Lighting Up Magnetized Mini-Disk Simulations about Binary Black Holes

1st LISA Astrophysics Working Group Workshop
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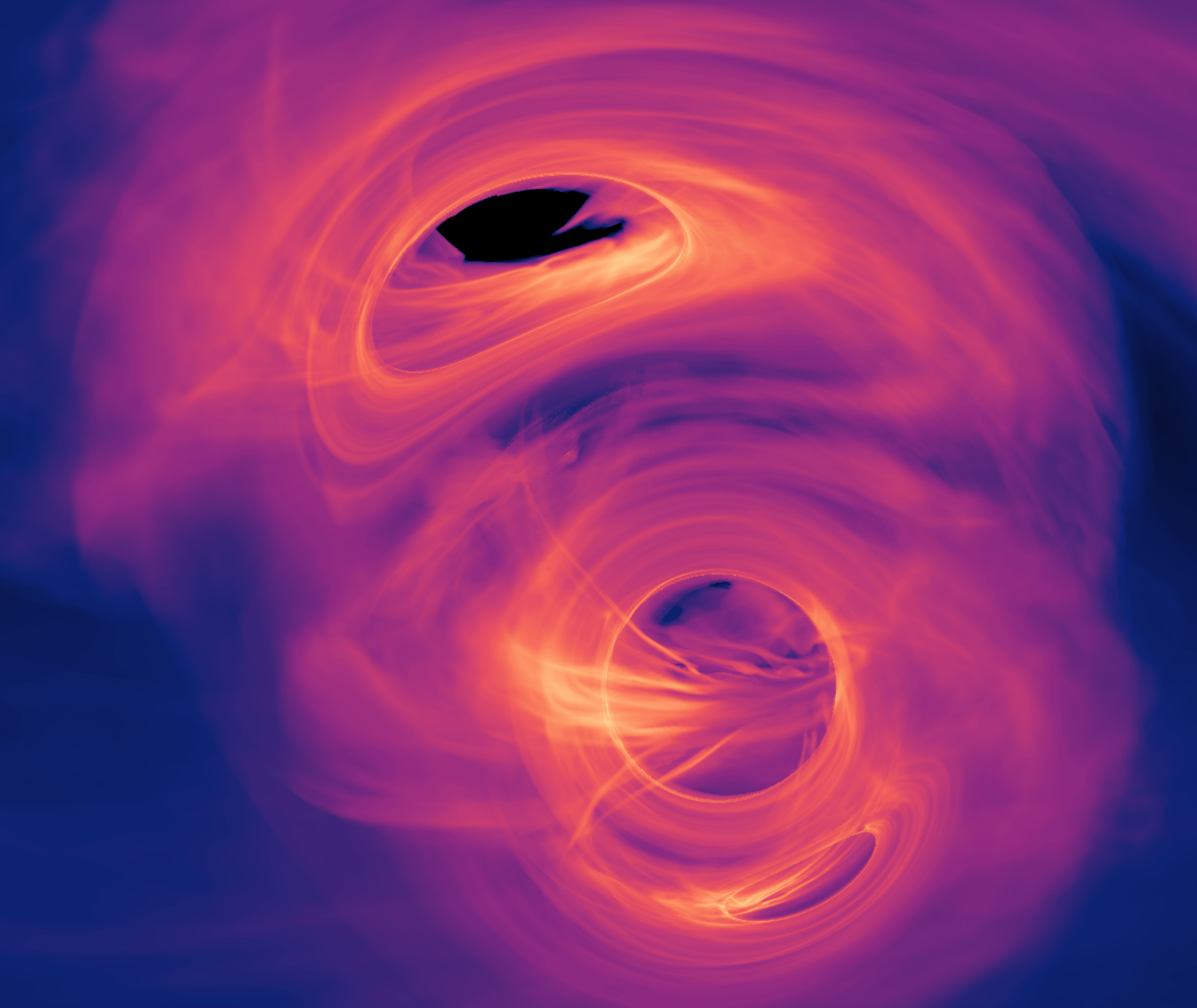

Based on:

- d'Ascoli++2018; arxiv:1806.05697
- Bowen++2017, Bowen++2018
- Noble++2012, Mundim++2014
- Zilhao & Noble 2014, Zilhao++2015

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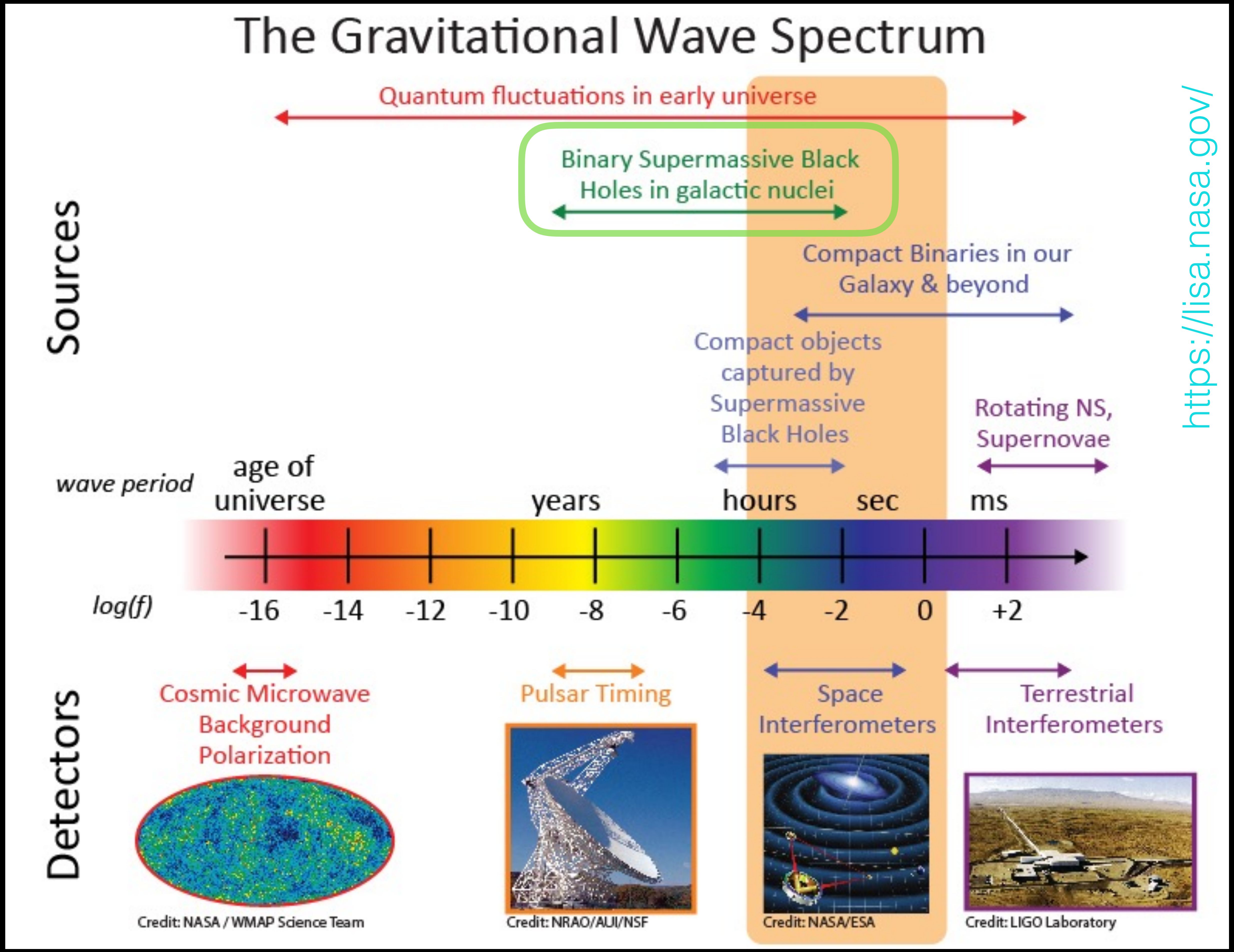
Why Binary SMBHs?

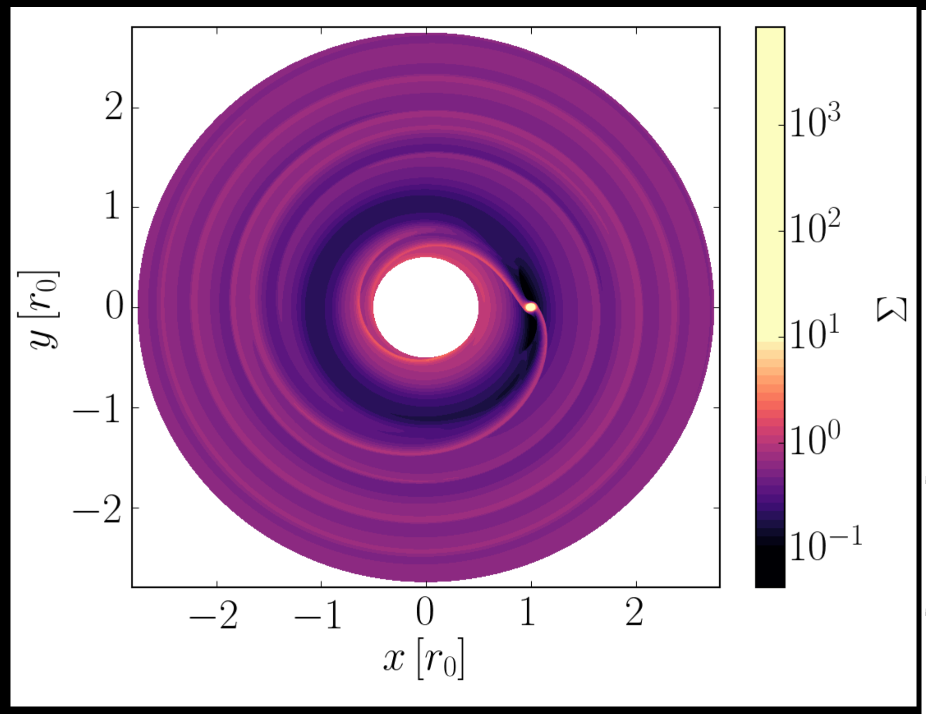
- Binary AGN are a primary multi-messenger source for LISA and PTA campaigns.
- Likeliest EM-bright binary black hole system, as embedded binaries in AGN disks may be too dim w.r.t. their host.
  - —> Best candidate for exploring plasma physics in the strongest and most dynamical regime of gravity.



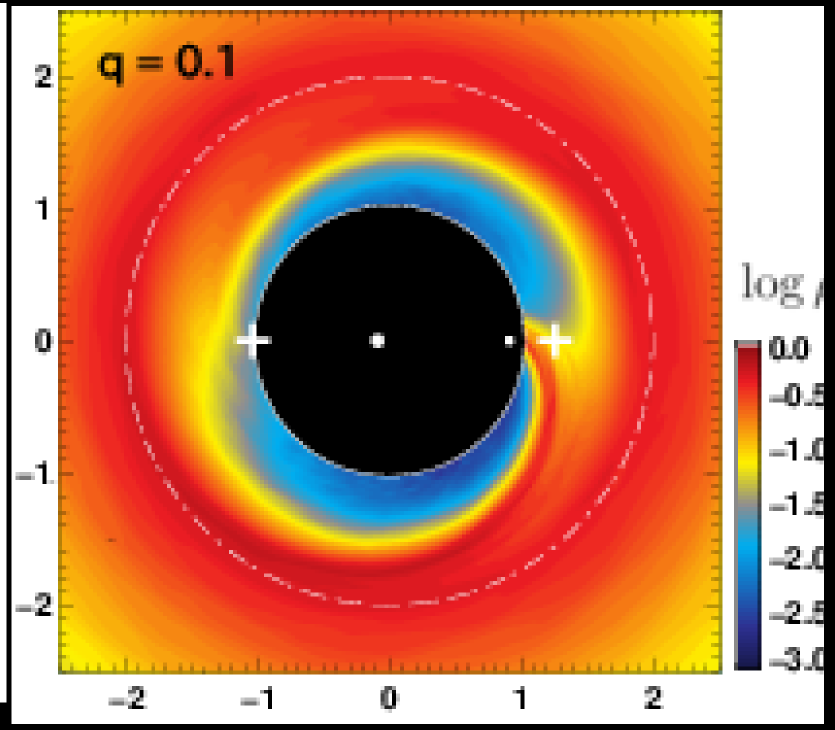
- Little is really known theoretically of these systems, in part because it is a tough problem:
  - Initial conditions >> size of formed binary >> horizon size >> turbulence scale
  - Requires MHD with dynamic/numerical GR, old hat by now…

