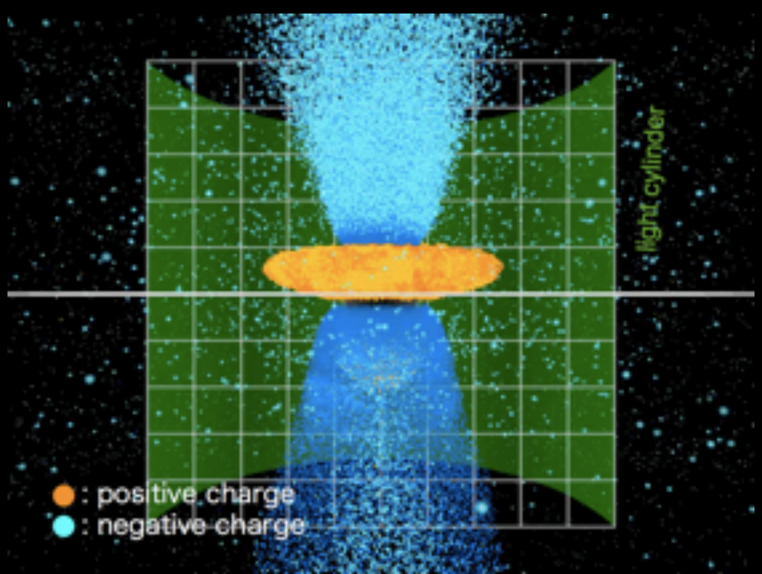
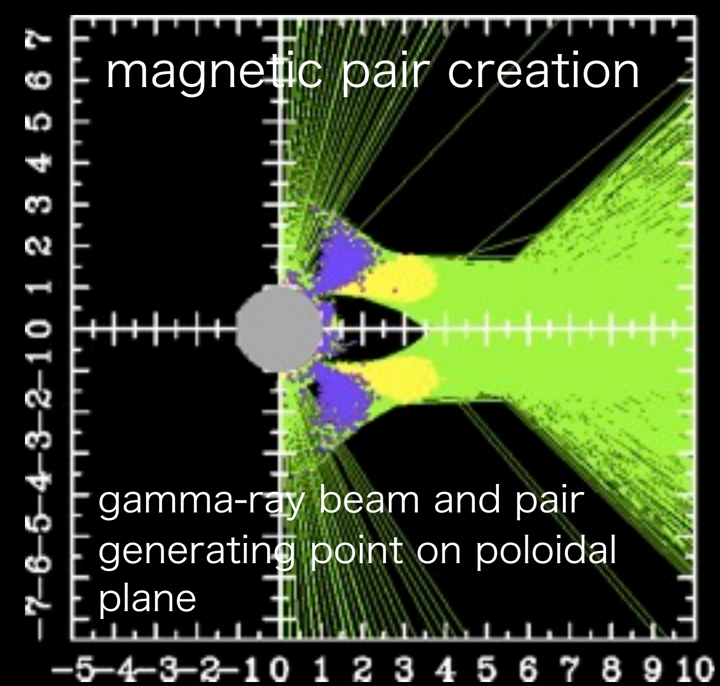
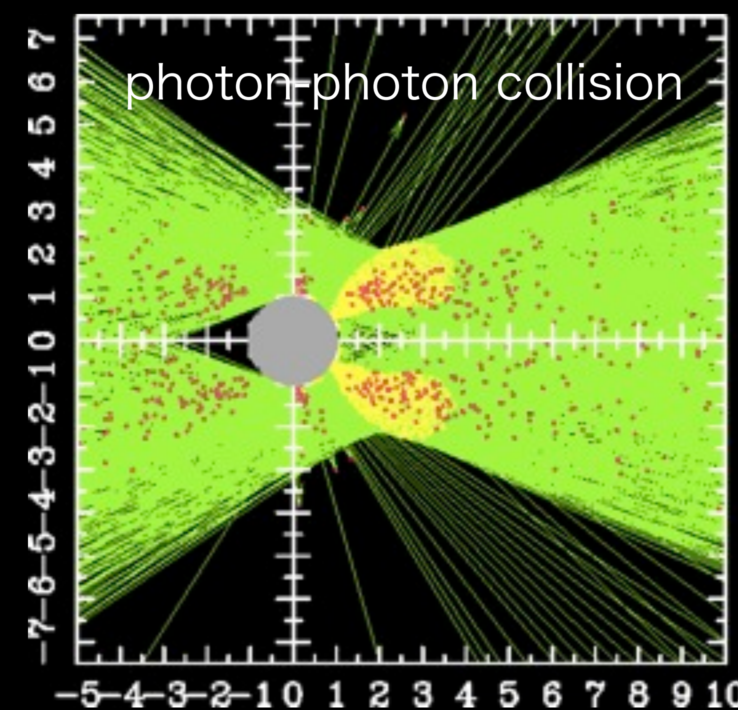
IAUS291-1-0258

Particle Simulation for Axisymmetric Pulsar Magnetosphere



3D distribution of plasma





- Radiation drag force for accelerated plasma
- Magnetic distortion by magneto-spheric current
- Quadrupole magnetic field (Octopole induced stellar electric field)
- Magnetic pair creation & pair generation by photon-photon collision in the gap

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Particle Simulation for Axisymmetric Pulsar Magnetosphere

IAU General Assembly XXVIII — 20-31 August 2012, Beijing, China

IAU Symposium 291 **Neutron Stars and Pulsars: Challenges and Opportunities after 80 years**

