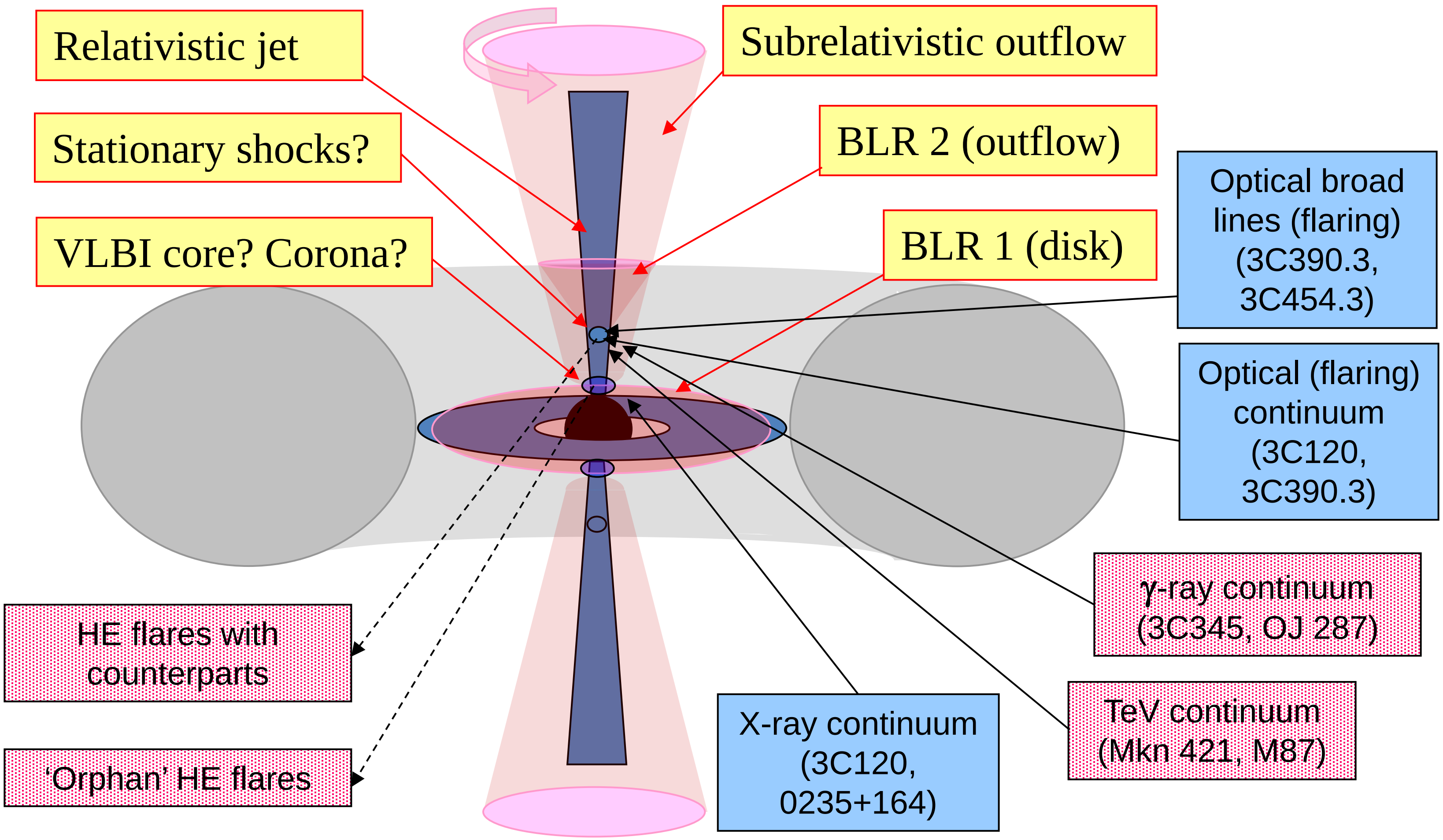
Close to the AGN Cores: Millimetre VLBI and Jet Formation

Andrei Lobanov

Radio-loud AGN

- Complex interplay between the BH magnetosphere, accretion disk, relativistic jets, virialized material and subrelativistic outflows.

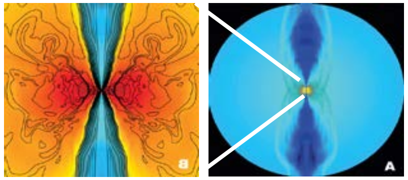


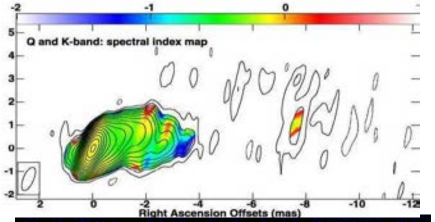
Arshakian+ 2010, León-Tavares+ 2010, 2015, Schinzel+ 2011, Agudo+ 2011, Acchiari+ 2012, Jorstad+ 2013, Hada+ 2014

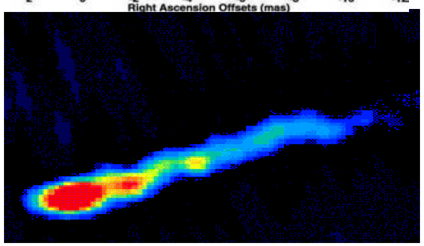
Basic Physics of Jets

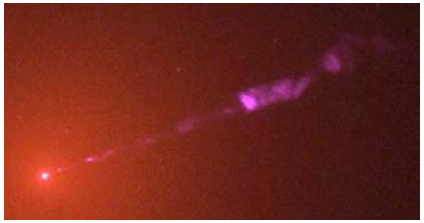
- **Launching Region: The Accretion Flow;**
  ~10 – 100 R_g: 0.05 – 0.5 mpc*, 0.01 – 0.1 μas*^
  - Probably unresolved or slightly resolved
- **Collimation Region:**
  ~10 – 10^3 R_g: 0.05 – 5 mpc, 0.01 – 1 μas
  - The Jet "Nozzle"
- **PFD/KD Transition and Acceleration Region:**
  ~10^3 – 10^5 R_g: 5 – 500 mpc, 1 – 100 μas
  - Poynting-Flux-Dominated (PFD) → KFD
- **Kinetic-Flux-Dominated (KFD) Jet:**
  ~10^5 – 10^9 R_g: 0.5 pc – 5 kpc, 100 μas – 1"
- **Hot Spot/Lobe:**
  >10^9 – 10^{10} R_g: 5 – 50 kpc, 1 – 10"
  - Dissipation into IGM, backflows

