Observing astrophysical jets at the highest-angular resolution

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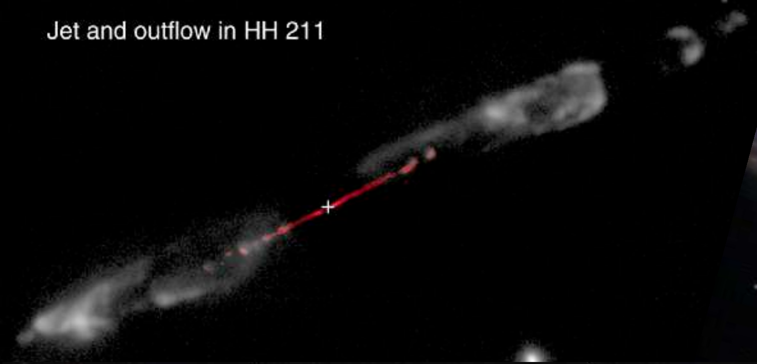
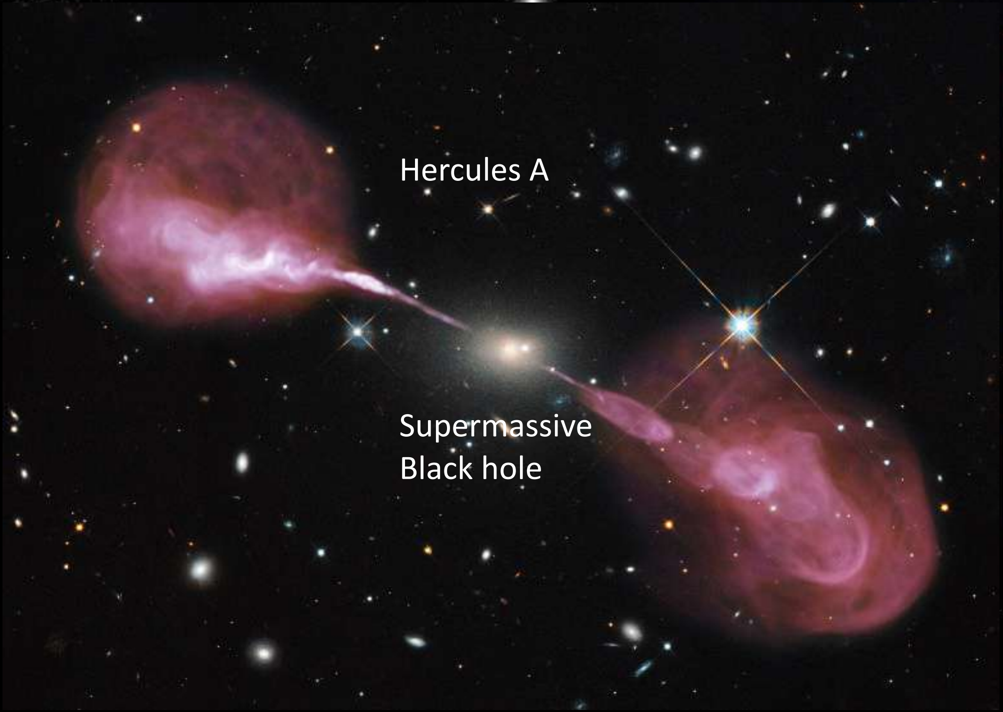
FAPESP

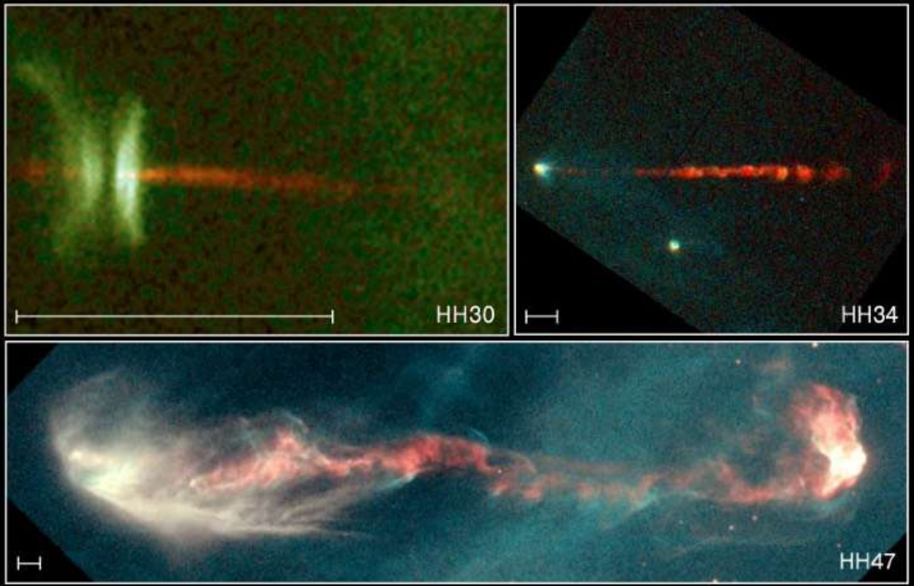
Event Horizon Telescope

INAF ISTITUTO NAZIONALE DI ASTROFISICA

Università degli Studi di Cagliari





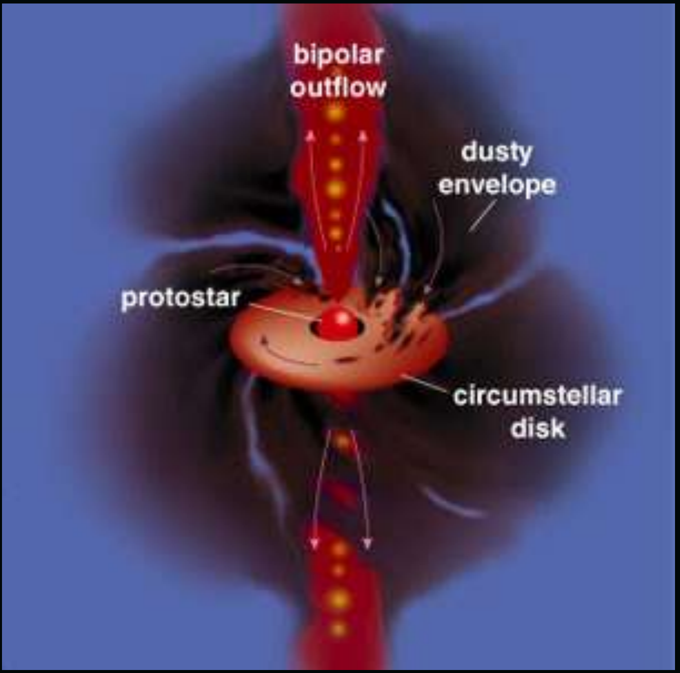


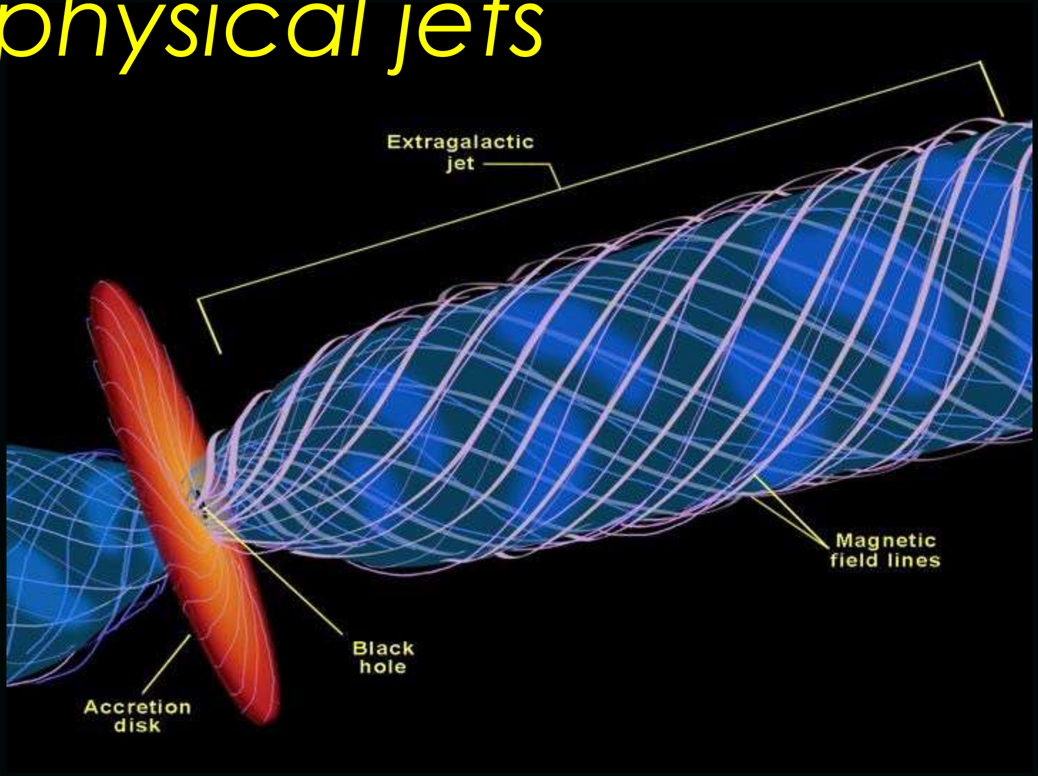
Jets from Young Stars HST • WFPC2

PRC95-24a • ST ScI OPO • June 6, 1995

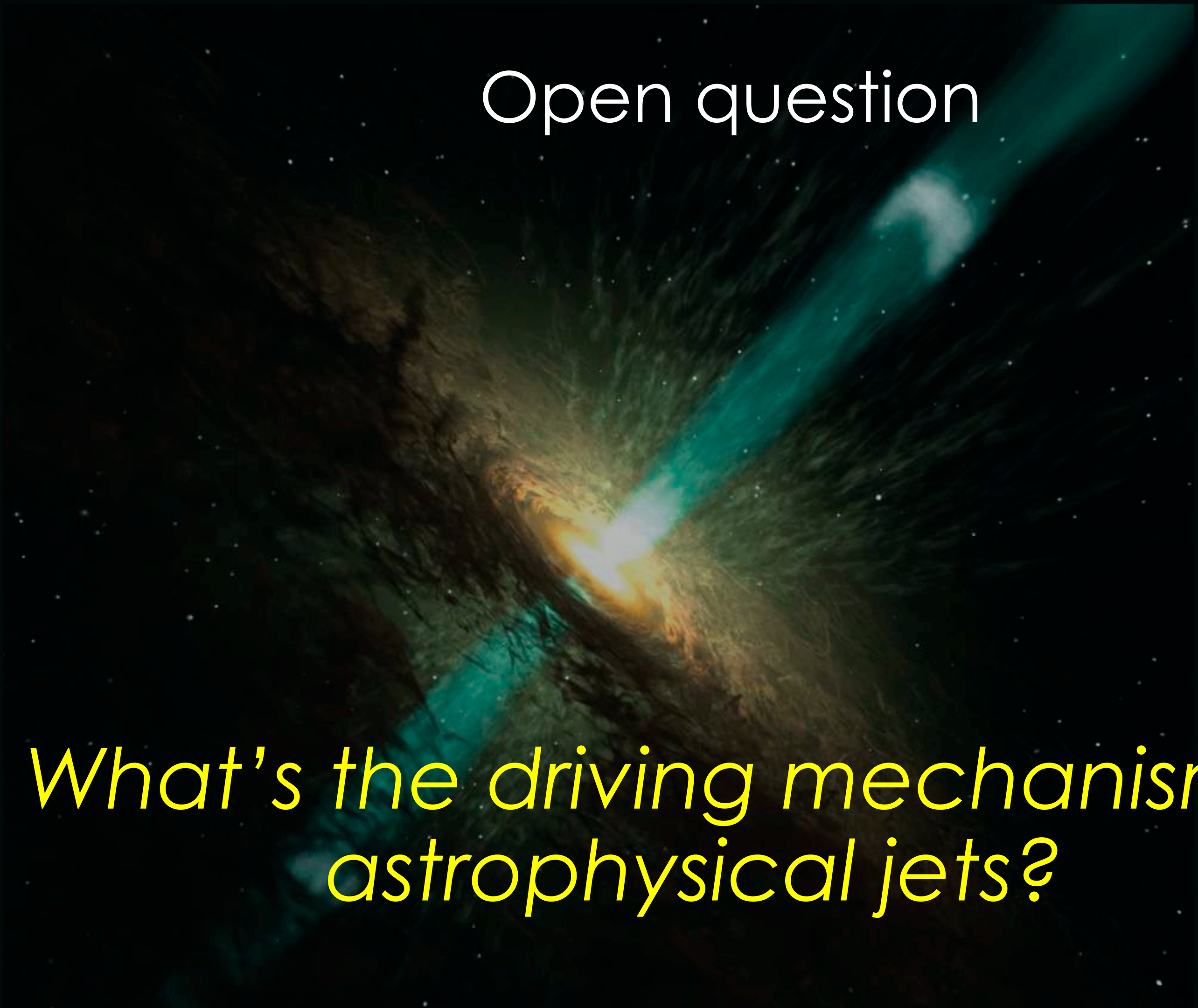
C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA

Astrophysical jets





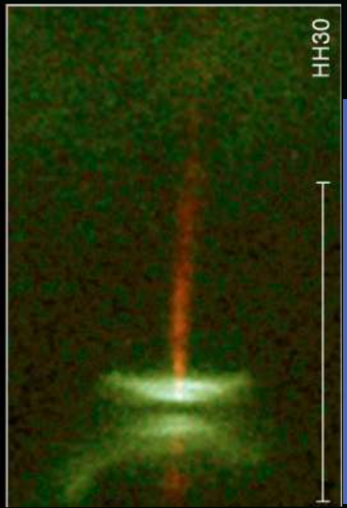
Open question

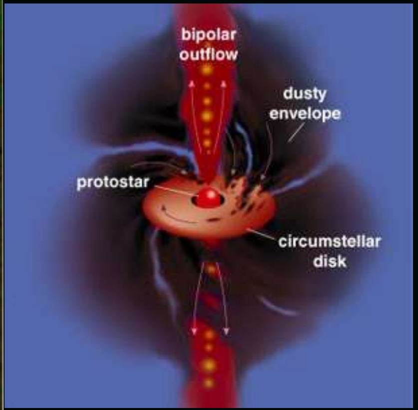


What's the driving mechanism of astrophysical jets?

