Title: Event-horizon-scale structure of M87 in the middle of the VHE enhancement in 2012

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Abstract: The radio galaxy M87 is an excellent laboratory for investigating the formation process of the relativistic jet and the production mechanism of high energy particles and photons in the vicinity of super-massive black holes. VLBI observations at 1.3 mm can address at least two issues concerning the fundamental nature of M87. The first is the event-horizon-scale structure of the jet launching region, and another one is the production mechanism of very high energy (VHE; > 100 GeV) photons at there. In this talk, I report on new 1.3 mm VLBI observations of M87 with the EHT during the VHE enhancement in 2012. These observations provide the first measurements of closure phase, imposing new constraints on accretion-disk/jet models for M87, and also the first constraints on the innermost structure of the relativistic jet on scales of a few Rs during VHE variability. I discuss results and their implications for jet/disk models and also VHE models for M87, as well as future prospects of EHT observations of M87.

Event-horizon-scale structure of M87 in the middle of the VHE enhancement in 2012

Kazunori Akiyama
(U. Tokyo / NAOJ / JSPS Research Fellow)

Collaborators

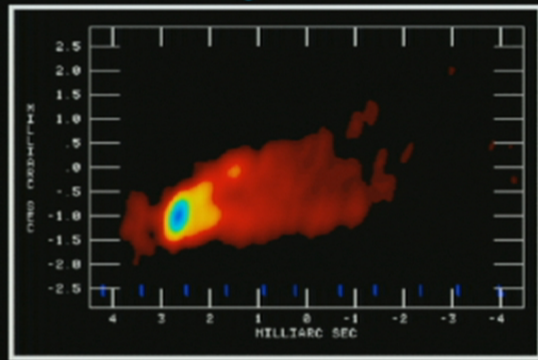
EHT works: R.-S. Lu (MPIfR), V.L Fish, S.S. Doeleman (MIT Haystack)
A.E. Broderick (Perimeter Institute), J. Dexter (MPE),
Event Horizon Telescope Collaboration

EHT Japan: K. Hada (NAOJ), M. Kino (KASI), A. Doi (ISAS/JAXA),
H. Nagai, F. Tazaki, M. Honma (NAOJ) et al.

SCHOOL OF SCIENCE THE UNIVERSITY OF TOKYO

NAOJ National Astronomical Observatory of Japan

M87: the nearest AGN jet / the first discovered AGN jet

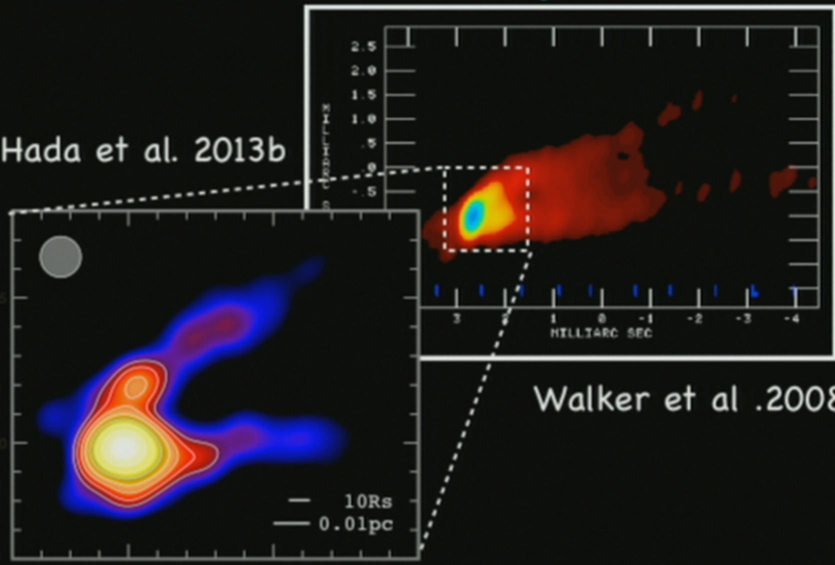


Walker et al .2008

- Secondary largest angular size of the SMBH
  1 mas = 0.08 pc = 140 R_{sch}
  (10 uas = 1.4 R_{sch})

M87: the nearest AGN jet / the first discovered AGN jet

Hada et al. 2013b



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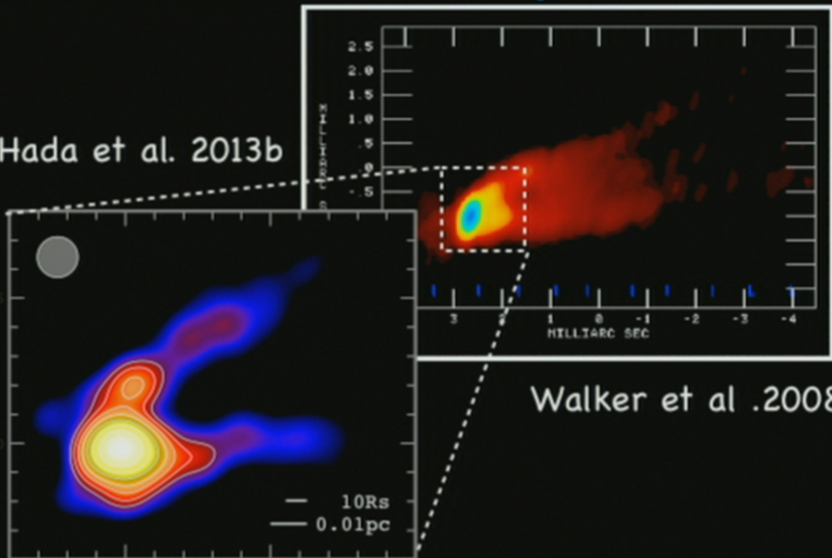
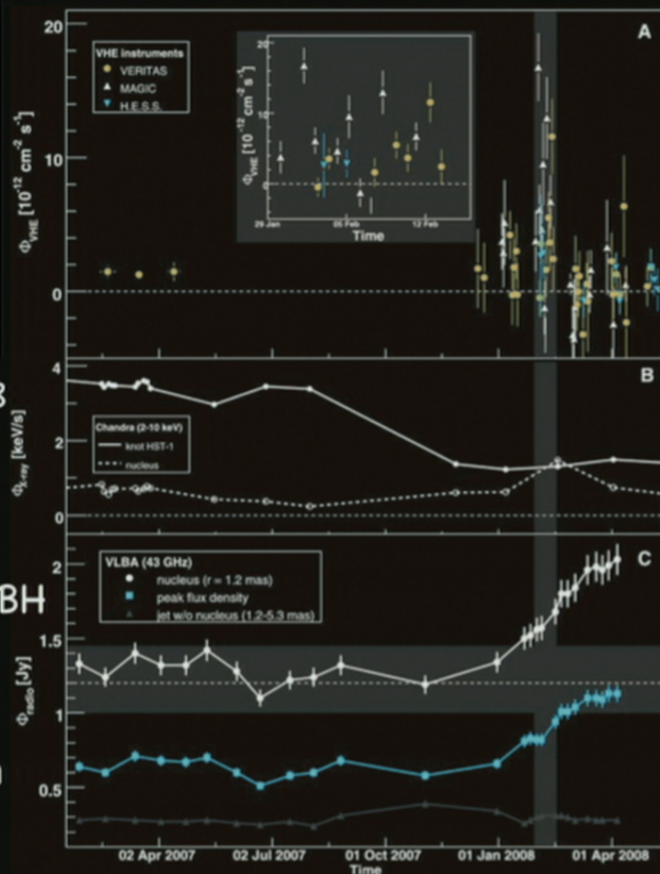


Walker et al .2008



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- VHE - X-ray - Radio Connection

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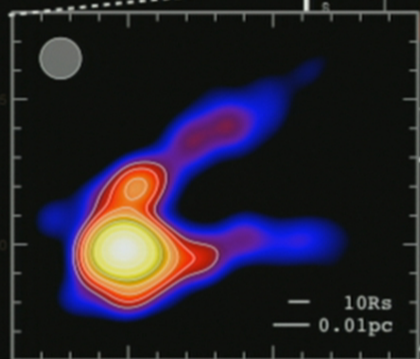
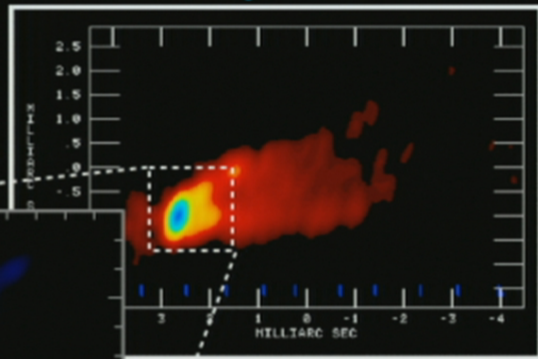
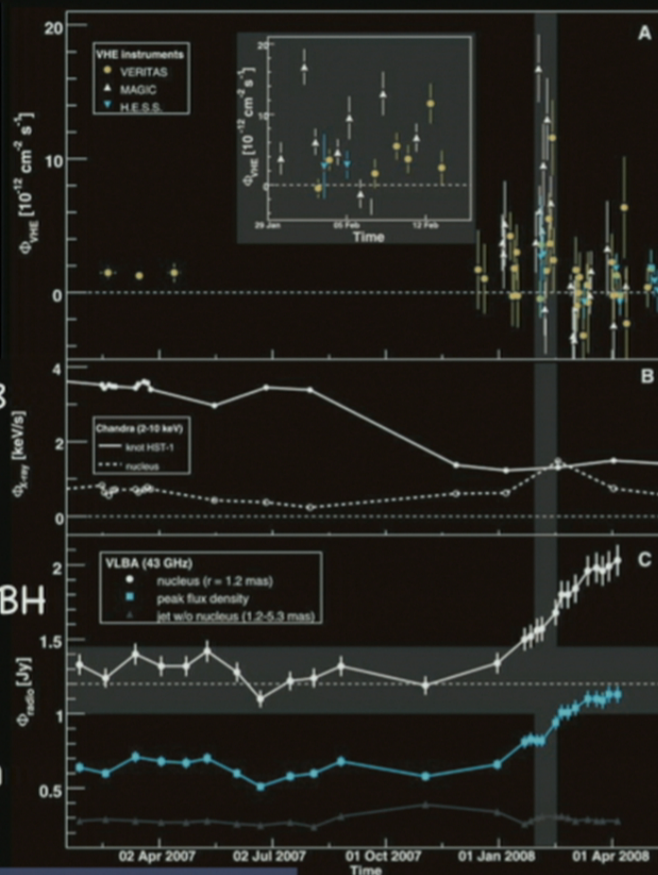




Walker et al .2008



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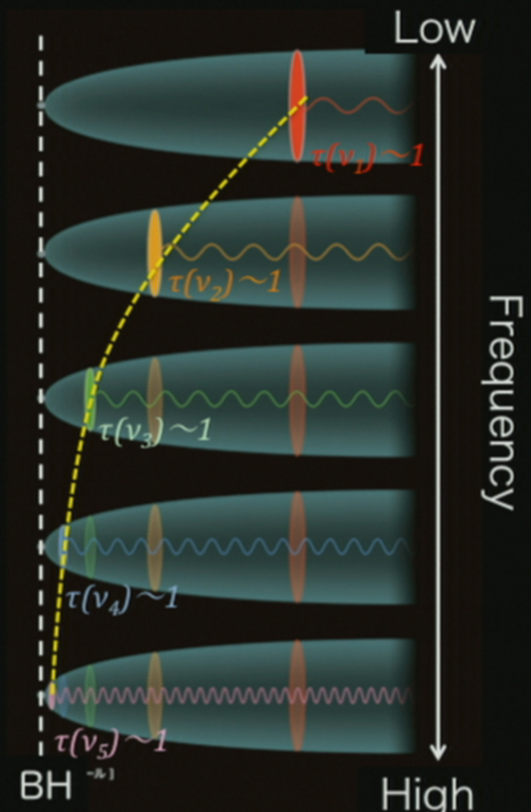
The best laboratory to study formation processes of the relativistic jet / high energy particles

The black hole location of M87 ~ 1.3 mm (230 GHz) core



$r_{core} \propto \nu^{-A}$ (Blandford & Konigl 1979)

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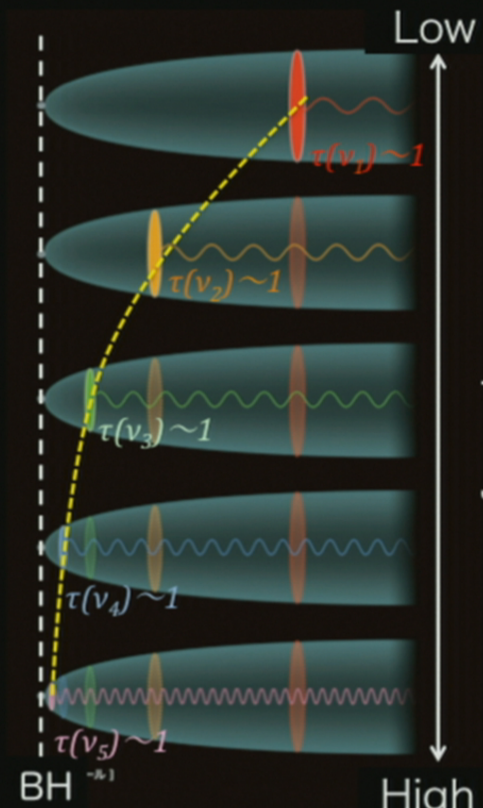

