

Title: Electromagnetic interaction of binary neutron star magnetospheres

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Abstract: Neutron star mergers represent one of the most promising sources of gravitational waves (GW), while that the presence of strong magnetic fields may offer the possibility of a characteristic electromagnetic signature allowing for concurrent detection. In this talk will be presented a new hybrid-passive approach to match the full GR-MHD evolutions of the binary neutron star mergers to the force-free equations in order to study numerically the dynamics and interaction of their magnetospheres.

Electromagnetic field dynamics in Binary Neutron Stars

Micra Meeting 2011, Waterloo
June 23, 2011

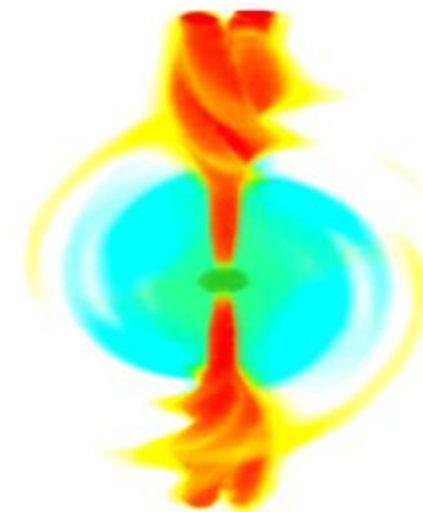
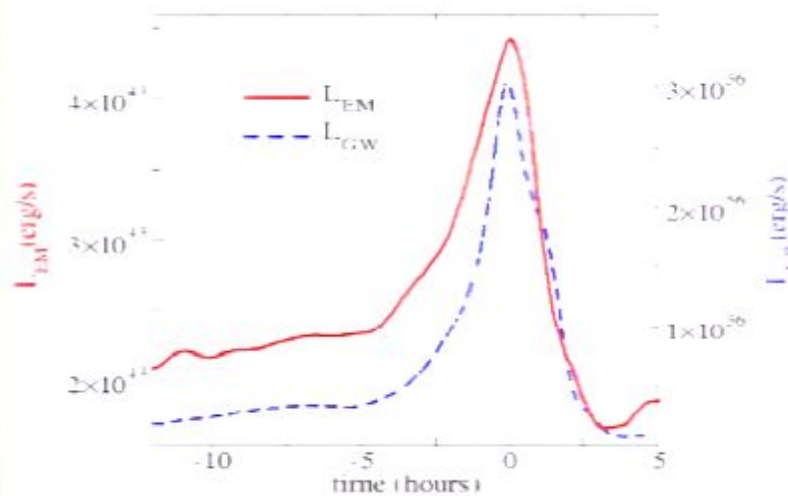
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L. Lehner (PI&UoG), S. Liebling (LIU), C. Thompson (CITA)

+ D. Neilsen, E. Hirschmann, M. Anderson, C. Hanna

I. Introduction

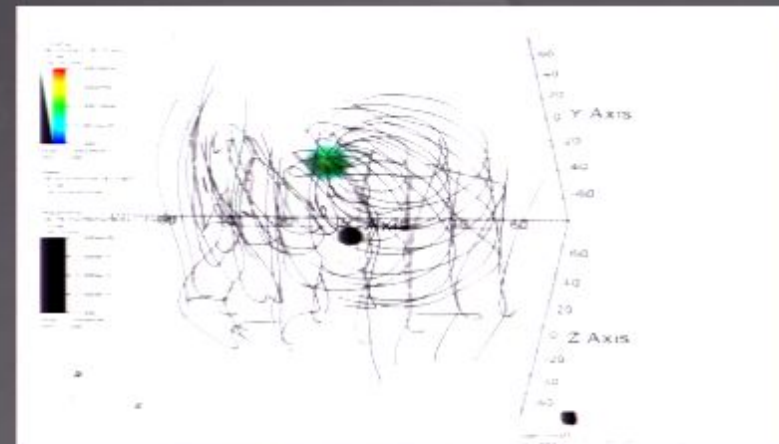
- **GW astronomy** (advanced LIGO)
- study systems emitting in both bands (**GW and EM**) to extract more information and have a deeper insight into the processes involved



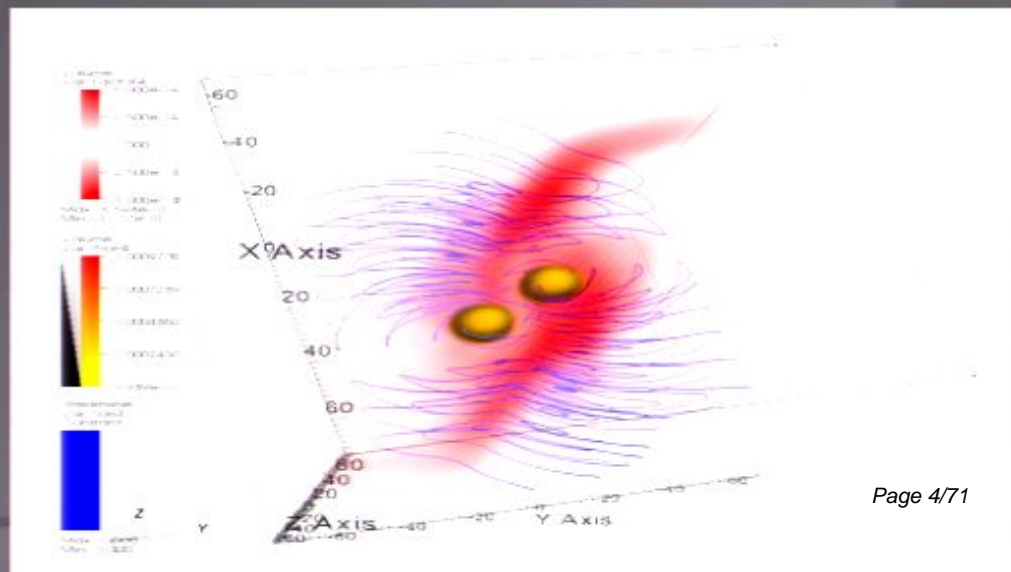
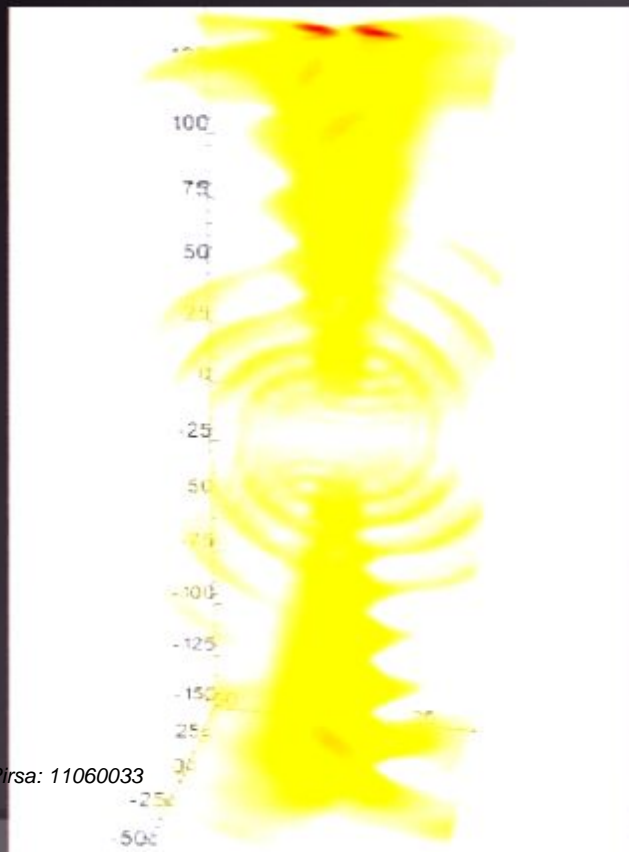
I. Ongoing projects

Binary BHs immersed
on external magnetic
fields (PTA & LISA)

BH-NS
binary
(LIGO)



NS-NS binary (LIGO)



II. Binary NS counterparts

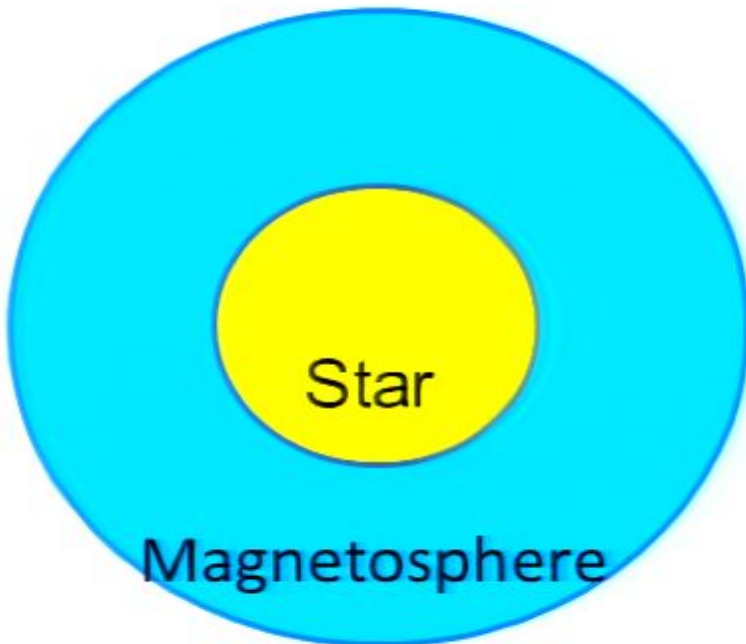
-Advanced LIGO will be able to detect ~ 10 binary NS mergers (and 1 BH-NS merger per year).



- The NS are compact objects (**GR**) of $R \sim 10$ km and $M \sim 1.5-2 M_{\odot}$ presenting **magnetic fields** ranging from $B \sim 10^8-10^{12}$ G

- These mergers will form a BH surrounded by a massive accretion disk, which is the scenario expected to produce short Gamma Ray Burst.

II. Simple model (fluid+EM)



- ❑ **Neutron star:**
dominated by the fluid
IDEAL MHD
- ❑ **Magnetosphere**
dominated by the EM
FORCE FREE
- ❑ **Vacuum(no sources)**

-You can solve one of the regions but it is not easy to solve two or all of them at the same time

II. Different regimes of Maxwell eq.

$$\begin{aligned}\partial_t \mathbf{E} - \nabla \times \mathbf{B} &= -\mathbf{J} \\ \partial_t \mathbf{B} + \nabla \times \mathbf{E} &= 0 \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \cdot \mathbf{E} &= q\end{aligned}$$

$$\mathbf{J} = \sigma (\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

σ : conductivity

IDEAL MHD

($\sigma \rightarrow \infty$)



$$\mathbf{E} = -\mathbf{v} \times \mathbf{B}$$

$$\partial_t \mathbf{B} - \nabla \times \mathbf{E} = 0$$

FORCE FREE

($q\mathbf{E} + \mathbf{J} \times \mathbf{B} = 0$)



$$\partial_t \mathbf{B} - \nabla \times \mathbf{E} = 0$$

$$\partial_t \mathbf{E} - \nabla \times \mathbf{B} = -\mathbf{J}$$

ELECTROVAC

($\sigma \rightarrow 0$)

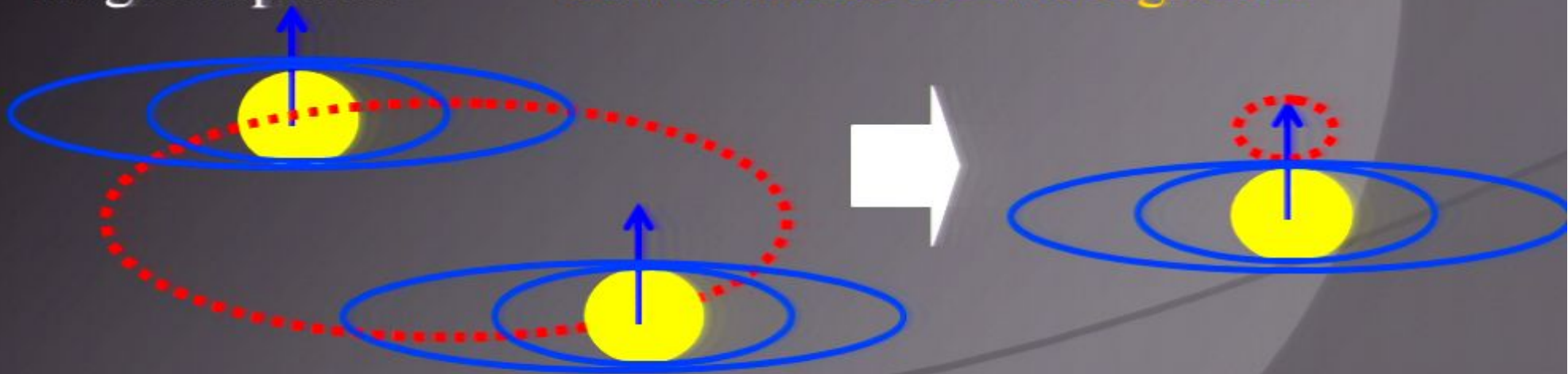


$$\partial_t \mathbf{E} - \nabla \times \mathbf{B} = 0$$

$$\partial_t \mathbf{B} + \nabla \times \mathbf{E} = 0$$

III. Magnetospheric interaction of BNS

- Consider a magnetized binary NS during the inspiral (Neilsen talk on efforts with Shen EOS); the interaction of the magnetospheres will change the topology of the magnetic field lines (reconnections)
 - the evolutions are performed with ideal MHD, which describes properly the fluid and the EM fields inside the NS, but not the magnetospheres
- How to match the two regions??



III. Hybrid method (MHD-forcefree)

0) Solve the Einstein equations

$$R_{ab} = 8 \pi (T_{ab} - T g_{ab}/2)$$

1) Solve the **MHD fluid equations** everywhere → good description of the magnetic fields in the **interior of the stars**

$$T_{ab} = [\rho(1 + \varepsilon) + p] u_a u_b + p g_{ab} + F_{ac} F^c_b - (F^{cd} F_{cd}) g_{ab}/4$$

$\nabla_a T^{ab} = 0$: conservation of energy-momentum

$\nabla_a *F^{ab} = 0 + u_a F^{ab} = 0$: Maxwell eqs. + ideal MHD condition

III. Hybrid method (MHD-forcefree)

2) Solve the **force-free equations** everywhere \rightarrow good description of the magnetic fields at the **exterior of the stars** (magnetically dominated plasmas)

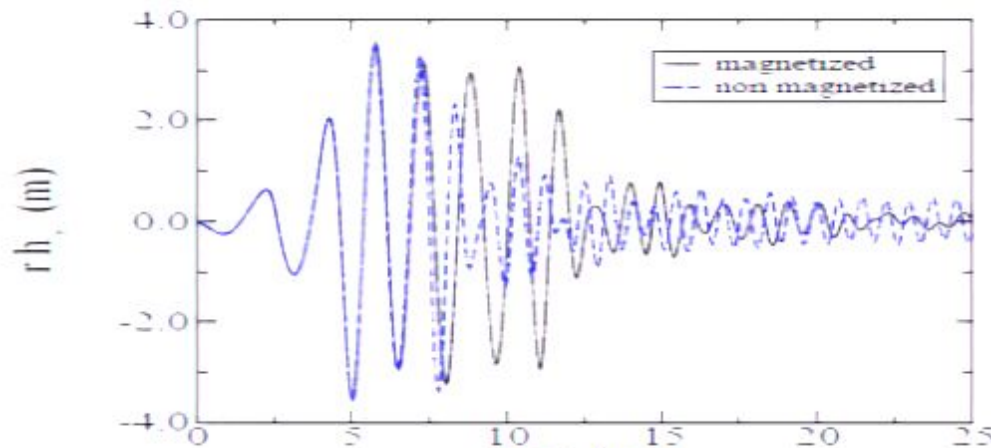
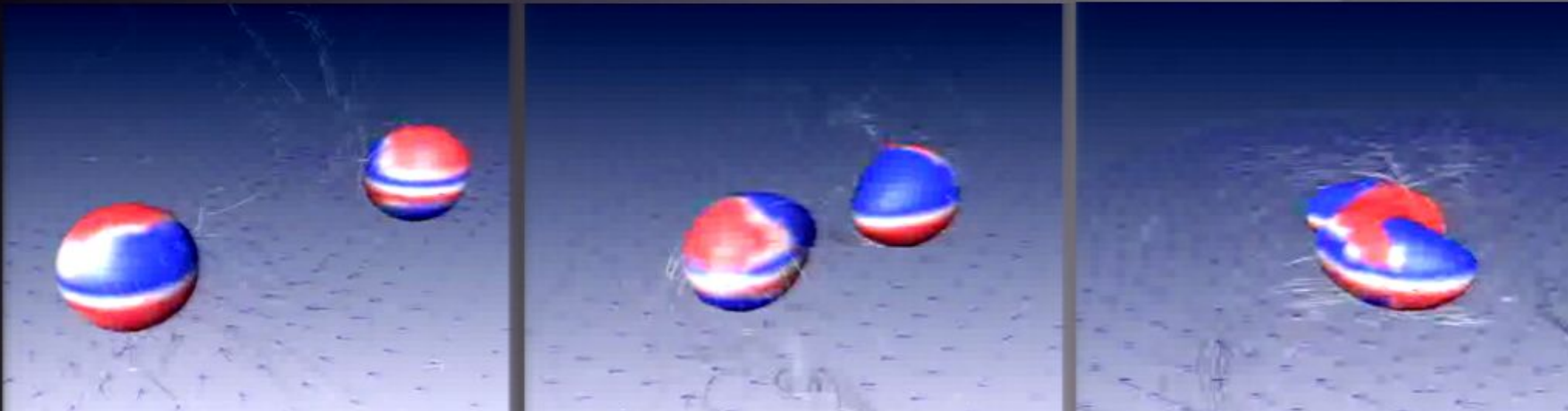
$$\nabla_a T^{ab}=0 \rightarrow \nabla_a T^{ab}(\text{fluid}) = -\nabla_a T^{ab}(\text{em}) = -F^{ab}I_a$$

$$\text{if } \rho, P \ll B^2 \rightarrow \nabla_a T^{ab}(\text{fluid}) \ll F^{ab} I_a \approx 0 \rightarrow \mathbf{q} \mathbf{E} + \mathbf{J} \times \mathbf{B} = 0$$

3) Drive the **force-free solution** to be the **ideal MHD solution** inside the stars \rightarrow provide an effective boundary condition for the force-free magnetosphere

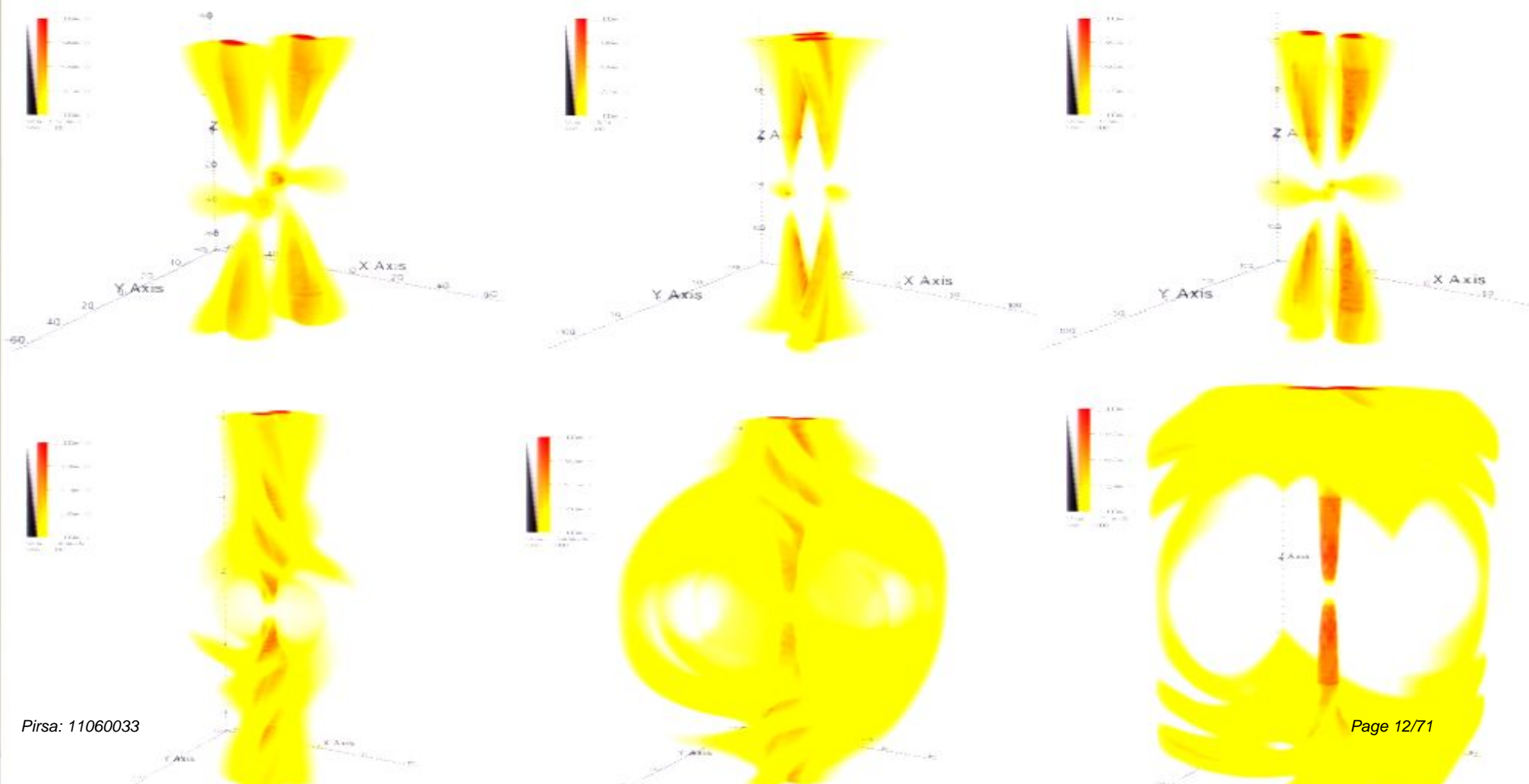
III. Test 1: magnetized binary NS

- Evolution of a magnetized binary with ideal MHD (PRL 2008)
- The EM fields are initially confined in the interior of the stars



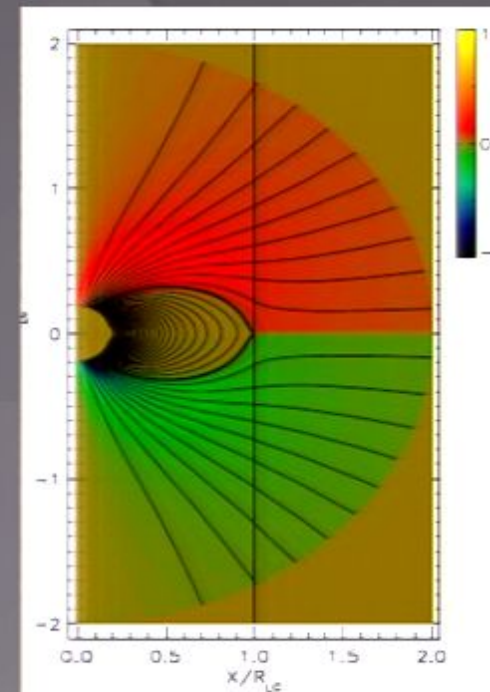
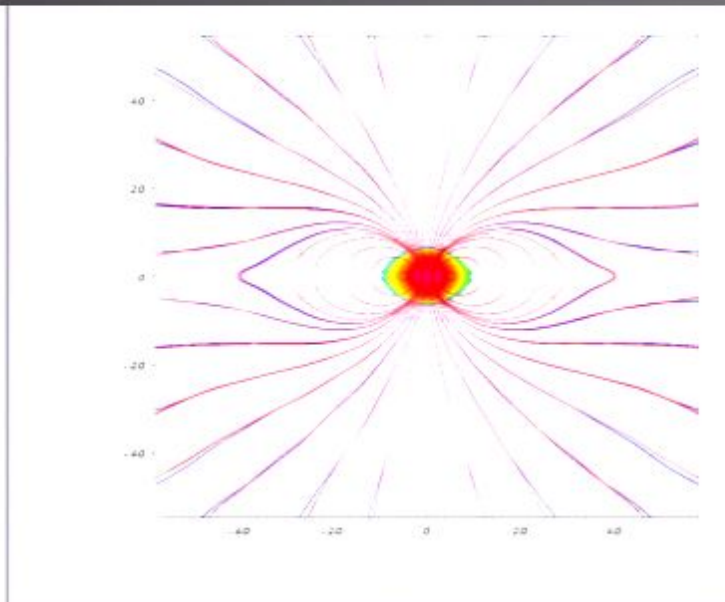
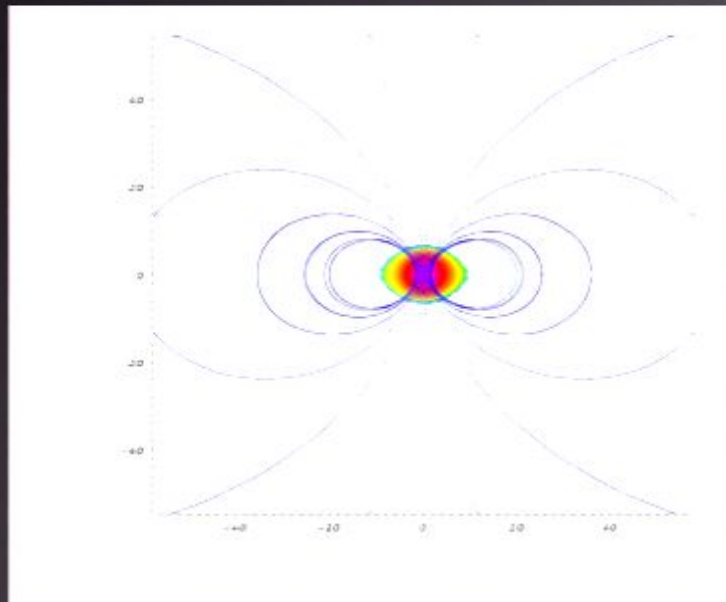
III. Test 2: SMBH binaries in force-free

- Binary black hole with external force-free fields (Science 2010)



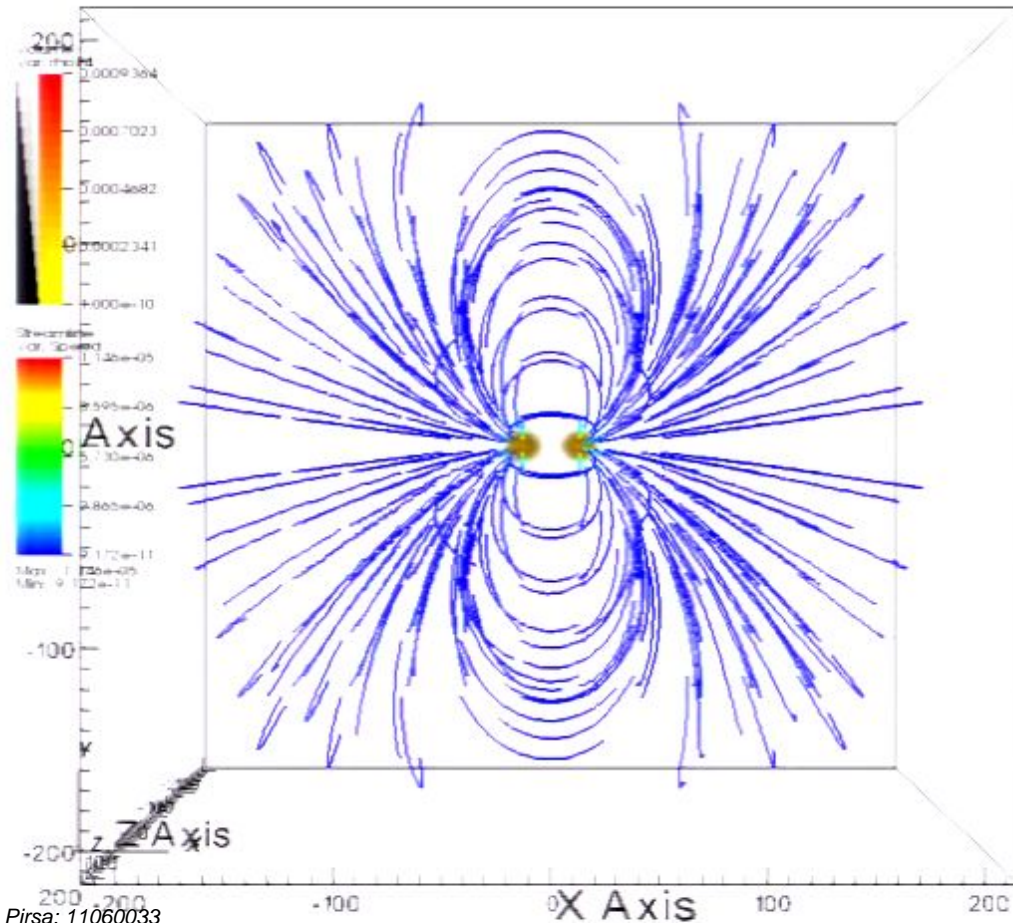
III. Test 3: Aligned rotator

- highly magnetized, rotating NS
with a force-free magnetosphere
(Komissarov, McKinney, Spitkovsky 200X)

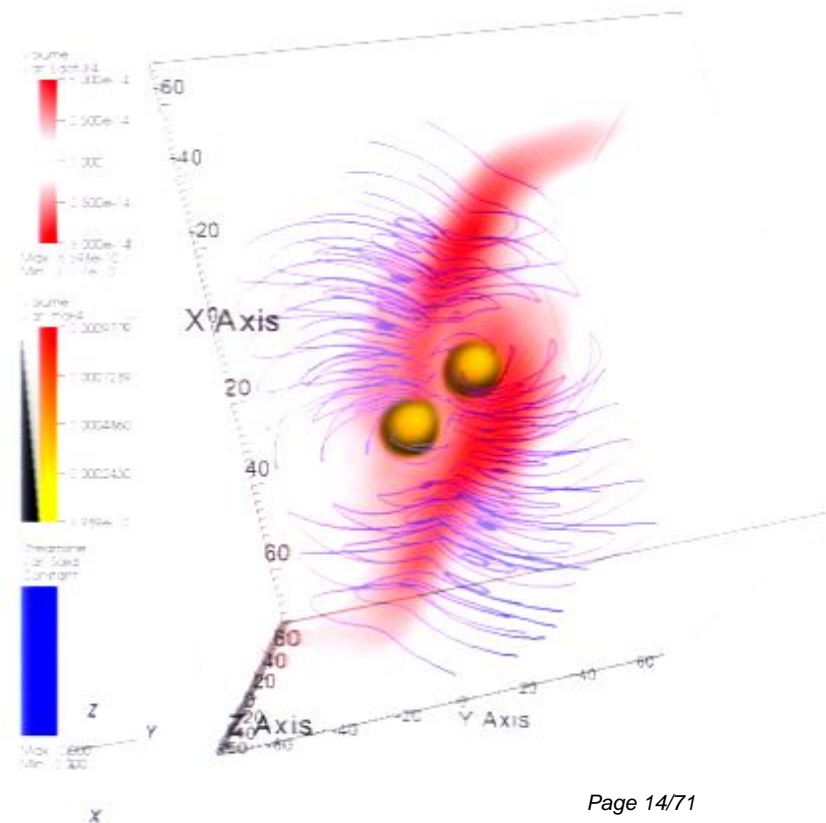


IV. Magnetic fields of BNS

- non-spinning NS with the magnetic moments up/up



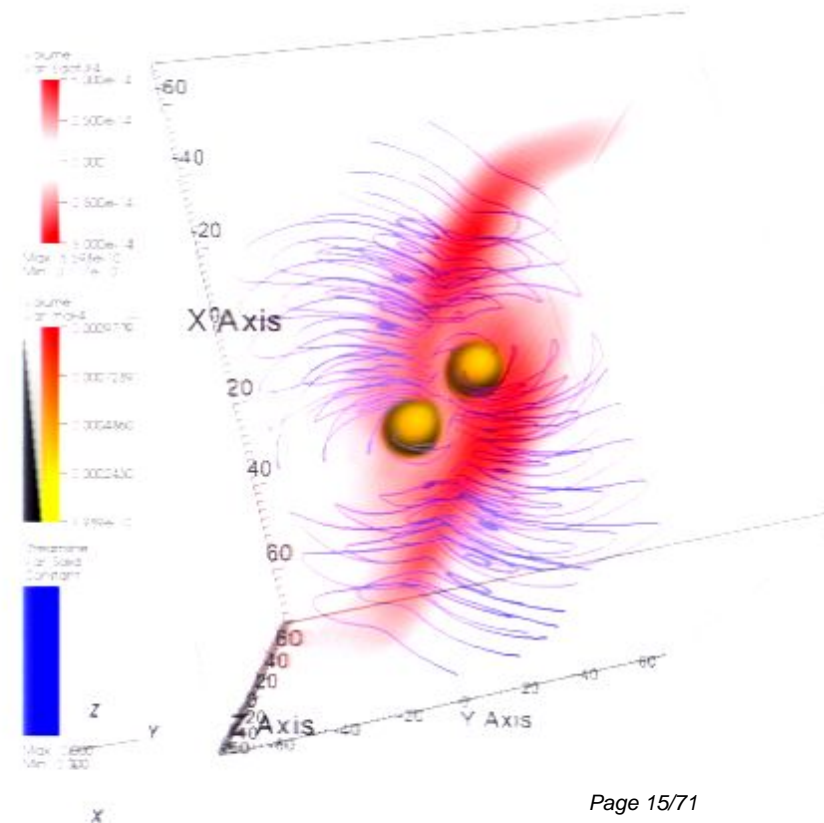
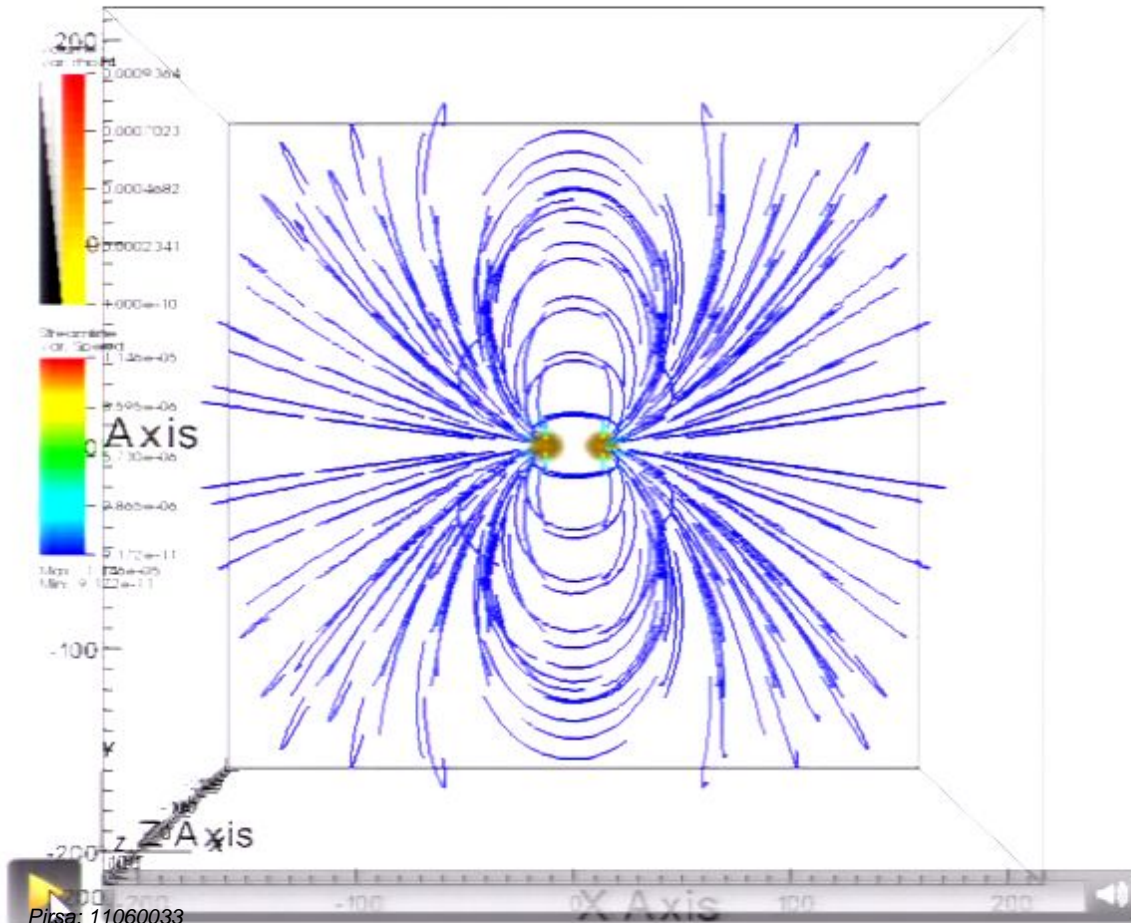
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Page 14/71

