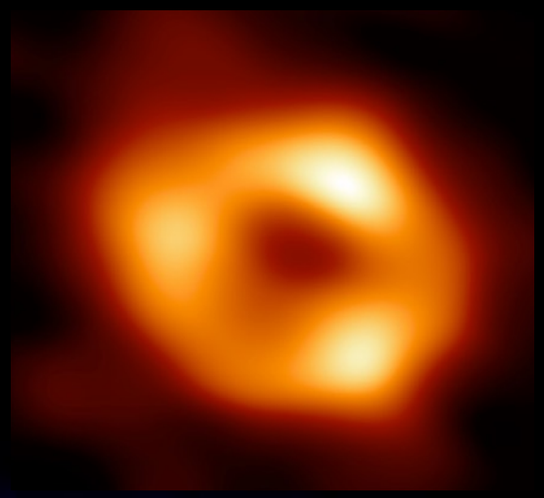
Observing Sagittarius A* with ALMA



Maciek Wielgus

Max Planck Institute for Radioastronomy

Goethe University, Frankfurt
9 May 2023

ALMA: connected element interferometric array

Atacama Large Millimeter/submillimeter Array

- US (25 dishes) / Europe (25 dishes) / Asia (16 dishes)
- 5000 m elevation, in Atacama Desert, North Chile
- Frequency 30 - 1000 GHz
- Resolution up to 20 mas (> 10 km baselines)

MPIfR

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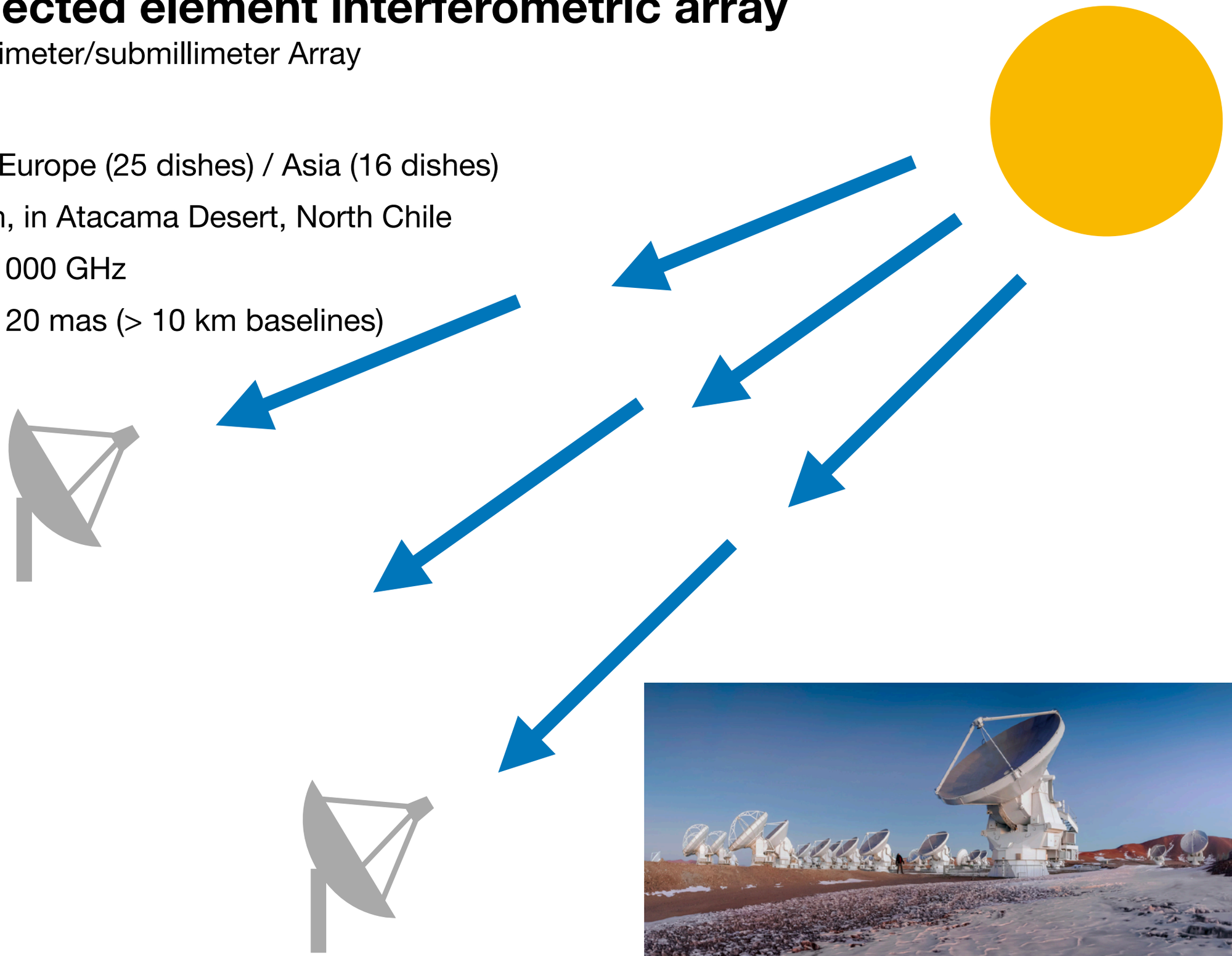

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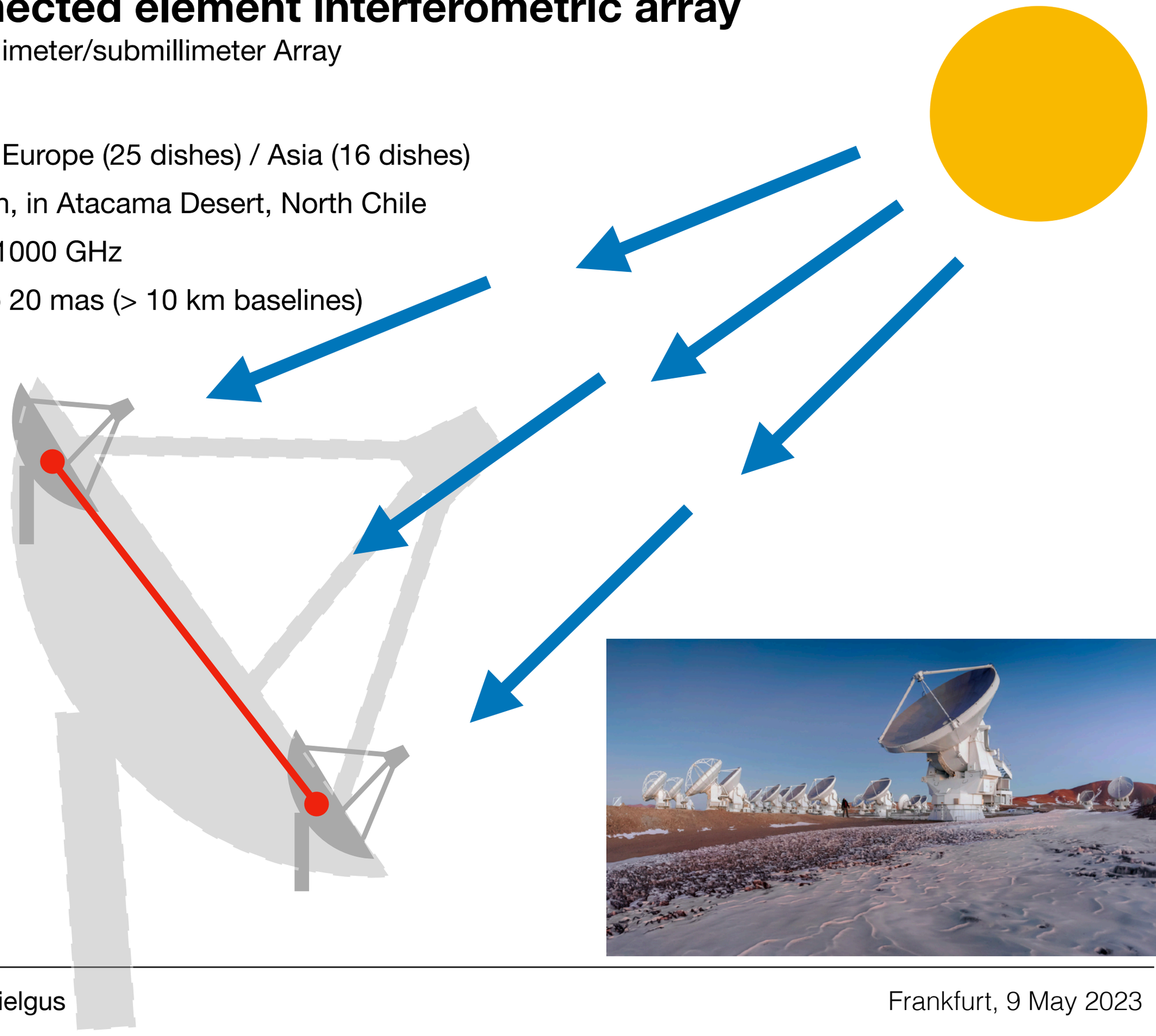
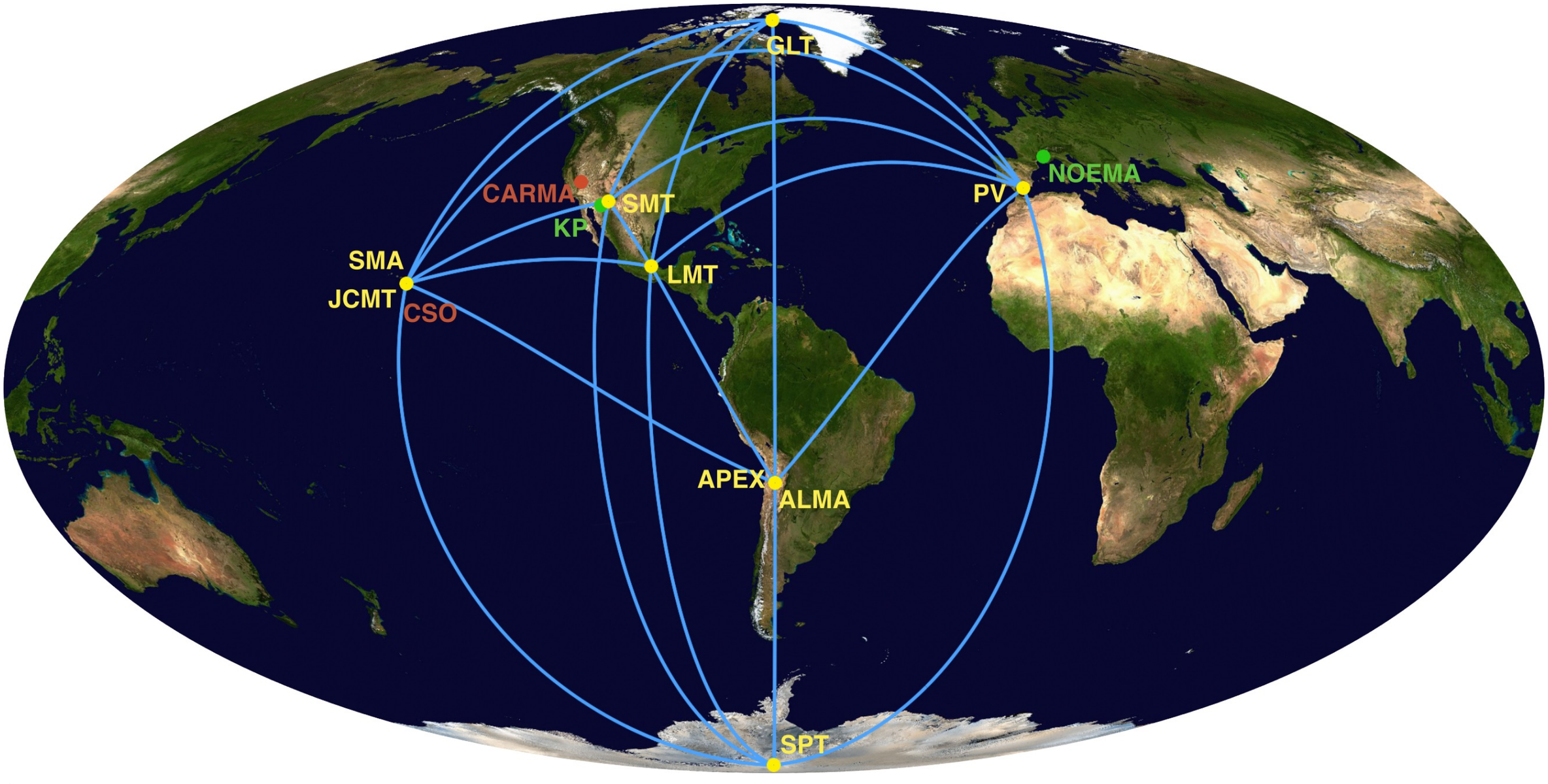


Event Horizon Telescope: very long baseline interferometric array



EHT 2019. Paper II. Instrument

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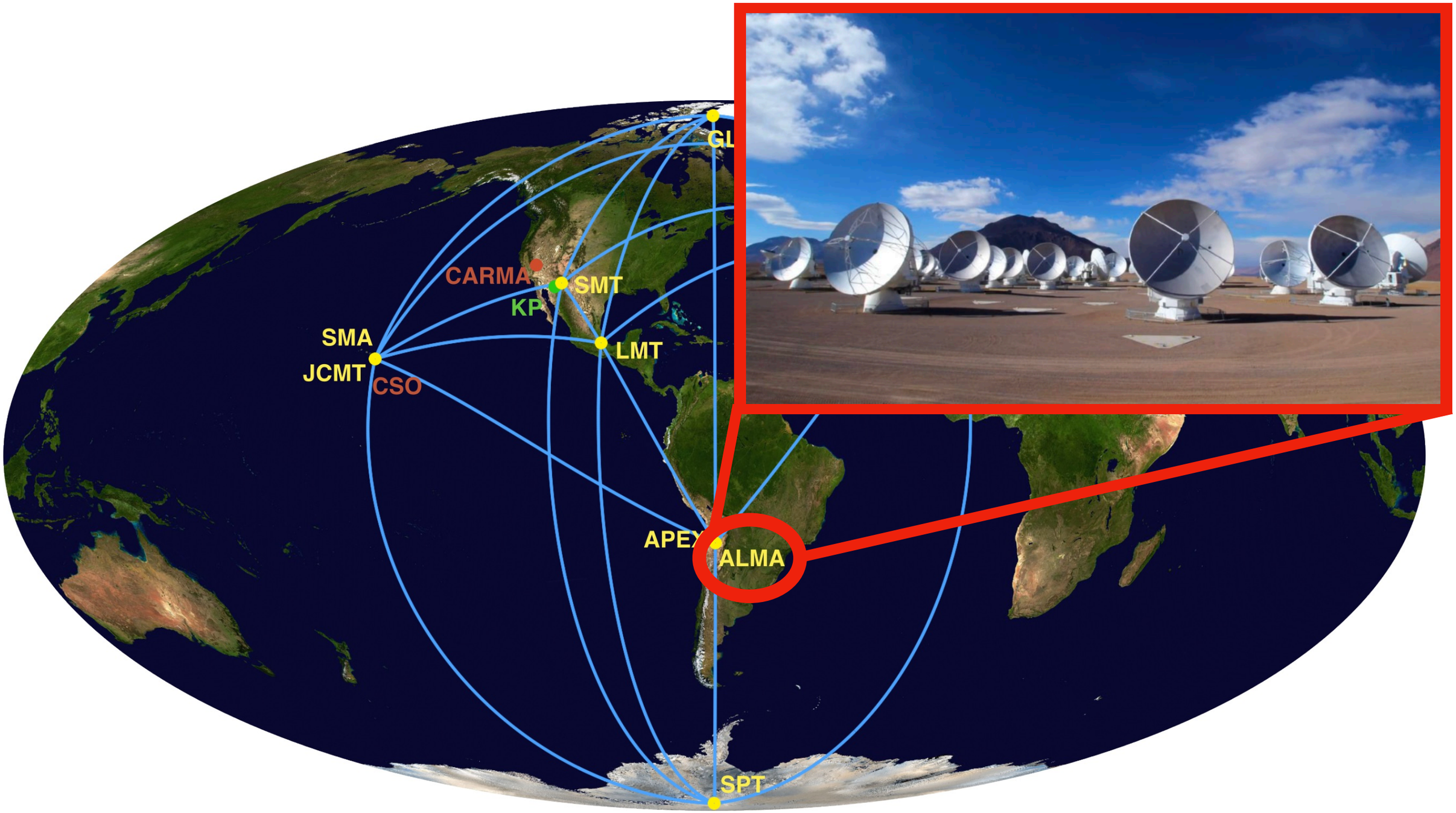

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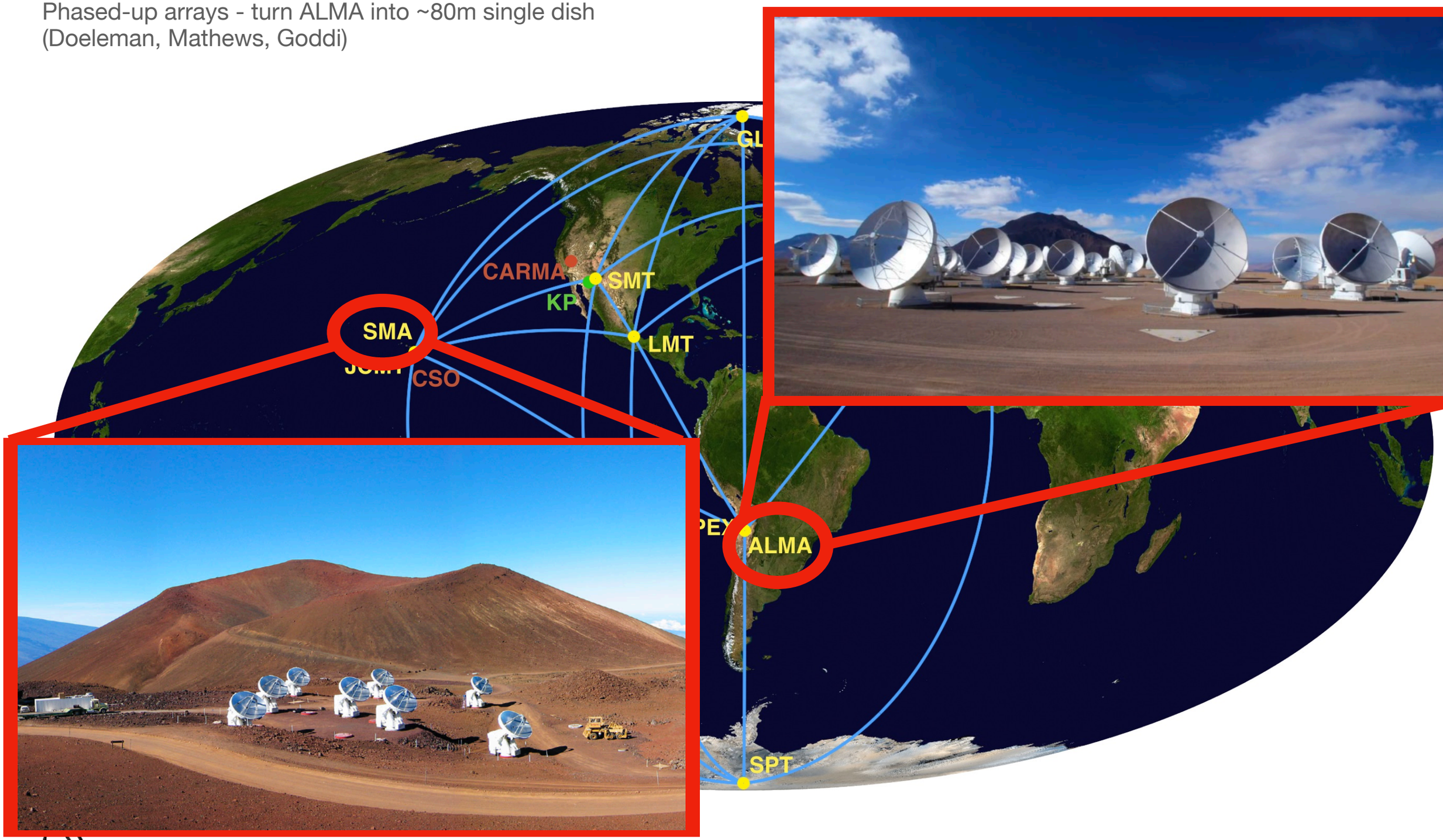
Phased-up arrays - turn ALMA into ~80m single dish
(Doeleman, Mathews, Goddi)



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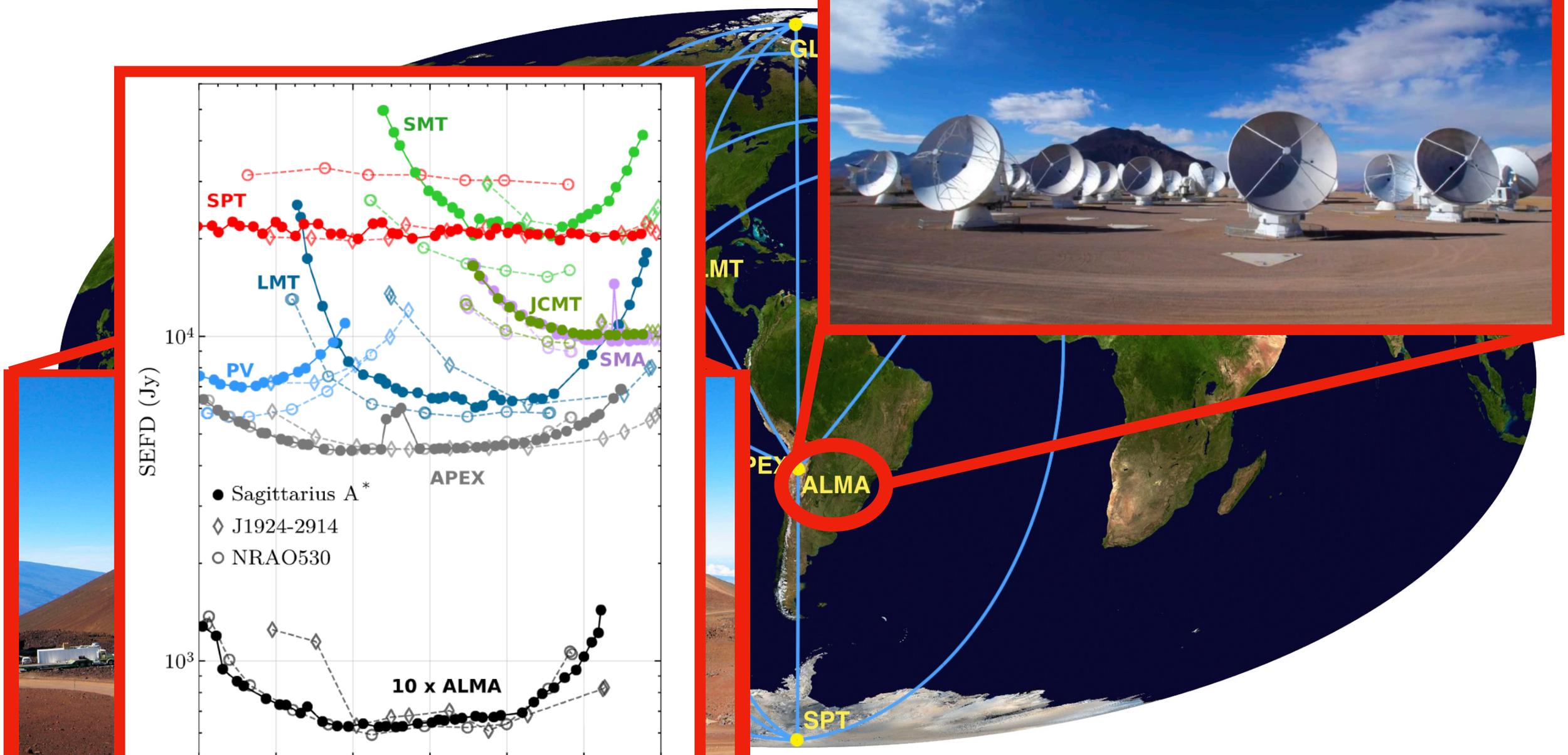
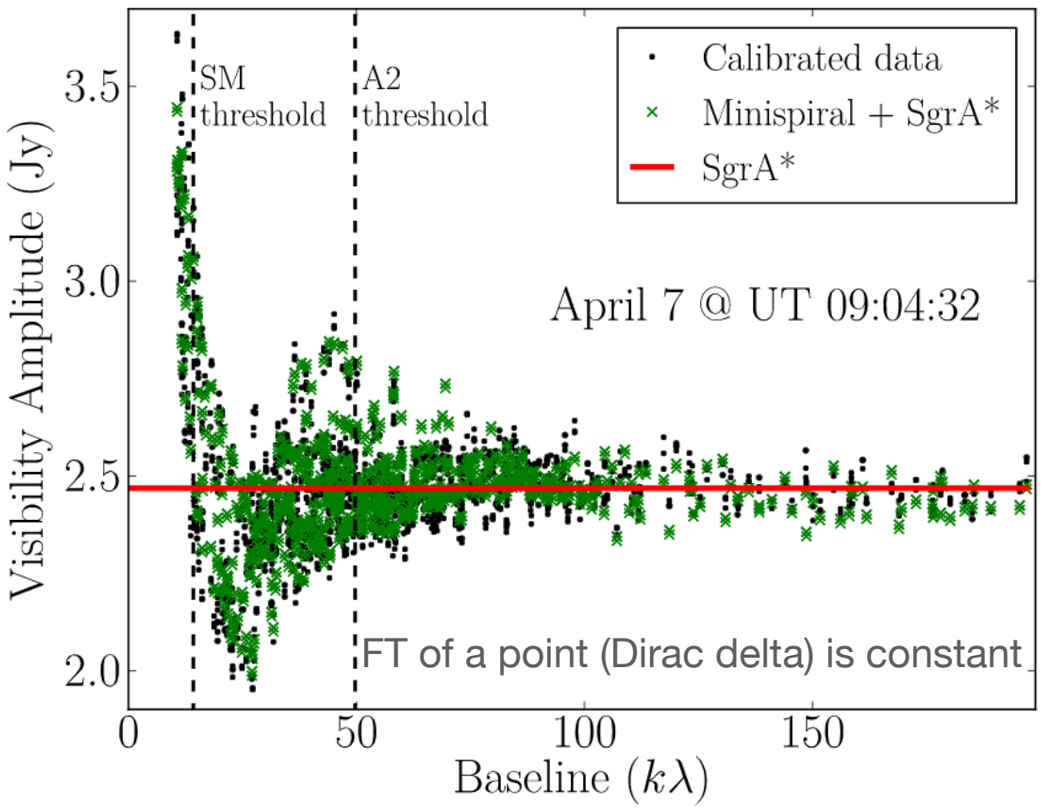