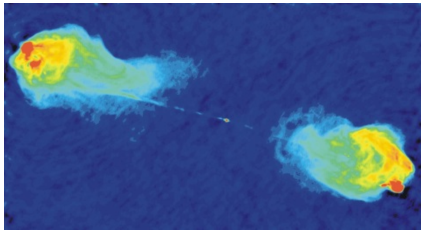
Millimetre VLBI imaging







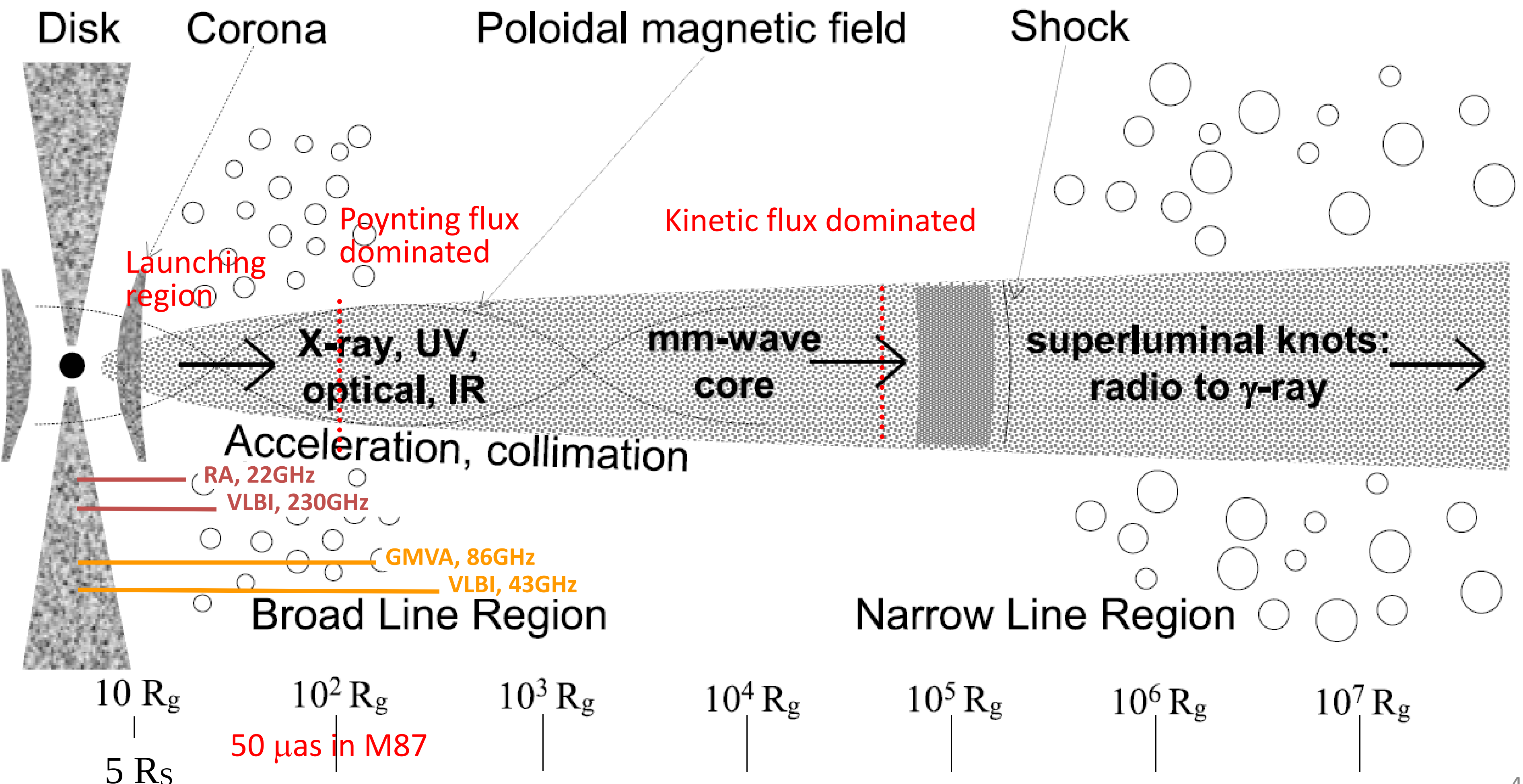




* – a 10^8 M_{sun} black hole at 1 Gpc (AGN) and ^ -- a 10 M_{sun} black hole at 100 pc (XRB).
In M87: 10 R_g ~ 0.02 mas, i.e. angular scale is larger by a factor of ~**1000**(!)

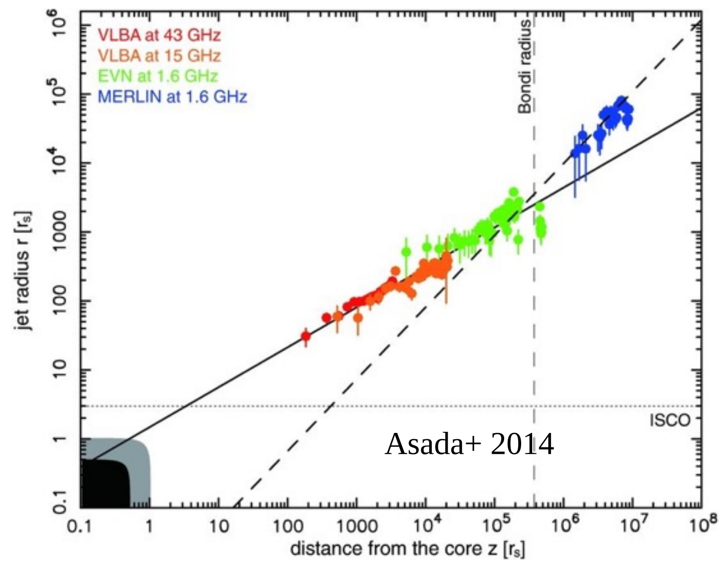
VLBI View of AGN Jets

- Space VLBI and millimetre VLBI are best direct probes of physics of the central engine in AGN: T_b, polarization, magnetic field, nuclear opacity.

