Exploring the Model Dependence of Electromagnetic Signals in Circumbinary Disk Simulations

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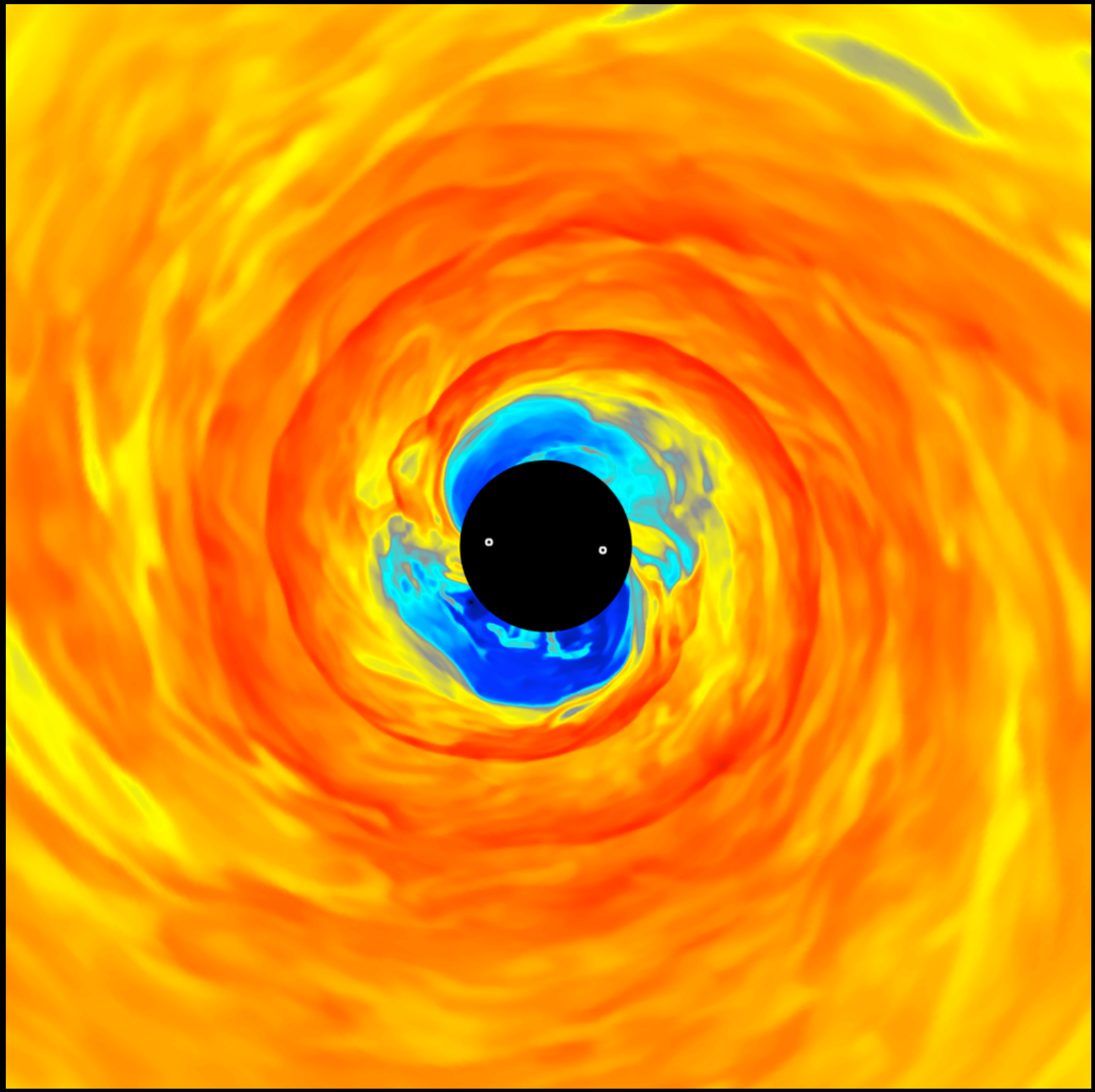


Based on:

- Noble++2012
- Mundim++2014
- Zilhao & Noble 2014
- Zilhao++2015
- Noble++in-prep

Thanks to NSF PRAC OCI-0725070 & NSF CDI AST-1028087

General Relativity & Gravitation: a Centennial Perspective, June 11, 2015

Multimessenger Synergy

Electromagnetic Surveys

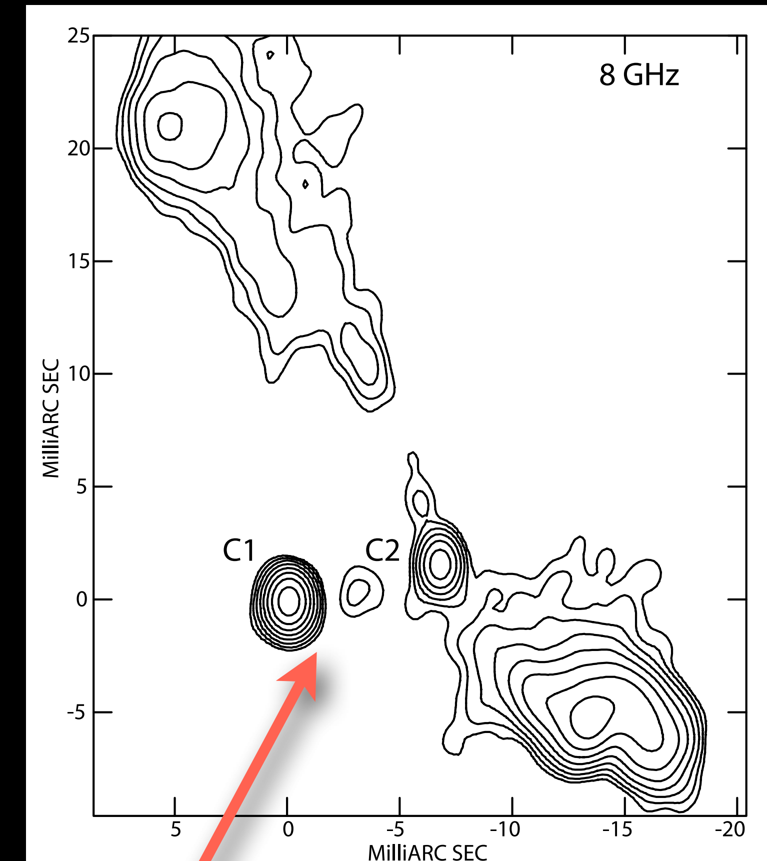
Pan-STARRS:
- Running
- 4 skies per month

Large Synoptic Survey Telescope (LSST):
- 2021-2032
- 1 sky every 3 days

Gravitational Wave Observatories

- GW Detection/Localization <---> EM Detection/Localization;
- GW and light are connected theoretically but originate in wholly different mechanisms
  - --> independently constrain models;
- Either GW or EM observations of close supermassive BH binaries would be the first of its kind!
- Follow up (X-ray, sub-mm) observations can often be made via coordinated alert systems;
- Cosmological "Standard Sirens": New Distance vs. Redshift Measurement
  Schutz 1986, Chernoff+Finn 1993, Finn 1996, Holz & Hughes 2005

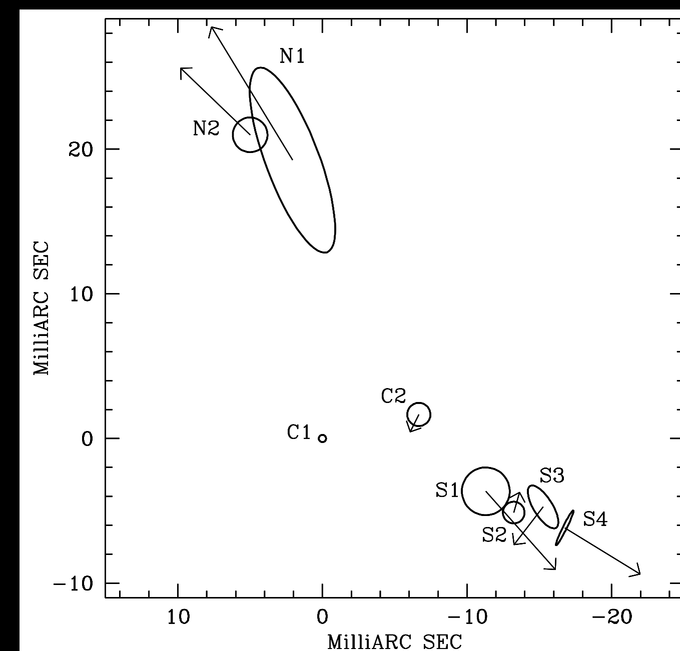
Supermassive Black Hole Binaries



0402+379:

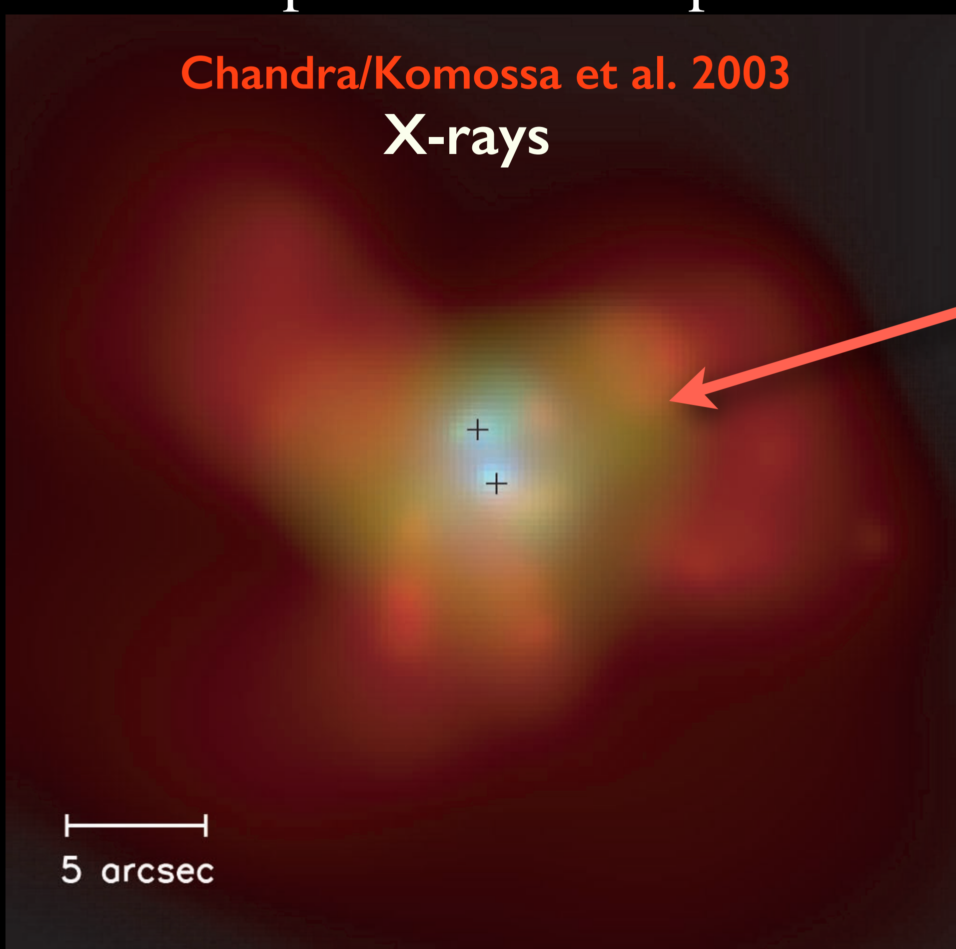
(Xu et al. 1994, Maness et al. 2004, Rodriguez et al. 2006):

- Radio observation
- Separation = 5 pc
- $M \sim 10^8 M_\odot$

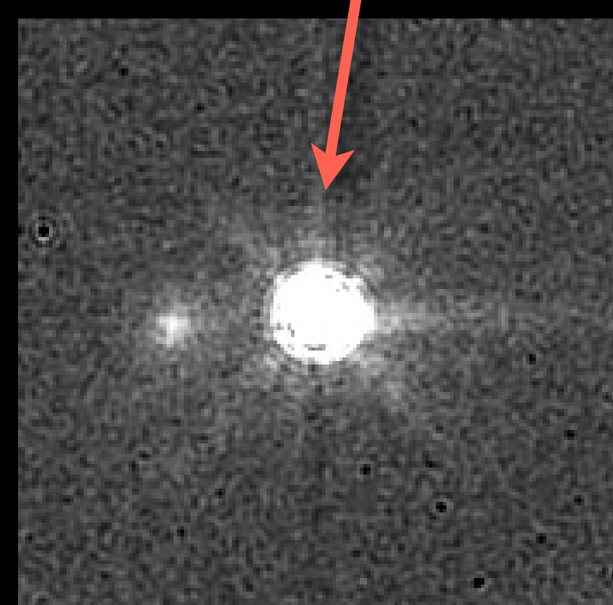


NGC 6240: (Komossa et al. 2003)

- Optical ID: (Fried & Schulz 1983)
- Separation = 0.5 kpc



Not close enough to make detectable gravitational waves!