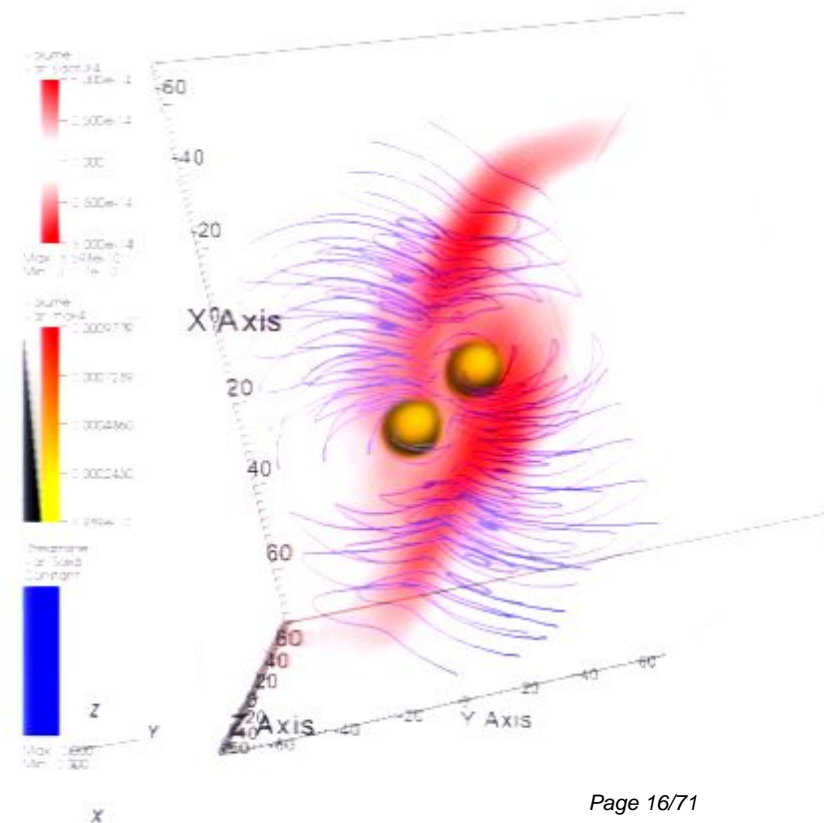
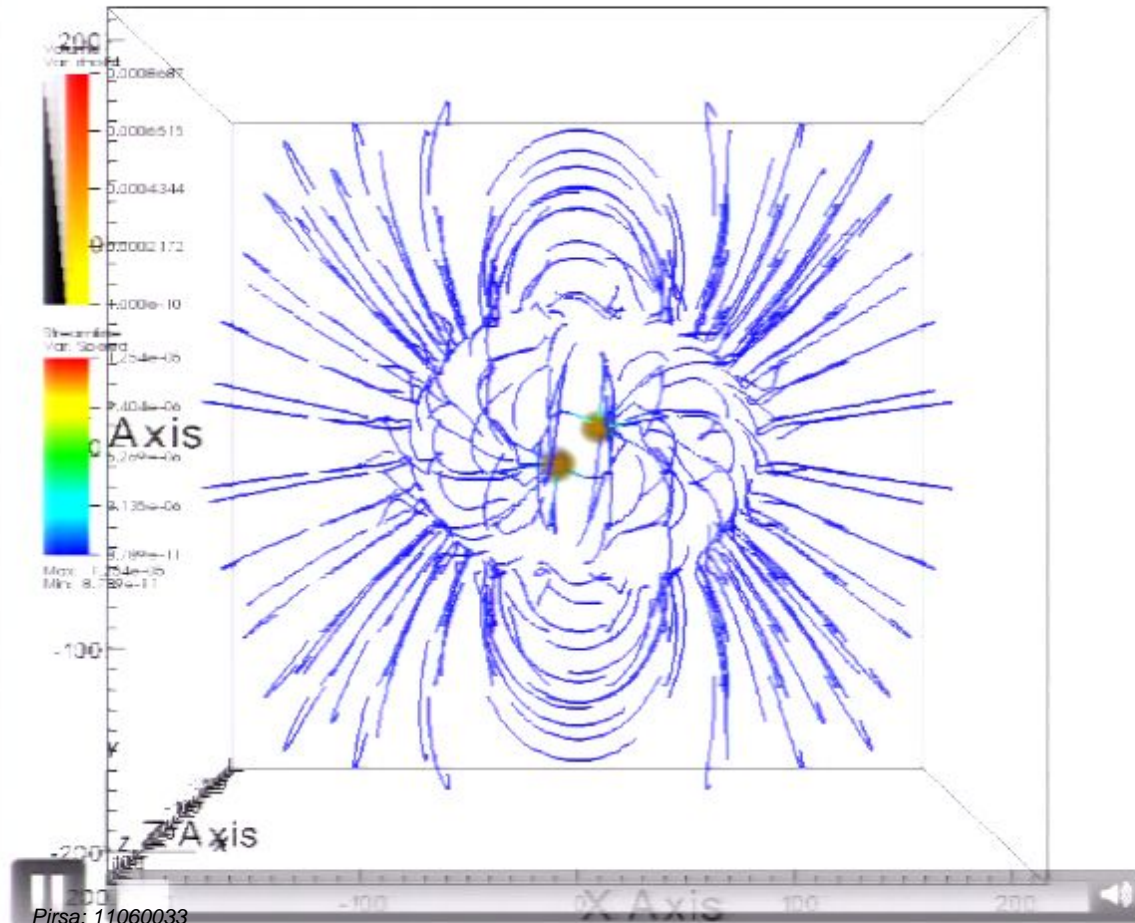
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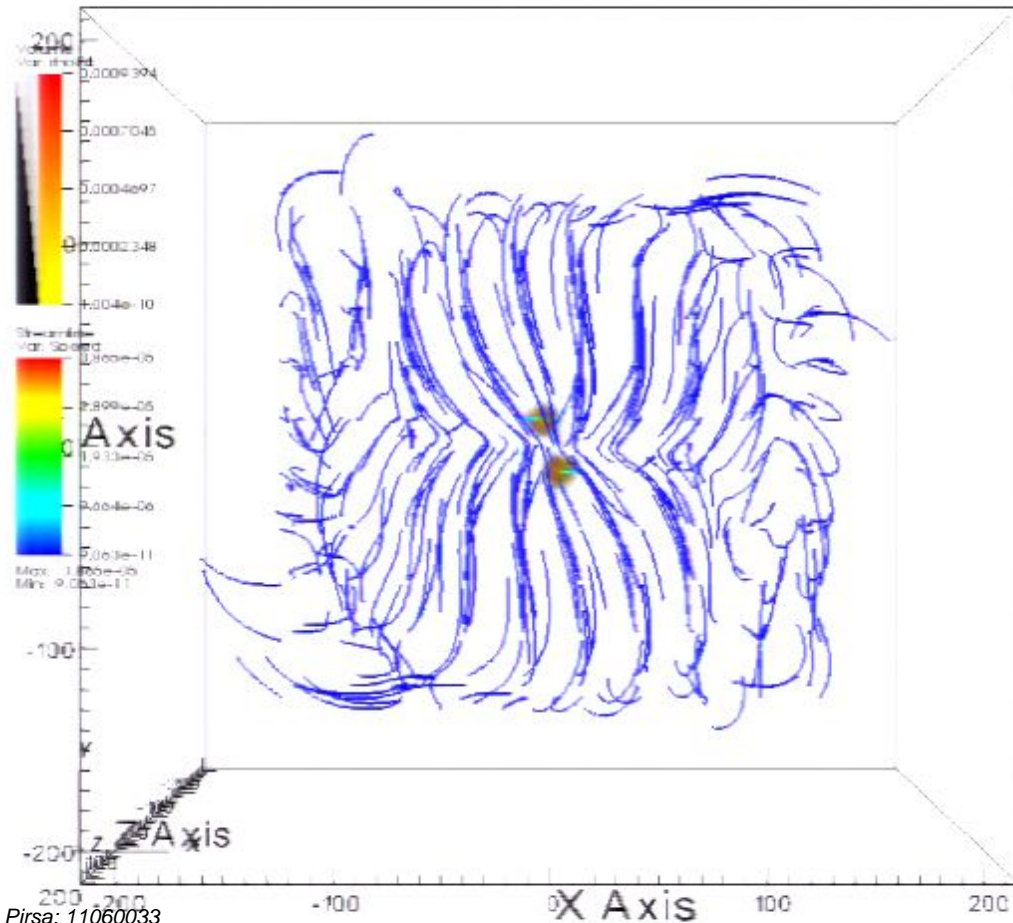
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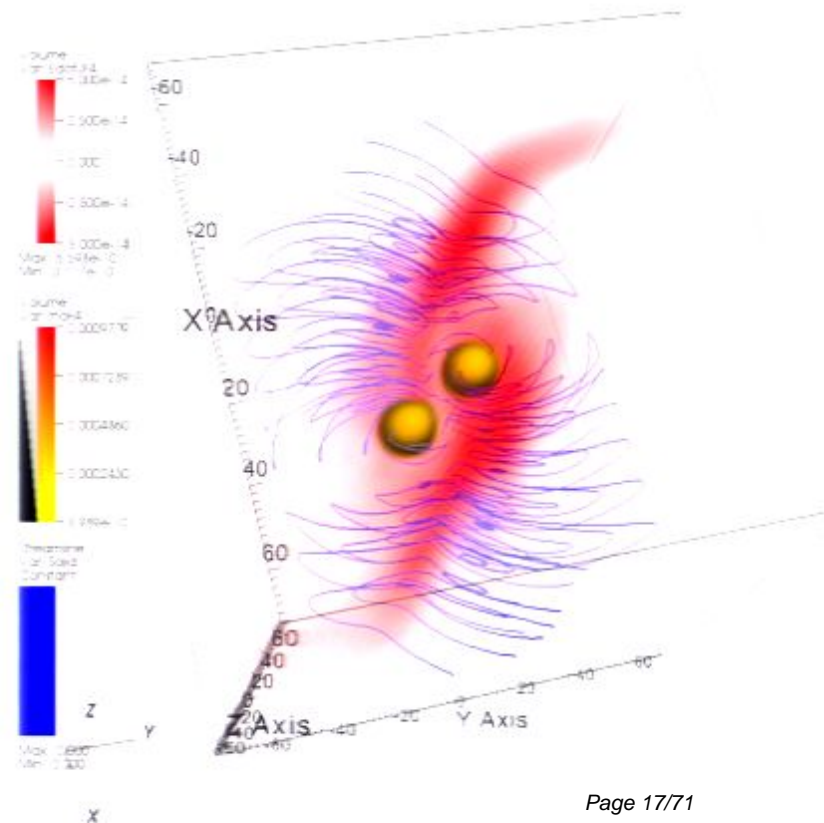


IV. Magnetic fields of BNS

- non-spinning NS with the magnetic moments up/up



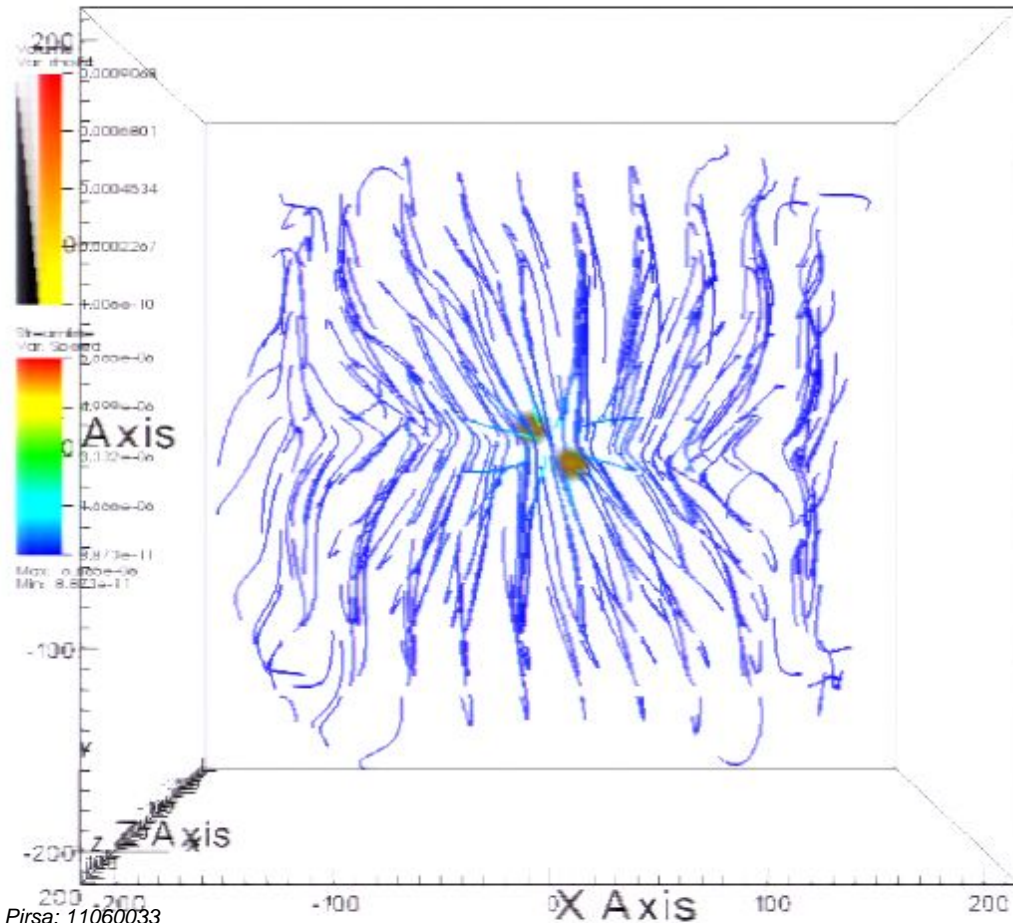
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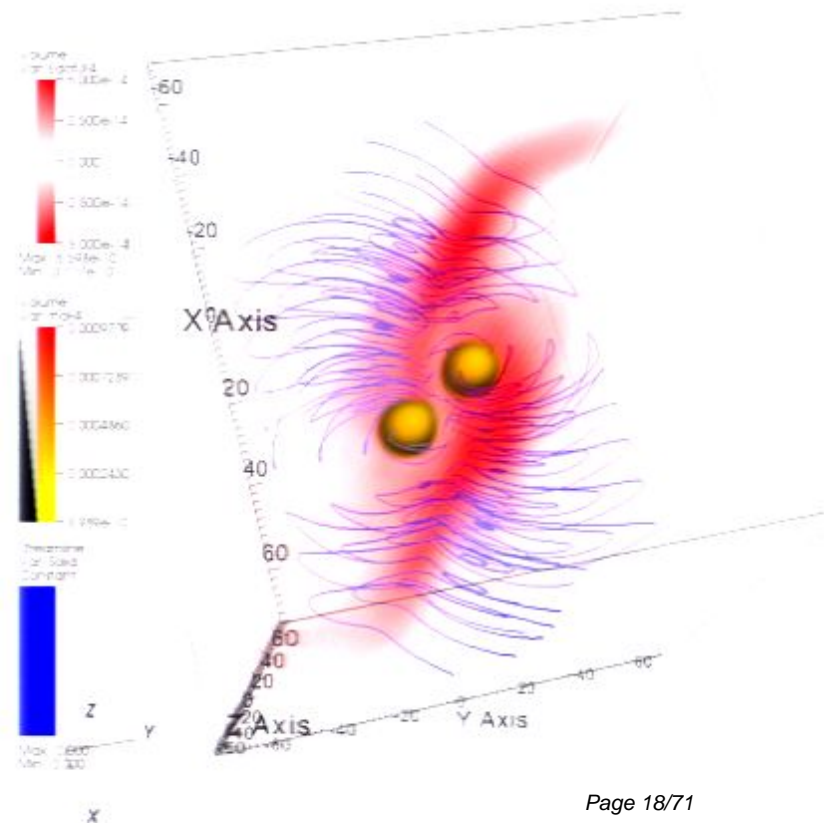
Page 17/71

IV. Magnetic fields of BNS

- non-spinning NS with the magnetic moments up/up



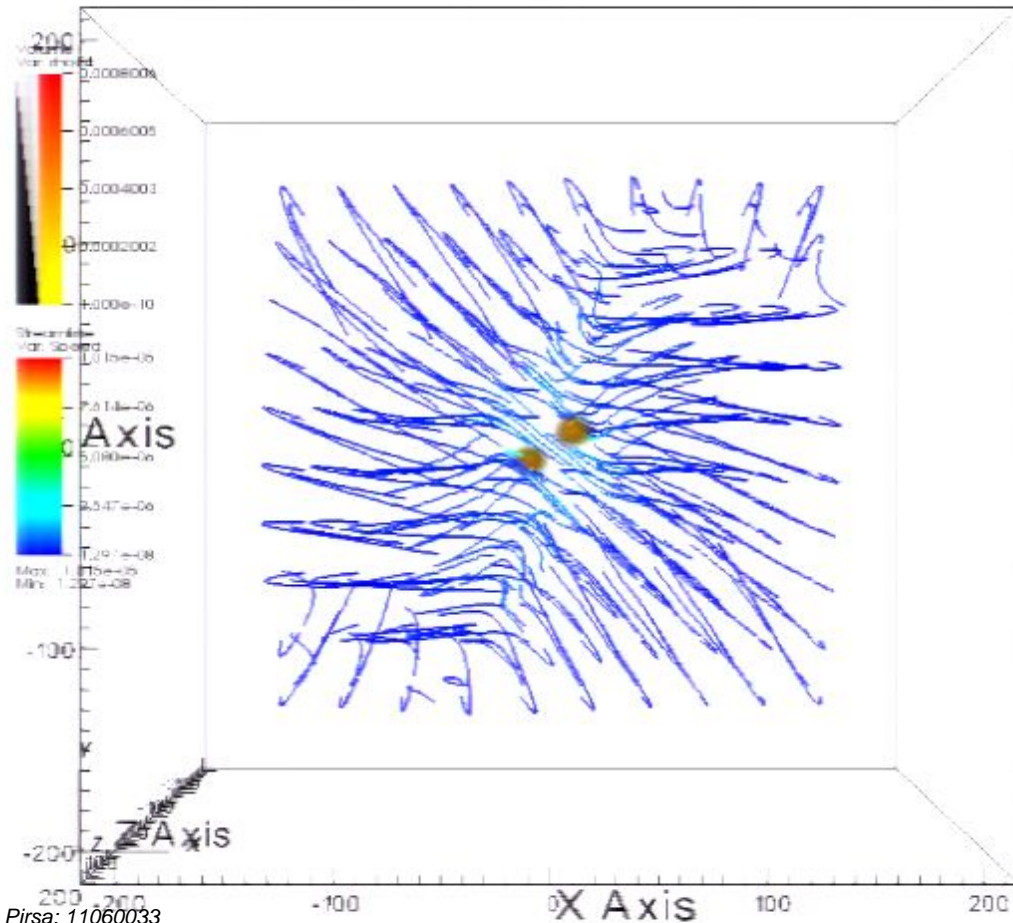
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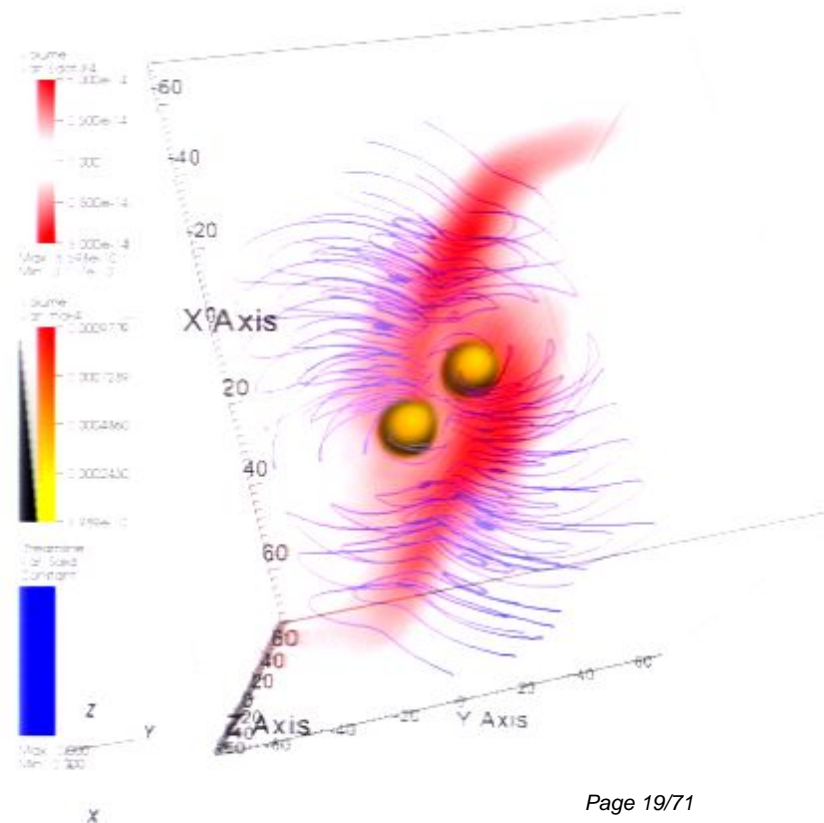
Page 18/71

IV. Magnetic fields of BNS

- non-spinning NS with the magnetic moments up/up



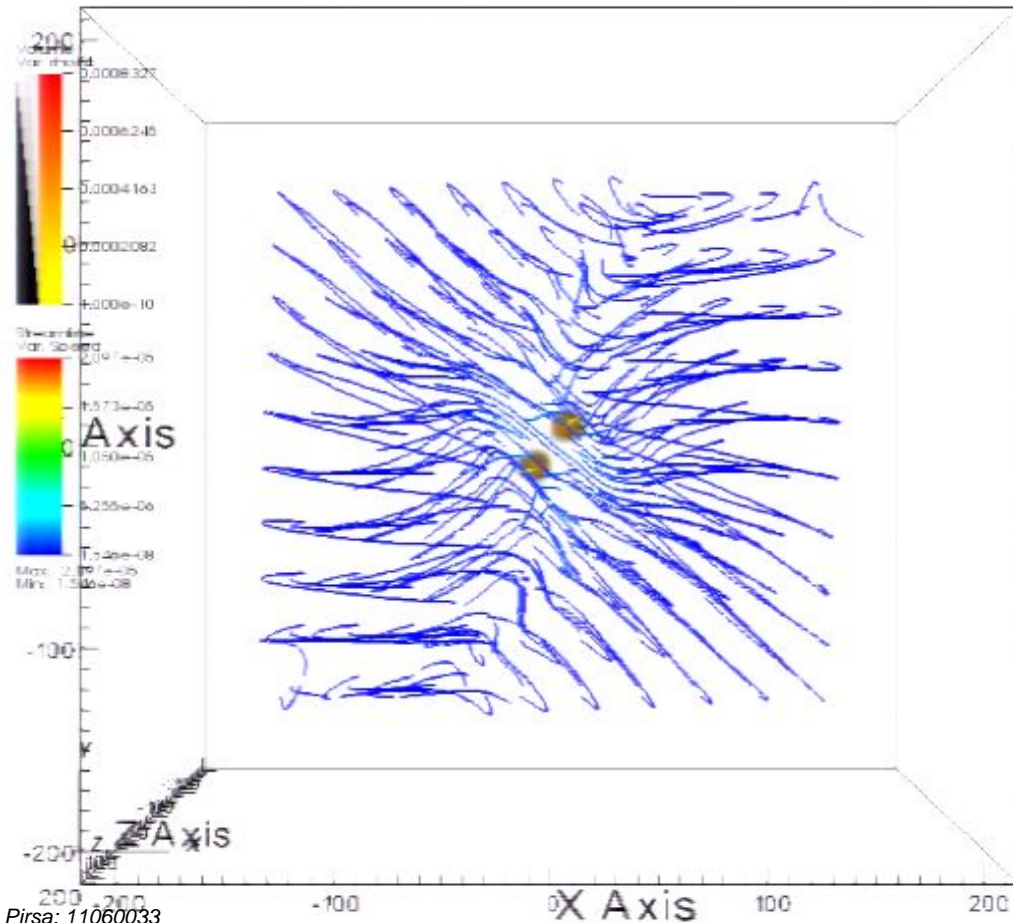
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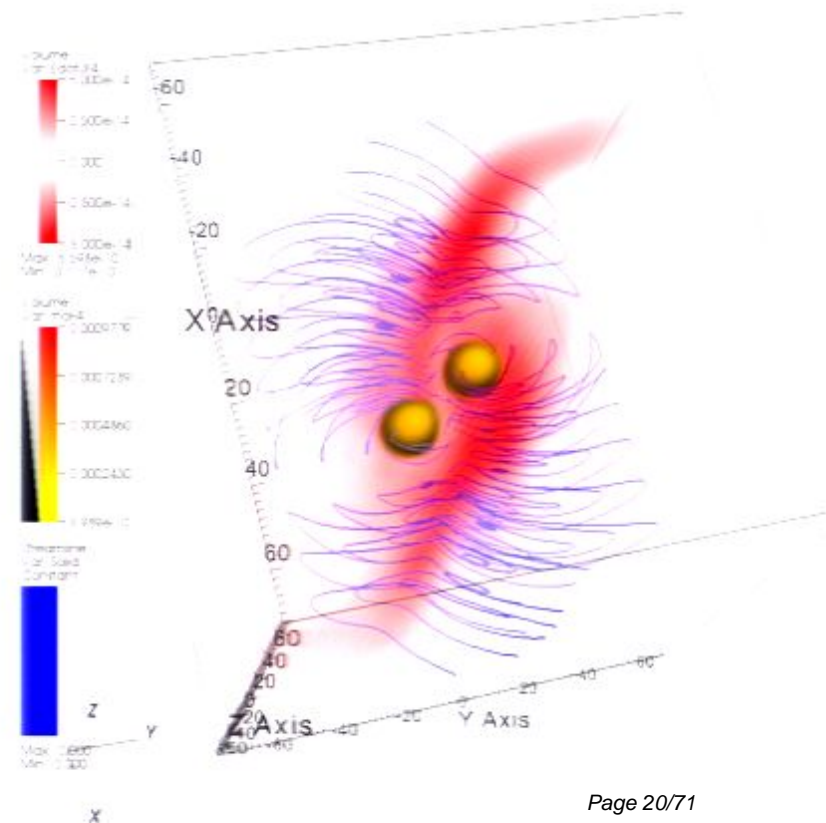
Page 19/71

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- non-spinning NS with the magnetic moments up/up



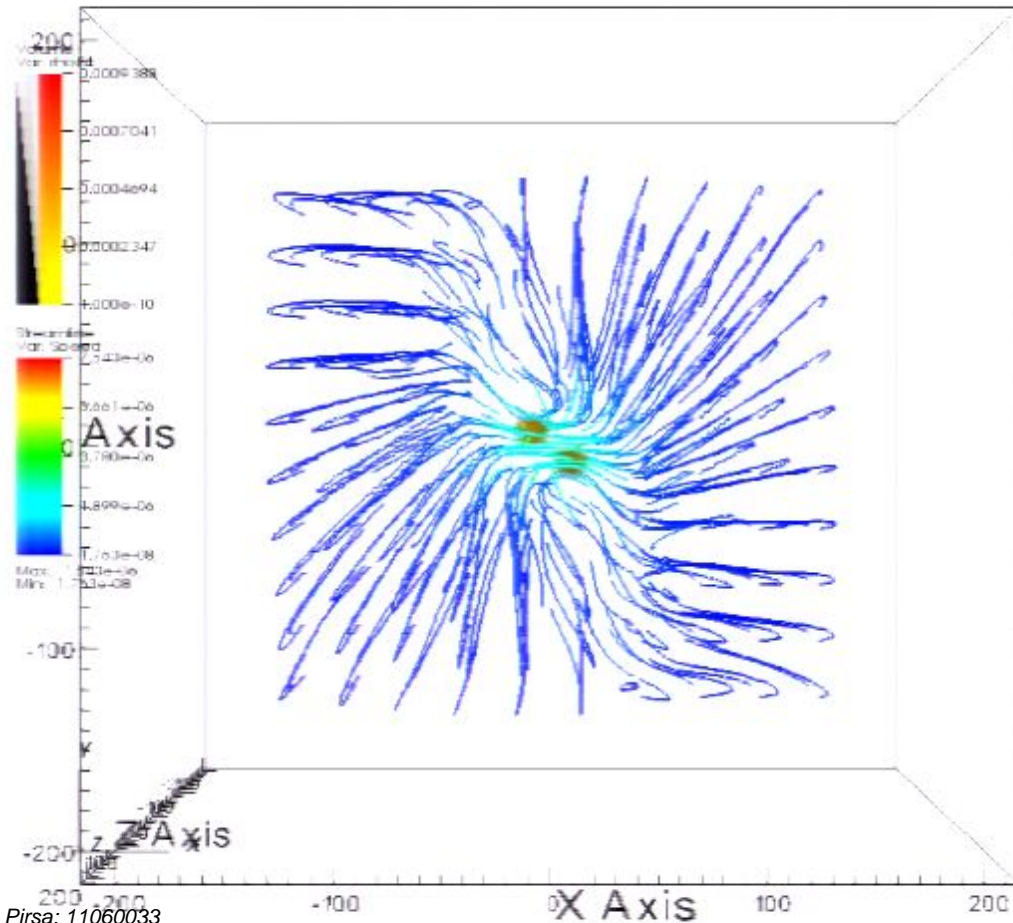
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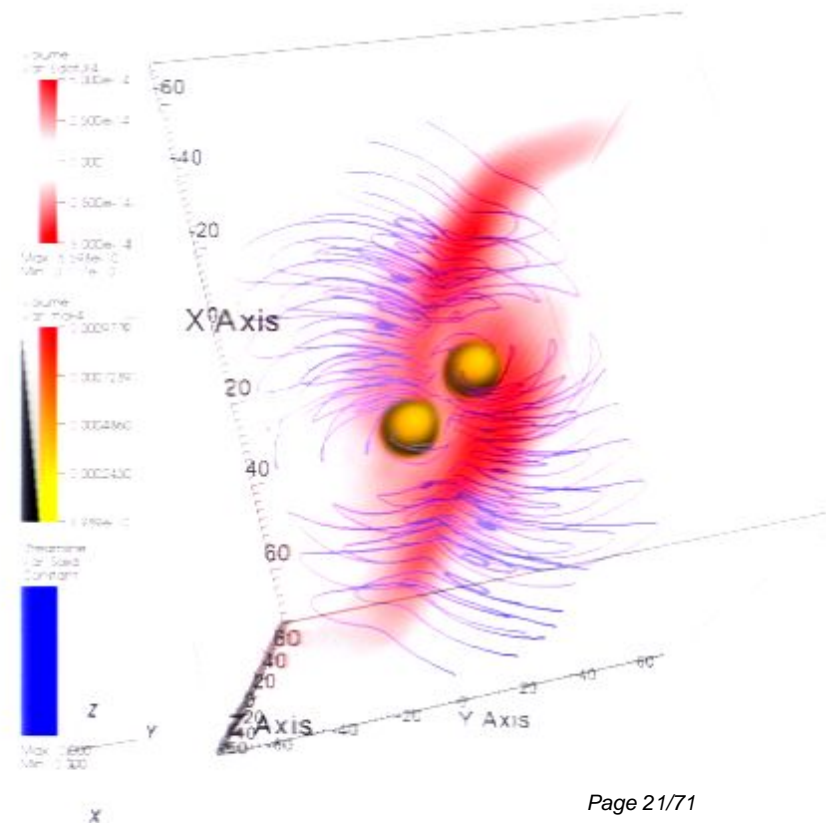
Page 20/71

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- non-spinning NS with the magnetic moments up/up



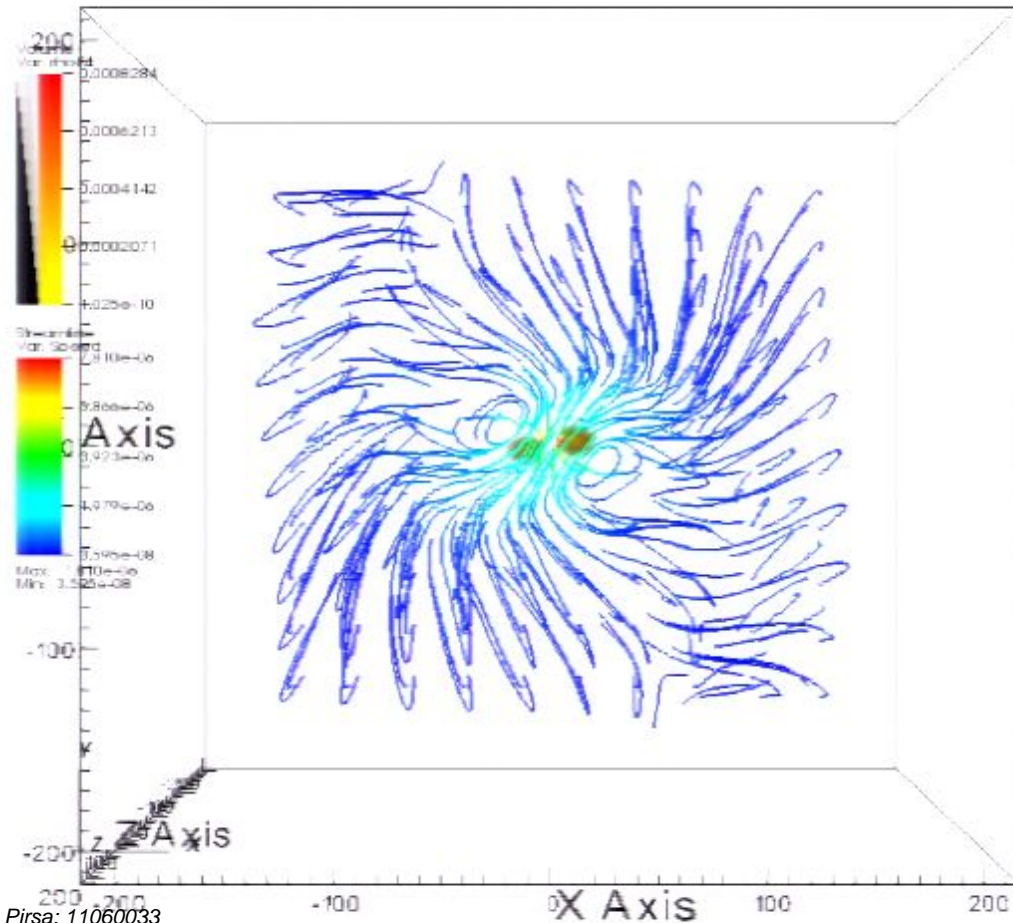
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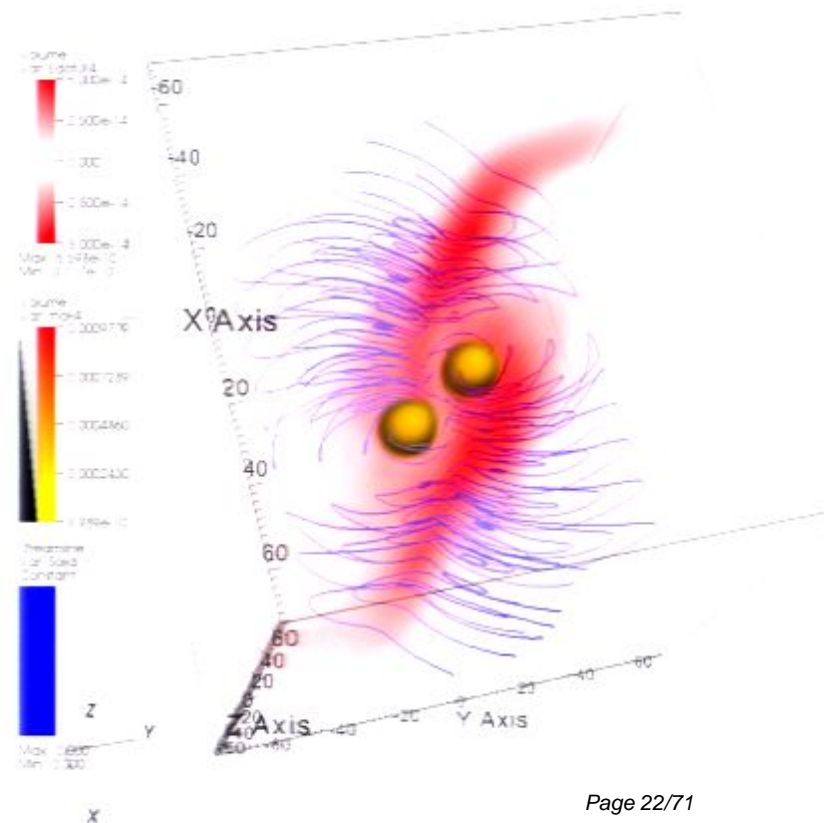
Page 21/71

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- non-spinning NS with the magnetic moments up/up



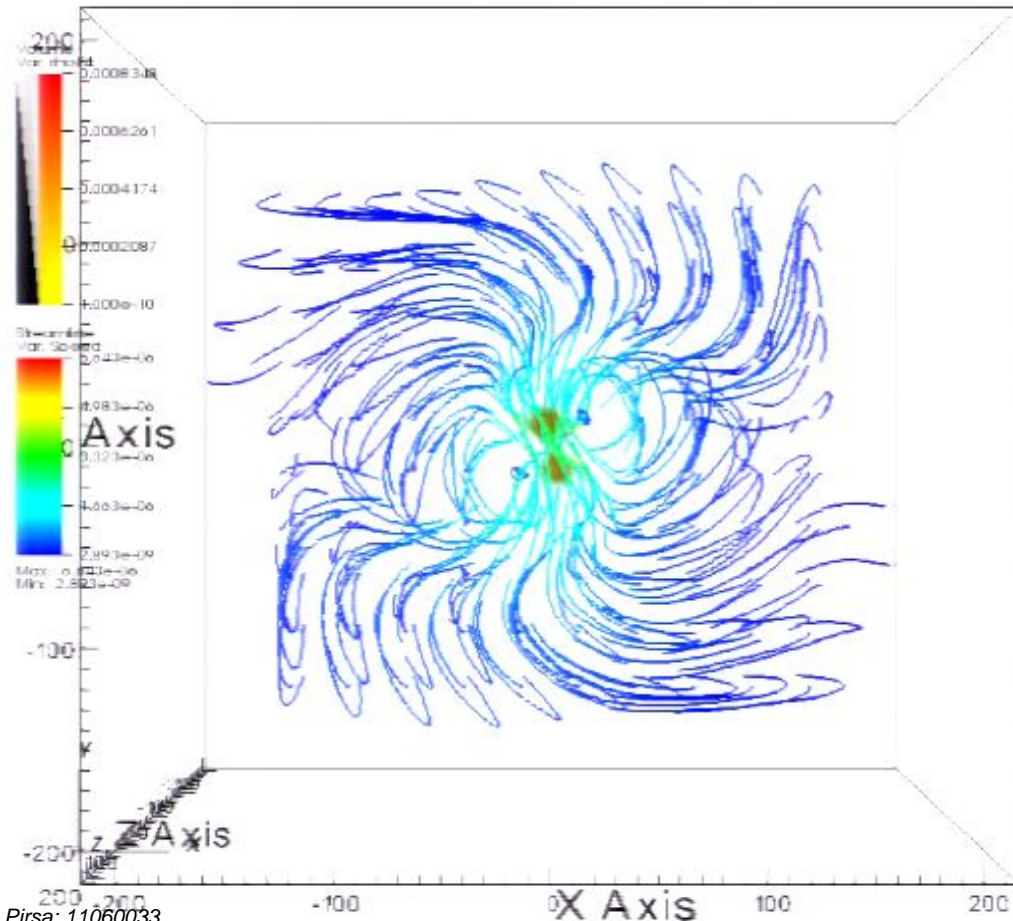
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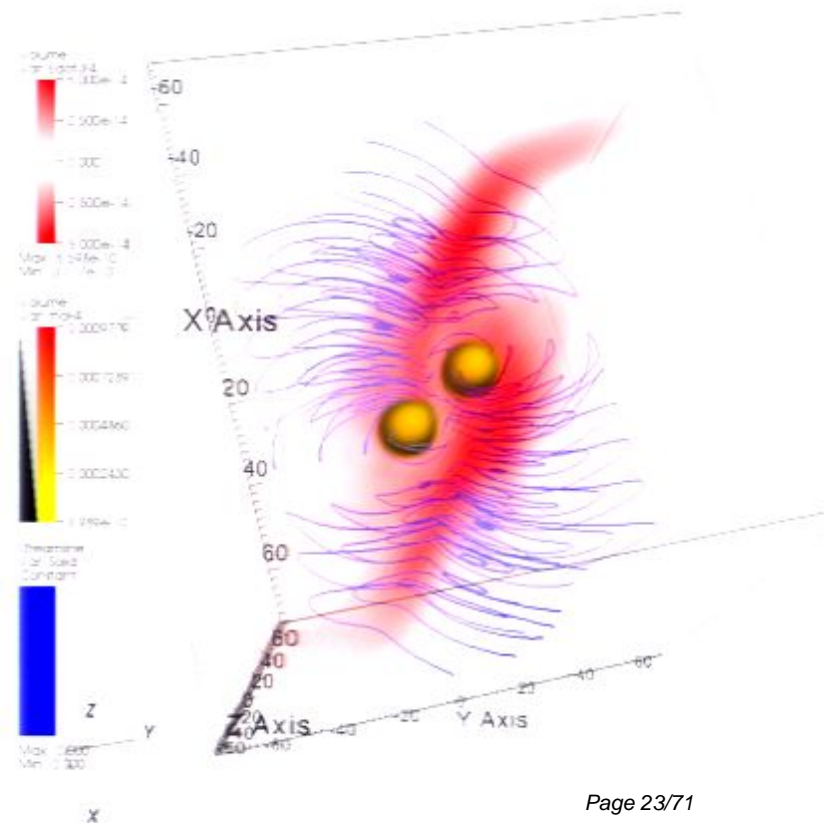
Page 22/71

