The Role of the Magnetic Field in Black Hole-Neutron Star Electromagnetic Counterparts

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Outline

- Background and motivations
- System
- Methods
- Results
- Ongoing work

Background and motivations

- Coalescing compact binaries

are the strongest gravitational wave (GW) emitters detectable by ground-based detectors,
e.g., LIGO, VIRGO, GEO, KAGRA, IndIGO
⇒ strong tool for verifying the existence of GWs as a prediction of general relativity (GR)

- Accompanying electromagnetic wave (EM) signature

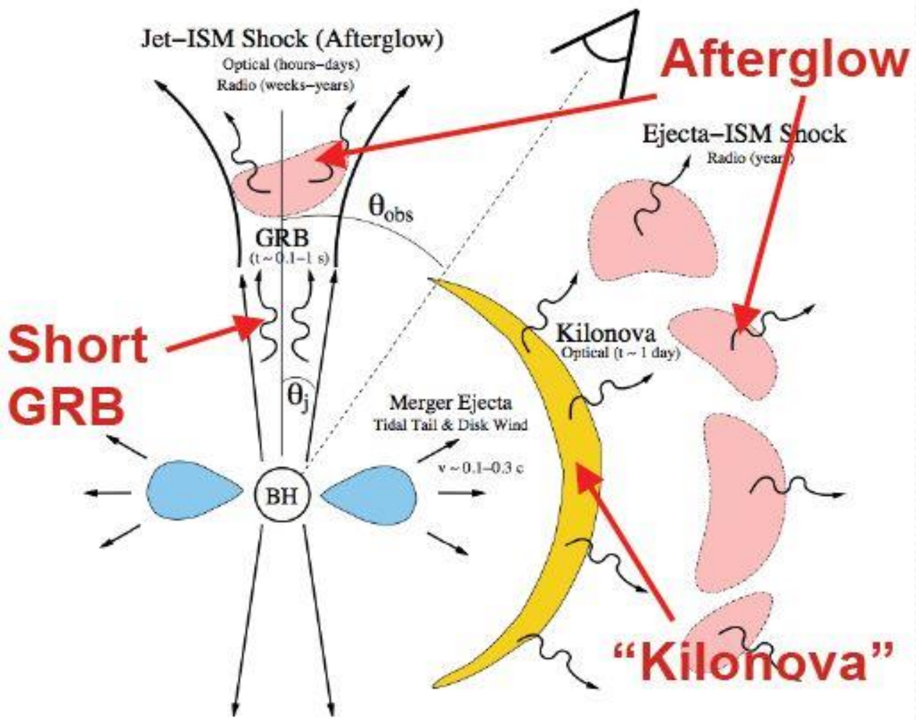
⇒ effectively localizes the source of GWs + its environment

⇒ improves confidence of GW detection

- Kilonova emission in conjuction with sGRB 130603B

⇒ compact binary progenitor hypothesis for short gamma-ray bursts (sGRBs) reinforced

⇒ sGRBs are strong EM counterparts for compact binaries



(Image: Metzger and Berger, 2012)

Background and motivations

(Nissanke, *et al*, 2012)

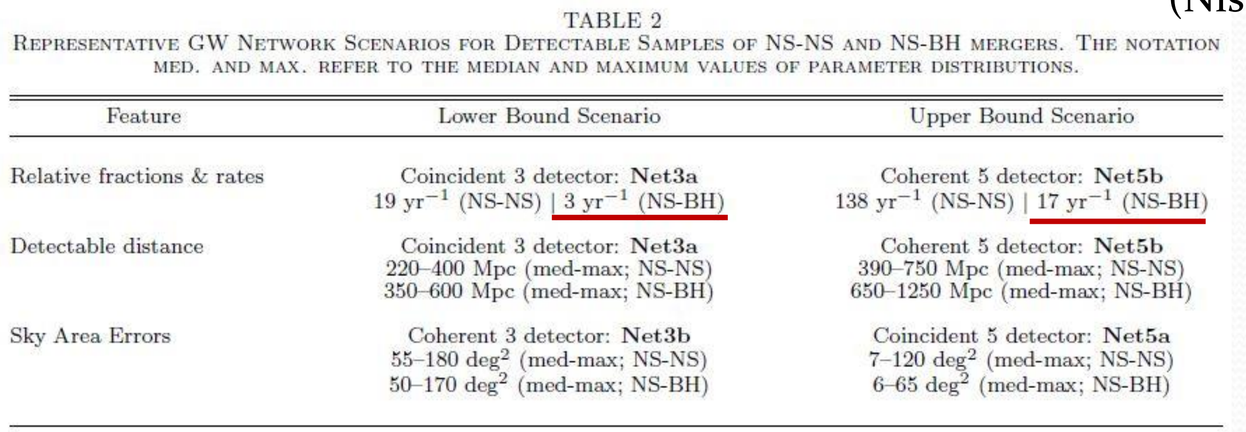


TABLE 2

Representative GW Network Scenarios for Detectable Samples of NS-NS and NS-BH mergers. The notation med. and max. refer to the median and maximum values of parameter distributions.

Feature	Lower Bound Scenario	Upper Bound Scenario
Relative fractions & rates	Coincident 3 detector: **Net3a** 19 yr^{-1} (NS-NS) | 3 yr^{-1} (NS-BH)	Coherent 5 detector: **Net5b** 138 yr^{-1} (NS-NS) | 17 yr^{-1} (NS-BH)
Detectable distance	Coincident 3 detector: **Net3a** 220–400 Mpc (med-max; NS-NS) 350–600 Mpc (med-max; NS-BH)	Coherent 5 detector: **Net5b** 390–750 Mpc (med-max; NS-NS) 650–1250 Mpc (med-max; NS-BH)
Sky Area Errors	Coherent 3 detector: **Net3b** 55–180 deg^2 (med-max; NS-NS) 50–170 deg^2 (med-max; NS-BH)	Coincident 5 detector: **Net5a** 7–120 deg^2 (med-max; NS-NS) 6–65 deg^2 (med-max; NS-BH)

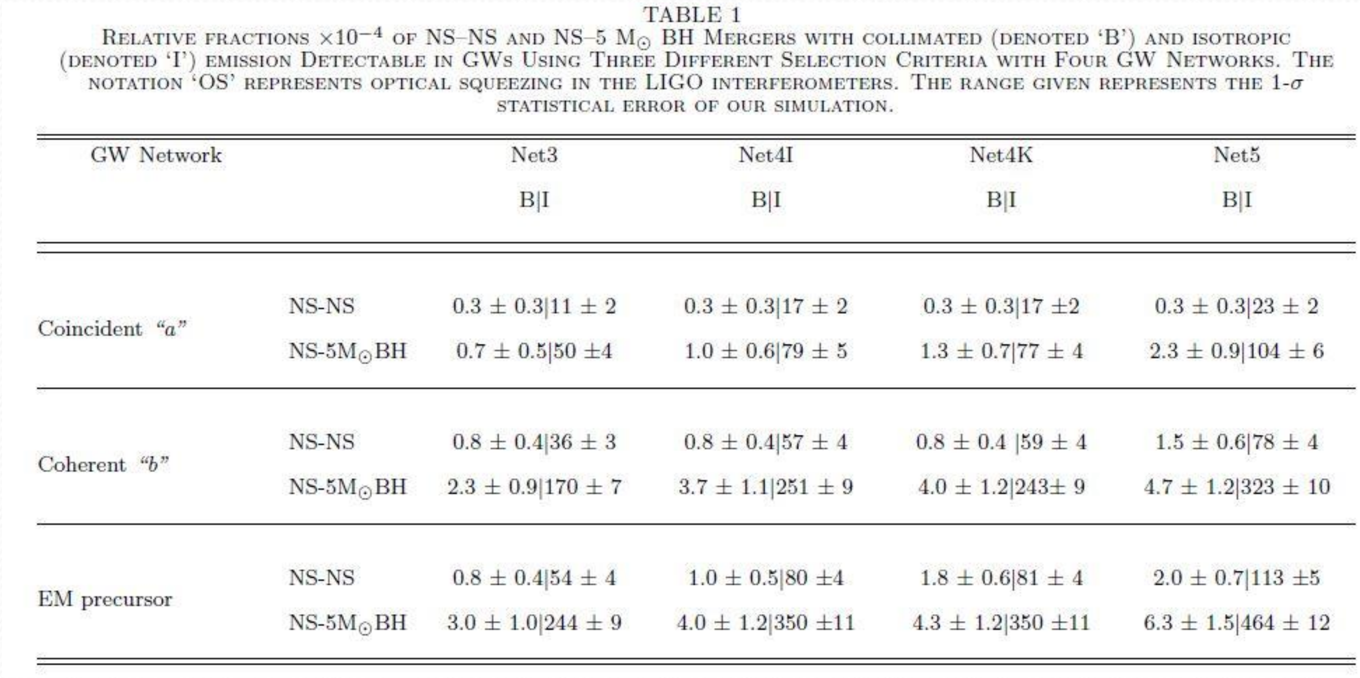


TABLE 1

Relative fractions $\times 10^{-4}$ of NS–NS and NS–5 $M_\odot$ BH Mergers with collimated (denoted 'B') and isotropic (denoted 'I') emission Detectable in GWs Using Three Different Selection Criteria with Four GW Networks. The notation 'OS' represents optical squeezing in the LIGO interferometers. The range given represents the 1-σ statistical error of our simulation.

