

Title: Superradiant instabilities and rotating black holes

Date: May 09, 2018 03:30 PM

URL: <http://pirsa.org/18050029>

Abstract:

PROBING SMBH SPACETIMES WITH THE EVENT HORIZON TELESCOPE

Avery E. Broderick



Event Horizon Telescope

Boris Georgiev

Britt Jeter

Mansour Karami

Paul Tiede

Carlos Wang

Roman Gold

Tim Johannsen

Alex Preciado

Hung-Yi Pu

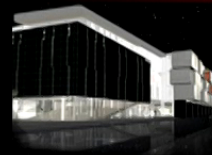
+

Many others



UNIVERSITY OF
WATERLOO

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PERIMETER

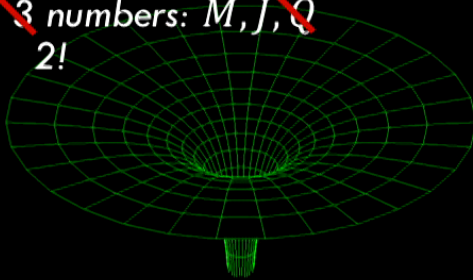


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WHAT ARE SUPERMASSIVE BLACK HOLES, AND WHAT ARE THEY DOING?

Fully characterized by

~~3~~ numbers: M, J, Q
2!

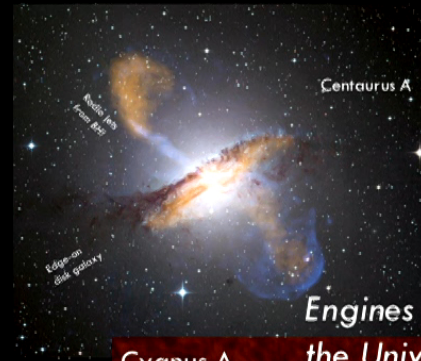


Physics:

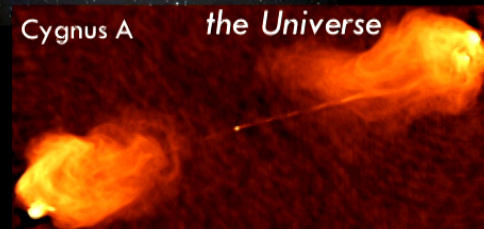
- Do black holes exist?
- Are they well described by GR?

Astronomy:

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



Engines of the
the Universe

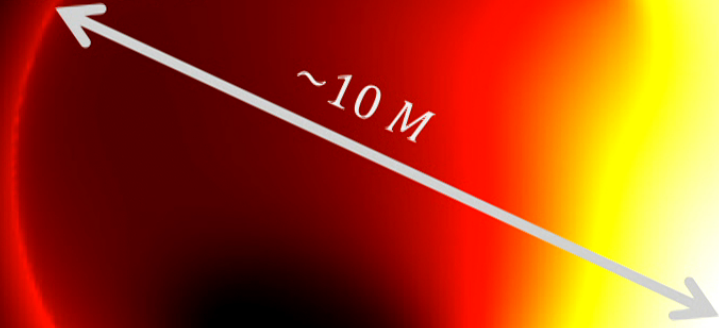


Answers found on horizon-scales

→ Direct imaging!

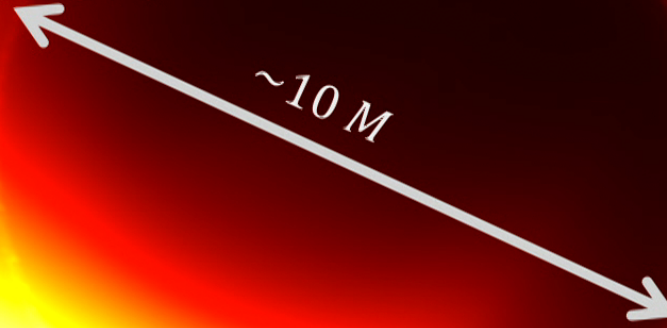
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“COMPACT” OBJECTS



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“COMPACT” OBJECTS



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"COMPACT" OBJECTS

Galactic
Center
(Sgr A*)

53 μas

$4.3 \times 10^6 M_{\odot}$
8 kpc

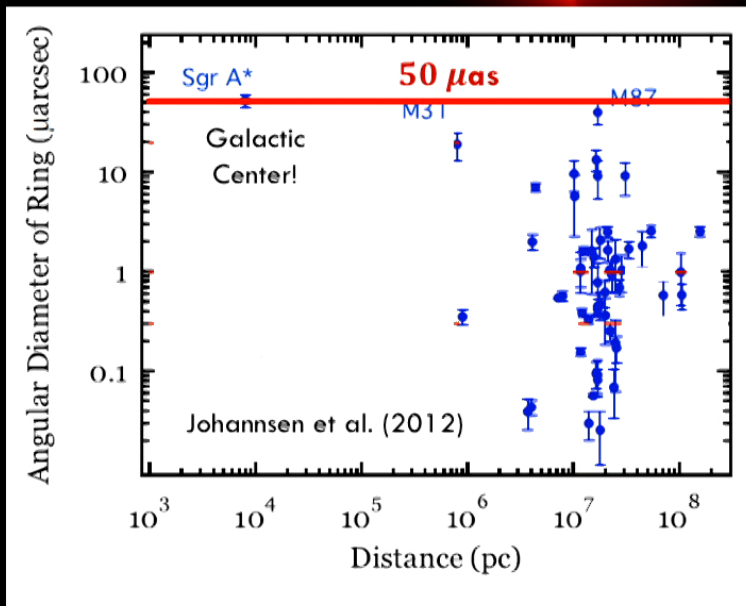
"COMPACT" OBJECTS

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Superradiance,

HOCKEY ON THE MOON AND THE DIFFRACTION LIMIT



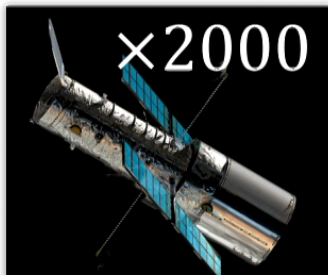
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HOCKEY ON THE MOON AND THE DIFFRACTION LIMIT



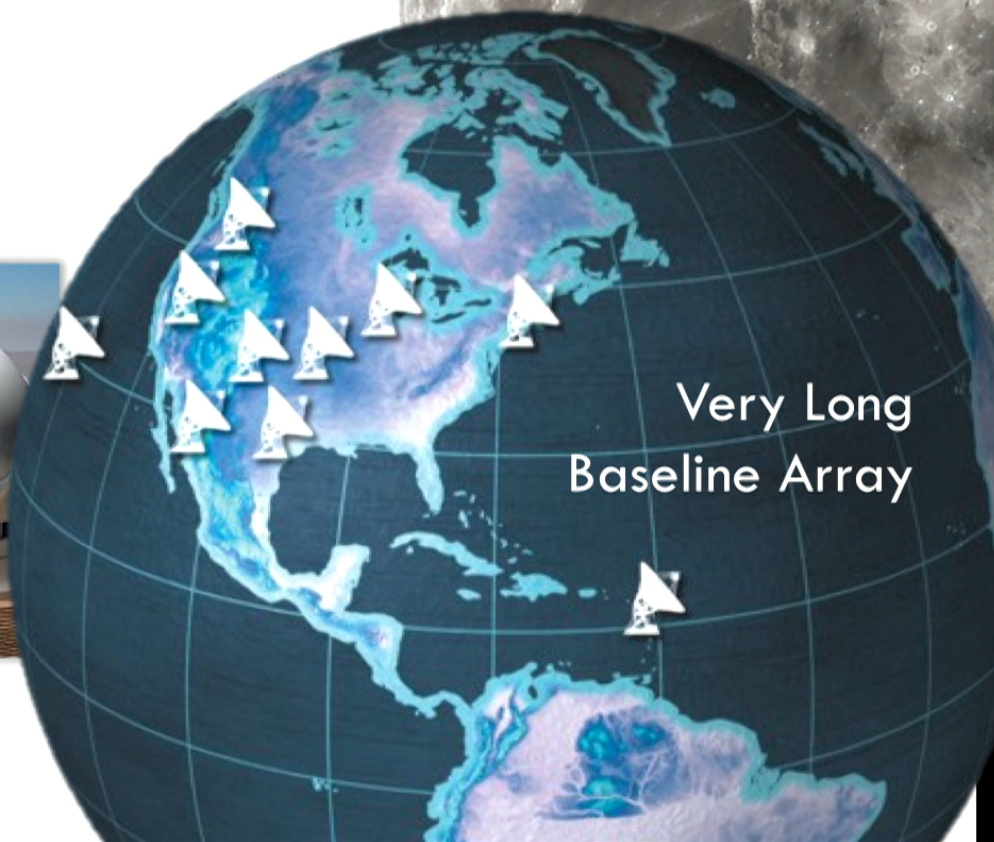
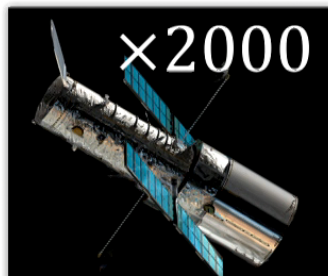
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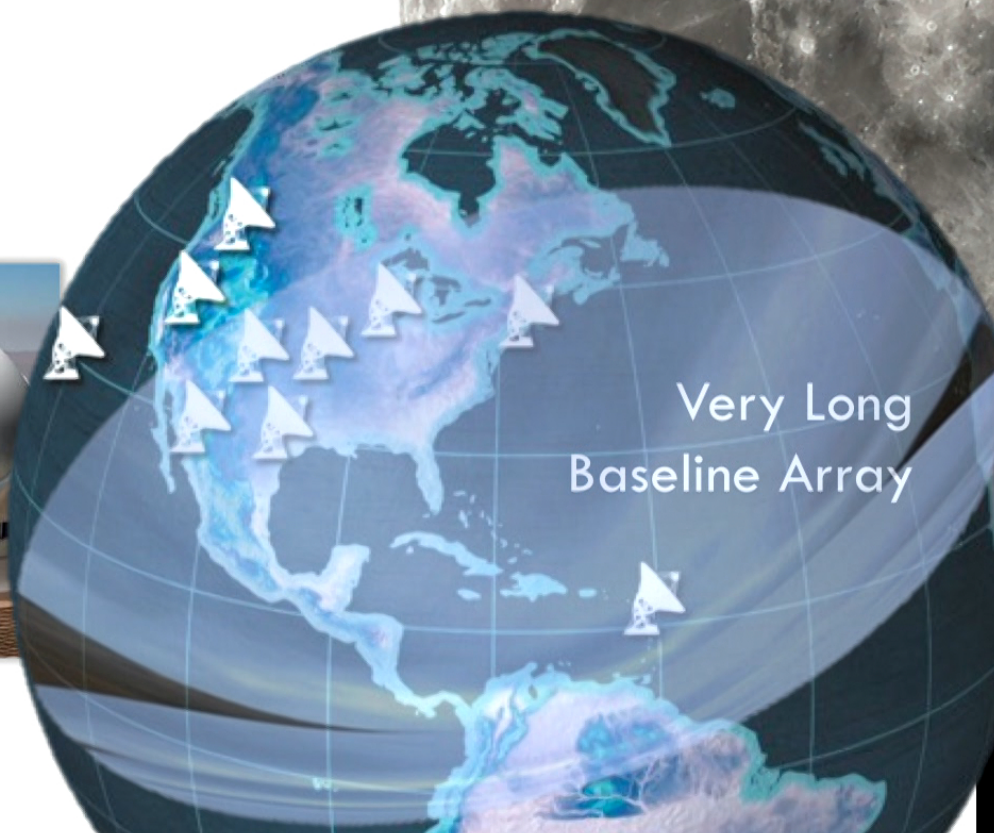
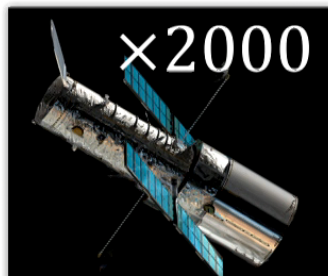
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HOCKEY ON THE MOON AND THE DIFFRACTION LIMIT



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HOCKEY ON THE MOON AND THE DIFFRACTION LIMIT



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THE EHT TODAY

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Event Horizon Telescope

www.eventhorizontelescope.org

GLOBAL COLLABORATION



Large Millimeter Telescope *Alfonso Serrano*



Max-Planck-Institut für Radioastronomie



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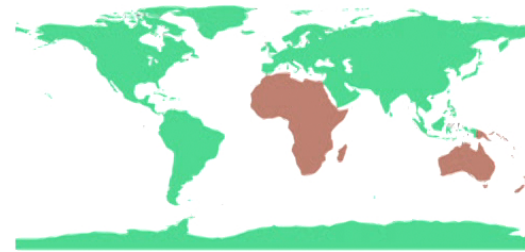
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Purple Mountain Observatory

University of Science and Technology of China

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Institute for Astrophysical Research

Brandeis University

California Institute of Technology

Cologne University

Cornell University

Huazhong University of Science & Technology

Joint Institute for VLBI ERIC

Korea Astronomy and Space Science Institute

University of Maryland

Max Planck Institute for Extraterrestrial Physics

National Astronomical Observatories of China

Peking University, Beijing

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Seoul National University

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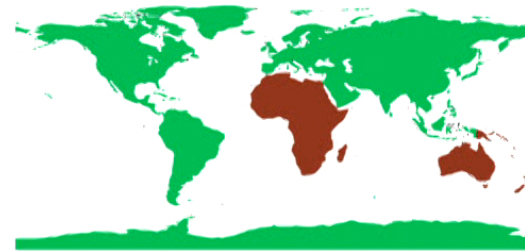
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Perimeter Institute is building a team of Faculty members, postdoctoral researchers, and graduate students to conduct leading-edge analysis of astrophysical data collected by the Event Horizon Telescope (EHT).

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Event Horizon Telescope "PROTO-EHT"

www.eventhorizontelescope.org



CARMA

SMA,
JCMT



ARO-SMT



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See Rusen LU's talk!

THE EHT IS DATA RICH

$$V(u) = \int d\alpha e^{2\pi i \alpha \cdot u / \lambda} I(\alpha)$$

- **Interferometric Quantities**
(Visibility Magnitudes, Closure Phases, Closure Amplitudes, etc.)
- **Polarization (I, Q, U, V)**
- **Frequency (230 GHz, 345 GHz)**
- **Short Time (hours)**
- **Long Time (decades)**
- **Targets (Sgr A*, M87, etc.)**

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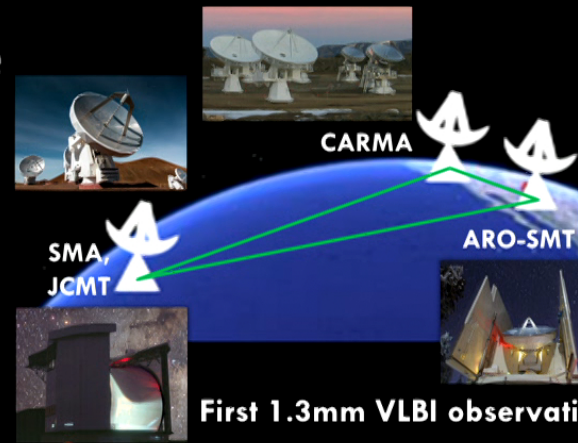
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Doeleman et al. 2008, Nature, 455, 78

Broderick et al. 2009, ApJ, 697, 45

Fish et al. 2011, ApJ, 727, 36

Broderick et al. 2011, ApJ, 735, 110

Doeleman et al. 2012, Science, 338, 355

Broderick et al. 2014, ApJ, 784, 7

Akiyama et al. 2015, ApJ, 807, 150

Johnson et al. 2015, Science, 350, 1242

Broderick et al. 2016, ApJ, 820, 137

First 1.3mm VLBI observation of Sgr A*

First physics-based modeling of EHT data

First detection of horizon-scale variability

**First demonstration that physics-based models
are preferred by EHT data**

First 1.3mm VLBI observations of M87

First constraints on BH hair from EHT data

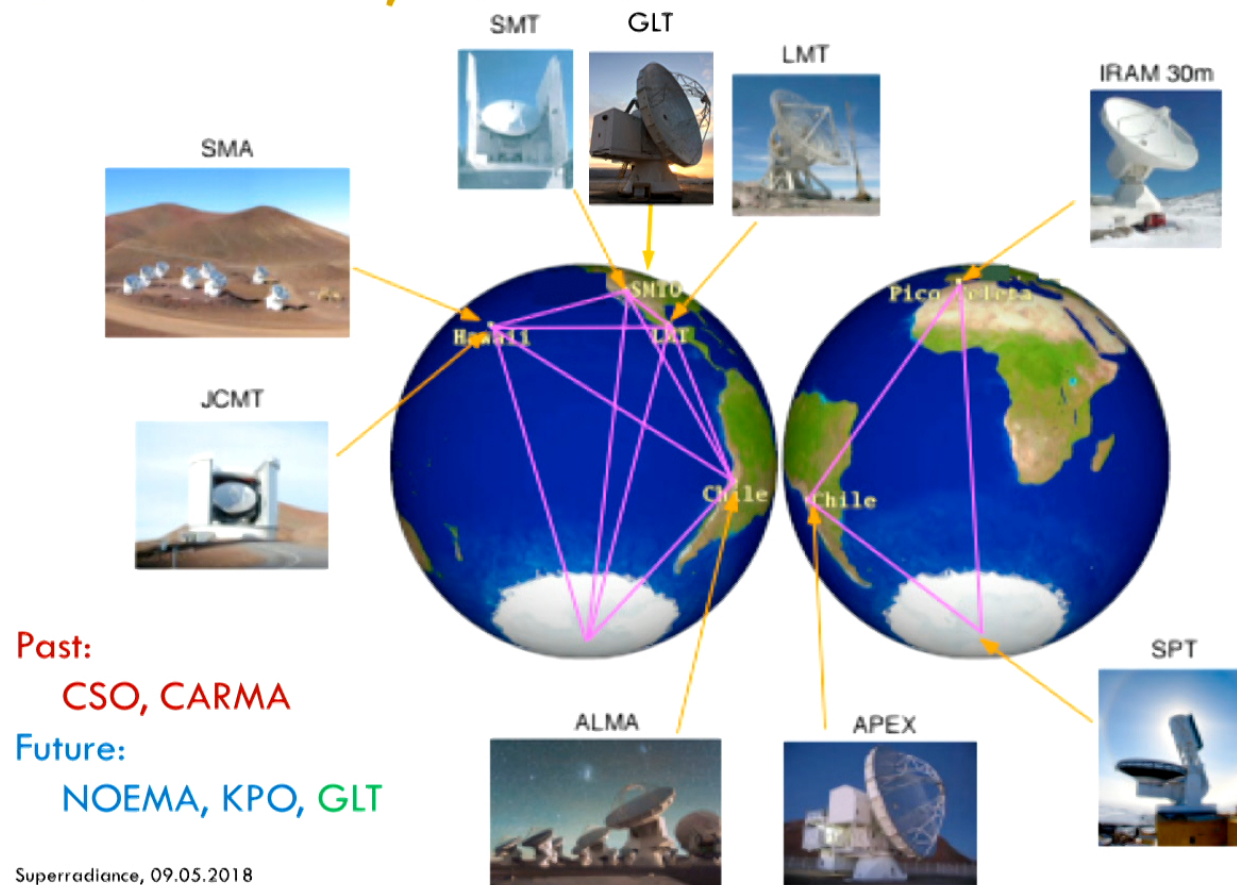
**First measurement of horizon-scale structure in
M87 coincident with TeV flares**

**First detection of ordered, horizon scale
polarization around a BH**

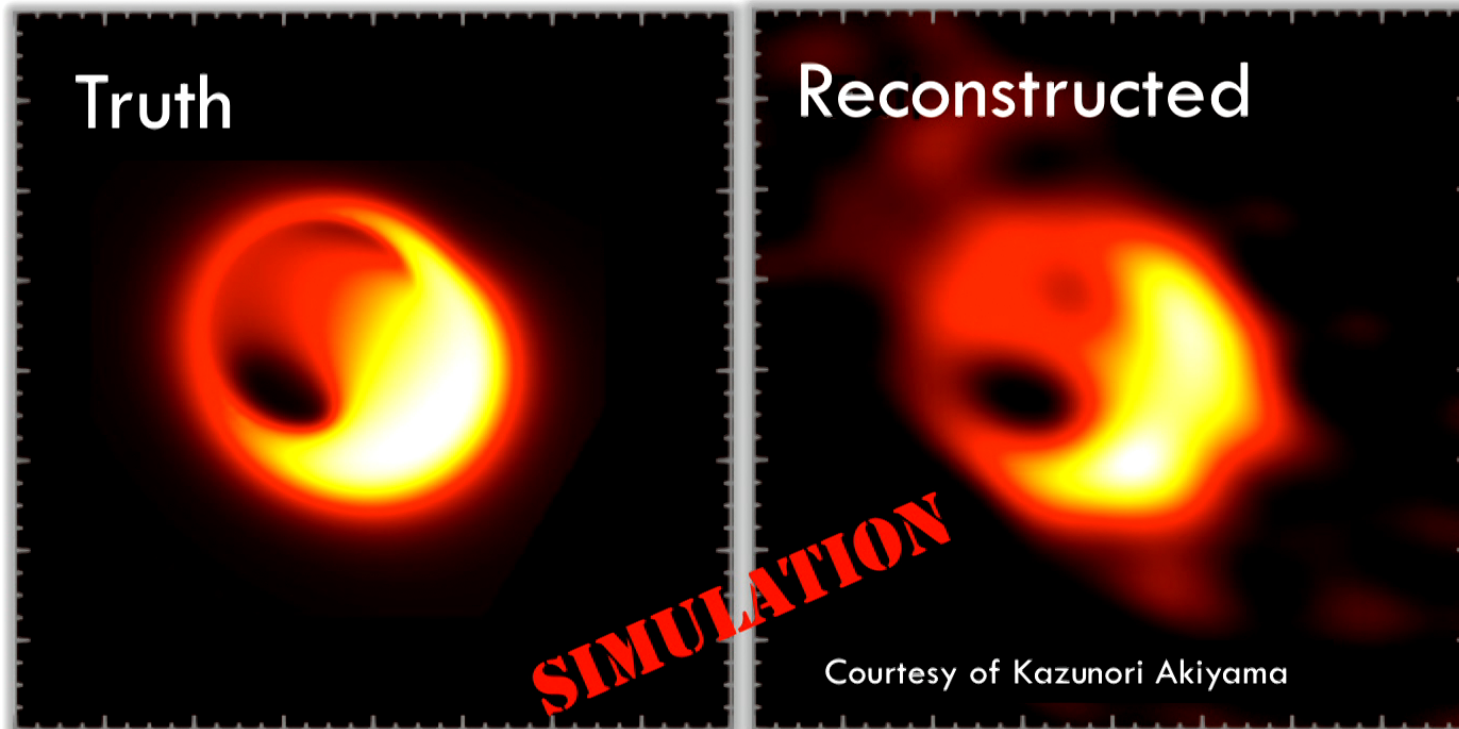
**First physics-based modeling of EHT data that
included closure phases**

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THE EVENT HORIZON TELESCOPE CIRCA APRIL, 2017 & 2018



FIRST TELESCOPE CAPABLE OF “SEEING” BLACK HOLES



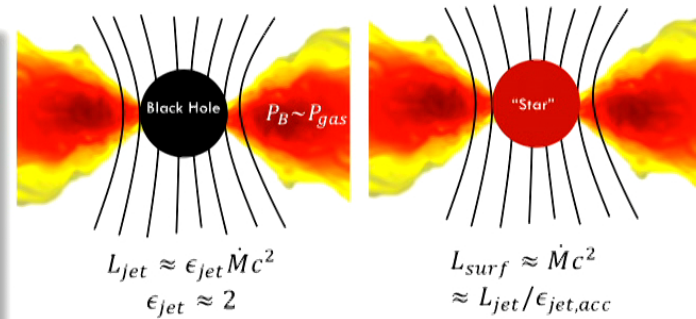
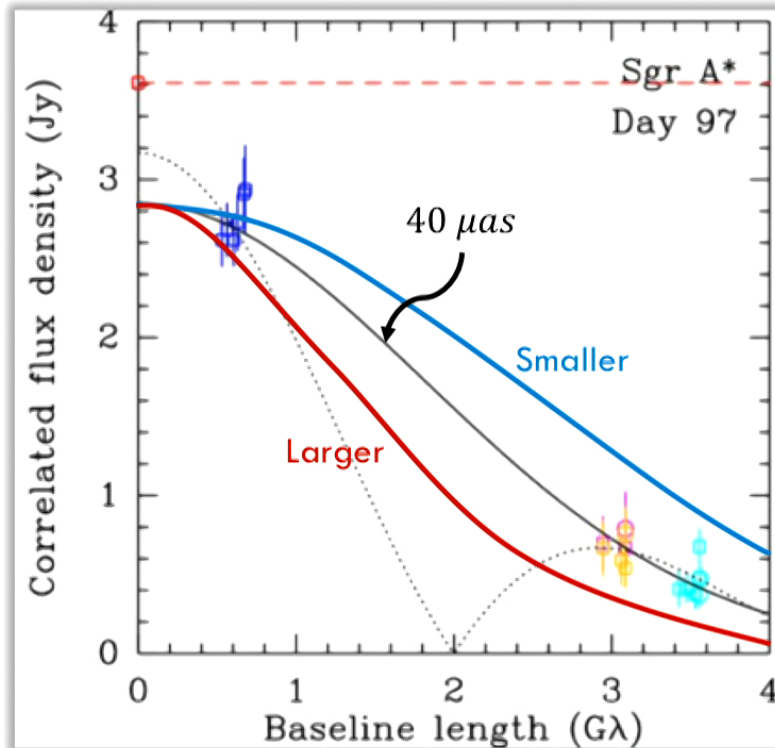
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LATEST RESULTS?

- **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!**

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DO BLACK HOLES EXIST?

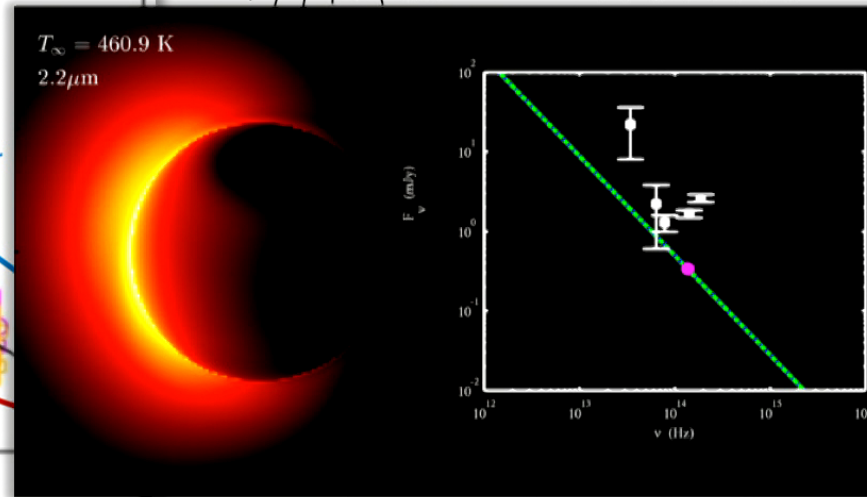
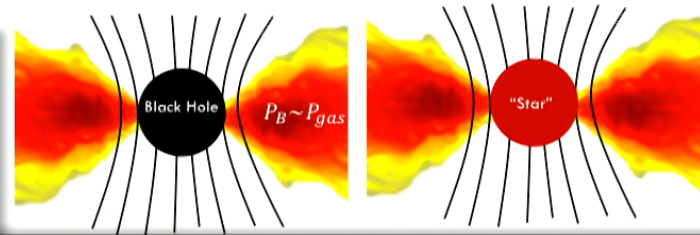
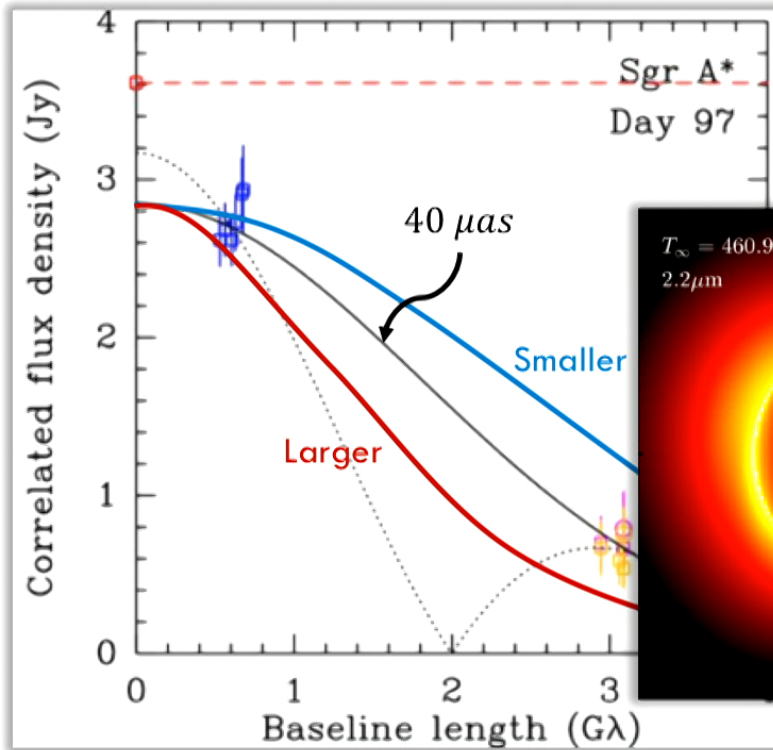


Assumes:

- Reached steady state (only logarithmically hard!)
- A notion of energy conservation for test particles
- No "magic" at object (but baryonic atmospheres!)

