3-D GRMHD Simulations of Accreting Binary Black Holes

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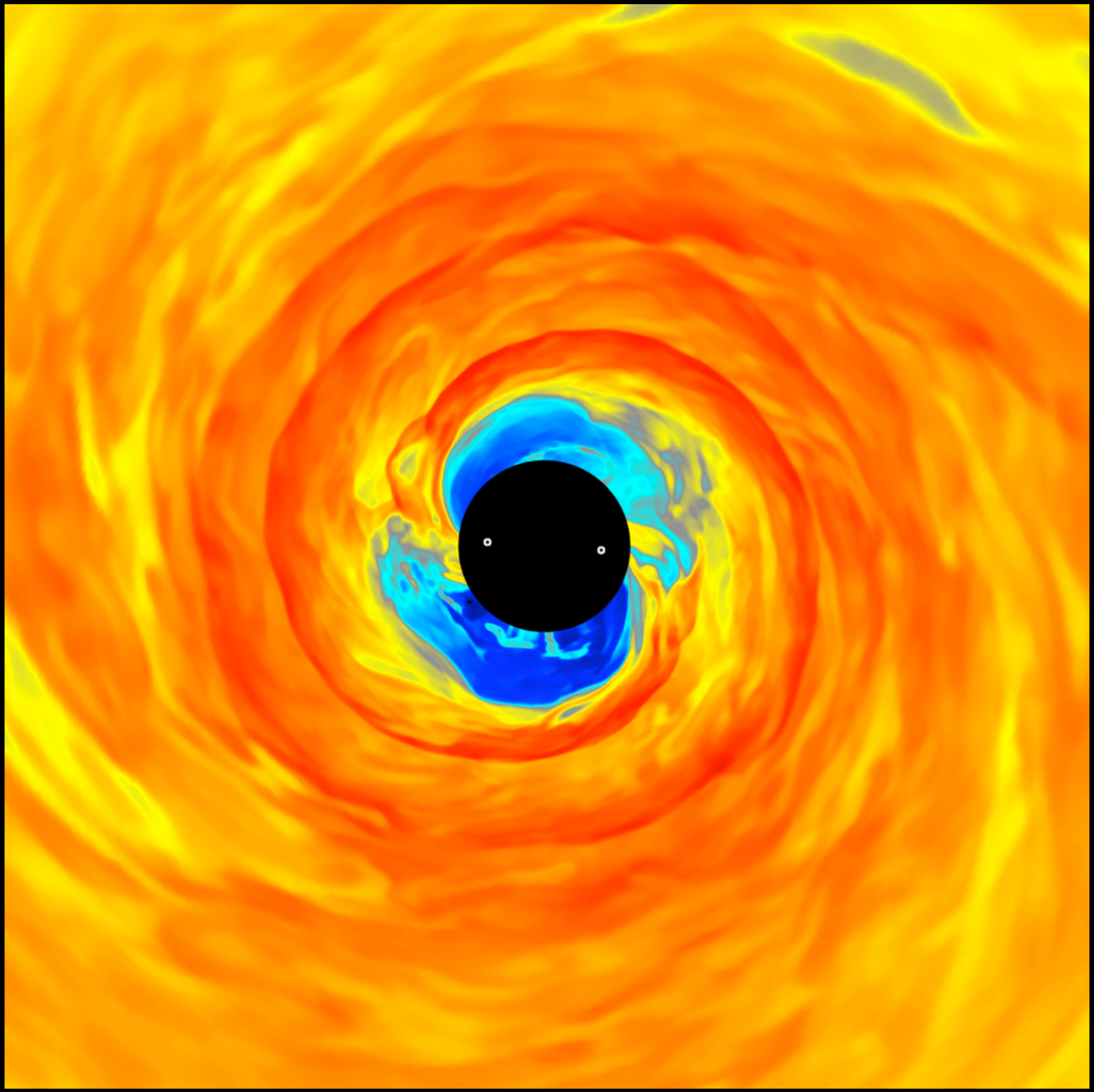

Based on:

- Noble++2012
- Zilhao & Noble 2014
- Zilhao++2015 (in press, PRD)
- Noble++in-prep

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"Black Holes in Dense Star Clusters" — Aspen — Winter — 2015

Motivation

Rare Events

+

Degeneracy of Interpretations

More Data
(Pan-STARRS, LSST, ZST, PST…)

+

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

Motivation

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

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

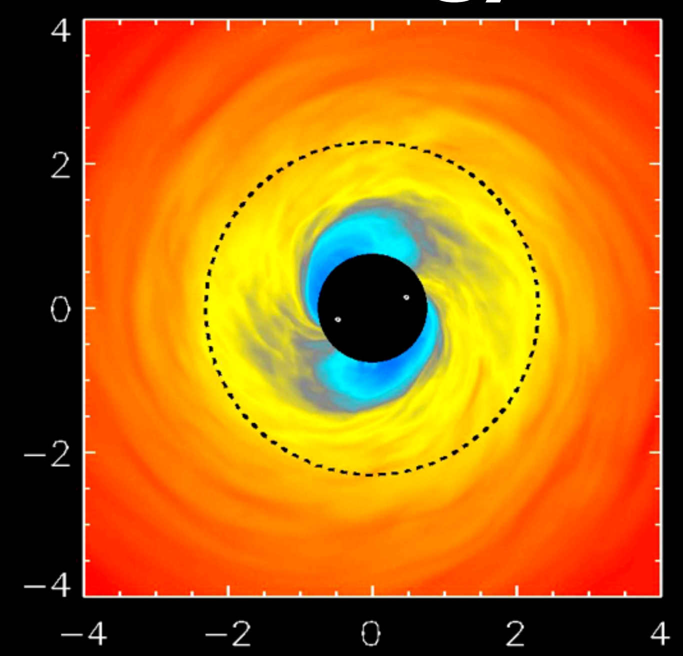
- Vertical, 3-d structure can only include dynamics of buoyancy;
- Cowling's Thm: no sustained turbulence in 2-d;

- 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);

- 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

Farris++2011

Physical Time (not to scale)