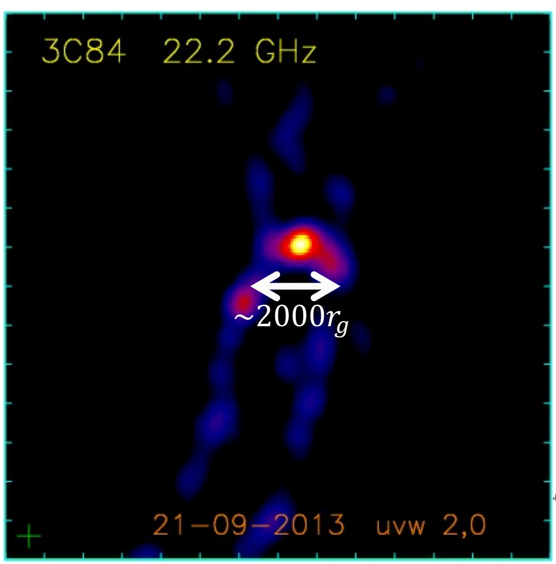


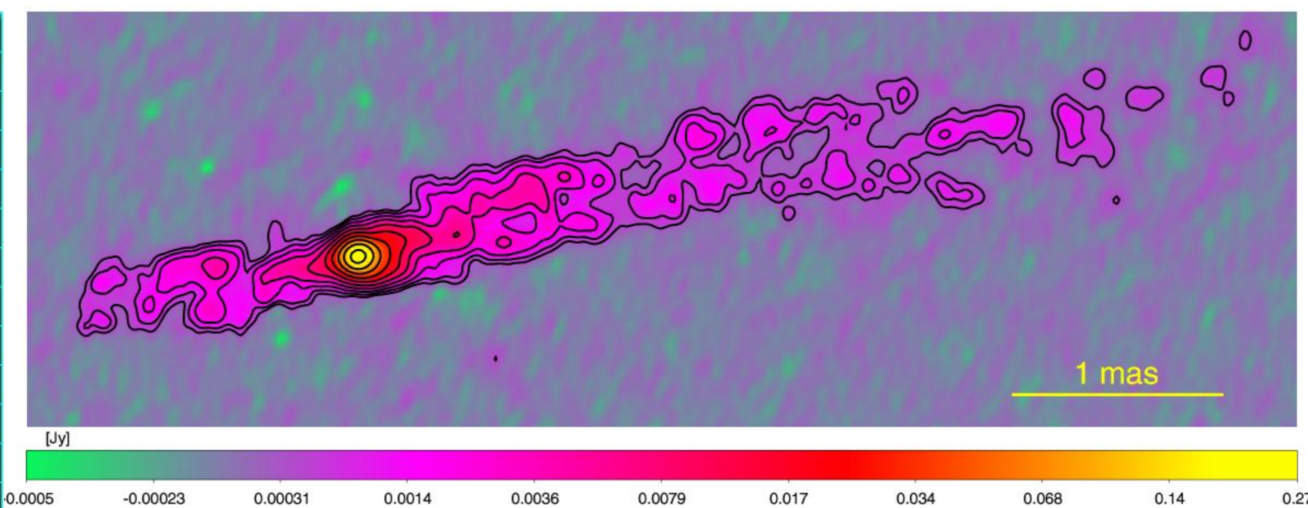
Basic Questions for mm VLBI

- Acceleration and collimation of the flow.
- Roles played by accretion disk and central black hole (Blandford-Payne vs. Blandford-Znajek)
- Magnetic field strength and structure on scales smaller than 1000 R_g.
- Emission from accretion disk and/or non-thermal corona.



Asada+ 2014



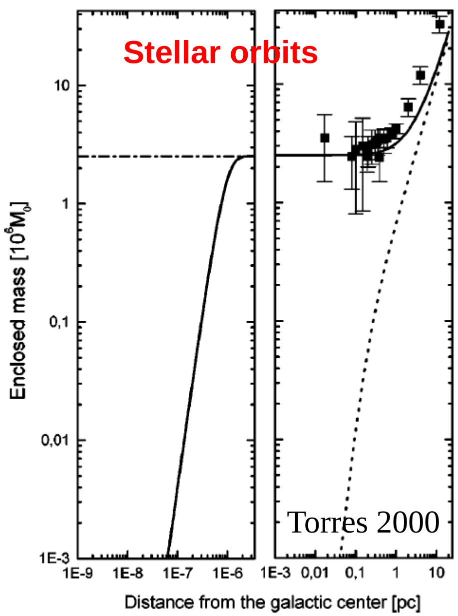


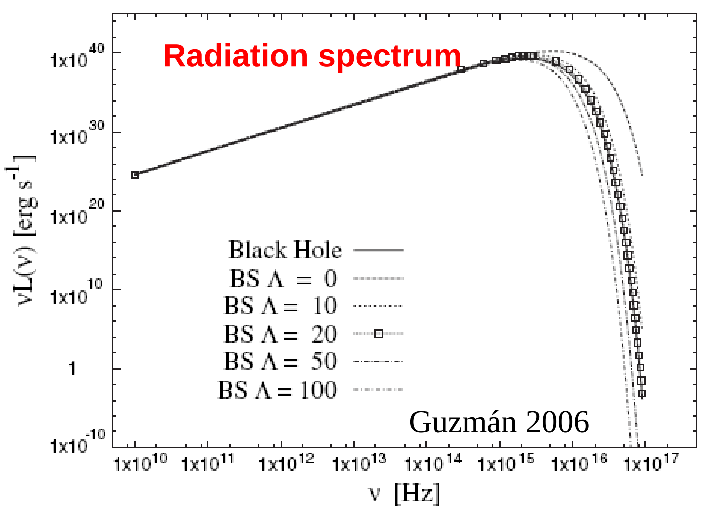
Giovannini+ 2018

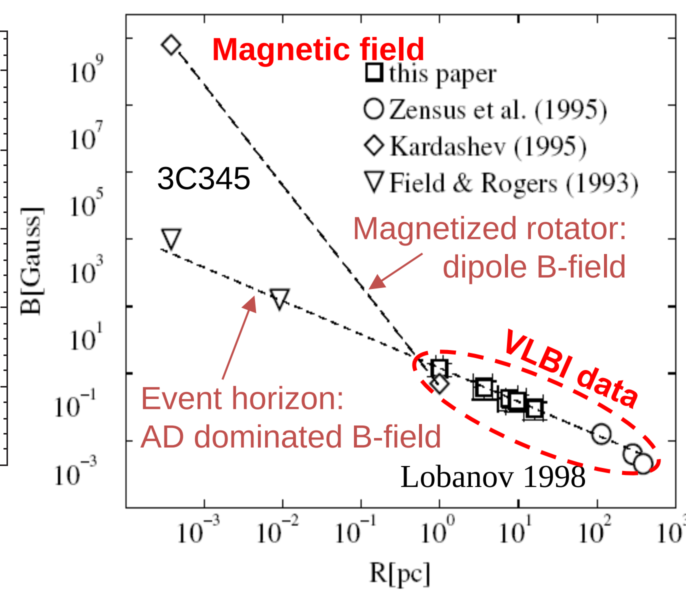
Boccardi+ 2016

VLBI Angle on Black Hole Physics

- ❑ All of the present evidence does not strictly prove existence of BH.
- ❑ Need to devise instruments and experiments to distinguish effectively between BH and their viable alternatives:
  - **stellar orbits:** (S1, Sgr A*) good enough for BH vs. ν condensate tests
  - **radiation spectrum:** high energies (BH vs. BS), ELF (BH vs. MECO)
  - **gravitation waves:** BH vs. anything (but need accurate templates)
  - **VLBI:** 2D imaging (BH vs. BS/MECO?), B-field (BH vs horizonless objects)



