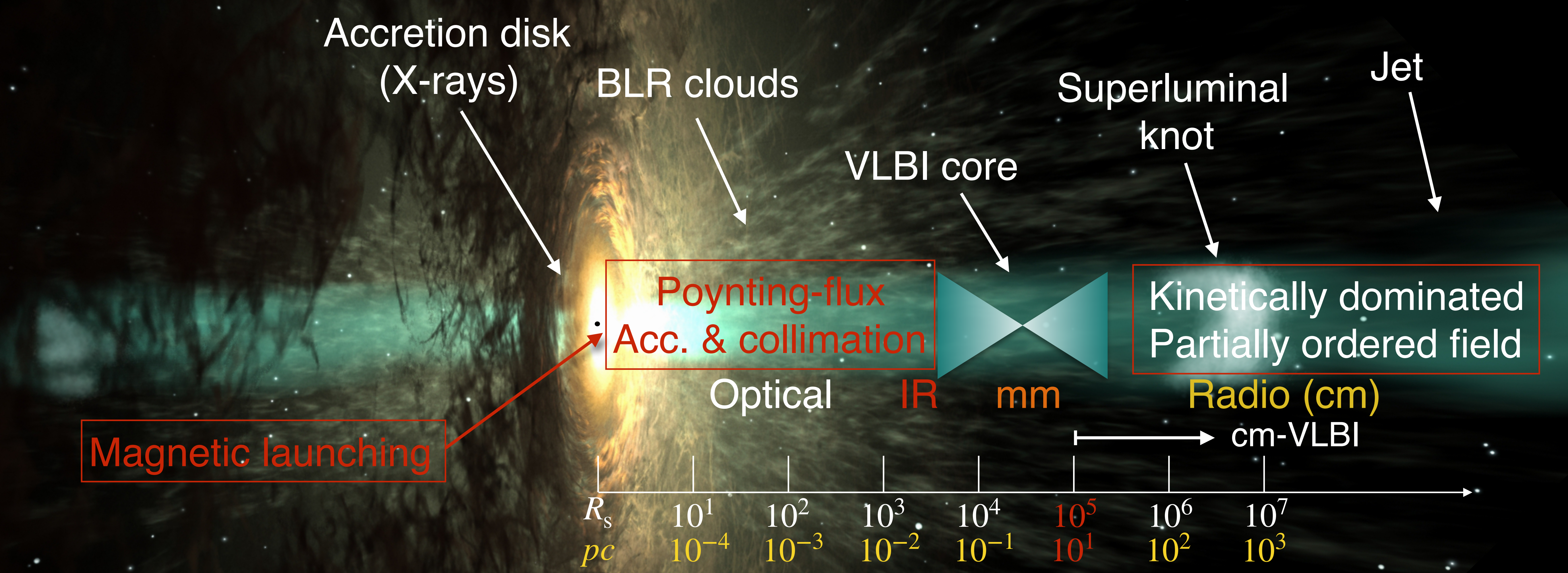


Asada+ (2002)

See talk and poster by Knuettel & Gabuzda



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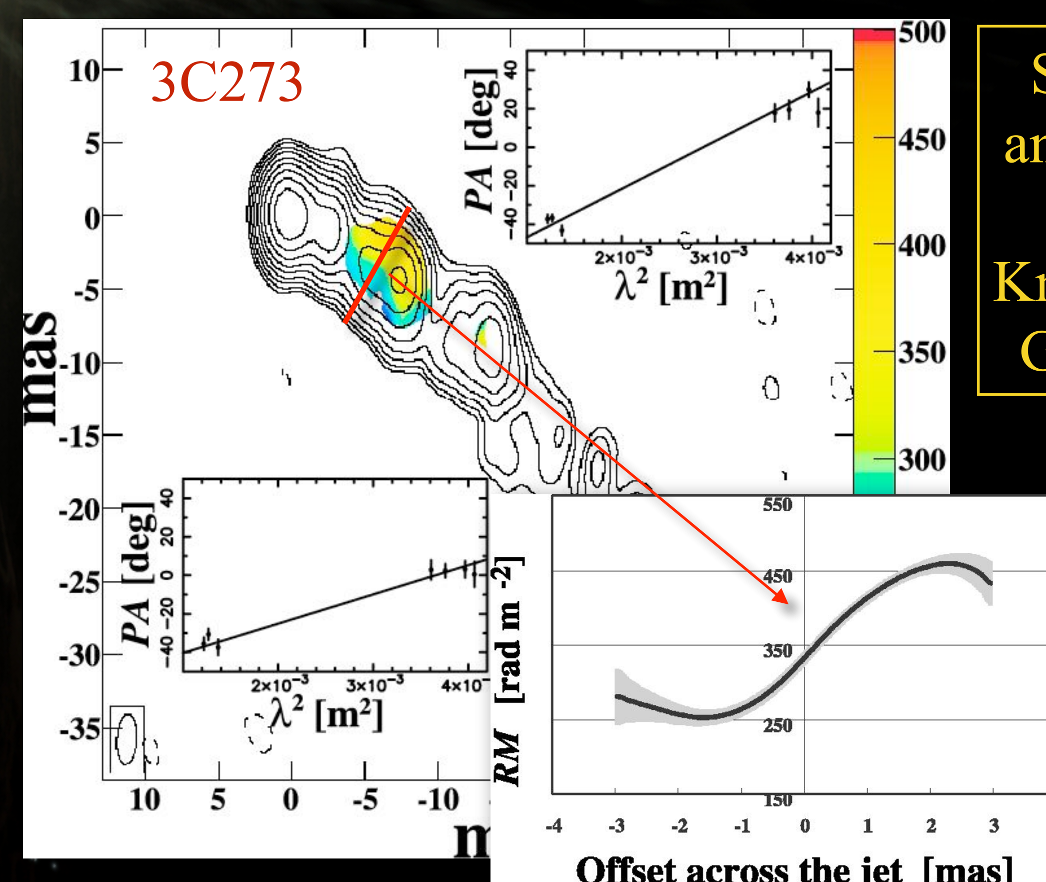

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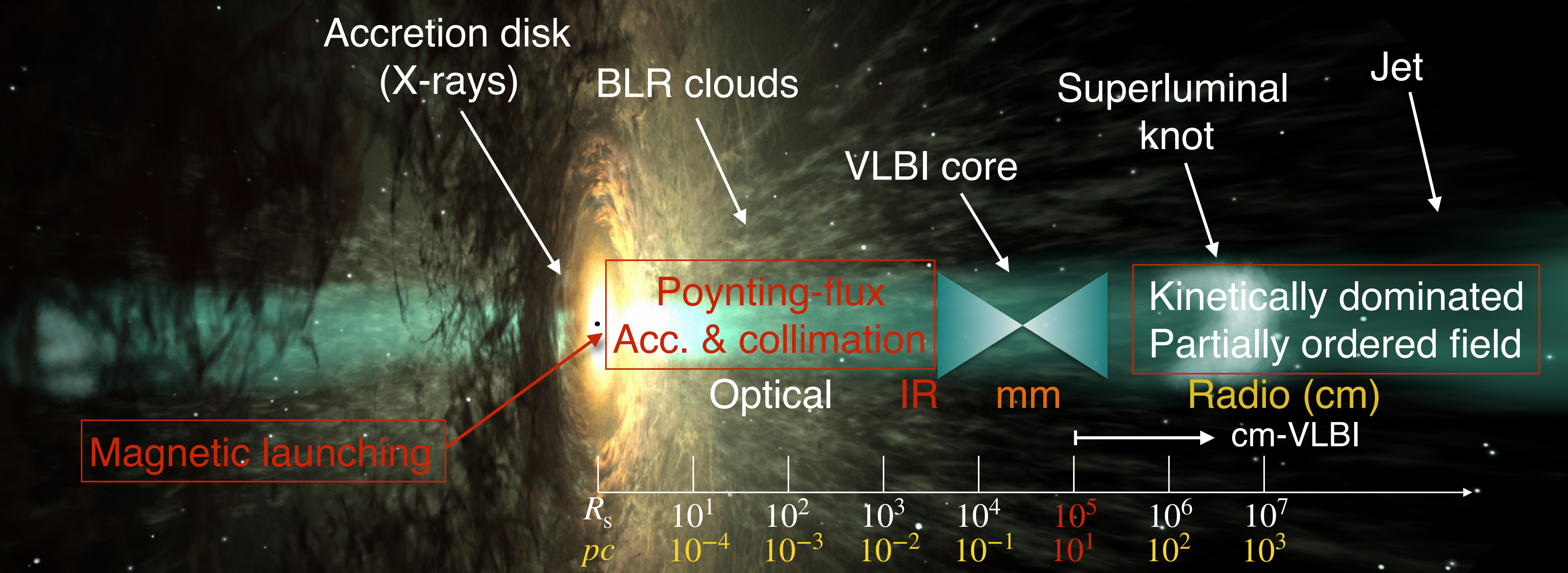
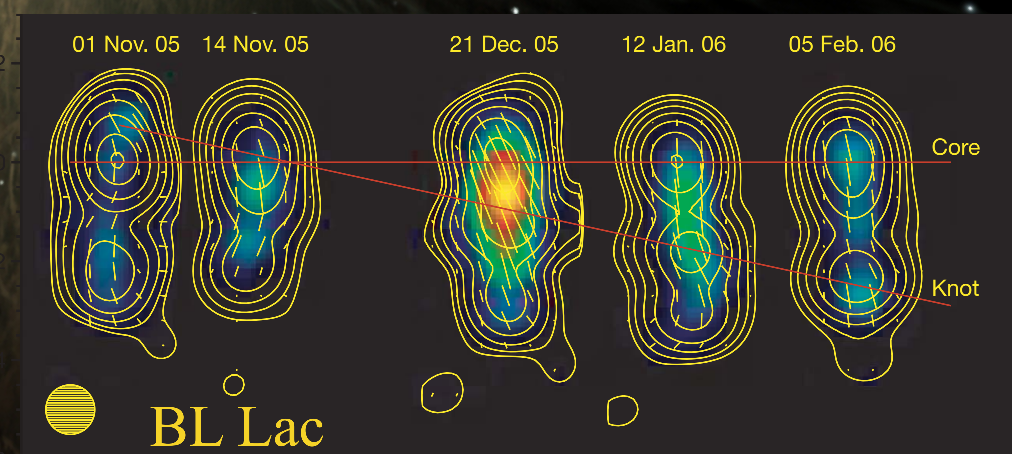
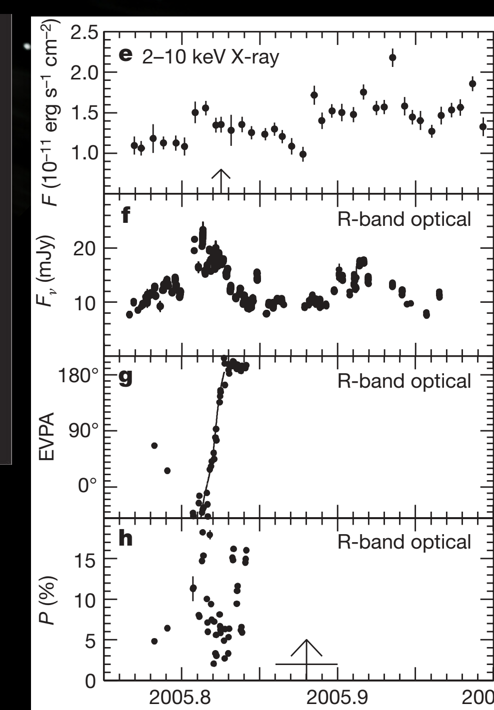


