Title: Black Hole Cinema

Date: May 07, 2018 03:00 PM

URL: http://pirsa.org/18050042

Abstract:

BLACK HOLE CINEMA

Avery E. Broderick

UNIVERSITY OF WATERLOO

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Boris Georgiev
Britt Jeter
Mansour Karami
Paul Tiede
Carlos Wang
Roman Gold
Tim Johannsen
Alex Preciado
Hung-Yi Pu
Mark Reid
Avi Loeb

Event Horizon Telescope

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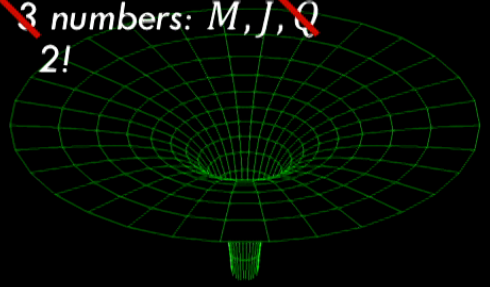
WHAT ARE SUPERMASSIVE BLACK HOLES, AND WHAT ARE THEY DOING?

Fully characterized by

~~3~~ *numbers:* $M, J, ~~Q~~$

2!

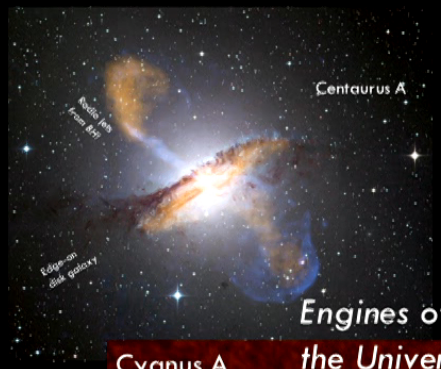


Physics:

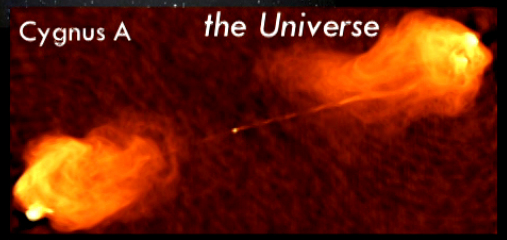
- *Do black holes exist?*
- *Are they well described by GR?*

Astronomy:

- *How do they grow?*
- *How are the enormous luminosities produced?*
- *How are outflows launched?*



Engines of the the Universe



Answers found on horizon-scales

→ Direct imaging!

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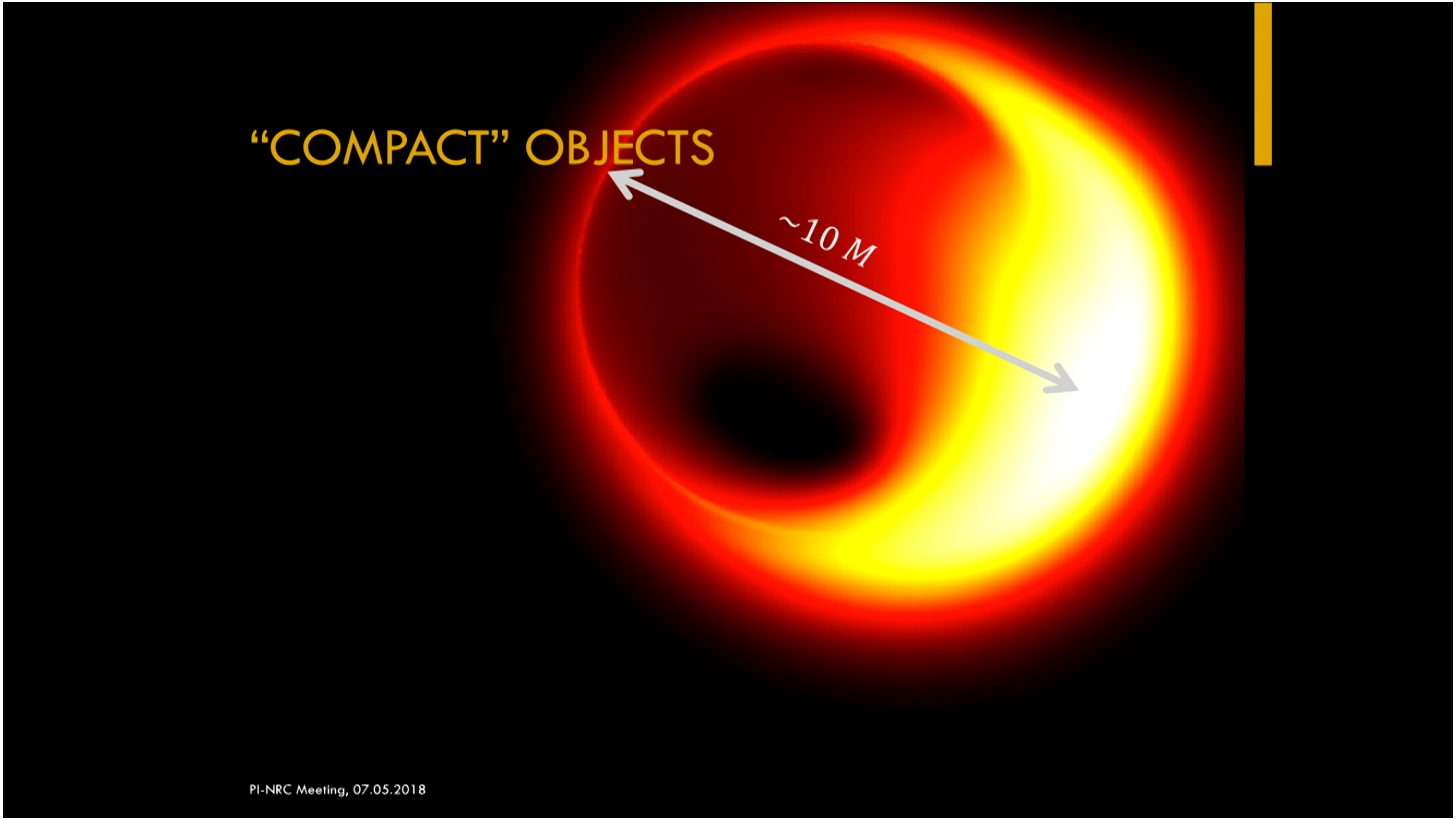
"COMPACT" OBJECTS
~10 M
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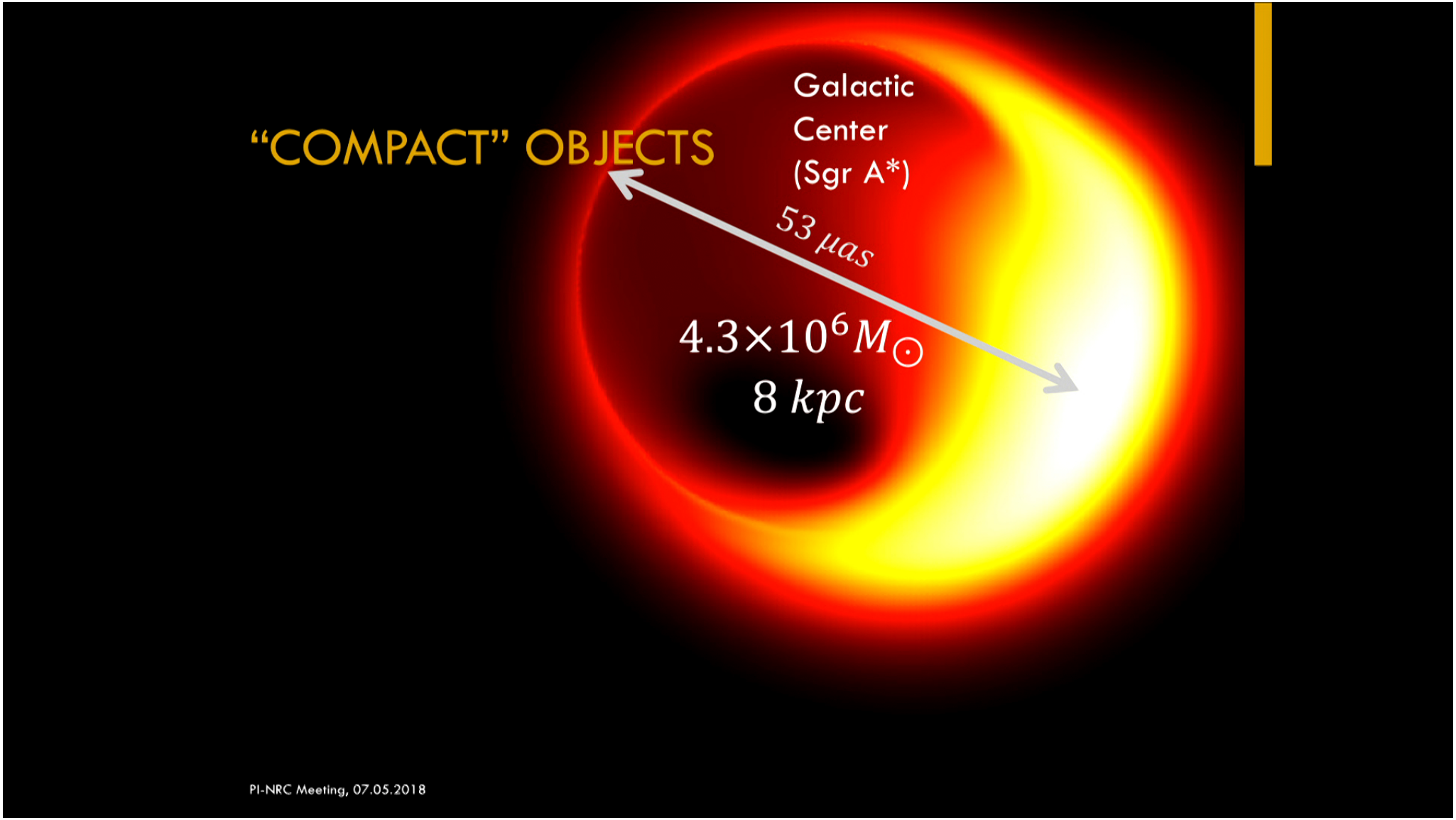
"COMPACT" OBJECTS
Galactic
Center
(Sgr A*)
53 μas
$4.3\times10^6 M_\odot$
8 kpc
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"COMPACT" OBJECTS

Galactic Center (Sgr A*)

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$4.3\times10^{6} M_{\odot}$

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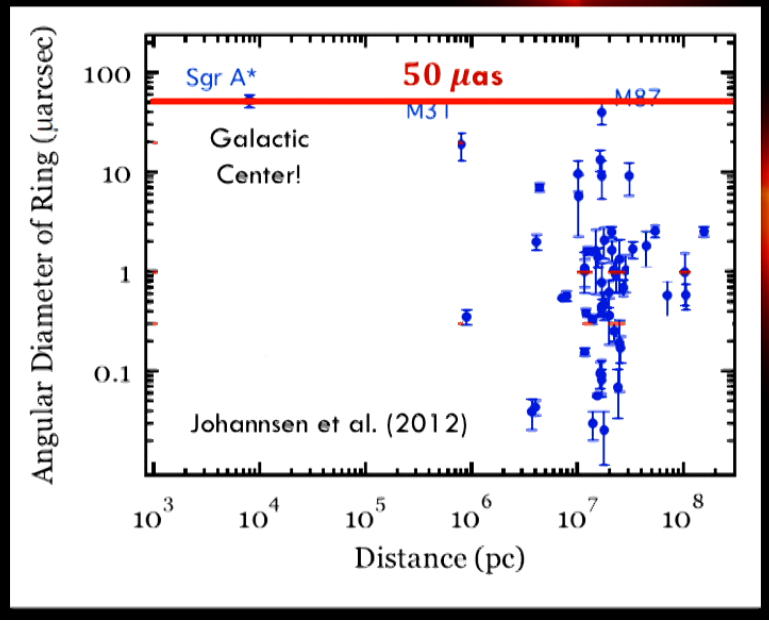

"COMPACT" OBJECTS

Galactic Center (Sgr A*)

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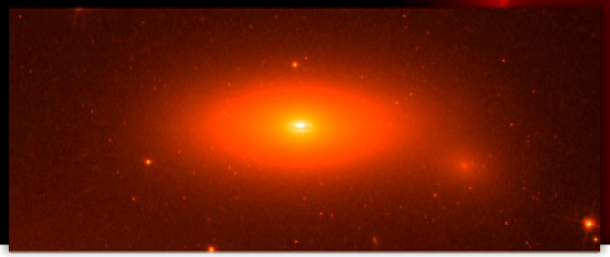

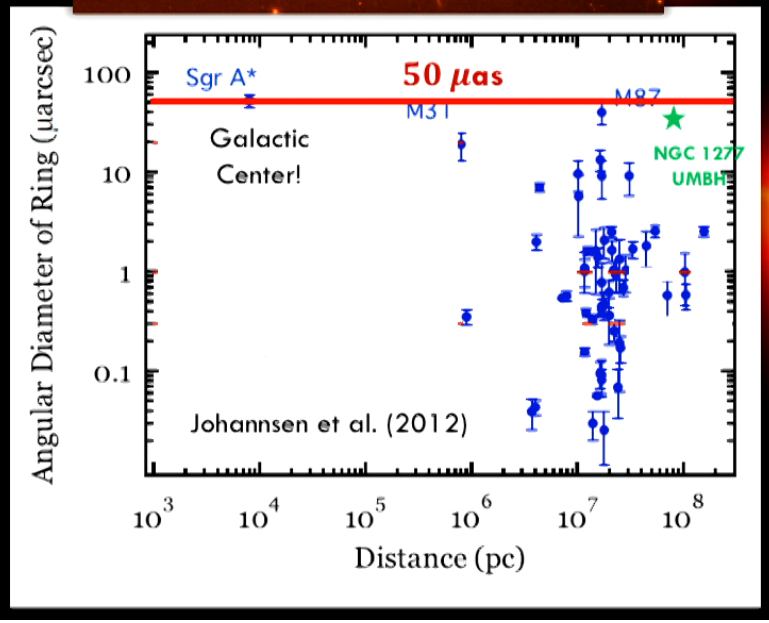

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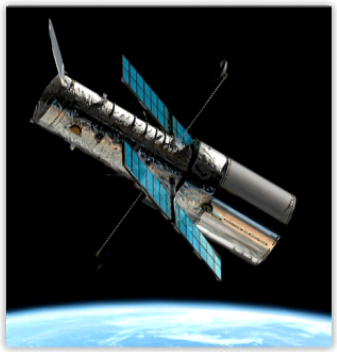
CANADA
2008
10 CENTS

HOCKEY ON THE MOON AND THE DIFFRACTION LIMIT



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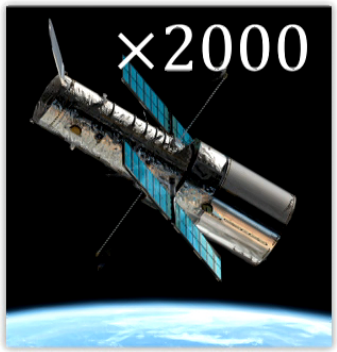

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HOCKEY ON THE MOON AND THE DIFFRACTION LIMIT

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HOCKEY ON THE MOON AND THE DIFFRACTION LIMIT

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THE EHT TODAY

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GLOBAL COLLABORATION

Max-Planck-Institut
für Radioastronomie

Radboud Universiteit Nijmegen

SAO

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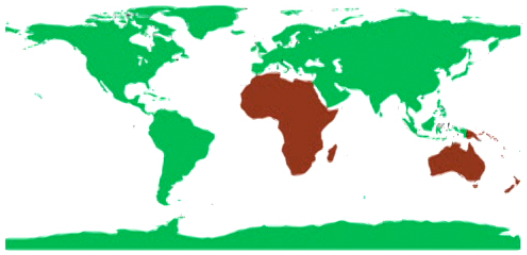

Aalto University

Arizona Radio Observatory

Instituto Nacional de Astrofísica, Óptica y Electrónica

Boston University

University of California, Berkeley

Chinese Academy of Sciences

Universidad de Concepción

Institute of High Energy Physics

University of Illinois

Kavli Institute for Astronomy and Astrophysics

Leiden University

University of Massachusetts Amherst

Nanjing University

Onsala Space Observatory

Purple Mountain Observatory

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Huazhong University of Science & Technology

Joint Institute for VLBI ERIC

Korea Astronomy and Space Science Institute

University of Maryland

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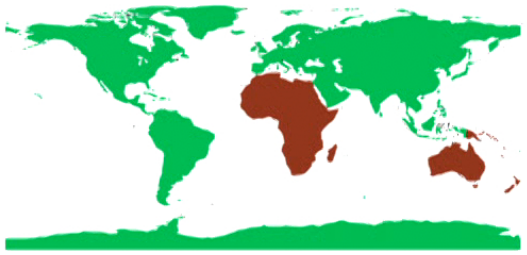

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California Institute of Technology
Cologne University
Cornell University
Huazhong University of Science & Technology
Joint Institute for VLBI ERIC
Korea Astronomy and Space Science Institute

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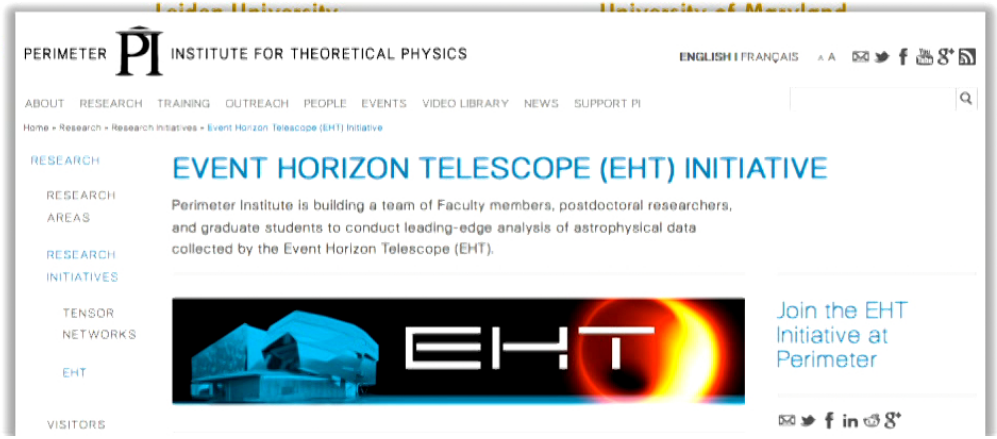

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"PROTO-EHT"

CARMA

SMA,
JCMT

ARO-SMT

See Rusen LU's talk!

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Event Horizon Telescope

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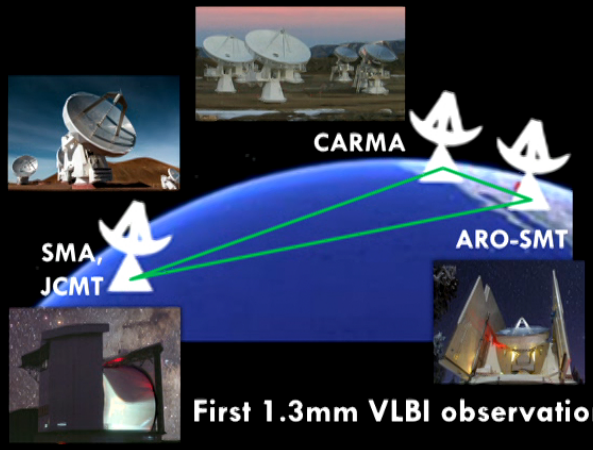
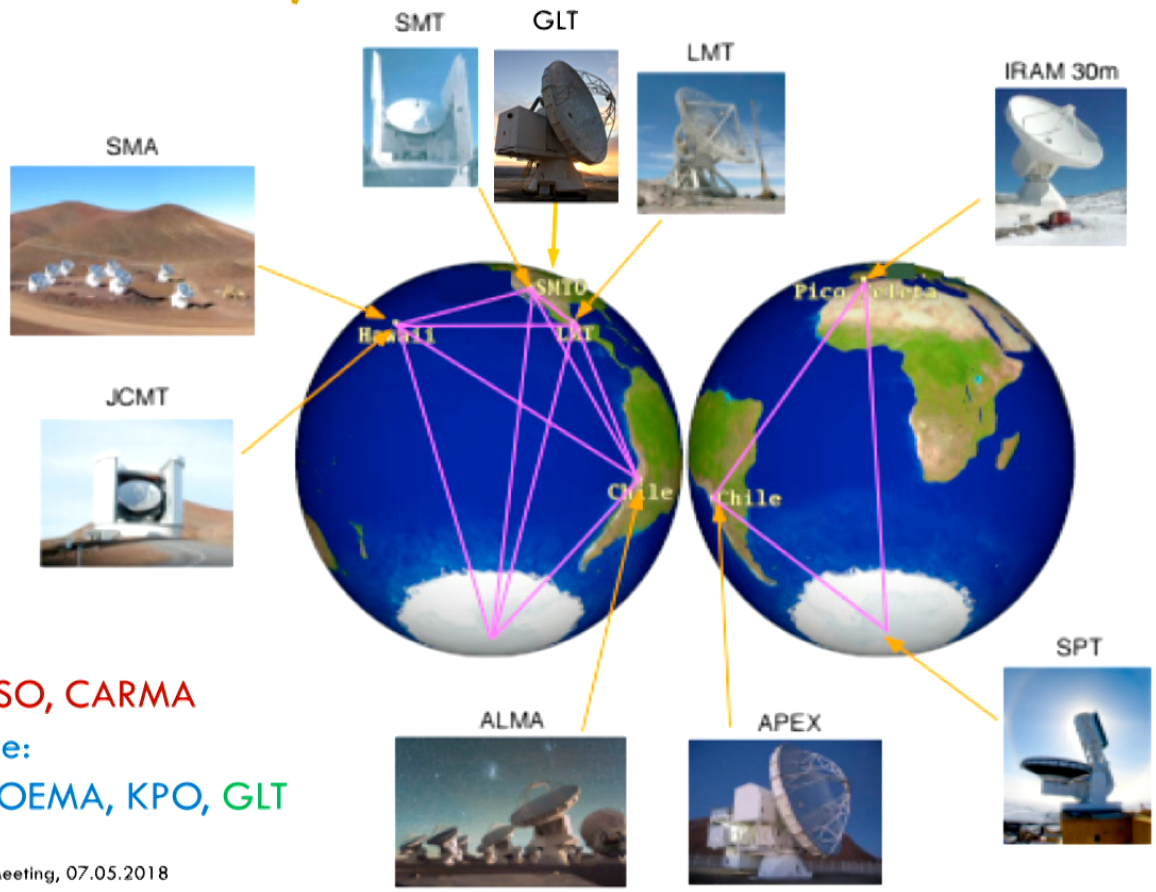


Doeleman et al. 2008, Nature, 455, 78	First 1.3mm VLBI observation of Sgr A*
Broderick et al. 2009, ApJ, 697, 45	First physics-based modeling of EHT data
Fish et al. 2011, ApJ, 727, 36	First detection of horizon-scale variability
Broderick et al. 2011, ApJ, 735, 110	First demonstration that physics-based models are *preferred* by EHT data
Doeleman et al. 2012, Science, 338, 355	First 1.3mm VLBI observations of M87
Broderick et al. 2014, ApJ, 784, 7	First constraints on BH hair from EHT data
Akiyama et al. 2015, ApJ, 807, 150	First measurement of horizon-scale structure in M87 coincident with TeV flares
Johnson et al. 2015, Science, 350, 1242	First detection of ordered, horizon scale polarization around a BH
Broderick et al. 2016, ApJ, 820, 137	First physics-based modeling of EHT data that included closure phases

