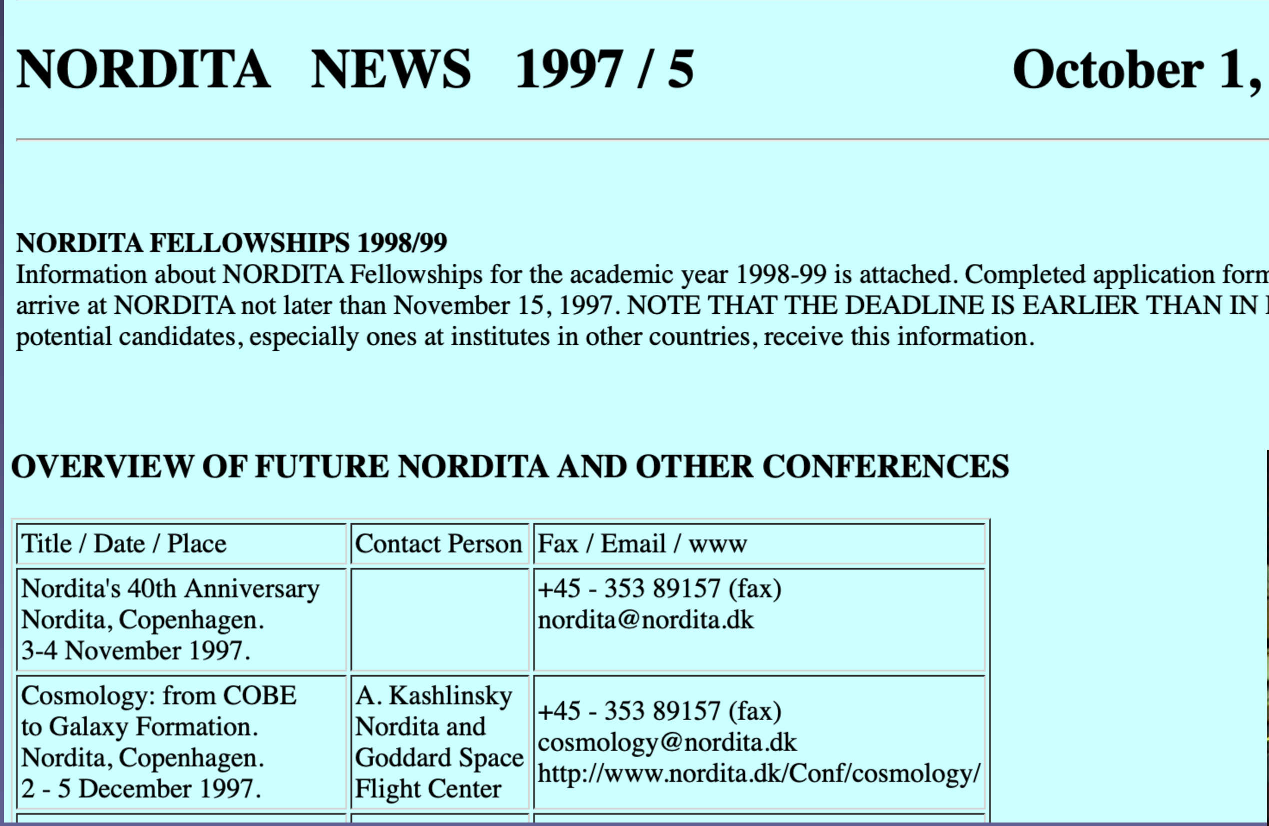
Gravitational wave and EM signatures of binary BHs with circumbinary gas

Zoltán Haiman

Columbia University

Gravity Seminar *NBIA, Copenhagen* *16 May, 2023*

Copenhagen and me



NORDITA NEWS 1997 / 5 October 1, 1997

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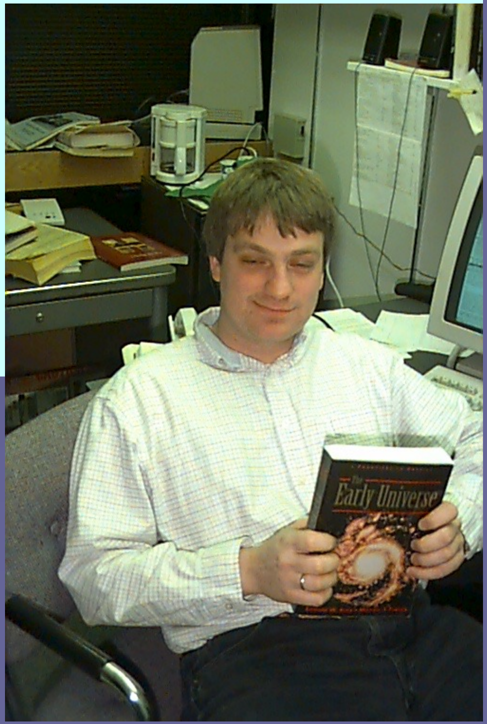
OVERVIEW OF FUTURE NORDITA AND OTHER CONFERENCES

Title / Date / Place	Contact Person	Fax / Email / www
Nordita's 40th Anniversary Nordita, Copenhagen. 3-4 November 1997.		+45 - 353 89157 (fax) nordita@nordita.dk
Cosmology: from COBE to Galaxy Formation. Nordita, Copenhagen. 2 - 5 December 1997.	A. Kashlinsky Nordita and Goddard Space Flight Center	+45 - 353 89157 (fax) cosmology@nordita.dk http://www.nordita.dk/Conf/cosmology/



Outline

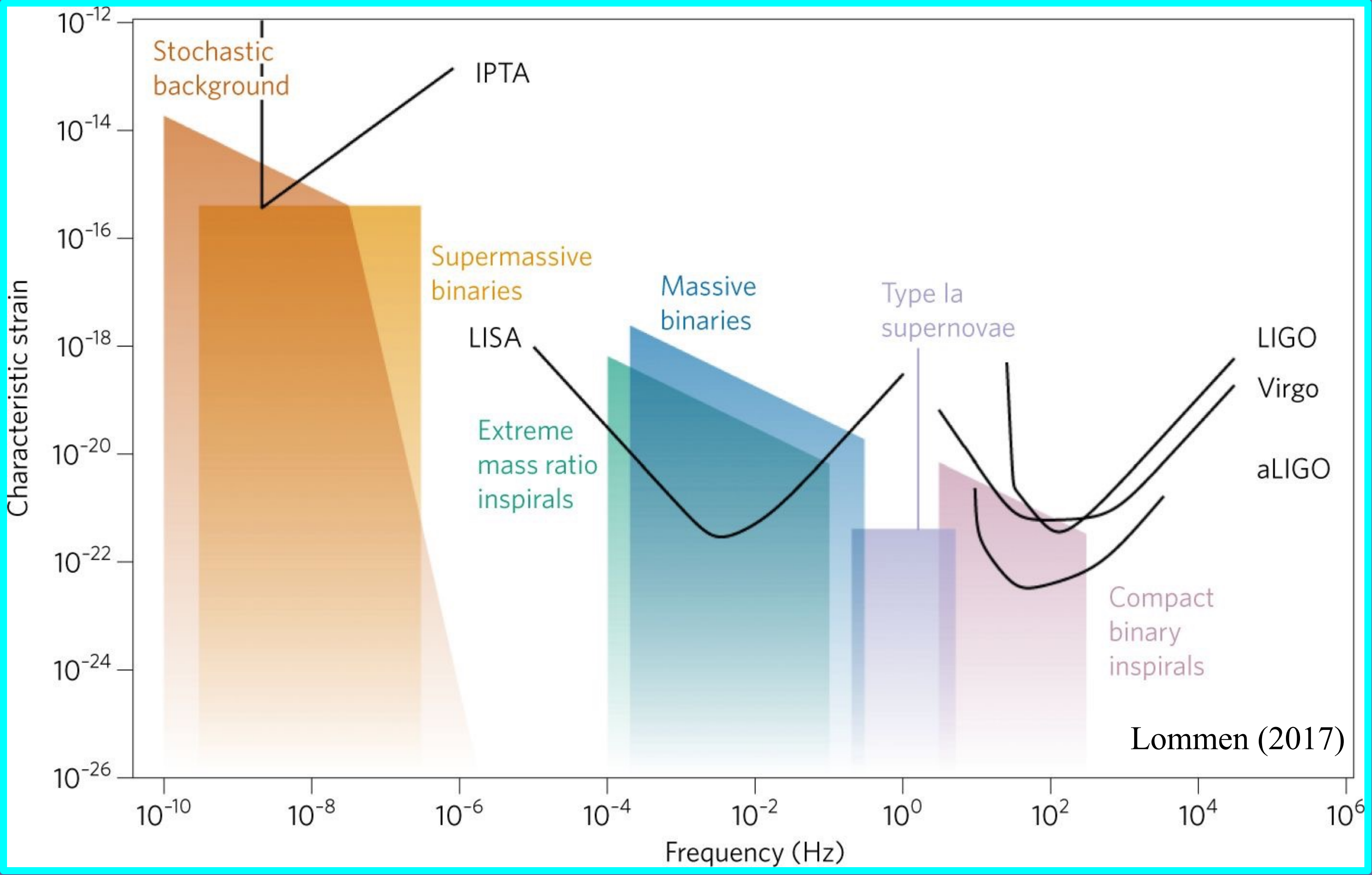
1. **Introduction: mergers of SMBHs in galactic nuclei**
   - observational background, motivation

2. **Theory: binary accretion**
   - bright variable emission from binary

3. **Observations: do we have to wait for GW detections?**
   - SMBH binary candidates in quasar surveys
   - forecasts for LSST & LISA era

4. **Stellar-mass BH binaries: mergers in AGN disks?**
   - BH binaries form in or captured by nuclear gas disks
   - Bright EM emission outshining AGN

Multi-band Gravitational Waves



Lommen (2017)

$(10^8\text{-}10^{10})M_\odot$ **$(10^4\text{-}10^7)M_\odot$** **$(10\text{-}10^2)M_\odot$**

pulsar timing **LISA** **LIGO**

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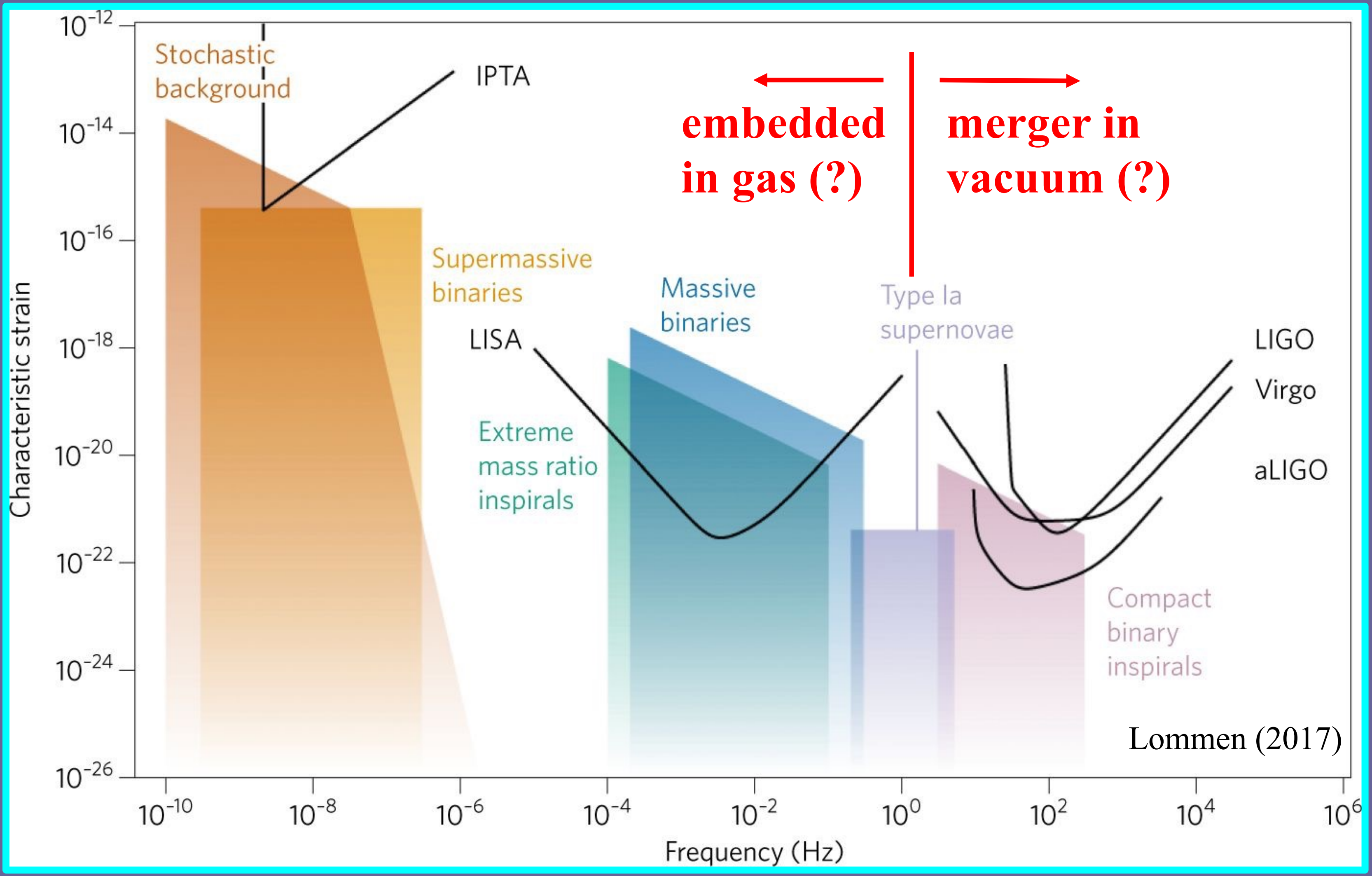


embedded in gas (?)

merger in vacuum (?)

Lommen (2017)

$(10^{8}-10^{10})M_\odot$
pulsar timing

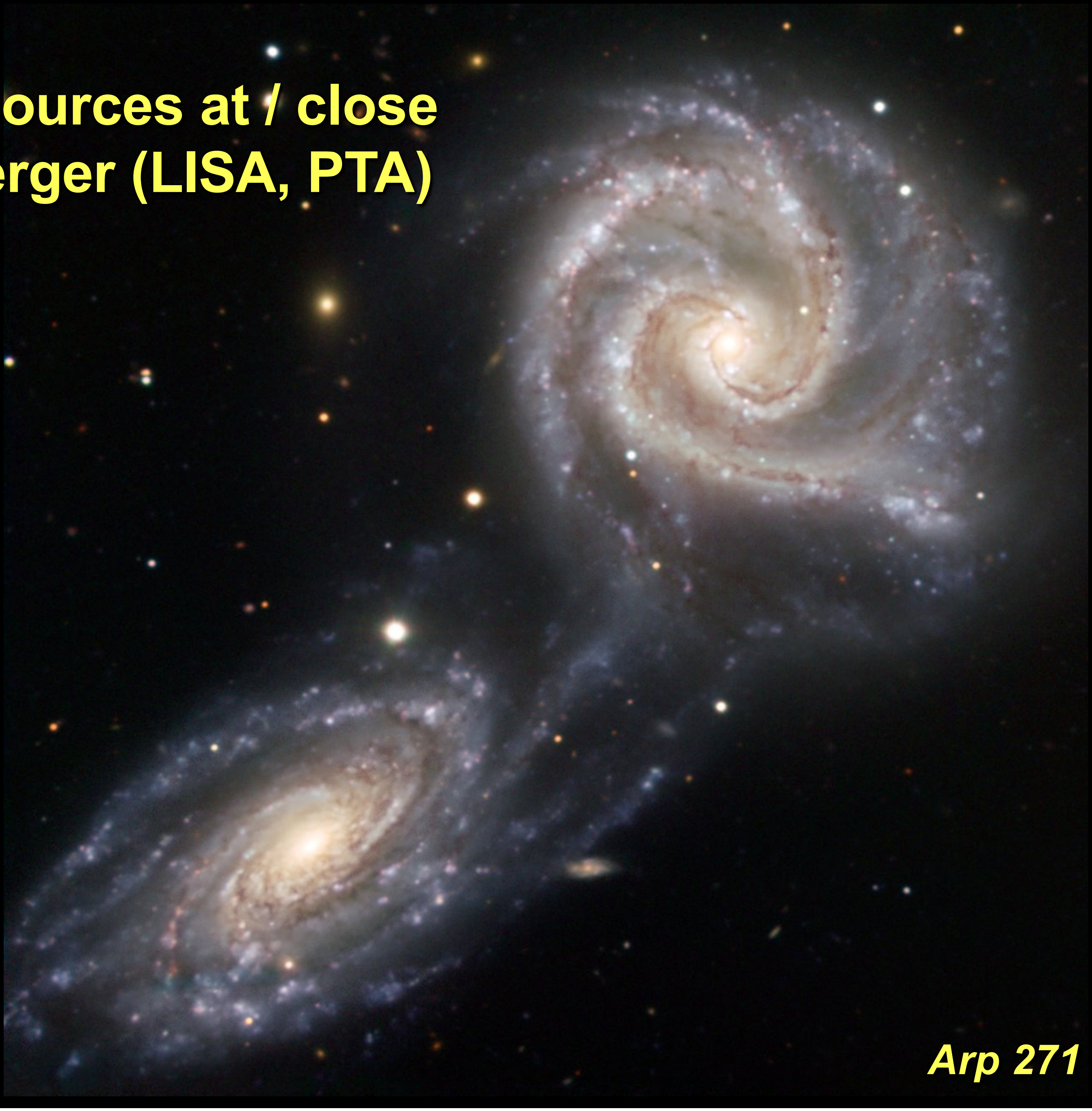
$(10^{4}-10^{7})M_\odot$
LISA

$(10-10^{2})M_\odot$
LIGO

Massive BH binaries in galactic nuclei

Arp 271 (credit: ESO)

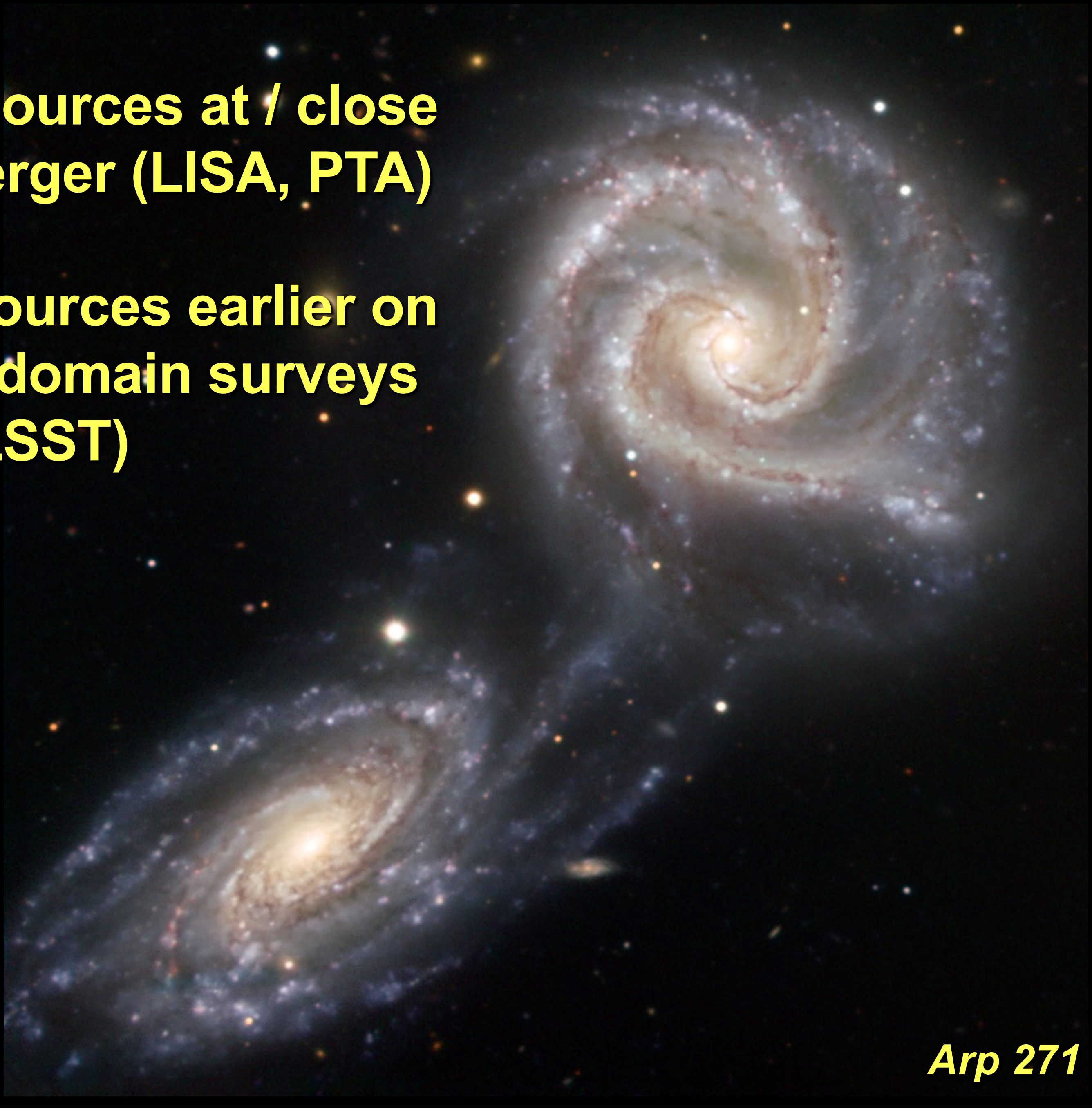
Massive BH binaries in galactic nuclei



→ GW sources at / close to merger (LISA, PTA)

Arp 271 (credit: ESO)

Massive BH binaries in galactic nuclei



→ GW sources at / close to merger (LISA, PTA)

→ EM sources earlier on (time-domain surveys e.g. LSST)

Arp 271 (credit: ESO)

Massive BH binaries in galactic nuclei

→ GW sources at / close to merger (LISA, PTA)

→ EM sources earlier on (time-domain surveys e.g. LSST)

how do we find them?

Arp 271 (credit: ESO)

Science from Multi-Messenger Astrophysics

Benefits of combining GWs and EM detections

(1) Astronomy and astrophysics

— *accretion physics*: EM emission with known BH parameters

— *accretion physics*: distortions to waveforms (Derdzinski + 2020, 2021)

— *quasar/galaxy (co)evolution:* BH vs host galaxy relations

(2) Fundamental physics & cosmology

— Hubble diagrams from standard sirens (Schutz 1986 + …)

— $d_L(z)$ from GWs + photons: test of non-GR gravity (Deffayet & Menou 2007)

— delay between arrival time of photons and gravitons:
extra dimensions, graviton mass ($\gamma m_0 c^2 = hf$; Kocsis et al. 2008)

(3) EM counterparts can also help with GW detection

— known EM source position helps break GW parameter degeneracies

— EM counterpart can increase confidence of marginal GW detections

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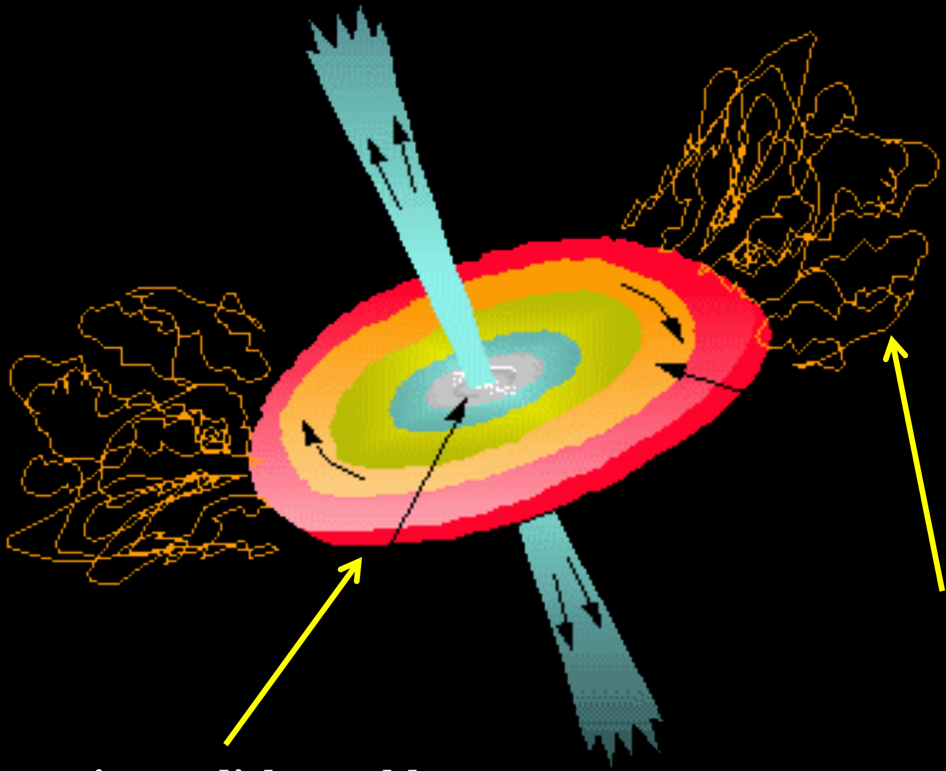
Binary quasars