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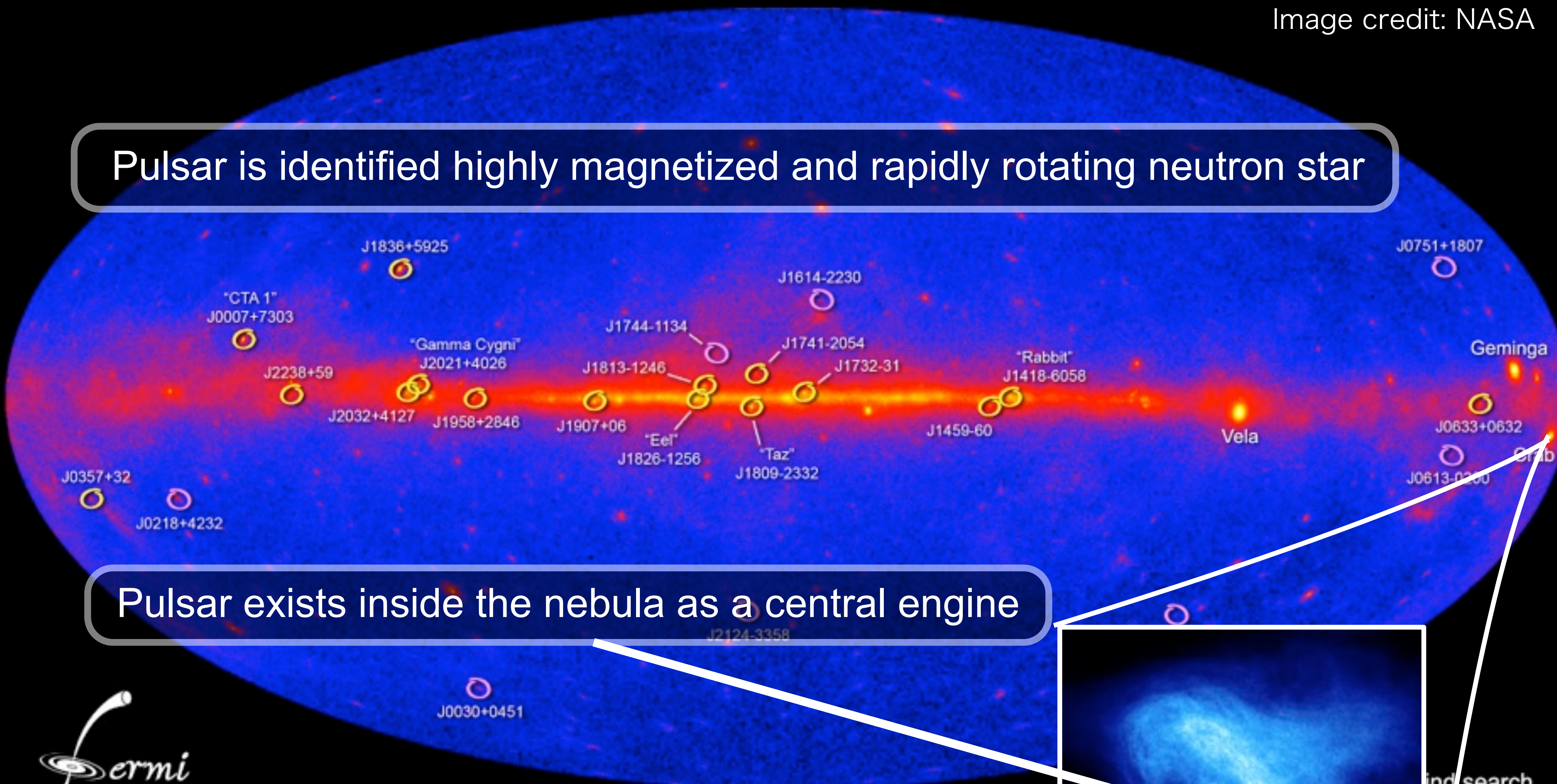
Outline of poster

How does pulsar(conventionally, believed magnetized rotating NS) **accelerate plasma?**

1. Observed feature of Gamma-ray Pulsar
2. Rotating magnetized neutron star
3. Aim of our study
4. Outline of particle simulation(method)
5. Results
6. Summary

