UNIVERSITY OF BELGRADE

MATΦ University of Belgrade

On the complementarity of time domain techniques for detecting close binary supermassive black hole candidates

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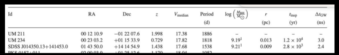
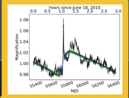
Time domain surveys



Graham +15,Liu+19

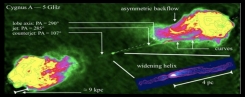
~>200 Binary SMBH candidates

Periodic emission , lensing



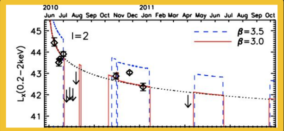
Graham+15, Hu+19

Jet morphology



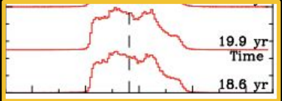
Gower +82, Krause +18

tidal disruptions by a binary



Liu, Li, Komossa+14 Huang+21

Emission-line dynamics



Bogdanović +09, Shen & Loeb +10;

((2)

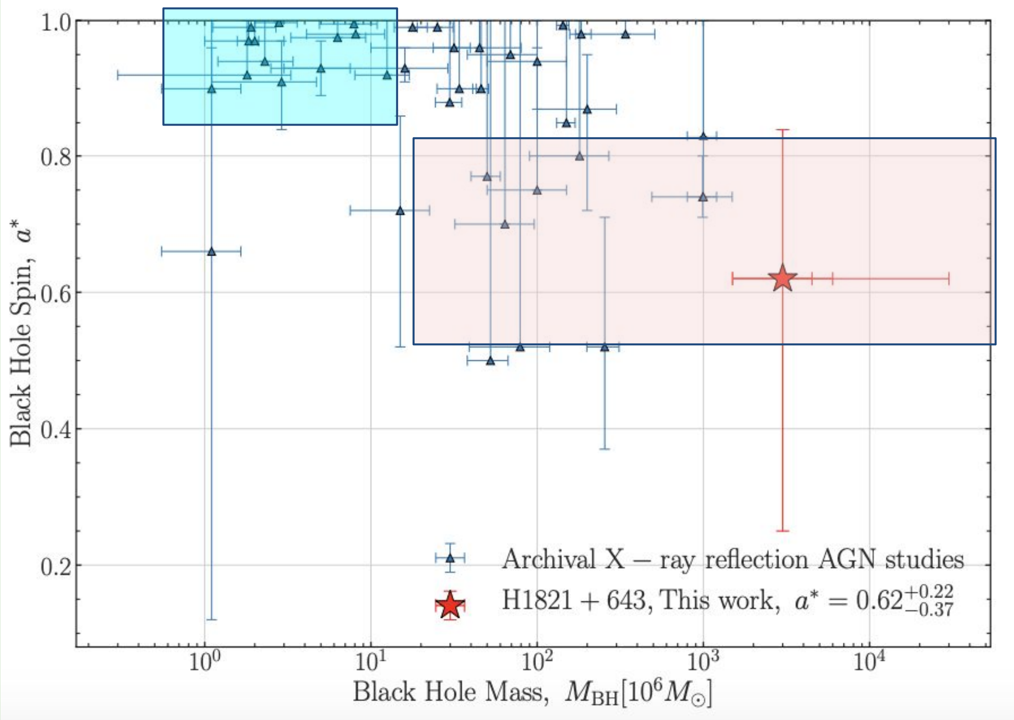
timeline

The spin conundrum

Not clear if SMBH should have a 'lot' of spin:

Angular speed of BH is
~[$10^5/M_{BH}/M_{sun}$]{a/(1+sqrt(1-a))} radians/sec

If a=0.9, mass=1e06Msun
~ 0.01 revolutions/sec

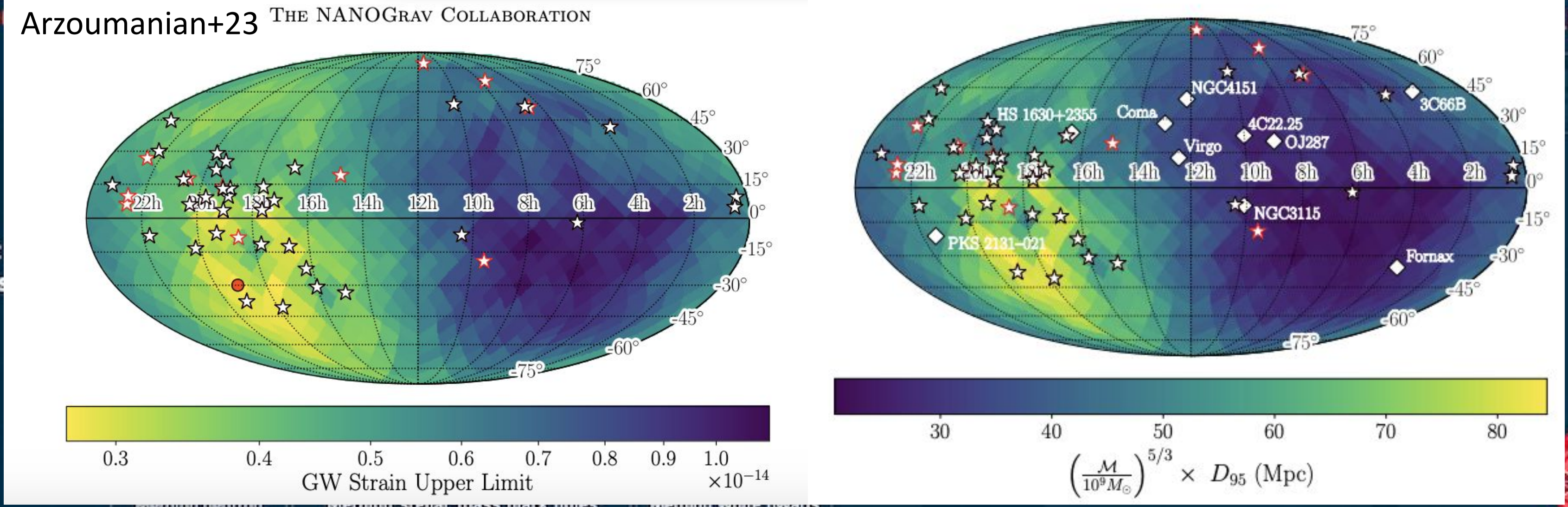


Raynolds+21,
Sisk-Reynes+22

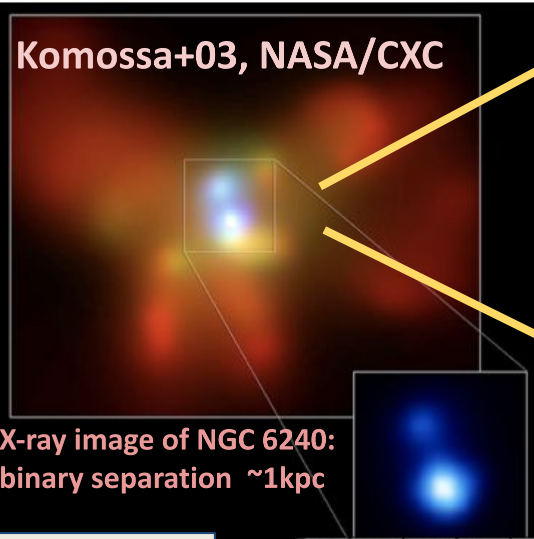
Gravitational waves from supermassive black hole binaries might be 'right around the corner'

NEWS!

