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Date: Oct 14, 2011 02:30 PM

URL: <http://pirsa.org/11100105>

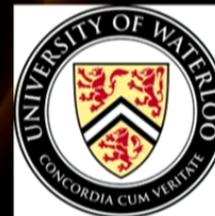
Abstract:

Portrait of a Black Hole

Avery E Broderick

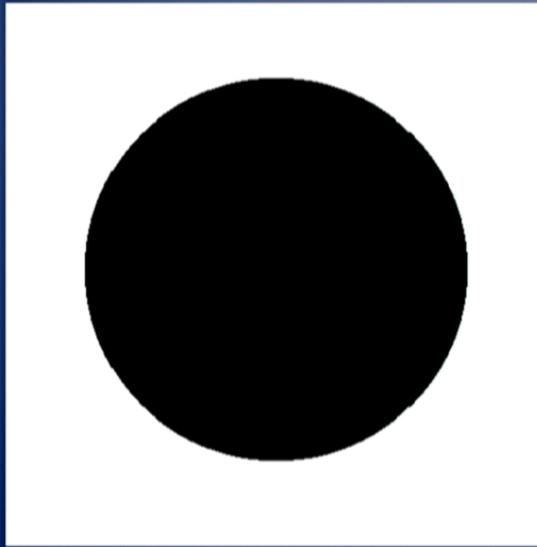
Sheperd Doeleman (MIT Haystack)
Vincent Fish (MIT Haystack)
Alan Rogers (MIT Haystack)
Dimitrios Psaltis (Arizona)
Tim Johannsen (Arizona)

Avi Loeb (Harvard)
Ramesh Narayan (Harvard)
Jonathan Bittner (Harvard)
Mark Reid (Smithsonian)
Mareki Honma (NAOJ)



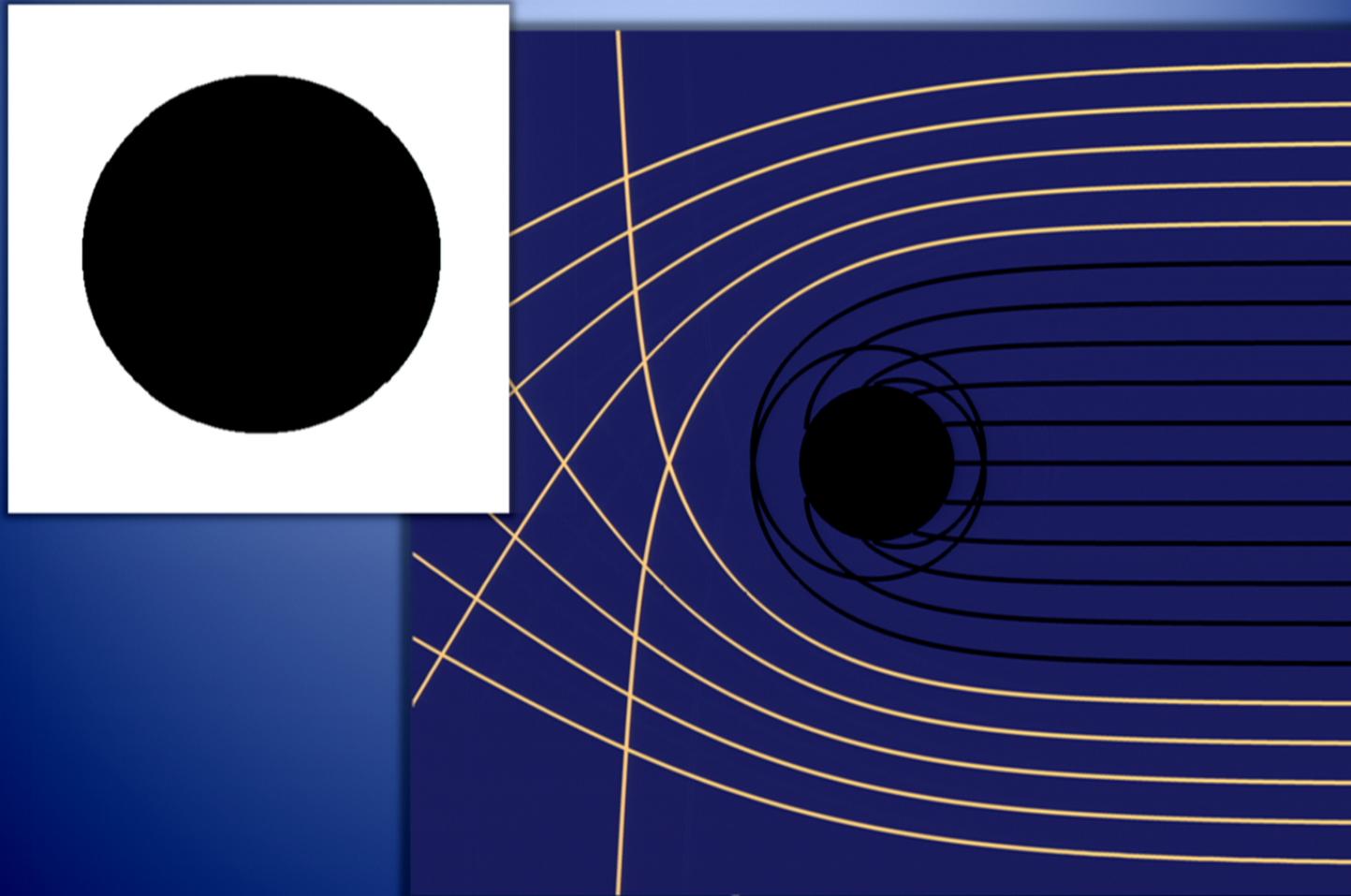
Conceptual Gems of Theoretical Physics,
Oct 14th 2011 @ PI

Black Holes in Silhouette

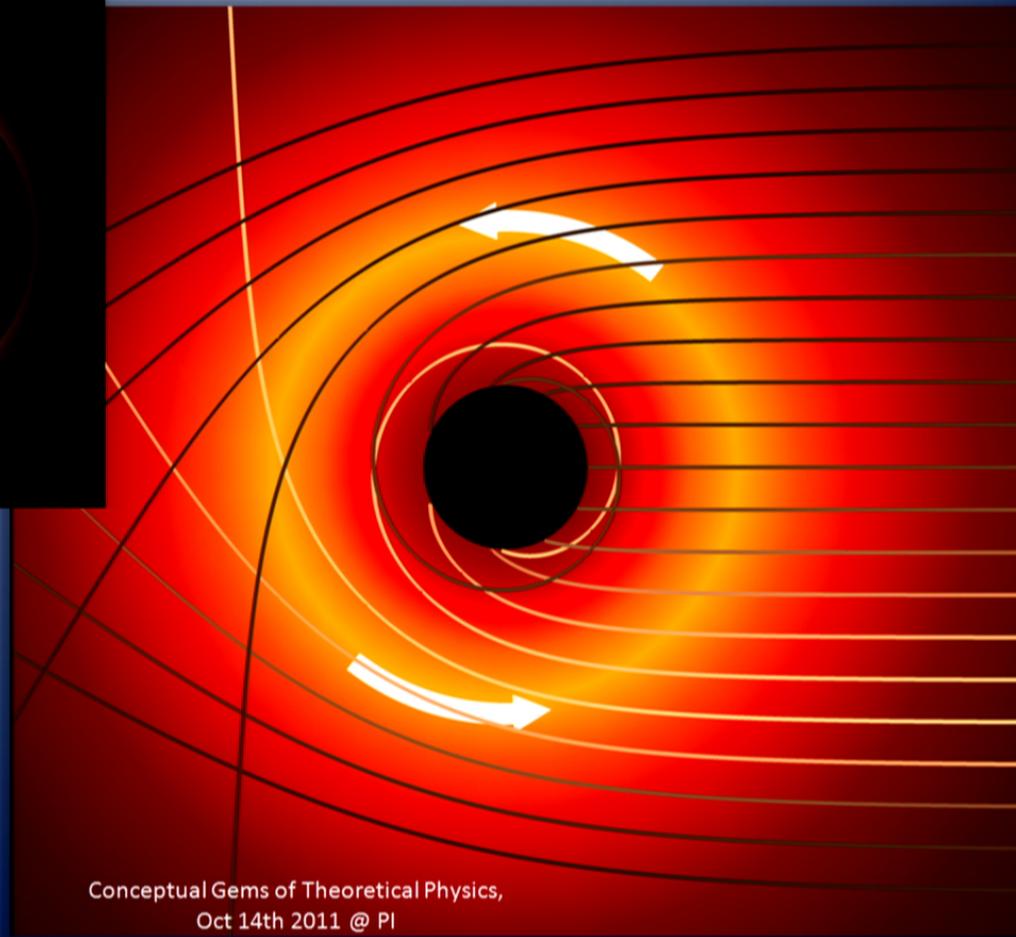
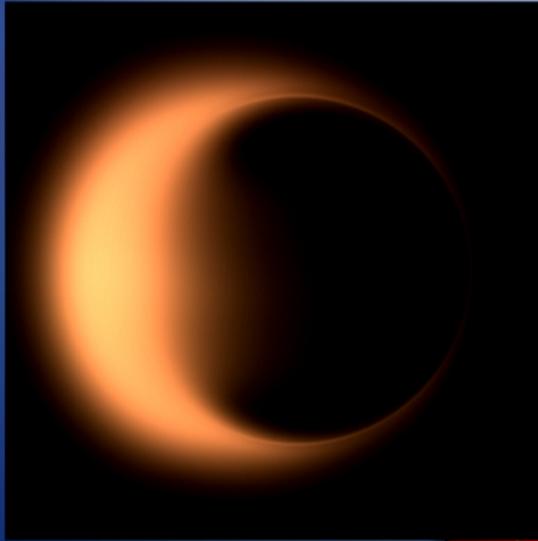


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Black Holes in Silhouette

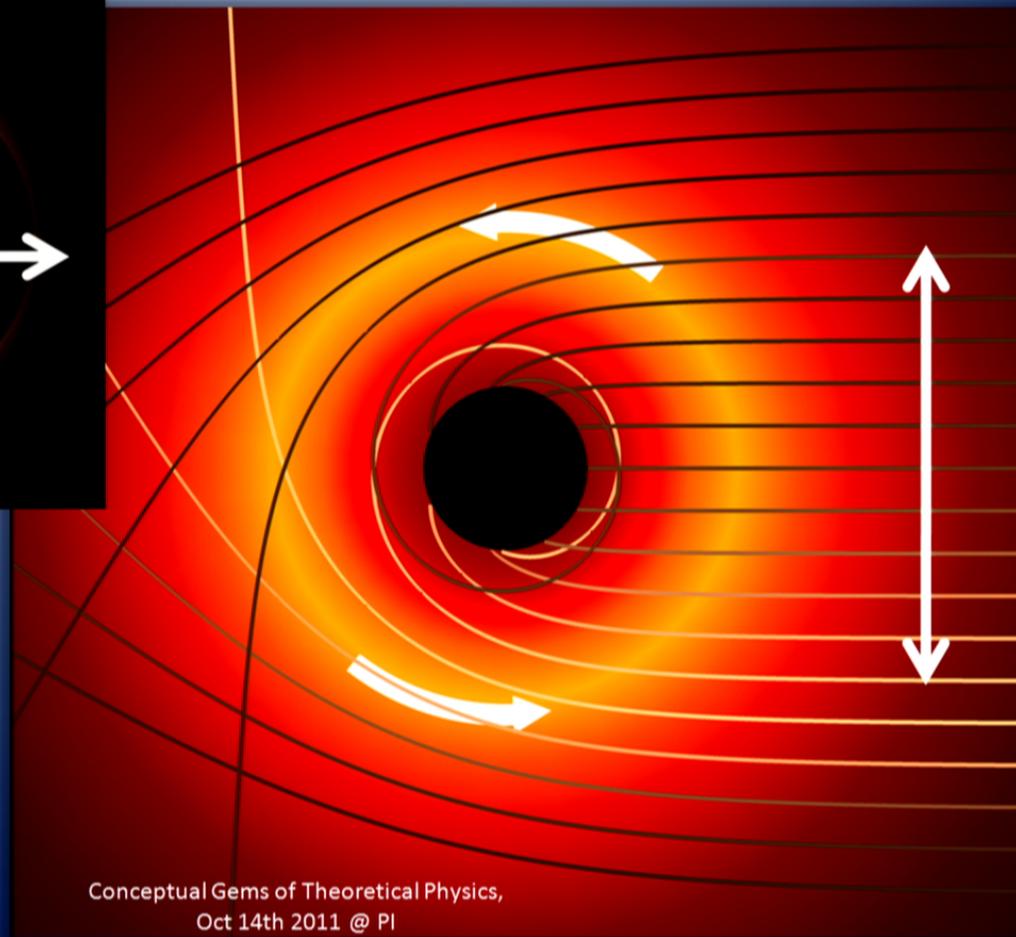
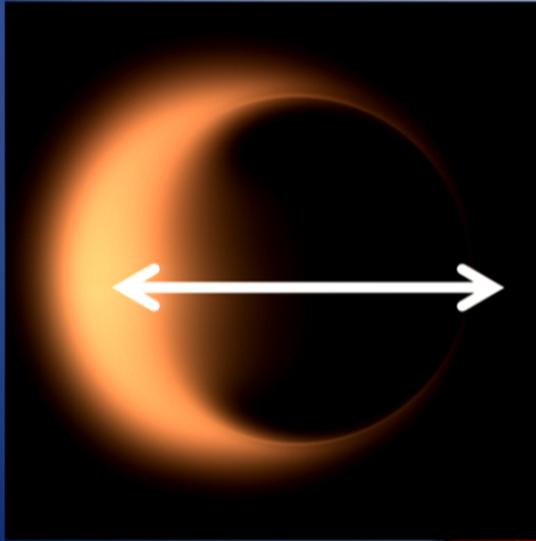


Black Holes in Silhouette, really



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Black Holes in Silhouette, really



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How big are Black Holes?



