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Session B1: Wed. July 13, 2016

Lighting Up Inspiraling Binary Black Hole Systems

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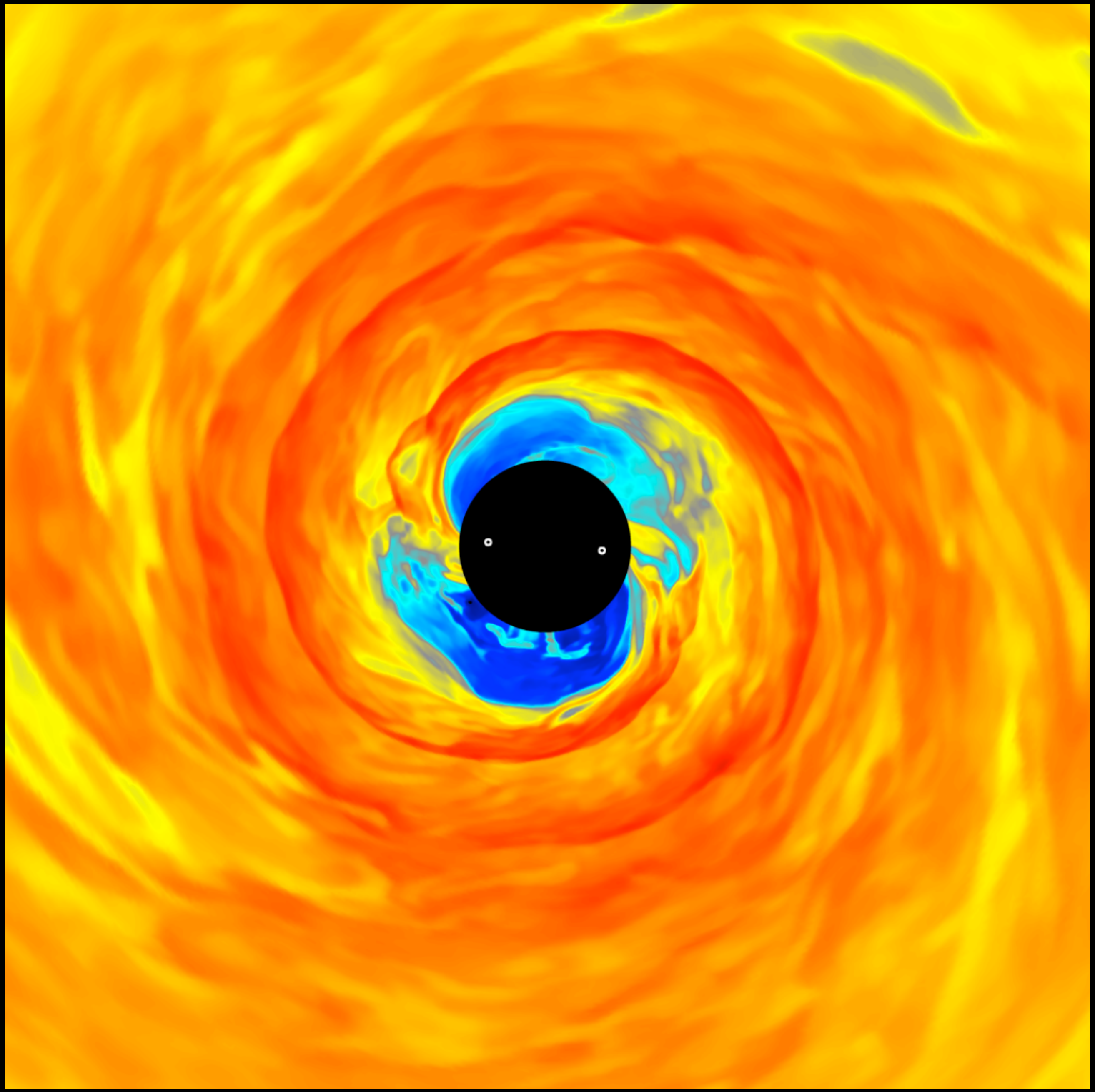
Based on:

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



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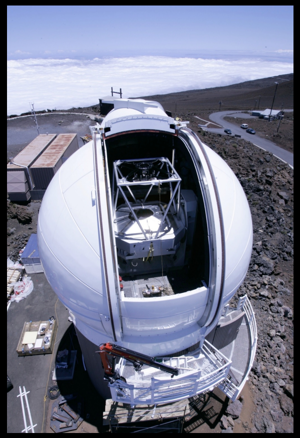
Multimessenger Synergy

Electromagnetic Surveys



Pan-STARRS:
- Running, 4 skies per month

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

All-Sky Automated Survey for Supernovae (ASAS-SN)
- Running, 1 sky a night, not very sensitive;

Gravitational Wave Observatories

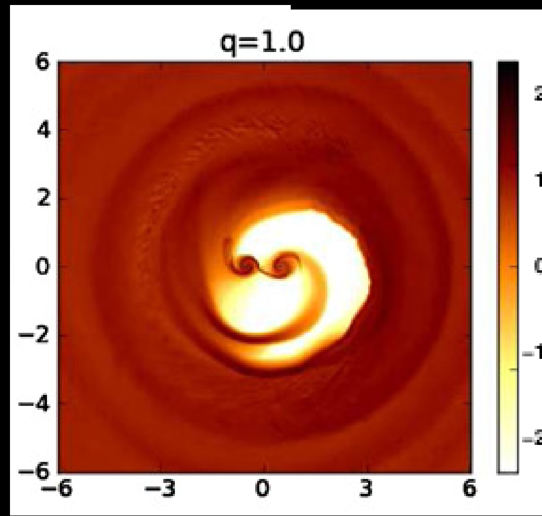
~2034?

