IMAGING BLACK HOLES

Avery E. Broderick

EHT Collaboration

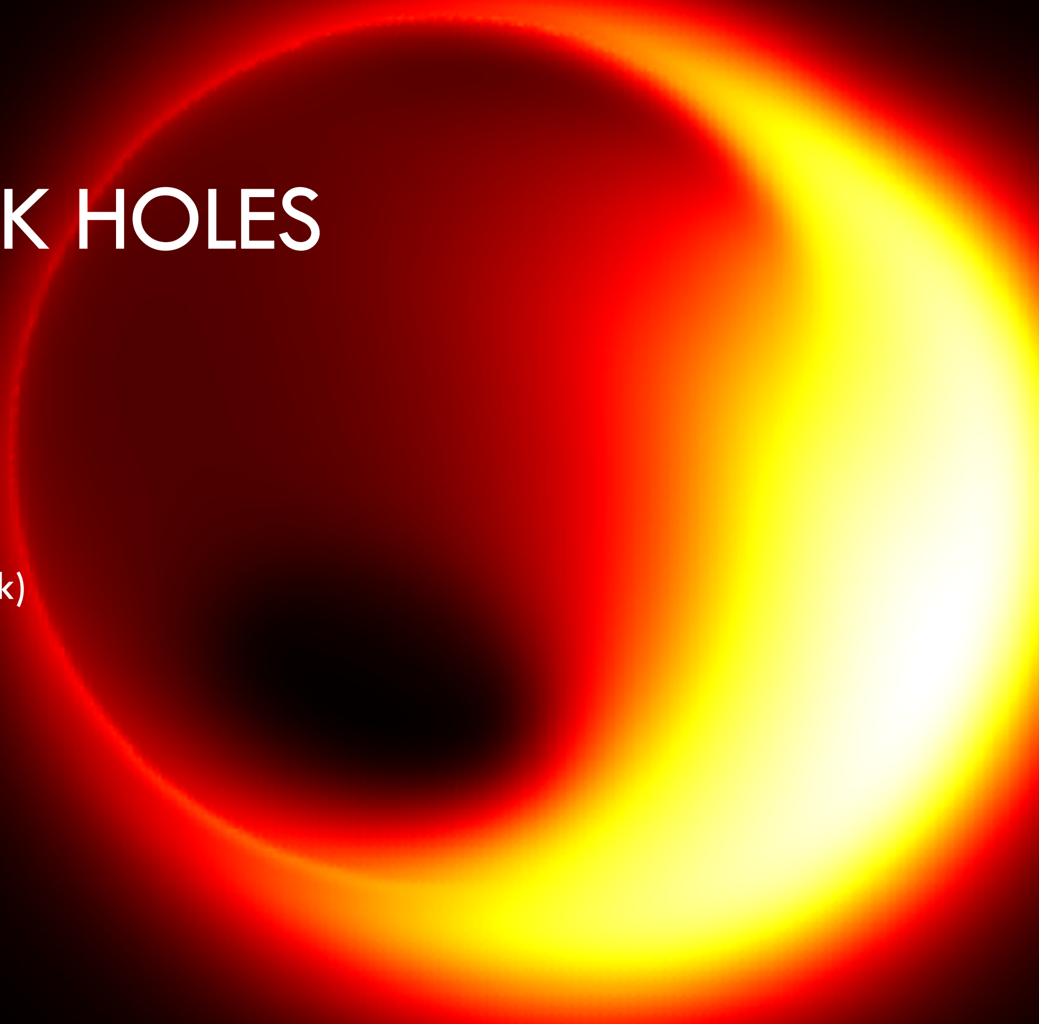
Sheperd Doeleman (MIT Haystack)
Vincent Fish (MIT Haystack)
Alan Rogers (MIT Haystack)
Ru-Sen Lu (MPIfR)
Michael D Johnson (CfA)
Dimitrios Psaltis (Arizona)
Tim Johannsen (UW-PI)
Avi Loeb (Harvard)
Carlos Wang (UW)
Elizabeth Griffin (UW)
Britt Jeter (UW)

UNIVERSITY OF WATERLOO

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

EGM2015 30.5.2015

IMAGING BLACK HOLES



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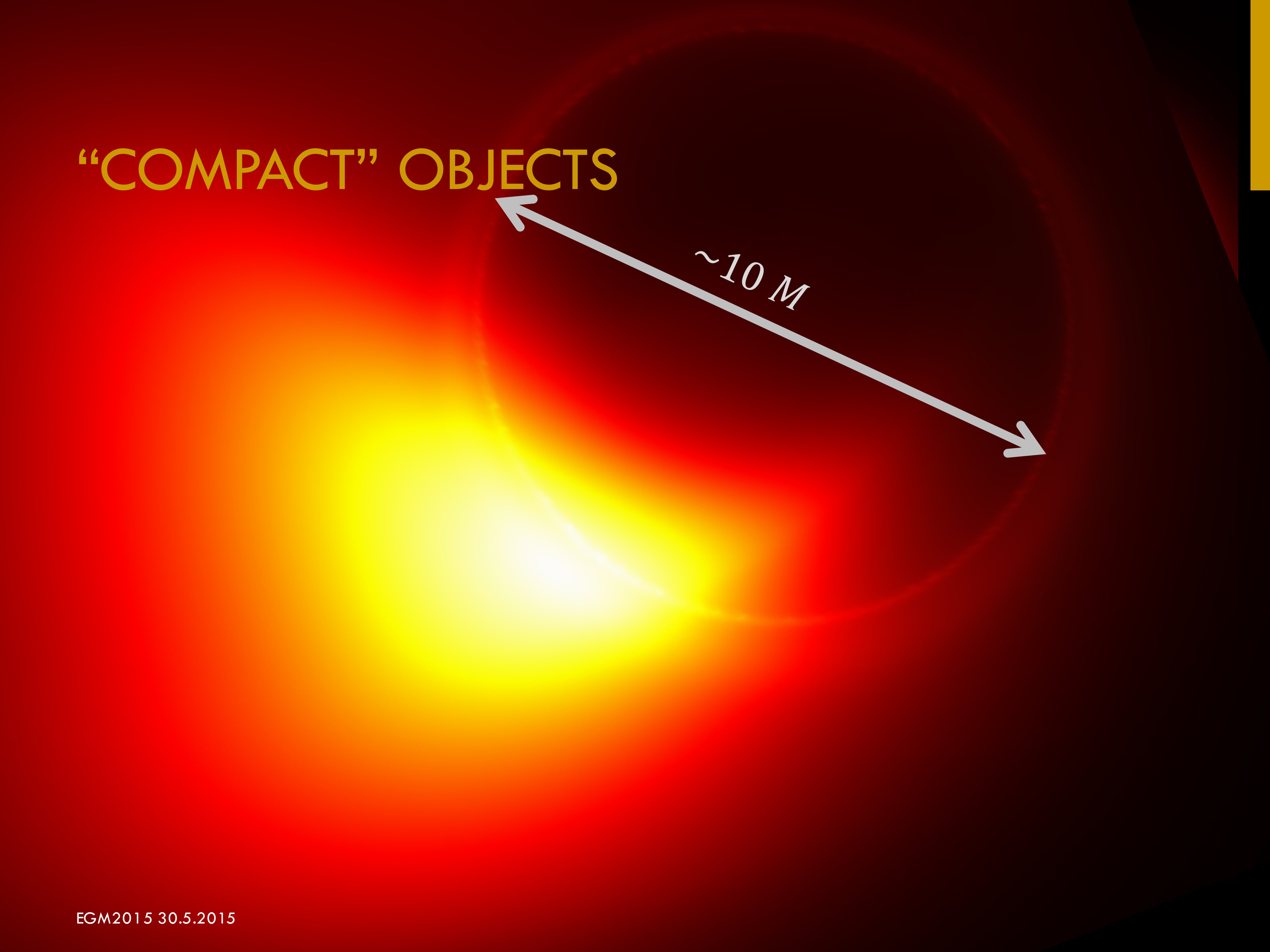
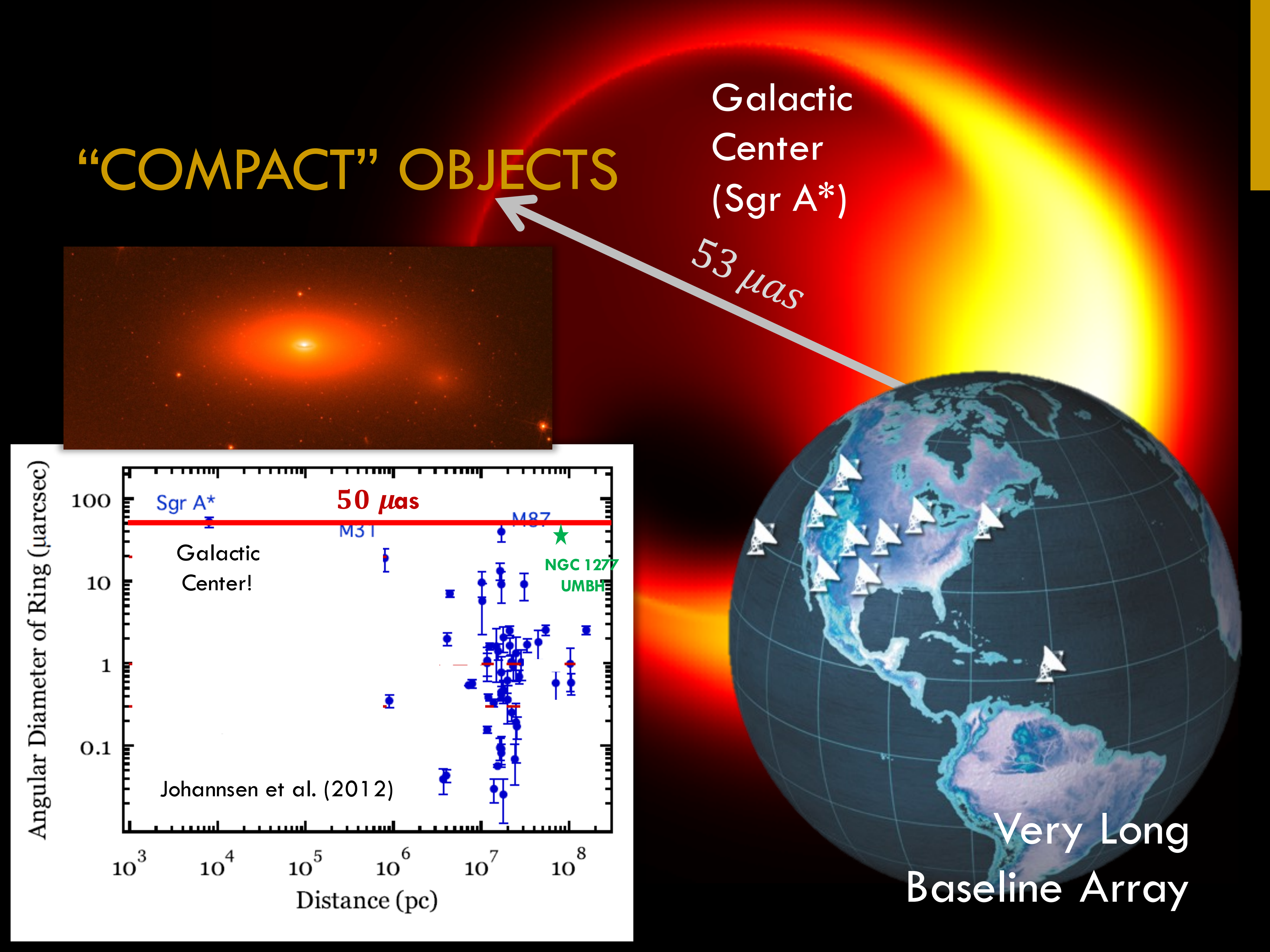
“COMPACT” OBJECTS



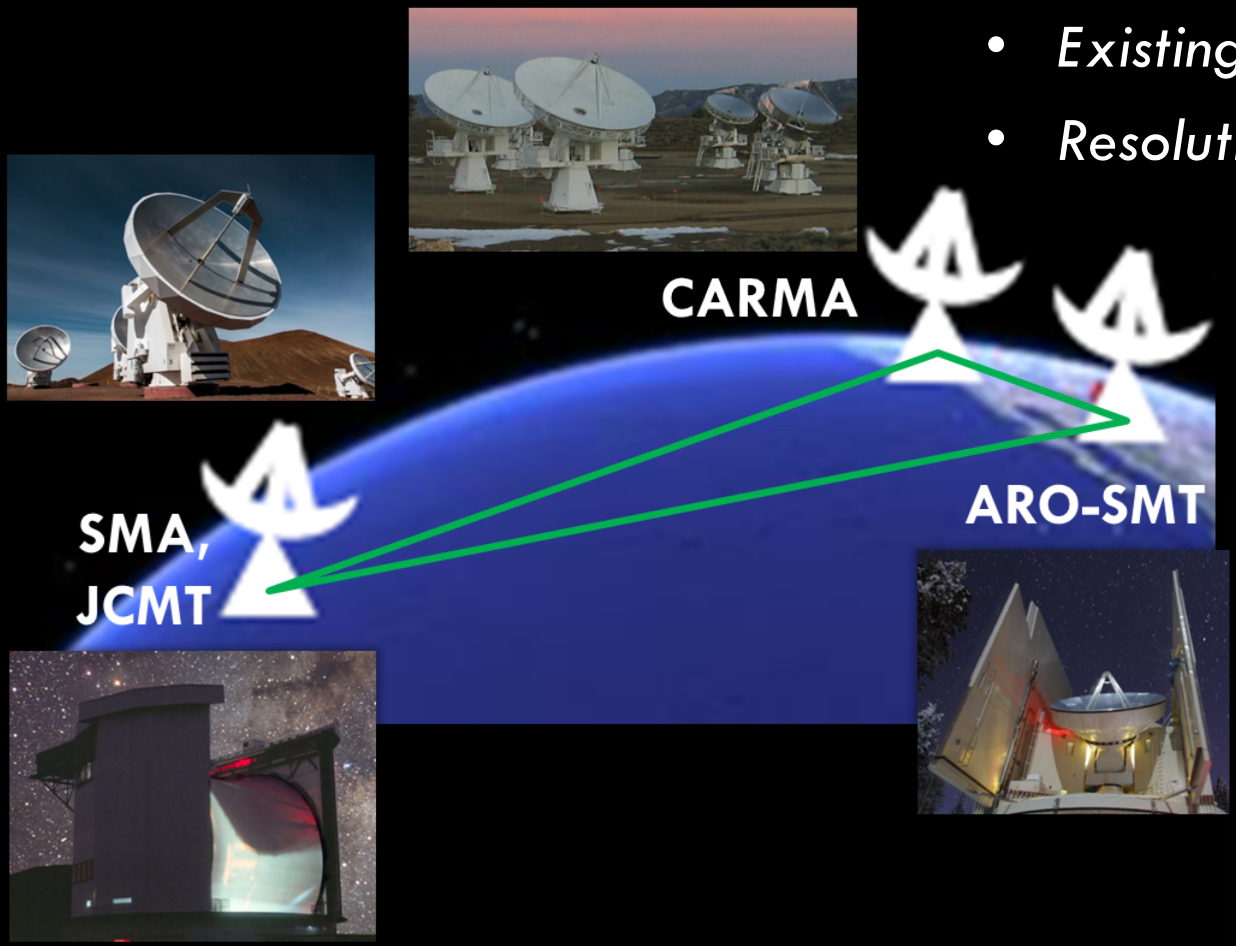


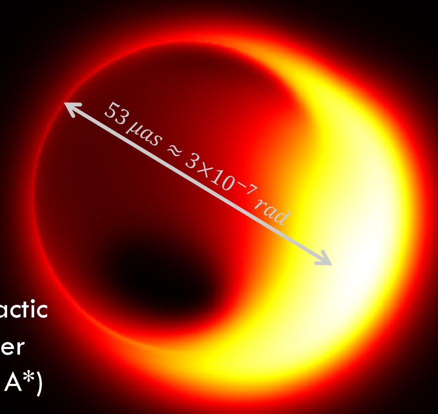
“COMPACT” OBJECTS
Galactic
Center
(Sgr A*)
53 μas
Very Long
Baseline Array
Angular Diameter of Ring (μarcsec)
100
10
1
0.1
Sgr A*
50 μas
M31
M87
NGC 1277
UMBH
Galactic
Center!
Johannsen et al. (2012)
10^3
10^4
10^5
10^6
10^7
10^8
Distance (pc)

“PROTO-EHT”

EventHorizonTelescope
http://www.eventhorizontelescope.org/

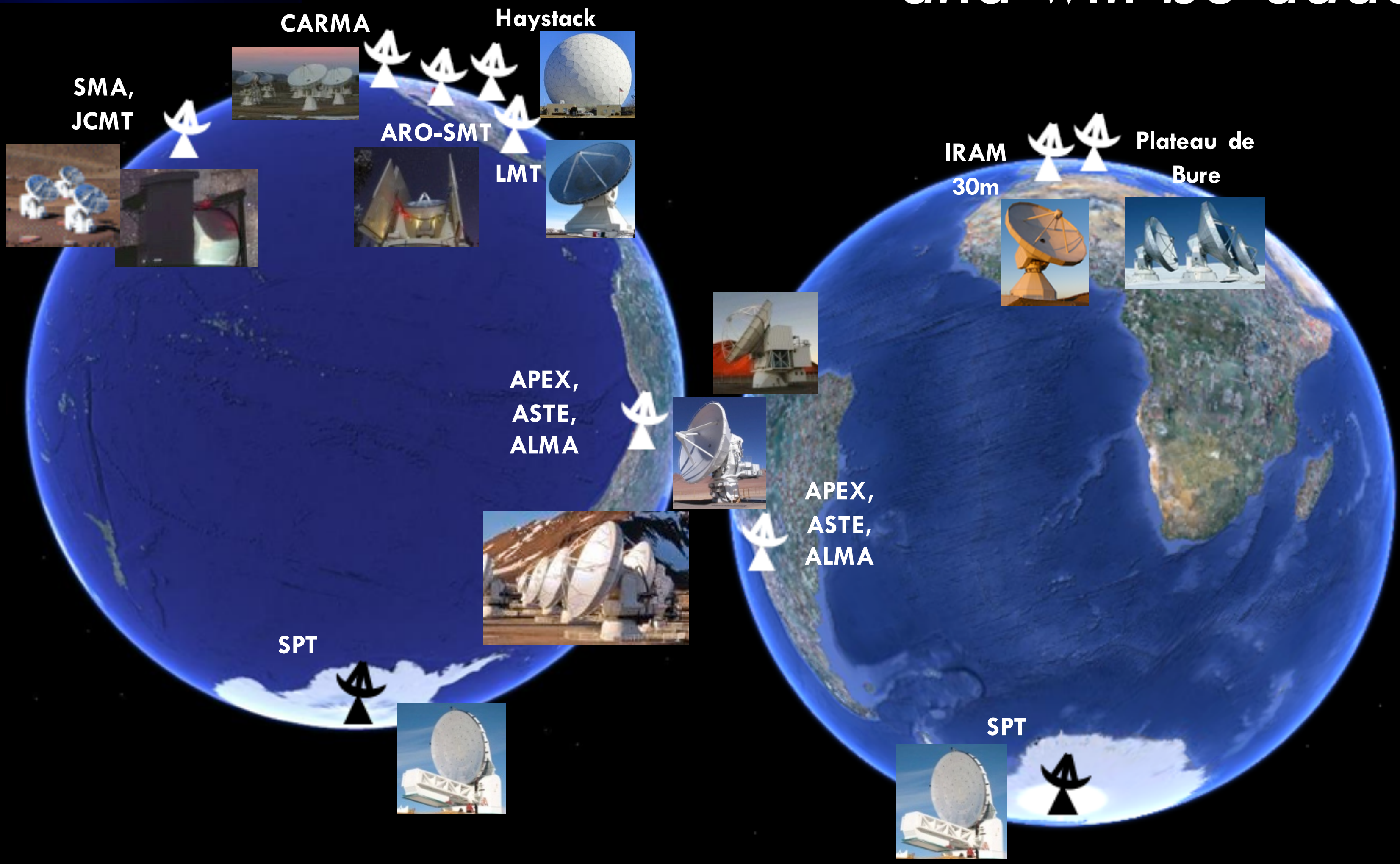
- *Earth-sized mm VLBI array*
- *Existing telescopes.*
- *Resolutions of* $\sim 10\ \mu as$





Galactic
Center
(Sgr A*)

Many stations can and will be added!



EventHorizonTelescope

Many stations have been added!

EHT on the cusp:

- SNR increase
- Long N-S baselines
- Intermediate baselines

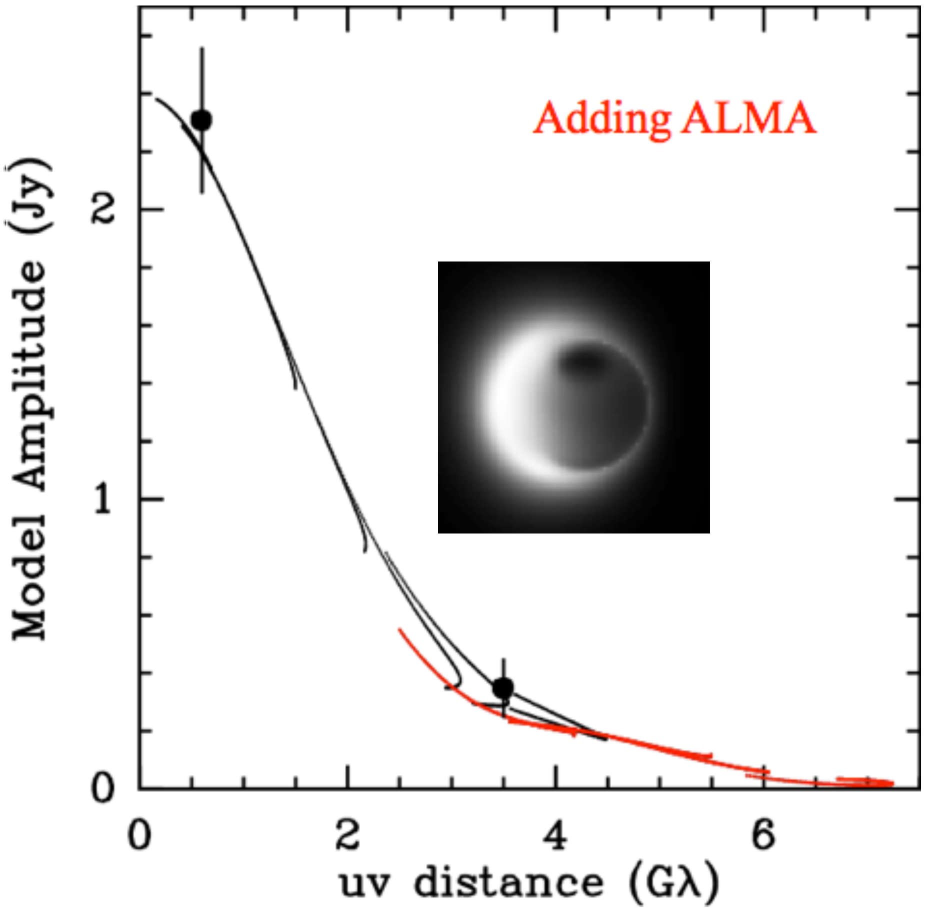
→ Imaging!

Status Update

- SPT: Fringes!
- ALMA: Phased & Fringes!
- LMT: Fringes!
- APEX & IRAM 30m already involved!

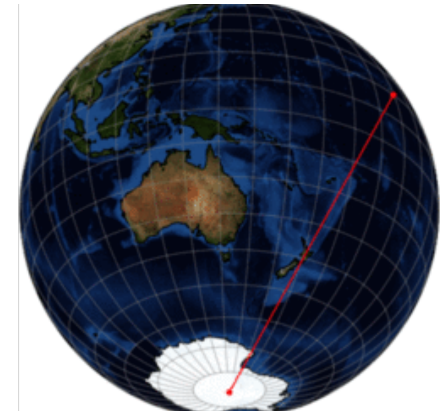
FILLING IN THE HOLES: SITES & PATIENCE

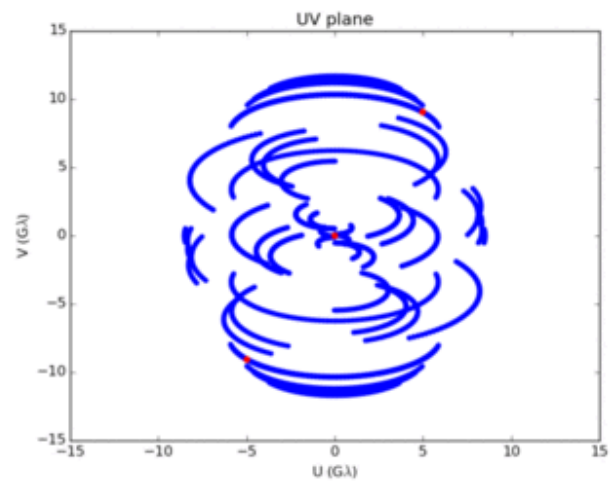
Correlated Flux



Spatial Frequency

Shep Doeleman





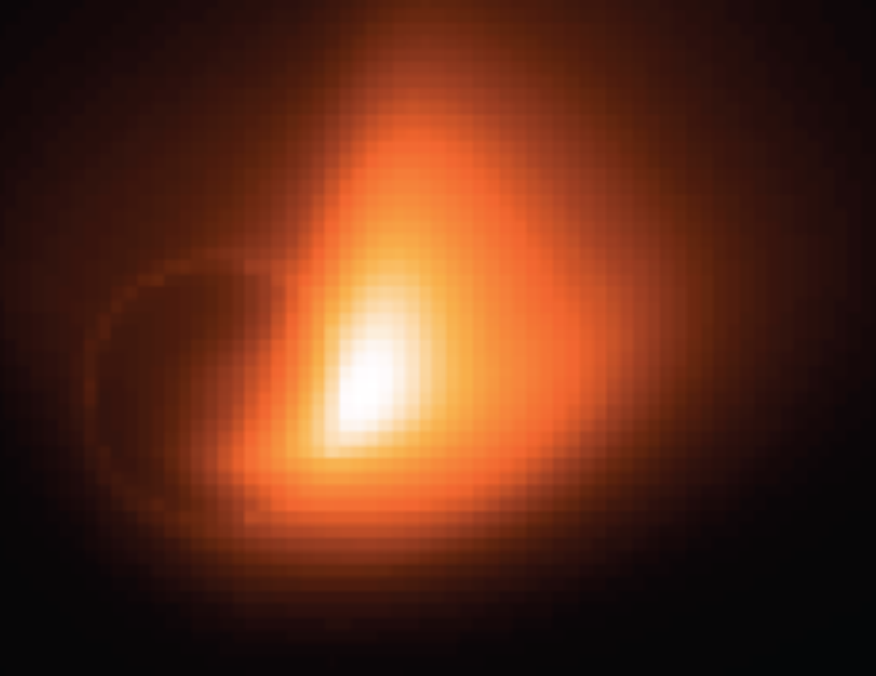
Laura Vertatschitsch

RECONSTRUCTING IMAGES OF SGR A* (DISKS)

cattering

Fish et al. (2014)

RECONSTRUCTING IMAGES OF M87 (JETS)

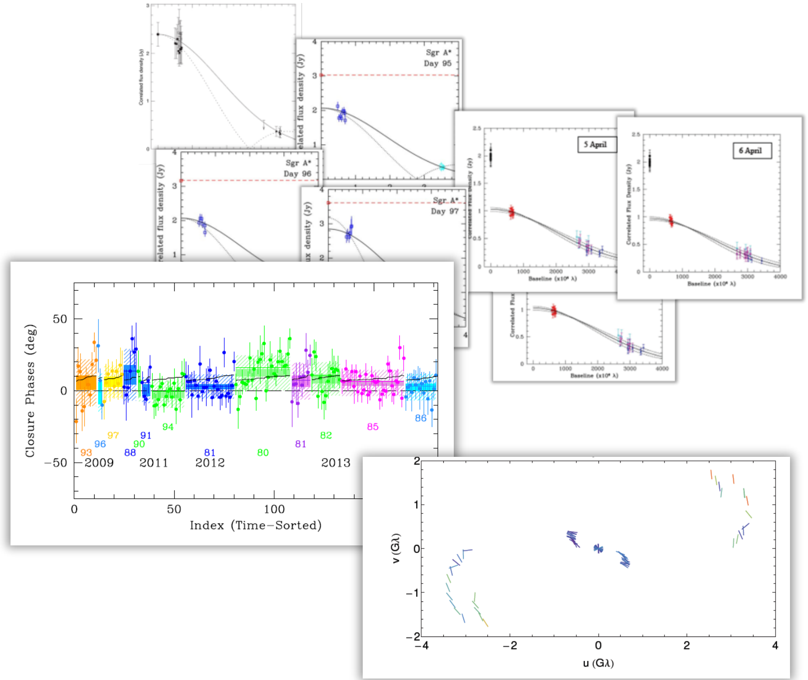


BSMEM

Lu et al. (2014)

DATA ZOO

- Visibility magnitudes at specific locations in spatial frequency, set by the particular pair of telescopes used, $|V_{ab}|$
- "Closure phases" defined by telescope triplets, $arg(V_{ab}V_{bc}V_{ca})$
- "Closure amplitudes" defined by telescope quadruplets, $\frac{|V_{ab}||V_{cd}|}{|V_{ad}||V_{bc}|}$



× Stokes I, Q, U, V

× 230 GHz (1.3 mm) and 345 GHz (0.87 mm)

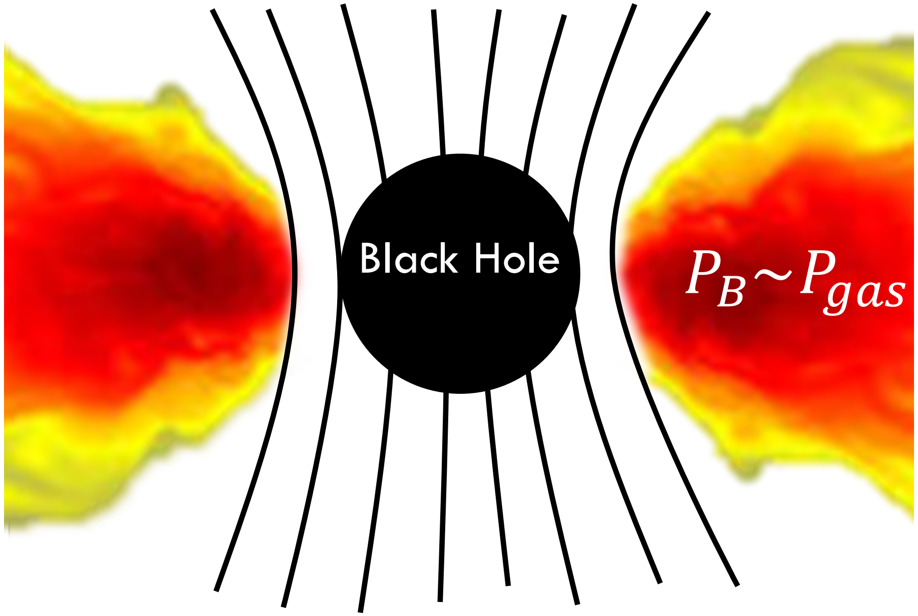
× Time × Sources!