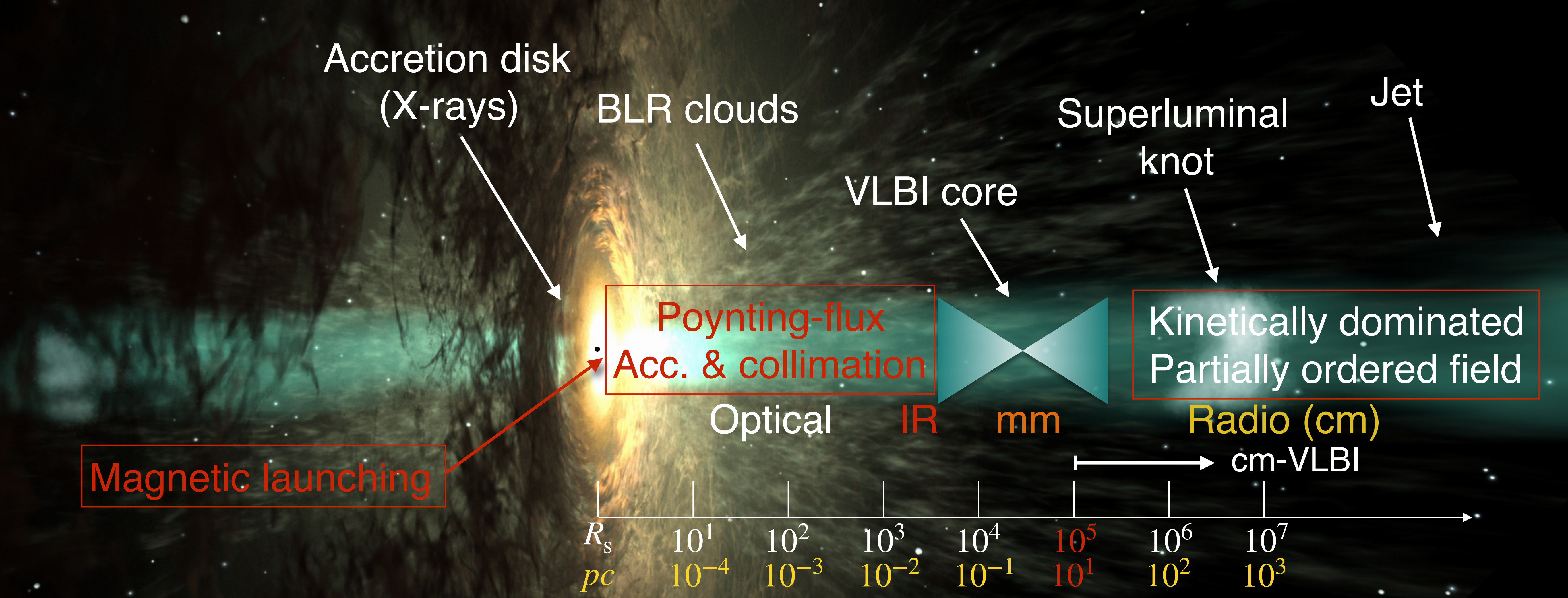
Magnetic field in collimation zone

- MWL observations of BL Lac revealed rapid optical polarization rotation associated with the motion of a component through a helical magnetic field in the acceleration and collimation zone (Marscher+2008)





Marscher et al. (2008)



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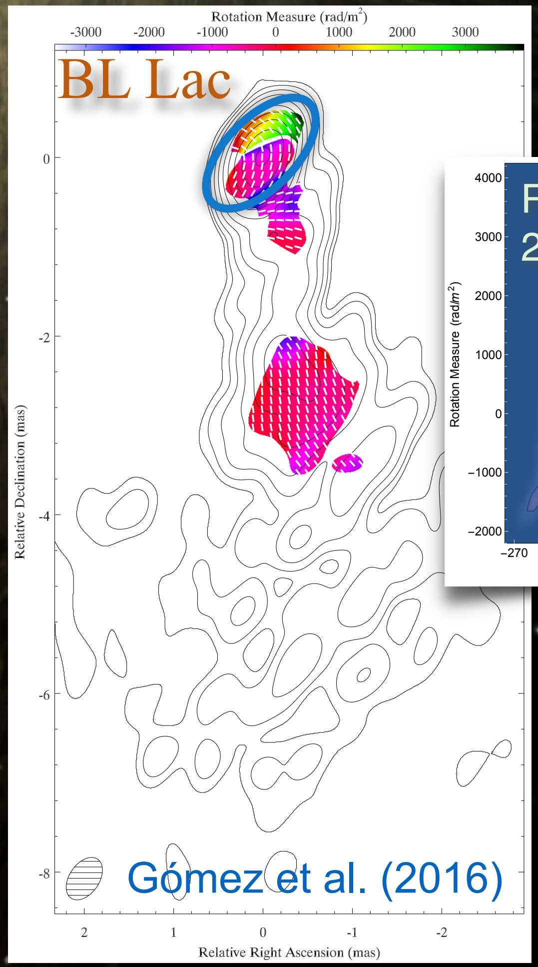
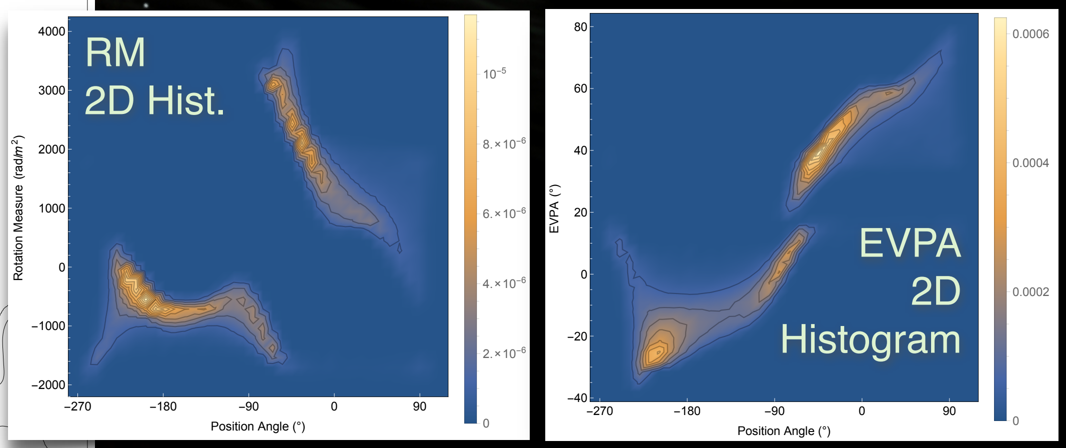
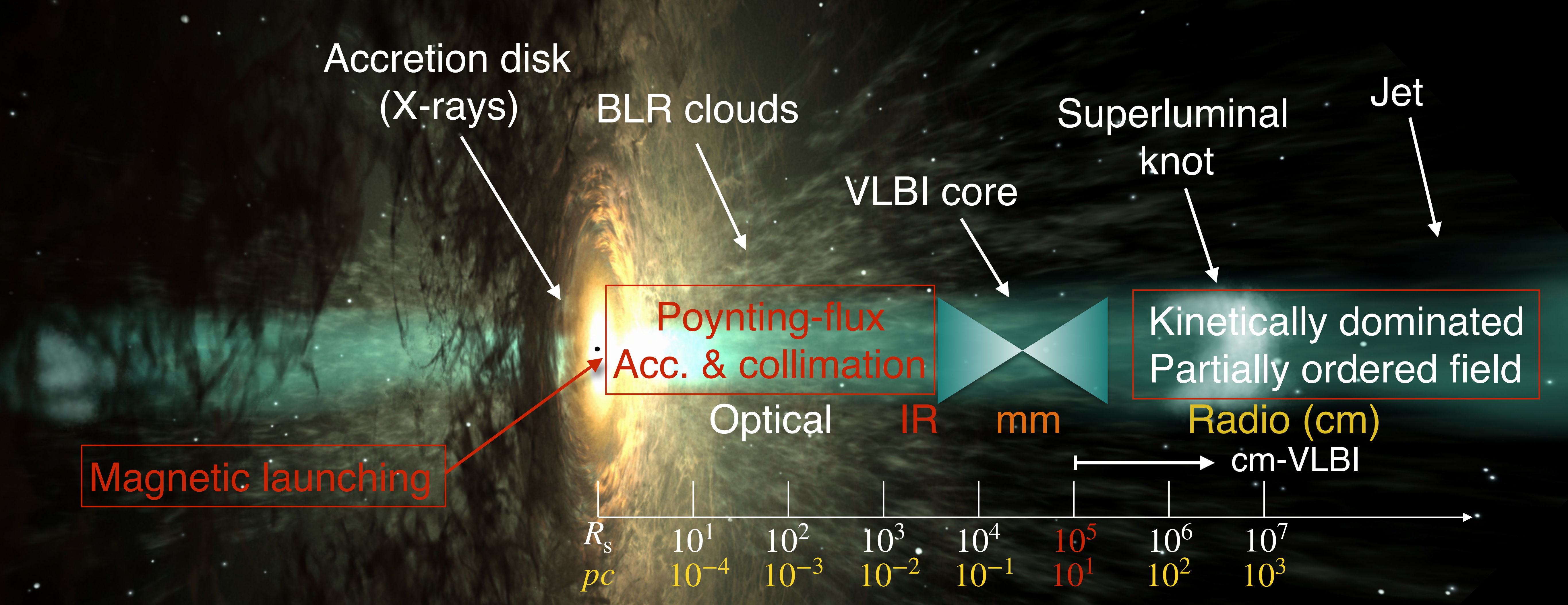


RadioAstron observations of BL Lac



The polarization structure is consistent with the existence of a helical magnetic field threading the jet (Gómez+ 2016).