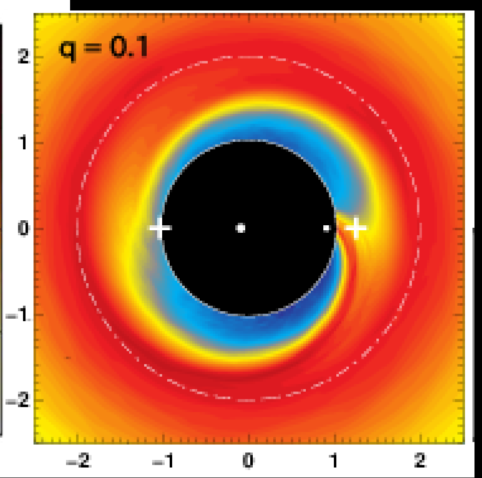
EPTA, NANOGrav, PPTA

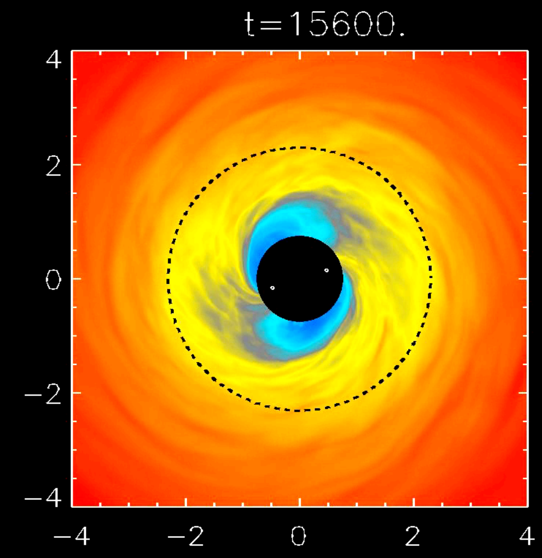
~2020

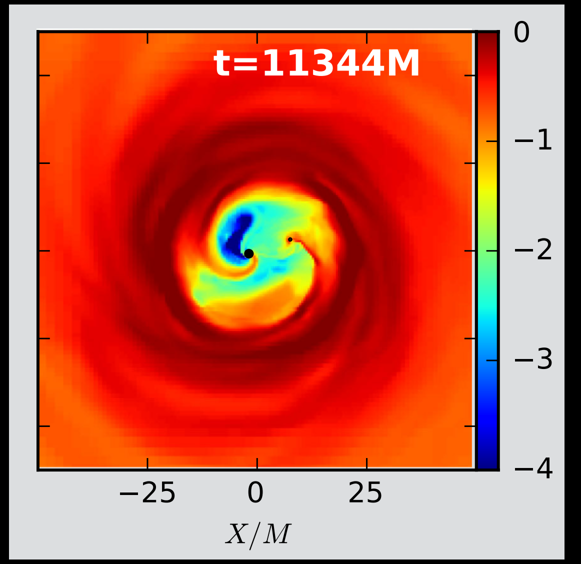
- GW Detection/Localization <---> EM Detection/Localization;
- GW and light are connected theoretically but originate in wholly different mechanisms
  - --> independently constrain models;
- Follow up (X-ray, sub-mm) observations can often be made via coordinated alert systems;
- Cosmological "Standard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

Strategy









Hopkins,Hernquist, Di Matteo, Springel++ | Farris++2014 | Shi++2014 | Noble++2012 | Gold++2014

Matter:	Viscous Hydro.	MHD	MHD	MHD
Gravity:	Newtonian	Newtonian	Post-Newtonian	GR

Physical Time (not to scale) →

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

Newtonian Gravity

Numerical Relativity

Post-Newtonian

Harm3d

DATA

DATA

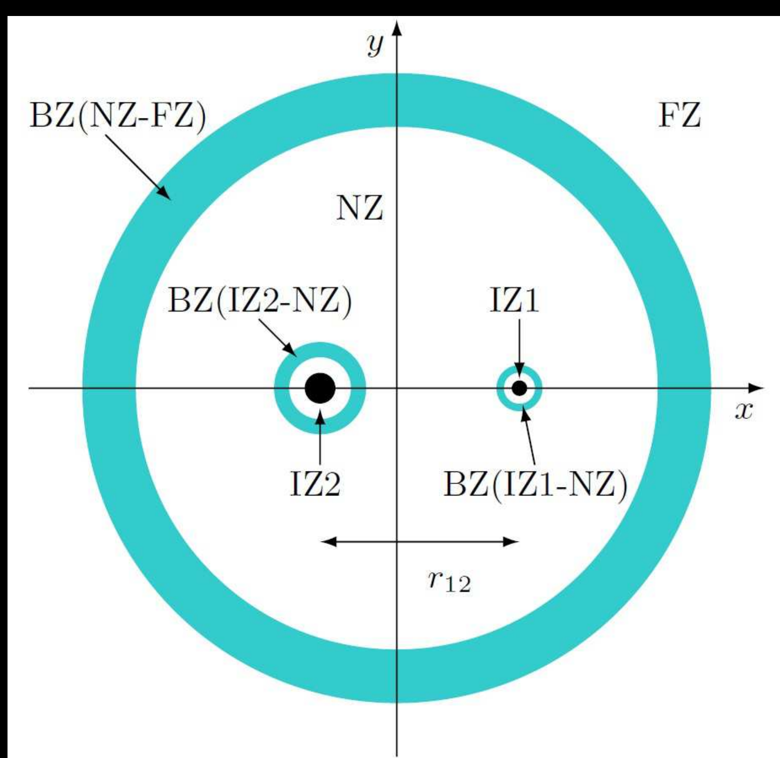
Static GR

Harm3d

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

Motivation of Simulation Design

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



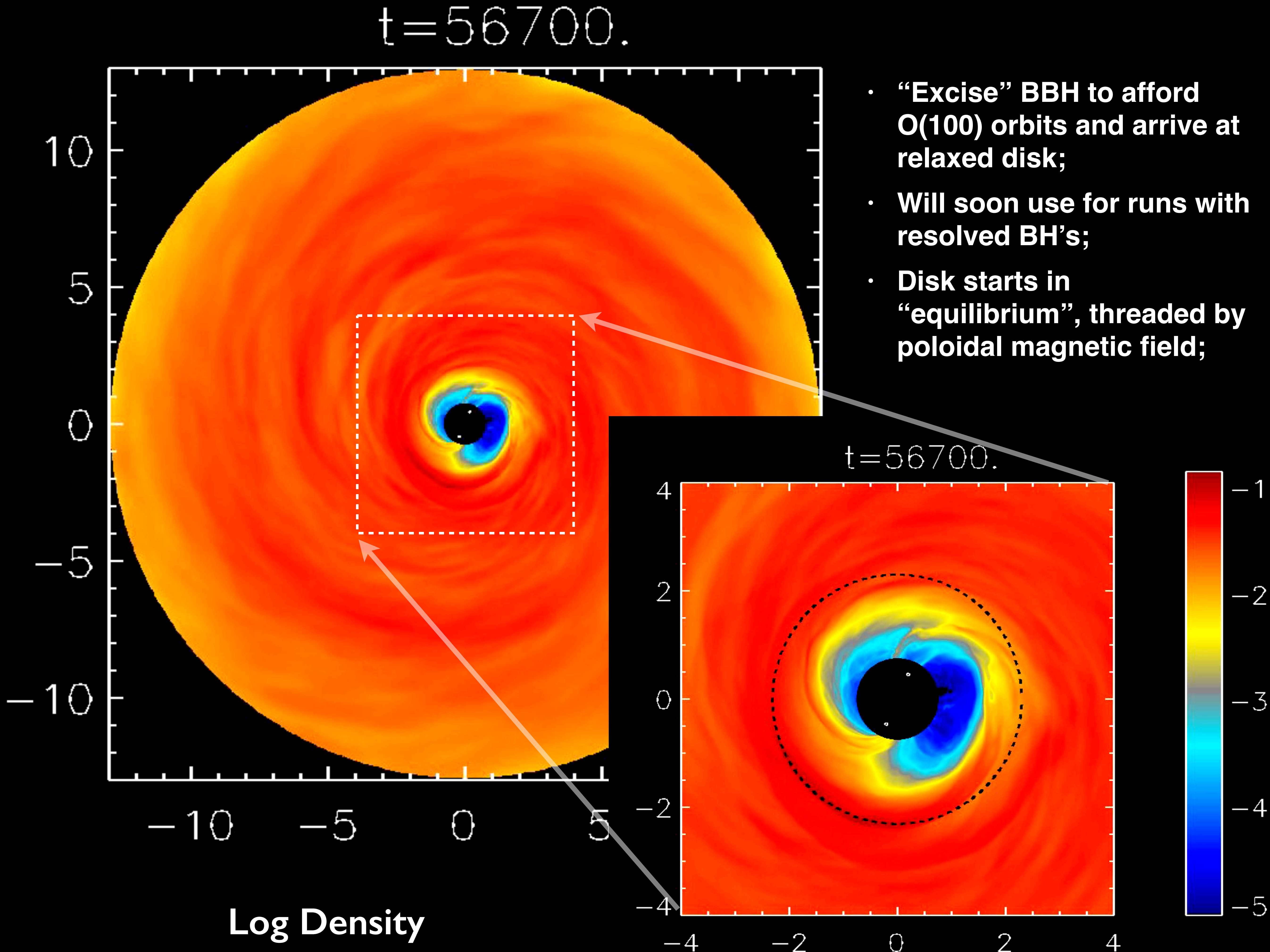
- **Mundim++2014**

- **MHD stresses —> Ang. Mom. transportation;**
- **Field dissipation and growth cannot be modeled w/ hydrodynamics;**