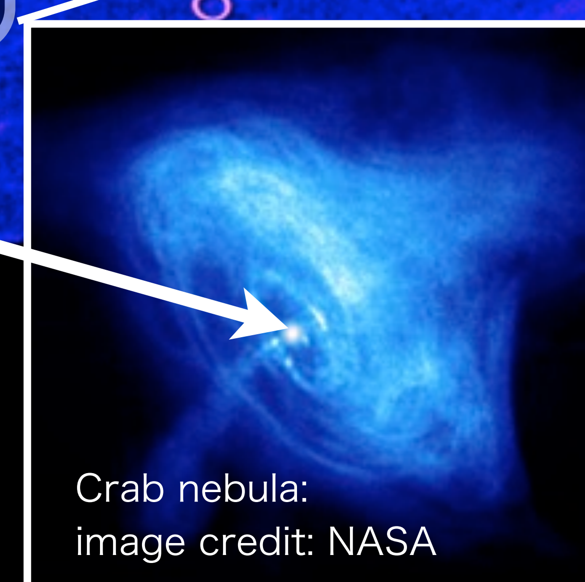
Gamma-ray pulsars

Image credit: NASA



Pulsar is identified highly magnetized and rapidly rotating neutron star

Pulsar exists inside the nebula as a central engine



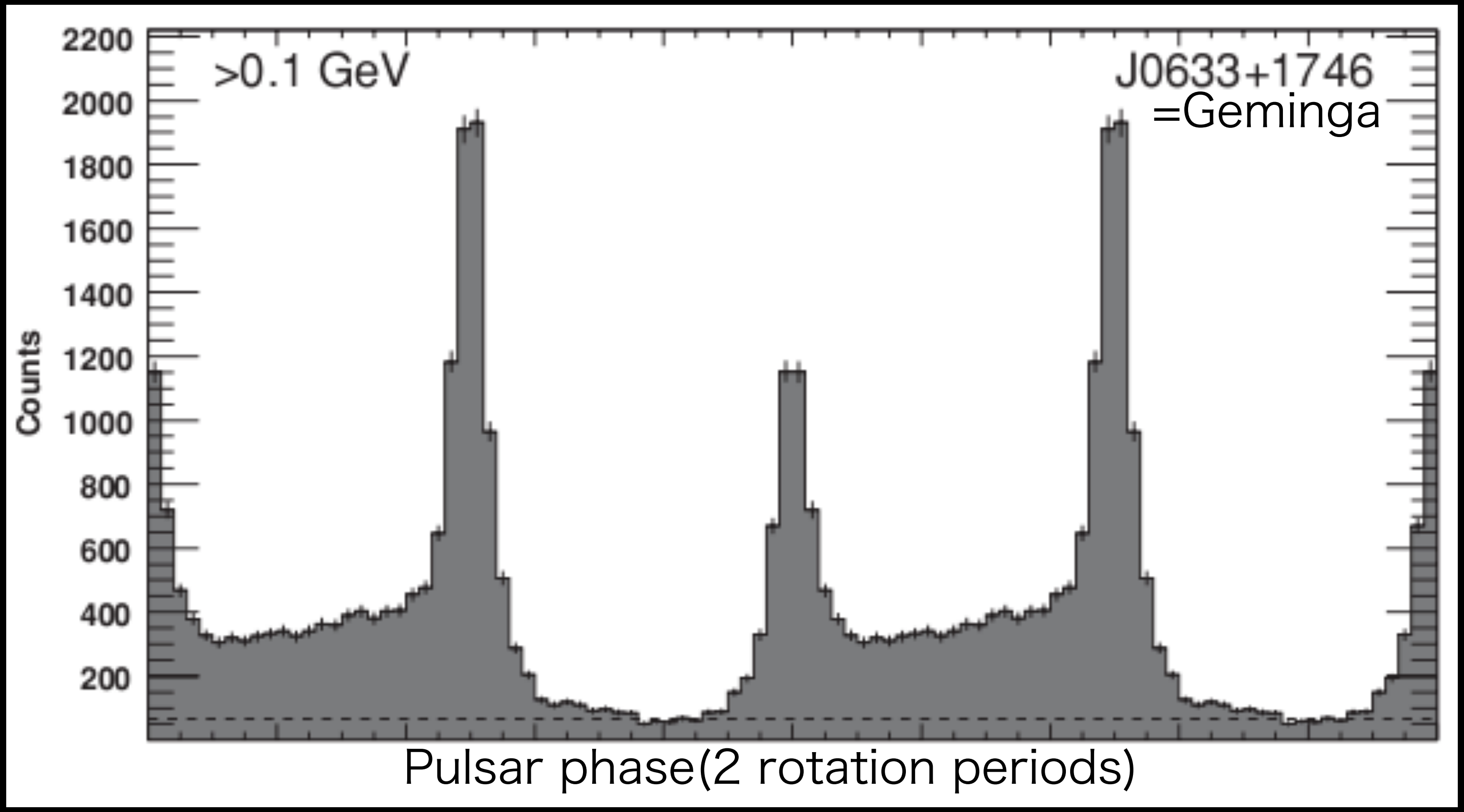
Crab nebula:
image credit: NASA

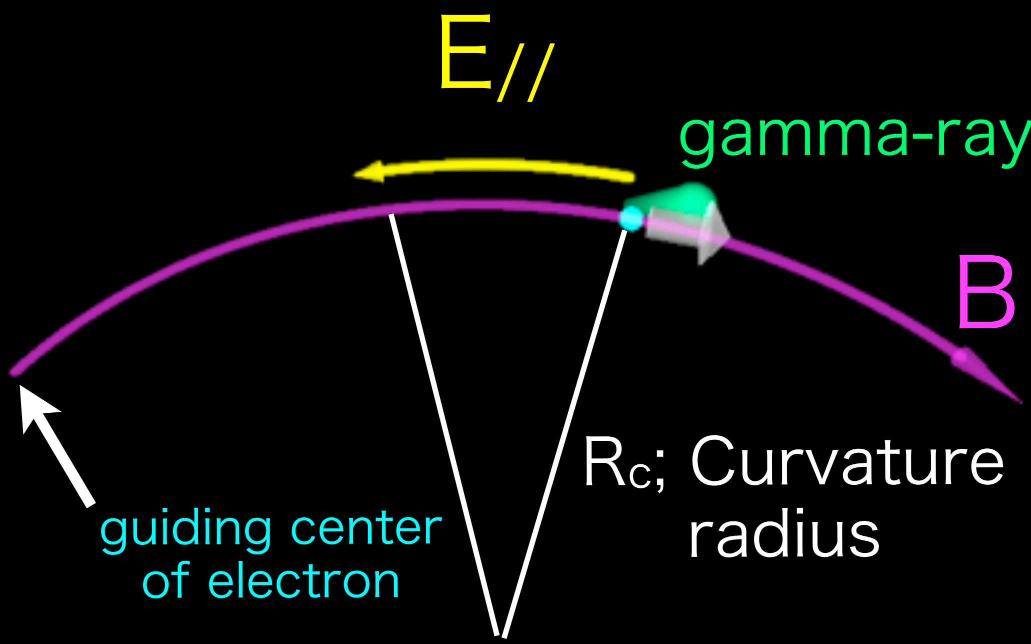
We focus on Rotation Powered Pulsar

Gamma-ray Beam

If plasma is accelarated along the magnetic fielde line, it emits gamma-ray by curvature radiation

Pulse profile of Geminga: Abdo et al., 2010 ApJS





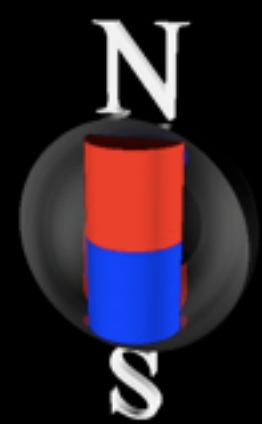
$$\epsilon_c = 0.1 \left(\frac{\gamma}{10^7}\right)^3 \left(\frac{R_c}{R_l}\right)^{-1} \mathrm{GeV}$$