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

Newtonian Gravity

Numerical Relativity

Post-Newtonian

Static GR

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

Harm3d

DATA

DATA

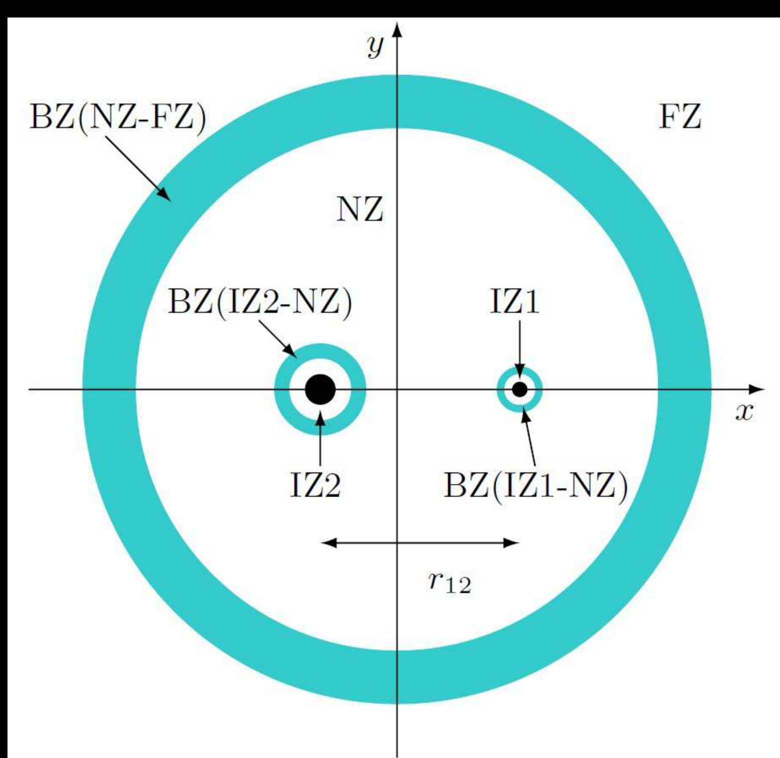
Harm3d

Approximate Two Black Hole Spacetimes

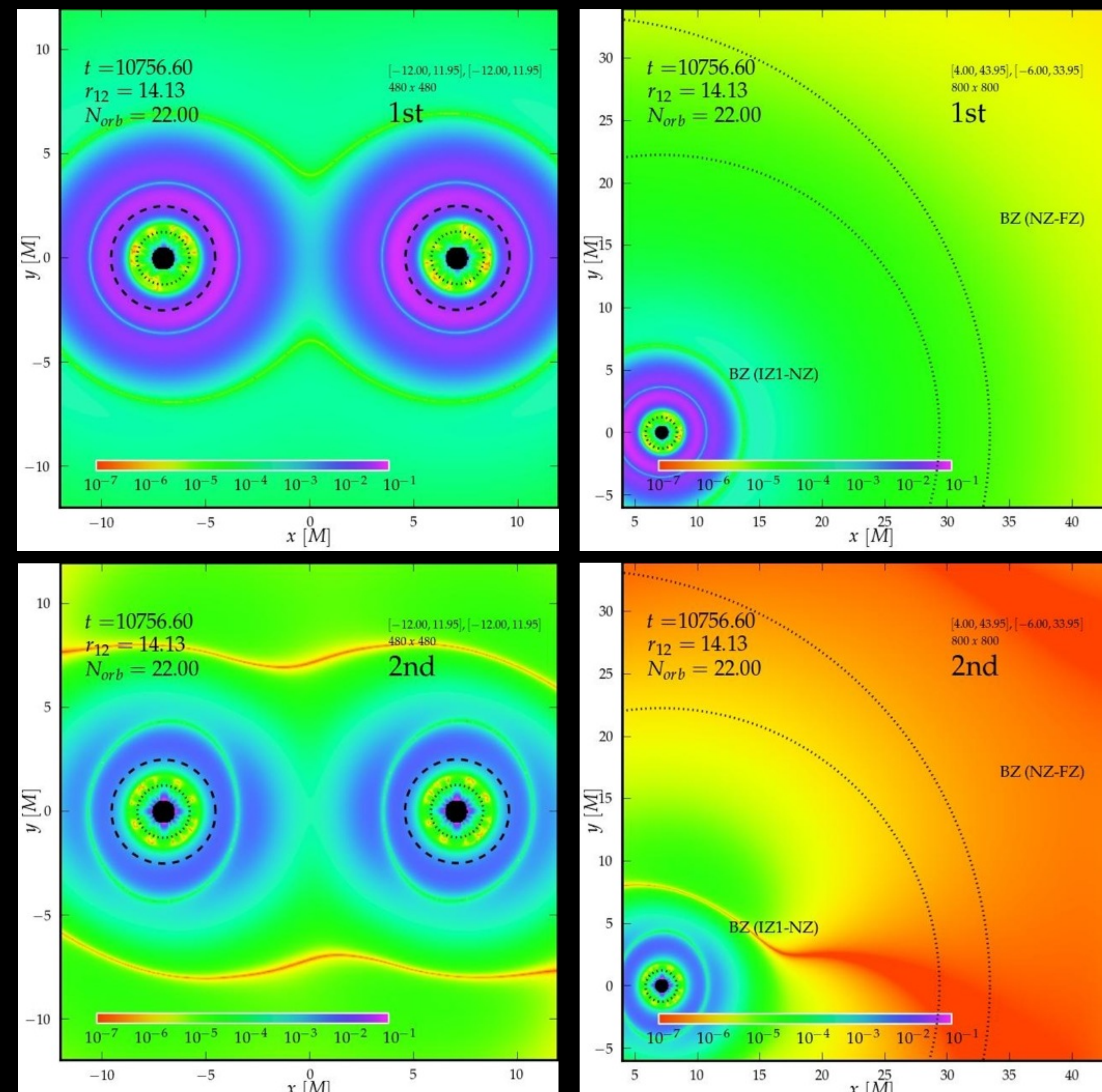
Yunes++2006, Noble++2012, Mundim++2014

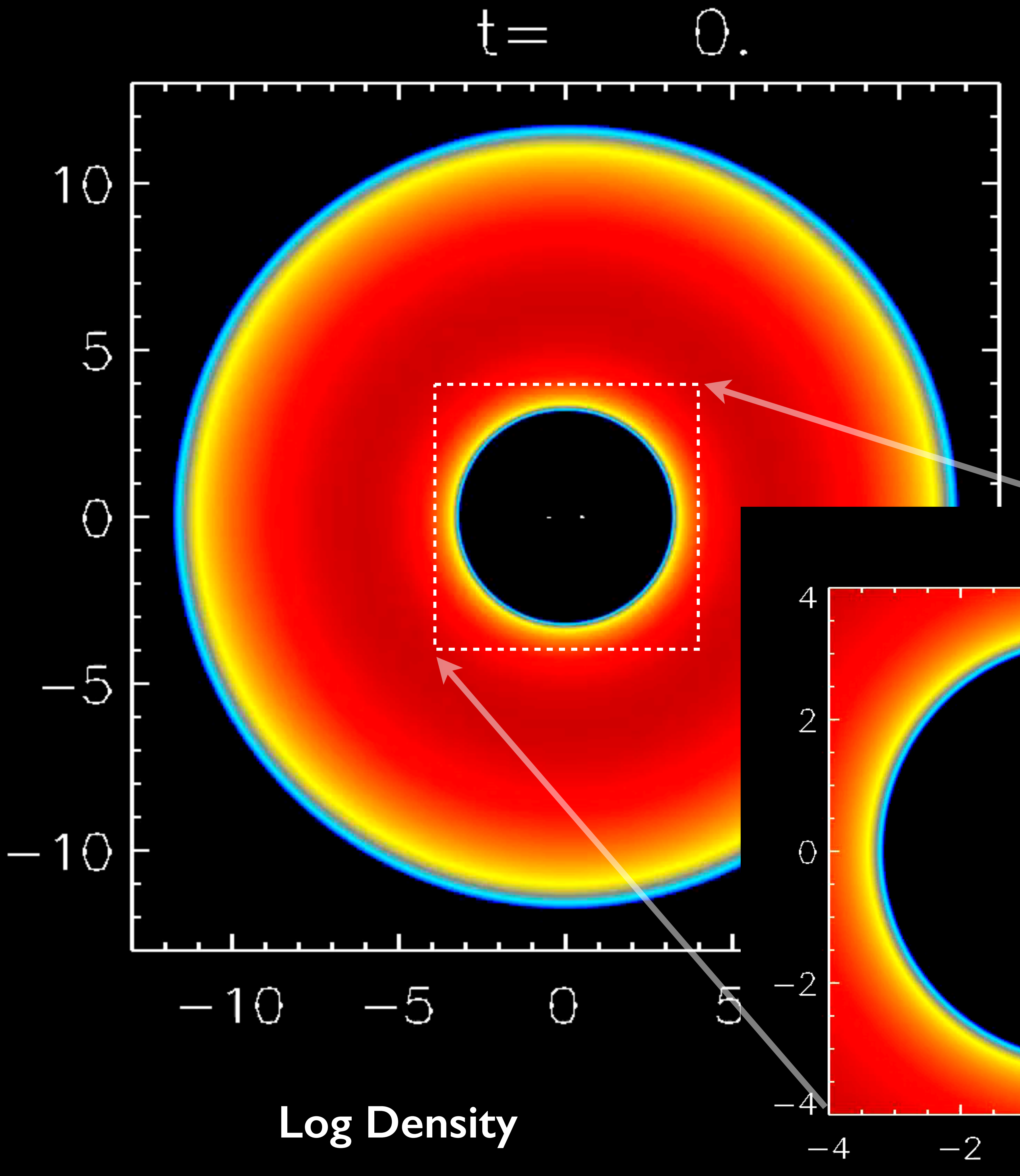
- Solve Einstein's Equations approximately, perturbatively to orders of 2.5 Post-Newtonian order;
- Used as initial data of Numerical Relativity simulations;
- Black hole orbits include radiation-reaction terms;
- BH event horizons are included!
- Closed-form expressions allow us to discretize the spatial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

