Title: The Event Horizon Telescope: Imaging Black Hole Horizons

Date: Jan 31, 2011 11:30 AM

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Abstract: Black holes are associated with a variety of the most extreme and counter-intuitive phenomena in astronomy and physics. However, despite the passage of nearly 40 years since the discovery of the first strong black hole candidate, we have scant evidence that general relativity provides an accurate description of gravity in the immediate vicinity of astrophysical black holes. Over the next few years this will change dramatically.

The Event Horizon Telescope: Imaging Black Hole Horizons

Avery E Broderick

CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique theorique

Many Thanks!

MIT HAYSTACK OBSERVATORY

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Vincent Fish
Roger Cappallo
Dan Smythe
Mike Titus
Alan Whitney

THE UNIVERSITY OF ARIZONA

Steward Observatory

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CARMA
Combined Array for Research in Millimeter-Wave Astronomy

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What is a “Black Hole”?

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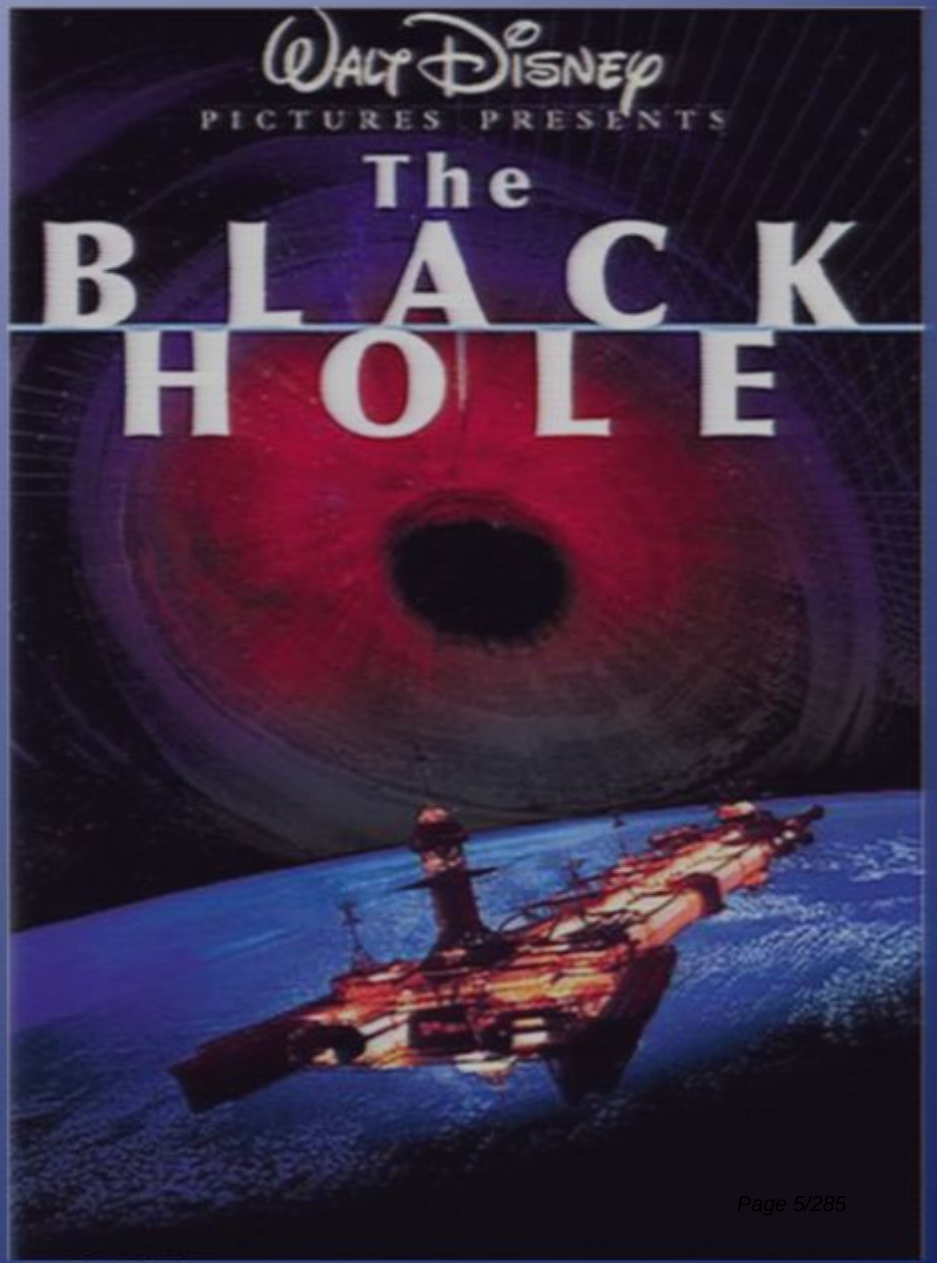
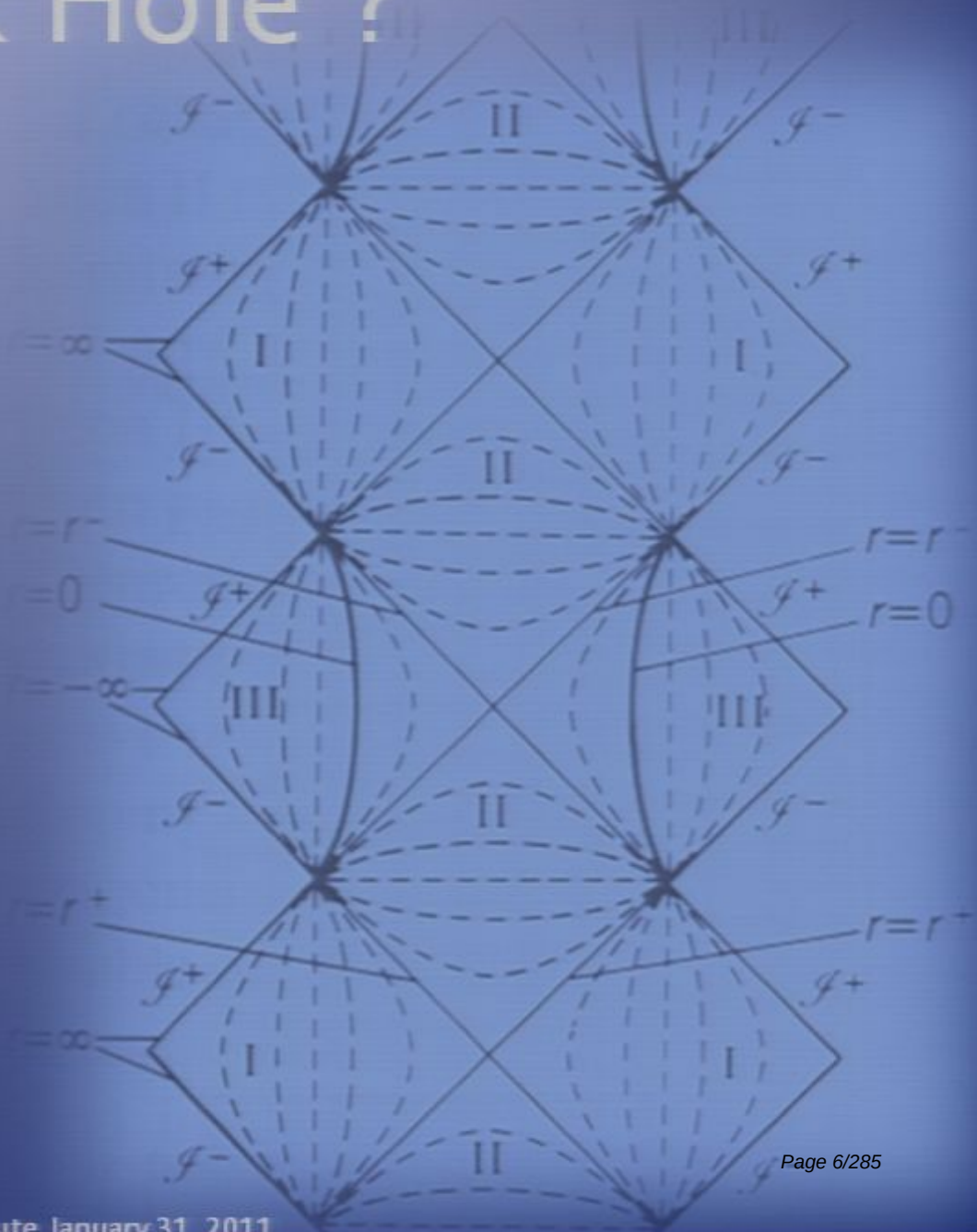


What is a "Black Hole"?

- Object with a compact horizon
- No Hair Theorem:
  All physical vacuum solutions
  asymptote to Kerr-Newman
  → (M,a,Q)



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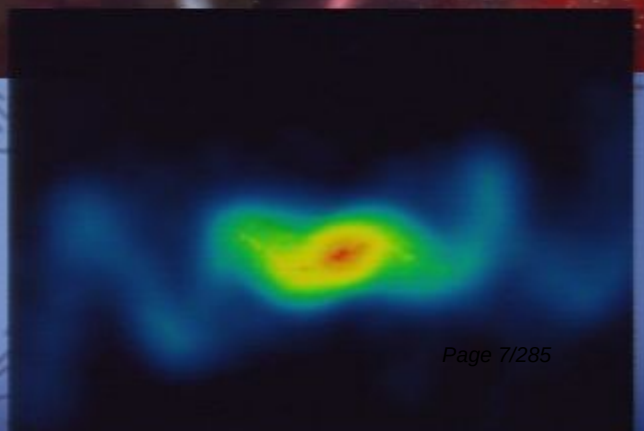

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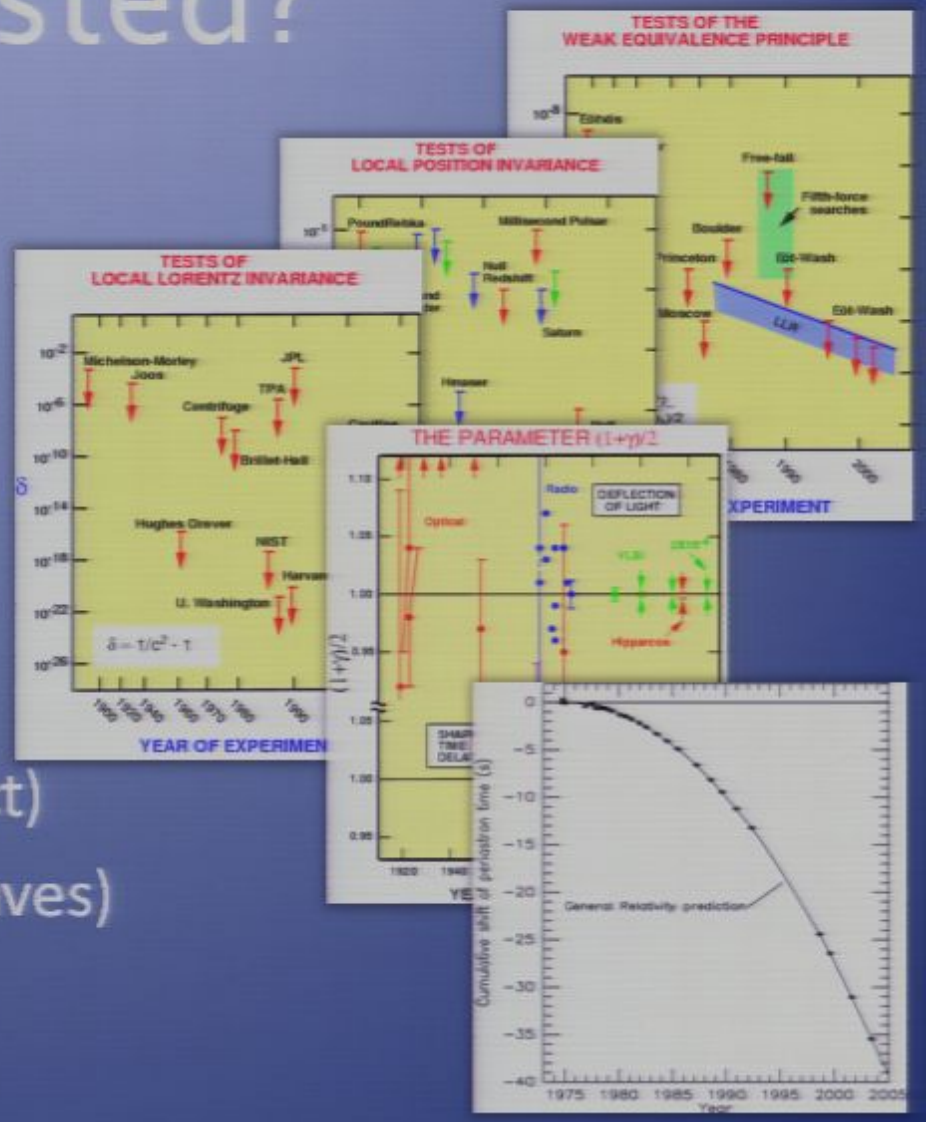
Testing GR using astrophysical hair

Hasn't GR *been* tested?

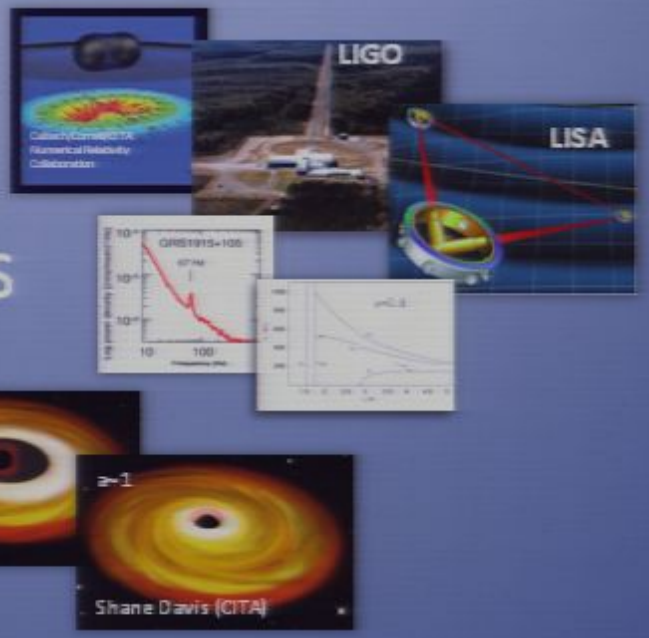
- Perihelion shift of Mercury
- Gravitational lensing of stars
- Gravitational redshift
- Shapiro time delay
- Relativistic geodetic precession
- Lunar-laser ranging (Nordtvedt effect)
- Hulse-Taylor pulsar (gravitational waves)

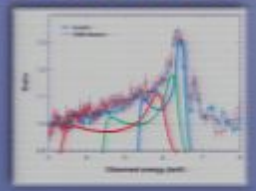
...



Strong Field Probes

- Compact Object Mergers
- Quasi-periodic Oscillations
- Iron Kα lines
- X-ray Binary Spectra





Strong Field Probes

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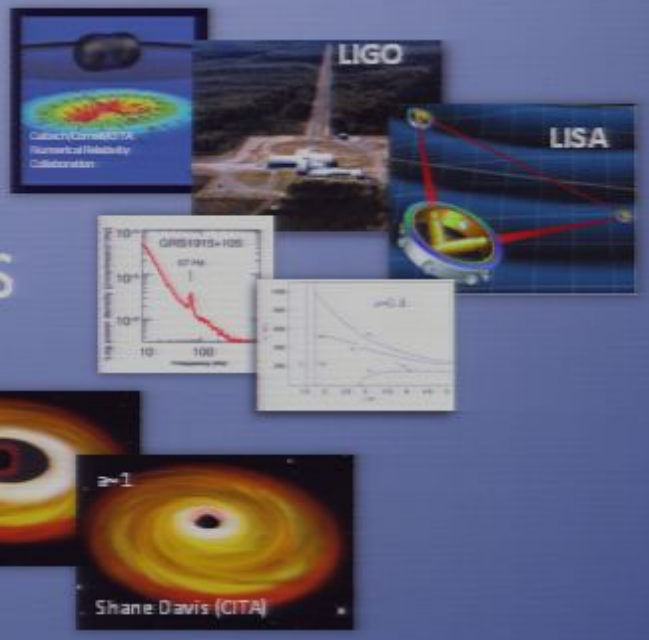
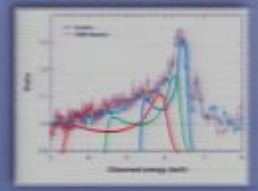
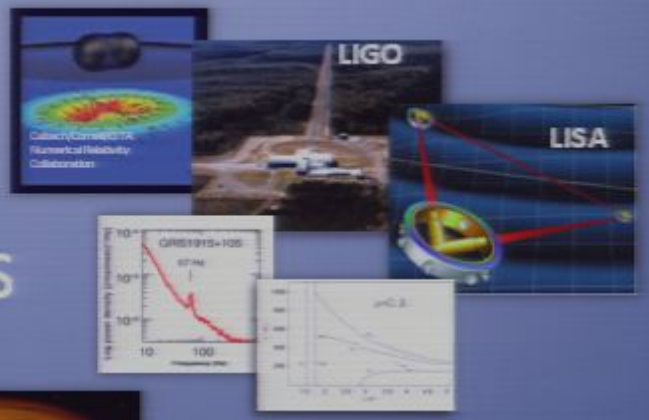
- Do black holes exist?

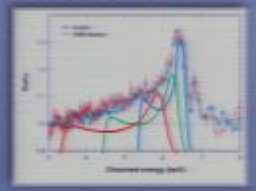


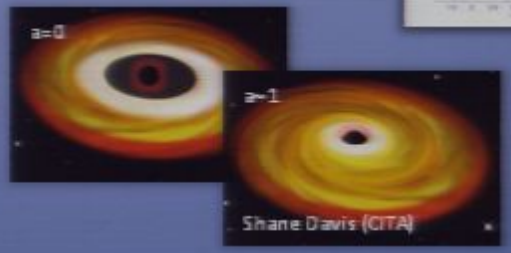


Strong Field Probes

- Compact Object Mergers
- Quasi-periodic Oscillations
- Iron Kα lines
- X-ray Binary Spectra
- Do black holes exist?
  - What else could it be?



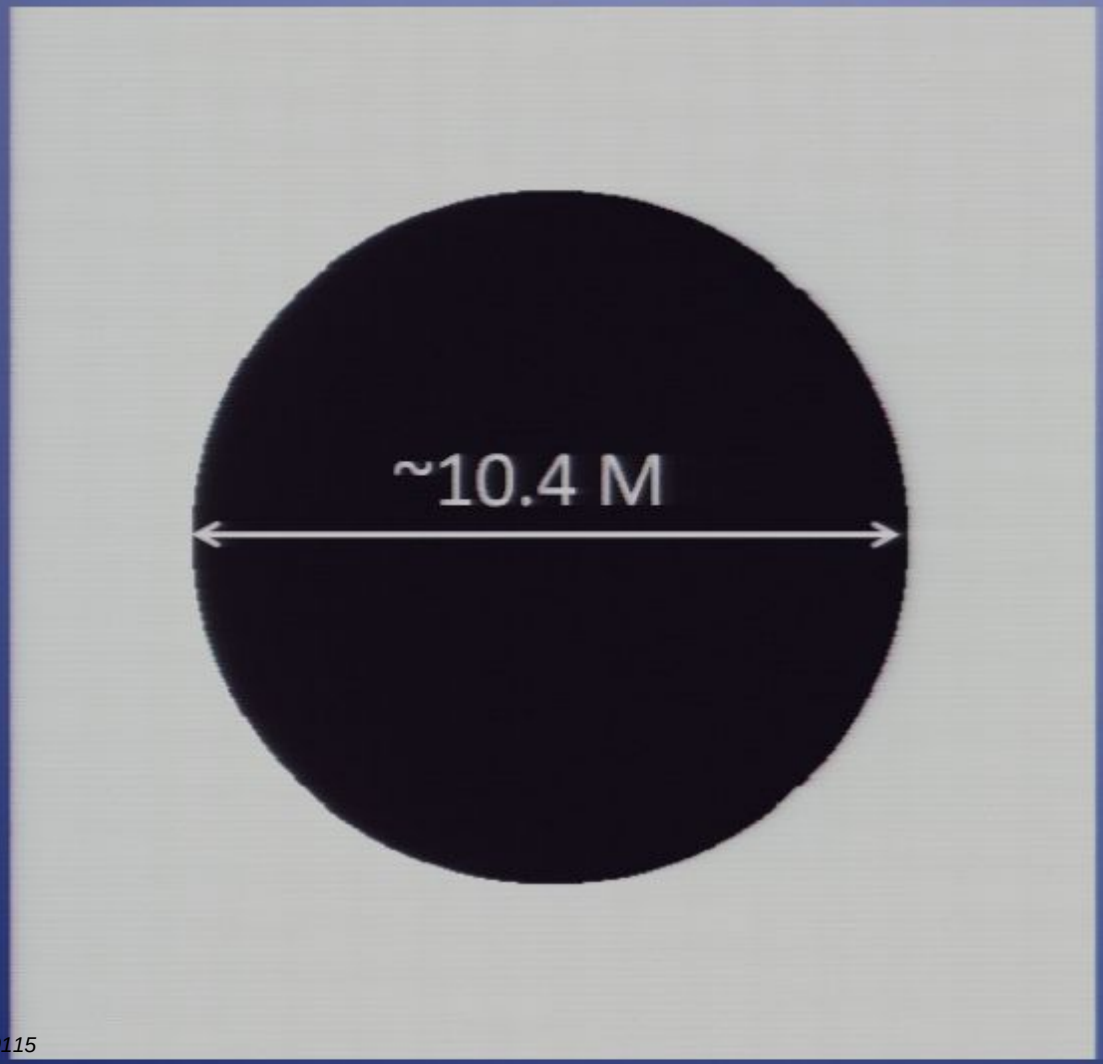


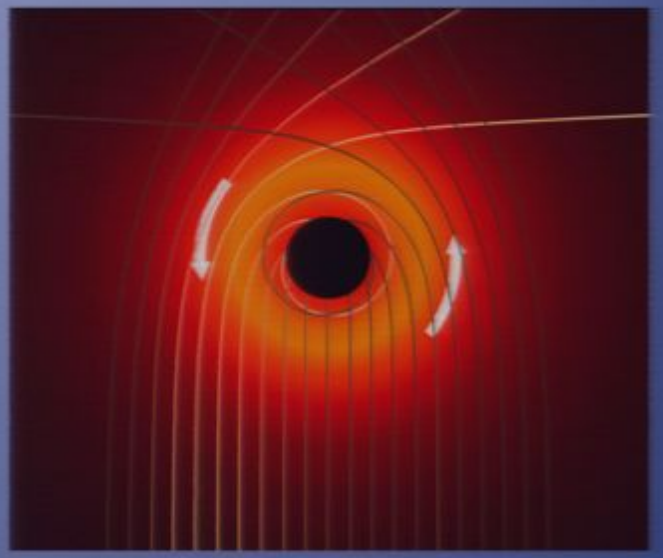


Getting Some Answers!

- What and How
- Generating images and taking BH portraits
- Horizons do exist!
- Testing Kerr with spots
- The Black Hole's retinue
- Conclusions

How big is a black hole?





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$$\frac{GM_{\text{Sun}}}{c^2} \approx 1.5\,\text{km}$$

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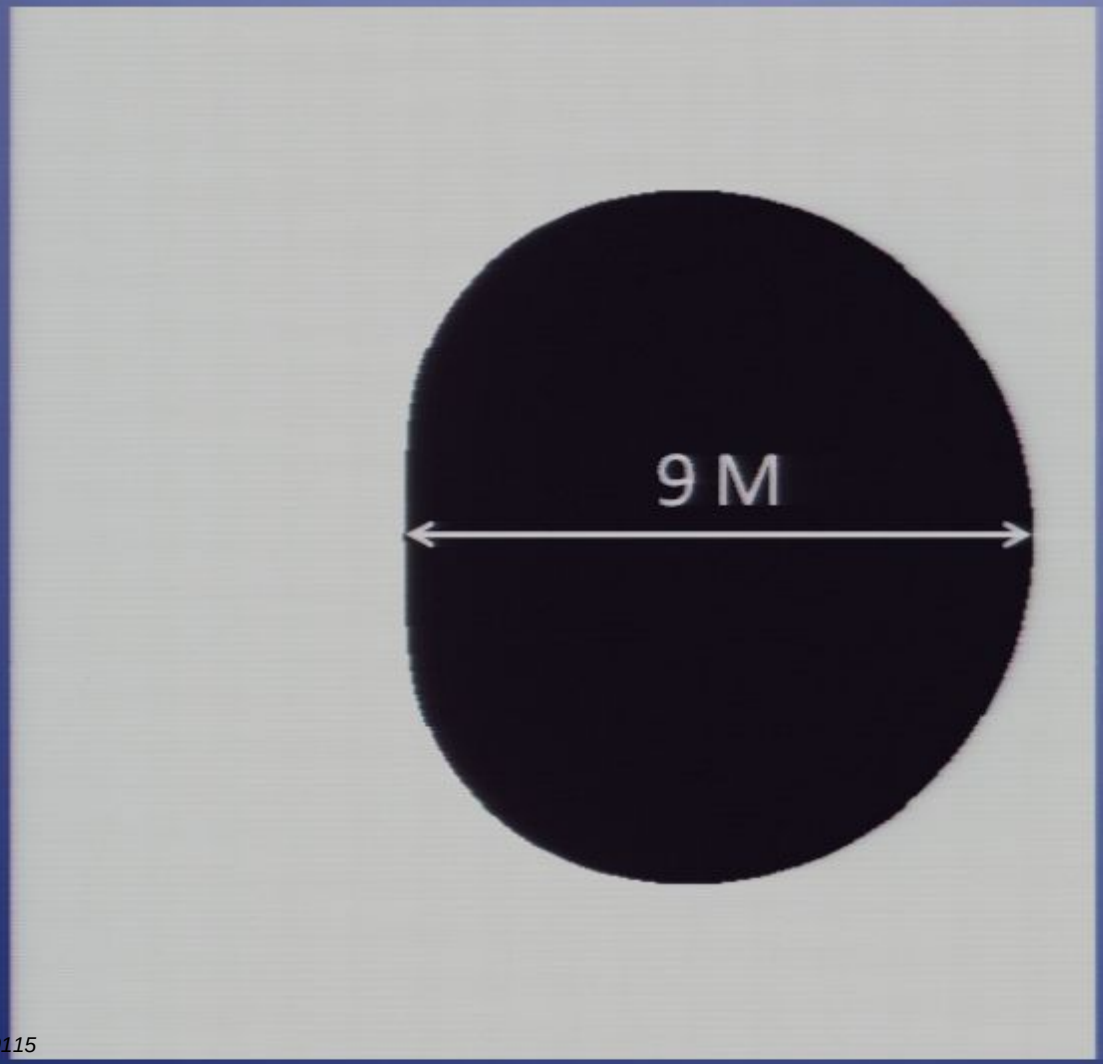

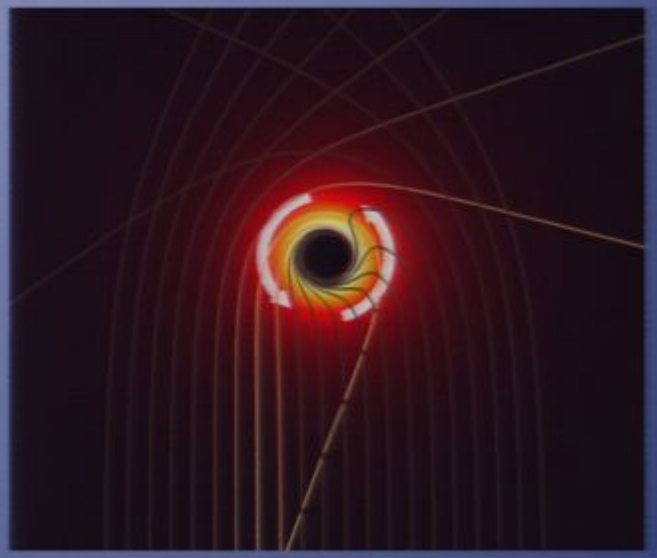

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	M (M_{Sun})	D	mm-flux	θ_a
Sgr A*	4.3×10^6	8.3 kpc	3 Jy	55 μas
M87*	6.6×10^9	17.9 Mpc	2 Jy	40 μas
M31*	1.4×10^8	728 kpc	30 mJy	20 μas
M60*	2.1×10^9	16.5 Mpc	30 mJy	13 μas
NGC 3115	9.6×10^8	10.2 Mpc	<0.4 Jy	10 μas
M84*	1.5×10^9	17 Mpc	0.1 Jy	10 μas
J1118+480	6.8	2 kpc	3 ms	0.4 nas!!!

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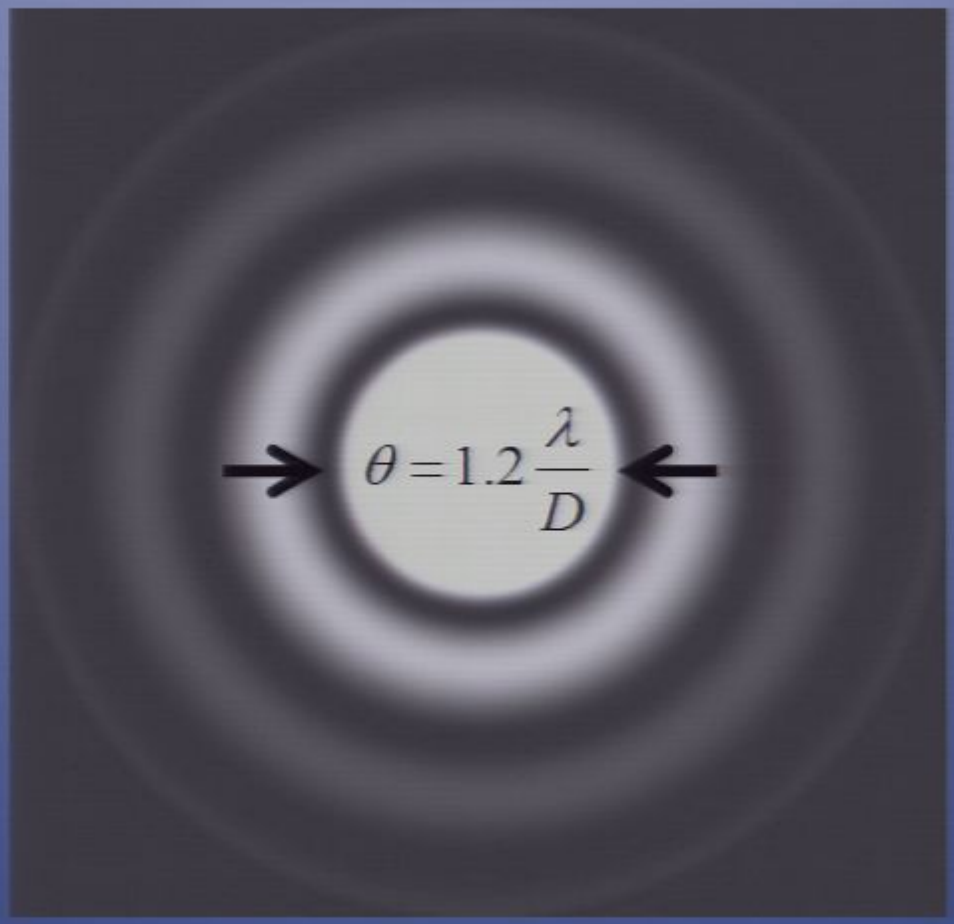
What and How

Limiting Resolution: Diffraction



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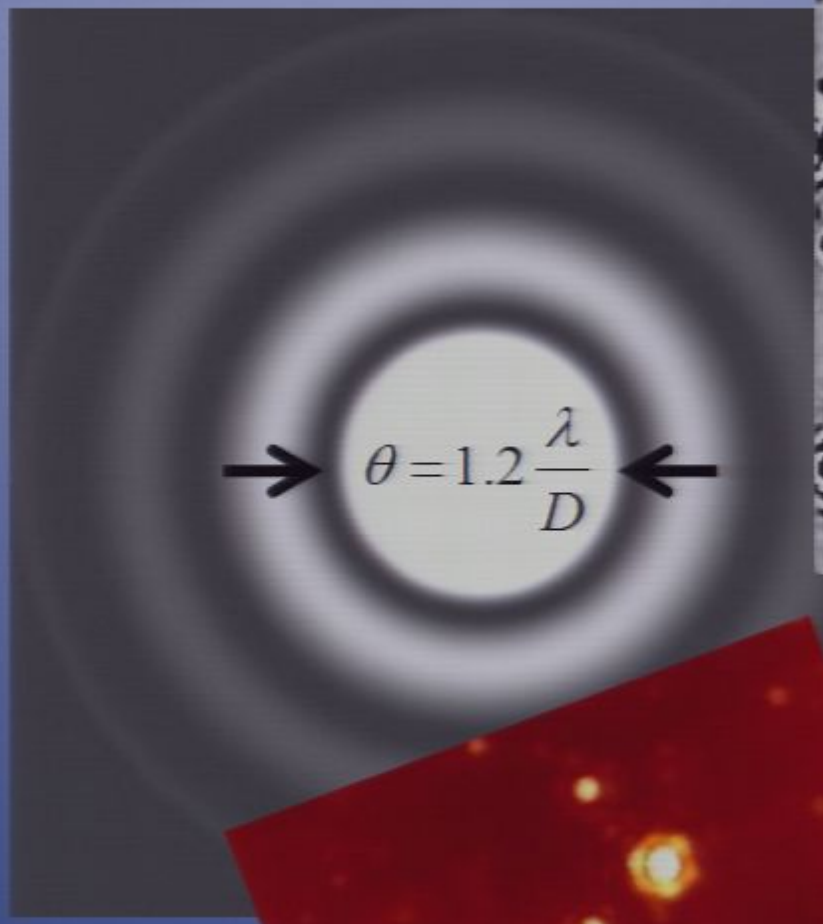

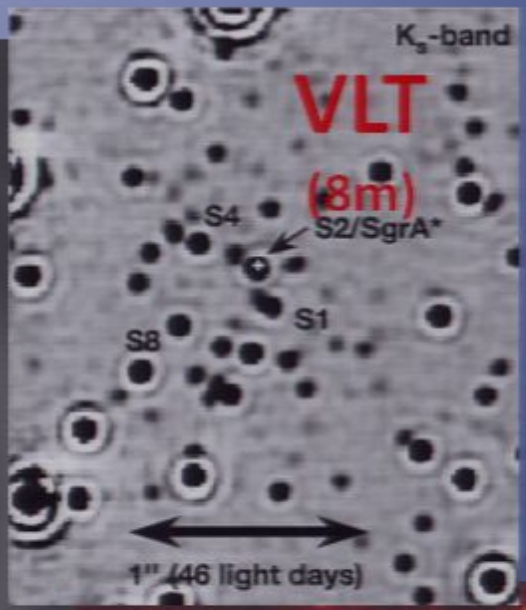

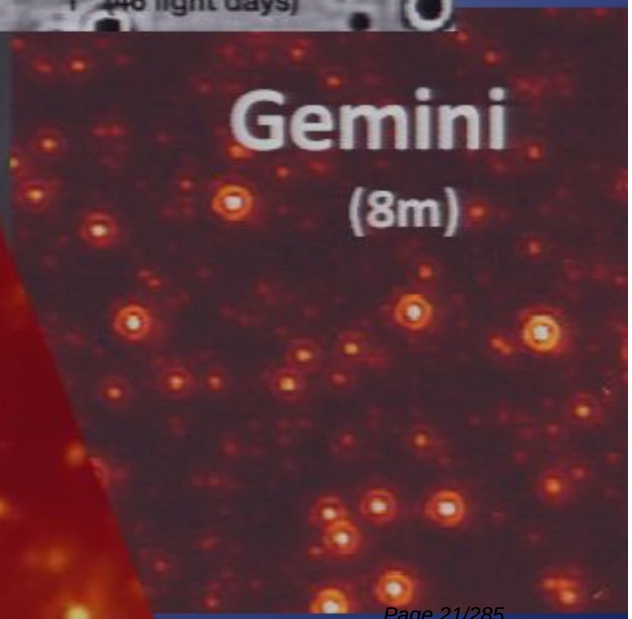

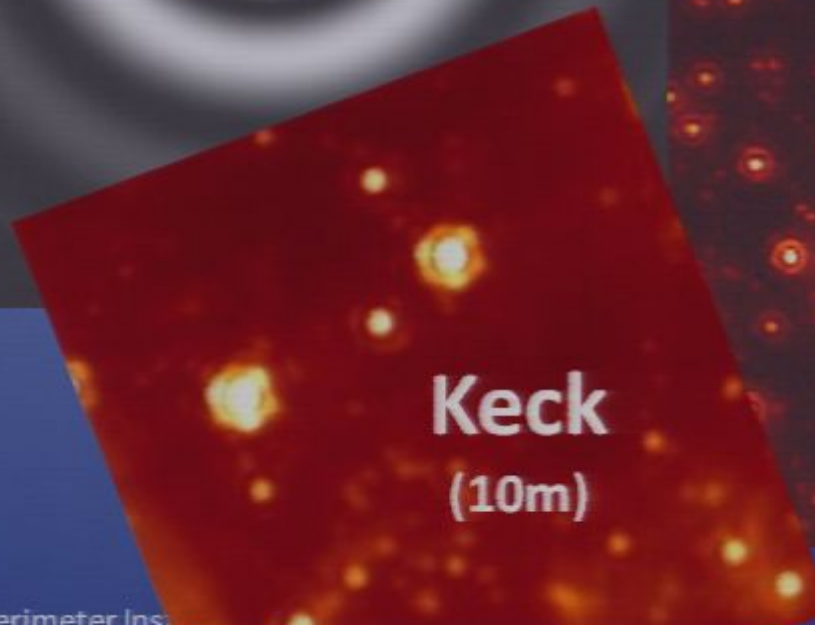

Example Diffraction Limits

$$\Delta\theta = 1.2\,\lambda/D$$

Instrument	λ	D	$\Delta\theta$ (μas)
SkyQuest XT8	0.5 μm	8”	6×10^5

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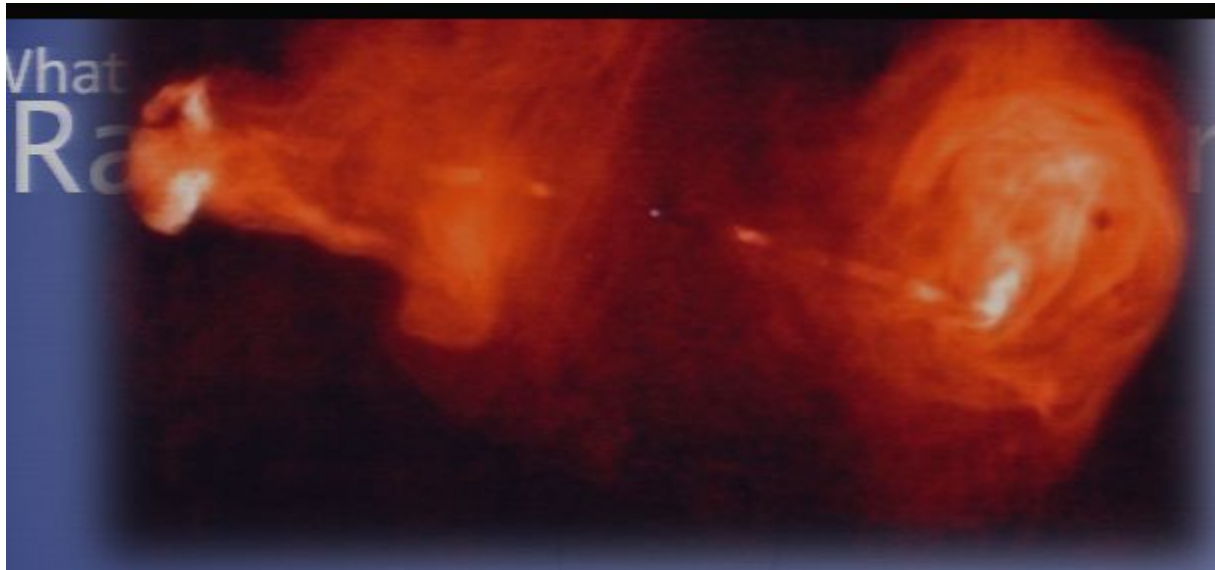
Radio Interferometry

$$E_1 = Ee^{i\omega t}$$

$$E_2 = Ee^{i\omega t + i\varphi}$$

$$\varphi = \omega\tau \approx 2\pi \frac{u\alpha}{\lambda}$$

$$\rightarrow \left\langle E_1 E_2^* \right\rangle = \left|E\right|^2 e^{2\pi i u\alpha / \lambda}$$



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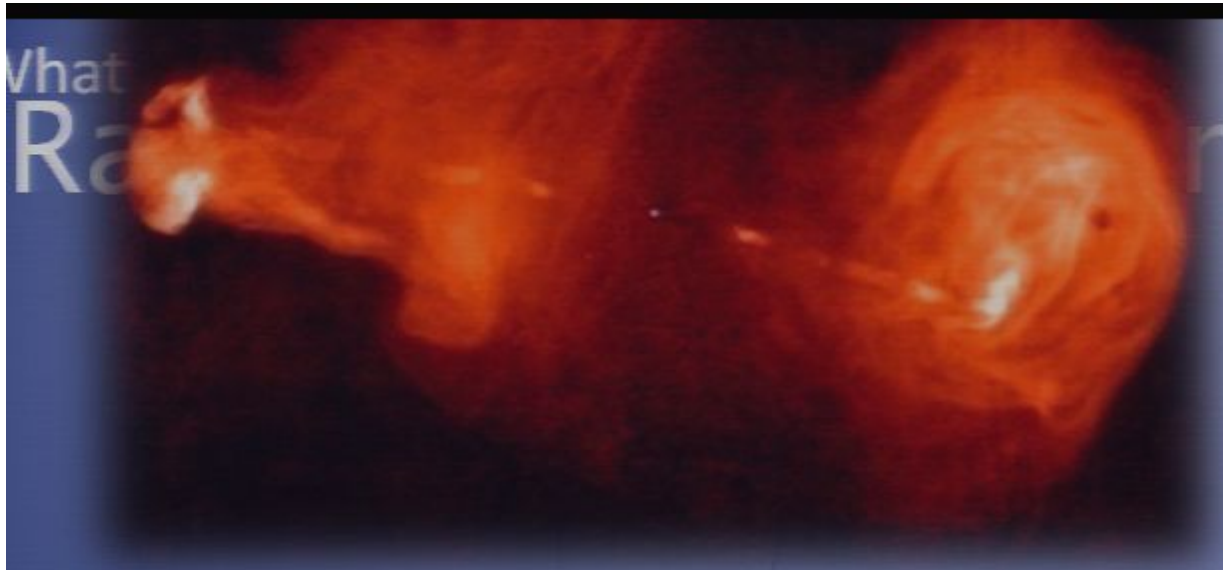

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$$\rightarrow V_{12} = \left\langle E_1 E_2^* \right\rangle = \int I(\alpha) e^{2\pi i u\alpha/\lambda} d\alpha$$

What and How

Imaging in Principle

1. Measure E-vector at a number of locations

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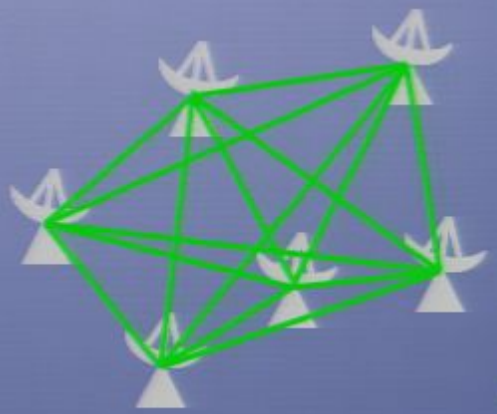

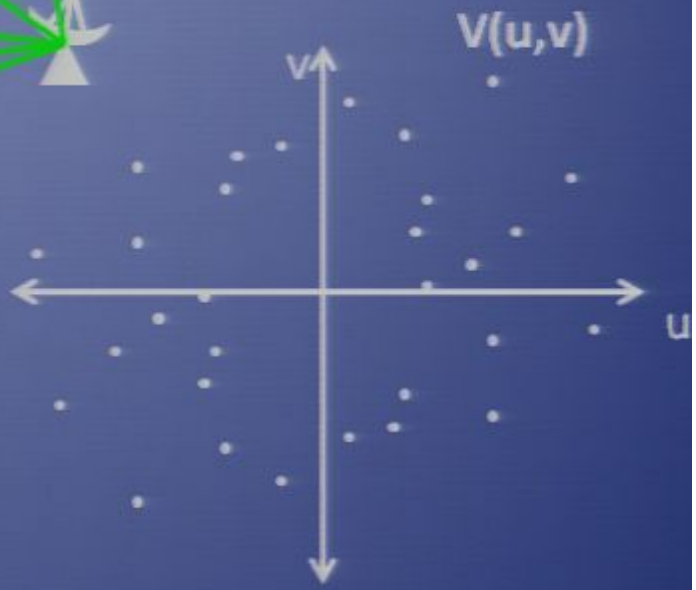

Imaging in Principle

1. Measure E-vector at a number of locations
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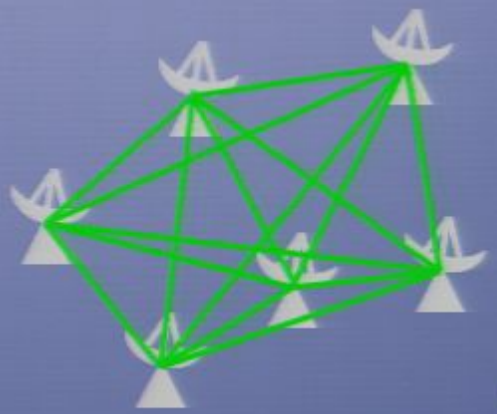
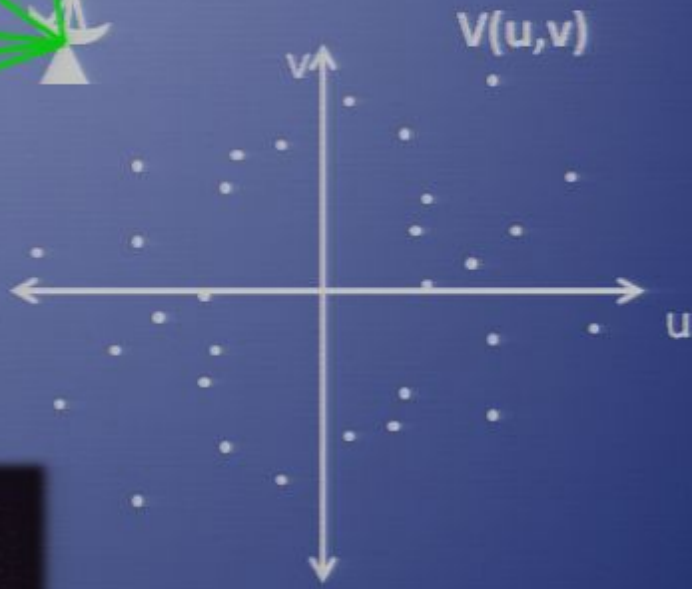
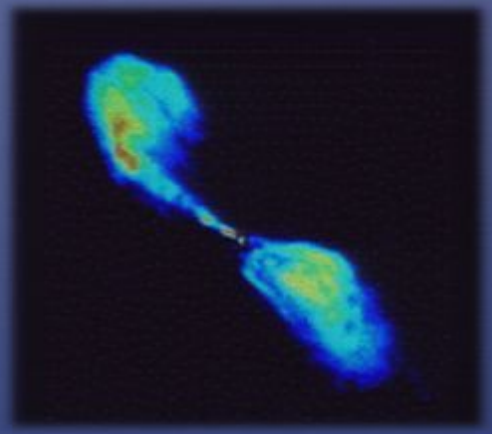
3. Invert the Fourier Transform to get image

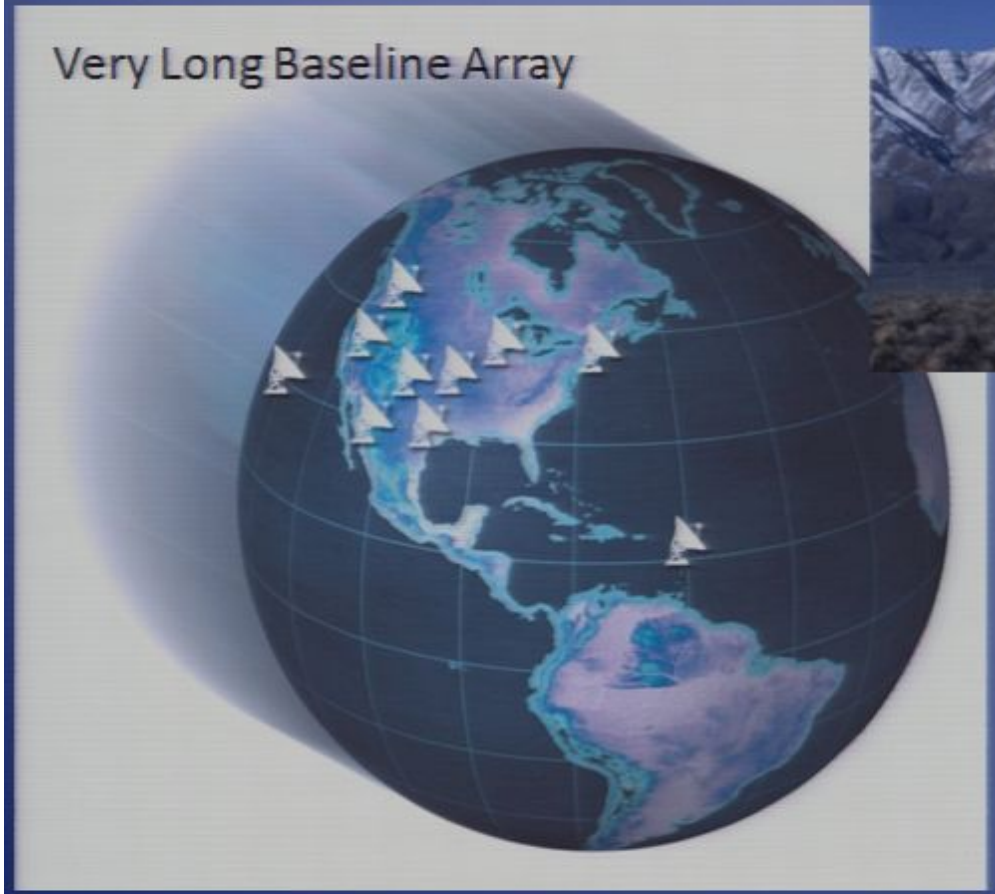






What and How
Very Long Baseline Interferometry

Very Long Baseline Array



Very Long Baseline Array has been doing this at 3mm and above for 2 decades!

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Keck/VLT/Gemini	1 μm	10 m	2×10^4
OWL	1 μm	100 m	2×10^3
VLBA	3 mm	6×10^3 km	10^2
EHT	**1.3 mm**	**10^4 km**	**30**
EHT	**0.87 mm**	**10^4 km**	**20**

What and How
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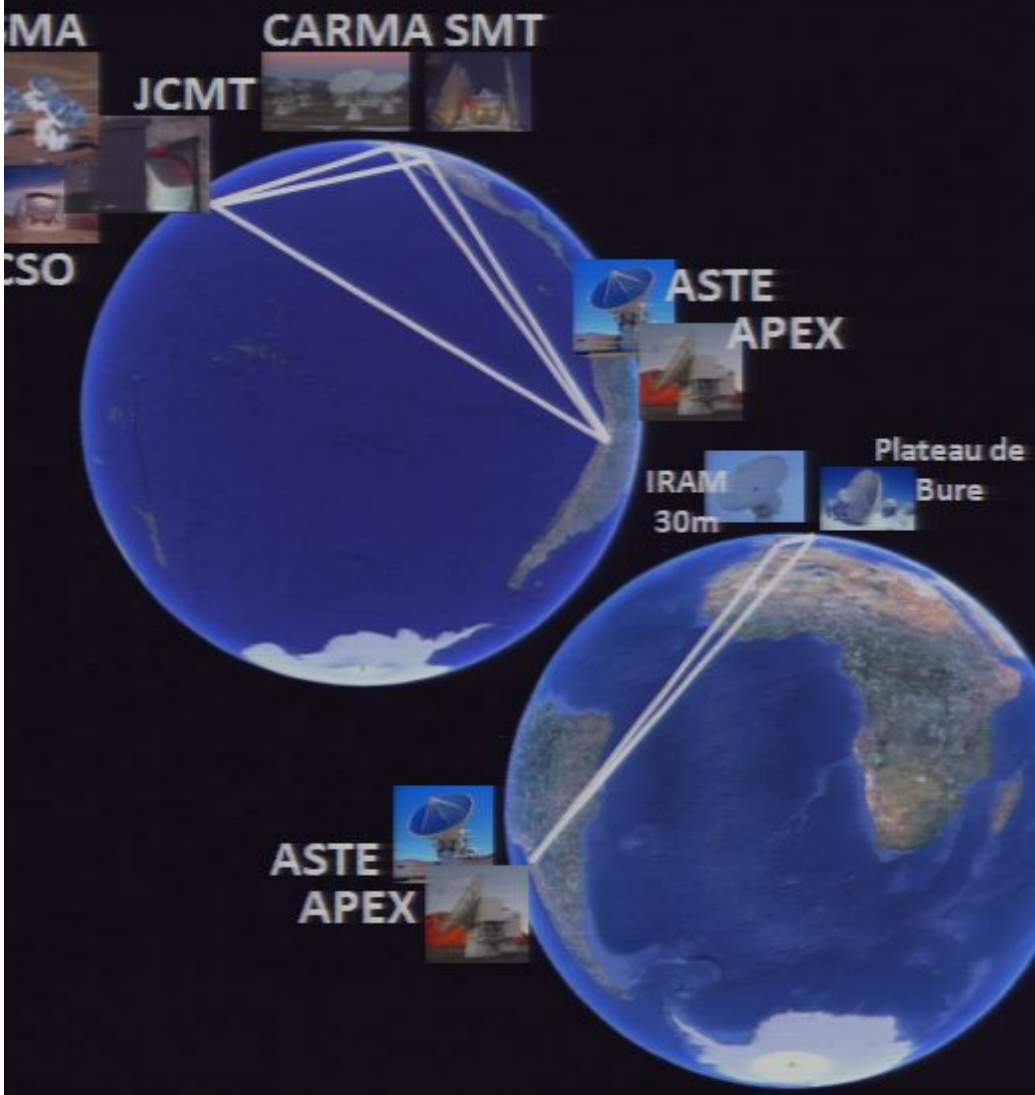

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Science Frontier Panels:

Galaxies across Cosmic Time
Cosmology and Fundamental Physics

http://arxiv.org/abs/0906.3899
ASTRO2010

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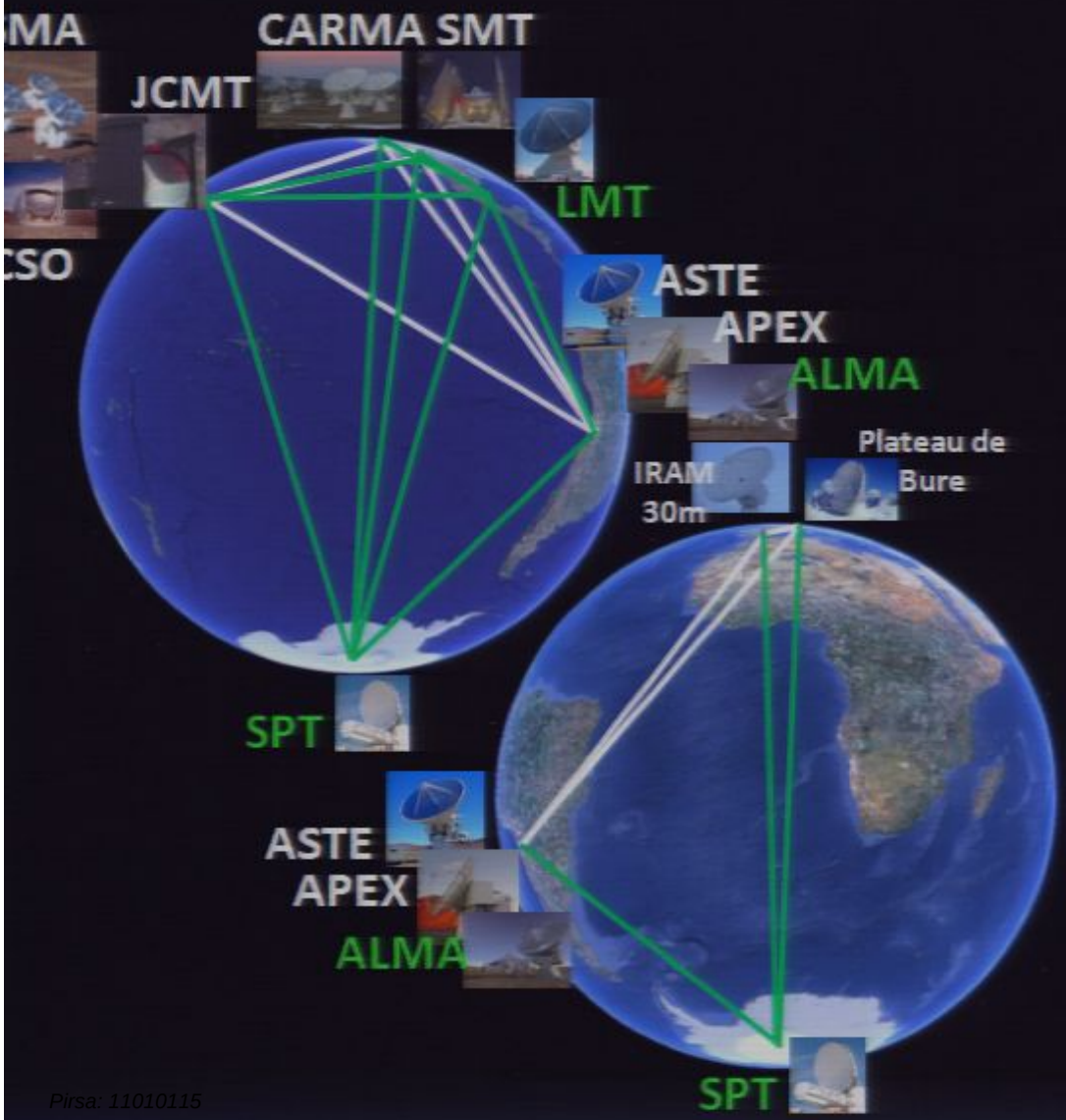

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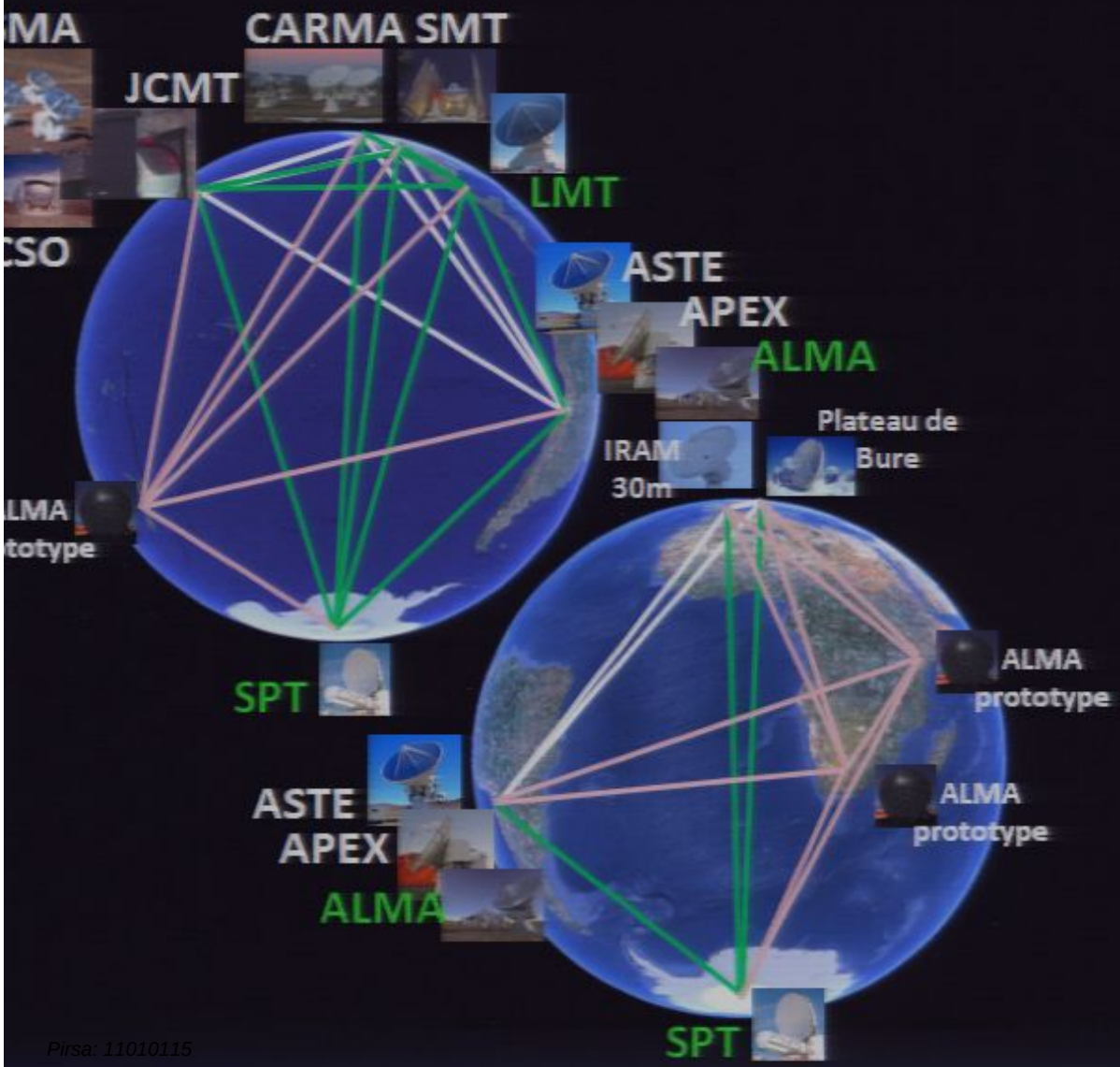

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Lucy Ziurys (U. Arizona Steward Observatory)

Science Frontier Panels:

Galaxies across Cosmic Time
Cosmology and Fundamental Physics

http://arxiv.org/abs/0906.3899
ASTRO2010

The Event Horizon Telescope

- Short atmospheric coherence time (10 s)
- Dish size ~12m → Need very large bandwidths! (4 Gbps, 16 Gbps, 64 Gbps)

$$P = F_\nu \Delta\nu A = 10^{-15} \left(\frac{F_\nu}{1\mathrm{Jy}}\right)\left(\frac{\Delta\nu}{1\mathrm{GHz}}\right)\left(\frac{D}{12m}\right)^2 \mathrm{W}$$

- Stable local oscillators
- Cross-correlation → need dish locations and time delays to sub-mm/sub-ns accuracy

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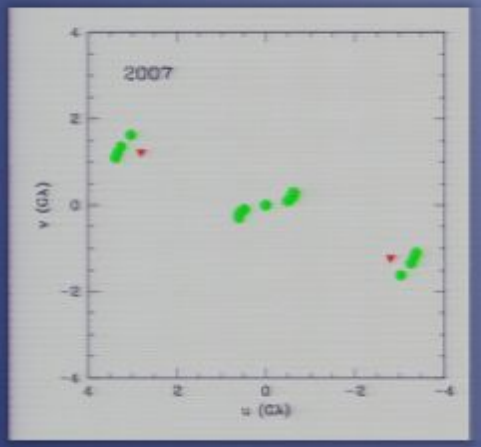
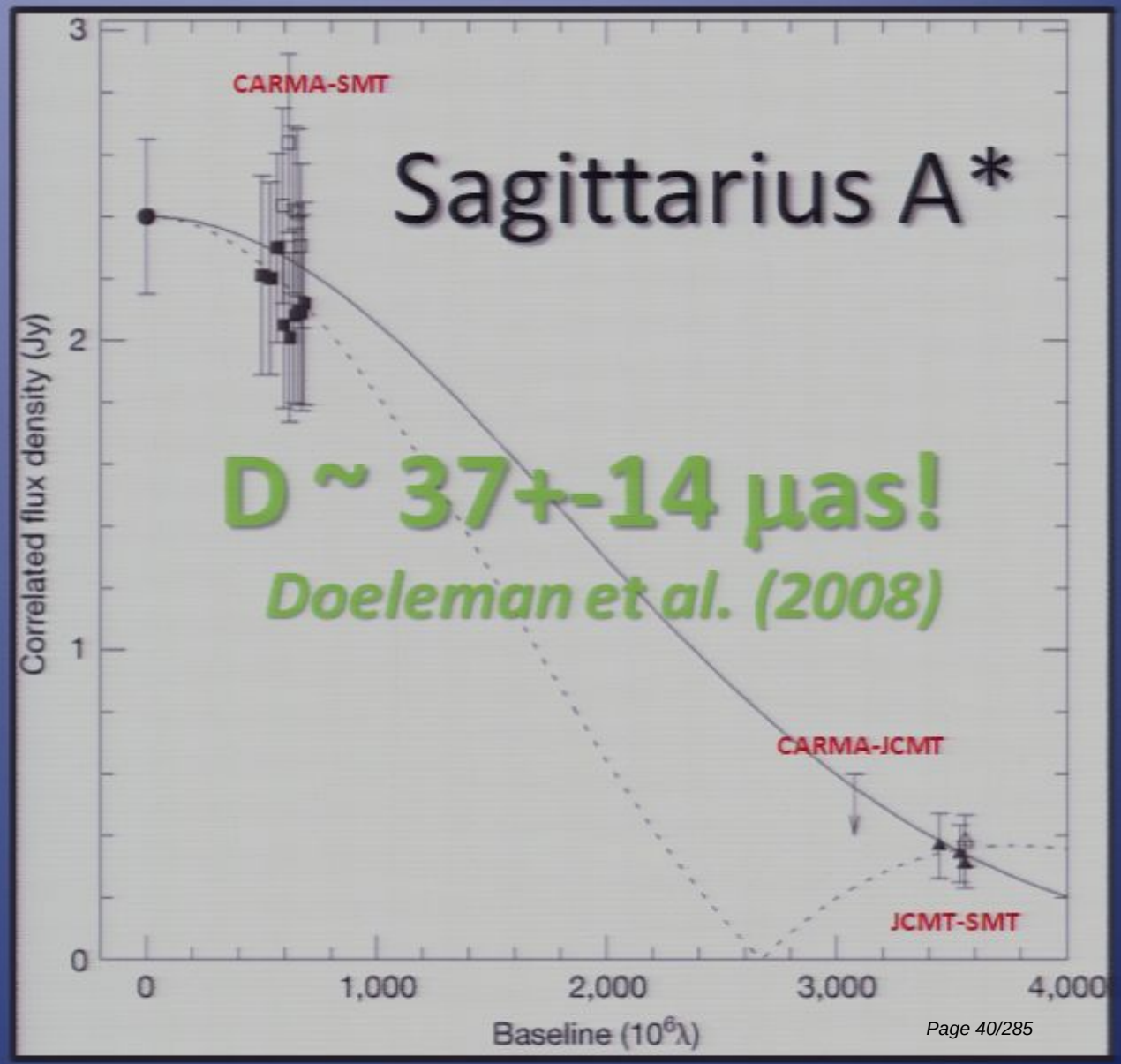
It Works!

