BH-NS MAGNETOSPHERE

YITP
和田知己
(Tomoki Wada)

collaborator
Masaru Shibata
(YITP, AEI)

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

高エネルギー宇宙物理学研究会 2018

GW ASTRONOMY

Binary Black Hole → GW150916, .. 5 detection

Binary Neutron Star → **GW170817**

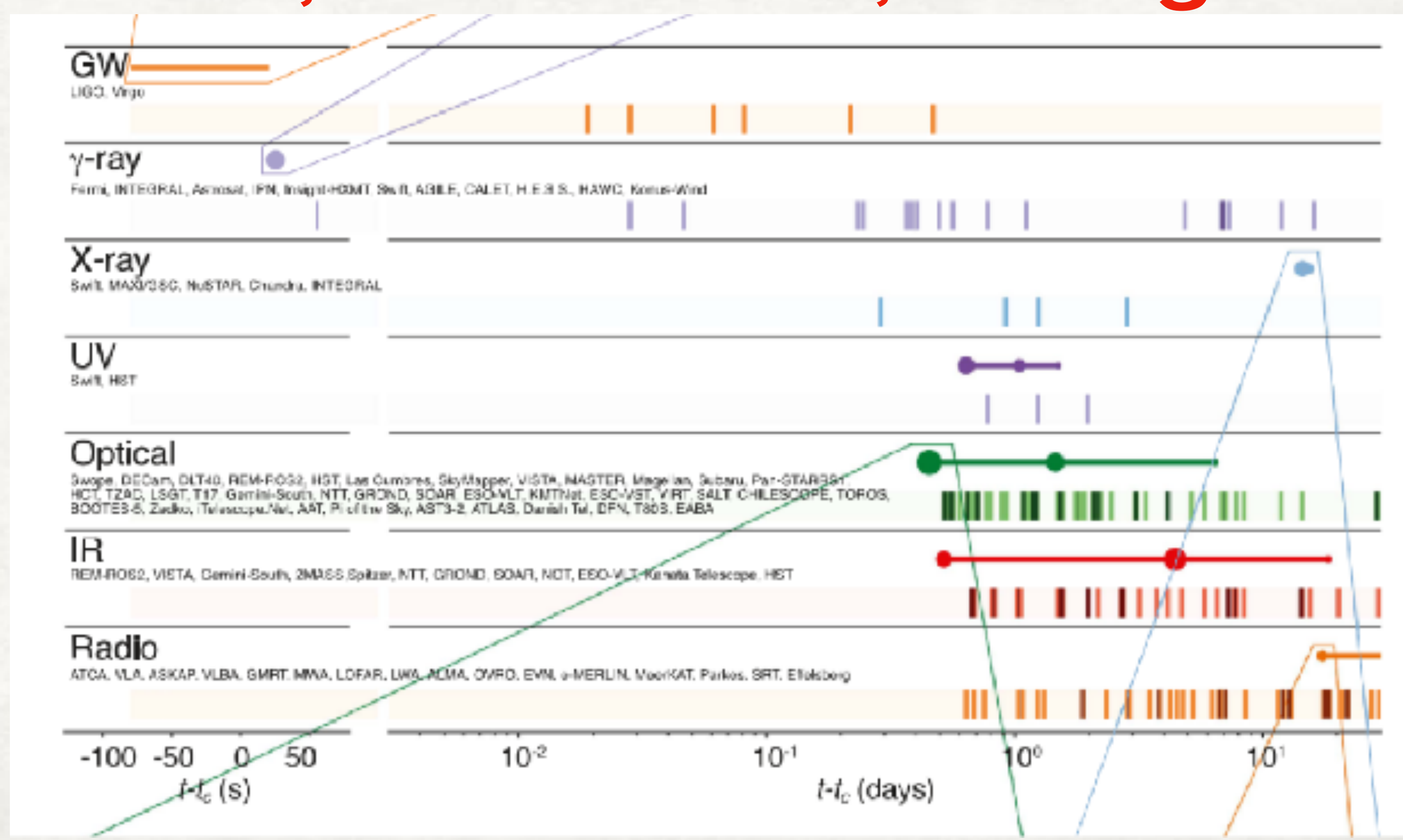
& **GRB170817A, macronova, afterglow**

γ-ray ～Radio

Electromagnetic

Counterpart

was detected !!!



GW ASTRONOMY

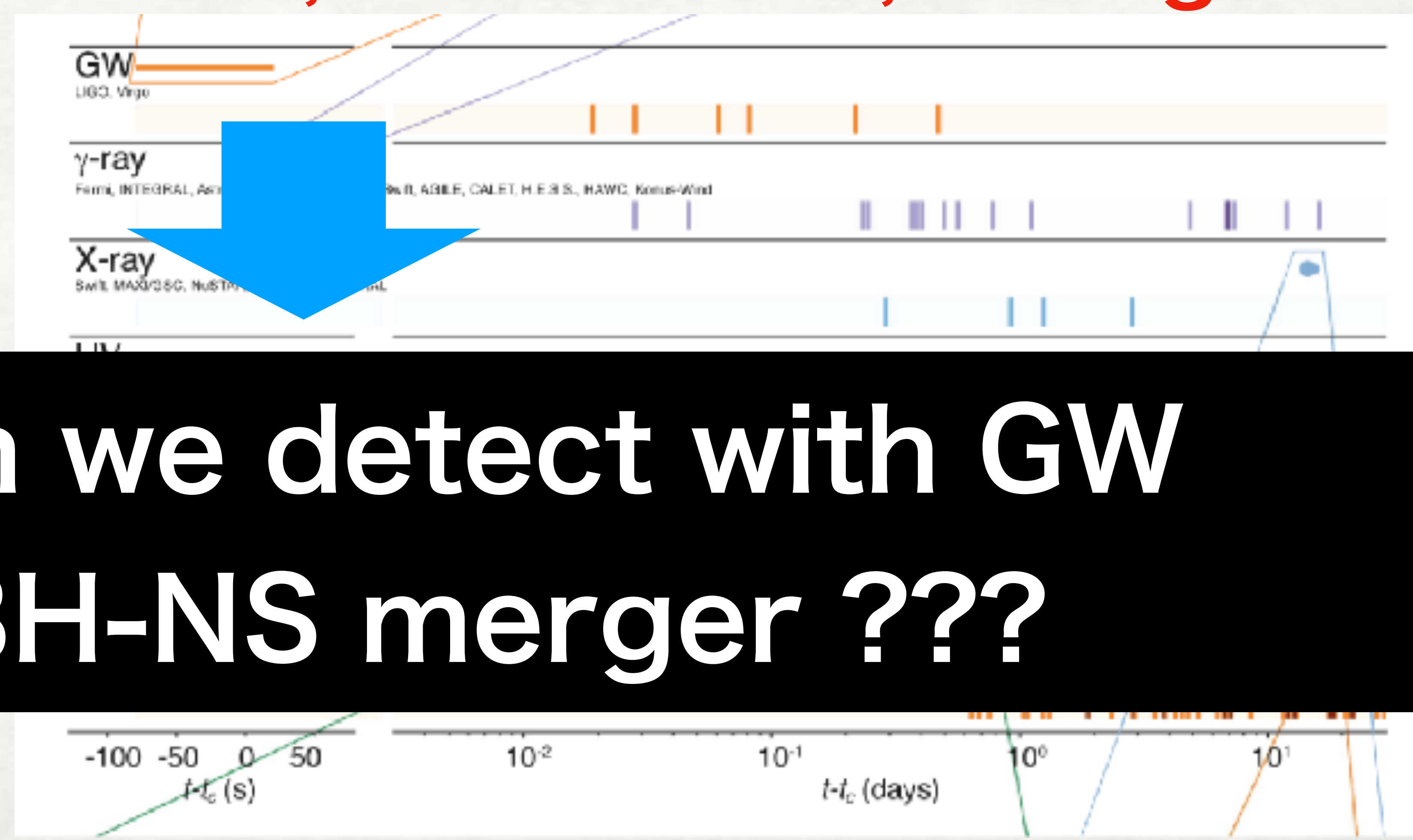
Binary Black Hole → GW150916, …5.5 detection

Binary Neutron Star → **GW170817**

& **GRB170817A, macronova, afterglow**

γ-ray ～Radio

Electromagnetic



What can we detect with GW from BH-NS merger ???

COUNTERPART WITH BH-NS MERGER

What happens with BH-NS merger ?

Typically

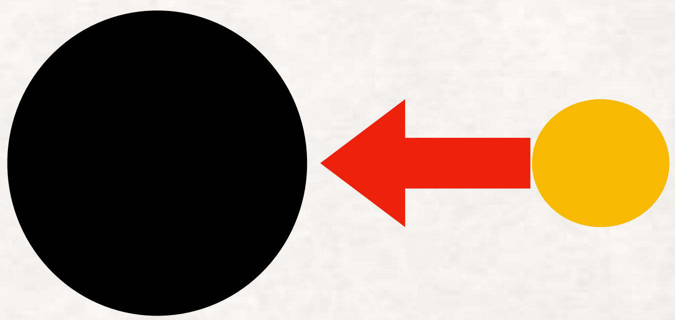
- **light BH** $(M_{\rm BH}/M_{\rm NS} \lesssim 5,\ \ a \gtrsim 0.5)$

  → tidal disruption ··· destroyed NS will light

- **heavy BH**   (Else)

  → NO tidal disruption

  ➡ Nothing will light ??



COUNTERPART WITH BH-NS MERGER

What happens with BH-NS merger ?

Typically

- **light BH** $(M_{\rm BH}/M_{\rm NS} \lesssim 5, \ \ a \gtrsim 0.5)$

  → tidal disruption … destroyed NS will light

- **heavy BH** (Else)

  → NO tidal disruption

  Nothing will light ??

NS … STRONG MAGNETIC FIELD
→ LIGHT EMISSION ?