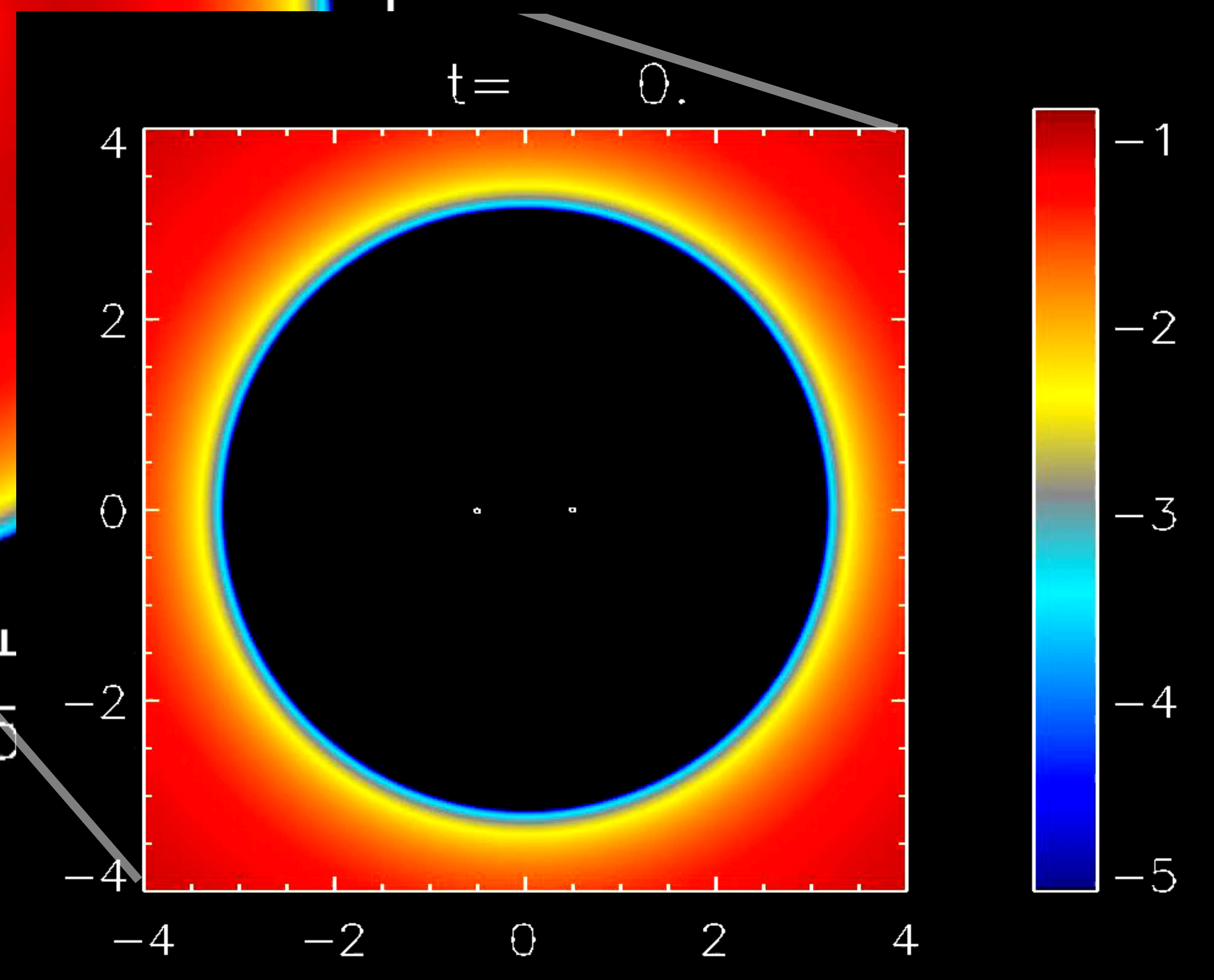
$$\epsilon_i = m_i / r_i \sim (v_i / c)^2$$



Ricci Scalar → 0







Log Density

- “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;

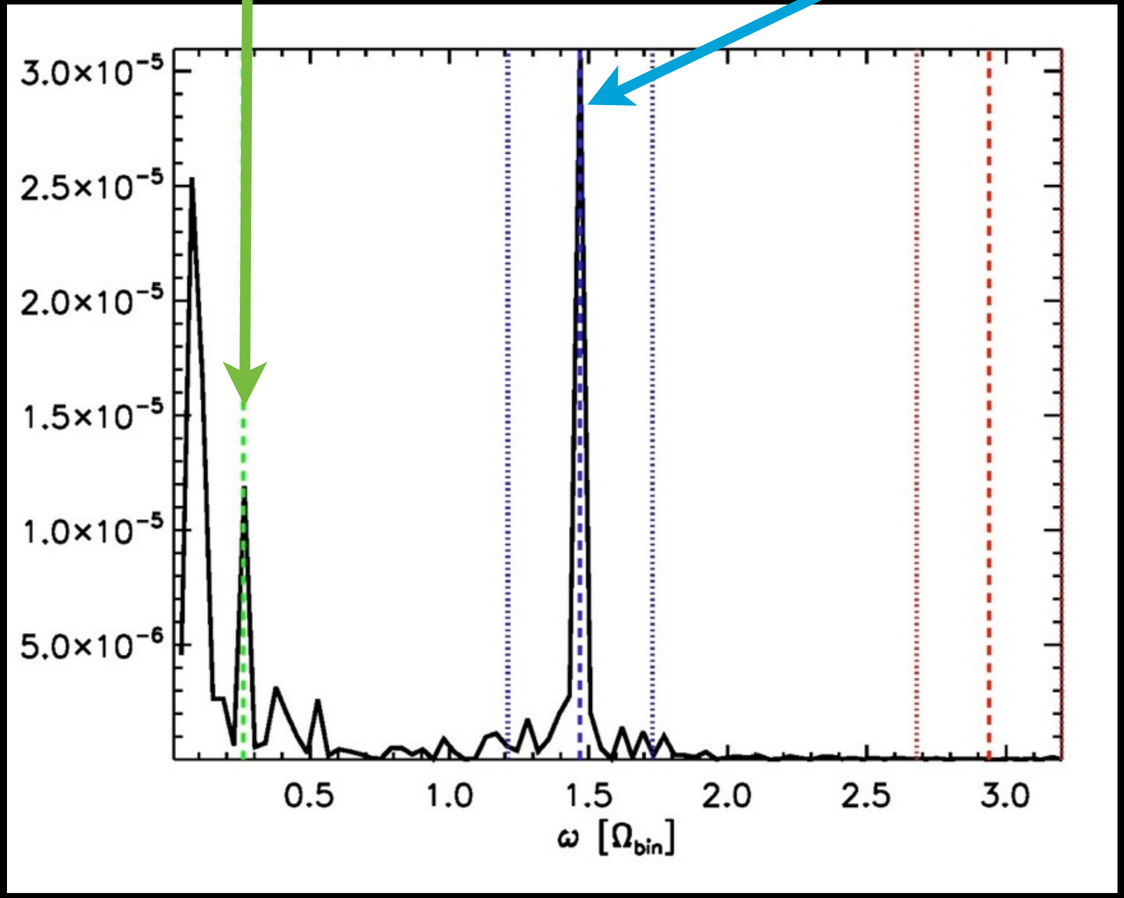
MHD Simulations with Unresolved BHs:

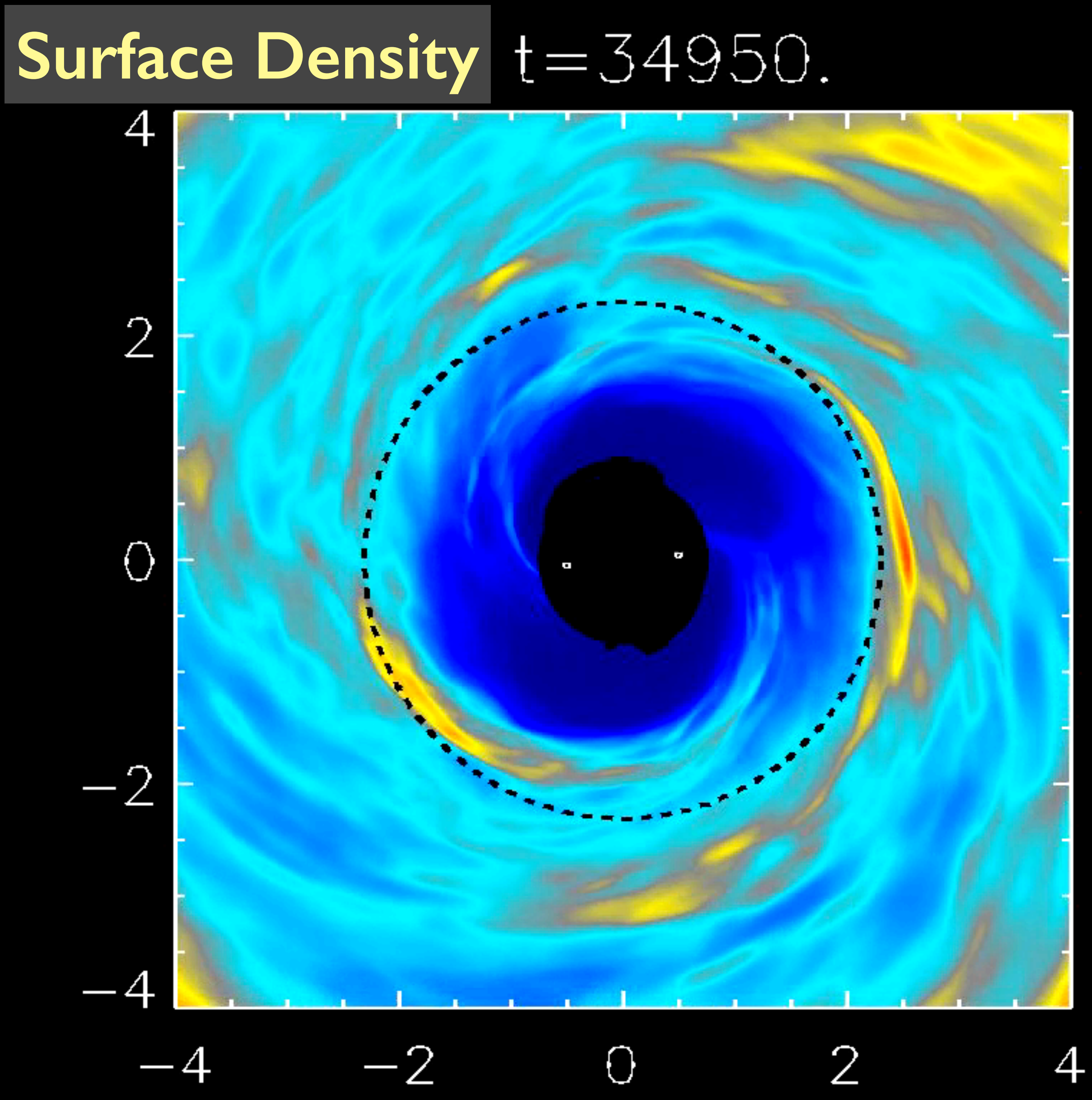
Noble++2012

Periodic Signal

$r_{\rm lump} \simeq 2.5a$
$\Omega_K(r_{\rm lump})$

$1.47\Omega_{\rm bin}$





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

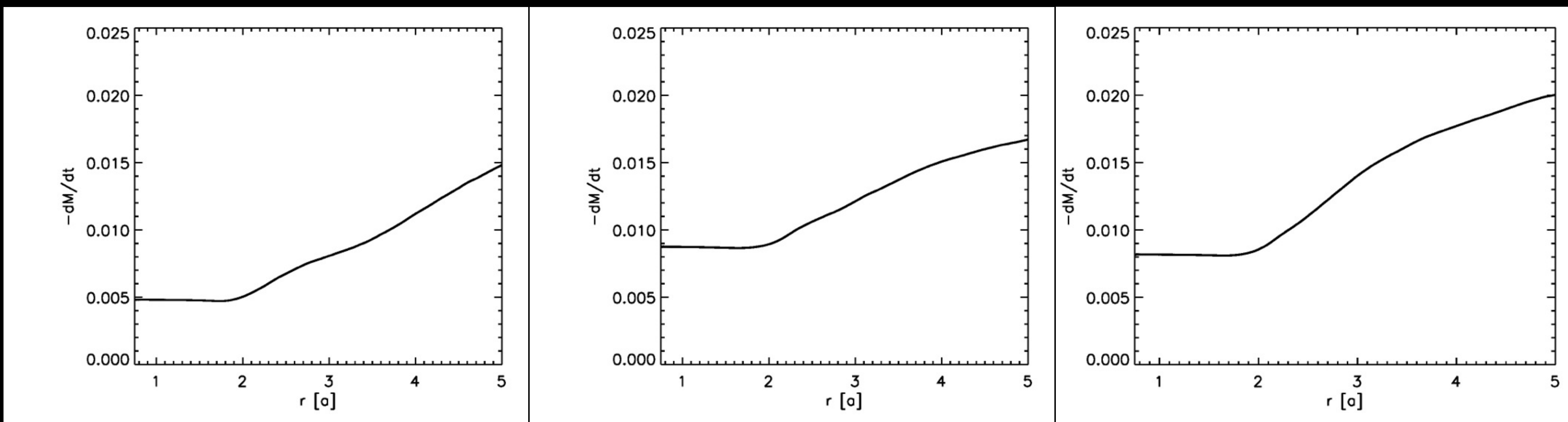
Accuracy of Gravity Model

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}[2PN]) != Disk(g_{ab}[1PN])
- Use two strategies for 1PN disk:
  - Disk1: Use *same* orbital parameters as 2PN disk, though it has *different* H/R;
  - Disk2: Use *different* orbital parameters as 2PN disk, so that disk has *same* H/R;

Variabality vs. Post-Newtonian Accuracy:

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



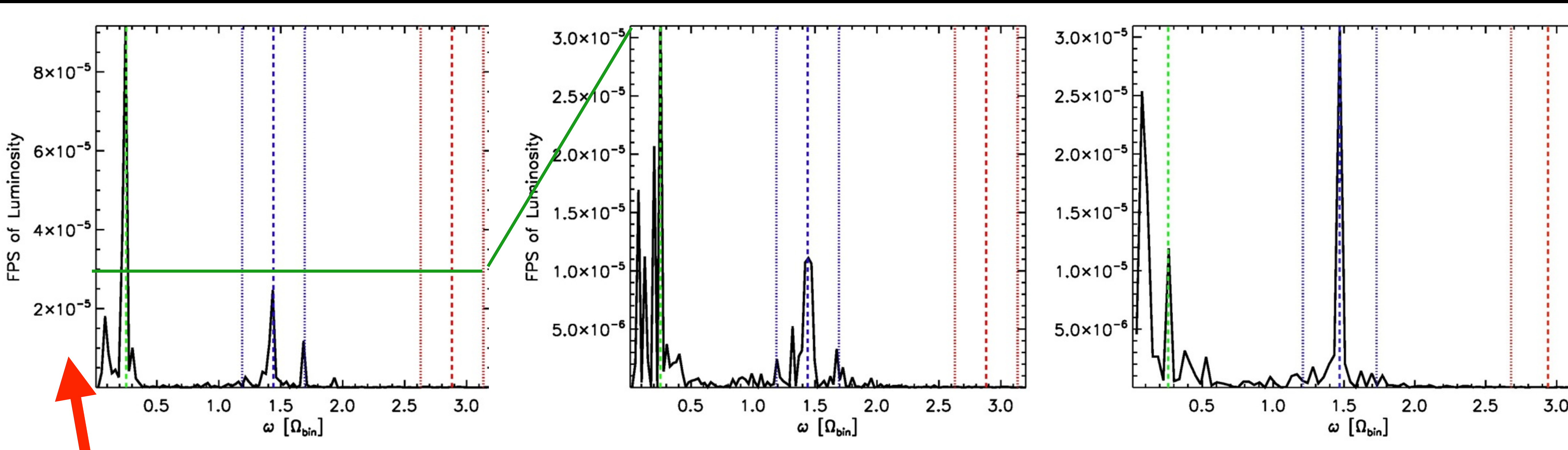
Less accurate metrics result in:

- 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!

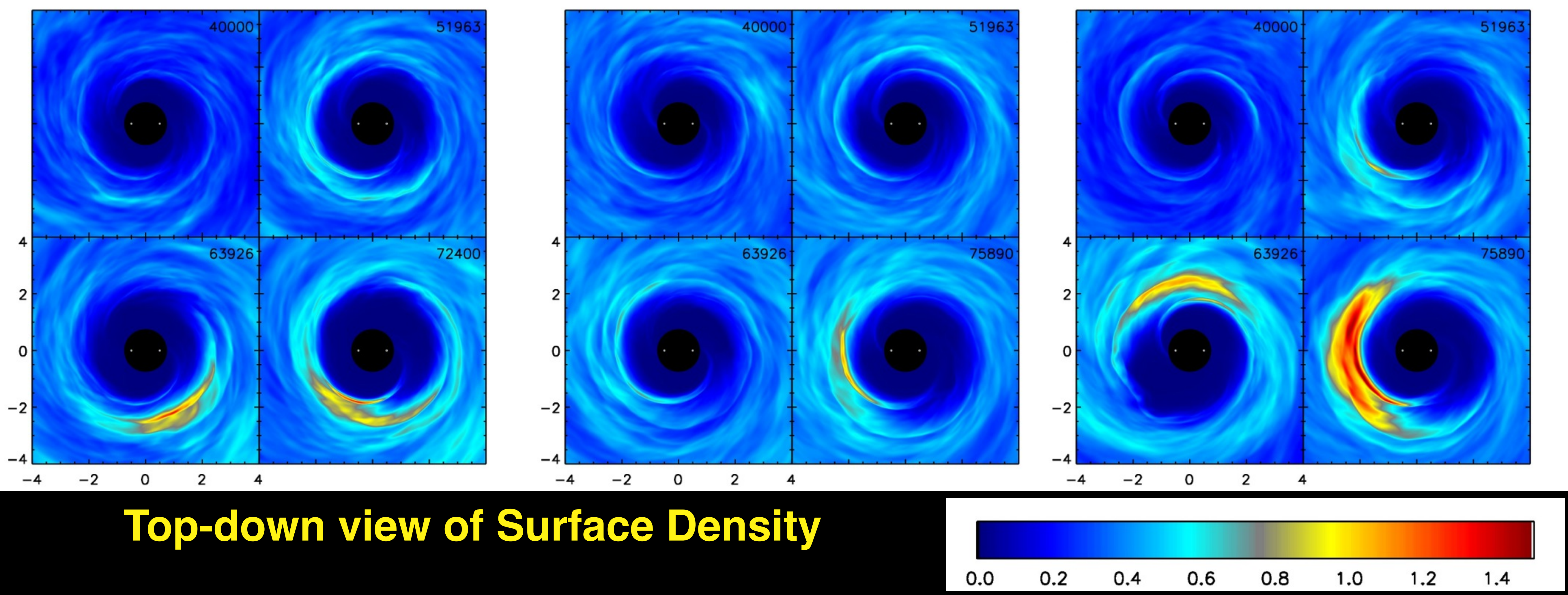
Less accurate metrics result in:

- Stronger variability at lump's orbital frequency;
- 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)



Top-down view of Surface Density

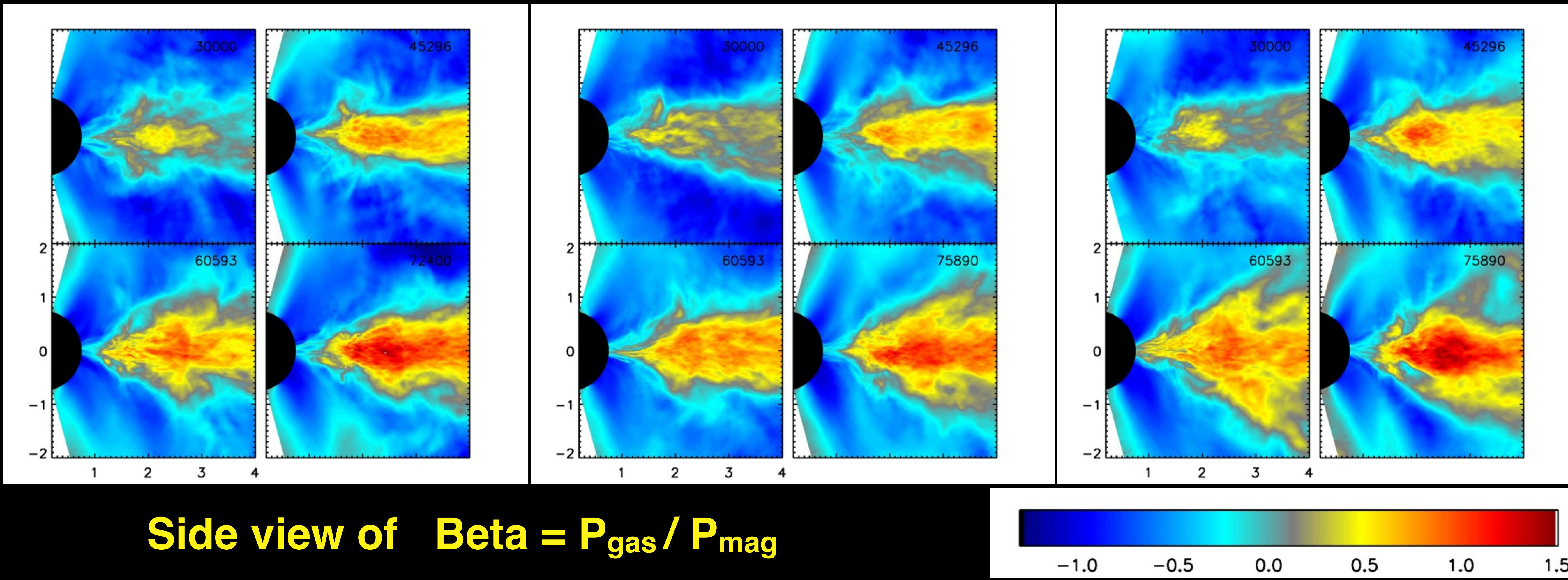
Less accurate metrics result in:

- Slightly weaker m=1 mode or over-density feature;
- Likely explains the increased power at the binary's orbital frequency;

Zilhao++2015

Variabality vs. Post-Newtonian Accuracy:

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



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

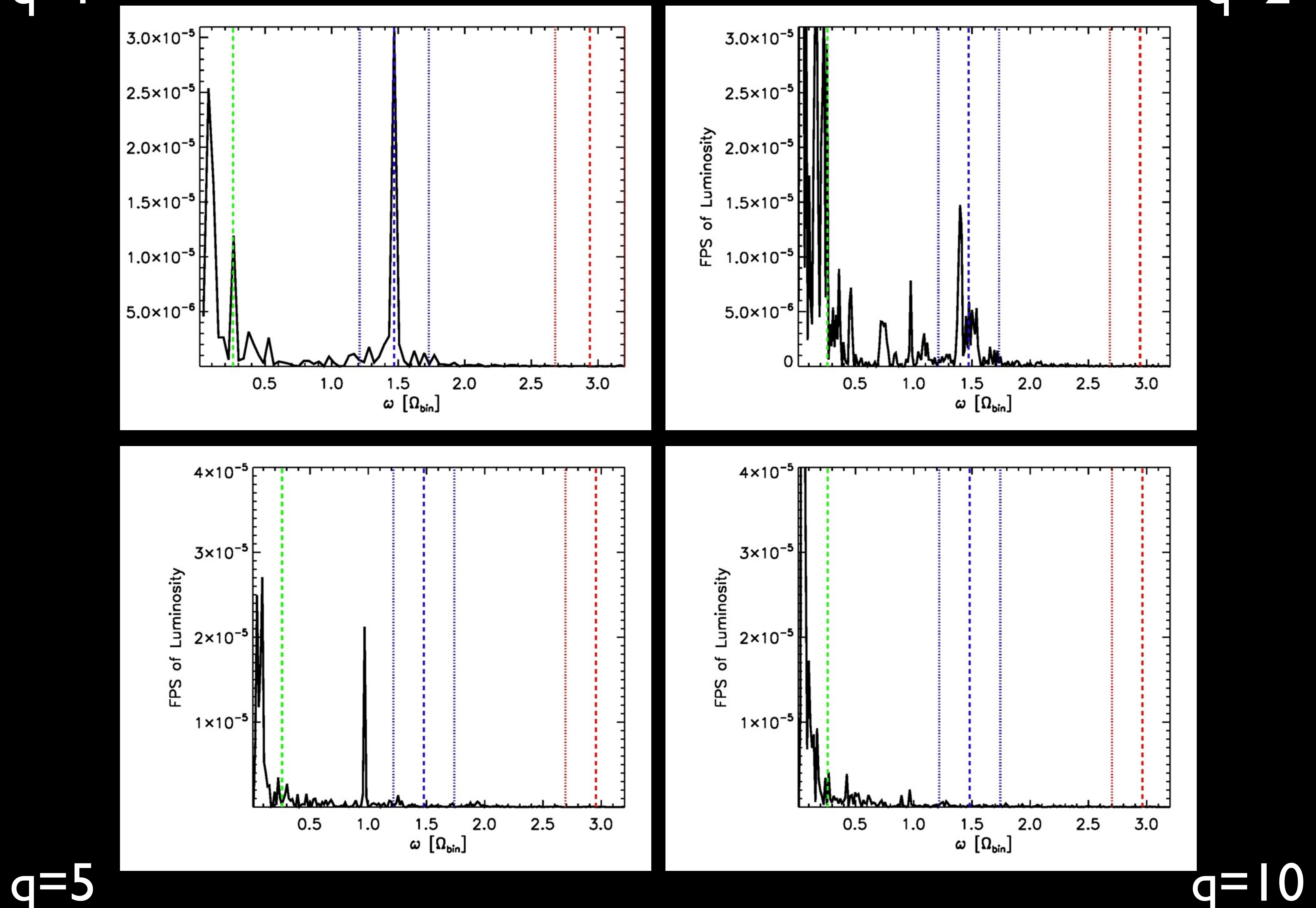
Zilhao++2015

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

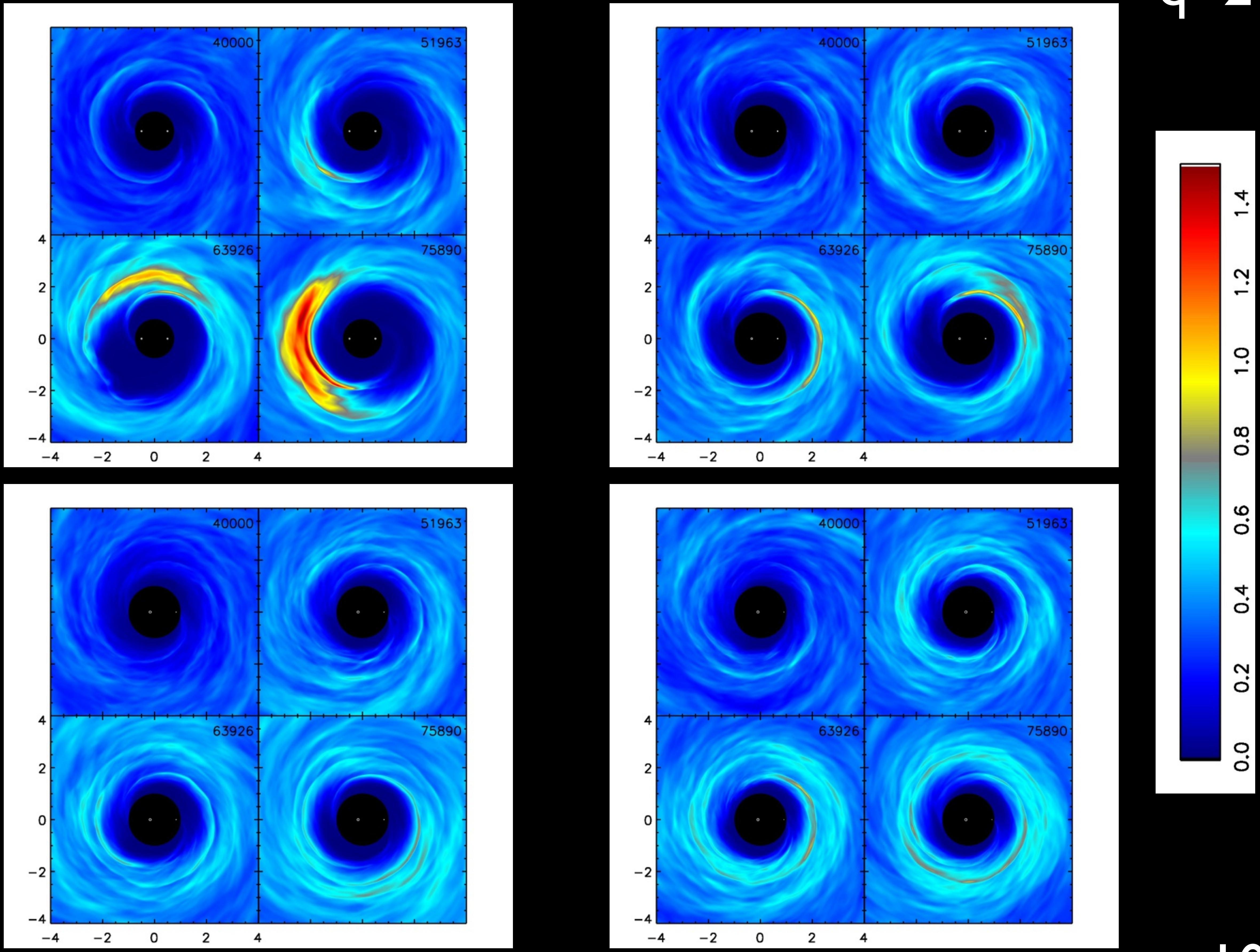


Mass Ratio

Noble++in-prep

q=1

q=2



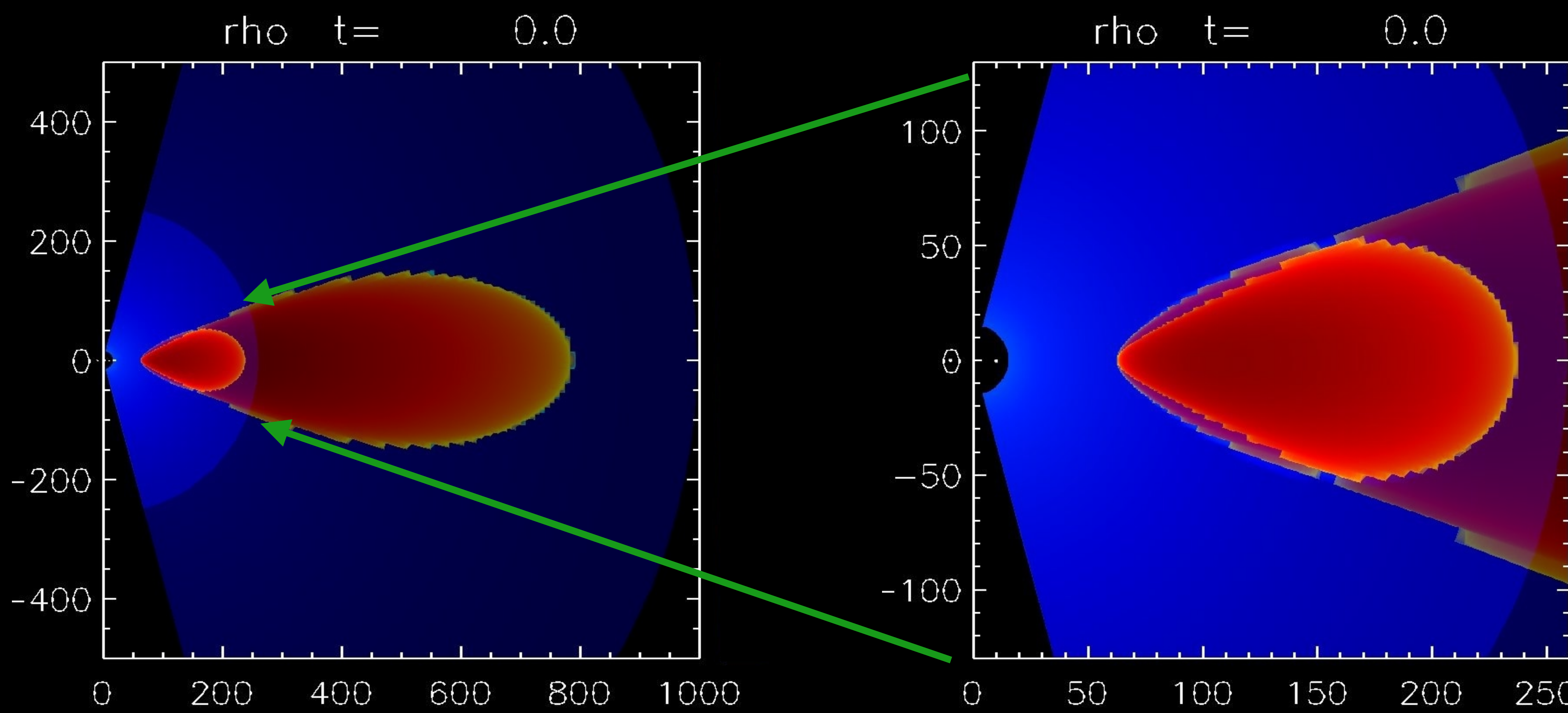
q=5

q=10

Top-down view of Surface Density

Disk's State

Noble++in-prep

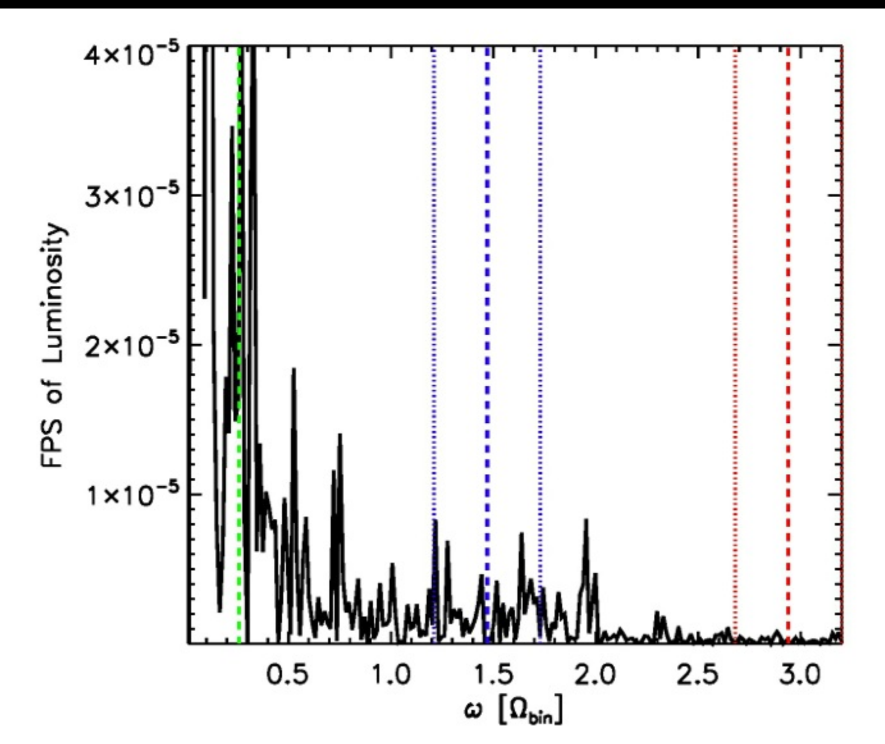


- Bigger disk:
  - "Center" moved from 5a to ~6a;
  - Large extent increases reservoir of magnetic flux and mass;
- Injected flux:
  - Magnetic flux from t=0 added late-time snapshot of original run;
  - Increases local magnetic energy density by only a few percent;

