# 3-D GRMHD Simulations of Accreting Binary Black Holes

Based on:

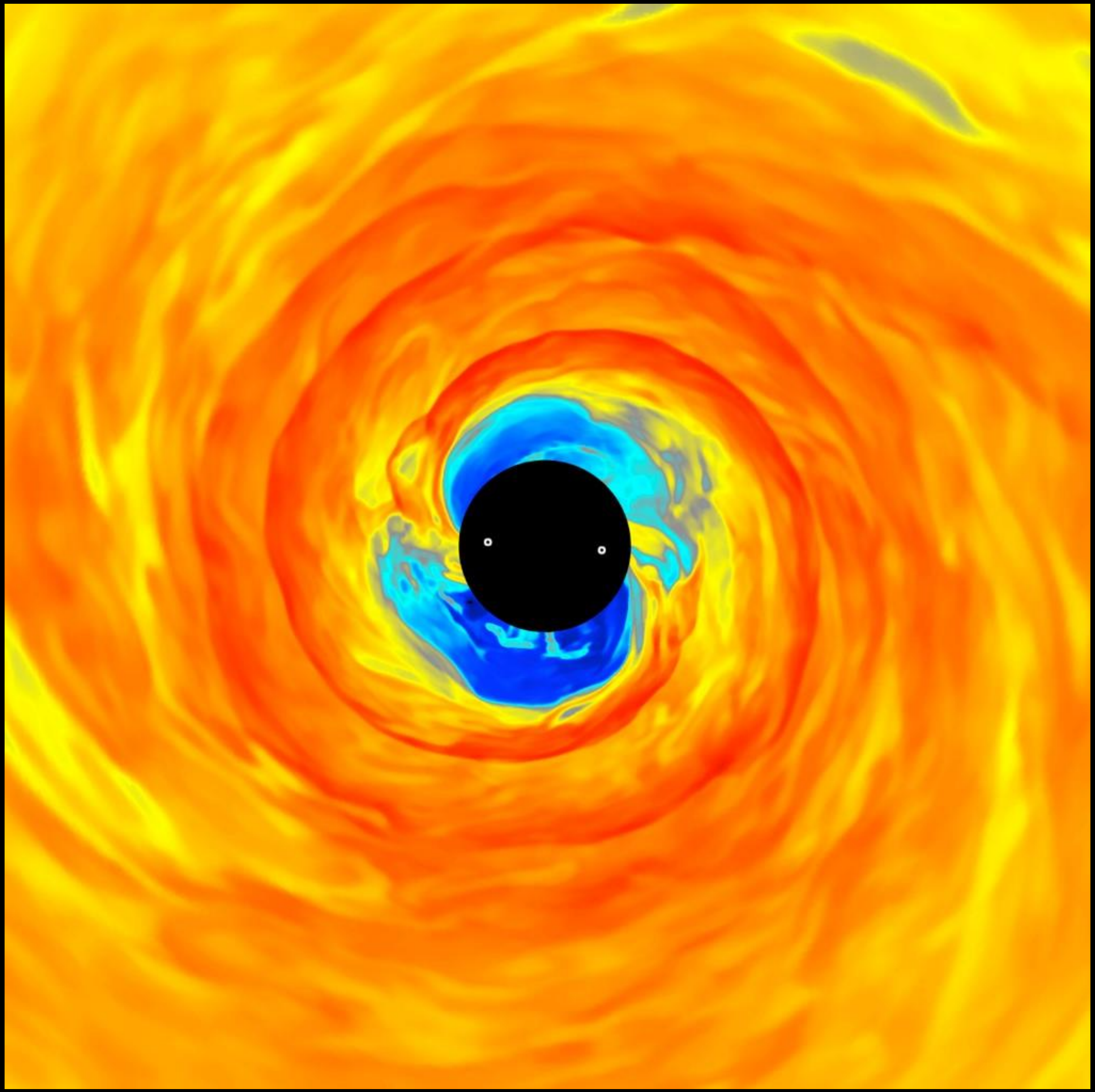
- Noble++2012
- Zilhao & Noble 2014
- Zilhao++2015 (in press, PRD)
- Noble++in-prep

Scott C. Noble (U. Tulsa)! [yes, that's in Oklahoma]

M. Campanelli (RIT)!
D. Bowen (RIT)!
J. Krolik (JHU) !
B. Mundim (Frankfurt U.)!
H. Nakano (Kyoto U.)!
M. Zilhao (Barcelona U.)!
Y. Zlochower (RIT)

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

"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

- **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;**

**Better Models!**

+MHD

+3-d

• Post-Newtonian (PN) accuracy required for binary separations below ~100M;!

+GR

• Necessary to self-consistently include binary inspiral from GW loss rate;!

+Radiation Cooling

+Radiation Feedback

• 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”)