Strategy & Techniques

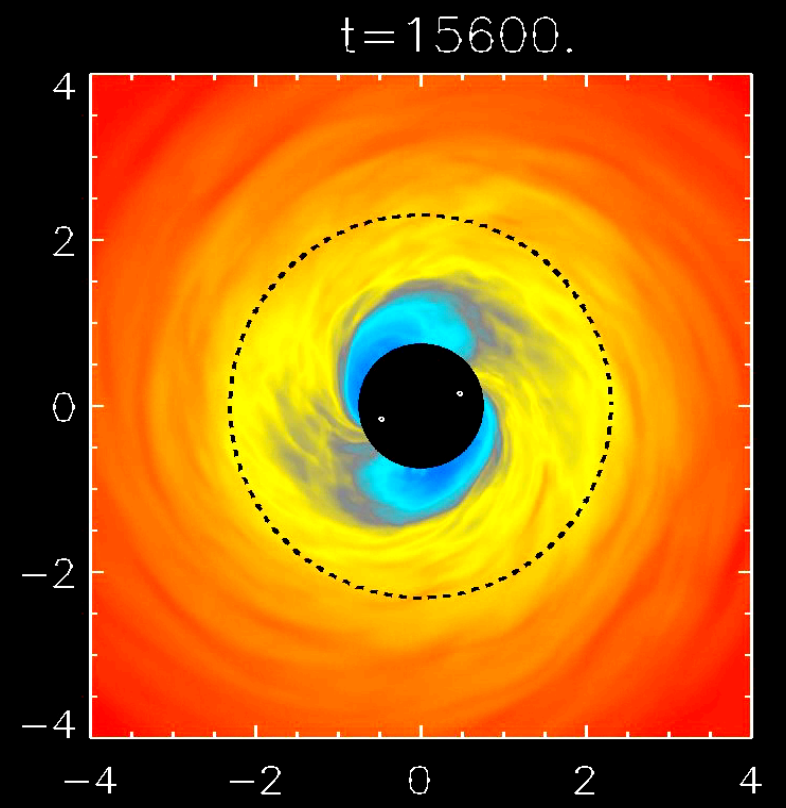
Hopkins, Hernquist,
Di Matteo, Holley-Bockelmann,
Springel



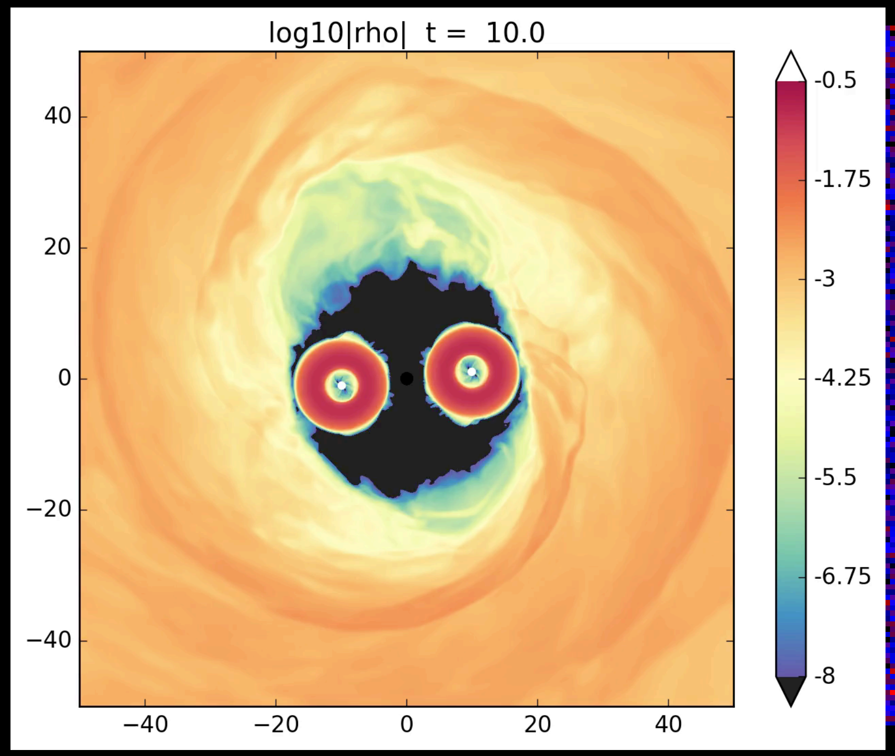
Derdzinski++2018,
Farris++2014, Lup++, etc…



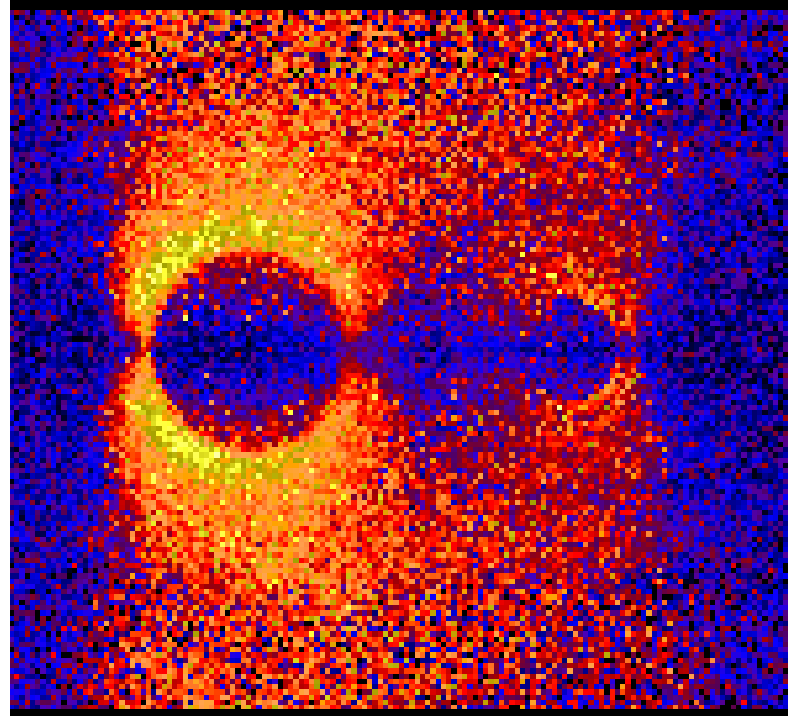
Shi++2014



Noble++2012

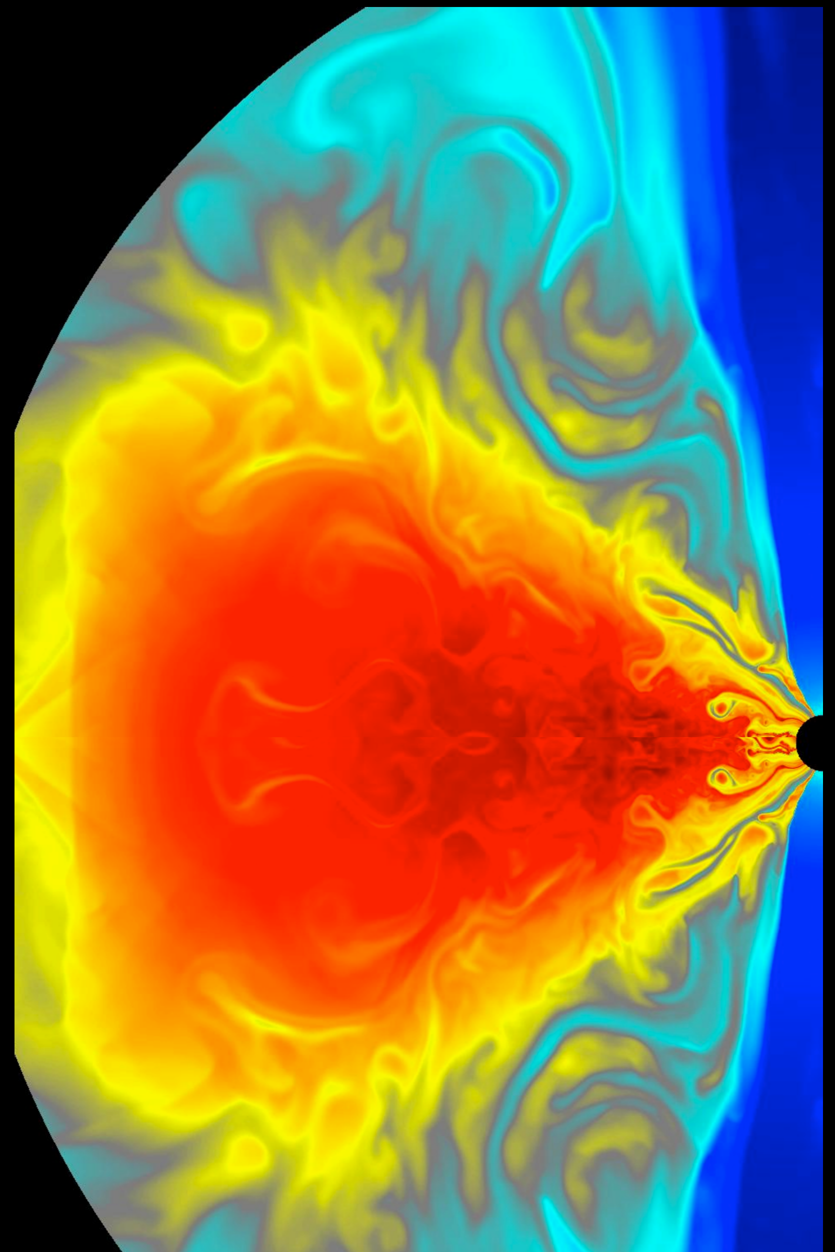


Bowen++2017b



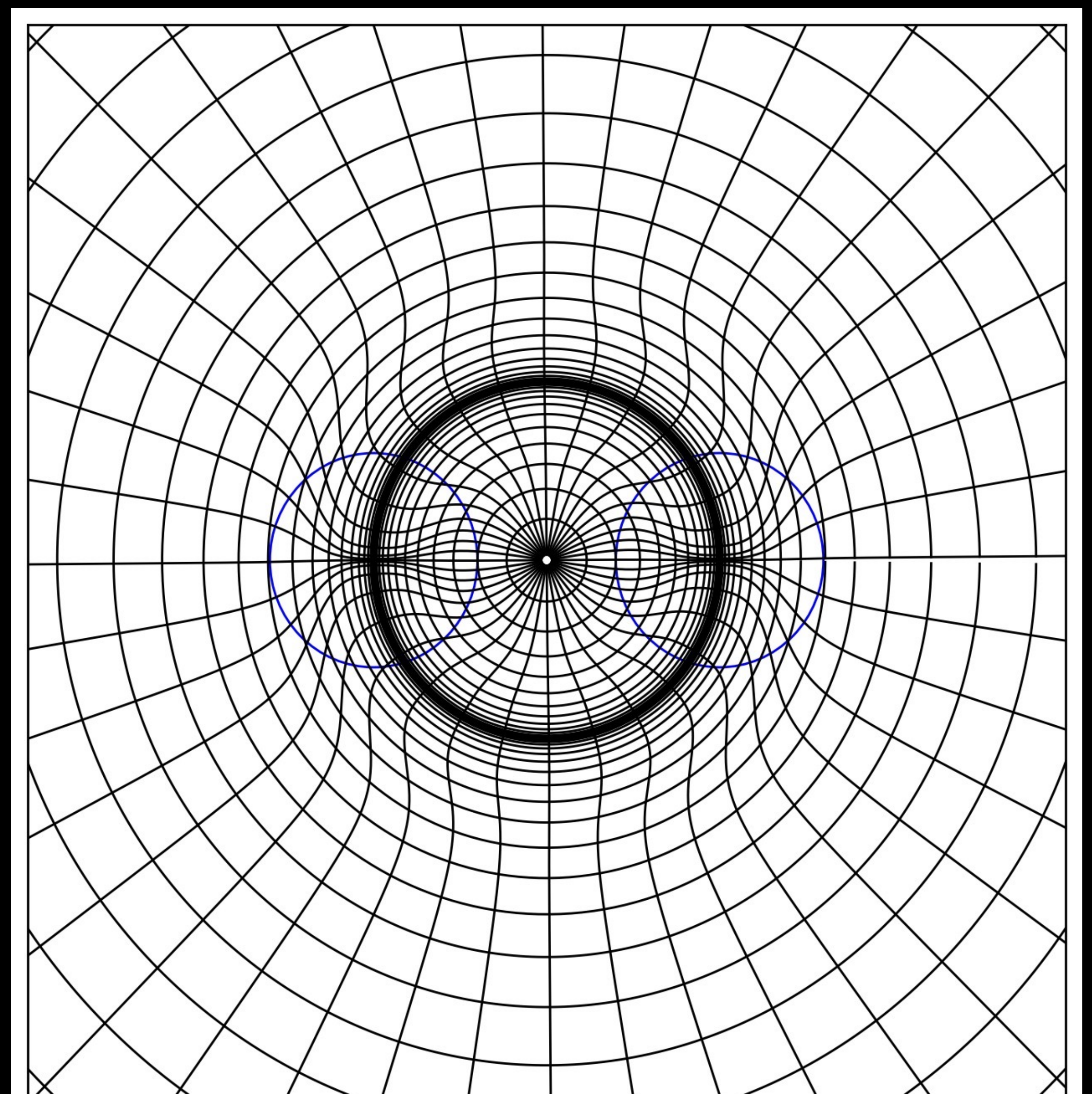
Kelly++2017
Gold++2014

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;