- **Buoyancy, and lasting turbulence only possible in 3-d.**

- **Post-Newtonian (PN) accuracy required for binary separations below ~100M;**
- **Significant mass can follow binary through much of this period (Noble++2012);**
- **NR needed for merger proper;**
- **Analytical metric provides freedom to grid for the gas instead of the spacetime. (Mundim++2014)**

- **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”)**



Log Density

- “Excise” BBH to afford O(100) orbits and arrive at relaxed disk;
- Will soon use for runs with resolved BH’s;
- Disk starts in “equilibrium”, threaded by poloidal magnetic field;

MHD Simulations Predict an EM Signature:

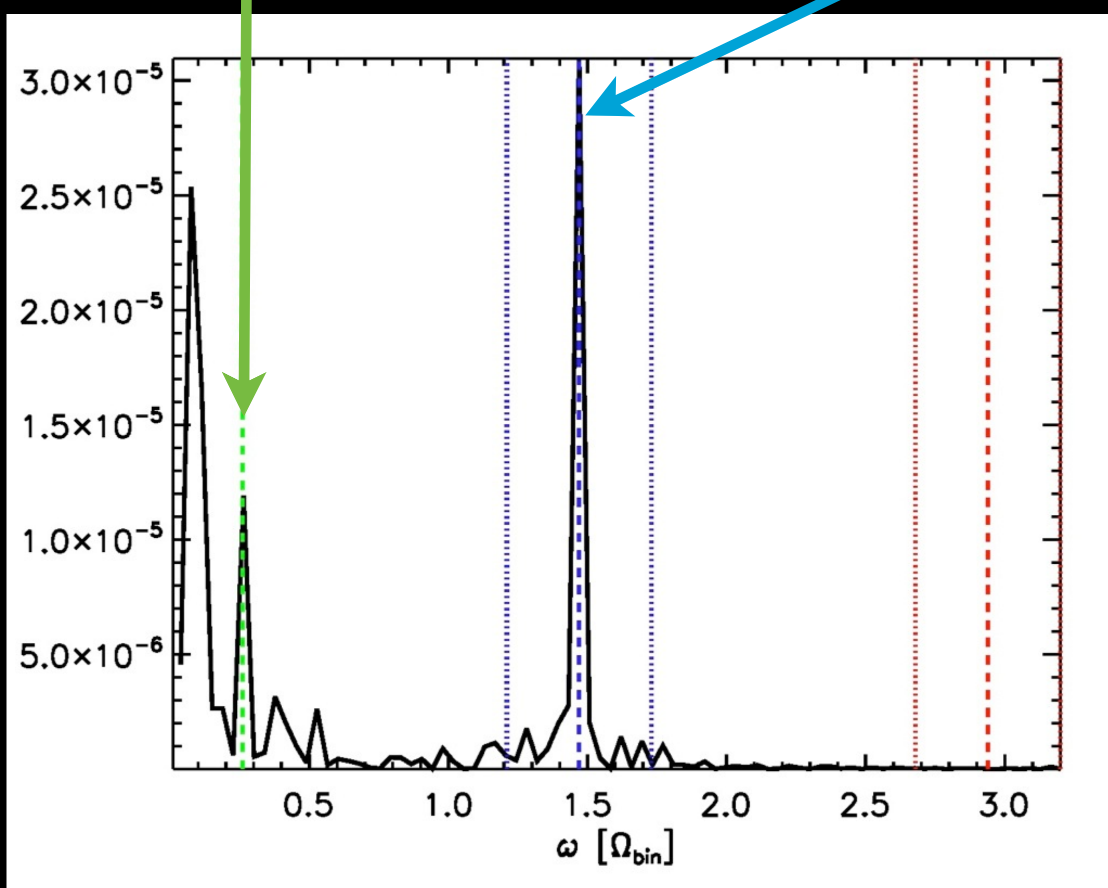
Noble++2012

Periodic Signal

$r_{\rm lump} \simeq 2.5a$

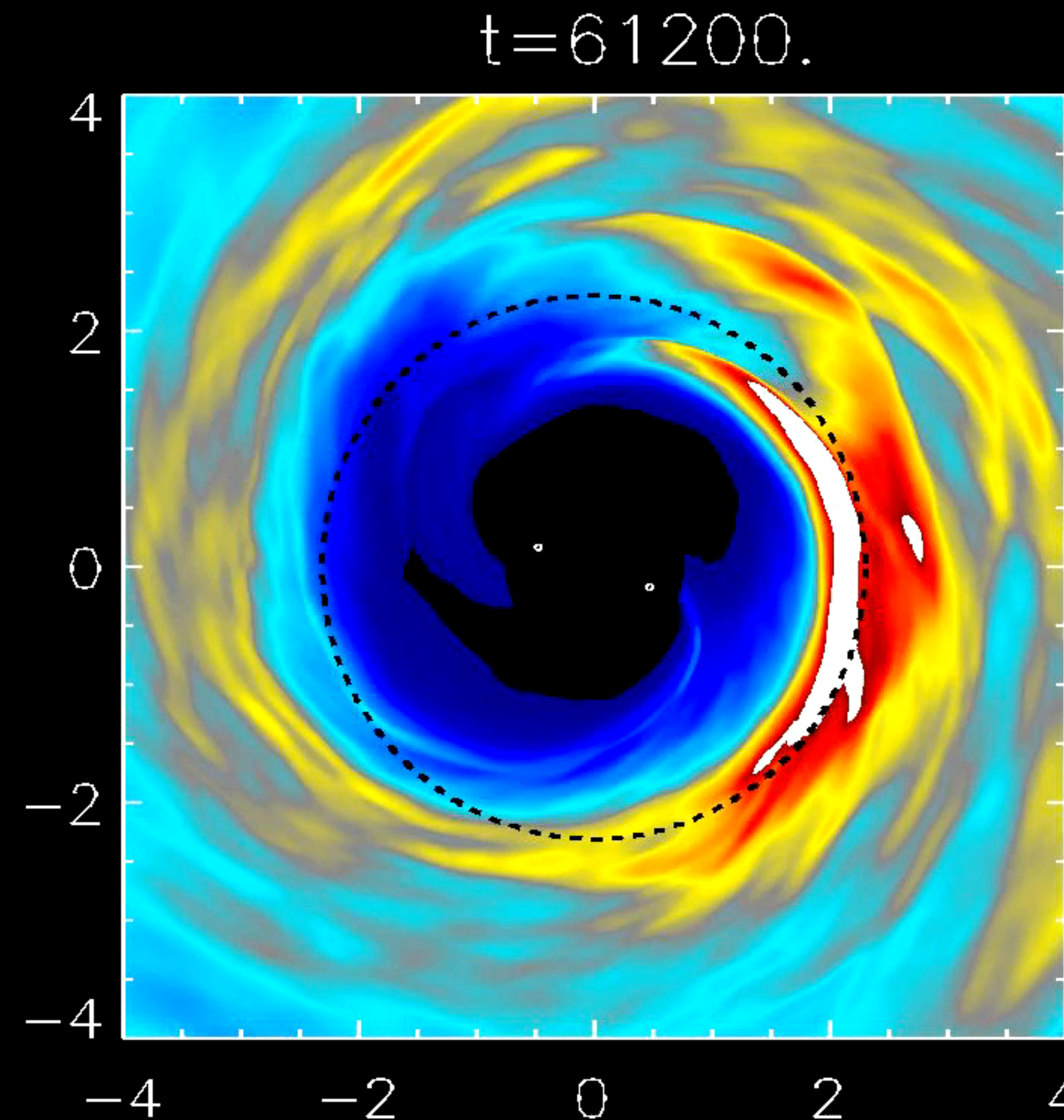
$\Omega_K(r_{\rm lump})$

$1.47\Omega_{\rm bin}$



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

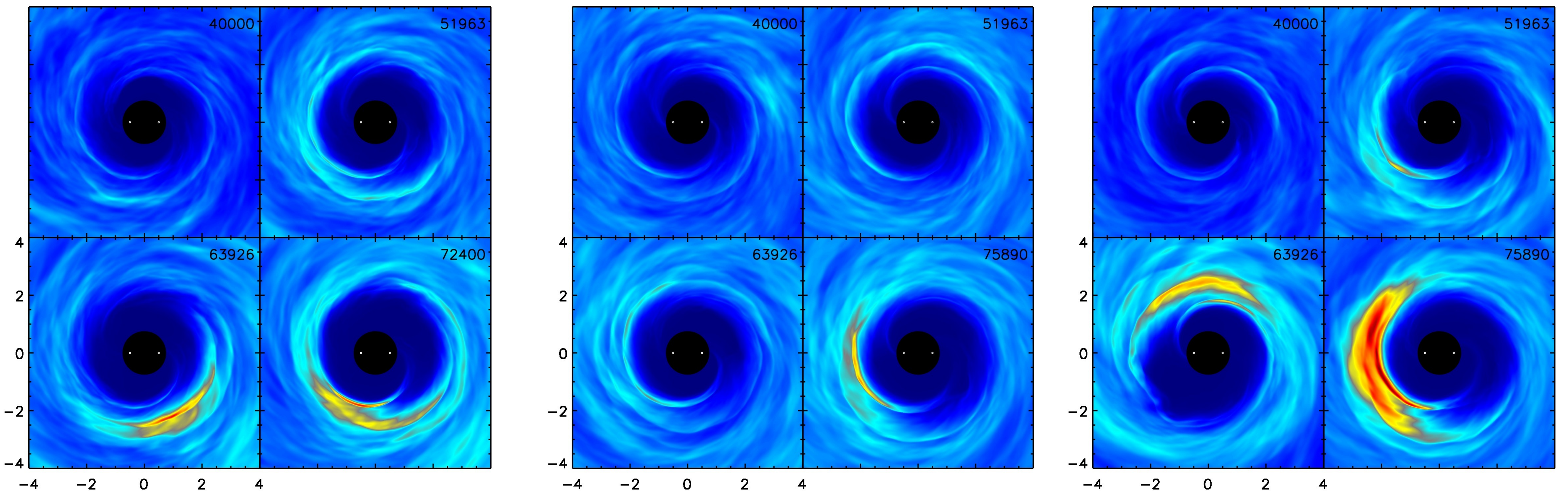