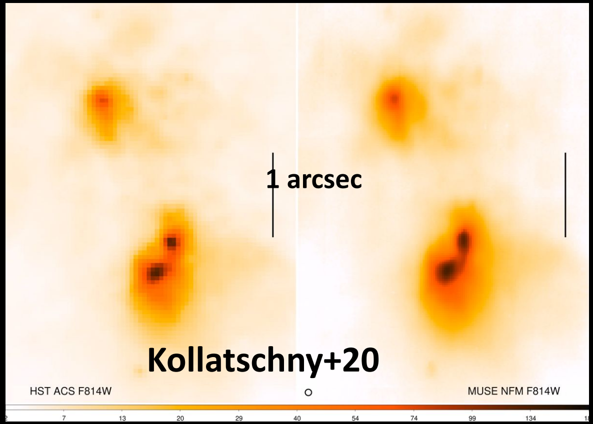
Arzoumanian+23



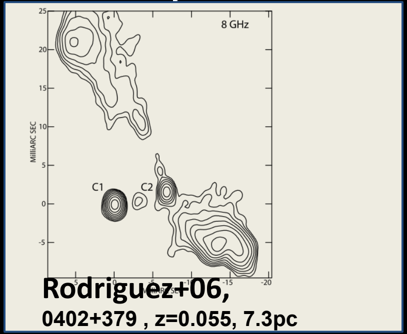
Astronomy images of the ~~day year~~ decade

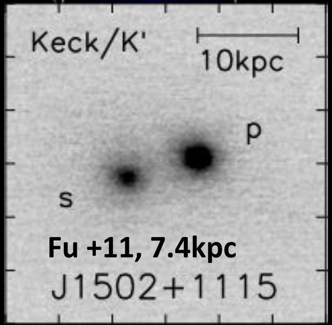


X-ray image of NGC 6240:
binary separation ~1kpc

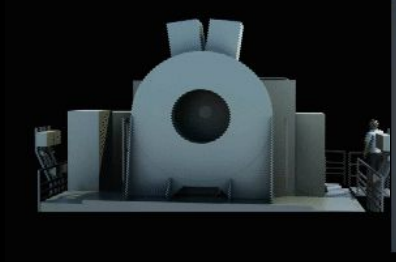


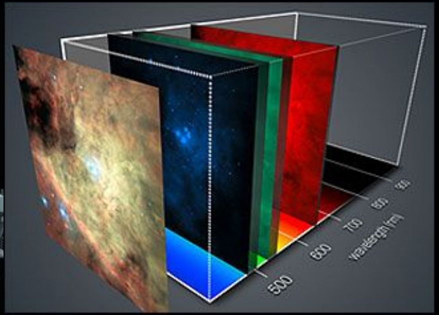
MUSE image of NGC 6240: A triple nucleus system in the advanced or final state of merging





MUSE@VLT ESO





Binary SMBH parameters hyperspace and imaging

IMAGE RECONSTRUCTION MODEL

Fredholm integral of the first kind

$$Y(r) = \int_{\Omega} h(r;r')\, X(r')\, dr',$$

observation — Response function — Image to reconstruct

Approximation

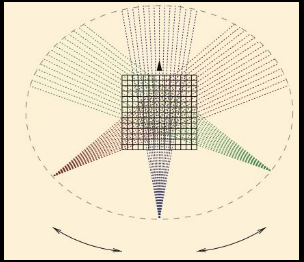
$$y = Hx + w.$$

$$(H)_{ij} = \int_{\Omega} h_i(r')\phi_j(r')\, dr', \; 1 \le i \le M, \; 1 \le j \le N,$$

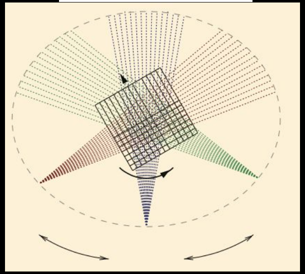
Discretization over pixels

$$X(r) = \sum_{j=1}^{N} x_j\, \phi_j(r).$$

Stationary Scenery



Kamalabadi +10



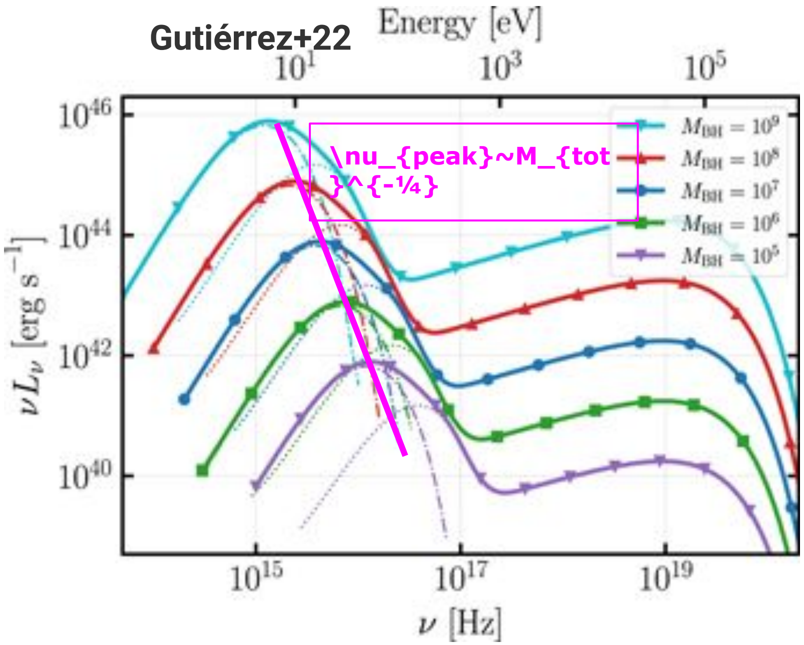
Non stationary Scenery

Inclusion of motion of object

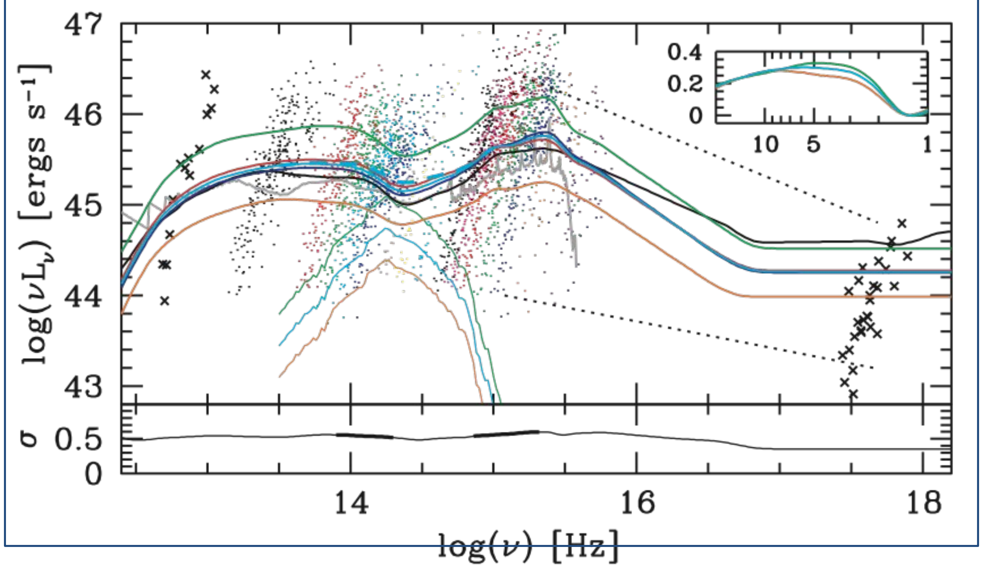
$$\begin{aligned} x_{i+1} &= F_i x_i + q_i \\ y_i &= H_i x_i + w_i \end{aligned}$$