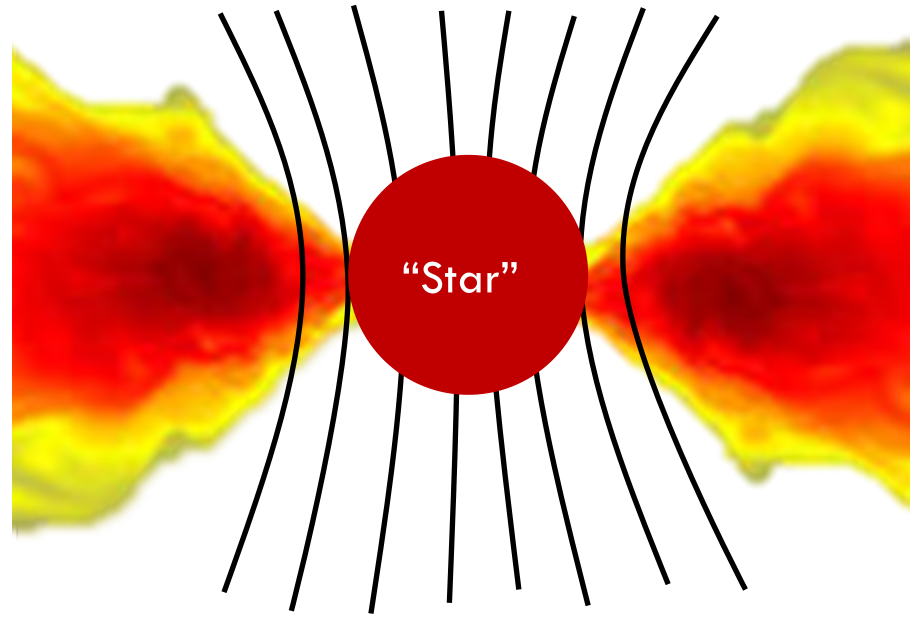
POSSIBLE WAYS FORWARD FOR TESTING GRAVITY (AND OTHER STUFF)

1. **Find questions that are insensitive to astrophysics**
   Tend to be qualitative or binary and rare.

2. **Perform detailed astrophysical modeling**
   How do we control our systematic errors without model certainty?
   Learn about high-energy astrophysics!

LIMITS ON HORIZONS





$$L_{jet} \approx \epsilon_{jet} \dot{M} c^2$$
$$\epsilon_{jet} \approx 2$$

$$L_{surf} \approx \dot{M} c^2$$
$$\approx L_{jet} / \epsilon_{jet}$$

- Compact ($r < r_\gamma$)
- Steady state ($t_{acc} \gg GM/c^3$)

→ ***Thermal!***

DO BLACK HOLES EXIST?

The Telegraph

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Wormhole to another galaxy may exist in Milky Way

A space-time tunnel could exist in the middle of the Milky Way and we could travel through it, say scientists

8K 463 1 79 9K Email

The Milky Way viewed from Dorset. A wormhole may exist at the centre of the galaxy Photo: ANDREW WHYTE / CATERS NEWS

By Sarah Knapton, Science Editor
4:50PM GMT 21 Jan 2015
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A giant doorway to another galaxy may exist at the centre of the Milky Way, a study suggests.

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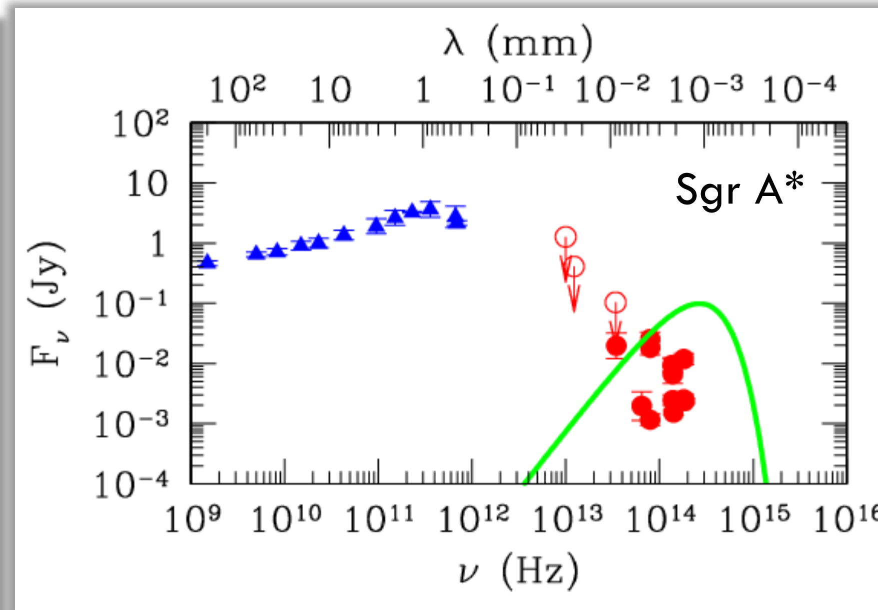
In Space

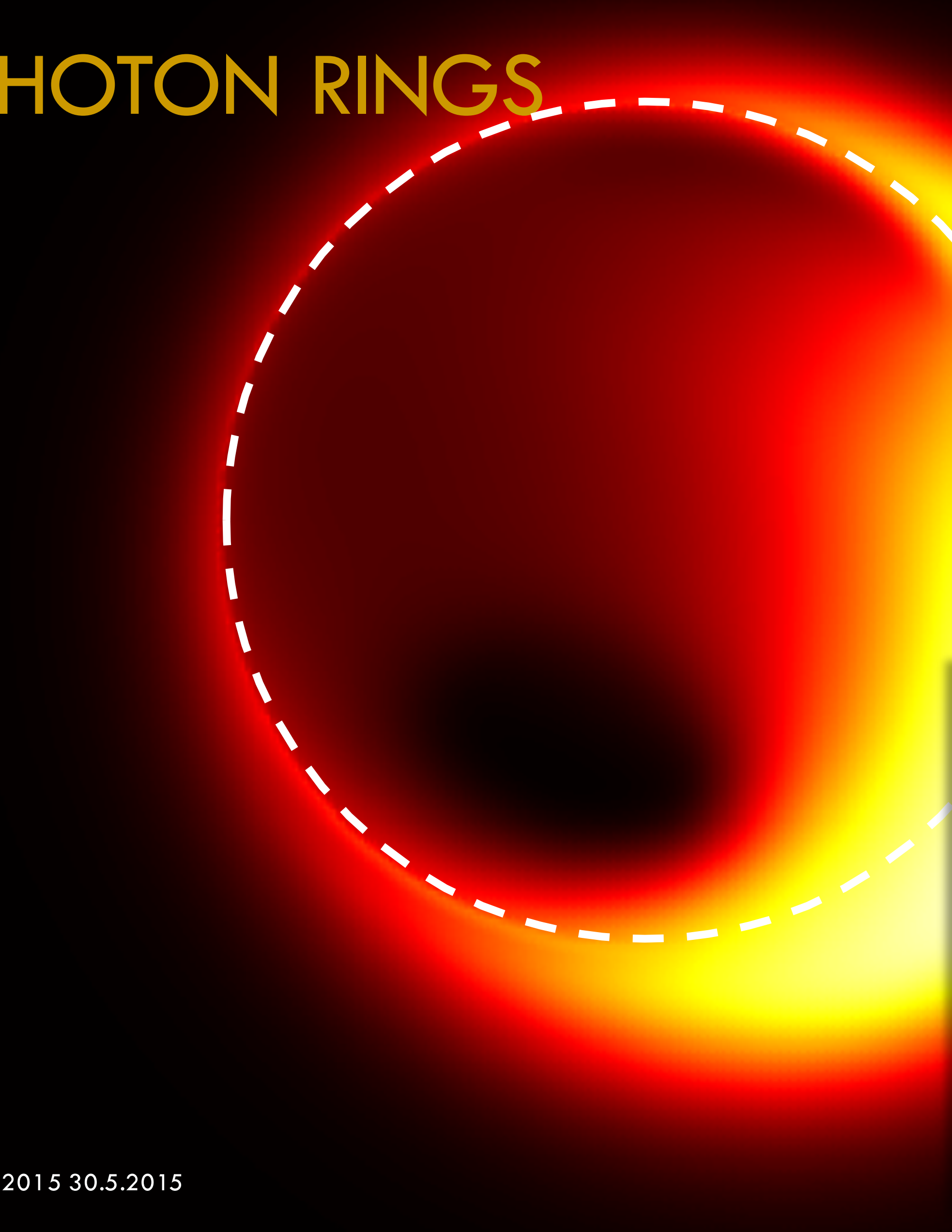


Horizons existence subject to:

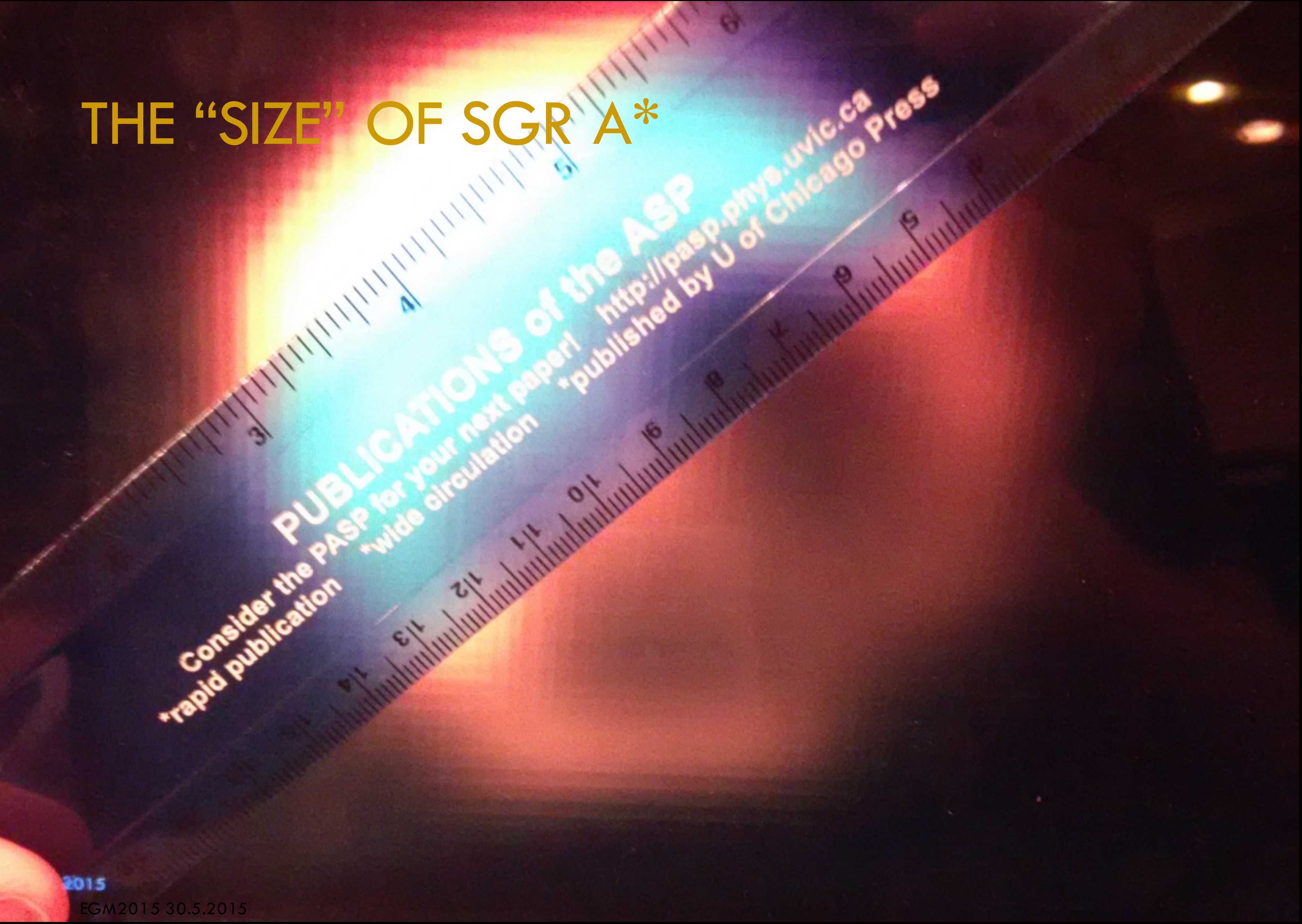
1. Steady state
2. Sufficiently compact or "normal"
3. No unknown channel for energy loss
4. Notion of energy conservation
5. M87: electromagnetic jets
6. Sgr A*: accretion powered

…, etc.

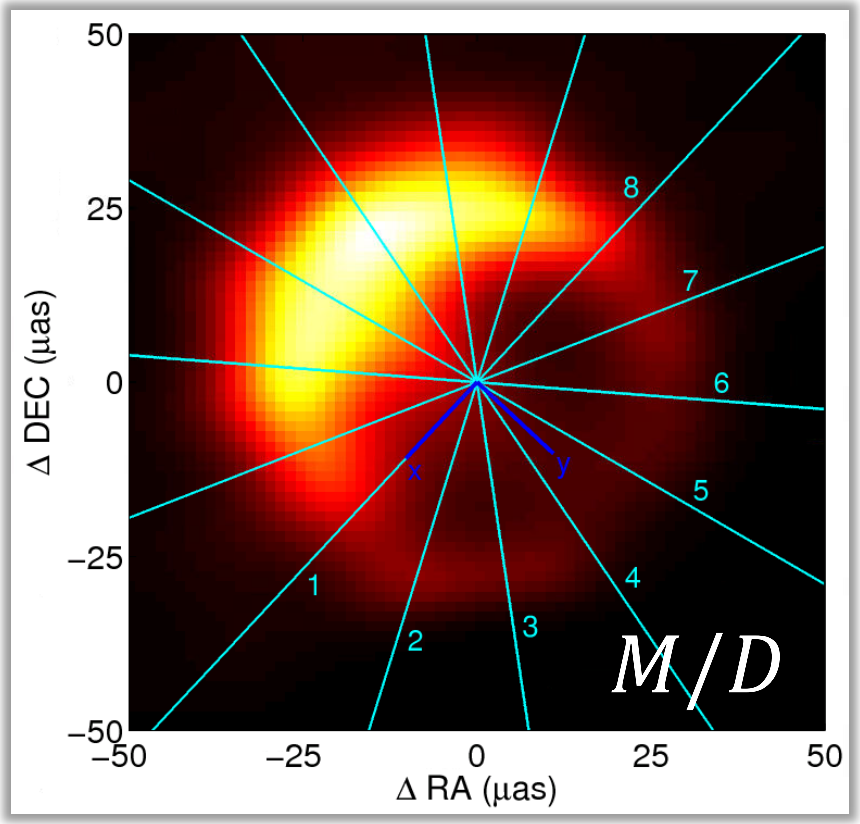
PHOTON RINGS

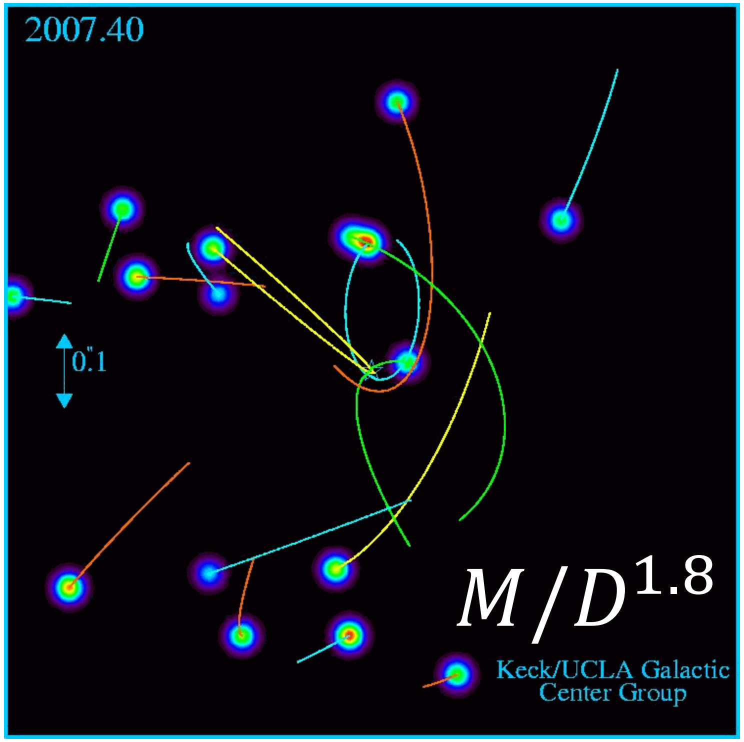


THE "SIZE" OF SGR A*



MEASURING "MASS"

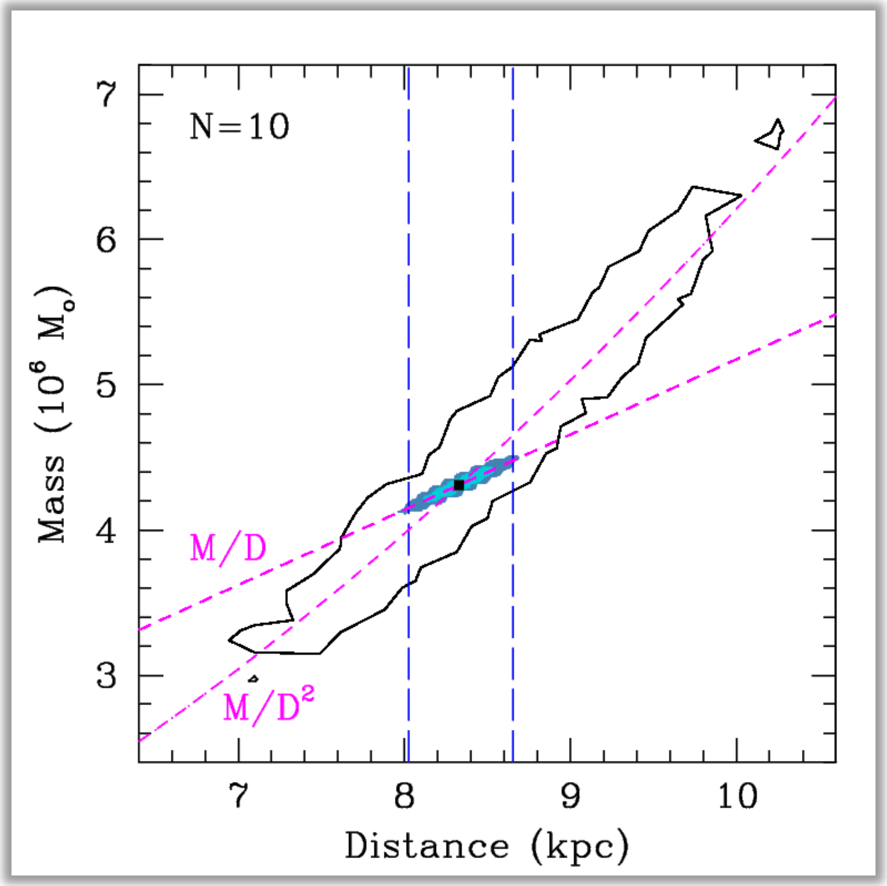


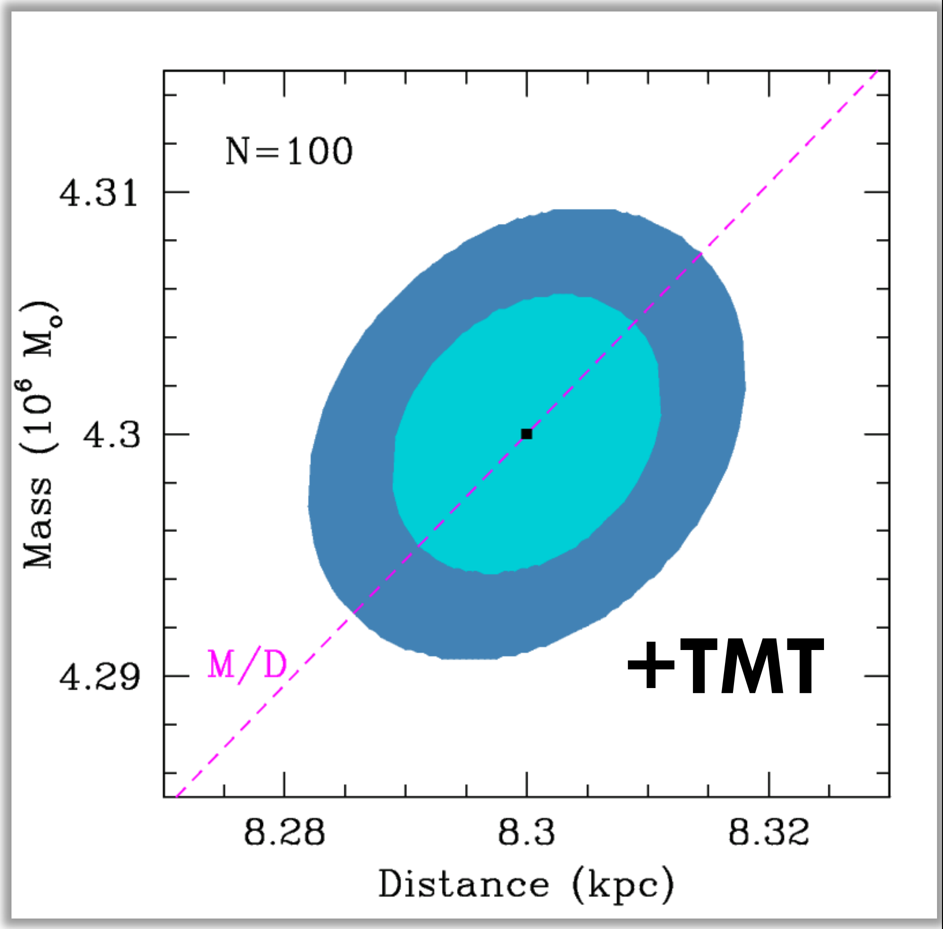


On horizon scales

On 3000x horizon scales

MEASURING "MASS" NOW AND IN THE FUTURE

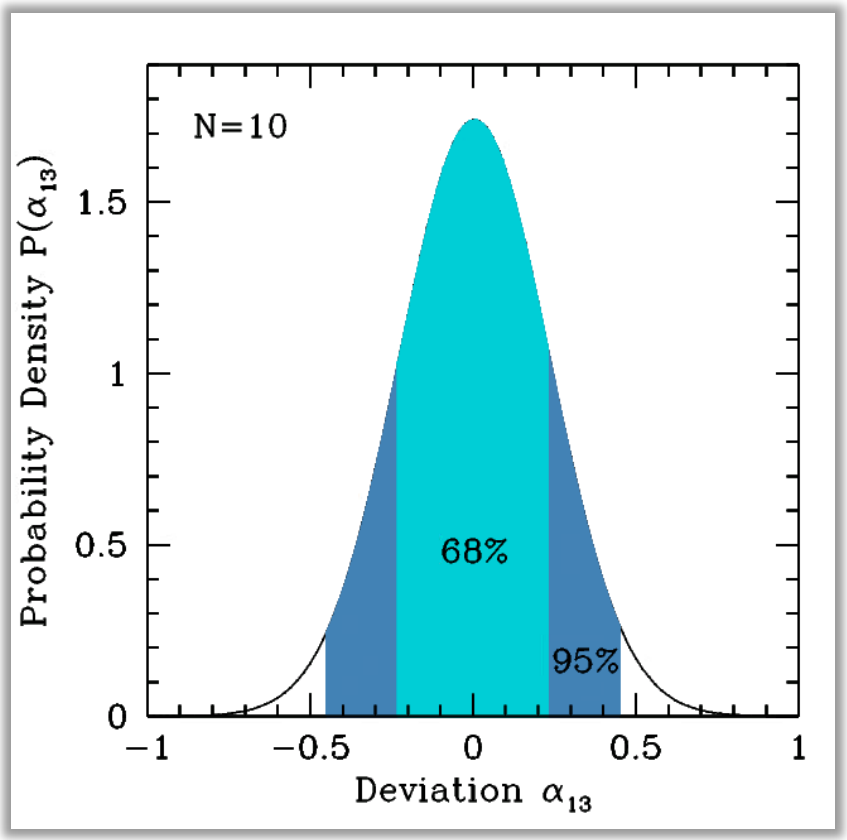


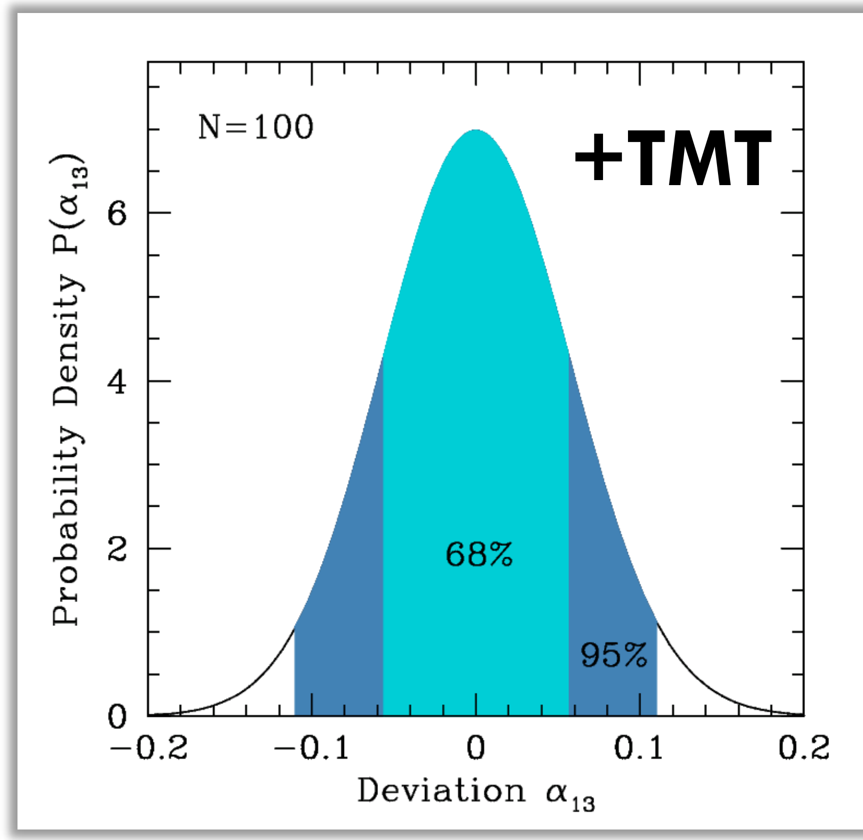


Tim Johannsen

CONSTRAINING MONOPOLE HAIR

$$ds^2 = -\left[1 + \alpha_{13}\left(\frac{M}{r}\right)^3\right]\left(1 - \frac{2M}{r}\right)dt^2 + \left(1 - \frac{2M}{r}\right)^{-1}dr^2 + r^2d\theta^2 + r^2\sin^2\theta\left[1 + \alpha_{13}\left(\frac{M}{r}\right)^3\right]d\phi^2$$

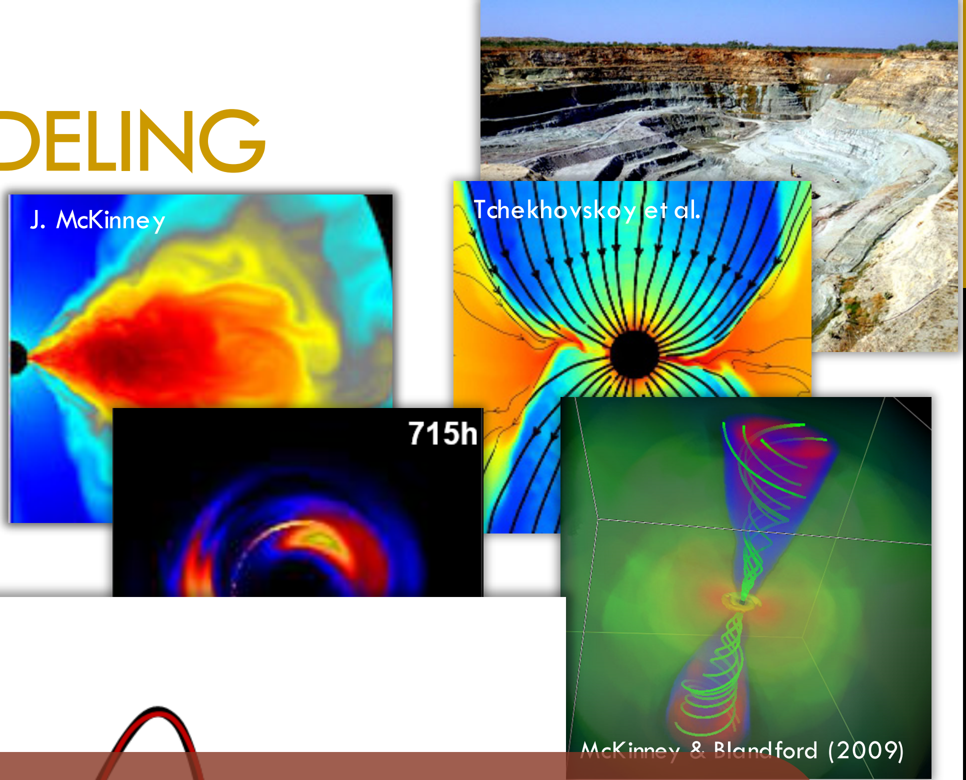




Tim Johannsen

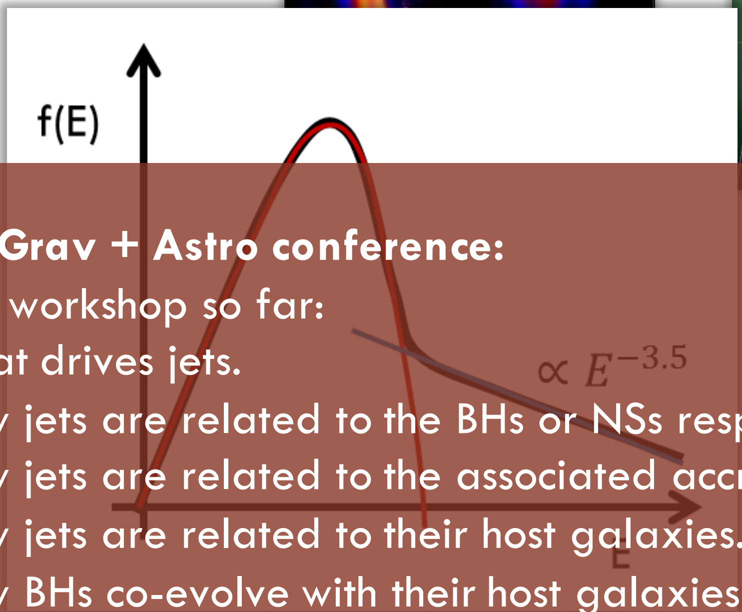
ASTROPHYSICAL MODELING OF EHT SOURCES

ASTROPHYSICAL MODELING OF EHT SOURCES



Key known unknowns:

- **Geometry & Dynamics of emission region**
- **Relativistic electron origin & distribution**



Comment at recent Grav + Astro conference:

"My summary of the workshop so far:

We don't know what drives jets.

We don't know how jets are related to the BHs or NSs responsible.