Surface Density



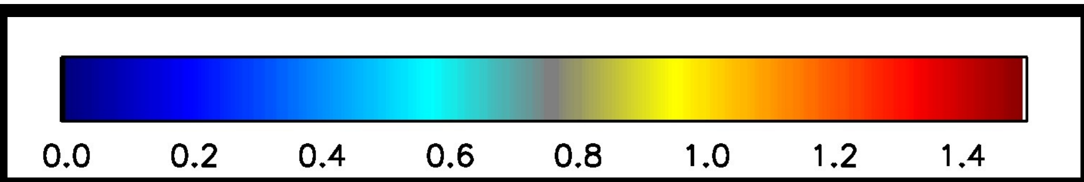
(in frame co-rotating with lump)

Variabality vs. Post-Newtonian Accuracy:

1.5PN	1.5PN-H	2.5PN
Same parameters thinner initial disk	Different parameters same initial thickness	Benchmark (Noble++2012)



Top-down view of Surface Density



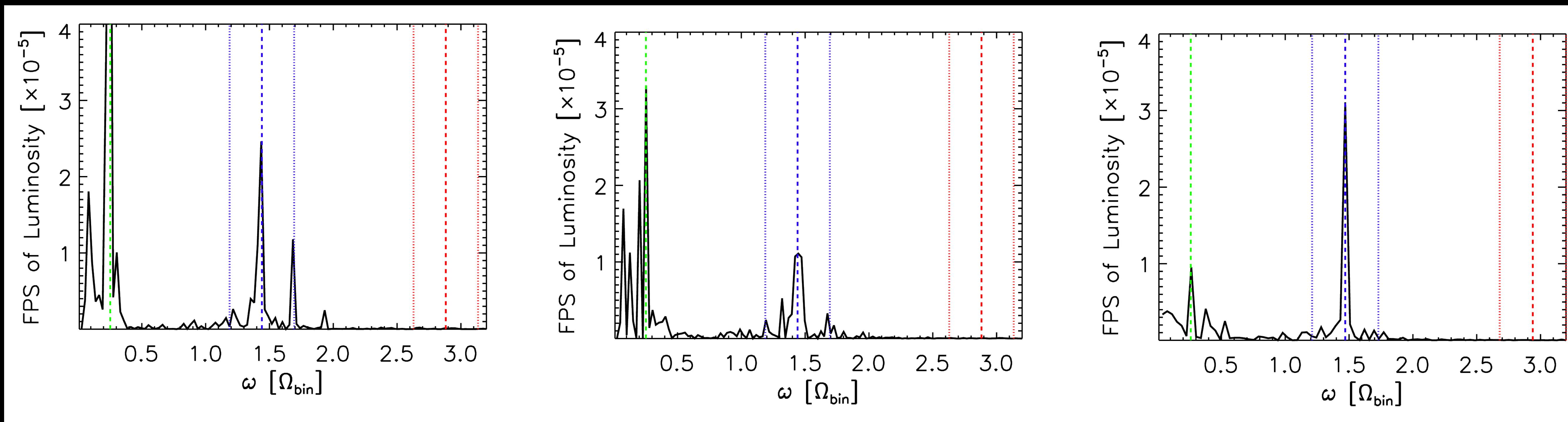
Less accurate metrics result in:

- Slightly weaker m=1 mode or over-density (lump) feature;
- Also, hints that thicker disks may weaken lump mode;

Zilhao++2015

Variabality vs. Post-Newtonian Accuracy:

1.5PN	1.5PN-H	2.5PN
Same parameters thinner initial disk	Different parameters same initial thickness	Benchmark (Noble++2012)



- Differences between PN orders is no larger than small differences in initial data that help determine the disks's evolution;
- These differences provide us with a measure of the systematic error involved in our predictions;
- MHD turbulence >> 2.5PN order terms at a=20M;