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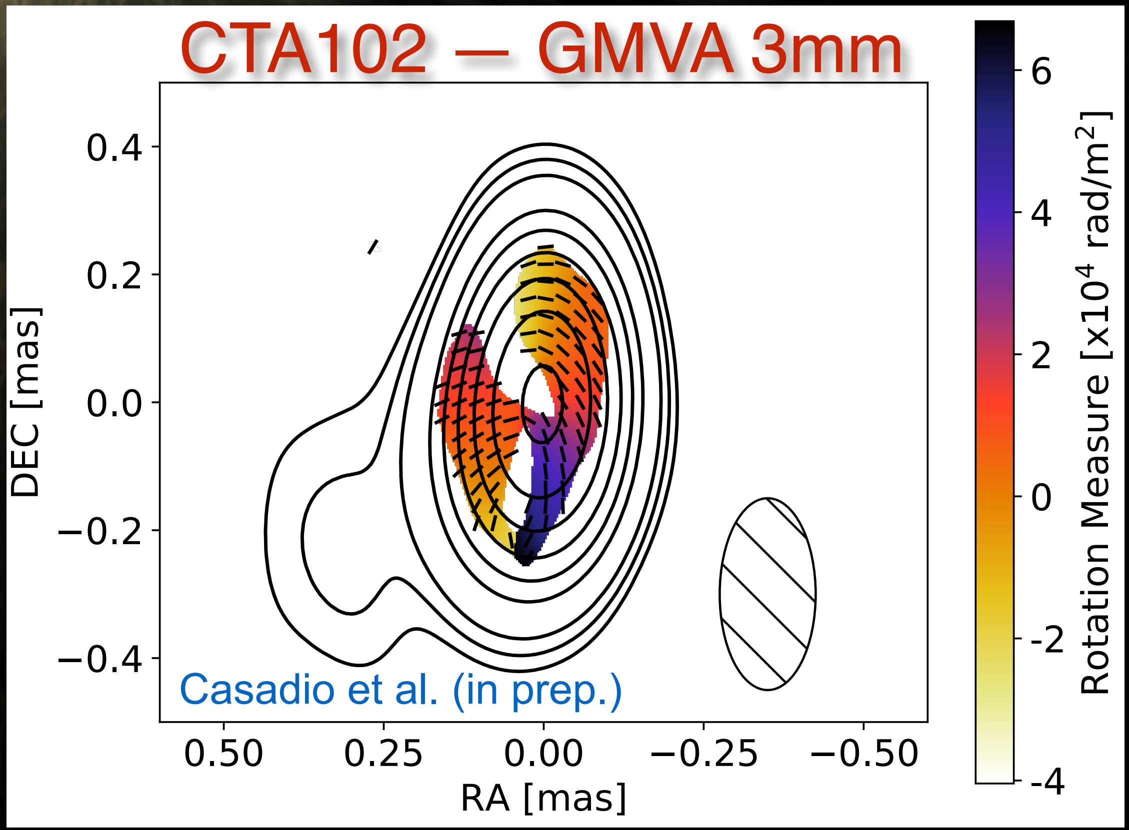
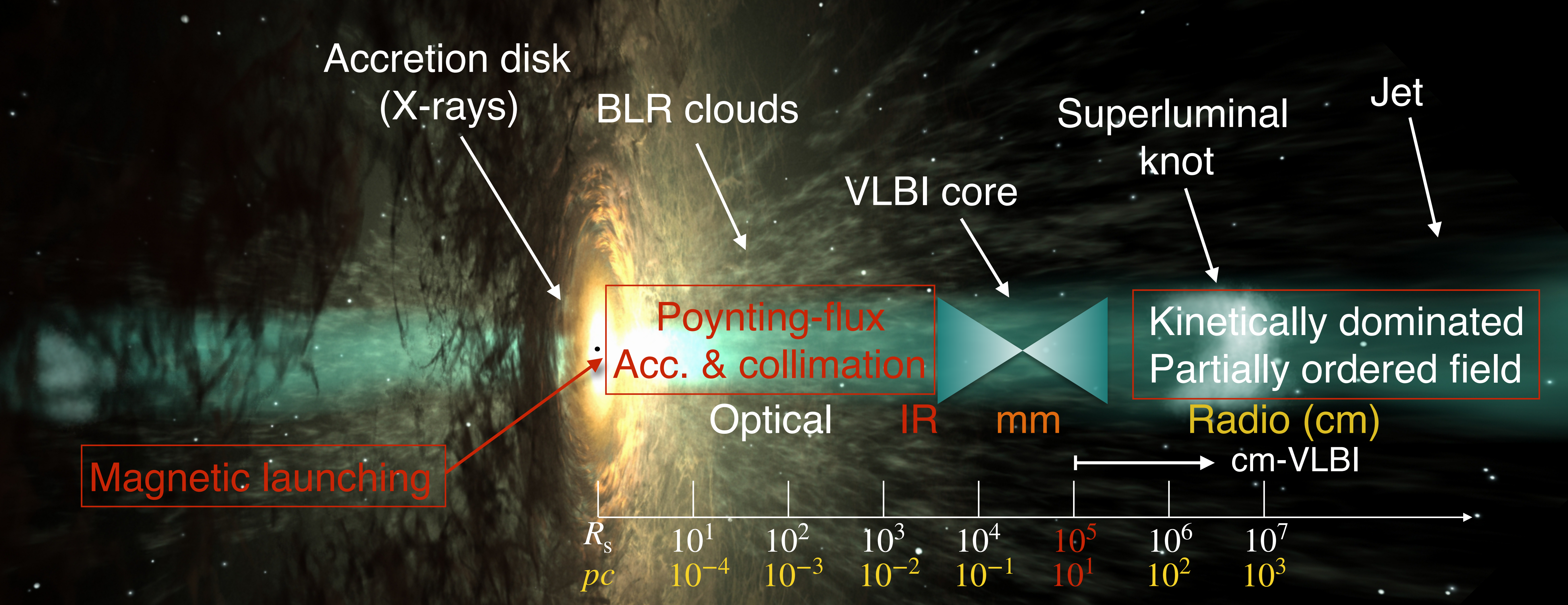


See poster by Casadio



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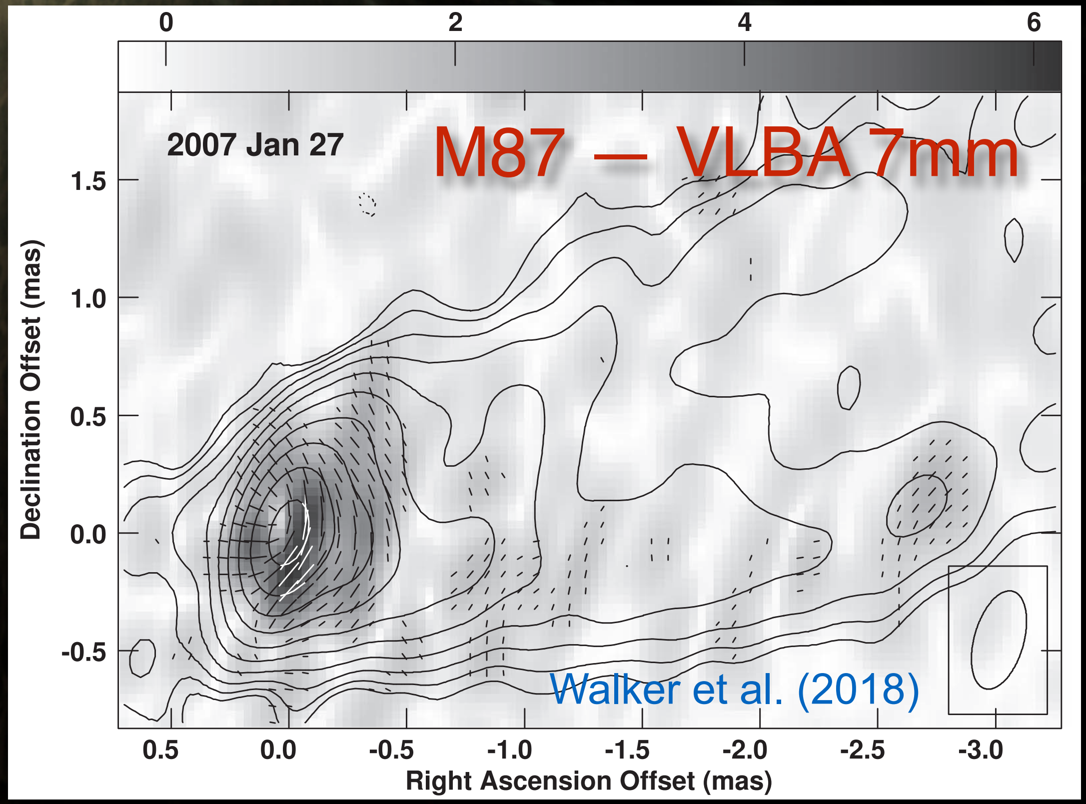
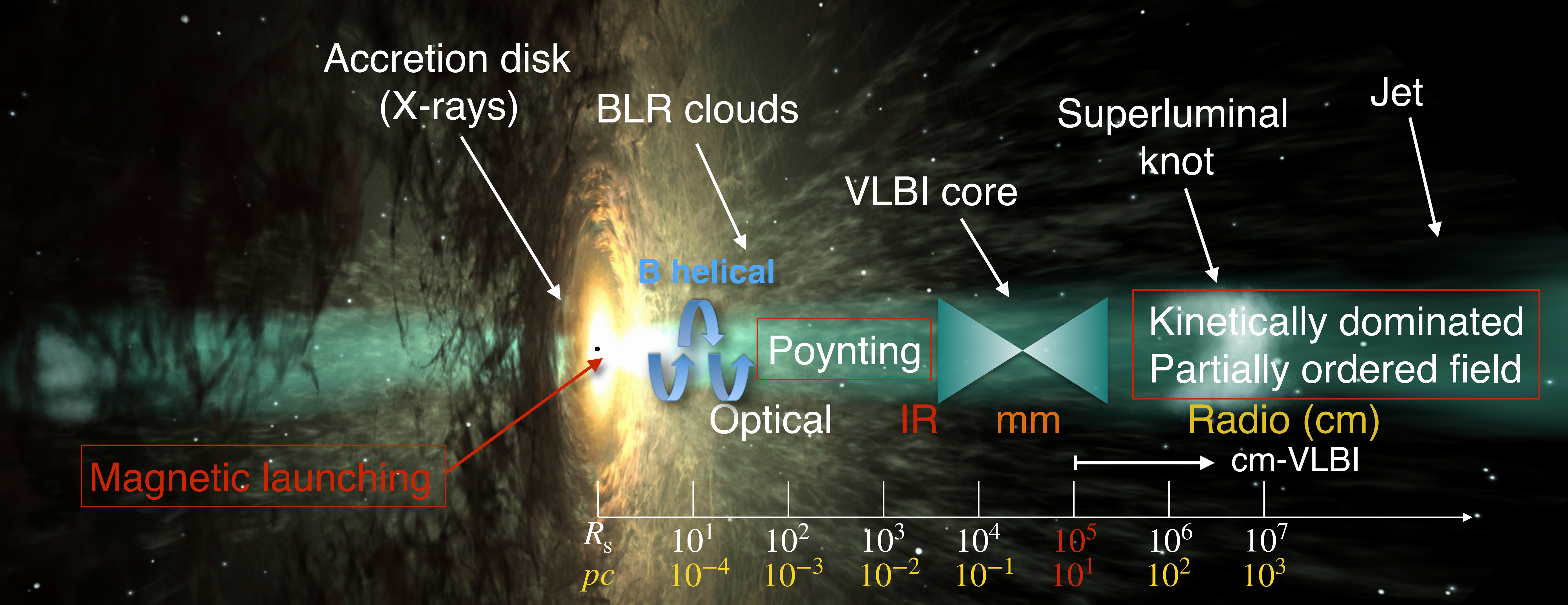


See talk by Nair and poster by Traianou for more recent GMVA results



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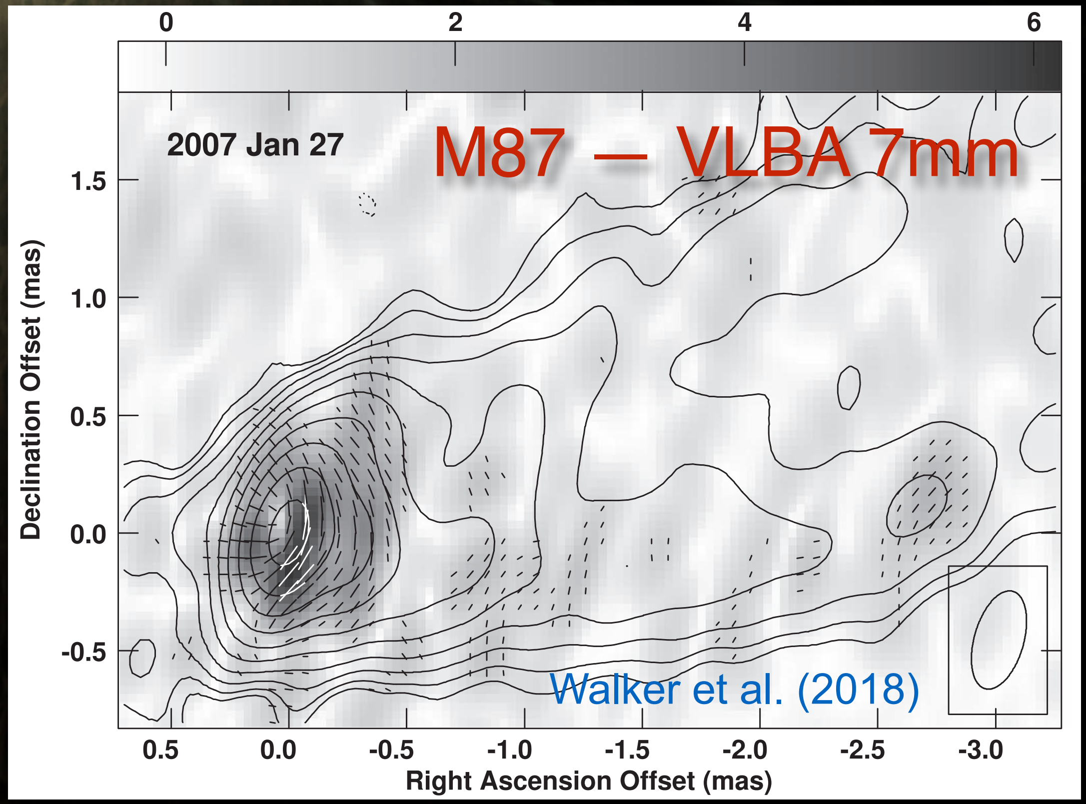