What and How

1.3mm-VLBI Data





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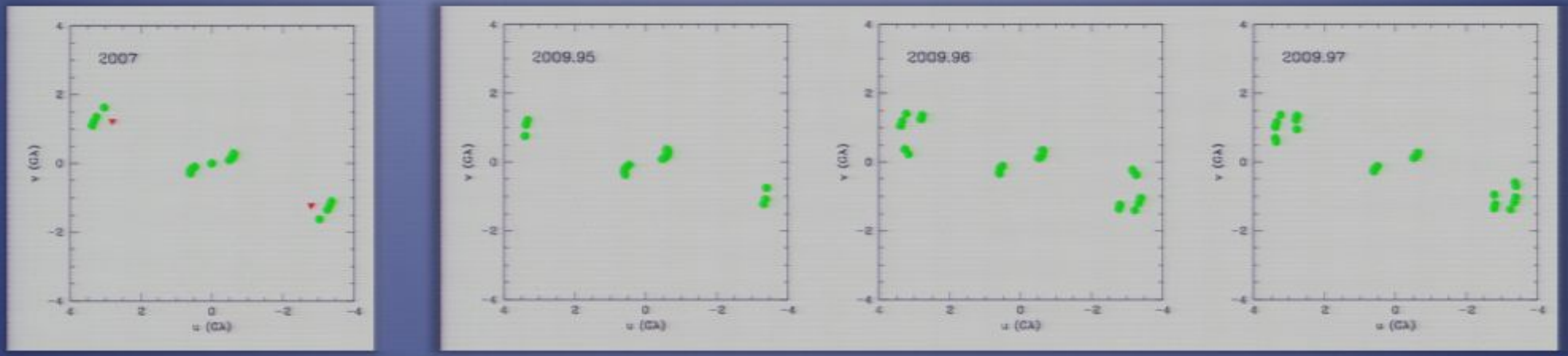
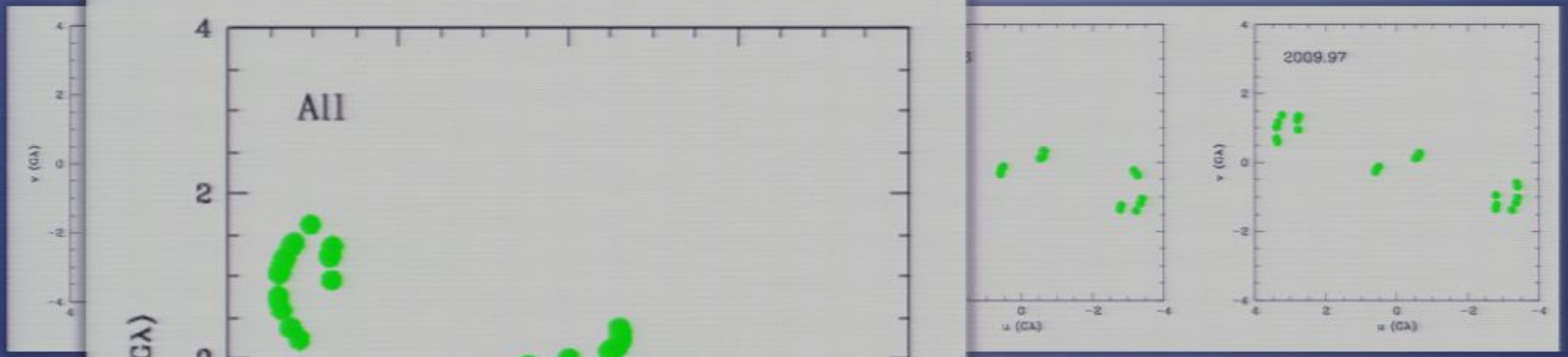
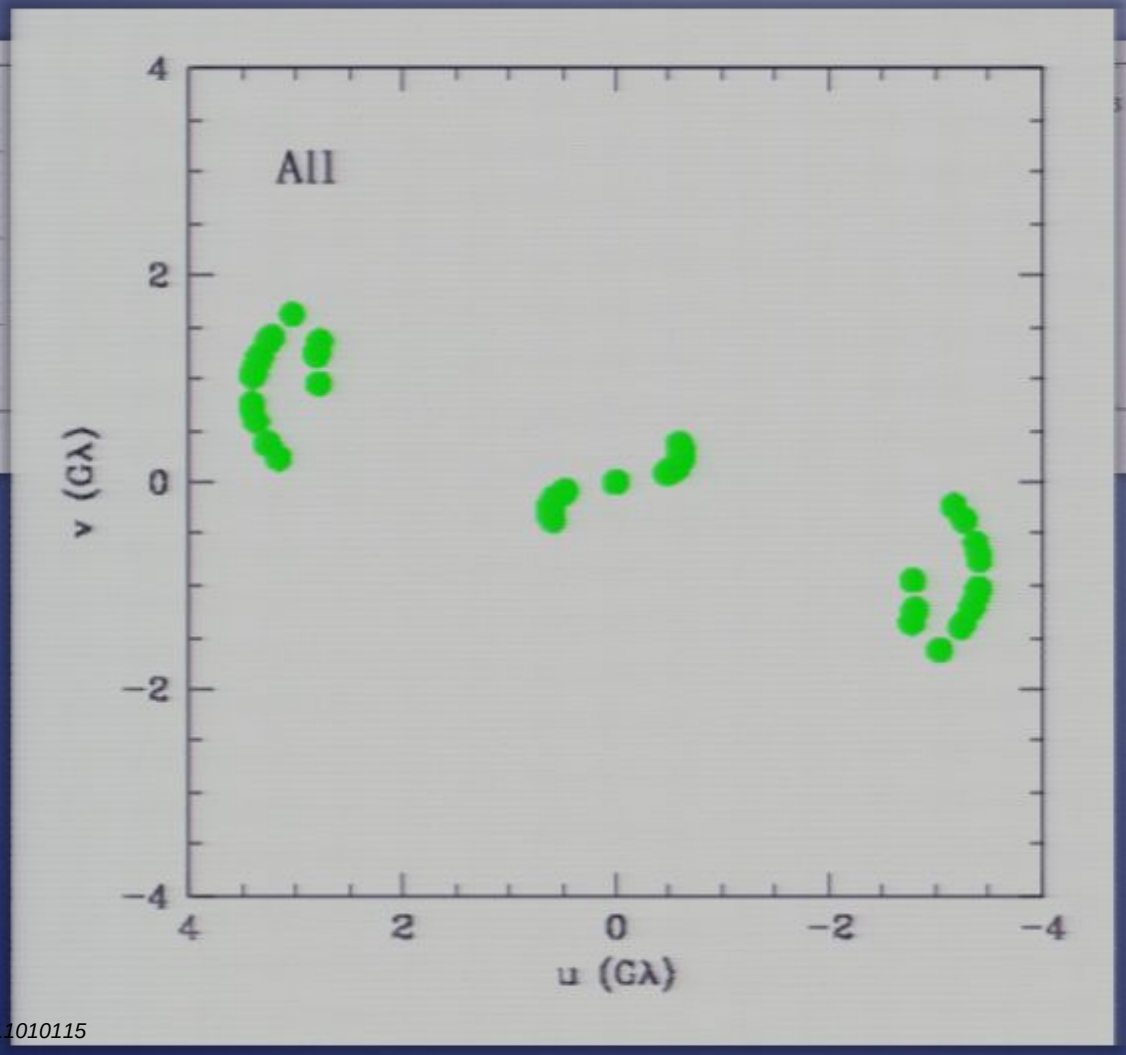


Fish et al. (2010)

What and How
1.3mm-VLBI Data





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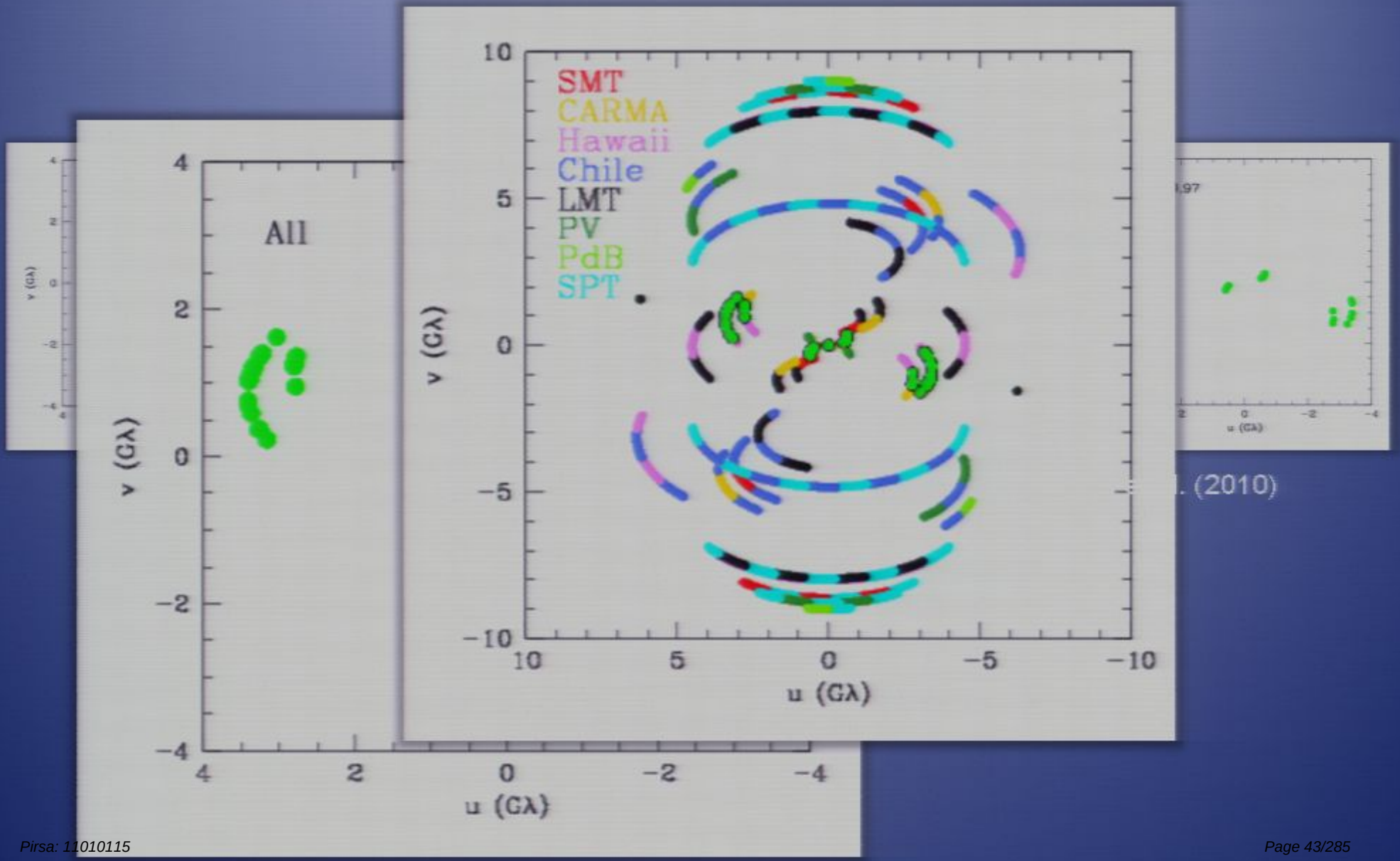
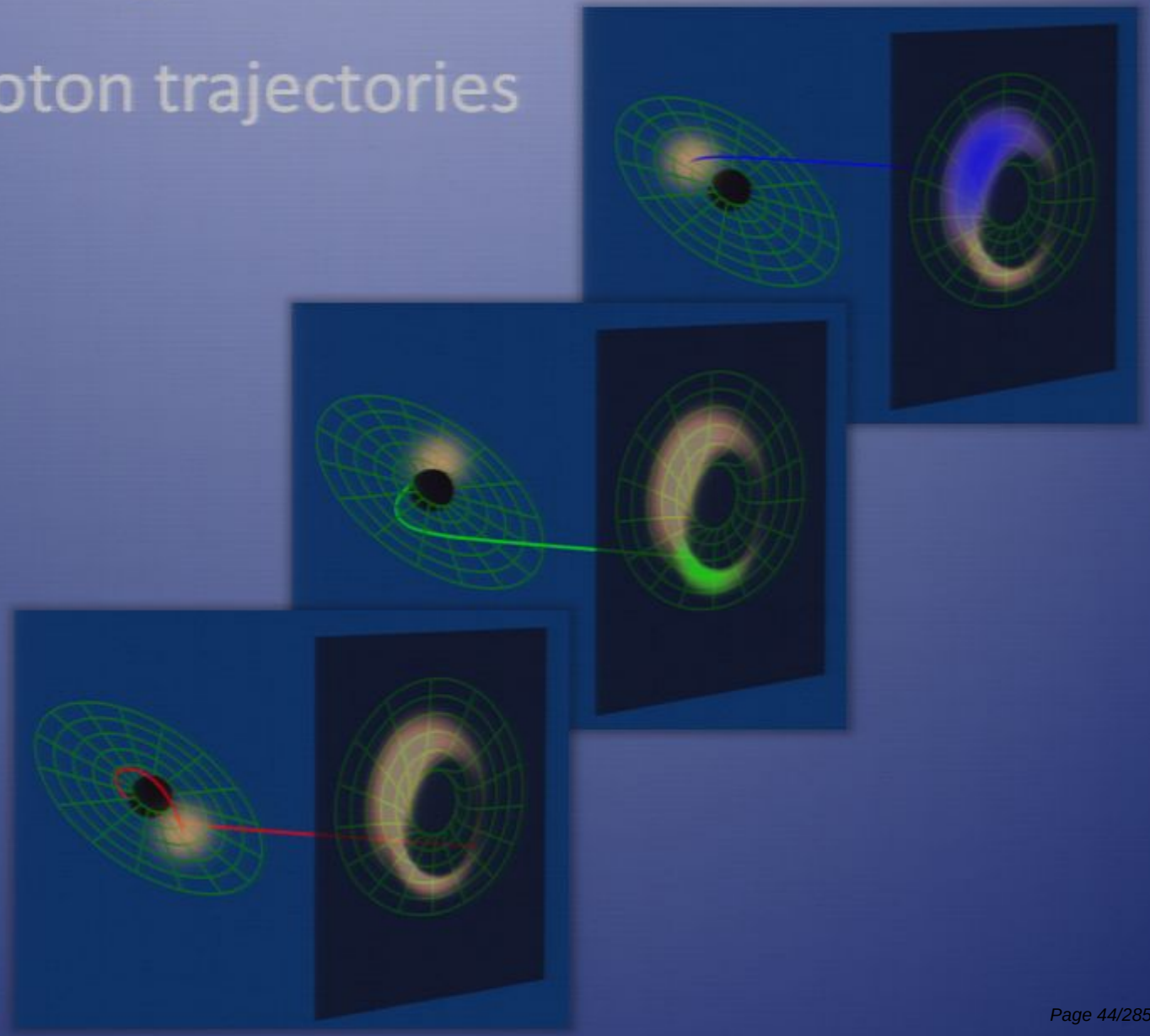


(2010)

Generating images ...

Computing images of accretion flows

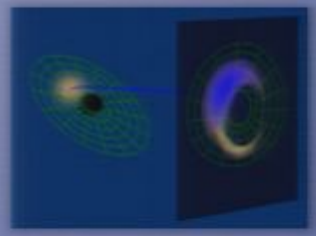
- Tracing photon trajectories

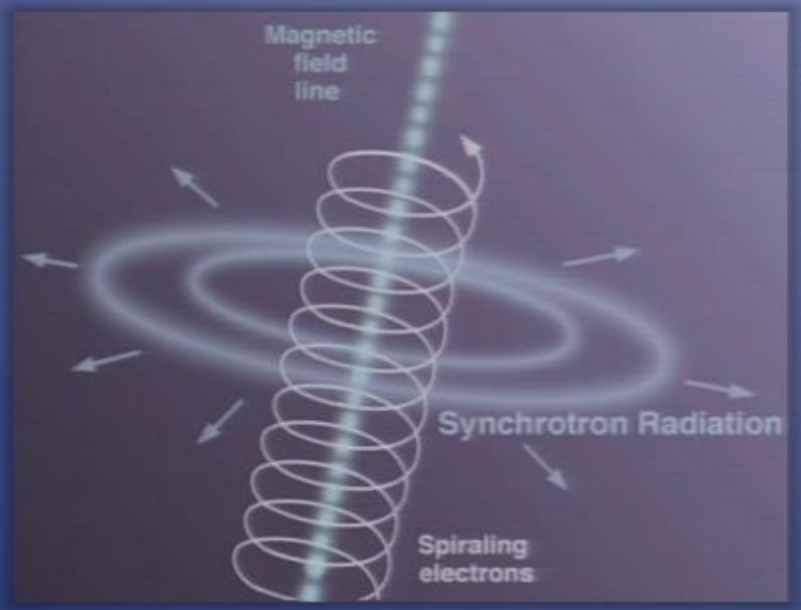


Generating images ...

Computing images of accretion flows

- Tracing photon trajectories
- Polarized radiative transfer
  (self-absorbed synchrotron)



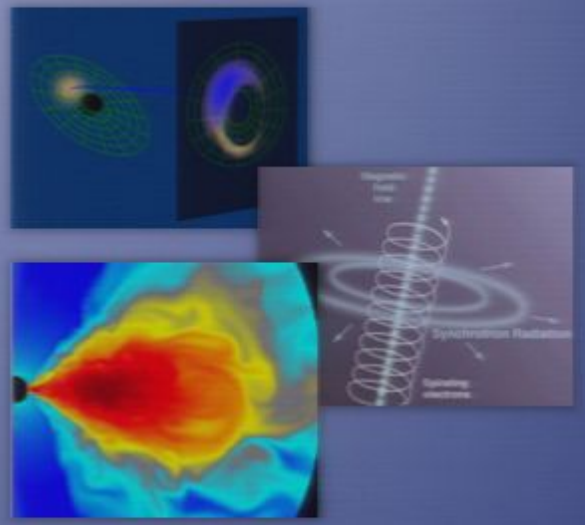


$$\frac{dS}{dl} = \mathbf{j} - \boldsymbol{\alpha} \cdot \mathbf{S}$$

Generating images …

Computing images of accretion flows

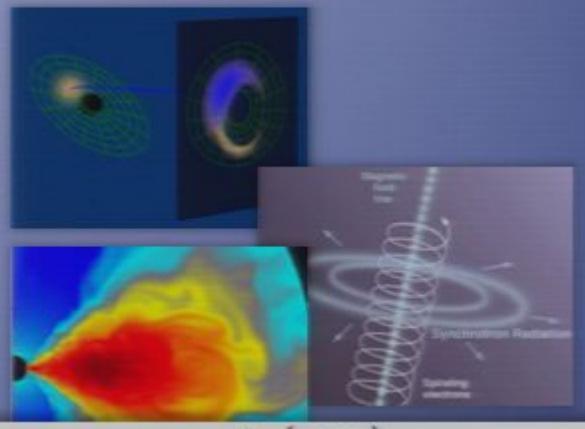
- Tracing photon trajectories
- Polarized radiative transfer
- Emitting plasma distribution
  - Thick, self-similar disk
  - Keplerian beyond ISCO, ballistic inside
  - Sub-equipartition magnetic field
  - "Thermal" and power-law electron components
  - Model defined by n_{th}, n_{nth}, T_e, and **a**

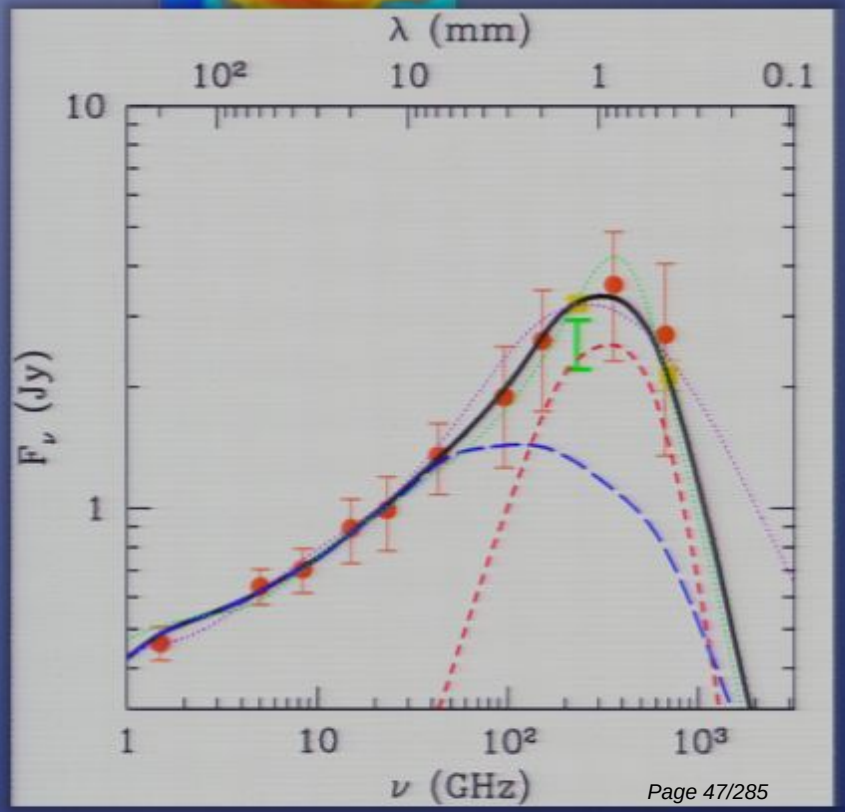


Generating images ...

Computing images of accretion flows

- Tracing photon trajectories
- Polarized radiative transfer
- Emitting plasma distribution
- Leveraging observations
  → library of models which fit spectra and polarization data





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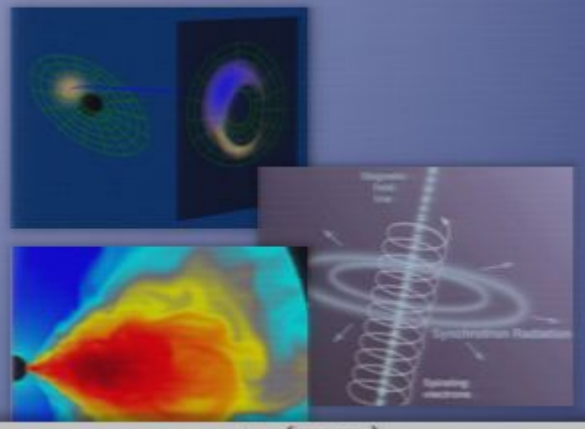

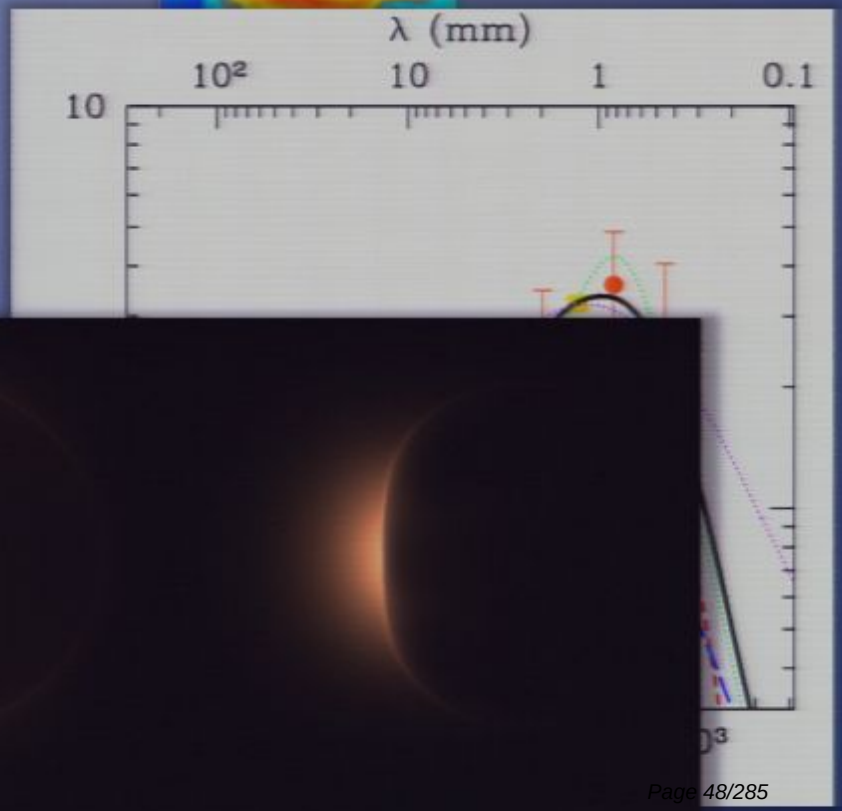

Generating images ...

Computing images of accretion flows

- Tracing photon trajectories
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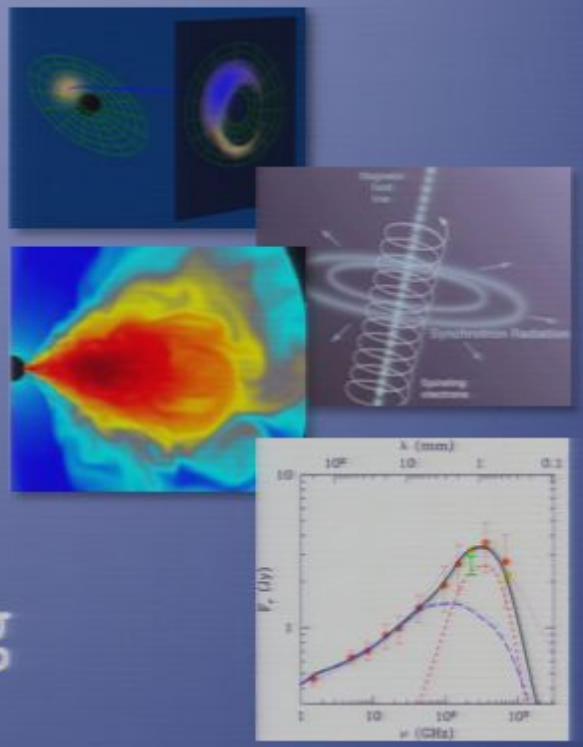
- Intervening electron scattering



. and taking black hole portraits

Comparing Models: ICs

- Bayesian Information Criterion $BIC = L + k \log N$
- Akaike Information Criterion $AIC = L + 2k + \frac{2k(k+1)}{N-k-1}$
- Relative significance

$$w_{ij} = e^{-(IC_i - IC_j)/2}$$

Jeffreys' Scale

ΔIC	Conclusion
0	Negative
0-1	Not worth more than a bare mention
1-3	Positive
3-5	Strong
5-10	Very Strong
>10	Conclusive

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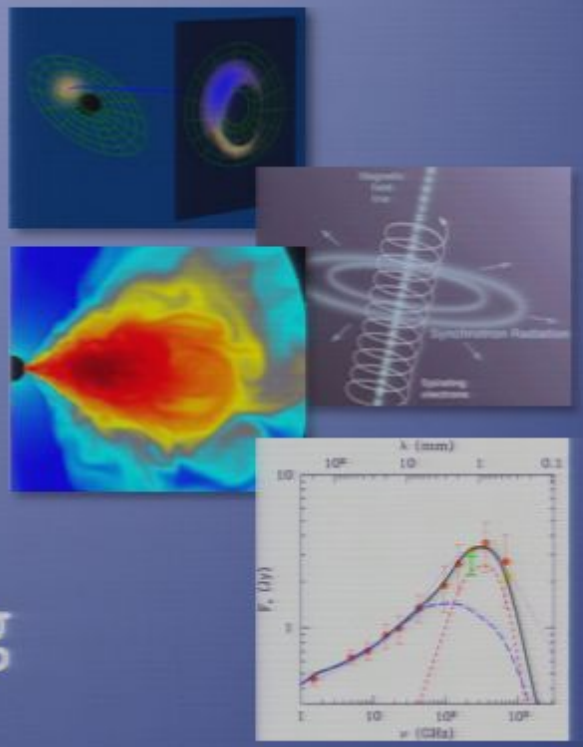

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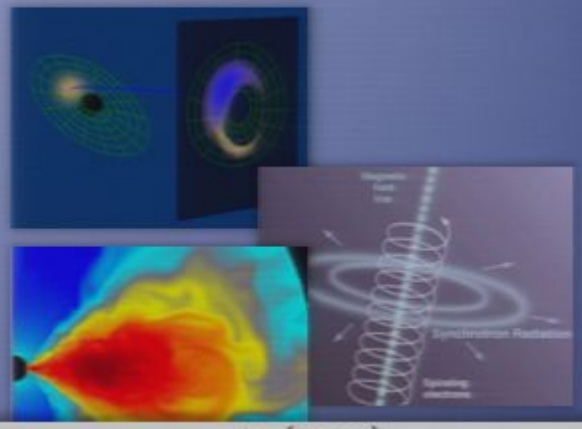

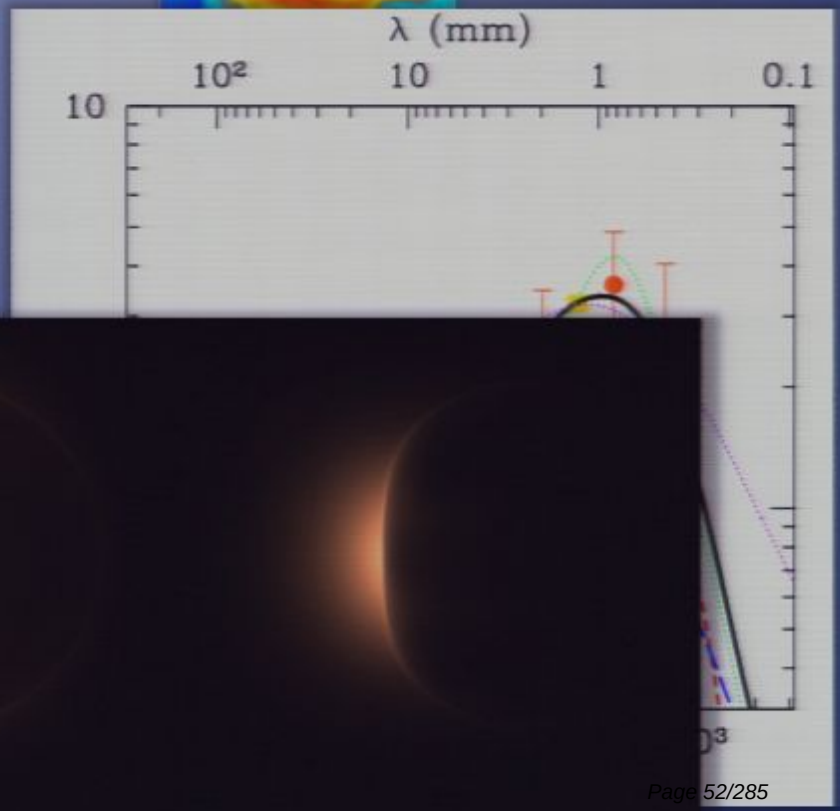

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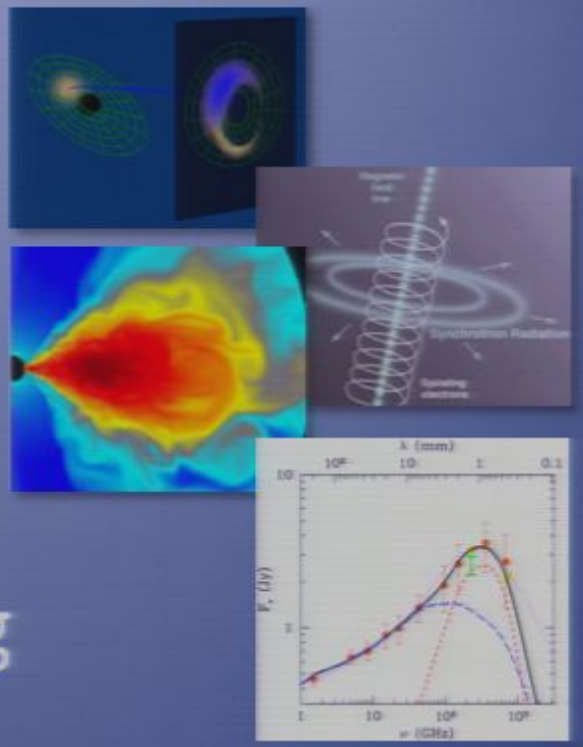

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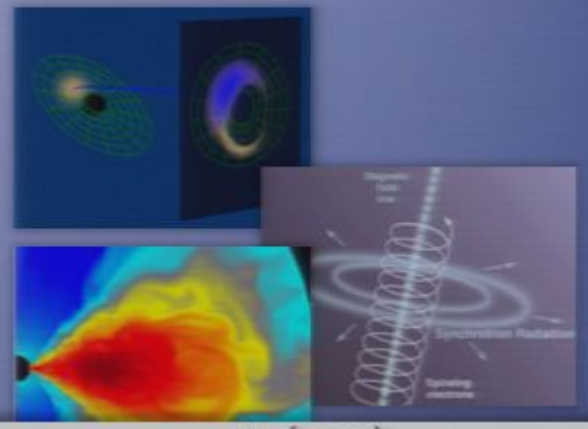

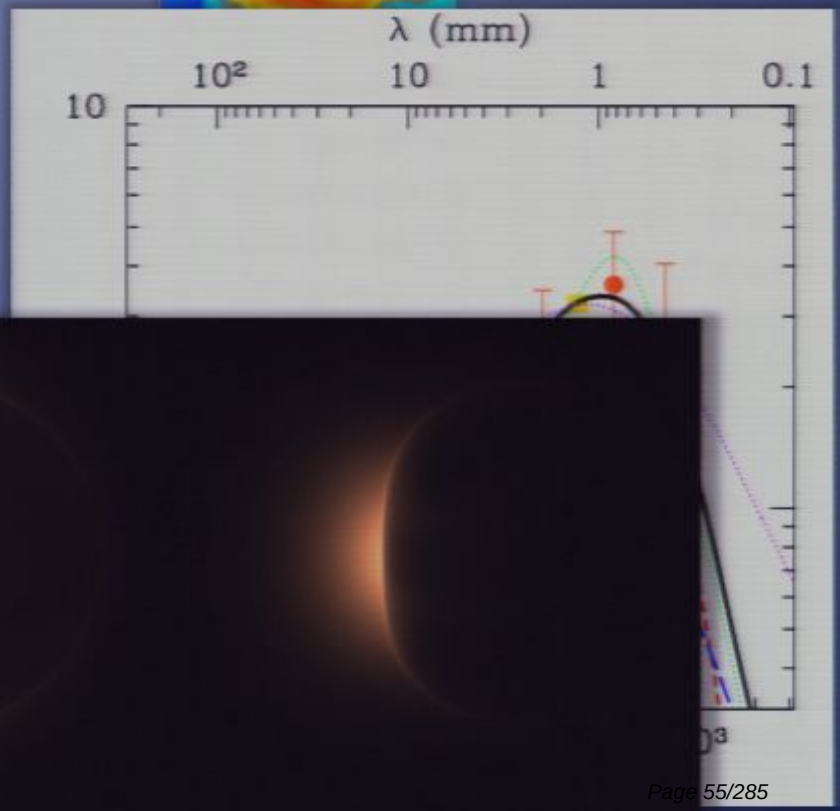

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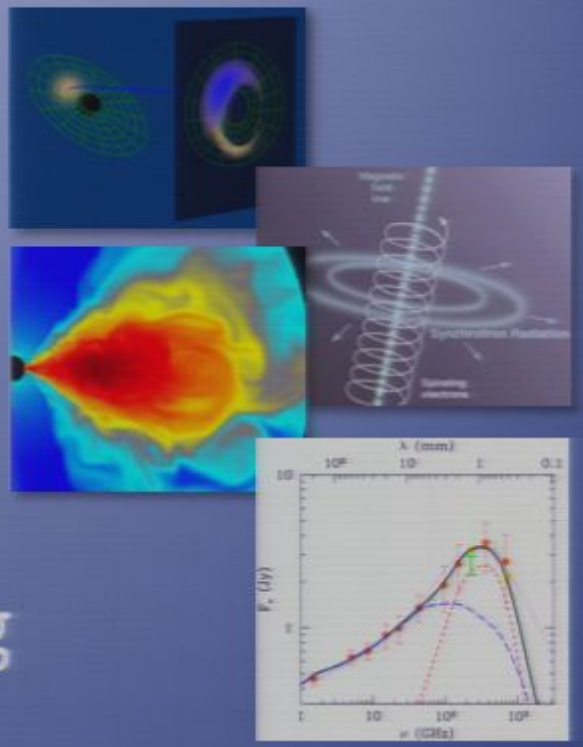

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- Lies, damn lies and statistics!

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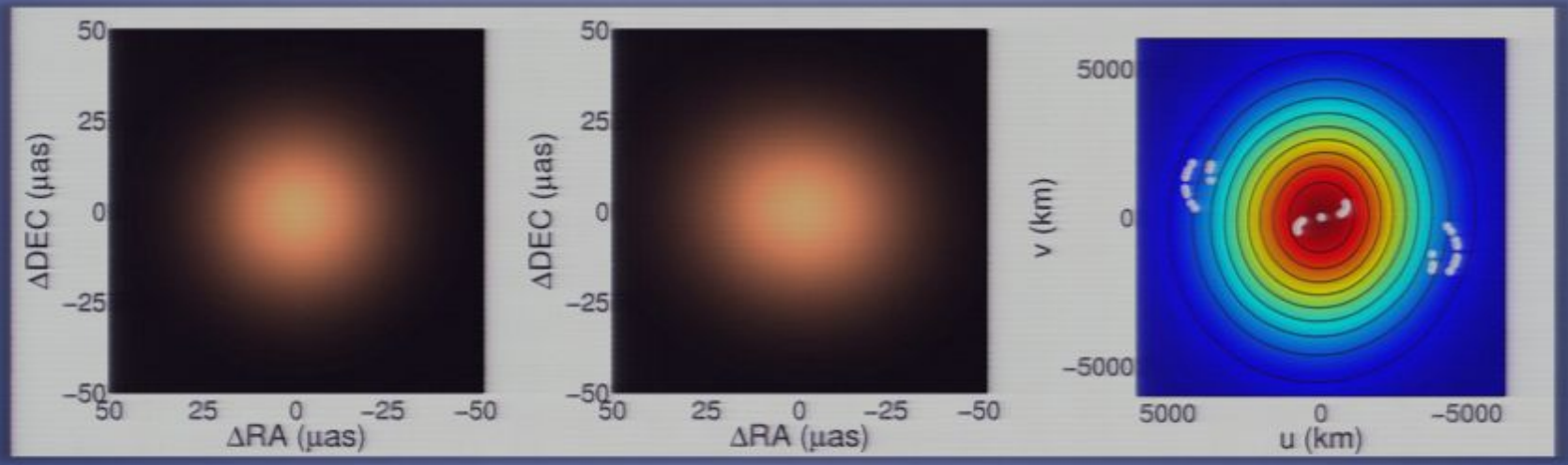
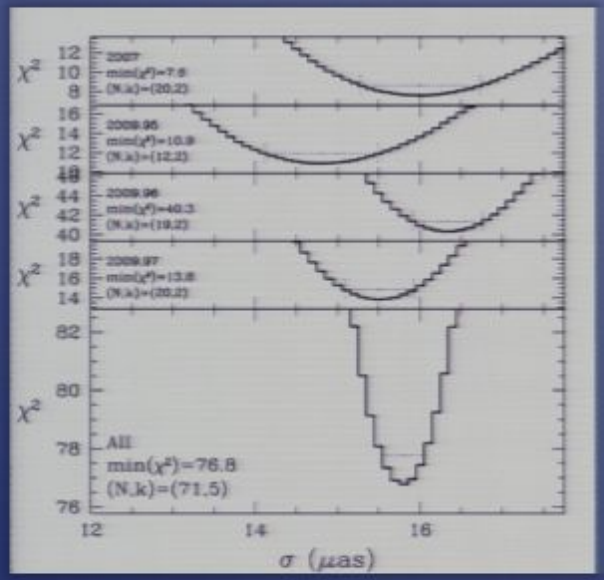
. and taking black hole portraits

Symmetric Gaussian





σ=15.8+-0.2 μas

χ^2/DoF=1.16

BIC=98.1

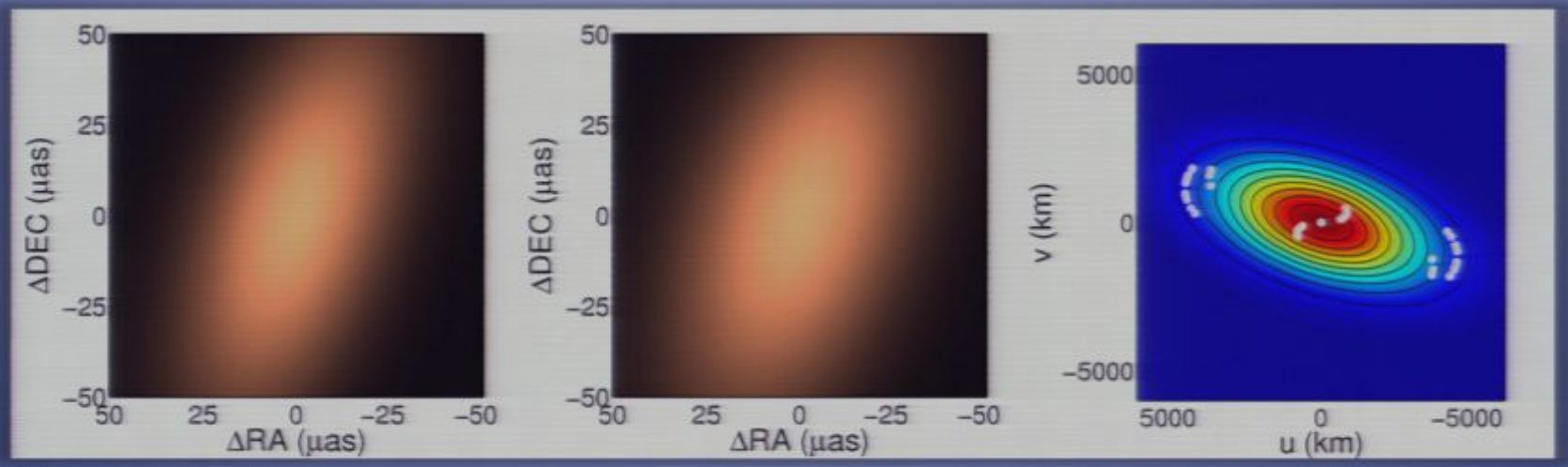
AIC=87.7

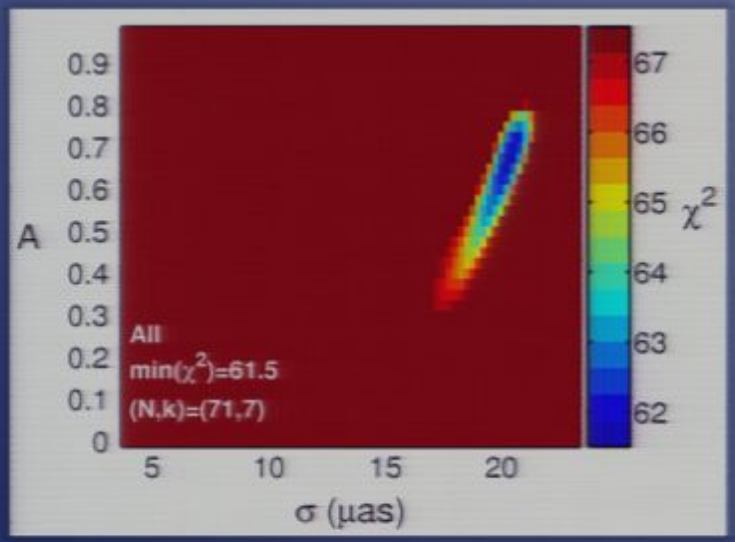
AEB, Fish, Doeleman & Loeb, arXiv:1011.2770

Pirsa: 11010115

. and taking black hole portraits

Asymmetric Gaussian





$$\sigma = \left[\frac{1}{2\sigma_m^2} + \frac{1}{2\sigma_M^2}\right]^{-1/2} = 20.5^{+0.3+0.5}_{-0.8-1.3}\ \mu\text{as}$$

$$A = \left[\frac{\sigma_M^2 - \sigma_m^2}{\sigma_M^2 + \sigma_m^2}\right]^{1/2} = 0.70^{+0.03+0.05}_{-0.1-0.18}$$

$$\xi = 19^{\circ}{}^{+3^{\circ}+6^{\circ}}_{-1^{\circ}-2^{\circ}}$$

χ^2/DoF=0.961

BIC=91.3 (-6.9)

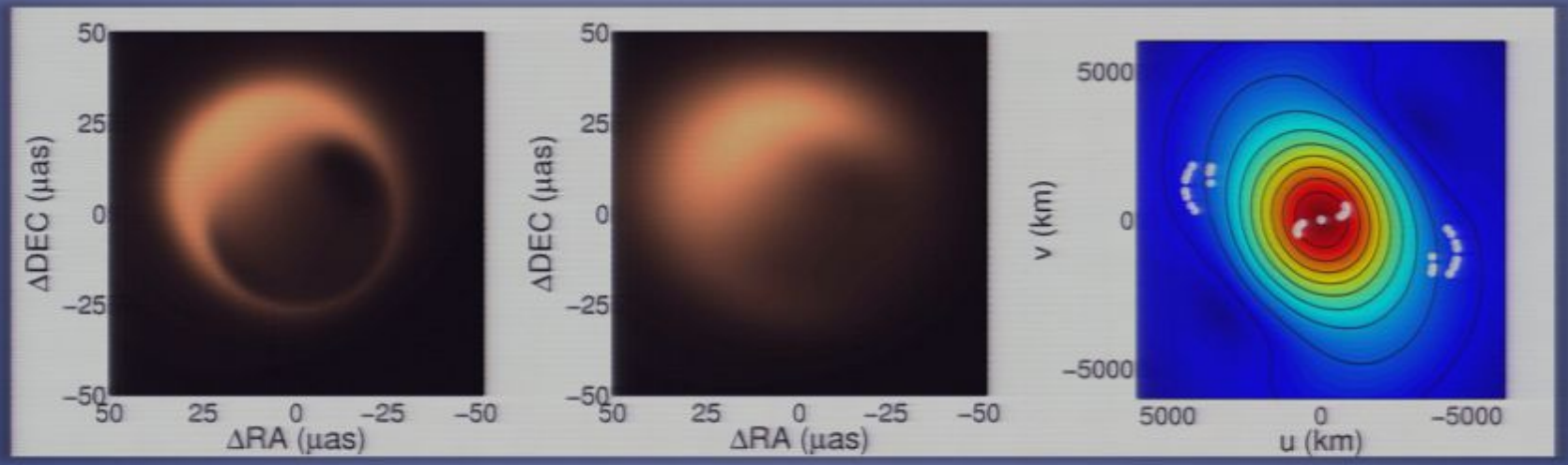
AIC=77.3 (-7.4)

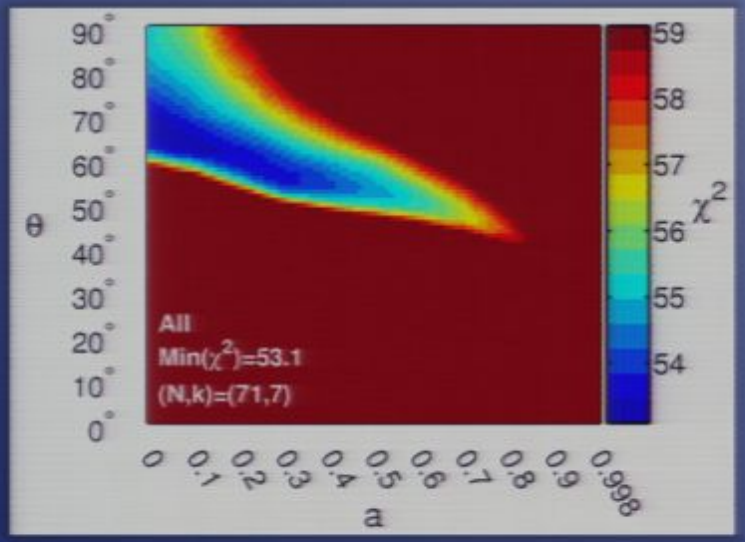
AEB, Fish, Doeleman & Loeb, arXiv:1011.2770

Perimeter Institute, January 31, 2011

. and taking black hole portraits

Radiatively inefficient accretion flow





χ^2/DoF=0.830

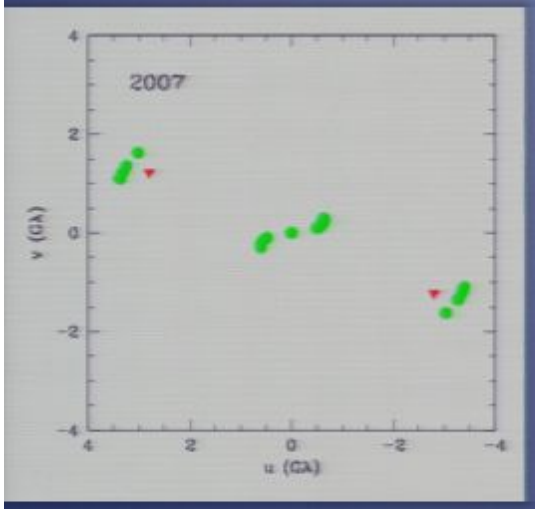
BIC=82.9 (-8.4, -15.3)

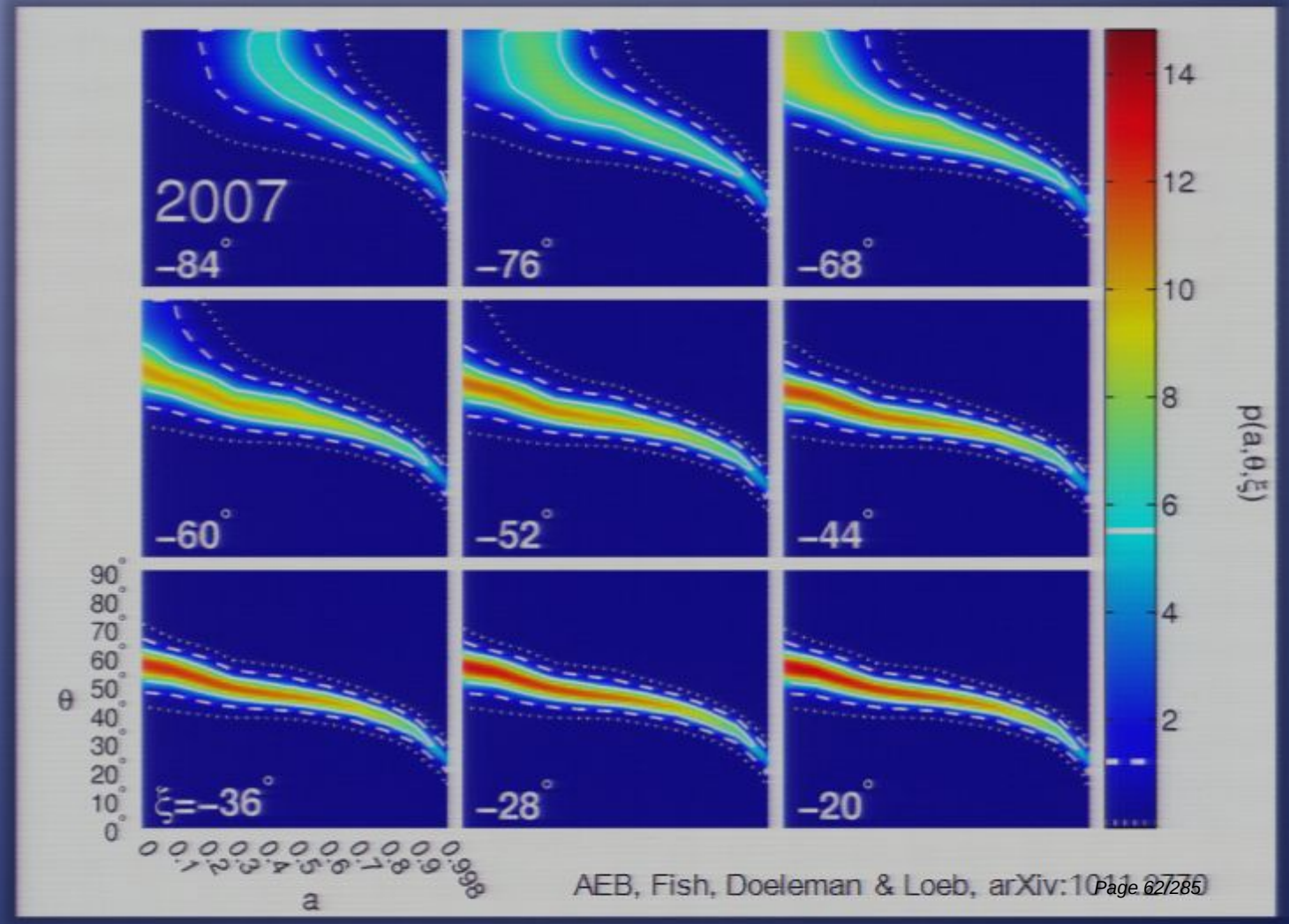
AIC=68.9 (-8.4, -15.8)

AEB, Fish, Doeleman & Loeb, arXiv:1011.2770

. and taking black hole portraits

Sgr A* Parameter Estimation: Then …





AEB, Fish, Doeleman & Loeb, arXiv:1011.2778

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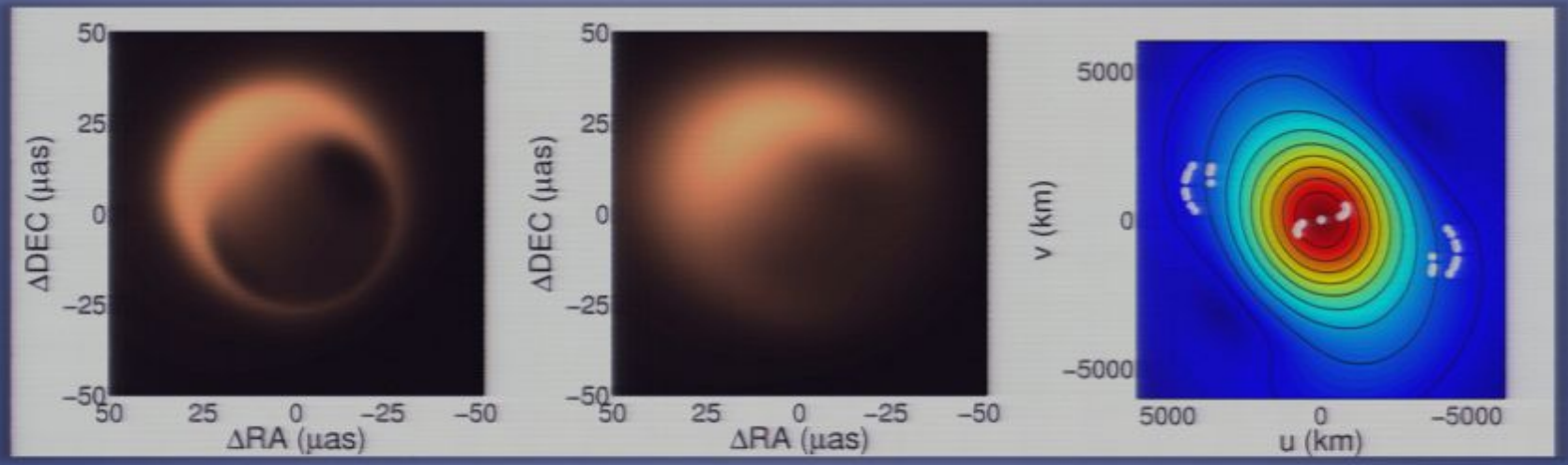
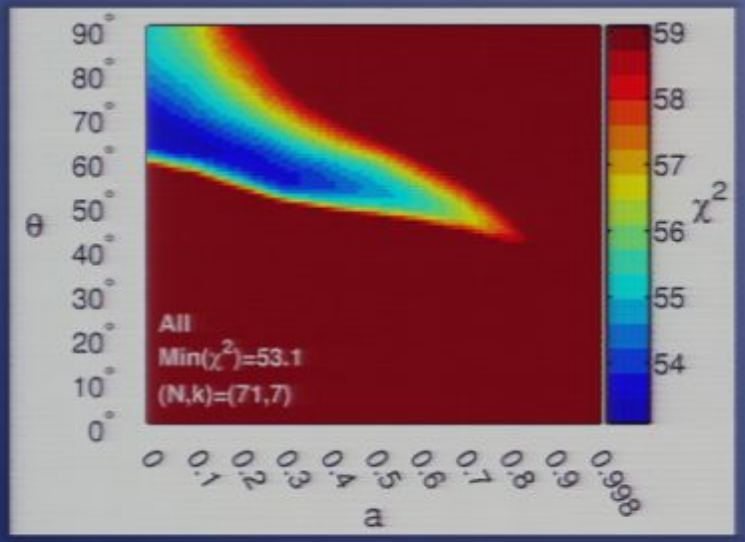
Radiatively inefficient accretion flow





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Pirsa: 11010115

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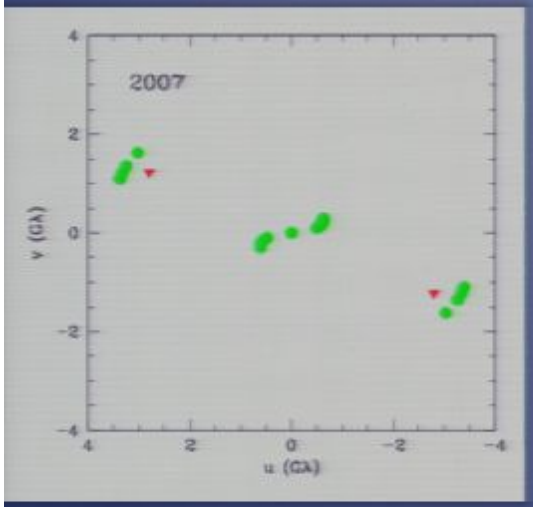