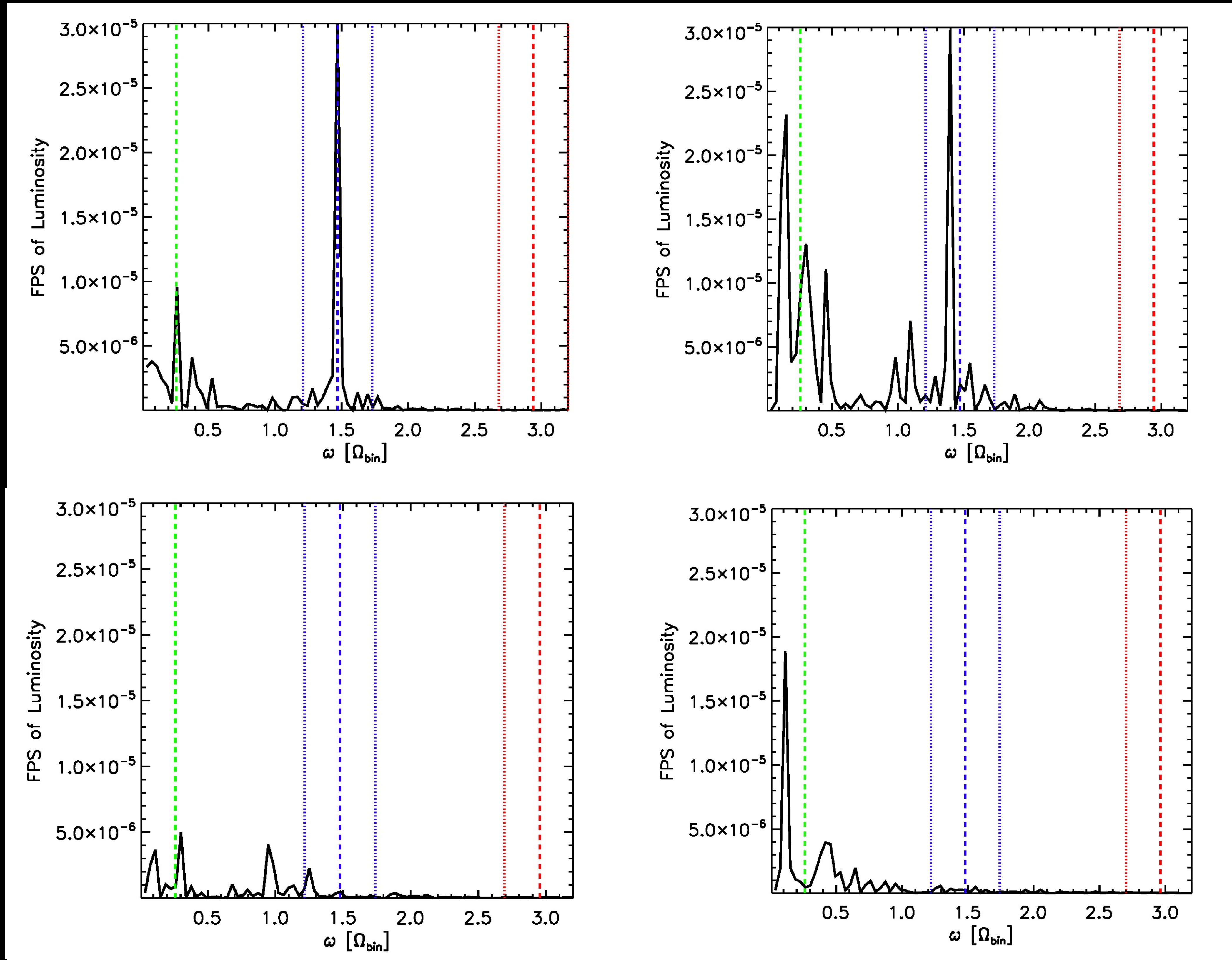
Zilhao++2015

Mass Ratio

Noble++in-prep

q=1

q=1/2



q=1/5

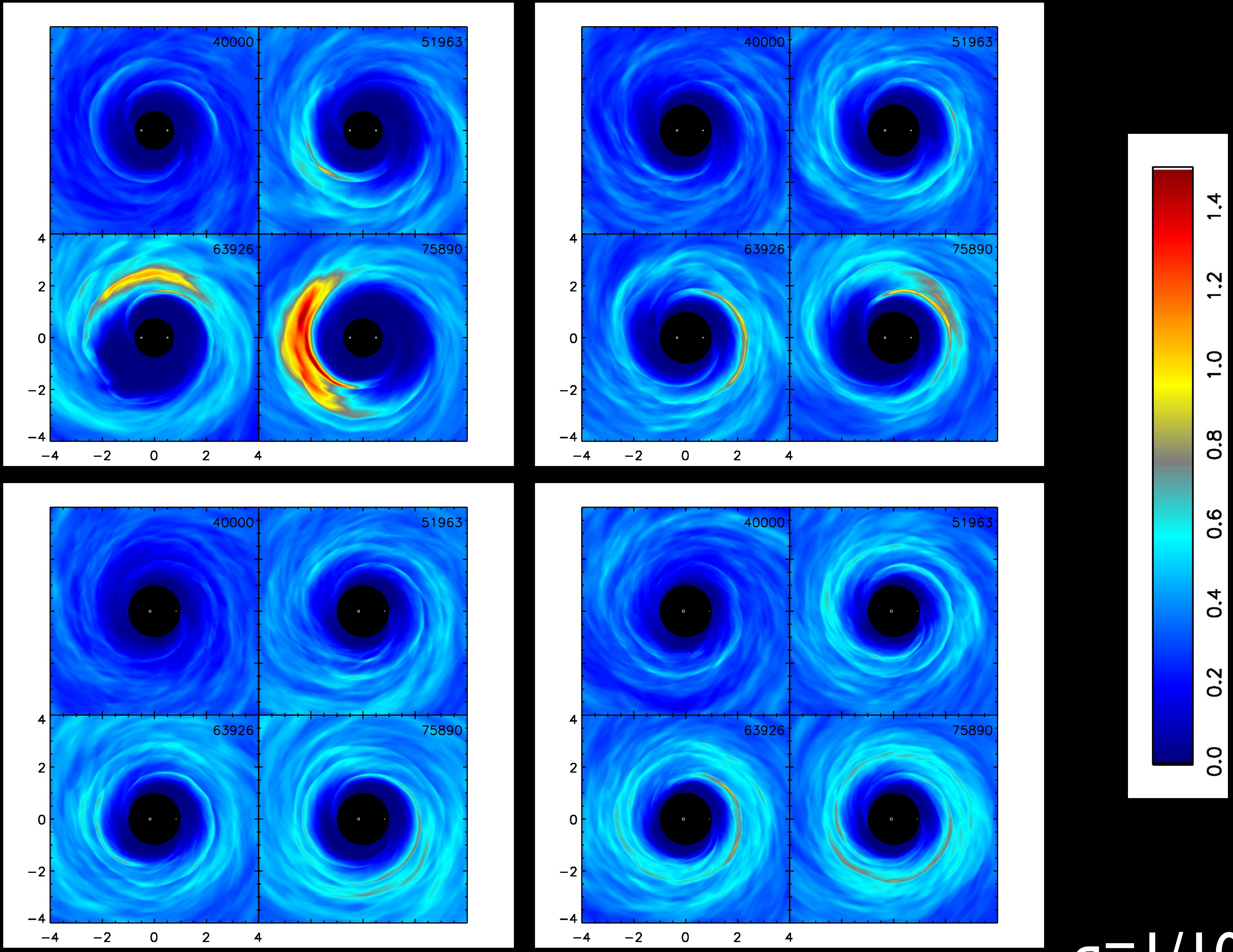
q=1/10

Mass Ratio

Noble++in-prep

q=1

q=1/2



q=1/5

q=1/10

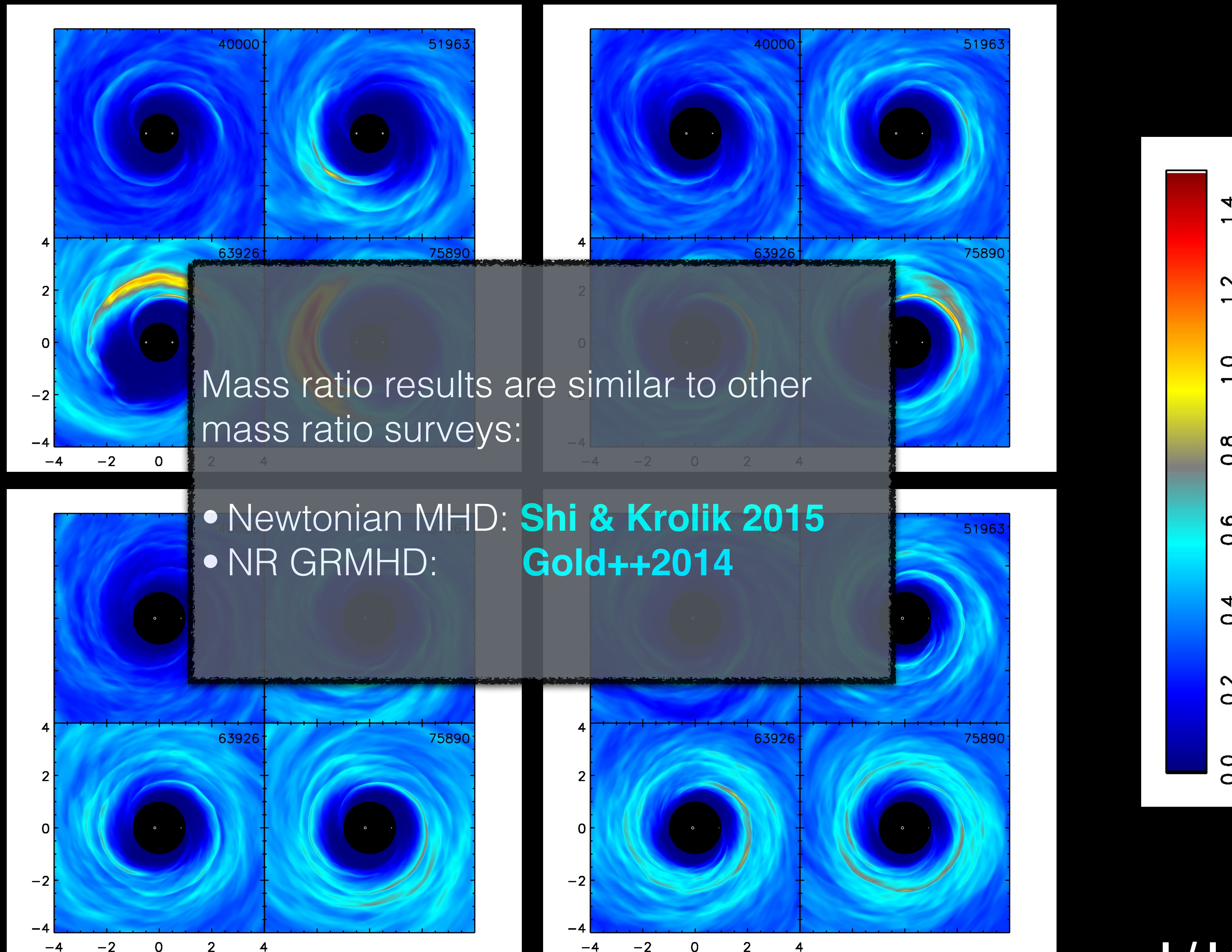
Top-down view of Surface Density

Mass Ratio

Noble++in-prep

q=1

q=1/2



Mass ratio results are similar to other mass ratio surveys:

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

q=1/5

q=1/10

Top-down view of Surface Density

The Lump Puzzle

Noble++in-prep

- Lump is also seen in:
  - Newtonian MHD (Shi & Krolik 2012,2015);