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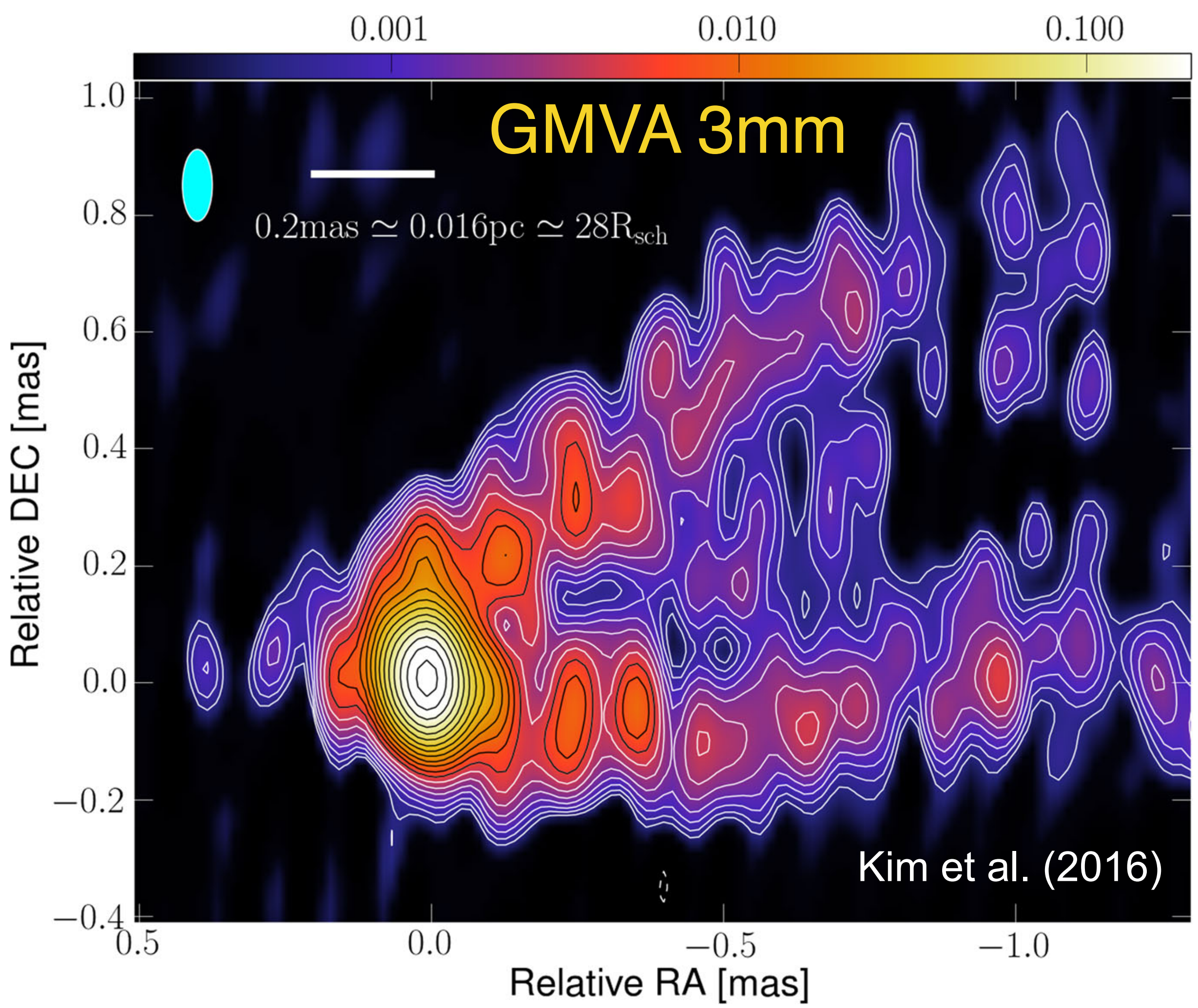
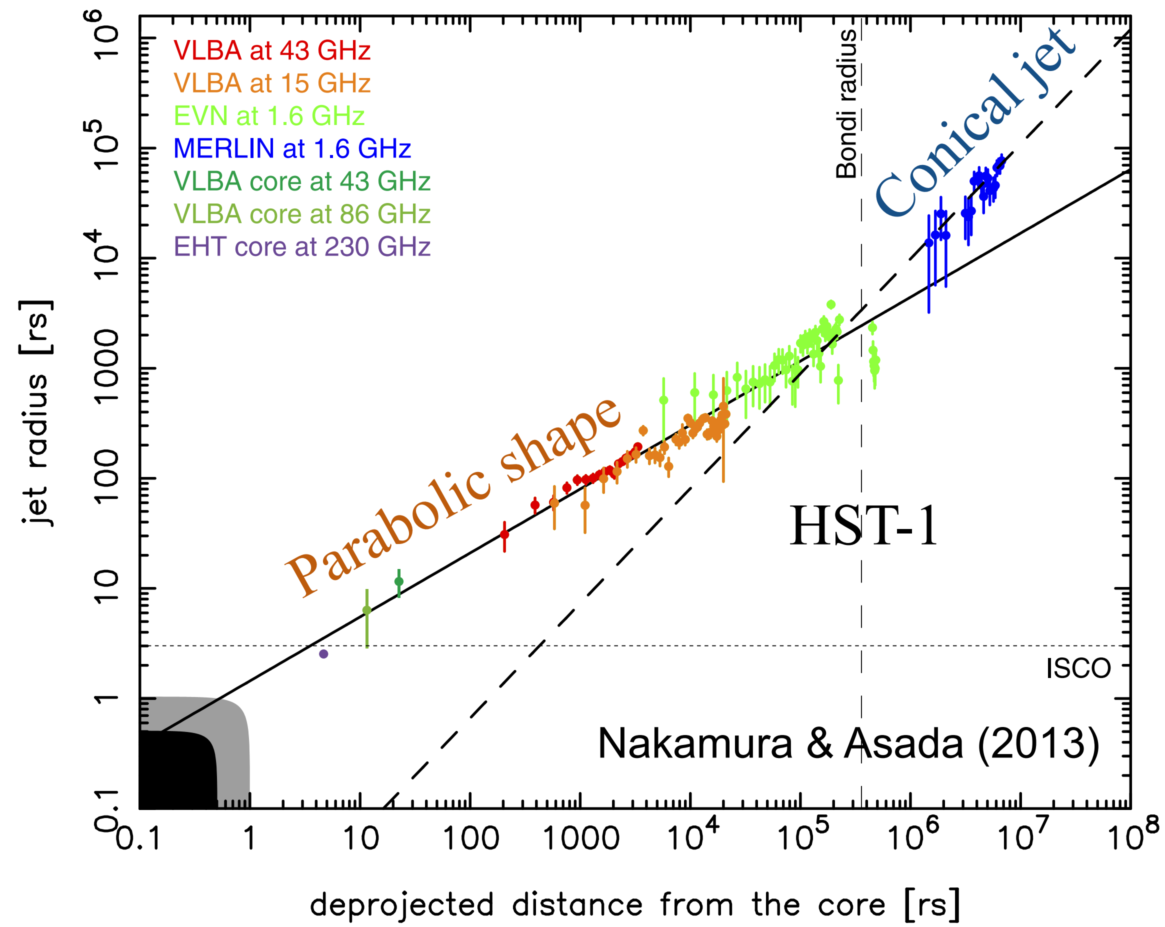
The poster-child case of M87





M87 is a nearby (16.7 Mpc), low-luminosity, slightly misaligned (18 deg) AGN featuring a very massive black hole of ~6x10^9 M$_\odot$.

Current VLBI arrays can probe the innermost jet regions in M87 at scales <100 R_s.

The jet shows a clear limb brightening (Kim+ 2016), with stratification in velocity (Mertens+ 2016).

The jet is already formed at tens of R_s (Hada+ 2011), suggesting BZ or inner accretion disk launching.

The collimation profile shows a transition between a parabolic (collimating) to a conical (free expanding) jet at the Bondi radius, where HST-1 is located. See also poster by Algaba.

HST-1 is a recollimation shock (Levinson & Globus 2017) at 5x10^5 R_s, and behaves as a VLBI core, with superluminal components emerging for its location (Giroletti+ 2012).

Are blazar (mm-)VLBI cores similar to HST-1?

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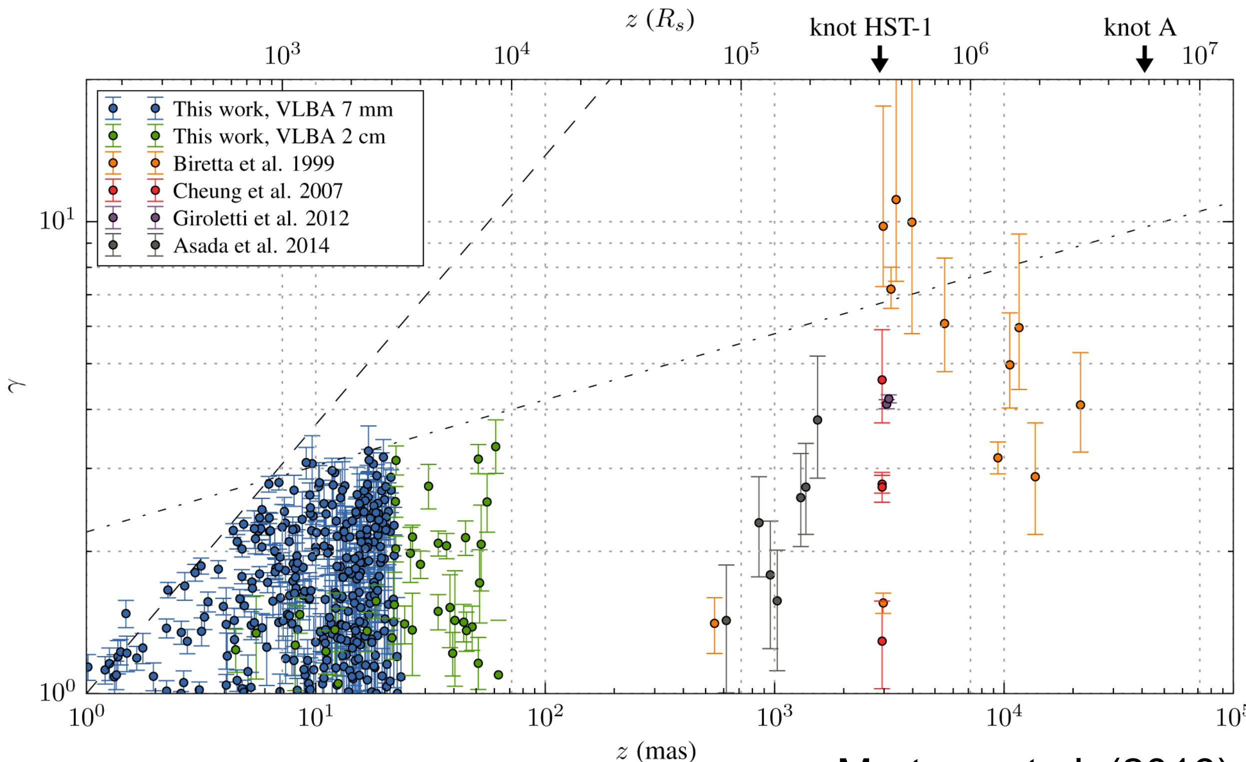
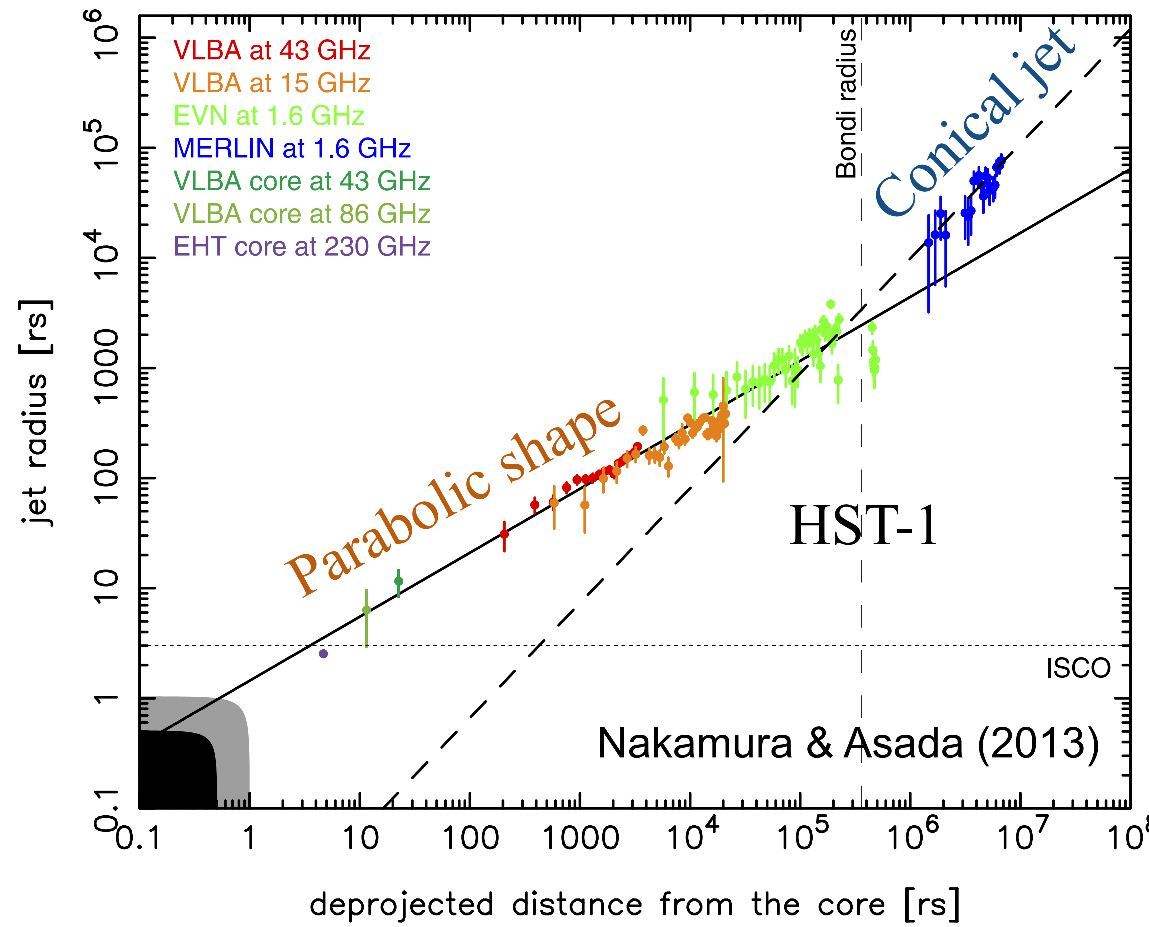


