

Title: What does a quantum black hole look like to the Event Horizon Telescope?

Date: Nov 10, 2017 03:50 PM

URL: <http://pirsa.org/17110102>

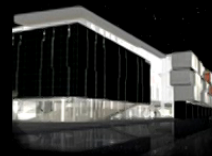
Abstract:

# WHAT DOES A QUANTUM BLACK HOLE LOOK LIKE? (TO THE EVENT HORIZON TELESCOPE?)

Avery E. Broderick



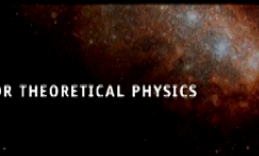
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PERIMETER



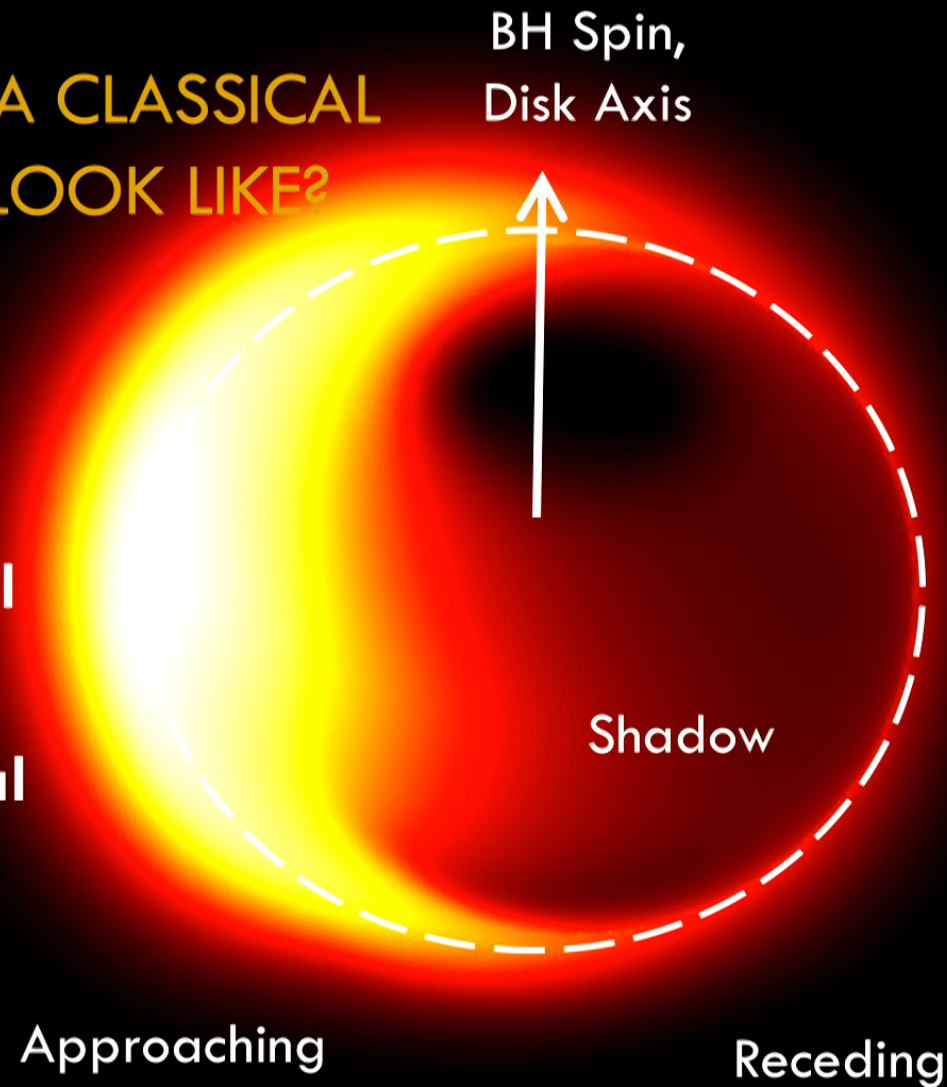
INSTITUTE FOR THEORETICAL PHYSICS





# WHAT DOES A CLASSICAL BLACK HOLE LOOK LIKE?

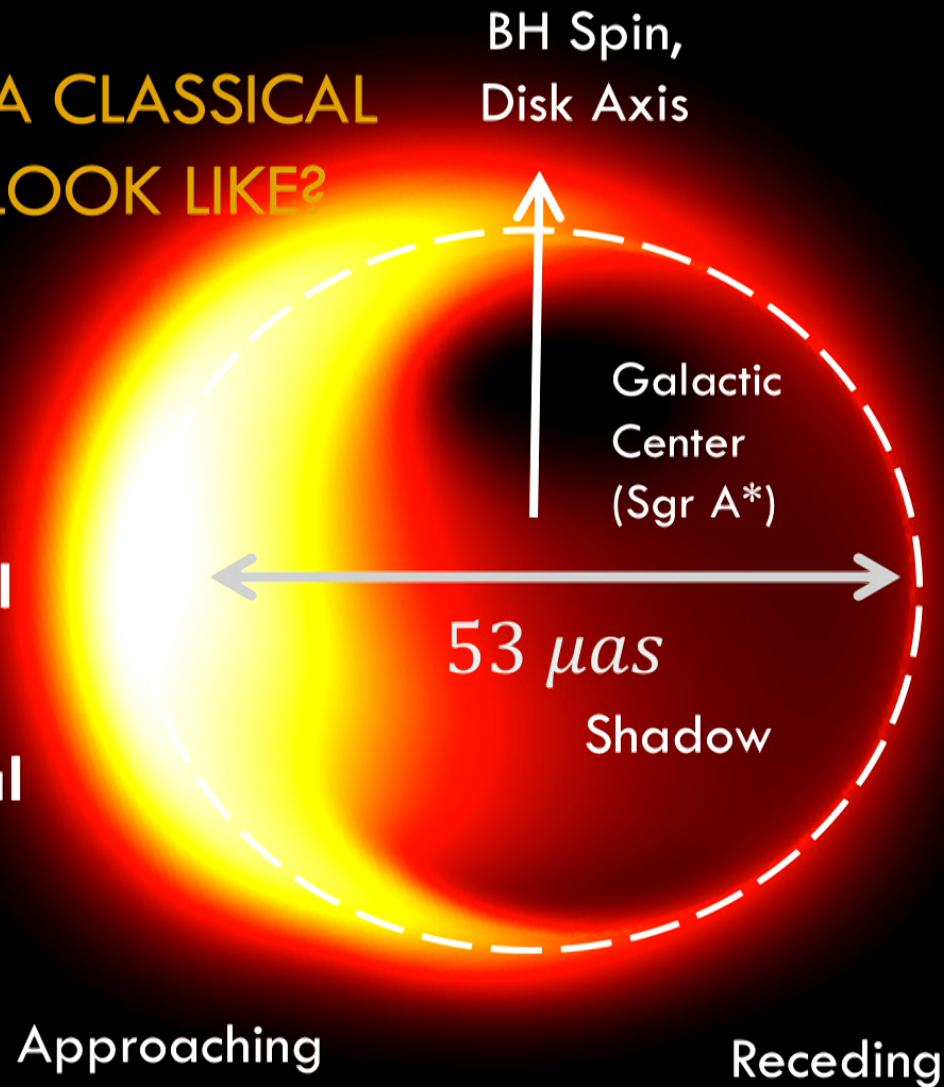
- **Relativistic motion**
- **Gravitational lensing**
- **Astrophysical processes**



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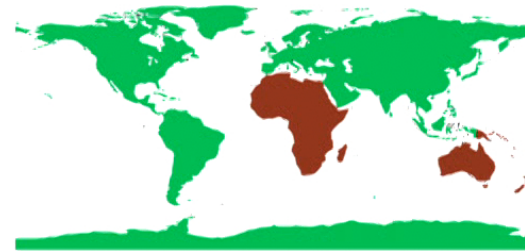
# WHAT DOES A CLASSICAL BLACK HOLE LOOK LIKE?

- **Relativistic motion**
- **Gravitational lensing**
- **Astrophysical processes**



Quantum Black Holes, 10.11.2017

# GLOBAL COLLABORATION



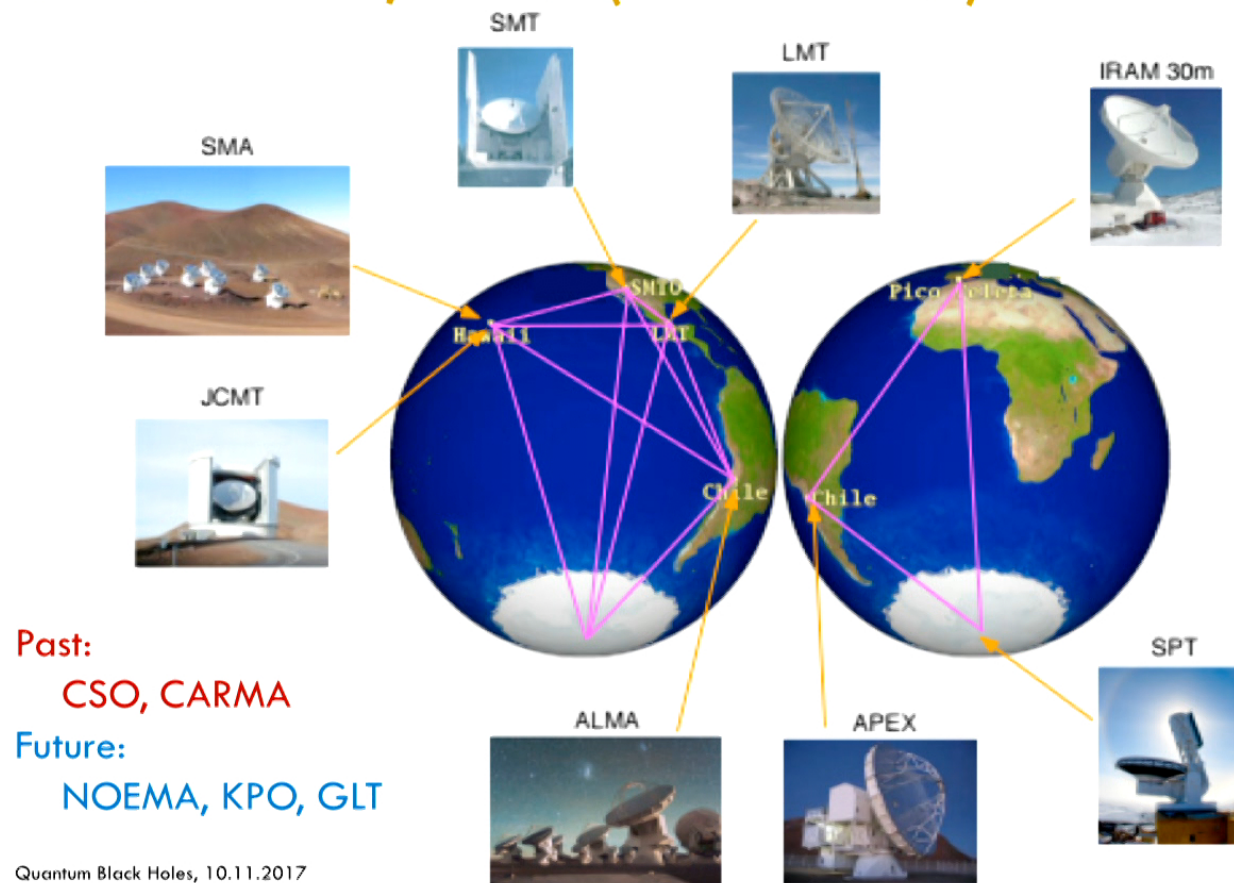
Aalto University  
Arizona Radio Observatory  
Instituto Nacional de Astrofísica, Óptica y Electrónica  
Boston University  
University of California, Berkeley  
Chinese Academy of Sciences  
Universidad de Concepción  
Institute of High Energy Physics  
University of Illinois

Kavli Institute for Astronomy and Astrophysics  
Leiden University  
University of Massachusetts Amherst  
Nanjing University  
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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  
University of Science and Technology  
Seoul National University  
Institute of Statistical Mathematics  
Yunnan Observatory

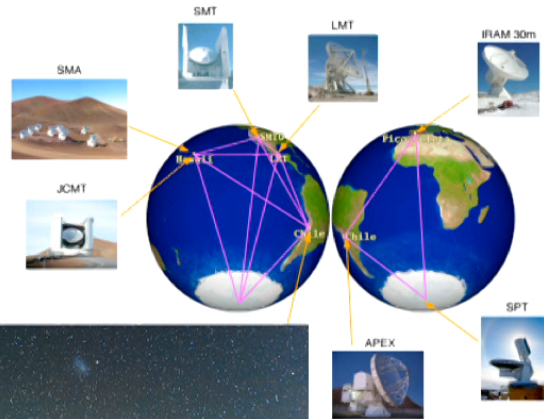
Quantum Black Holes, 10.11.2017

# THE EVENT HORIZON TELESCOPE CIRCA APRIL, 2017 (AND 2018!)



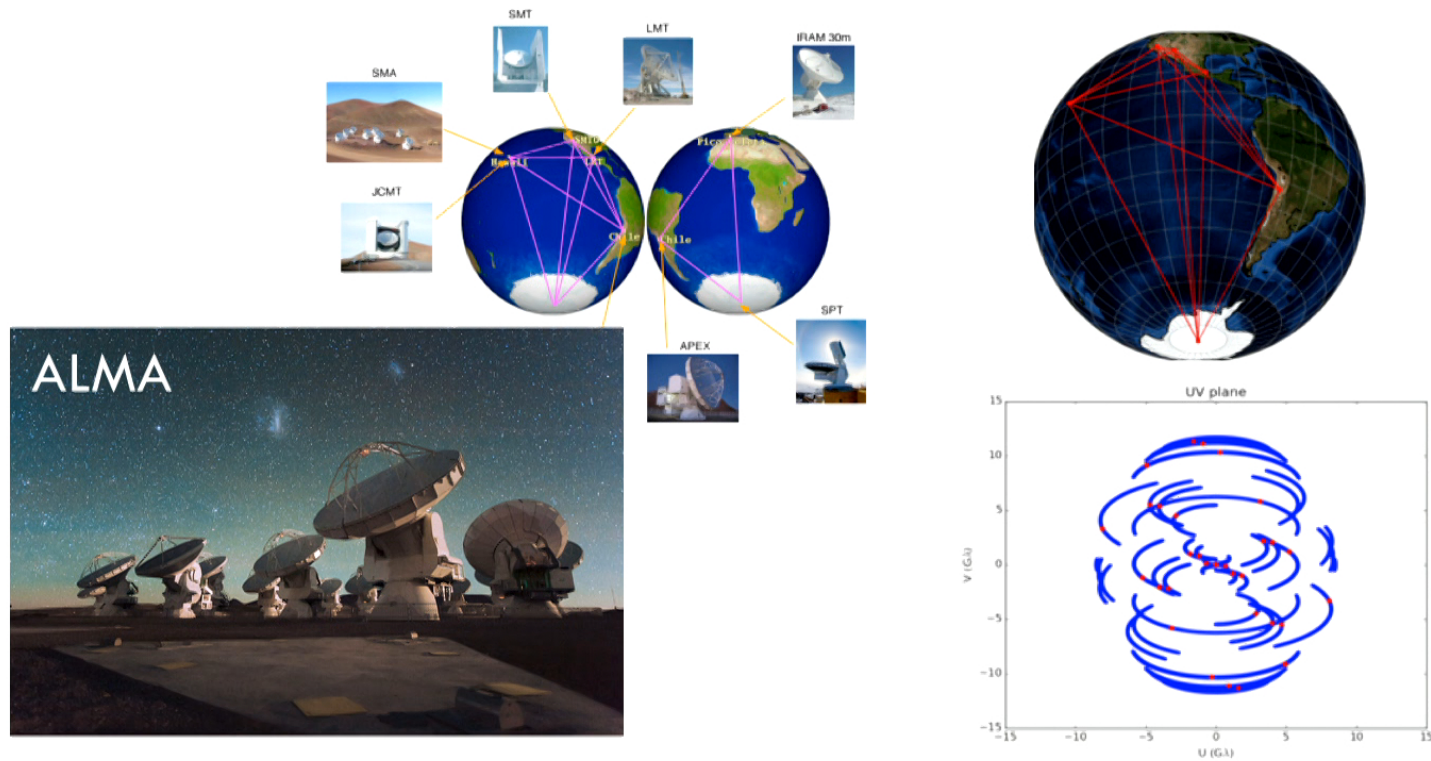


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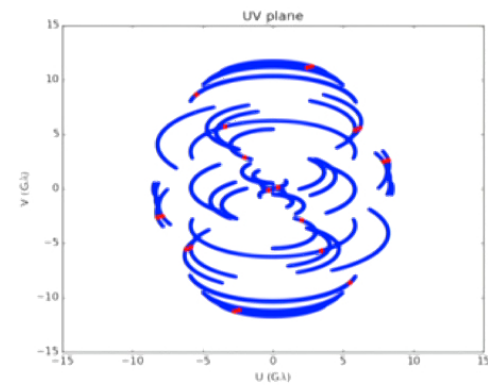
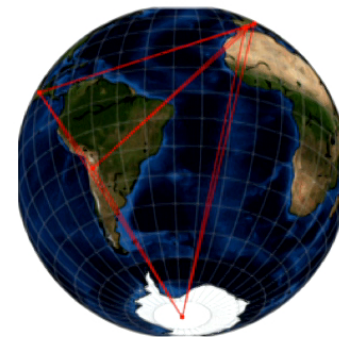
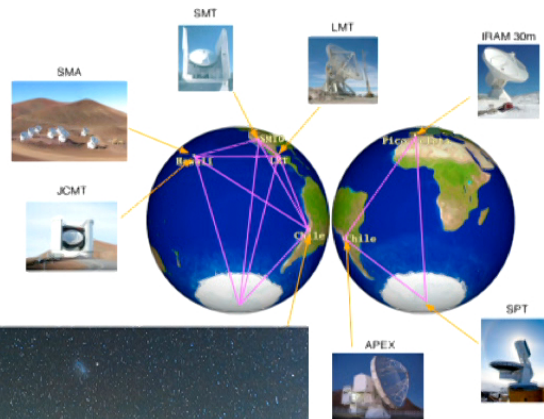
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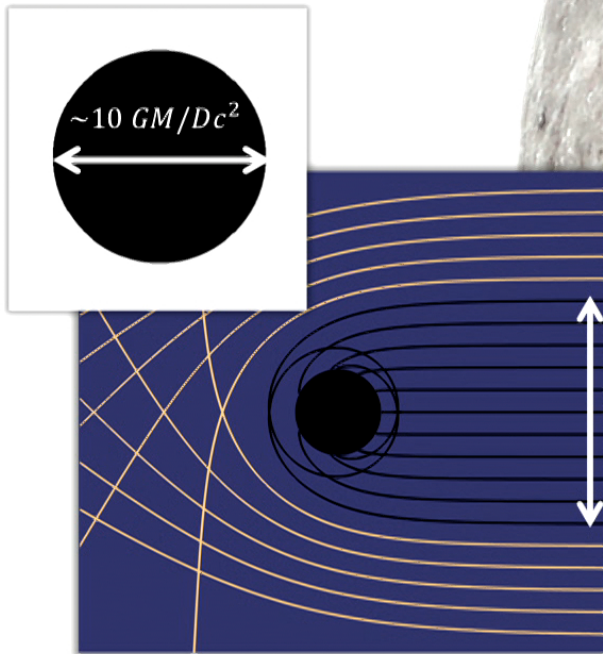
# THE EVENT HORIZON TELESCOPE CIRCA APRIL, 2017 (AND 2018!)