THE EVENT HORIZON TELESCOPE
CIRCA APRIL, 2017 & 2018



Past:

CSO, CARMA

Future:

NOEMA, KPO, GLT

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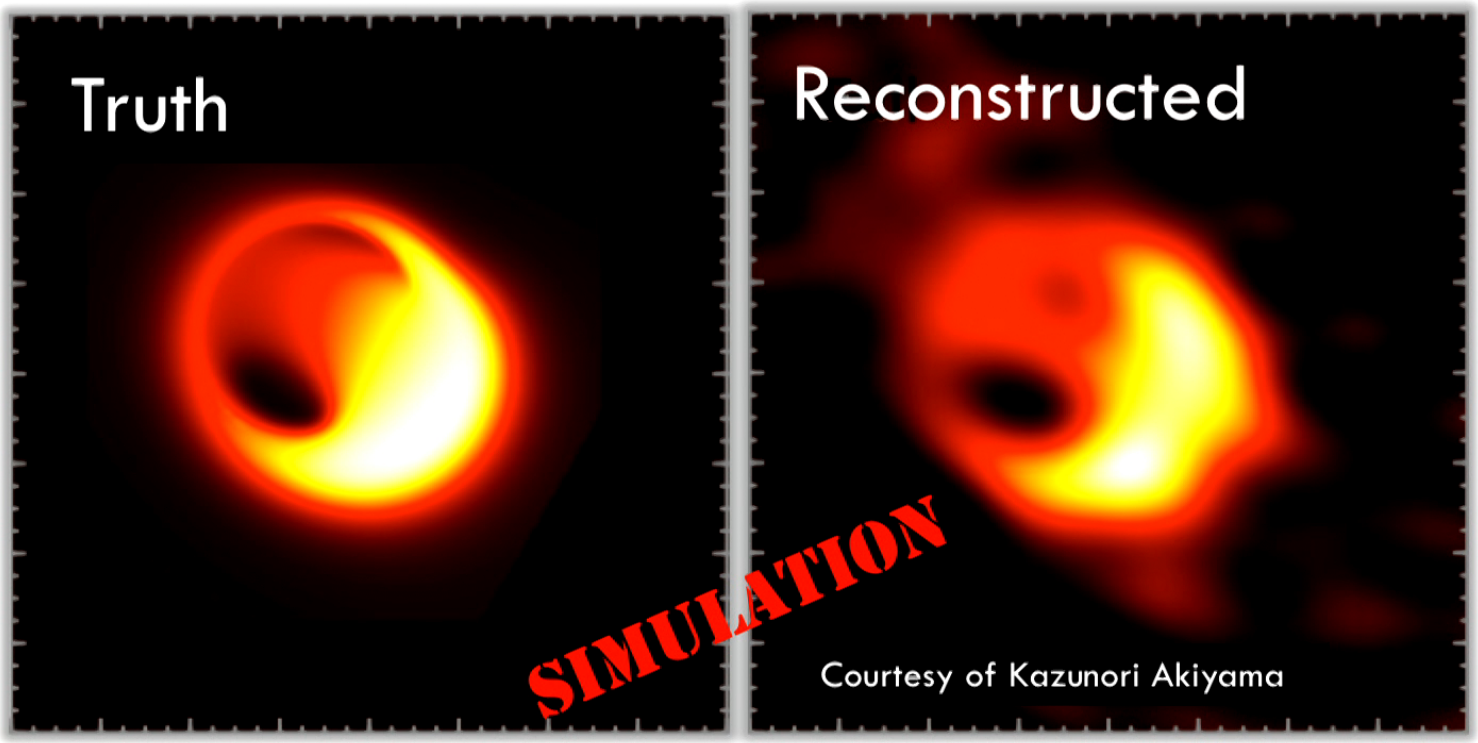
FIRST TELESCOPE CAPABLE OF "SEEING" BLACK HOLES



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LATEST RESULTS?

- April 2017 Observations went great!
- April 2018 Observed again!
- All things look good; data from the SPT arrived in Nov.
- Will have multiple (>4) epochs on the Galactic center and M87
- Have begun imaging/analysis of AGN
- Will begin imaging/analysis of M87 & Sgr A* this summer
- Can't say anything publicly yet!

KEY MESSAGE

The *first* image is great, but …

EHT targets should exhibit *structural* variability over many time scales, each telling a story about the physics of black holes and their environments,

… so, the next 100 images are even better!

SMBH JITTER

DECADES

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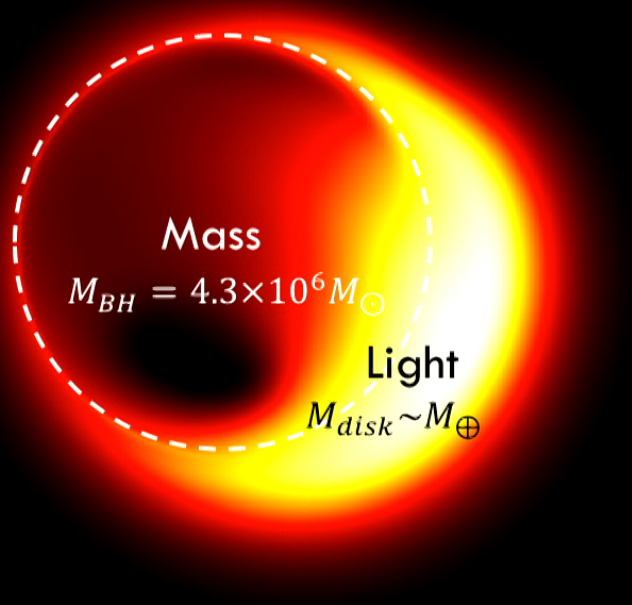
BEYOND THE SMBH: JITTER IN SGR A*



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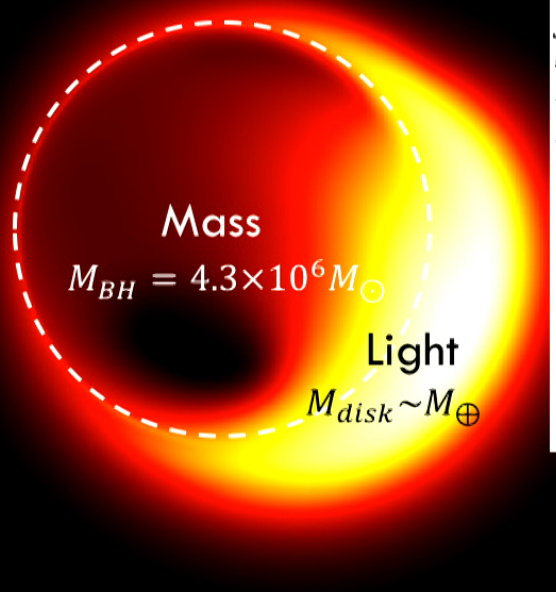

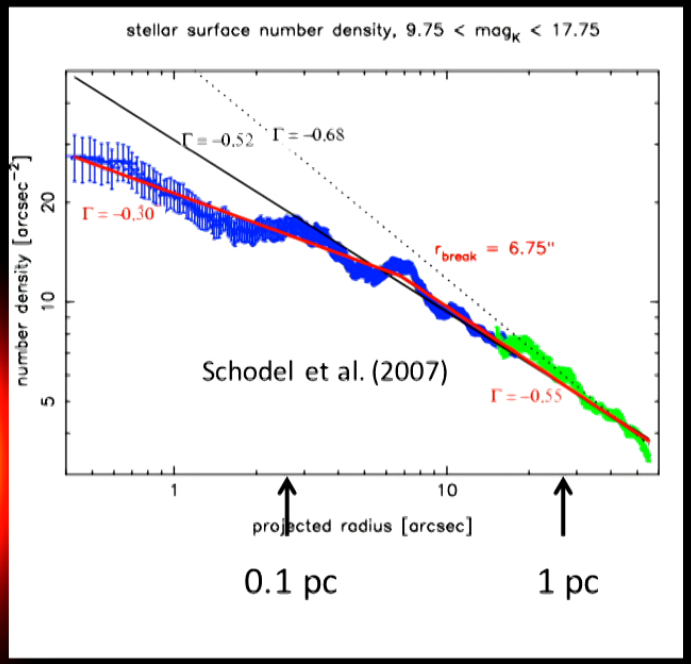

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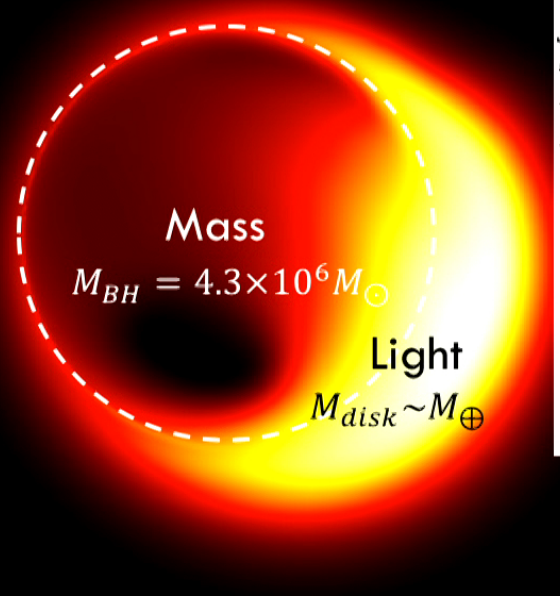

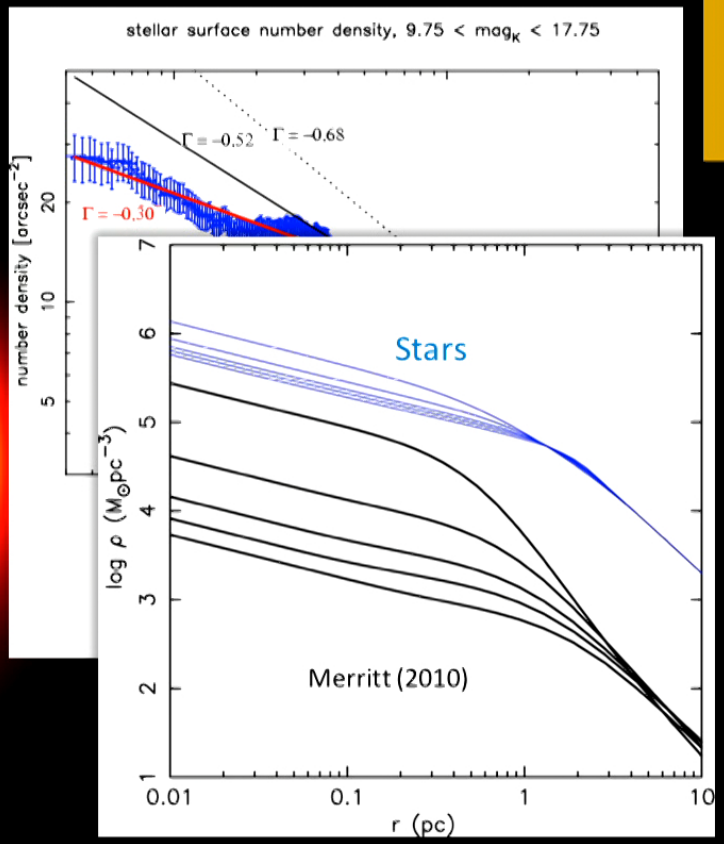

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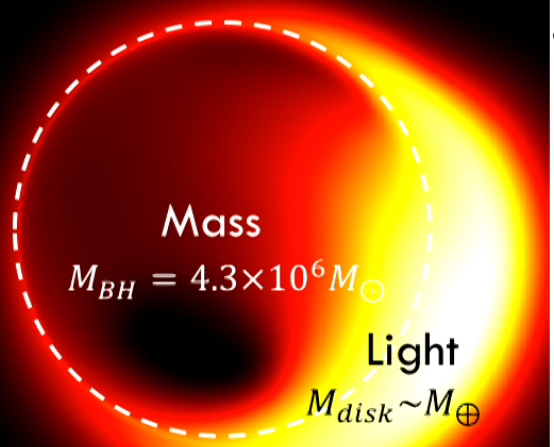

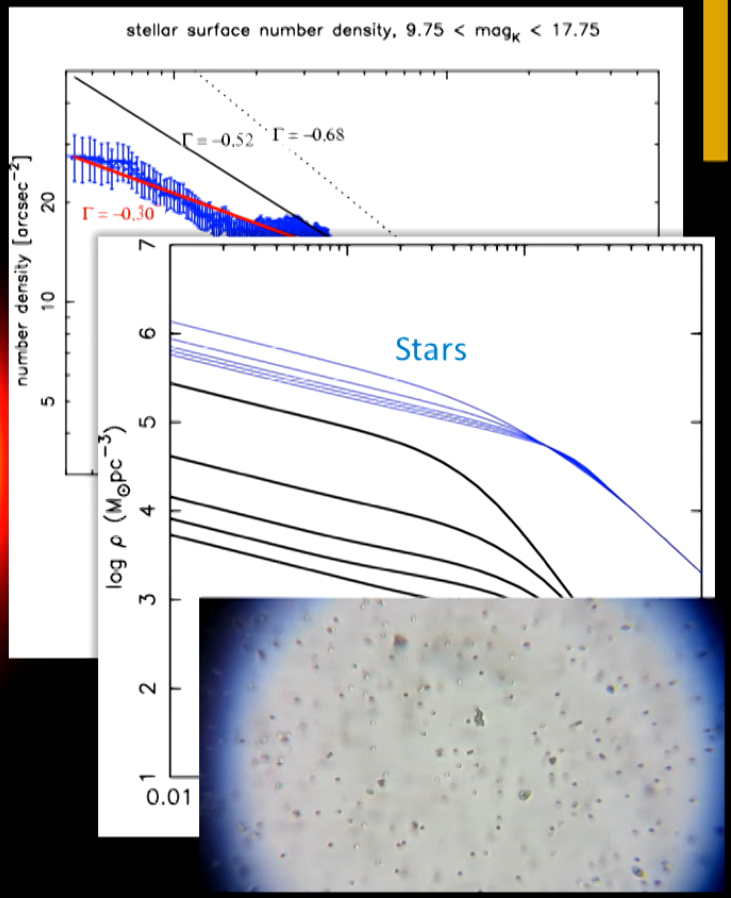

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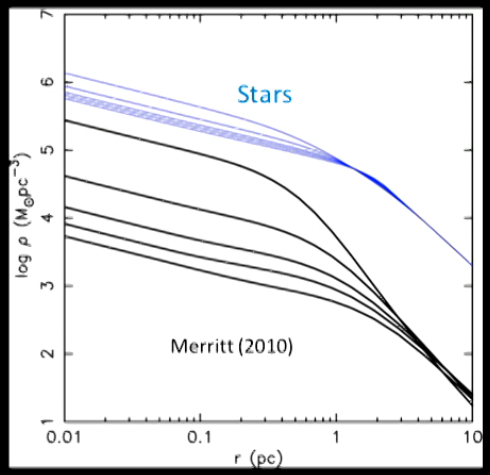
BEYOND THE SMBH: JITTER IN SGR A*



- Absolute astrometry
  - Need references.
- 10s atm coherence time
  - Need sub-arrays.

(ALMA, SMA, NOEMA)

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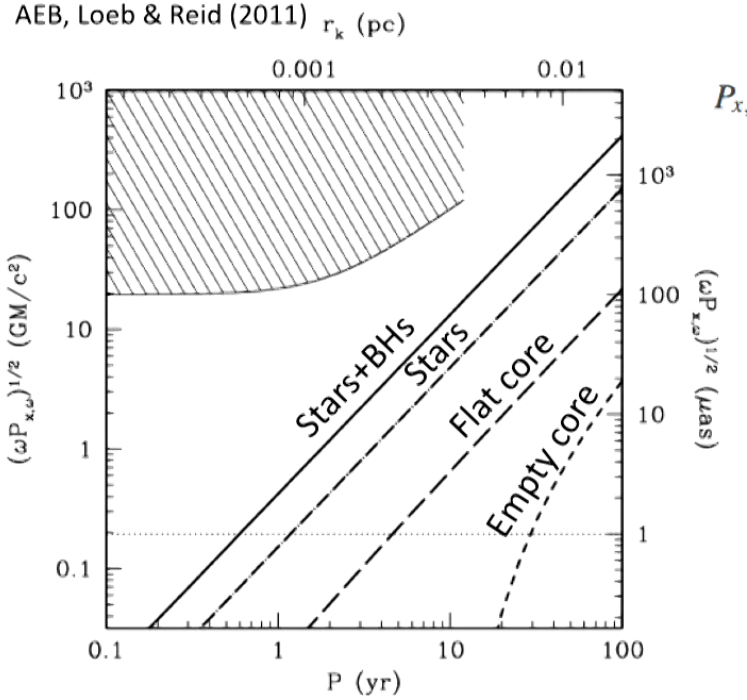
BEYOND THE SMBH: REMNANT CUSPS

AEB, Loeb & Reid (2011)



$$P_{x,\omega} \simeq \omega^{-4} \int_0^\infty dr \, \frac{2(2\pi)^{3/2}}{3} \frac{G^2\mu^2}{r^2} \frac{n}{\Omega_k} e^{-\omega^2/2\Omega_k^2}$$

- **Remnant cusp formation & evolution**
- **LIGO BH-BH rates?**
- **LISA EMRI rates?**

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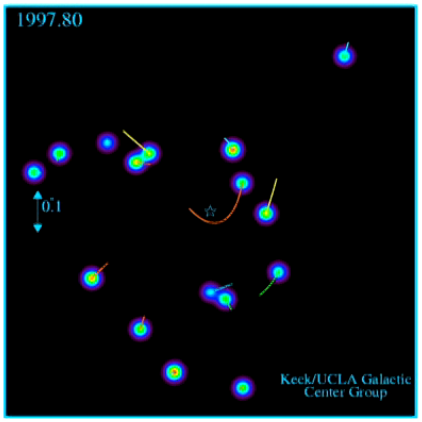
ORIGIN OF THE S-STARS: MASSIVE COMPANION?



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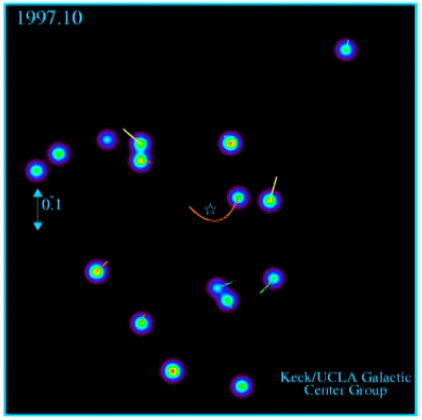

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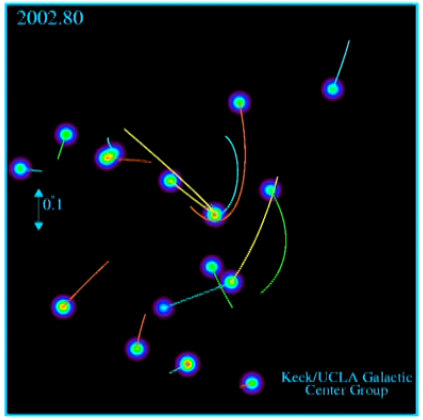

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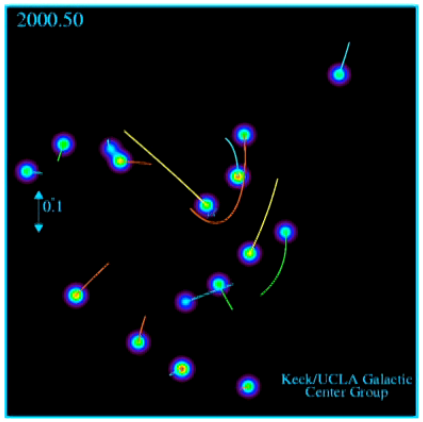
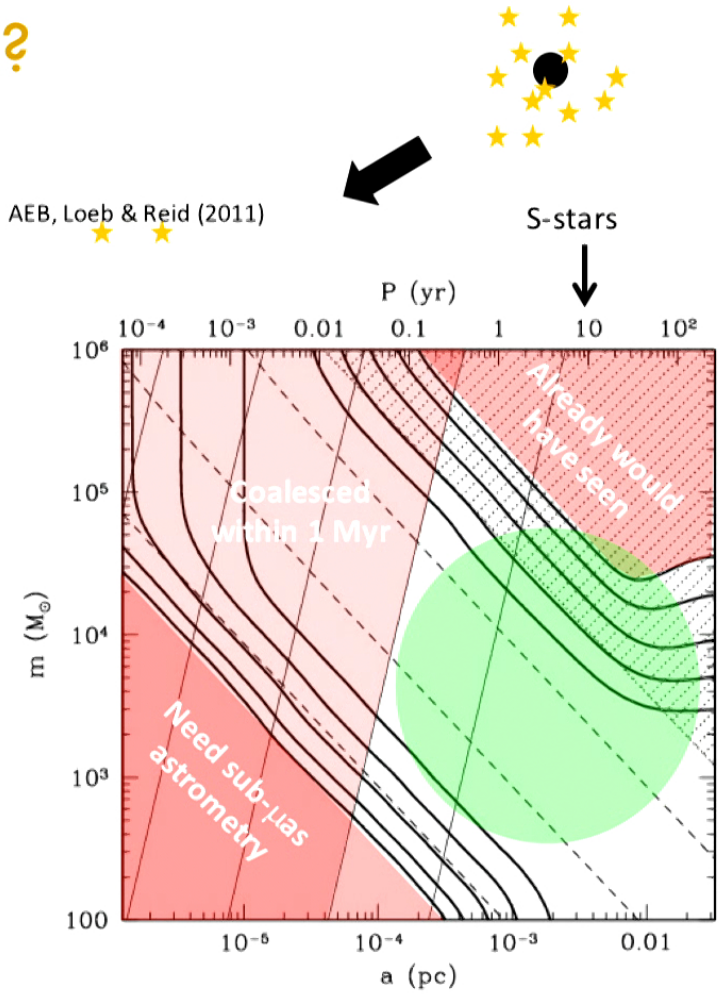
ORIGIN OF THE S-STARS: MASSIVE COMPANION?

Massive companion entered <0.01pc orbit with Sgr A* within last 10^6 yr!