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How big are Black Holes?



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Diffraction Limited Optics

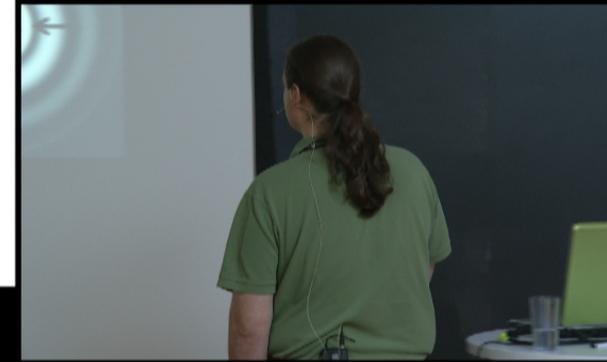
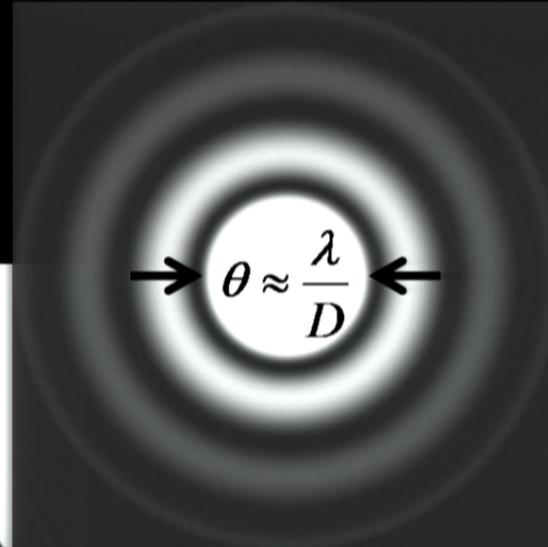
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Diffraction Limited Optics



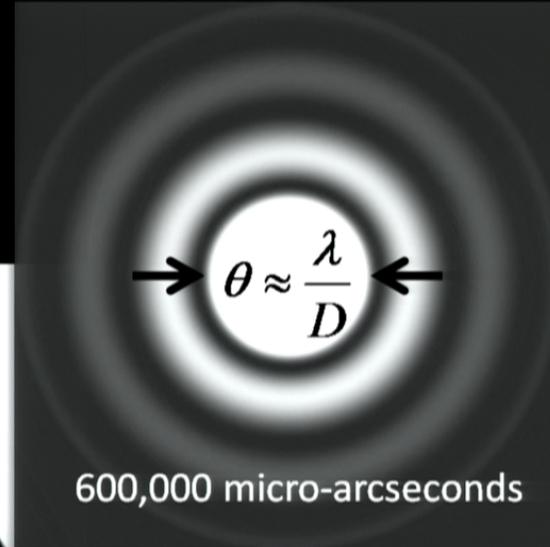
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Diffraction Limited Optics



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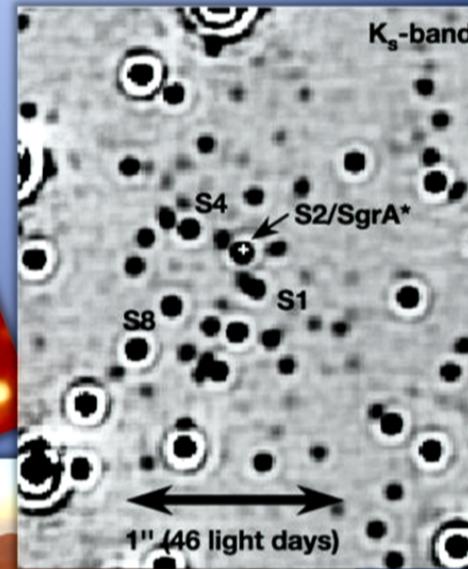
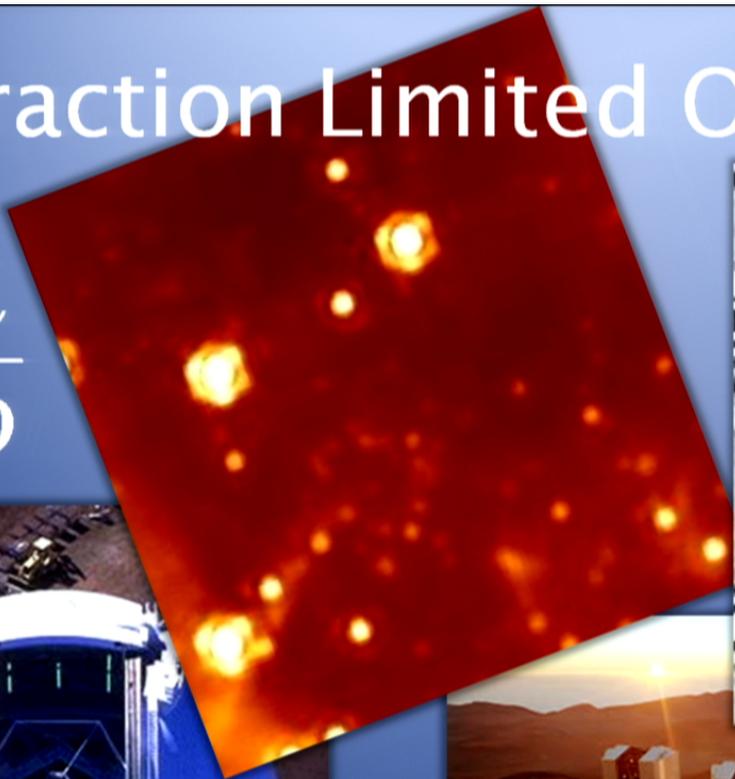
Diffraction Limited Optics



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Diffraction Limited Optics

$$\theta \approx \frac{\lambda}{D}$$

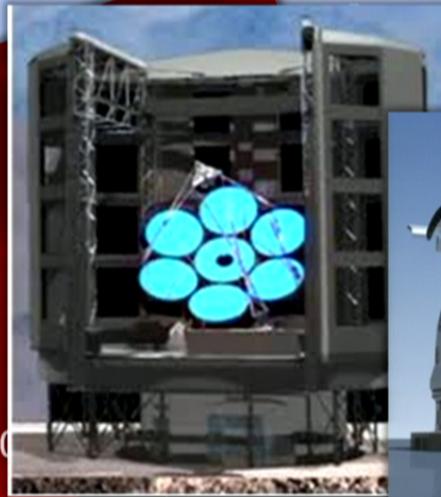
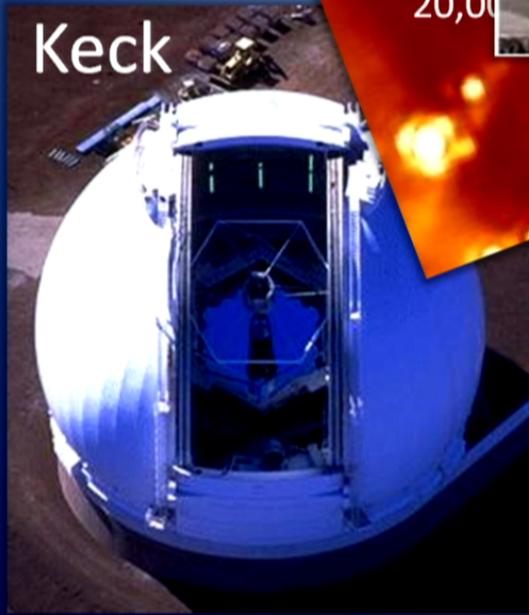


Diffraction Optics

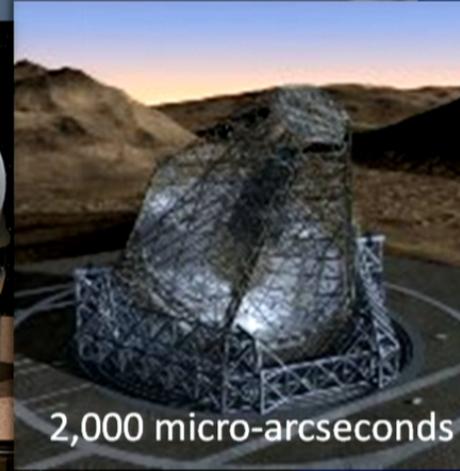
$$\theta \approx \frac{\lambda}{D}$$

20,000

Keck



Conceptual
O

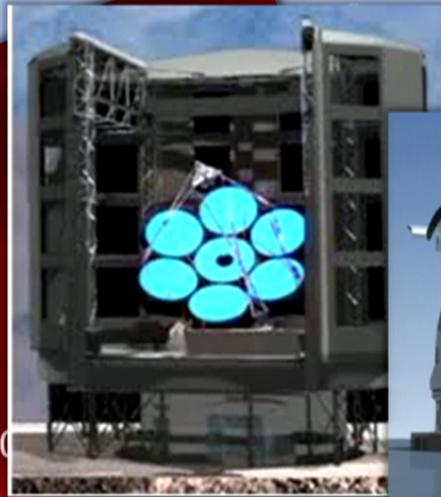
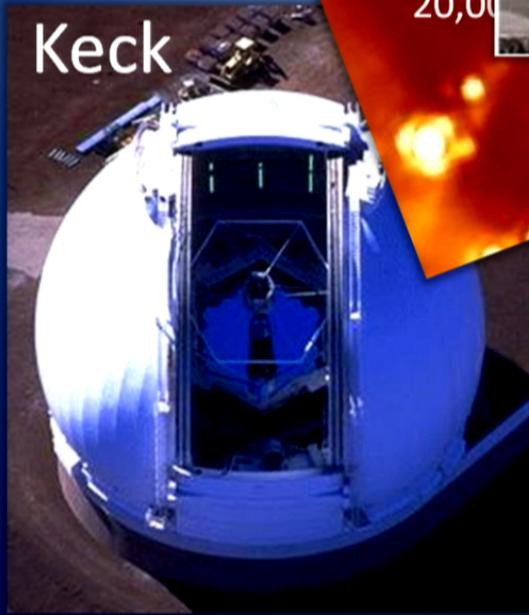