Mertens et al. (2016)



The jet accelerates in parabolic stream lines up to the location of the recollimation shock HST-1 at the Bondi radius.

We *can* study the collimation and acceleration region in M87 through direct mm-VLBI imaging, as well as in other nearby misaligned AGN (Cygnus A, 3C84, NGC 1052, Can A). See talks by Bach, Baczko, and Kim.

Do powerful blazar jets behave the same as M87?

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Are blazar (mm-)VLBI cores similar to HST-1?

Polarimetric VLBI imaging at ≲50 μas (≲10^4 R_s) is required

VLBI Observations at the highest angular resolution

Studying the innermost regions of AGN jets requires the highest possible angular resolution, which is given by λ/D, can be achieved with either:

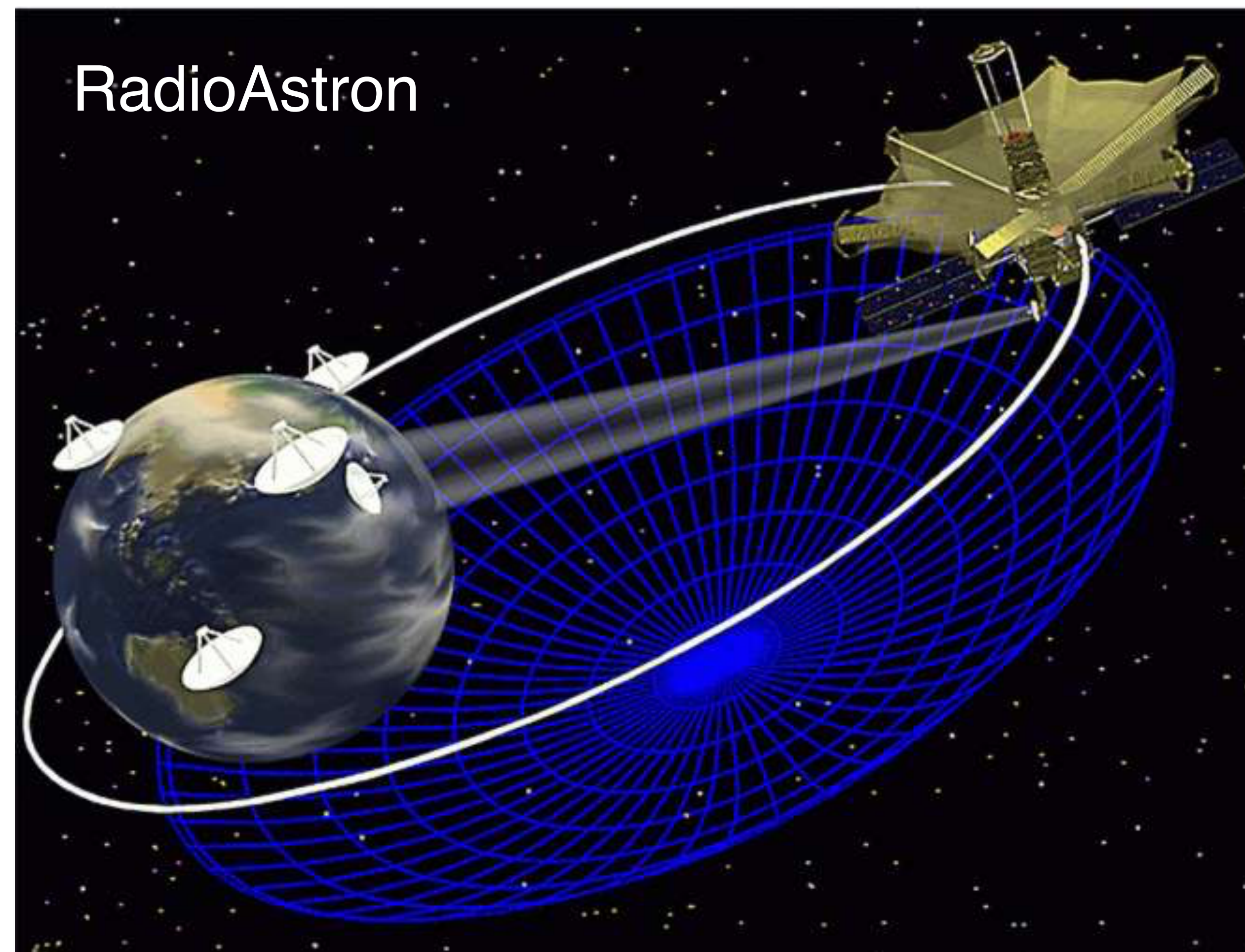
Shorter wavelengths

Ground-based VLBI at millimeter wavelengths, such as the **Event Horizon Telescope**, including phased-ALMA, and GMVA.

See Falcke's talk on Thursday

Larger baselines

Space VLBI observations such as the **RadioAstron** mission.



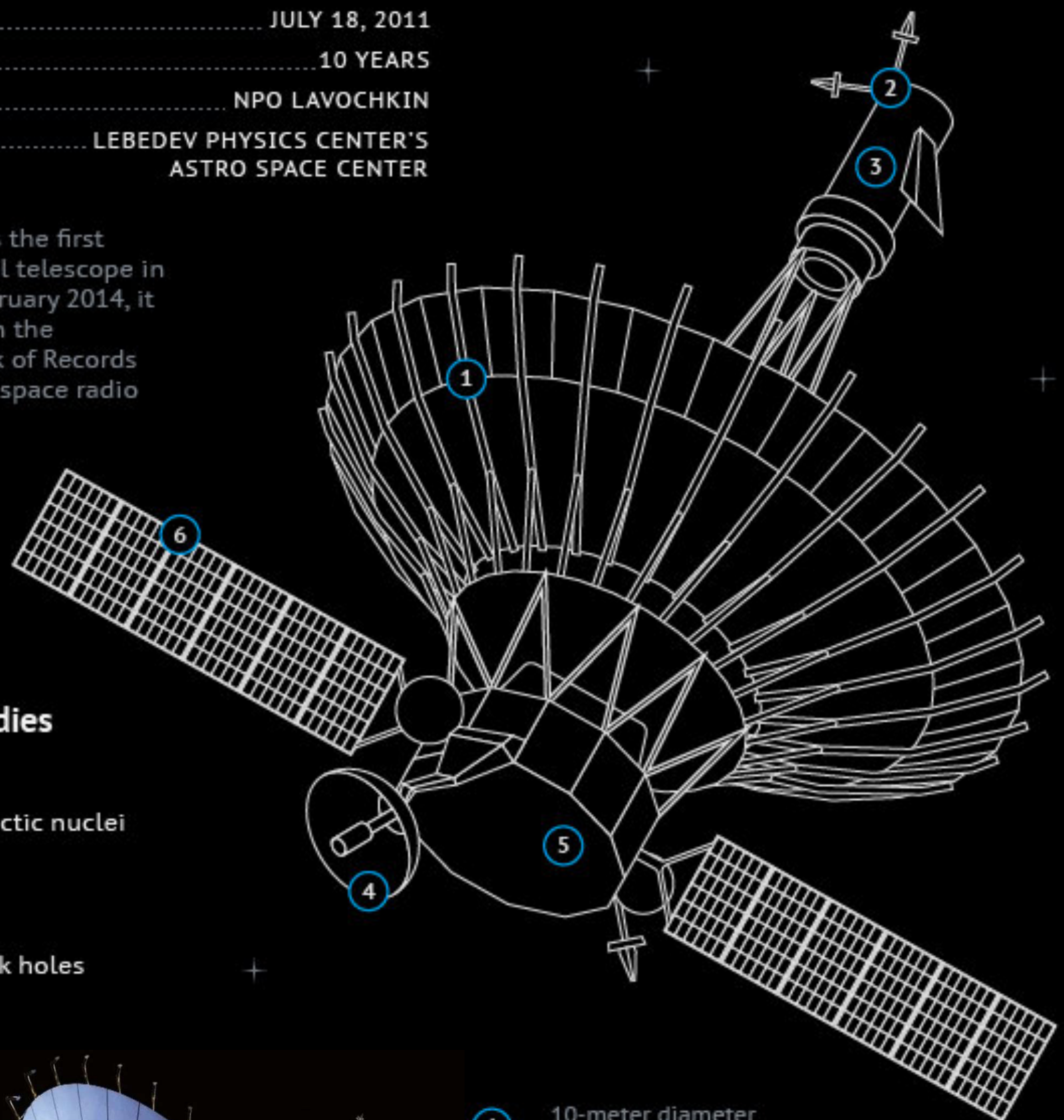
RadioAstron Russian Space Observatory

The RadioAstron project allows us to see distant space objects with unprecedented resolution

«RadioAstron»

COMMISSIONER	ROSCOSMOS
LAUNCH	JULY 18, 2011
SERVICE LIFE	10 YEARS
CONTRACTOR	NPO LAVOCHKIN
DEVELOPER	LEBEDEV PHYSICS CENTER'S ASTRO SPACE CENTER

RadioAstron is the first Russian orbital telescope in history. In February 2014, it was entered in the Guinness Book of Records as the largest space radio telescope



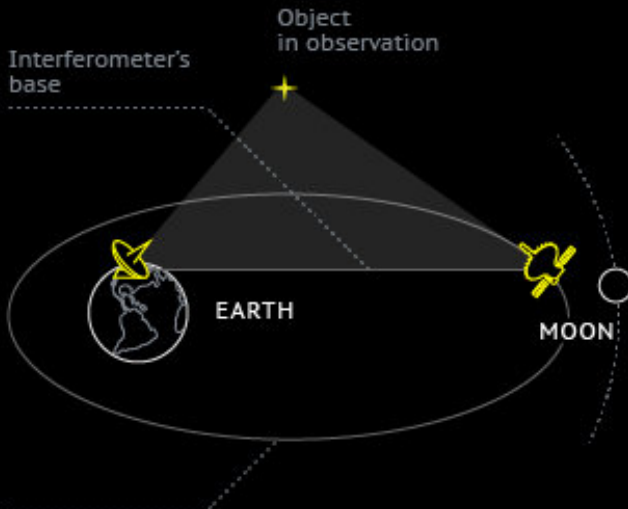
What it studies

Galactic nuclei

Black holes

How it works

RadioAstron operates in conjunction with an international network of ground-based telescopes, forming a giant ground-space telescope and interferometer. This makes it possible to obtain images of distant objects which are a thousand times more detailed than those obtained by the Hubble telescope



Orbit: HEO
Apogee: 330,000 km
Perigee: 600 km
Circulation period: 8.2 days

1. 10-meter diameter parabolic antenna
2. Low-gain antennae
3. Focal module
4. High-information radio system
5. Navigator service module
6. Solar batteries

The ground-based telescopes that RadioAstron works with are located in Australia, Germany, Spain, Italy, the Netherlands, Russia, USA, Ukraine and Japan

The RadioAstron project has made it possible to achieve a record angular resolution * of 27 microseconds

* The angular resolution is the minimum angle at which two celestial objects can be seen separately from each other

10 m orbiting antenna.