DISK PRECESSION YEARS

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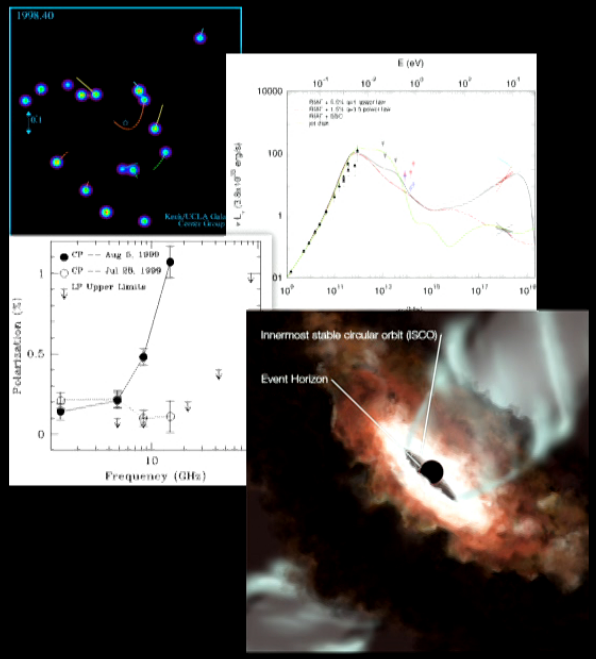
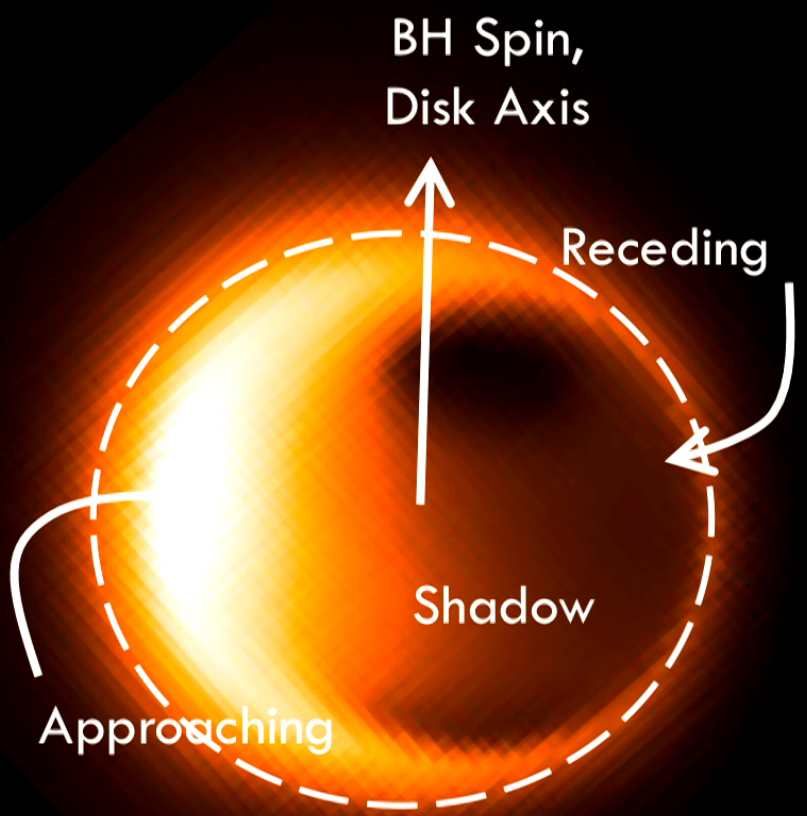
MODELING SGR A*





Geometrically thick, orbiting, synchrotron emitting disk.

$$I(x, y; a, \theta, \xi)$$

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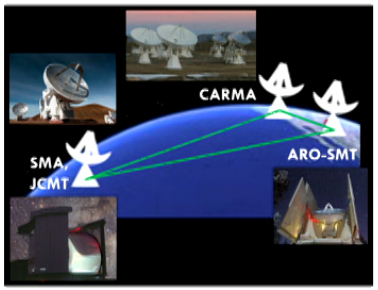
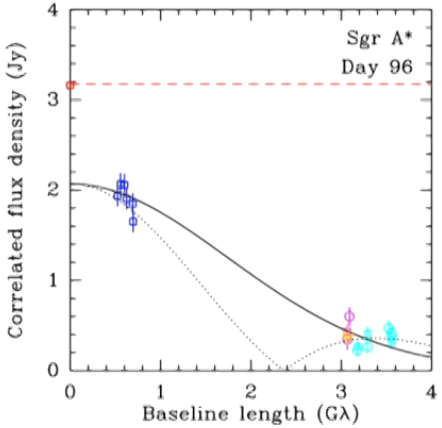


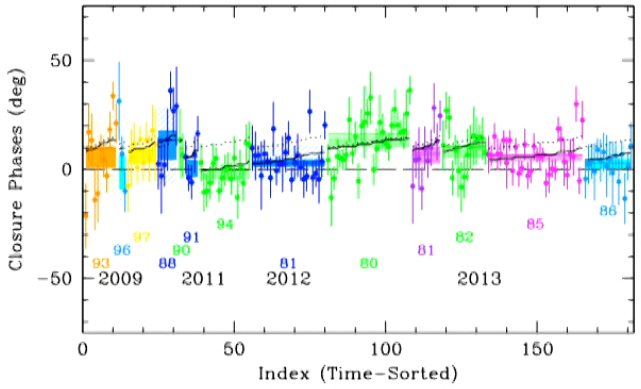
SGR A* EHT DATA

Table 1
Data Epochs

	Epoch	Year	Day(s)	Time	N[a]	Type[b]	Ref[c]
Visibility Magnitudes $\lvert\tilde{I}\rvert$	1	2007	100-101	11.00-13.67	19	VM	D8
	2	2009	95	11.11-13.08	12	VM	F11
	3	2009	96	11.50-13.56	19	VM	F11
	4	2009	97	11.50-13.67	20	VM	F11
	Totals	...	...	11.73 hrs	70		
Closure Phases $\sim\arg(\tilde{I})$	5	2009	93	11.54-13.87	11	CP	F15
	6	2009	96	12.46-12.79	3	CP	F15
	7	2009	97	11.96-14.38	10	CP	F15
	8	2011	88	12.37-13.52	7	CP	F15
	9	2011	90	13.67-14.02	2	CP	F15
	10	2011	91	11.93-13.53	7	CP	F15
	11[d]	2011	94	[illegible]	7	CP	F15
	12	2012	81	[illegible]	25	CP	F15
	13	2013	80	12.55-15.43	28	CP	F15
	14	2013	81	12.97-15.27	10	CP	F15
	15	2013	82	12.97-14.88	15	CP	F15
	16	2013	85	12.15-15.17	32	CP	F15
	17	2013	86	12.55-13.95	16	CP	F15
	Totals	...	...	25.58 hrs	181		

[a] Number of data points, including detections only
[b] Data types are visibility magnitudes (VM) and closure phases (CP)
[c] D8=DOEL8, F11=FISH11, F15=FISH15
[d] Contaminated by flare activity





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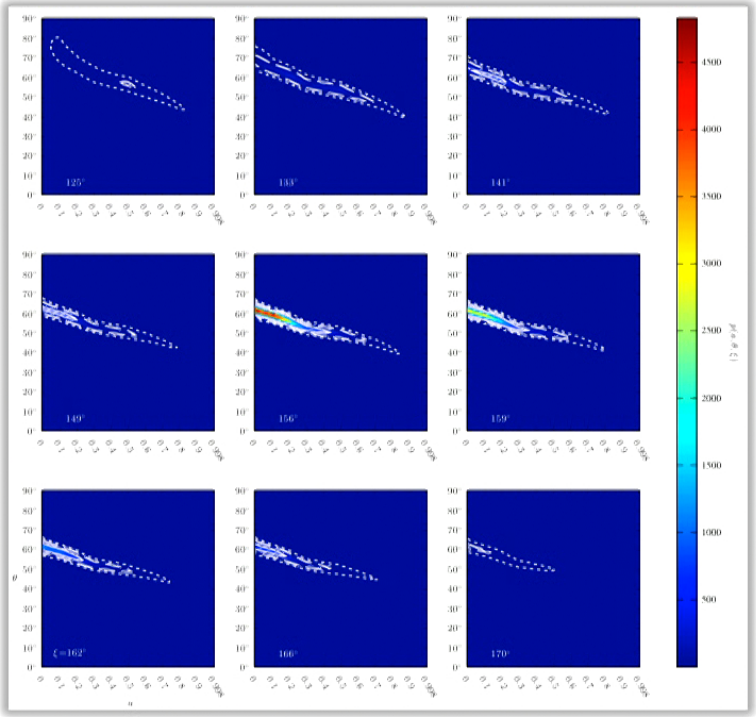
PROBING ACCRETION WITH 7 YEARS OF EHT DATA



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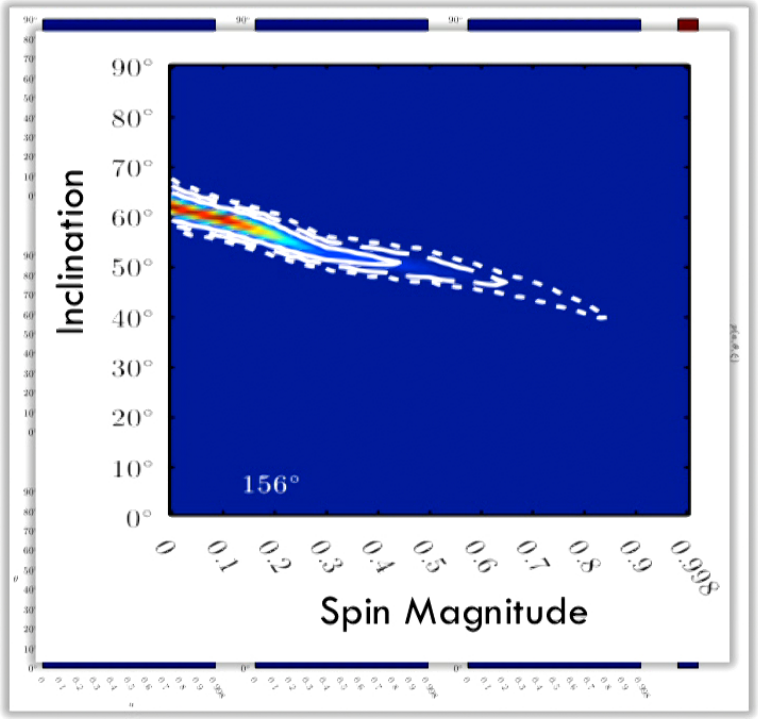

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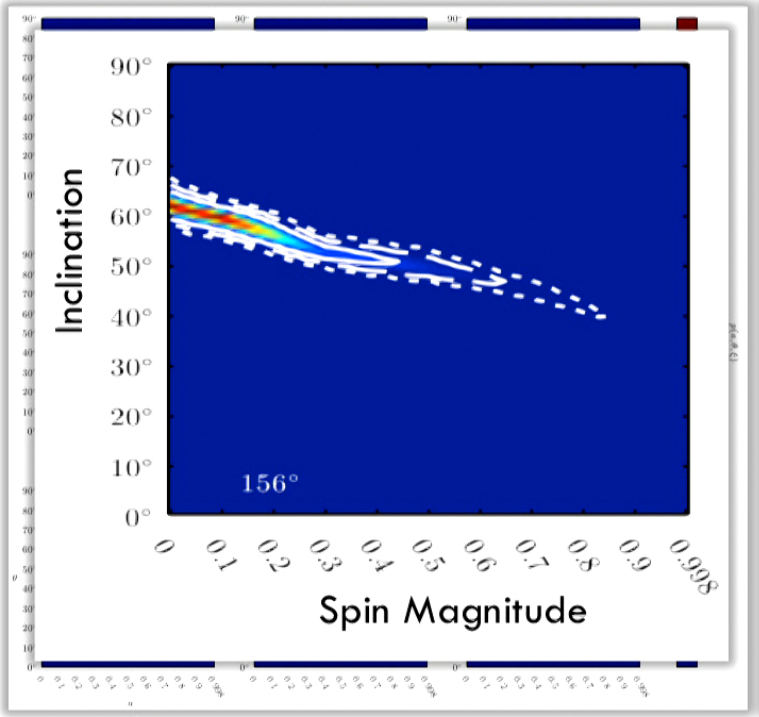

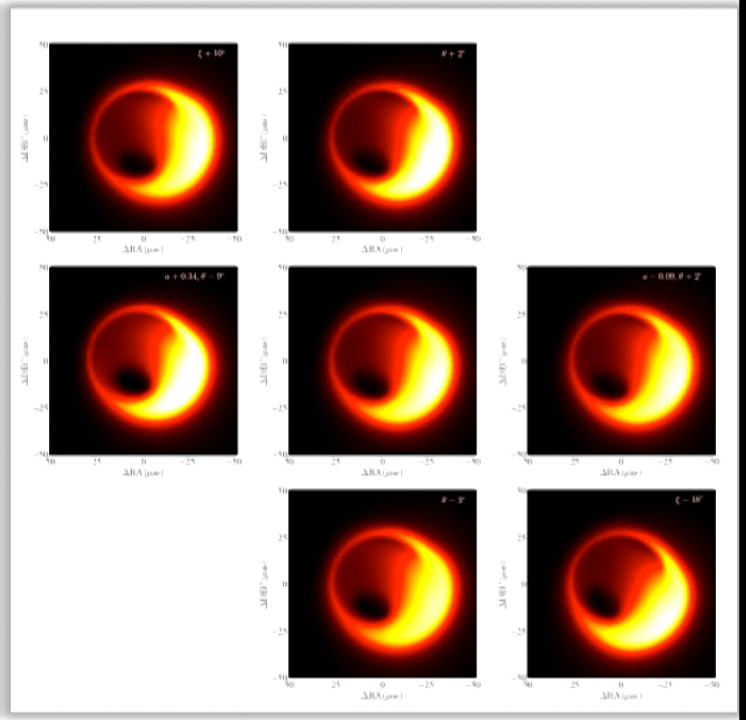

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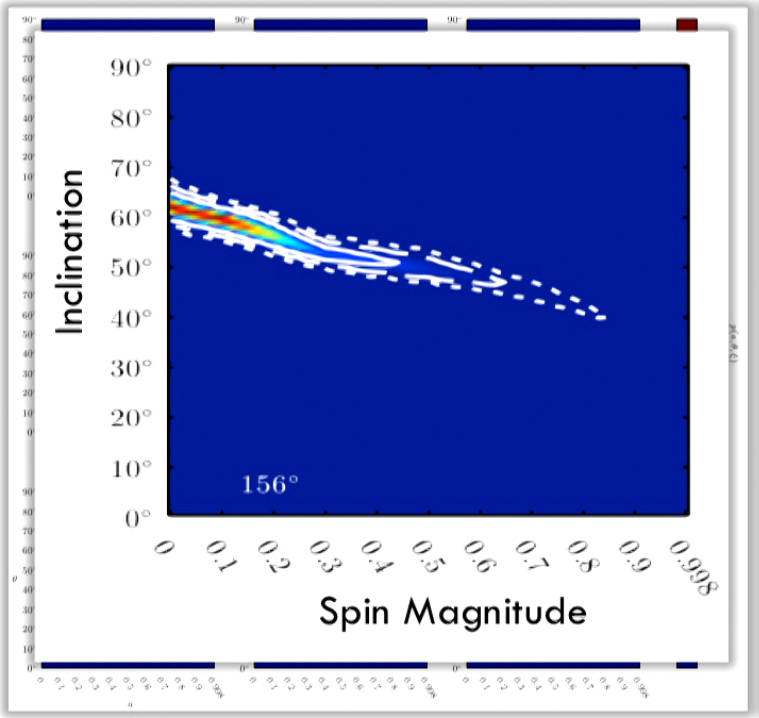
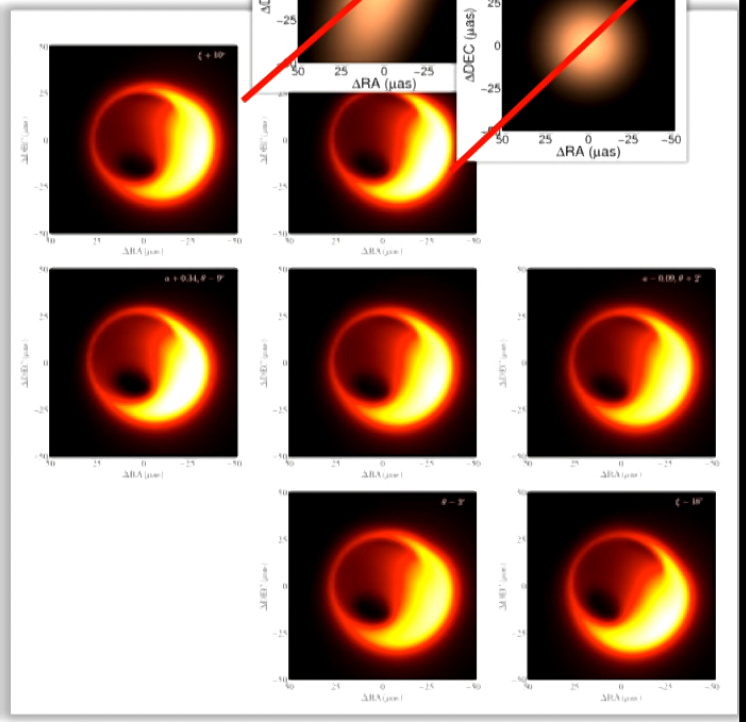
PROBING ACCRETION WITH 7 YEARS OF EHT DATA



Excluded!



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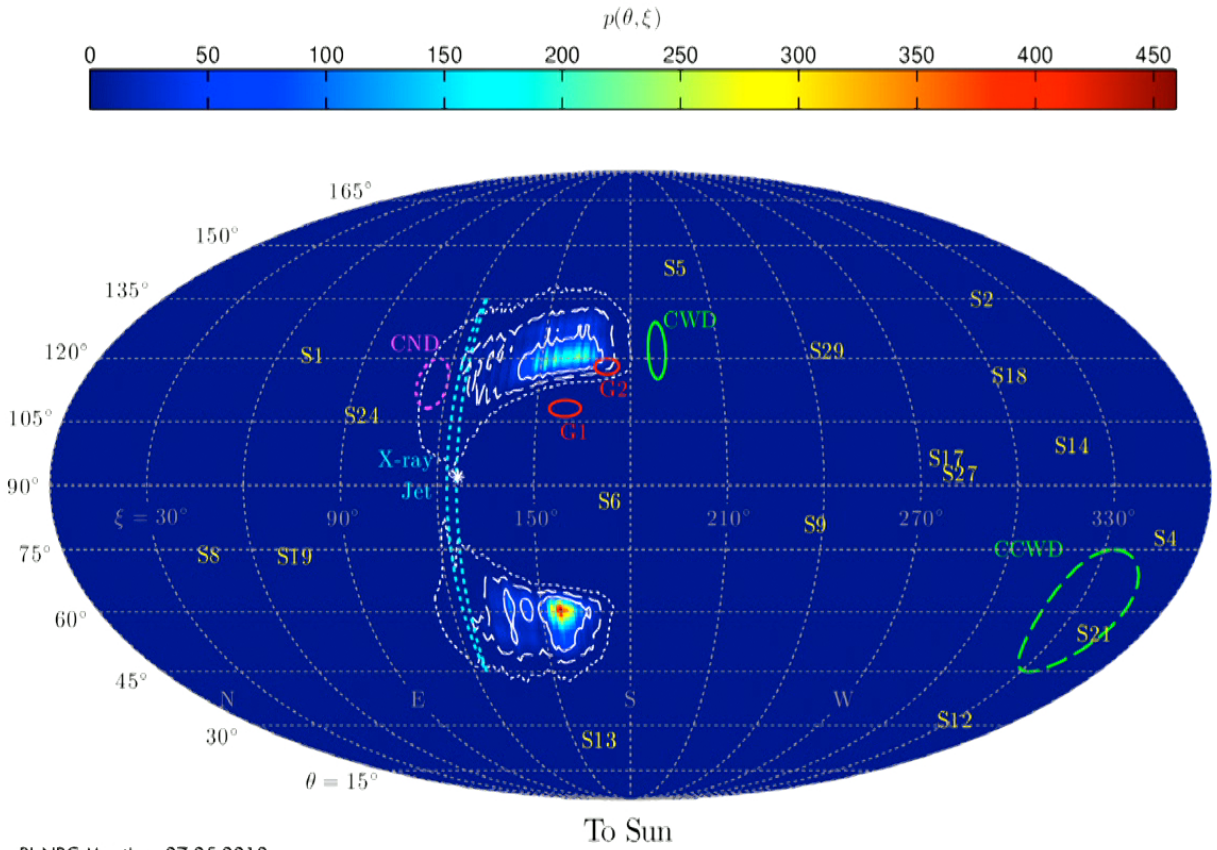
ORIENTATION AND THE GALACTIC CENTER STORY



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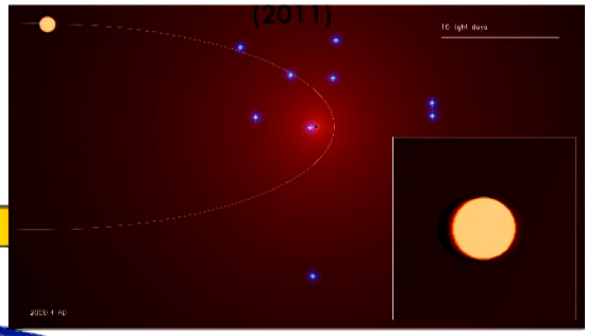
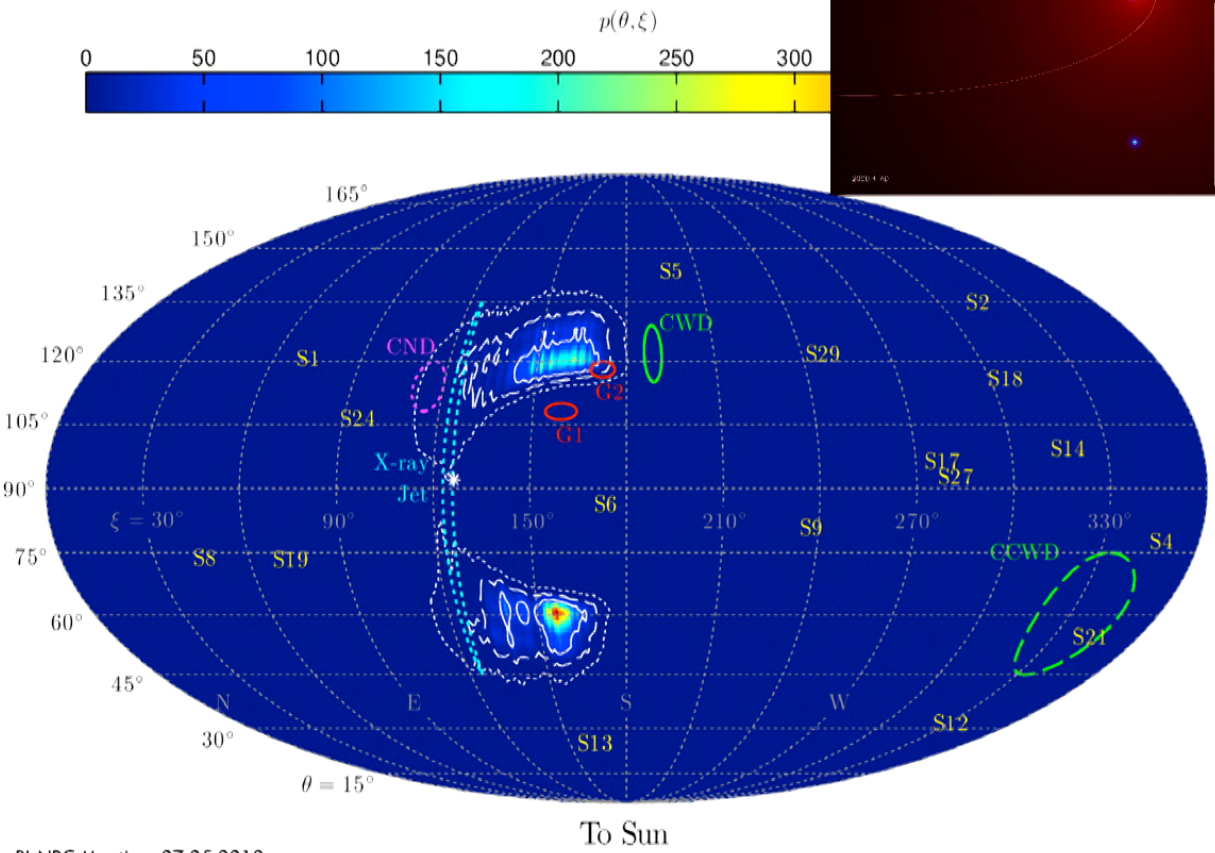
ORIENTATION AND THE GALACTIC CENTER STORY