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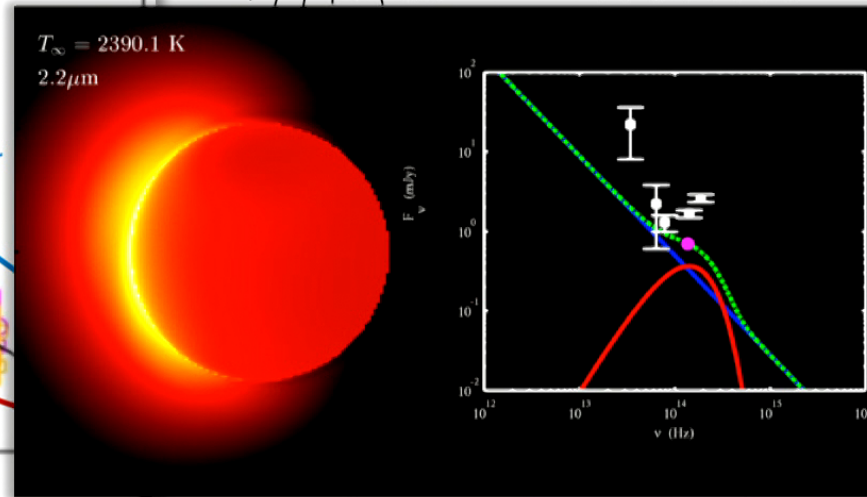
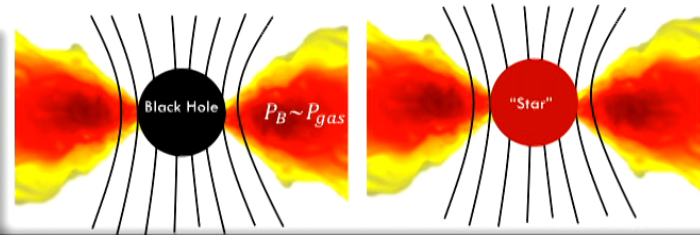
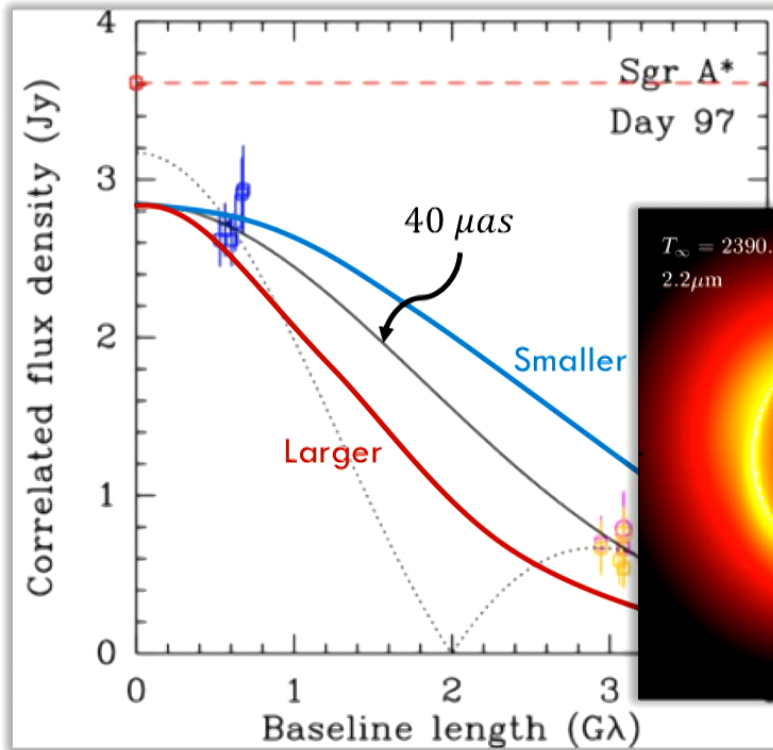
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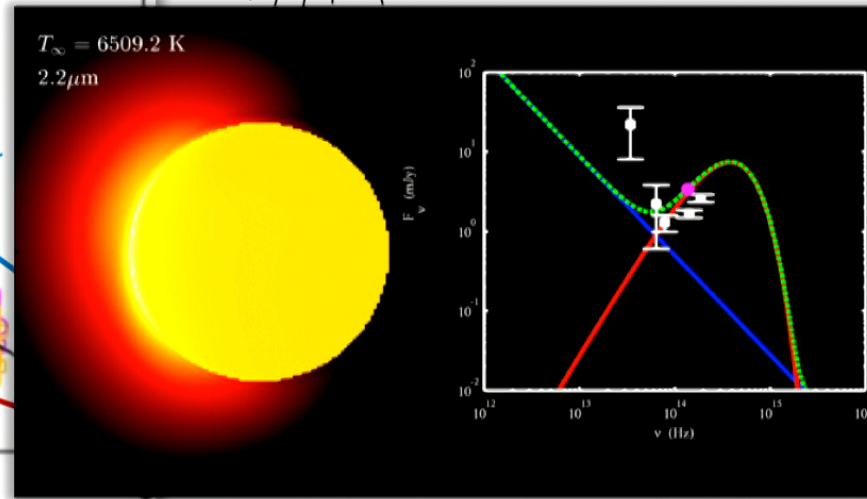
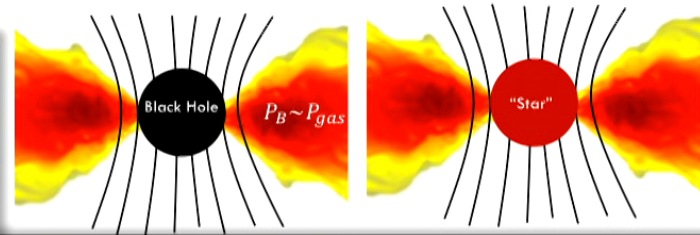
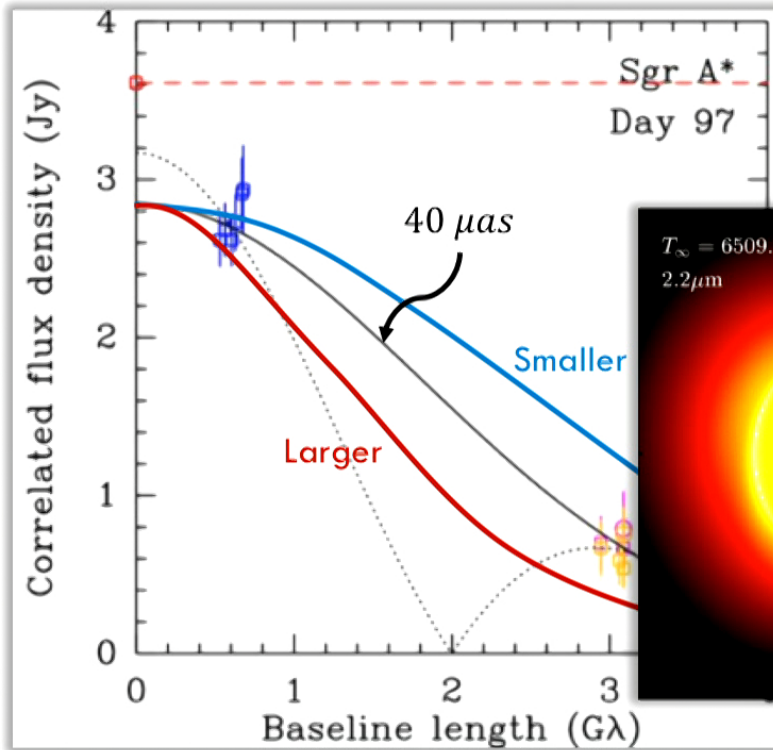
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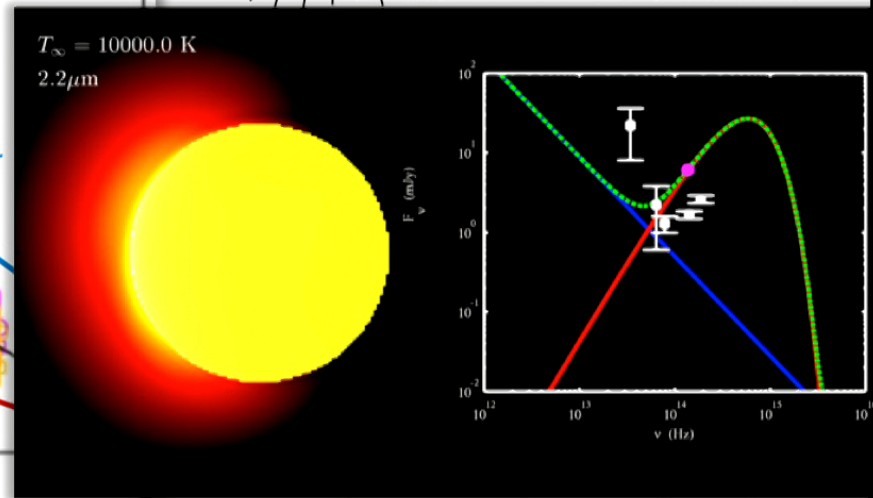
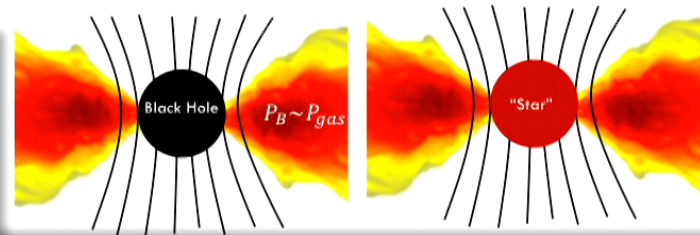
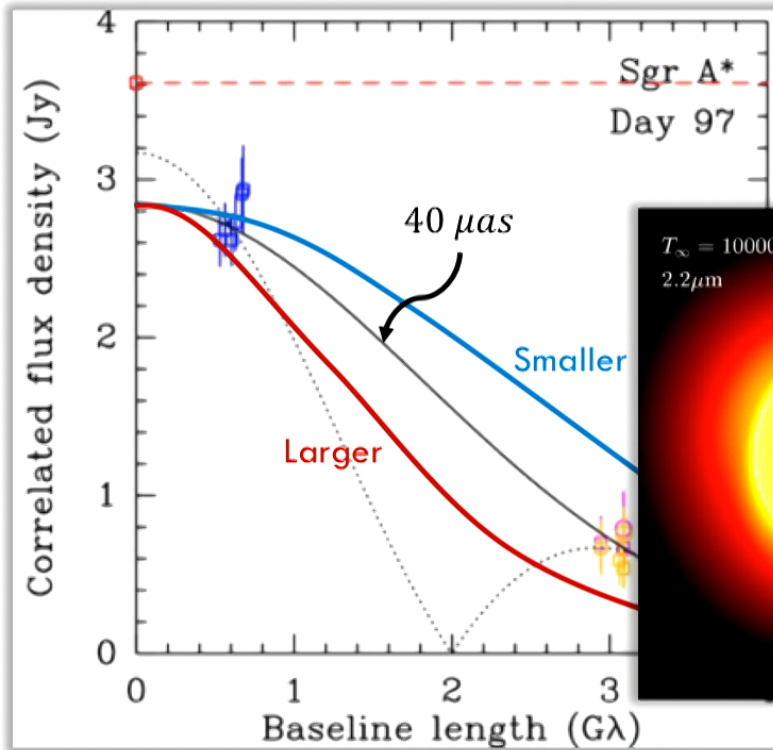
DO BLACK HOLES EXIST?



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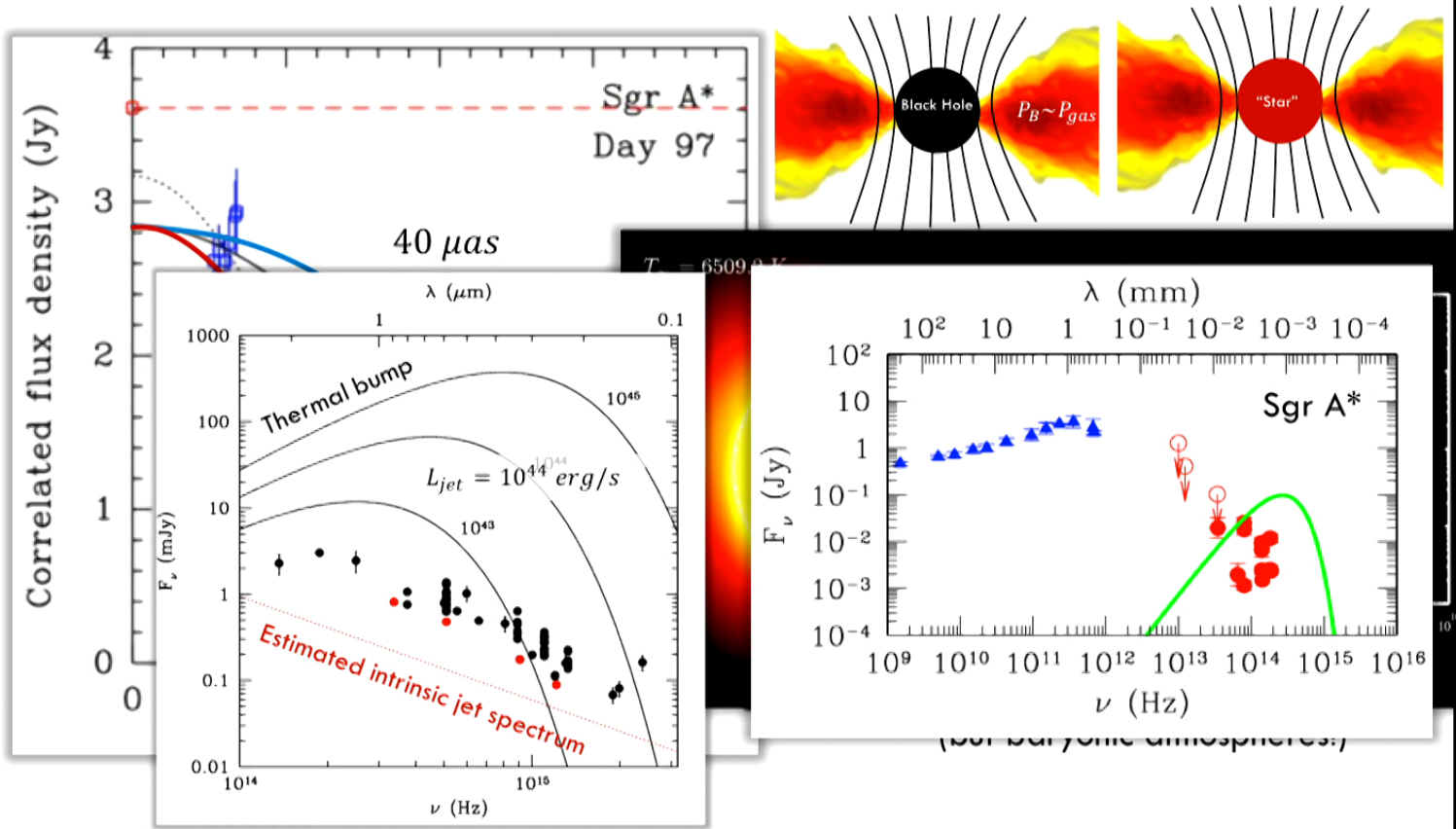
DO BLACK HOLES EXIST?



(but baryonic atmospheres!)

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DO BLACK HOLES EXIST?



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APPARENT VS. EVENT HORIZONS?

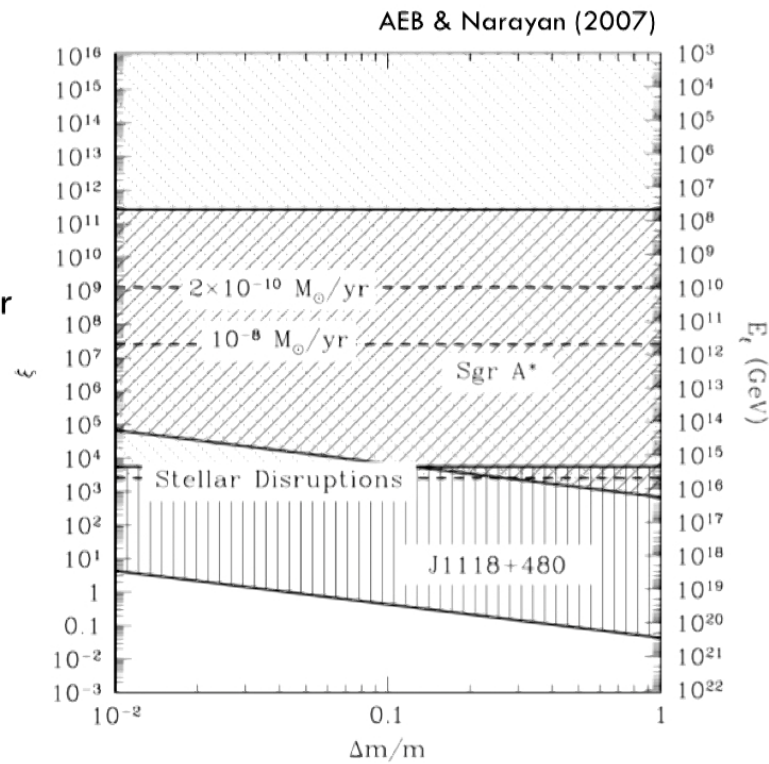
History of accretion

→ Traction on “when”

- Today for Sgr A*
 $\dot{M} \approx 10^{-8} M_{\odot}/\text{yr}$
- “Average” for Sgr A*
 $\dot{M} \approx 10^{-4} M_{\odot}/\text{yr}$ over 10 Gyr

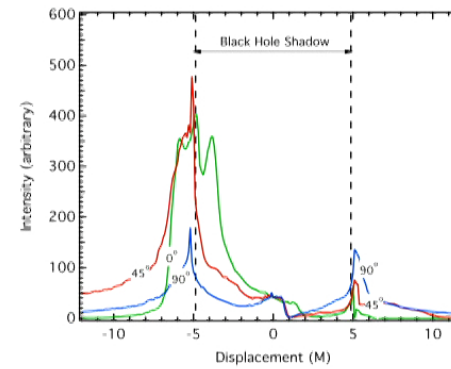
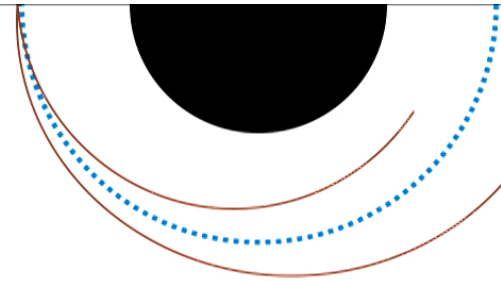
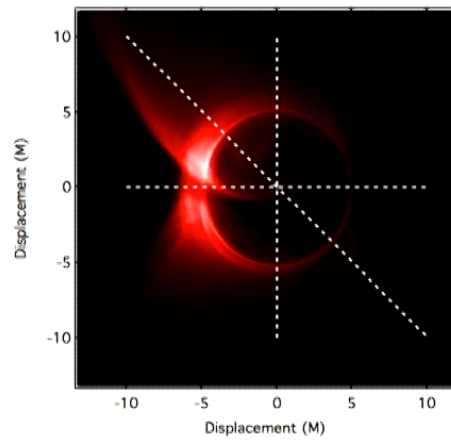
Other objects?

- High heat capacity
 (slow to heat, slow to cool!)
- Long equilibration times
- Not in steady state



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PHOTON RING DETECTION

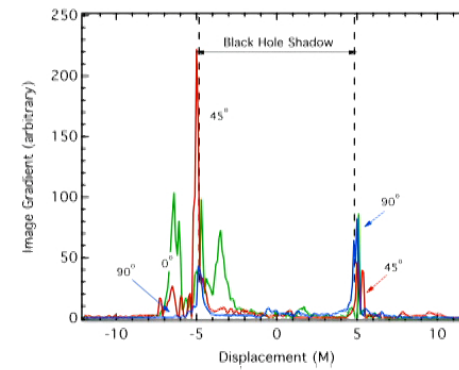
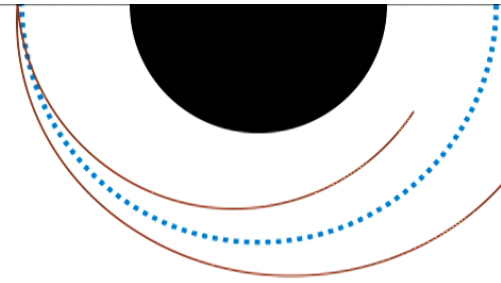
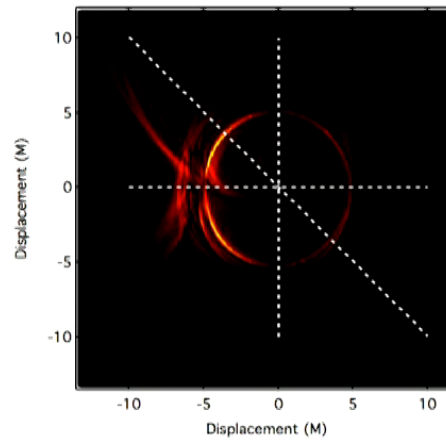
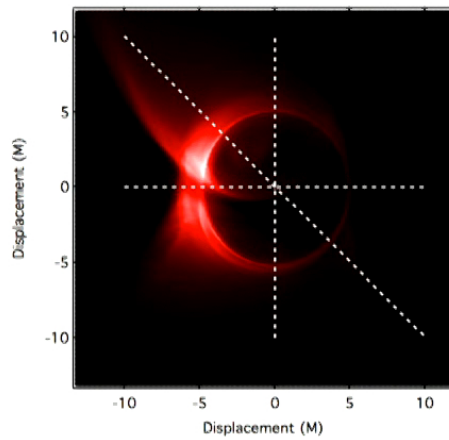


Hough/Radon Transforms
(Circular Edge Detection)

Psaltis et al. (2015)

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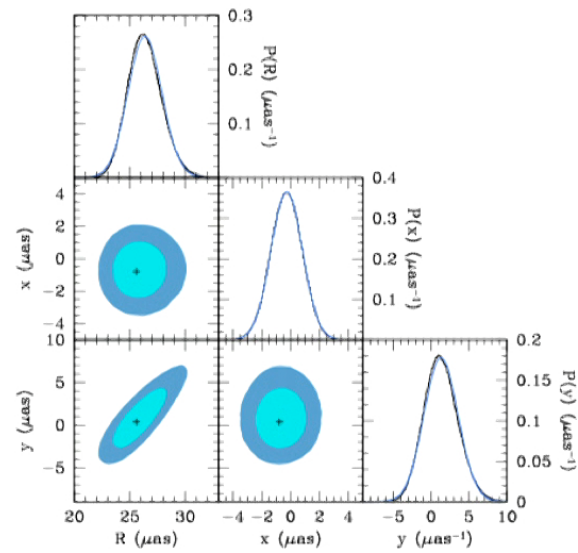
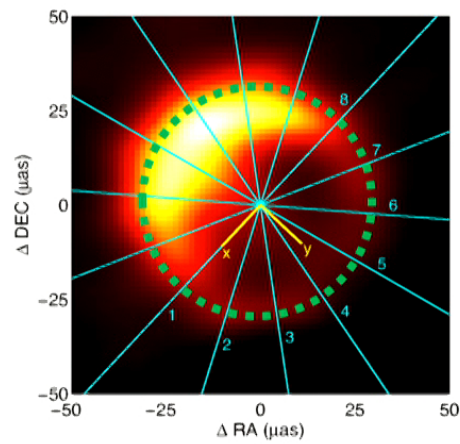


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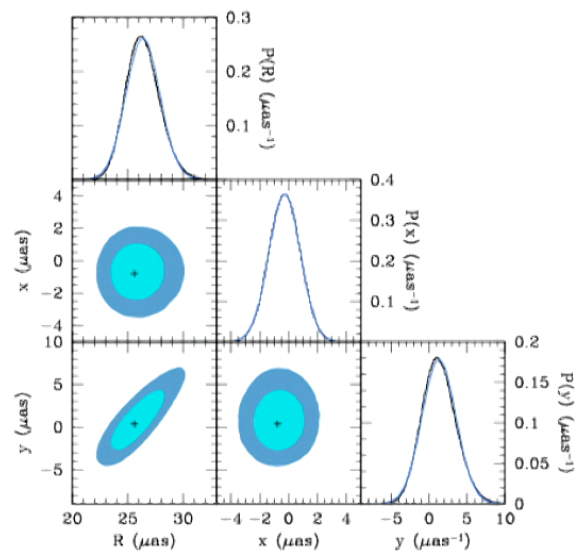
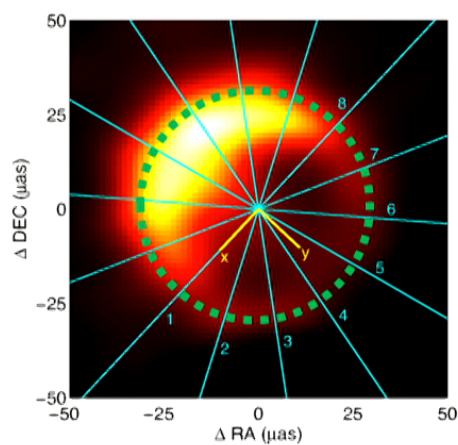
PHOTON RING DETECTION, IF WE'RE LUCKY



Johannsen et al. (2016)

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Johannsen et al. (2016)

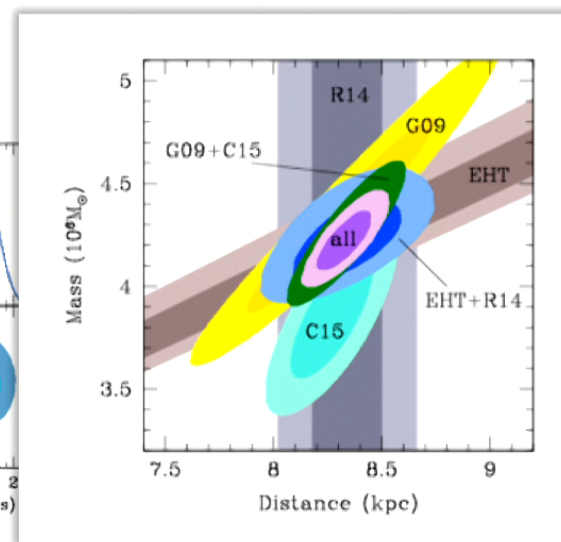
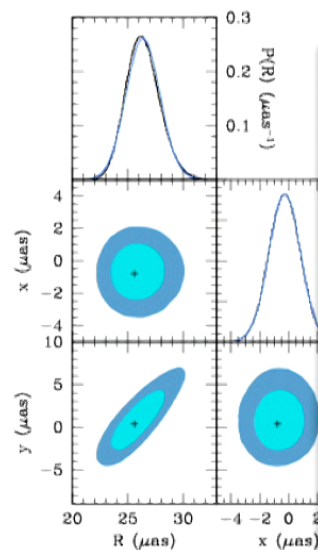
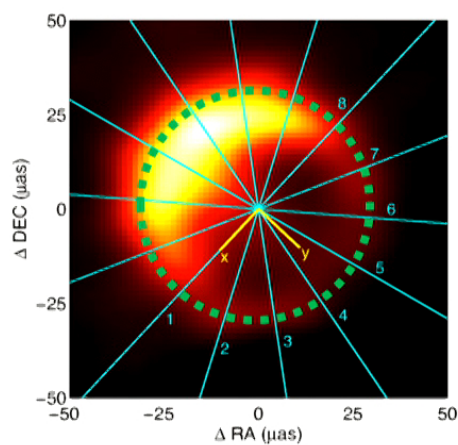
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Cuhna et al. (2016)

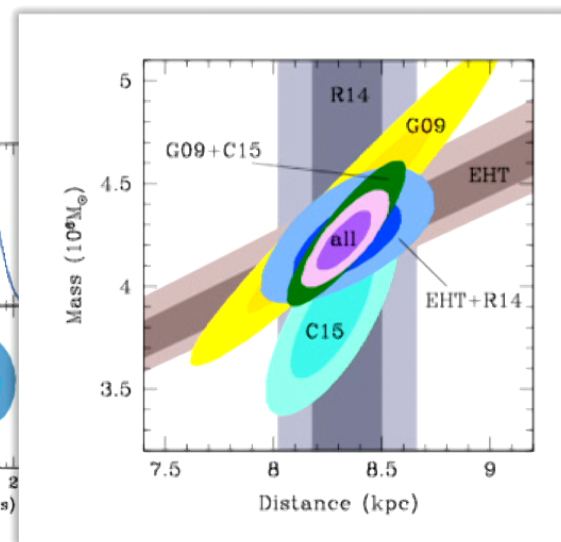
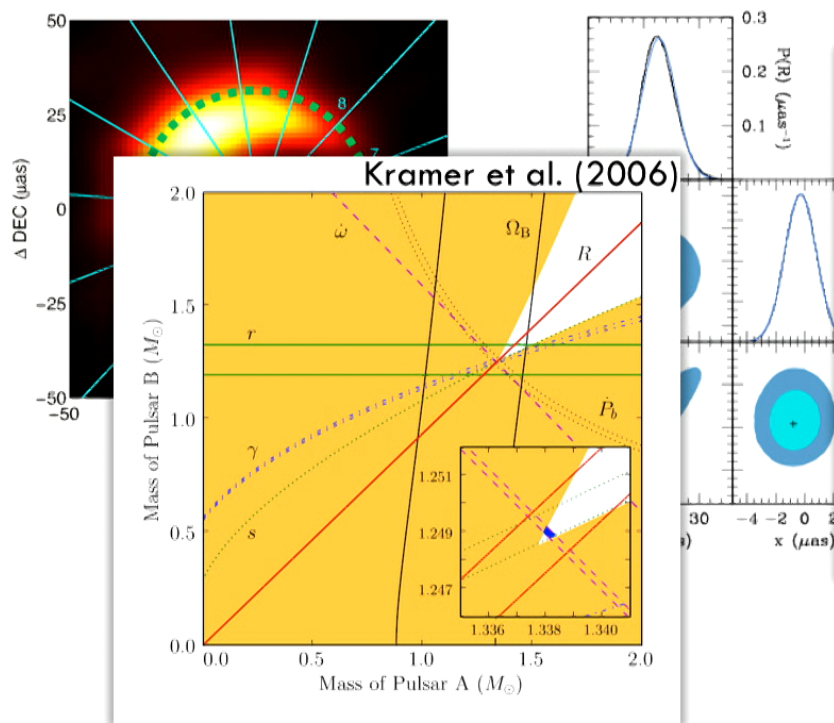
Scalar hair?