Launched in 2011.

9 days period, with perigee at 600 km.

Apogee of 350,000 km allows a maximum angular resolution of ~7 µas (at 1.3 cm).

Dual polarization receivers at 18 cm and 1.3 cm.

Bit rate 128 Mbps.

Mission extended until 2019.

Three imaging ***Key Science Programs (KSP):***

- ☑ **"Powerful AGN".** Flow transition from magnetic to kinetic flux domination and plasma instabilities in power blazars (i.e., 3C273, 3C345, 0836+710). **See talks by Lobanov and Vega-García**
- ☑ **"Nearby AGN".** Nearby AGN (i.e., M87, 3C84) under the magnifying glass of RadioAstron. **See talks by Savolainen and Giovannini**
- ☑ **"AGN Polarization".** Probing the innermost structure and magnetic field in the vicinity of the central black hole in a sample of highly polarized blazar jets at tens of μas angular resolution to test jet formation models. **See also talk by Kravchenko and poster by Pötzl**

Ground support array for RadioAstron

RadioAstron "Polarization" KSP Observations

Target	Date	Exp.	λ	Corr.	Status
0642+499	9 Mar. 2013	GK047	L	Yes	Early Science — Lobanov et al. (A&A, 583, A100, 2015)
BL Lac	29 Sep. 2013	GA030A	L	Yes	Data analysis
BL Lac	11 Nov. 2013	GA030B	K	Yes	Gómez et al. (ApJ, 817, 96, 2016)
3C273	18 Jan. 2014	GA030C	K	Yes	Bruni et al. (A&A, 604, A111, 2017)
3C273	13 June 2014	GA030F	L	Yes	*In preparation (Bruni+)*
3C279	10 Mar. 2014	GA030D	K	Yes	Data analysis
OJ287	04 Apr. 2014	GA030E	K	Yes	*In preparation (Gómez+)*
0716+714	3 Jan. 2015	GL041A	K	Yes	*In preparation (Kravchenko+)*
3C345	30 Mar. 2016	GG079A	L	Yes	Data analysis
OJ287	16 Apr. 2016	GG079B	L	Yes	Data analysis
OJ287	25 Apr. 2016	GG079C	K	No	
3C345	4 May 2016	GG079D	K	No	
3C454.3	8 Oct. 2016	GG081A	K	No	Complementary GMVA observations
CTA102	17 Oct. 2016	GG081B	K	No	GMVA
OJ287	7 Mar. 2017	GG081C	K	Yes	EHT+ALMA and GMVA+ALMA
BL Lac	8 Oct. 2017	GG083A	K	No	GMVA
3C279	15 Jan. 2018	GG083B	K	No	GMVA+ALMA
3C120	1 Feb. 2018	GG083C	K	No	GMVA
3C273	9 Feb. 2018	GG083D	K	No	GMVA+ALMA
OJ287	22 Apr. 2018	GG083E	K	No	EHT+ALMA and GMVA+ALMA

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OJ287	22 Apr. 2018	GG083E	K	No	EHT+ALMA and GMVA+ALMA

First time *polarimetric* VLBI-imaging of blazar jet at the highest angular resolution (*20-40 μas*) combining 3 wavelengths (1.3 mm, 3 mm, and 1.3 cm) with *almost matching beam and quasi-simultaneously*.

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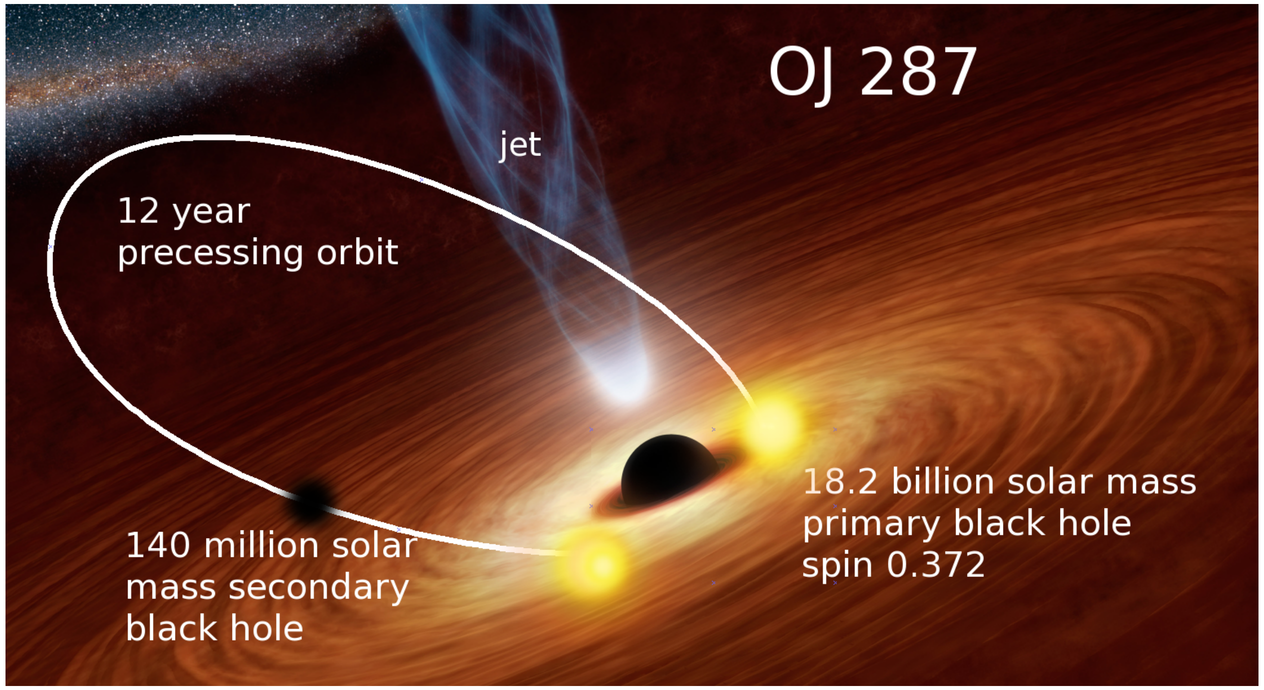
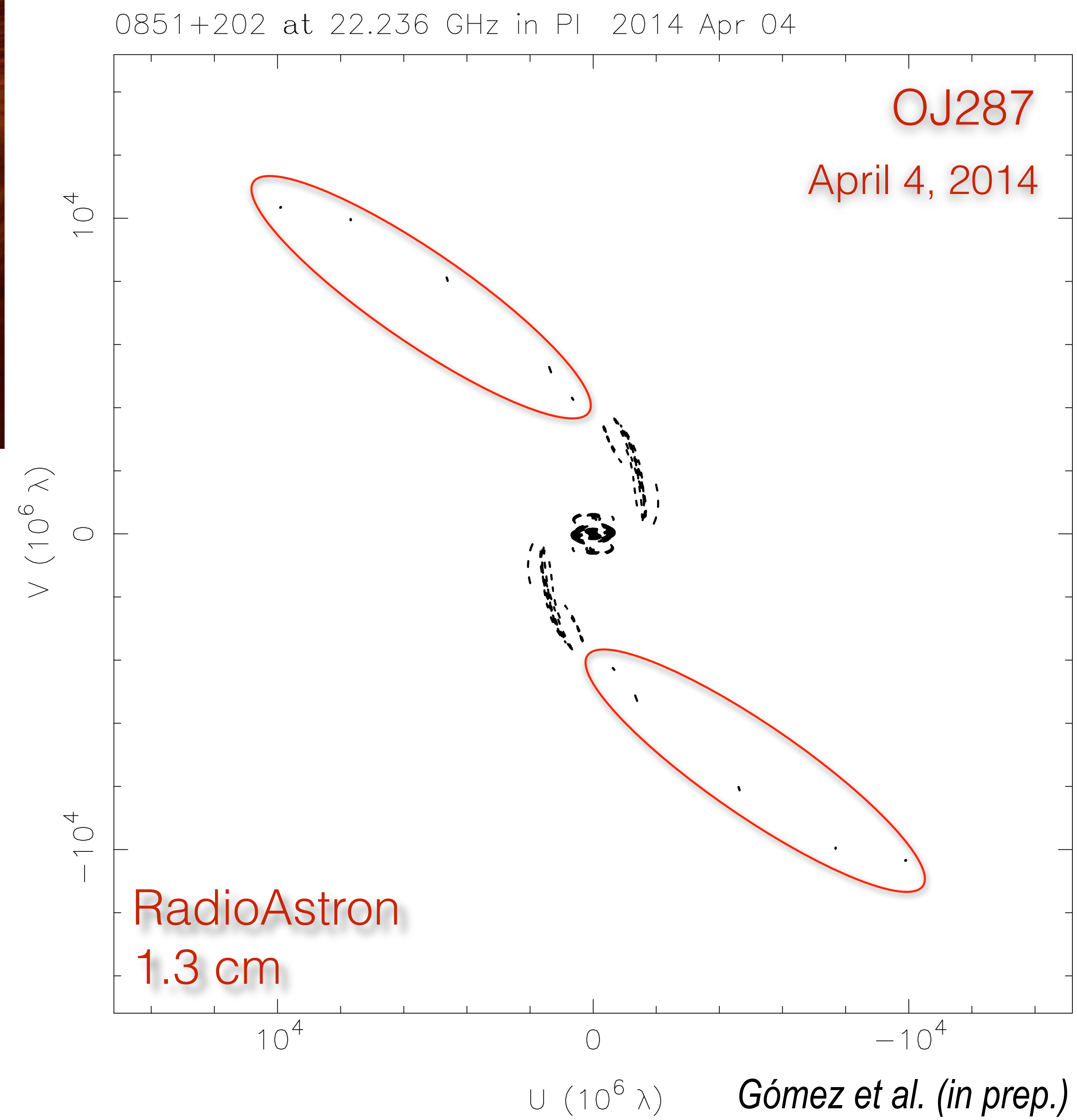
First time *polarimetric* VLBI-imaging of blazar jet at the highest angular resolution (*20-40 μas*) combining 3 wavelengths (1.3 mm, 3 mm, and 1.3 cm) with *almost matching beam and quasi-simultaneously*.

RadioAstron Polarization KSP



OJ287 is the **best candidate for hosting a supermassive binary black hole** system.

