GRMHD Simulations of Binary Black Holes in magnetized disks

Roman Gold

Vasileios Paschalidis, Zachariah Etienne, Milton Ruiz, Brian Farris, Stuart Shapiro, Harald Pfeiffer

University of Maryland
Joint Space Science Institute

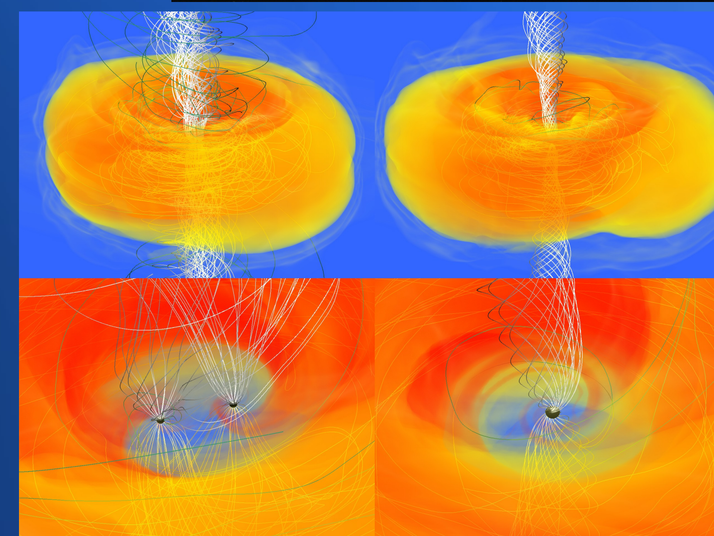
Astro Coffee, ITP/FIAS Frankfurt, Dec 16th 2014

Phys. Rev. Lett. 109, 221102 Phys. Rev. D89, 064060 Phys. Rev. D90, 104030

Outline

- Astrophysical context & Motivation

- BHBH+disks modeling

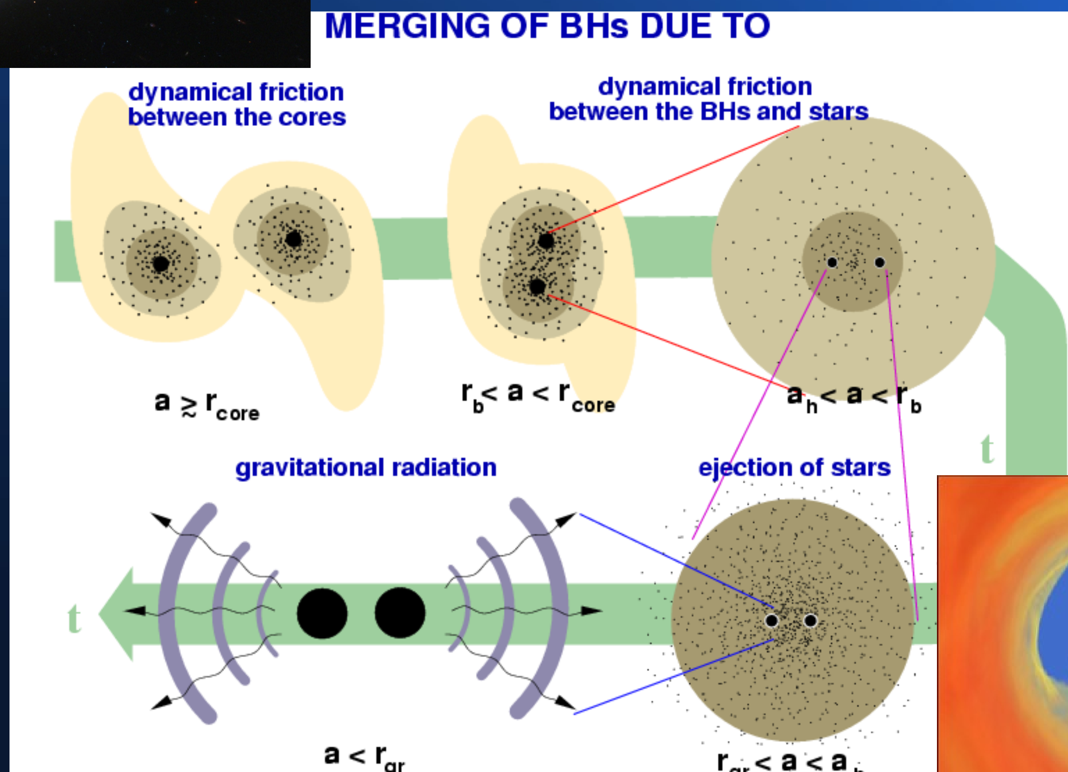


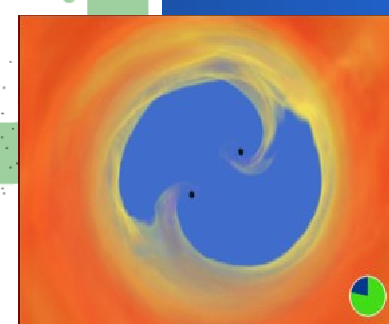
- Results, highlights
- Summary & Outlook

Galaxies merge!

Formation of SMBH binaries

Benson 2013





Farris et al 2011

Begelman et al 1980

Astrophysical evidence

- SMBHs grow through accretion & merger
- SMBHs accrete & shine throughout cosmic evolution
  → SMBH merger with EM counterpart

Observational facilities:

- GWs: Pulsar Timing Arrays ~2017, eLISA 2032+
- EM transients: e.g. PanStarrs, WFIRST, LSST

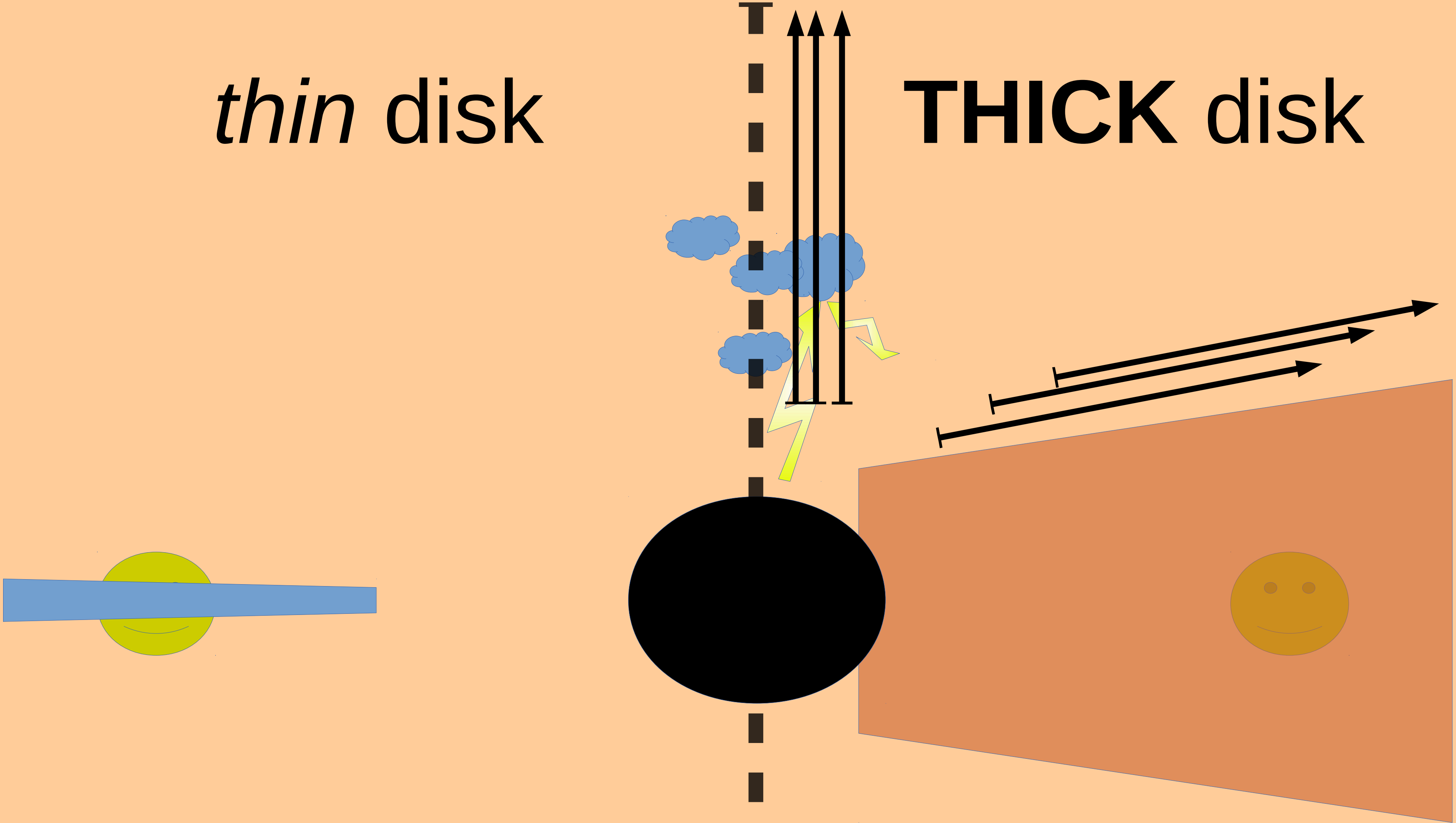
EM counterparts

- BHBH in vacuum: well understood system
- Now: BHBH in (magnetized) gaseous environments
- Goal: Identify EM counterpart
- Precursor (periodicities, jets, fainting, ...)
- Afterglow (merger aftermath, rebrightening, …)