Johannsen et al. (2016)

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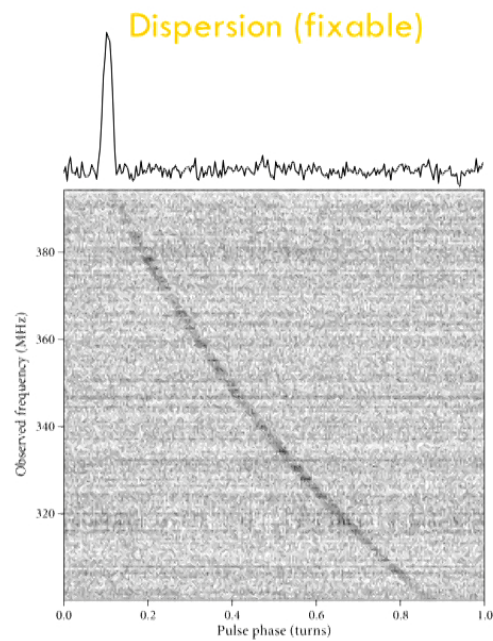


Johansen et al. (2016)

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COMMENSAL SCIENCE: PHASED ALMA RESOLUTION VS SENSITIVITY

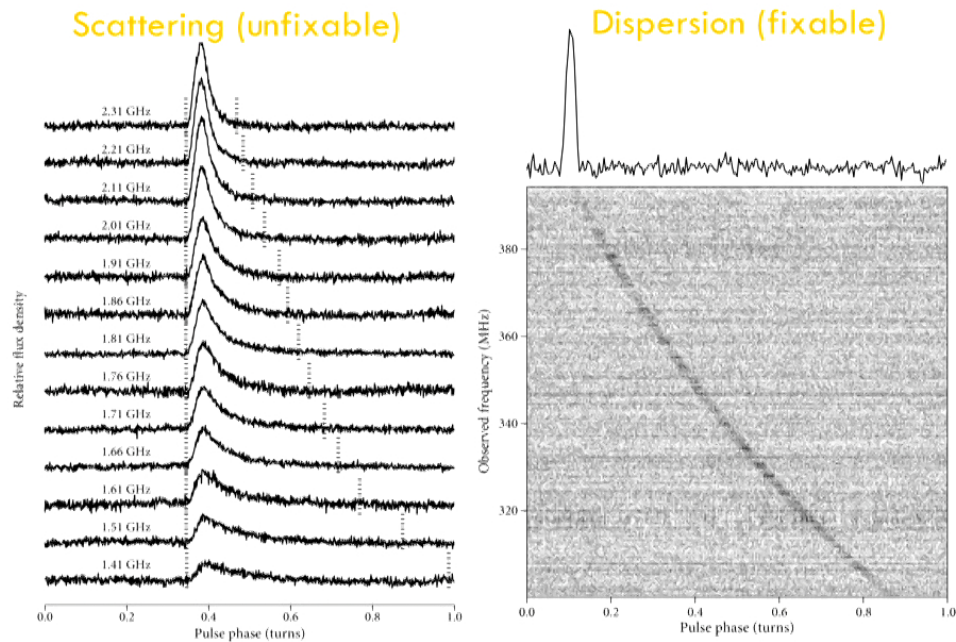
Pulse Broadening



<http://www.cv.nrao.edu/~sransom/web/xxx.html>
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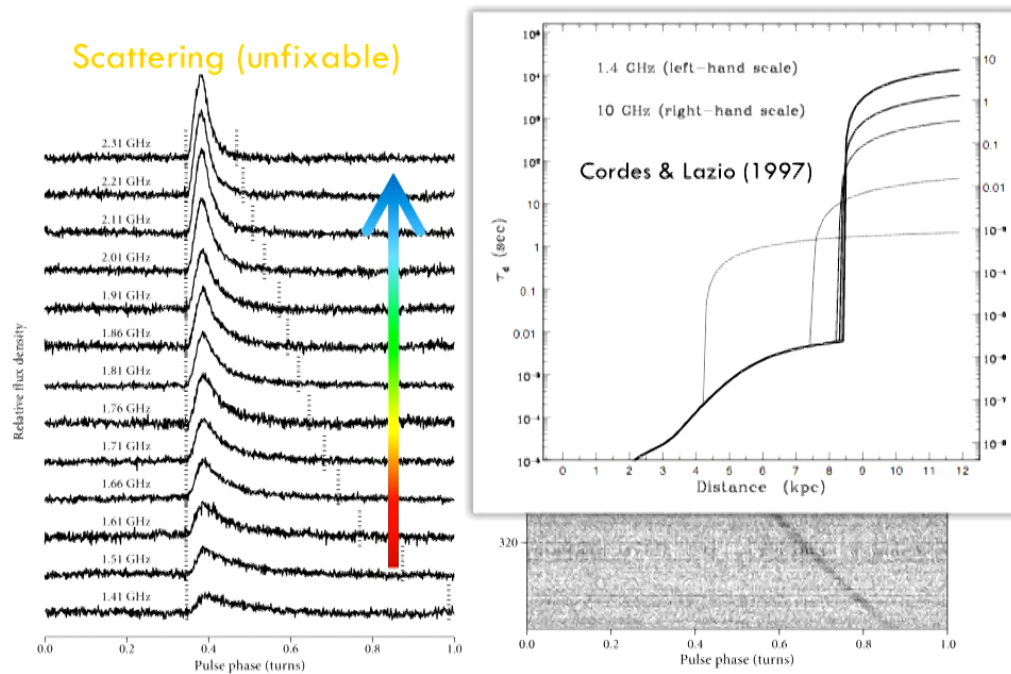
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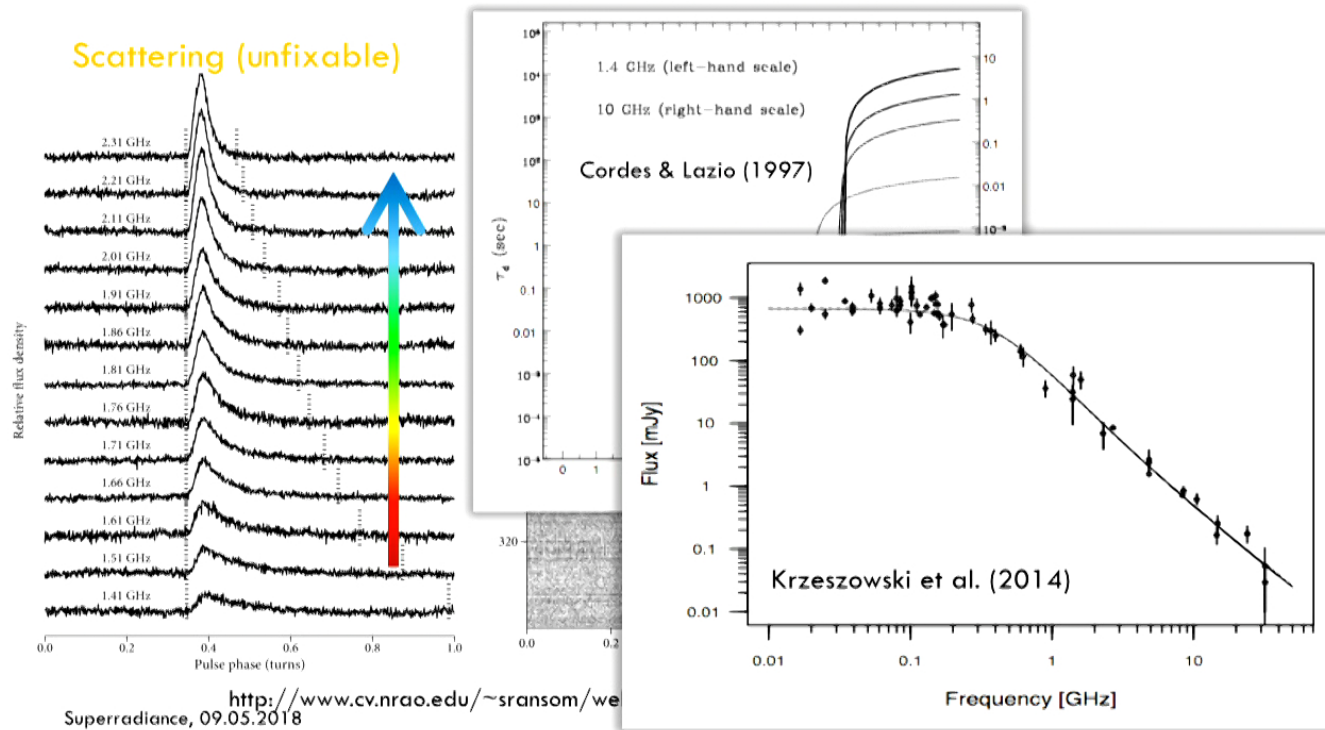
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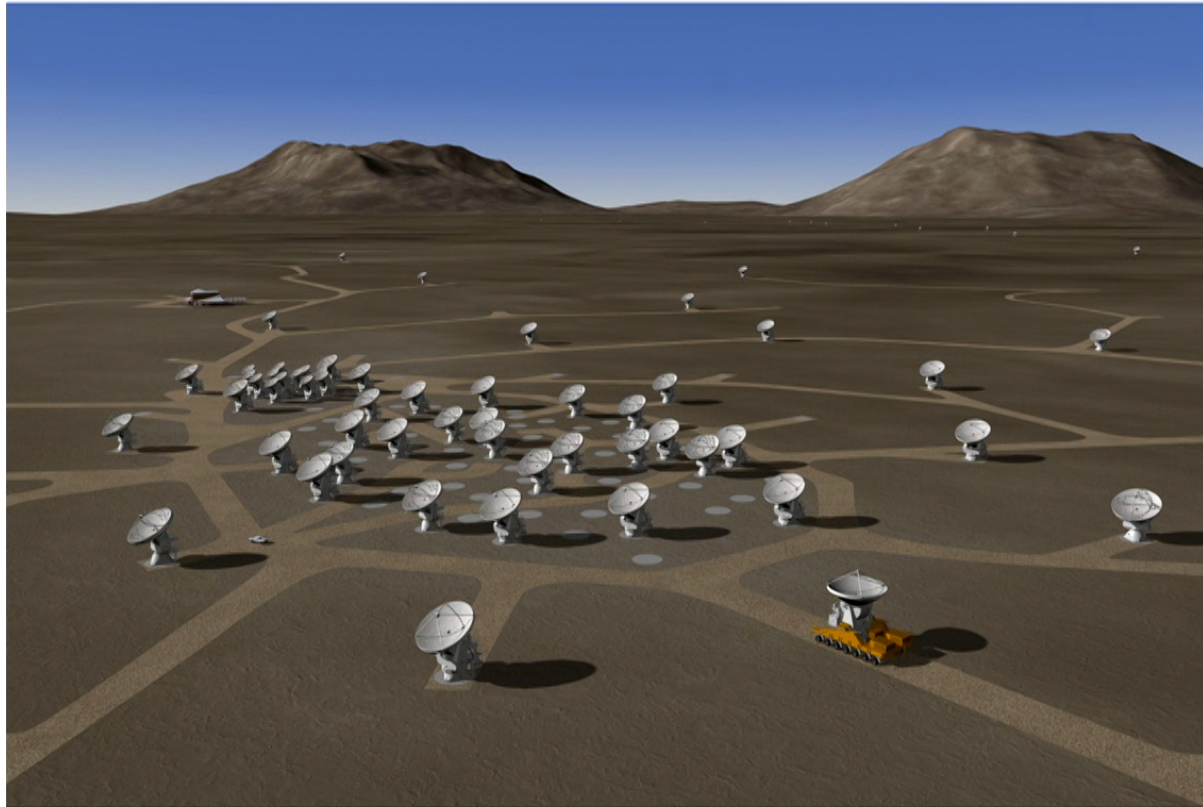
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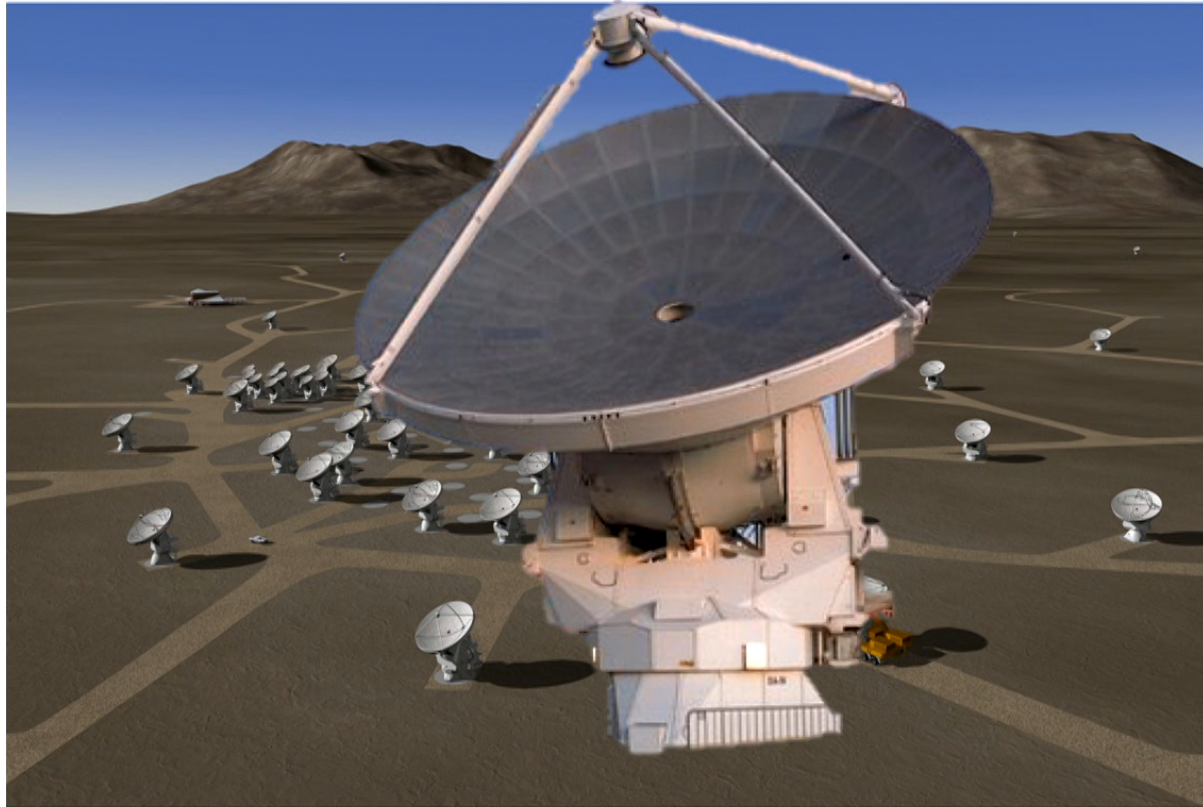


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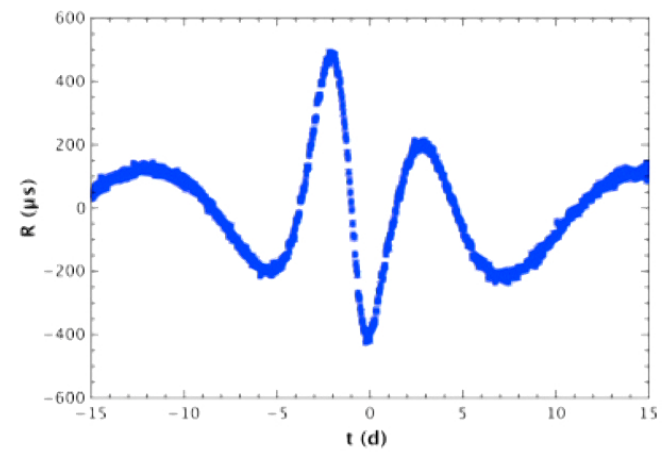
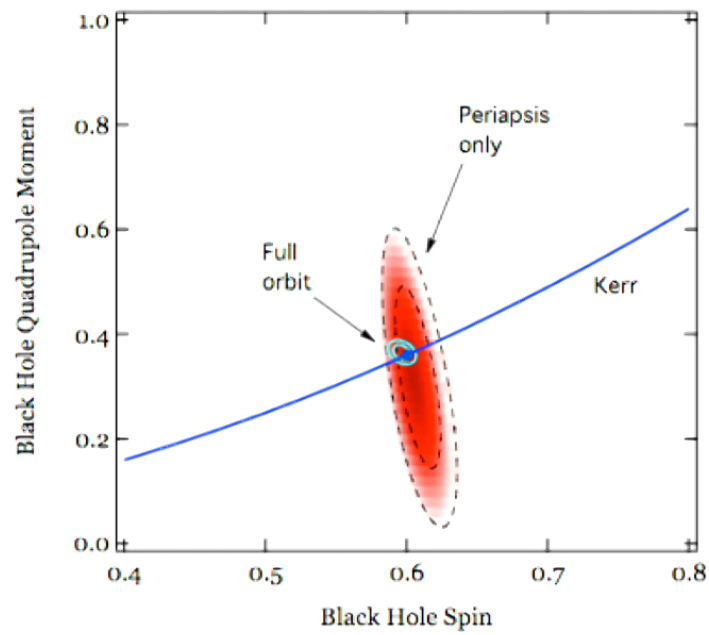
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Superradiance, 09.05.2018

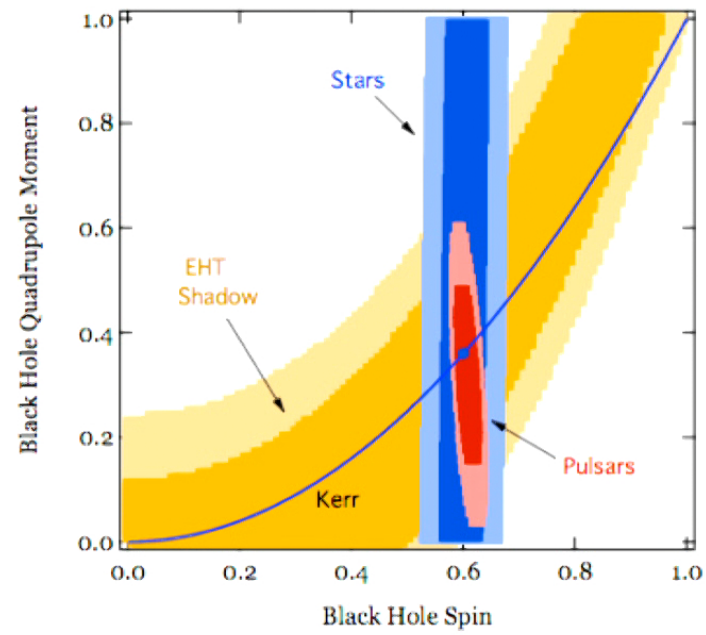
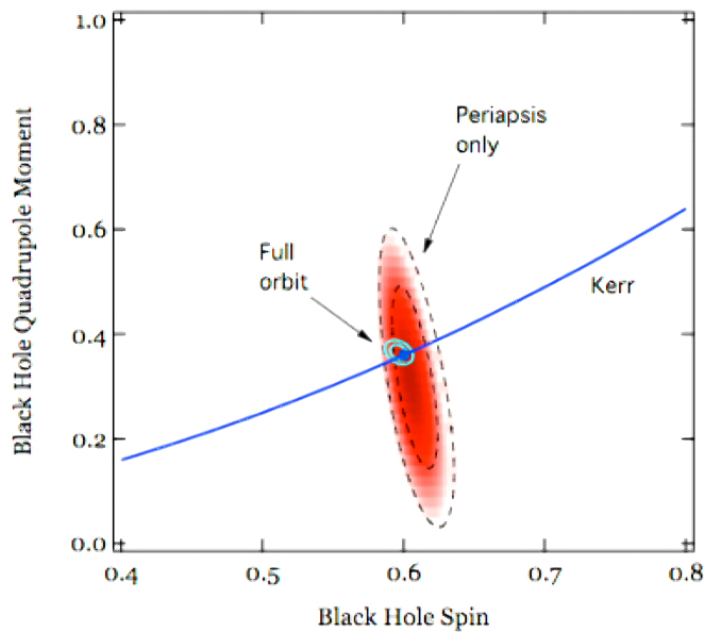
WITH PULSARS (<1 YR)?



Psaltis, Wex, Kramer (2016)

Superradiance, 09.05.2018

WITH PULSARS (<1 YR)?



