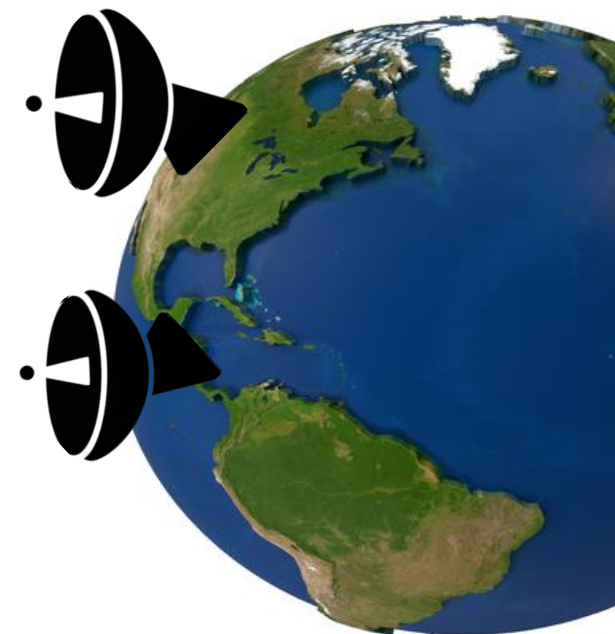
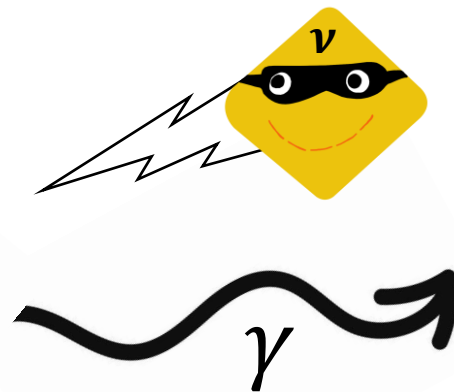
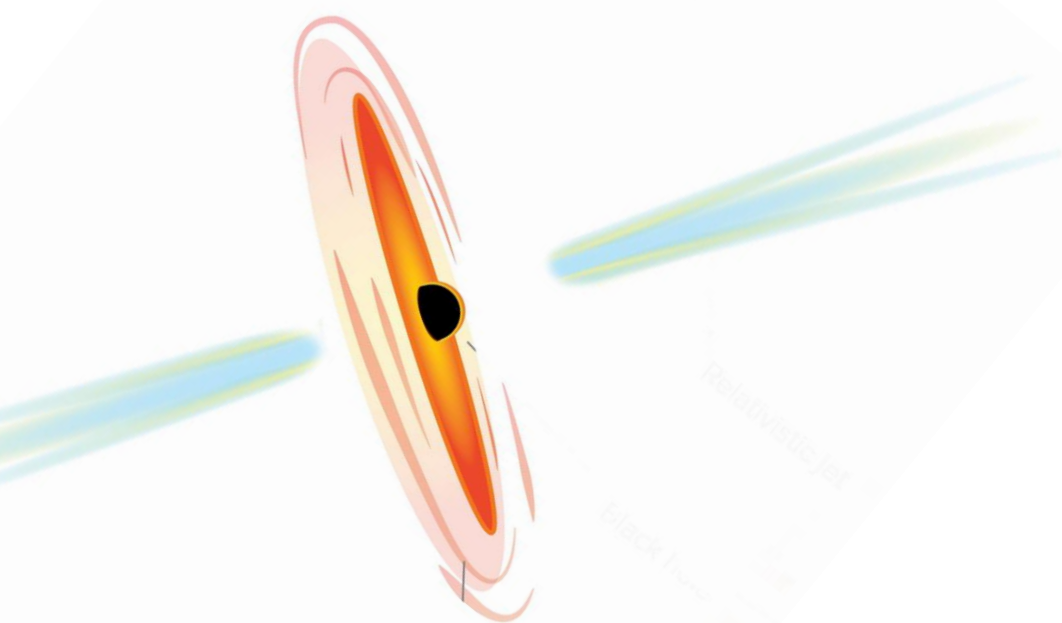


Constraining the Physics of Very-High-Energy Emission of Blazars through radio observations

Florian Eppel

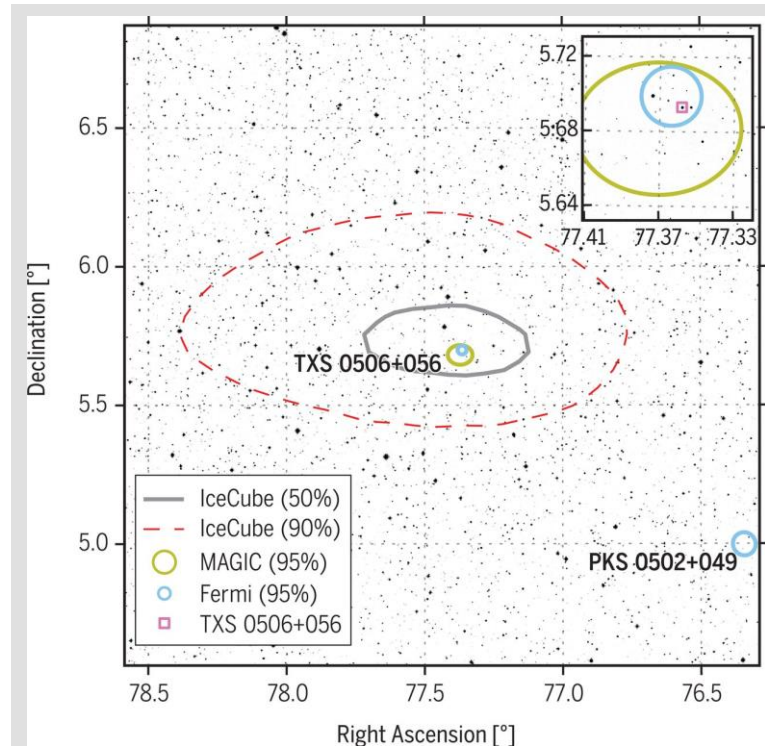
JMU Würzburg & MPIfR Bonn



On behalf of AG Kadler: M. Kadler, J. Eich, L. Haury, J. Heßdörfer, D. Kirchner, L. Ricci, F. Rösch, W. Schulga, H. Shetgaonkar, C. Wendel, J. Wongphechauxsorn + many collaborators

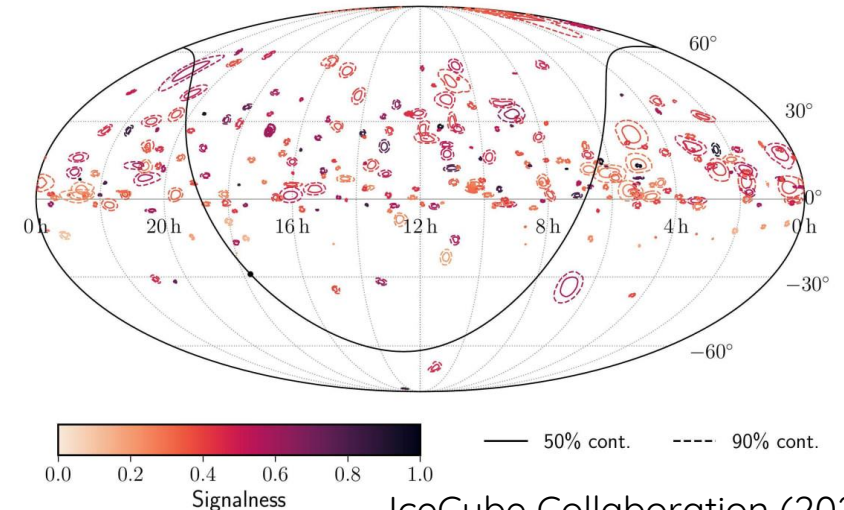
Credit: Sophia Dagnello, NRAO/AUI/NSF

High-Energy Neutrinos

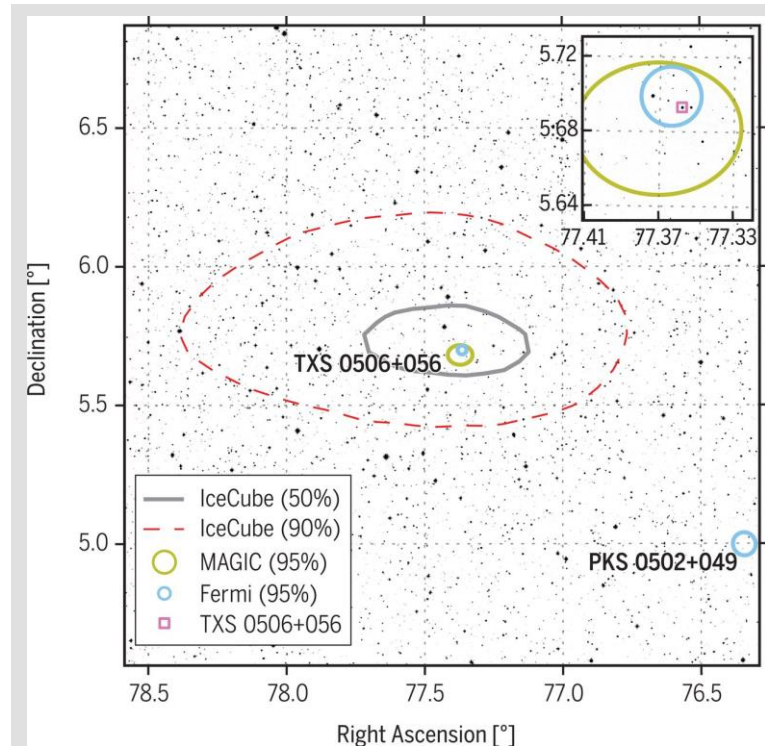


Localization Region of IC170922A (IceCube Collaboration et al. 2018)