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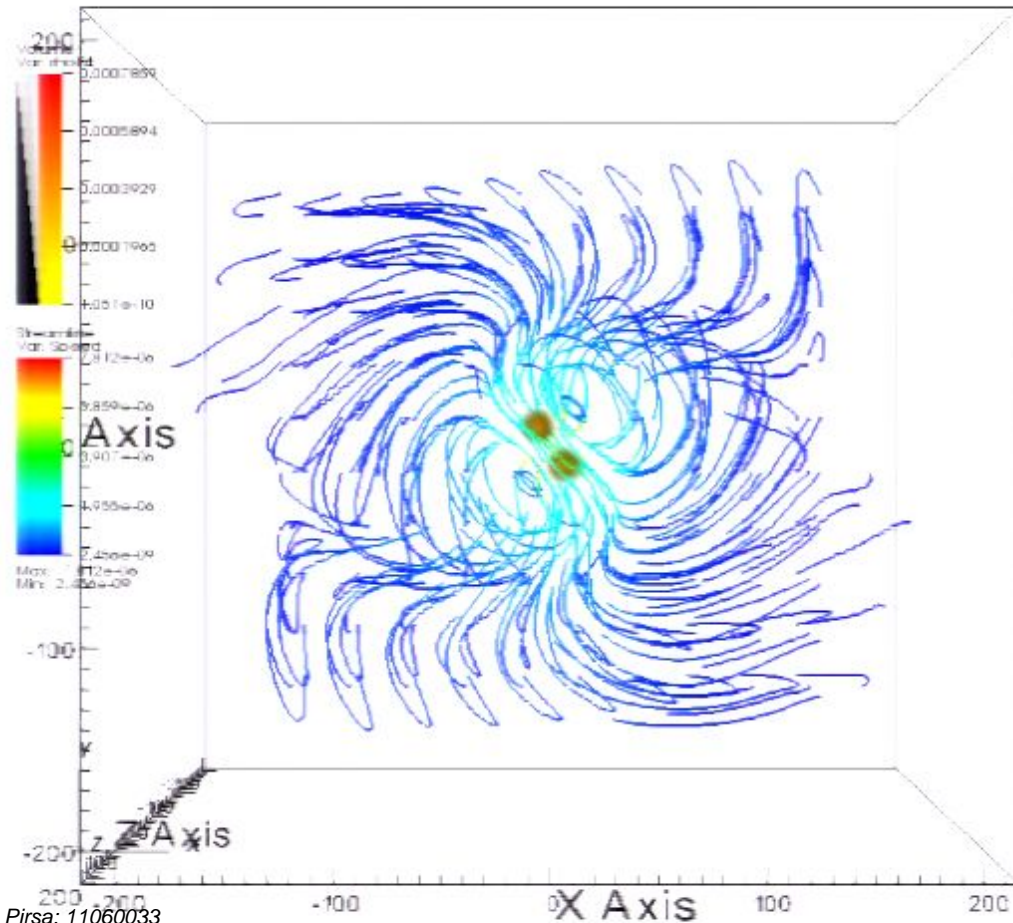
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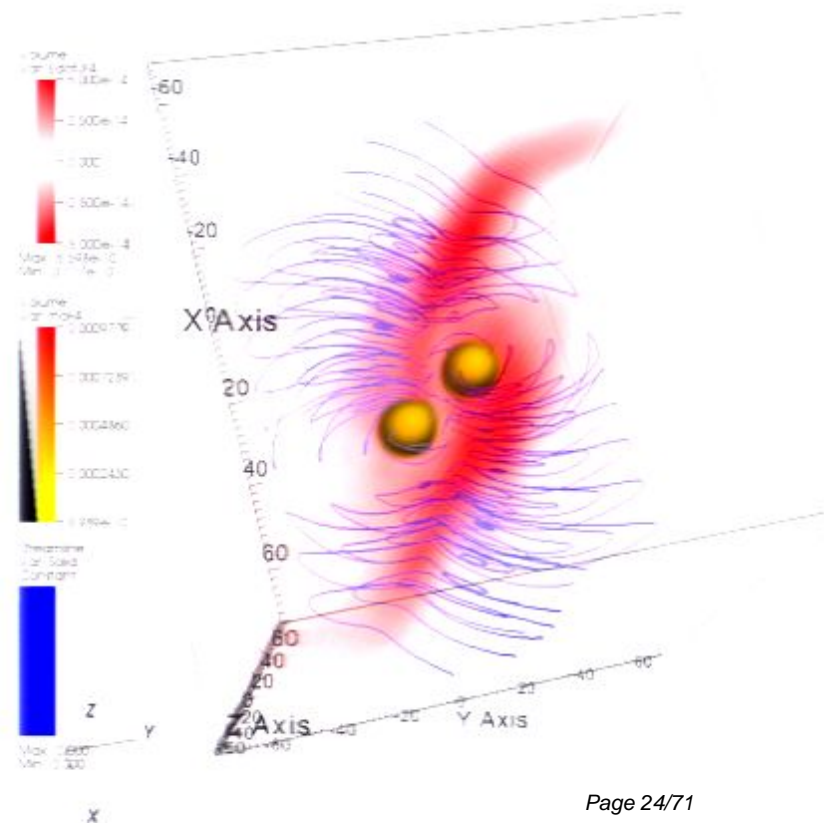
Page 23/71

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- non-spinning NS with the magnetic moments up/up



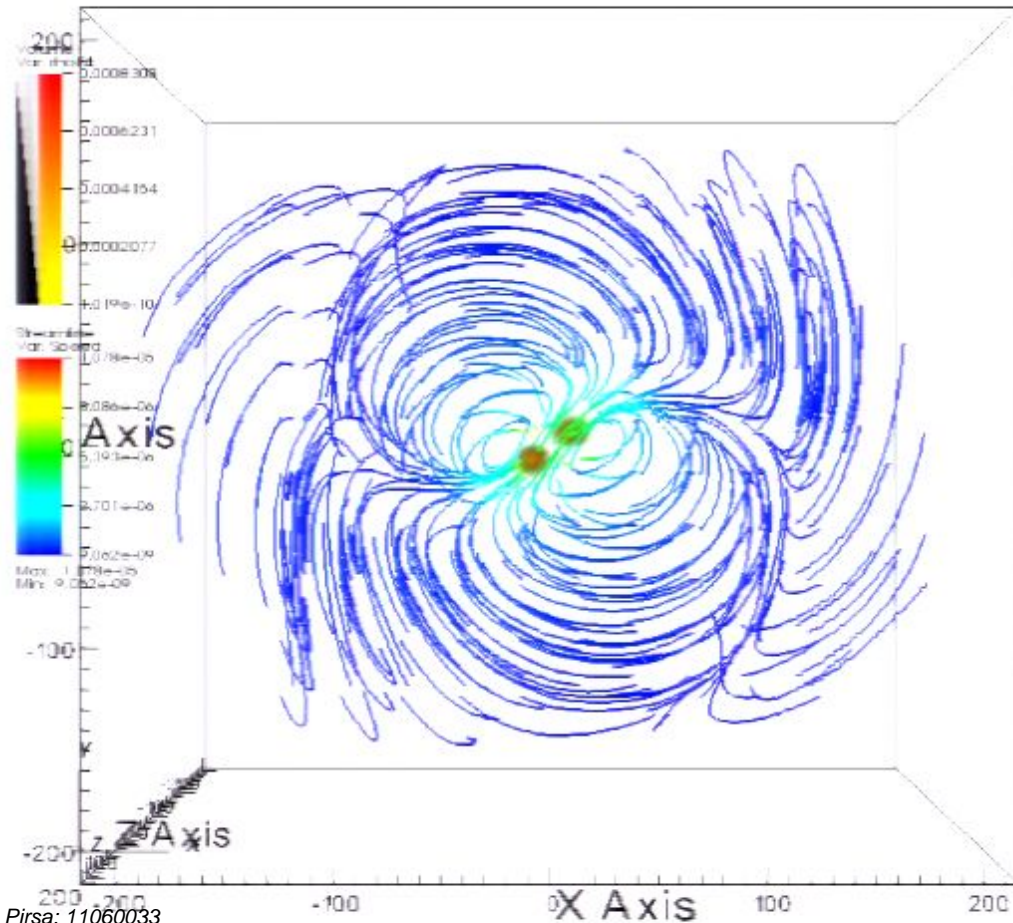
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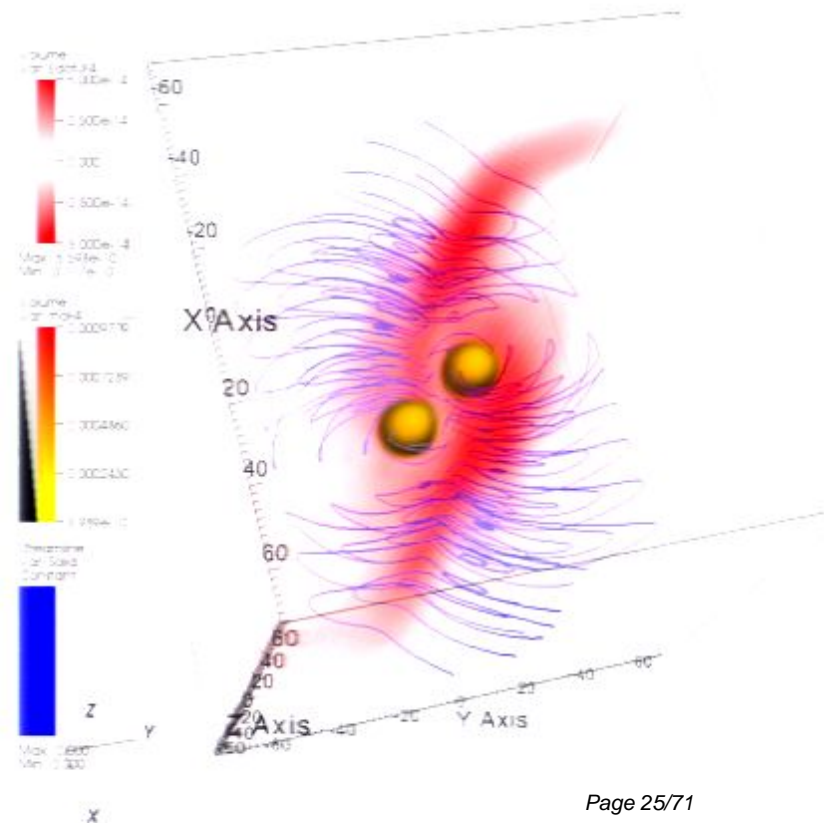
Page 24/71

IV. Magnetic fields of BNS

- non-spinning NS with the magnetic moments up/up



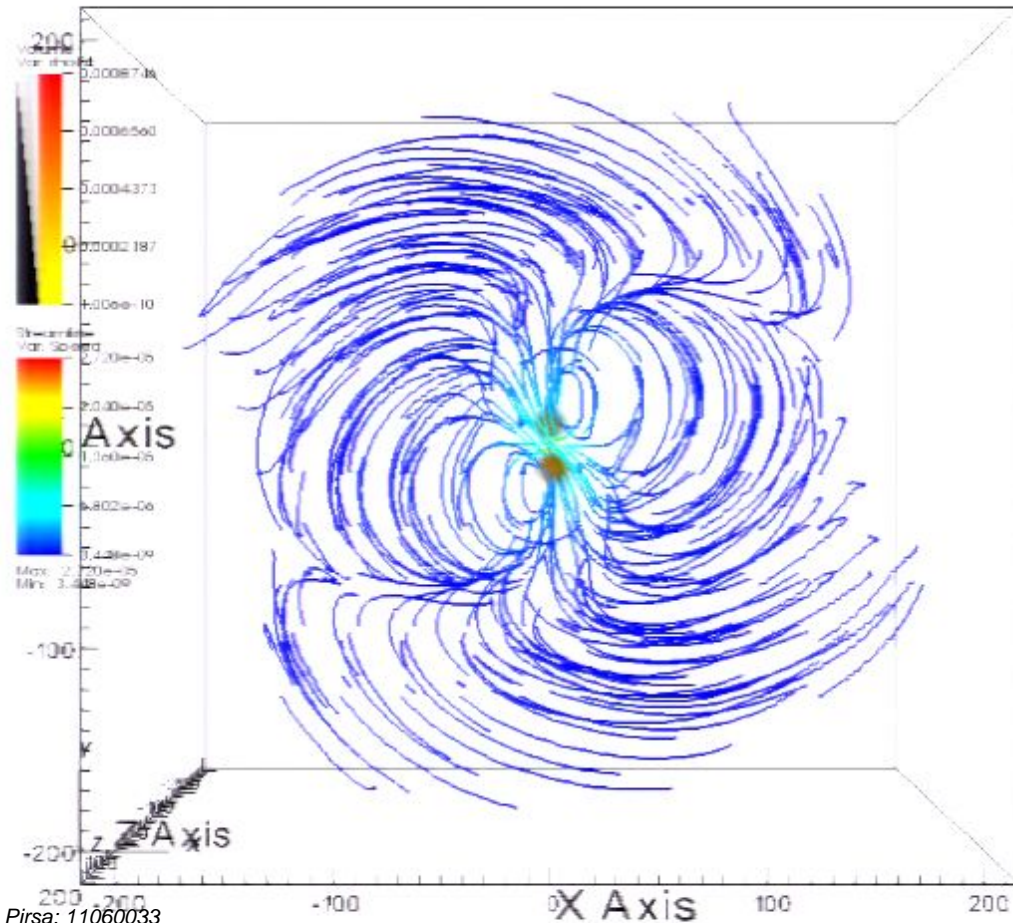
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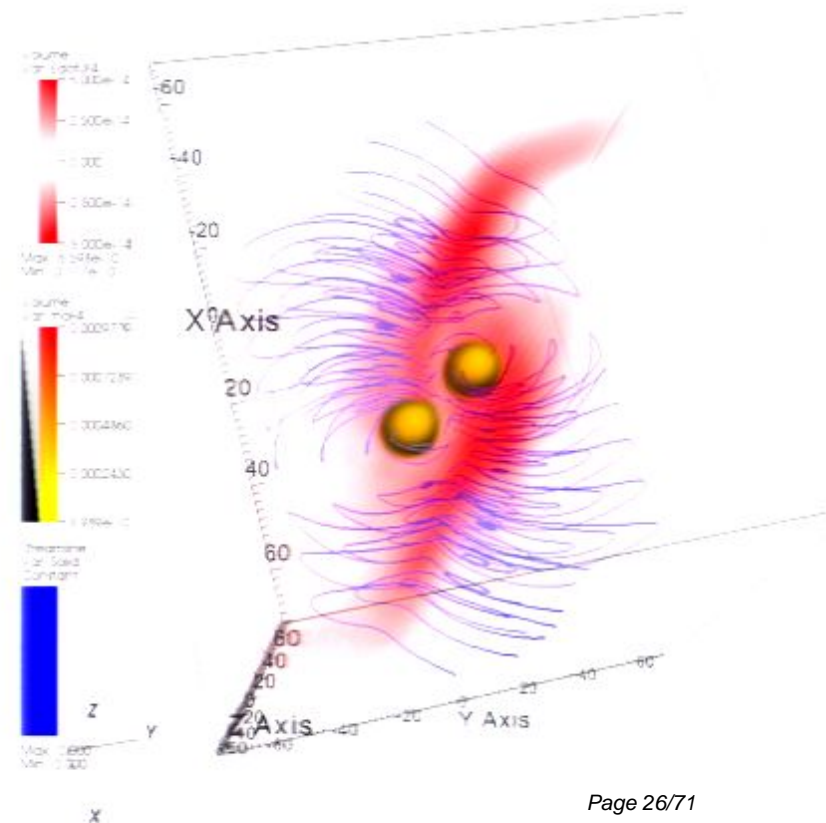
Page 25/71

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- non-spinning NS with the magnetic moments up/up



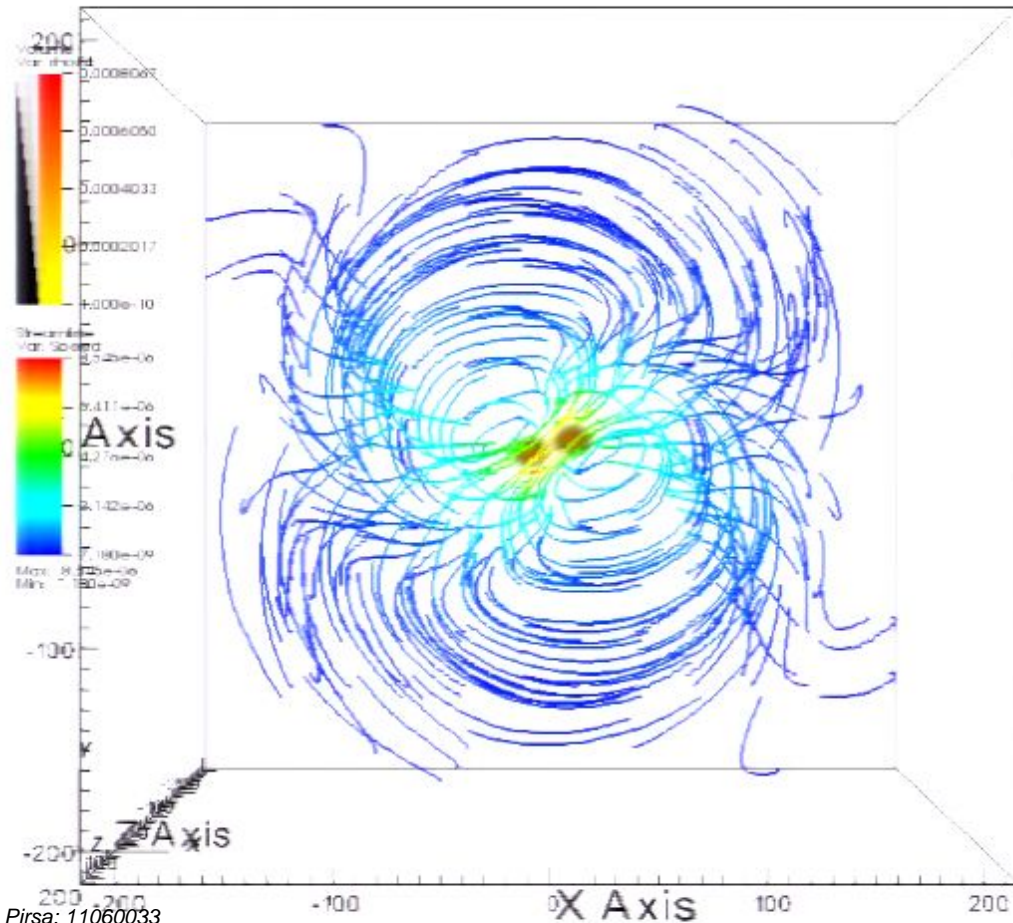
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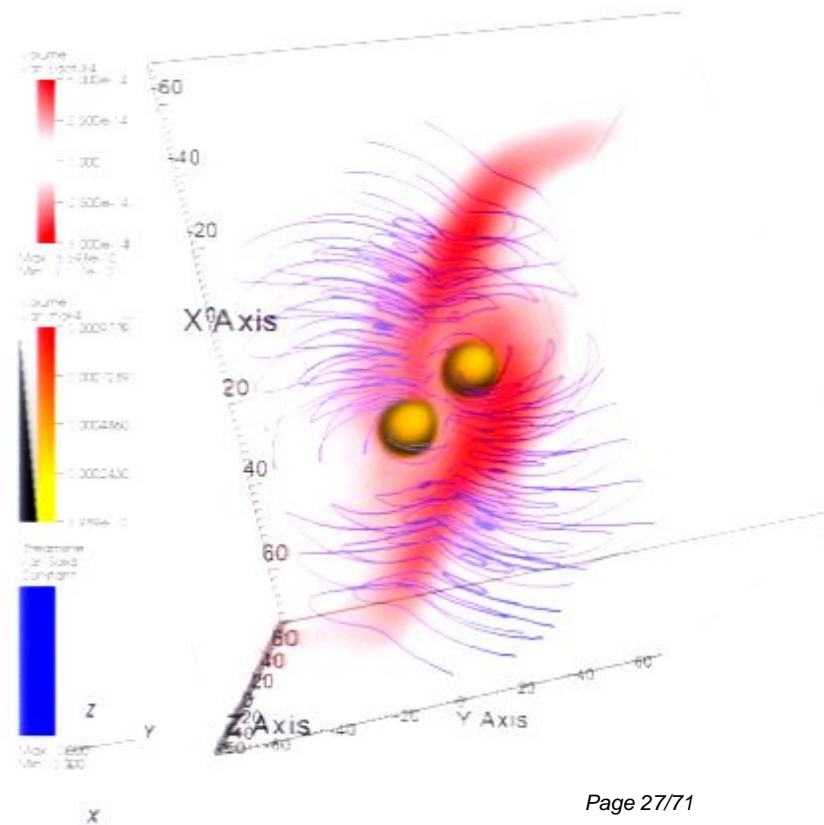
Page 26/71

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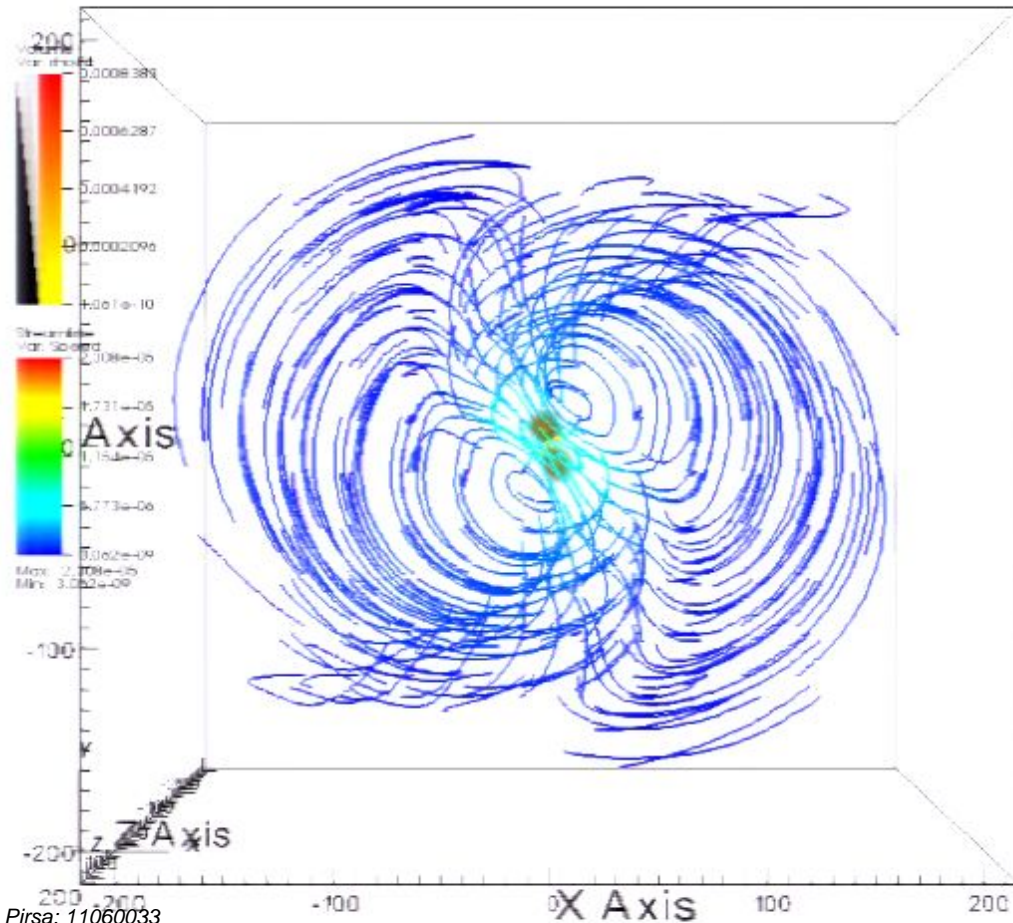
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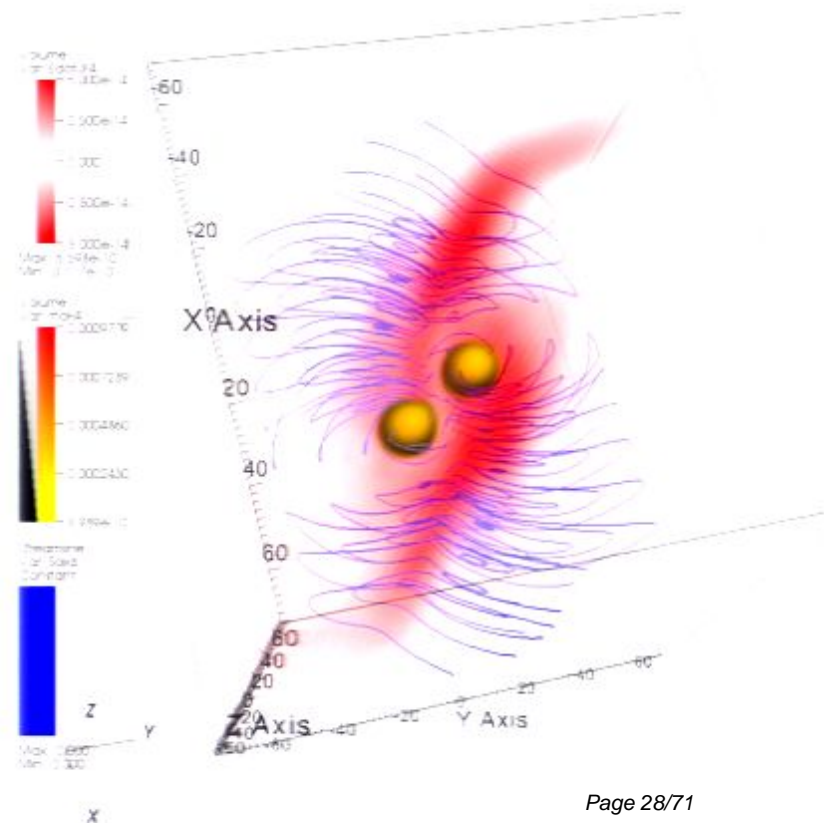
Page 27/71

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- non-spinning NS with the magnetic moments up/up



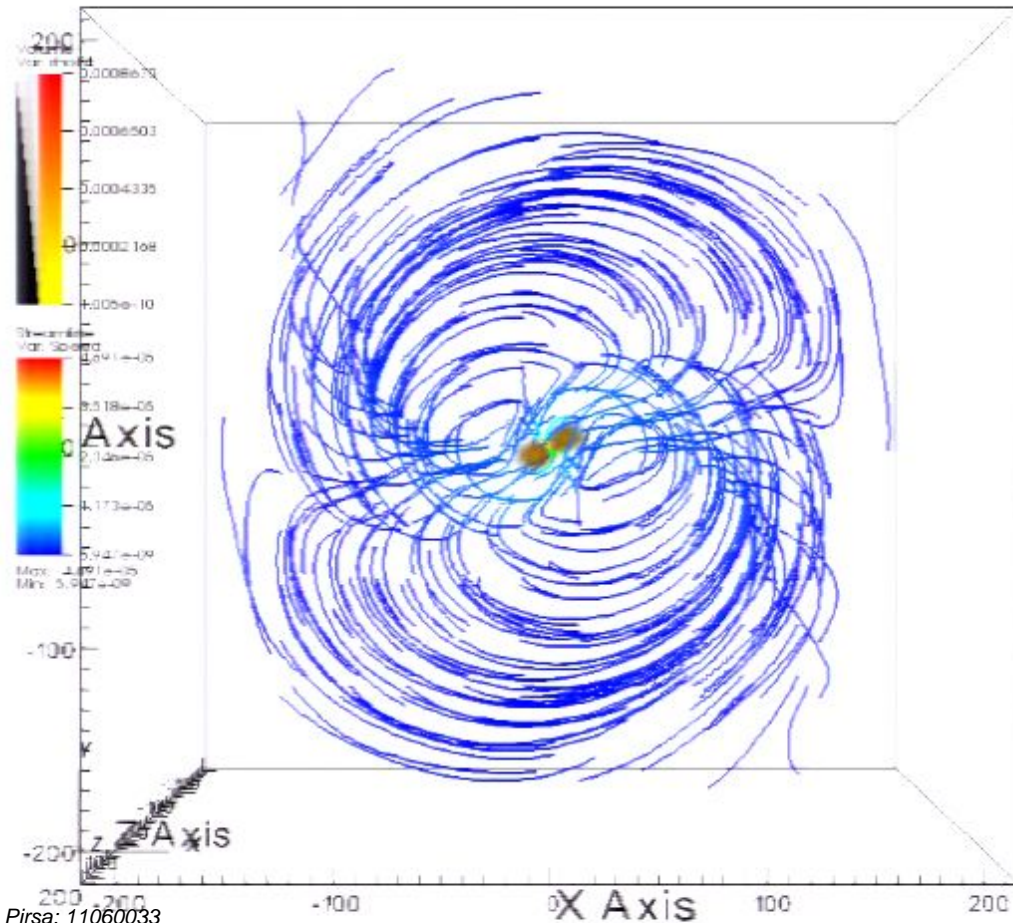
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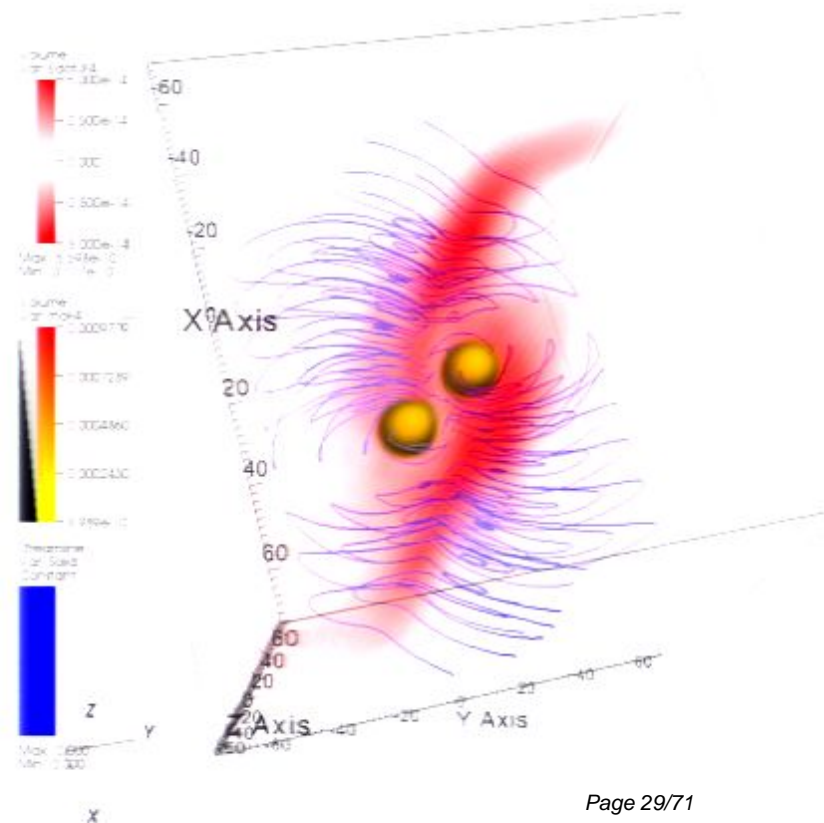
Page 28/71

IV. Magnetic fields of BNS

- non-spinning NS with the magnetic moments up/up



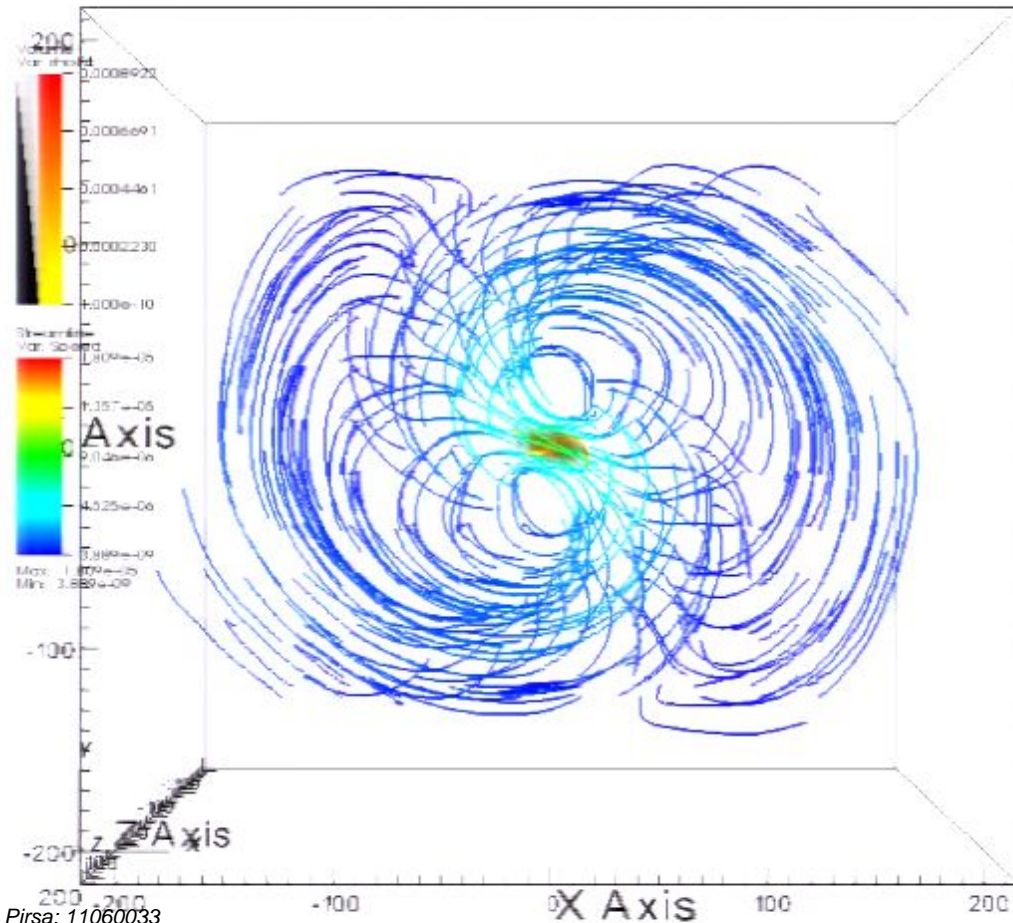
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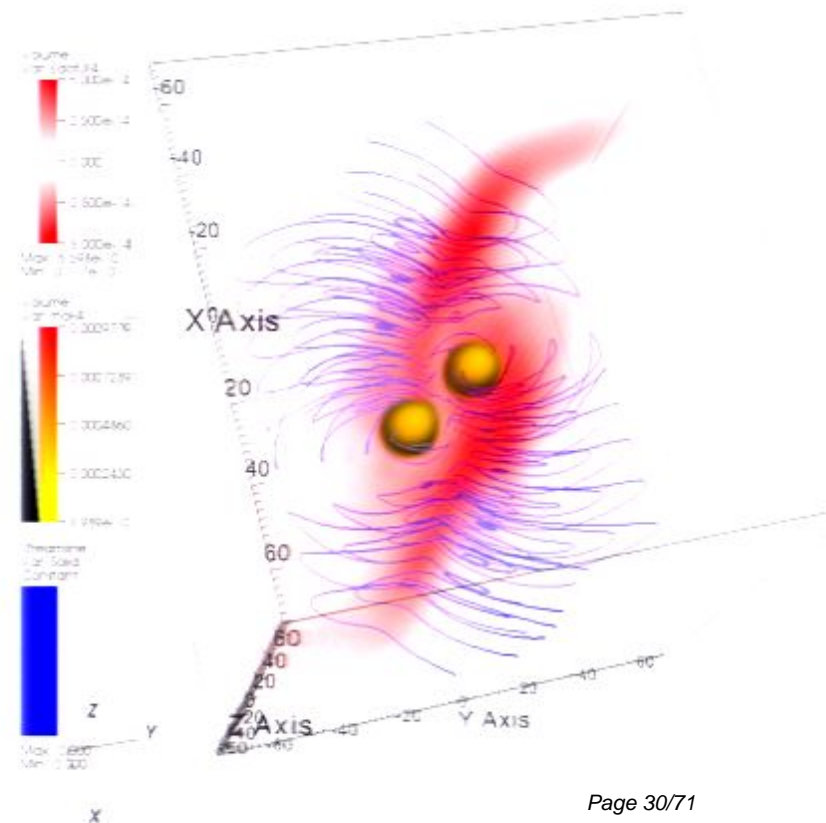
Page 29/71

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- non-spinning NS with the magnetic moments up/up



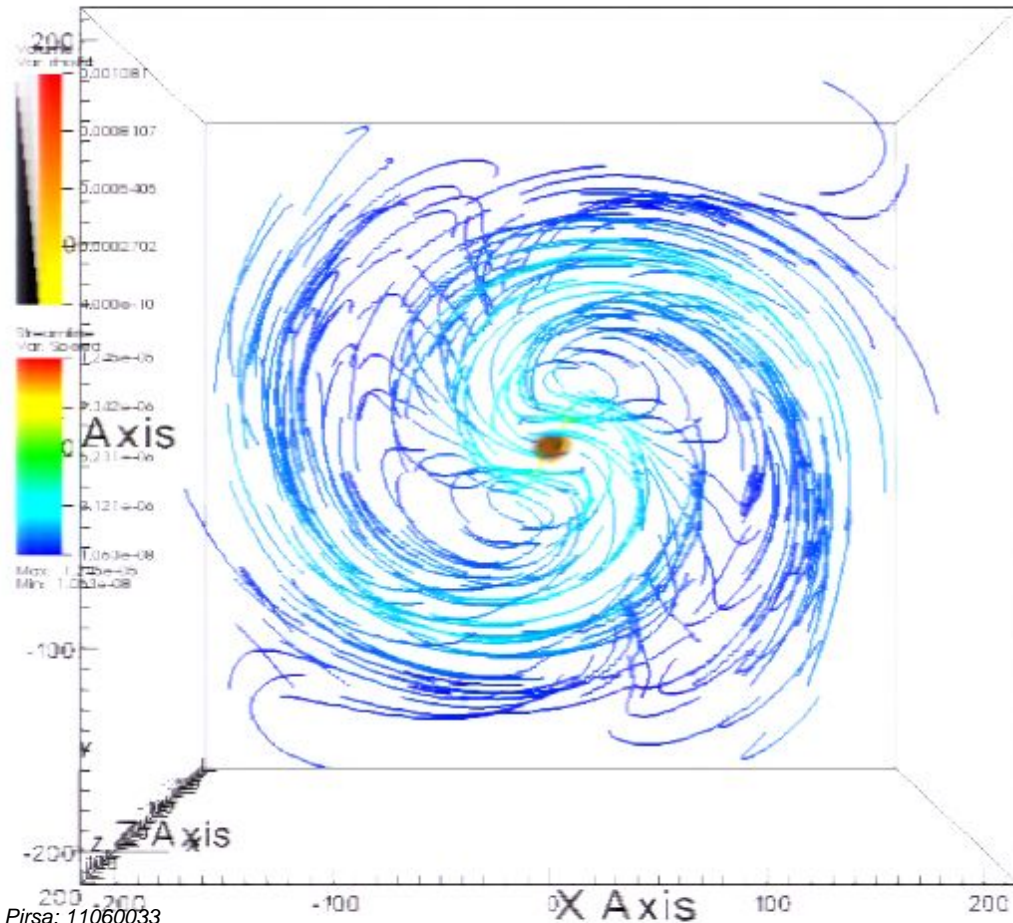
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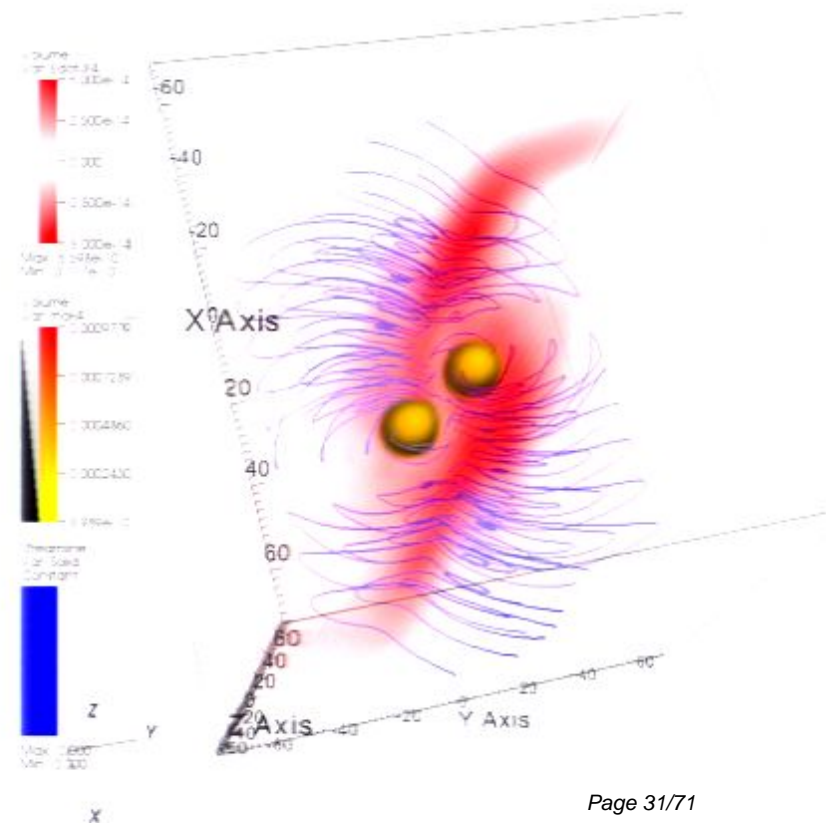
Page 30/71