Psaltis, Wex, Kramer (2016)

Superradiance, 09.05.2018

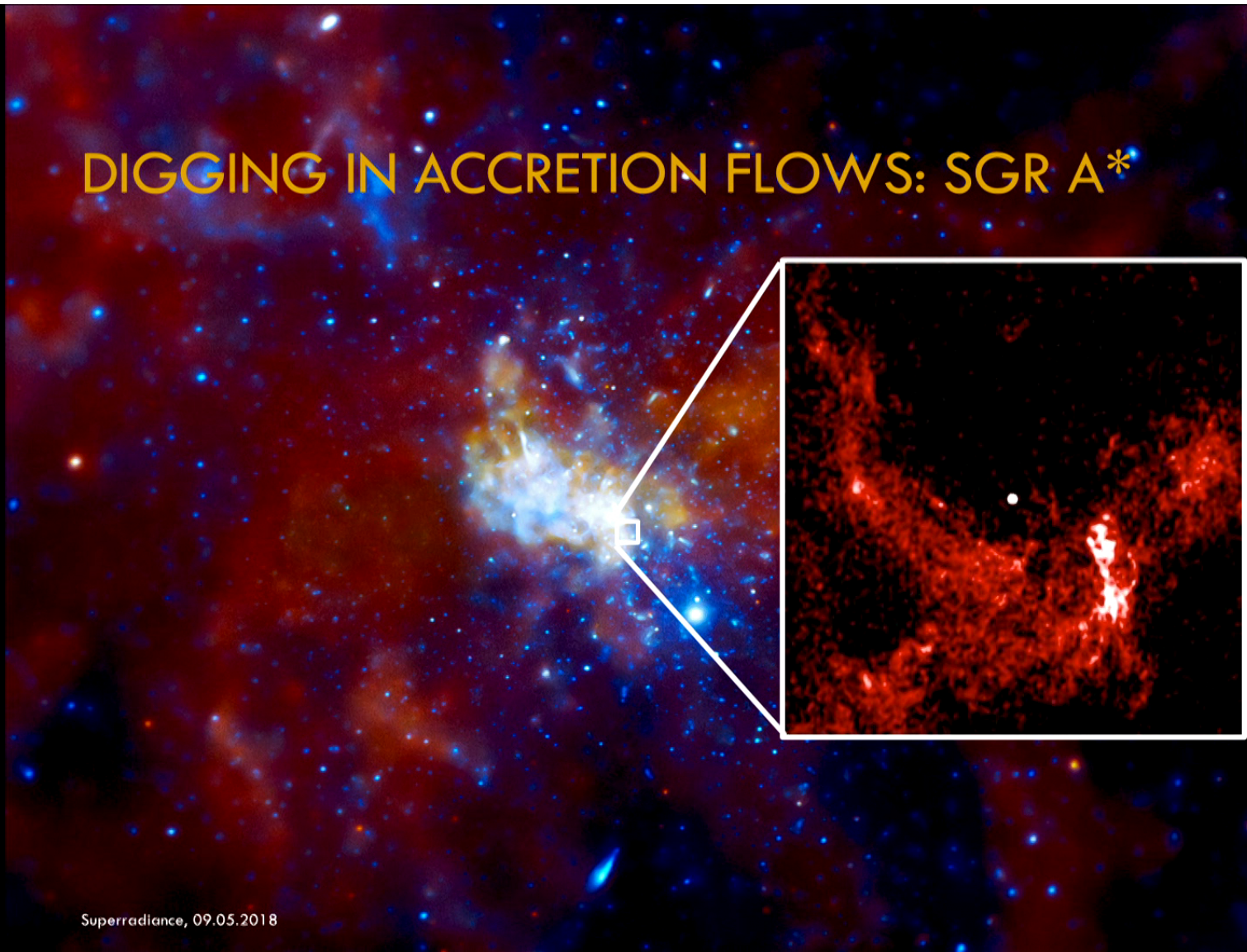
ACCRETION MODELING

Superradiance, 09.05.2018

DIGGING IN ACCRETION FLOWS: SGR A*

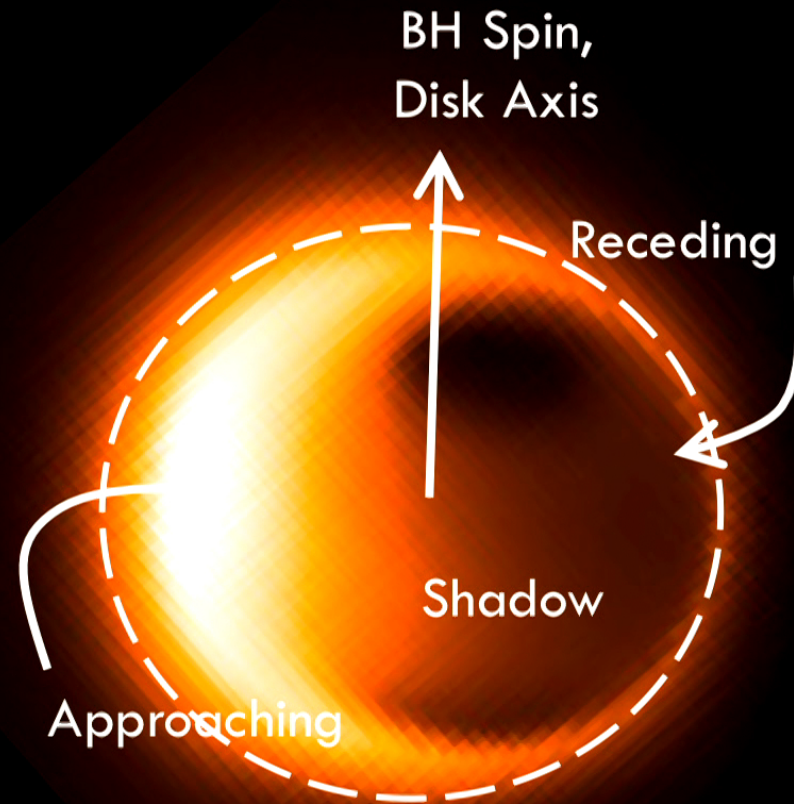
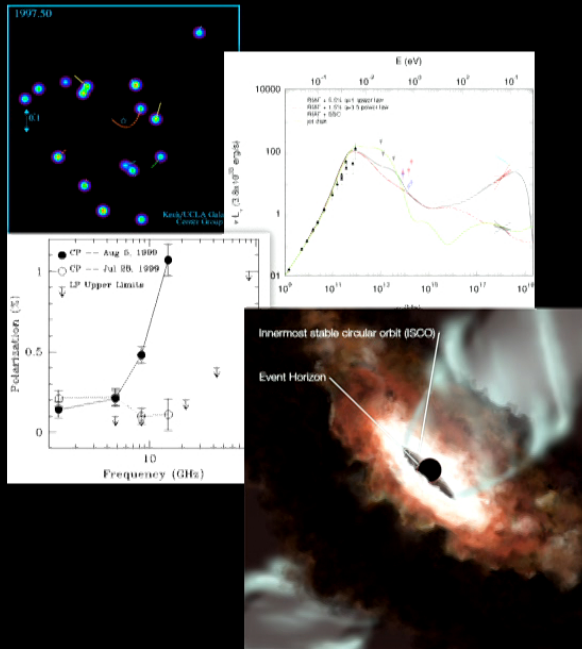
Superradiance, 09.05.2018

DIGGING IN ACCRETION FLOWS: SGR A*



Superradiance, 09.05.2018

MODELING SGR A*



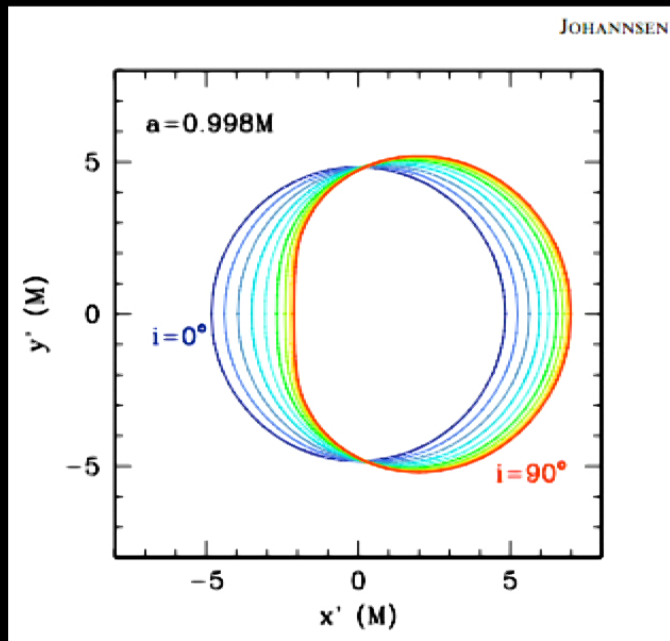
$$I(x, y; a, \theta, \xi)$$

Superradiance, 09.05.2018

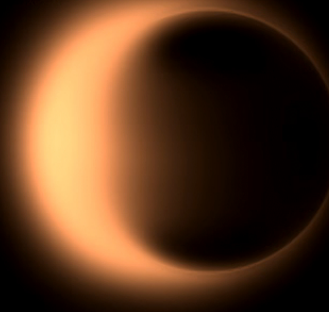
ORIGIN OF SPIN/SPACETIME SENSITIVITY

Photon Rings

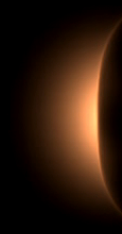
Fixed SED Images



Low Spin



High Spin



Spacetime
+
Dynamics

POSTDICTIONS ARE EASY, PREDICTIONS ARE HARD!

Table 1
Data Epochs

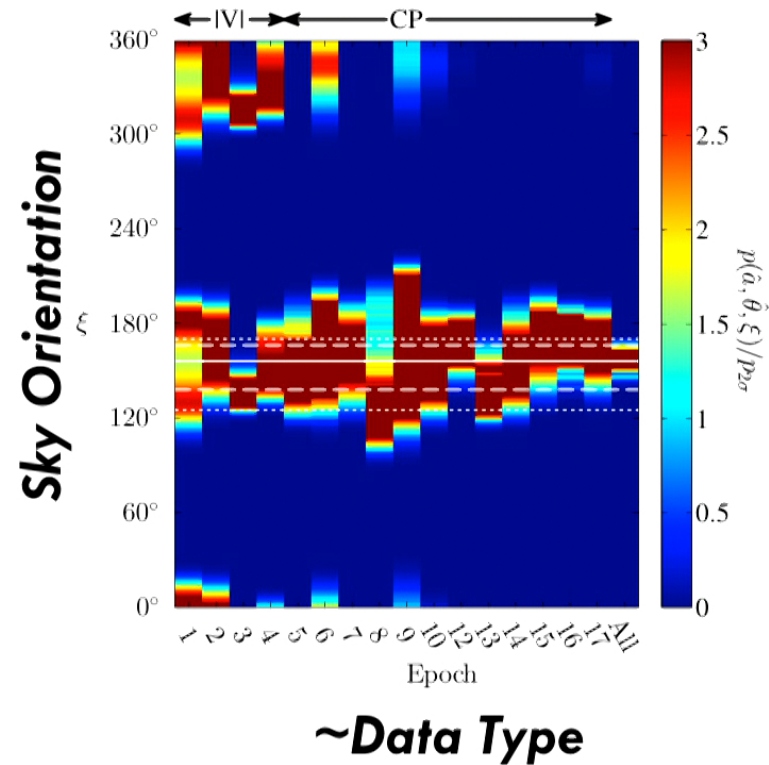
Epoch	Year	Day(s)	Time	N ^a	Type ^b	Ref ^c
1	2007	100-101	11.00-13.67	19	VM	D8
2	2009	95	11.17-15.00	12	VM	F11
3	2009	96	11.50-14.56	19	VM	F11
4	2009	97	11.50-13.67	20	VM	F11
Totals	11.73 hrs	70		
5	2009	93	11.54-13.87	11	CP	F15
6	2009	96	12.46-12.79	3	CP	F15
7	2009	97	11.96-14.38	10	CP	F15
8	2011	88	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)

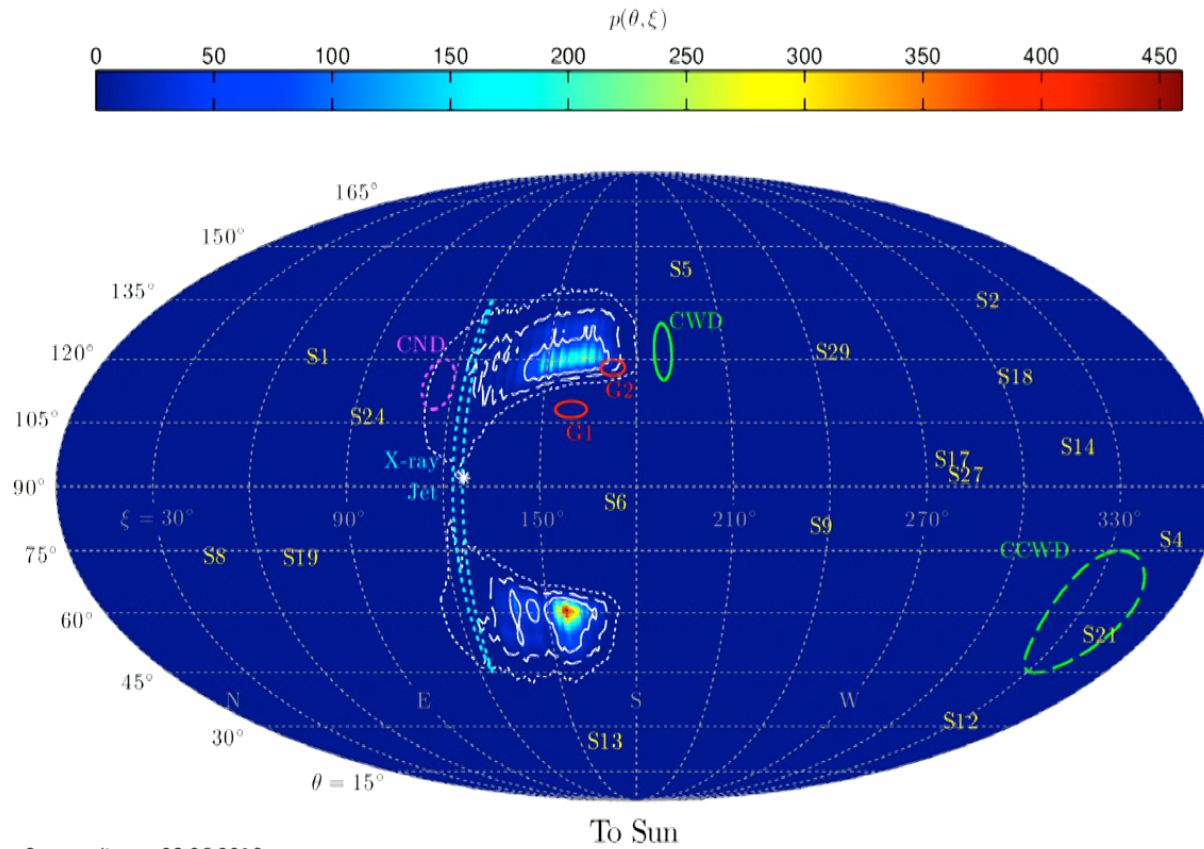
^c D8=DOEL8, F11=FISH11, F15=FISH15

^d Contaminated by flare activity



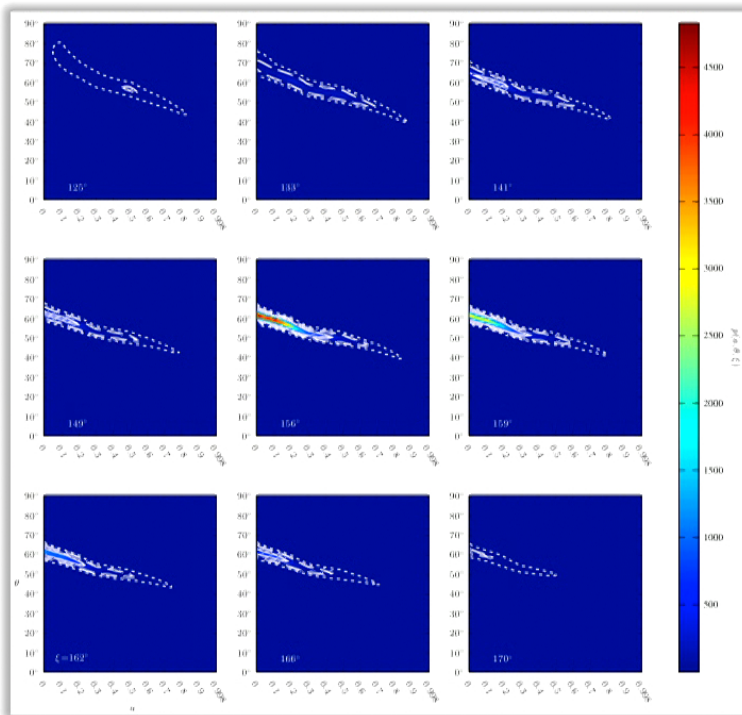
Superradiance, 09.05.2018

ORIENTATION AND THE GALACTIC CENTER STORY



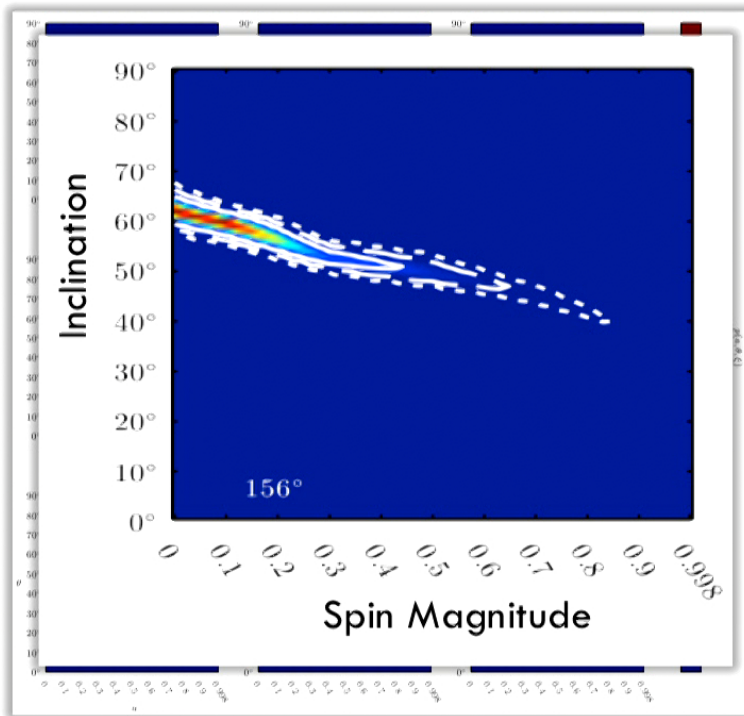
Superradiance, 09.05.2018

PROBING ACCRETION WITH 7 YEARS OF EHT DATA



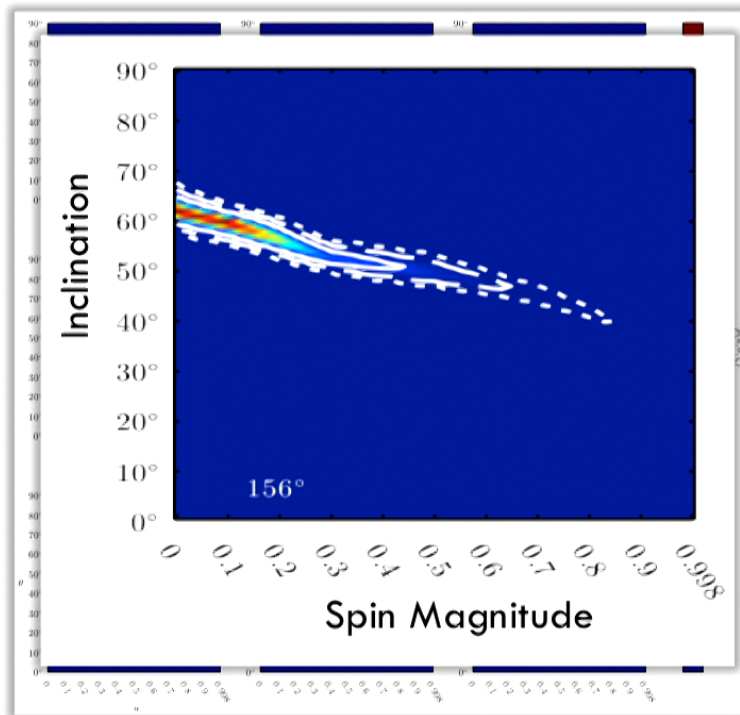
Superradiance, 09.05.2018

PROBING ACCRETION WITH 7 YEARS OF EHT DATA

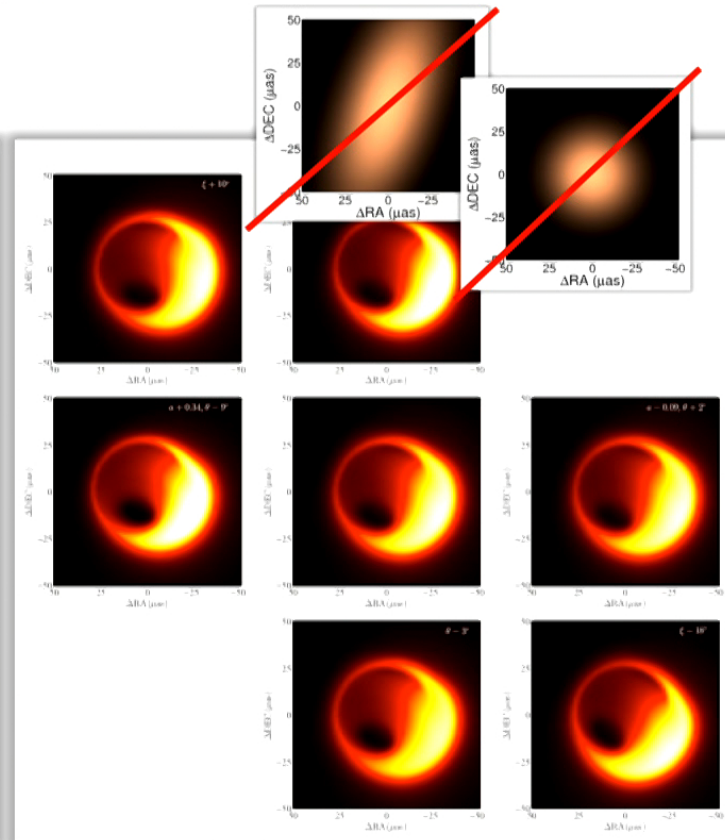


Superradiance, 09.05.2018

PROBING ACCRETION WITH 7 YEARS OF EHT DATA

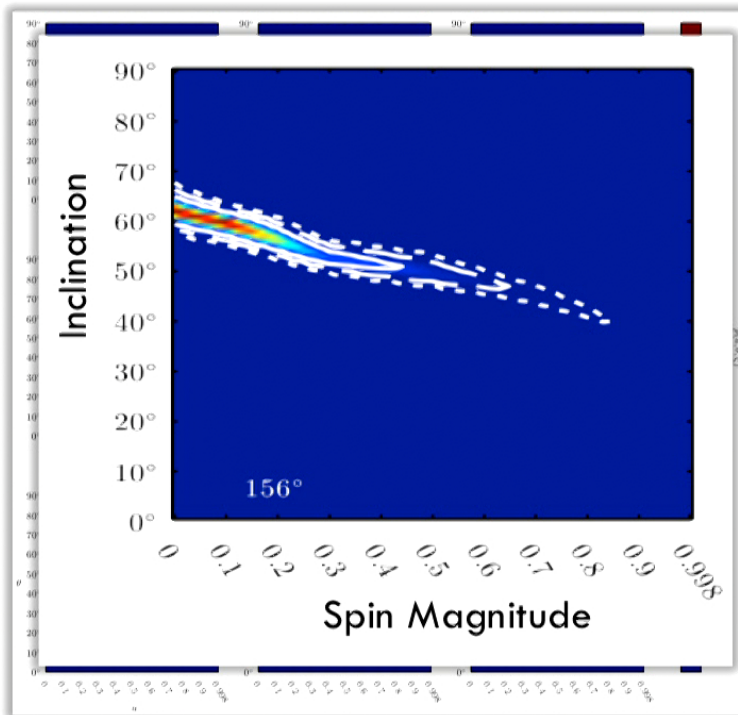


Excluded!

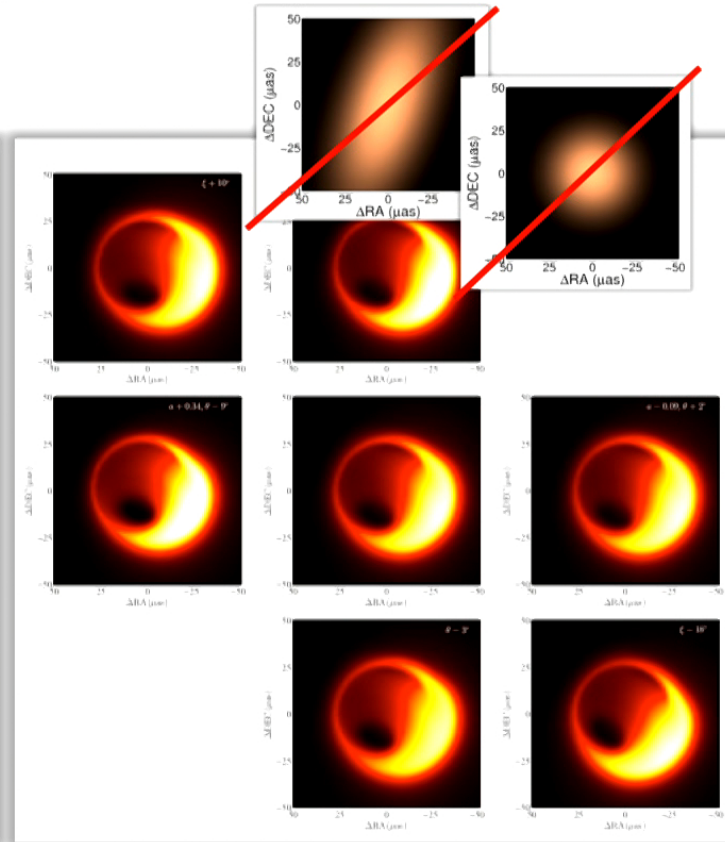


Superradiance, 09.05.2018

PROBING ACCRETION WITH 7 YEARS OF EHT DATA

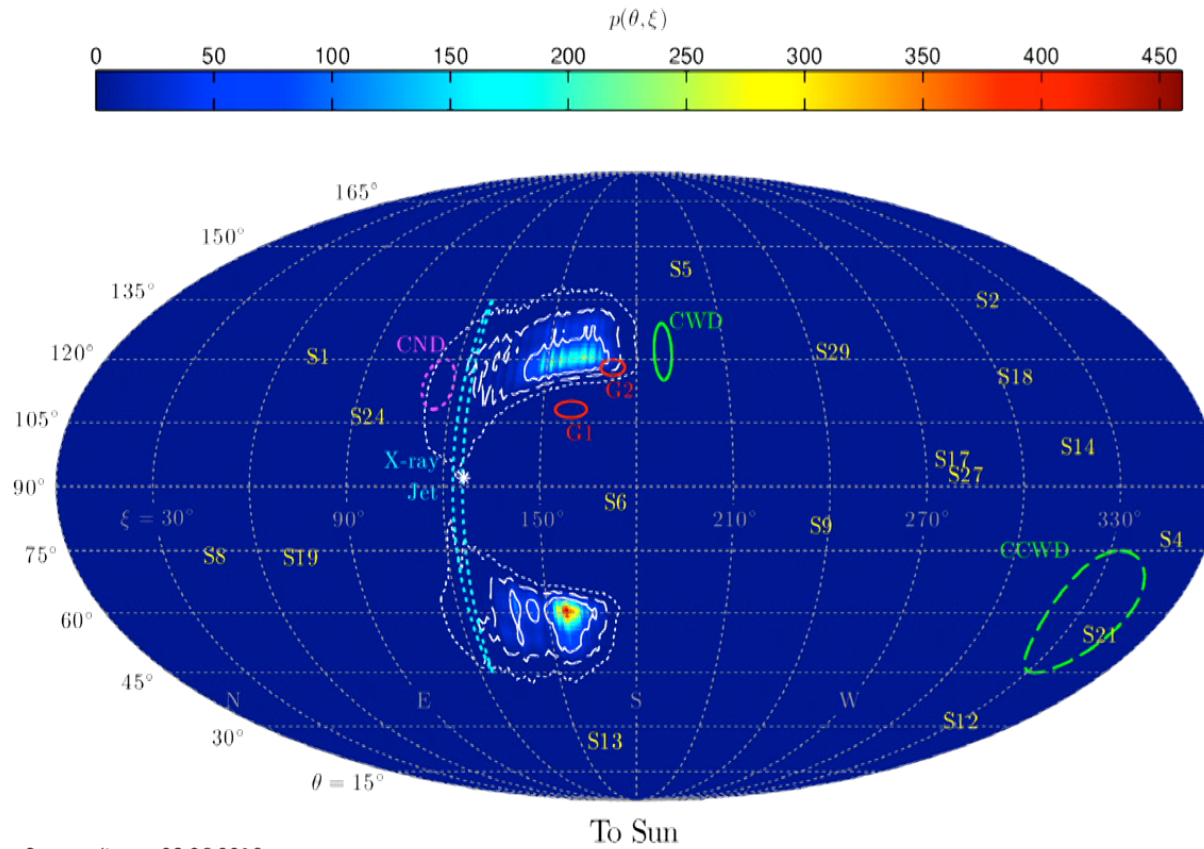


Excluded!