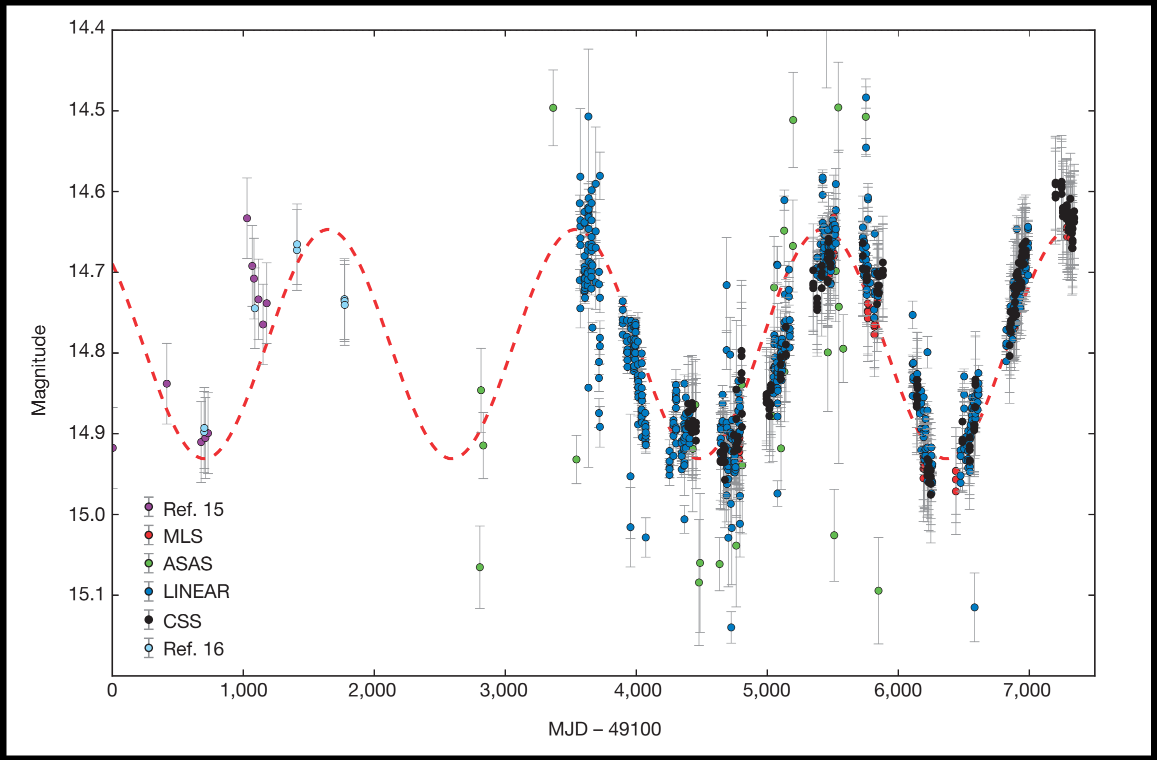
SDSS J153636.22+044127.0

(Lauer & Boroson 2009)

Separation = 0.1pc

1pc = 1 parsec = 3.26 light-years
= 1.9×10^{13} miles

Graham++2015, Nature



Catalina Real-Time Transient Survey

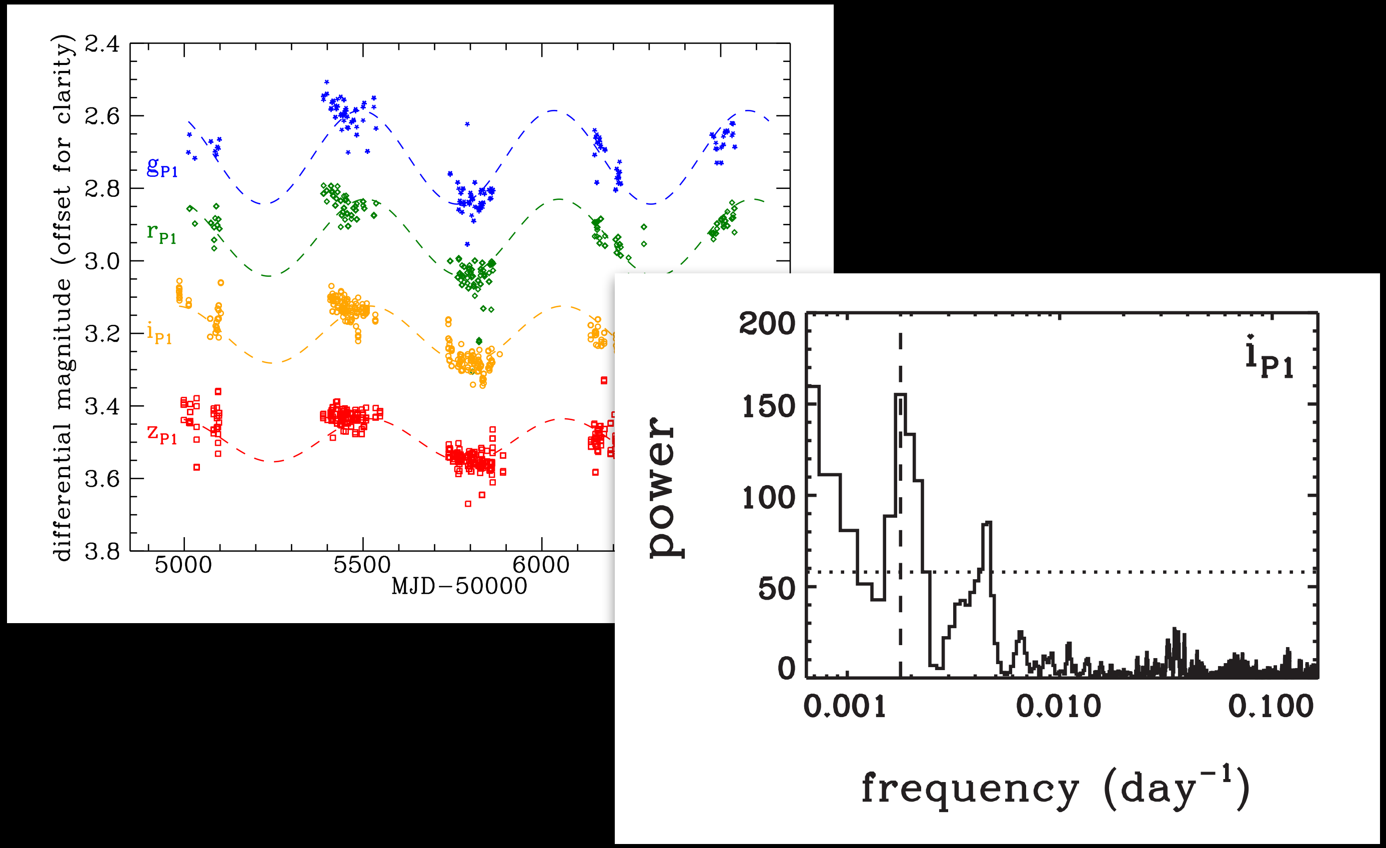
$$z = 0.278 \qquad P_{\rm rest} \simeq 5.2{\rm yr}$$

$$M \sim 10^{8} - 10^{9.5} M_{\odot}$$

$$a_{\rm sep} = 140 - 1400 M$$

$$t_{\rm inspiral} \sim 10^{6} - 10^{16}{\rm yr}$$

Liu, Gezari,++2015, APJL



Pan-STARRS1

$$z \simeq 2 \qquad P_{\rm rest} \simeq 0.5{\rm yr}$$

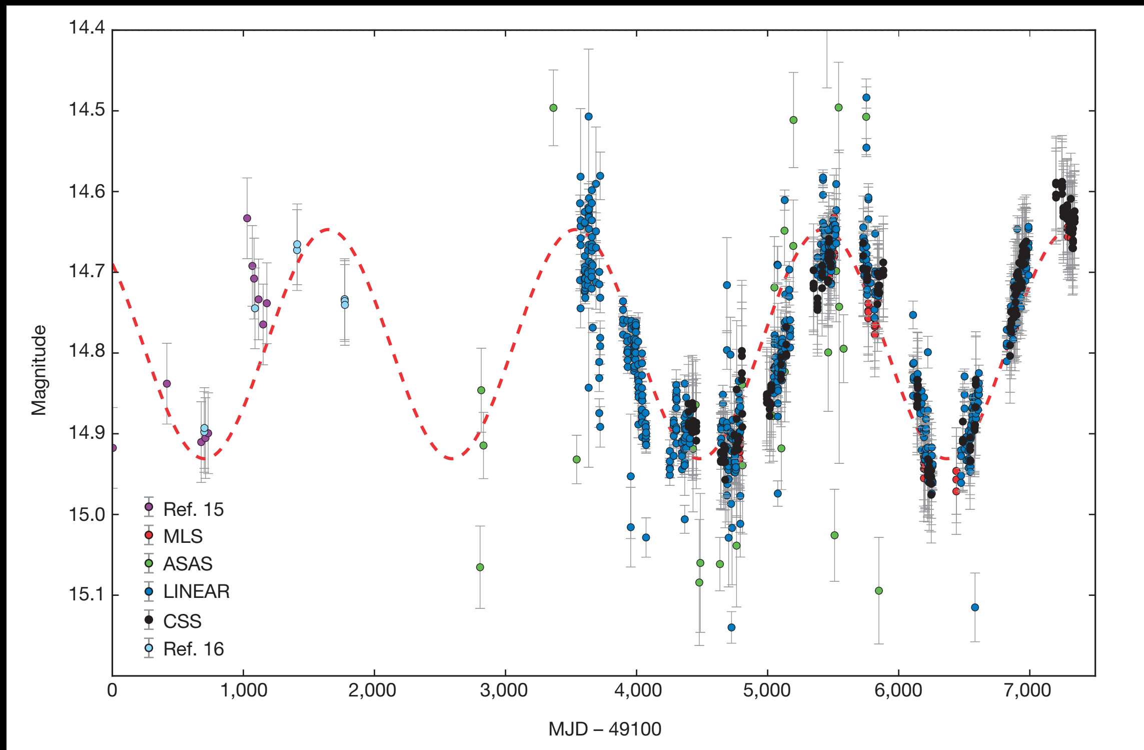
$$M \simeq 10^{10} M_{\odot}$$

$$a_{\rm sep} \simeq 14 M$$

$$t_{\rm inspiral} \simeq 7(1+z){\rm yr}$$

"…[LSST will find] potentially 1000s of SMBHBs periodically varying on the timescale of years, fated to coalesce."

Graham++2015, Nature



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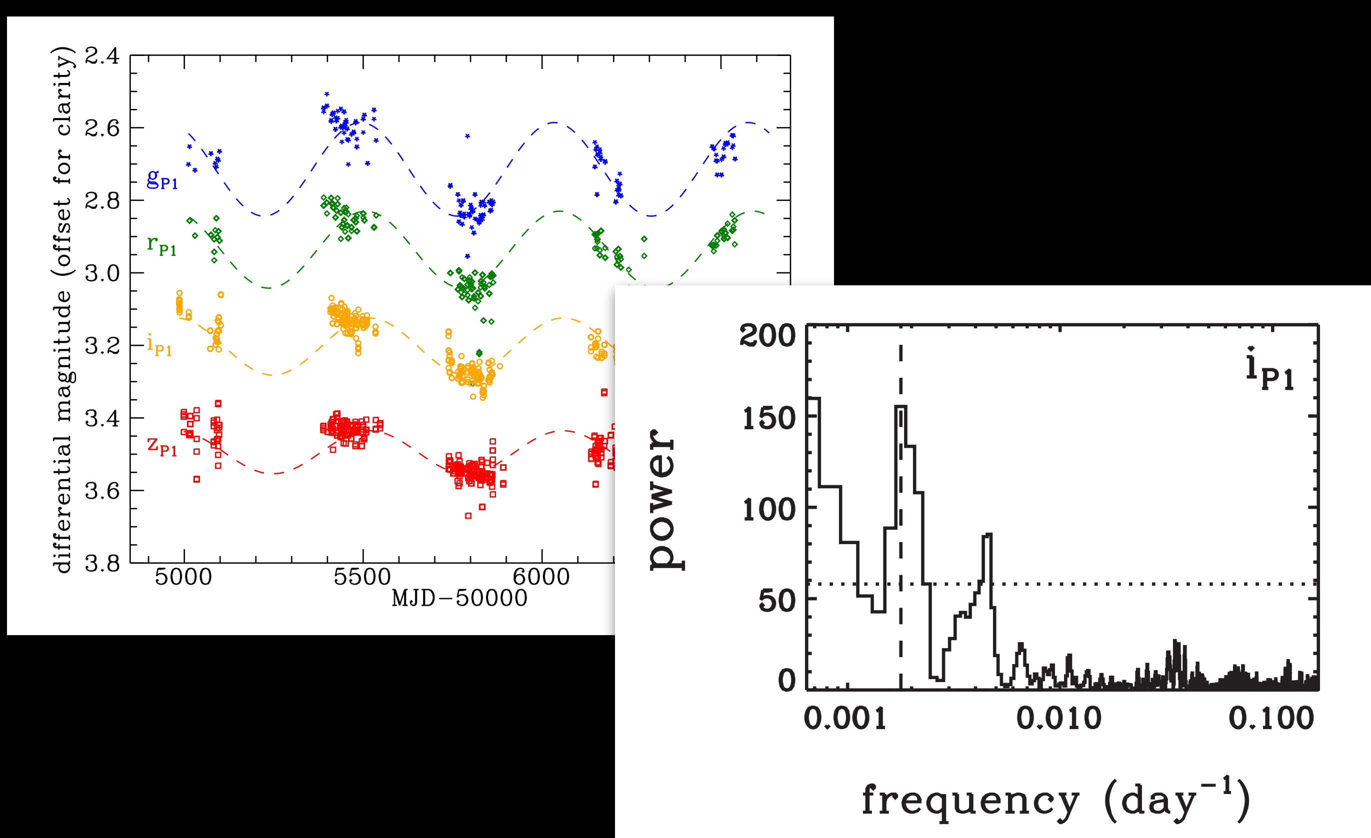

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"…[LSST will find] potentially 1000s of SMBHBs periodically varying on the timescale of years, fated to coalesce."