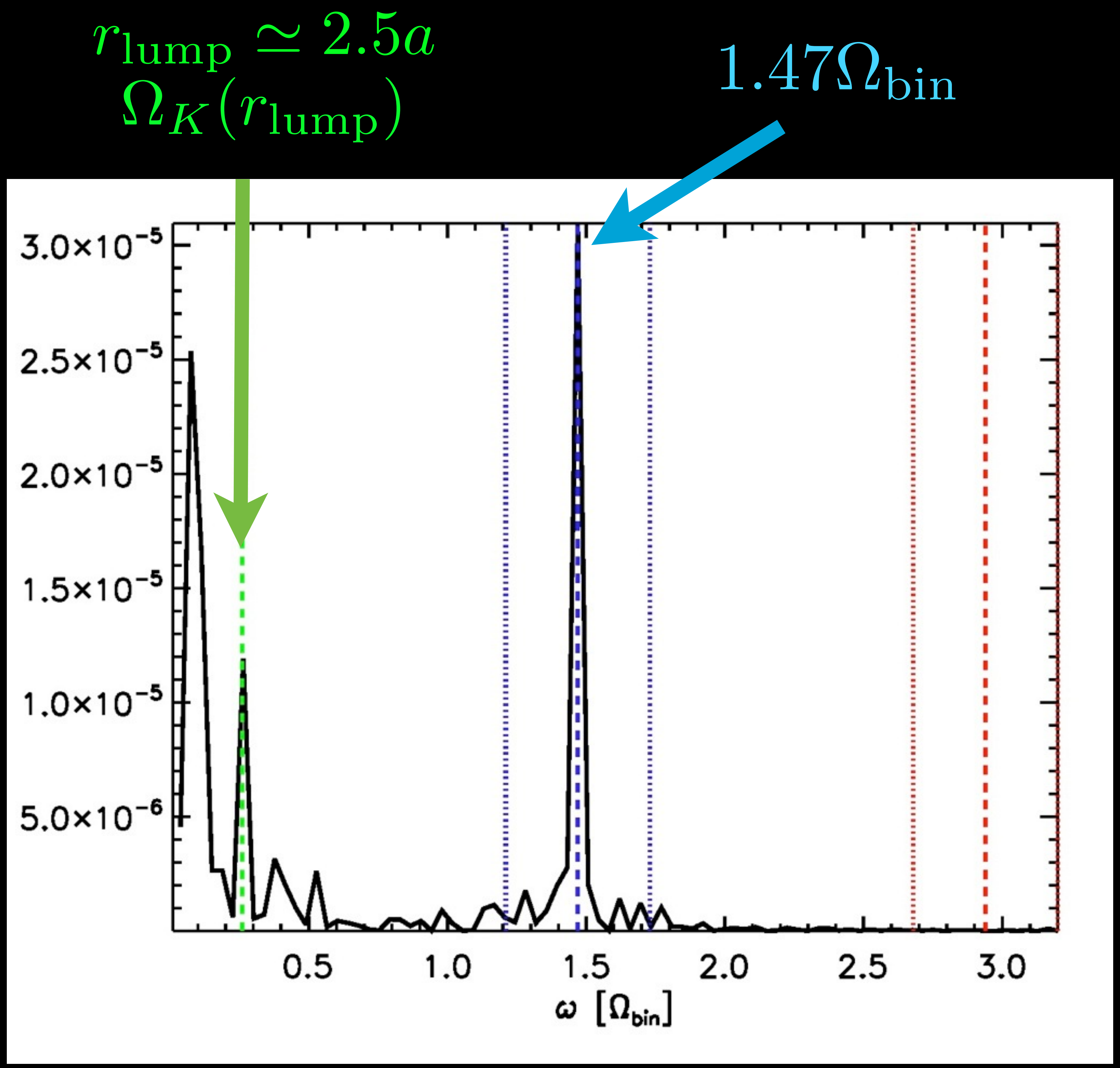
➡ Able to evolve accreting binaries while resolving the MRI and MHD dynamics at the scale of the event horizons in the inspiral regime—***key for establishing pre-merger conditions***.



MHD Simulations Predict a New EM Signature:

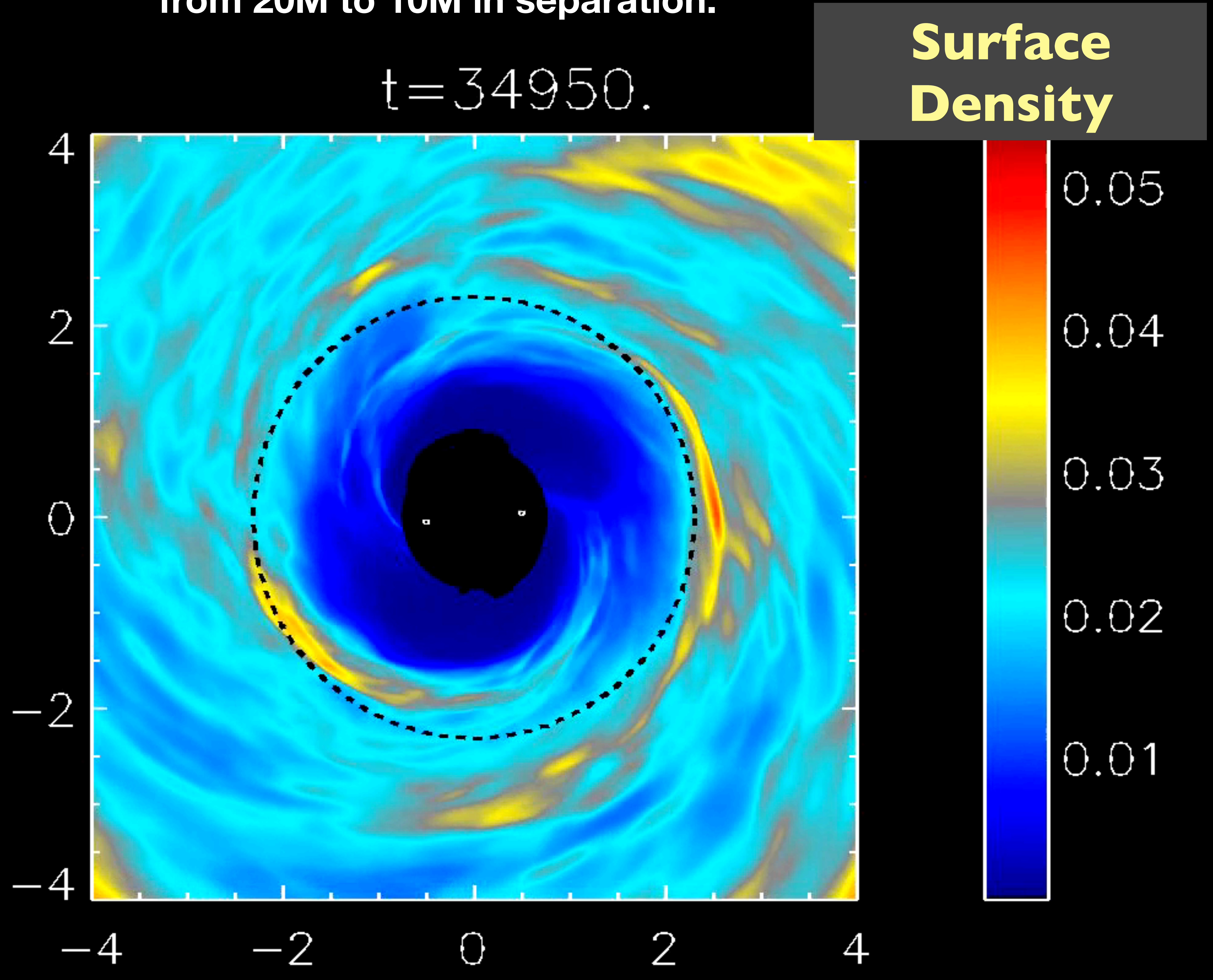
Noble++2012

Periodic Signal



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

- Gas follows binary as it shrinks from 20M to 10M in separation.



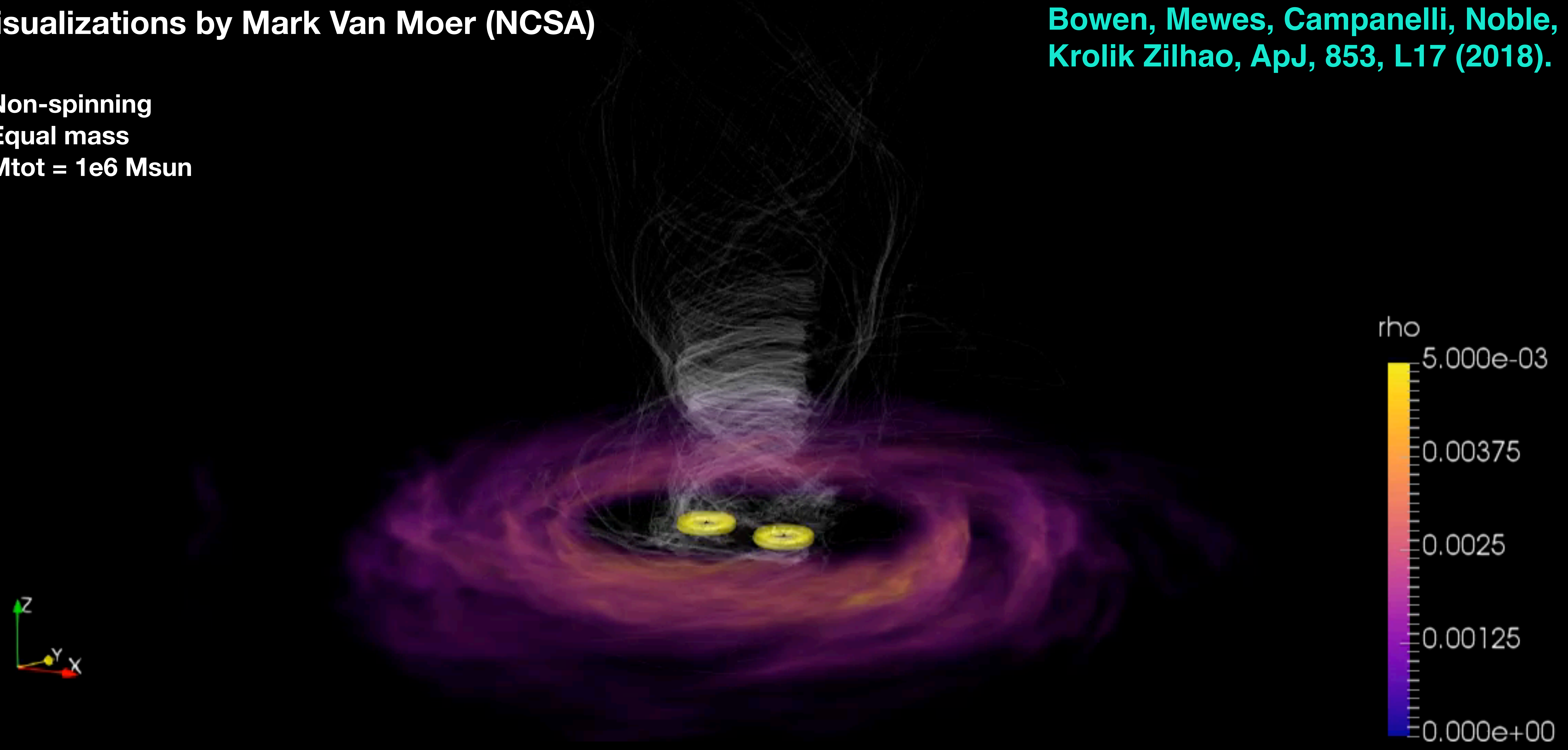
(in frame co-rotating with lump)

3-d GRMHD Mini-disk Evolutions

Visualizations by Mark Van Moer (NCSA)

Bowen, Mewes, Campanelli, Noble, Krolik Zilhao, ApJ, 853, L17 (2018).

Non-spinning
Equal mass
Mtot = 1e6 Msun



3-d GRMHD Mini-disk Evolutions

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GR Radiative Transfer Methodology

d'Ascoli, Noble, Bowen, Campanelli, Krolik, Mewes, ApJ, 865, 140 (2018).