GW Network		Net3	Net4I	Net4K	Net5
		B|I	B|I	B|I	B|I
Coincident *"a"*	NS-NS	0.3 ± 0.3|11 ± 2	0.3 ± 0.3|17 ± 2	0.3 ± 0.3|17 ±2	0.3 ± 0.3|23 ± 2
	NS-5$M_\odot$BH	0.7 ± 0.5|50 ±4	1.0 ± 0.6|79 ± 5	1.3 ± 0.7|77 ± 4	2.3 ± 0.9|104 ± 6
Coherent *"b"*	NS-NS	0.8 ± 0.4|36 ± 3	0.8 ± 0.4|57 ± 4	0.8 ± 0.4 |59 ± 4	1.5 ± 0.6|78 ± 4
	NS-5$M_\odot$BH	2.3 ± 0.9|170 ± 7	3.7 ± 1.1|251 ± 9	4.0 ± 1.2|243± 9	4.7 ± 1.2|323 ± 10
EM precursor	NS-NS	0.8 ± 0.4|54 ± 4	1.0 ± 0.5|80 ±4	1.8 ± 0.6|81 ± 4	2.0 ± 0.7|113 ±5
	NS-5$M_\odot$BH	3.0 ± 1.0|244 ± 9	4.0 ± 1.2|350 ±11	4.3 ± 1.2|350 ±11	6.3 ± 1.5|464 ± 12

Background and motivations

- Can a black hole-neutron star (BHNS) merger be an sGRB progenitor?/ What are the possible EM counterparts that can be generated by a BHNS merger?
- What is the role of the NS magnetic field in generating these EM counterparts?
- How does the NS magnetic field amplitude and configuration evolve under various amplification mechanisms?

Background and motivations

Numerical relativity

- Etienne+ ’12:

BHNS mergers can power *jets* along funnel above and below equatorial plane
with a strong enough poloidal field
threading the accretion disk

- Giacomazzo+ ’14:

small-scale dynamo acting
inside hypermassive neutron star (HMNS) formed from BNS mergers;
dissipation of amplified B field can generate sGRB precursor flares

- Paschalidis+ ’14:

BHNS mergers can power *jets* along funnel above and below equatorial plane
via the action of NS magnetosphere;
role of the MRI in the accretion disk is not clear
due to insufficient resolution

Background and motivations

- Topology of B field configuration in NS

$\Rightarrow$ generation of a large-scale poloidal field in merger remnant

\+ effective *jet collimation*

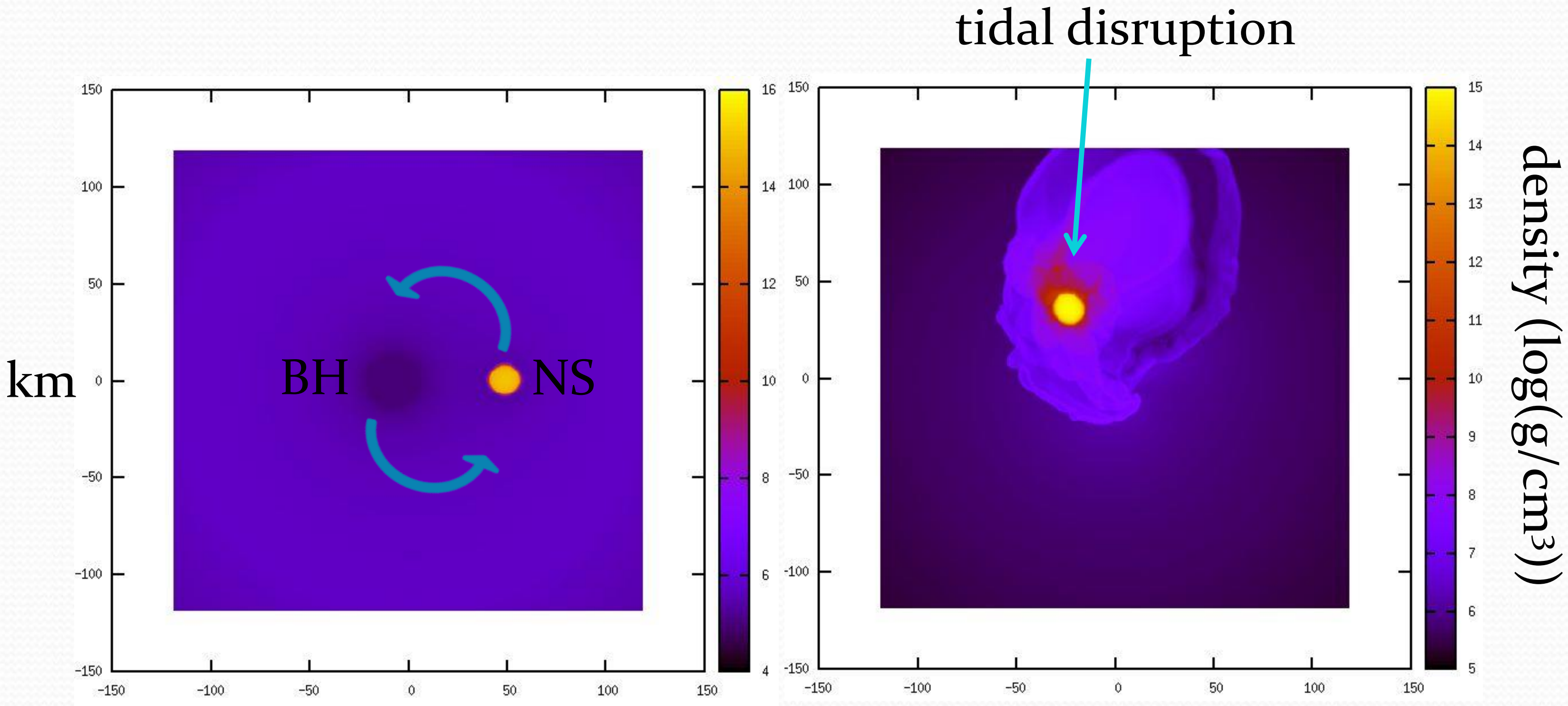
- Magneto-rotational instability (MRI) in merger remnant

$\Rightarrow$ amplification of toroidal + poloidal field in merger remnant

- Our way:

Can the MRI work to generate a large-scale poloidal field
in the accretion disk + surrounding corona
after a BHNS merger?

System

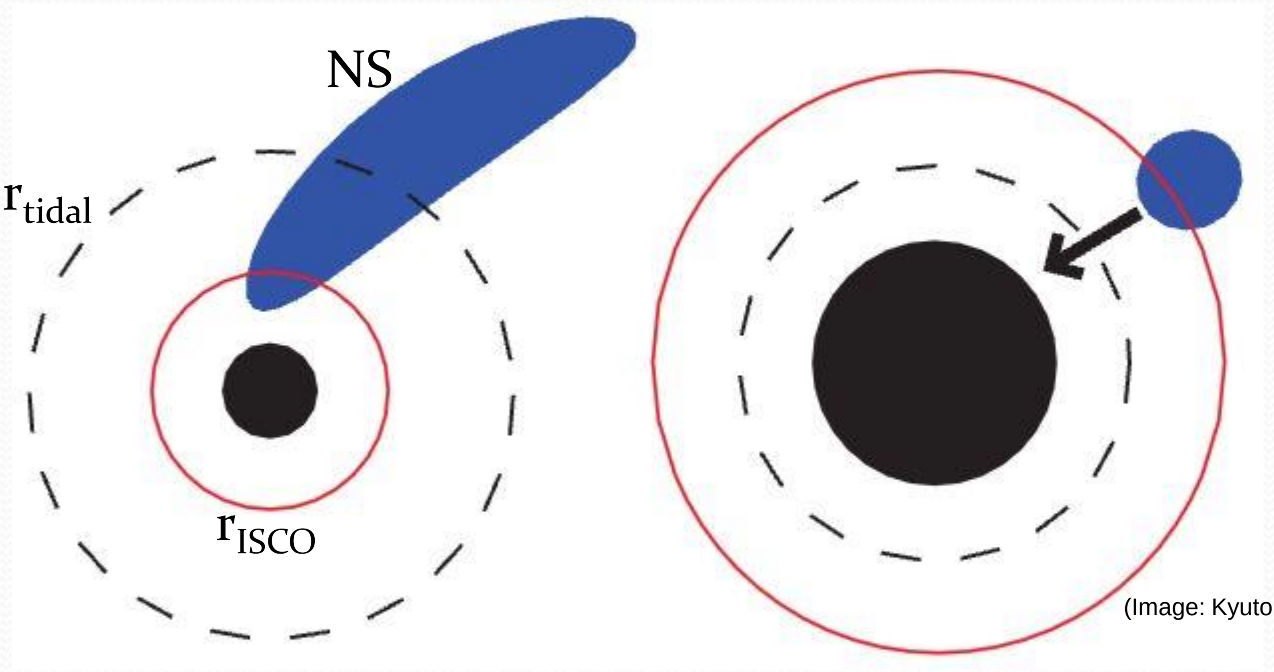


(Image: Wan, *et al*, 2015)

BH spin = 0.75 X extreme Kerr
BH mass = 4 X NS mass
NS with APR EOS

1.28ms later

System



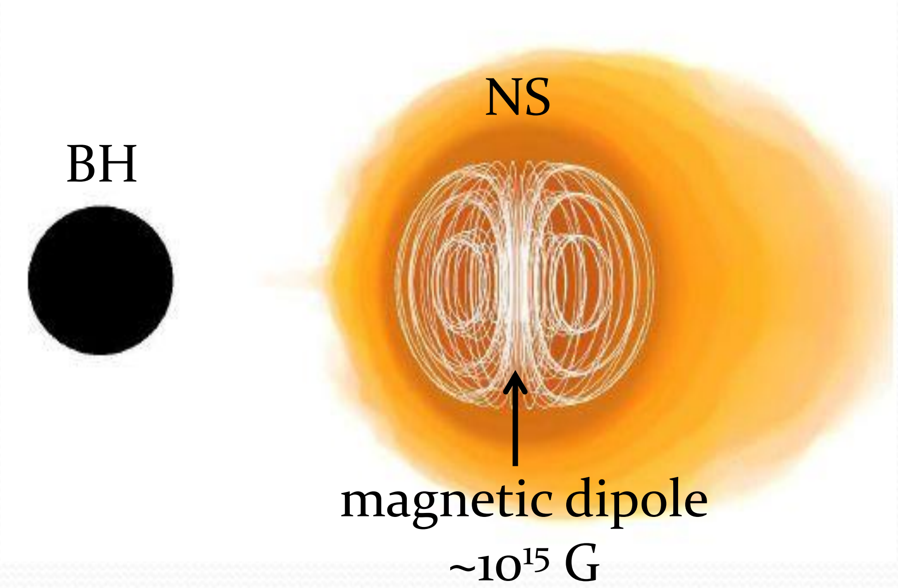
(Image: Kyutoku, *et al*, 2011)

