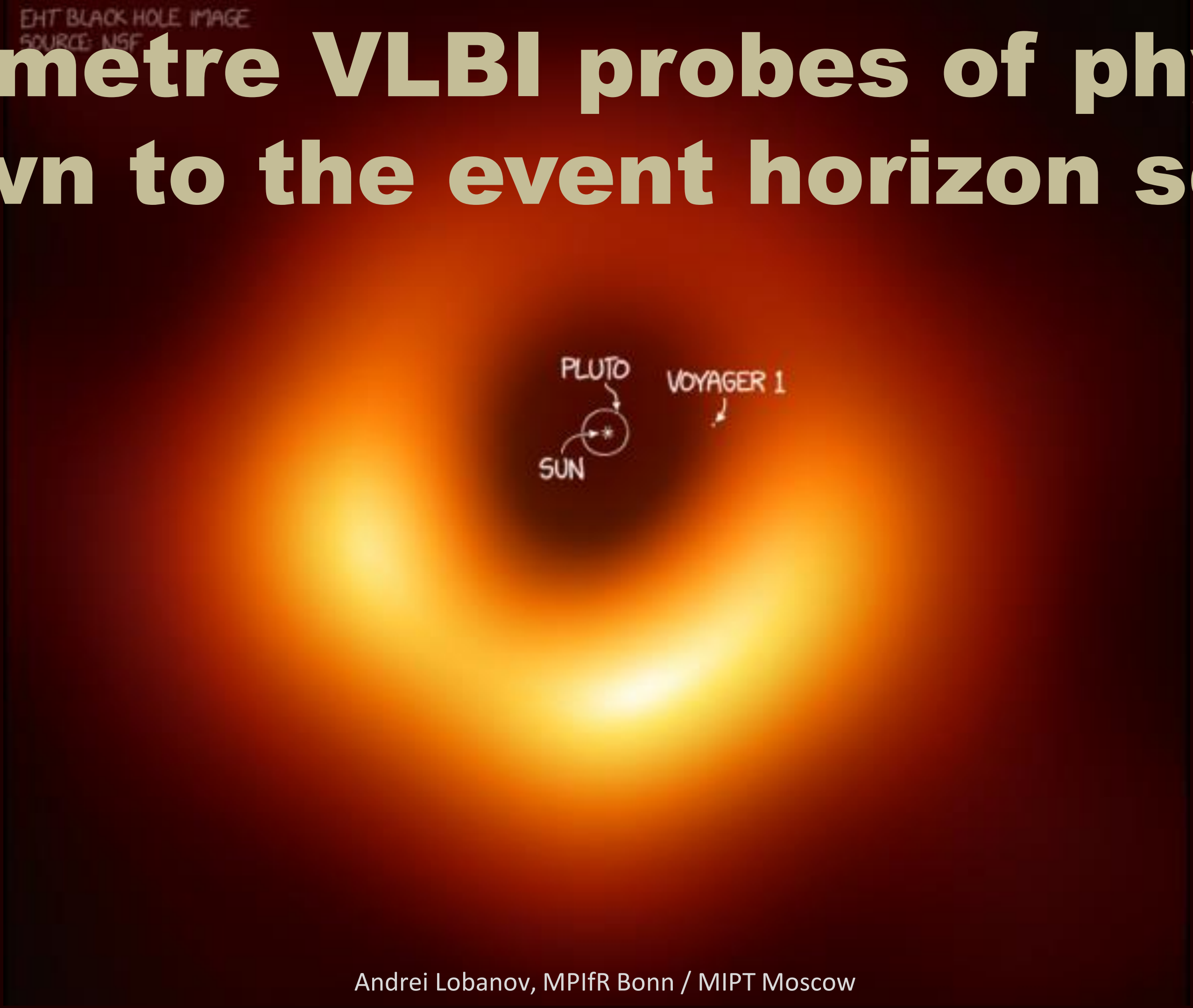
Millimetre VLBI probes of physics down to the event horizon scale



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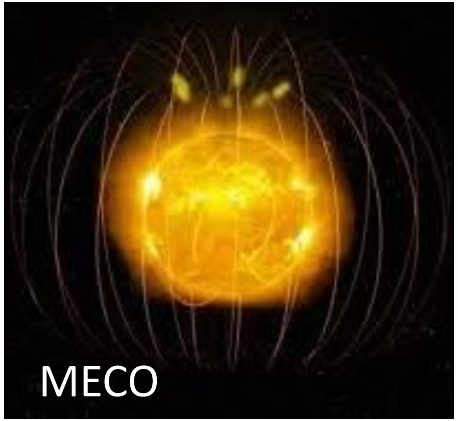
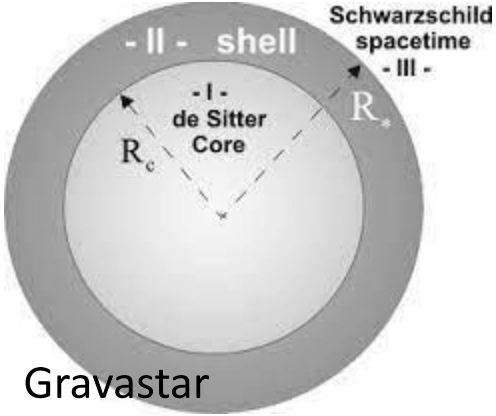
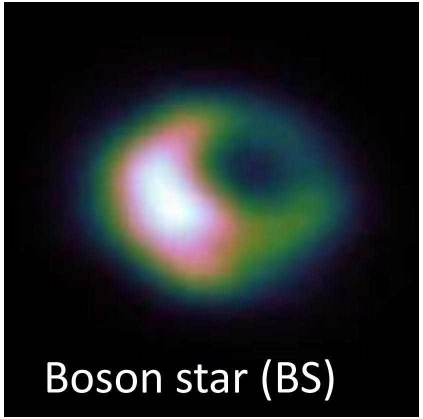
Black Holes and Their Exotic Cousins

- Black holes: Resulting from gravitational collapse of matter (if nothing stops it).
- (some) Ways to stop the collapse :
  – Radiative pressure: magnetospheric eternally collapsing objects (MECO)
  -- Vacuum pressure: gravitational vacuum stars (gravastars).
- (some) Other exotic cousins of black holes (BH):
  -- Boson/quark/Planck and other „strange“ stars
  -- Wormholes