We don't know how jets are related to the associated accretion disk.

We don't know how jets are related to their host galaxies.

We don't know how BHs co-evolve with their host galaxies.

We don't know how AGN feedback works.

We don't know anything.“

LESSONS FROM PRECISION COSMOLOGY

Planck Collaboration: Diffuse component separation: Foreground maps

Table 4. Summary of main parametric signal models for the temperature analysis. For polarization, the same parametric functions are employed, but only CMB, synchrotron, and thermal dust emission are included in the model, with spectral parameters fixed to the result of the temperature analysis. The symbol "~" implies that the respective parameter has a prior as given by the right-hand side distribution; Uni denotes a uniform distribution within the indicated limits, and N denotes a (normal) Gaussian distribution with the indicated mean and standard devation.

Component	Free parameters and priors	Brightness temperature, s_ν [μK_{RJ}]	Additional information
CMB[a]	$A_{cmb} \sim \mathrm{Uni}(-\infty, \infty)$	$x = \frac{h\nu}{k_B T_{CMB}}$ $g(\nu) = (\exp(x)-1)^2/(x^2 \exp(x))$ $s_{CMB} = A_{CMB}/g(\nu)$	$T_{CMB} = 2.7255\,K$
Synchrotron[a]	$A_s > 0$ $\alpha > 0$, spatially constant	$s_s = A_s \left(\frac{\nu_0}{\nu}\right)^2 \frac{f_s(\frac{\nu}{\alpha})}{f_s(\frac{\nu_0}{\alpha})}$	$\nu_0 = 408\,MHz$ $f_s(\nu)$ = Ext template
Free-free	$\log EM \sim \mathrm{Uni}(-\infty, \infty)$ $T_e \sim N(7000 \pm 500\,K)$	$g_{ff} = \log\left\{\exp\left[5.960 - \sqrt{3}/\pi \log(\nu_9\ T_4^{-3/2})\right] + e\right\}$ $\tau = 0.05468\ T_e^{-3/2}\ \nu_9^{-2}\ EM\ g_{ff}$ $s_{ff} = 10^6\, T_e\,(1 - e^{-\tau})$	$T_4 = T_e/10^4$ $\nu_9 = \nu/(10^9\,Hz)$
Spinning dust	$A^1_{sd}, A^2_{sd} > 0$ $\nu^1_p \sim N(19 \pm 3\,GHz)$ $\nu^2_p > 0$, spatially constant	$s_{sd} = A_{sd} \cdot \left(\frac{\nu_0}{\nu}\right)^2 \frac{f_{sd}(\nu \cdot \nu_{p0}/\nu_p)}{f_{sd}(\nu_0 \cdot \nu_{p0}/\nu_p)}$	$\nu^1_0 = 22.8\,GHz$ $\nu^2_0 = 41.0\,GHz$ $\nu_{p0} = 30.0\,GHz$ $f_{sd}(\nu)$ = Ext template
Thermal dust[a]	$A_d > 0$ $\beta_d \sim N(1.55 \pm 0.1)$ $T_d \sim N(23 \pm 3\,K)$	$\gamma = \frac{h}{k_B T_d}$ $s_d = A_d \cdot \left(\frac{\nu}{\nu_0}\right)^{\beta_d+1} \frac{\exp(\gamma\nu_0)-1}{\exp(\gamma\nu)-1}$	$\nu_0 = 545\,GHz$
SZ	$y_{sz} > 0$	$s_{sz} = 10^6\, y_{sz}/g(\nu)\, T_{CMB} \left(\frac{x(\exp(x)+1)}{\exp(x)-1} - 4\right)$	
Line emission	$A_i > 0$ $h_{ij} > 0$, spatially constant	$s_i = A_i h_{ij} \frac{F_i(\nu_j)}{F_i(\nu_0)} \frac{g(\nu_0)}{g(\nu_j)}$	$i \in$ {CO $J=1\rightarrow0$, CO $J=2\rightarrow1$, CO $J=3\rightarrow2$, 94/100} j = detector index F = unit conversion

[a] Polarized component.

Planck Collaboration: Diffuse component separation: Foreground maps

Table 5. Summary of full-sky foreground products available from the PLA. Each entry in the first column corresponds to one multi-column and (optionally) multi-extension FITS file, named `COM_CompMap_{label}-commander_{nside}_R2.00.fits`. The various columns in each extension list the posterior maximum, mean, and rms maps, in that order, when available. The values reported in columns 5 to 7 in this table are the mean and standard deviations of these posterior statistic maps.

File	FITS extension	Parameter	ν_{ref} [GHz/band]	Posterior outside LM93 P_{max}	Mean	RMS	Unit
TEMPERATURE AT 1° FWHM, N_{side} = 256							
AME	0	A_{sd1}	22.8	93 ± 118	92 ± 118	11 ± 3	μK_{RJ}
		ν_{sd1}	···	19 ± 1	19 ± 1	2.0 ± 0.8	GHz
	1	A_{sd2}	41	14 ± 21	18 ± 22	4.1 ± 2.8	μK_{RJ}
CMB	0	A_{cmb}	···	3 ± 67	3 ± 67	1.5 ± 0.8	μK_{cmb}
CO	0	A_{CO10}	100-ds1	0.3 ± 1.3	0.4 ± 1.3	0.06 ± 0.05	K_{RJ} km s^{-1}
	1	A_{CO21}	217-1	0.22 ± 0.57	0.29 ± 0.57	0.04 ± 0.01	K_{RJ} km s^{-1}
	2	A_{CO32}	353-ds2	0.16 ± 0.21	0.26 ± 0.26	0.05 ± 0.01	K_{RJ} km s^{-1}
dust	0	A_d	545	163 ± 228	163 ± 228	0.66 ± 0.11	μK_{RJ}
		T_d	···	21 ± 2	21 ± 2	1.1 ± 0.7	K
		β_d	···	1.53 ± 0.05	1.51 ± 0.06	0.05 ± 0.03	···
freefree	0	EM	···	15 ± 35	13 ± 35	2.3 ± 2.4	cm^{-6} pc
		T_e	···	7000 ± 11	7000 ± 11	···	K
Synchrotron	0	A_s	0.408	20 ± 15	20 ± 15	1.1 ± 0.2	K^a_{RJ}
SZ	0	A_{sz}	···	1.4 ± 1.4[b]	2.0 ± 1.3[b]	0.8 ± 0.2[b]	$10^{-6}\ y_{sz}$
xline[c]	0	$A_{94/100}$	100-ds1	0.09 ± 0.06	0.9 ± 0.8	0.7 ± 0.6	μK_{cmb}
TEMPERATURE AT 7.′5 FWHM, N_{side} = 2048							
CO21[d]	0	A_{CO21}	217-1	0.2 ± 0.8	···	···	K_{RJ} km s^{-1}
ThermalDust[d]	0	A_d	545	0.2 ± 0.8	···	···	μK_{RJ}
		β_d	···	1.54 ± 0.07	···	···	···
POLARIZATION AT 40′ FWHM, N_{side} = 256							
SynchrotronPol[d]	0	P^e_s	30	12 ± 9	···	···	μK_{RJ}
POLARIZATION AT 10′ FWHM, N_{side} = 1024							
DustPol[d]	0	P^e_d	353	8 ± 10	···	···	μK_{RJ}

[a] The data file unit is μK_{RJ} but for convenience we list numbers in K_{RJ} in this table.
[b] Evaluated only over the Coma and Virgo regions.
[c] This is the 94/100 GHz line emission component.
[d] Only the full-mission maps are summarized in this table, but the data files also include corresponding maps for half-mission, half-year, and half-ring data splits.
[e] Data files contains Stokes Q and U parameters, not the polarization amplitude, $P = \sqrt{Q^2 + U^2}$, listed here.

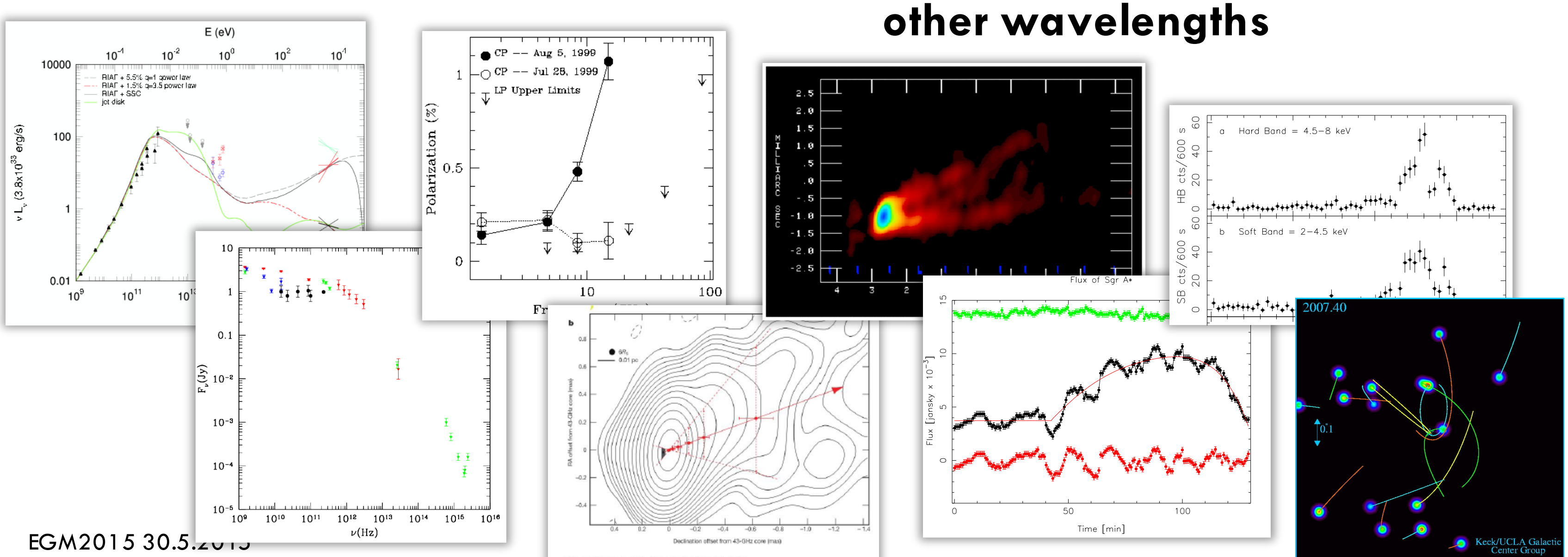
EHT CONTEXT

Modeling Priors

- **Theories of accretion flows**
- **Theories of jet formation**
- **Radiative physics (synchrotron!)**
- **General relativity**

Empirical Priors:

- **Spectral information**
- **Polarization information**
- **Morphologies at other wavelengths**
- **Dynamical measurements at other wavelengths**

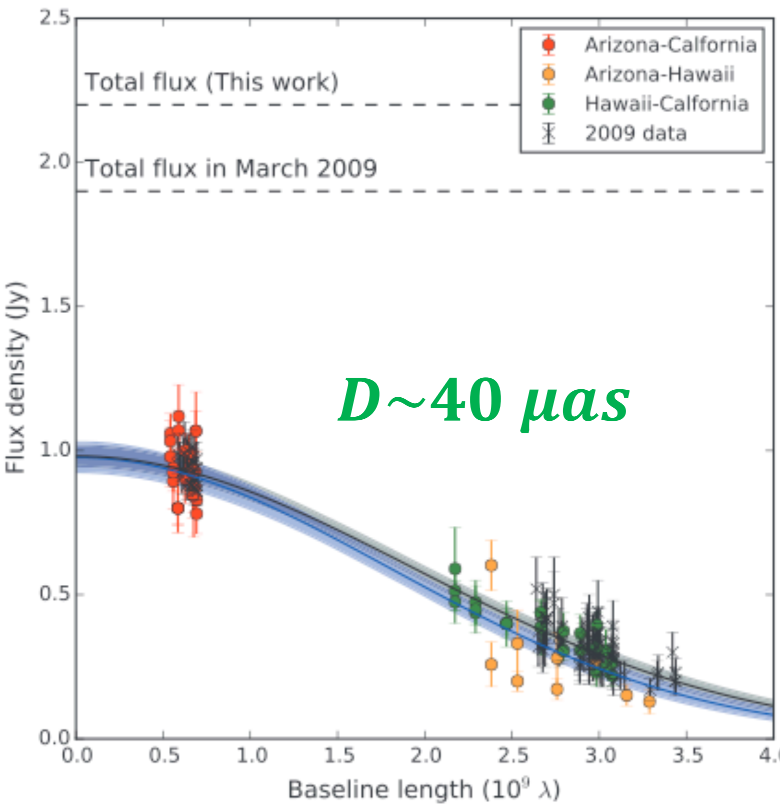


DIGGING IN JETS: M87

DIGGING IN JETS: M87 EHT DATA

230 GHz VLBI observations of M87 in March 2012 5

Correlated Flux

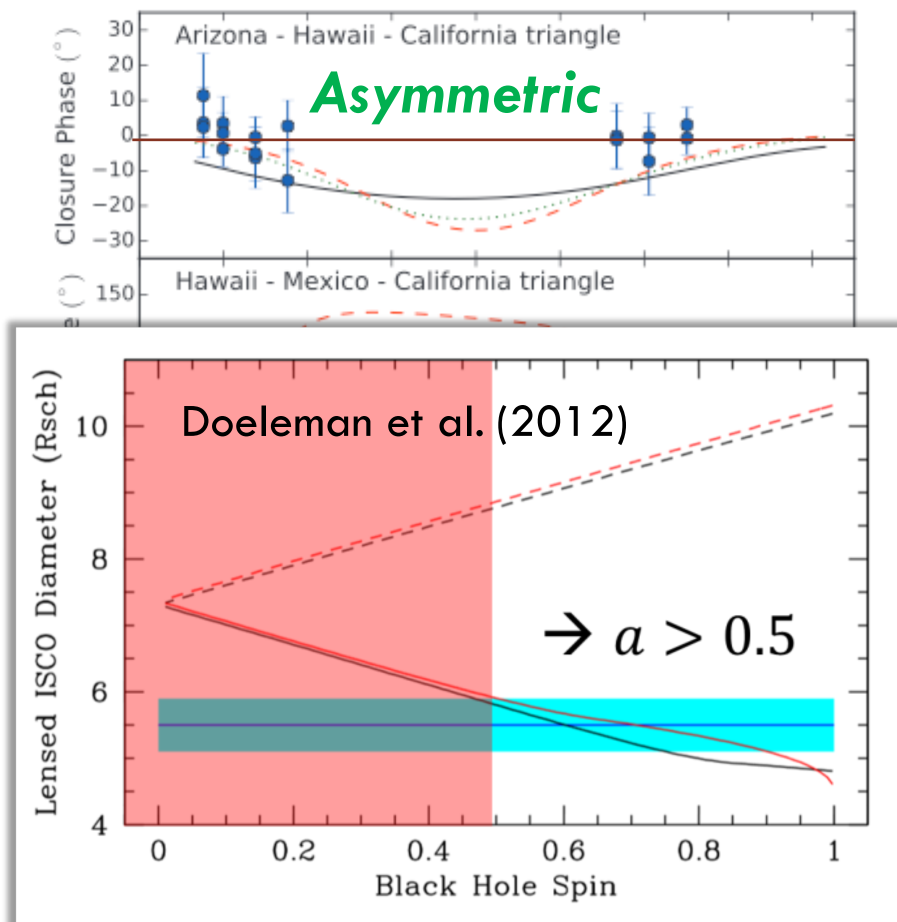


D~40 μas

Spatial Frequency

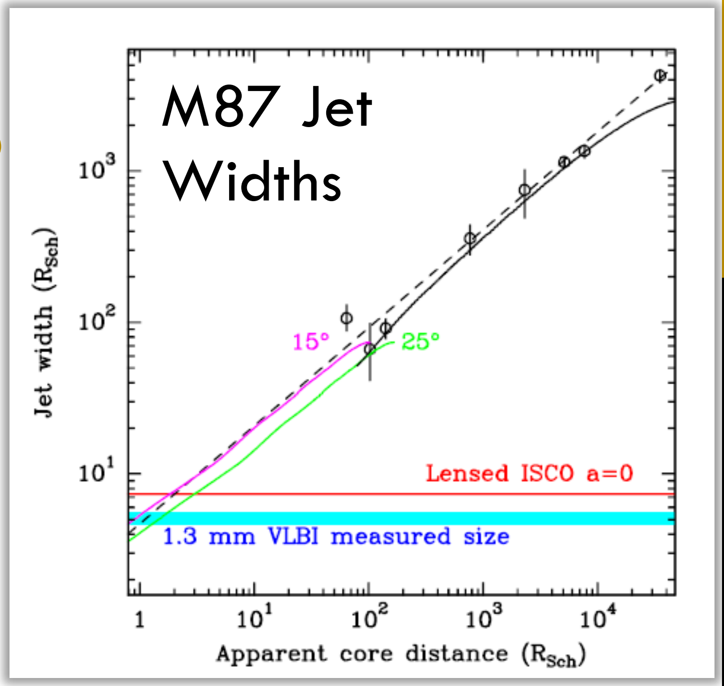
Closure Phases

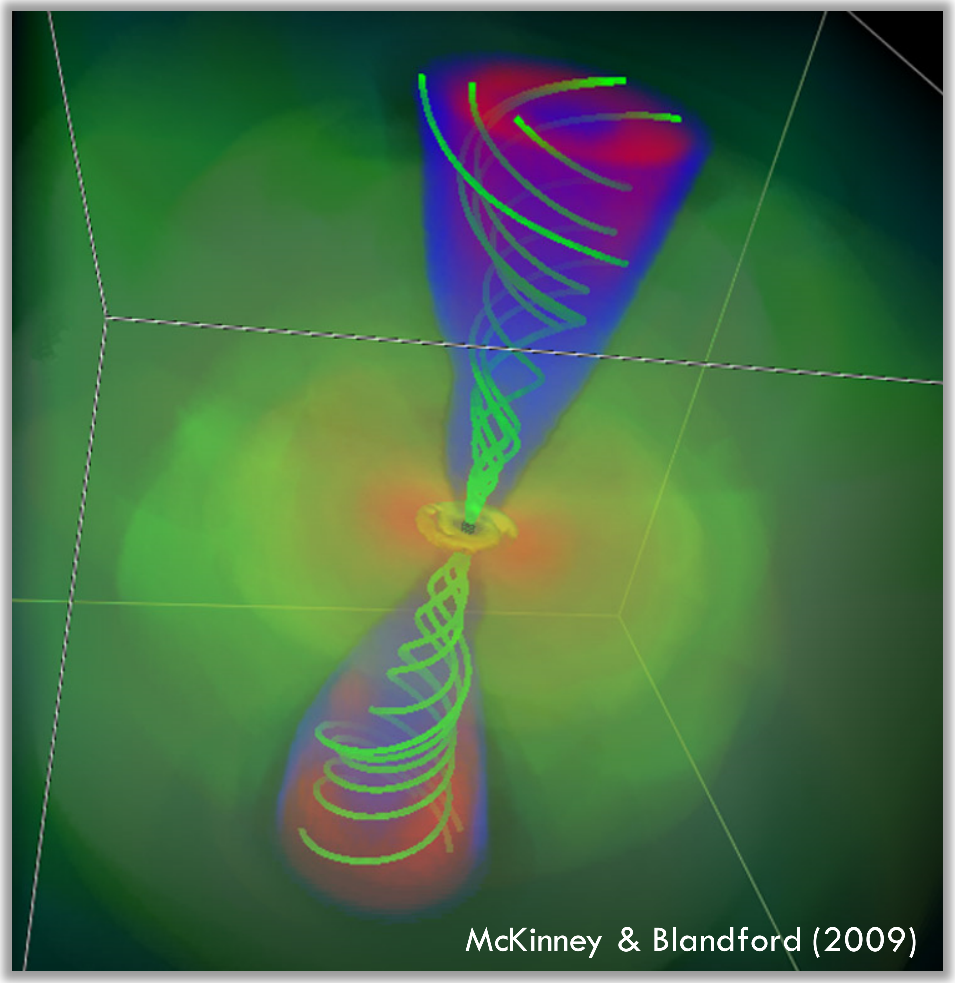
Asymmetric



Akiyama et al. (2015)

"COMPLICATED" JET MODELS





- **Blanford-Znajek/Blandford-Payne:** **Electromagnetic extraction of black hole spin/disk angular momentum.**
- **Large-scale ordered magnetic fields**
- **Canonical Structure:**
  - MHD Disk
  - Magnetically dominated wind
  - Force-free, roughly parabolic jet

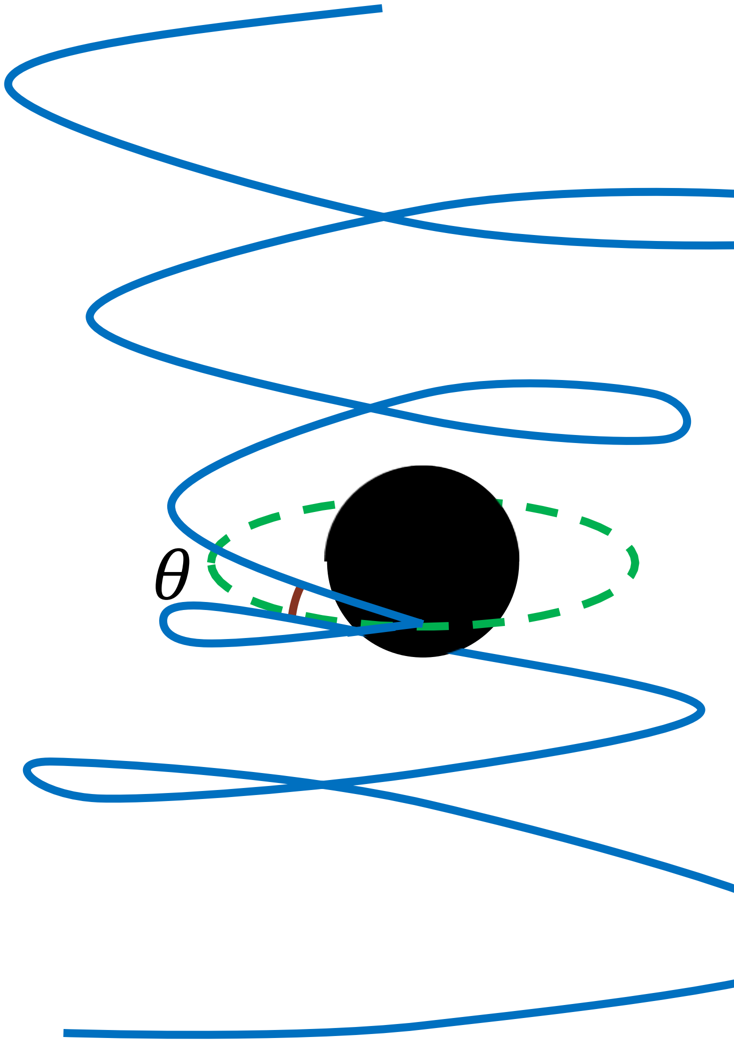
“SIMPLE” JET MODELS

- **Axisymmetric & Stationary (+poloidal struc)**
- **Particle inertia irrelevant:**

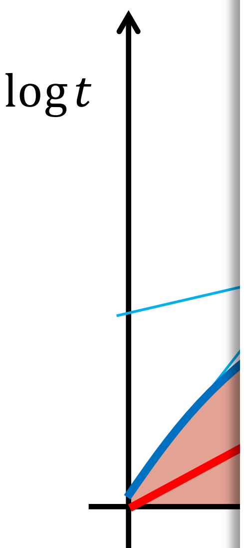
$$\boldsymbol{F}_L = \rho \boldsymbol{E} + \boldsymbol{j} \times \boldsymbol{B} = 0$$

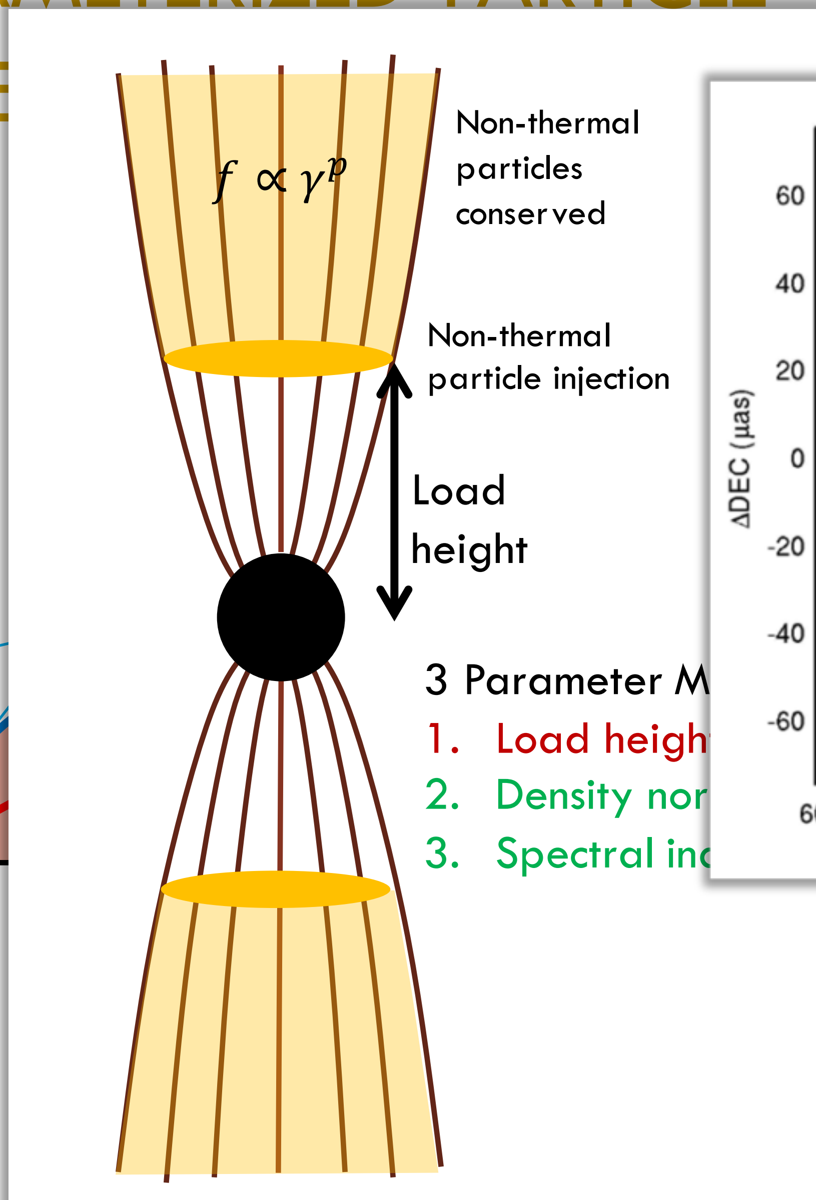
- **+ Boundary conditions at disk/black hole!**

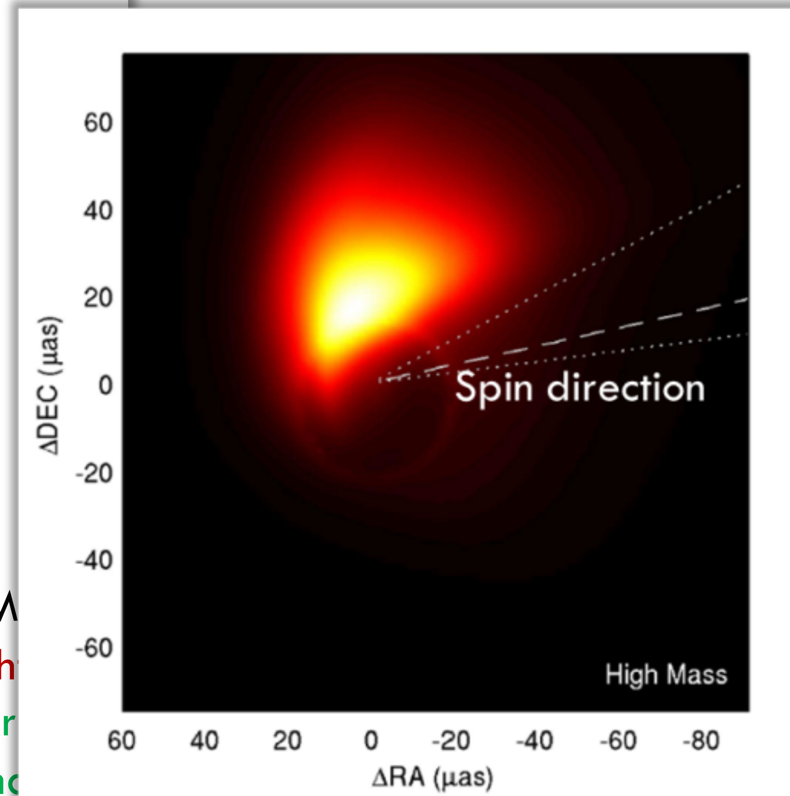
$$\Omega_{\mathrm{field}}(r) \text{ and } \tan\theta \sim \frac{v_A}{R\Omega} \sim \frac{B^P}{B^\phi} \sim \beta_\infty^{-1}$$



PARAMETERIZED PARTICLE ACCE

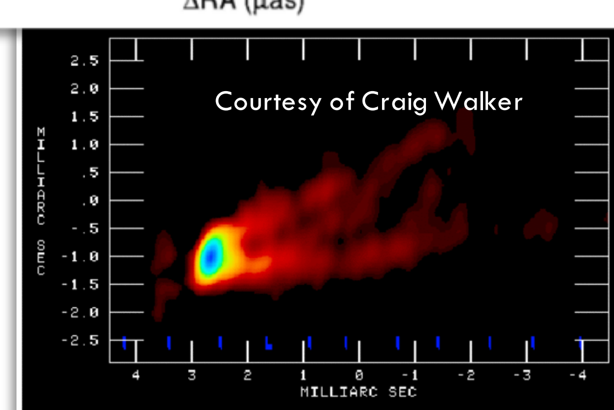




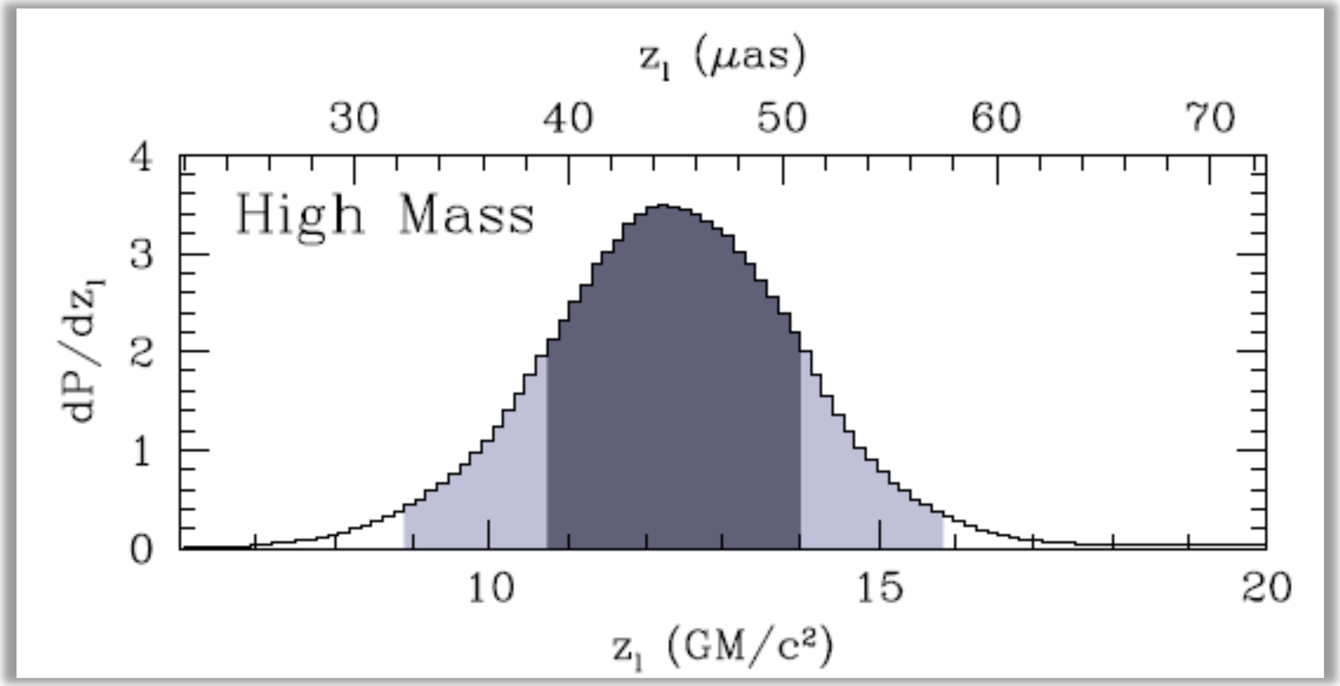


HT

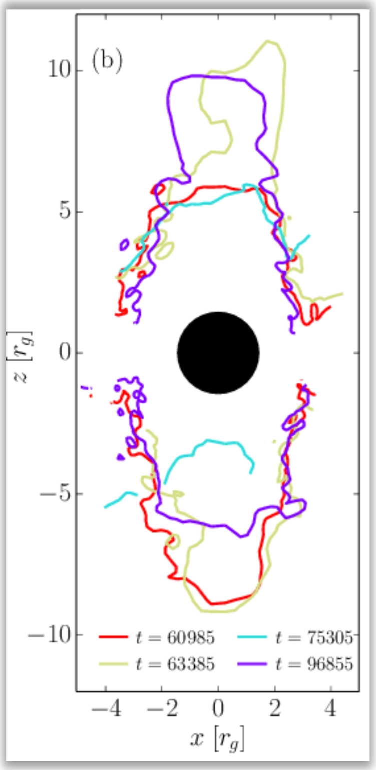
m



ASTROPHYSICAL PAYOFFS!
WHERE DOES M87 BEGIN TO SHINE?