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# HIGHEST RESOLUTION TELESCOPE IN THE HISTORY OF ASTRONOMY



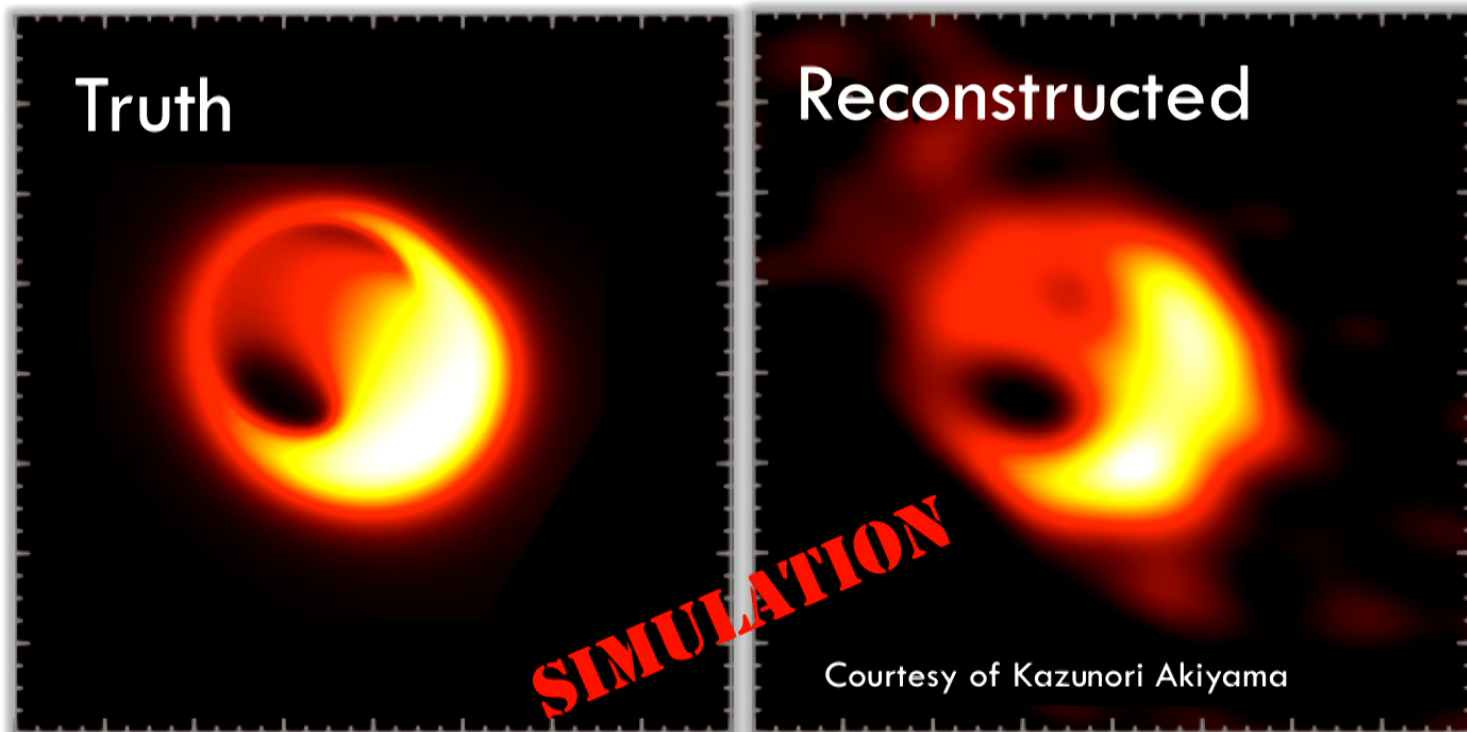
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# FIRST TELESCOPE CAPABLE OF “SEEING” BLACK HOLES



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EventHorizonTelescope

<http://www.eventhorizontelescope.org/>

“PROTO-EHT”



CARMA

SMA,  
JCMT



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ARO-SMT

## 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** (seconds)
- **Long Time** (decades)
- **Targets** (Sgr A\*, M87, etc.)



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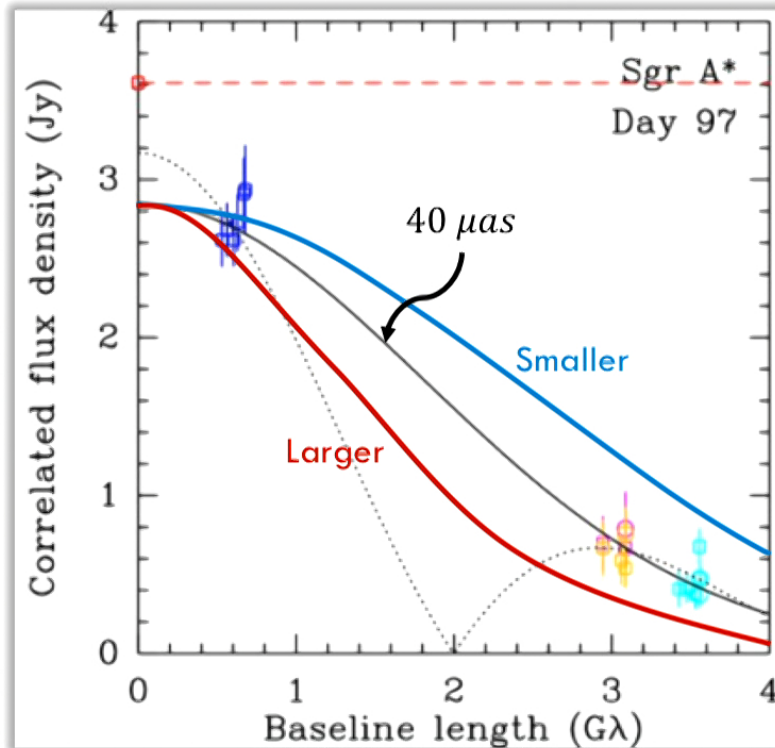
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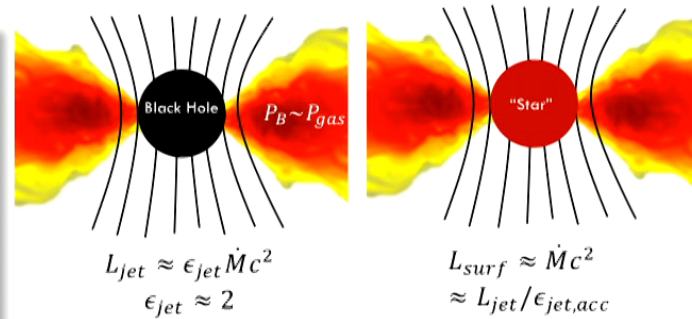
# PROBING CLASSICAL GRAVITY

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# DO BLACK HOLES EXIST?



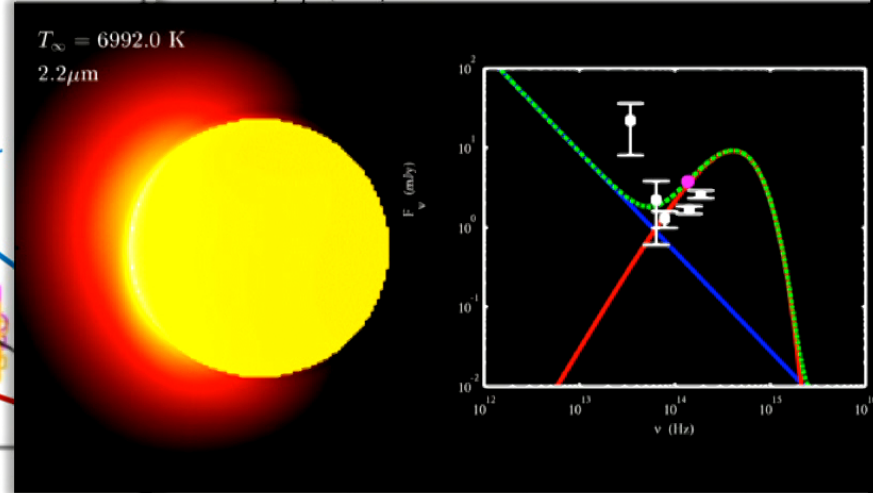
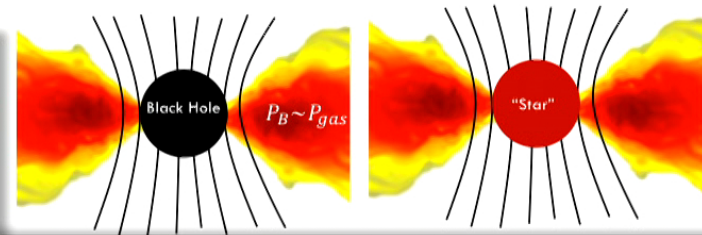
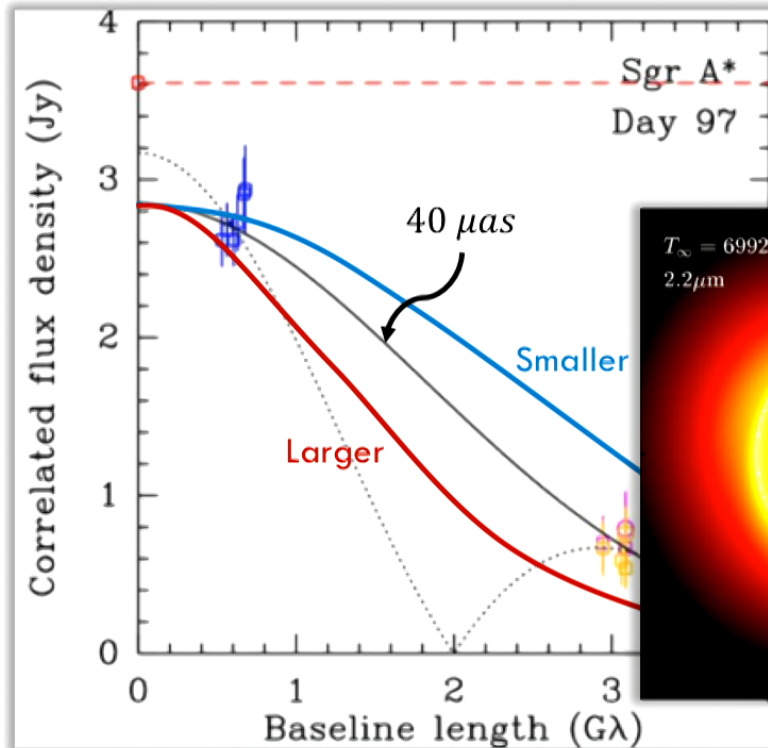
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Assumes:

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

# DO BLACK HOLES EXIST?

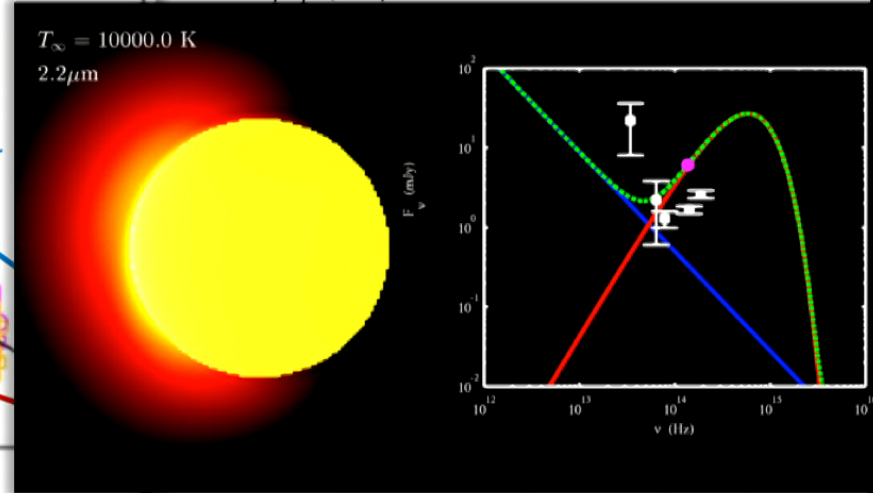
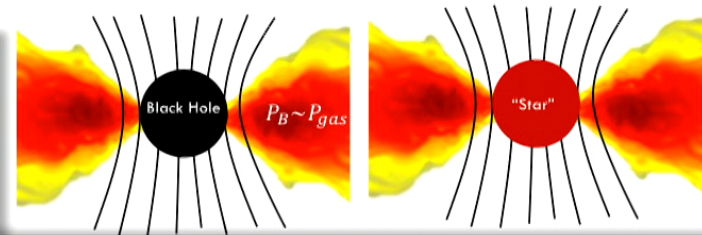
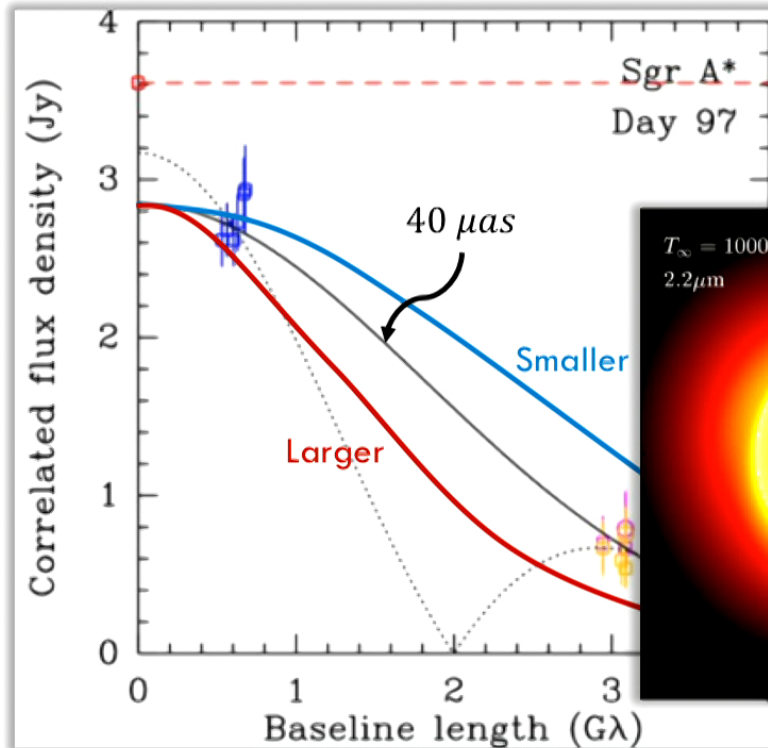


(but baryonic atmospheres!)