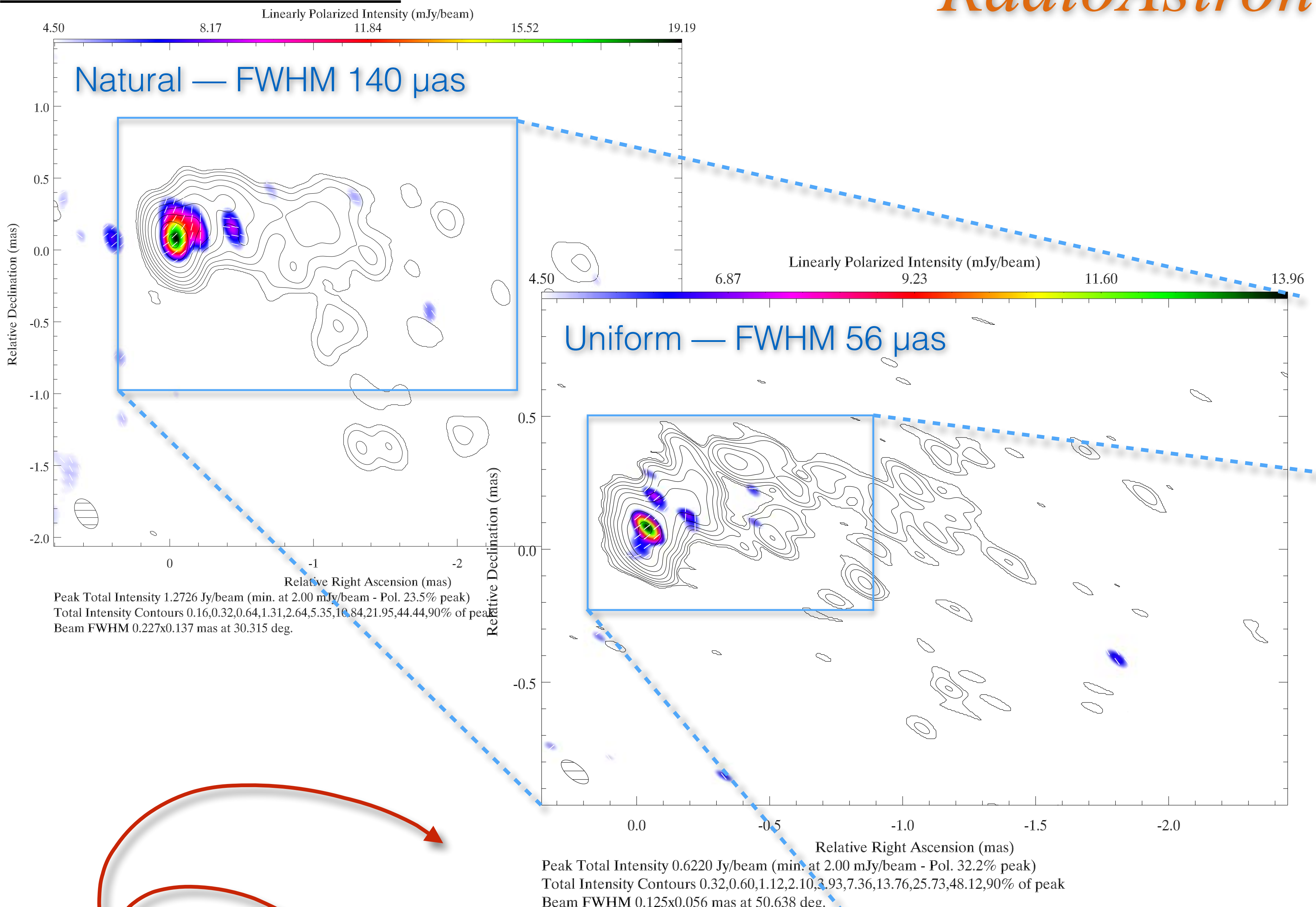
RadioAstron imaging in 2014 combining **perigee** imaging **and long-baseline snapshots** during the same orbit with **fringes detected (SNR~11) at a record spacing of 15.2 D_{Earth}.**



Gómez et al. (in prep.)

OJ287 at K-band

RadioAstron Polarization KSP

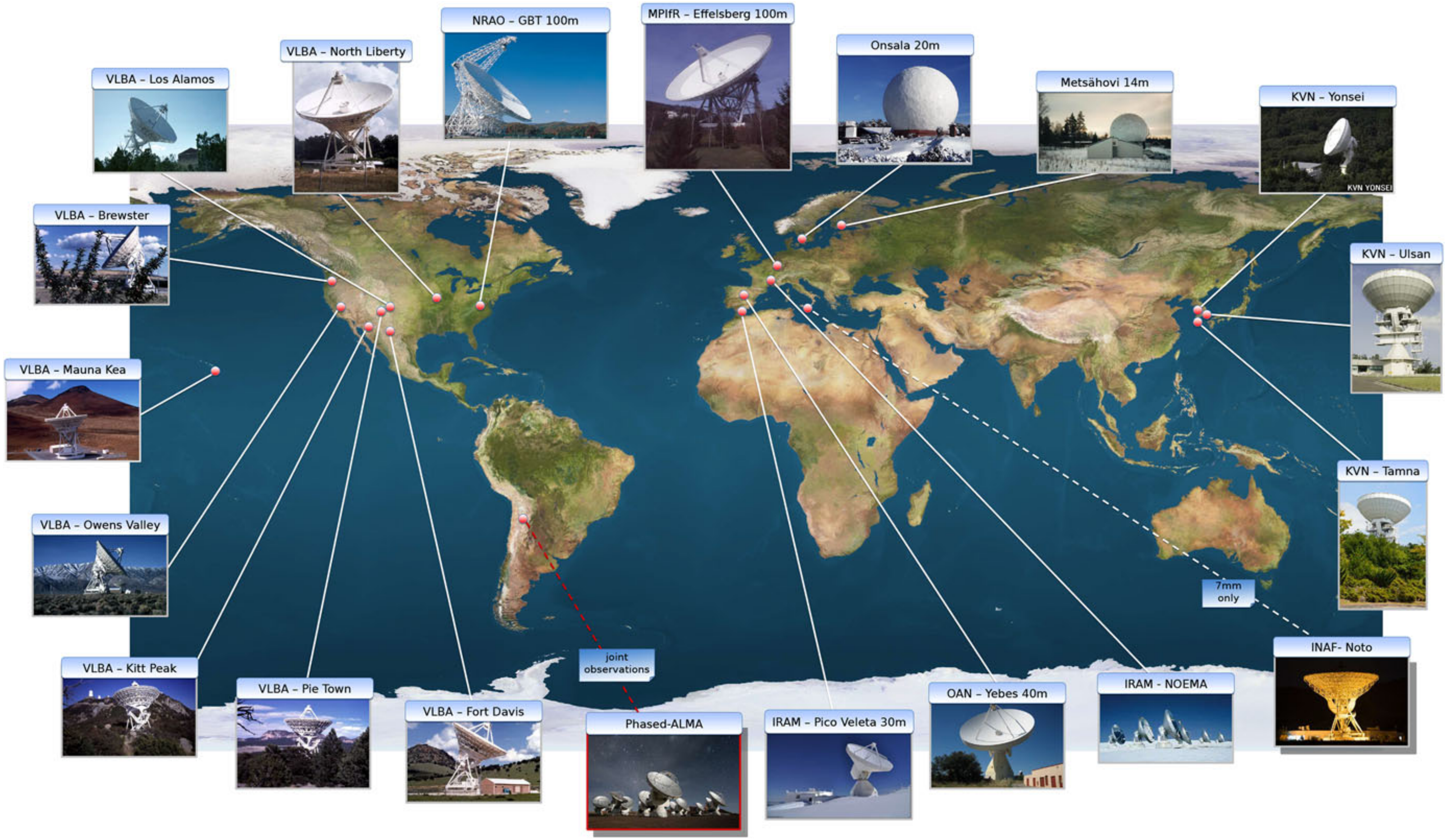


Omitted unpublished results

OJ287 progressive inner jet bending with increasing resolution, in agreement with a **precessing jet** produced by a **binary BH system**.

Gómez et al. (in prep.)

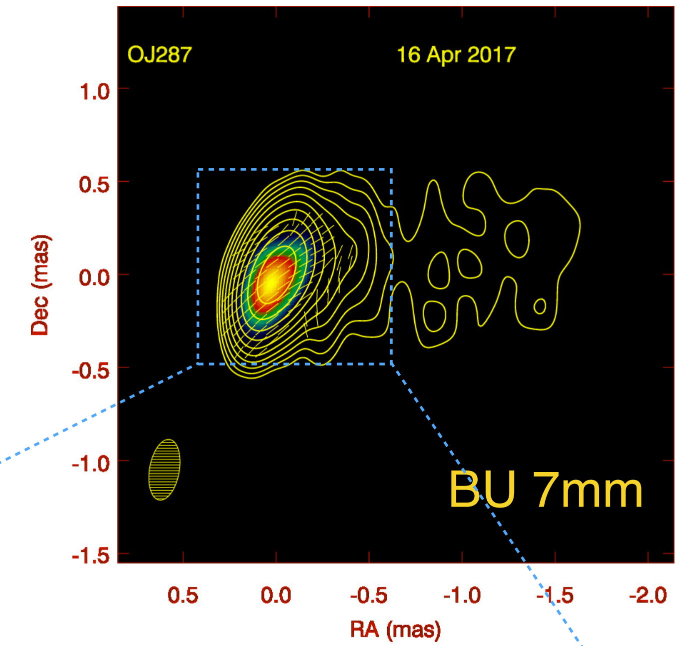
First GMVA+ALMA observations



First participation of phased-ALMA in GMVA 3mm observations took place in March/April 2017, targeting three sources: SgrA* (P.I. Brinkerink), 3C273 (P.I. Akiyama), and OJ287 (P.I. Gómez).

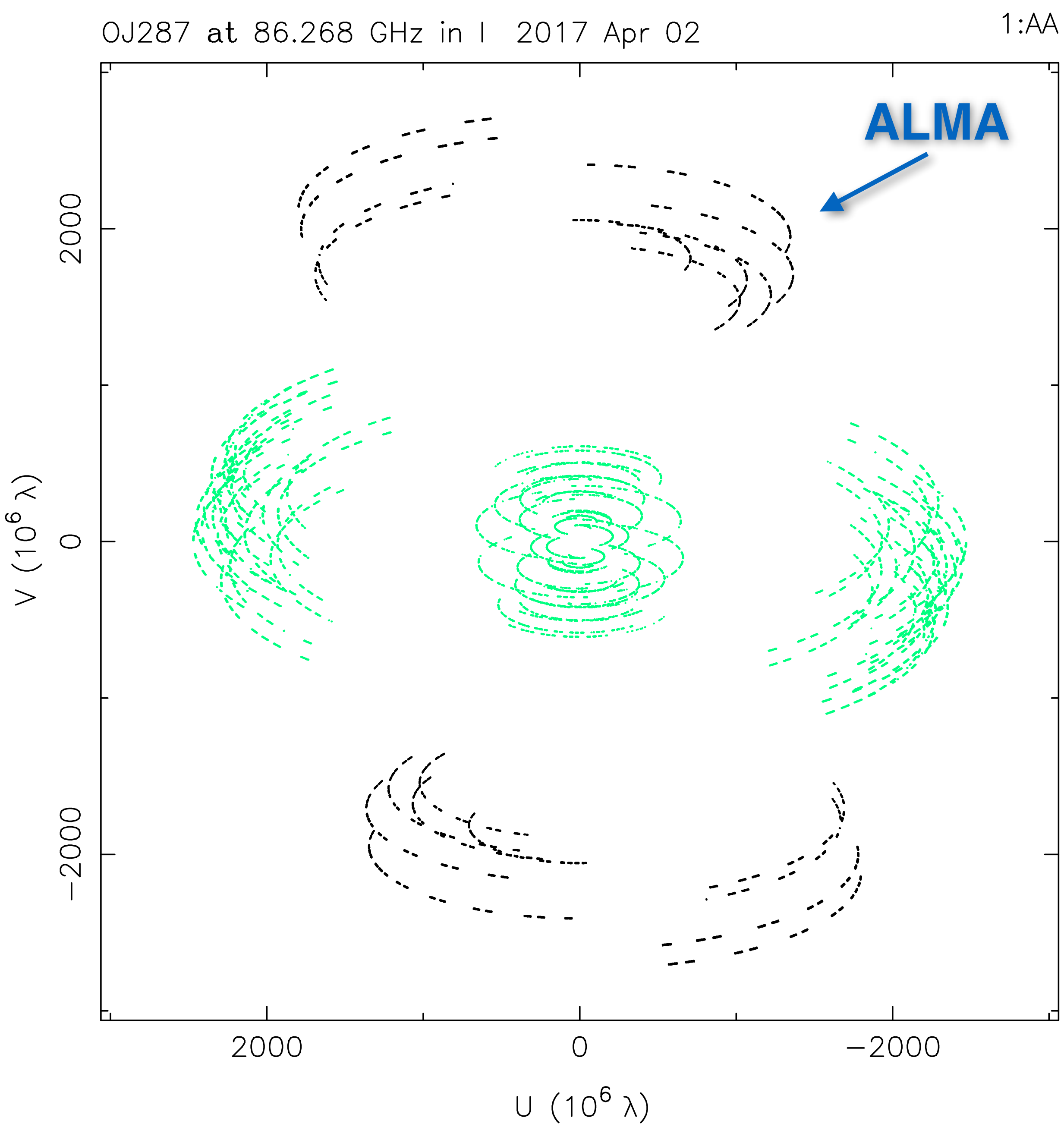
The GMVA now features an array of 17 antennas plus phased-ALMA, with GLT added in 2018 and IRAM-NOEMA in the near future.