→ **Need source modeling! Know what to look for!**

thin disk

THICK disk

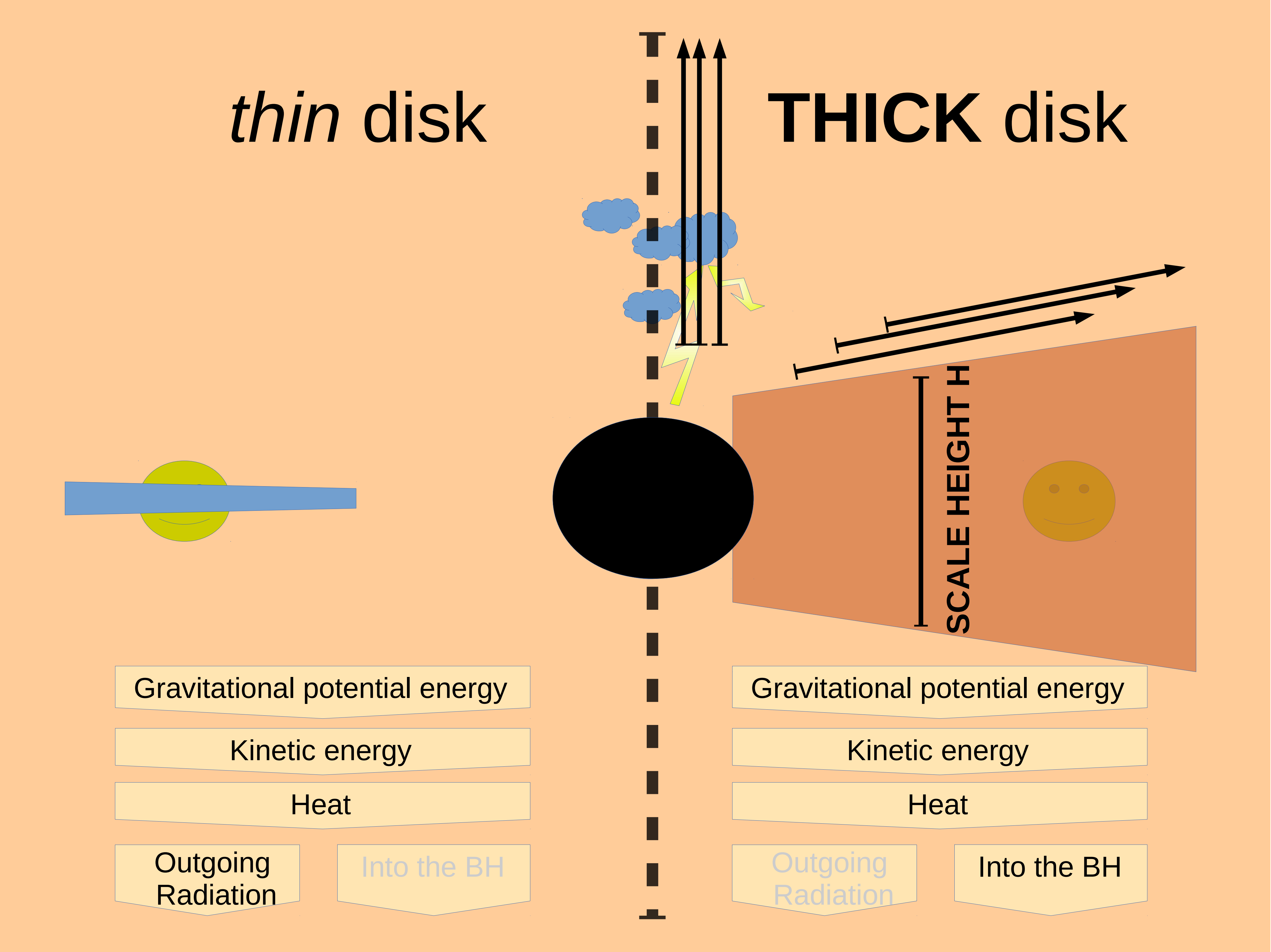


→ *Geometrically* thin
→ *Optically* thick (opaque)
→ Cold
→ Truncated near BH?
→ thermal spectrum

Refs: Shakura & Sunyaev 1973
Novikov & Thorne 1974

→ *Geometrically* thick
→ *Optically* thin (transparent)
→ Hot
→ Outflows, Jets, Winds
→ non-thermal spectrum

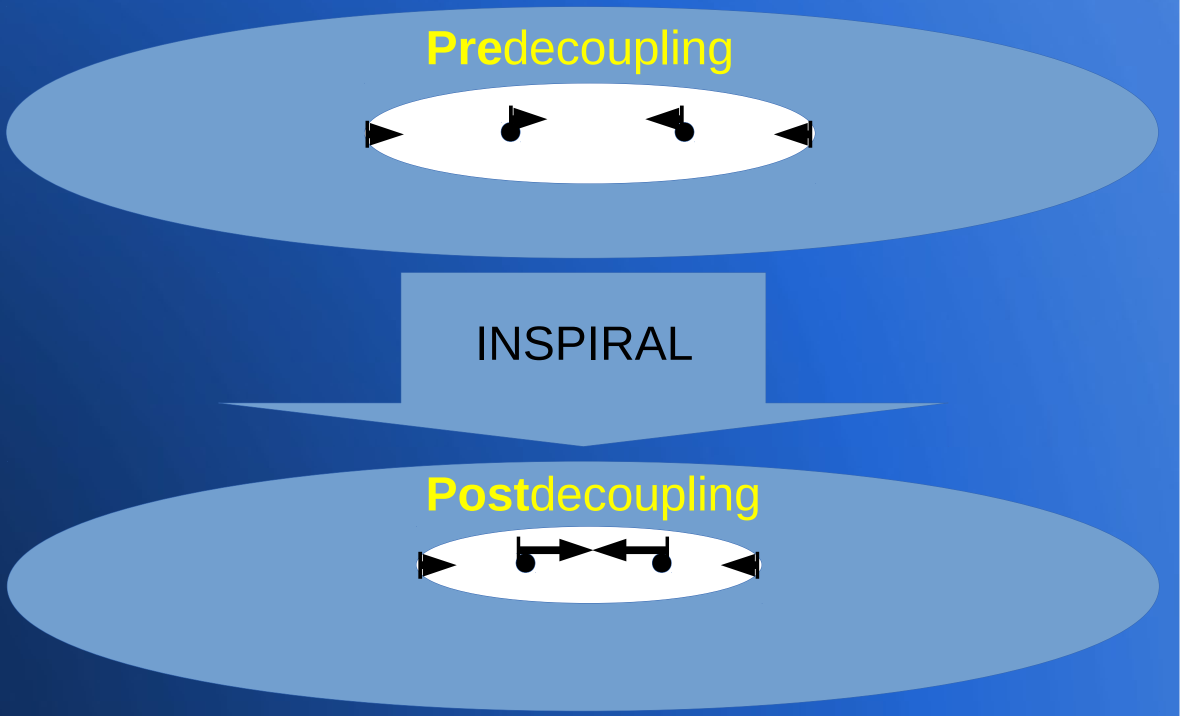
Refs: Narayan & Yi 1994



thin disk
THICK disk
SCALE HEIGHT H
Gravitational potential energy
Kinetic energy
Heat
Outgoing Radiation
Into the BH
Gravitational potential energy
Kinetic energy
Heat
Outgoing Radiation
Into the BH