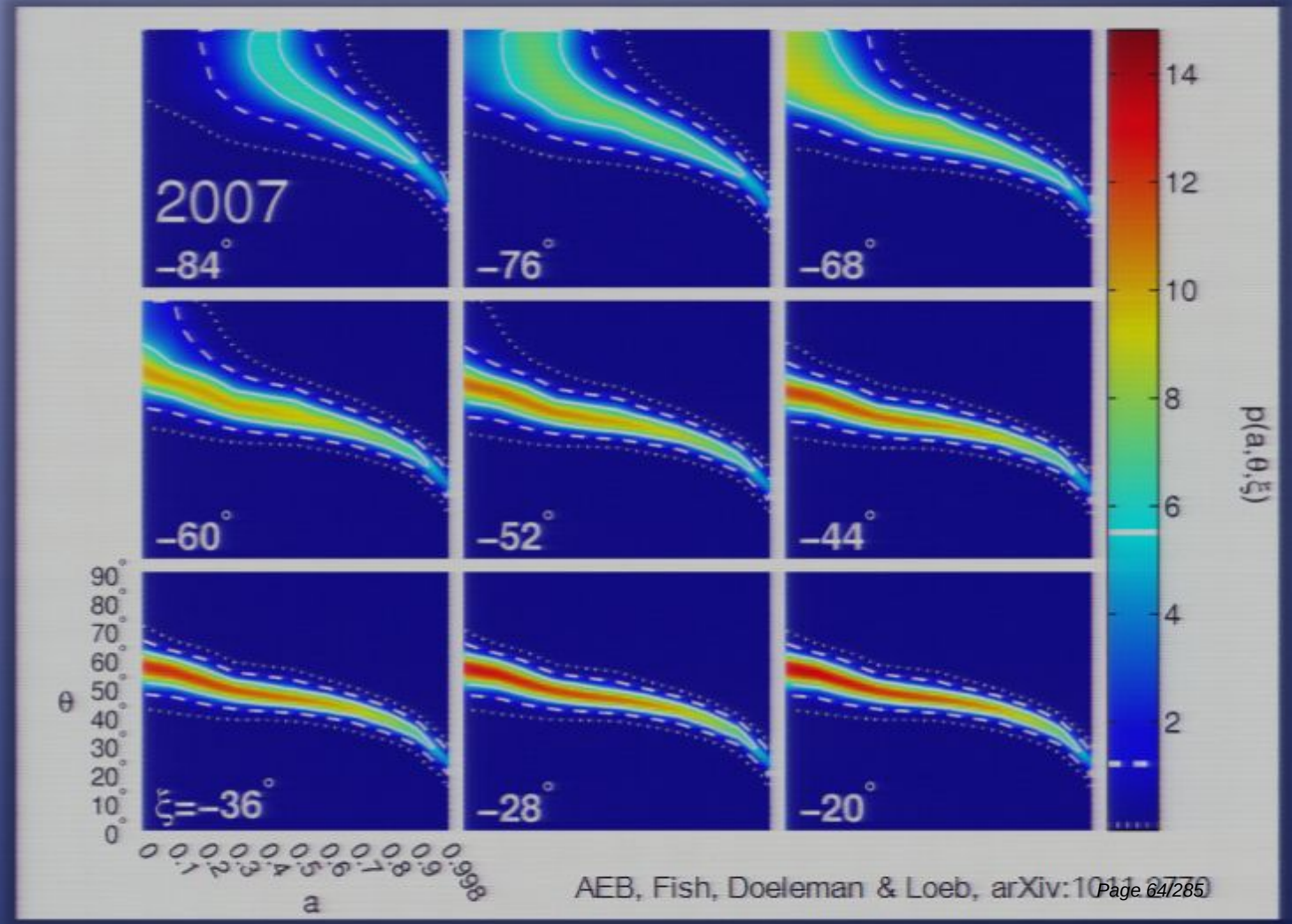

AEB, Fish, Doeleman & Loeb, arXiv:1011.2778

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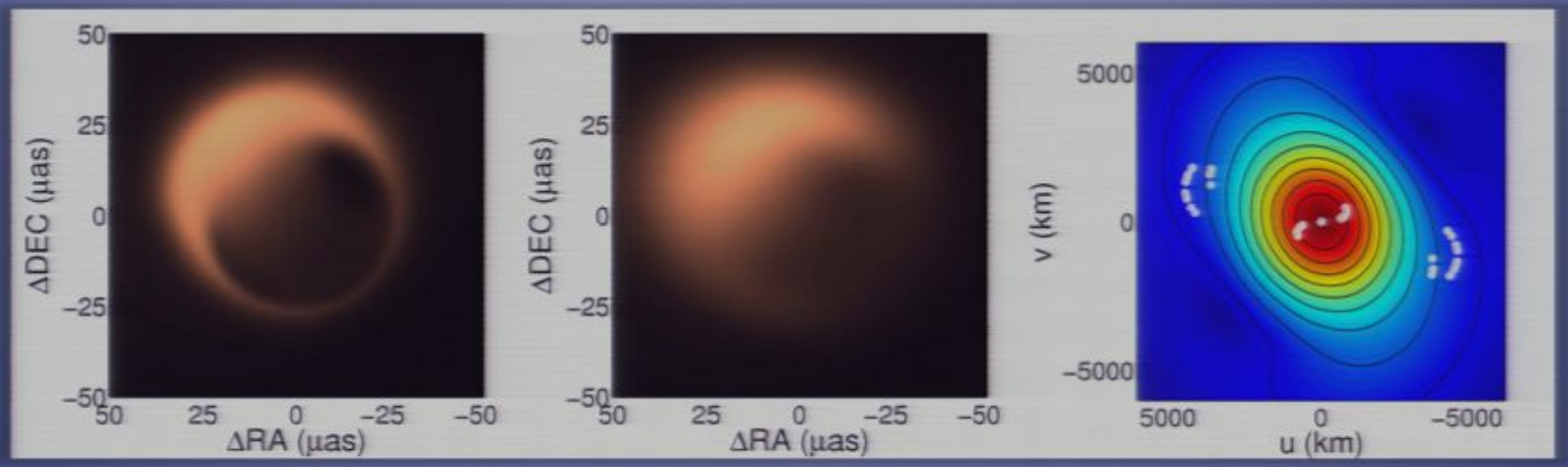

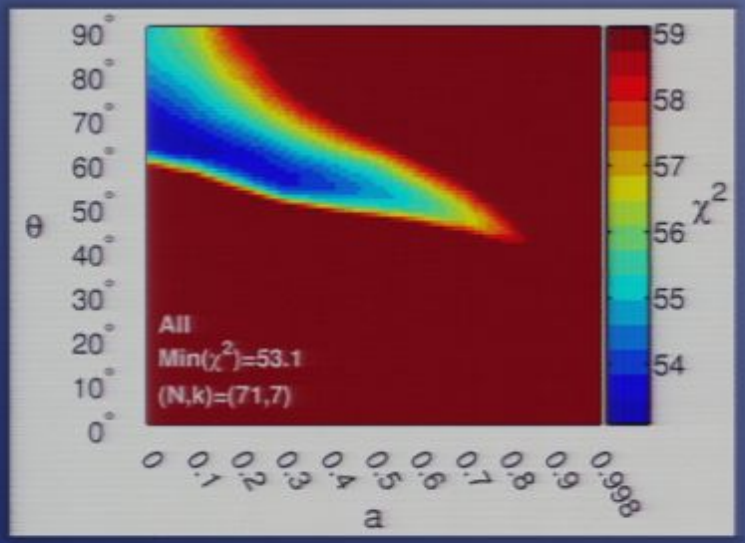

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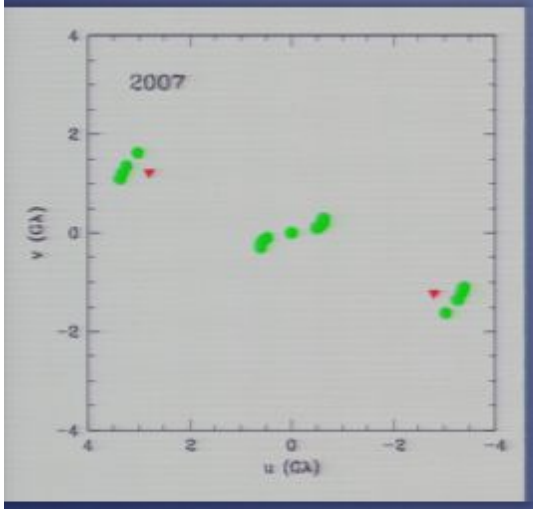

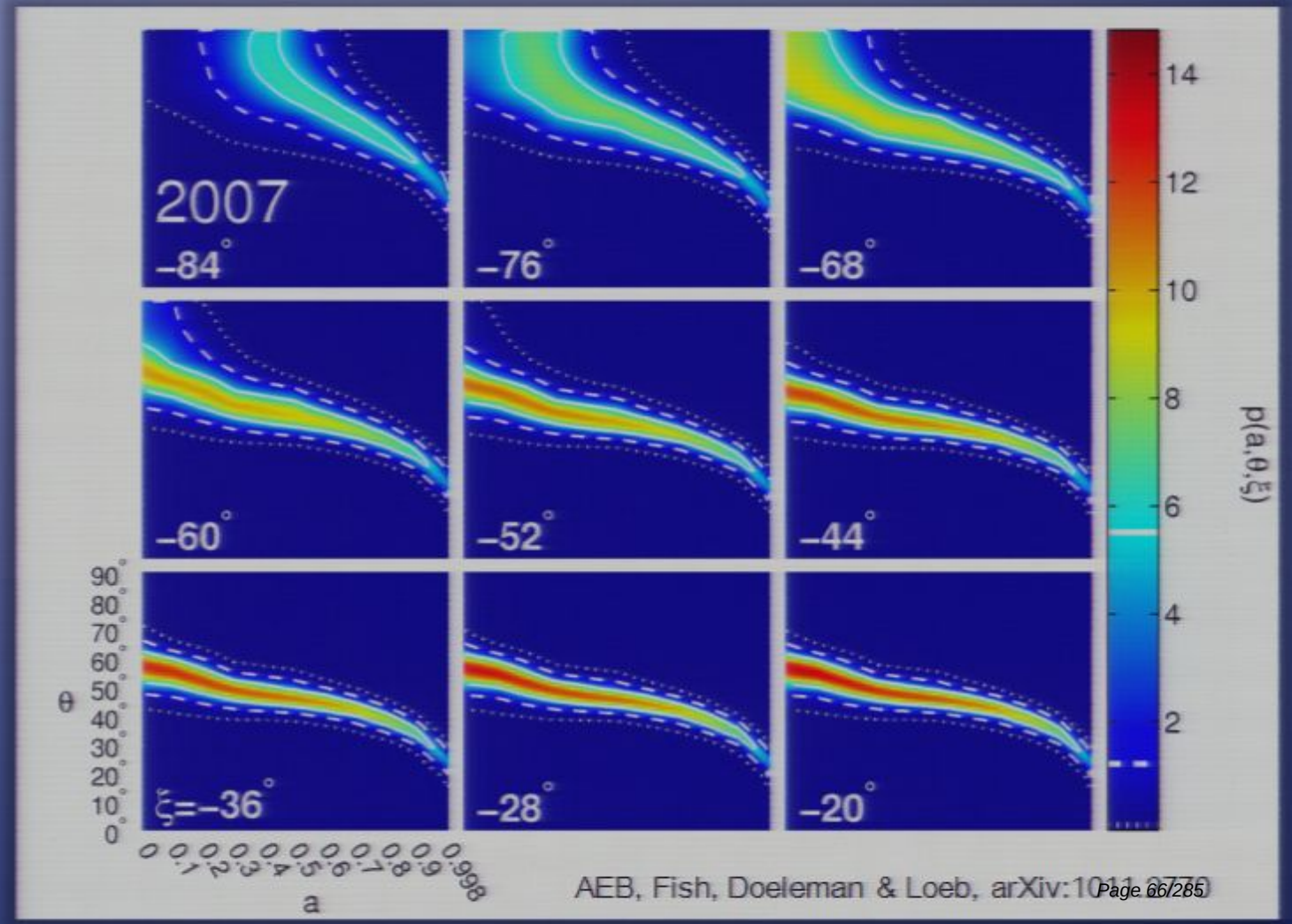

AEB, Fish, Doeleman & Loeb, arXiv:1011.2778

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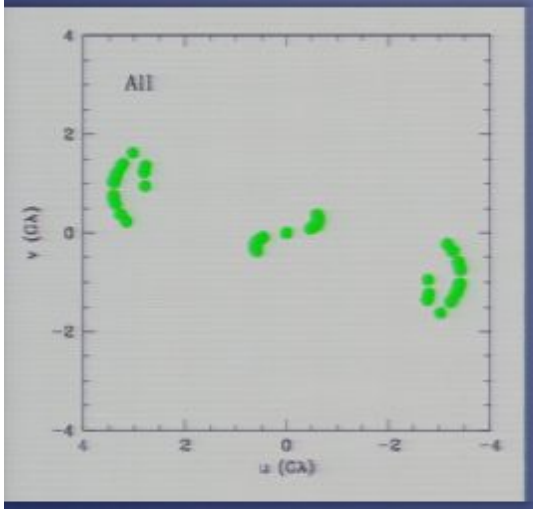
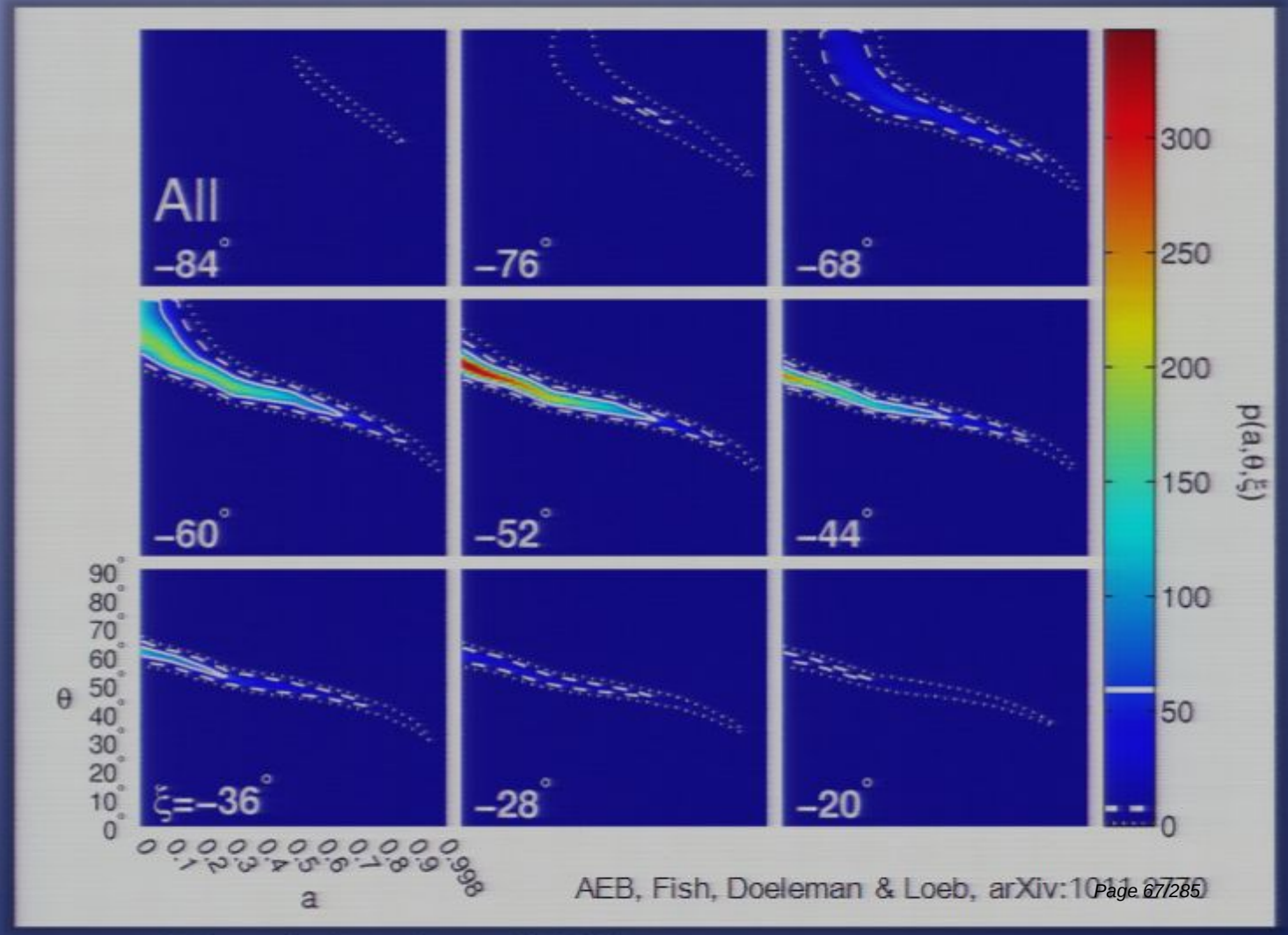
Sgr A* Parameter Estimation: Then and Now!





AEB, Fish, Doeleman & Loeb, arXiv:1011.2778

Perimeter Institute, January 31, 2011

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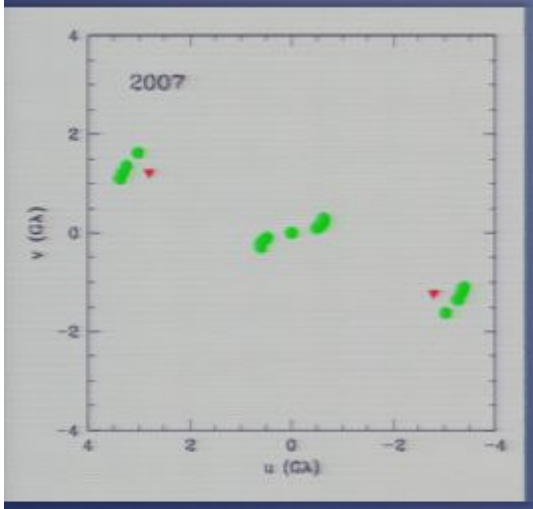

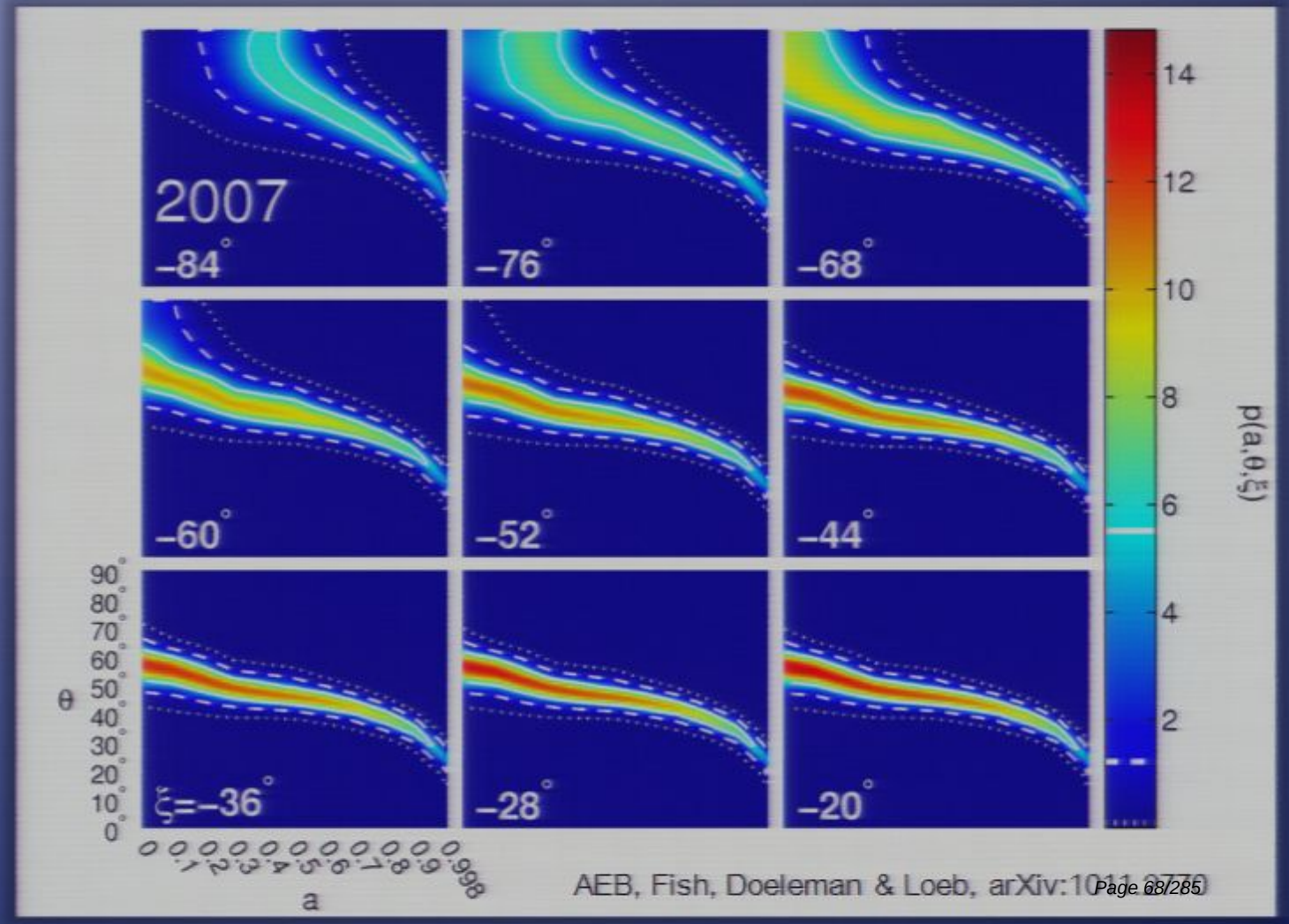

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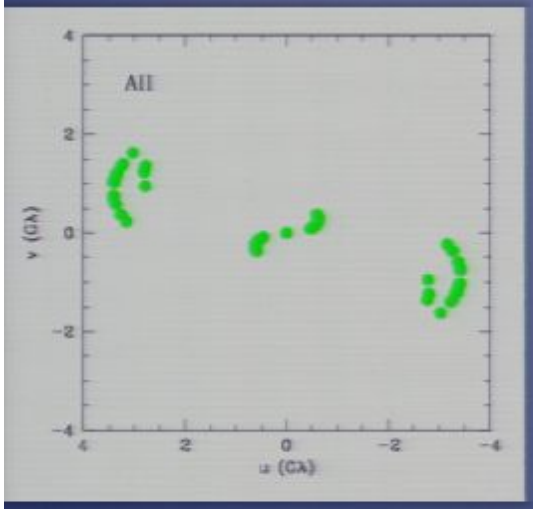
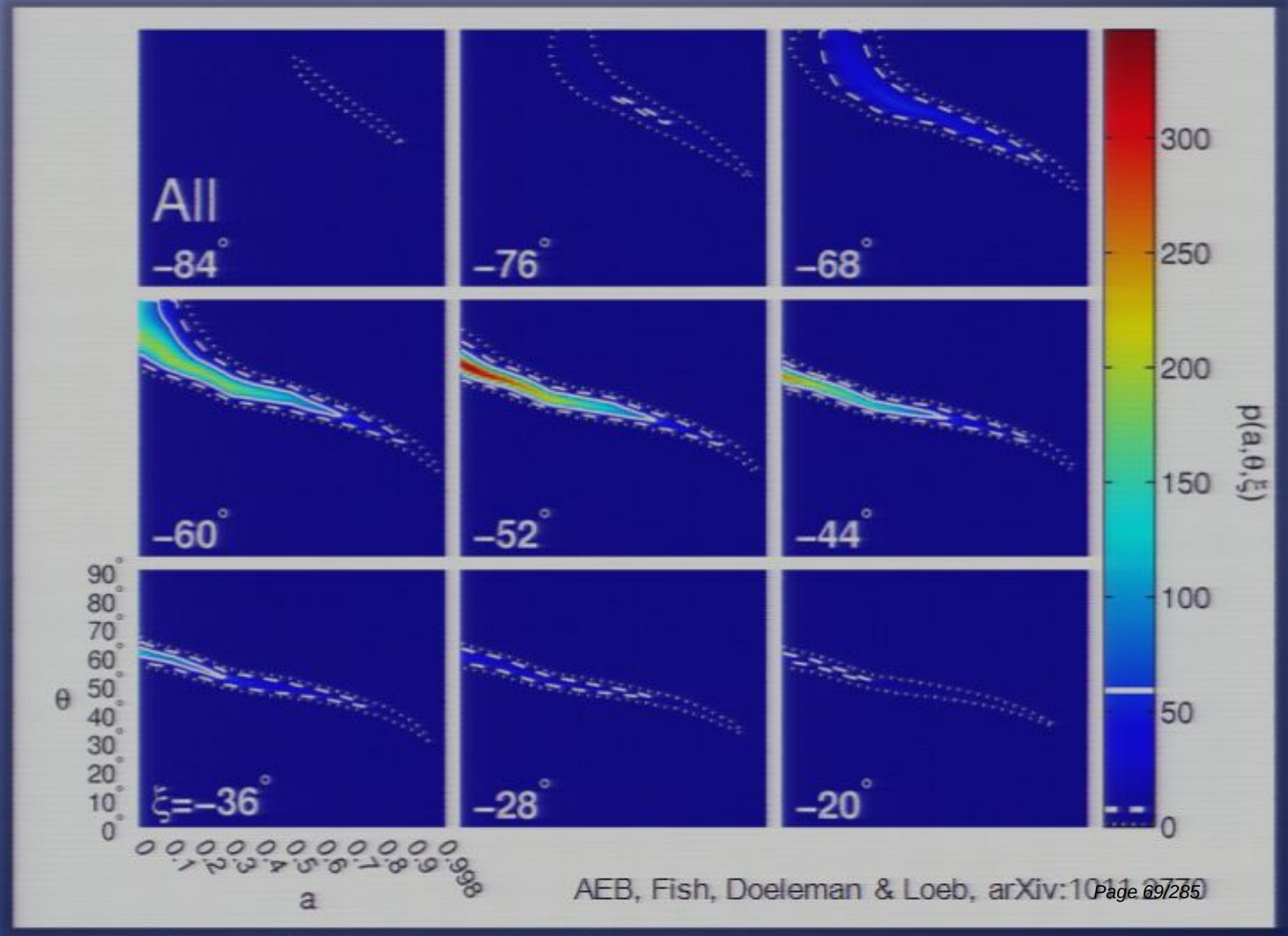


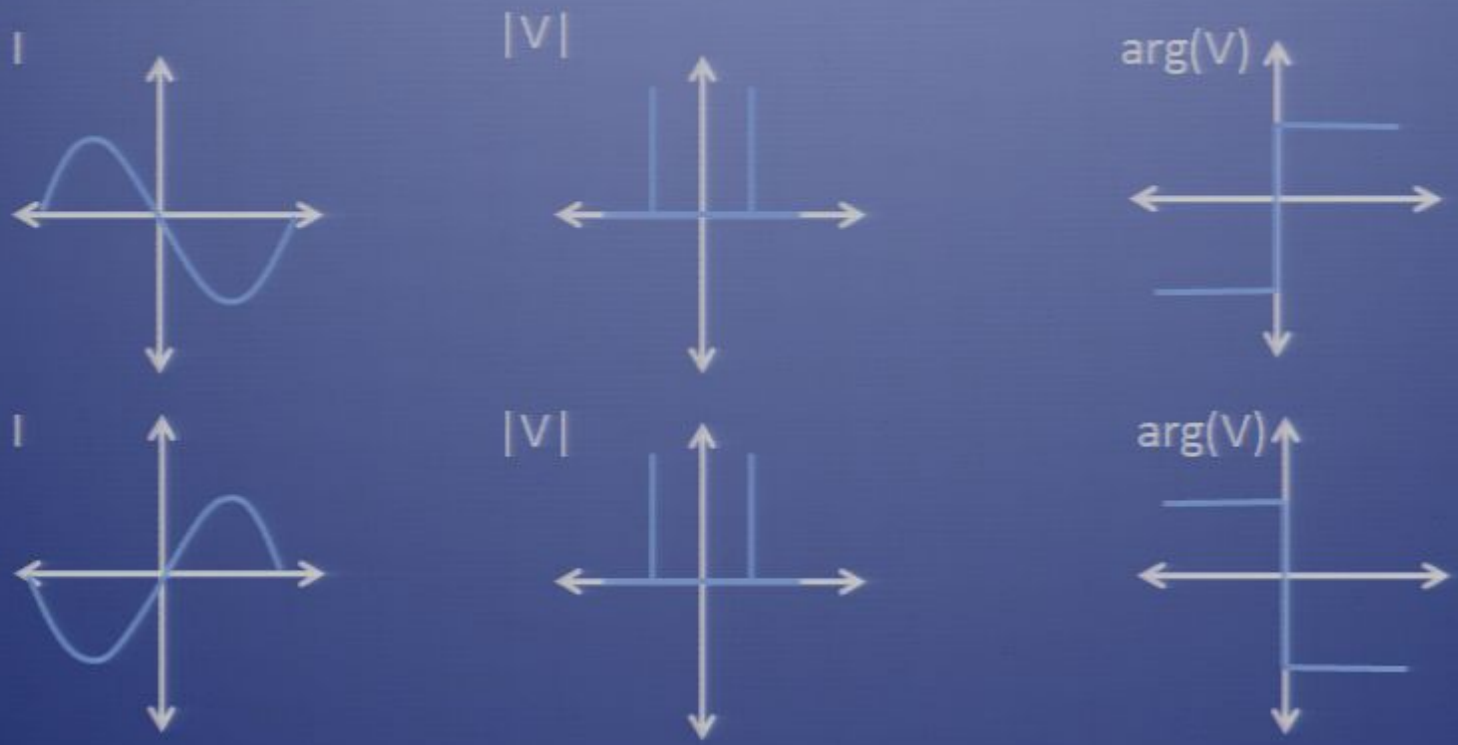


AEB, Fish, Doeleman & Loeb, arXiv:1011.2778

. and taking black hole portraits

First Phase Measurements!

- Lack of phase info gives $\xi \rightarrow \xi + 180°$ degeneracy!

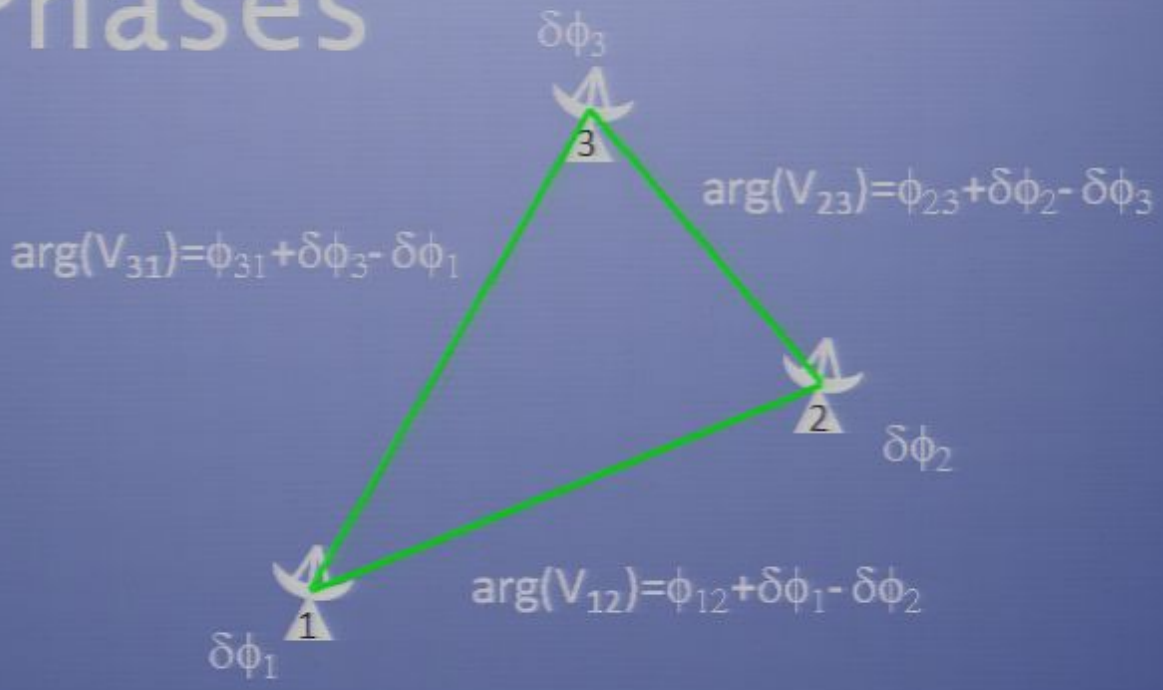


. and taking black hole portraits

Closure Phases

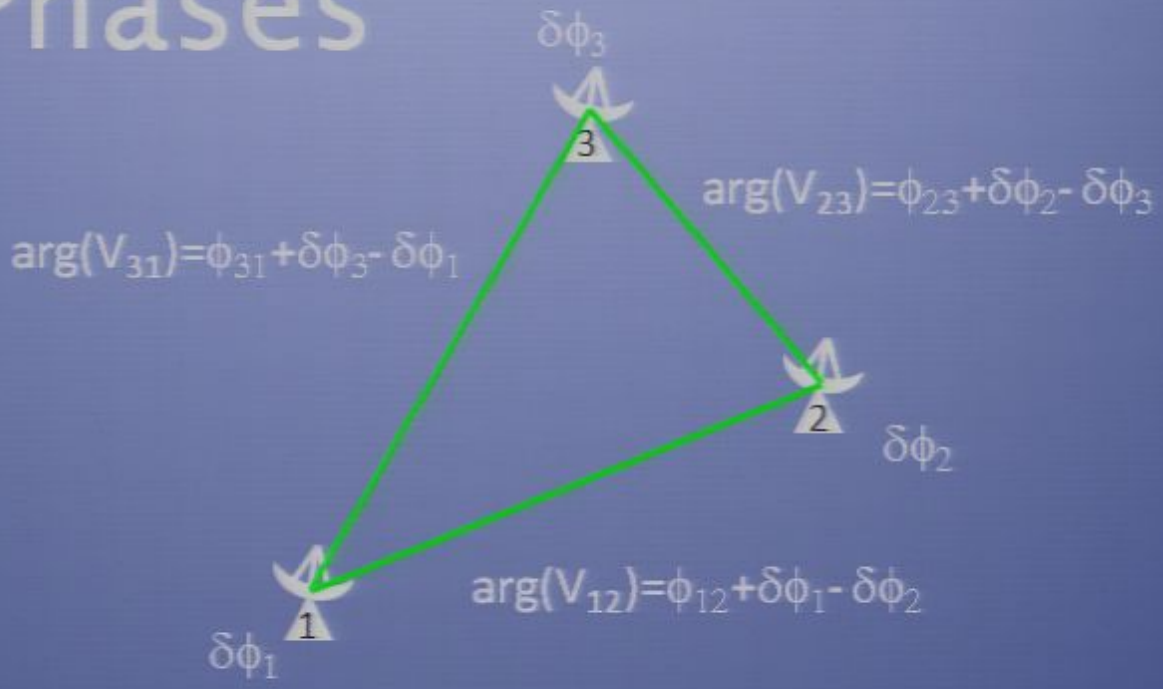
. and taking black hole portraits

Closure Phases



. and taking black hole portraits

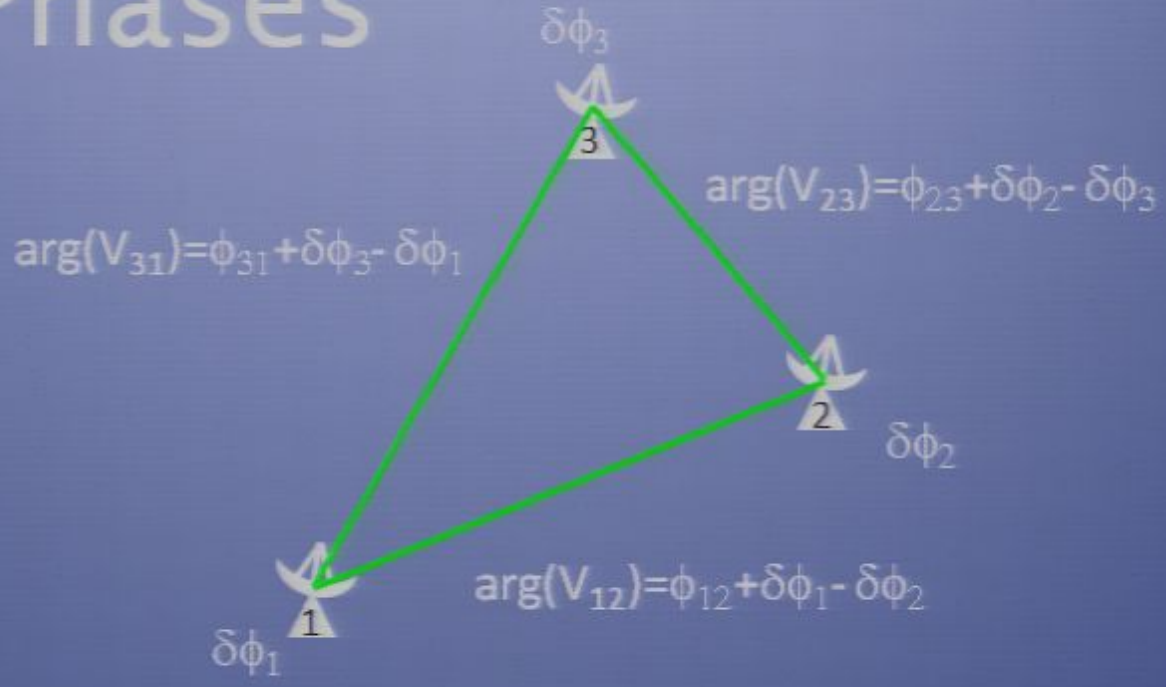
Closure Phases



$$\Phi_{123} = \arg(V_{12})+\arg(V_{23})+\arg(V_{31}) = \phi_{12}+\phi_{23}+\phi_{31}$$

. and taking black hole portraits

Closure Phases

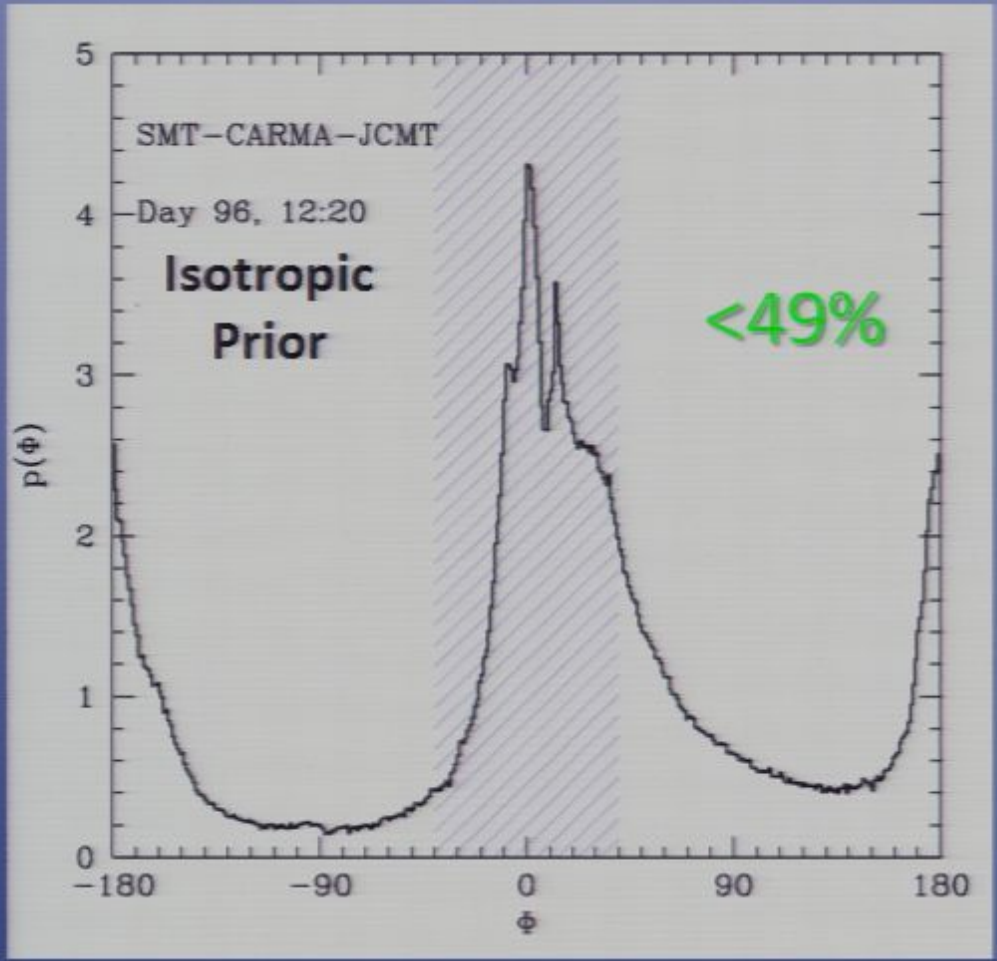


$$\Phi_{123} = \arg(V_{12})+\arg(V_{23})+\arg(V_{31}) = \phi_{12}+\phi_{23}+\phi_{31}$$

$$\Phi_{\text{SMT-CARMA-JCMT}} = 0^{o} +- 40^{o}$$

. and taking black hole portraits

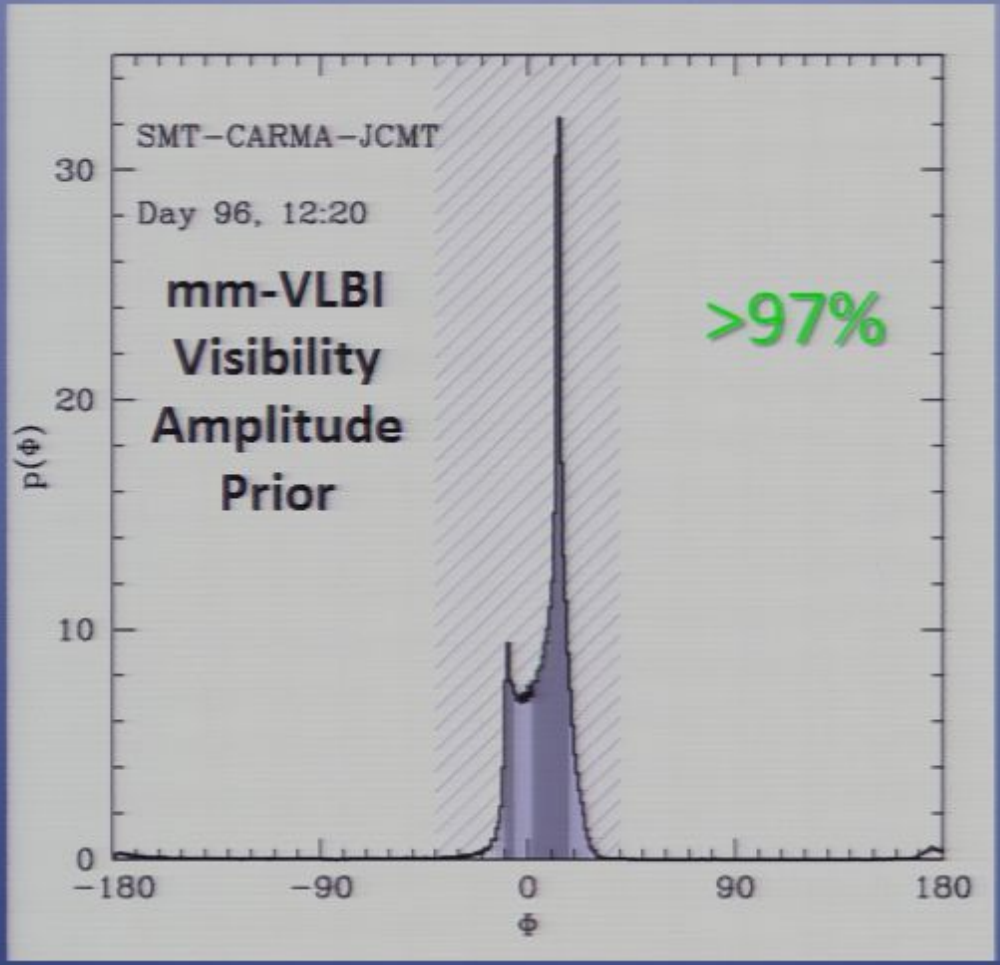
Sgr A* Closure Phase



AEB, Fish, Doeleman & Loeb (2011)

. and taking black hole portraits

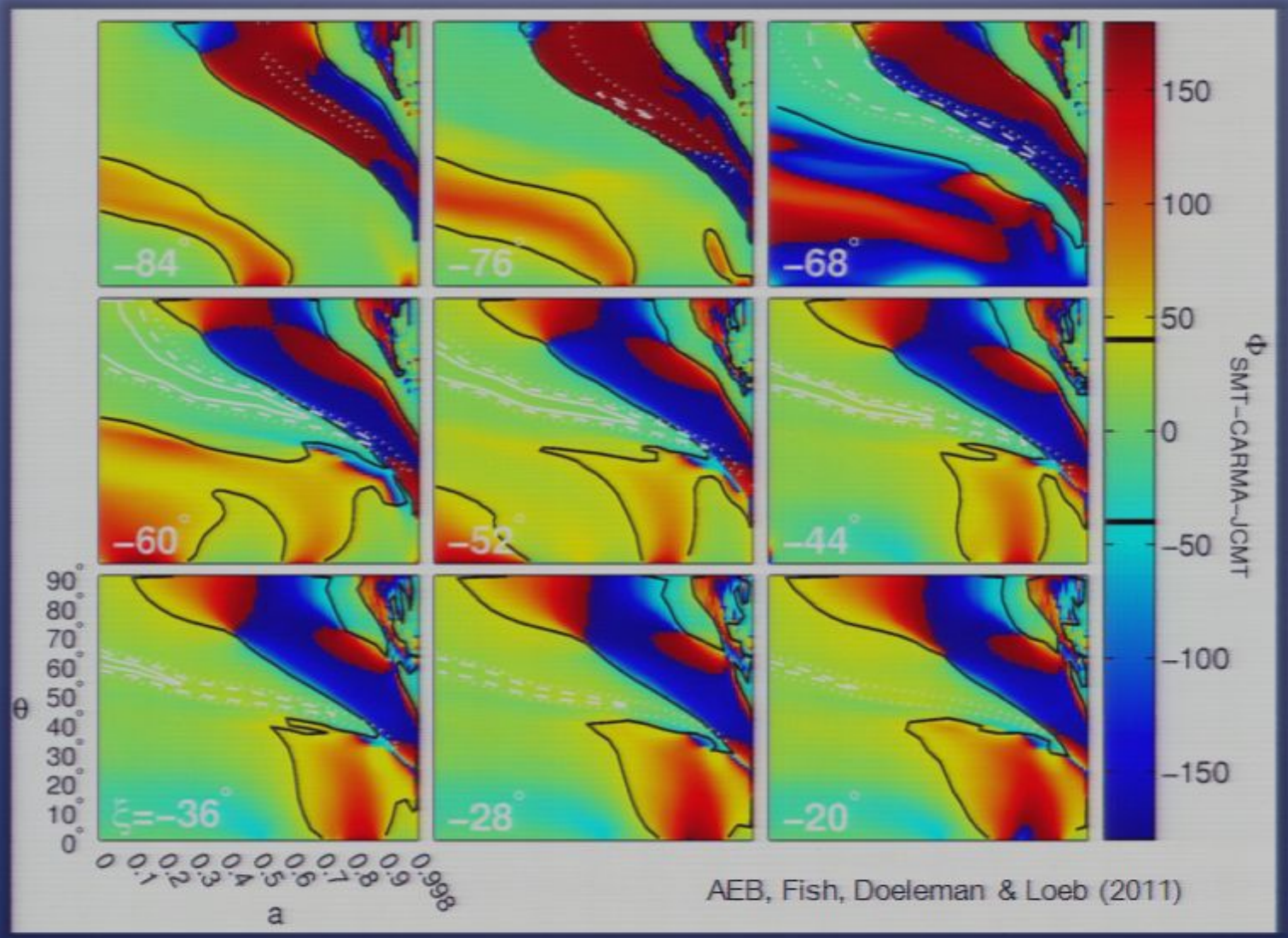
Sgr A* Closure Phase



AEB, Fish, Doeleman & Loeb (2011)

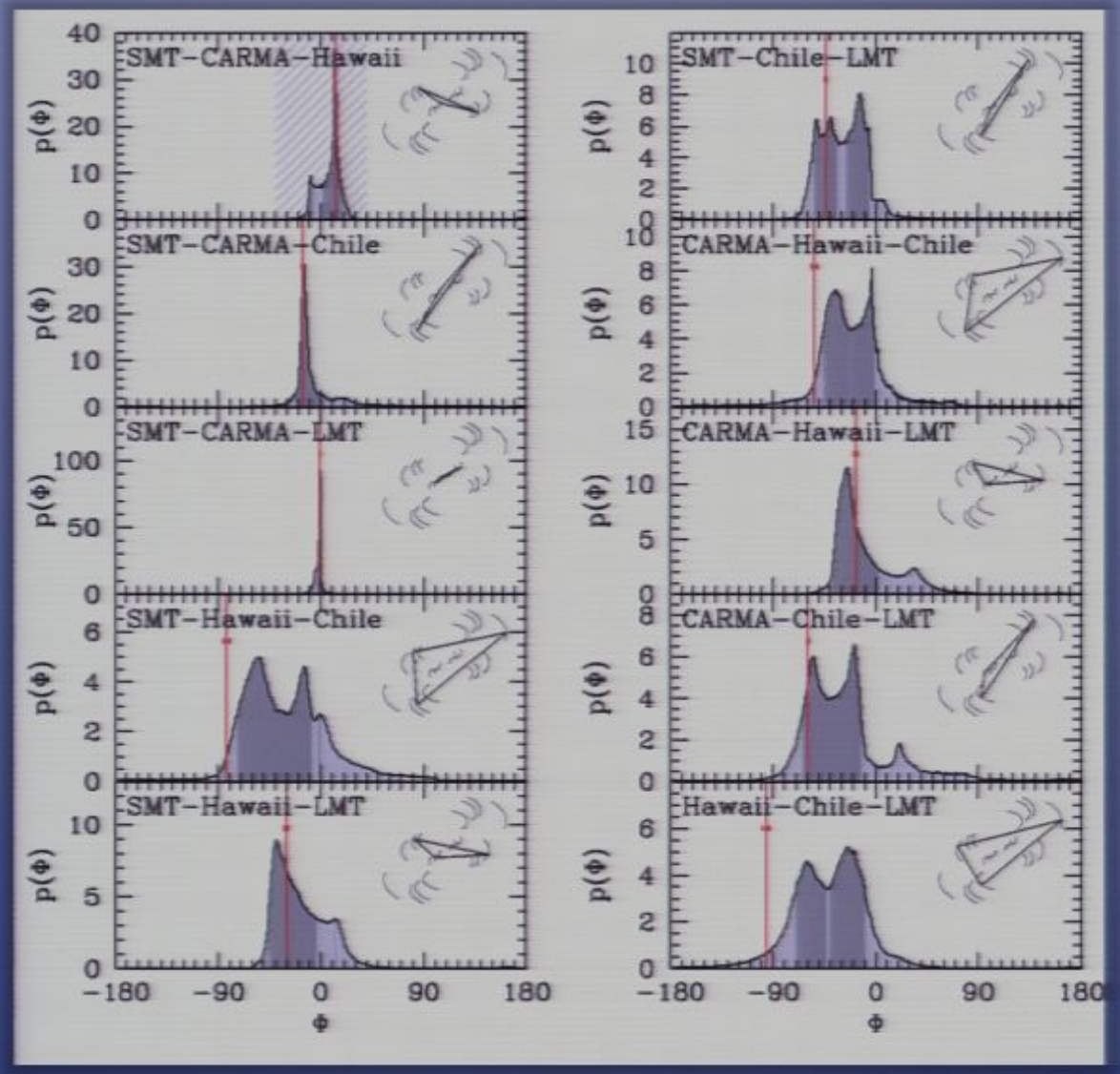
. and taking black hole portraits

Sgr A* Closure Phase



. and taking black hole portraits

Sgr A* Closure Phases

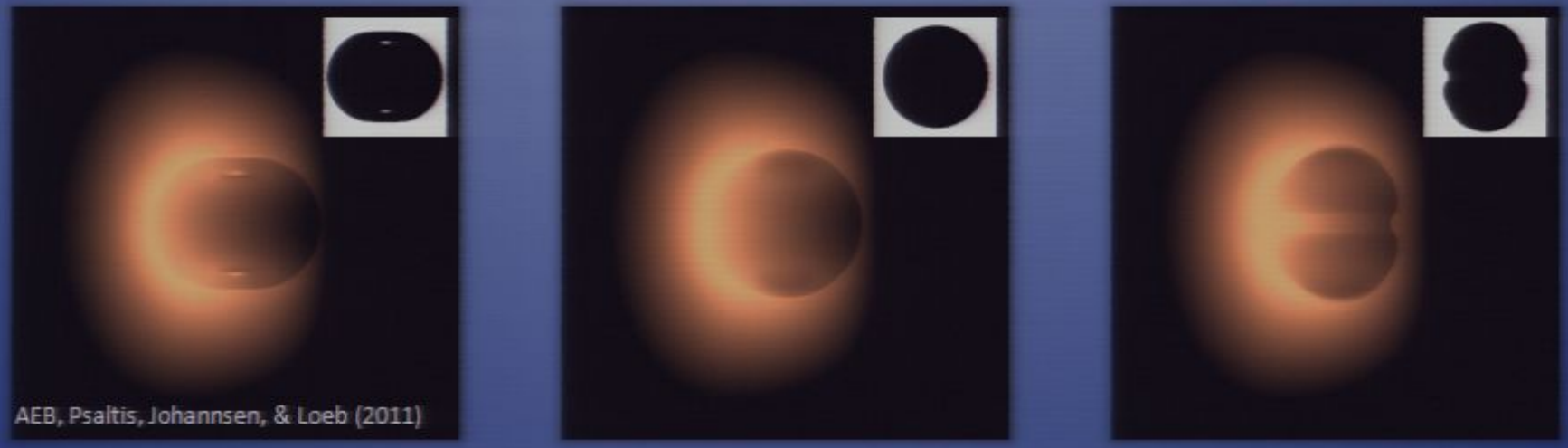


AEB, Fish, Doeleman & Loeb (2011)

. and taking black hole portraits

"Bumpy" Spacetimes and testing GR

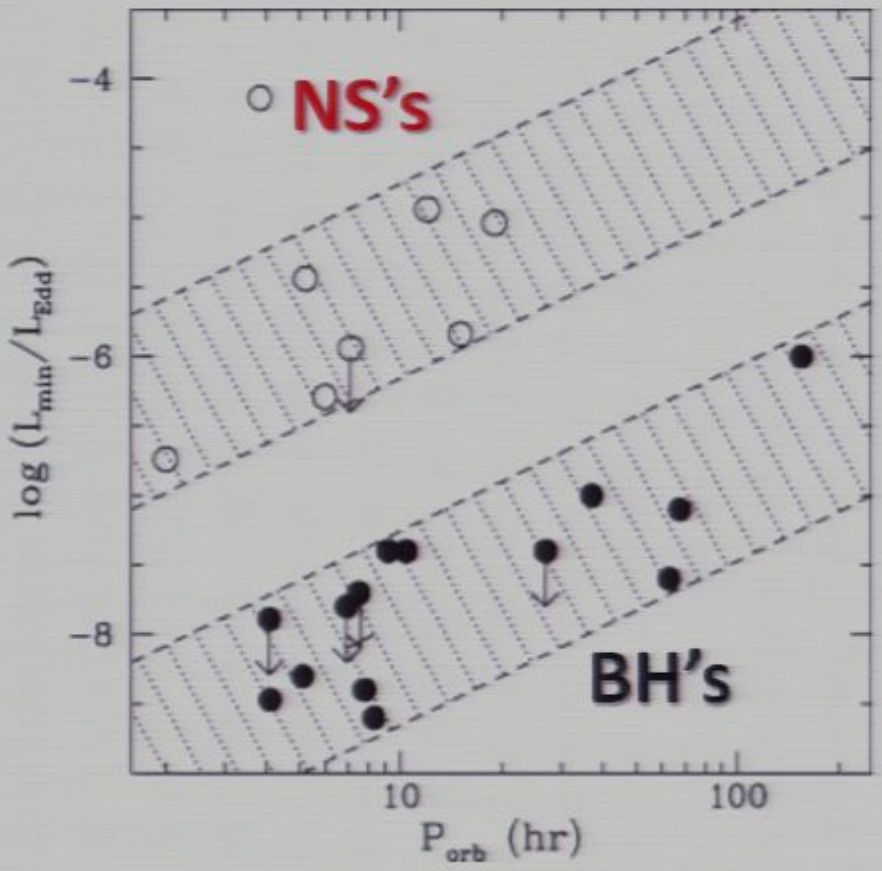
- Weak Field → PPN ($\gamma,\beta,\alpha_{1,2,3},\zeta_{1,2,3,4},\xi$)
  → "reasonable" set of perturbations!
- Strong Field → complicated!
  - Add perturbations that satisfy the Einstein equations.
  - Hartle-Thorne gives some physical context far away



  - Vigeland & Hughes (2010) gives many multipoles

lorizons do exist!

Probing horizons



Narayan & McClintock, New AR (2008)
Garcia et al. (2001)

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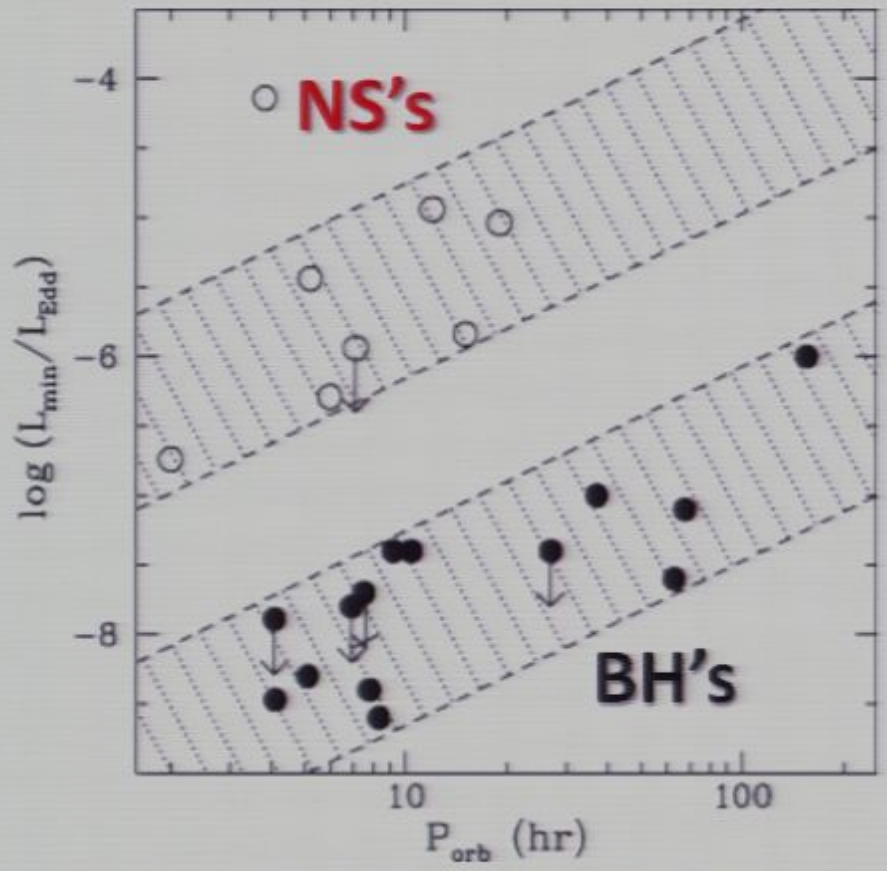

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$$L_{obs} = \eta_r \Delta\varepsilon_g \dot{M} c^2$$

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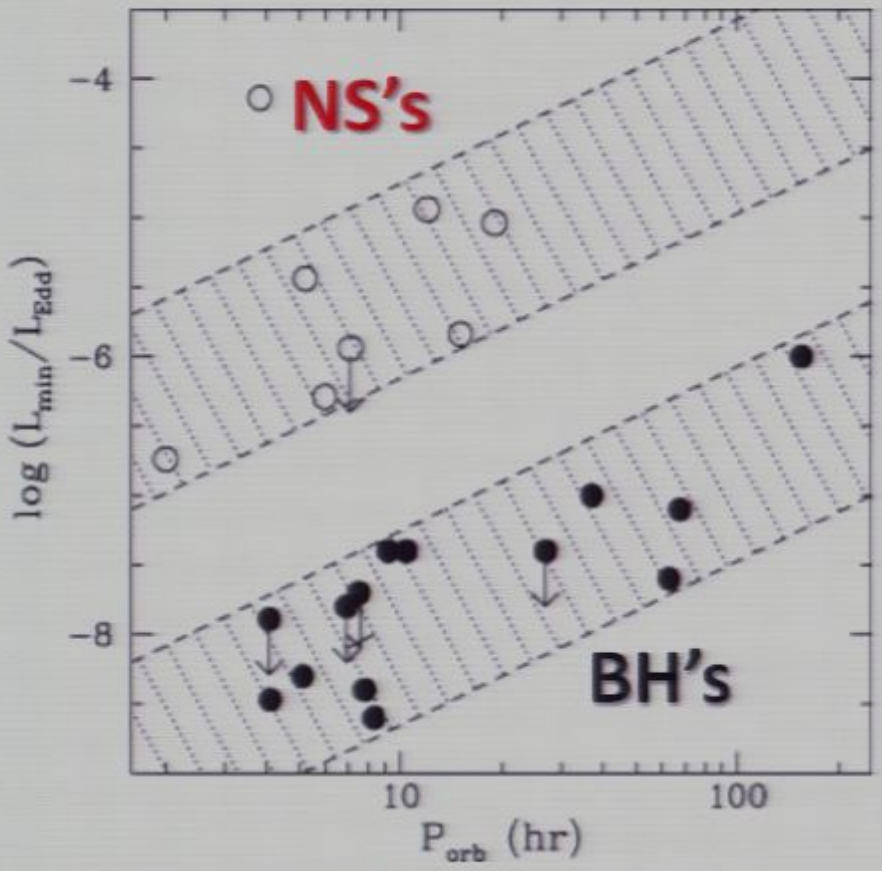

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Garcia et al. (2001)

$$L_{obs} = \eta_r \Delta\varepsilon_g \dot{M} c^2$$

Source	η_r
Sgr A*	~0.1%
Quasar	~10%

lorizons do exist!