PULSAR MAGNETOSPHERE

- assume pulsar is dipole → $\overrightarrow{B}^{\mathrm{NS}} \quad \overrightarrow{B}^{\mathrm{out}}$
- NS is conductor → $\overrightarrow{E}^{\mathrm{NS}} = -\dfrac{(\overrightarrow{\Omega} \times \vec{r})}{c} \times \overrightarrow{B}^{\mathrm{NS}}$

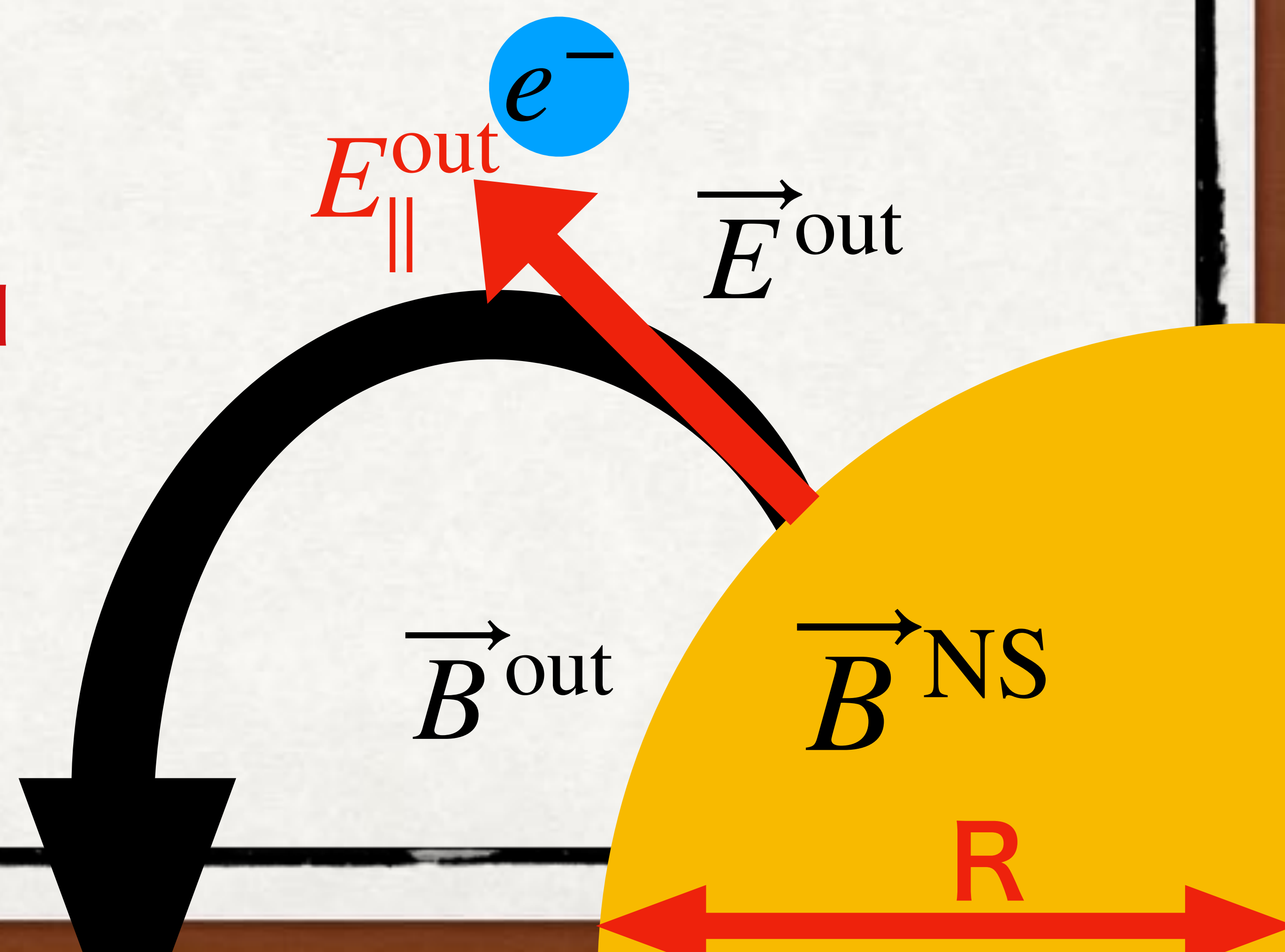
  $\rightarrow . \overrightarrow{E} = \overrightarrow{0}$ in coronation frame
- Poisson equation → $E^{\mathrm{out}} \sim \dfrac{\Omega B^{\mathrm{NS}} R^5}{c r^4}$

- Electric field parallel to

Magnetic field $E_{\parallel}^{\mathrm{out}} \sim \dfrac{\Omega R}{c} B$ will

accelerate charged particles

→ LIGHT EMISSION



PULSAR MAGNETOSPHERE

- assume pulsar is dipole → $\vec{B}^{\rm NS}$ $\vec{B}^{\rm out}$
- NS is conductor → $\vec{E}^{\rm NS} = -\frac{(\vec{\Omega} \times \vec{r})}{c} \times \vec{B}^{\rm NS}$

  →$\cdot \vec{E} = \vec{0}$ in coronation frame
- Poisson equation → $E^{\rm out} \sim \frac{\Omega B^{\rm NS} R^5}{}$

IF THIS HAPPENS IN BH-NS BINARY,
CHARGED PARTICLE WILL EMIT LIGHT
→THIS CAN BE COUNTERPART
OF GW FROM BH-NS MERGER

→ LIGHT EMISSION

PROBLEM

Pulsar $\cdots$ $E_{\parallel}^{\rm out}$ accelerates particles

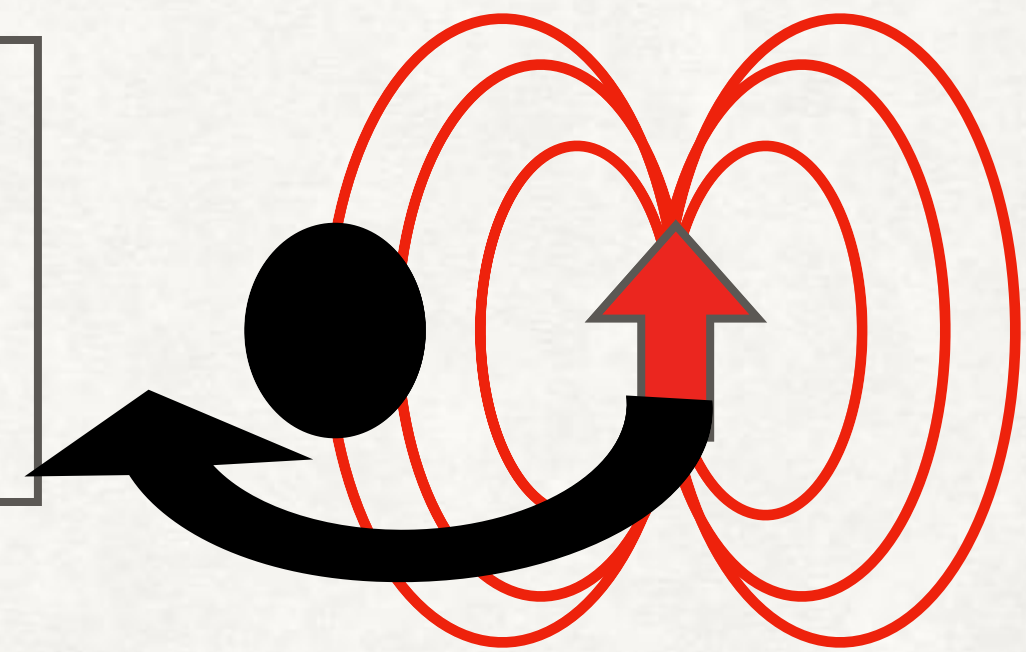
パ

→ Does $E_{\parallel}^{\rm out}$ exist in binary ??

Setting

Consider magnetic dipole

rotating BH



↓

Calculate induced electric field

Is there $E_{\parallel}^{\rm out}$ which accelerate particles from NS ??

AIM

Pulsar magnetosphere

Assume NS is dipole which is spinning

→ Calculate induced electric field

→ $E_{\parallel}^{\mathrm{out}}$ will accelerate particles

Binary magnetosphere

Assume NS is dipole which is rotating BH

→ Calculate induced electric field

→ is there $E_{\parallel}^{\mathrm{out}}$?

BASIC EQUATIONS

Maxwell equations (in flat spacetime)

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \partial_t \vec{B} + \vec{\nabla} \times \vec{E} = 0$$

$$\vec{\nabla} \cdot \vec{E} = 4\pi\rho \qquad \partial_t \vec{E} - \vec{\nabla} \times \vec{B} = -4\pi \vec{J}$$

Current is rotating dipole

$$J^\mu(x) = -\nabla_\lambda \int d\tau\, m^{\lambda\mu} \frac{\delta(x^\mu - x^\mu_{NS}(\tau))}{\sqrt{-g}}$$

$m^{\lambda\mu}$: magnetic moment

$x^\mu_{\rm NS}(\tau)$: orbit of NS

VECTOR HARMONICS EXPANSION

Expand vector fields using vector harmonics

$$B_i = \sum_{l,m}\left[B_1^{lm}\left(Y_{lm}(\theta,\phi),0,0\right) + B_2^{lm}\left(0, Y_{lm,\theta}(\theta,\phi), Y_{lm,\phi}(\theta,\phi)\right) + B_3^{lm}\left(0, -\frac{Y_{lm,\phi}(\theta,\phi)}{\sin\theta}, \sin\theta\, Y_{lm,\phi}(\theta,\phi)\right)\right]$$

Maxwell equations

Time evolution equation

B_1^{lm} : radial direction

B_2^{lm} : angular direction

party even

B_3^{lm} : angular direction

party odd

$$\partial_t{}^2 \tilde{B}_1^{lm}(t,r) = \partial_r\left(\partial_r \tilde{B}_1^{lm}(t,r)\right) - \frac{l(l+1)}{r^2}\tilde{B}_1^{lm} - 4\pi l(l+1) \quad J_3^{lm}(r)$$

$$\tilde{B}_1^{lm}(t,r) = r^2 B_1^{lm}(t,r)$$

$$\partial_r \tilde{B}_1^{lm}(t,r) = l(l+1) B_2^{lm}(t,r)$$

$$\partial_t{}^2 \tilde{B}_3^{lm}(t,r) = \partial_r\left(\partial_r \tilde{B}_3^{lm}(t,r)\right) - \frac{l(l+1)}{r^2}\tilde{B}_3^{lm} - 4\pi \left[J_1^{lm}(r) - \partial_r\left(J_2^{lm}(r)\right)\right]$$

GREEN FUNCTION METHOD

- Fourier transformation

$$\frac{d^2}{dr^2}\tilde{B}_1^{lm}(\omega,r)+\left(\omega^2-\frac{l(l+1)}{r^2}\right)\tilde{B}_1^{lm}(\omega,r) \quad = \quad 4\pi l(l+1)J_3^{lm}(\omega,r)$$

$$\frac{d^2}{dr^2}B_3^{lm}(\omega,r)+\left(\omega^2-\frac{l(l+1)}{r^2}\right)B_3^{lm}(\omega,r) \quad = \quad 4\pi\left(J_1^{lm}(\omega,r)-\partial_r J_2^{lm}(\omega,t)\right)$$