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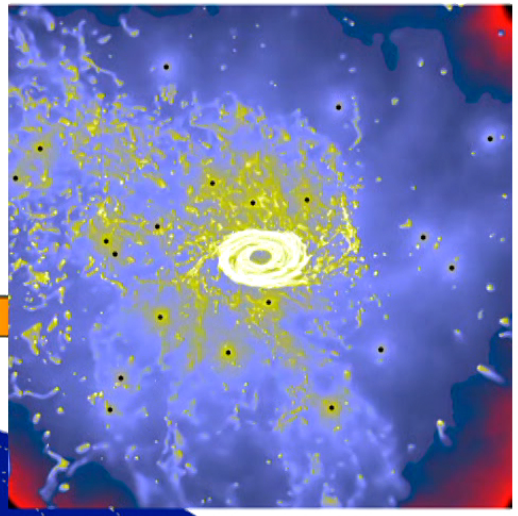
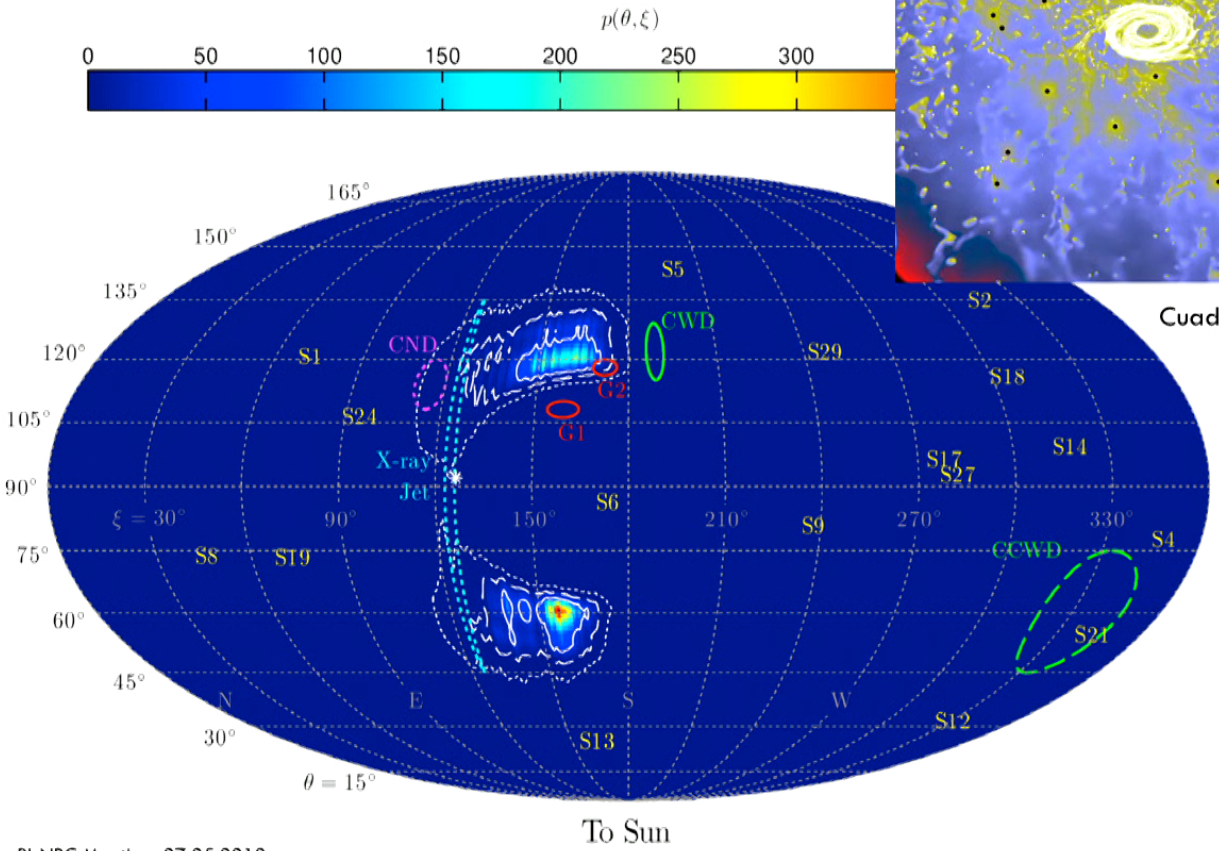
ORIENTATION AND THE GALACTIC CENTER STORY



Cuadra et al. (2005)



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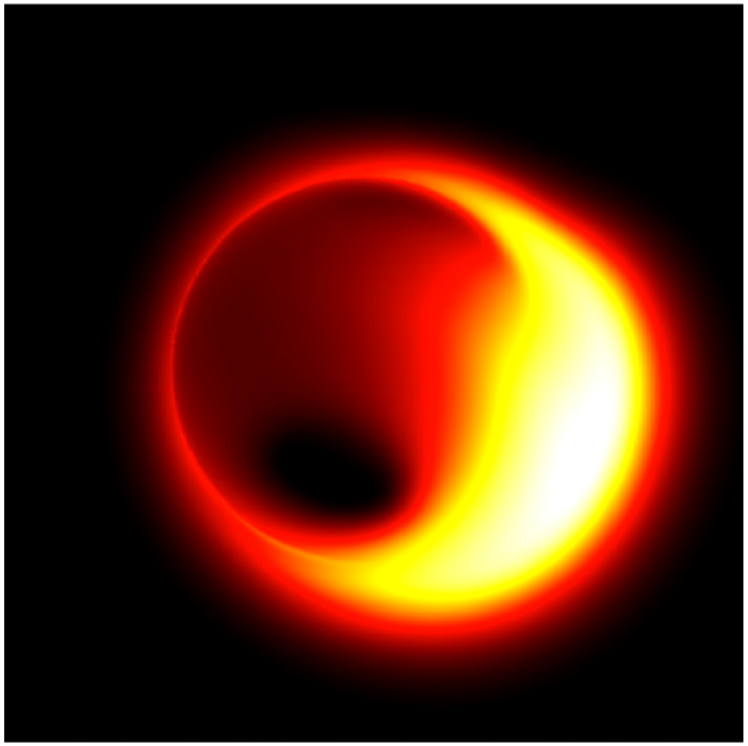
1 MODEL – 7 YEARS

Table 1
Data Epochs

Epoch	Year	Day(s)	Time	N[a]	Type[b]	Ref[c]
1	2007	100-101	11.00-13.67	19	VM	D8
2	2009	95	11.17-15.00	12	VM	F11
3	2009	96	11.50-14.56	19	VM	F11
4	2009	97	11.50-13.67	20	VM	F11
Totals	...	...	11.73 hrs	70		
5	2009	93	11.54-13.87	11	CP	F15
6	2009	96	12.46-12.79	3	CP	F15
7	2009	97	11.96-14.38	10	CP	F15
8	2011	88	12.37-13.52	7	CP	F15
9	2011	90	13.67-14.02	2	CP	F15
10	2011	91	11.93-13.53	5	CP	F15
11[d]	2011	94	11.78-14.51	17	CP	F15
12	2012	81	12.52-15.68	25	CP	F15
13	2013	80	12.55-15.43	28	CP	F15
14	2013	81	12.97-15.27	10	CP	F15
15	2013	82	12.97-14.88	15	CP	F15
16	2013	85	12.15-15.17	32	CP	F15
17	2013	86	12.55-13.95	16	CP	F15
Totals	...	...	25.58 hrs	181		

[a] Number of data points, including detections only
[b] Data types are visibility magnitudes (VM) and closure phases (CP)
[c] D8=DOEL8, F11=FISH11, F15=FISH15
[d] Contaminated by flare activity



AEB et al. 2016, ApJ, 820, 137

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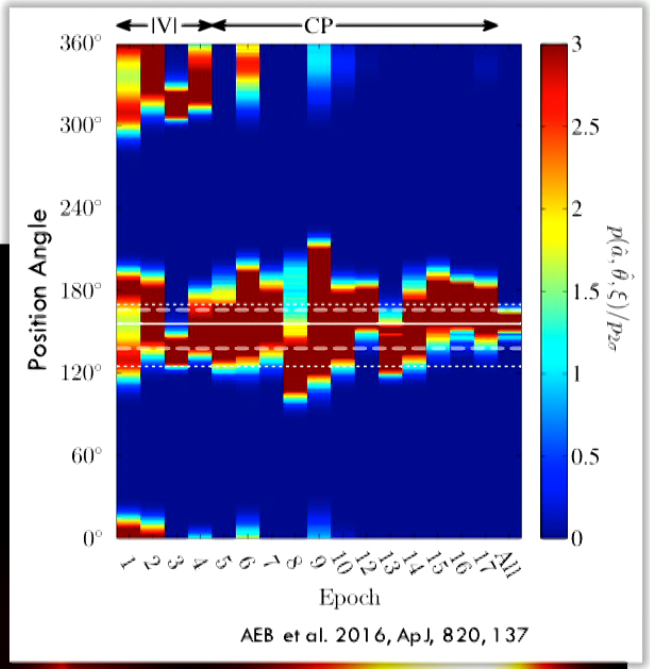
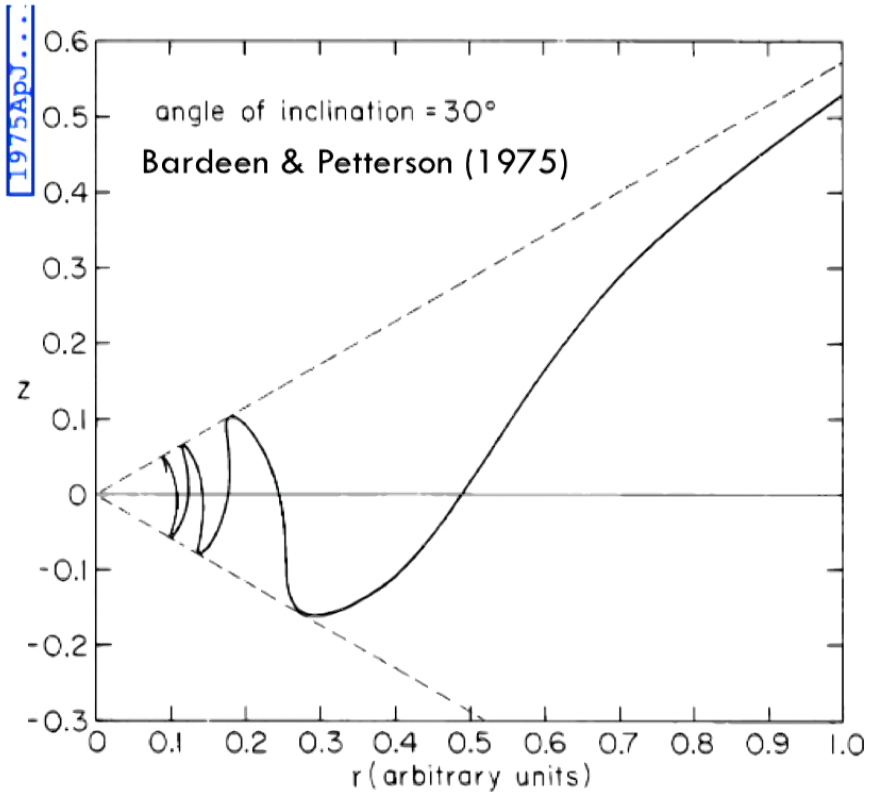
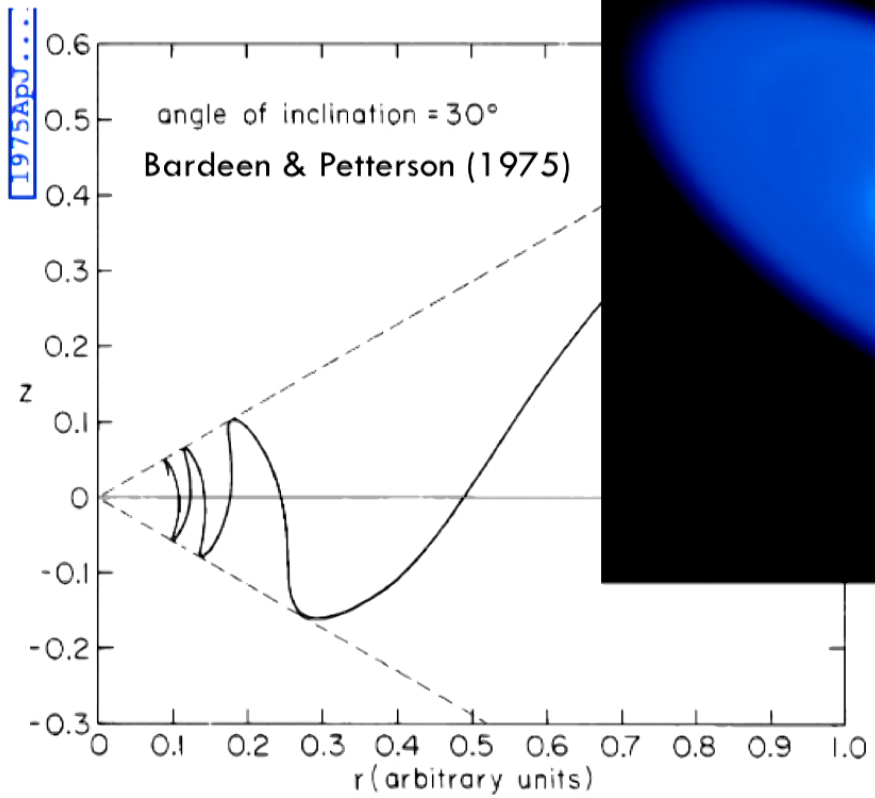


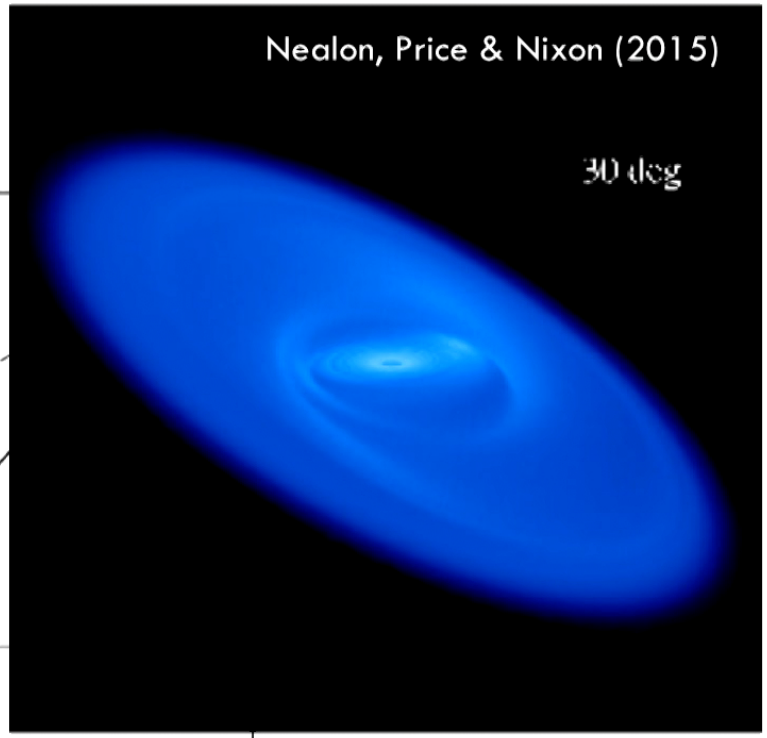
AEB et al. 2016, ApJ, 820, 137

BLACK HOLE SPIN & DISK WARPS

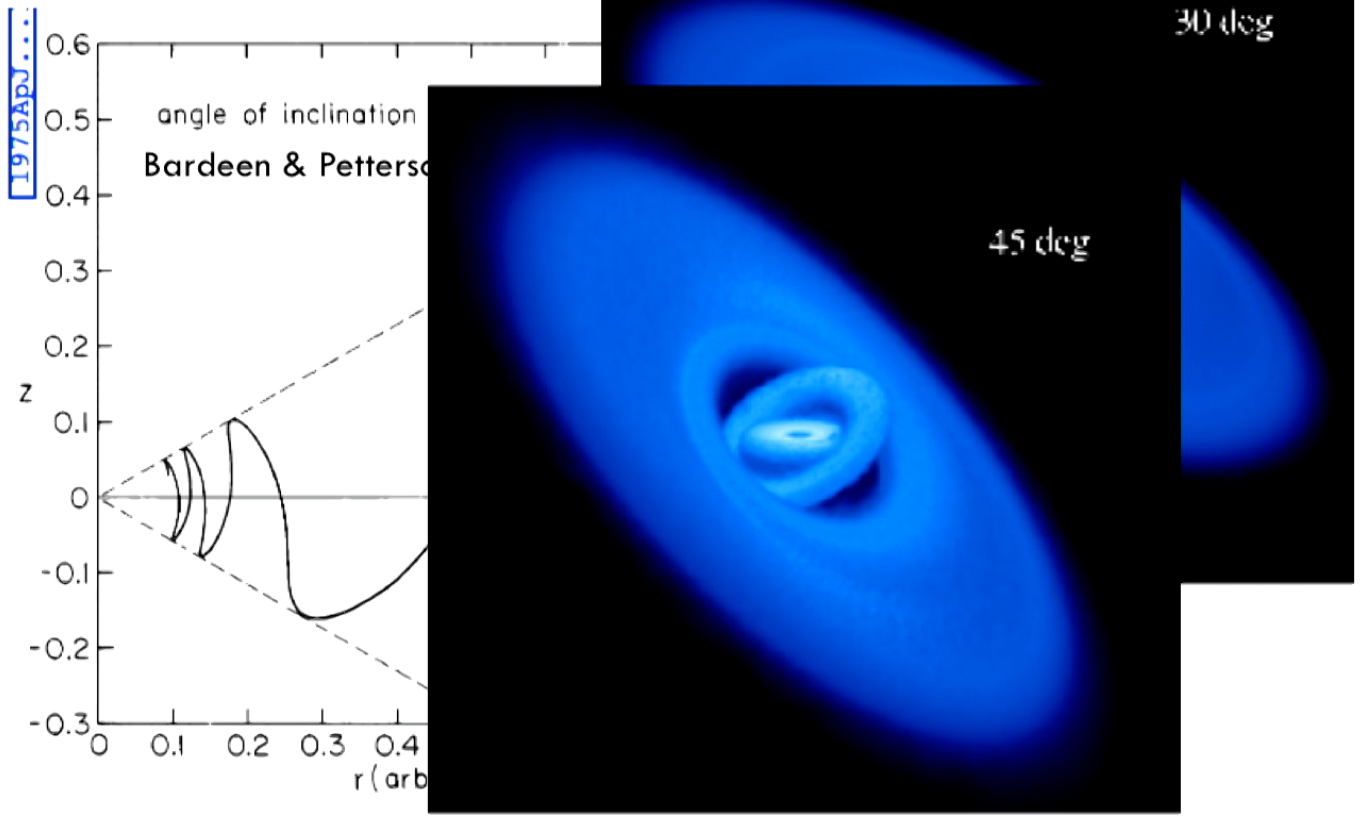


BLACK HOLE SPIN & DISK WARPS



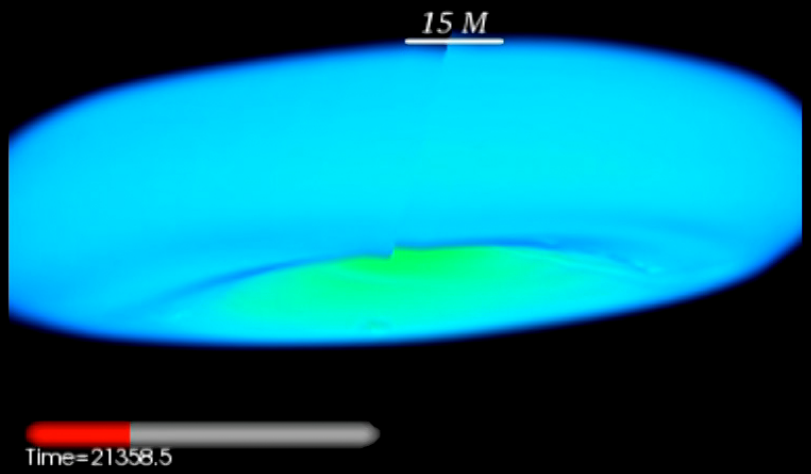


BLACK HOLE SPIN & DISK WARPS



LENSE-THIRRING AND THE EHT

Courtesy of Chris Fragile



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LENSE-THIRRING AND THE EHT

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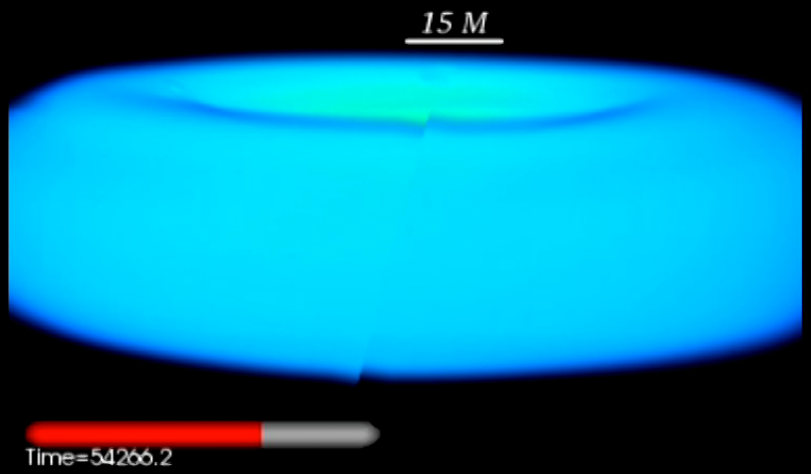