MECO



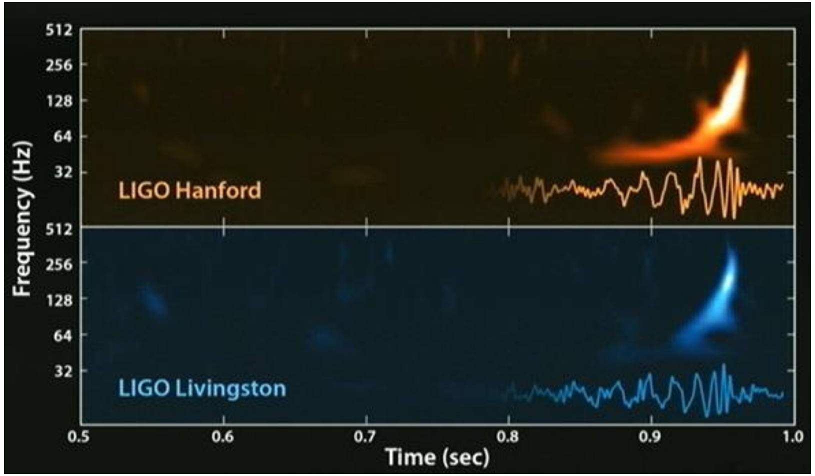
Gravastar

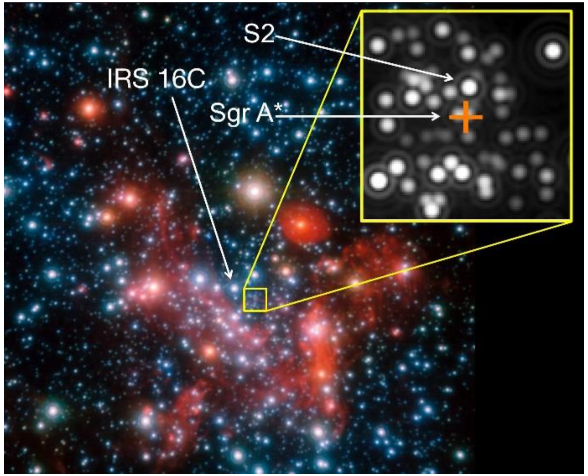

Boson star (BS)

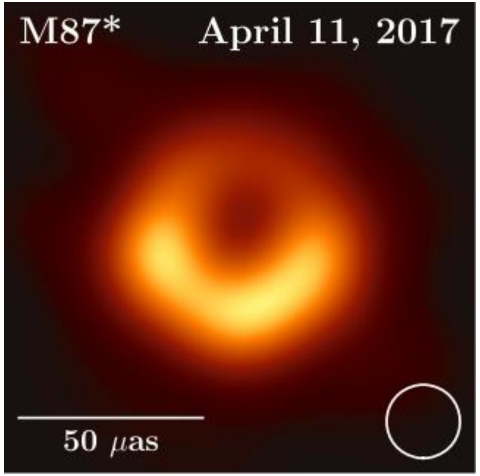

Wormhole

Evidence for Black Holes

- The generic argument: enclosed mass.
- Specific arguments: merger events and relativistic effects near the event horizon scale.
- LIGO/VIRGO: Gravitational waves from BH mergers
- GRAVITY / Keck: Stellar orbits near the event horizon scale in Sgr A*
- EHT: Strong gravitational lensing near the event horizon scale in M87

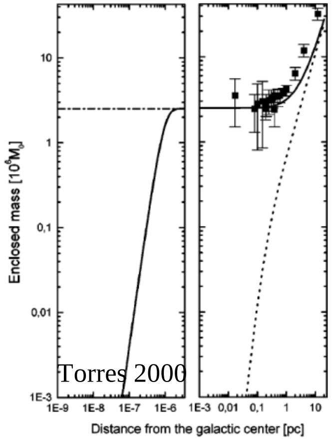




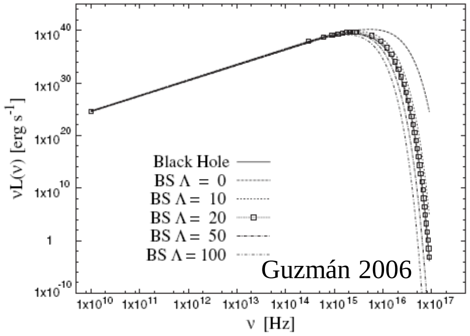


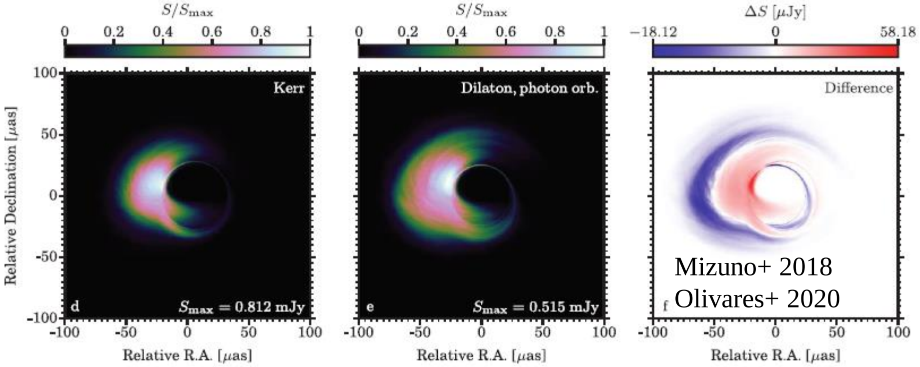
How Black is Black?

- ❑ Despite all recent successes, present measurements still do not unequivocally establish the physical reality of black holes. Conclusive tests are needed.
- ❑ **Radiation spectrum**: BH vs. BS (at high energies), BH vs. MECO (at very low energies)
- ❑ **Stellar orbits**: BH vs BS
- ❑ **Gravitational waves**: BH vs. anything (in principle). But need right templates
- ❑ **GR effects** (lensing, photon rings etc.): BH vs. BS/MECO, alternative theories of gravity



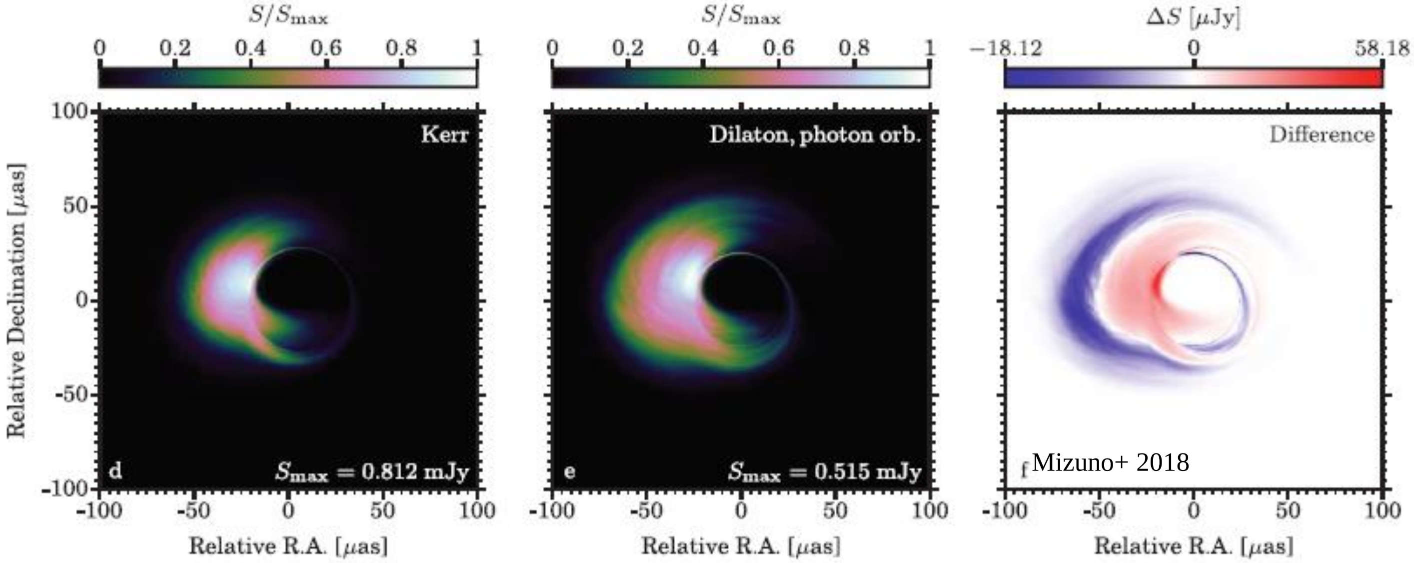
Need clever design for both new instruments and new measurements