Binary-disk decoupling

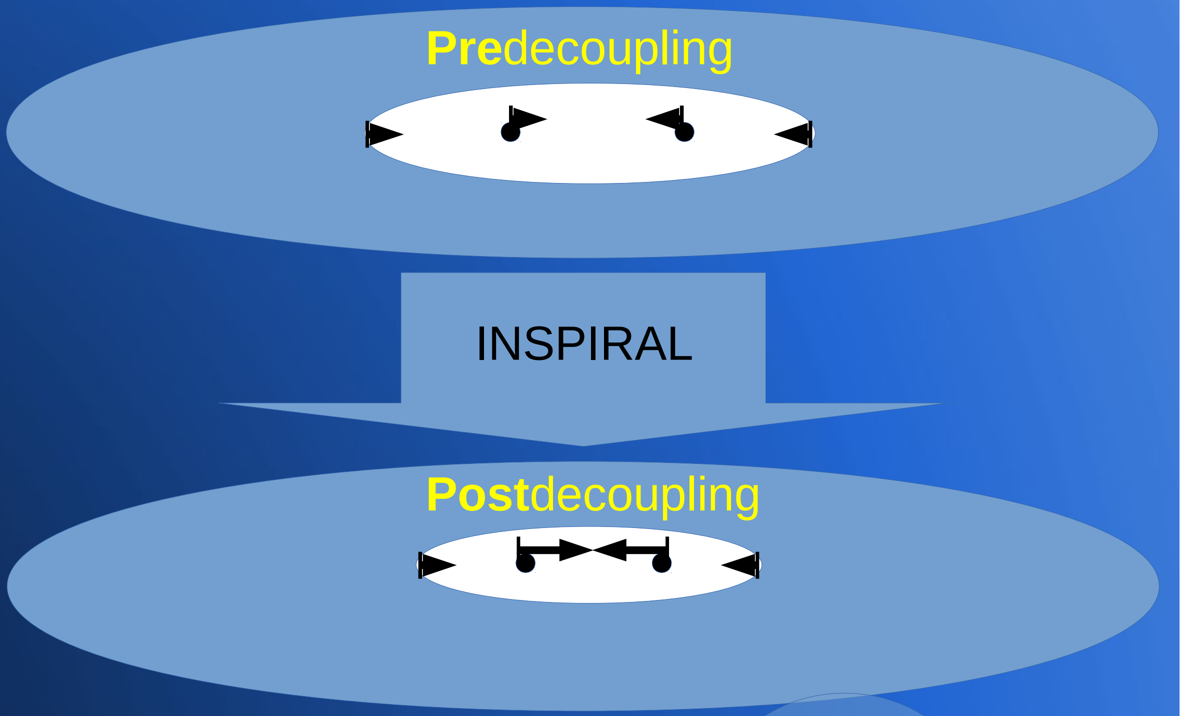
- Disc dynamics determined by interplay between viscous and binary tidal torque
- Equate disk response (→viscous) time scale with inspiral rate (→GW time scale)
- solve for separation → decoupling radius



$$\frac{a_d}{M} \approx 13 \left(\frac{R_{in}}{1.8 a_d}\right)^{3/5} \left(\frac{\alpha}{0.13}\right)^{-2/5} \left(\frac{H/R}{0.3}\right)^{-4/5} \left(\frac{\tilde{\eta}}{1}\right)^{2/5}$$

Binary-disk decoupling

- Disc dynamics determined by interplay between viscous and binary tidal torque
- Equate disk response (→viscous) time scale with inspiral rate (→GW time scale)
- solve for separation → decoupling radius

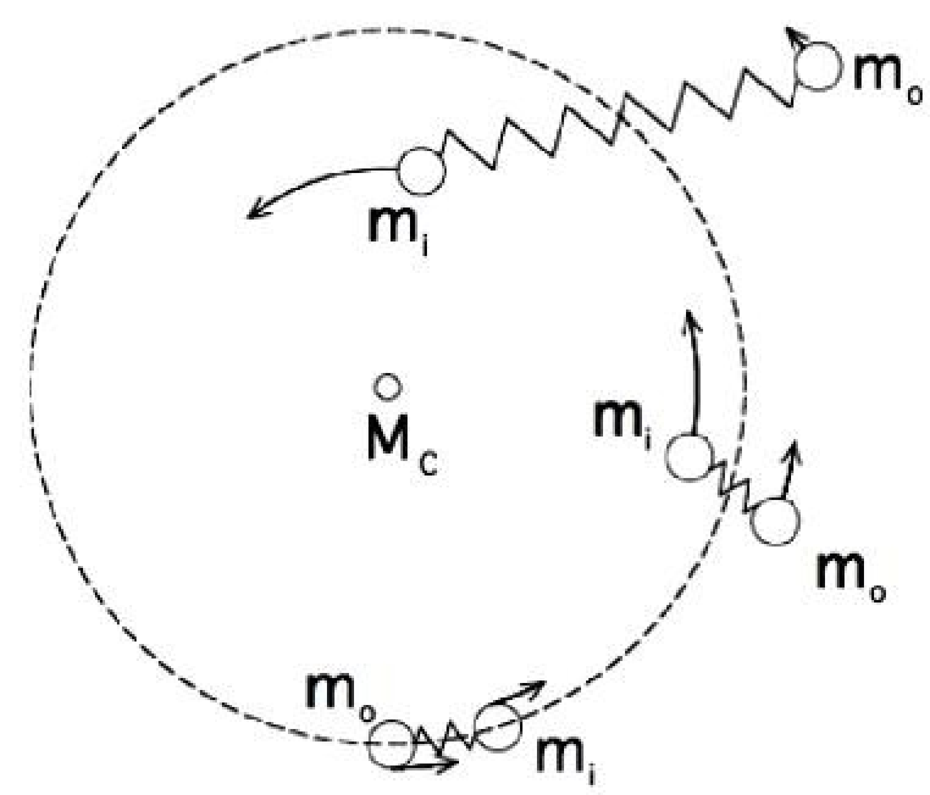


$$\frac{a_d}{M} \approx 13 \left(\frac{R_{in}}{1.8 a_d}\right)^{3/5} \left(\frac{\alpha}{0.13}\right)^{-2/5} \left(\frac{H/R}{0.3}\right)^{-4/5} \left(\frac{\tilde{\eta}}{1}\right)^{2/5}$$

Magneto-rotational instability (MRI)

- disk embedded in a weak magnetic field is
  stable to the MRI
  if and only if: $\frac{d\Omega^2}{dR} \geq 0$

  → non-linear outcome is
  MHD turbulence
- On average the turbulence acts like an **effective source of viscosity**
- Viscous torques redistribute angular momentum
  → causes **accretion**



Length and time scales: Computational Challenge

Length scales	Time scales
Resolve horizons $\Delta r \sim 10^{-2} M$	Time step $dt_{CFL} \sim 10^{-2} M$
MRI wavelength $\lambda_{MRI} \sim 10^{-1} M$	$r_g / c = M$
Horizon $r_{AH} \sim r_g = M$	$T^{binary}_{Kepler} \sim 2 \cdot 10^2 M$
binary separation $a \sim 10 M$	T^{disk}_{Kepler} & $\omega^{-1}_{MRI} \lesssim 10^3 M$
disk inner edge $r_{in} \sim 20 M$	$t_{GW} \sim 10^3 M$
disk outer edge $r_{out} \sim 200 M$	(near ρ_{max}:) $t_{vis} \sim 10^4 M$

→ Adaptive-Mesh-Refinement (AMR)

Previous numerical work (*very* abbreviated, see papers)

Hydro (B=0):

Newtonian (SPH): Artymowicz & Lubow 1994, Cuadra et al 2008, Roedig et al 2011, 2012

MacFadyen et al 2008

GR: Farris et al 2011, Bode et al, Bogdanovic et al

Force-free (all in GR):

Palenzuela et al 2010

Moesta et al 2010, Alic et al 2012

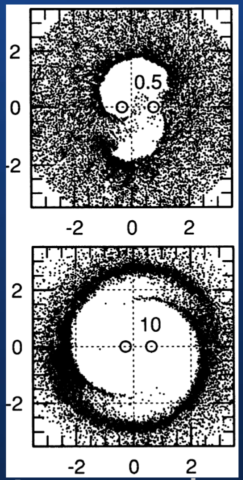
MHD:

Shi 2011 (Newtonian)

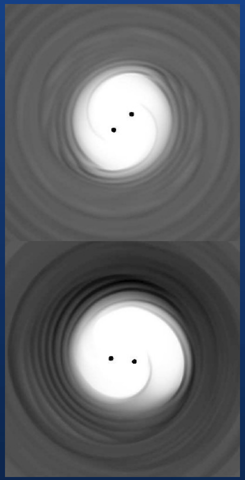
Noble et al 2012 (Post-Newtonian)