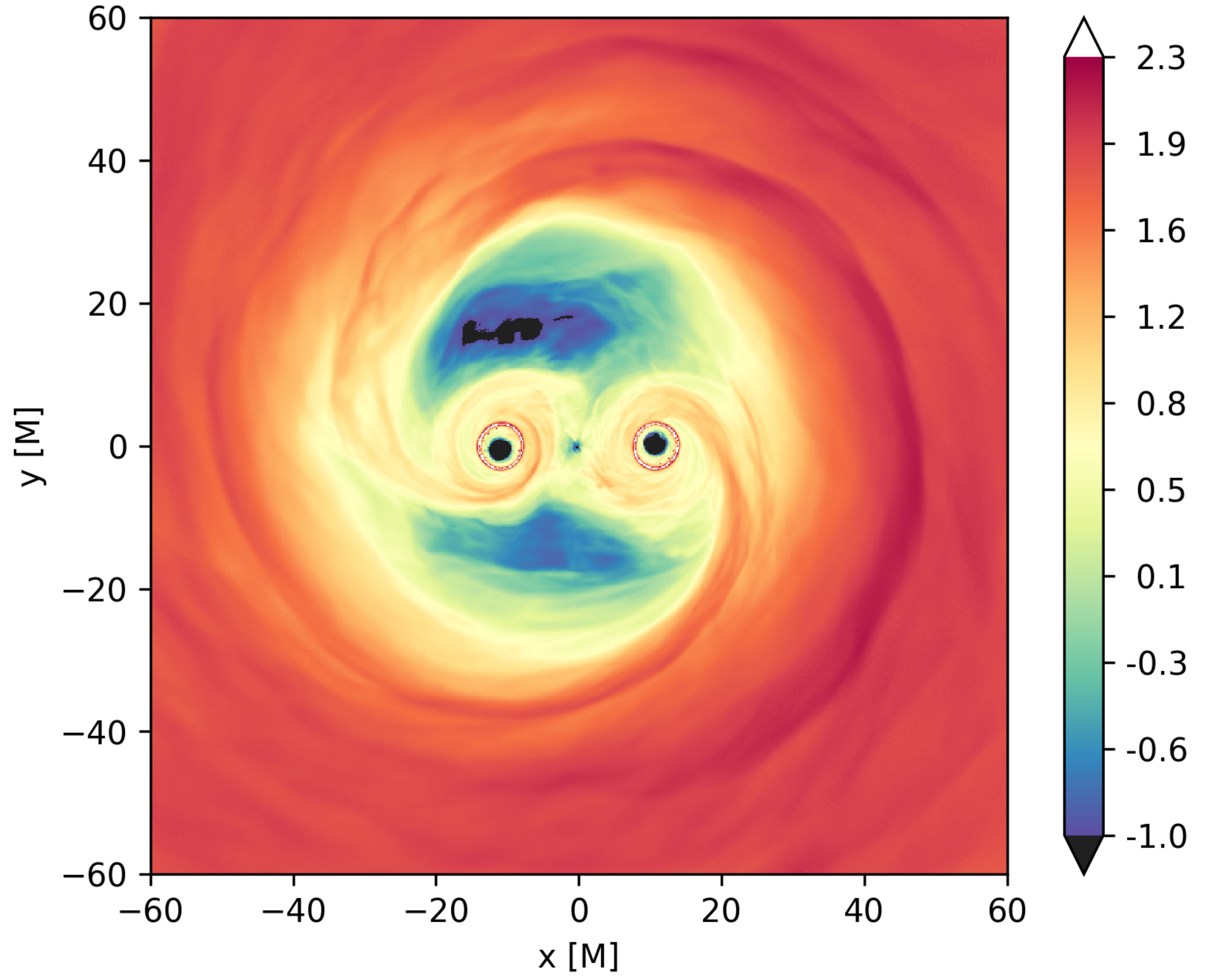
Thermal Photosphere: $$\frac{\partial I}{\partial \lambda} = j - \alpha I$$

$$I_\nu = B_\nu(\nu, T_{\rm eff}) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT_{\rm eff}}} - 1}.$$

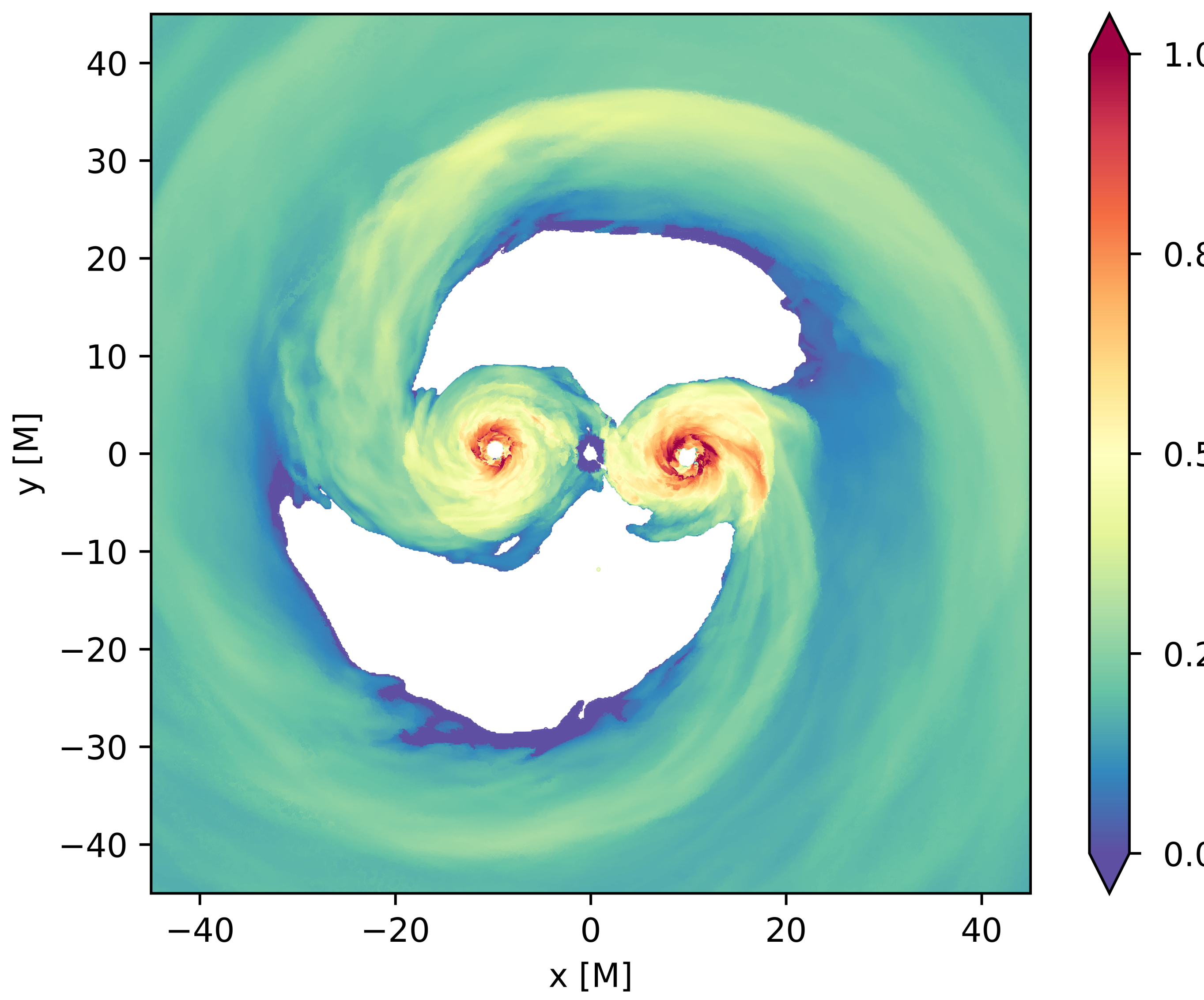
Non-thermal Coronal Emissivity: $$j_\nu \propto \mathcal{W}_\nu = \left(\frac{h\nu}{\Theta}\right)^{-1/2} e^{-\frac{h\nu}{\Theta}}$$

$$\Theta = kT/m_e c^2 = 0.2$$

Trakhtenbrot++2017
Krolik 1999, Roedig++2014



Log10 Optical Depth
Grey Thomson Opacity



Map of Photosphere's Location & Temperature

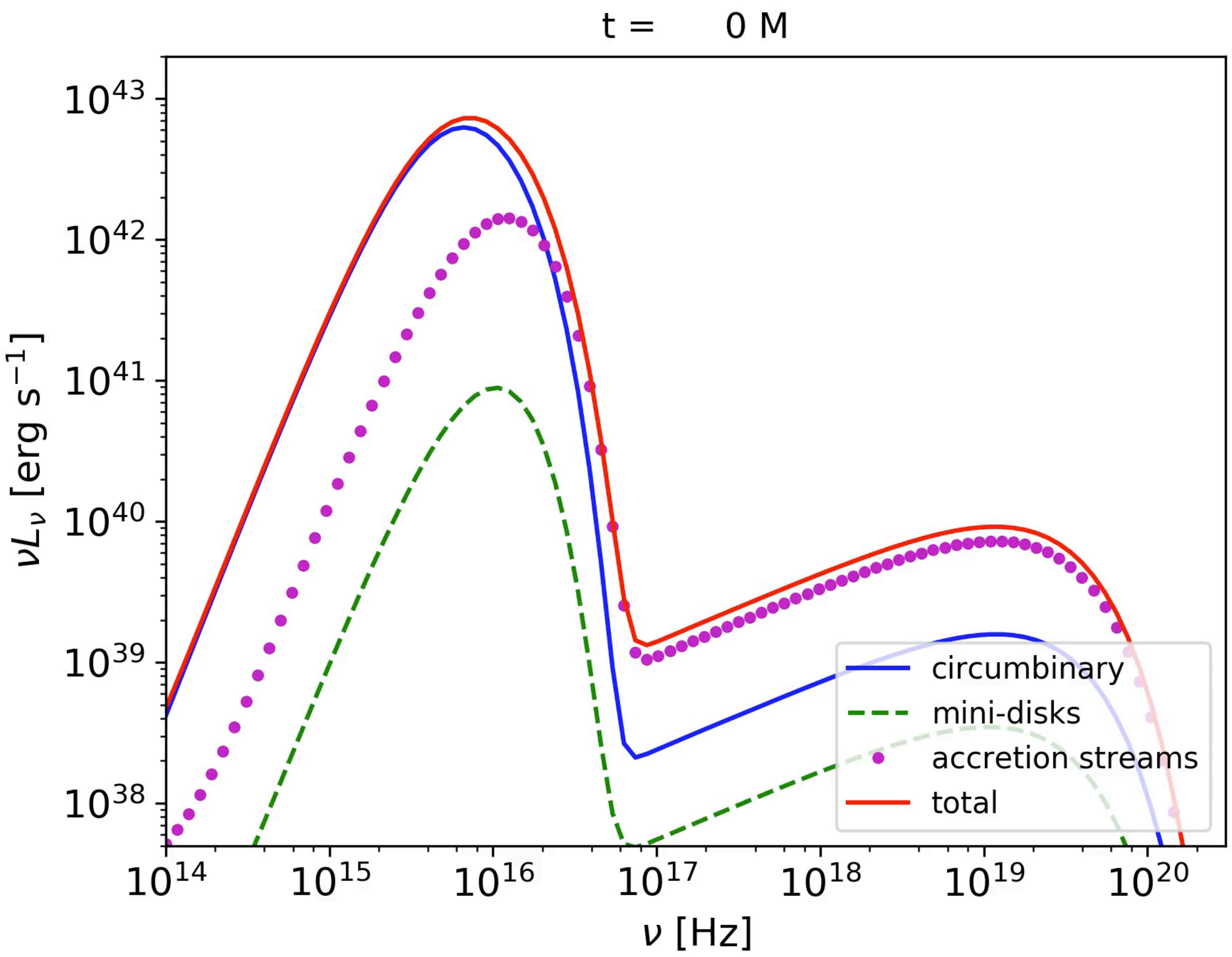
- **Radiative transfer integrated back along geodesics.**
- **Photons starting at photosphere start as black-body.**
- **Above photosphere, corona emission modeled as non-thermal component with temperature 100 keV.** $\dot{m} = 8 \times 10^{-4}$
- **Explore opt. thin and thick cases.** $\dot{m} = 0.5$

- **3-d dynamic simulation data acts as source;**
- **Local cooling rate = local bolometric emissivity;**
- **Emissivity ignored in low-density regions in which scattering processes are important (and unavailable to us for now);**


Energy Spectrum vs. Time
Face-on View,
Optically Thick Case
UV
X-rays

Energy Spectrum vs. Time

Face-on View, Optically Thick Case



- **Gap in UV not obvious (Roedig+ +2014).**
- **Though UV peak is broadened by mini-disk emission.**
- **Higher X-ray luminosity fraction than typical AGN:**
  - **Shocked gas from stream/mini-disk interaction.**