Map of High-Energy Neutrino Alerts

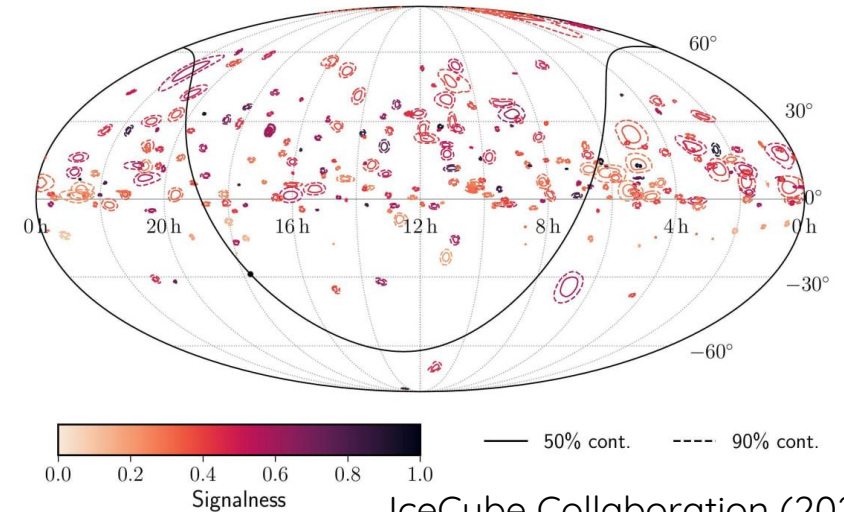


High-Energy Neutrinos



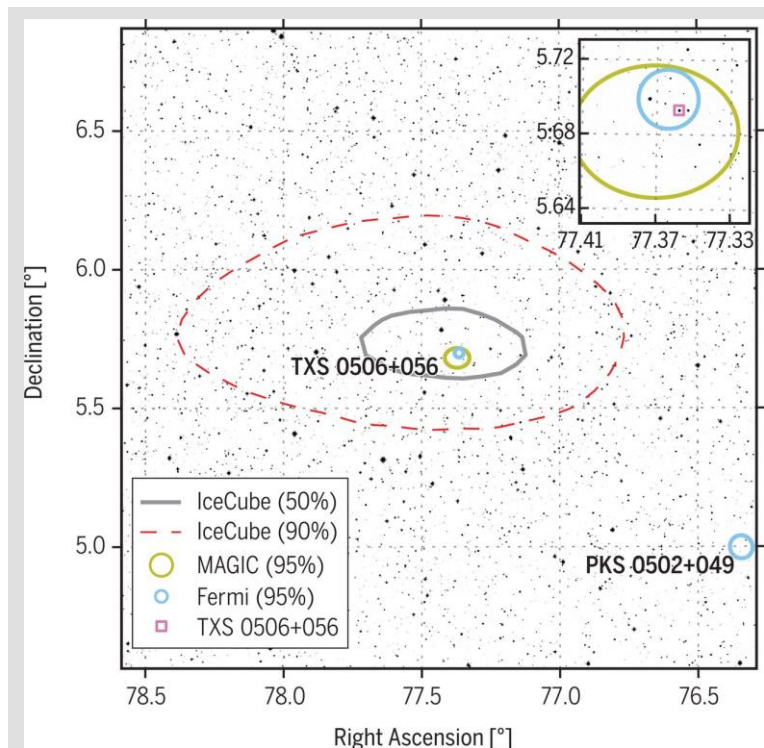
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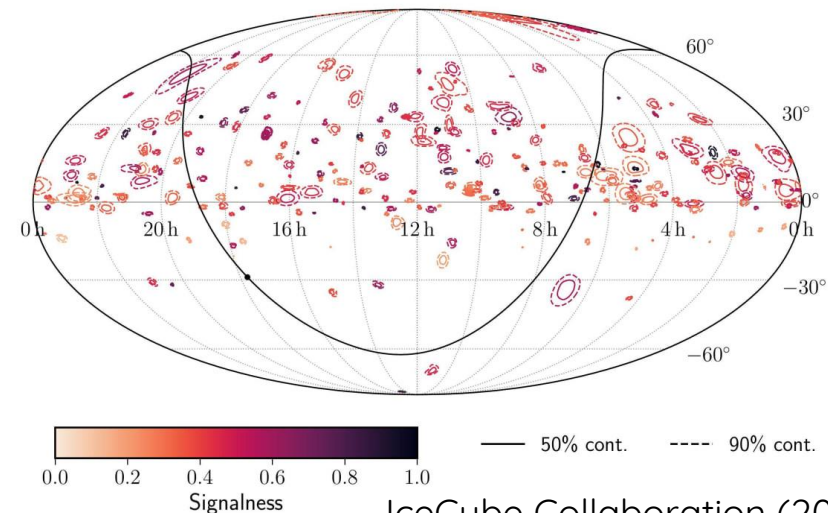
Where do high-energy neutrinos come from?

High-Energy Neutrinos



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Where do high-energy neutrinos come from?

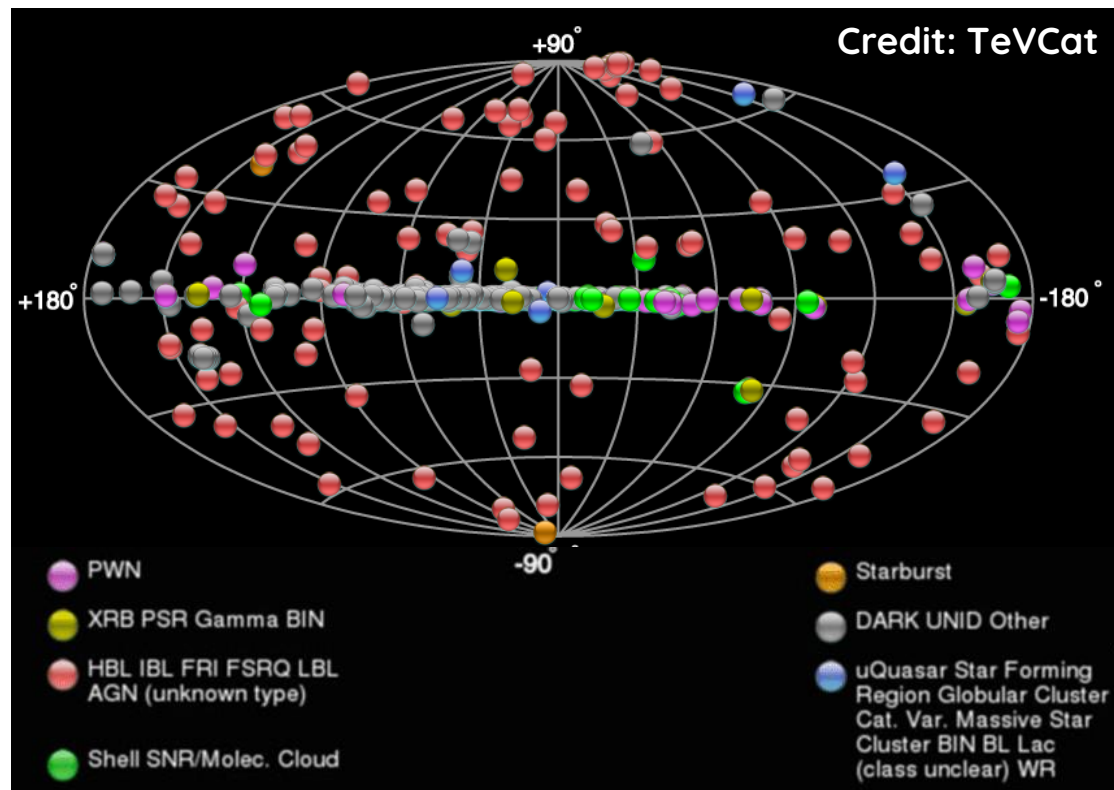
-> Some indications hint towards blazars!

What are the physics behind it?