Farris et al 2012, Gold et al 2013,2014 (GR)

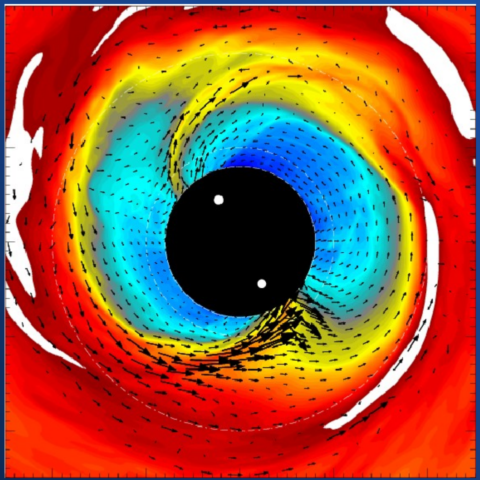
Modeling of circumbinary disks



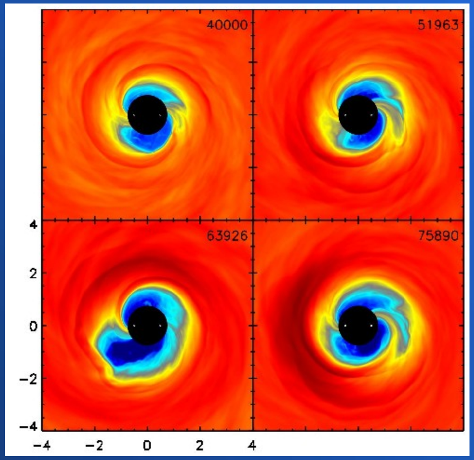
Artymowicz et al 1994

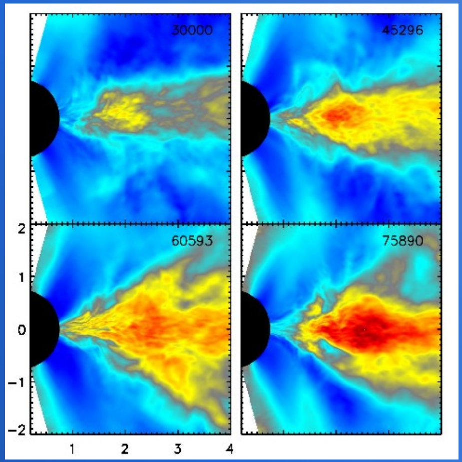


MacFadyen et al 2008

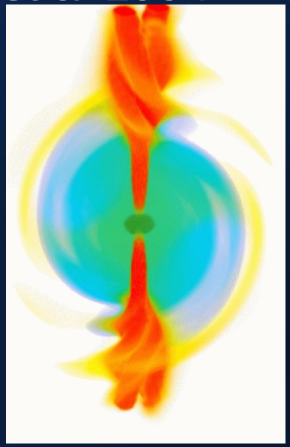


Shi et al 2011



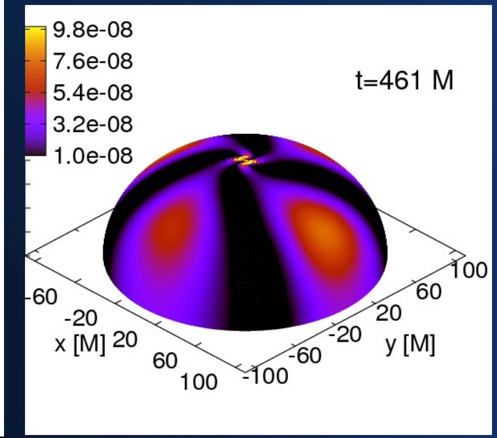


Noble et al 2012

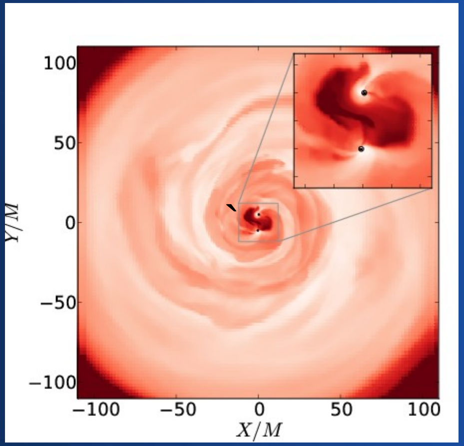


Palenzuela et al 2010

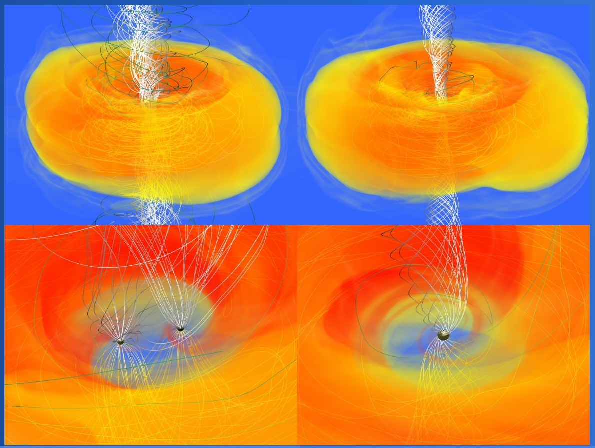
Alic et al 2012



Moesta et al 2012



Farris et al 2012



Gold et al 2014

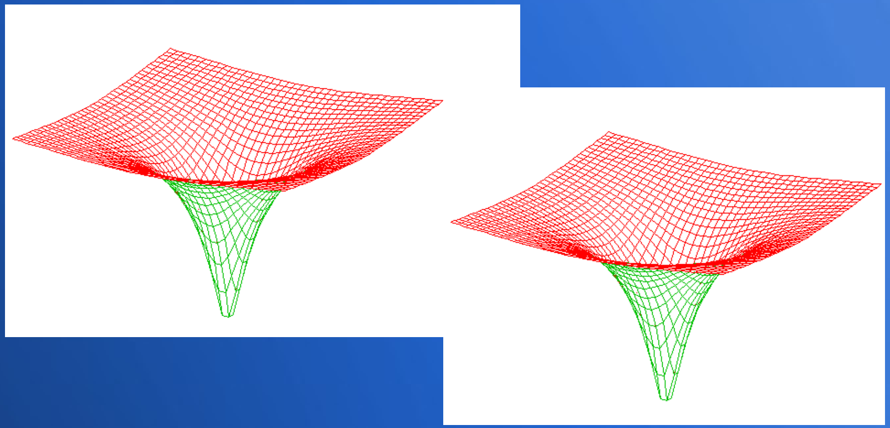
Methods (I): Numerical Relativity

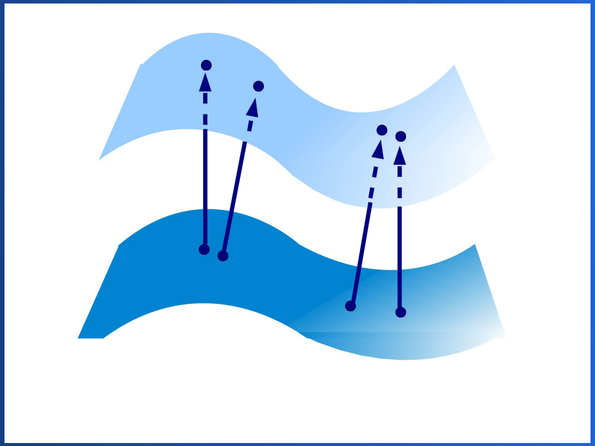
- *3+1 split (foliate spacetime)*
- *Initial data:*
  Conformal-Thin-Sandwich Formalism
  → quasi-equilibrium data
  → helical Killing vector
- *Predecoupling:*
  Analytically rotate CTS metric ID
- *Postdecoupling:*

  BSSN formulation

  “moving punctures” gauge conditions

  → system is strongly hyperbolic
  → Vacuum Cauchy Problem is well-posed
  → Slices penetrate horizons
  → Singularities at origin can be handled





Methods (II): ideal GRMHD
Illinois GRMHD AMR code

- Perfect fluid stress energy tensor

$$T^{\mu\nu} = (\rho_0 h + b^2) u^\mu u^\nu + \left(P + \frac{b^2}{2}\right) g^{\mu\nu} - b^\mu b^\nu$$