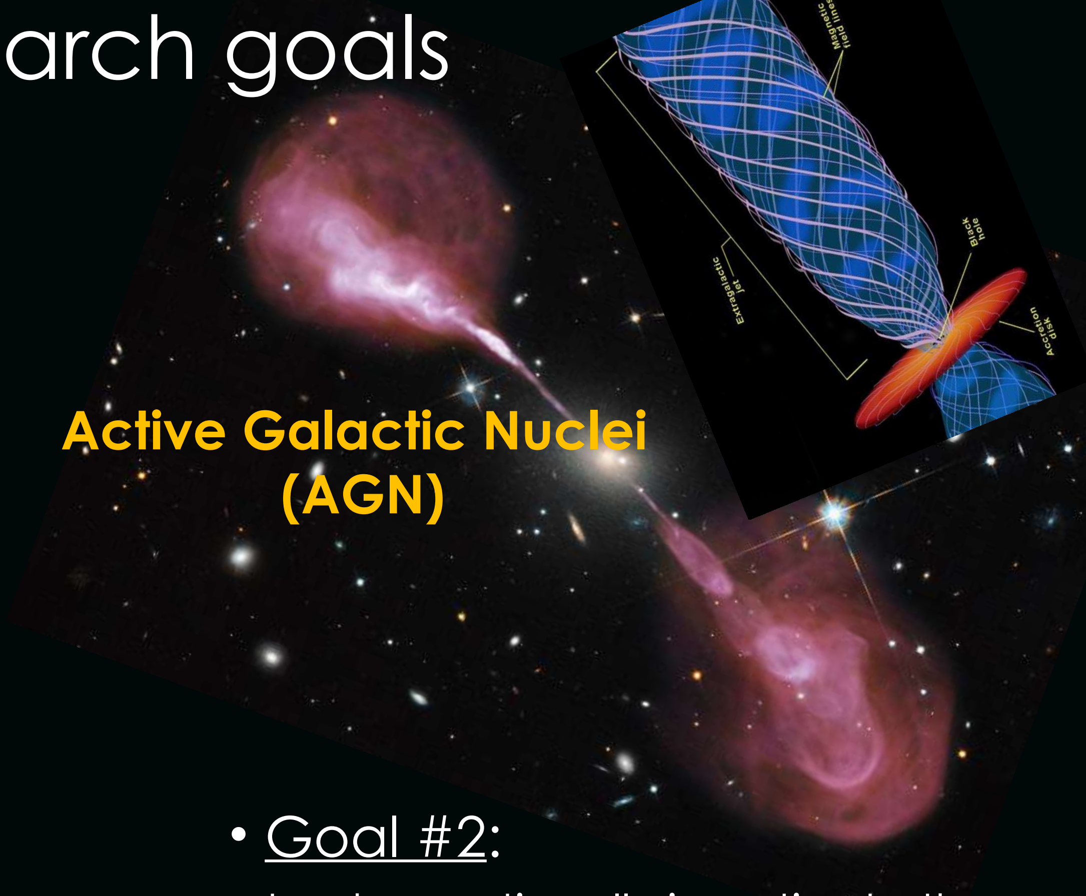
Research goals

Protostars





Active Galactic Nuclei (AGN)



- Goal #1:

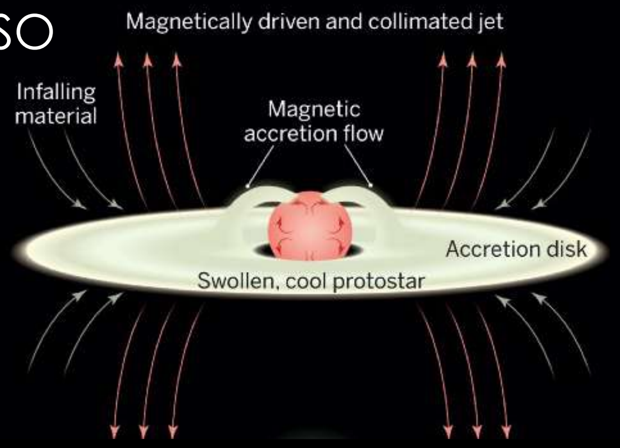
  to observationally investigate the interplay between gas dynamics and magnetic fields in high-mass protostars

- Goal #2:

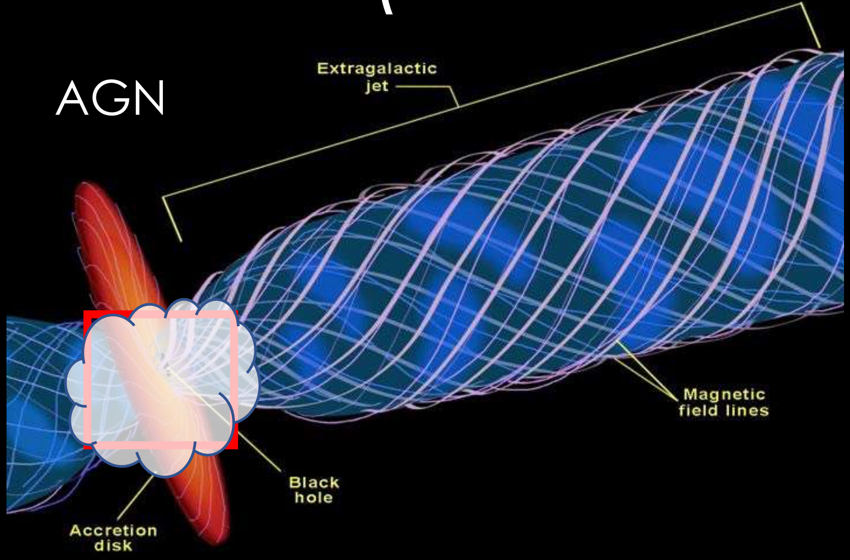
  to observationally investigate the role of magnetic fields in launching and shaping jets from AGN

Main Observational Limitations (& Solutions)

YSO



AGN



1. *Jet launching region is small* ⇒ High angular resolution
2. *Innermost regions of AGN are opaque* ⇒ High radio frequency
3. *Magnetic fields are hard to measure* ⇒ Sensitive and accurate polarimetry

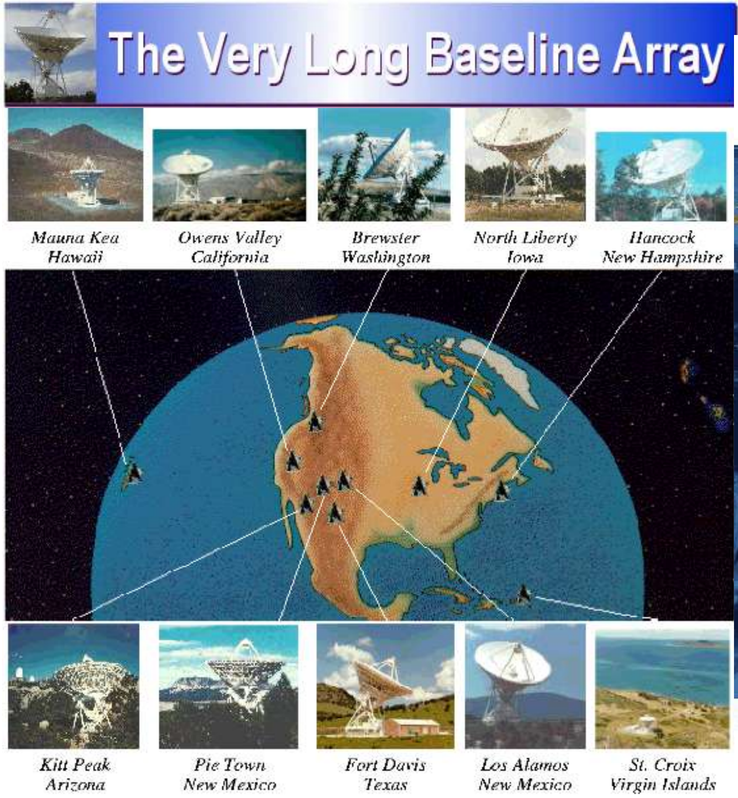
Ingredient 1. Beating the resolution limit

$$\text{Angular resolution} \sim \frac{\text{Wavelength}}{\text{Telescope Size}} = \boxed{\frac{\lambda}{D}}$$

LMT 50-m telescope (Mexico)

Very Large Array (VLA)

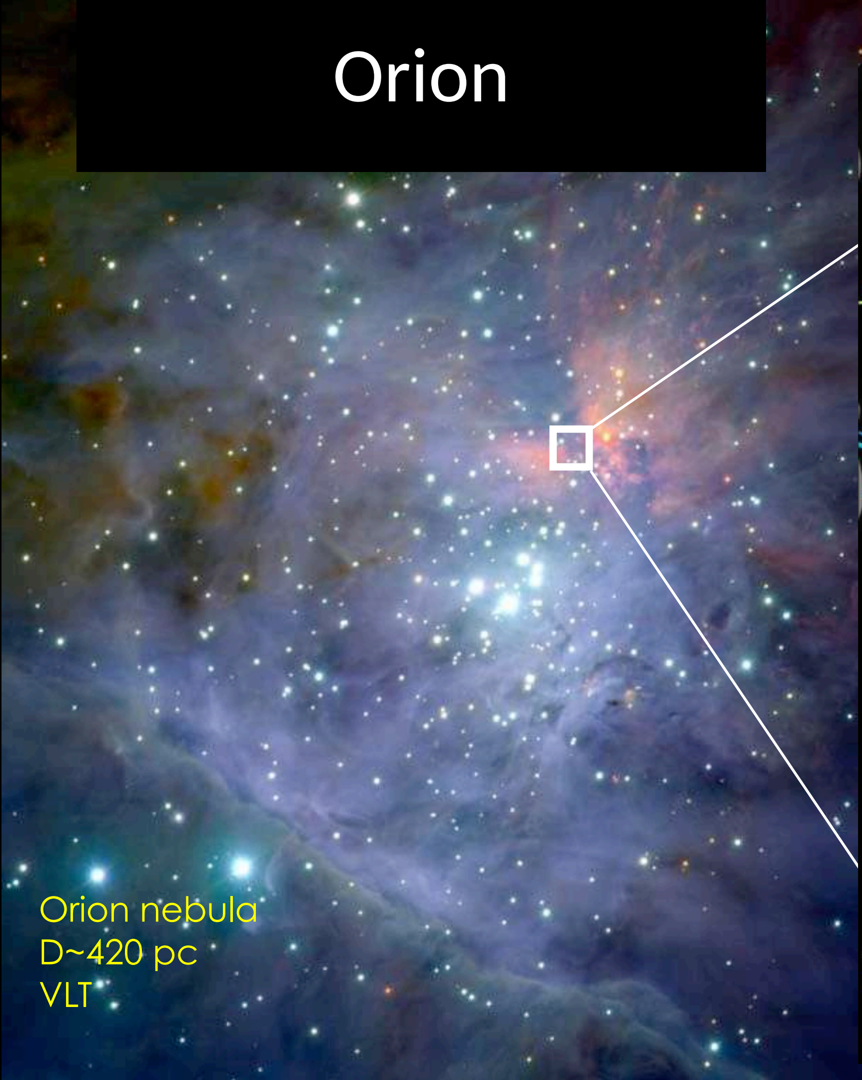
Very Long Baseline Interferometry (VLBI)