Diffraction Optics

$$\theta \approx \frac{\lambda}{D}$$

20,000

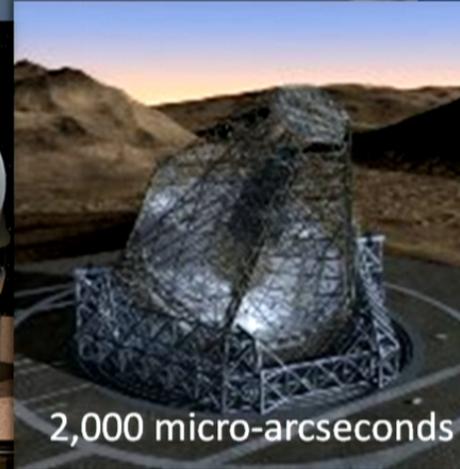
Keck



band

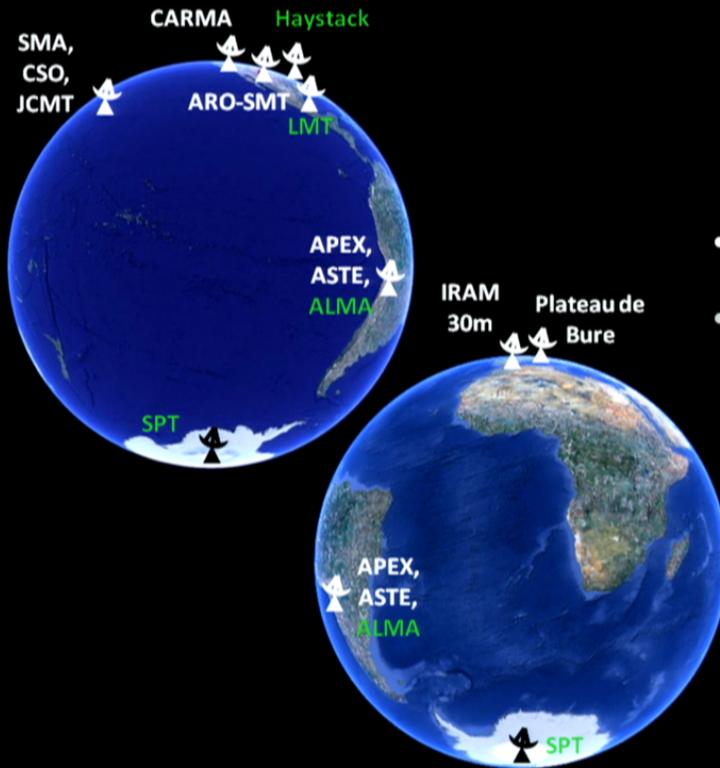


Conceptual
O



2,000 micro-arcseconds

The Event Horizon Telescope



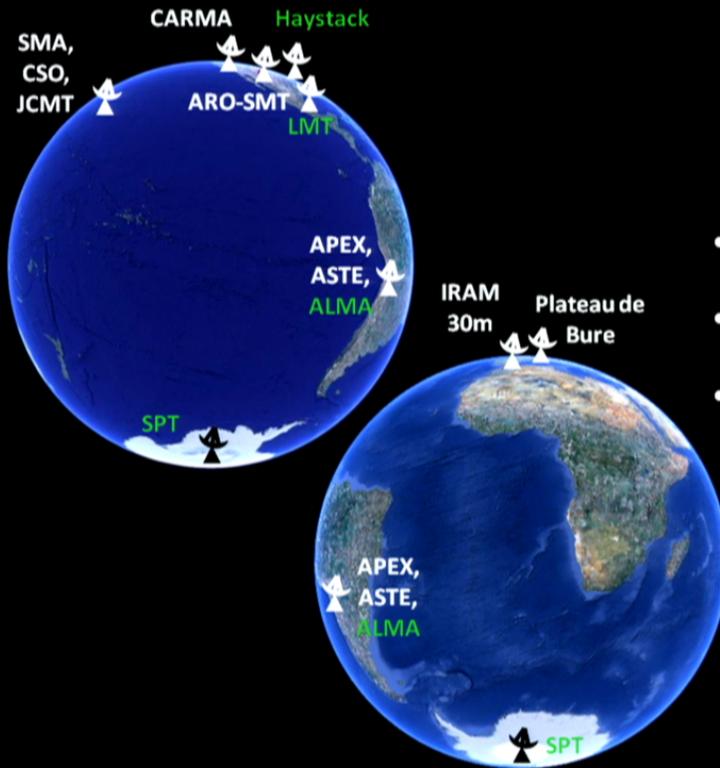
$\lambda=1 \text{ mm}$

→ $D=10,000 \text{ km!}$

- Earth-sized mm/sub-mm VLBI array
- Existing and **Planned** telescopes.



The Event Horizon Telescope



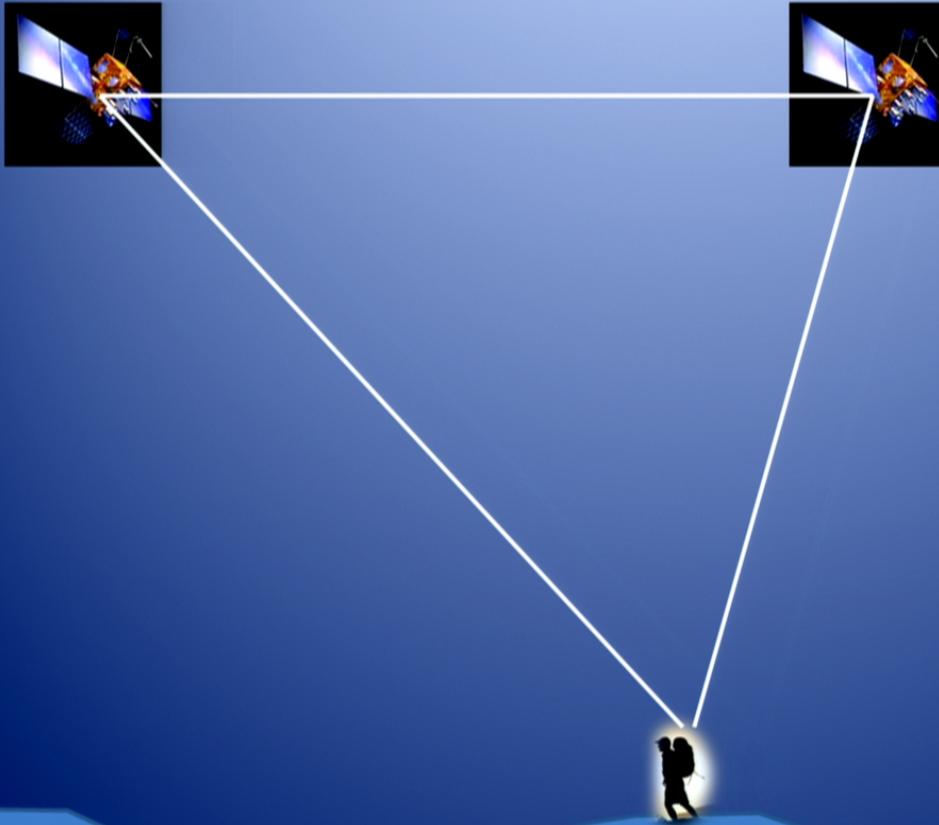
$\lambda = 1 \text{ mm}$

$\rightarrow D = 10,000 \text{ km!}$

- Earth-sized mm/sub-mm VLBI array
- Existing and **Planned** telescopes.
- Accesses resolutions of $\sim 10 \mu\text{as}$,
 \rightarrow Sufficient to resolve Sgr A*'s horizon!



How does the EHT work?



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Oct 14th 2011 @ PI

How does the EHT work?

α



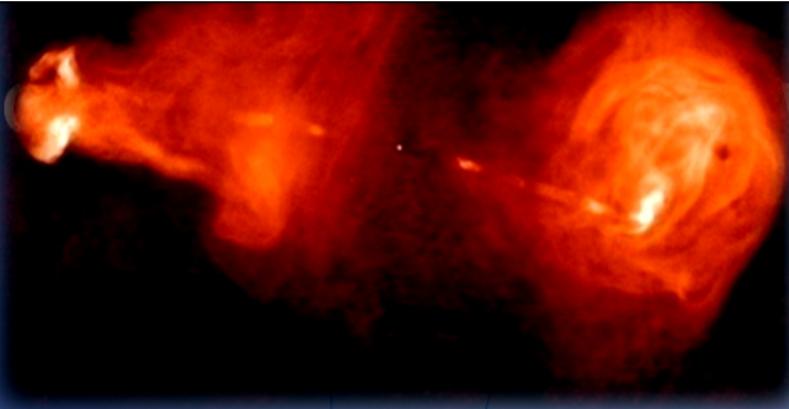
2



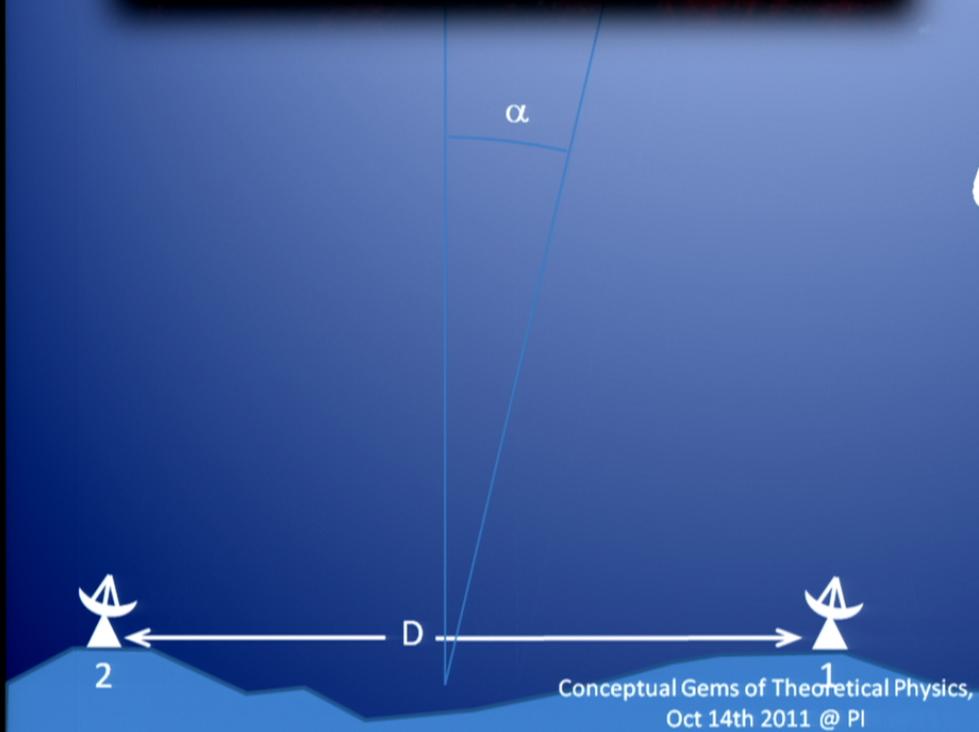
1

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H... work?



$$\theta \approx \frac{\lambda}{D}$$

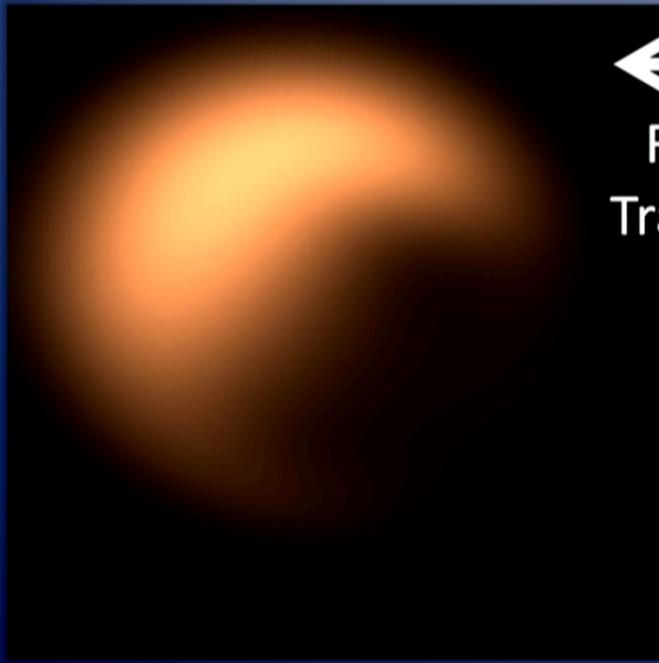


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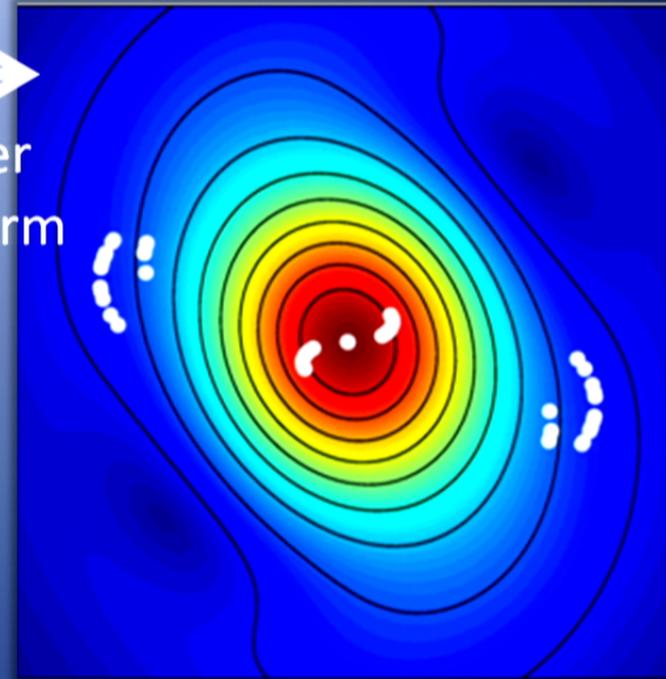
Images vs. Visibilities

Desired Image



Fourier Transform

Measured Visibilities



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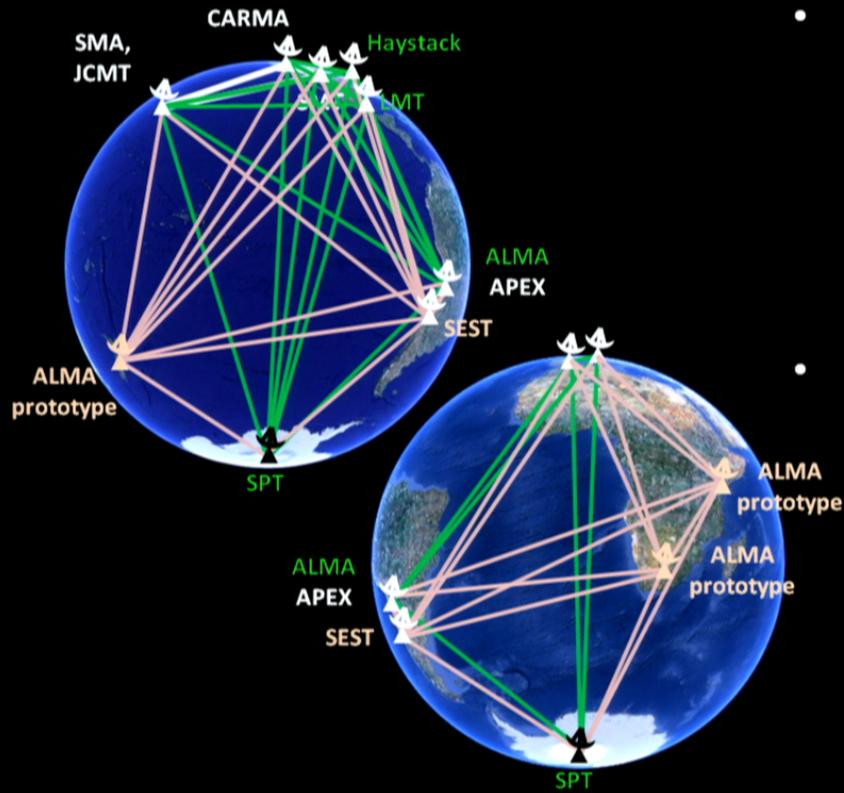
Taking snapshots with the EHT



