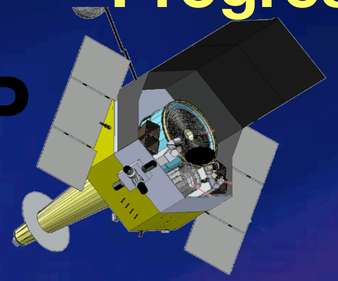
State of the AGN:
Progress Toward Understanding Black Hole Accretion Processes

TAP



43rd COSPAR Scientific Assembly
Connecting space research for global impact

lisa

COSPAR-21-E1.18:
PROBING ENERGY EXTRACTION FROM SUPERMASSIVE BLACK HOLES
January 31, 2021

BBHDiskers:

L. Combi (RIT, I. Argentino Radioastronomia)
F. Lopez Armengol (RIT)
M. Avara (Cambridge)
E. Gutierrez (RIT)
M. Campanelli (RIT)
J. Krolik (JHU)

D. Bowen (LANL)
V. Mewes (ORNL)
B. Mundim (SciNet/U. Toronto)
H. Nakano (Ryukoku U.)
M. Zilhao (Lisboa U.)
Y. Zlochower (RIT)

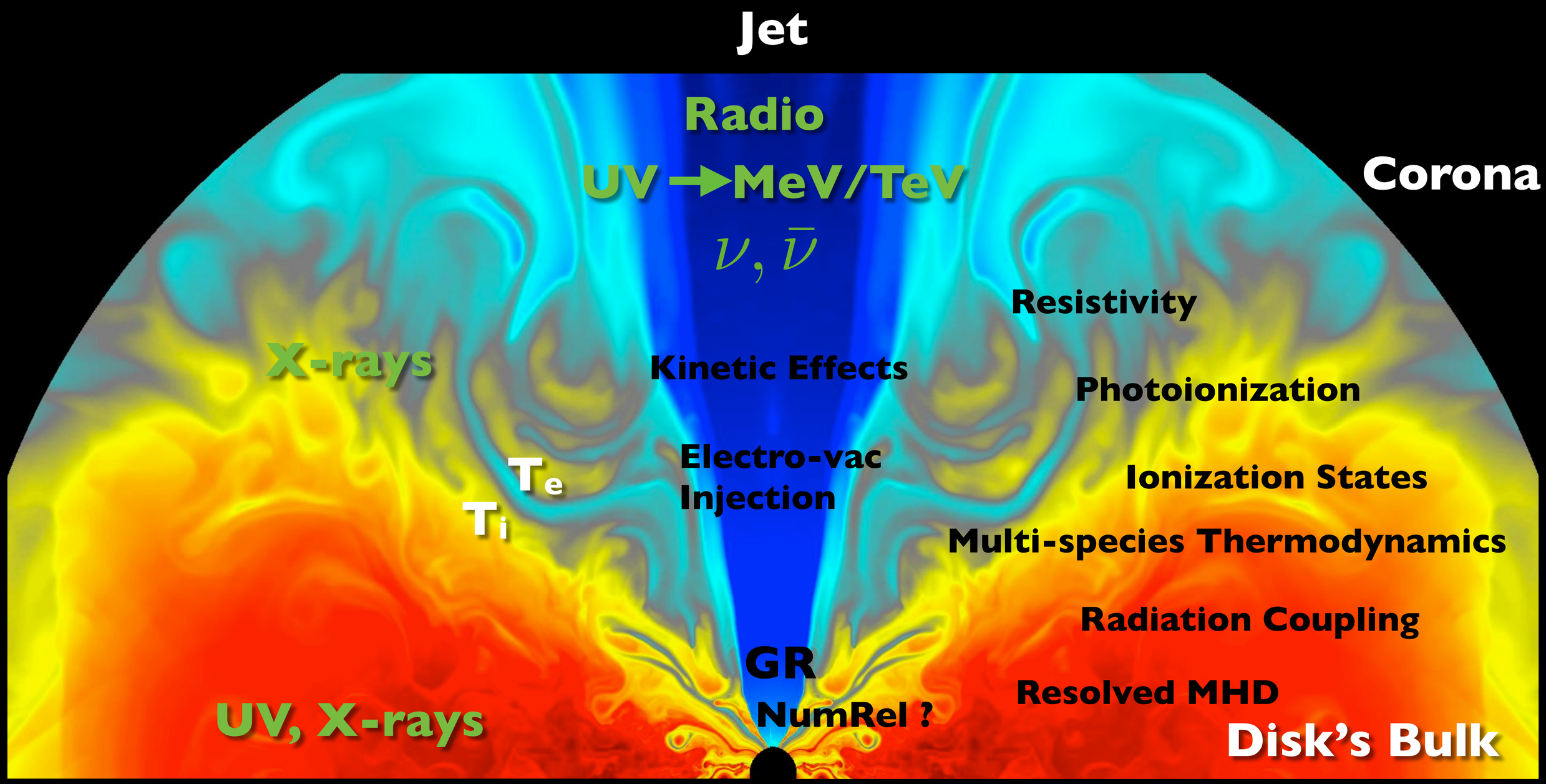
Scott C. Noble

Research Astrophysicist
Gravitational Astrophysics Lab
NASA Goddard Space Flight Center

@therealscn

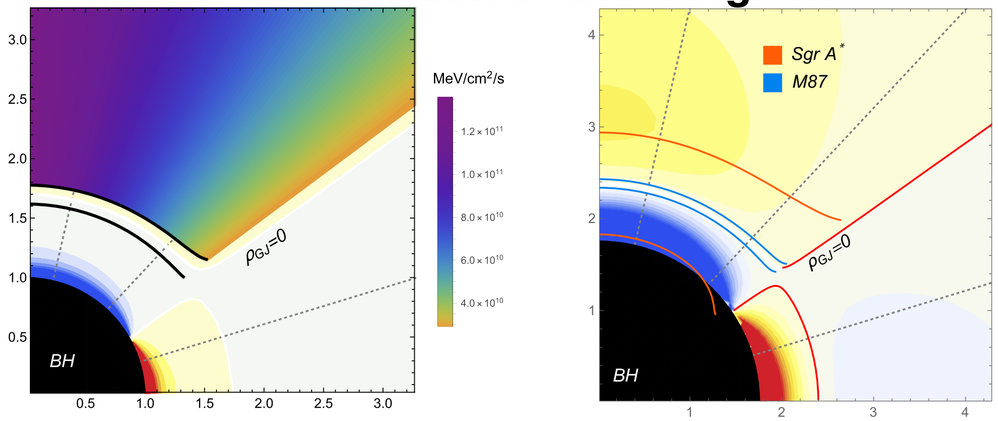
Thanks to NASA LISA Project, NASA TCAN-80NSSC18K148
NSF PRAC ACI-1515969, NSF AST-1515982, NSF PRAC OAC-1811228, NSF PHY-2001000, NSF AST-20021

Black Hole Accretion Anatomy



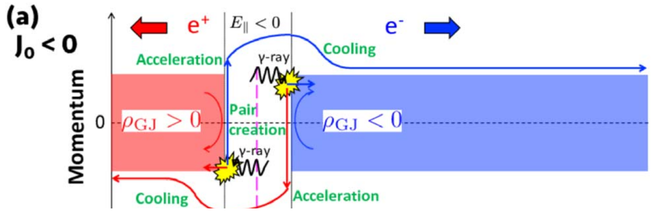
Local R-PIC & GR-PIC Physics

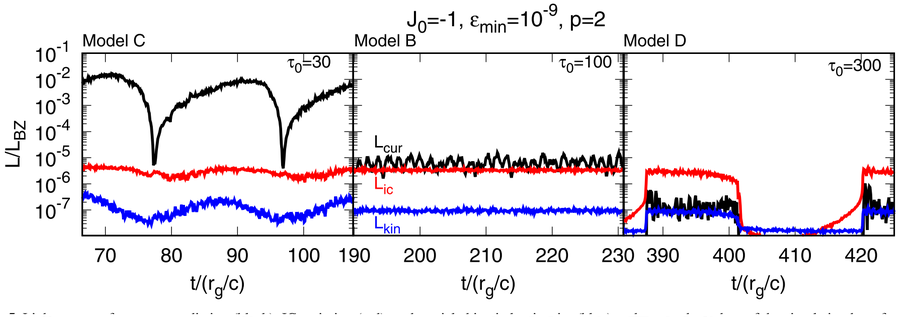
What feeds the evacuated funnel region?



Ford, Keenan, Medvedev, PRD 98, 063016 (2018)

Also: Beskin, Istomin, Parev SvA 36, 642 (1992), Hiortani & Okamoto, ApJ 497, 563 (1998), …



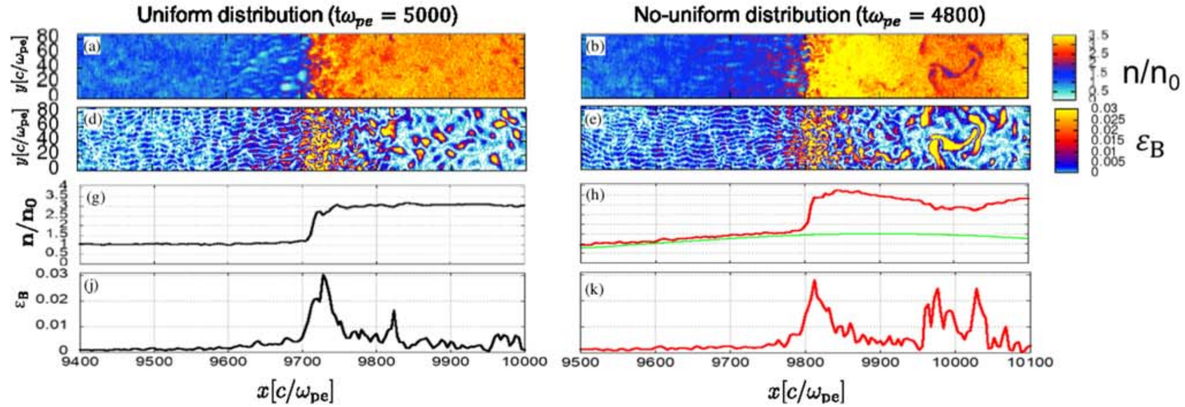


- Curvature radiation can explain M87's TeV flux;

Kisaka, Levinson, Toma, ApJ 902, 80 (2020)

Also: Levinson & Cerutti, A&A 616, A184 (2018), Chen & Yuan, ApJ 895, 121 (2020)

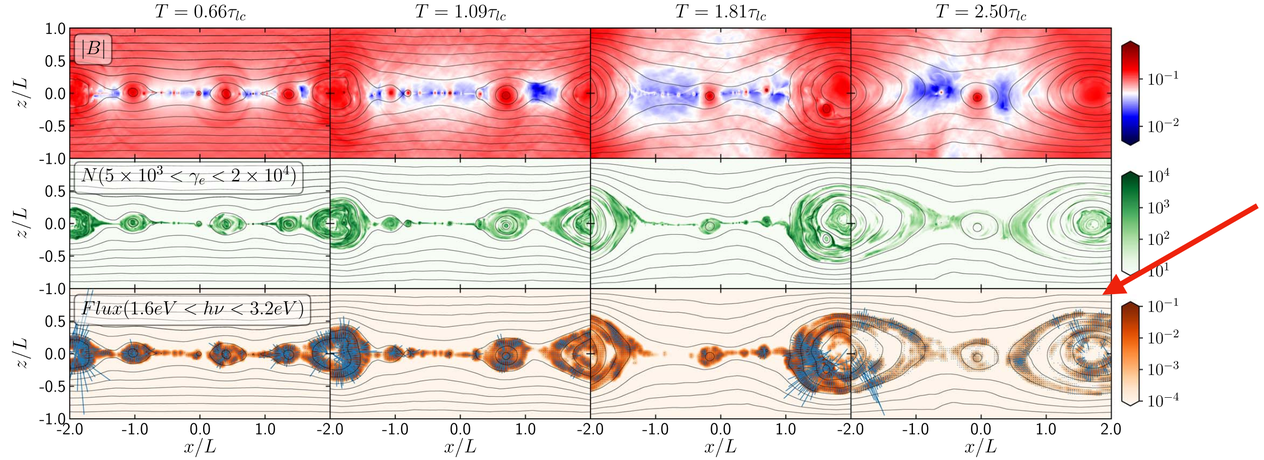
How is Poynting flux converted to high-energy radiation?



Can inhomogeneities retard B-field decay and foster acceleration in relativistic shocks? Tomita, Ohira, Yamazaki, ApJ 497, 563 (1998) [TALK 28: Sara Tomita]

Also: Crumley, Caprioli, Markoff, Spitovsky MNRAS 485, 5105 (2019);

How does reconnection/resistivity along the funnel wall play a role?

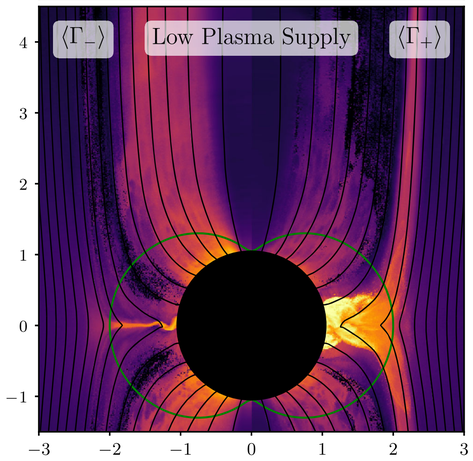


Also: Ball, Sironi, Ozel, Apj 862, 80 (2018); Petropoulou, Sironi, Spitkovsky, Giannios, ApJ 880, 37 (2019); Guo, Liu, Li, Li, Daughton, Kilian, Phys. Plasmas 27, 0805010 (2020); Hakobyan, Philippov, Spitkovsky, ApJ, 877, 53 (2019);

- New physics like synch. cooling & 2-photon pair production;

Global GR PIC and Resistive Astrophysics

How is plasma formed and accelerated in the jet?



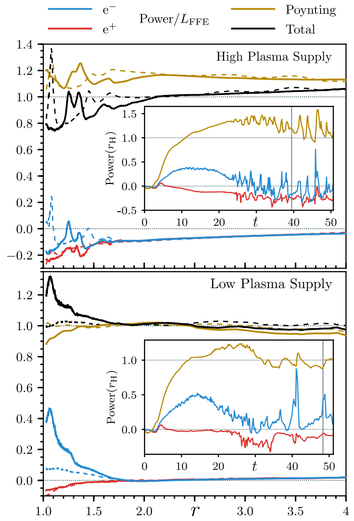
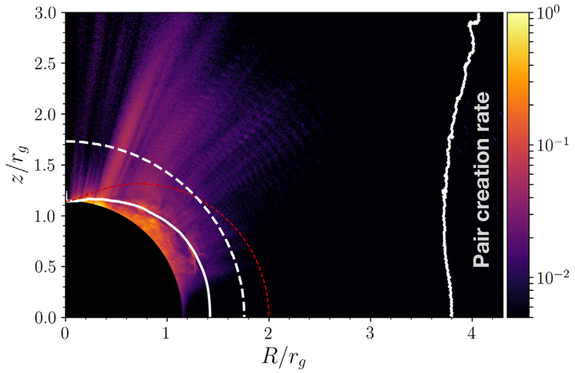
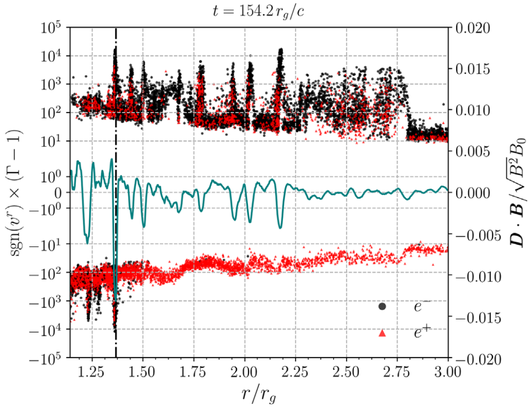


FIG. 3. Average FIDO-measured Lorentz factors in the two steady states; the full potential corresponds to $\Gamma_{max} \sim 10^3$.

- First full 2-d GRPIC of force-free BH magnetosphere w/ injected e+/e-;

Parfrey, Philippov, Cerutti, PRL 122, 035101 (2019) [TALK 6: Kyle Parfrey]

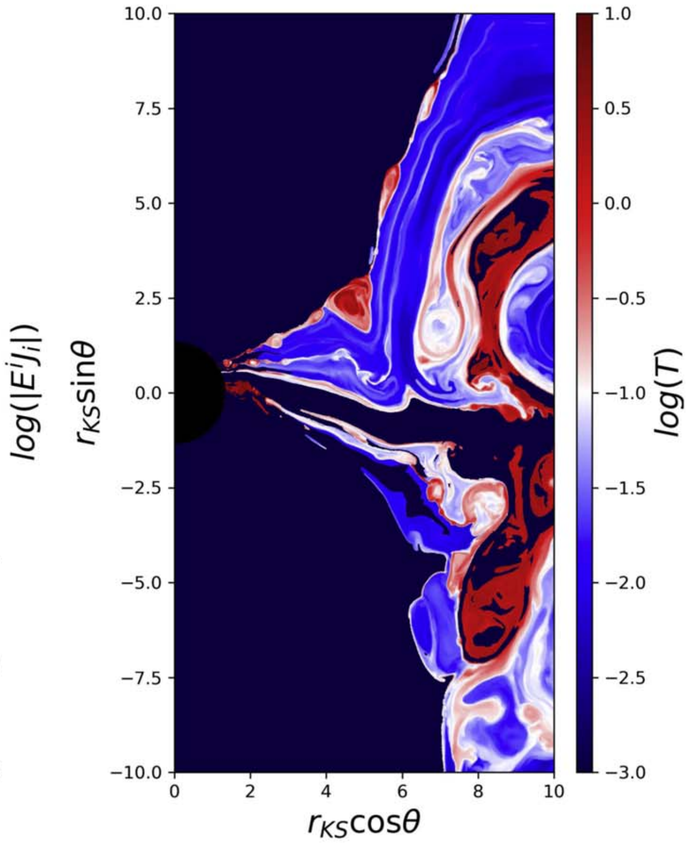




- First full 2-d GRPIC of force-free BH magnetosphere w spark gap & radiation transfer, IC + pair-creation;

Crinquand, Cerutti, Philippov, Parfrey, Dubus, PRL 124, 145101 (2020) [TALK 6: Kyle Parfrey]

How does reconnection/resistivity along the funnel wall play a role?