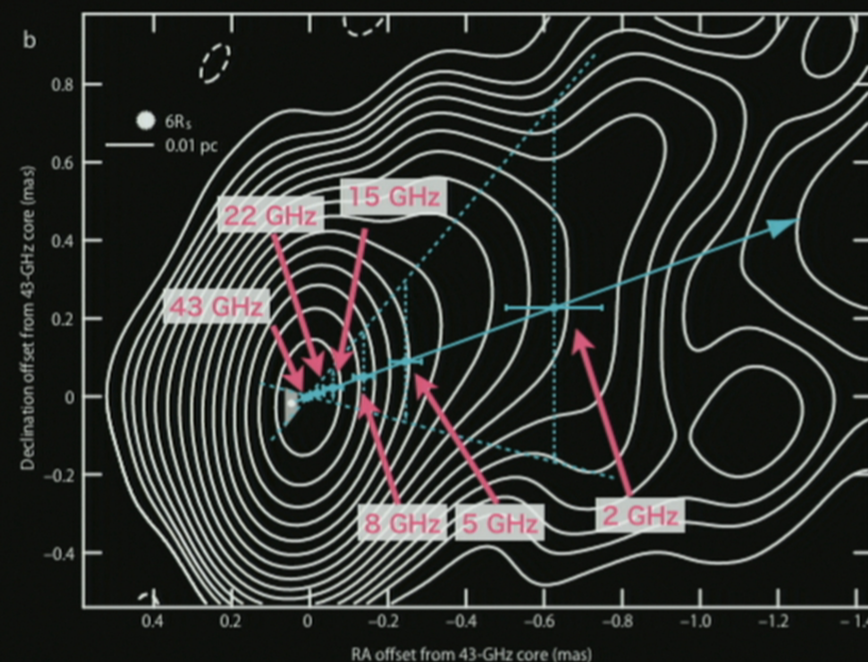

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Hada et al .2011, Nature

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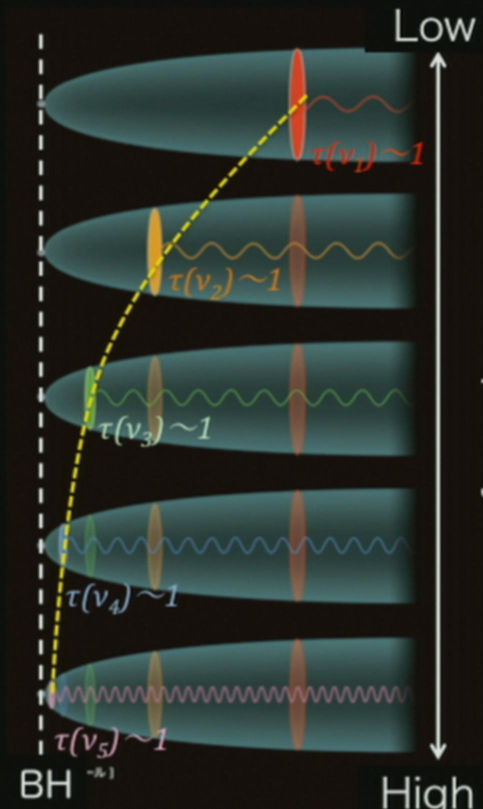

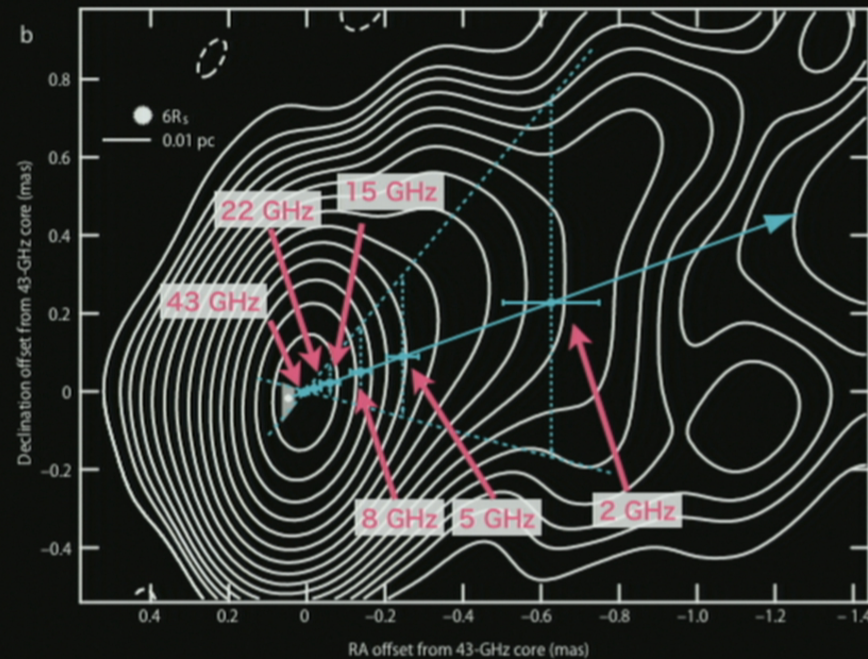

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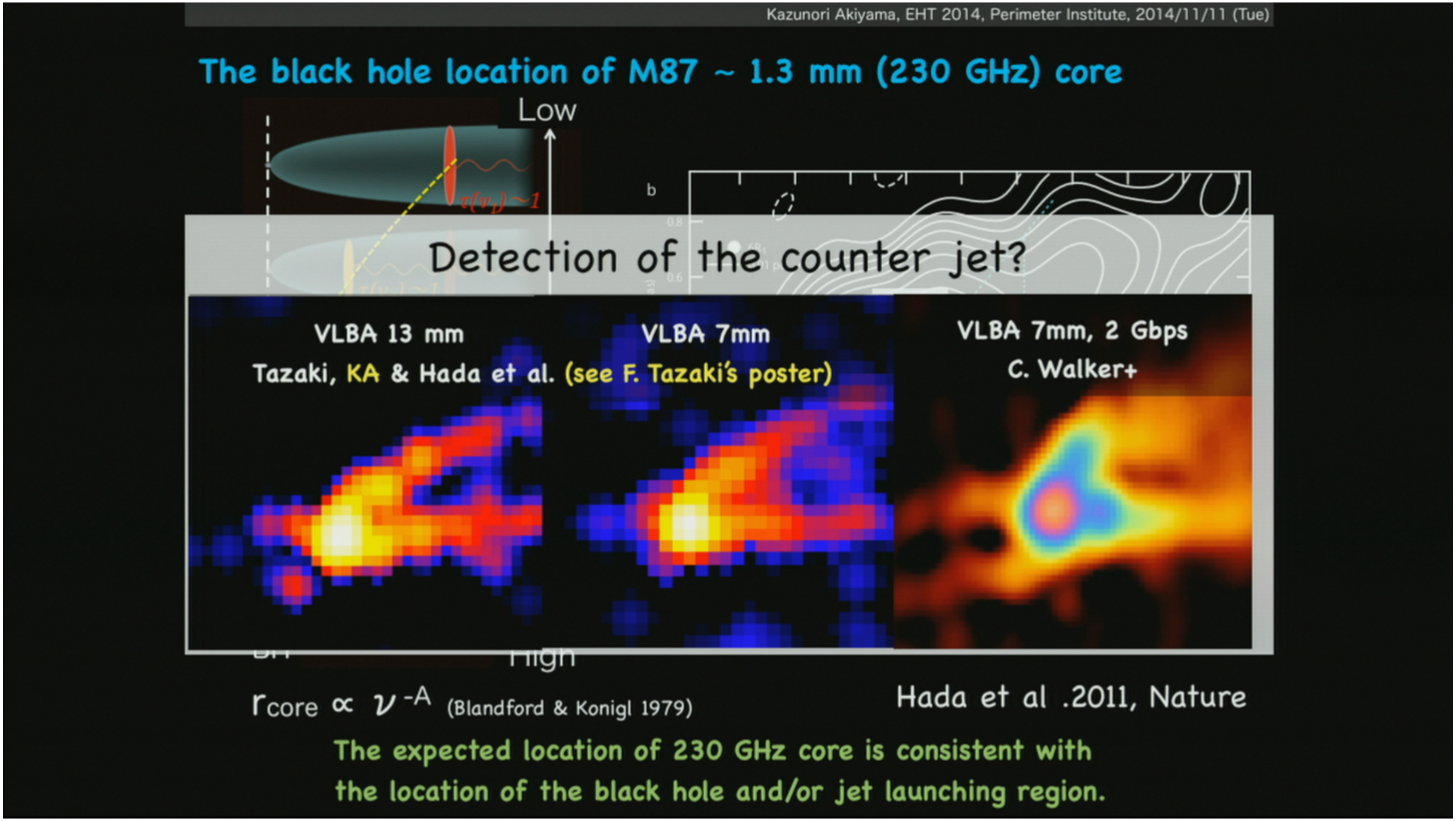
The expected location of 230 GHz core is consistent with the location of the black hole and/or jet launching region.


Kazunori Akiyama, EHT 2014, Perimeter Institute, 2014/11/11 (Tue)
The black hole location of M87 ~ 1.3 mm (230 GHz) core
Low
b
Detection of the counter jet?
VLBA 13 mm
VLBA 7mm
Tazaki, KA & Hada et al. (see F. Tazaki's poster)
VLBA 7mm, 2 Gbps
C. Walker+
High
$r_{core} \propto \nu^{-A}$ (Blandford & Konigl 1979)
Hada et al .2011, Nature
The expected location of 230 GHz core is consistent with
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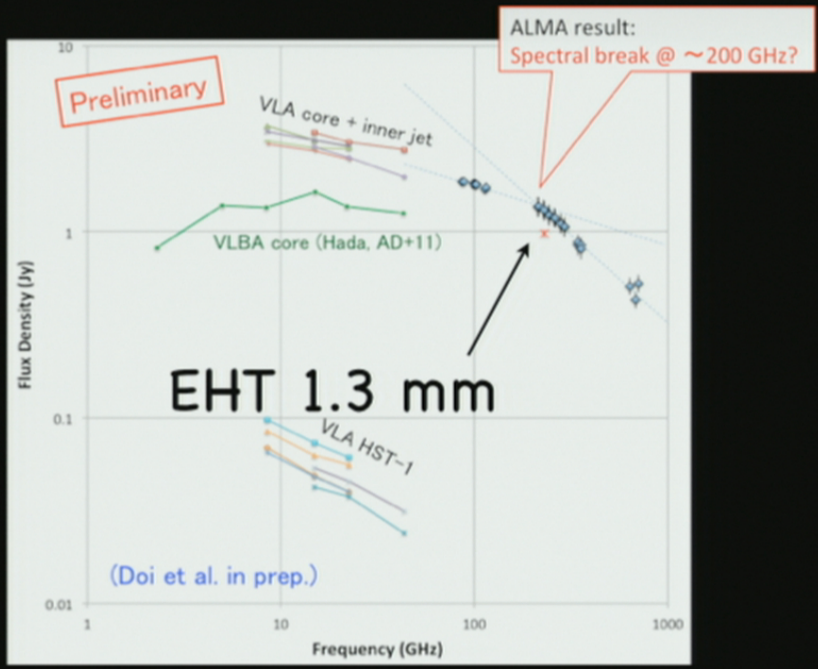
The black hole location of M87 ~ 1.3 mm (230 GHz) core

ALMA Cycle-0 observations of M87



Doi, Hada, ..., **KA+** in progress.

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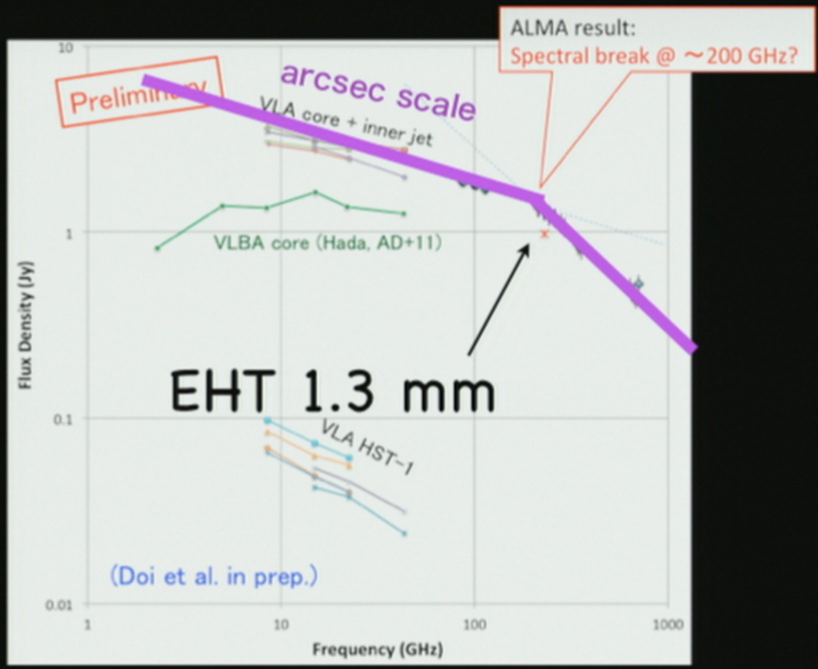

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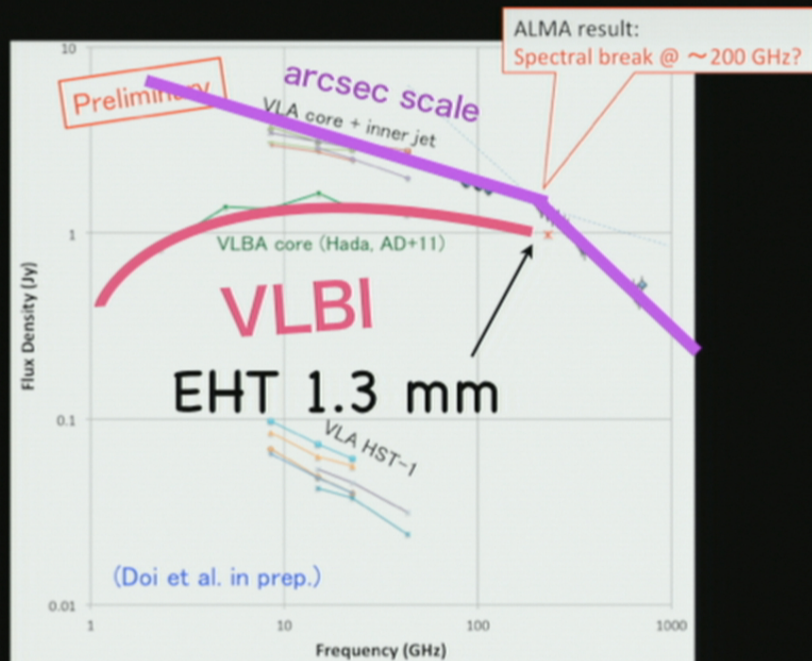