EHTC 2022, Sgr A* Paper 2

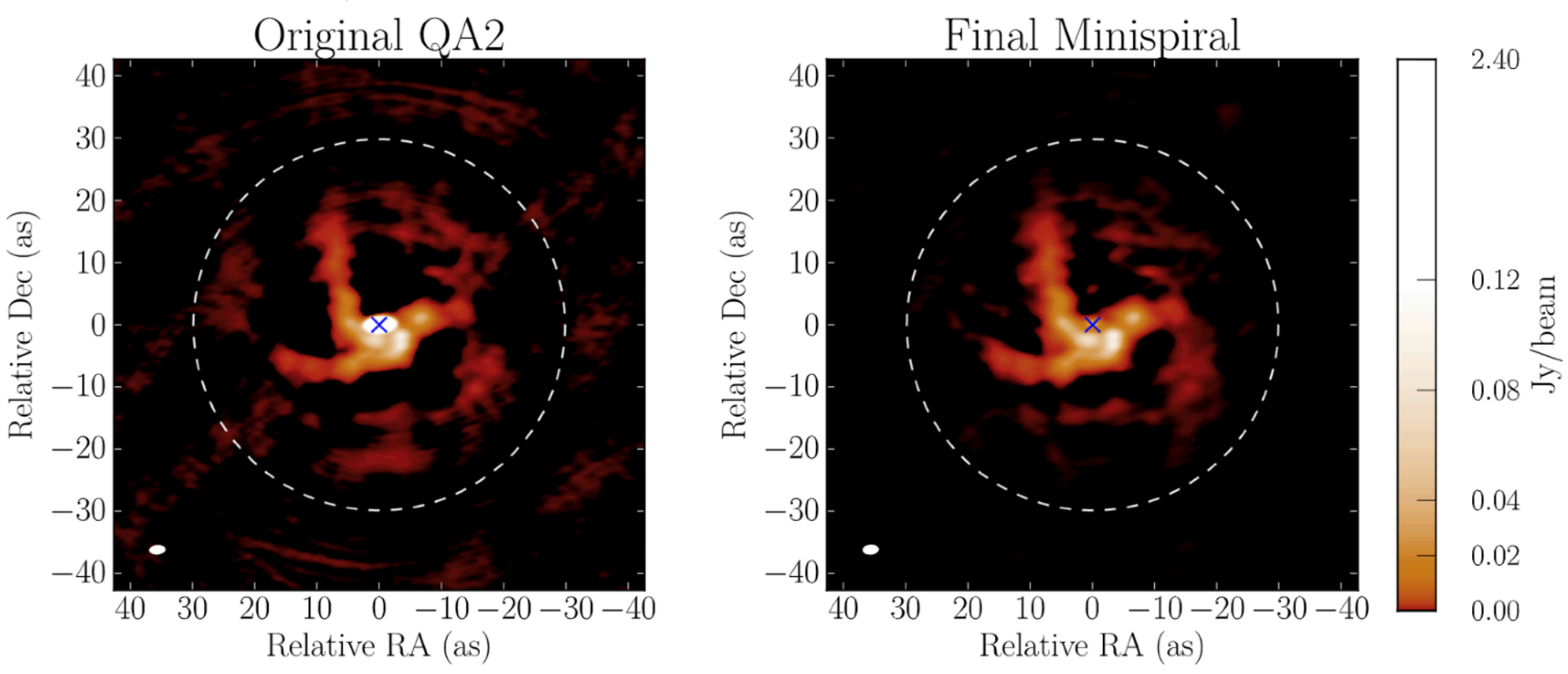
EHT 2019. Paper II. Instrument

ALMA image from the EHT campaign



Problem: extracting light curves from phased arrays (coherent sum, compact array configuration) Goddi et al. 2019, Goddi et al. + EHTC 2021, Wielgus et al. + EHTC 2022

Data reduction: Ivan Marti-Vidal, Garrett Keating, Venkatessh Ramakrishnan, Ed Fomalont



MPIfR

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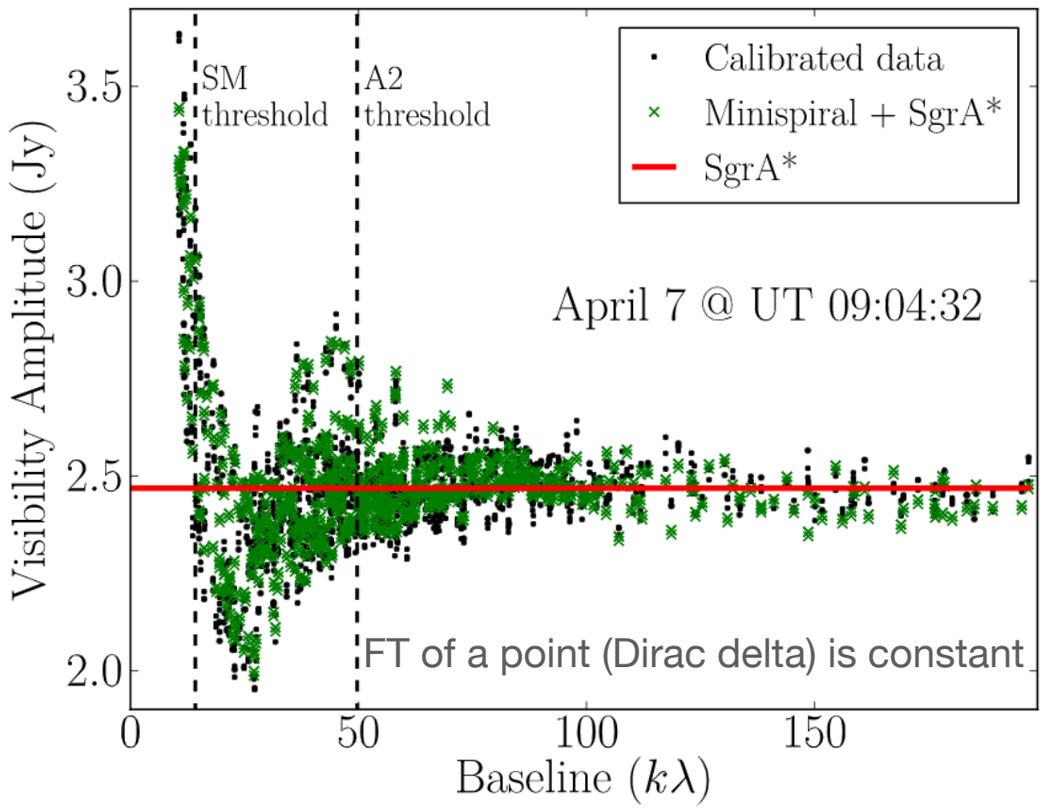

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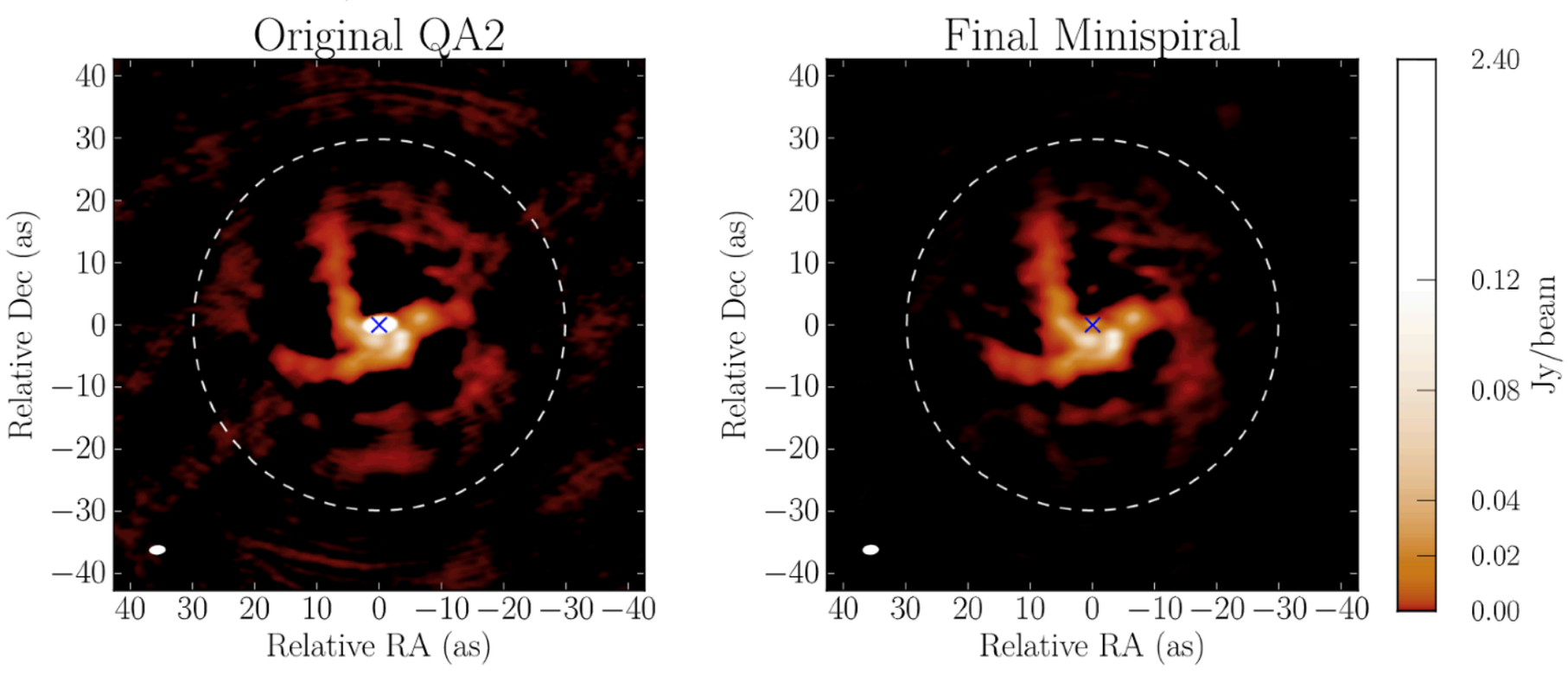
A single snapshot of ALMA data:
minispiral +Sgr A* point source unresolved
at 1 arc sec

$$V(u,v,t) = G(t)\left[V_{SgrA*}(t) + V_{bckg}(u,v)\right]$$



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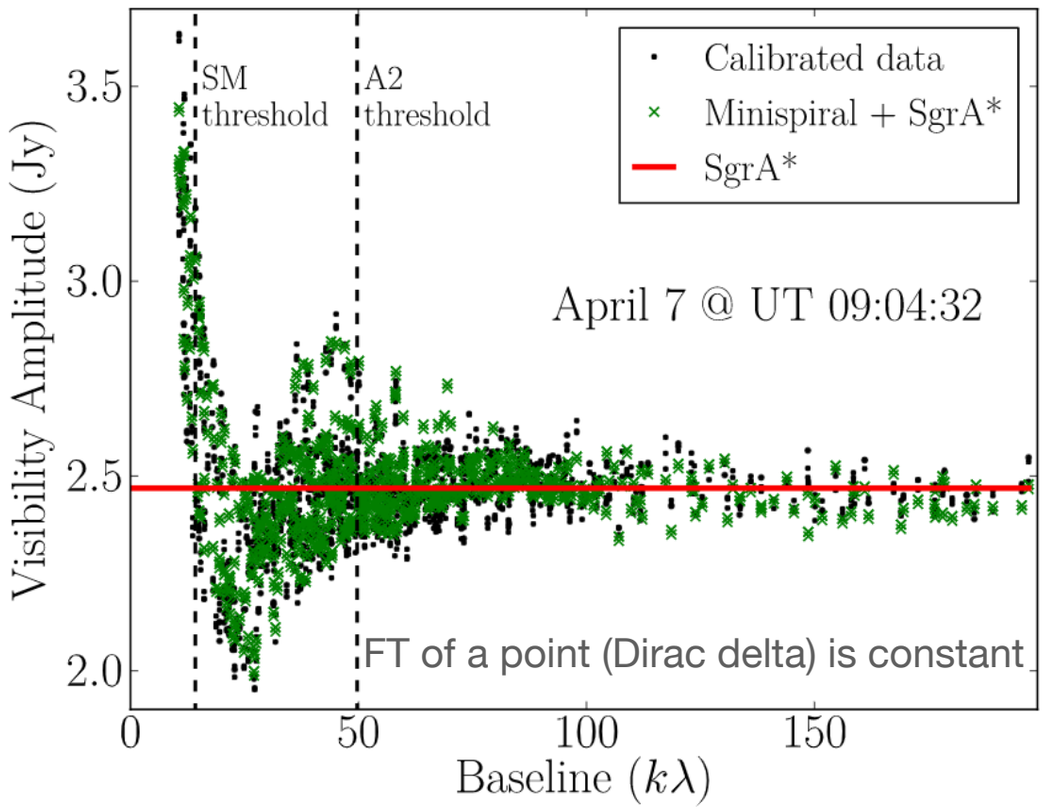

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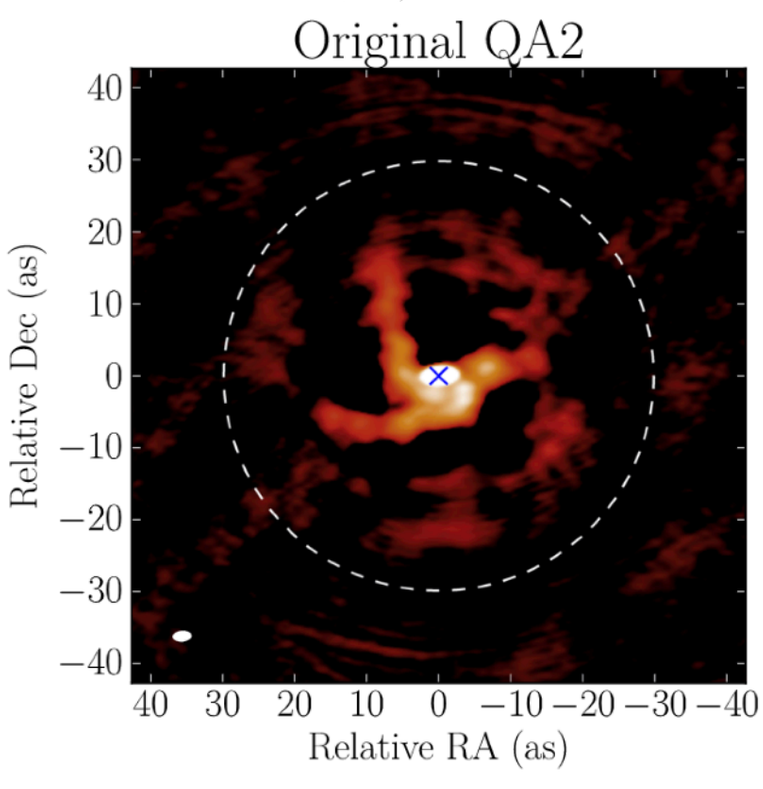
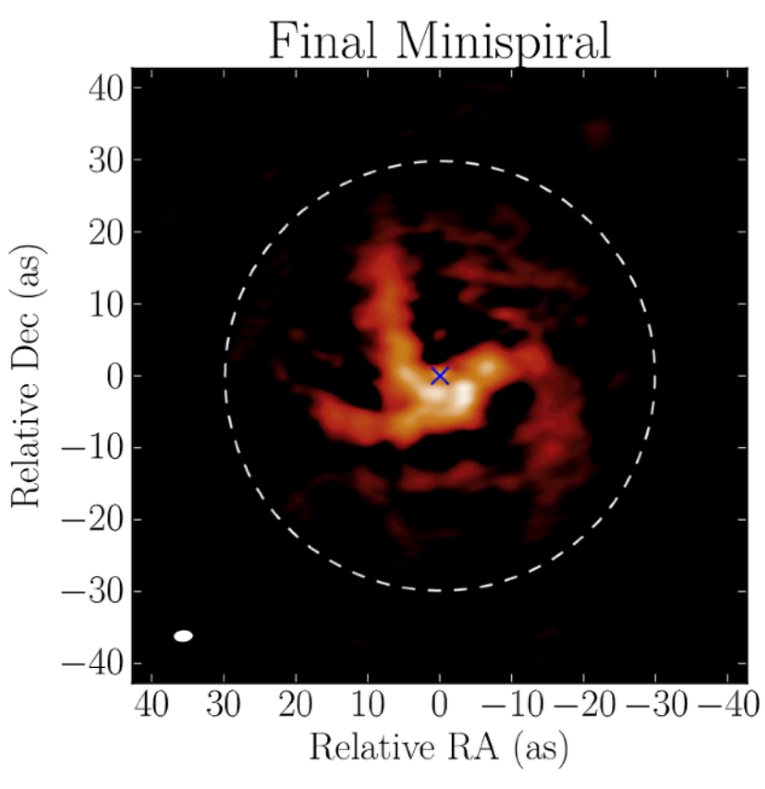
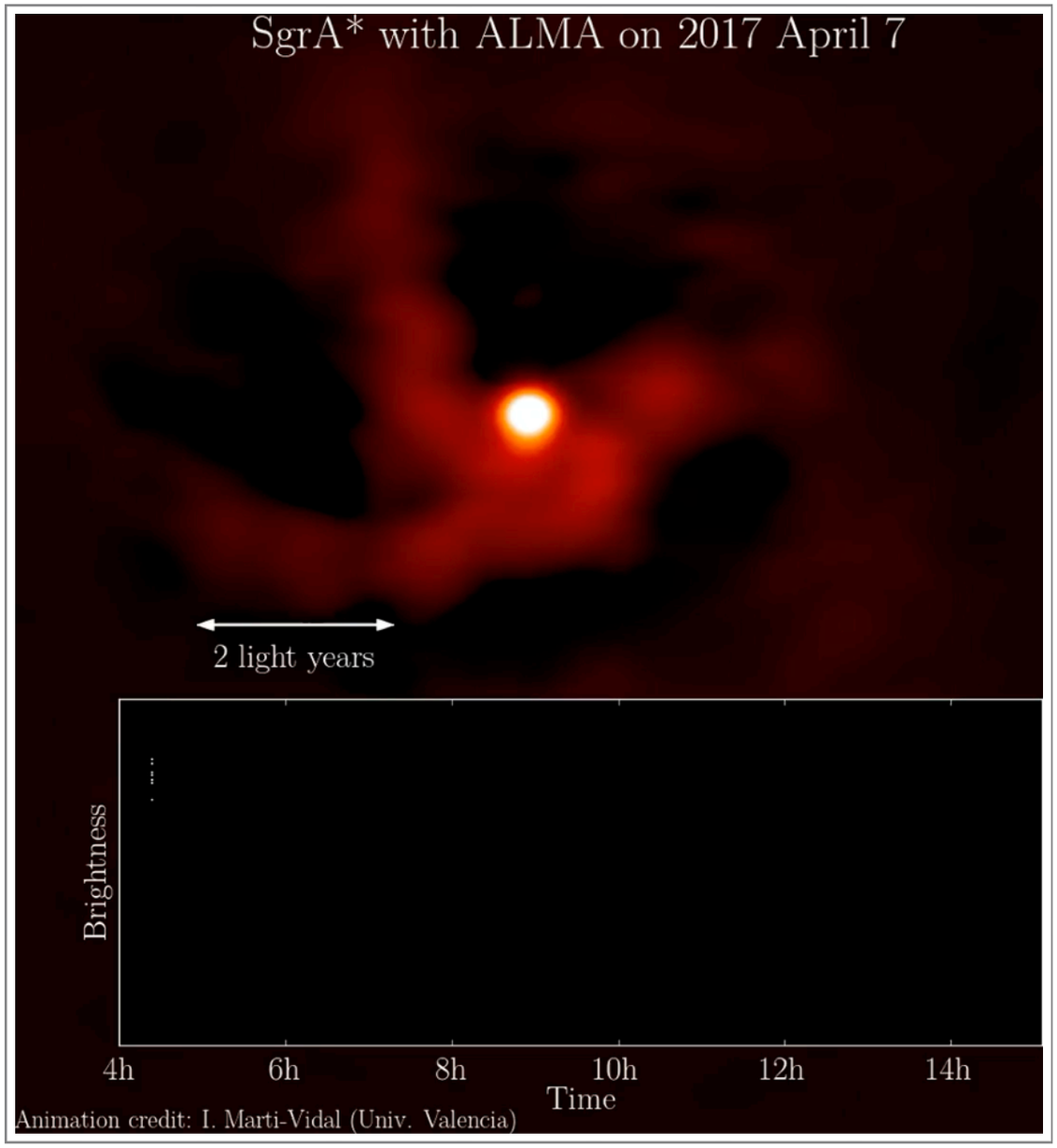