IV. Magnetic fields of BNS

- non-spinning NS with the magnetic moments up/up



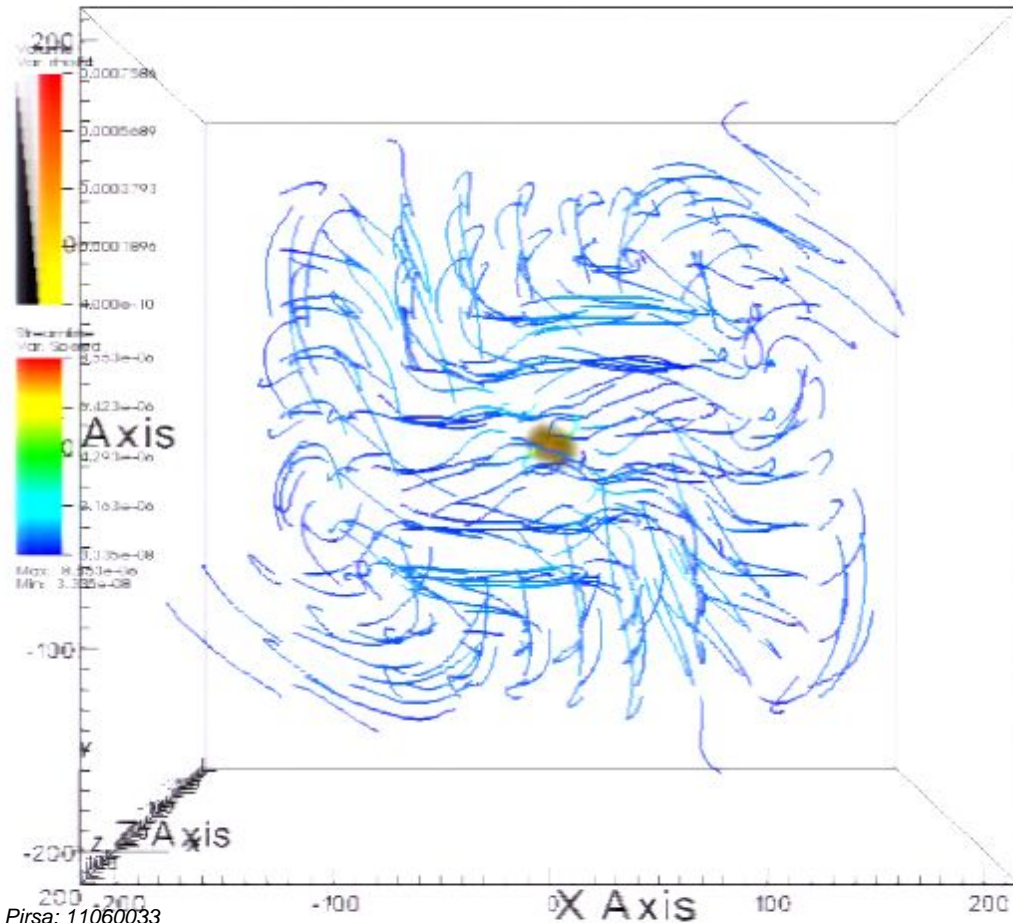
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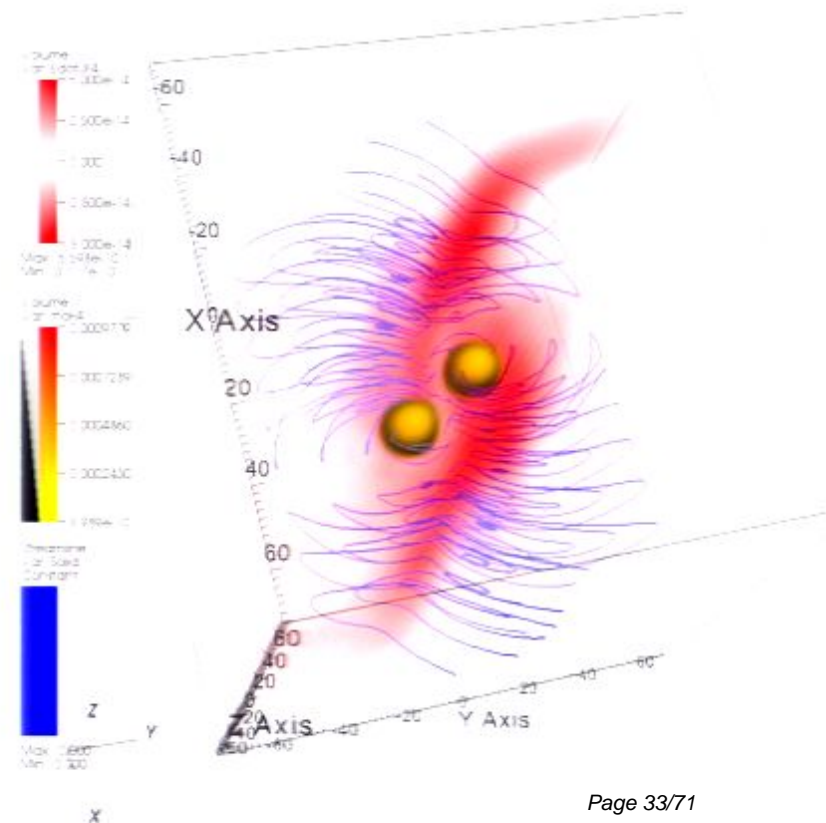
Page 31/71

IV. Magnetic fields of BNS

- non-spinning NS with the magnetic moments up/up



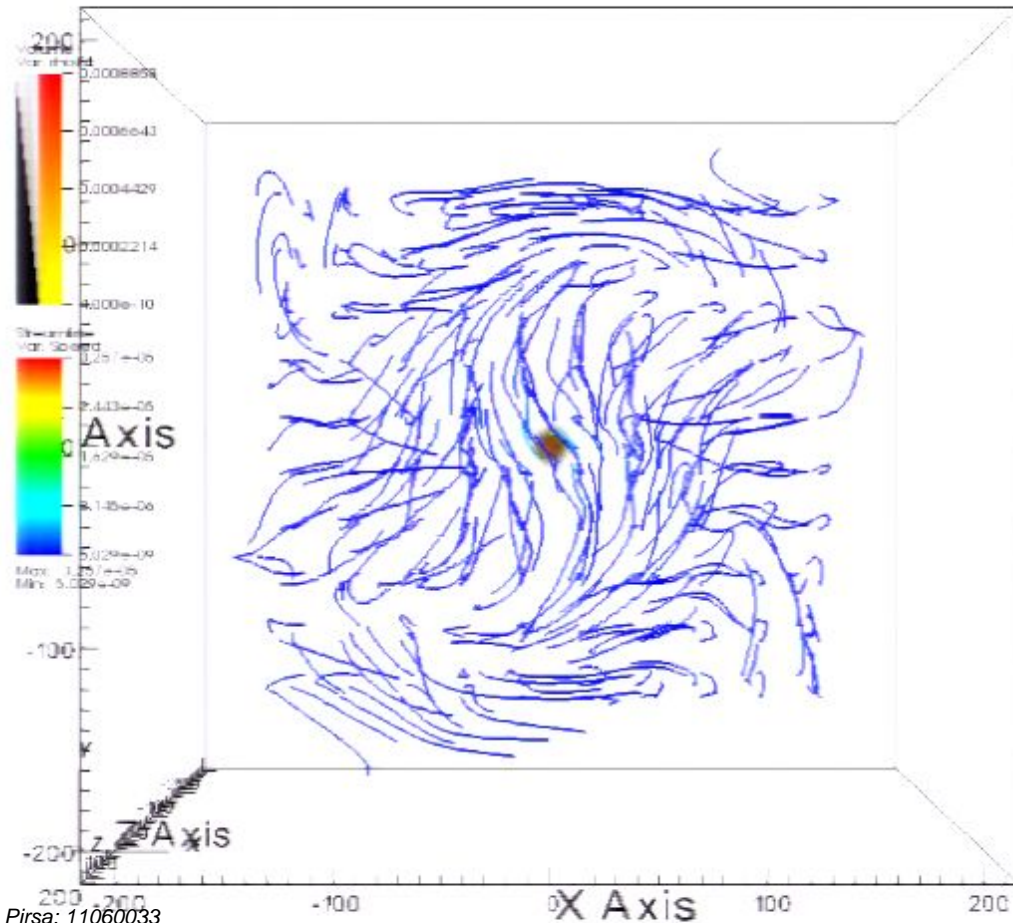
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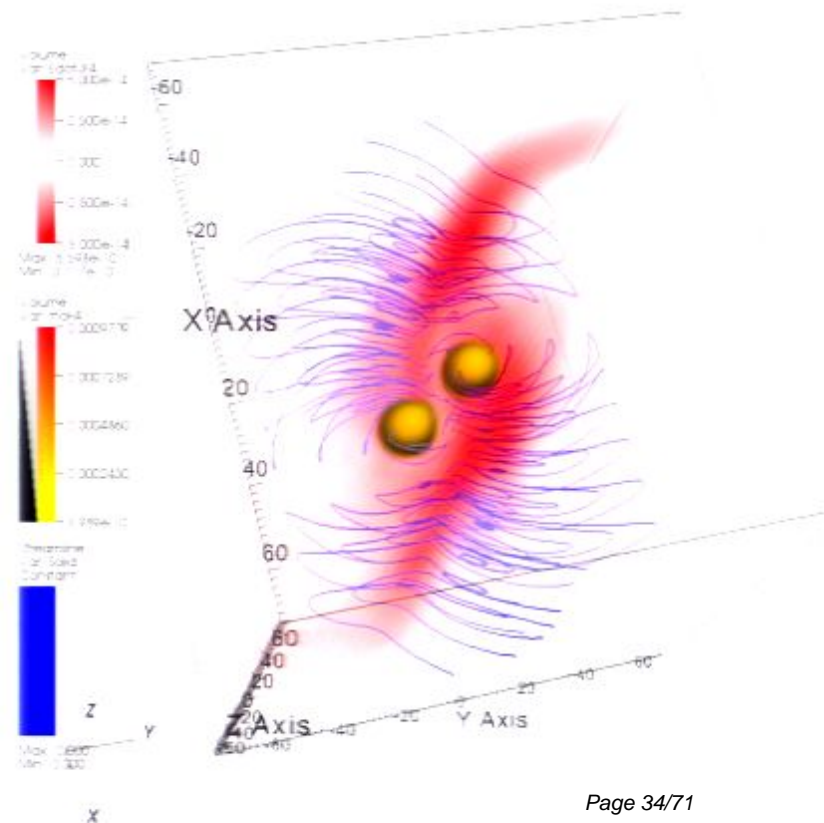
Page 33/71

IV. Magnetic fields of BNS

- non-spinning NS with the magnetic moments up/up



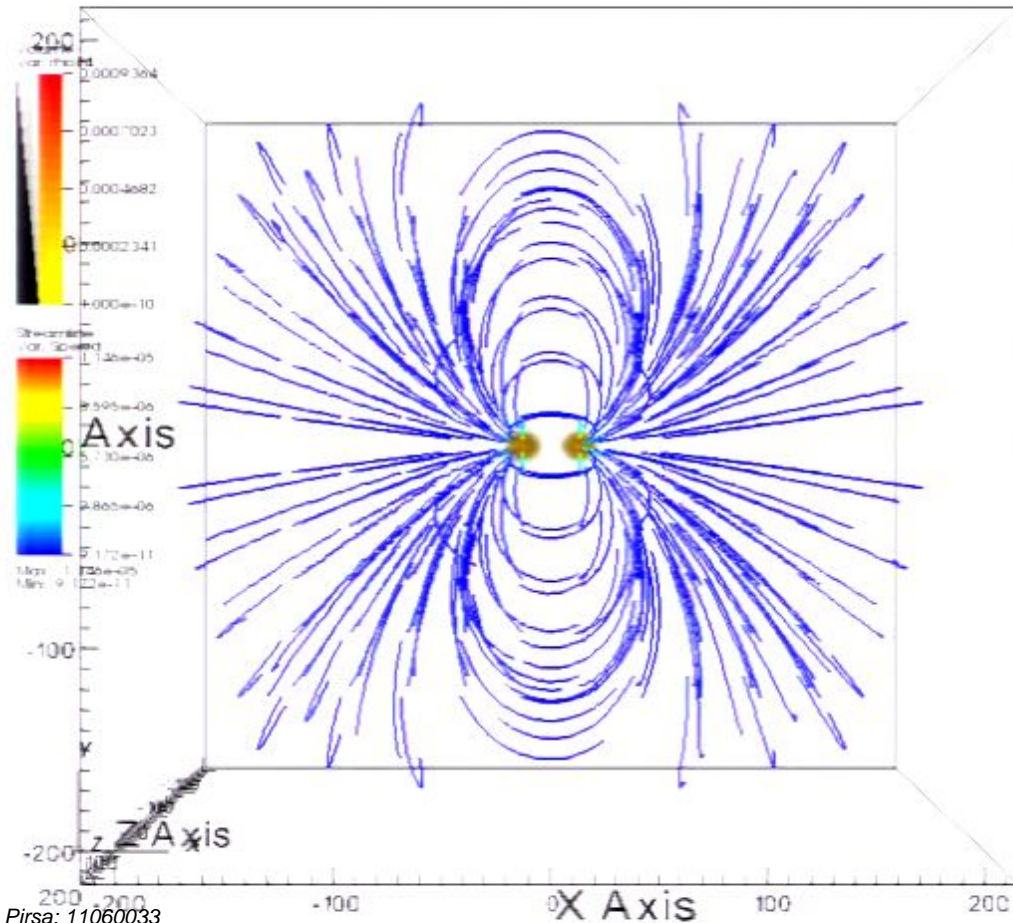
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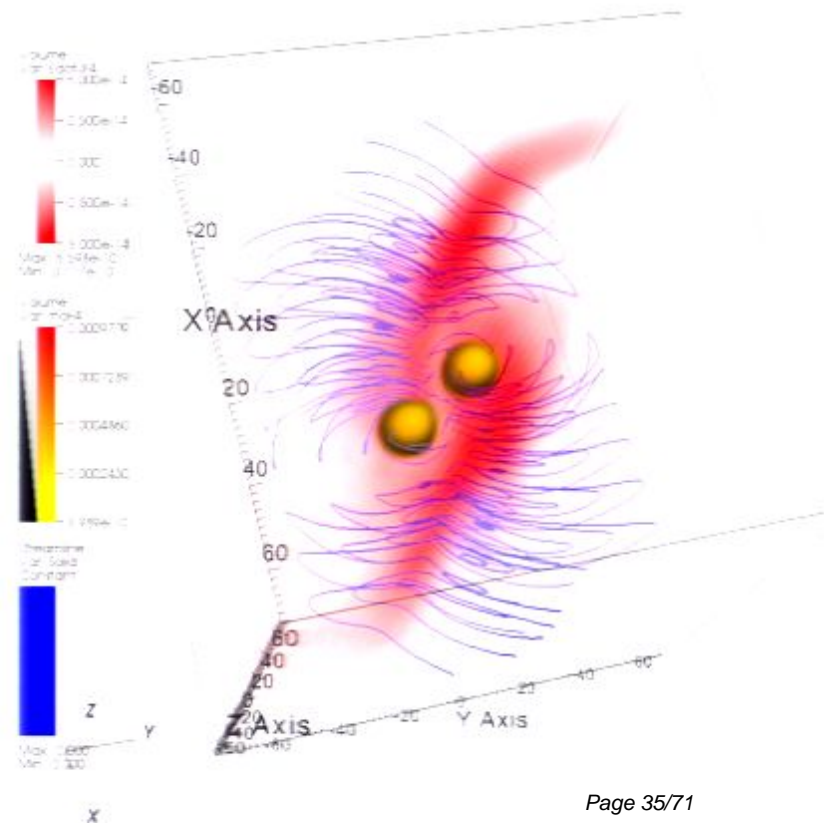
Page 34/71

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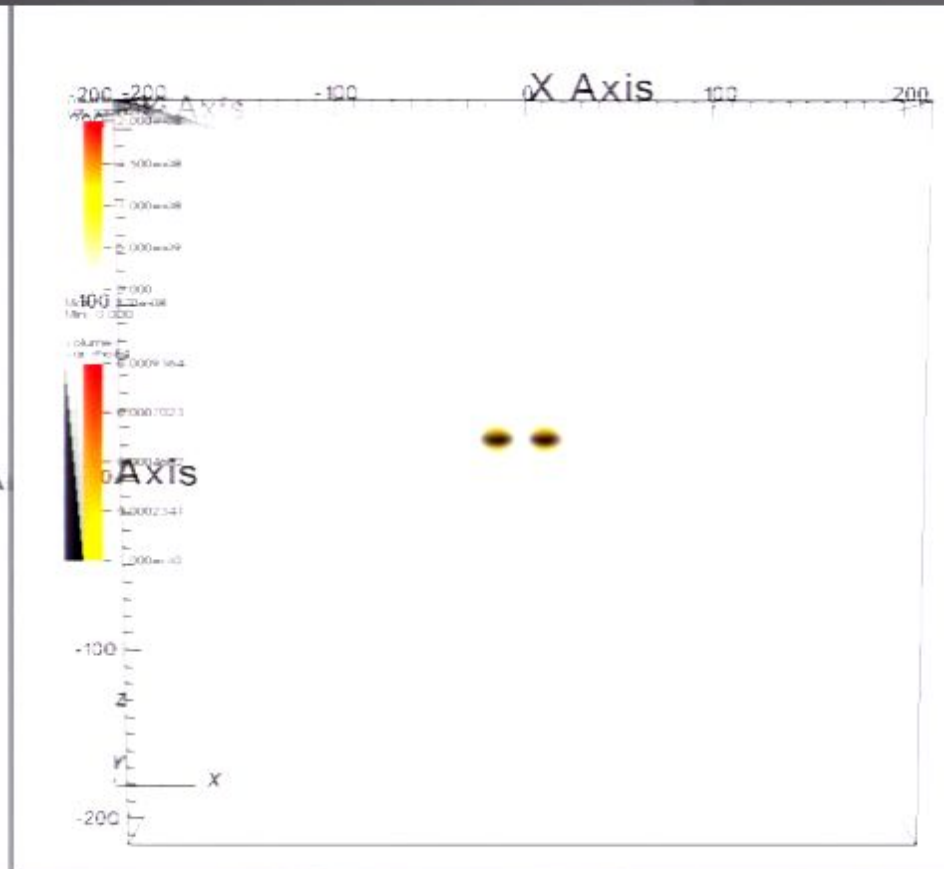
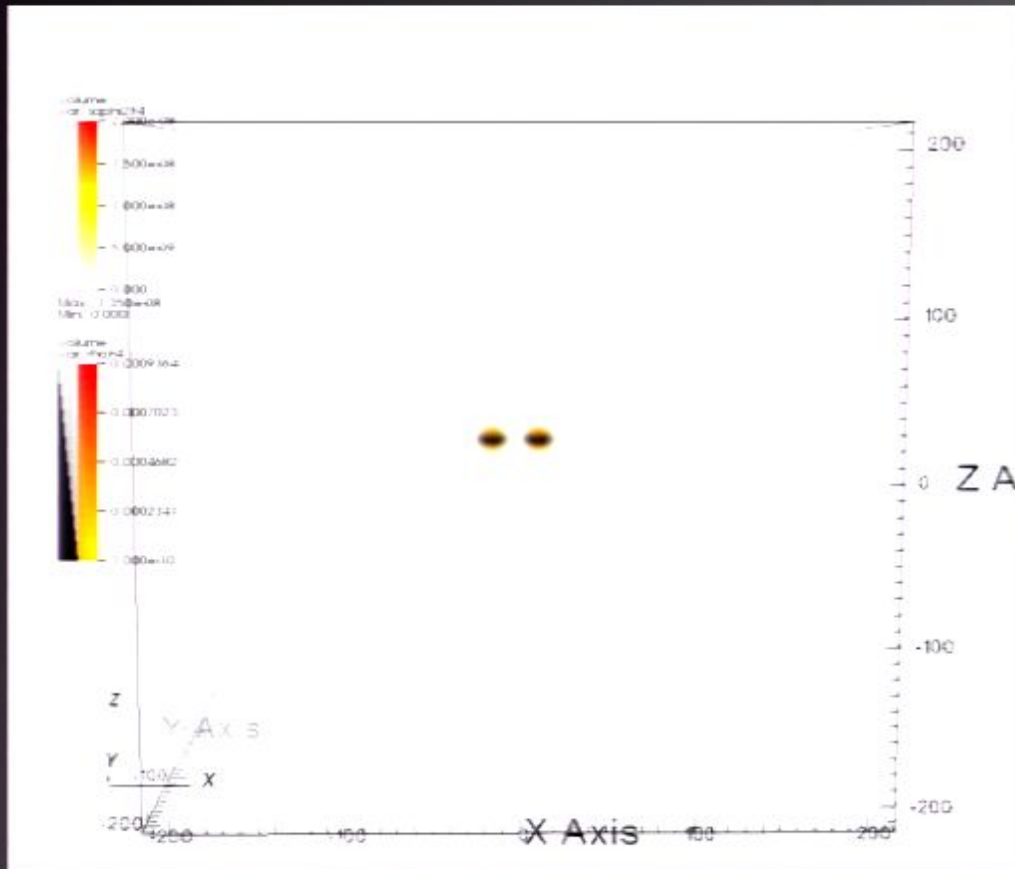


Page 35/71

IV. EM radiation of BNS

up/up

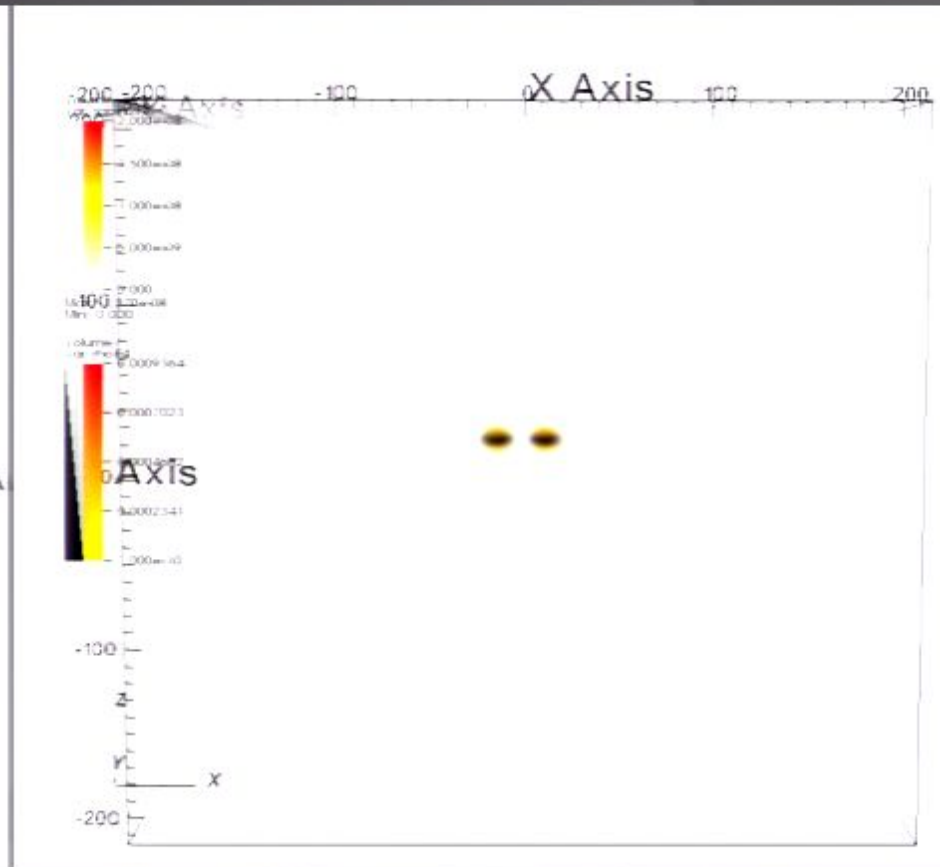
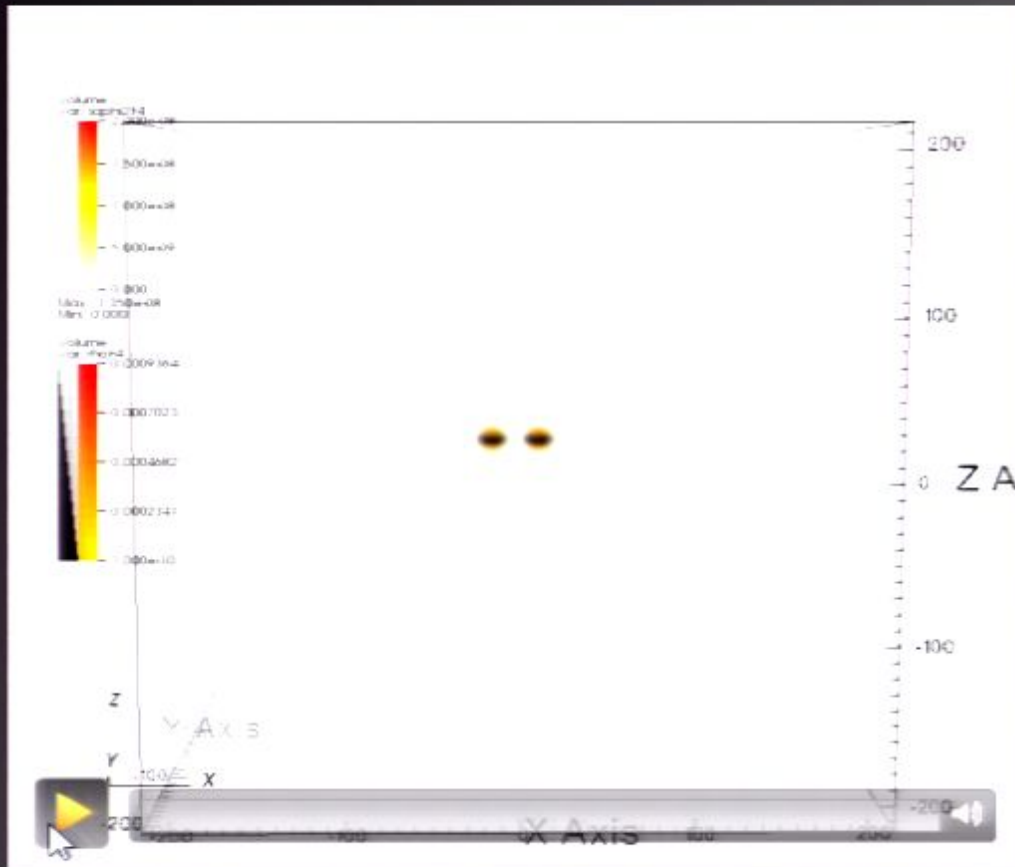
up/down



IV. EM radiation of BNS

up/up

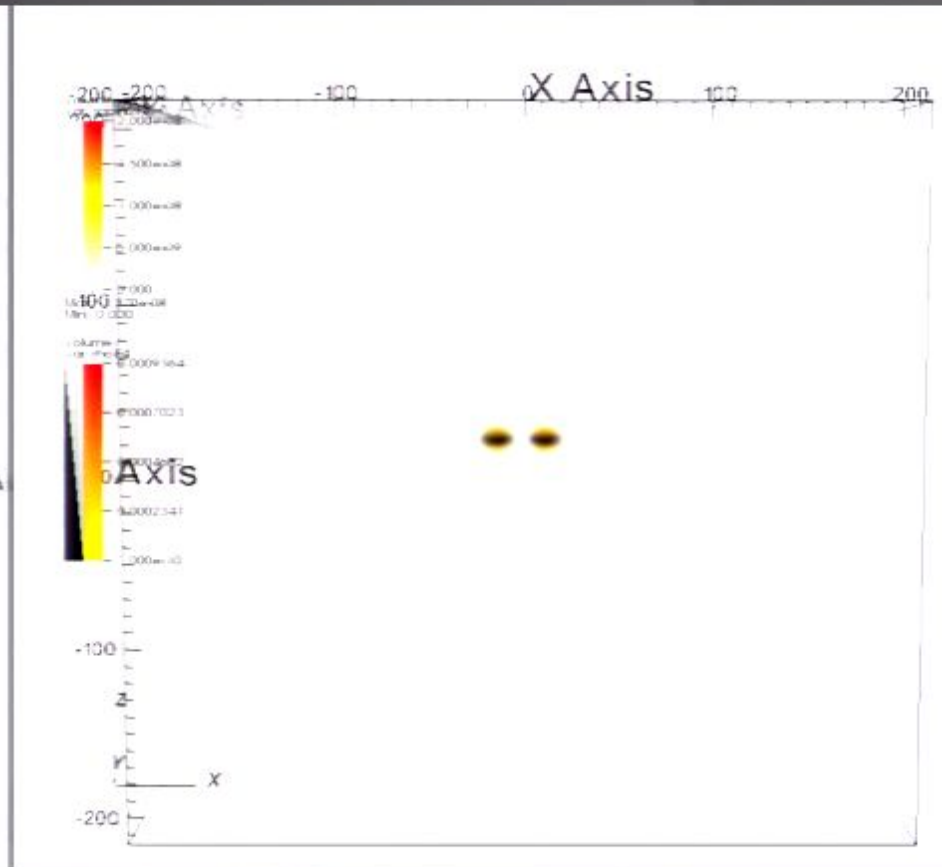
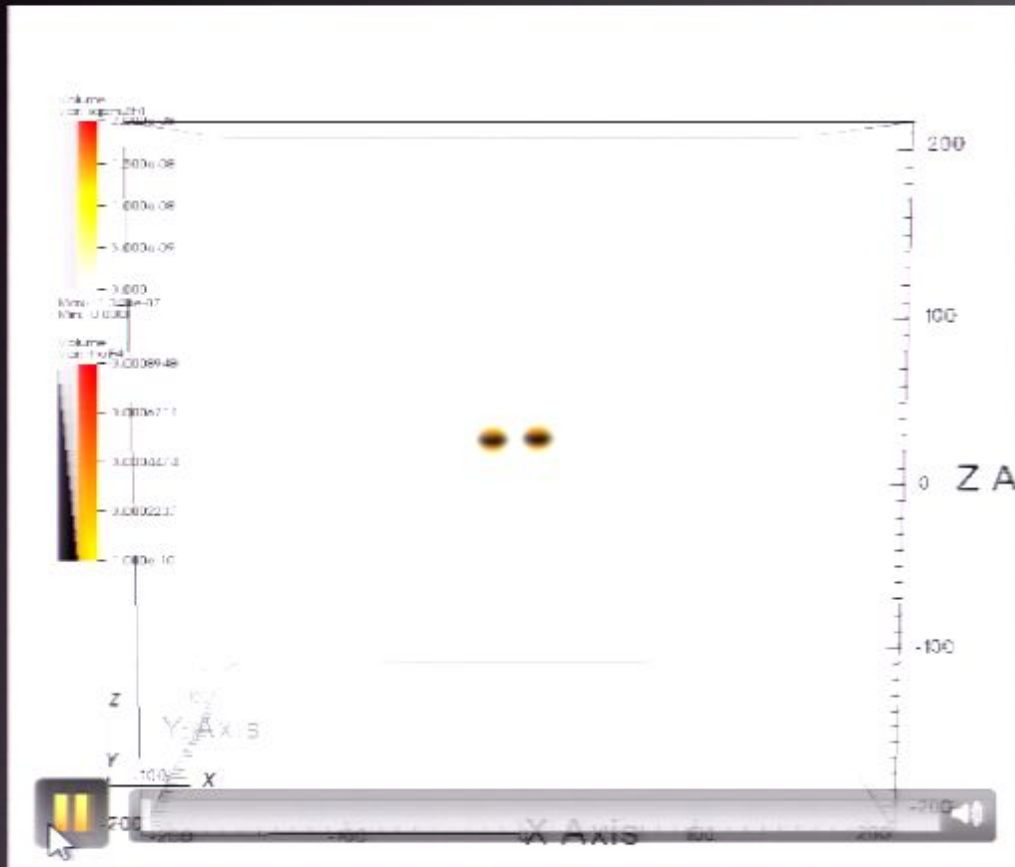
up/down



IV. EM radiation of BNS

up/up

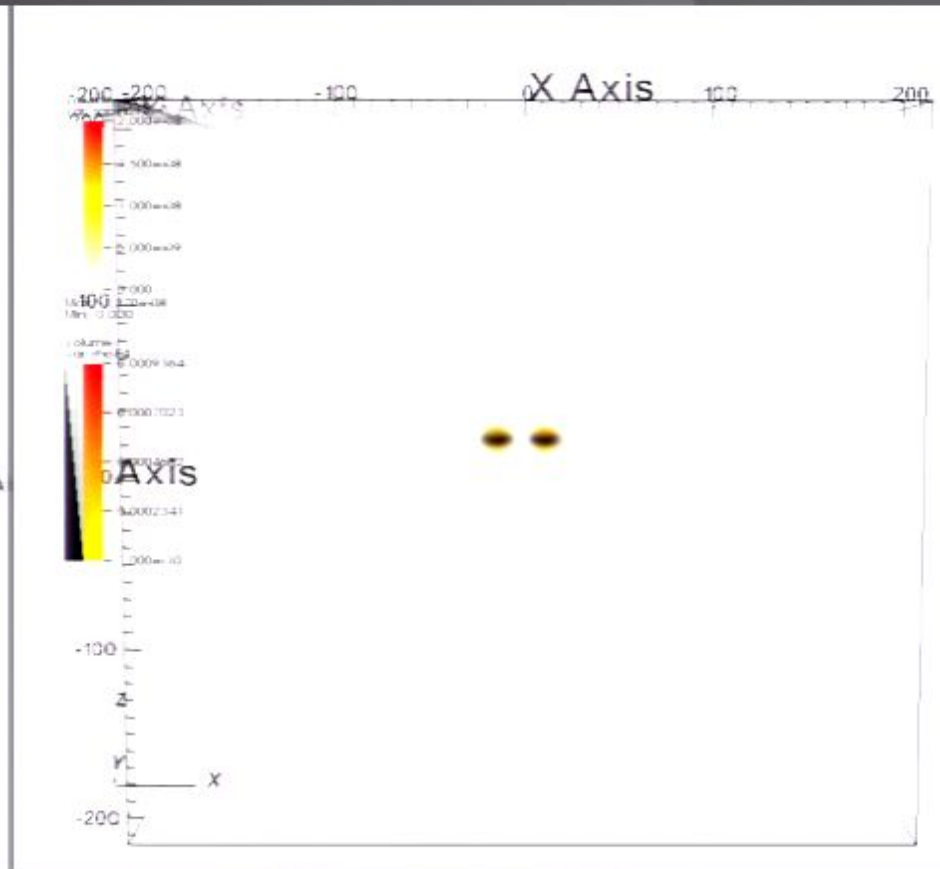
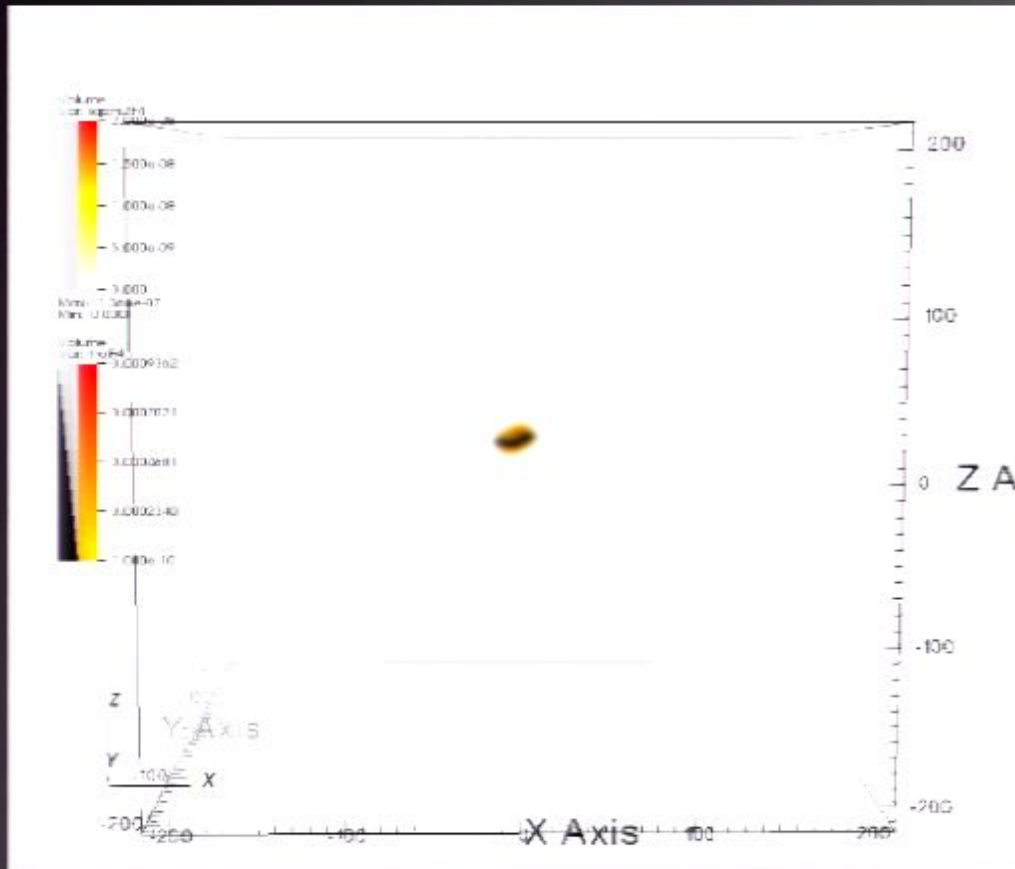
up/down