The Name of the Game

Rare Events

+

Degeneracy of Interpretations

More Data
PTAs,
Pan-STARRS,
LSST, CRTS,
PTF/ZTF…

+

Better Models
+MHD
+3-d
+GR
+Radiation Cooling
+Radiation Feedback

Motivation

Better Models

+MHD

+3-d

+GR

+Radiative Cooling

+Radiation Feedback

- MHD turbulence = Ang. Mom. transporter;
- Field dissipation and growth cannot be modeled w/ 2-d hydrodynamics;

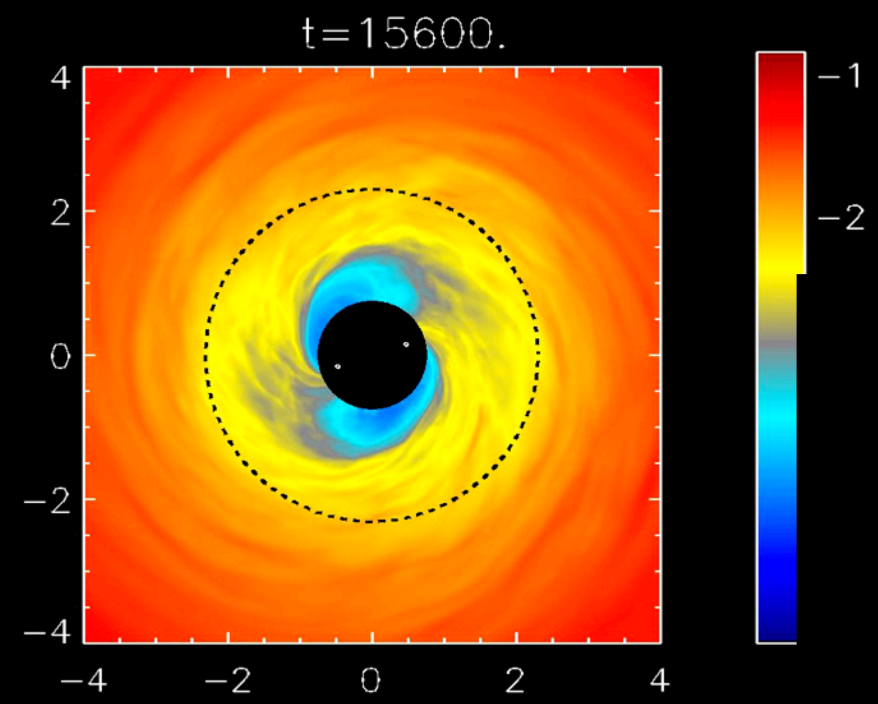
- Inclusion of buoyancy requires including disk's vertical extent;
- Cowling's Thm: no sustained turbulence in 2-d;

- Post-Newtonian (PN) accuracy required for binary separations below ~100M;
- Necessary to self-consistently include binary inspiral from GW loss rate;
  - We know that significant mass can follow binary through much of this period (Noble++2012);
- NR needed for merger proper;

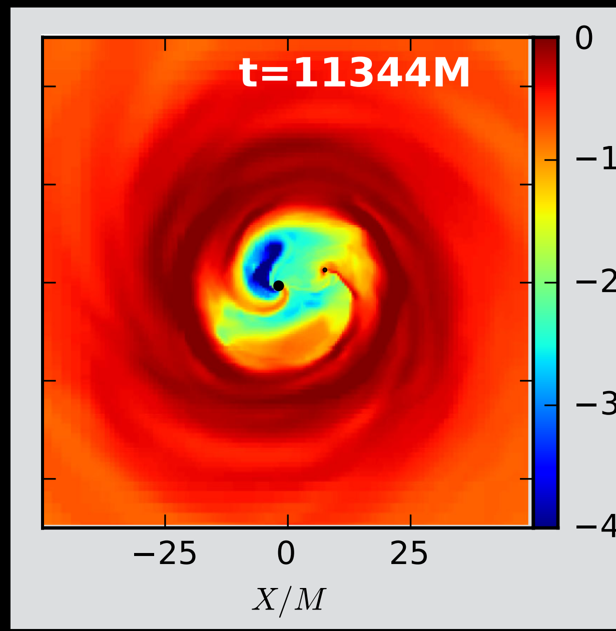
- Cooling required to regulate vertical thickness;
- Cooling provides a way to include more realistic thermodynamics consistent with its luminosity predictions;
  - No longer have to rely on L ~ Mdot ;
- Eventually radiation feedback important in regions of non-smooth optical depths (e.g., "gap")

Strategy

Hopkins, Hernquist, Di Matteo, Springel++



Noble++2012



Gold++2014

Physical Time (not to scale)

Galactic Merger | Binary Formation | Inspiral | Merger | Re-equilibration

Newtonian Gravity

Numerical Relativity

Post-Newtonian

Harm3d

DATA

DATA

Static GR

Harm3d

Eulerian, high-resolution/shock-capturing, 3-d, ideal MHD, dynamical GR, HLL fluxes, parabolic reconstruction, dynamical FMR

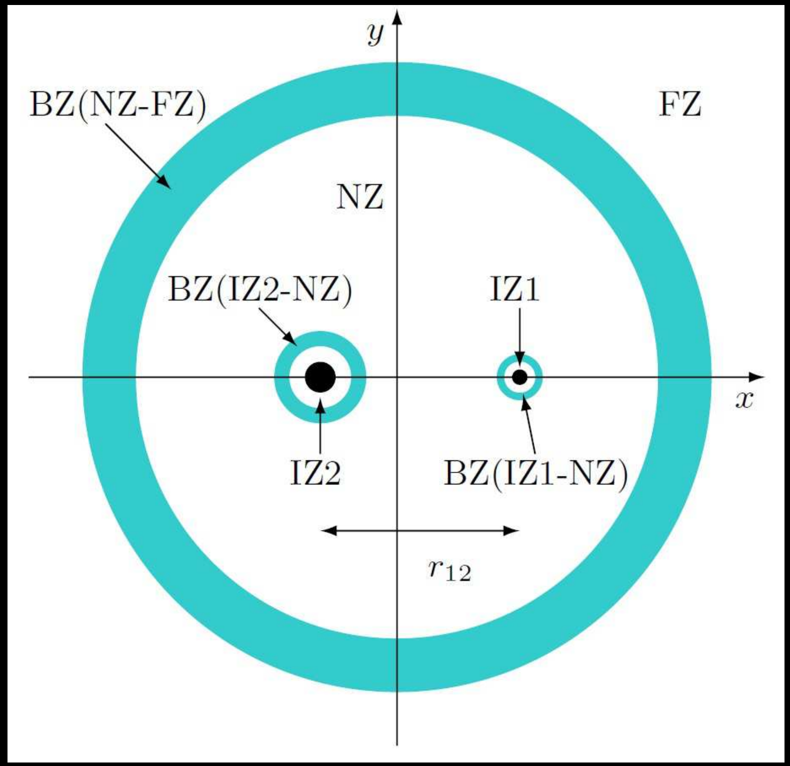
Approximate Two Black Hole Spacetimes

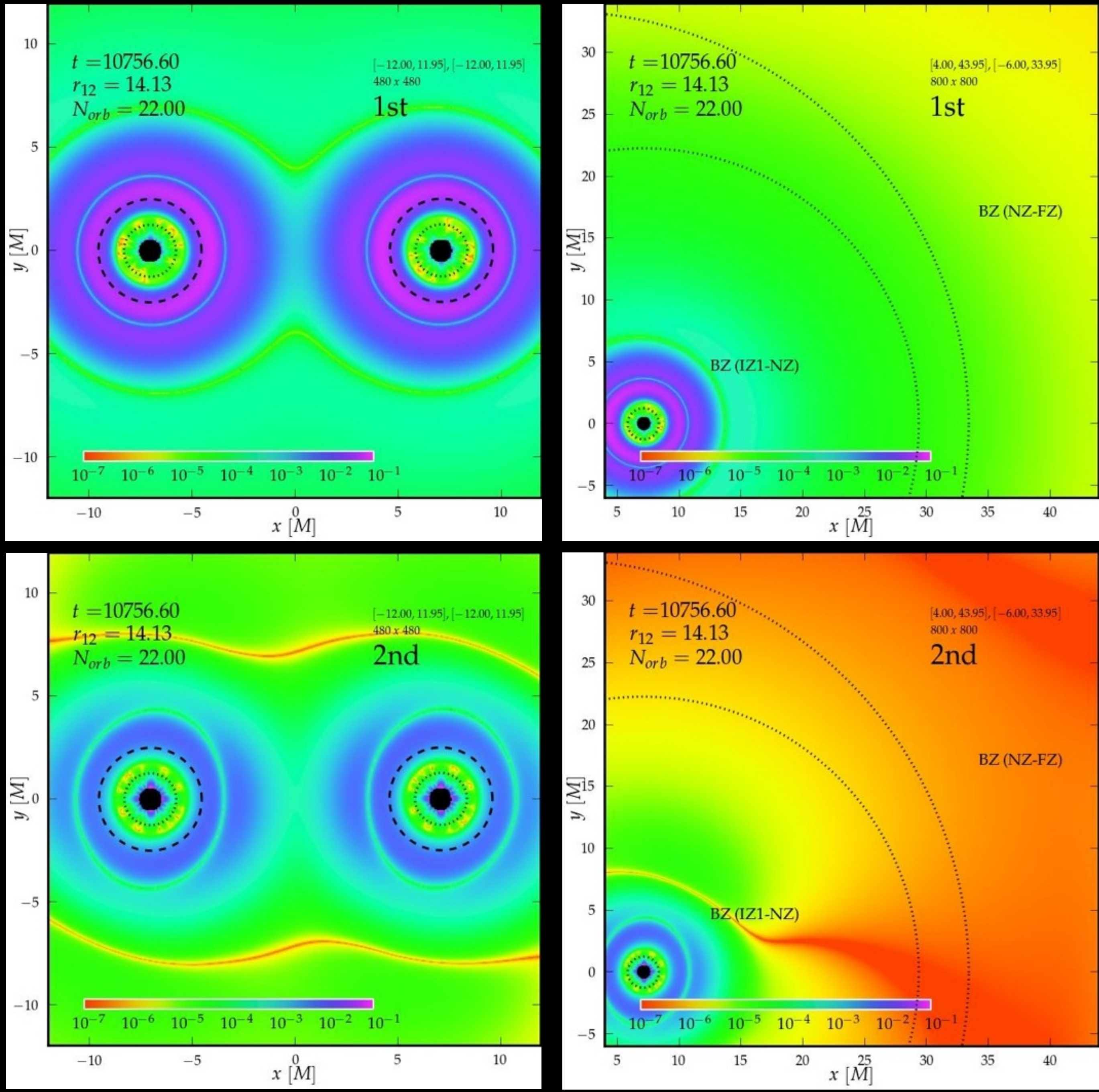
Yunes++2006, Noble++2012, Mundim++2014

- Solve Einstein's Equations approximately, perturbatively to orders of 2.5 Post-Newtonian order;
- Used as initial data of Numerical Relativity simulations;
- Black hole orbits include radiation-reaction terms;
- BH event horizons are included!
- Closed-form expressions allow us to discretize the spatial domain best for accurate matter solutions and is much simpler to implement;

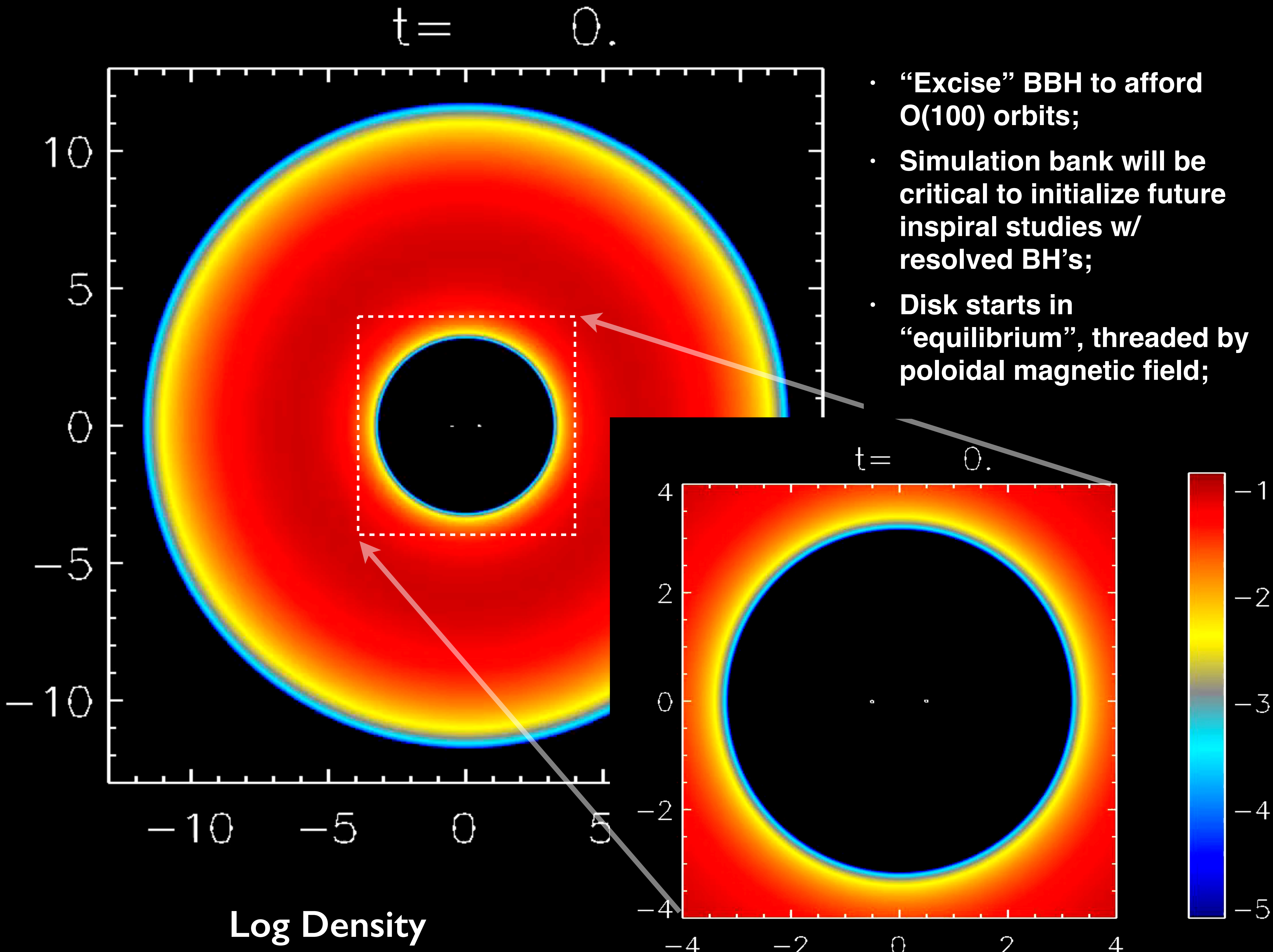
$$\epsilon_i = m_i / r_i \sim (v_i / c)^2$$