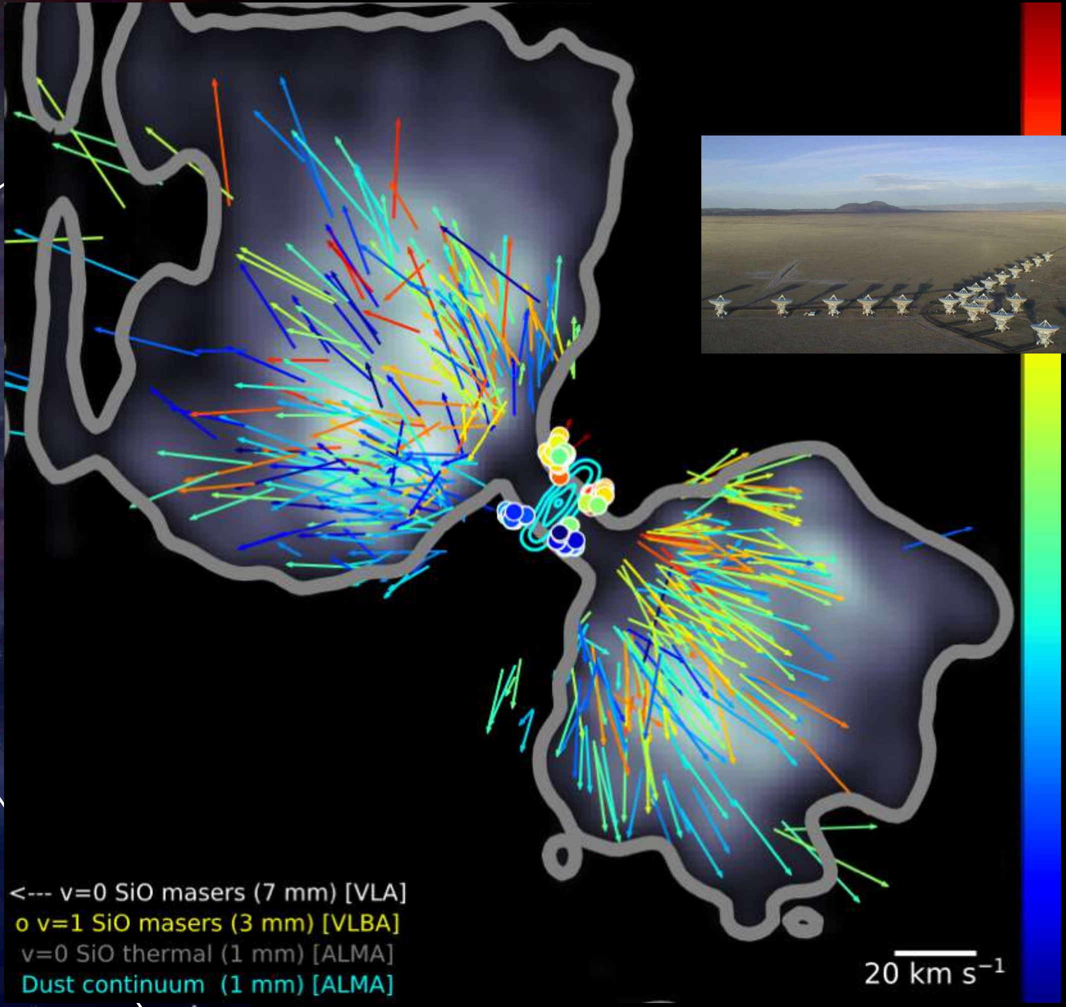


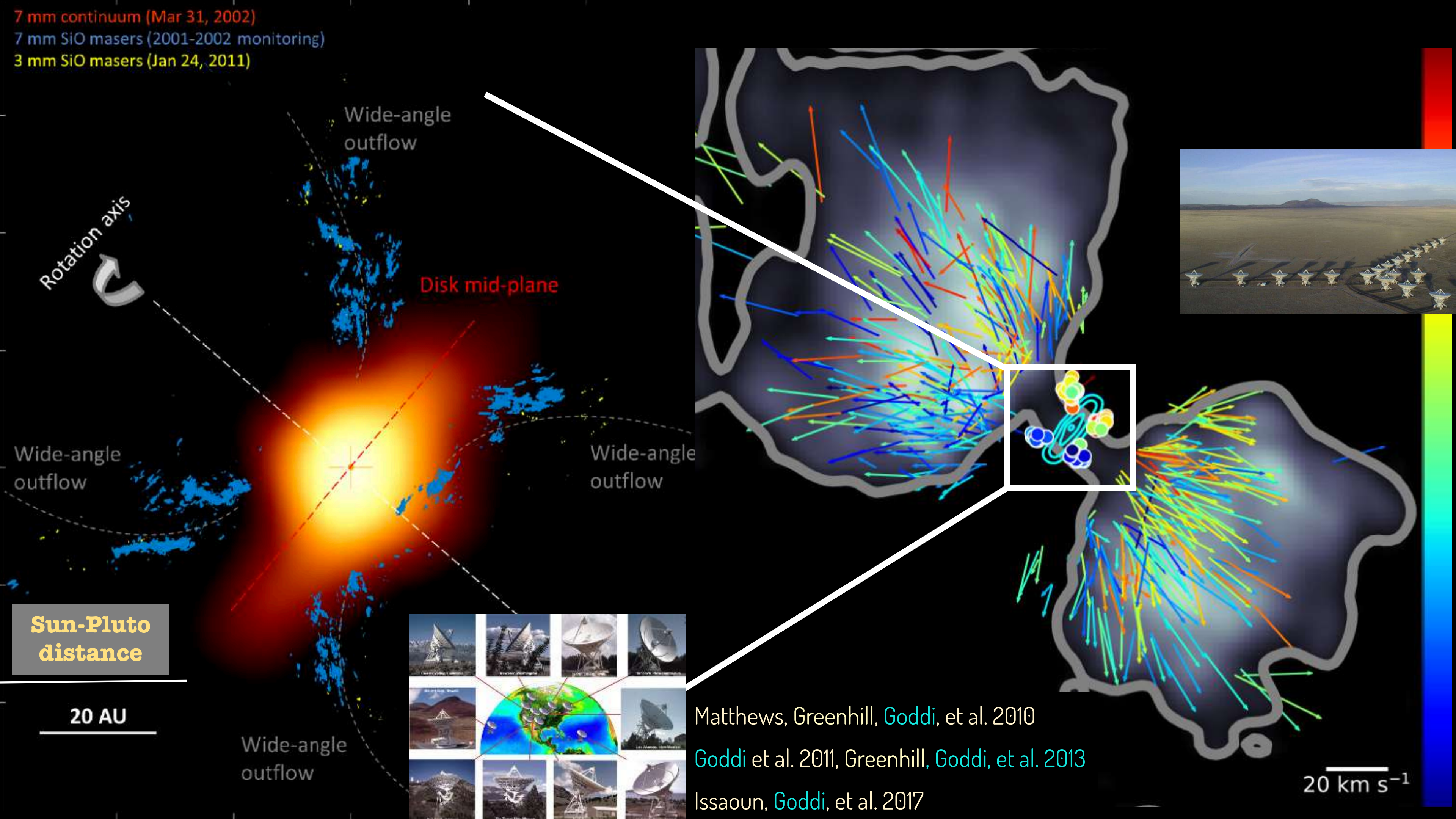
Main global VLBI Networks in the radio

Frequencies: 1-86 GHz, Wavelengths: 1dm-3mm

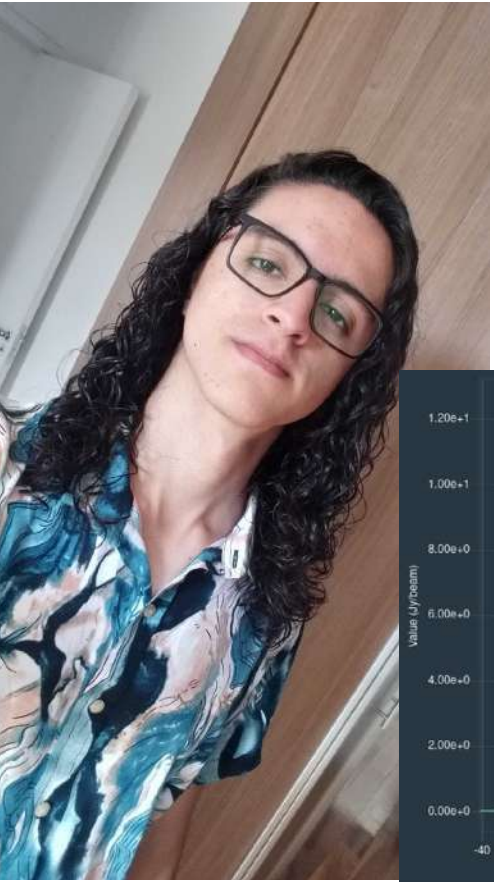
Orion


Orion nebula
D~420 pc
VLT

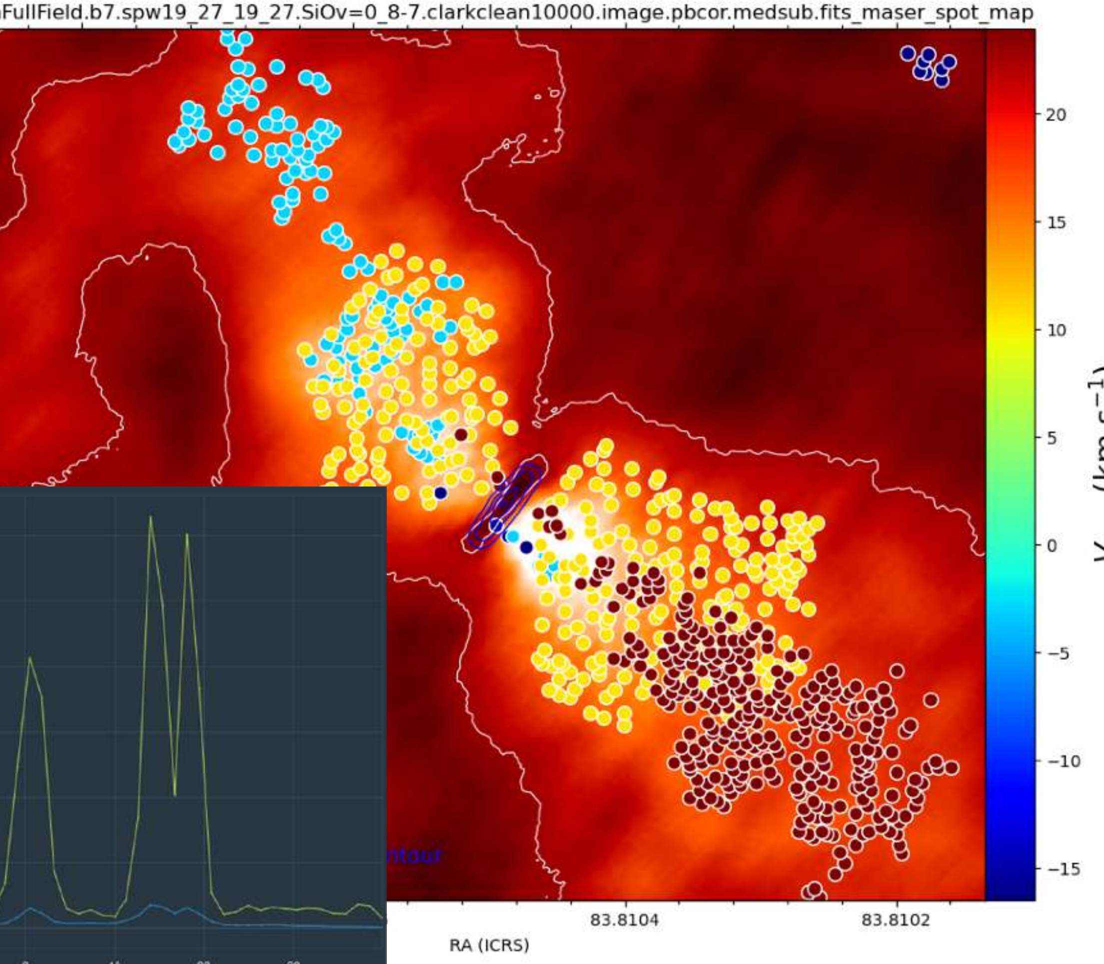

<--- v=0 SiO masers (7 mm) [VLA]
o v=1 SiO masers (3 mm) [VLBA]
v=0 SiO thermal (1 mm) [ALMA]
Dust continuum (1 mm) [ALMA]
20 km s^{-1}

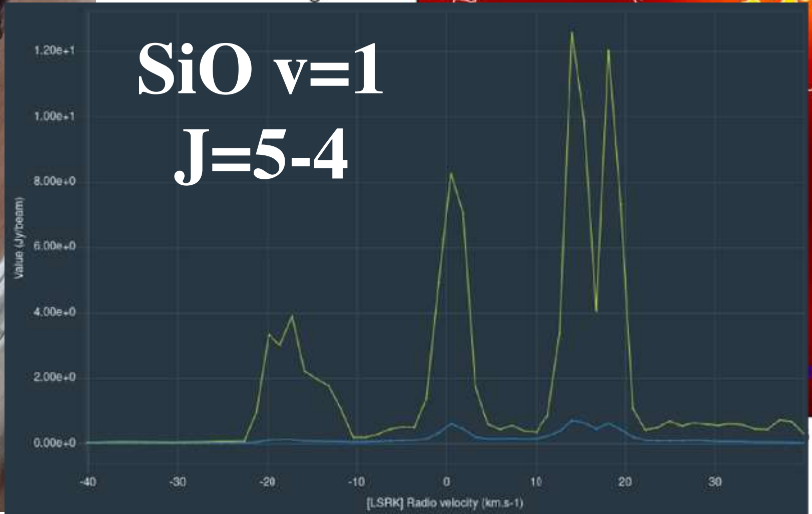

7 mm continuum (Mar 31, 2002)
7 mm SiO masers (2001-2002 monitoring)
3 mm SiO masers (Jan 24, 2011)
Wide-angle outflow
Rotation axis
Disk mid-plane
Wide-angle outflow
Wide-angle outflow
Wide-angle outflow
Sun-Pluto distance
20 AU
20 km s^{-1}
Matthews, Greenhill, Goddi, et al. 2010
Goddi et al. 2011, Greenhill, Goddi, et al. 2013
Issaoun, Goddi, et al. 2017

ALMA data being analysed by
Vinicius Ruedas
Undergraduate student at USP



Mm SiO maser distribution from ALMA (from 86 GHz to 350 GHz)





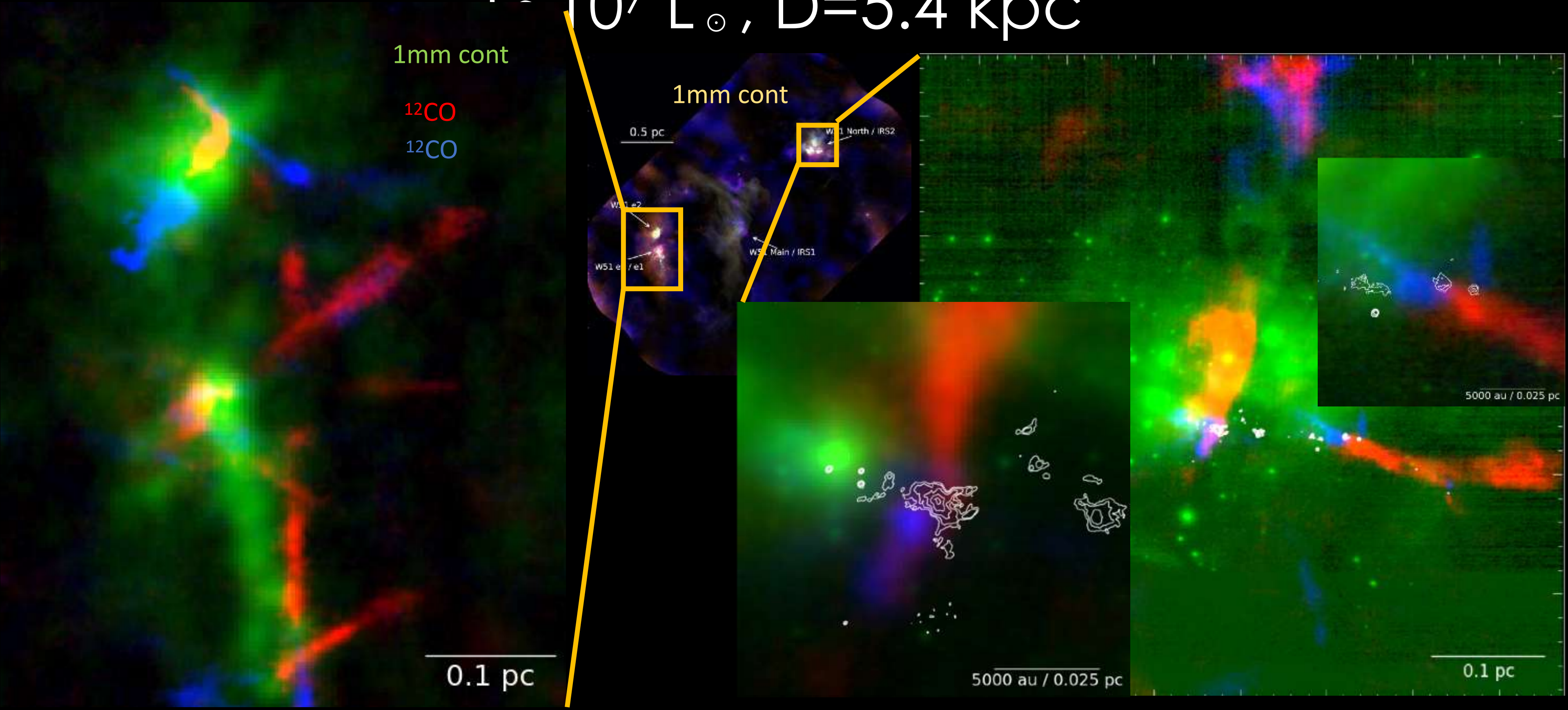
Ingredient 2: High frequencies

<u>Tracers:</u>

- Thermal molecular lines (CO, SiO, …)
- Hydrogen recombination lines (HRLs)
- Mm dust and synchrotron continuum emission