Gas cools and forms a compact (~ sub-pc) nuclear accretion disk

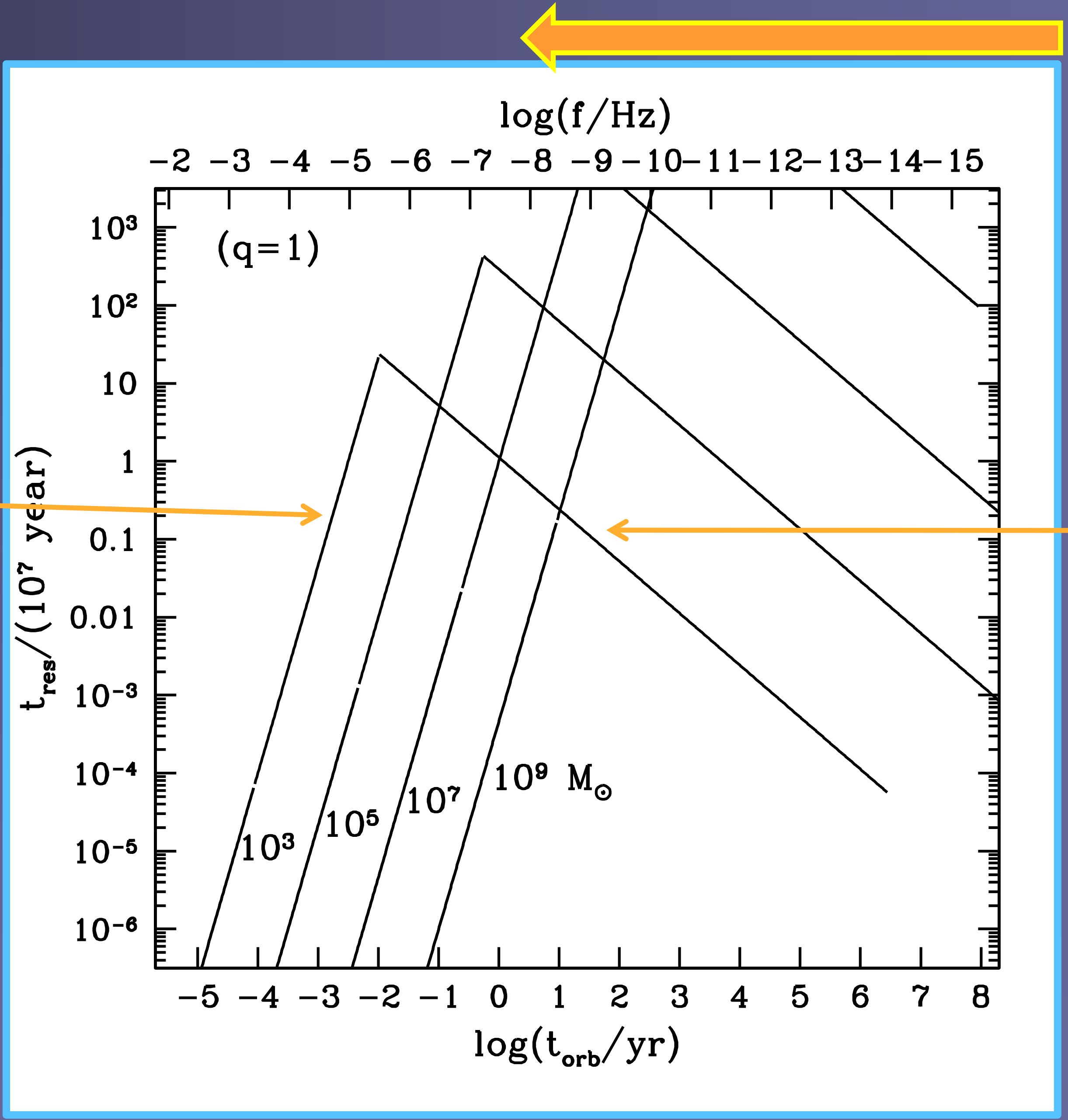


inner disk: stable,
geometrically thin,
optically thick,
$M_{disk} \ll M_{bh}$

Gravitationally
unstable region
Q(Toomre) < 1

→ What if second black hole is present ? ←

Residence time

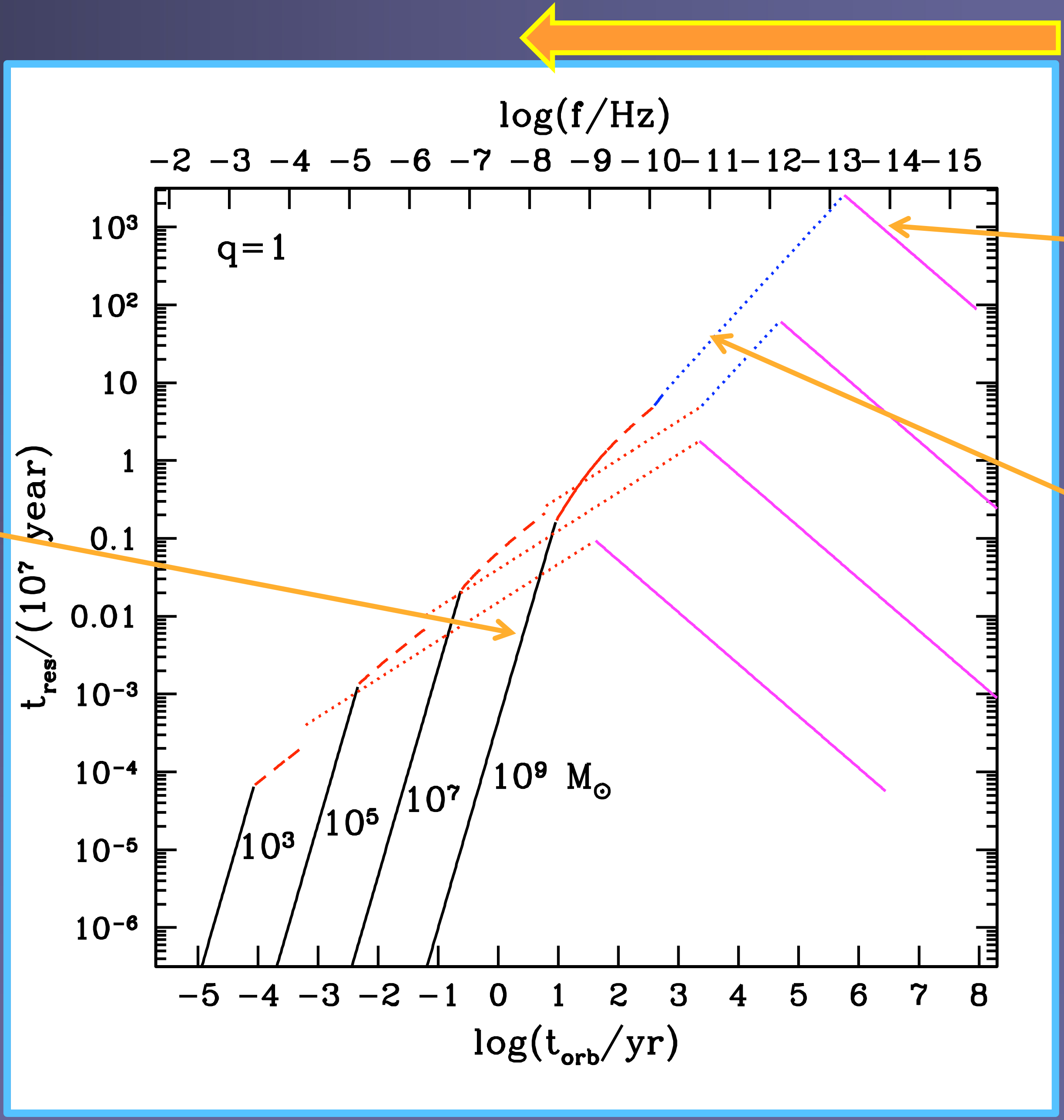


GW-driven decay

Stellar Scattering driven decay

ZH, Kocsis, Menou (2009)

Residence time



Stellar Scattering driven decay

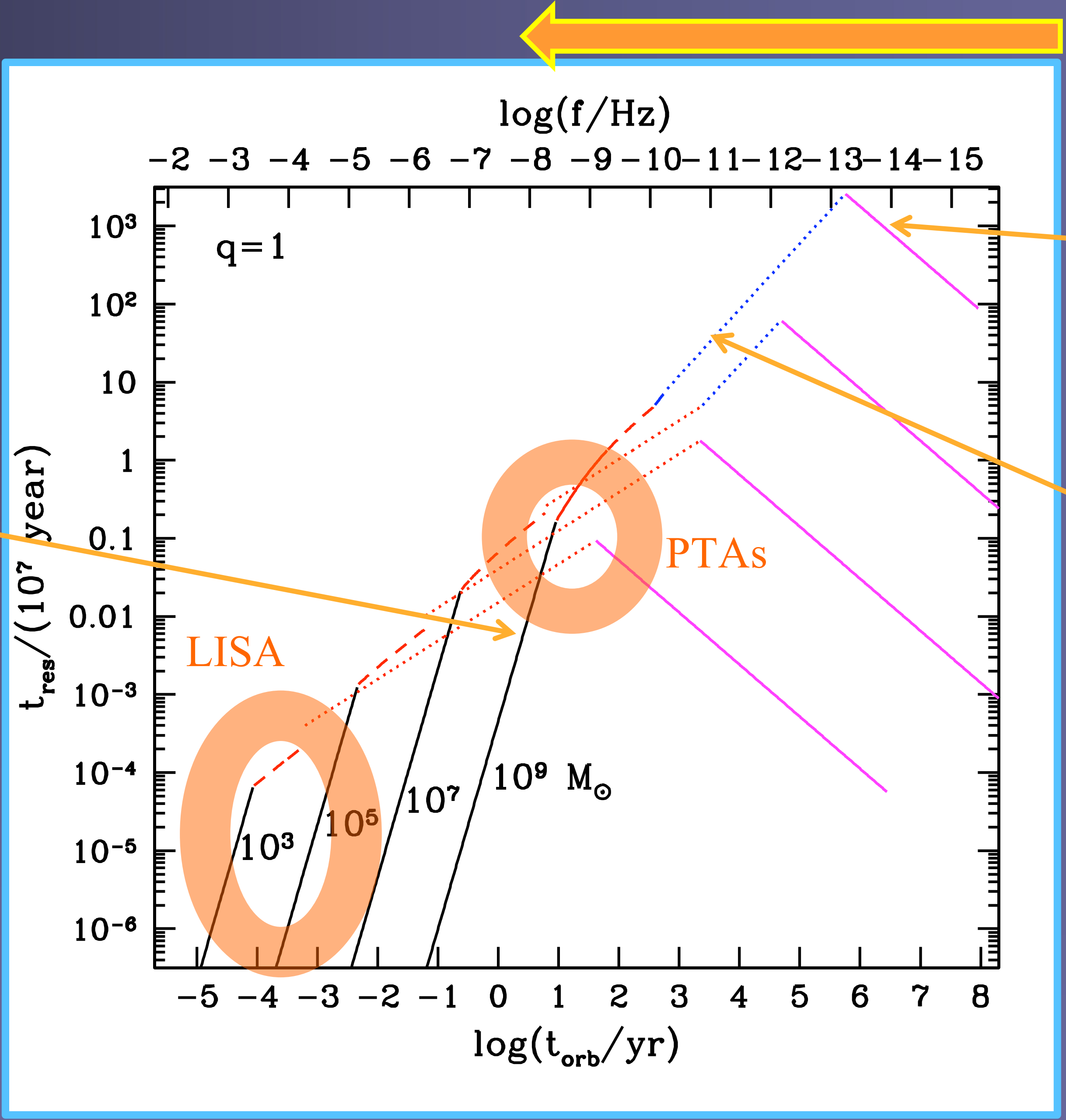
GW-driven decay

Gas disk Driven decay

[sensitive to accretion disk model]

ZH, Kocsis, Menou (2009)

Residence time



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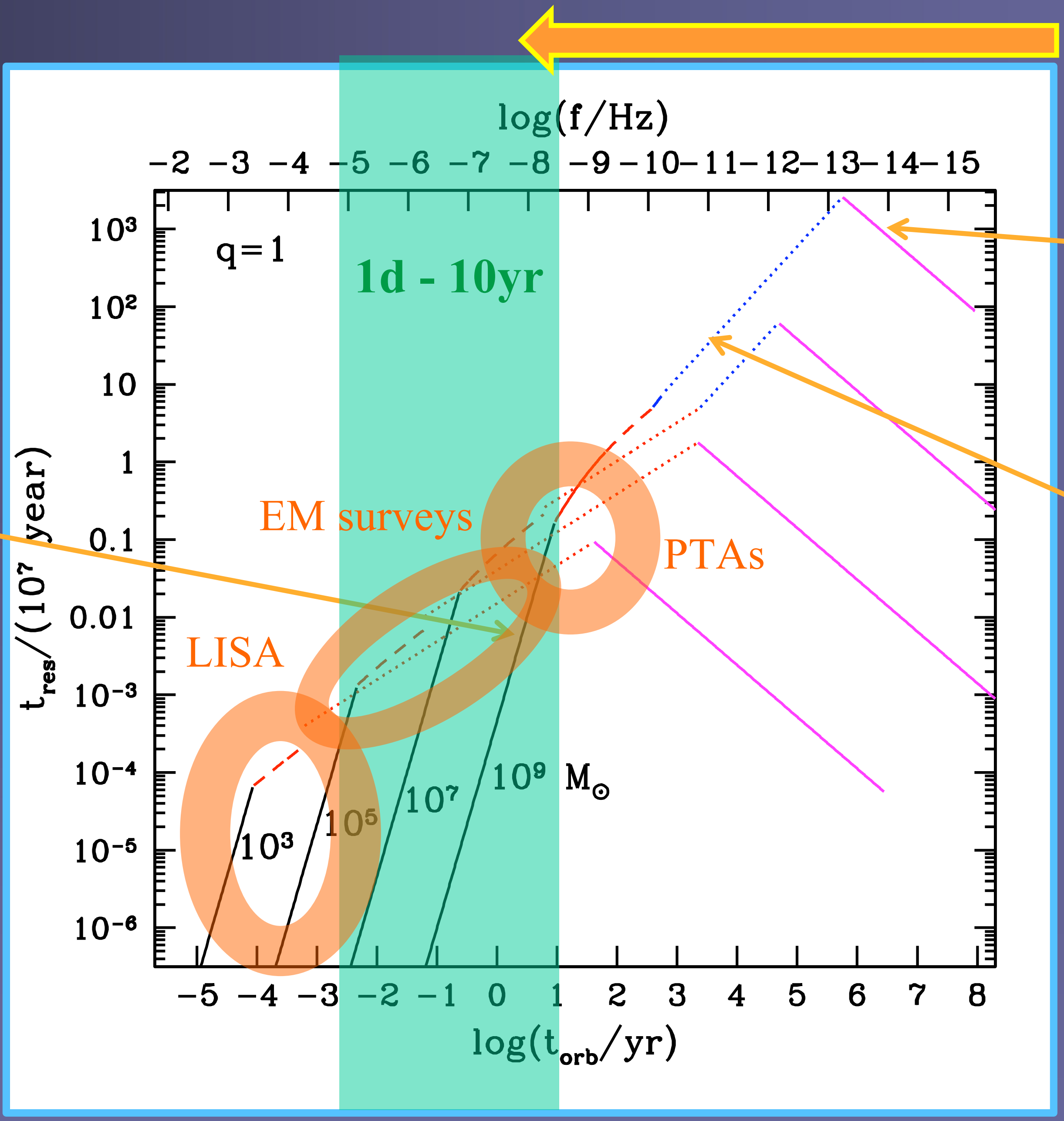

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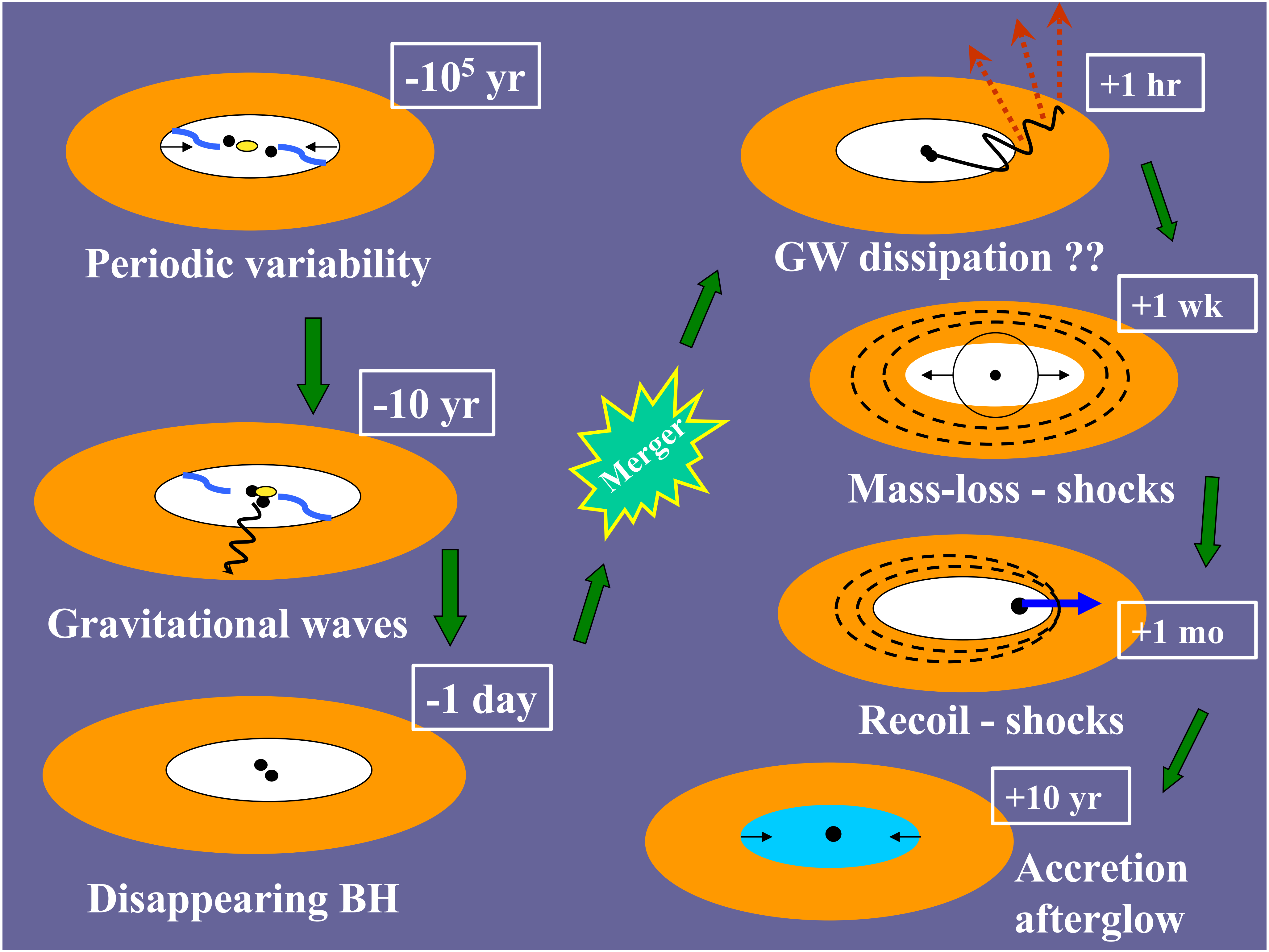


-10^5 yr

Periodic variability

-10 yr

Gravitational waves

-1 day

Disappearing BH

Merger

+1 hr

GW dissipation ??

+1 wk

Mass-loss - shocks

+1 mo

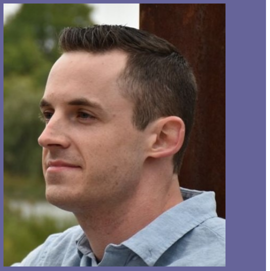
Recoil - shocks

+10 yr

Accretion afterglow

Equal-mass, circular binary

Westernacher-Schneider et al. (2022)

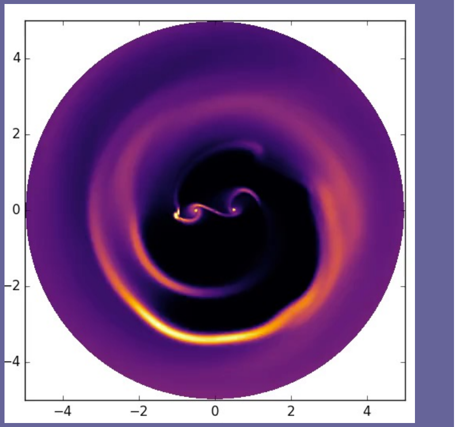


Ryan Westernacher -Schneider

Sailfish; **GPU-enabled 2D hydro code, Cartesian coö's**

mass ratio (q), eccentricity (e), temperature ($\mathscr{M}$)

Key Features of Binary Accretion



Central cavity:

- Lack of stable orbits within ~twice the binary separation
- Density suppressed by factor of ~100

Lopsided cavity wall with lump:

- circumbinary disk strongly lopsided (nonlinear instability)
- dense lump appears at cavity wall, modulating accretion

Streamers:

- enter cavity wall via strong shocks, extend into tidal region of BHs
- fuel accretion is via gravity and shocks --- not viscosity/MRI !

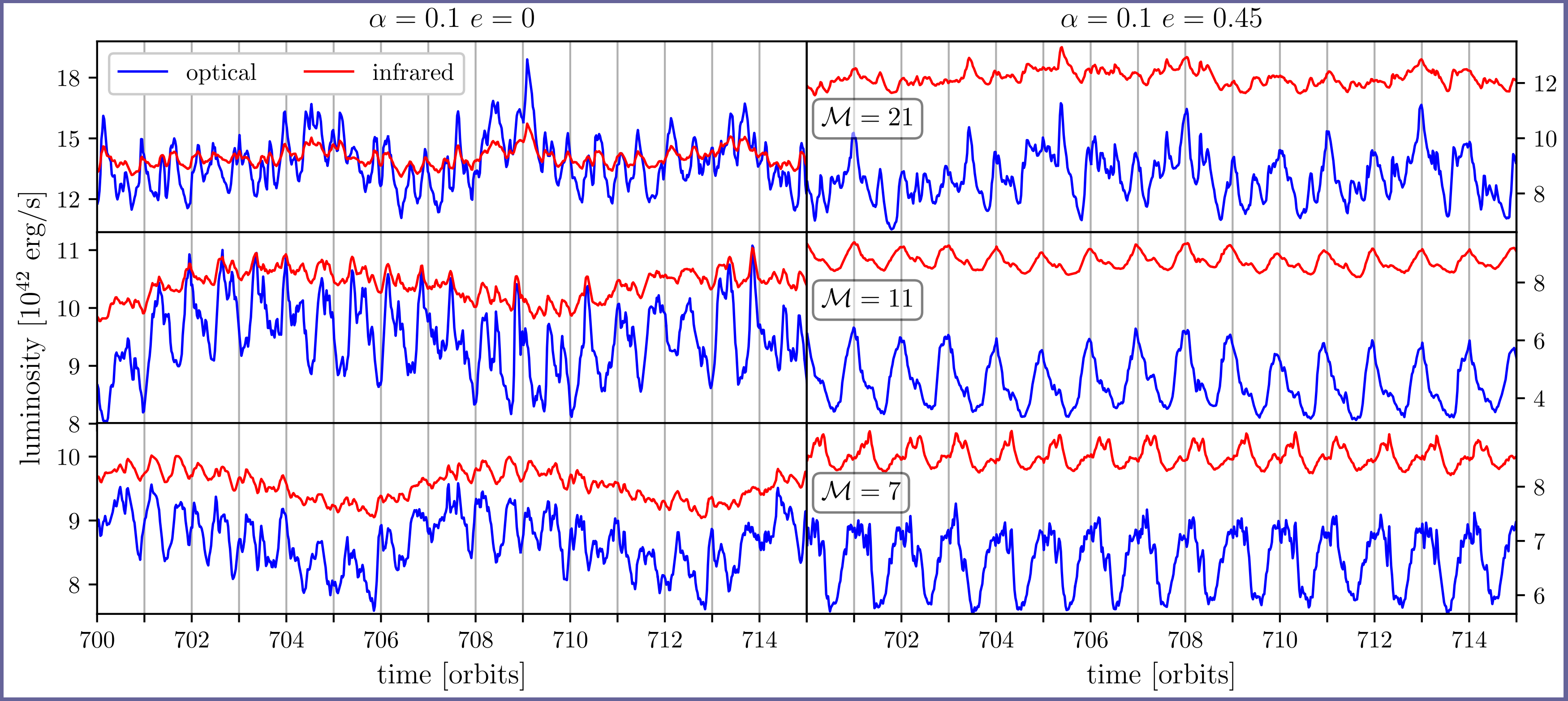
Minidisks:

- fueled by streamers -- net accretion rate matches that of single BH
- strong shocks periodically appear and disappear