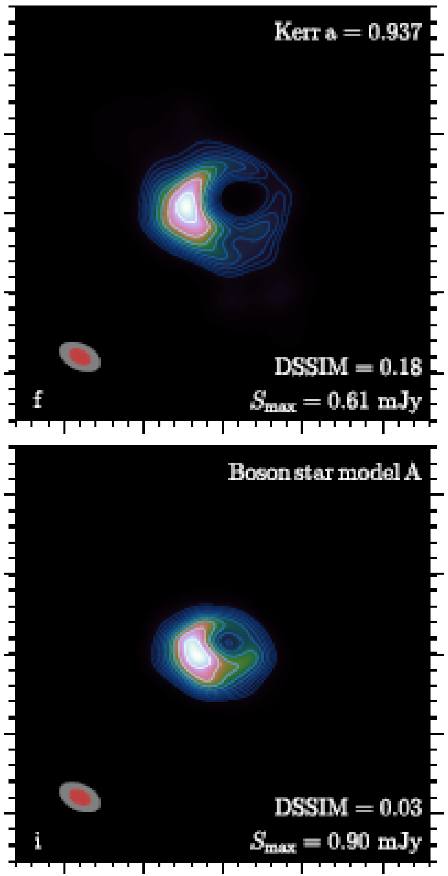


VLBI Prospects

- The EHT image of black hole shadow in M87: Effective dynamic range of about 30:1
- Mizuno+2018, Olivares+2020: Need dynamic ranges in excess of 1000:1 to be able to use 2D brightness distribution for discerning between Kerr BH and its alternatives such as dilaton BH and BS.



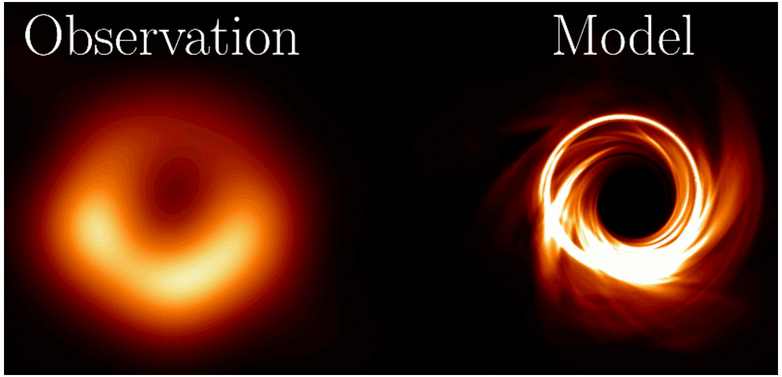
Mizuno+ 2018



Olivares+ 2020

The Need for Improved Imaging

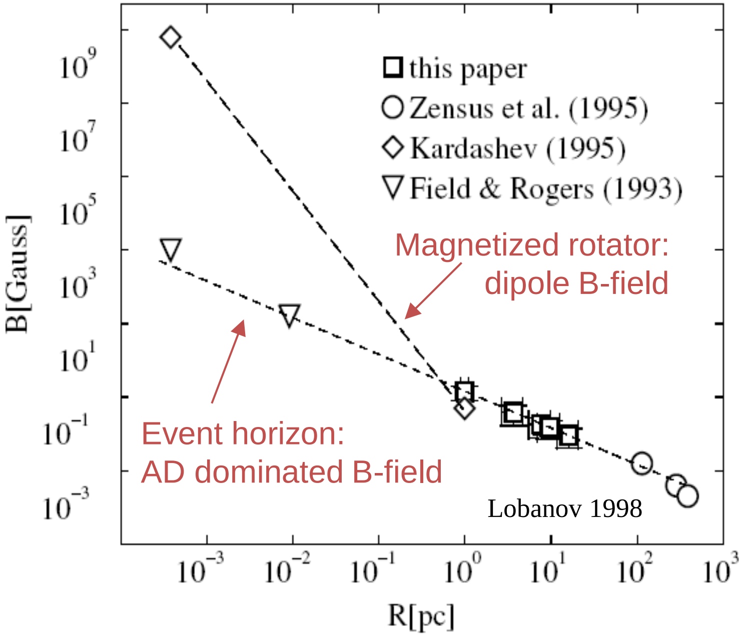
- EHT Science:
  -- Dynamic range of > 1000 is needed for distingiushing between different models of central source (hence a factor of ~50 improvement from the present day performance.



- Ways to achieve it:
  - Broader bandwidth
    -- $\sigma_{rms} \propto BW^{-1/2}$, but uv-coverage is rhe same
  - Phase stability
    -- from broader BW (better SNR)
    -- with large antennas (NOEMA, LMT, ALMA)
    -- Frequency-phase transfer (*22*/43/86/230 GHz)
  - Better uv-coverage
    -- Snapshot capability
    -- MFS capability
    -- Maximum improvement with minimum number of additional antennas

Other Diagnostics?