Dense protostellar cluster in W51

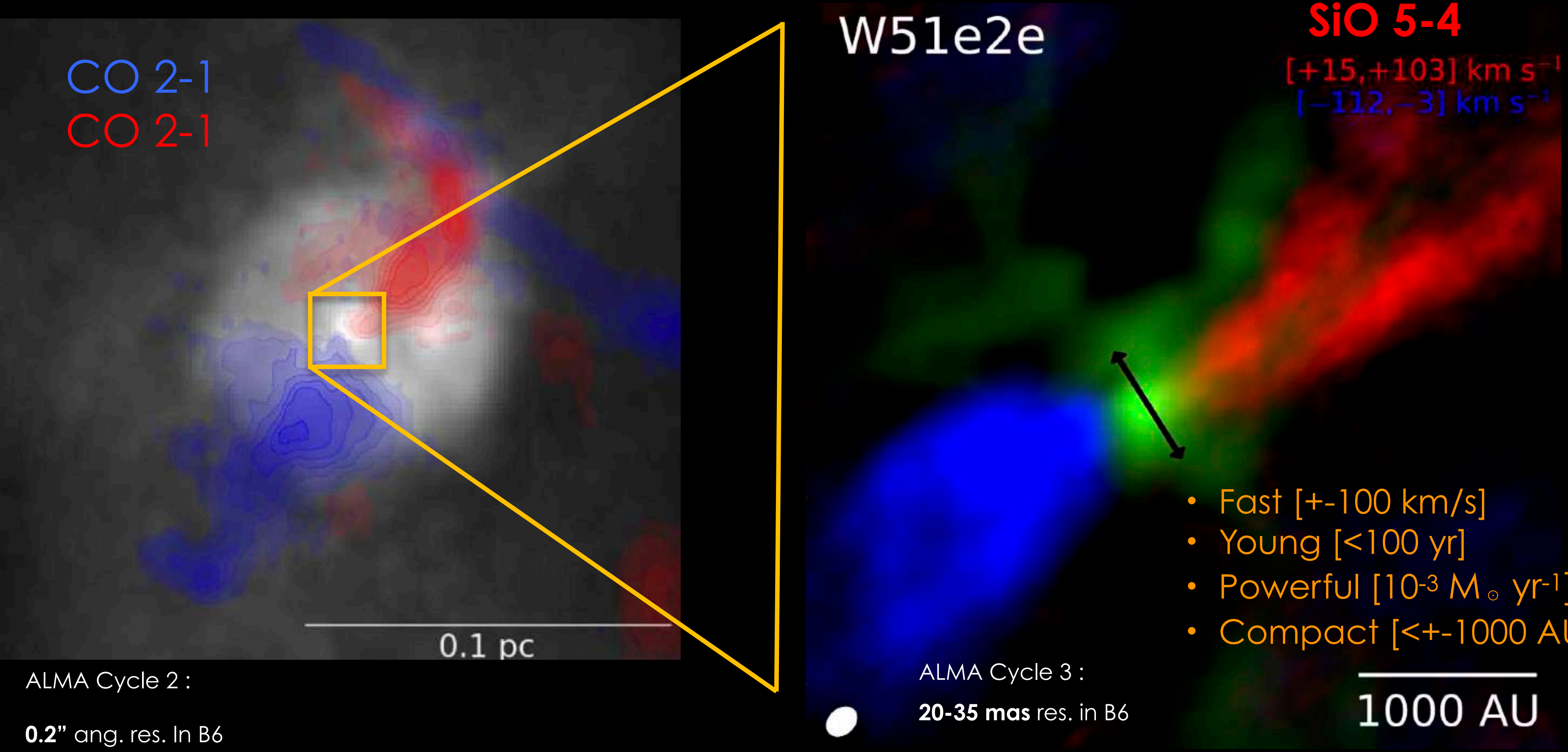
L ~ 10^7 $L_\odot$, D=5.4 kpc



A spectacular multiple system of collimated CO outflows

Ginsburg, Goddi, et al. 2017

ALMA longest baselines reveal ultra-compact collimated outflows

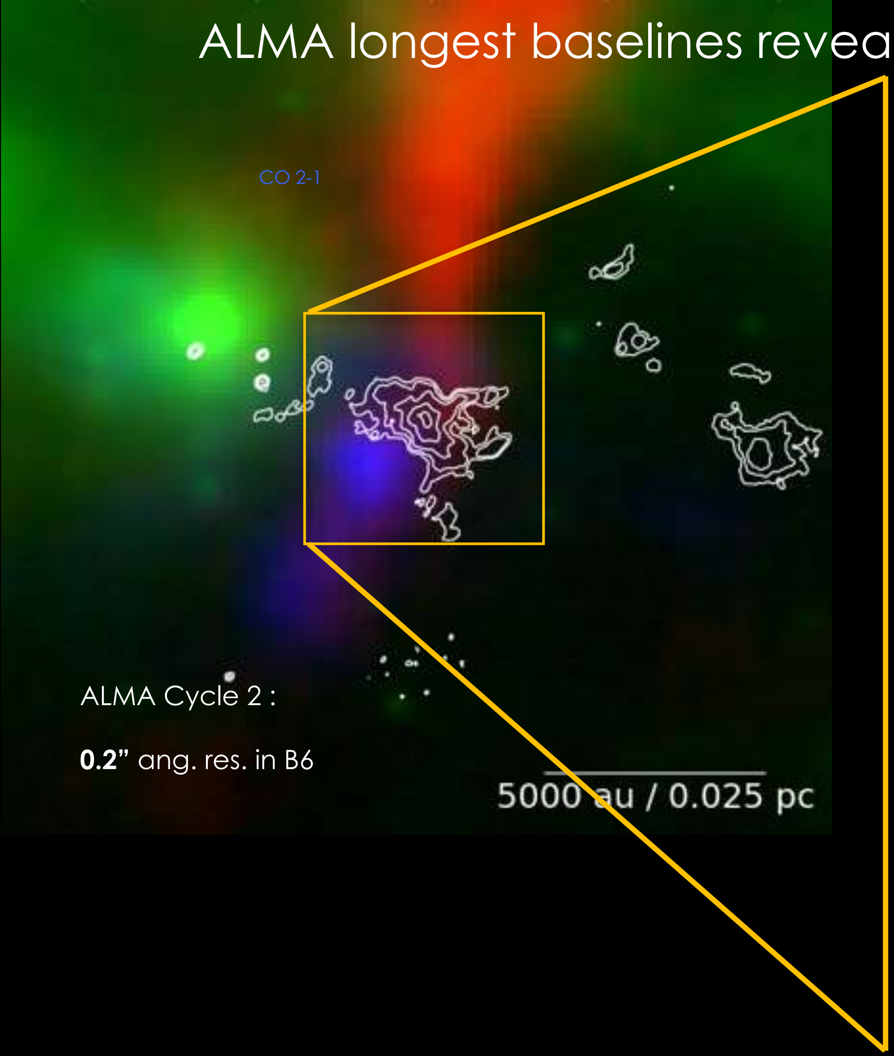


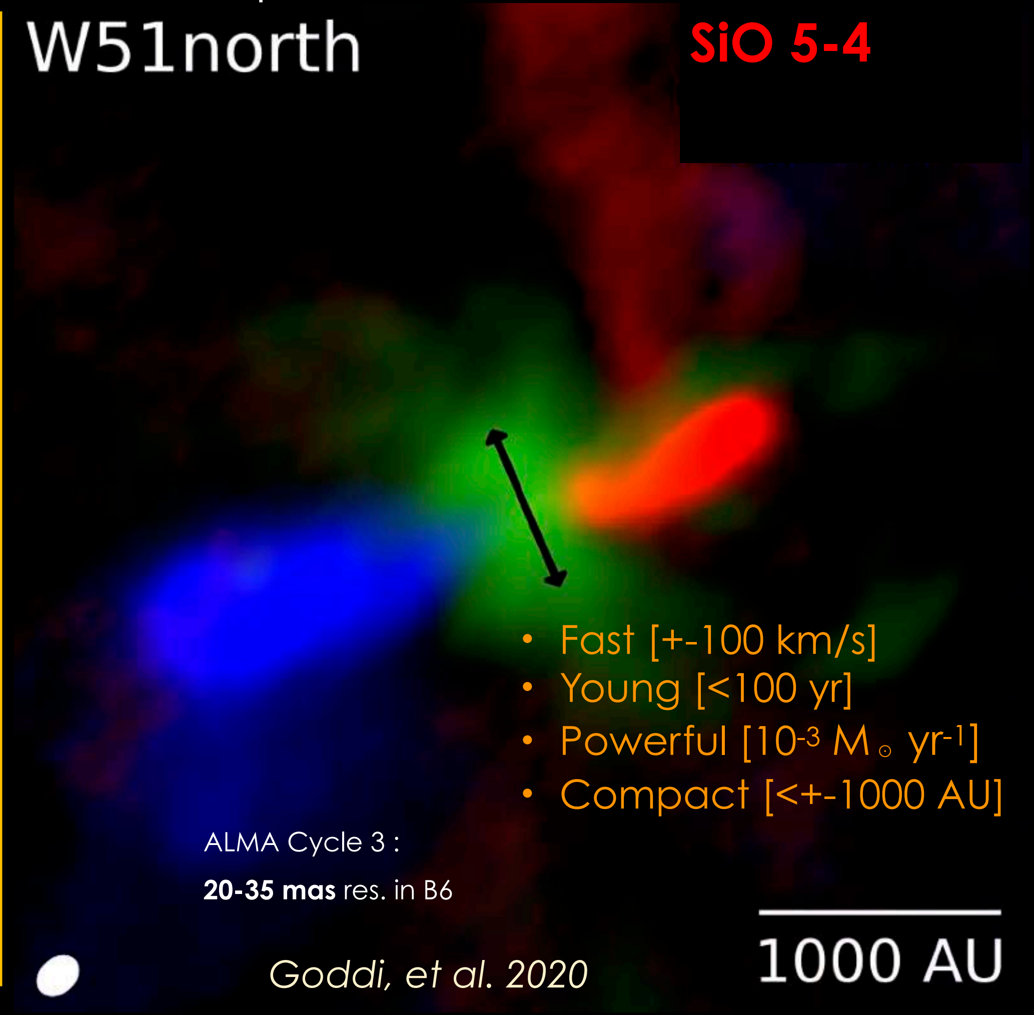
ALMA Cycle 2 :

0.2" ang. res. In B6

Goddi, et al. 2020

ALMA longest baselines reveal ultra-compact collimated outflows





- Fast [+-100 km/s]
- Young [<100 yr]
- Powerful [10^{-3} $M_\odot$ yr^{-1}]
- Compact [<+-1000 AU]

National Radio Astronomy Observatory

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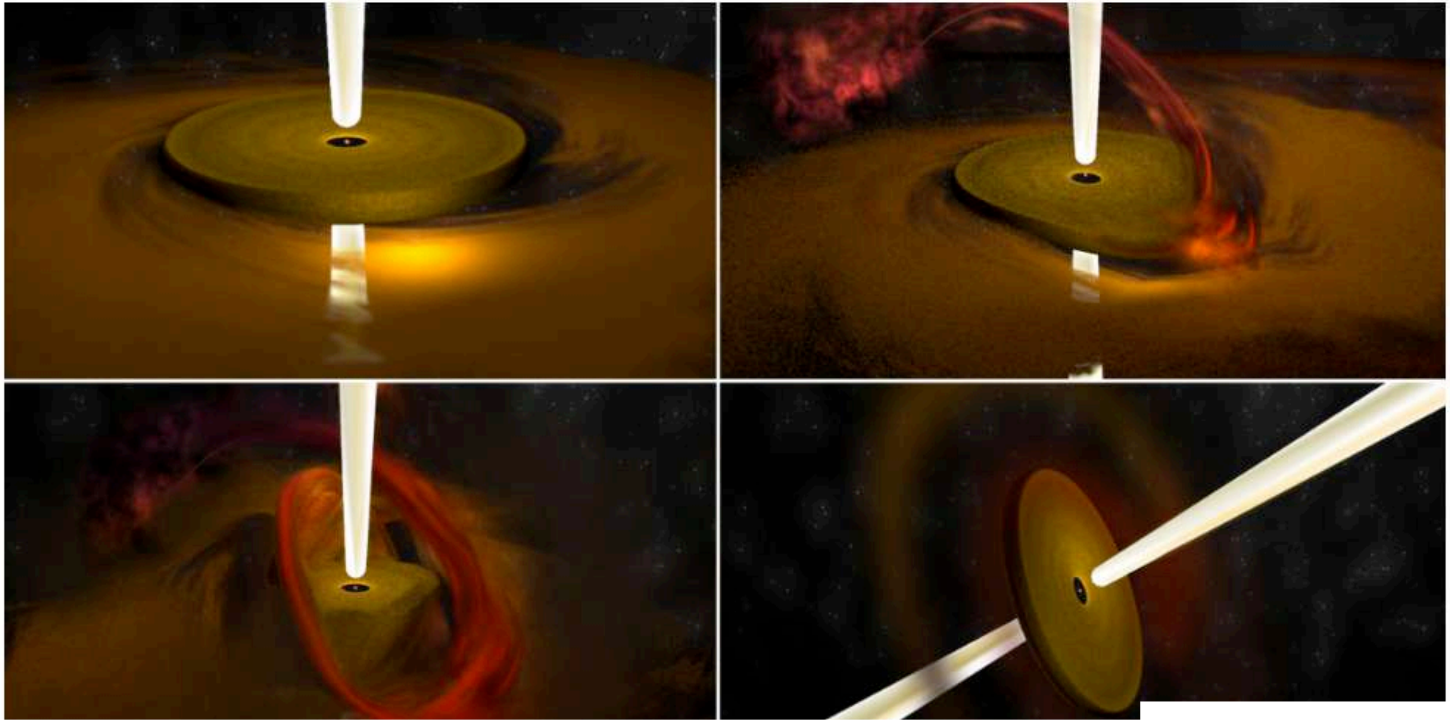
ALMA Shows Massive Young Stars Forming in “Chaotic Mess”

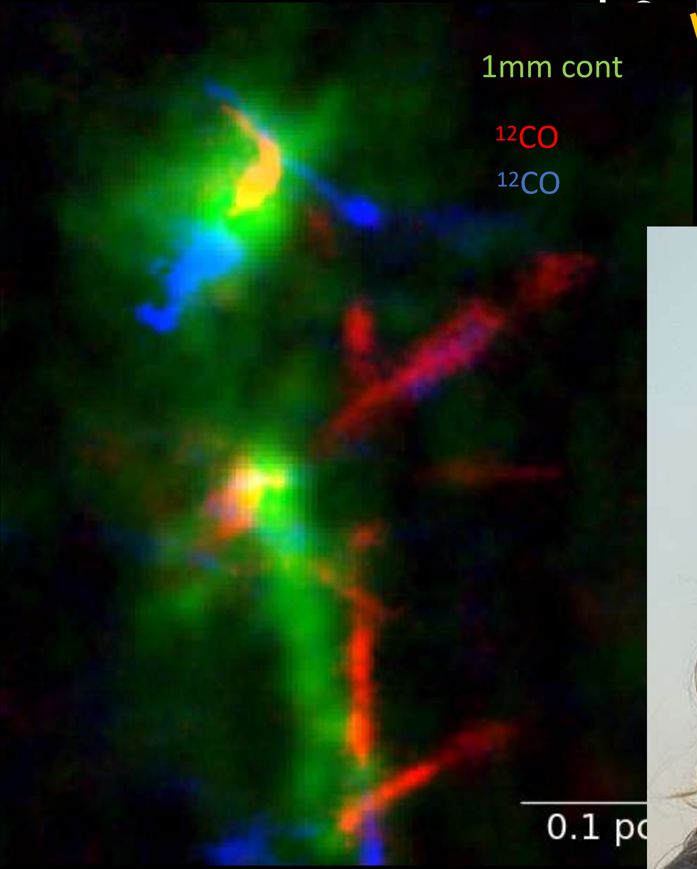


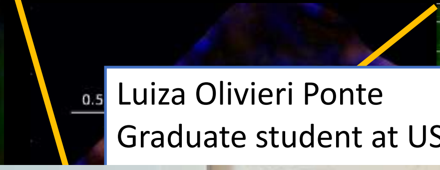
NRAO Press Release: https://public.nrao.edu/news/massive-young-stars-forming/