- give boundary condition → Construct Green function & Solve equation

Regular at $r=0$ outgoing wave at infinity

$\omega r\, j_l(\omega r)$ $\omega r\, h_l^{(1)}(\omega r)$

MAGNETIC FIELD

$$B_1^{lm}(t,r) = -i\frac{4\pi m^z}{|\dot{t}|}\frac{1}{r^2}Y^*_{lm,\theta}\left(\frac{\pi}{2},0\right)e^{-im\Omega t}\left\{\theta(r-R)\left[\frac{1}{r'}\partial_{r'}\left(r'\,j_l(m\Omega r')\right)\right]_{r'=R} m\Omega r\,h_l^{(1)}(m\Omega r)\right.$$
$$\left.+\theta(R-r)\left[\frac{1}{r'}\partial_{r'}\left(r'\,h_l^{(1)}(m\Omega r')\right)\right]_{r'=R} m\Omega r\,j_l(m\Omega r)\right\} \quad (47)$$

$$B_2^{lm}(t,r) = -i\frac{4\pi m^z}{|\dot{t}|}\frac{1}{l(l+1)}Y^*_{lm,\theta}\left(\frac{\pi}{2},0\right)e^{-im\Omega t}\left\{\theta(r-R)\left[\frac{1}{r'}\partial_{r'}\left(r'\,j_l(m\Omega r')\right)\right]_{r'=R}\frac{d}{dr}\left[m\Omega r\,h_l^{(1)}(m\Omega r)\right]\right.$$
$$\left.+\theta(R-r)\left[\frac{1}{r'}\partial_{r'}\left(r'\,h_l^{(1)}(m\Omega r')\right)\right]_{r'=R}\frac{d}{dr}\left[m\Omega r\,j_l(m\Omega r)\right]-\frac{i}{R}\delta(r-R)\right\} \quad (48)$$

$$B_3^{lm}(t,r) = \frac{4\pi m^z}{|\dot{t}|}\frac{m}{l(l+1)}Y^*_{lm}\left(\frac{\pi}{2},0\right)e^{-im\Omega t}\left\{\theta(r-R)(m\Omega)^2 j_l(m\Omega R)m\Omega r\,h_l^{(1)}(m\Omega r)\right.$$
$$\left.+\theta(R-r)(m\Omega)^2 h_l^{(1)}(m\Omega R)m\Omega r\,j_l(m\Omega r)-\frac{i}{R}\delta(r-R)\right\} \quad (49)$$

times vector harmonics

& sum up l, m

ELECTRIC FIELD

$$E_1^{lm}(t,r) = \frac{4\pi m^z}{|\dot{t}|}\frac{im}{r^2}Y_{lm}^*\left(\frac{\pi}{2},0\right)e^{-im\Omega t}\left\{\theta(r-R)\,m\Omega\,j_l(m\Omega R)m\Omega r\,h_l^{(1)}(m\Omega r)\right.$$
$$\left.+\theta(R-r)\,m\Omega\,h_l^{(1)}(m\Omega R)m\Omega r\,j_l(m\Omega r)\right\}$$

$$E_2^{lm}(t,r) = -\frac{4\pi m^z}{|\dot{t}|}\frac{im}{l(l+1)}Y_{lm}^*\left(\frac{\pi}{2},0\right)e^{-im\Omega t}\left\{\theta(r-R)\,m\Omega\,j_l(m\Omega R)\frac{d}{dr}\left(m\Omega r\,h_l^{(1)}(m\Omega r)\right)\right.$$
$$\left.+\theta(R-r)\,m\Omega\,h_l^{(1)}(m\Omega R)\frac{d}{dr}\left(m\Omega r\,j_l(m\Omega r)\right)\right\}$$

$$E_3^{lm}(t,r) = -\frac{4\pi m^z}{|\dot{t}|}\frac{m\Omega}{l(l+1)}Y_{lm,\theta}^*\left(\frac{\pi}{2},0\right)e^{-im\Omega t}\left\{\theta(r-R)\left[\frac{1}{r'}\partial_{r'}\left(r'\,j_l(m\Omega r')\right)\right]_{r'=R}m\Omega r\,h_l^{(1)}(m\Omega r)\right.$$
$$\left.+\theta(R-r)\left[\frac{1}{r'}\partial_{r'}\left(r'\,h_l^{(1)}(m\Omega r')\right)\right]_{r'=R}m\Omega r\,j_l(m\Omega r)\right\}$$

times vector harmonics

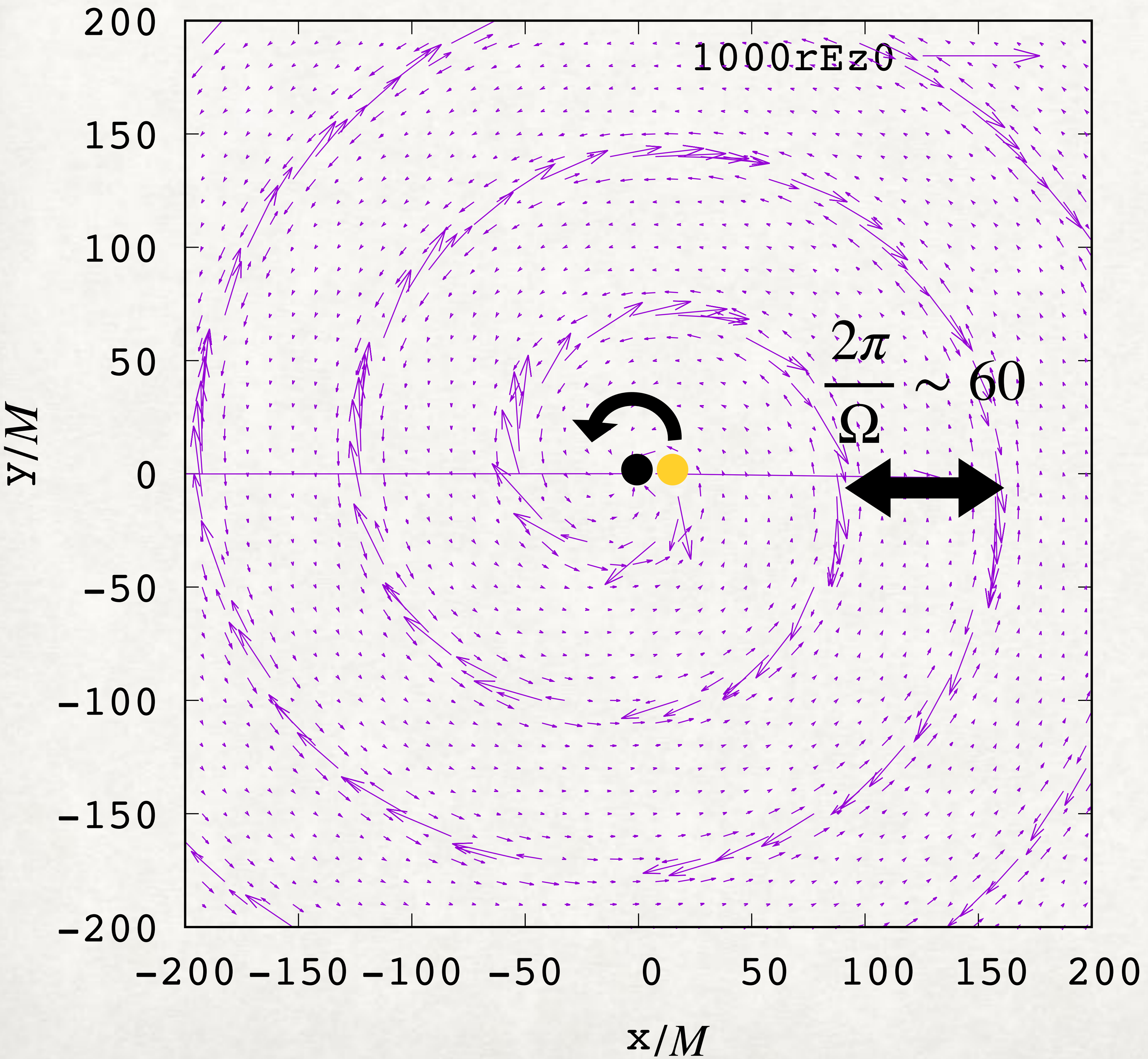
sum up l, m

ELECTRIC FIELD

$$E_1^{lm}(t,r) = \frac{4\pi m^z}{|\dot{t}|}\frac{im}{r^2}Y^*_{lm}\left(\frac{\pi}{2},0\right)e^{-im\Omega t}\Big\{\theta(r-R)\,m\Omega\,j_l(m\Omega R)m\Omega r\,h_l^{(1)}(m\Omega r)$$
$$+\theta(R-r)\,m\Omega\,h_l^{(1)}(m\Omega R)m\Omega r\,j_l(m\Omega r)\Big\}$$

WHAT IS HAPPENING ????

NUMERICAL ELECTRIC(Z=0)