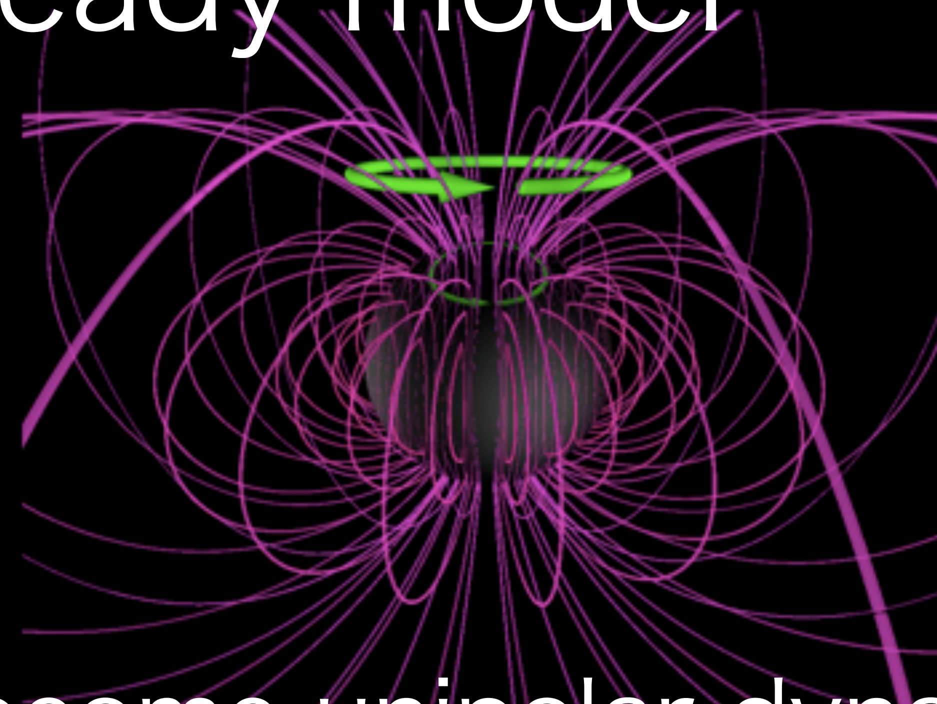
R_l; light radius

Gamma-ray pulse; localized accerating region corotating with star

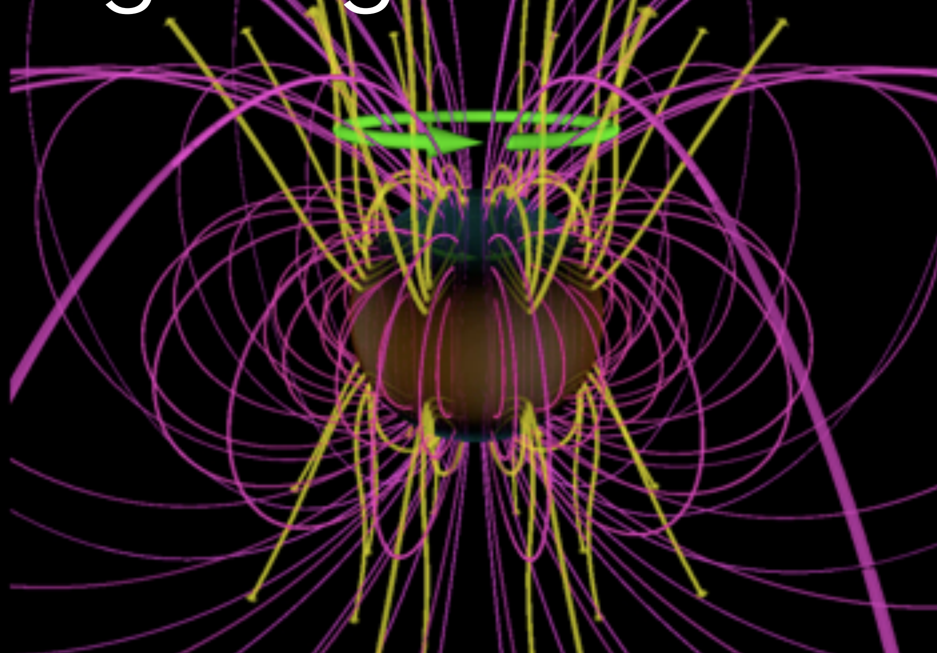
Axisymmetric steady model