- Magnetic field? – It should be very different in objects with/without even horizon
- Recognized early on (Ginzburg 1964, Kardashev 1995): magnetized rotators with dipole magnetic field of up to ~10^{12} G
- Expectations:
  -- Wormholes: radial field of ~10^9G near the „neck“ (Novikov+ 2007)
  -- Gravastars: dipole field of ~10^{10} G (Mazur & Mottola 2006)
  -- MECO: dipole field of up to ~10^{20} G (Leiter & Robertson 2003)

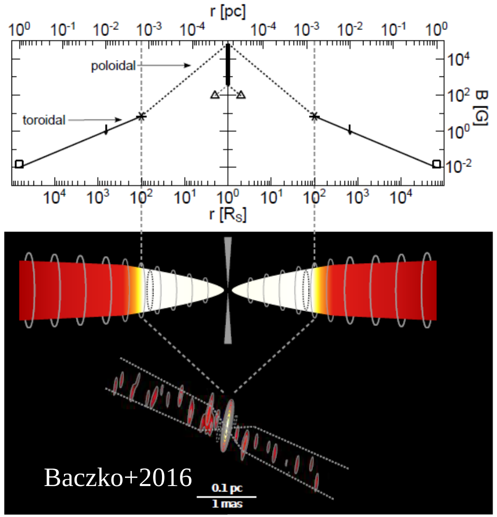


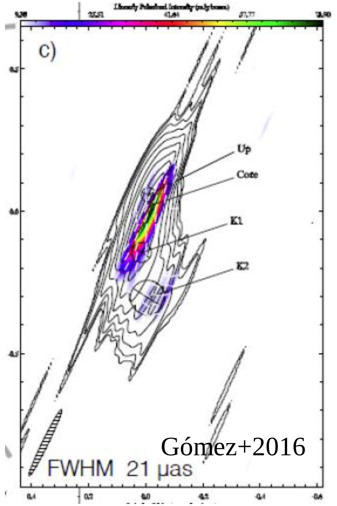
- BH: Magnetic field dominated by accretion disk/jet, with strengths of up to 10^4 G (Field & Rogers 1993, Meier 2001, Chael+ 2019)
- Magnetic field of the central horizonless object will dominate at r < 1000 R_g

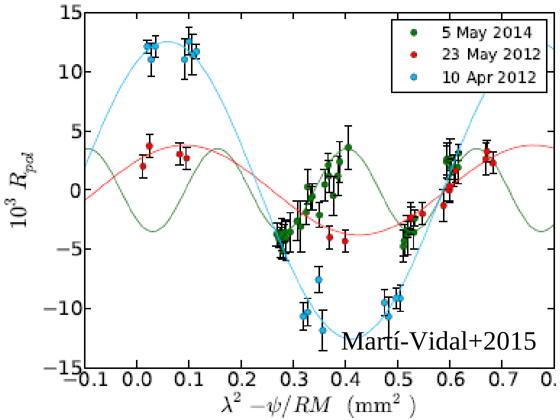
Where Can Those B-Fields Hide?

- ❑ Collimation profiles of inner jet in NGC 1052: $B>10^4$ G (Baczko+2016)
- ❑ Strong polarization in BL Lac, potentially indicating a radial B-field (Gómez+ 2016)
- ❑ Extreme opacity profiles in IC 310, suggesting $B>10^5$ G (Schulz+ 2015)
- ❑ Rotation measures in excess of 10^7 rad/m^2 (Martí-Vidal+ 2015)

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







Brightness Temperature

- Strong B-fields may also be evidenced by high brightness temperature
- Taking a look at a „normal“ IC-loss dominated plasma in a strong magnetic field gives:

$$T_{b,max} \sim 7 \times 10^9 \text{ K} \left(\frac{B^{3/4}}{\text{G}}\right)$$

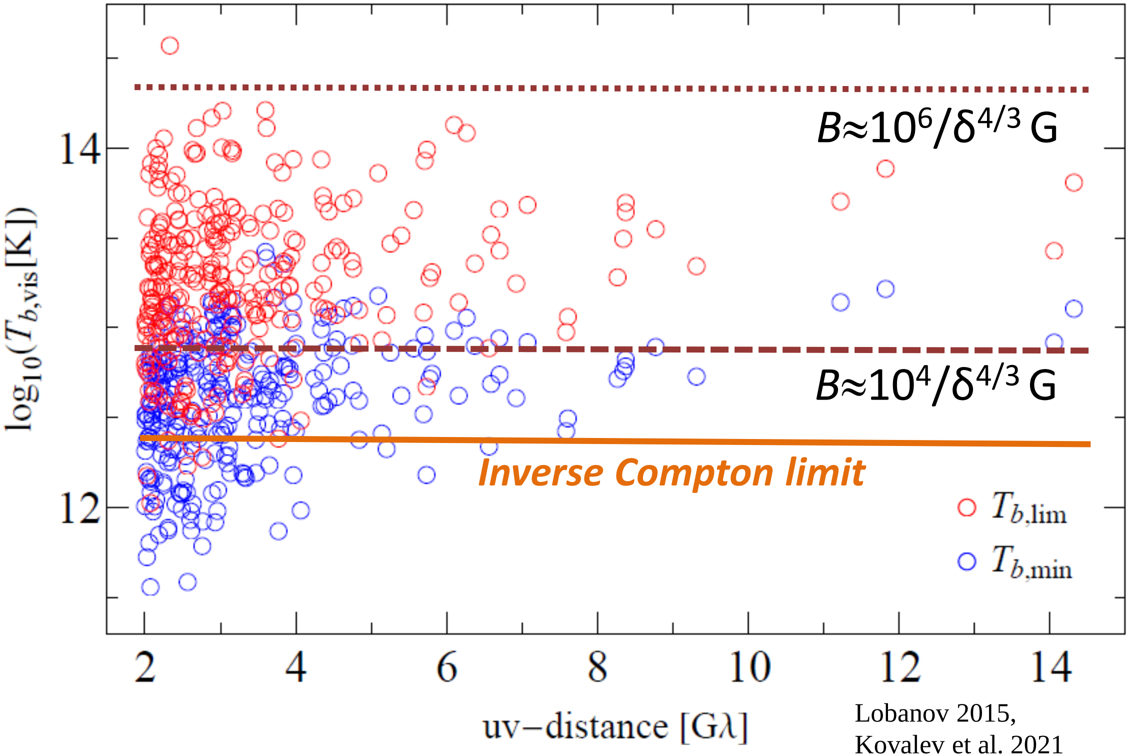
- This, of course, implies a sky-rocketing $\nu_m \propto B^{1/2}$.
- However, the rogue ν_m can be kept low if the plasma particle density $N_0 \propto B^{-7/2}$.
- This is actualy pretty feasible for:
  – a „runaway“ cell in a turbulent flow (Marscher 2014);
  – a BZ beam inside of BP jet;
  – a truly „indigenous“ pair creation (for $B > 10^{13}$ G)

Brightness Temperatures from RadioAstron

- AGN survey: $T_{\rm b,vis}$ from visibility measurements for 230+ AGN, bracketing $T_{\rm b,vis}$ between its minimum, $T_{\rm b,min}$, and limiting, $T_{\rm b,lim}$, values.
- Most AGN show the IC violation, with $T_{b,\rm min} \geq 10^{13}$ K and $T_{b,lim} \geq 10^{14}$ K. Requires Doppler factors $\delta \geq 100$.
- Measured $T_{\rm b,lim}$ indicate possible $B > 10^4/\delta^{4/3}$ G, as one can expect

$$T_{b,max} \sim 7 \times 10^9 \text{ K } \left(\frac{B^{3/4}}{\text{G}}\right)$$

in a rarefied plasma with $N_0 \propto B^{-7/2}$.