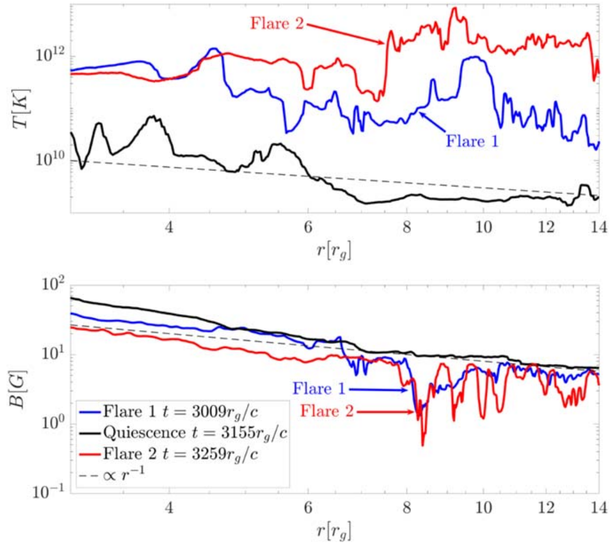


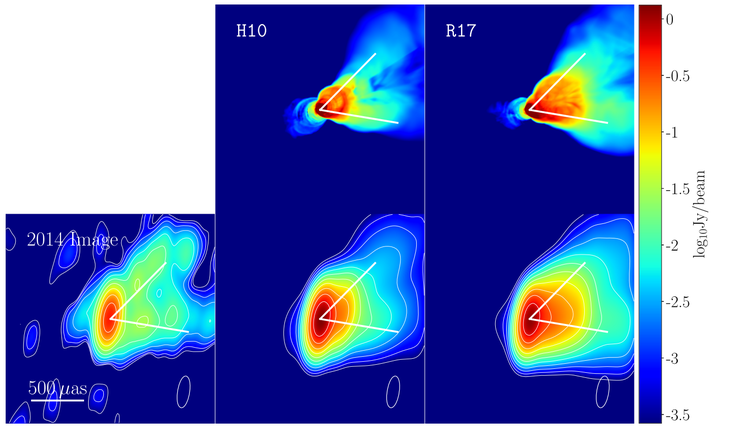
Figure 14. Radial cuts of the temperature T and magnetic field strength B, assuming Sgr A* parameters, of the flares in Figures 10 (flare 1, at $t = 3009 r_g/c$) and 13 (flare 2, at $t = 3259 r_c/c$). The black lines show T and B during quiescence. The magnetic field shows a clear drop from ∼10–20 G to ∼1–5 G between $7r_g$ and $13r_g$, while the temperature significantly increases, both for flares 1 and 2.

- Including resolved physical resistivity instead of letting grid-scale numerics to reconnect the field;
- Resolving plasmoids leads to variable emission, e.g. SgrA* flares;

Ripperda, Bacchini, Philippov, ApJ 900, 100 (2020) [TALK 8: Fabio Bacchini]

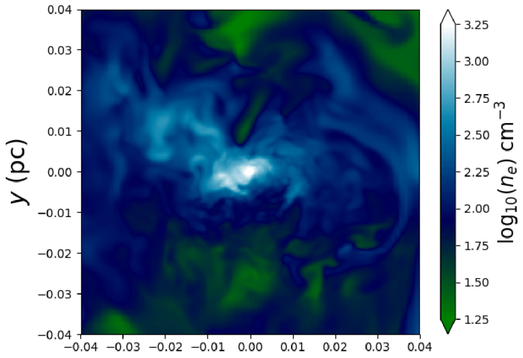
Also: **Vourellis, Fendt, Qian, Noble, ApJ 882, 2 (2019); Yuan, Spitovsky, Blandford, Wilkins, MNRAS 487, 4114 (2019); Tomei, Del Zanna, Bugli, Bucciantini, MNRAS 491, 2346 (2020)**

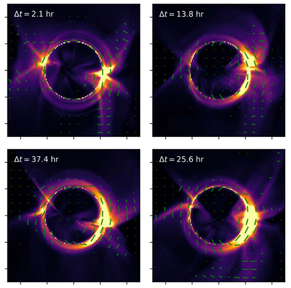
Imaging Accretion on Horizon-scales

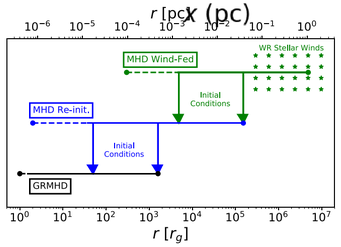


2-T 3d GRMHD MAD can reproduce jet/disk appearance over micro-arcsec to milli-arcsec scales; Chael, Narayan, Johnson, MNRAS 486, 2873 (2019). [TALK 13: Andrew Chael]

Also: Chatterjee, Liska, Tchekhovskoy, and Markoff, MNRAS, 490, 2200 (2019)
Chael, Rowan, Narayan, Johnson, Sironi, MNRAS 478, 5209 (2018);
Nakamura, Asada, Hada, Pu, Noble, Tseng, Toma, Kino, Nagai, Takahashi, et al., ApJ 868, 146 (2018);



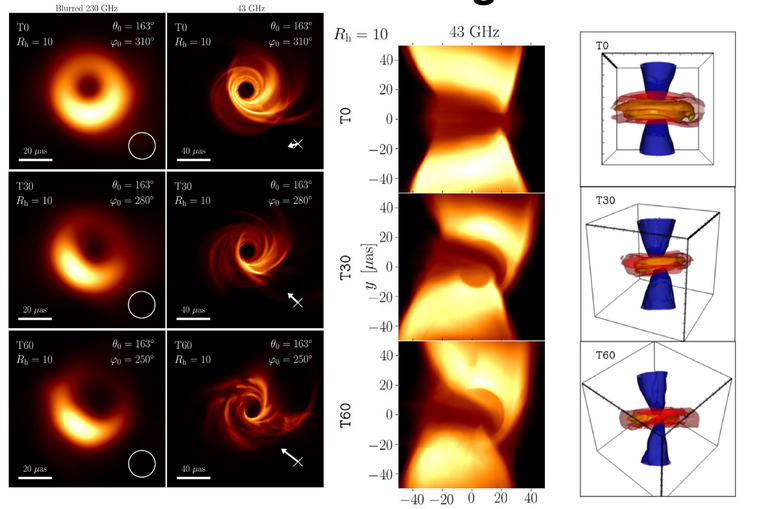




"Ab initio" GRMHD sims from Wolf-Rayet stellar wind initial data;

Ressler, Quataert, Stone, MNRAS 478, 3544 (2018).
Ressler, Quataert, Stone, MNRAS 482, L123 (2019).
Ressler, Quataert, Stone, MNRAS 492, 3272 (2020).
Ressler, Quataert, Stone, ApJL 896, L6 (2020).

Are M87* and Sgr A* tilted?



Chatterjee, Younsi, Liska, Tchekhovskoy, Markoff, Yoon, van Eijnatten, Hesp, Ingram, van der Klis, MNRAS 499, 362 (2020). [TALK 25: Koushik Chatterjee]

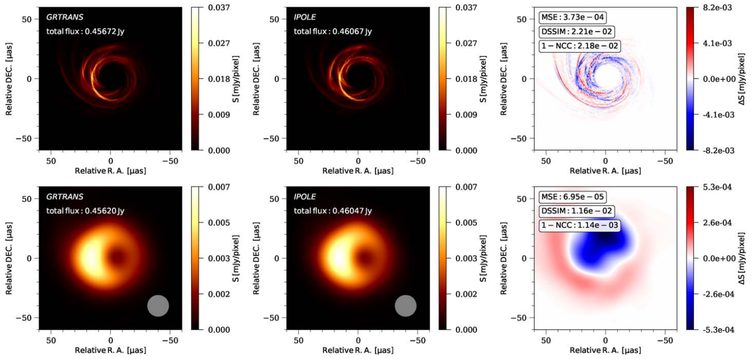
Also: White, Dexter, Blaes, Quataert, ApJ 894, 14 (2020)

GRMHD w/ non-thermal e- distributions for flares

Chatterjee, Markoff, Neilsen, Younsi, Witzel, Tchekhovskoy, Yoon, Ingram, van der Klis, Boyce, Do, Haggard, Nowack, MNRAS 499, 362 (2020). [TALK 25: Koushik Chatterjee]

First M87 Event Horizon Telescope Results I-VI

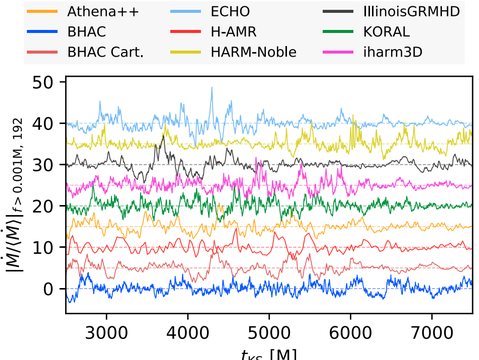
Verification of Radiative Transfer Schemes for the EHT



Gold, Broderick, Younsi, Fromm, Gammie, Mościbrodzka, Pu, Bronzwaer, Davelaar, Dexter, Ball, Chan, Kawashima, Mizuno, Ripperda, and EHT Collaboration, ApJ 897, 148 (2020).

The Event Horizon General Relativistic Magnetohydrodynamic Code Comparison Project

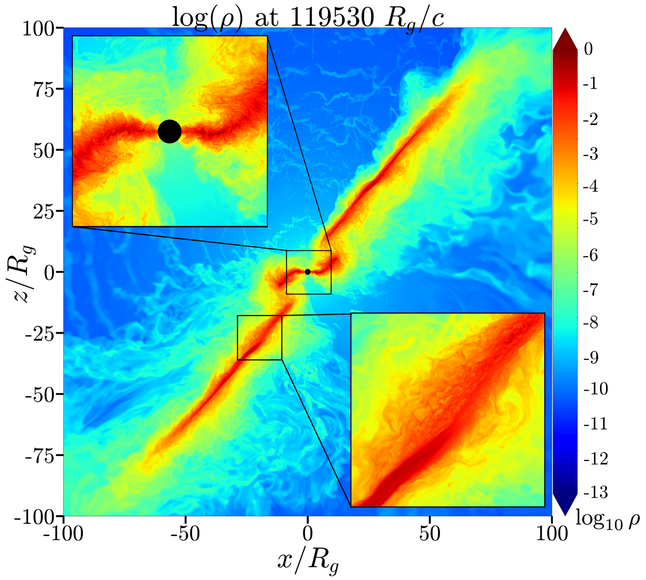
Porth, Chatterjee, Narayan, Gammie, Mizuno, Anninos, Baker, Bugli, Chan, Davelaar, Del Zanna, Etienne, Fragile, Kelly, Liska, Markoff, McKinney, Mishra, Noble, Olivares, Prather, Rezzolla, Ryan, Stone, Tomei, White, Younsi,, and EHT Collaboration, ApJ 897, 148 (2020).



New Enabling Techniques with GRMHD

(In addition to the advances w/ GR-PIC w/ coupled radiation transfer….)

GPU optimization: H-AMR



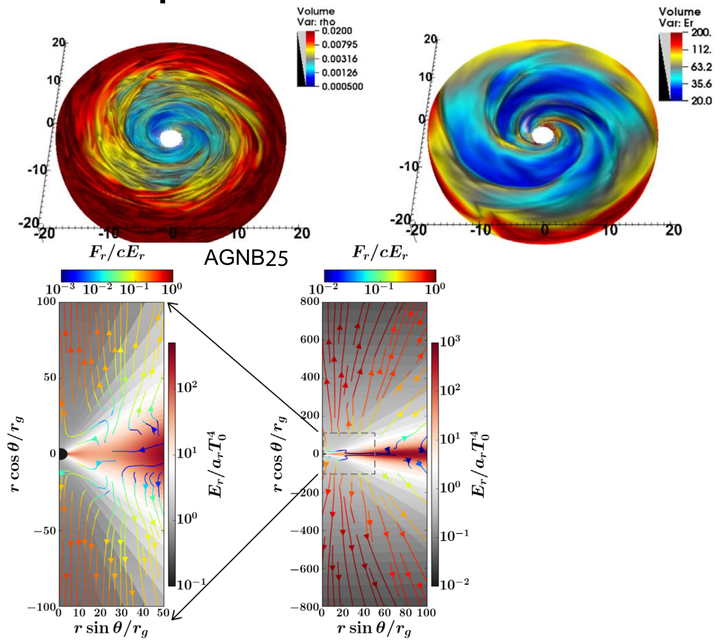
- Exploit GPU's many-core efficient architecture;
- Orders of magnitude performance gains;
- 2e10 cells over 1e5 M in time;

Liska, Hesp, Tchekhovskoy, Ingram, van der Klis, Markoff, and Van Moer, MNRAS (2020)
Liska, Chatterjee, Tchekhovskoy, Yoon, van Eijnatten, Hesp, Markoff, Ingram, and van der Klis, arXiv, arXiv:1912.10192 (2019)
Liska, Tchekhovskoy, Ingram, and van der Klis, MNRAS, 487, 550 (2019)
Liska, Hesp, Tchekhovskoy, Ingram, van der Klis, and Markoff, MNRAS, 474, L81 (2018)
[TALK 25: Koushik Chatterjee]

Toroidal magnetic fields can generate jets!

Liska, Tchekhovskoy, and Quataert, MNRAS, 494, 3656 (2020)

Full Coupled GRMHD & Radiation Transfer Eq.



Super-Eddington AGN:

Jiang, Stone, Davis, ApJ 880, 67 (2019).

$$\eta_{\rm rad}[\dot{M}\sim 500\dot{L}_{\rm Edd}/c^2]\simeq 5\%-7\%$$
$$\eta_{\rm rad}[\dot{M}\sim 1500\dot{L}_{\rm Edd}/c^2]\simeq 1\%$$
$$\eta_{\rm kinetic}\simeq(15\%-30\%)\eta_{\rm rad}$$

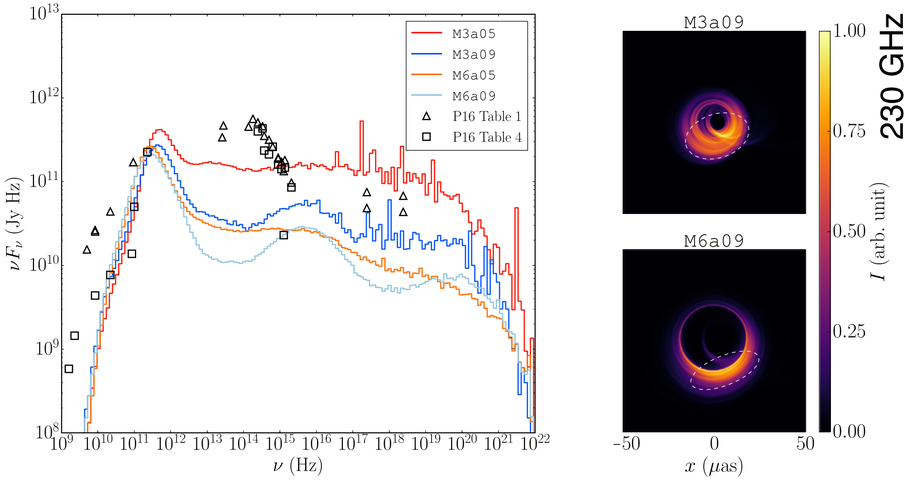
Sub-Eddington AGN:

Jiang, Blaes, Stone, Davis, ApJ 885, 144 (2019).

$$\eta_{\rm rad}[\dot{M}\sim(0.7-2)\dot{L}_{\rm Edd}/c^2]\simeq 1\%-4\%$$

- Differences from thin disk theory:
  - Disk has constant H/R, not H;
  - Surface density is 10 times smaller;

Full Coupled GRMHD & Multi-wavelength Monte Carlo Radiation Transport



2-T 2d GRMHD w/ frequency dependent rad. trans. incl. self-absorb. synch. And Compton scattering

Ryan, Ressler, Dolence, Gammie, Quataert, ApJ 864, 126 (2018).
Ryan, Ressler, Dolence, Tchekhovskoy, Gammie, Quataert, ApJL 844, L24 (2017).

Task Management

- Athena++: full radiation transport and GRMHD w/ original task handler; **Stone, Tomida, White, Felker, ApJS 249, 4 (2020).**
- Spectre: NumRel GRMHD code using Charm++ for task handler; **Kidder, Field, Foucart, Schnetter, Teukolsky, Bohn, Deppe, Diener, Hébert, Lippuner, Miller, Ott, Scheel, and Vincent, J Comp Phys 335, 84 (2017).**

Photoionization Simulations

Kinch, Schnittman, Kallman, Krolik, ApJ 873, 71 (2019)

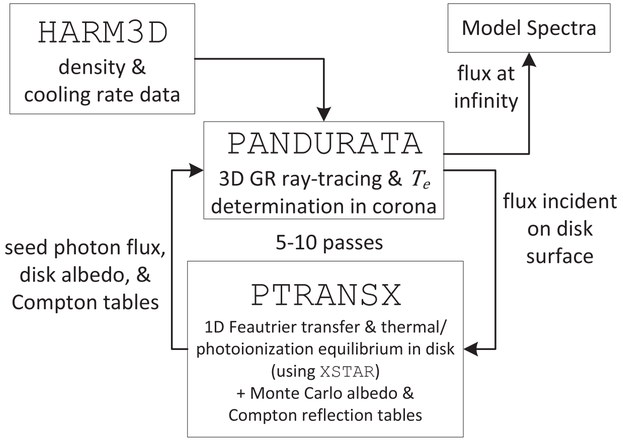
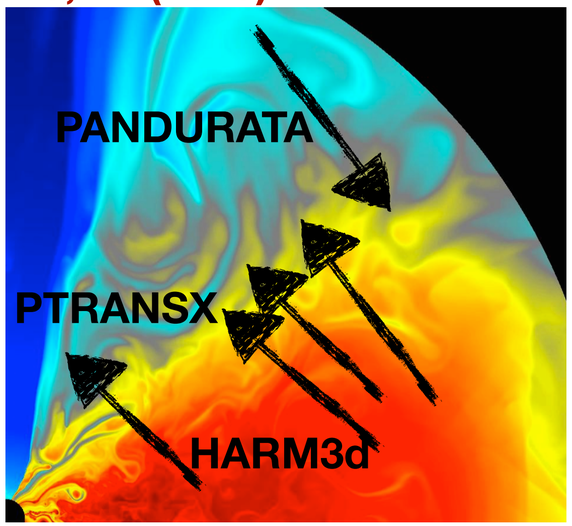


Figure 1. A schematic overview of the general procedure.



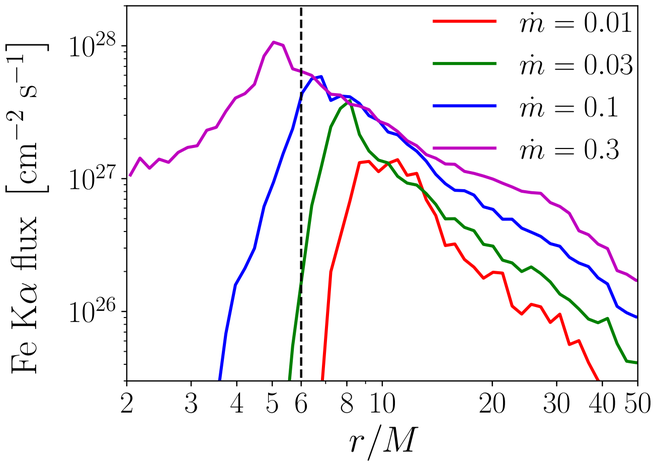


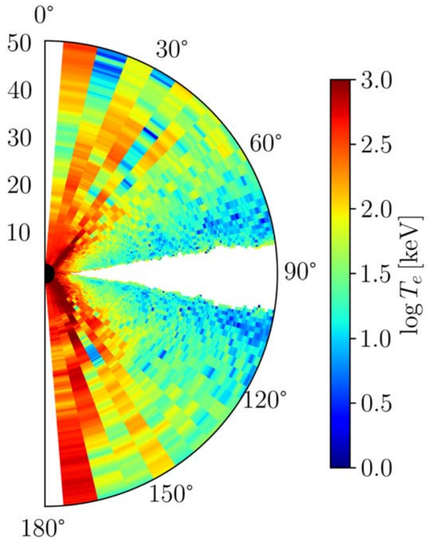
Figure 14. Fe Kα surface brightness, averaged over azimuth and both disk surfaces, for four accretion rates. Note the location of the peaks with respect to the ISCO at $r = 6\,M$.