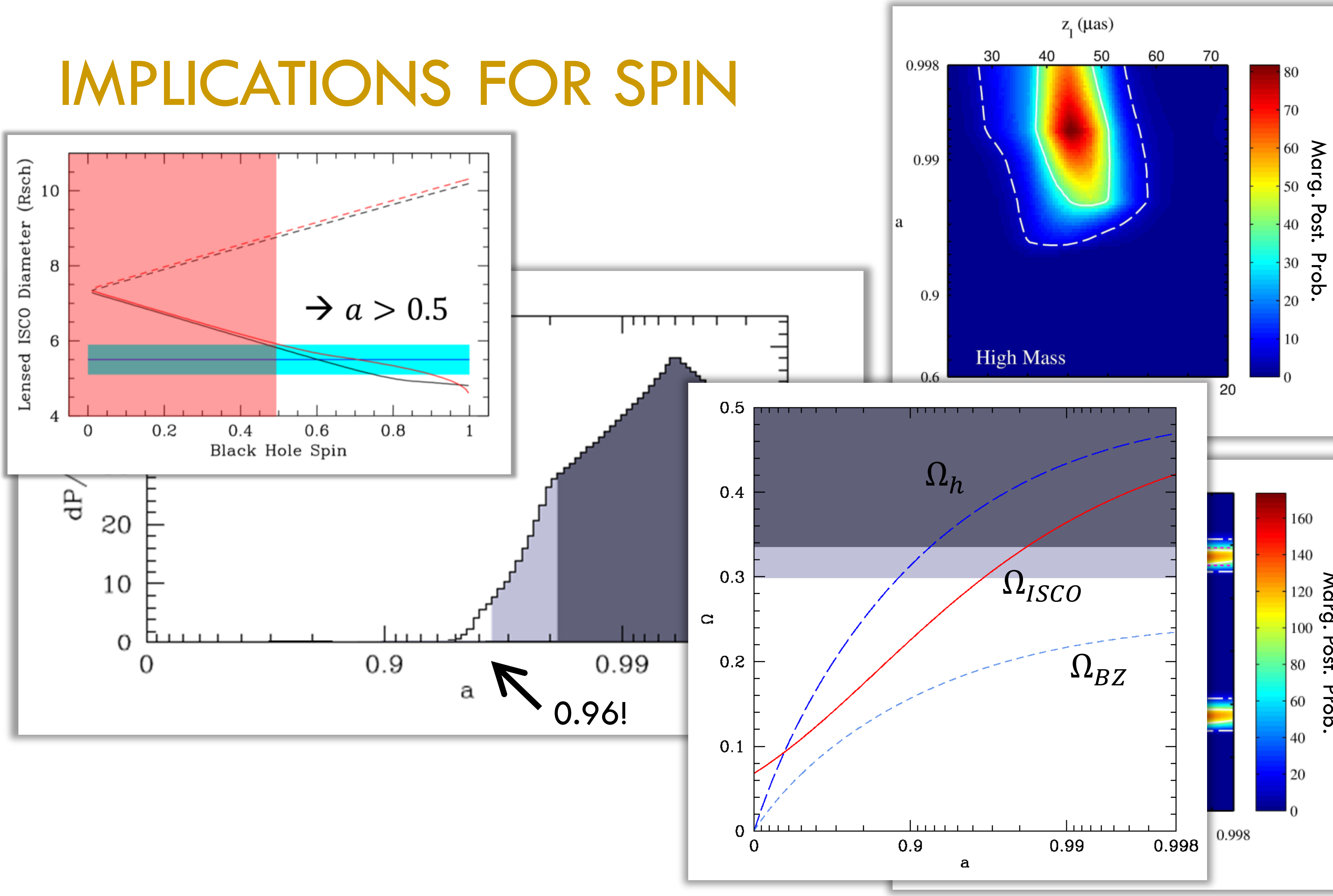
Stagnation Surface



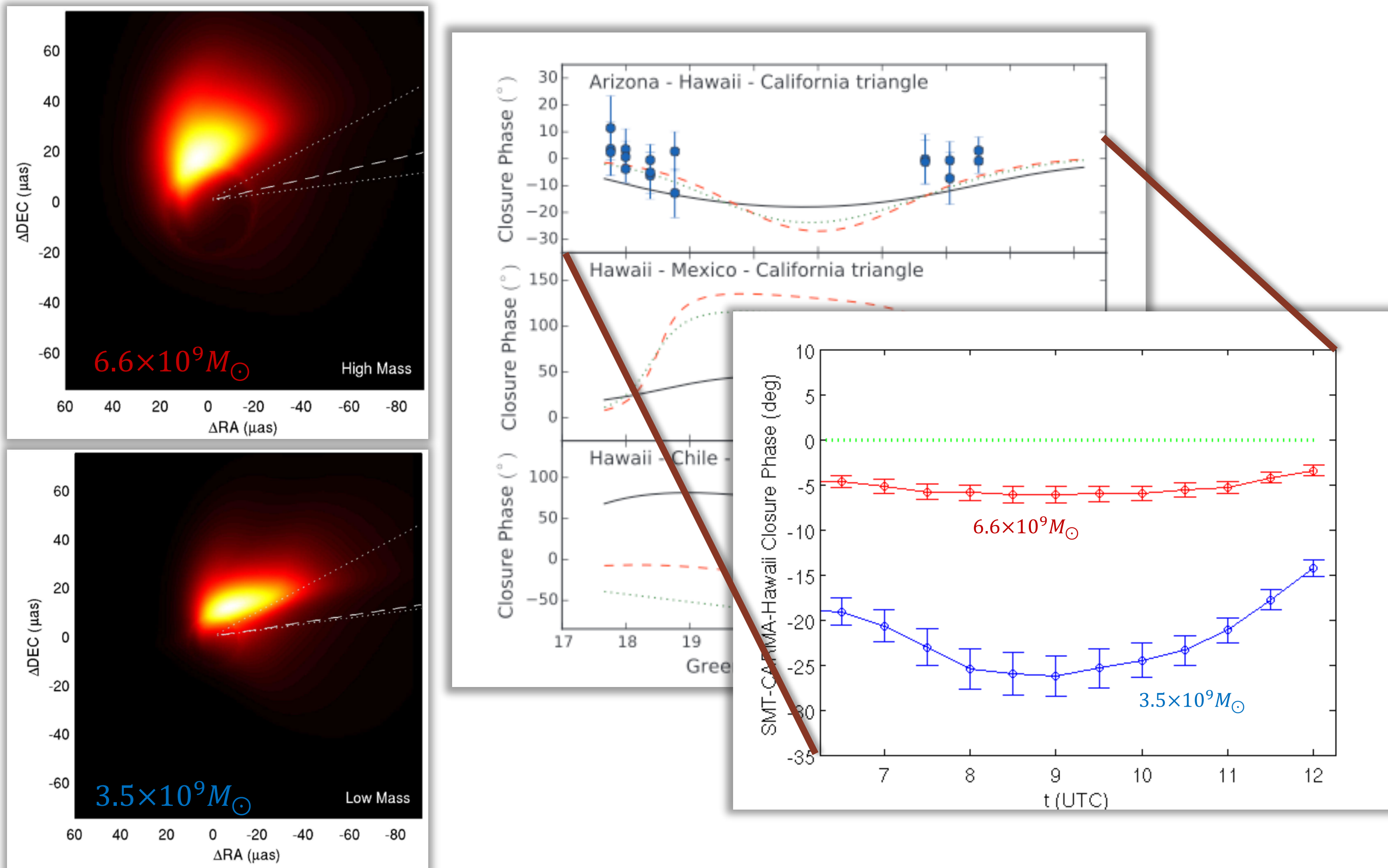
What is probably *not* injecting particles

- **Internal shocks (maybe external?)**
- **MHD turbulence**
- **Accretion disk**

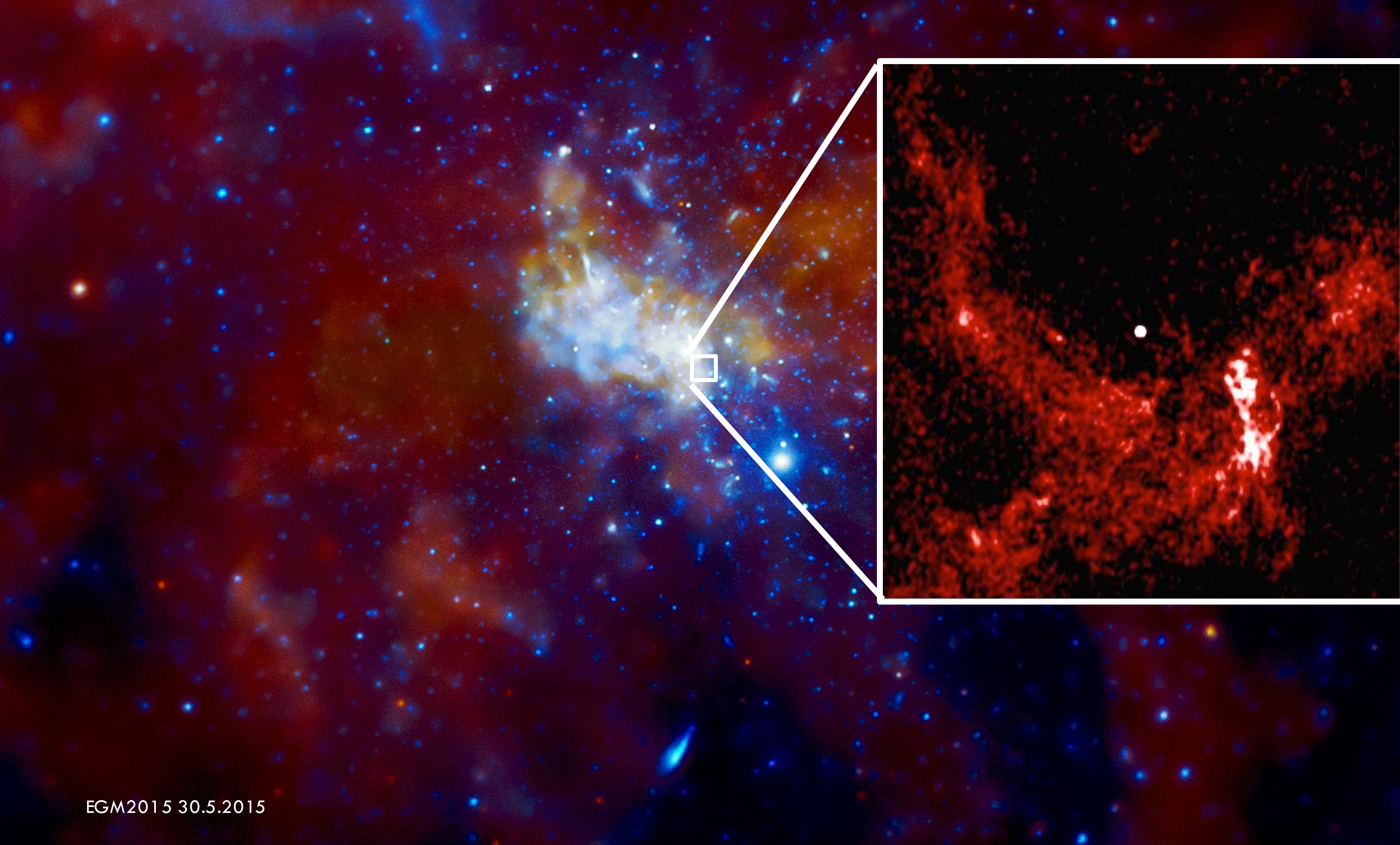
IMPLICATIONS FOR SPIN



DIFFERENTIATING MASSES



DIGGING IN ACCRETION FLOWS: SGR A*

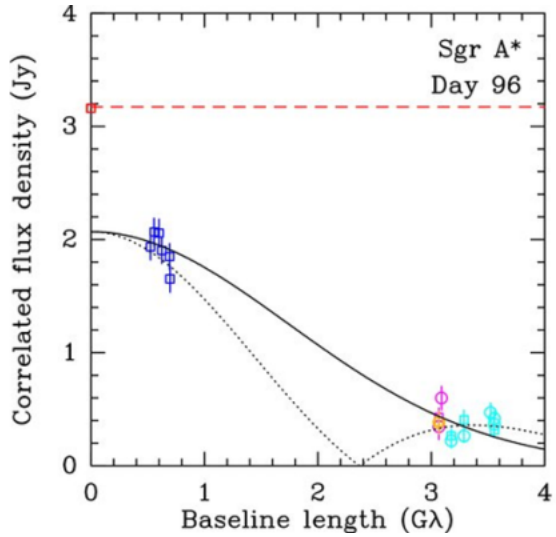


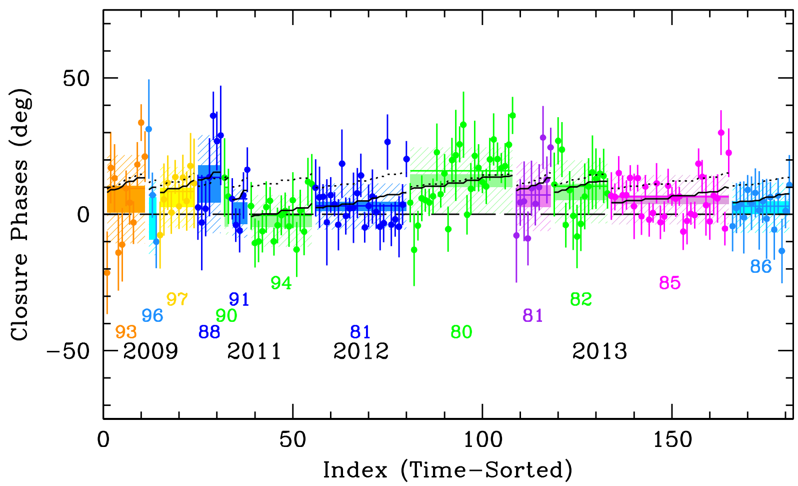
DIGGING IN ACCRETION FLOWS: SGR A* EHT DATA

Table 1
Data Epochs

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

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





DIGGING IN ACCRETION FLOWS: SGR A* EHT DATA

Table 1
Data Epochs

Visibility Magnitudes

Epoch	Year	Day(s)	Time	N[a]	Type[b]	Ref[c]
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Totals	...	...	11.73 hrs	70		

Closure Phases

5	2009	93	11.54-13.87	11	CP	F15
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8	2011	88	12.37-13.52	7	CP	F15
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Totals	...	...	25.58 hrs	181		

[a] Number of data points, including detections only
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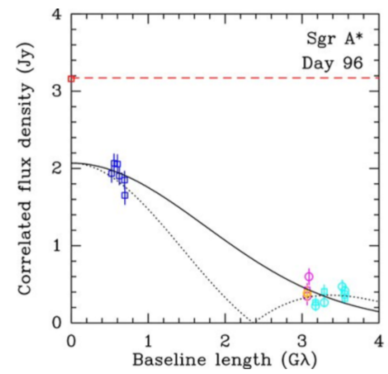
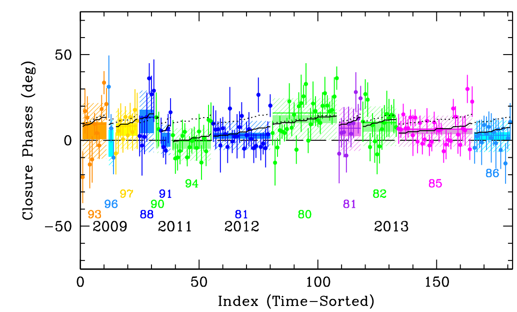
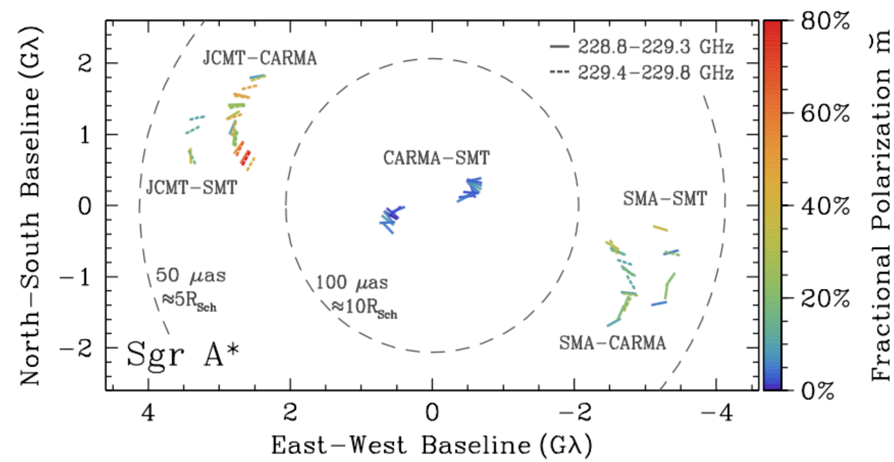
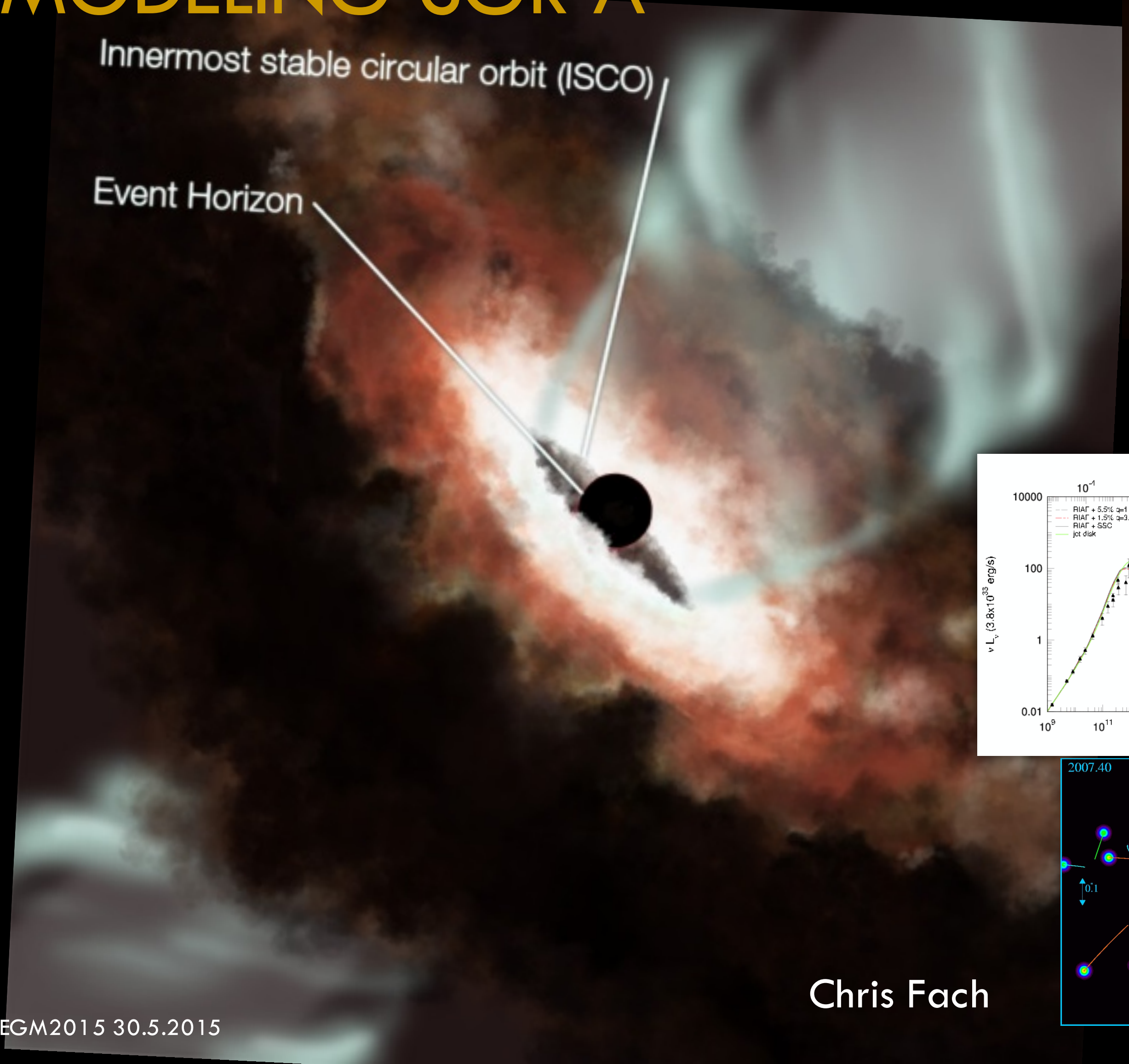


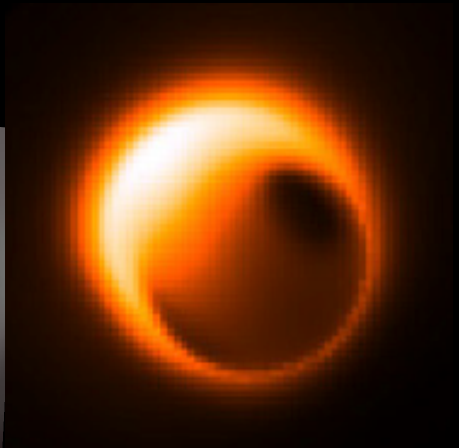




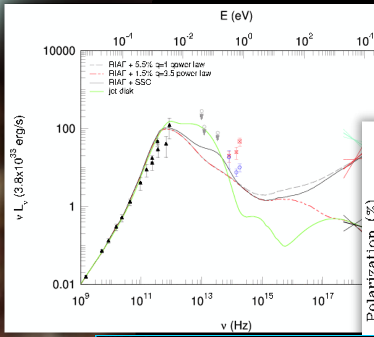
MODELING SGR A*

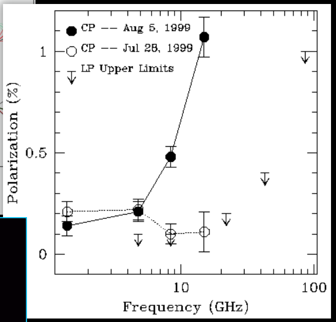


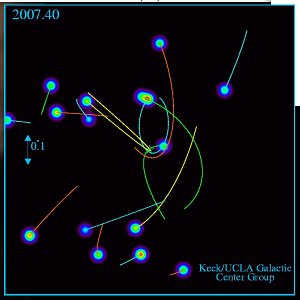
Chris Fach



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







1 MODEL – 7 YEARS

Table 1
Data Epochs

Epoch	Year	Day(s)	Time	N[a]	Type[b]	Ref[c]
1	2007	100-101	11.00-13.67	19	VM	D8
2	2009	95	11.17-15.00	12	VM	F11
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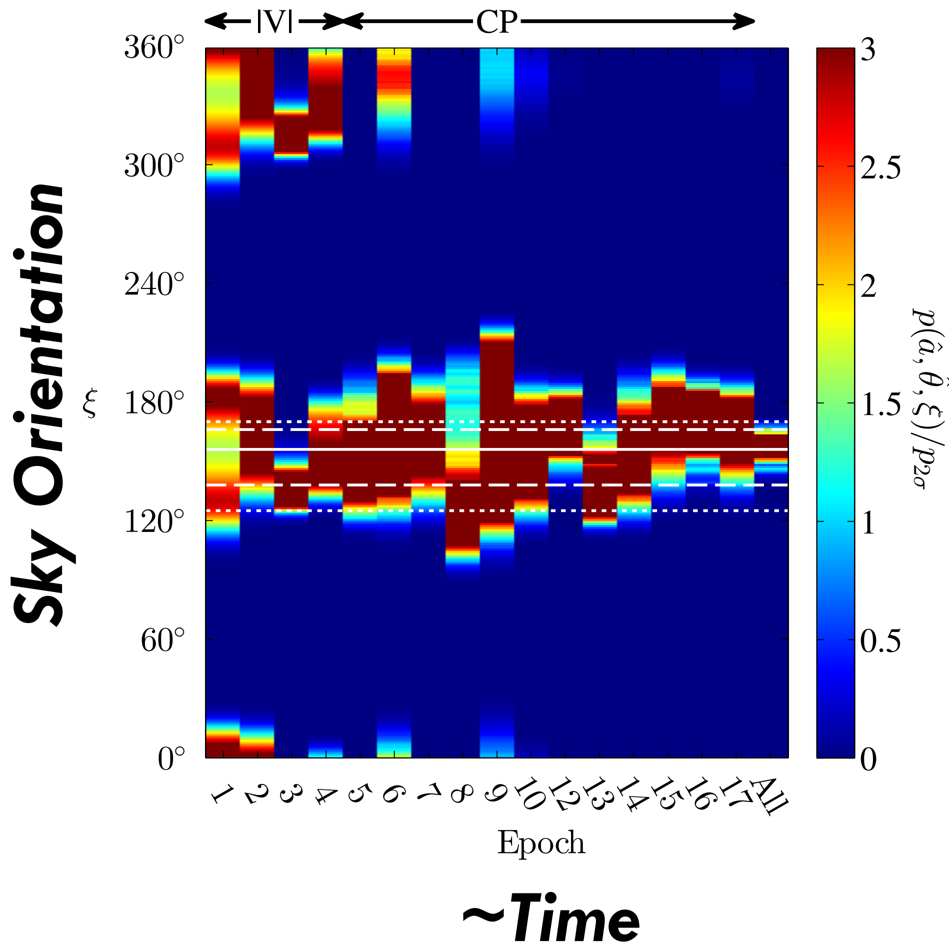
9	2011	90	13.67-14.02	2	CP	F15
10	2011	91	11.93-13.53	5	CP	F15
11[d]	2011	94	11.78-14.51	17	CP	F15
12	2012	81	12.52-15.68	25	CP	F15
13	2013	80	12.55-15.43	28	CP	F15
14	2013	81	12.97-15.27	10	CP	F15
15	2013	82	12.97-14.88	15	CP	F15
16	2013	85	12.15-15.17	32	CP	F15
17	2013	86	12.55-13.95	16	CP	F15
Totals	...	...	25.58 hrs	181		

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



POSTDICTIONS ARE EASY, PREDICTIONS ARE HARD!