Galactic Merger Binary

Inspiral

FormationMerger

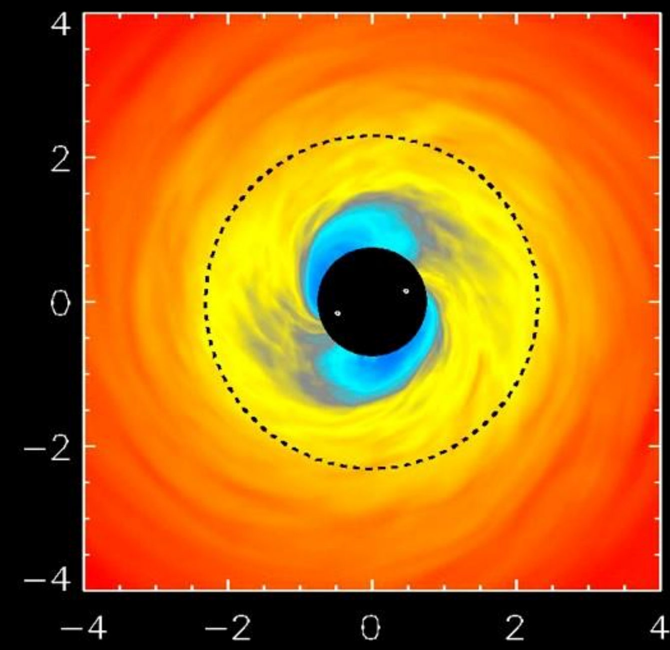
Newtonian Gravity

Eulerian, high-resolution/shockcapturing, 3-d, ideal MHD,

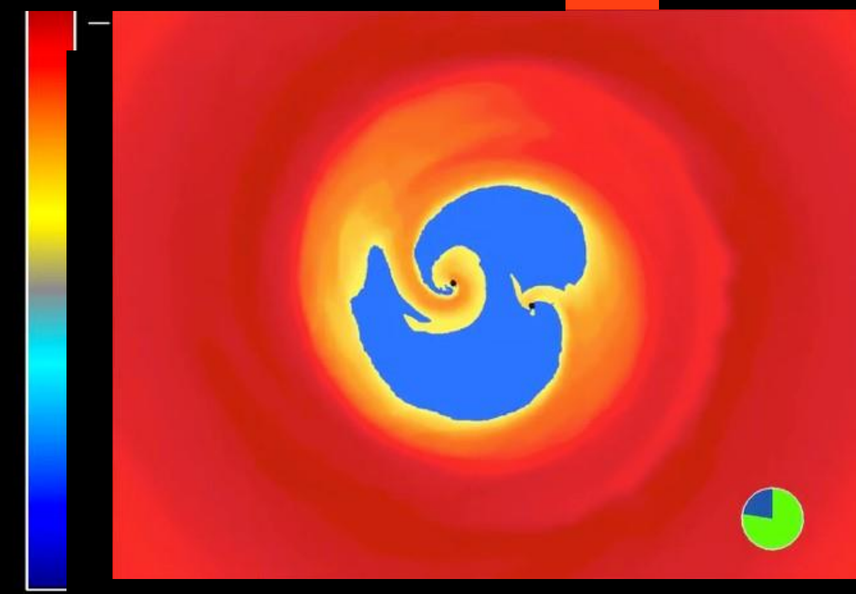
Re-equilibration

# Strategy


Hopkins, Hernquist, Di Matteo, Springel++




Noble++2012



Farris++2011

**Physical Time (not to scale)**

dynamical GR, HLL fluxes, parabolic reconstruction, dynamical FMR

Numerical Relativity

Post-Newtonian

Harm3d

Static GR

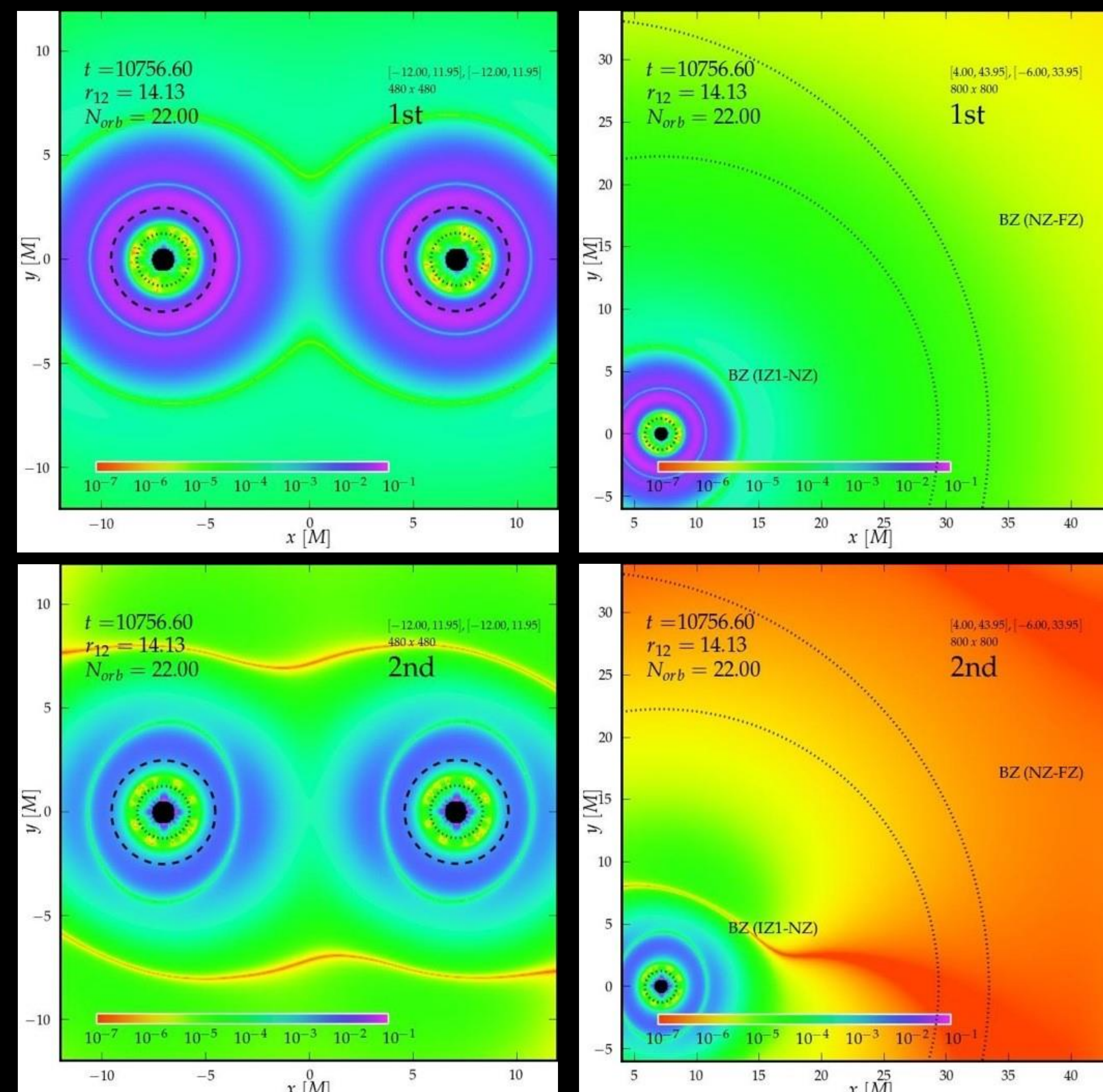
Harm3d

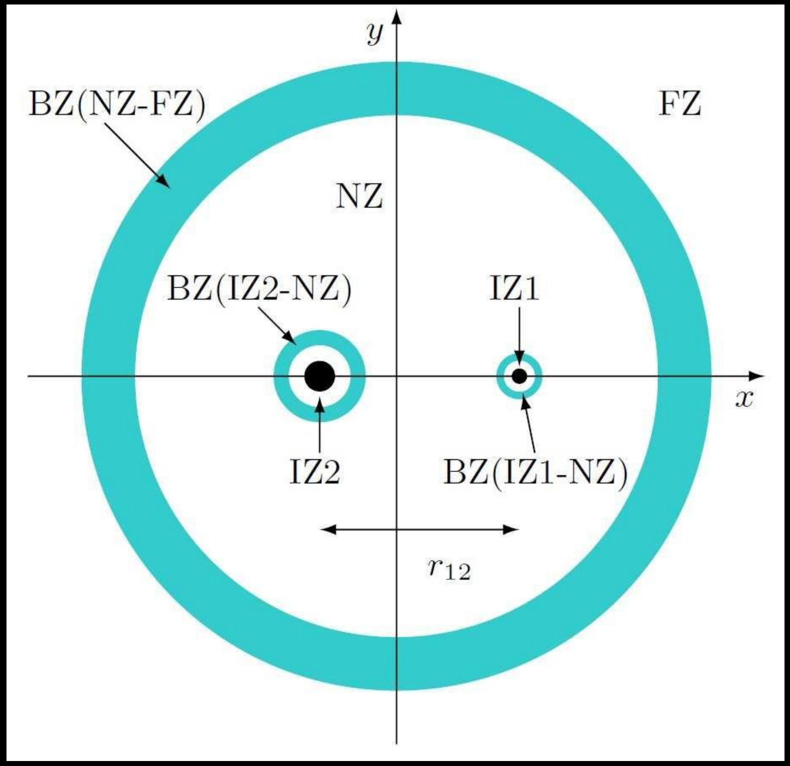
**Approximate Two Black Hole Spacetimes**