Lobanov 2015, Kovalev et al. 2021

- Feasible for a „runaway" cell in a turbulent flow (Marscher 2014) or a Blandford-Znajek beam inside a Blandford-Payne jet. Accretion disk supports $B \lesssim 10^4$ G. Where could the stronger fields come from?

Measuring B-field within 1000 R_g

- **Core shift** measurements at frequencies probing suffiecently small linear scales (typically, 86+ GHz), to detect strong magnetic fields ($B > 10^4$G) or their gradients ($B(r) \propto r^{-3}$).

  -- GMVA, EHT, (SVLBI)

- **Brightness temperature** measurements reaching the sensitivity to $B > 10^4$G, which corresponds to

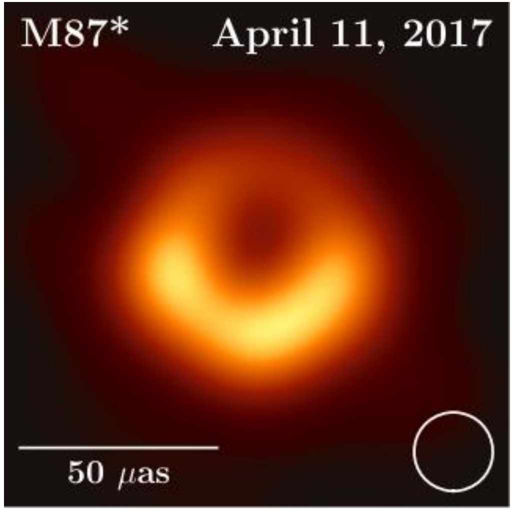
$$S_{cor}[\mathrm{Jy}] > 2.3 \times 10^{12}/(b[\mathrm{km}])^2$$

  -- SVLBI

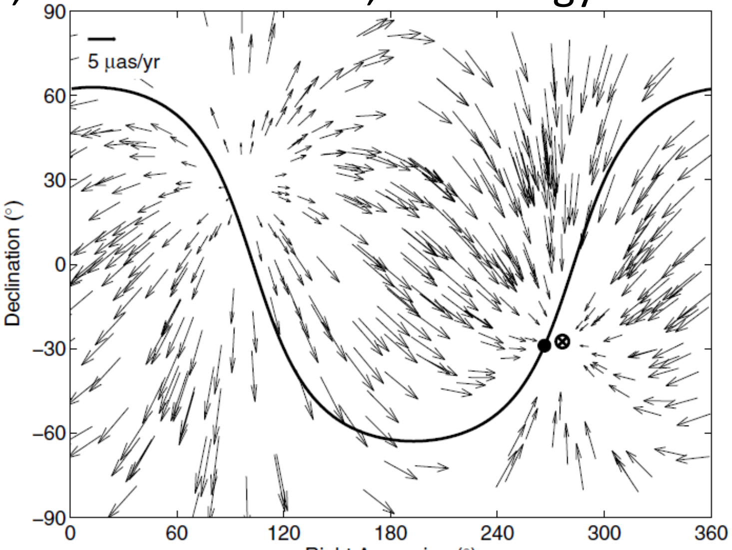
Both approaches rely on making measurements at extremely high resolution.

VLBI Imaging: Where We Stand

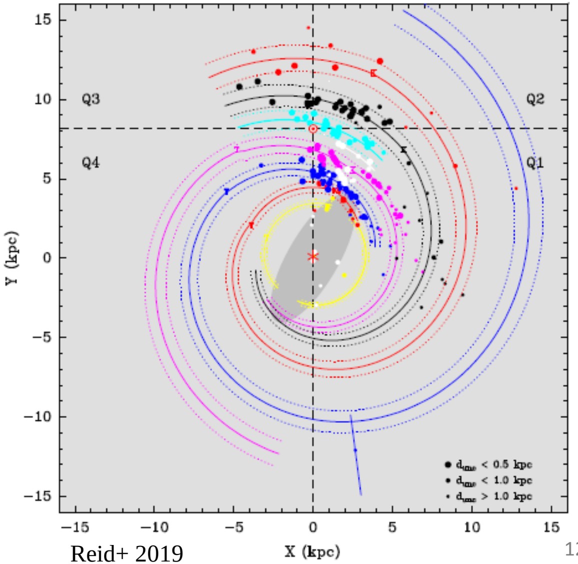
- **Resolution:** ~10-30 µas (RadioAstron @ 22GHz, EHT @ 230 GHz).
- **Dynamic range:** ~ 10,000/ν[GHz], limited by *uv*-coverage (low ν) and phase noise (high ν)
- **Positional accuracy:** ~0.1 mas (absolute) ~0.05 mas (relative).
- Addressing a number of fundamental problems, including the BH event horizon, galactic structure and kinematics, reference frames, cosmology.



EHT Collaboration 2019a



Titov & Lambert 2013



Reid+ 2019

Effect of the 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 $SNR_{\mathrm{ph}} \to 0$...

Effects of Noise on Imaging

- Reducing amplitude noise increases effective resolution:

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

- Reducing phase noise improves positional accuracy:

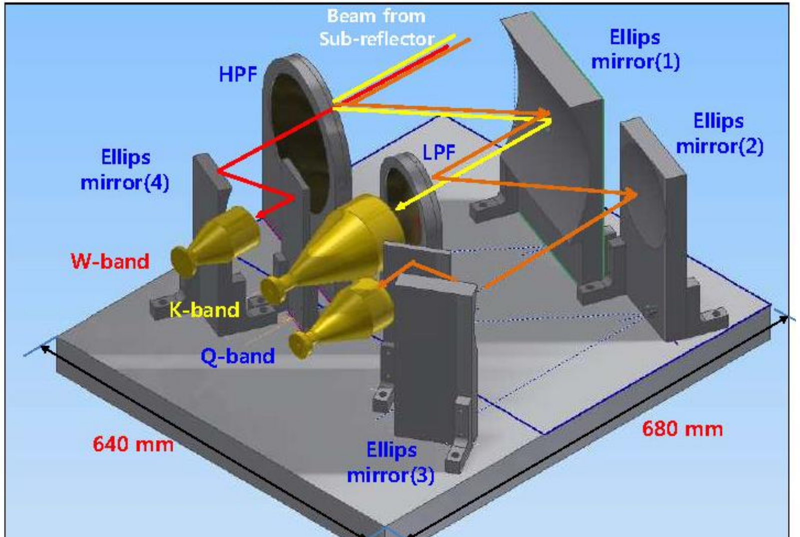
$$\Delta_{pos} \propto \frac{FWHM_{\mathrm{beam}}}{SNR_{\mathrm{phase}}}$$

- Frequency Phase Transfer (FPT) and Source Frequency Phase Referencing (SFPR) with KVN (see Dodson+ 2018, NewAR, 79, 85):
  -- Reaching $\Delta_{pos} \approx 30$ µas on baselines of ~500 km, with an effective $SNR_{\mathrm{ph}} \sim 40$ at 86 GHz.