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up/up

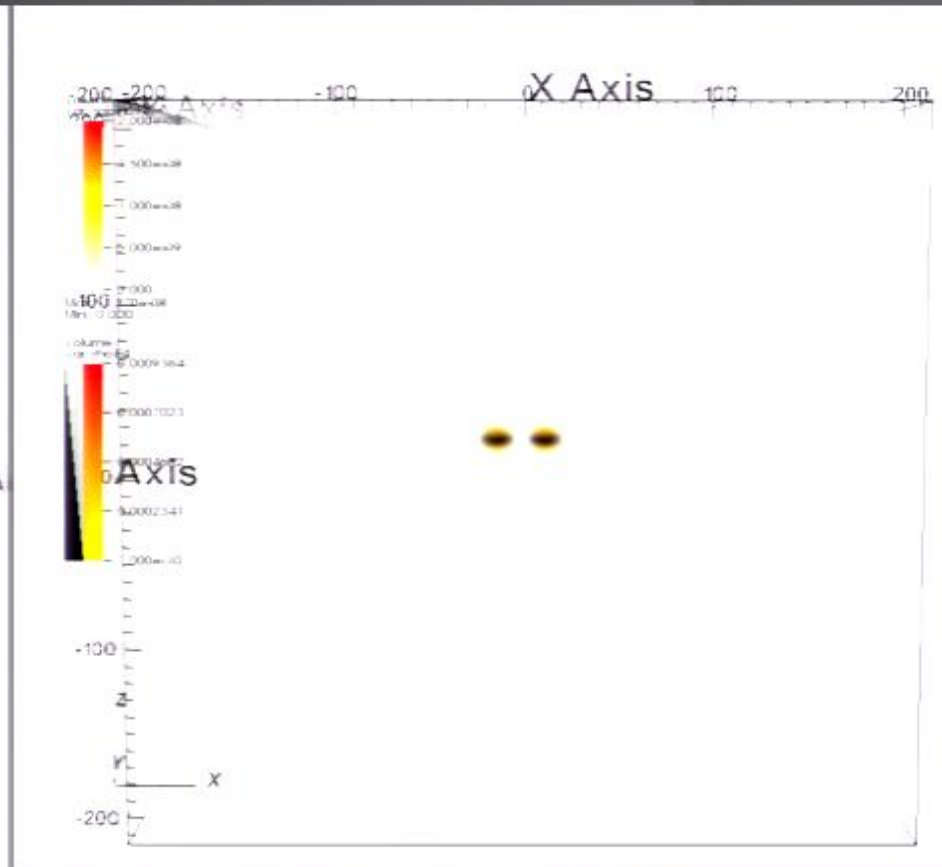
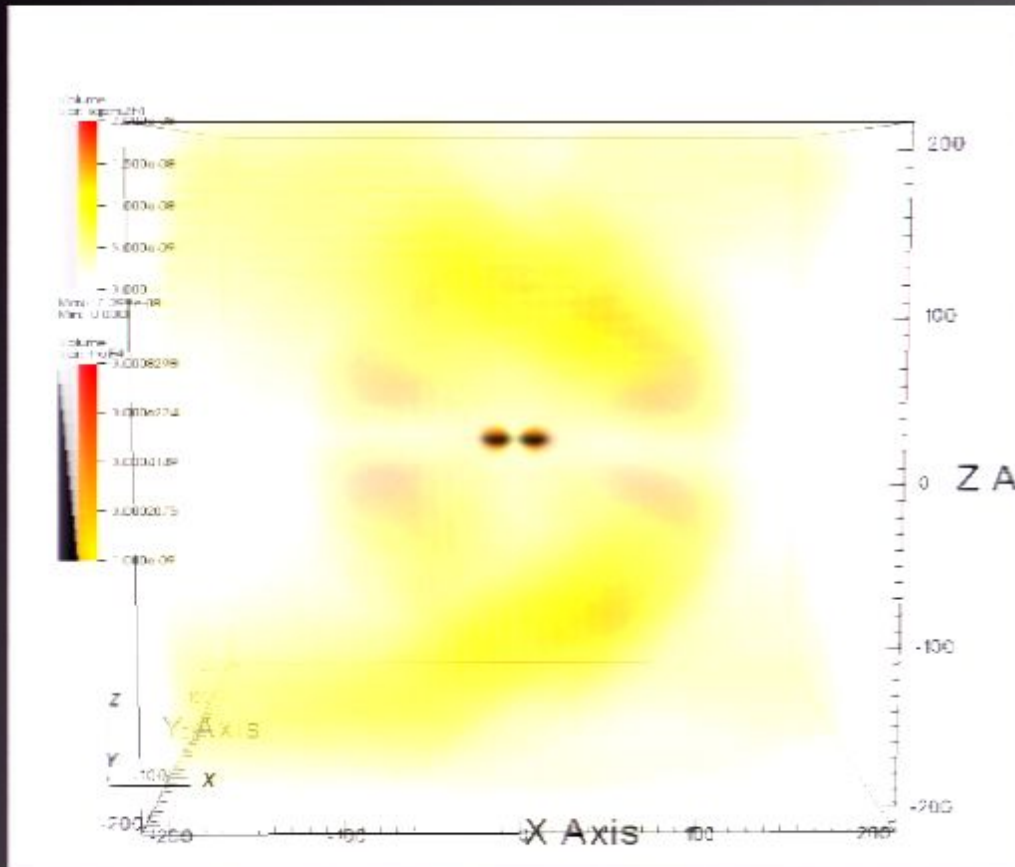
up/down



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up/up

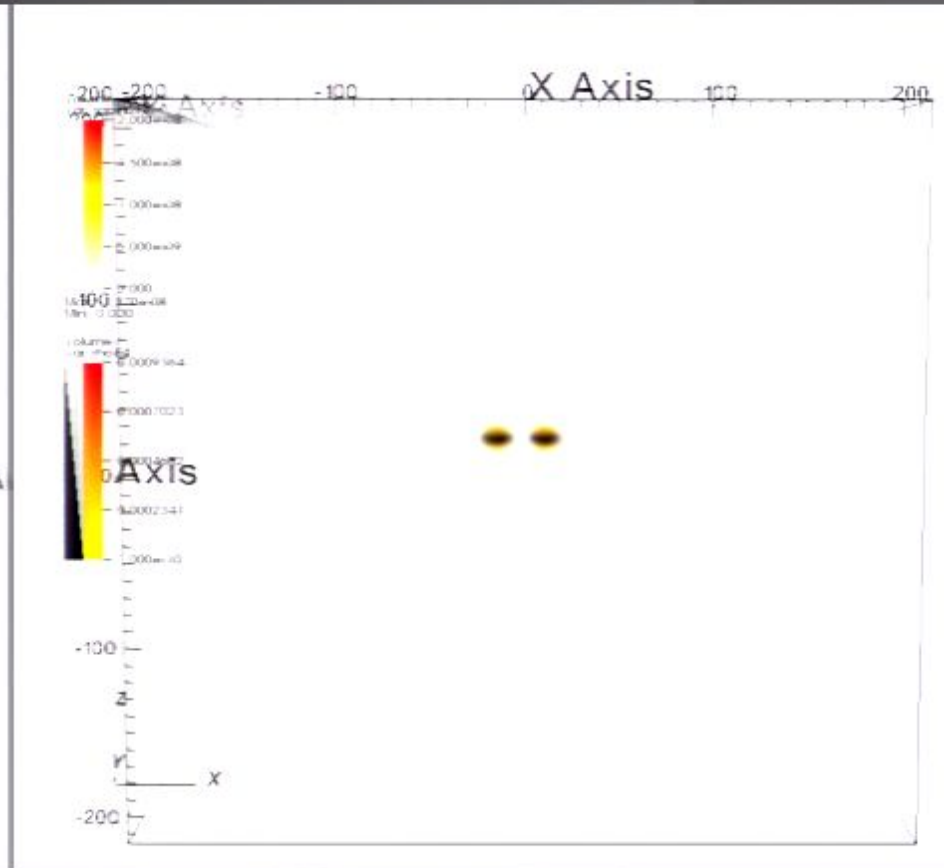
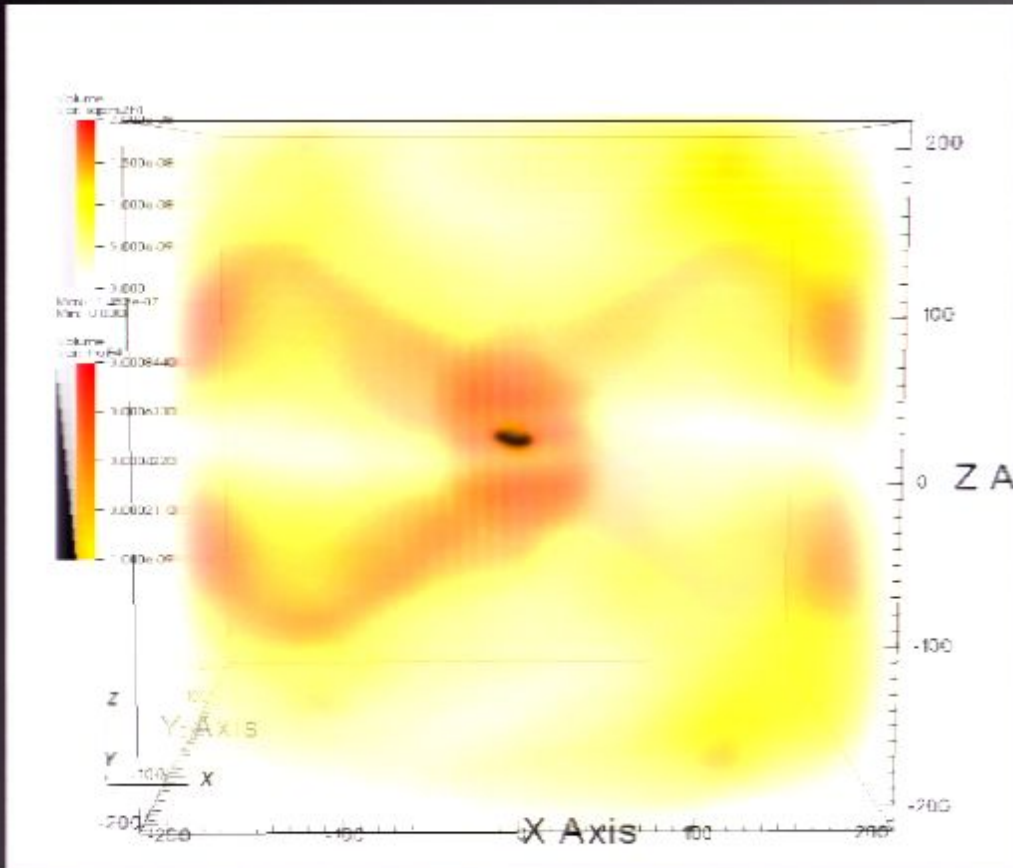
up/down



IV. EM radiation of BNS

up/up

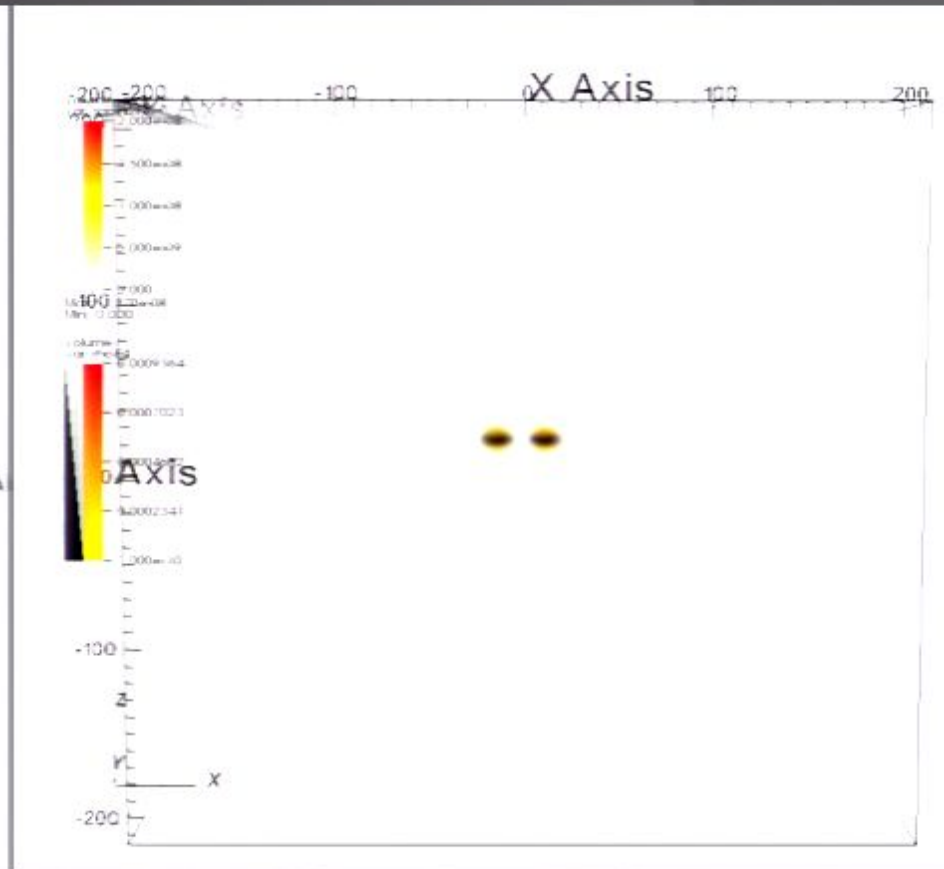
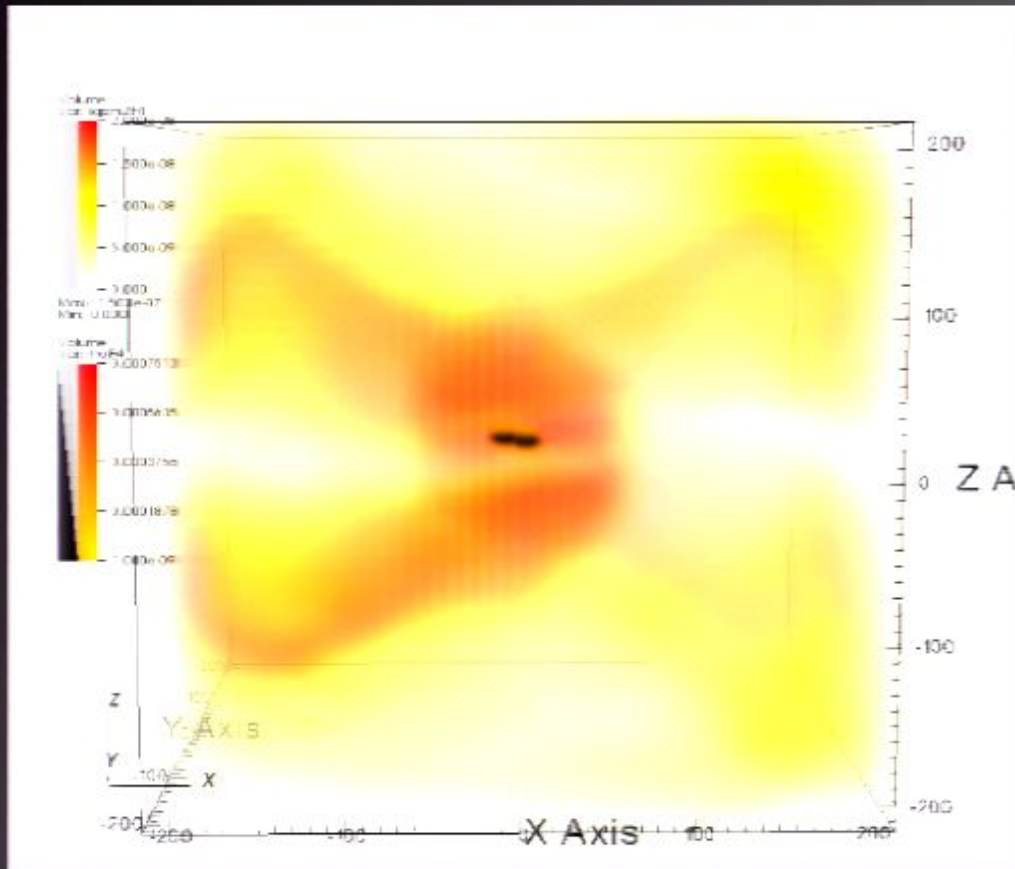
up/down



IV. EM radiation of BNS

up/up

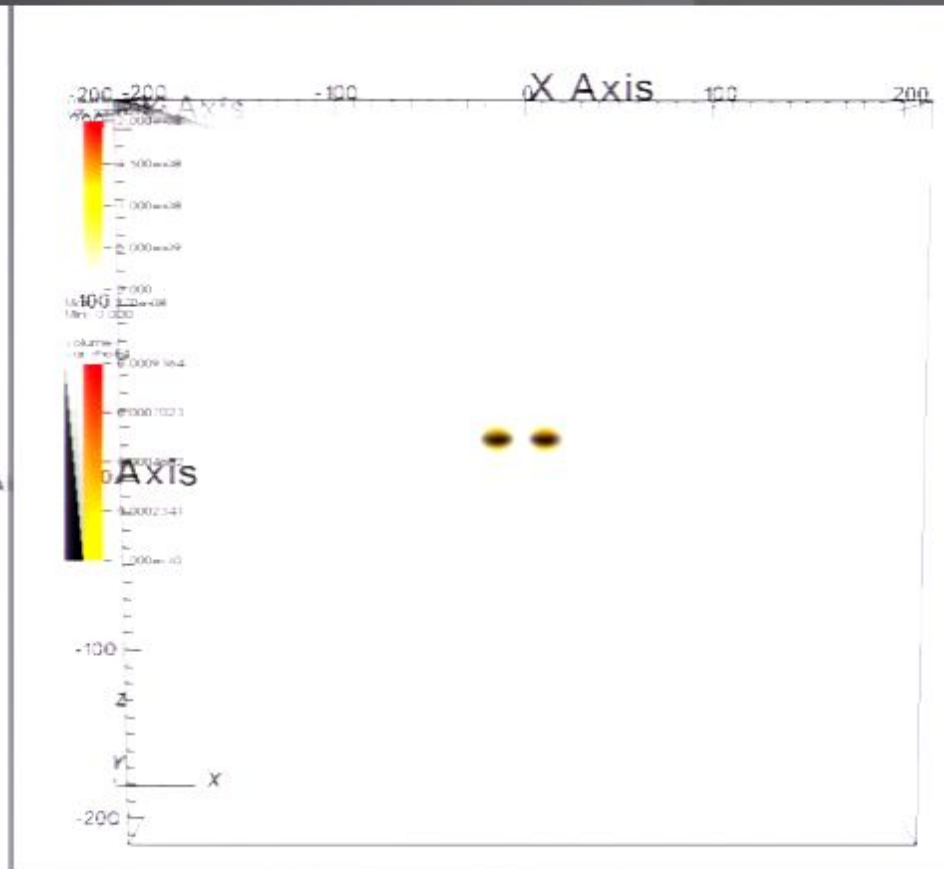
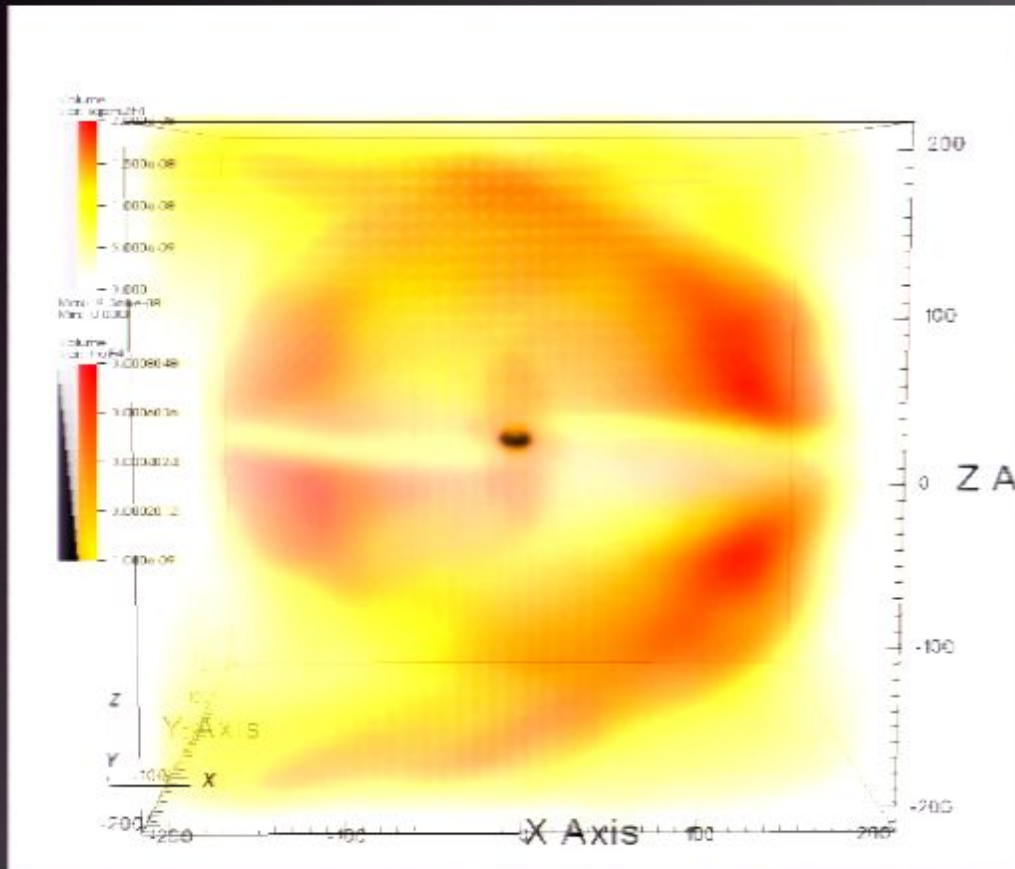
up/down



IV. EM radiation of BNS

up/up

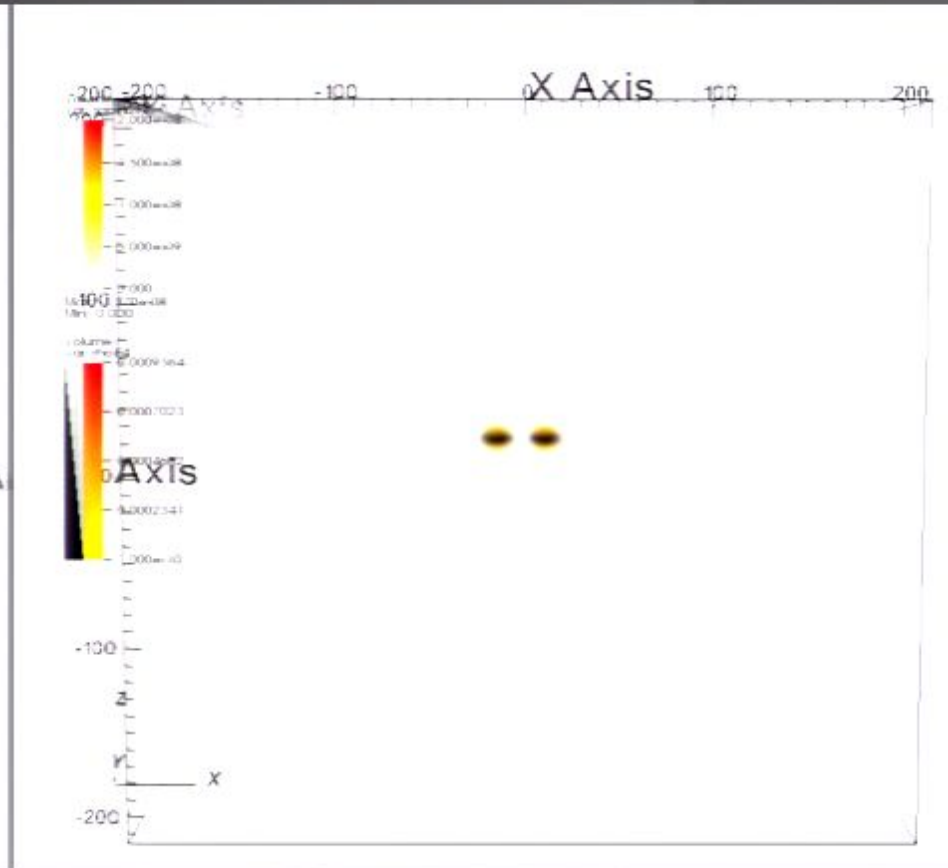
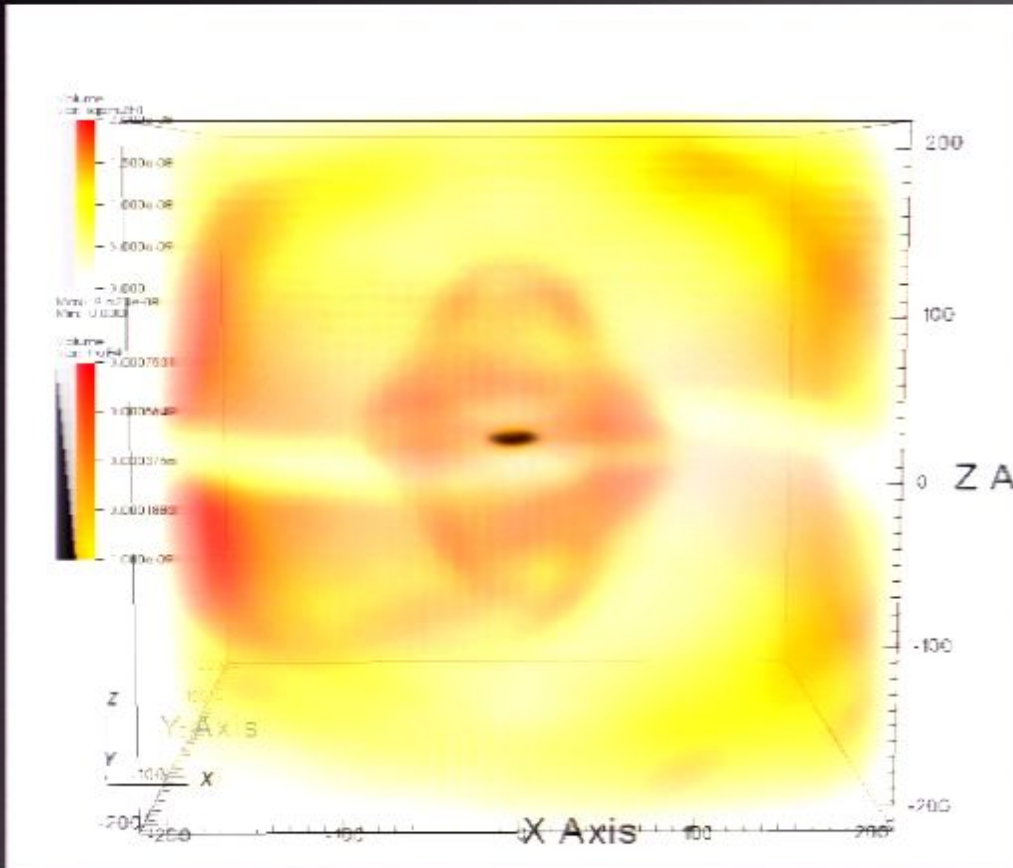
up/down



IV. EM radiation of BNS

up/up

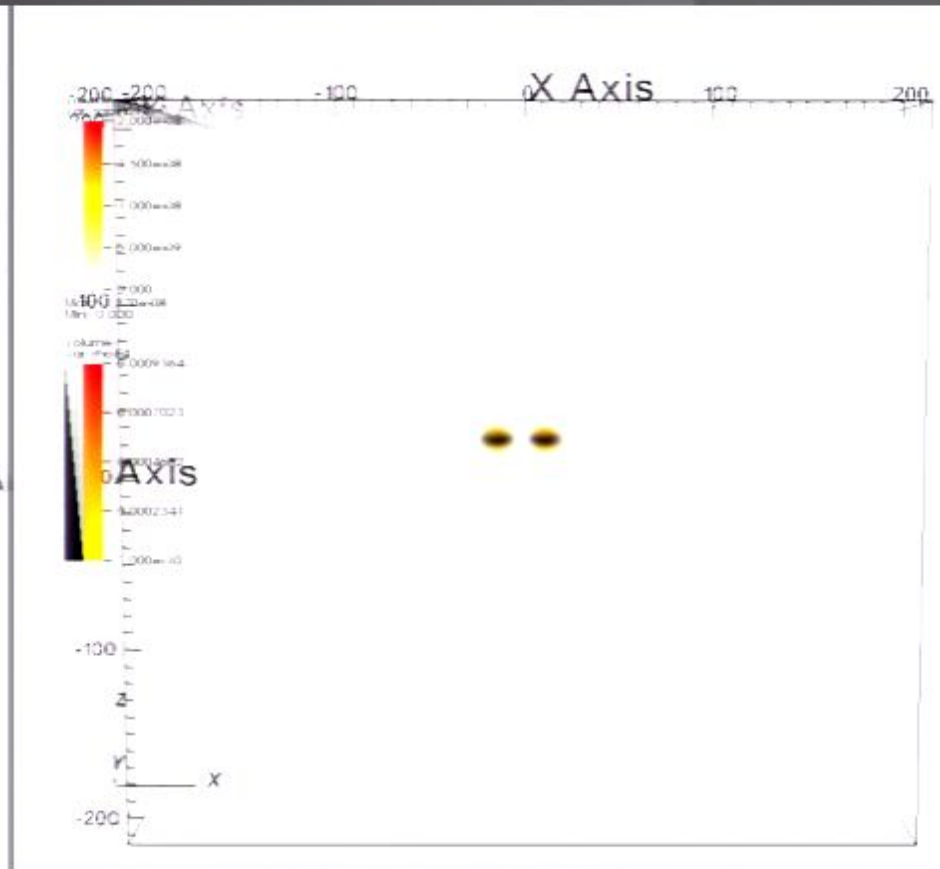
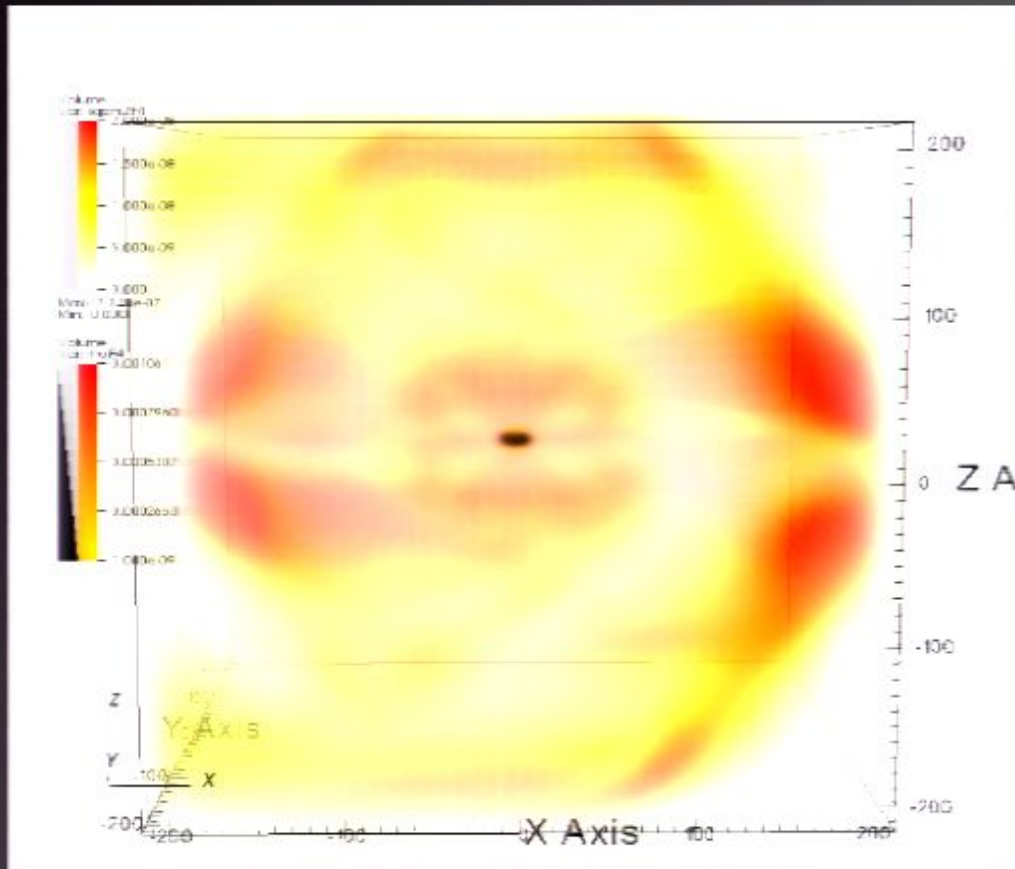
up/down



IV. EM radiation of BNS

up/up

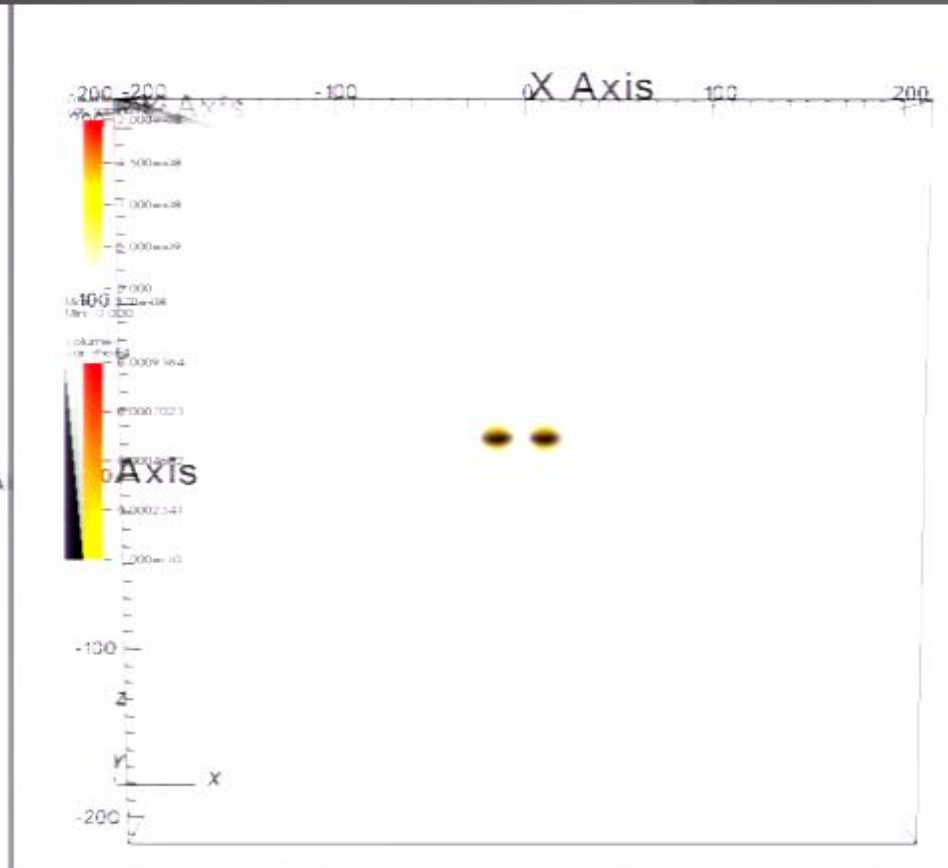
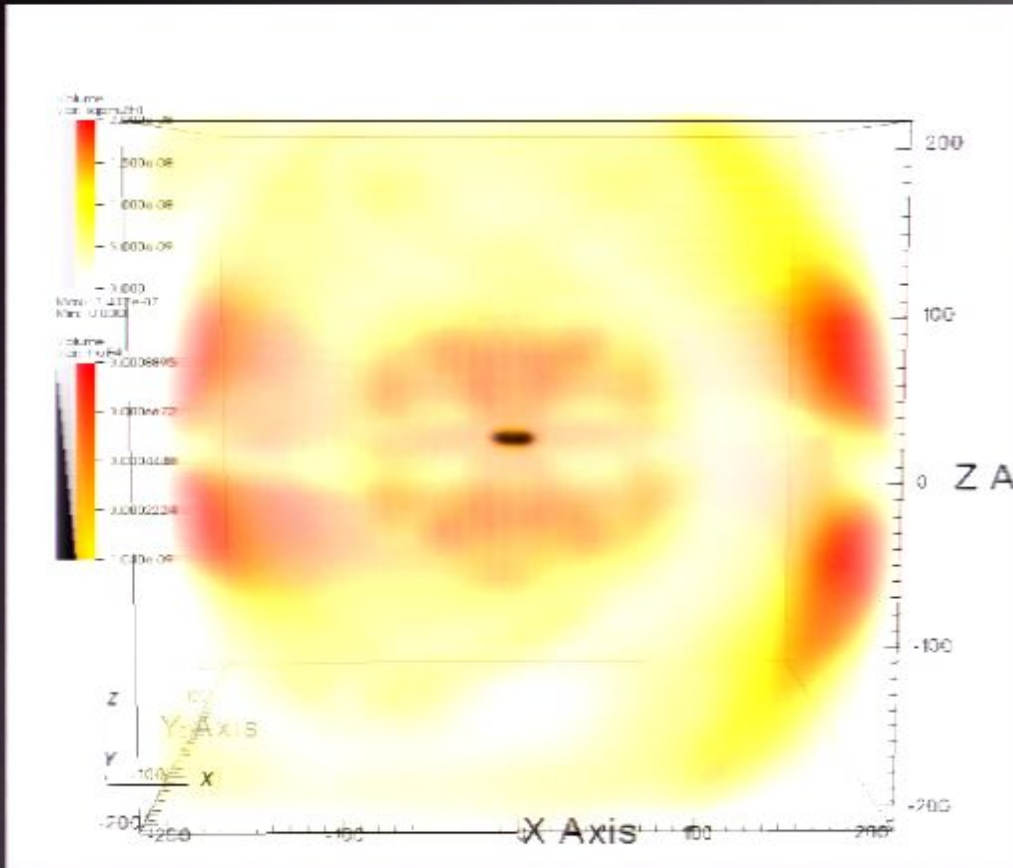
up/down