MPIfR

ALMA image from the EHT campaign

50 uas x 400 = 20 mas ; 20 mas x 50 = 1 as



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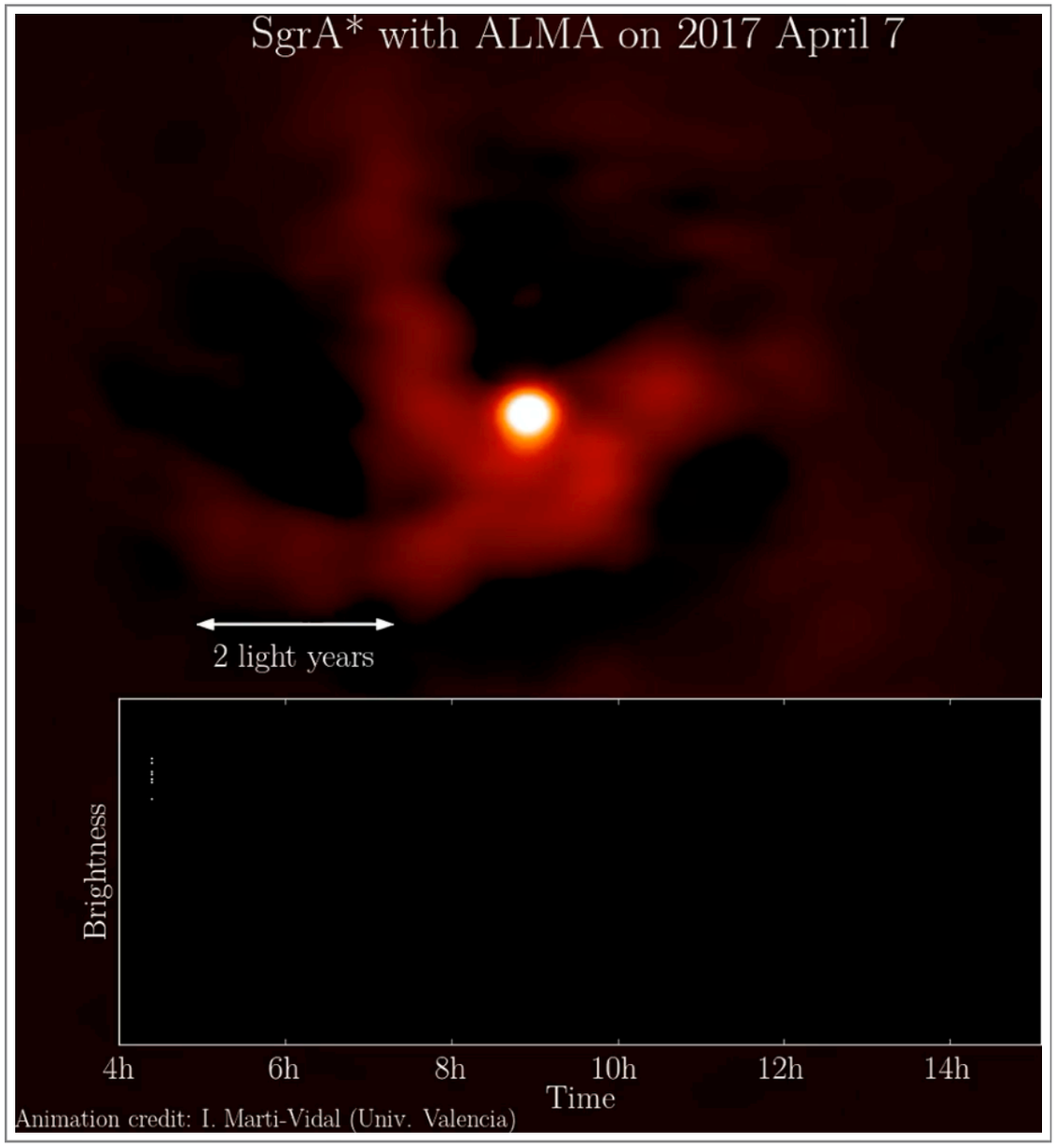

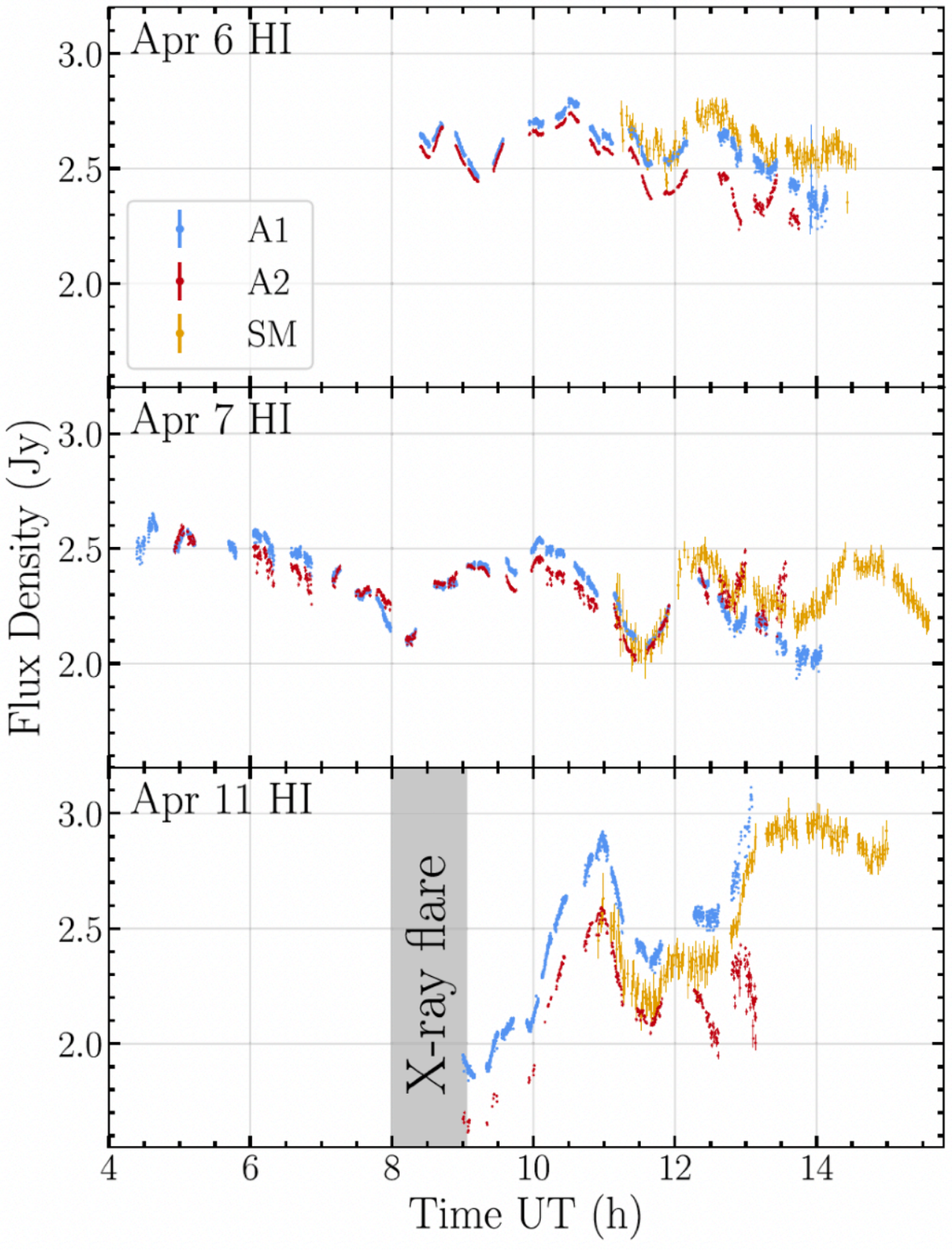

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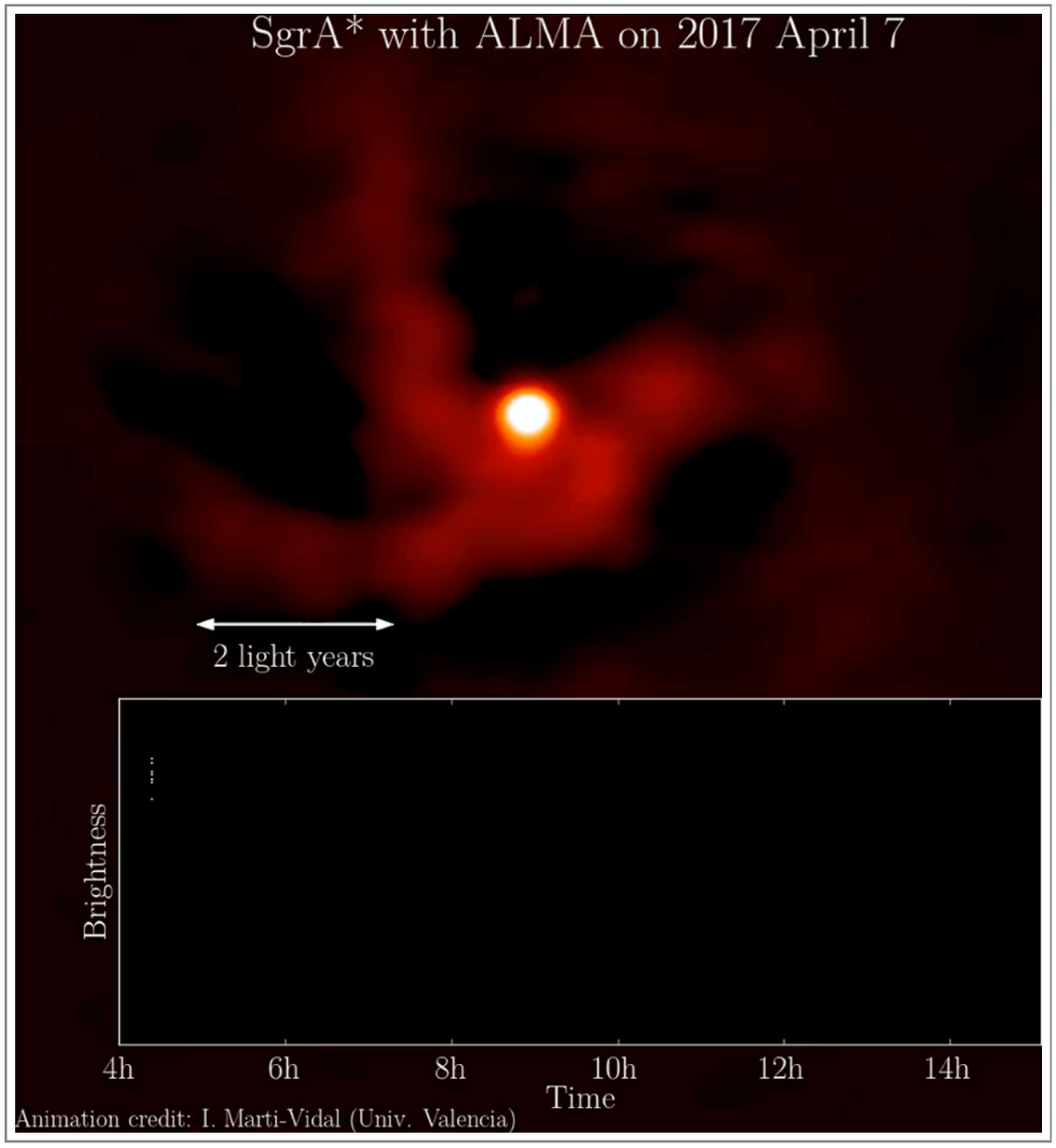
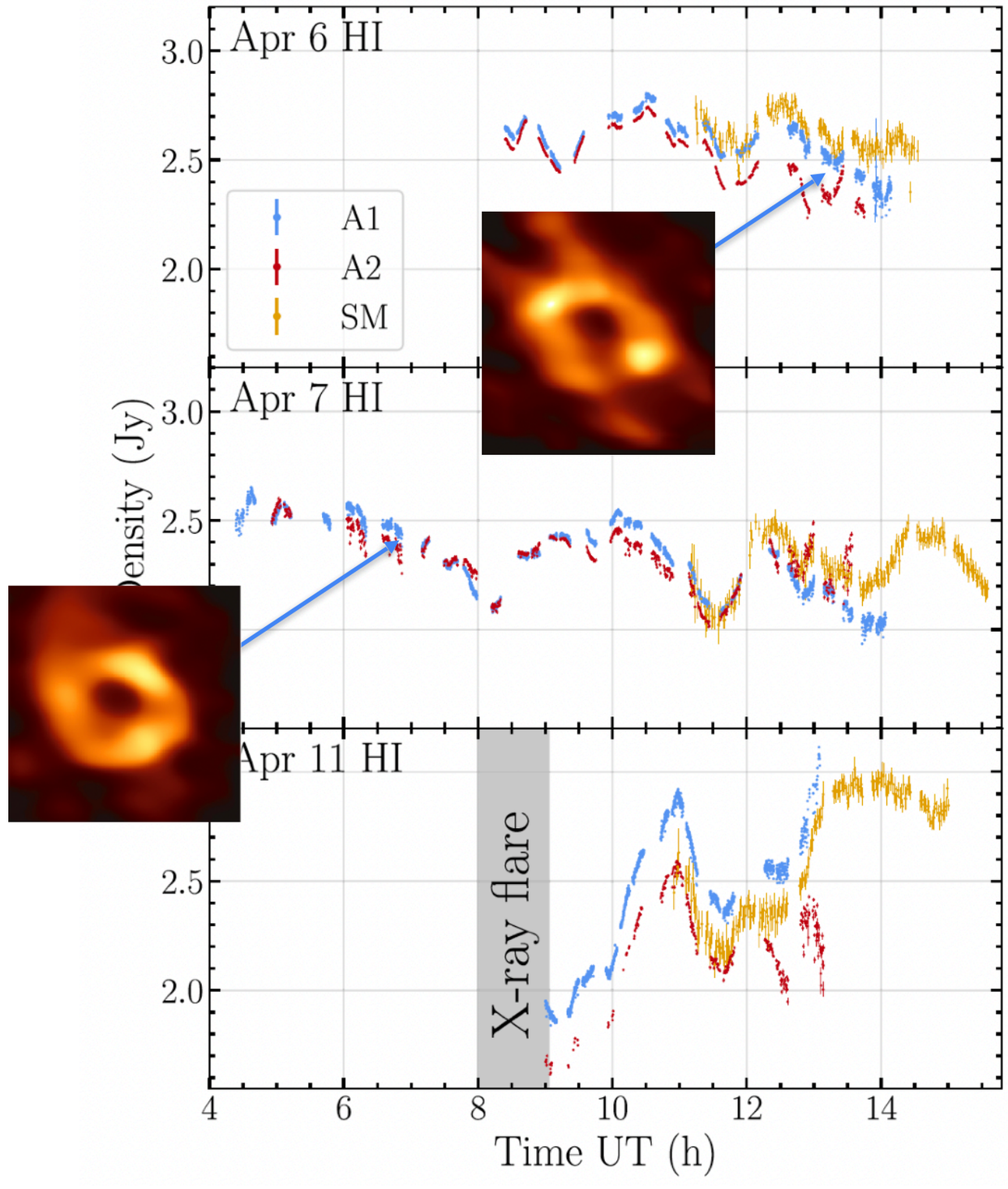
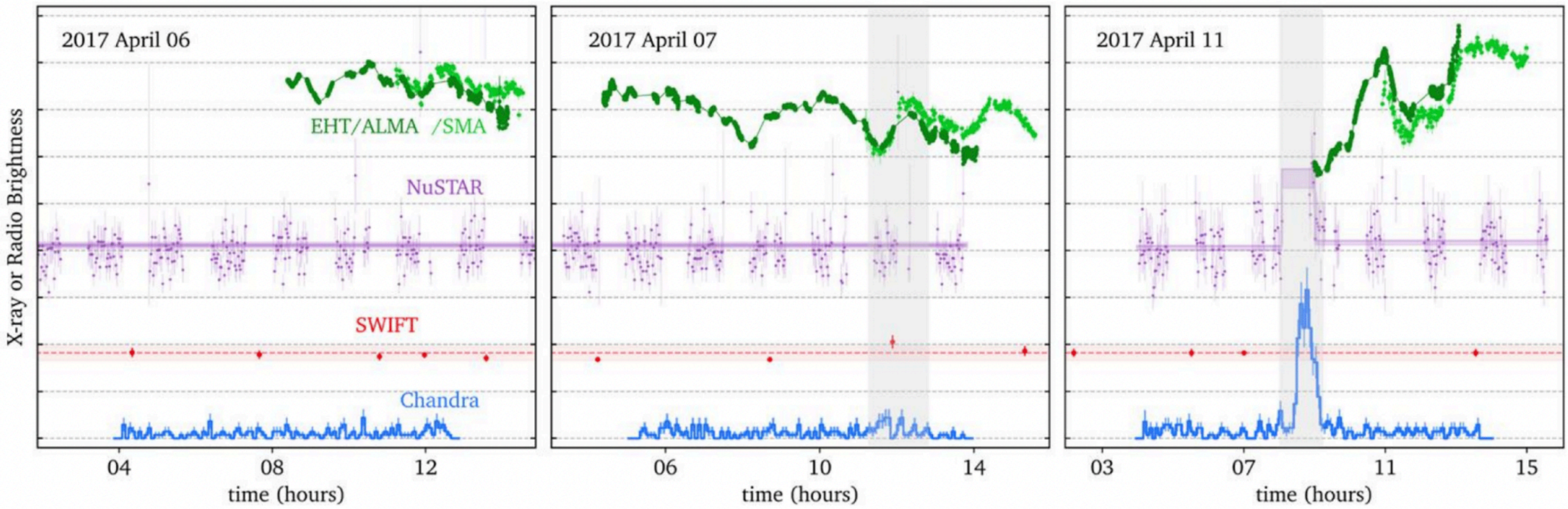




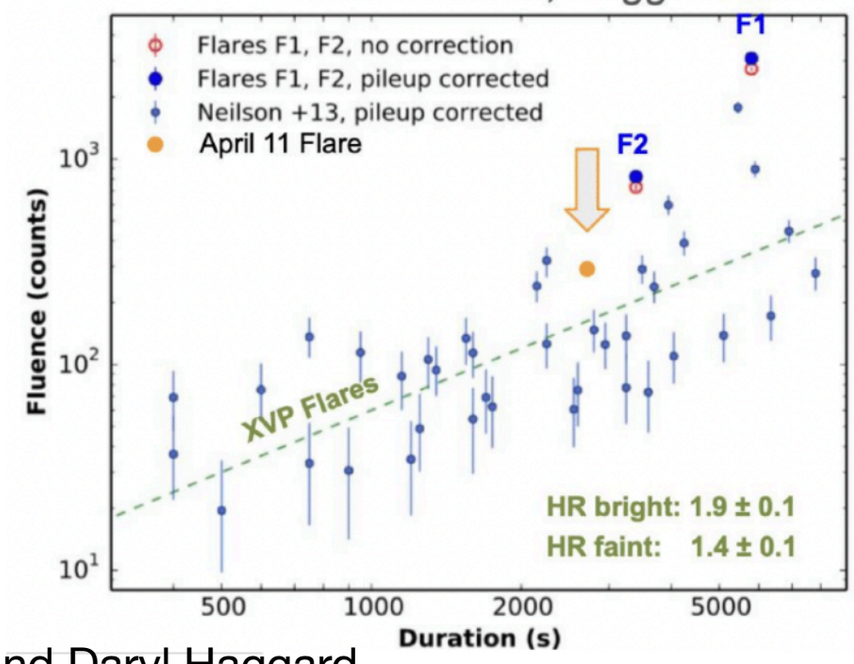
2017 April 11 X-ray flare

EHTC, ApJL 930, L13 (2022)



The 2017 Apr 11 X-ray flare
was **strong** but **not unusual**

Neilsen+2013; Haggard+2019



courtesy of Hope Boyce and Daryl Haggard

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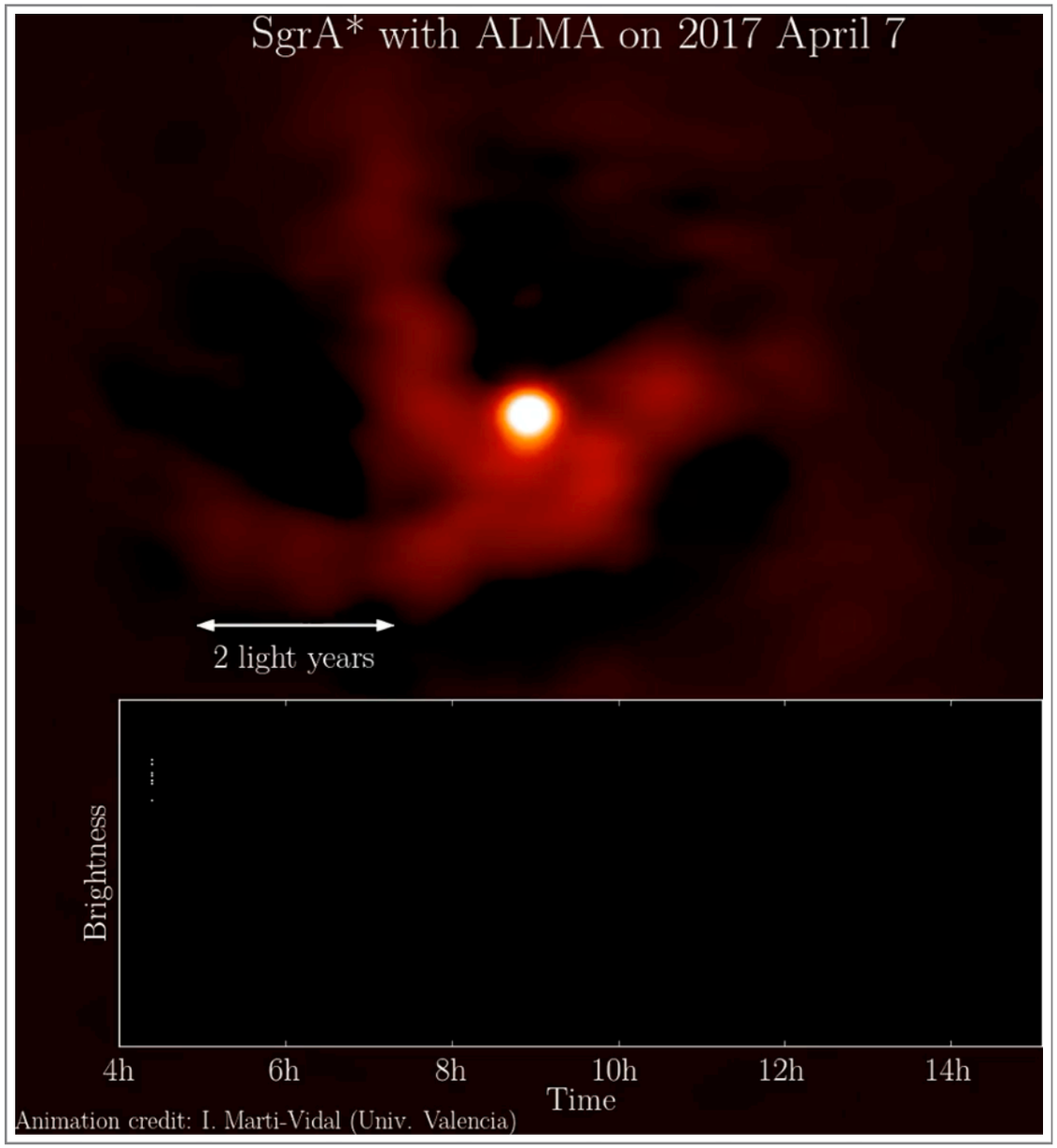
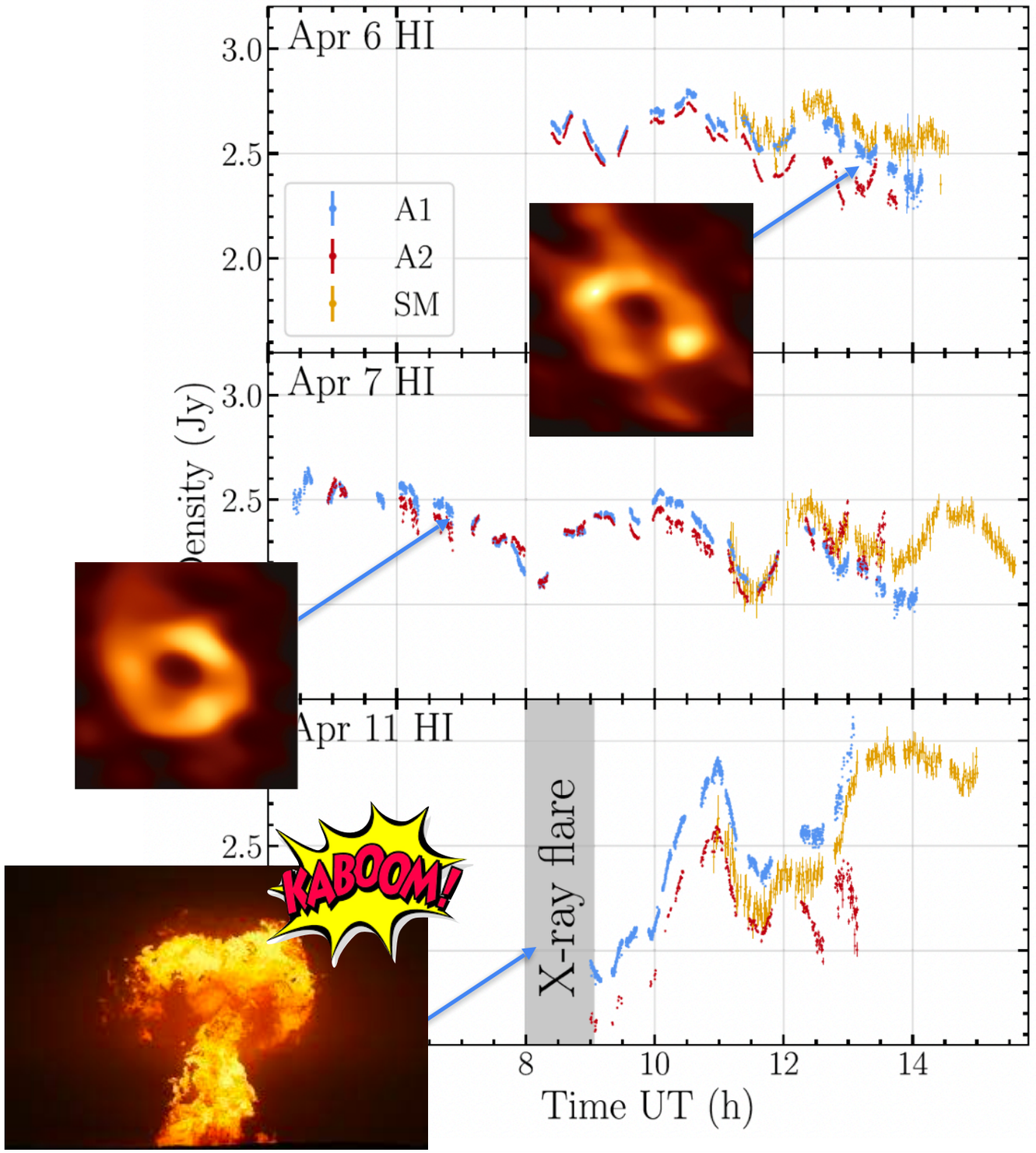
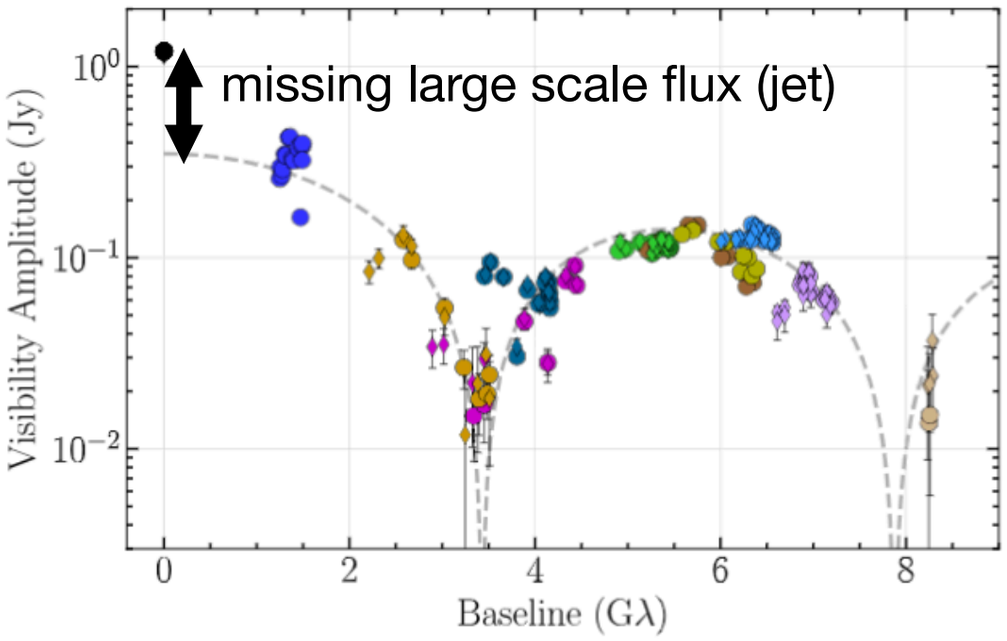