Signature I: binary quasars are periodic

Thermal emission; optical and IR

Circular *Eccentric*

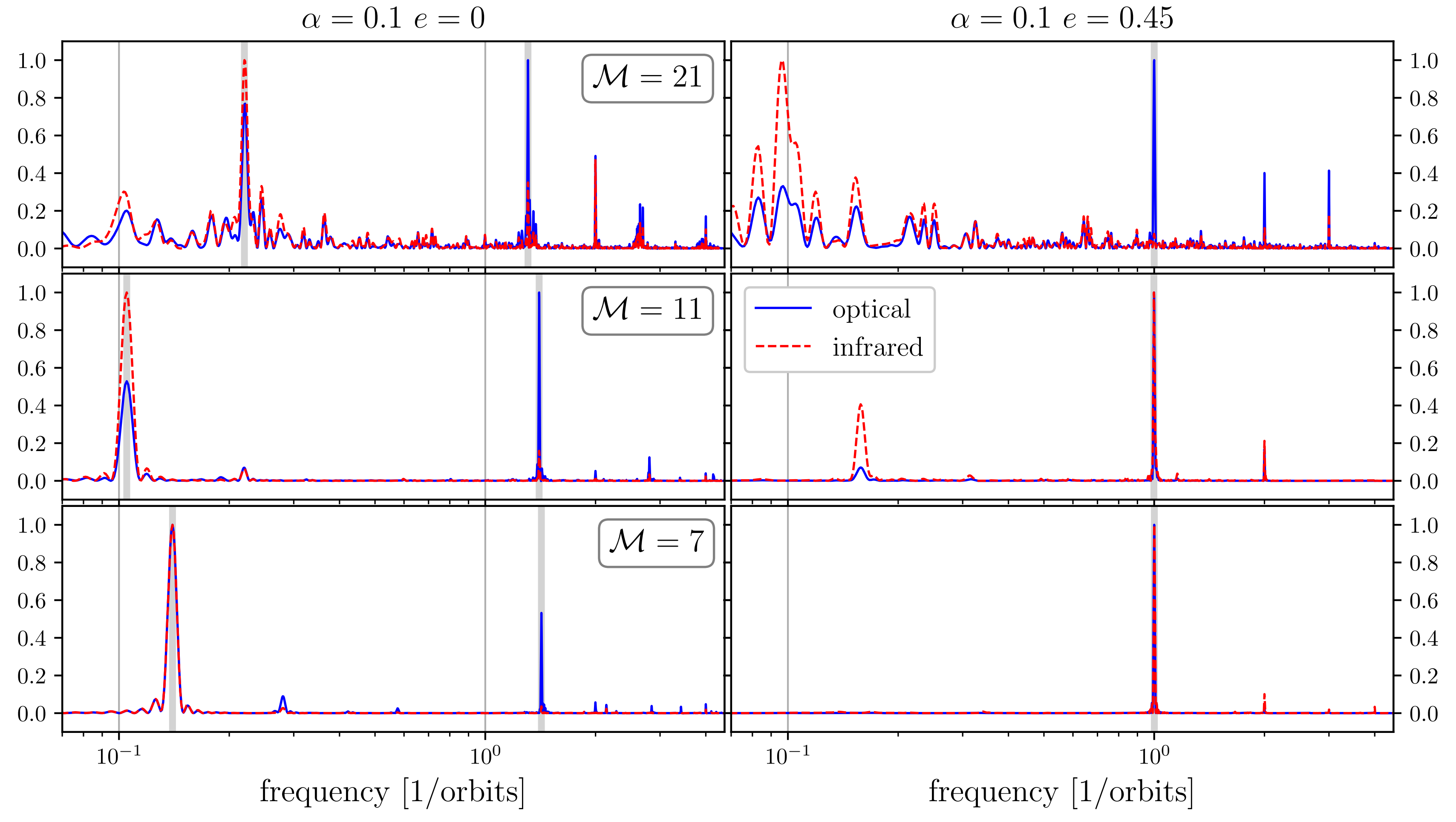


colder

warmer

Binary quasars are periodic

Circular *Eccentric*



colder

warmer

lump

beat between orbit & minidisk precession

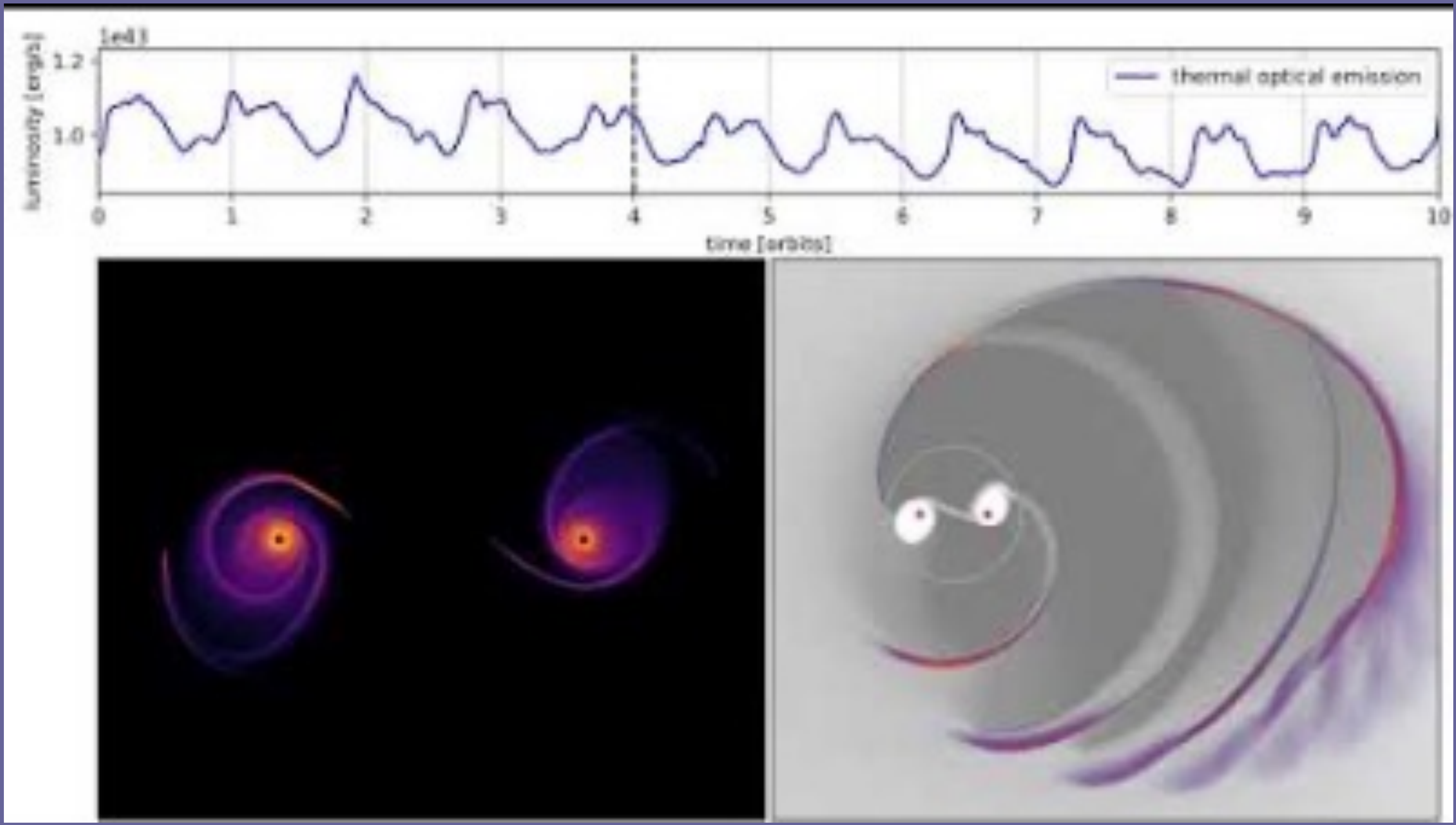
no lump

orbit

Periodicity from Minidisks

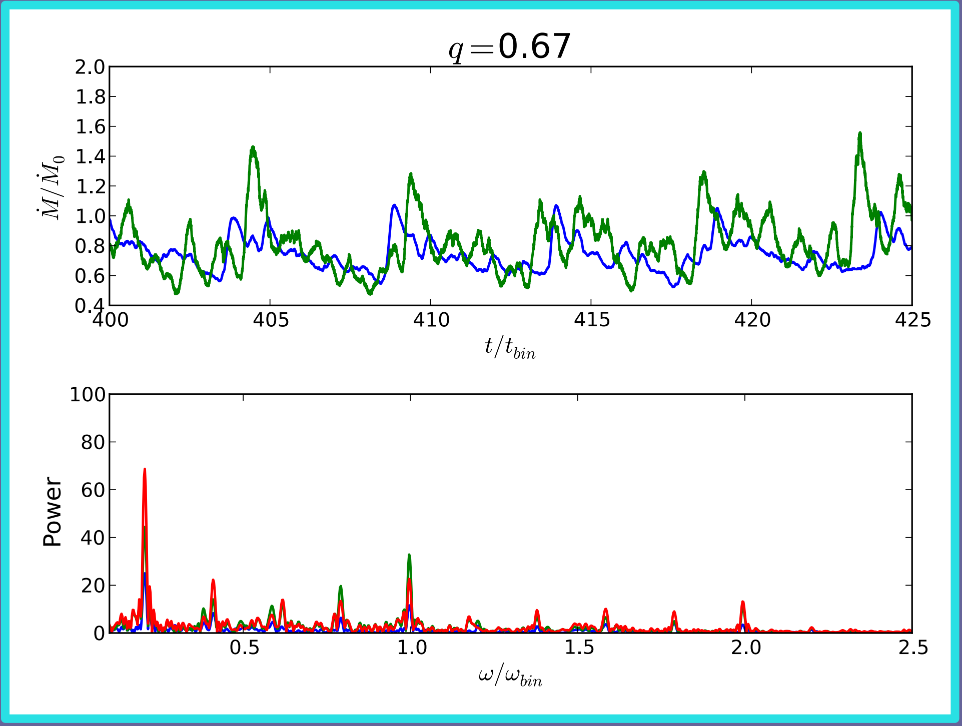
Westernacher-Schneider et al. (2023, in prep)

With **Sailfish**; resolved lopsided minidisks with retrograde precession



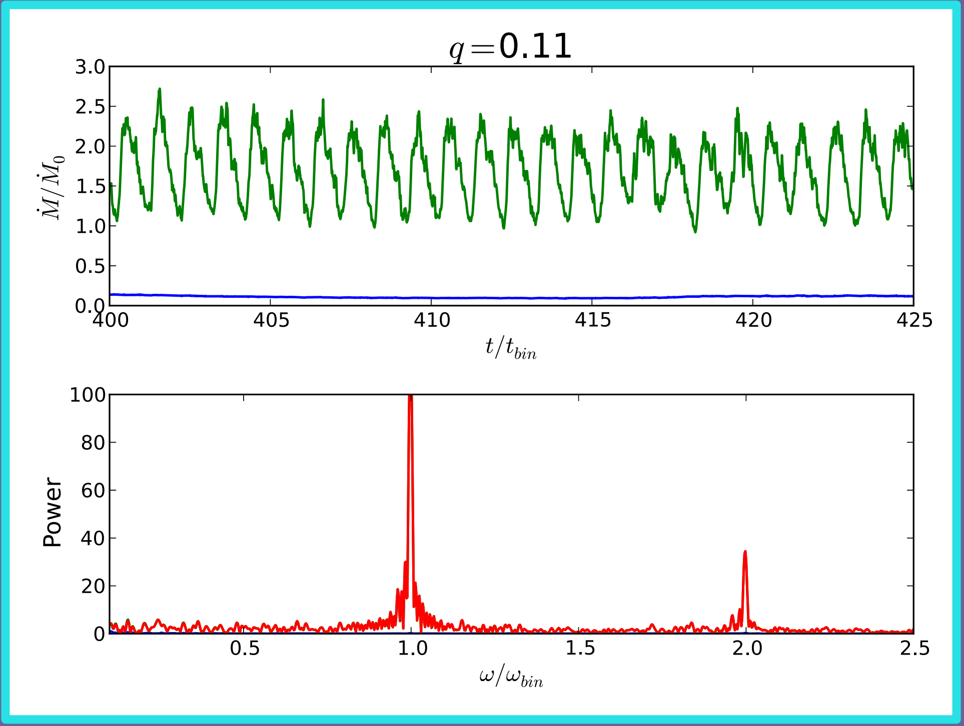
Impact of mass ratio

$0.3 < q < 1$



Sawtooth/bursty variability,
on **orbital time at cavity wall**

$0.05 < q < 0.3$



more sinusoidal variability,
on **orbital timescale**

Accretion rate not suppressed – similar to bright quasar
→ periodic variability down to mass ratio of ~0.05

Periodicity from Doppler boost (EM "chirp")

ZH (2017)

LISA binary

Wide (P ~ yr) binary

X-ray emission from quasars from few R_g

Minidisk → X-ray corona bound to single BH

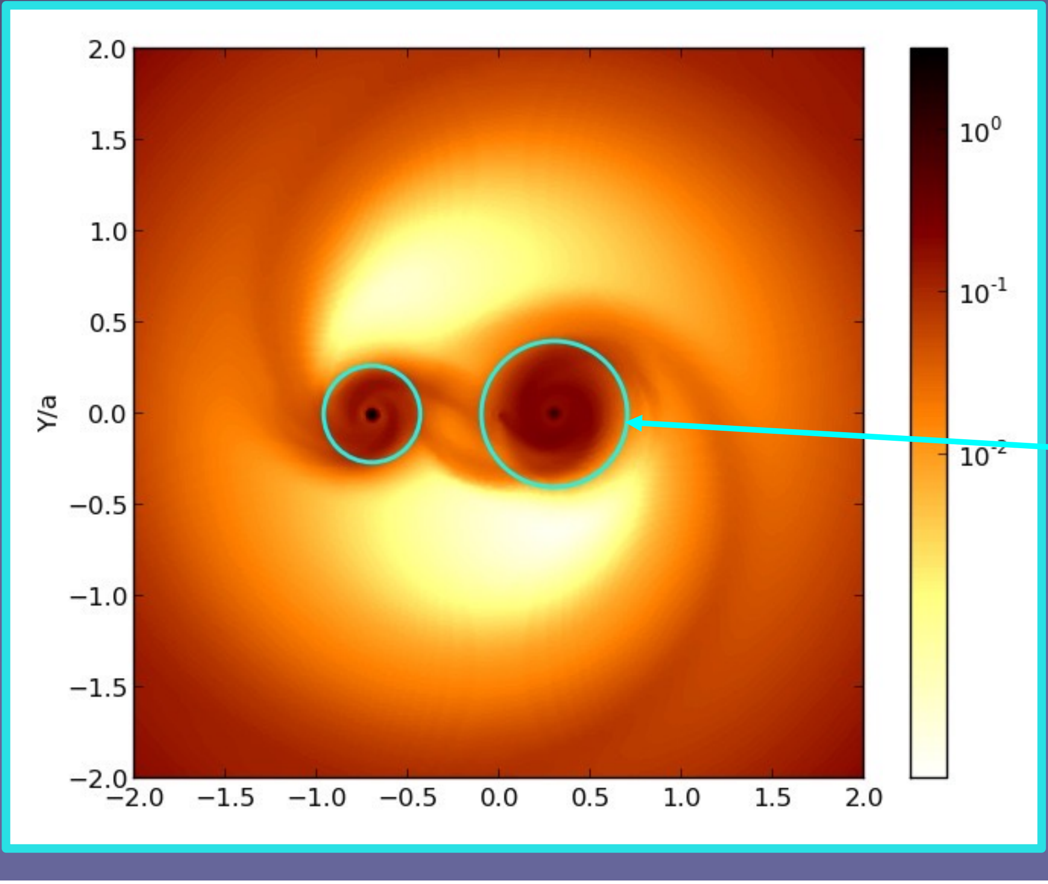
Doppler effect modulates brightness at O(v/c) ~0.1

optical: ~ few 100 R_g

minidisk=quasar disk

v/c~ 0.01

→ *dominates over hydro-variability for* $q \lesssim 0.05$ ←

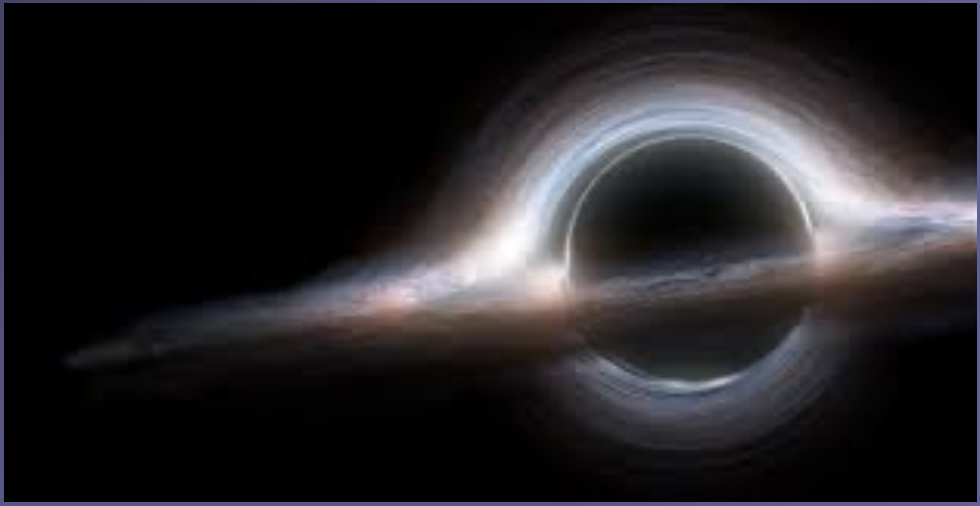


Tidal force
from companion
truncates minidisk

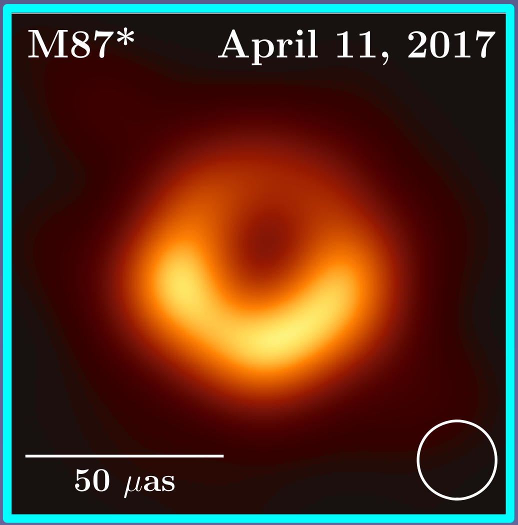
D'Orazio et al. (2016)
Duffell et al. (2020)

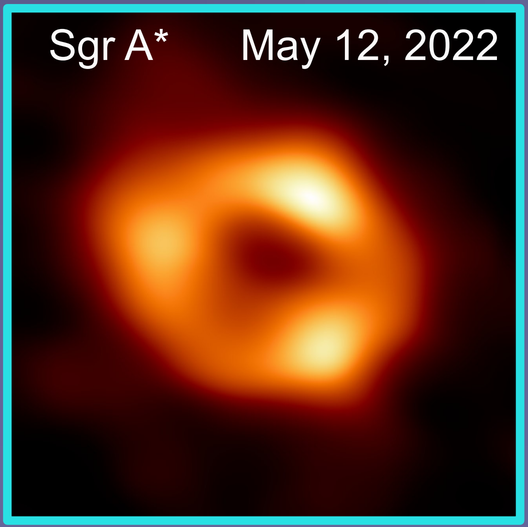
Periodic binary self-lensing

Interstellar (2014)



Event Horizon Telescope (EHT) 2017, 2022





Binary self-lensing

D'Orazio & Di Stefano (2016)

Jordy Davelaar & ZH (2022a,b – PRL, PRD)

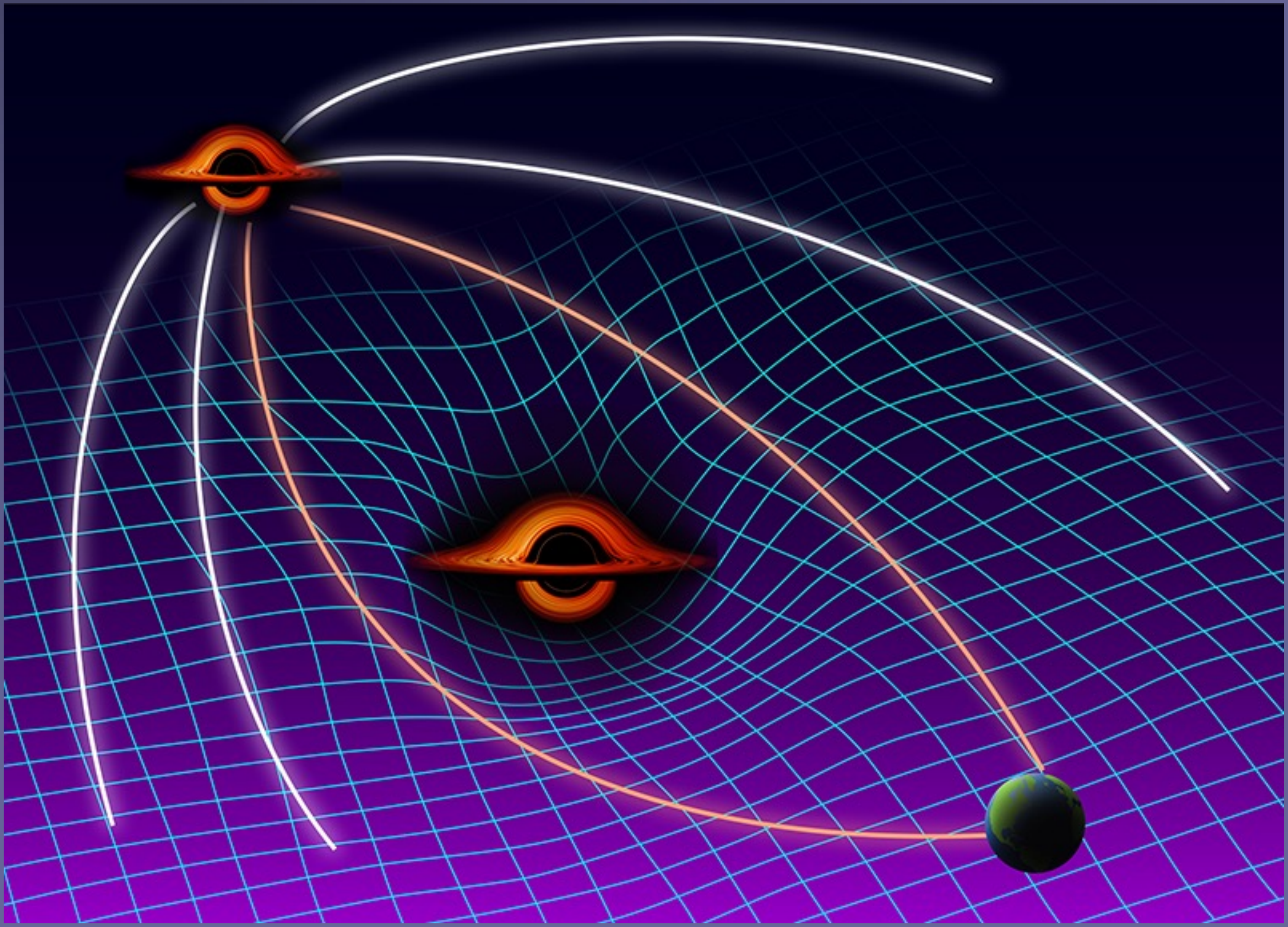
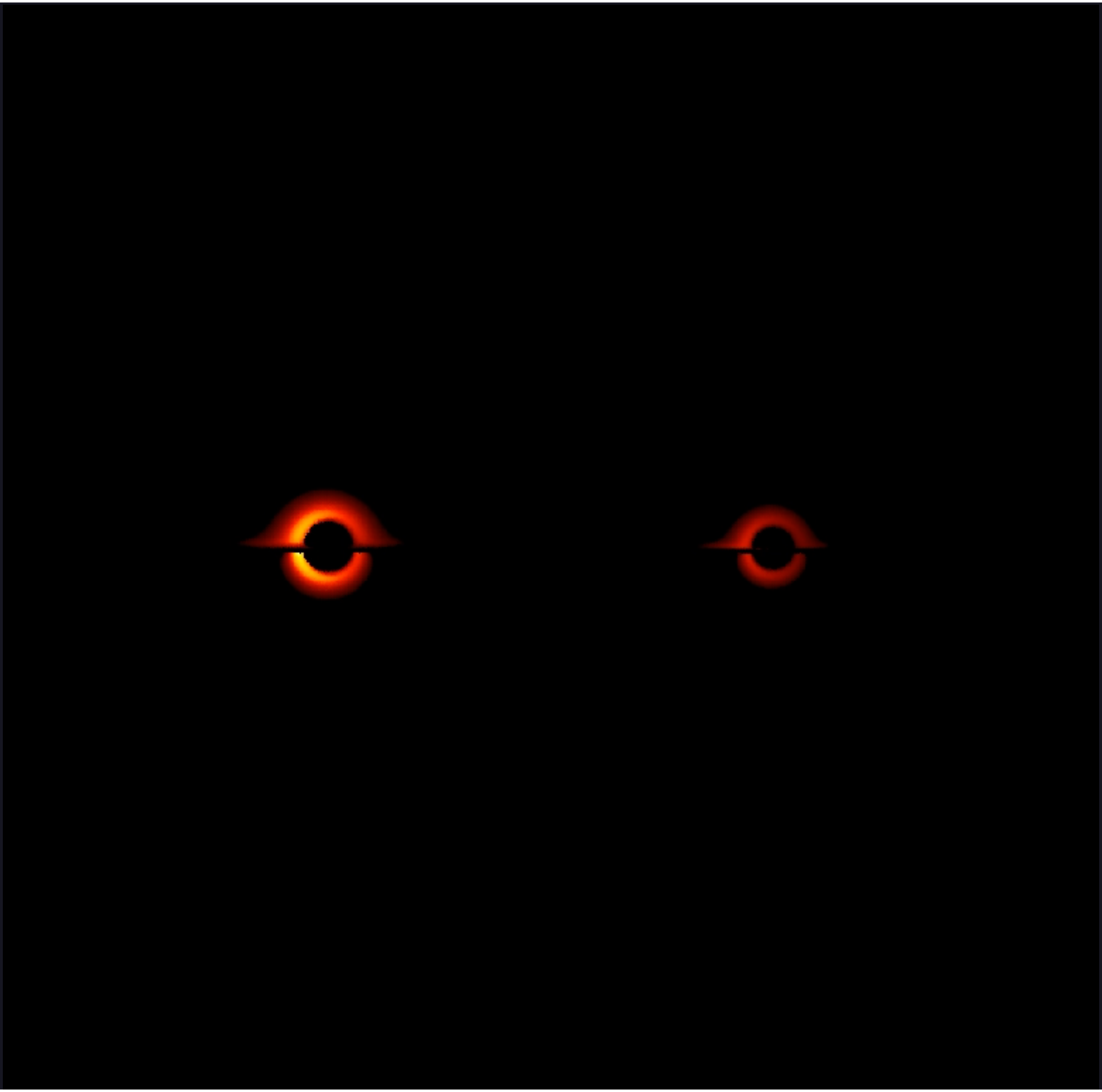