Ricci Scalar → 0





- “Excise” BBH to afford O(100) orbits;
- Simulation bank will be critical to initialize future inspiral studies w/ resolved BH’s;
- Disk starts in “equilibrium”, threaded by poloidal magnetic field;

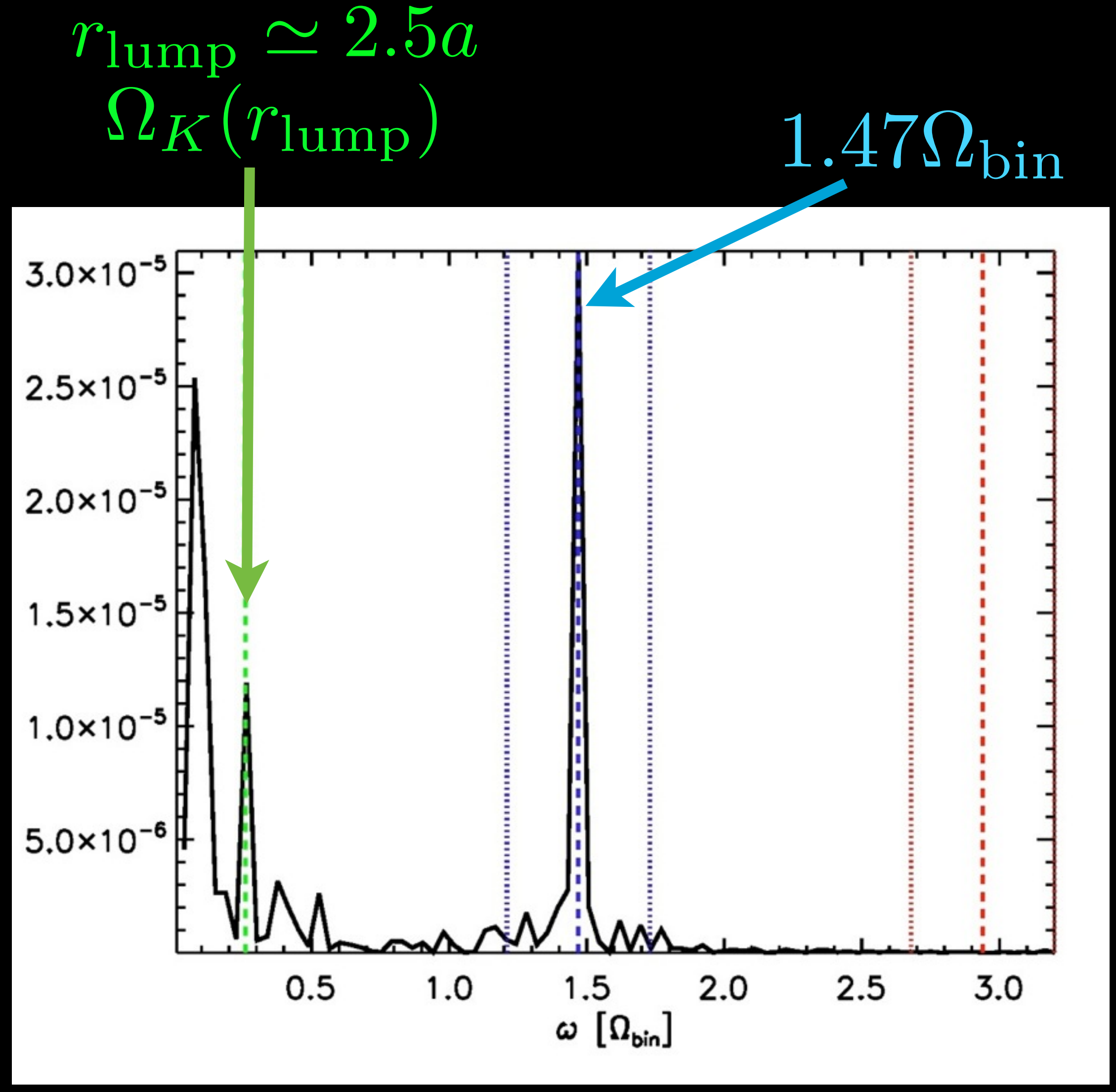


Log Density

MHD Simulations with Unresolved BHs:

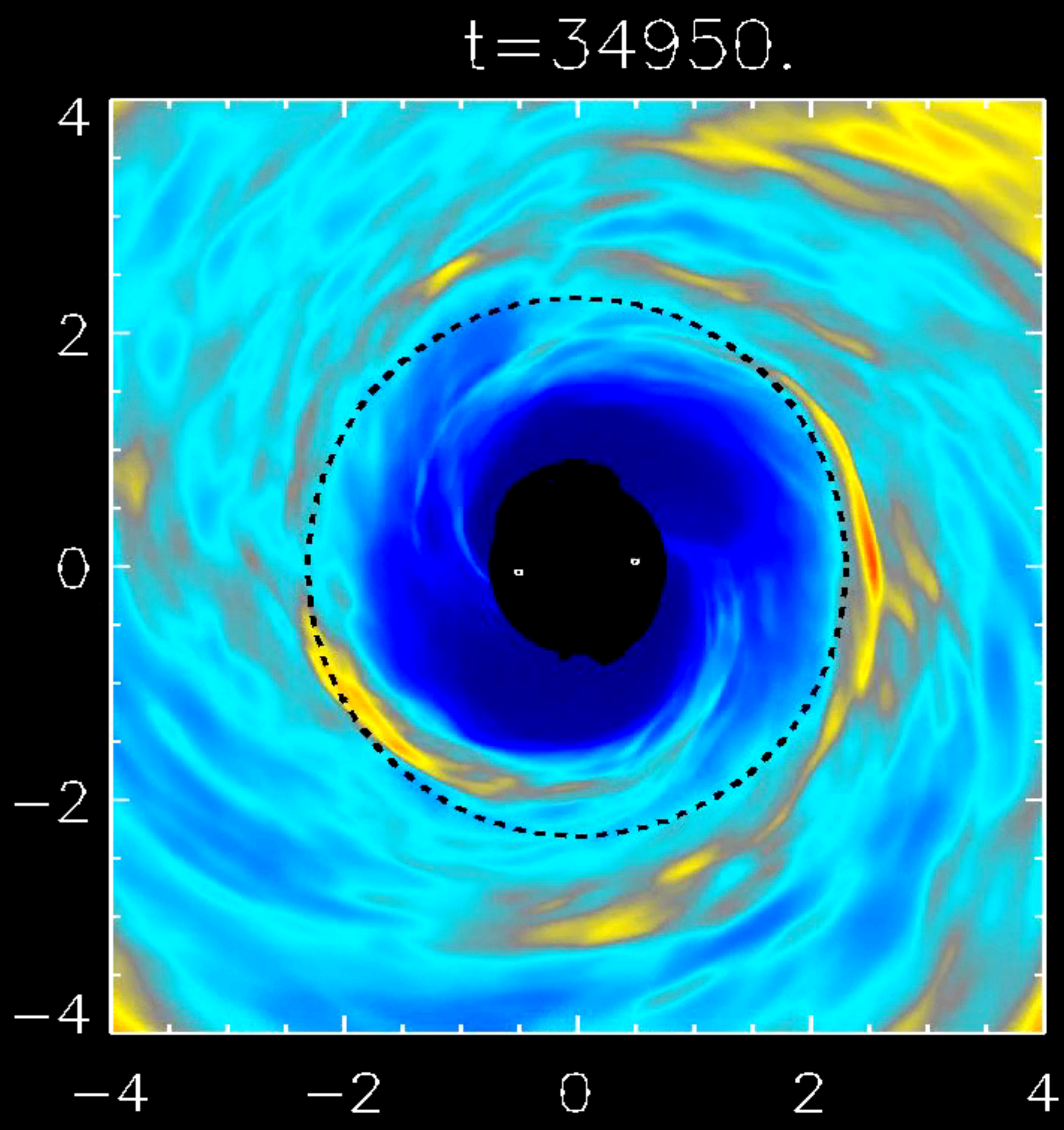
Noble++2012

Periodic Signal



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

Surface Density



Hydrodynamic Response to PN-Order and Binary Separation

Zilhao++2015

Relative deviations of density from initial conditions averaged in azimuth, plotted versus radius and time:

Tori of gas in orbit of the binary responds in different ways at closer separations between the two orders of Post-Newtonian accuracy;

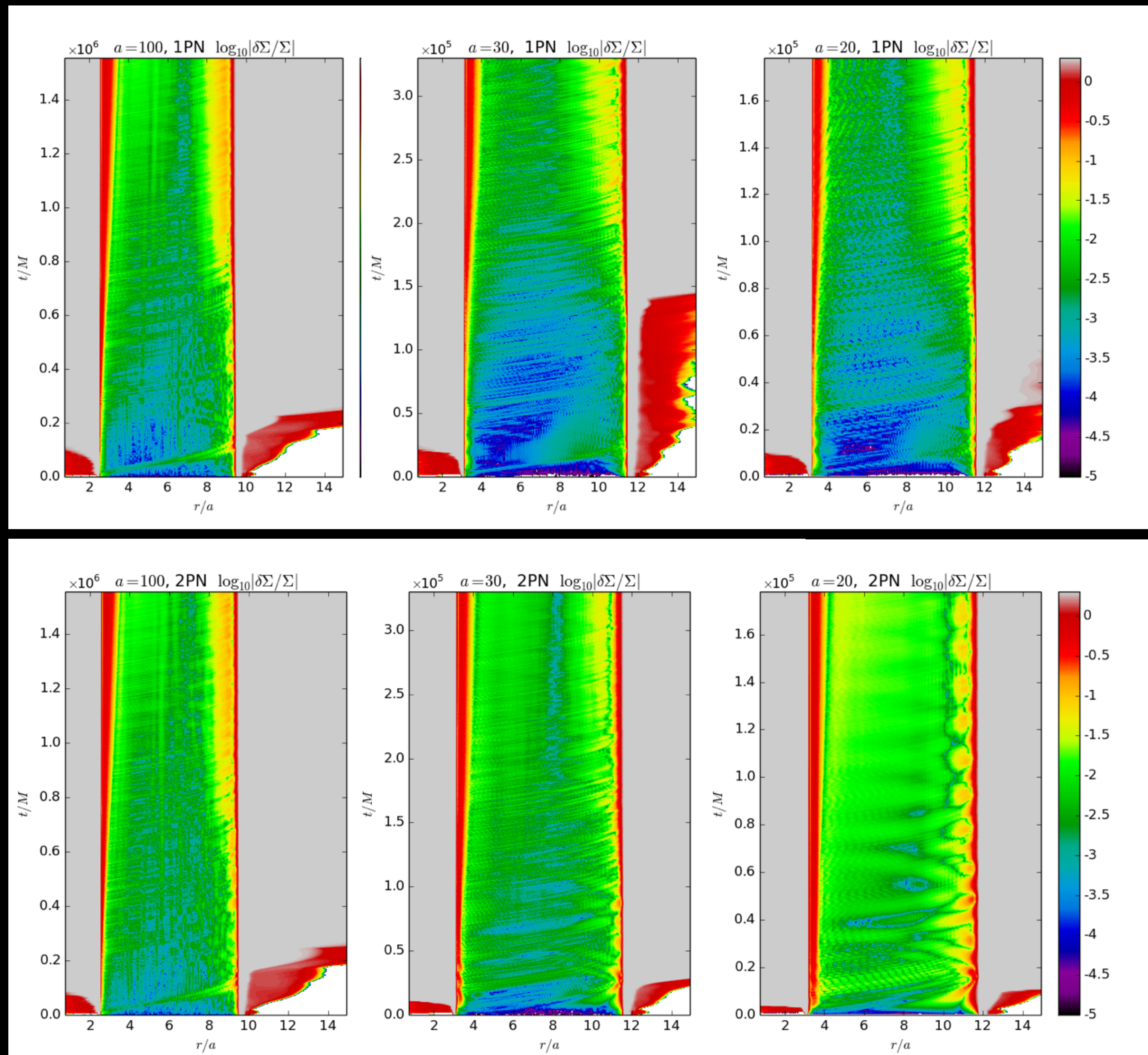
Implies that ~20M is a good starting point for our runs with the 2.5PN spacetime, but 1.5PN is valid for larger separations.