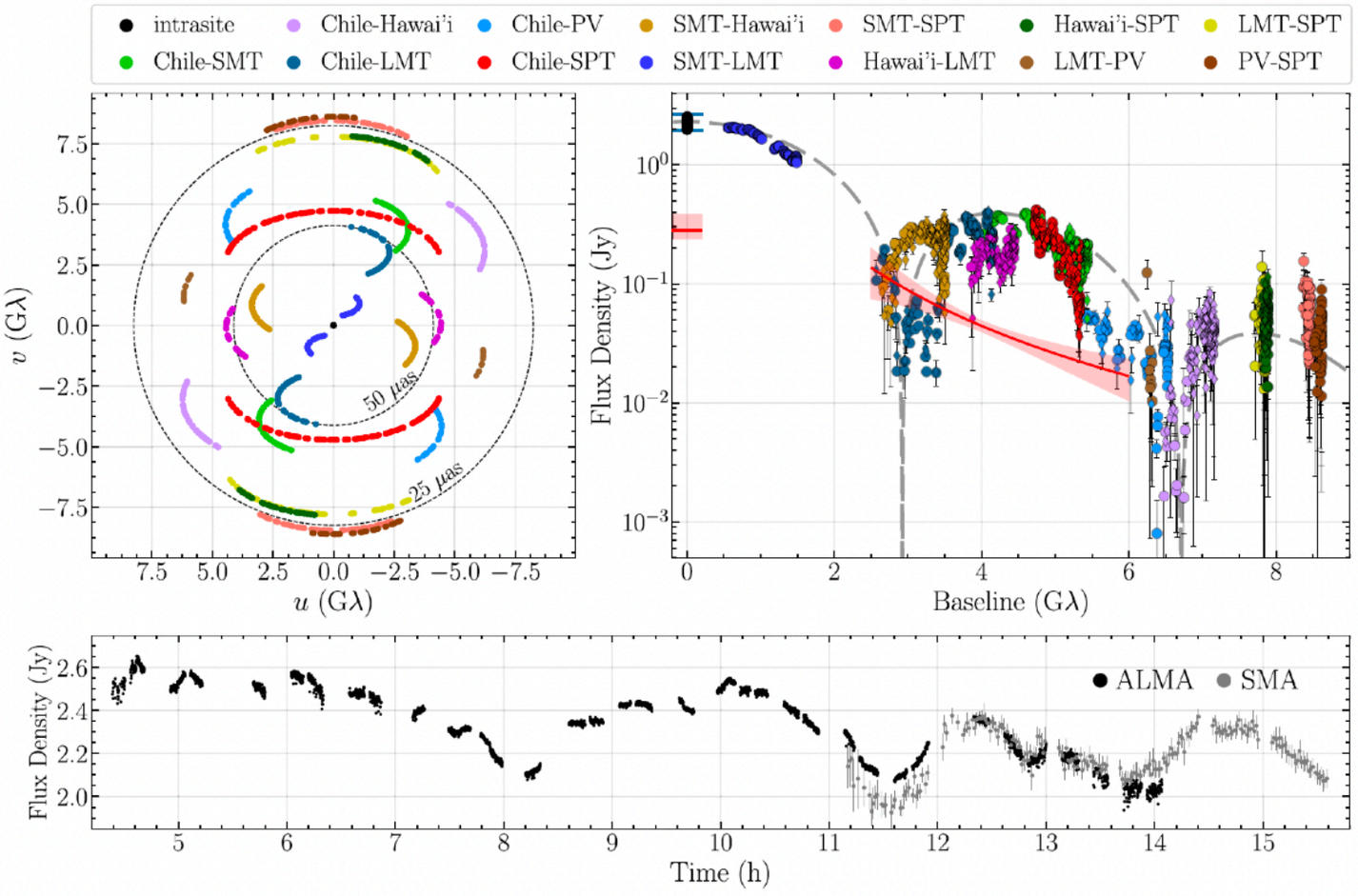


ALMA light curves calibrate EHT data

M87*, EHTC 2019



Sgr A*, EHTC 2022 L12



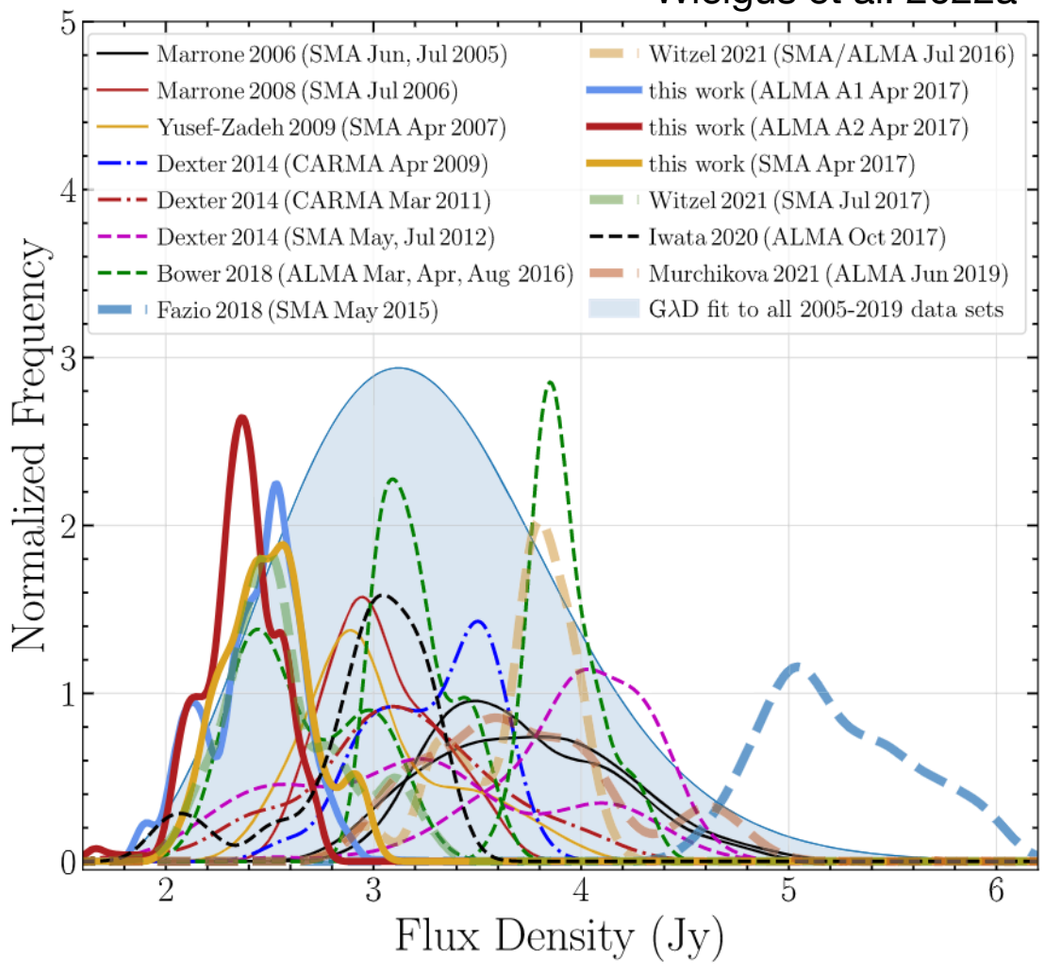
We use light curves in EHT VLBI calibration:

- ALMA gains derived from mini spiral self cal,
- ALMA-APEX, JCMT-SMA absolute calibration to light curve in 10s segments,
- Erratic gains of LMT constrained with a Gaussian x light curve model on shortest baseline (LMT-SMT),
- Normalization of the flux density to mitigate intrinsic variability (EHTC 2022 L15, L18, L19, L20, L21)

ALMA observations of Sagittarius A*

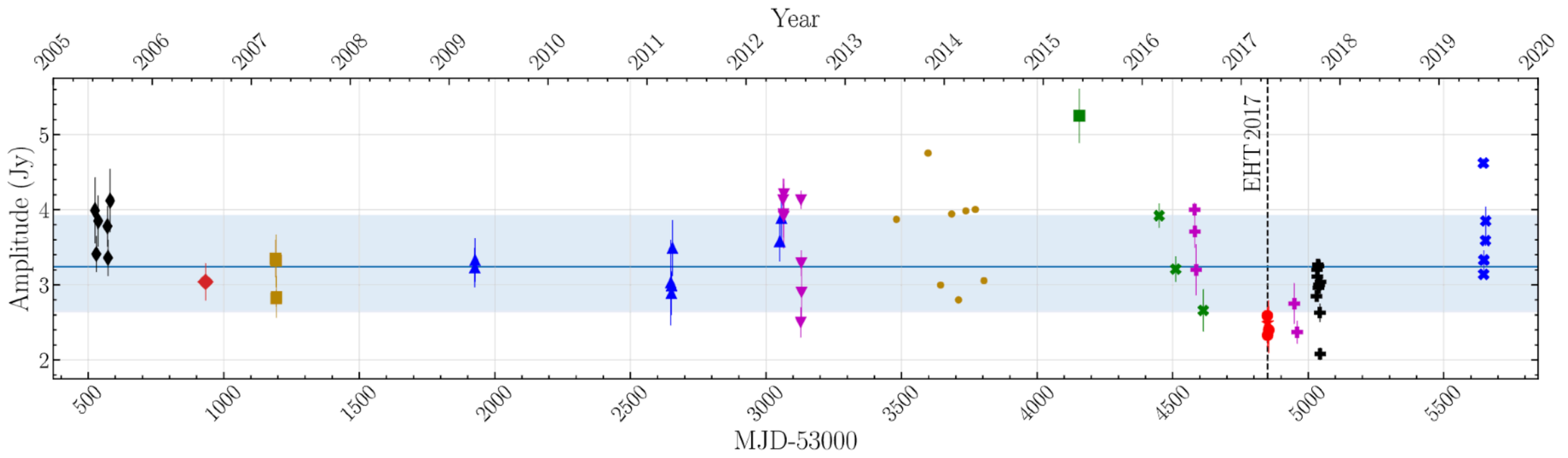
- Bower et al. 2015, 2018, 2019
- Brinkerink et al. 2015
- Liu et al. 2016
- Iwata et al. 2020
- Witzel et al. 2021
- Murchikova et al. 2021
- Wielgus et al. 2022a,b

Wielgus et al. 2022a



1mm flux density: $3.24^{+0.68}_{-0.60}$ Jy

Gaussian works ok, the high energy tail is weak



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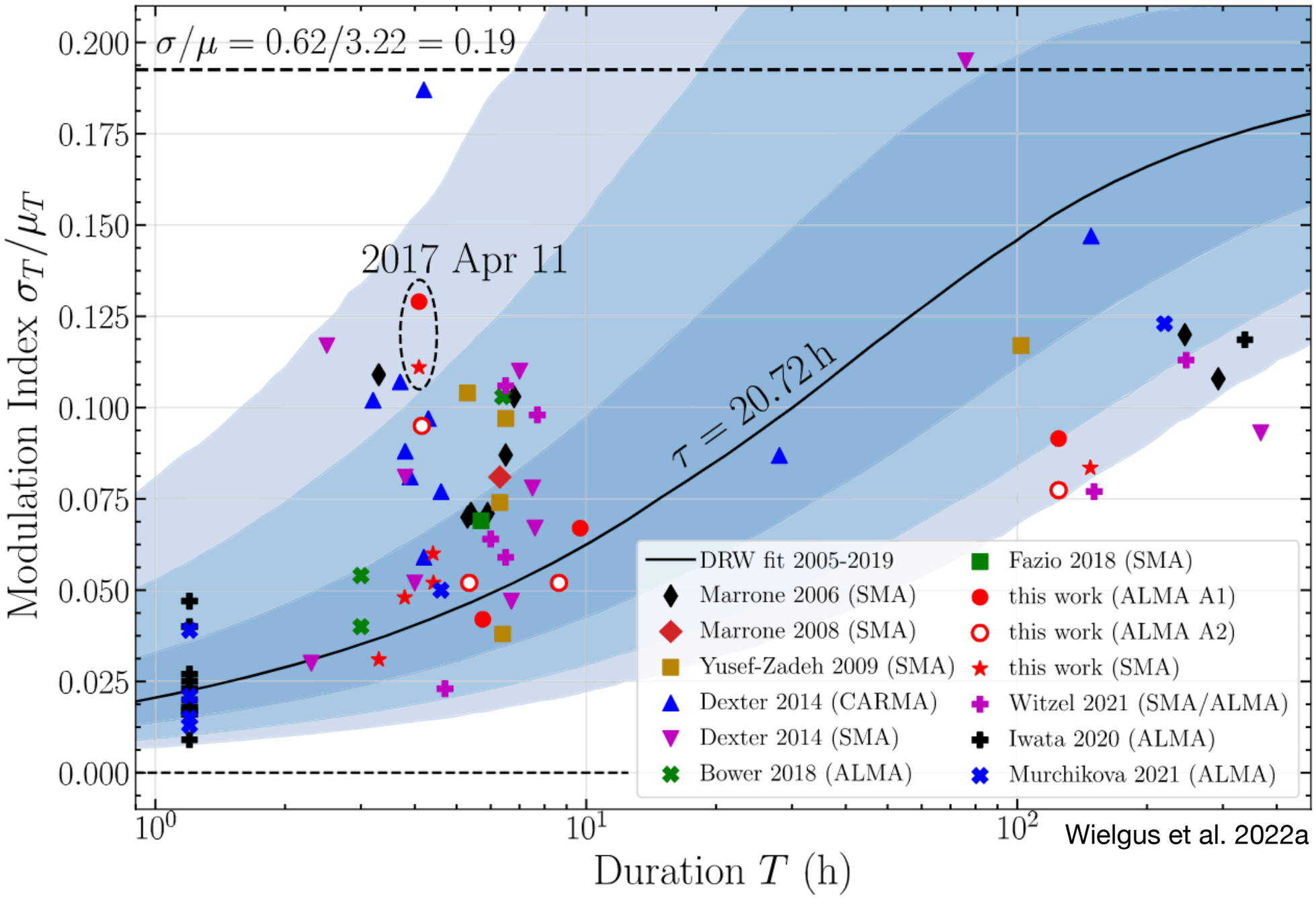
Red noise character

Gaussian process framework **decorrelation timescale ~10 h** (Dexter et al. 2014, Wielgus et al. 2022a)



Wielgus et al. 2022a

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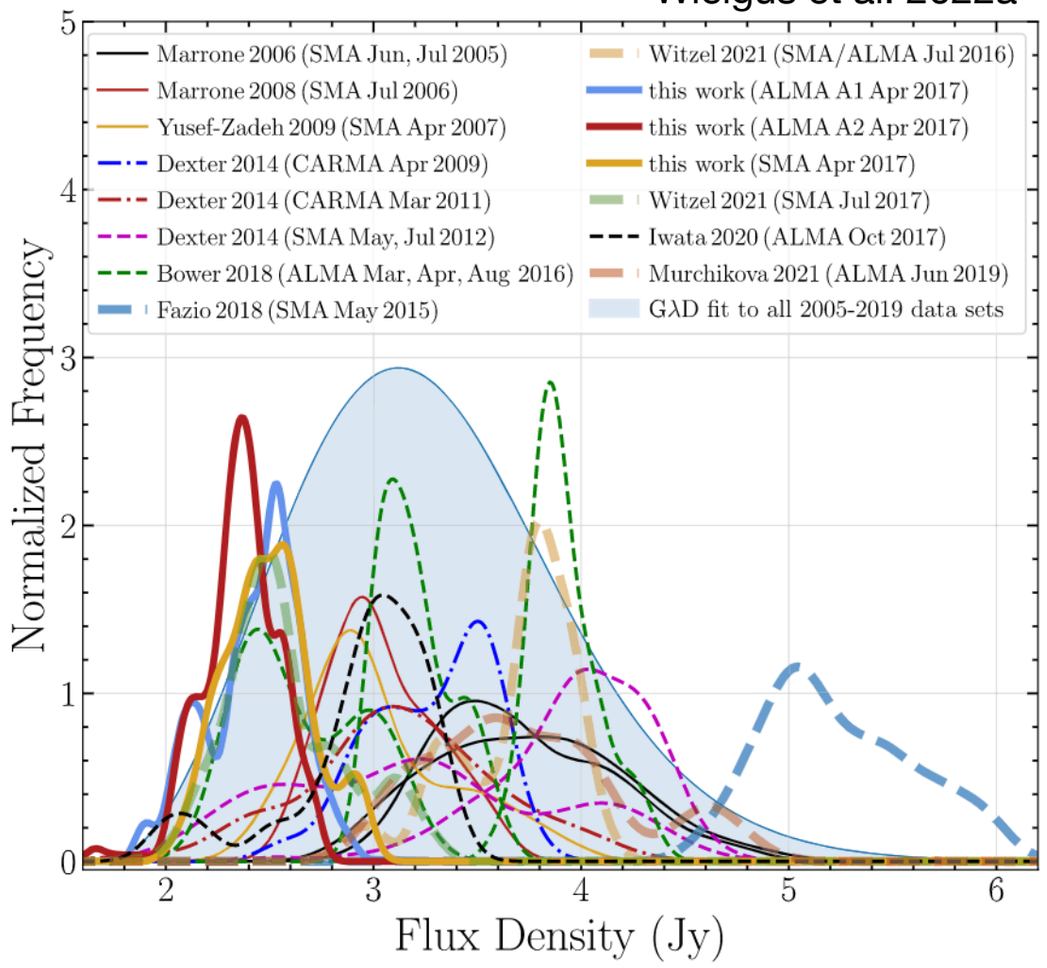
Wielgus et al. 2022a



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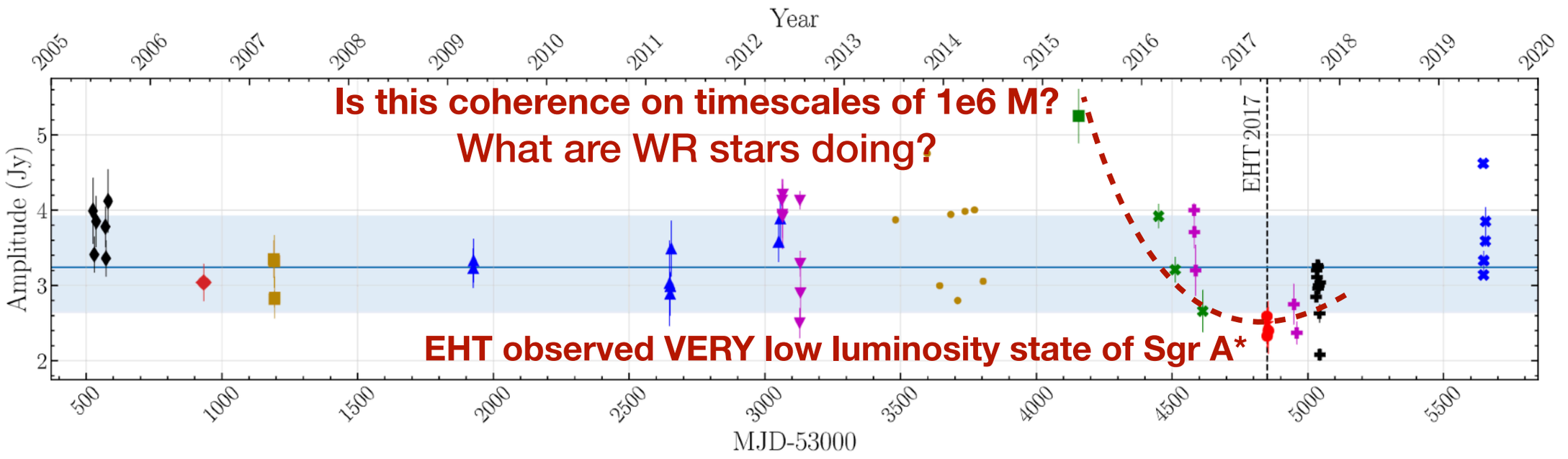