discernible spectral binary SMBH signatures

Gutiérrez+22



Richards+06



L_tot~M_{tot},

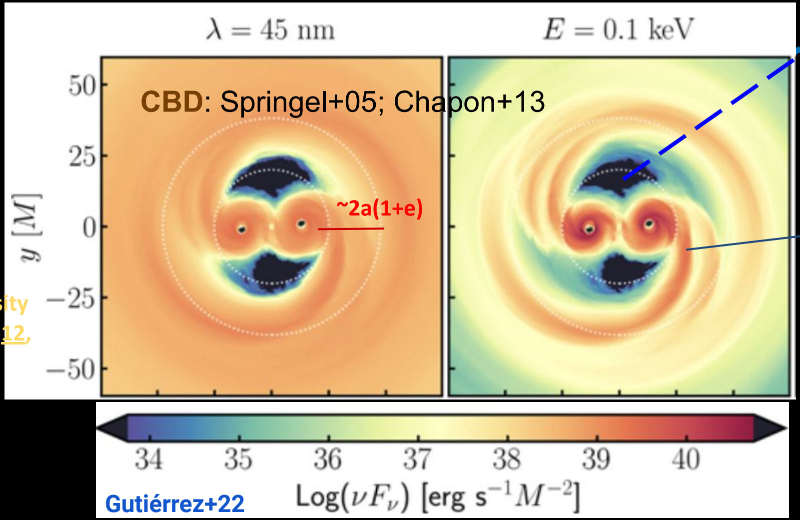
P~M_{tot}⇨ [<2 days, few years]

ELECTROMAGNETIC EMISSION AND INFORMATION LOSS

SCHEME OF BINARY SMBH EM

MINIDISC~f(*r*ISCO/*r*trunc)
*r*trunc ~0.35–0.4 *r*12
(Bowen+17);

LUMP: *q* > 0.1, *m* = 1 density mode, the lump, (Noble +12, Shi +12, Farris +14, Noble+21)



CAVITY:MacFadyen&Milosavljević08,D'Orazio+13,Farris+14,D'Orazio+16,Miranda+17,Muñoz+19,+20,Tiede+20,Derdzinski+21,Newtonian3D-MHD Shi+12,
3D-GRMHD Noble+12, +21, Bowen+18, +19 Farris +11
Paschalidis +21, Cattorini +21

thin ballistic stream Shi & Krolik 15

$\Omega_{\rm beat} \equiv \Omega_B - \langle\Omega_{\rm lump}\rangle \sim 0.72\,\Omega_B$

$\langle\Omega_{\rm lump}\rangle = 0.28\,\Omega_B$ Lopez Armengol+21; Noble+21

minidisc masses modulation freq $\sim \Omega_{beat}$

minidisc masses+ lump ang.vel. $\Omega_{\rm lump}$ modulation freq $\sim (0.2-0.4)\Omega_{\rm binary}$ and $2\Omega_{beat}$

binary torques do not completely halt mass accretion (MacFadyen & Milosavljević 08; Shi +12; Farris +14; Shi & Krolik 15).

Hydro variab < Doppler, q<~0.05 Farris+14, D'Orazio+15,+16

Doppler < hydro variab. In q=1, orbital Mach v_kep/cs<~20 Tang+18

ordered spikey/noisy

$$L^{\rm obs}_{\rm tot}(t) = \langle L_{\rm tot}\rangle\,(1 + \delta_{\rm Doppler}(t) + \delta_{\rm hydro}(t)),$$

Non-face-on Face-on
⇑with sin i

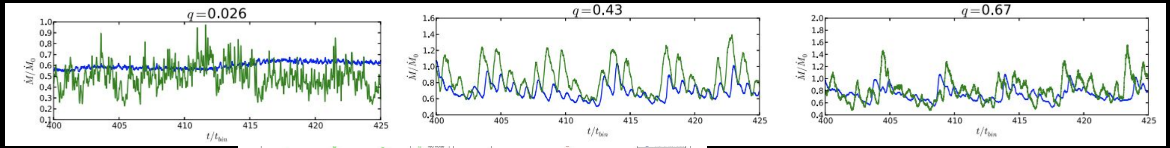
Parity of Doppler and hydro when:

$$v/c \simeq \frac{1.5}{3.44\,b}\left(\frac{1+f}{1-f}\right)\max\{b\bar{A}_{\rm MD},(1-b)\bar{A}_{\rm CBD}\}$$

→ very high orbital velocities, v/c ~ 0.12 − 0.16

Gutiérrez+22

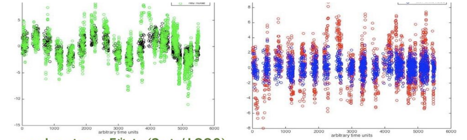
Red Noise: Mimicking ordered information



Burst model (Farris+14)

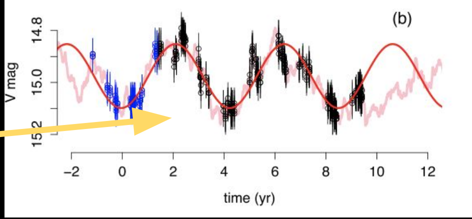
Periodicity signal immersed in red noise

Red Noise mimics periodicity (Vaughan+16)



red noise +5*sin(2pit/1880)
white noise+ 5*+sin(2pit/1880)

red noise +0.1*sin(2pit/1880)
white noise + 0.1*+sin(2pit/1880)



The power spectral density (PSD) for the DRW is (Kelly+09)

$$dX(t) = -\frac{1}{\tau}X(t)dt + \sigma\sqrt{dt}\,\epsilon(t) + b\,dt, \quad \tau, \sigma, t > 0. \quad (1)$$

$$\mathrm{PSD}(f) = \frac{\tau^2 \mathrm{SF}_\infty^2}{1 + (2\pi f \tau)^2}.$$

$$PSD \propto f^{-2}, for\ f > 1/(2\pi\tau)\ red\,noise$$

$$PSD \propto const(i.e. const \times SF_\infty^2), for\ f < 1/(2\pi\tau)\ white\ noise$$

light crossing time scale

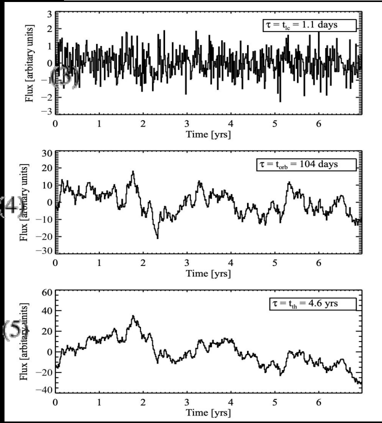
$$t_{\rm lc} = 1.1 \times \left(\frac{M_{\rm BH}}{10^8\,M_\odot}\right)\left(\frac{R}{100R_S}\right)\ \text{days},$$