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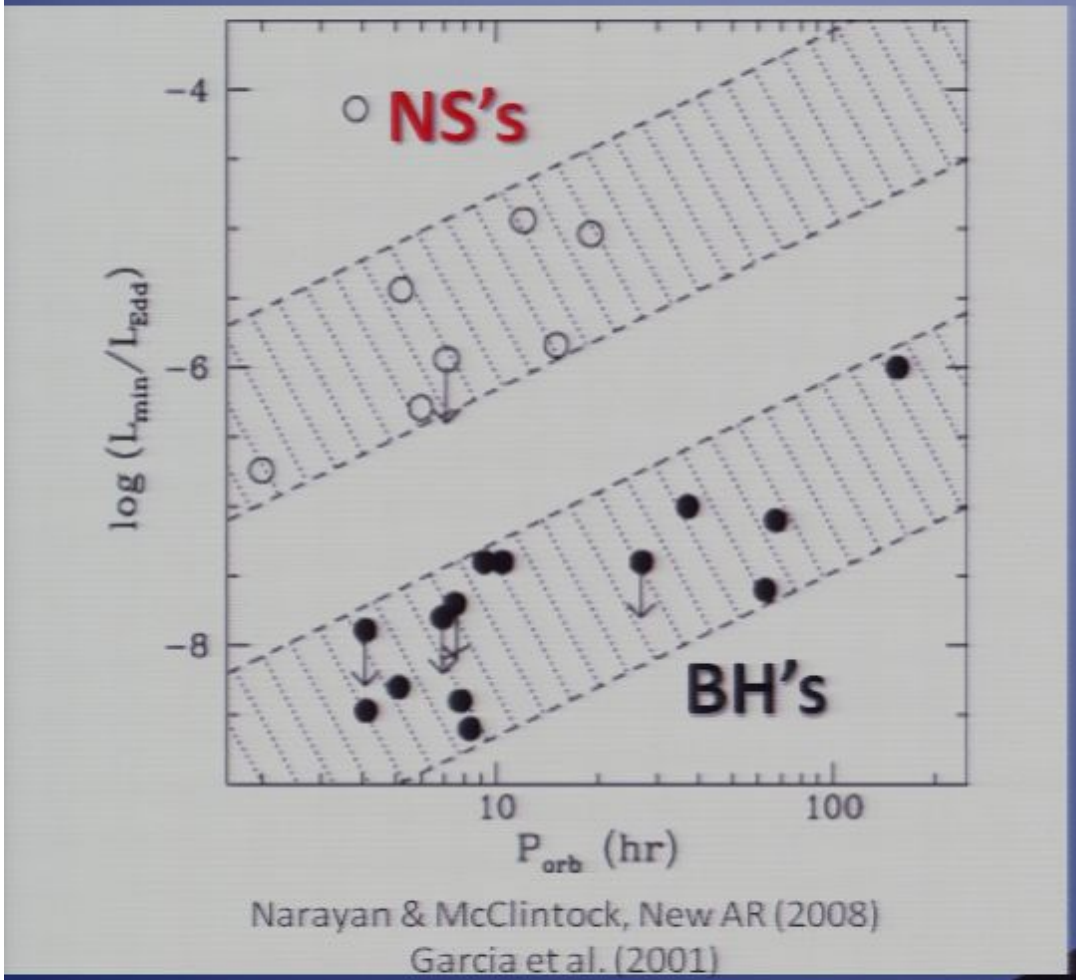

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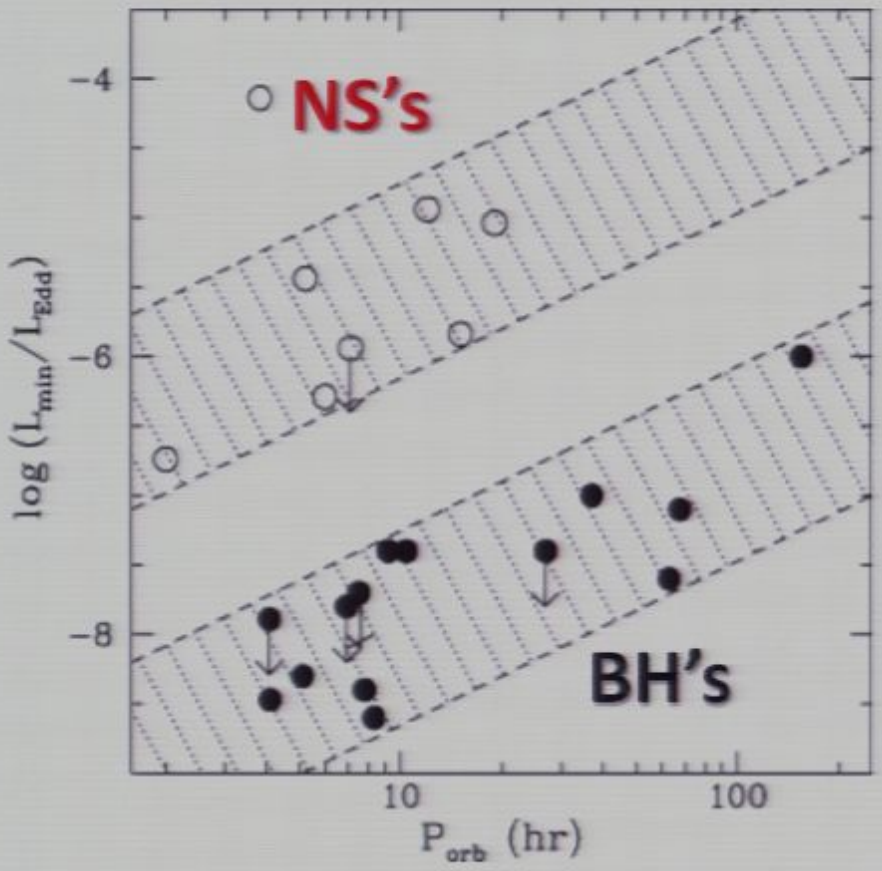

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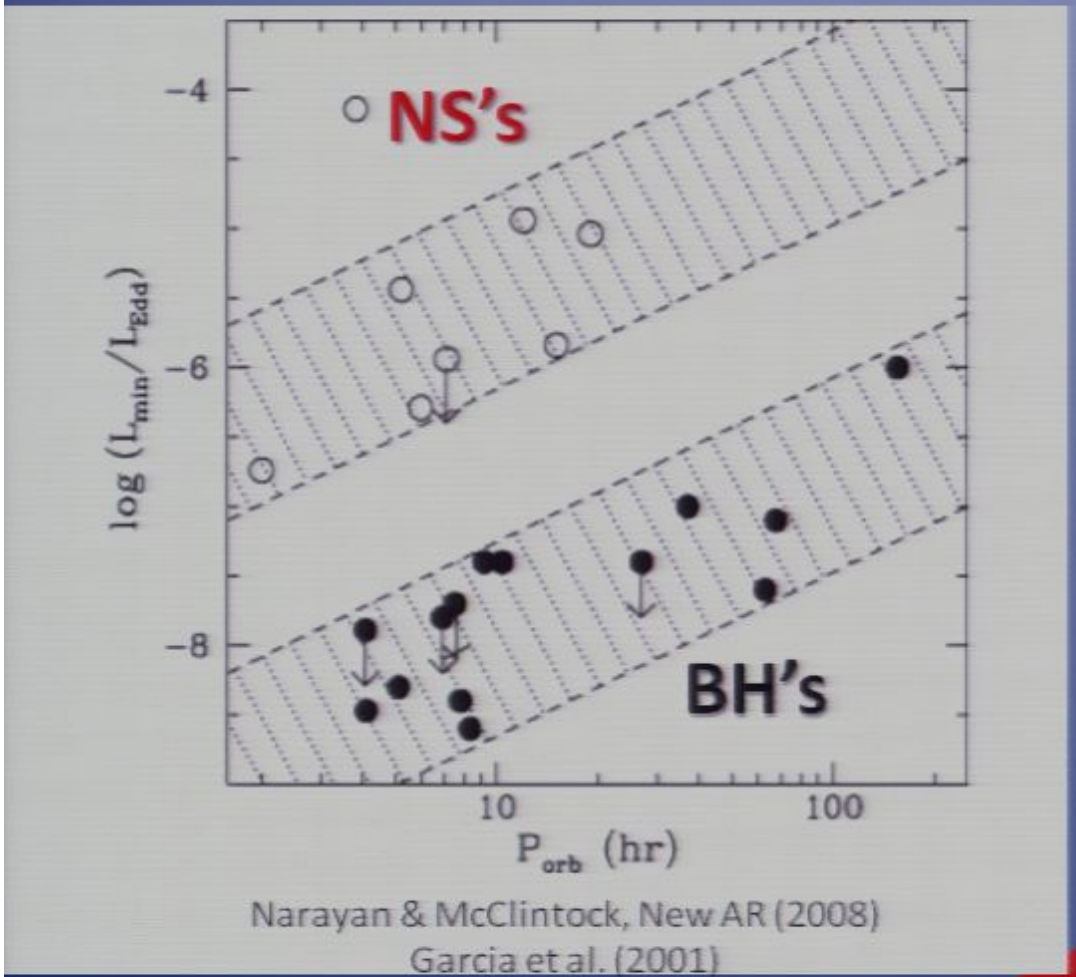

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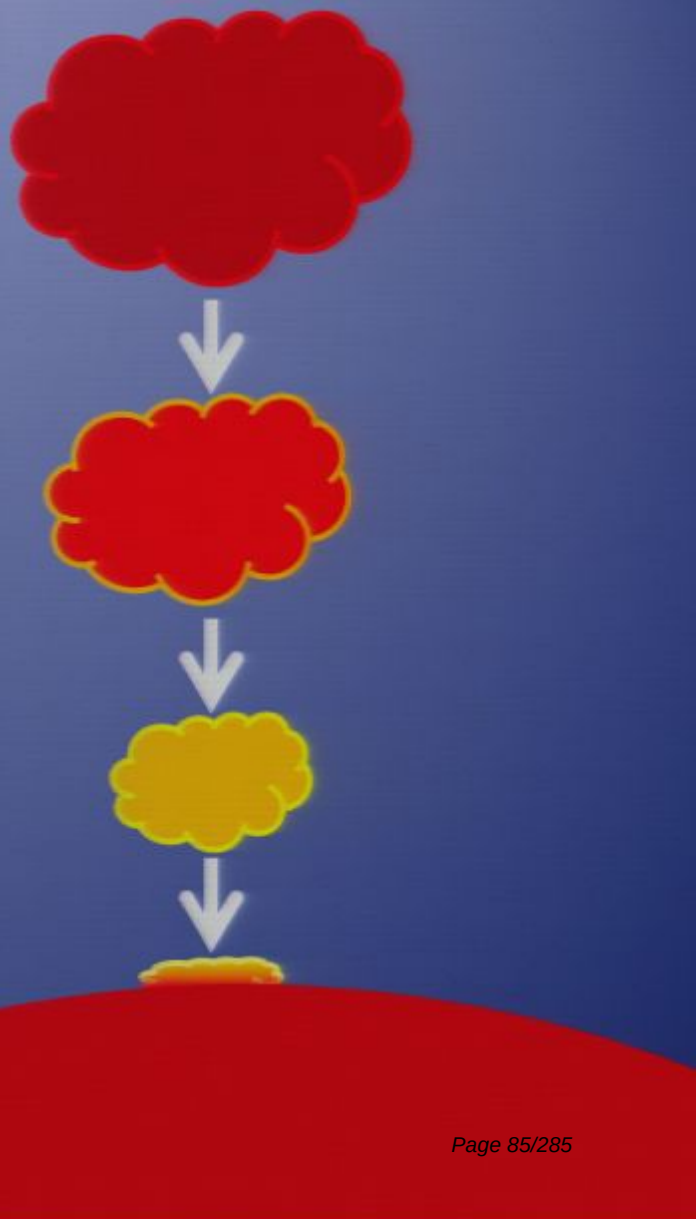

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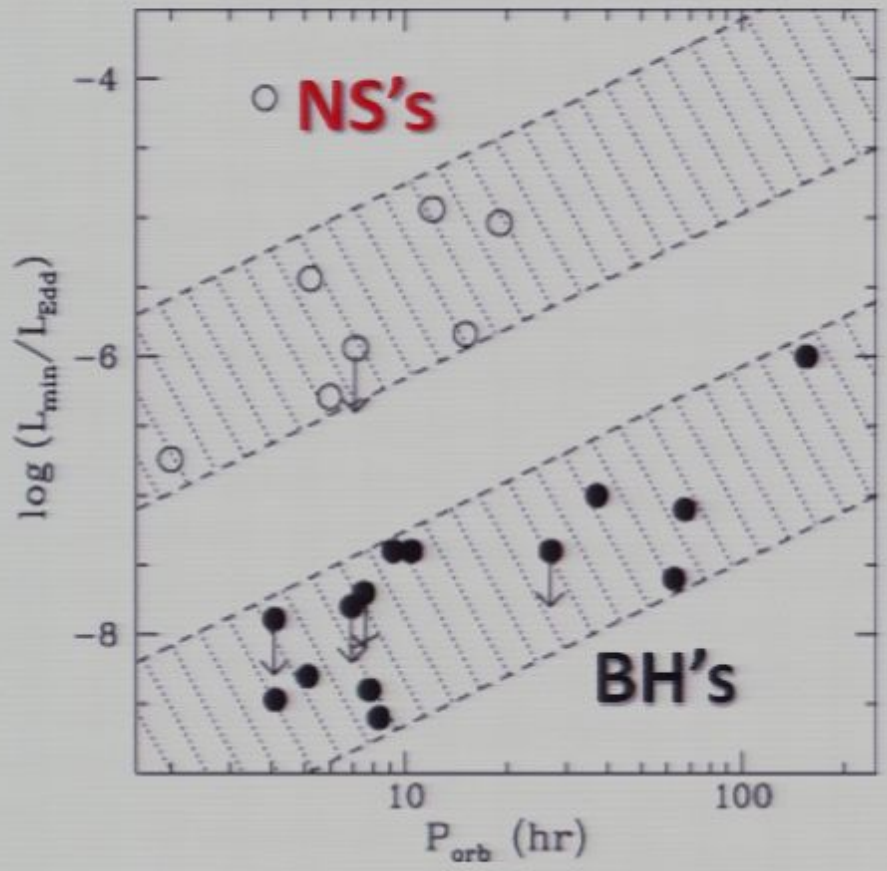

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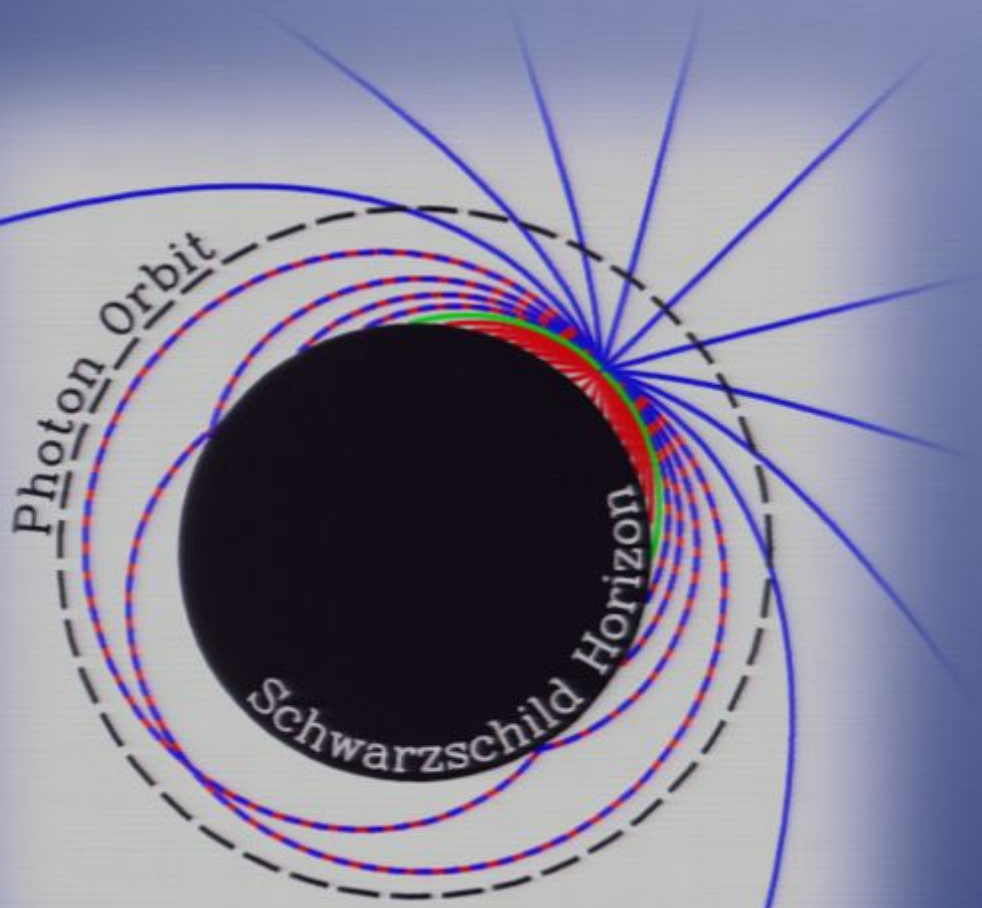
$$L_{obs} = \eta_r \Delta \varepsilon_g \dot{M} c^2$$

$$L_{surf} = (1 - \eta_r - \eta_k) \Delta \varepsilon_g \dot{M} c^2$$

$$\geq \frac{1 - \eta_r - \eta_k}{\eta_r + \eta_k} L_{obs}$$

lorizons do exist!

Probing horizons



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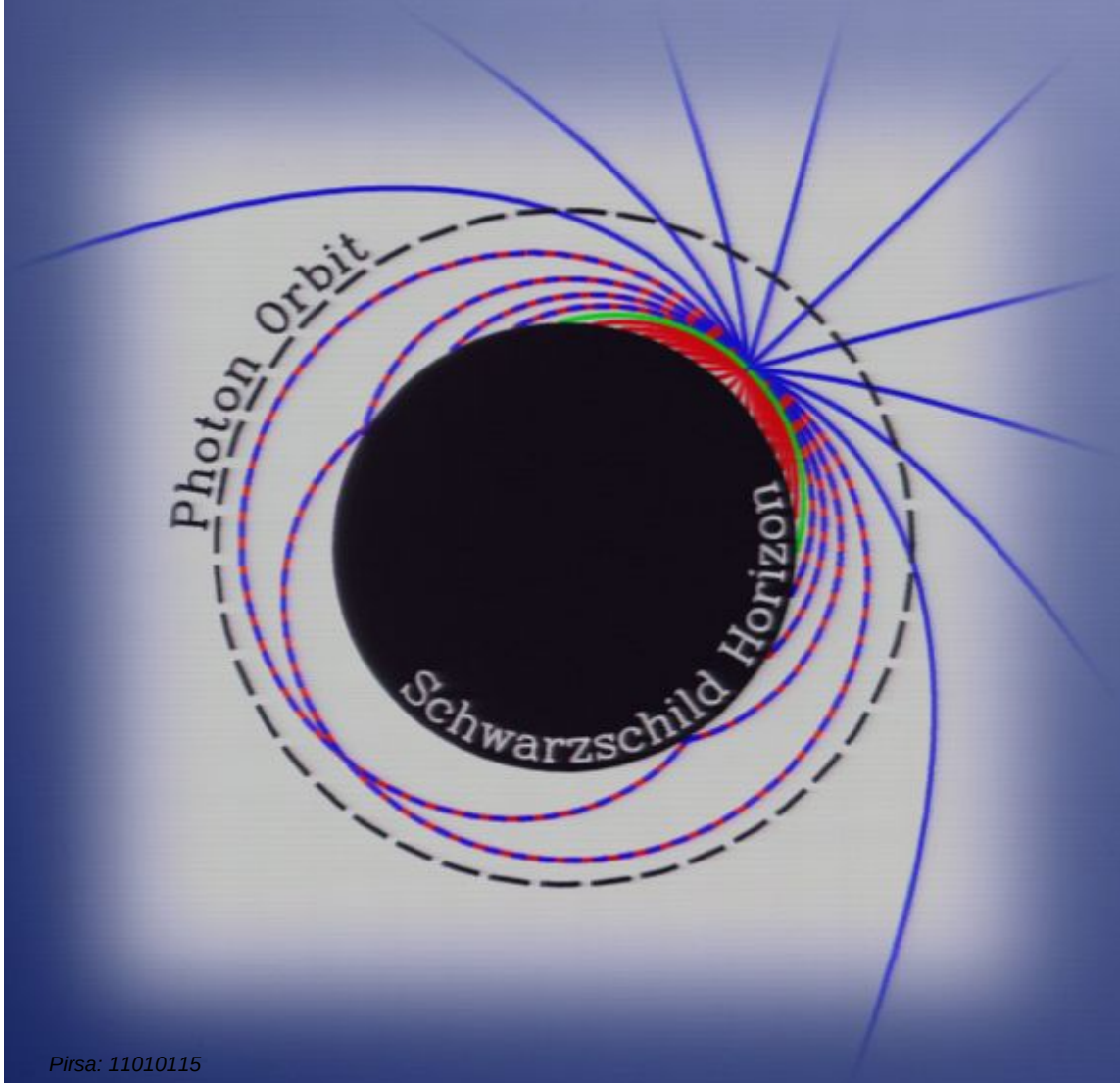

Blackbody Cavity

lorizons do exist!

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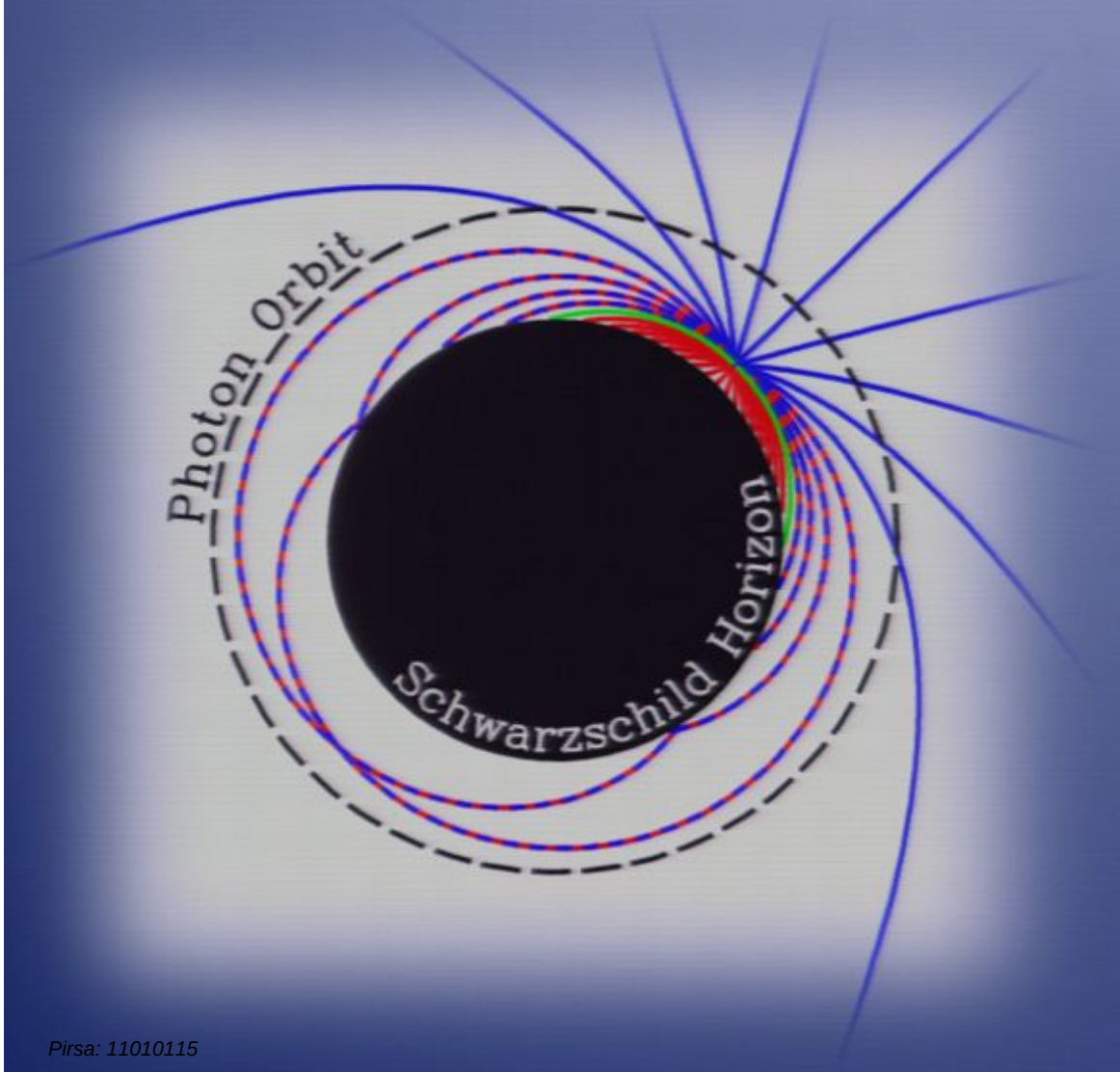

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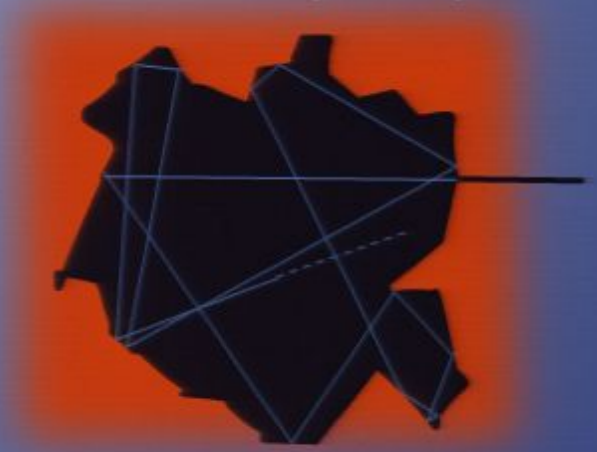

Compact surfaces are ***blackbodies***!

$$L_{surf} = 4\pi R_a^2 \sigma T_\infty^4$$

$$\rightarrow \quad T_\infty\left(L_{surf}, R_a\right)$$

lorizons do exist!

Probing horizons

lorizons do exist!

Probing horizons

0. Gravity is a metric theory admitting stationary solutions.
   - Some idea of energy conservation for test particles
   - Horizons surrounded by photon orbits → "compact" surfaces are BB's

lorizons do exist!

Probing horizons

0. Gravity is a metric theory admitting stationary solutions.
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1. Sgr A* is accretion powered
   - Embarrassment of riches
   - RM implied accretion rate near BH
   - Nested structure

$$L_{obs} = \eta_r \Delta\varepsilon_g \dot{M} c^2$$

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   - M ~ 20 s, T ~ 10^{10} yrs ~ 10^{16} M
   - Only log. dependent upon redshift
   - BH's violate this!

$$L_{obs} = \eta_r \Delta\varepsilon_g \dot{M} c^2$$

$$L_{surf} \geq \frac{1-\eta_r-\eta_k}{\eta_r+\eta_k} L_{obs}$$

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lorizons do exist!

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lorizons do exist!

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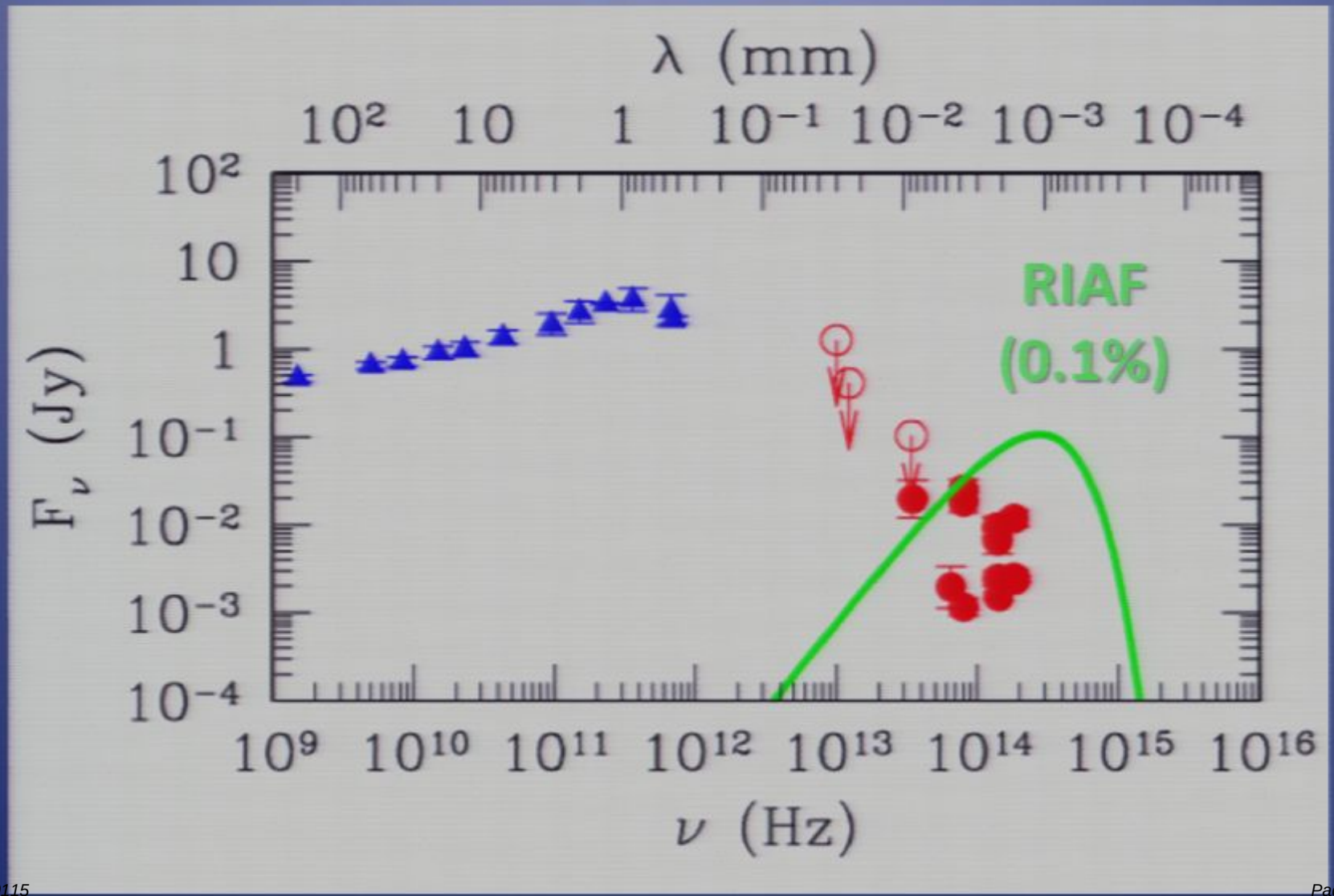

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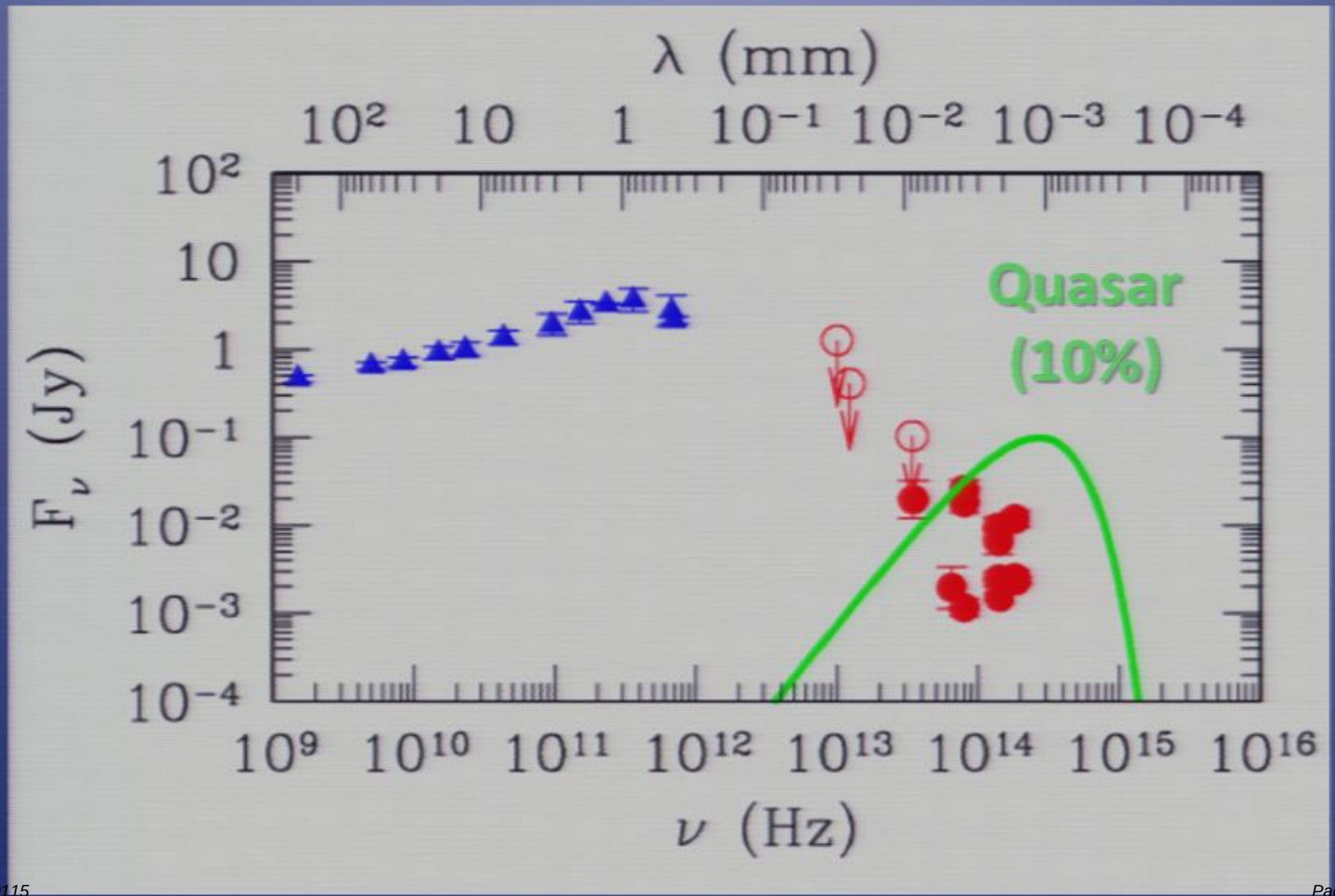

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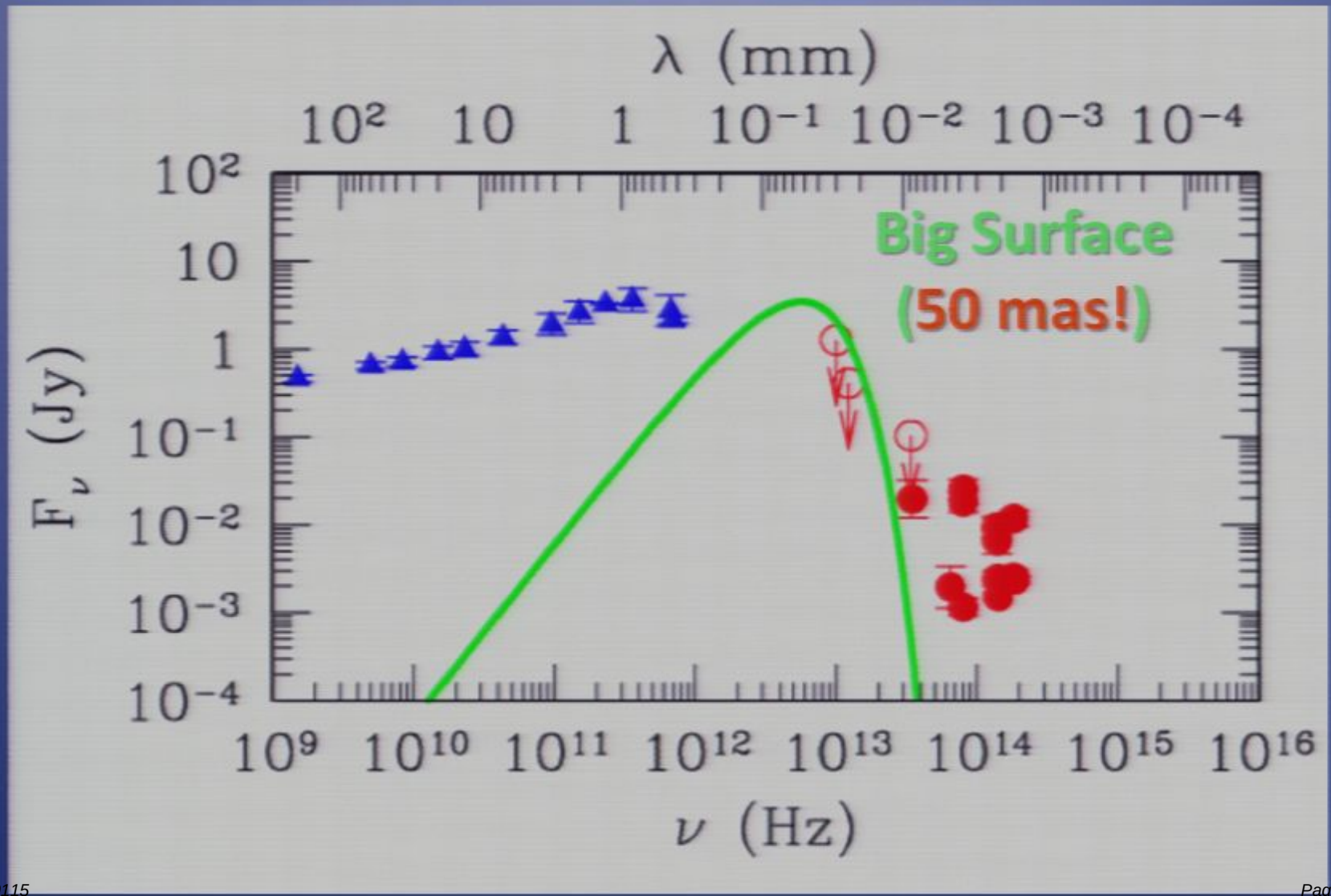

lorizons do exist!

Probing horizons

AEB, Loeb & Narayan (2009)

lorizons do exist!

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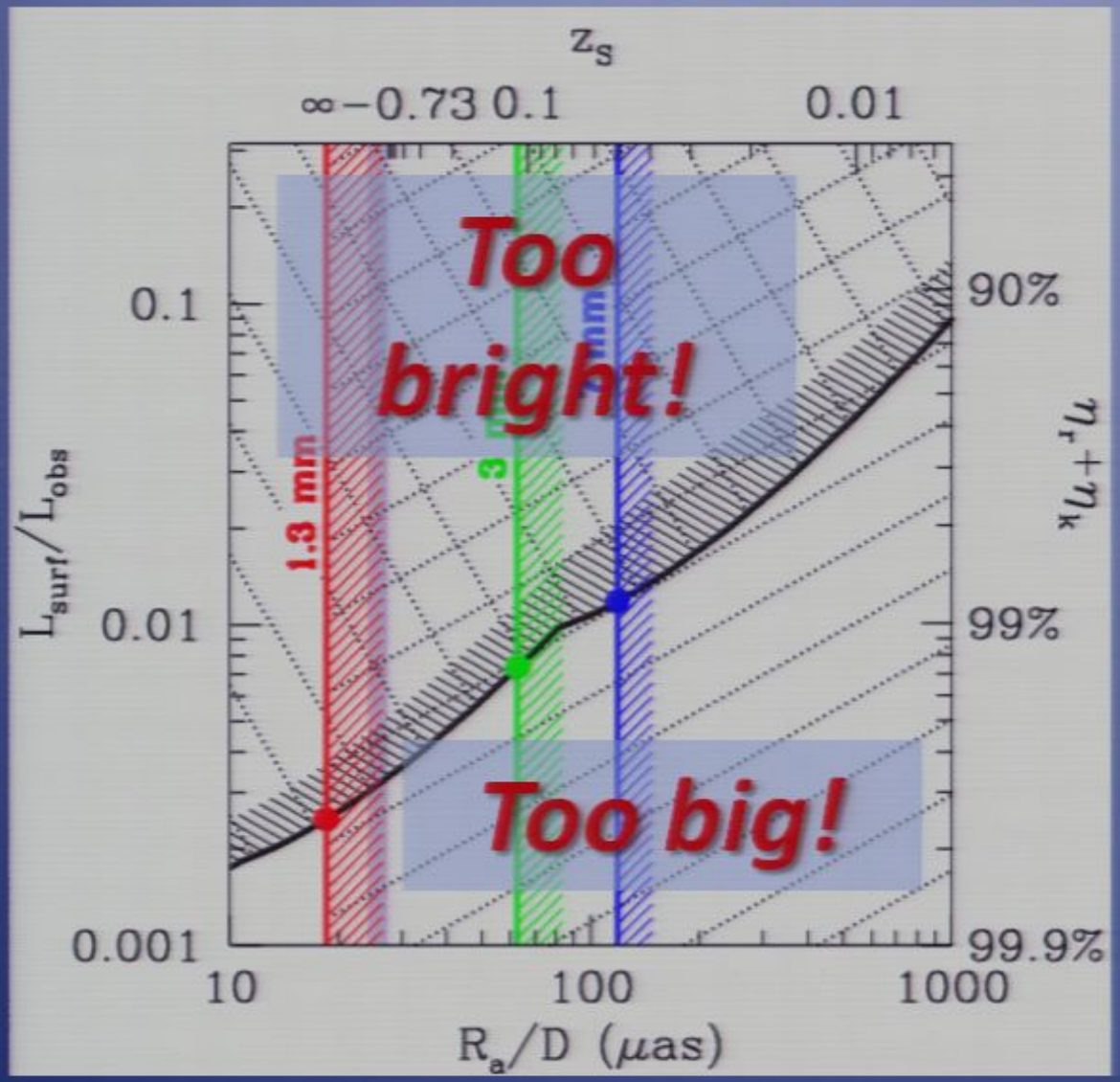

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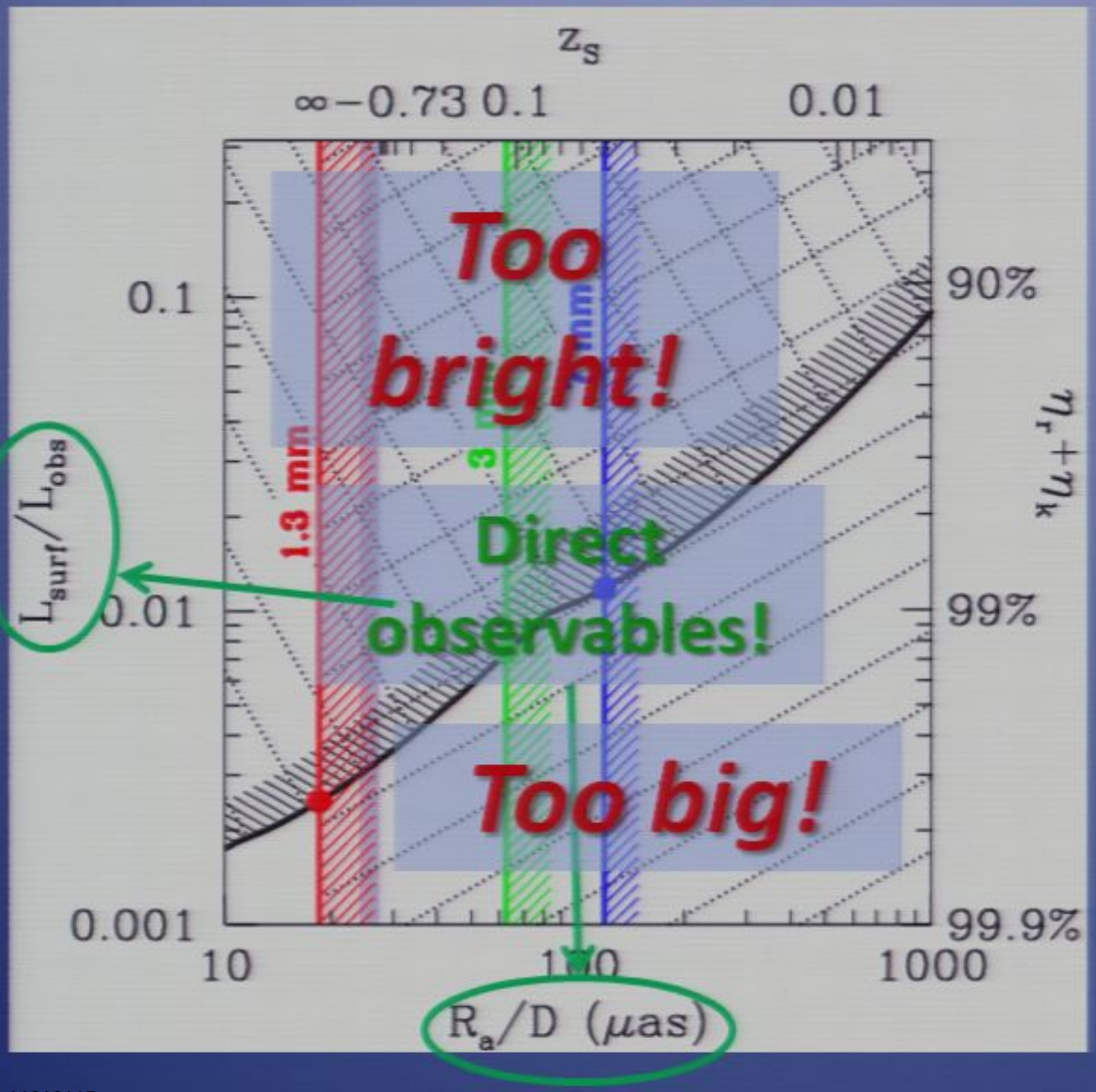

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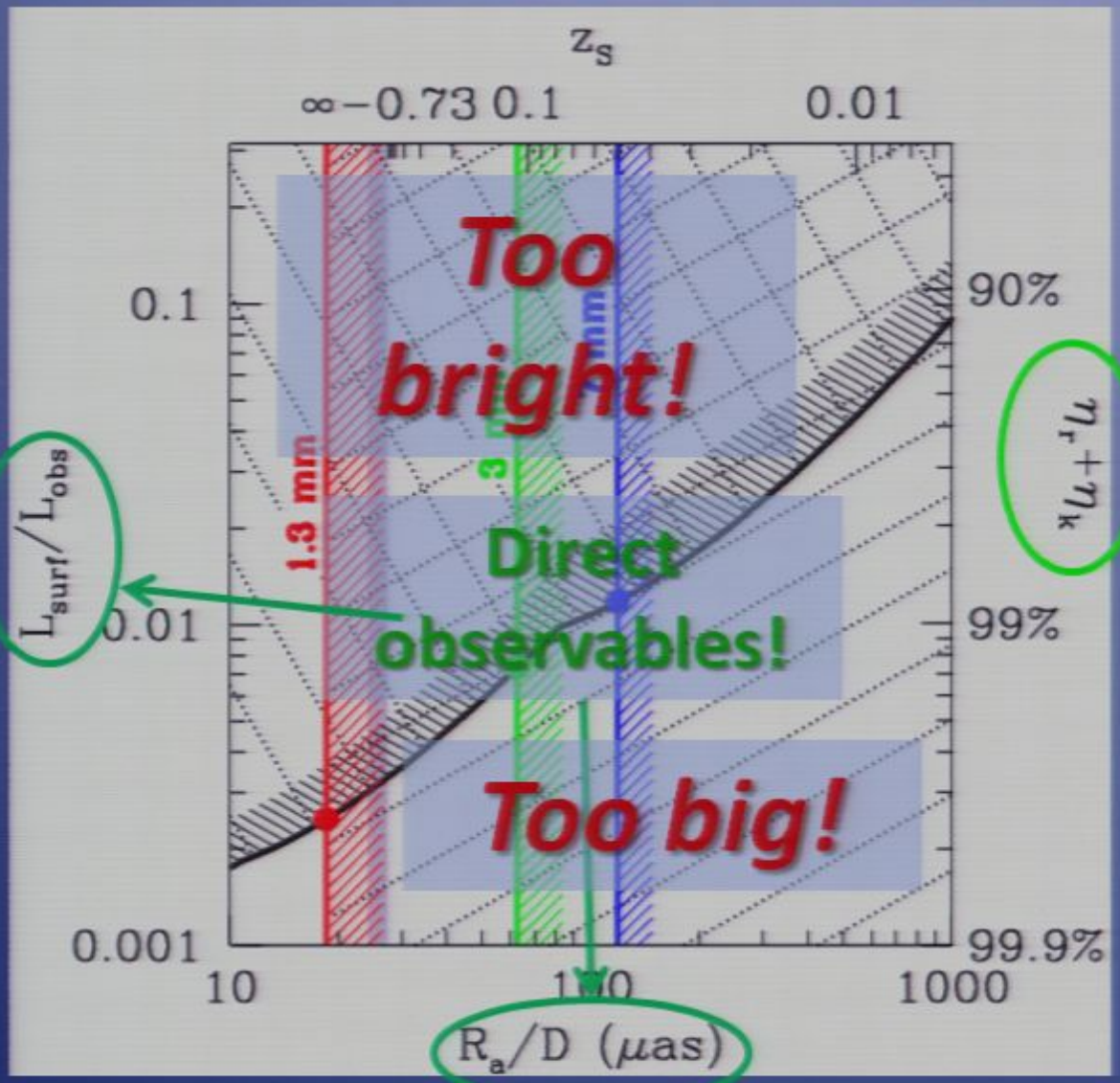


AEB, Loeb & Narayan (2009)

Property of the accretion flow!

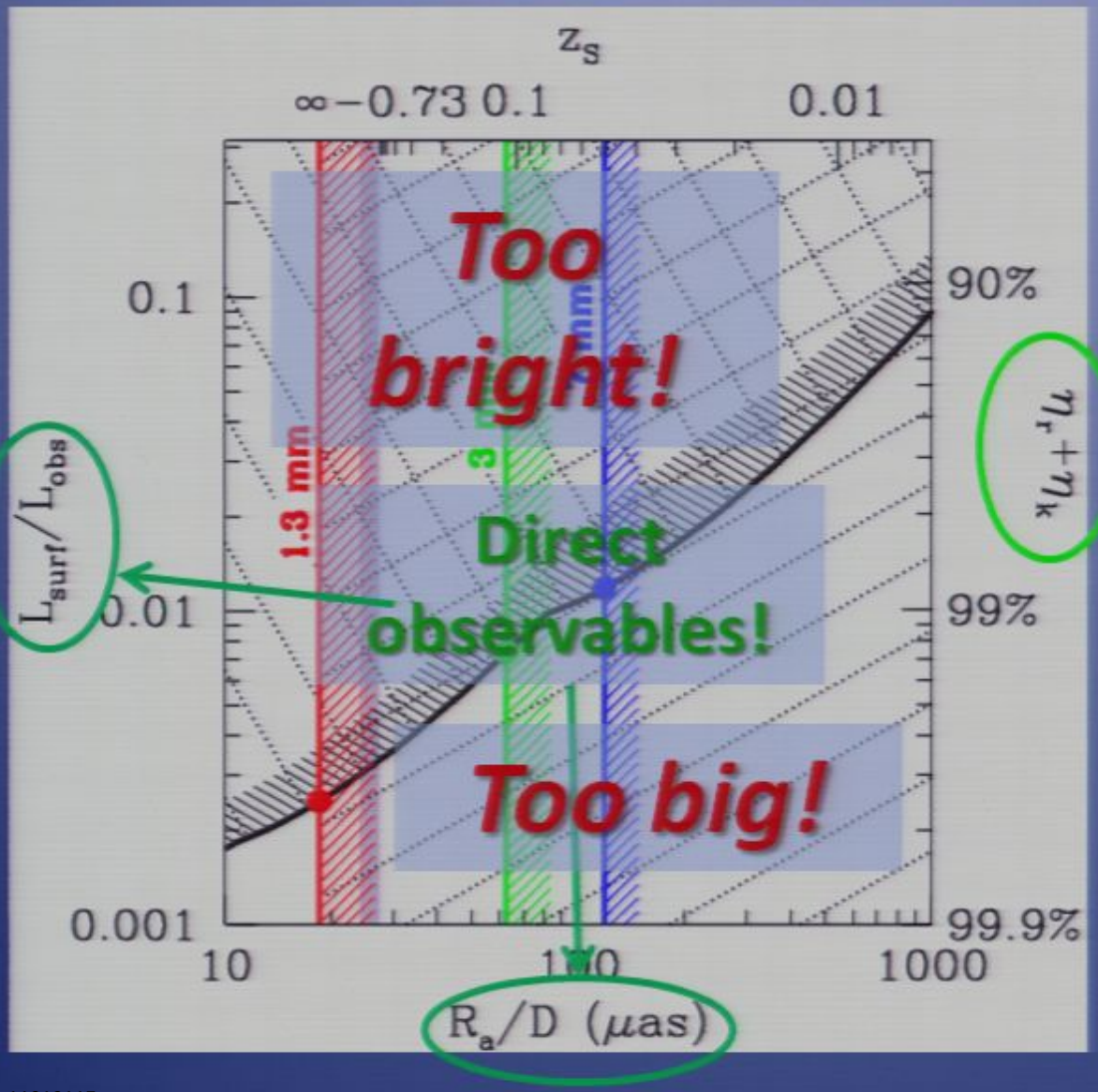
- lab densities
- lab temperatures
- lab B-fields

$$L_{surf} \leq 0.004 L_{obs}!$$

$$\eta_r + \eta_k \geq 99.6\%!$$

lorizons do exist!

Probing horizons



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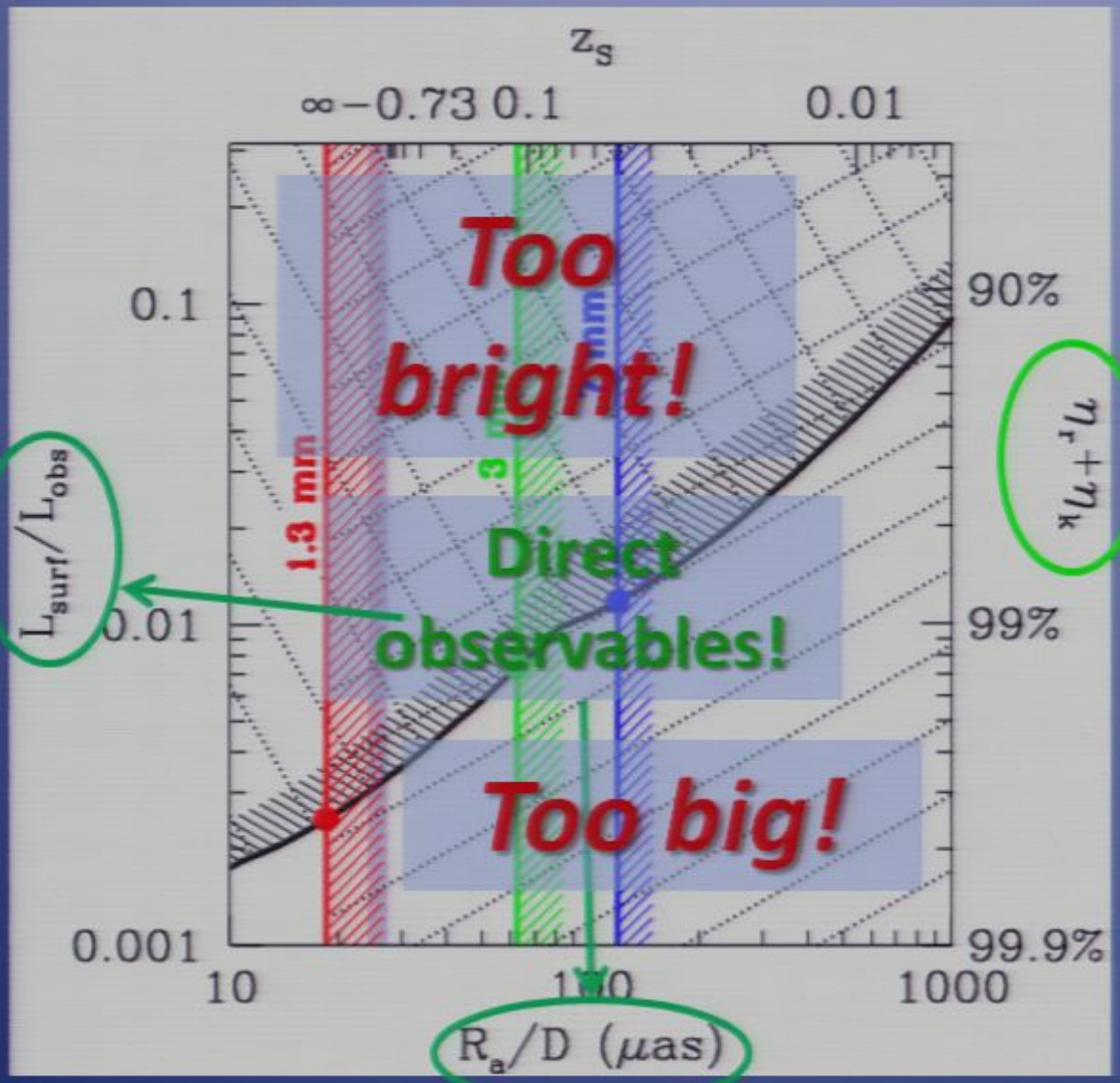
Does Sgr A* have a horizon?

lorizons do exist!

Probing horizons



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Does Sgr A* have a horizon?

Yes!

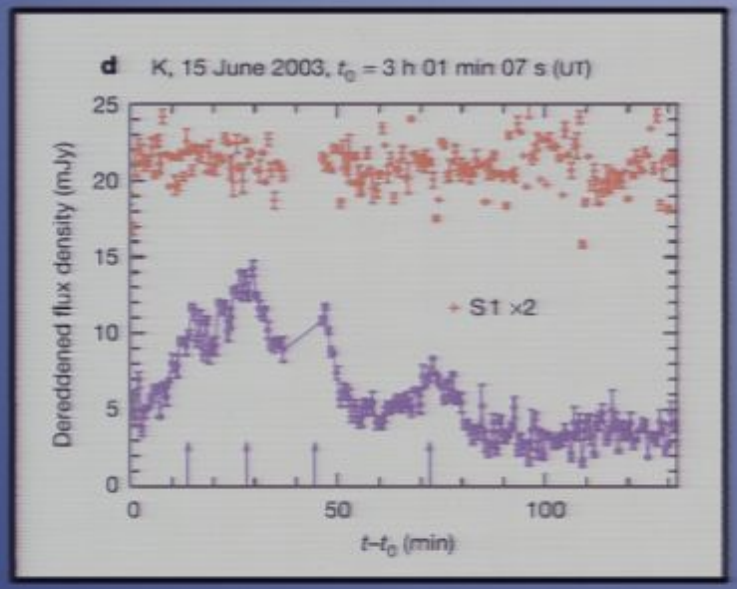
esting Kerr with Spots

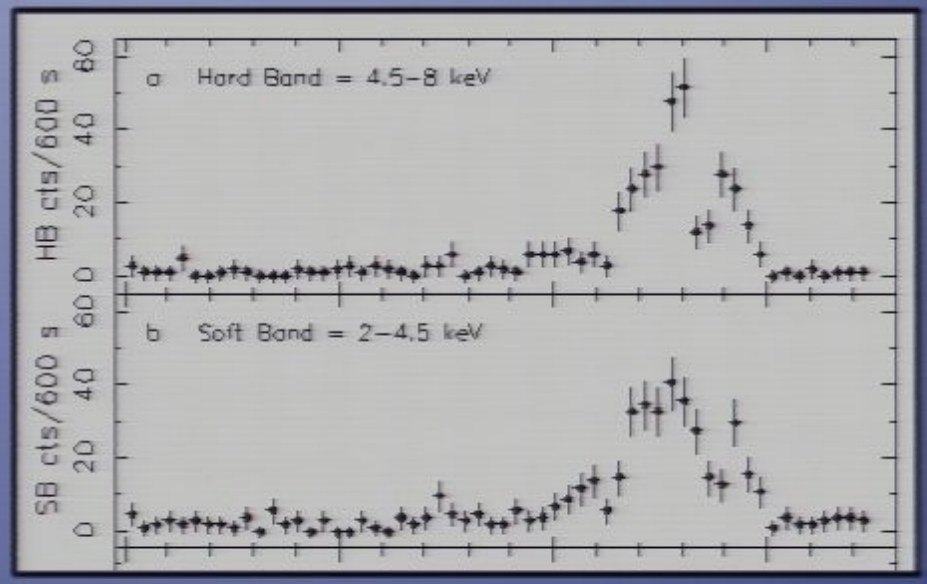
Timescales

- Light crossing time: 20 s
- ISCO orbital time: 4 – 30 min
- Sub-mm synchrotron cooling time: hours
- Shearing timescale: P r/dr

esting Kerr with Spots

Sgr A*'s flares





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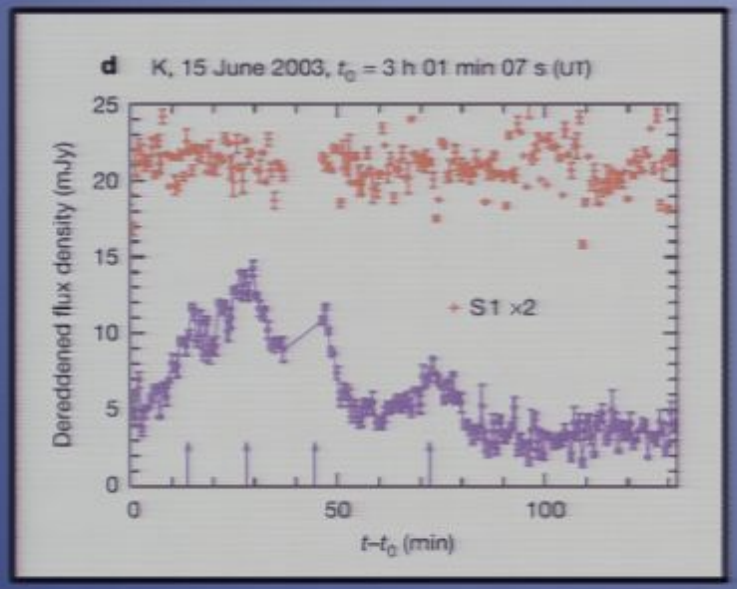

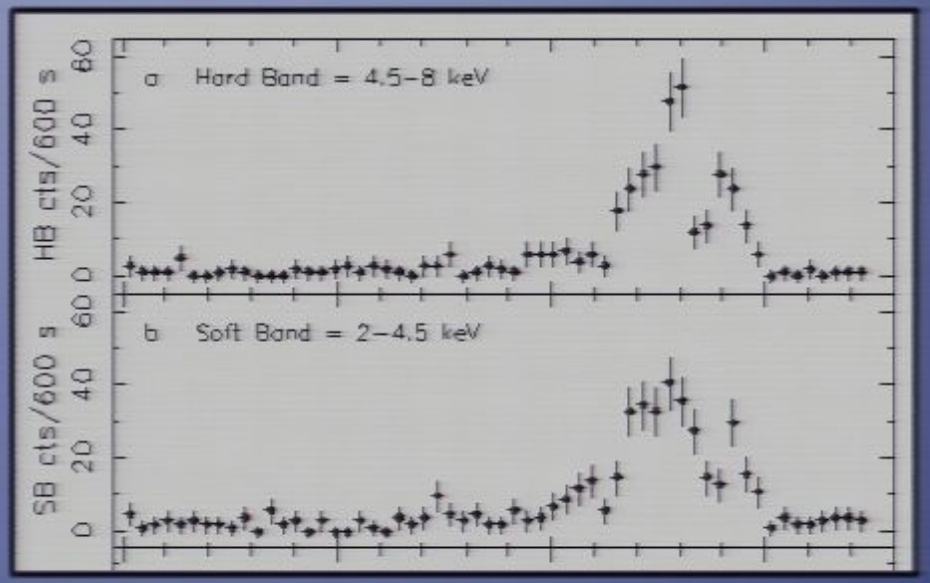

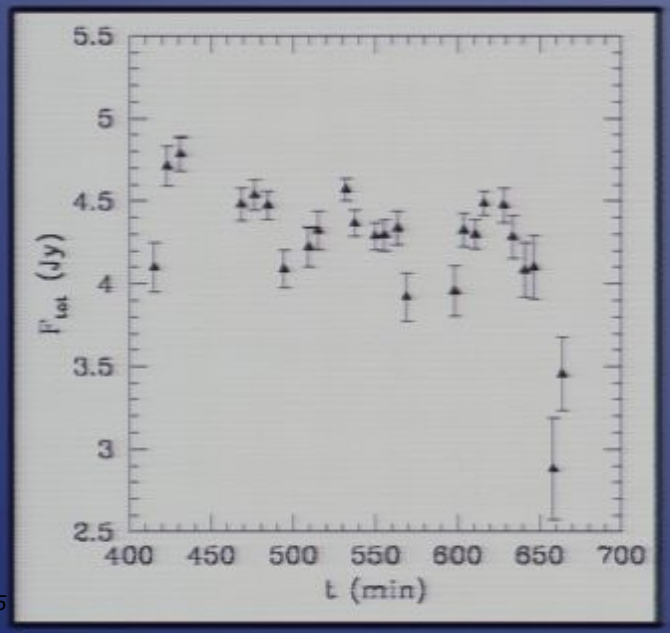

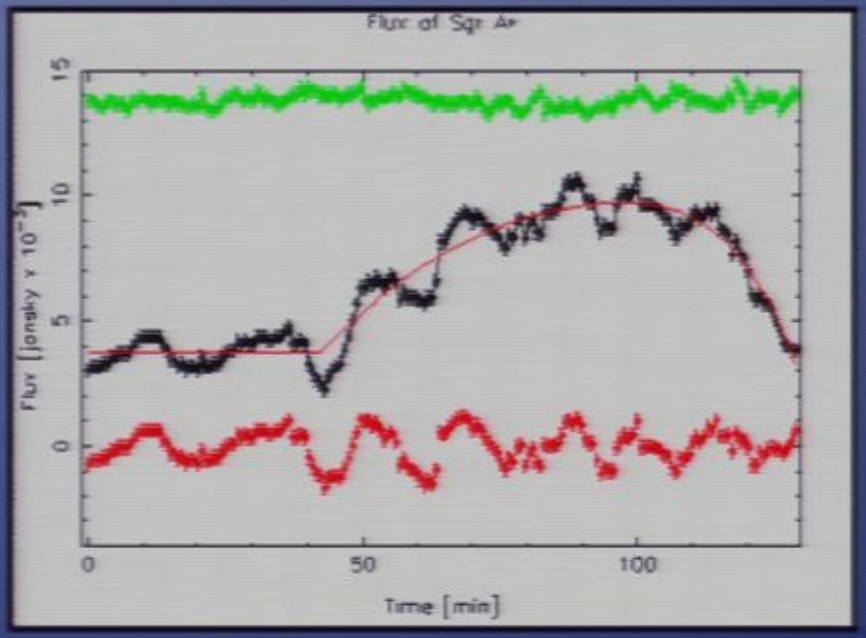

esting Kerr with Spots

Sgr A* vs the Sun

- Rapid conversion of energy into non-thermal electrons
- Electrons stream along field lines and cool via synchrotron

esting Kerr with Spots

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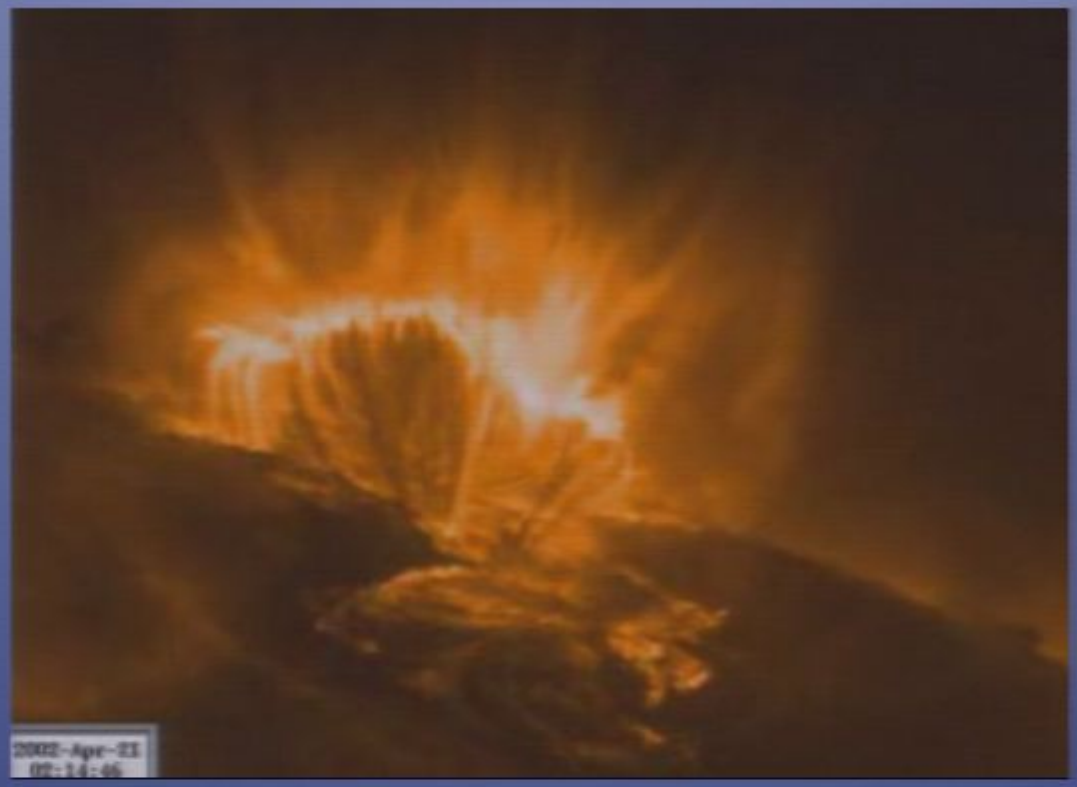