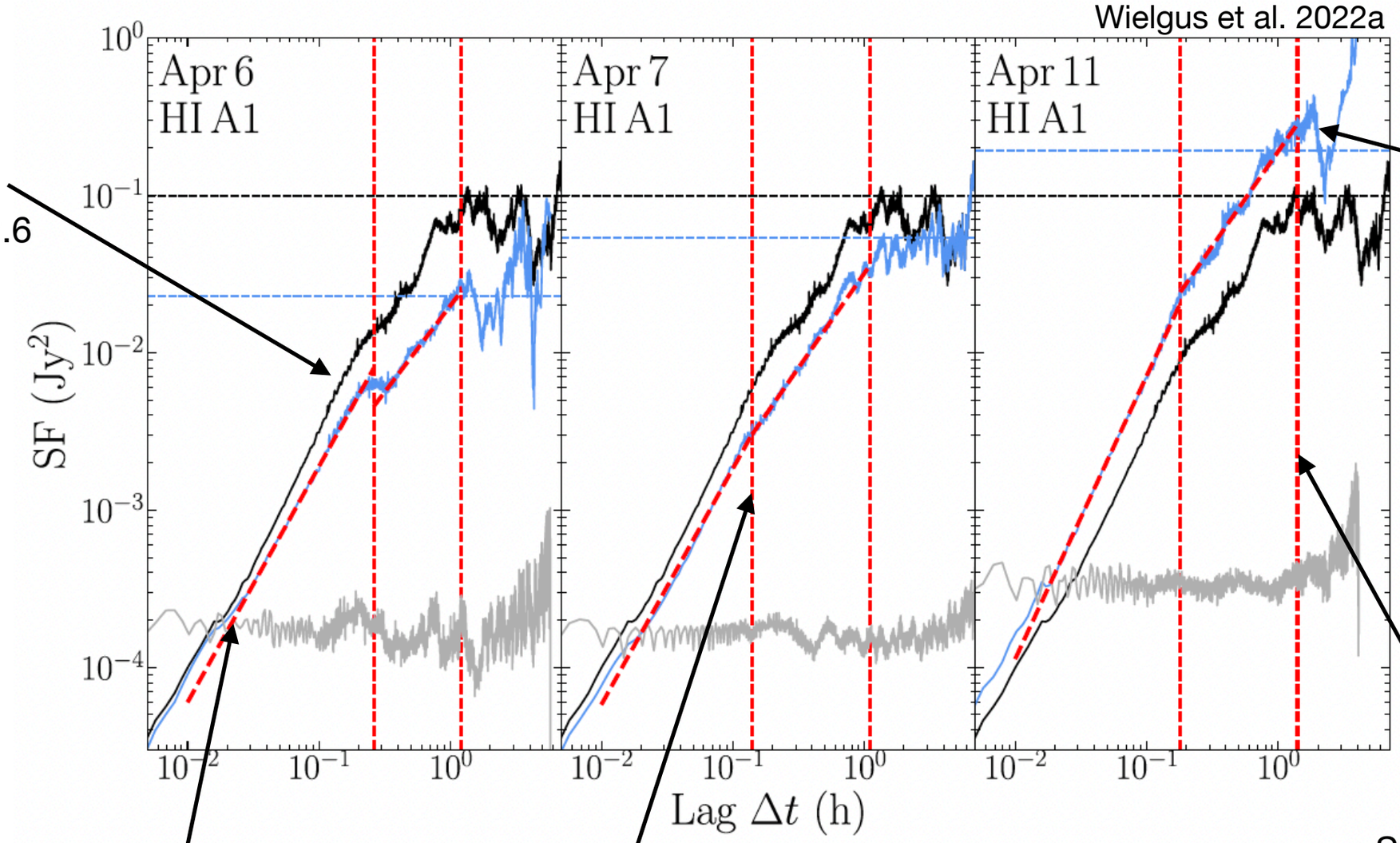
MPIfR

Structure functions

Structure function: variability power across timescales $\mathrm{SF}(\Delta t) = \sum_t [x(t) - x(t - \Delta t)]^2$

(with Nicola Marchili)

Wielgus et al. 2022a



Red noise character, PSD slope -2.6

Flare day MUCH more variable

Robust variability detection on timescales as short as 1 minute - must be intrinsic and structural at the EHT angular scales true SNR ~200

Change of slope at 10-20 min

Second change of slope at 1-2 h NOT ROBUST

Structure functions

Structure function: variability power across timescales (with Nicola Marchili)

$$\mathrm{SF}(\Delta t) = \sum_t [x(t) - x(t - \Delta t)]^2$$

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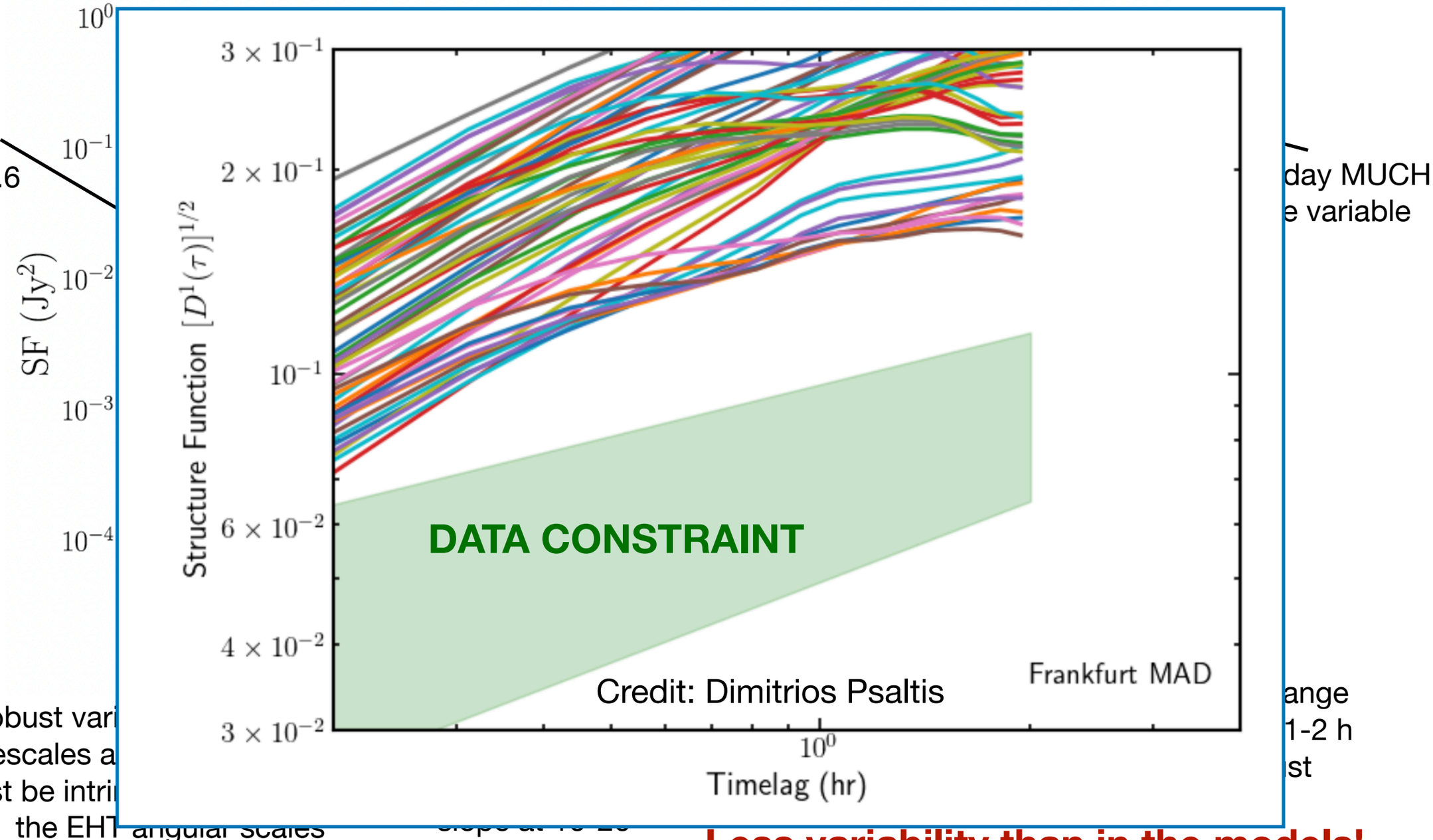


day MUCH e variable

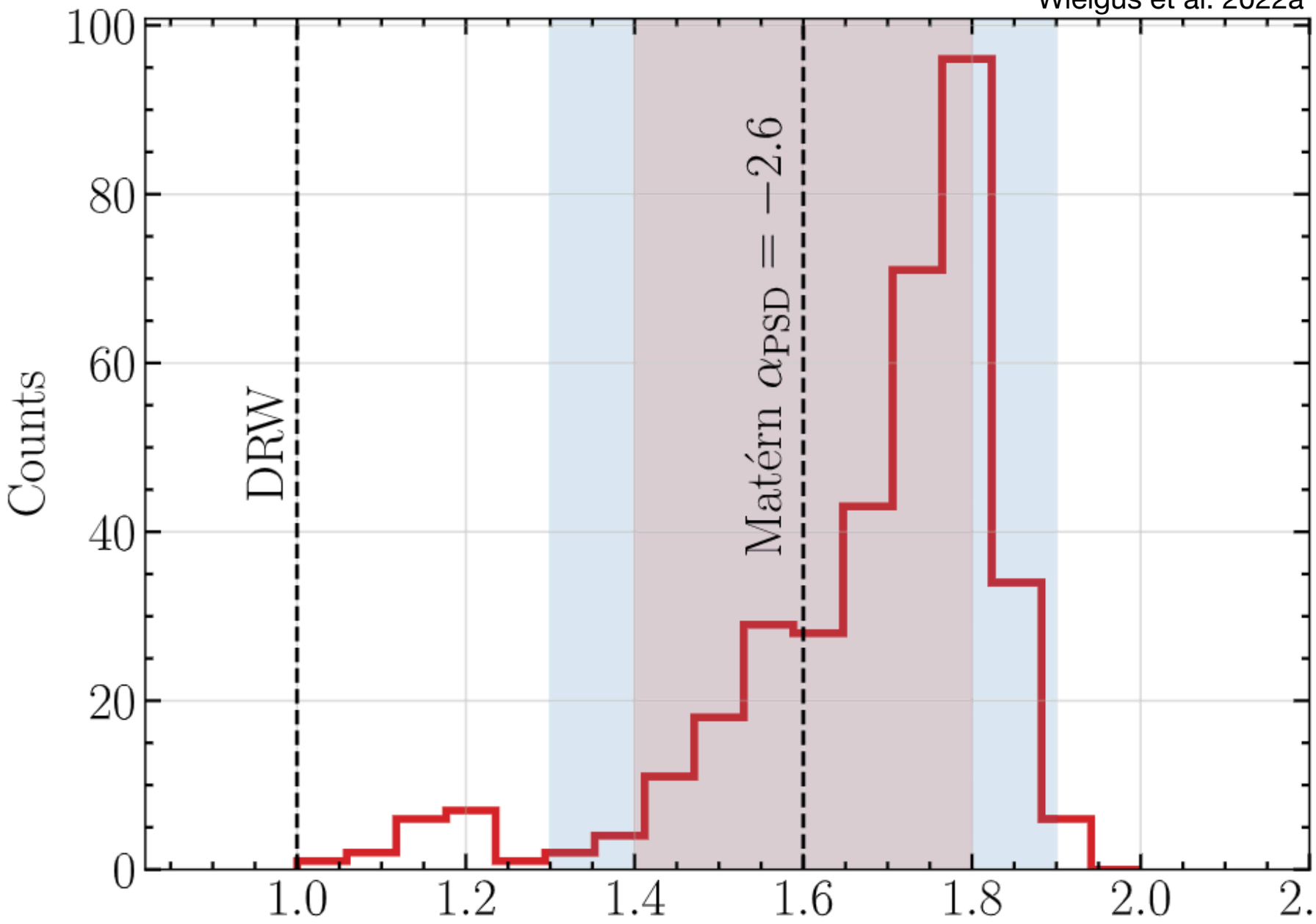
Robust vari ange
timescales a 1-2 h
must be intri st
the EHT angular scales
min

Less variability than in the models!

Slope of the PSD

- structure functions
- Gaussian process modeling
- Comparison with GRMHD library

Wielgus et al. 2022a

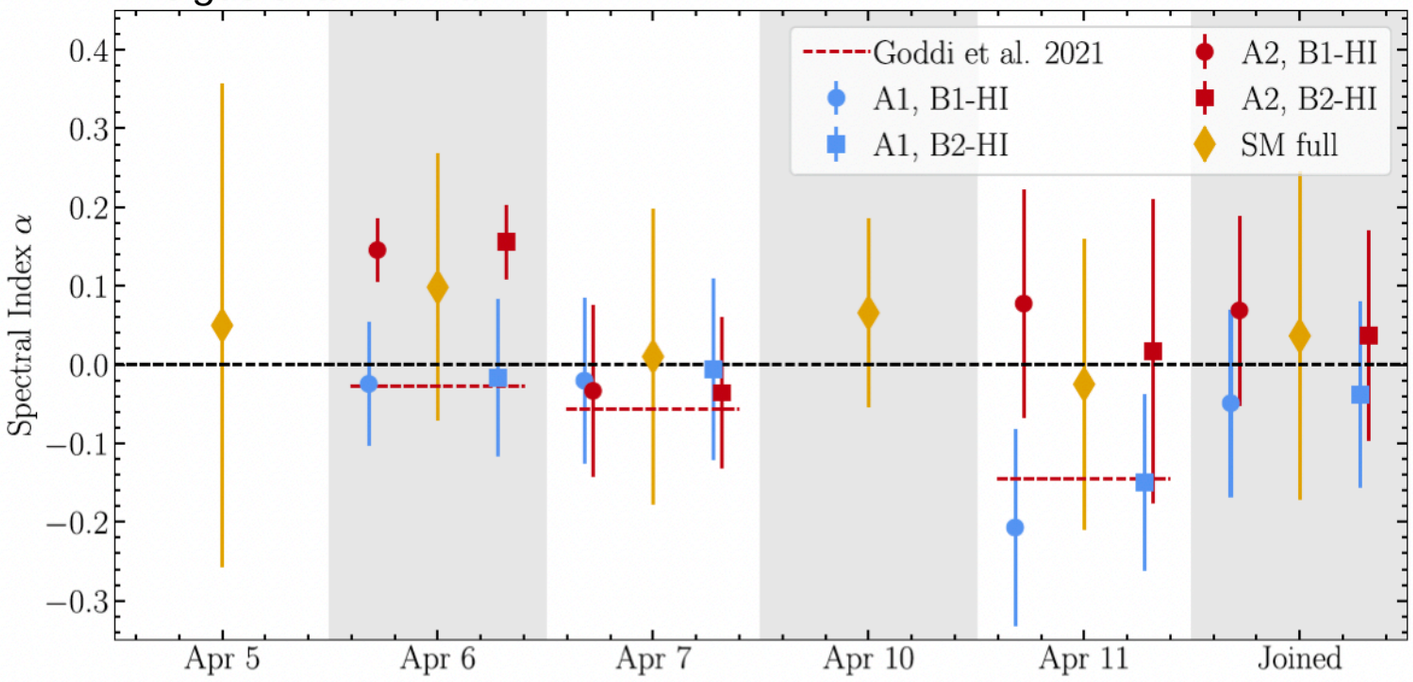


MPIfR

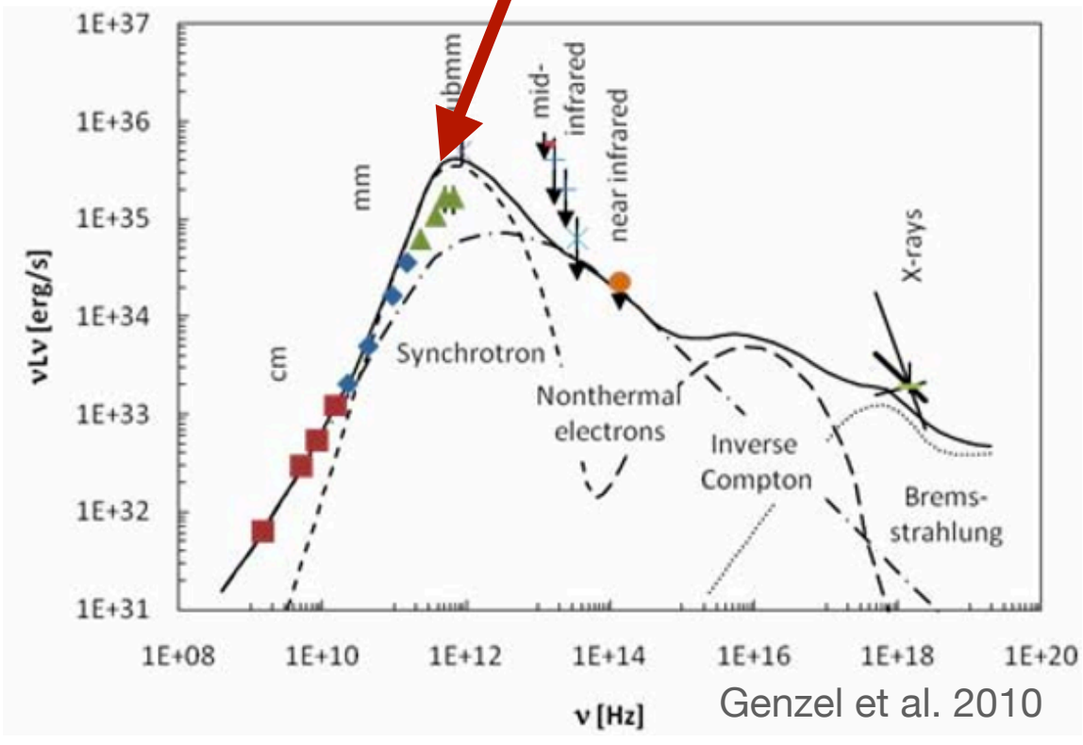
Optically thin flow on the event horizon scale

Wielgus et al. 2022a

Flat SED at 1mm



With EHT/ALMA 1mm we're here with spectral index = 0



Genzel et al. 2010

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Wielgus et al. 2022a

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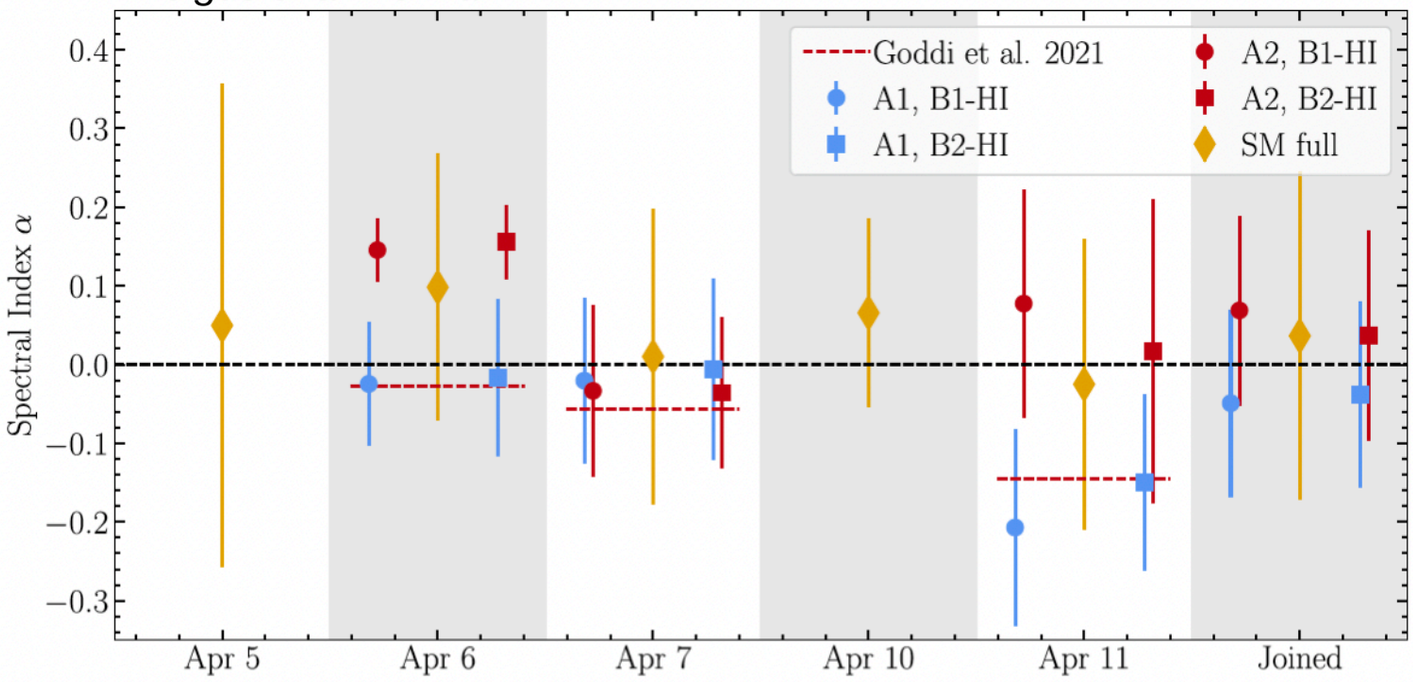