the gas orbital timescale

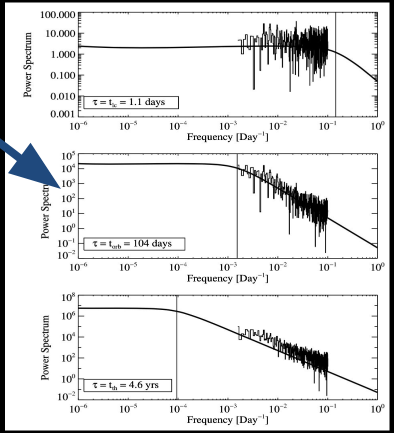
$$t_{\rm orb} = 104 \times \left(\frac{M_{\rm BH}}{10^8\,M_\odot}\right)\left(\frac{R}{100R_S}\right)^{3/2}\ \text{days},$$

accretion disk thermal timescale

$$t_{\rm th} = 4.6 \times \left(\frac{\alpha}{0.01}\right)^{-1}\left(\frac{M_{\rm BH}}{10^8\,M_\odot}\right)\left(\frac{R}{100R_S}\right)^{3/2}\ \text{yr},$$

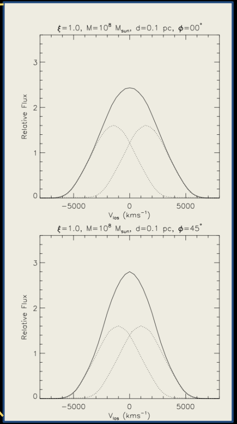


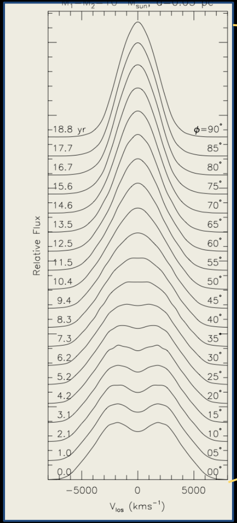
Fourier transform



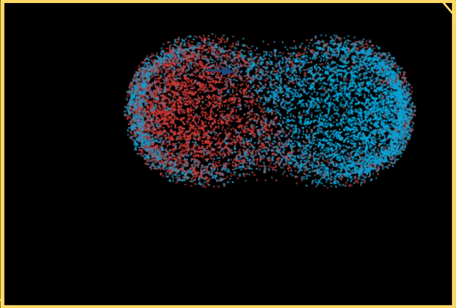
Kelly+09

LOSS OF BINARY INFORMATION

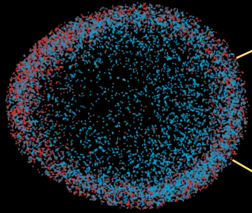


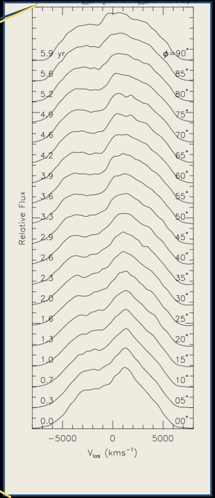


optimal



Shen &Loeb+10

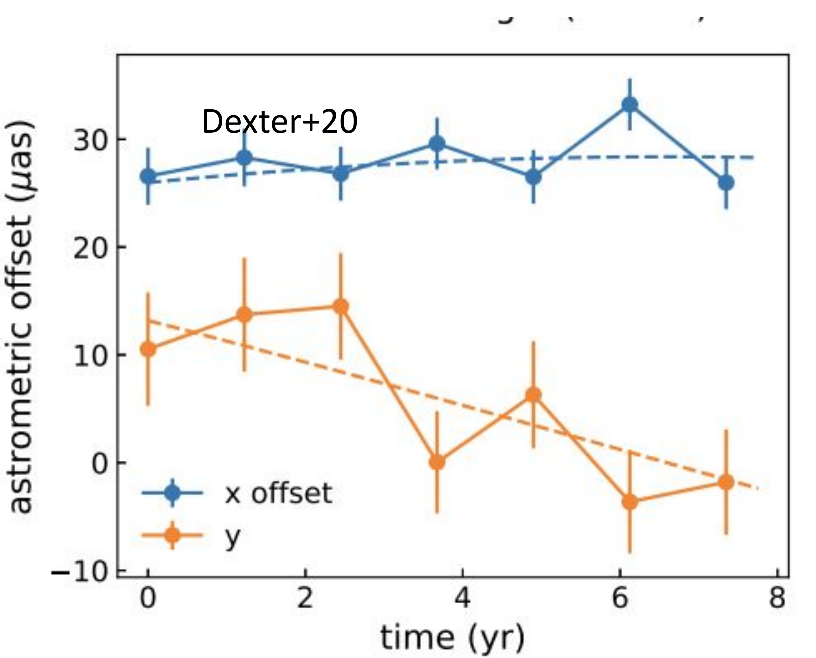


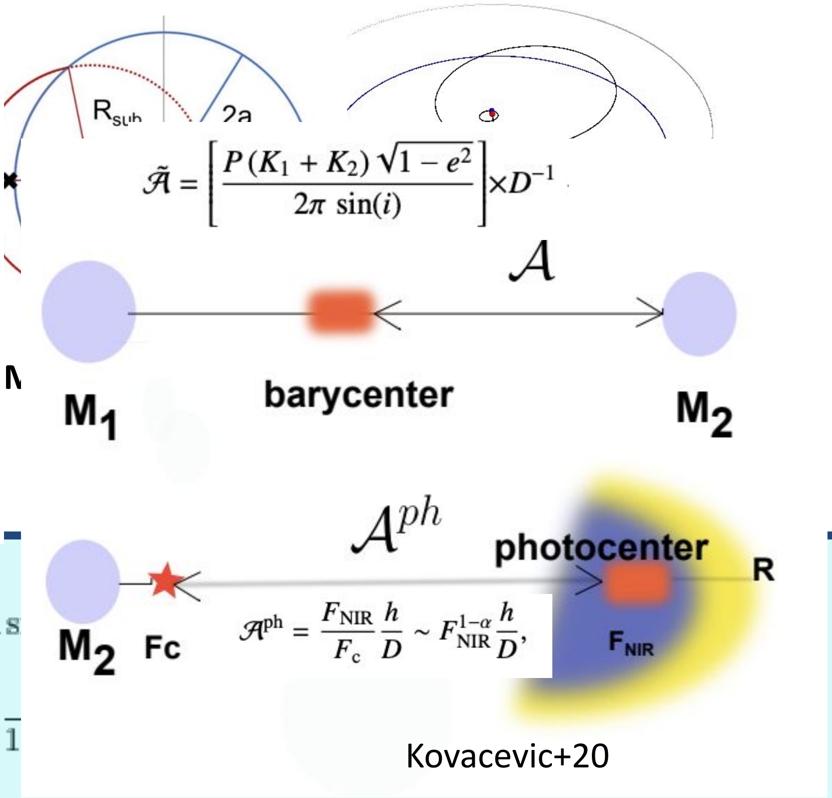


Early works: Popovic+00, Comerford +09; Bogdanovic+09a,b; Boroson & Lauer+09; Xu & Komossa+09; Wang+09; Smith+10; Liu+10, Chornock+10; Gaskell+10 Koss+11; Eracleous+11