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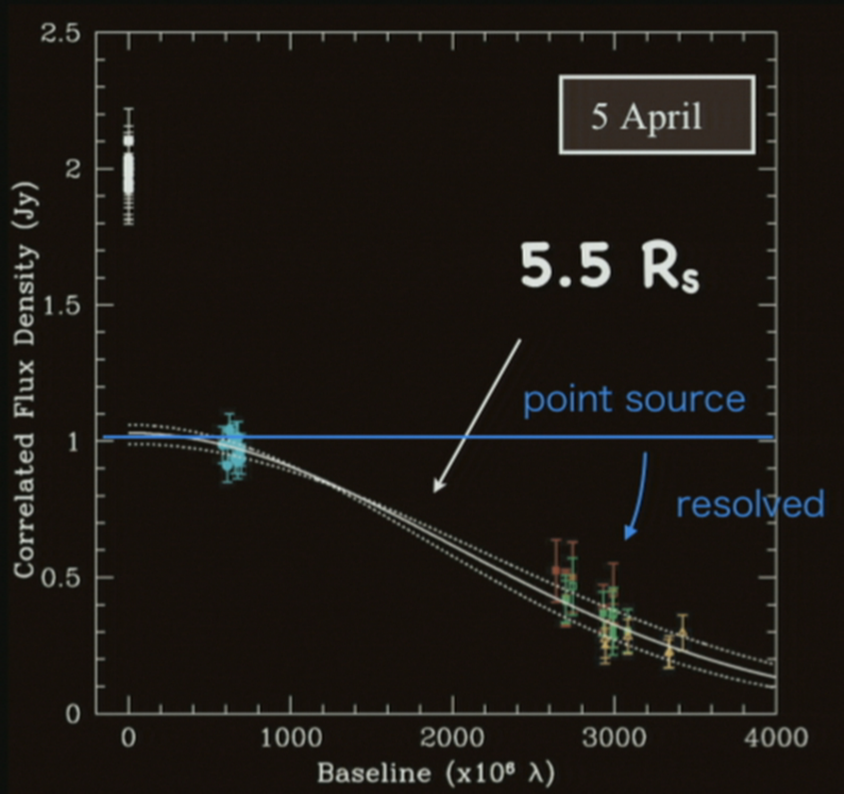
EHT observations in 2009: Evidence of ISCO-scale structure



Doeleman et al. 2012, Science

1.3 mm emission is very compact (~5.5 R_s)

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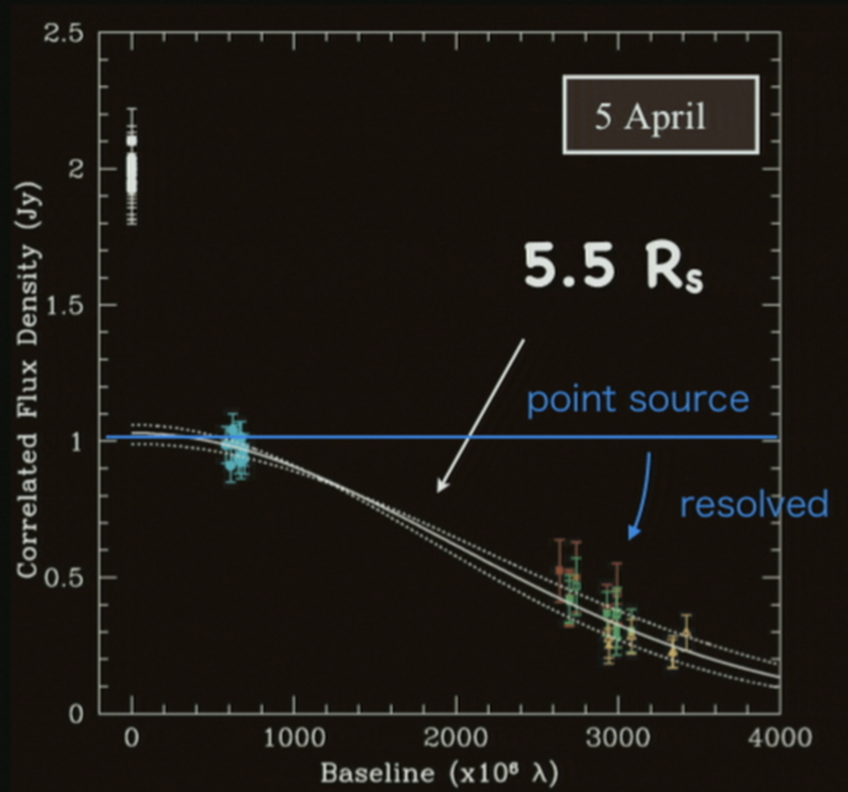

Doeleman et al. 2012, Science

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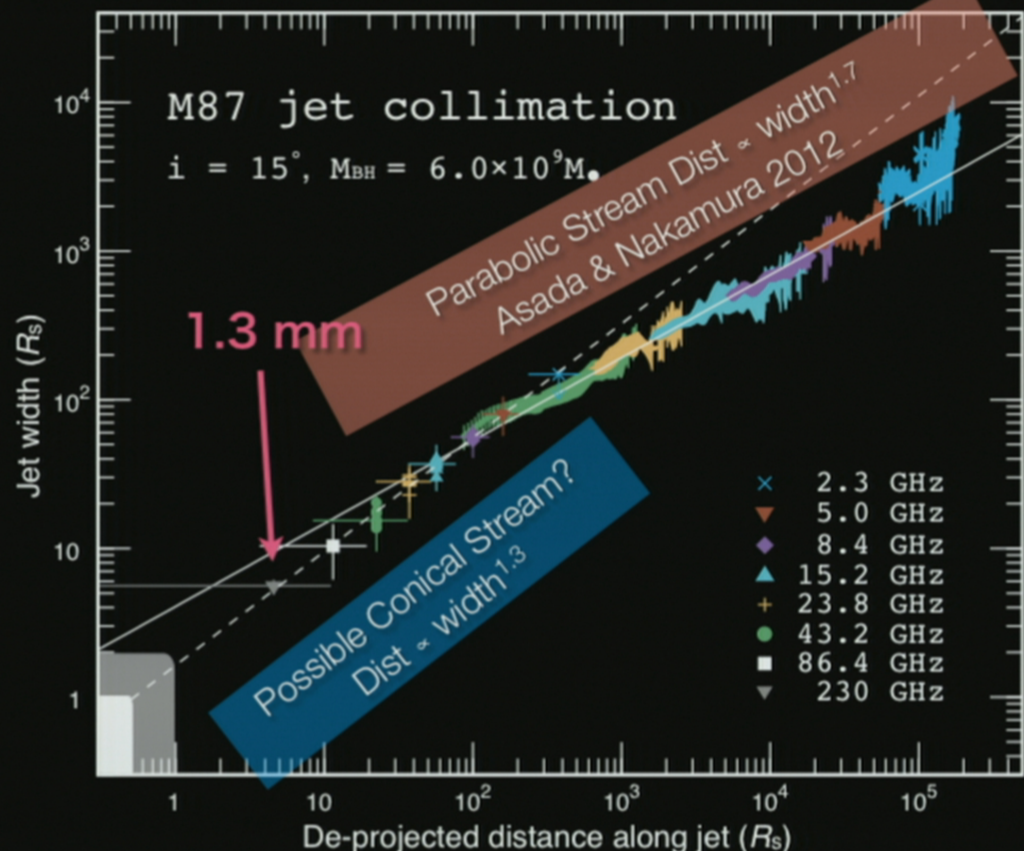
EHT observations in 2009: Consistency with the stream line of jet



Hada et al. 2013b

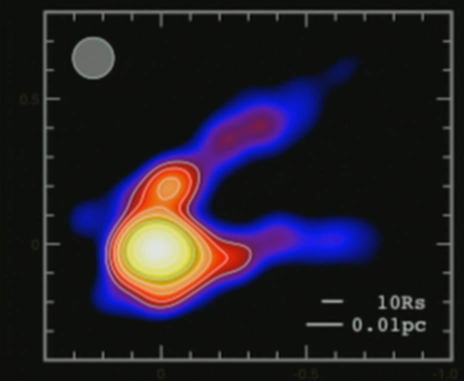
Stream line of the jet (M. Nakamura's talk)

Asada & Nakamura 2012

Doeleman et al. 2012

Nakamura & Asada 2013

Hada et al. 2013b



EHT observations in 2009: estimation of B_{tot}, U_B/U_e ....

Poynting Power Crisis ?

Magnetic field of SSA-thick radio core
(e.g. Marscher 1983)

$$B = 340\,\mathrm{G} \times \left(\frac{\nu}{230\,\mathrm{GHz}}\right)^5 \left(\frac{\theta_{\mathrm{FWHM}}}{40\,\mu\mathrm{as}}\right)^4 \times \left(\frac{S_\nu}{1\,\mathrm{Jy}}\right)^{-2} \frac{\delta}{1+z}$$

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- Poynting Power at 1.3 mm: 10^{47} erg/s
  >> Total Jet Power: 10^{44} erg/s

  (Bicknell & Begelman 1996; Owen et al. 2000; Stawarz et al. 2006)

- Fast cooling of electrons ~ 14 min.

→ 1.3 mm emission is only partially SSA-thick?

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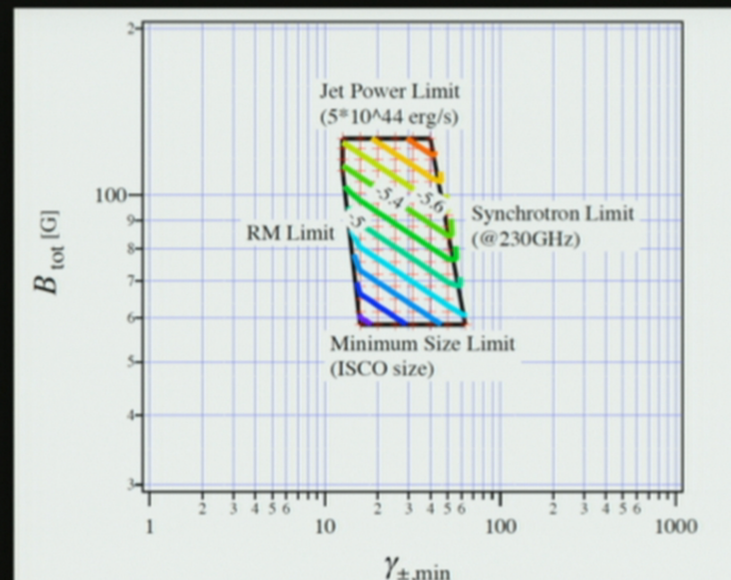
Constraints on B-field strength of SSA-thick region at 1.3 mm