- Increasing Sensitivity:
 - Phasing Arrays
 - Hawaii (Done!)
 - CARMA (In progress!)
 - ALMA (Approved!)
 - Expanding Bandwidth to 4GHz
 - Building New Receivers

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Taking snapshots with the EHT



• Incr

—

• Adc

—



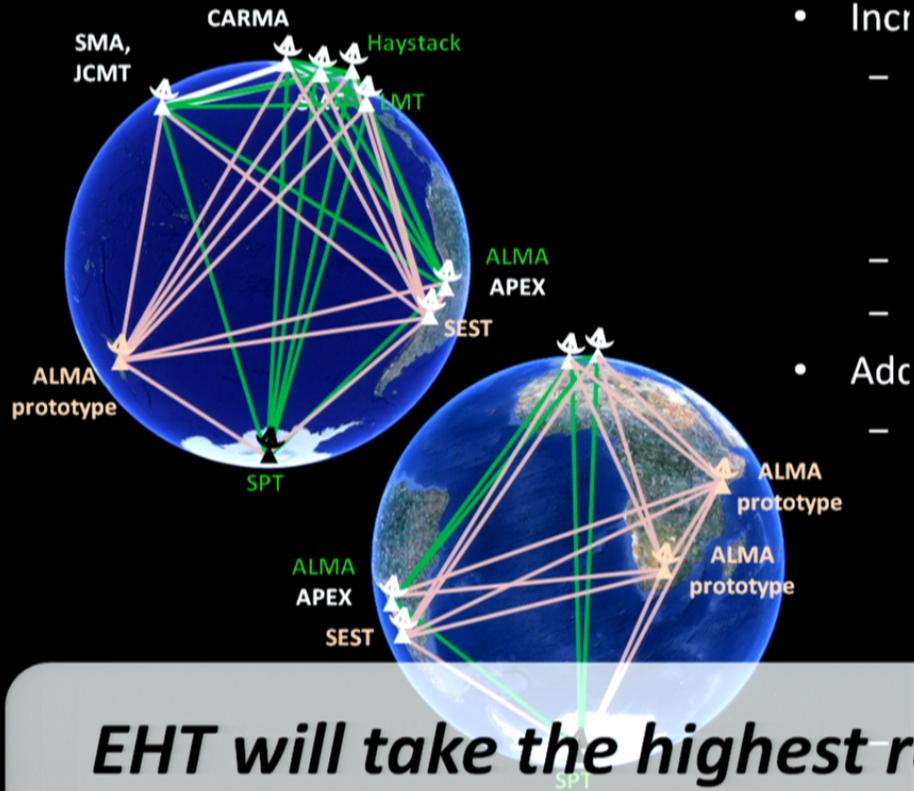
ALMA APEX

7



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Taking snapshots with the EHT

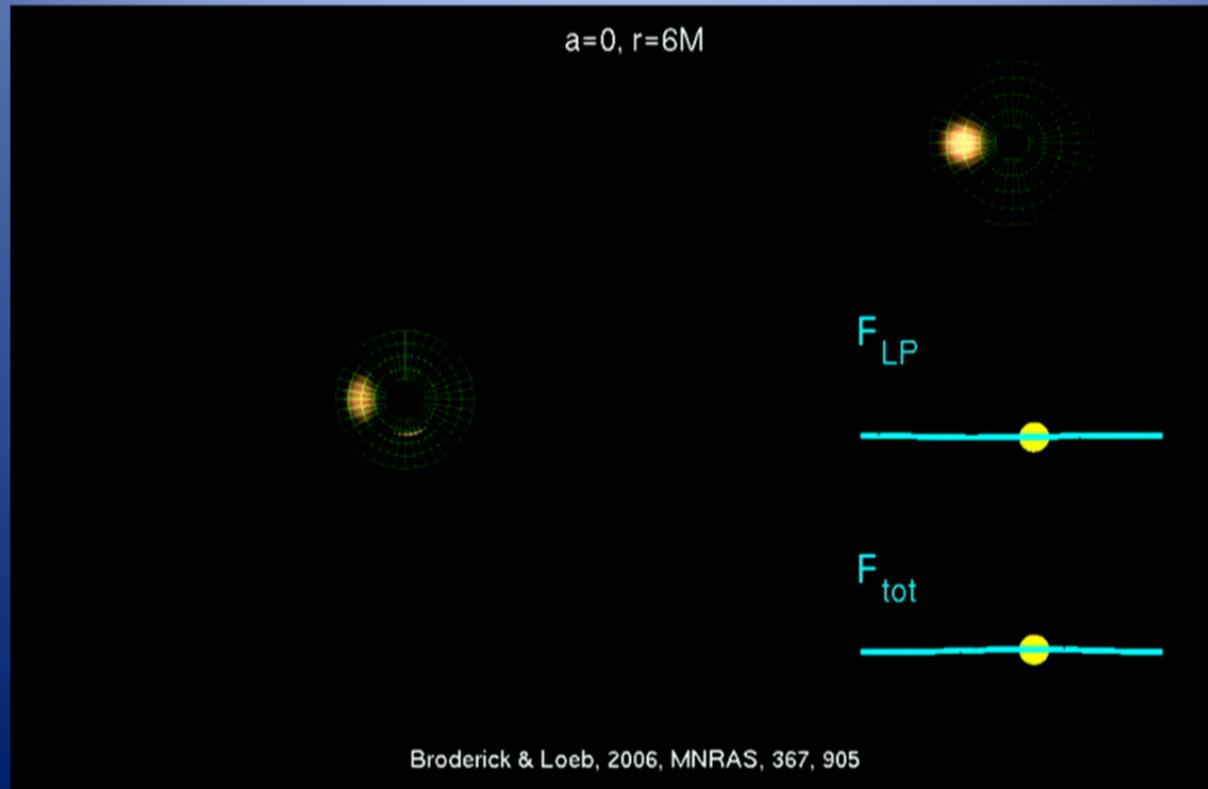


13

EHT will take the highest resolution images in the history of astronomy!

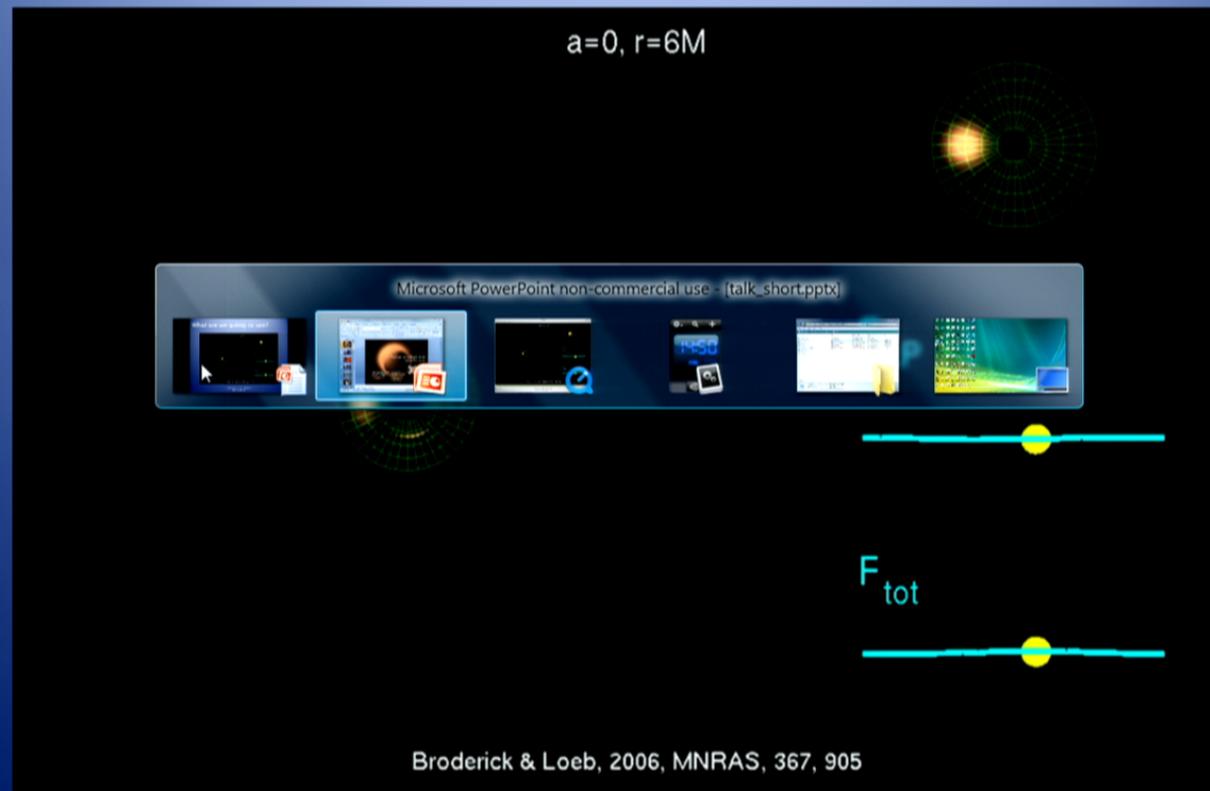
Conceptual Gems of Theoretical Physics,
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What are we going to see?



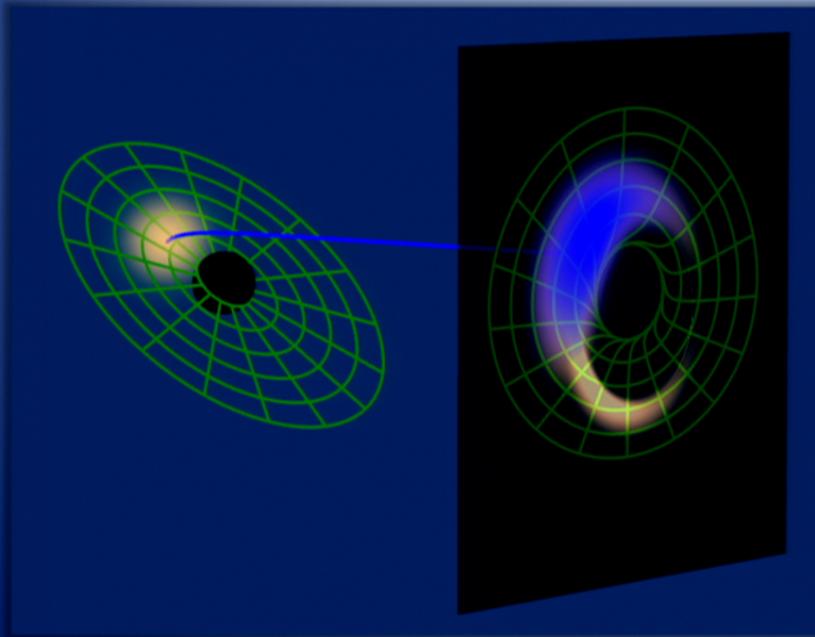
Conceptual Gems of Theoretical Physics,
Oct 14th 2011 @ PI

What are we going to see?