TeV-Gamma Rays

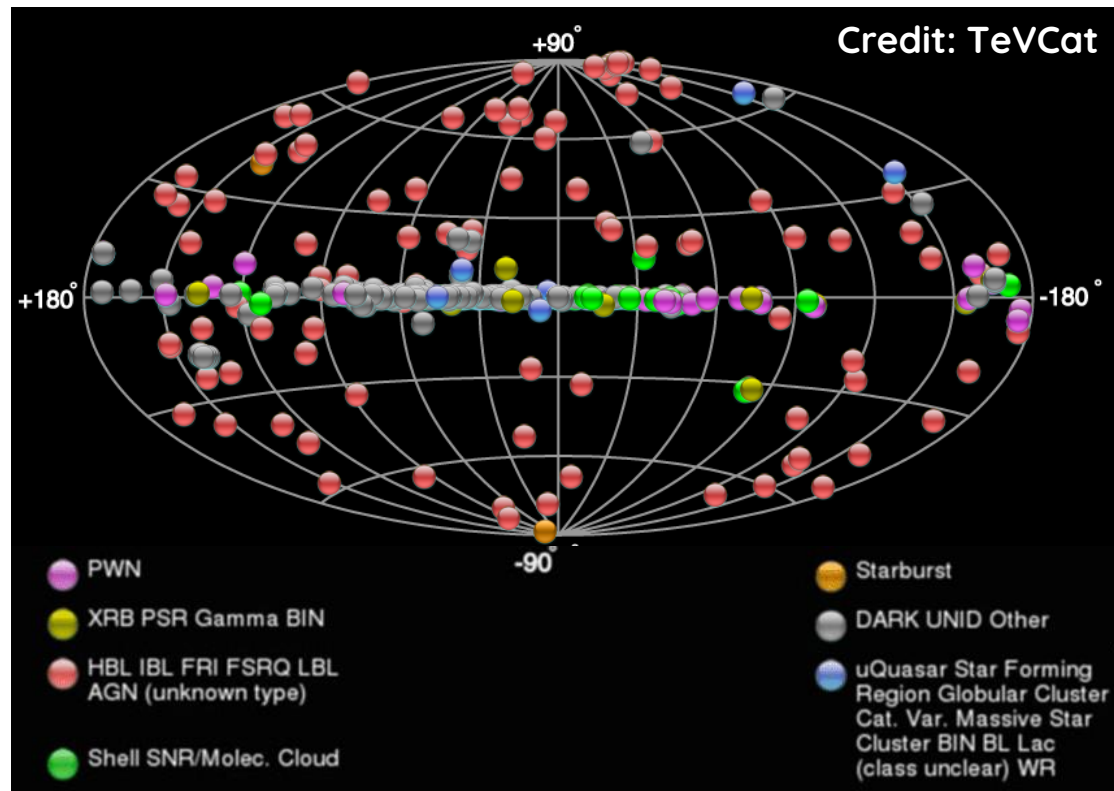
TeV-Gamma Rays

TeV-detected sources



TeV-Gamma Rays

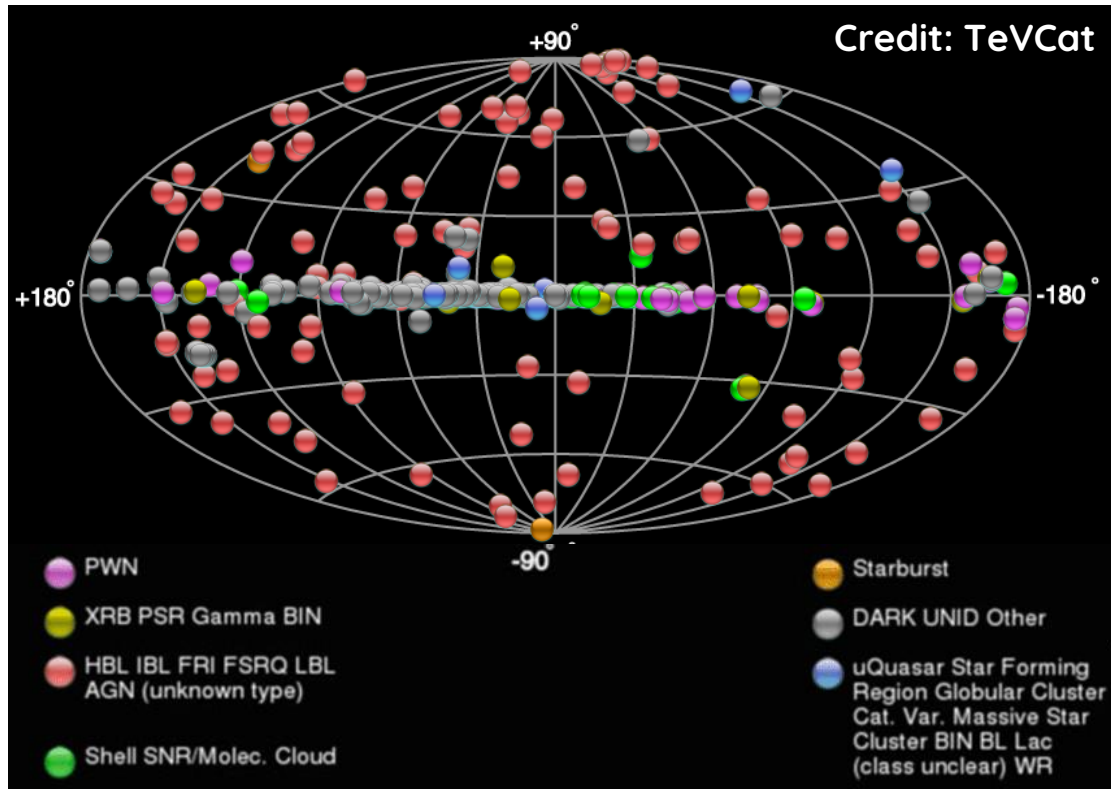
TeV-detected sources



-> Extragalactic population dominated by blazars

TeV-Gamma Rays

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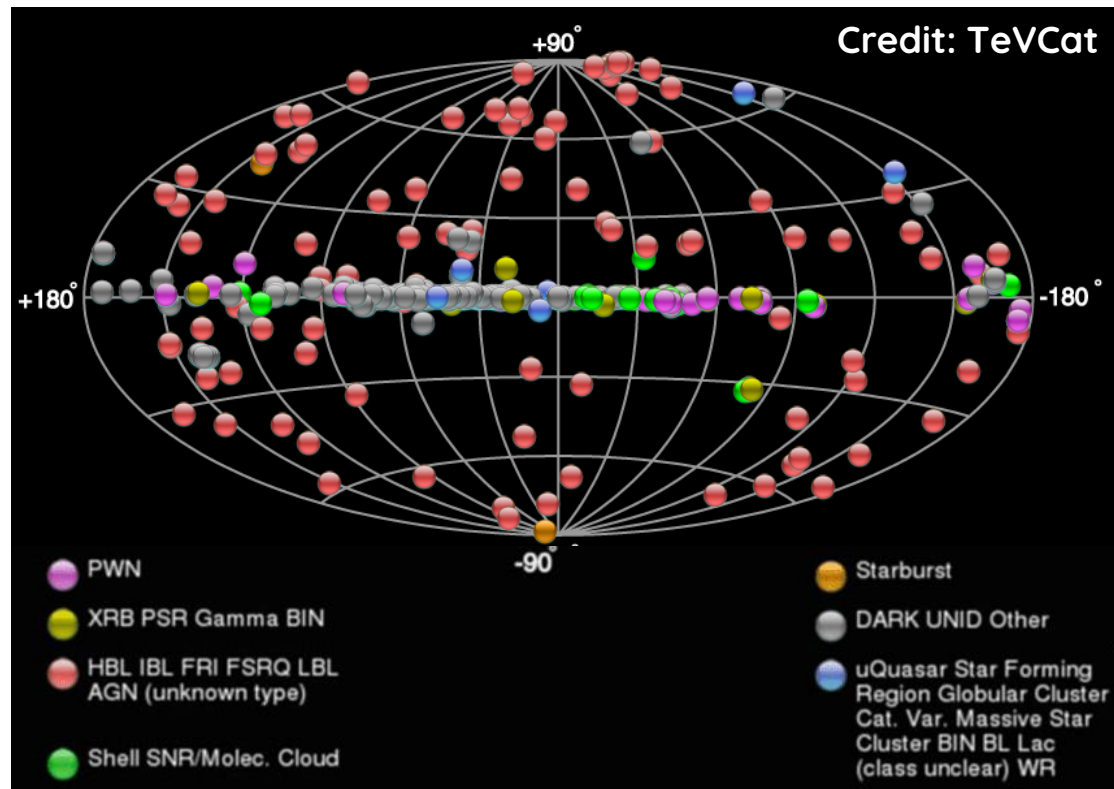


Doppler Crisis

-> Extragalactic population dominated by blazars

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TeV-detected sources



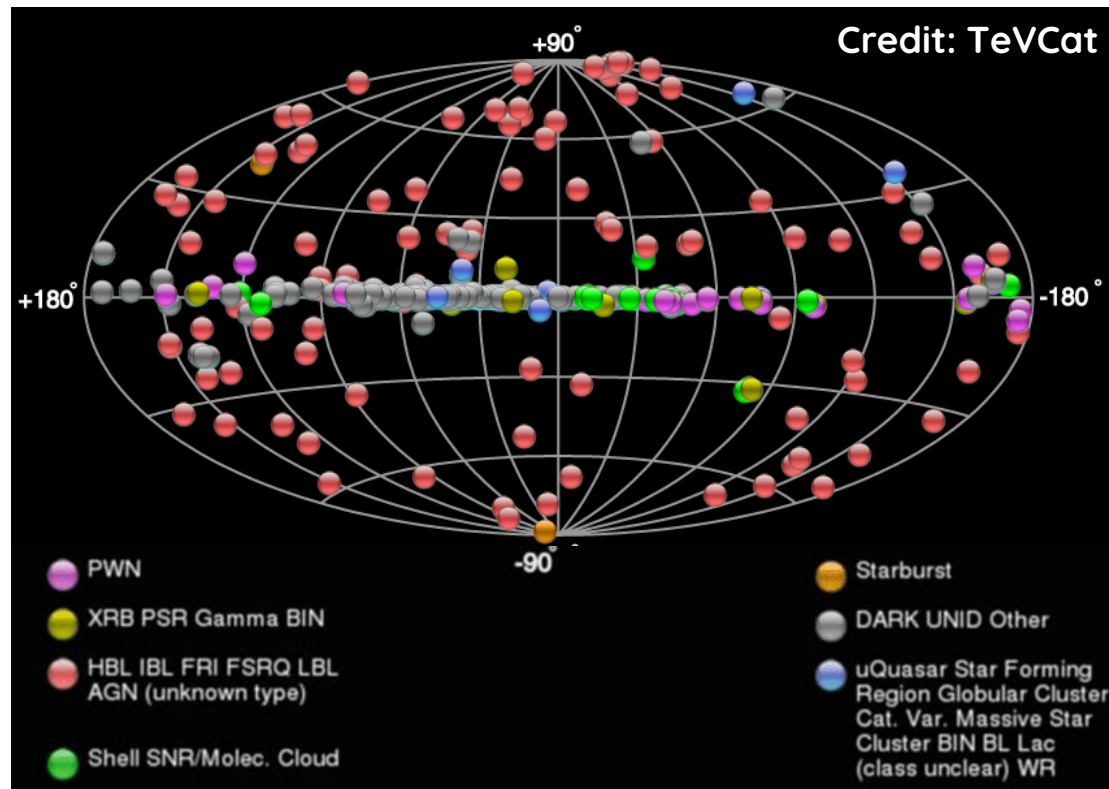
Doppler Crisis

- Highly variable TeV-emission requires high Doppler factors up to $D > 40$ (e.g., Tavecchio et al. 2010)

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TeV-Gamma Rays

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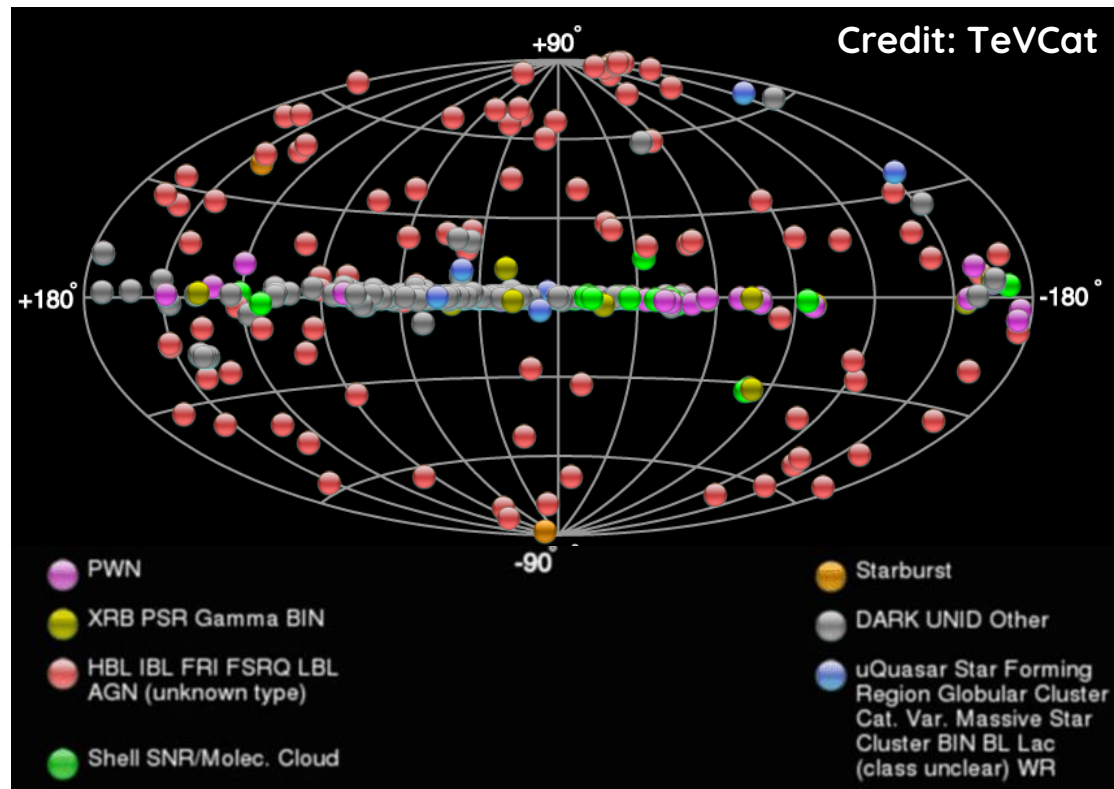
Doppler Crisis