Kinch, Noble, Schnittman, Krolik, ApJ 904, 117 (2020)

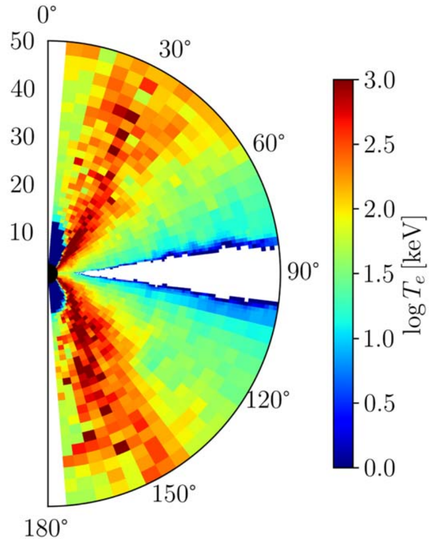
- Ad hoc cooling schemes typically underestimate coronal emission;
- Approx. u_{rad} calculation yields similar results to MC photon density;
- 1T model:
  - IC provides energy heat/loss rate:

$$\mathcal{L}_{\rm IC} = \frac{4\sigma_{\rm T} c \chi}{m_{\rm i}} \rho u_{\rm rad} \Theta_{\rm e}(1 + 4\Theta_{\rm e}).$$

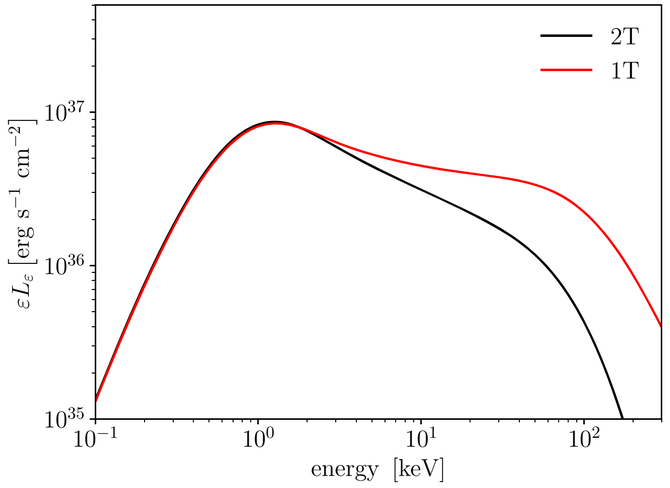
- 2T model:
  - Solve Coulomb heating exchange rate per cell for T_e & T_i ala Stepney, Stepney & Gilbert (1983);
  - Solutions tabulated beforehand;



HARM3d + IC Eq.



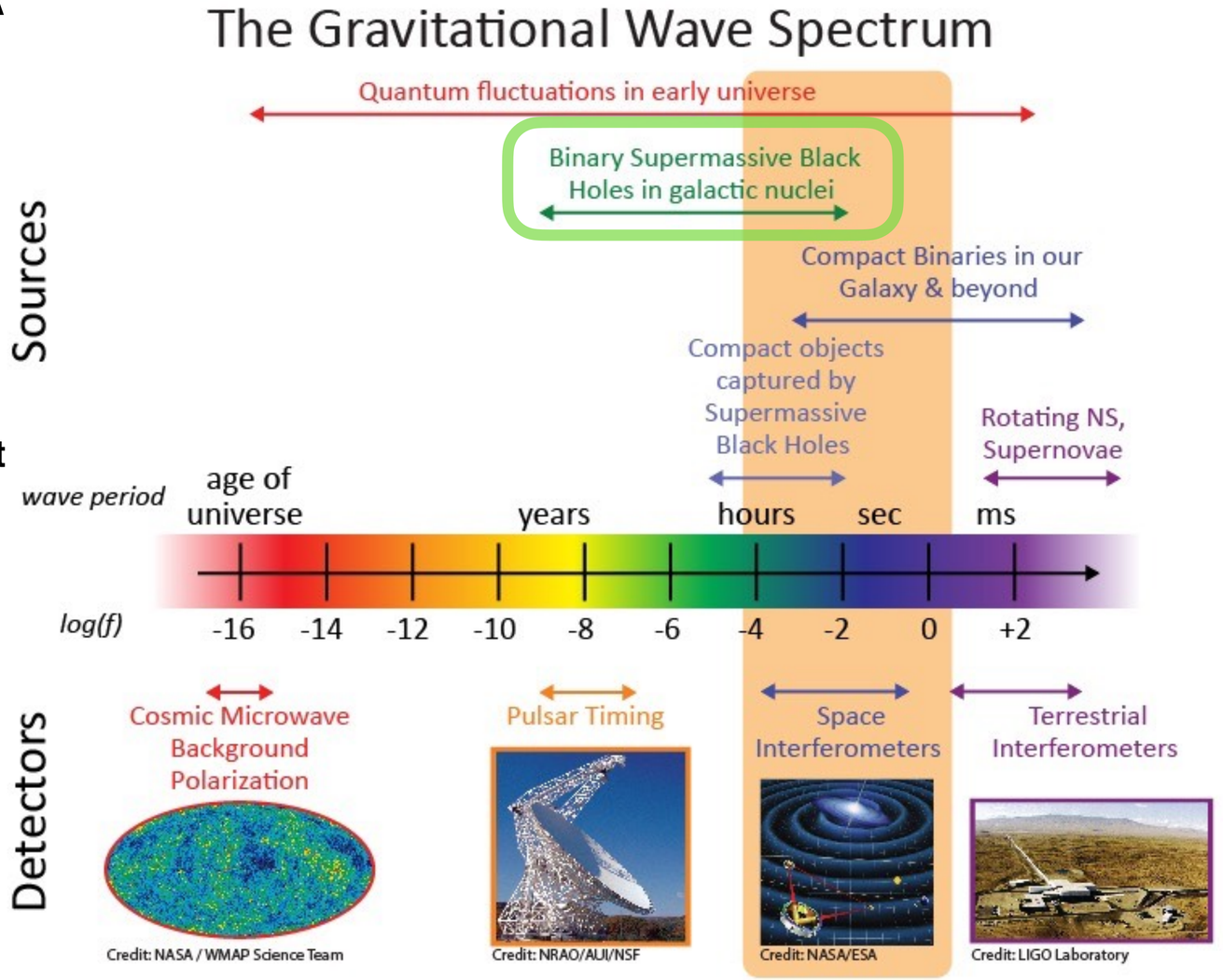
PANDURATA



- XRB example, but AGN coming soon;
- 2T model is too soft—> actual ions/e coupling is stronger than Coulomb collisions;

Supermassive Binary Black Holes

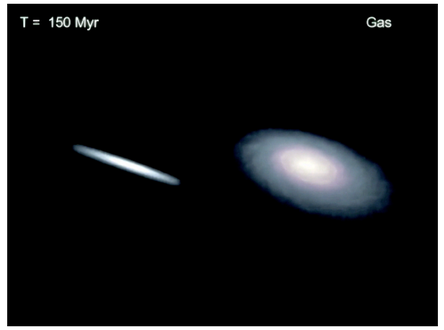
- Binary AGN are a primary multi-messenger source for LISA (inspirals, mergers, ringdowns) and PTA (inspirals).
- Likeliest EM-bright binary black hole system.
  - [TALK 33: Maria Charisi]
- Best candidate for exploring plasma physics in the strongest and most dynamical regime of gravity.
- GWs with LISA aid localization, & with smart pointing strategies with fast-slewing X-ray telescopes (e.g. Transient Astrophysics Probe) one may find O(1-5) systems before merger.
  Dal Canton++, ApJ 886 (2019).
- Only (?) likely opportunity to see EM/GW through all phases: inspiral to merger to ring-down.
- LSST will identify 100k's of AGN, so even a "small" binary fraction implies many sources.
- EM identification will be critical for detection and characterization—> realistic simulations and their EM output are needed!



https://lisa.nasa.gov/

LISA: Gravitational wave observation from space:
- **ESA lead, NASA contributing [TALK 41: Gudrun Wanner]**

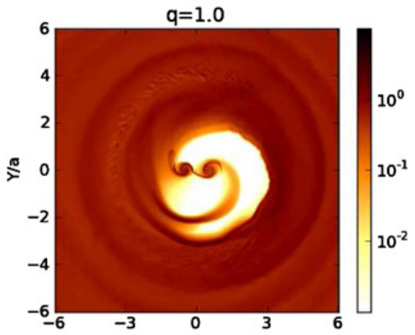
Strategy & Techniques

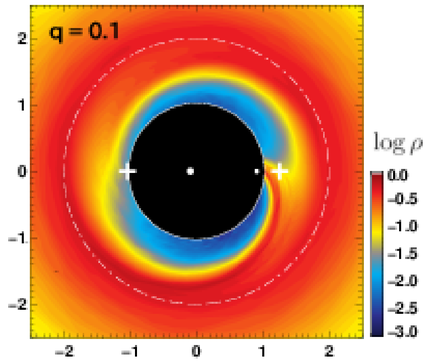


Hopkins, Hernquist, Di Matteo, Springel++,

Sayeb, Blecha, Kelley, Gerosa, Kesden, and Thomas, MNRAS (2020)

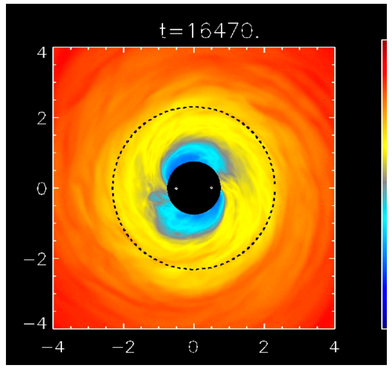
[TALK 42: Luke Kelley]



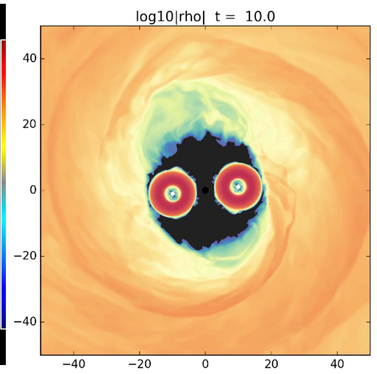


Farris++2014, d'Orazio++2015—, Munoz, Miranda, Lai (2017-2020), Moody++(2019), Tang++(2017-2019) Samsing++2020, Zrake++2020

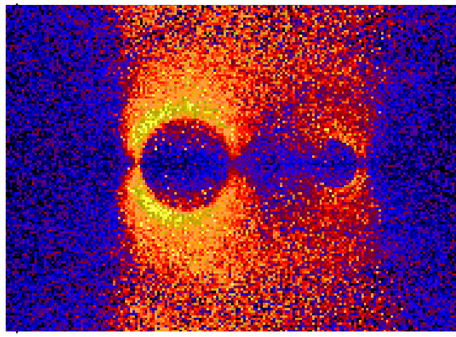
Shi & Krolik (2014-2016)



Noble++2012–15
Noble++2020-in-prep
Lopez Armengol++2020-in-prep



Bowen++2018
Combi++2020-in-prep

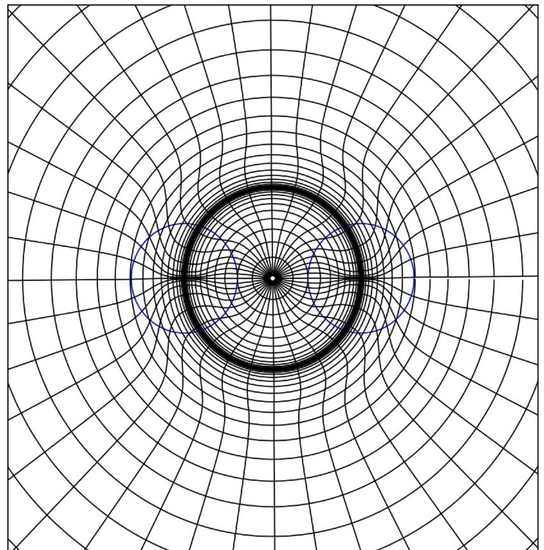


Kelly++2017
Gold++2014

Matter:	**Viscous Hydro.**	**MHD**	**GR MHD**	**GR MHD**
Gravity:	**Newtonian**	**Newtonian**	**Post-Newtonian**	**Numerical Relativity**

- **Use well-tested GRMHD code for accretion disks: *HARM3d;***
- **Novel methods tailored for accuracy and affordability:**
  - **Dynamic warped grids;**
  - **Perturbative solutions for gravity consistent with Einstein's equations in our regime;**

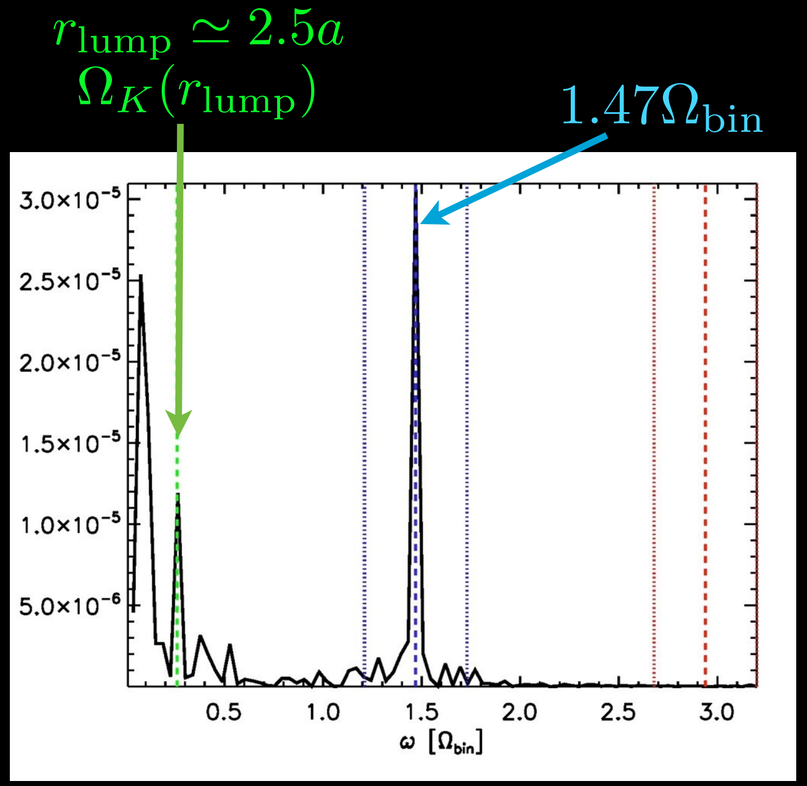
➡ **Key Challenges: Ability to evolve accreting binaries while resolving the MRI and MHD dynamics at the scale of the event horizons in the inspiral regime—*key for establishing pre-merger conditions*.**



MHD Simulations Predict an EM Signature:

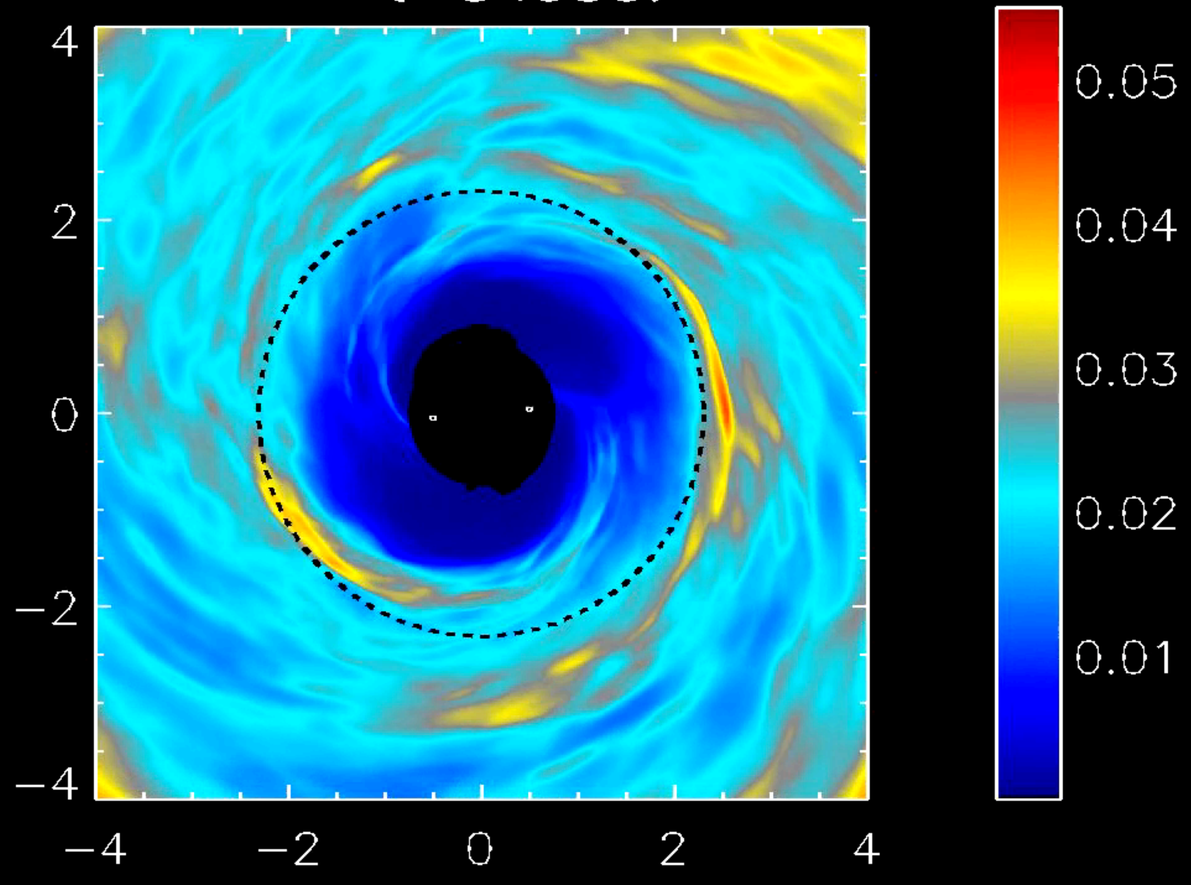
Noble++2012

Periodic Signal



$$\omega_{\rm peak} = 2\left(\Omega_{\rm bin} - \Omega_{\rm lump}\right)$$

Surface Density



(in frame co-rotating with lump)