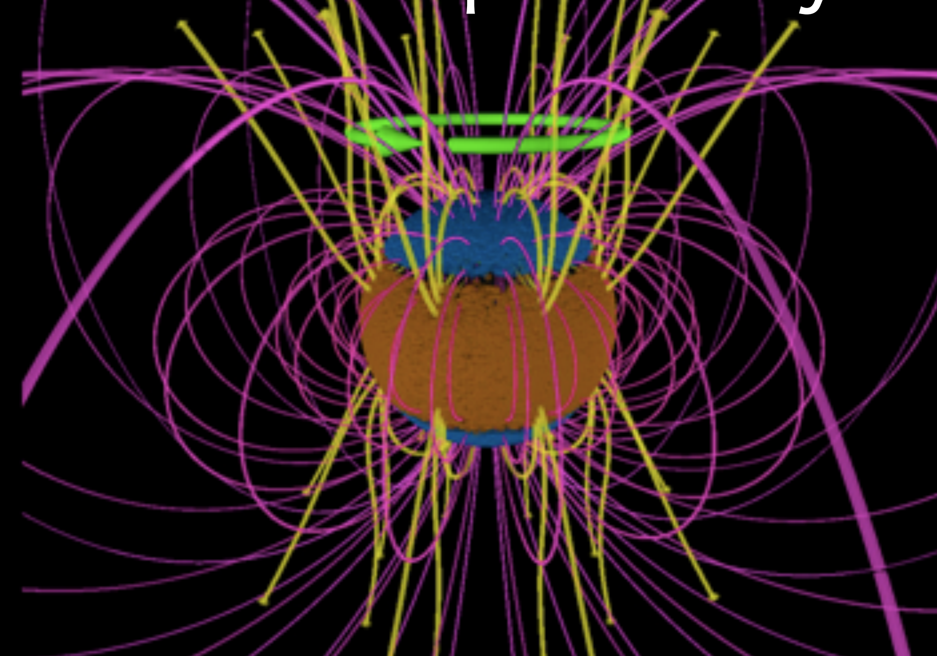
: positive charge
: negative charge
: magnetic field line
: electric field line





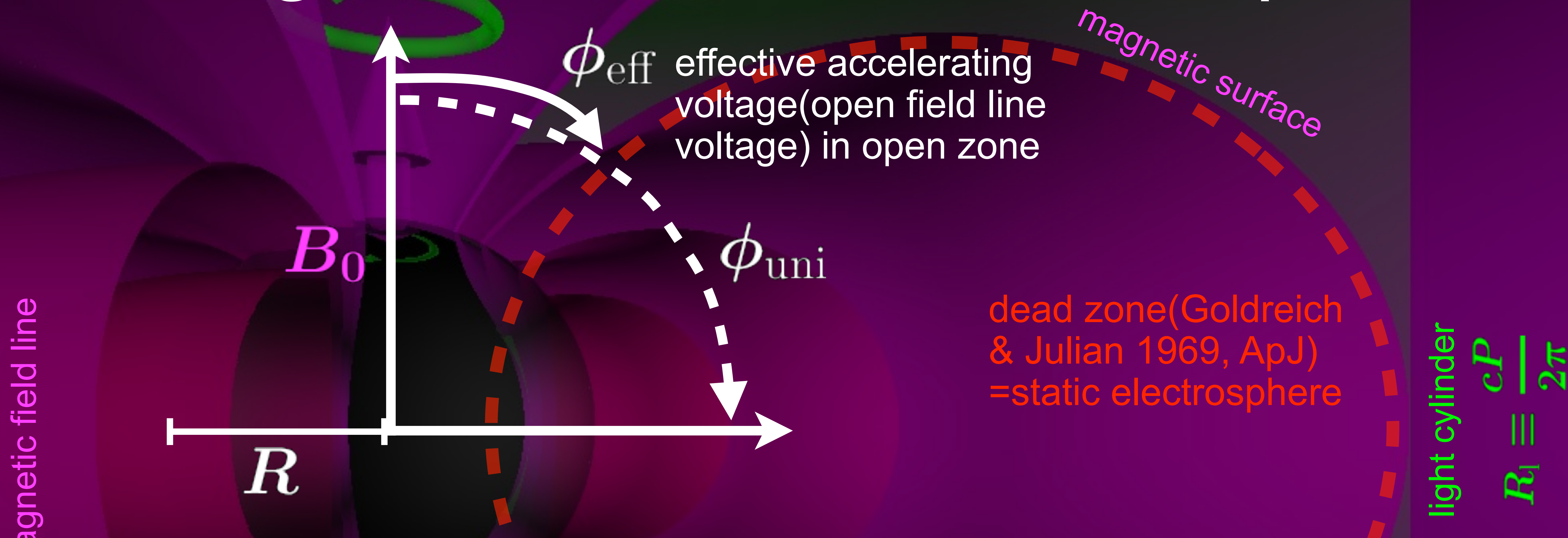
Rotating magnetized star become unipolar dynamo!