IV. EM radiation of BNS

up/up

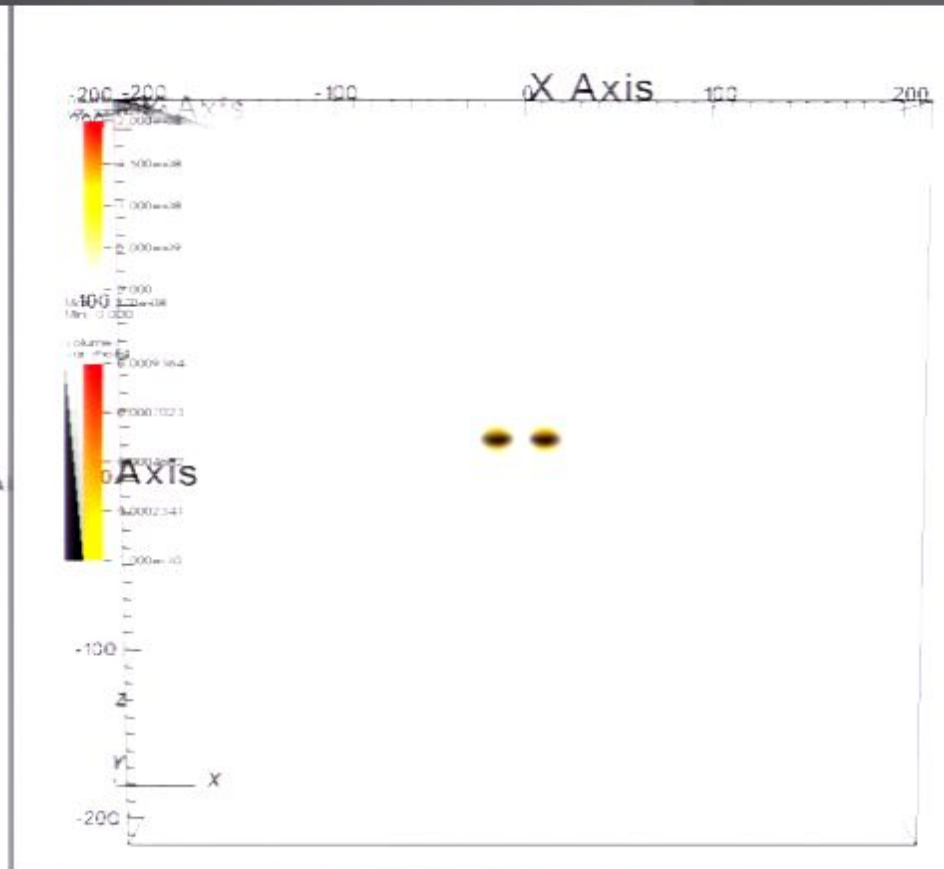
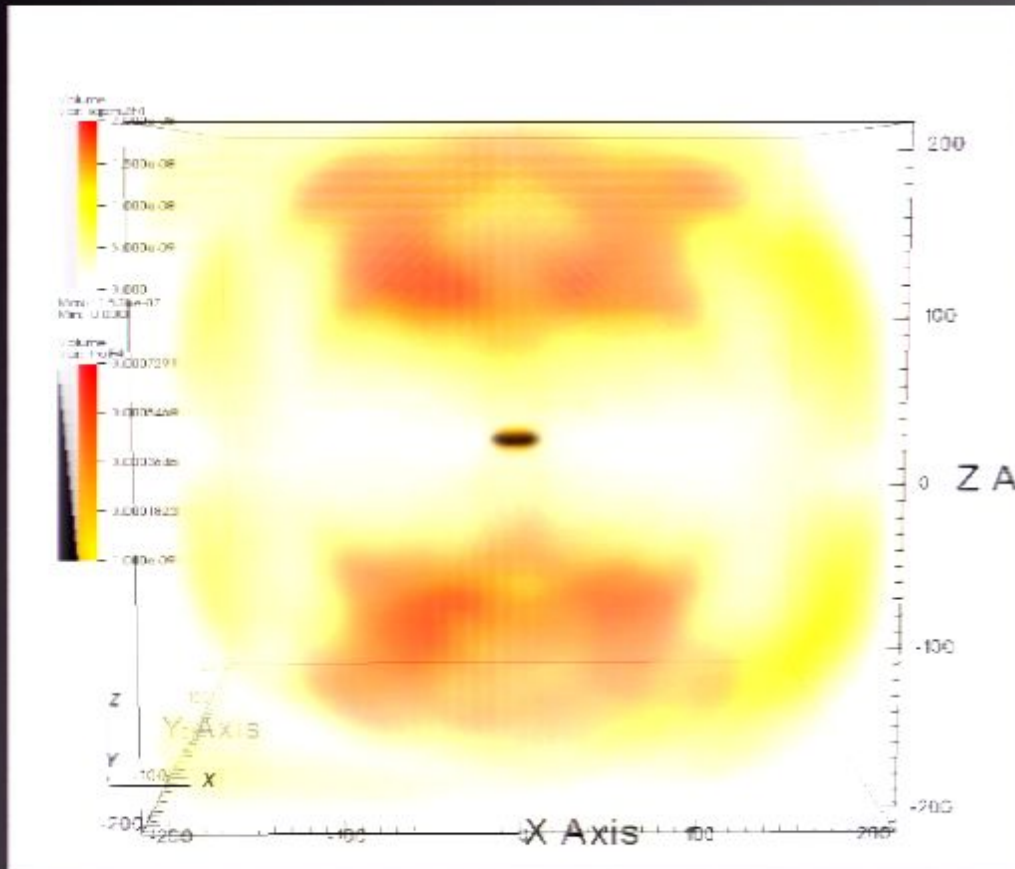
up/down



IV. EM radiation of BNS

up/up

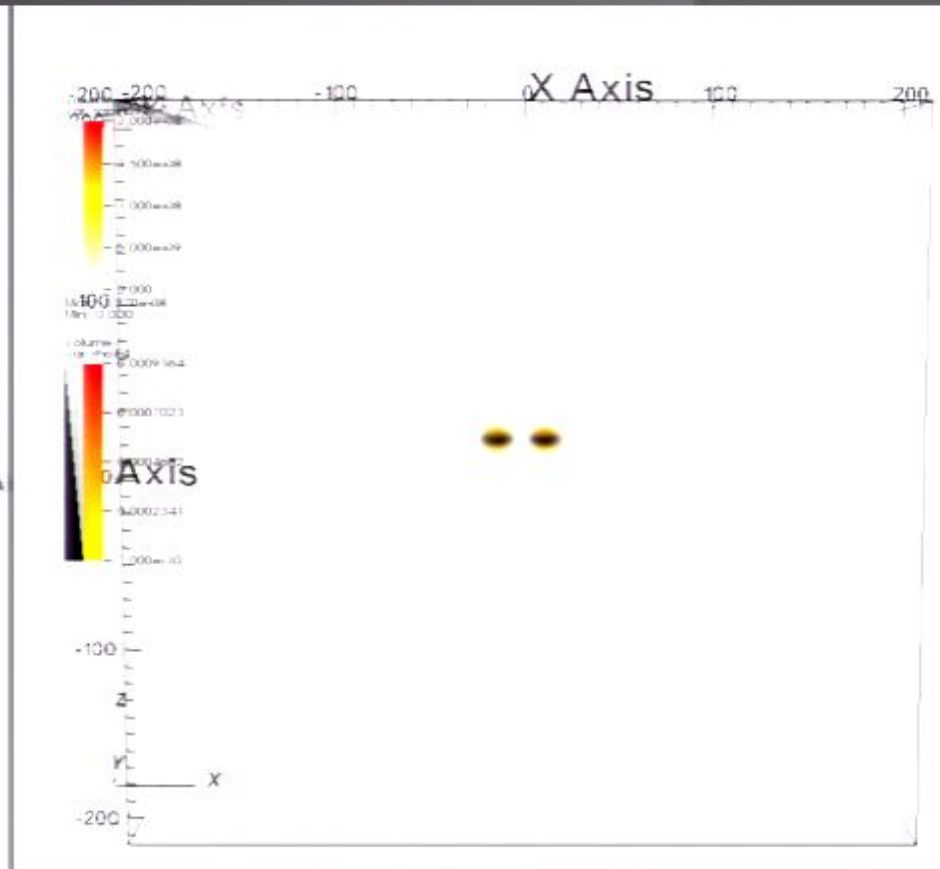
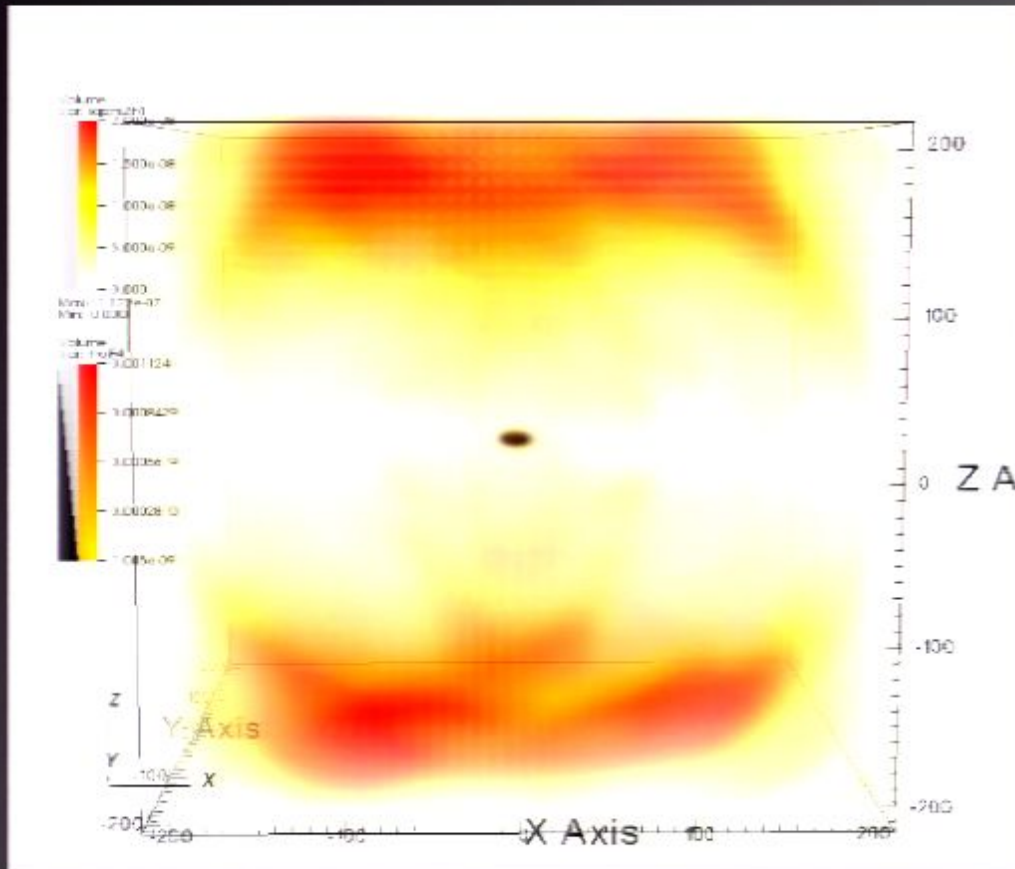
up/down



IV. EM radiation of BNS

up/up

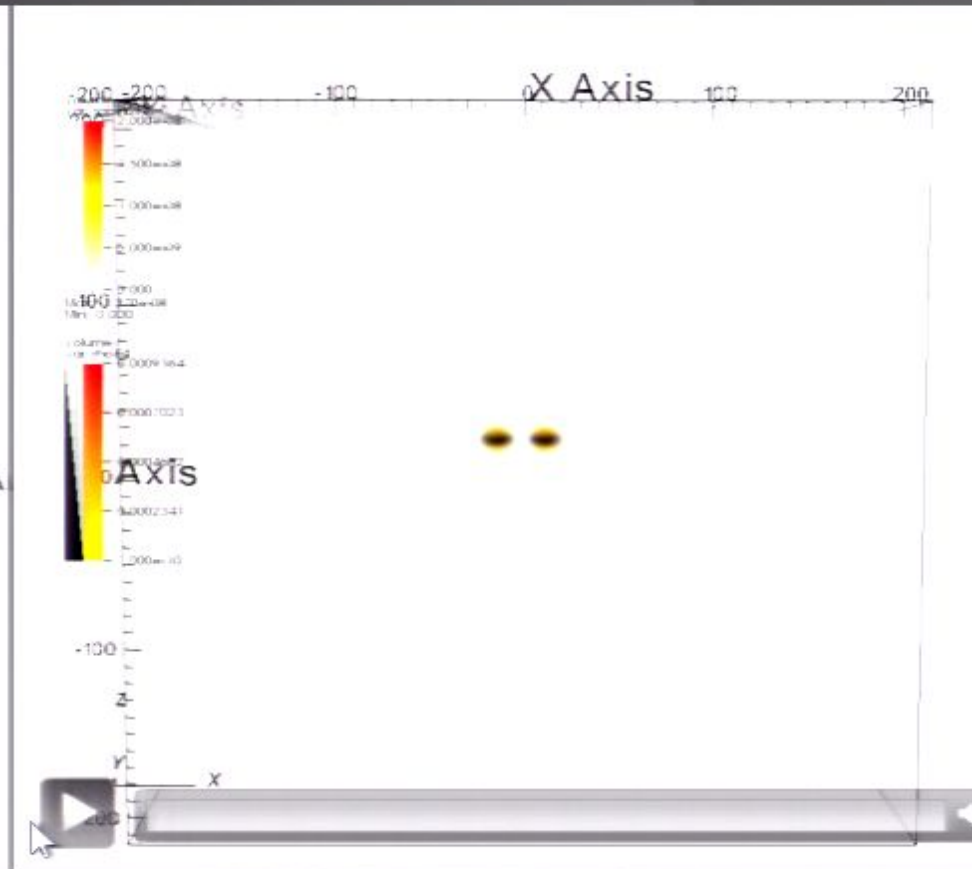
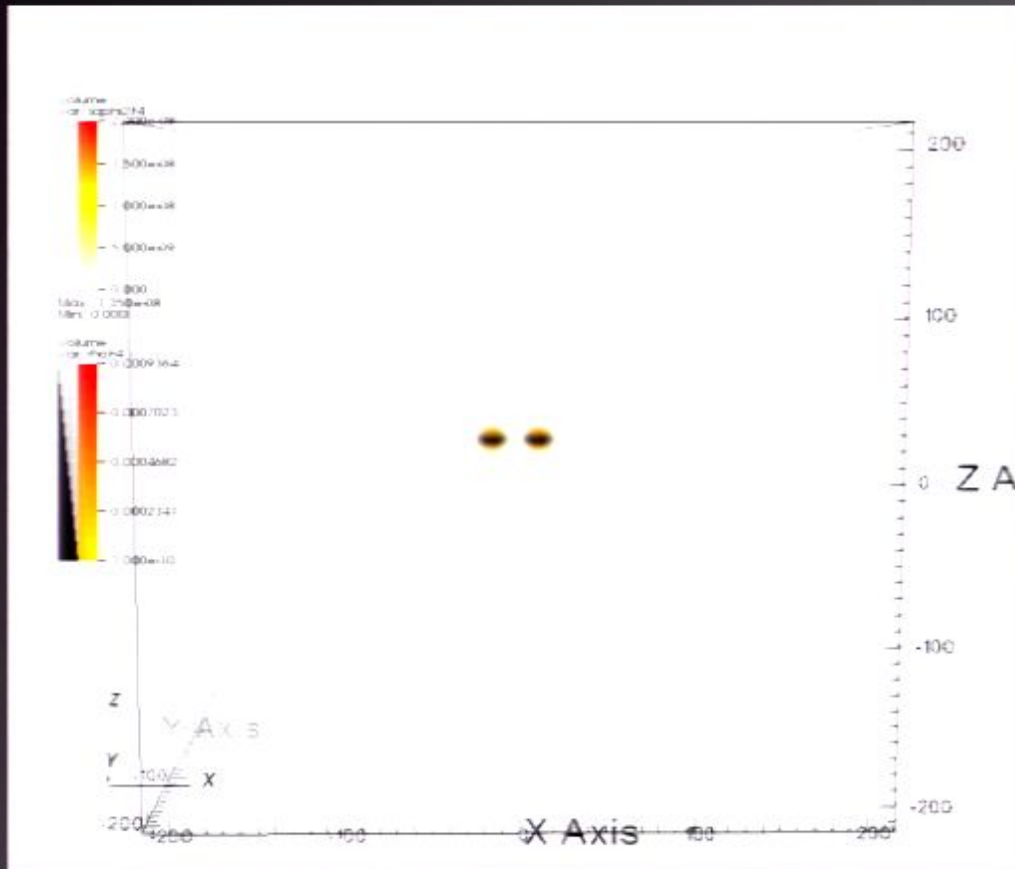
up/down



IV. EM radiation of BNS

up/up

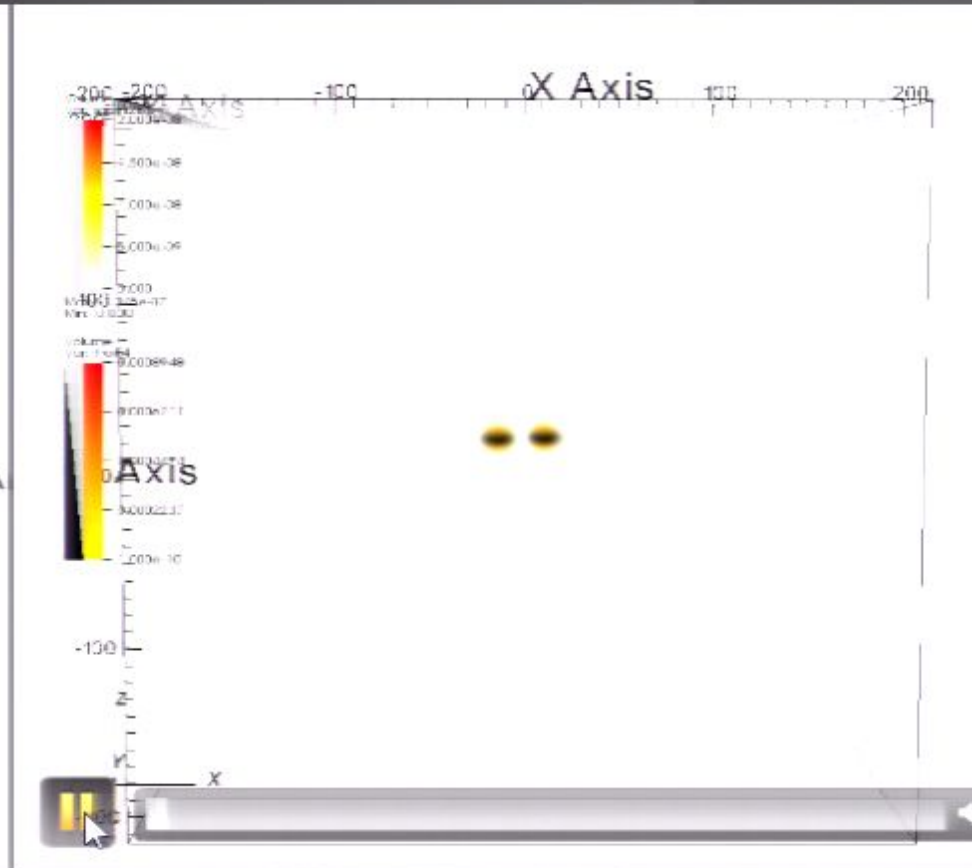
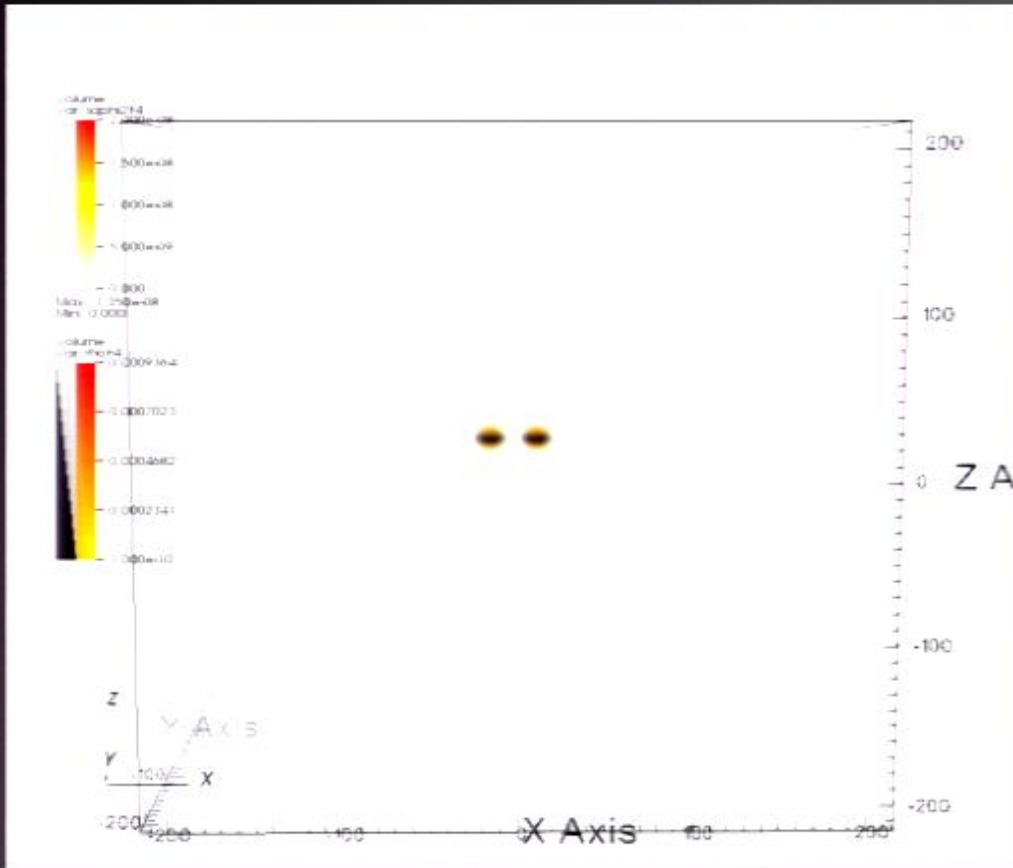
up/down



IV. EM radiation of BNS

up/up

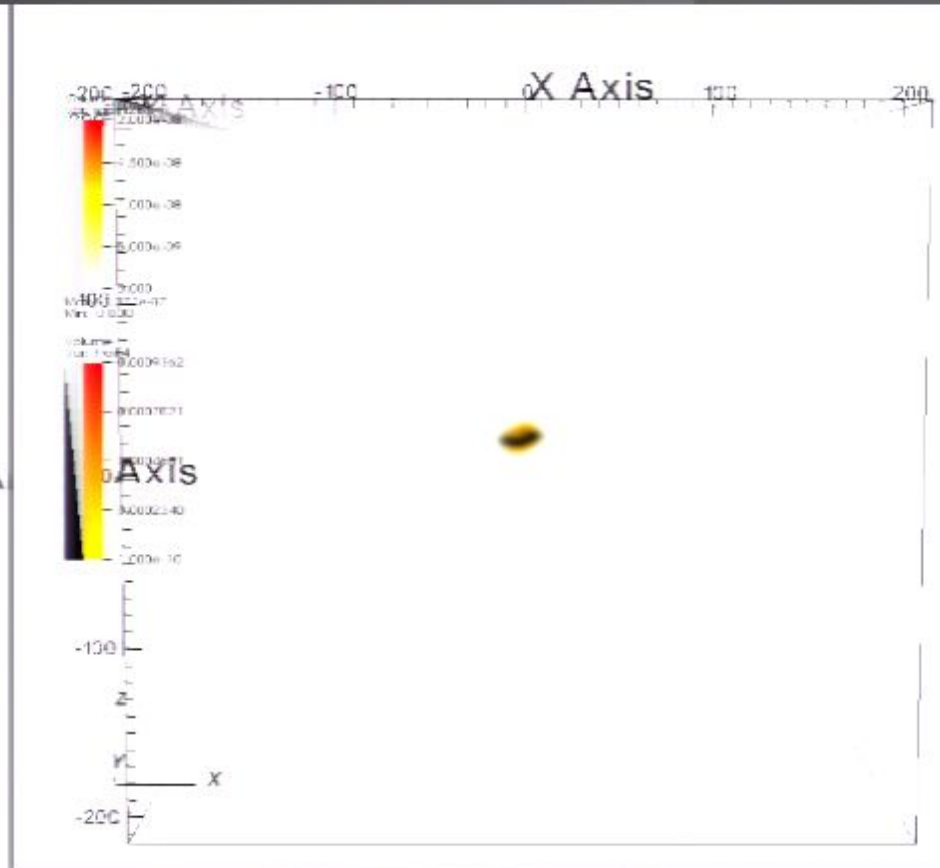
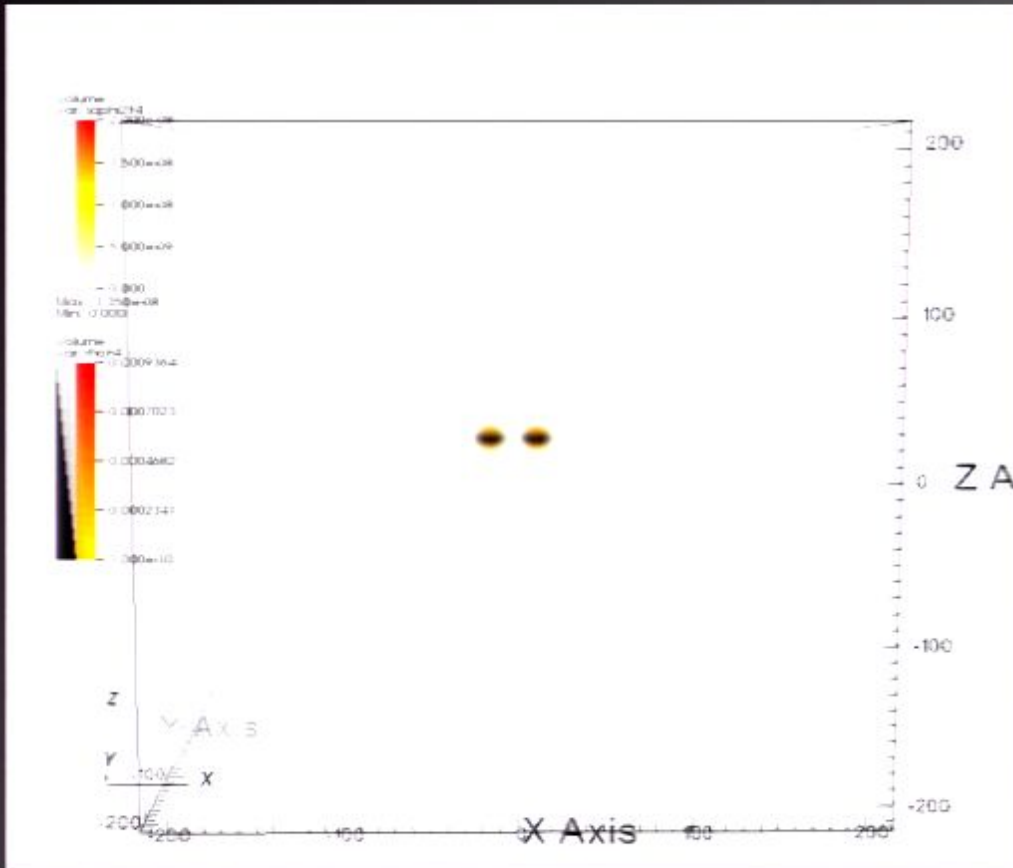
up/down



IV. EM radiation of BNS

up/up

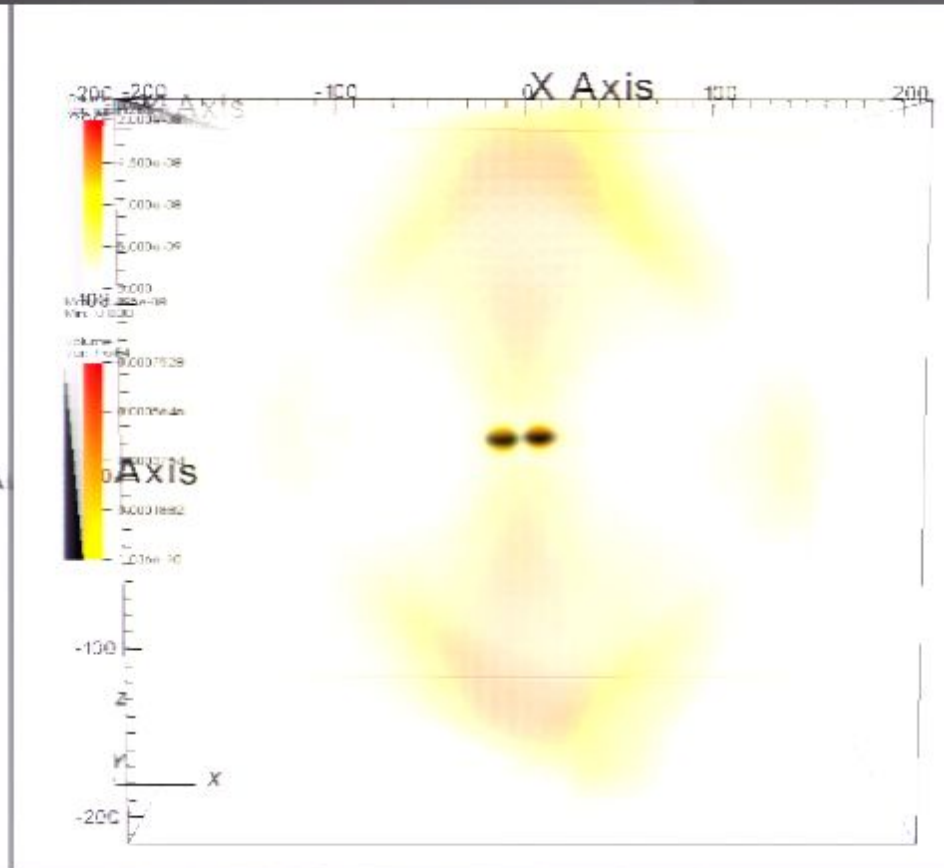
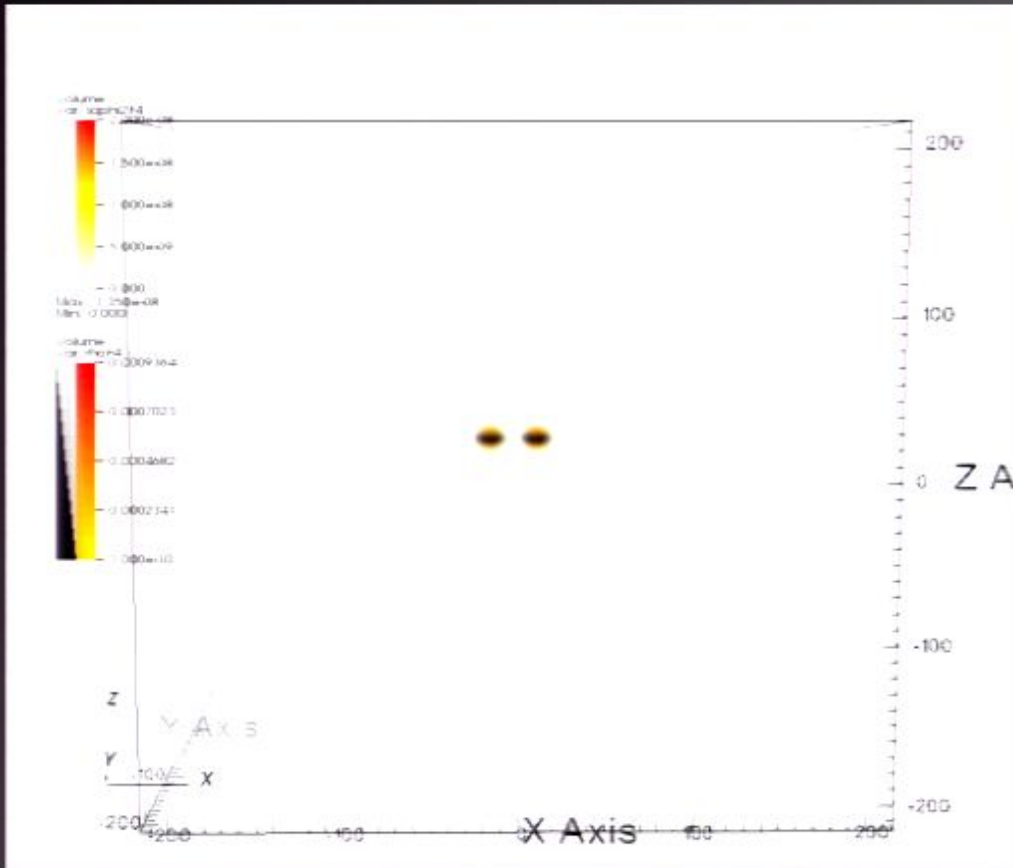
up/down



IV. EM radiation of BNS

up/up

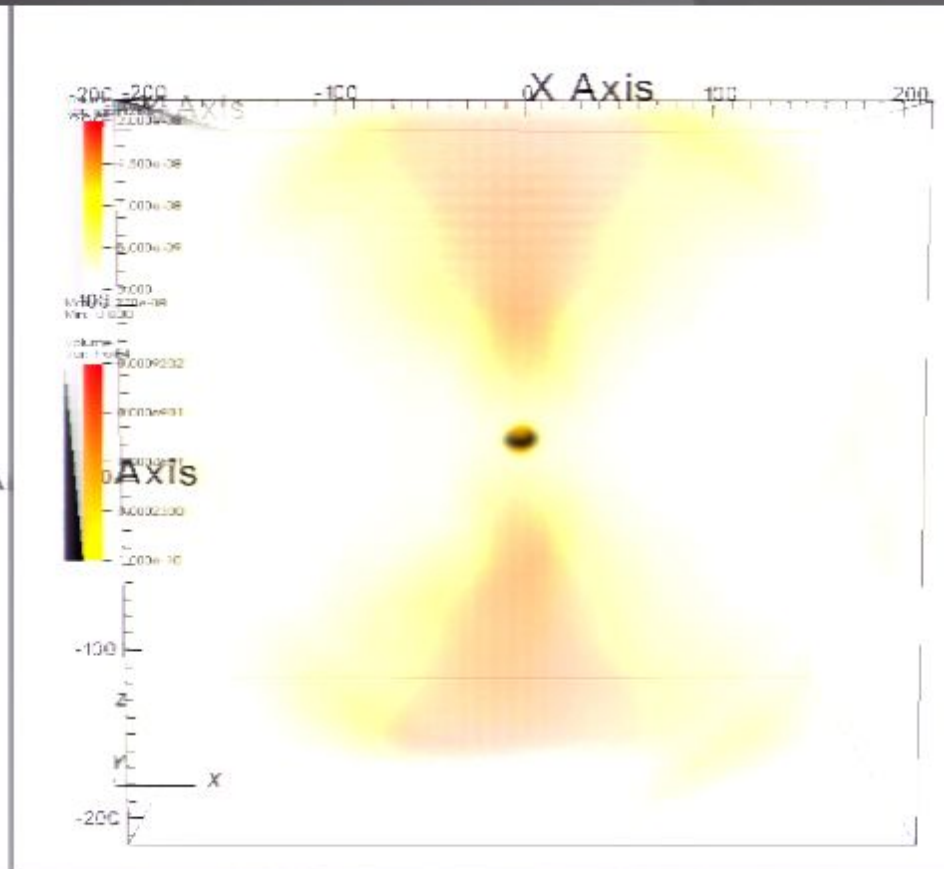
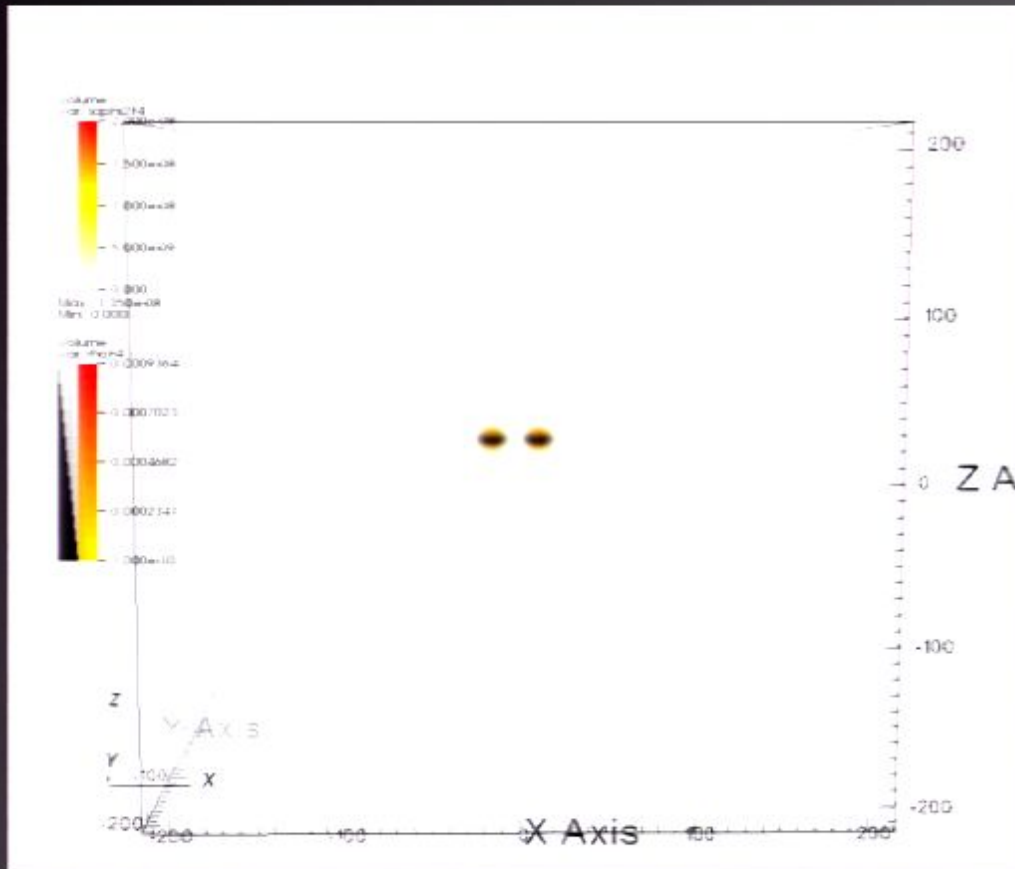
up/down



IV. EM radiation of BNS

up/up

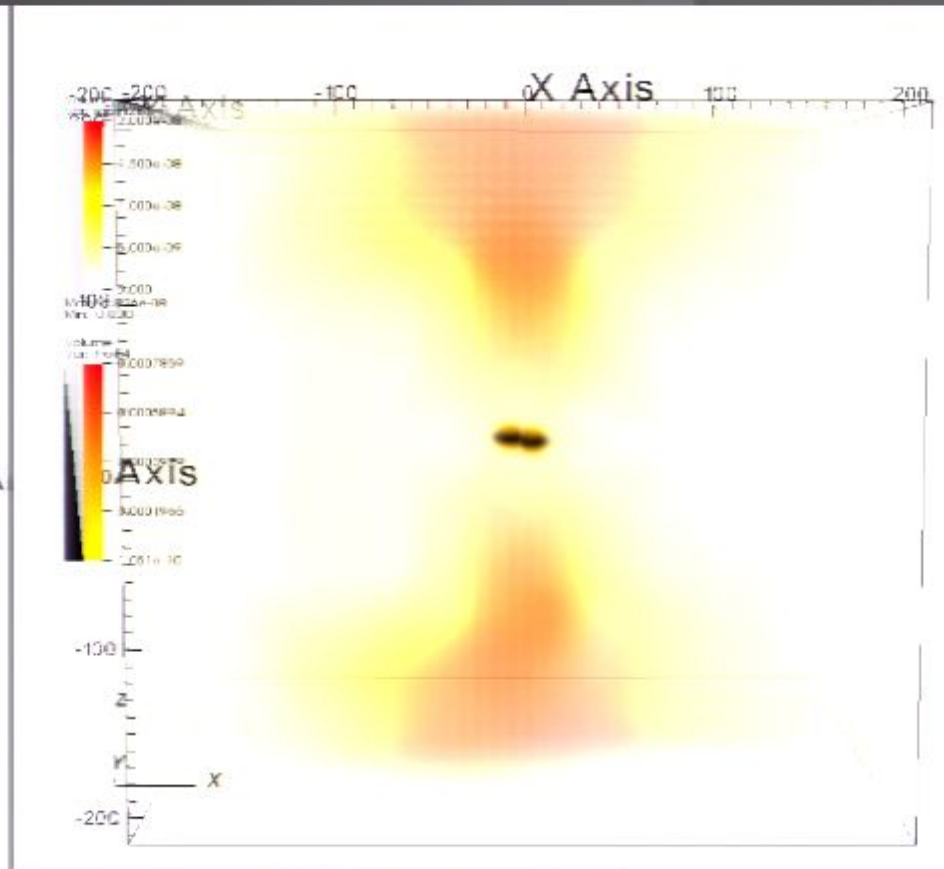
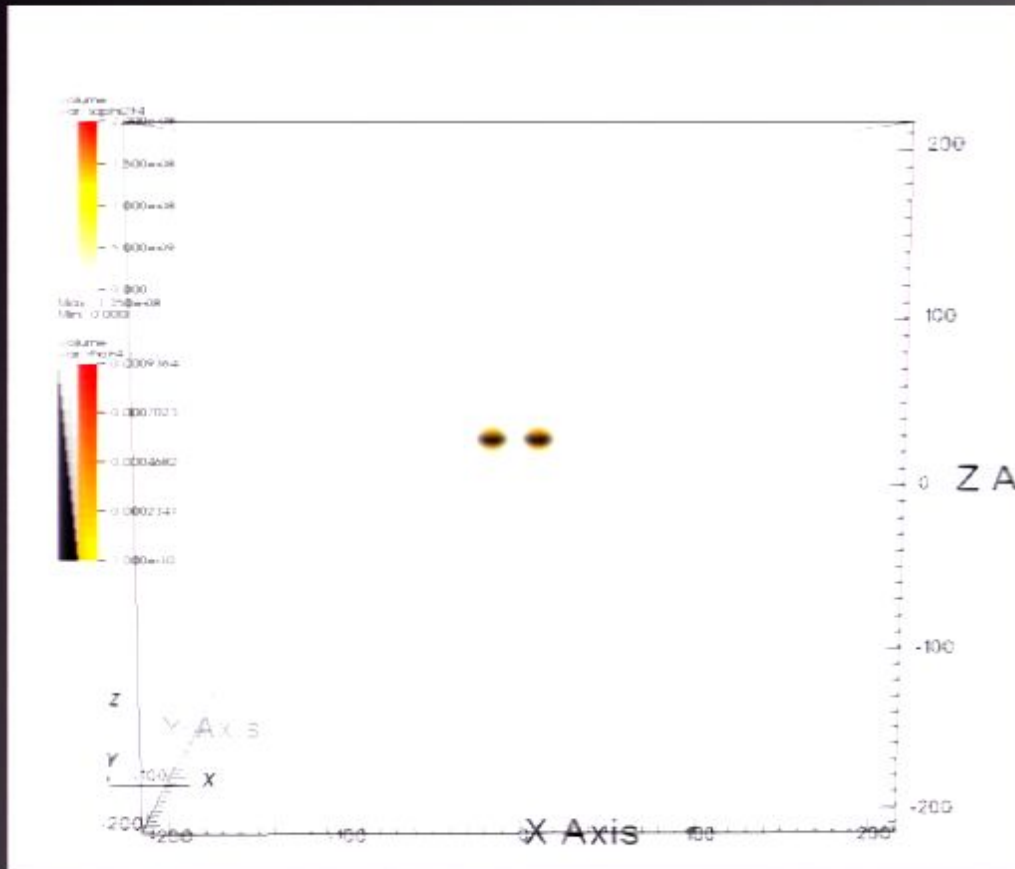
up/down