## 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;

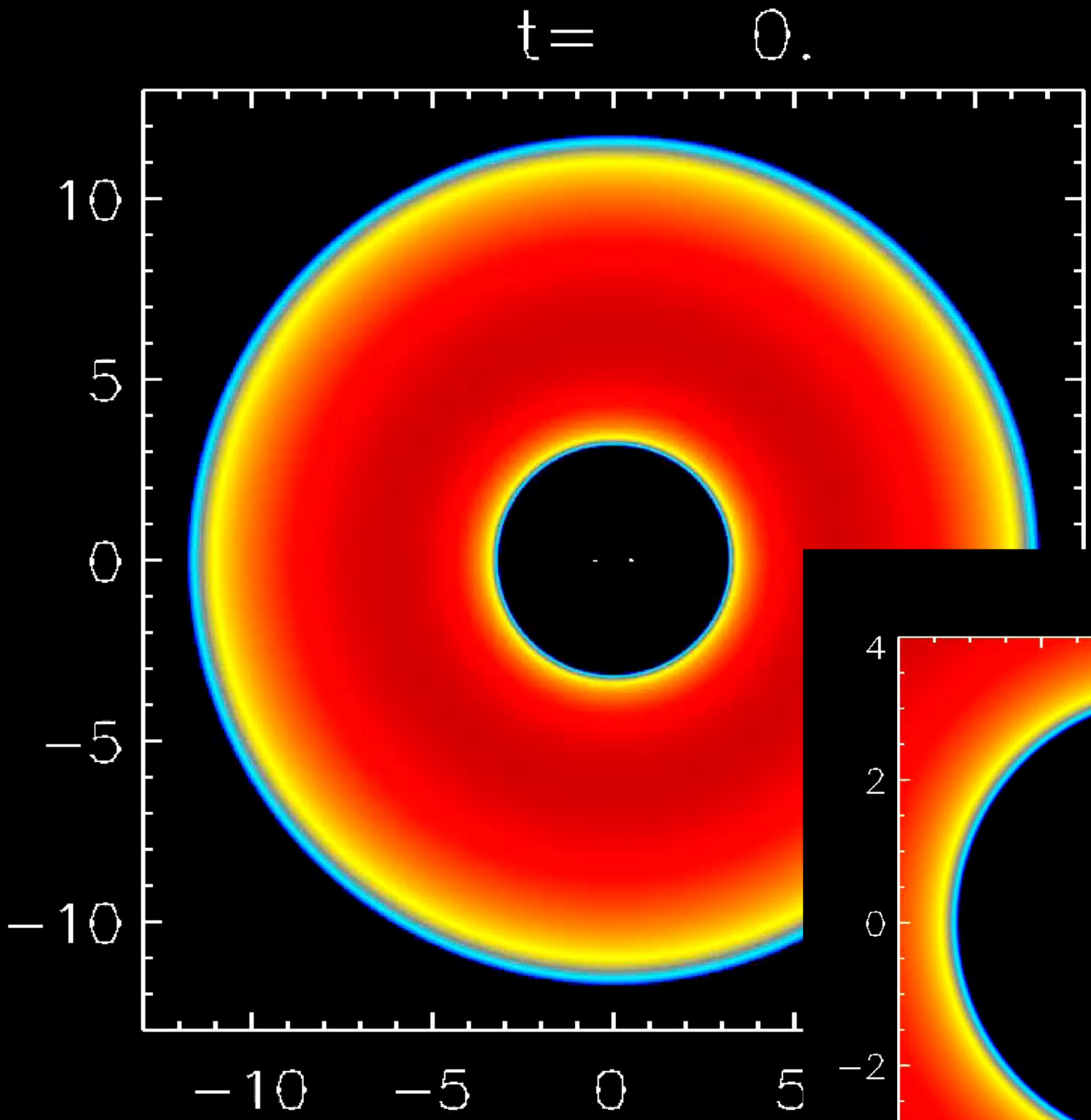
**Ricci Scalar ▶ 0**

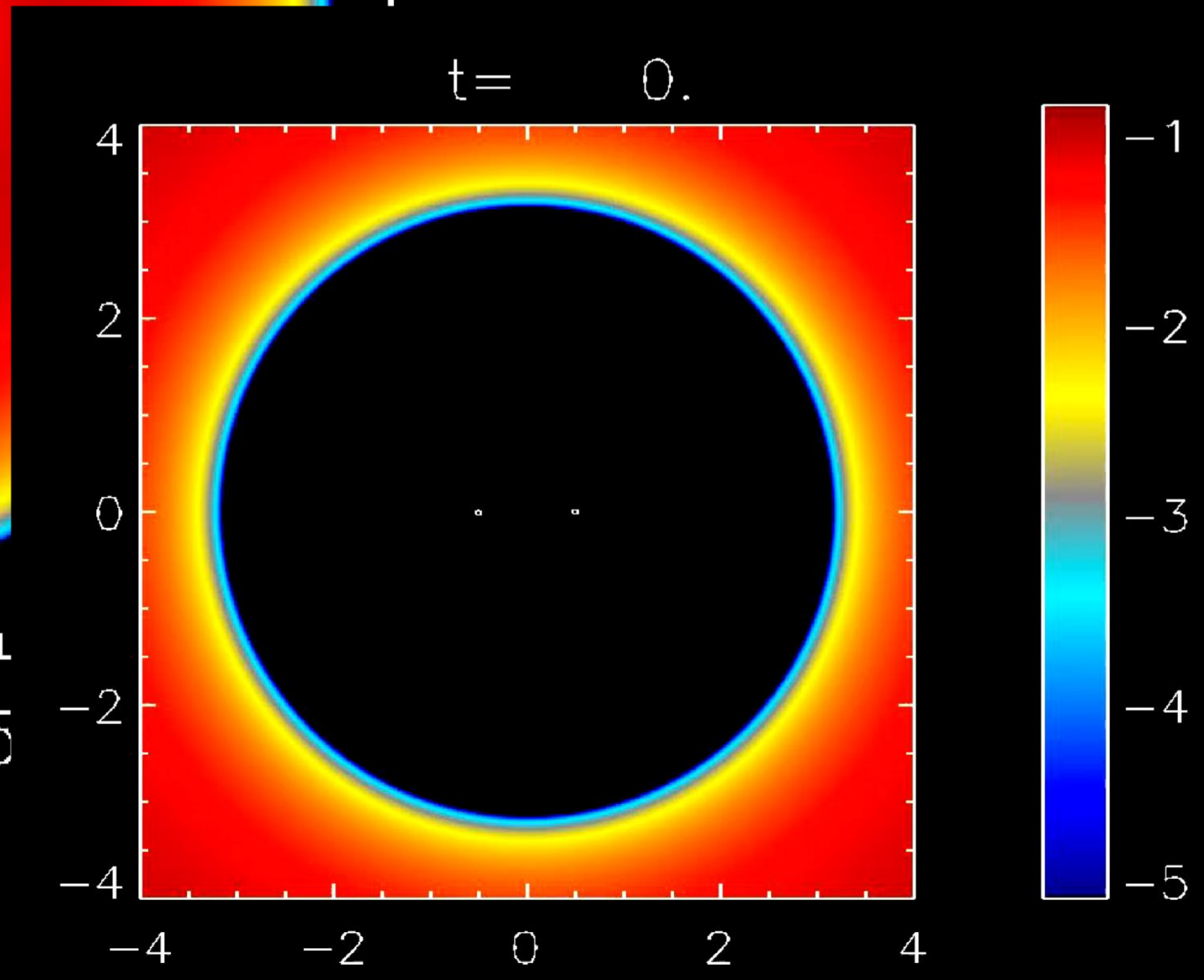




y
BZ(NZ-FZ)
FZ
NZ
BZ(IZ2-NZ)
IZ1
x
IZ2
BZ(IZ1-NZ)
$r_{12}$

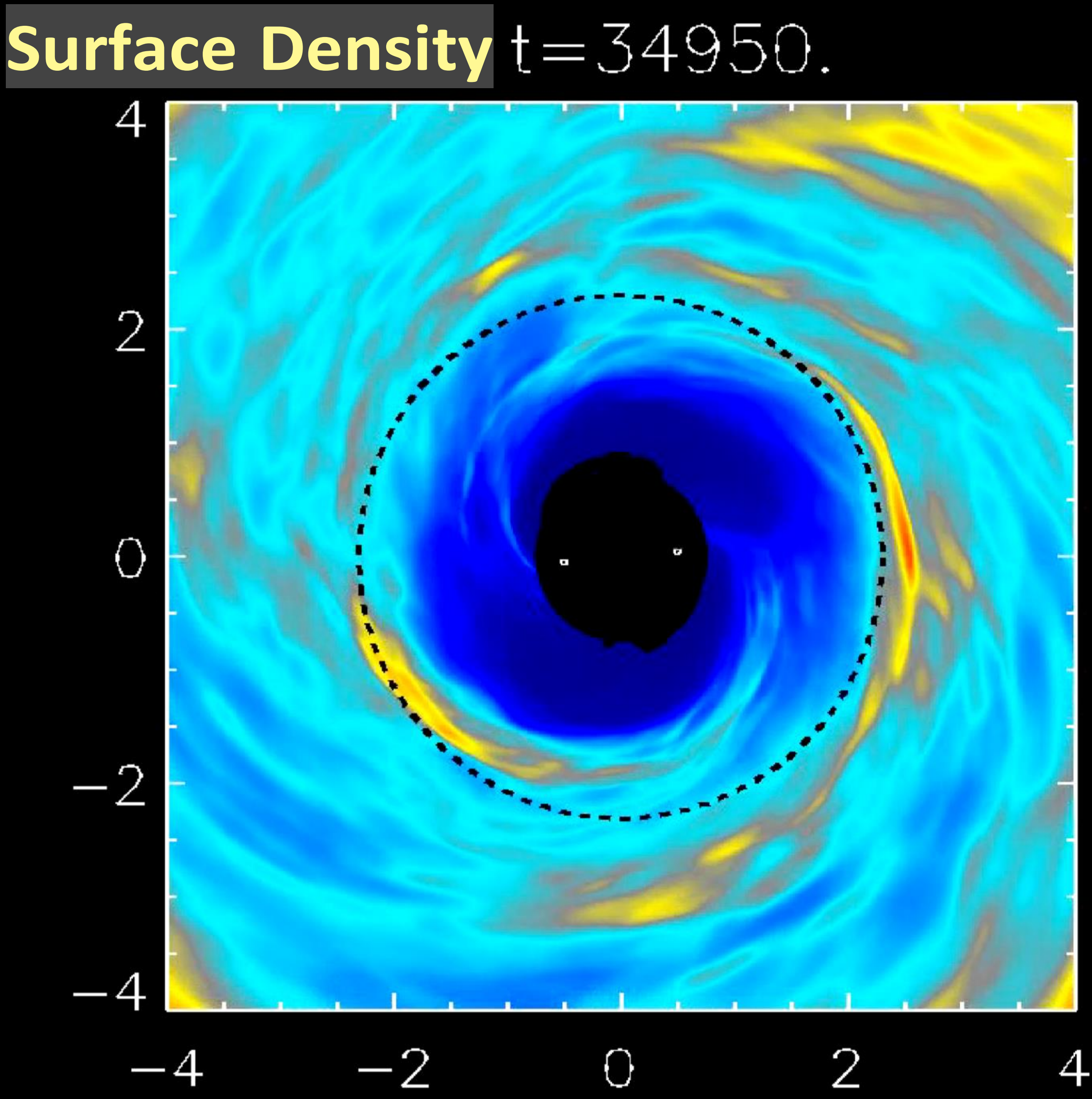
- **“Excise” BBH to afford O(100) orbits;!**
- **Simulation bank will be critical to initialize future inspiral studies w/ resolved BH’s;!**
- **Disk starts in “equilibrium”, threaded by poloidal magnetic field;**