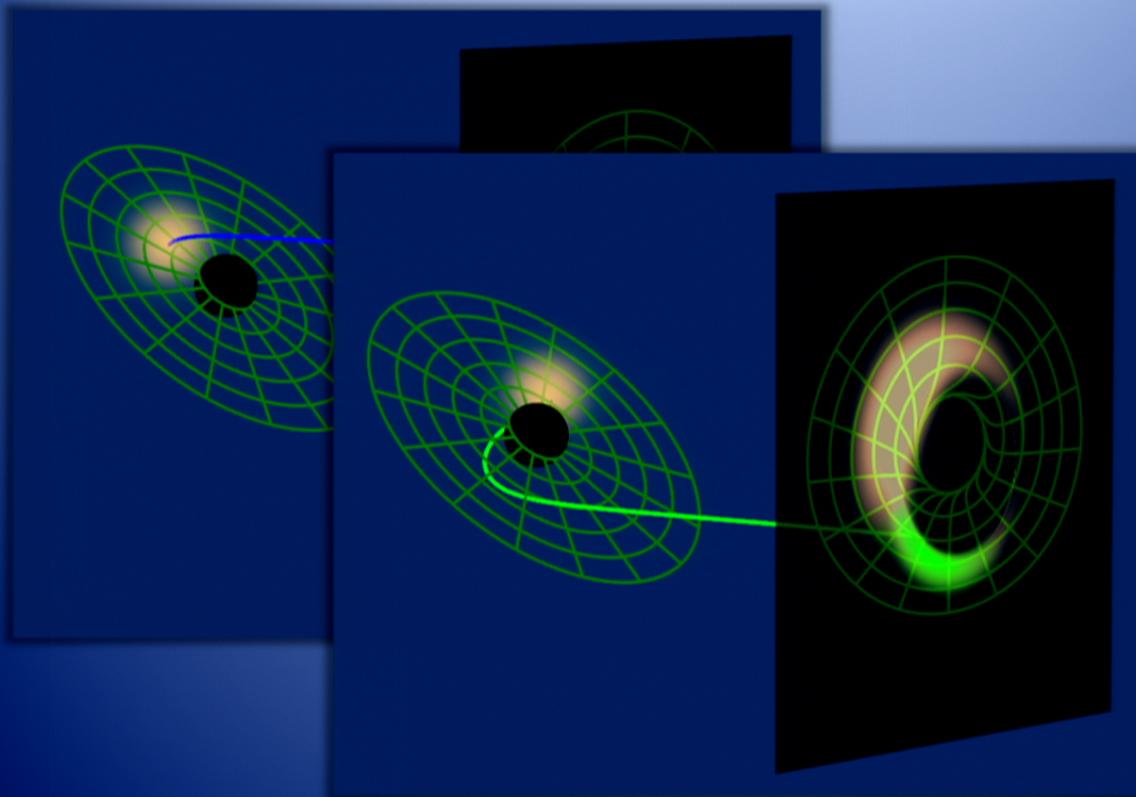
Conceptual Gems of Theoretical Physics,
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Anatomy of a spot



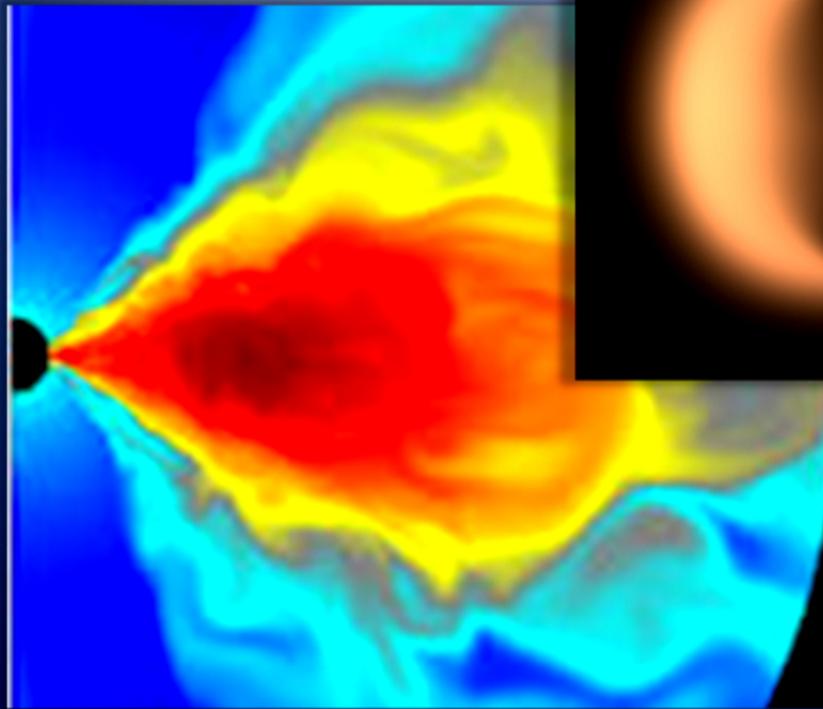
Conceptual Gems of Theoretical Physics,
Oct 14th 2011 @ PI

Anatomy of a spot



Conceptual Gems of Theoretical Physics,
Oct 14th 2011 @ PI

Imaging Accretion Flows



Low Spin

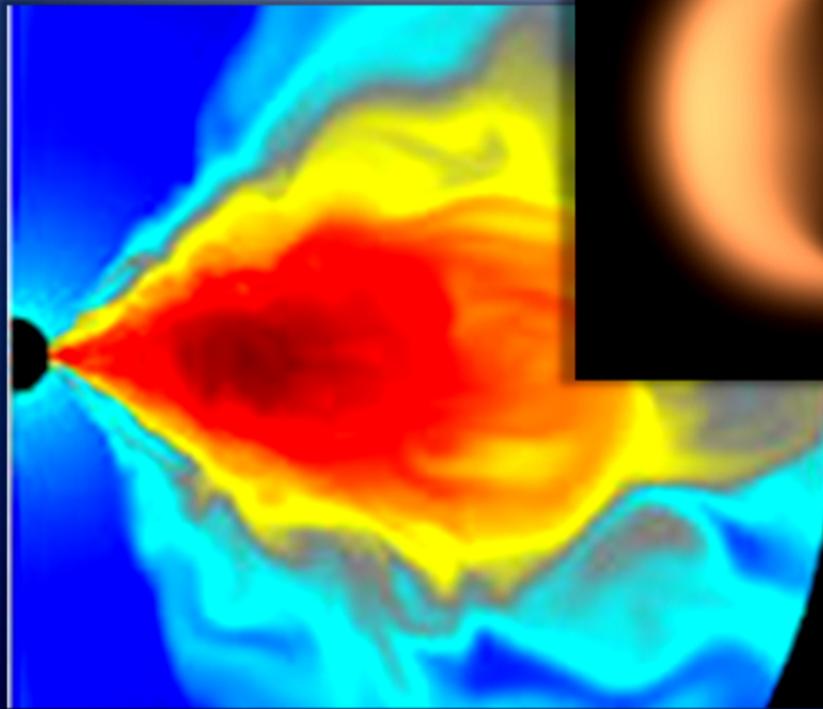


High Spin



Conceptual Gems of Theoretic
Oct 14th 2011 @ PI

Imaging Accretion Flows



Low Spin



High Spin



Conceptual Gems of Theoretic
Oct 14th 2011 @ PI

Varying the gastrophysics

Hot, Thick,
sub-Keplerian Disk



Hot, Thick,
Keplerian Disk



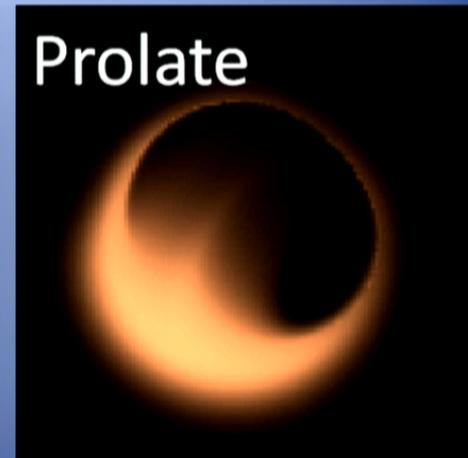
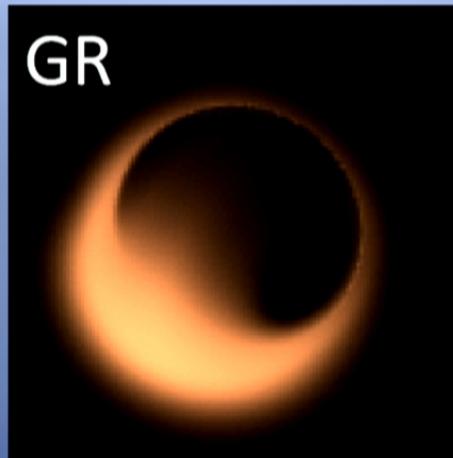
Bittner, AEB & Loeb (2012)

Cold, Thin
Keplerian Disk



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Varying gravity

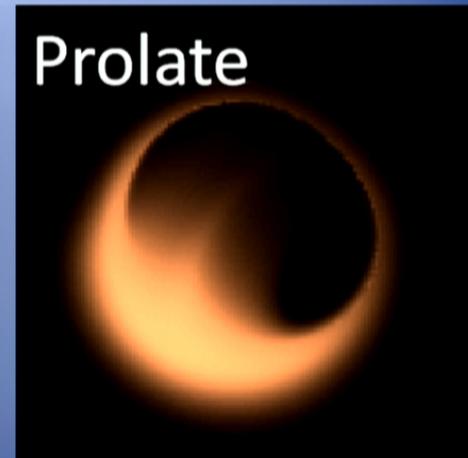
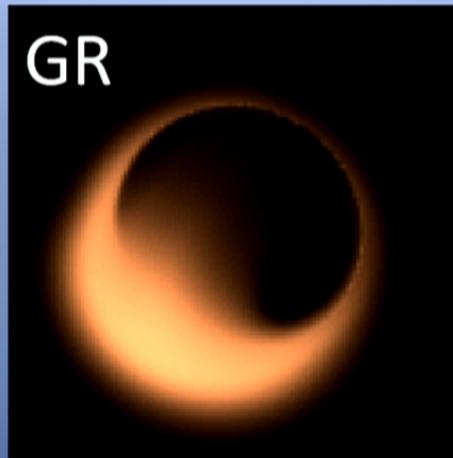


Can already be distinguished!

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Varying gravity



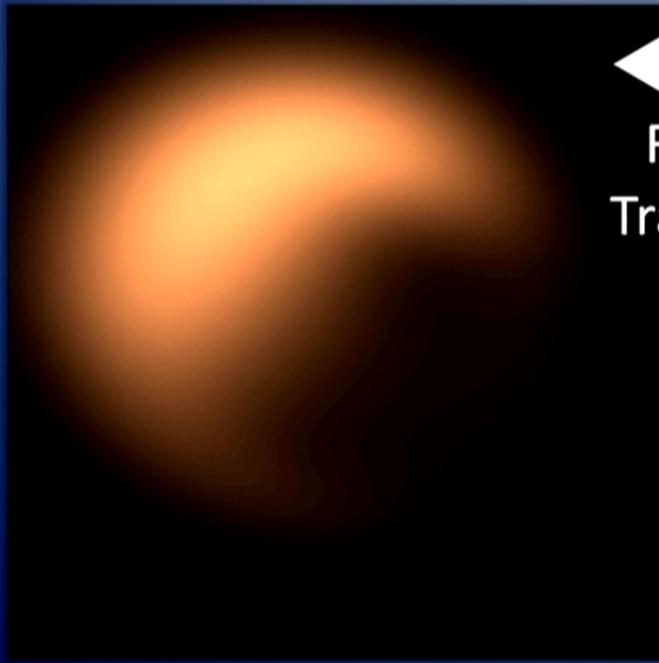
Can already be distinguished!

Encoded in images are important insights about strong gravity and extreme astrophysics!

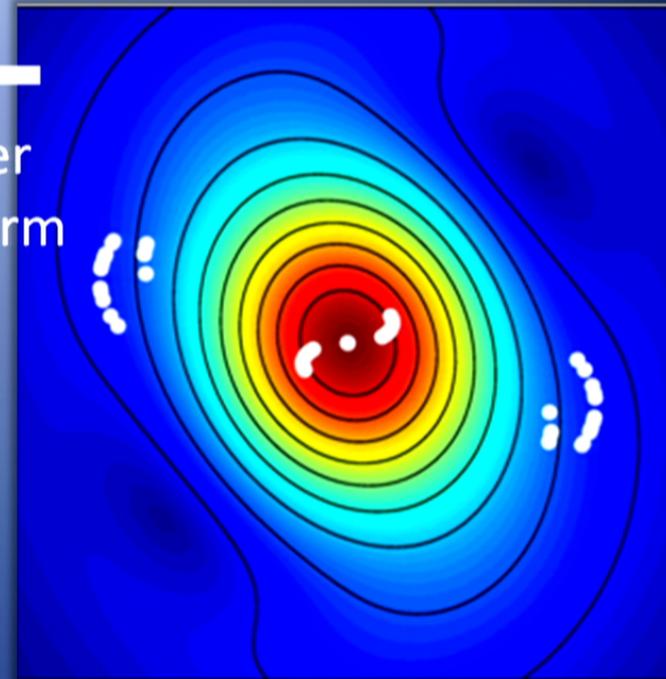
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Non-imaging image analysis!