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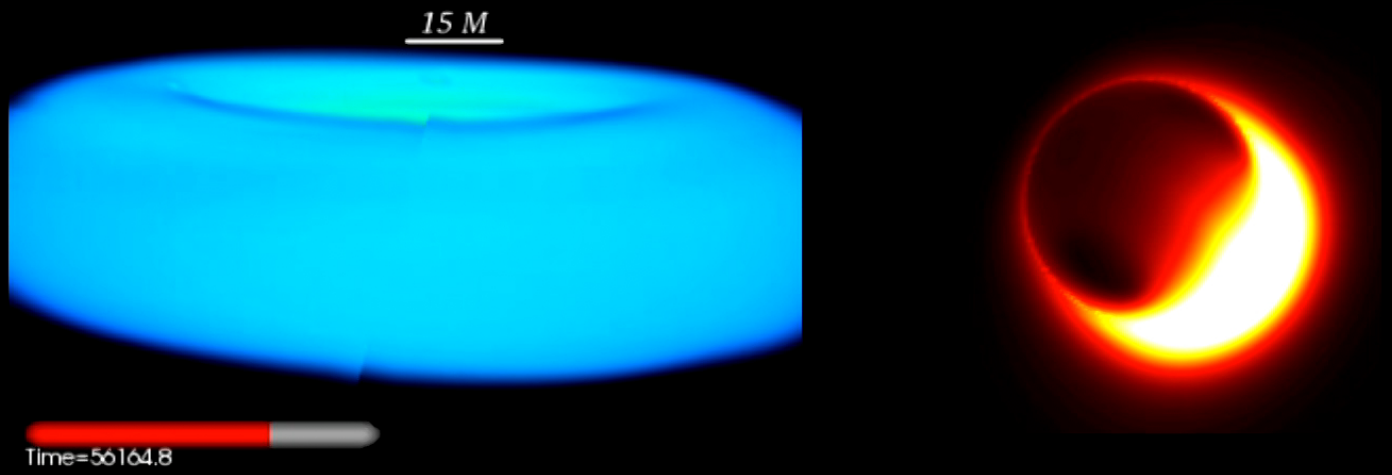

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LENSE-THIRRING AND THE EHT

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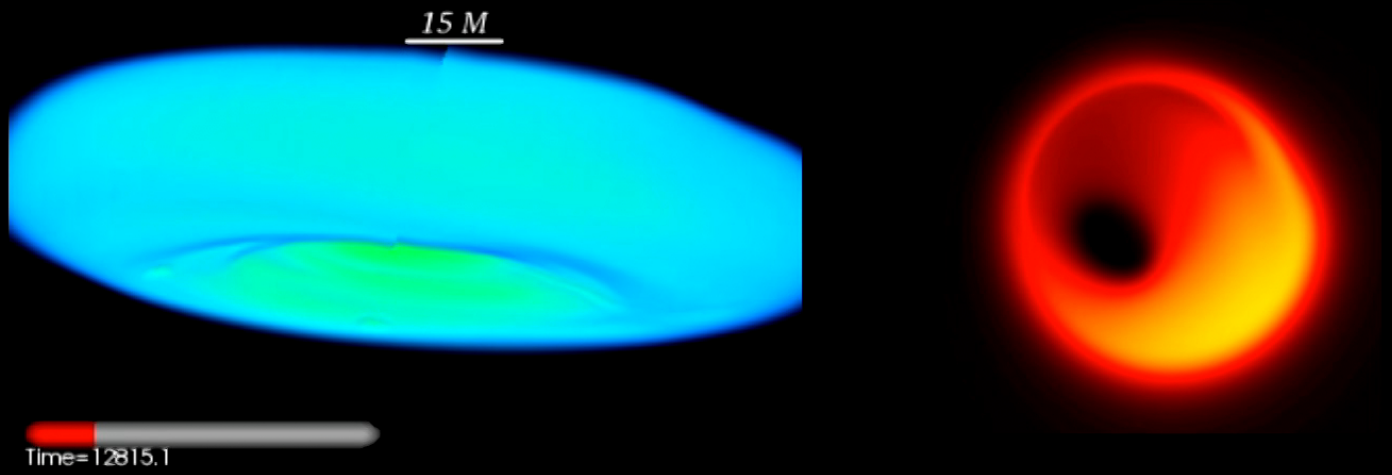

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LENSE-THIRRING AND THE EHT

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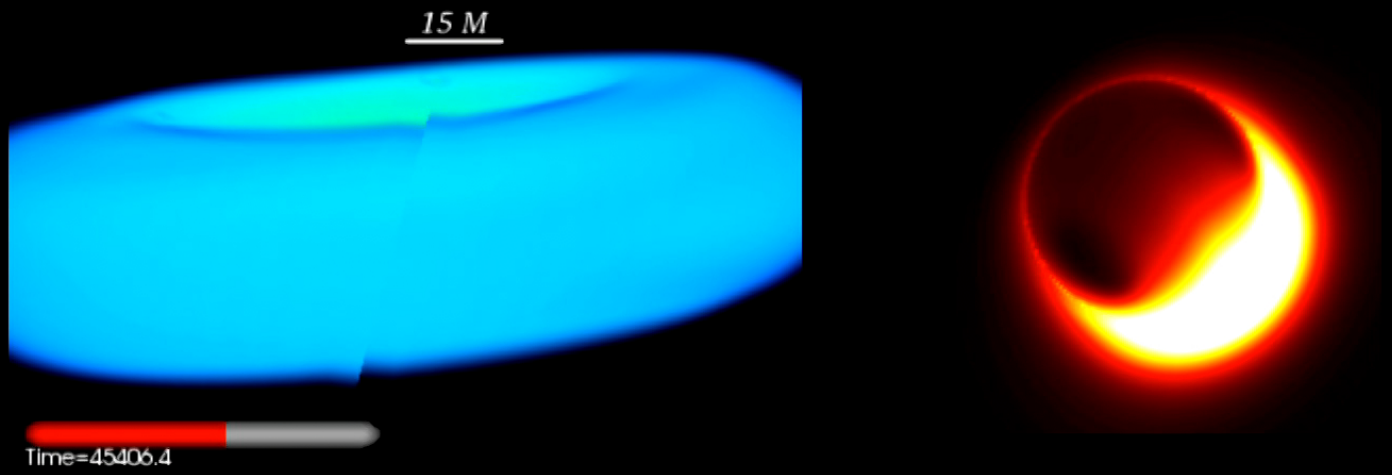

$$T_{prec} \sim \frac{L_{disk}}{\tau_{LT}} \sim \frac{2}{a \sin\Theta} \left(\frac{r_o}{10^3}\right)^{5/2} \text{yr}$$

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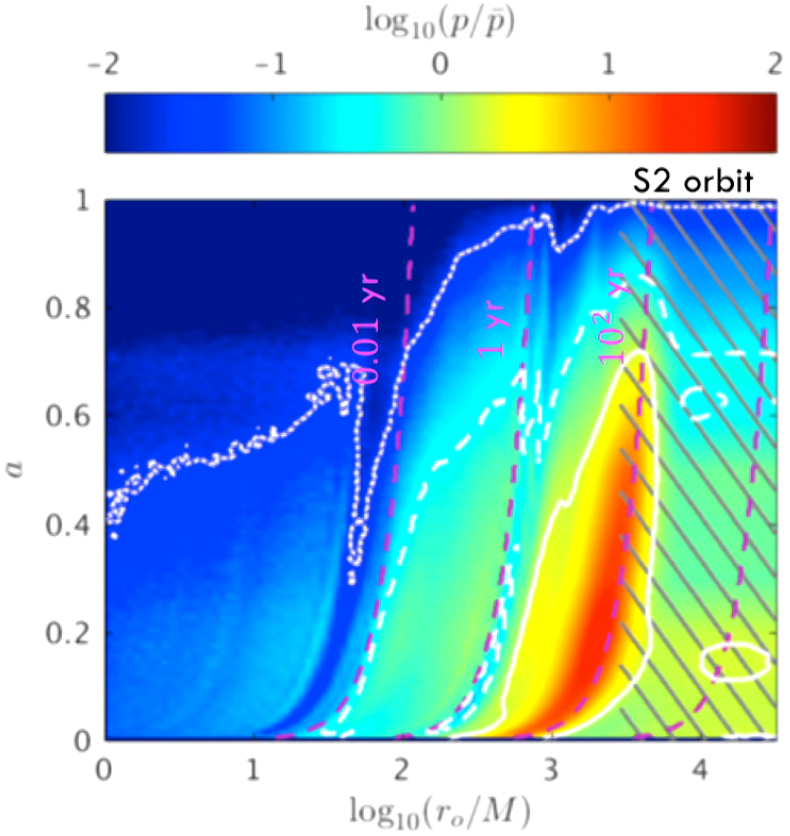
ACCRETION DISK SIZE FROM 7 YEARS OF EHT



$$\chi^2(a, \hat{L}) = \sum_{\text{nights}} \chi_j^2(a, \hat{L})$$

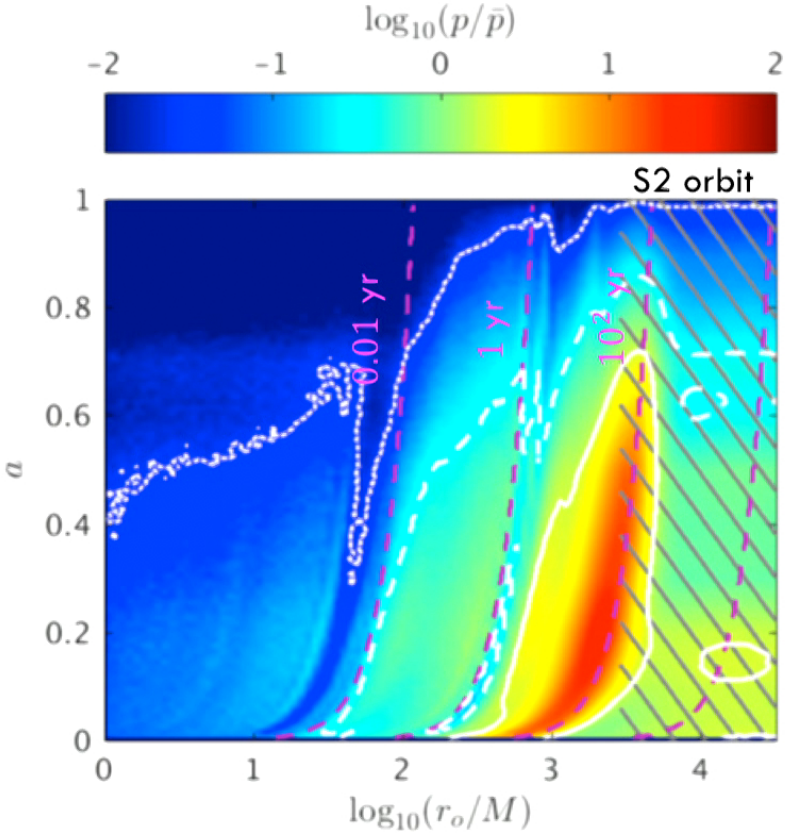
$$\downarrow$$

$$\chi^2(a, r_o, \hat{n}_{\text{prec}}, \hat{L}_0)$$

$$= \sum_{\text{nights}} \chi_j^2[a, \hat{L}(a, r_o, \hat{n}_{\text{prec}}, \hat{L}_0, t_j)]$$

Carlos Wang,
Mansour Karami

ACCRETION DISK SIZE FROM 7 YEARS OF EHT



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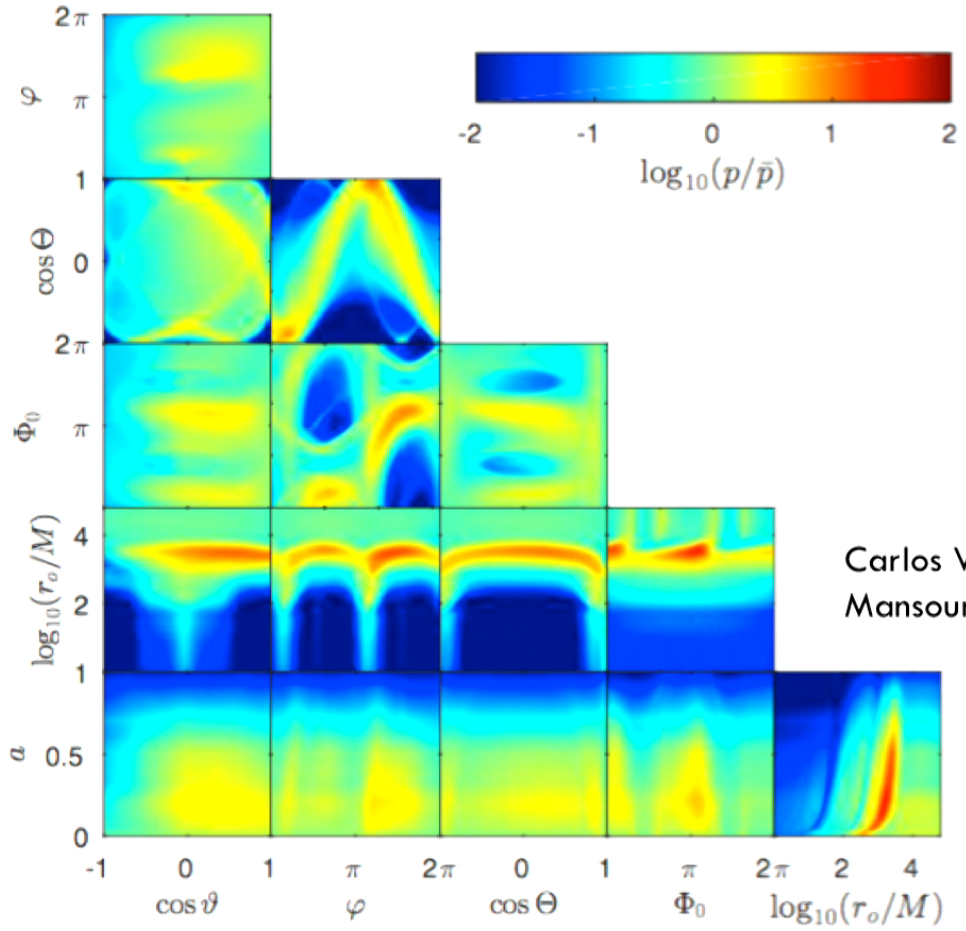
Carlos Wang,
Mansour Karami

HIGHLY DEGENERATE, BUT …



Carlos Wang,
Mansour Karami

JET ORIGINS DAYS

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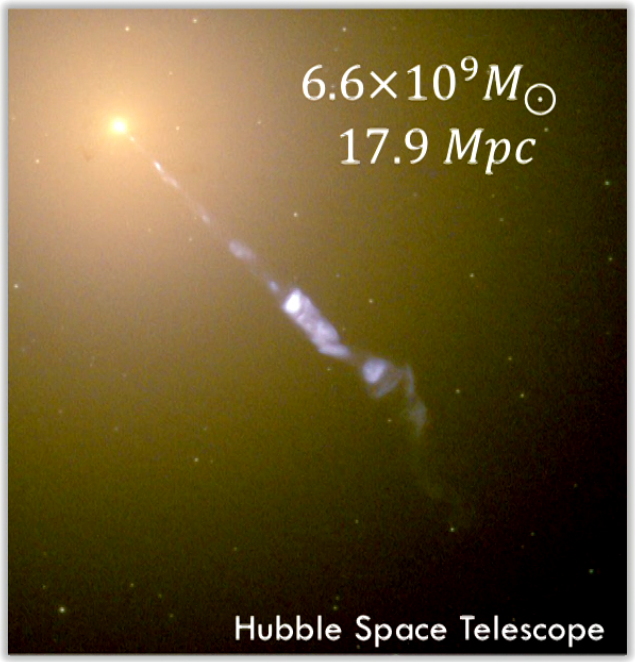
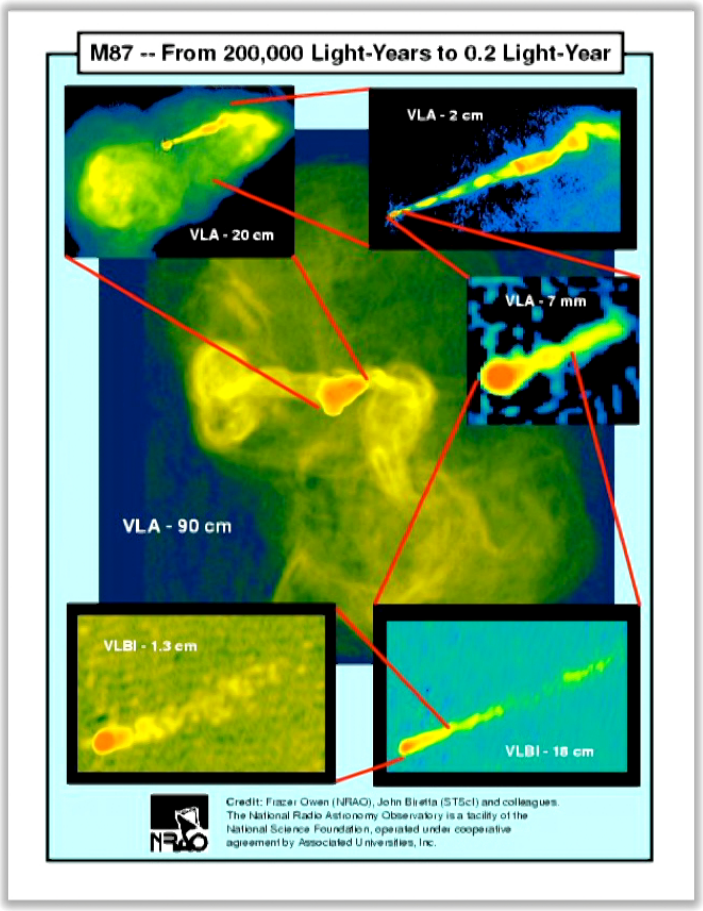
M87 – PROTOTYPICAL BLACK HOLE JET





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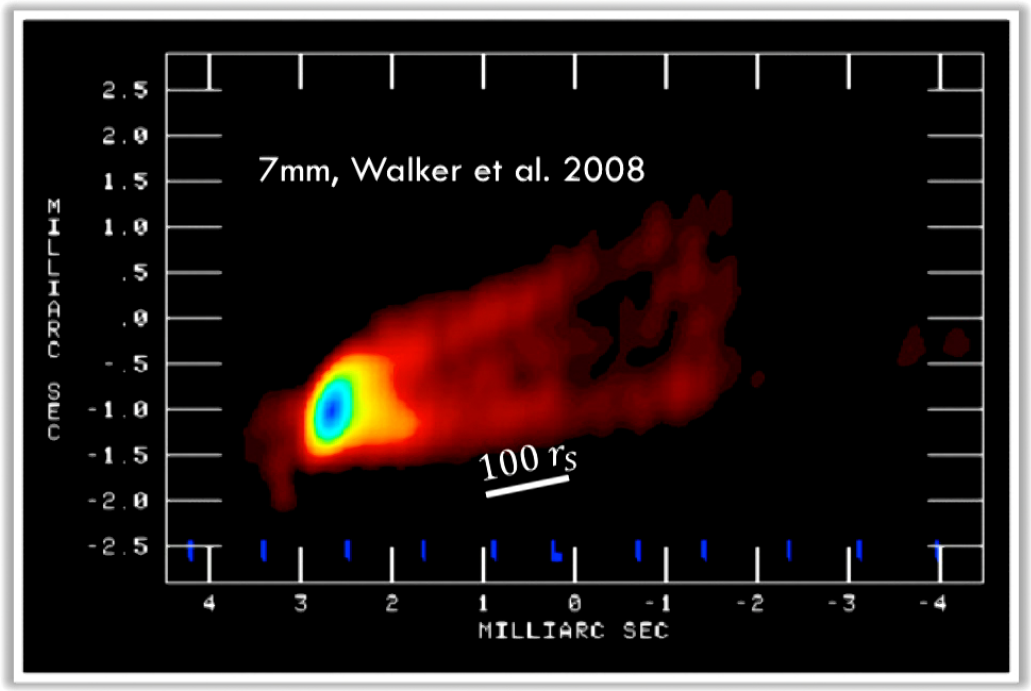
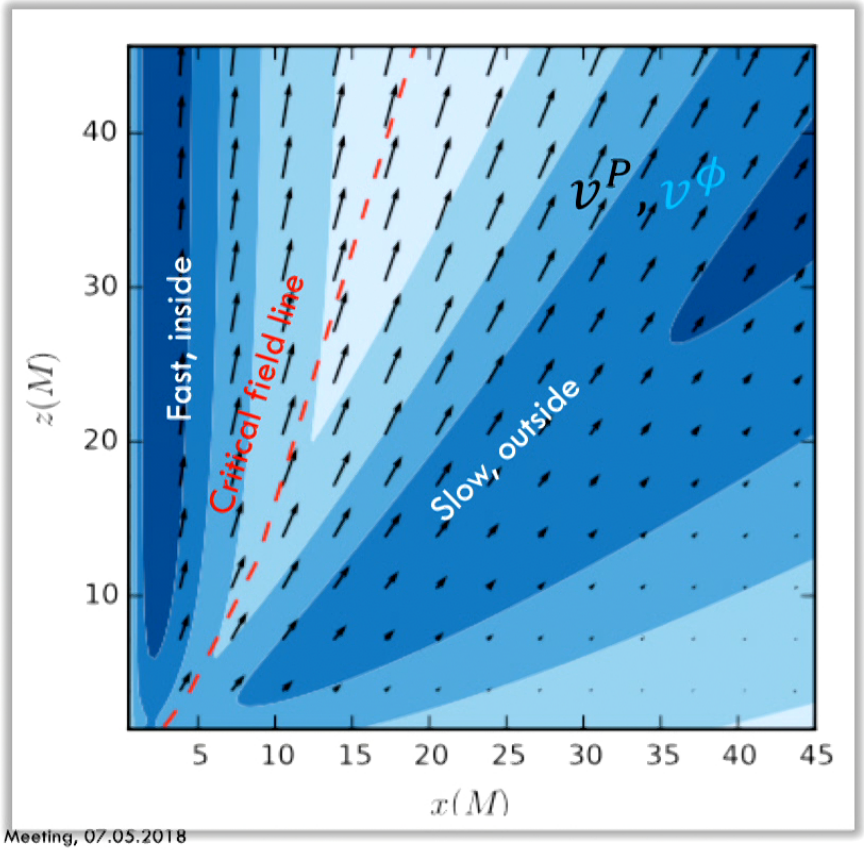
FLARES IN M87?



JET STRUCTURES

Spin driven, Poynting Blandford-Znajek?