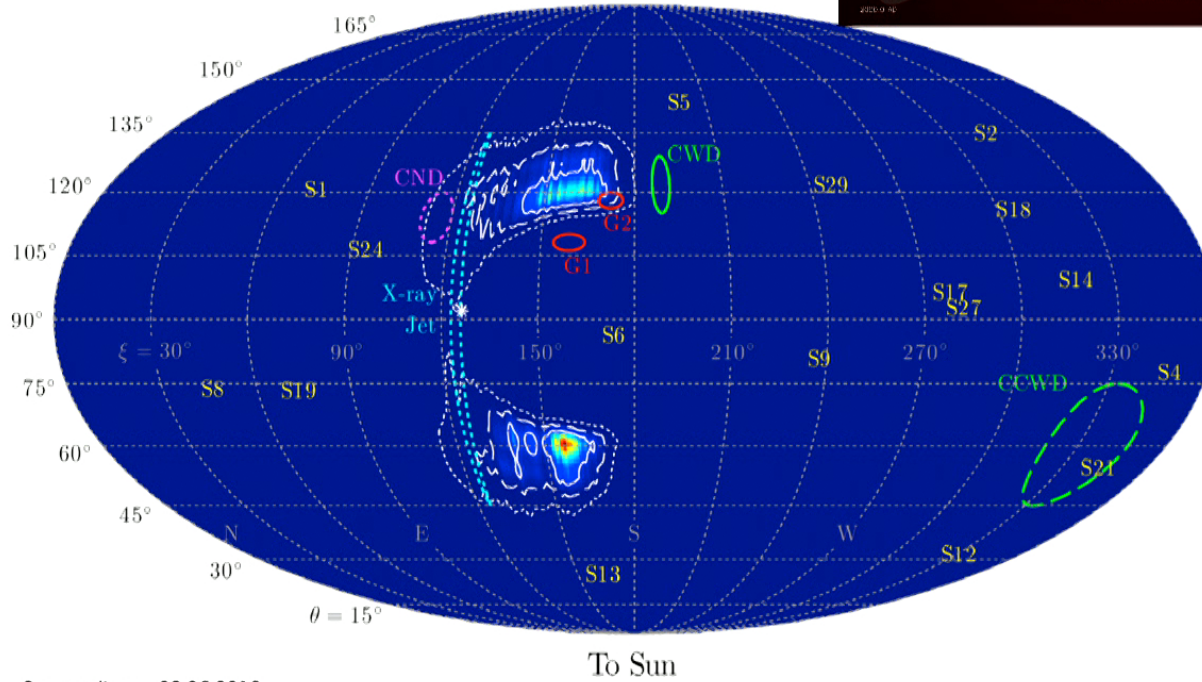
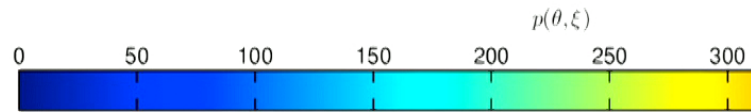
Superradiance, 09.05.2018

ORIENTATION AND THE GALACTIC CENTER STORY



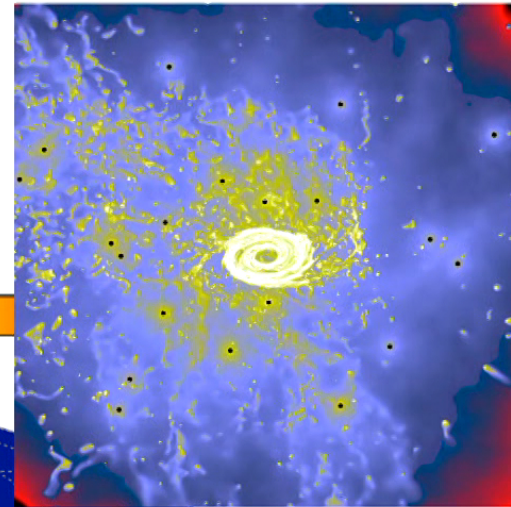
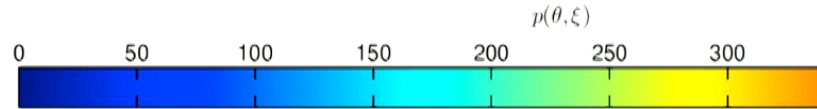
Superradiance, 09.05.2018

ORIENTATION AND THE GALACTIC CENTER STORY

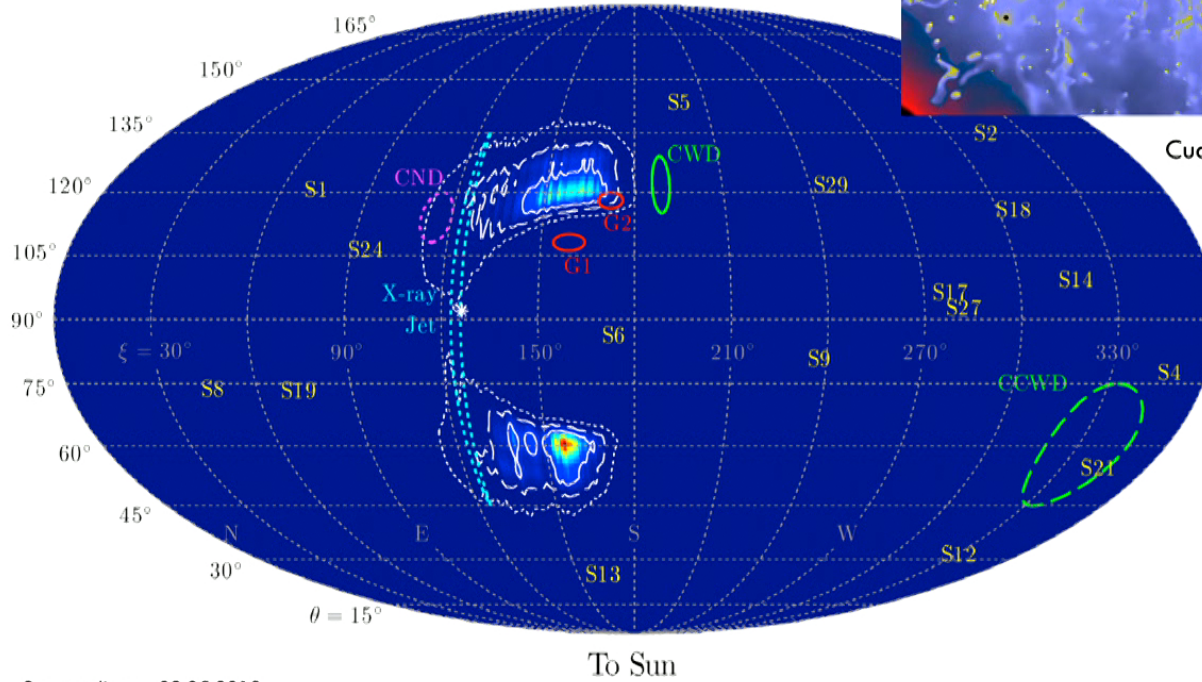


Superradiance, 09.05.2018

ORIENTATION AND THE GALACTIC CENTER STORY

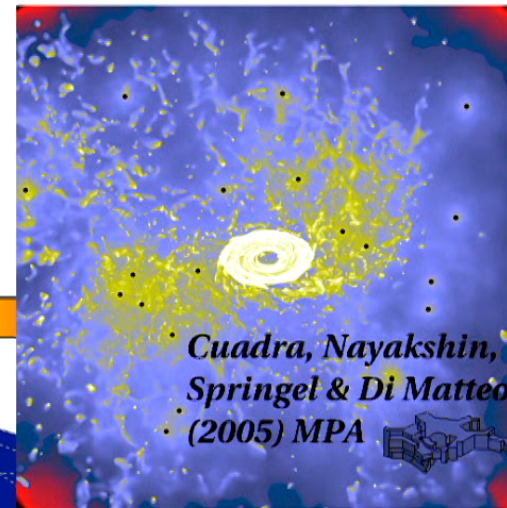
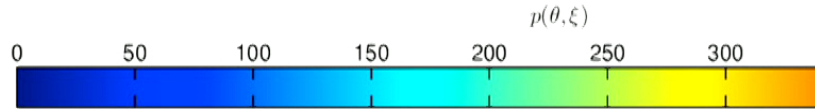


Cuadra et al. (2005)

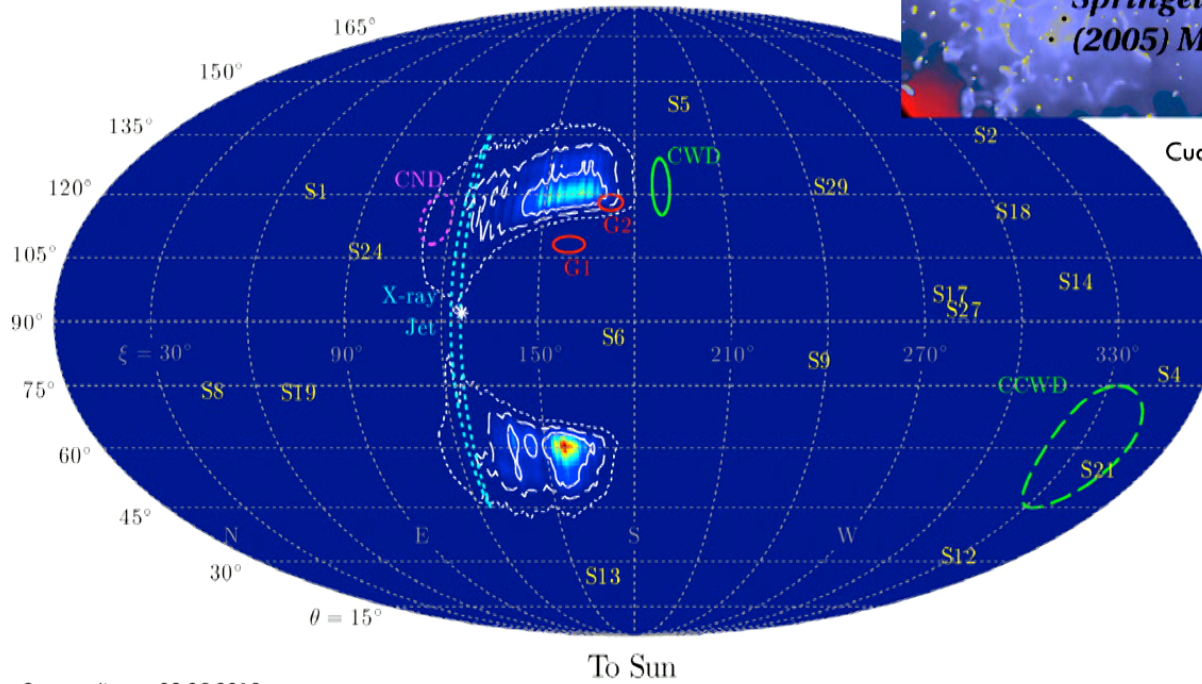


Superradiance, 09.05.2018

ORIENTATION AND THE GALACTIC CENTER STORY



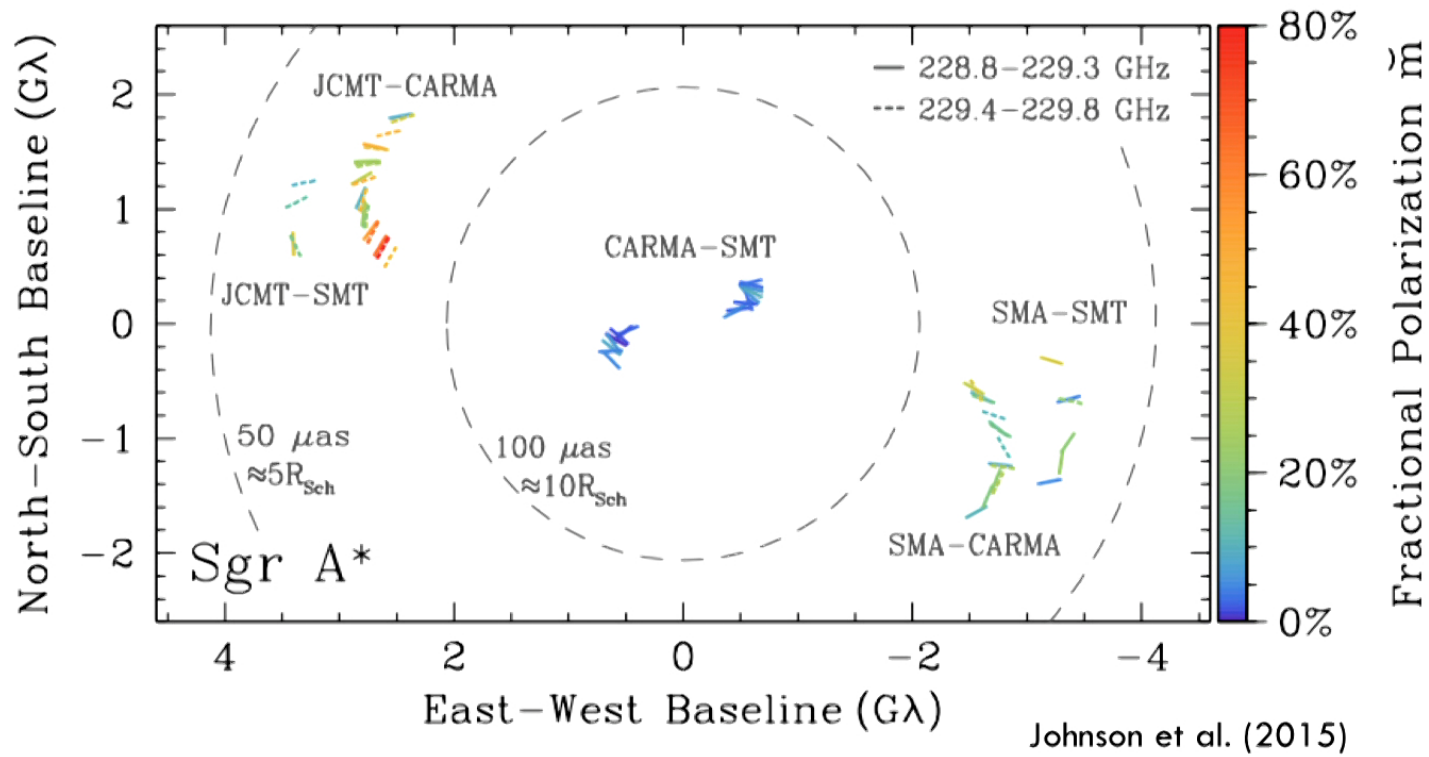
Cuadra et al. (2005)



Superradiance, 09.05.2018

LARGE SMALL-SCALE POLARIZATION!

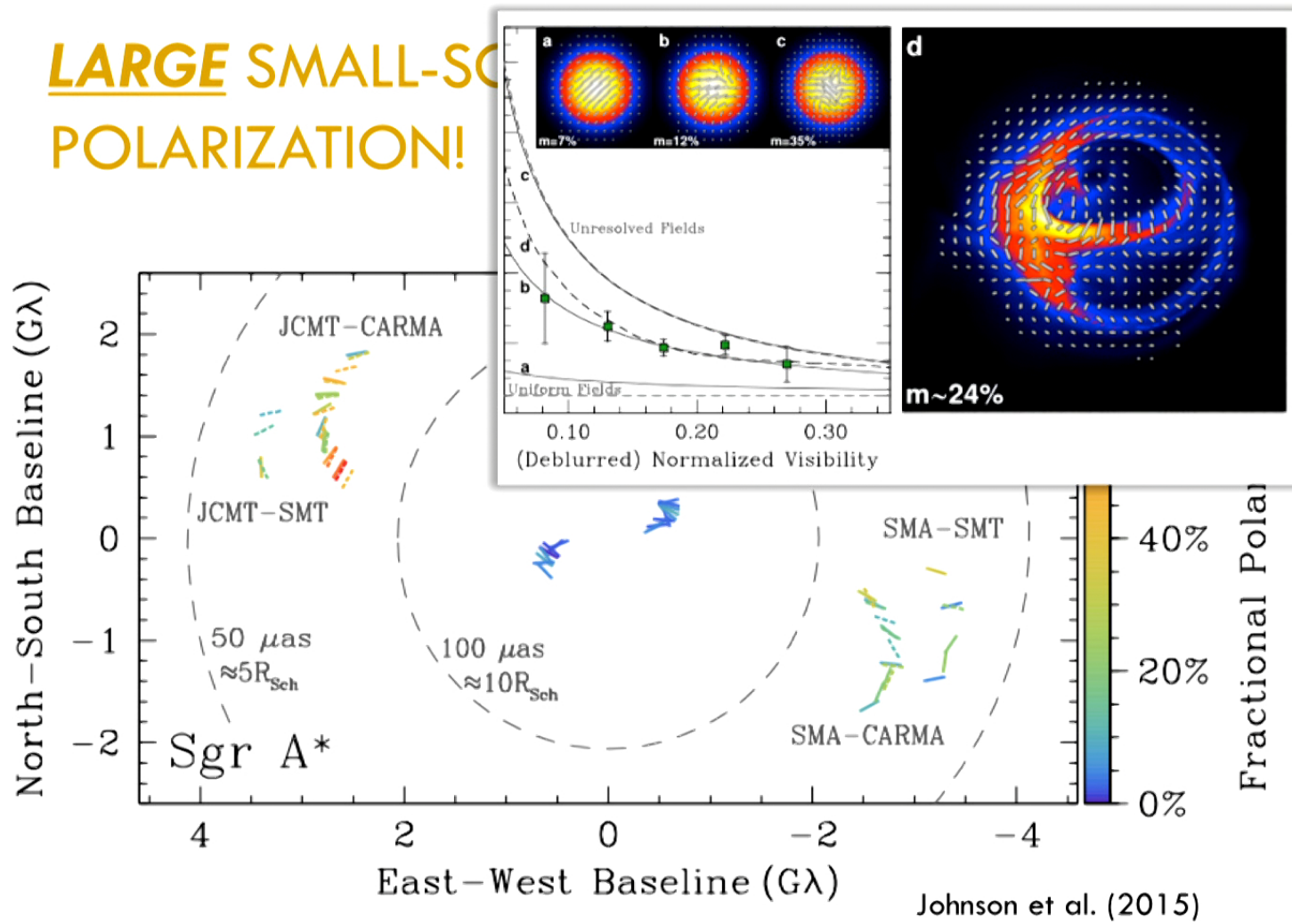
$$\tilde{m} = \frac{\tilde{Q} + i\tilde{U}}{\tilde{I}}$$



Johnson et al. (2015)

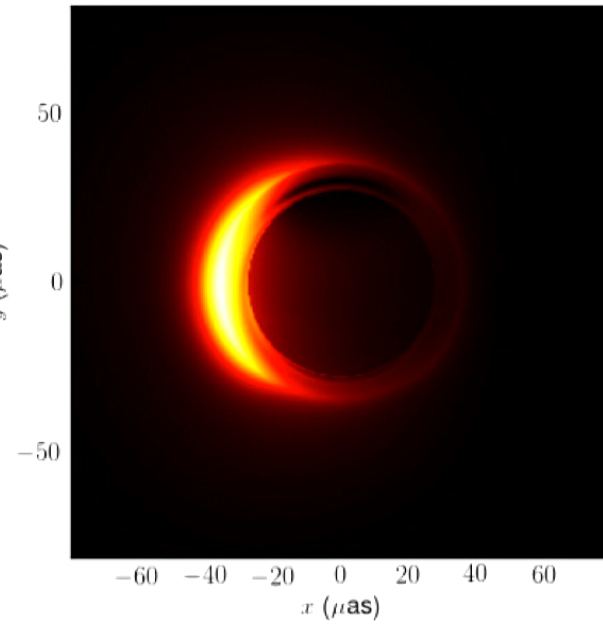
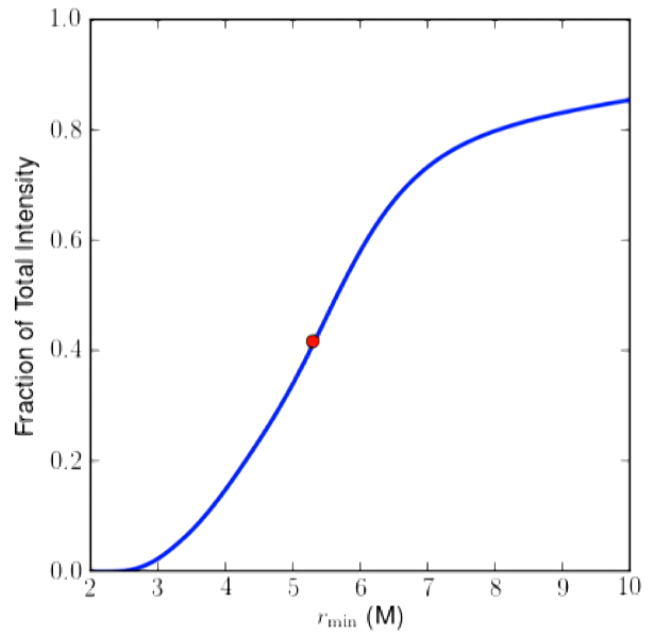
Superradiance, 09.05.2018

LARGE SMALL-SCALE POLARIZATION!



Superradiance, 09.05.2018

EMISSION FROM WHERE?

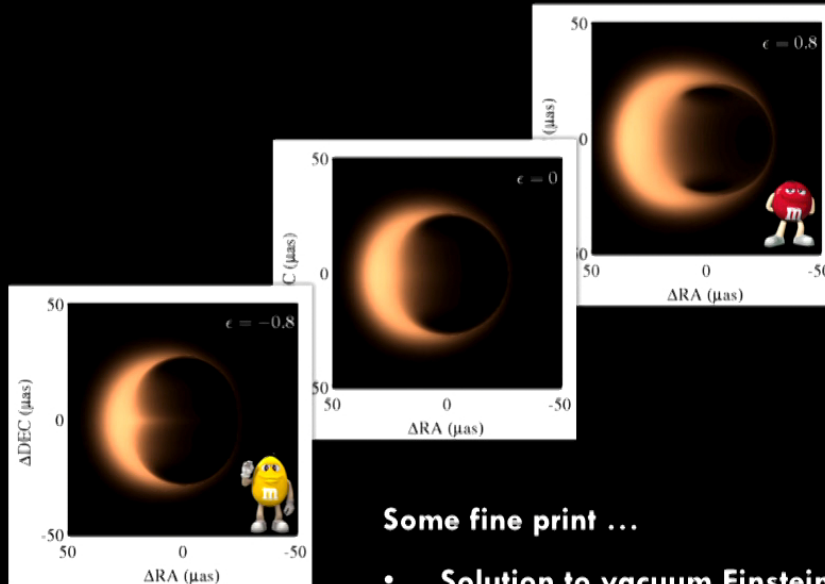


H.-Y. Pu & AEB (2018)

Superradiance, 09.05.2018

HAIRY MULTIPOLES

Quasi-Kerr Metric: Parameterized Deviation



$$g_{\mu\nu} = g_{\mu\nu}^K + \epsilon h_{\mu\nu}$$

$$M = M, \quad J = aM,$$

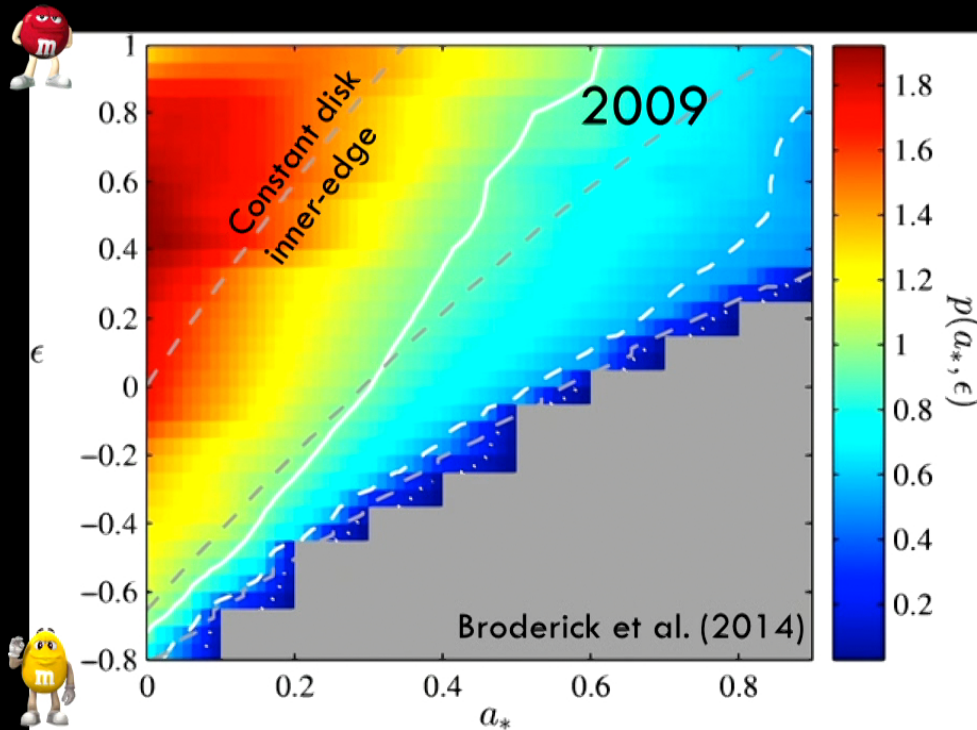
$$Q = -a^2M - \epsilon M^3$$

Some fine print ...

- Solution to vacuum Einstein equations when $|a| \ll M$
- Adds quadrupolar perturbation (based on Hartle-Thorne metric for slowly spinning neutron stars!)
- No-hair theorems \rightarrow Quasi-Kerr metric must be sick! It is inside $2M$.

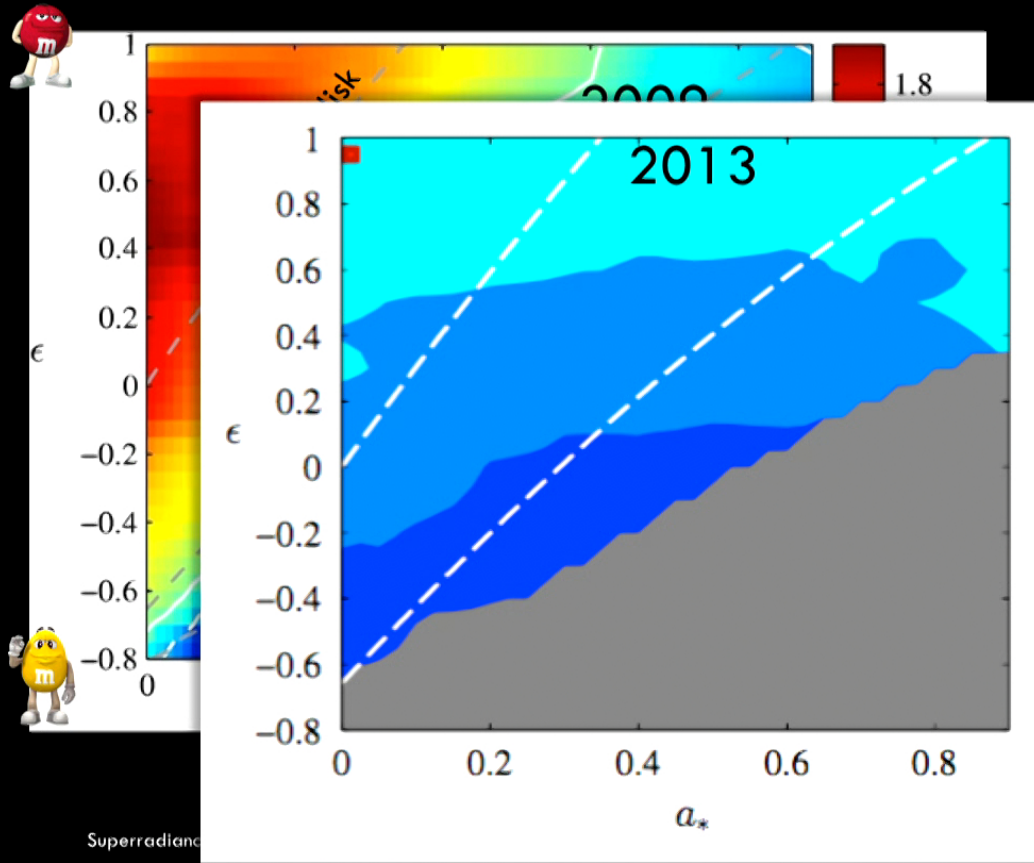
Superradiance, 09.05.2018

HAIRY MULTIPOLES

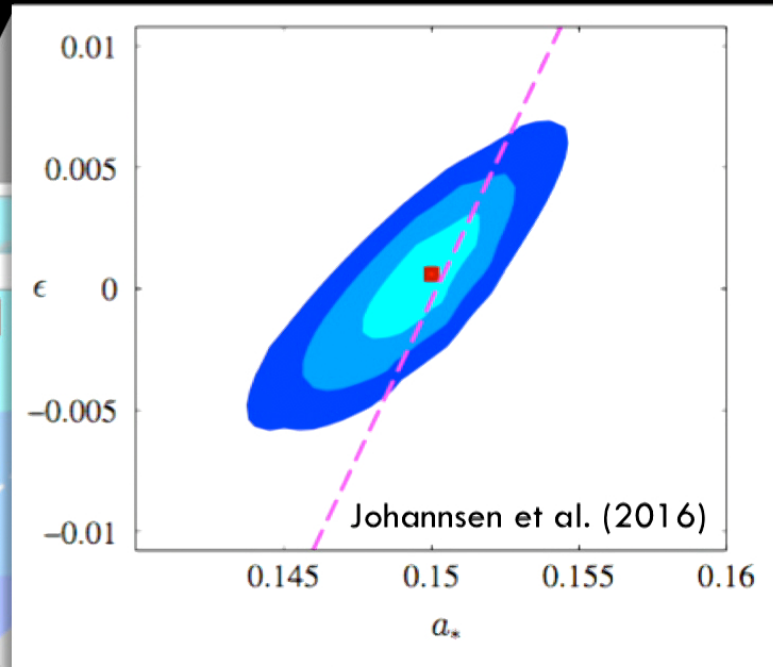
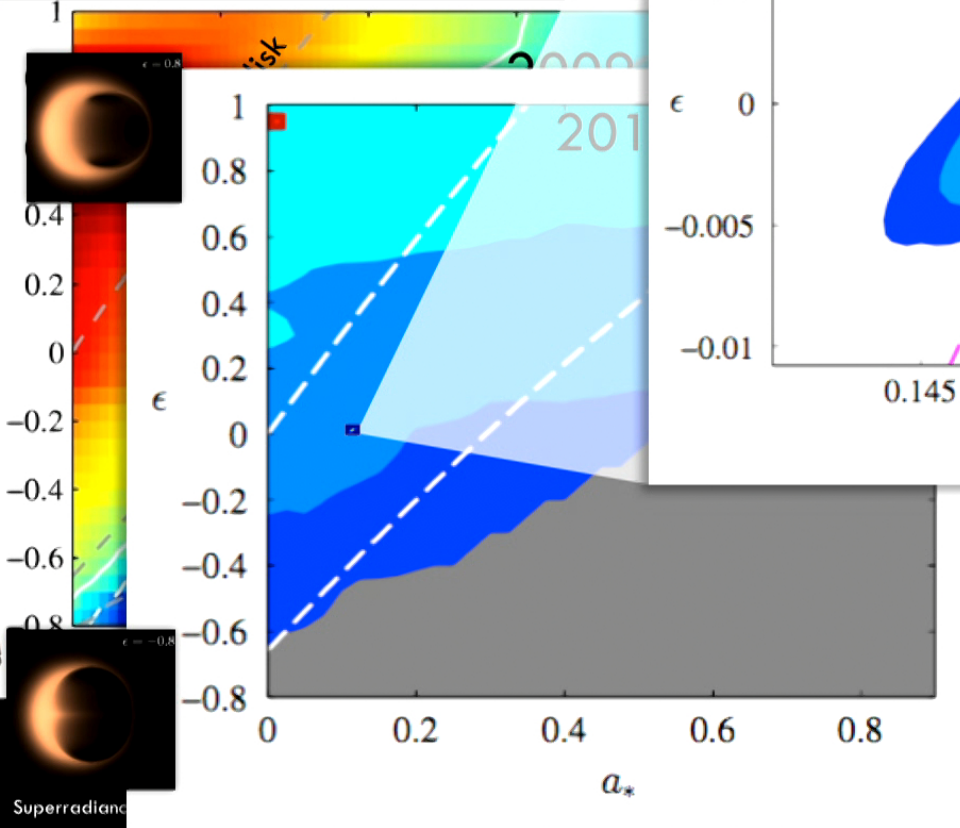