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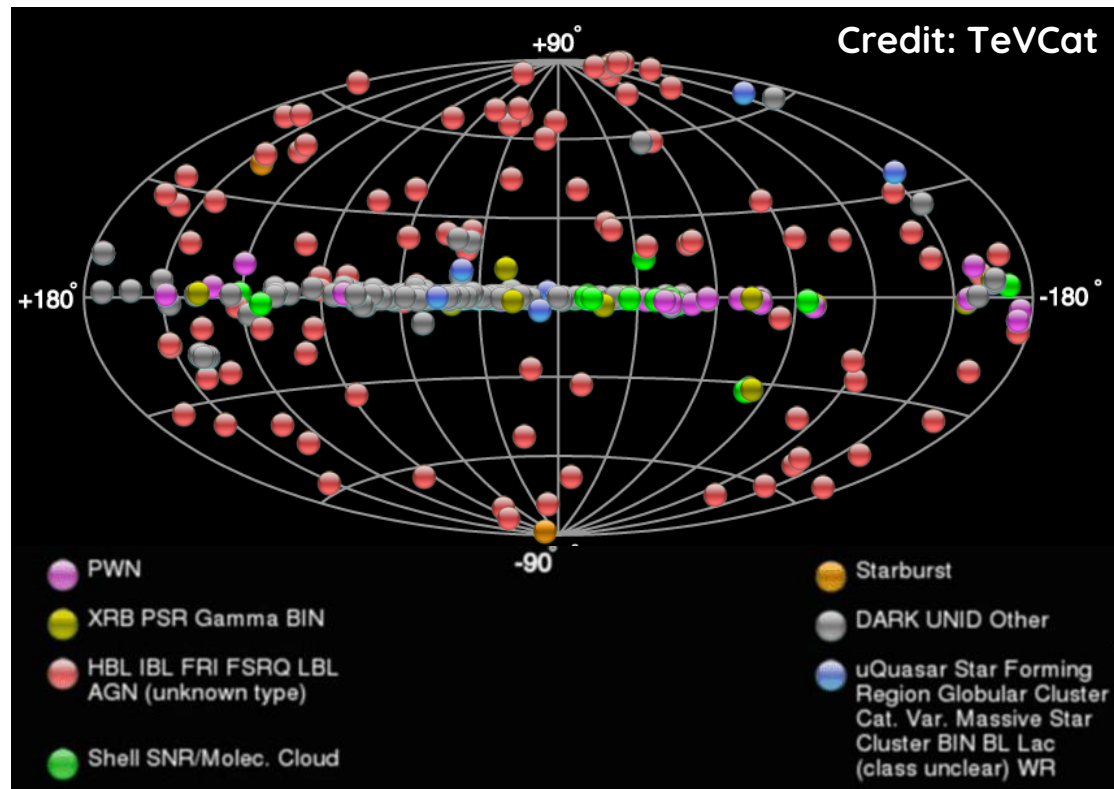
Possible Scenarios:

-> Spine-Sheath Structure (Ghisellini et al., 2005)

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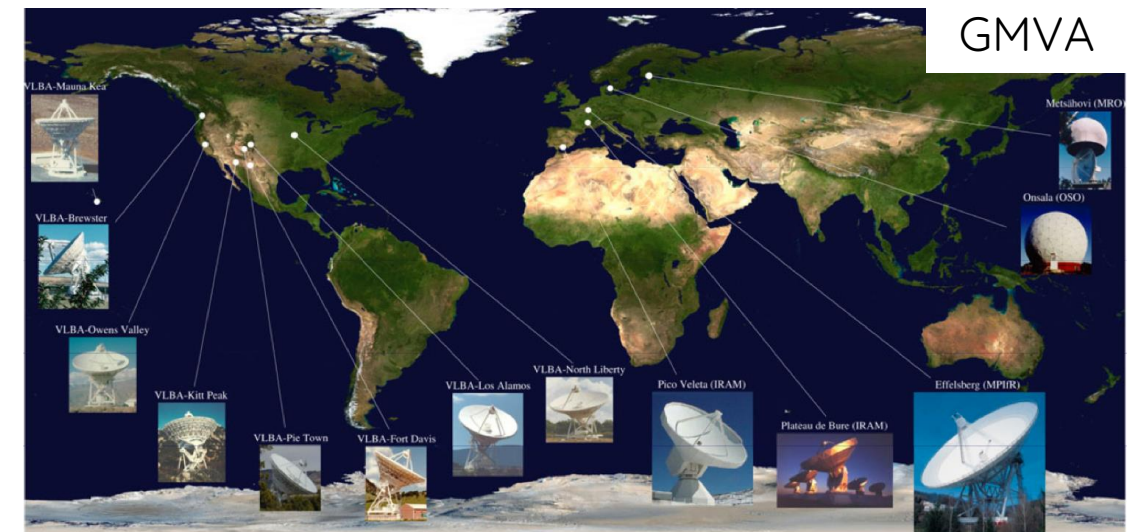
Possible Scenarios:

- > Spine-Sheath Structure (Ghisellini et al., 2005)
- > Standing Recollimation Shocks (Hervet et al., 2019)

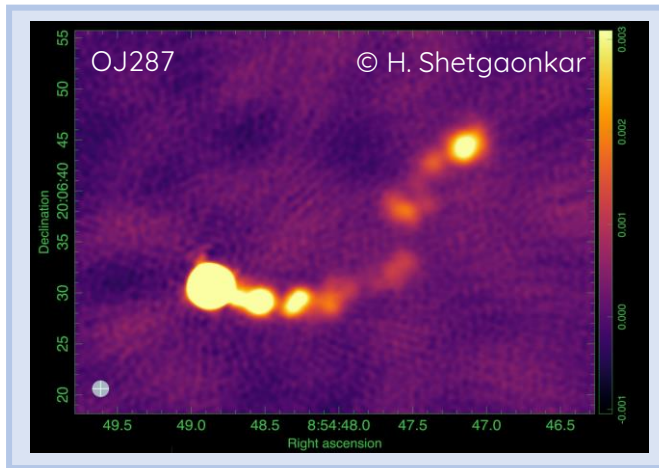
-> Extragalactic population dominated by blazars

Why Radio?

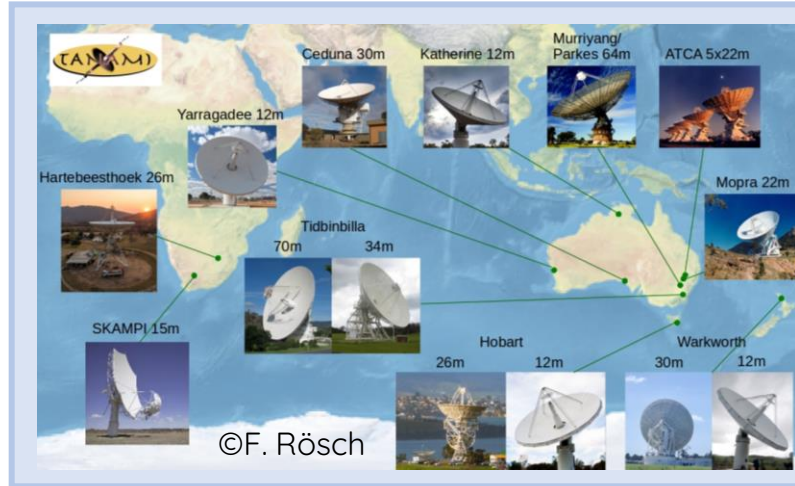
- Radio emission originates almost entirely from the plasma jet close to the central engine
- Synchrotron radiation from the jet/shocks helps to constrain models in MWL-studies
- Known correlation of high-energy and radio emission in blazars (e.g., Giroletti et al. 2016)
- Monitoring can yield important information about energy production and reasons for activity
- With **VLBI**, scales down to the the jet base can be investigated, as well as the **jet-speed, jet-geometry, doppler factor and magnetic-field**



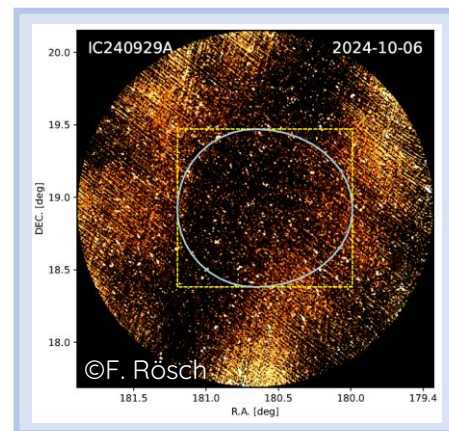
Group activities



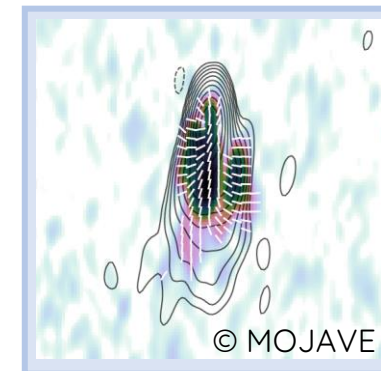
LOFAR-VLBI



©F. Rösch



MeerKAT



TANAMI+MOJAVE

TELAMON



mm-VLBI+GMVA+EHT



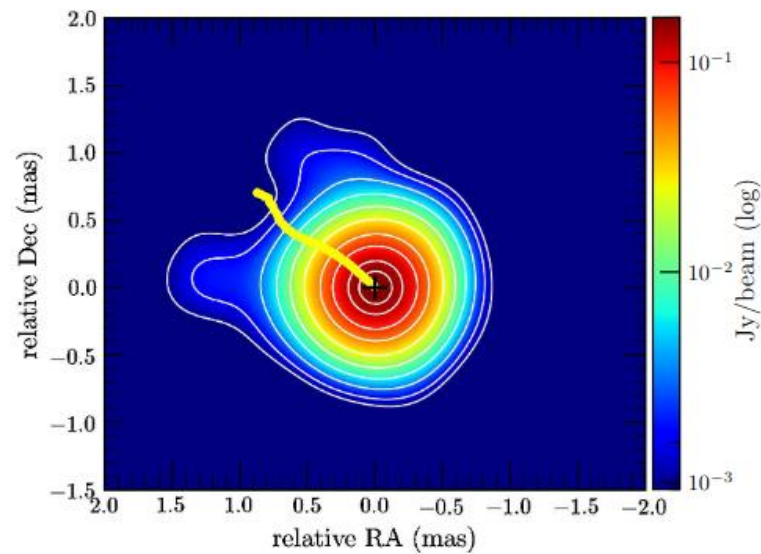
Constraining the Physics of Very-High-Energy Emission of Blazars through radio observations