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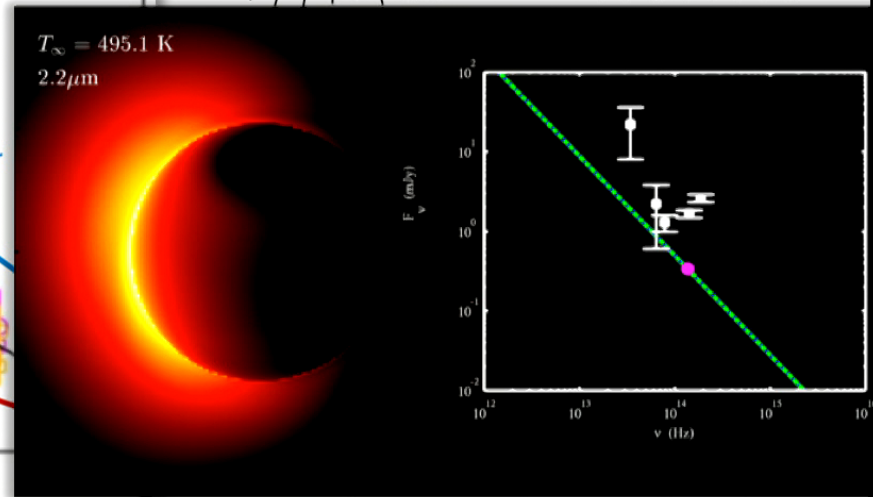
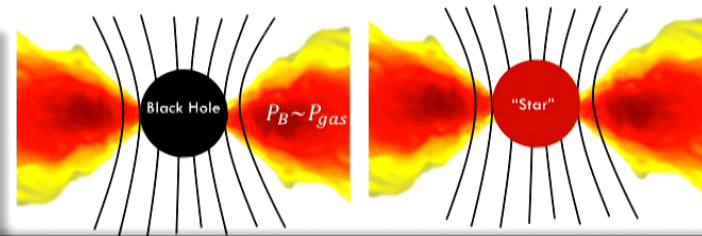
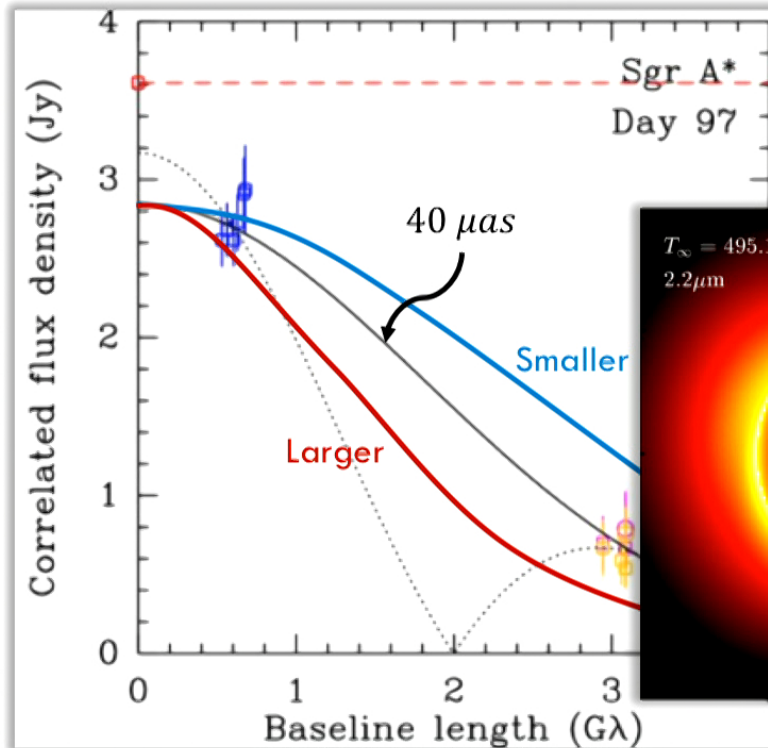
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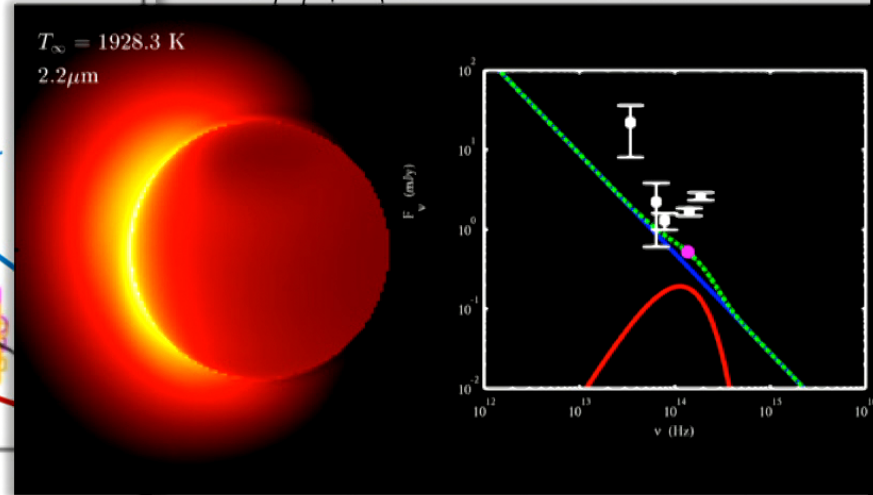
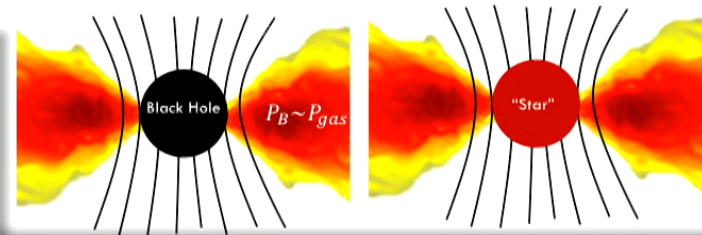
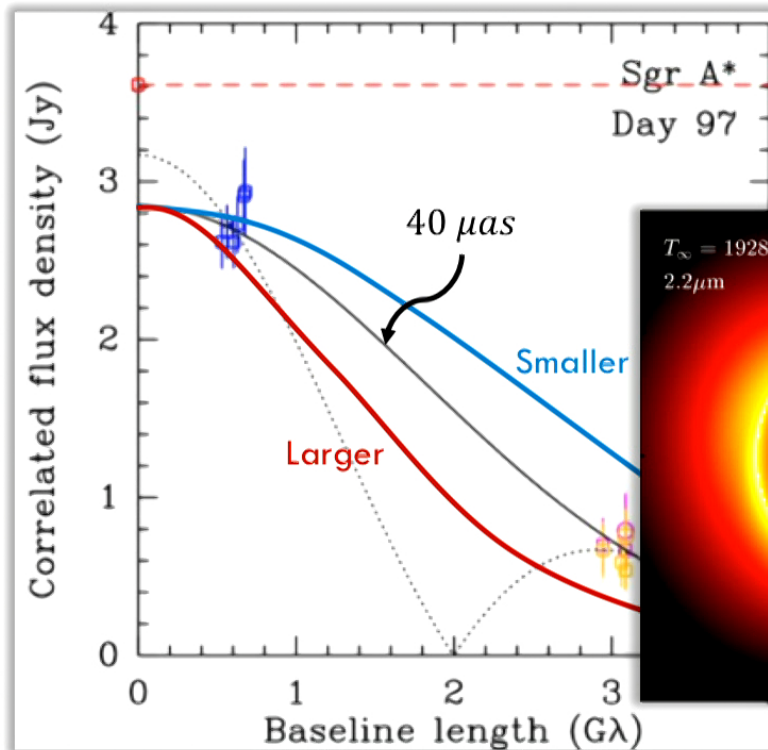
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(but baryonic atmospheres!)

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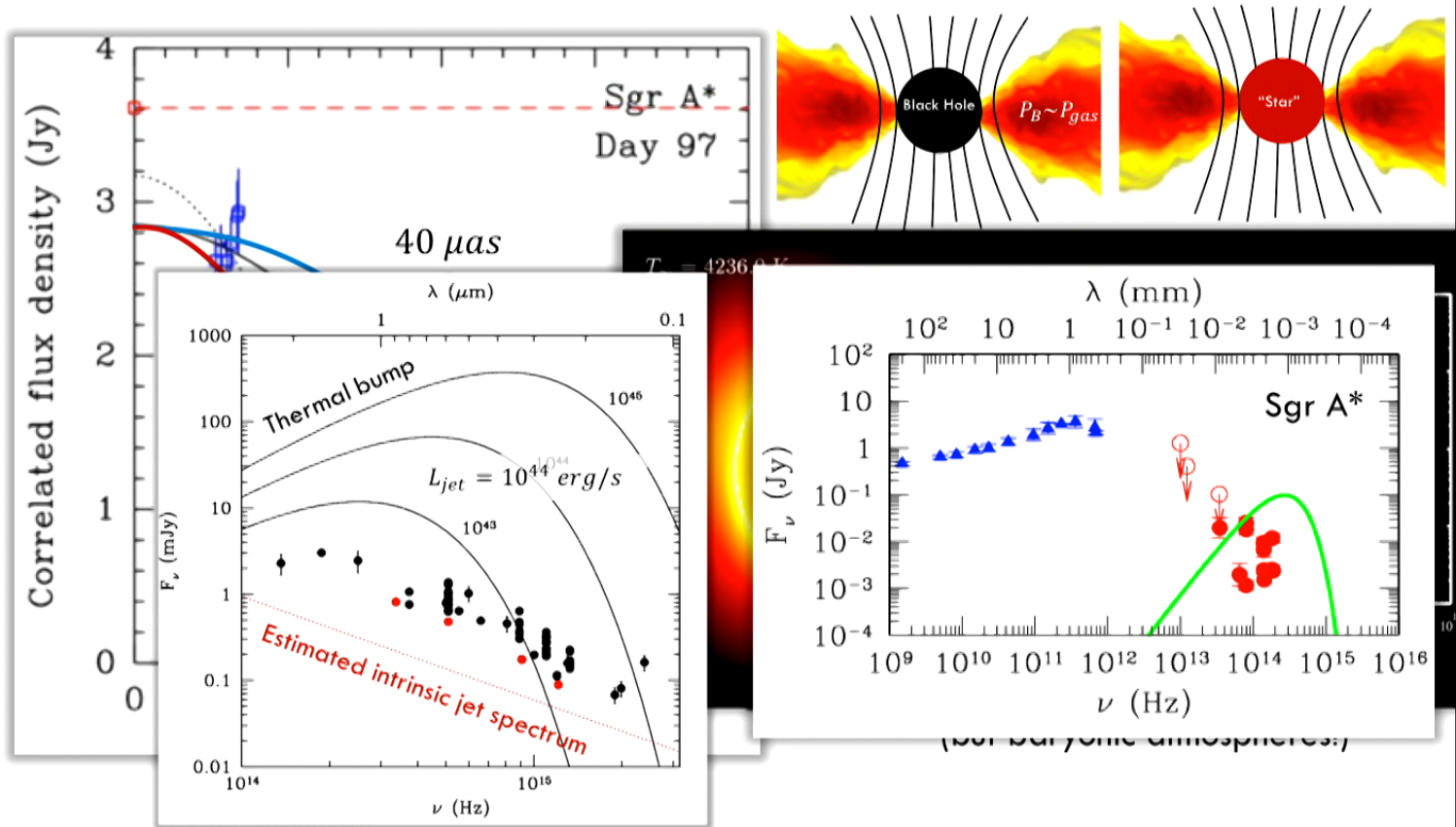
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(but baryonic atmospheres!)

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# DO BLACK HOLES EXIST?



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# APPARENT VS. EVENT HORIZONS?

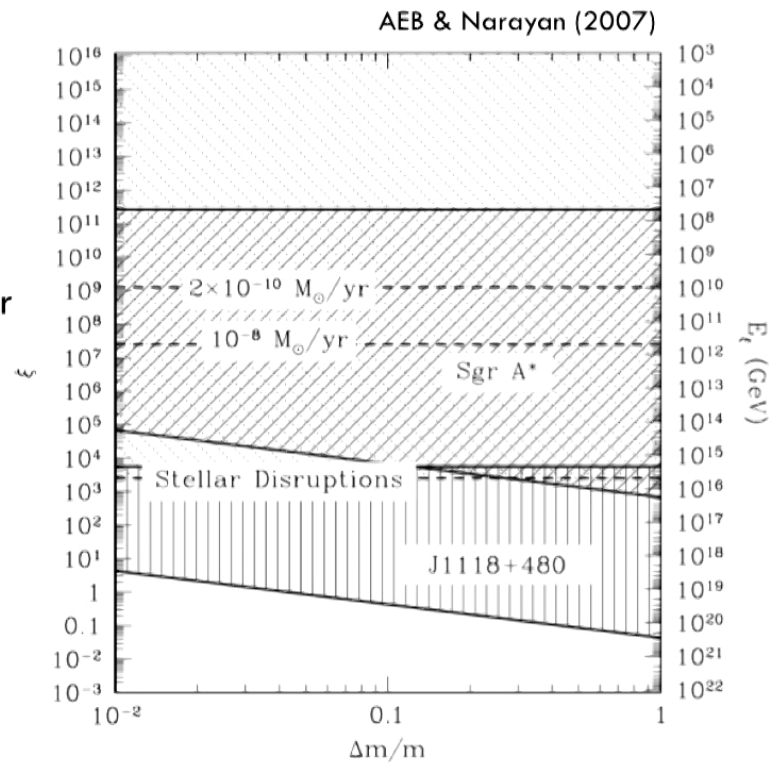
## History of accretion

→ 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?

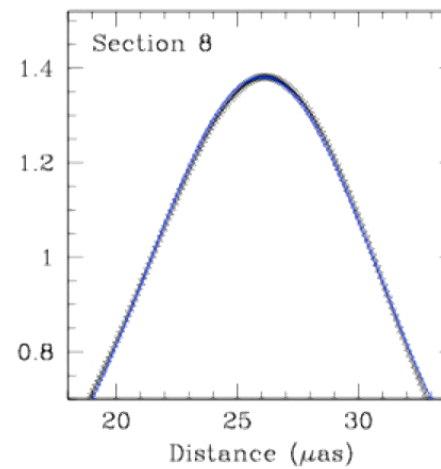
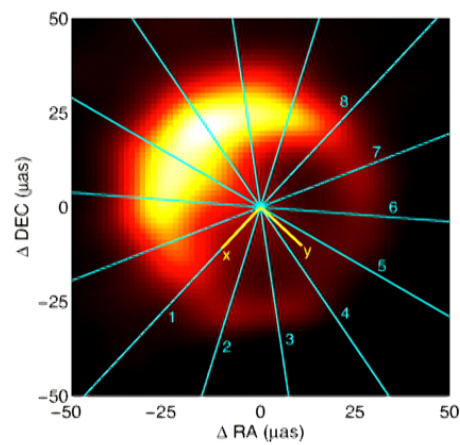
- High heat capacity  
 (slow to heat, slow to cool!)
- Long equilibration times
- Not in steady state



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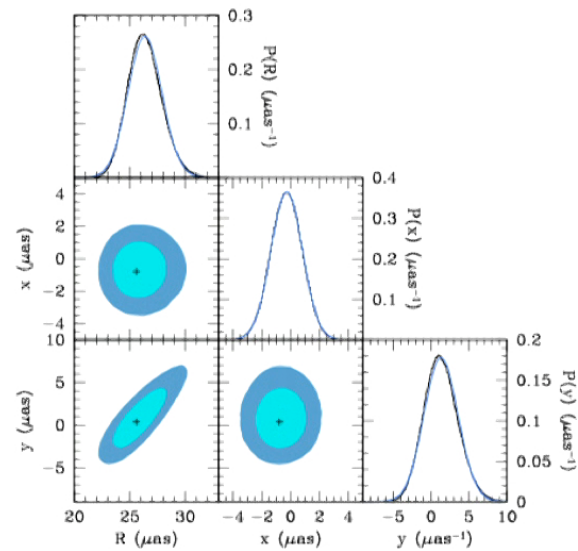
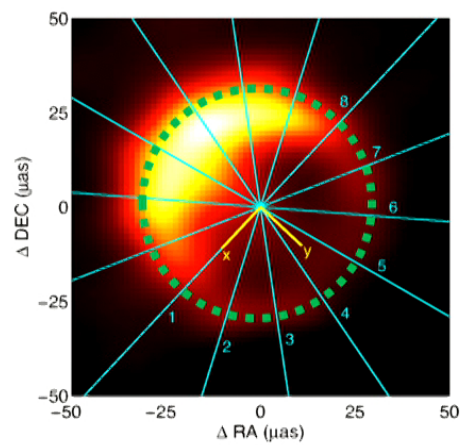
# PHOTON RINGS



Johannsen, AEB et al. (2016)