Table 1
Data Epochs

Epoch	Year	Day(s)	Time	N[a]	Type[b]	Ref[c]
1	2007	100-101	11.00-13.67	19	VM	D8
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4	2009	97	11.50-13.67	20	VM	F11
Totals	...	...	11.73 hrs	70		
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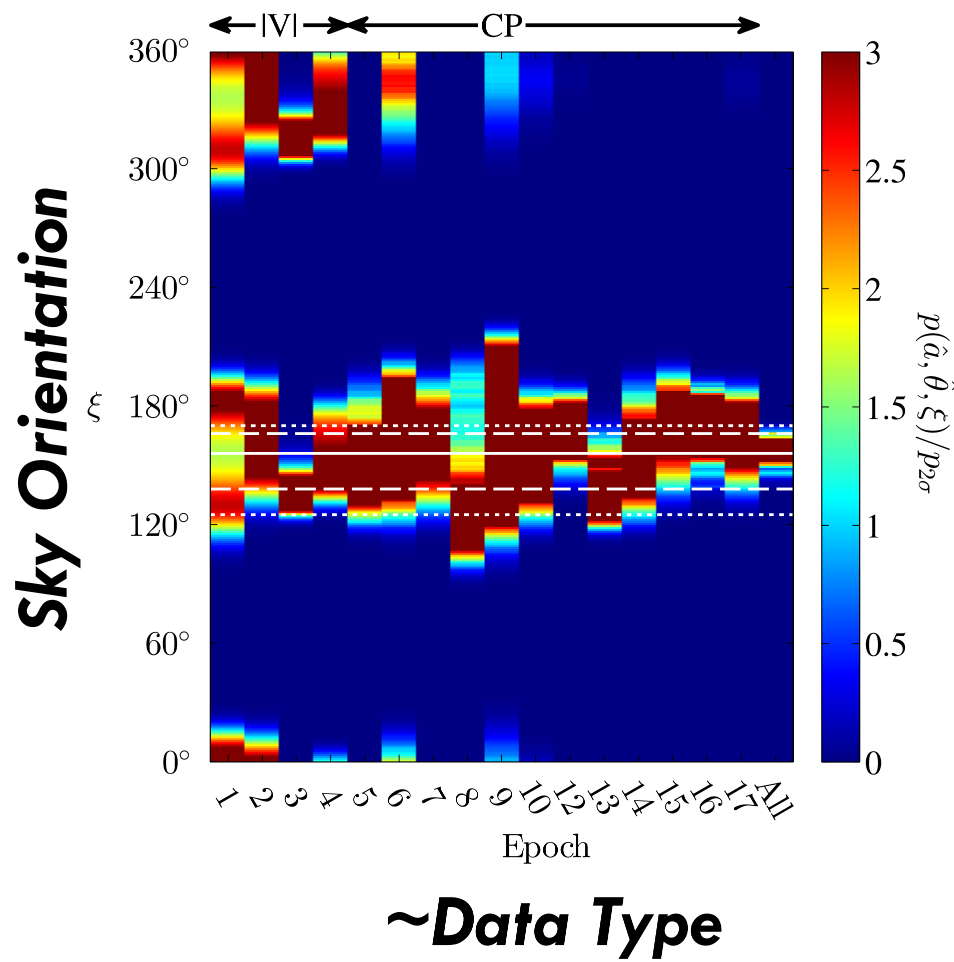
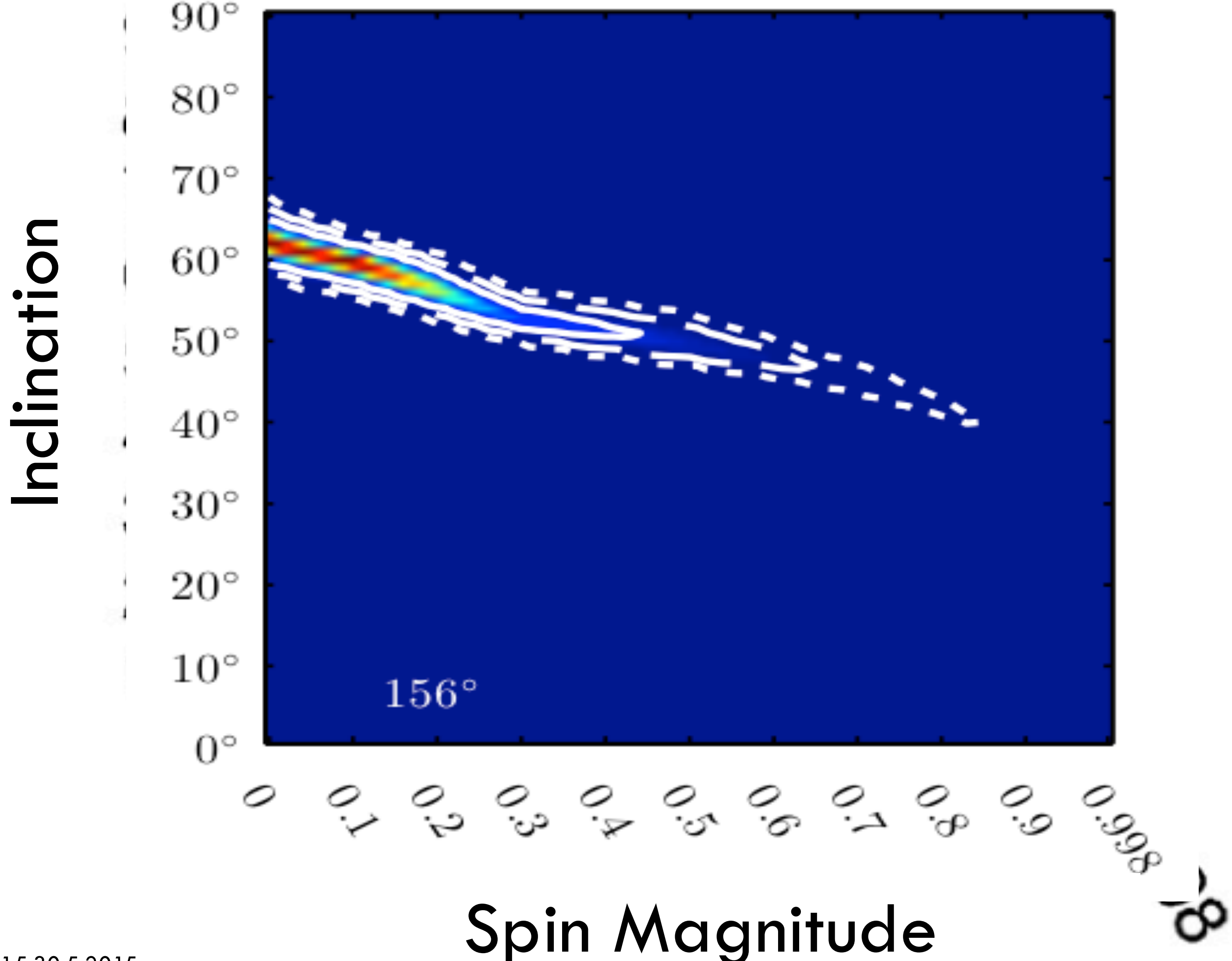
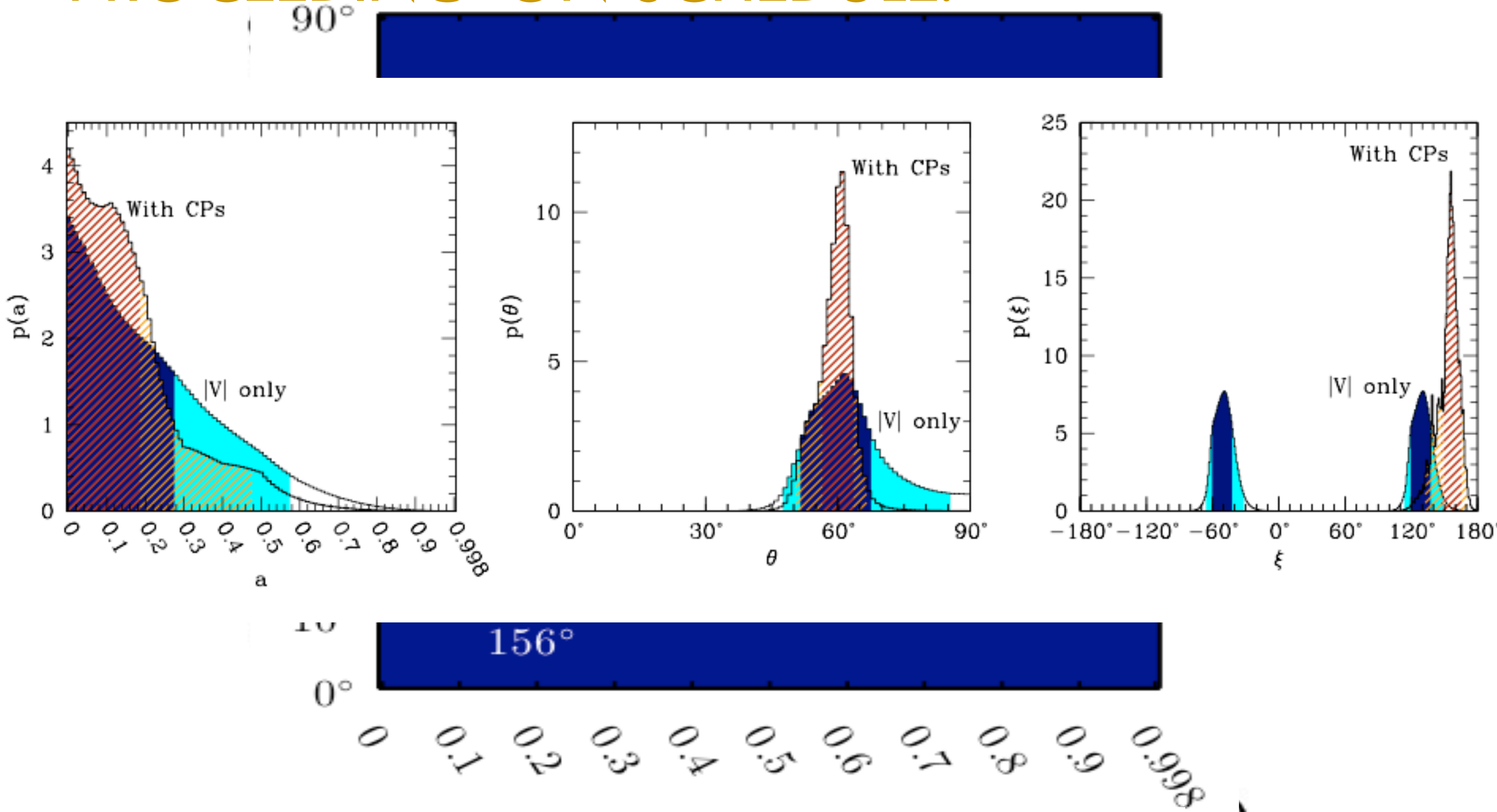


PARAMETER ESTIMATE IMPROVEMENTS PROCEEDING ON SCHEDULE!

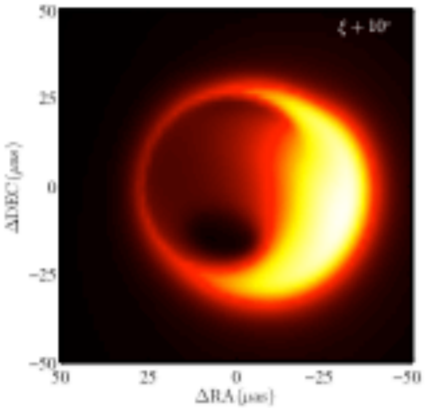


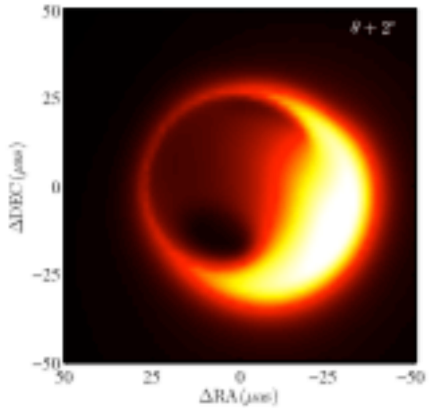
PARAMETER ESTIMATE IMPROVEMENTS PROCEEDING ON SCHEDULE!

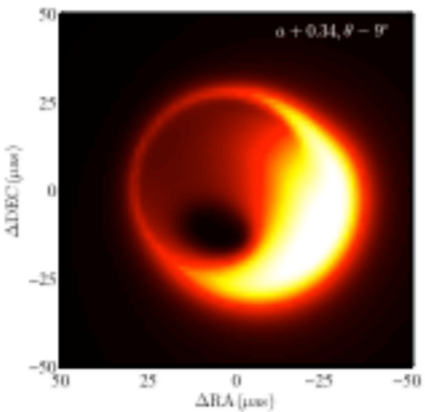


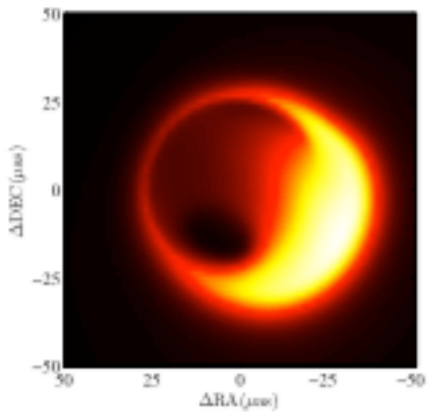
Spin Magnitude

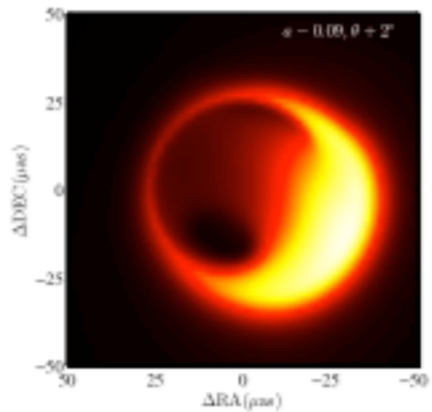
1-SIGMA IMAGE FAMILY

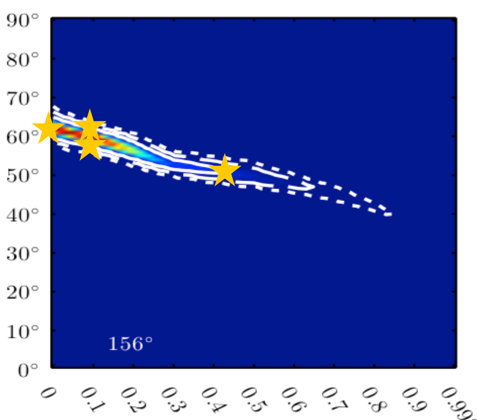




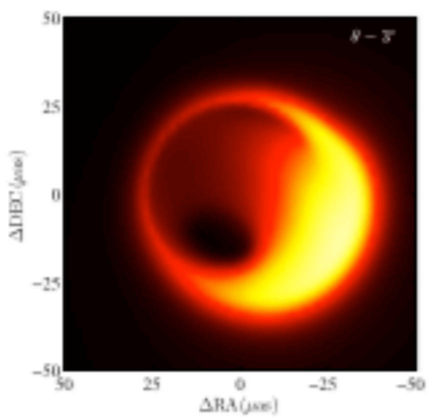


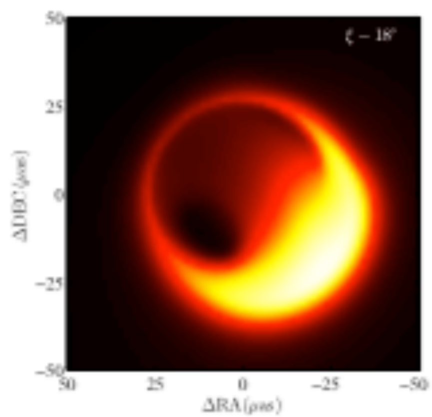




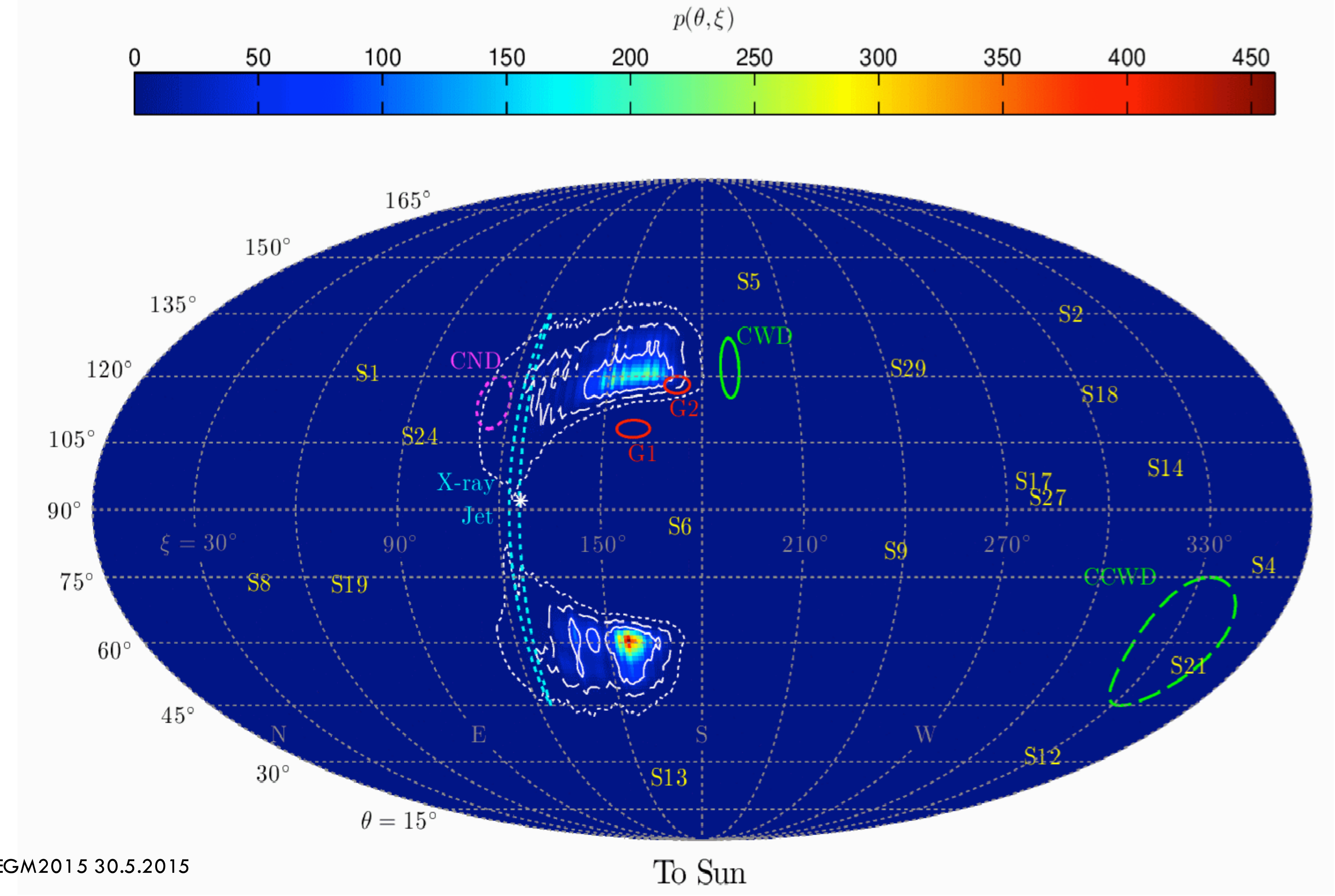


EGM2015 30.5.2015



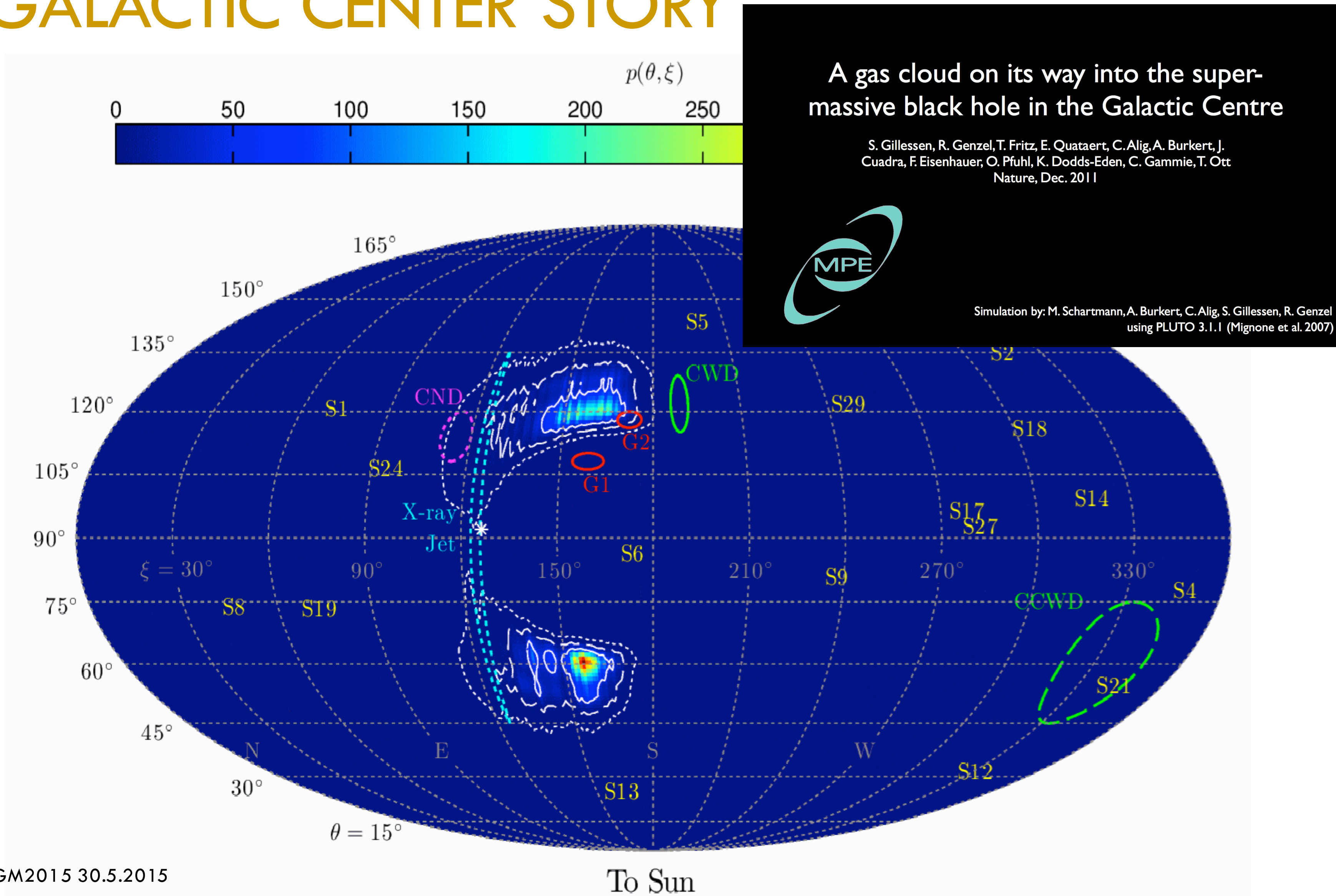


ORIENTATION AND THE GALACTIC CENTER STORY

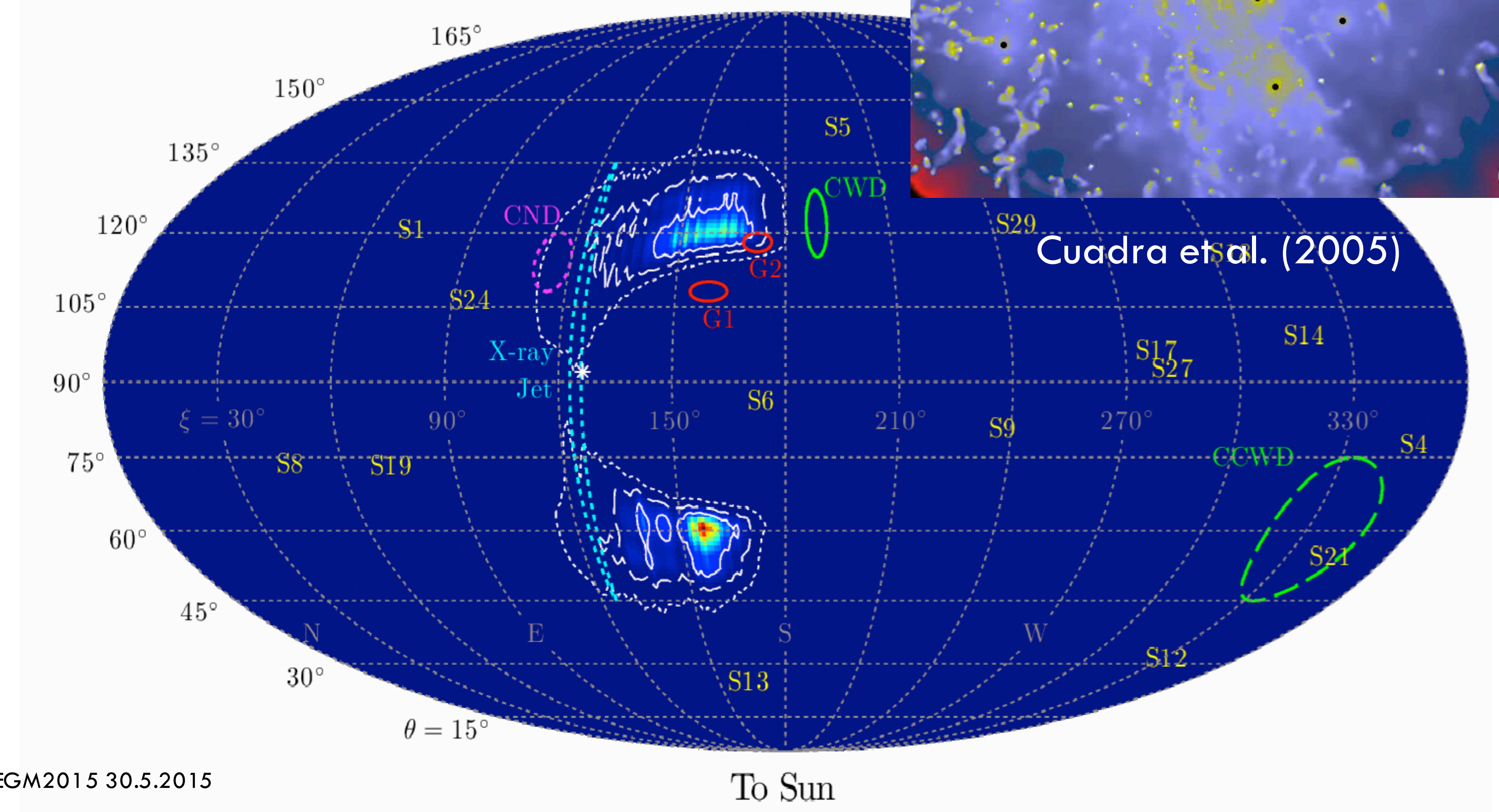


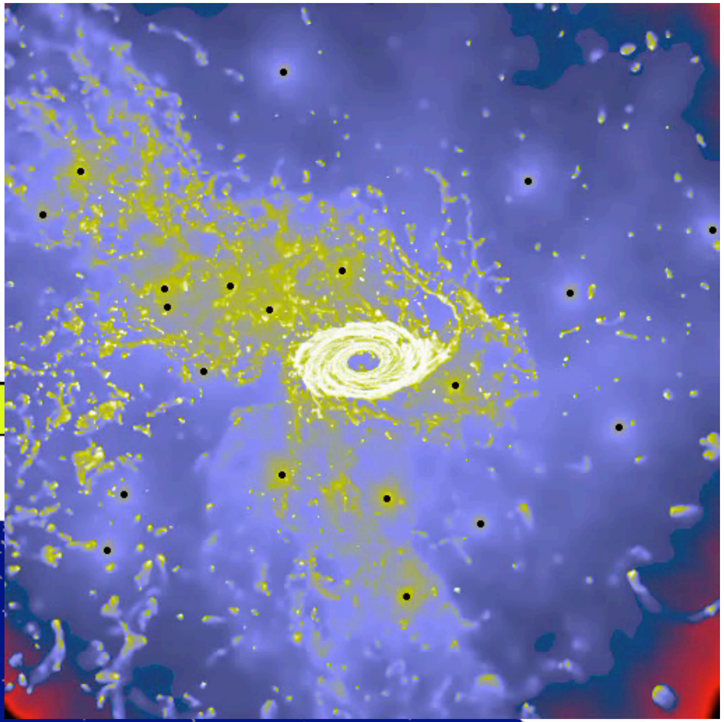
ORIENTATION AND THE GALACTIC CENTER STORY

Gillessen et al. (2011)



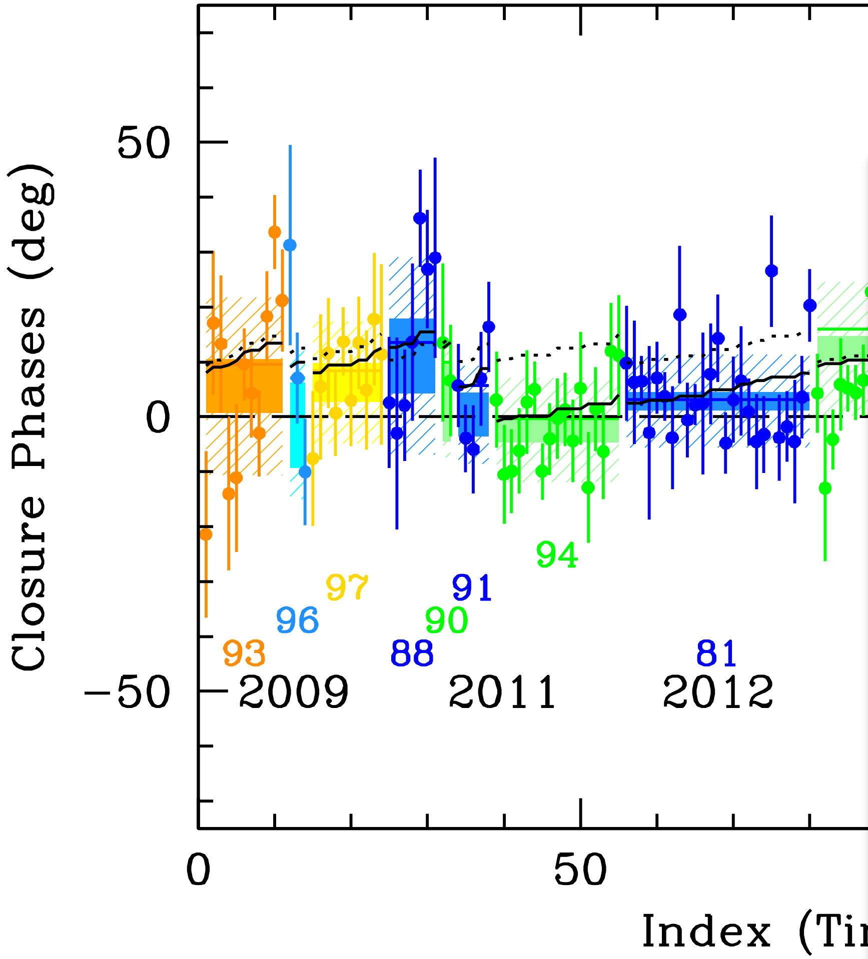
ORIENTATION AND THE GALACTIC CENTER STORY

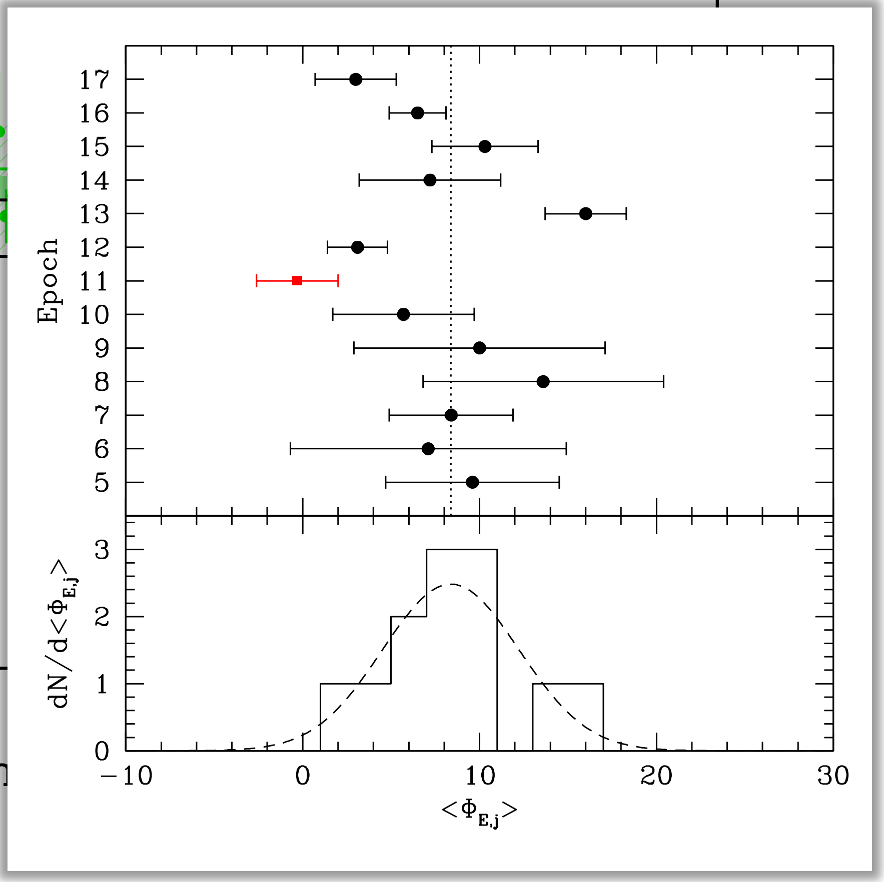




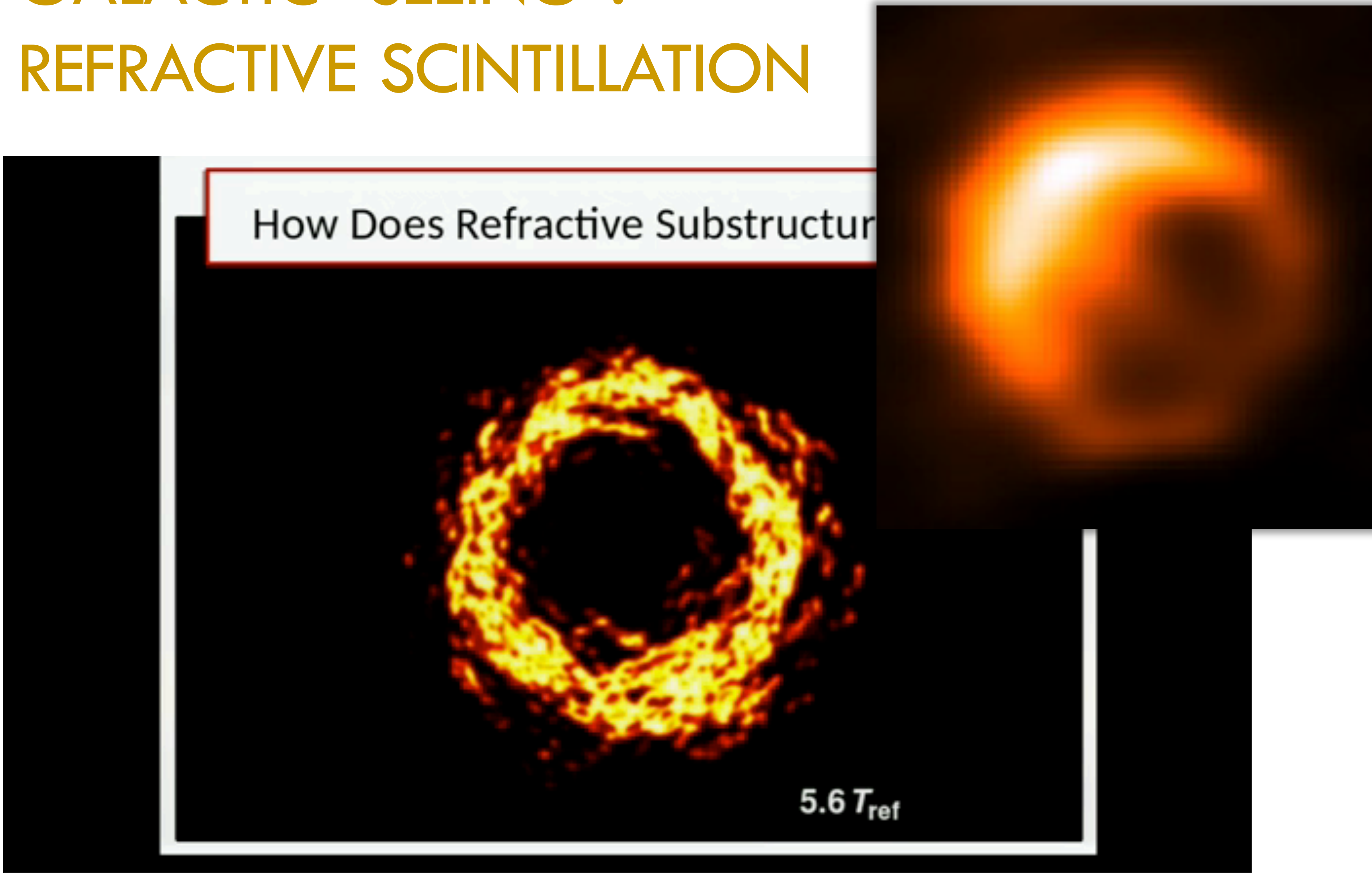
Cuadra et al. (2005)