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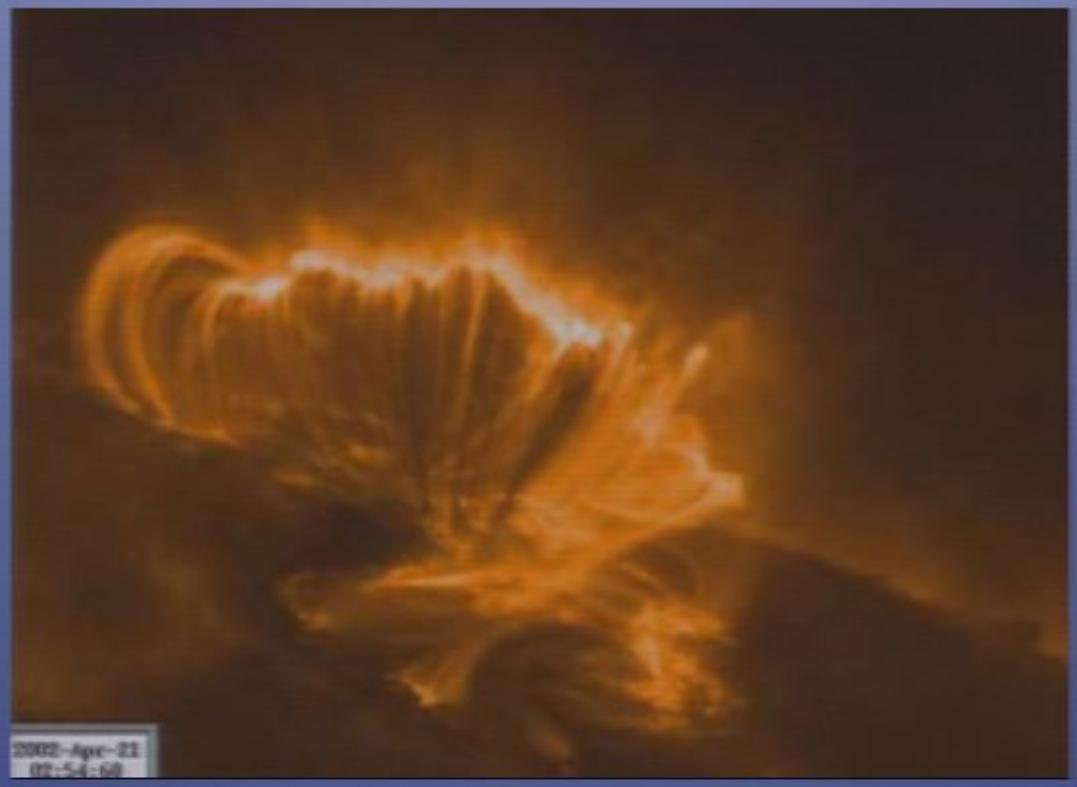

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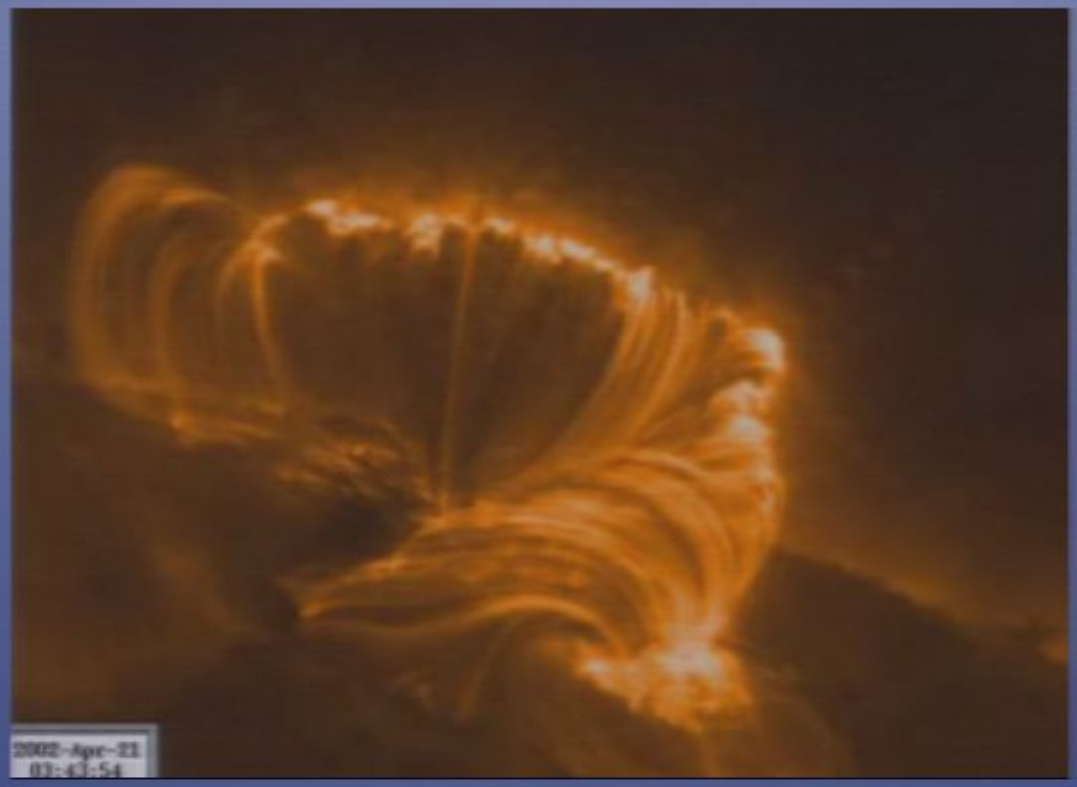

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esting Kerr with Spots

Sgr A* vs the Sun

- Electrons are vastly subdominant → are localized on magnetic turbulence scale
- Electrons radiate rapidly → any extra energy goes straight into luminosity
- Spots are long lived, $T \sim \min(T_{cool}, T_{shear} \sim P\, r/dr)$
- Spots are local

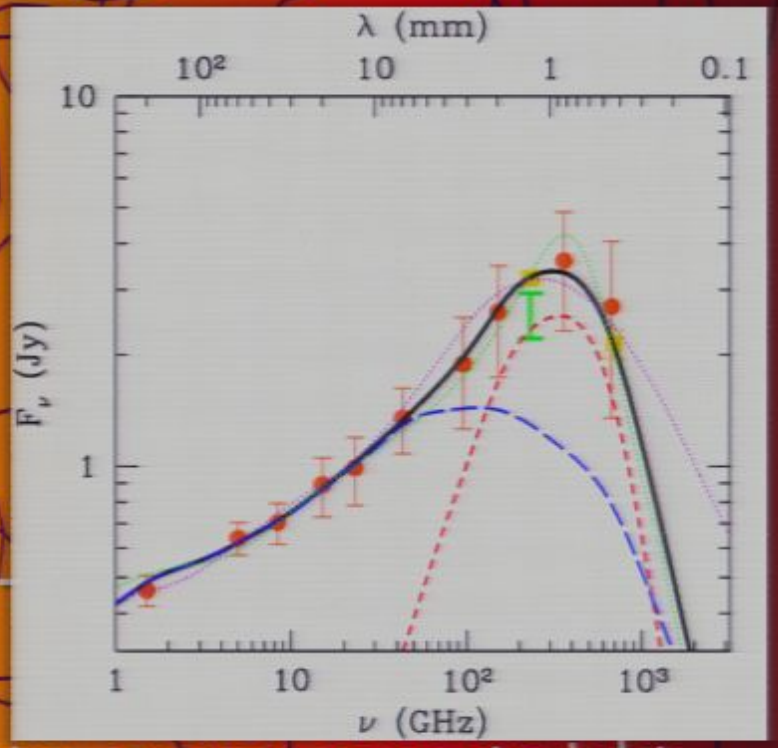
esting Kerr with Spots

Sgr A* vs the Sun

- Electrons are vastly subdominant → are localized on magnetic turbulence scale
- Electrons radiate rapidly → any extra energy goes straight into luminosity
- Spots are long lived, $T \sim \min(T_{cool}, T_{shear} \sim P\, r/dr)$
- Spots are local

esting Kerr with Spots

Sgr A* vs the Sun



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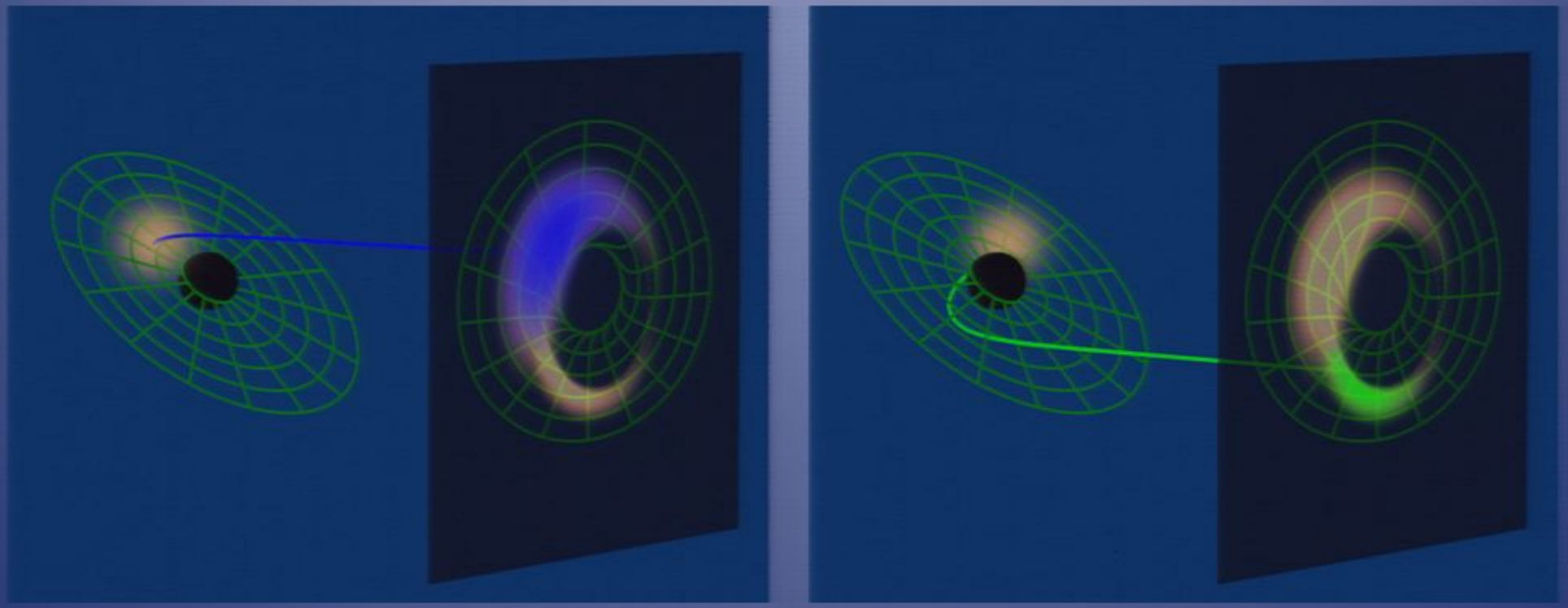
esting Kerr with Spots

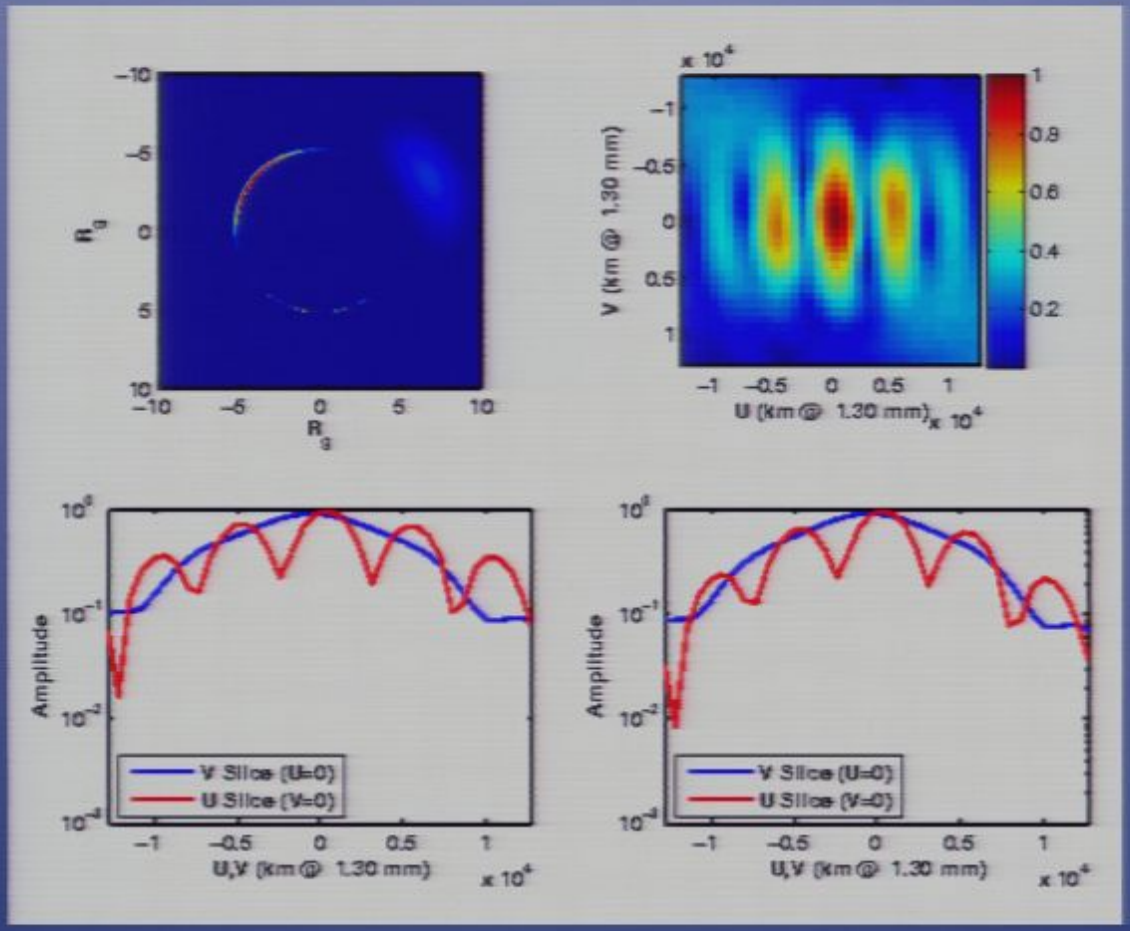
Anatomy of a Hot Spot Image



- Black hole spin encoded in relationship between primary & secondary
- Ideal for VLBI study!

esting Kerr with Spots

Beating spots!



esting Kerr with Spots

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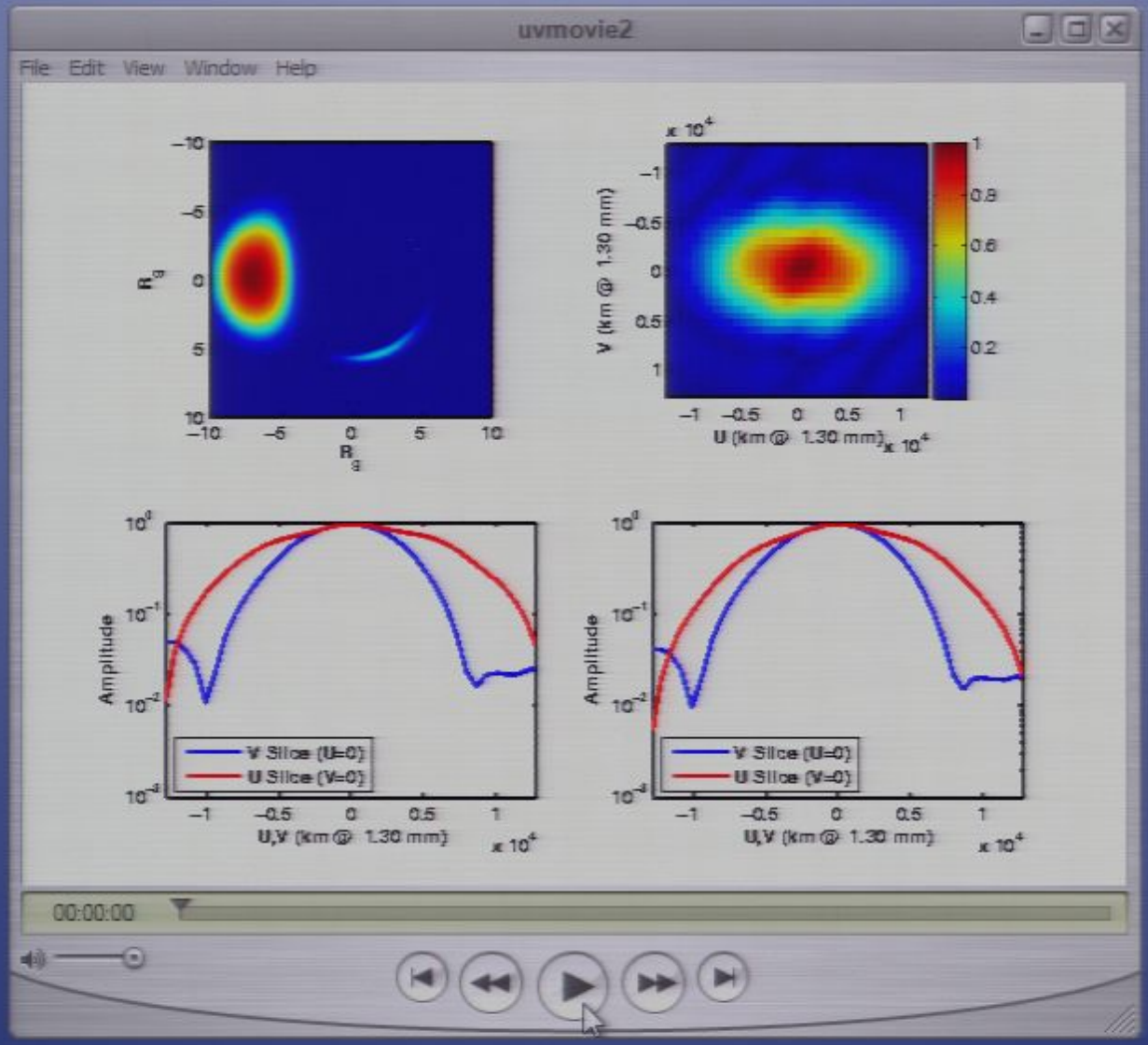

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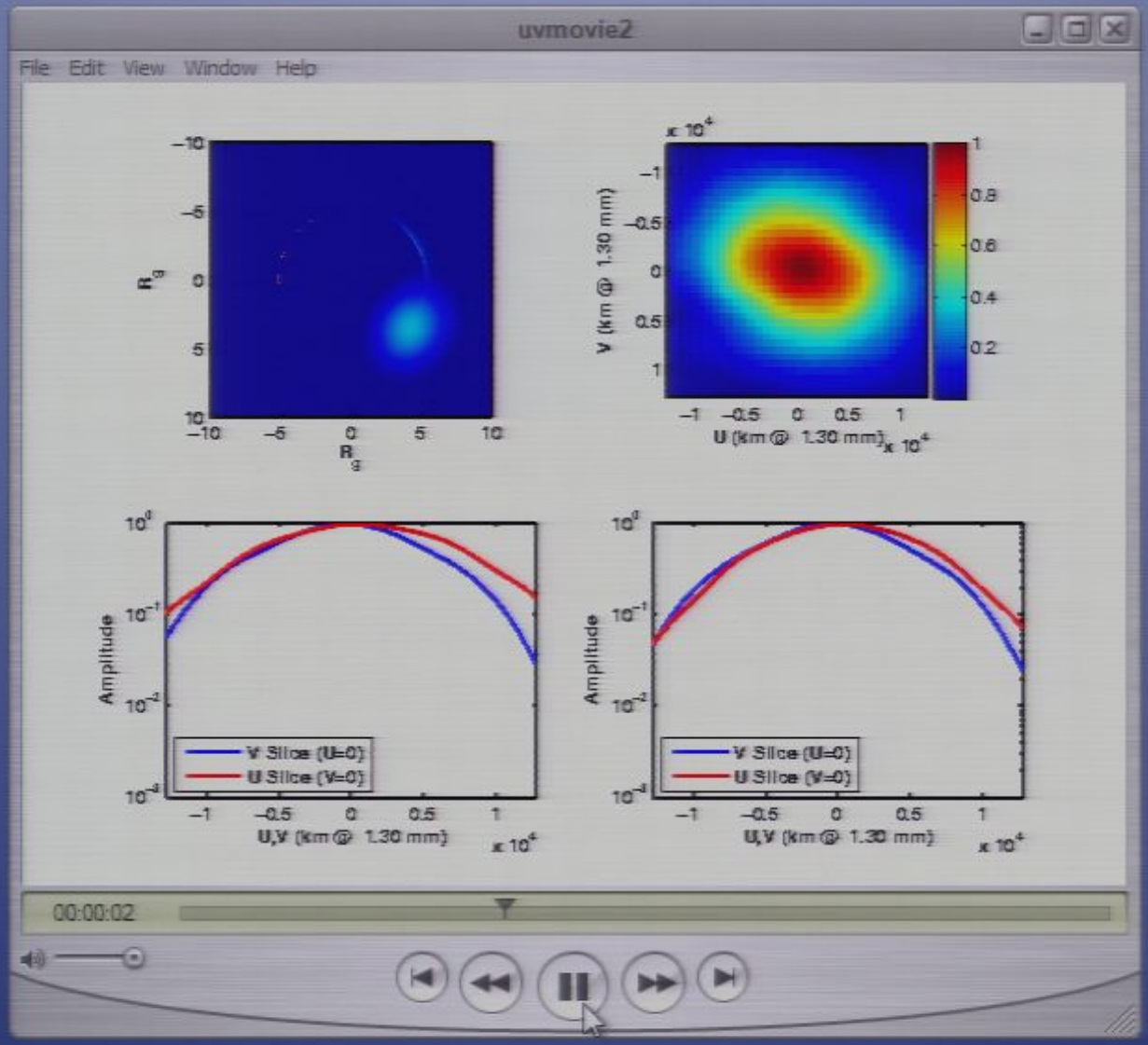
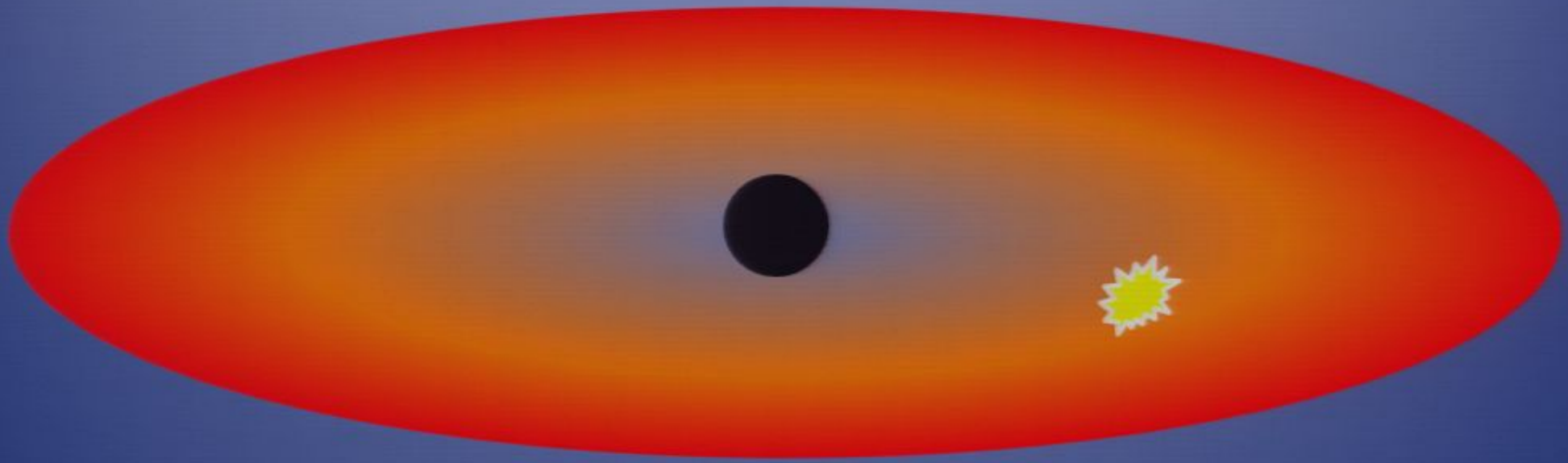


esting Kerr with Spots

Testing Kerr



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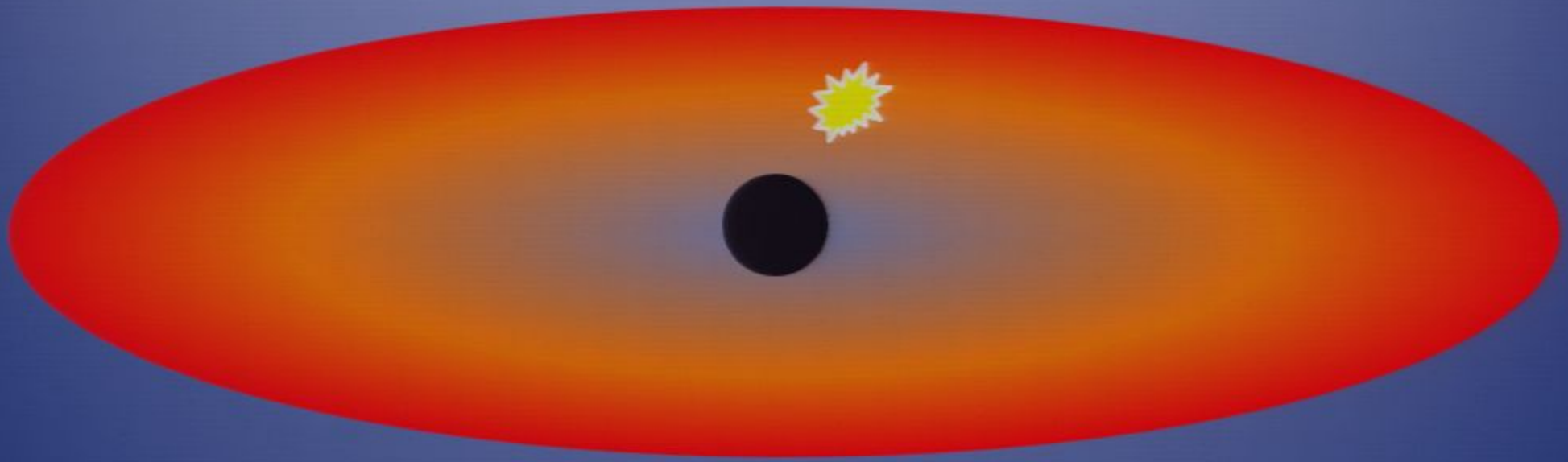

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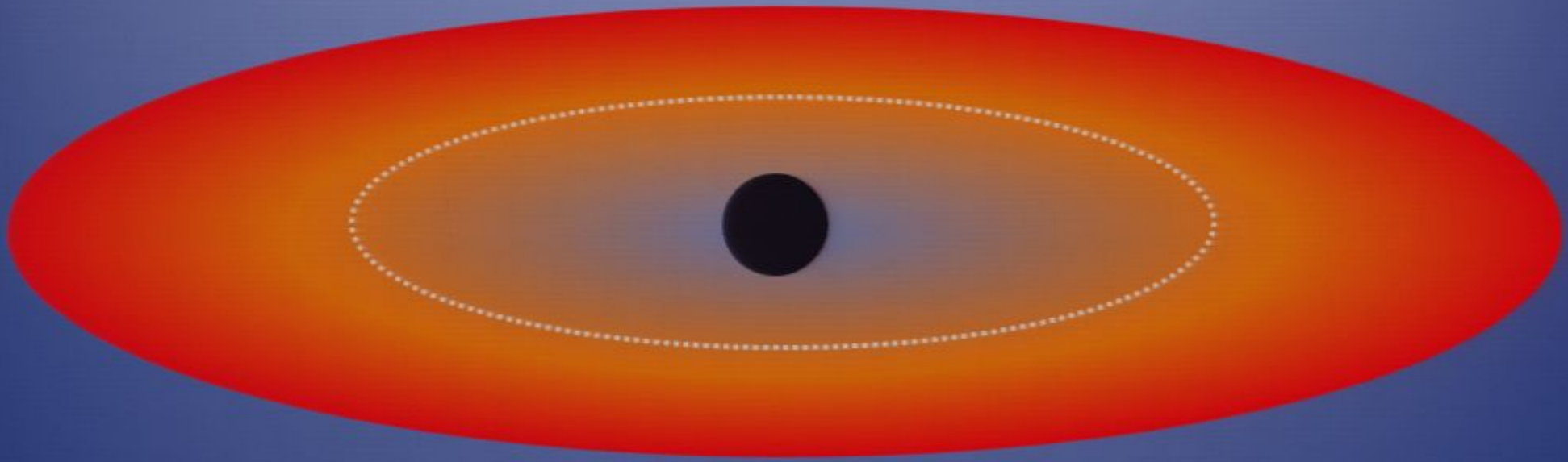

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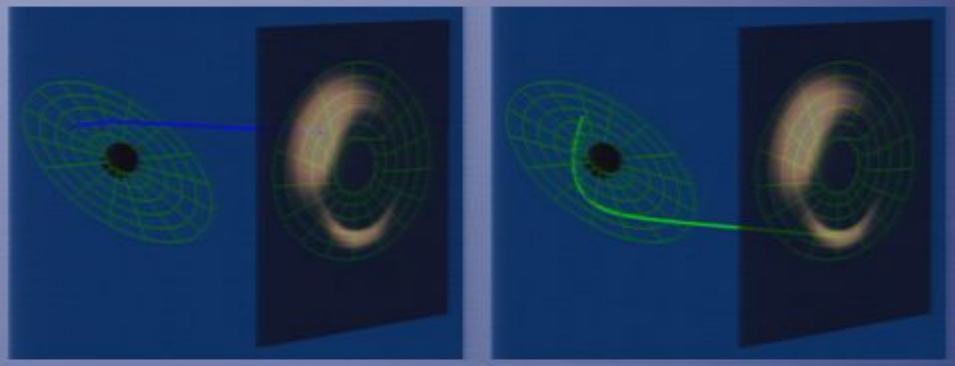
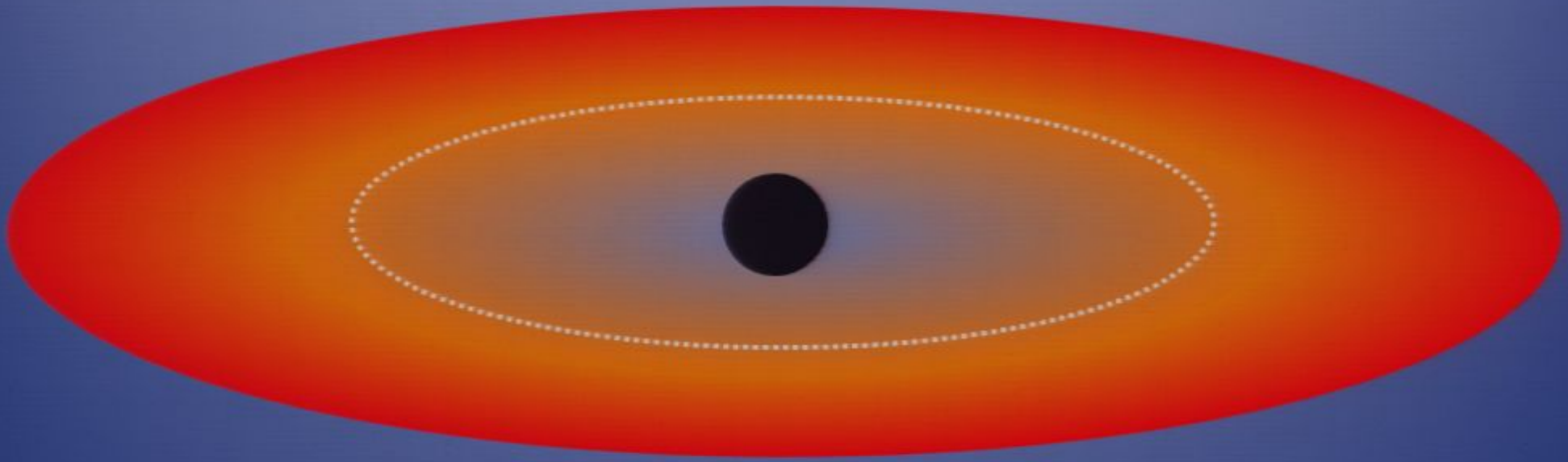
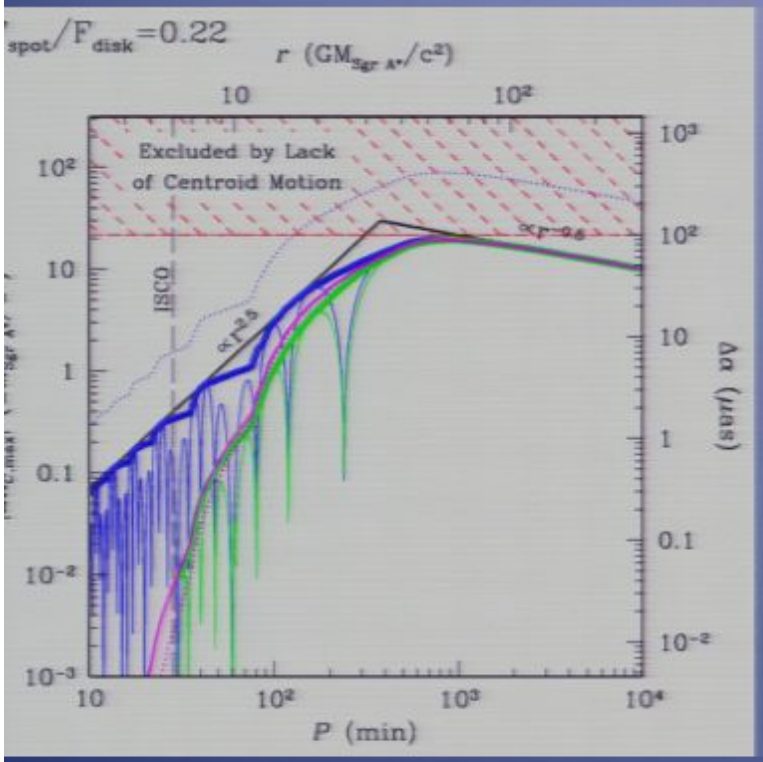
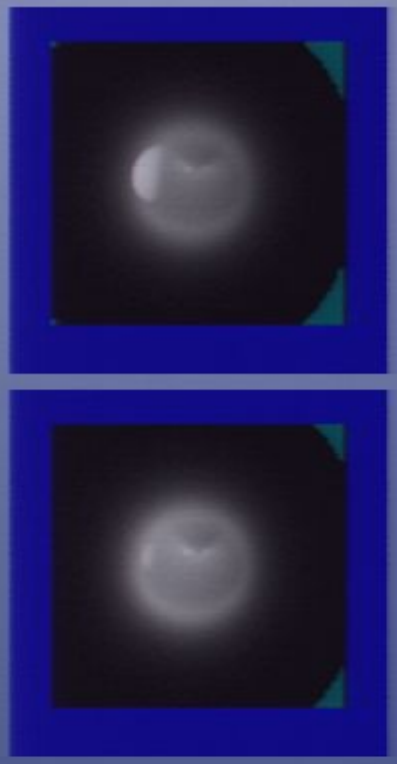


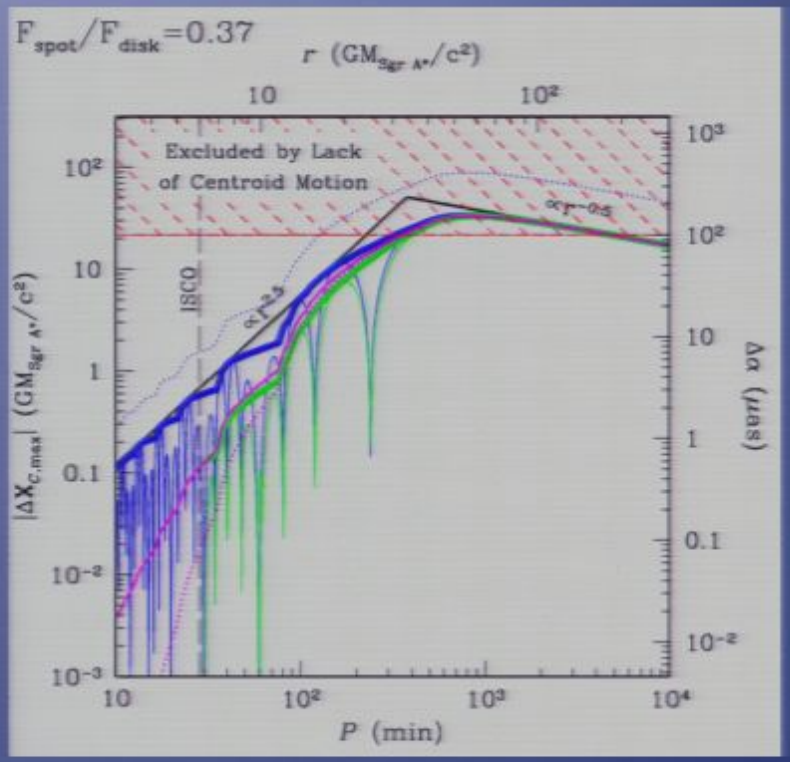


esting Kerr with Spots

Validation! 7mm centroids





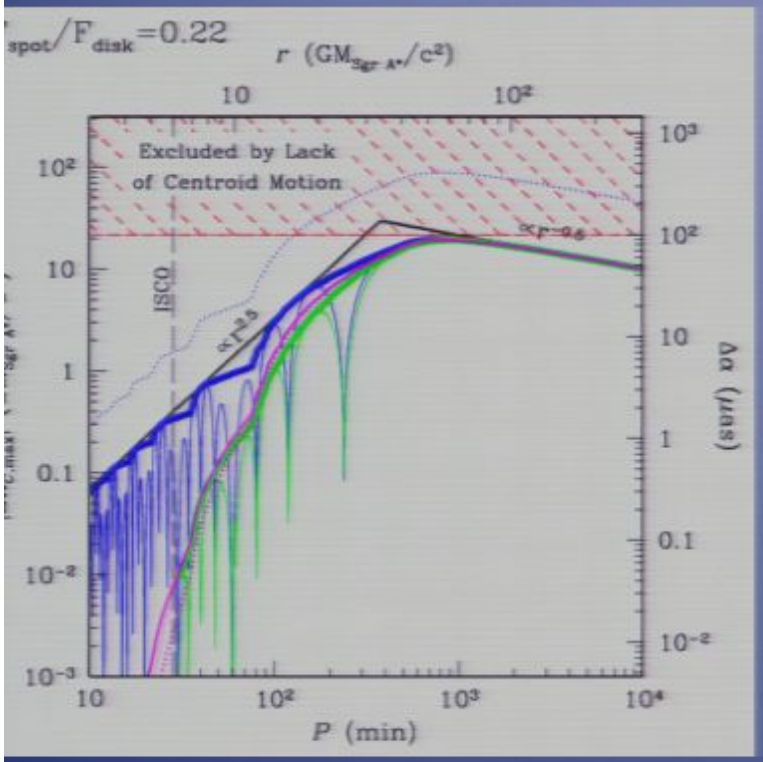


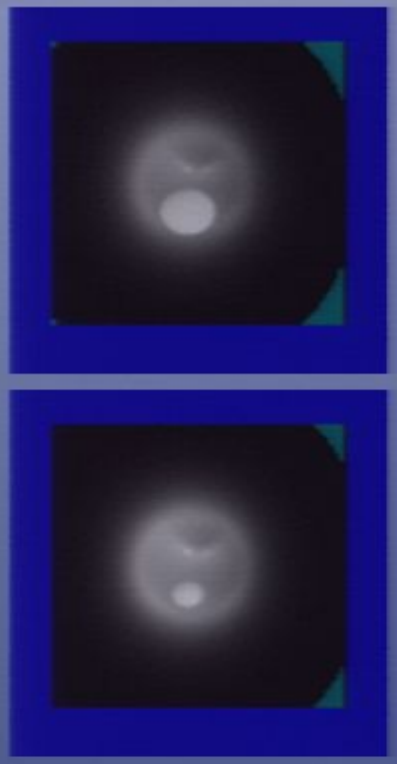
Reid, AEB, Loeb, Honma & Brunthaler (2008)

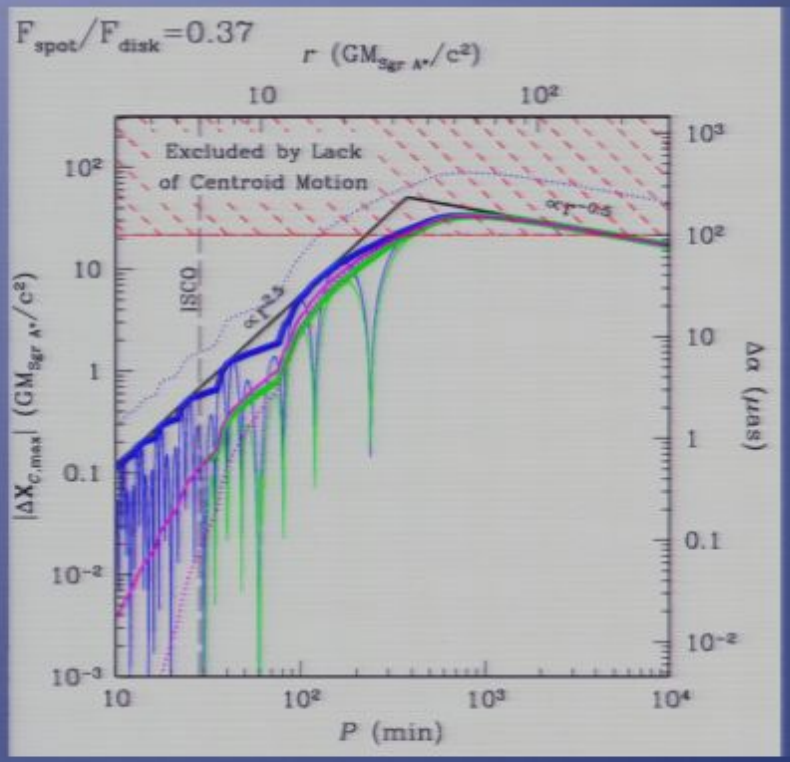
- Look for short-timescale centroid wander at 7mm
- Not yet, but should work for a very bright spot.

esting Kerr with Spots

Validation! 7mm centroids







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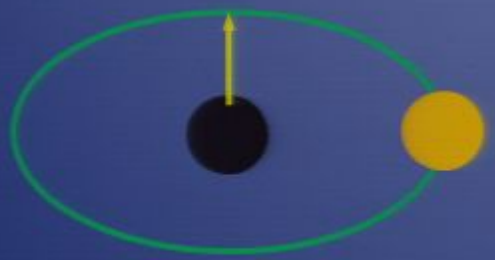
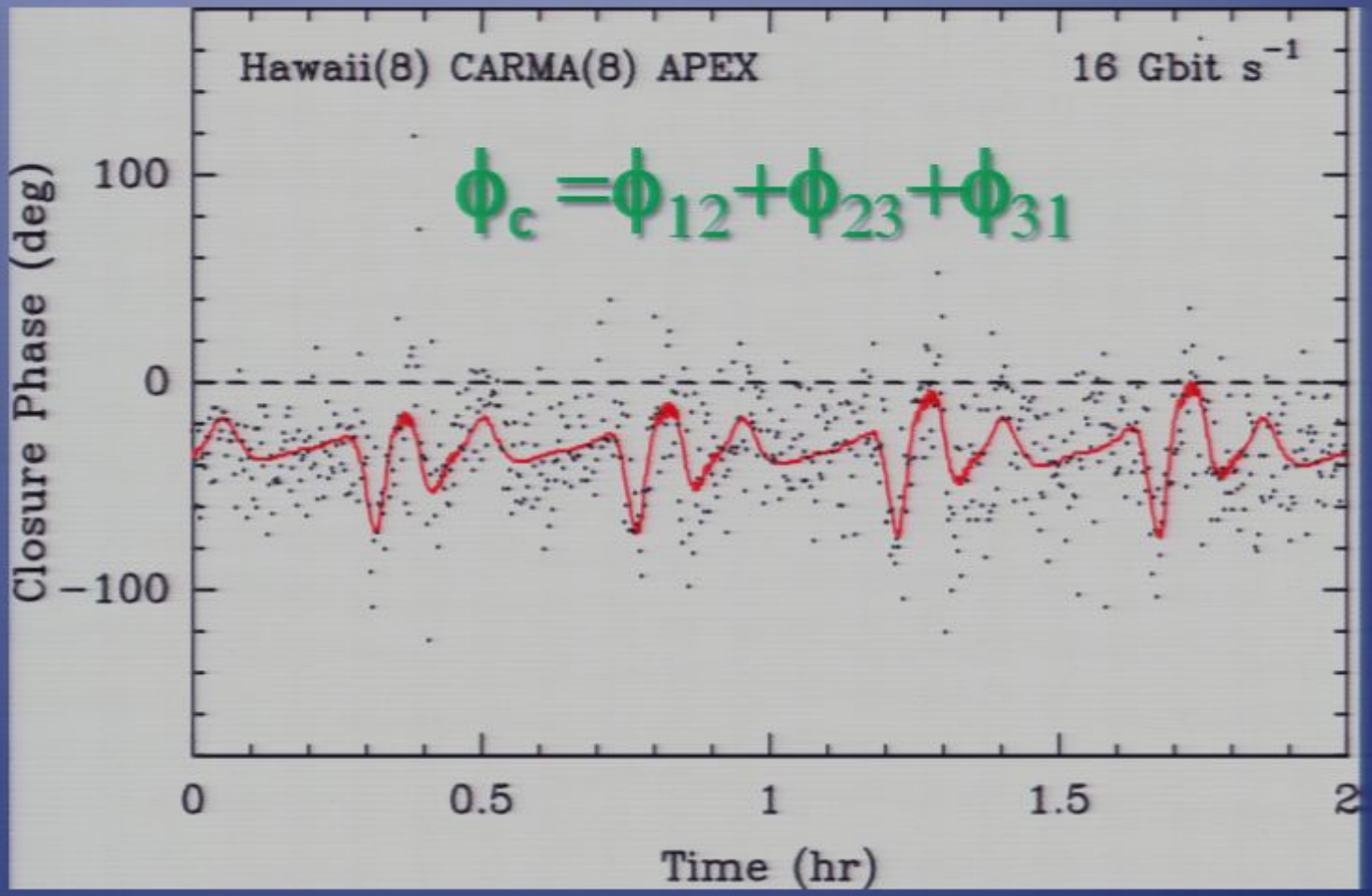
esting Kerr with Spots

Validation! Closure phase evolution



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



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

esting Kerr with Spots

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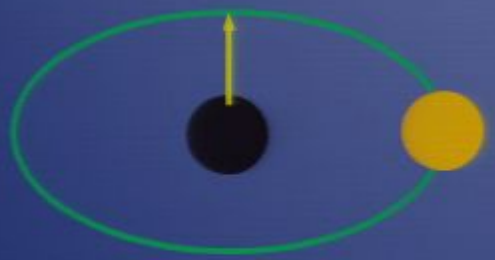

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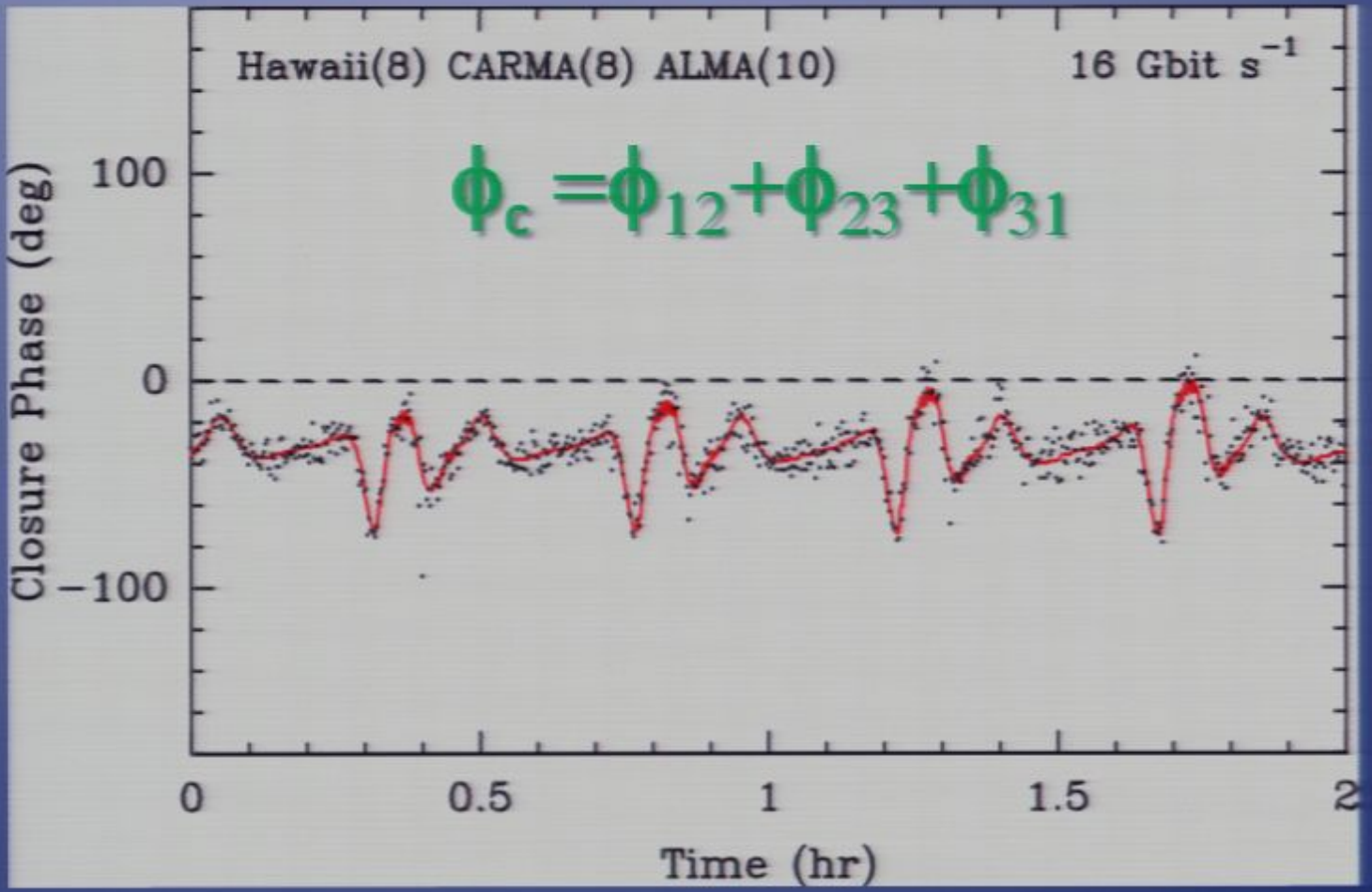

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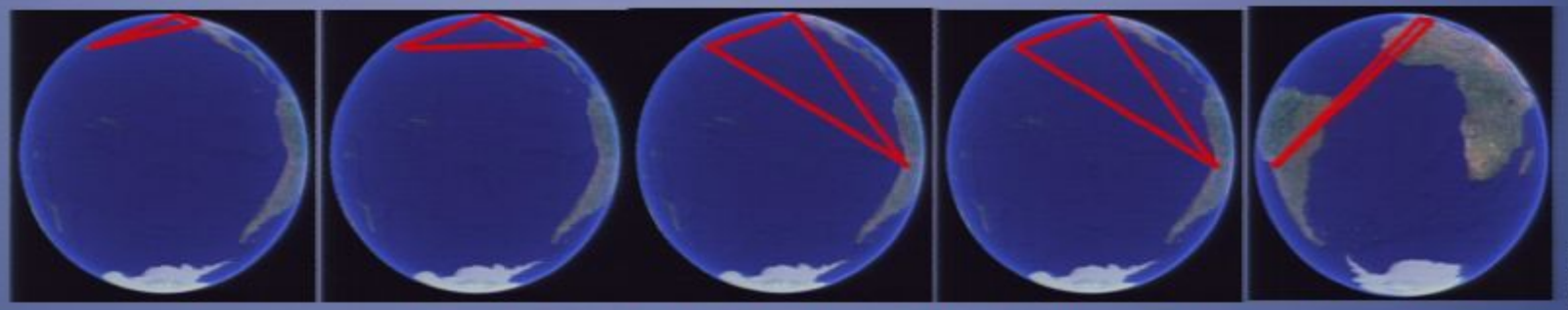

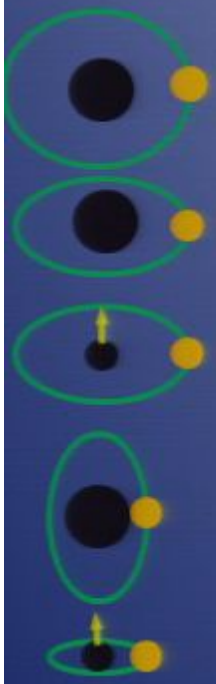

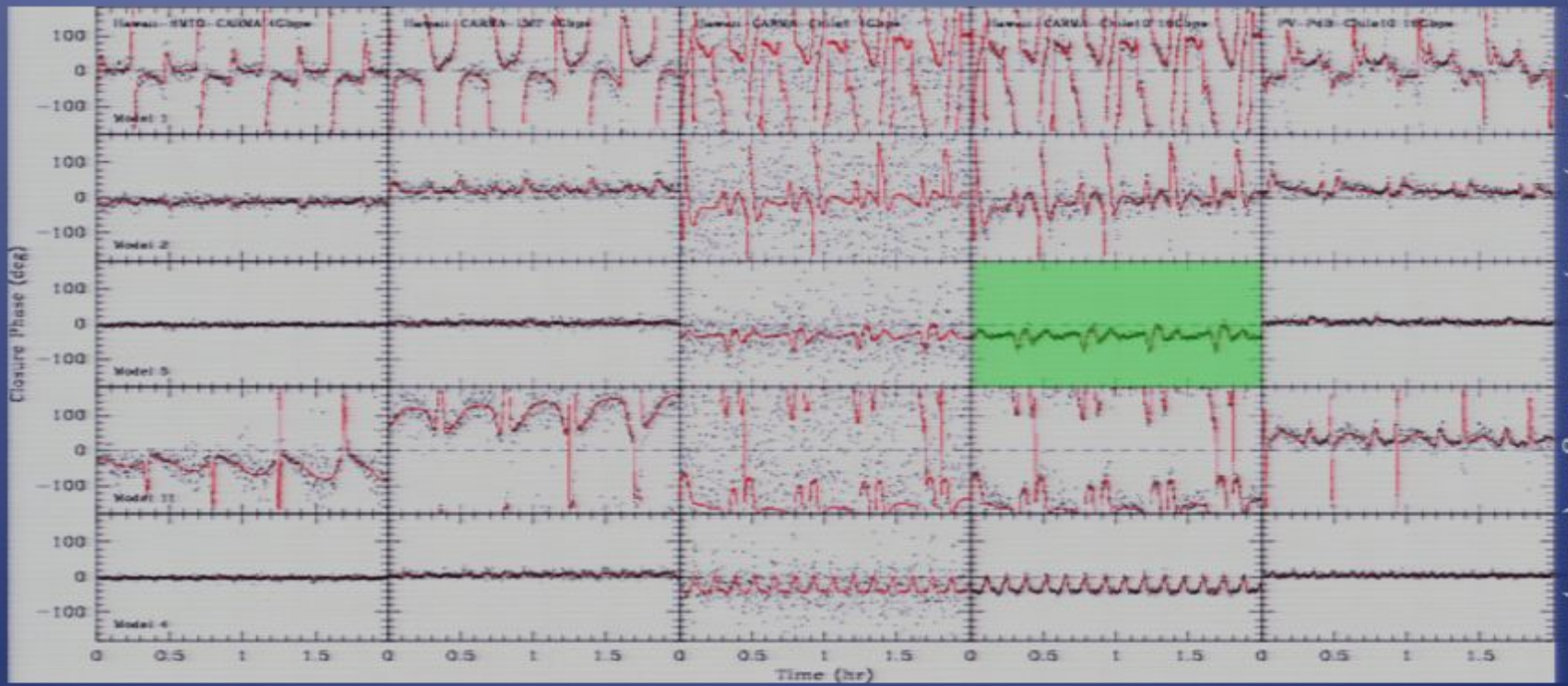

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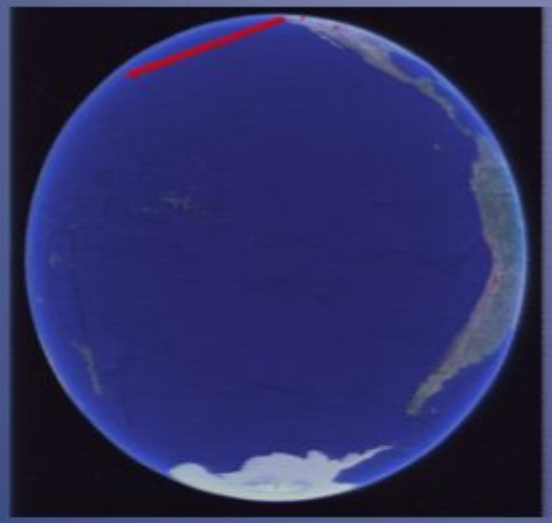
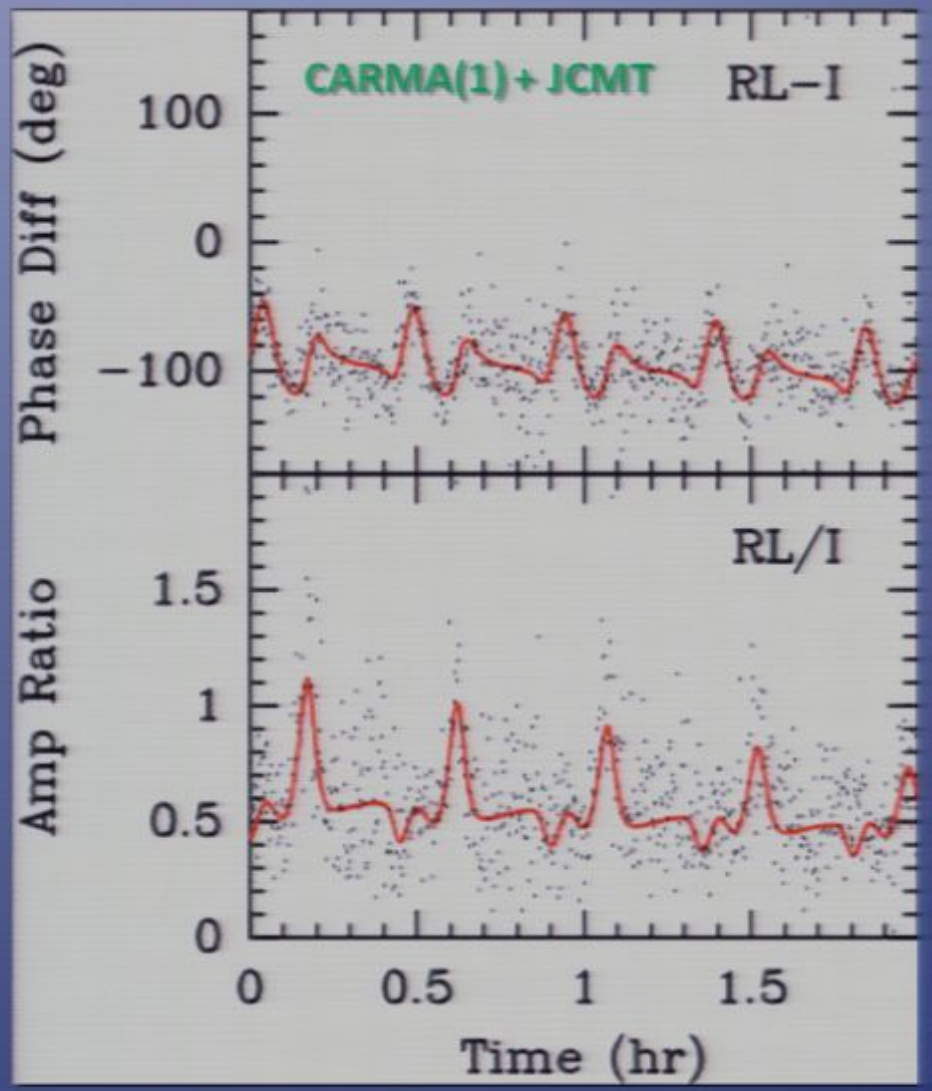
esting Kerr with Spots

Validation! Polarization evolution





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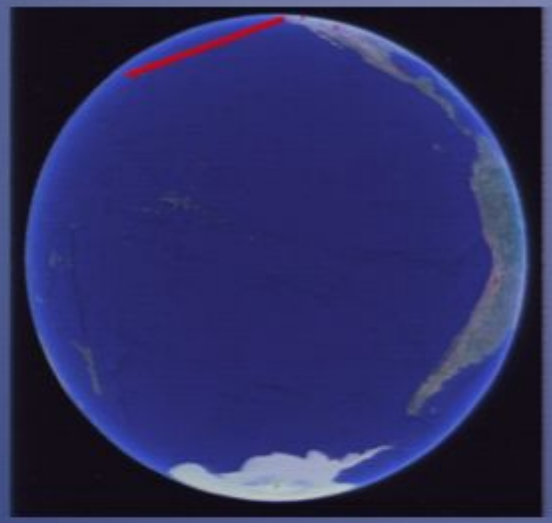