Goddi+ 2020, ApJ

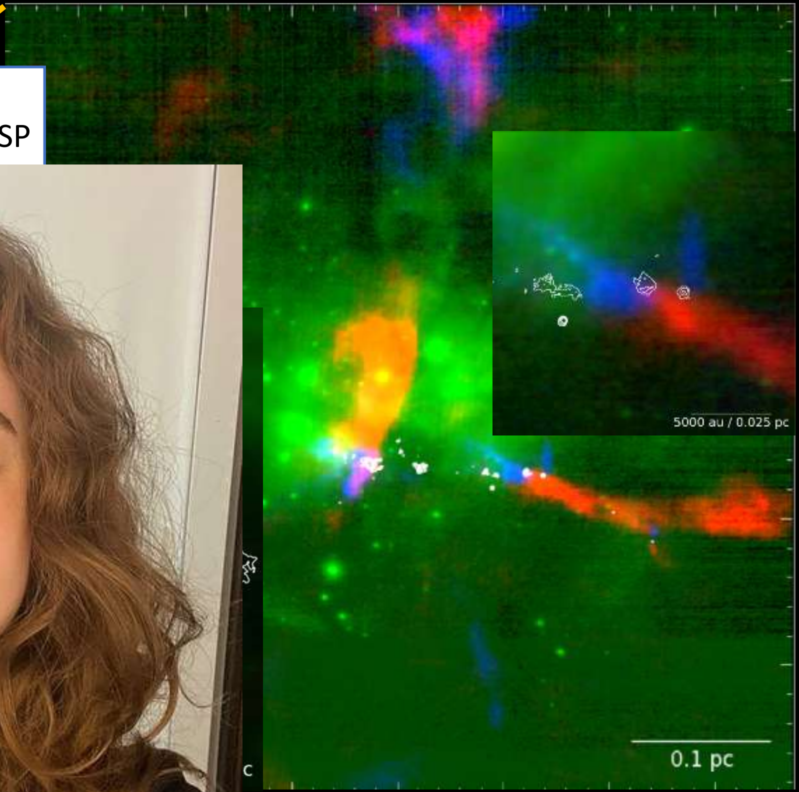
Dense protostellar cluster in W51

$L \sim 10^7 L_\odot$, D=5.4 kpc





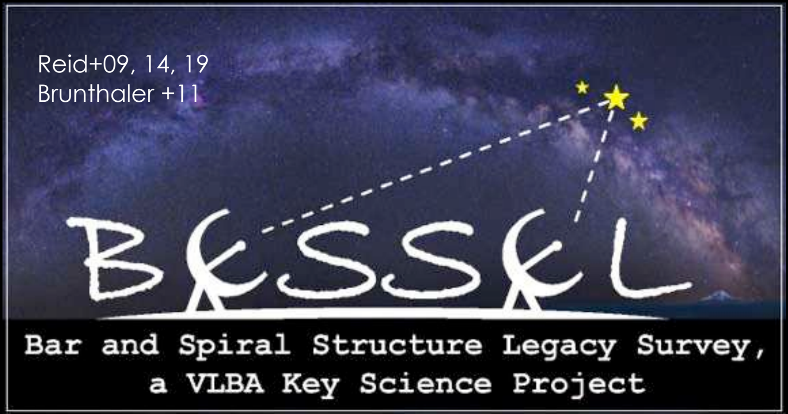
Luiza Olivieri Ponte
Graduate student at USP

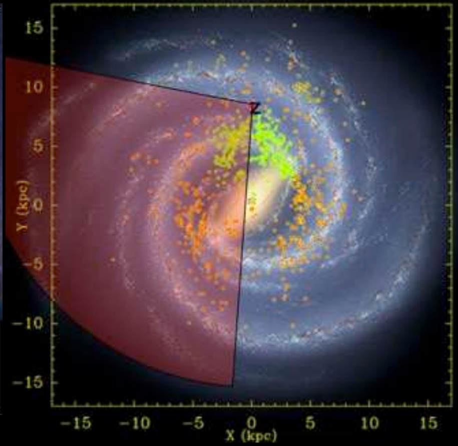


insburg, Goddi, et al. 2017

POETS: Protostellar Outflows at the EarliesT Stages

A a statistically significant sample of massive YSOs studied with maser VLBI from the BeSSeL VLBA Survey





- VLBA observations of 22 GHz H_2O & 6.7 GHz CH_3OH masers [1000 hrs observed]
- VLA observations of radio continuum (in bands S, C, Ku, K, Q) [140 hrs observed]
- ALMA observations of thermal lines: (to be) proposed

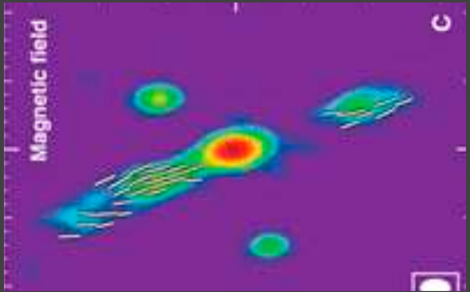
Moscadelli, Sanchez-Monge, Goddi, et al. 2016
Sanna, Moscadelli, Goddi, et al. 2018, 2019
Moscadelli, Sanna,, Goddi, et al. 2019, 2020

POETS: Protostellar Outflows at the EarliesT Stages

- VLA full-polarization observations of non-thermal radio continuum sources
- A- and B-conf.

- Bands
  - (1) S-band at 13 cm (2-4 GHz),
  - (2) C-band at 6 cm (4-8 GHz),
  - (3) X-band at 3 cm (8-12 GHz),
  - (4) Ku-band at 2 cm (12-18 GHz),
  - (5) K-band at 1.3~cm (18-26 GHz)

- **A pilot on W3(H_2O) already observed [20 hours, PI: Goddi]**

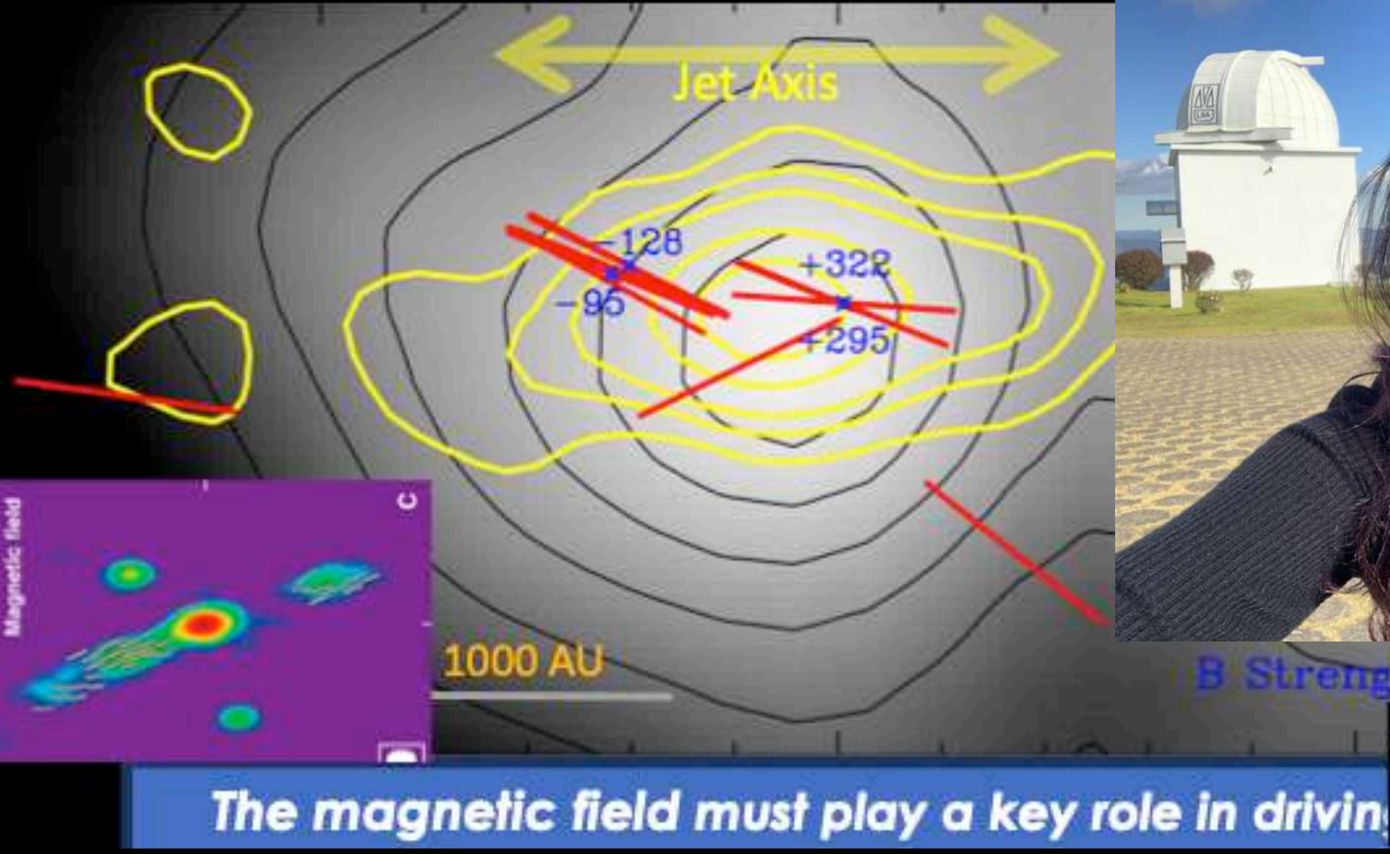


Carrasco-Gonzalez+2010
Padovani+2015

Science goals:

1. Map the jet structure.
2. Build spectral index maps
3. Measure the magnetic field strength
4. Infer the magnetic field morphology
5. Investigate particle acceleration (DSA/Fermi acceleration)

W3(OH) : Best example of a synchrotron jet from a high-mass protostar [Elis]



Elis Sales
PhD student at USP

Goddi+ 2017, A&A

Event Horizon Telescope (EHT)

A Global Network of Radio Telescopes

Observatories

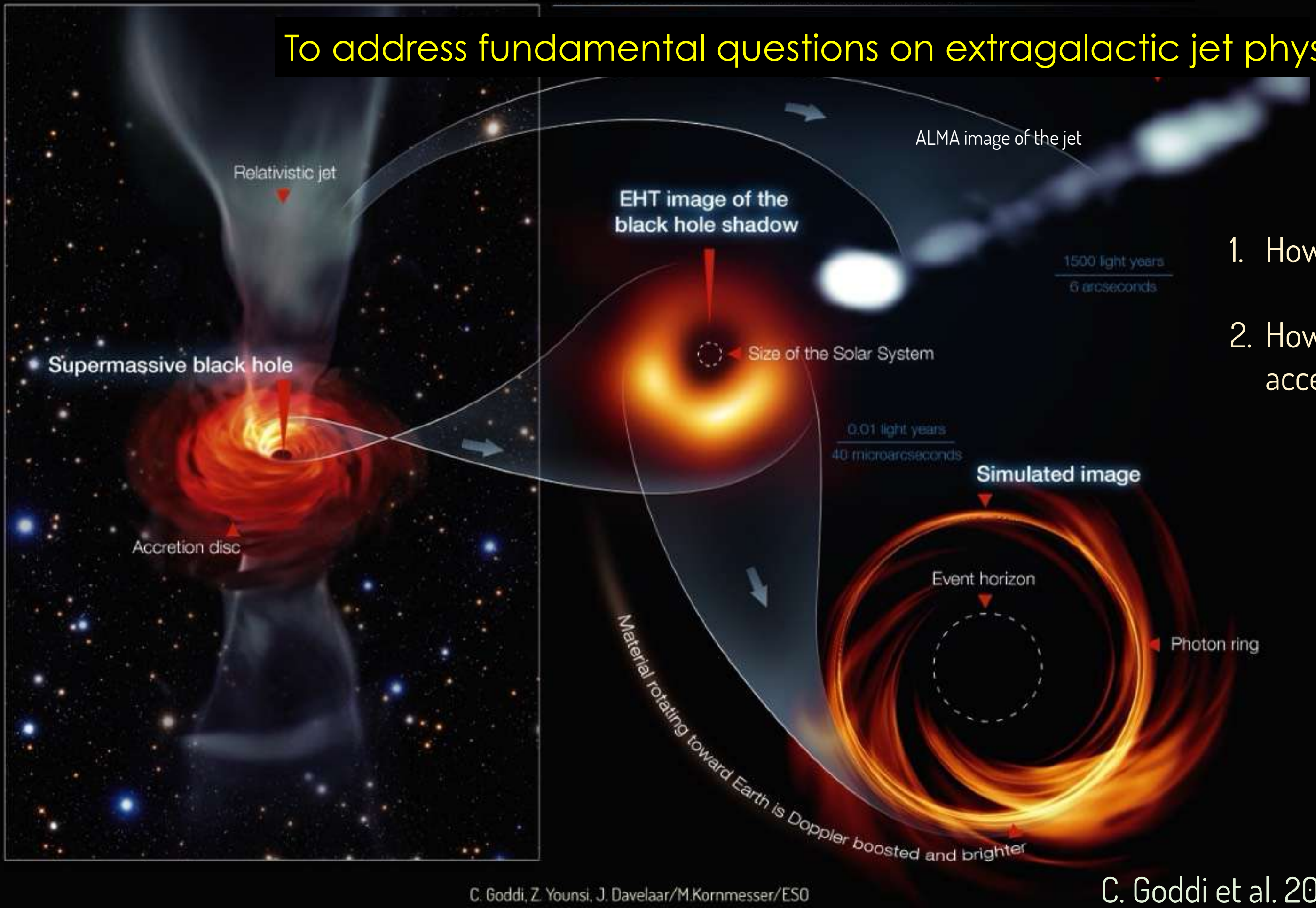
- ALMA — Atacama Large Millimeter/submillimeter Array, CHAJNANTOR PLATEAU, CHILE
- APEX — Atacama Pathfinder EXperiment, CHAJNANTOR PLATEAU, CHILE
- PV — IRAM 30-meter Telescope, PICO VELETA, SPAIN
- JCMT — James Clerk Maxwell Telescope, MAUNA KEA, HAWAII
- LMT — Large Millimeter Telescope, SIERRA NEGRA, MEXICO
- SMA — Submillimeter Array, MAUNA KEA, HAWAII
- SMT — Submillimeter Telescope, MOUNT GRAHAM, ARIZONA
- SPT — South Pole Telescope, SOUTH POLE STATION
- GLT — Greenland Telescope Project, THULE AIR FORCE BASE