NEW TECHNIQUES FOR FURTHER VETTING OF BINARY CANDIDATES

DYNAMICAL+BRIGHTNESS ASTROMETRY GRAVITY+





Circular SMBBH

$$tech \sim \Delta t_P = \frac{P}{T_{obse\_base\_line}}$$

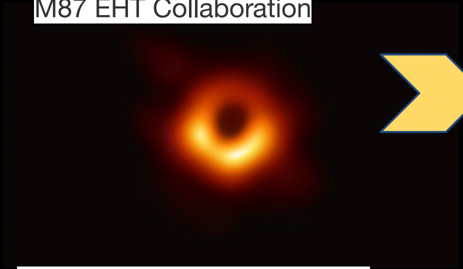
$\mathcal{O}(t) \sim As$

$A \in \{$

Radial velocity Dynamical Astrometry

Astrometry with ngEHT, ng VLA

M87 EHT Collaboration

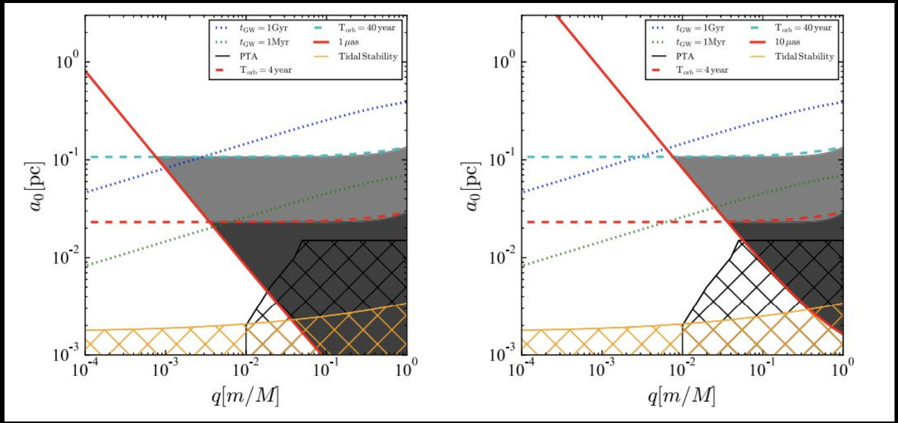


Brighter Jy levels
230 GHz (1.3 mm)