Longterm 3-d GRMHD Mini-disk Evolutions

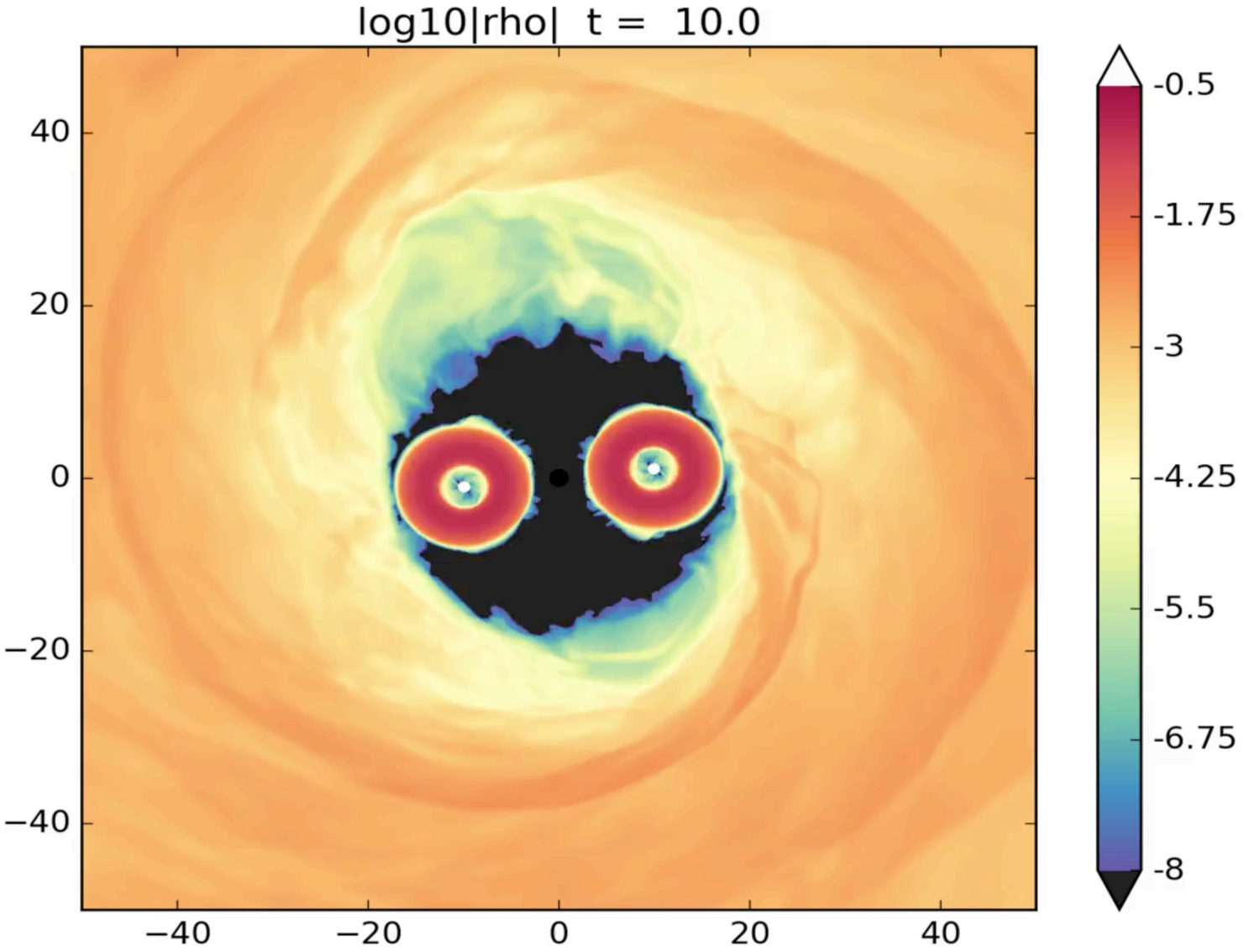
- Noble++2012 circumbinary disk plus mini-disks, with domain covering black hole region;

- Extending Bowen++2018 run from 3 orbits to 12 orbits.
  - Resolved GRMHD simulation of an accreting binary with relaxed circumbinary disk data and mini-disks evolved to *steady mini-disk phase*.

  - First measurement with GRMHD of quasi-periodic interactions in the *steady state* between mini-disks and circumbinary disks in the inspiral regime of the binary, the longest phase observable by LISA.

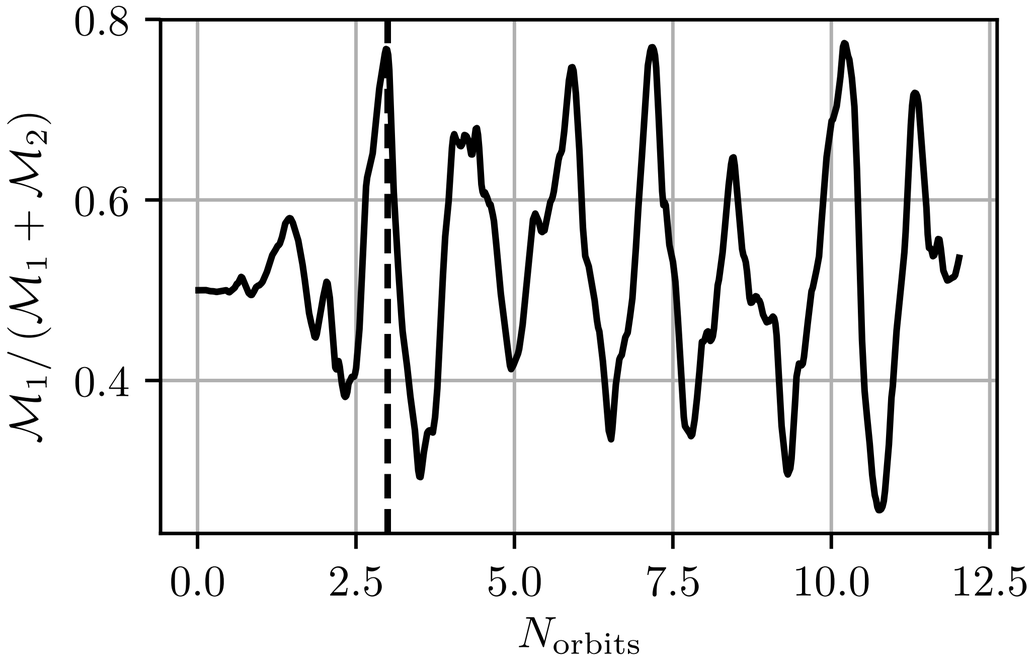
- Enough time series data to calculate light curve.

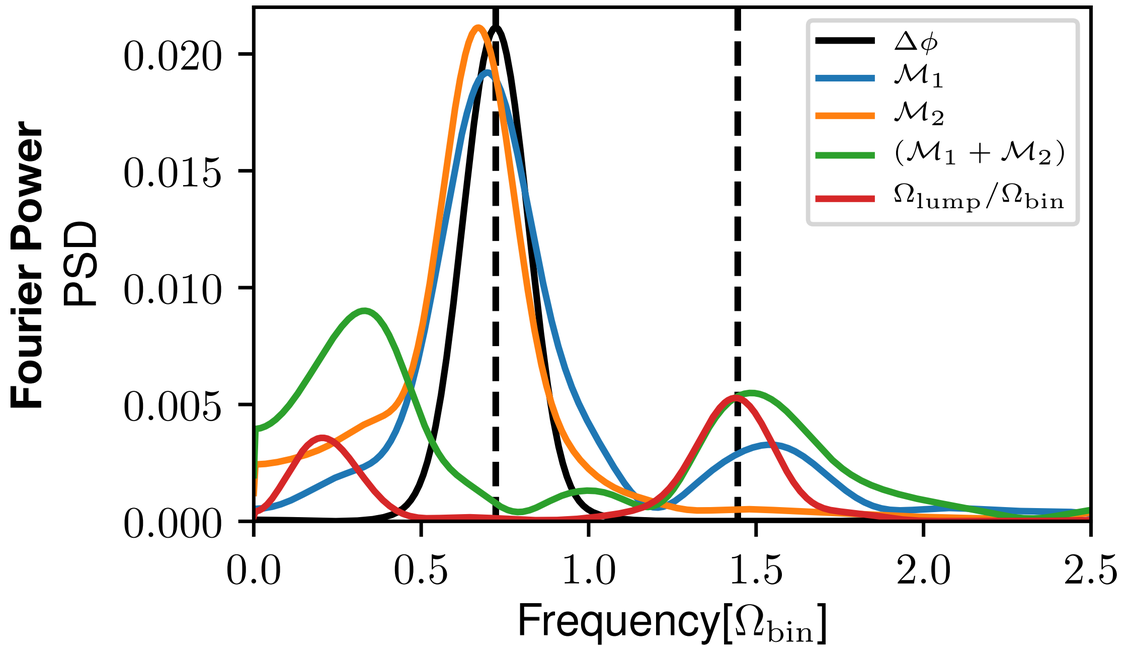
Bowen et. al, ApJ (2019).



Longterm 3-d GRMHD Mini-disk Evolutions

Bowen et. al, ApJ (2019).





- **Mini-disks settle to a steady-state after several binary orbits.**
- **Mini-disks replenish with material in alternating fashion as they pass by the circumbinary disk's lump, then drain at time scale close to one orbit period.**
- **At these close separations and cooling rate, accretion through mini-disks is driven primarily through spiral shocks.**

- **Significant modulation in each mini-disk's mass —> possible EM signal?**
- **If light follows mass, EM period would be a ~1.5 times the binary period, the beat frequency between the orbital periods of the lump and mini-disks.**
- **Dimmer circumbinary lump modulated at the same frequency plus its local orbital rate (Noble++2012).**

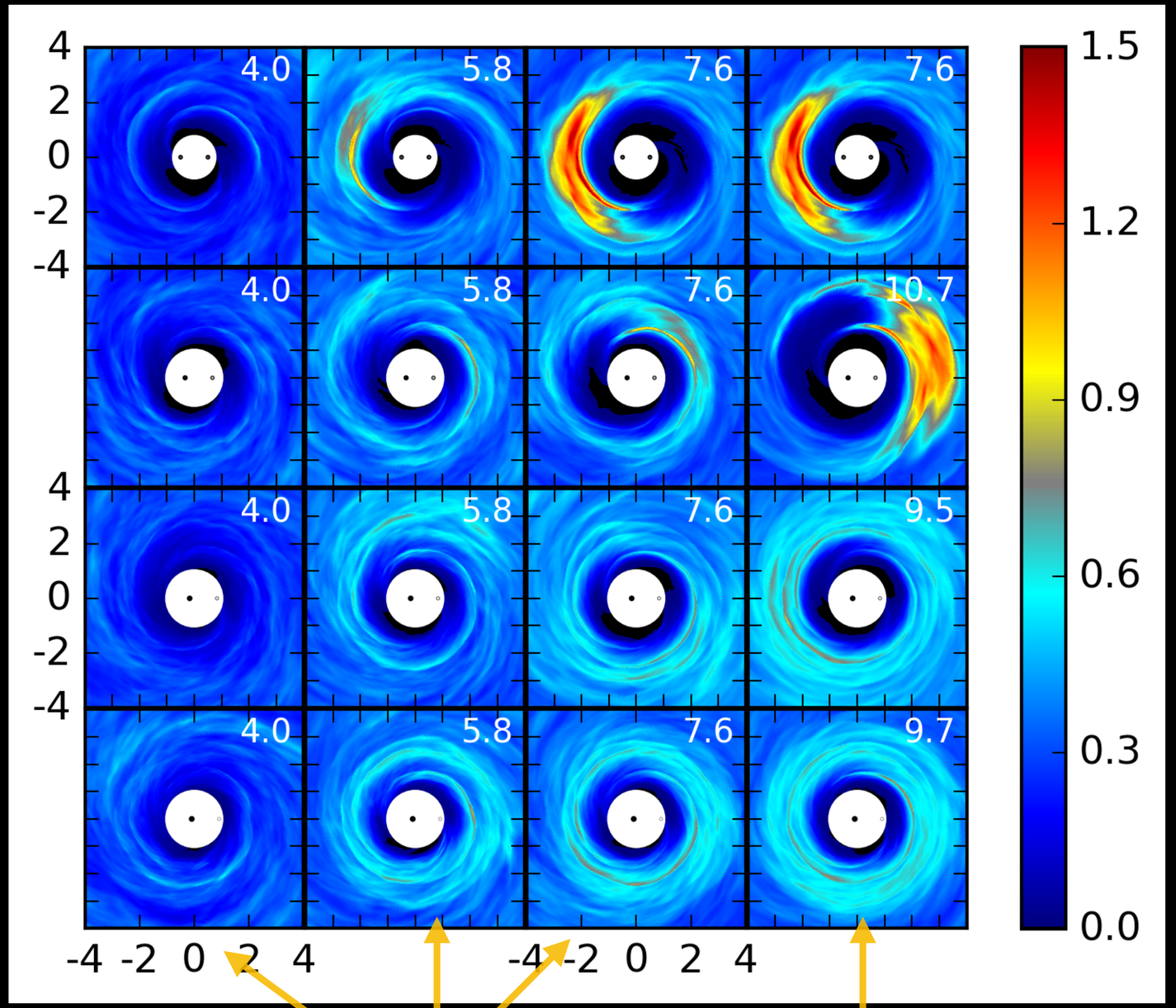
Mass Ratio Survey : Circumbinary Disks

Noble++(in prep)

$q=M_2/M$

Surface Density

(Top-down view)



q=1

q=0.5

q=0.2

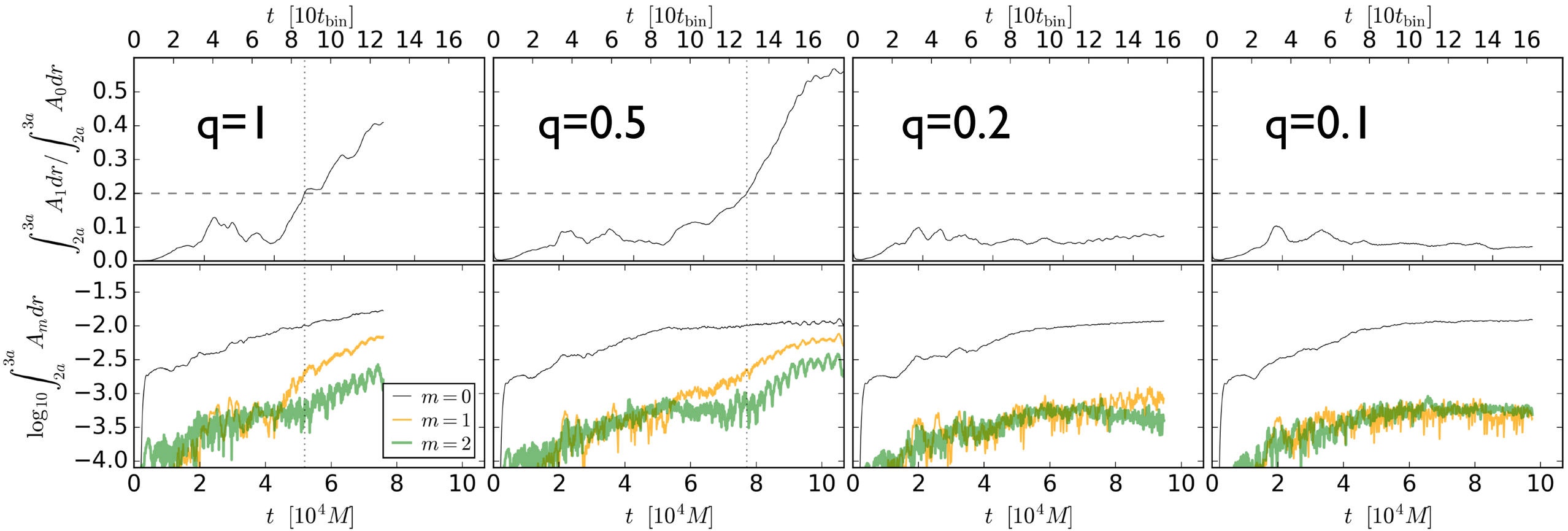
q=0.1

- Simulations of only circumbinary disk region, starting from Noble++2012 conditions, only changing q.
- As mass-ratio diminishes, so does gravitational torque density of the binary, asymptoting to “single BH” disk;
- Weaker torques also diminish strength of the lump feature.
- Weaker torques (smaller mass ratio binaries) take longer to form lumps.
- Duffel++2019, see transition in lump’s relevance at q~0.2 for viscous Newtonian hydro. disks; See also Shi & Krolik 2016, Munoz+2019, Moody+2019.

Mass Ratio Survey

Lump Formation Criterion: Ratio of m=1 to m=0 Amp.

Noble++(in prep)

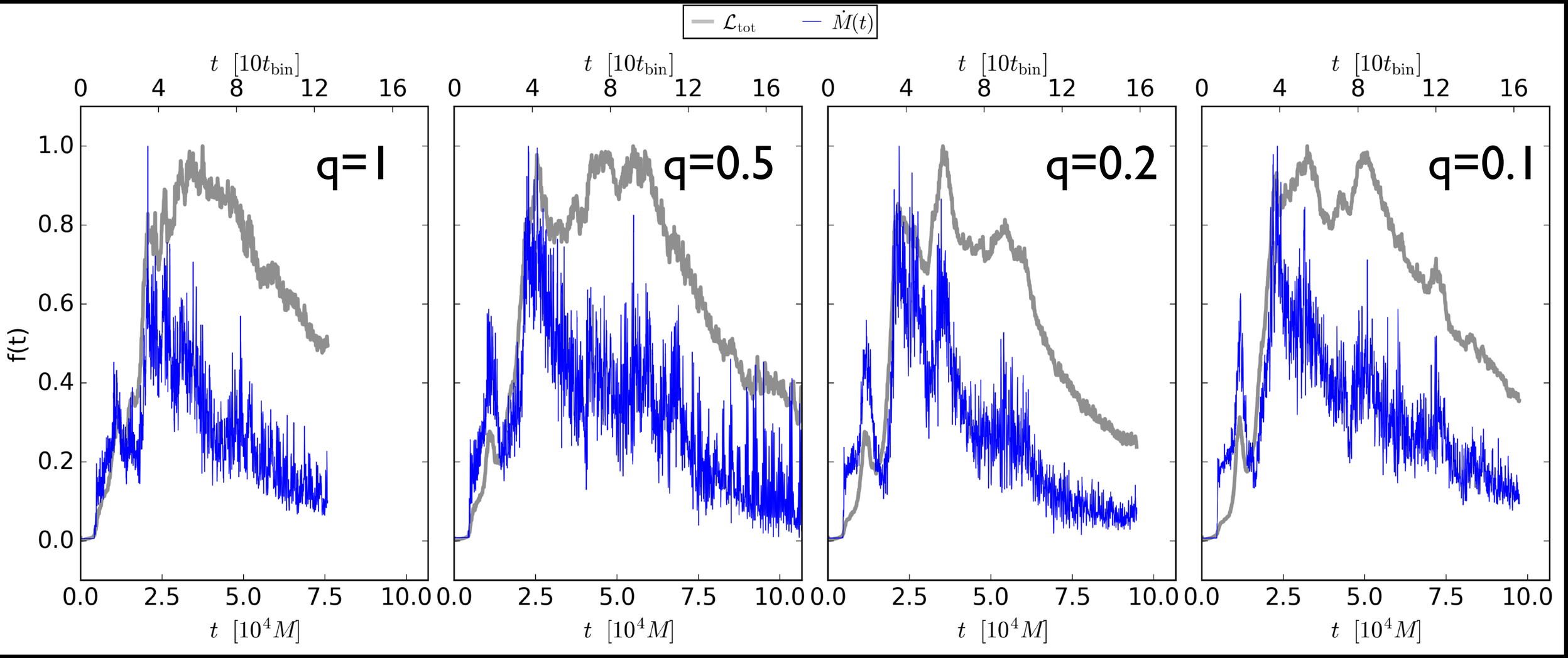


- **Lump is well-described by relatively stronger m=1 azimuthal mode amplitude.**
- **A quantitative threshold is found for the m=1 relative amplitude above which the lump continues to at least persist or grow.**
- **Threshold value is consistent across different mass ratios and initial disk configurations.**
- **Provides a quantifiable means of recognizing the lump's genesis and strength.**