Jet Launching Needs:

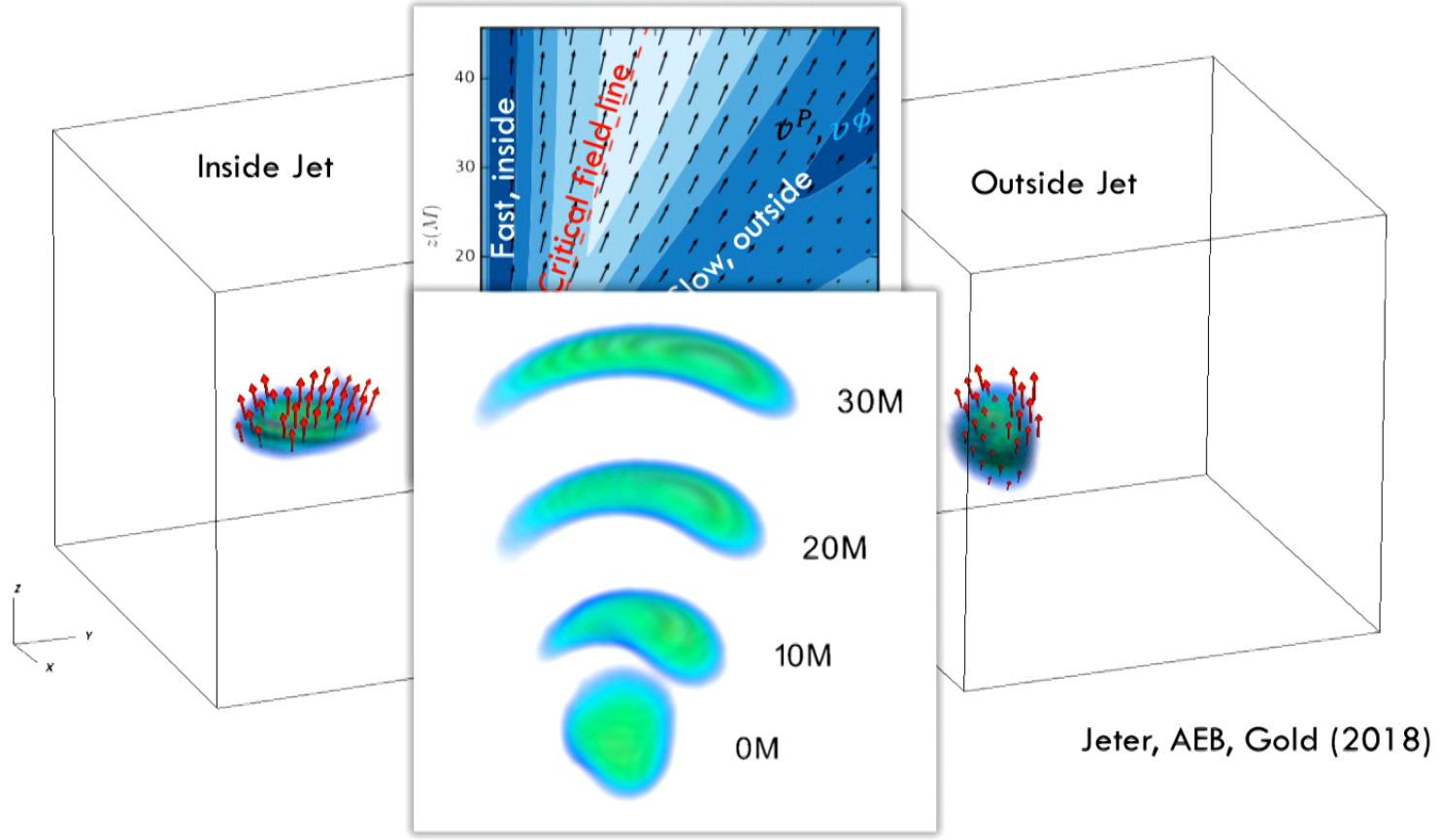
- Angular momentum
- Magnetic fields
- Roger Blandford

But …

Winds
Blandford-Payne?

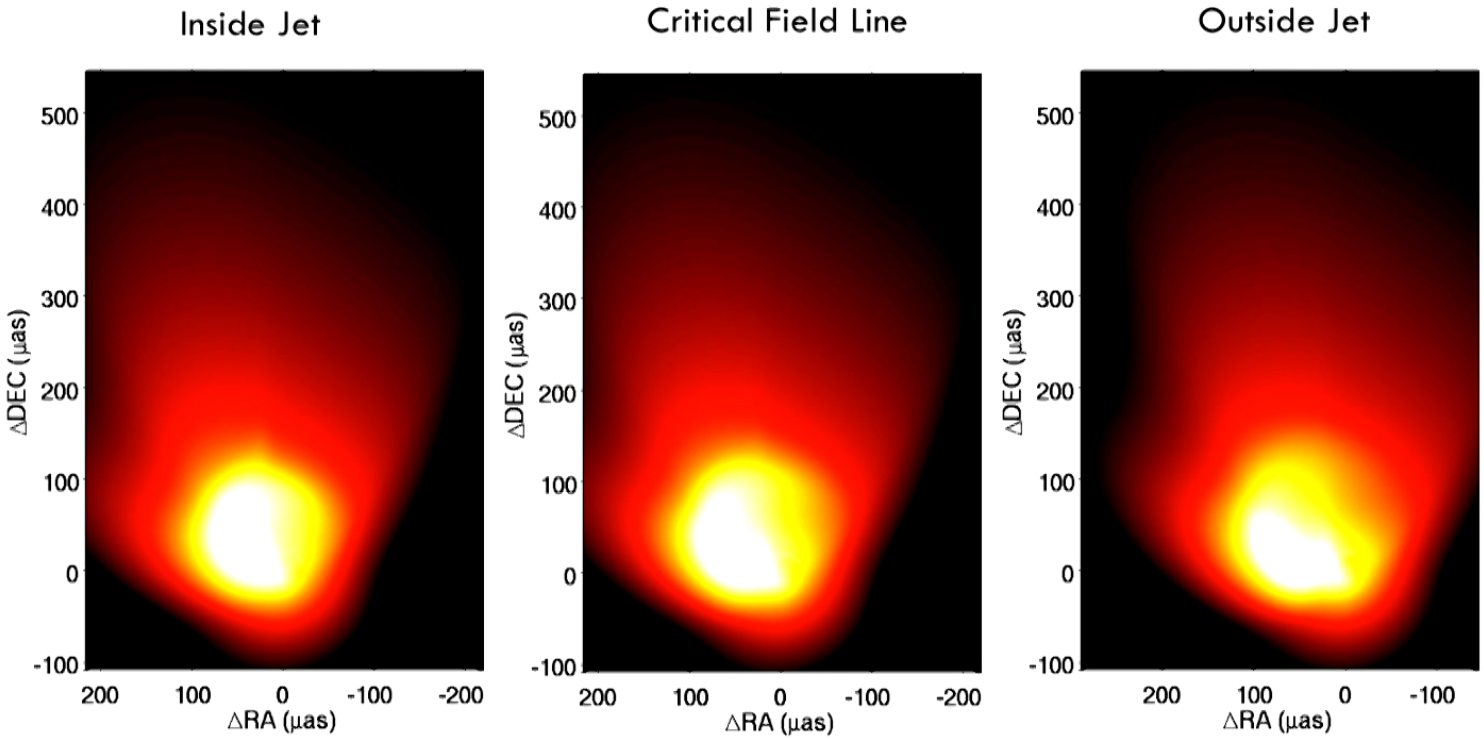
Jeter, AEB, Gold (2018)

SHEARING SPOTS AND ACCELERATING VELOCITY FIELDS



Jeter, AEB, Gold (2018)

IMAGES OF SHEARING SPOTS: BLANDFORD-ZNAJEK VS BLANDFORD-PAYNE



Britt Jeter

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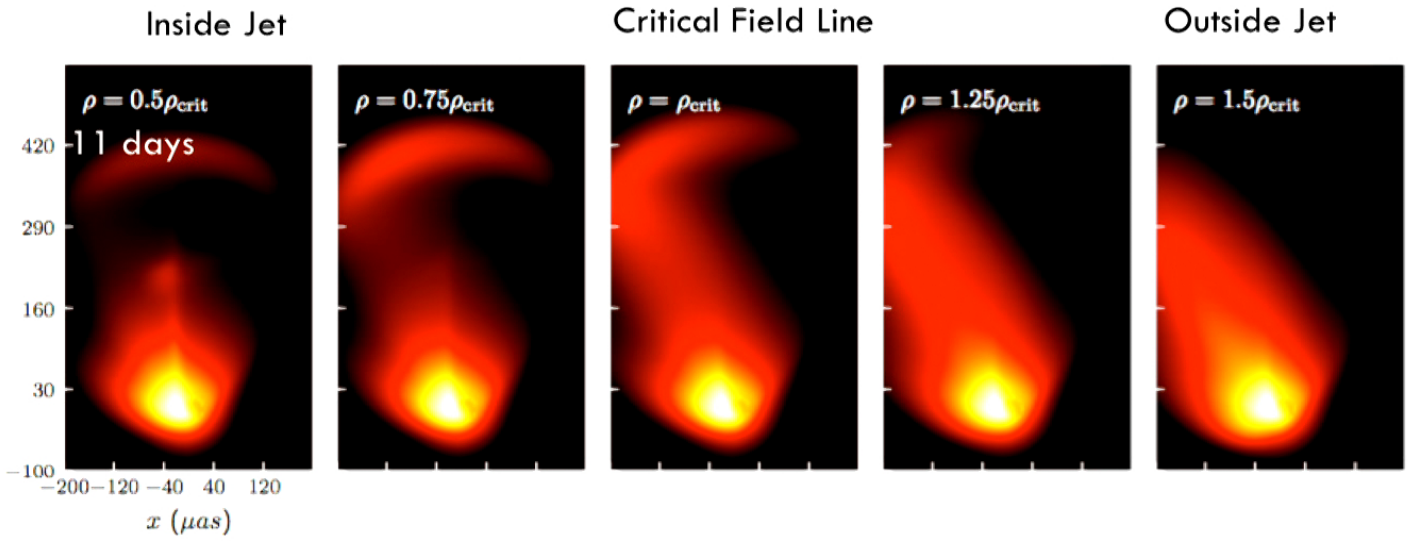
Note: Different angular scale,
Different intensity scale!

IMAGES OF SHEARING SPOTS: BLANDFORD-ZNAJEK VS BLANDFORD-PAYNE



Jeter, AEB, Gold (2018)

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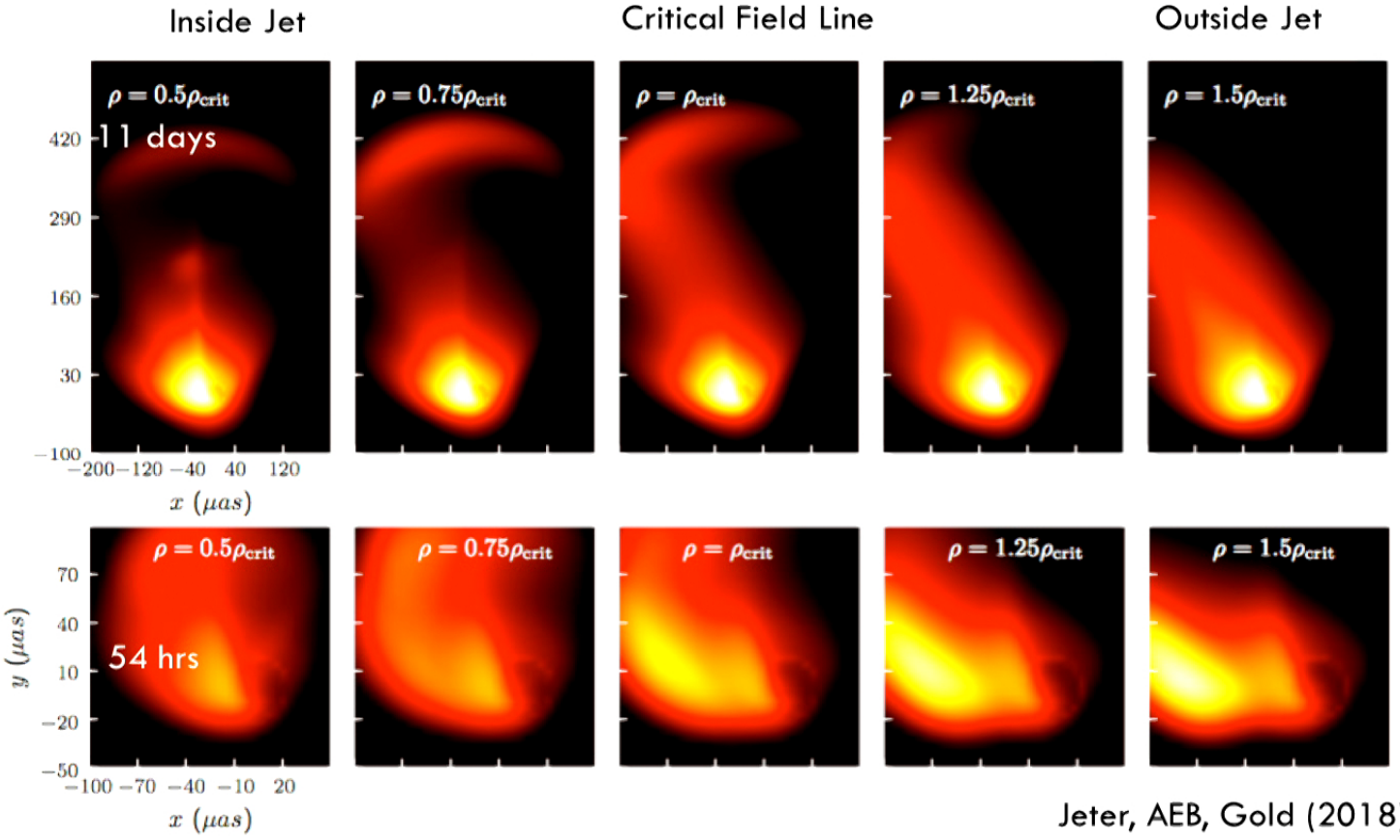
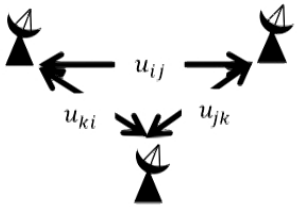
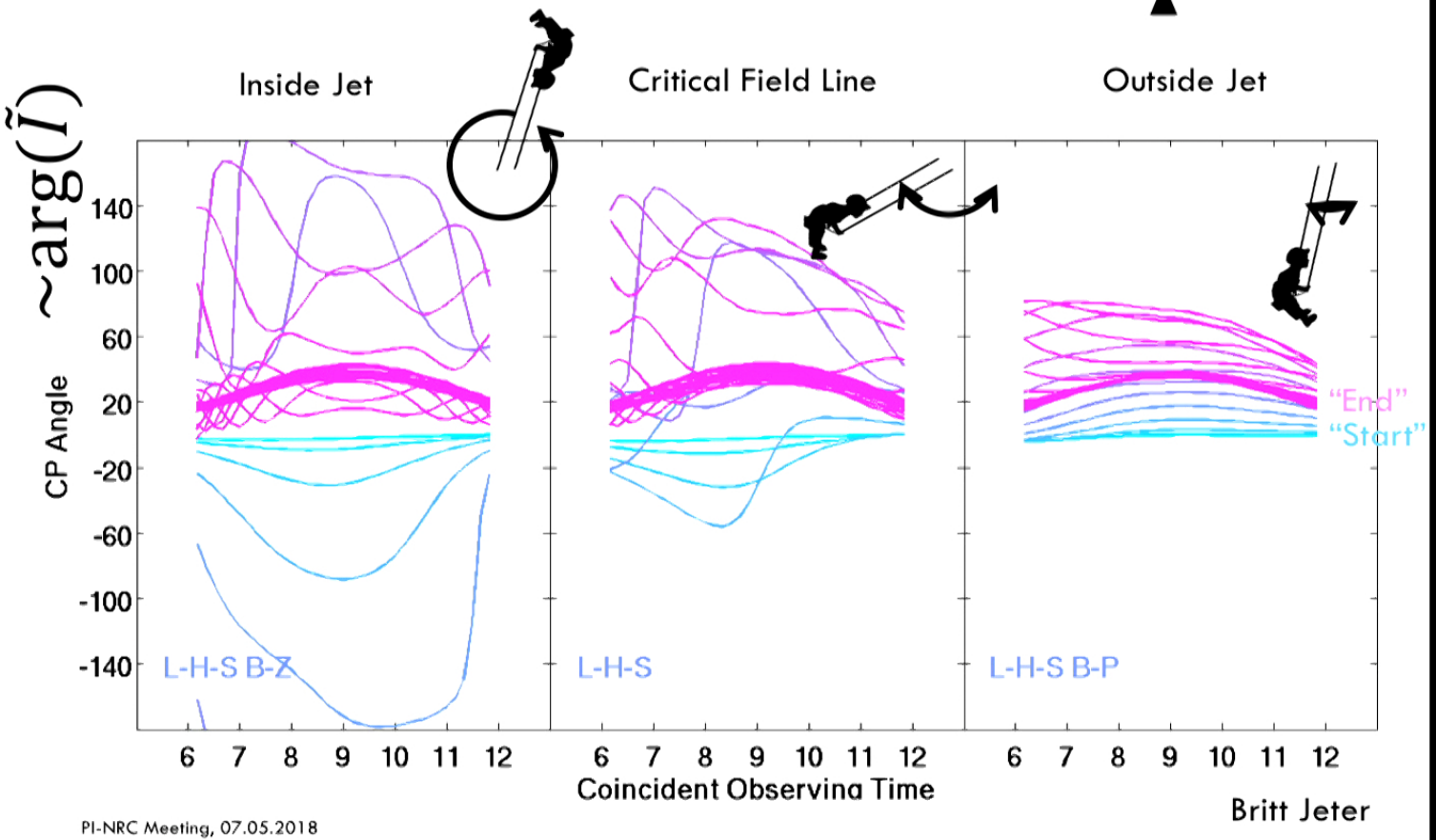


Jeter, AEB, Gold (2018)

MOVIES WITHOUT IMAGES: TRIPLETS OF STATIONS





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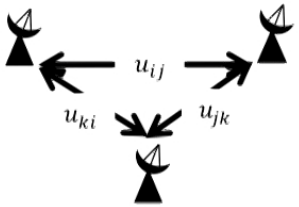

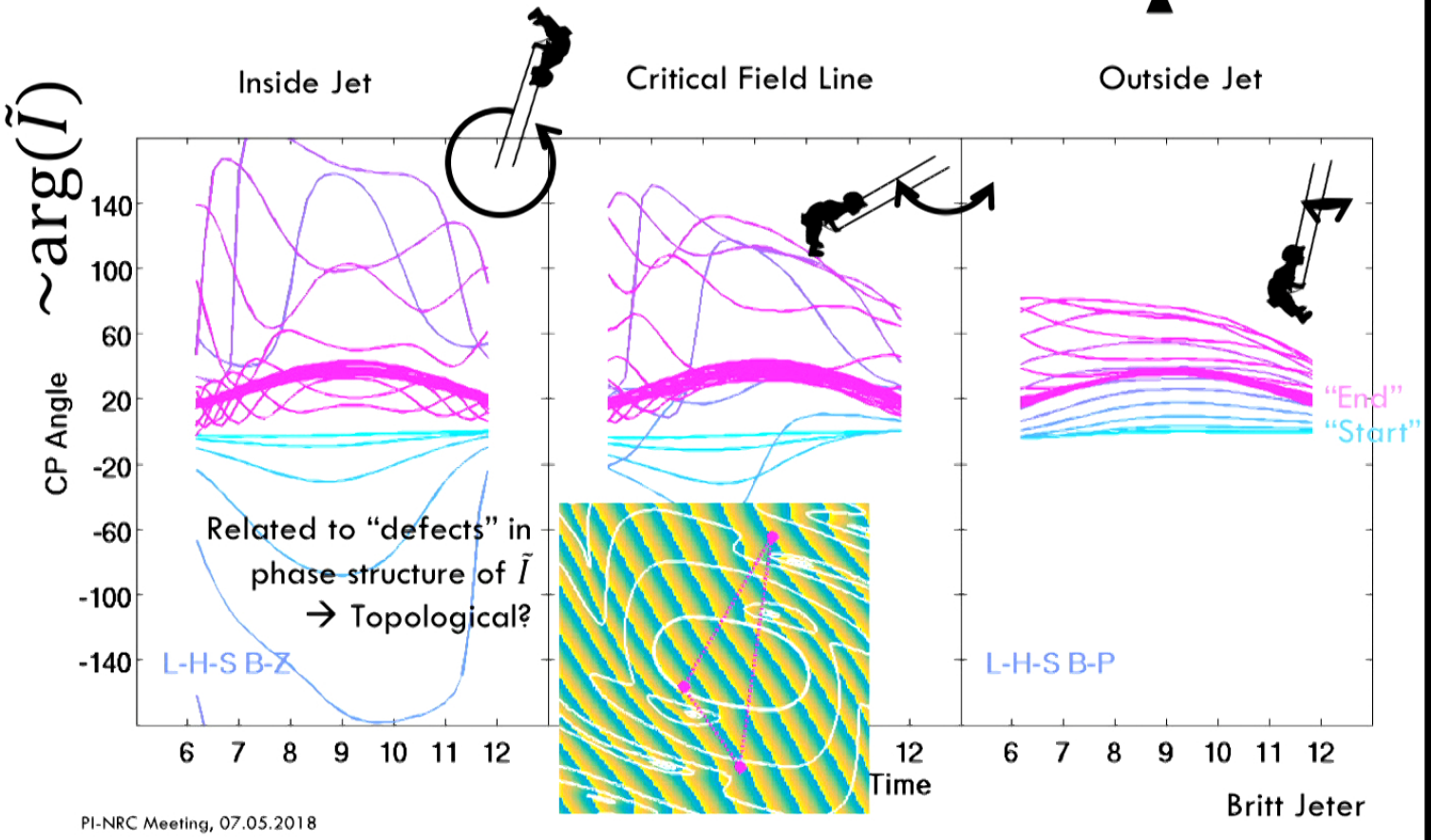

SPACETIME TOMOGRAPHY MINUTES

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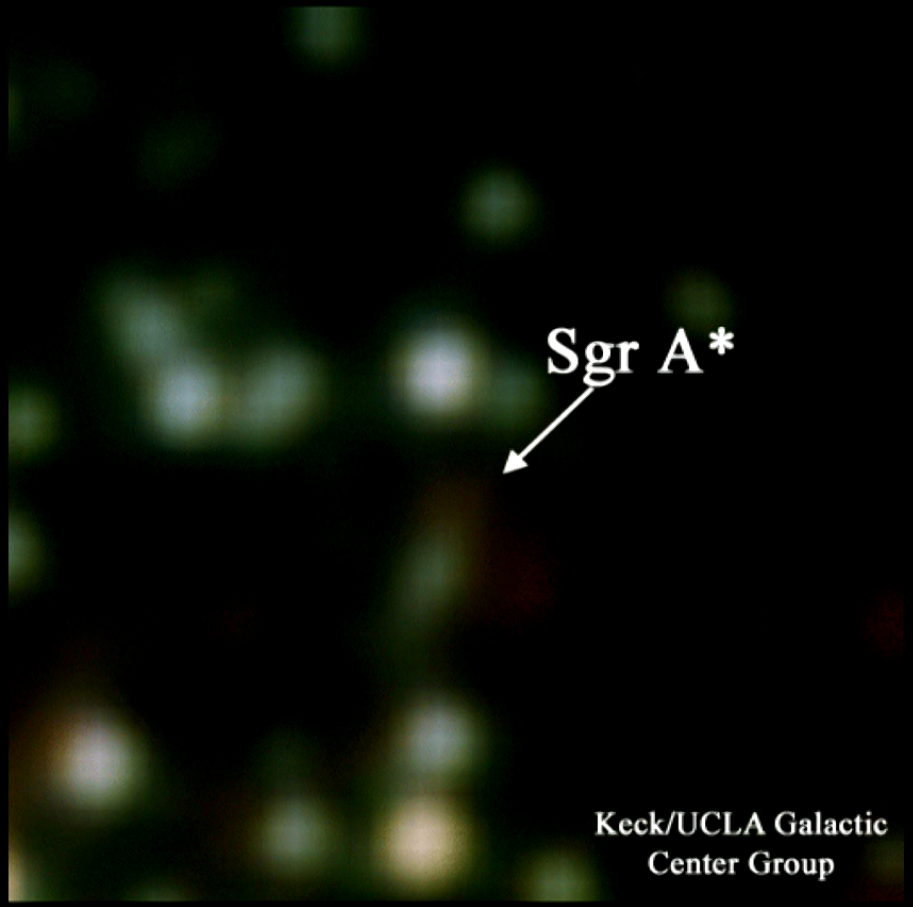
FLARES IN THE GALACTIC CENTER