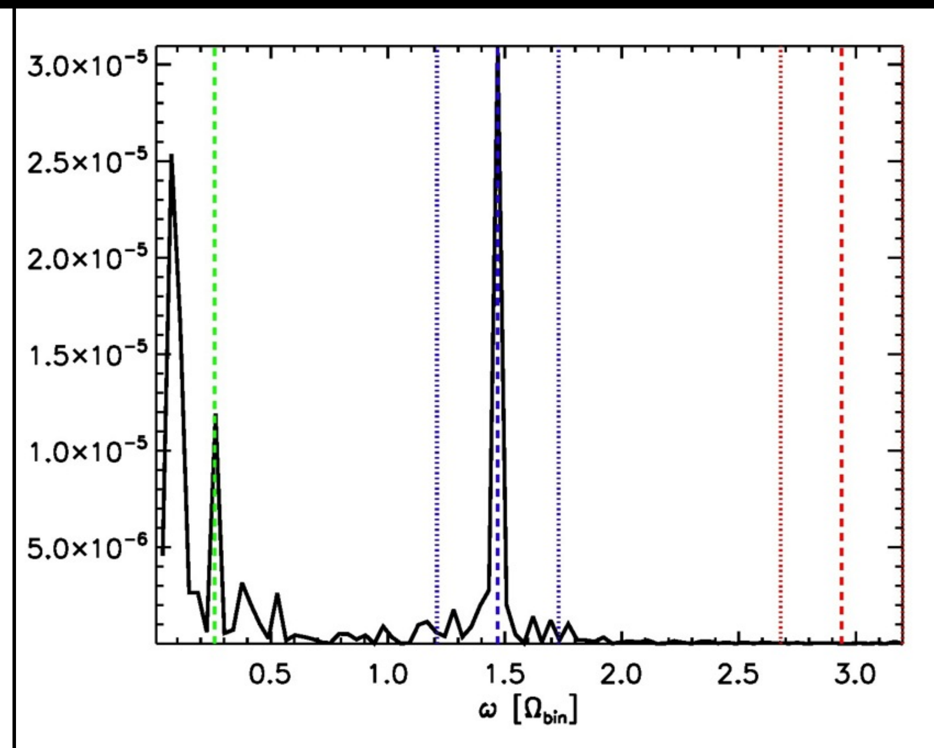
Disk's State

Noble++in-prep

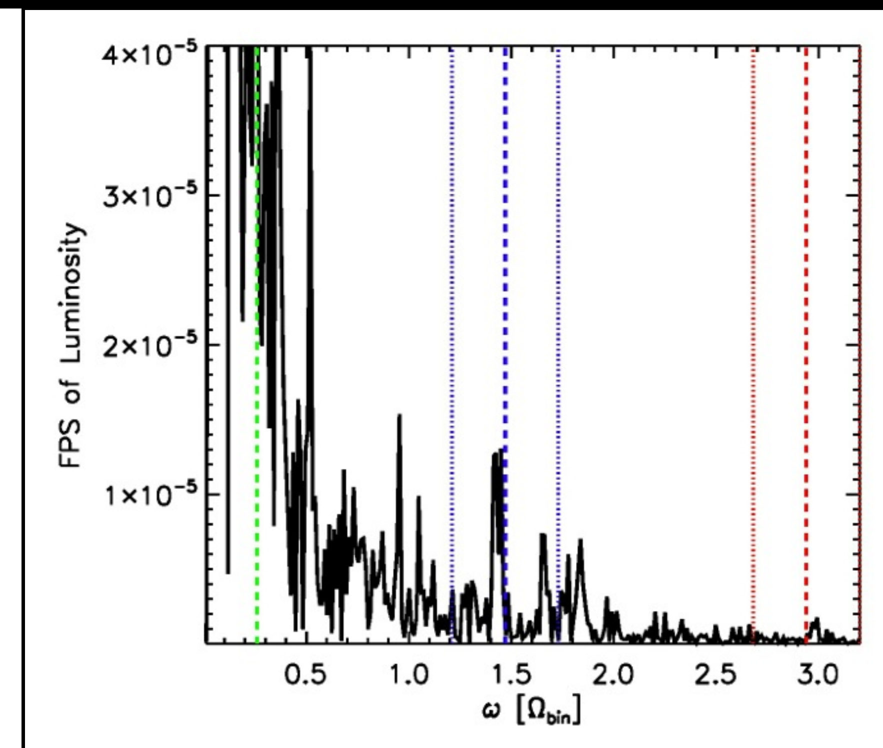
Bigger Disk



Original



Flux-Injected



Again, please note different scales

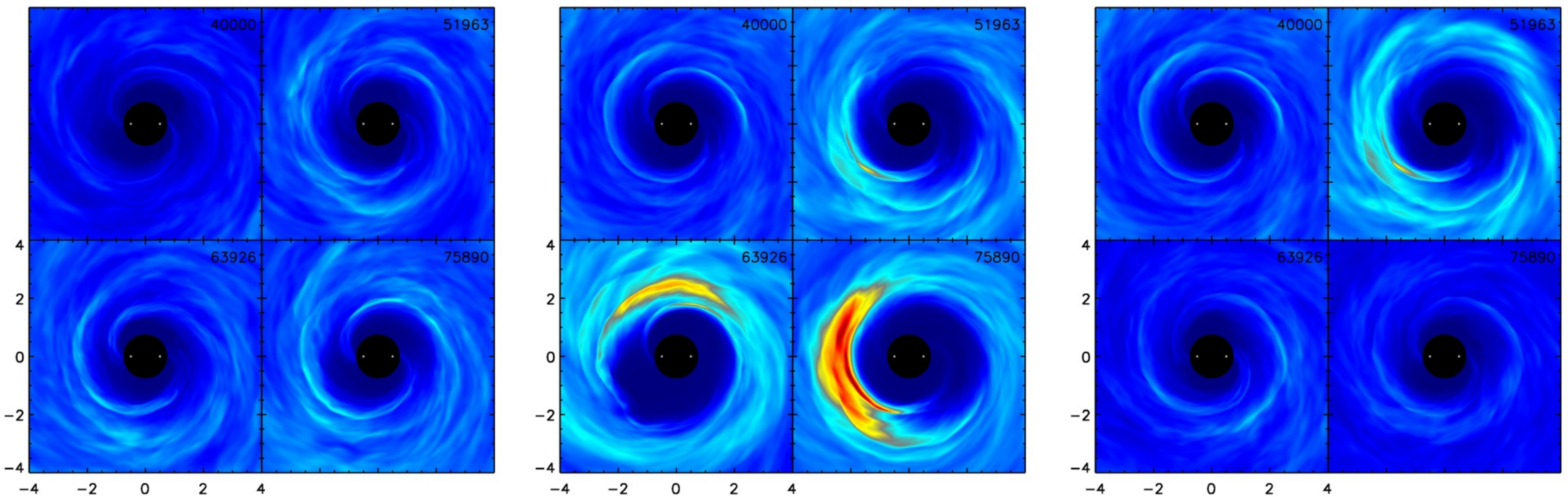
More magnetic flux led to:

- 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?