$r \cdot E$

@ constant time surface

separation

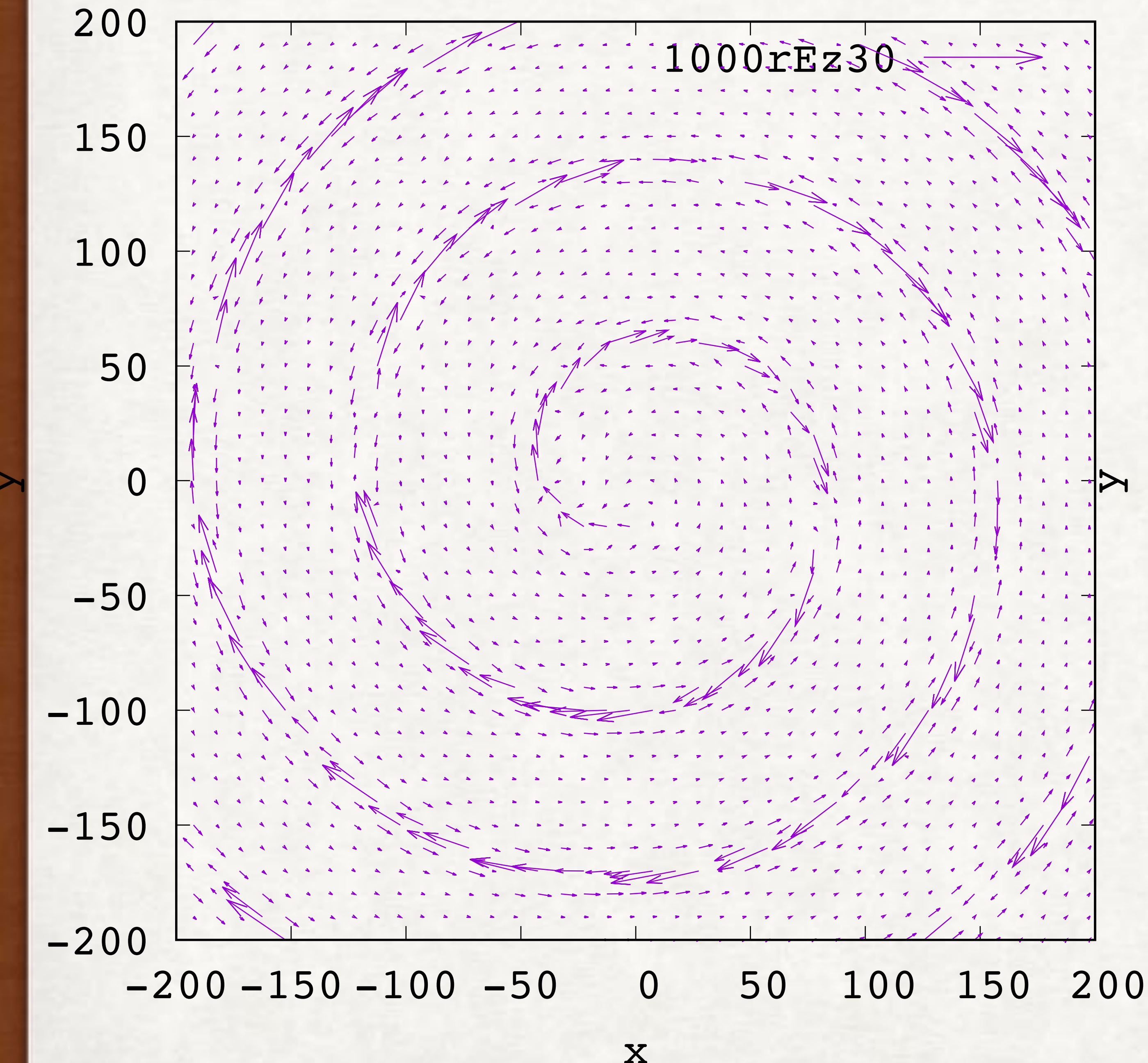
$R = 5$

total mass

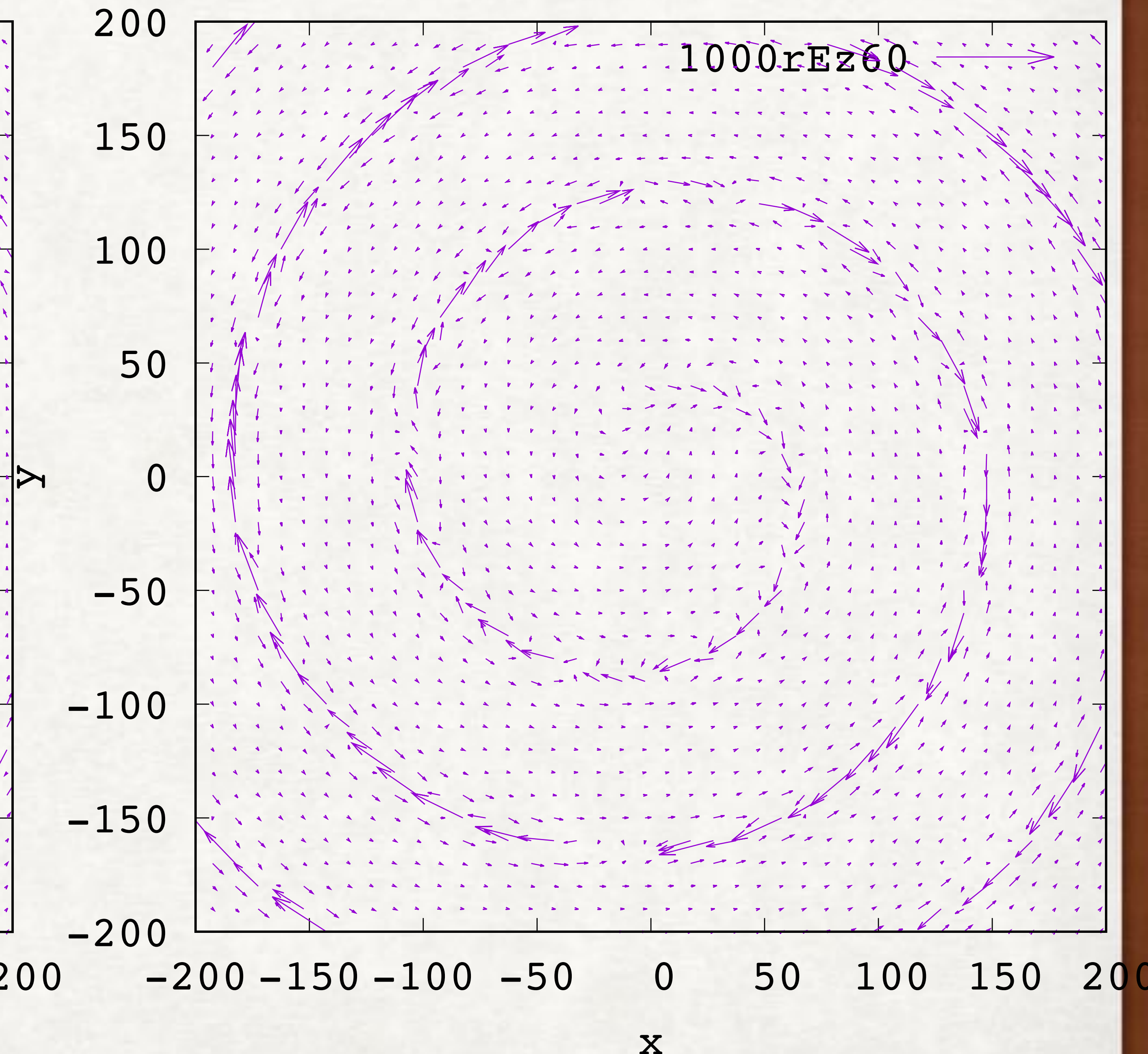
$M_{\text{tot}} = 10 M_\odot$

NUMERICAL ELECTRIC (rE)