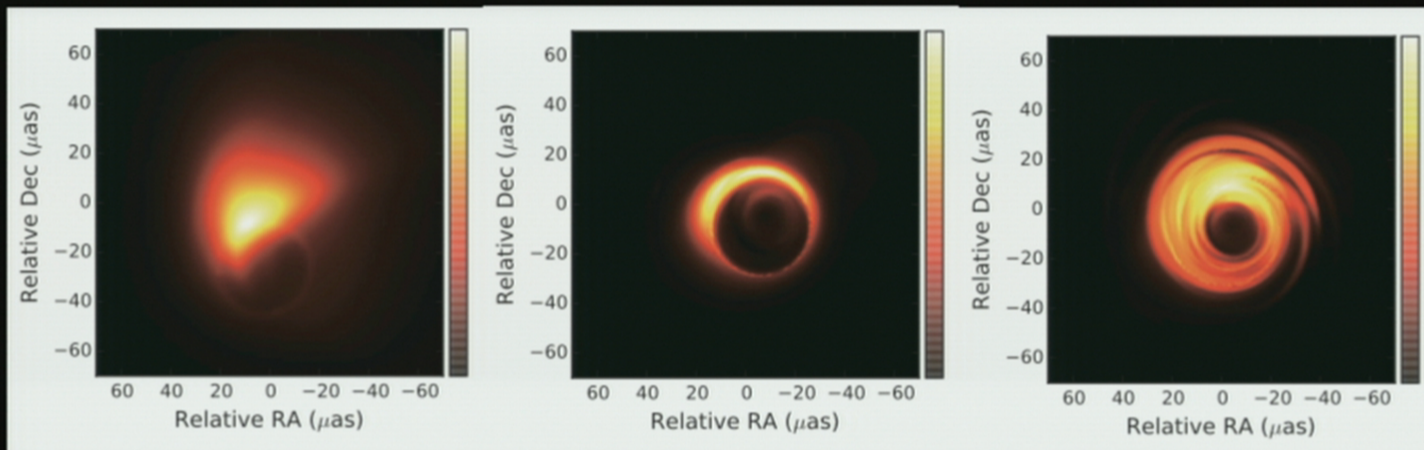


Kino, Takahara, Hada & KA+ to be submitted

see M. Kino's Poster

EHT observations in 2009: Consistency with physical models

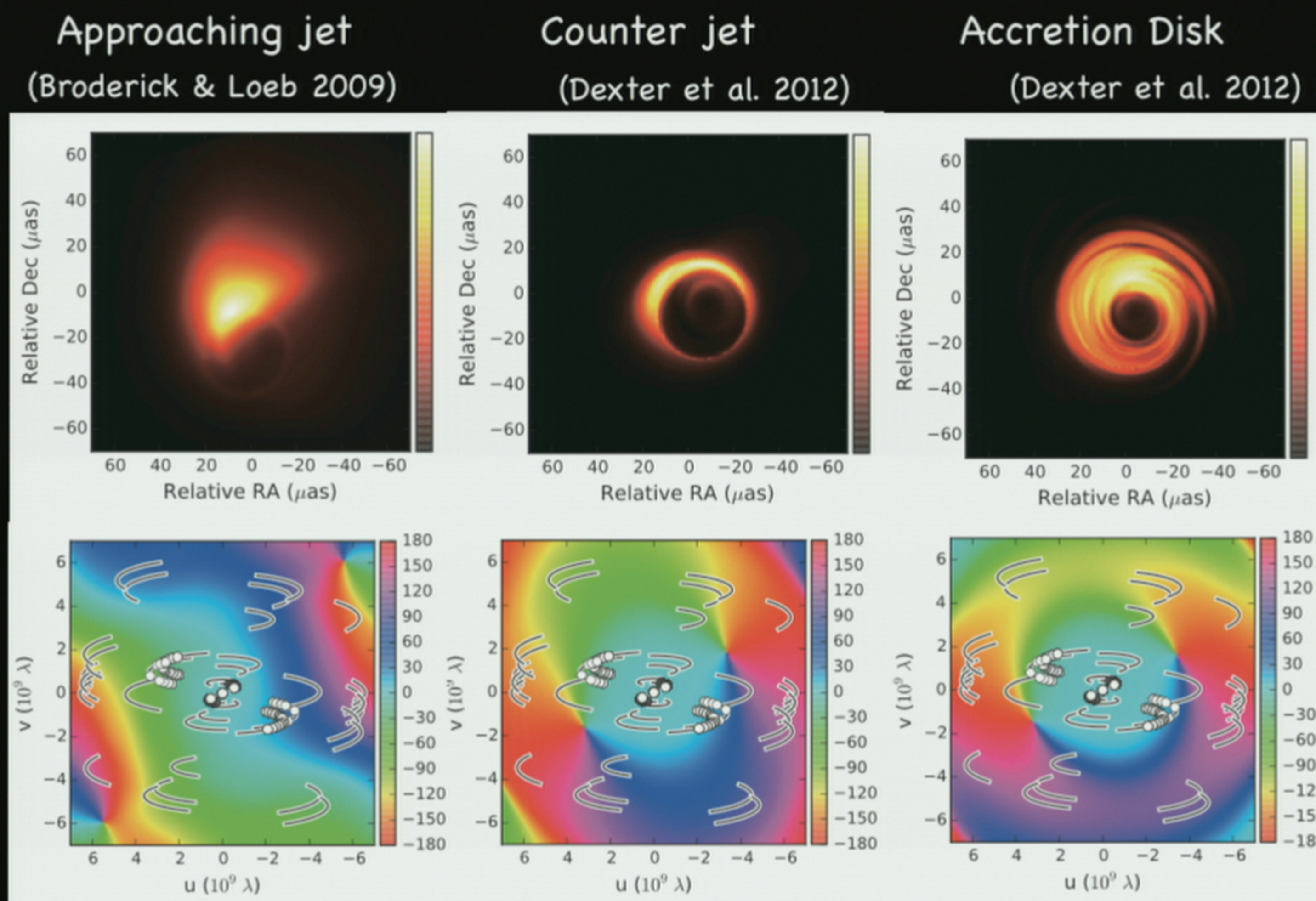
Approaching jet (Broderick & Loeb 2009) | Counter jet (Dexter et al. 2012) | Accretion Disk (Dexter et al. 2012)



All models are broadly consistent with 2009 data.

(A. Broderick's talk, J. Dexter's talk)

Next Question: How is the closure phase?



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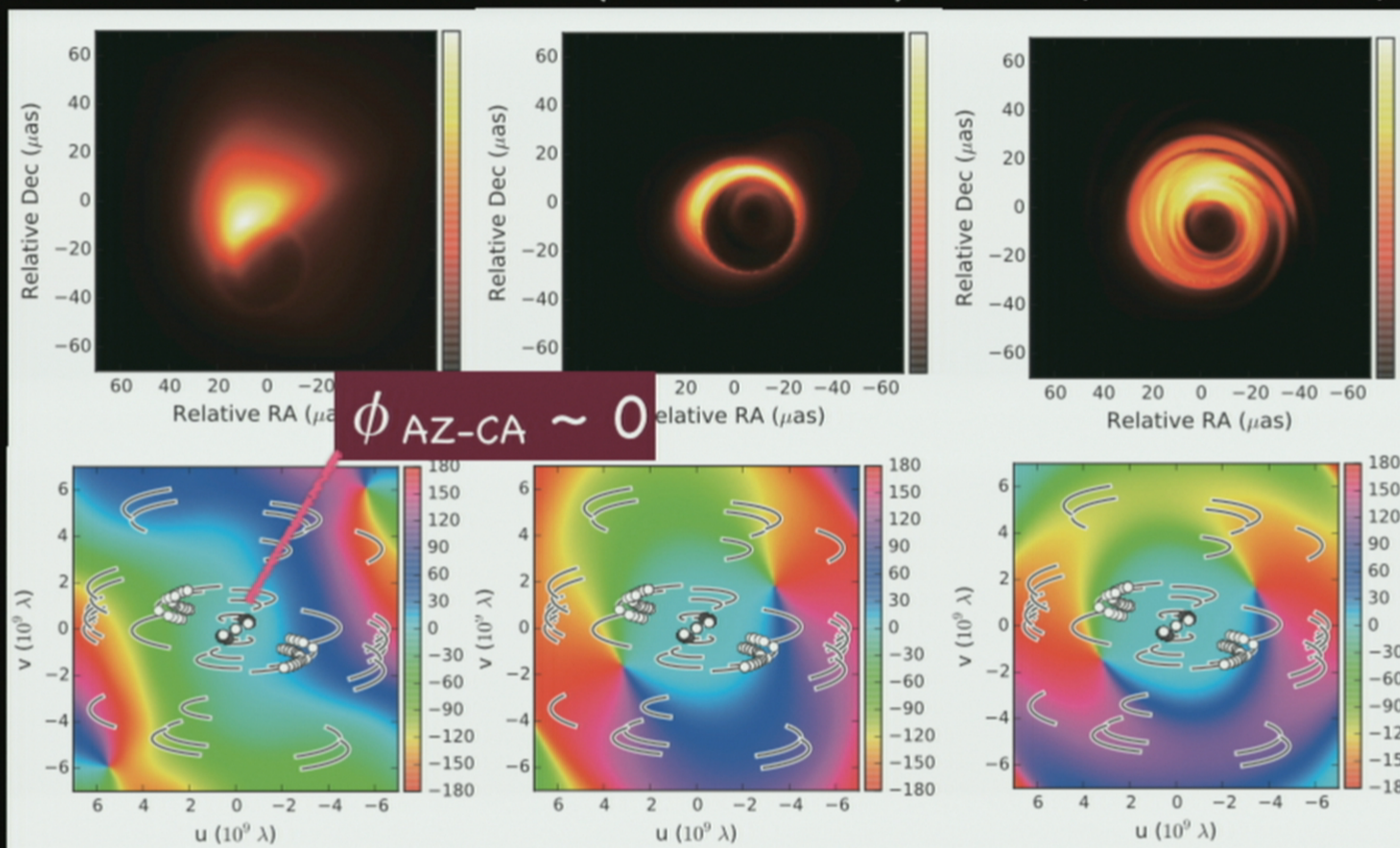

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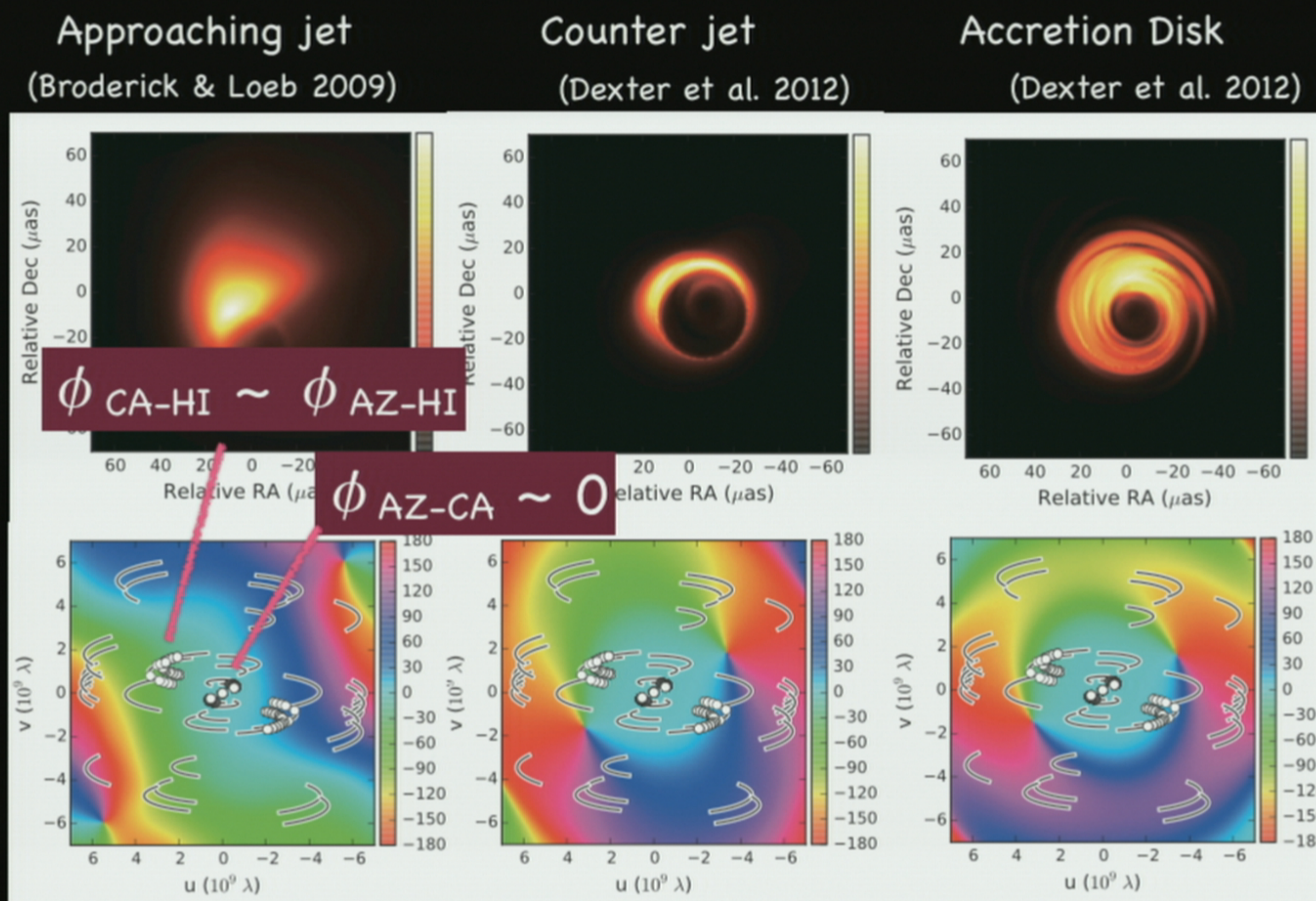