Mass Ratio Survey

Global Trends of the Lump

Noble++(in prep)

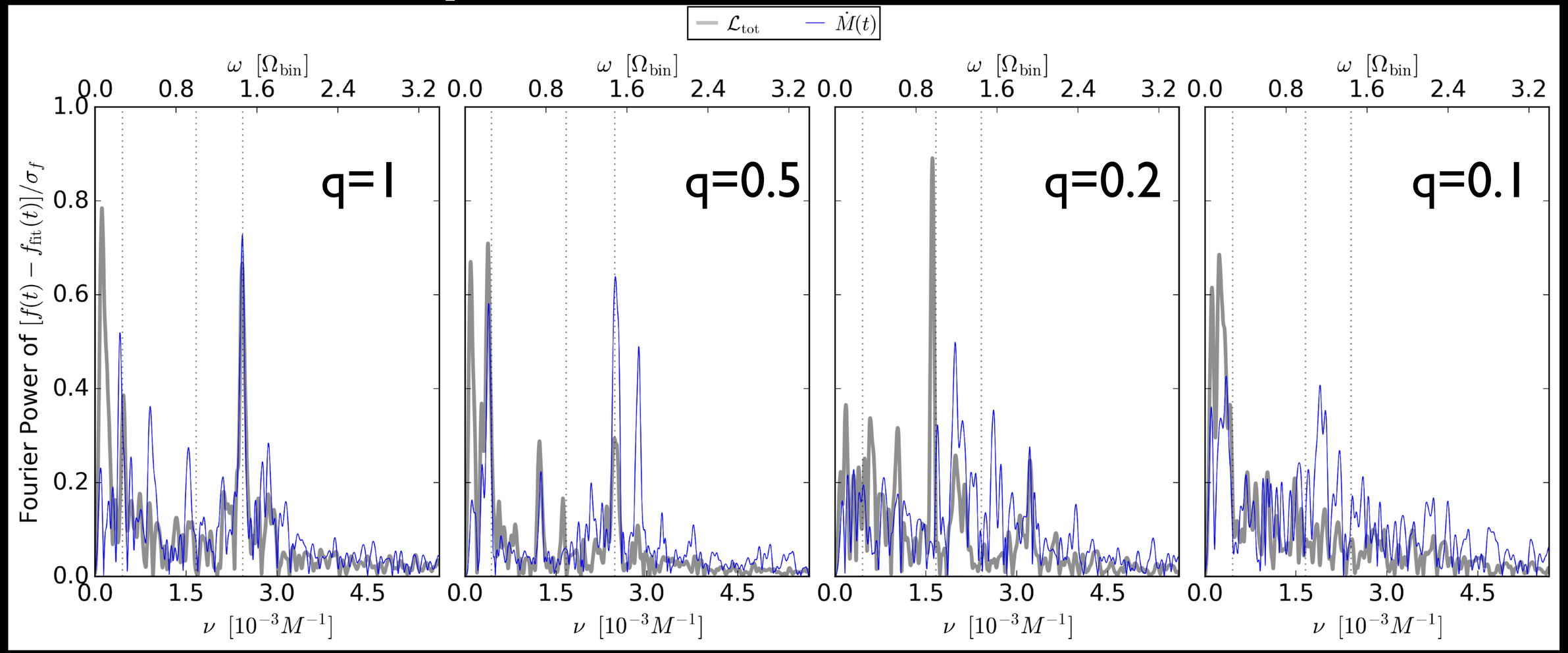


- **Accretion rate and bolometric luminosity histories follow similar trends, largely dictated by initial data of the disk;**
- **Radiative efficiency improves over time as more mass fills the interior region, likely due to more dissipative binary torque;**

Mass Ratio Survey

Global Trends of the Lump

Noble++(in prep)

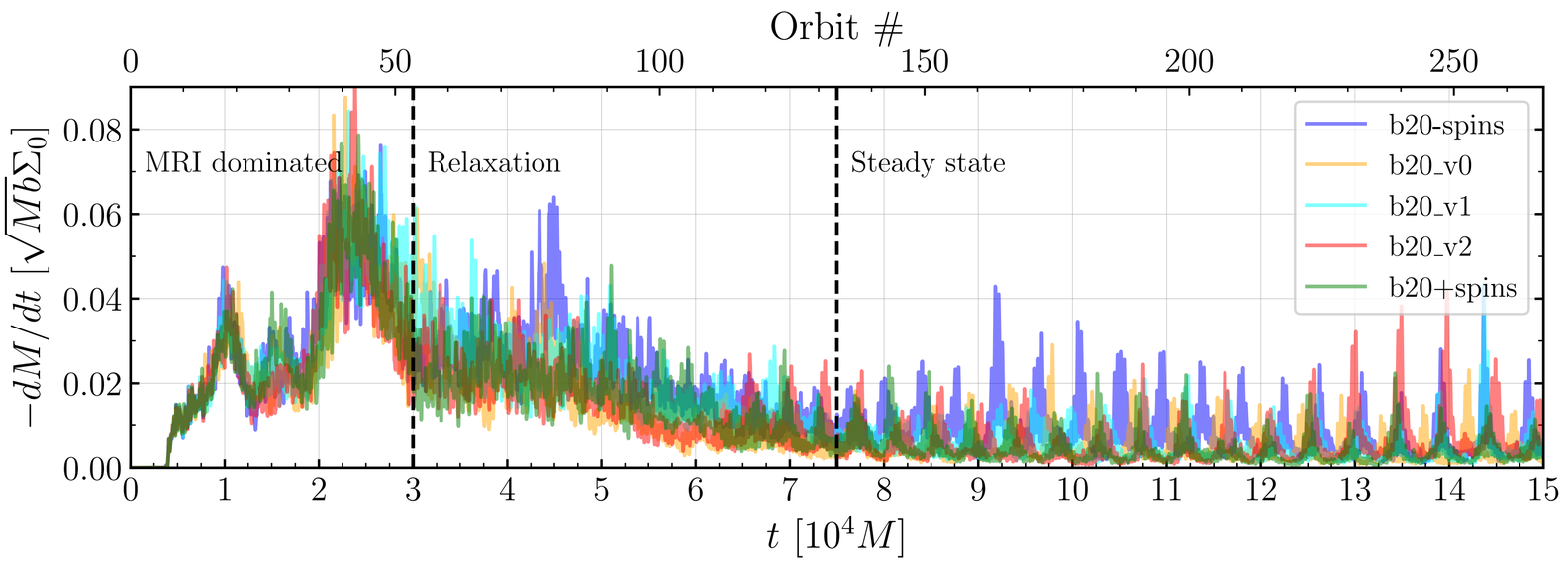


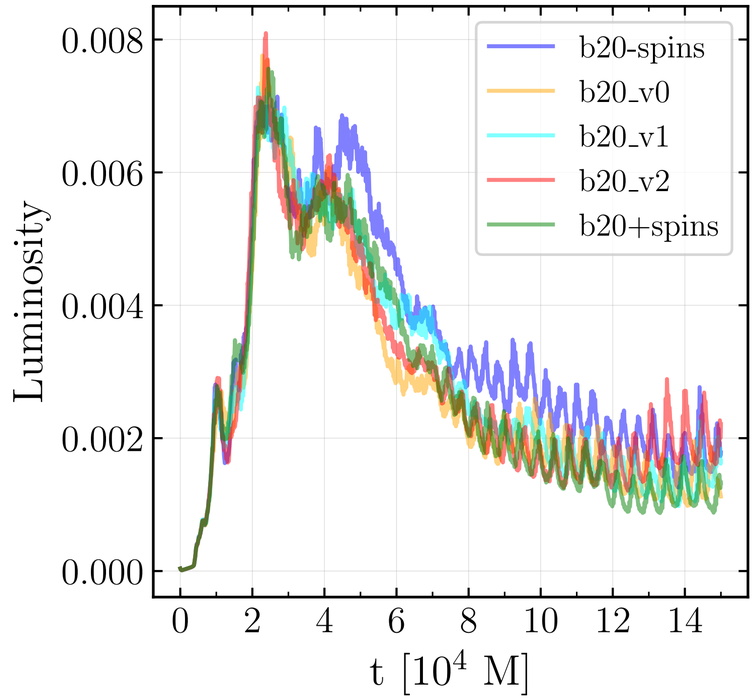
- **Non-trivial signals apparent in L(t) and Mdot(t) at 2x(beat between lump and binary orbital freq.);**
- **Signals in accretion rate and luminosity are not always shared;**
- **Small-q binaries show red-noise dominated power spectrum like single-BH disks;**
- **Intermediate-q binary shows strongest signal at binary frequency, as the disk interacts primarily with BH#2;**
- **Mdot modulations will likely modulate mini-disk luminosities, which are brightest high-energy component;**

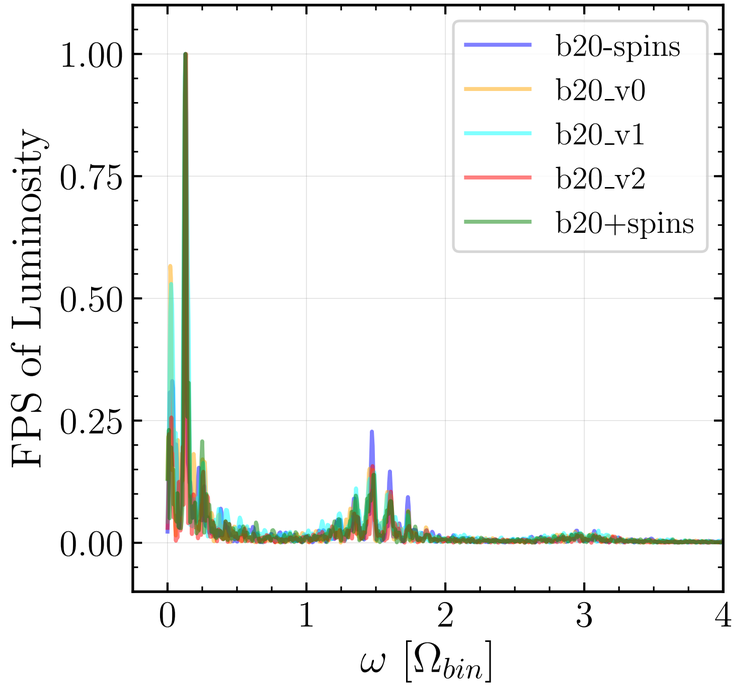
Accretion onto Spinning BBHs

Circumbinary Disk Region

Lopez Armengol, Combi++(in prep)







- "b20" = 20M separation
- "-spins" = spins retrograde to orbit
- "+spins" = spins prograde to orbit
- "v0-2" = no spins, different random 1% pressure noise

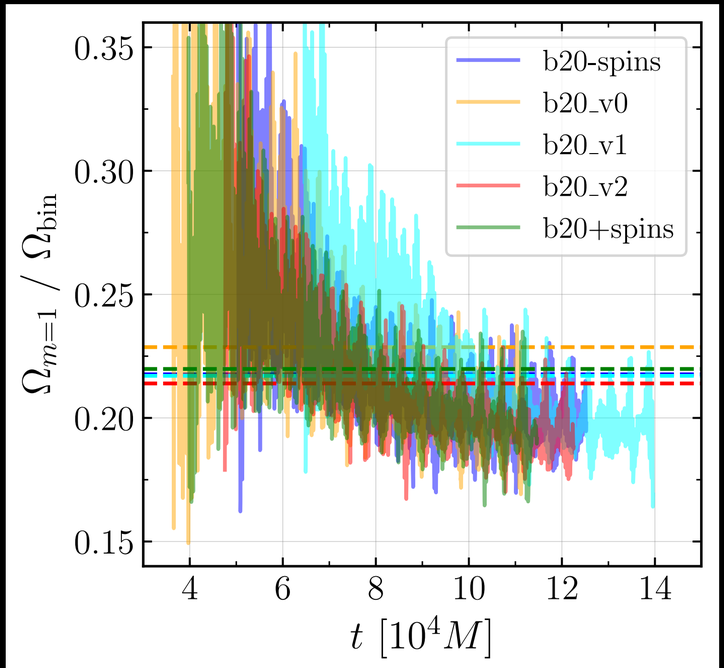
$a_{1,2}/M_{1,2}$ = +/- 0.9

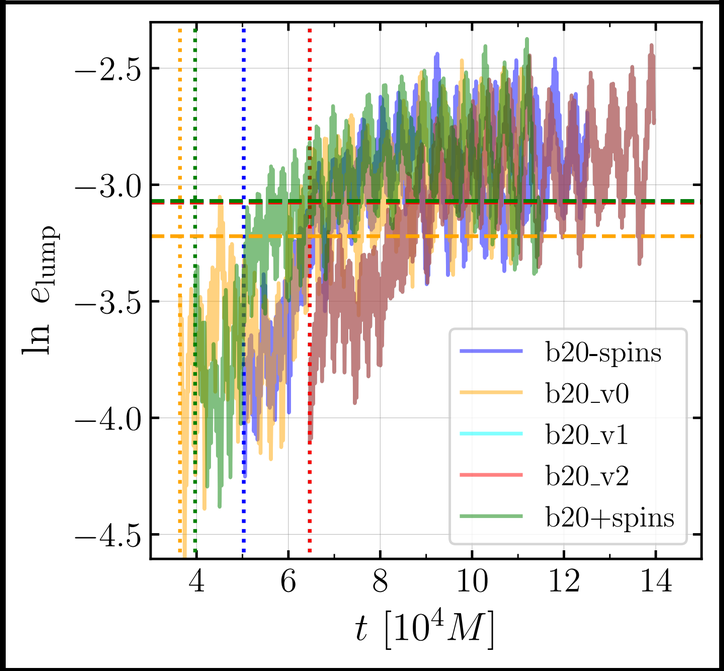
- Simulations of only circumbinary disk region, starting from Noble++2012 conditions, only changing spin and using Superimposed metric; Equal masses, q=1;
- Ran longer than before, reached a better steady state;
- Circumbinary dynamics largely unaffected by spin aligned with orbital angular momentum;
- Again, light curve modulated by the beat mode and the lump's orbital frequency;
- Measured the realization variance due to the nonlinearity of these chaotic systems;

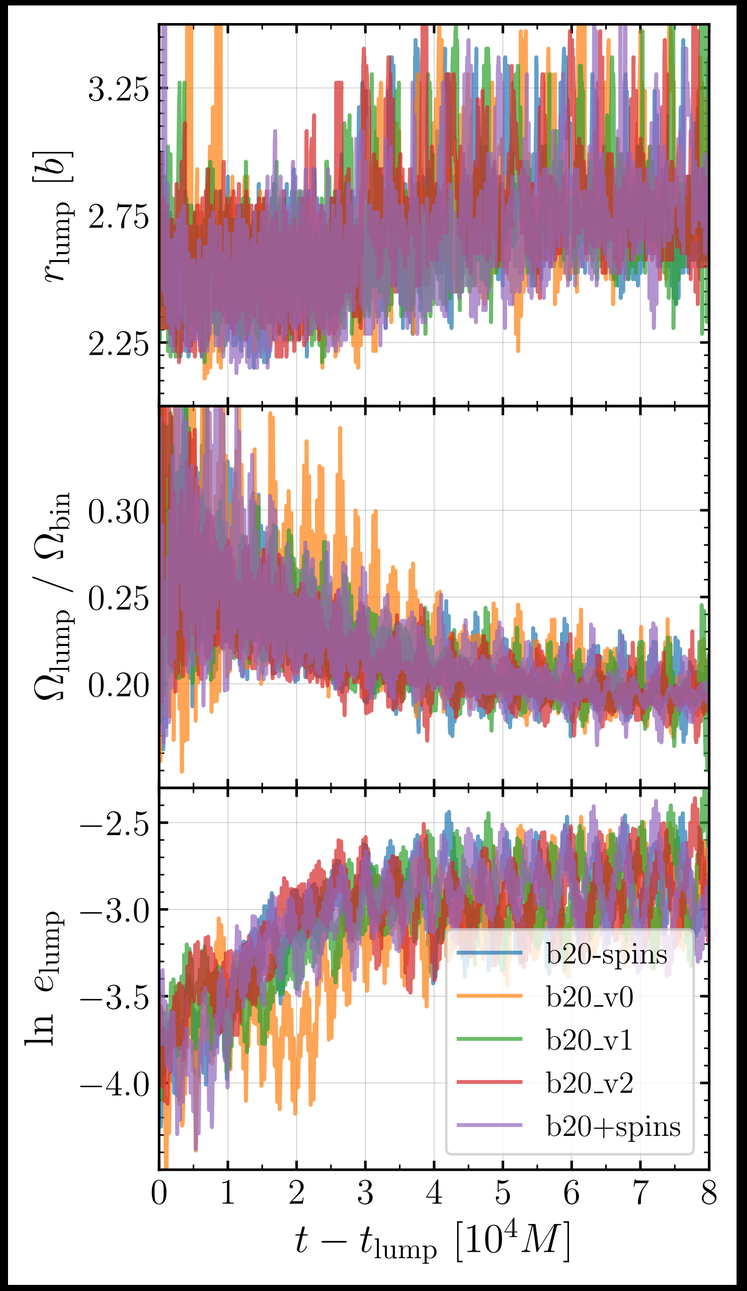
Accretion onto Spinning BBHs

Circumbinary Disk Region

Lopez Armengol, Combi++(in prep)







- Lump's orbit stabilizes after ~200 binary orbits;
- Lump's frequency is ~ 1/5 of binary's, at the background flow's local Keplerian rate at $r_{\rm lump}$;
- Lump gains eccentricity, asymptotic to 0.05,
- $t_{\rm lump}$ determined using "lump criterion" already mentioned;
- Even though each run yields different $t_{\rm lump}$, all runs' trends coincide when displayed offset to $t_{\rm lump}$.

  —> Transition to lump dominance is stochastic, while subsequent lump dynamics is not.

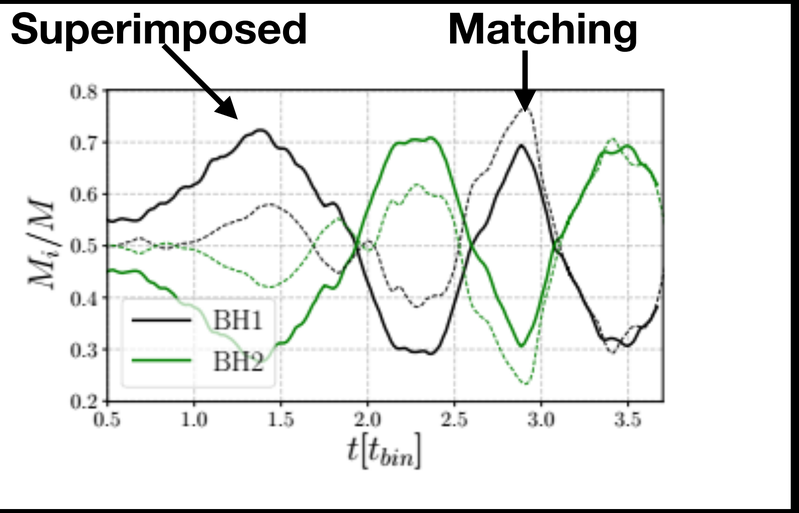
  —> Lump's dynamics is a relatively robust phenomenon.