- Eom: Conservation laws (incl. cooling)

$$\nabla_\alpha (T^{\alpha\beta} + R^{\alpha\beta}) = 0$$

$$\nabla_\mu (\rho_0 u^\mu) \; = \; 0$$

- Induction equation for A-field

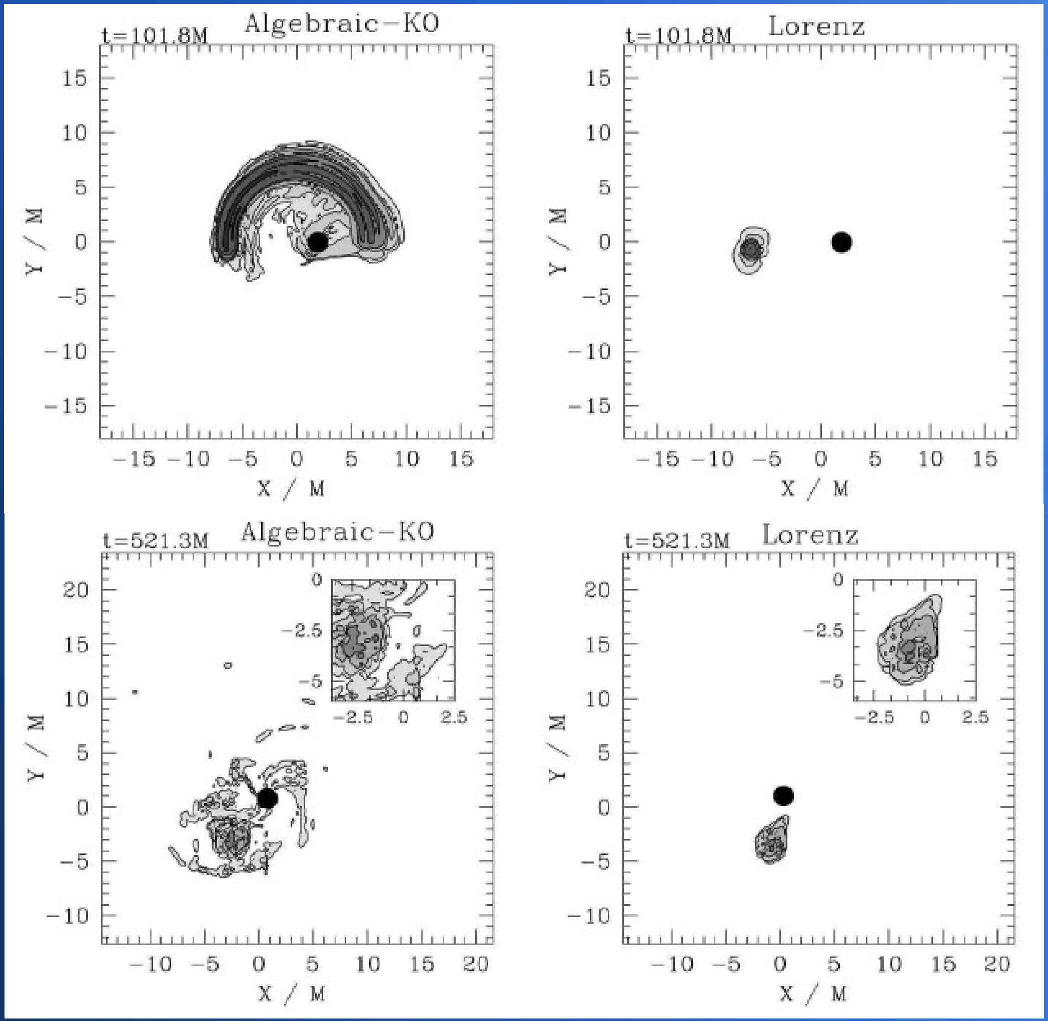
$$\partial_t A_i = \tilde{\epsilon}_{ijk} v^j \tilde{B}^k - \partial_i (\alpha \Phi - \beta^j A_j)$$

- Generalized Lorenz gauge condition

$$\nabla_\mu \mathcal{A}^\mu = \xi n_\mu \mathcal{A}^\mu \qquad \mathcal{A}_\mu \; = \; \Phi n_\mu + A_\mu$$

Methods III: Generalized Lorenz gauge

- Previously used gauge conditions have zero speed modes
- Lorenz gauge modes propagate at c *
- Generalized Lorenz gauge **damps gauge modes** to zero *
  → * Reduce spurious generation of B-field near AMR boundaries
- ***Crucial*** for long-term simulations



Farris et al 2012

Etienne et al 2012, Paschalidis et al 2012

Method (III): Artificial Cooling

- Realistic cooling depends on detailed microphysics
  - Consider two extreme opposite limiting cases

(I) no-cooling

(II) radiate away all shock generated entropy on a local Keplerian time scale

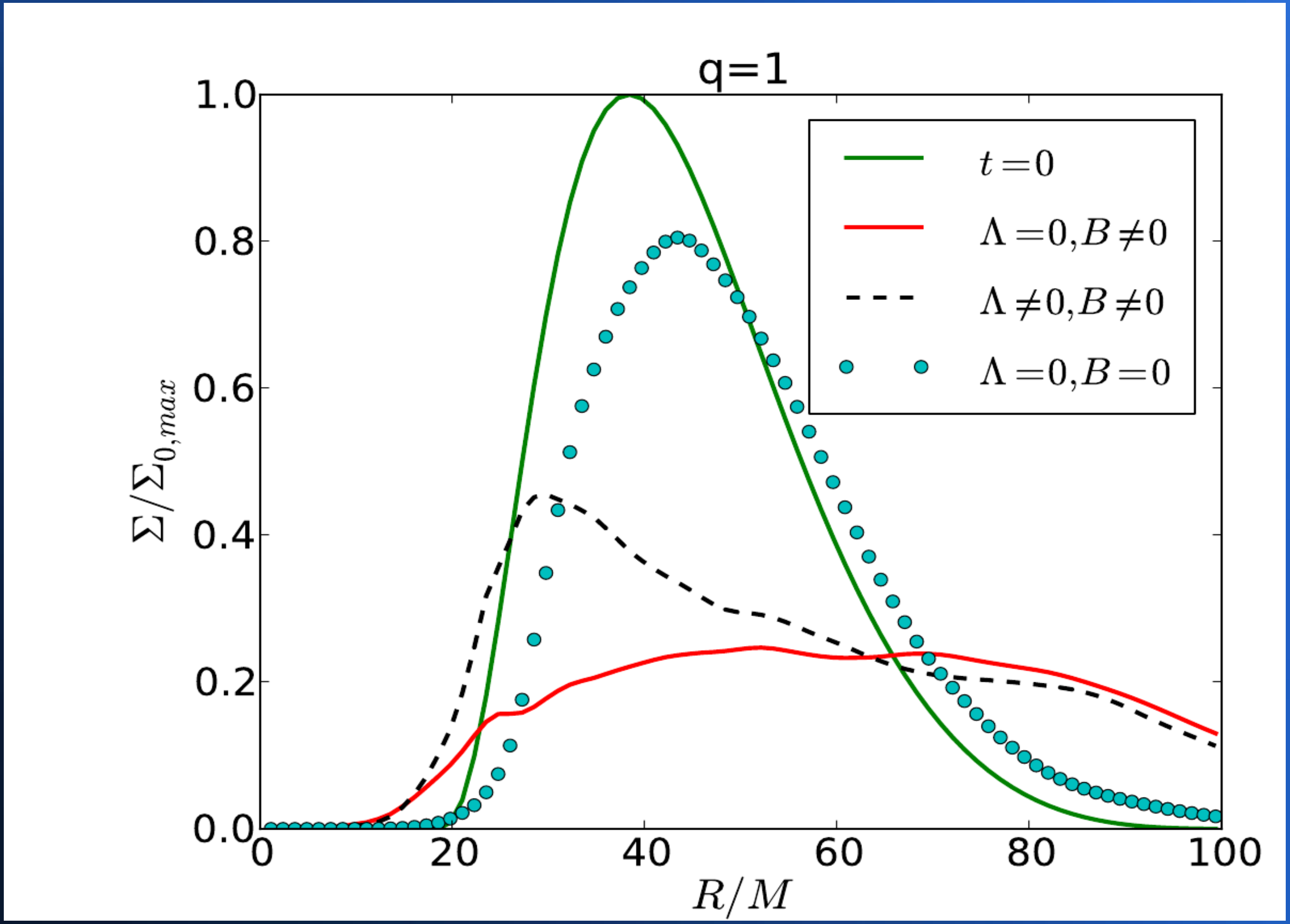
$$\nabla_\nu T^{\mu\nu}_{MHD} = -\nabla_\nu T^{\mu\nu}_{RAD} = -\Lambda u^\mu$$