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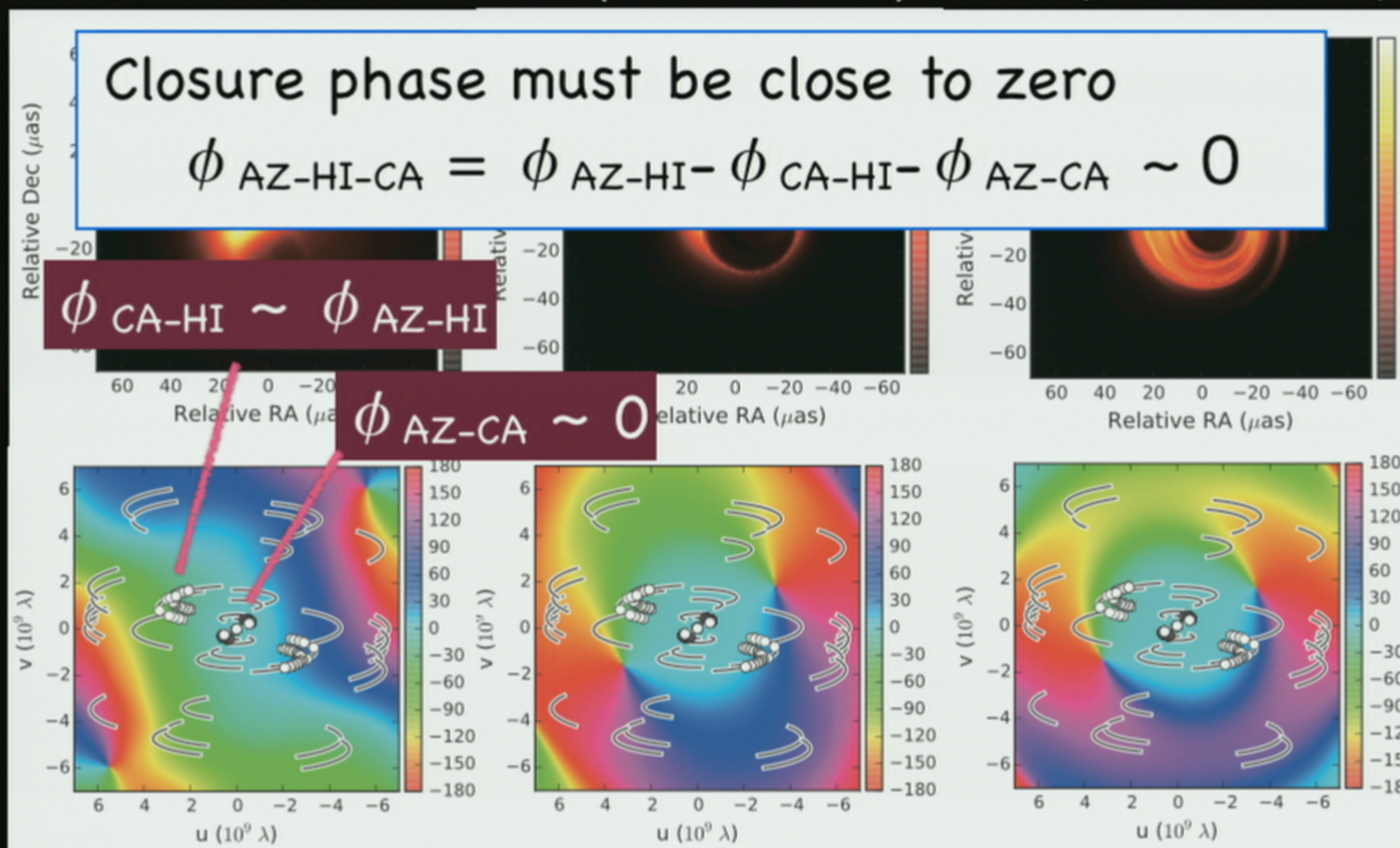
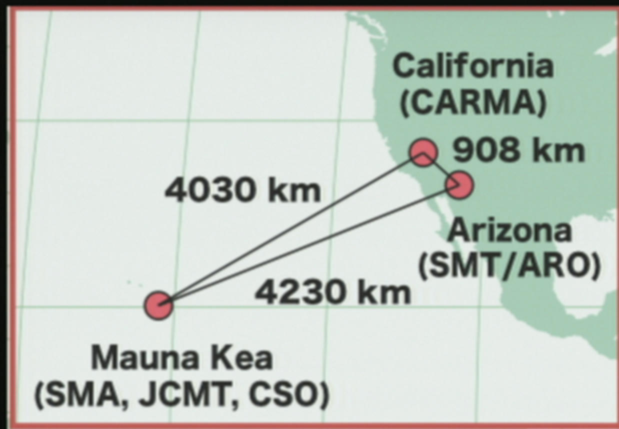
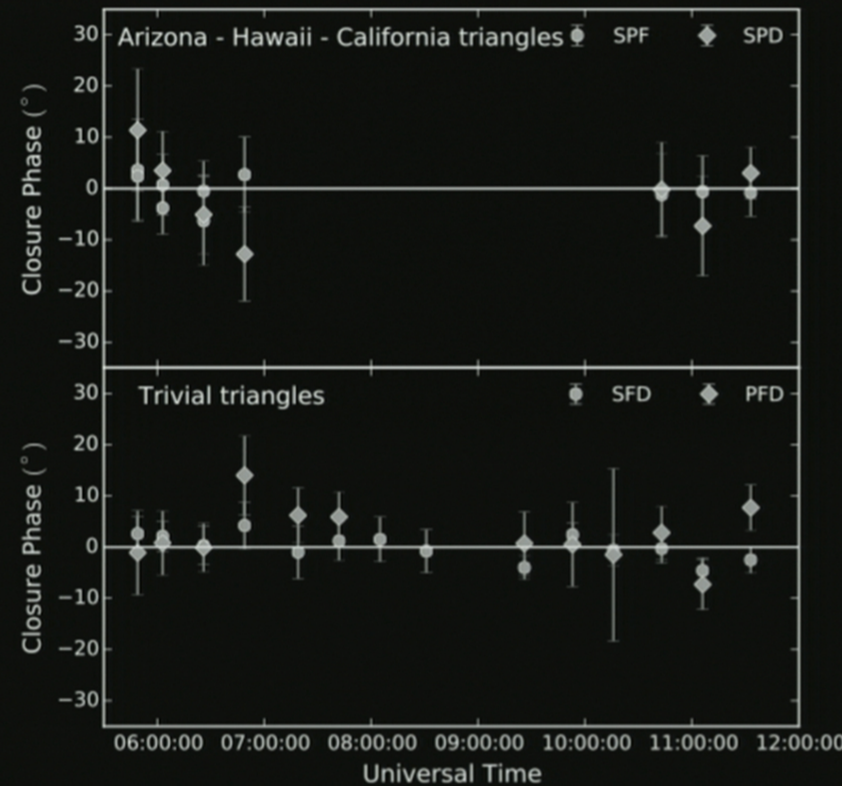


2012 EHT observations: (1) the first closure phase measurements





KA, Lu & Fish et al., submitted

Closure phases are actually close to zero.

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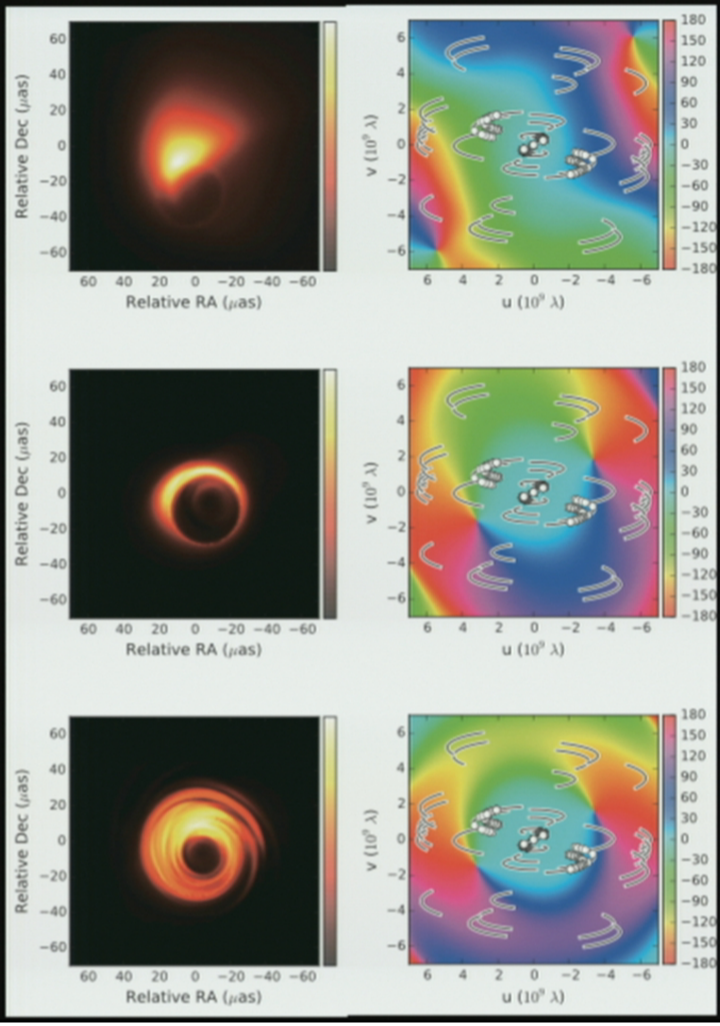

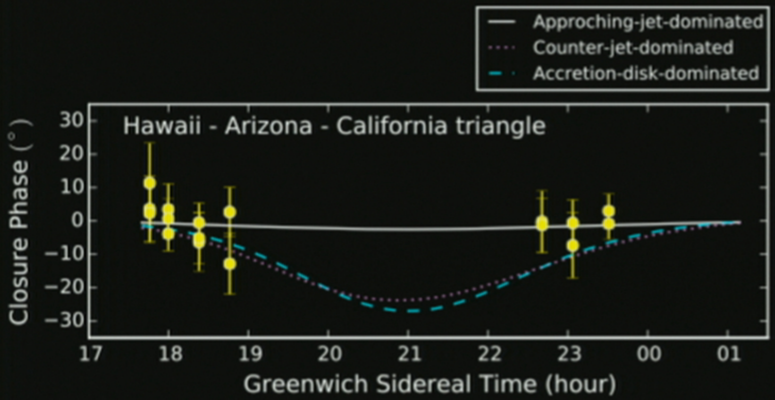

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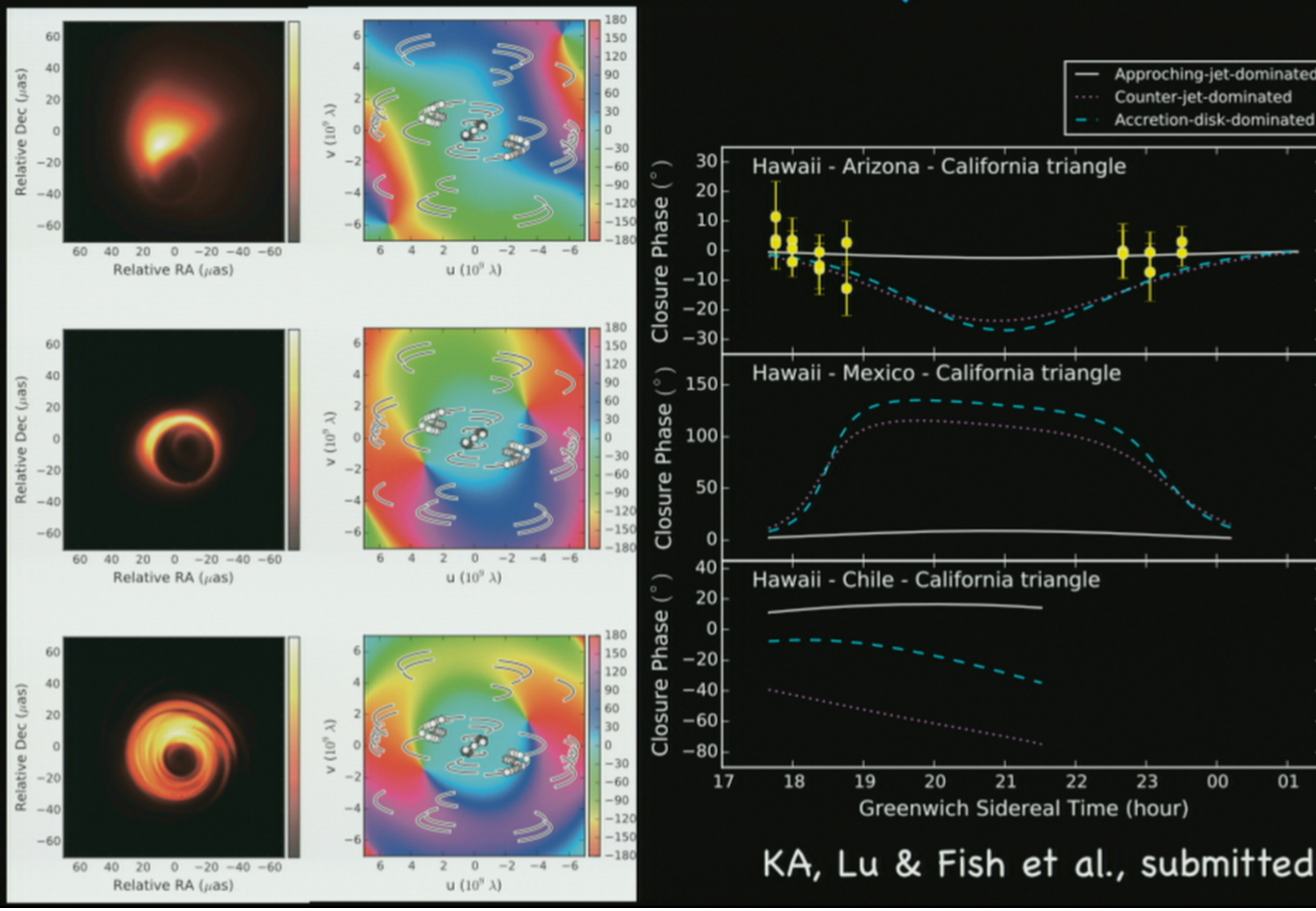

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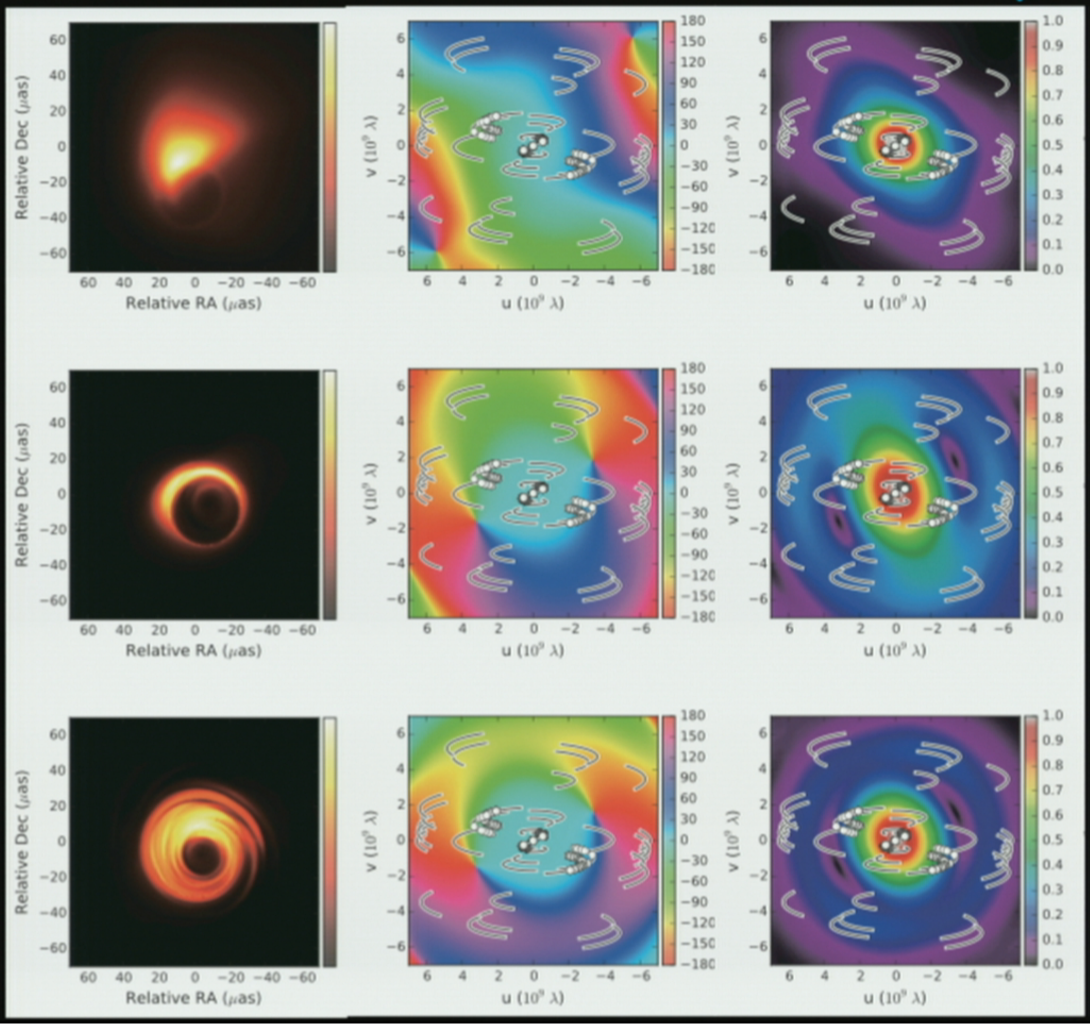