z=30

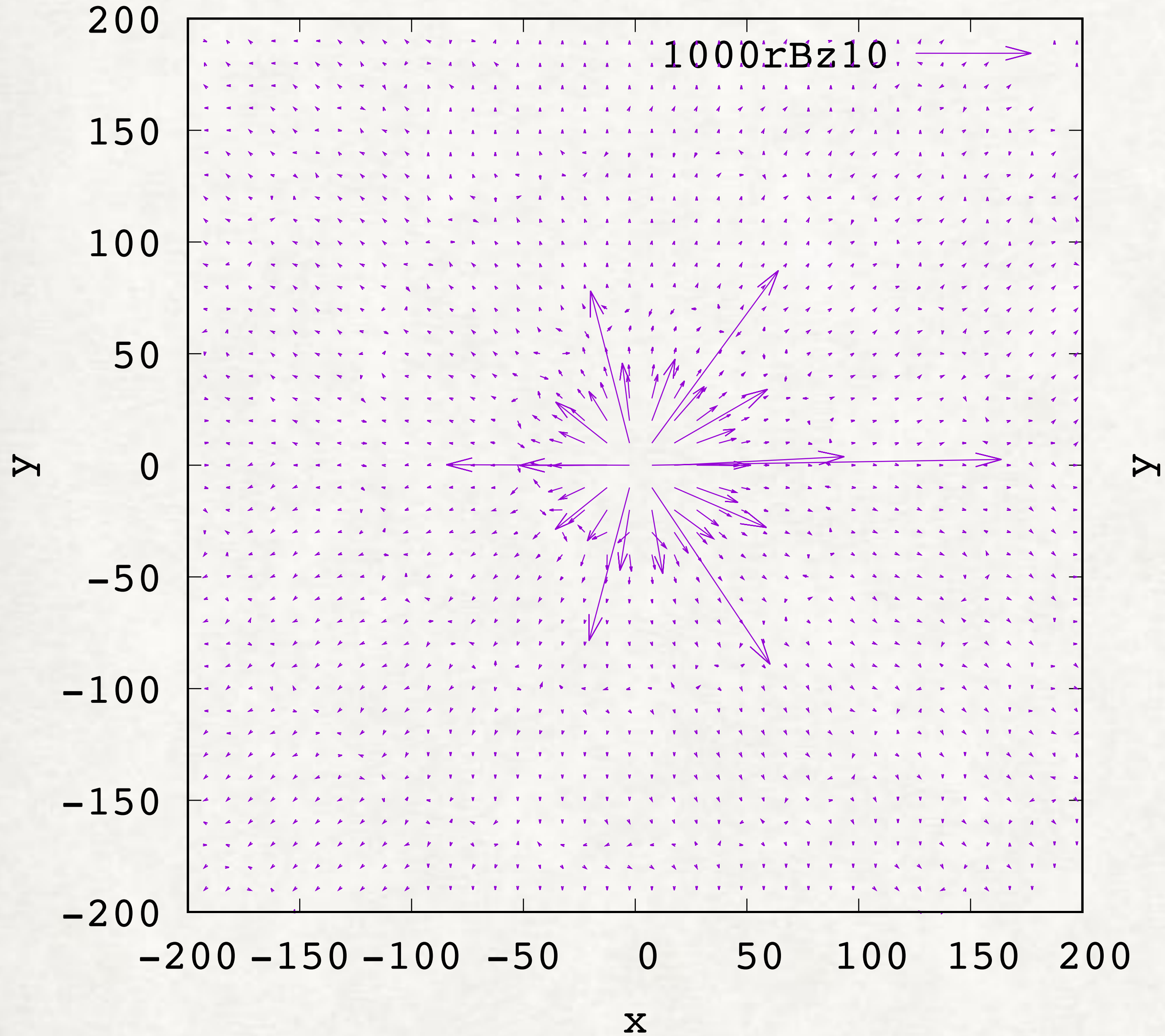


z=90

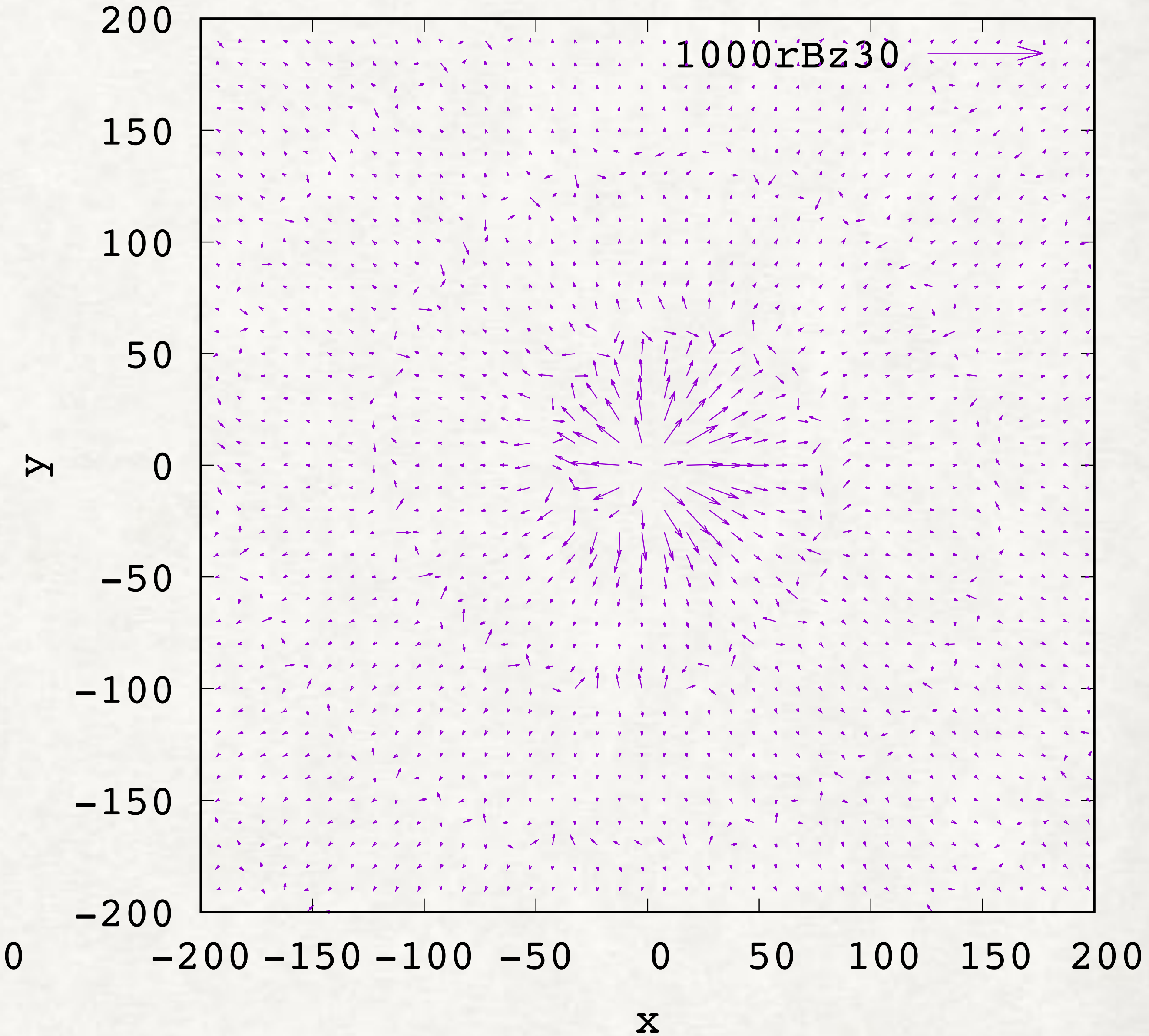


NUMERICAL MAGNETIC $(r \cdot B)$

z=10



z=30

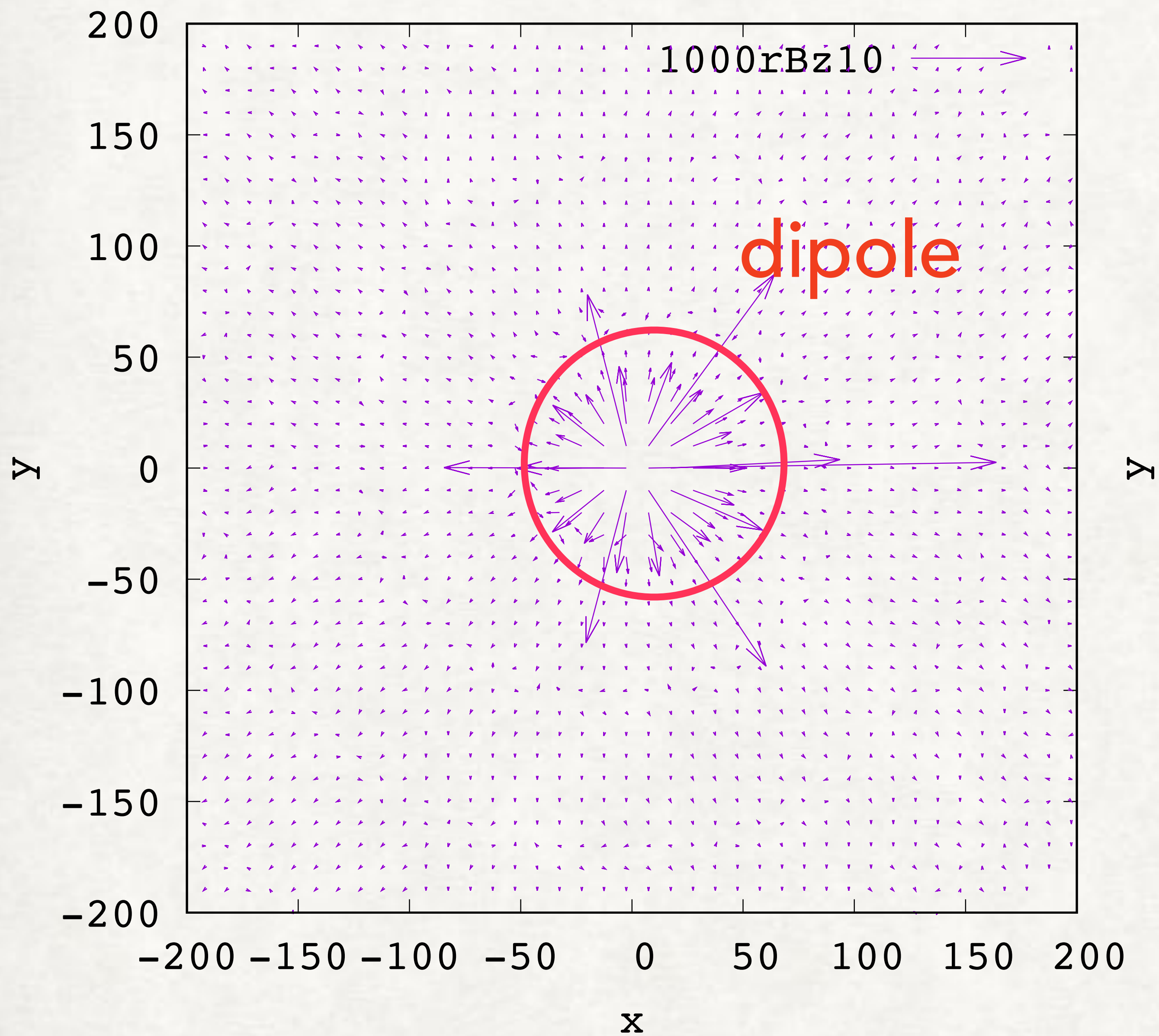


almost dipole

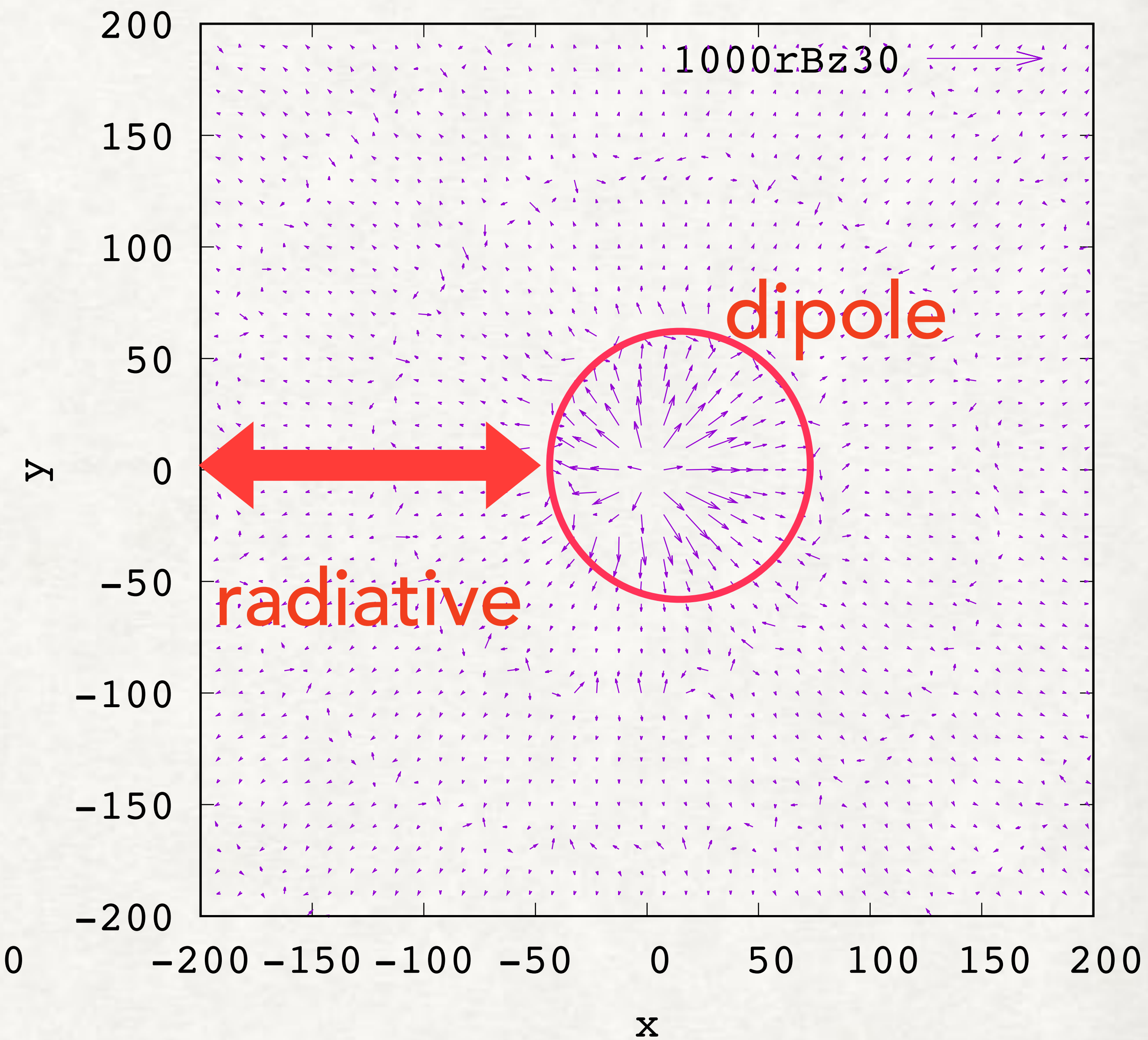
dipole + spiral arm (radiation)