  - 2-d viscous hydrodynamic simulations (e.g.,D'Orazio++2012);

- Lump is coincident with degradation of "MRI Quality Factor" or resolution *within lump*;
  - Is it numerical? Do we lack the resolution to resolve the low B-field in the lump?
  - Is it artificial? Are we draining the region of sufficiently magnetized material?
  - Is it physical? Could the lump be a"dead zone" in which magnetic field is dissipated at a rate faster than can be brought in?

MRI Quality Factor:

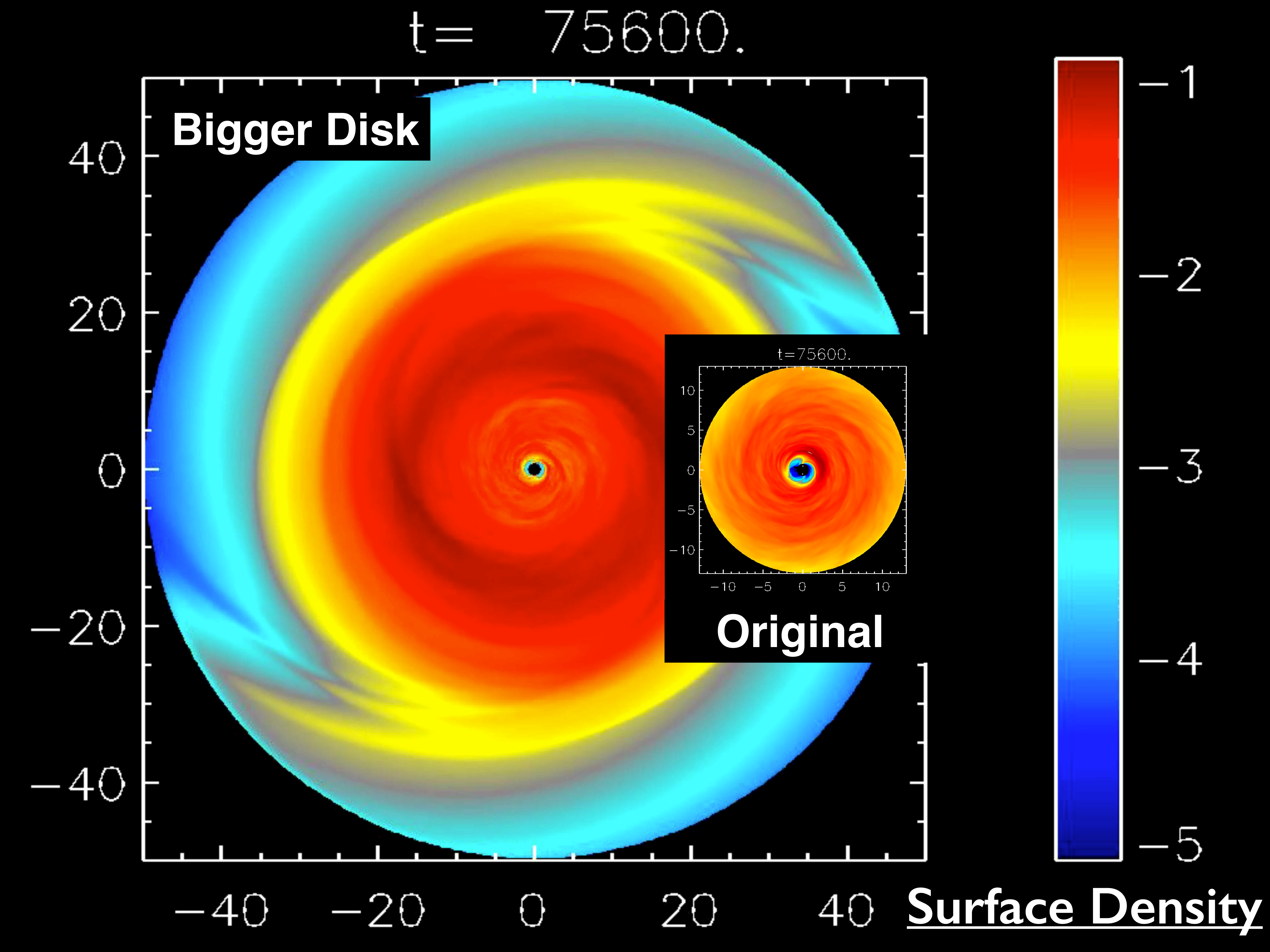
$$Q^{(i)} = \frac{2\pi\,|b^i|}{\Delta x^{(i)}\,\Omega_K(r)\,\sqrt{\rho h + 2p_m}}.$$