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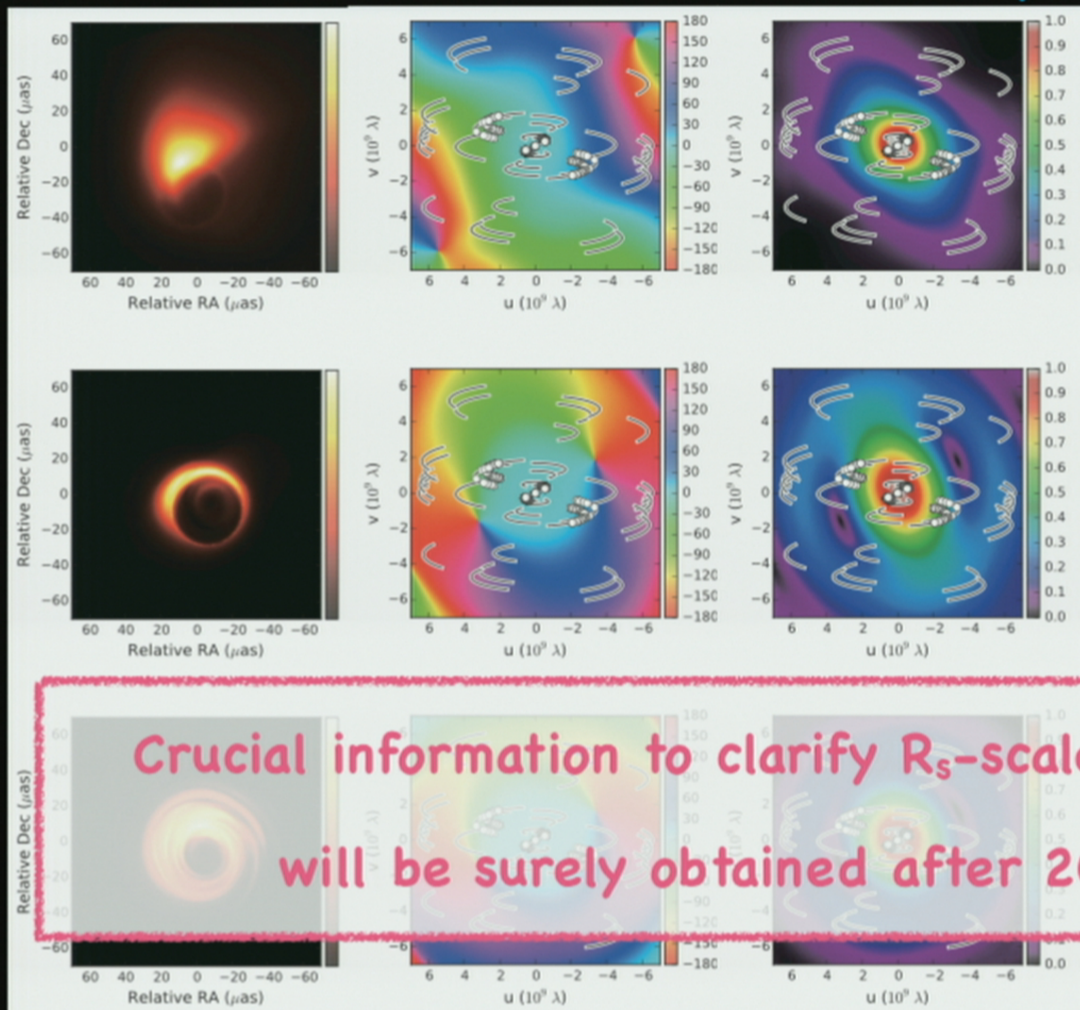
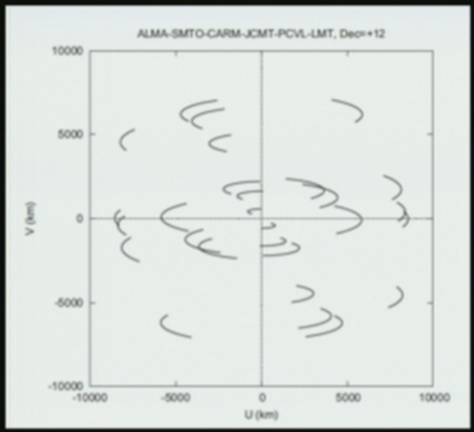


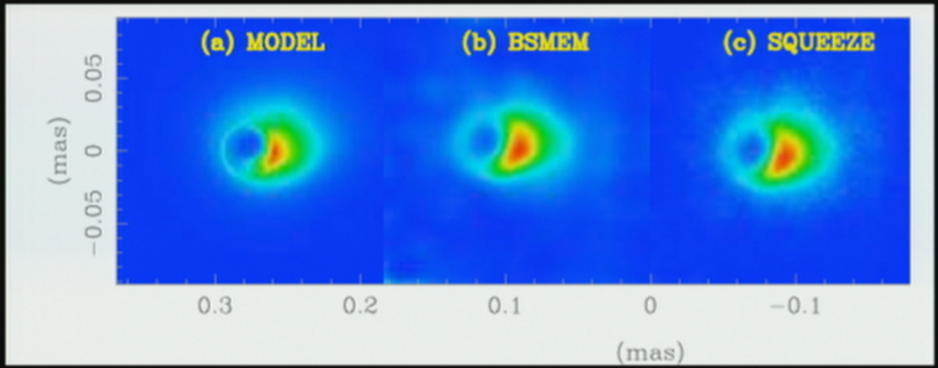
Crucial information to clarify R_s-scale structure will be surely obtained after 2015 !!

Imaging capability of EHT after 2015

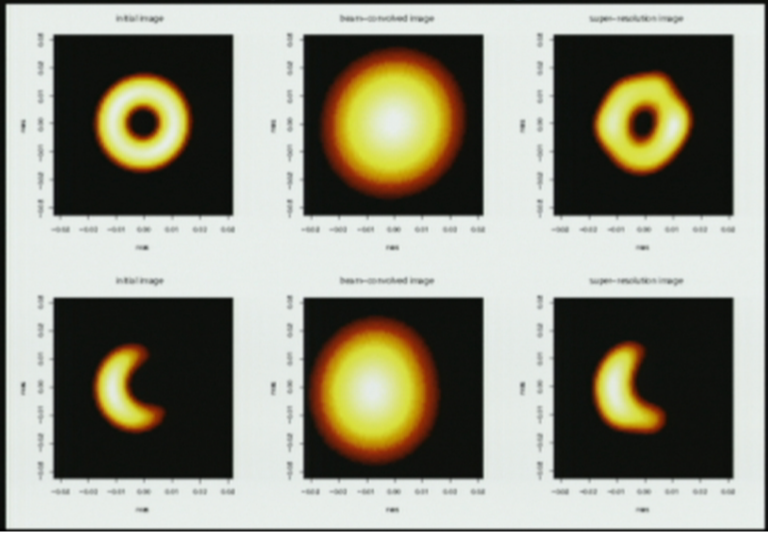
EHT (2015)



High Mass case + BSMEM / SQUEEZE (Lu et al. 2014)

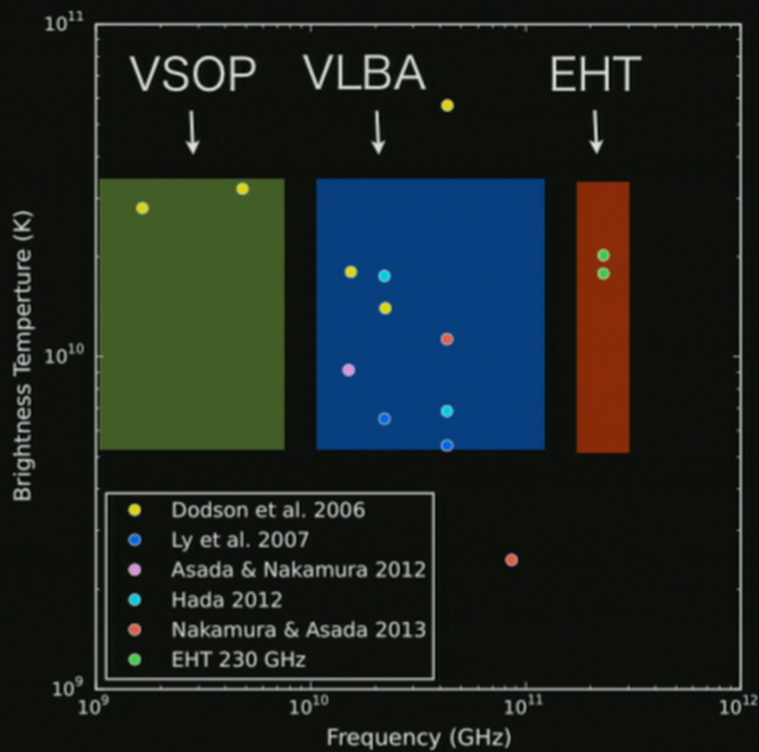


Low Mass case + Sparse Modeling (Honma & KA et al. 2014)



M. Honma's Talk (Friday)

2009 & 2012 EHT observations: the brightness temperature



several x 10^{9} K - few x 10^{10} K

SSA-thick radio core case
(e.g. Marscher 1983)

$$B_{tot} \propto \nu \, T_b^{-2}$$

core-shift relation
(Hada+2011)
$\nu \propto r^{-1}$

$$B_{tot} \propto r^{-1} \, T_b^{-2} \propto r^{-1}$$

Classical Conical Jet model

(e.g. Begelman 1984)

$$B_{\phi} \propto r^{-1}$$

Dominance of Toroidal / Poloidal B-field becomes a major concern of the jet formation in inner 10^2 R_s .

For understanding the magnetic field structure in inner 10^2 R_s

B_{total} : measurement of Tb (EHT, RadioAstron)

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B_ϕ : $R(z)v_z(z)B_\phi(z) = \text{Const.}$ $\longleftarrow$ Ideal MHD case (steady state) $\vec{\nabla} \times (\vec{v} \times \vec{B}) = 0$

$B_{||}$: $R(z)^2 B_{||} = \text{Const.}$

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$R(z)$: Stream Line + Core size

$v_z(z)$: Acceleration Profile

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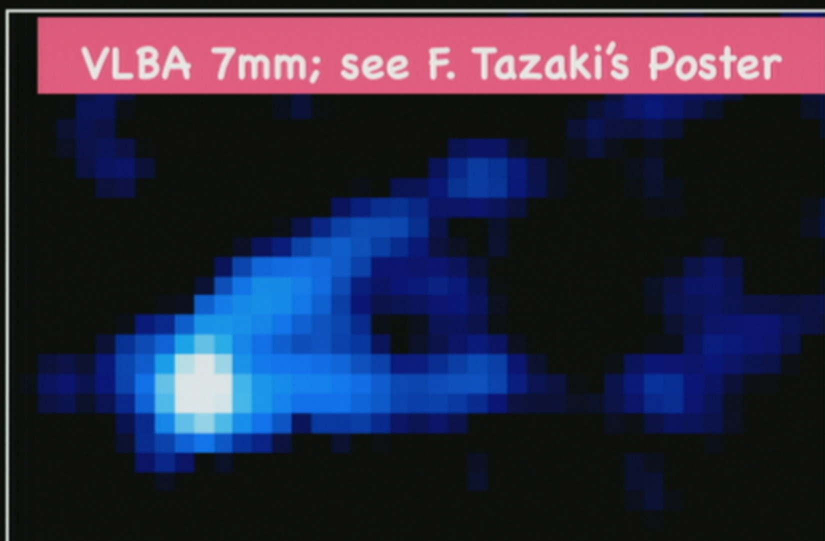
High Resolution imaging with Sparse Modeling