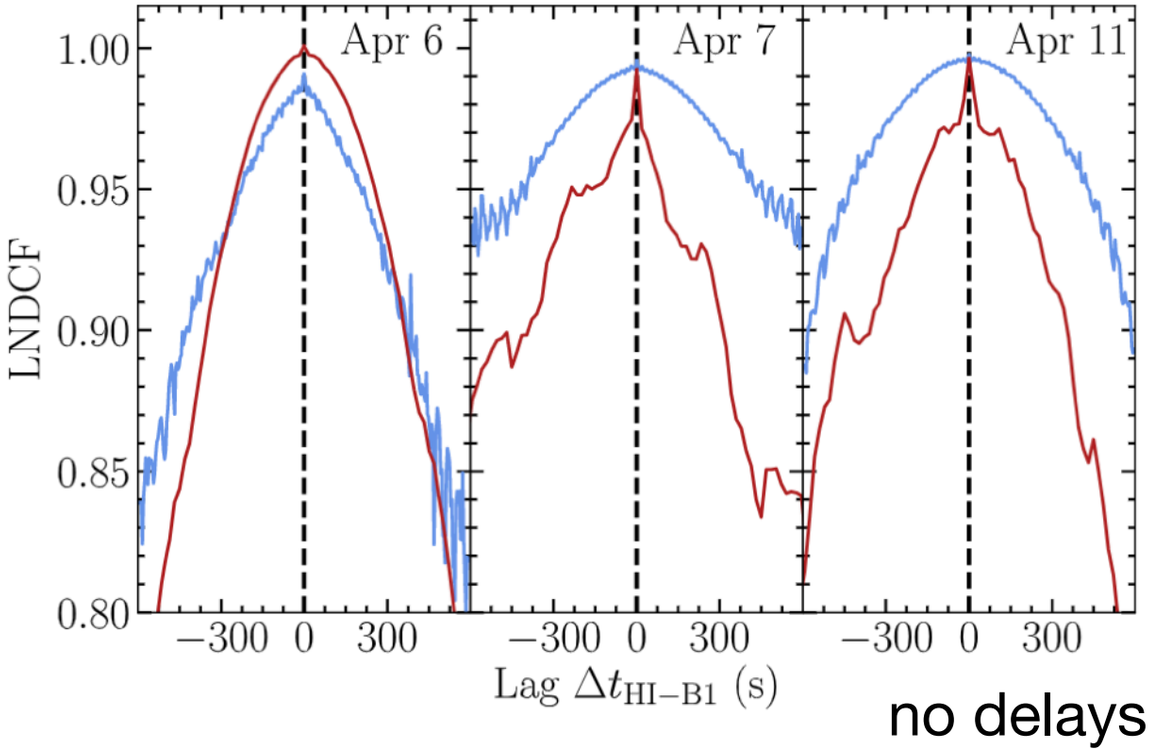

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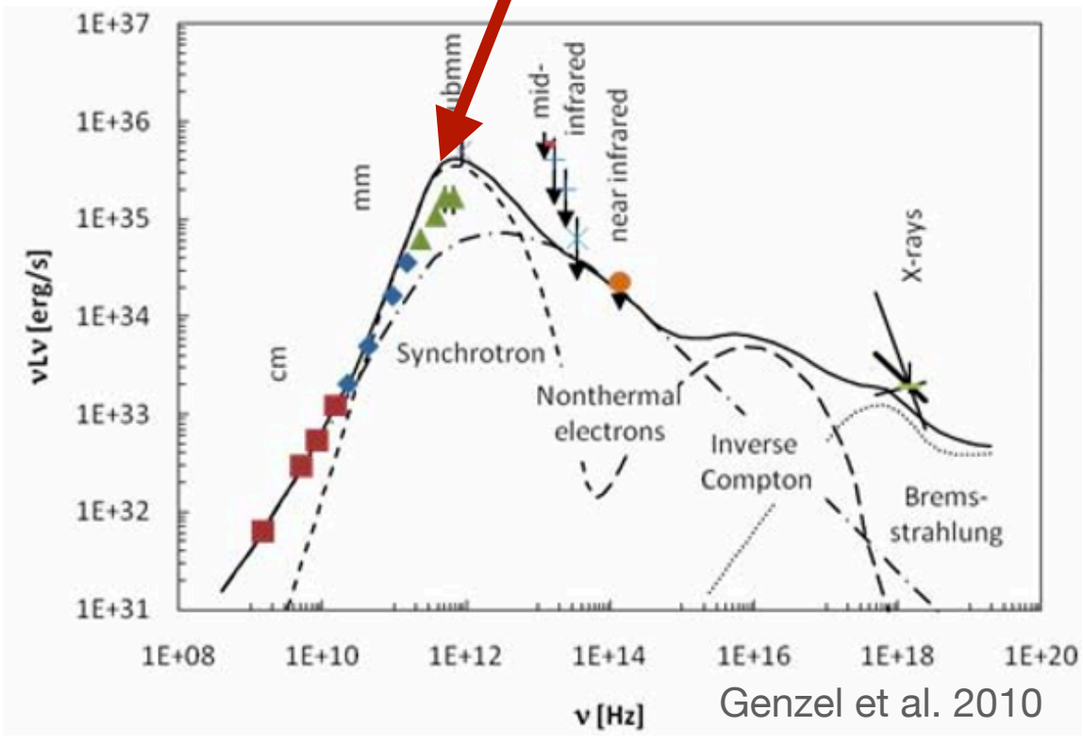
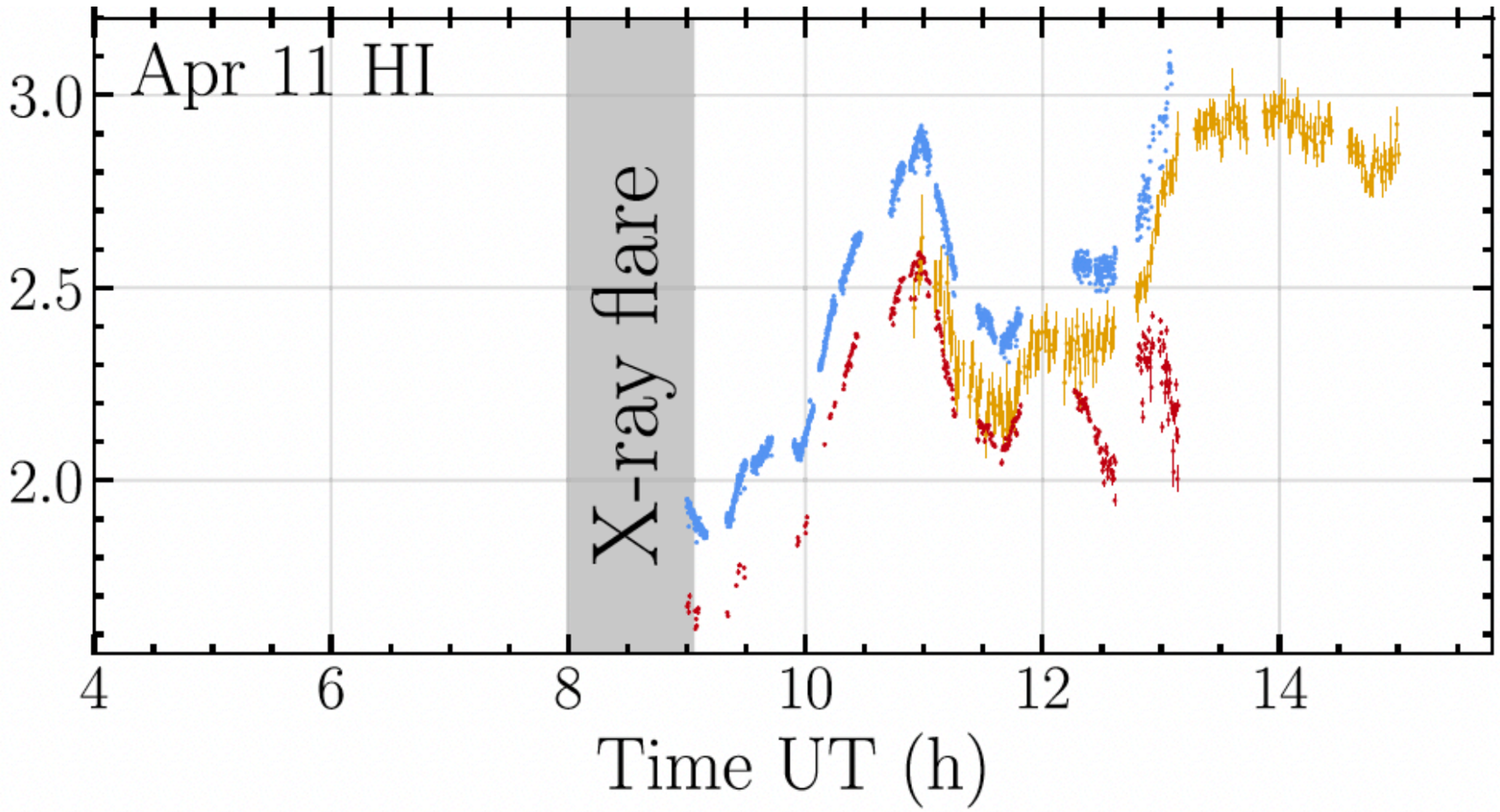


Genzel et al. 2010

no delays in 212-230 GHz window

Time-resolved spectral index



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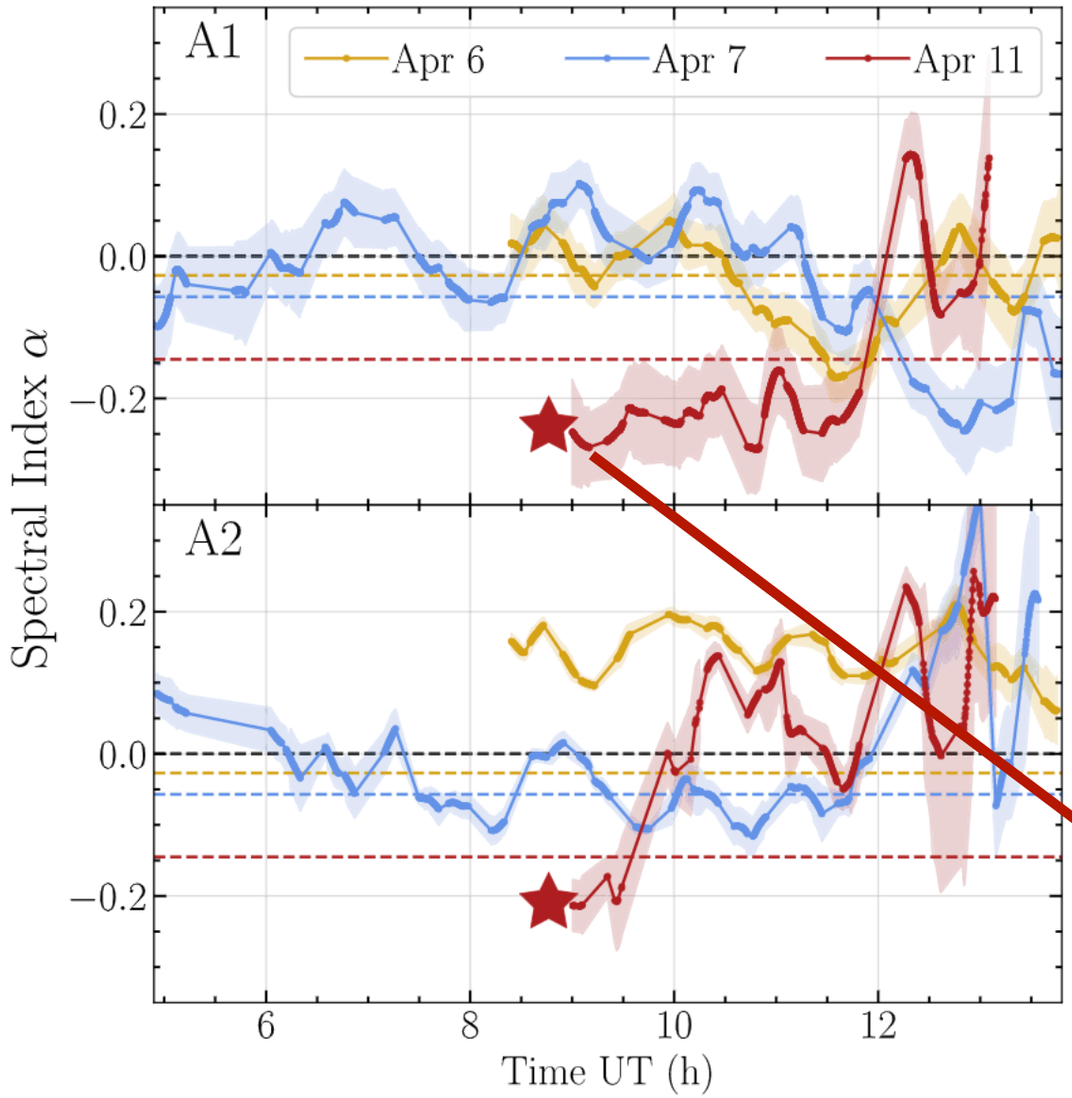
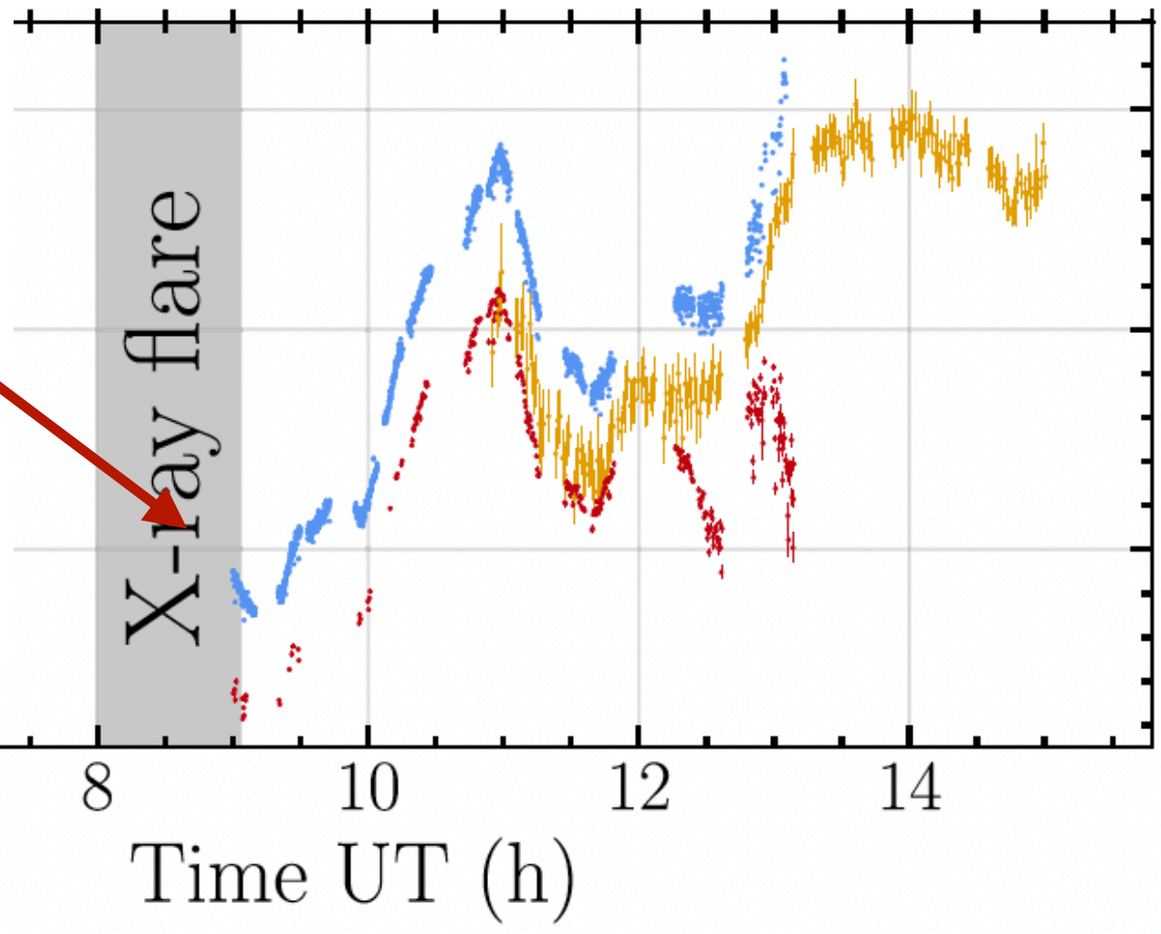


Immediately after the flare:

- decreasing mm flux density, recovering in ~2h
- more negative spectral index, recovering in 1-3h
- decreased optical depth?



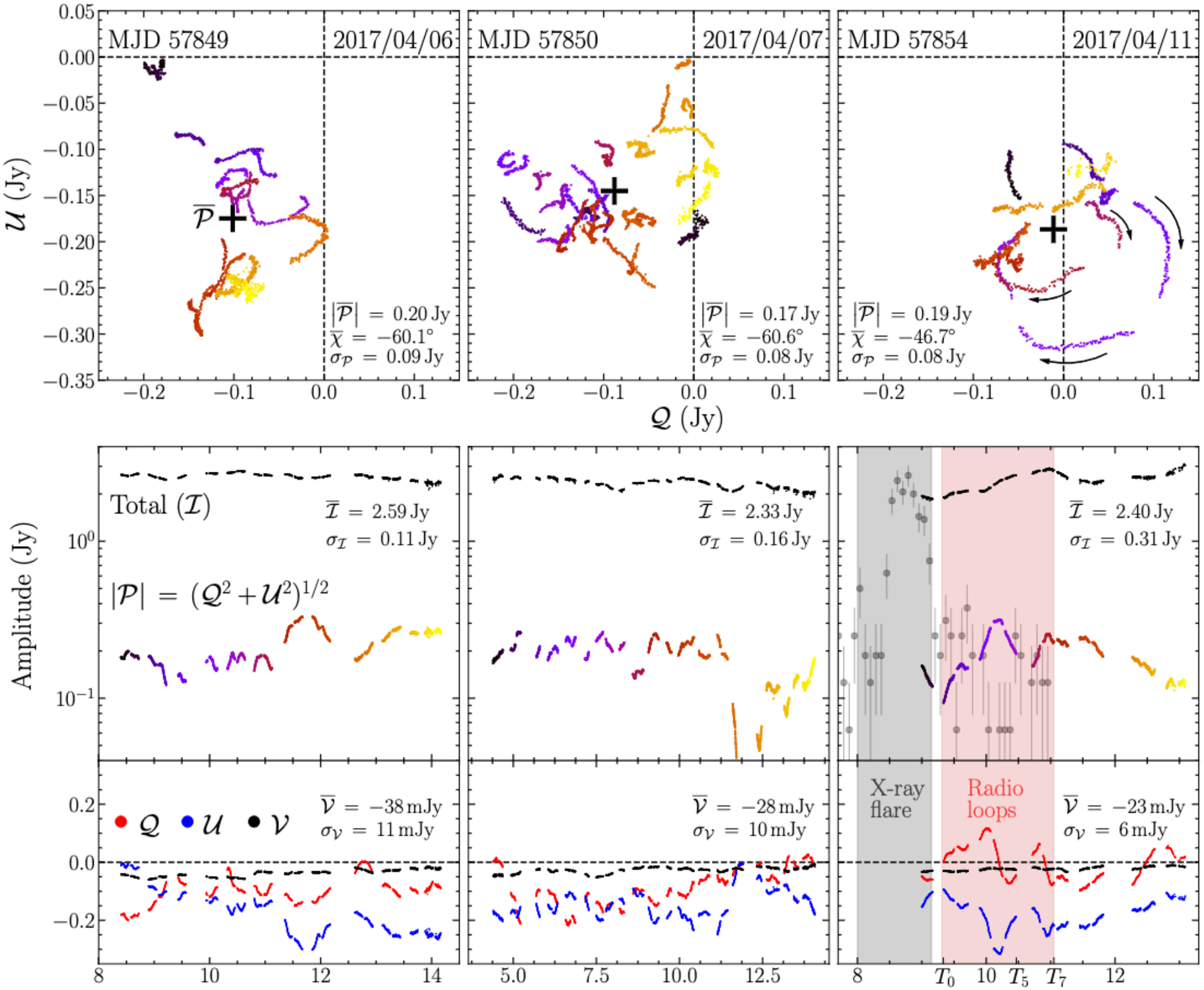
Full Stokes ALMA light curves in April 2017

2.5 Jy total flux

7-8% mean LP

persistent EVPA -60 deg

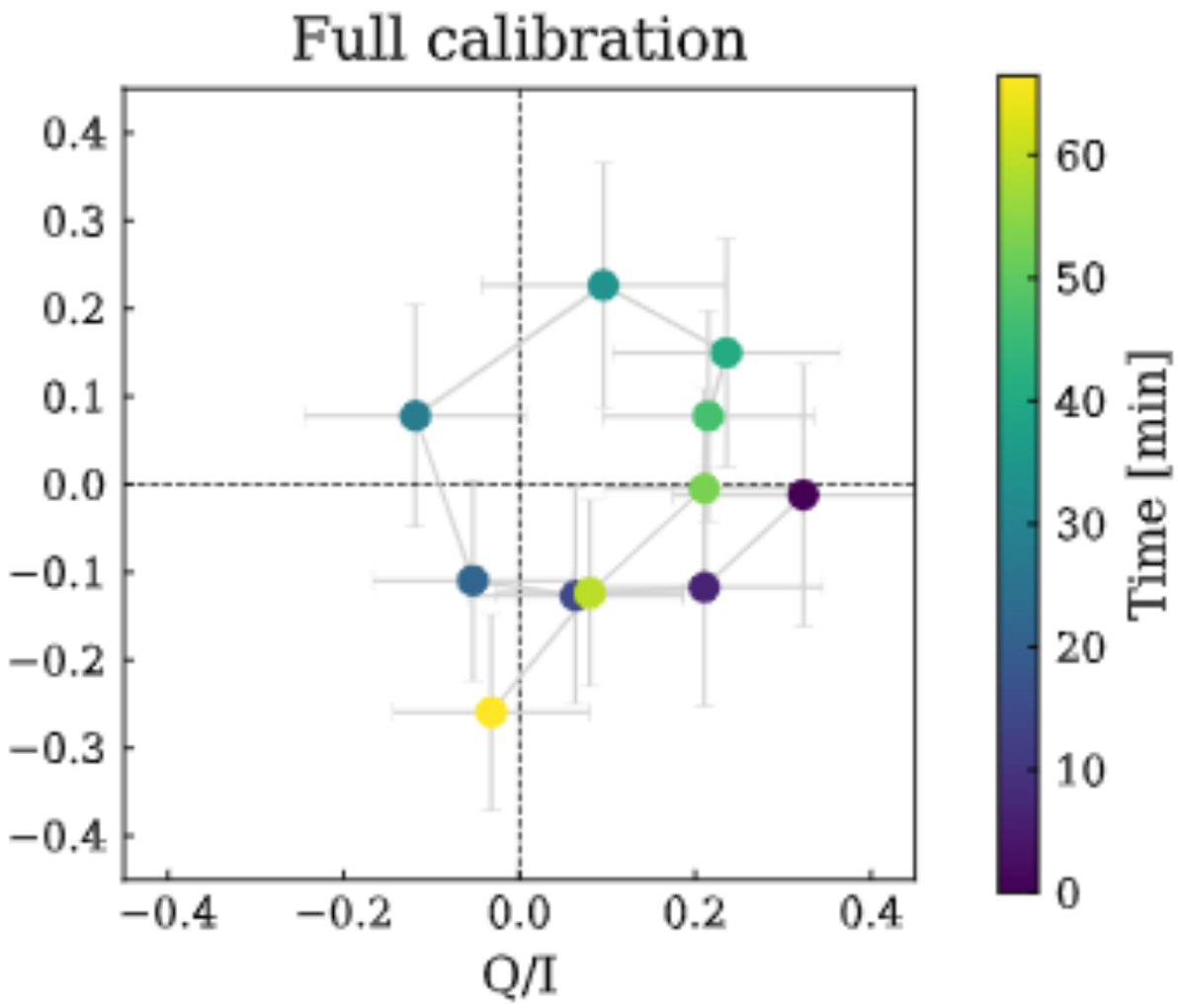
CP at -1.2%



Wielgus, Moscibrodzka, Vos et al., A&A Lett 2022

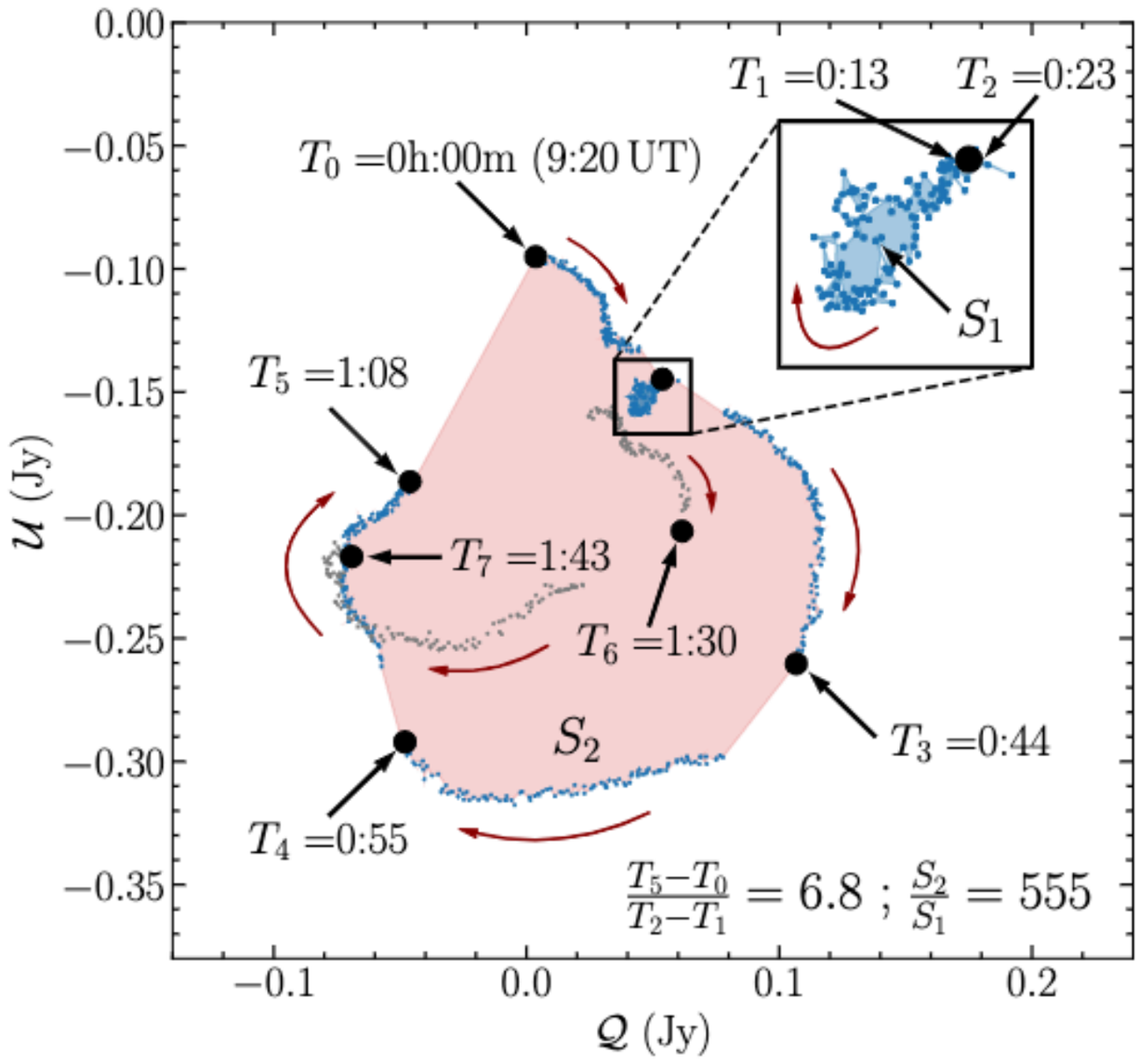
MPIfR

Loops on the LP plane



GRAVITY 2018

Jimenez-Rosales + GRAVITY, 2020



Wielgus, Moscibrodzka, Vos et al., A&A Lett 2022

Orbit ~70 min => Keplerian at 10-11M

MPIfR

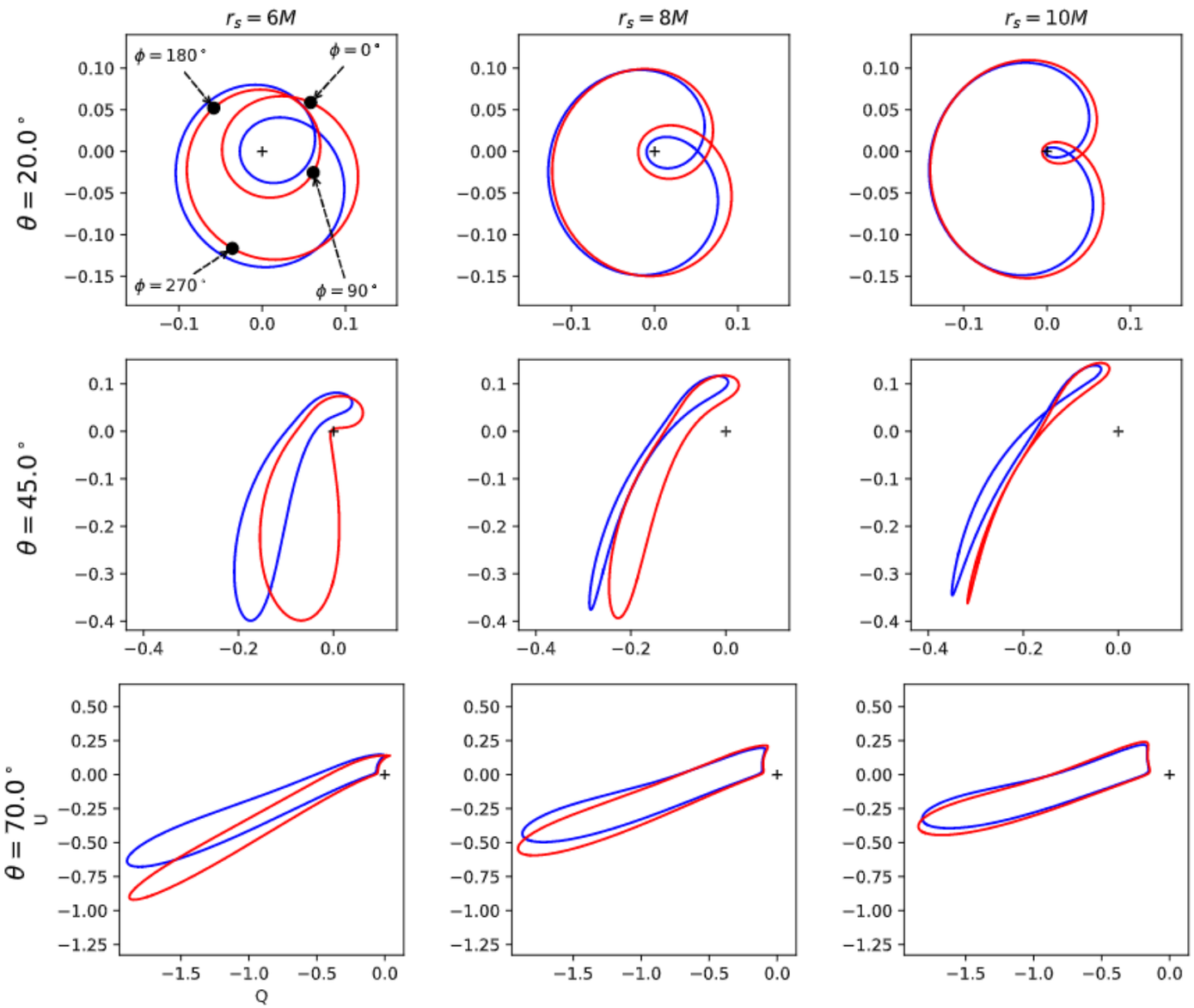
Toy model of a hot spot

QU loops appearance is a combination of synchrotron emission (kxB), special relativity (Doppler), general relativity (lensing, redshift, secondary images) - so in principle they carry the imprint of:

- magnetic field geometry
- viewing angle
- spacetime geometry
- hot spot orbit

QU signatures NOT super-intuitive, some pedagogical discussions:

Narayan, Palumbo, Johnson + EHTC ApJ 2021
Gelles, Himwich, Johnson et al. PRD 2021
Vos, Moscibrodzka and Wielgus, A&A 2022



Gelles, Himwich, Johnson, Palumbo, PRD 2021
(Keplerian orbits, vertical magnetic field)

formalism of Gralla & Lupsasca 2020 (following Carter 1970s) + Penrose-Walker constant

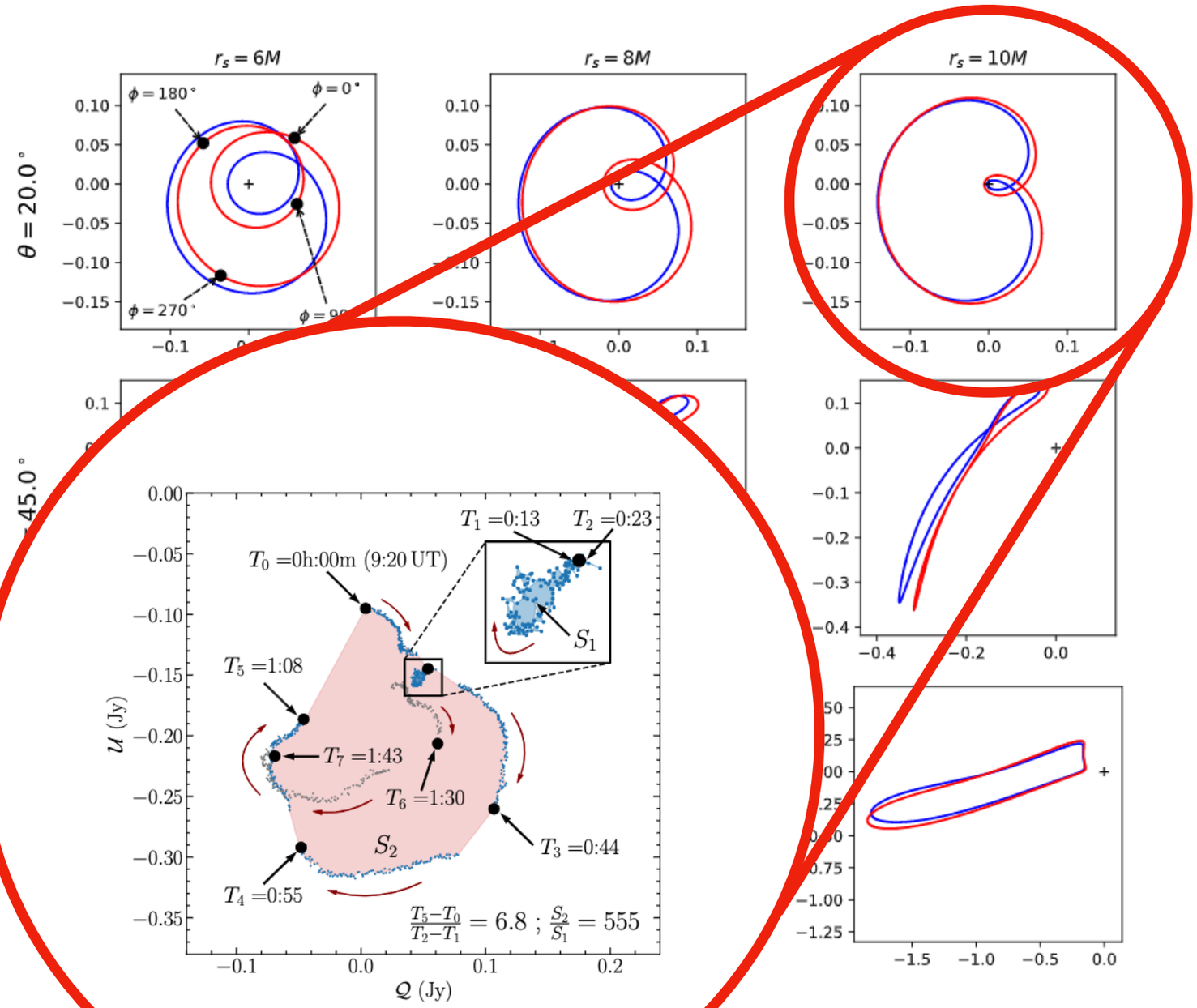
Toy model of a hot spot

QU loops appearance is a combination of synchrotron emission (kxB), special relativity (Doppler), general relativity (lensing, redshift, secondary images) - so in principle they carry the imprint of:

- magnetic field geometry
- viewing angle
- spacetime geometry
- hot spot orbit

QU signatures NOT super-intuitive, some pedagogical discussions:

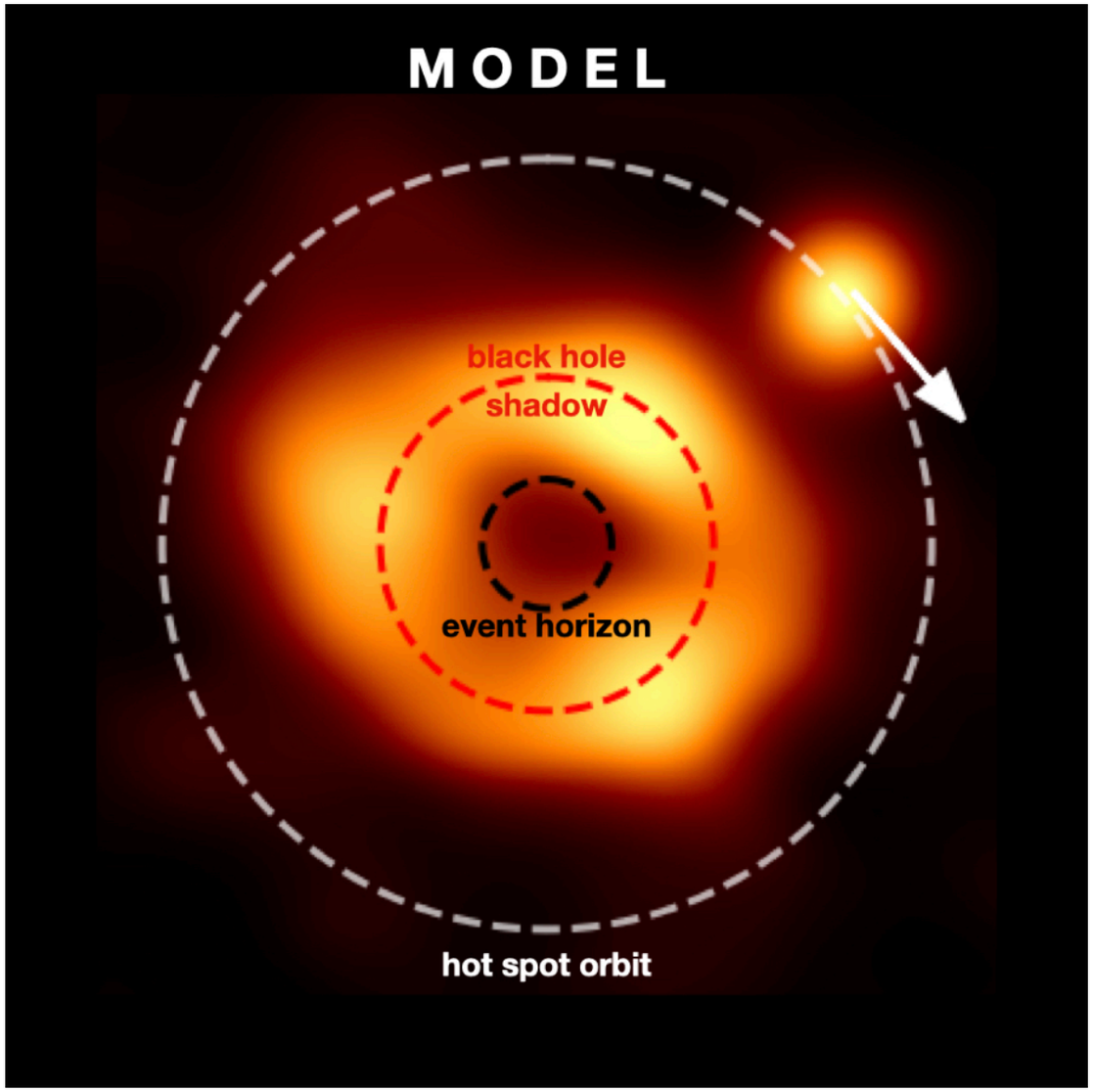
Narayan, Palumbo, Johnson + EHTC ApJ 2021
Gelles, Himwich, Johnson et al. PRD 2021
Vos, Moscibrodzka and Wielgus, A&A 2022

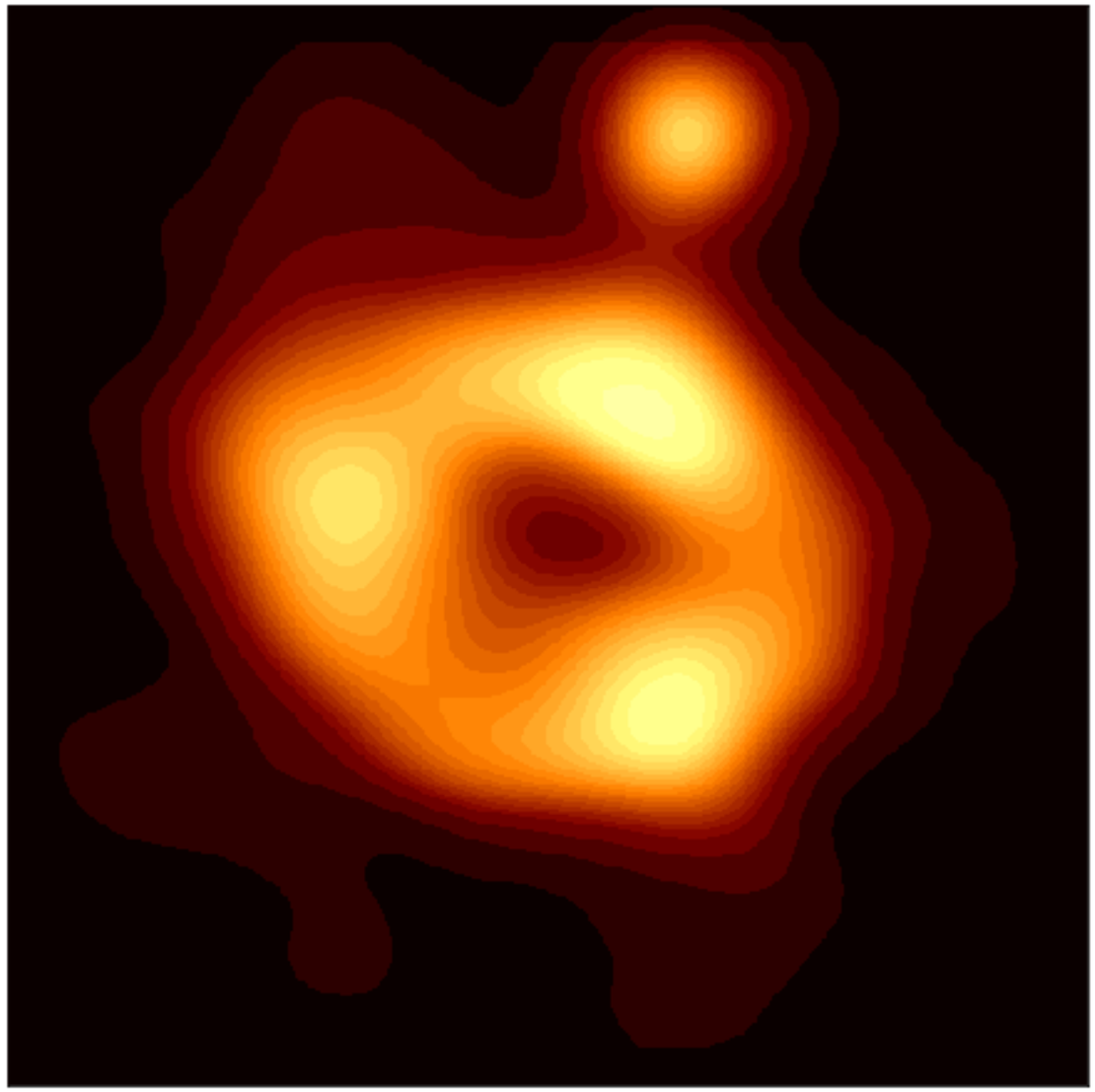


G alumbo, PRD 2021
(K tical magnetic field)

formalism of Gralla & Lupsasca 2020 (following Carter 1970s) + Penrose-Walker constant

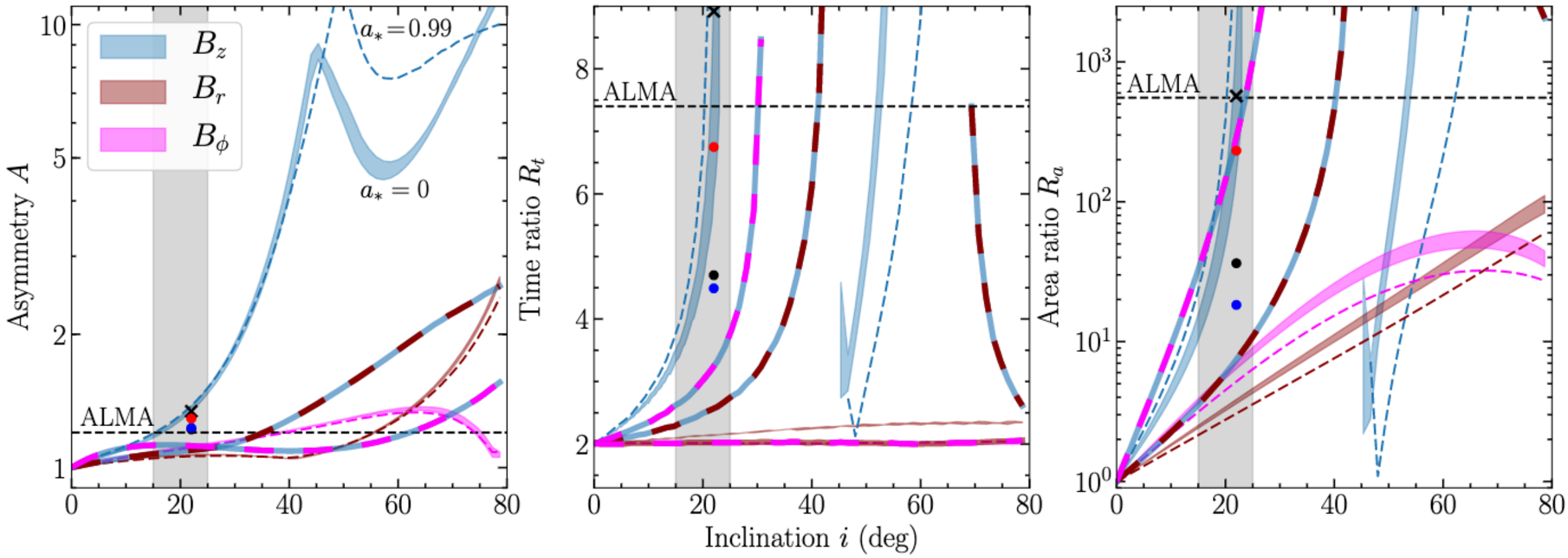
Toy model of a hot spot





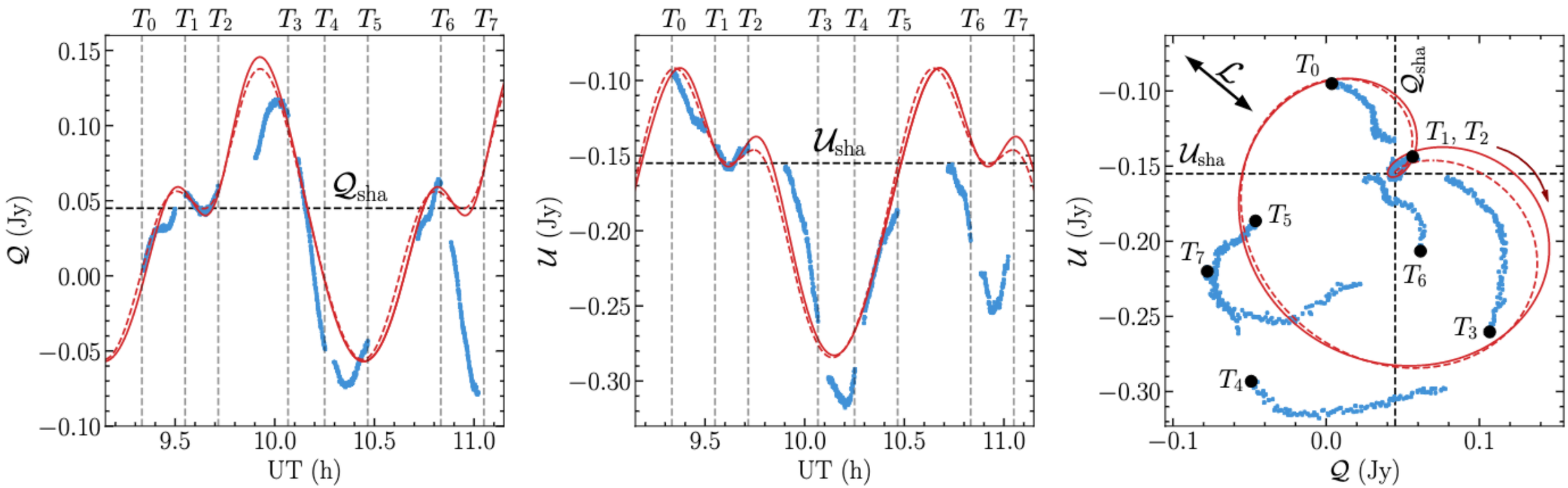
- inclination 22 deg, clockwise Keplerian orbit at 11M

Toy model of a hot spot - grid search



The toy model of Gelles et al. 2021 suggests **vertical magnetic field**, and low **inclination ~ 20 deg**

Toy model of a hot spot



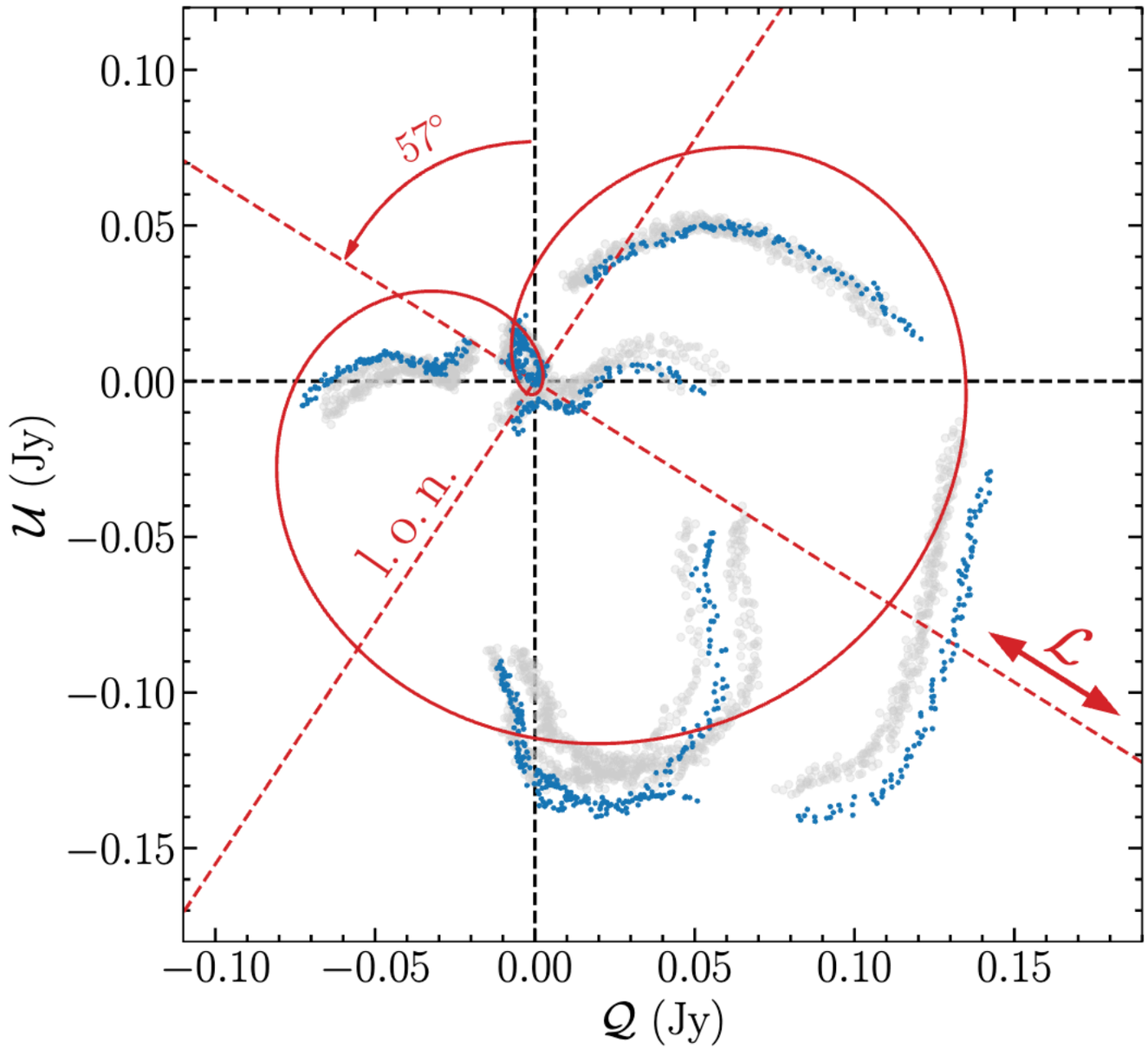
"Fiducial" model (full radiative transfer, slow light, finite size of the hot spot)
ipole model by Vos and Moscibrodzka