Differences seen between PN orders are because circular orbits are less stable in the 2.5PN spacetime and its higher-order terms result in a greater gravitational torque on the gas;

a = 100M **30M** **20M**

1.5 PN

2.5 PN



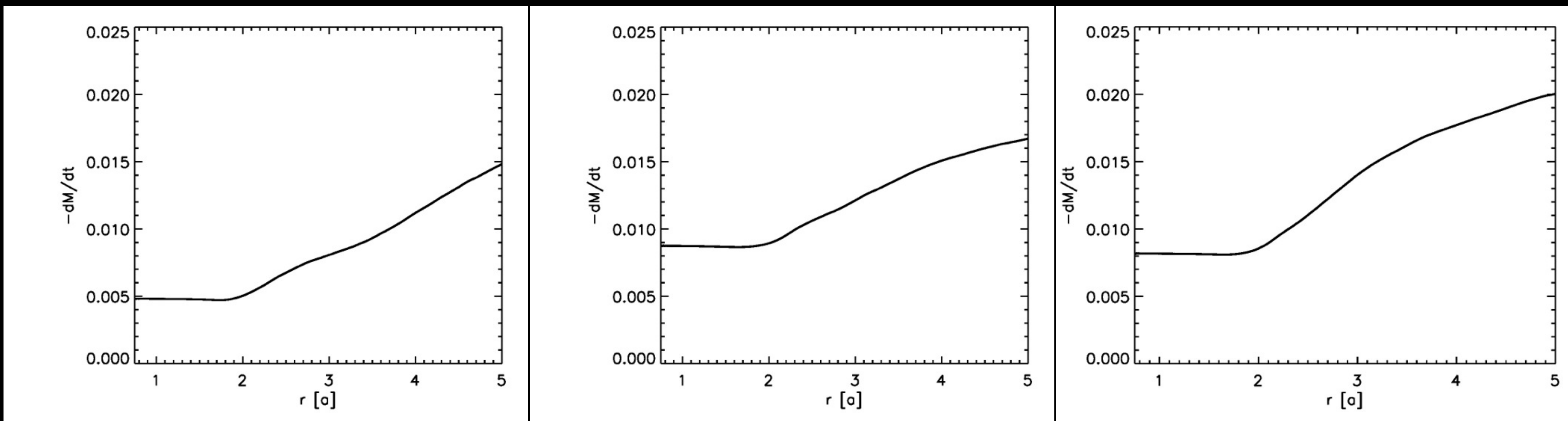
MHD Response to PN-Order and Binary Separation

Zilhao++2015

- Turn off highest order PN terms in metric and use the "same" matter initial data;
- Initial Data = Pressure+Rotation Equilibrium;
  - —> Disk = Disk(g_{ab})
  - —> Disk(g_{ab}[2.5PN]) != Disk(g_{ab}[1.5PN])
- Use two strategies for 1.5PN disk:
  - Disk1: Use *same* orbital parameters as 2.5PN disk, though it has *different* H/R;
  - Disk2: Use *different* orbital parameters as 2.5PN disk, so that disk has *same* H/R;

Variability vs. Post-Newtonian Accuracy:

1.5PN (Disk1)	1.5PN (Disk2)	2.5PN (Original)



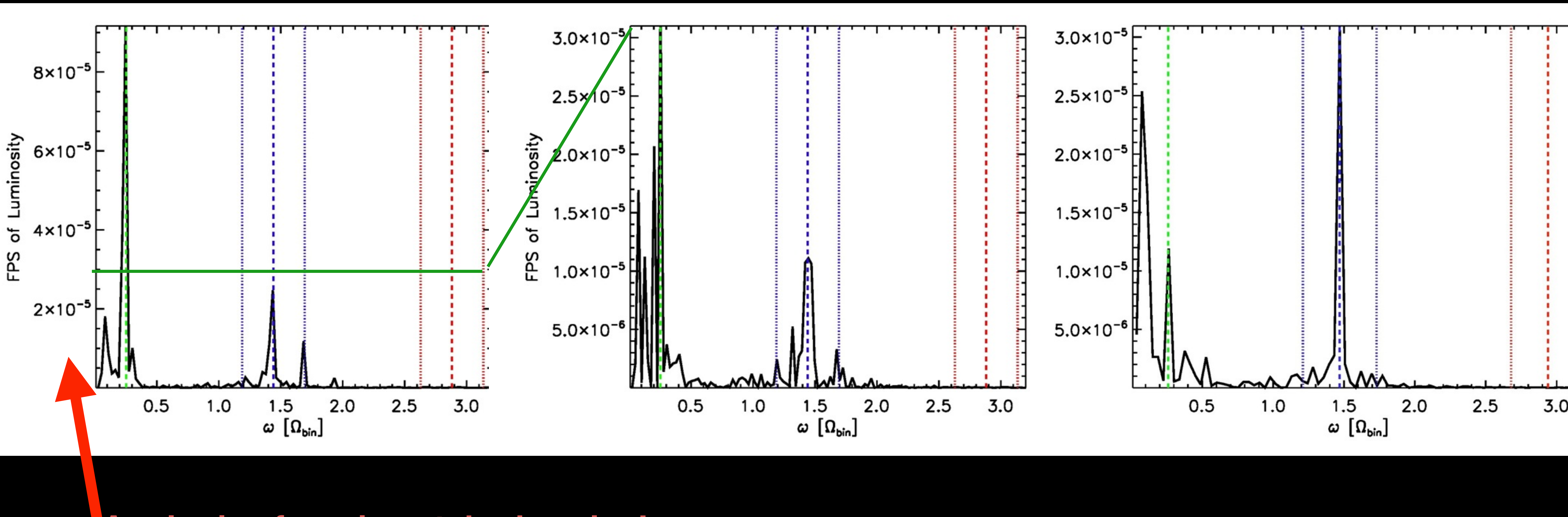
Less accurate metrics result in:

- Fraction of accretion rate through "gap" is approximately the same;
- All other runs we have done also show significant "leakage" rates;

Zilhao++2015

Variabality vs. Post-Newtonian Accuracy:

1.5PN (Disk1) | 1.5PN (Disk2) | 2.5PN (Original)



Apologies for mismatched scales!

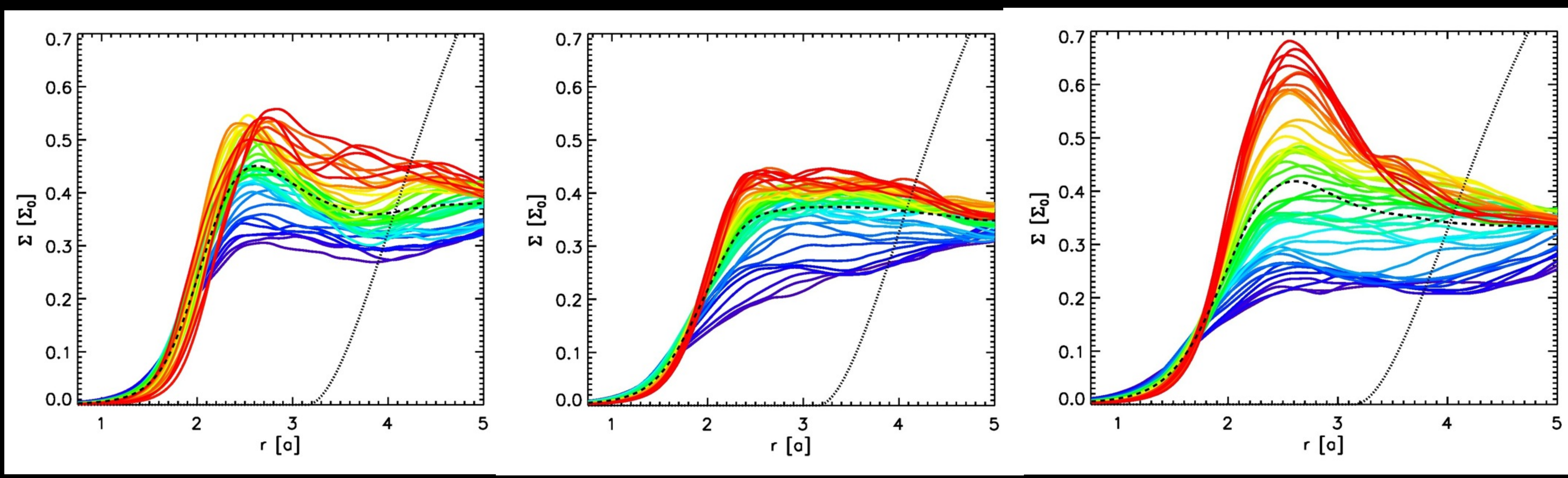
Less accurate metrics result in:

- Stronger variability at lump's orbital frequency, similar power at beat freq.;
- Power at beat frequency spread to larger range of frequencies;
- More complex lump/binary modulation;

Zilhao++2015

Variabality vs. Post-Newtonian Accuracy:

1.5PN (Disk1) | 1.5PN (Disk2) | 2.5PN (Original)



Early Times —> Late Times

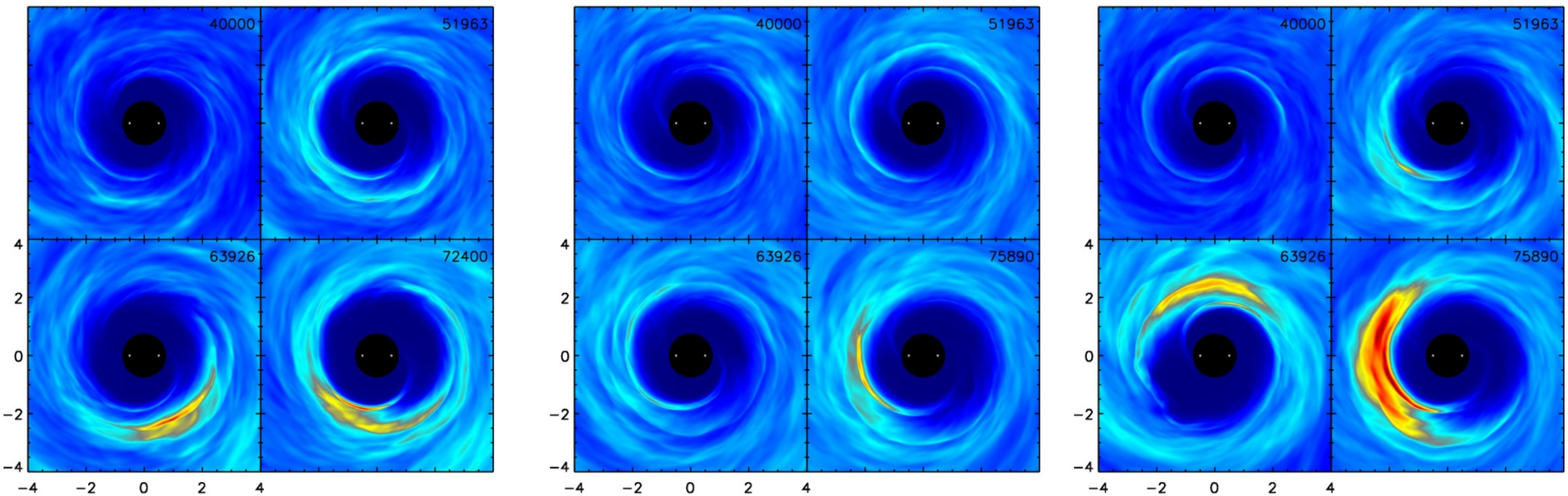
Less accurate metrics result in:

- Weaker build-up at gap's edge;
- Less secular evolution of edge's peak density;

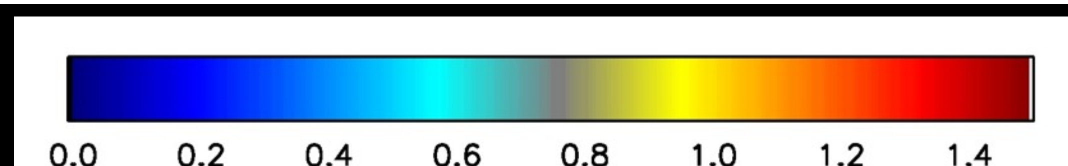
Zilhao++2015

Variabality vs. Post-Newtonian Accuracy:

1.5PN (Disk1) | 1.5PN (Disk2) | 2.5PN (Original)



Top-down view of Surface Density



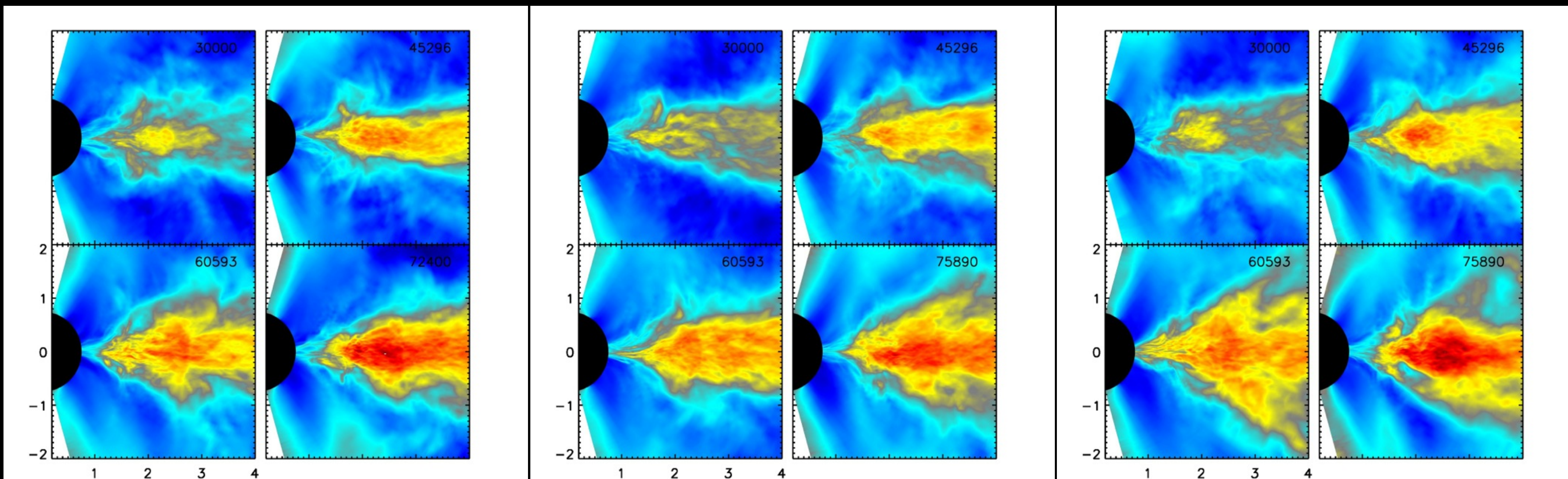
Less accurate metrics result in:

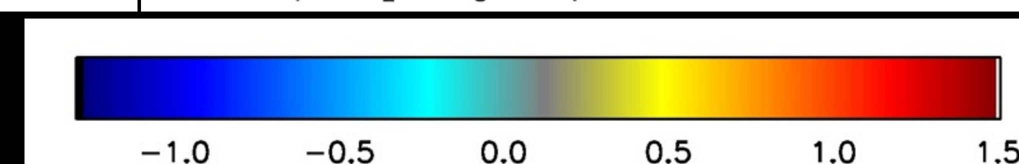
- Slightly weaker m=1 mode or over-density feature;
- Likely explains the weaker role of the beat mode in the power spectrum;

Zilhao++2015

Variabality vs. Post-Newtonian Accuracy:

1.5PN (Disk1)	1.5PN (Disk2)	2.5PN (Original)