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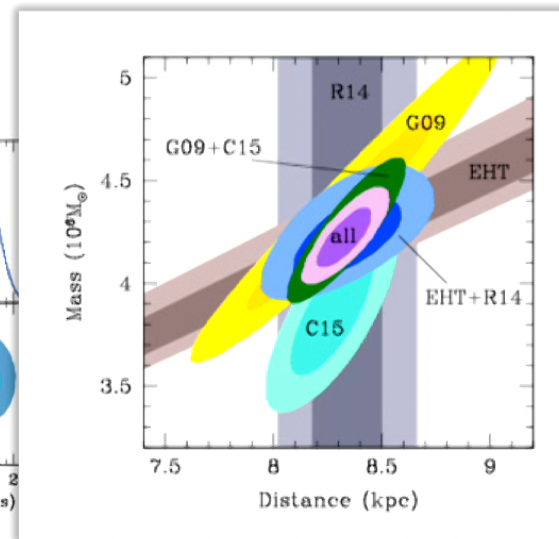
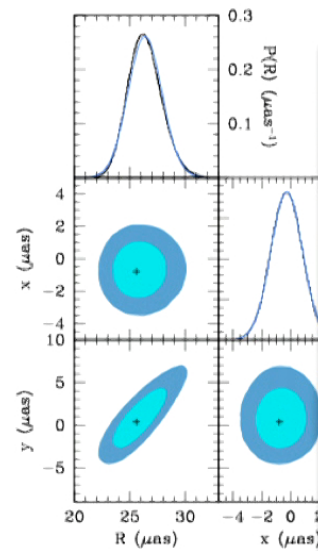
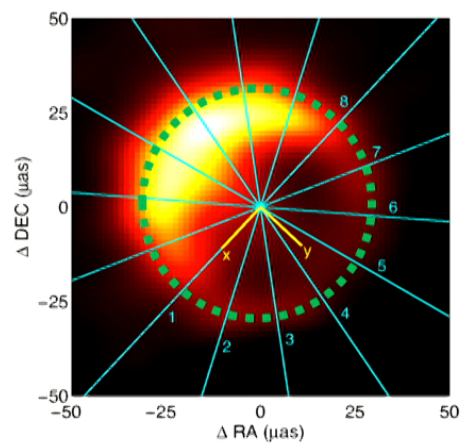
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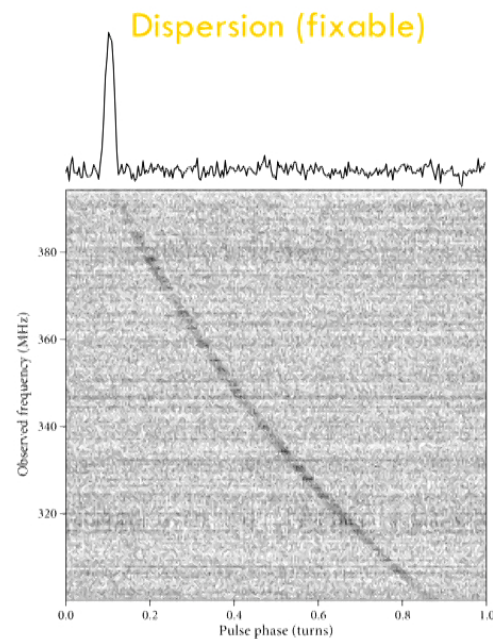


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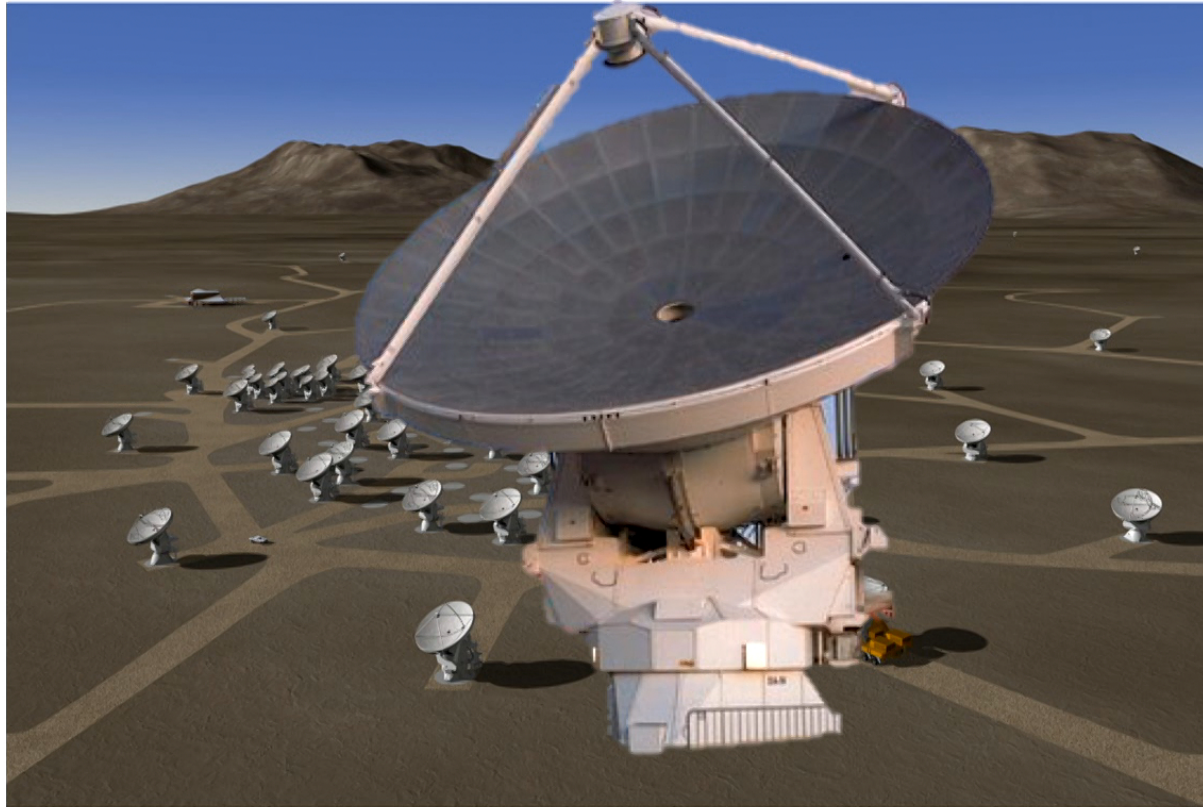
# COMMENSAL SCIENCE: PHASED ALMA RESOLUTION VS SENSITIVITY

## Pulse Broadening



<http://www.cv.nrao.edu/~sransom/web/xxx.html>  
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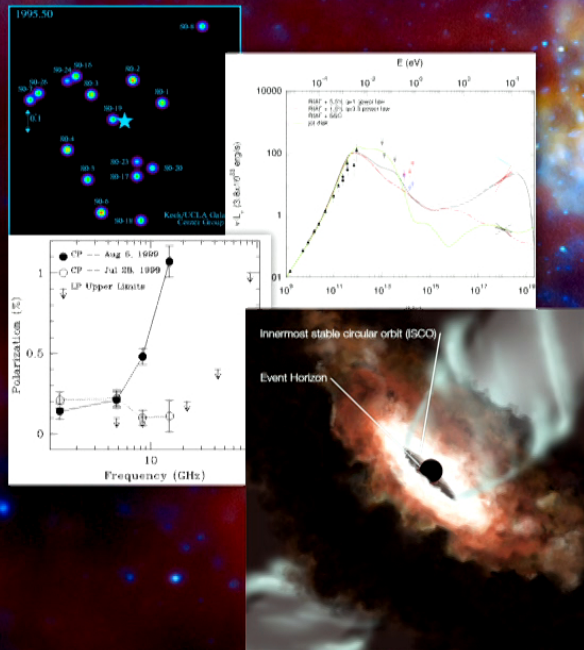
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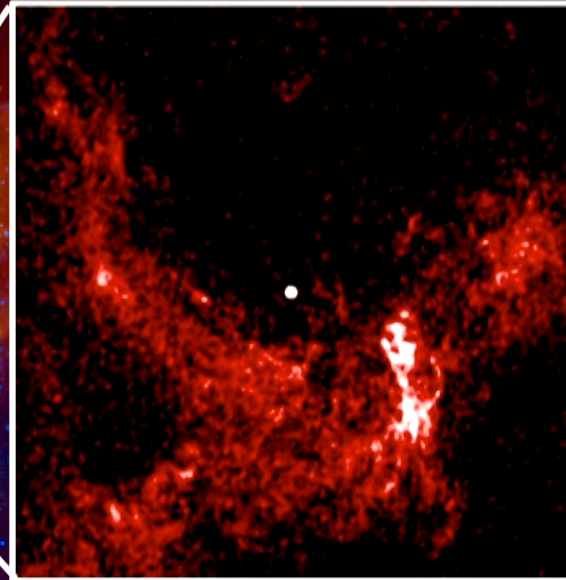
Quantum Black Holes, 10.11.2017



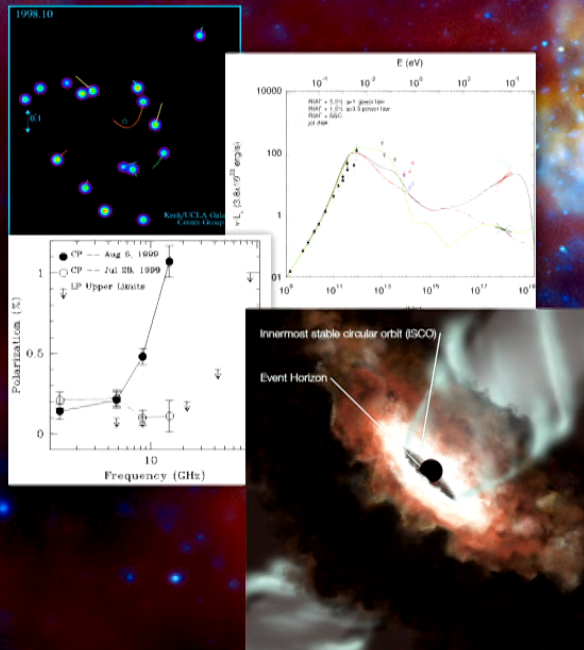
# MODELING ACCRETION FLOWS



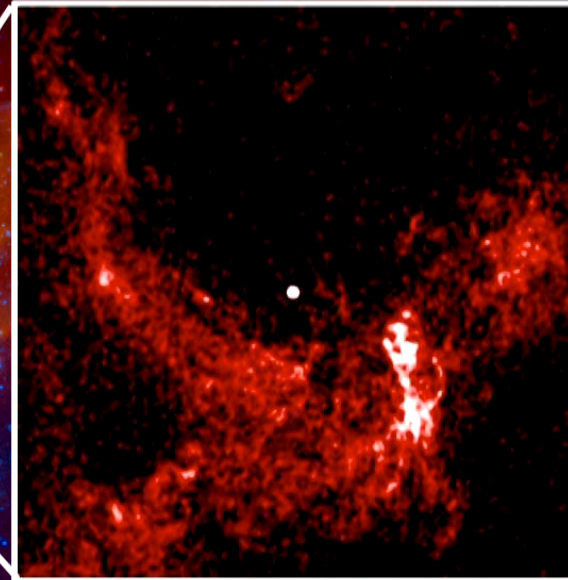
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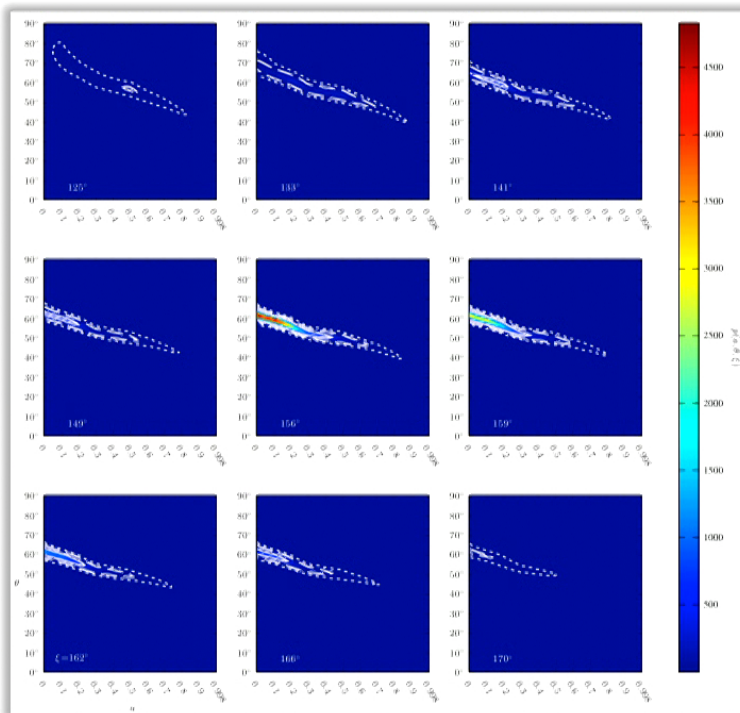
# MODELING ACCRETION FLOWS



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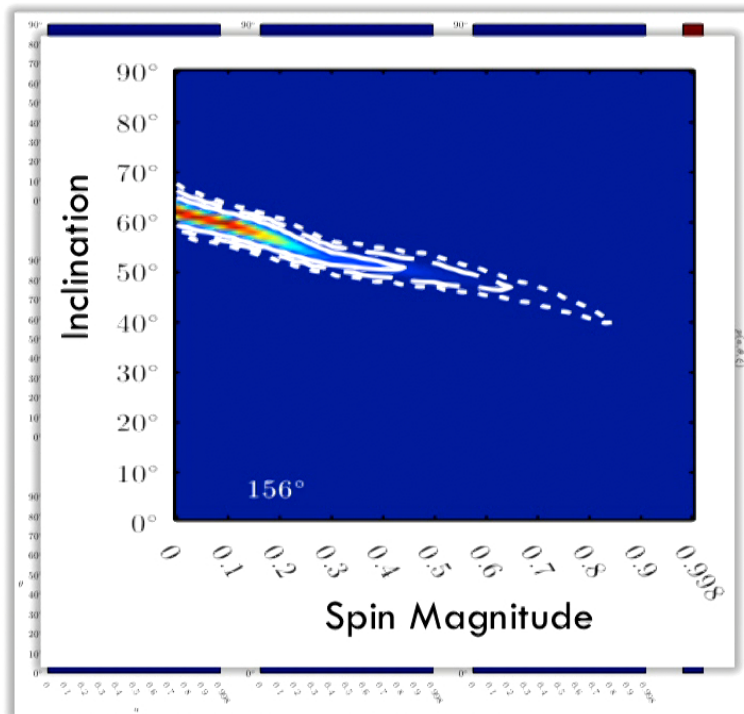
# ONE MODEL, 7 YEARS



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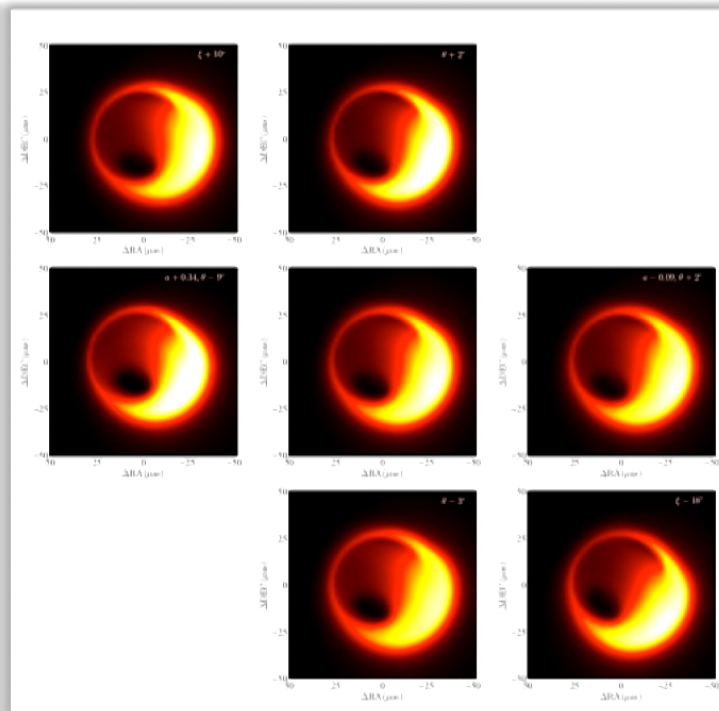
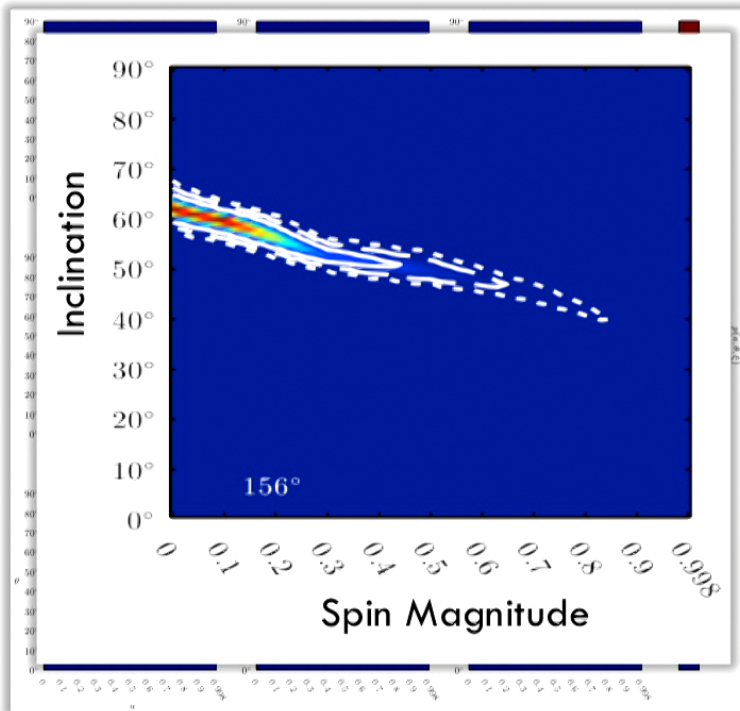