Superradiance, 09.05.2018

HAIRY MULTIPOLES

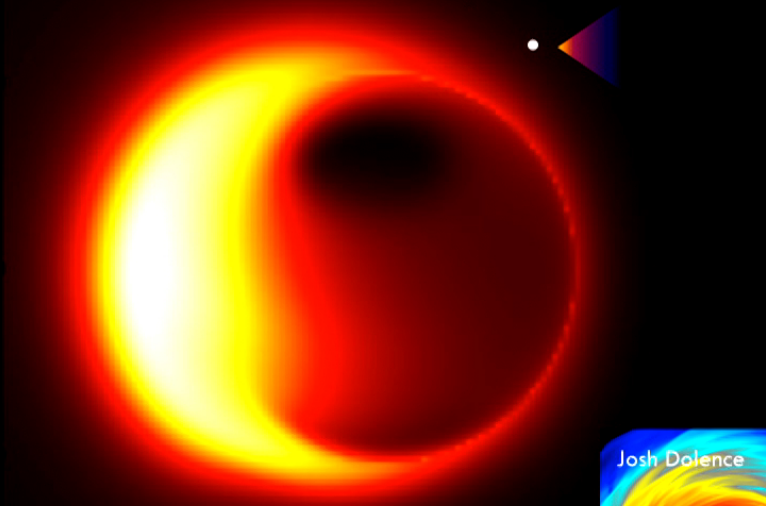


HAIRY MULTIPOLES

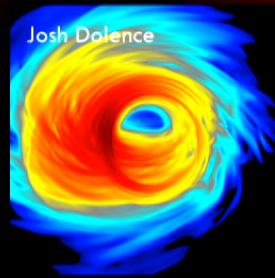
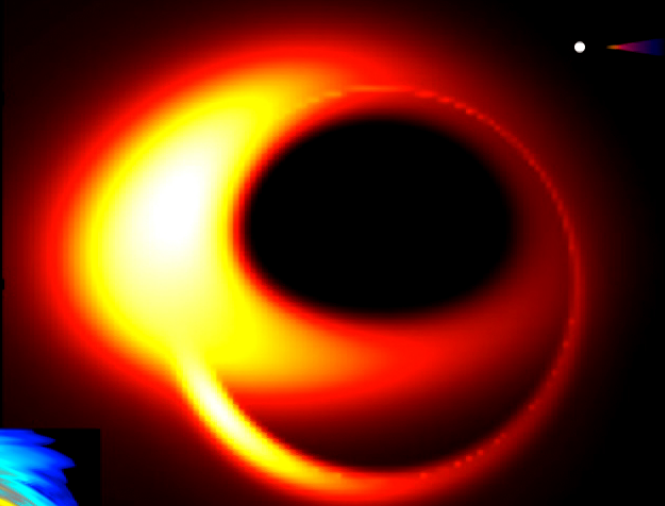


ONE BIG MODEL FAMILY

Hot/Thick Disk



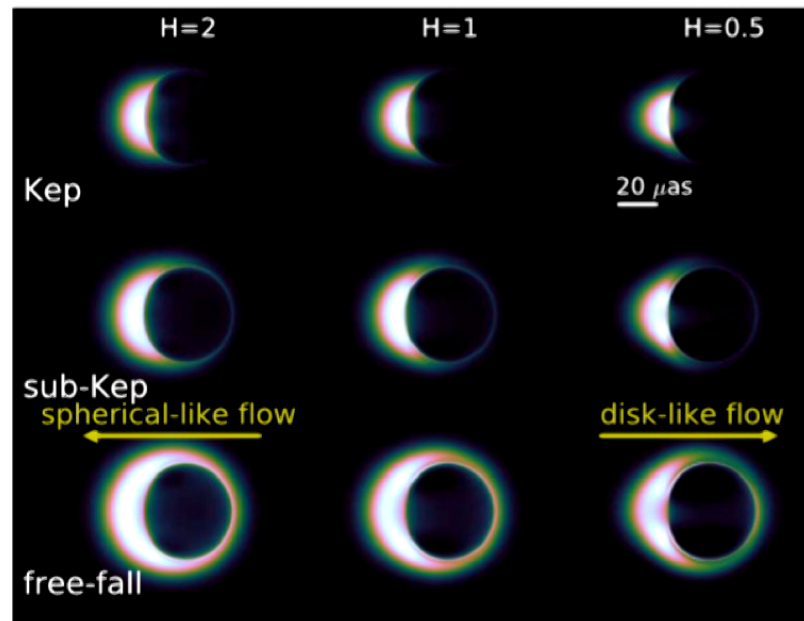
Cold/Thin Disk



Superradiance, 09.05.2018

WHAT ABOUT ASTROPHYSICS?: DISK PARAMETERS

- **Dynamics – How sub-Keplerian are RIAs?**
- **Vertical Structure – Hot & Thick? SANE vs MAD?**

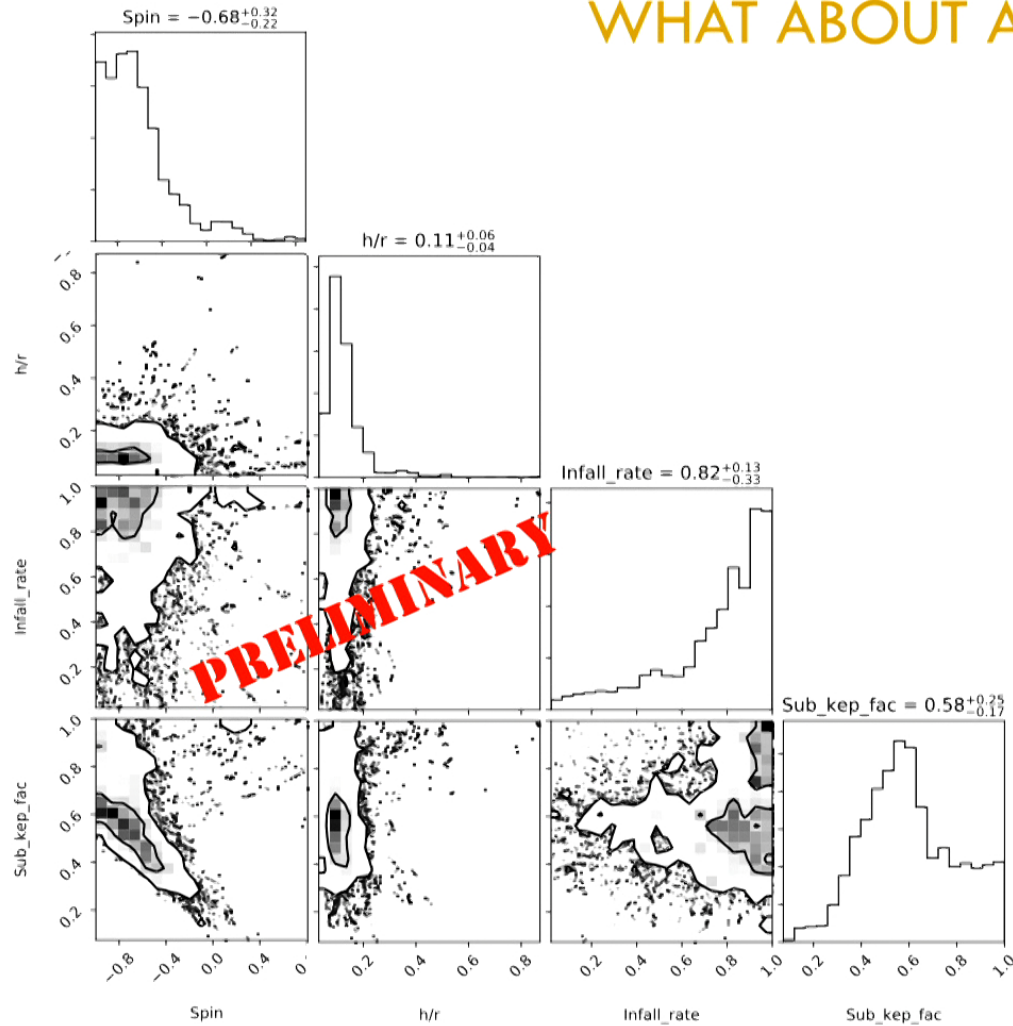


Superradiance, 09.05.2018

Hung-Yi Pu & AEB

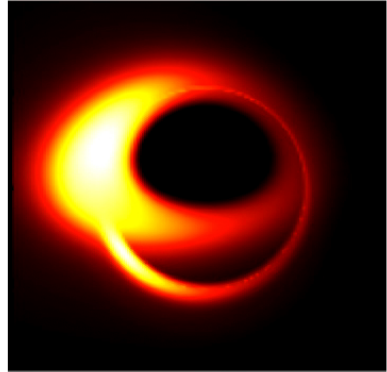
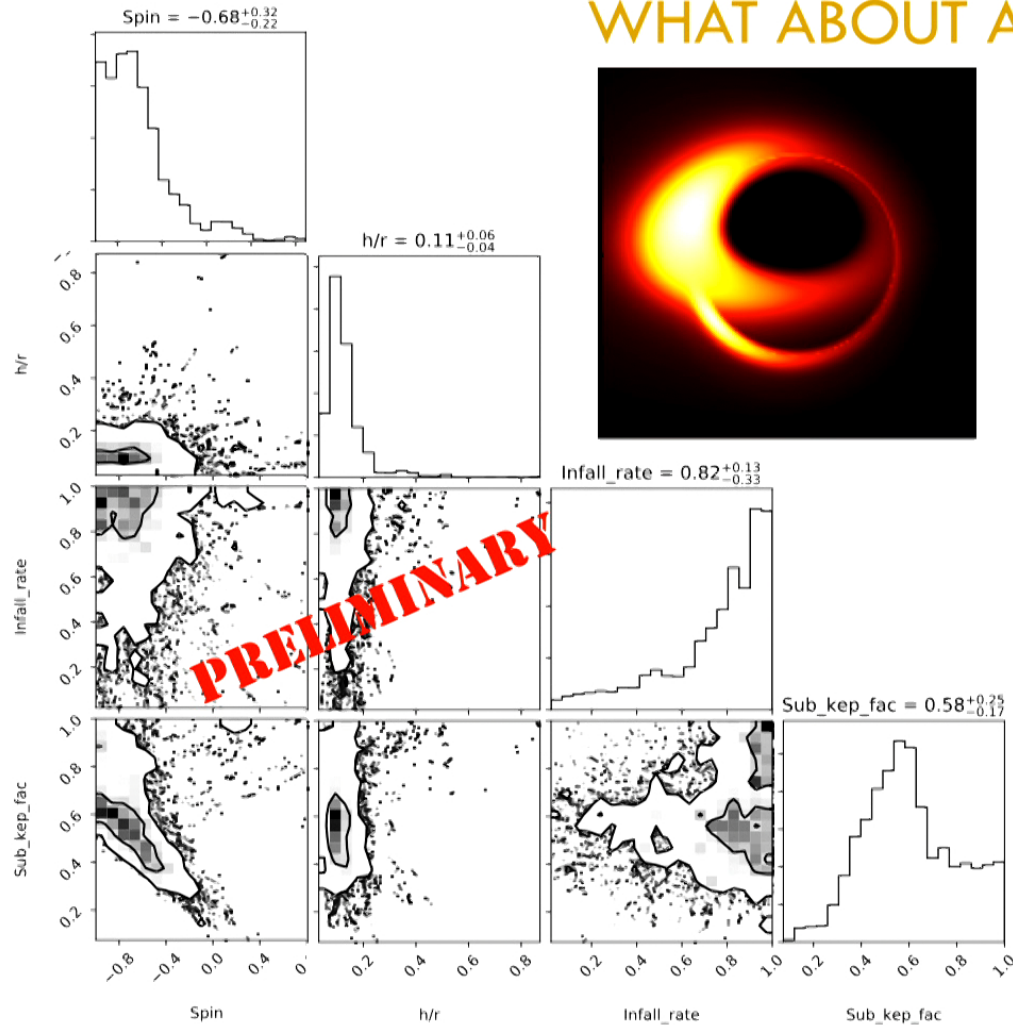
Mansour Karami

WHAT ABOUT ASTROPHYSICS?: SANE VS MAD?



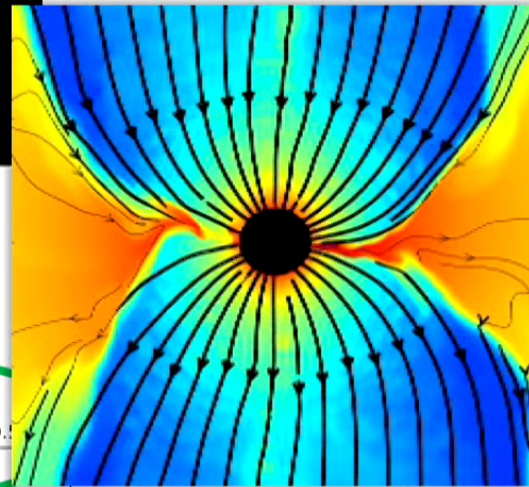
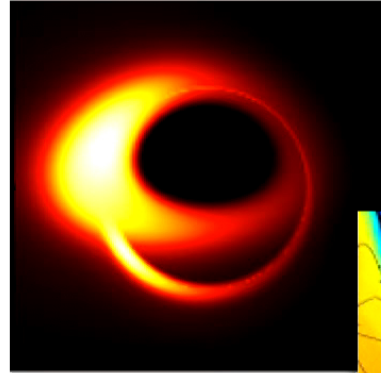
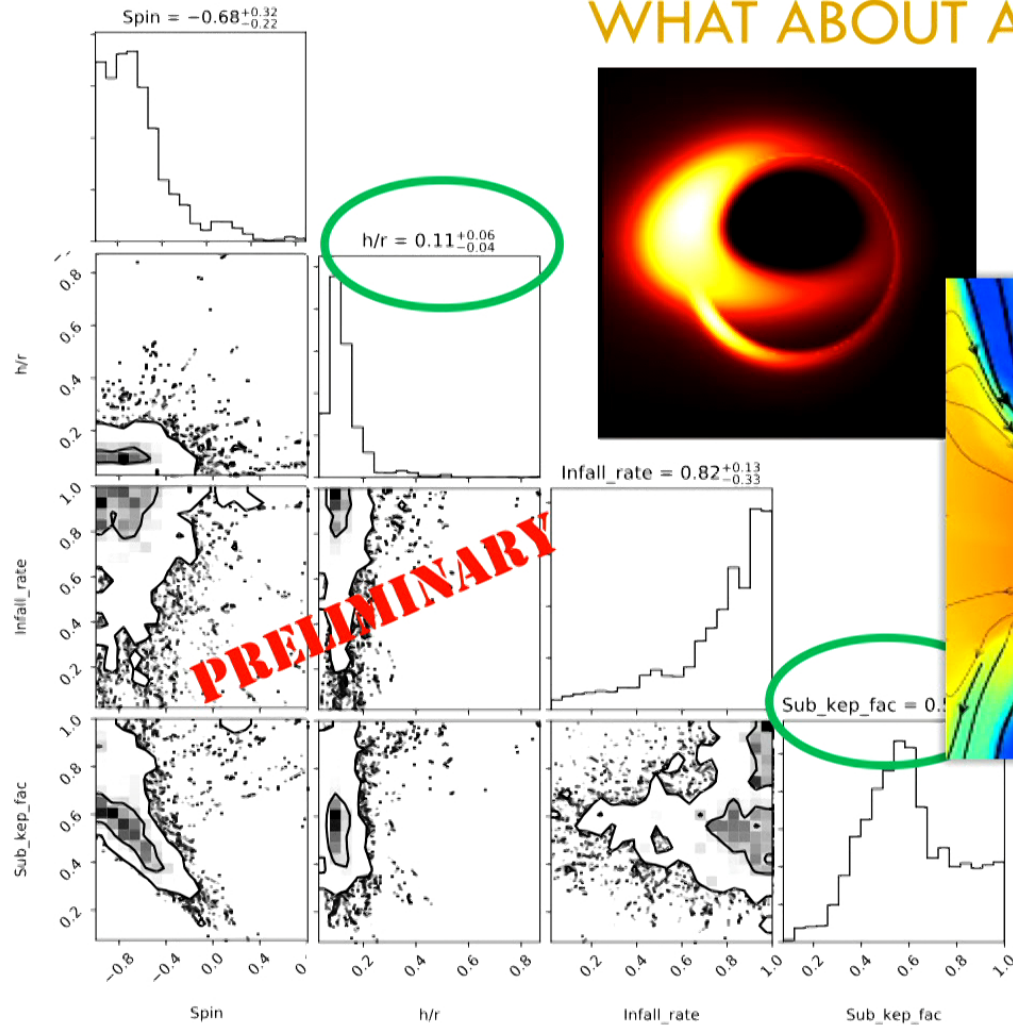
Mansour Karami

WHAT ABOUT ASTROPHYSICS?: SANE VS MAD?



Mansour Karami

WHAT ABOUT ASTROPHYSICS?: SANE VS MAD?



Tchekhovskoy et al. (2011)

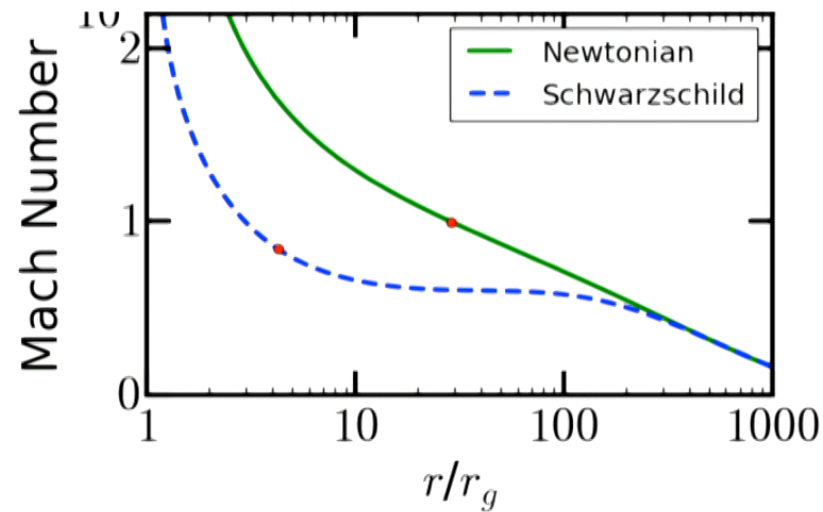
WHAT ABOUT ASTROPHYSICS?: DISK PARAMETERS AND GRAVITY

- **Gravitational modifications of disk structure?**

Radial Euler eq. (schematically):

$$\underbrace{\left(1 - \frac{c_s^2}{v^2}\right)}_{\text{Critical pt.}} \frac{\partial v}{\partial r} = (\text{Residual of Gravity} - \text{Pressure})$$

Boris Georgiev
Luis Lehner



Superradiance, 09.05.2018

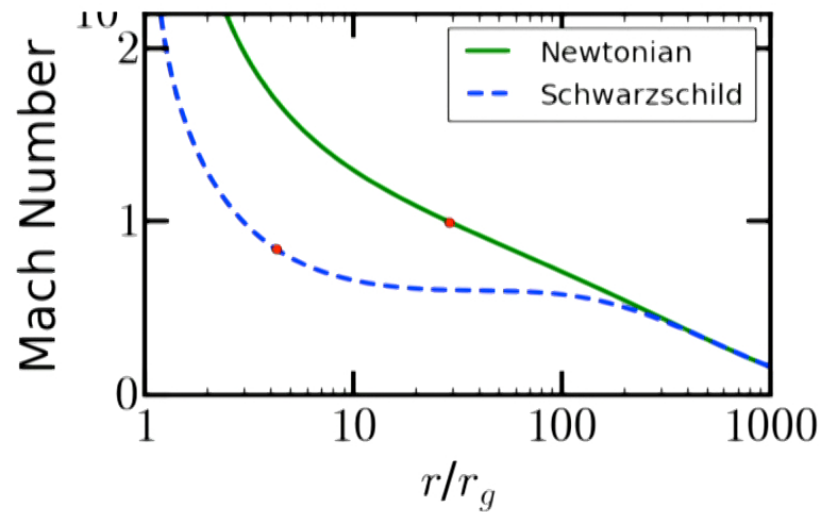
WHAT ABOUT ASTROPHYSICS?: DISK PARAMETERS AND GRAVITY

- **Gravitational modifications of disk structure?**

Radial Euler eq. (schematically):

$$\frac{\partial \Delta v_{GR-N}}{\partial r} = \frac{(g - \nabla P)_{GR} - (g - \nabla P)_N}{1 - c_s^2/v^2}$$

Boris Georgiev
Luis Lehner



Superradiance, 09.05.2018

WHAT ABOUT ASTROPHYSICS?: DISK PARAMETERS AND GRAVITY

- **Gravitational modifications of disk structure?**

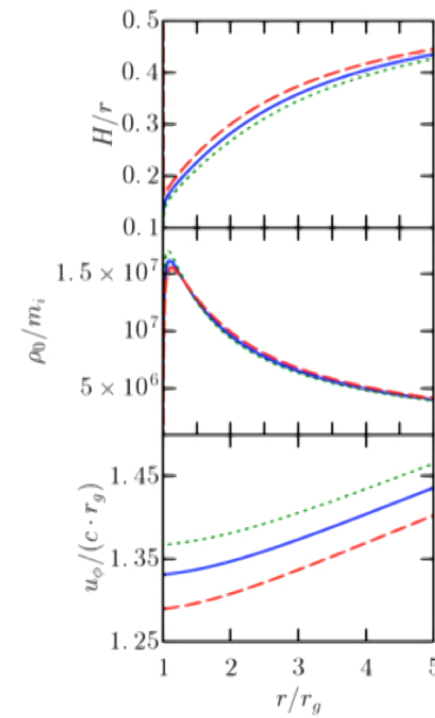
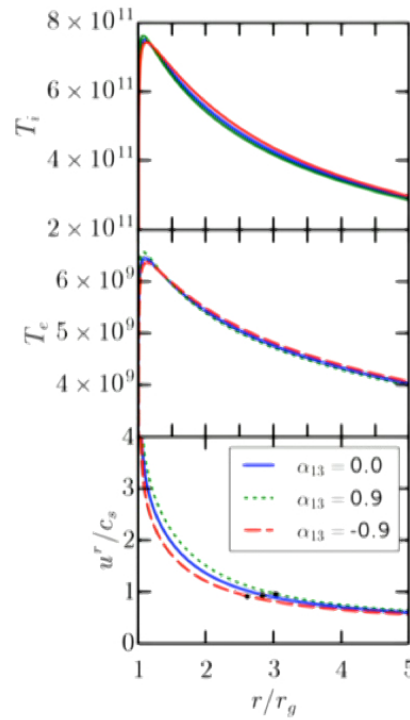
Ingredients:

- Covariant ADAF model
- Johannsen (2013) metric

Even big gravitational perturbations



Small changes in accretion flow!