Side view of Beta = P_{gas} / P_{mag}

Zilhao++2015

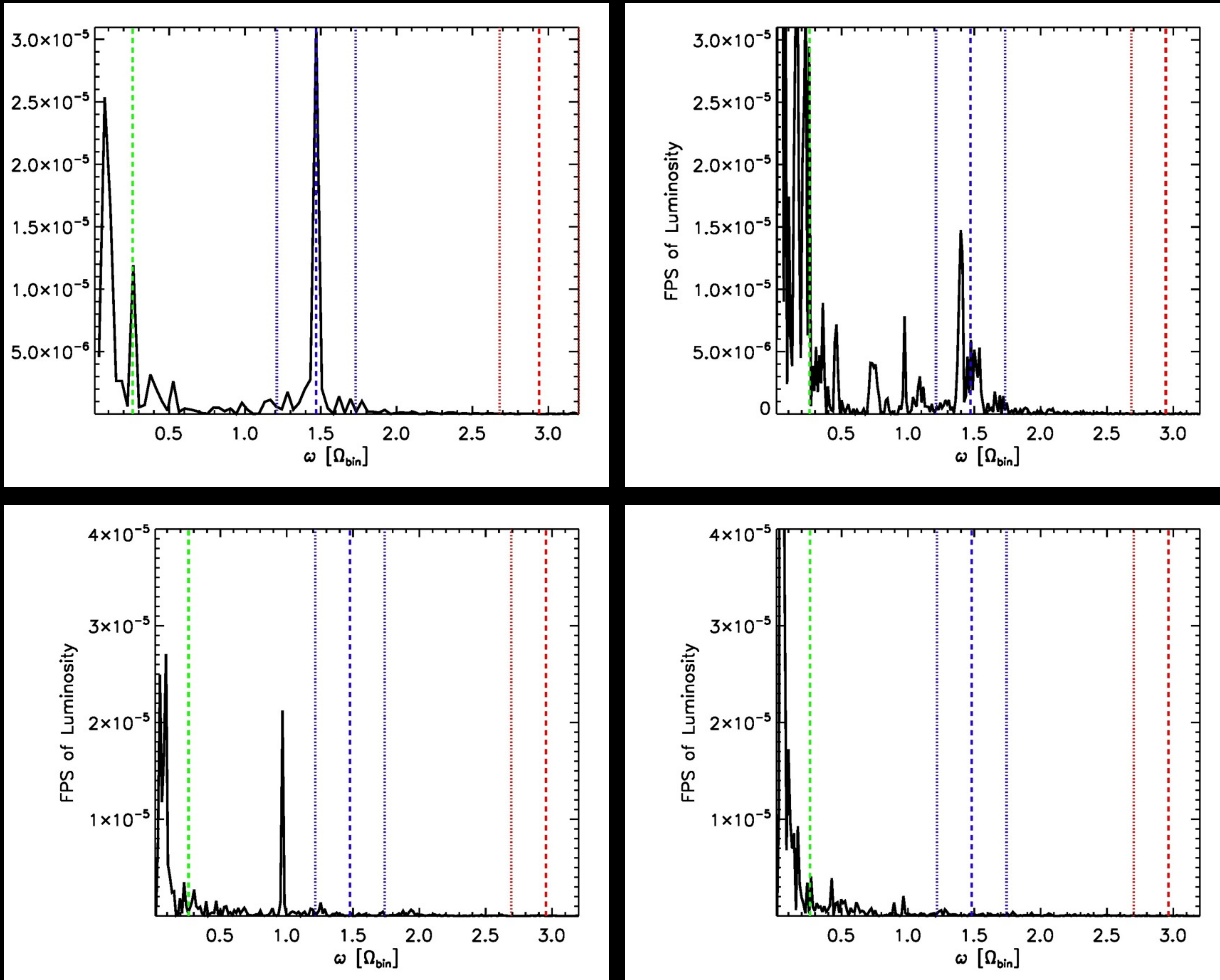
Less accurate metrics result in:

- Slightly less loss of magnetization;
- Possibly due to weaker torque, less dissipation of field from flung out material;
  - Weak torques from "weaker" quadrupole potential;
- Note thicker disk leads to less loss of magnetization;