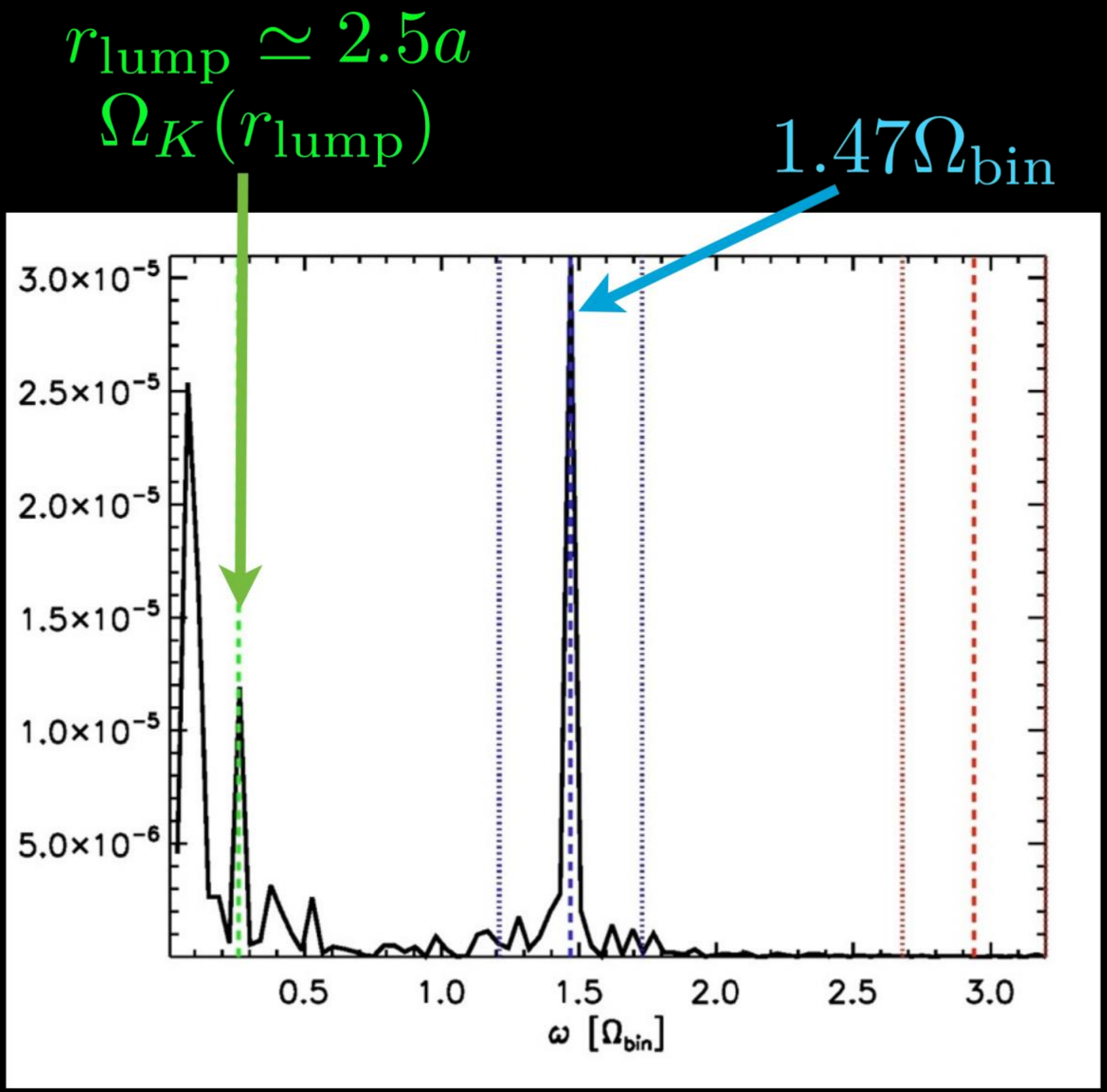

**Log Density**

# MHD Simulations with Unresolved BHs:




Noble++2012

# Periodic Signal




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

## Accuracy of Gravity Model

Zilhao++2015

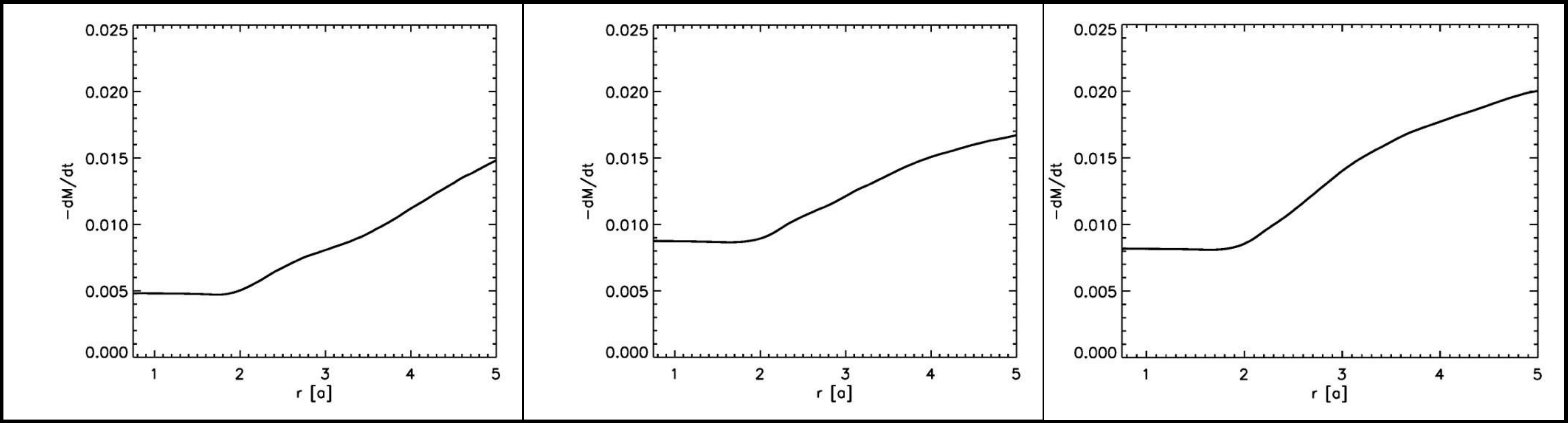
- Turn off highest order PN terms in metric and use the “same” matter initial data;
- Initial Data = Pressure+Rotation Equilibrium;
- —> Disk = Disk($g_{ab}$)
- —> Disk($g_{ab}$[2PN]) != Disk($g_{ab}$[1PN])
- Use two strategies for 1PN disk:
- Disk1: Use *same* orbital parameters as 2PN disk, though 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
2.5PN
(Disk1)

(Disk2)

1.5PN
(Original)