IV. EM radiation of BNS

up/up

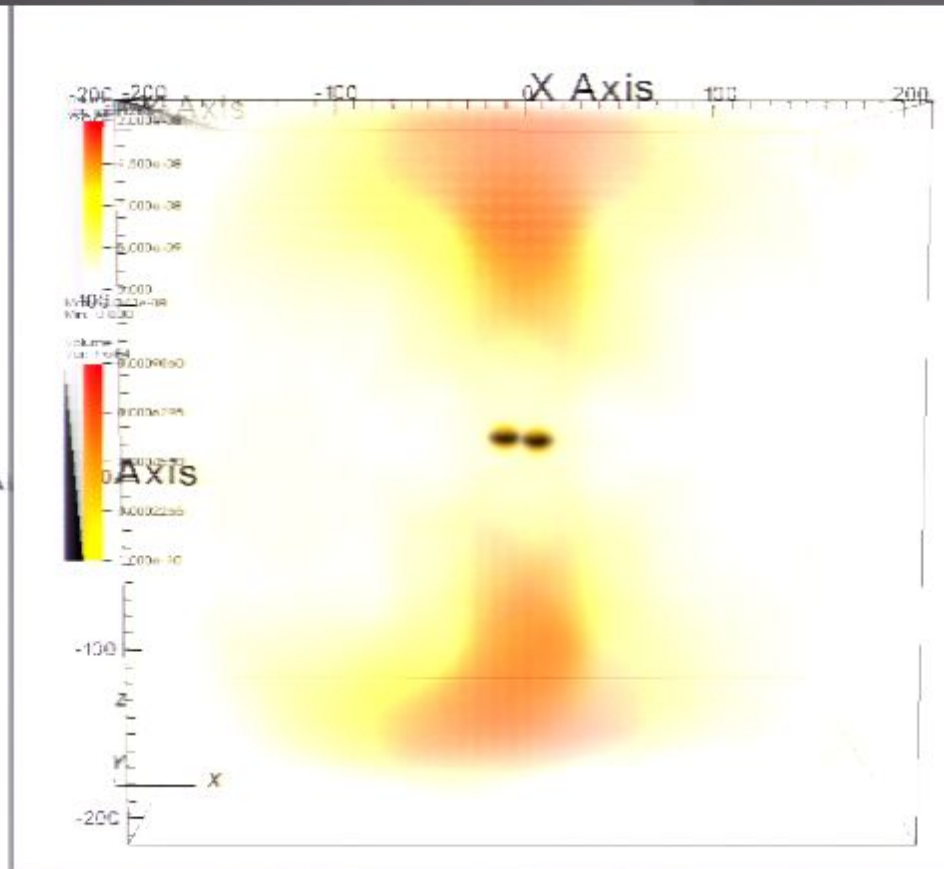
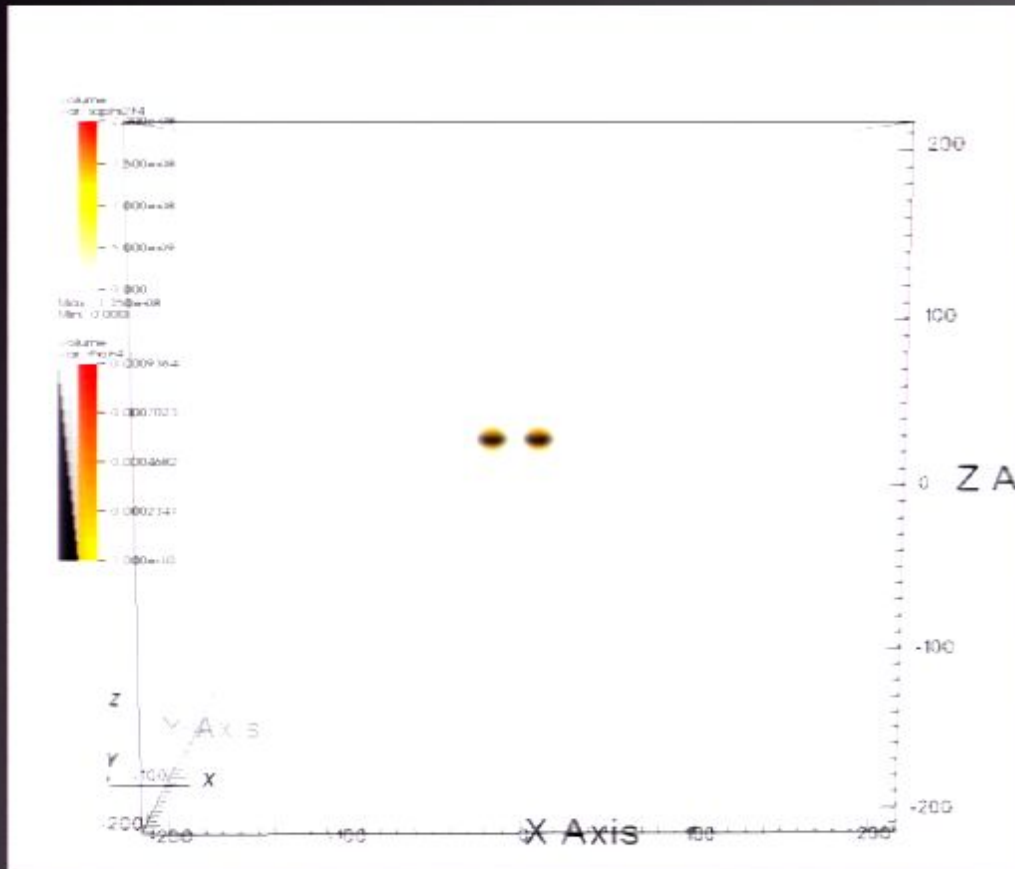
up/down



IV. EM radiation of BNS

up/up

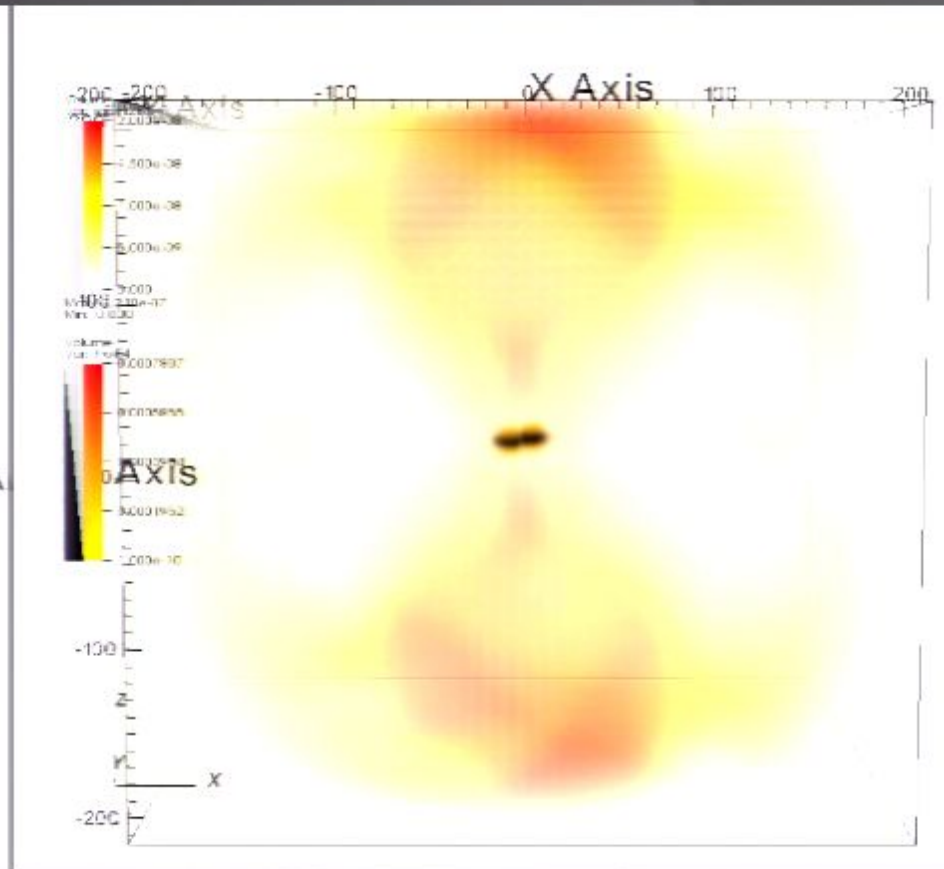
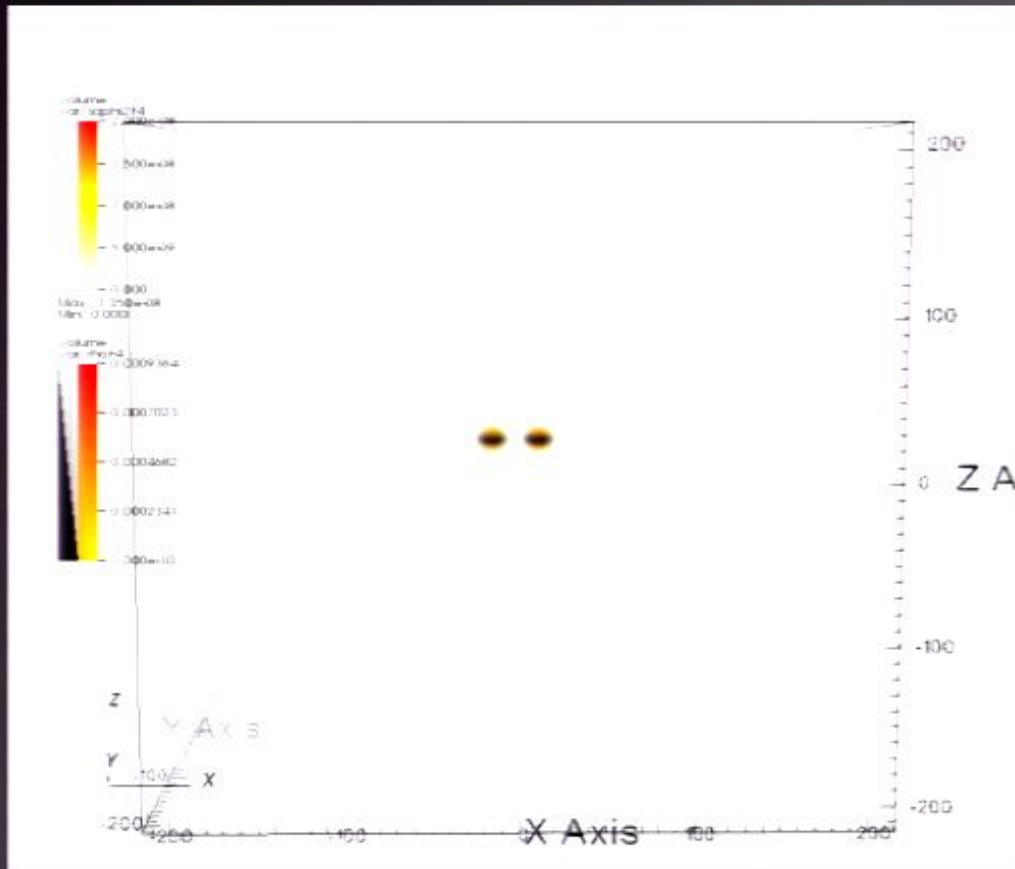
up/down



IV. EM radiation of BNS

up/up

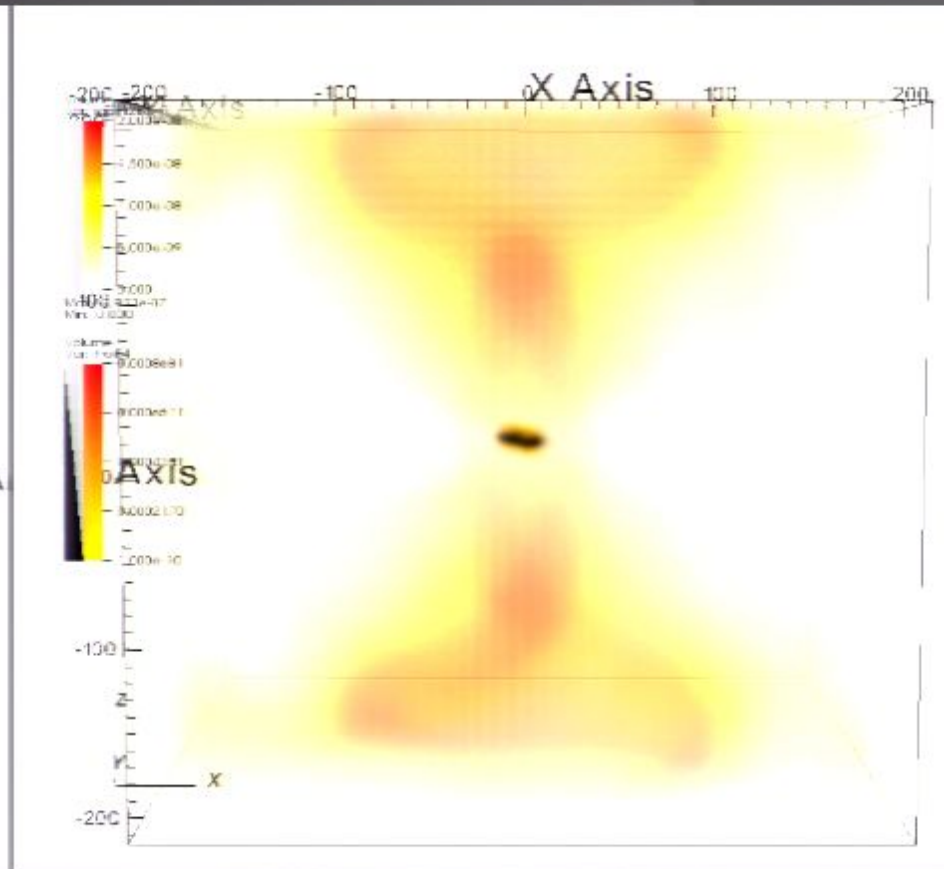
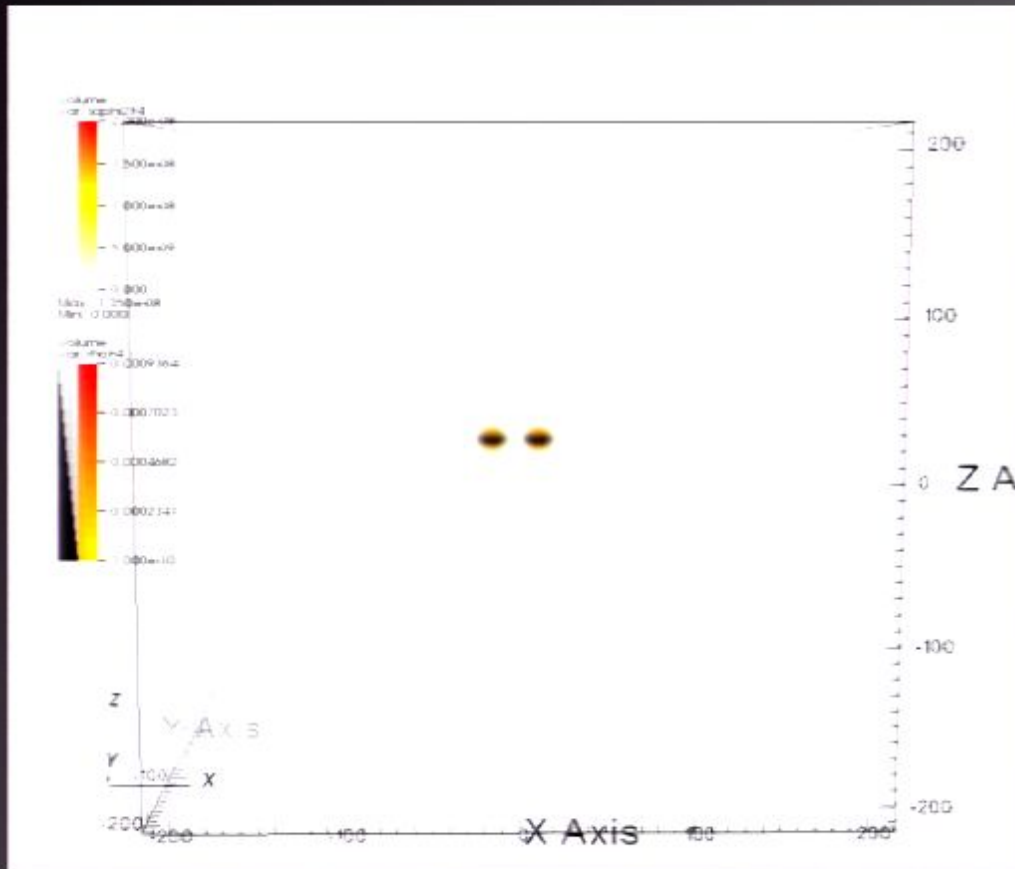
up/down



IV. EM radiation of BNS

up/up

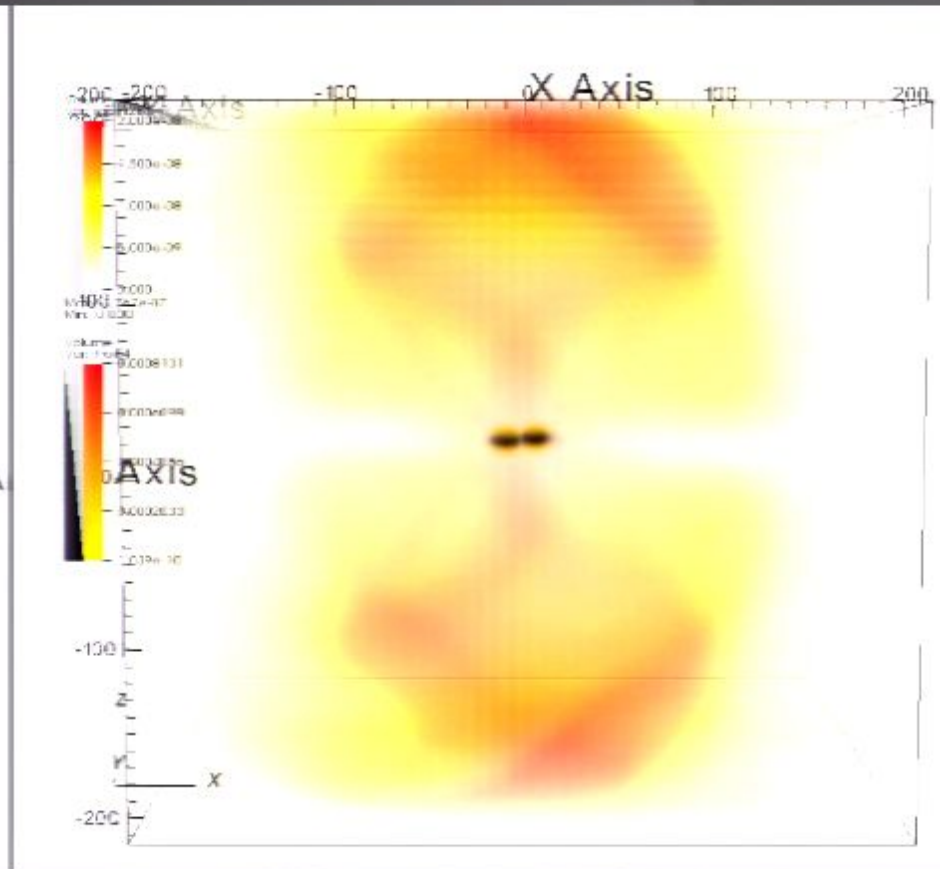
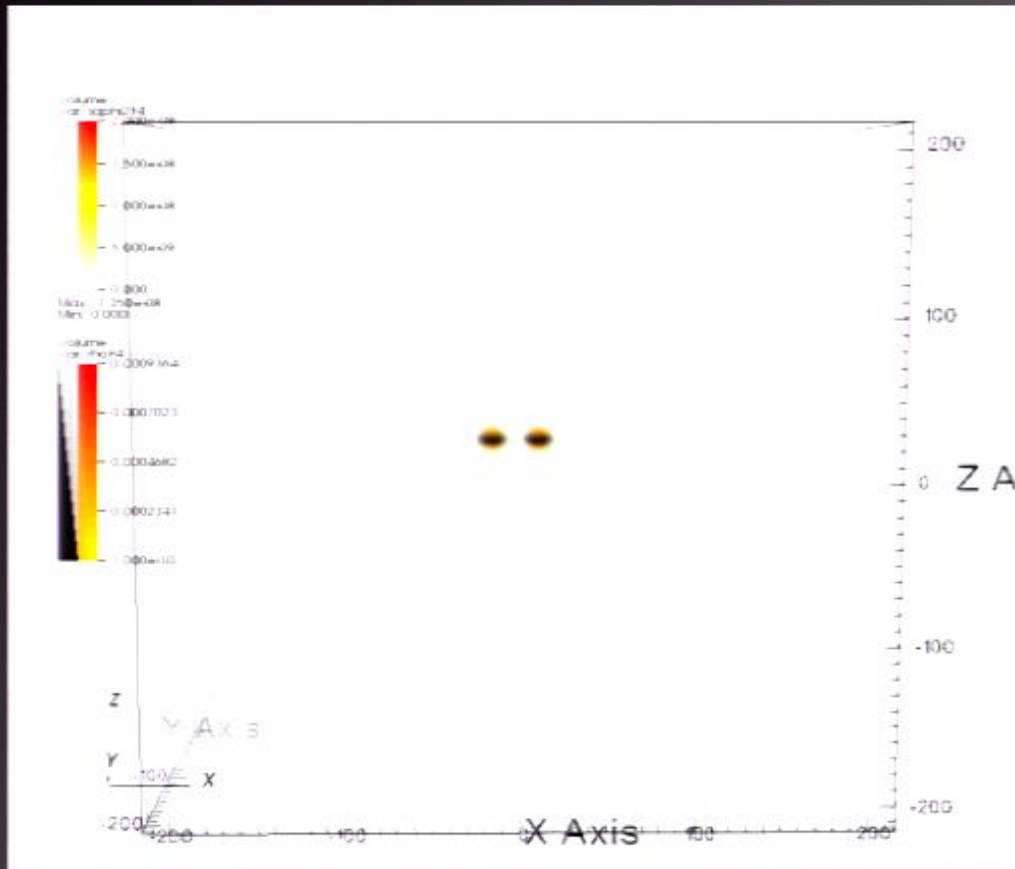
up/down



IV. EM radiation of BNS

up/up

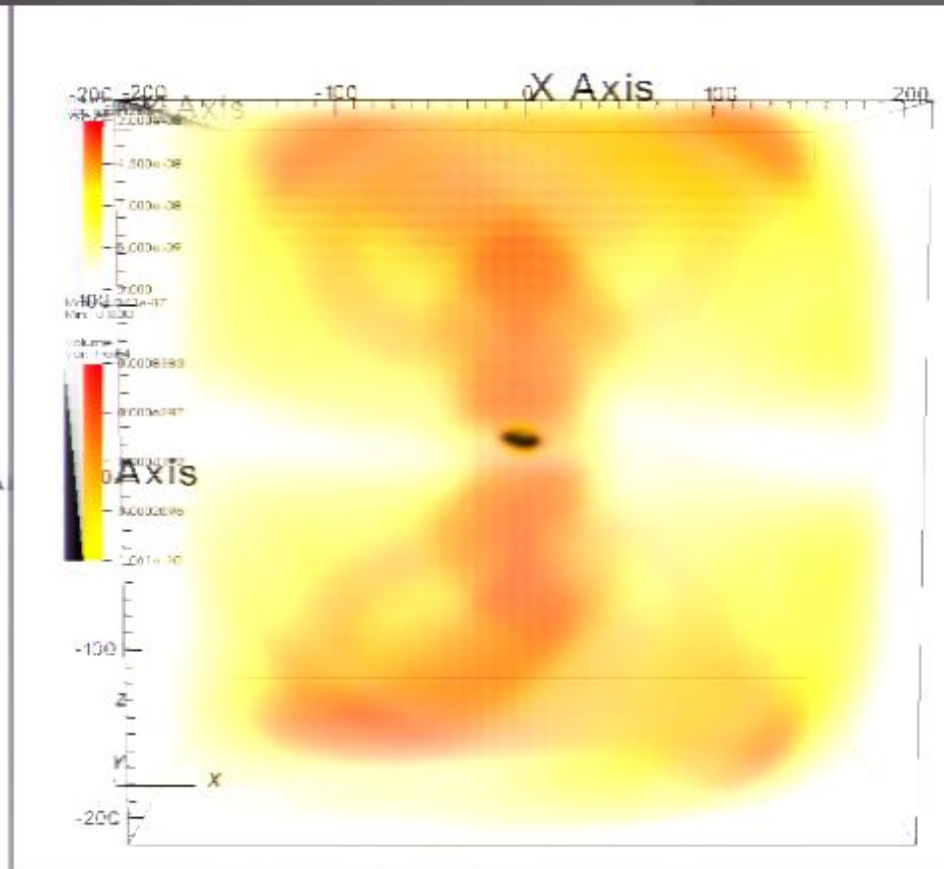
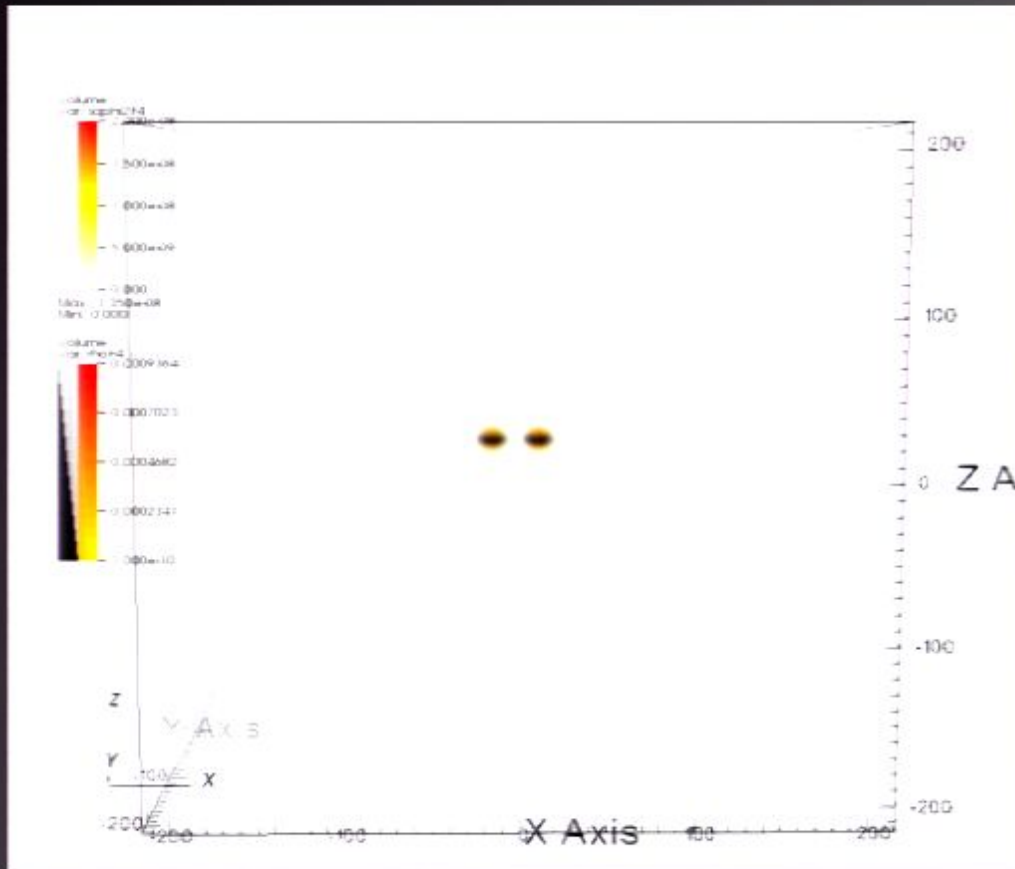
up/down



IV. EM radiation of BNS

up/up

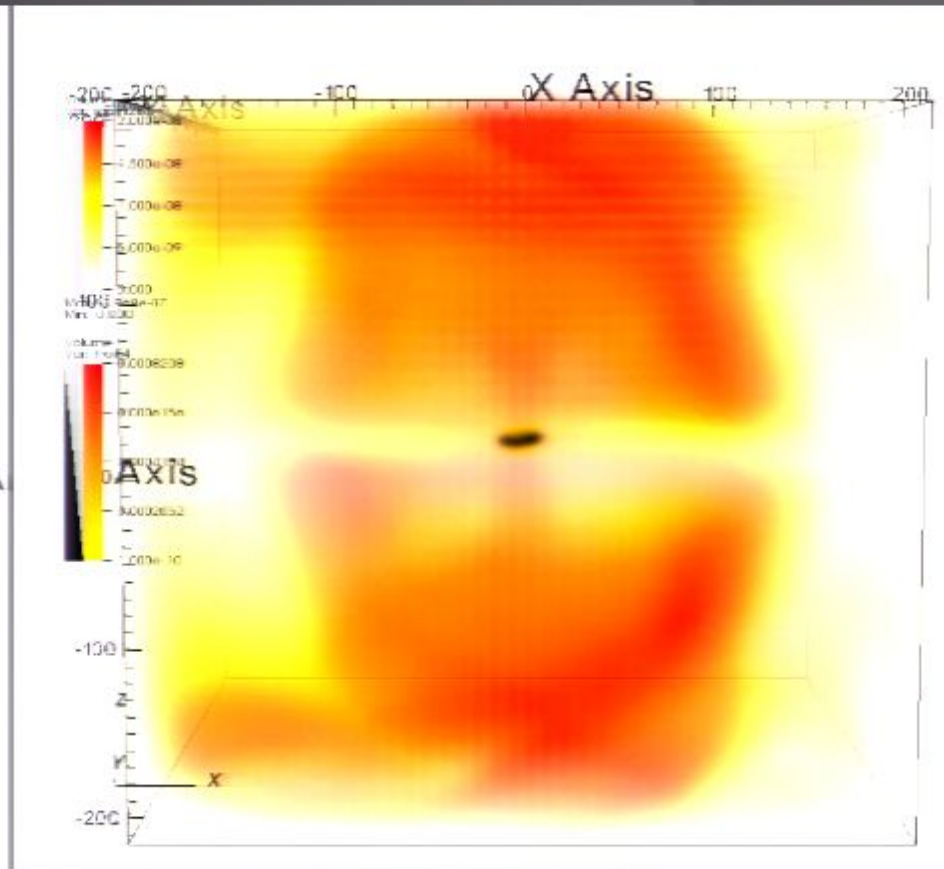
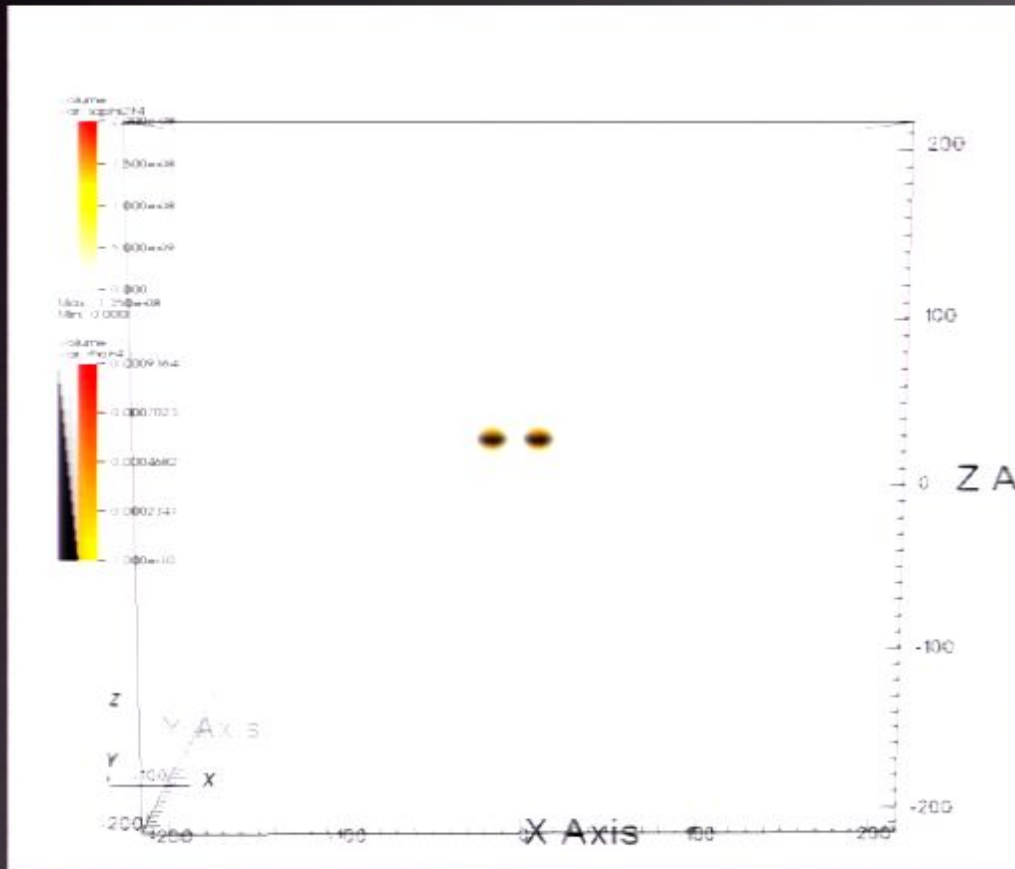
up/down



IV. EM radiation of BNS

up/up

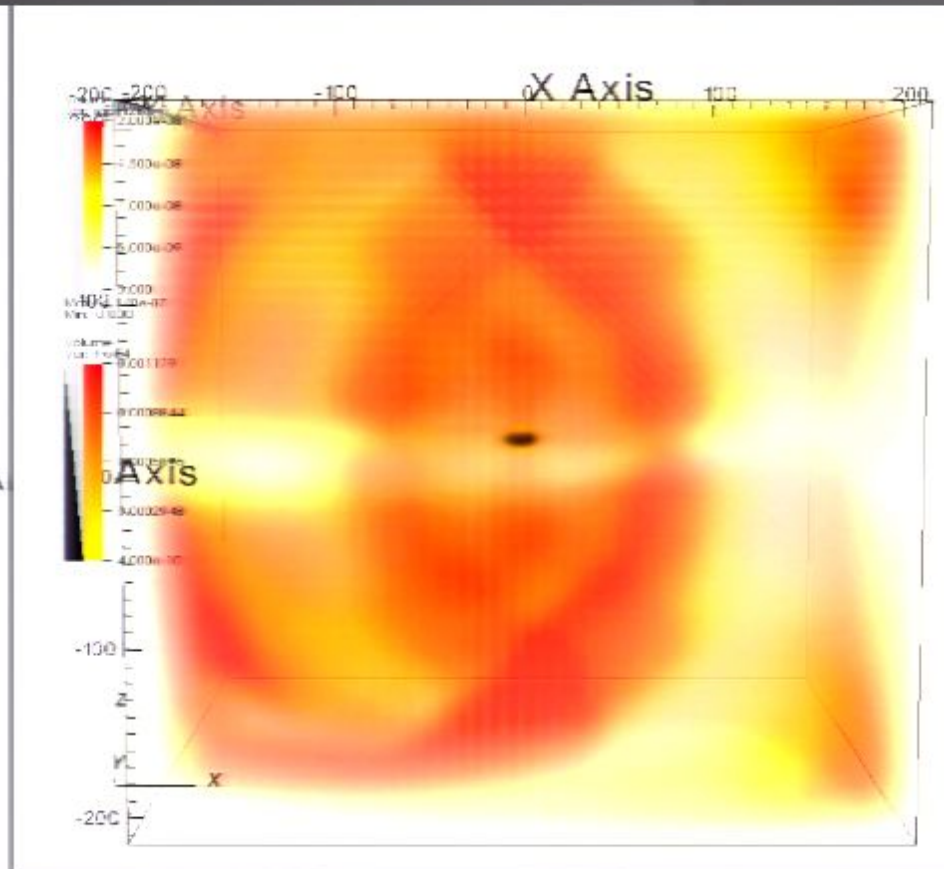
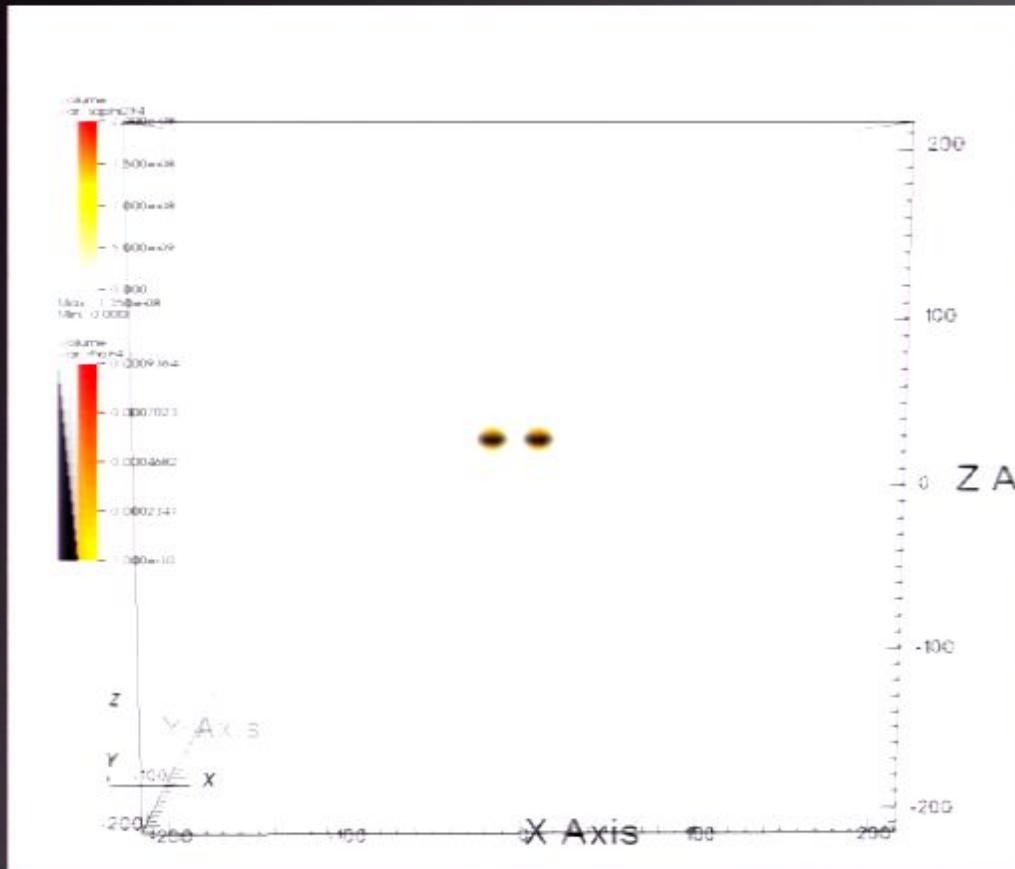
up/down