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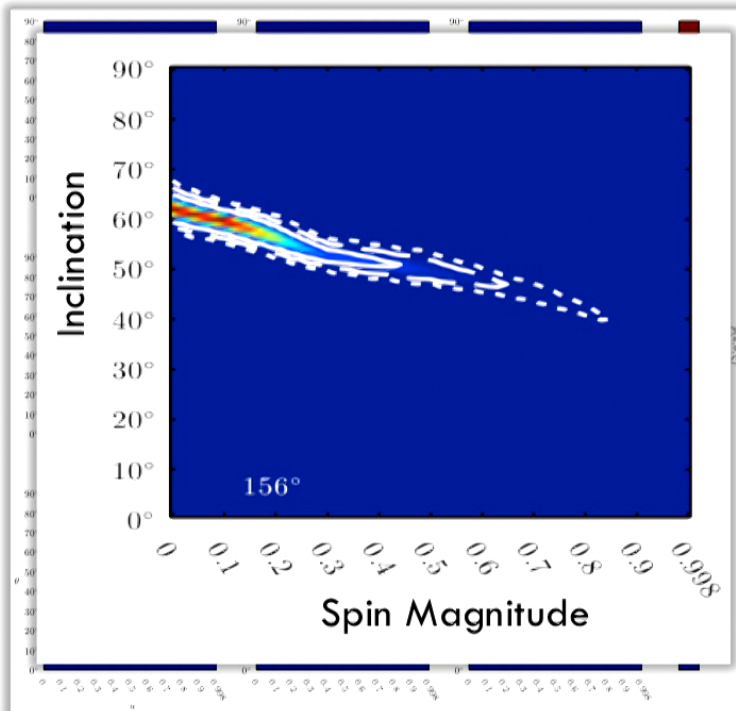
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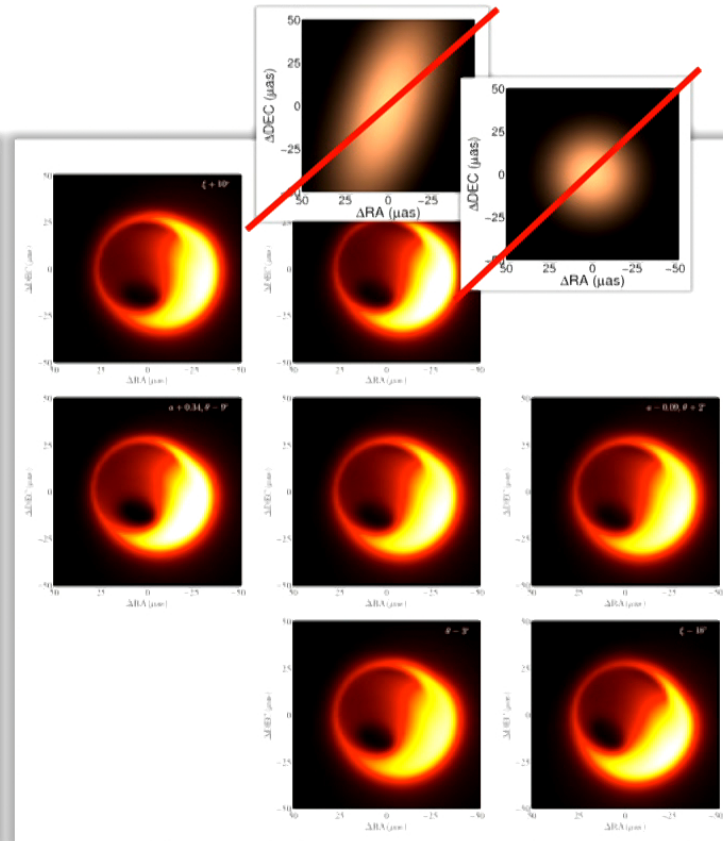
Quantum Black Holes, 10.11.2017



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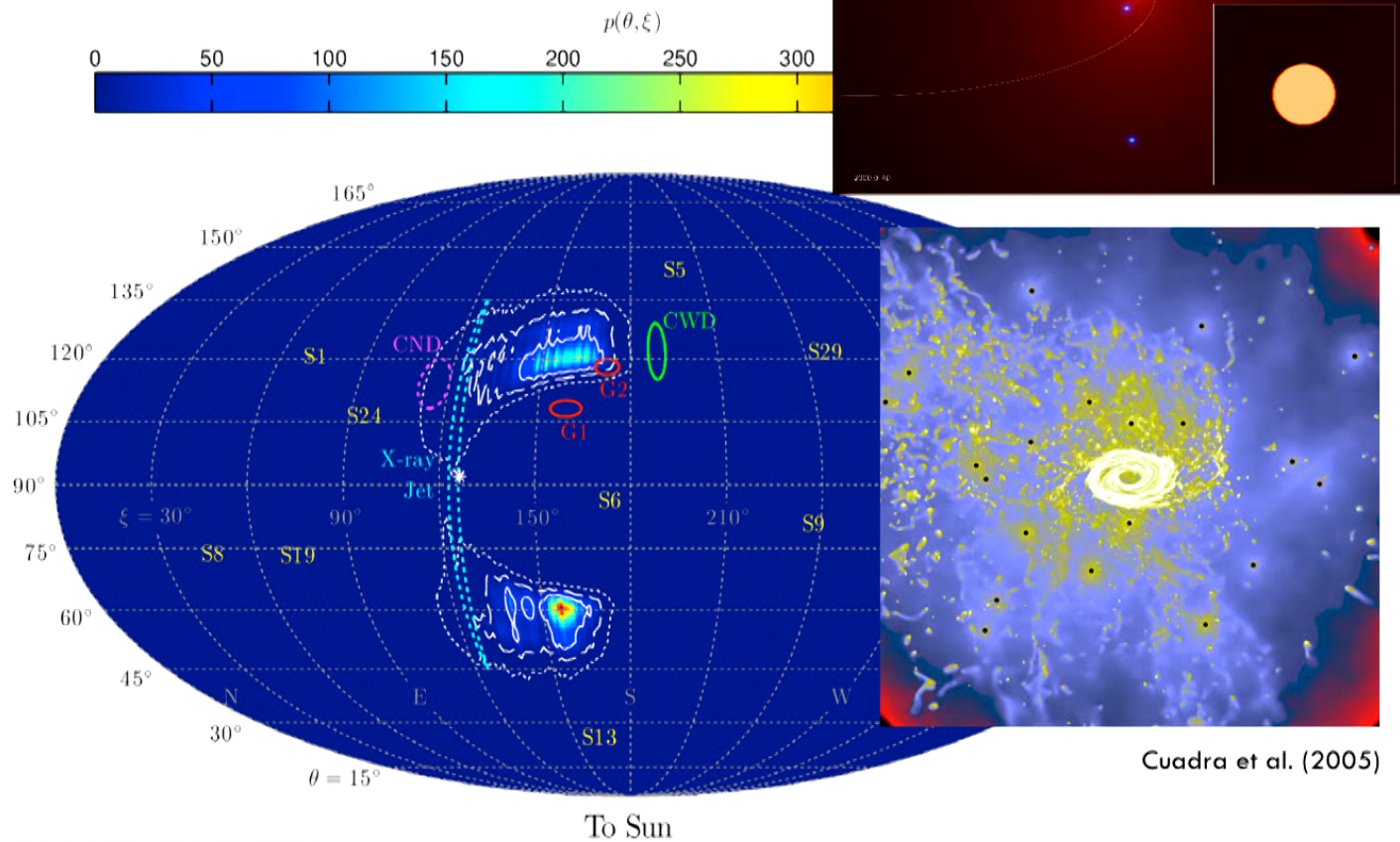
**Excluded!**



**Transparent gravastars?**

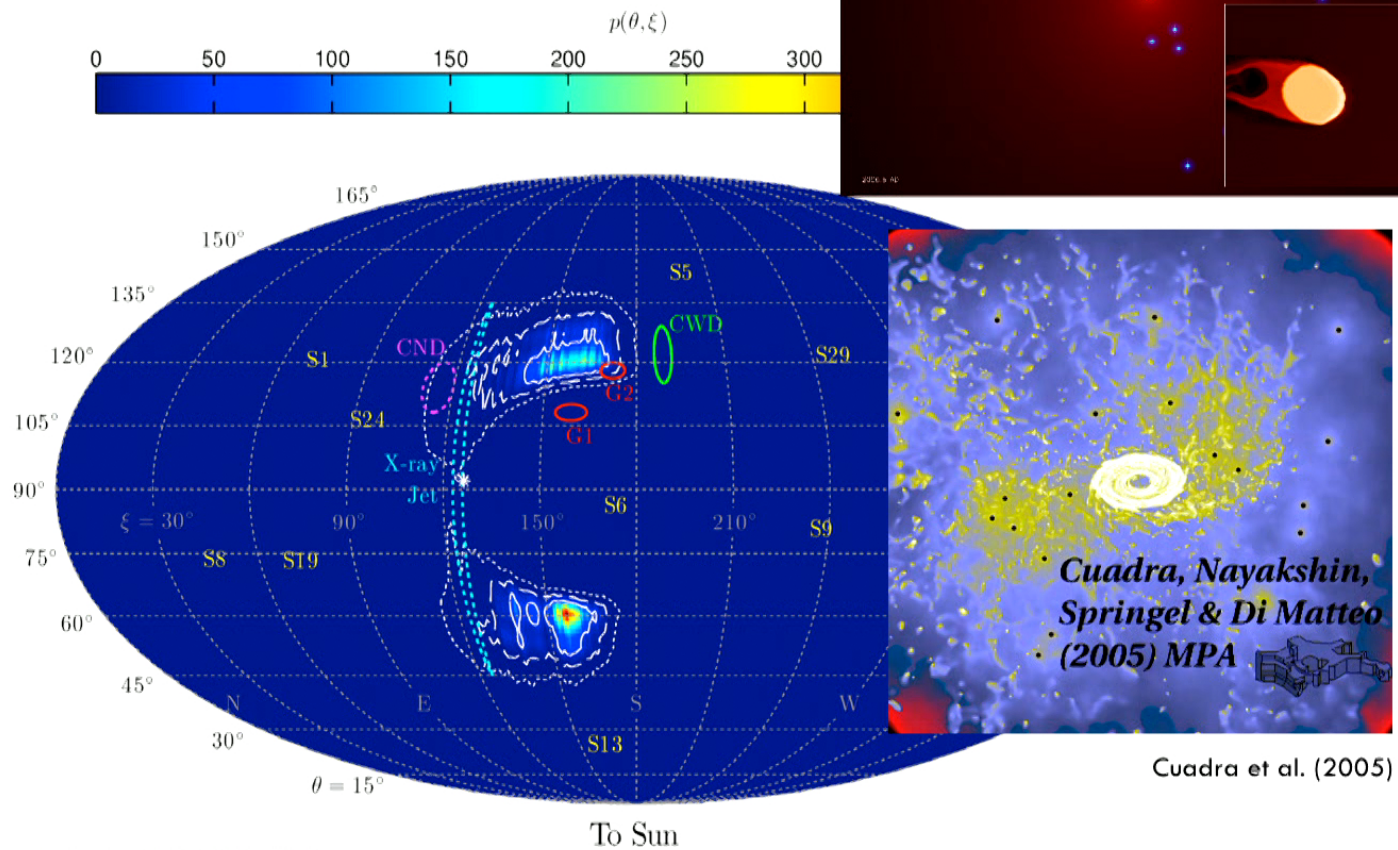
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# ORIENTATION AND THE GALACTIC CENTER STORY



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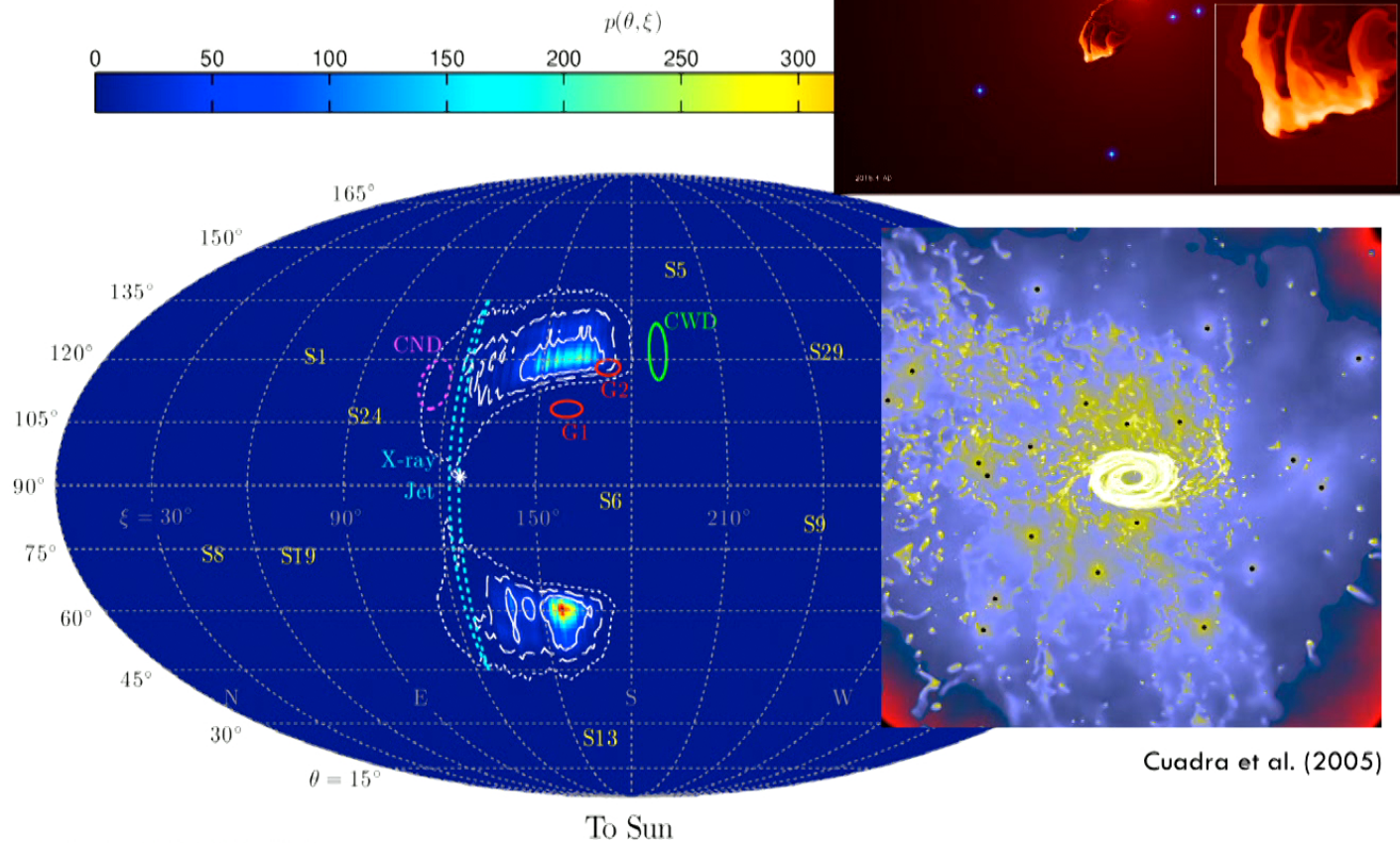
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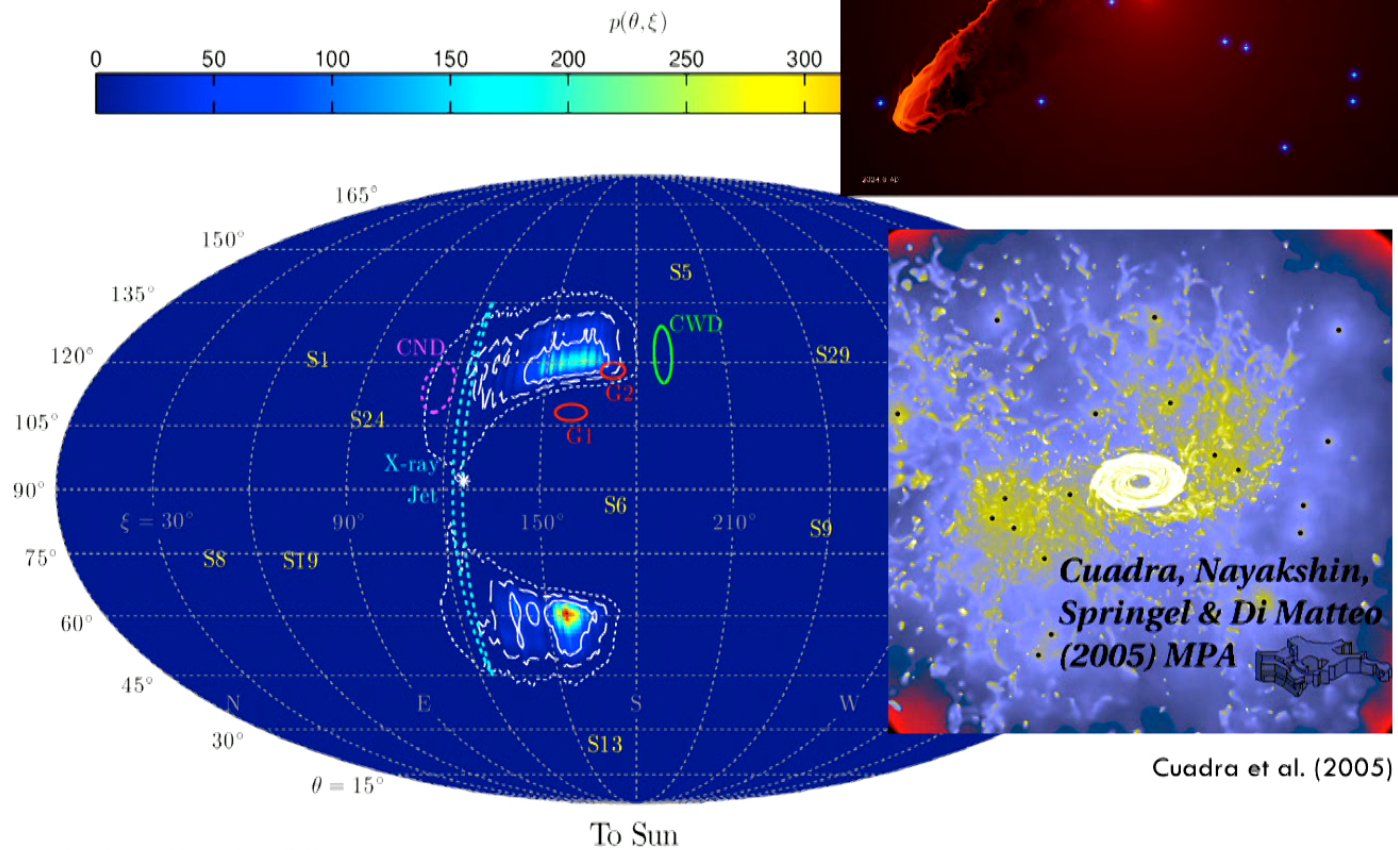