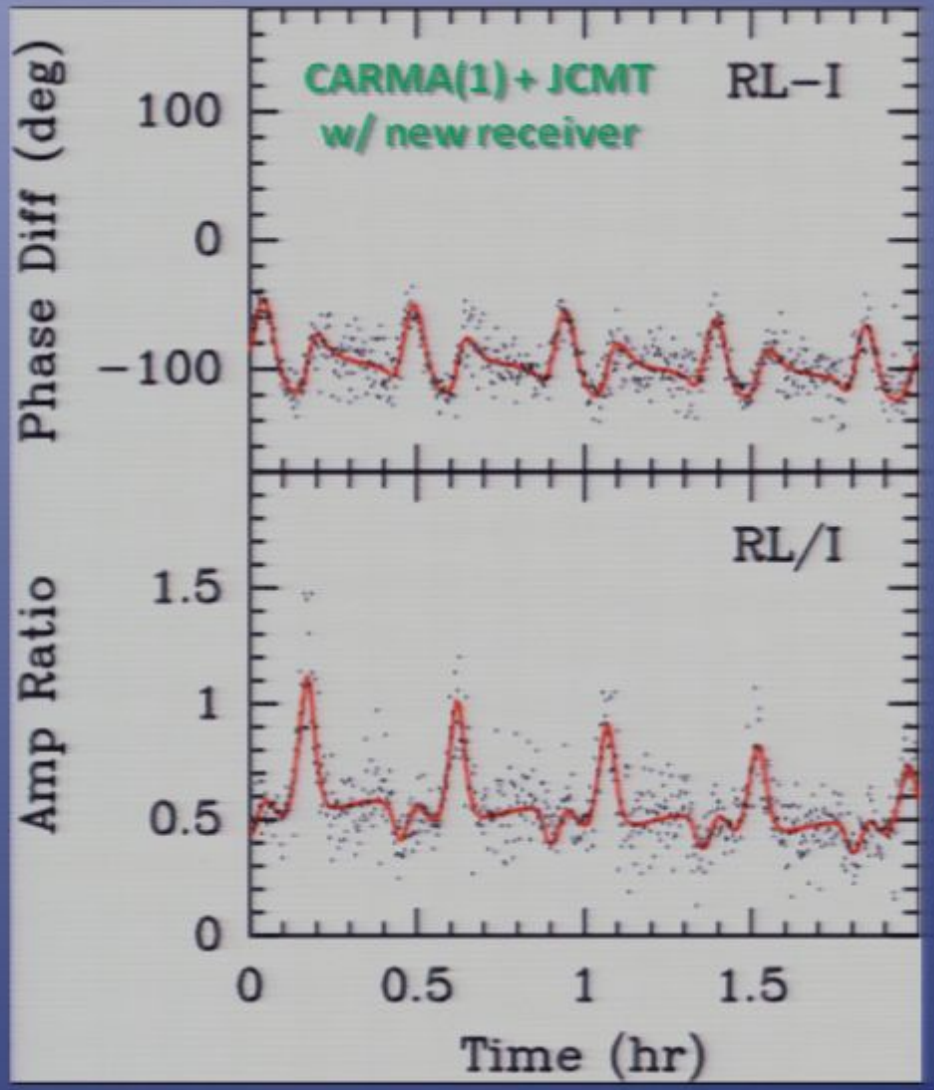

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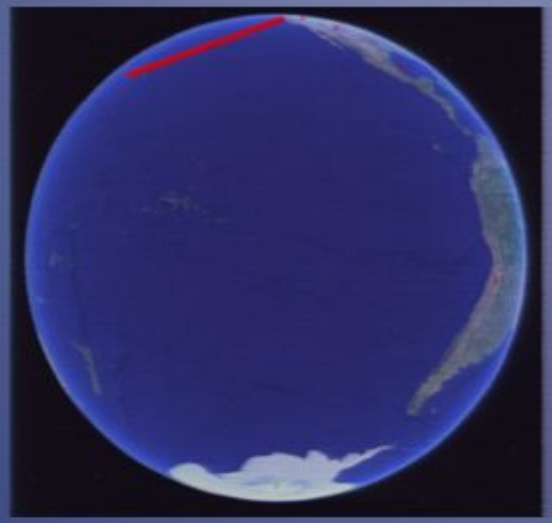

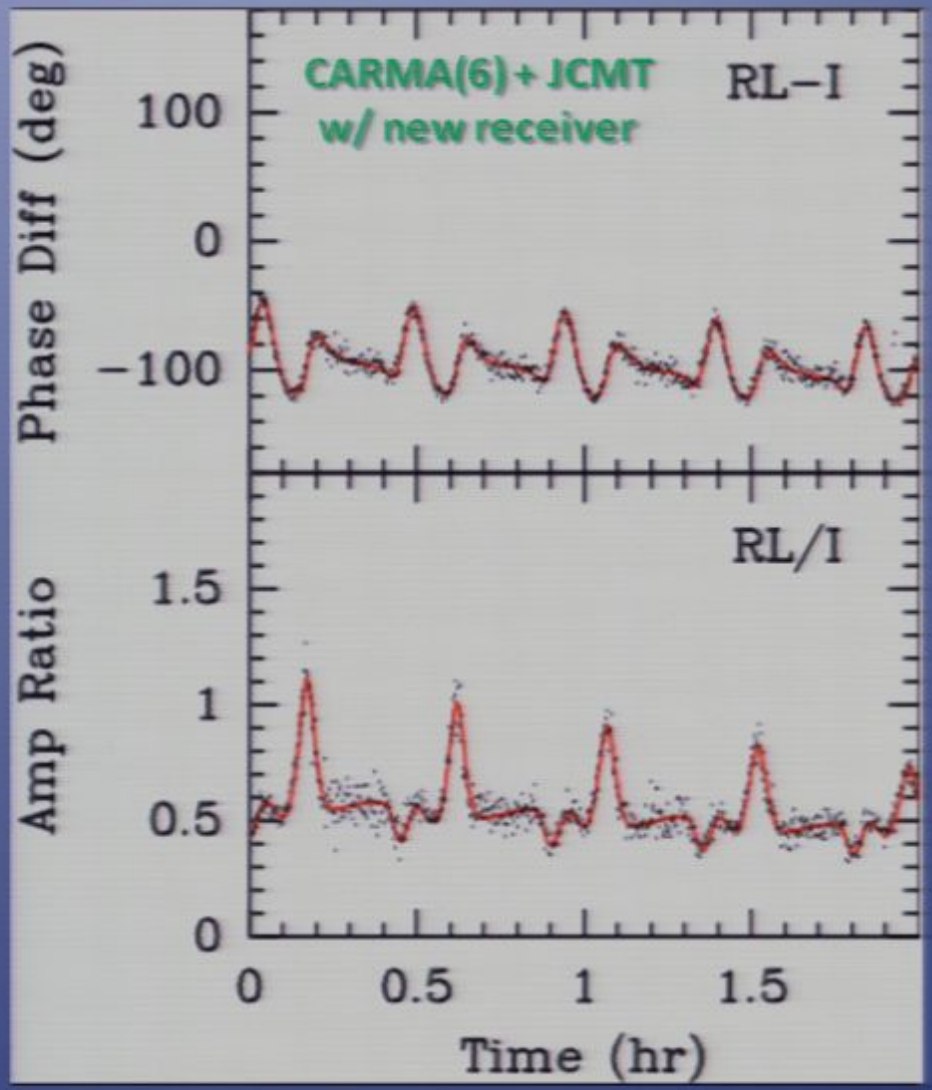

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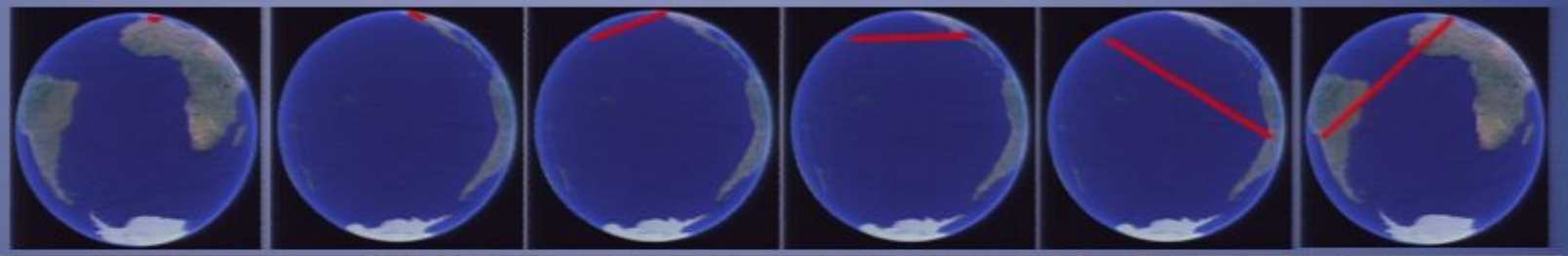
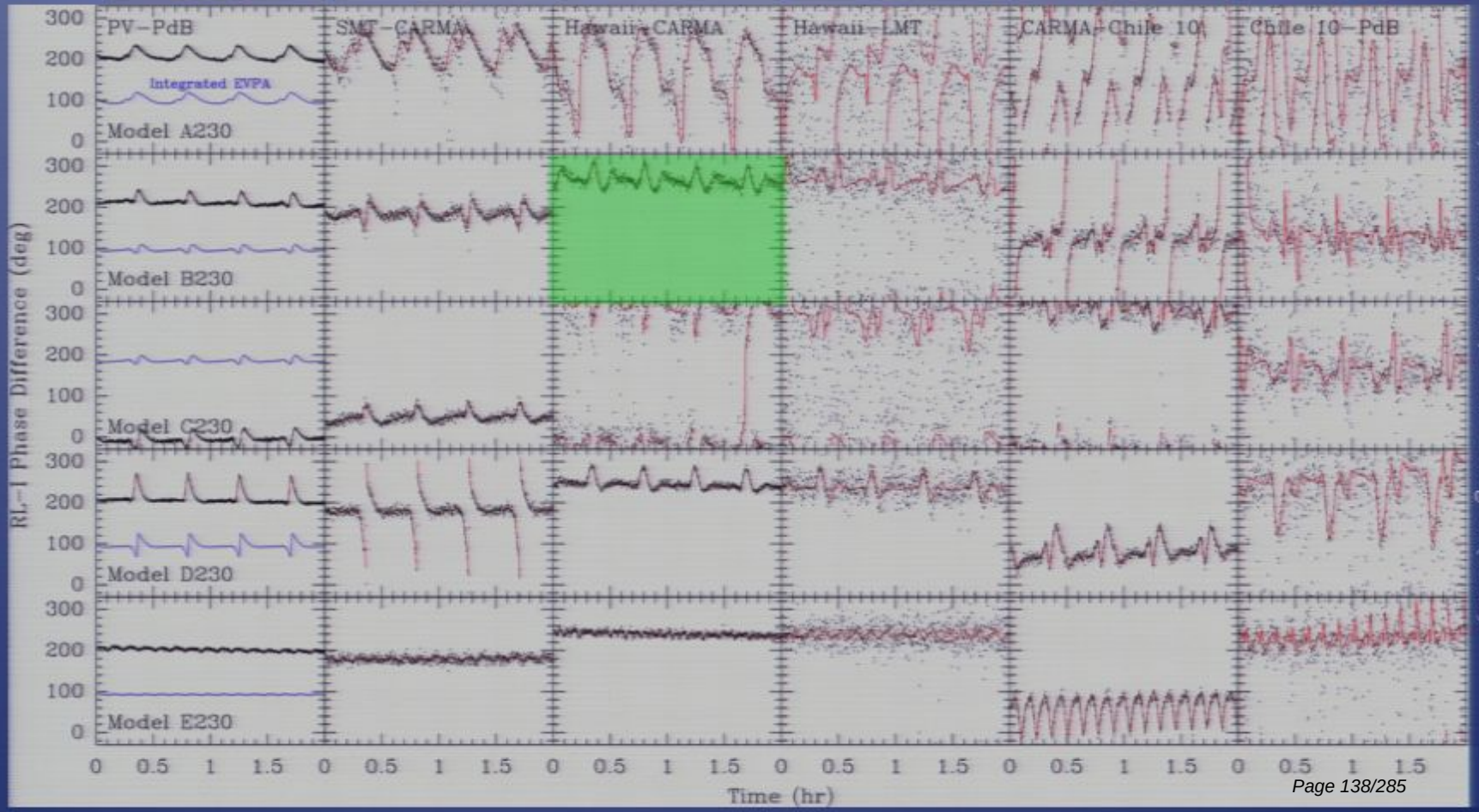
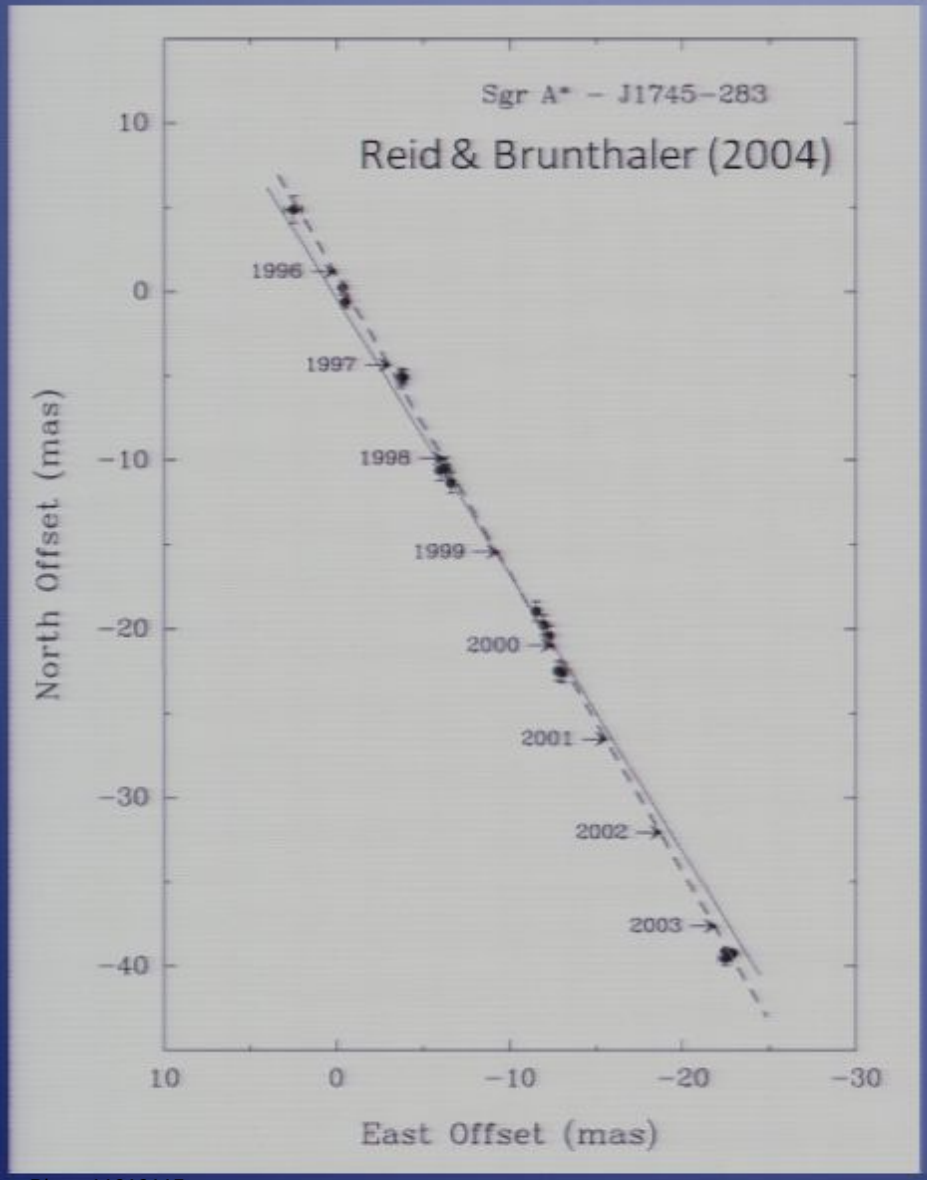




Fish, Doeleman, AEB, Loeb & Rogers (2009)

he Black Hole's retinue

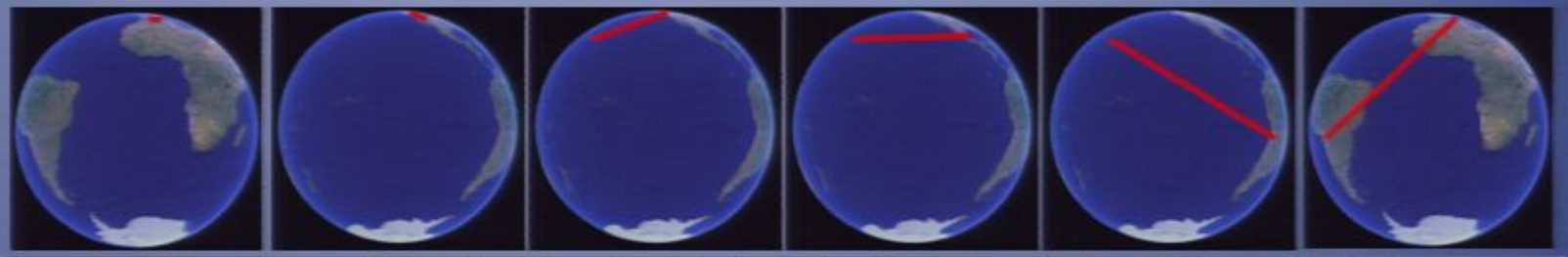
EHT Astrometry

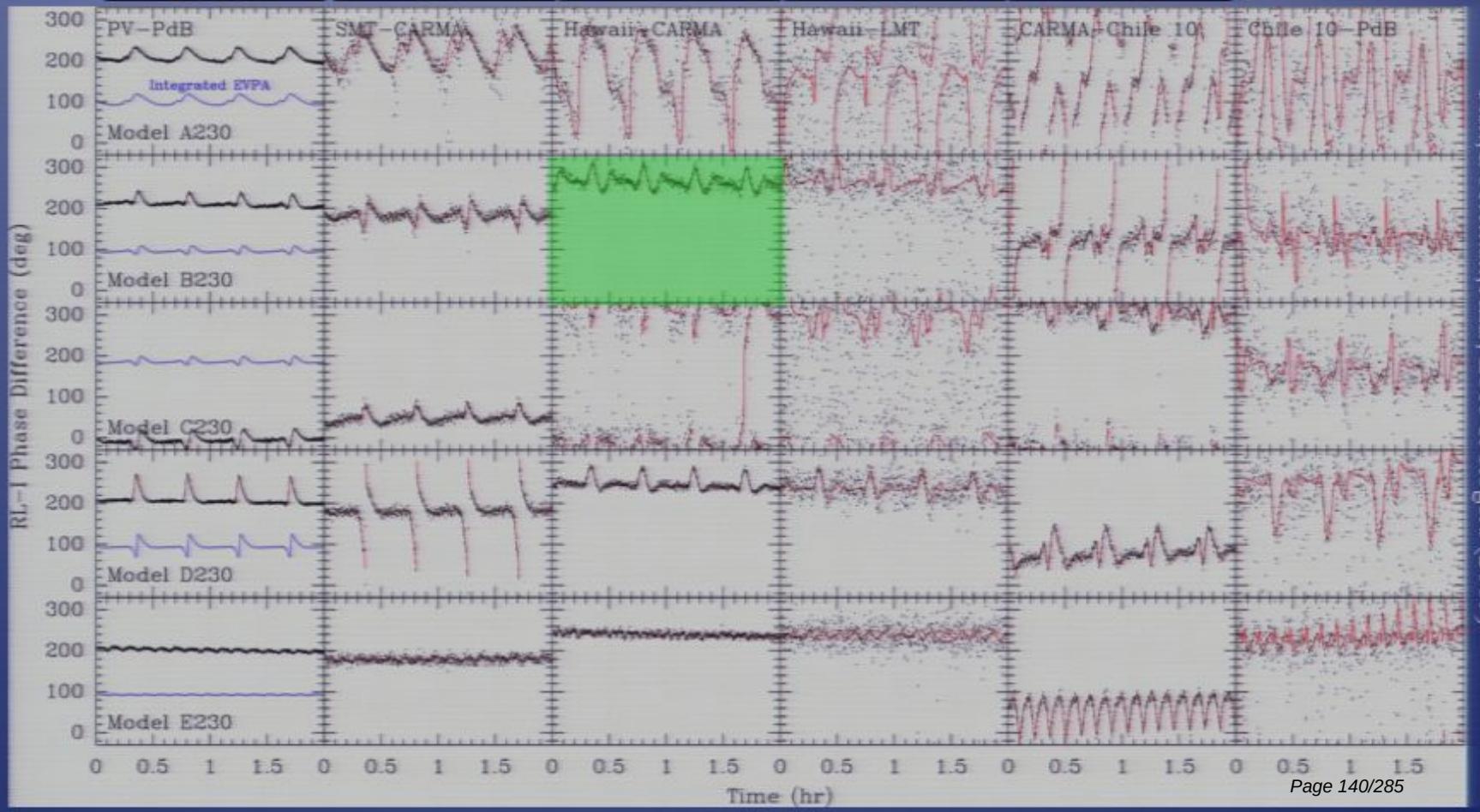


- Absolute astrometry impossible

esting Kerr with Spots

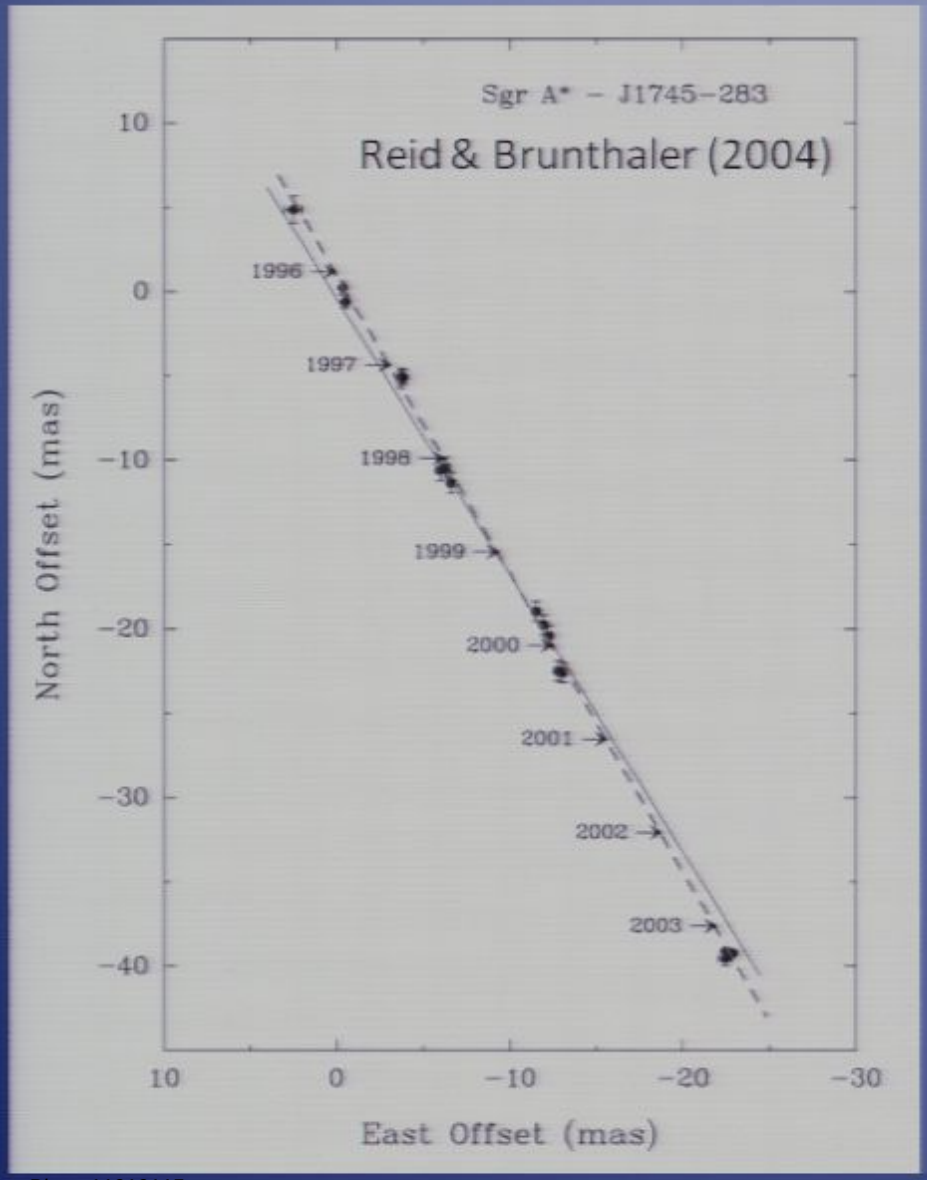
Validation! Polarization evolution





he Black Hole's retinue

EHT Astrometry



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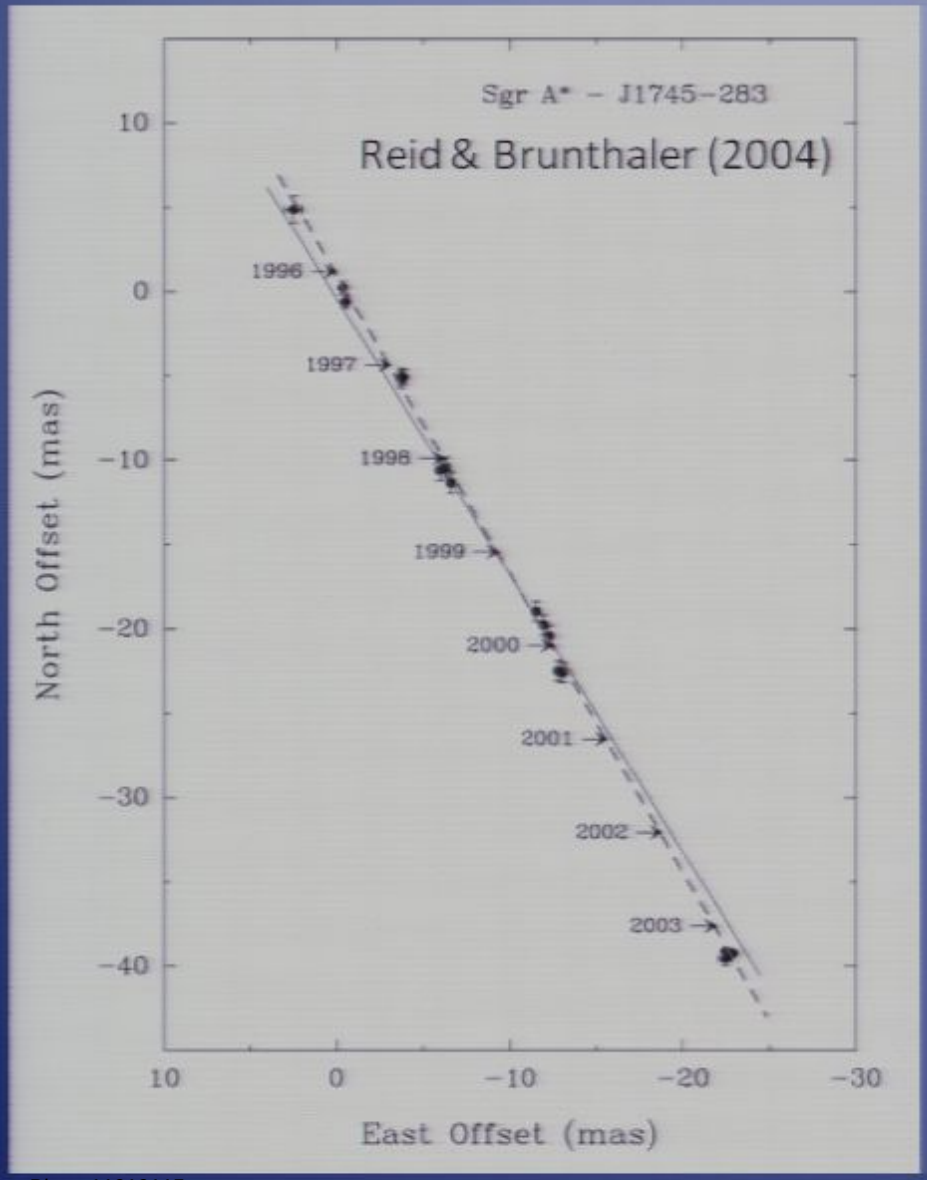

- Absolute astrometry impossible
  → Differential astrometry with nearby sources (<1°)

he Black Hole's retinue

EHT Astrometry

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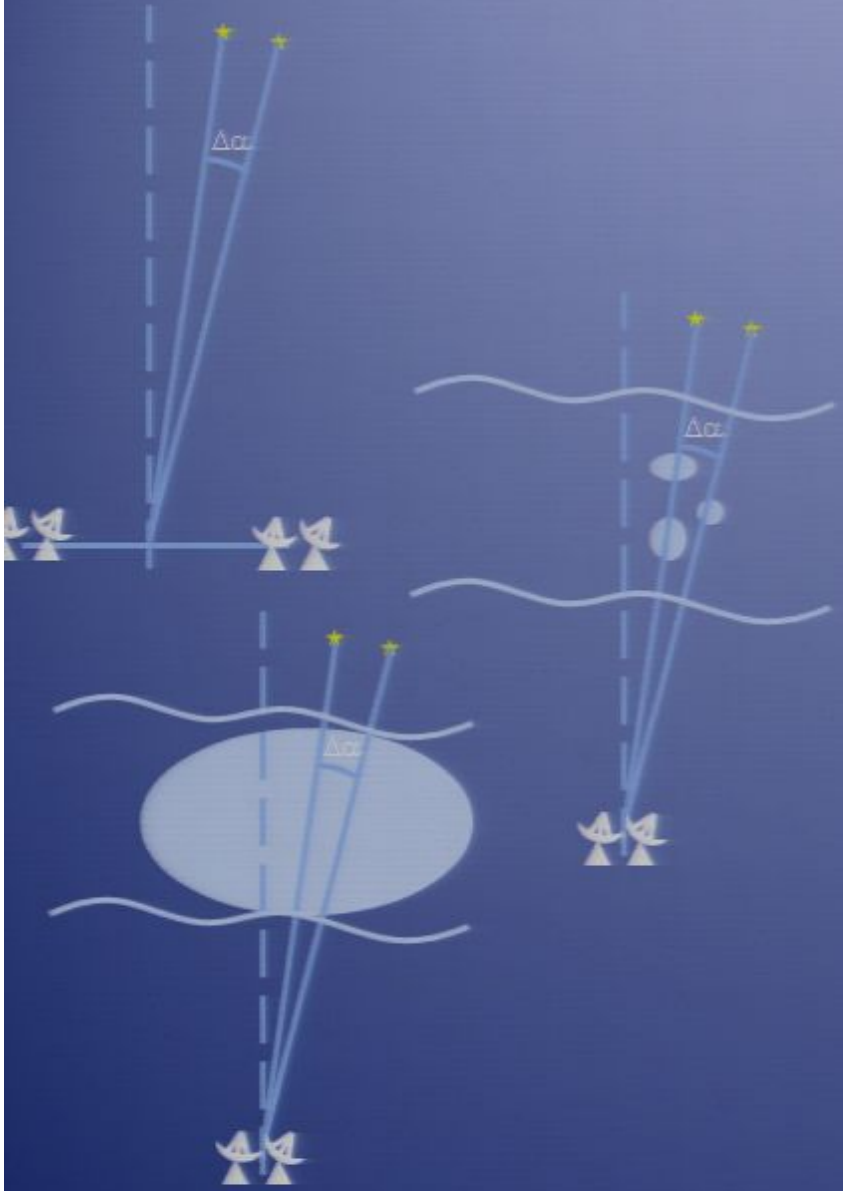
he Black Hole's retinue

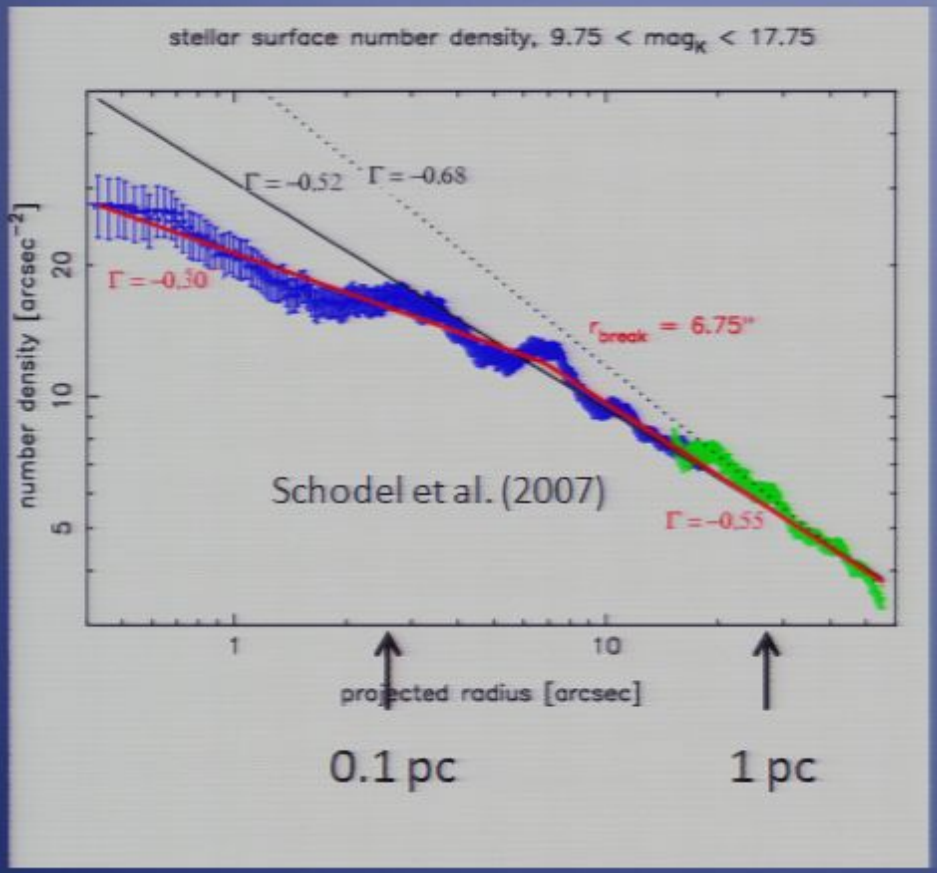
EHT Astrometry

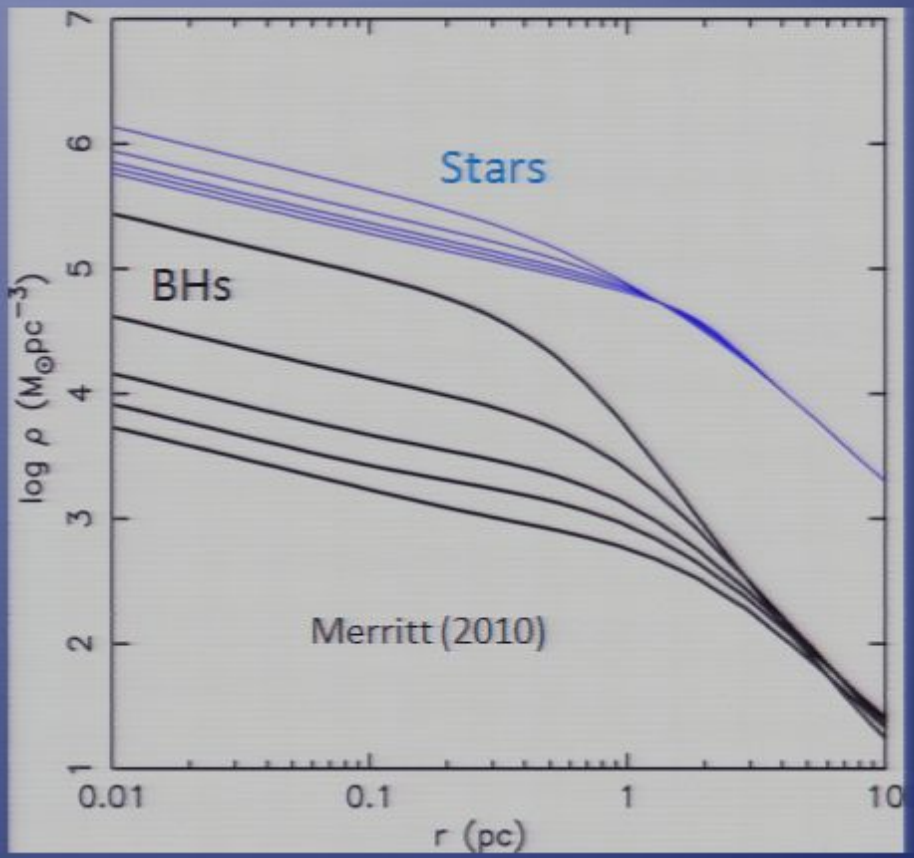


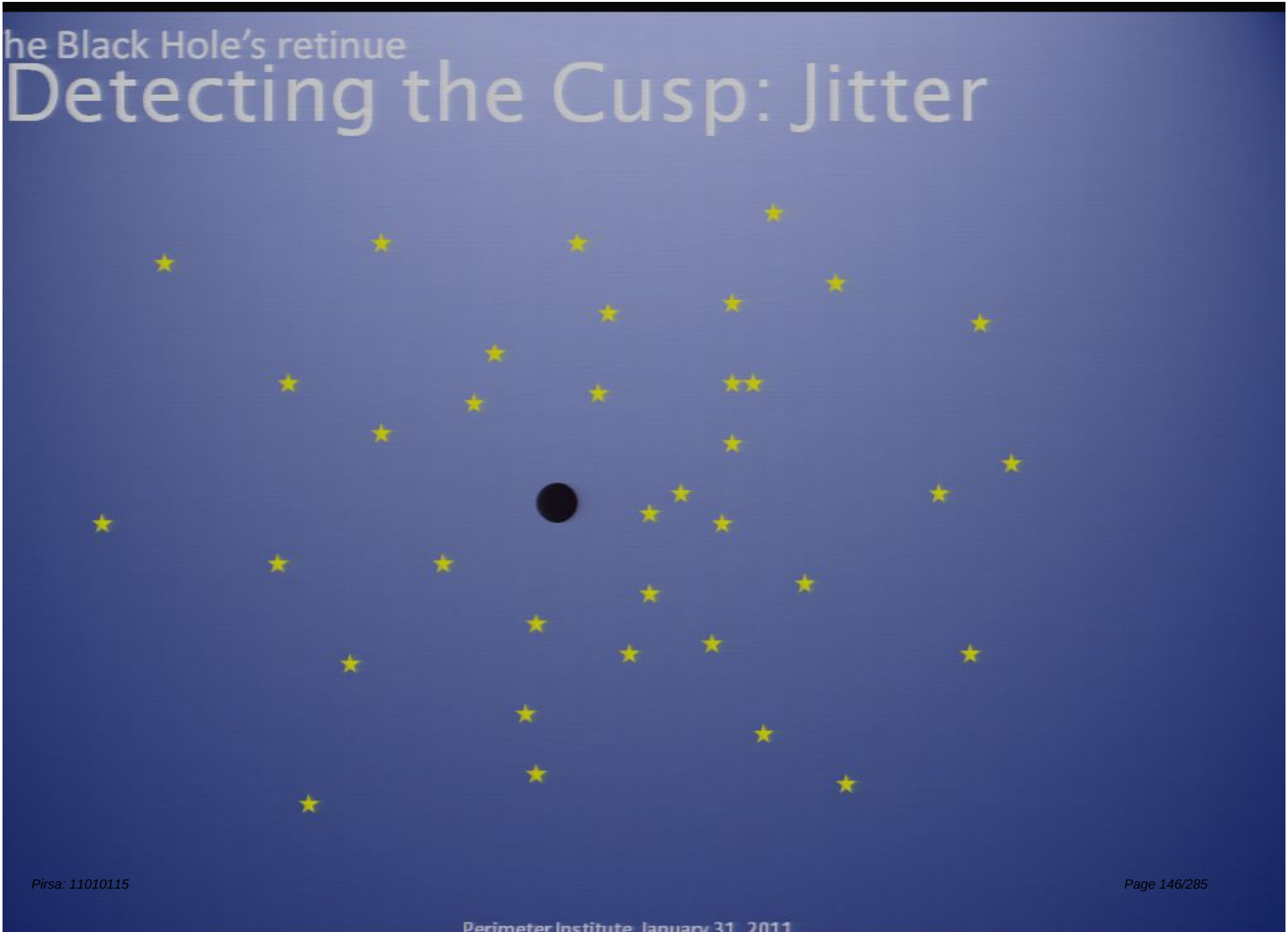
- Absolute astrometry impossible
  → Differential astrometry with nearby sources (<1°)
- Short coherence time
  → use sub-arrays
- Short-time scale atmospheric phase errors average out
- Long-time scale atmospheric phase errors require careful calibration
  - Geodetic blocks
  - GPS
  - Multiple references
  - Time!

he Black Hole's retinue

Detecting the Cusp

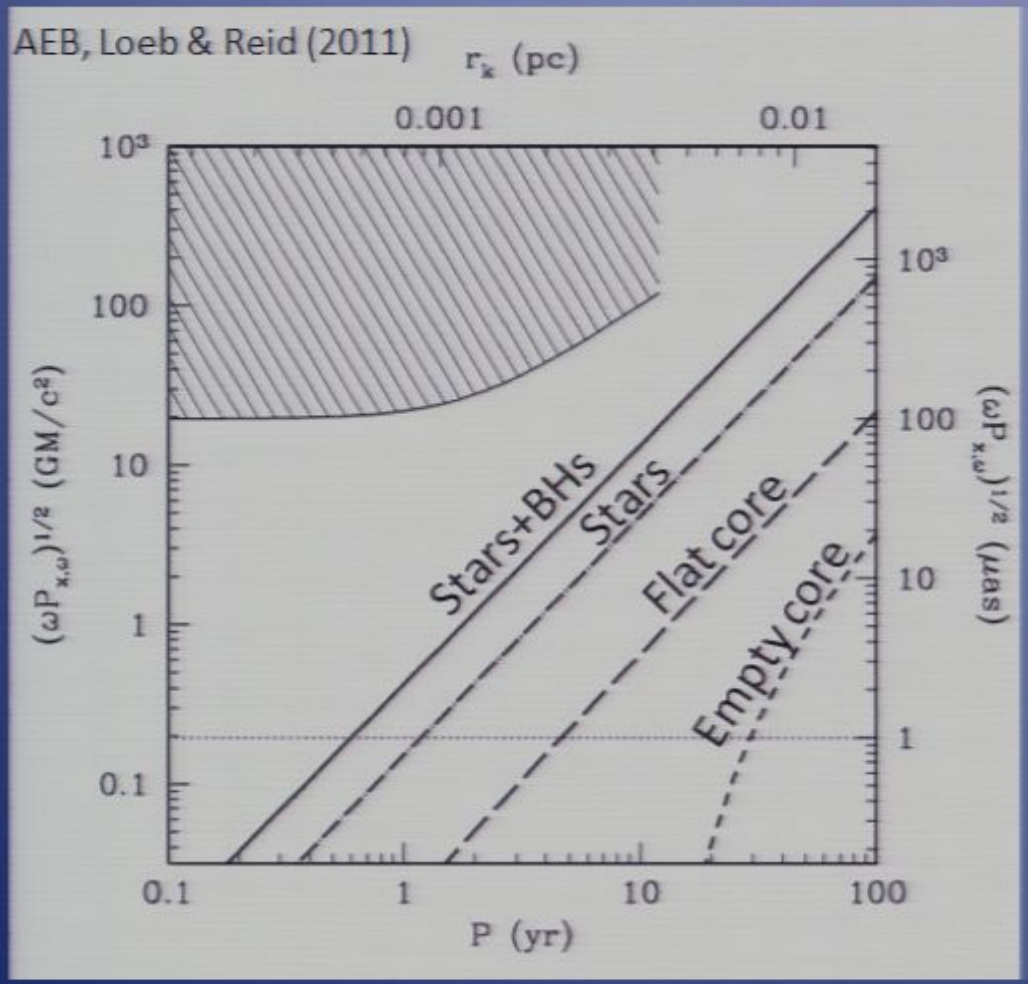





he Black Hole's retinue
Detecting the Cusp: Jitter

he Black Hole's retinue

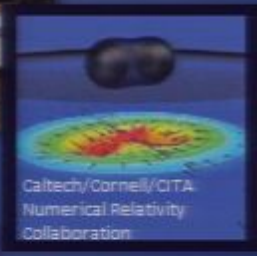
Detecting the Cusp Jitter

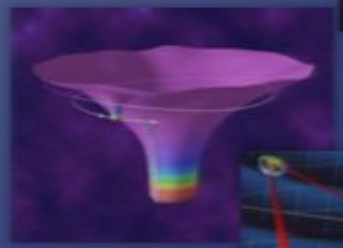


- SMBH Cusp formation and evolution

- LIGO BH-BH merger rates

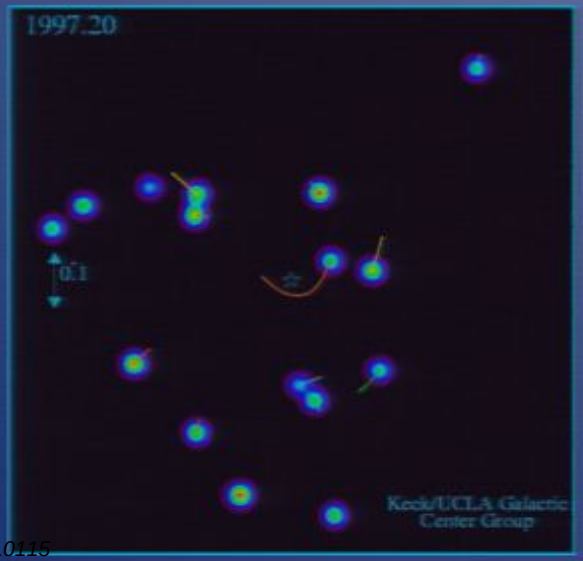
- LISA EMRI rates





he Black Hole's retinue

Massive Companion



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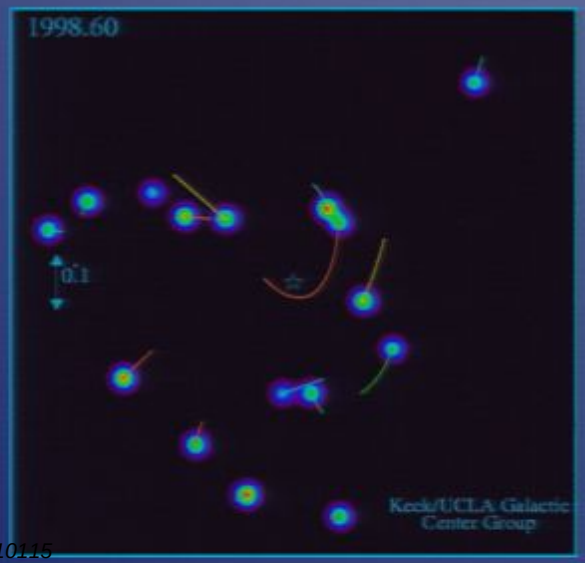

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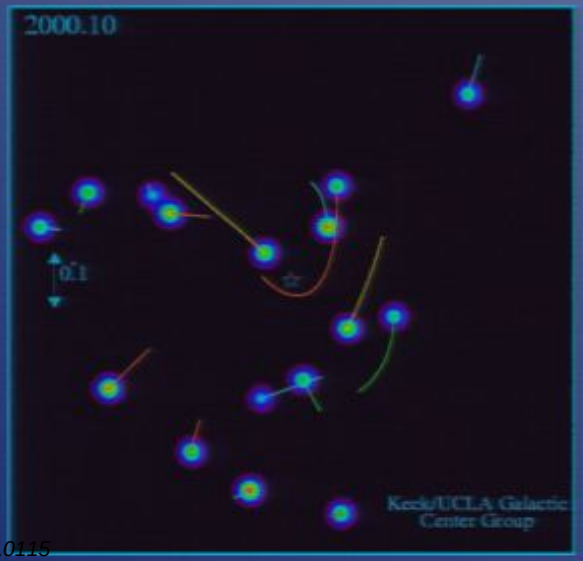

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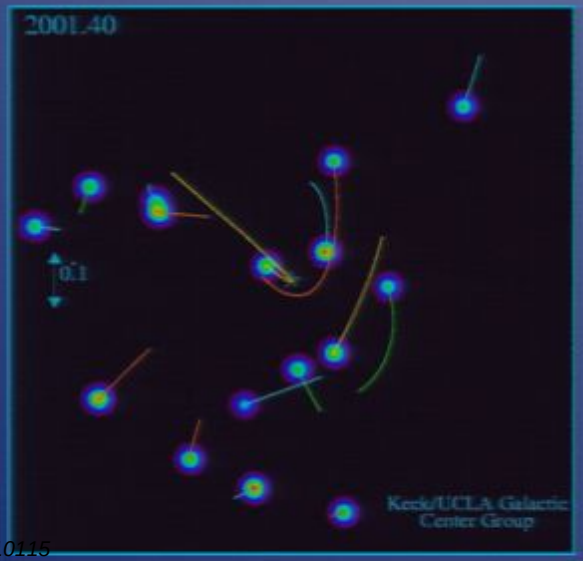

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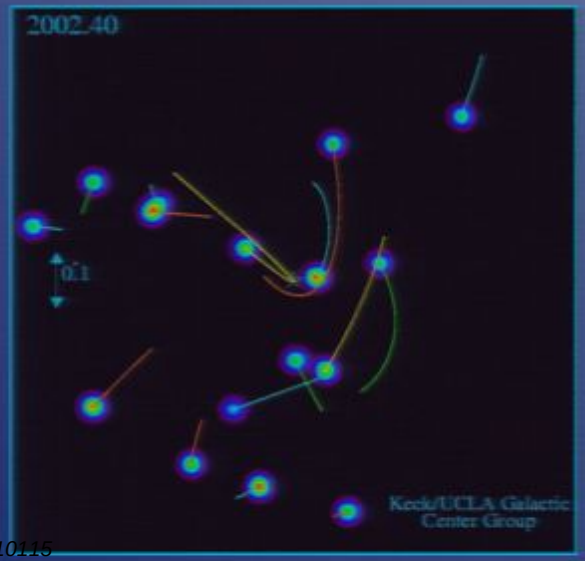

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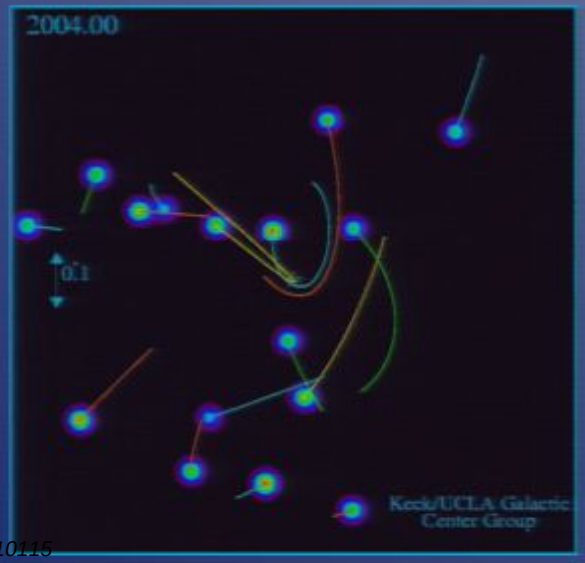

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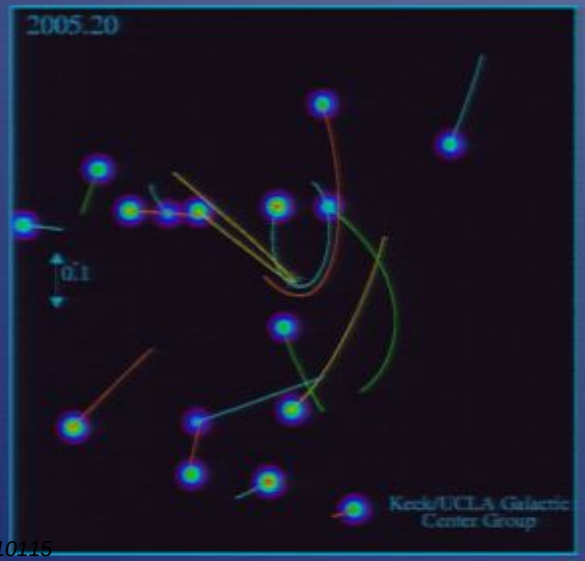

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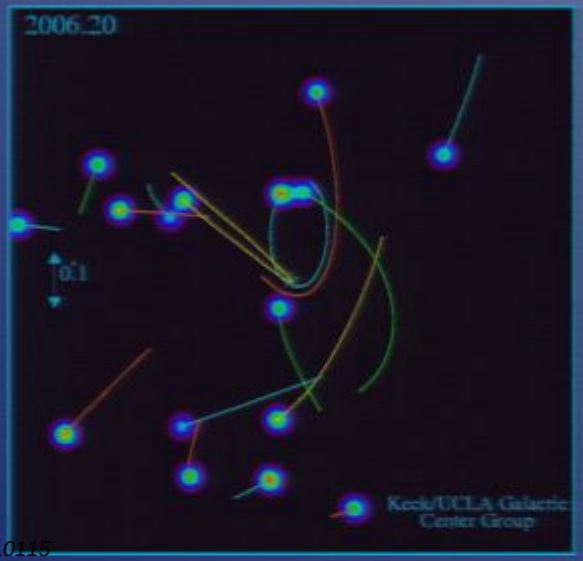

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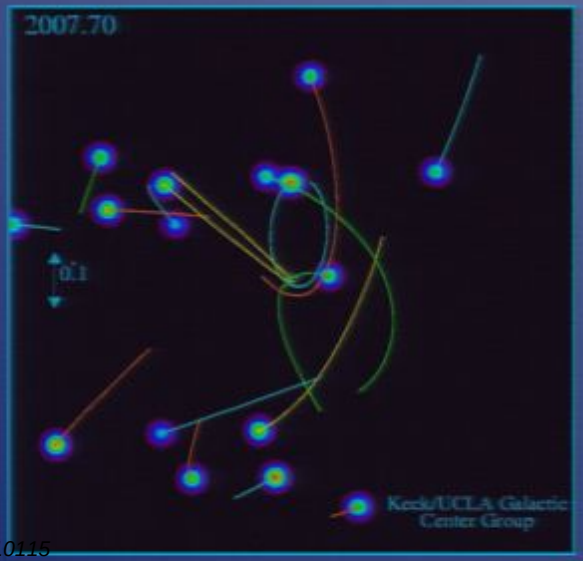

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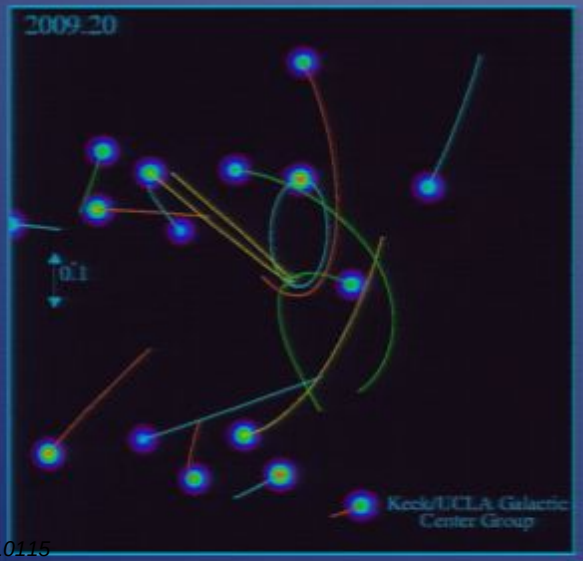

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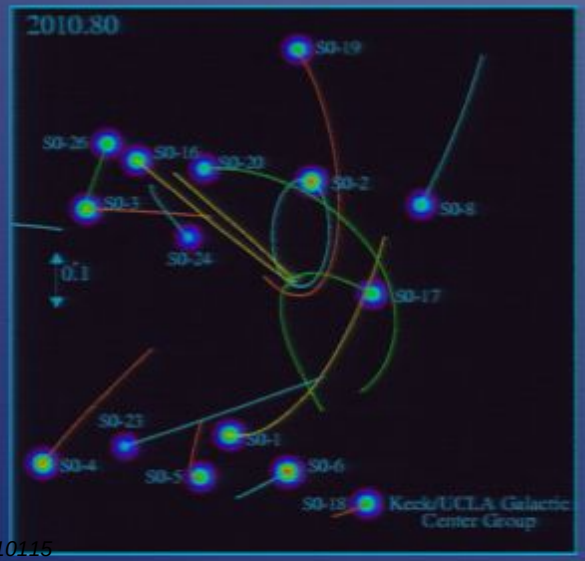
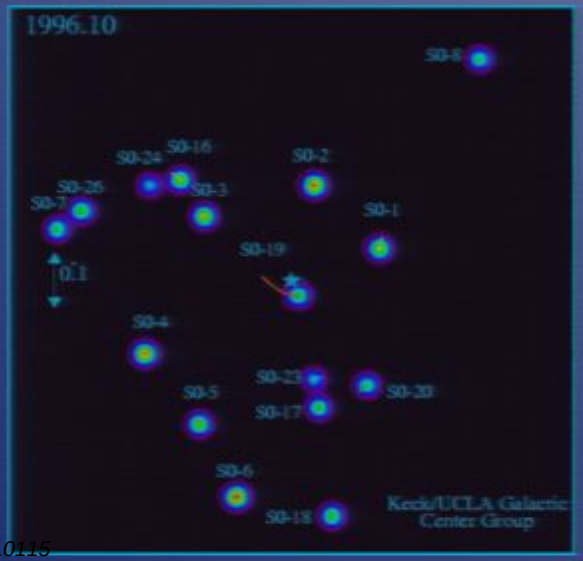


he Black Hole's retinue

Massive Companion



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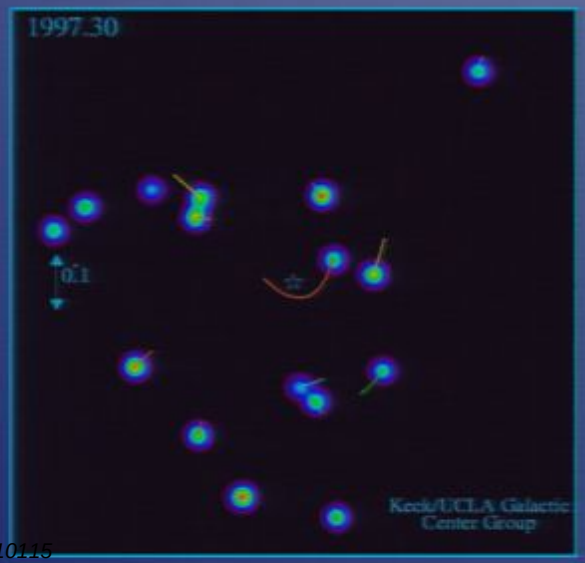

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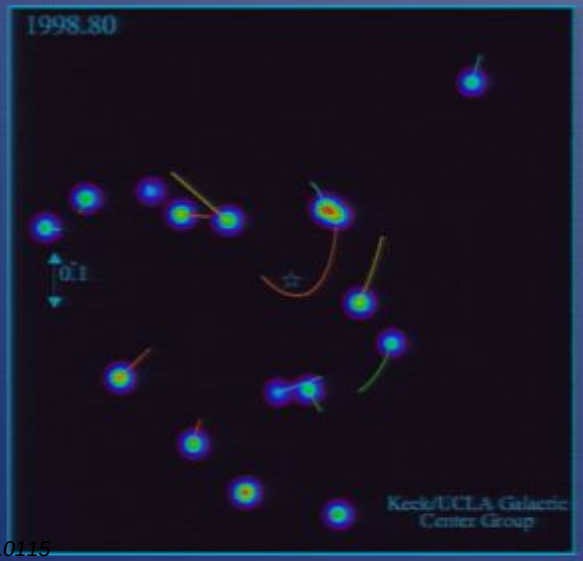

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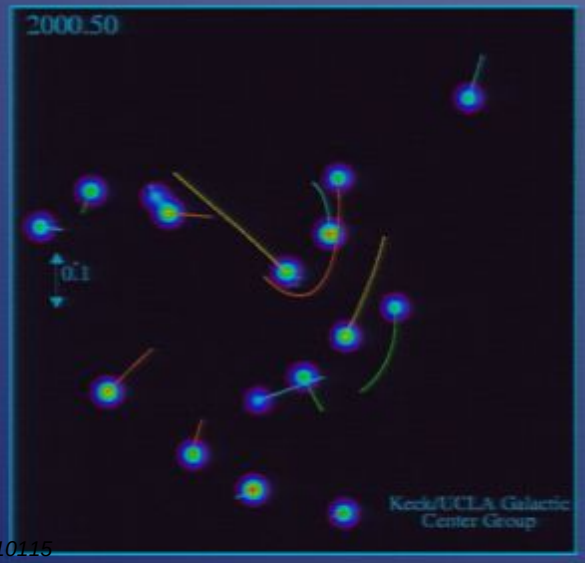

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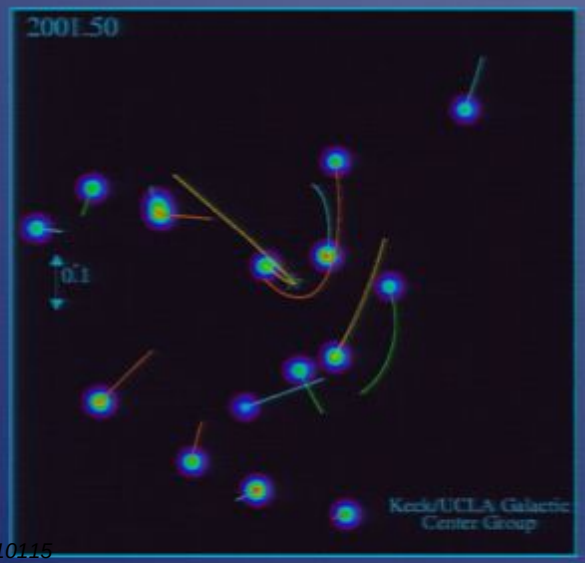

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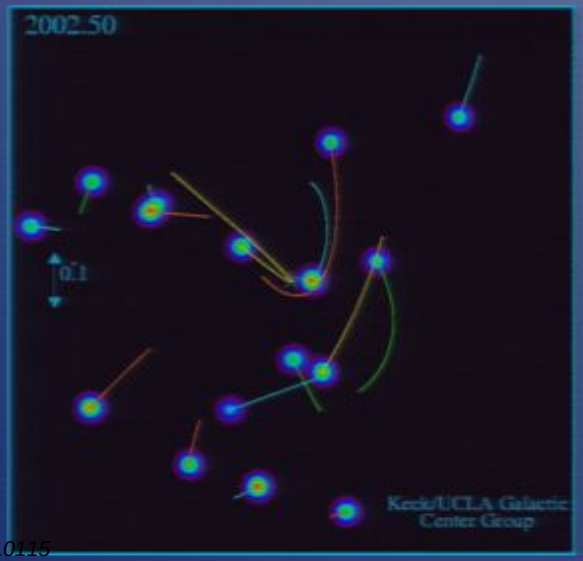

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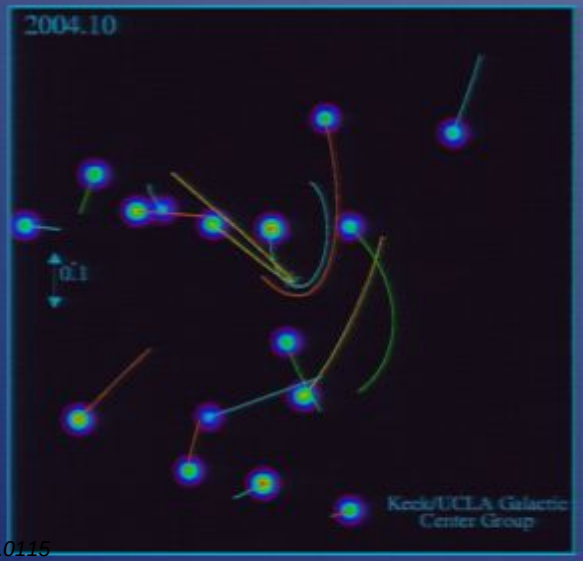

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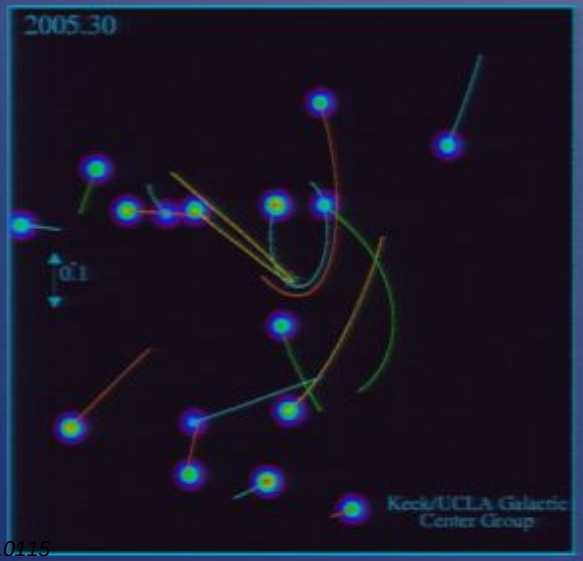