Angle Dependence

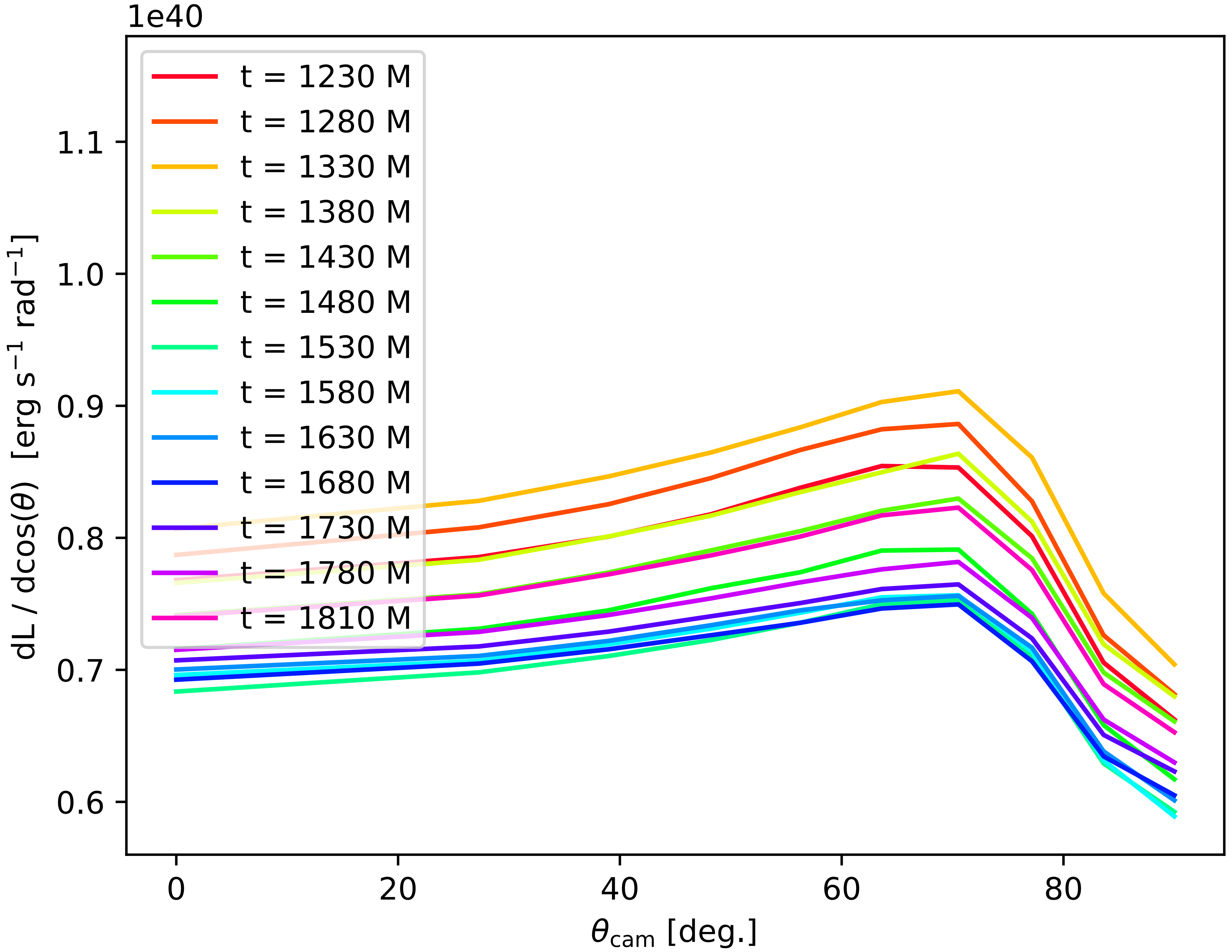
Optically Thin Case

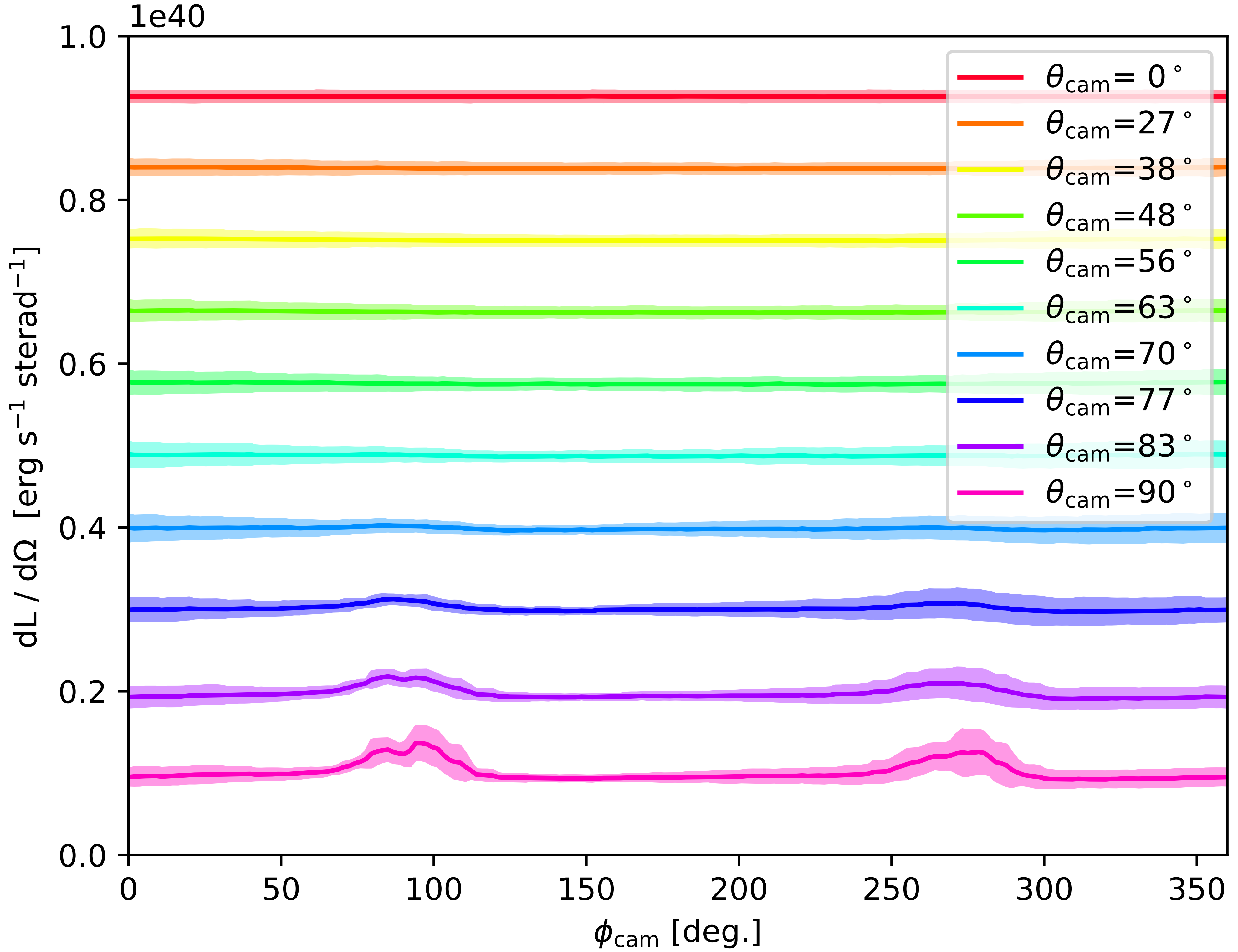
X-rays


Angle Dependence
Optically Thin Case
X-rays

Inclination Angle Dependence

Optically Thin Case





- **Near edge-on views see more relativistic beaming/boosting from line-of-sight motion of the disks and binary.**
- **Extreme edge-on views obscured by significantly larger column densities (absorption), making these views dimmer on average.**

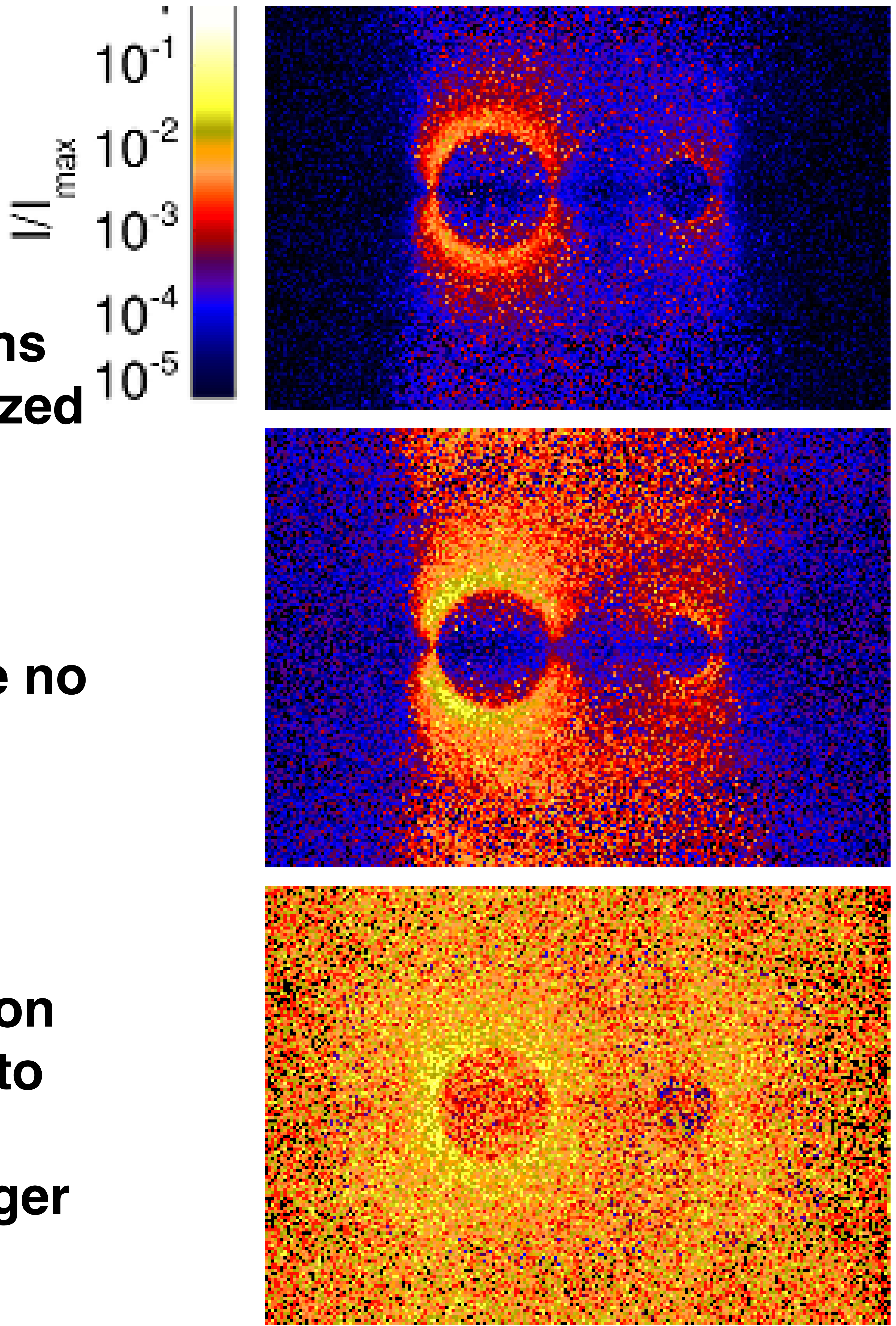
- **Near edge-on views see more relativistic beaming from line-of-sight motion of the disks and binary.**
- **Phase modulation only significant for near edge-on views.**
- **The curves (shaded regions) show time averages (std. deviations) over each orbit.**

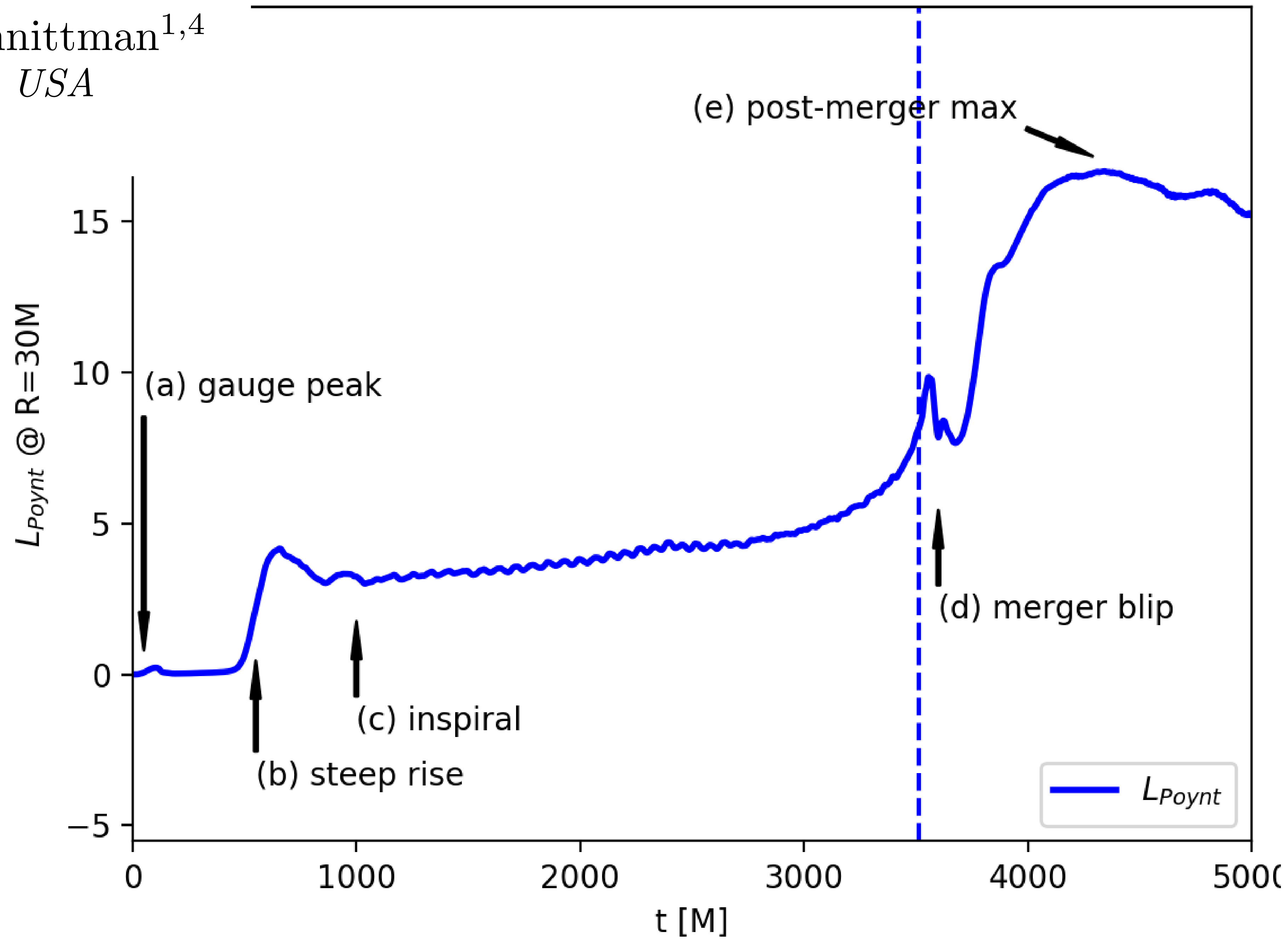
Prompt Electromagnetic Transients from Binary Black Hole Mergers