Noble++2010, Hawley++2011,2013

Strategy:

- **"Bigger Disk":**
  - Increase radial extent of the disk, keeping H/R the same;
  - 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.
  - Emulates proposed explanations of state transitions in LXRB disks.

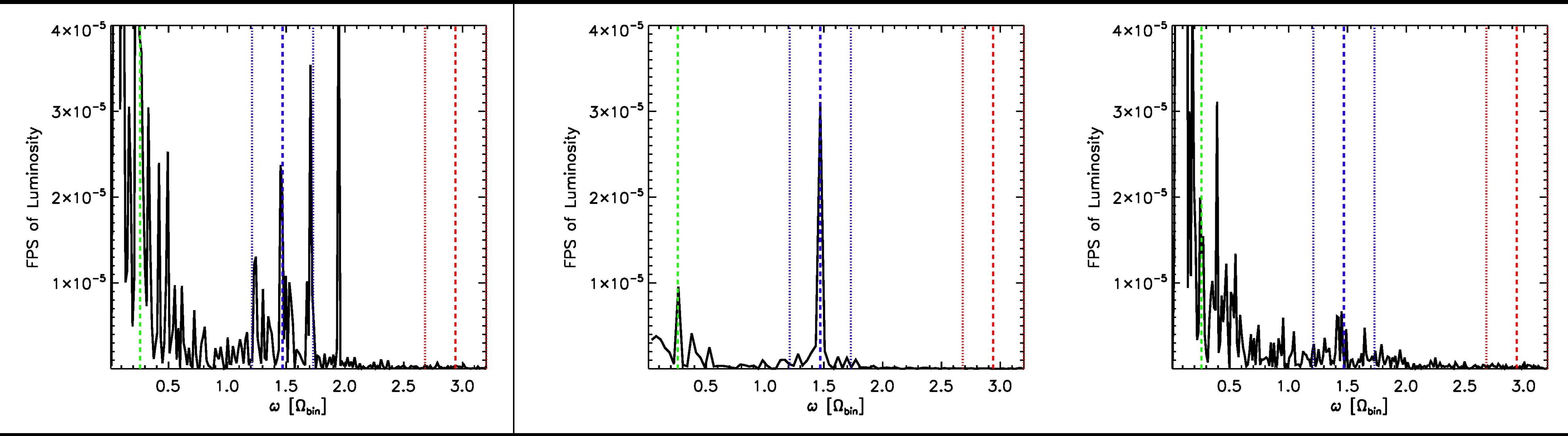


t= 75600.
Bigger Disk
40
20
0
−20
−40
−40
−20
0
20
40
t=75600.
10
5
0
−5
−10
−10
−5
0
5
10
Original
−1
−2
−3
−4
−5
Surface Density

Disk's State

Noble++in-prep

Bigger Disk | Original | Flux-Injected



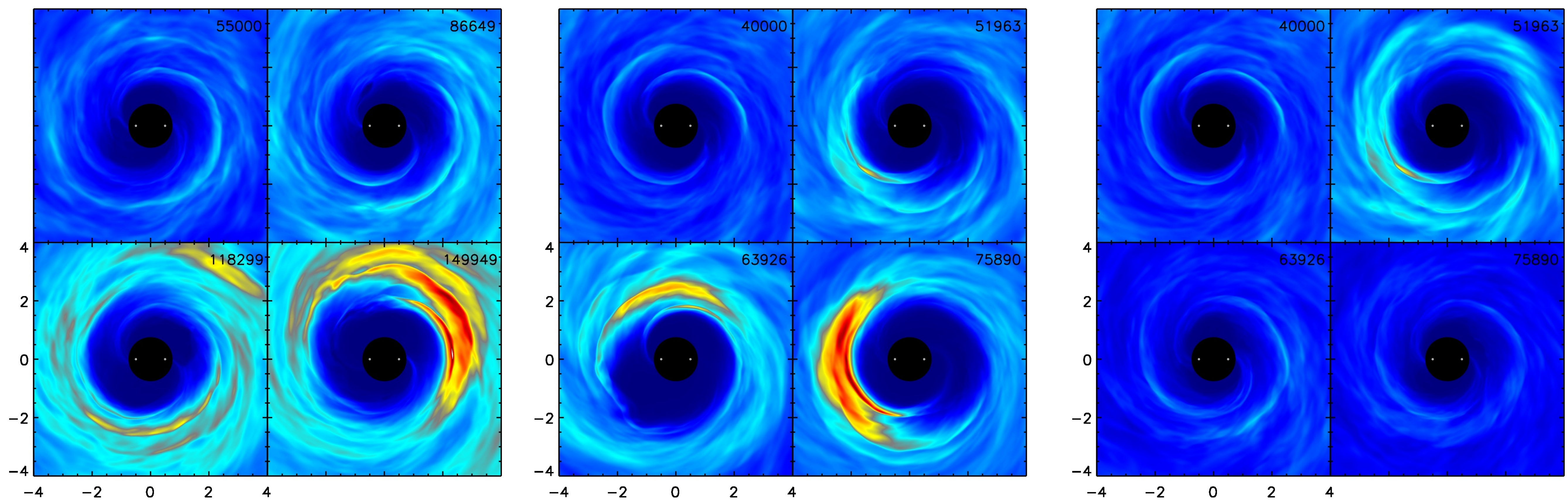
More magnetic flux led to:

- Without lump, less coherent temporal power spectrum, resembling more a slightly bent power law like those seen in single black hole disks.
- Richer spectral including more beat mode present with a larger reservoir.
- Periodic signals are present as long as there is a strong m=1 (lump) mode.