2017

2018

Goal #2

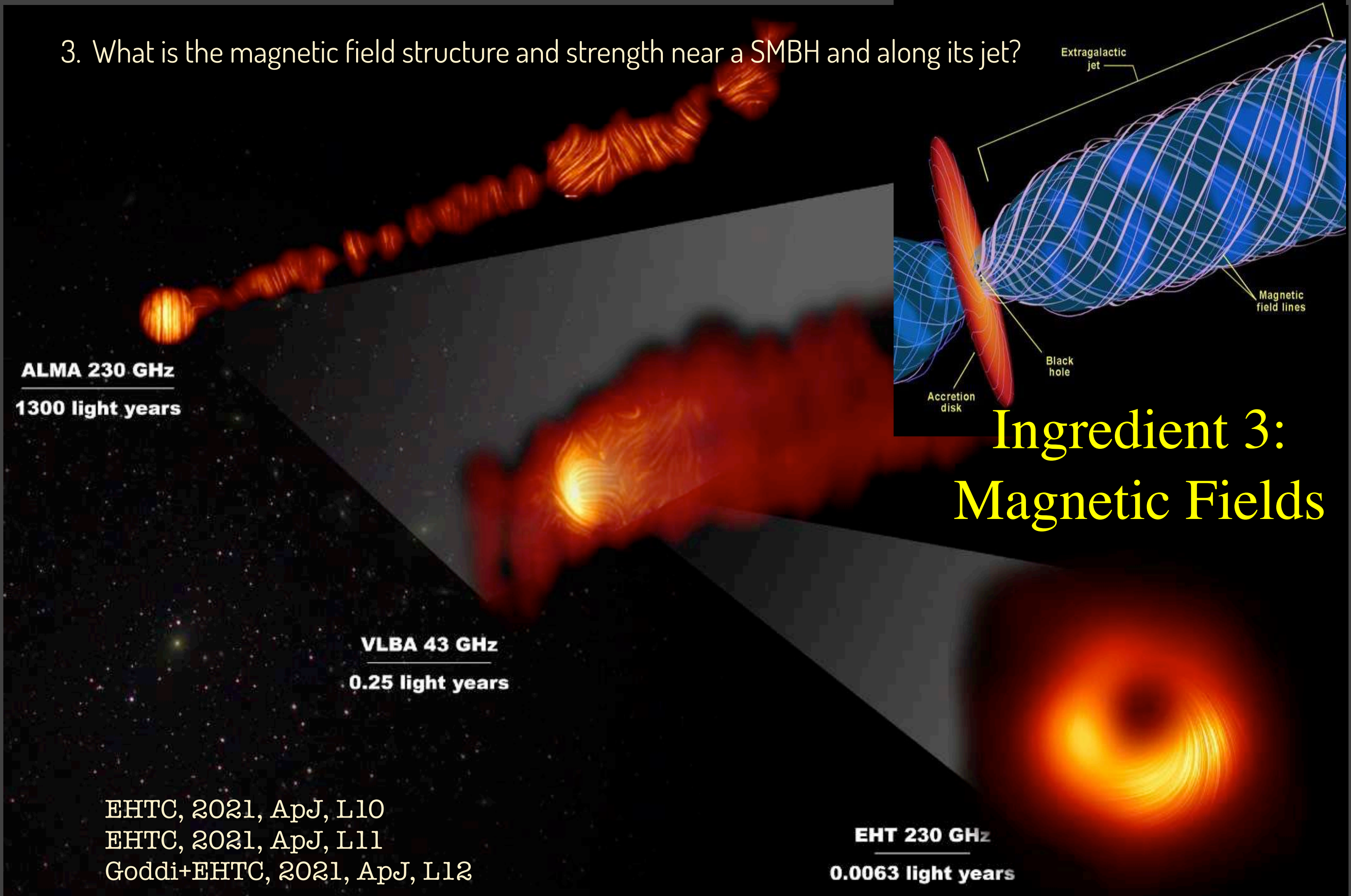
To address fundamental questions on extragalactic jet physics:



1. How do SMBHs form jets?
2. How are they collimated and accelerated?

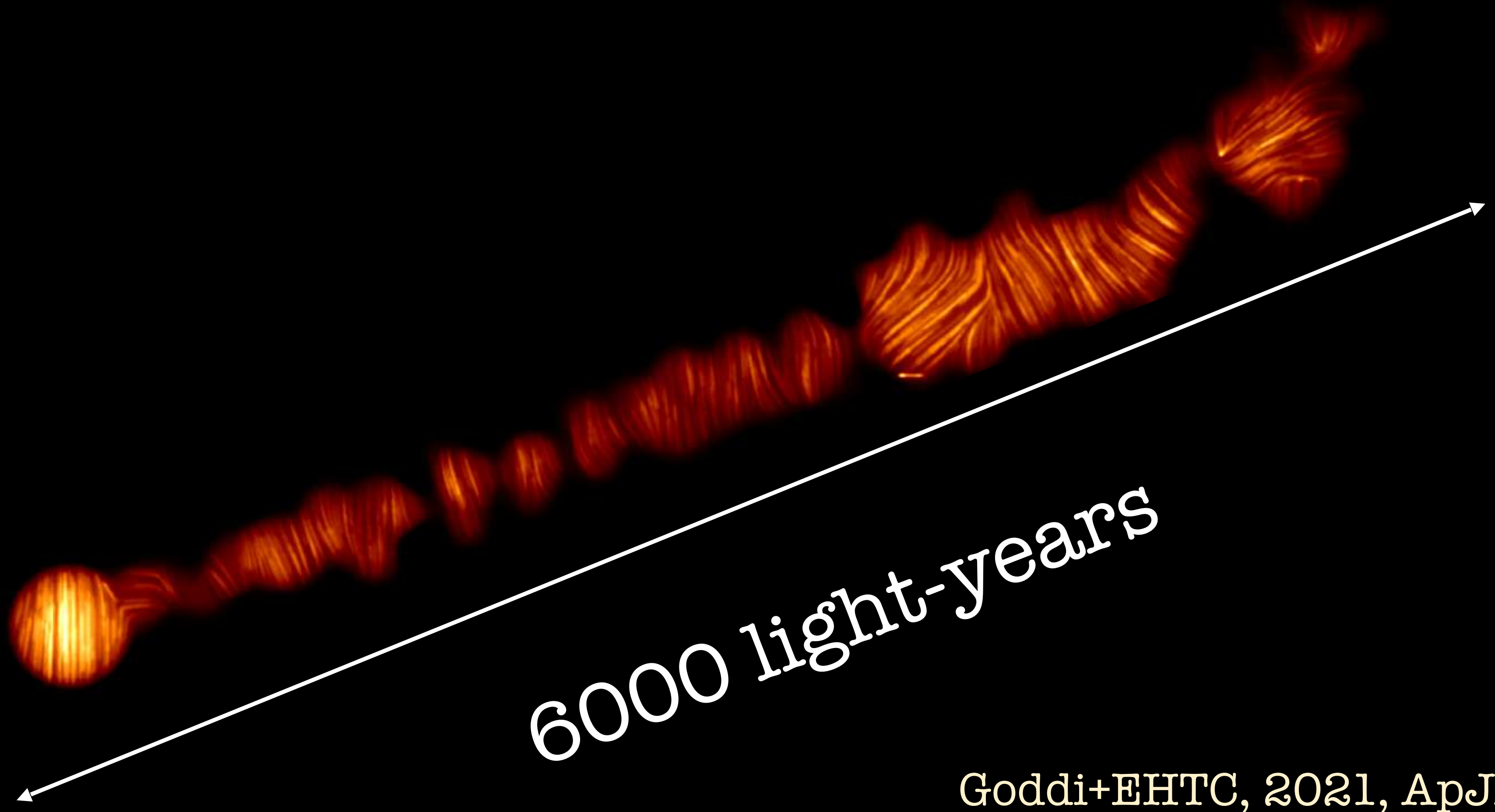
C. Goddi et al. 2019, The Messenger, 177, 25

3. What is the magnetic field structure and strength near a SMBH and along its jet?



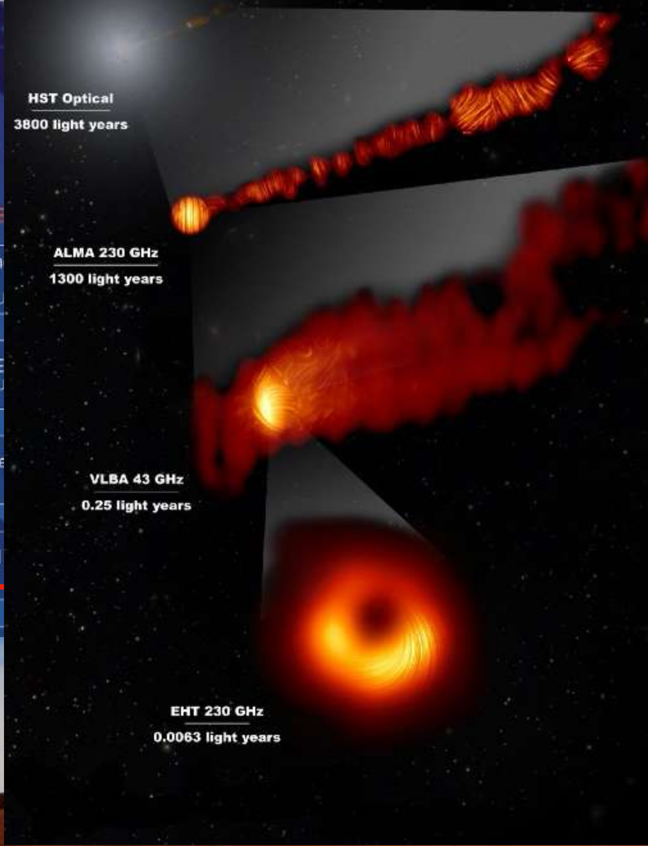
Ingredient 3: Magnetic Fields

EHTC, 2021, ApJ, L10
EHTC, 2021, ApJ, L11
Goddi+EHTC, 2021, ApJ, L12



Goddi+EHTC, 2021, ApJL

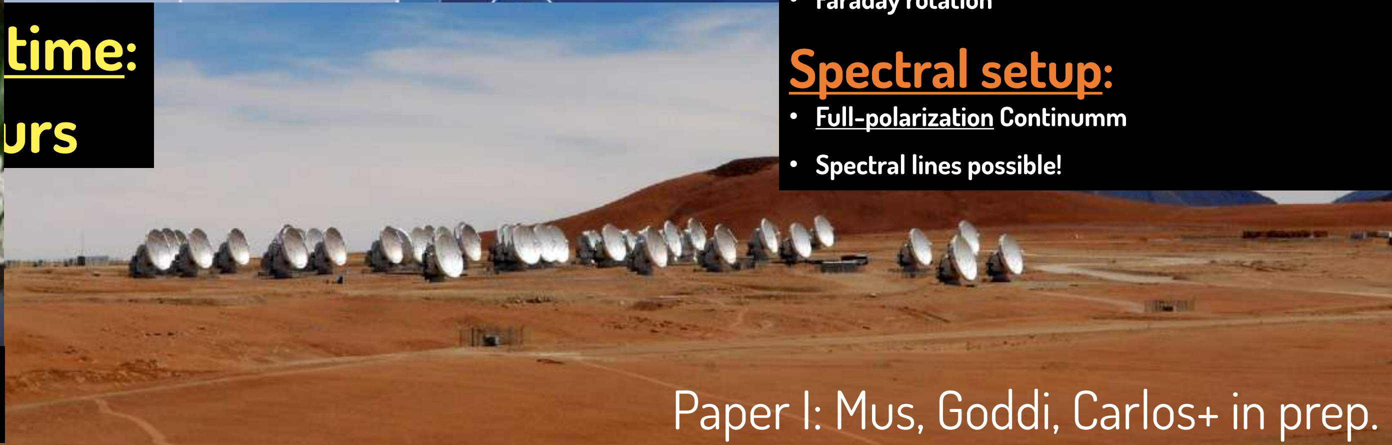

Event Horizon Telescope (EHT)
A Global Network of Radio Telescopes
2017 OBSE
JCMT
SMA
SMT
LMT
30-M
ALMA
APEX
ALMA
Atacama Large Millim
submillimeter Array
CHAJNANTOR PLATEAU
APEX
Atacama Pathfinder E
CHAJNANTOR PLATEAU
30-M
IRAM 30-M Telescope
PICO VELETA, SPAIN
JCMT
James Clerk Maxwell


HST Optical
3800 light years
ALMA 230 GHz
1300 light years
VLBA 43 GHz
0.25 light years
EHT 230 GHz
0.0063 light years

VAPOLA
A multi-year, multi-band polarization survey of AGN with ALMA

time:

urs



Alejandro Mus
Former Postdoc at INAF & UNICA

Targets: ~40 AGN + Sgr A*
- Radio galaxies, Blazars, QSOs

Years: 2017, 2018, 2021, 2022, 2023, 2024, …
- Long-term monitoring of AGN

Cadence: multiple consecutive days in a week
- Time-domain (inter-day) studies

Bands: 3, 6, 7
- Spectral index
- Faraday rotation

Spectral setup:
- Full-polarization Continumm
- Spectral lines possible!

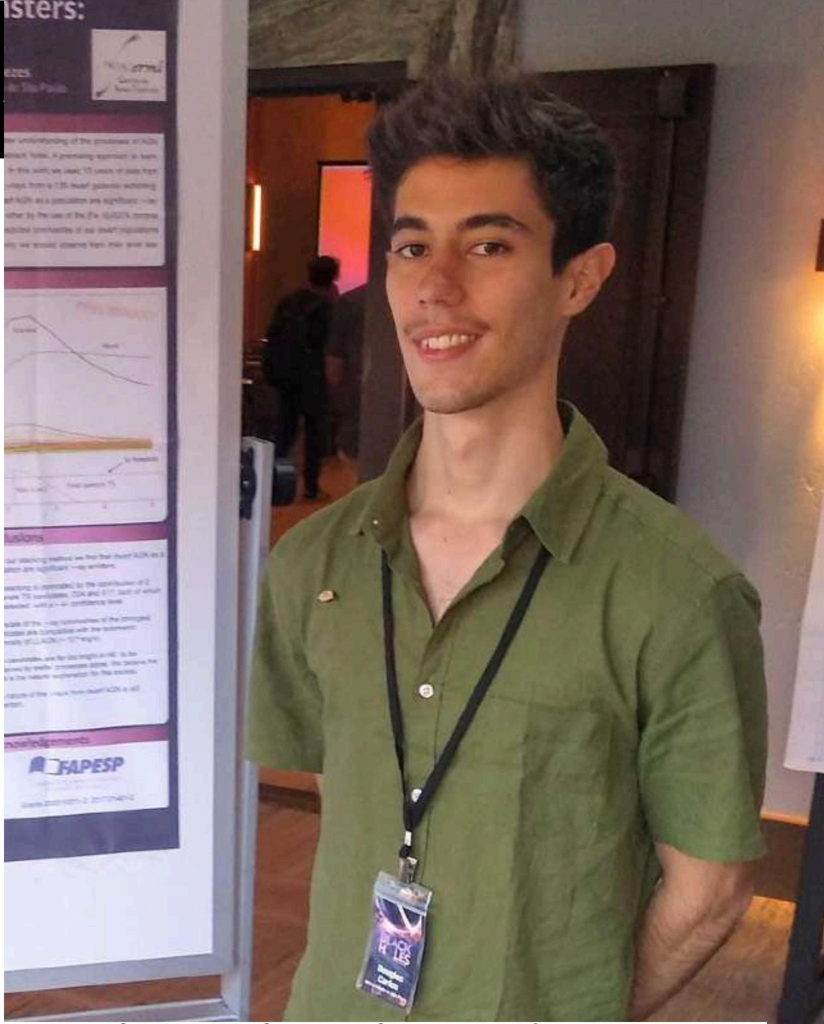
Paper I: Mus, Goddi, Carlos+ in prep.