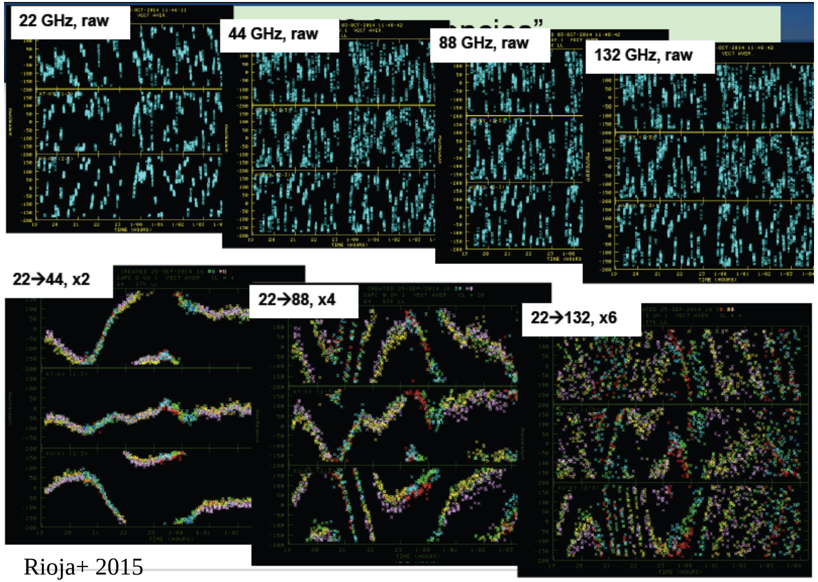
- This is a wonderful benchmark for designing new mm-VLBI instruments.

Frequency Phase Transfer

- Frequency phase transfer (FPT) at KVN enables achieving remarkable phase stability.
- The phase noise is reduced down to ~10° at 86 GHz and ~ 15° at 130 GHz
- A three-frequency (22/43/86 GHz) design can already be implemented on several GMVA antennas.
- Testing and establishing this capability at 230 GHz (with 43/86/230/*345* GHz receiver) is an area of critical impact for the EHT.



Han+ 2013

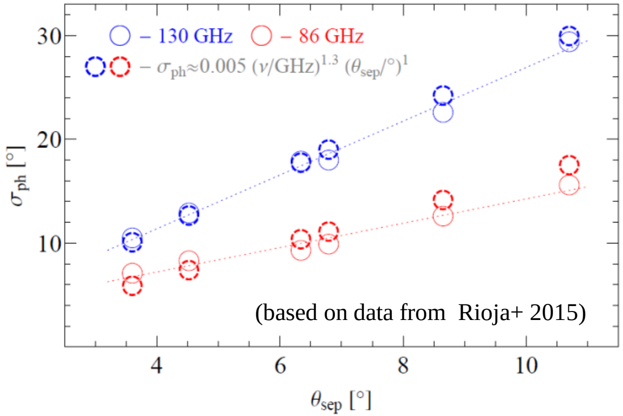


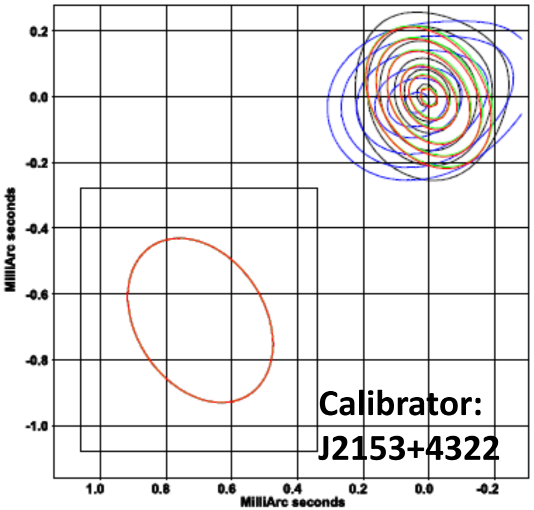
Rioja+ 2015

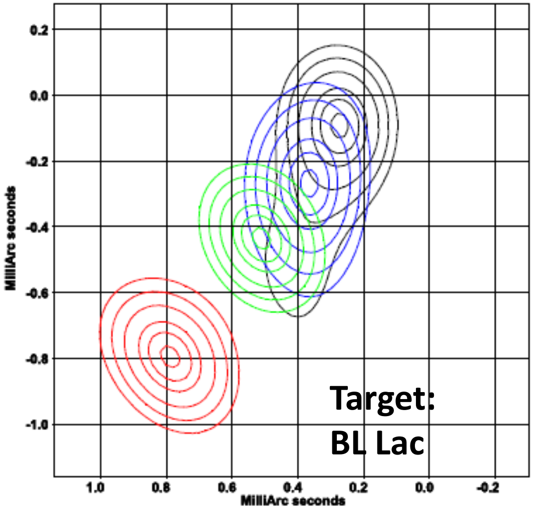
Source Frequency Phase Referencing

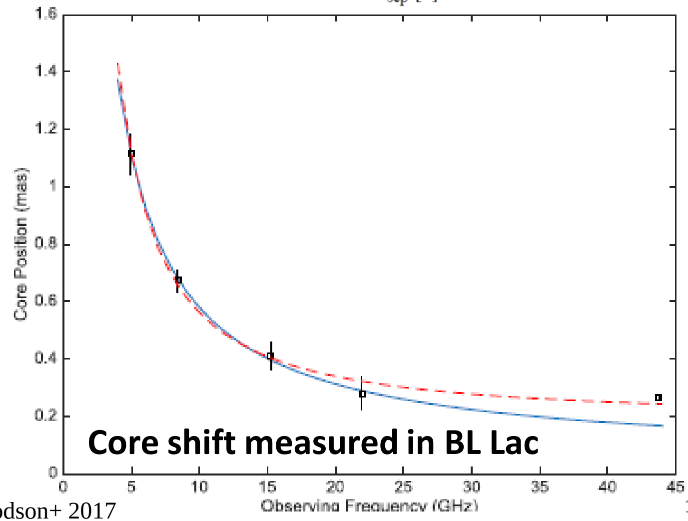
- SFPR at KVN: $\sigma_{\mathrm{ph}} \approx 0.005^\circ \left(\frac{\nu}{\mathrm{GHz}}\right)^{1.3} \left(\frac{\theta_{\mathrm{sep}}}{1^\circ}\right)^{1}$.

- Implementation of SFPR on intercontinental baselines with the VLBA has been shown to provide a ~10 μas accuracy for relative astrometry measurements.