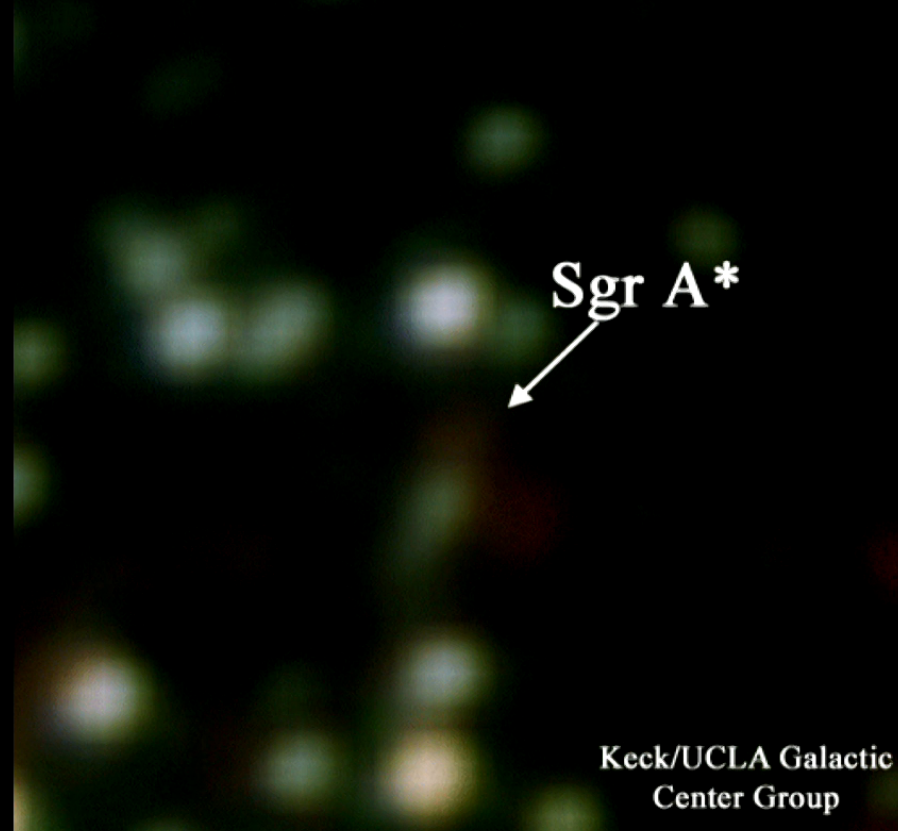
Boris Georgiev
Luis Lehner

Superradiance, 09.05.2018

SPACETIME TOMOGRAPHY

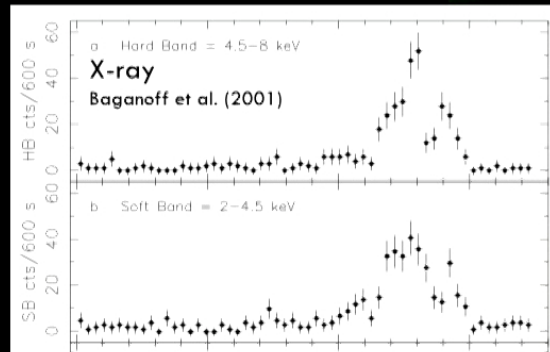
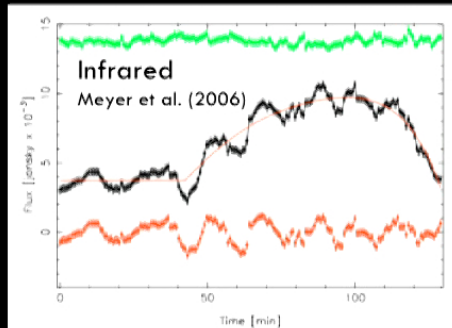
Superradiance, 09.05.2018

FLARES IN THE GALACTIC CENTER



Superradiance, 09.05.2018

FLARES IN THE GALACTIC CENTER

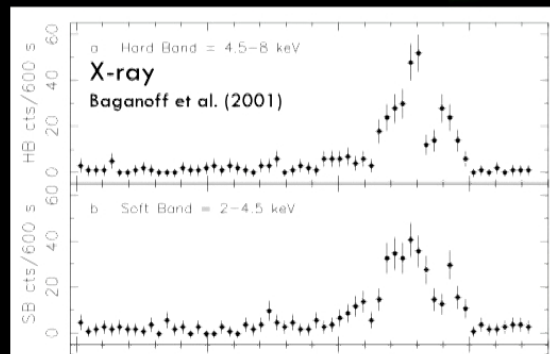
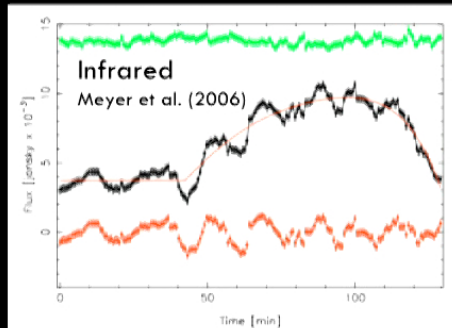


Sgr A*

Keck/UCLA Galactic
Center Group

Superradiance, 09.05.2018

FLARES IN THE GALACTIC CENTER



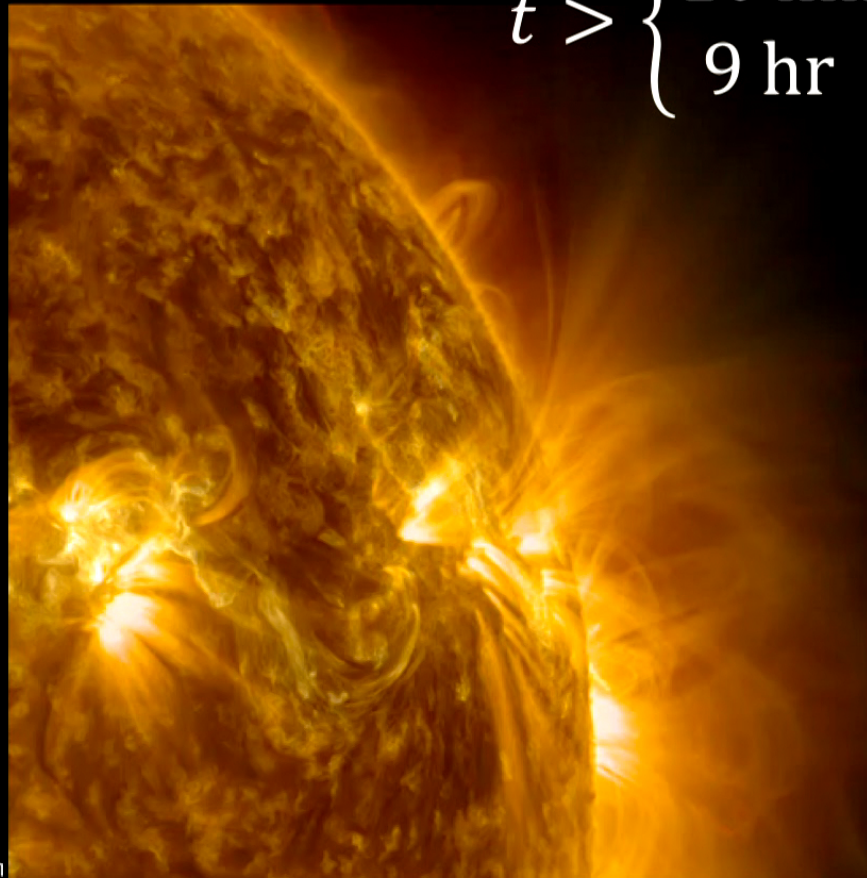
Sgr A*

Keck/UCLA Galactic
Center Group

Superradiance, 09.05.2018

SOMETIMES
BY A LOT

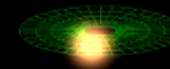
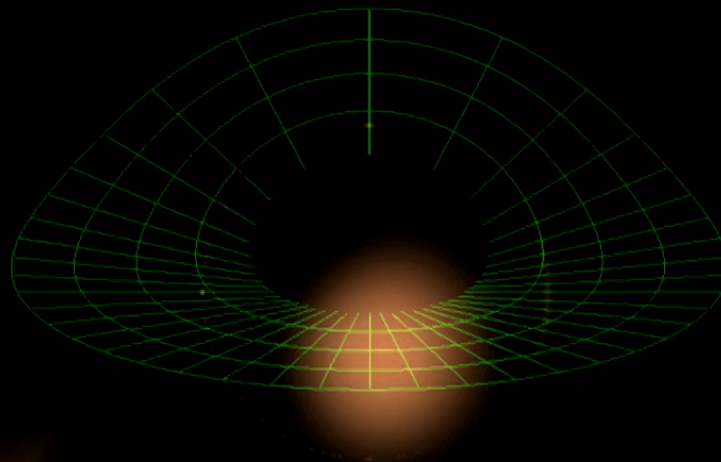
$$t > \begin{cases} 10 \text{ min Sgr A} * \\ 9 \text{ hr M87} \end{cases}$$



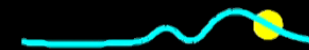
Superradiance, 09.05.201

FLARES IN SGR A*: NONTHERMAL CATASTROPHES

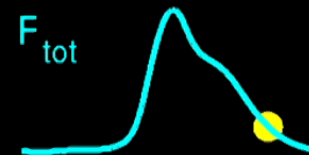
$a=0, r=6M$



F_{LP}



F_{tot}

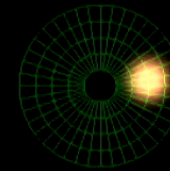
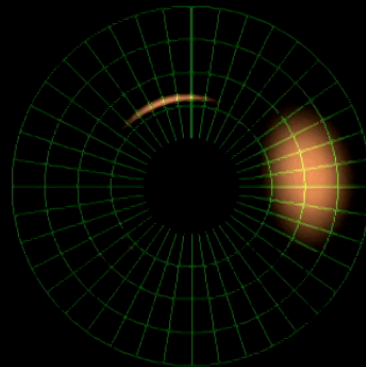


Superradiance, 09.05.2018

Broderick & Loeb, 2006, MNRAS, 367, 905

FLARES IN SGR A*: NONTHERMAL CATASTROPHES

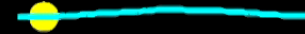
$a=0, r=6M$



F_{LP}

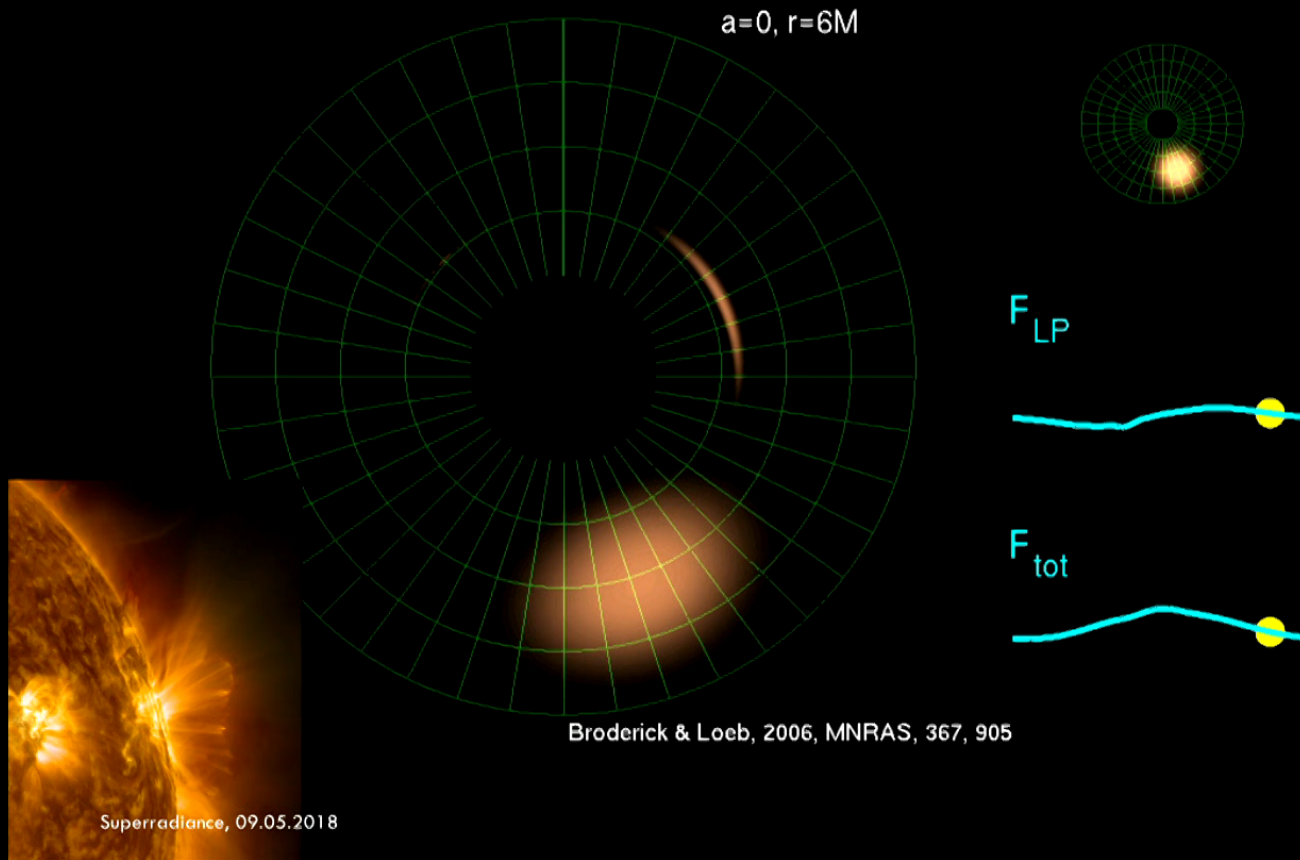


F_{tot}

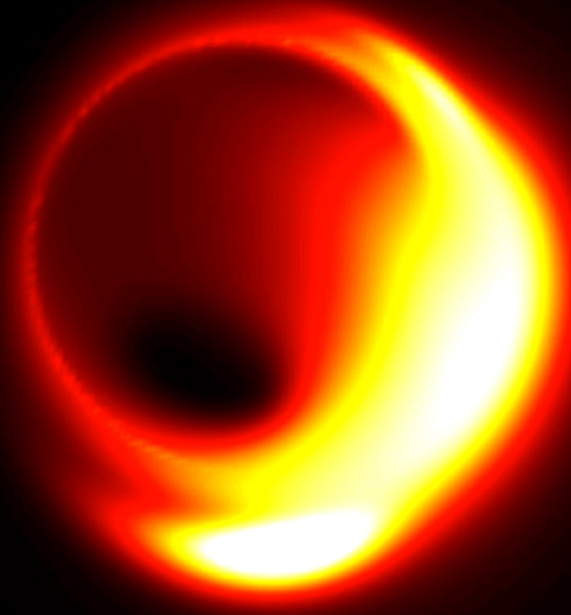


Broderick & Loeb, 2006, MNRAS, 367, 905

FLARES IN SGR A*: NONTHERMAL CATASTROPHES

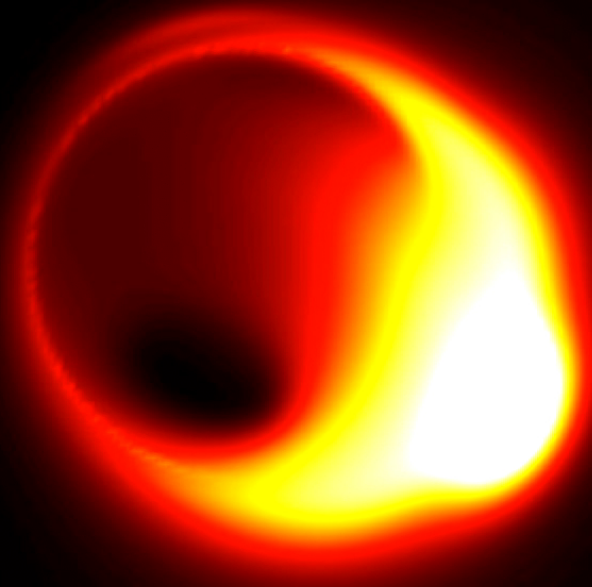


THE SHAPE OF SPACETIME II: SPACETIME TOMOGRAPHY



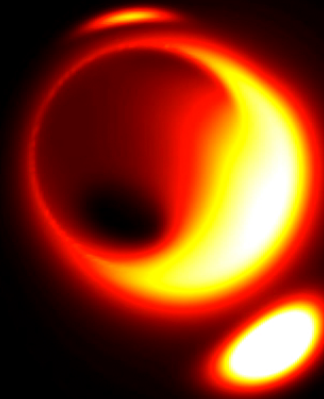
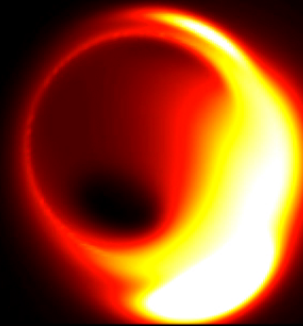
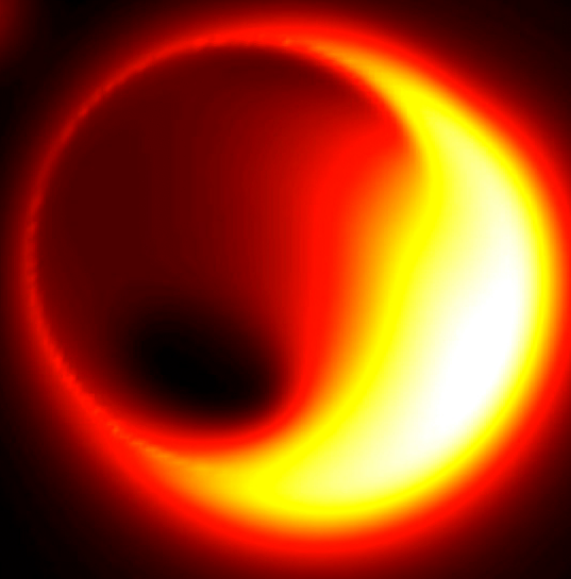
Superradiance, 09.05.2018

THE SHAPE OF SPACETIME II: SPACETIME TOMOGRAPHY



Superradiance, 09.05.2018

THE SHAPE OF SPACETIME II: SPACETIME TOMOGRAPHY



Superradiance, 09.05.2018

THE SHAPE OF SPACETIME III: SPACETIME TOMOGRAPHY WITH POLARIZATION

Total Intensity



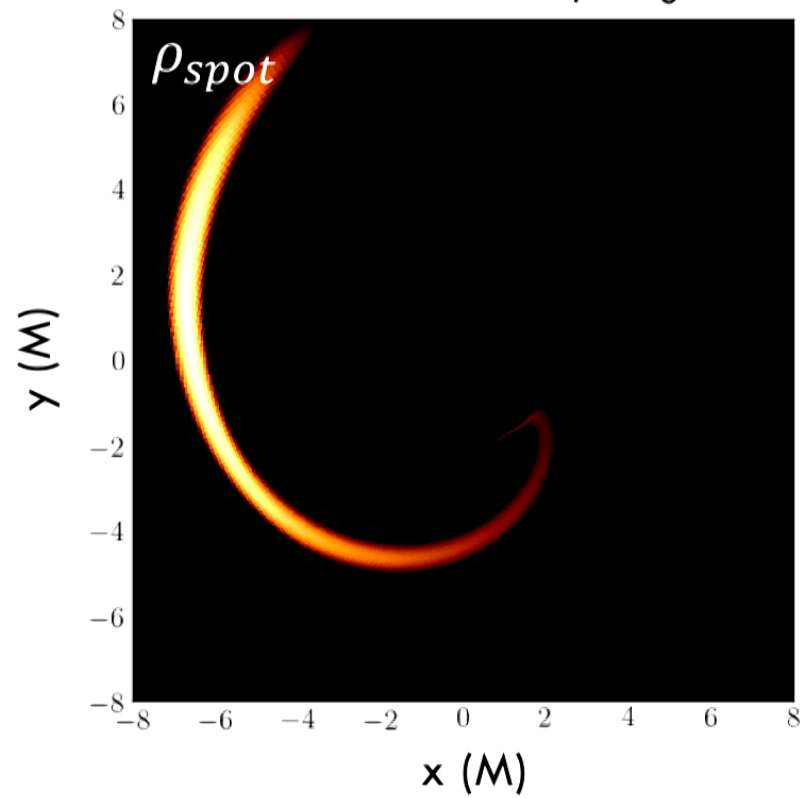
Polarized Intensity



Superradiance, 09.05.2018

SHEARING VS. STATIC SPOTS

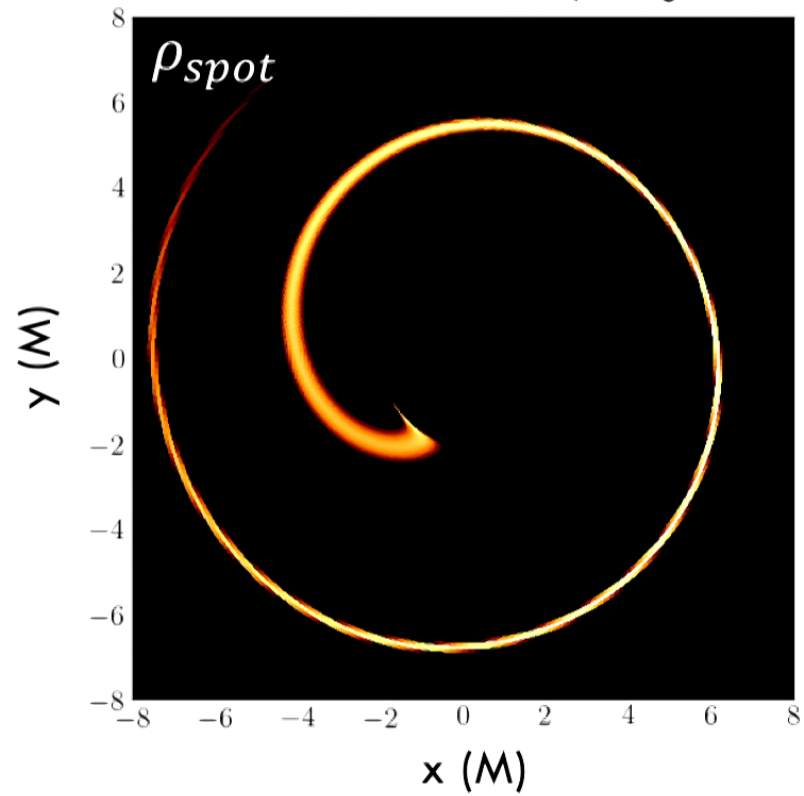
Paul Tiede, Hung-Yi Pu



Superradiance, 09.05.2018

SHEARING VS. STATIC SPOTS

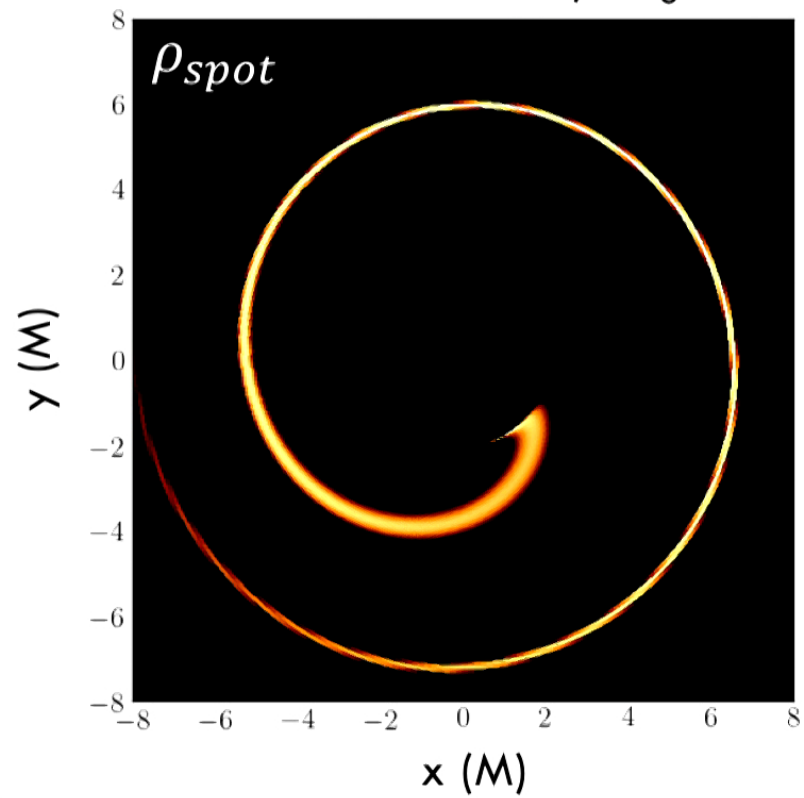
Paul Tiede, Hung-Yi Pu



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SHEARING VS. STATIC SPOTS

Paul Tiede, Hung-Yi Pu

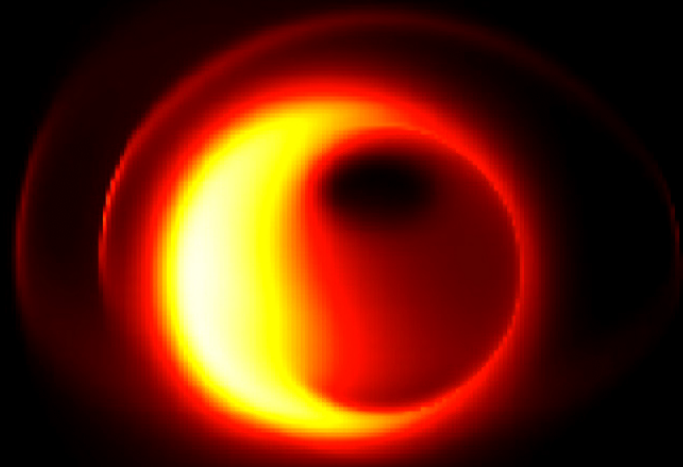


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TURBULENCE: ANGULAR MOMENTUM TRANSPORT



Courtesy of Hotaka Shiokawa



Britt Jeter

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TURBULENCE: ANGULAR MOMENTUM TRANSPORT



Courtesy of Hotaka Shiokawa

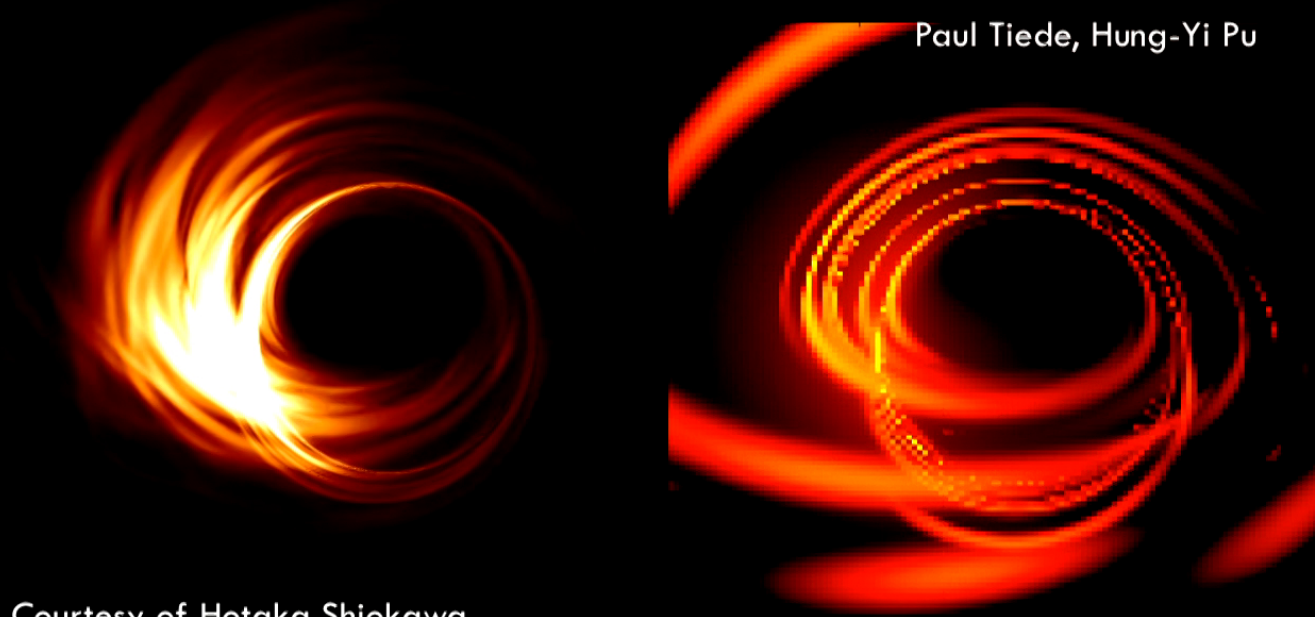


Britt Jeter

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TURBULENCE: ANGULAR MOMENTUM TRANSPORT

Paul Tiede, Hung-Yi Pu



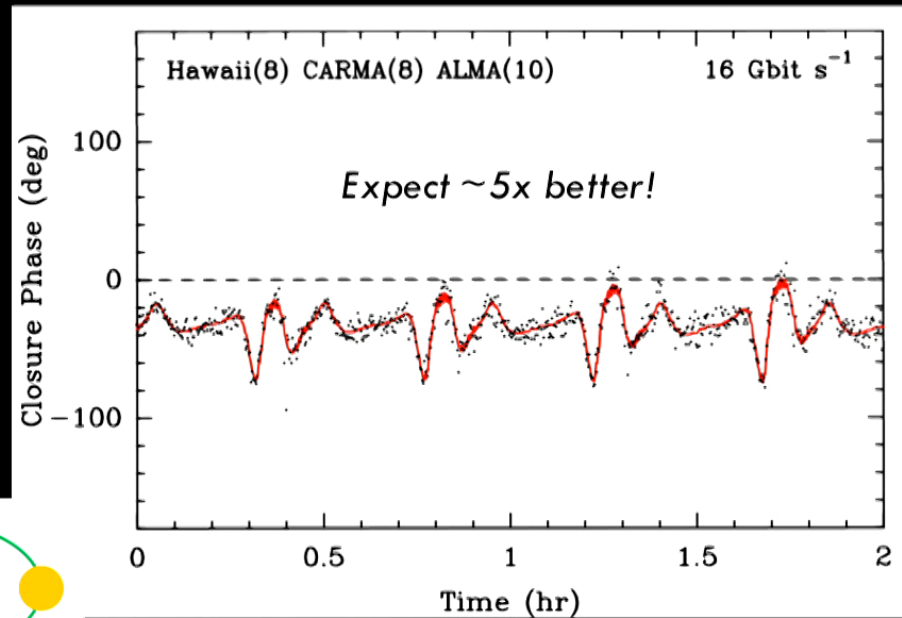
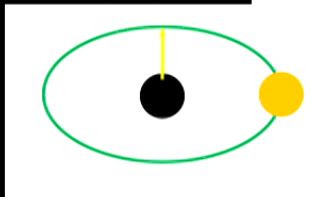
Courtesy of Hotaka Shiokawa

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THE SHAPE OF SPACETIME II: SPACETIME TOMOGRAPHY



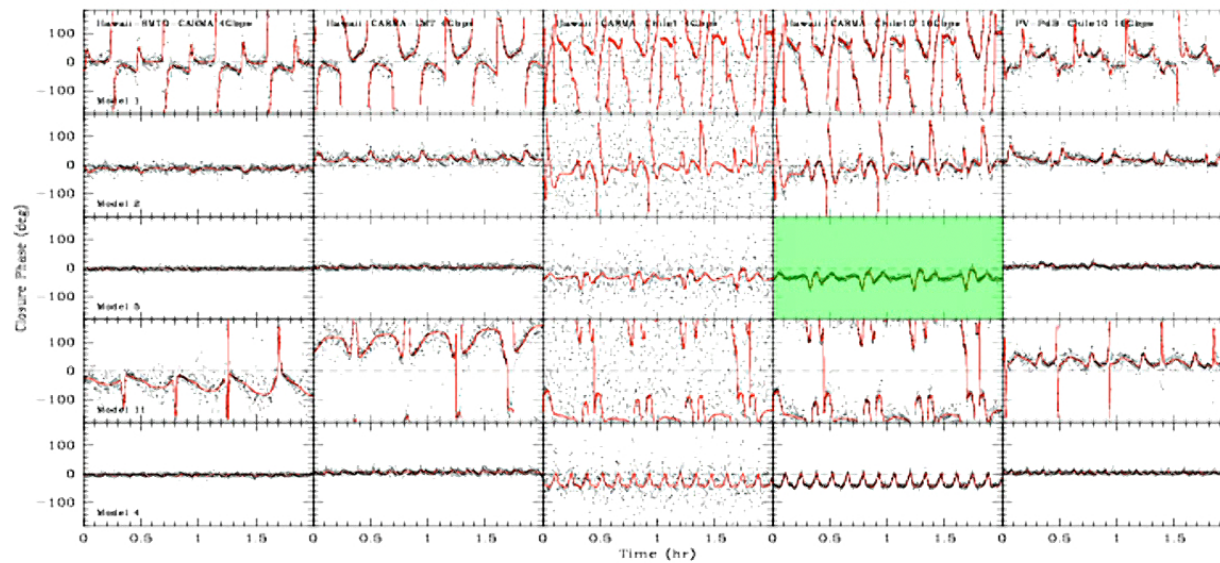
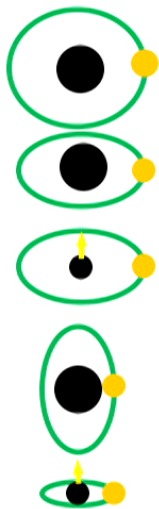
$\alpha = 0.9$
Hot-spot at $\sim 6M$
Period = 27 min.