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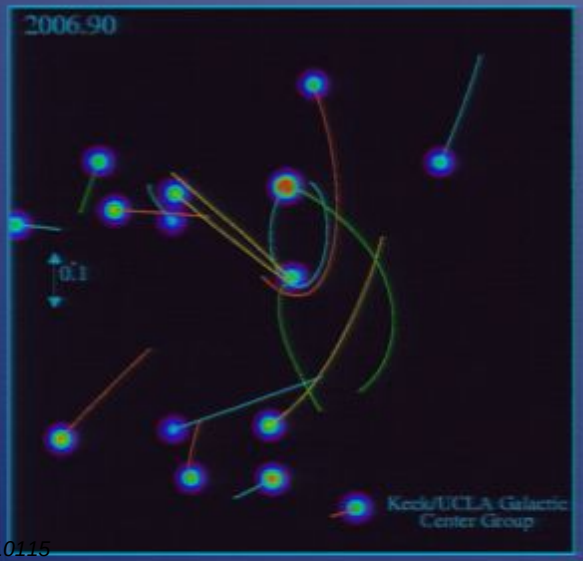

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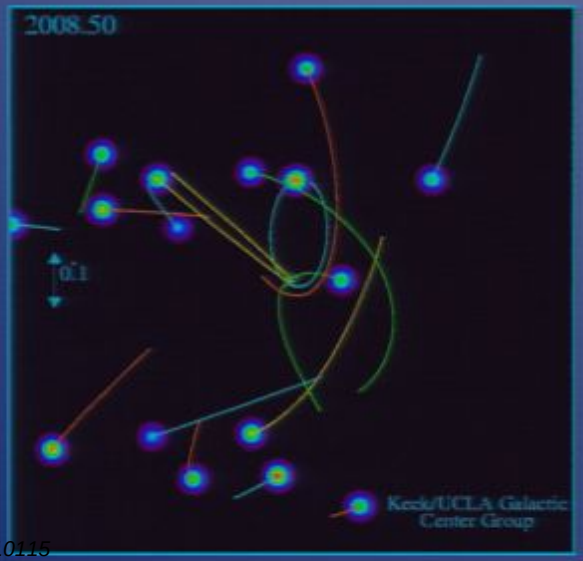

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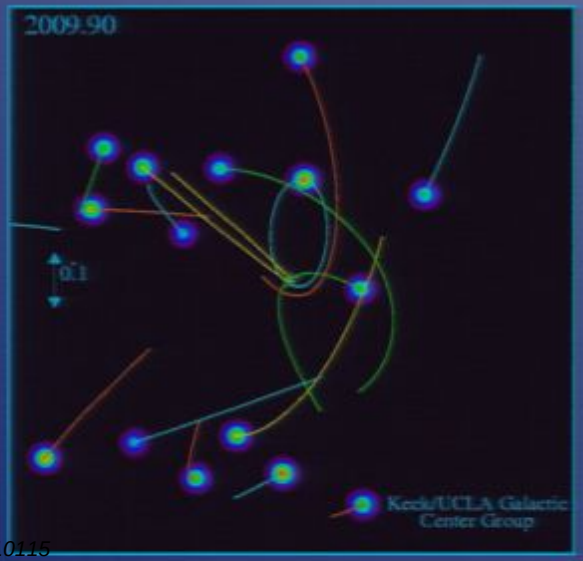

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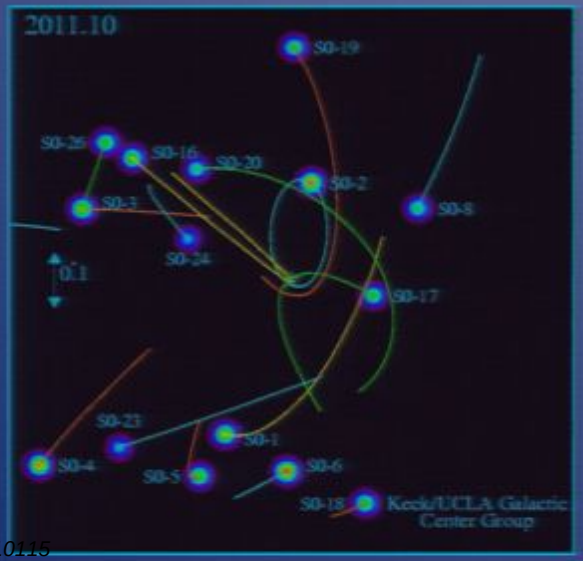

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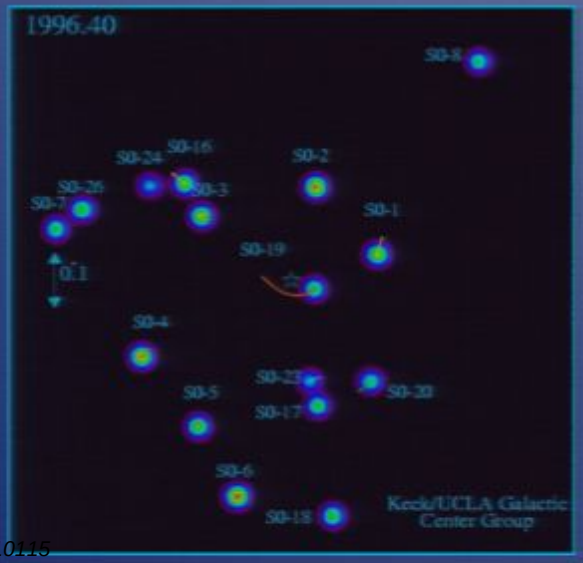

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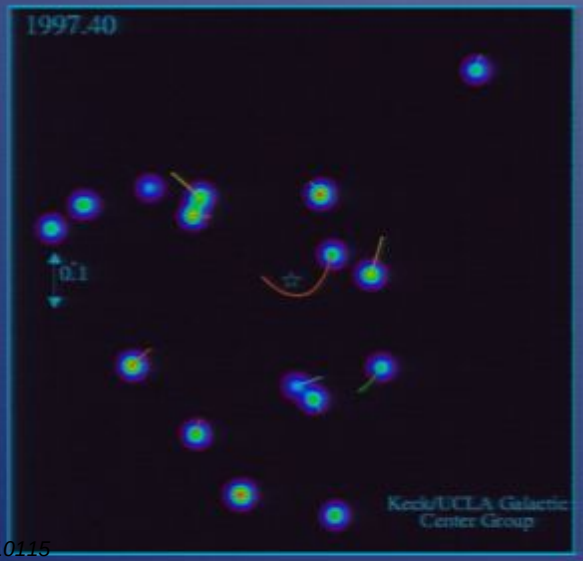

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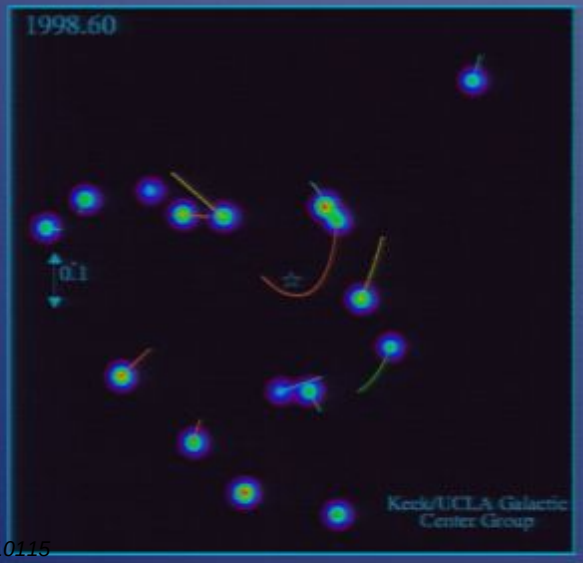

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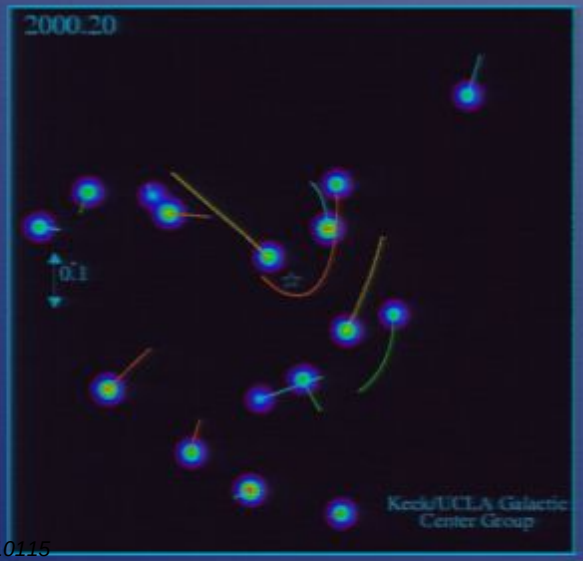

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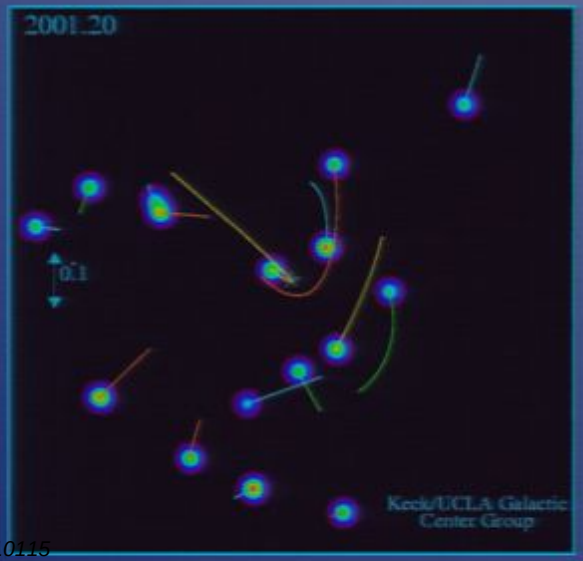

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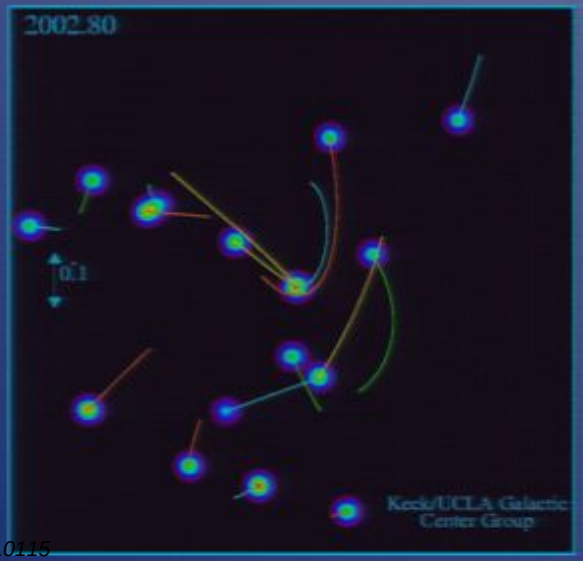

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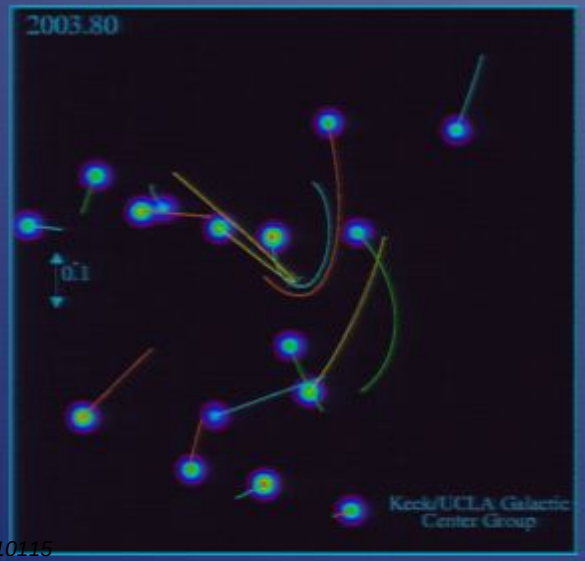

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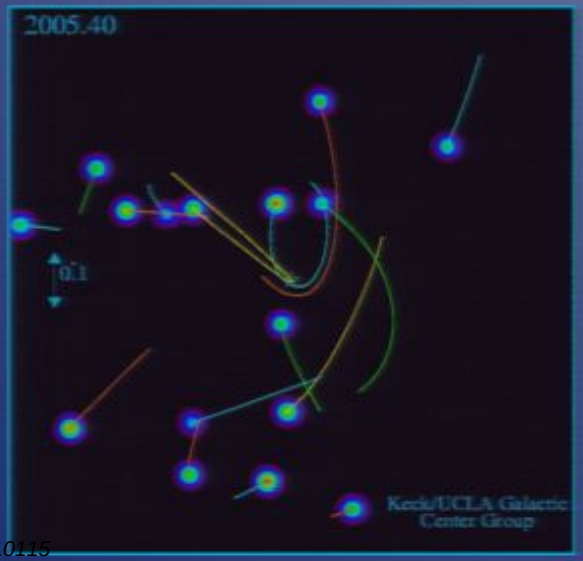

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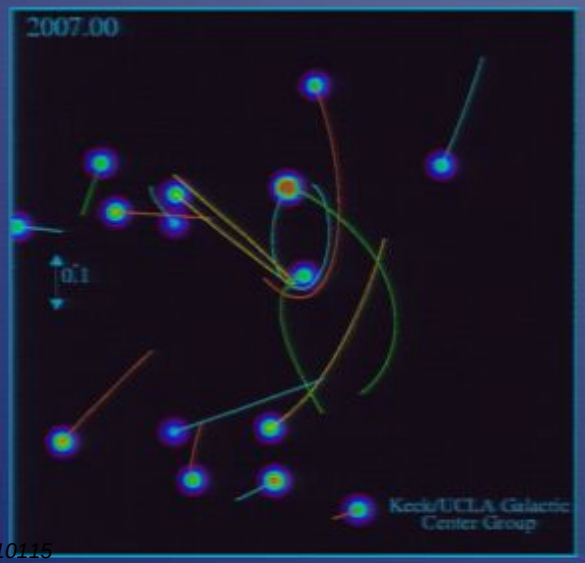

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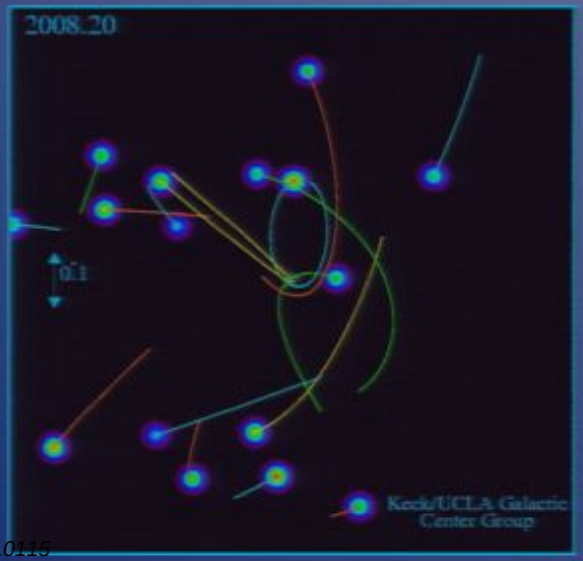

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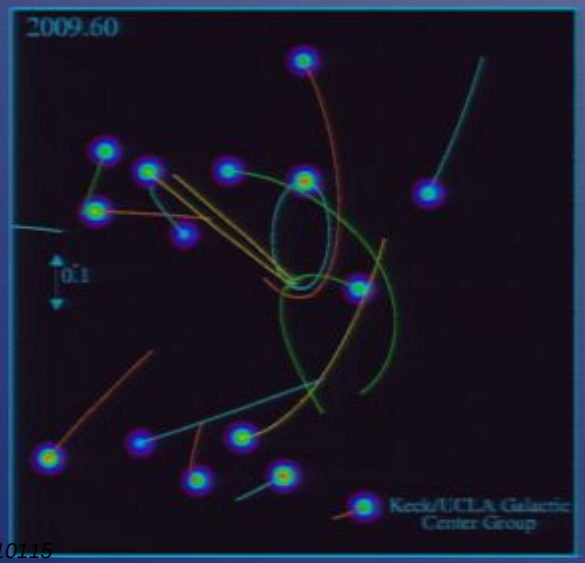

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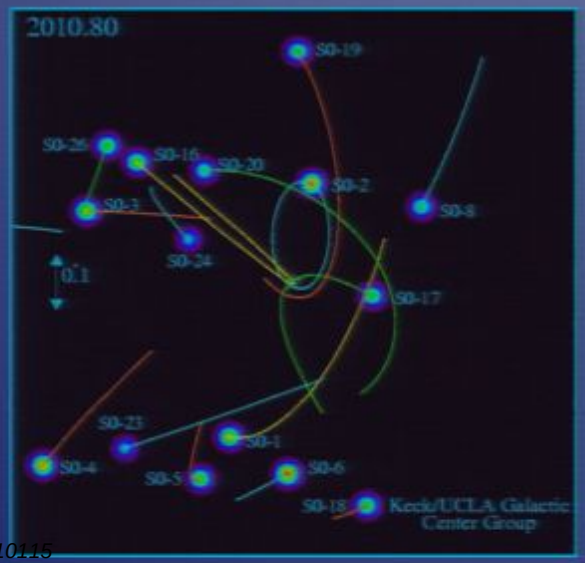

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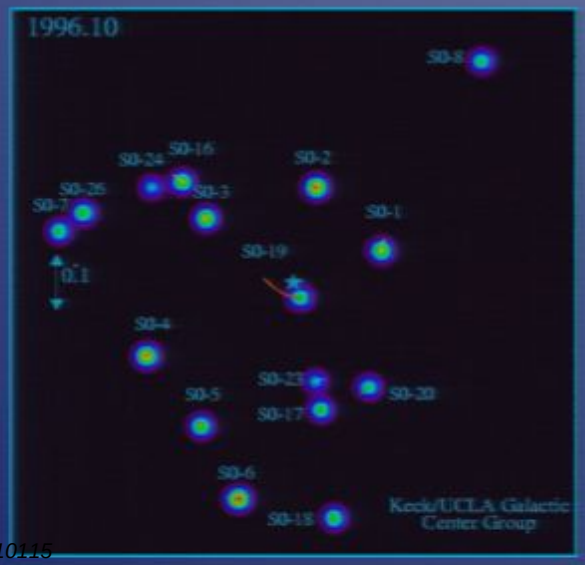

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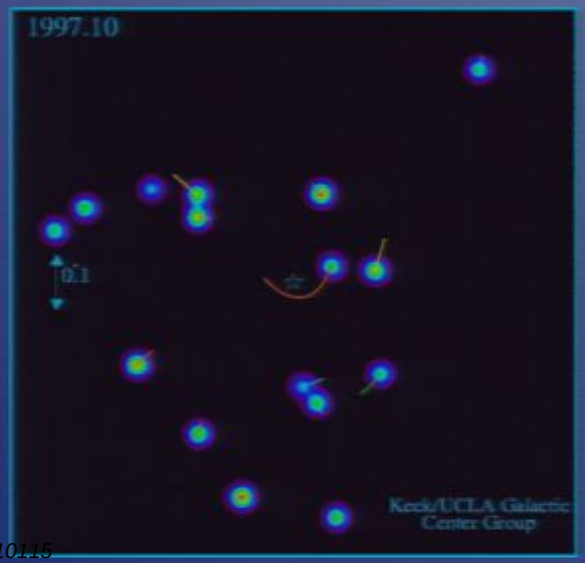

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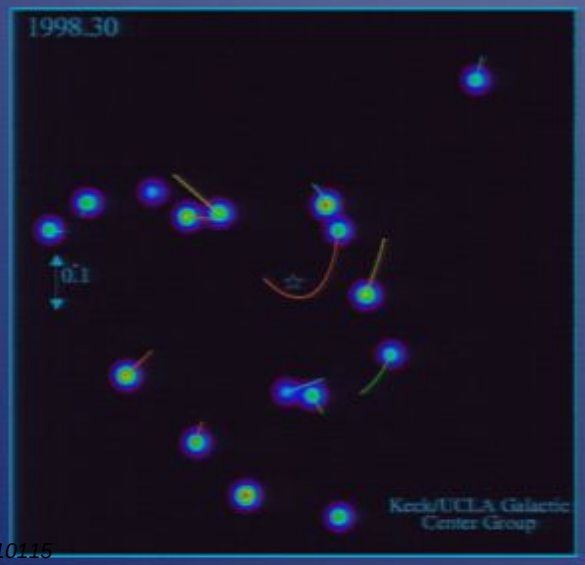

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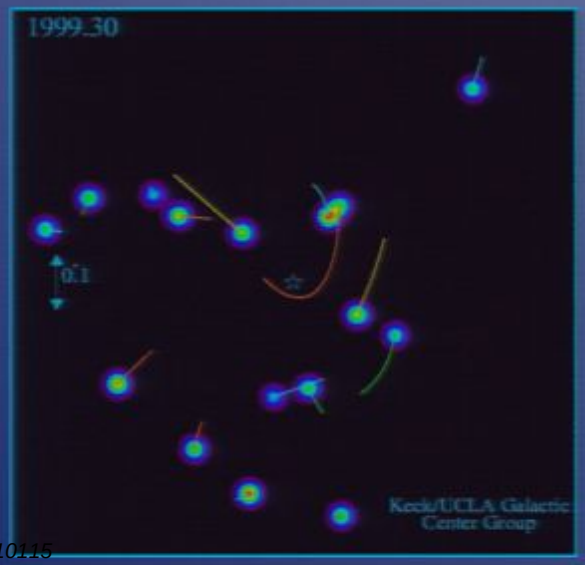

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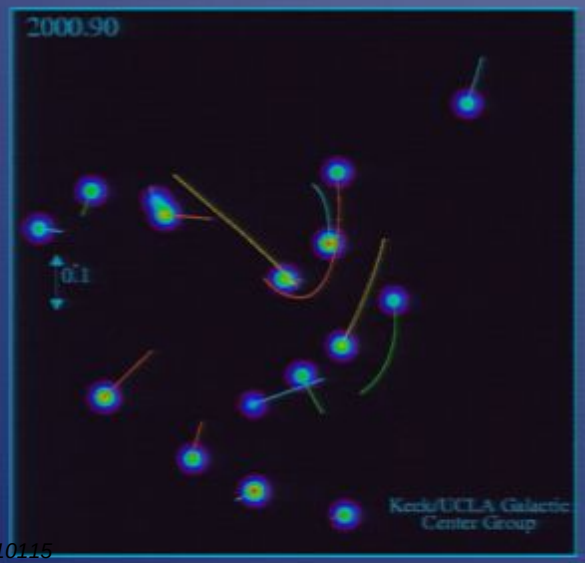

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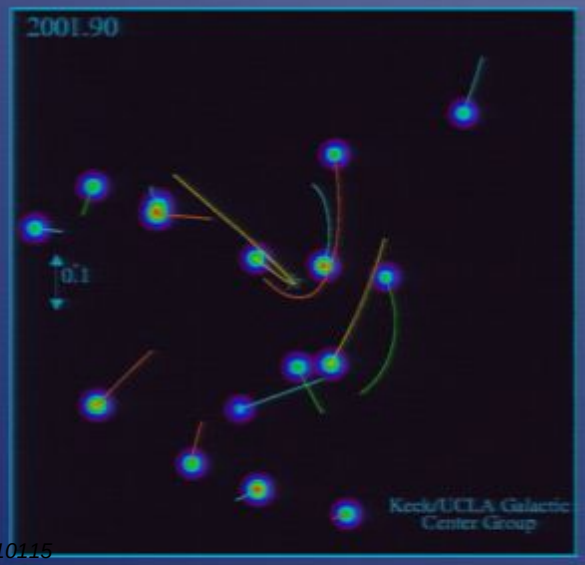

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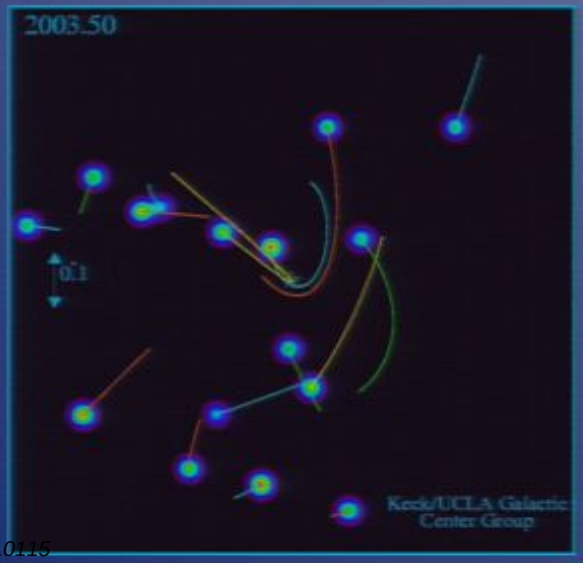

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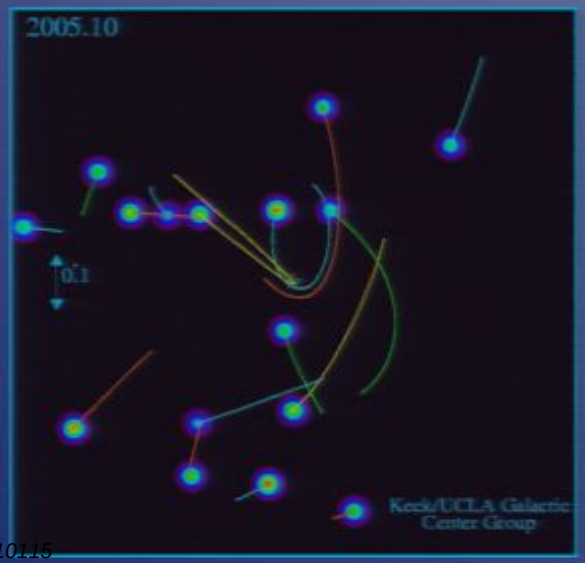

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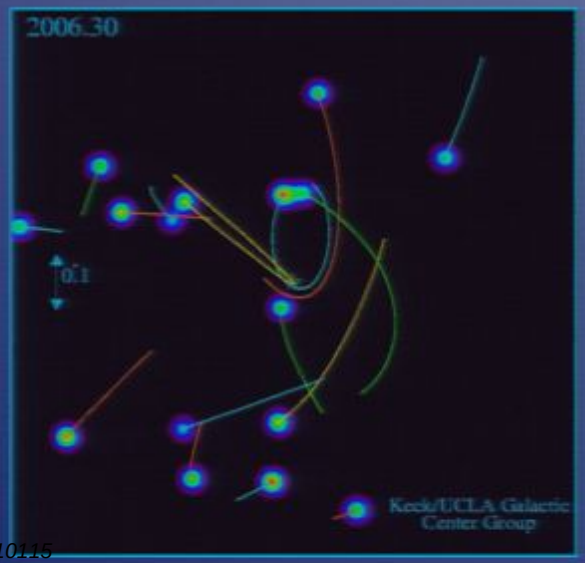

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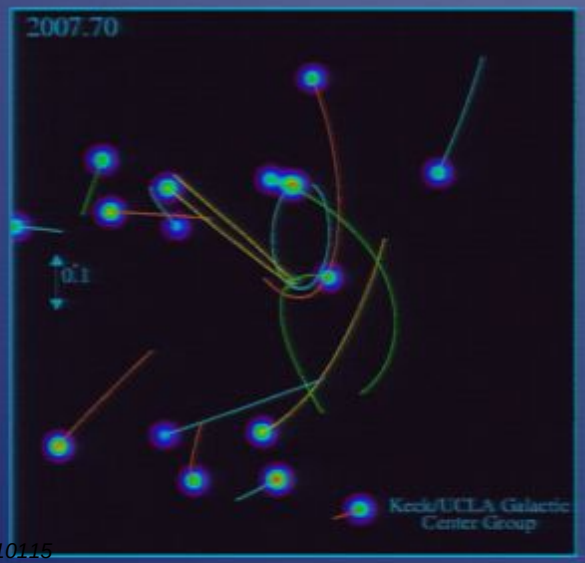

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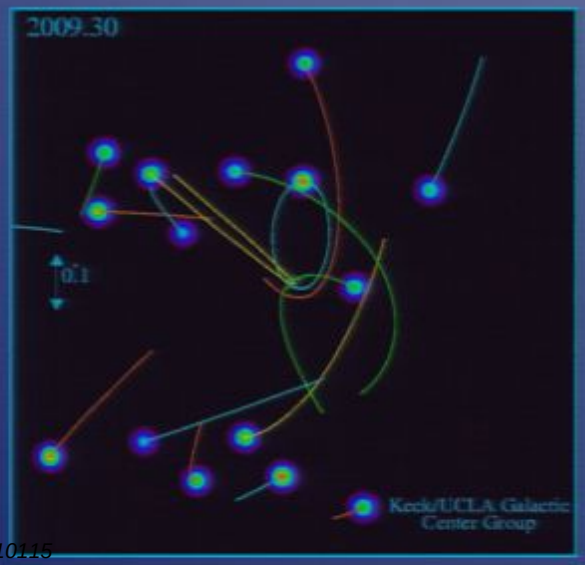

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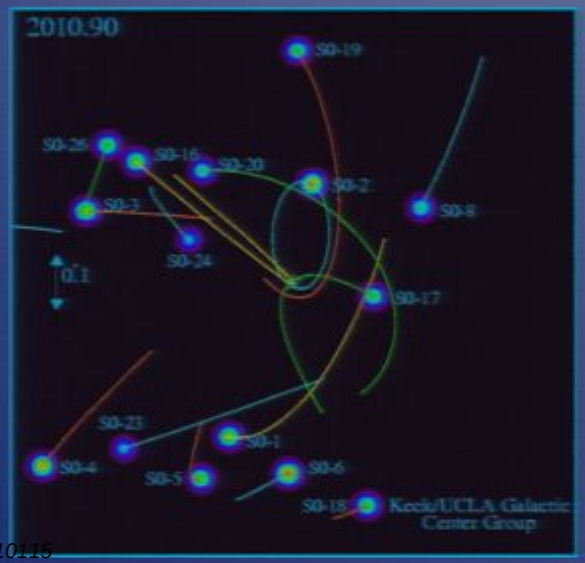

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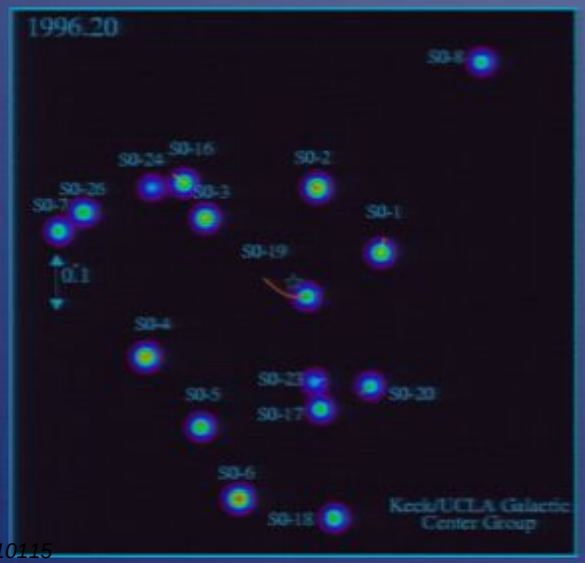

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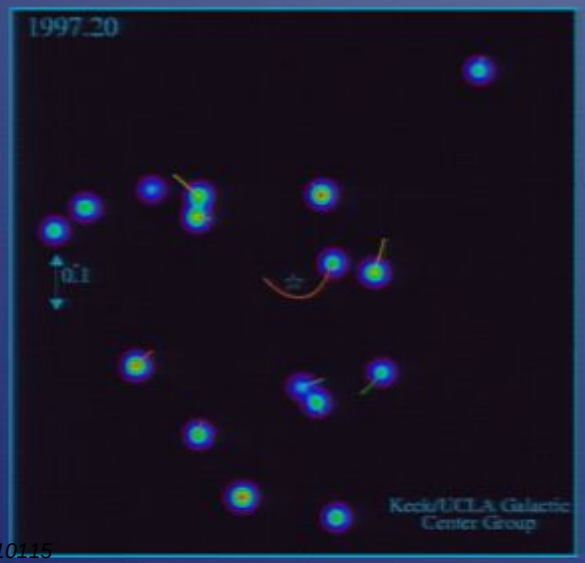

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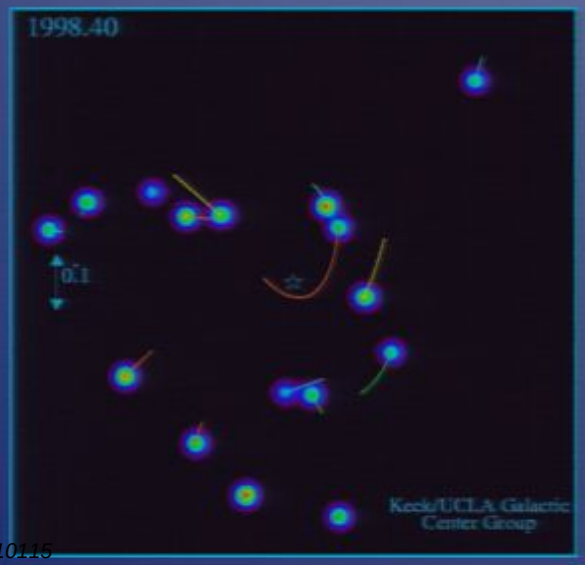

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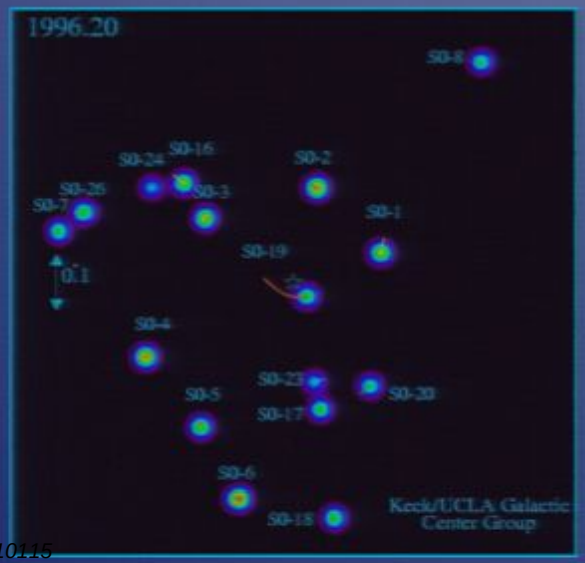

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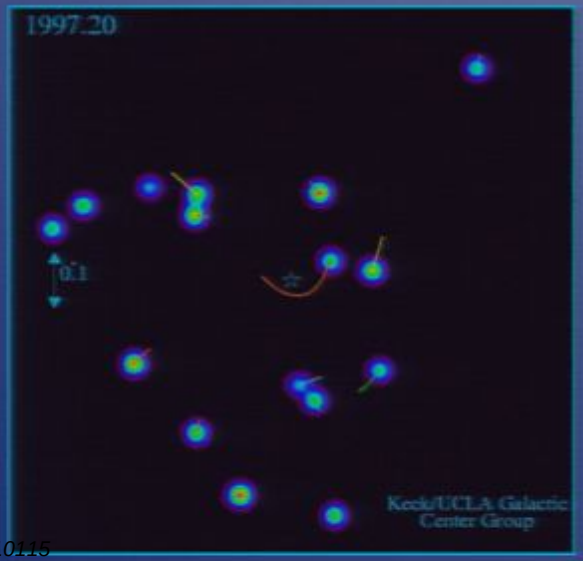

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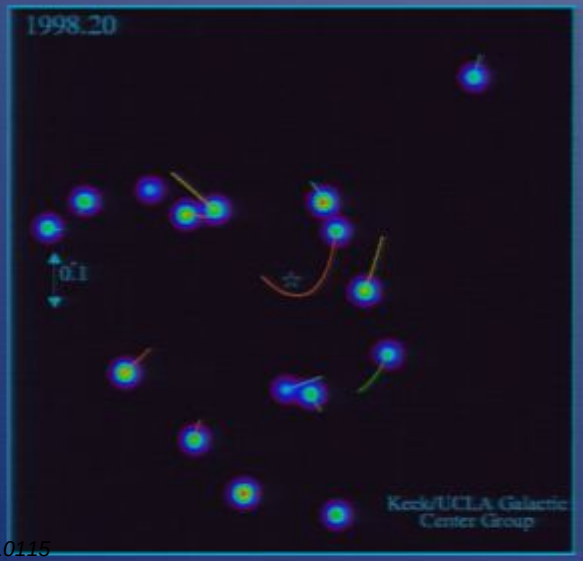

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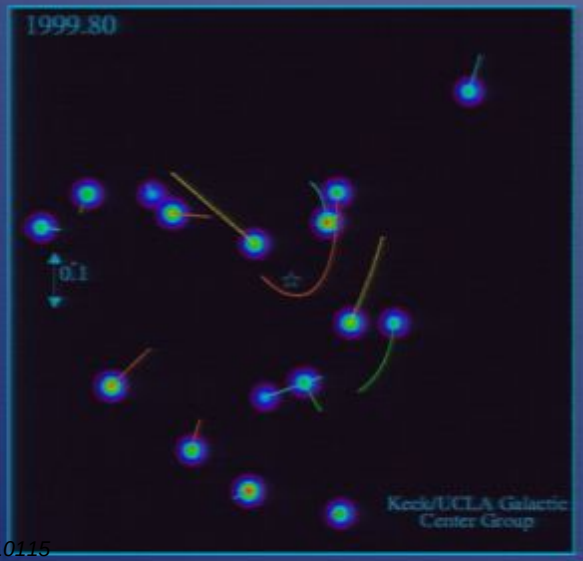

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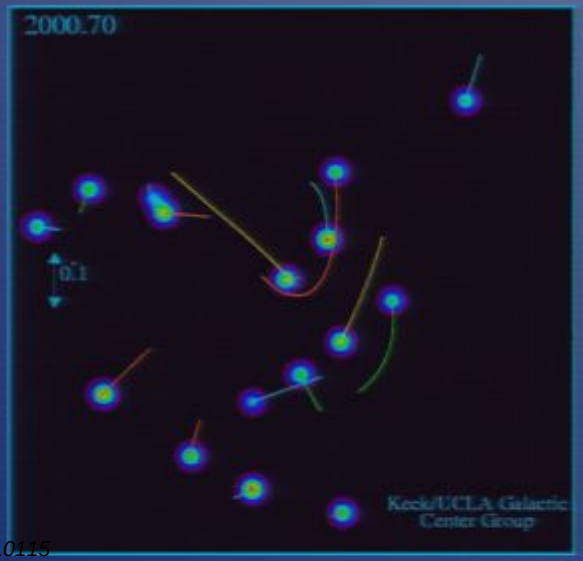

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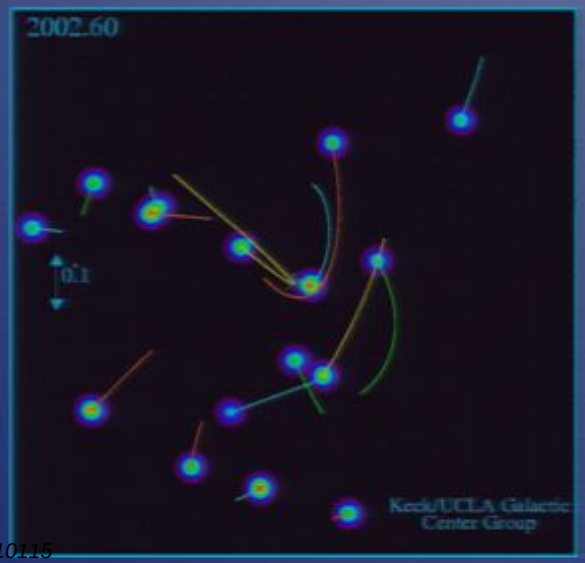

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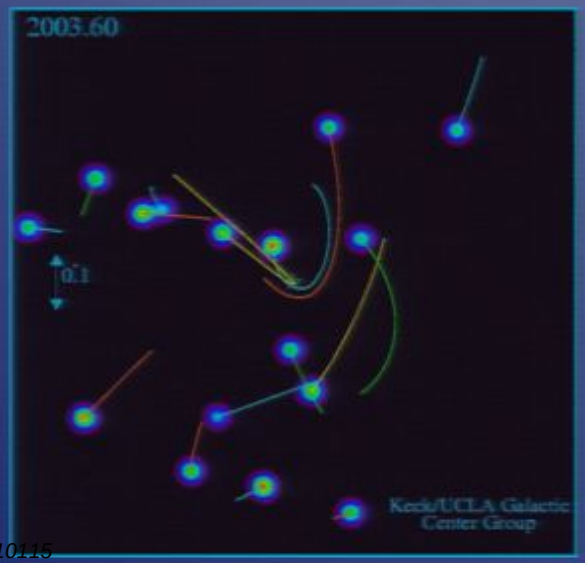

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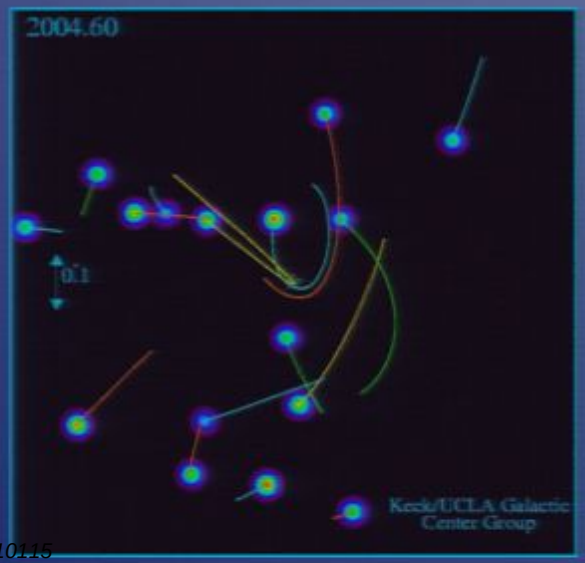

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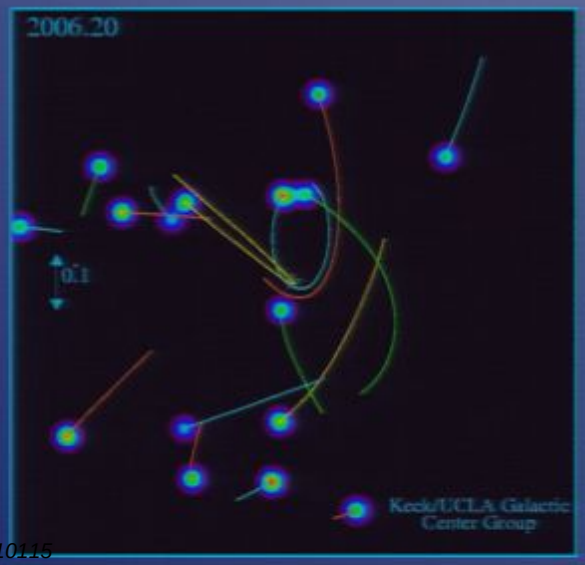

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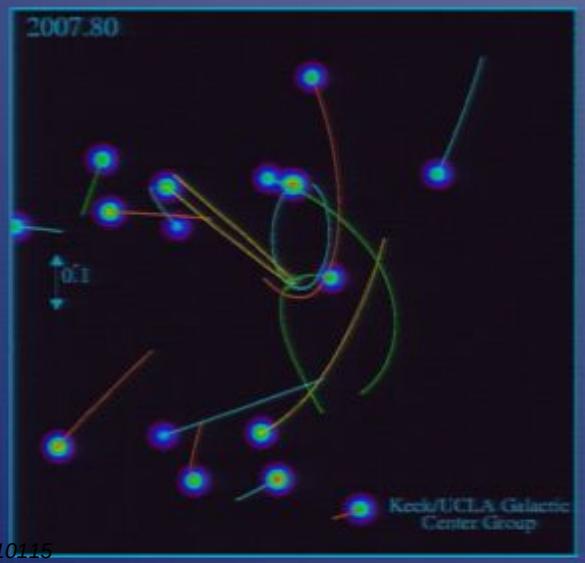

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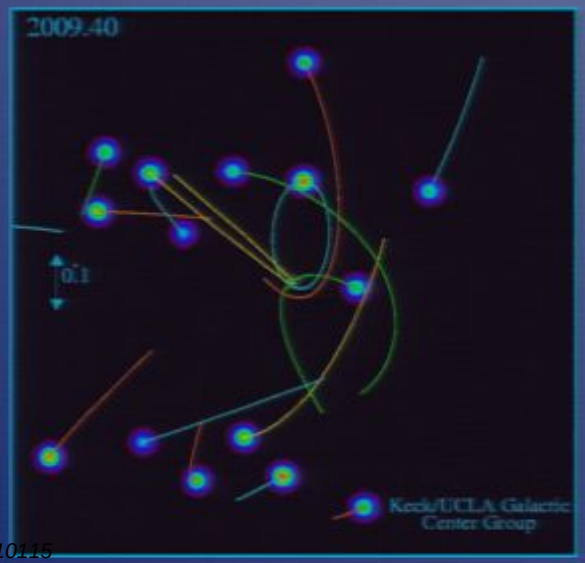

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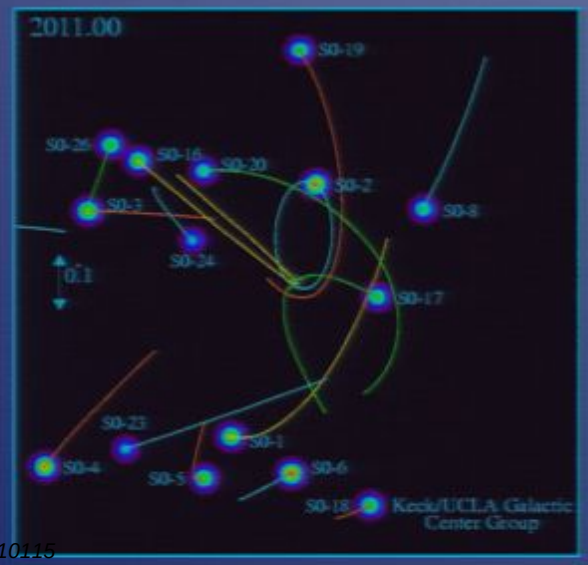

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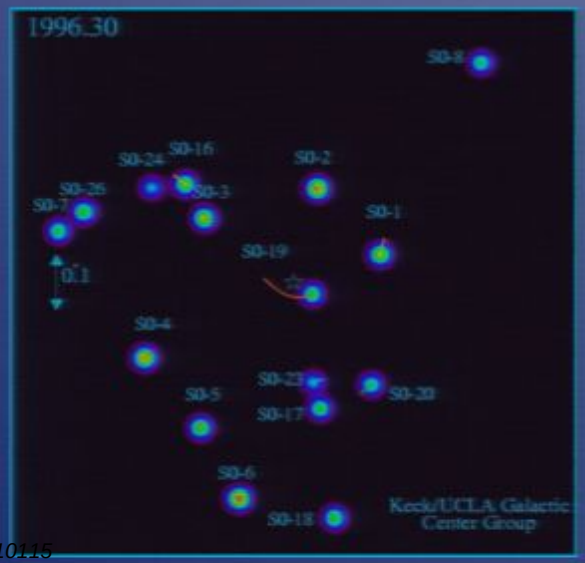
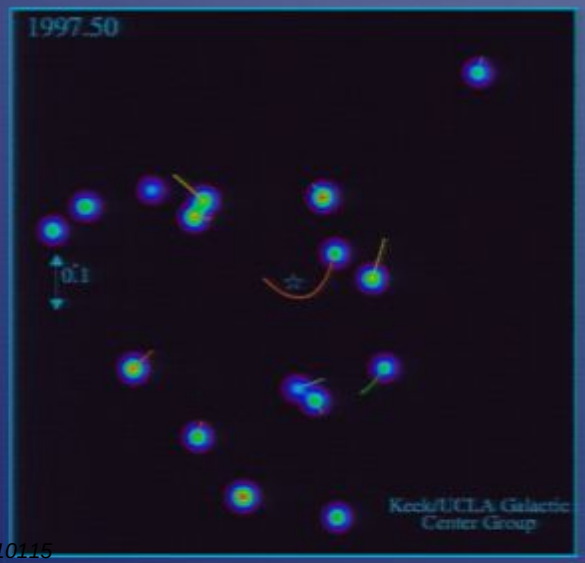


Massive companion entered <0.01pc orbit with Sgr A* within last 10^5 yr!

he Black Hole's retinue

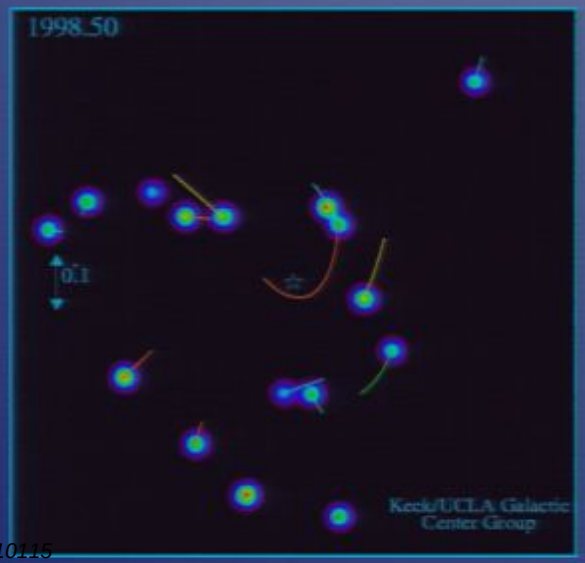
Massive Companion



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

he Black Hole's retinue

Massive Companion



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

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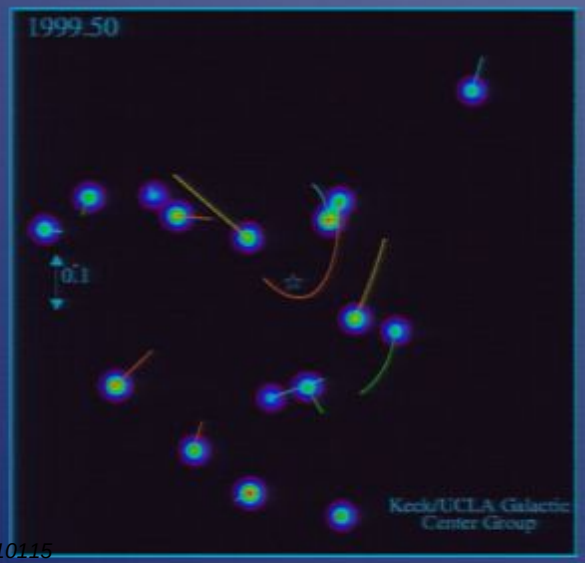
Massive Companion



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

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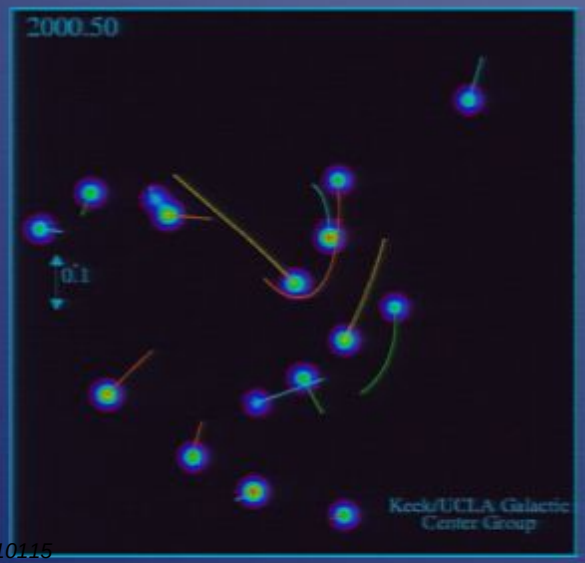
Massive Companion



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

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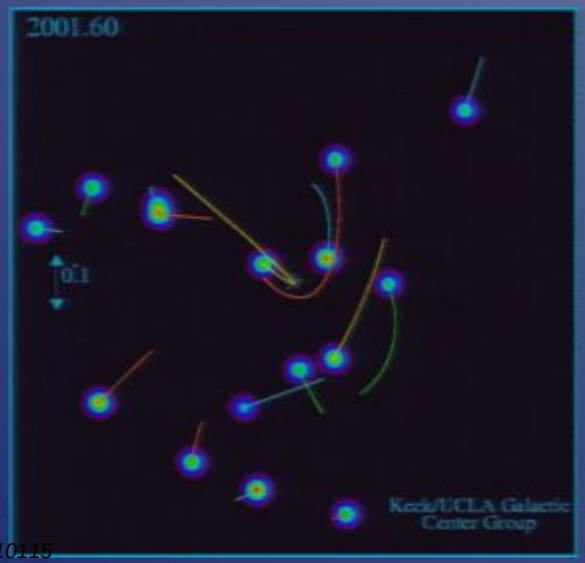
Massive Companion



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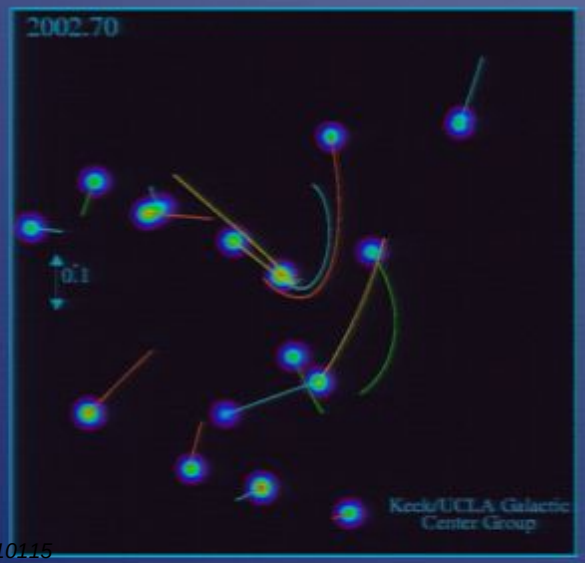

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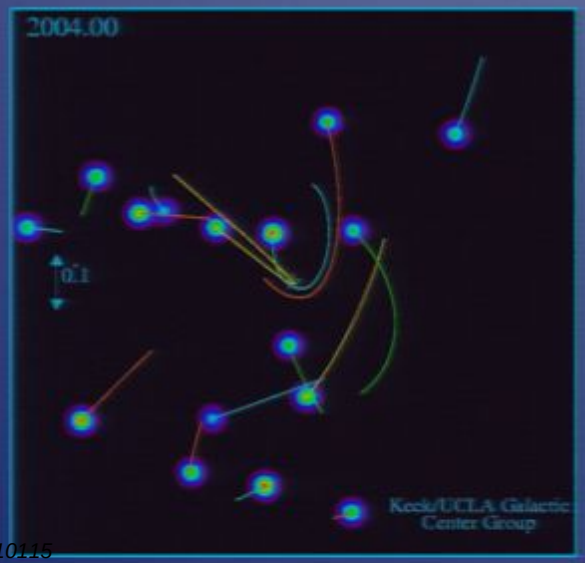

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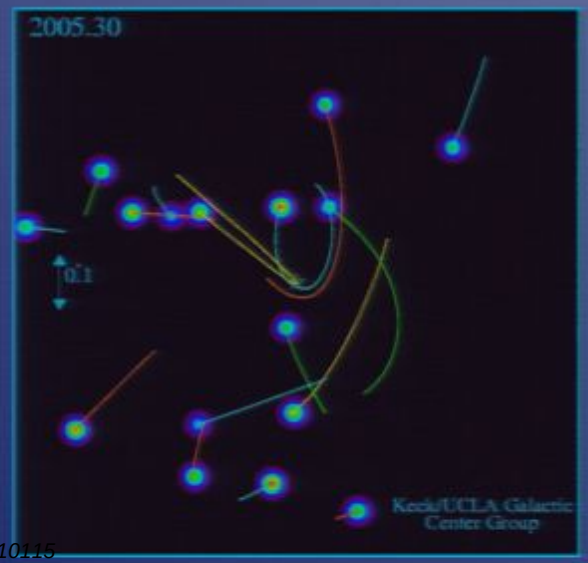

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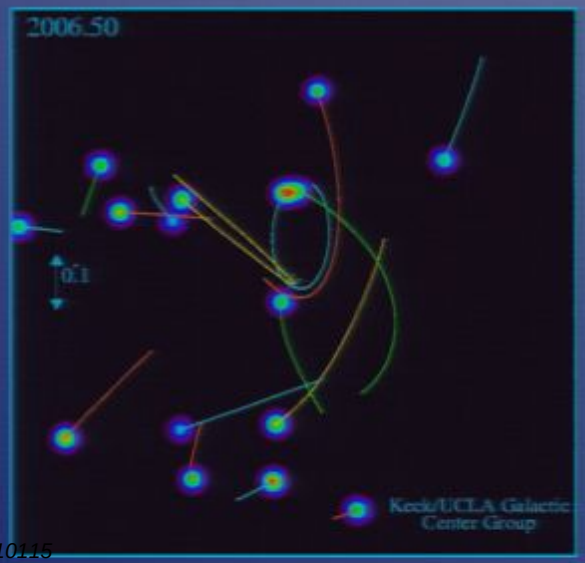

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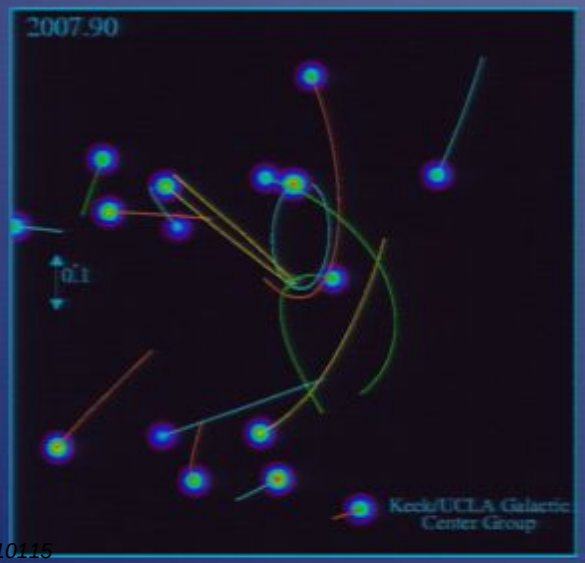

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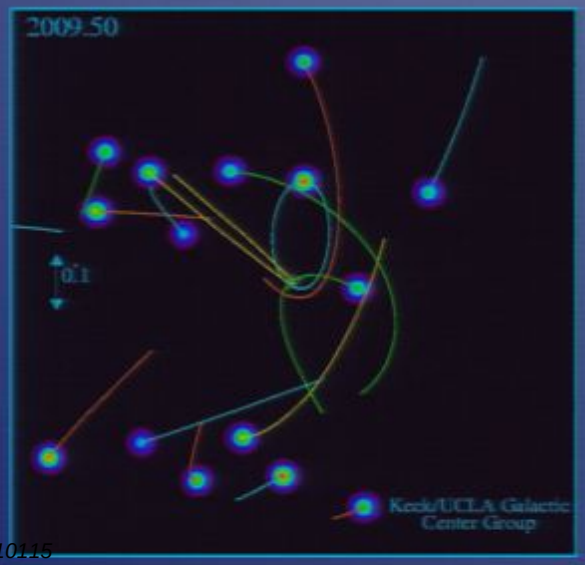

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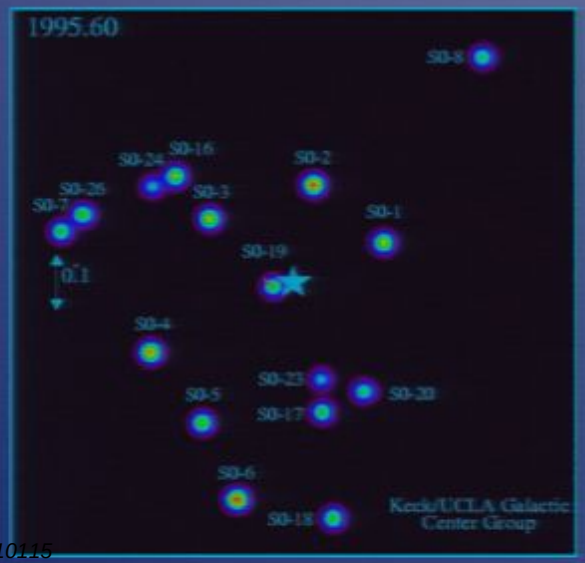

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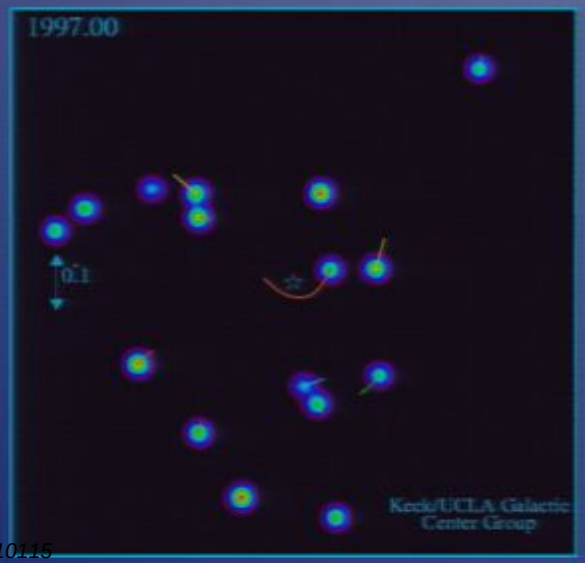

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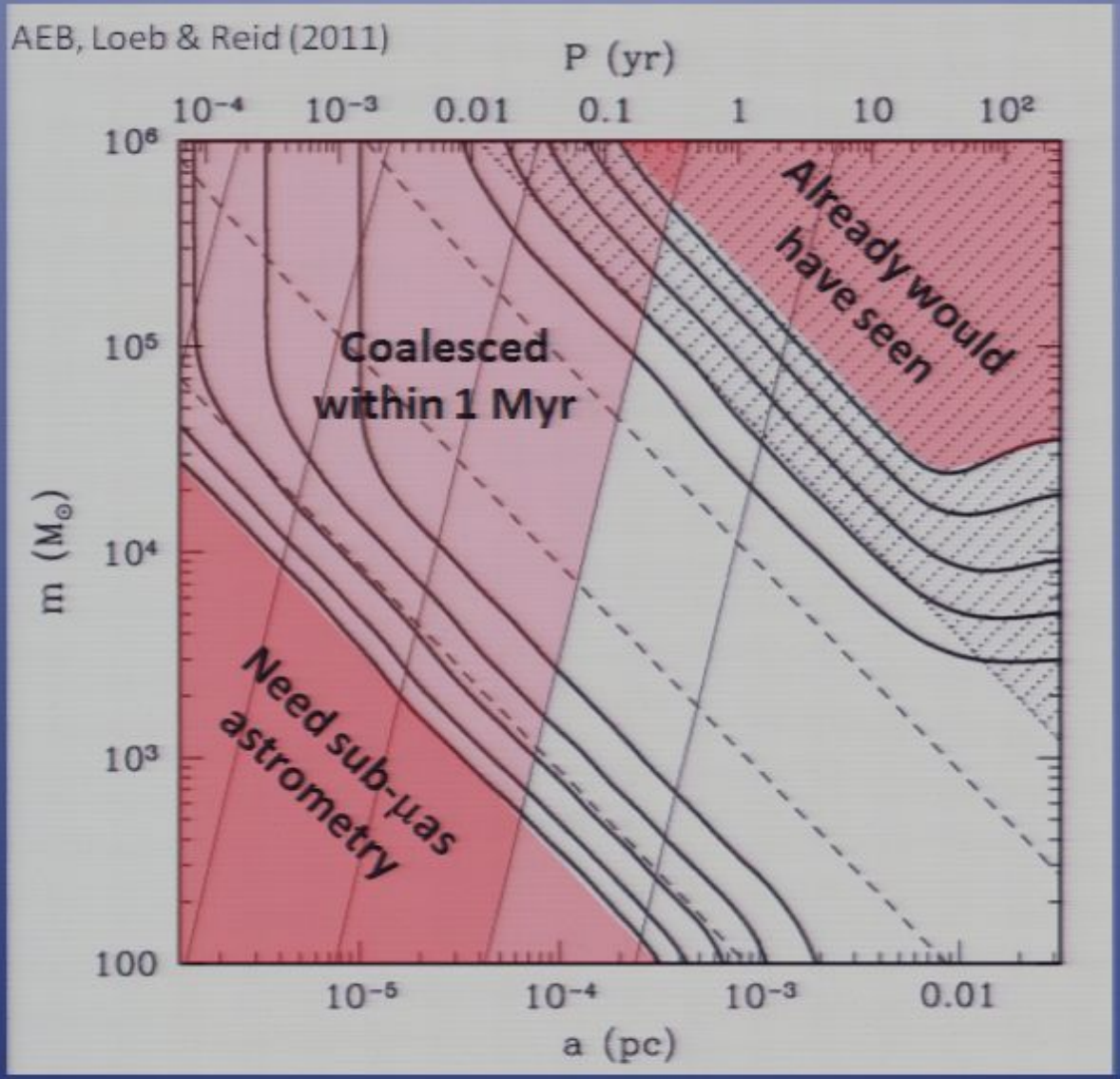