Rotating manetized star (conductive sphere) become unipolar dynamo. Induced E pushes out plasma from the surface.
We can follow Jackson's Gedankenexperiment (Jackson 1976 ApJ) with particle simulation.

Voltage for acceleration of plasma



rotation period; $P_{0.2} = P/(0.2\,{\rm sec})$

stellar radius; $R_6 = R/(10^6\,{\rm cm})$

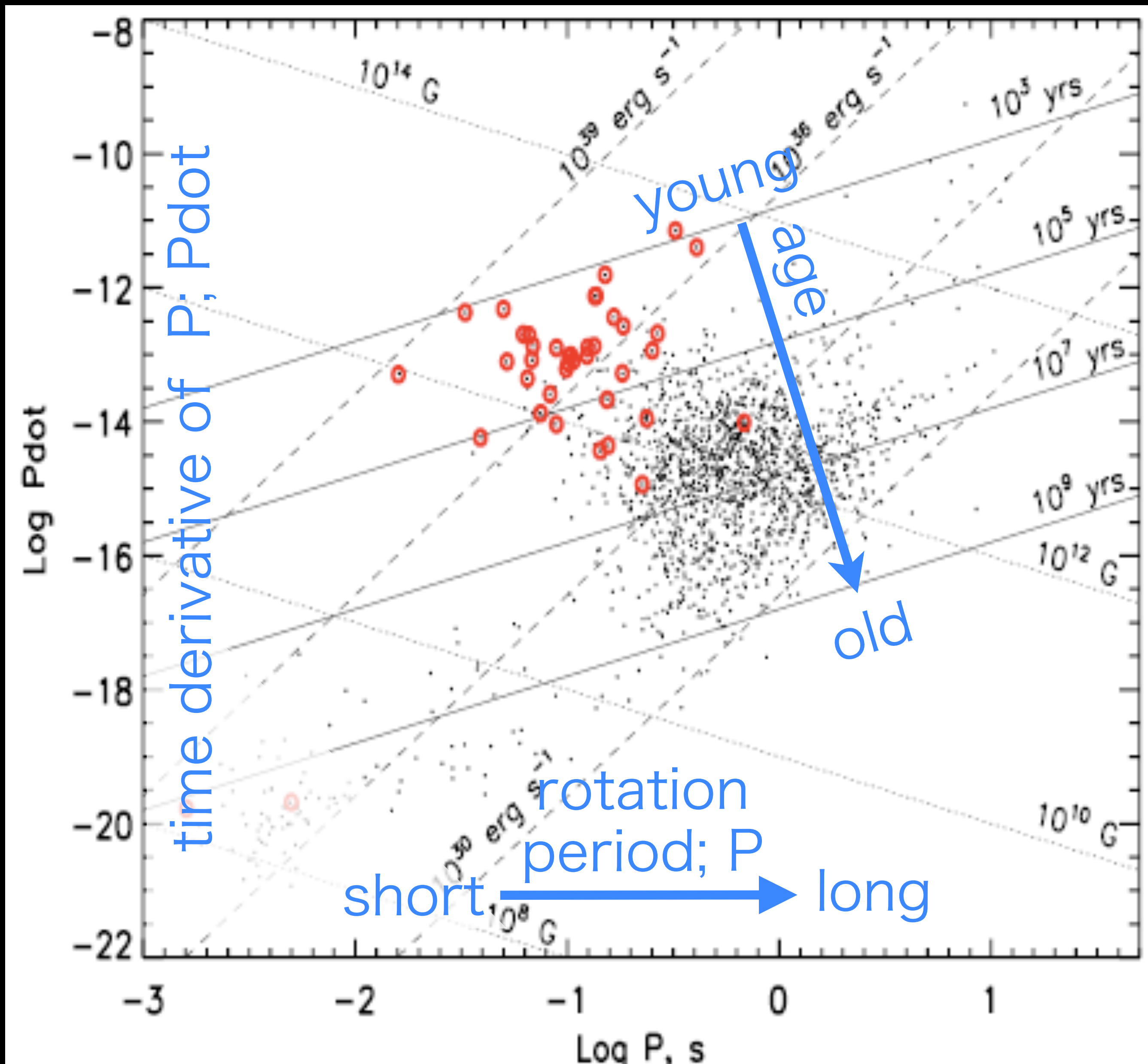
surface magnetic field intensity; $B_{12} = B_0/(10^{12}{\rm gauss})$

voltage by unipolar induction; $\phi_{\rm uni} = 3 \times 10^{17} B_{12} R_6 P_{0.2}^{-1}\,{\rm Volt}$

open field line voltage; $\phi_{\rm eff} = 1.6 \times 10^{14} B_{12} R_6^3 P_{0.2}^{-2}\,{\rm Volt}$