NS tidal disruption occurs when

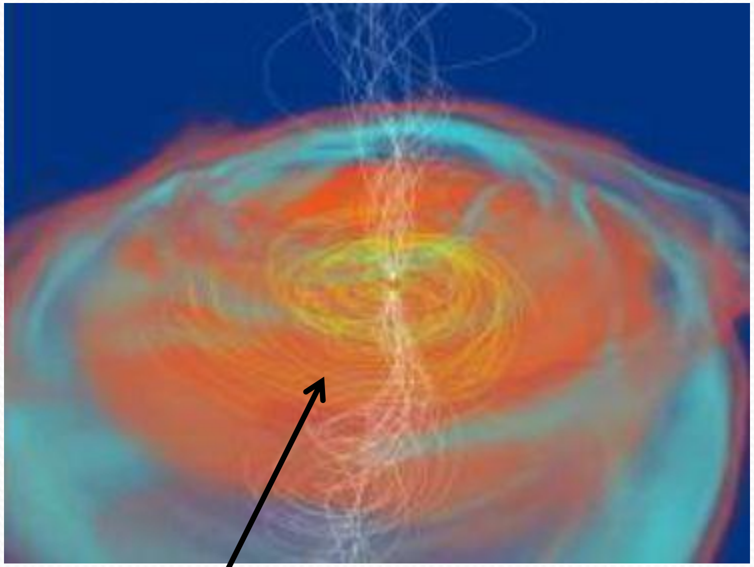
BH tidal force > NS self gravity $\equiv r_{ISCO} < r_{tidal}$

$$\left.\begin{array}{l}\text{Mass ratio} \downarrow \\ \text{NS compactness} \downarrow \\ \text{BH spin} \uparrow\end{array}\right\} \text{tidal disruption} \uparrow \Rightarrow M_{disk} \uparrow$$

System



(Image: Etienne, *et al*, 2012)



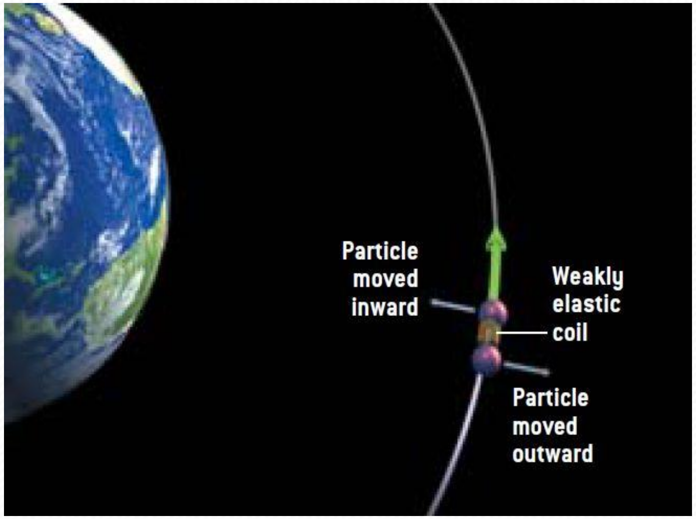
- angular momentum transport
- magnetic field winding:

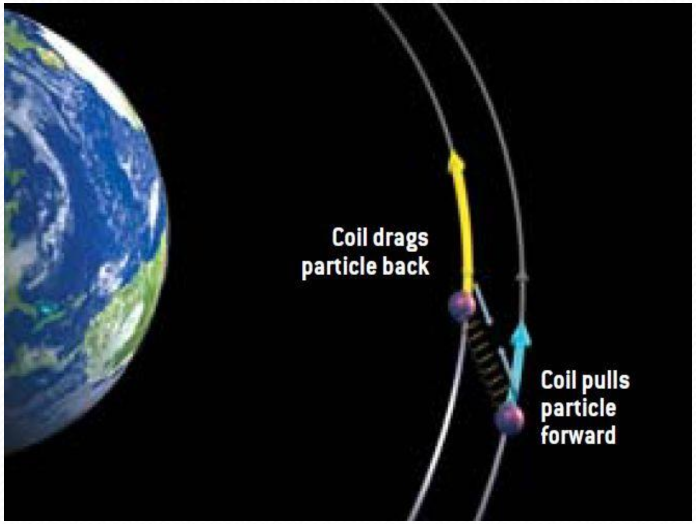
poloidal field in NS → toroidal field in accretion disk

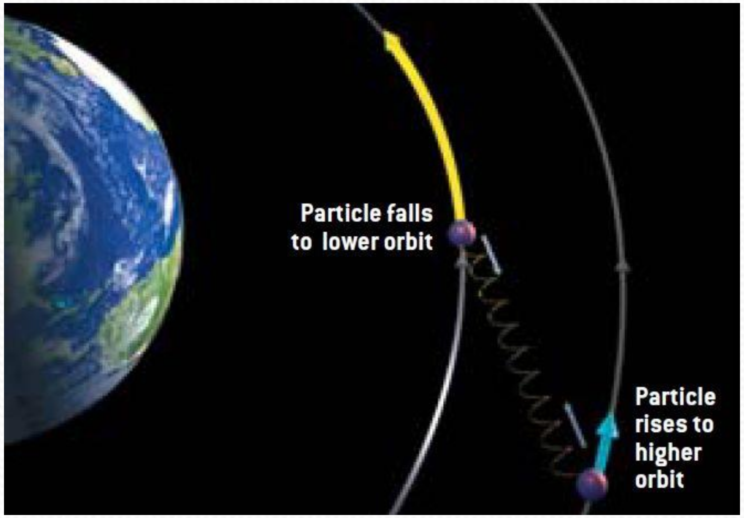
System

Physics of MRI

(Image: Blaes, 2004)







- central potential → outwardly decreasing angular momentum
- magnetic tension ≡ tension of elastic coil connecting 2 orbiting particles

→ resisting stretching → stabilizing
→ resisting shearing → de-stabilizing

System

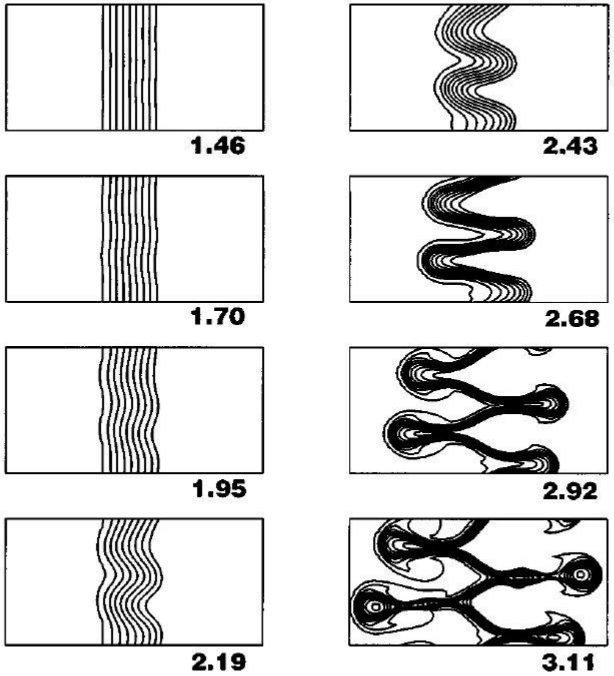
linear solution of the wave equation

$$\ddot{\xi}_R - 2\Omega\dot{\xi}_\phi = -\left(\frac{d\Omega^2}{d\ \ln\ R} + (\mathbf{k}\cdot\mathbf{u_A})^2\right)\xi_R$$

$$\ddot{\xi}_\phi + 2\Omega\dot{\xi}_R = -(\mathbf{k}\cdot\mathbf{u_A})^2\xi_\phi$$

$=$

exact non-linear solution
of the full axisymmetric
hydrodynamic equations
≡ “channel” solution
for accretion disk
(Goodman & Xu, ’94)



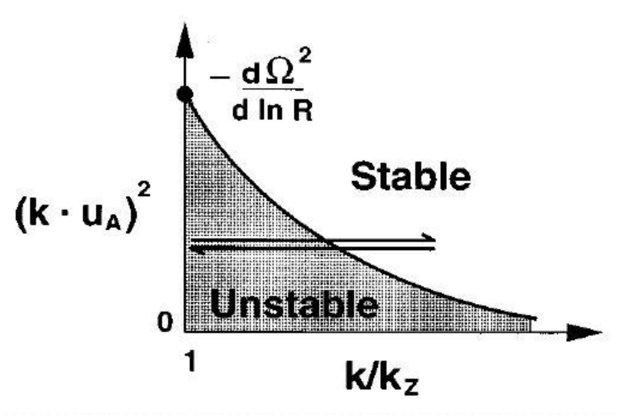
(Figure: Balbus & Hawley, 1998)

System

- Instability criteria

a) $$\frac{d\Omega^2}{d\ \ln\ R} < 0$$

b) $$(\mathbf{k}\cdot\mathbf{u_A})^2 < -\frac{d\Omega^2}{d\ \ln\ R}$$



(Image: Balbus & Hawley, 1998)