SMALL-SCALE VARIABILITY





GALACTIC "SEEING": REFRACTIVE SCINTILLATION



Michael D. Johnson (CfA) at EHT 2014

GALACTIC "SEEING" MITIGATION: THEORETICAL "ADAPTIVE OPTICS"

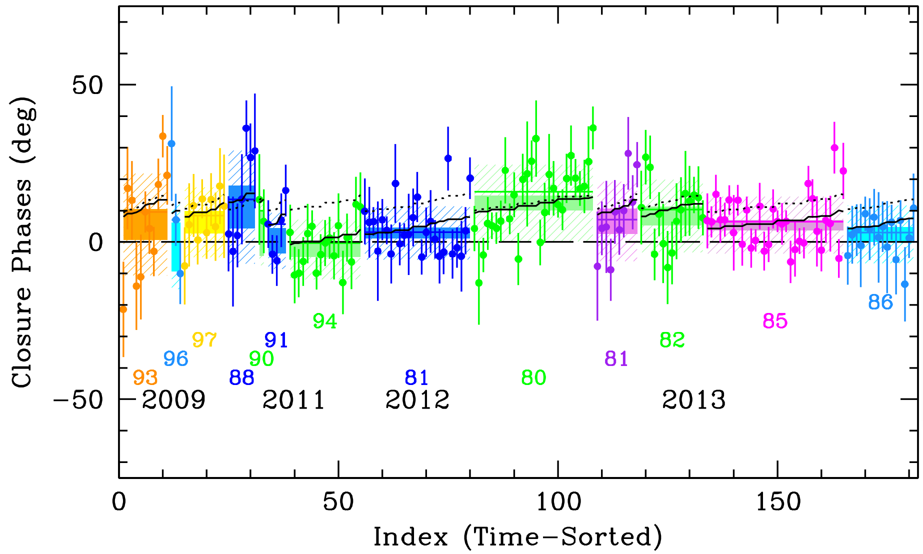


Table 3
Model Comparison

5.2σ!

Model Class	N^a	k^a	min χ^2	ΔAIC	Odds Ratio
$\theta \geq 90°$ with $\phi_E = 0$	234	7	306.9	41.0	1.6×10^{-7}
$\theta \leq 90°$ with $\phi_E = 0$	234	7	309.7	43.8	1.3×10^{-8}
$\theta \geq 90°$ with $\phi_E \neq 0$	234	19	239.9	0.96	0.99
$\theta \leq 90°$ with $\phi_E \neq 0$	234	19	238.9	...	...

[a] Number of data points, including detections only
[b] Number of fit parameters

$$I(\mathbf{x},t) = \bar{I}[\mathbf{x} + \boldsymbol{\xi}(\mathbf{x},t)]$$

$$\delta\Phi_{123} \approx \boldsymbol{\delta}\mathbf{u} \cdot \boldsymbol{\nabla}_{\mathbf{u}} \frac{2\pi \mathbf{u} \cdot \boldsymbol{\xi}(\mathbf{u},t)}{\lambda} \approx \left(\frac{2\pi u}{\lambda}\xi\right)\left(\frac{\delta u}{u}\right) \approx \text{few}°$$

Also turbulence!

AN ARRAY OF OBSERVATIONAL TIMESCALES

Table 1
Data Epochs

Epoch	Year	Day(s)	Time	N[a]	Type[b]	Ref[c]
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4	2009	97	11.50-13.67	20	VM	F11
Totals	...	...	[illegible] hrs	70		
5	2009	93	11.54-13.87	11	CP	F15
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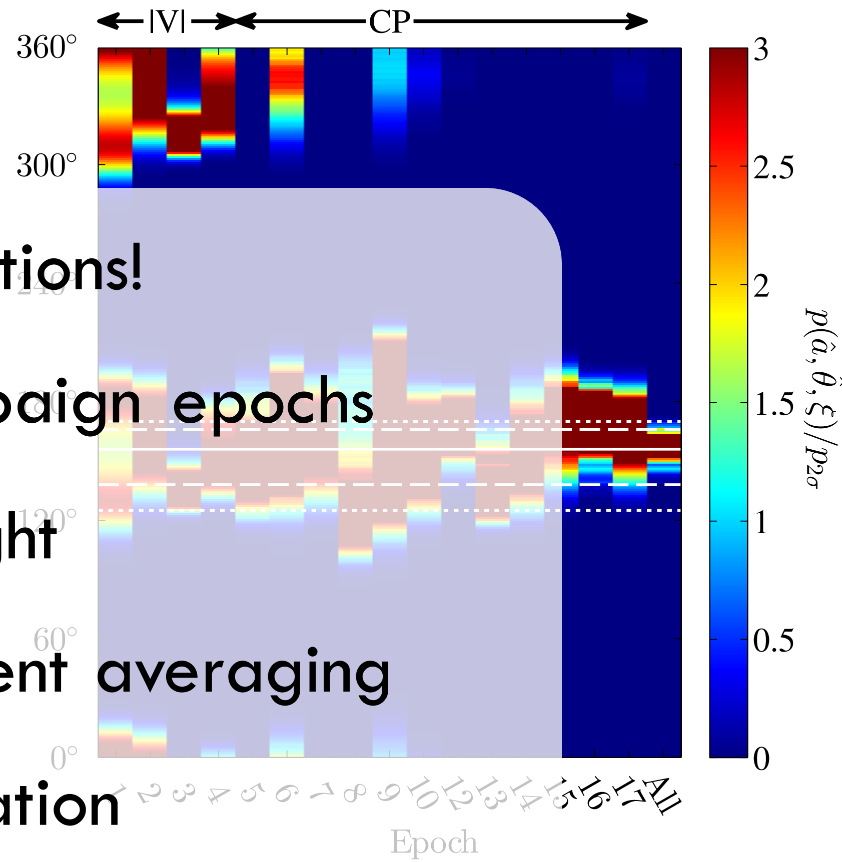
7	2009	97	11.96-14.38	10	CP	F15
8	2011	88	12.37-13.52	7	CP	F15
9	2011	90	[illegible]	[illegible]	[illegible]	[illegible]
10	2011	91	[illegible]	[illegible]	[illegible]	[illegible]
11[d]	2011	94	11.78-14.51	17	CP	F15
12	2012	81	12.52-15.68	25	CP	F15
13	2013	80	12.55-15.43	28	CP	F15
14	2013	81	[illegible]	[illegible]	[illegible]	[illegible]
15	2013	82	[illegible]	15	[illegible]	[illegible]
16	2013	85	12.15-15.17	32	CP	F15
17	2013	86	12.55-13.95	16	CP	F15
Totals	...	...	25.58 hrs	181		

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

- 7 years: Operations!
- Days: Intra-campaign epochs
- Hours: Single night
- Minutes: Incoherent averaging
- Seconds: Correlation



LONG-TIMESCALE VARIABILITY?

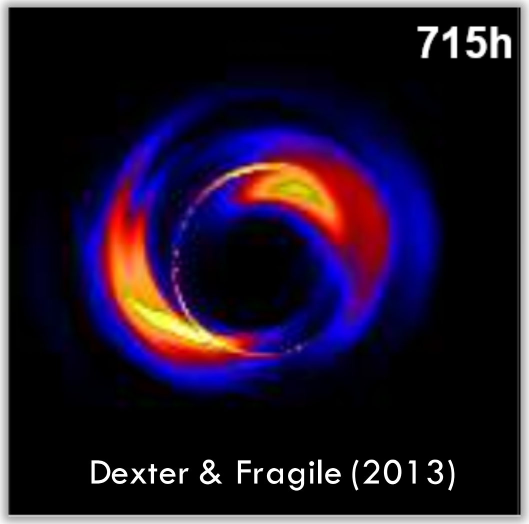
- **Misaligned environment** **(massive perturbers, collective impact of bulge)**
- **Misaligned Disk-Spin**

Accretion streams

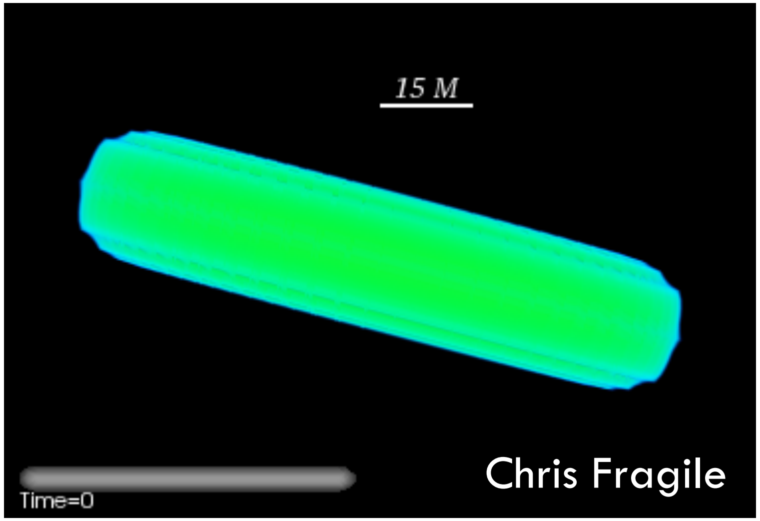
$$T_{prec} \sim T_{orb} \sim \text{hours} - \text{days}$$

Lense-Thirring torques
(periastron advance!)

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

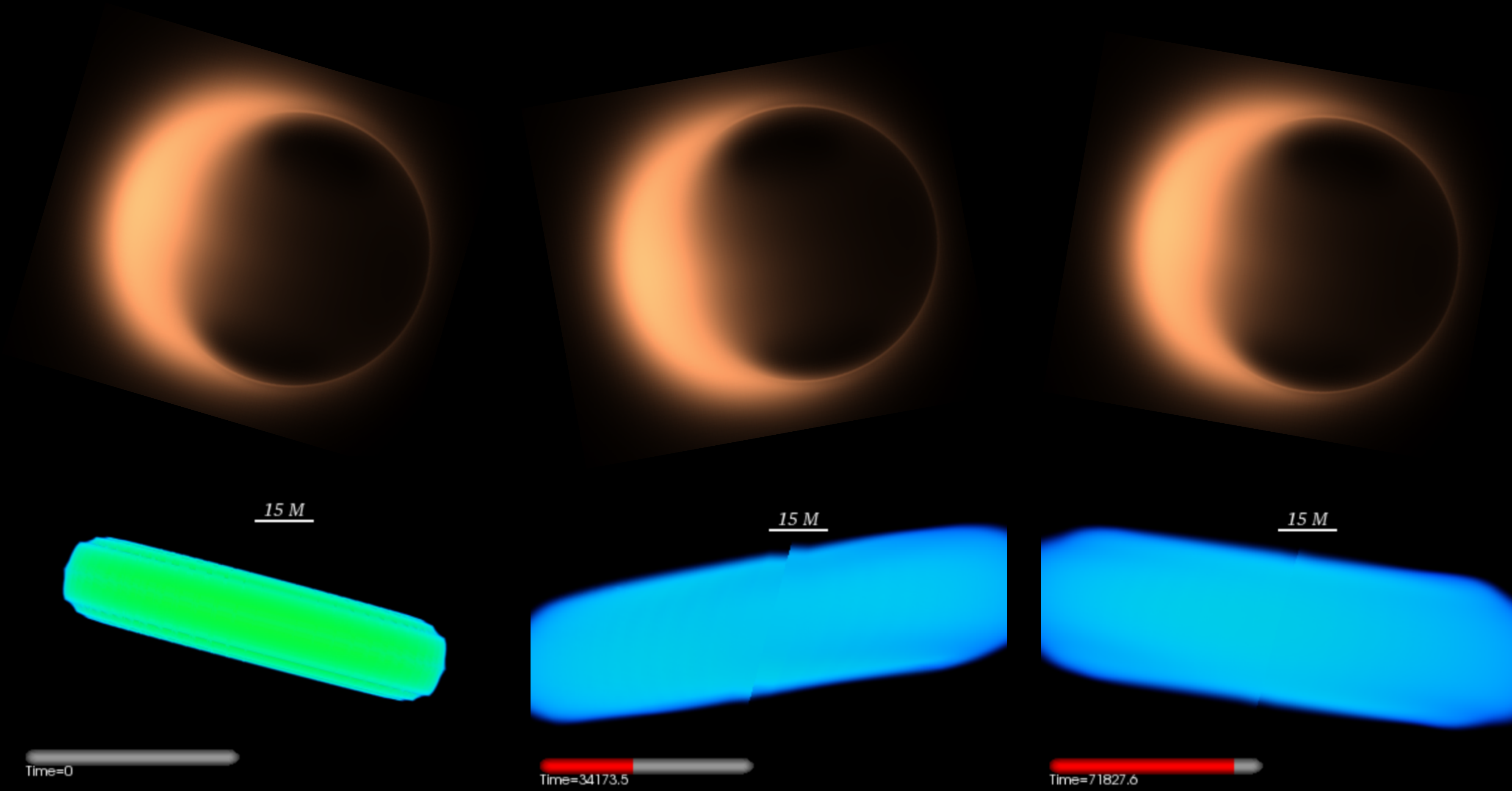


Dexter & Fragile (2013)



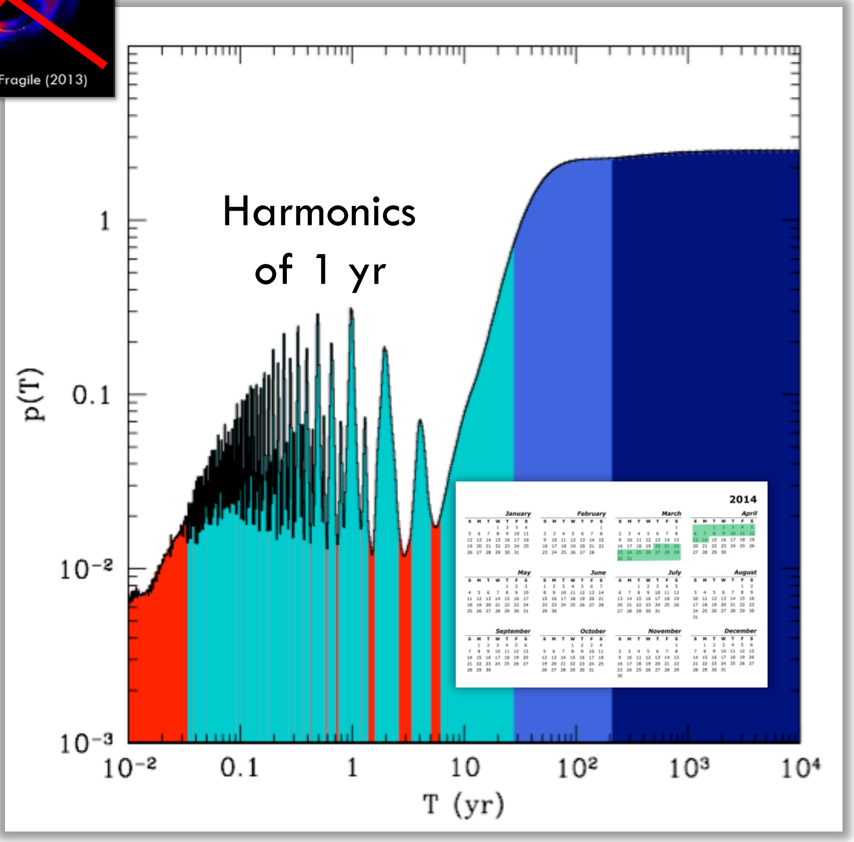
Chris Fragile

SIGNATURES OF PRECESSION

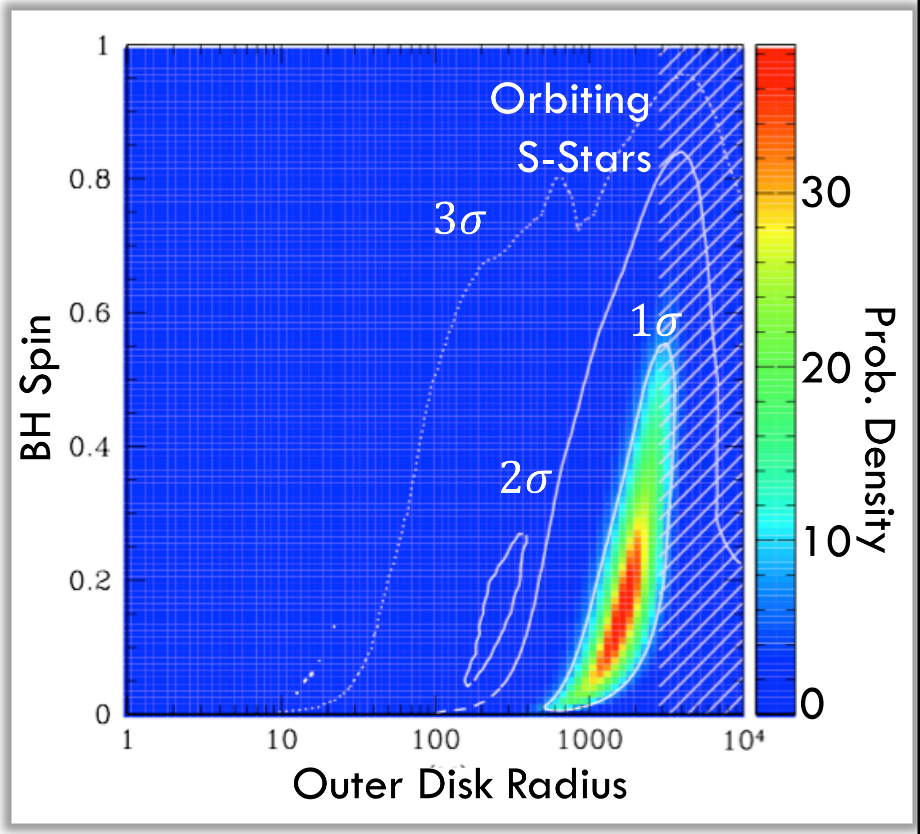


SEARCHING FOR PRECESSION: (LIMITING MISALIGNMENT & SPIN)

Any precession at all

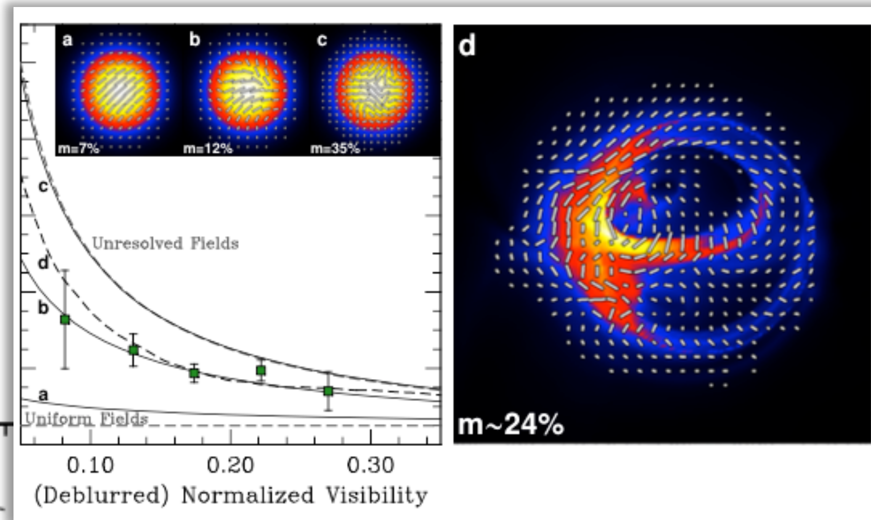


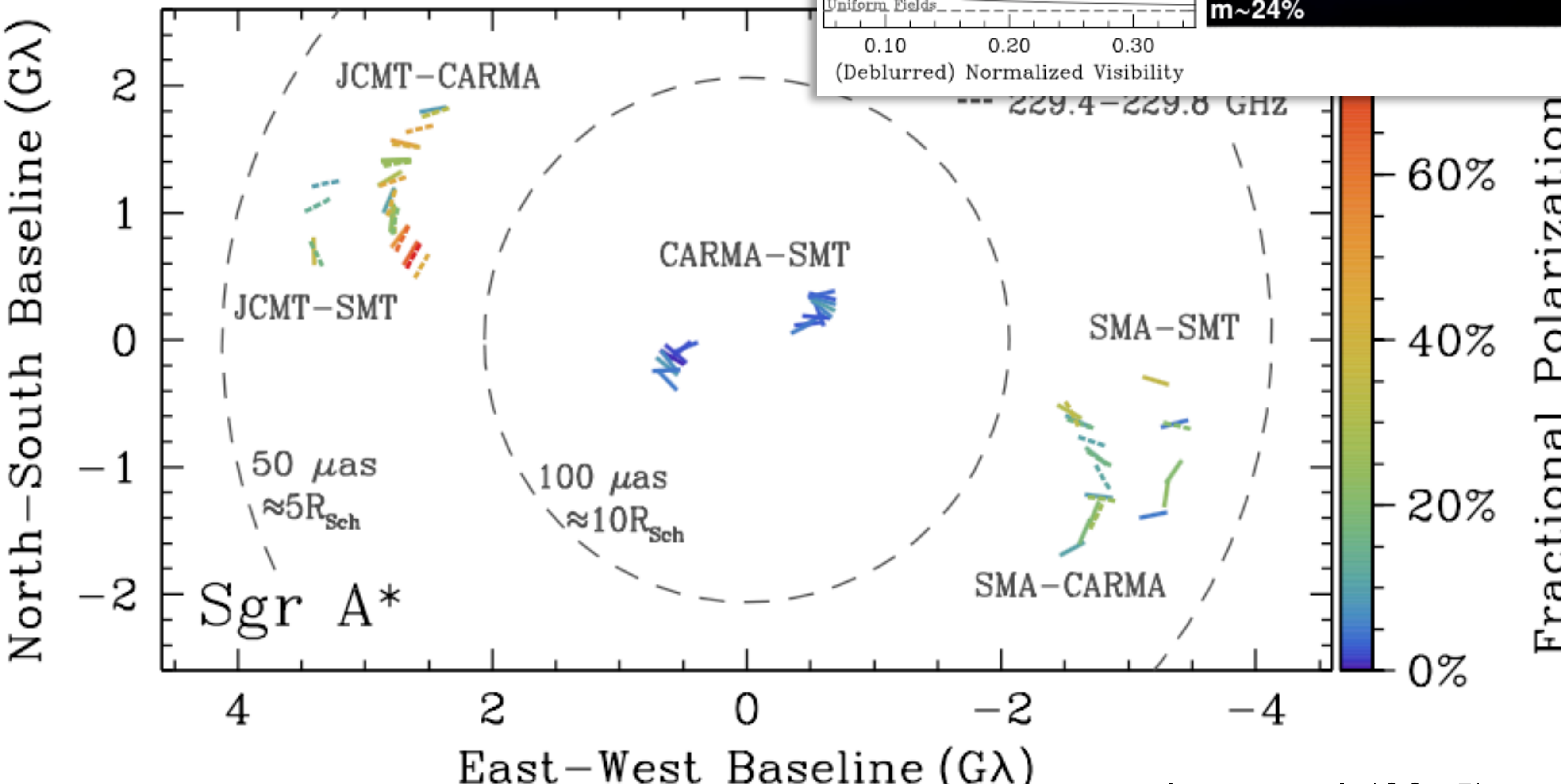
Lense-Thirring precession



Carlos Wang

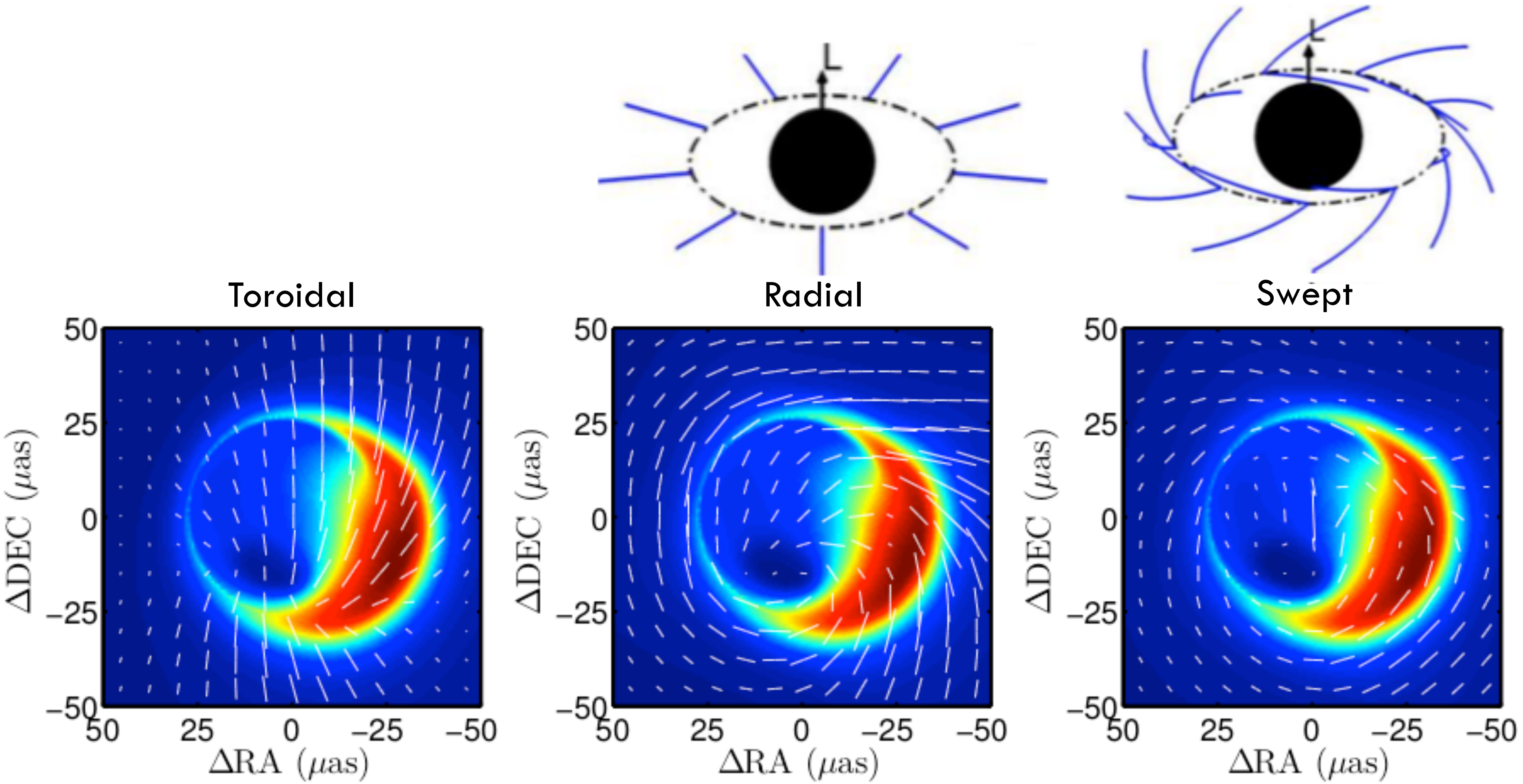
LARGE SMALL-SCALE POLARIZATION!