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

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CLOSURE PHASE EVOLUTION

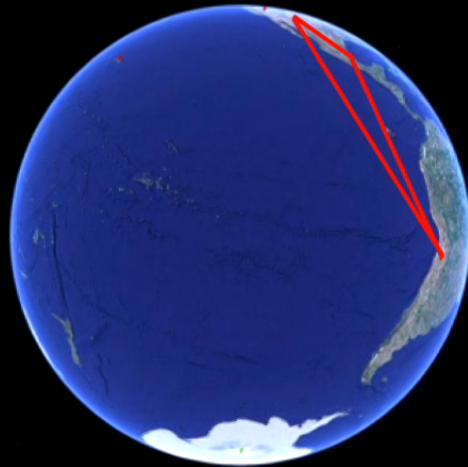


Doeleman, Fish, A.E.B., Loeb & Rogers (2009)

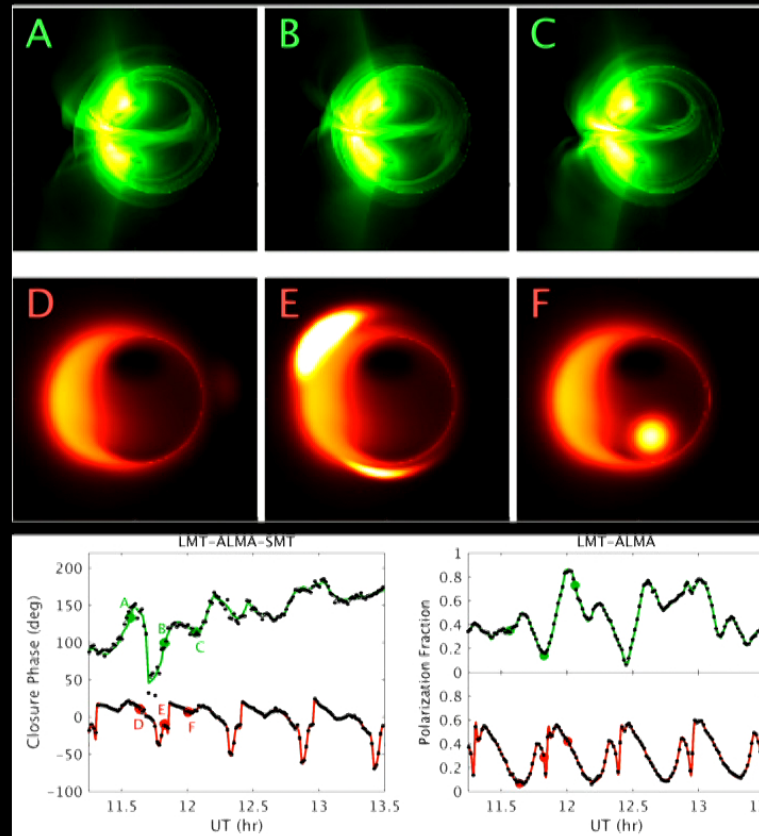
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THE SHAPE OF SPACETIME: SPACETIME TOMOGRAPHY

Roman Gold & AEB



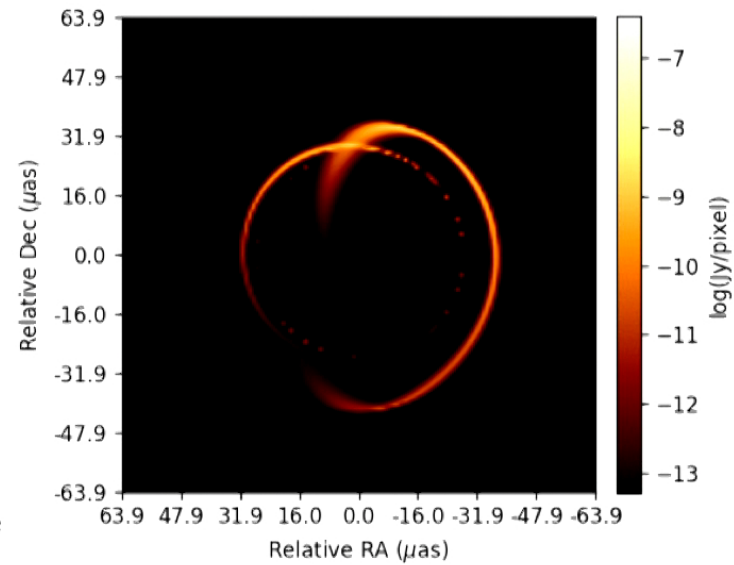
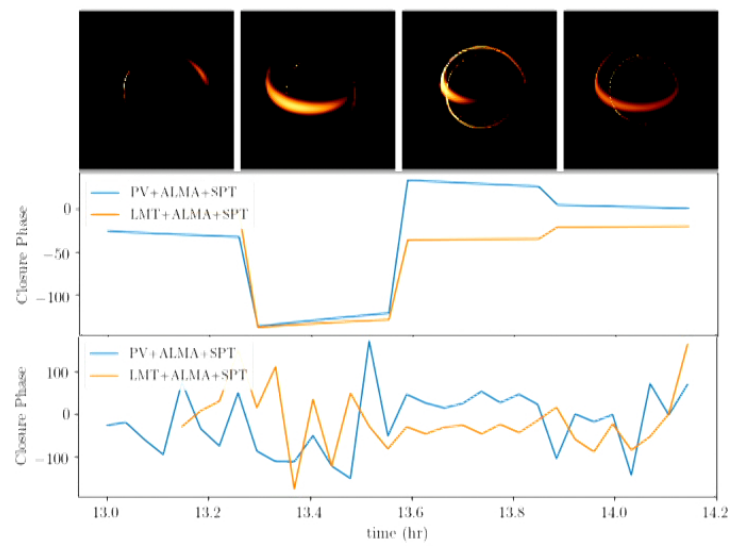
$\alpha = 0$
Hot-spot at $\sim 6M$
Period = 27 min.



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MAPPING SPACETIME?

4-frame "movie"

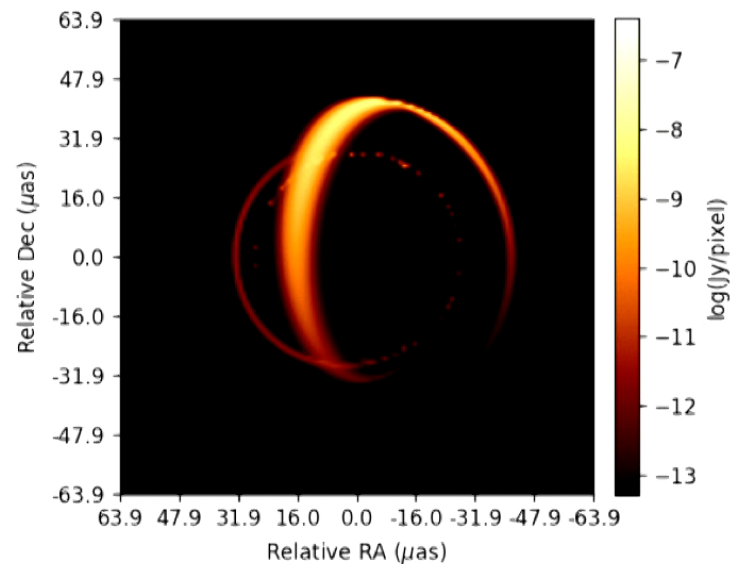
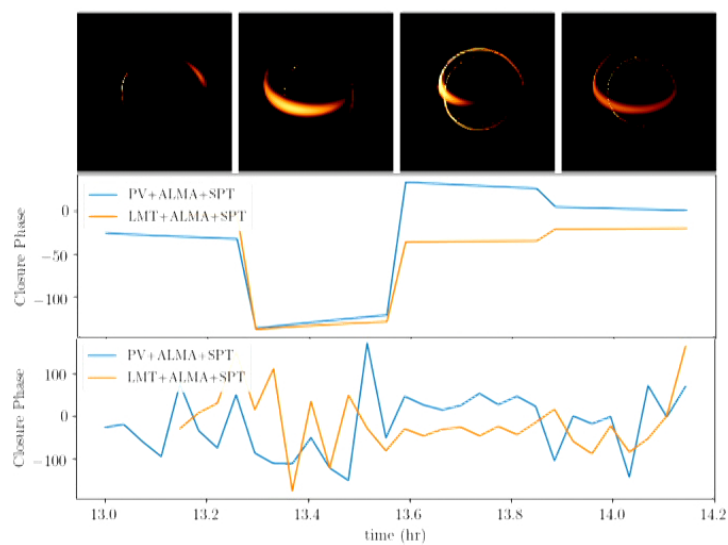


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MAPPING SPACETIME?

4-frame "movie"



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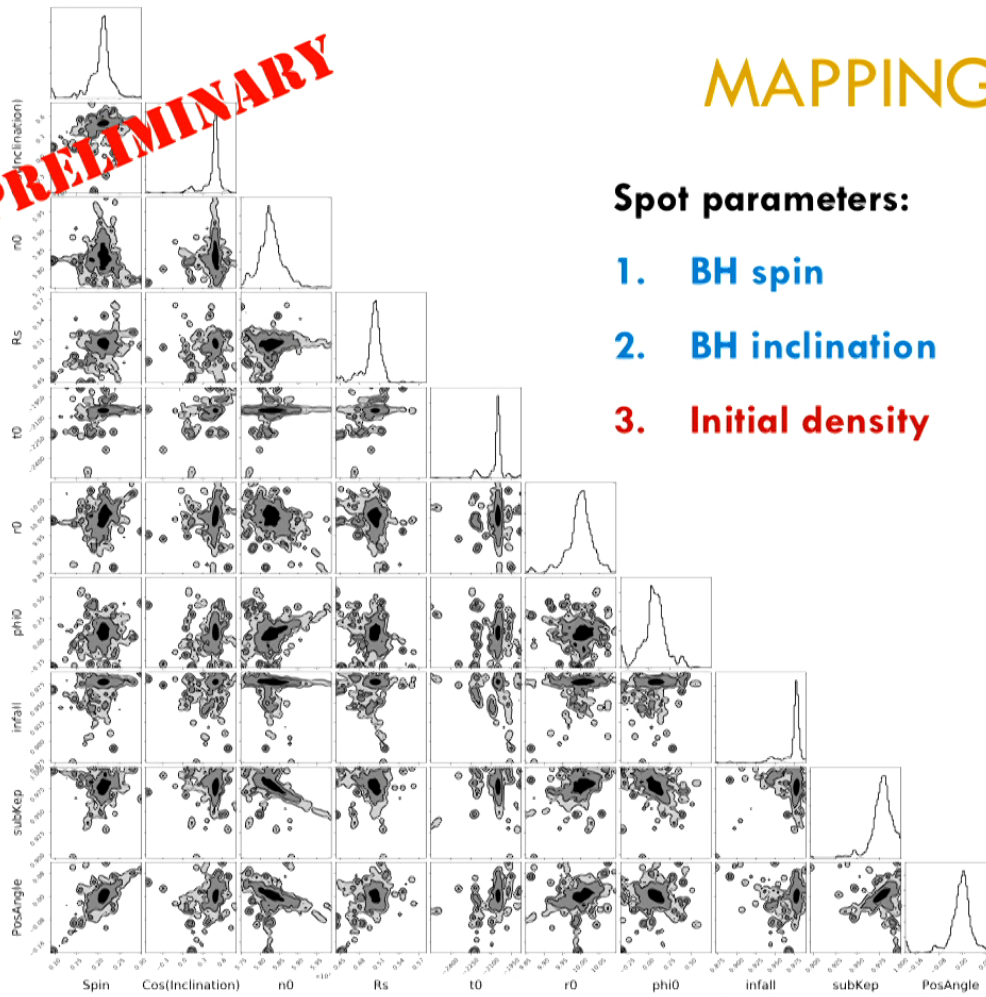
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PRELIMINARY

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 velocity
10. BH position angle

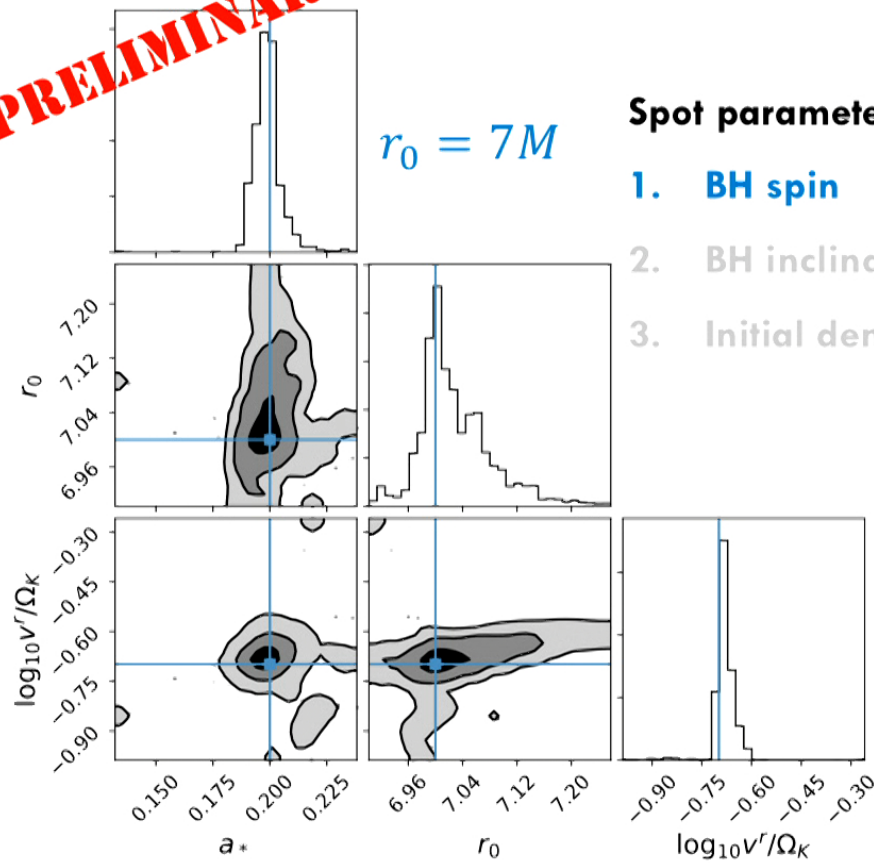


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MAPPING SPACETIMES?

PRELIMINARY



Spot parameters:

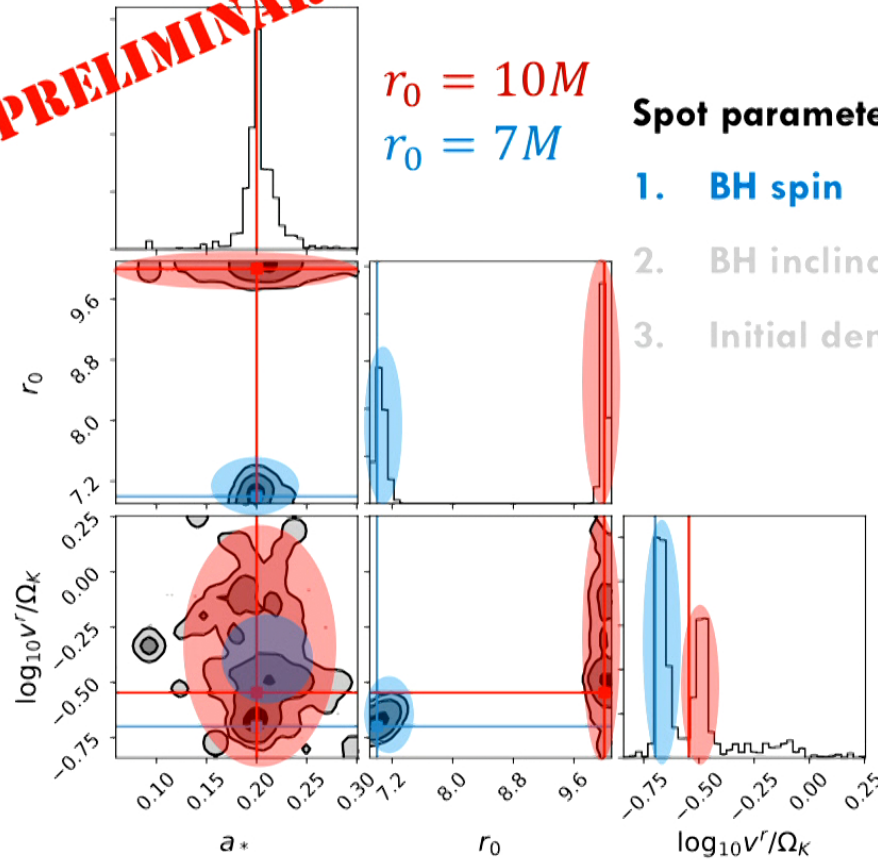
1. BH spin
2. BH inclination
3. Initial density
4. Initial size
5. Initial time
6. Initial radius
7. Initial azimuth
8. Infall velocity
9. Angular velocity
10. BH position angle

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MAPPING SPACETIMES?

PRELIMINARY



$$r_0 = 10M$$

$$r_0 = 7M$$

Spot parameters:

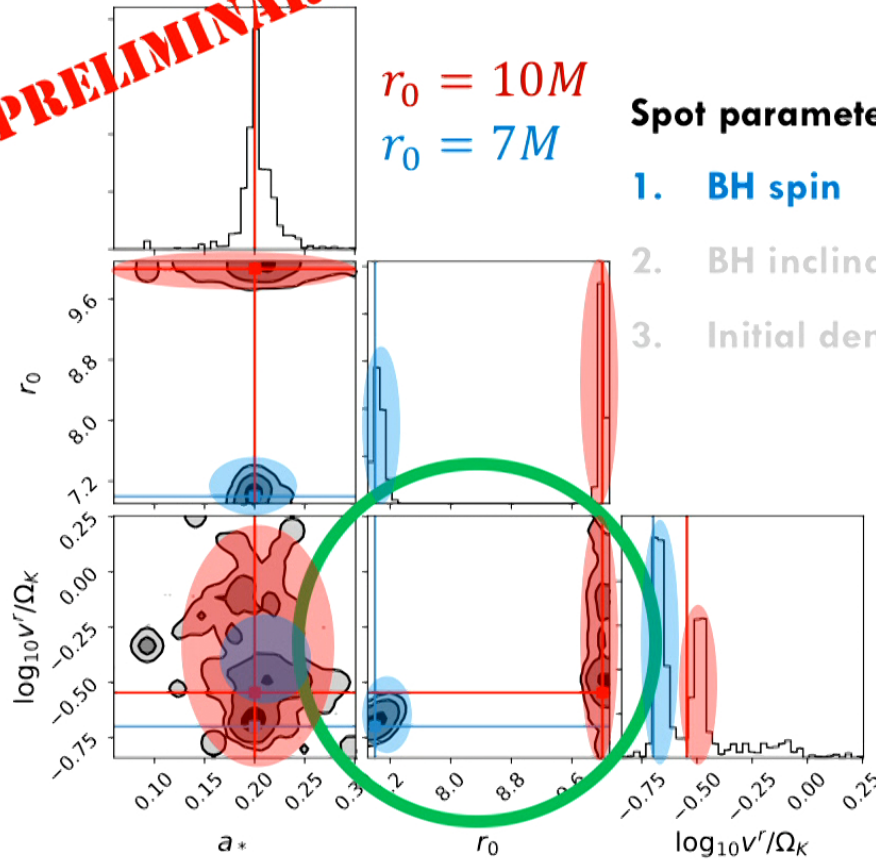
1. BH spin
2. BH inclination
3. Initial density
4. Initial size
5. Initial time
6. Initial radius
7. Initial azimuth
8. Infall velocity
9. Angular velocity
10. BH position angle

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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 velocity
10. BH position angle

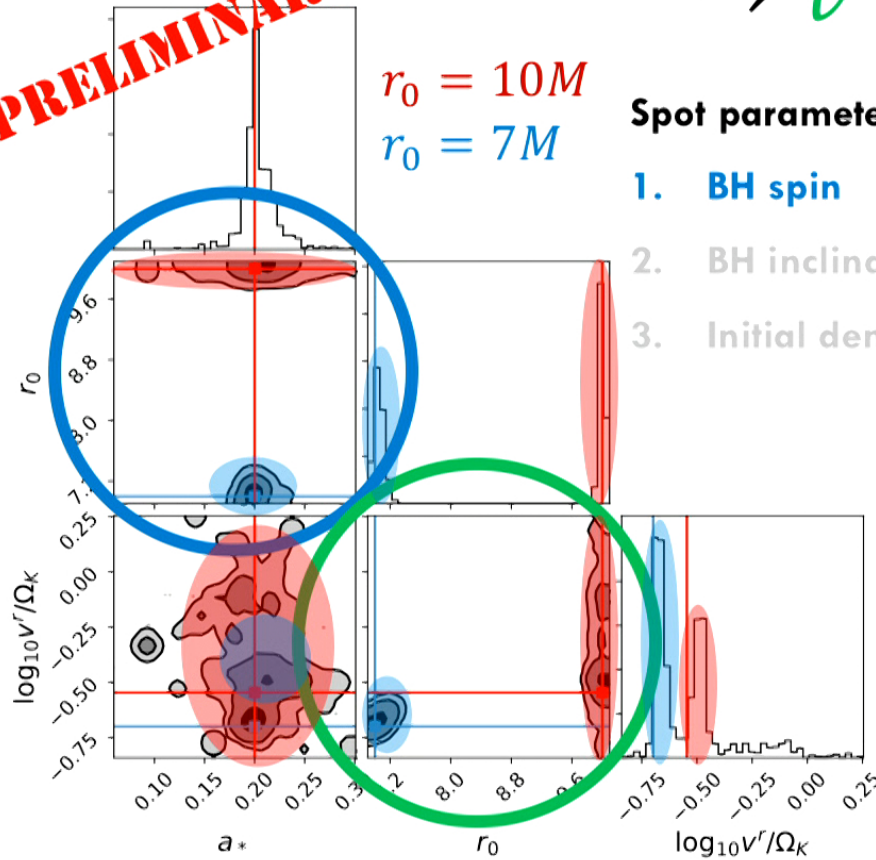
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MAPPING SPACETIMES?

$$\rightarrow v^r(r_0)$$

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 velocity
10. BH position angle

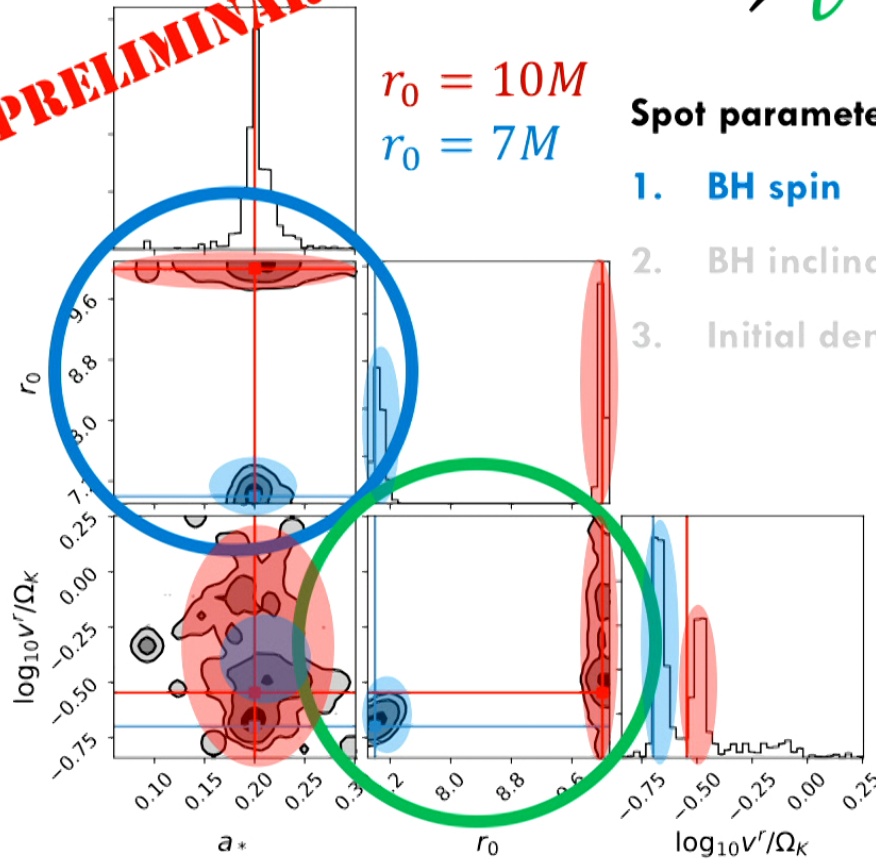
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MAPPING SPACETIMES?

→ $v^r(r_0)$, $a(r_0)$, ...

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 velocity
10. BH position angle

Much left to do!

CONCLUDING THOUGHTS

- **First horizon-resolving black hole images are immanent.**
- **These provide many different potential handles on the spacetime structure:**
 - Apparent (Event?) horizons
 - Photon rings – generic 10% (or better)
 - Astrophysical modeling – sub-percent precision
 - Many forms of variability (flares, polarization, turbulence, precession, Brownian motion, etc.)
- **We have built an extensible EHT analysis framework, capable of rapidly including and constraining additional models.**
→ **Alternative spacetimes needed!**



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