- (not shown) Spin does alter accretion rate and its surface density phase within the cavity;

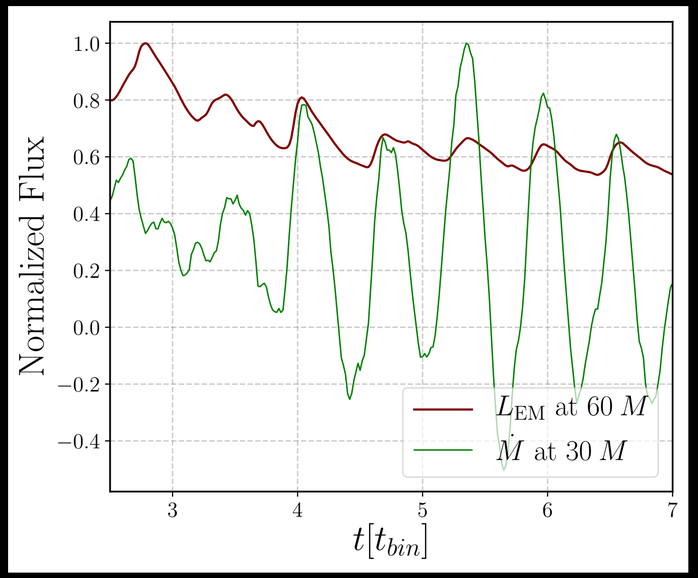
Accretion onto Spinning BBHs

Combi, Lopez Armengol++(in prep)

Circumbinary + Mini- Disk Regions

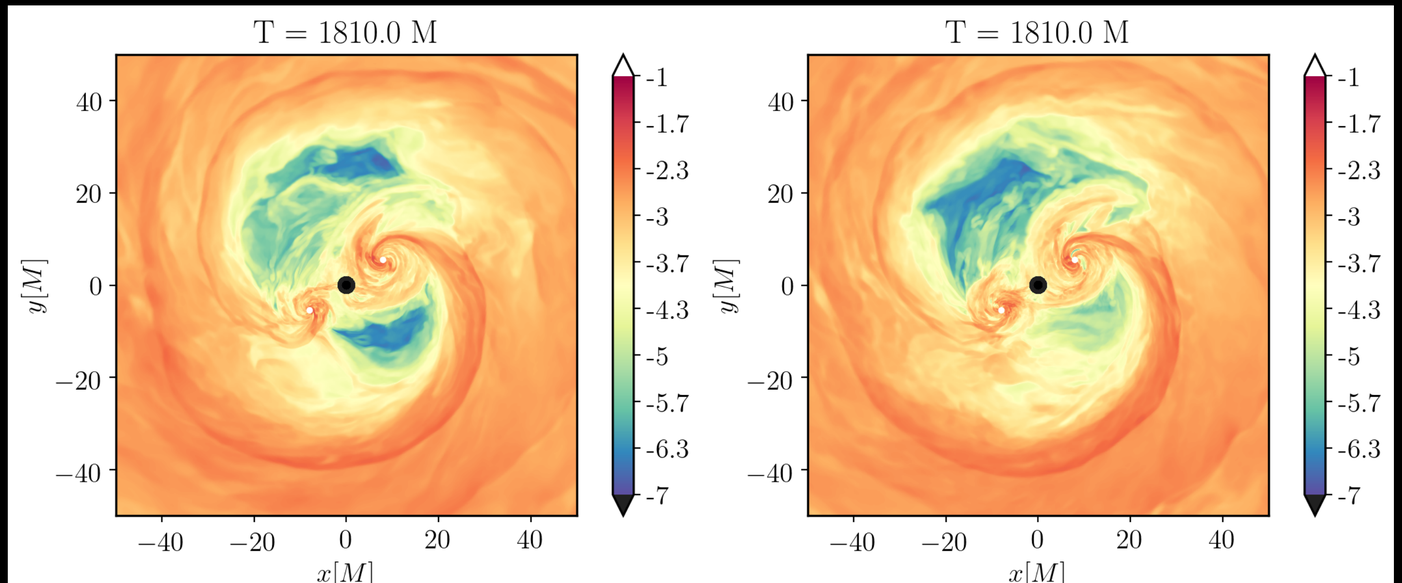


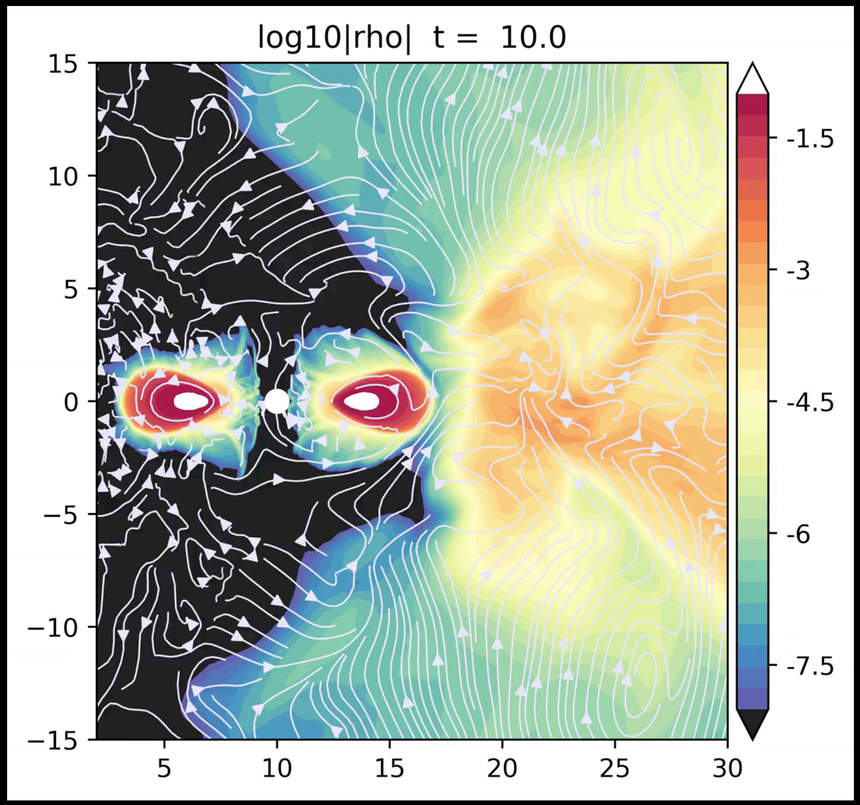
- **Spinning black holes launch jets!**
- **BH jets are powerful radio sources;**
  - **Possible signature of helical field orientation in emission's polarization?!**
- **Poynting luminosity modulated by accretion rate from circumbinary disk (aka the lump).**
- **All sorts of exciting possibilities with binary jet dynamics!**



Matching

Superimposed

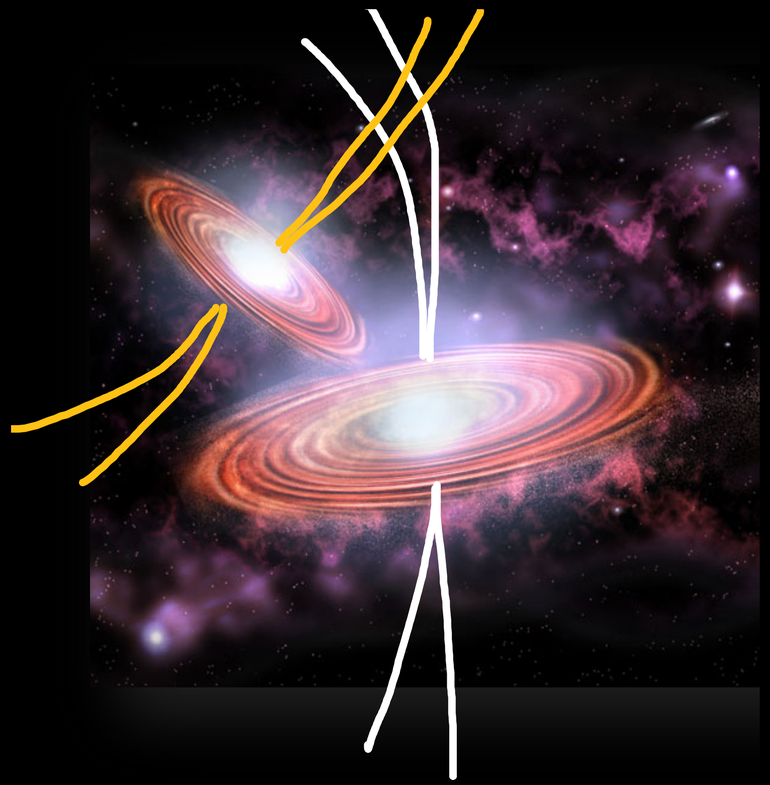




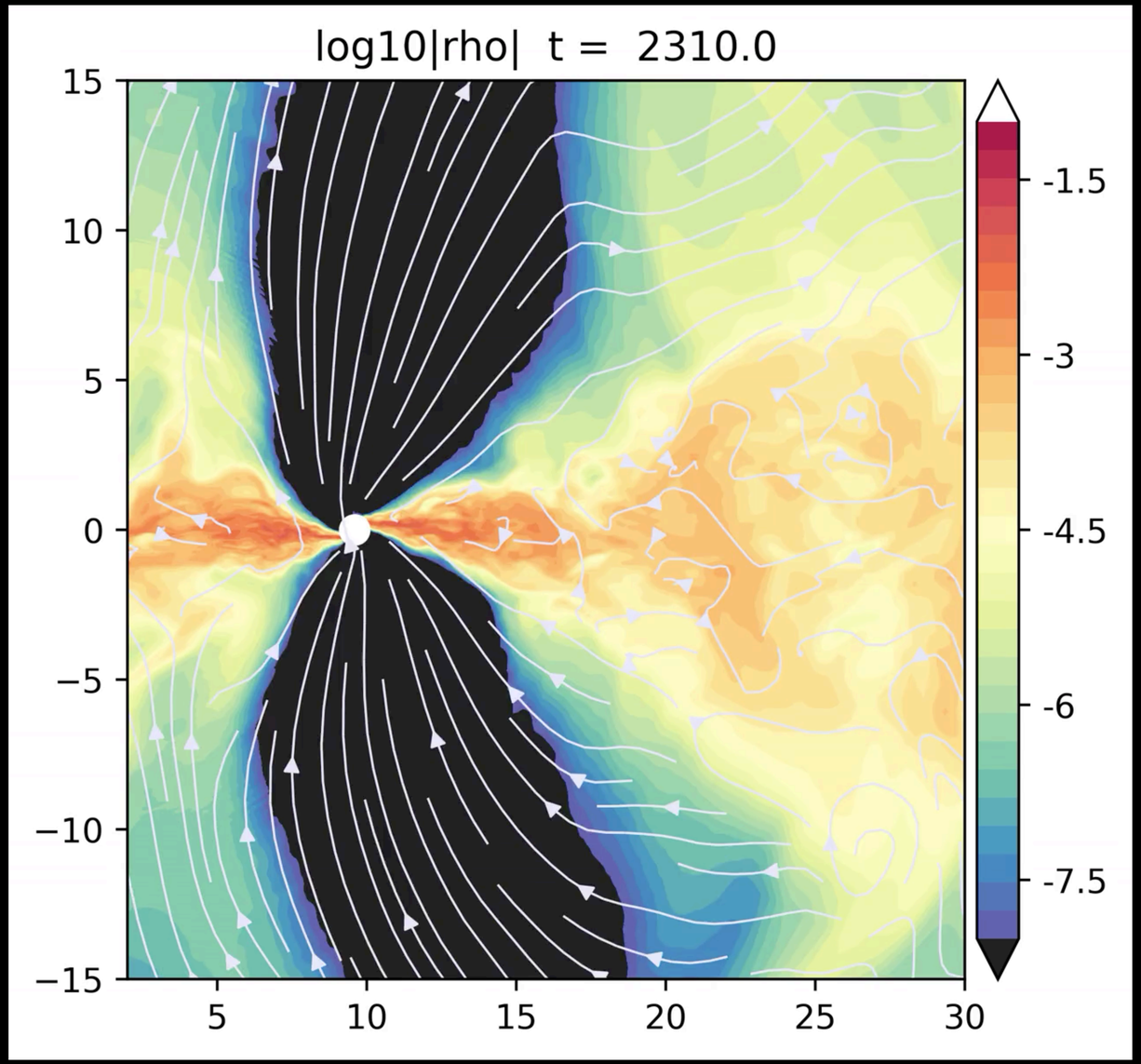
Accretion onto Misaligned Spinning BBHs

Circumbinary + Mini- Disk Regions

- **Jet Interaction?!**
- **Additional variability in the emission possible from hot spots in collisions between jet-wind, or jet-jet regions.**
- **Inclined BH spins to circumbinary disk leads to tilted mini-disks, complicating mini-disk replenishment cycle and modulation.**



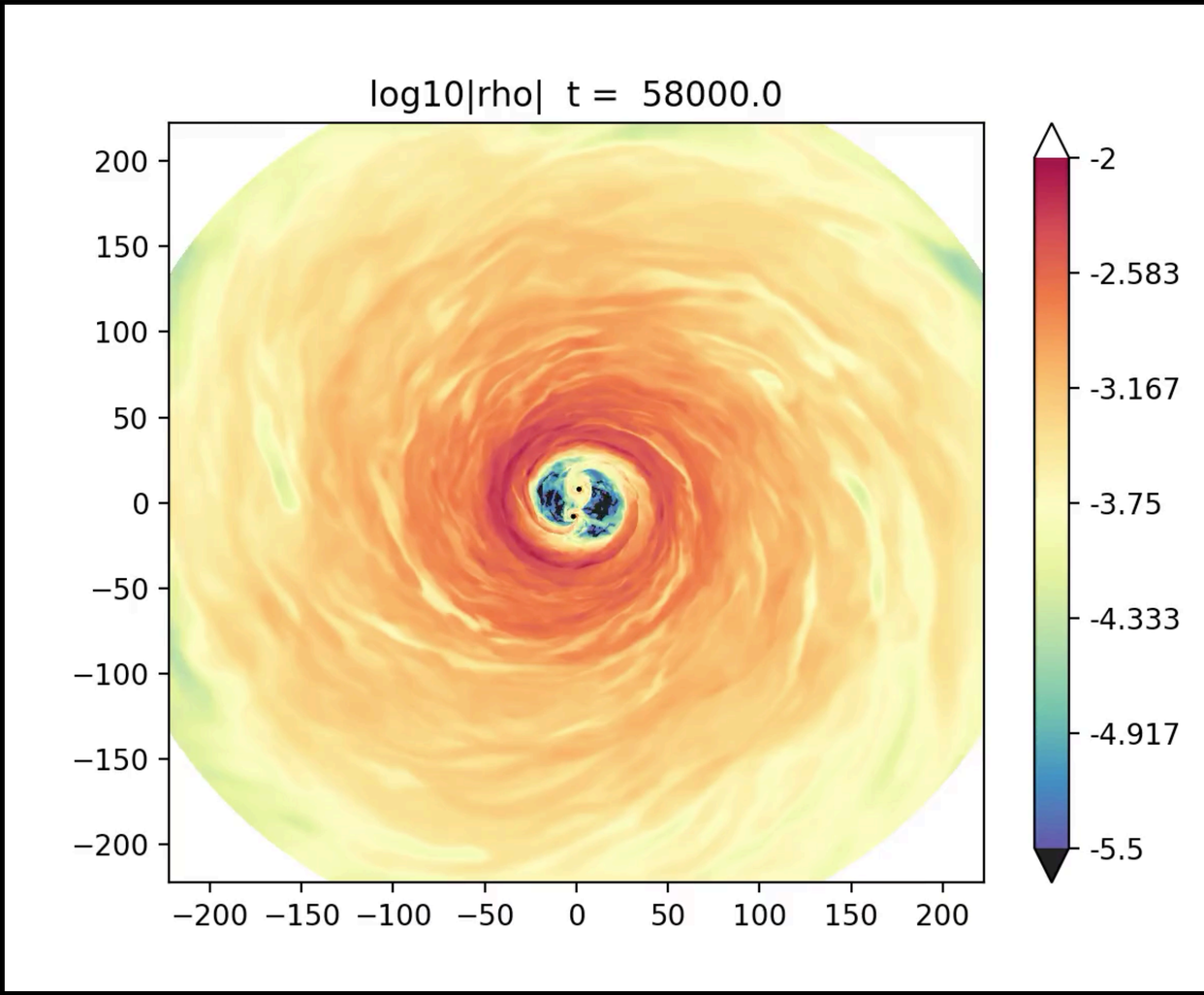
Combi, Gutierrez, Lopez Armengol++(in prep)



PatchworkMHD : Mini-disks + Circumbinary Disk

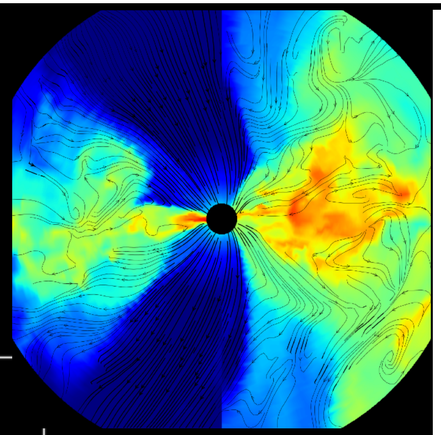
Avara et. al, (in prep)

- Key Challenges: How do we efficiently simulate 10^7-10^8 cells for 10^6-10^7 steps? **PatchworkMHD!**
- Starting from circumbinary disk data of Noble++2012, let mini-disks fill in.
- 31 binary orbits (from 12 orbits before);
- Grid the domain dictated by local symmetries/ asymmetries of the solution.
- Cartesian Patch:
  - Uniform in x,y but graded in z.
- Spherical Patch:
  - Same grid as Noble++2012, no interpolation required.
- Cartesian patch avoids the focusing of cells near the origin and axis, increasing the size of time steps we can take, plus covers the missing volume.
- **No cutout!**