- Maximum unstable growth rate

a) axisymmetric analysis

$$|\omega_{max}| = \frac{1}{2}\left|\frac{d\Omega}{d\ \ln\ R}\right|, \quad (\mathbf{k}\cdot\mathbf{u_A})^2_{max} = -\left(\frac{1}{4} + \frac{\kappa^2}{16\Omega^2}\right)\frac{d\Omega^2}{d\ \ln\ R}$$

b) non-axisymmetric analysis

$$k_Z \gg k_R \sim k_R(0) \gg m\frac{d\ \ln\ \Omega}{dR}$$ → axisymmetric limit

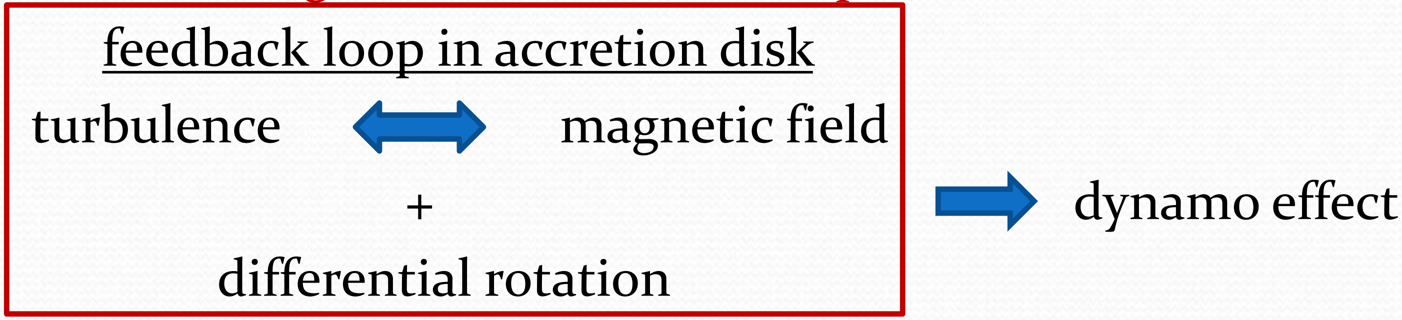
⇒ poloidal field magnitude determines maximum growth rate

⇒ wavelength of maximum growth mode, $\lambda_{\mathrm{MRI}} \sim \left(\frac{2\pi}{\Omega}\right)\left(\frac{B_i e^i_k}{\sqrt{4\pi\rho}}\right)$

System

- Outcome of MRI

⇒ outward angular momentum transport + turbulence

- 

<u>feedback loop in accretion disk</u>

turbulence ⇔ magnetic field

\+

differential rotation

⇒ dynamo effect

- Non-axisymmetric B field in accretion disk

→ violates the anti-dynamo theorem

- Non-zero mean B field in merger remnant

→ sustained turbulence

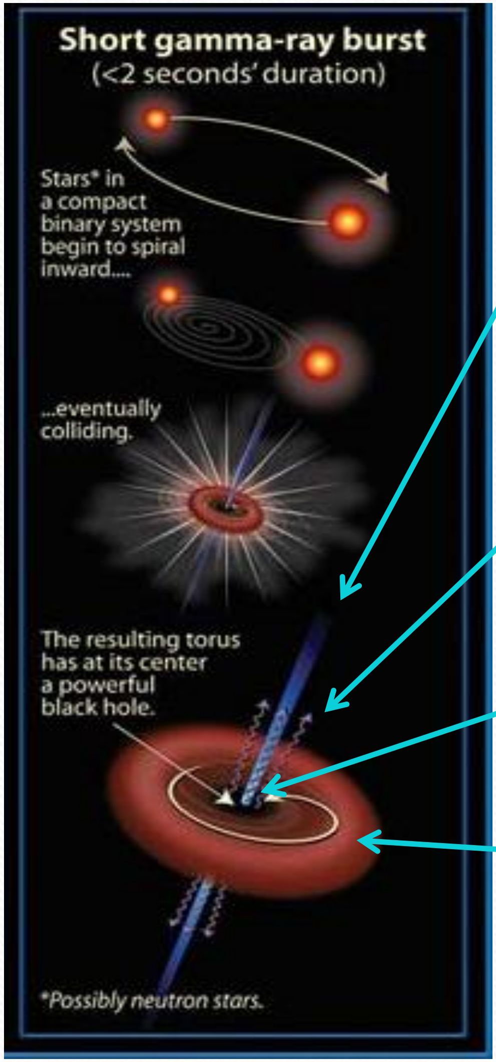
- Growth rate counterbalanced by dissipation { resistivity, reconnection

→ saturation

- B field becomes dynamically important

→ equipartition with plasma kinetic energy

System



(Image: daviddarling.info/encyclopaedia)

high-velocity *matter jet*
collimated by B field

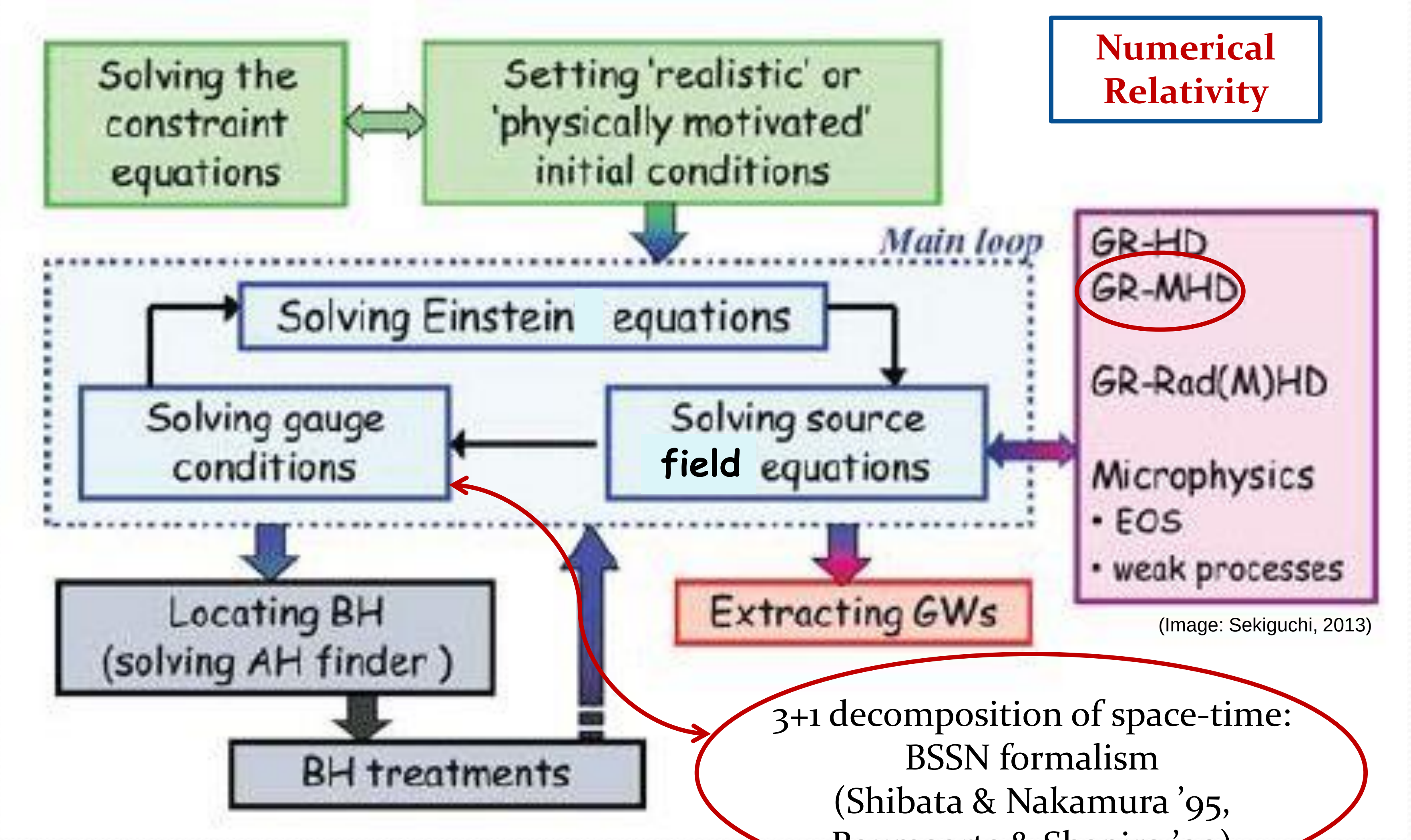
luminous short burst
of gamma rays

initially matter-poor region
along BH rotation axis

hot
dense
massive

accretion
disk

Methods

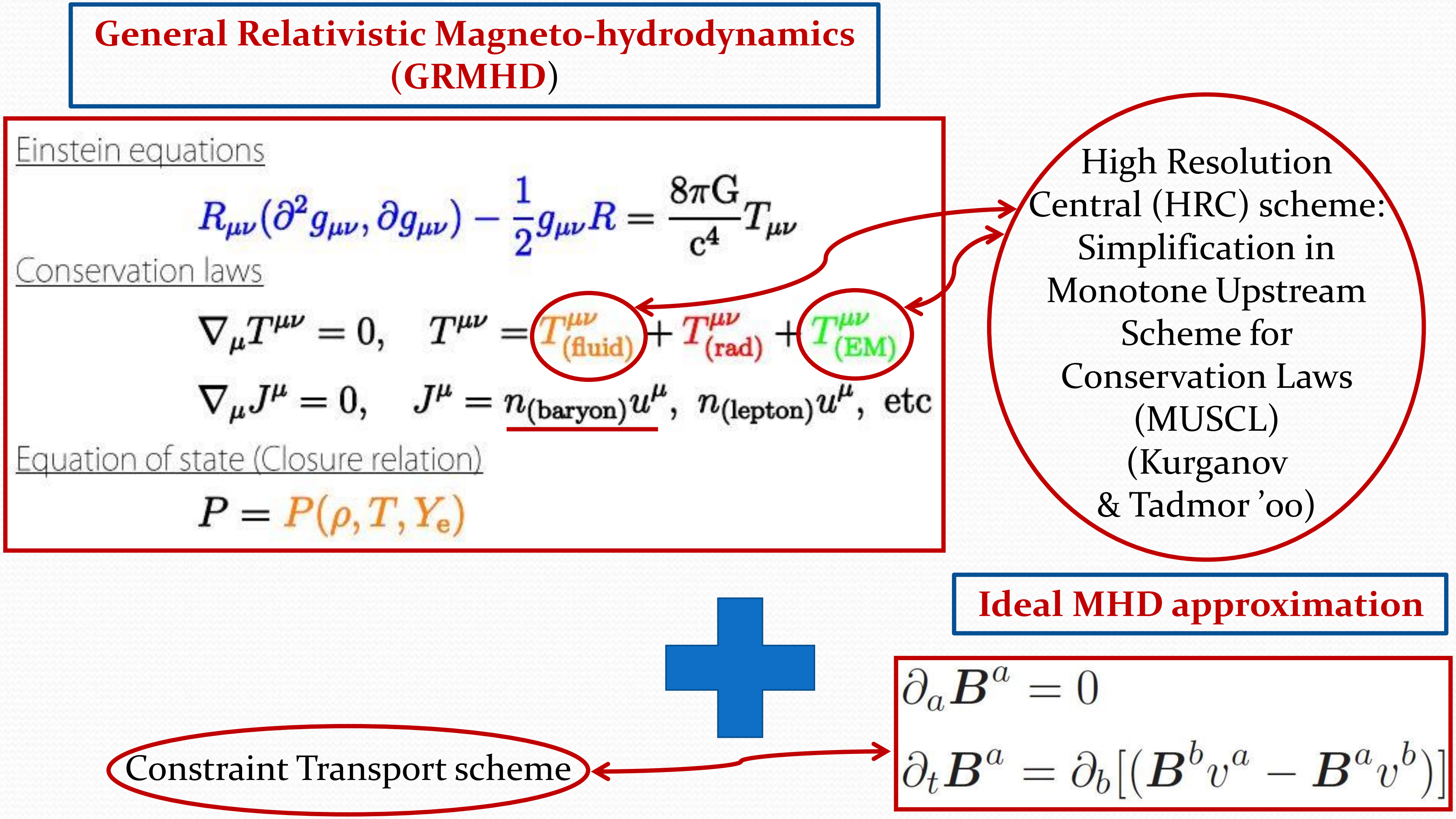


Numerical Relativity

(Image: Sekiguchi, 2013)