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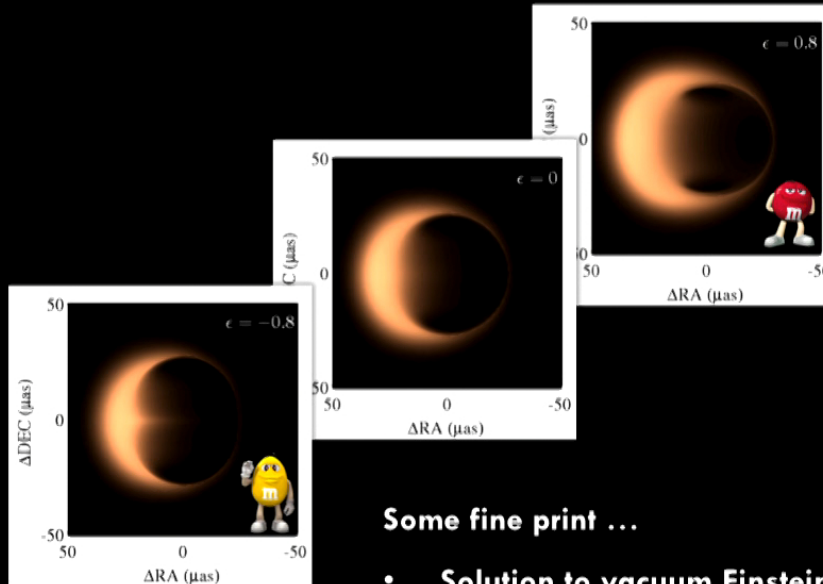


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# THE SHAPE OF SPACETIME: HAIRY MULTIPOLES

## Quasi-Kerr Metric: Parameterized Deviation



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

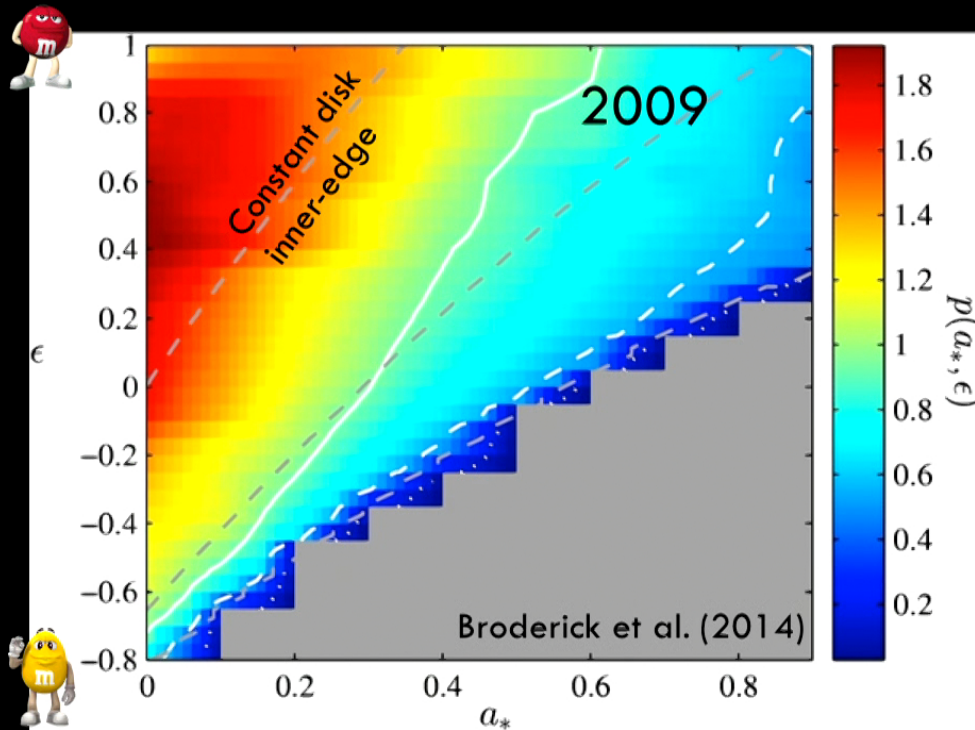
$$M = M, \quad J = aM,$$

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

Some fine print ...

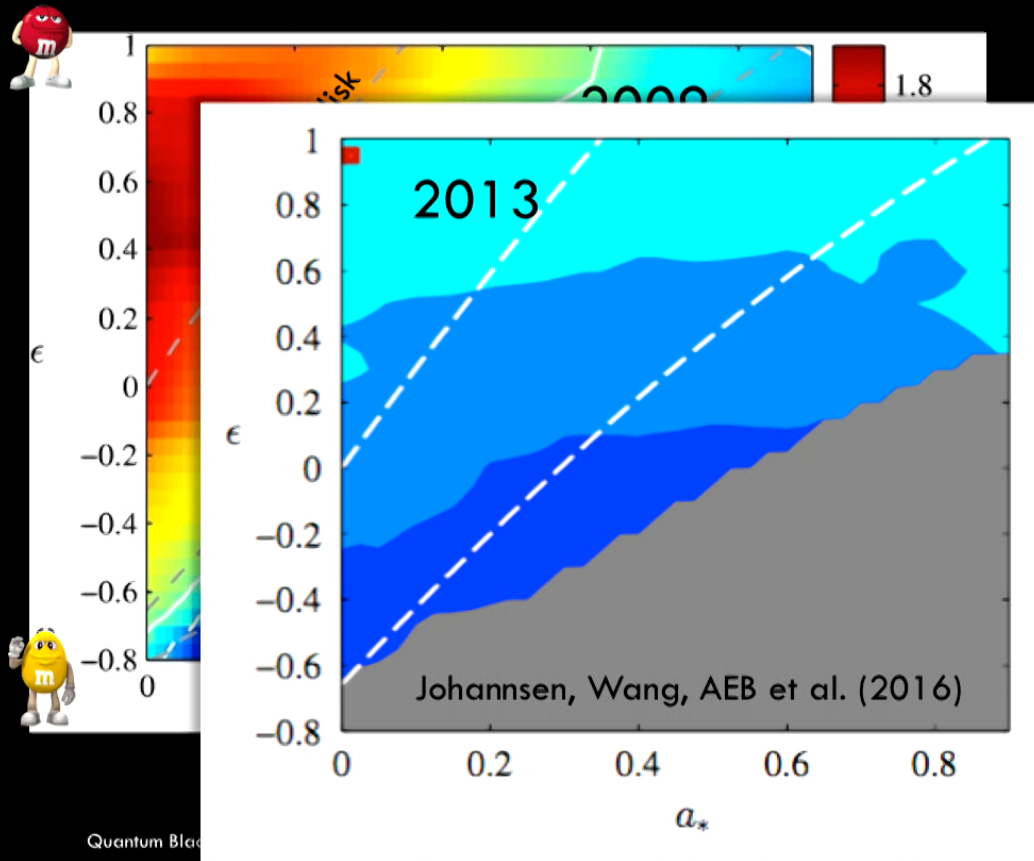
- Solution to vacuum Einstein equations when  $|a| \ll M$
- Adds quadrupolar perturbation  
(based on Hartle-Thorne metric for slowly spinning neutron stars!)
- No-hair theorems  $\rightarrow$  Quasi-Kerr metric must be sick! It is inside  $2M$ .

# THE SHAPE OF SPACETIME: HAIRY MULTIPOLES

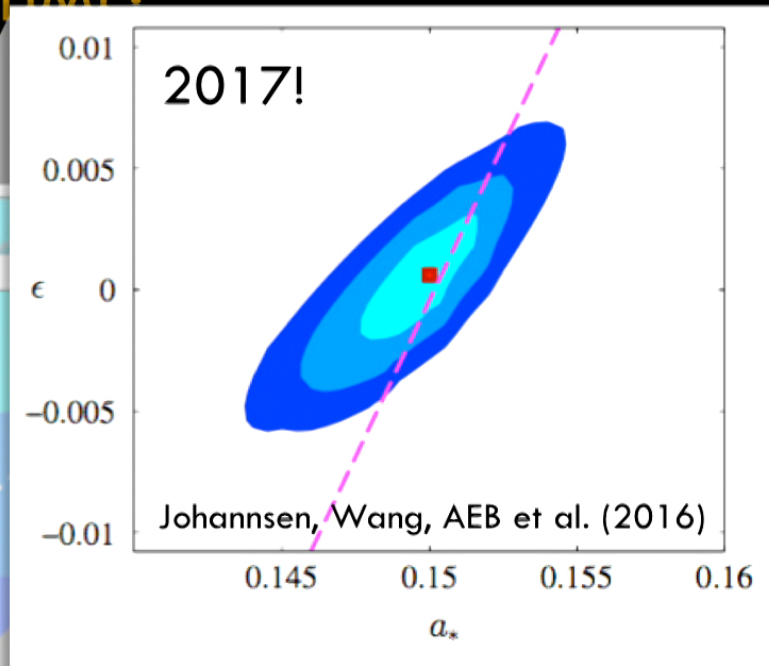
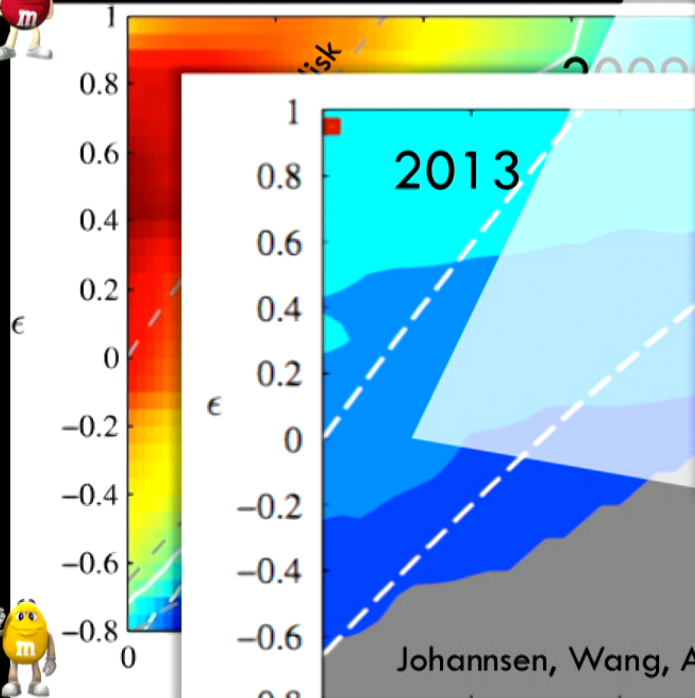


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# THE SHAPE OF SPACETIME: HAIRY MULTIPOLES



# THE SHAPE OF SPACETIME. HAIRY MULTIPOLES





# WHAT ABOUT ASTROPHYSICS?

## Ingredients:

- Covariant ADAF model
- Johannsen (2013) metric

## Conclusion:

Even big gravitational  
perturbations

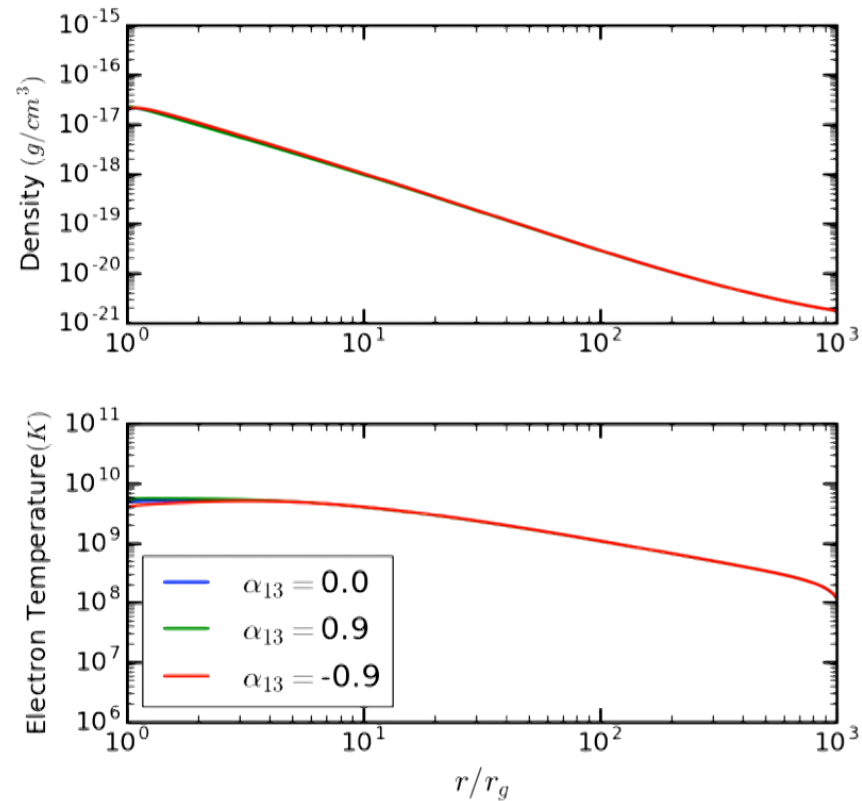


Small changes in  
accretion flow!

**Done? No!**

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Boris Georgiev



# THE SHAPE OF SPACETIME: SPACETIME TOMOGRAPHY

Courtesy of Hotaka Shiokawa



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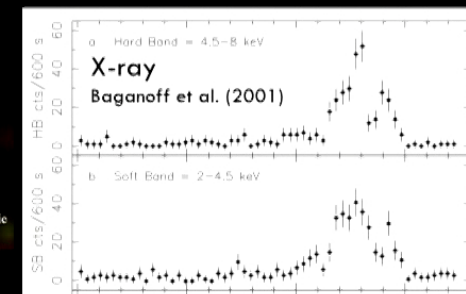
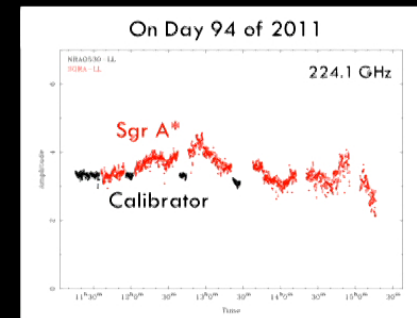
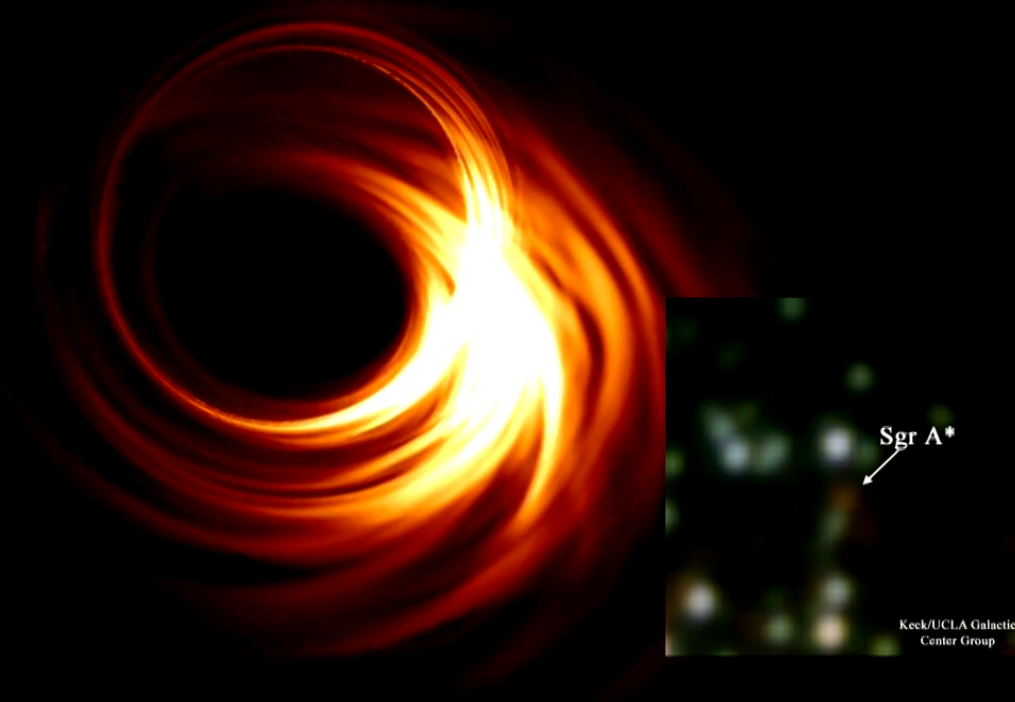