arXiv:1710.02132v1

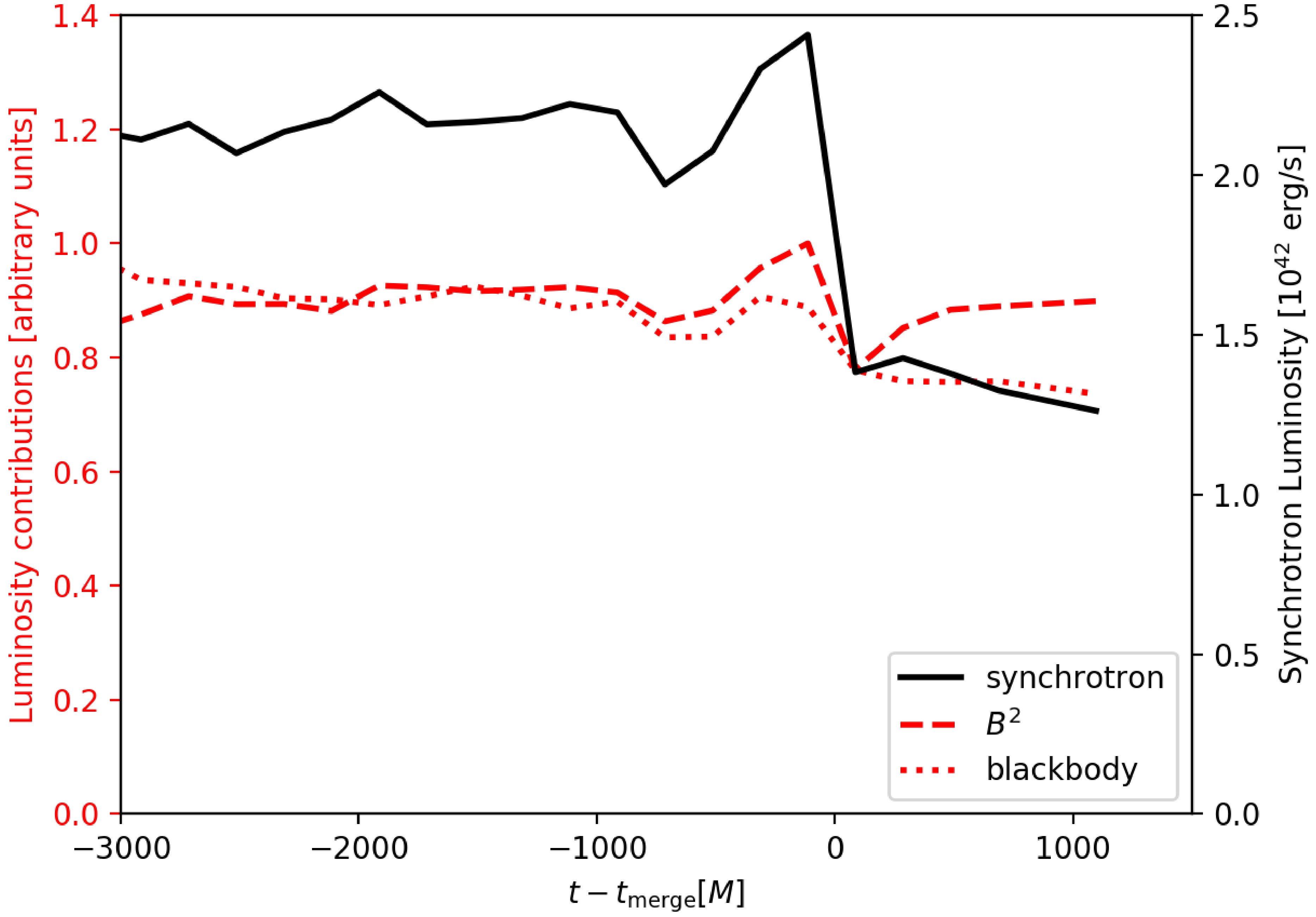
Bernard J. Kelly[1,2,3], John G. Baker[1,4], Zachariah B. Etienne[5,6], Bruno Giacomazzo[7,8], Jeremy Schnittman[1,4]
[1] Gravitational Astrophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

- a=0, q=1
- M=10[8] Msun
- Full Numerical Relativity simulations of BHs in a magnetized gas cloud;
- Scenario for separations < 20M, when mini-disks are no longer stable;
- Post-processed radiative transfer (Monte Carlo) synchrotron emission with NR-like metric to calculate through merger to post-merger phase;





Poynting Flux



Synchrotron Flux

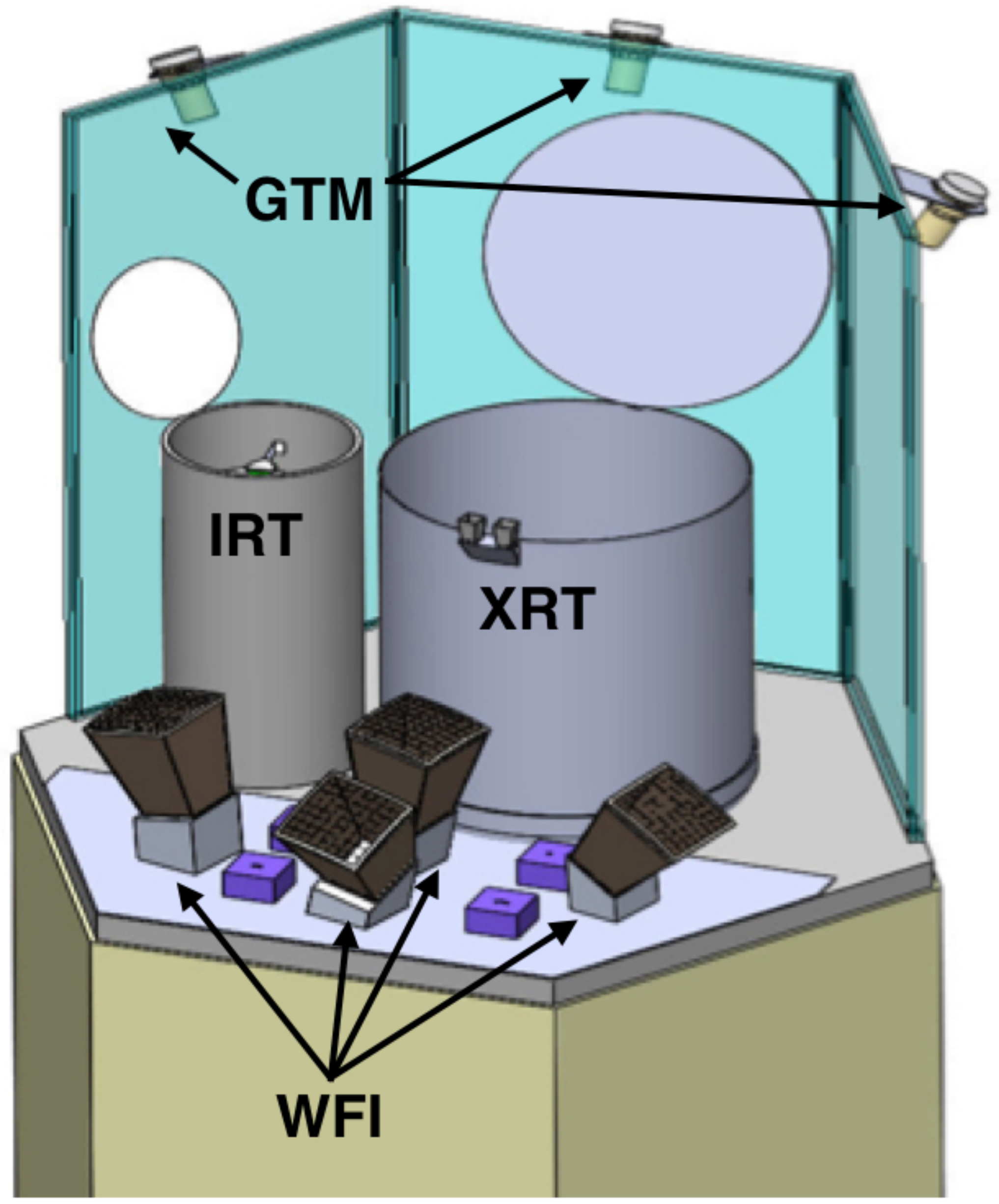
Detectability of modulated x-ray lightcurves from LISA's supermassive black-hole mergers

Tito Dal Canton, Alberto Mangiagli, Scott Noble, Jeremy Schnittman, Andy Ptak, and Jordan Camp

(to be submitted)

Idea:

- LISA detects an imminent MBH merger
- Sky localization is too broad to single out the correct x-ray point source
- Start scanning the sky localization repeatedly
- Search the collected photons for pulsations phase-locked with the GW signal
- Detecting the modulation identifies the correct source
- Question: how feasible is it?

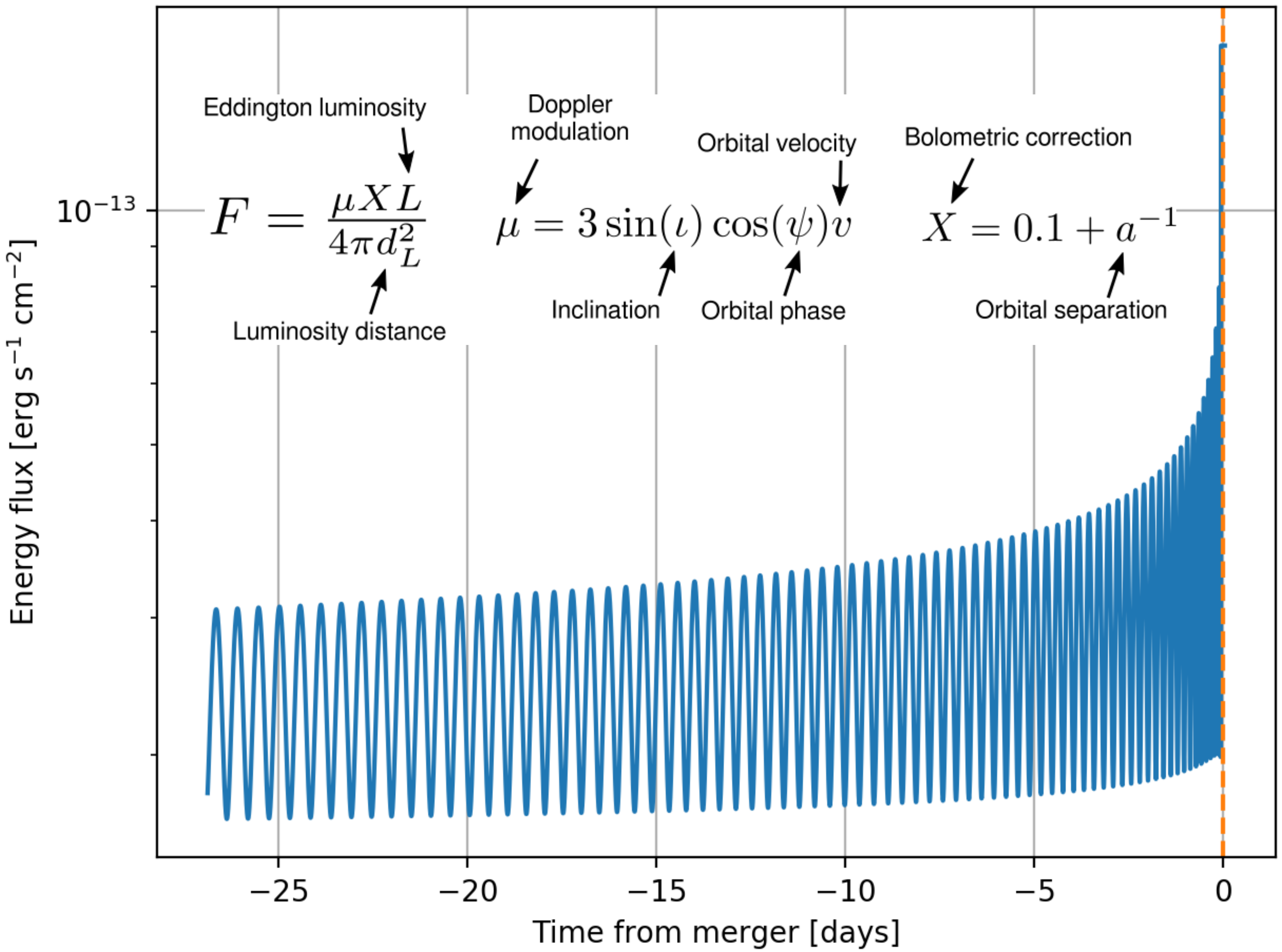


TAP (NASA)