Johnson et al. (2015)

POLARIZATION & MAGNETIC FIELD GEOMETRY



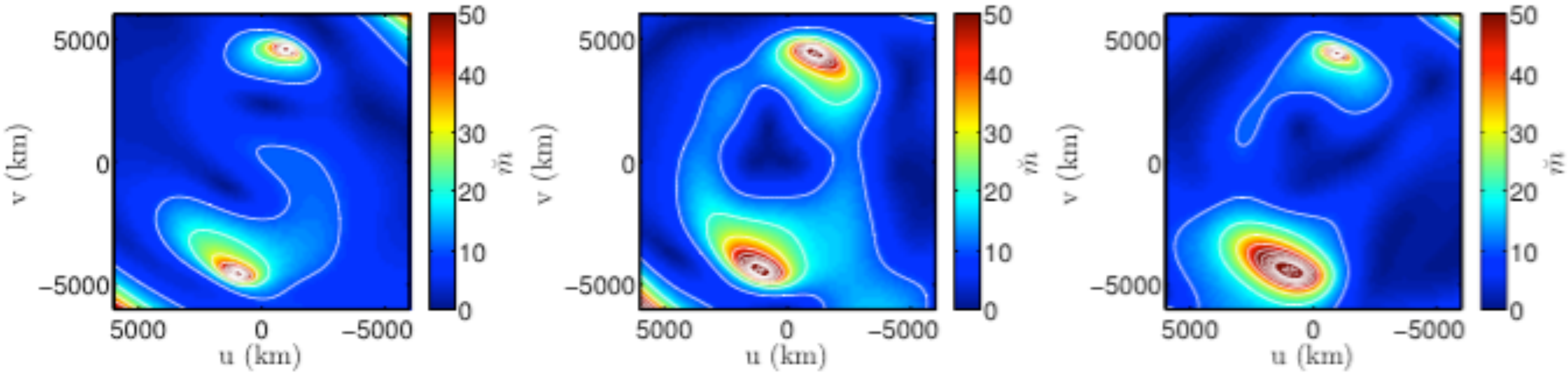
Elizabeth Griffin

POLARIZATION & PARTICLE DISTRIBUTION

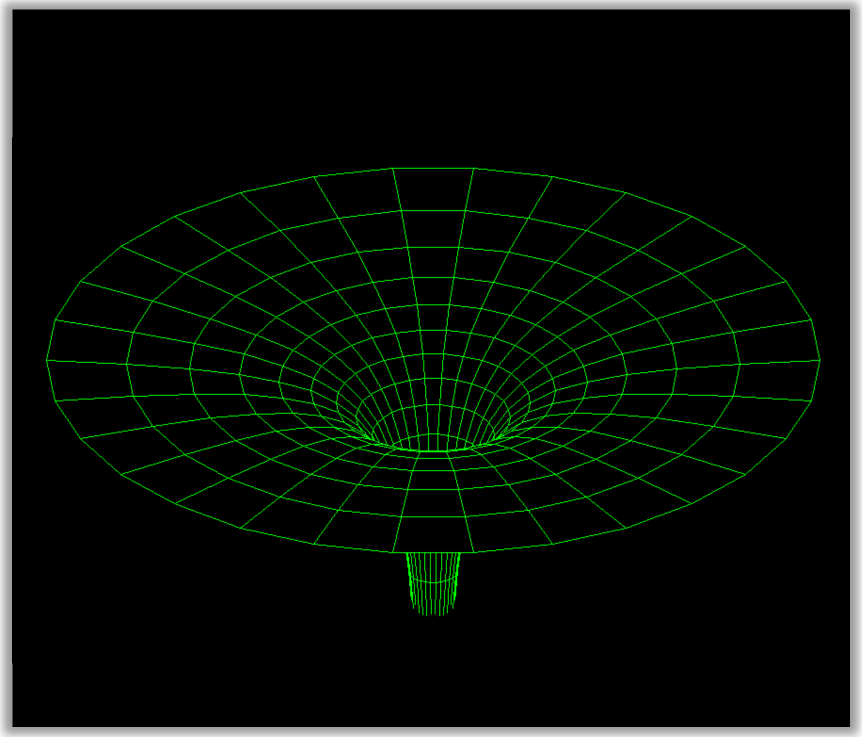
$$\breve{m} = \frac{\tilde{Q} + i\tilde{U}}{\tilde{I}}$$

Toroidal Radial Swept

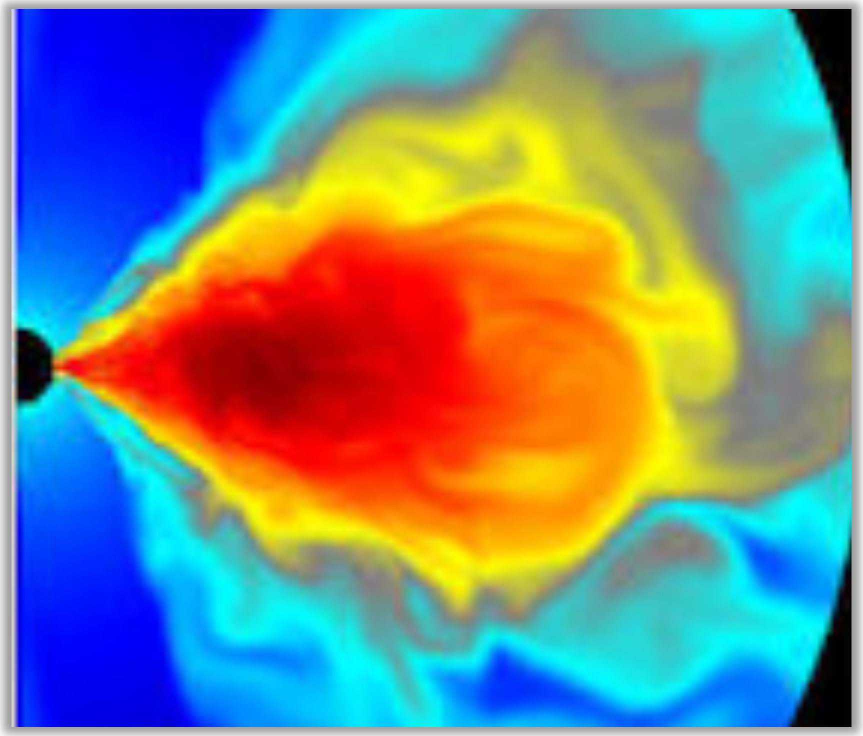
Mixed



GRAVITY NEAR THE HORIZON



Measure



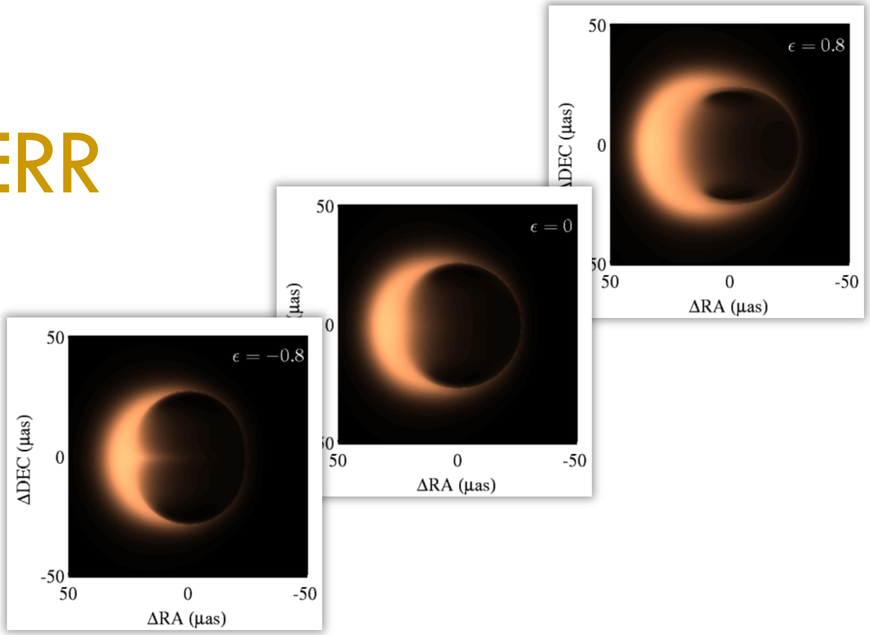
Assume

HAIRY BLACK HOLES: LIMITS FROM QUASI-KERR

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

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

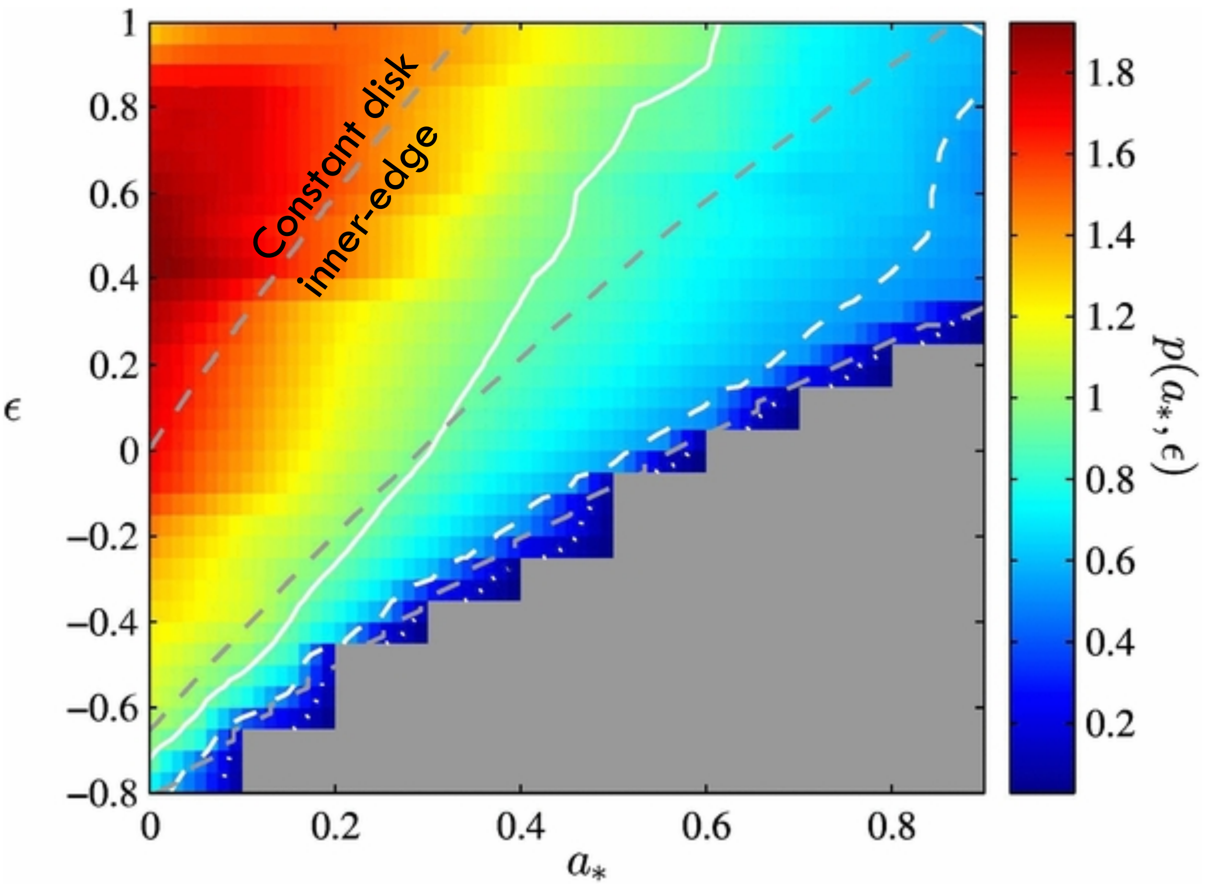
$$Q = -a^2 M - \epsilon M^3$$



Some fine print …

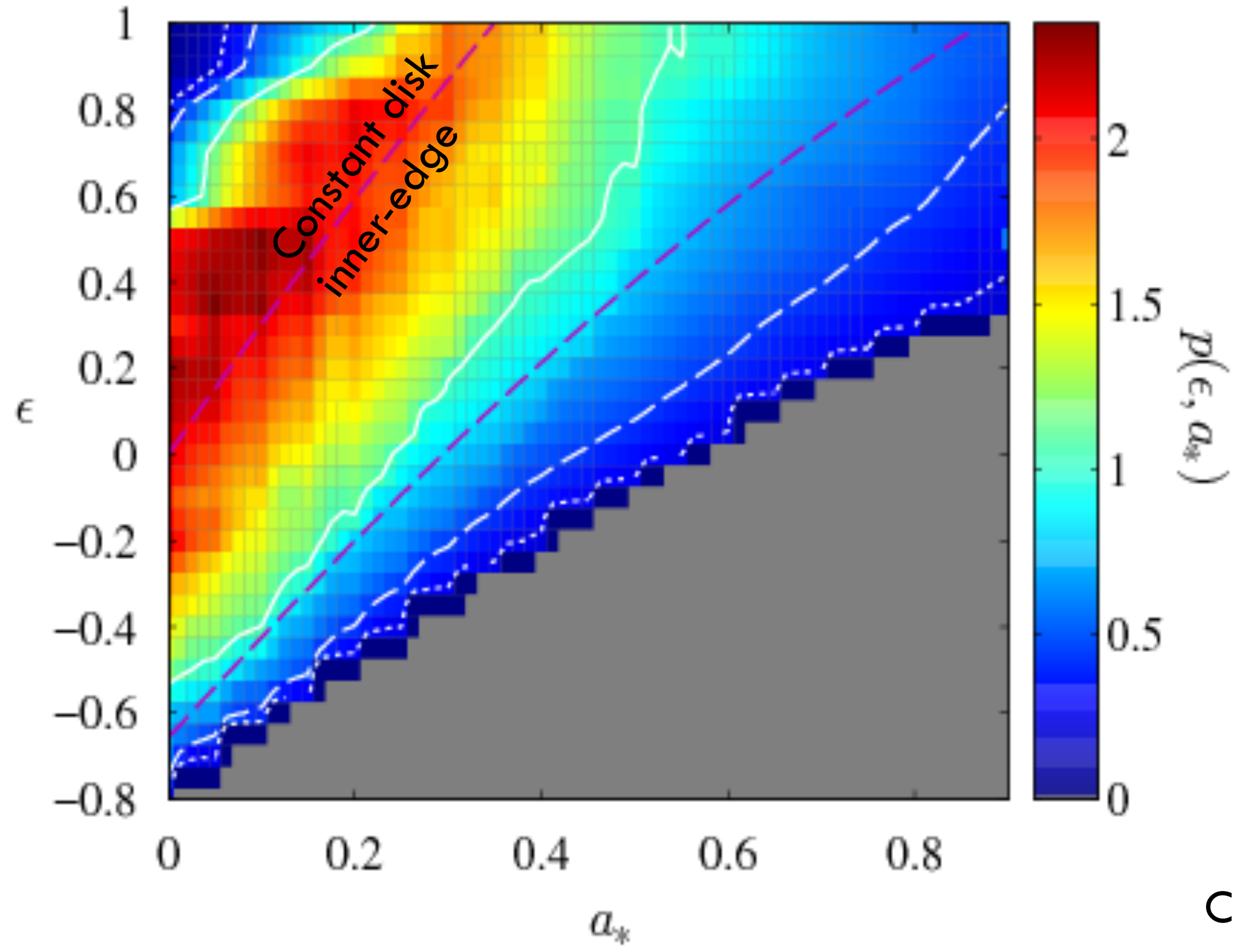
- **Solution to vacuum Einstein equations when $|a| \ll M$**
- **Adds quadrupolar perturbation (based on Hartle-Thorne metric for slowly spinning neutron stars!)**
- **No-hair theorems → Quasi-Kerr metric must be sick! It is inside $2M$.**

LIMITS ON VIOLATIONS OF GR ($|V|$ THROUGH 2009)



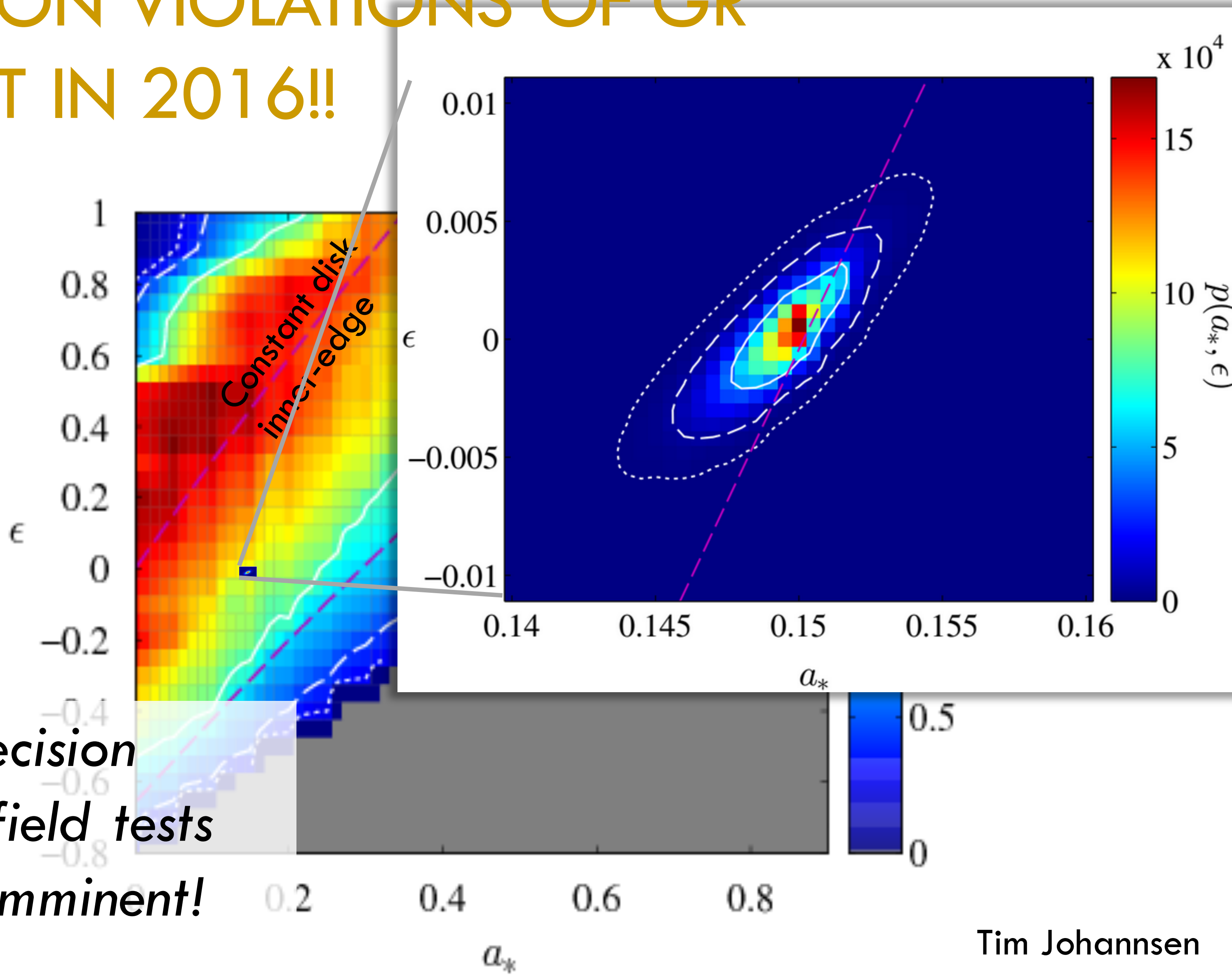
Broderick et al. (2014)

LIMITS ON VIOLATIONS OF GR (+ CP THROUGH 2013)



Carlos Wang

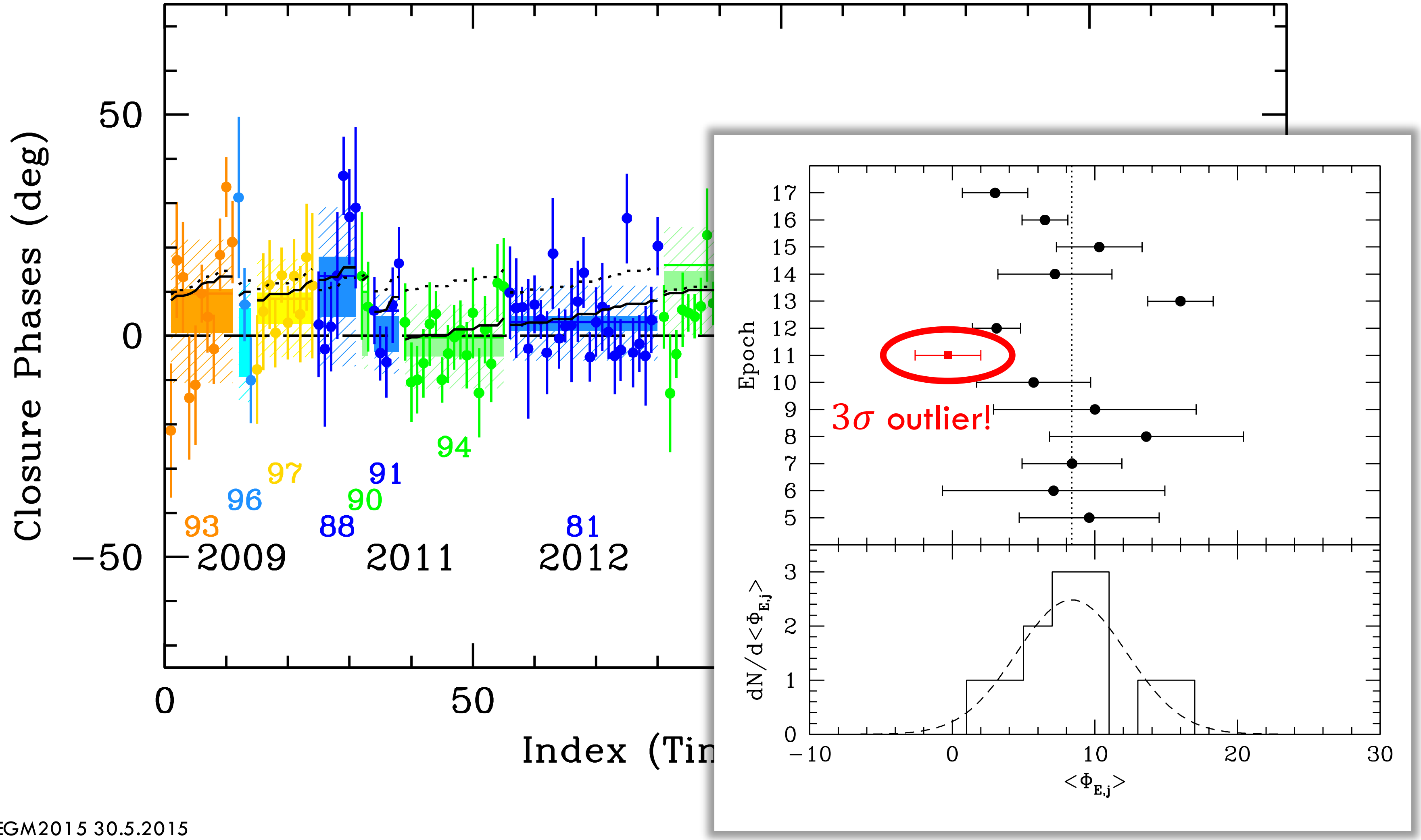
LIMITS ON VIOLATIONS OF GR 1NIGHT IN 2016!!



1% precision strong-field tests of GR imminent!

Tim Johannsen

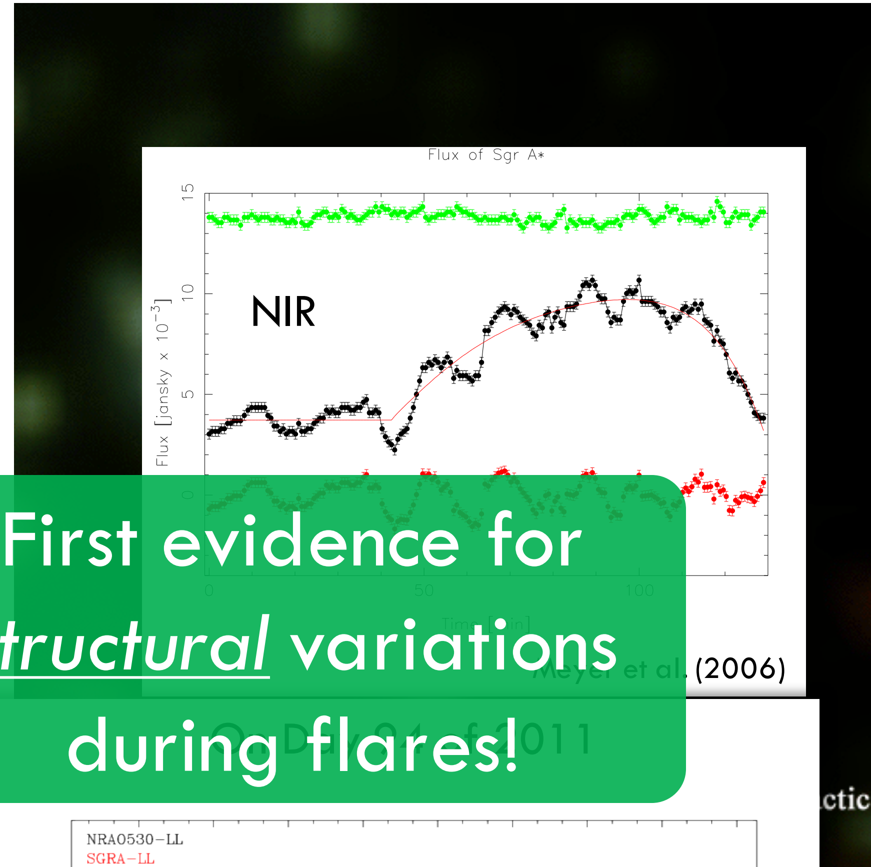
OUTLIERS



Closure Phases (deg)
50
0
−50
0
50
Index (Tin
93
96
97
88
90
91
94
81
2009
2011
2012
Epoch
17
16
15
14
13
12
11
10
9
8
7
6
5
3σ outlier!
dN/d<Φ_E,j>
3
2
1
0
−10
0
10
20
30
<Φ_E,j>

FLARING IN SGR A*

- Light crossing time: $M \sim 20$ s
- Orbital time at ISCO: $P \sim 4 - 30$ min
- Synchrotron cooling time: hrs
- Hot spot shearing timescale: $P(r/\delta r)$
- Rate of ~ 1/day!



Meyer et al. (2006)

First evidence for
structural variations
during flares!

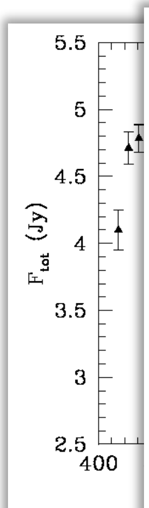
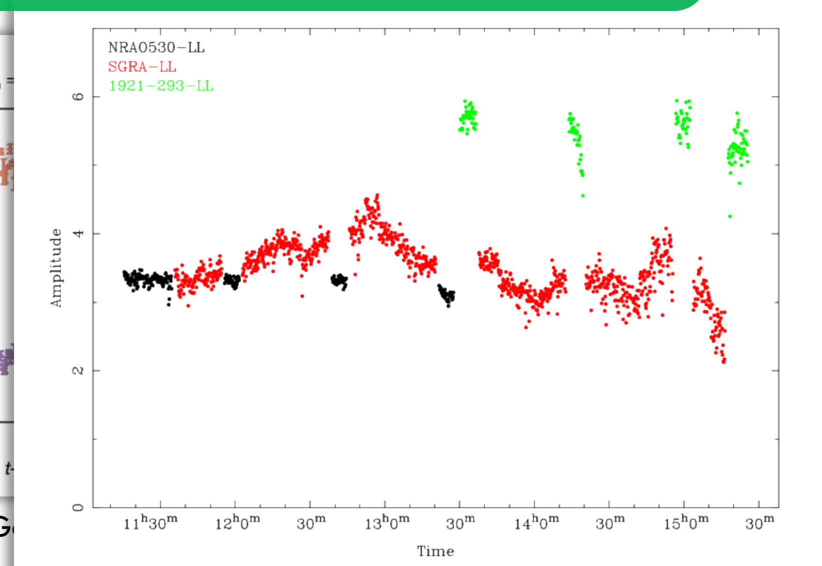
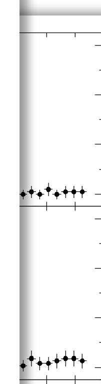


Table 1
Data Epochs

Epoch	Name	Year	Day(s)	Time	N[a]	Type[b]
1	2007-VM	2007	100-101	11.00-13.67	19	VM
2	2009.95-VM	2009	95	11.17-15.00	12	VM
3	2009.96-VM	2009	96	11.50-14.56	19	VM
4	2009.97-VM	2009	97	11.50-13.67	20	VM
Totals	...	...	...	11.73 hrs	70	
5	2009.93	2009	93	11.54-13.87	11	CP
6	2009.96	2009	96	12.46-12.79	3	CP
7	2009.97	2009	97	11.96-14.38	10	CP
8	2011.88	2011	88	12.37-13.52	7	CP
9	2011.90	2011	90	13.67-14.02	2	CP
10	2011.91	2011	91	11.93-13.53	5	CP
11	2011.94	2011	94	11.78-14.51	17	CP
12	2012	2012	81	12.52-15.68	25	CP
13	2013.80	2013	80	12.55-15.43	28	CP
14	2013.81	2013	81	12.97-15.27	10	CP
15	2013.82	2013	82	12.97-14.88	15	CP
16	2013.85	2013	85	12.15-15.17	32	CP
17	2013.86	2013	86	12.55-13.95	16	CP
Totals	...	...	...	25.58 hrs	181	

[a] Number of data points, including detections only
[b] Data types are visibility magnitudes (VM) and closure phases (CP)