IV. EM radiation of BNS

up/up

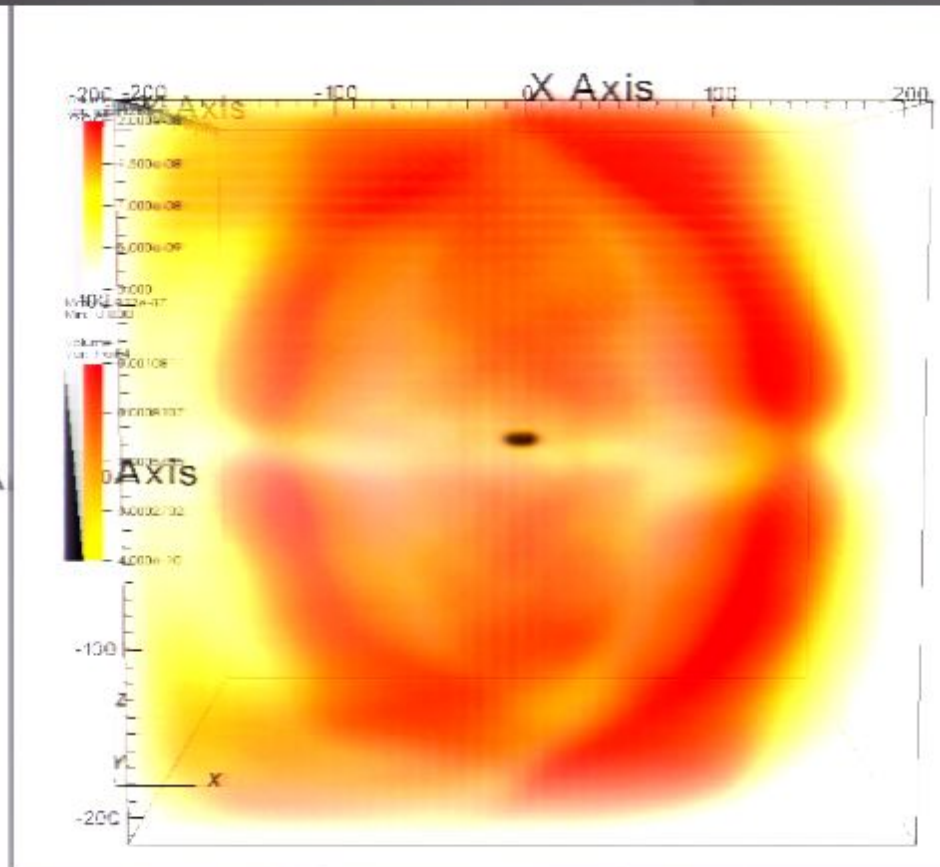
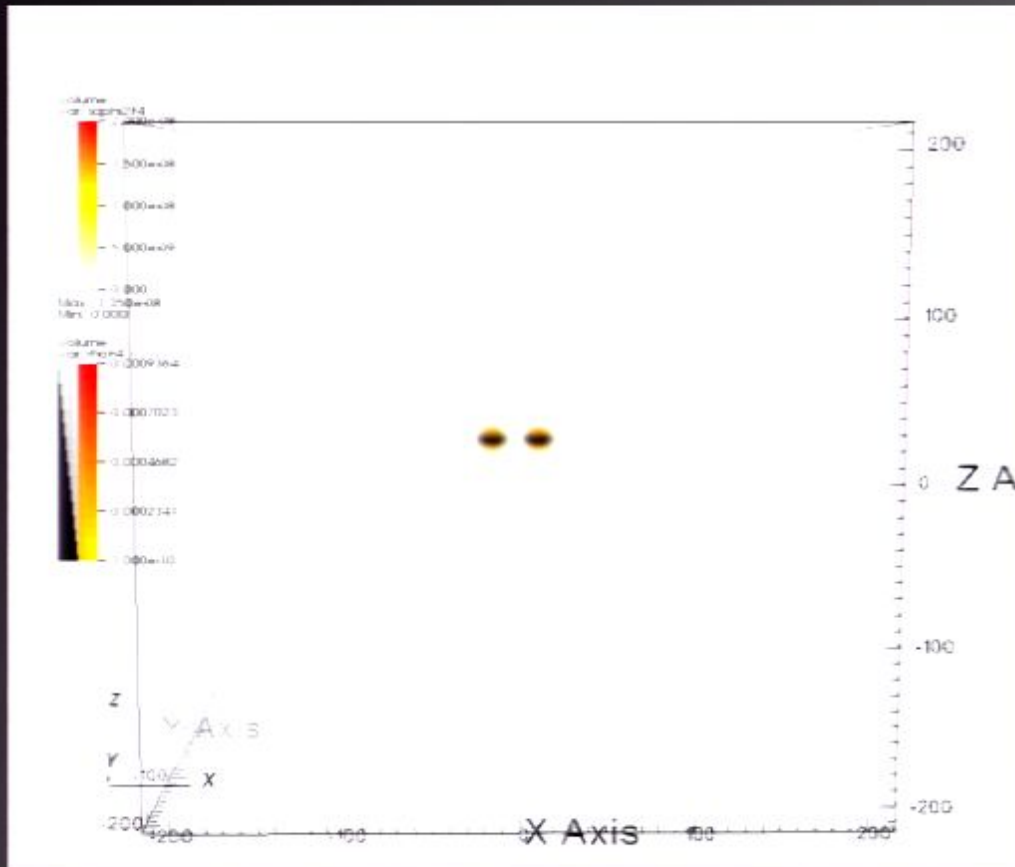
up/down



IV. EM radiation of BNS

up/up

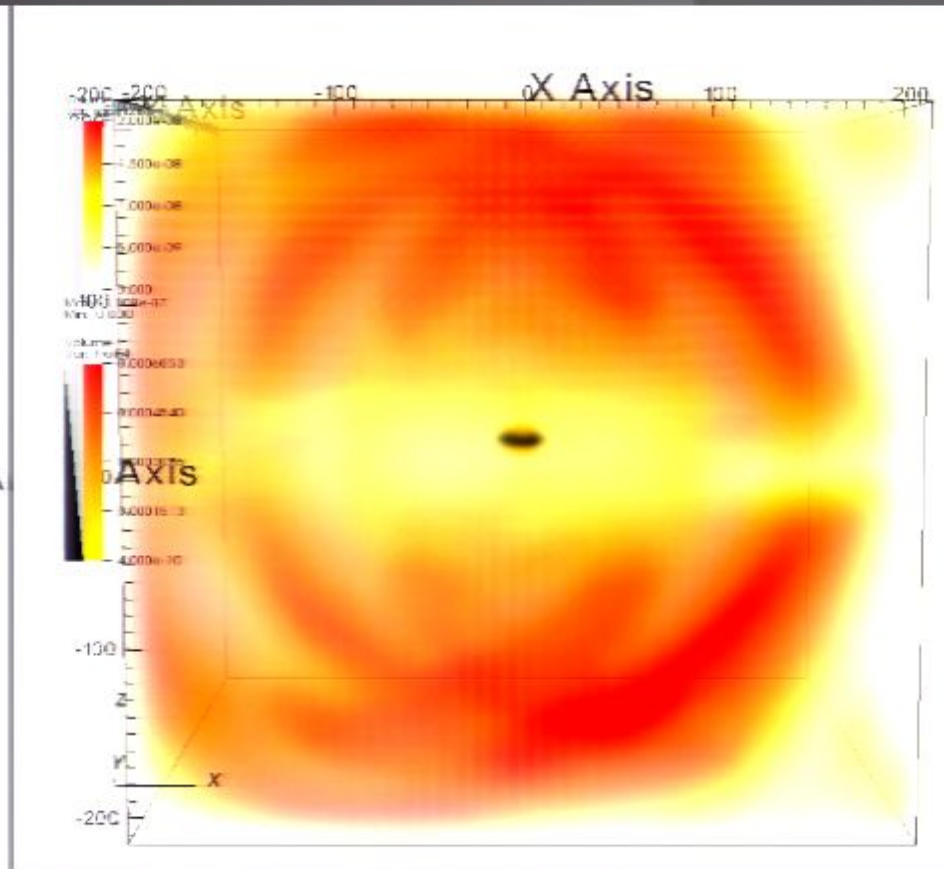
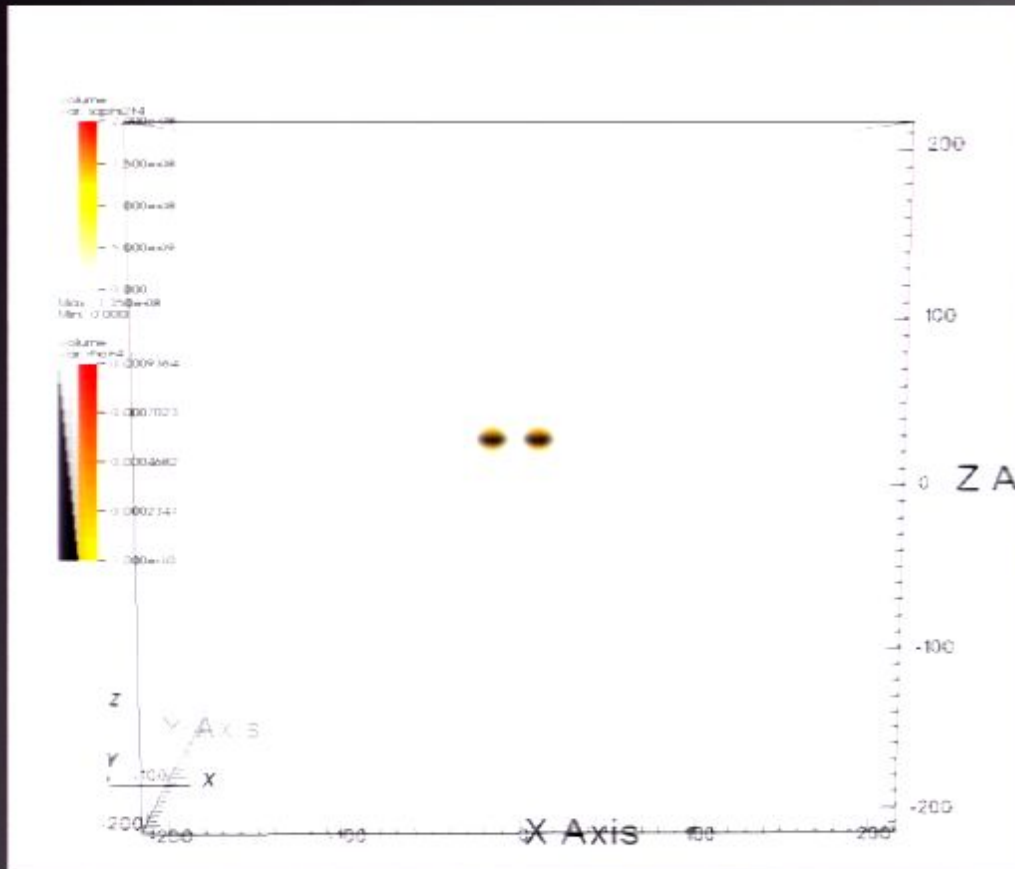
up/down



IV. EM radiation of BNS

up/up

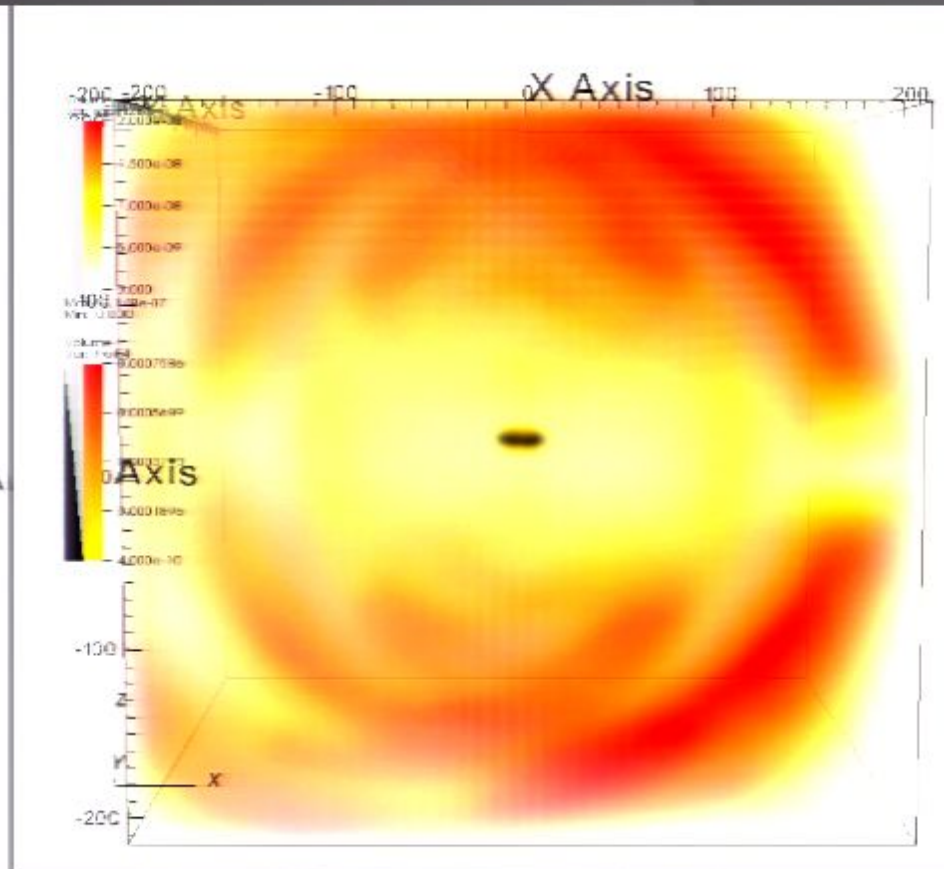
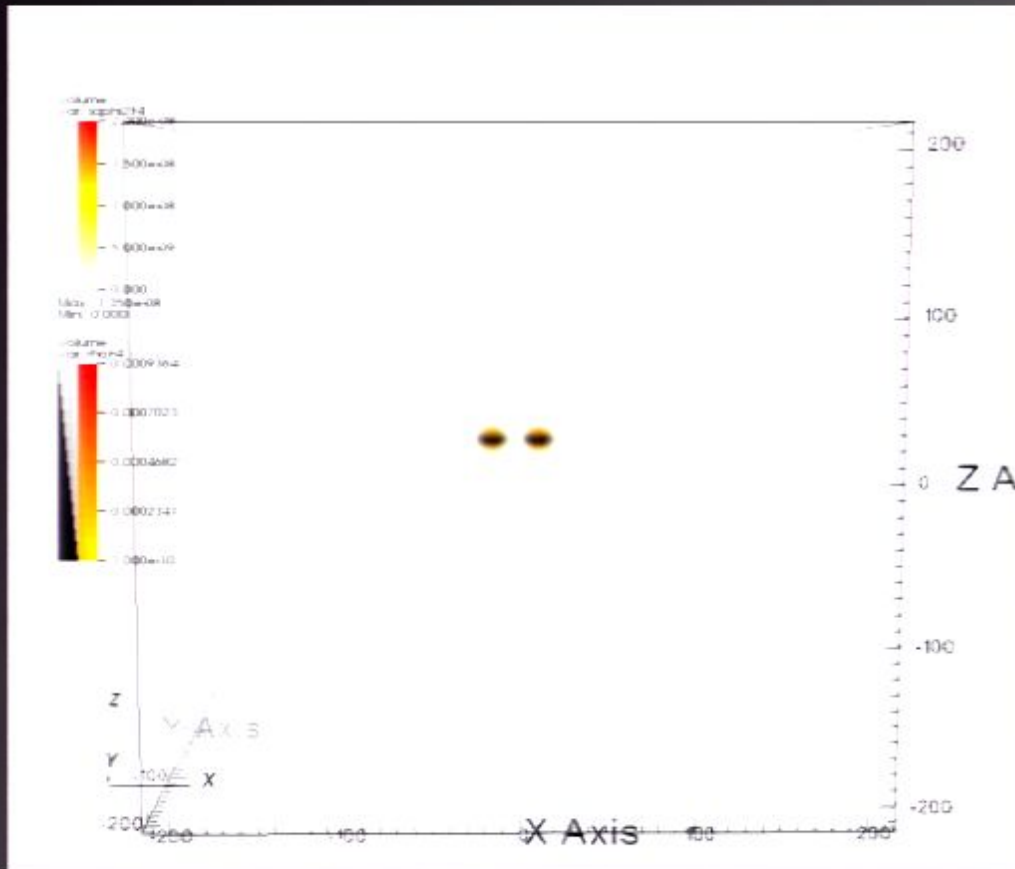
up/down



IV. EM radiation of BNS

up/up

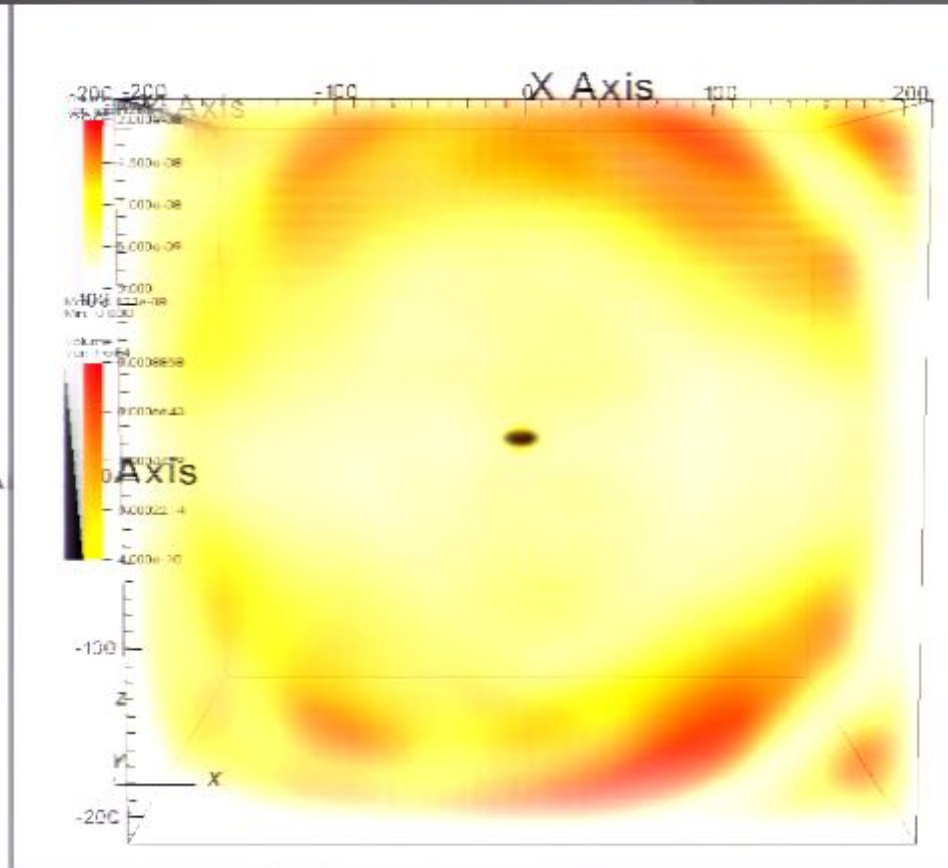
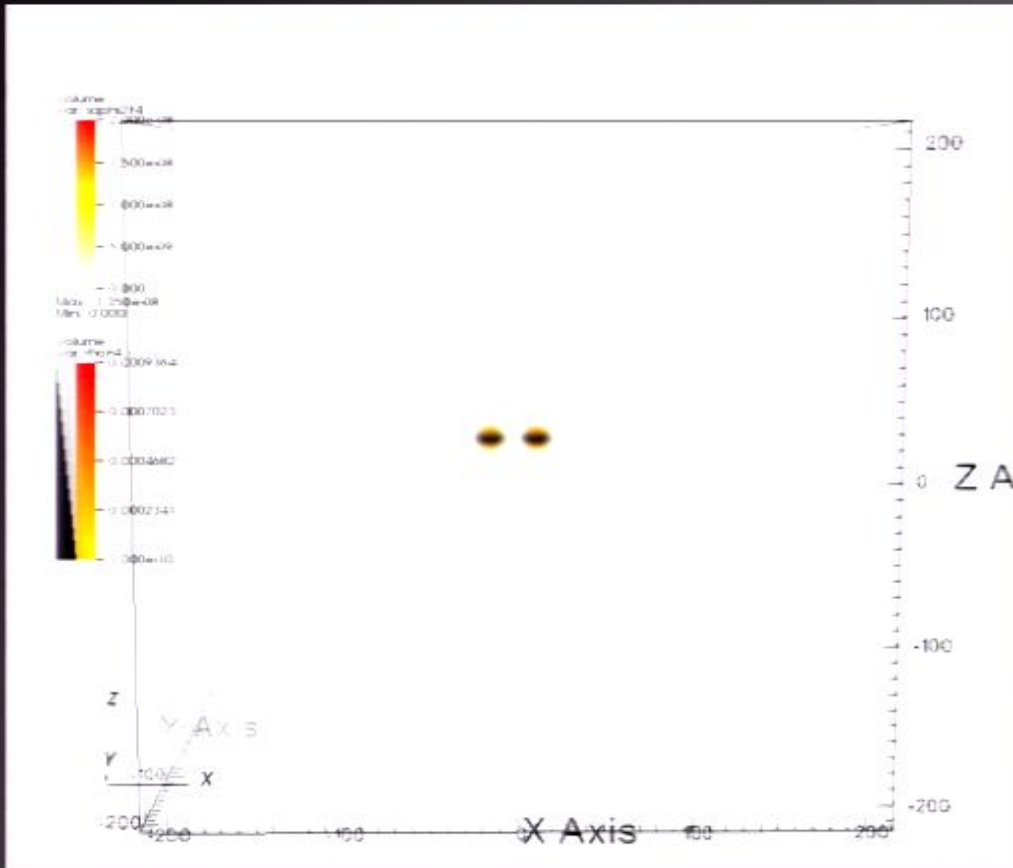
up/down



IV. EM radiation of BNS

up/up

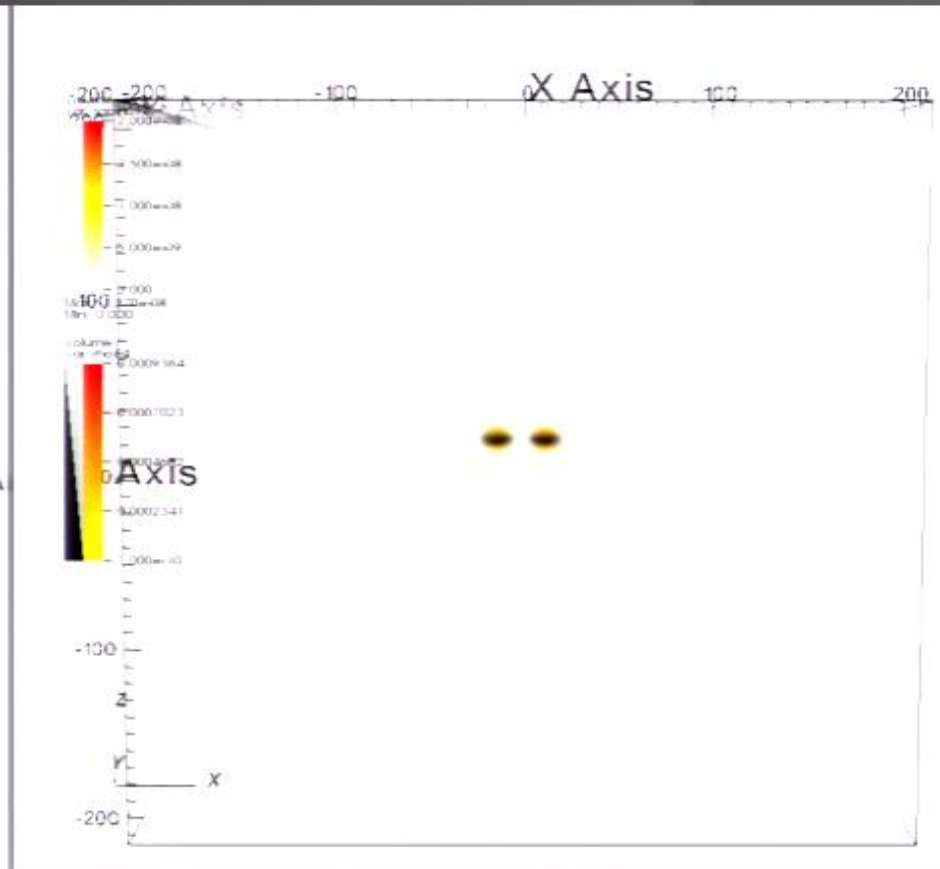
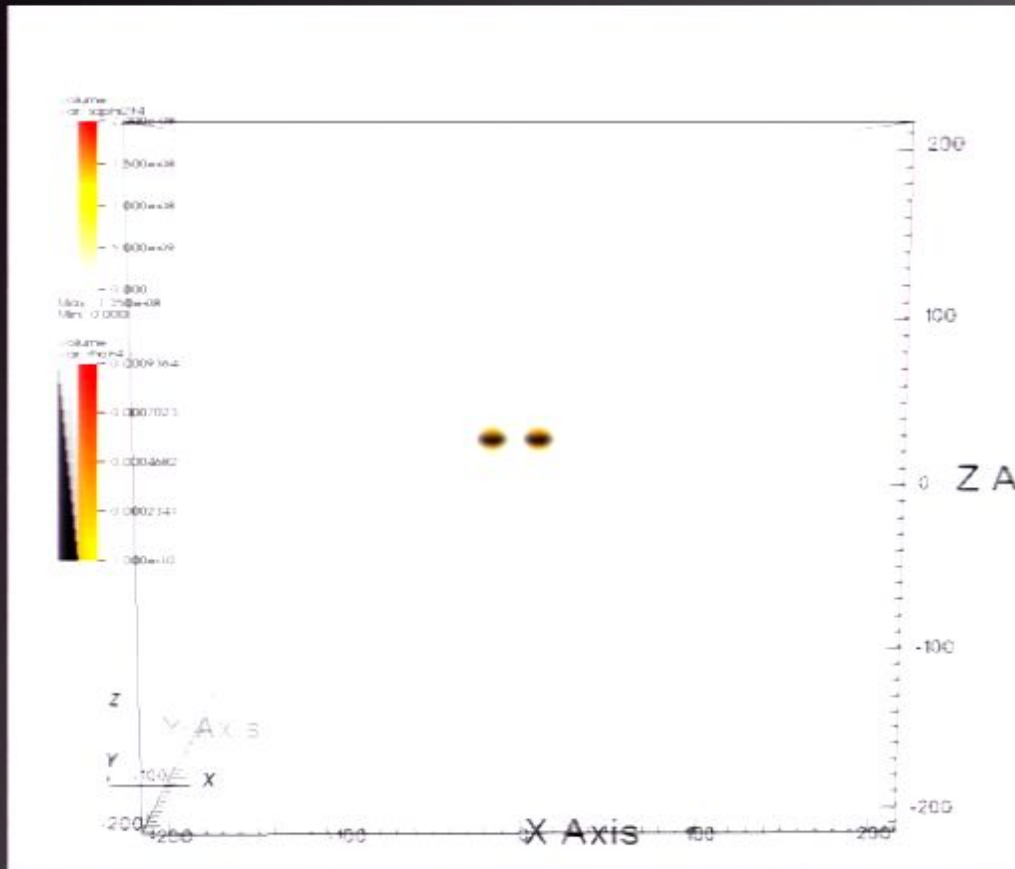
up/down



IV. EM radiation of BNS

up/up

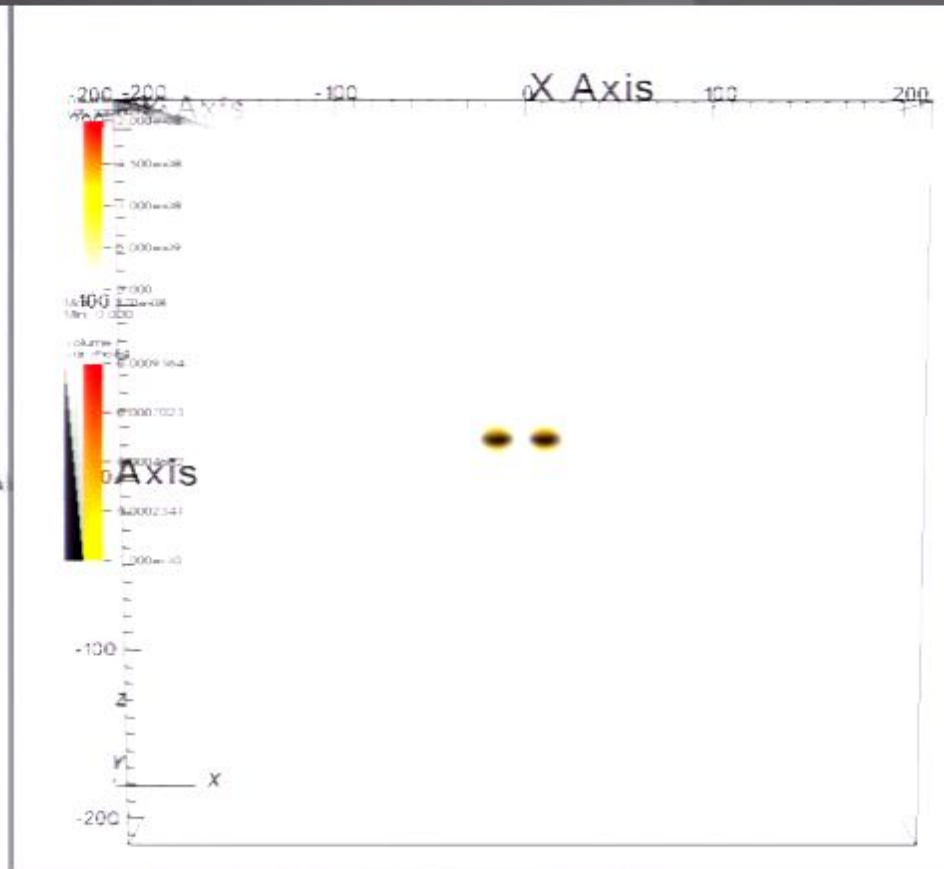
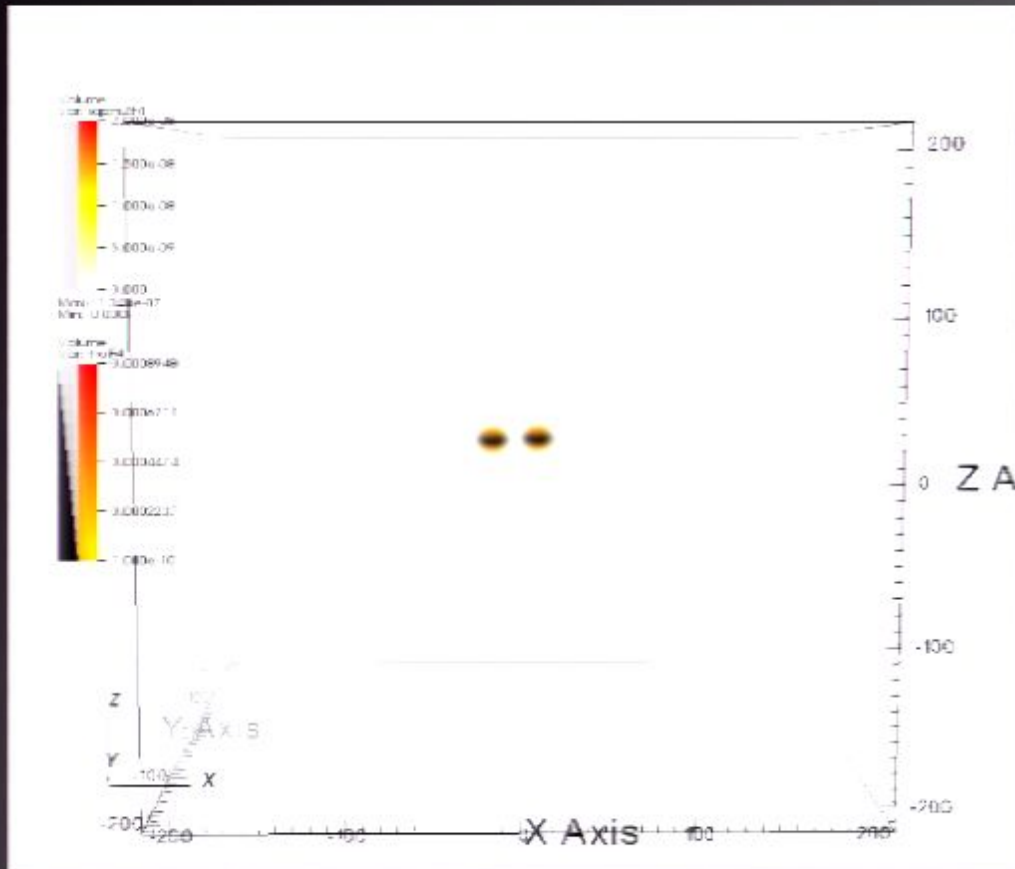
up/down



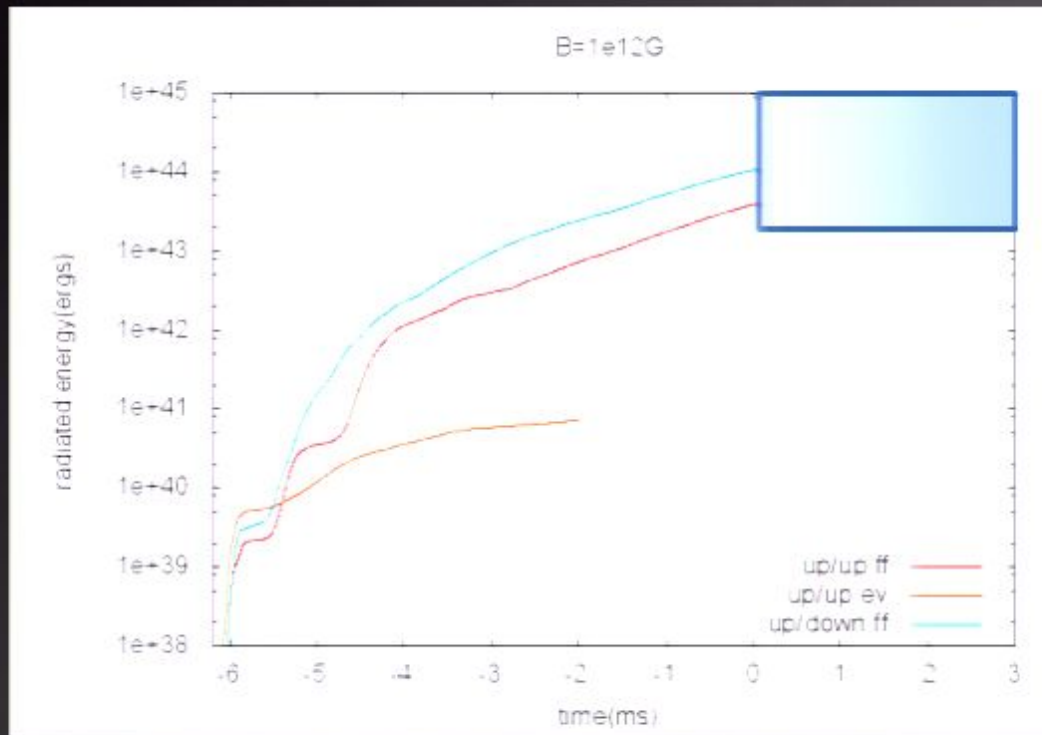
IV. EM radiation of BNS

up/up

up/down



IV. Luminosity of BNS



$$E_{\text{rad}} \sim 10^{44} \text{ ergs}, \quad \tau \sim 10 \text{ ms}$$

$$L \sim 10^{46} \text{ ergs/s}$$

Dense and hot plasma around the NS: optically thick (black body)

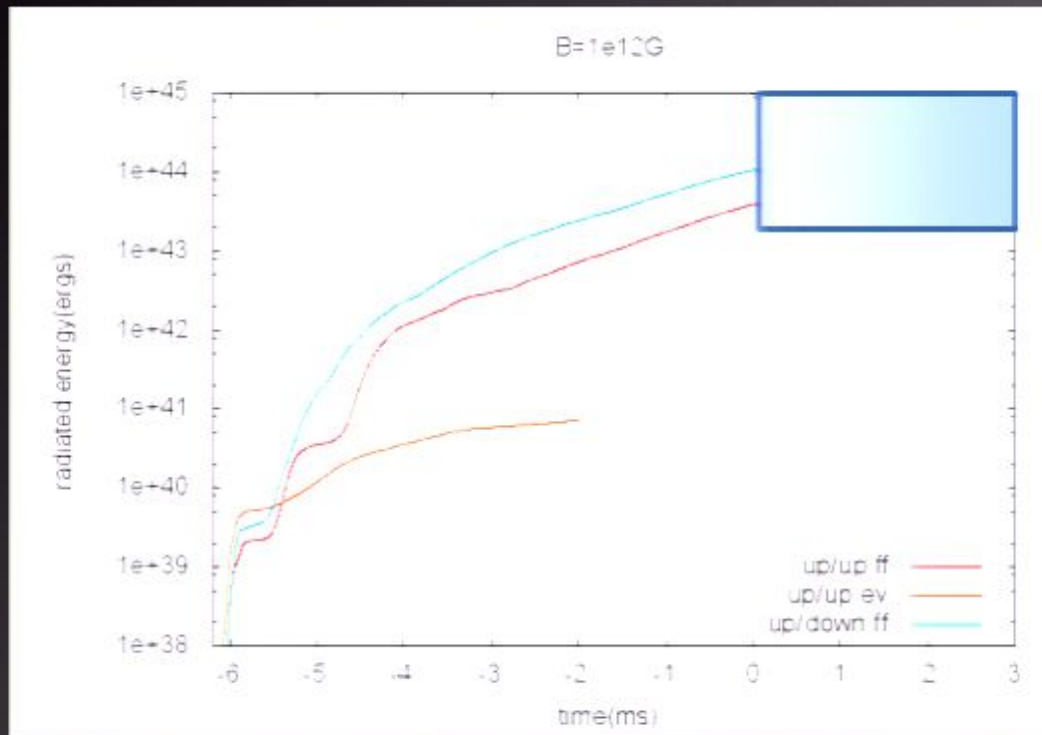
$$L = 4\pi R^2 \sigma T_{\text{eff}} \rightarrow T_{\text{eff}} \sim 8 \cdot 10^8 \text{ K} \rightarrow \nu = 4 \cdot 10^{19} \text{ Hz}$$

Summary

- Different **EM counterparts**
 - **binary NS and mixed binaries** for LIGO, supermassive BH in a circumbinary disk for LISA/PTA,...
- The **force-free regime is a good approximation** for the EM fields in the magnetospheres
- The **magnetic field can extract** energy from both the **rotational and kinetic energy** of the compact object.
- **The interaction of the magnetospheres** changes the topology of the EM fields and produces a (collimated?) radiation before/at the merger (precursor of the sGRB?)

End of slide show, click to exit.

IV. Luminosity of BNS



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