Illustration: APS, Carin Cain

Jordy Davelaar

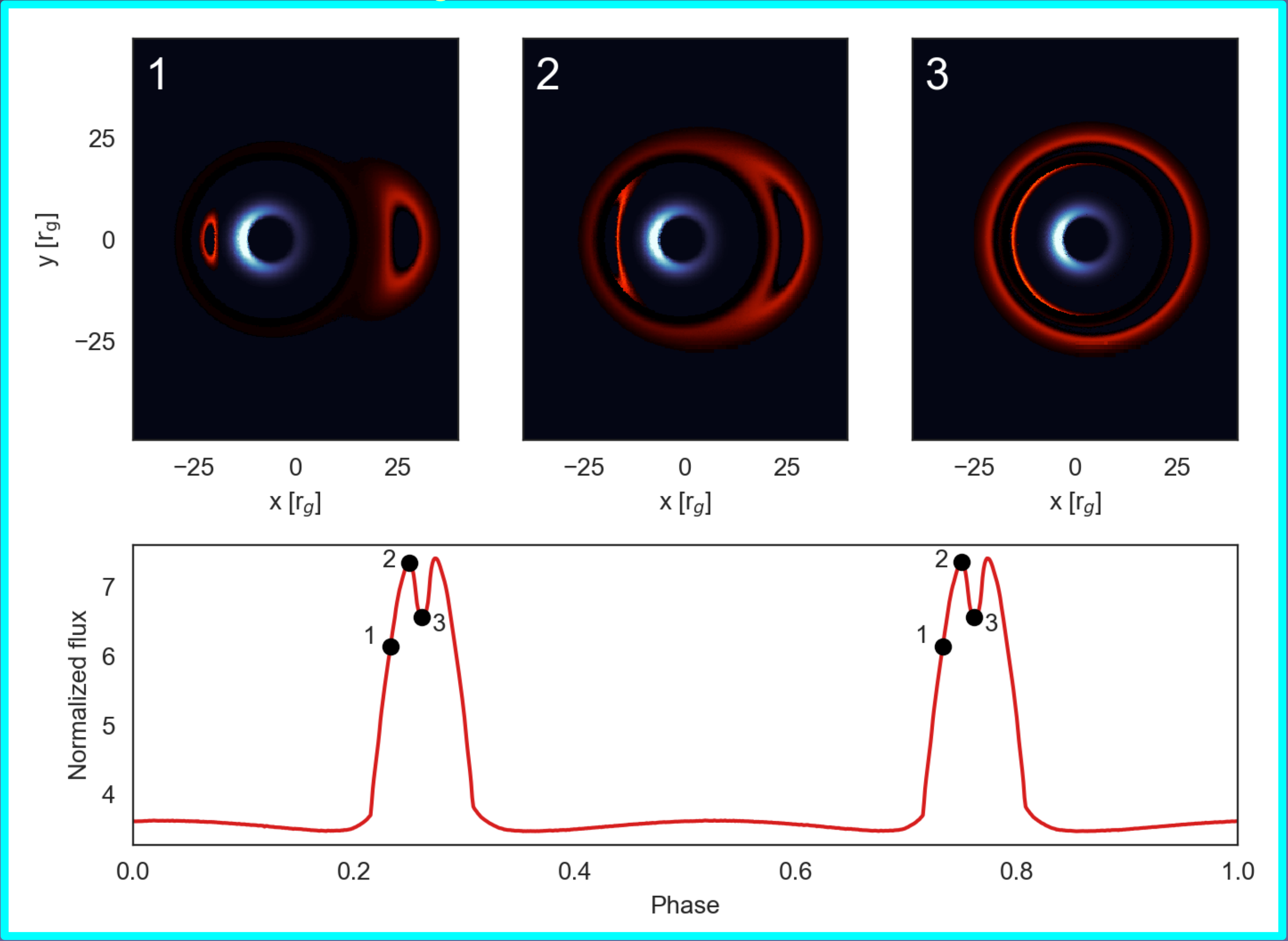


Recurring Self-Lensing Spikes

Davelaar & ZH (2022a,b)

note: $\theta_e/\theta_{bin} = (2a_{bin}/R_s)^{-1/2}$

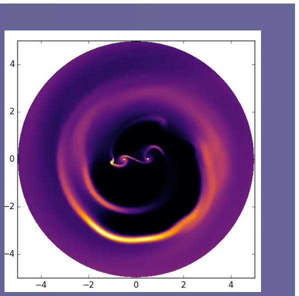
compact (d=100 R_g) edge-on binary i= 90°



- flares visible within ±3-30° of edge-on
- shadow visible if ±1-10° of edge-on
- week-long flares in periodic quasars
- 10x higher chance for LISA binaries (already compact)

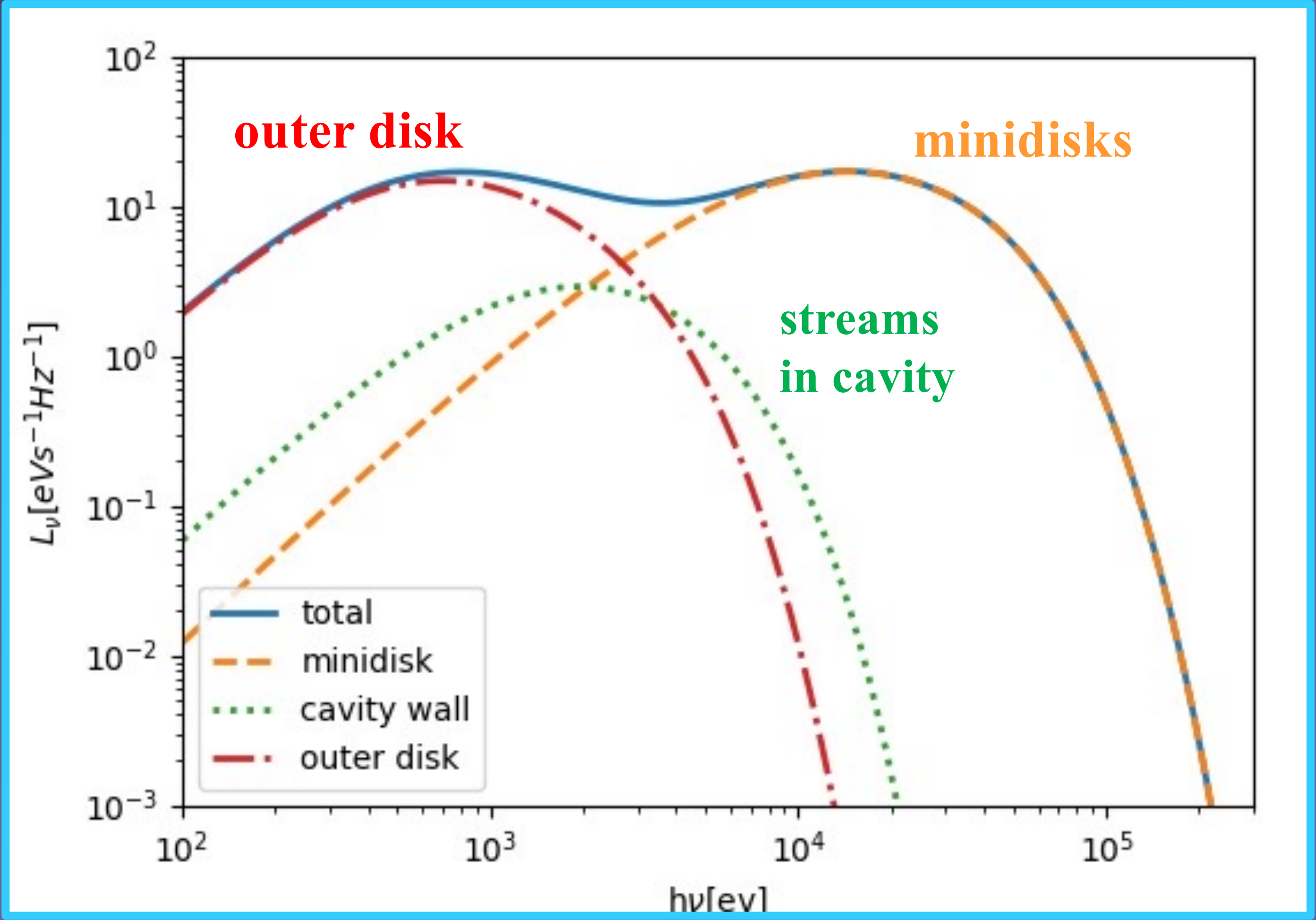
→ 100s detectable by Vera Rubin Observatory (LSST, 2024+)

Signature II: Hard spectrum



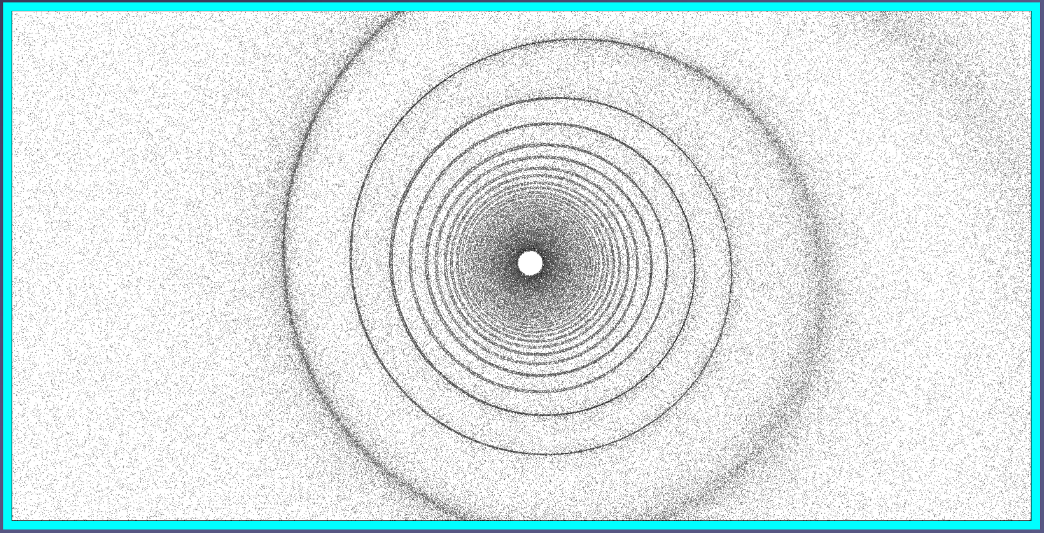
Tang et al. (2017)

Thermal emission extends to hard X-rays from inner regions around each BH



$q = M_2/M_1 = 1$

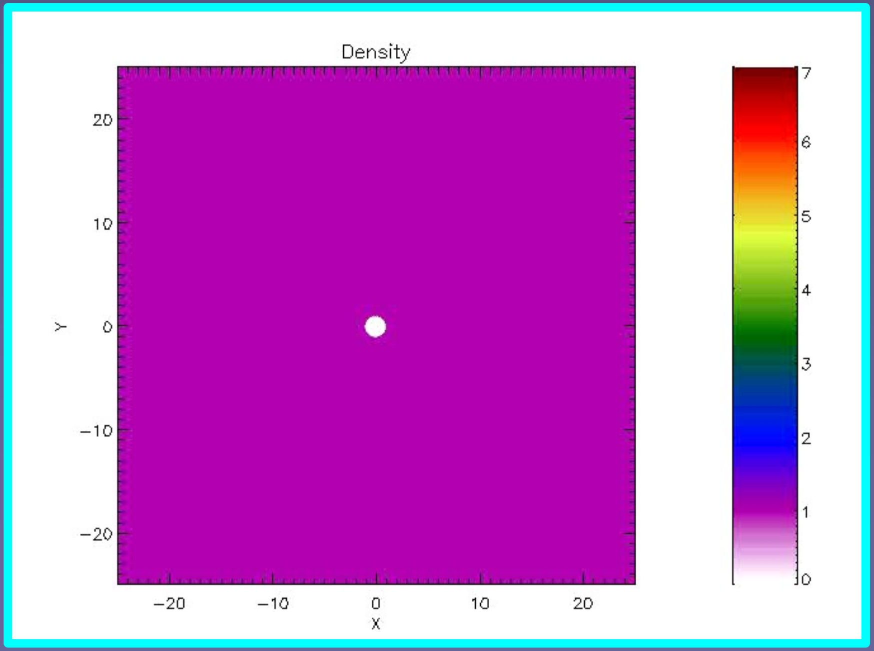
Signature III: Post-merger afterglow



Anisotropic GW emission causes BH to recoil and lose few % of its mass

Orbit crossings– spiral caustics

Lippai, Frei, ZH (2008)
Penoyre & ZH (2018)



Outward-propagating shocks

Corrales, ZH & MacFadyen (2010)
Rossi et al. (2009, 2010)
Megevand et al. (2010)
O'Neill et al. (2009)

→ afterglow on weeks/months timescale, unique evolution

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Searching for Periodic Quasars

inspiral time: $t_{GW}(P{\sim}yr) \sim t_{visc} \sim 10^5$ yr

quasar lifetime: $t_{QSO} {\sim} 10^8$ yr

expected periodic fraction: $f_{bin} \sim t_{GW}/t_{QSO} \sim 10^{-3}$

Maria Charisi

- Catalina Real-Time Transient Survey (CRTS)

  Graham et al. (2015)

  111 candidates with periods 1-5 years

  250,000 quasars to V~20, 9-year uniform baseline

- Palomar Transient Factory (PTF)

  Charisi et al. (2016)

  33 candidates with periods 60-400 days

  36,000 quasars R~22, 5 years non-uniform sampling

- Zwicky Transient Factory (PTF)

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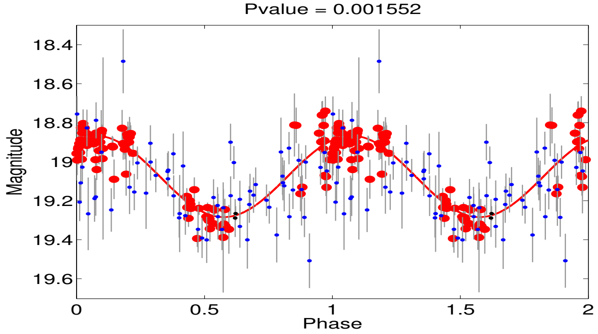
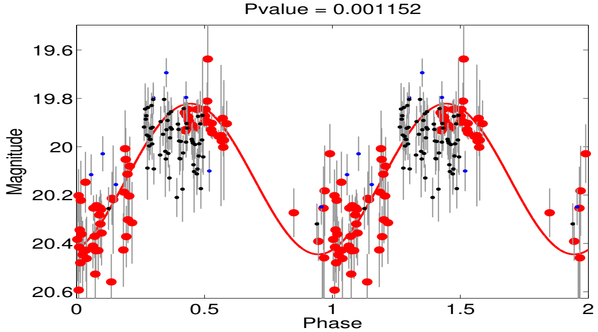
  127 candidates with periods 500-950 days

  143,000 quasars r~20, 5 years non-uniform sampling





Pvalue = 0.01508

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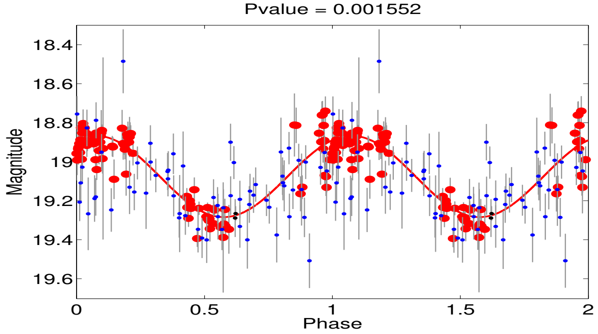
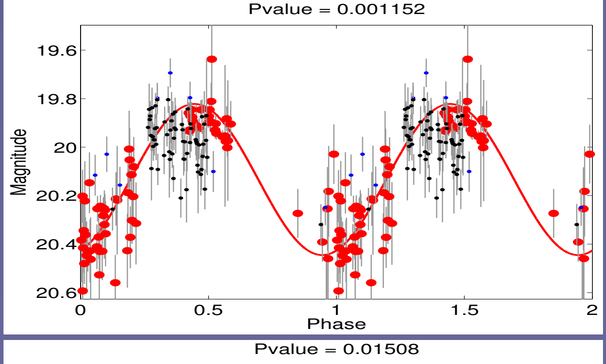




how do we know they're binaries?

Doppler-modulation is chromatic

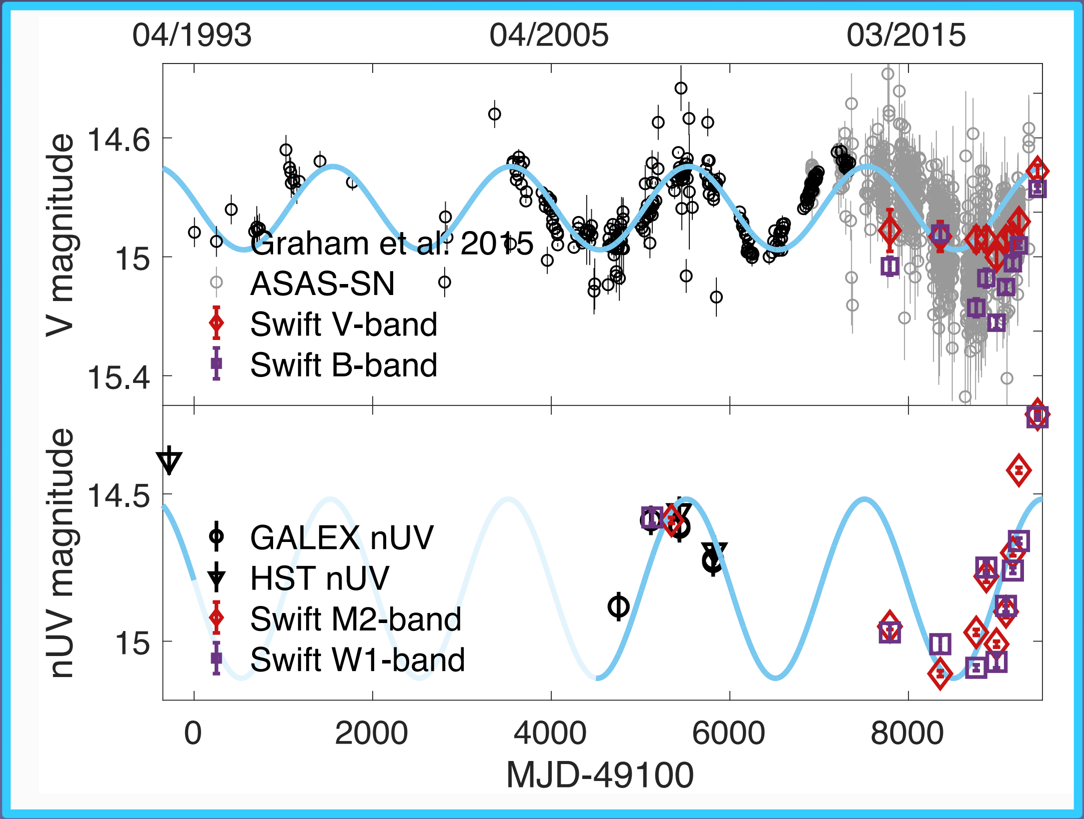
PG1302-102 D'Orazio, ZH, Schiminovich (2015)

Bright z=0.3 quasar $M_{bh}=10^{8.3}\text{-}10^{9.4}\,M_\odot$ a=0.01 pc (280 R_S)
±14% variability with 5.16 ± 0.2 yr period (in 250,000 quasars)

Incl. follow-up Swift data (Xin, Charisi, ZH et al. 2020)

Optical

nUV



Chromaticity:

$\Delta F_\nu/F_\nu = (3-\alpha)\,(v_{||}/c)$

$\alpha = d\ln F_\nu / d\ln\nu$

Optical variability vs. **UV** variability consistent with Doppler boost

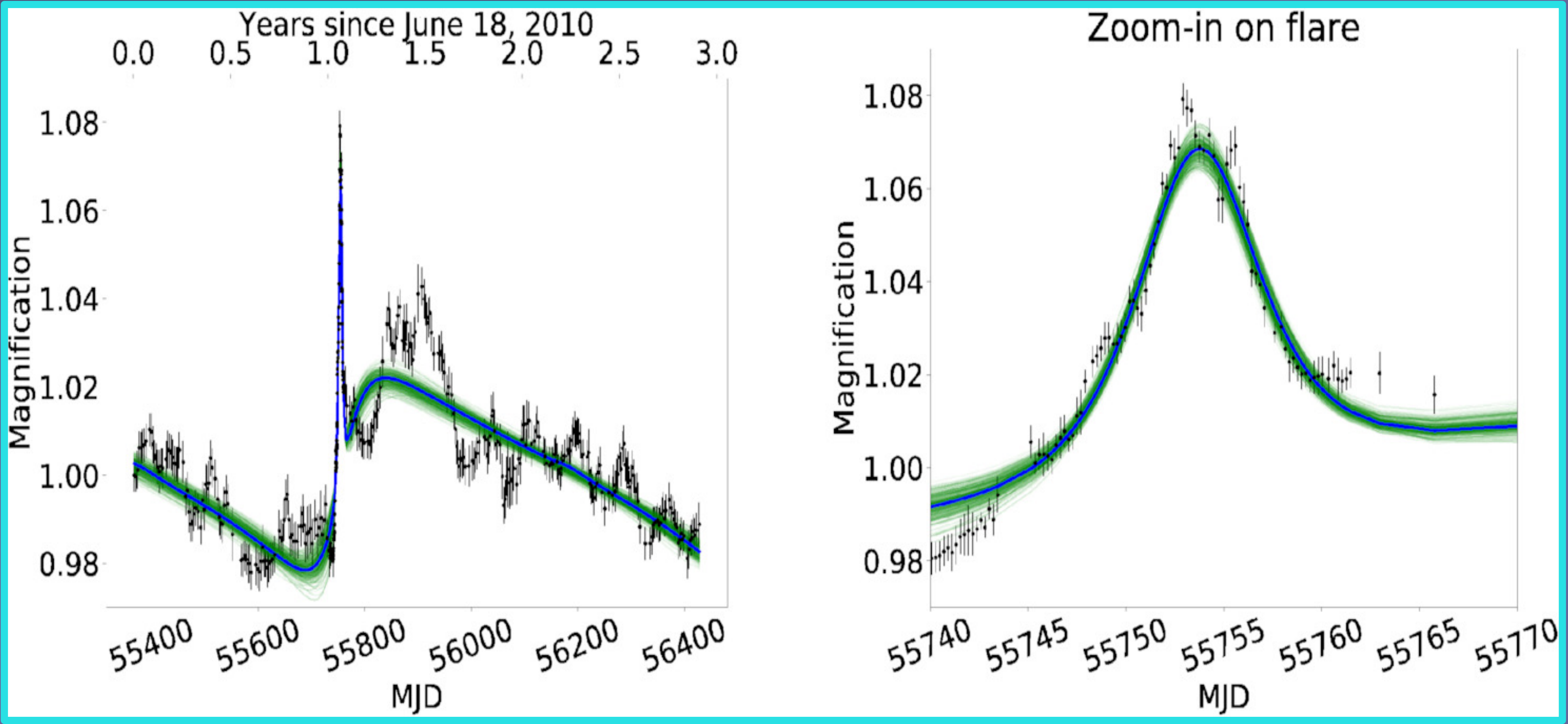
Search for Recurring Self-Lensing Spikes

KIC 11606854, a.k.a. "Spikey" Betty Hu, Dan D'Orazio, ZH et al. (2020)

Rare case of a quasar in the Kepler field (z=0.92), with symmetric spike

Well fit by eccentric SMBH binary:

$M_{tot}=3\times10^{7}M_{\odot}$, $q = 0.2$, $T = 418$ d, $e = 0.5$, inclination = 8°

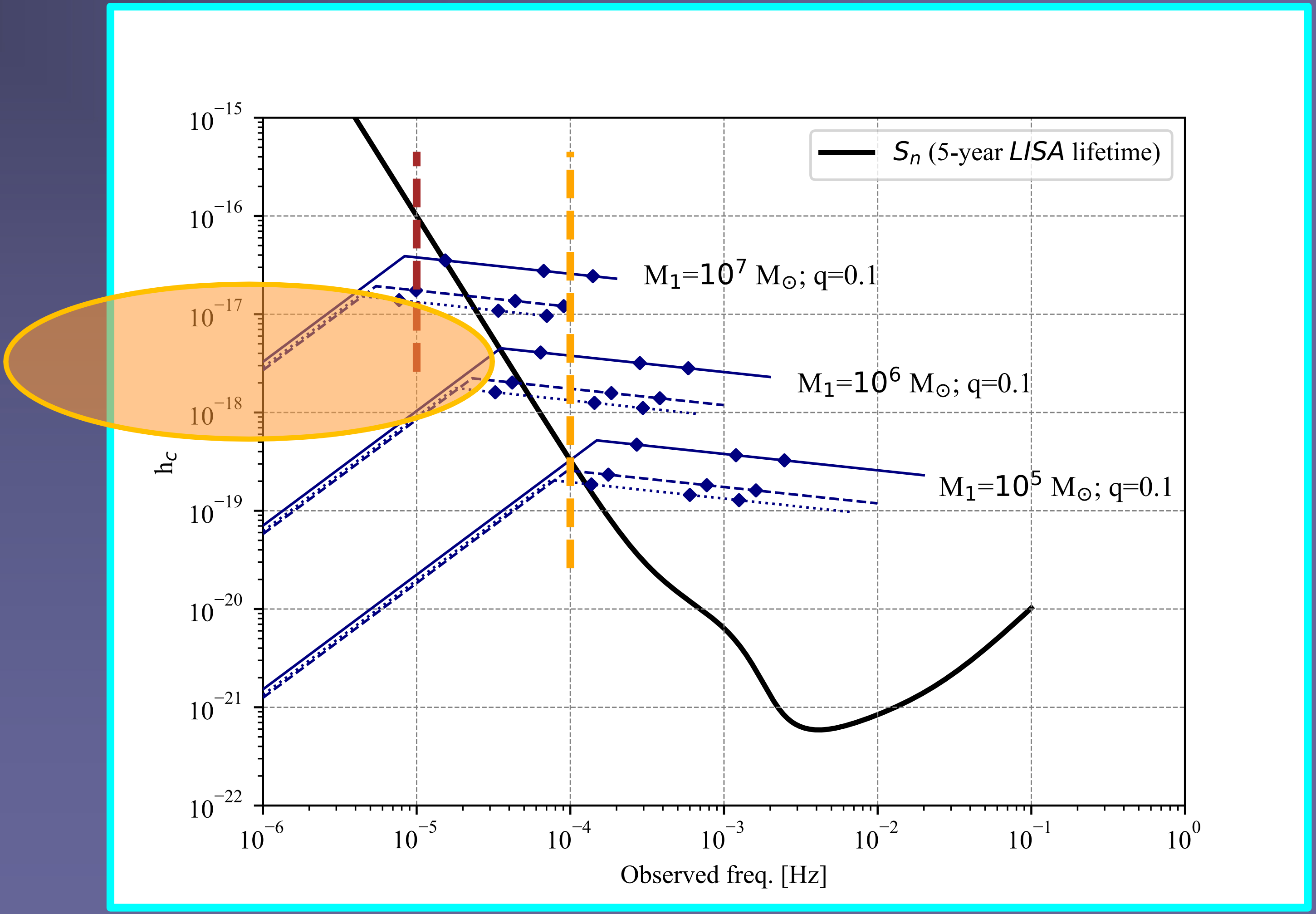


Chengcheng Xin

Binaries in LSST

Xin & ZH (2021)