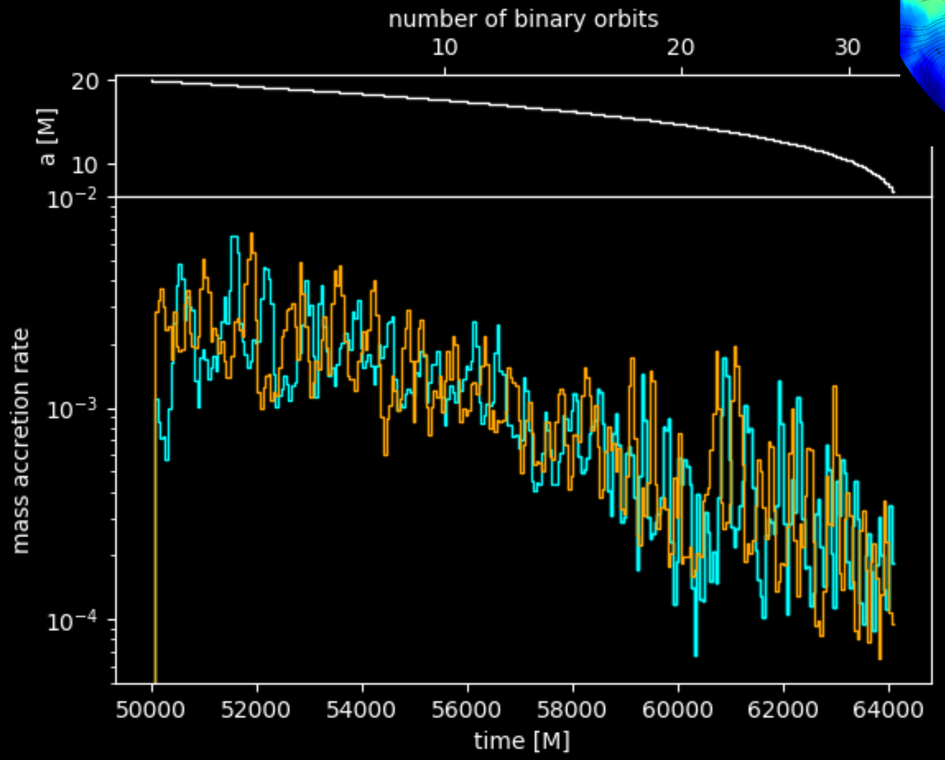


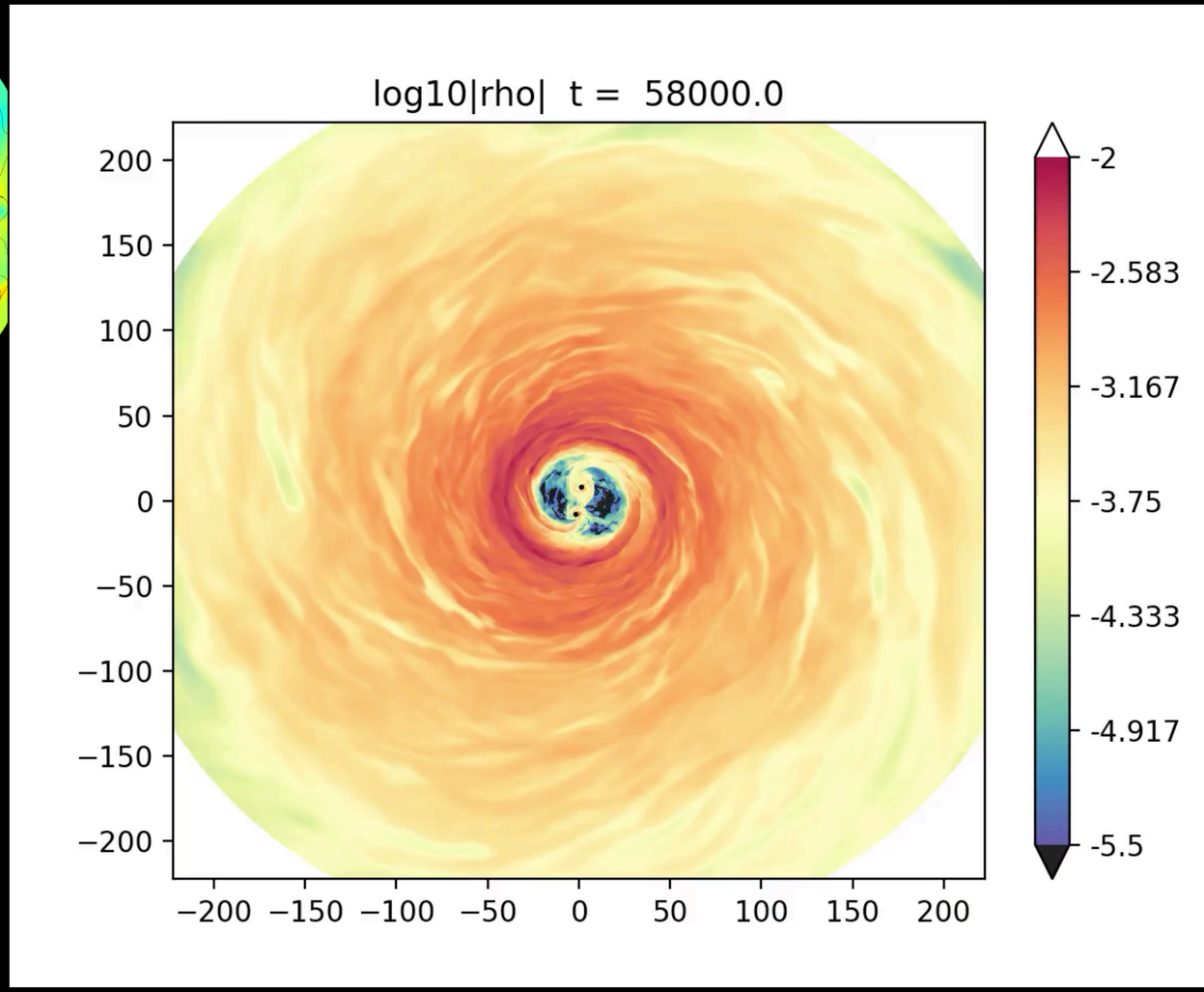
PatchworkMHD : Mini-disks + Circumbinary Disk

Avara et. al, (in prep)



Mini-disk side view





- **Accretion rate onto each BH modulated by their passage near the lump.**
- **PWMHD allows us to measure the mass exchange between mini-disks for the first time!**
- **Accretion rate still significant even while BBH rapidly inspirals.**

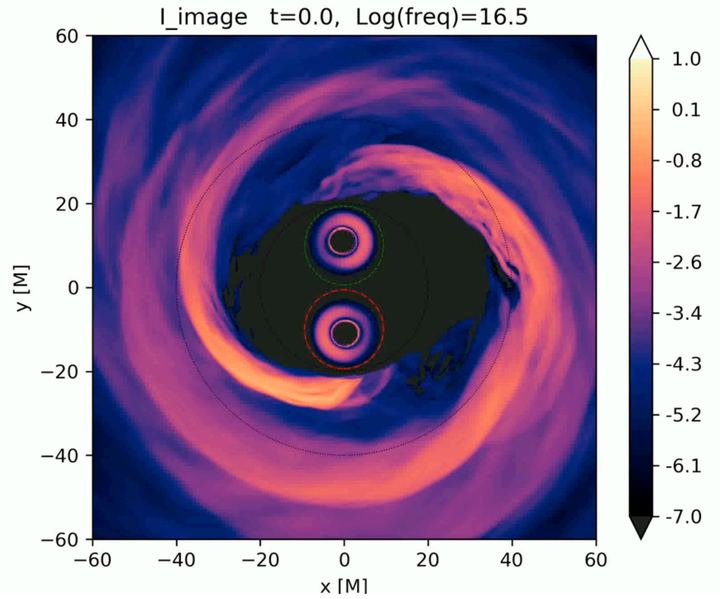
Light Curves from Accretion onto Spinning BBHs

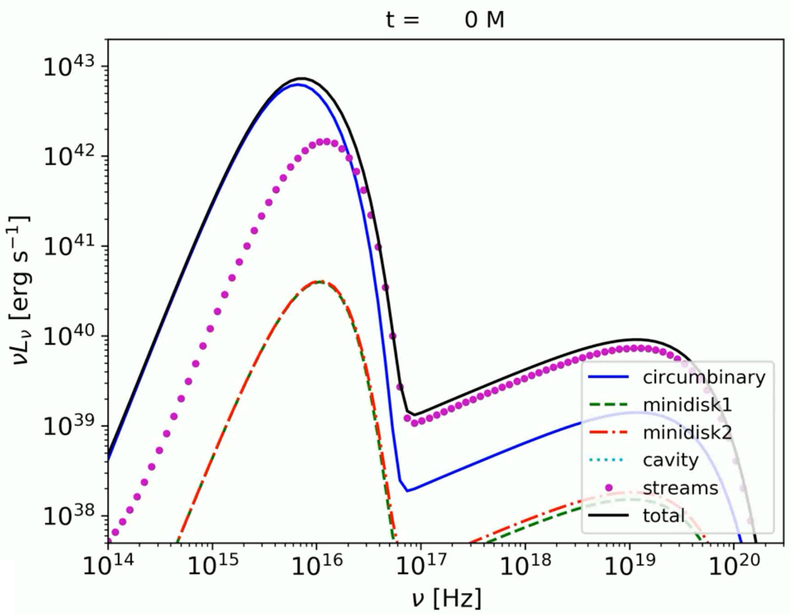
- Following d'Ascoli et. al, ApJ, (2018).
- BH spins (even at these modest values):
  - Brighter mini-disks;
  - More variable mini-disks;
  - More substantial mini-disks broaden the circumbinary disk's thermal peak;

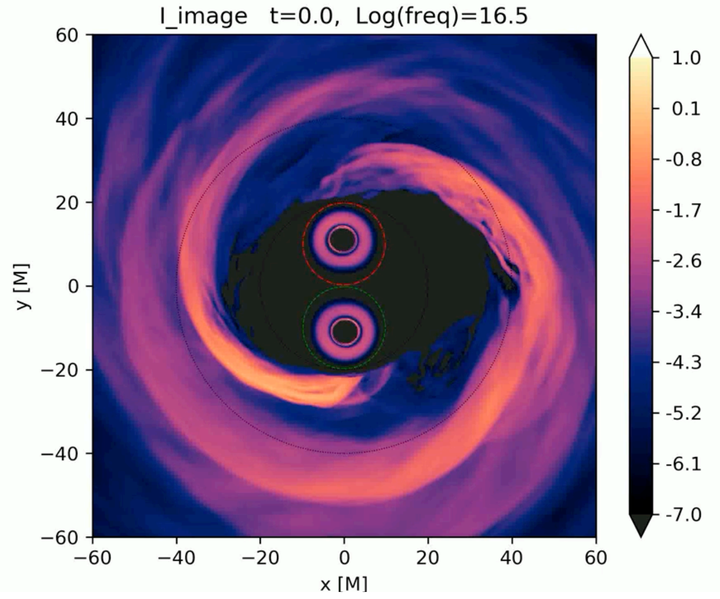
- The spinning case provides new signatures to search for:
  - Broaden thermal peak in optical-UV;
  - Variability in the UV on the binary's orbital timescale;
  - Stronger variability in X-rays;

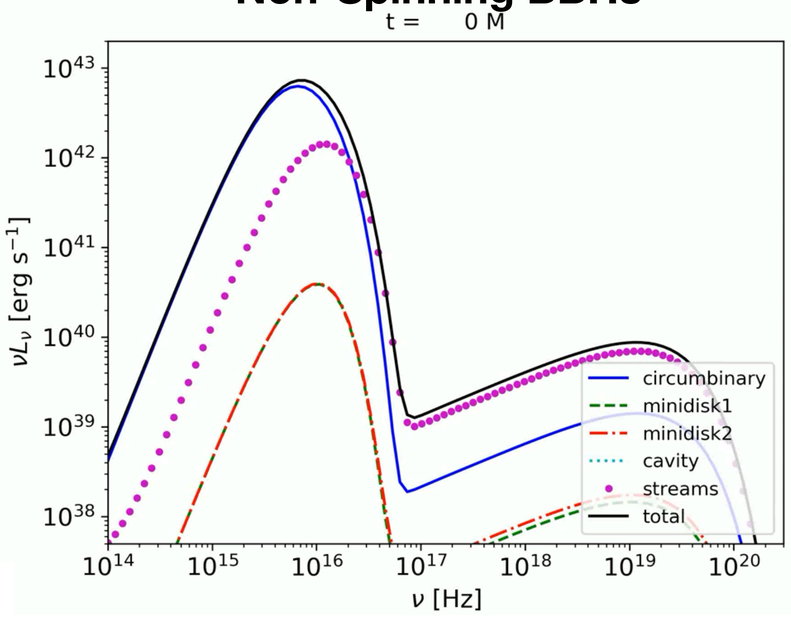
- We expect SMBBHs, especially in gaseous environments, to be spinning even faster, these effects may be even stronger in real systems.

Gutierrez, Combi, Lopez Armengol++(in prep)



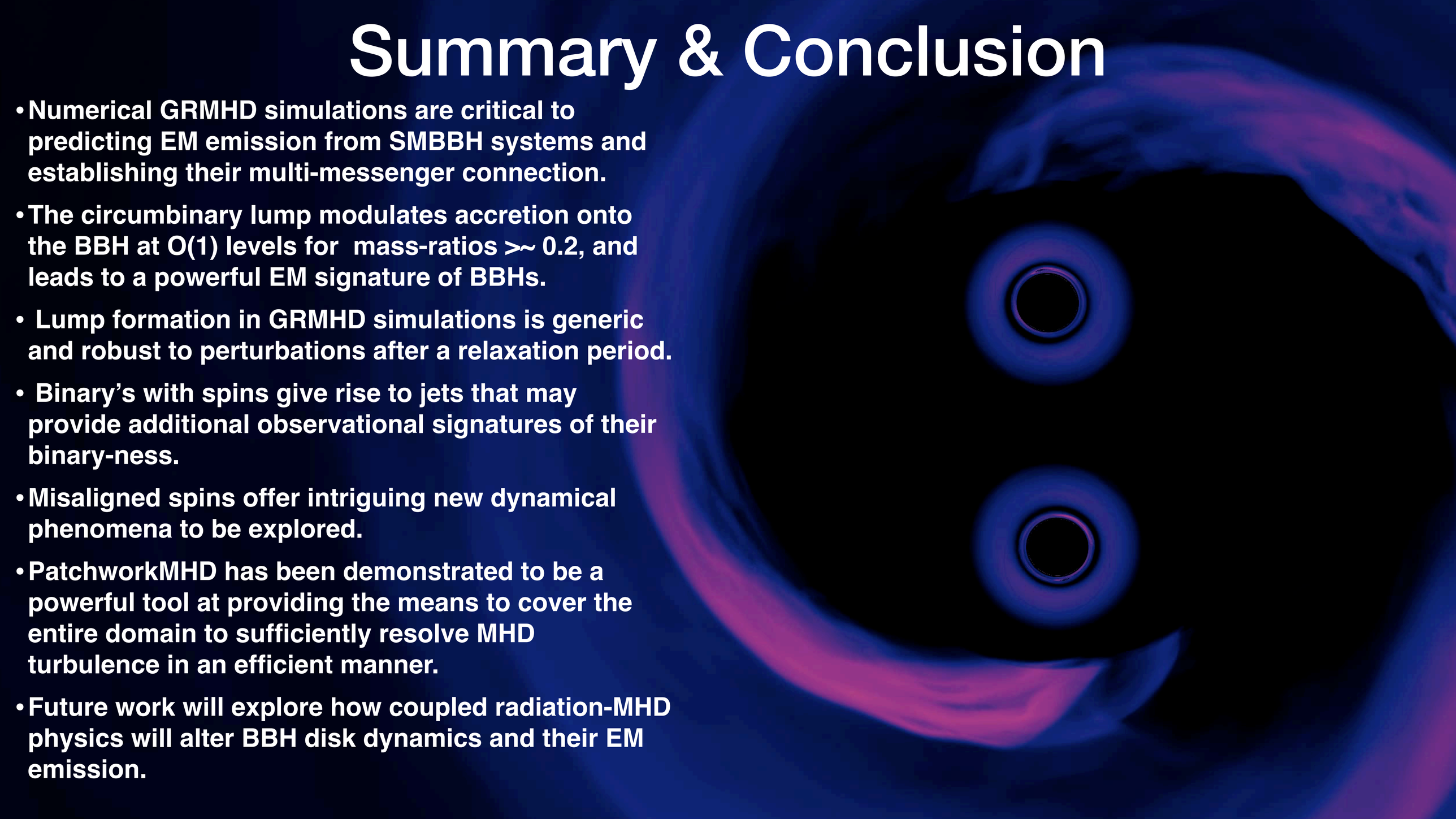






Summary & Conclusion

- Numerical GRMHD simulations are critical to predicting EM emission from SMBBH systems and establishing their multi-messenger connection.
- The circumbinary lump modulates accretion onto the BBH at O(1) levels for mass-ratios $\gtrsim$ 0.2, and leads to a powerful EM signature of BBHs.
- Lump formation in GRMHD simulations is generic and robust to perturbations after a relaxation period.
- Binary's with spins give rise to jets that may provide additional observational signatures of their binary-ness.
- Misaligned spins offer intriguing new dynamical phenomena to be explored.
- PatchworkMHD has been demonstrated to be a powerful tool at providing the means to cover the entire domain to sufficiently resolve MHD turbulence in an efficient manner.
- Future work will explore how coupled radiation-MHD physics will alter BBH disk dynamics and their EM emission.



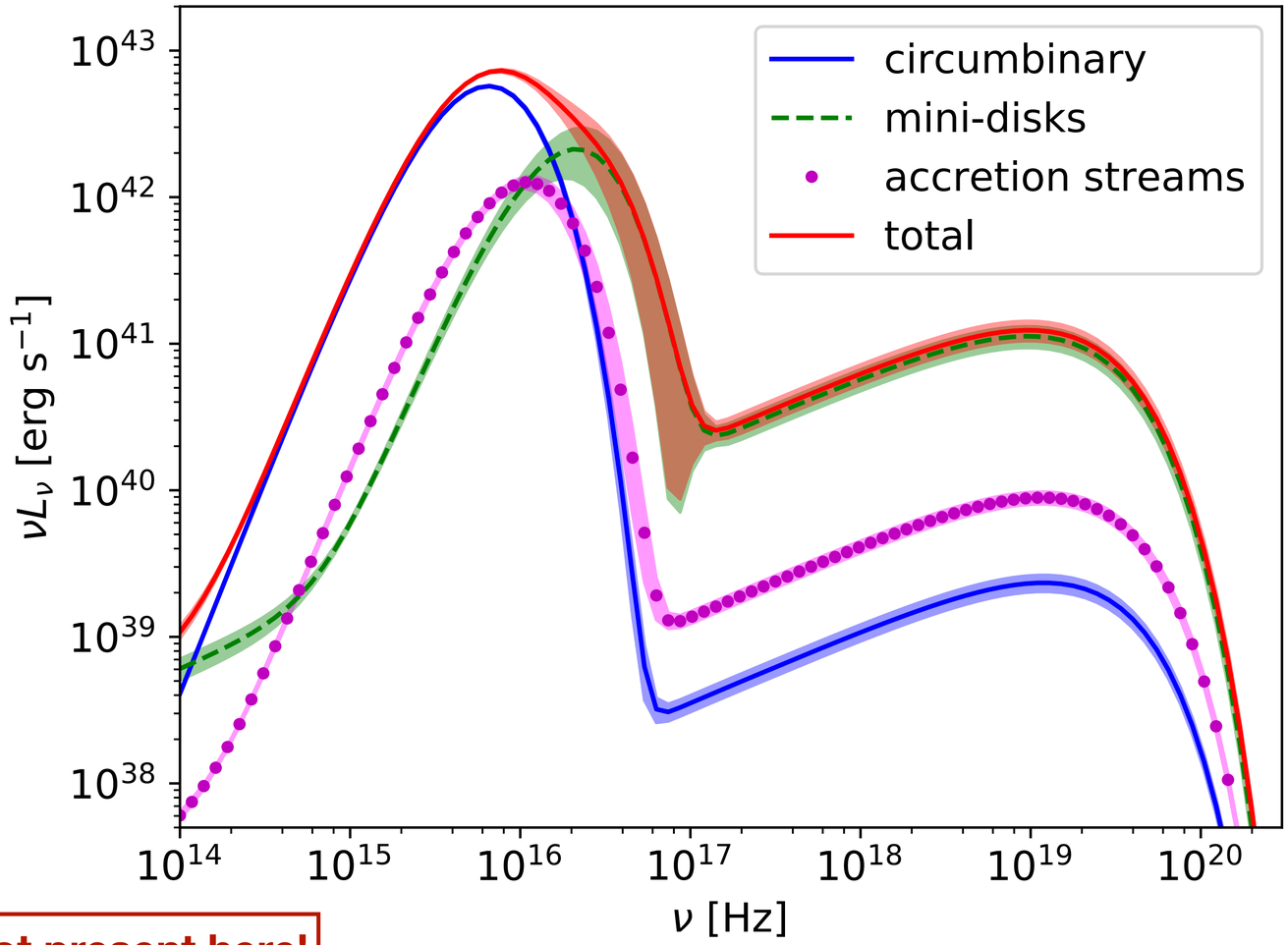
Light from GRMHD Mini-disks

d'Ascoli et. al, ApJ, (2018).