- pure vertical mf, inclination 22 deg, spin 0, clockwise Keplerian orbit at 11M
- 0.2 Jy bubble with 50% fractional LP, large bubble ~3-5 M diameter
- $n_e = 5 \times 10^5 \mathrm{cm}^{-3}$
- B = 10 G
- $\Theta_e = kT_e/m_e c^2 = 50$

May not look great, but given systematics and model simplicity, this is
REMARKABLY CONSISTENT

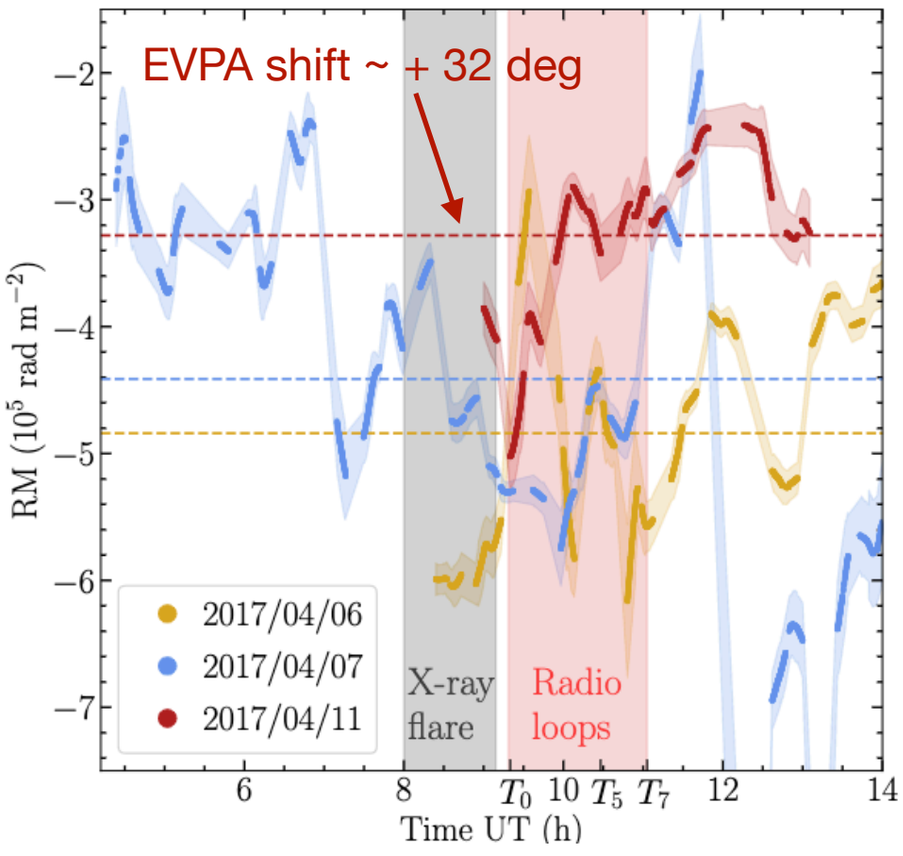
Toy model of a hot spot

Perpendicular to Galaxy angular momentum,
but consistent with GRAVITY nIR



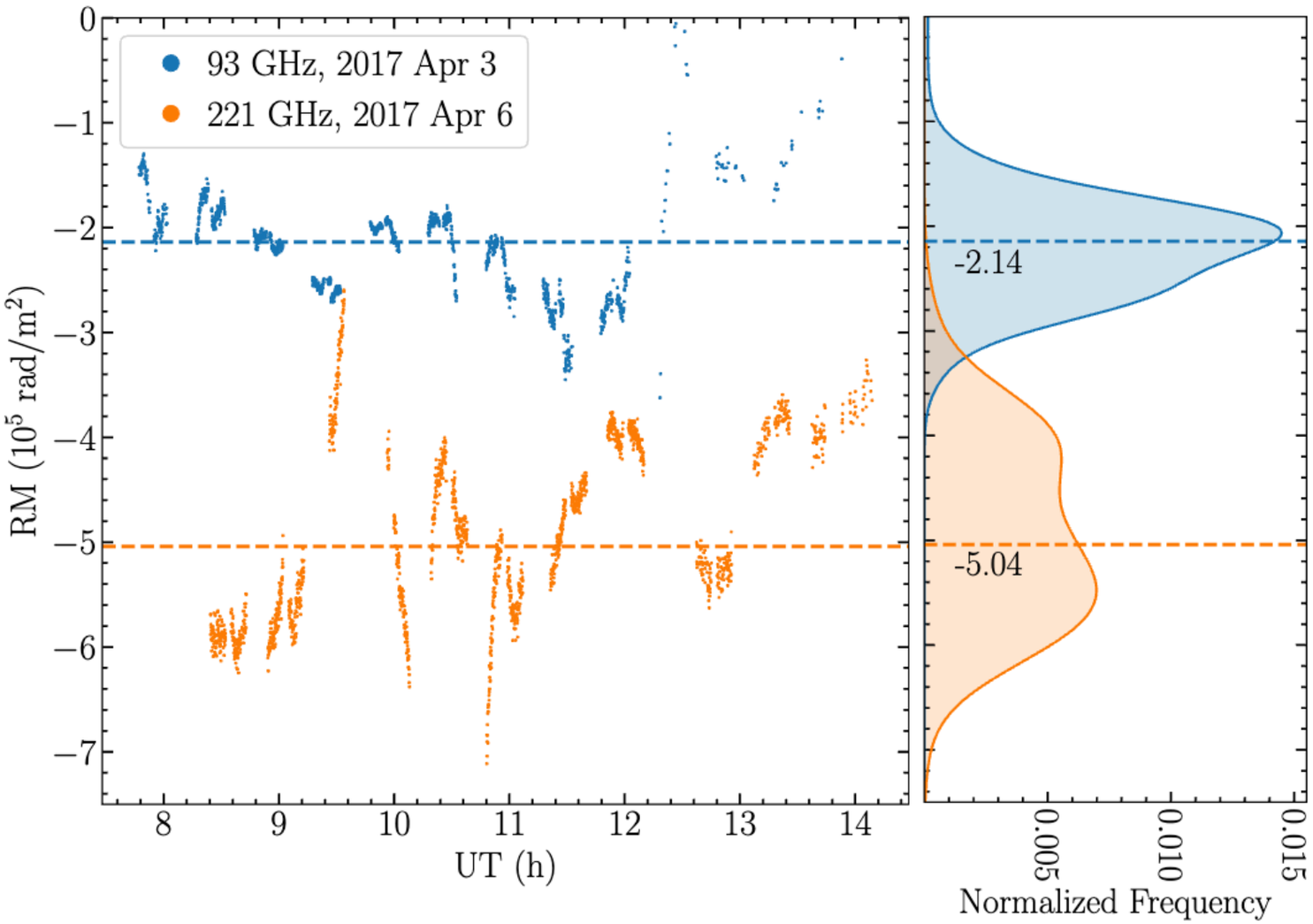
Rotation Measure

Lower Faraday depth during loopy period
Consistent sign across epochs
Variability on timescales of ~30min
Likely intrinsic Faraday screen is important

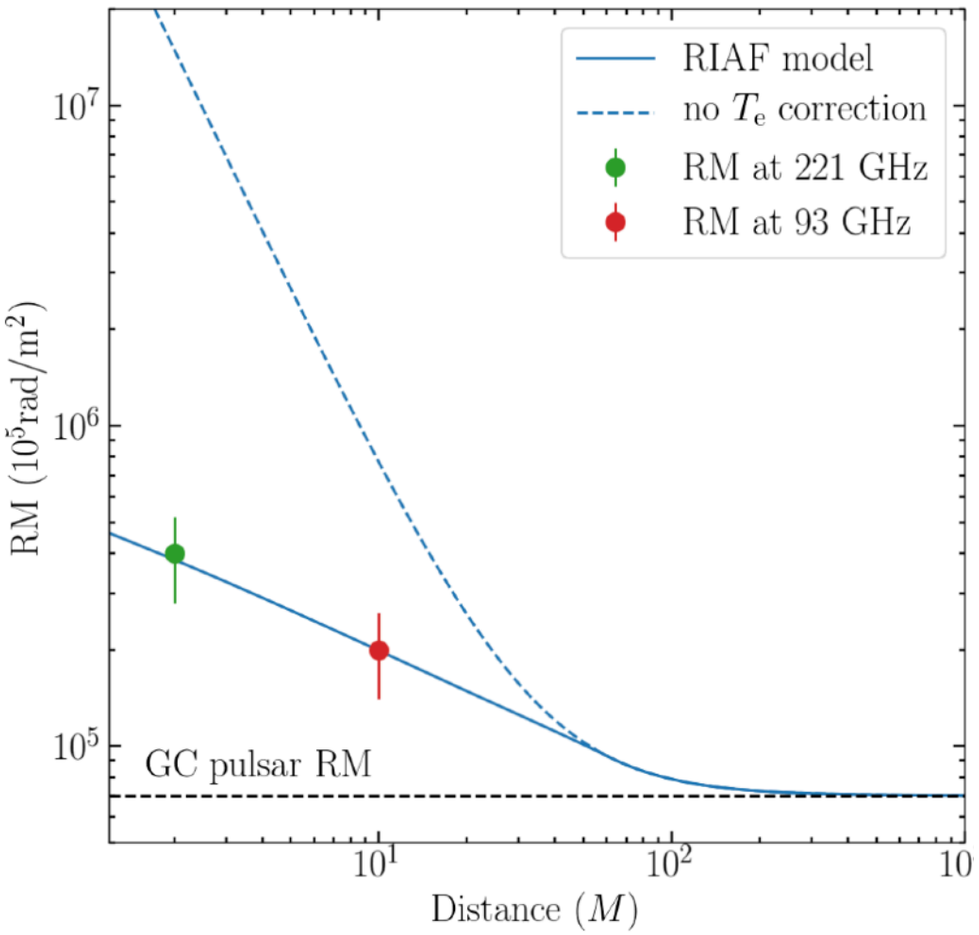


Caveat: removing mean Faraday rotation effects may involve large systematics of ~ 10 deg

A very recent update on the Faraday rotation



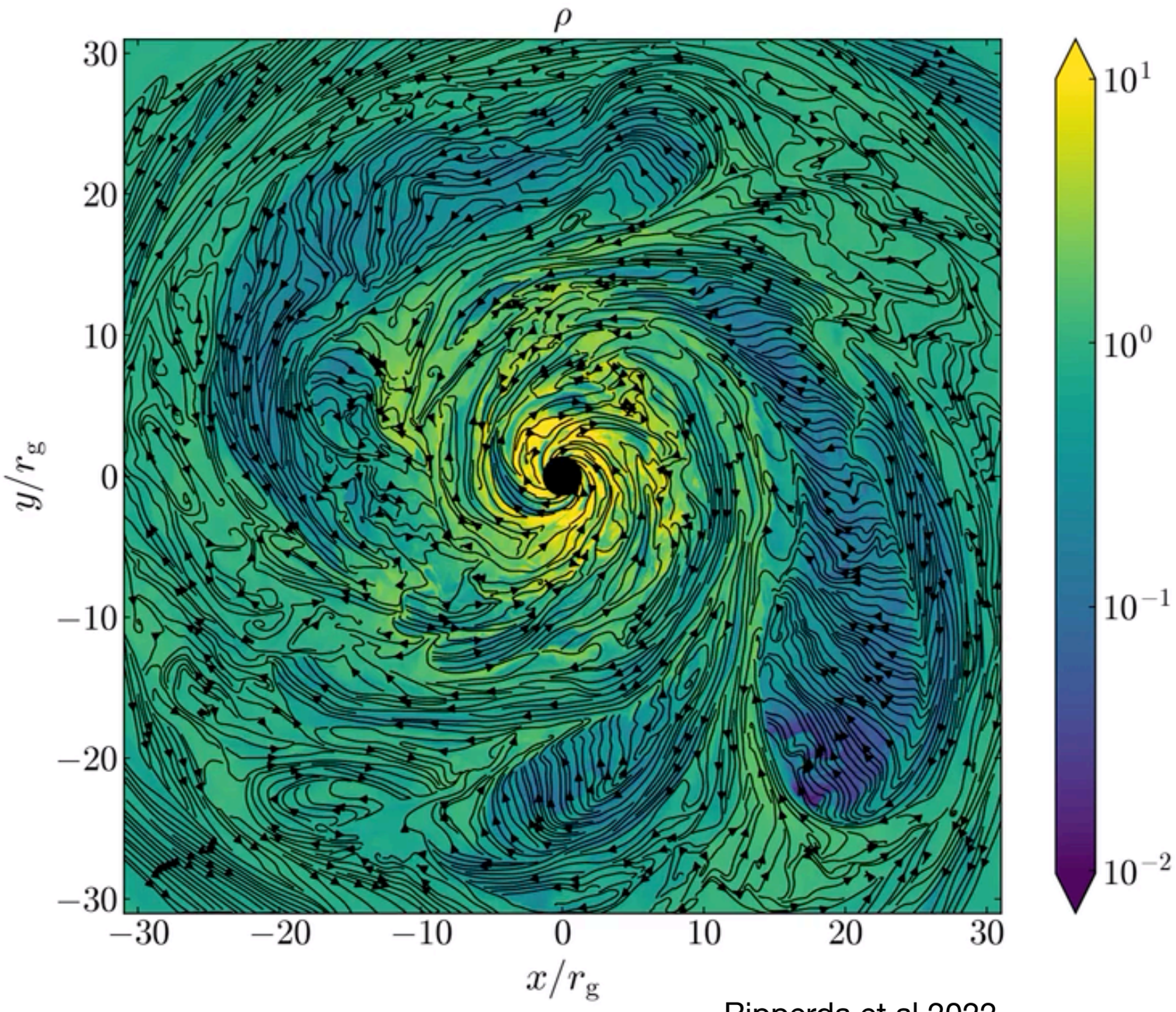
It appears that about half of the Faraday rotation takes place inside inner 10M!



Wielgus, Marti-Vidal, Issaoun, Emami, Moscibrodzka, et al. in prep

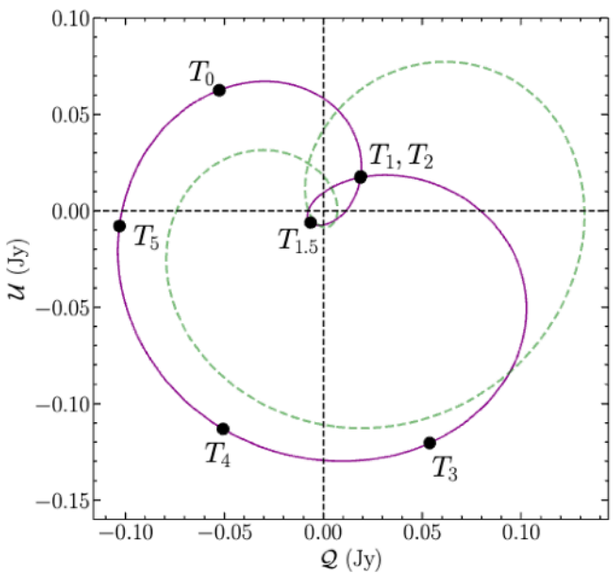
MPIfR

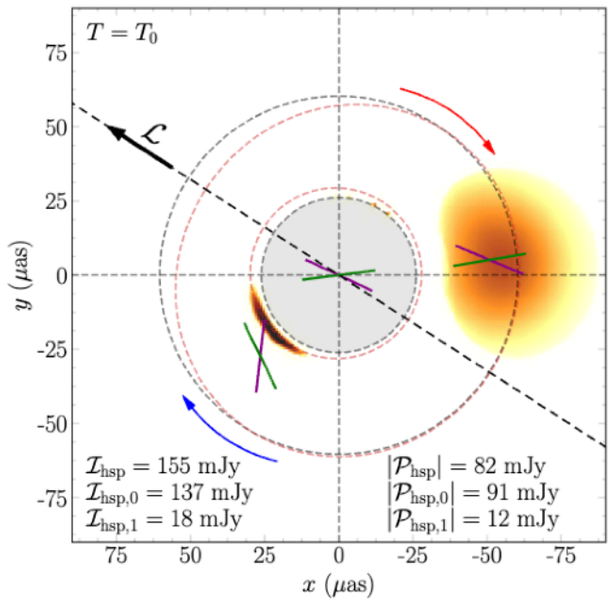
A flux tube? A “dark spot”? A bubble?

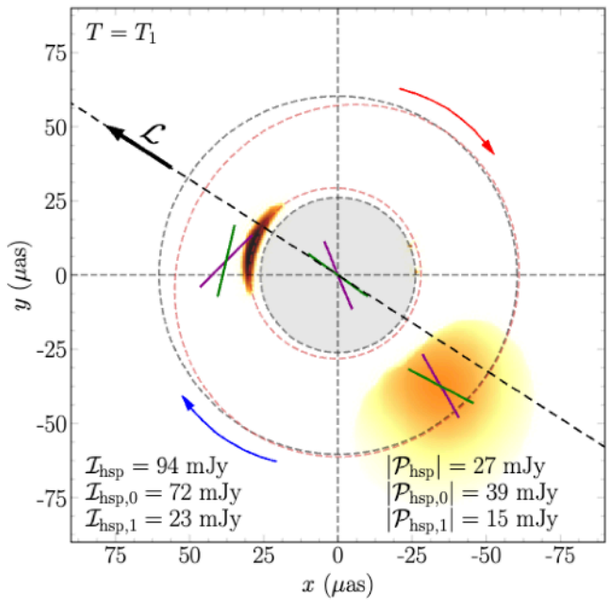


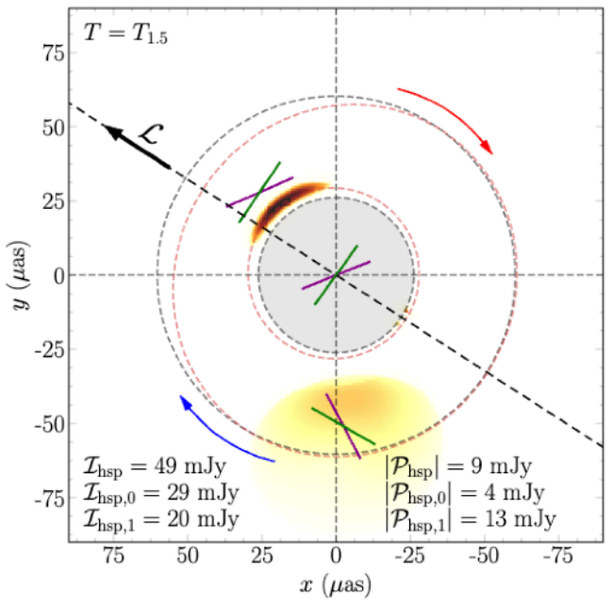
Ripperda et al 2022

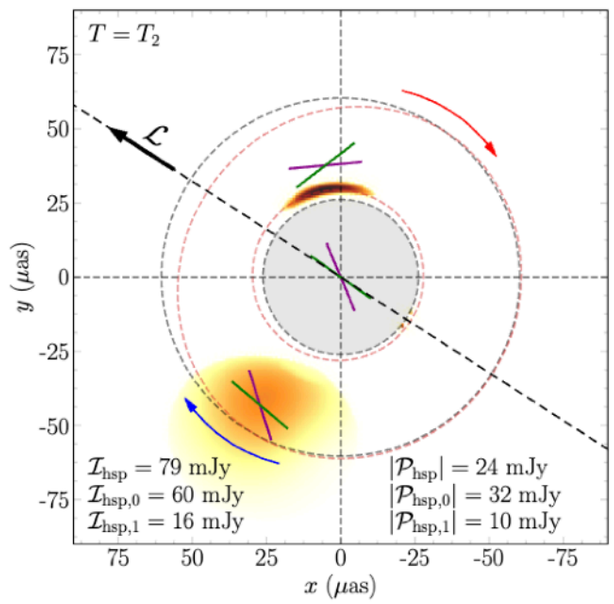
A prediction for the EHT analysis of the flaring day 11 Apr 2017

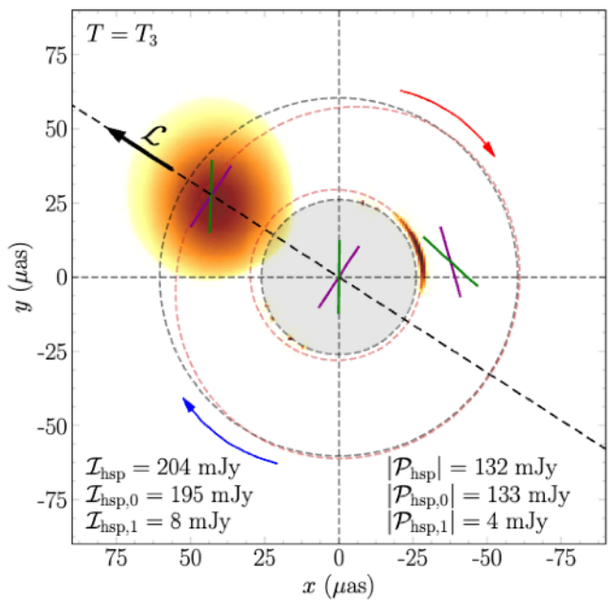


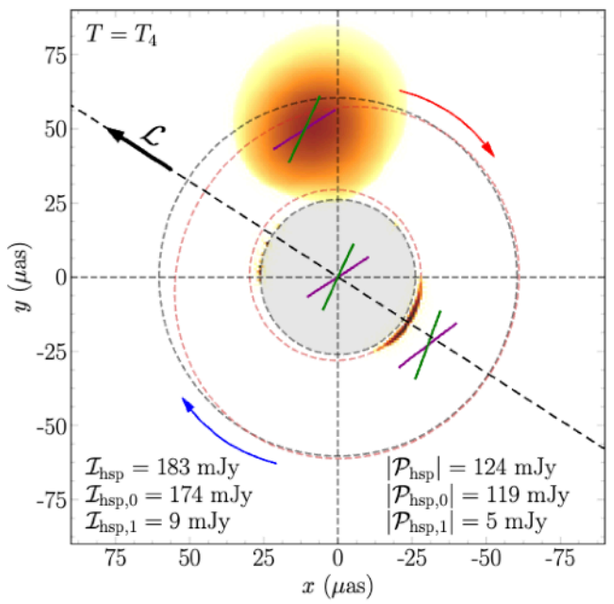


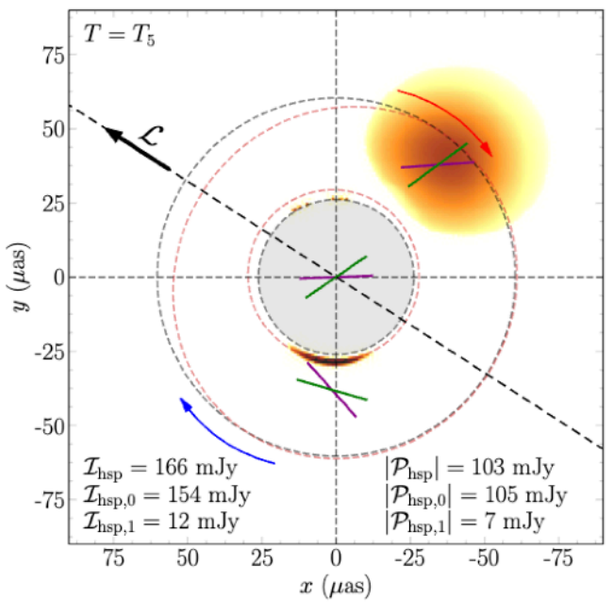












Wielgus, Moscibrodzka, Vos et al., A&A Lett 2022

Caveat: EHT observed with a very sparse array at that time…

Summary

- ALMA offers amazing SNR / time resolution to study Sgr A*
- constant sign of RM and CP - something about persistent magnetic structure in the compact source?
- flaring day much more variable in mm, flare affects spectral index, total flux drops and recovers in ~2h
- signatures of orbital motion in the flare aftermath, inclination, magnetic field, line of nodes, direction quite consistent with nIR
- I think it's MAD, spinning clockwise, model-dependent hints of positive spin
- GRMHD overproduce absolute variability but seem to be doing ok for the red noise slope
- probing lensing and secondary images?