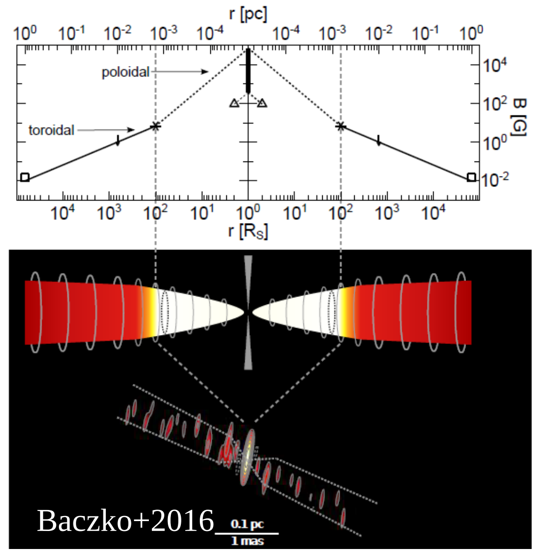


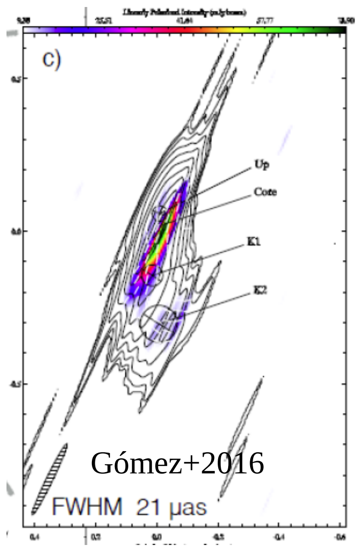


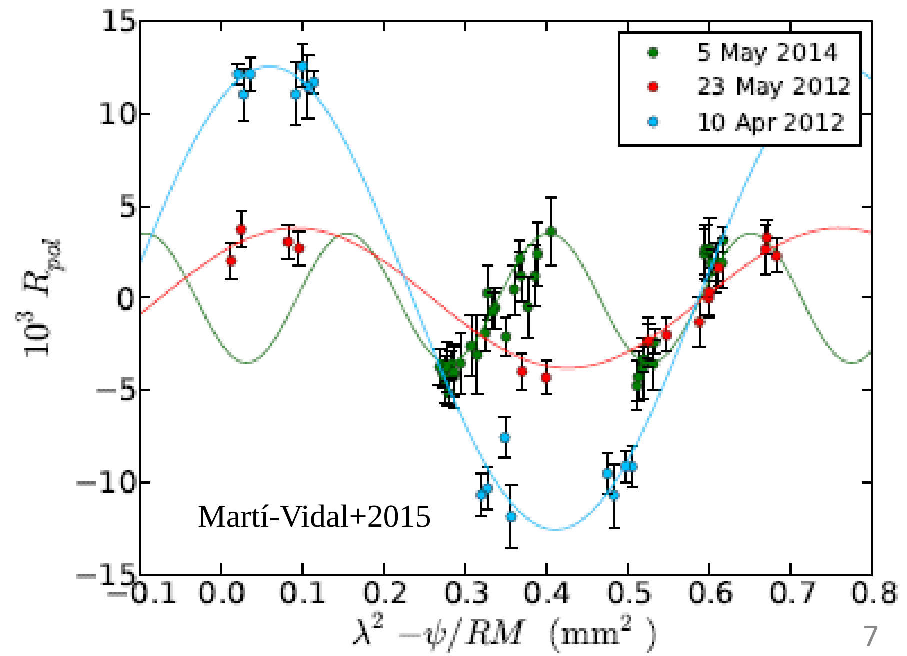
Evidence for Strong B-fields

- In the collimation profiles of inner jet (NGC1052, Baczko+ 2016)
- In extremely well structured polarization pointing towards a radial B-field
- In extreme opacity profiles (e.g. IC 310, Schulz+ 2015)
- In extremely high rotation measures (Martí-Vidal+ 2015)
- In extremely high brightness temperatures, too

Millimetre VLBI observations are instrumental for dealing with each of these aspects of compact jets.







VLBI Studies of Black Hole Vicinity

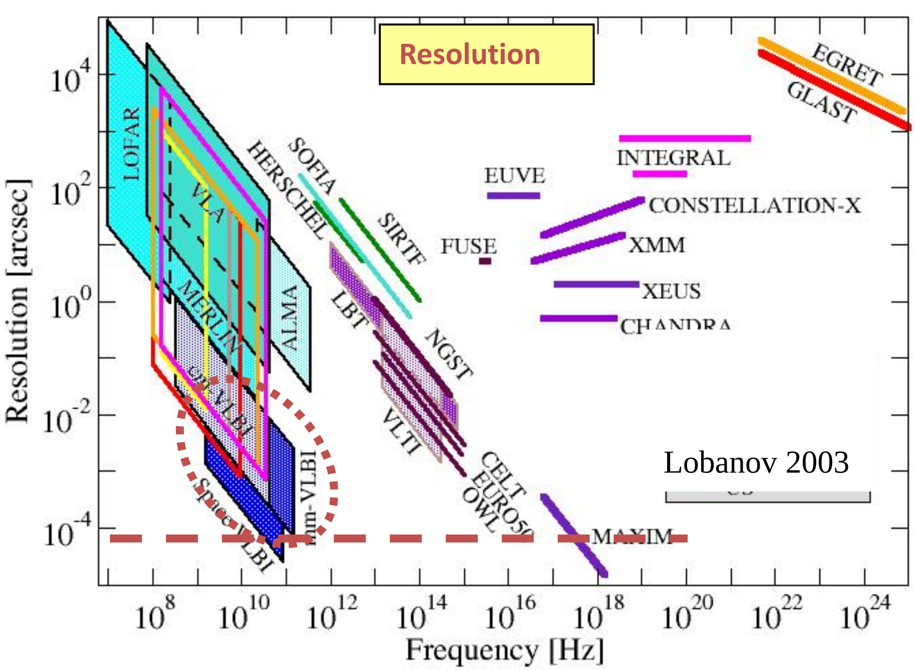
- Effective studies of black hole vicinity requires imaging with: **~10 μas resolution** and **spatial dynamic range of >500**