VAPOLA II

Spectropolarimetric properties and their evolut

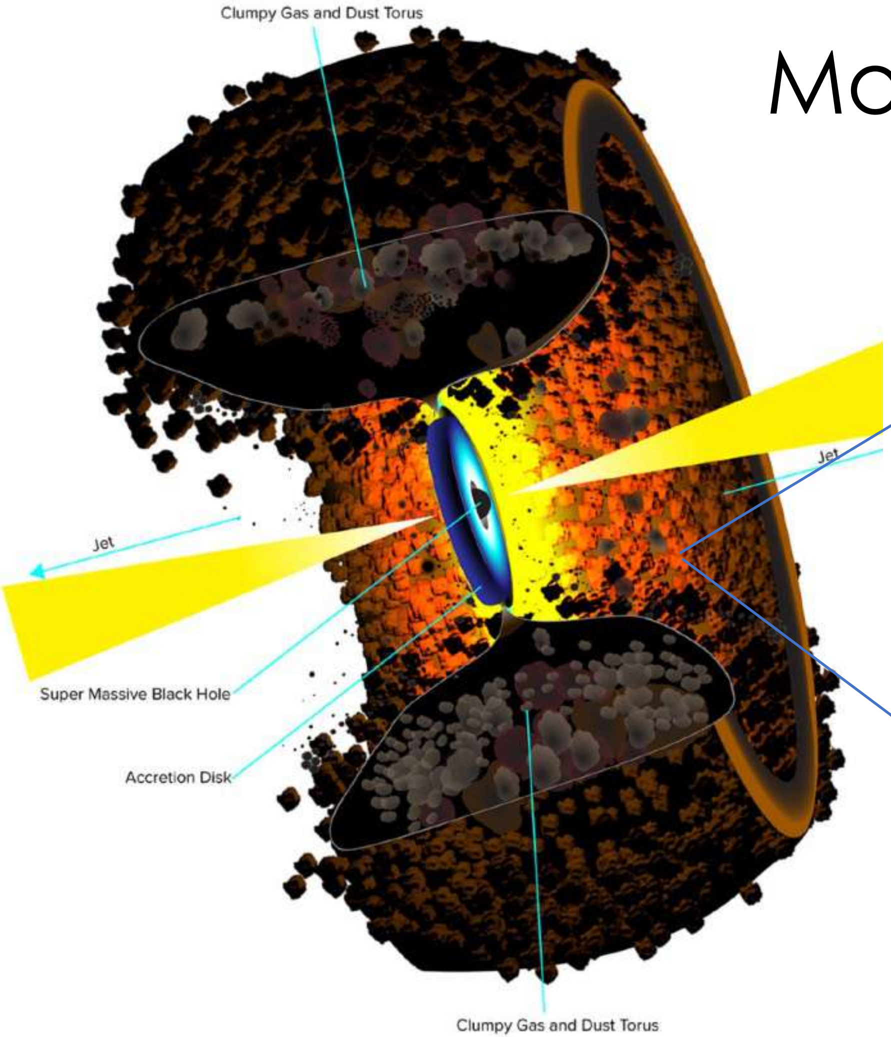
Source	J2000 name	RA (h:m:s)	DEC (deg:m:s)	z[a]	D_L (Mpc)	Class[b]	# Epochs[c]	Bands[d]
3C279	J1256-0547	12:56:11.167	−5:47:21.525	0.536	2957	B	46	B3,B6,B7
QSOB1921-293	J1924-2914	19:24:51.056	−29:14:30.121	0.353	1798	F	28	B3,B6,B7
SgrA*	–	17:45:40.036	−29:0:28.170	-2.7×10^{-5}	0.008	SgrA*	27	B3,B6,B7
M87	J1230+1223	12:30:49.411	12:23:28.283	0.004	17.66	G	19	B3,B6,B7
NRAO530	J1733-1304	17:33:2.706	−13:4:49.548	0.899	5559	F	16	B3,B6
3C273	J1229+0203	12:29:6.700	2:3:8.600	0.158	726.1	F	15	B3,B6,B7
4C01.28	J1058+0133	10:58:29.605	1:33:58.824	0.894	5518	B	15	B3,B6,B7
J1744-3116	J1744-3116	17:44:23.578	−31:16:36.292	–	–	U	7	B3,B6
PKS1741-03	J1743-0350	17:43:58.856	−3:50:4.616	1.054	6767	F	6	B6
PKS1335-127	J1337-1257	13:37:39.783	−12:57:24.693	0.539	2975	F	6	B6,B7
OJ287	J0854+2006	8:54:48.875	20:6:30.641	0.306	1522	B	6	B3,B6
J1957-3845	J1957-3845	19:57:59.819	−38:45:6.356	0.626	3567	F	6	B6
J0510+1800	J0510+1800	5:10:2.369	18:0:41.582	0.416	2183	B	4	B3,B6
PKS1243-072	J1246-0730	12:46:4.232	−7:30:46.575	1.286	8655	F	3	B6,B7
PKS1510-089	J1512-0905	15:12:50.533	−9:5:59.830	0.360	1842	F	3	B6,B7
M84	J1225+1253	12:25:3.743	12:53:13.138	0.003	13.98	G	2	B3,B6
J1224+0330	J1224+0330	12:24:52.422	3:30:50.292	0.956	6000	F	2	B3,B6
3C345	J1642+3948	16:42:58.810	39:48:36.993	0.593	3342	F	2	B6
NRAO005	J0006-0623	0:6:13.893	−6:23:35.335	0.347	1762	B	2	B6
3C84	J0319+4130	3:19:48.160	41:30:42.103	0.018	73.6	G	2	B6
OC −150	J0132-1654	1:32:43.489	−16:54:48.567	1.020	6498	F	2	B6
NGC1052	J0241-0815	2:41:4.799	−8:15:20.752	0.005	21.47	G	2	B6
4C09.57	J1751+0939	17:51:32.819	9:39:0.729	0.322	1617	B	2	B3
OI280	J0750+1231	7:50:52.046	12:31:4.828	0.889	5484	F	2	B6
J0837+2454	J0837+2454	8:37:40.246	24:54:23.122	1.125	7337	F	2	B6
3C275.1	J1243+1622	12:43:57.649	16:22:53.393	0.555	3084	F	2	B6
4C +04.42	J1222+0413	12:22:22.550	4:13:15.776	0.966	6078	F	2	B3,B6
J1215+1654	J1215+1654	12:15:3.979	16:54:37.957	1.131	7384	F	2	B6
AP Librae	J1517-2422	15:17:41.813	−24:22:19.476	0.049	208.9	B	1	B6
4C +29.45	J1159+2914	11:59:31.834	29:14:43.826	0.725	4265	F	1	B6
3C454.3	J2253+1608	22:53:57.748	16:8:53.561	0.859	5256	F	1	B3
Mrk501	J1653+3945	16:53:52.218	39:45:36.615	0.033	139	F	1	B6
Cen A	J1325-4301	13:25:27.615	−43:1:8.805	0.002	7.511	G	1	B6
NGC4261	NGC4261	12:19:23.216	5:49:29.701	0.007	30.01	G	1	B6
NGC4278	NGC4278	12:20:6.825	29:16:50.713	0.002	8.912	G	1	B6
S4 1144+40	J1146+3958	11:46:58.298	39:58:34.282	1.088	7037	F	1	B7
PKS1124-186	J1127-1857	11:27:4.392	−18:57:17.442	1.052	6751	F	1	B6
J1816-3052	J1816-3052	18:16:12.278	−30:52:7.930	–	–	U	1	B3

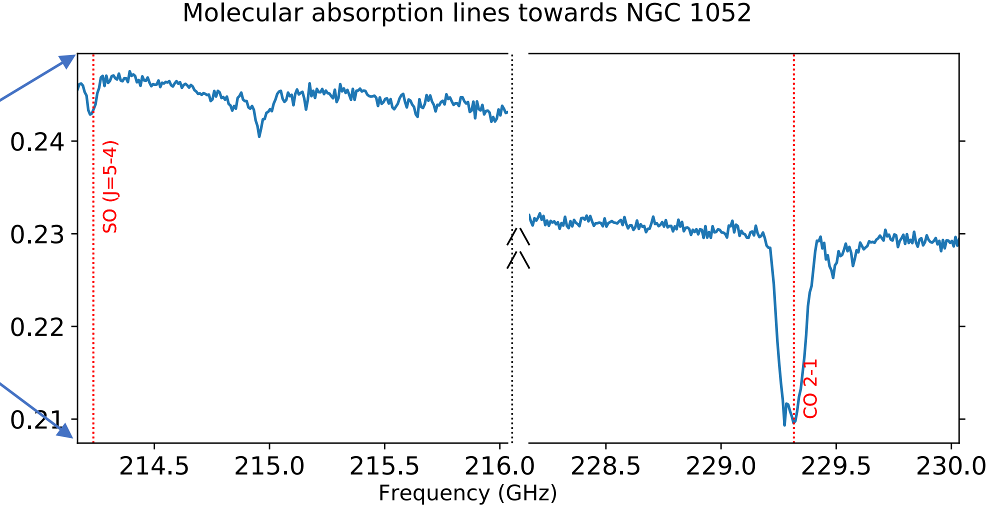
Carlos, Goddi+ in prep.



Douglas Carlos, PhD student at USP

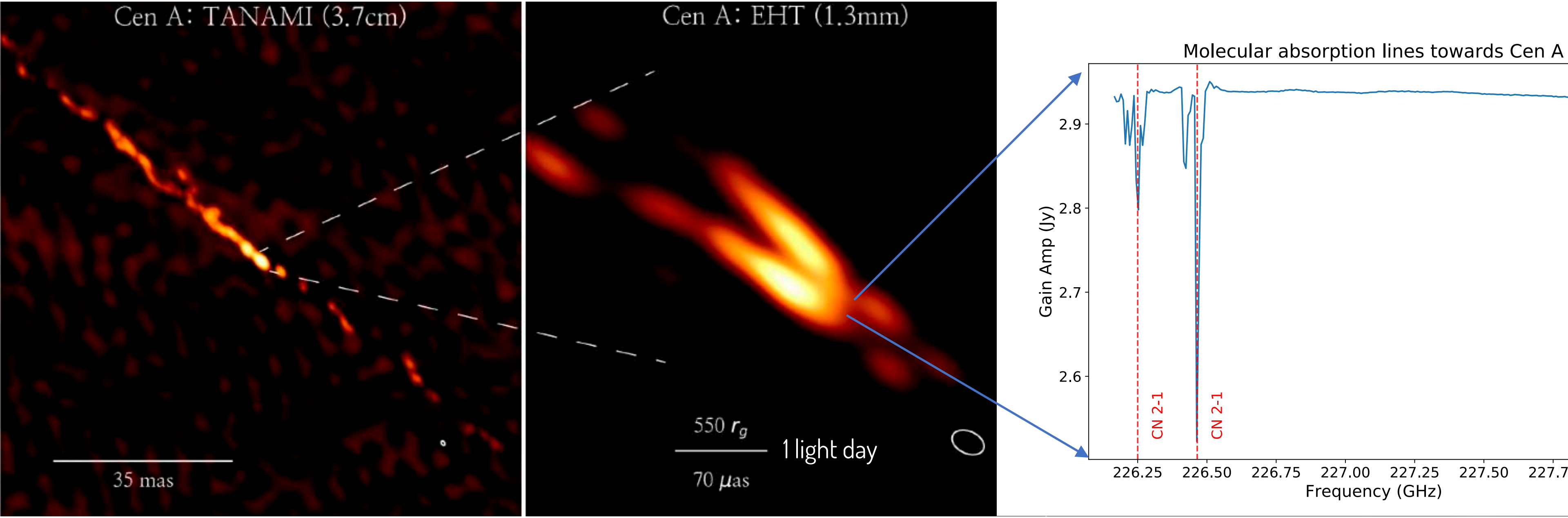
Molecular Torii in AGN





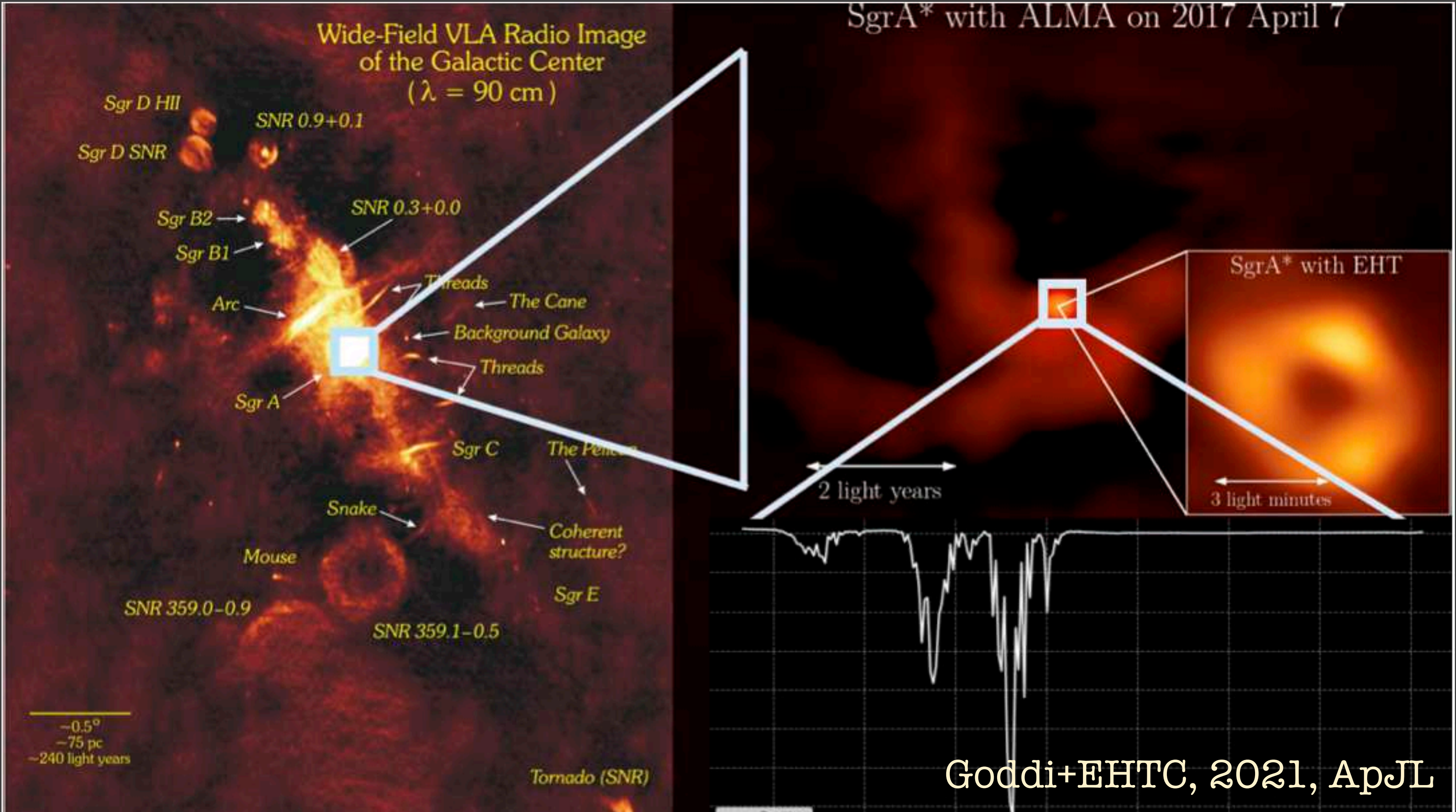
Mus, Goddi, Carlos+ in prep.