LSST →



perfect for this search:

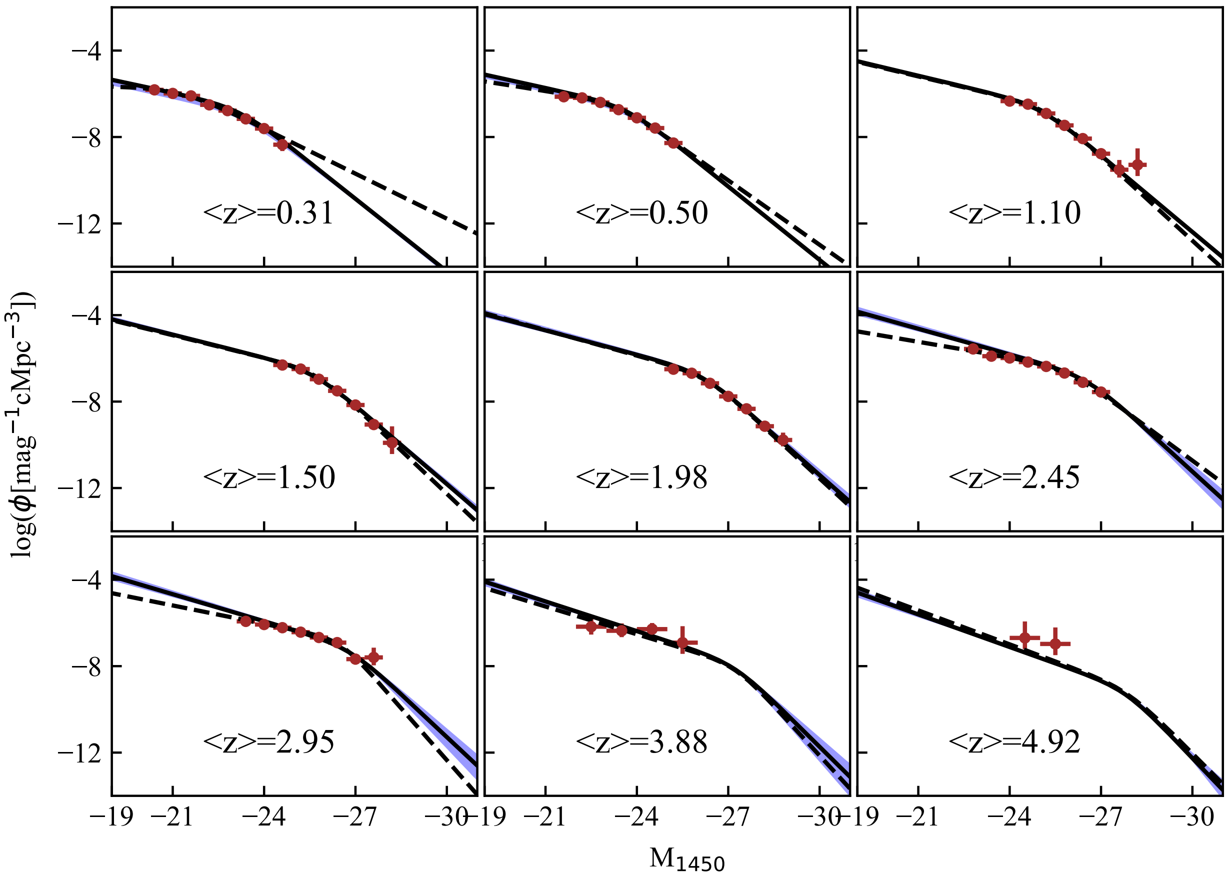
1. wide
2. deep
3. high cadence

1 year

1 day

How many do we expect in LSST?

Xin & ZH (2021)



Extrapolate quasar LF

Assume fraction f_{bin} of quasars are binaries:

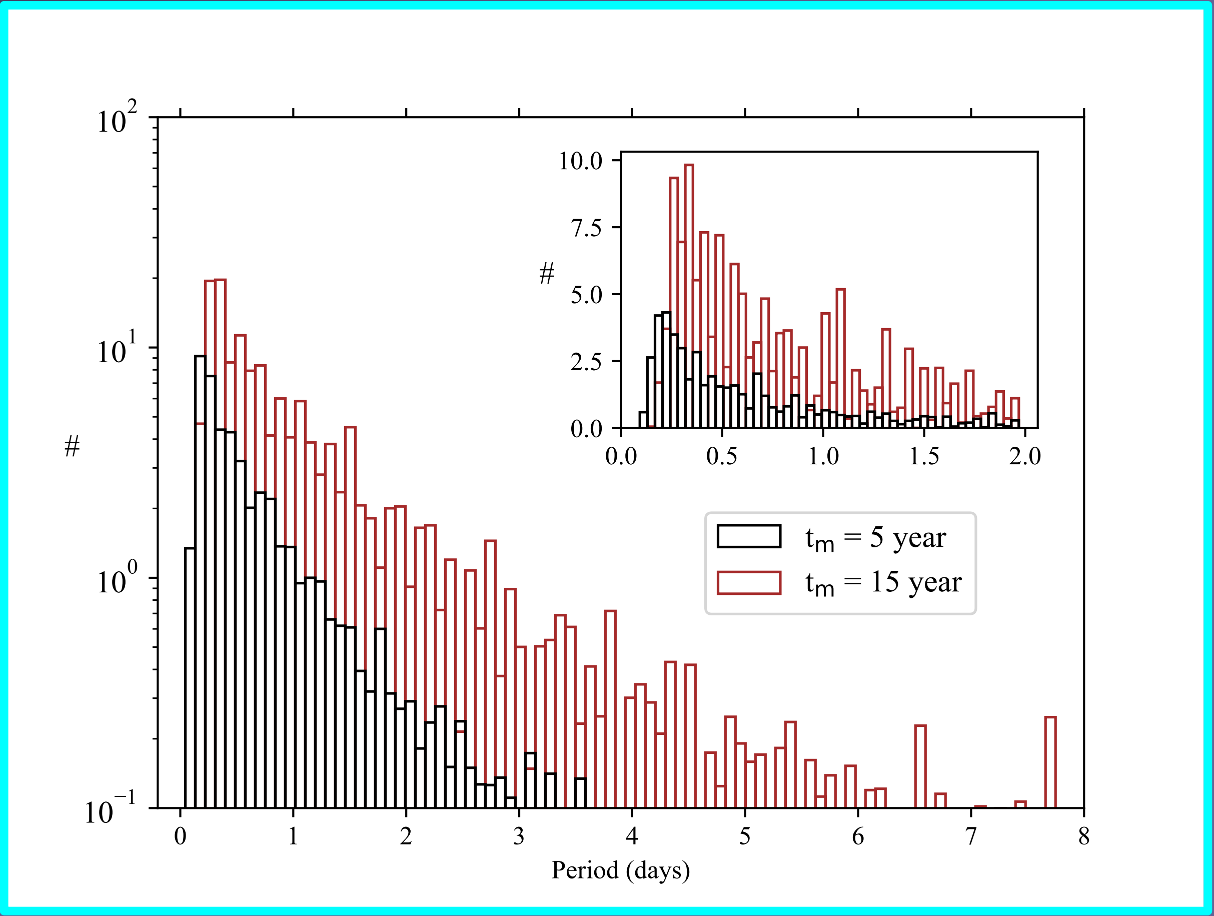
N_{bin} (P_{orb}) =

[t_{res} (P_{orb}) / t_Q] f_{bin} N_Q

Side-steps modeling of cosmology/mergers

LISA “verification” binaries in LSST

Xin & Haiman (2021)



* O(100) binaries with P $\lesssim$ 1 day: Redshift z ~ 1-2 Mass ~10^5 - 10^6 $M_\odot$
* Many more at longer periods but still well in GW inspiral regime
* Can identify them in archival data after LISA detection

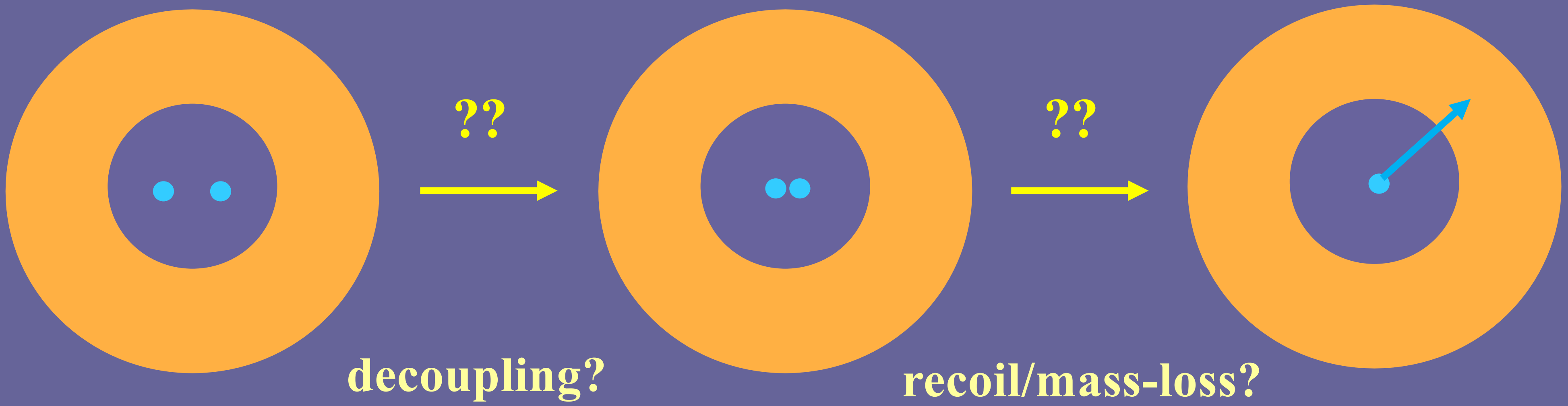
EM signatures near merger

Luke Krauth et al. (2023)


Luke Krauth

Follow GW inspiral (10^6 $M_\odot$) for **last ~month** before merger (~400 orbits)

Follow post-merger disk including recoil and mass-loss of remnant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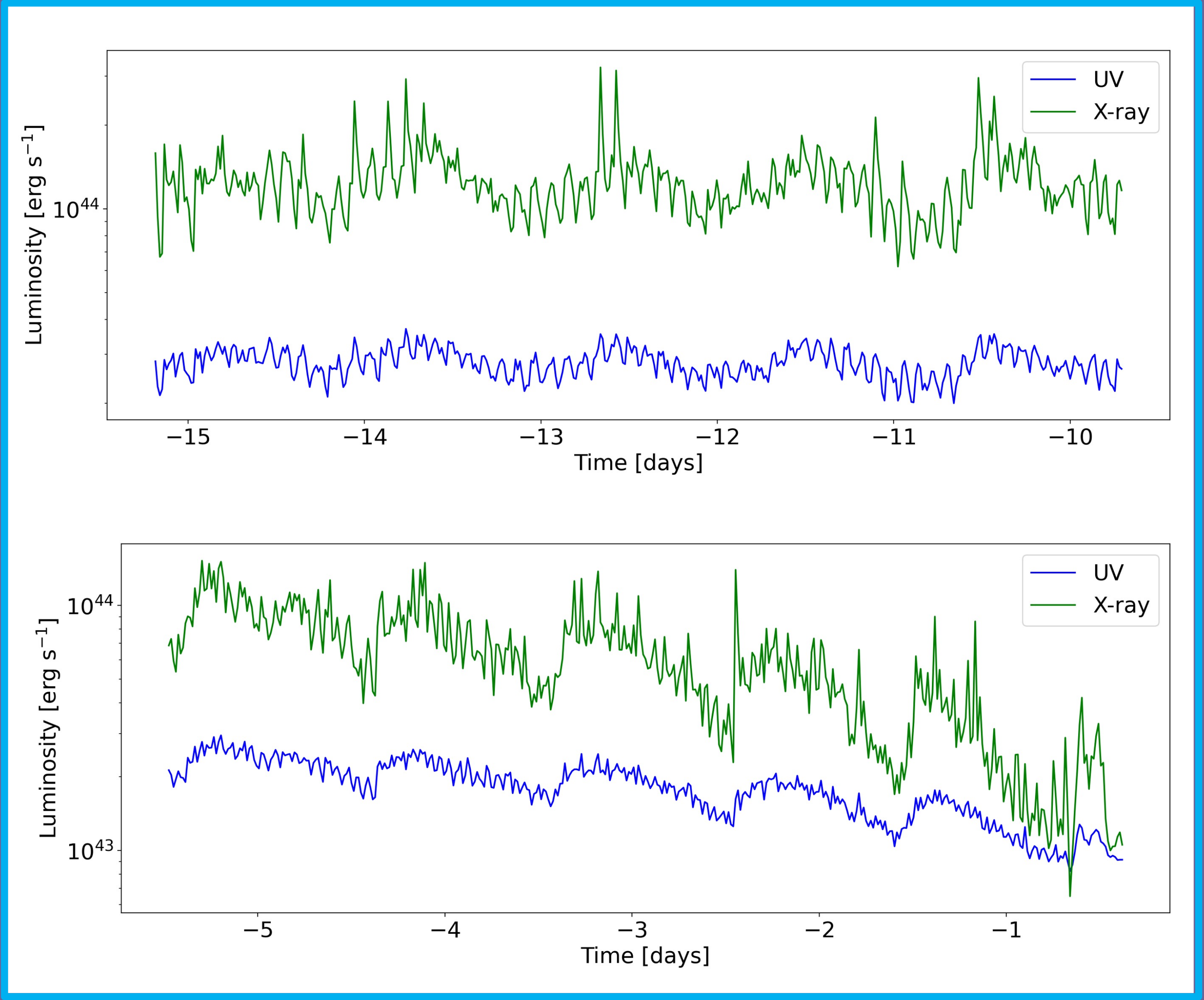
decoupling?

recoil/mass-loss?

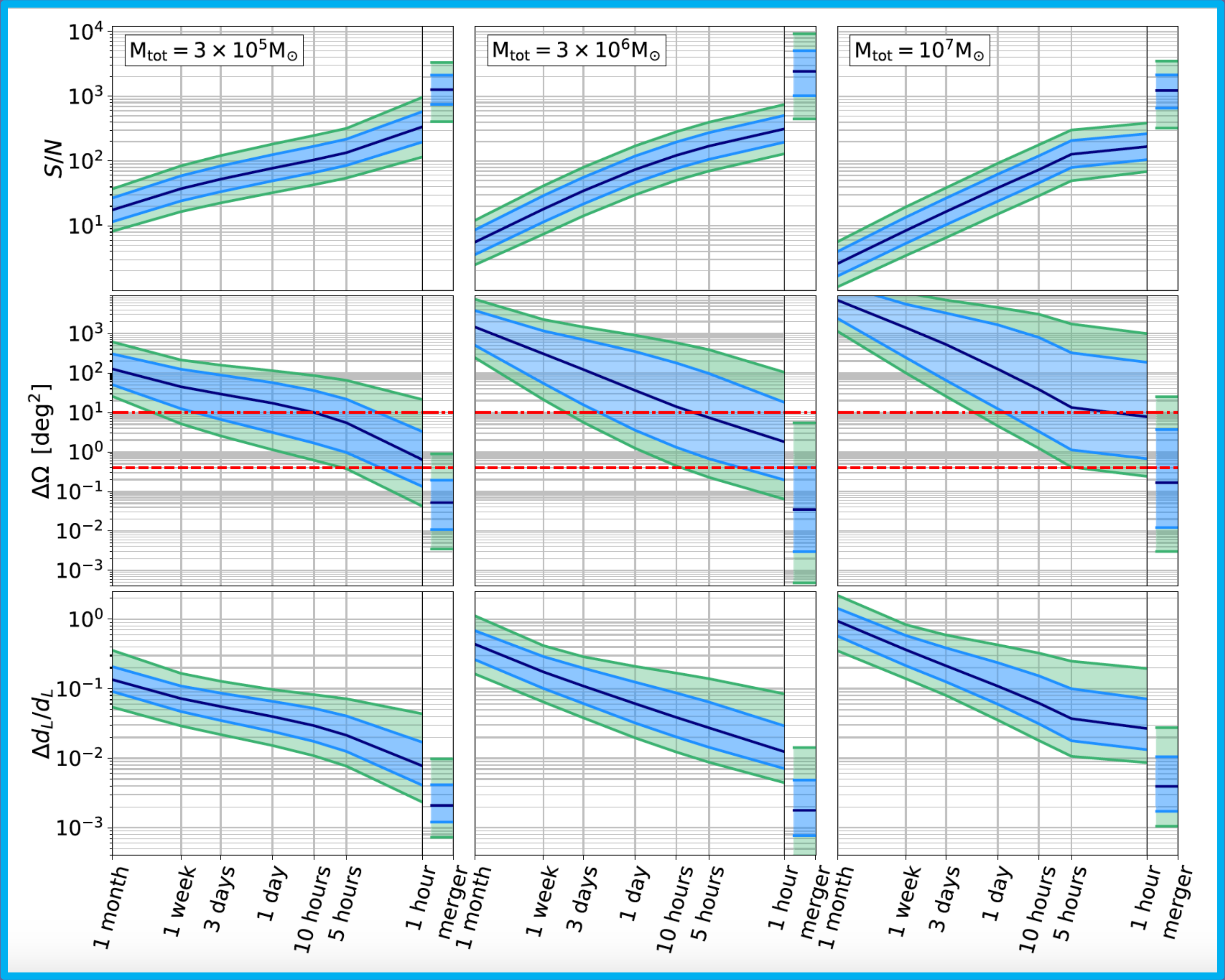
EM chirp follows GW chirp



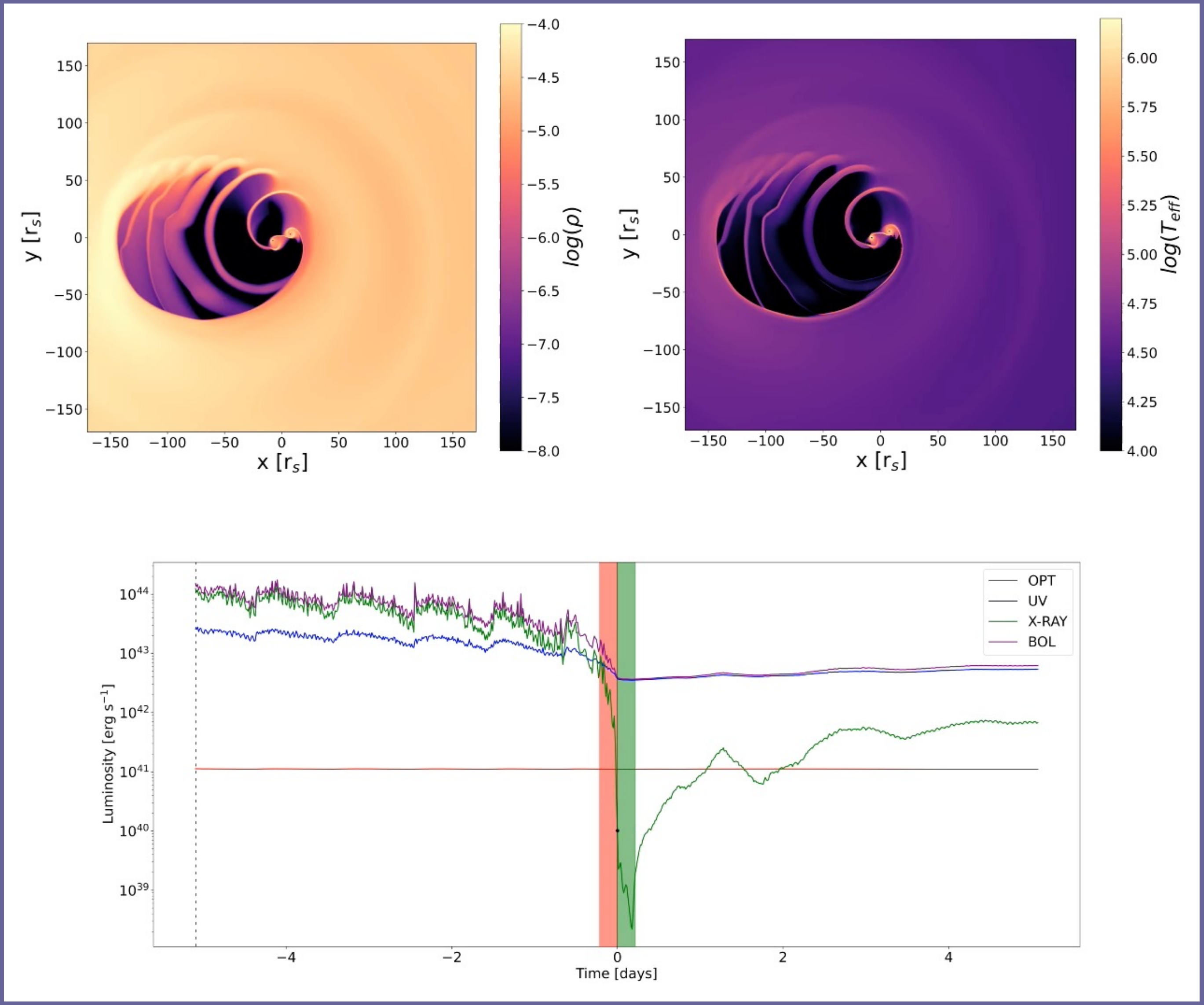
cf. earlier work by **Tang et al. 2018**

Pre-merger localization - ouch

Mangiagli et al. 2020



Disappearing black holes!



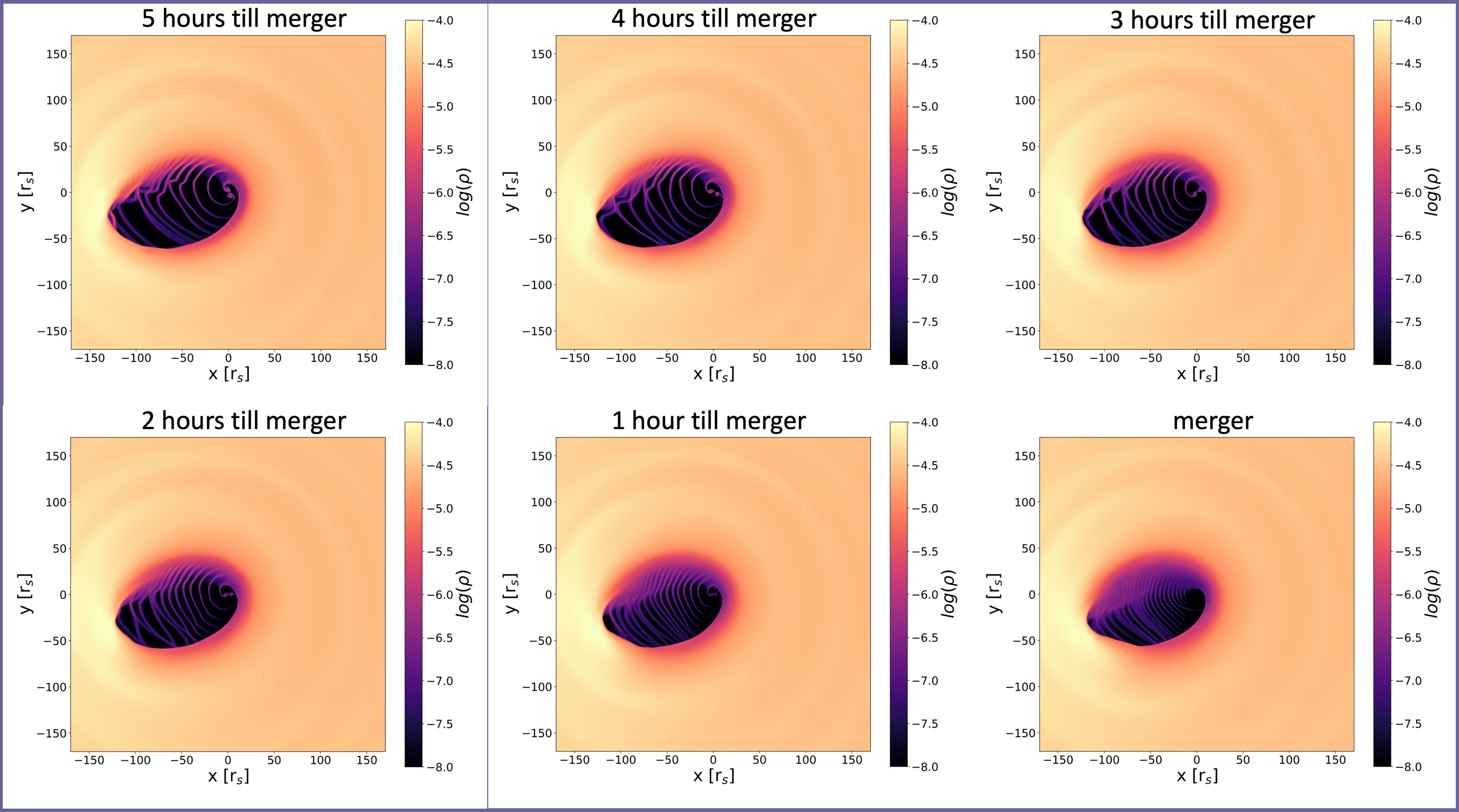
Binary suddenly vanishes in X-rays

But stays in optical UV and infrared

Can catch this with Athena (use LSST or its archival data)

No immediate effect of mass-loss or recoil

Disappearing minidisks and streams


5 hours till merger

4 hours till merger

3 hours till merger

2 hours till merger

1 hour till merger

merger

Summary

1. Binaries quasars are periodic: hydro ($q\sim1$) and Doppler ($q\lesssim0.05$)
2. Some may have been already detected: chromatic periodicity
3. Additional recurring self-lensing flares present (esp. if Doppler)

   BH shadows detectable as further "dips" on top of lensing flares
4. O(100) rare ultra-compact binaries in LSST → LISA sources
5. Binary disappears in X-ray but not opt/IR in last ~20 orbits (~day)