**Less accurate metrics result in:**

Zilhao++2015

# Variabality vs. Post-Newtonian Accuracy:

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

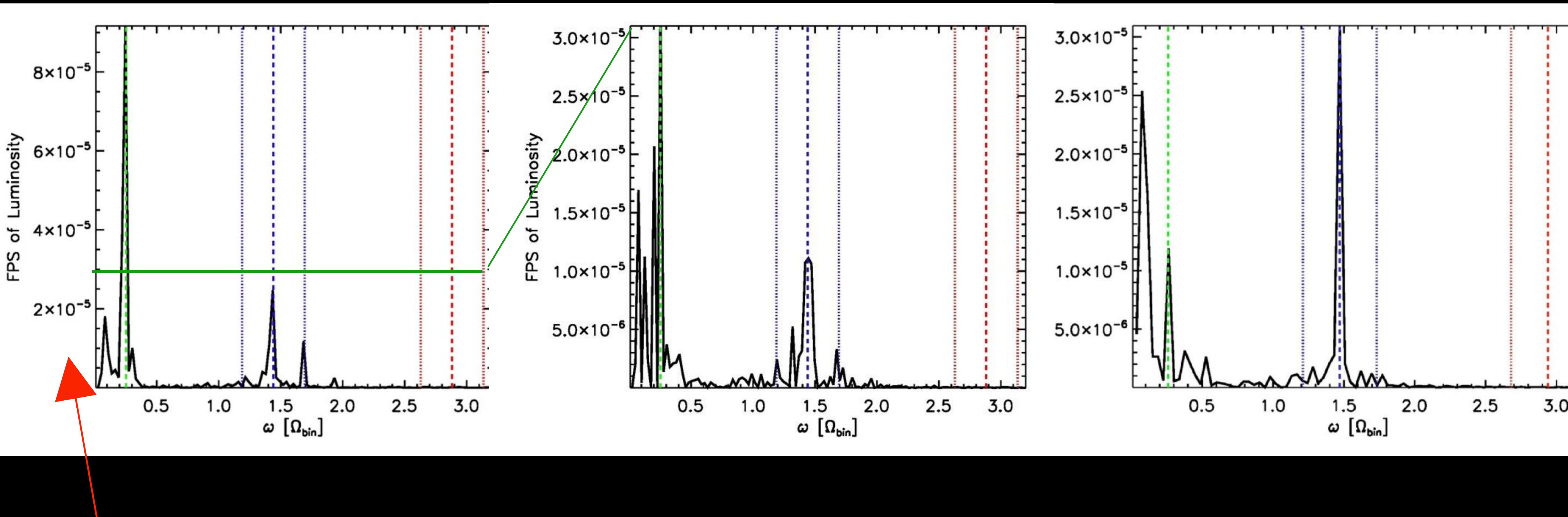
**Apologies for mismatched scales!**

**Less accurate metrics result in:**

Zilhao++2015

# Variabality vs. Post-Newtonian Accuracy:

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



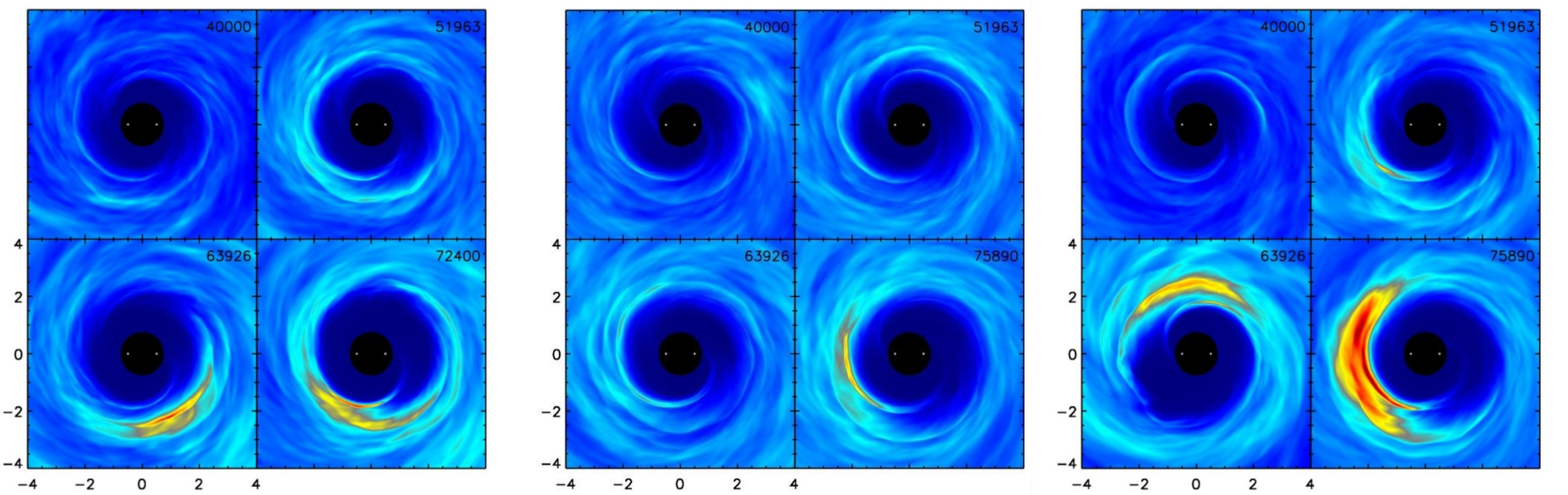

- Stronger variability at lump's orbital frequency;
- Power at beat frequency spread to larger range of frequencies;
- More complex lump/binary modulation;

Zilhao++2015

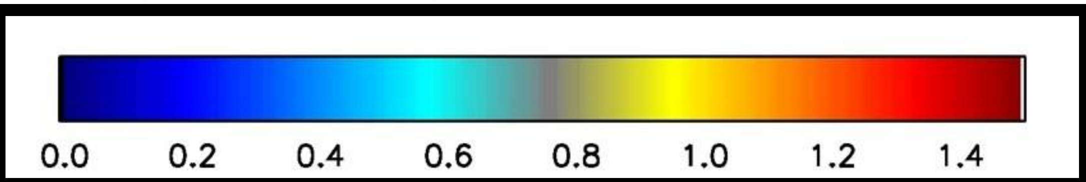
# Variabality vs. Post-Newtonian Accuracy:

1.5PN

1.5PN




**Top-down view of Surface Density**




2.5PN

(Disk1)

(Disk2)

(Original)