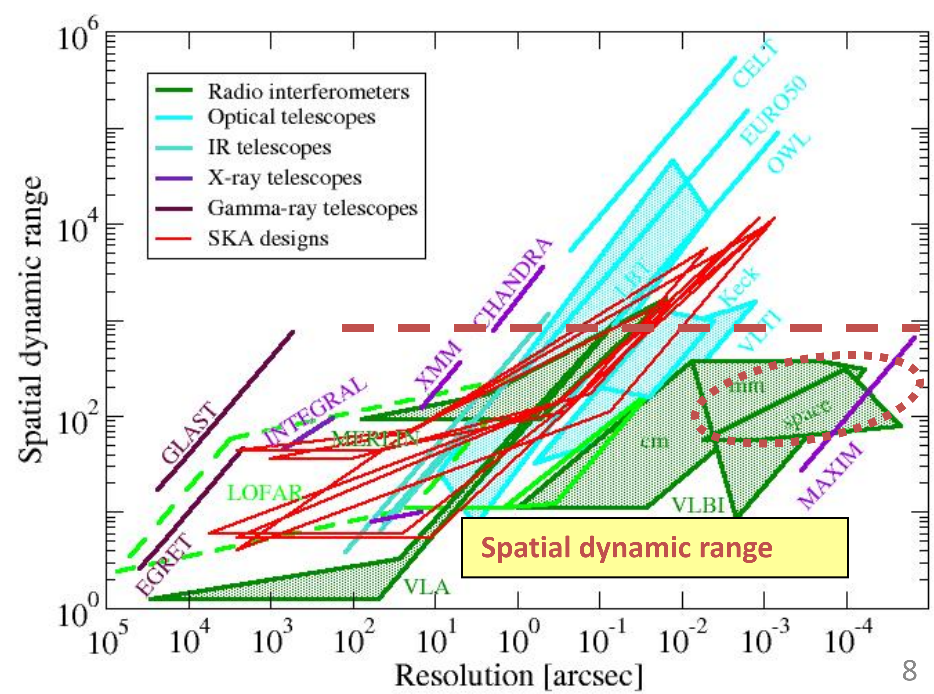
  Millimetre and space VLBI are the tools of choice for such studies.

Major VLBI arrays operating at mm-wavelengths

Array	43 GHz		86 GHz		132 GHz		230 GHz		345 GHz	
	SEFD	σ_{ph}	SEFD	σ_{ph}	SEFD	σ_{ph}	SEFD	σ_{ph}	SEFD	σ_{ph}
GVLBI	25 K	10°								
KVN	1110 K	5°	1862 K	10°	3436 K	15°				
GMVA			86 K	30°						
GMVA+ALMA			50 K	20°*						
EHT							675 K	100°	780 K	100°
EHT+ALMA							185 K	25°*		

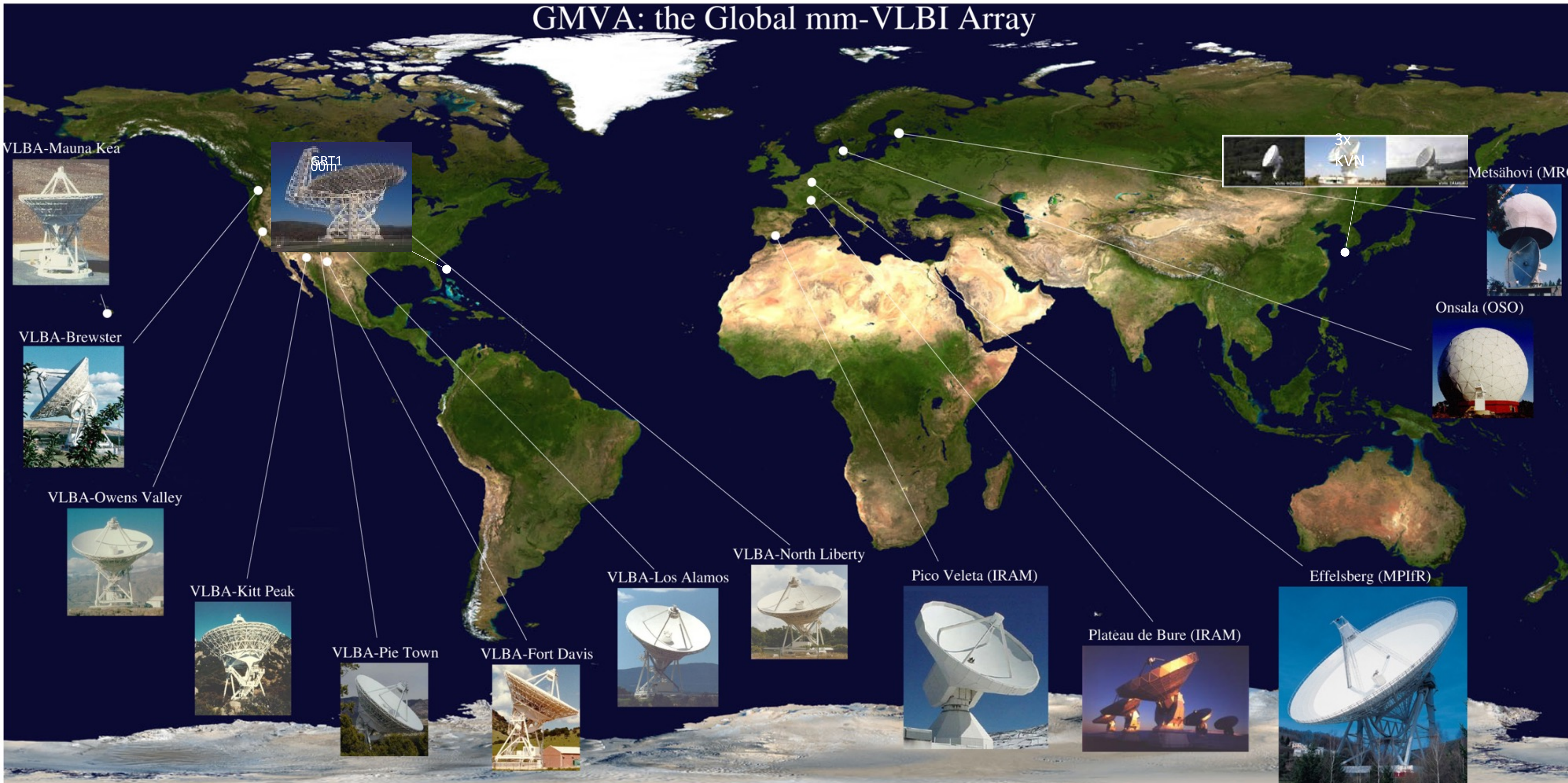
* -- rms phase on baselines to ALMA





Global Millimetre VLBI Array

- Prime array for high-sensitivity imaging at a ~50 μas resolution at 86 GHz
- Amplitude calibration and phase stability are the main limiting factors