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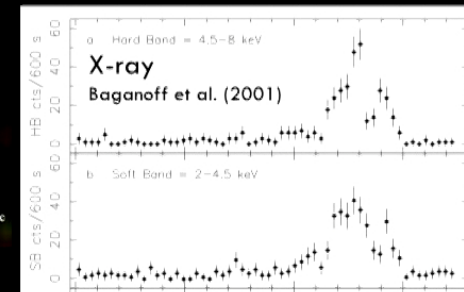
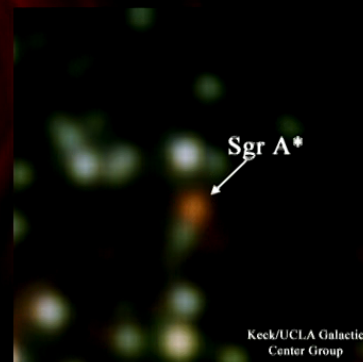
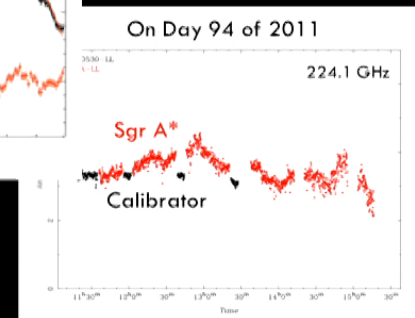
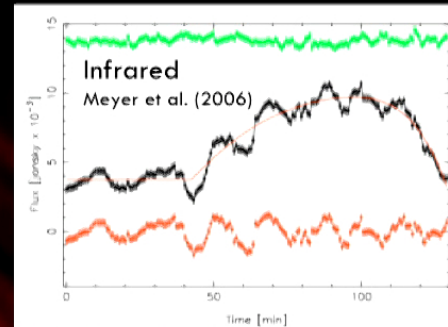
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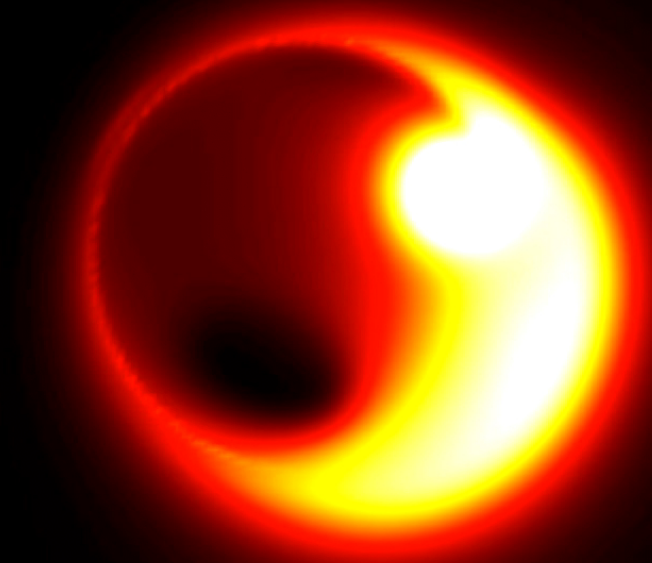
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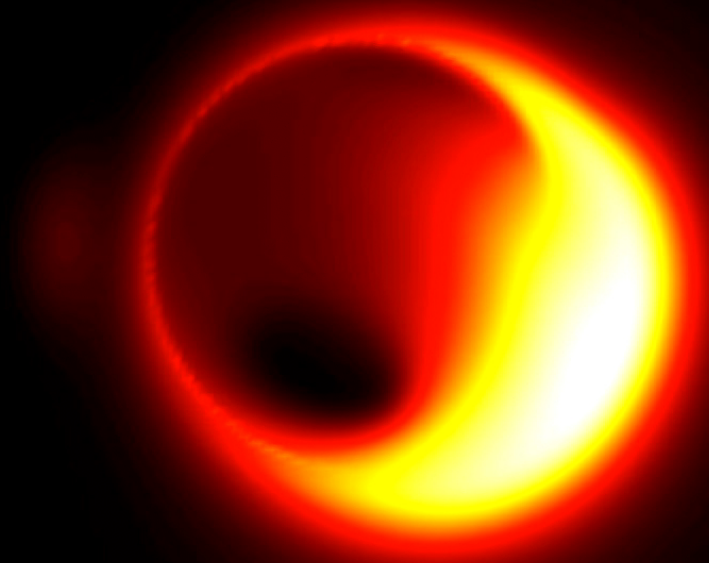
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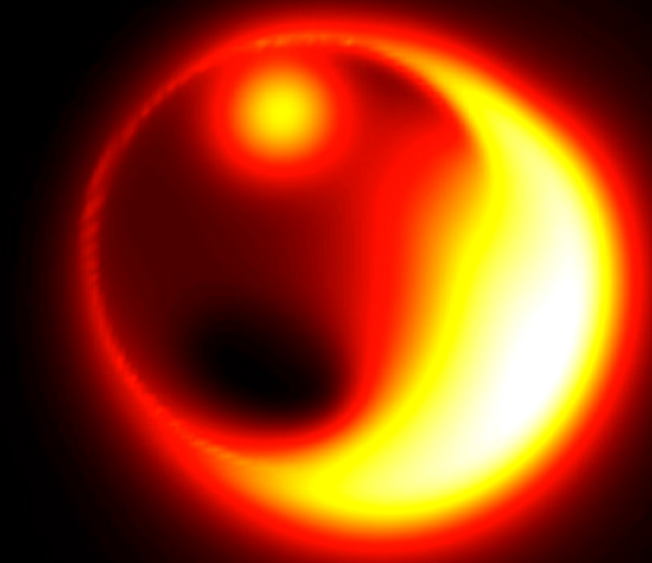
Quantum Black Holes, 10.11.2017

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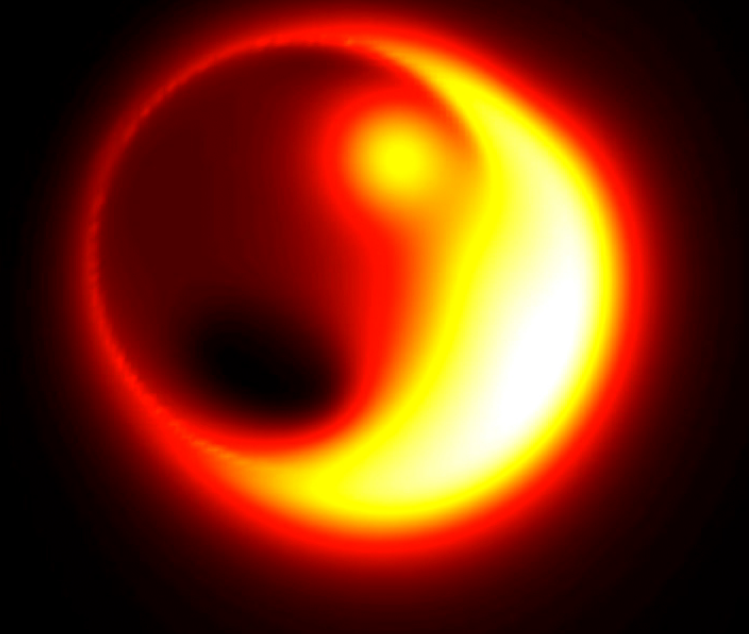
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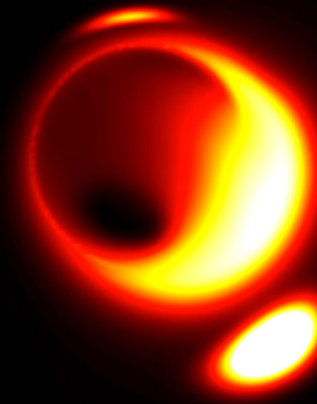
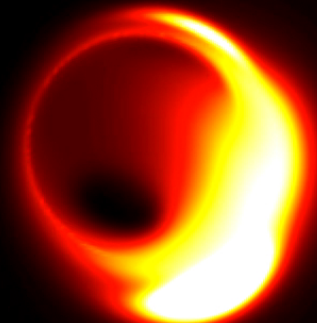
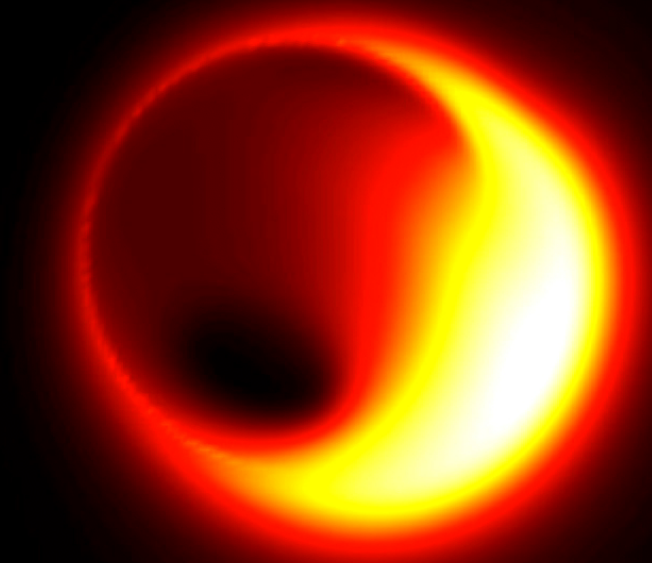


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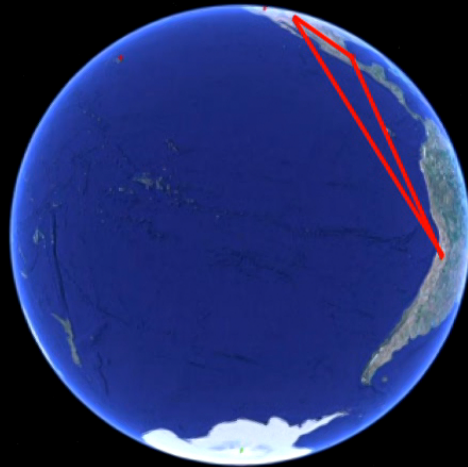
# THE SHAPE OF SPACETIME: SPACETIME TOMOGRAPHY



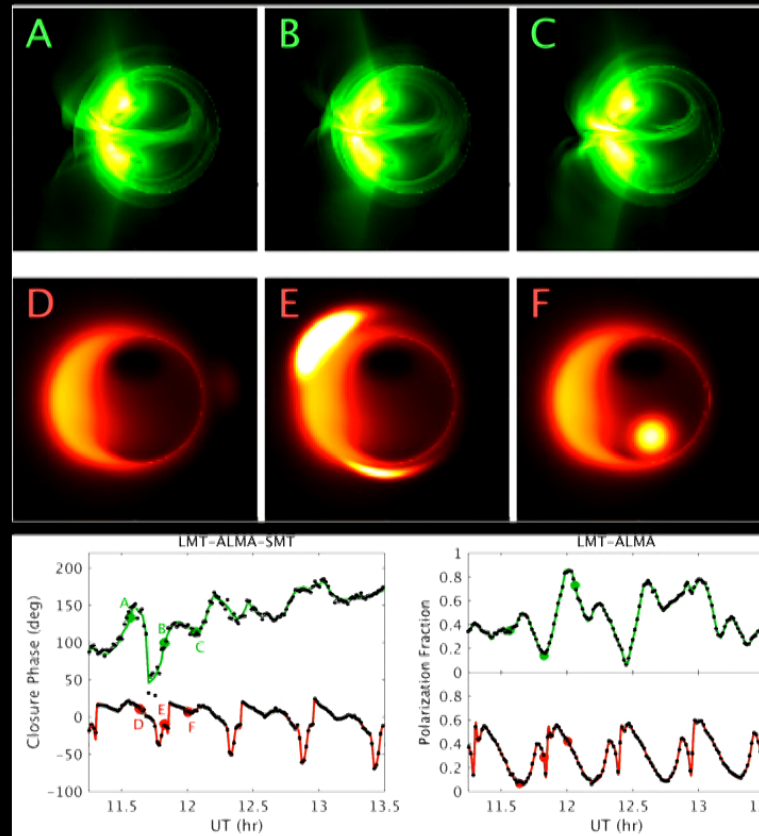
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# THE SHAPE OF SPACETIME: SPACETIME TOMOGRAPHY

Roman Gold & AEB



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

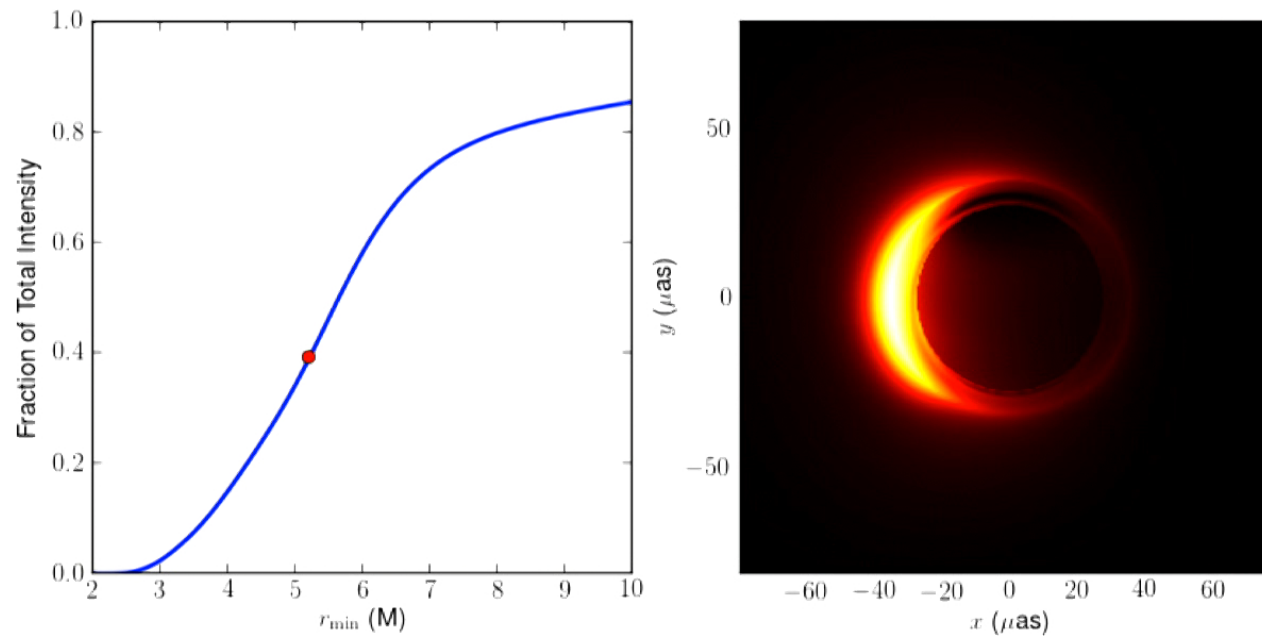


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# PROBING QUANTUM GRAVITY?

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## EMISSION FROM WHERE?

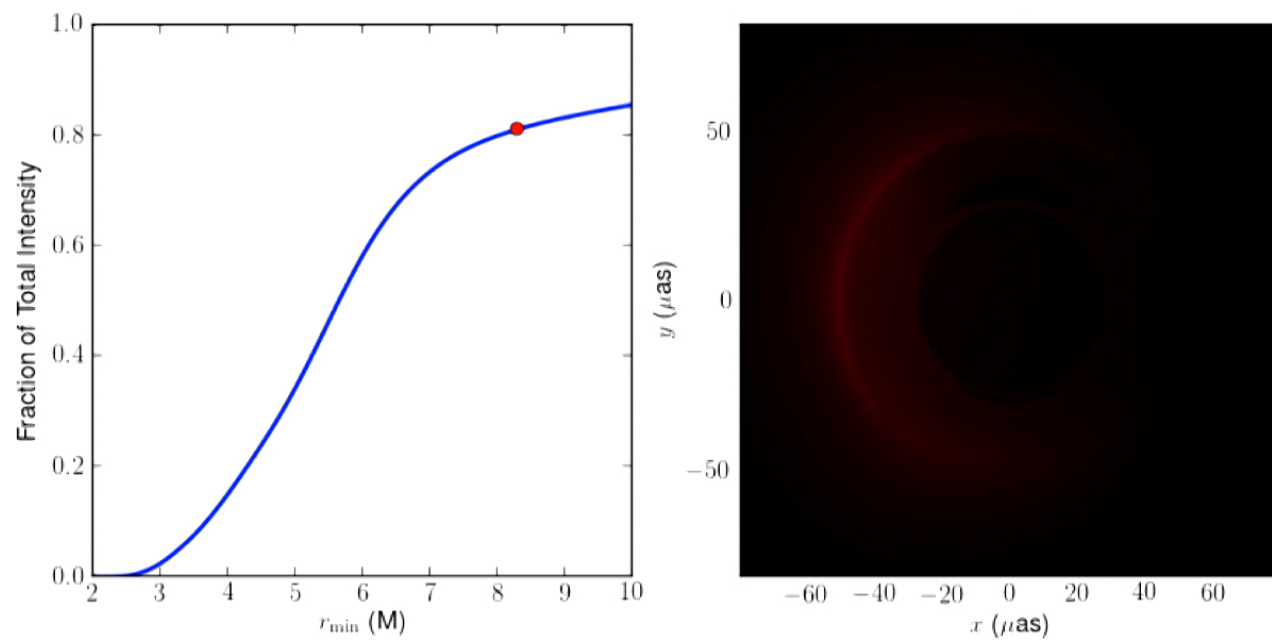


H.-Y. Pu, AEB, et al. (2017)

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## EMISSION FROM WHERE?



H.-Y. Pu, AEB, et al. (2017)

Quantum Black Holes, 10.11.2017

# DO FUZZY BLACK HOLES MAKE FUZZY IMAGES?

$$\langle g \rangle \quad \text{vs.} \quad |g\rangle$$

No! But ...