Dodson+ 2017

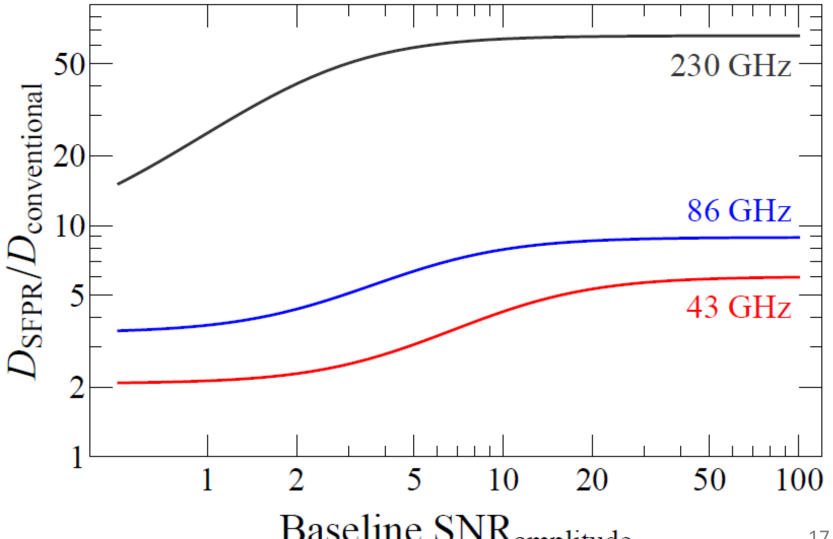
Frequency Phase Transfer

- If demonstrated to work as expected at 230 GHz, application of the FPT method should lead to factors of 15—50 improvement of the dynamic range
- Arguably the cheapest way to achive the required improvement of the dynamic range of the EH imaging.
- Need to build a set of 3 FPT-capable receievers and use them for testing the method.

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°		*30°*		*40°*
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



FPT and SFPR at 86 GHz

- Dynamic range, structural sensitivity and effective resolution of VLBI images depend on a range of factors.

- Improvements of amplitude and phase noise provided by FPT can potentially lead to 86 GHz FPT GMVA outperforming the EHT working in the canonical observational mode.

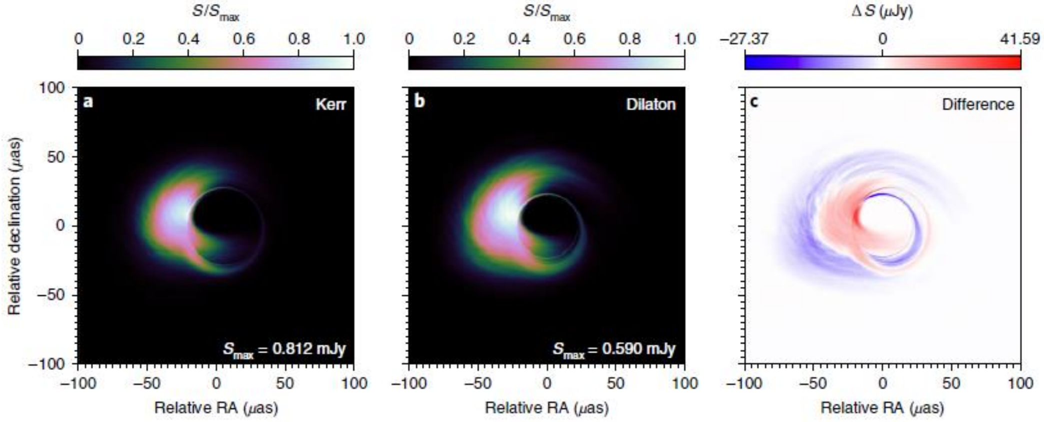
- Combined aspects of FPT and SFPR provide a very attractive option for astrophysical and astrometric studies at 22/43/86 GHz .

Factors in imaging	Dependence on frequency	FPT GMVA @ 86 GHz / EHT @ 230 GHz
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	$\propto \nu^{+1}$	$\mathbf{10/1 \quad (10/81)}$
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	$\propto \boldsymbol{\nu^{+1/4-\alpha}}$	$\mathbf{3/4\ 3^{-\alpha}}$

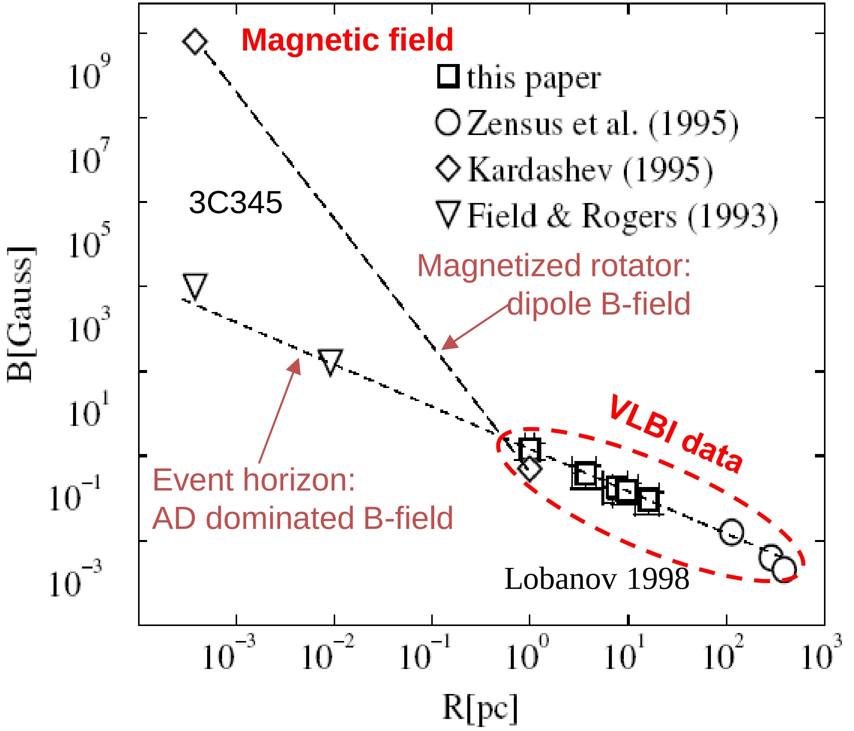
Science Examples: Black Holes

- Imaging of the event horizon: the factor of ~50 improvement of dynamic range expected from FPT at 230 GHz is essential for distinguishing between black holes and their „mimickers“.

- Core shift measurements at 43+ GHz offer the best probe of magnetic field near the event horizon scale: potentially most effective way to rule out the black hole „mimickers“.