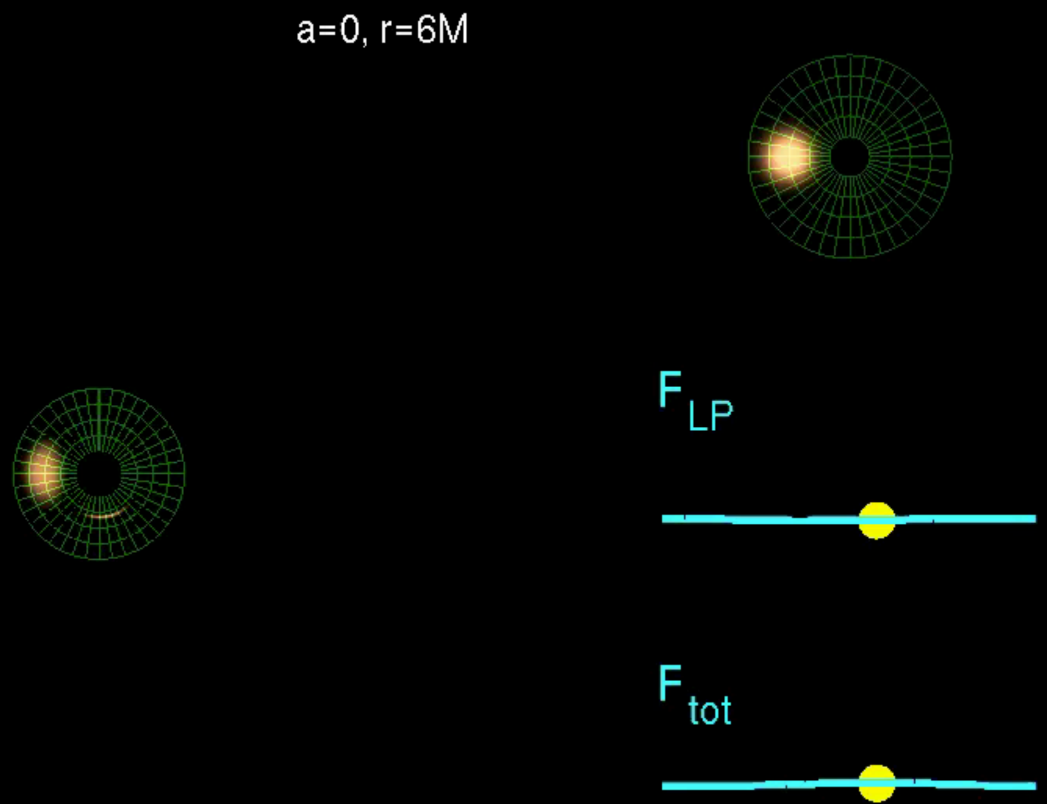


EGM2015 3

G

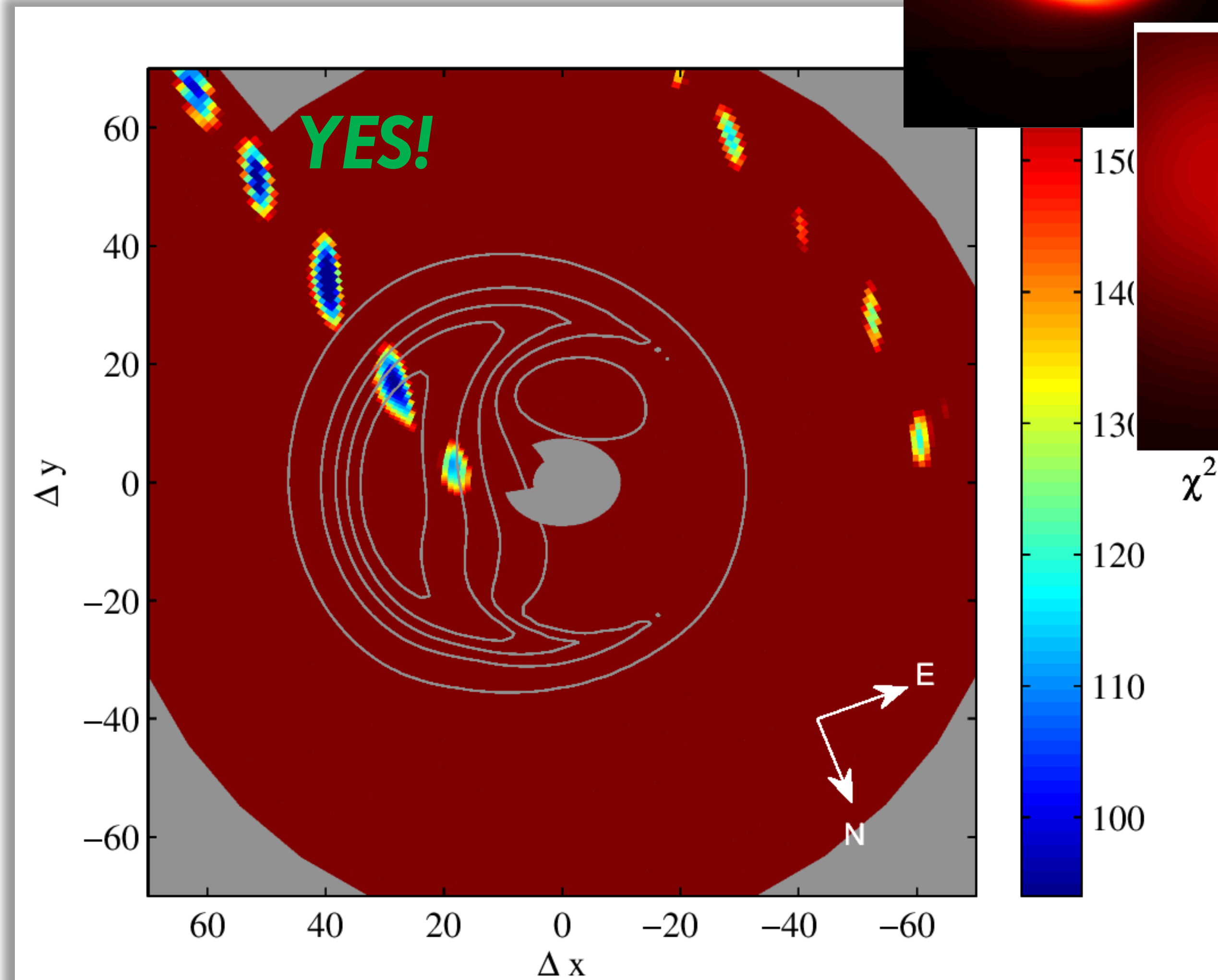
01)

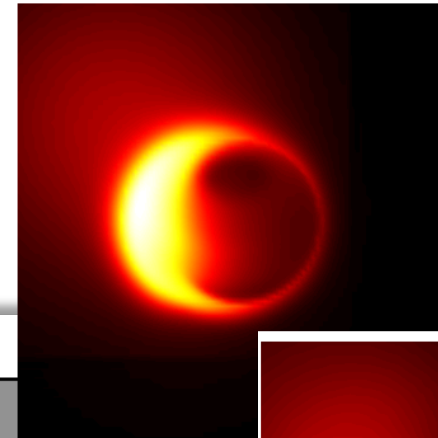
COULD THIS BE A HOT SPOT?

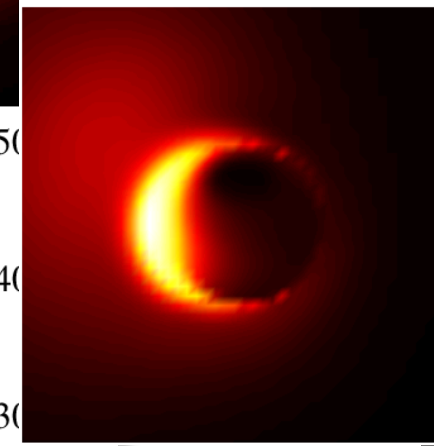


Broderick & Loeb, 2006, MNRAS, 367, 905

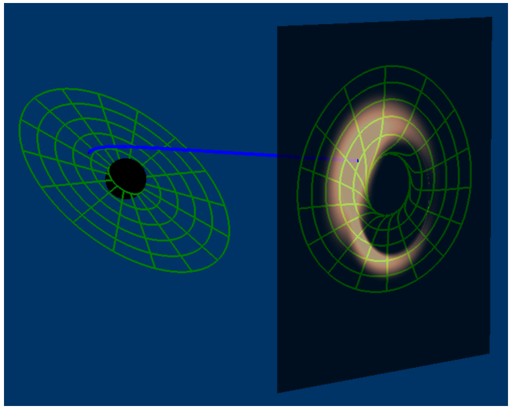
COULD THIS BE A HOT SPOT?

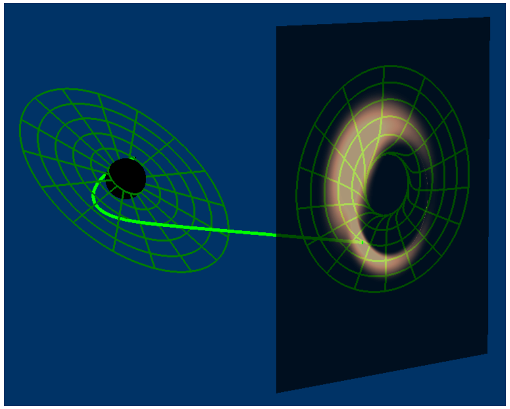


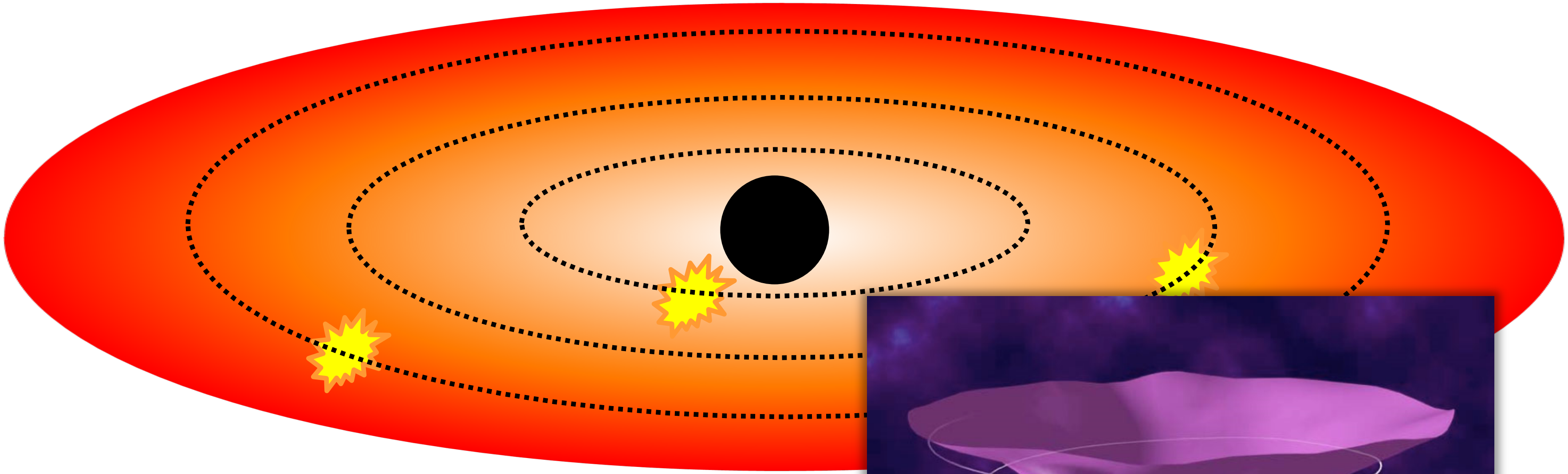


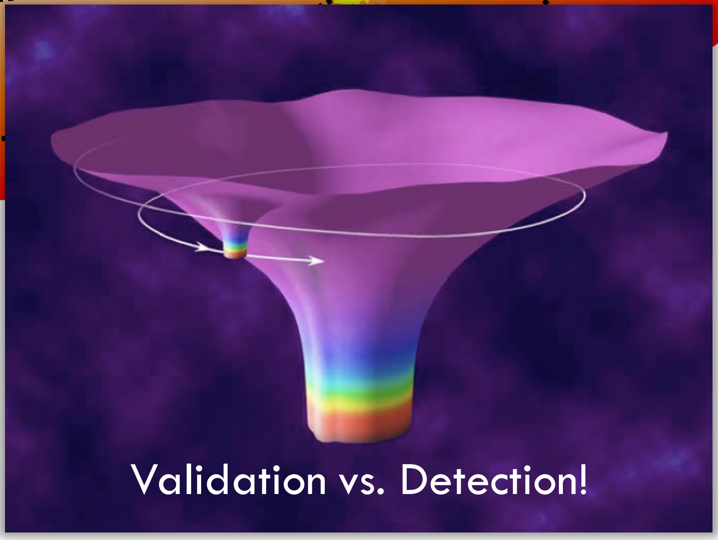


SPACETIME TOMOGRAPHY



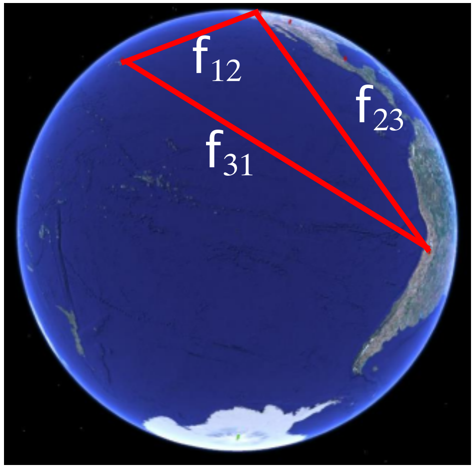


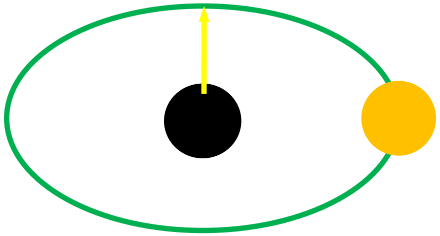


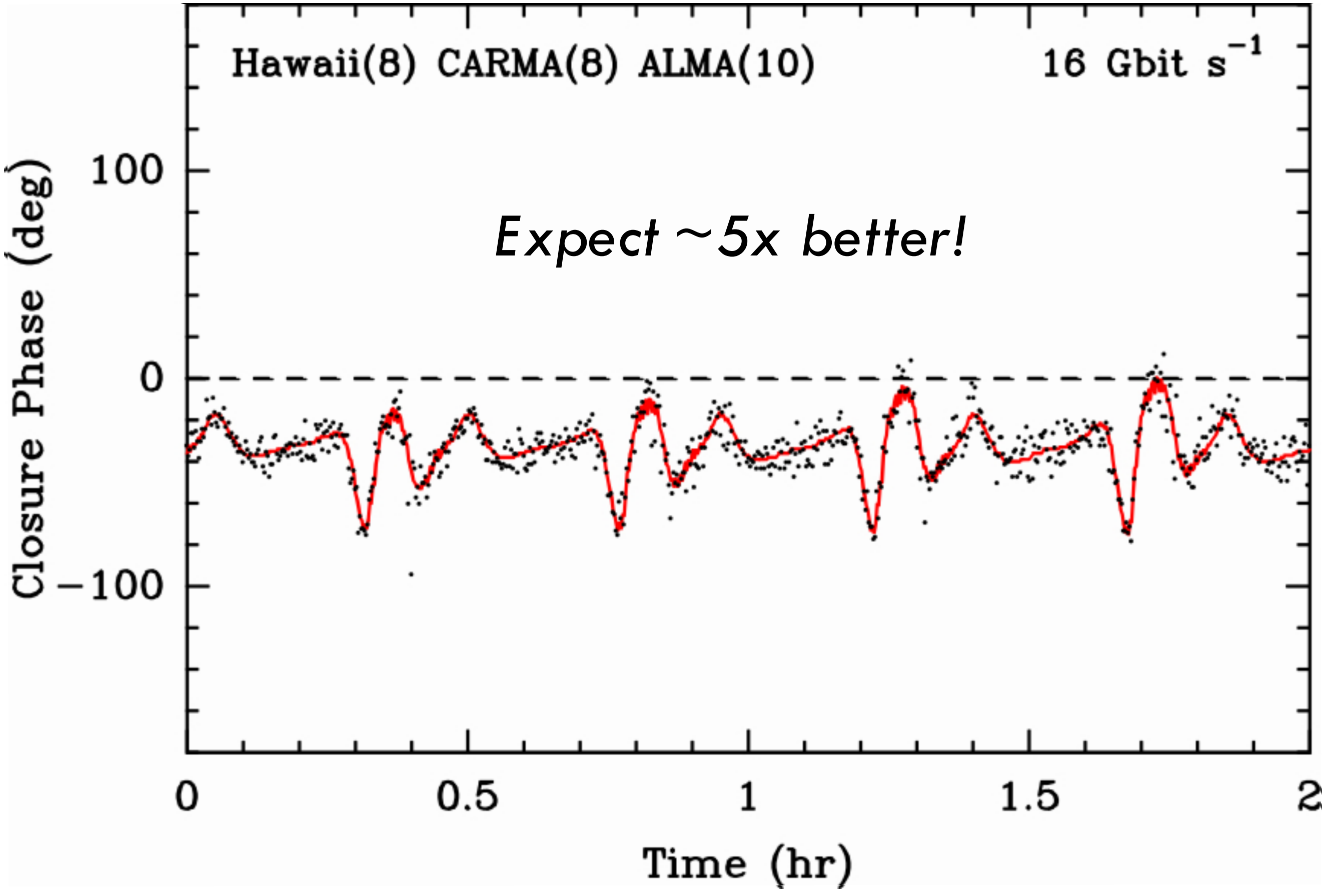


Julian: “eLISA launch: 2034??”

CLOSURE PHASE VARIABILITY REVISITED!



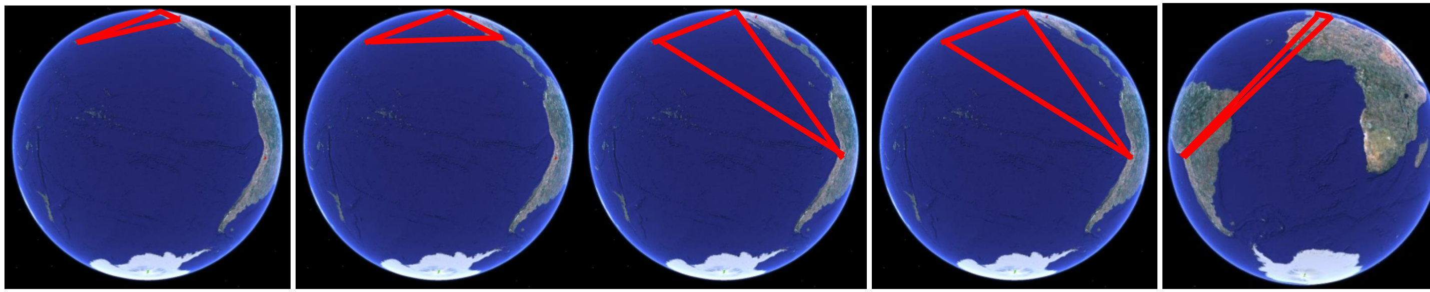


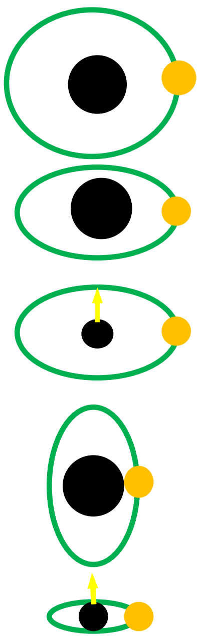


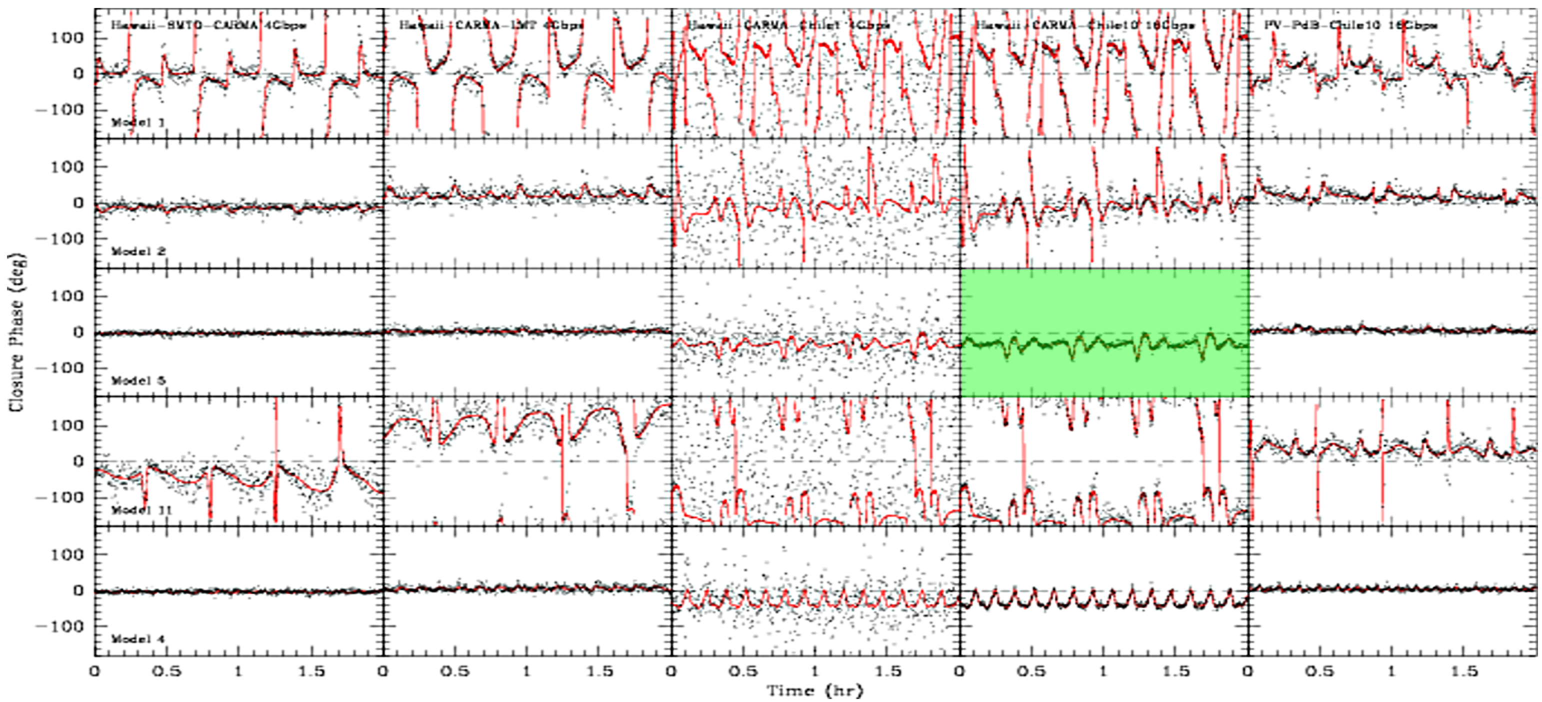
a = 0.9
Hot-spot at ~ 6M
Period = 27 min.

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

VALIDATION! CLOSURE PHASE EVOLUTION



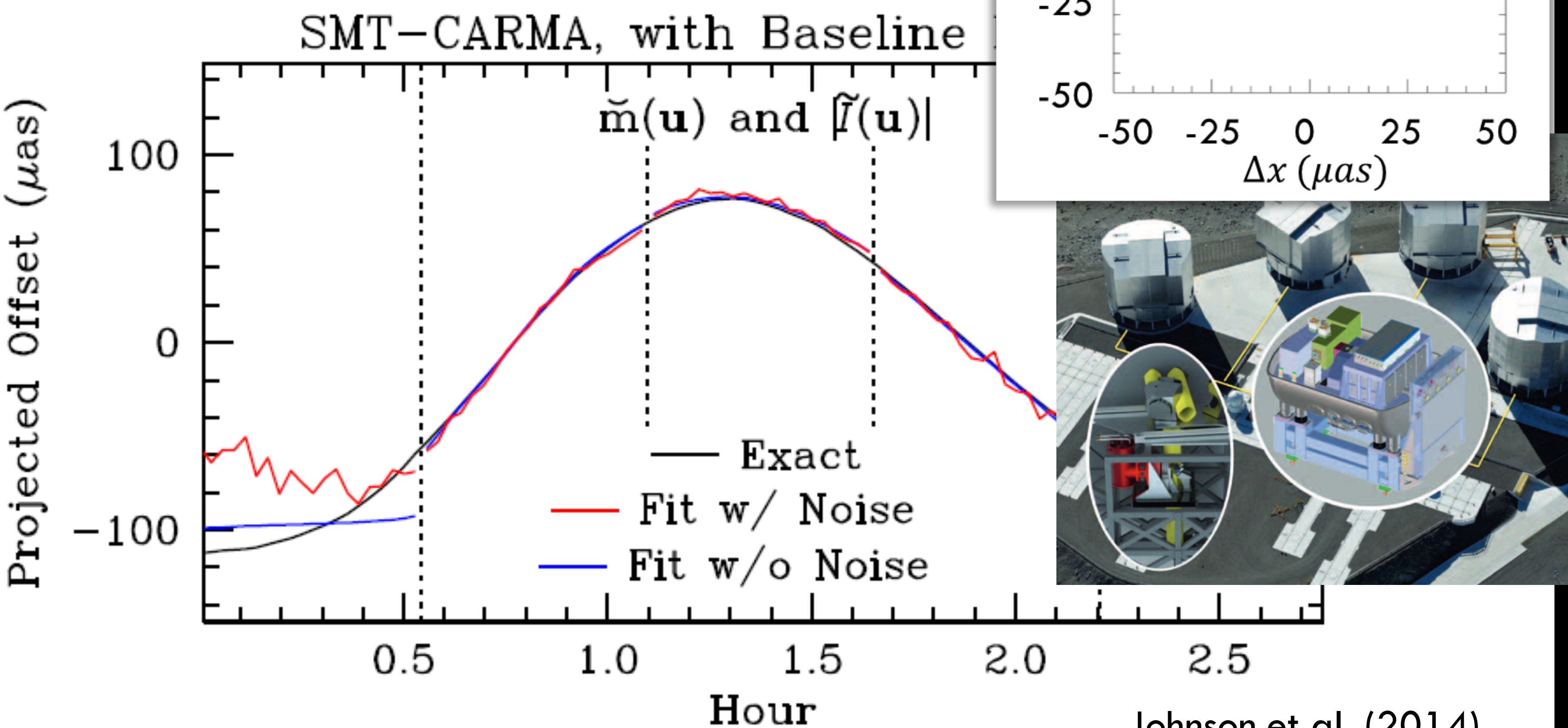


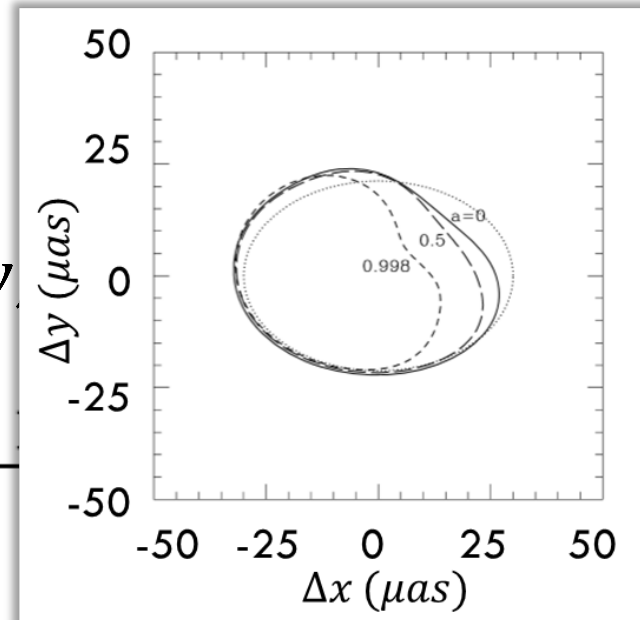


Doeleman, Fish, A.E.B., Loeb & Rogers (2009)

TRACKING SPOTS WITH POLARIZATION

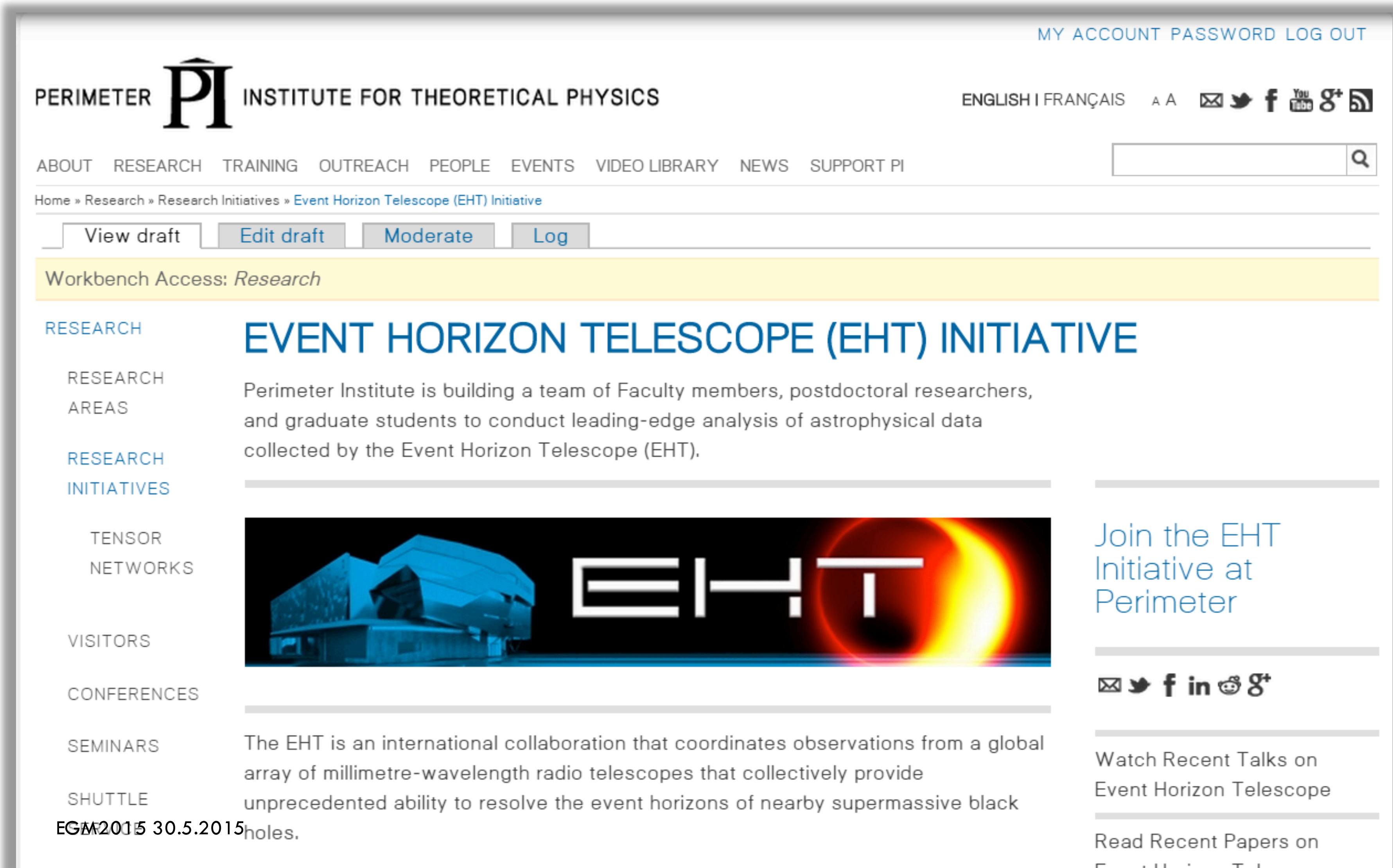
$L(x, y, t)$ vs. $I(x, y, t)$





Johnson et al. (2014)

LOTS OF WORK TO BE DONE: CONTROLLING ASTROPHYSICAL SYSTEMATICS



SUMMARY

- **EHT expansion happening now!**
- **A zoo of EHT data (+ context)**
- **Simple Jet models work well**
  - High spin! and mass?
  - Jet particle acceleration?
- **Simple RIAF models work well (too well?!)**
  - No discernable precession
  - Orientation aligns with stellar disks & gas clouds in GC
  - Already see evidence for refraction/turbulence
  - Polarization probing magnetic fields & particle distributions
- **Strong gravity tests at sub-percent level coming in a variety of ways with a variety of difficulty settings**
- **EHT Initiative at PI!**