Measured Image



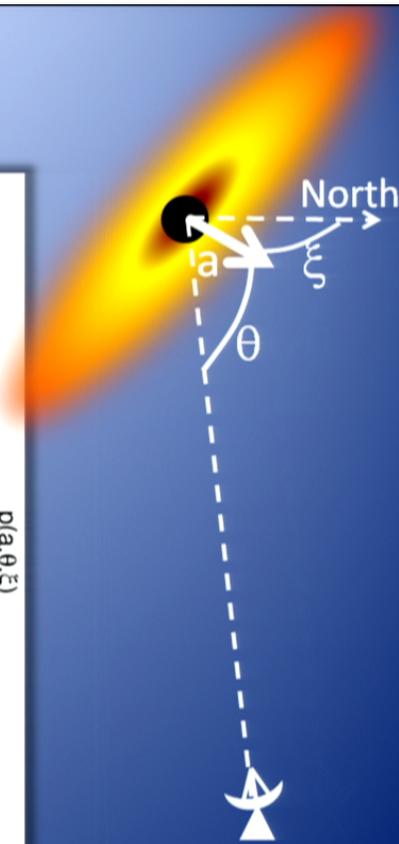
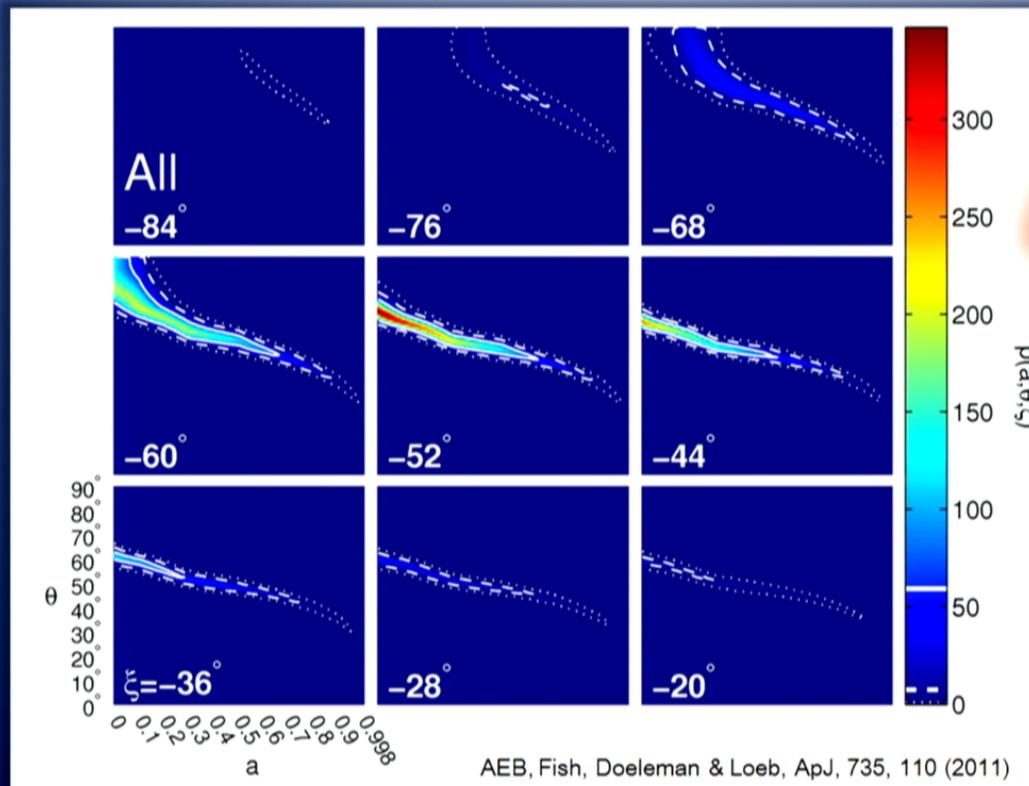
Measured Visibilities



←
Fourier
Transform

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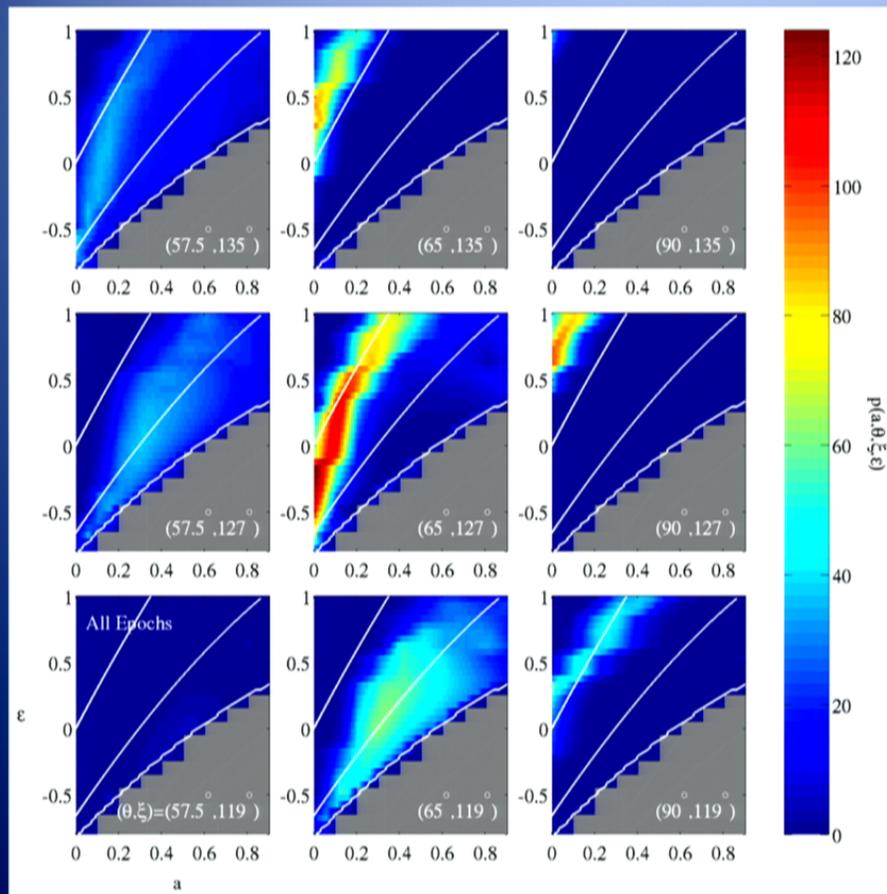
The Spin of Sgr A*!



$$a \sim 0^{+0.64+0.86}, \theta = 68^{+5+8}_{-20-28} \text{ deg.}, \xi = -52^{+17+33}_{-15-24} \text{ deg.}$$

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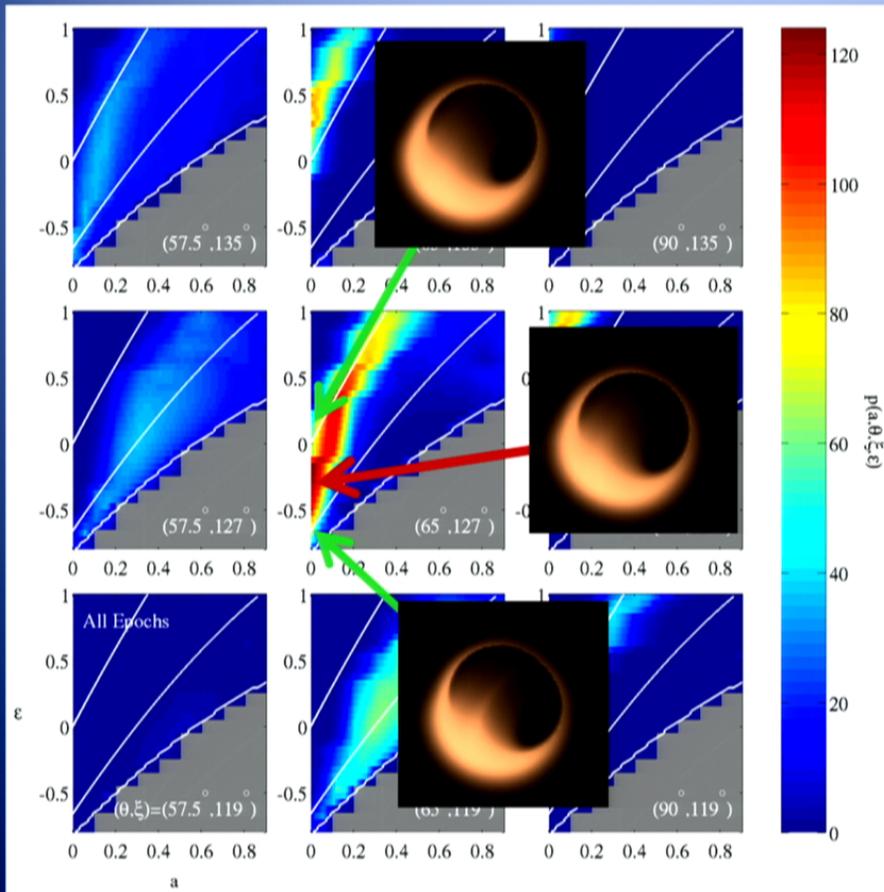
Testing general relativity



- Highly correlated 4-D parameter space!
- Wrong quadrupole (measured by ϵ)
- Already best fit model clearly has nonzero ϵ !

Johannsen, AEB, Psaltis & Loeb (2012) *Conceptual Gems of Theoretical Physics*, Oct 14th 2011 @ PI

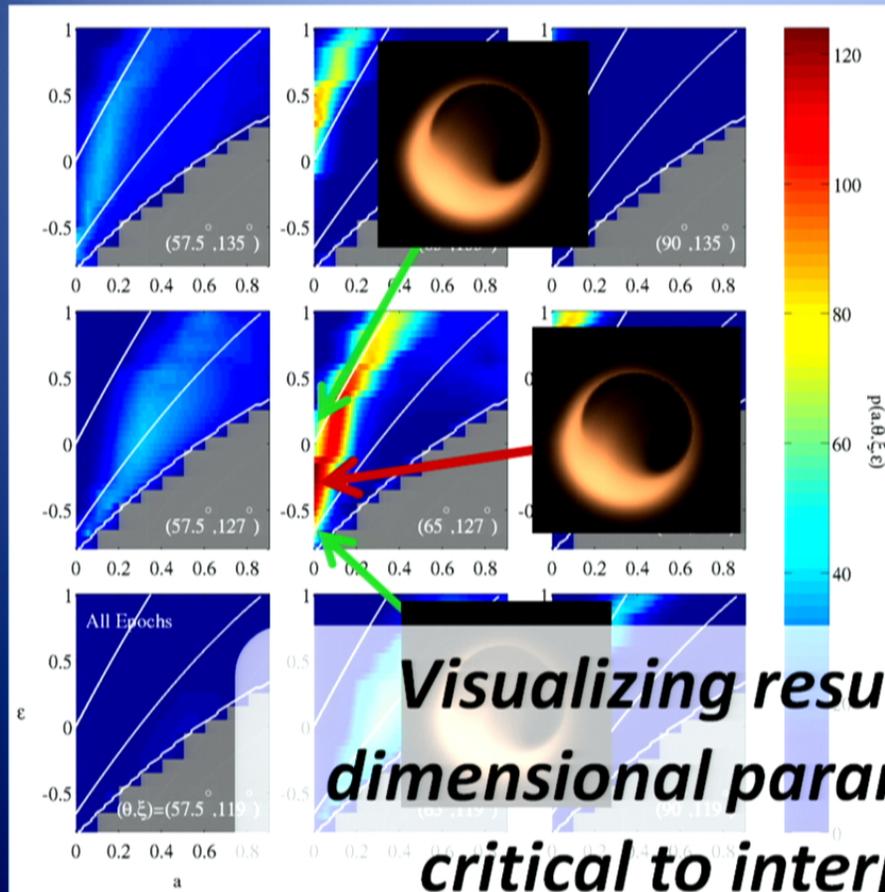
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Johannsen, AEB, Psaltis & Loeb (2012) Conceptual Gems of Theoretical Physics, Oct 14th 2011 @ PI

Testing general relativity

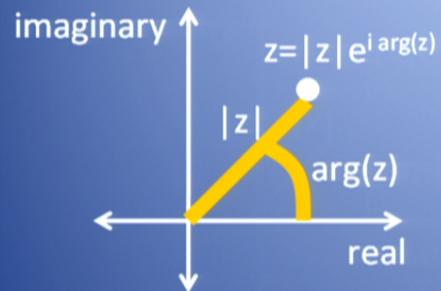


- Highly correlated 4-D parameter space!
- Wrong quadrupole (measured by ϵ)
- Already best fit model clearly has nonzero ϵ !

Visualizing results in high-dimensional parameter spaces critical to interpretation.

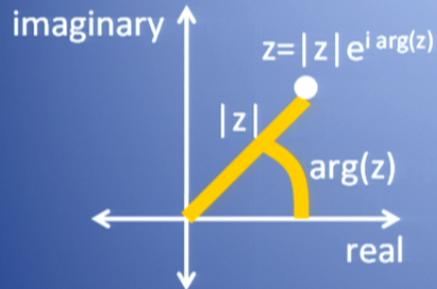
Johannsen, AEB, Psaltis & Loeb (2012) *Conceptual Gems of Theoretical Physics*, Oct 14th 2011 @ PI

What matters in an image: Complex visibilities



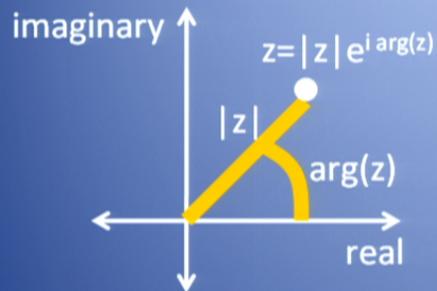
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What matters in an image: Complex visibilities

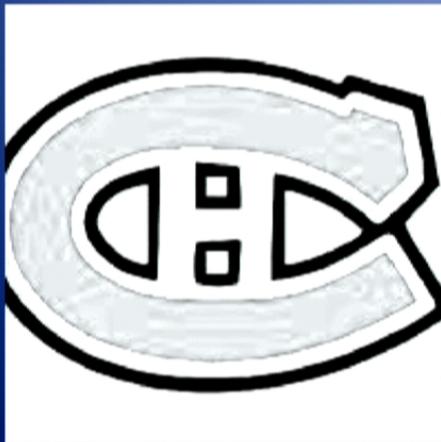


- $|V|$ is easiest to measure
- $\arg(V)$ is very hard to measure

What matters in an image: Complex visibilities

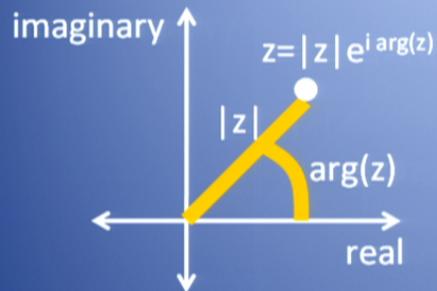


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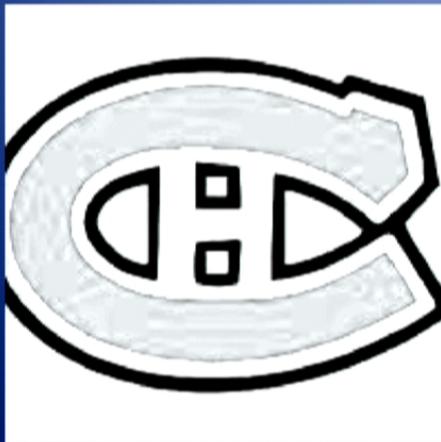