Outline

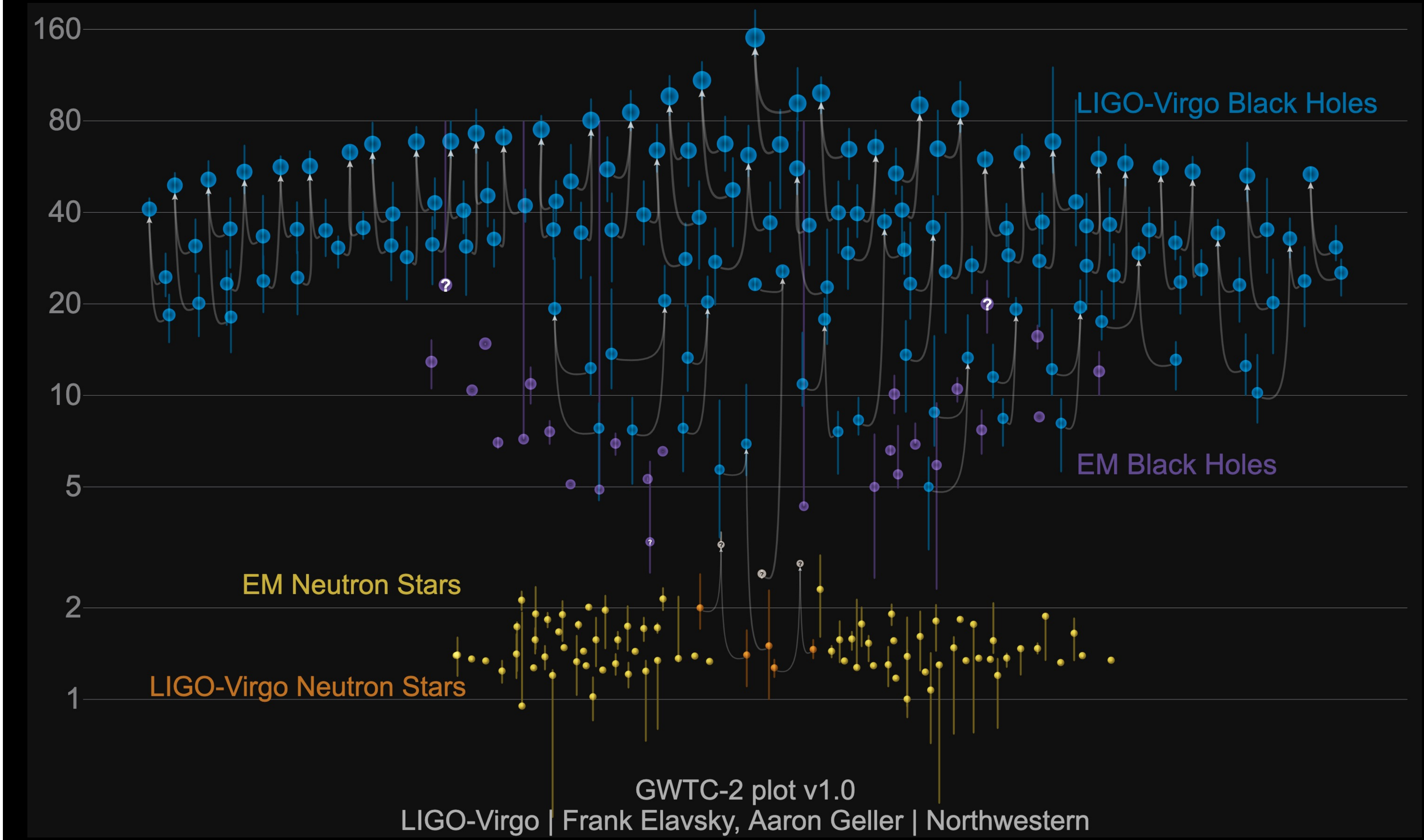
1. **Introduction: mergers of SMBHs in galactic nuclei**
   - observational background, motivation

2. **Theory: binary accretion**
   - bright variable emission from binary

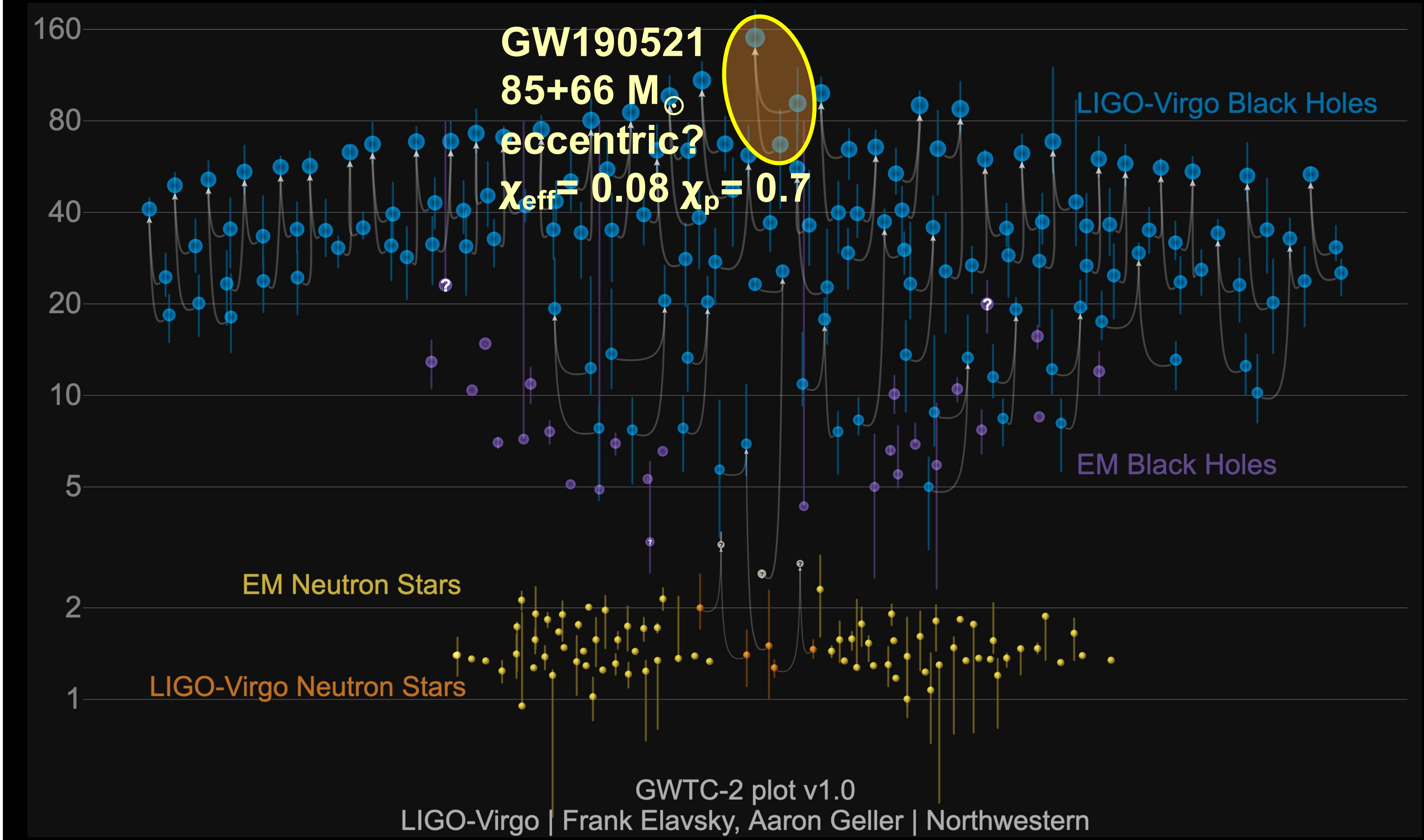
3. **Observations: do we have to wait for GW detections?**
   - SMBH binary candidates in quasar surveys
   - forecasts for LSST & LISA era

4. **Stellar-mass BH binaries: mergers in AGN disks?**
   - BH binaries form in or captured by nuclear gas disks
   - Bright EM emission outshining AGN

Stellar remnant black hole mergers



Stellar remnant black hole mergers

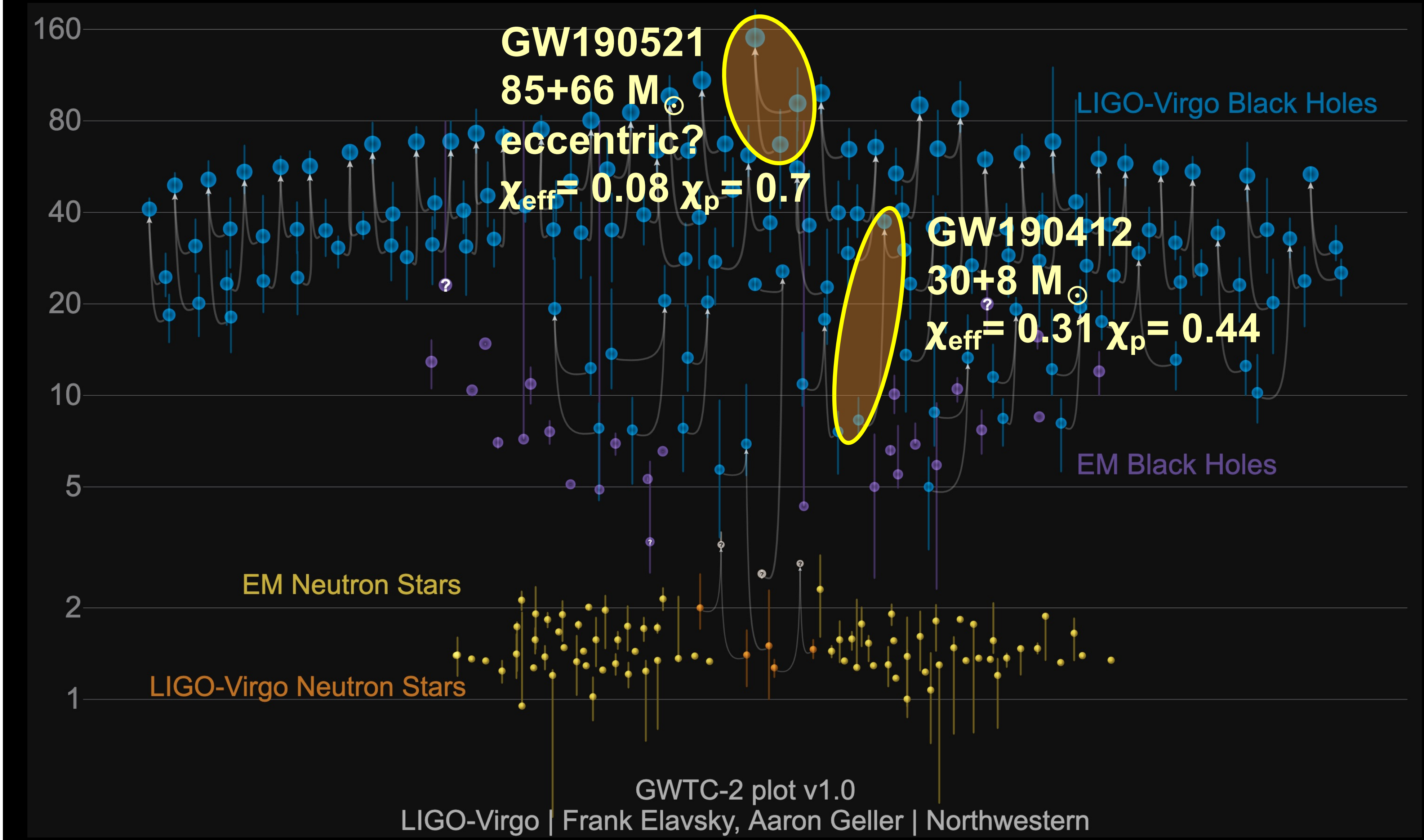

GW190521

85+66 $M_\odot$

eccentric?

$\chi_{eff} = 0.08$ $\chi_p = 0.7$

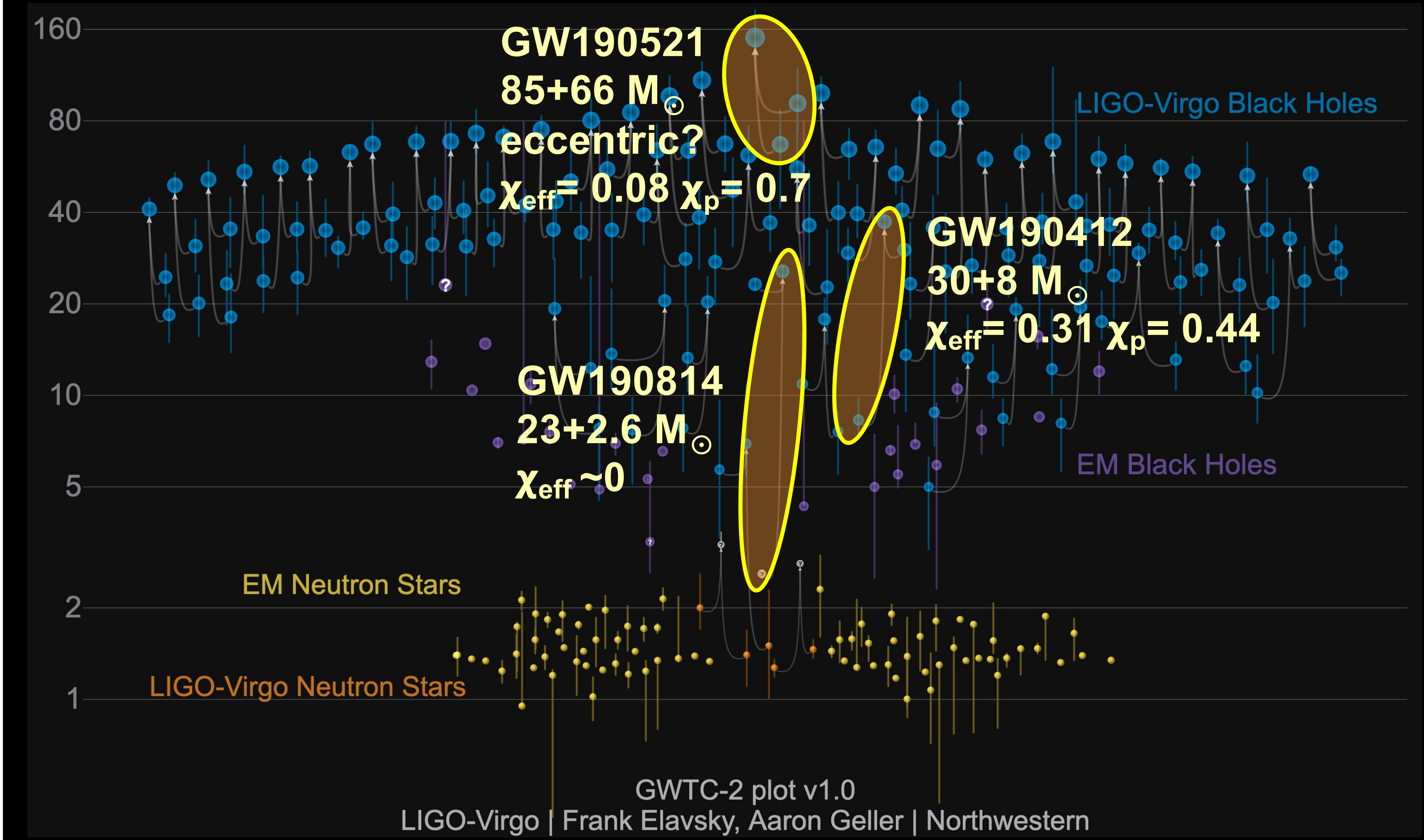
Stellar remnant black hole mergers



GW190521
85+66 $M_\odot$
eccentric?
χ_{eff}= 0.08 χ_p = 0.7

GW190412
30+8 $M_\odot$
χ_{eff}= 0.31 χ_p= 0.44

Stellar remnant black hole mergers



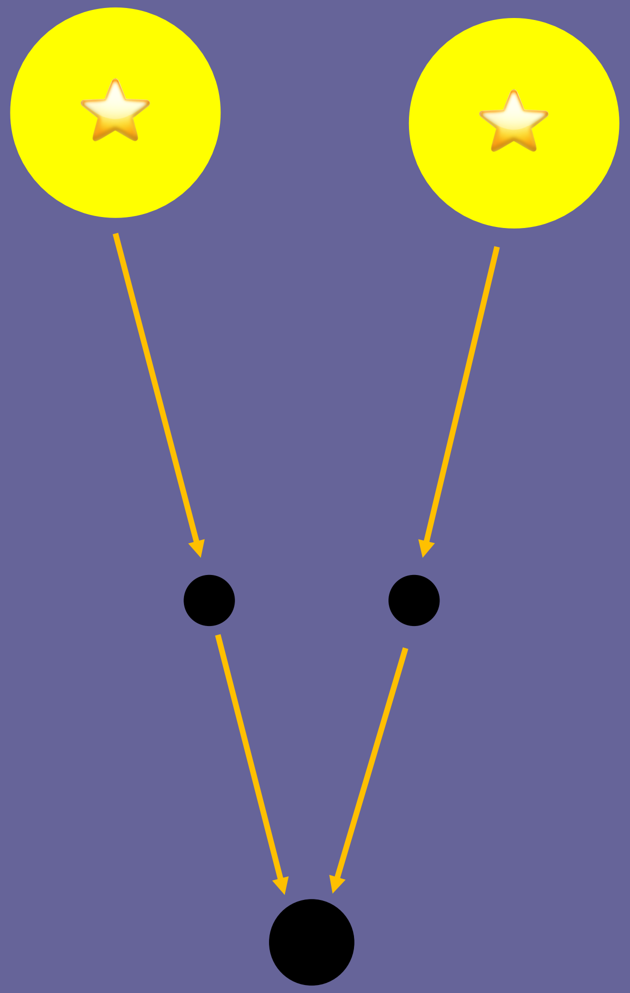
GW190521
85+66 $M_\odot$
eccentric?
χ_{eff}= 0.08 χ_p = 0.7

GW190412
30+8 $M_\odot$
χ_{eff}= 0.31 χ_p= 0.44

GW190814
23+2.6 $M_\odot$
χ_{eff} ~0

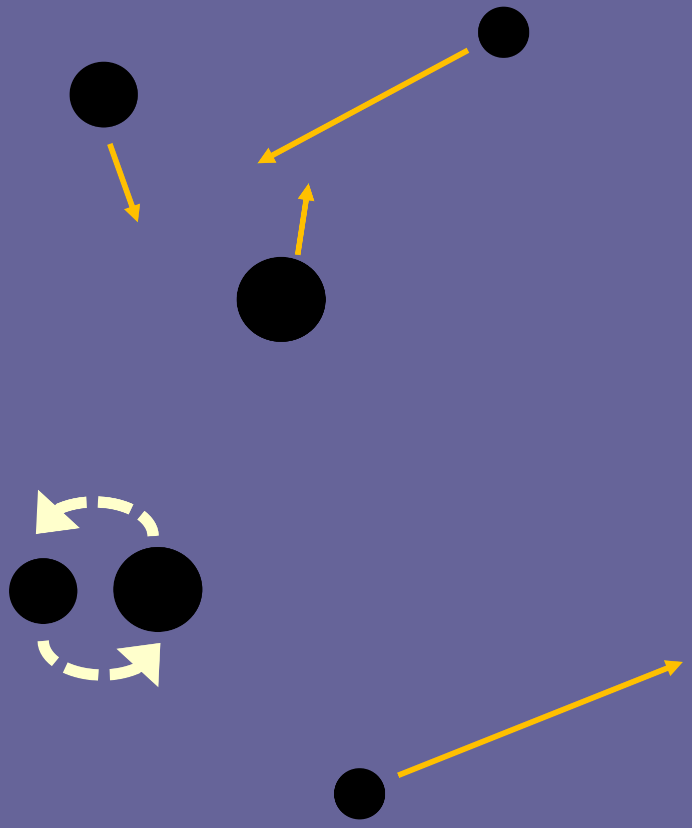
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

isolated binary evolution



~ equal mass
~ aligned spin

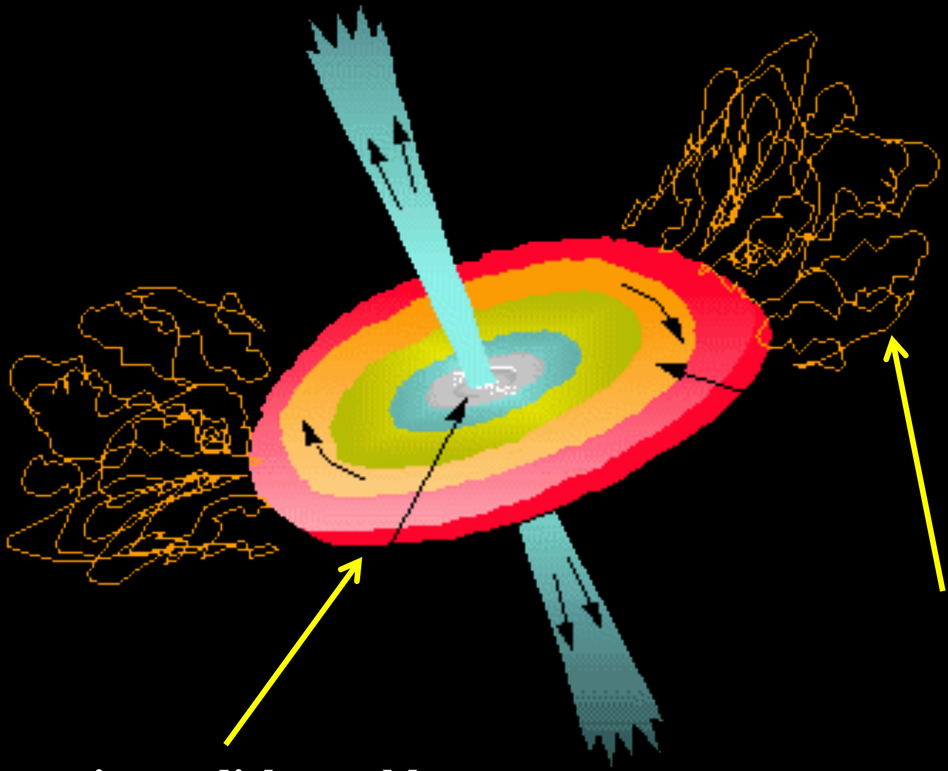
N-body dynamics in dense clusters



~ equal mass
~ random birth spins

Stellar-mass BHs in quasar disks

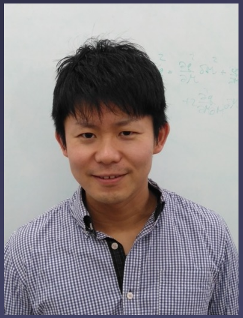
Gas cools and forms a compact (~ sub-pc) nuclear accretion disk



Gravitationally unstable region Q(Toomre) < 1

inner disk: stable,
geometrically thin,
optically thick,
$M_{disk} \ll M_{bh}$

→ What if second black hole is present ? ←

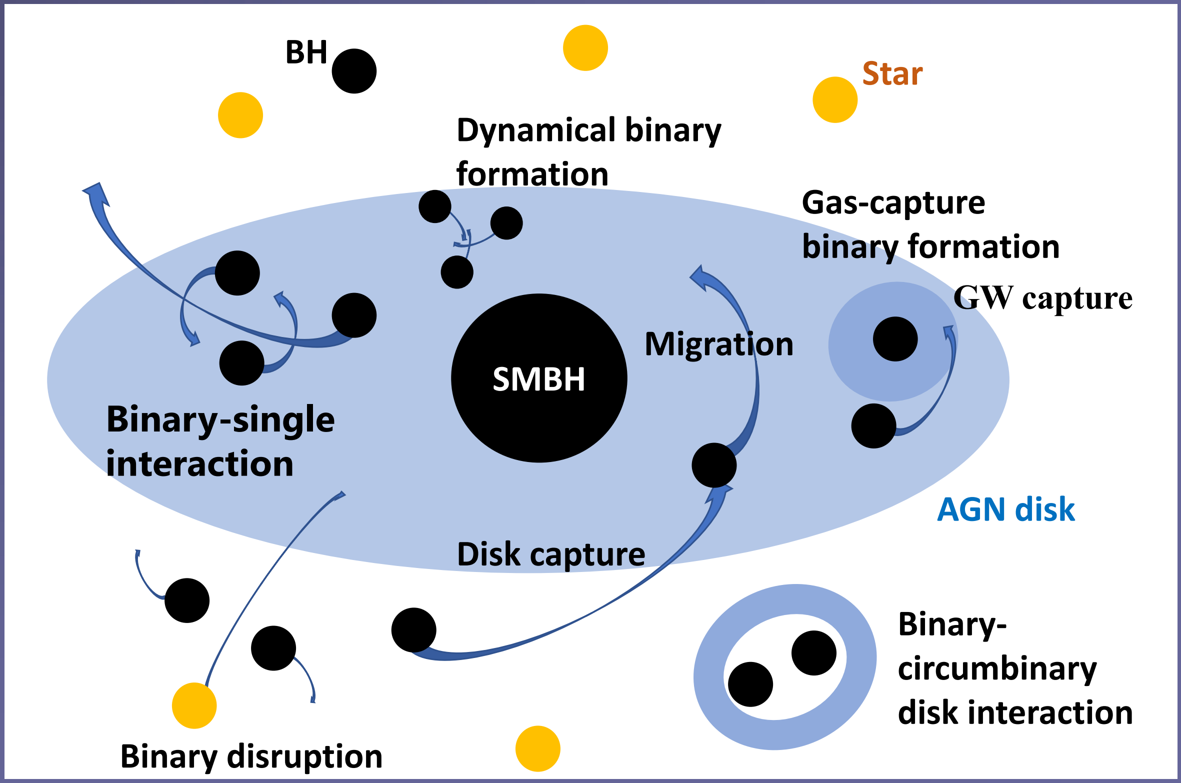


Hiromichi Tagawa

“1D” N-body simulation

SMBH, gas disk, stars+BHs in 3D cluster, in 2D disk

Tagawa, ZH, Kocsis (2020a)



I. **Binary formation**
(2-body, 3-body)

II. **Binary disruption**
(binary-single scattering)

III. **Binary evolution**
(circumbinary gas, GWs, binary-single scattering)

IV. **Radial migration**
(Type I/II torque)

Merger characteristics

* Most binaries in AGN form via dissipative gas capture

* Most LIGO events probably not from AGN disks, but properties of some recent events naturally expected:

1. **Unequal mass** ✓
   → different generations
2. **High mass** ✓
   → 2g+ (and some accretion)
3. **High spin** ✓
   → due to prior merger, correlates with mass
4. **Misaligned spin ($\chi_{eff} \sim 0$ but $\chi_p > 0$)** ✓
   → scattering with 3rd body
5. **Eccentricity** ✓
   → scattering with 3rd body
   with GWs (if coplanar)
   → GW capture in inner region
   (if rapid migration to $<10^{-3}$ pc)

Gas Capture Model

De Laurentiis, Epstein-Martin & ZH 2023

3-body problem with gas dynamical friction, REBOUND

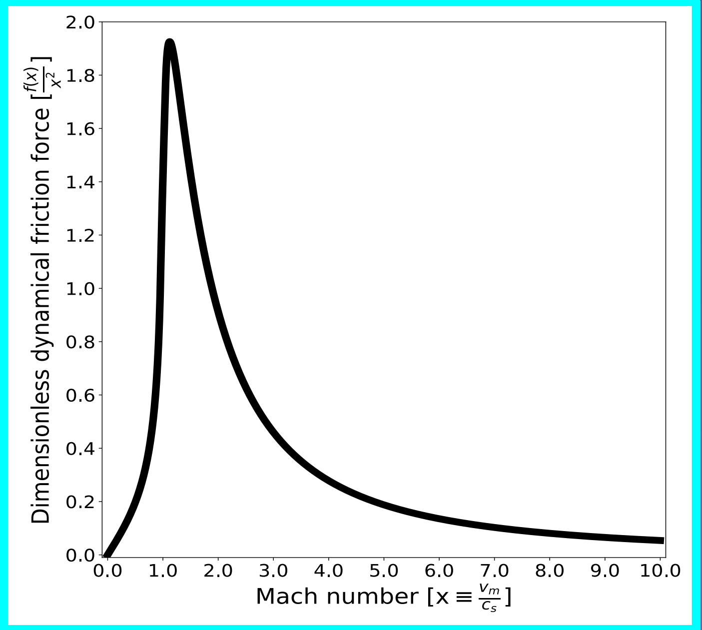
Stan de Laurentiis

Marguerite E.-M.