NUMERICAL MAGNETIC $(r \cdot B)$

z=10



z=30



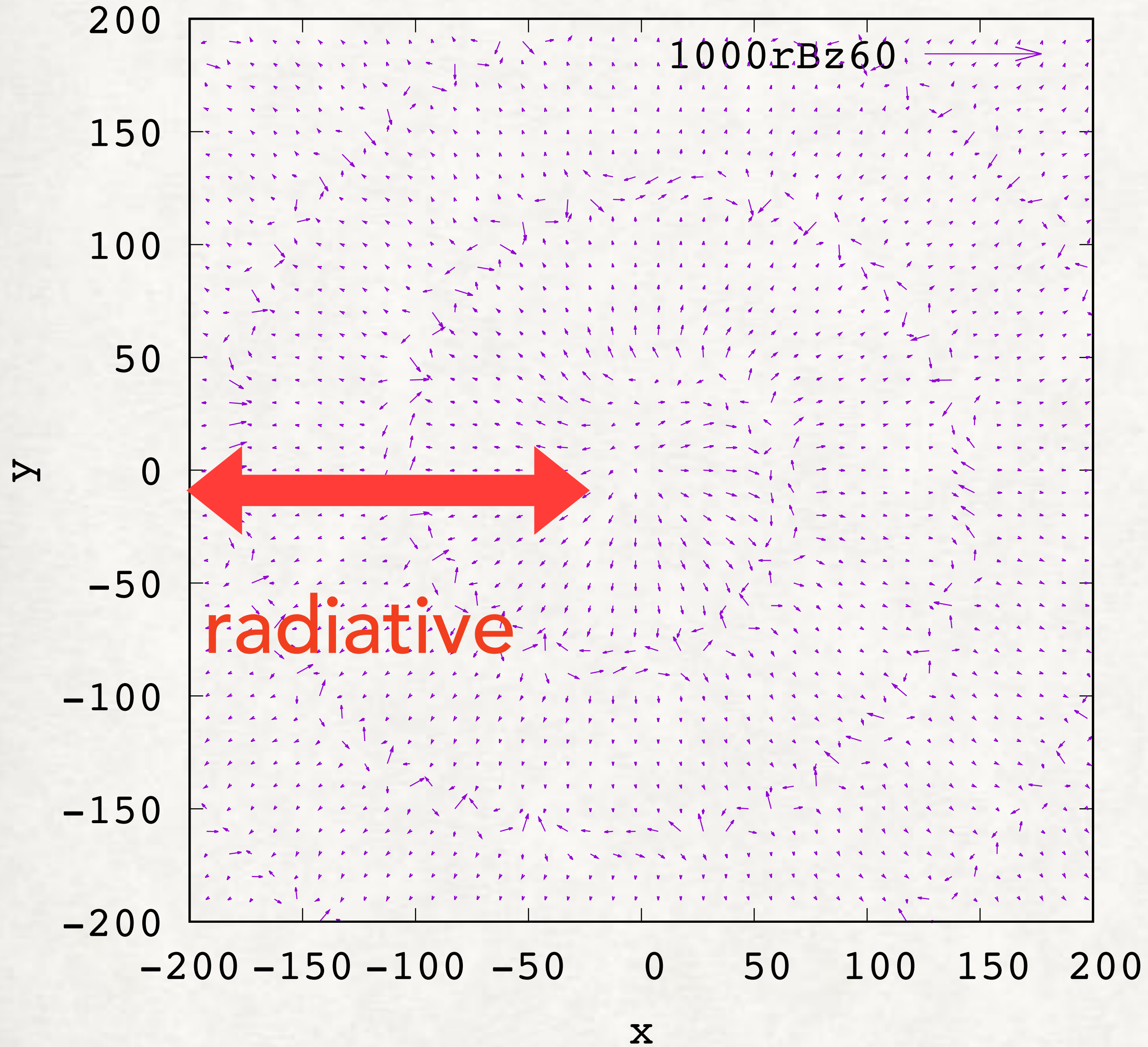
almost dipole

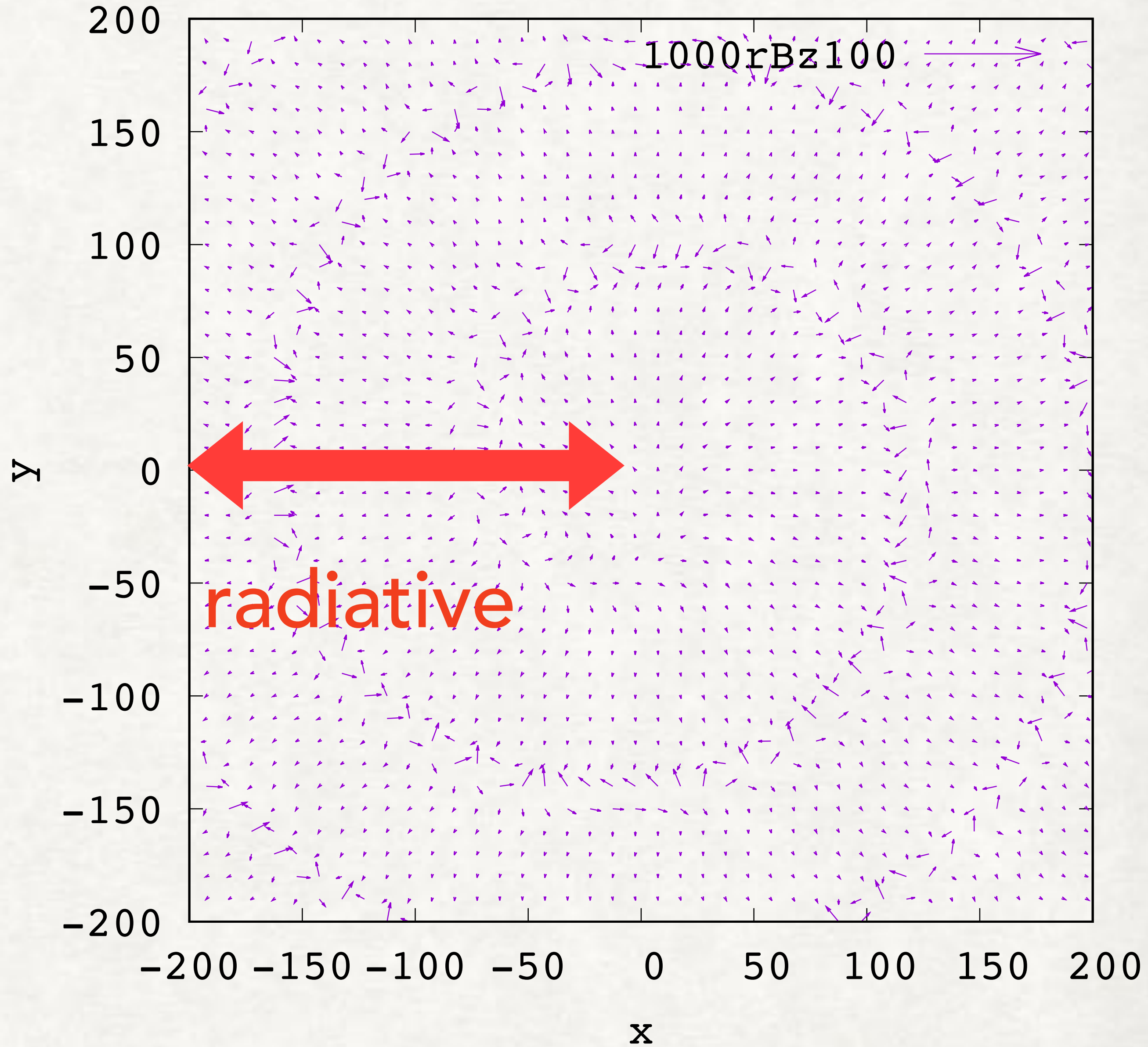
dipole + spiral arm (radiation)