Molecular Torii in AGN



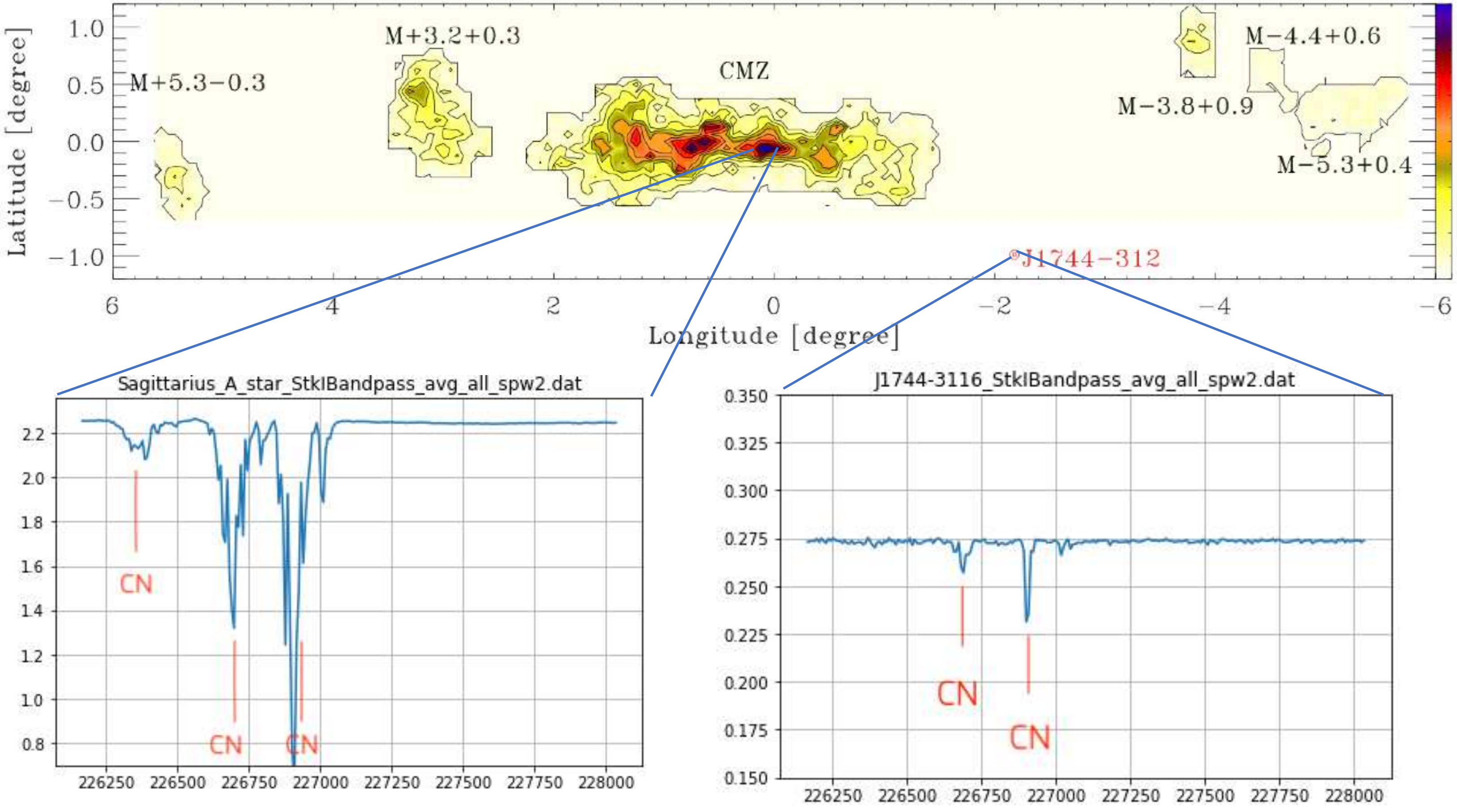
- BH mass = 55 10^6 $M_\odot$
- D = 3.8 Mpc

Janssen, ..., Goddi+ 2021
Mus, Goddi, Carlos+ in prep.

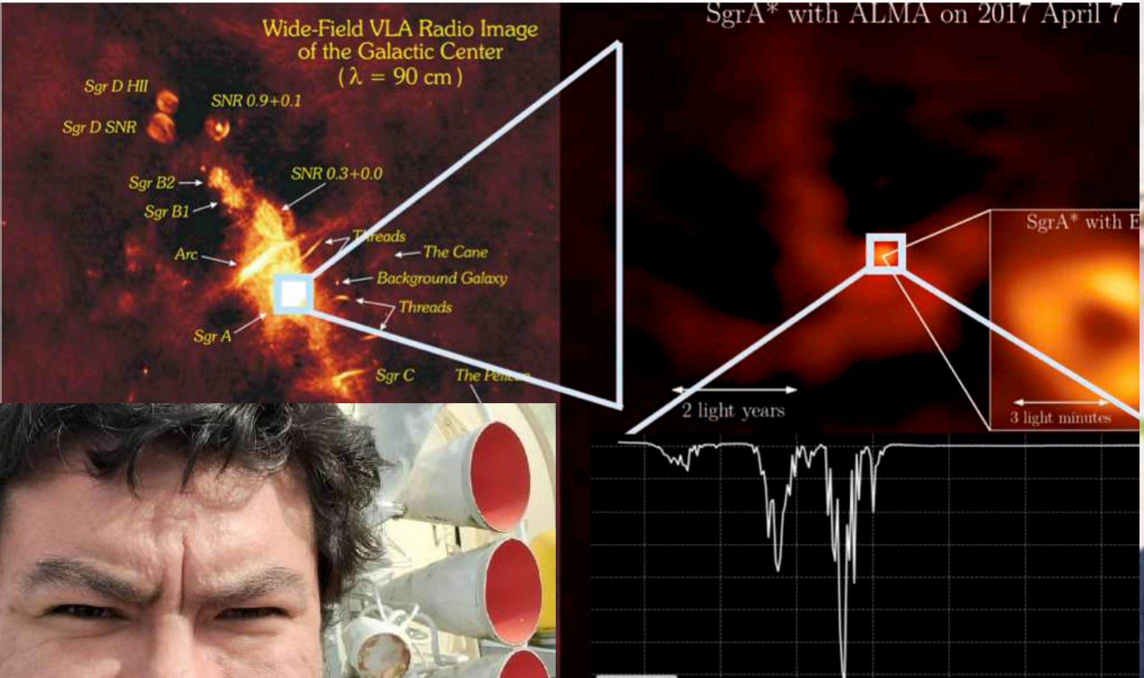


Goddi+EHTC, 2021, ApJL

Cyanide absorption towards Sgr A* and a nearby Quasar



AGN and Black Hole Physics through Spectral Line observations with ALMA and EHT



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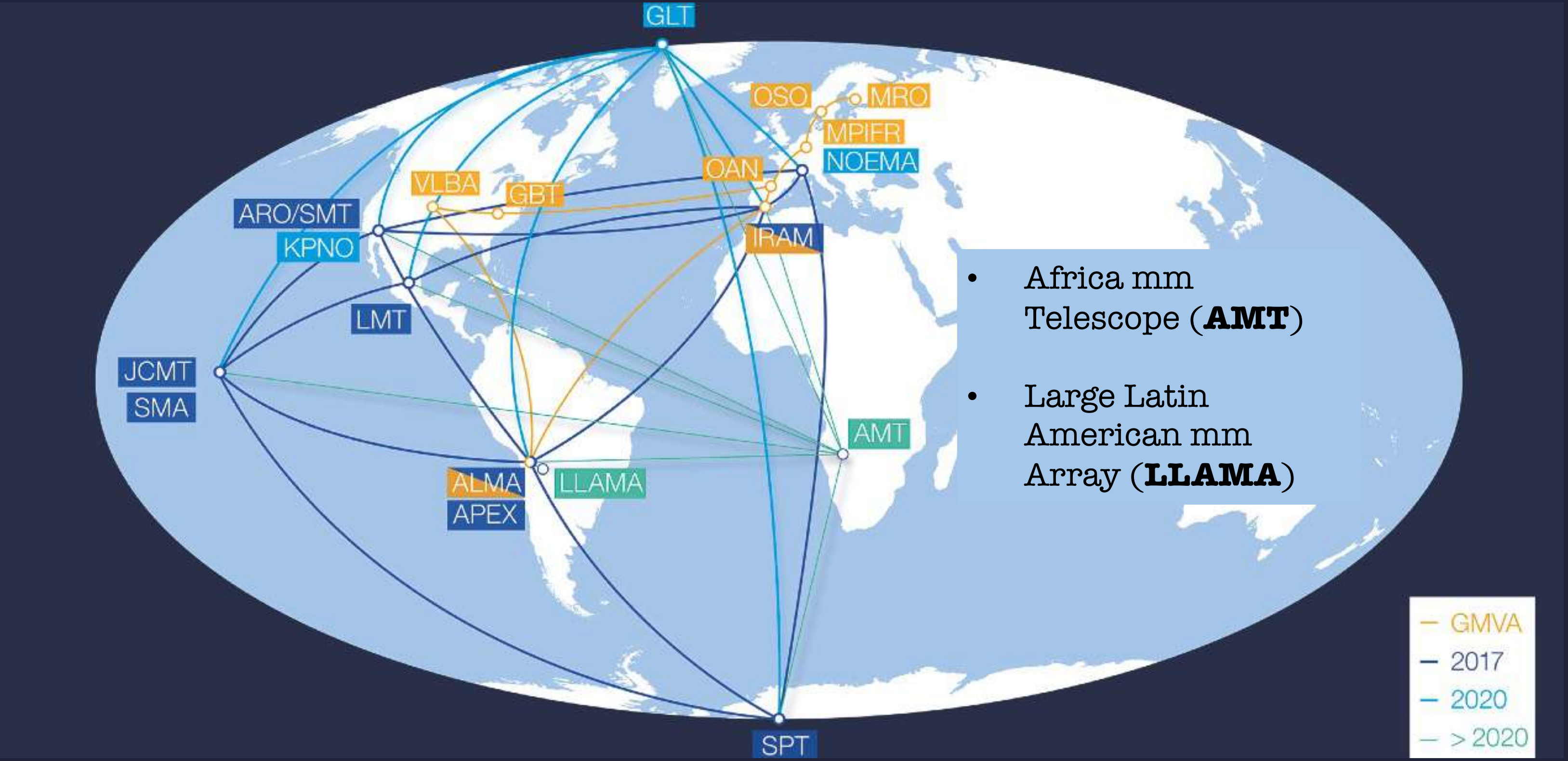
LLAMA
Large Latin American Millimeter Array

Lead the efforts for the inclusion of the new Argentine-Brazil Large Latin American Millimeter Array (LLAMA) in the EHT network

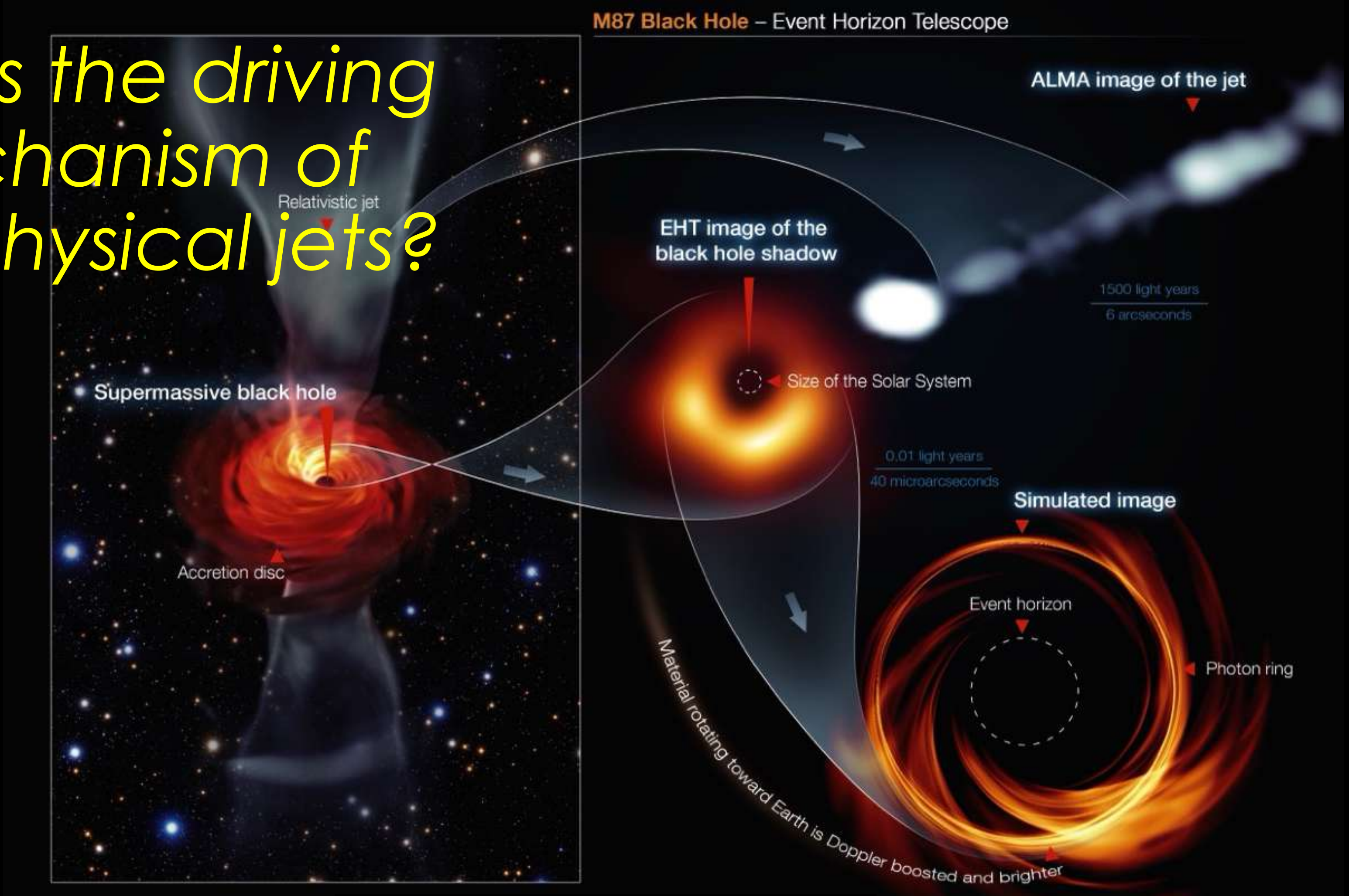
LLAMA joins the EHT



- Africa mm Telescope (**AMT**)
- Large Latin American mm Array (**LLAMA**)

Goddi et al. 2019b

What's the driving mechanism of astrophysical jets?



C. Goddi et al. 2019, The Messenger, 177, 25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