Λ: remove any (shock-)generated entropy

→ Bracket real situation by two limiting cases

EOS: Ideal Gamma-law

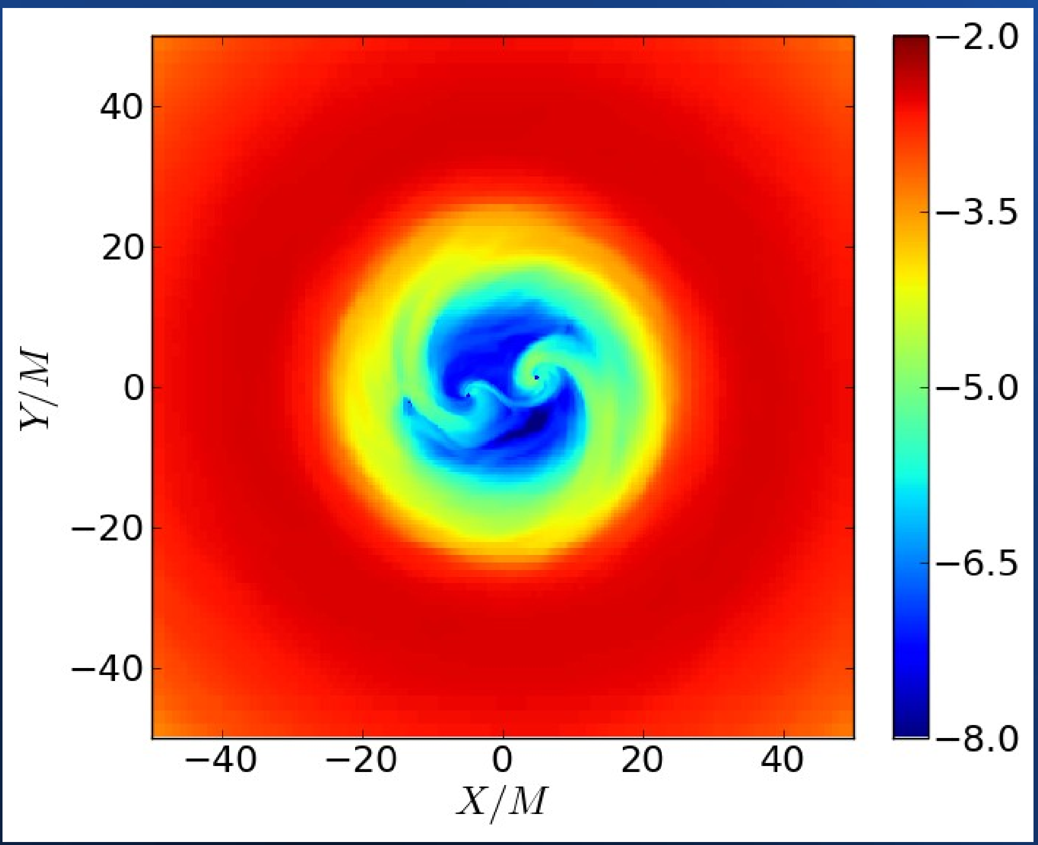
Surface density profiles



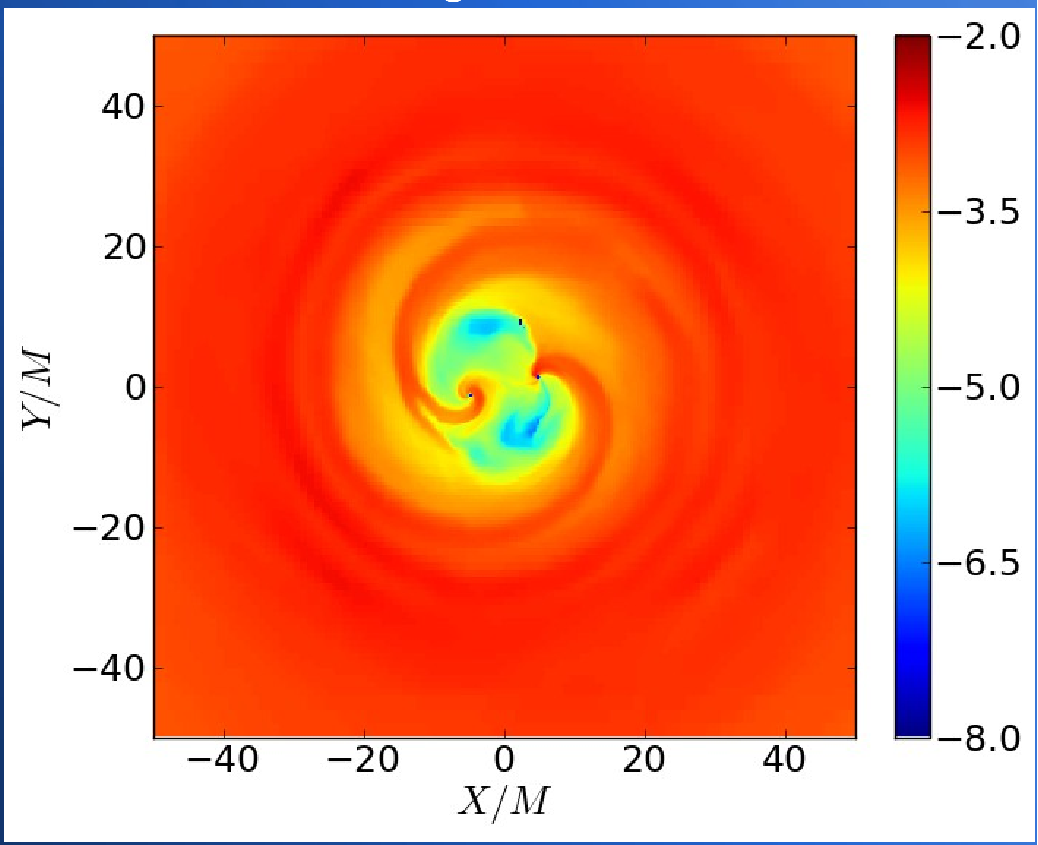
RESULTS

Importance of magnetic fields

Pure hydro



Magnetized



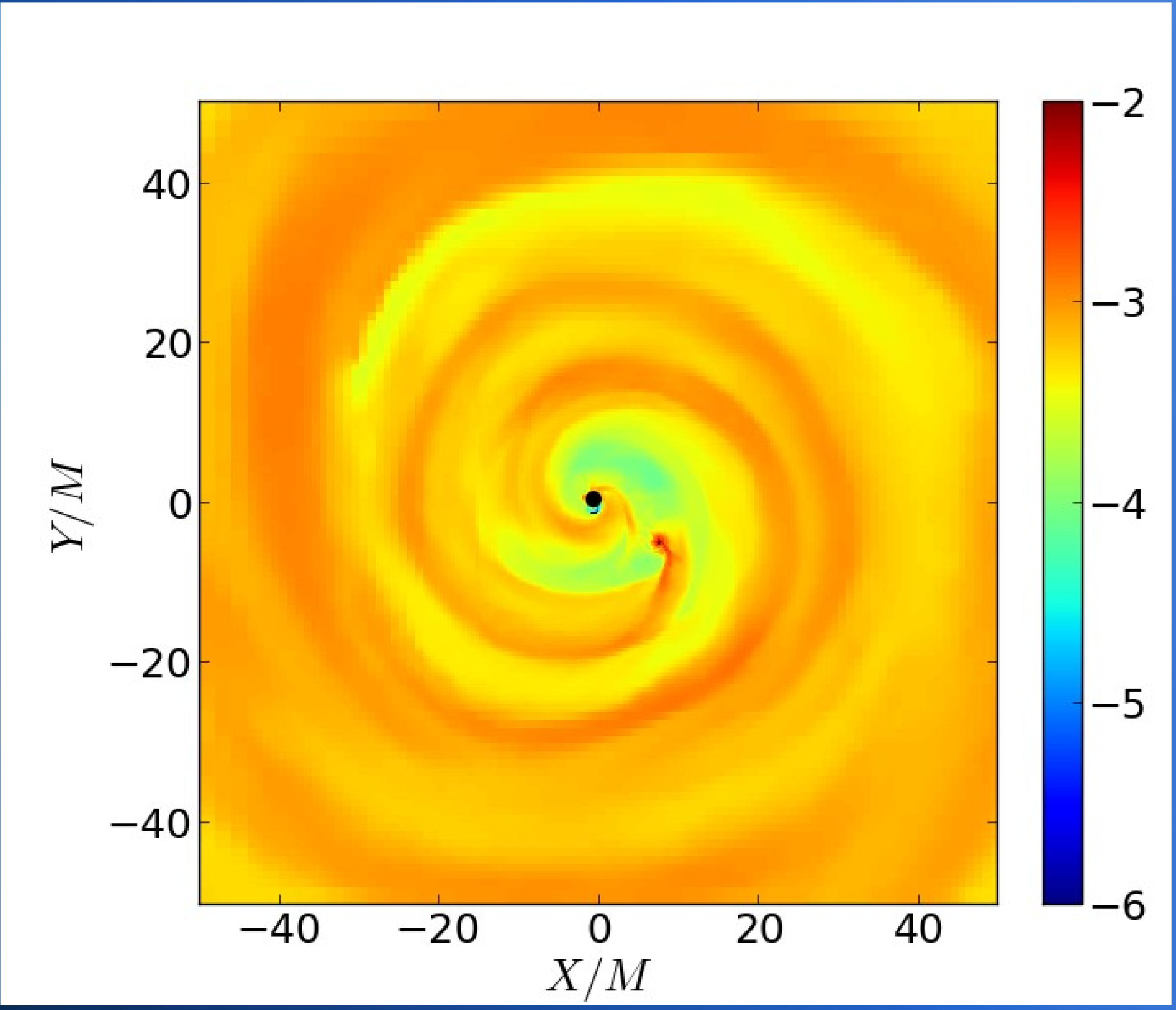
→ **accretion / luminosities underestimated by orders of magnitude!**