3+1 decomposition of space-time:
BSSN formalism
(Shibata & Nakamura '95,
Baumgarte & Shapiro '99)

Methods



General Relativistic Magneto-hydrodynamics (GRMHD)

Einstein equations

$$R_{\mu\nu}(\partial^2 g_{\mu\nu}, \partial g_{\mu\nu}) - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi \mathrm{G}}{\mathrm{c}^4} T_{\mu\nu}$$

Conservation laws

$$\nabla_\mu T^{\mu\nu} = 0, \quad T^{\mu\nu} = T^{\mu\nu}_{(\mathrm{fluid})} + T^{\mu\nu}_{(\mathrm{rad})} + T^{\mu\nu}_{(\mathrm{EM})}$$

$$\nabla_\mu J^\mu = 0, \quad J^\mu = \underline{n_{(\mathrm{baryon})}} u^\mu, \; n_{(\mathrm{lepton})} u^\mu, \; \mathrm{etc}$$

Equation of state (Closure relation)

$$P = P(\rho, T, Y_{\mathrm{e}})$$

High Resolution Central (HRC) scheme: Simplification in Monotone Upstream Scheme for Conservation Laws (MUSCL) (Kurganov & Tadmor '00)

Ideal MHD approximation

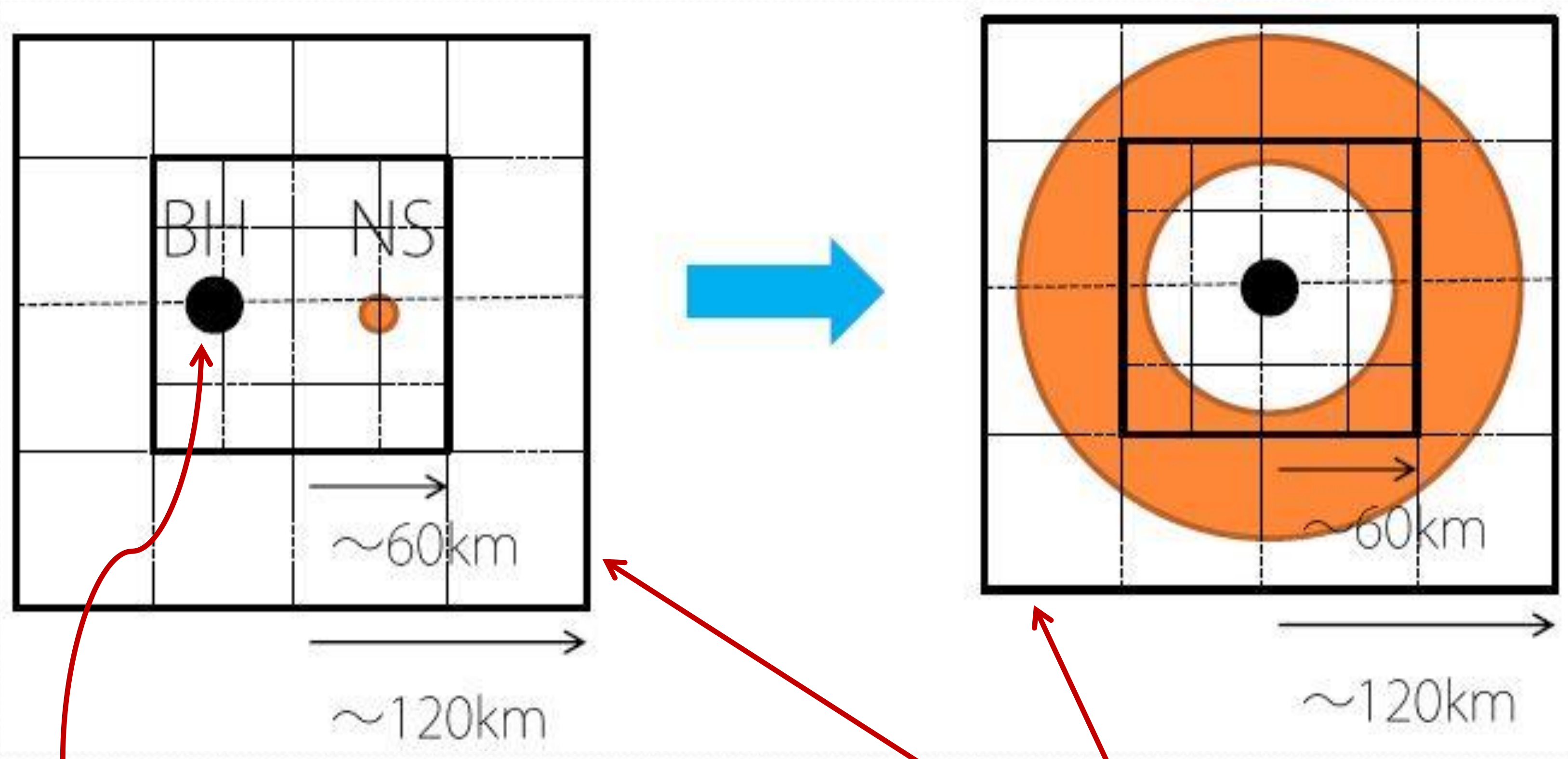
$$\partial_a B^a = 0$$

$$\partial_t B^a = \partial_b [(B^b v^a - B^a v^b)]$$

Constraint Transport scheme

Methods

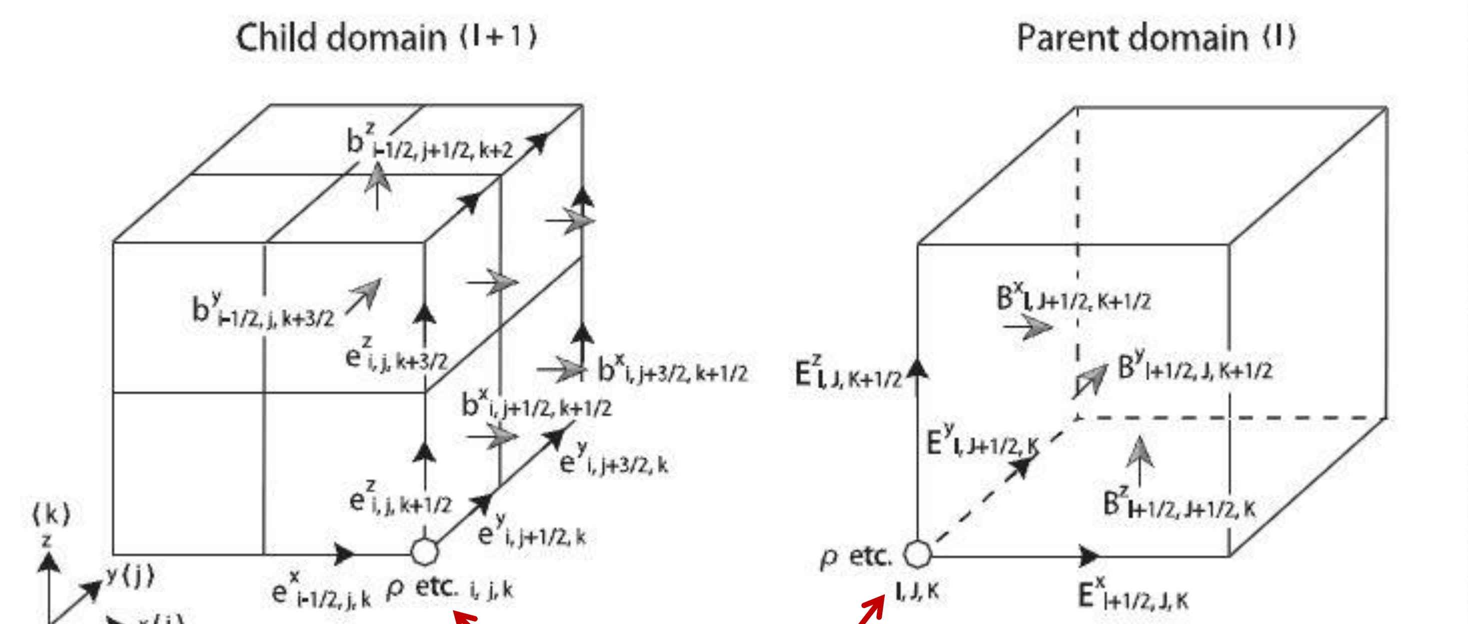
(Image: Kiuchi, 2013)