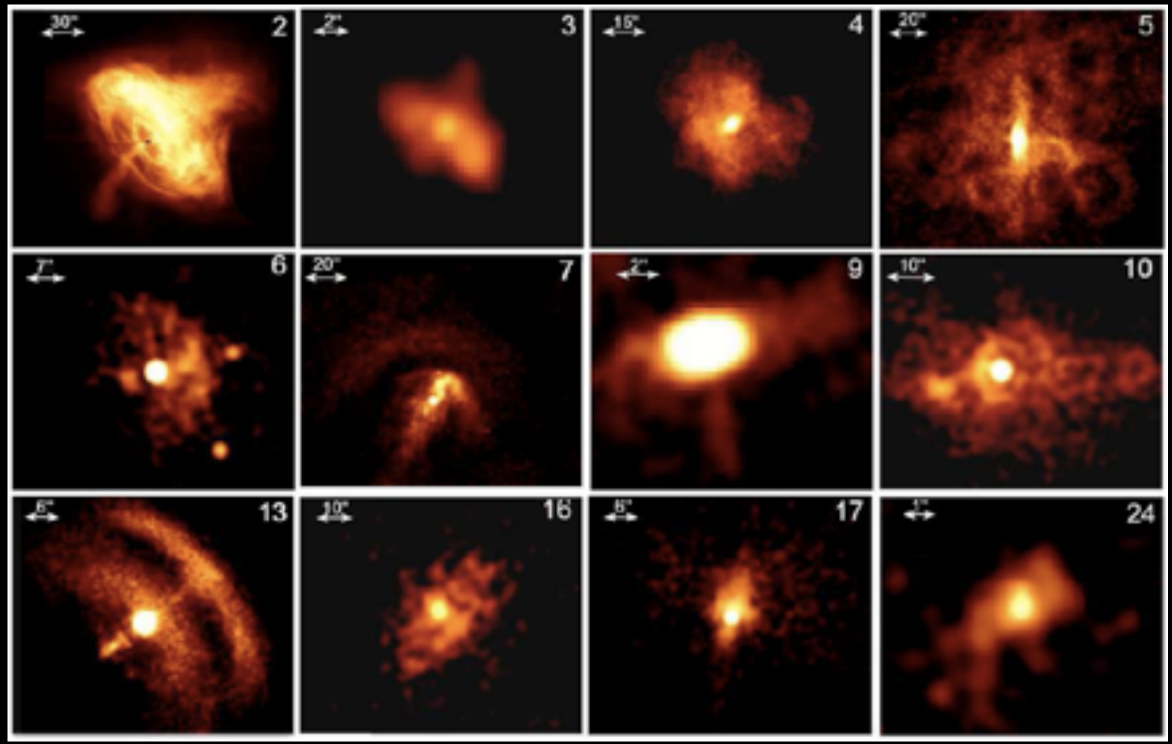
Pulsar Wind Nebula(PWN)