→ **can't ignore magnetic fields!**

Gold et al 2013

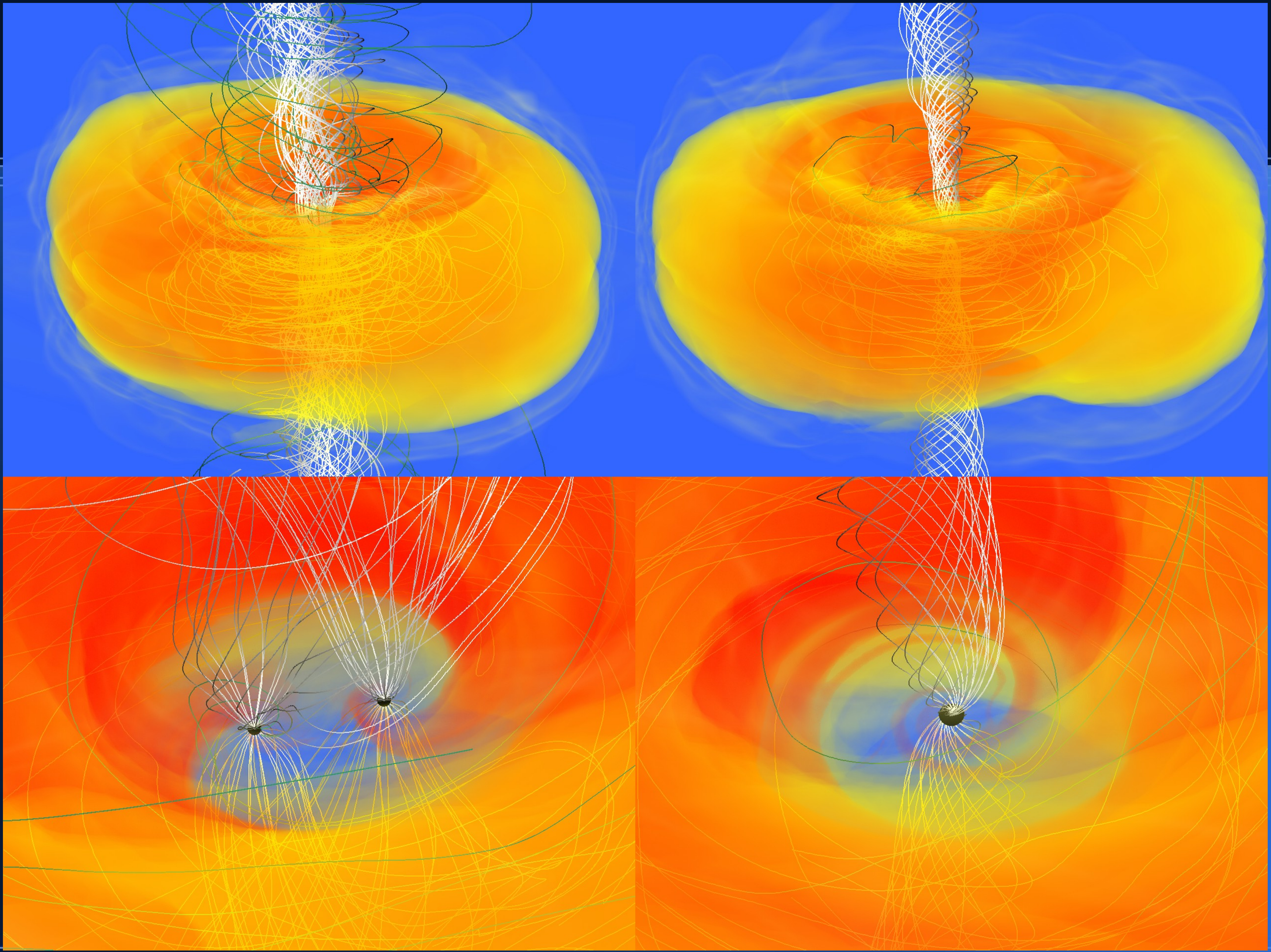
1:10 (no-cooling)

- Refilling of gap/cavity
- Binary fully emersed in highly magnetized gas
- Densest gas is near the (smaller) horizon



Gold et al 2013

predecoupling   Just after merger



Total view

Zoom-in view

REU team: Taylor, Kong, Khan, Connelly, Kim, Walsh

Gold et al 2014

Outflows

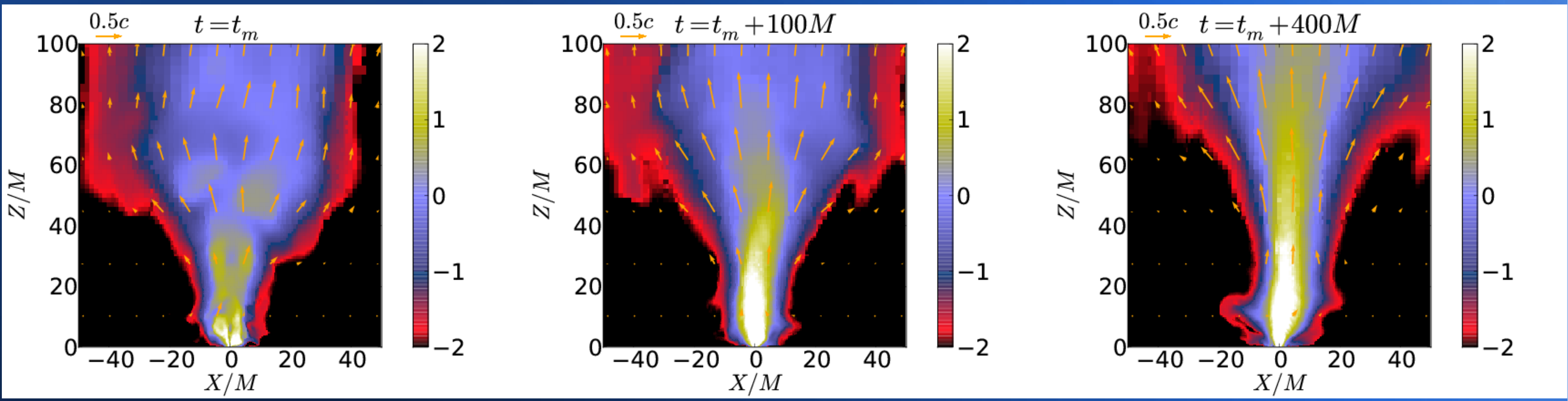
Density (log scale)