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What matters in an image: Complex visibilities



- $|V|$ is easiest to measure
- $\arg(V)$ is very hard to measure



$|V|$

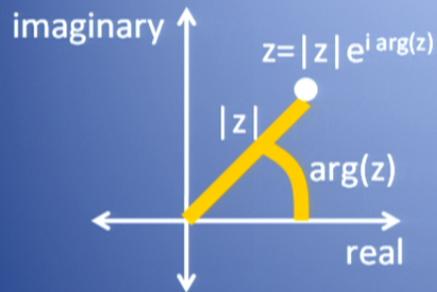


$\arg(V)$



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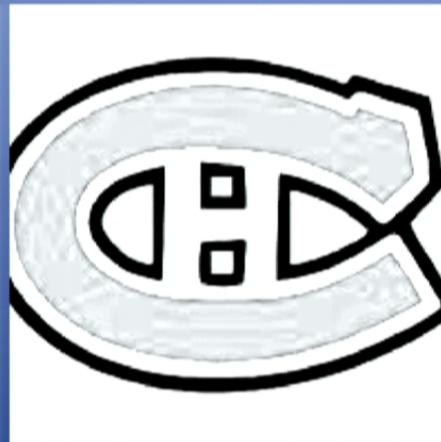
What matters in an image: Complex visibilities



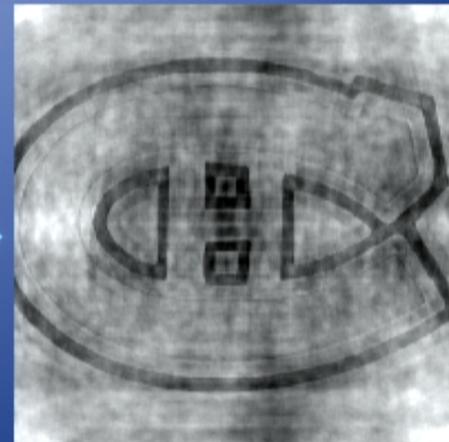
- $|V|$ is easiest to measure
- $\arg(V)$ is very hard to measure



$|V|$



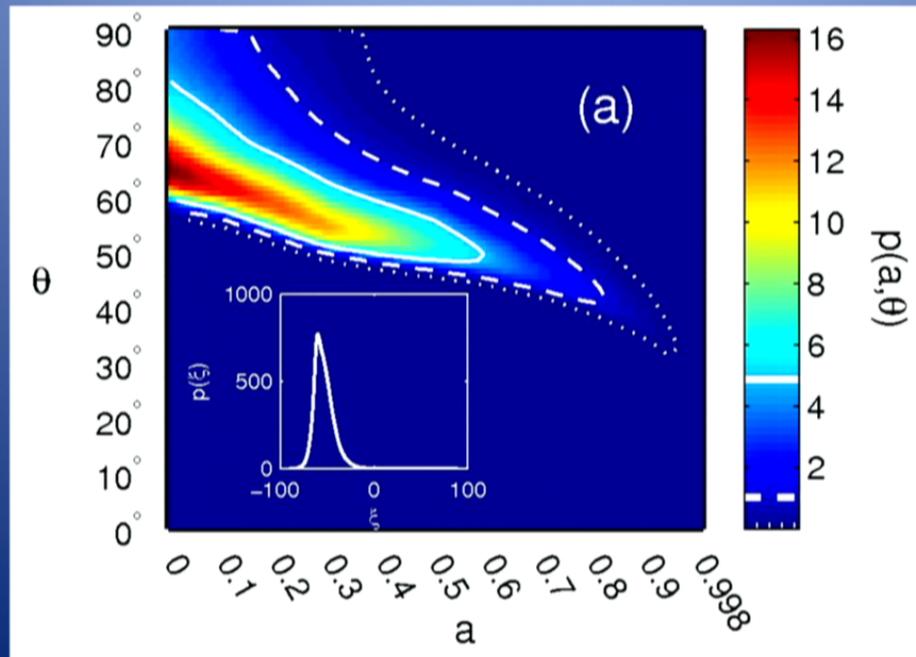
$\arg(V)$



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The power of $\arg(V)$!

$|V|$ Only



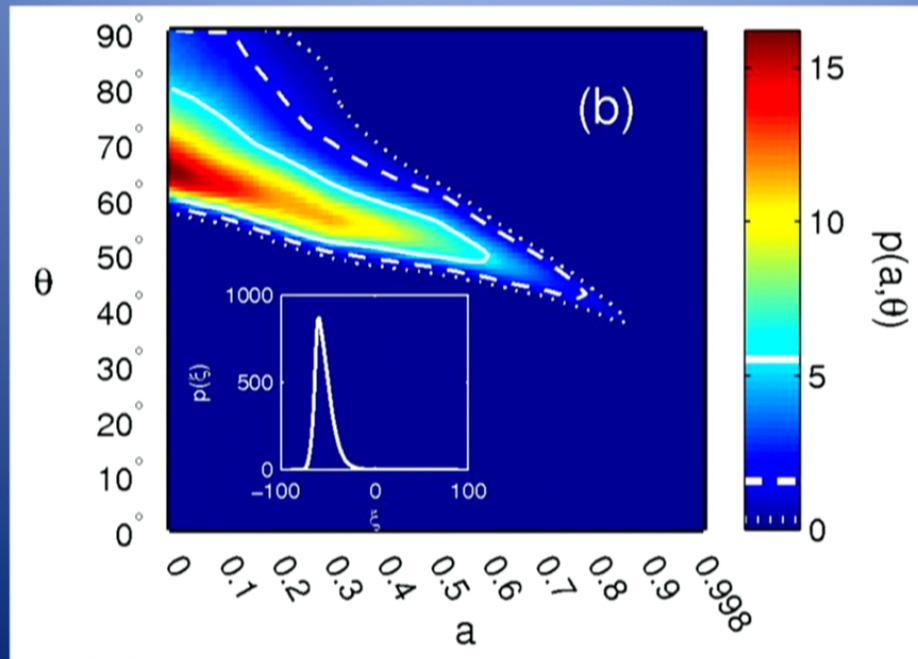
AEB, Fish, Doeleman & Loeb, ApJ, 738, 38 (2011)

Conceptual Gems of Theoretical Physics,

Oct 14th 2011 @ PI

The power of $\arg(V)$!

$|V|$ + Fish et al. (2011)

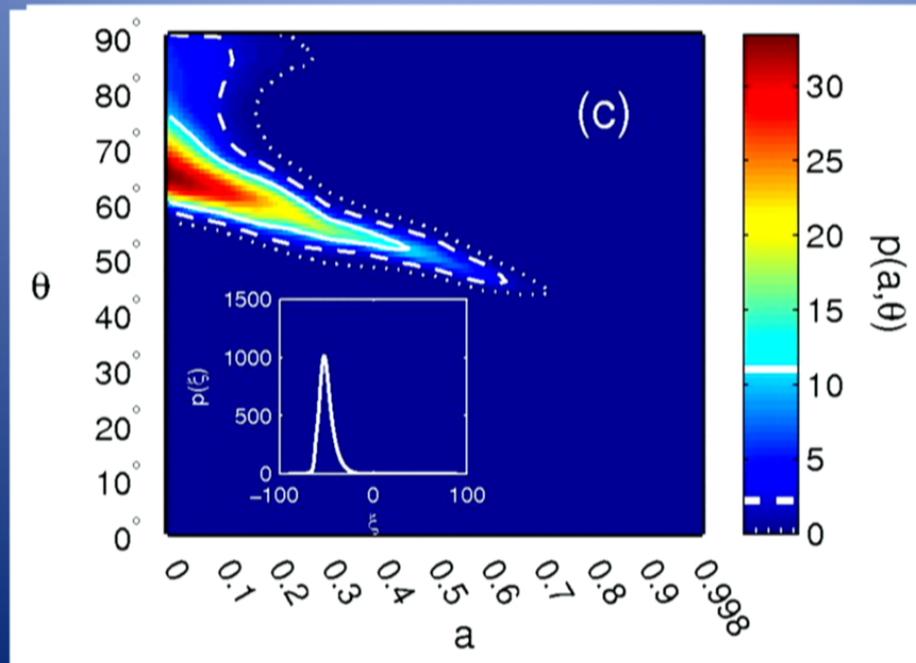


AEB, Fish, Doeleman & Loeb, ApJ, 738, 38 (2011)

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The power of $\arg(V)$!

$|V|$ & $12.6^\circ \pm 5^\circ$ on SMT-Hawaii-CARMA



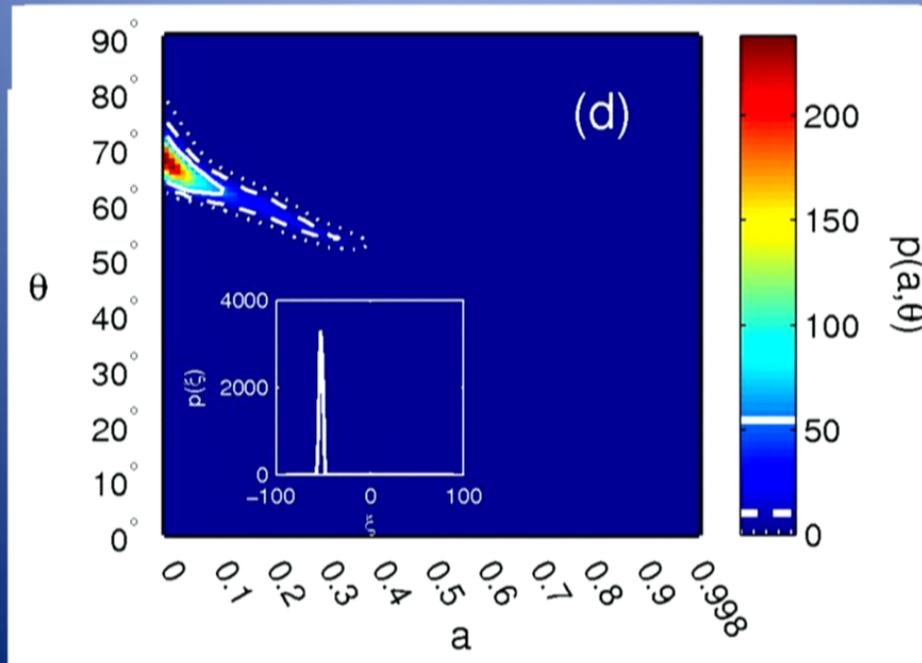
AEB, Fish, Doeleman & Loeb, ApJ, 738, 38 (2011)

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The power of $\arg(V)$!

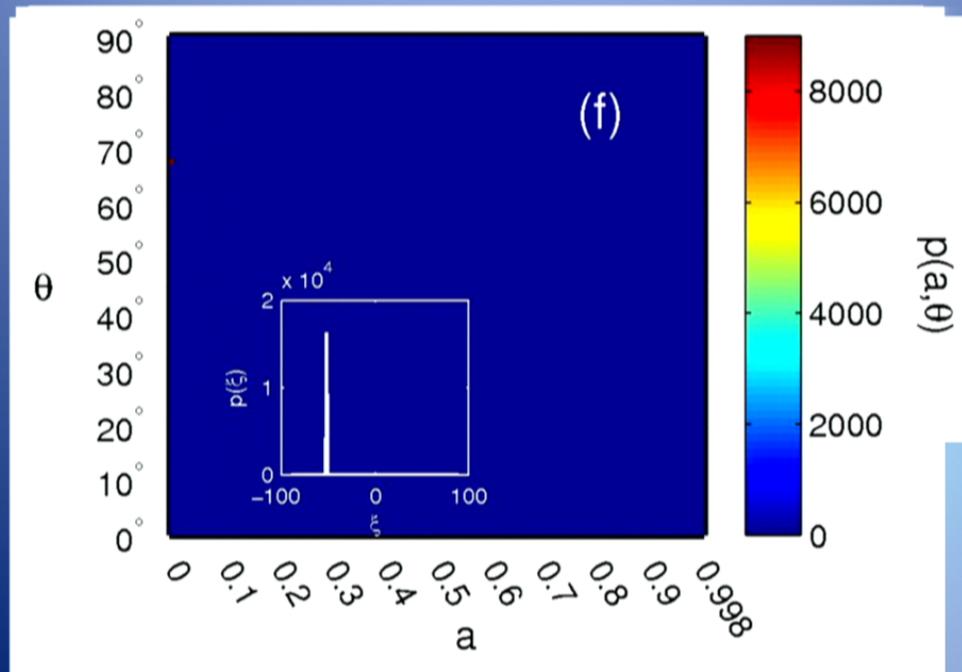
$|V|$ & Anticipated Precision on all triangles in an SMT-Hawaii-CARMA-APEX



AEB, Fish, Doeleman & Loeb, ApJ, 738, 38 (2011)
Conceptual Gems of Theoretical Physics,
Oct 14th 2011 @ PI

The power of $\arg(V)$!