- Florian Eppel -

PG 1553+113: HBL and SMBBH

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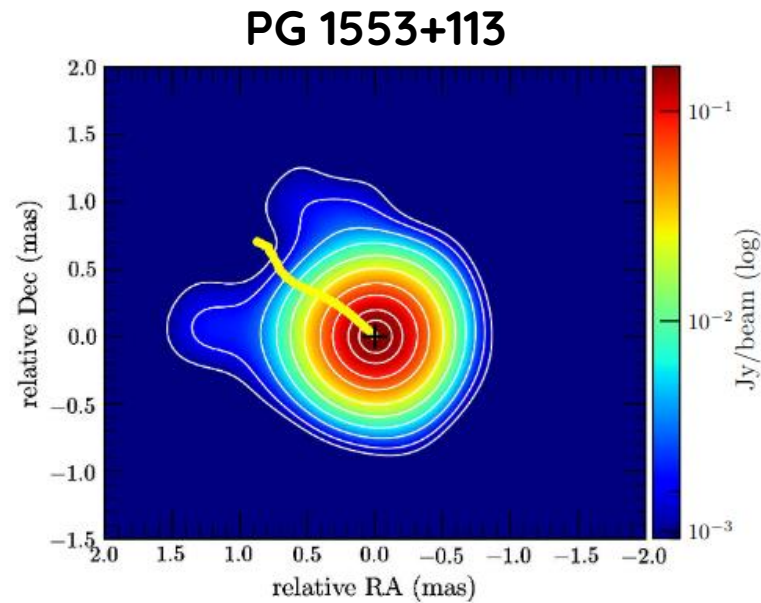
PG 1553+113



15 GHz VLBA image of PG 1553+113
(Lico et al. 2020)

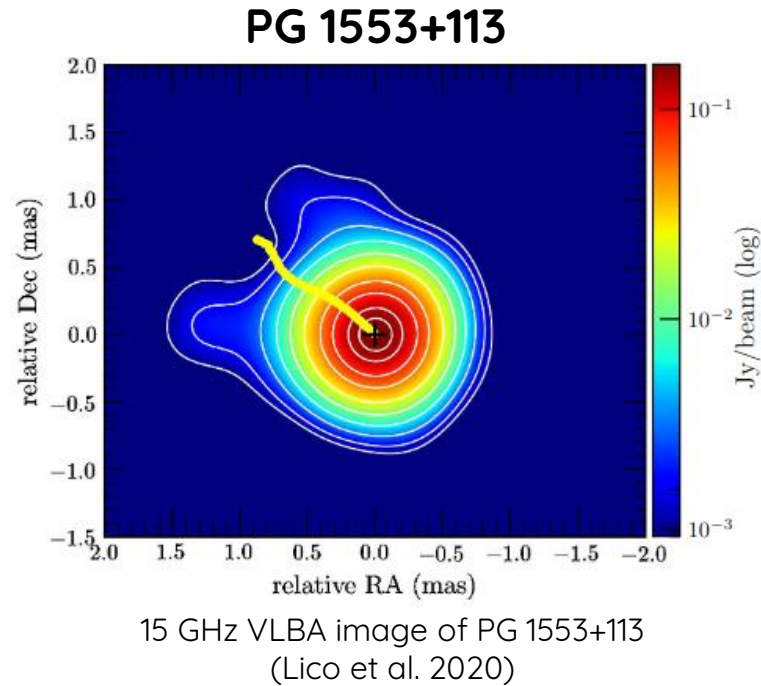
PG 1553+113: HBL and SMBBH

- Well studied HBL object with a known 2.2-year gamma-ray periodicity -> **super massive binary blackhole candidate**

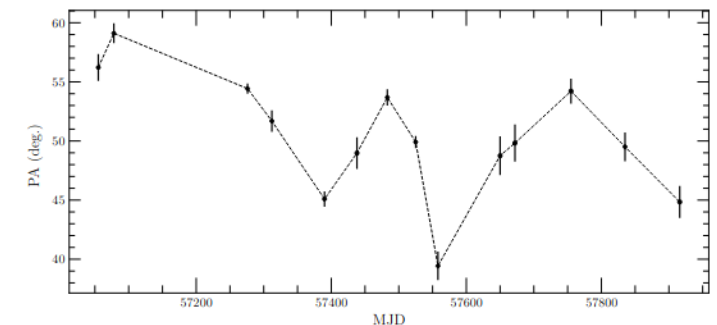
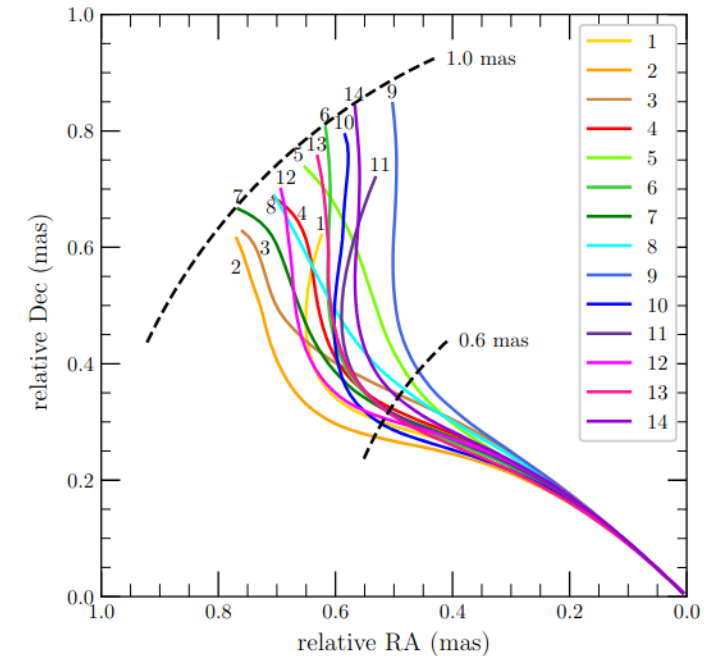


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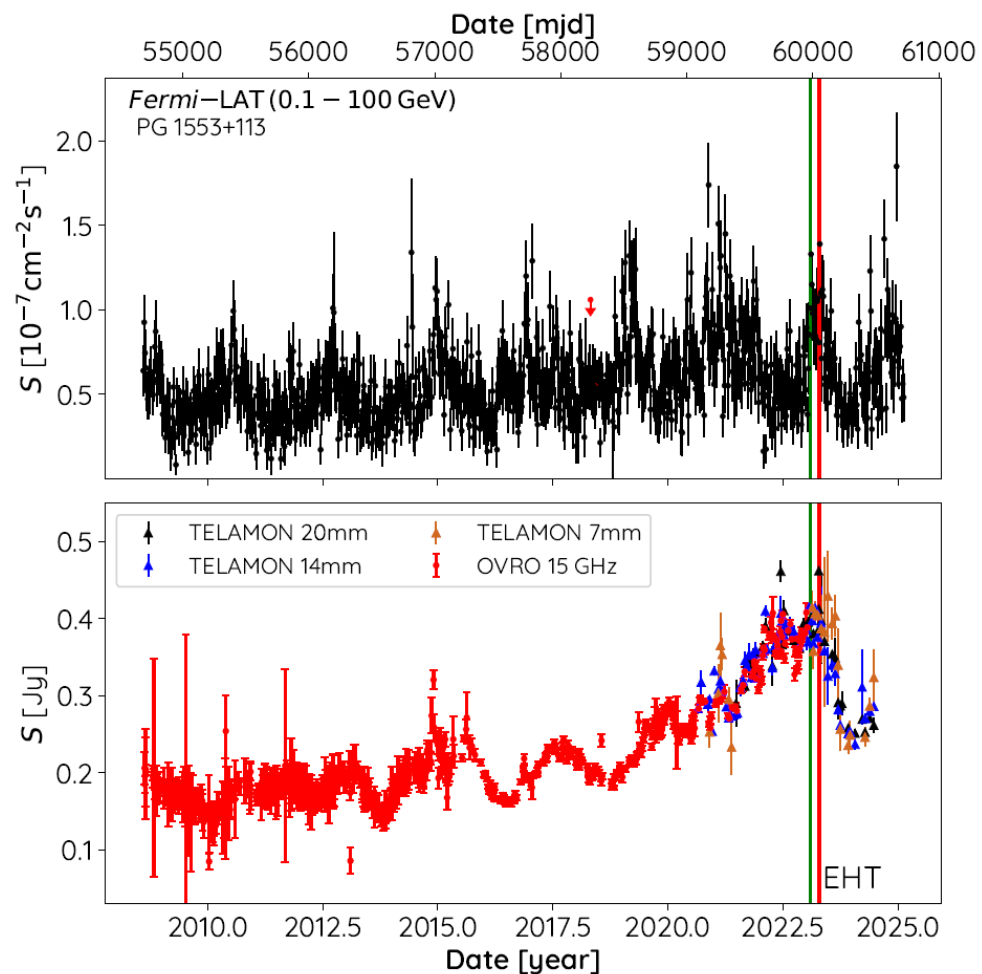
PG 1553+113: HBL and SMBBH



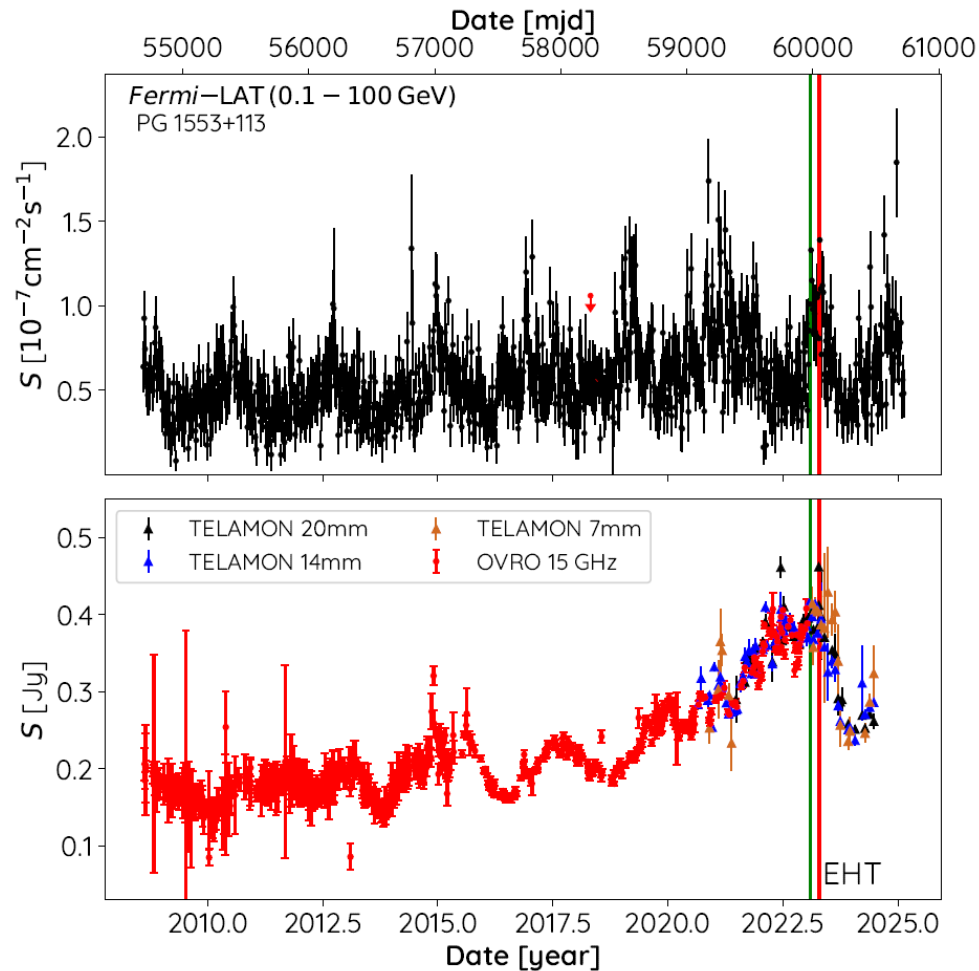
- Well studied HBL object with a known 2.2-year gamma-ray periodicity -> **super massive binary blackhole candidate**
- Previous VLBI study by Lico et al. (2020) revealed possible jet wobbling and hints of limb-brightening
- Source is affected by the Doppler-crisis (high TeV-Doppler factors, low radio Doppler factors)