Imaging FOM for mm VLBI

- Standard procedure: optimizing A_{eff}/T_{sys} and leaving everything else to calibration / self-calibration:

  – effectively optimizes only amplitude part of the noise
  – does not always work even for large arrays (*e.g.*, SKA)
  – even less important for smaller arrays (like VLBI)

- One always needs to consider (at least) two other optimization dimensions:

  – structural sensitivity (effects of *uv*-coverage)
  – phase noise and phase errors (critical for high-frequency VLBI)

Optimising for *uv*-coverage

- Difficult for VLBI arrays because of their quasi ad hoc nature (VLBA is the only exception so far).
- FOM accounting for the generic effect of array design on imaging: Spatial dynamic range (SDR) – the ratio between largest and smallest adequately imaged scales.
- SDR reflects a number of other aspects of array design, including the type of primary receiving element (antenna), signal processing, and distribution of antennas/stations.
- Array configuration contribution to the SDR can be expressed as a function of a „gap“, $\Delta u/u$, between adjacent baselines (u_1,u_2):

$$\Delta u/u = (u_2 - u_1)/u_2 \quad (u_2 > u_1)$$

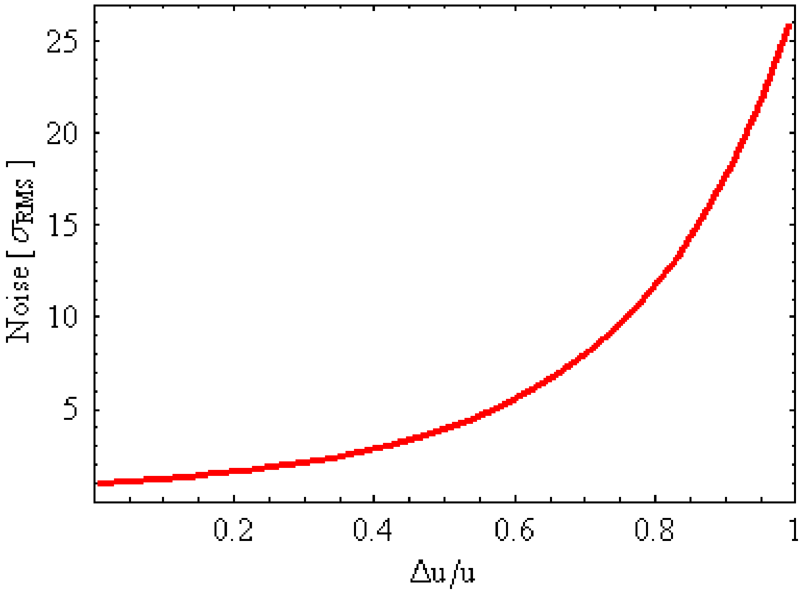
- Uniform structural sensitivity is provided by $\Delta u/u = const$ over the entire range of *uv*-spacings measured.

FoM for Imaging

- Uniform structural sensitivity is provided by $\Delta u/u = const$

- For non-uniform uv-coverages,

$$\Delta u / u \rightarrow \langle \Delta u / u \rangle \left[1 + \left(\frac{\sigma_{\Delta u/u}}{\langle \Delta u / u \rangle} \right)^2 \right]^{1/2}$$



- Structural sensitivity

$$\eta_{uv} = \exp\left[\frac{\pi^2}{16 \ln 2} \frac{\Delta u}{u} \left(\frac{\Delta u}{u} + 2 \right) \right]^{-1}$$

Structural sensitivity η_{uv}=1 for filled aperture (with $\Delta u/u$=0)

- Scale-dependent image noise

$$\sigma_{uv} = \sigma_{rms} / \eta_{uv}$$

Scale-dependent noise can only be reduced by improving η_{uv}, *i.e.*, by reducing $\Delta u/u$

Lobanov 2010

VLBI Arrays and *uv*-gap

- In a sparse *N*-antenna array, average *uv*-gap parameter can be approximated as $\langle \Delta u/u \rangle \sim 1 - \left({}^{B_{\min}}/_{B_{\max}}\right)^{2/N}$
- Compare:

Array	$\langle \Delta u/u \rangle$	σ_{uv}
86 GHz VLBI (GMVA)	0.43	2.6 σ_{rms}
230 GHz VLBI (EHT)	0.69	5.3 σ_{rms}

- In both cases, *uv*-gap affects image noise (but the effect on finest scales will be smaller than the array average).

With this, we have to live... unless we can build more antennas.

Optimising for Phase Noise

- Dynamic range:

$$D \approx \sqrt{\frac{N_{\mathrm{scan}}\, N_{\mathrm{bas}}}{{\sigma_{\mathrm{amp}}}^2 + {\sigma_{\mathrm{ph}}}^2}} = \frac{SNR_{\mathrm{amp}}\, SNR_{\mathrm{ph}}}{\sqrt{{SNR_{\mathrm{amp}}}^2 + {SNR_{\mathrm{ph}}}^2}} \sqrt{N_{\mathrm{scan}} N_{\mathrm{bas}}}$$

- Brute force solution: Increase $N_{\mathrm{scan}} N_{\mathrm{bas}}$.
  May work for SKA, but difficult to realize for mm-VLBI.

- In VLBI, careful optimisation for both SNR_{amp} and SNR_{ph} is required.

- At frequencies above 43 GHz, optimisation for SNR_{ph} becomes crucial. For instance, $\sigma_{\mathrm{ph}} \approx 100°$ in „live“ plain EHT data at 230 GHz (without phased ALMA), essentially implying $SNR_{\mathrm{ph}} \rightarrow 0$...