moving puncture method
for evolving BH

fixed nested grids;
resolution of finest grid ~ 270 m

Methods



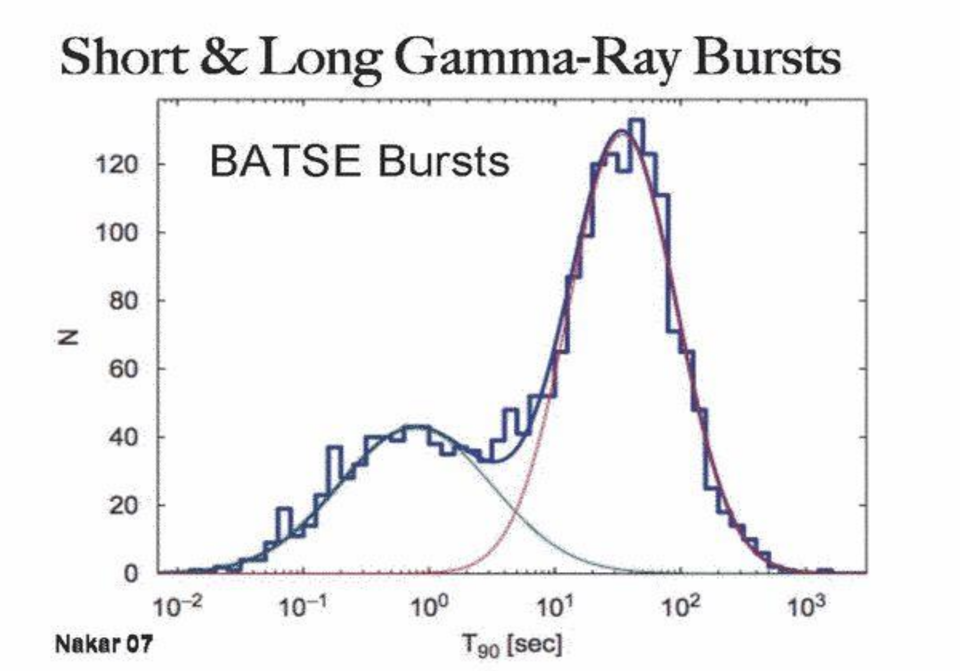
(Image: Kiuchi, 2012)

grids preserving ∇.B=0 well by Balsara's method ('09):

- WENO5 volume and surface reconstruction for magnetic field
- offset in the electric field during restriction
- all GRMHD variables evolved at grid vertices

Methods

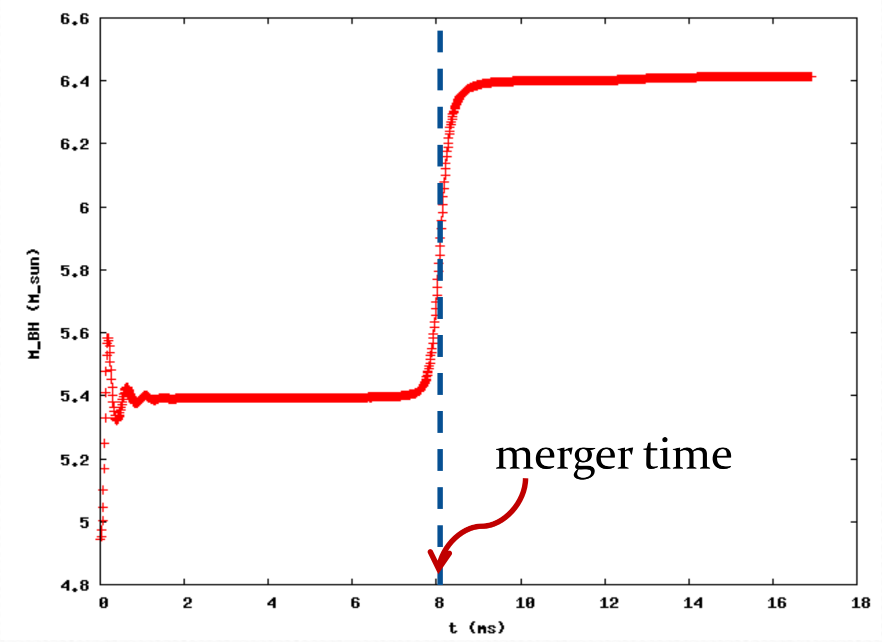
- Time-scale of sGRB observed by BATSE



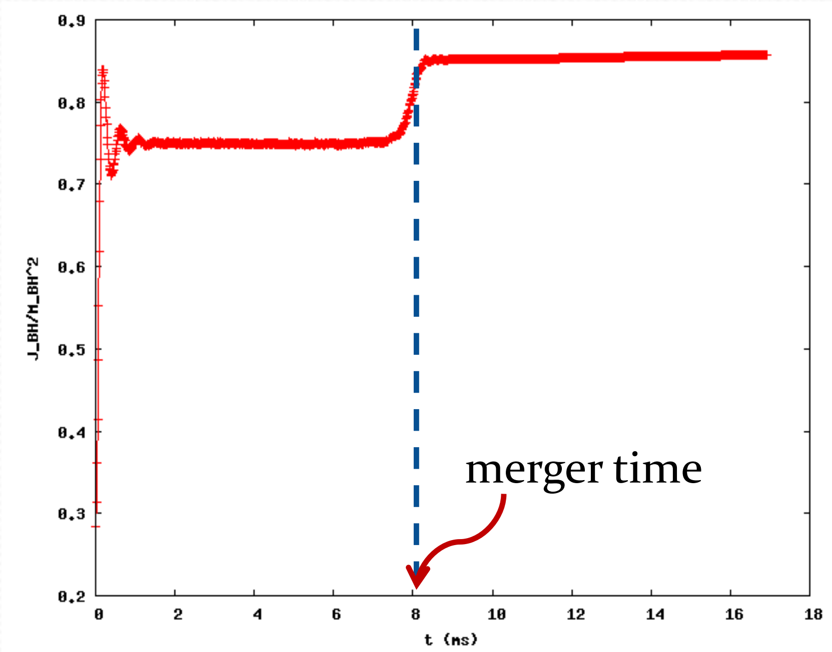
⇒ long-term simulation in the time scale of sGRB (~100 ms)

Results

Evolution of BH mass



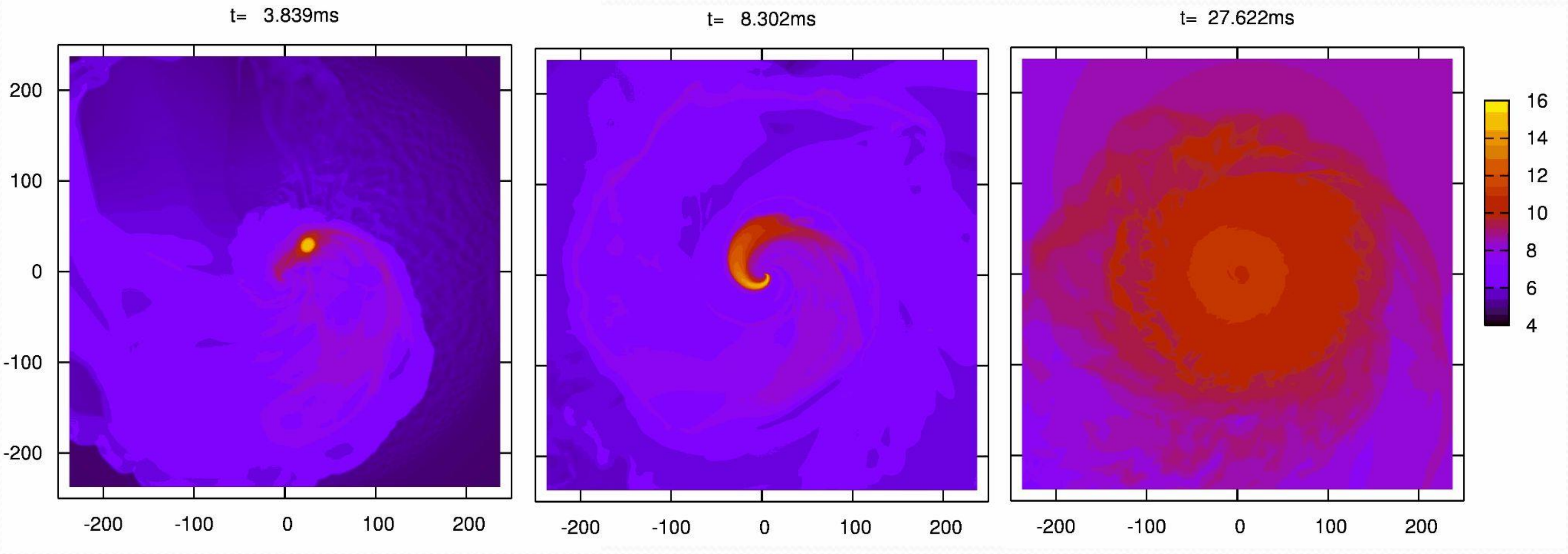
Evolution of BH spin



- Disk mass 0.35 M_s ⇒ massive disk
- Angular momentum of BH increased due to accreted mass

Results

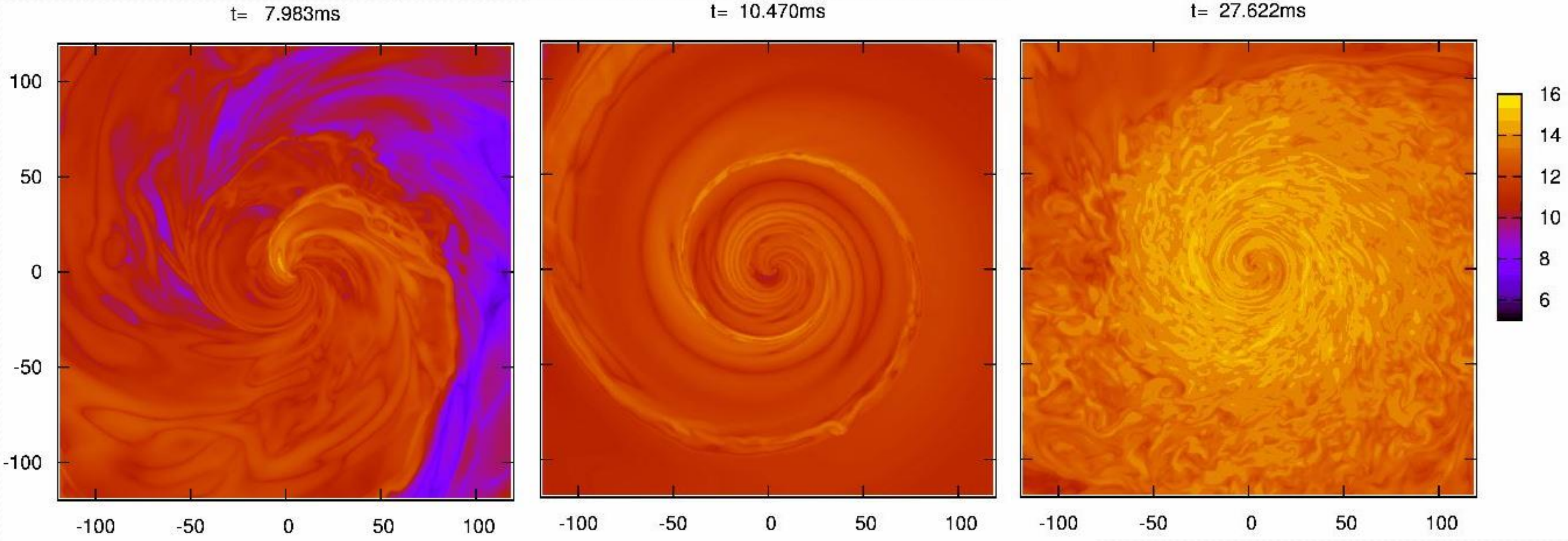
ρ [log(g/cm3)]



km

Results

B [log(G)]