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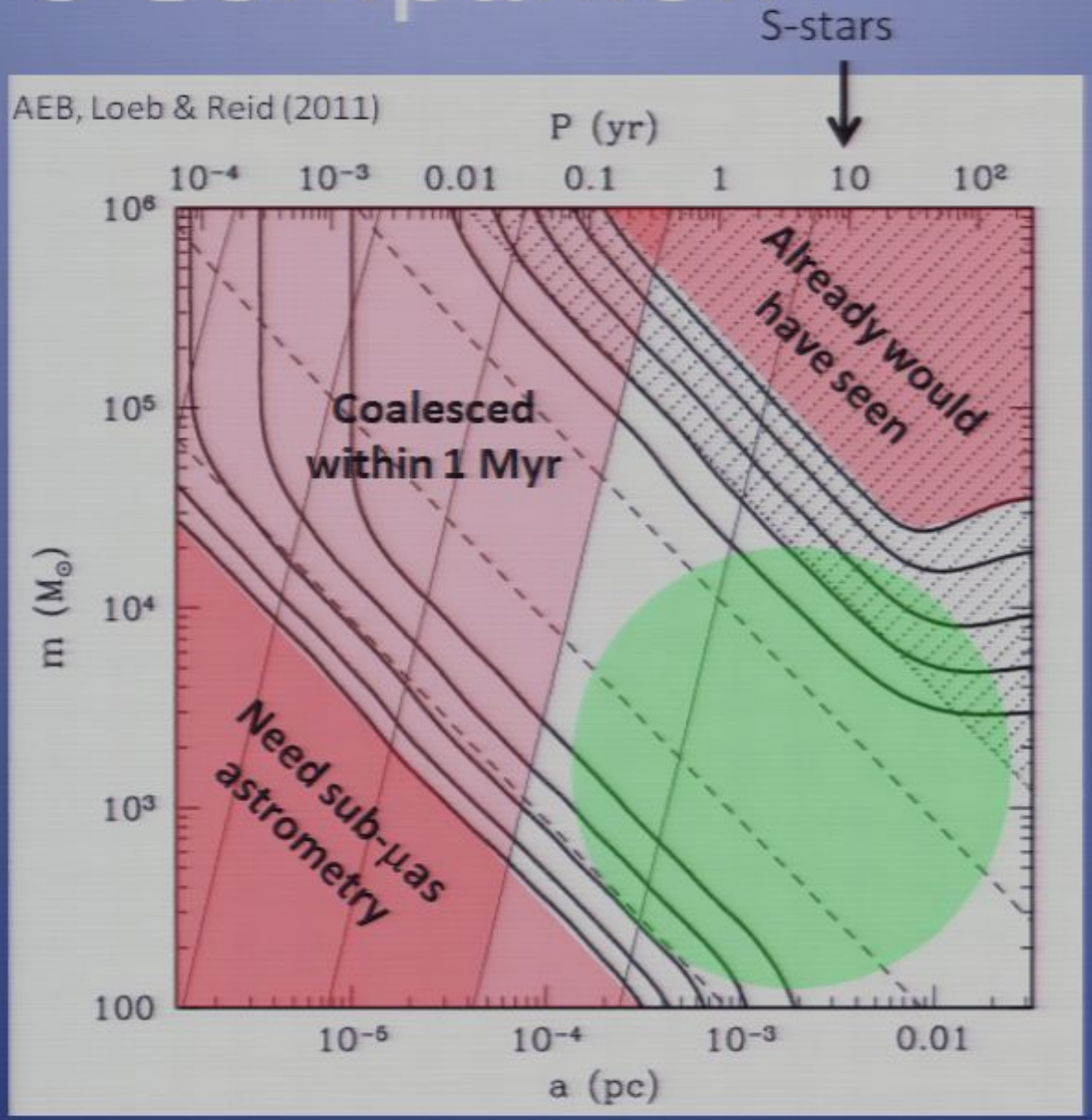

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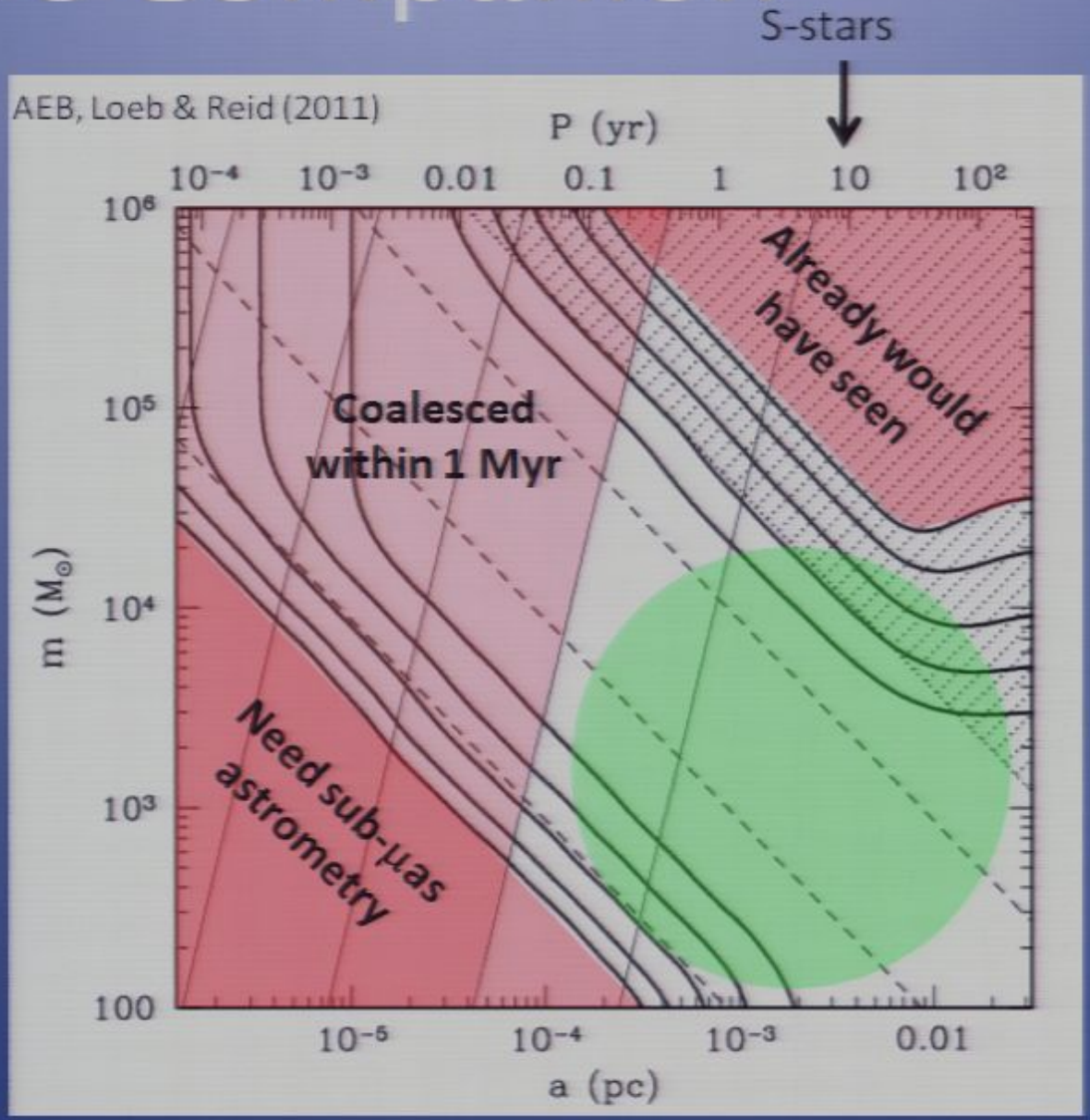

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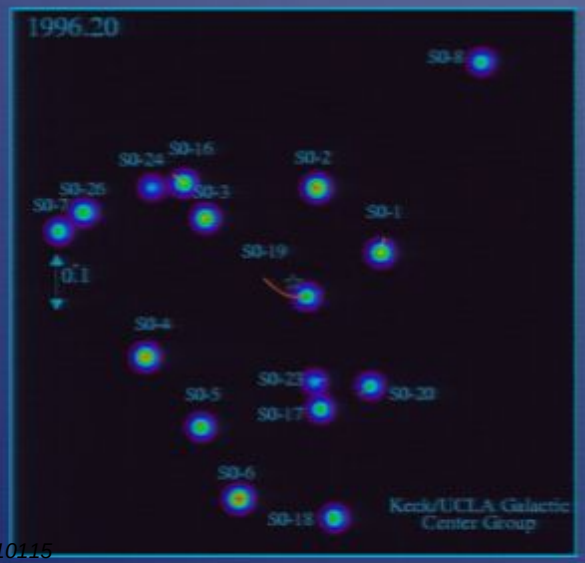

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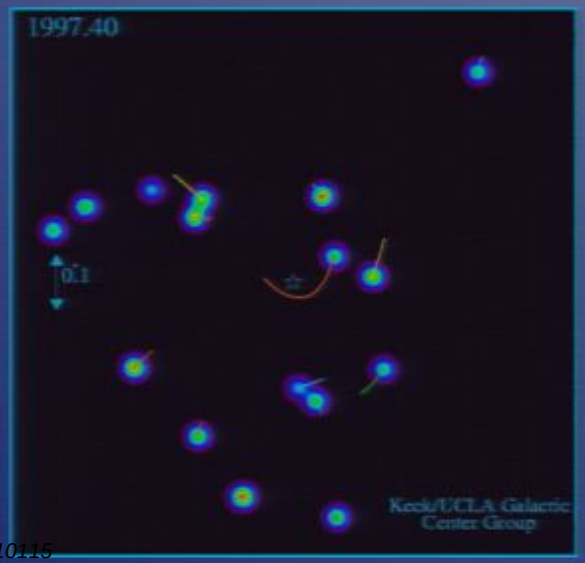

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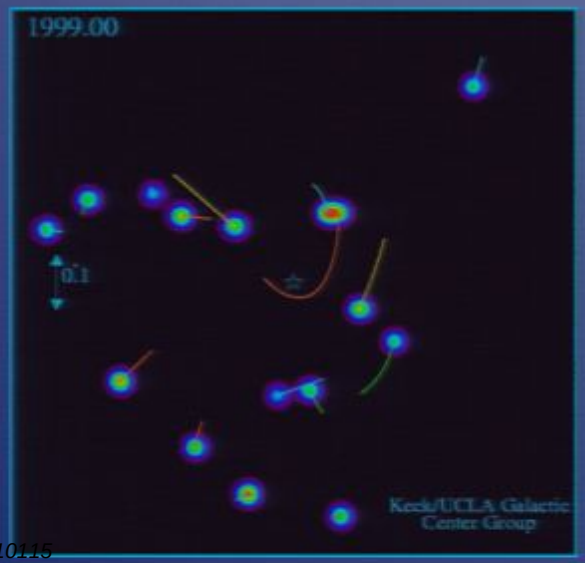

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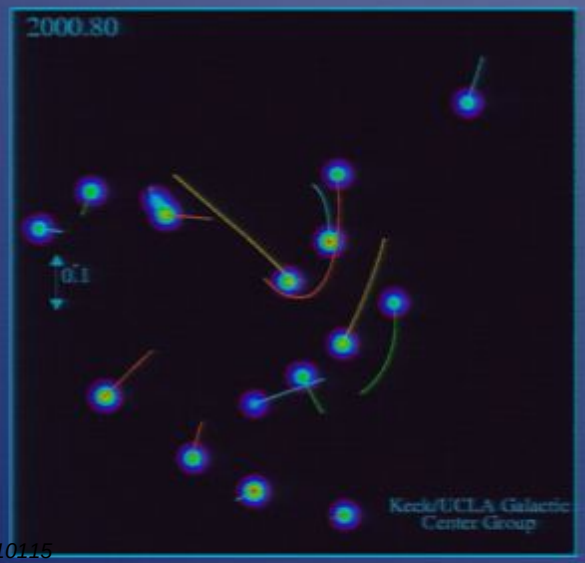

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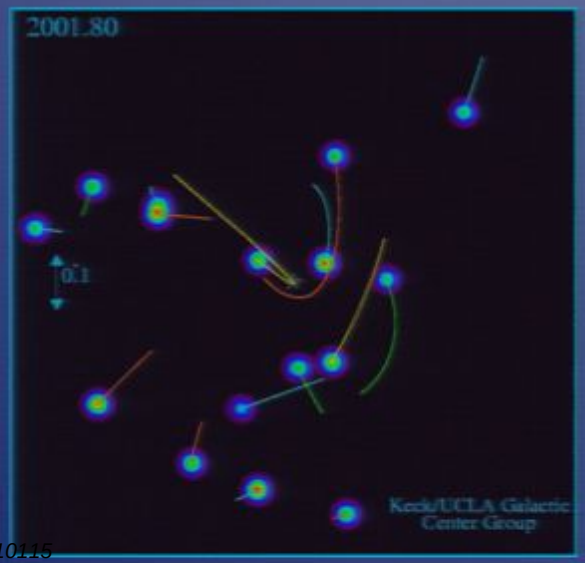

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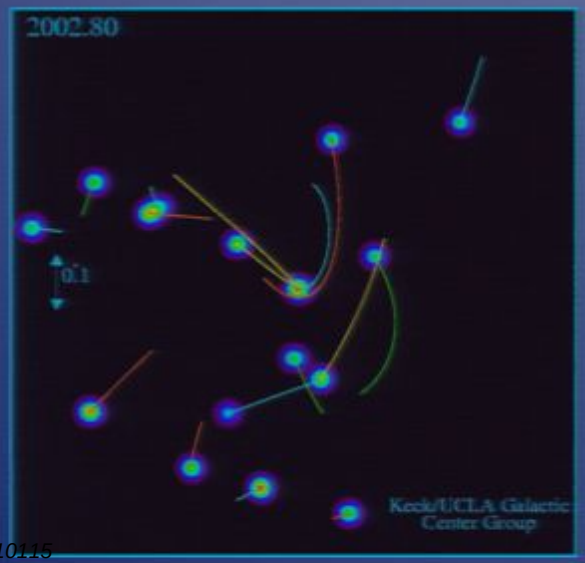

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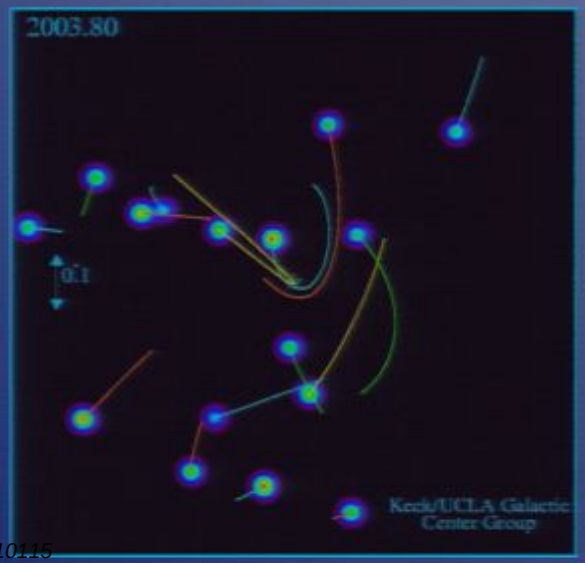

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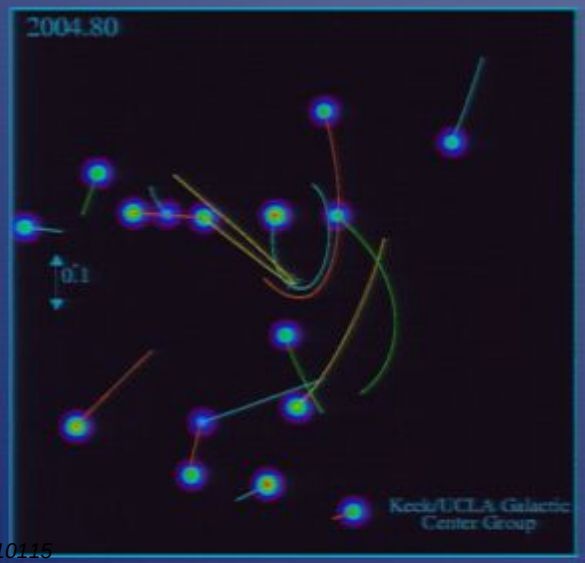

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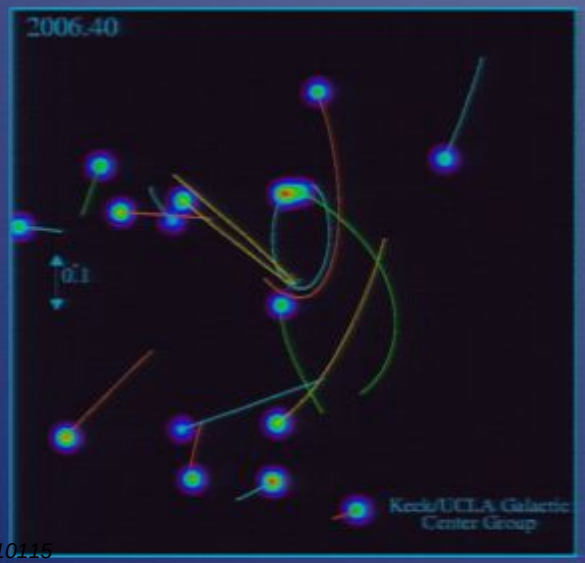

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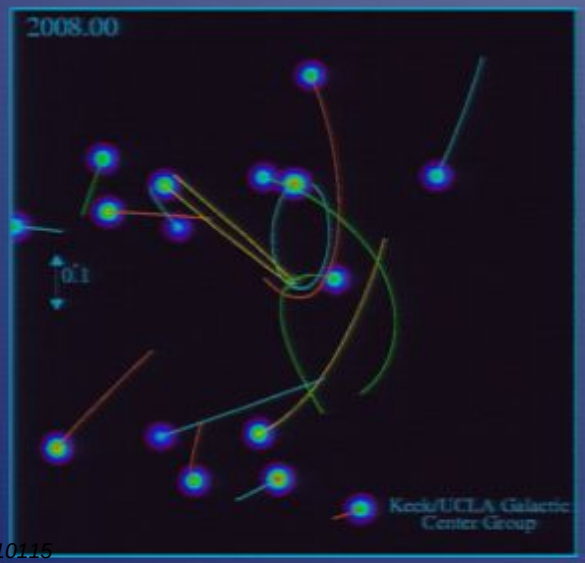

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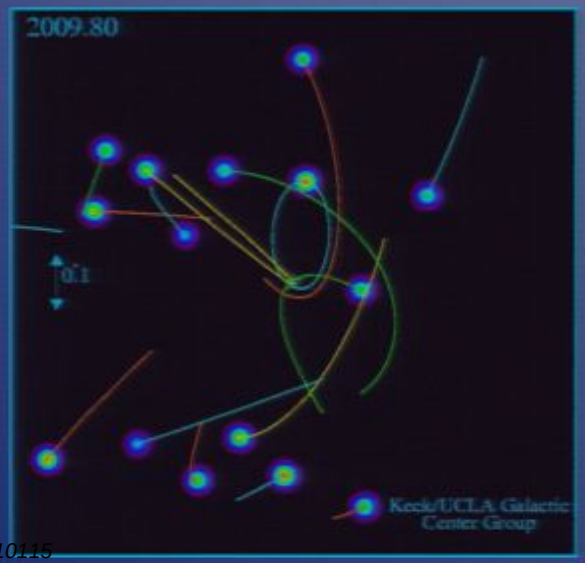

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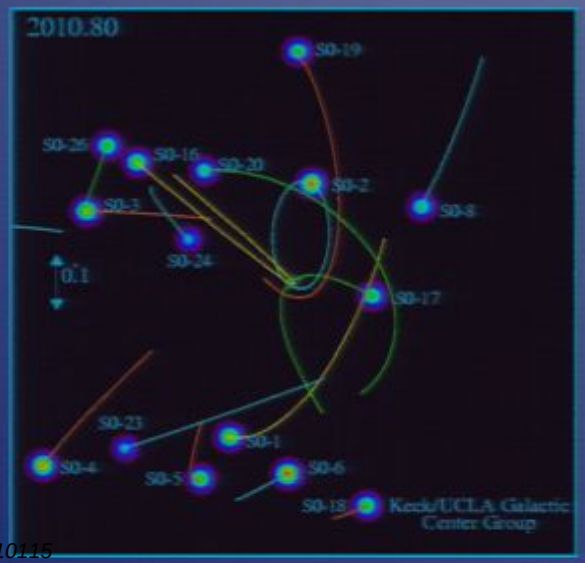

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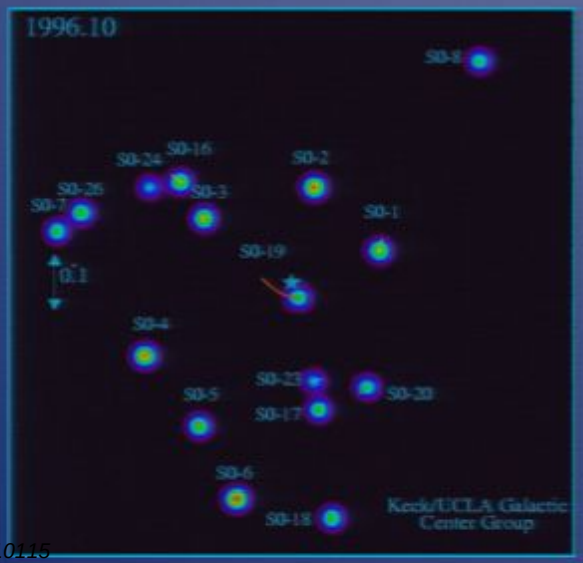

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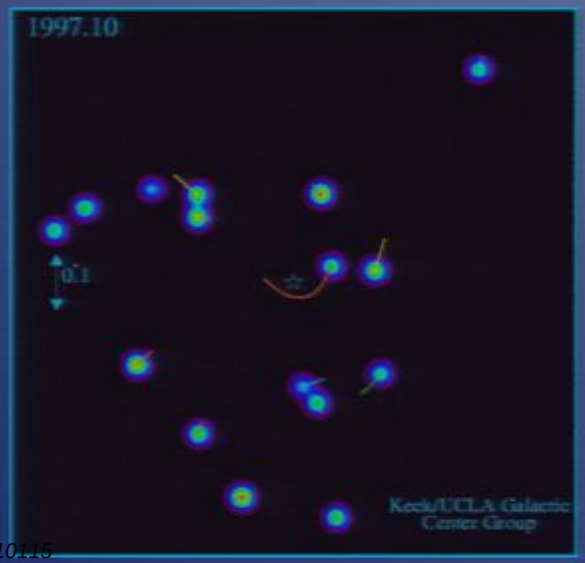

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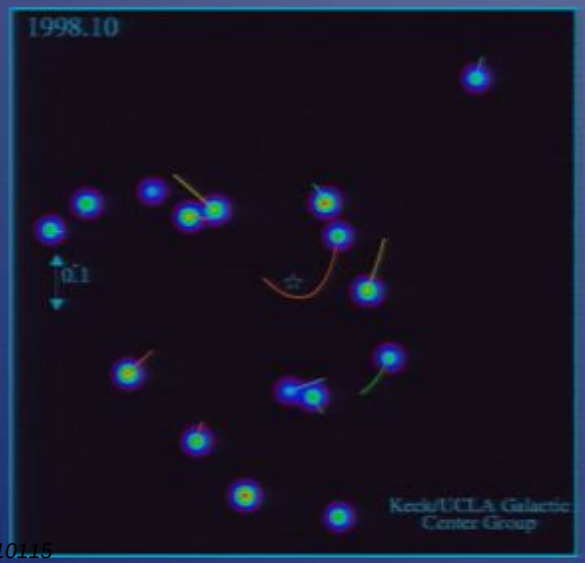

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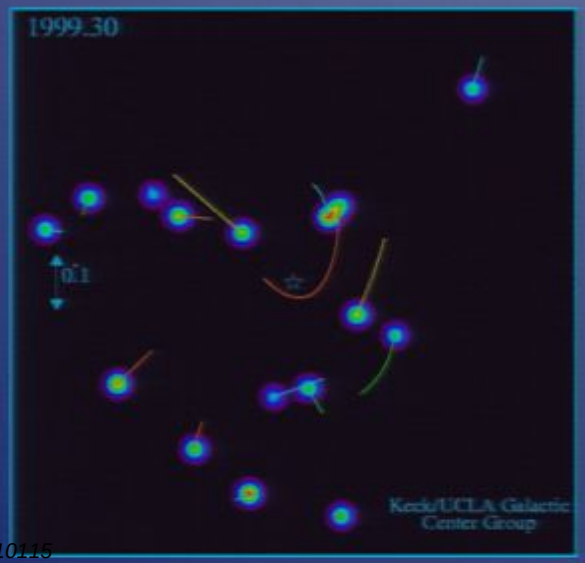

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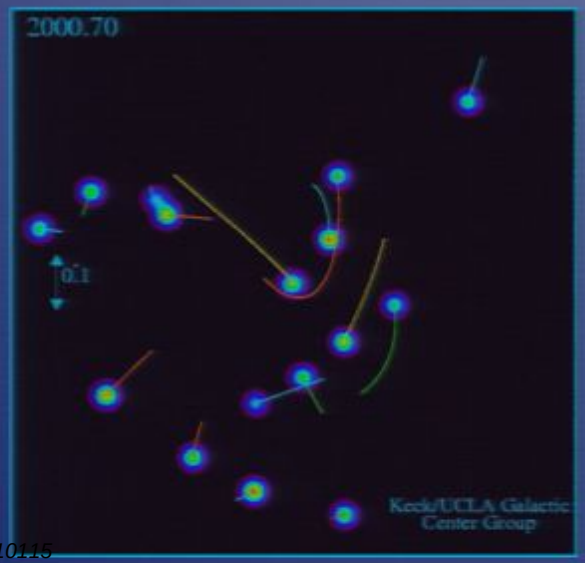

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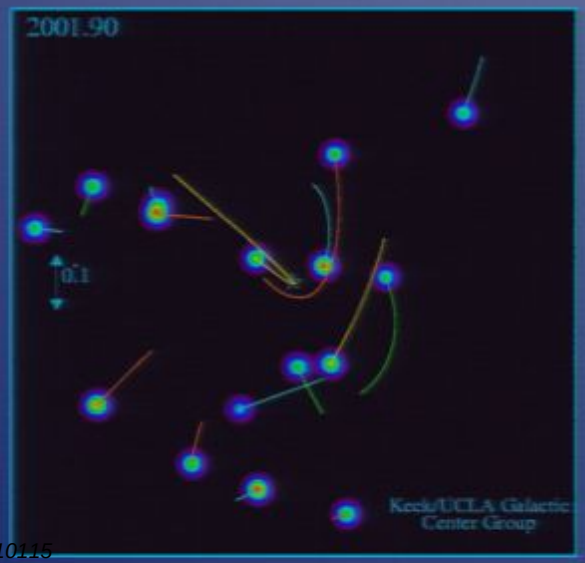

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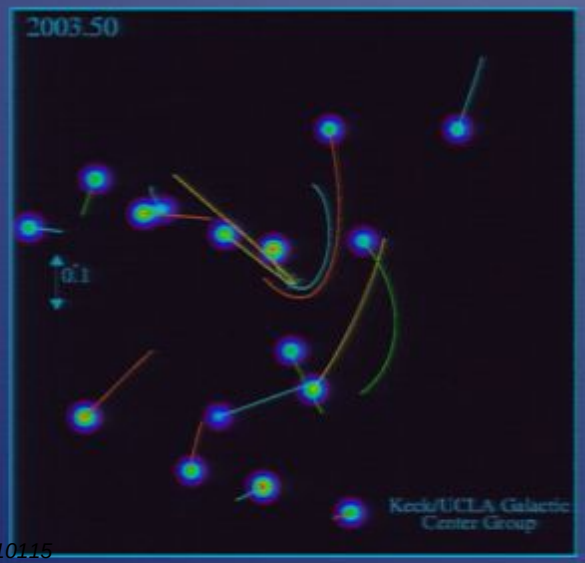

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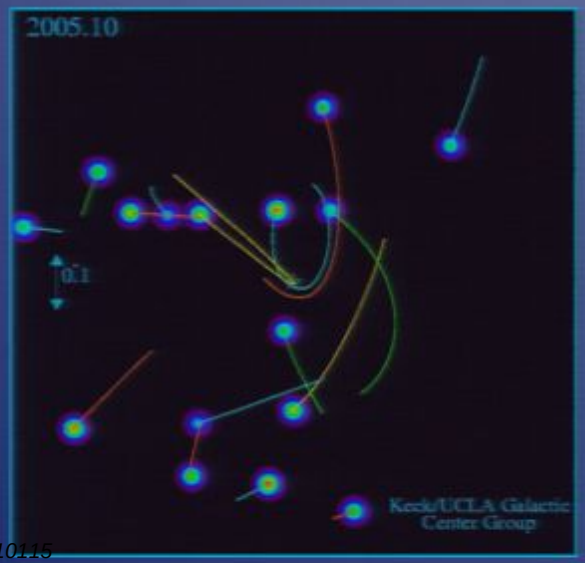

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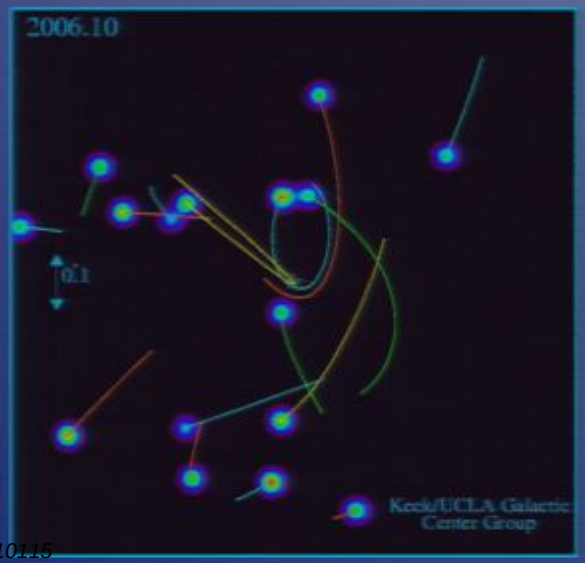

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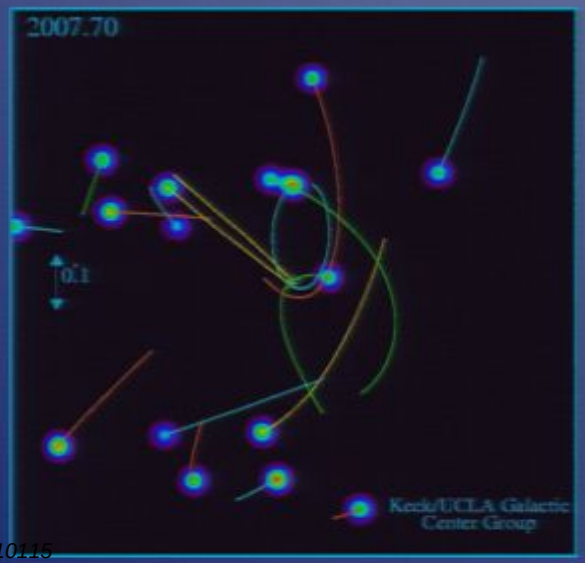

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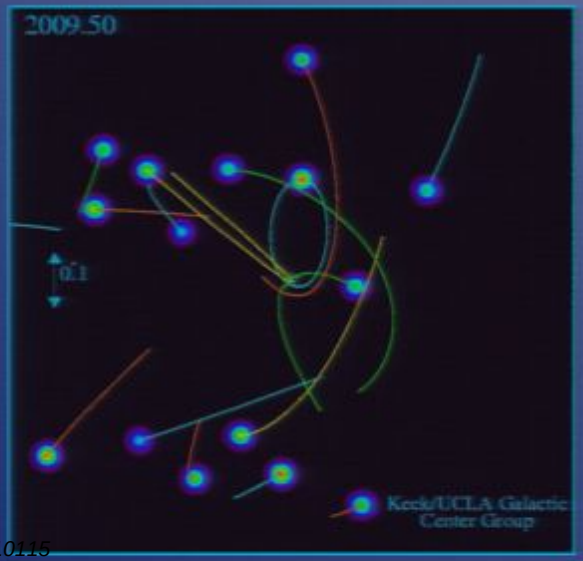

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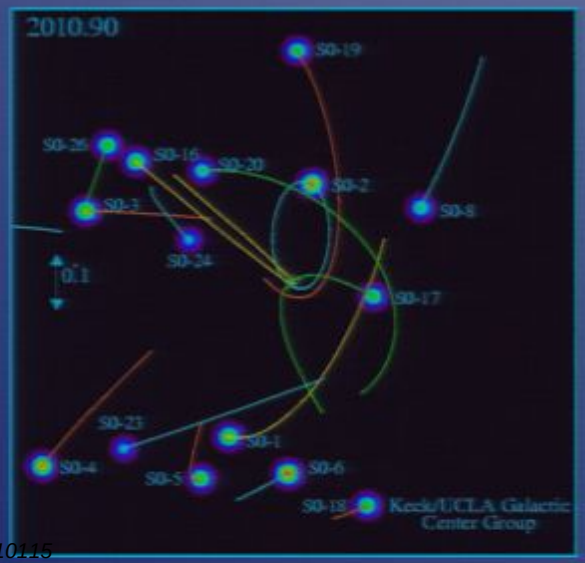

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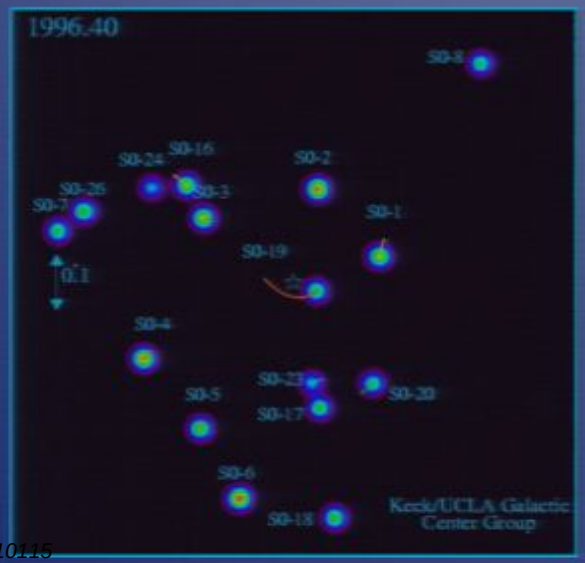

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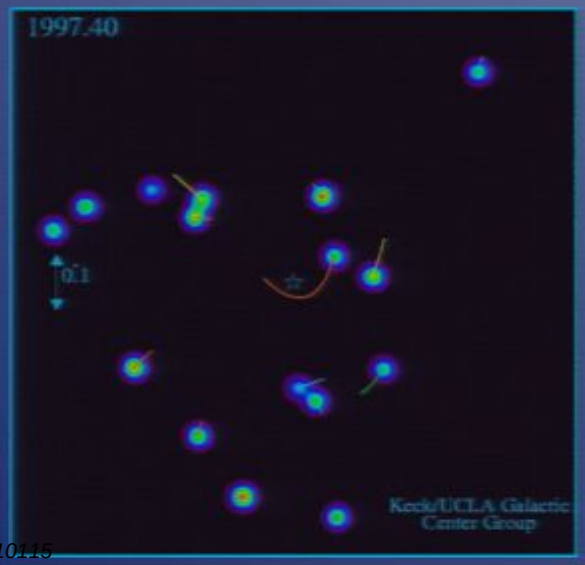

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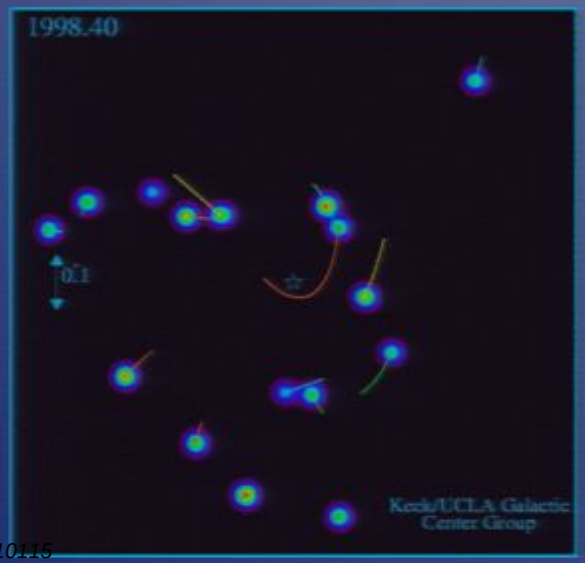

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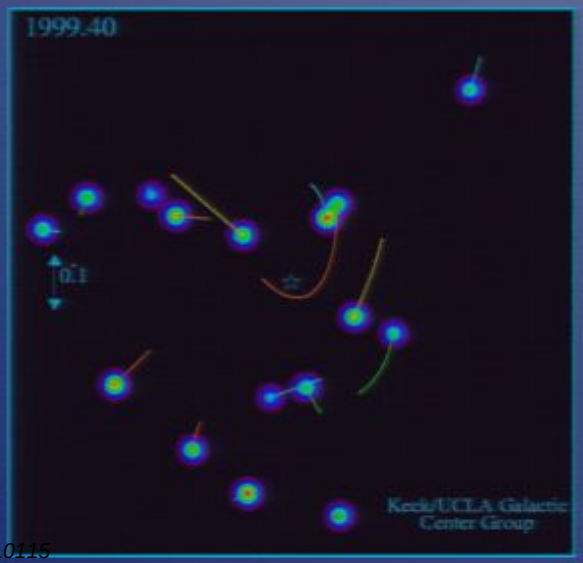

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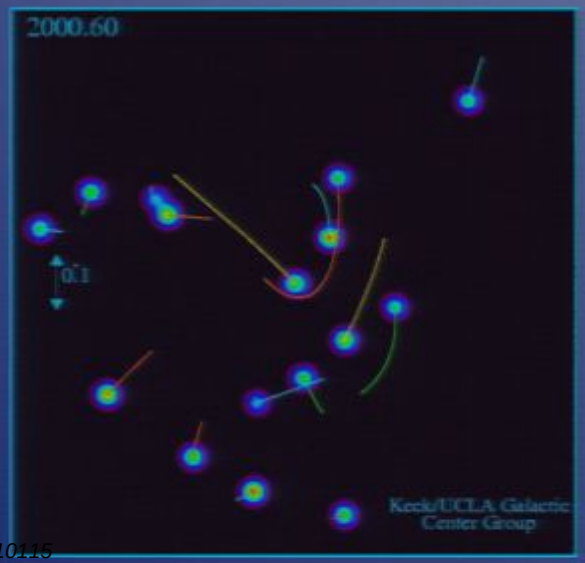

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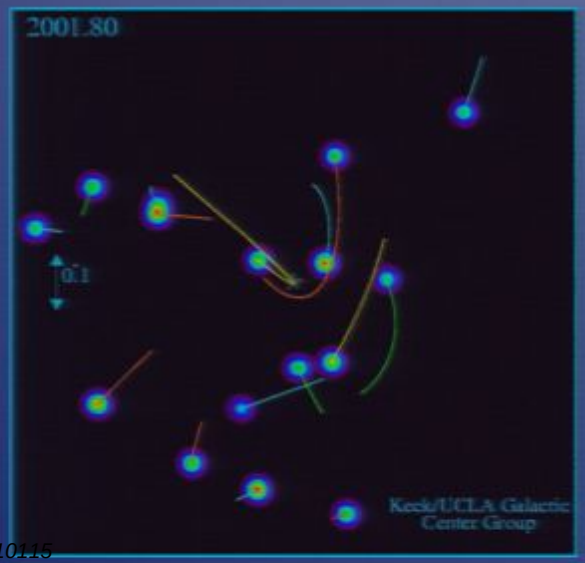

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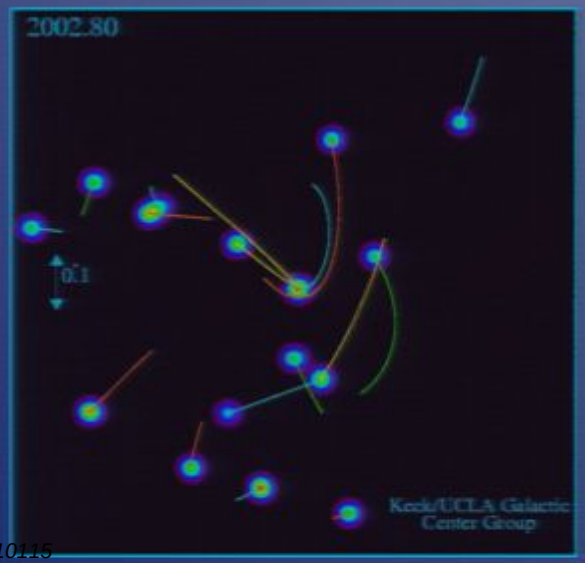

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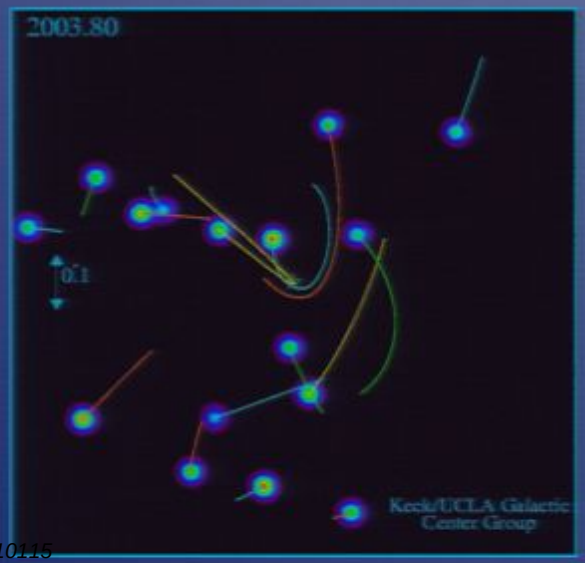

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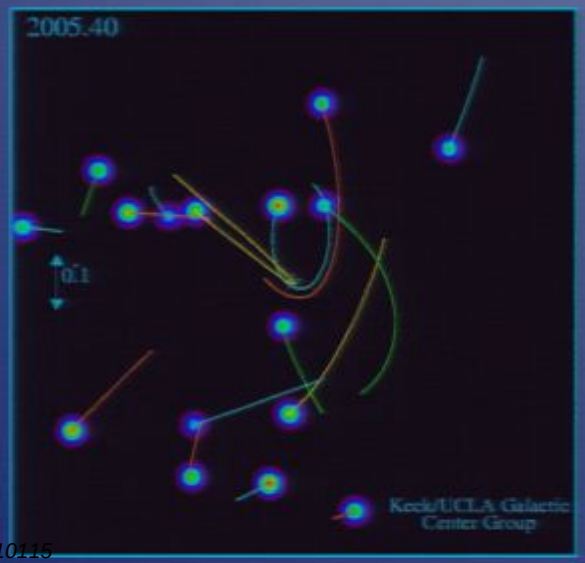

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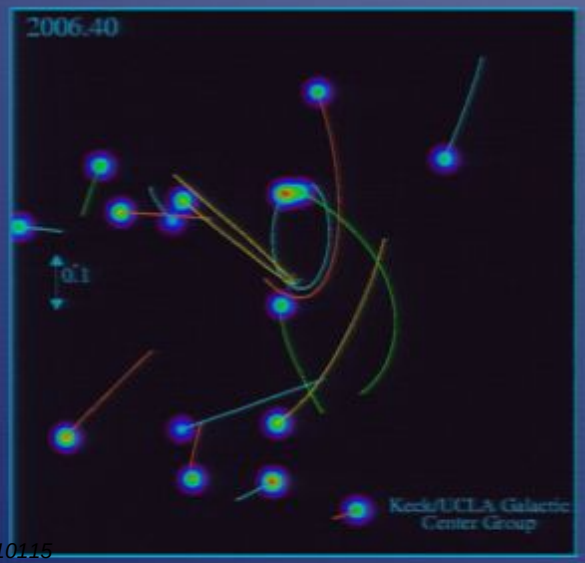

Massive companion entered <0.01pc orbit with Sgr A* within last 10^6 yr!

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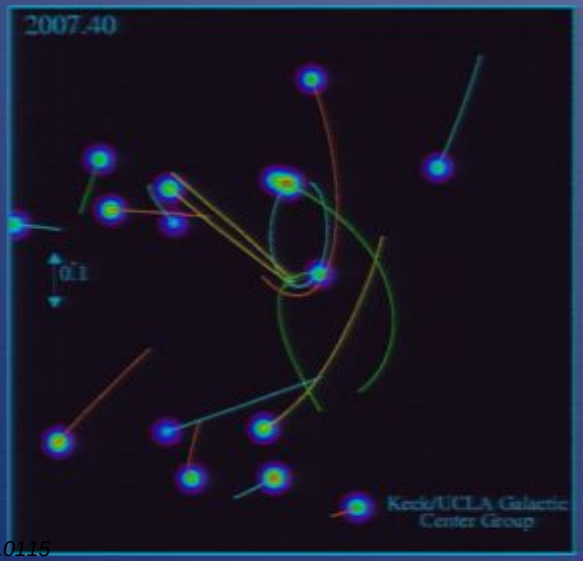

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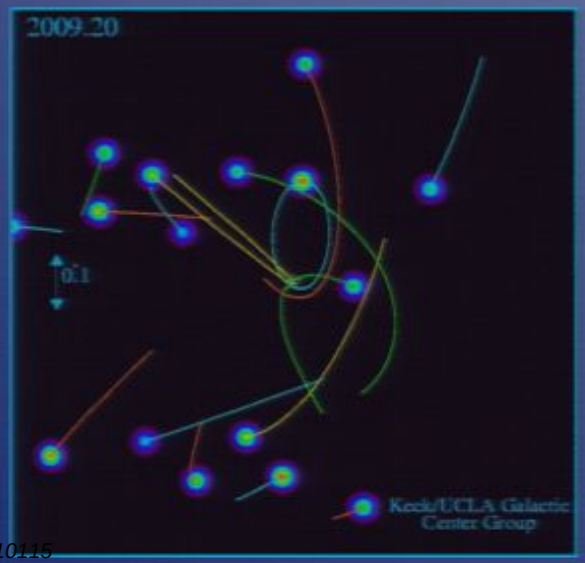

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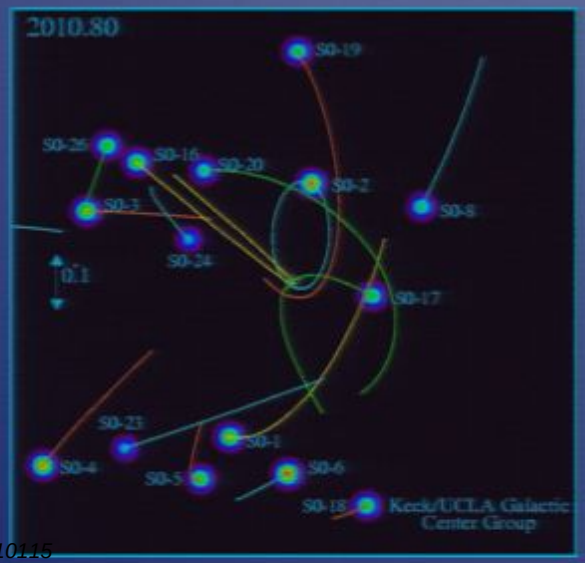

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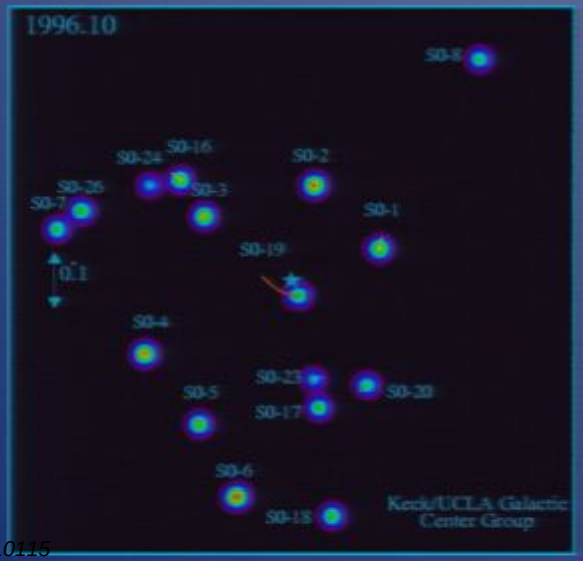

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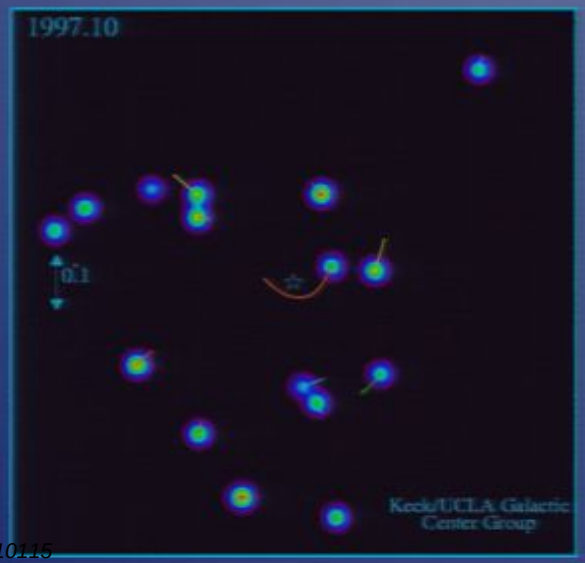

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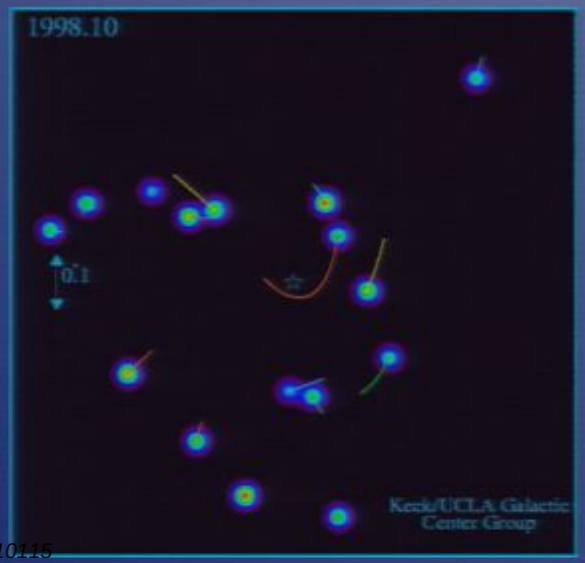

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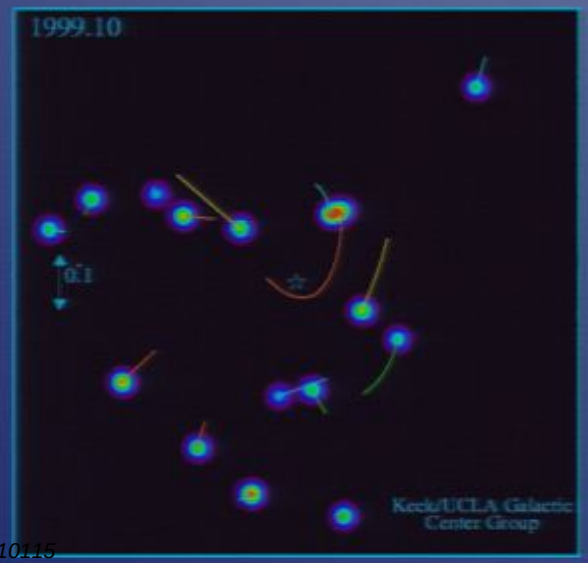

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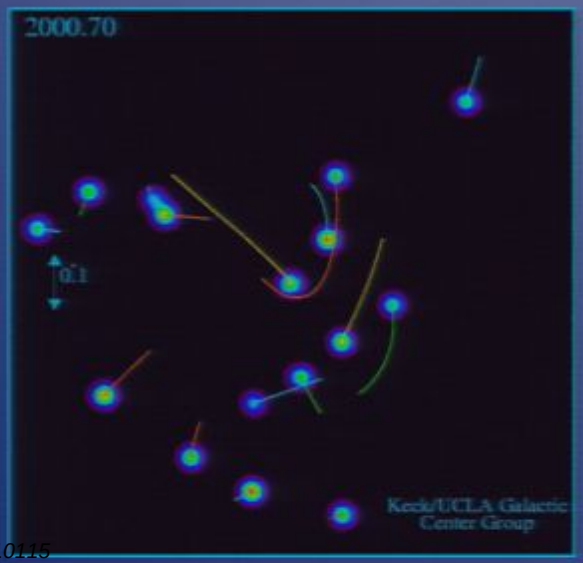

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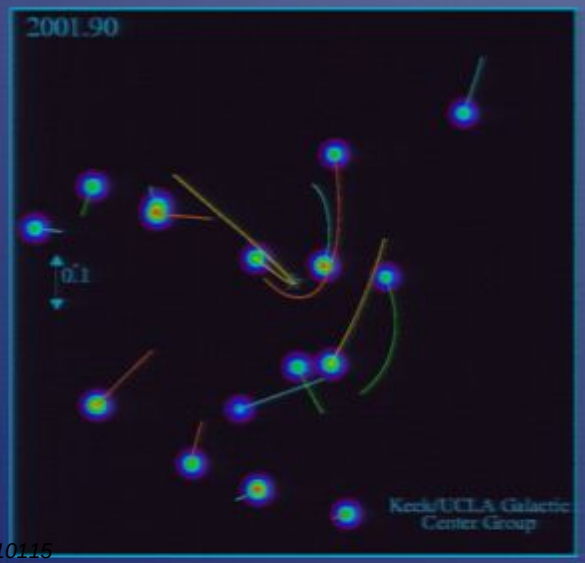

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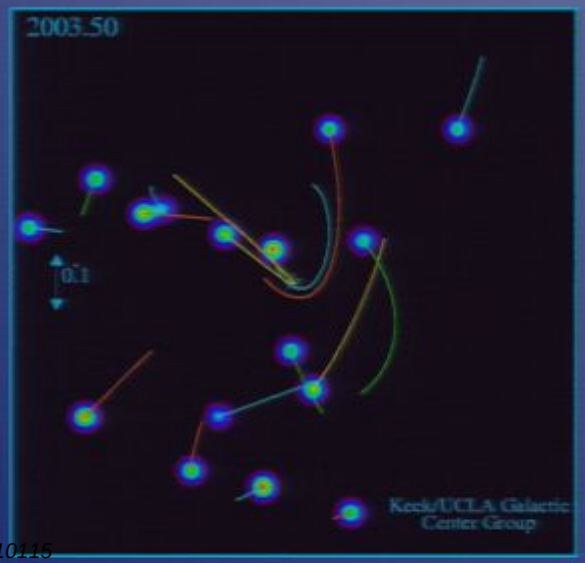

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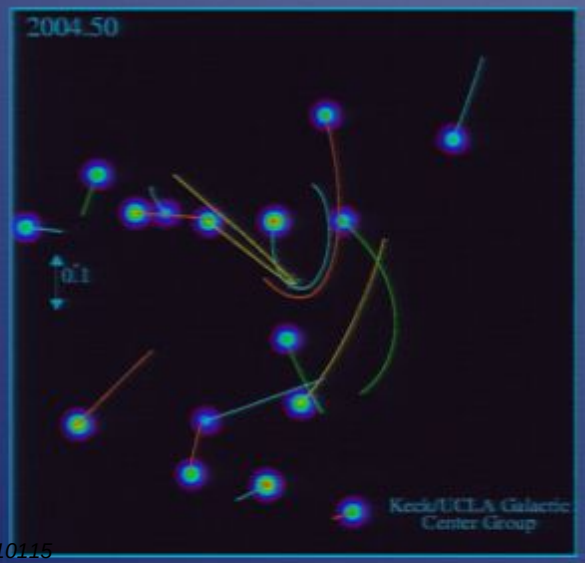

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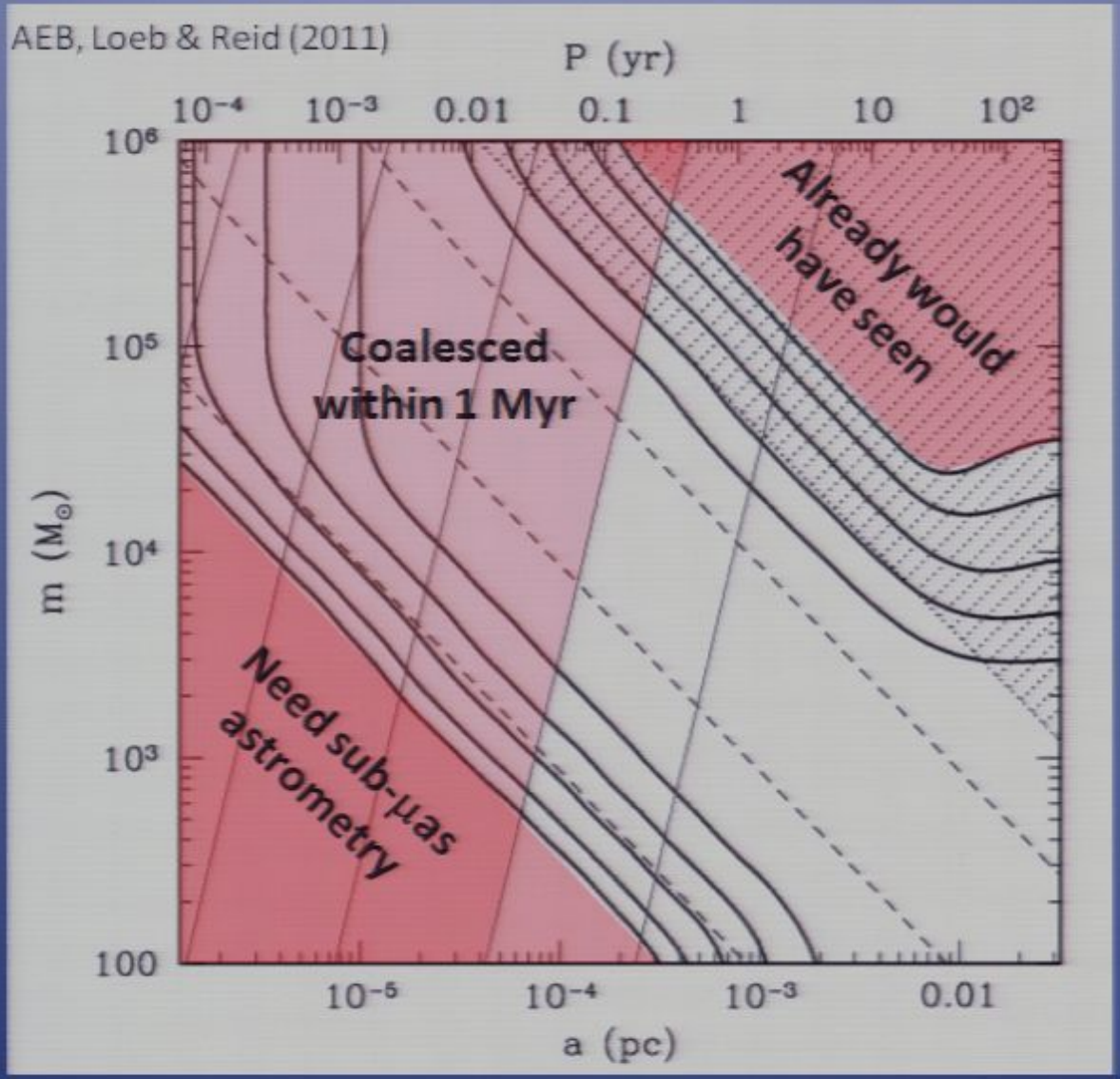

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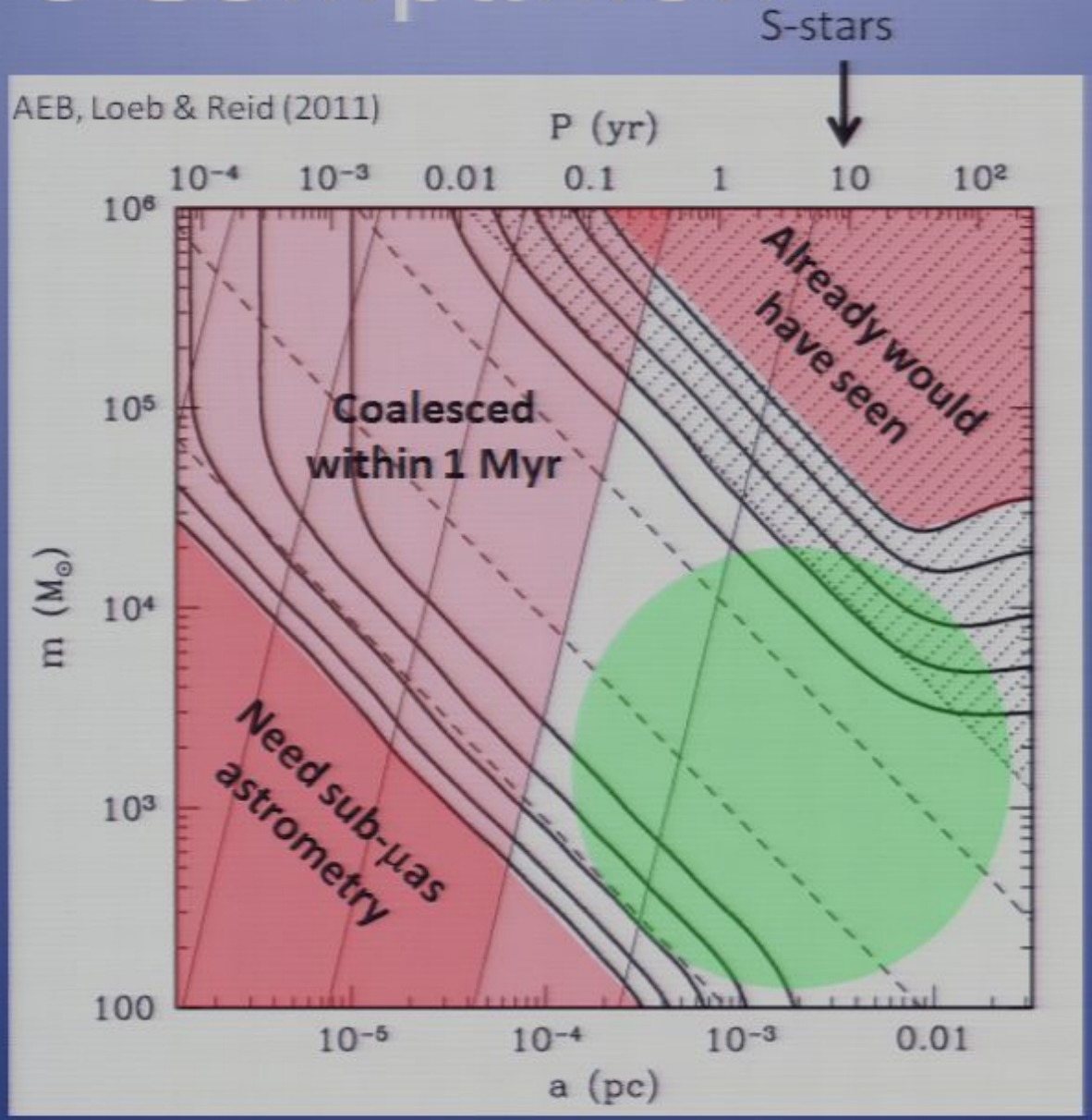

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