Zilhao++2015

# Variabality vs. Post-Newtonian Accuracy:

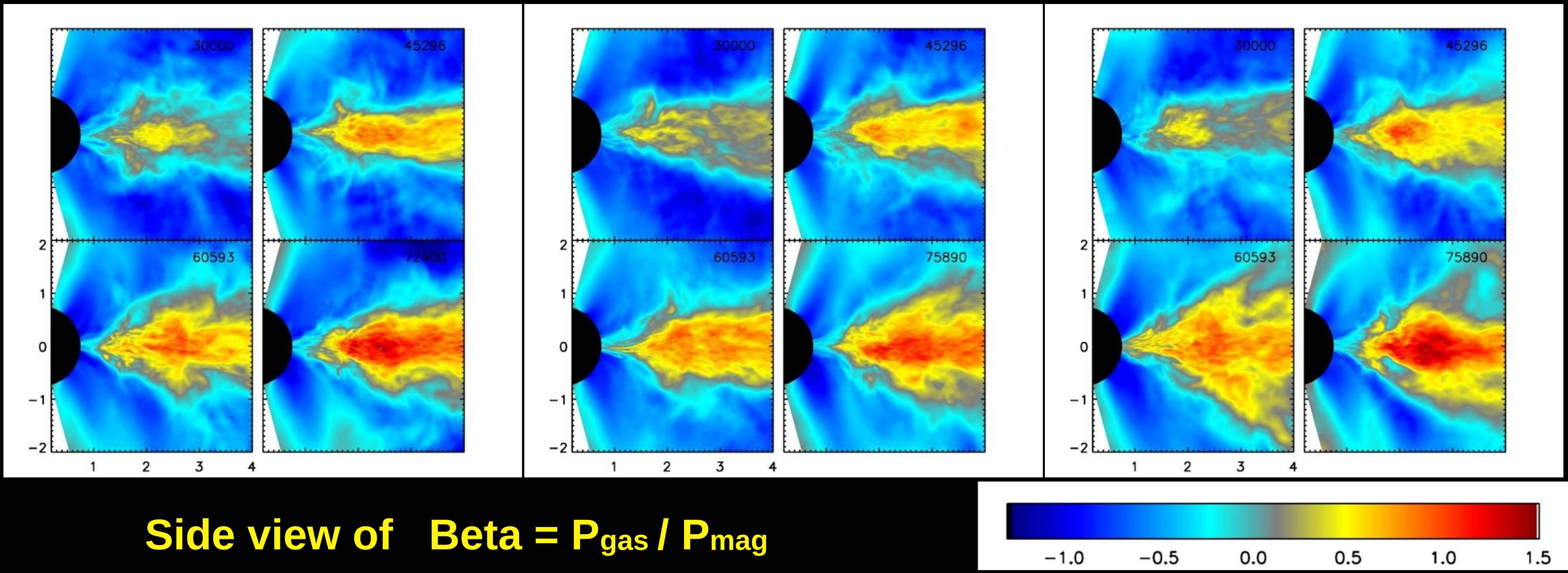
**Less accurate metrics result in:**

- 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 1.5PN




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

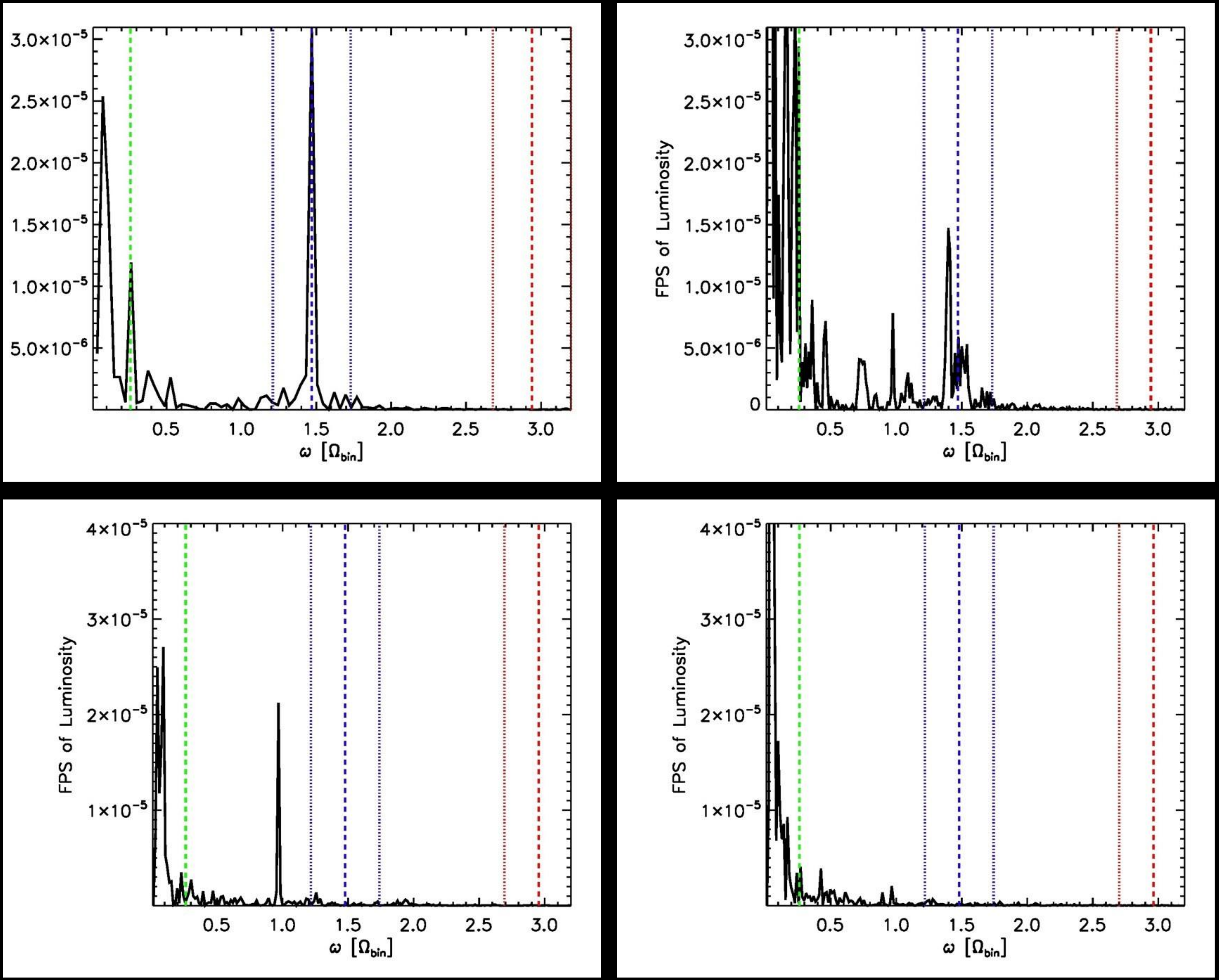
2.5PN

(Disk1) (Disk2) (Original)

**Less accurate metrics result in:** Zilhao++2015

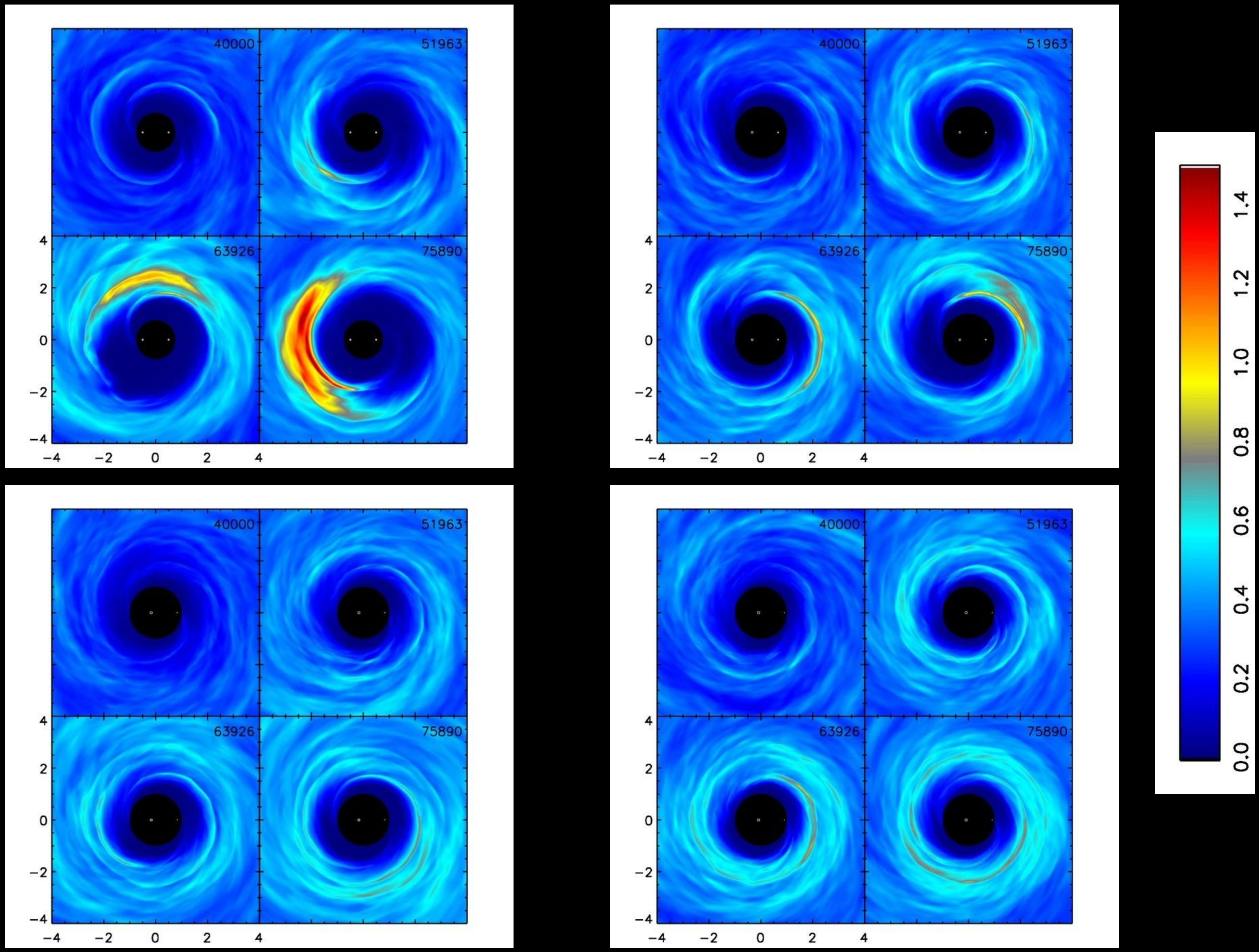
- Slightly less loss of magnetization;
- Possibly due to weaker torque, less dissipation of field from flung out material;
  - Weak torques from “weaker” quadrupole potential;
- Note thicker disk leads to less loss of magnetization;

q=1 **Mass Ratio** Noble++in-prep q=2



3.0×10⁻⁵
2.5×10⁻⁵
2.0×10⁻⁵
1.5×10⁻⁵
1.0×10⁻⁵
5.0×10⁻⁶
0.5
1.0
1.5
2.0
2.5
3.0
ω [Ω_bin]
FPS of Luminosity
0
4×10⁻⁵
3×10⁻⁵
2×10⁻⁵
1×10⁻⁵