PG 1553+113: HBL and SMBBH



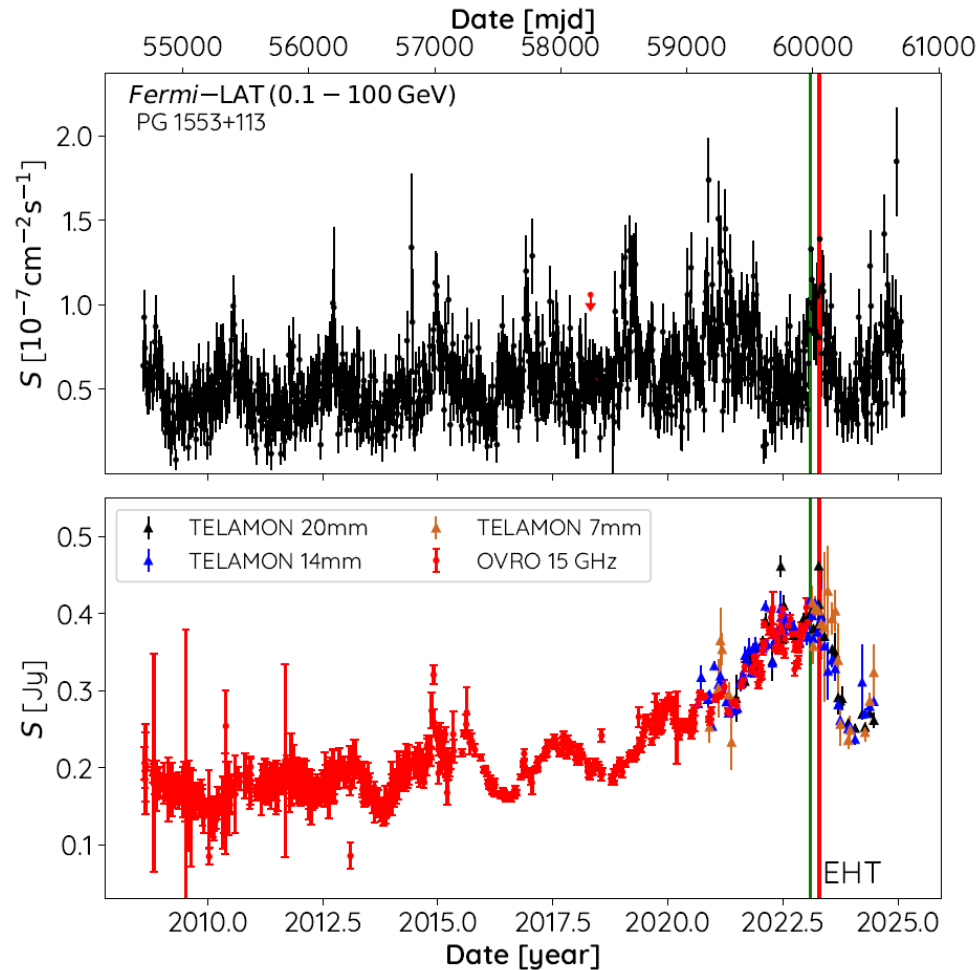
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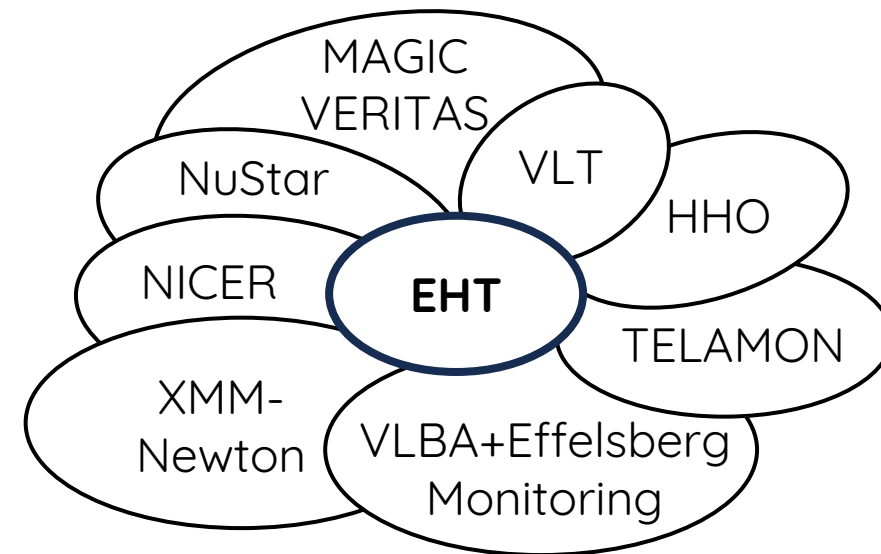
- **April 2023:** New (expected) gamma-ray maximum coupled with historical radio flare
- Triggered EHT observation with simultaneous MWL campaign

EHT

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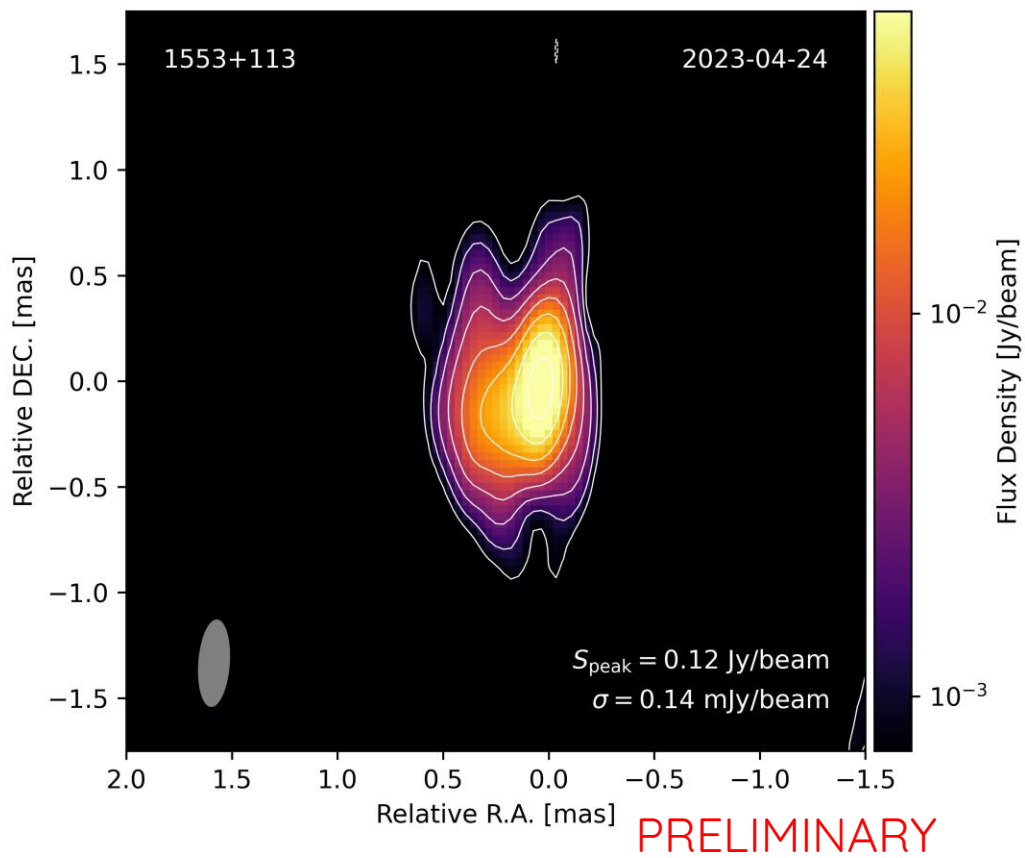


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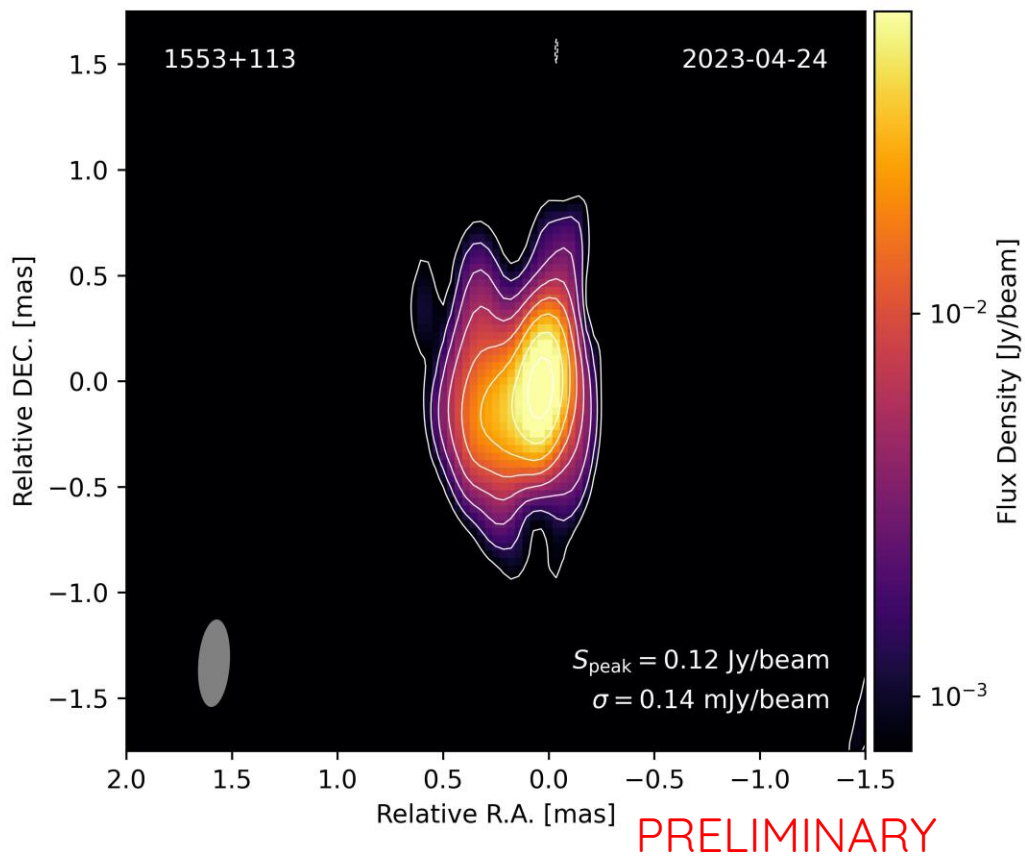
VLBA+Effelsberg 43 GHz