Transient Astrophysics Probe

- **1 sq. degree XRT FOV;**
- **Sensitivity ~10^{-16} erg cm^{-2} s^{-1}**

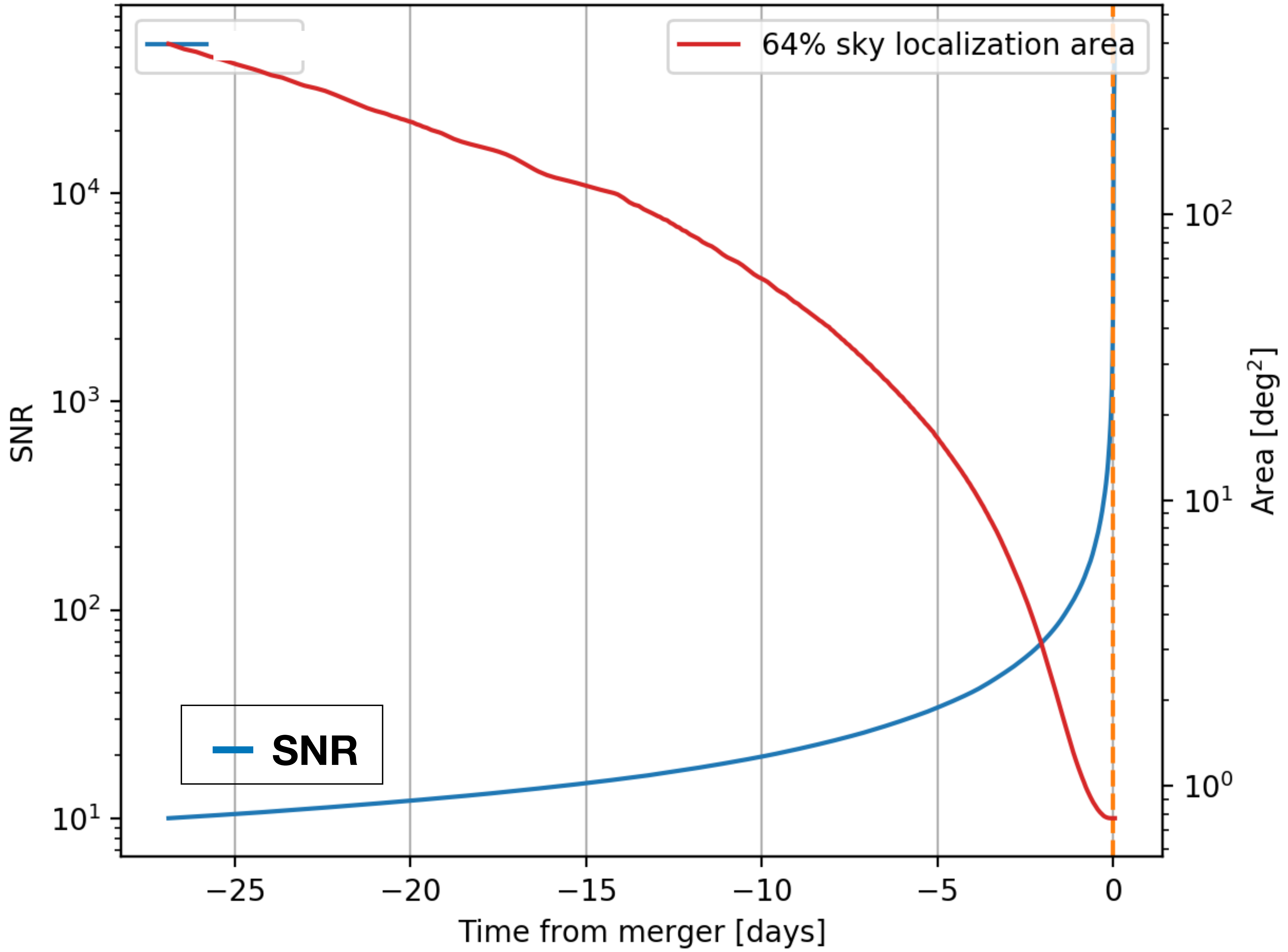
Simulate x-ray lightcurve

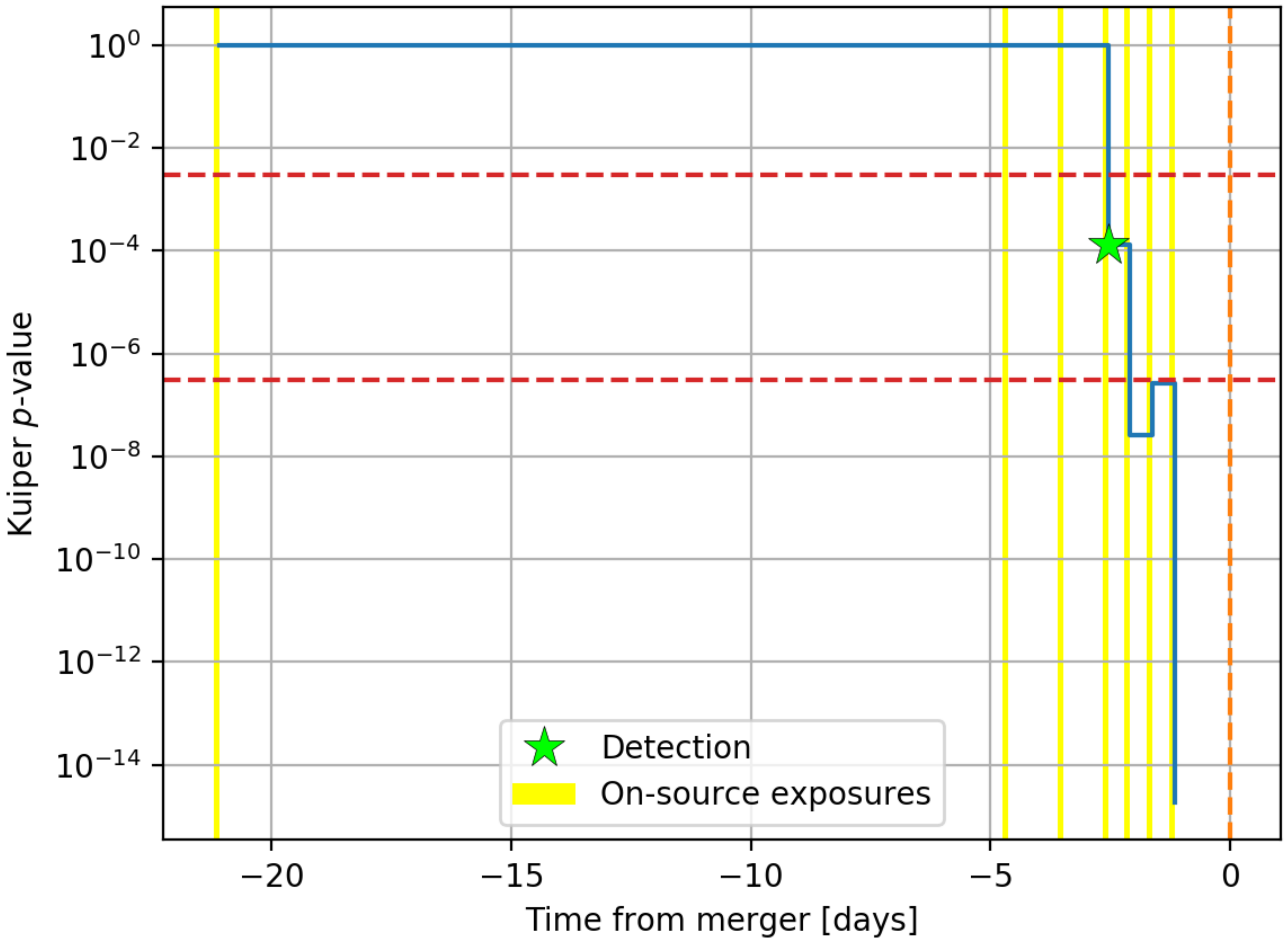


- **oppler-modulated EM Chirp Signal (Schnittman++2018, Kelly++2017, Haiman 2017);**
- **Parameterized to a fraction of Eddington;**
- **First step toward using simulation-informed light curves, e.g. accretion-modulated signals, partially obscured sources;**
- **See Kelley, Haiman, Sesana, Hernquist++2018 for similar work on the observability of PTA-band sources;**