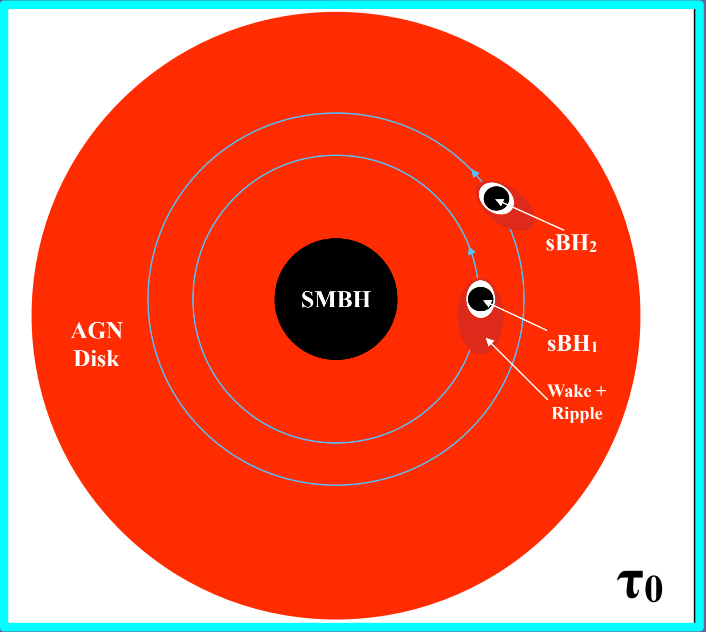
$$F_{DF} = \frac{-4\pi G^2 M^2 \rho}{v_M^3} f\left(\frac{v_M}{c_s}\right)\boldsymbol{v_M}$$

$$f(x) = \begin{cases} 0.5\ln\left(\frac{1+x}{1-x}\right) - x & 0 < x < 1 \\ 0.5\ln(x^2-1) + \ln(\lambda_C) & x > 1. \end{cases}$$

(Ostriker 1999)



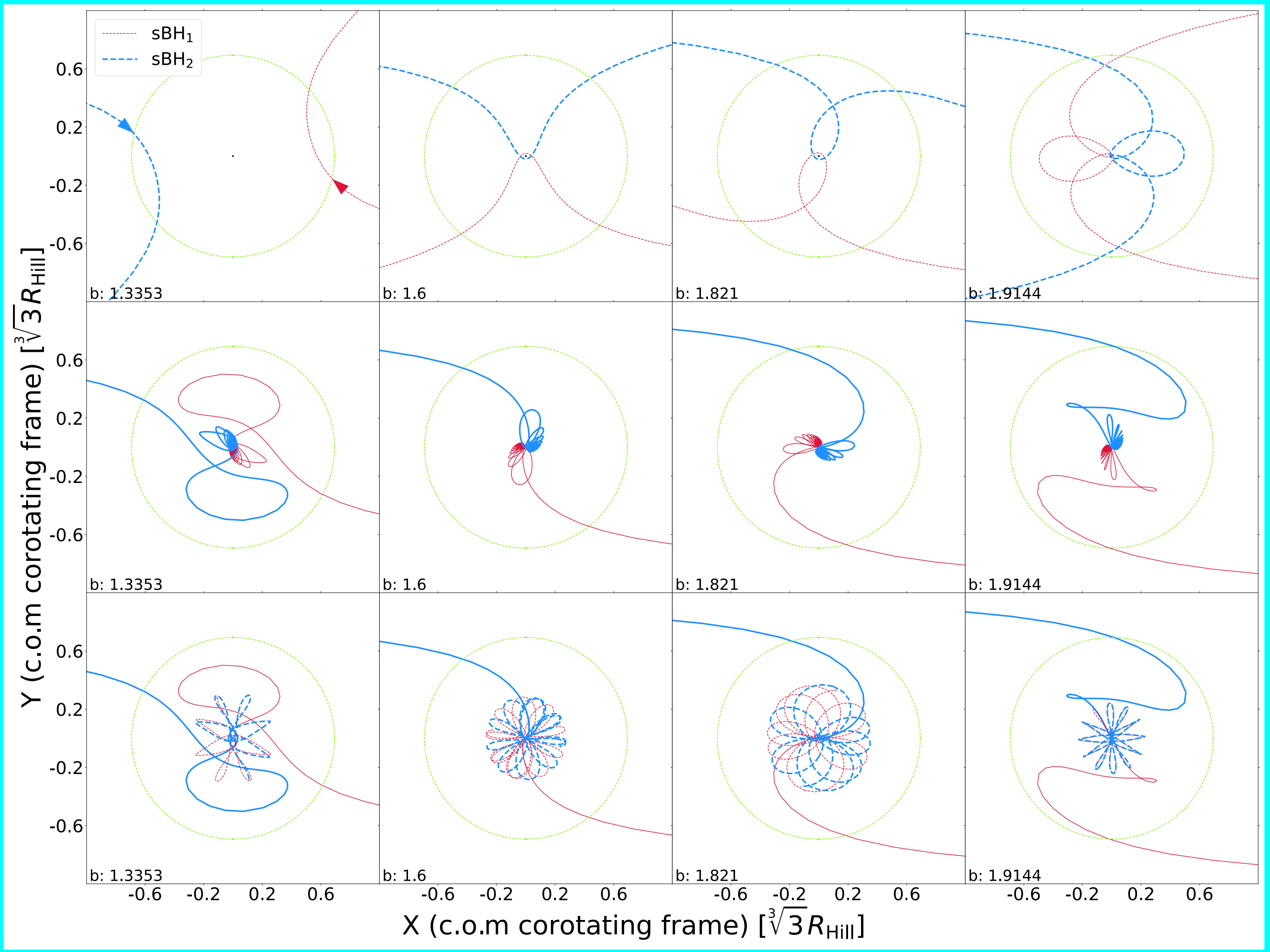
→



Selected Examples of Encounters

De Laurentiis, Epstein-Martin & ZH 2023

→ impact parameter →



dynamical friction:
OFF

dynamical friction:
ON

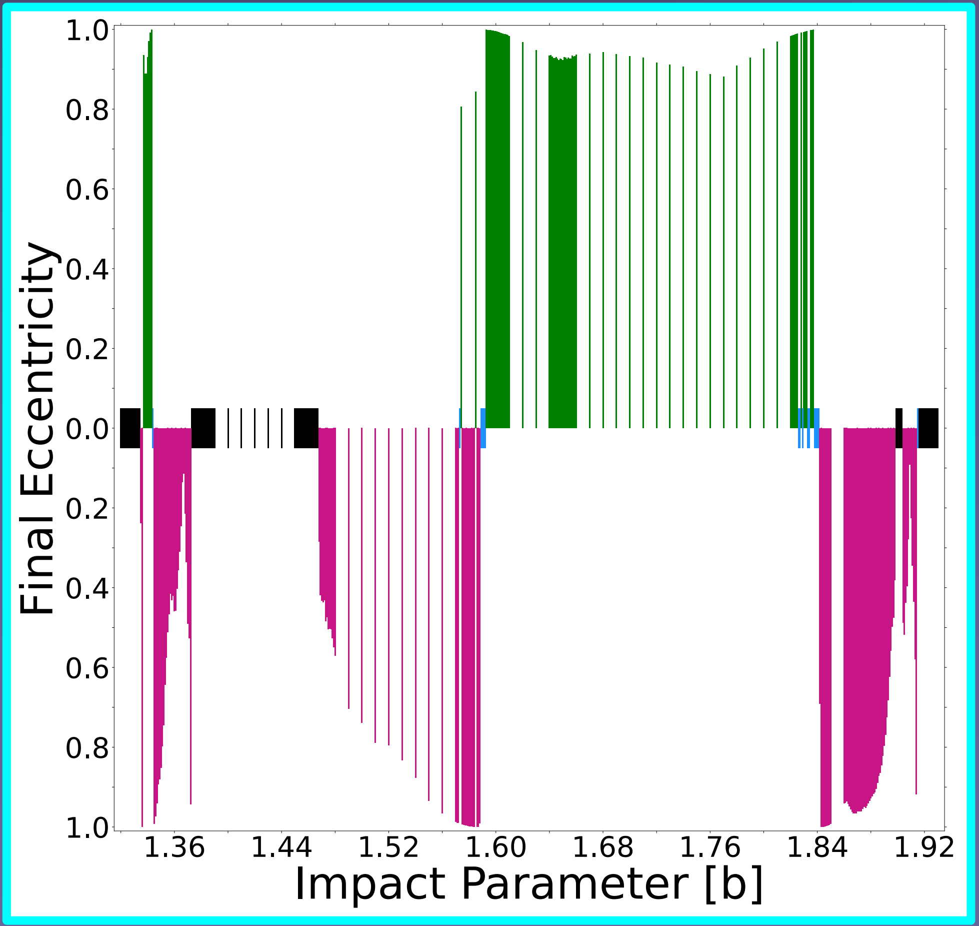
dynamical friction:
ON → OFF

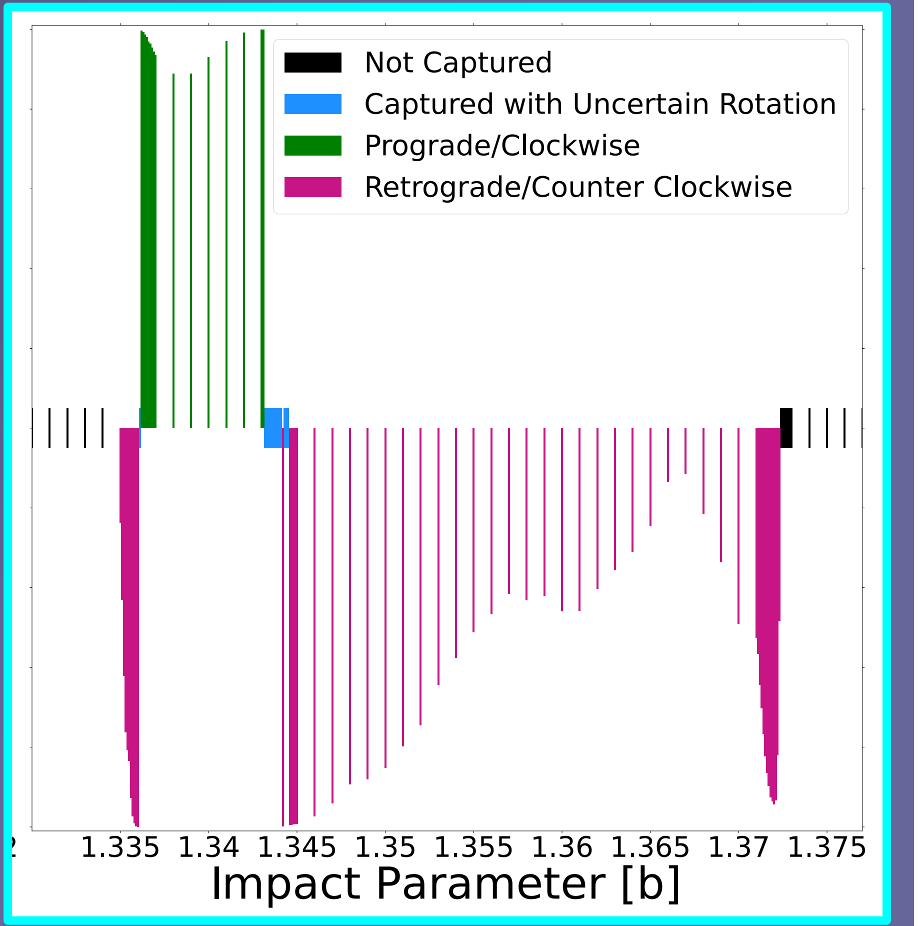
binary bound between Hill radius & pericenter

Fate vs Impact parameter

wide and smooth bands of capture with effective cross section b ~ O(R_{Hill})

cf. fractal structure of frictionless “Jacobi capture”; Boekholt+2022



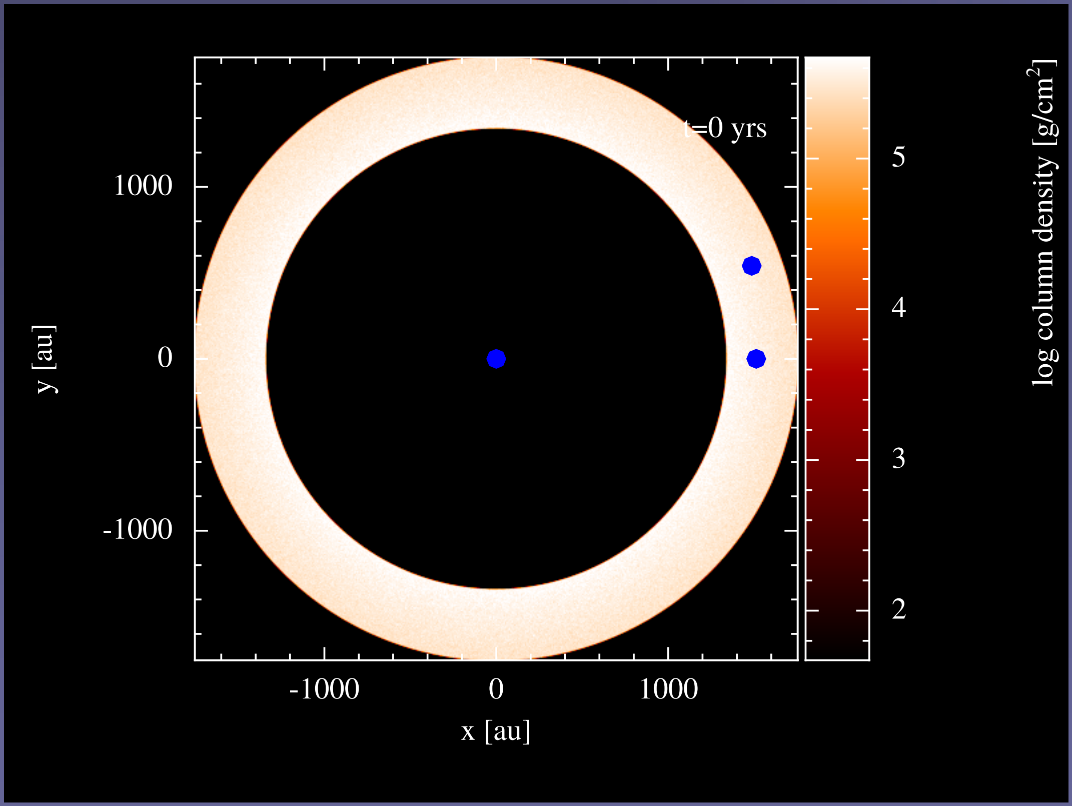


Connar Rowan

Gas Capture – 3d simulations

Rowan, Boekholt, Kocsis & ZH (2023)

SPH (Phantom), 3D, global disk annulus



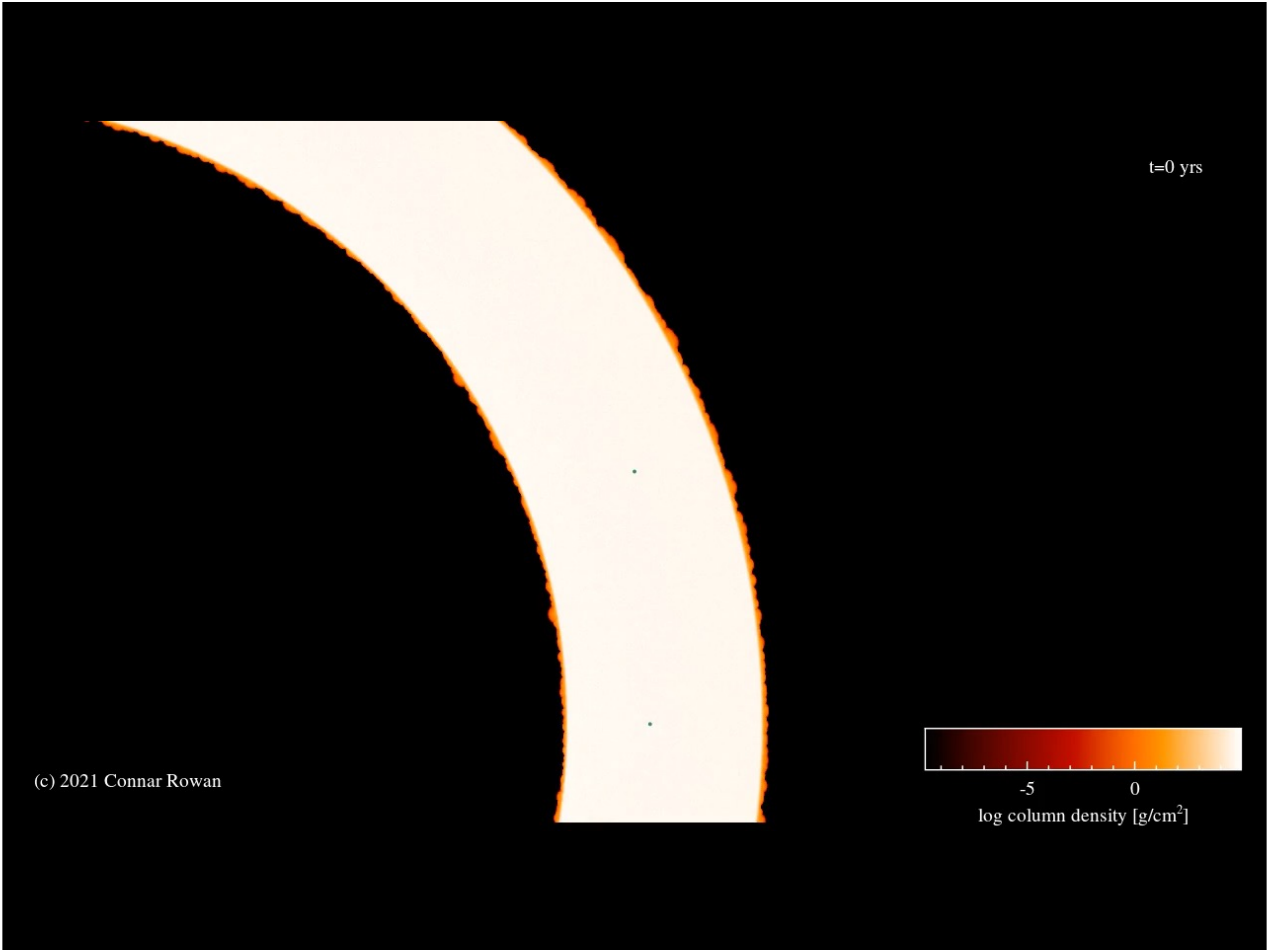
Parameters:

$M_{\mathrm{SMBH}} = 4\times10^6 M_\odot$
$\dot{M}_{\mathrm{inflow}} = 0.1\ \dot{M}_{\mathrm{edd}}$
$\mathrm{H/R} = 0.005$ $(\alpha=0.1)$

$m_1 = m_2 = 25\ M_\odot$
$R_{1,2} \sim 0.01\mathrm{pc}$ $(\mathrm{P}_{\mathrm{orb}} \sim 30\ \mathrm{yr})$
$\Delta R_{sim} = 20\ \mathrm{r}_{\mathrm{Hill}}$ $\Delta\Theta = 20°$

$N = 2.5\times10^7$ particles
$r_{\mathrm{sink}} = 0.01\ r_{\mathrm{Hill}}$
$r_{\mathrm{soft}} = 0.01\ r_{\mathrm{sink}}$

3 disk mass (23, 110, 570 $\mathrm{M}_\odot$) × 5 impact para (2.5-3.5 $\mathrm{r}_{\mathrm{Hill}}$) = 15 sims


t=0 yrs
(c) 2021 Connar Rowan
-5
0
log column density [g/cm^2]

Gas Capture – Summary of Fiducial Sims

Rowan, Boekholt, Kocsis & ZH (2023)

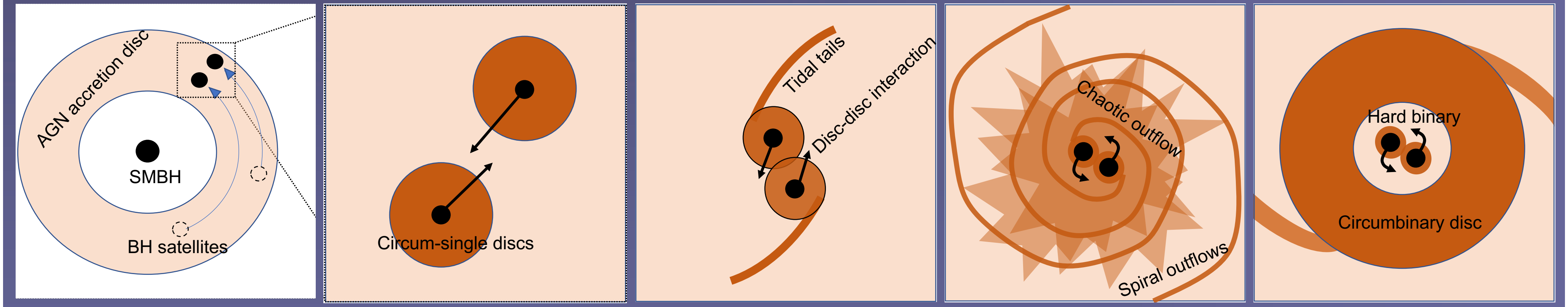
initial condition

minidisk formation

minidisk collision

accretion + outflow

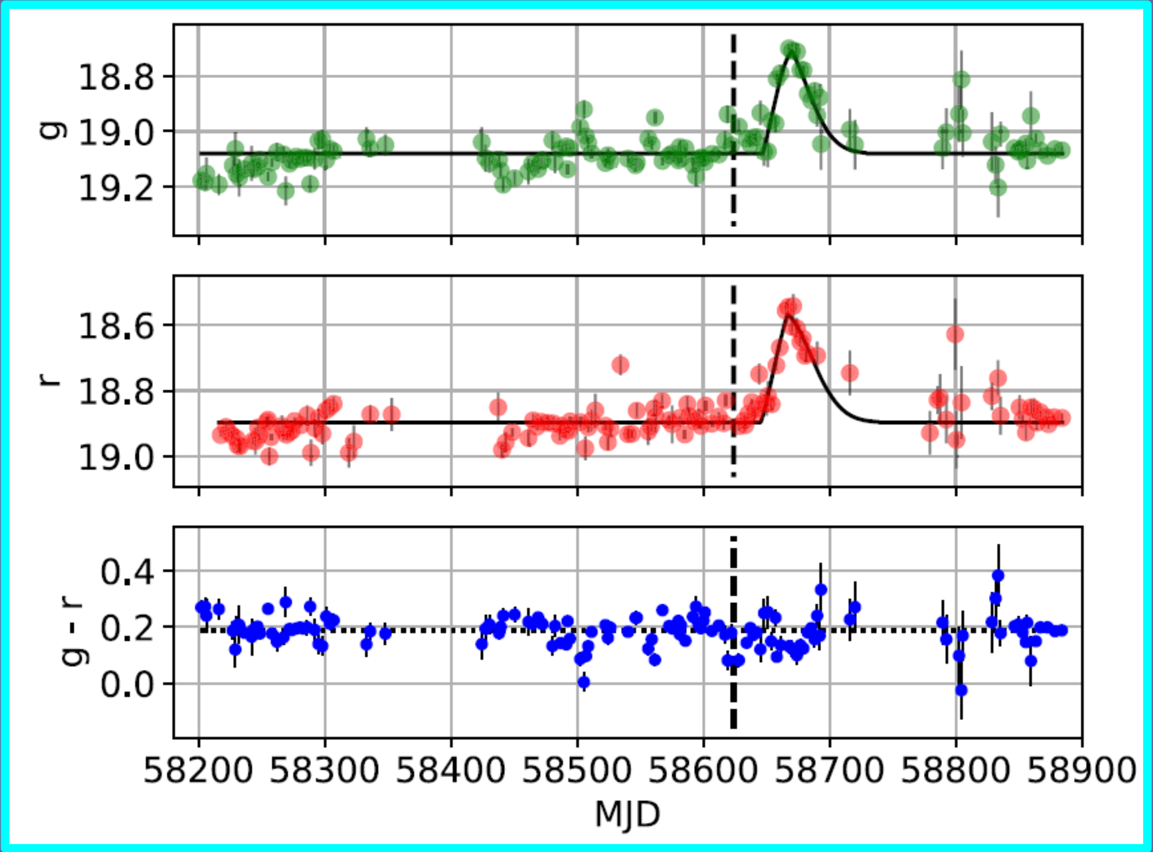
captured binary w/CBD



Optical counterpart to GW190521 (?)