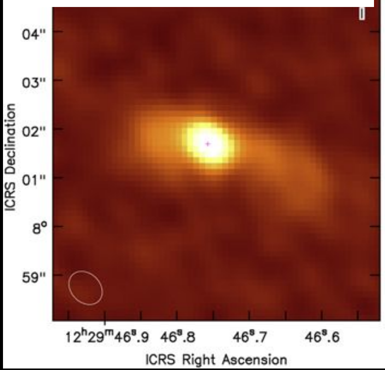
Safarzadeh+19

$$a = \frac{q}{1+q} \times a_0$$

$$a_t = r(1 + q^{1/3})$$



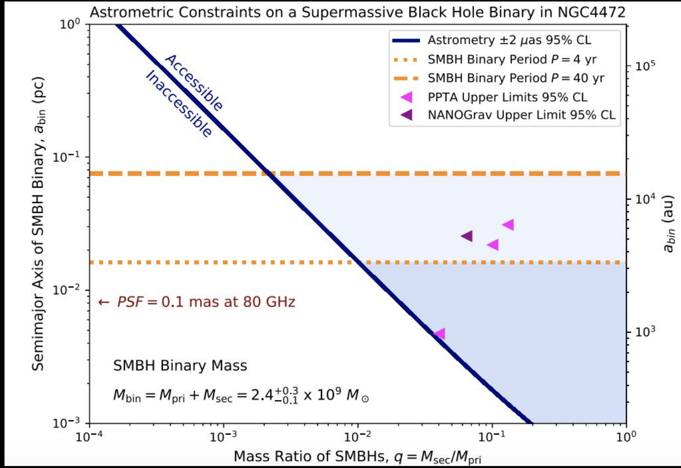
NGC 4472 ALMA 98 GHz



Fainter mJy level

80 GHz (3.7 mm)

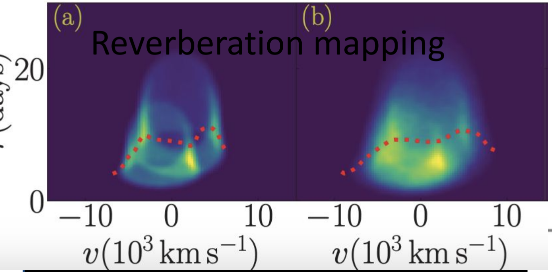
Wrobel & Lazio+22

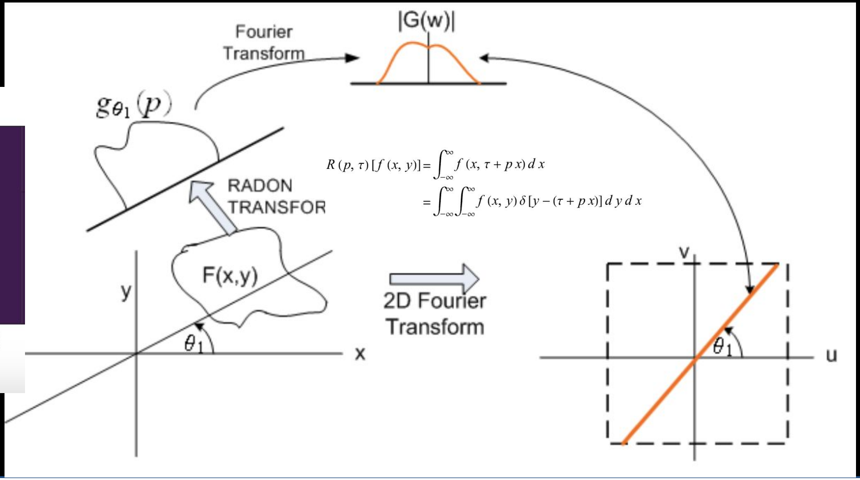


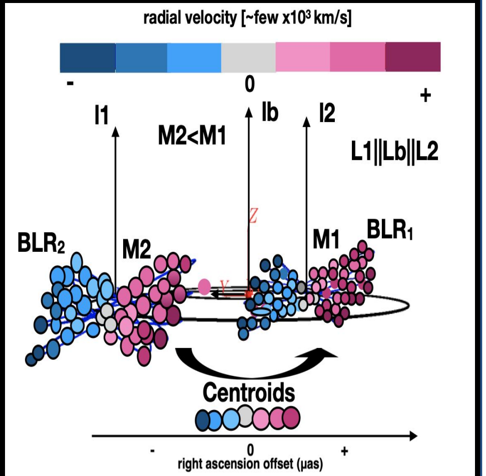
ng VLA

2D REVERBERATION MAPPING ⊥ INTERFEROMETRY OF BINARY SMBH

2D RM Circular SMBBH
Wang+18





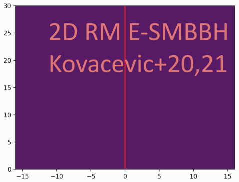


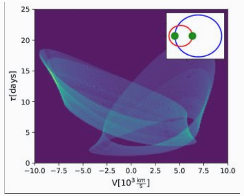
circular binary

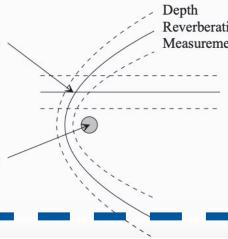
elliptical binary

RM+OI

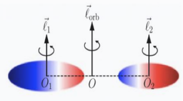
2D RM E-SMBBH
Kovacevic+20,21



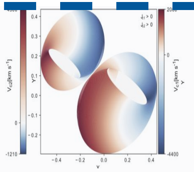




Woillez+03



Songsheng+19



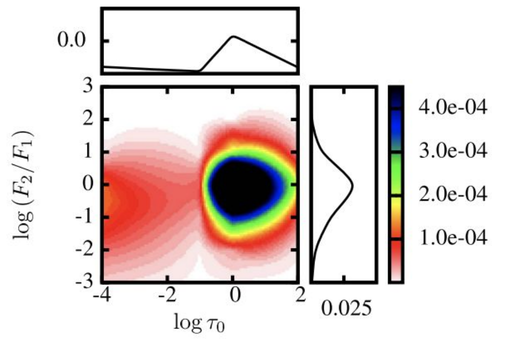
Kovačević+20

Reverberation mapping-taking into account motion of binary SMBH

First Atlases of kinematic signatures

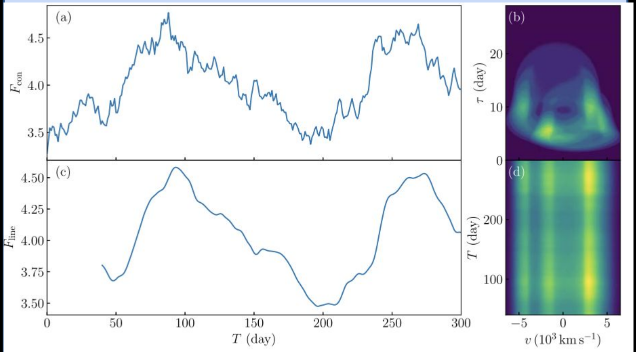
PCA of 1D RM data
Nguyen+20

Circular SMBBH
Songsheng +20



$$w(\boldsymbol{F}^s, \boldsymbol{F}^o) = \begin{cases} e^{-5\,d/d_c}, & \{a, q, e, i\} \text{ repeat} \\ 0, & \{a, q, e, i\} \text{ do not repeat} \end{cases}$$

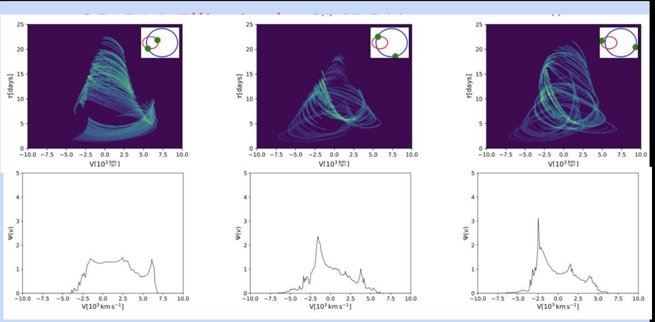
$$\Pr(x = x') = \frac{\sum_{s=1}^{\mathcal{N}} \mathrm{w}(\boldsymbol{F}^s, \boldsymbol{F}^o)\colon x(\boldsymbol{F}^s) = x'}{\sum_{s=1}^{\mathcal{N}} \mathrm{w}(\boldsymbol{F}^s, \boldsymbol{F}^o)},$$



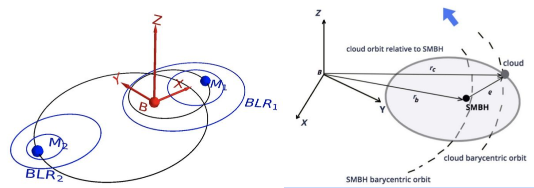
$$\Psi_{1,2}(v, t) = \int d\boldsymbol{R}_{1,2}\, \mathcal{H}_{1,2}(v, \boldsymbol{R}_{1,2})\,\delta(t_{1,2}),$$

$$\Psi_{\rm tot}(v, t) = \frac{\Psi_1(v, t)}{1 + \Gamma_0} + \frac{\Psi_2(v, t)}{1 + \Gamma_0^{-1}},$$

$$\tau = \frac{\int t\,\Psi_{\rm tot}(v, t)\,dt}{\int \Psi_{\rm tot}\,dt}.$$



$$\Psi(v, \tau) = \epsilon_0 \int_{R_{\rm in}}^{R_{\rm out}} \varrho^{-q} d\varrho \int_0^{2\pi} d\Omega \int_{-i_{\rm min}}^{i_{\rm max}} \sin i\, di \int_0^{2\pi} \delta(X_1)\delta(X_2) dE,$$



OPTICAL STATISTICS OF SMBBH

Interferometry

$$Q(\boldsymbol{u},\lambda) = \iint I(\boldsymbol{\sigma},\lambda) e^{-2\pi i \boldsymbol{\sigma}\cdot\boldsymbol{u}} d\alpha\, d\beta,$$

moments of intensity distribution

$$\mu_{lm} = \iint I\delta\lambda(\boldsymbol{\sigma},\lambda)\alpha^l\beta^m\, d\alpha\, d\beta.$$

centroids

$$p_\alpha(\lambda) = \frac{\mu_{10}}{\mu_{00}} = \frac{\iint \alpha I(\boldsymbol{\sigma},\lambda) d\alpha d\beta}{\iint I(\boldsymbol{\sigma},\lambda) d\alpha d\beta}$$

$$p_\beta(\lambda) = \frac{\mu_{01}}{\mu_{00}} = \frac{\iint \beta I(\boldsymbol{\sigma},\lambda) d\alpha d\beta}{\iint I(\boldsymbol{\sigma},\lambda) d\alpha d\beta}.$$

Fringe phase

$$-\operatorname{Arg}\left(\frac{Q(\boldsymbol{u},\lambda)}{\mu_{00}}\right) \sim \frac{\int \sin(2\pi\boldsymbol{\sigma}\cdot\boldsymbol{u}) I(\boldsymbol{\sigma},\lambda) d\alpha d\beta}{\int \cos(2\pi\boldsymbol{\sigma}\cdot\boldsymbol{u}) I(\boldsymbol{\sigma},\lambda) d\alpha d\beta}$$

$$\sim 2\pi \frac{\int I(\boldsymbol{\sigma},\lambda)\,\boldsymbol{\sigma} d\alpha d\beta}{\int I(\boldsymbol{\sigma},\lambda) d\alpha d\beta}\boldsymbol{u}$$

$$\sim 2\pi\boldsymbol{u}\cdot\boldsymbol{\xi}(\lambda)$$

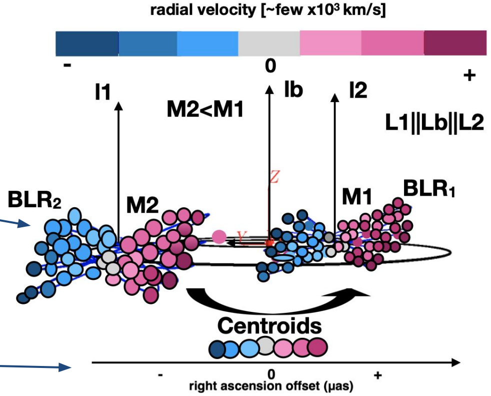
$$= 2\pi u \xi_\alpha(\lambda) + 2\pi v \xi_\beta(\lambda).$$

centroids vs fringe phase

$$\xi_\alpha(\lambda) = \frac{\mu_{10}}{\mu_{00}} = p_\alpha(\lambda) \qquad \xi_\beta(\lambda) = \frac{\mu_{01}}{\mu_{00}} = p_\beta(\lambda).$$