**Magnetic pressure/
Density (log scale)**

→ highly magnetized, relativistic outflows

Gold et. al. 2014

Transient jet feature around merger

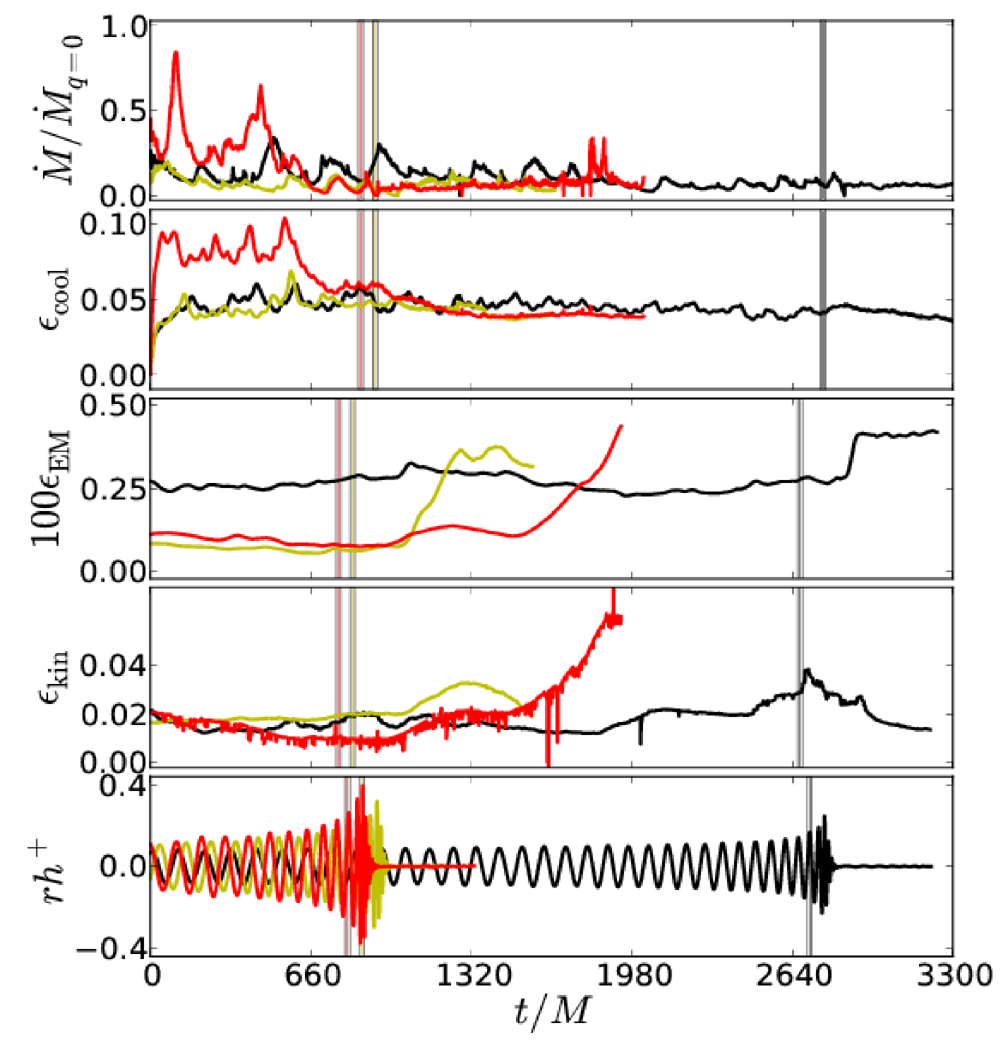


AFTER MERGER:

- Enhanced collimation
- Increase in magnetic energy in outflows
- Speed up of outflow

Gold et al 2014

Accretion rates / Luminosities



Colors: Binary mass-ratio 1:1, 1:2, 1:4

→ **Mass accretion rates:**
comparable to single BH case

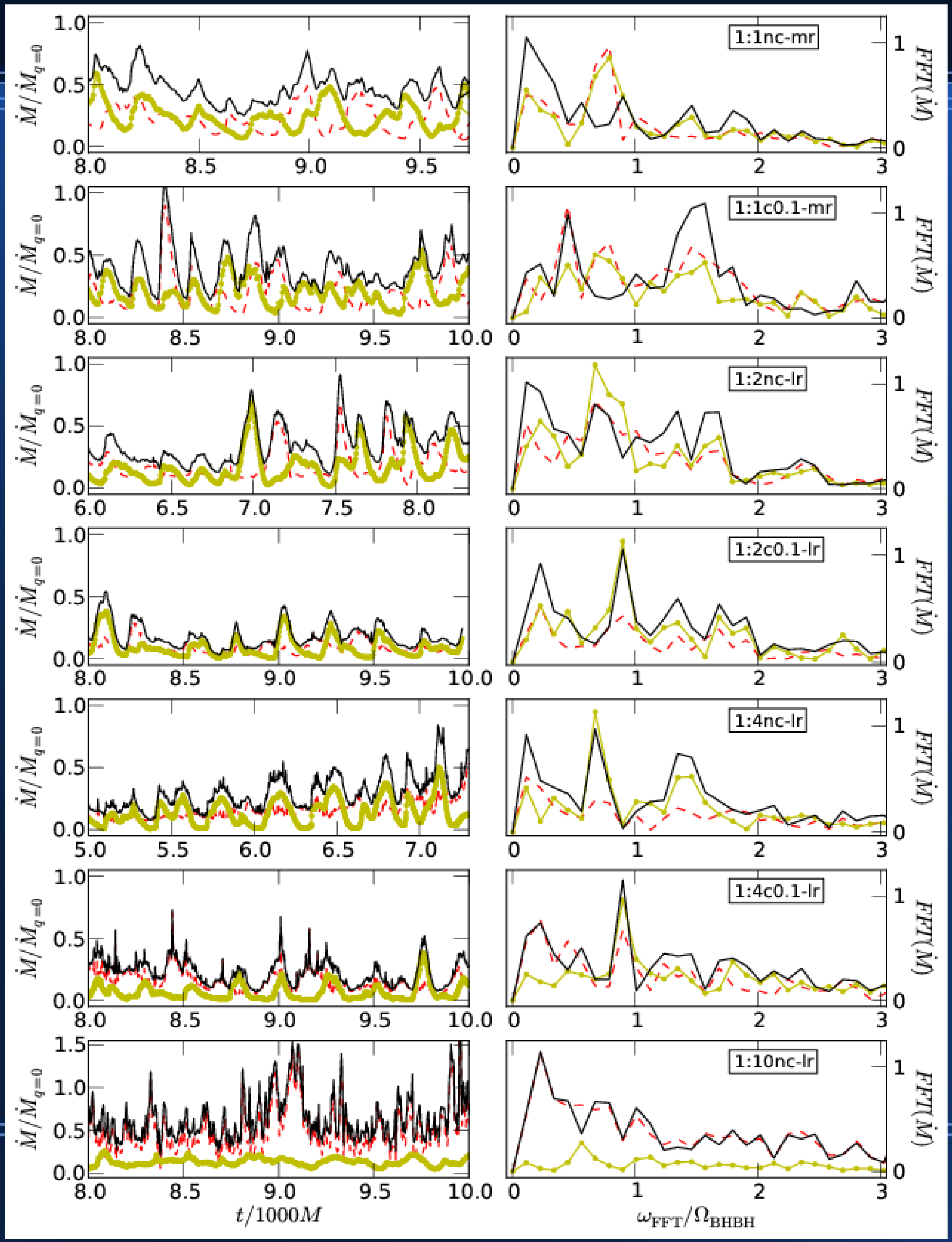
→ **Cooling luminosity:**
not sensitive to mass ratio
(except 1:1 predecoupling)

→ **EM+KIN Luminosities**:
Characteristic rises/peaks
just after merger
L_cool > L_kin > L_EM

→ **GW amplitude:**
well known chirp

Gold et al 2014

Variability



- far from clean (compare to 2D-thin disk studies)
- Not necessarily at binary orbital period
- Highest variability at intermediate mas ratios (confirming d'Orazio, Haiman et al)
- Little variability at larger mass ratios (as expected: → single BH limit)

Conclusions

- Predecoupling: Gold et. al. 2013

  high accretion rates, dense material remains near horizons, persistent jets

- inspiraling and merger: Farris et al 2012 Gold et. al. 2014

  Luminosity peaks/rises, enhanced jet collimation

- First GRMHD parameter study: Gold et. al. 2013
  binary mass ratio, e.g. 1:10 cavity refills

→ ***Now: Time for more physics !***

The next steps...

- Radiative transport (synchrotron, Compton)
  ...in progress...
- Rebrightening (viscous refilling of the hollow)
  ...in progress...
- BH spins
  ...in progress...

Thank you for your attention!

References:

arXiv:1410.1543, PRD 90, 10, 104030
arXiv:1312.0600, PRD 89, 6, 064060
arXiv:1207.3354, PRL 109, 221102