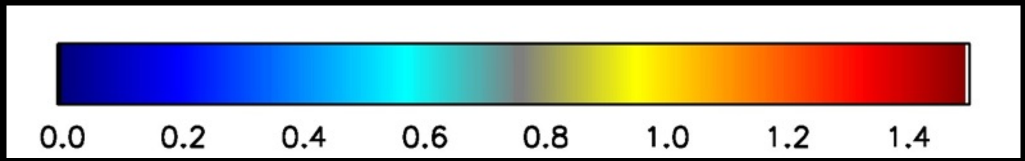
Disk's State

Noble++in-prep

Bigger Disk | Original | Flux-Injected



Top-down view of Surface Density



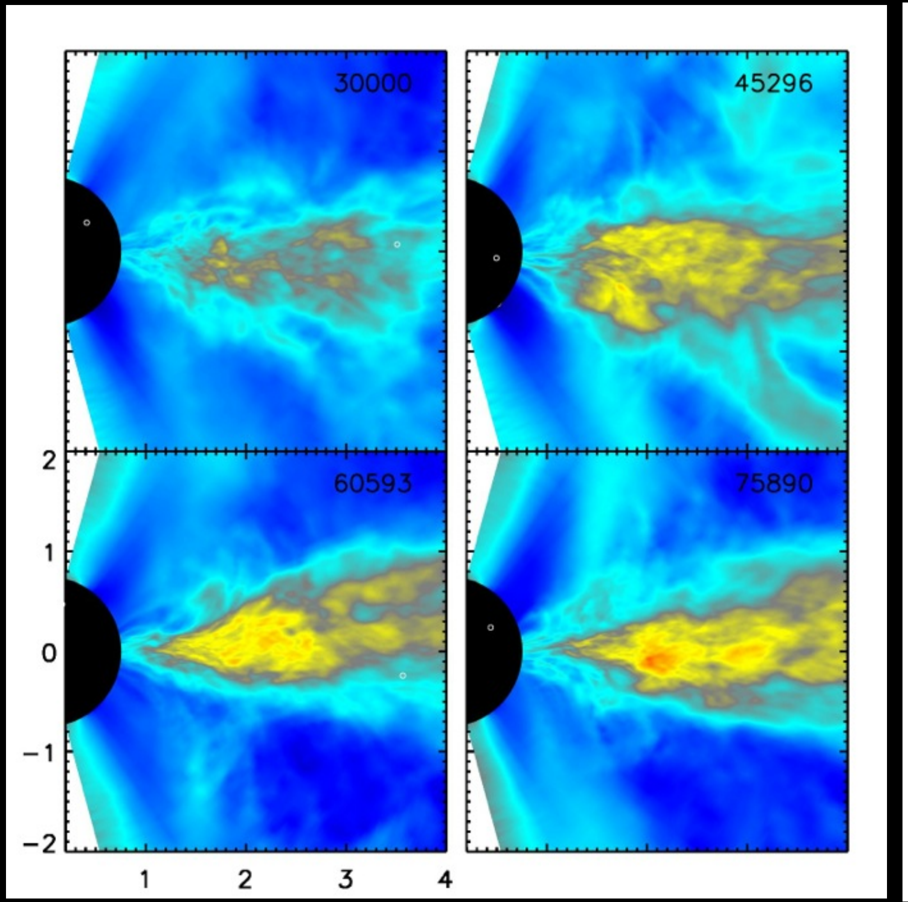
More magnetic flux led to:

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

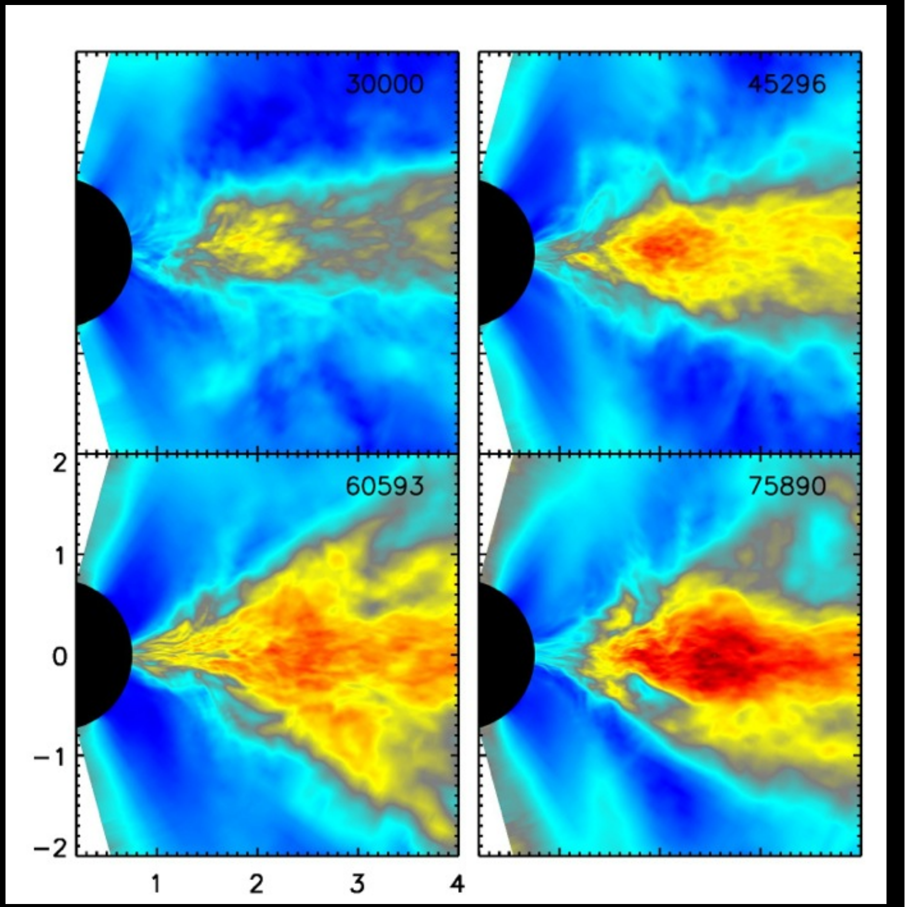
Disk's State

Noble++in-prep

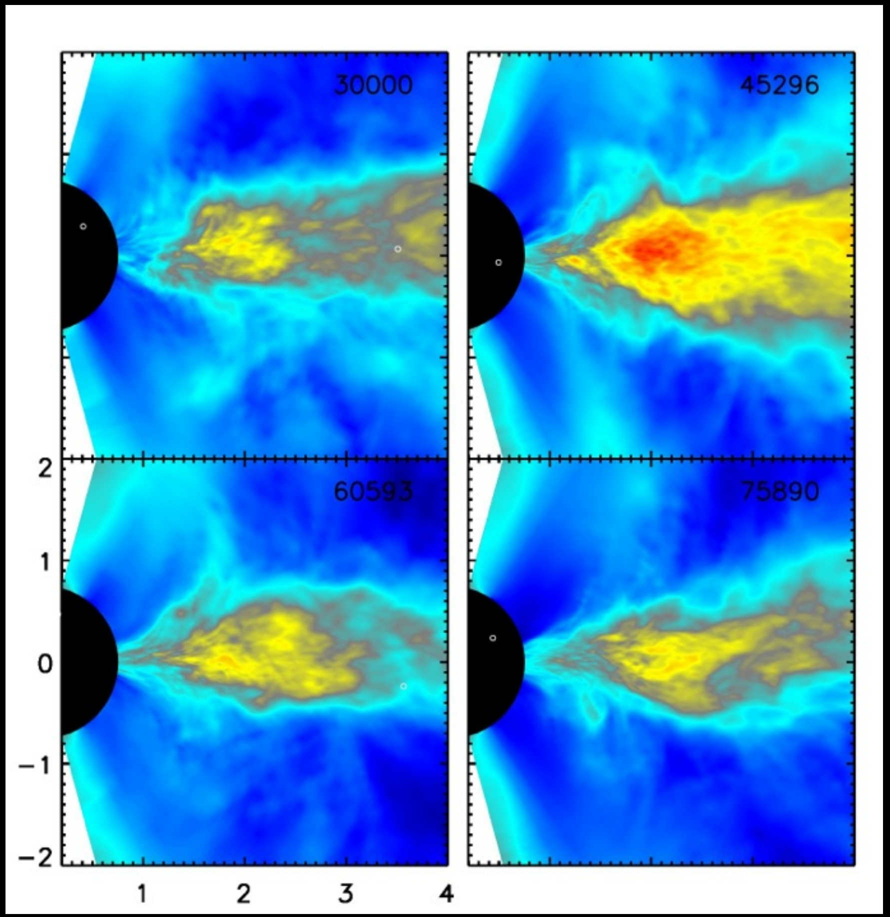
Bigger Disk



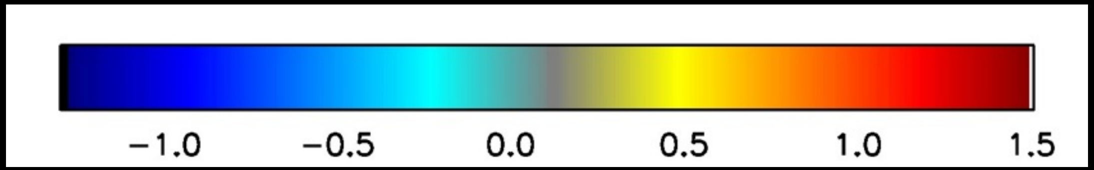
Original



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 $q=10$;