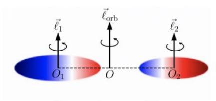
Differential phase

$$\Delta\phi = -2\pi\boldsymbol{u}\cdot(\boldsymbol{\xi}(\lambda) - \boldsymbol{\xi}(\lambda_r)).$$



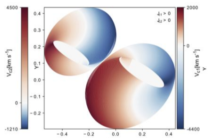
distribution of projected velocity fields

circular binary

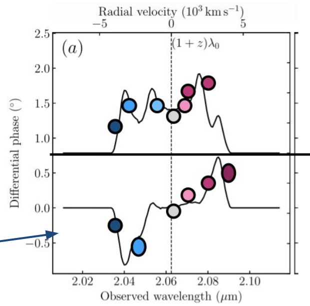


Songsheng+19

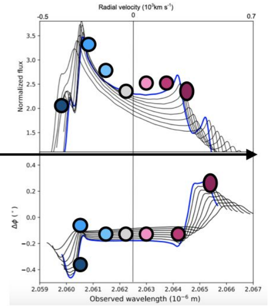
elliptical binary



Kovačević+20



Songsheng+19



Kovačević+20

Generalized binary signal

$$I(\boldsymbol{\sigma},\lambda) = I_1(\boldsymbol{\sigma_1},\lambda) + I_2(\boldsymbol{\sigma_2},\lambda).$$

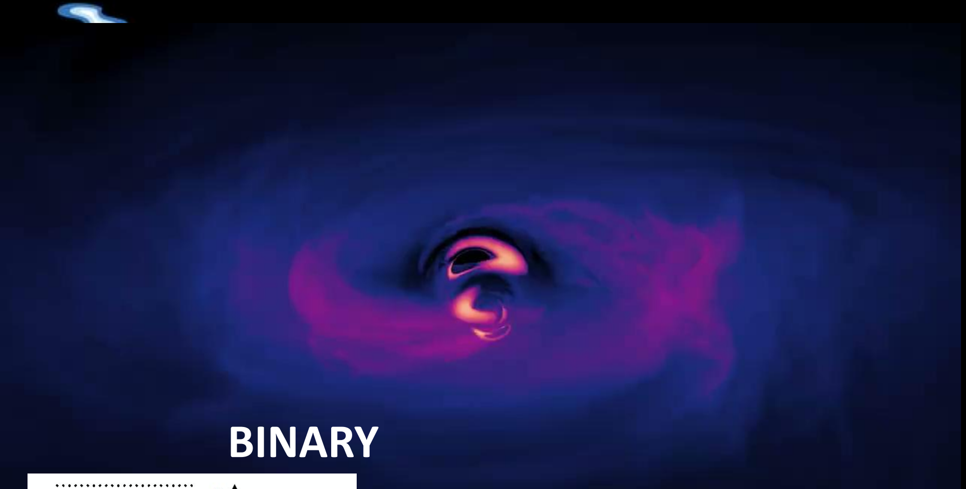
$$Q(\boldsymbol{u},\lambda) = Q_1(\boldsymbol{u},\lambda) + Q_2(\boldsymbol{u},\lambda) = F_1 e^{-2\pi i \sigma_1\cdot u} + F_2 e^{-2\pi i \sigma_2\cdot u},$$

$$Q_n(\boldsymbol{u},\lambda) = \frac{F_1 e^{-2\pi i \boldsymbol{\sigma_1}\cdot\boldsymbol{u}} + F_2 e^{-2\pi i \boldsymbol{\sigma_2}\cdot\boldsymbol{u}}}{F_1 + F_2}$$

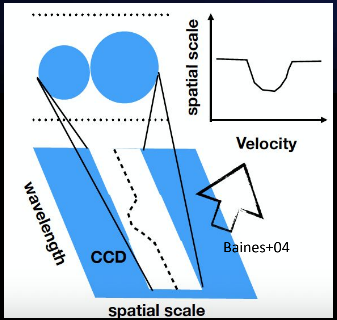
$$\operatorname{Arg}(Q_n(\boldsymbol{u},\lambda)) \sim \arctan\left(\frac{Im(Q_n(\boldsymbol{u},\lambda))}{Re(Q_n(\boldsymbol{u},\lambda))}\right)$$

Kovacevic+20 $\tilde{}\ 2\pi\boldsymbol{u}\cdot\frac{F_1\boldsymbol{\sigma_1} - F_2\boldsymbol{\sigma_2}}{F_1 + F_2}.$

SA+RM



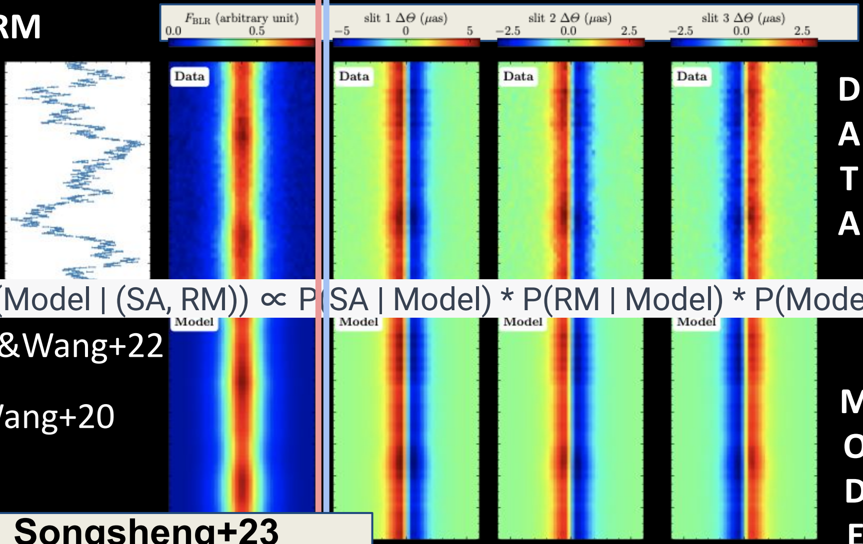
BINARY



$$\mathbf{F} = (F1, F2) \text{ and}$$
$$\mathbf{E} = \left(\exp\left(i \cdot \frac{2\pi S}{\lambda}\right), \exp\left(i \cdot \frac{2\pi(S - a\sin(i))}{\lambda}\right)\right).$$

$$T \propto \langle \mathbf{F}, \mathbf{E} \rangle.$$

RM



P(Model | (SA, RM)) ∝ P(SA | Model) * P(RM | Model) * P(Model)