Mass Ratio

Noble++in-prep

q=1 q=2

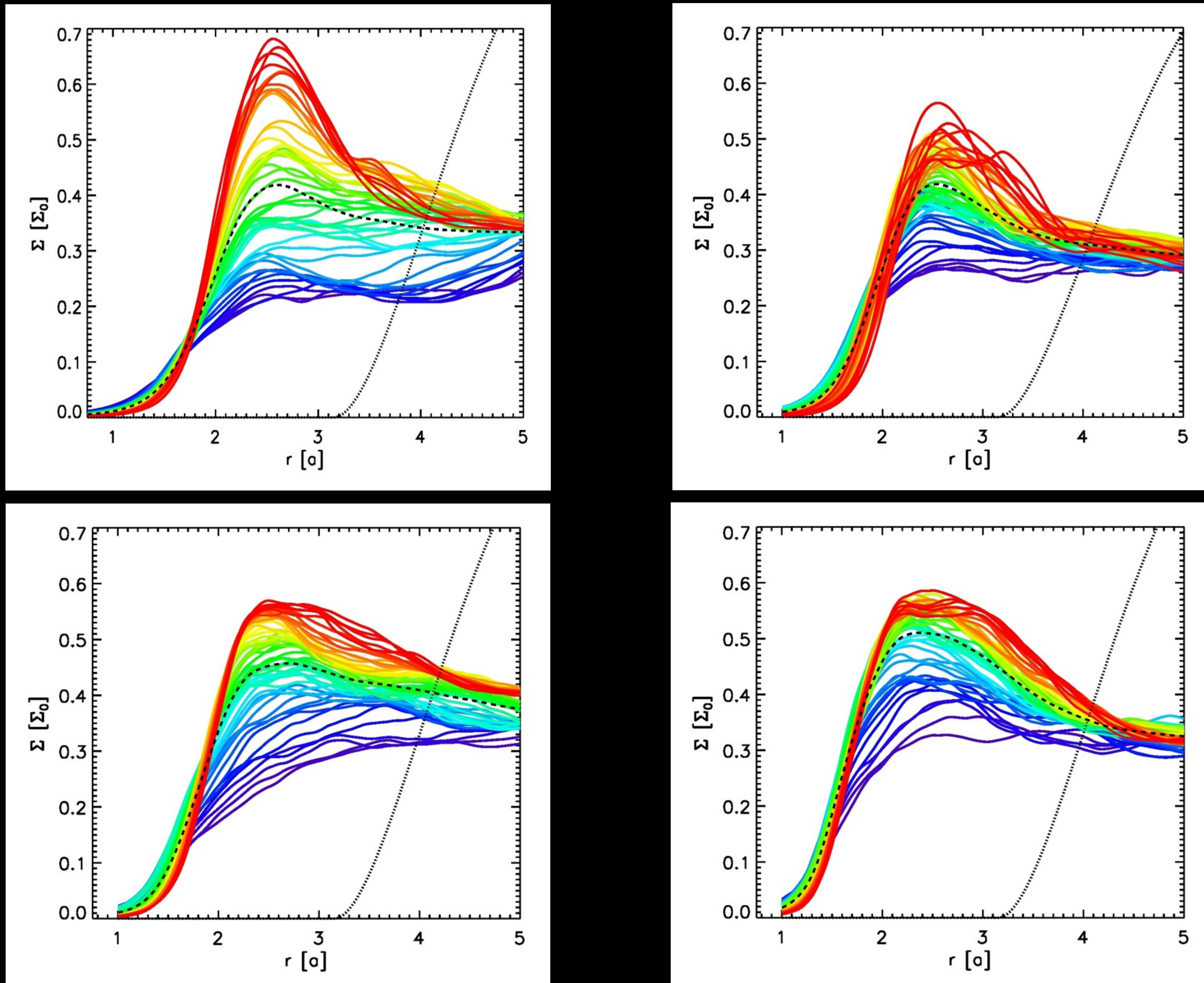


q=5 q=10

Mass Ratio

Noble++in-prep

q=1 q=2



q=5 q=10

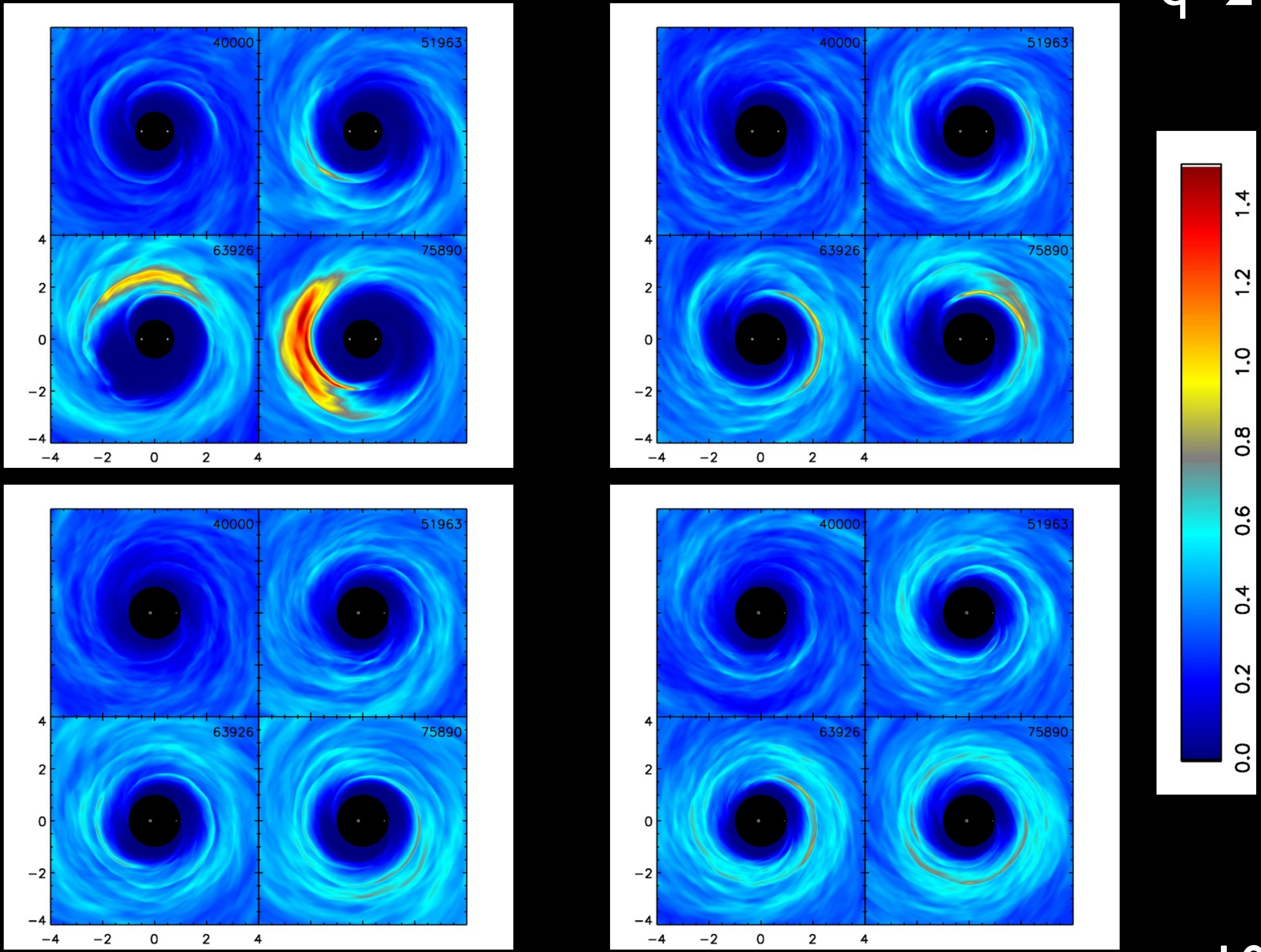
Early Times —> Late Times

Mass Ratio

Noble++in-prep

q=1

q=2



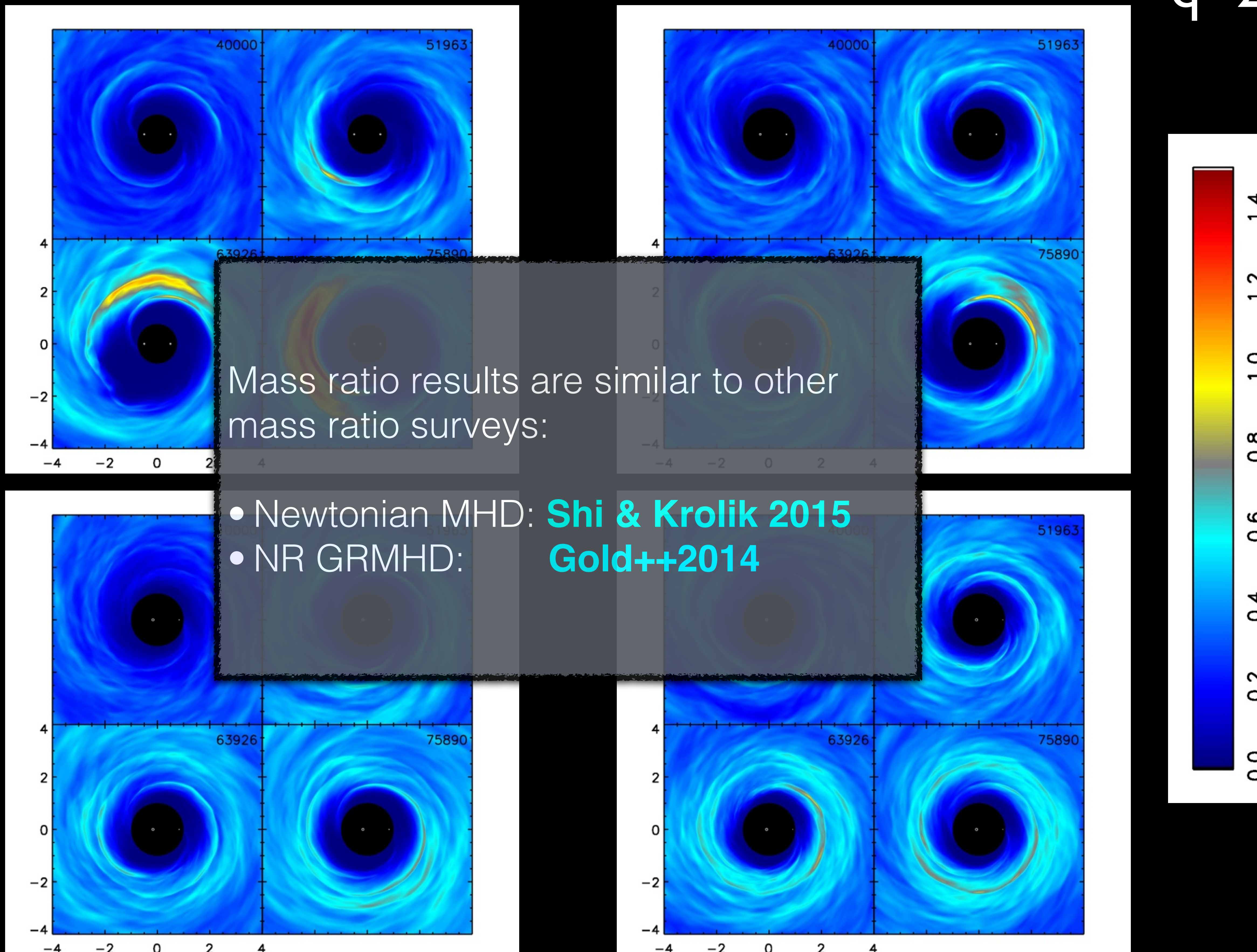
q=5

q=10

Top-down view of Surface Density

Mass Ratio

Noble++in-prep



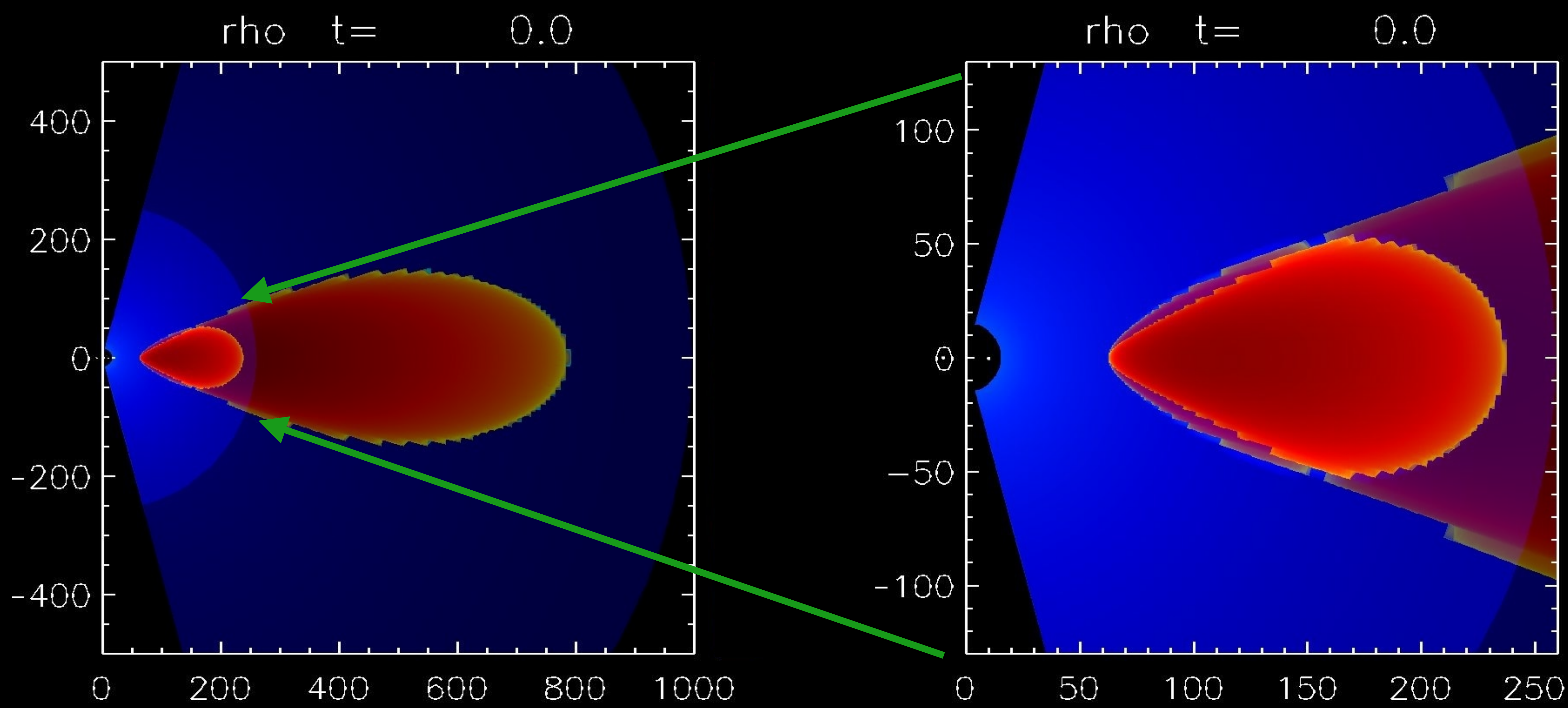
Mass ratio results are similar to other mass ratio surveys:

- Newtonian MHD: **Shi & Krolik 2015**
- NR GRMHD: **Gold++2014**

Top-down view of Surface Density

Disk's State

Noble++in-prep

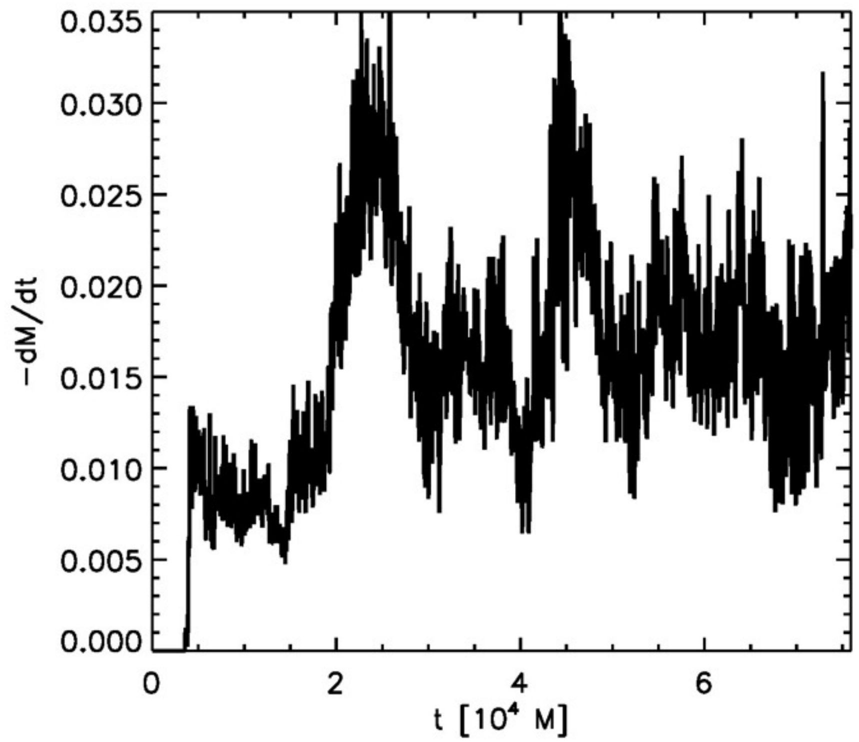


- Bigger disk:
  - "Center" moved from 5a to ~6a;
  - Large extent increases reservoir of magnetic flux and mass;
- Injected flux:
  - Magnetic flux from t=0 added to late-time snapshot of original run;
  - Net "vertical flux" can amplify other components and MRI;
  - Increases local magnetic energy density by only a few percent;

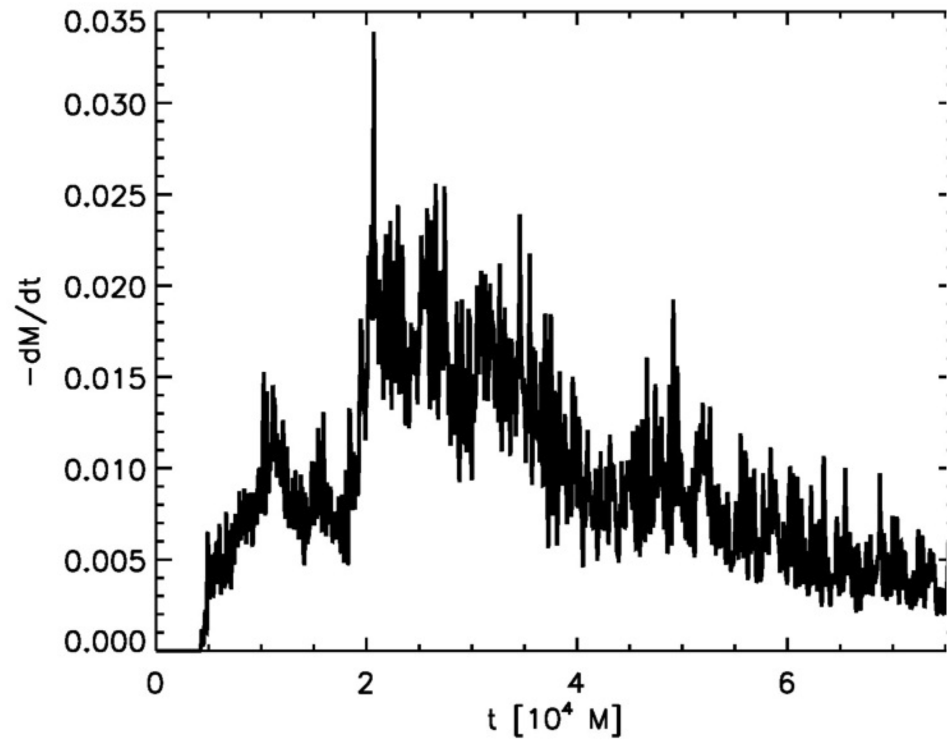
Disk’s State

Noble++in-prep

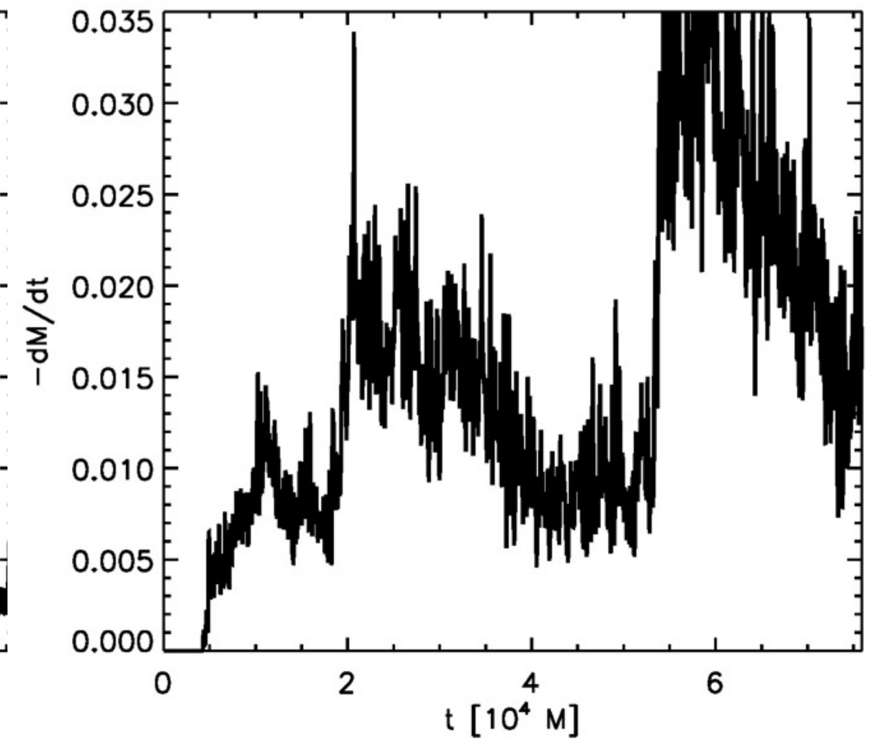
Bigger Disk



Original



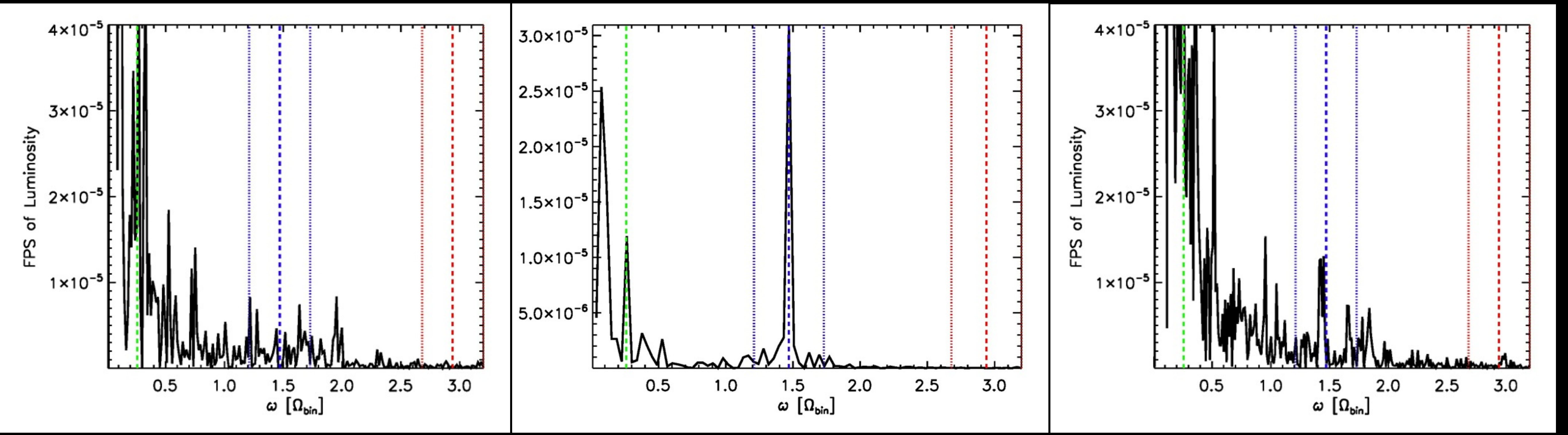
Flux-Injected



- Bigger disks achieve steady accretion for longer and at higher levels;
- Injected flux able to “reignite” accretion—-forcing existing material to accrete;
  - Side effect: drains the available mass faster;
  - Common model for state transitions often seen in galactic binaries;