- **Predicted spectrum from accreting binary black holes in the inspiral regime.**
- **The systems will likely be too distant to be spatially resolved, so we need to understand their spectrum and how it varies in time.**
- **Key distinctions from single black hole (AGN) systems:**
  - **Brighter X-ray emission relative to UV/EUV.**
  - **Variable and broadened thermal UV/EUV peak.**
  - **"Notch" between thermal peaks of mini-disks and circumbinary disk will likely be more visible at larger separations and for spinning black holes.**

Face-on View,
Optically Thick Case

Variability over 1 orbit



Variability on longer lump's time scale not present here!

Accretion onto Spinning BBHs

Combi, Lopez Armengol++(in prep)

- Use an approximate spacetime leading up to merger to most efficiently build accretion flow to a “steady” or more natural state.

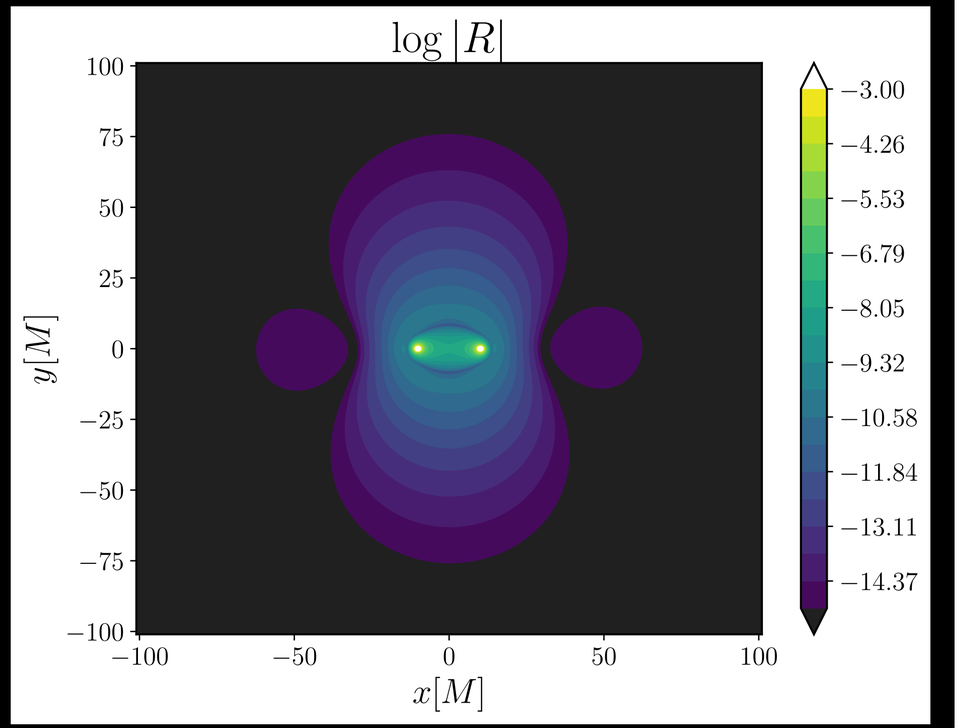
- Old Method: Matching : Kerr+Post-Newt.+Post-Minkowski
  - Non-spinning version used in all our previous BBH-Disk work;
  - Spinning version is too expensive:
    - Includes retarded time integral for all x^a;

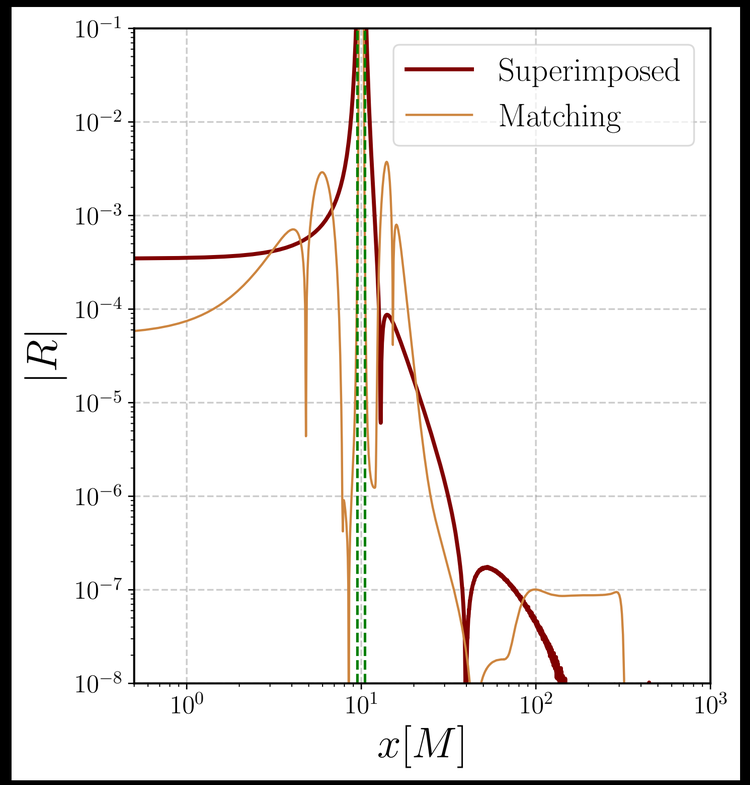
$$g_{ab} = (1 - f_{\rm FZ})\Big\{ f_{\rm NZ}\left[f_{{\rm IZ},1}\, g_{ab}^{\rm (NZ)} + (1 - f_{{\rm IZ},1})\, g_{ab}^{\rm (IZ1)} \right] + (1 - f_{\rm NZ})\left[f_{{\rm IZ},2}\, g_{ab}^{\rm (NZ)} + (1 - f_{{\rm IZ},2})\, g_{ab}^{\rm (IZ2)} \right] \Big\} + f_{\rm FZ}\, g_{ab}^{\rm (FZ)} \qquad (30)$$

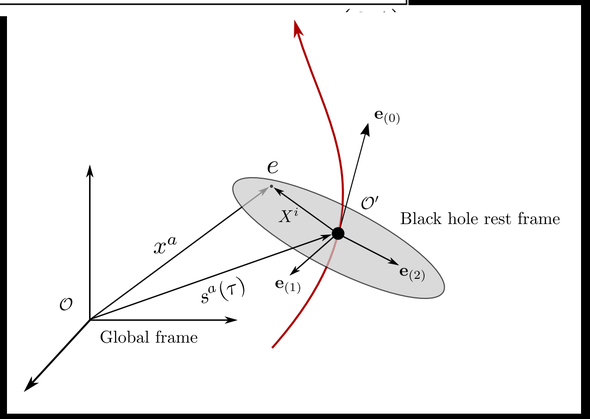
- New Method: Superimposed Kerr-Schild:
  - Boosted set of Spinning BHs in Harmonic Cook-Scheel coordinates;
  - Signficantly more computationally efficient than Matching;
  - BH trajectories still governed by 2.5PN theory;
  - Yields comparable vacuum sol’n as that of Matching;

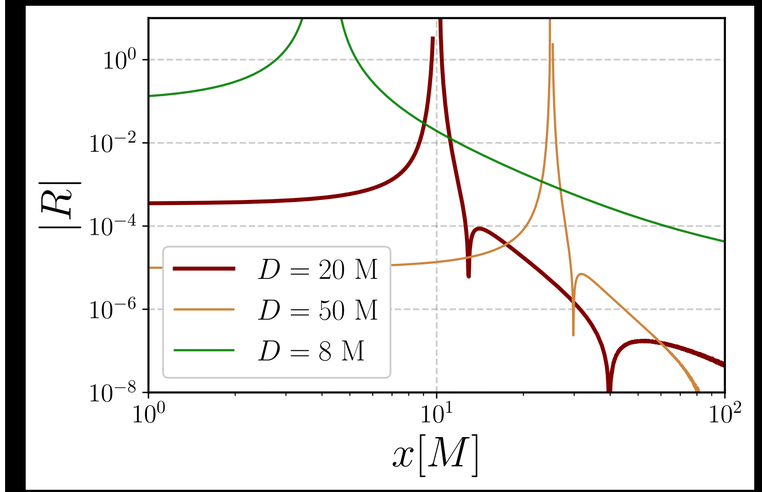
$$g_{ab} = \eta_{ab} + M_1\left(\frac{\partial X_1^{\bar a}}{\partial x^a}\frac{\partial X_1^{\bar b}}{\partial x^b}\mathcal{H}_{\bar a\bar b}\right) + M_2\left(\frac{\partial X_2^{\bar a}}{\partial x^a}\frac{\partial X_2^{\bar b}}{\partial x^b}\mathcal{H}_{\bar a\bar b}\right),$$

$$\mathcal{H}_{ab} := 2H l_a^H l_b^H + \mathcal{A}_{ab}.$$





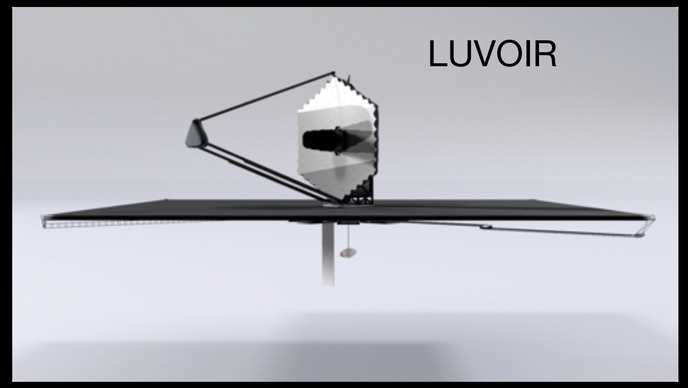


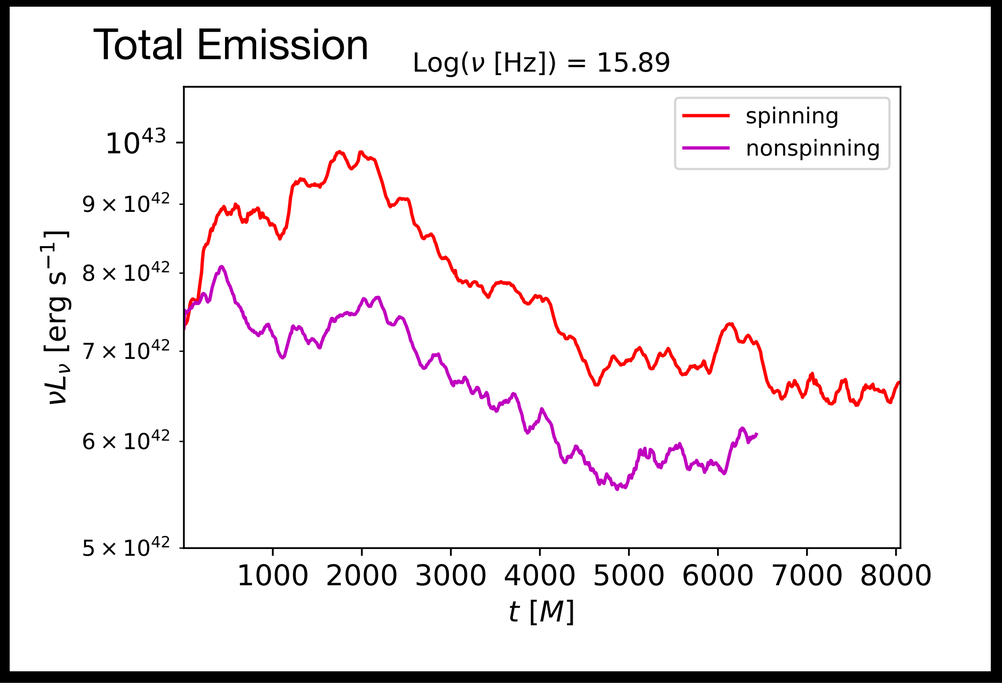


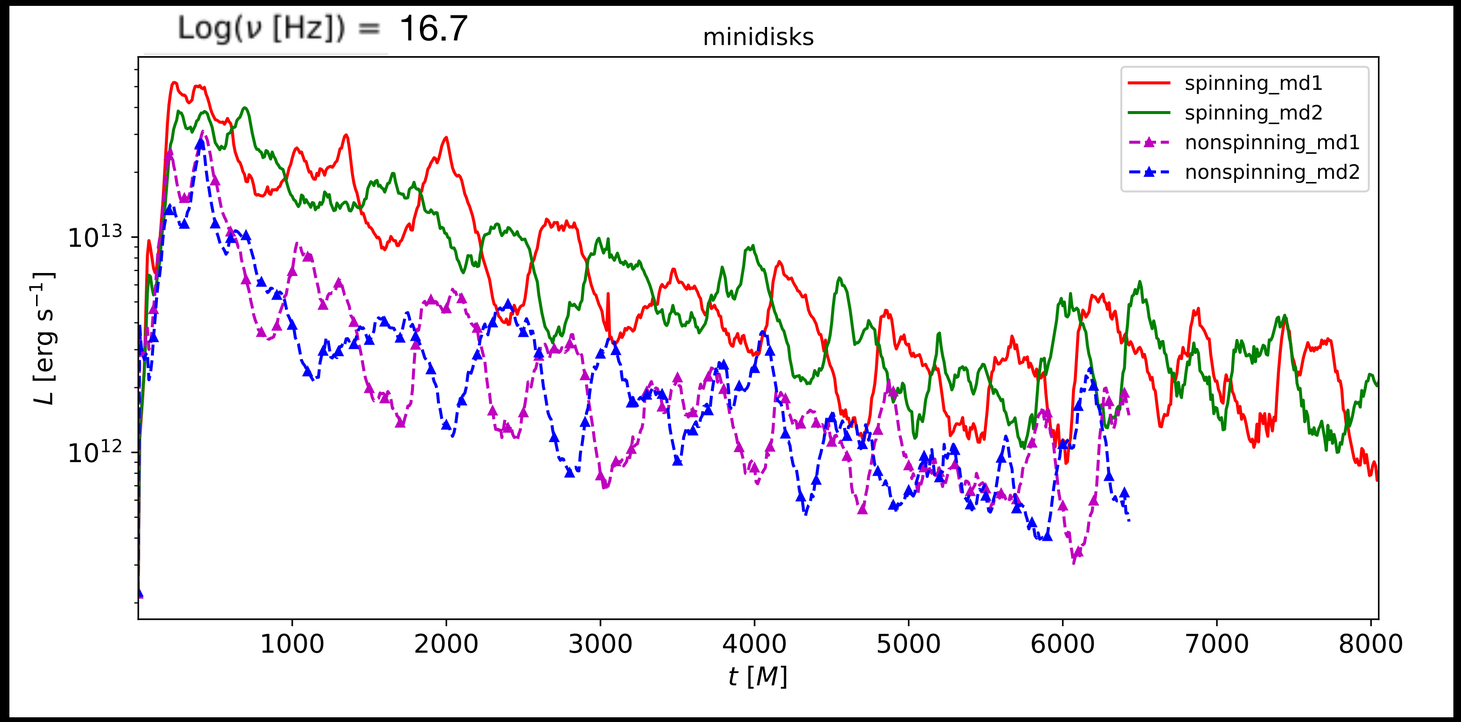
Light Curves from Accretion onto Spinning BBHs

Gutierrez, Combi, Lopez Armengol++(in prep)

- **Binary signature is most significant in X-rays;**
  - **TAP, Athena, LYNX, Strobe-X, AXIS…;**
- **UV offers interesting opportunity too as this is where the mini-disk's thermal disk spectrum peaks;**
  - ✤ **LUVOIR, Dorado possibilities;**



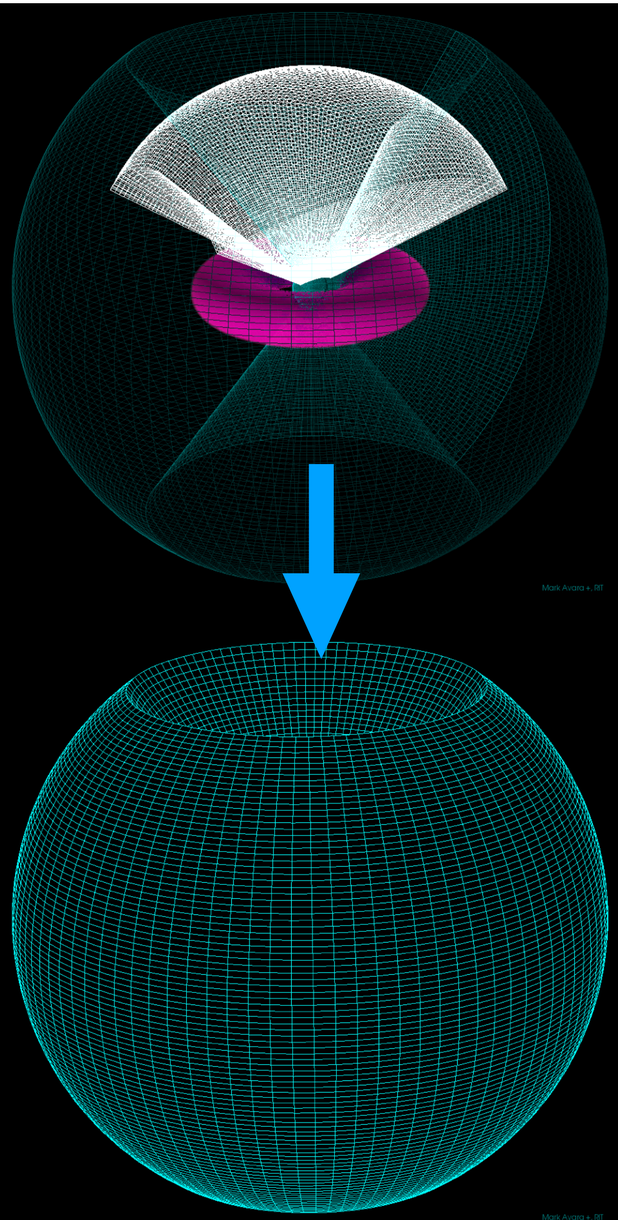




PatchworkMHD : Single BH Test

Avara et. al, (in prep)

- Allows us to stitch together coordinate patches that follow local symmetries efficiently and eliminate coordinate singularities that arise in spherical/cylindrical coordinates.
- Adding support for MHD and preservation of solenoidal (aka “no magnetic monopoles”) constraint into the hydrodynamic *Patchwork* code (Shiokawa++2018).
- Generalize *Patchwork* for the wide range of coordinate systems and patch situations (e.g., patch motion/rotation/overlap) desirable to execute our planned simulations.
- Developed method to adjust fluxes along patch boundaries to dissipate monopoles and flux differences.



- Test: Single accreting black hole.
- 3 spherical patches:
  - 1 aligned with z-axis;
  - 2 aligned with x-axis covering the poles;
- Avoids coordinate singularity along the z-axis and admits larger time steps;