- First image (VLBA+Effelsberg) suggests ejection of a new jet component

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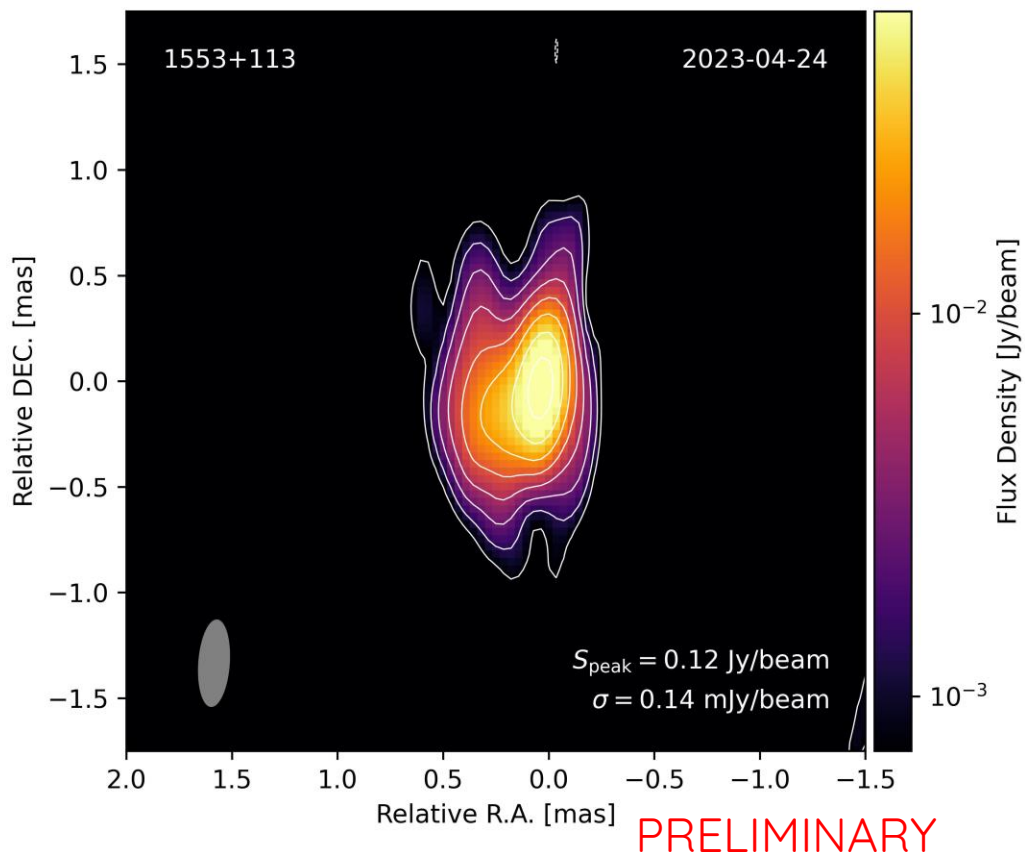
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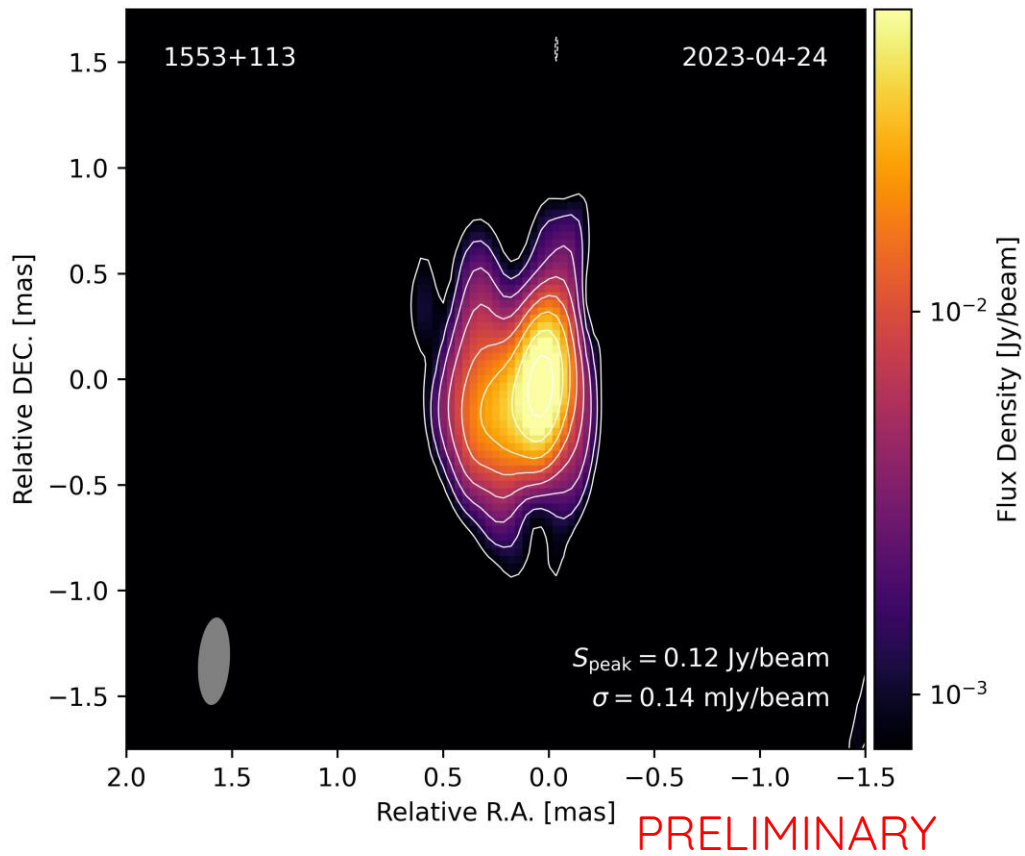
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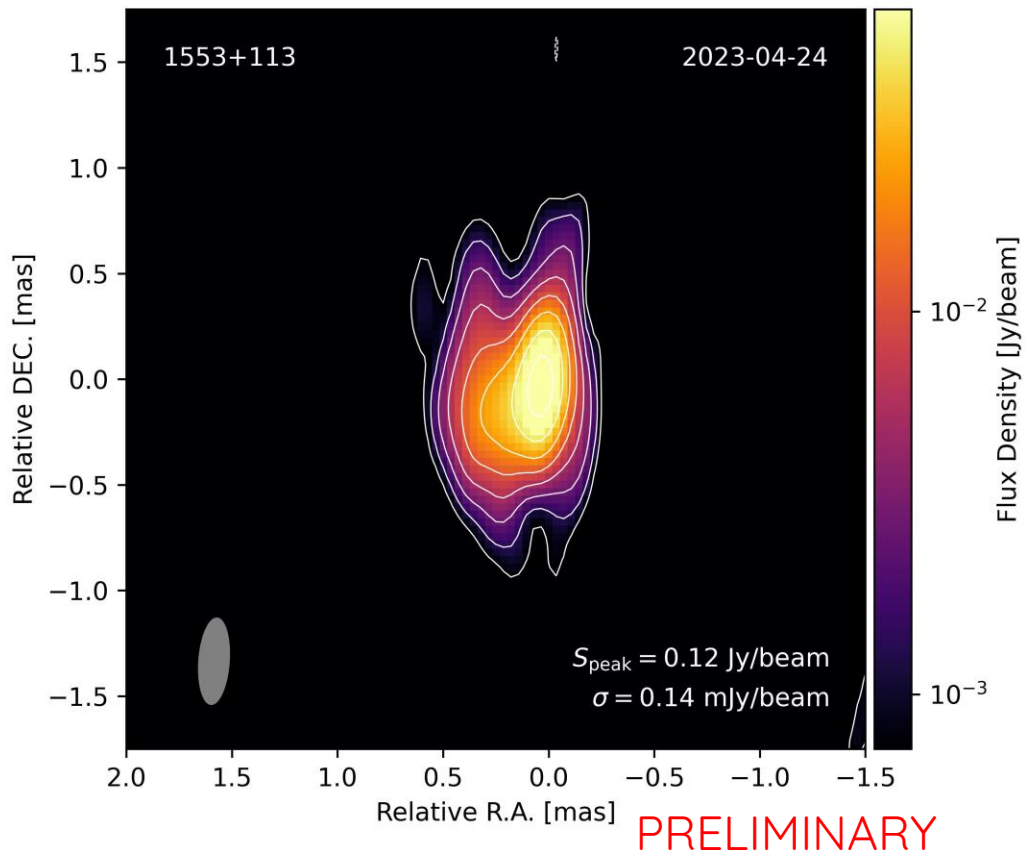
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- will enable us to constrain MWL short-term (intra-day) variability at the high state close to the EHT observation

New GMVA monitoring upcoming



Source	Class ^a	$S_{3\text{mm}}^b$ [Jy]	Redshift	ALMA Band 3	ATCA	TELAMON 19–44 GHz	MOJAVE 15 GHz	BEAM-ME 43 GHz	TANAMI 8 GHz
S2 0109+22 ¹	IBL	0.6–2	0.265	✓	✓	✓	✓		
3C 84 [†]	RG	13.5–26	0.0176	✓			✓	✓	
PKS 0346-27	FSRQ	0.5–2.7	0.991	✓	✓		(✓)		✓
TXS 0506+056 ^ν	IBL/HBL	0.5–2.3	0.3365	✓	✓	✓	✓		
S5 0716+714	IBL	1–10	0.2304			✓	✓	✓	
PKS 0736+017	FSRQ	0.9–3.2	0.18941	✓	✓	✓	✓	✓	
OJ 287 [†]	LBL	2.3–8.8	0.306	✓	✓		✓	✓	
S4 0954+65	LBL	0.5–7	0.3694			✓	(✓)	✓	
TON 0599	FSRQ	0.3–6.7	0.724745	✓	✓	✓	✓	✓	
4C +21.35	FSRQ	0.3–2.0	0.43	✓	✓	✓	✓	✓	
M87 ^{†,2}	RG	3–4	0.00436		✓		✓		
3C 279 ^{†,2}	FSRQ	5–30	0.536	✓	✓		✓	✓	✓
OP 313	FSRQ	0.4–2.9	0.997	✓		✓	✓	(✓)	
PKS 1510-089	FSRQ	0.9–5.0	0.36	✓	✓		✓	✓	✓
Ap Lib	LBL	1.3–4.1	0.049	✓	✓		(✓)		✓
OT 081 ^{†,ν}	LBL	1.5–6.8	0.32	✓	✓	✓	✓	✓	
BL Lac [†]	IBL	1–8	0.0686	✓		✓	✓	✓	