Li&Wang+22

Wang+20

Songsheng+23

DATA

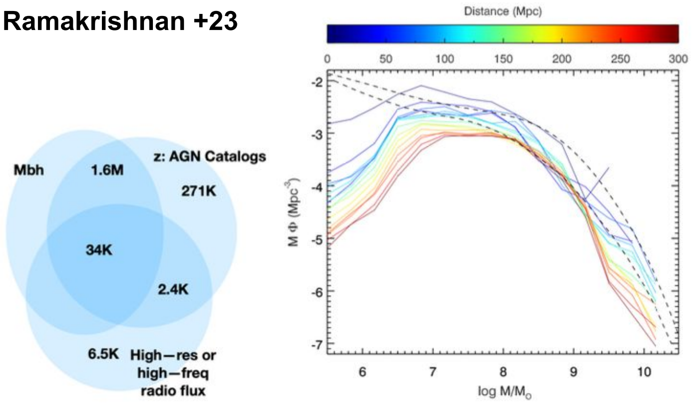
MODEL

SA

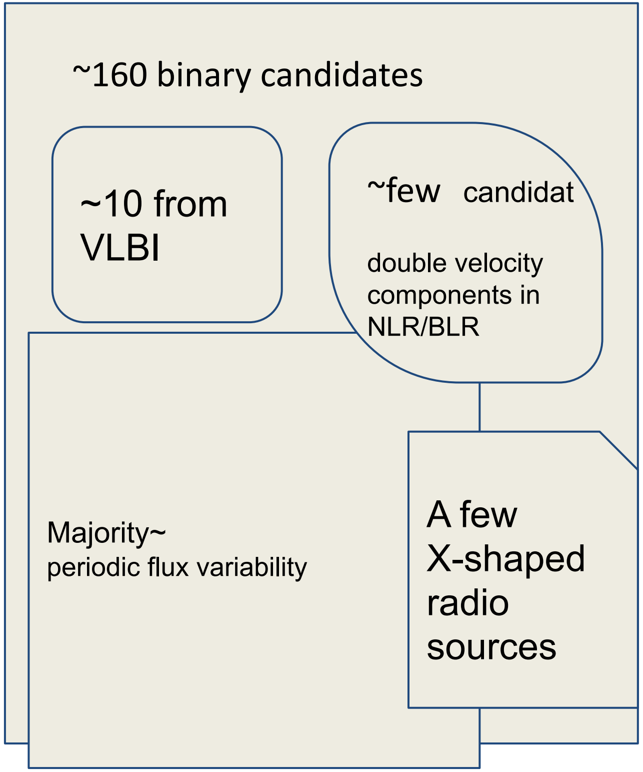
$$\Theta(v,t) = \frac{F'_{\rm c}(t)\Theta_{\rm c}(v,t) + F_{\rm BLR}(v,t)\Theta_{\rm BLR}(v,t)}{F'_{\rm c}(t) + F_{\rm BLR}(v,t)}$$

Event Horizon and Environs (ETHER): A Curated Database for EHT and ngEHT Targets and Science

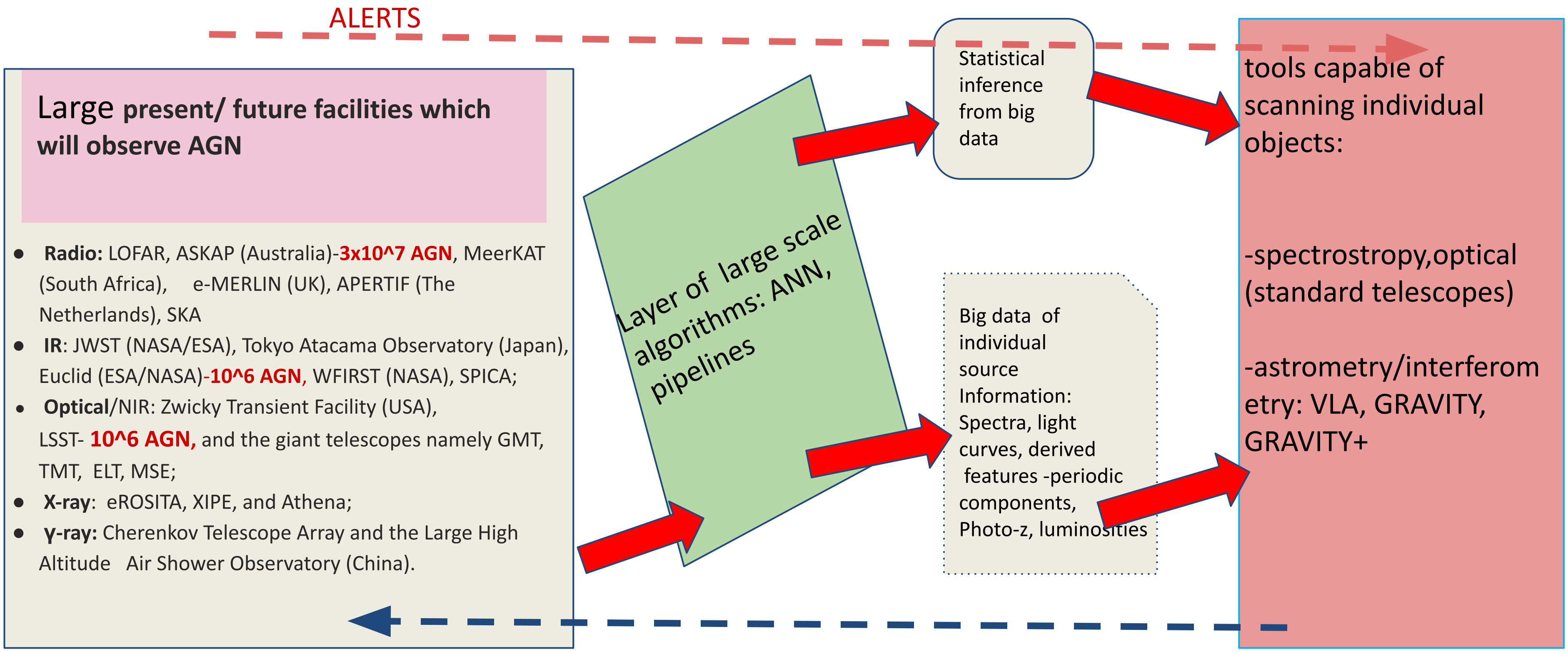
Ramakrishnan +23



The Vera C. Rubin Observatory will enable extensive studies of periodic flux variability, and is thus expected to significantly enlarge the sample of binary black hole candidates



Move forward **instead of** *looking* back.

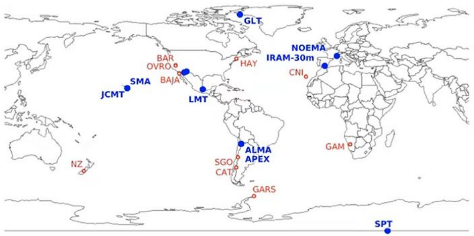


Feedback for statistical premises of cadences, observational priorities

PILLARS OF MULTIMESSINGER ASTRONOMY

ZWICKY TRANSIENT FACILITY

INTERNATIONAL PULSAR TIMING ARRAY
IPTA



ngEHT Telescope Array Example 1

NASA esa
LISA
Laser Interferometer Space Antenna
Announcements