q=5q=10 q=1 **Mass Ratio** Noble++in-prep q=2

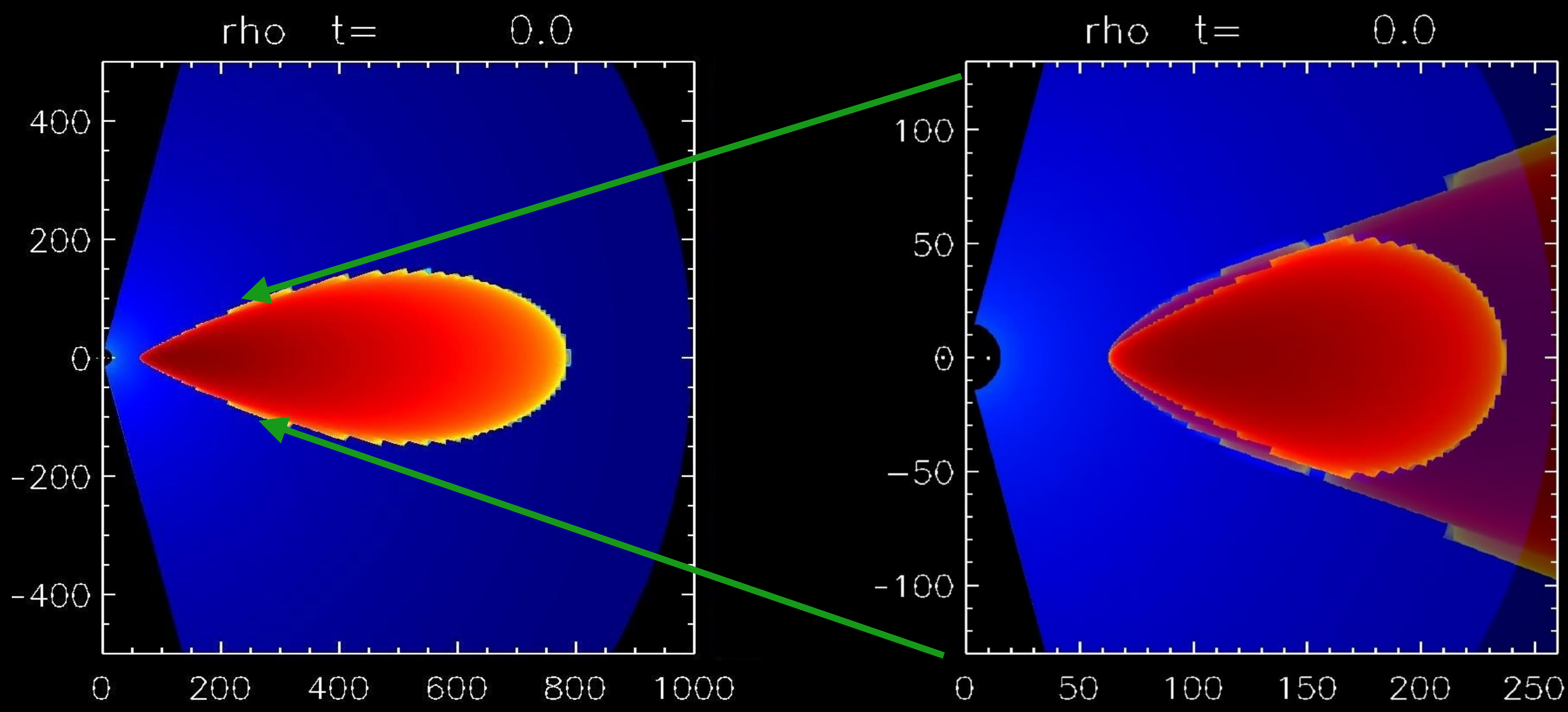

40000
51963
63926
75890
4
2
0
−2
−4
−4
−2
0
2
4
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

q=5

# Top-down view of Surface Density

q=10

# Disk's State Noble++in-prep

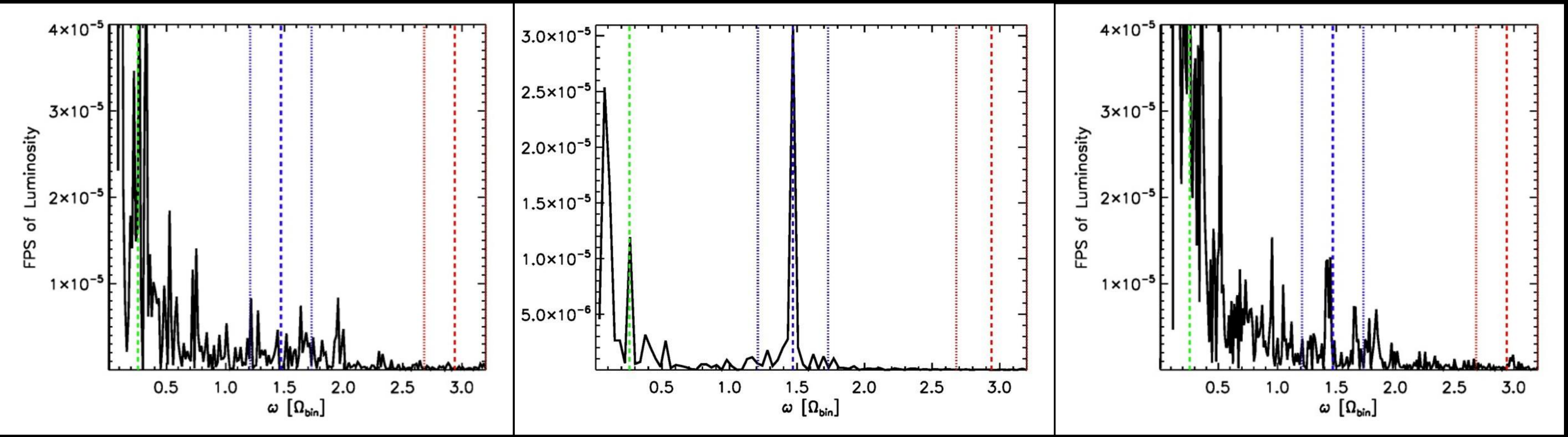



- Bigger disk:
- "Center" moved from 5a to ~6a;
- Large extent increases reservoir of magnetic flux and mass;

- Injected flux:
- Magnetic flux from t=0 added late-time snapshot of original run;

# Disk's State Noble++in-prep

Bigger Disk | Original | Flux-Injected




- Increases local magnetic energy density by only a few percent;

**Again, please note different scales**

**More magnetic flux led to:**

- Less coherent temporal power spectrum;
- Spectra resembling more a slightly bent power law;

# Disk's State Noble++in-prep

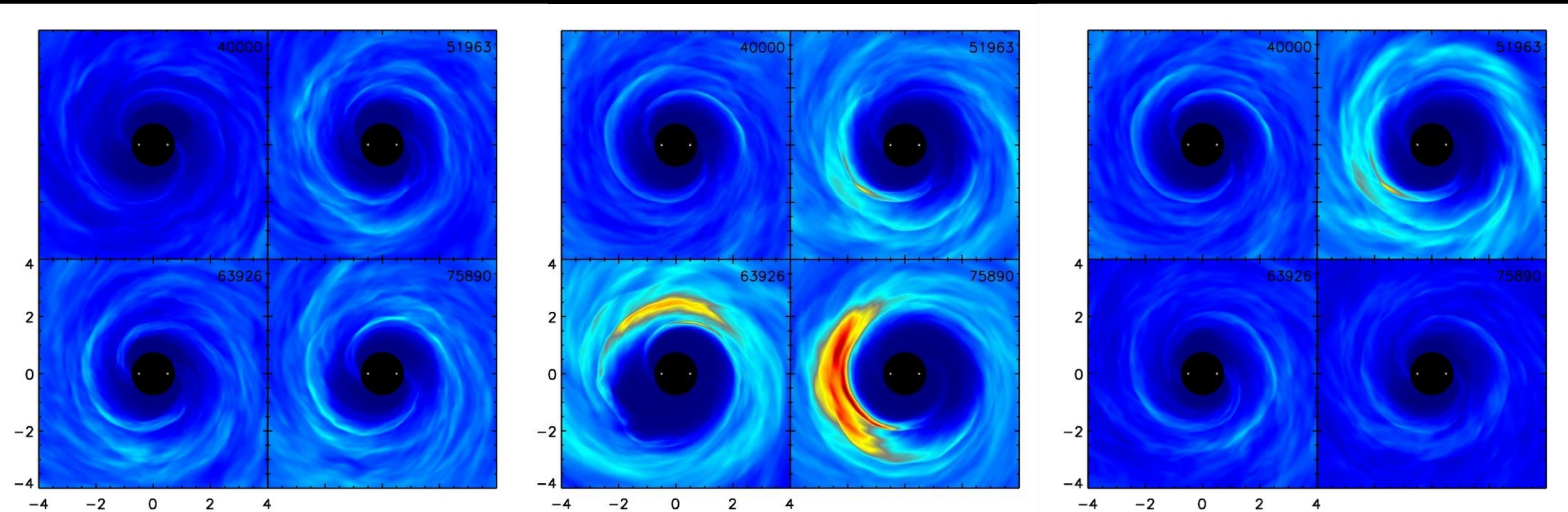
Bigger Disk | Original | Flux-Injected

- Spectra resembling more spectra from simulations of single black hole disks;
- Is there no over-density?