Disk's State
Noble++in-prep

Bigger Disk | Original | Flux-Injected



Again, please note different scales

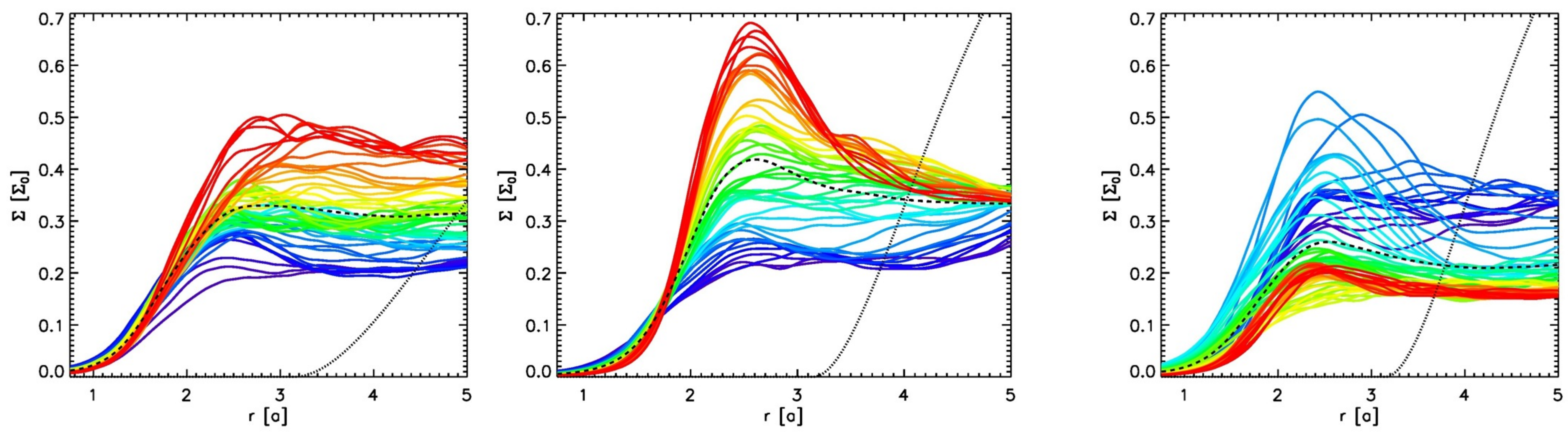
More magnetic flux led to:

- Less coherent temporal power spectrum;
- Spectra resembling more a slightly bent power law;
- Spectra resembling more spectra from simulations of single black hole disks;
- Is there no over-density?

Disk's State

Noble++in-prep

Bigger Disk | Original | Flux-Injected



Early Times —> Late Times

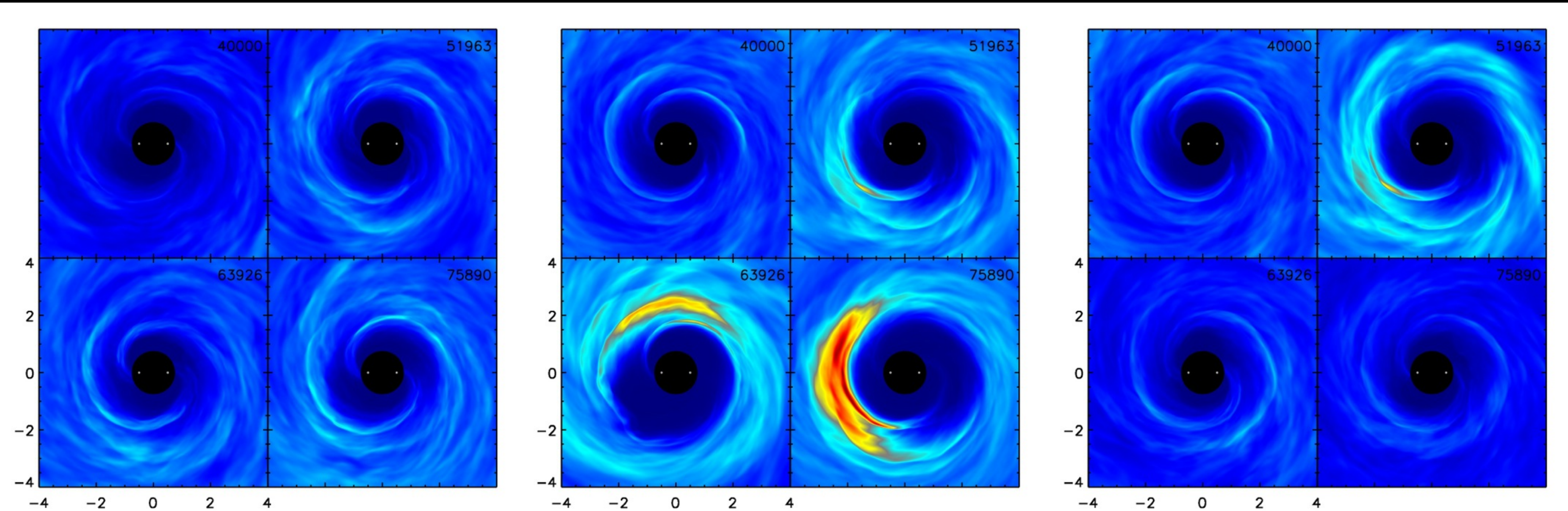
<u>More magnetic flux led to:</u>

- Less pile-up at the inner edge of the gap;
- Material flowed more easily through to binary;
- Therefore, less material for binary to "beat" against;

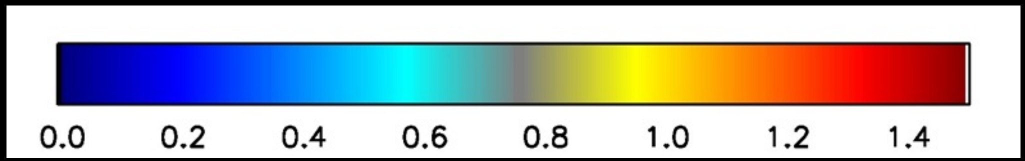
Disk's State

Noble++in-prep

Bigger Disk | Original | Flux-Injected



Top-down view of Surface Density



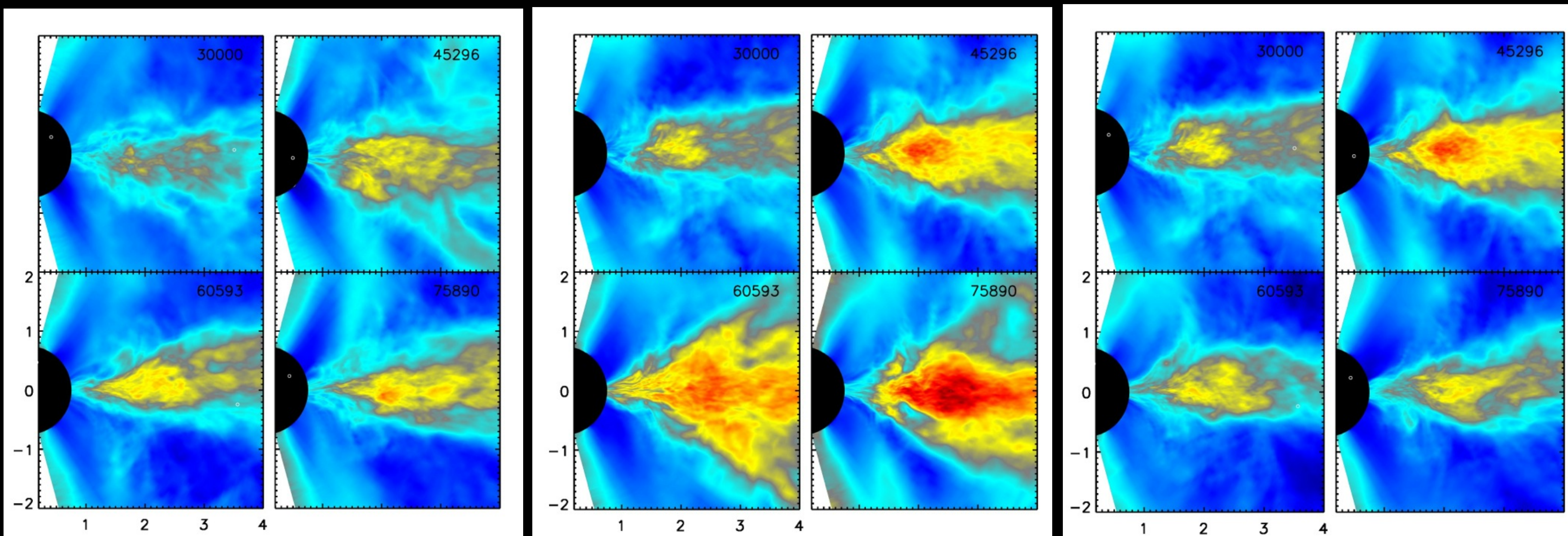
More magnetic flux led to:

- Much weaker m=1 mode, if any.
- Therefore, no means of developing coherent beat;
- Fluctuations arise just from turbulence;

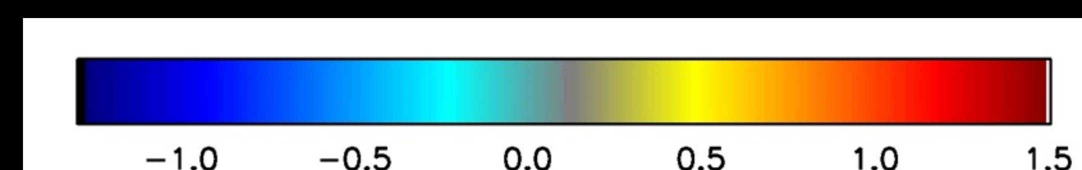
Disk's State

Noble++in-prep

Bigger Disk | Original | Flux-Injected



Side view of Beta = P_{gas} / P_{mag}

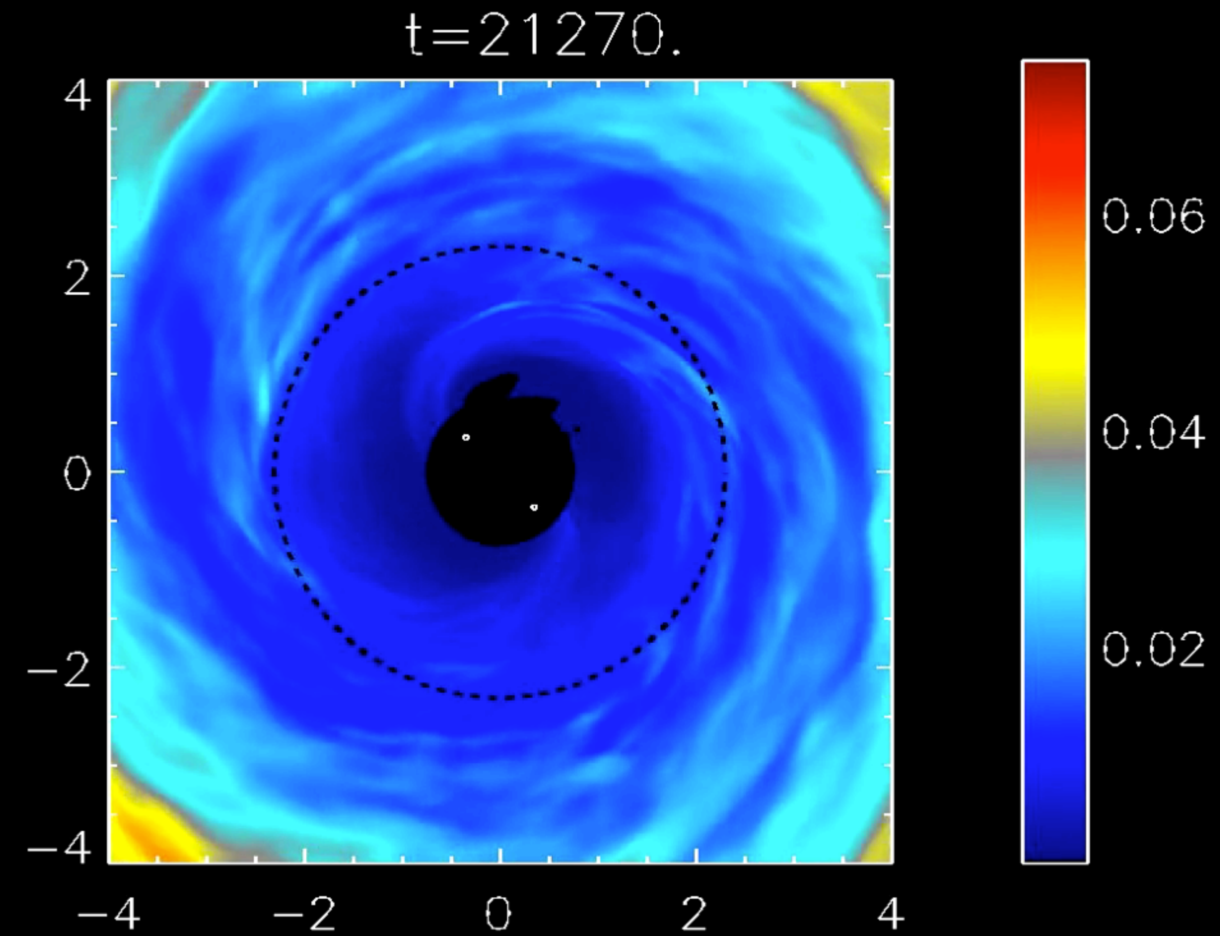


- Injected flux led to sustained magnetization throughout over-density region;
- Larger reservoir of flux and mass seems to hinder development of the lump;

Summary & Conclusions

- Our 3-d MHD simulations in the PN-regime develop a high-Q signal that is non-trivially connected to the binary's orbit;
- We have unexpectedly seen how MHD dynamics can affect the quality of this signal and quash the development of the overdensity;
- At a separation of 20M, with equal-mass binaries, differences in the metric at 1.5PN and 2.5PN orders are insignificant compared to stochastic error;
- The PN-accuracy effects will likely be even smaller for smaller mass ratios;
- Overdensity and the "beat signal" disappear somewhere $2 < q < 5$;
- No coherent signal of any kind seen at $q=10$;

Surface Density



Log Emissivity