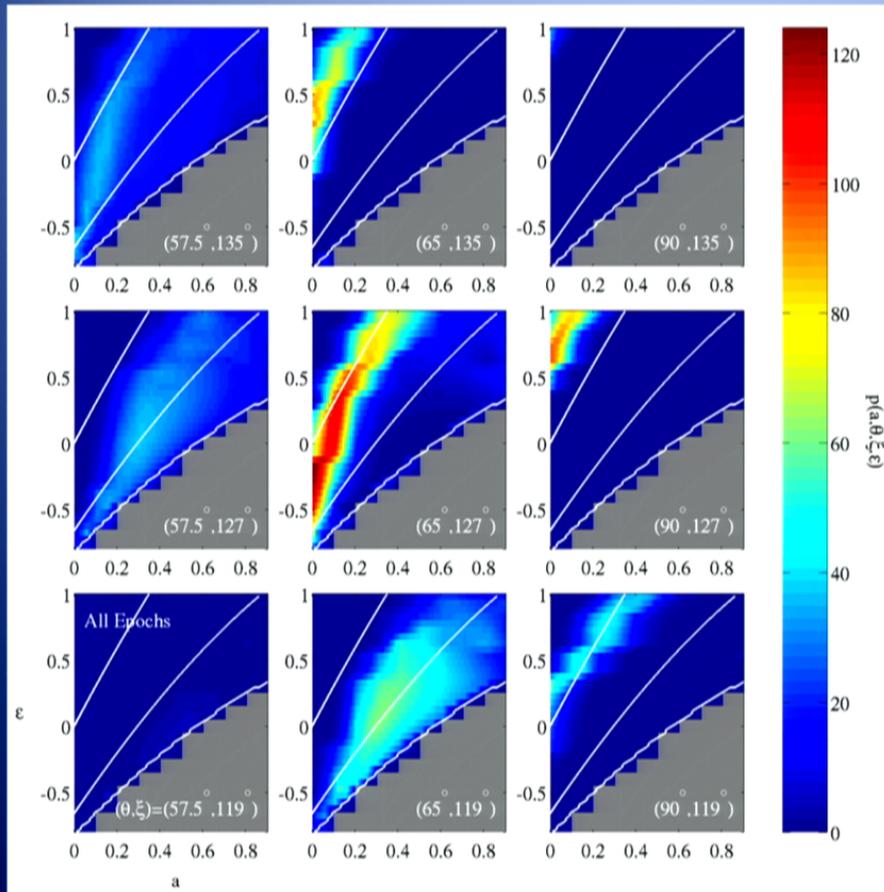
$|V|$ & Anticipated Precision on all triangles
in an SMT-Hawaii-CARMA-ALMA10-LMT



AEB, Fish, Doeleman & Loeb, ApJ, 738, 38 (2011)
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Putting Einstein to the test!

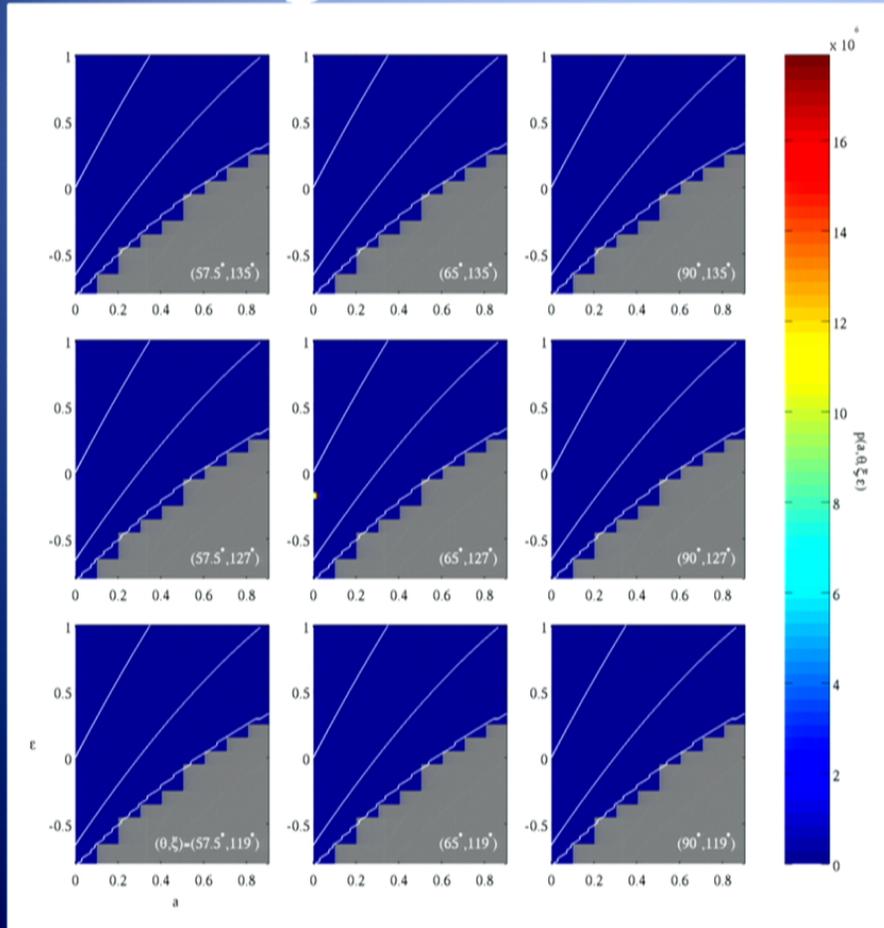


- Bandwidth: 1GHz
- Observatories
 - SMT
 - JCMT, SMA (LO)
 - CARMA (2 ind. dishes)
- $|V|$ only

– JCMT, SMA (LO)
 – CARMA (2 ind. dishes)
 $|V|$ only

Johannsen, AEB, Psaltis & Loeb (2011) Conceptual Gems of Theoretical Physics, Oct 14th 2011 @ PI

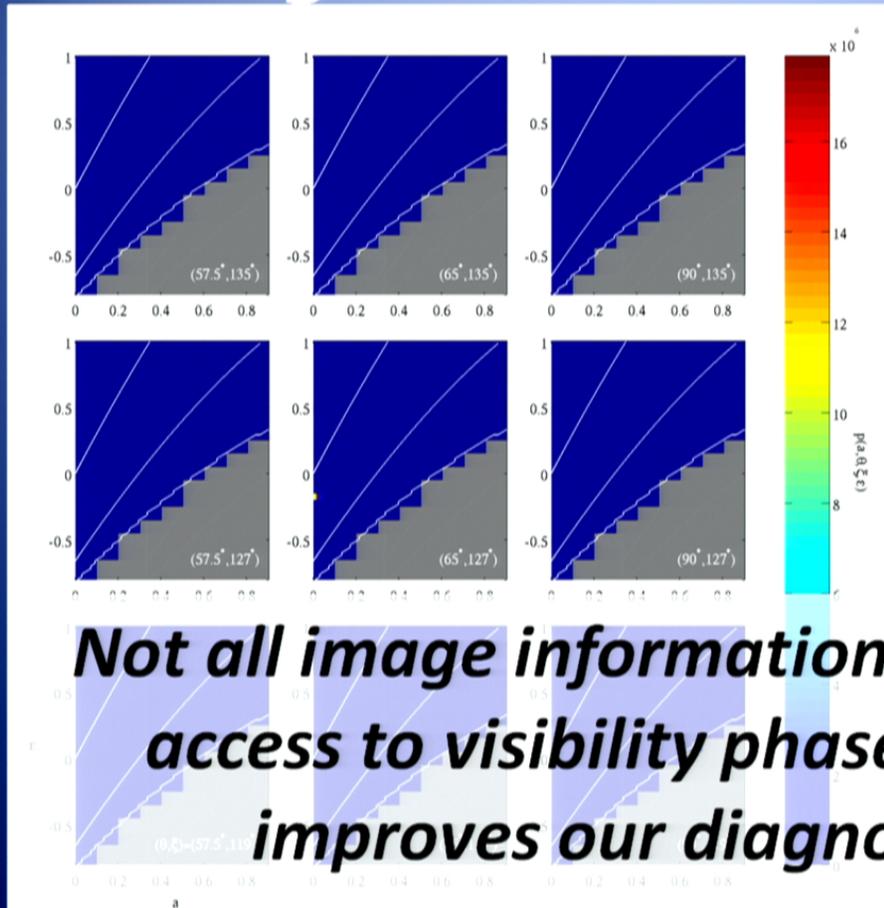
Putting Einstein to the test!



- Bandwidth: 4GHz
- Observatories
 - SMT
 - Phased Hawaii
 - Phased CARMA (8)
 - Phased ALMA (10)
- $|V|$
- **+ Closure Phases**

Johansen, AEB, Psaltis & Loeb (2011) Conceptual Demos of Theoretical Physics, Oct 14th 2011 @ PI

Putting Einstein to the test!

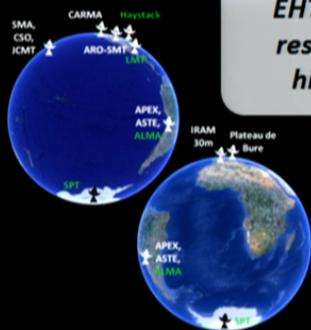


- Bandwidth: 4GHz
- Observatories
 - SMT
 - Phased Hawaii
 - Phased CARMA (8)
 - Phased ALMA (10)
- $|V|$
- **+ Closure Phases**

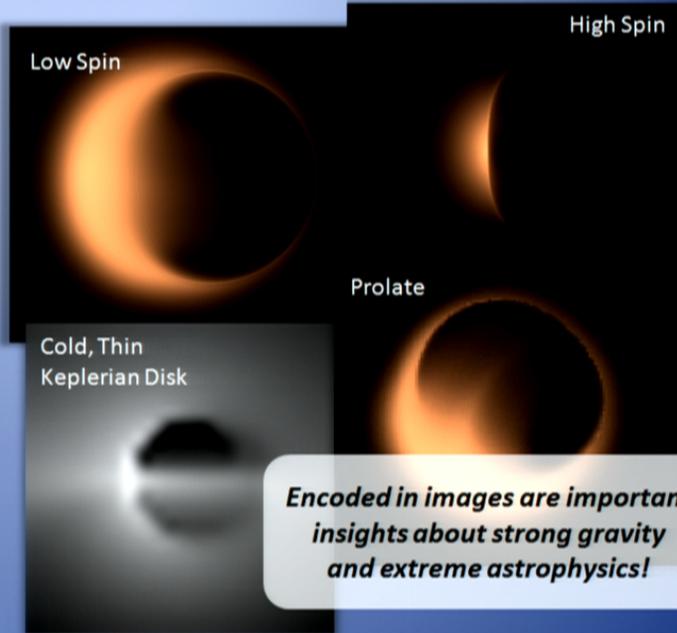
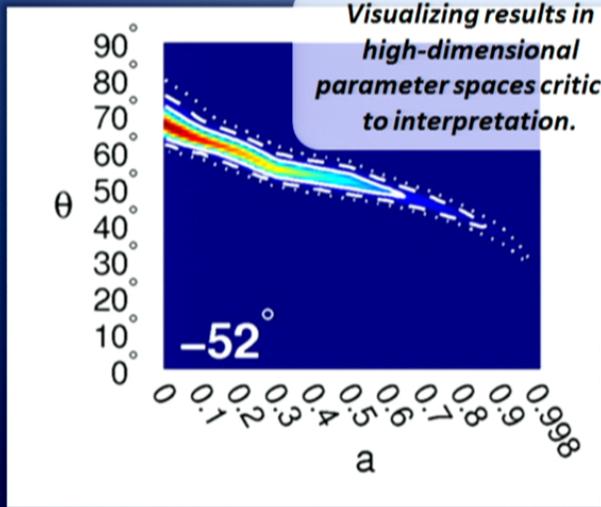
***Not all image information is created equal;
access to visibility phases dramatically
improves our diagnostic ability!***

Johannsen, AEB, Psaltis & Loeb (2011) *Conceptual Demos of Theoretical Physics*, Oct 14th 2011 @ PI

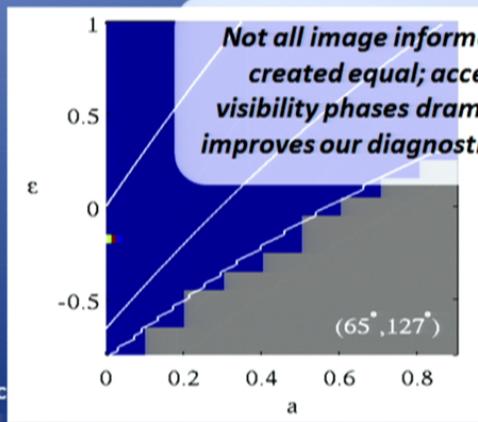
Summary



EHT will take the highest resolution images in the history of astronomy!



Encoded in images are important insights about strong gravity and extreme astrophysics!



...ms of Theoretic
14th 2011 @ PI