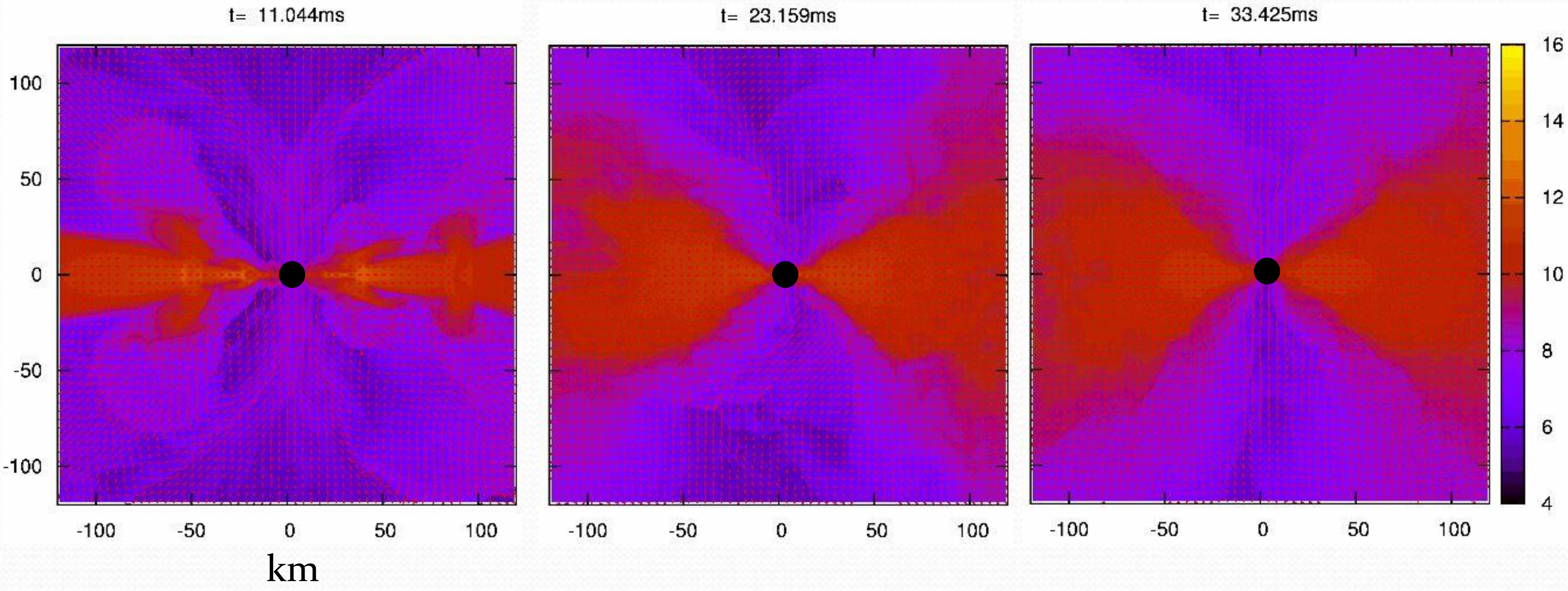
km

merger

magnetic winding
by spiral arm

turbulent cascade

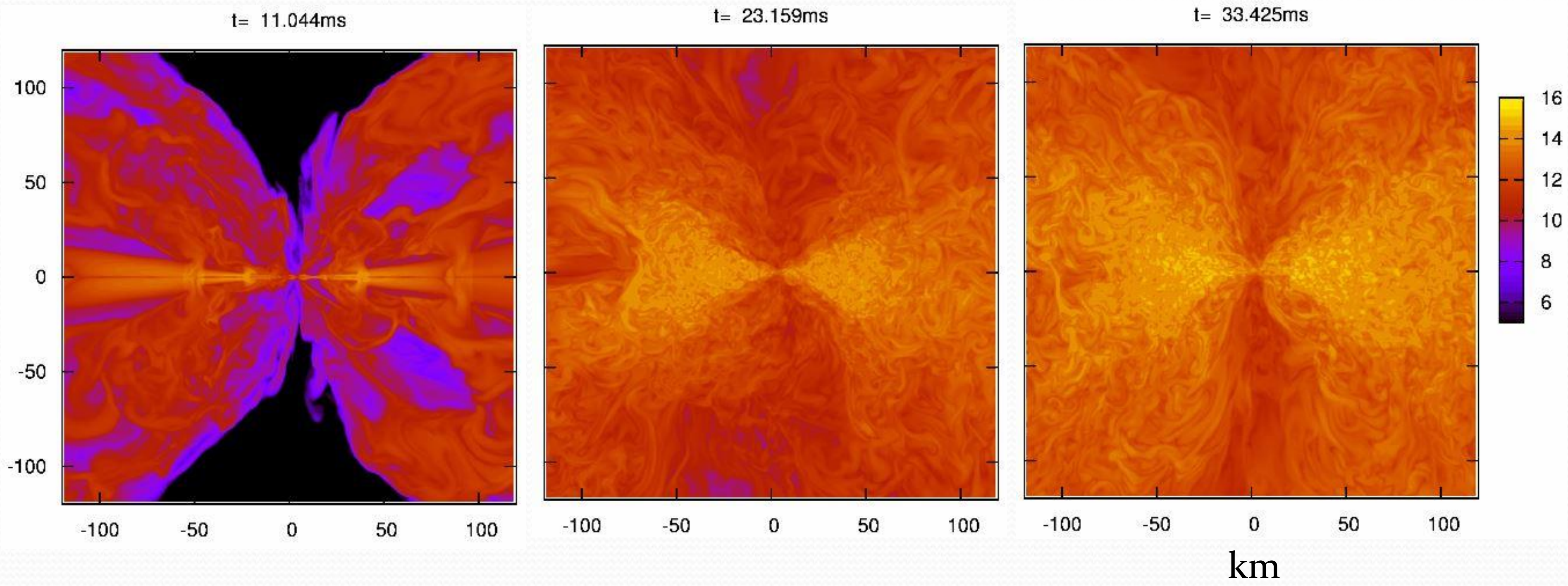
Results



- Ram velocity of matter in funnel → fallback
- Wind on disk edges starts to develop at t~25ms after merger

→ net mass outflow

Results

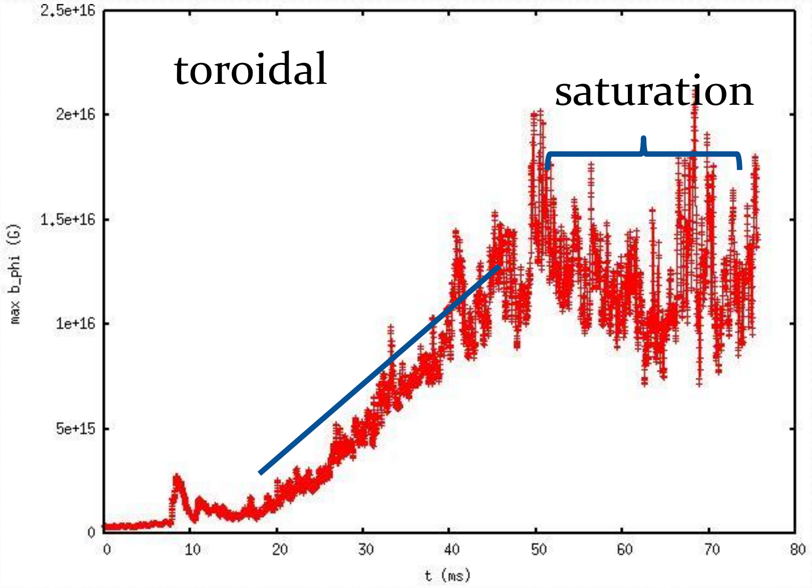


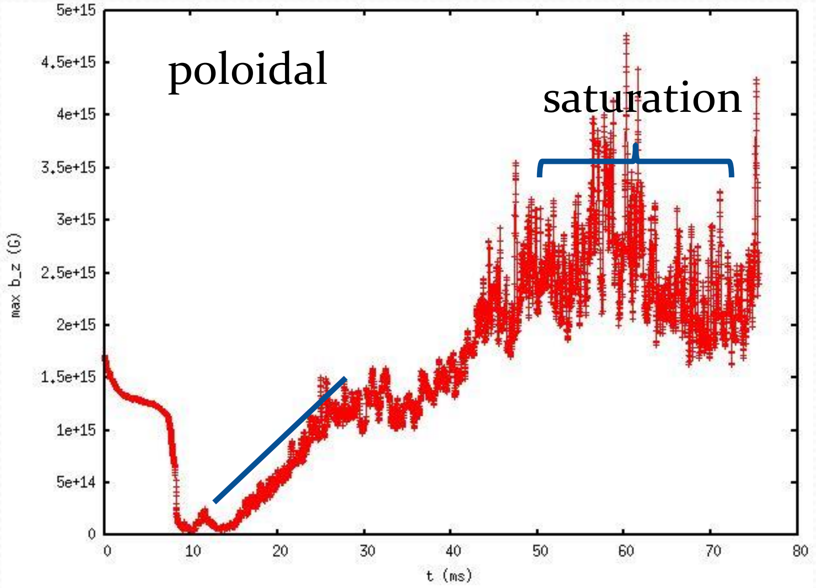
- B field advected by in-falling matter
- Turbulent cascade