NUMERICAL MAGNETIC

z=60 $\sim \frac{2\pi}{\Omega}$

z=100

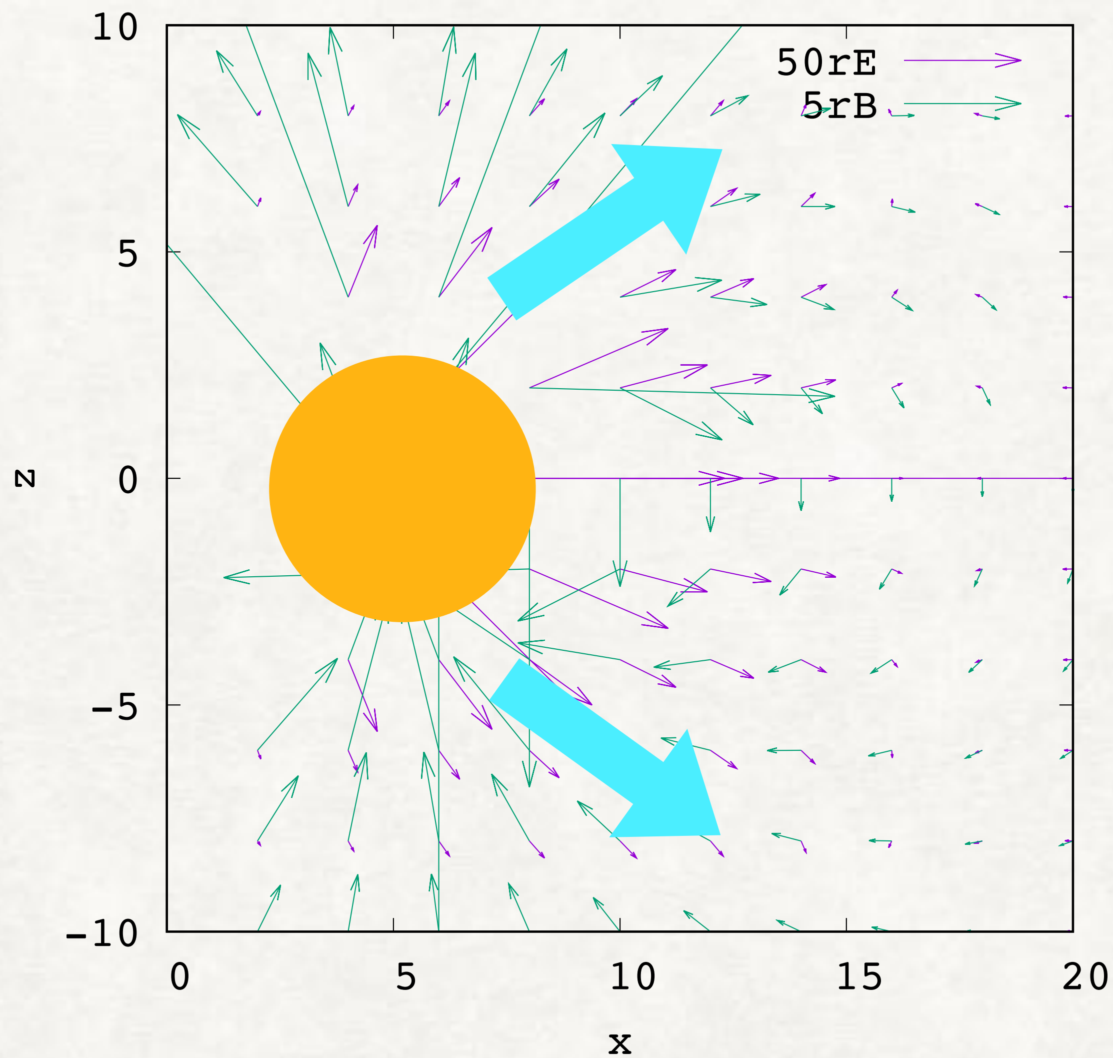


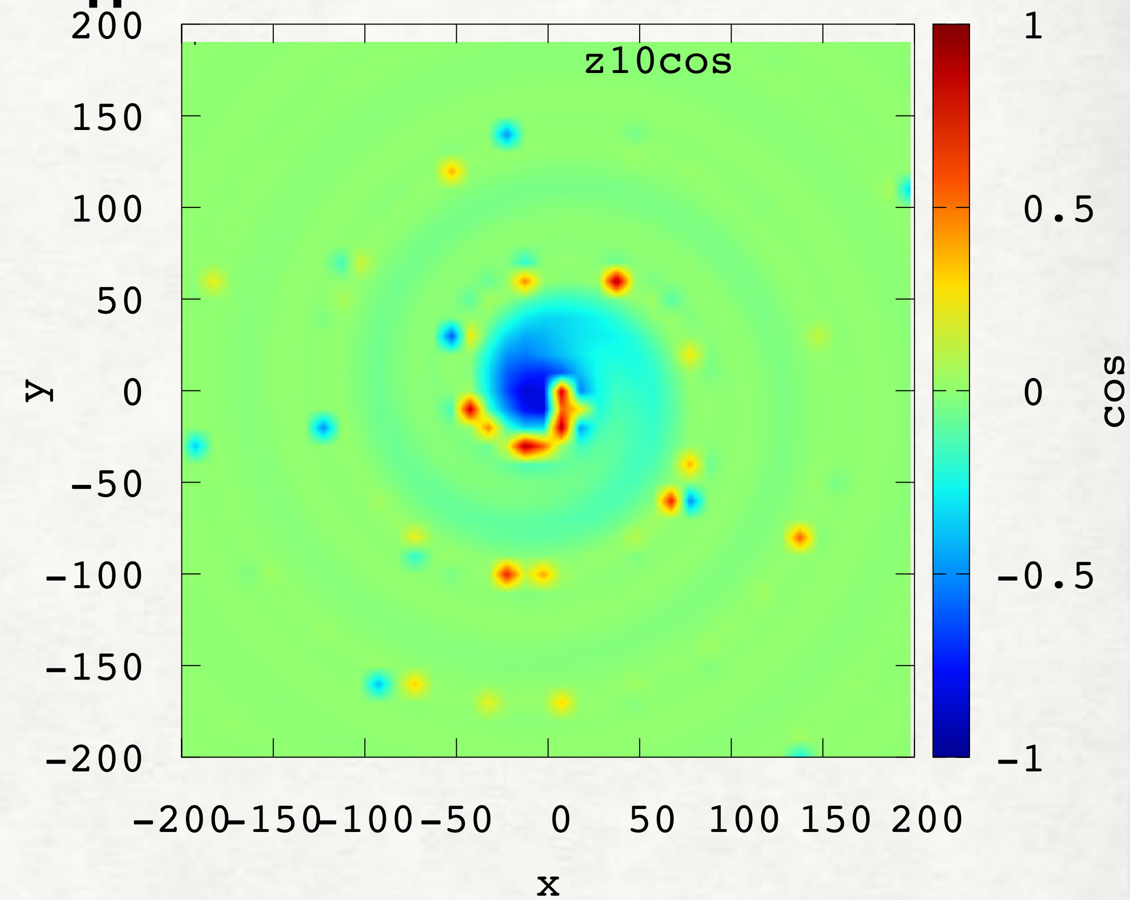


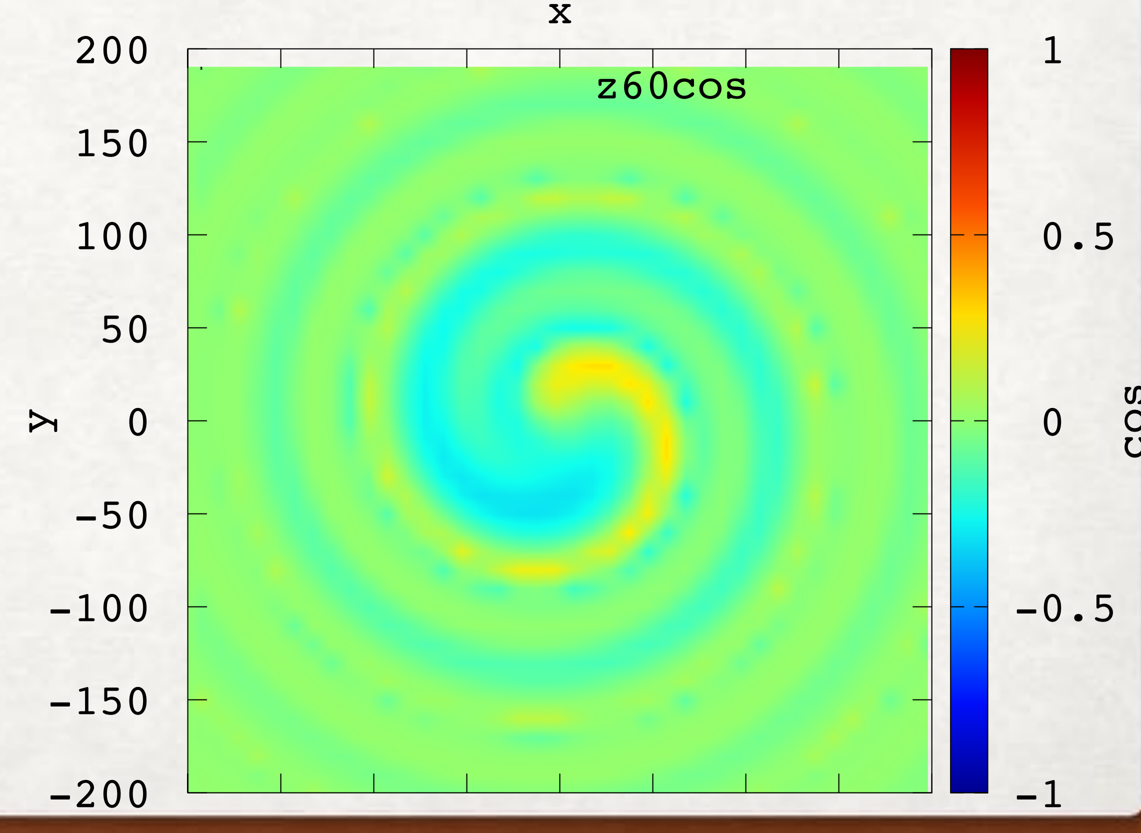
almost spiral arm (radiation)

spiral arm (radiation)

IS THERE $E_{\parallel}^{\rm out}$??







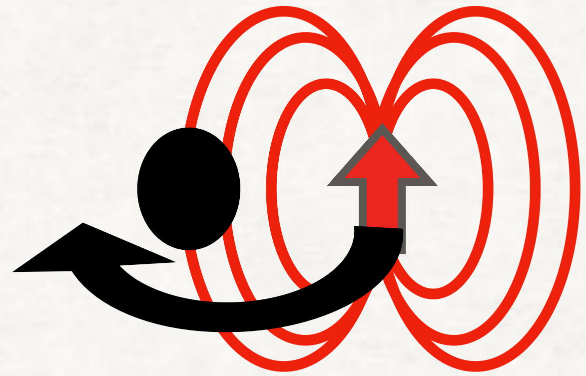
PARTICLE ACCELERATION

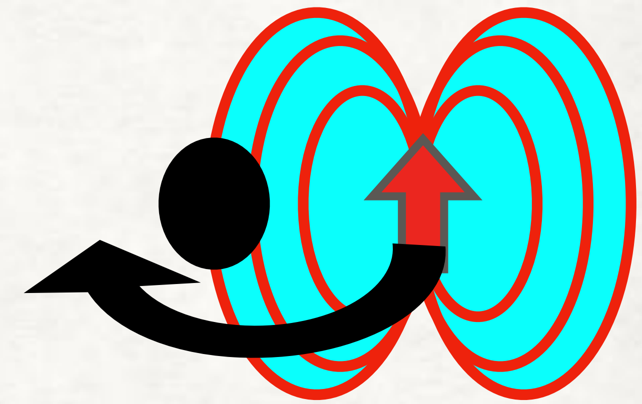
There is $E_{\parallel}^{\rm out}$ and

Particle acceleration

will happen

BINARY MAGNETOSPHERE





There is $E_{\parallel}^{\mathrm{out}}$

→ magnetosphere can’t be vacuum

and may filled with plasma..

There are gaps in co-rotating magnetosphere

→ particle acceleration

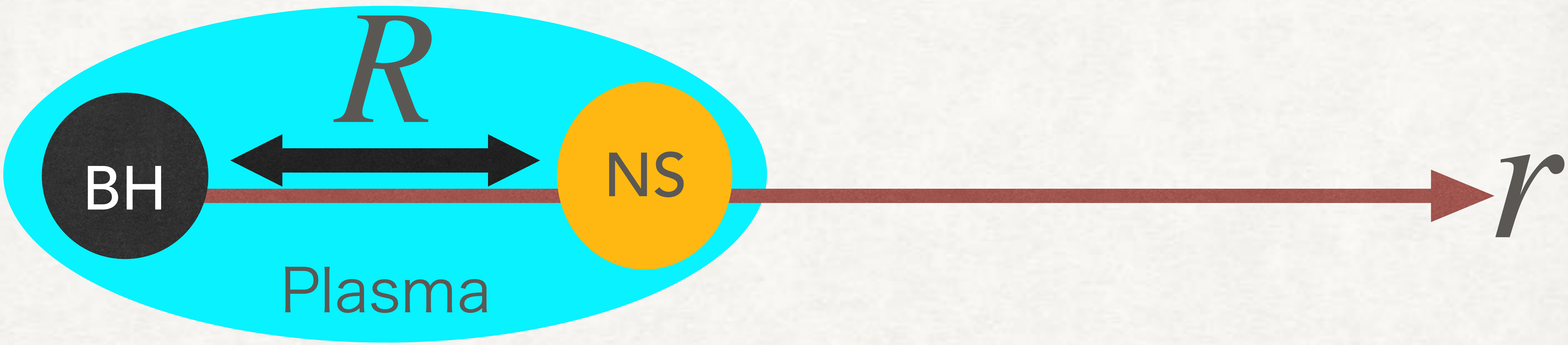
& charged particle emits light

In binary, electromagnetic field changes dynamically

→ there must be many gaps

PARTICLE ACCELERATION

Order estimate of particle acceleration



$$B_1^{lm}(t,r) = -i\frac{4\pi m^z}{|\dot{t}|}\frac{1}{r^2}Y^*_{lm,\theta}\left(\frac{\pi}{2},0\right)e^{-im\Omega t}\left\{\theta(r-R)\left[\frac{1}{r'}\partial_{r'}\left(r' j_l(m\Omega r')\right)\right]_{r'=R} m\Omega r\, h_l^{(1)}(m\Omega r) + \theta(R-r)\left[\frac{1}{r'}\partial_{r'}\left(r' h_l^{(1)}(m\Omega r')\right)\right]_{r'=R} m\Omega r\, j_l(m\Omega r)\right\} \quad (47)$$