Effects of SNR_{amp} and SNR_{ph}

- Reducing amplitude noise increases effective resolution:

$$\theta_{res} \propto \frac{FWHM_{\mathrm{beam}}}{\sqrt{SNR_{\mathrm{amp}}}}$$

- Reducing phase noise improves positional accuracy:

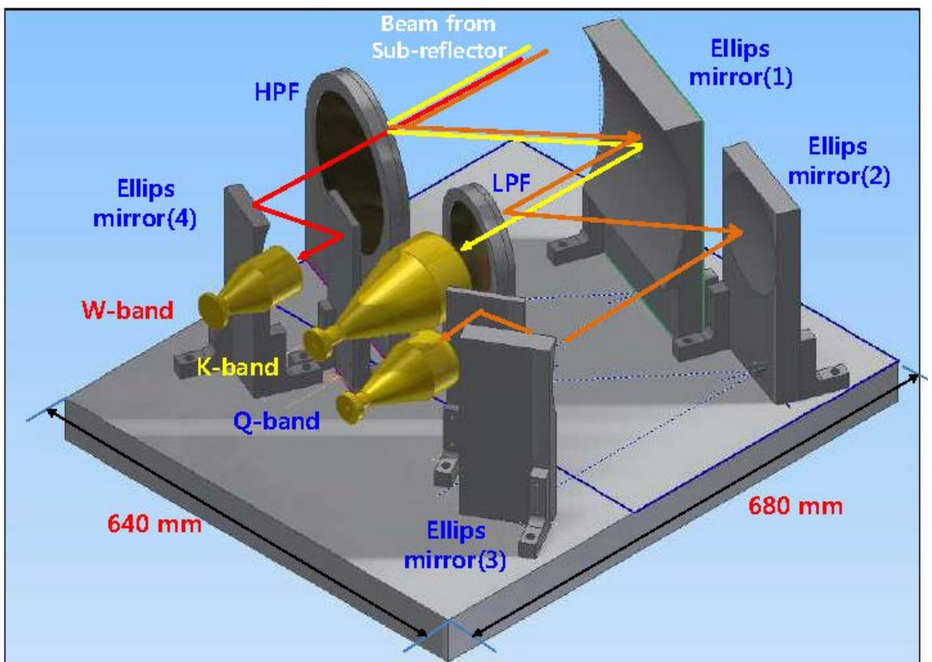
$$\Delta_{pos} \propto \frac{FWHM_{\mathrm{beam}}}{SNR_{\mathrm{phase}}}$$

- SFPR with KVN: reaching $\Delta_{pos} \approx 30\ \mu\mathrm{as}$, with an effective $SNR_{\mathrm{ph}} \sim 40$ at 86 GHz.

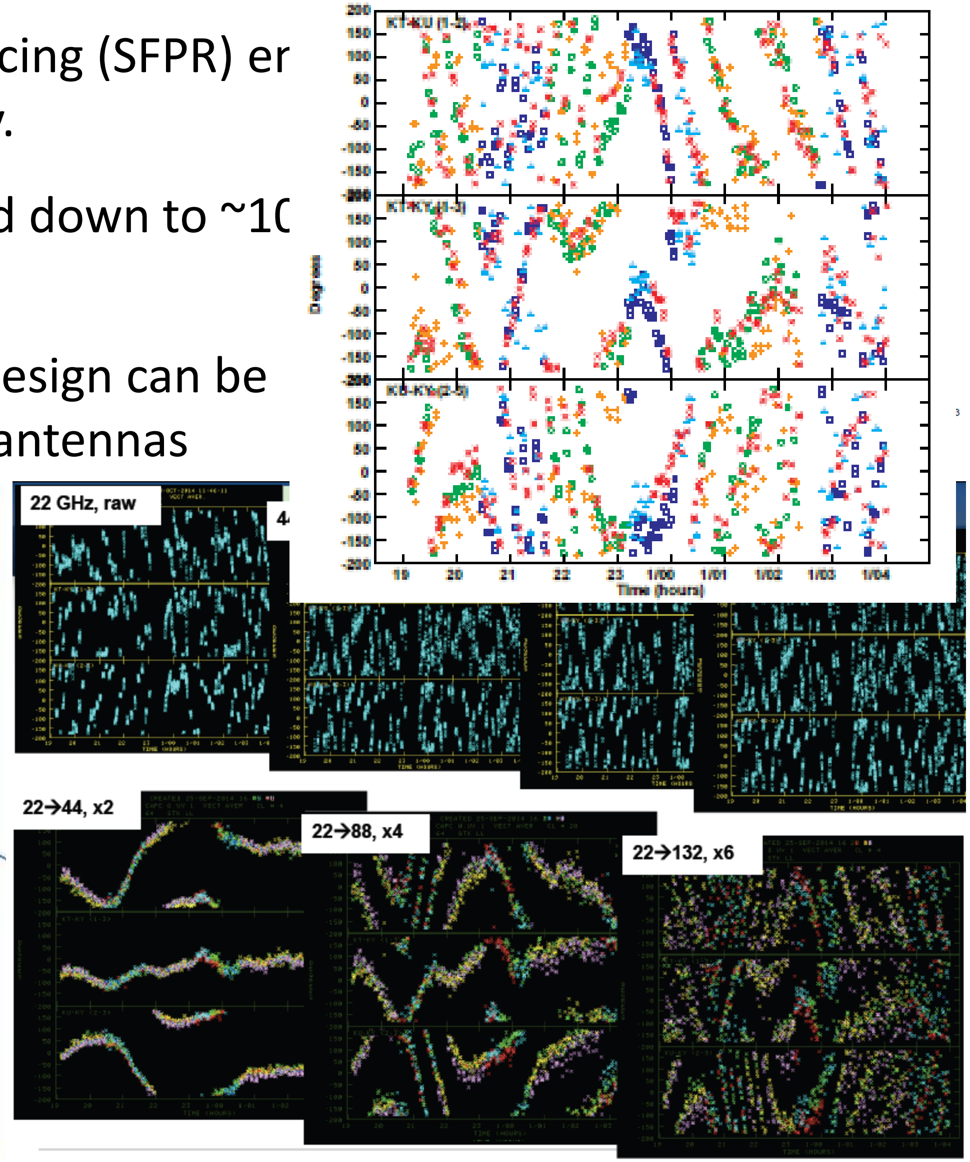
- This is a wonderful benchmark for designing new mm-VLBI instruments.