- Expanding individual case studies to a larger sample
- Observations granted for **Oct 25, Apr+Oct 26 at 3mm**
- Using upgraded GMVA array (incl. APEX, KVN and GLT) for highest-resolution possible at 86 GHz/3mm

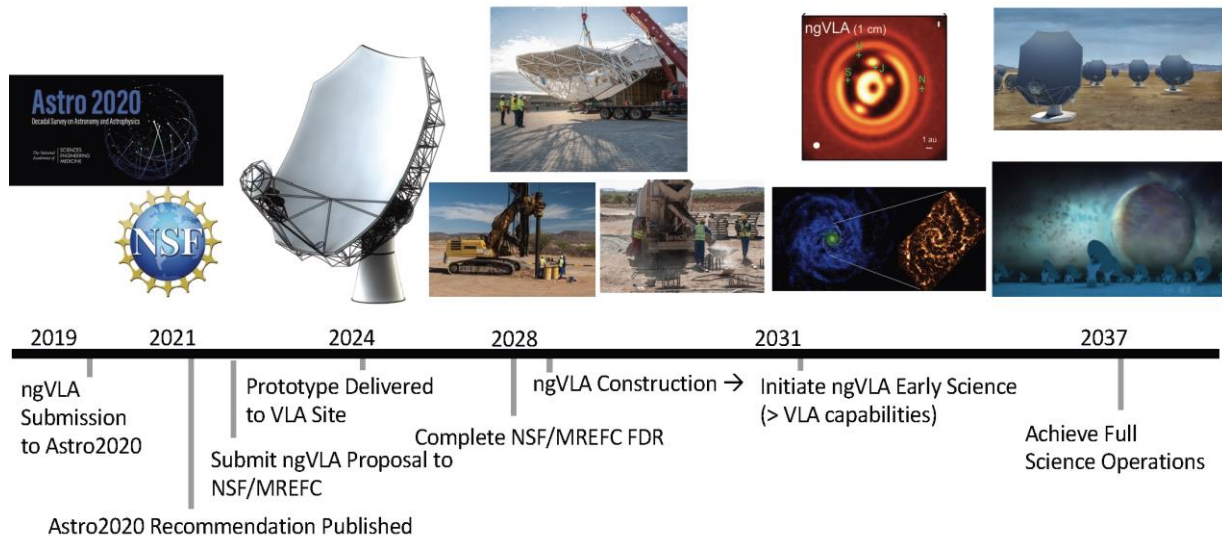
Next-Generation VLBI

New major radio facilities coming up in the next 10-20 years



operating at 1 - 120 GHz

operating at 0.35 - 15.4 GHz (SKA-Mid)



Will enable unique synergies with CTAO, IceCube-Gen2, KM3NeT and many more

Constraining the Very-High-Energy Emission of Blazars through high-frequency radio monitoring

- Florian Eppel -

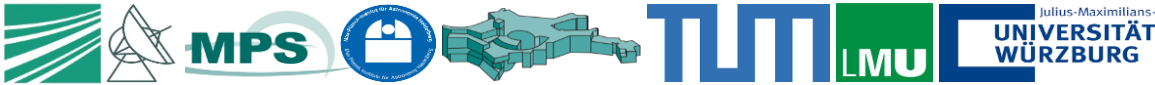
Wetterstein Millimeter Telescope



Germany's highest altitude research station (2650m)



UFS Schneefernerhaus 



Constraining the Physics of Very-High-Energy Emission of Blazars through radio observations

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Wetterstein Millimeter Telescope



Germany's highest altitude research station (2650m)

- High altitude data collection for climate, atmospheric, bio, hydro, geosphere and environmental research and medicine
- 11-story building, former hotel, since 1990 research station

UFS Schneefernerhaus



Bayerisches Staatsministerium für
Umwelt und Verbraucherschutz



Constraining the Physics of Very-High-Energy Emission of Blazars through radio observations

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Wetterstein Millimeter Telescope



Wetterstein Millimeter Telescope



18m ngVLA Design

- 1.2-120 GHz (goal 230 GHz)
- Single dish and VLBI facility
- Immediate integration with the EVN & GMVA
- German contribution to ngVLA
- German antenna for SKA-VLBI
- First element of future LEVERAGE concept

LEVERA(G)E



Wetterstein Millimeter Telescope



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Science Program

- Black Holes and Relativistic Jets (JMU, MPIfR)
 - Protoplanetary Disks (LMU)
 - Dark Matter (MPA)
 - Galaxy Evolution (MPIA)
 - Additional partnerships invited!
- +interdisciplinary topics
and environmental research

LEVERAGE



Summary & Outlook

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Summary & Outlook

- The origin of high-energy emission in blazars is unclear, single zone models are challenged by the Doppler Crisis and possible Neutrino association
- Radio observations can help to distinguish between different scenarios to understand the physics of VHE production for Doppler-Crisis blazars and Neutrino-Candidate sources
- Upcoming next-generation high-energy facilities like KM3Net, IceCube-Gen2, and CTAO will enable unique synergies with next-generation radio facilities like ngVLA, SKA, and WMT



Time for questions (and lunch)!

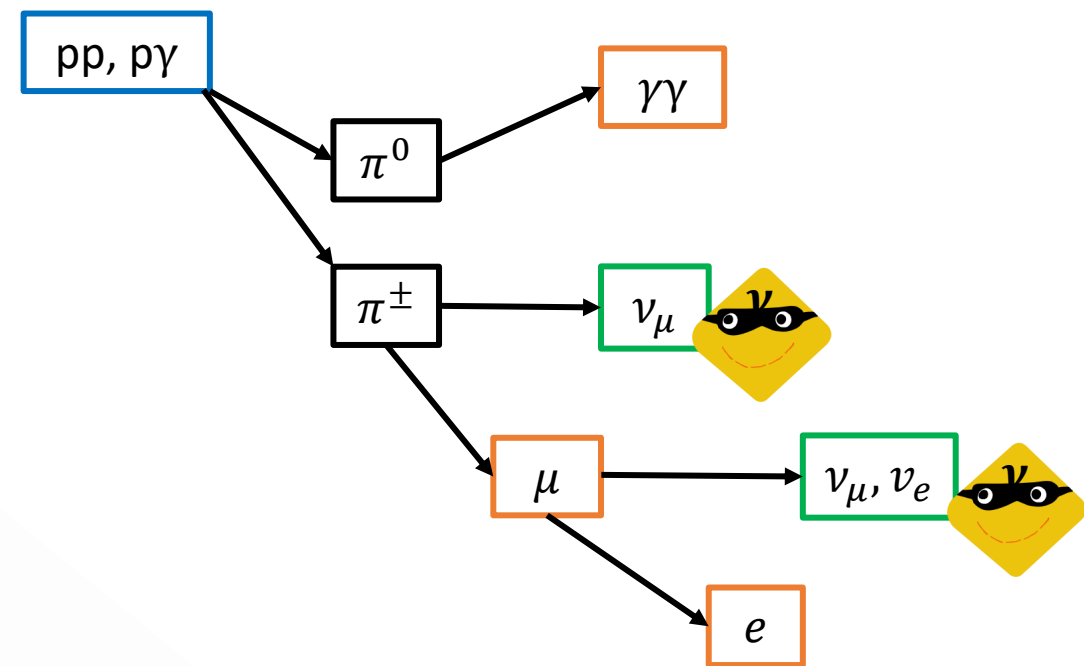
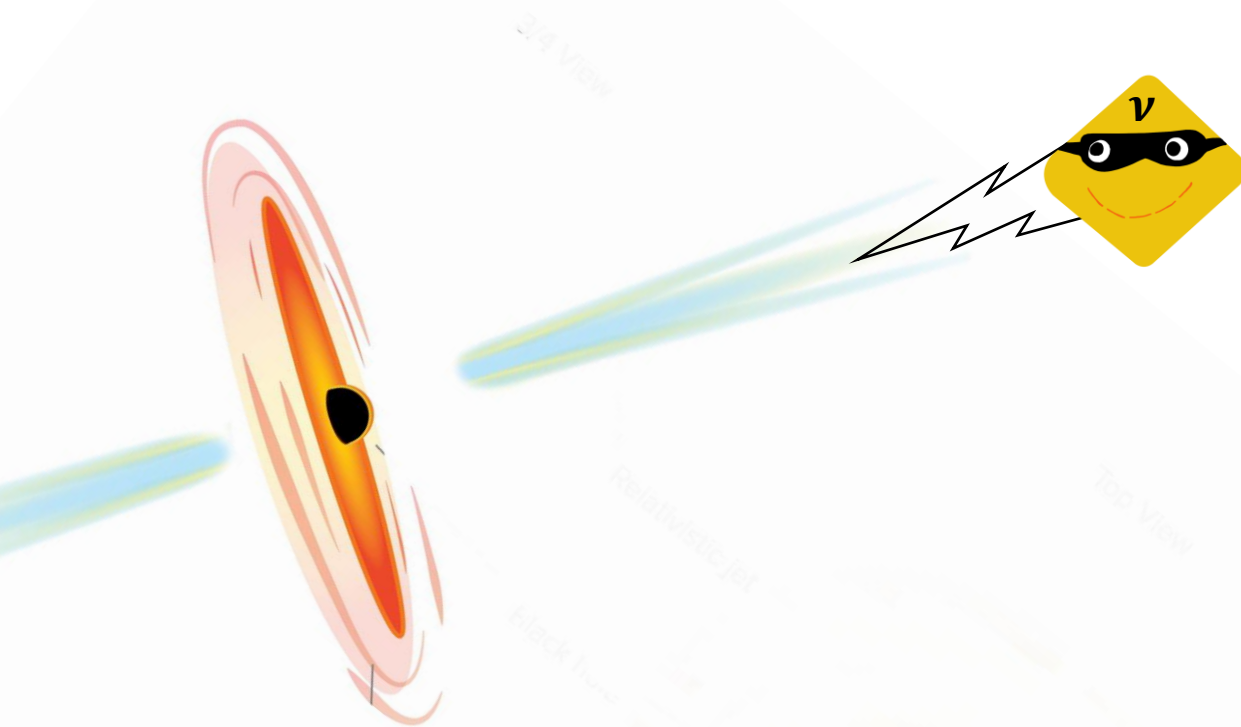


some lunch suggestions from your friendly neighborhood radio astronomer
- with inspiration from the AIPS Cookbook



Neutrino production in blazars

- High energy protons required $E > 10^{16}$ eV
- pp or p γ process



Credit: Sophia Dagnello, NRAO/AUI/NSF