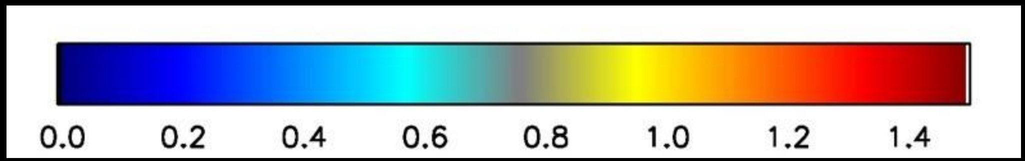
**More magnetic flux led to:**

# Disk's State Noble++in-prep

Bigger Disk | Original | Flux-Injected



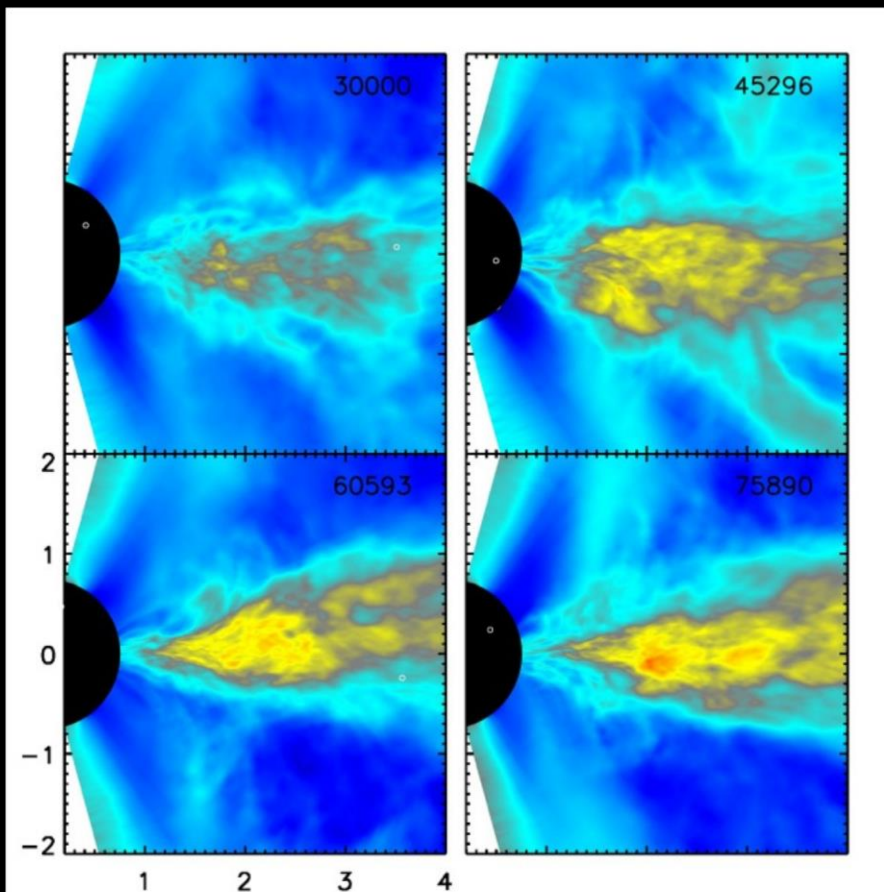

**Top-down view of Surface Density**



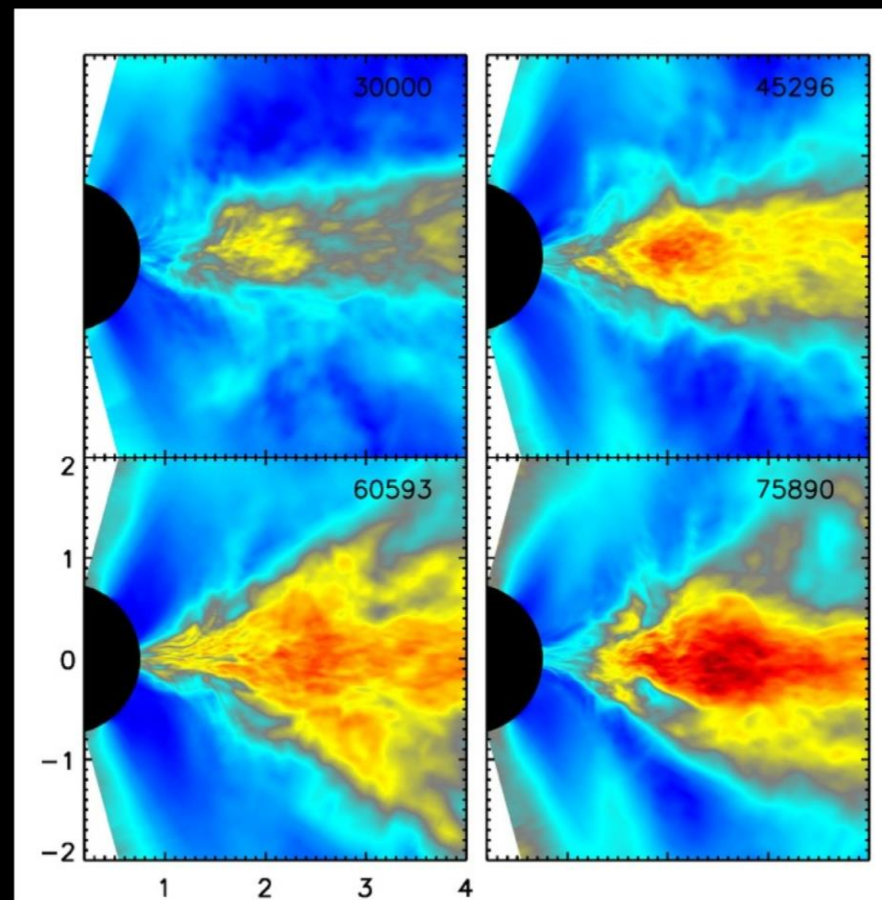

- Much weaker m=1 mode, if any.
- Therefore, no means of developing coherent beat;
- Fluctuations arise just from turbulence;

# Disk's State Noble++in-prep

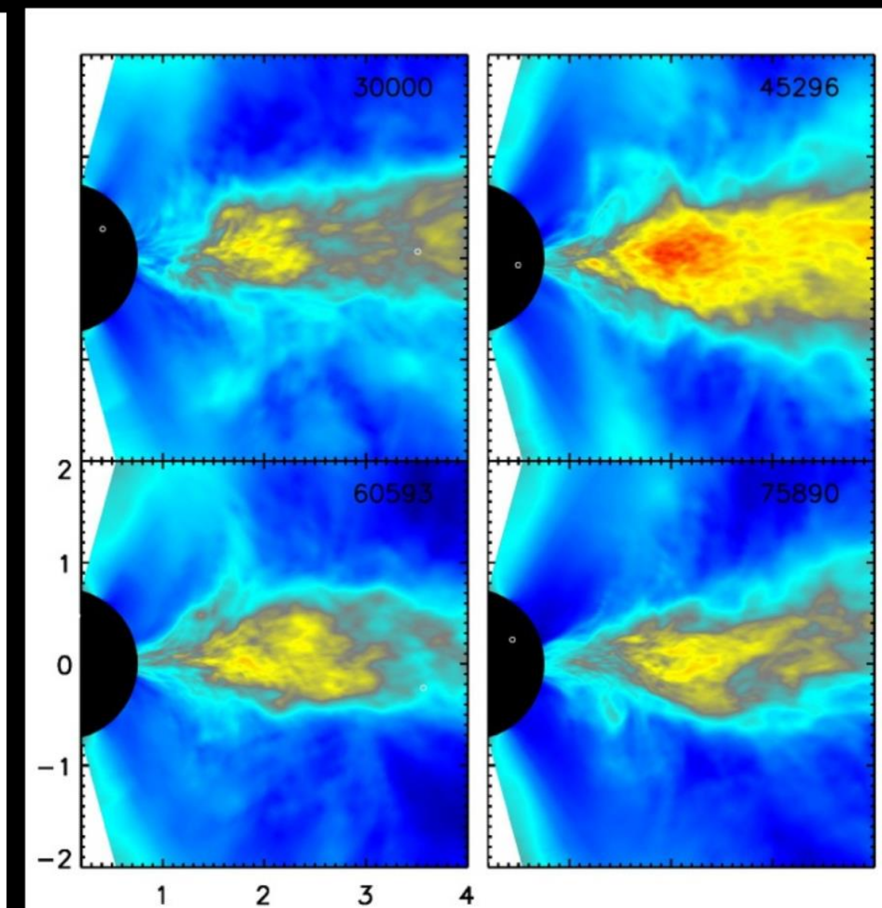
Bigger Disk



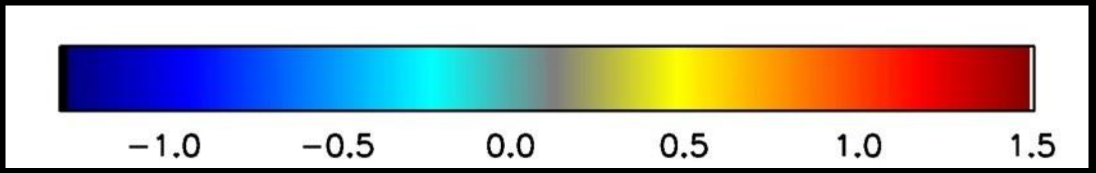

Original




Flux-Injected




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



# Disk's State Noble++in-prep

Bigger Disk | Original | Flux-Injected

- 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 $q=10$;