$$B_2^{lm}(t,r) = -i\frac{4\pi m^z}{|\dot{t}|}\frac{1}{l(l+1)}Y^*_{lm,\theta}\left(\frac{\pi}{2},0\right)e^{-im\Omega t}\left\{\theta(r-R)\left[\frac{1}{r'}\partial_{r'}\left(r' j_l(m\Omega r')\right)\right]_{r'=R}\frac{d}{dr}\left[m\Omega r\, h_l^{(1)}(m\Omega r)\right] + \theta(R-r)\left[\frac{1}{r'}\partial_{r'}\left(r' h_l^{(1)}(m\Omega r')\right)\right]_{r'=R}\frac{d}{dr}\left[m\Omega r\, j_l(m\Omega r)\right] - \frac{i}{R}\delta(r-R)\right\} \quad (48)$$

$$B_3^{lm}(t,r) = \frac{4\pi m^z}{|\dot{t}|}\frac{m}{l(l+1)}Y^*_{lm}\left(\frac{\pi}{2},0\right)e^{-im\Omega t}\left\{\theta(r-R)(m\Omega)^2 j_l(m\Omega R)m\Omega r\, h_l^{(1)}(m\Omega r) + \theta(R-r)(m\Omega)^2 h_l^{(1)}(m\Omega R)m\Omega r\, j_l(m\Omega r) - \frac{i}{R}\delta(r-R)\right\} \quad (49)$$

$$E_1^{lm}(t,r) = \frac{4\pi m^z}{|\dot{t}|}\frac{im}{r^2}Y^*_{lm}\left(\frac{\pi}{2},0\right)e^{-im\Omega t}\left\{\theta(r-R)\, m\Omega\, j_l(m\Omega R)m\Omega r\, h_l^{(1)}(m\Omega r) + \theta(R-r)\, m\Omega\, h_l^{(1)}(m\Omega R)m\Omega r\, j_l(m\Omega r)\right\}$$

$$E_2^{lm}(t,r) = -\frac{4\pi m^z}{|\dot{t}|}\frac{im}{l(l+1)}Y^*_{lm}\left(\frac{\pi}{2},0\right)e^{-im\Omega t}\left\{\theta(r-R)\, m\Omega\, j_l(m\Omega R)\frac{d}{dr}\left(m\Omega r\, h_l^{(1)}(m\Omega r)\right) + \theta(R-r)\, m\Omega\, h_l^{(1)}(m\Omega R)\frac{d}{dr}\left(m\Omega r\, j_l(m\Omega r)\right)\right\}$$

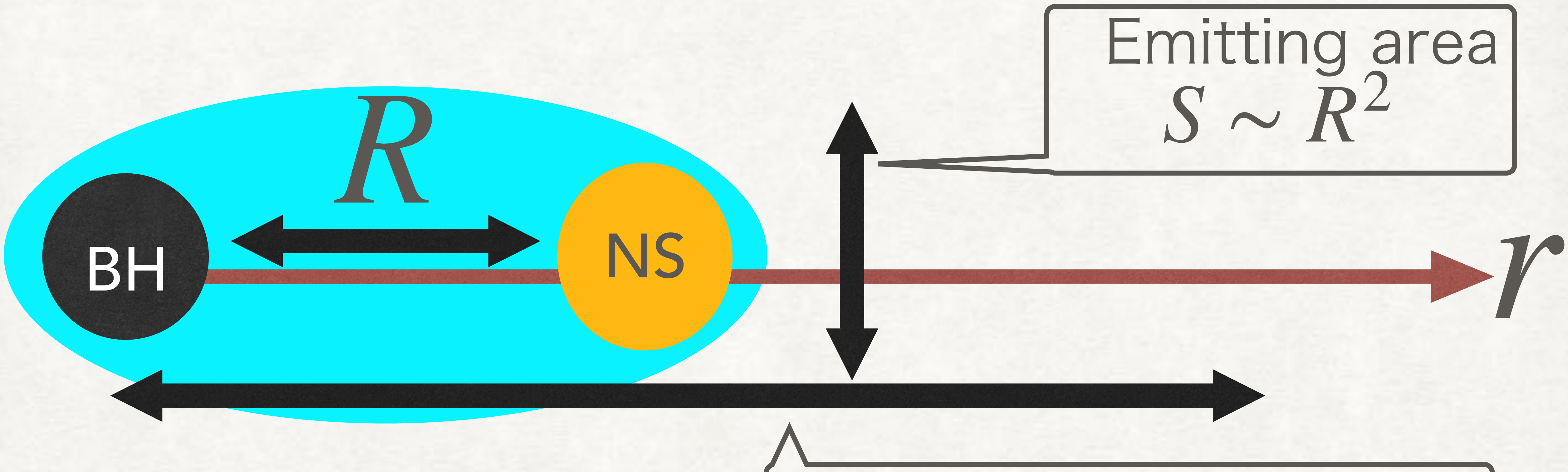
$$E_3^{lm}(t,r) = -\frac{4\pi m^z}{|\dot{t}|}\frac{m\Omega}{l(l+1)}Y^*_{lm,\theta}\left(\frac{\pi}{2},0\right)e^{-im\Omega t}\left\{\theta(r-R)\left[\frac{1}{r'}\partial_{r'}\left(r' j_l(m\Omega r')\right)\right]_{r'=R} m\Omega r\, h_l^{(1)}(m\Omega r) + \theta(R-r)\left[\frac{1}{r'}\partial_{r'}\left(r' h_l^{(1)}(m\Omega r')\right)\right]_{r'=R} m\Omega r\, j_l(m\Omega r)\right\}$$

Considering only $l = 1$ mode

$$\rho \sim \frac{E}{R} \sim v\frac{B(R)}{R} \sim \frac{m^z\Omega}{R^3}$$

$$E_r \sim \frac{m^z\Omega^2 R}{r^2}$$

PARTICLE ACCELERATION



Accelerating region

$$R_{\rm acc} \sim \Omega^{-1}$$

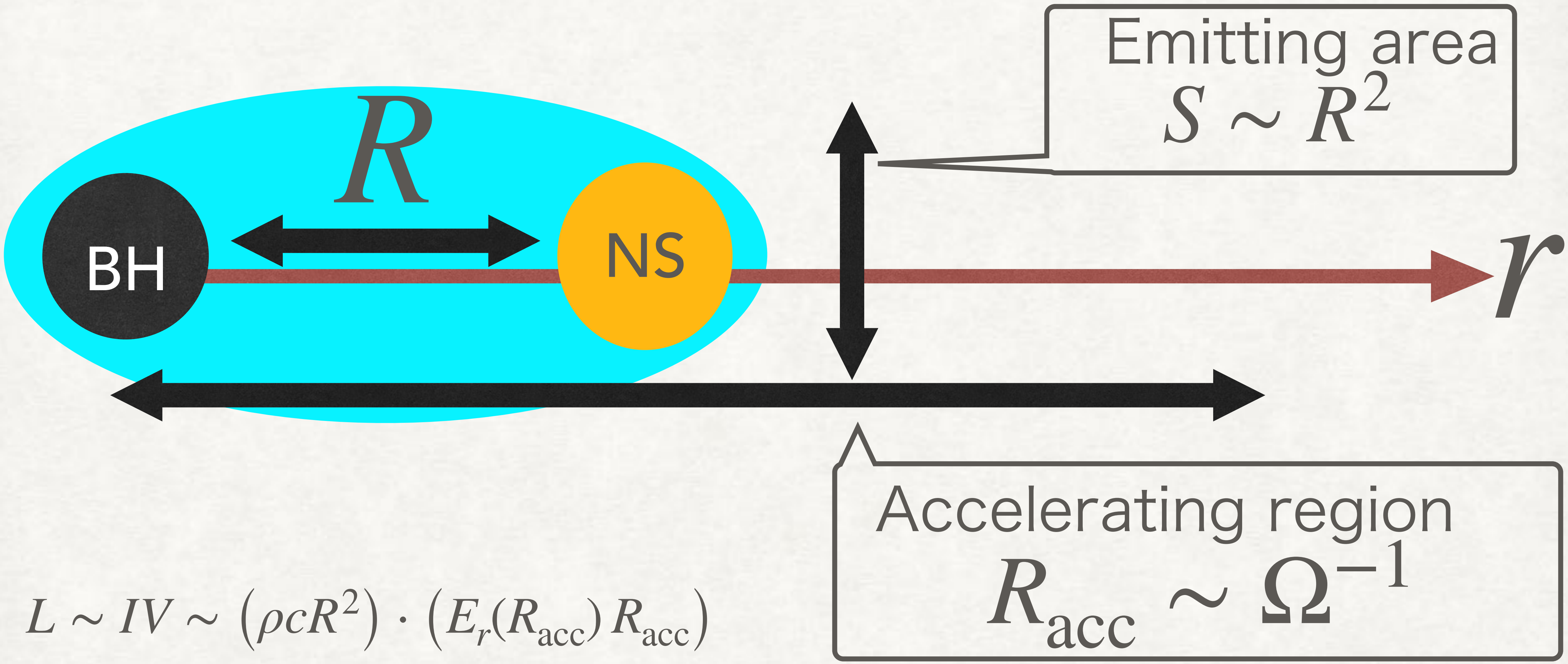
$$\rho \sim \frac{E}{R} \sim v\frac{B(R)}{R} \sim \frac{m^z\Omega}{R^3}$$

$$E_r(r) \sim \frac{m^z\Omega^2 R}{r^2}$$

$$L \sim IV \sim \left(\rho c R^2\right) \cdot \left(E_r(R_{\rm acc})\, R_{\rm acc}\right)$$

$$\sim (m^z)^2\Omega^3 R_{\rm acc}^{-1} \qquad \propto R^{-6}$$

PARTICLE ACCELERATION



$$L \sim IV \sim \left(\rho c R^2\right) \cdot \left(E_r(R_{\mathrm{acc}})\, R_{\mathrm{acc}}\right)$$

$$\sim (m^z)^2 \Omega^3 R_{\mathrm{acc}}^{-1} \qquad \propto R^{-6}$$

cf. rotating dipole

$$L \sim \propto R^{-7}$$

$$L \sim (m^z)^2 \Omega^3 R_{\mathrm{acc}}^{-1}$$

$$\sim 10^{42}\ \mathrm{erg/s}$$

SUMMARY

- BH-NS binary ··· there is $E_{\parallel}^{\mathrm{out}}$
  especially near binary
  → **magnetosphere must filled with plasma**

- charged particle may be **accelerated**
  → luminosity $L \sim 10^{42}$ erg/s
  → it can be electromagnetic counterpart
  as precursor

FUTURE WORK

- frequency
- evaluate acceleration
- effect of plasma
- effect of GR