- **Small  $N_\gamma$ :**

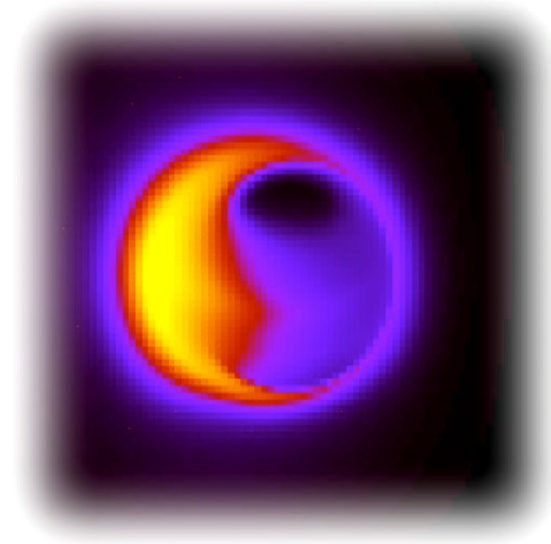
$$N_\gamma \sim 10^{10} \text{ but } N_{\text{States}} \sim e^{10^{90}} \\ \rightarrow \text{Weak measurement limit!}$$

- **Interactions:**

$$\epsilon_\gamma \gg \epsilon_H \gtrsim \Delta\epsilon \\ \rightarrow \text{Transitions on } M \text{ timescales from "accretion"} \\ \text{interactions (much less than astrophysical time scales)}$$

Quantum Black Holes, 10.11.2017

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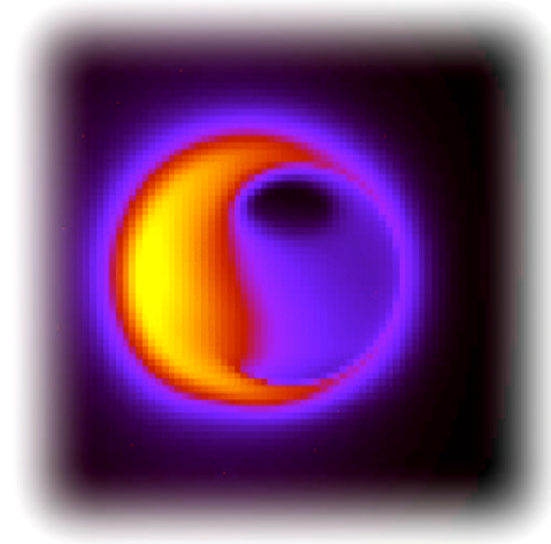
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Quantum Black Holes, 10.11.2017

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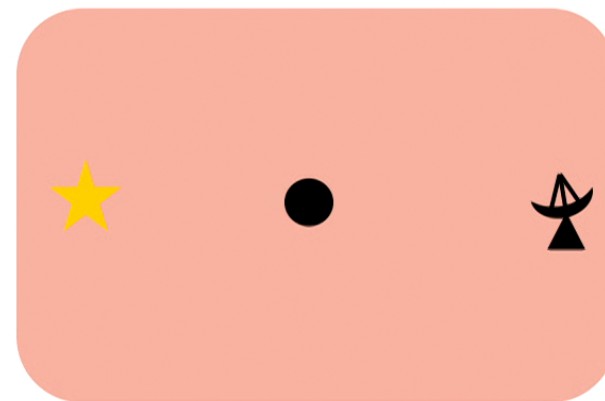
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## A GROSS SIMPLIFICATION



1. **Separate source from black hole region**
2. **Source produces a sequence of *identically prepared* photons**

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# SINGLE PHOTON & PURE BH STATES

Source



$|\gamma_A\rangle$

Initial photon state

Quantum  
Black Hole



$|L\rangle$

Black hole state

“Screen”

$|x\rangle$  or  $|k\rangle$



$$|\gamma_A, L\rangle = \sum_j a_j |L_j\rangle |\gamma_j\rangle$$

“Scattered” photon states in  
terms of scattering eigenstates.

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“Scattered” photon states in terms of scattering eigenstates.

$$\begin{aligned} I(k) &= |\langle k | \gamma_A, L \rangle|^2 = \sum_j \underbrace{|a_j|^2}_{p_j} \underbrace{|\langle k | \gamma_j \rangle|^2}_{I_j(k)} \\ &= \sum_j p_j \underbrace{I_j(k)}_{\text{“Image” for state } |L_j\rangle} \end{aligned}$$

Quantum Black Holes, 10.11.2017

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“Image” for state  $|L_j\rangle$

→ Fuzzy image?

# MANY PHOTONS & BH PURE STATES

Source



$$(|\gamma_A\rangle|\gamma_B\rangle \dots |\gamma_N\rangle)$$

Initial photon state

Quantum  
Black Hole



$$|L\rangle = \sum_j a_j |L_j\rangle$$

Black hole state

“Screen”

$|x\rangle$  or  $|k\rangle$

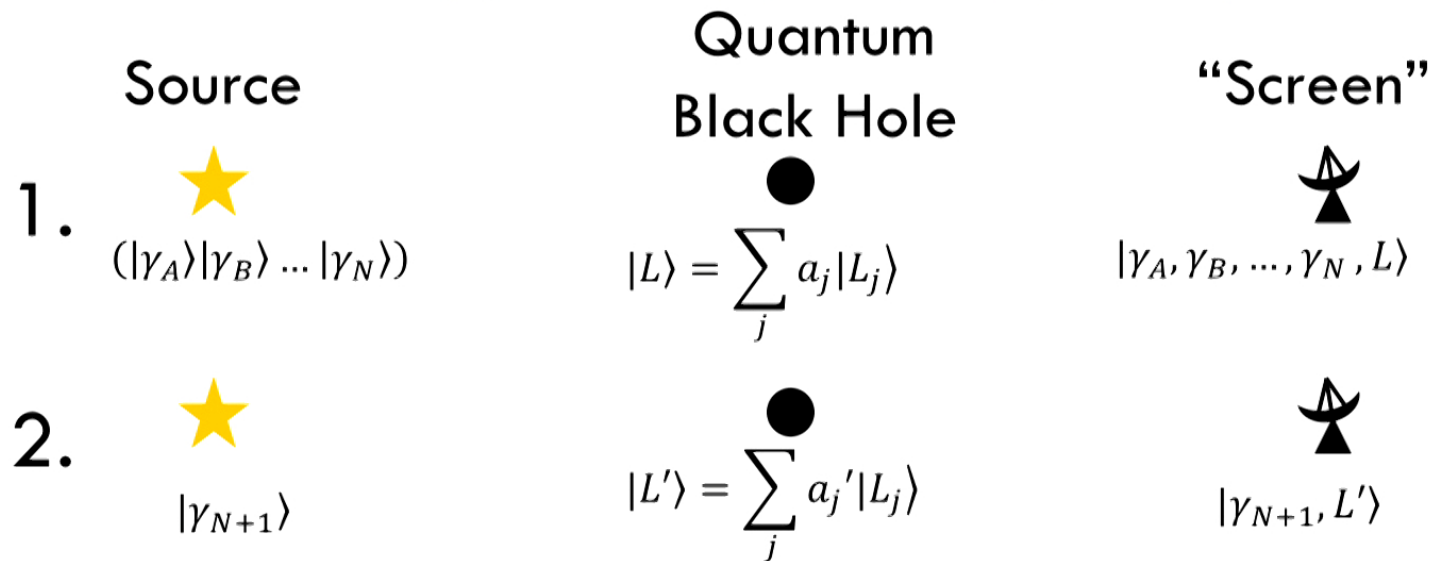


$$|\gamma_A, \gamma_B, \dots, \gamma_N, L\rangle$$

$$= \sum_j a_j |L_j\rangle |\gamma_j\rangle |\gamma_j\rangle \dots |\gamma_j\rangle$$

$$I(\{k\}) = \sum_j p_j I_j(k_A) I_j(k_B) \dots I_j(k_N)$$

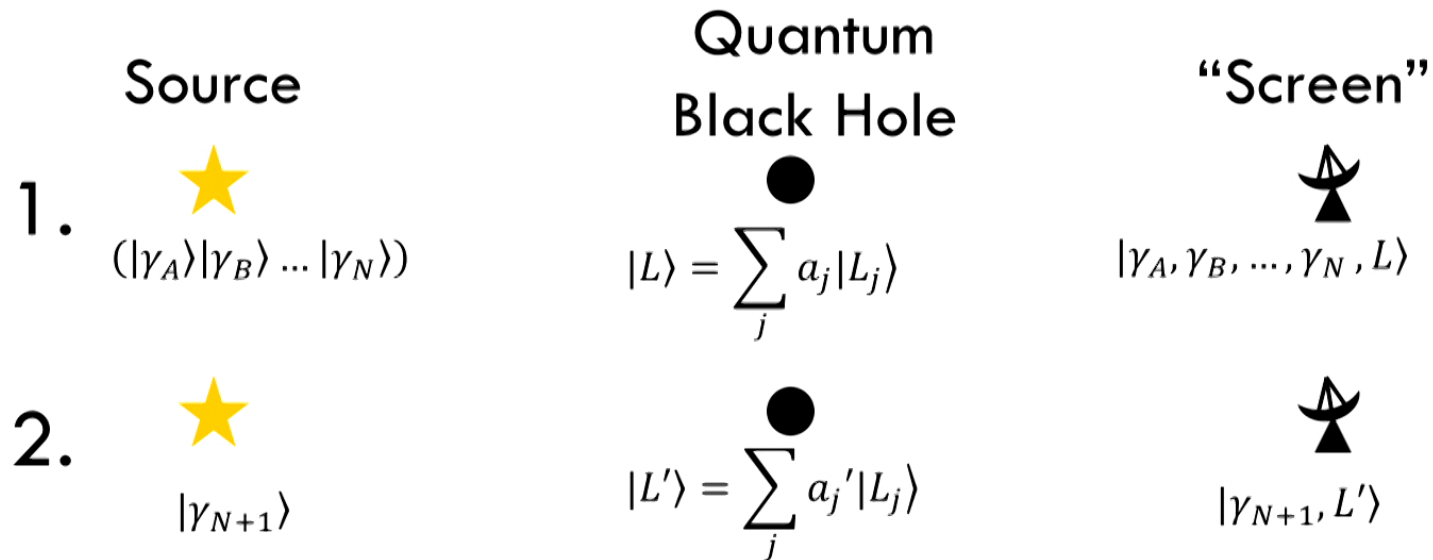
# WEAK MEASUREMENTS AND COLLAPSE



Quantum Black Holes, 10.11.2017

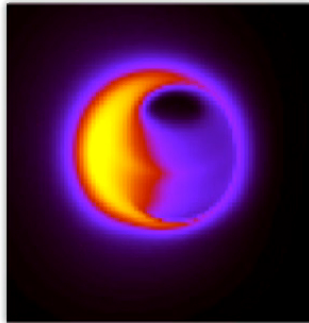


# WEAK MEASUREMENTS AND COLLAPSE

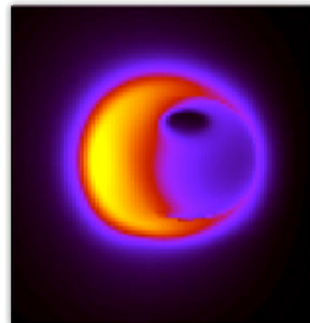


$$\left\langle \sqrt{|a_n'|^2 |a_m'|^2} \right\rangle = \sqrt{|a_n|^2 |a_m|^2} \left[ \int d^2k \sqrt{I_n(k) I_m(k)} \right]^N \quad n \neq m$$

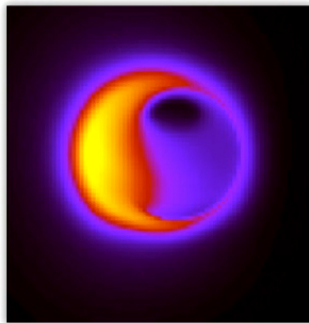
## PROJECTING OUT “IMAGE STATES”



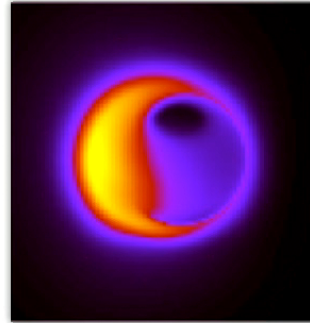
vs.



Easy!  
(smaller  $N$ )



vs.



Hard!  
(larger  $N$ )

→ Natural basis is set by observation technique.

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## COMPLICATIONS ...

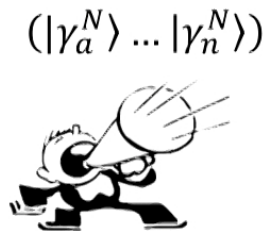
- **Mixed states:**  $|L\rangle \rightarrow \rho_{nm}$

$$\left\langle \sqrt{\rho_{nn'} \rho_{mm'}} \right\rangle = \sqrt{\rho_{nn} \rho_{mm}} \left[ \int d^2k \sqrt{I_n(k) I_m(k)} \right]^N \quad n \neq m$$

- **Noise:**

★  
 $(|\gamma_A^S\rangle \dots |\gamma_N^S\rangle)$

●  
 $|L\rangle$



Instrumental, backgrounds,  
 TV stations, ...

⦿  
 $(|\gamma_A^S, \dots, \gamma_N^S, L\rangle |\gamma_a^N\rangle \dots |\gamma_n^N\rangle)$

## COMPLICATIONS ...

$$\left\langle \sqrt{\rho_{nn'} \rho_{mm'}} \right\rangle = \sqrt{\rho_{nn} \rho_{mm}} \exp \left[ -\frac{SNR^2}{8} \int d^2k \frac{[I_n^S(k) - I_m^S(k)]^2}{I^N(k)} \right]$$

$$SNR = \frac{N_S}{\sqrt{N_N}} \simeq \frac{F_v \sqrt{2BT}}{SEFD} \simeq 10^{3.5} - 10^{4.5}$$

$$\int d^2k \frac{[I_n^S(k) - I_m^S(k)]^2}{I^N(k)} \approx 10^{-3.5} - 10^{-4.5} \sim 0.01\%$$

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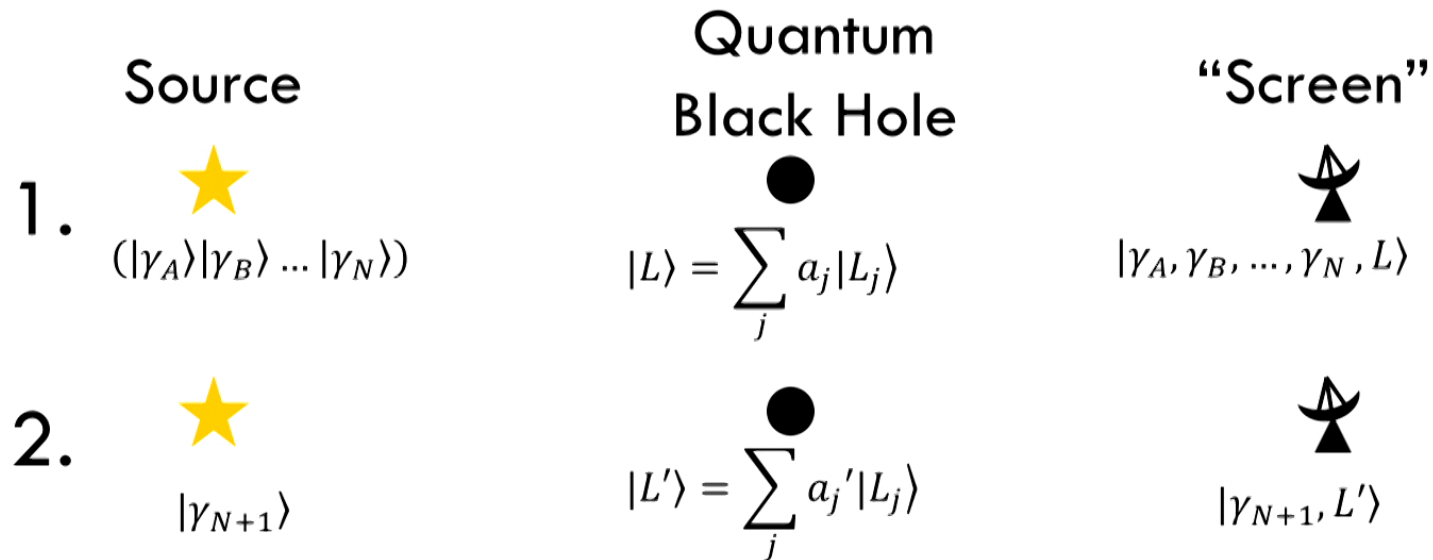
$$\frac{m_{pl}}{M} \approx 10^{-45}$$

## CONCLUDING REMARKS

- **First imaging-quality observations of EHT in the can!**
- **Evidence for apparent horizons, how to get to event horizons?**
- **Generic gravitational features exist (photon ring), 10%-level tests of GR**
- **Astrophysical models yield sub-percent *precision* probes of gravity**
- **Variability offers a multitude of probes of Kerr (e.g. orbital dyn., etc.)**
- **Quantum gravity signatures are clear for extreme? QG pictures.**



# WEAK MEASUREMENTS AND COLLAPSE



$$\left\langle \sqrt{|a_n'|^2 |a_m'|^2} \right\rangle = \sqrt{|a_n|^2 |a_m|^2} \left[ \int d^2k \sqrt{I_n(k) I_m(k)} \right]^N \quad n \neq m$$