Claim of coincident flare in ZTF

Graham et al. 2020



AGN:

- $z = 0.438$ (~2-3 Gpc)
- $M_{\mathrm{SMBH}} = (1\text{-}10) \times 10^8\, M_\odot$
- $L_{\mathrm{bol}}/L_{\mathrm{Edd}} = 0.02 - 0.23$

Flare:

- $t_{\mathrm{duration}} \sim 28$ days
- $t_{\mathrm{delay}} \sim 18$ days
- $L_{\mathrm{opt}} \sim 10^{45}$ erg/s
- g, r band : ~ 480, 650 nm

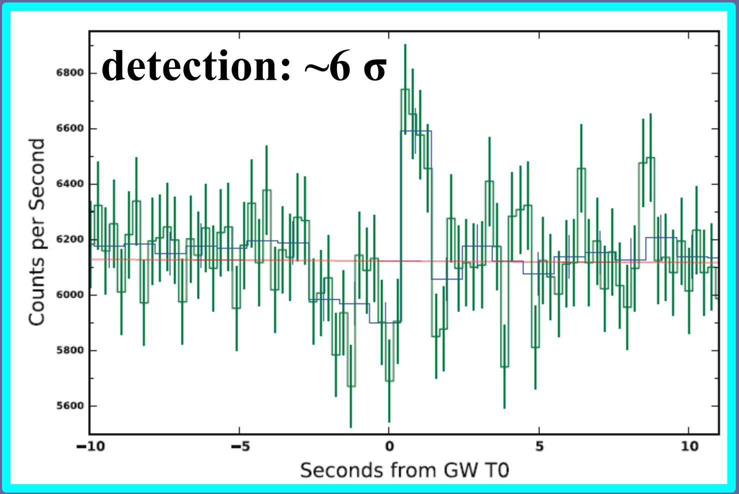
~ $10^5\, L_{\mathrm{Edd}}$ for ~100 $M_\odot$ BH

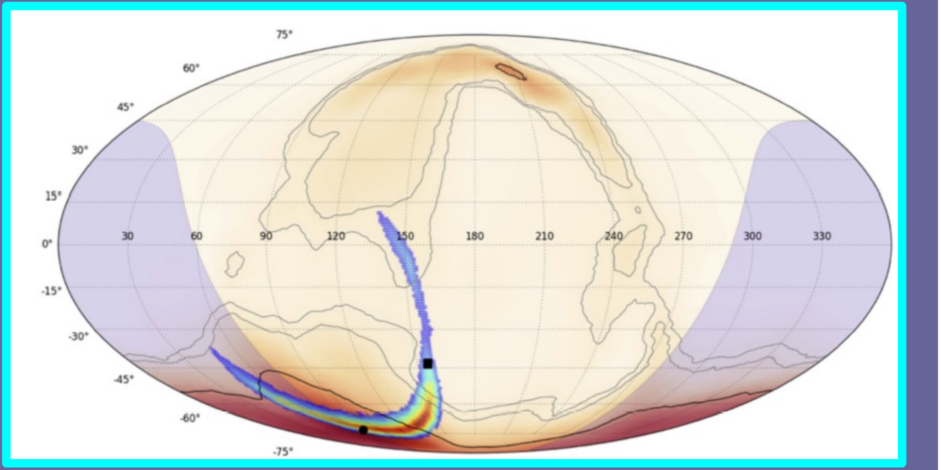
Gamma-ray counterpart to GW150914 (??)

Claim of coincident flare in Fermi GBM:

- GW150914 ($1^{\rm st}$ event, $M_{\rm rem} \sim 62\, M_{\odot}$)
- $L_{\rm max} \sim 2 \times 10^{49}$ erg/s (10 keV-10 MeV)
- $t_{\rm duration} \sim 1$ s
- $t_{\rm delay} \sim 0.4$ s from GW150914
- $E \sim 2 \times 10^{49}$ erg
- $d_{\rm L} \sim 410$ Mpc
- association significance: 2.9 σ

  (prob. of high S/N event within 30 s)


detection: ~6 σ



Connaughton+18

Controversy:

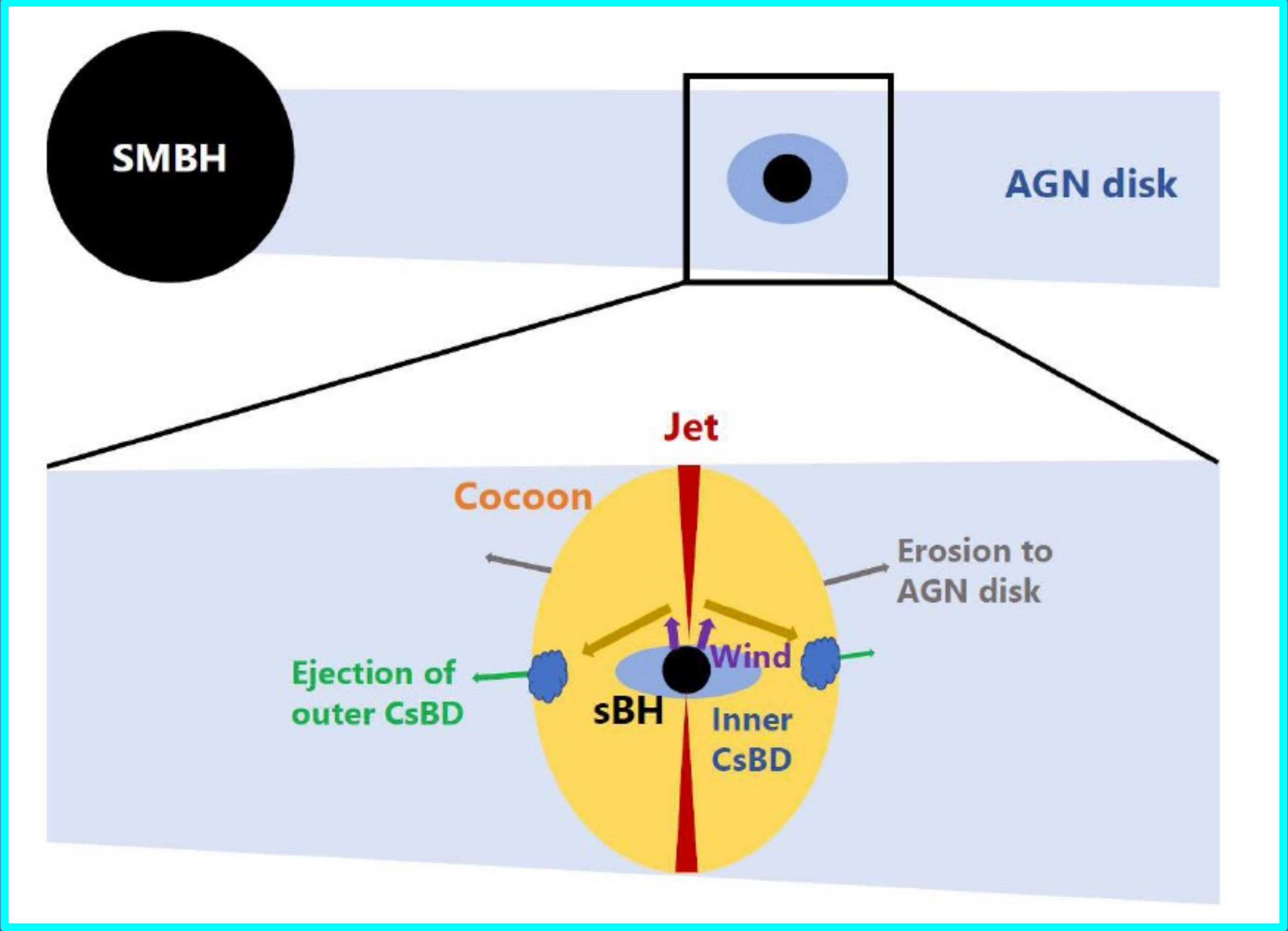
Criticism: background value, detectors (Greiner+16)

Rebuttal: binning, sky location, complex geometry, used detectors (Connaughton+18)

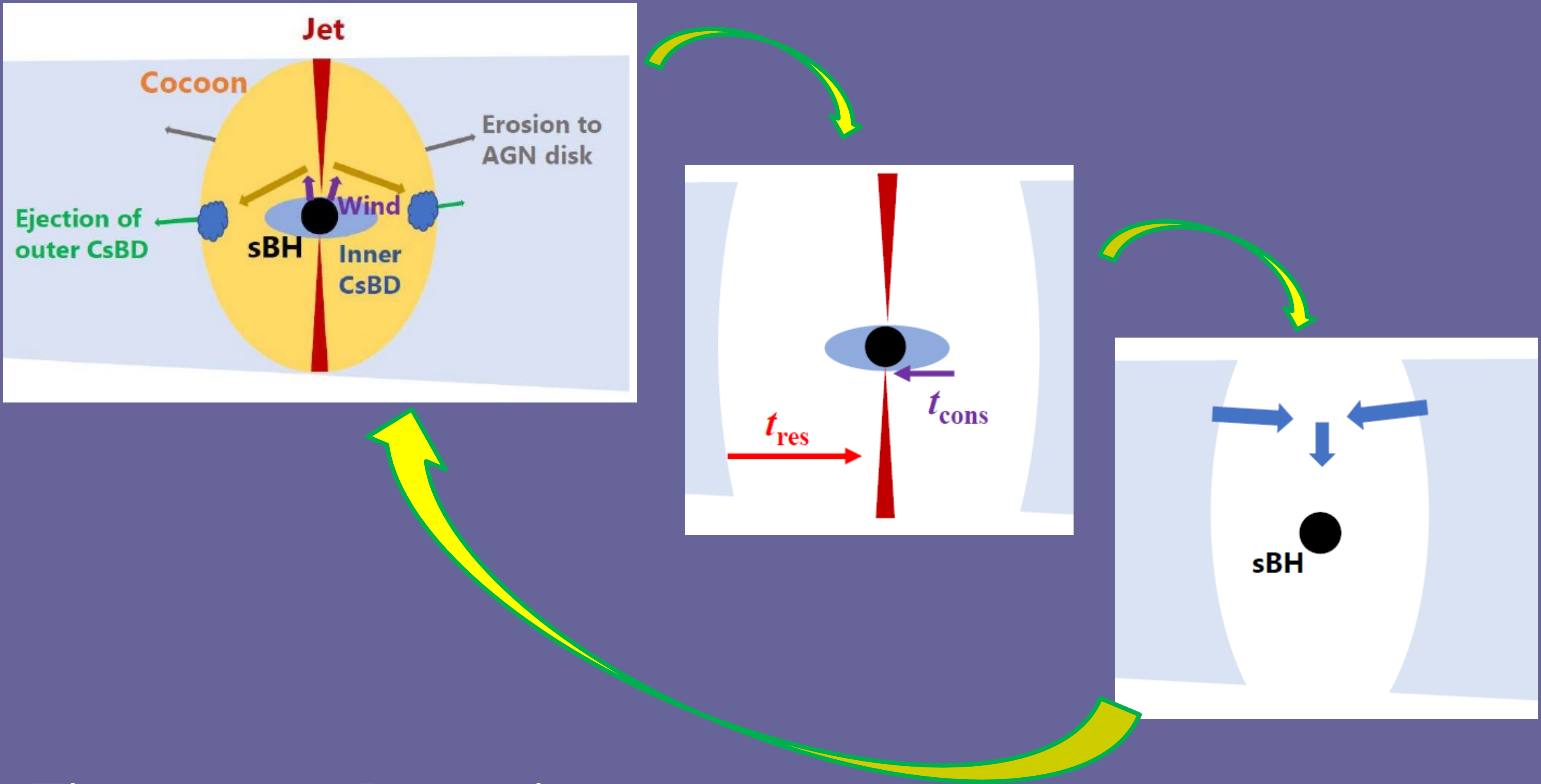
Jets and cocoons from BHs in AGN disks

$\dot{M}_{BHL} \gg \dot{M}_{edd}$ → spinning BH → jet (cf. GRB) → $L \gg L_{edd}$

Tagawa, Kimura, ZH, Perna Tanaka, Bartos (2022)



Episodic accretion / jet activity



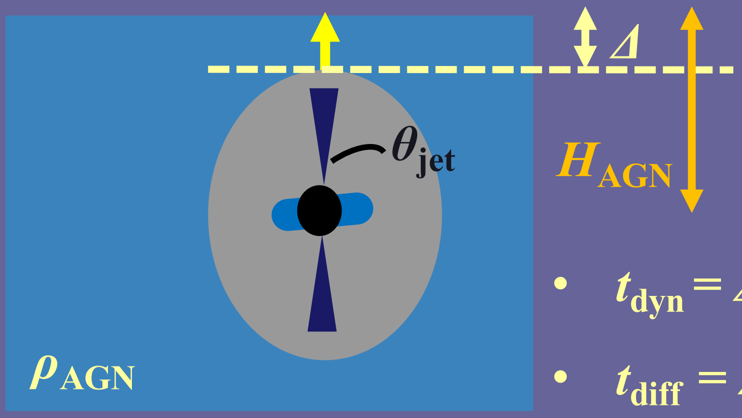
Time-averaged accretion rate is reduced by a factor $\gtrsim 10$

EM emission

Disk parameters (H_{AGN}, ρ_{AGN}) as a function of distance from SMBH follow from M_{SMBH}, $\dot{M}_{\mathrm{SMBH}}$, α_{eff} (Thompson+05)

BH accretion: $\dot{m}_{\mathrm{BHL}} \rightarrow$ jet power: $L_{\mathrm{jet}} \sim a_{\mathrm{BH}}^2\, \dot{m}_{\mathrm{BHL}}\, c^2$

v_{sh} assuming θ_{jet} (Bromberg+11)



- $t_{\mathrm{dyn}} = \Delta / v_{\mathrm{sh}}$
- $t_{\mathrm{diff}} = \Delta\tau_{\Delta} / c$

$$t_{\mathrm{delay}} \sim H_{\mathrm{AGN}} / v_{\mathrm{sh}}$$

$$\Delta t_{\mathrm{BO}} = t_{\mathrm{diff}} \;\; @ \;\; t_{\mathrm{diff}} = t_{\mathrm{dyn}}$$

$$= c / (\rho_{\mathrm{AGN}}\, v_{\mathrm{sh}}^2\, \kappa)$$

$$T_{\mathrm{BO}} \sim (18\, \rho_{\mathrm{AGN}}\, v_{\mathrm{sh}}^2 / 7a)^{1/4}$$

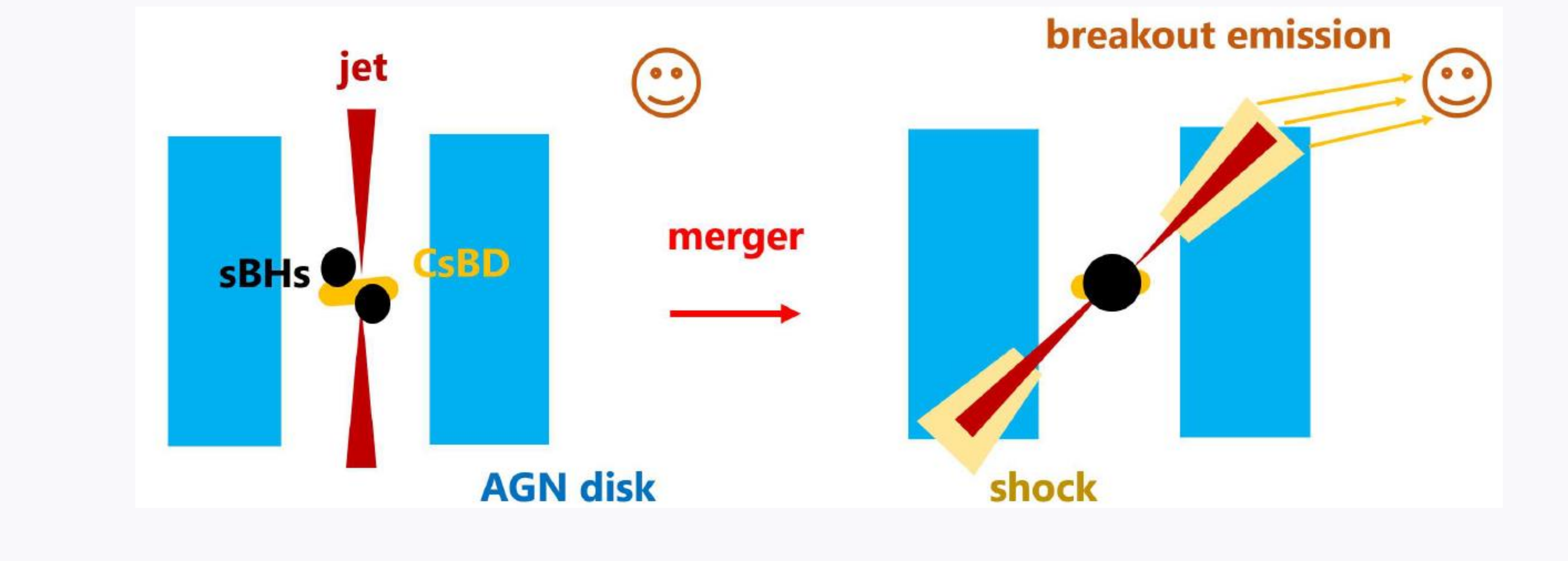
$$L_{\mathrm{BO}} \sim L_{\mathrm{jet}}$$

$$L_{\mathrm{NT}} \sim \varepsilon_{\mathrm{e}} L_{\mathrm{BO}} \qquad (N_{e\gamma} \sim \gamma^{-p})$$

1. **thermal shock-breakout emission**
2. **non-thermal emission from shocks: synchrotron, inverse Compton**
3. **high-energy emission from internal shocks**

Post-merger EM emission from binary BHs

Tagawa, Kimura, ZH, Perna Bartos (2023)

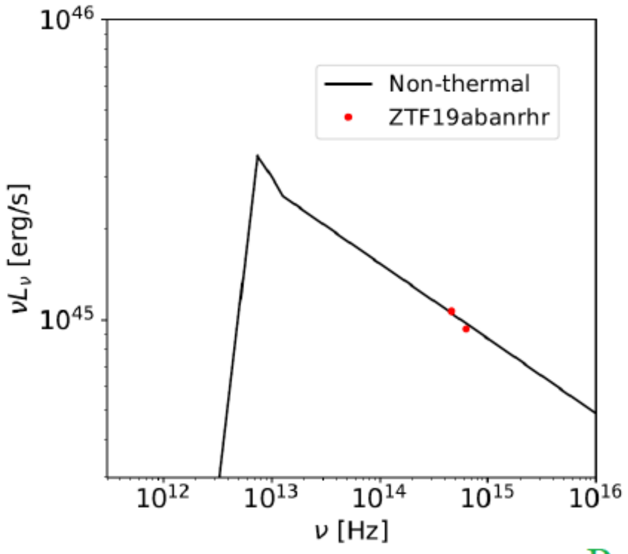


Examples: LIGO EM counterpart claims

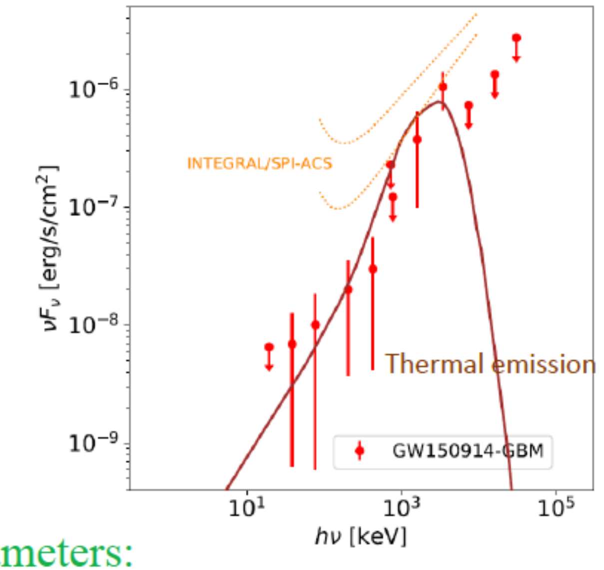
Tagawa et al. 2023

Match **luminosity**, **color, delay time**, and **duration**

GW190521-ZTF19abanrhr



GW150914-GBM

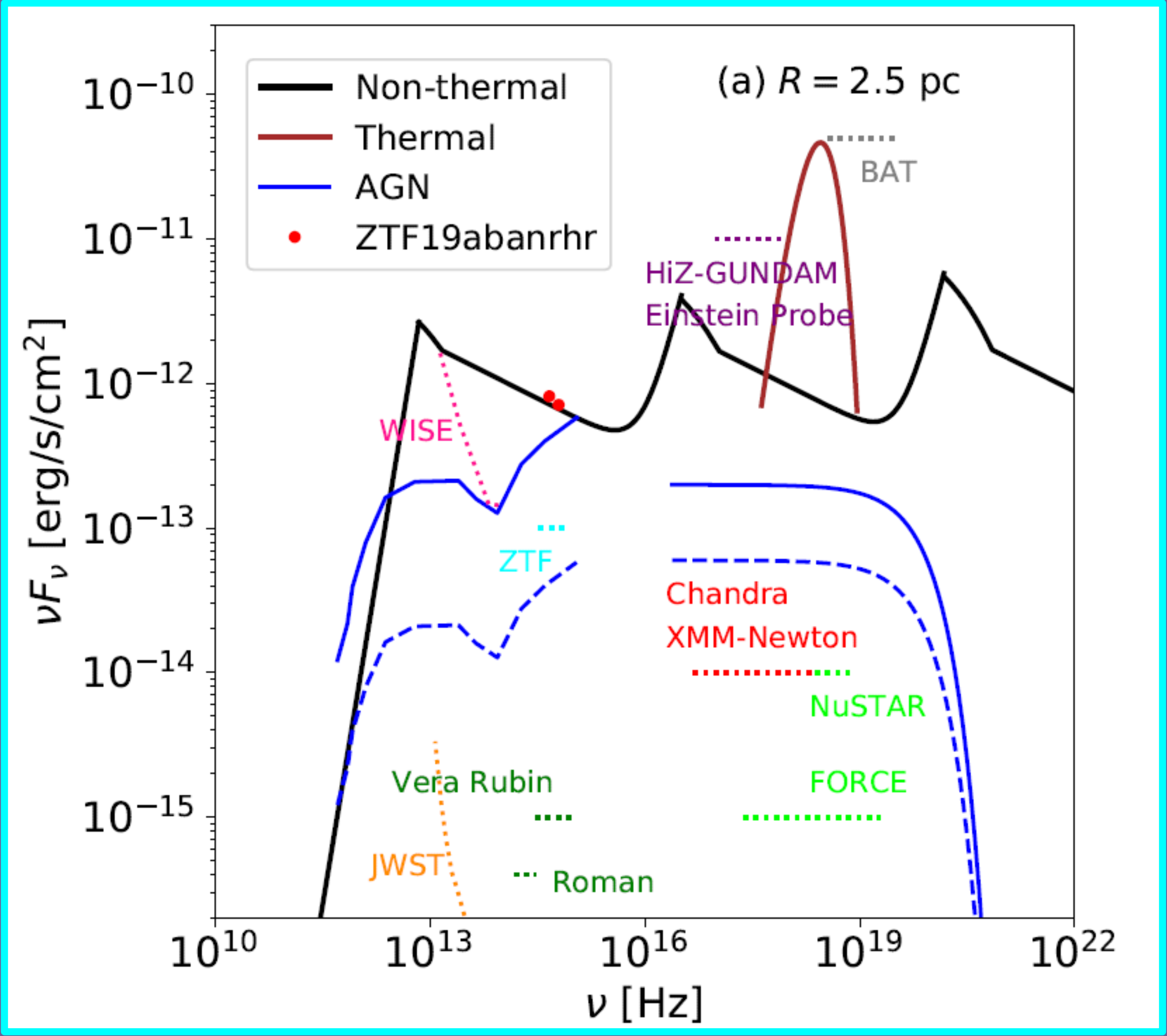


Parameters:

- The distance to SMBH, $R = 3$ pc
- Merger remnant BH mass, $m = 150\ \mathrm{M_{sun}}$
- Conversion efficiency $\eta_{\mathrm{j}} = 0.5$
- Enhancement factor of accretion due to shocks $f_{\mathrm{acc}} = 15$
- SMBH mass, $M_{\mathrm{SMBH}} = 10^8\ \mathrm{M_{sun}}$
- Accretion rate onto the SMBH, $\dot{M} = 2\ L_{\mathrm{Edd}} c^2$
- Energy fraction of electrons in shocks, $\varepsilon_{\mathrm{e}} = 0.3$
- Energy fraction of magnetic fields in shocks, $\varepsilon_{\mathrm{B}} = 0.1$

- $R = 10^{-4}$ pc
- $m = 60\ \mathrm{M_{sun}}$
- $\eta_{\mathrm{j}} = 0.5$
- $f_{\mathrm{acc}} = 1$
- $M_{\mathrm{SMBH}} = 10^6\ \mathrm{M_{sun}}$
- $\dot{M} = 0.2\ L_{\mathrm{Edd}} c^2$

EM emission – full spectrum



Summary

1. Some LIGO events' properties naturally produced in AGN disks:

   → *large mass & mass ratio, nonzero eccentricity, unusual spins*

2. Also natural environment for EM emission related to jets

   → *hot shocked cocoon: thermal + non-thermal emission*

3. Optical/IR and gamma-ray flares like those claimed for LIGO

4. Internal shocks → high-energy ν's, cosmic rays, MeV $\boldsymbol{\gamma}$-rays

The End