First GMVA+ALMA observations of OJ287



OJ287 was observed in April 2, 2017, showing fringes to ALMA with SNRs as high as 150.

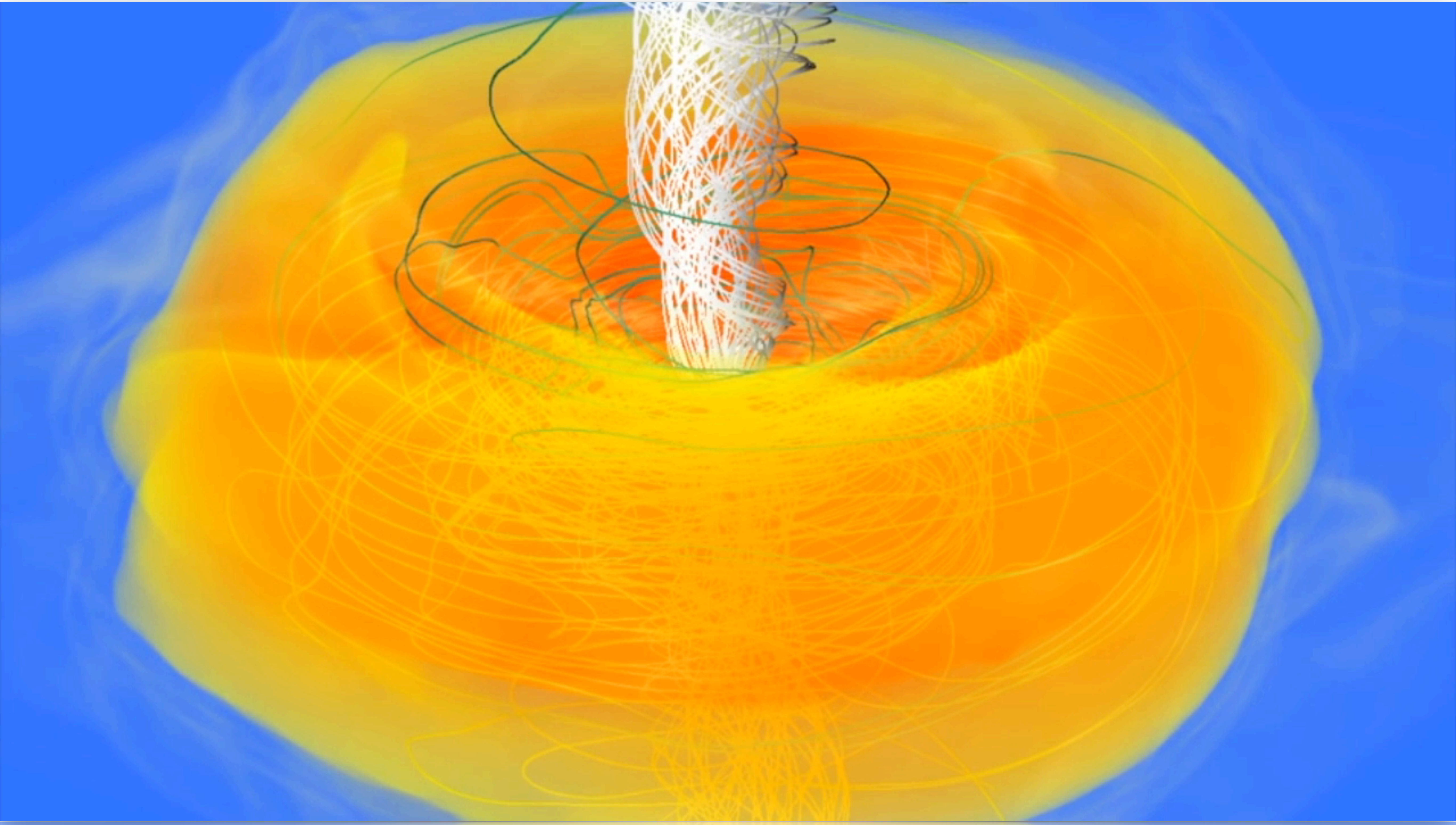
ALMA provides an increase in north-south resolution by a factor of ~4.



Omitted unpublished results

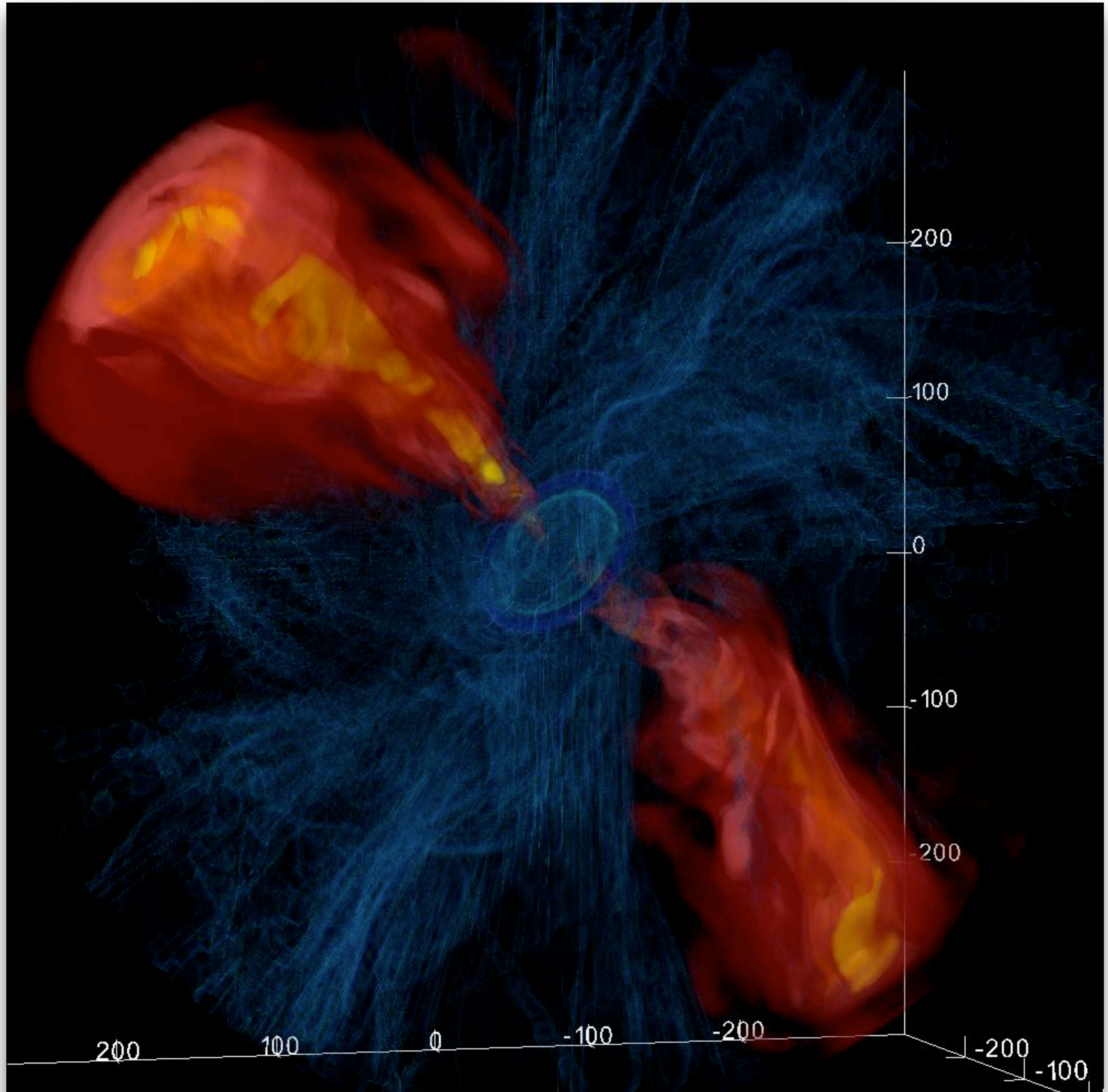
Observations of OJ287 at K-band

RMHD simulations with a frozen in magnetic field of a binary black hole system with a mass ratio of q=1:1. Twin jets are produced from the poles of the two black holes.



Simulations by Roman Gold & Avery Broderick (Perimeter Institute)

Observations of OJ287 at K-band



Movie by Hesp. Simulation by Liska & Tchekhovskoy (in prep.)

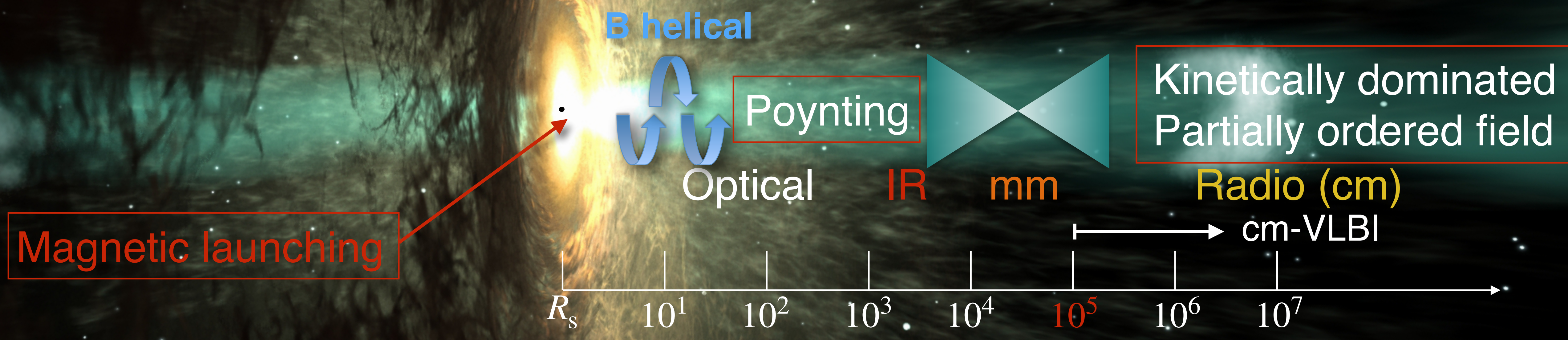
Alternatively, the innermost jet structure may result from the **precession of a tilted accretion disk.**

Simulations by Tchehovskoy+ showing a 45 deg. titled accretion disk around a spinning black hole (spin vertically upward).

The disk undergoes regular precession with the jet following the disk.

Summary

(current view of blazar jets)



But we still don't have a (good) answer for:

- What is the dominant launching mechanism, BZ or BP? What determines the accretion rate and jet power? What is the typical scale length for the acceleration and collimation?
- How and where is the transition from Poynting-flux to kinetically dominated jets? Is the mm-VLBI a recollimation shock that determines this transition?
- Did I mention we don't know the jet composition, what accelerate particles, or how is the high-energy produced?

VLBI is in its second youth … exciting times wait ahead for the new generations of astronomers

- Millimeter VLBI (EHT, GMVA) and space VLBI (RadioAstron) are opening a new window in our study of blazar jets allowing us for the first time to study how they are launched. Will we be able to image the event horizon of a supermassive black hole with the EHT?