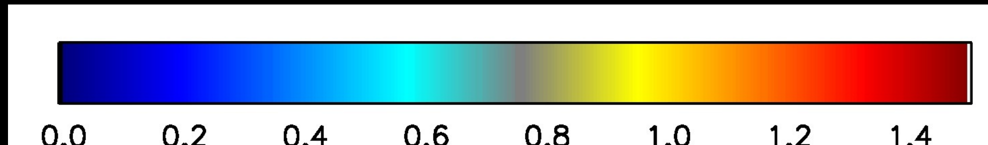
Disk's State

Noble++in-prep

Bigger Disk | Original | Flux-Injected



Top-down view of Surface Density



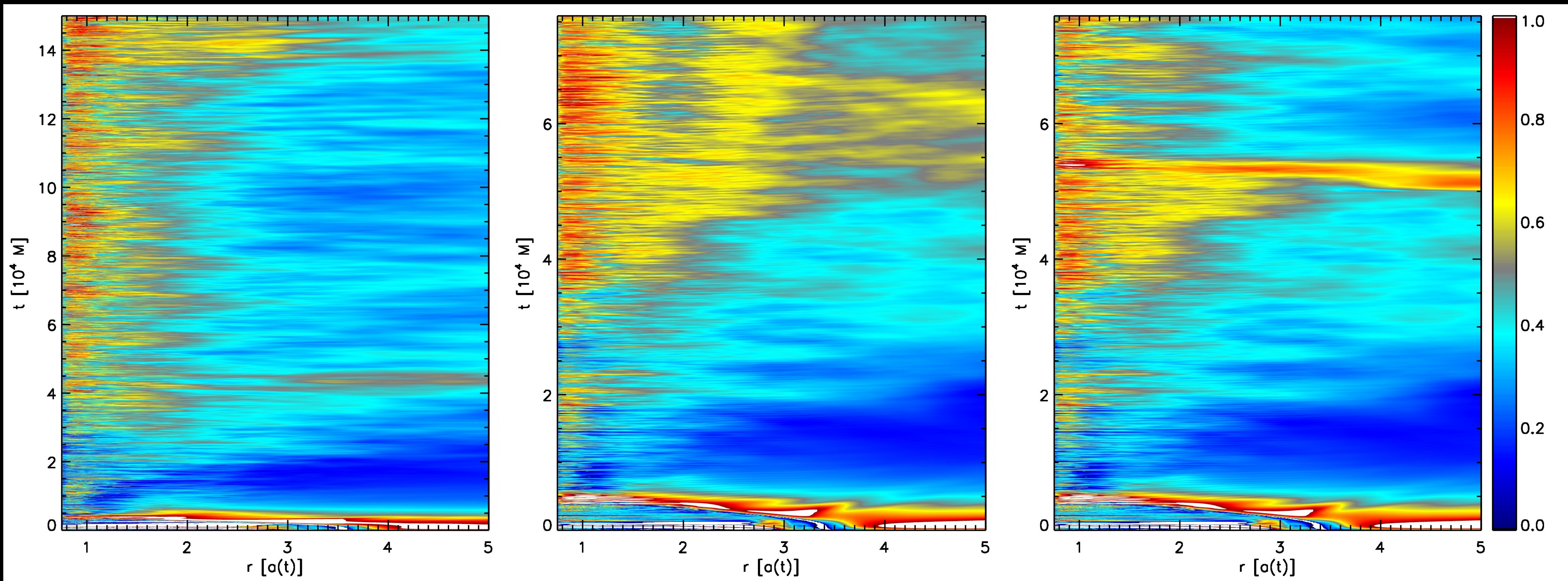
More magnetic flux led to:

- Injected flux erased and prevented eventual development of m=1 mode.
- Bigger disk developed lump later, once surface density reached its steady state.

Disk's State

Noble++in-prep

Bigger Disk Original Flux-Injected



$$\alpha_{\rm mag} = \frac{\langle B^r B_\phi \rangle}{\langle p_{\rm mag} \rangle} > 0.4 \Rightarrow$$ "Resolved MRI Turbulence"

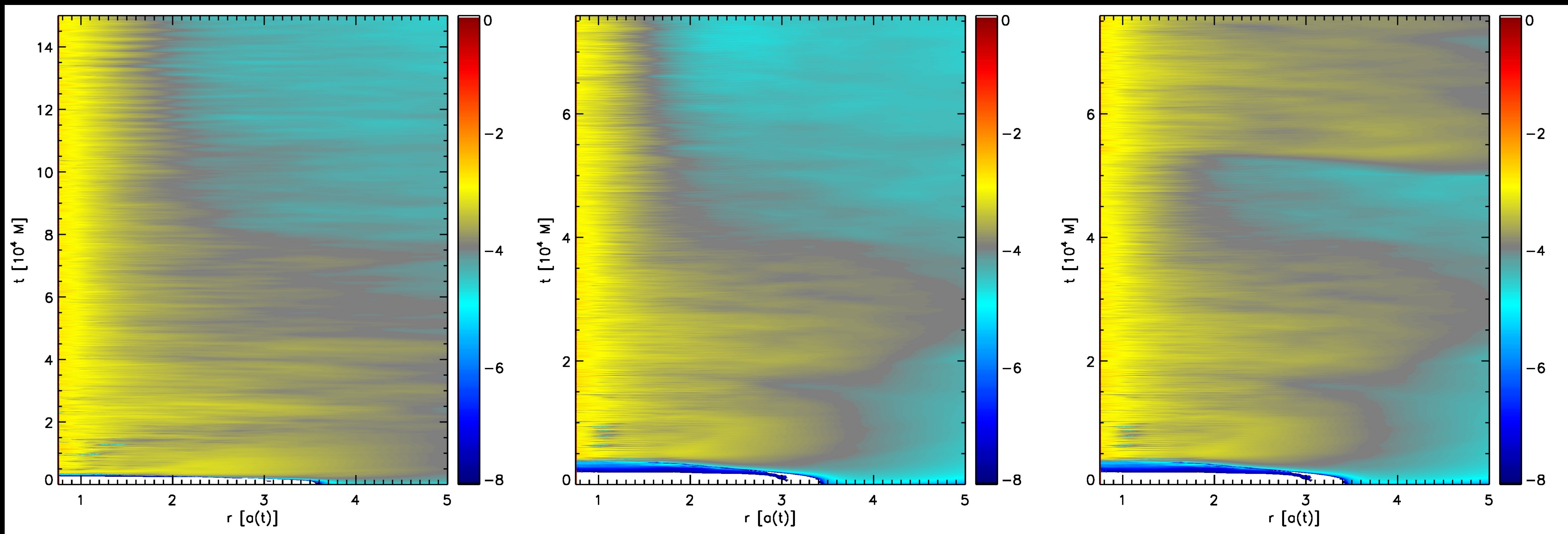
Guan & Gammie 2009, Sorathia++2012, Hawley++2011,2013

- Disks have resolved MRI throughout.
- No transition seen in "Bigger Disk" run across transition to the lump phase.
- Equivalent resolution in run without the lump.

Disk's State

Noble++in-prep

Bigger Disk   Original   Flux-Injected



Average Specific Stress = $\frac{\langle B^r B_\phi \rangle}{\langle \rho \rangle} \lesssim 10^{-4} \Rightarrow$ **Lump Formation**

- From gradual redistribution of mass and flattening of surface density from initial conditions, stress per unit mass decreases.
- Transition to lump phase is evident, appears there is a threshold ~ 1e-4 below which lump forms;.
- We are trying to understand original of the this threshold value.

Summary & Conclusions

- Our 3-d MHD, PN-regime simulations develop a high-Q signal that is non-trivially connected to the binary's orbit, but tied to the period of the beat mode between lump's orbit and the binary's orbit.

- The signal's strength degrades with decreasing mass ratio, implying that it can help diagnose properties of the binary, and it disappears altogether between $1/5 < q < 1/2$;

- At a separation of 20M, with equal-mass binaries, differences in the metric at 1.5PN and 2.5PN orders are smaller than stochastic and systematic uncertainties, with PN-accuracy effects being even smaller for smaller mass ratios.

- Over density m=1 mode (lump), develops while disk's MRI is resolved and for different conditions, implying that the lump is physical and typical for similar disks.

- Beat signal is expected as long as the stress per unit mass is not too large, i.e. the disk is magnetically-submissive.

The Future is Bright!

Stay-tuned to this channel for Dennis Bowen's talk on minidisk dynamics next!

Visualization by M. Vanmoer (NCSA)