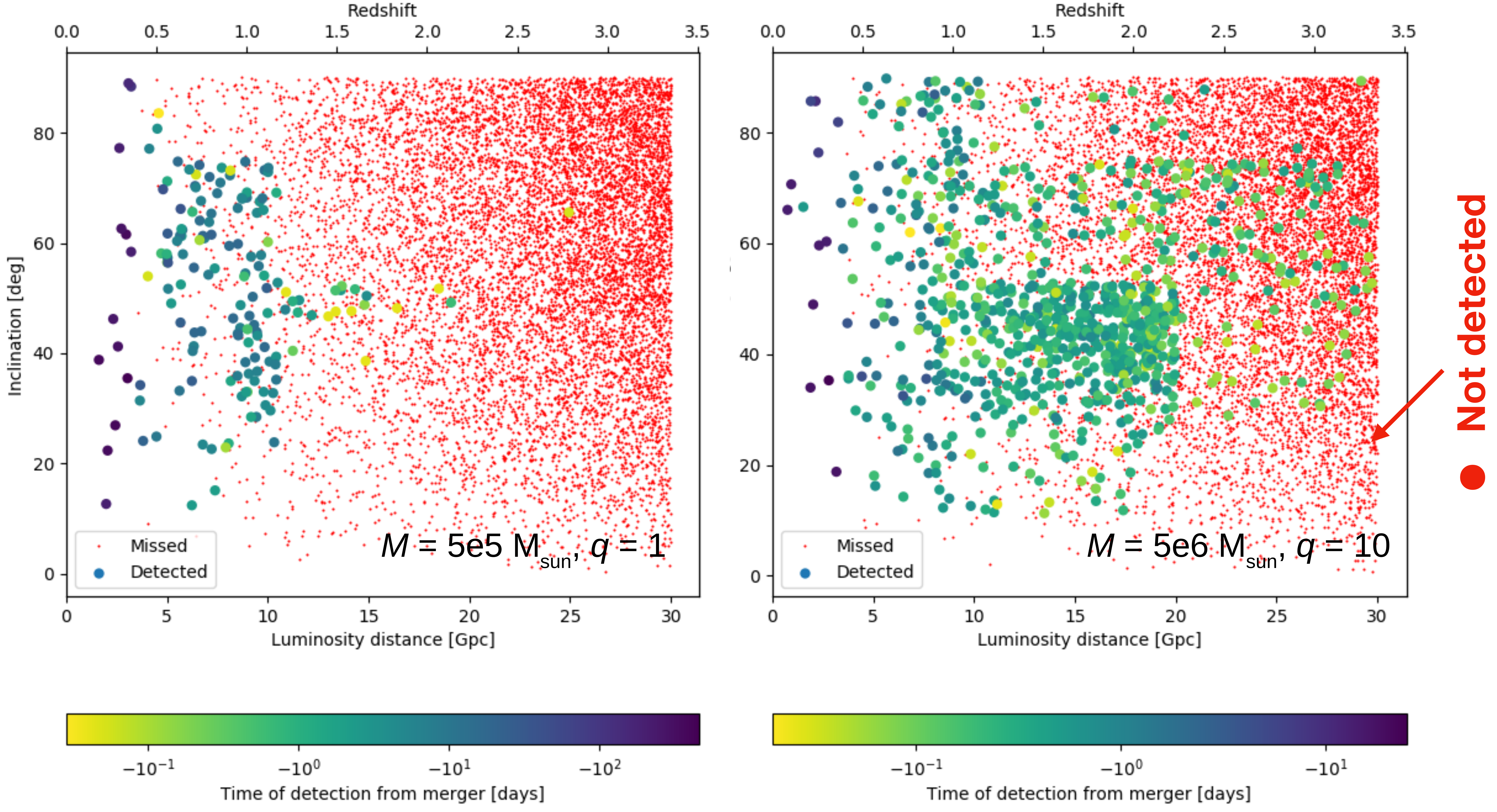
Simulate LISA SNR and sky localization

Search for pulsation with Kuiper's test

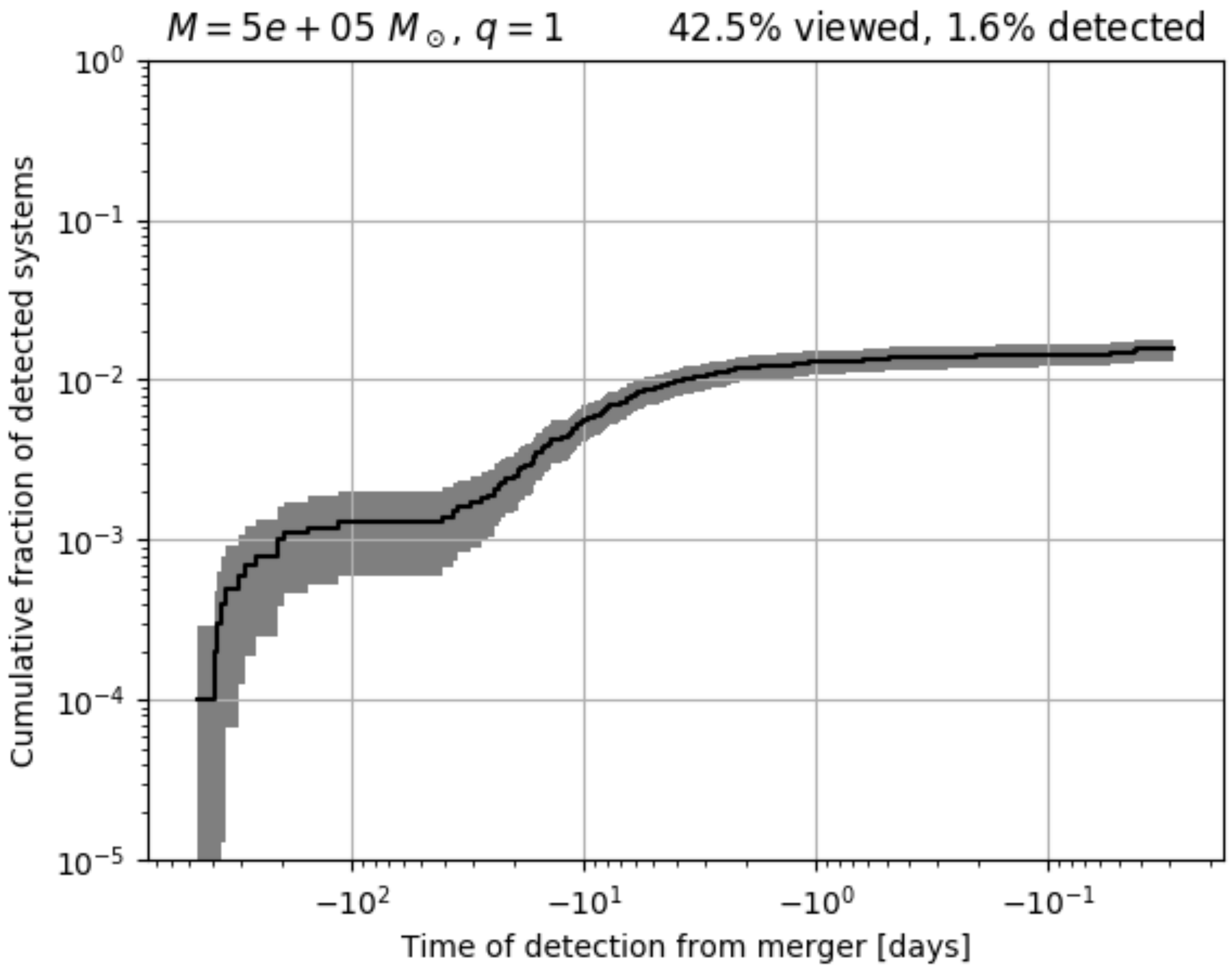


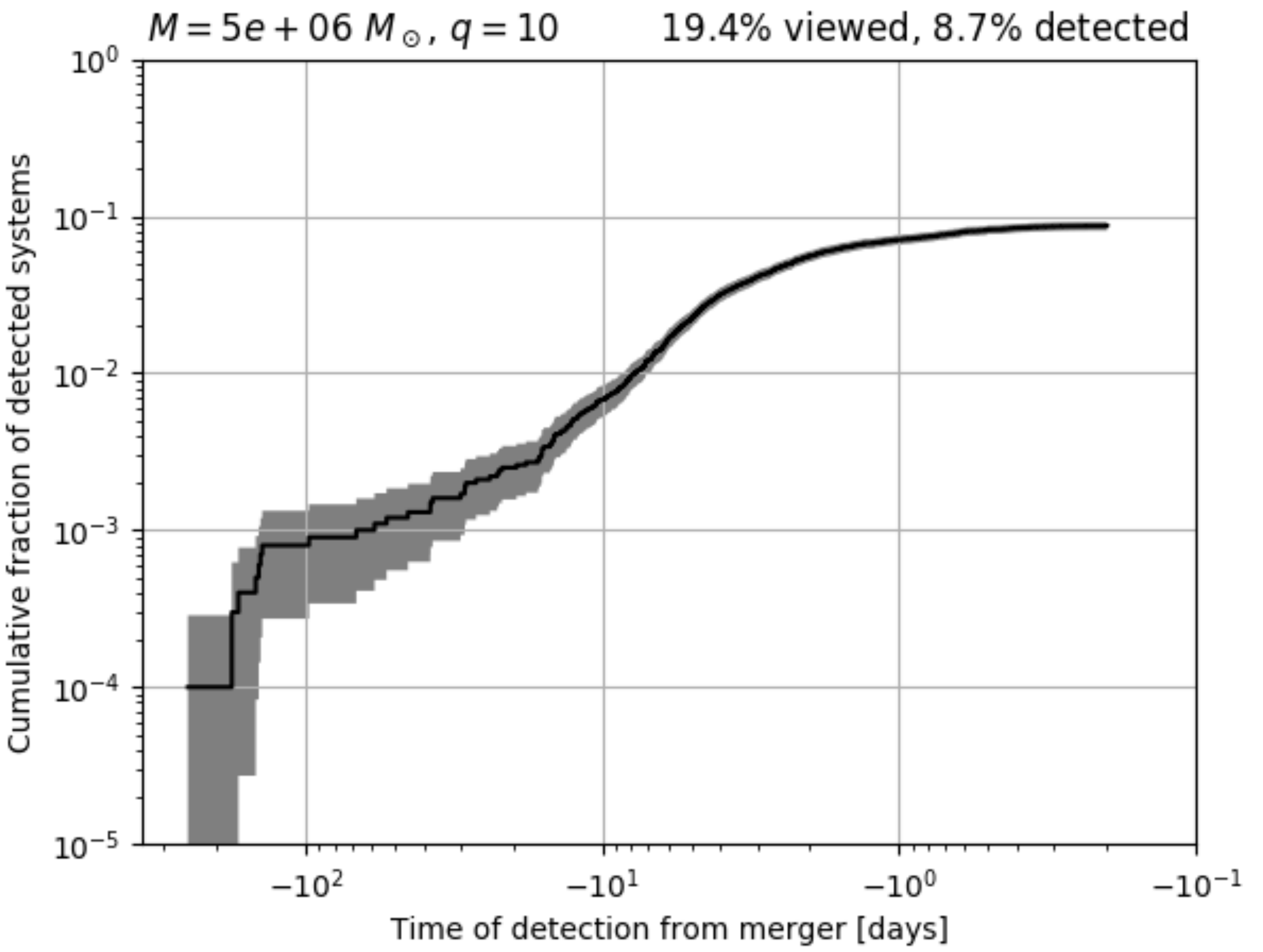


Detections from the Source Sample



Detections from the Source Sample: Likelihood of Detection vs. Time Prior to Merger





Summary

- 1st prediction of the electromagnetic spectrum radiated by 3-d magnetized disks about binary black holes in GR using radiative transfer consistent with simulation data's thermodynamics.
- Not the final word of course, but provides a picture of what is possible.
- SMBBHs in gaseous environments (with the same parameters) will likely have:
  - Typical AGN luminosities;
  - Broader thermal spectrum with breadth modulated by the mini-disk refilling period.
  - Higher X-ray to UV luminosity ratio than typical AGN, largely due to mini-disk dynamics.
  - Phase modulation apparent at low inclinations, though absorbed for higher accretion rates.
- LISA-informed pointing strategy is expected to identify sources out to z~3 depending on parameters!

Future Directions & Questions

- How does the circumbinary overdensity (aka "lump") modulate refilling of the mini-disks?
  - Simulation is now past 6 orbits…
- Dependence on :
  - Cooling rate or disk thickness;
  - Accretion rate;
  - Mass ratio;   (we have +10 years, right?)
- Improved corona thermodynamic and radiation physics:
  - Kinch, Schnittman, Kallman, Krolik (2018).
- What level of absorption of close binaries should we expect and how does it affect our search strategy? (likely need galaxy simulations and more surveys)
- Are there more robust EM signatures? How real do we need to get?

https://www.nasa.gov/feature/goddard/2018/new-simulation-sheds-light-on-spiraling-supermassive-black-holes/

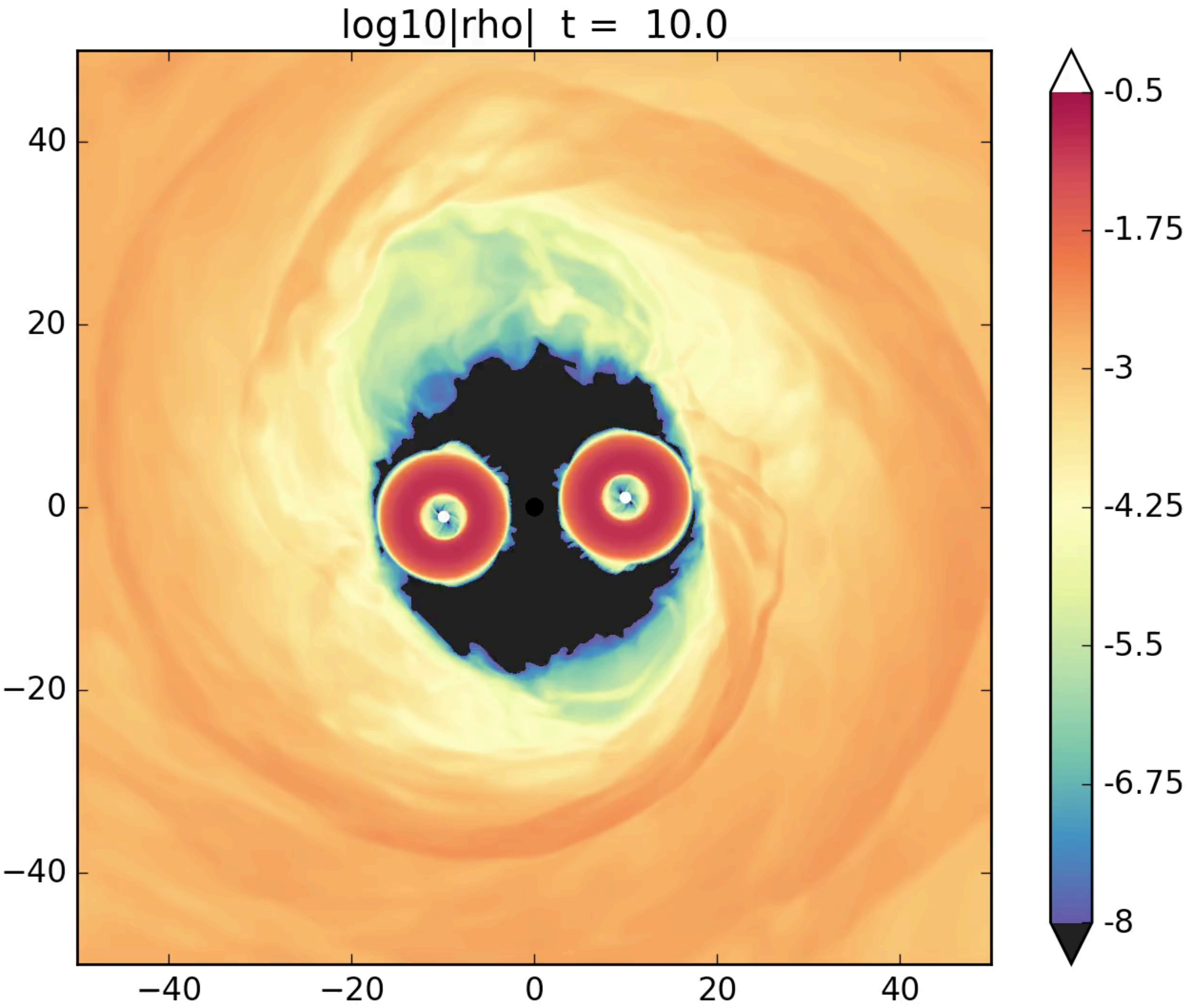
Extra Slides

Angle Dependence

Optically Thin Case

Energy Spectrum vs. Time

Inclining View
Optically Thick Case



log10|rho| t = 10.0
40
20
0
−20
−40
−40
−20
0
20
40
-0.5
-1.75
-3
-4.25
-5.5
-6.75
-8