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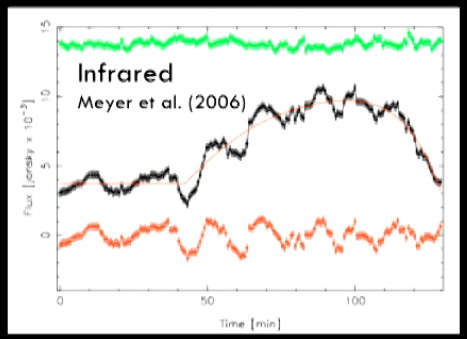

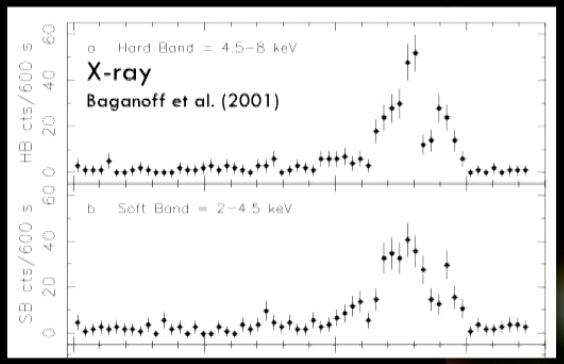

Sgr A*

Keck/UCLA Galactic Center Group

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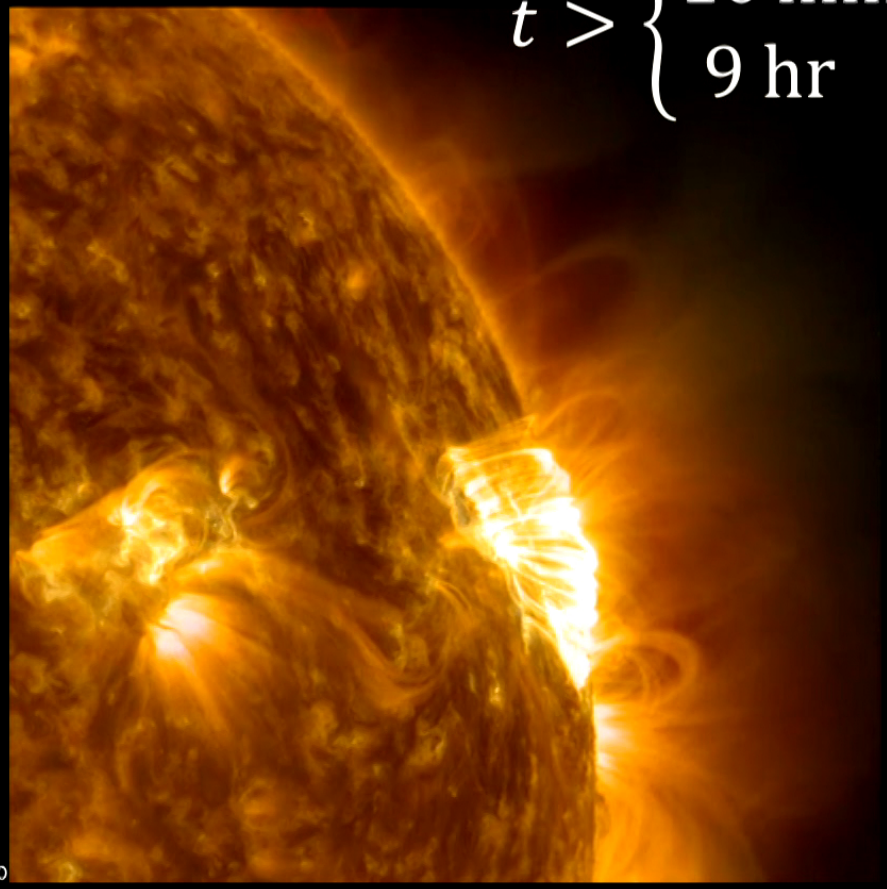
SOMETIMES BY A LOT

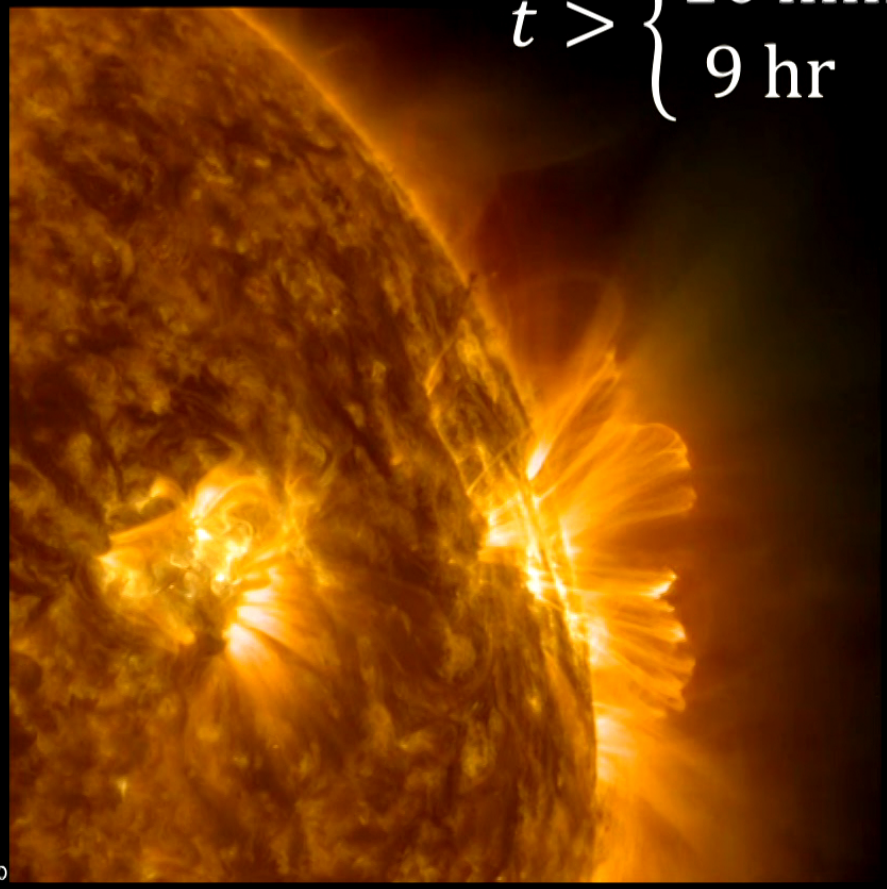
$$t > \begin{cases} 10\ \text{min Sgr A} * \\ 9\ \text{hr} \quad \text{M87} \end{cases}$$



PI-NRC Meeting, 07.05.20

SOMETIMES BY A LOT

$$t > \begin{cases} 10\ \text{min Sgr A} * \\ 9\ \text{hr} \quad \text{M87} \end{cases}$$



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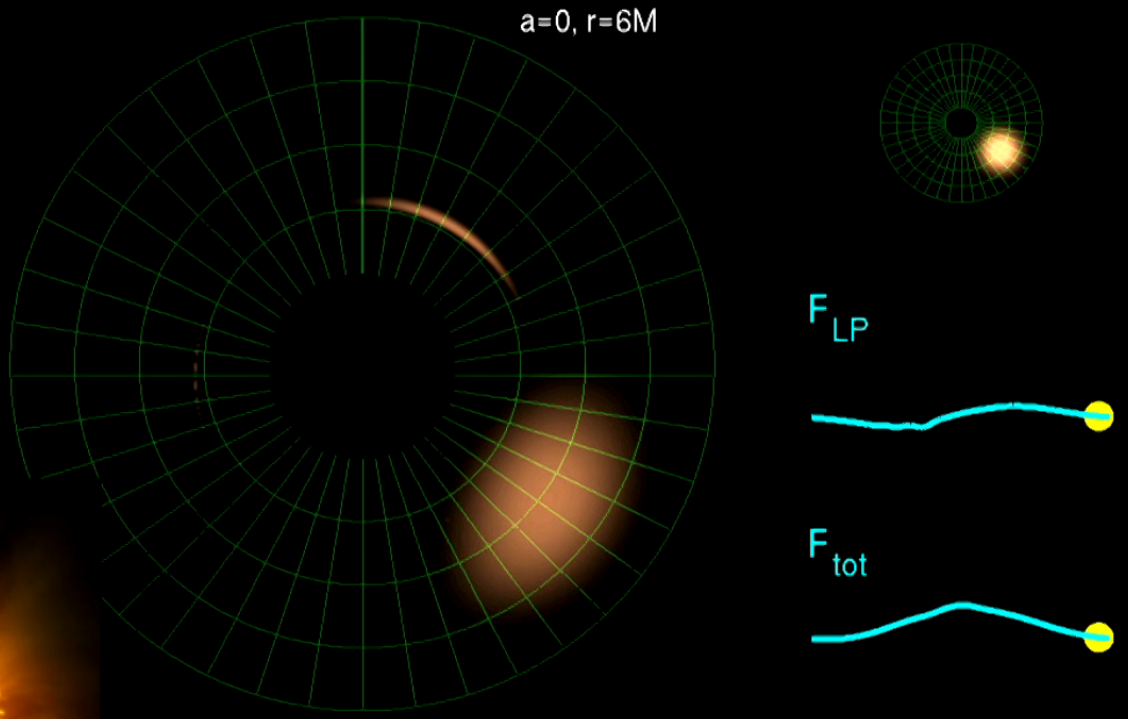
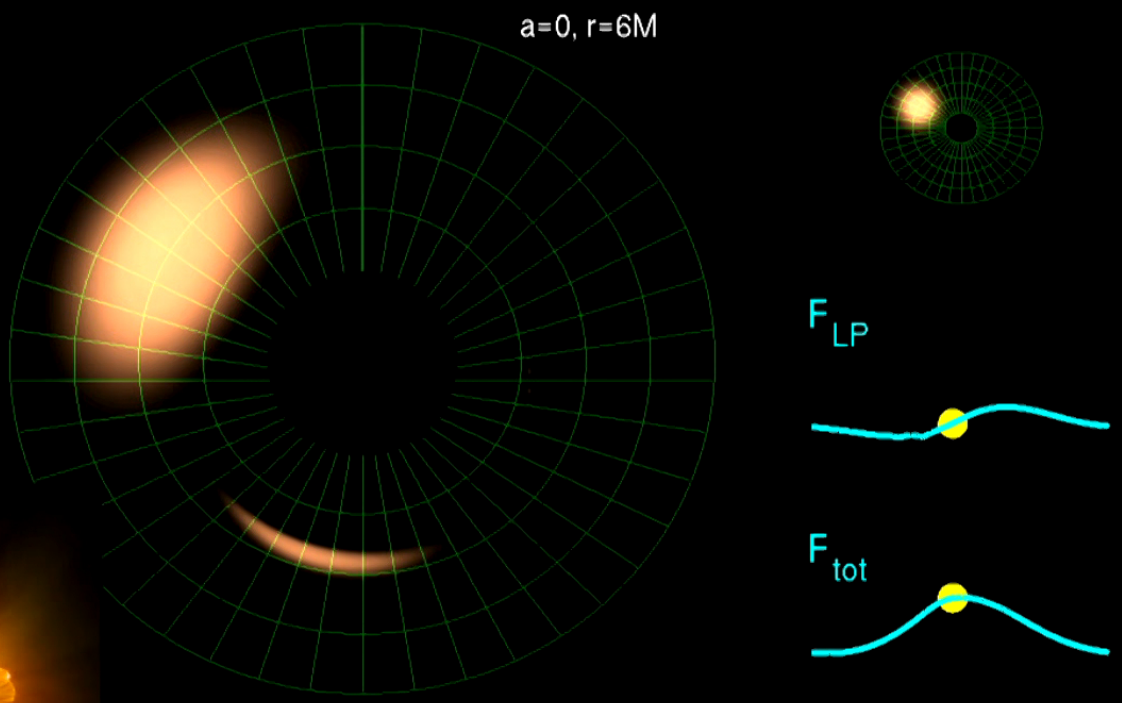
FLARES IN SGR A*: NONTHERMAL CATASTROPHES



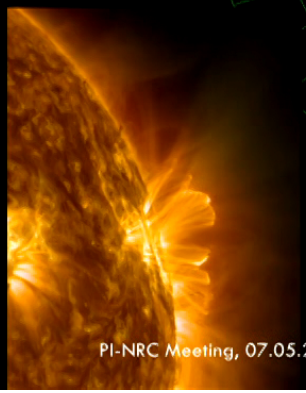
Broderick & Loeb, 2006, MNRAS, 367, 905

PI-NRC Meeting, 07.05.2018

FLARES IN SGR A*: NONTHERMAL CATASTROPHES



Broderick & Loeb, 2006, MNRAS, 367, 905



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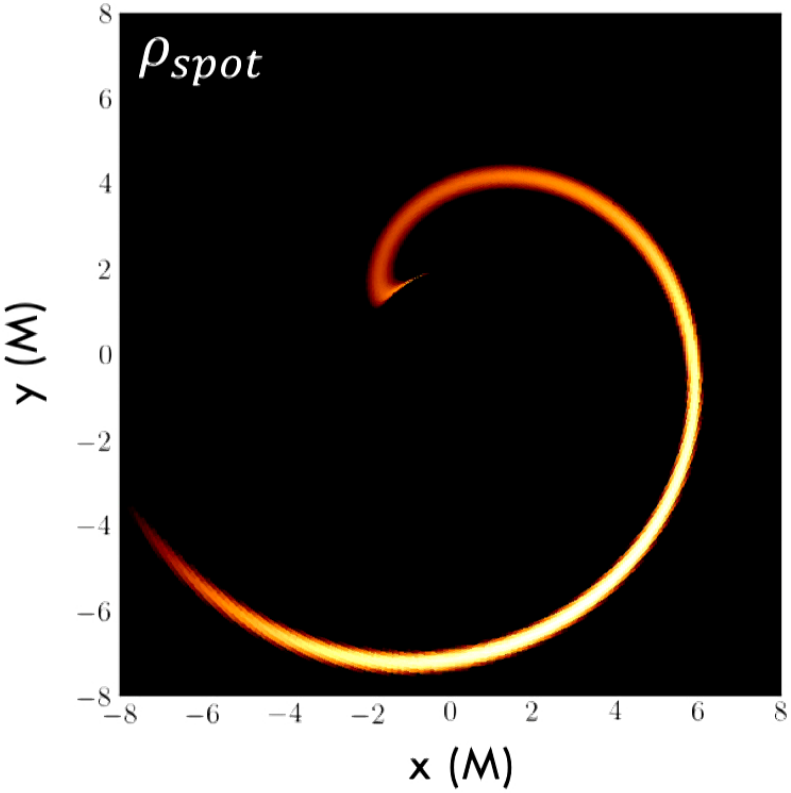
SHEARING VS. STATIC SPOTS

Paul Tiede, Hung-Yi Pu



PI-NRC Meeting, 07.05.2018

TURBULENCE: ANGULAR MOMENTUM TRANSPORT

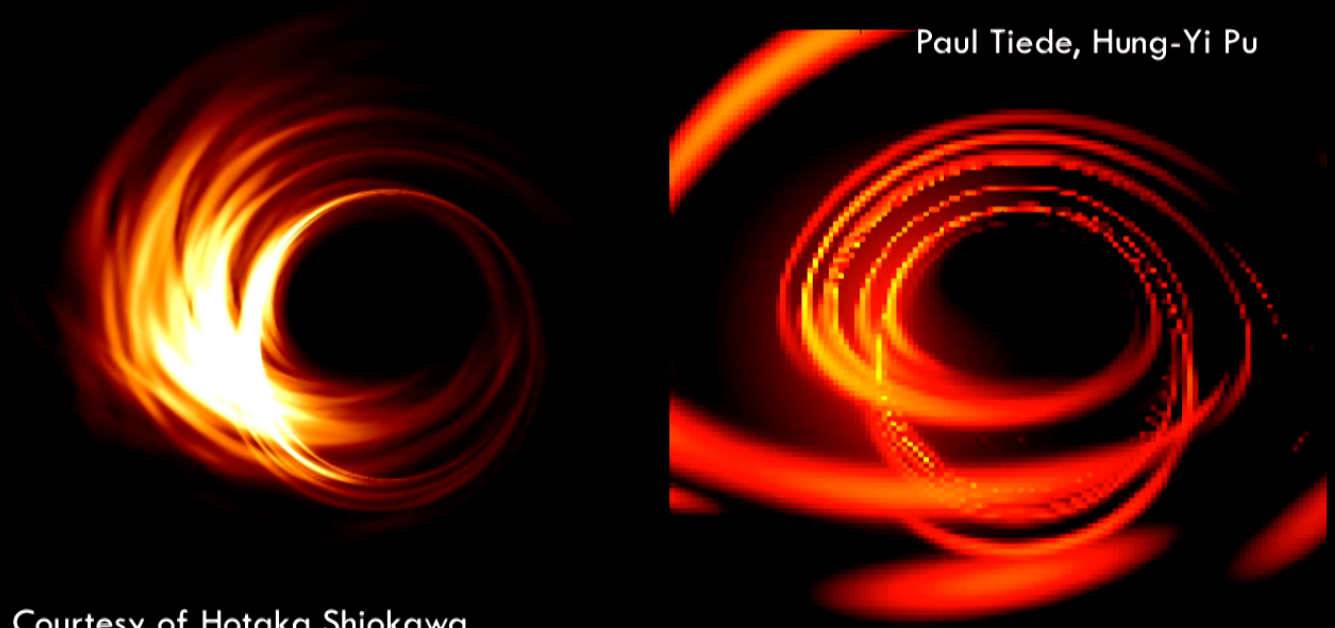
Courtesy of Hotaka Shiokawa

Britt Jeter

PI-NRC Meeting, 07.05.2018

TURBULENCE: ANGULAR MOMENTUM TRANSPORT

Paul Tiede, Hung-Yi Pu



Courtesy of Hotaka Shiokawa

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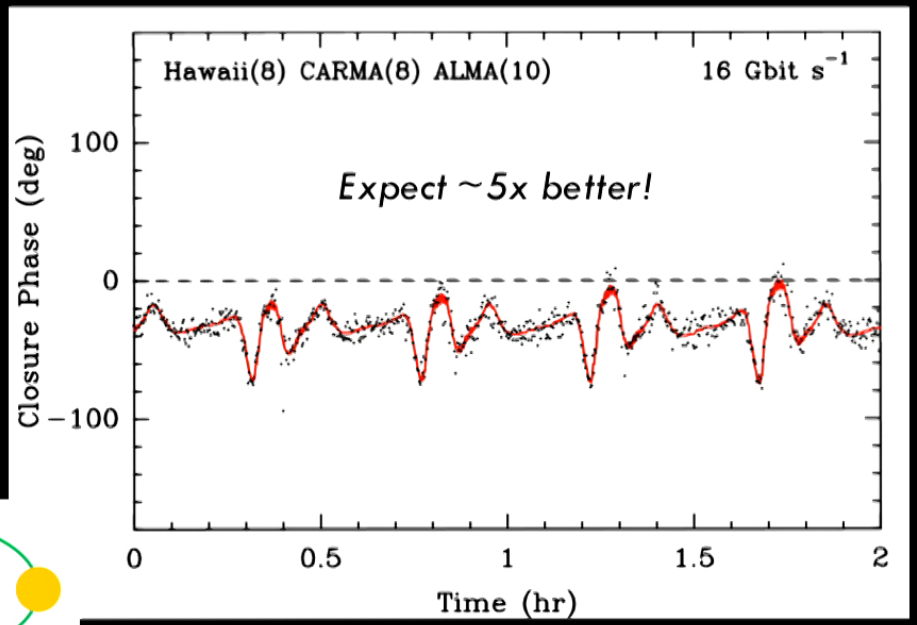
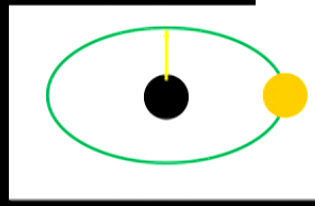
THE SHAPE OF SPACETIME II: SPACETIME TOMOGRAPHY

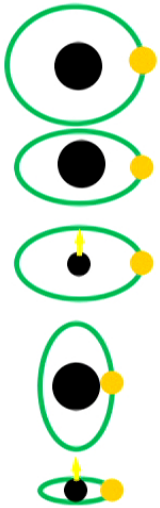


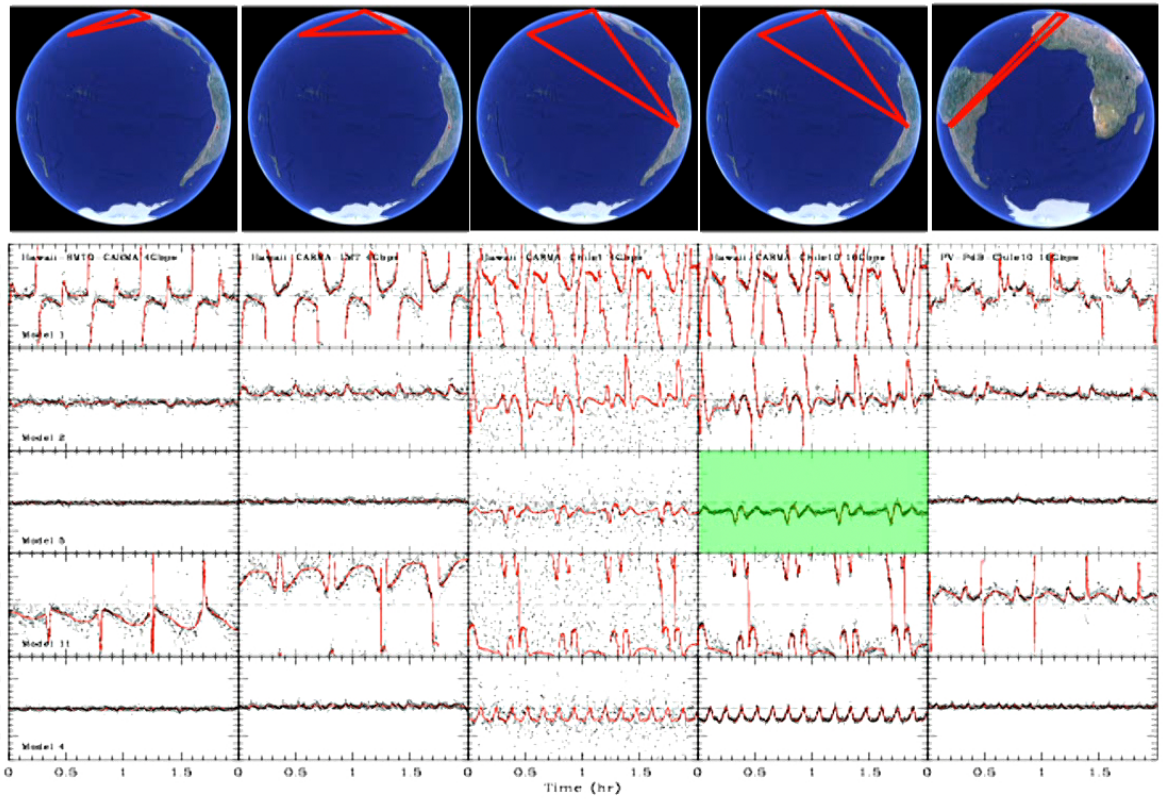
a = 0.9
Hot-spot at ~ 6M
Period = 27 min.