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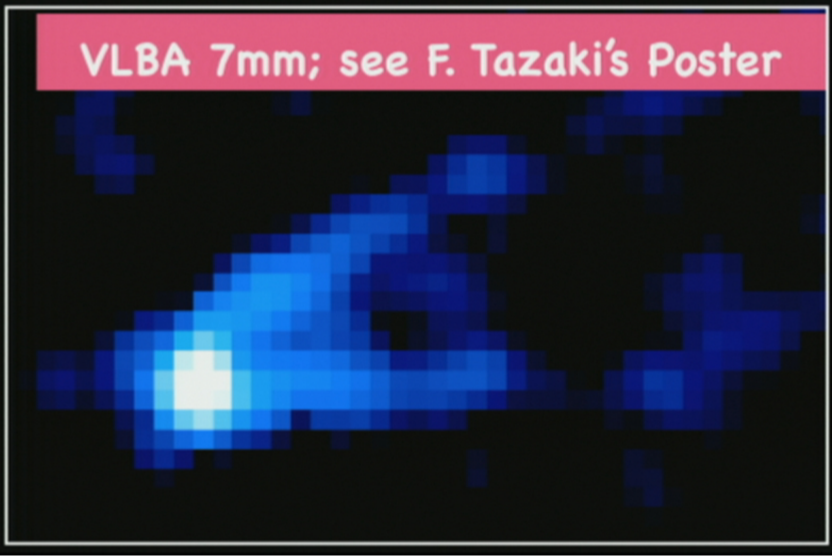
Stream Line + Core size (↑ $R(z)$)

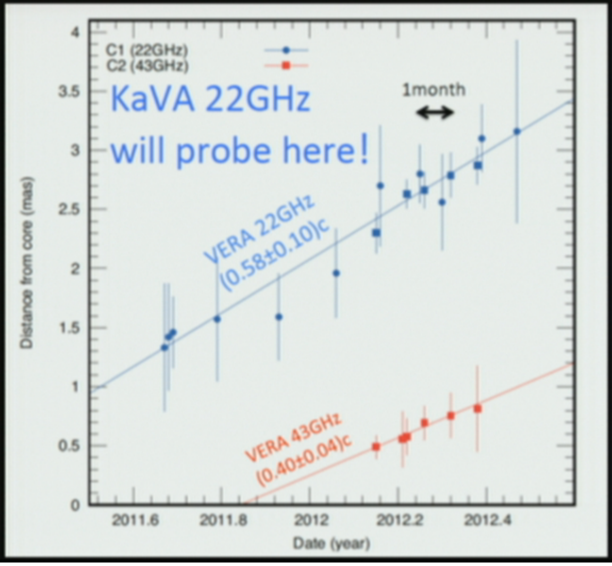
Acceleration Profile (↑ $v_z(z)$)

High Resolution imaging with Sparse Modeling

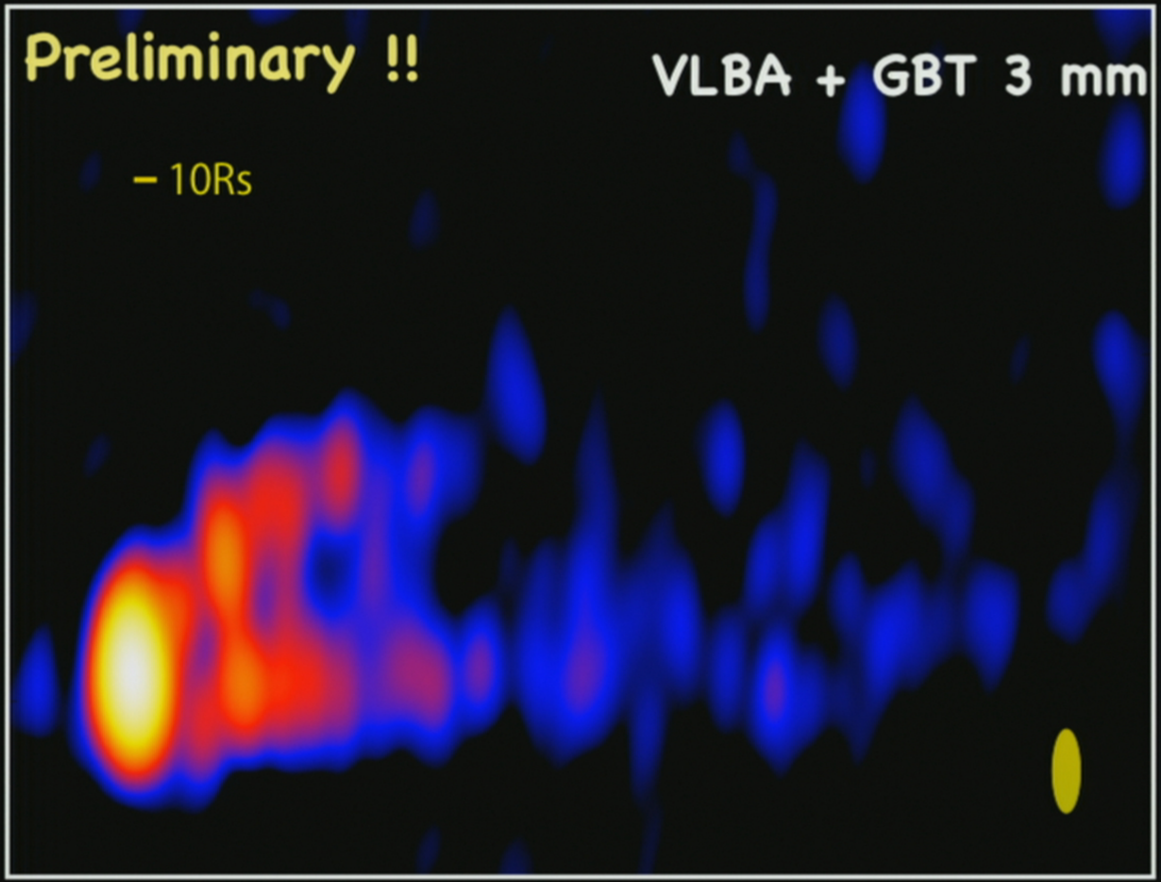
VLBA 7mm; see F. Tazaki's Poster



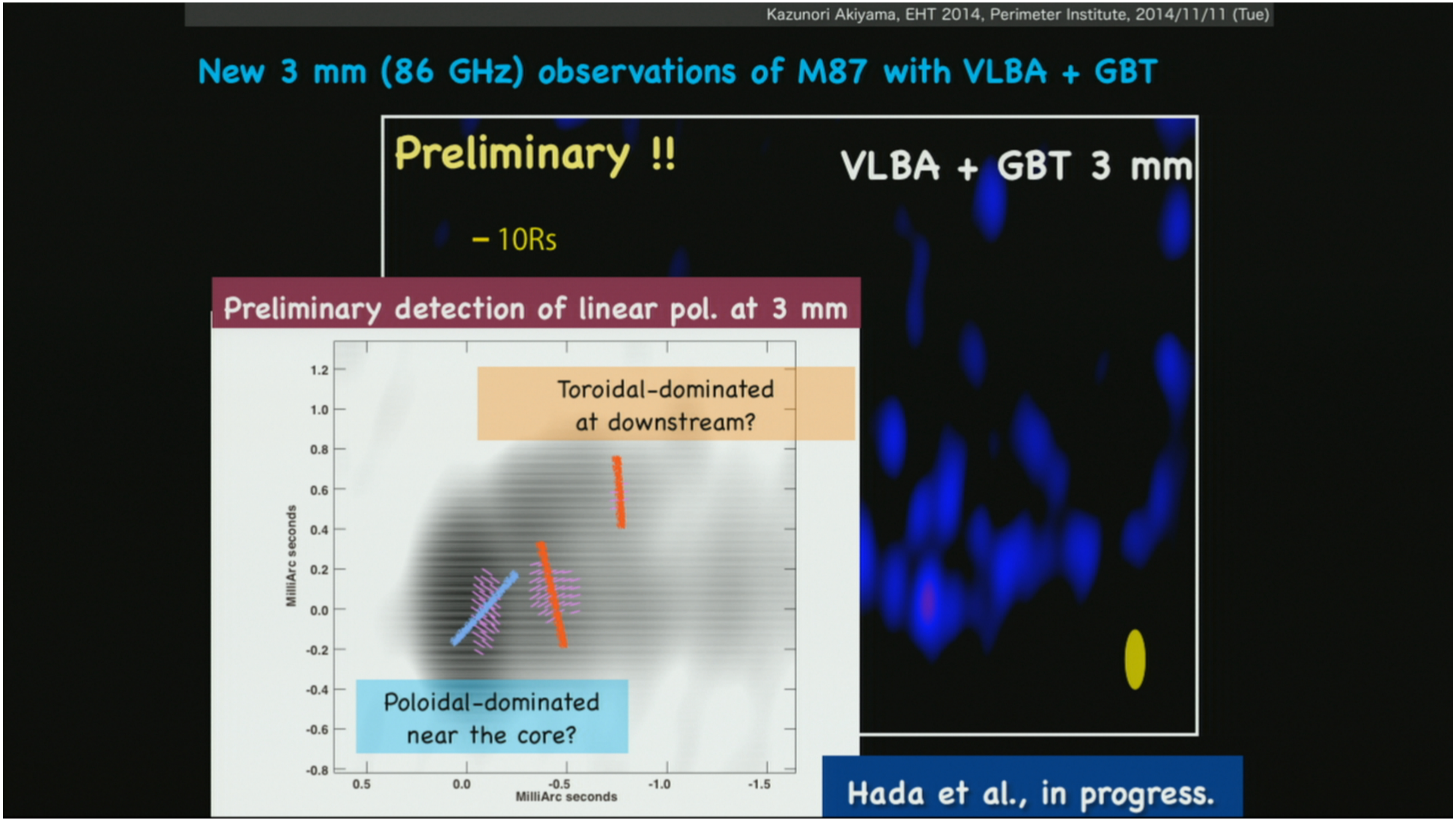
VERA, KaVA Monitoring is on-going



New 3 mm (86 GHz) observations of M87 with VLBA + GBT

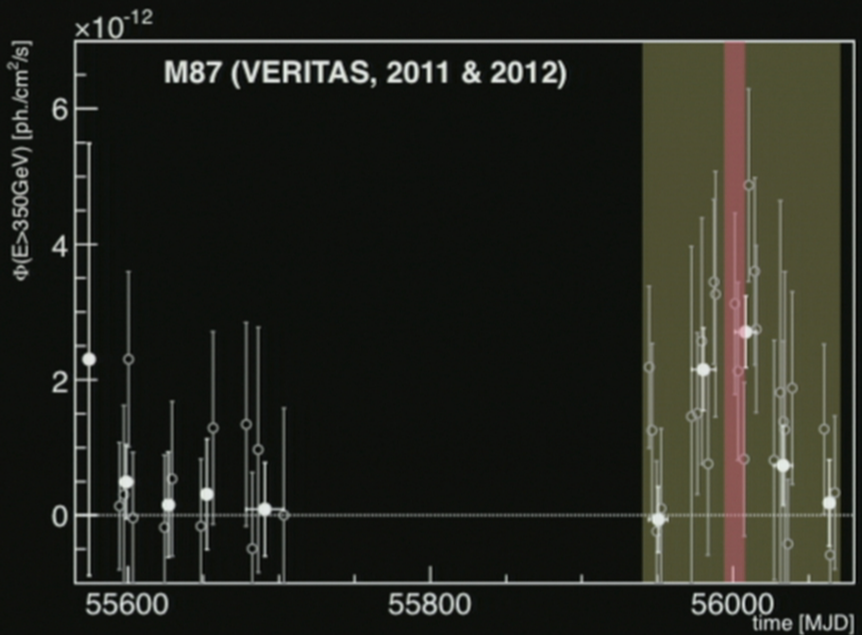


Hada et al., in progress.



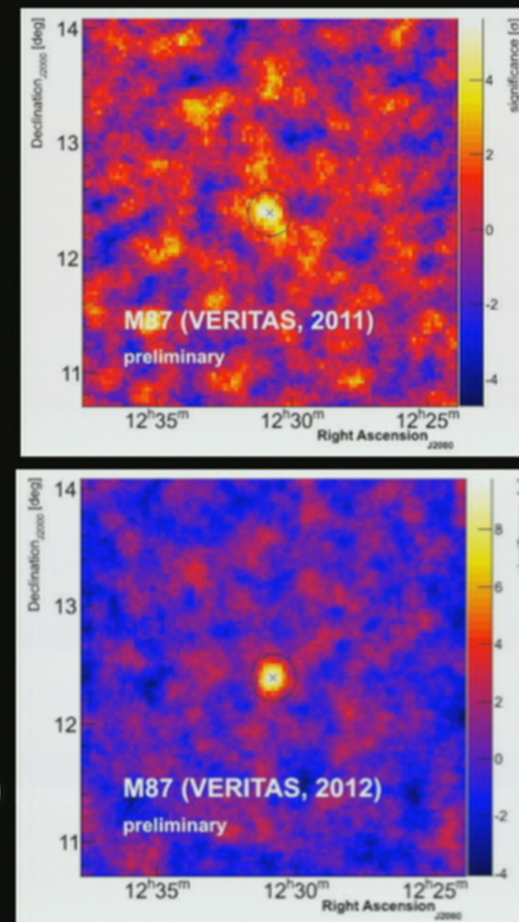
Kazunori Akiyama, EHT 2014, Perimeter Institute, 2014/11/11 (Tue)
New 3 mm (86 GHz) observations of M87 with VLBA + GBT
Preliminary !!
VLBA + GBT 3 mm
10Rs
Preliminary detection of linear pol. at 3 mm
Toroidal-dominated at downstream?
Poloidal-dominated near the core?
MilliArc seconds
MilliArc seconds
Hada et al., in progress.