Reducing the Phase Noise with SFPR

- ❑ KVN source frequency phase referencing (SFPR) er achieving remarkable phase stability.
- ❑ The resulting phase noise is reduced down to ~1(at 86 GHz and ~ 15° at 130 GHz
- ❑ A three-frequency (22/43/86 GHz) design can be implemented on most of the GMVA antennas



Han+ 2016



Rioja+ 2015, Dodson+ 2017

SFPR with EVN and Global Arrays

- Minimum option: SFPR astrometry with KVN + some EVN antennas:
  - – positional measurements
  - – radio-optical reference frame connection
  - – opacity and magnetic field measurements (core shifts)

Array	43 GHz		86 GHz		132 GHz		230 GHz		345 GHz	
	SEFD	σ_{ph}	SEFD	σ_{ph}	SEFD	σ_{ph}	SEFD	σ_{ph}	SEFD	σ_{ph}
GVLBI	25 K	10°								
KVN	1110 K	5°	1862 K	10°	3436 K	15°		*30°*		
GMVA			86 K	30°						
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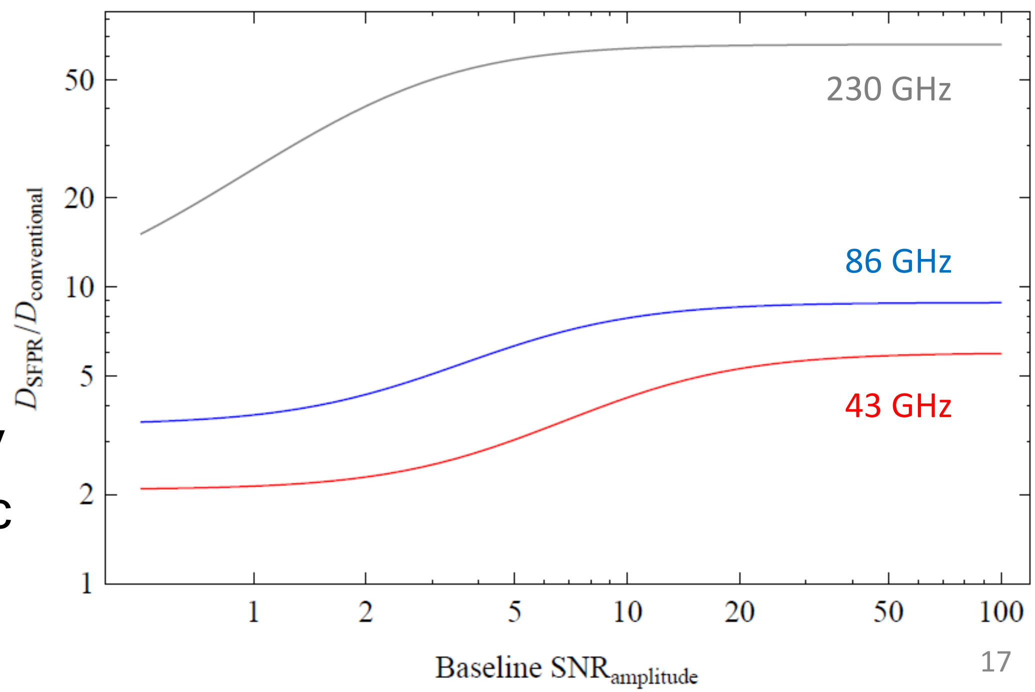
EHT							675 K	100°	780 K	100°
EHT+ALMA							185 K	25°*		

- Full option: SFPR imaging with KVN + VLBA/GMVA:
  - – substantial improvement of image fidelity at 86 GHz
  - – full-fledged 86GHz imaging array with $\sigma_{ph} \sim 10°$ (!)
  - – if shown to work at 230 GHz, could yield $\sigma_{ph} \sim 30°$, strongly improving fidelity and dynamic range.



Example: Core Shifts

- Detection SNR for the KVN to detect the median and maximum measured core shifts in samples of AGN jets (Kovalev+2008, Pushkarev+2012)

- SNR are calculated for the default specifications of the KVN, assuming a flat spectrum in the core.

  Baseline length dependence:

$$\mathrm{SNR}\,(B) = \mathrm{SNR}_{\mathrm{KVN}}\,(\frac{500\ km}{B})$$

Median core shifts			
$\nu_1 \setminus \nu_2$	**43 GHz**	**86 GHz**	**129 GHz**
22 GHz	380	250	235
43 GHz		625	495
86 GHz			1990

Maximum core shifts			
$\nu_1 \setminus \nu_2$	**43 GHz**	**86 GHz**	**129 GHz**
22 GHz	42	28	26
43 GHz		70	55
86 GHz			220

SFPR for Imaging at 86 GHz

- Combined aspects of imaging at 86+ GHz makes SFPR a very attractive option for AGN and BH studies:

Imaging consideration:	Generic dependence on ν	86/230 GHz: SFPR GMVA/EHT
Fringe spacing	$\propto \nu^{-1}$	$1/3 \quad (1/3)$
Scattering	$\propto \nu^{-2}$	$1/9 \quad (1/27)$
AGN opacity	$\propto \nu^{-1}$	$1/3 \quad (1/81)$
Phase noise	$\propto \nu^{+1}$	$\mathbf{10/1} \quad (\mathbf{10/81})$
Effective antenna area	$\propto \nu^{-1/2}$	$\sqrt{3}/1$
SEFD	$\propto \nu^{+1}$	$3/1$
Amplitude noise	$\propto \nu^{+3/2}$	$9/\sqrt{3} \quad (10/9\sqrt{3})$
Filling of uv-plane	$\propto \nu^{+1}$	$3/1 \quad (10\sqrt{3}/9)$
Effective structural sensitivity	$\propto \boldsymbol{\nu^{+1/2}}$	$\mathbf{10\sqrt{3}/9}$
Effective dynamic range	$\propto \boldsymbol{\nu^{-3/2+\alpha}}$	$\mathbf{21\sqrt{3}\,3^{-\alpha}}$
Effective resolution	$\propto \boldsymbol{\nu^{+1/4-\alpha}}$	$\mathbf{3/4\ 3^{-\alpha}}$

What Does It All Mean?

- For VLBI at 86+ GHz, phase noise is both the worst adversary and the factor where the strongest improvement can (*and must!*) be achieved.

- Implementing SFPR at 86 GHz on a GMVA scale array may even result in achieving imaging performance surpassing that of the EHT – for any structural detail larger than the scattering size.

- SFPR should be seriously considered for a new standard mode of VLBI imaging at 86+ GHz.

Potential Recommendations

- **Implementing SFPR imaging at 43 and 86 GHz** should provide substantial improvements of image fidelity: astrometric accuracy and effective resolution.
- **Small scale implementation** (KVN, 1-3 antennas in Europe): would provide astrometric accuracy of ~10 μas.
  - accurate absolute kinematic measurements
  - opacity and magnetic field measurements
  - radio/optical reference frames.
- **Large scale implementation** (GMVA): would provide the most effective VLBI imaging at 43+ GHz:
  - *it will turn 3-mm VLBI into a powerful imaging machine, with an effective resolution similar to that of the EHT and a better structural sensitivity.*