Doeleman, Fish, A.E.B., Loeb & Rogers (2009)

CLOSURE PHASE EVOLUTION





Doeleman, Fish, A.E.B., Loeb & Rogers (2009)

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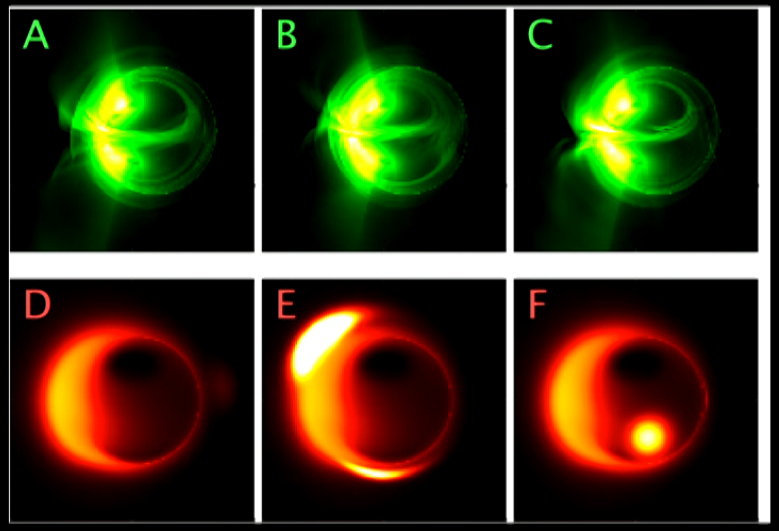
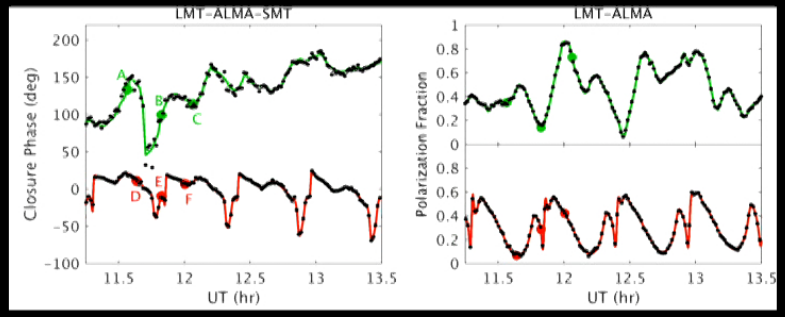
THE SHAPE OF SPACETIME: SPACETIME TOMOGRAPHY

Roman Gold & AEB

a = 0
Hot-spot at ~ 6M
Period = 27 min.





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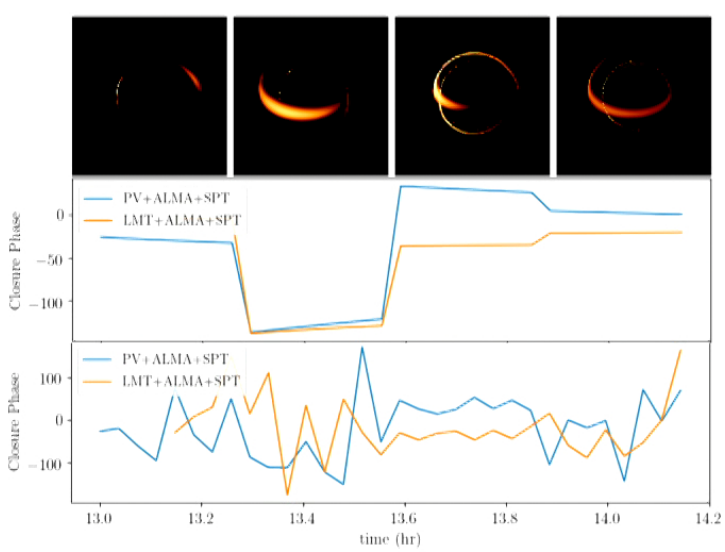
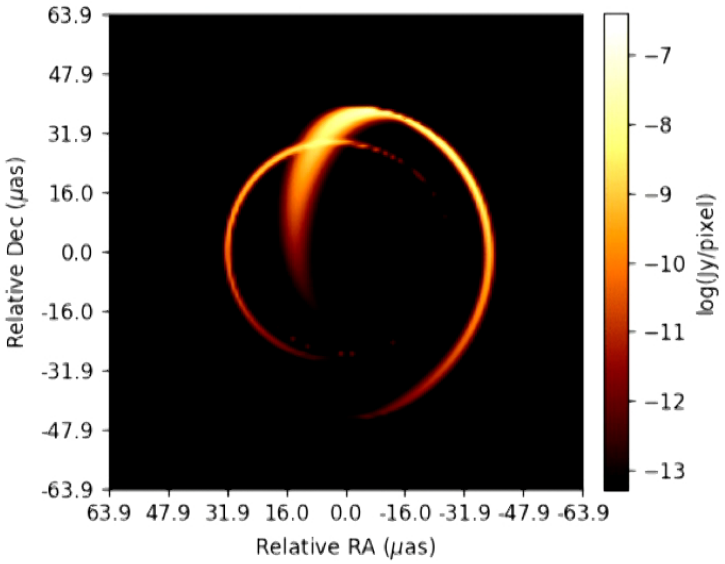
MAPPING SPACETIME?

4-frame "movie"





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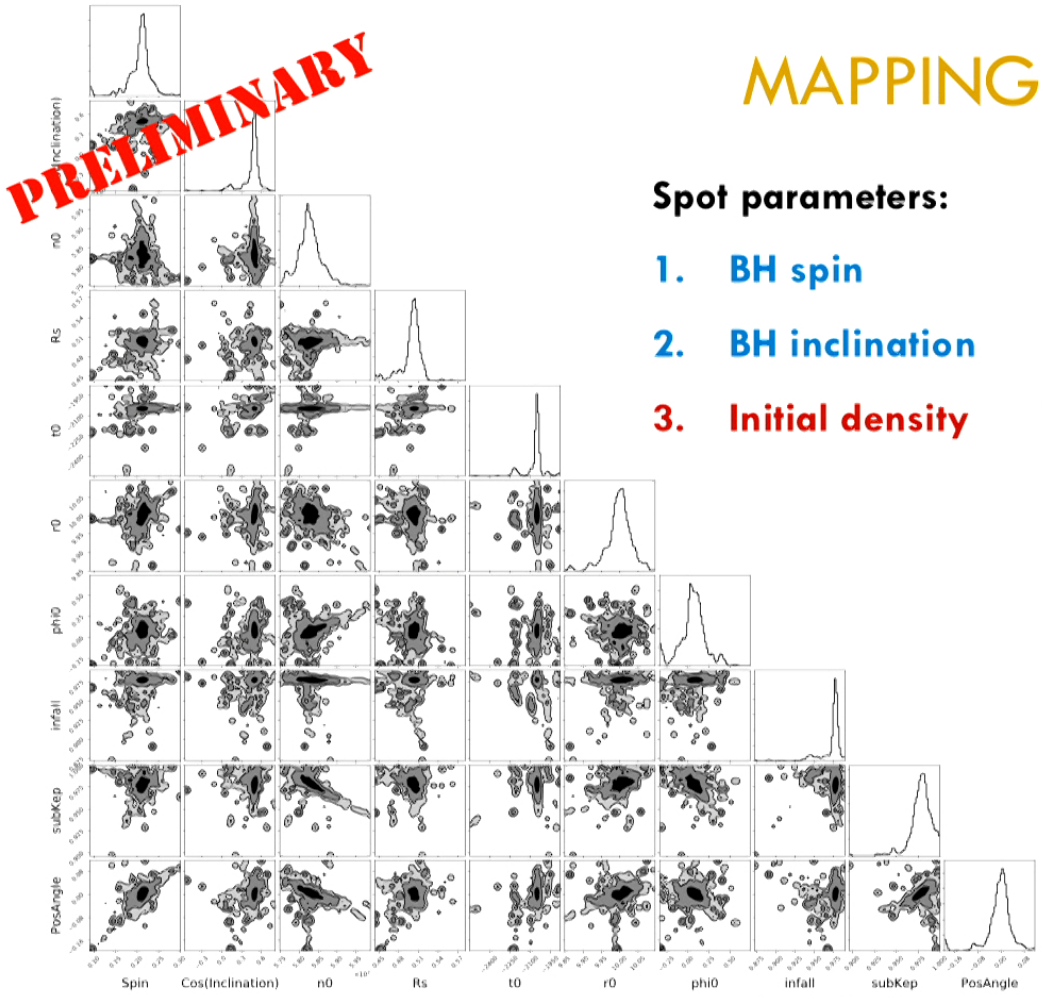
MAPPING SPACETIMES?



Spot parameters:

1. BH spin
2. BH inclination
3. Initial density
4. Initial size
5. Initial time
6. Initial radius
7. Initial azimuth
8. Infall velocity
9. Angular velosity
10. BH position angle

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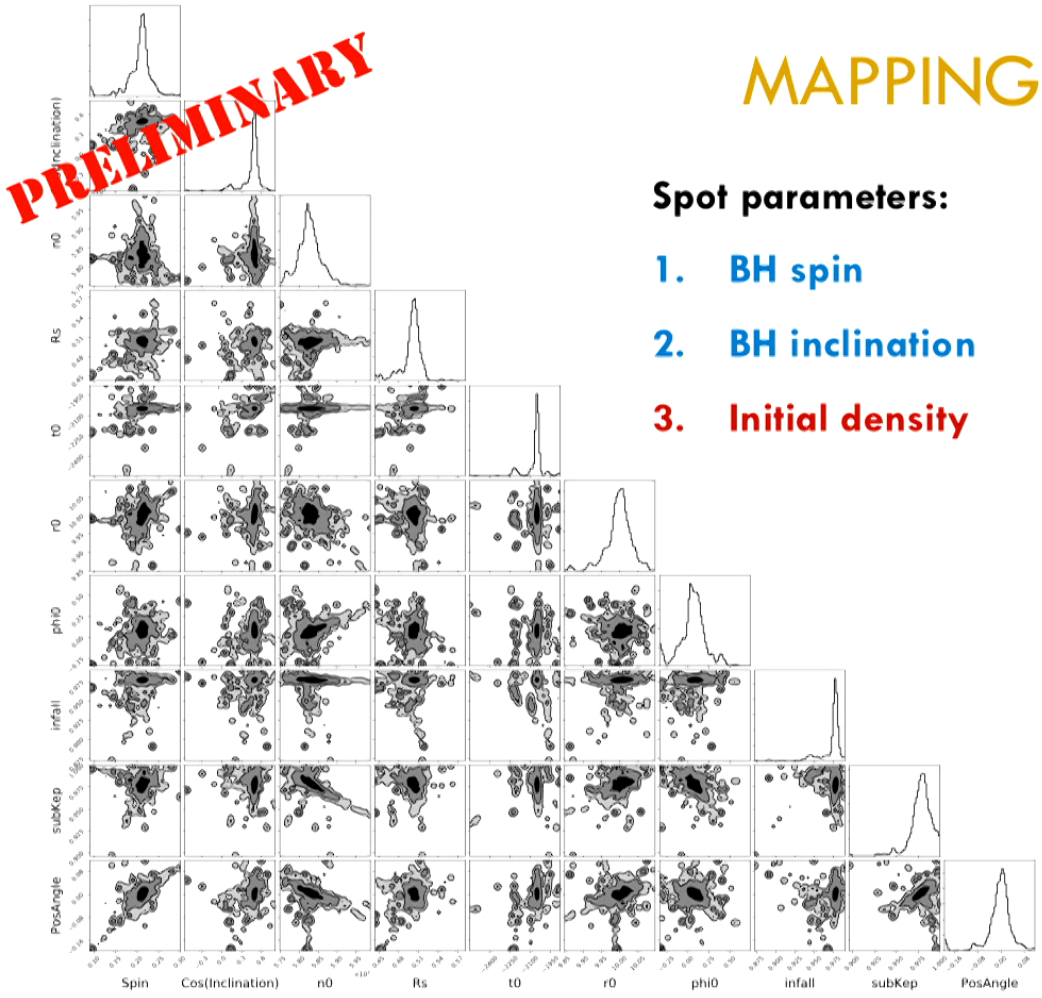
MAPPING SPACETIMES?



Spot parameters:

1. BH spin
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3. Initial density
4. Initial size
5. Initial time
6. Initial radius
7. Initial azimuth
8. Infall velocity
9. Angular velosity
10. BH position angle

Mostly local!

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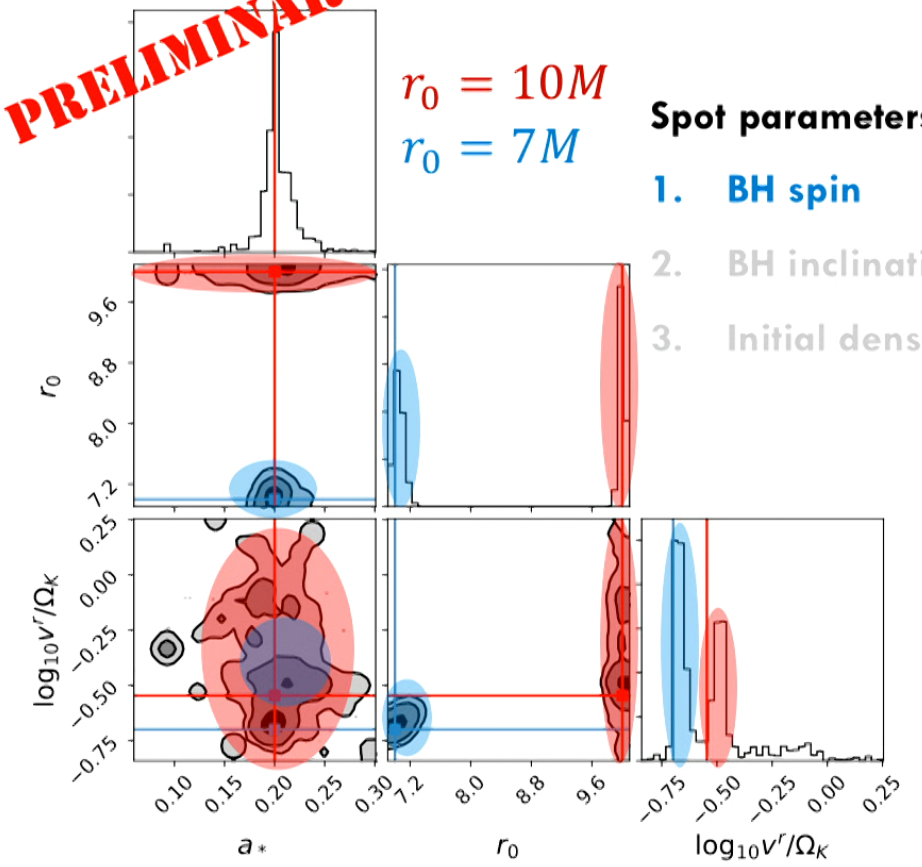
MAPPING SPACETIMES?

PRELIMINARY



Spot parameters:

1. **BH spin**
2. BH inclination
3. Initial density
4. Initial size
5. Initial time
6. **Initial radius**
7. Initial azimuth
8. **Infall velocity**
9. Angular velosity
10. BH position angle

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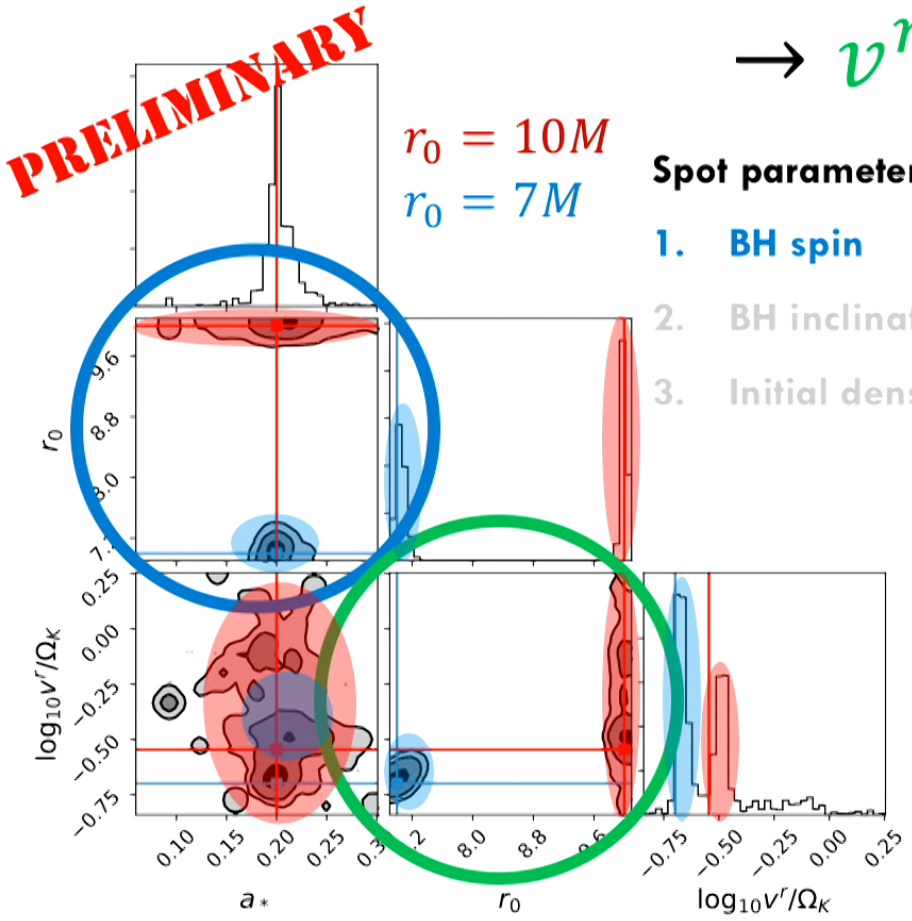
MAPPING SPACETIMES?



$\rightarrow v^r(r_0), a(r_0), \ldots$

Spot parameters:

1. **BH spin**
2. BH inclination
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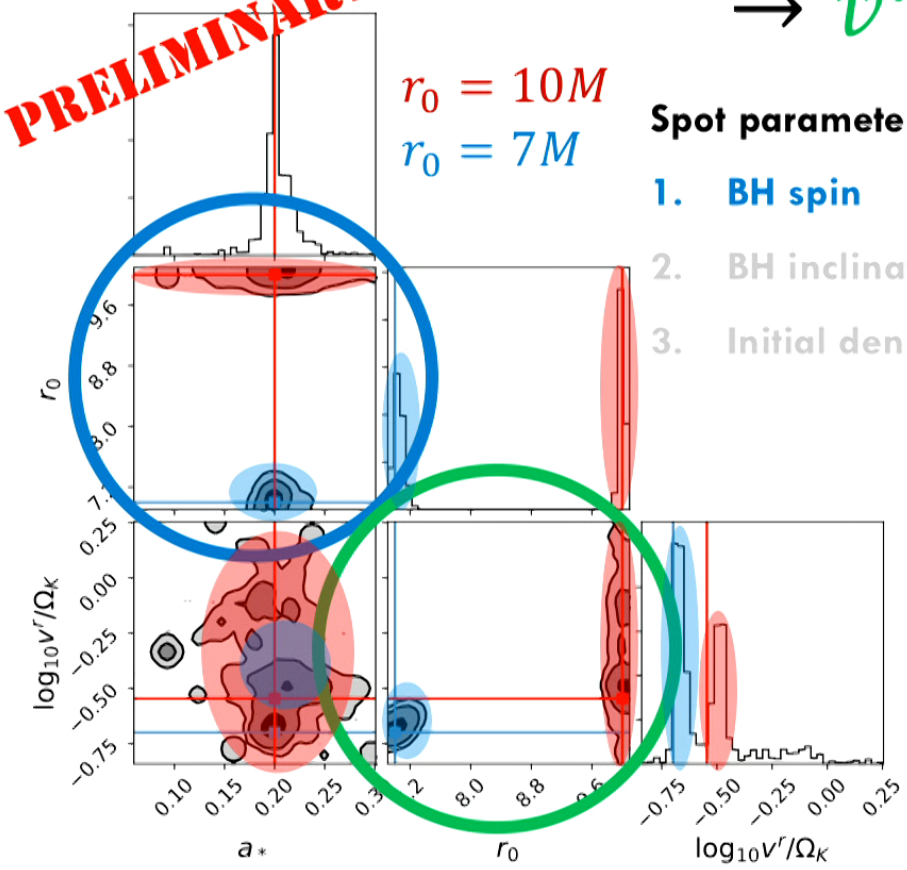
MAPPING SPACETIMES?

PRELIMINARY



$\rightarrow v^r(r_0), a(r_0), \ldots$

Spot parameters:

1. **BH spin**
2. BH inclination
3. Initial density
4. Initial size
5. Initial time
6. **Initial radius**
7. Initial azimuth
8. **Infall velocity**
9. Angular velosity
10. BH position angle

Much left to do!

Paul Tiede

WHAT I DIDN'T TALK ABOUT

- **Imaging – sparse coverage + Earth aperture synthesis for intrinsically variable systems!**
- **Mitigation of observational systematics (station calibration, interstellar scattering, etc.)**
- **Timescales less than minutes – MHD turbulence on very short timescales, can access statistically**
- **Non-parametric analyses (power spectra, phenomenological models, photon rings, etc.)**
- **Polarization (Q,U and V!) – Magnetic fields morphologies**
- **Accretion flow modeling in extensio**
- **Modification of the underlying spacetime**
- **Multi-wavelength studies – modeling from radio to gamma-rays *with* horizon-scale structure!**
- **Non-horizon science targets (e.g., OJ 287, 3C 239, pulsars, etc.)**
- **Analysis tool development (THEMIS – a flexible framework for EHT and beyond)**

SUMMARY: VARIABILITY ACROSS SCALE

Exciting times – images expected soon!

EHT targets should exhibit *structural* variability over many time scales, each telling a story about the physics of black holes and their environments.

Minutes, $1 - 10M$ Flares in disks → Gravity

Days, $10 - 100M$ Flares in jets → Jet launching mechanism (BZ vs. BP)

Years, $100 - 10,000M$ Lense-Thirring precession → Accretion source

Decades, $10,000 - 10^6 M$ Black hole jitter → Nuclear remnant population

… so, the next 100 images are even better!

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