Mizuno+ 2018

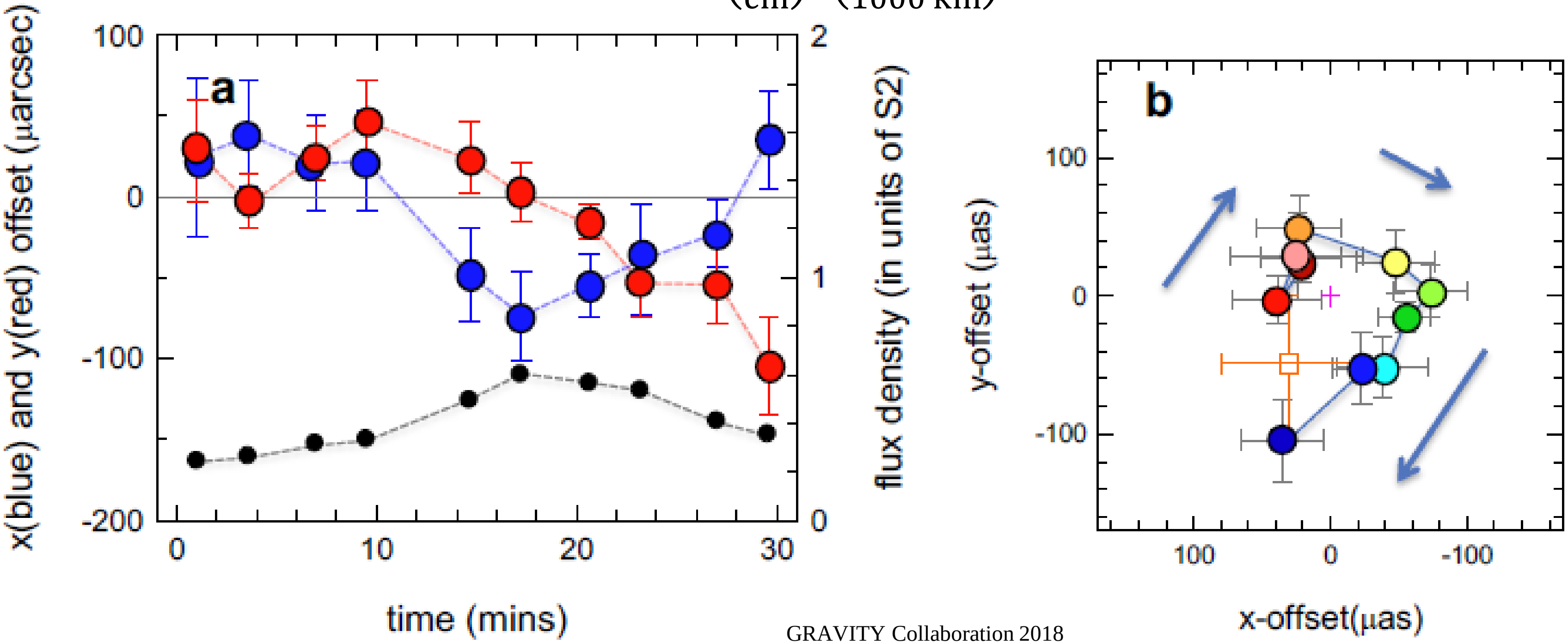


Science Examples: Sgr A* Hotspot

- Kinematic monitoring of a hotspot orbiting Sgr A*.

- To detect the hotspot motion at an N_σ accuracy, while beating the scattering, need

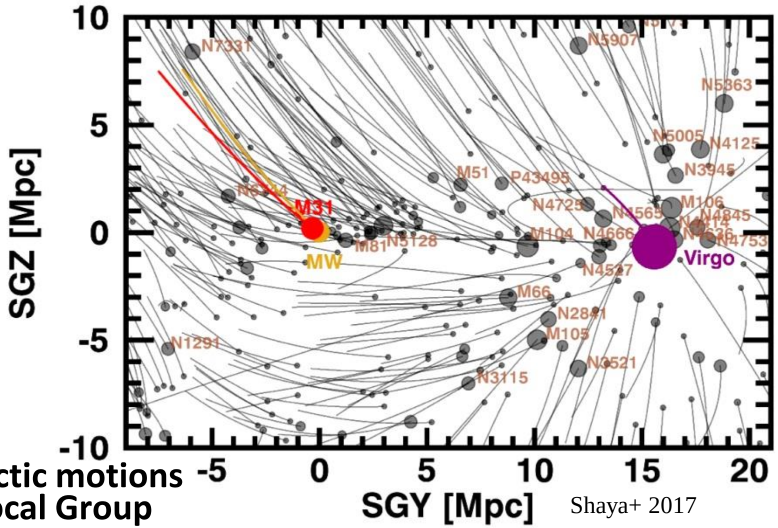
$$SNR \approx 40\ N_\sigma \left(\frac{\lambda}{\text{cm}}\right) \left(\frac{B_{\max}}{1000\ \text{km}}\right)^{-1}$$



GRAVITY Collaboration 2018

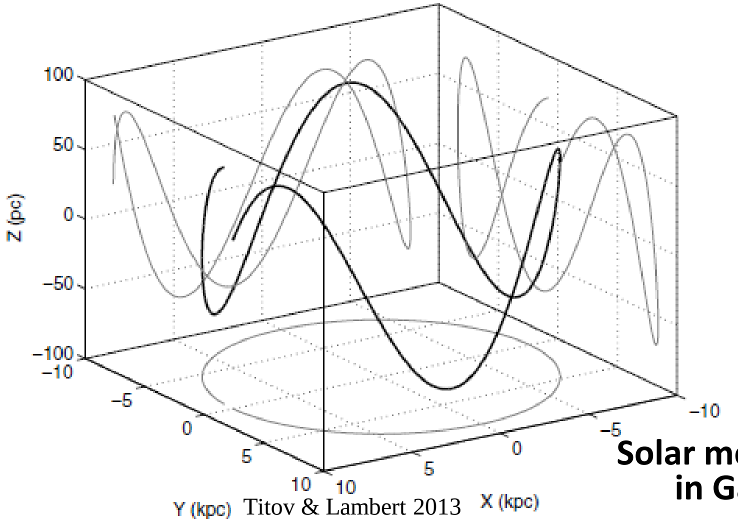
Science Examples: AGN Astrometry

- Yearly parallaxes up to distances of $\approx 100\ \mathrm{kpc}\,\sqrt{N_{\mathrm{obs}}/6}$.
- Proper motions up to distances of $\approx 20\ \mathrm{kpc}\,\left(\frac{v}{\mathrm{km/s}}\right)\left(\frac{\Delta t}{\mathrm{yr}}\right)\sqrt{N_{\mathrm{obs}}/6}$.
- „CMB parallaxes“ up to distances of $\approx 78\ \mathrm{Mpc}\,\left(\frac{\Delta t}{\mathrm{yr}}\right)\sqrt{N_{\mathrm{obs}}/6}$.
- Accurate Hubble constant measurements from yearly and CMB parallaxes
- Most accurate determination of Solar motion in MW and wrt. CMB reference frame.



galactic motions in Local Group

Shaya+ 2017



Titov & Lambert 2013

Solar motion in Galaxy

Potential Developments

- **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 efficient 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.*

Antennas on sites in Northern Caucasus and Central Asia would strongly improve imaging quality of FPT KVN+, GMVA, and EHT observations .

- **Testing the FPT technique at 230 GHz** (tests with 3-4 antennas): if proven to work, it would provide arguably the strongest boost to the dynamic range and fidelity of EHT imaging.