VHE enhancement in March 2012



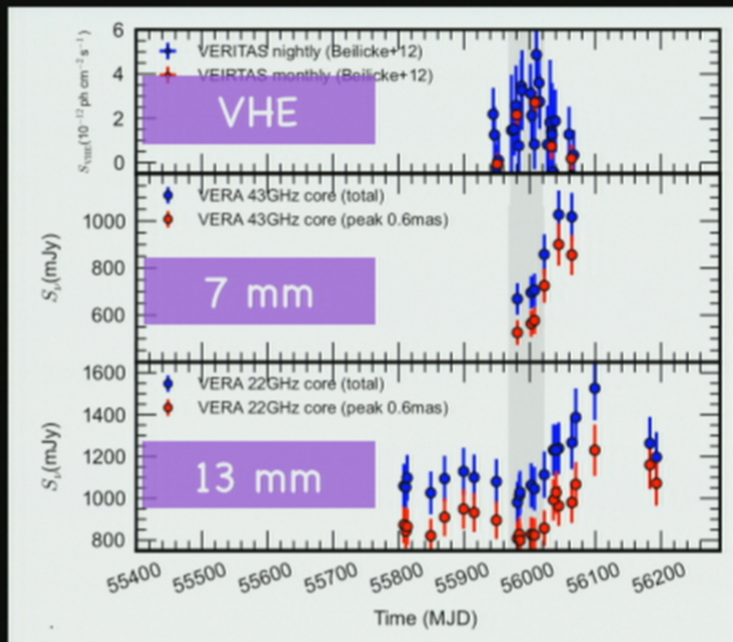
- **Very weak** (~10 times weaker than previous flares) but with reliable significance (> 5 σ)
- **Very long** (- 2 month) >> few days (previous flares) emitting region size < 60 δ light days ~ 100 δ R_{sch}

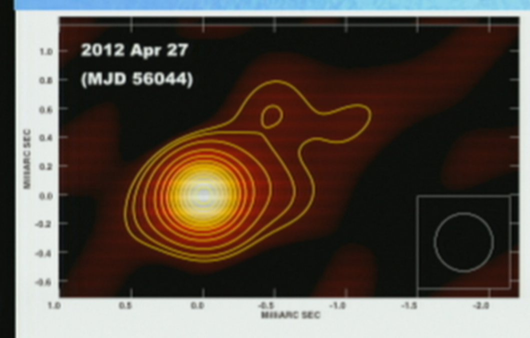
=> New kind of VHE enhancement ?



Beilicke et al. 2012

Following-up VLBI observations with Japanese VERA at 7 / 13 mm



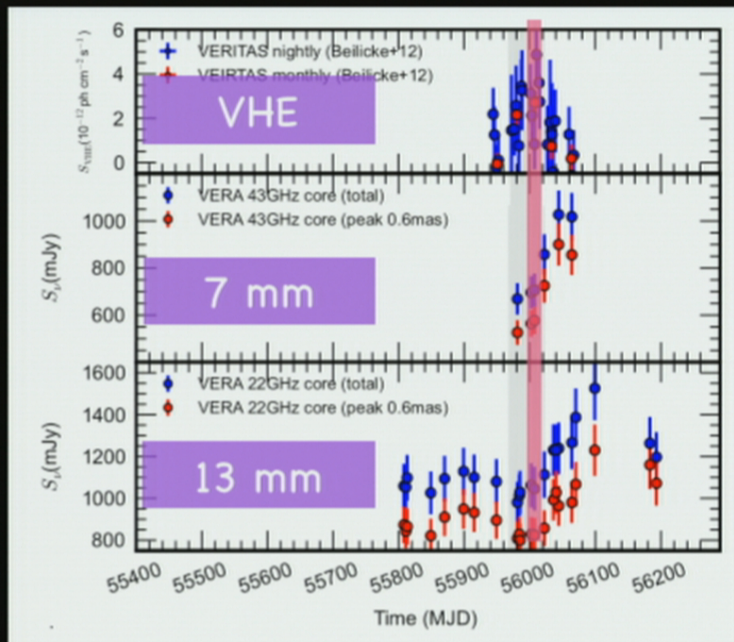


(Hada, Giroletti, Kino,.., KA et al. 2014 ApJ)

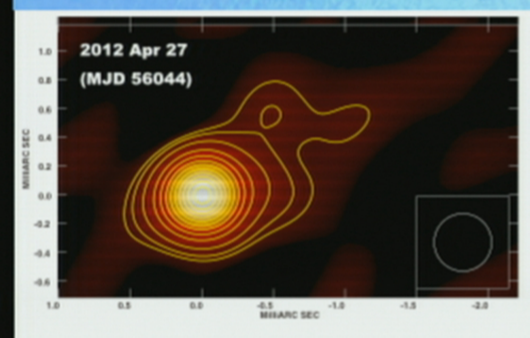
Clear radio - VHE connection at the radio core

VHE emission region should be close to 43 GHz core

Following-up VLBI observations with Japanese VERA at 7 / 13 mm



(Hada, Giroletti, Kino,.., KA et al. 2014 ApJ)

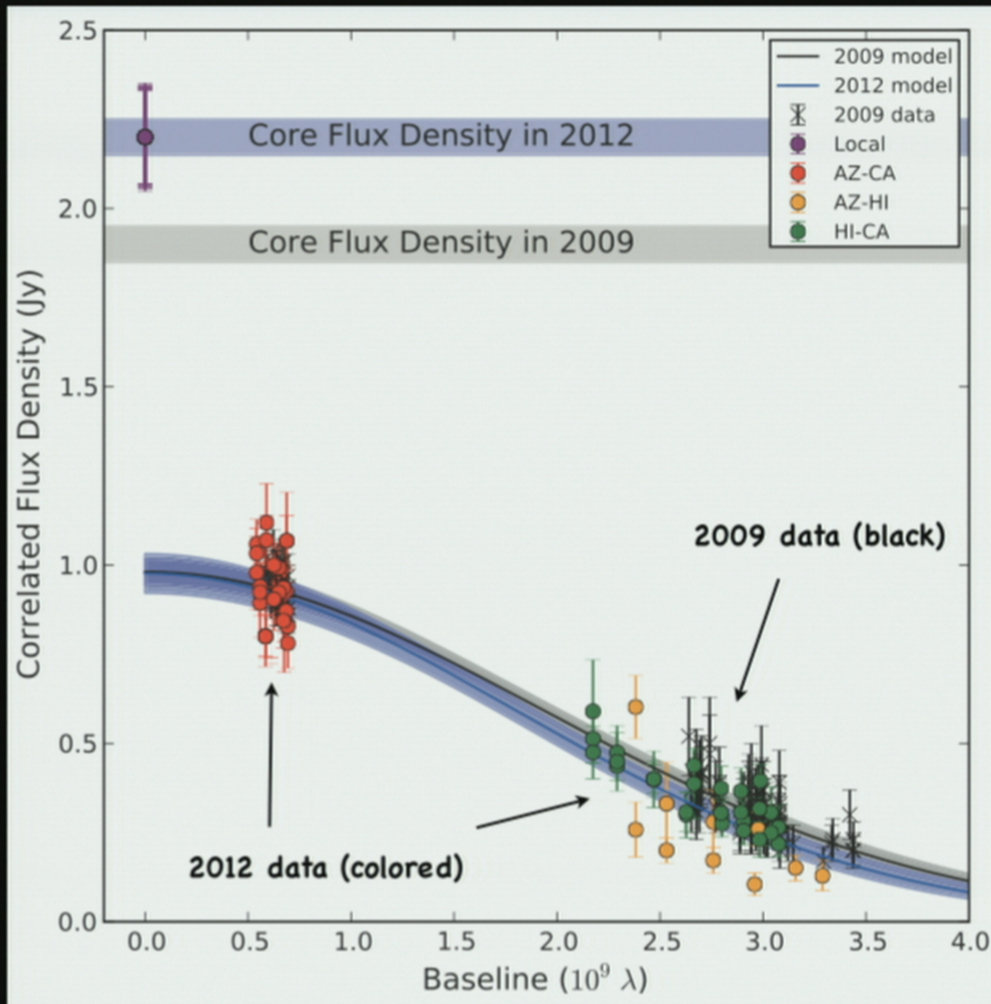


Clear radio - VHE connection at the radio core

VHE emission region should be close to 43 GHz core

EHT observations were performed in the middle of this event.

EHT observations in 2012 (2): Stable structure on ISCO scale?



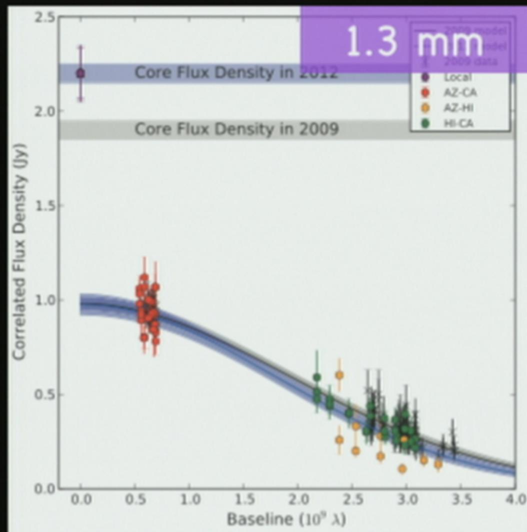
core flux on arcsec scales:
18 % higher than 2009

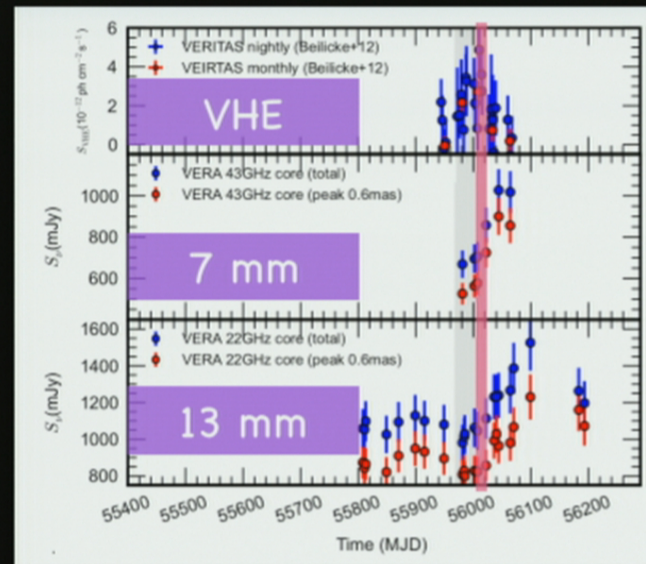
No significant changes in March 2012

- Compact flux density
  - 2009: 0.98 ± 0.04 Jy
  - 2012: 0.98 ± 0.06 Jy
- Size
  - 2009: 40.0 ± 1.8 uas
  - 2012: 42.9 ± 2.3 uas

KA, Lu & Fish et al., submitted

EHT observations in 2012 (2): A plausible scenario





VHE region had an extended structure resolved out in VLBI baselines at 1.3 mm.

=> Lower limit size : R_{VHE} ~0.14 mas = ~20 R_s

- VERA Obs.: R_{VHE} < ~0.4 mas = ~60 R_s, Causality Argument: R_{VHE} < ~60 ld = ~100 R_s
- VHE photon would not be affected by $\gamma - \gamma$ absorption effect for the large R_{VHE}

VHE emission region size could be constrained to ~0.14 - ~0.4 mas (~20 - 60 R_s)

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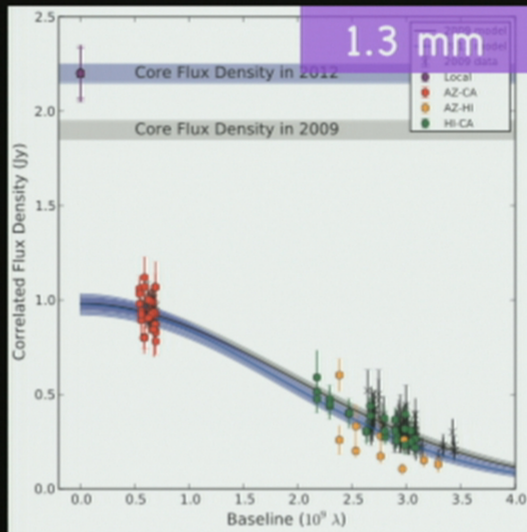

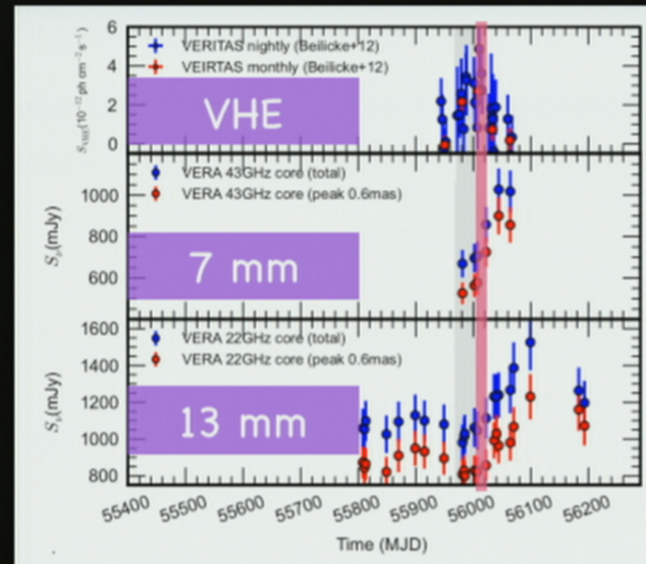

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Summary of EHT 2012 observations

The first measurements of closure phases

- Observed closure phases are close to zero as expected by theoretical models.
- Future EHT after 2015 will be able to distinguish theoretical models.
- Actually, R_s-scale structure will be properly imaged by new imaging techniques

The brightness temperature at 1.3 mm

- The brightness temperature at 1.3 mm is 2×10^{10} K, broadly consistent with peak brightness of the radio cores at lower frequencies inner $10^2\ R_s$.
- We showed a simple analysis the constant brightness temperature may give the magnetic-field prole of $B \propto r^{-1}$ in inner $10^2\ R_s$

The ISCO-scale structure in the middle of VHE enhancement

- There were no significant changes in ISCO-scale structure compared with 2009 observations when no VHE activities detected.
- One of plausible scenarios is that the VHE emission region has "the extended structure" resolved out in EHT observations, requiring a constraint on its size of ~20 - 60 R_s.