- in accretion disk

- near funnel above and below merger remnant

Results





- Amplification via MRI of both toroidal and poloidal field by ~1 order of magnitude
- Saturation reached at t~42ms after merger
- Resolution of wavelength of fastest mode

a) toroidal direction: ~10 points

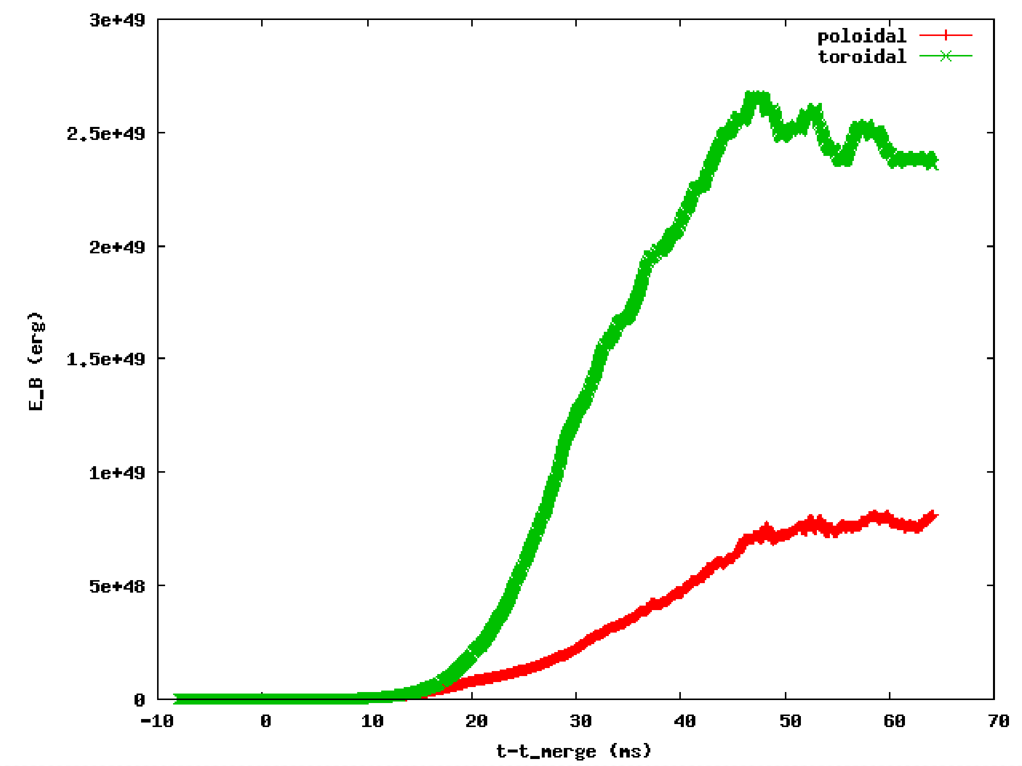
b) poloidal direction: ~1 point

Results

- $E_{toroidal} > E_{poloidal}$ by 1 order of magnitude
- saturation:

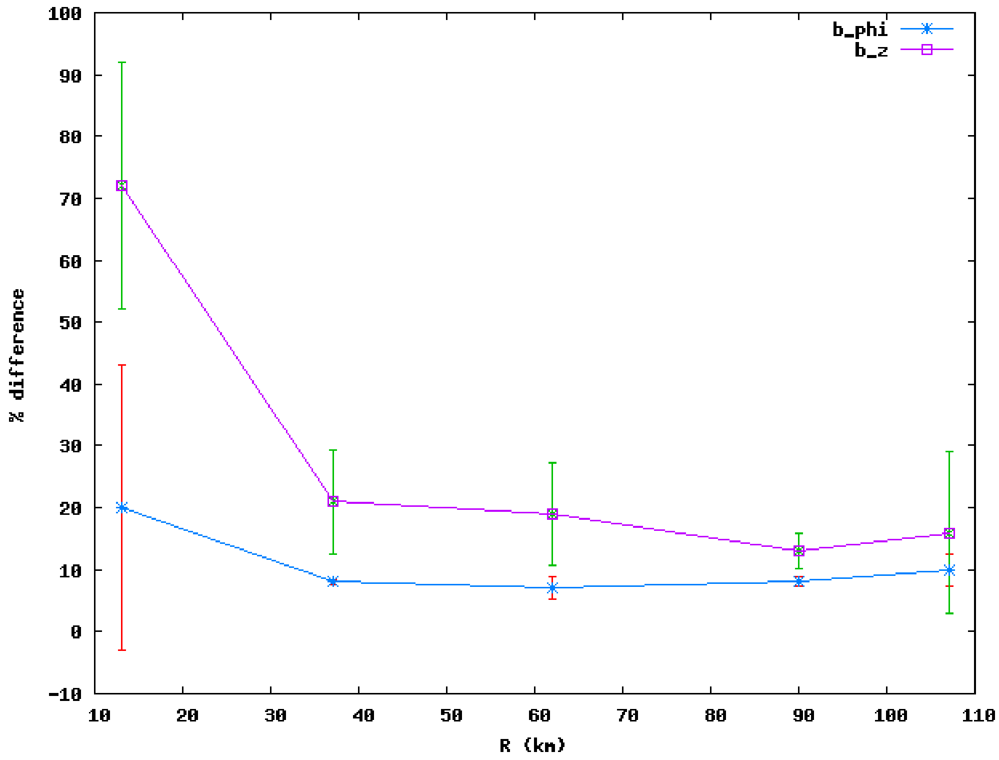
  $E_{poroidal}/KE_{plasma}$ ~ 0.1-0.2%

  $E_{toroidal}/KE_{plasma}$ ~ 0.4-0.6%



Results

Comparison with
non-axisymmetric
linear analysis
(Balbus & Hawley, '92):
% difference averaged
from 40 points on equatorial plane
along both
toroidal and radial directions
$13 \leq R \leq 107$km



- both poloidal and toroidal fields amplified

more readily by MRI in linear regime
further away from black hole/low density regions of disk
⇒ large-scale poloidal field may emerge starting from outer edges of disk

Ongoing work

- Thompson & Duncan '93:

direction of dipole in NS

not aligned with axis of its rotation axis

$\Rightarrow$ vary configuration of magnetic field inside NS

Expectations:

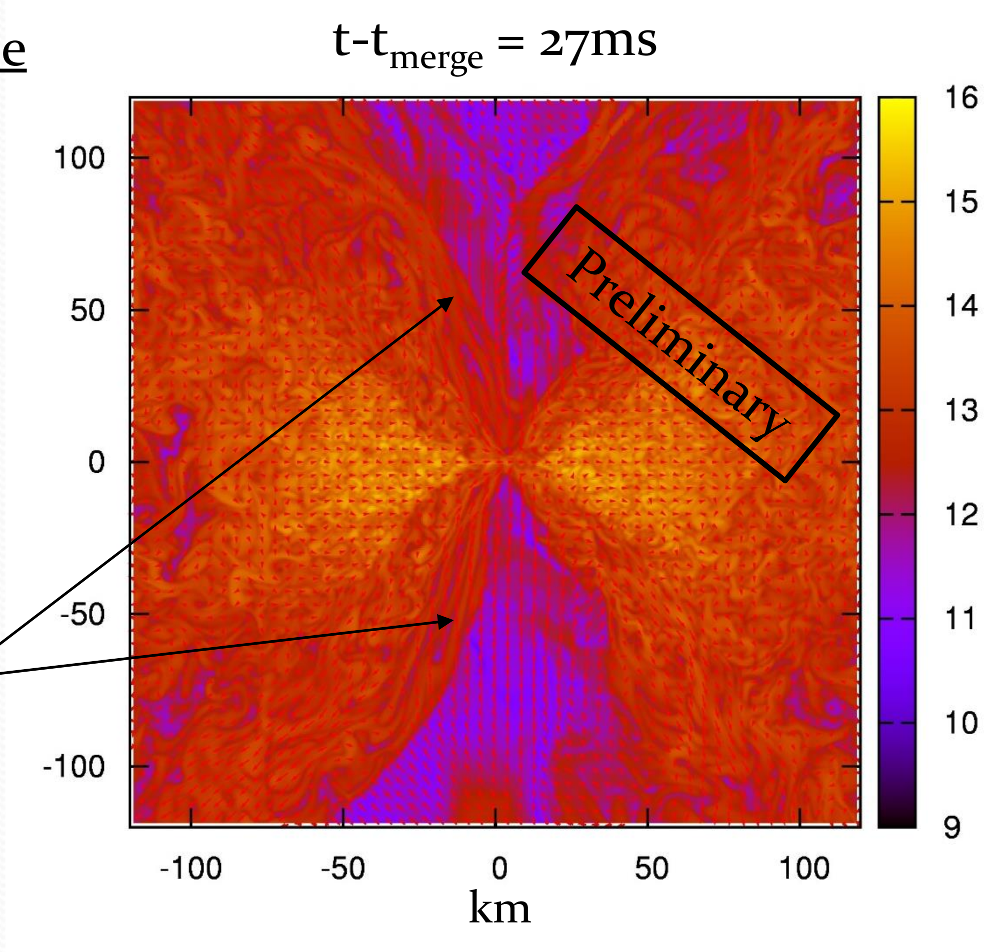
a) increase in resolution of wavelength of fastest MRI mode in poloidal field

b) saturation → equipartition

c) jet collimation → sGRB?

Ongoing work

tilted embedded NS dipole



onset of
coherent poloidal field
in steady
wind+fallback region:
$b^2/\rho_0 = O(10^{-3})$