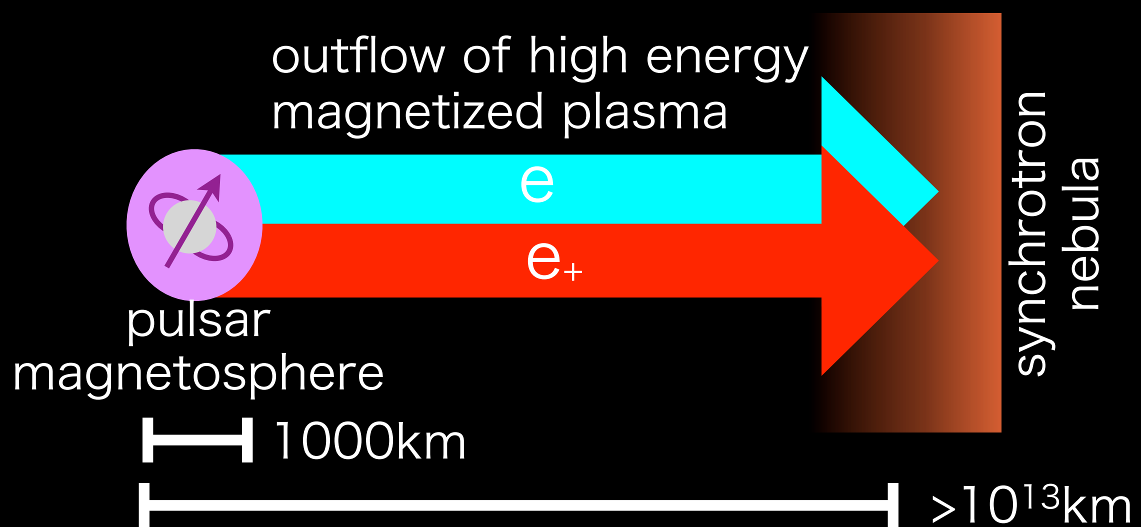
P-Pdot diagram



Kargaltsev & Pavlov 2008 AIPC

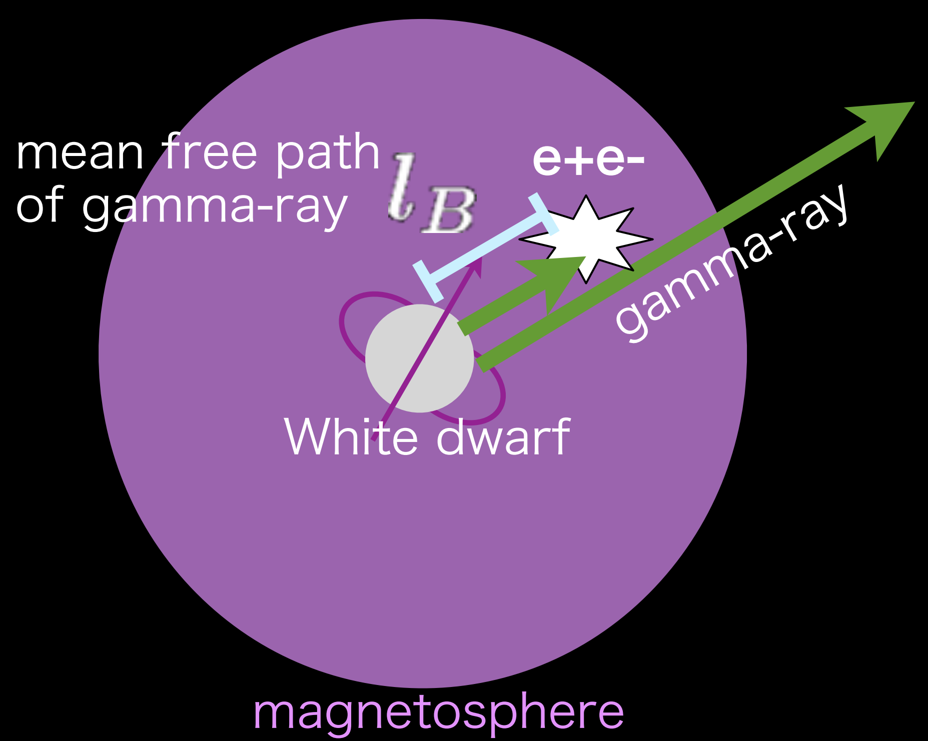
Kargaltsev & Pavlov 2008 AIPC

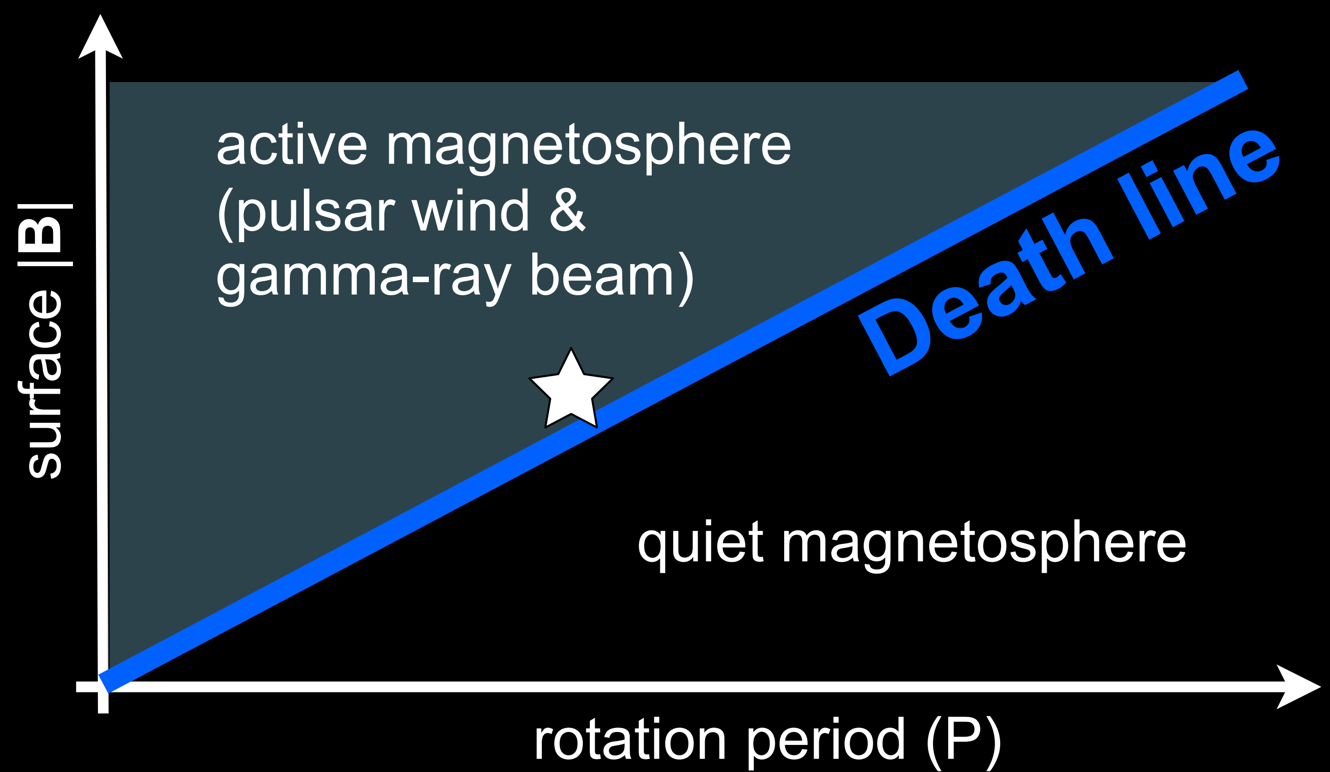




PWN; steady outflow by accelerated plasma(e+e-)
-> pair cascading in the magnetosphere

Death line





$$l_B = \frac{4.4}{\alpha}\frac{\hbar}{mc}\frac{B_\mathrm{q}}{B_\perp}\exp\left(\frac{4}{3\chi}\right) \propto l_B\left(\epsilon_\gamma(\phi_\mathrm{eff}, R_\mathrm{c}), |\vec{B}(\vec{x})|\right)$$

$$\chi = \frac{\epsilon_\gamma}{2mc^2}\frac{B_\perp}{B_\mathrm{q}}$$

$$B_\mathrm{q} = \frac{m^2c^3}{c\hbar} = 4.41 \times 10^{13}\,\mathrm{G}$$

$$B_\perp = B\sin\theta$$

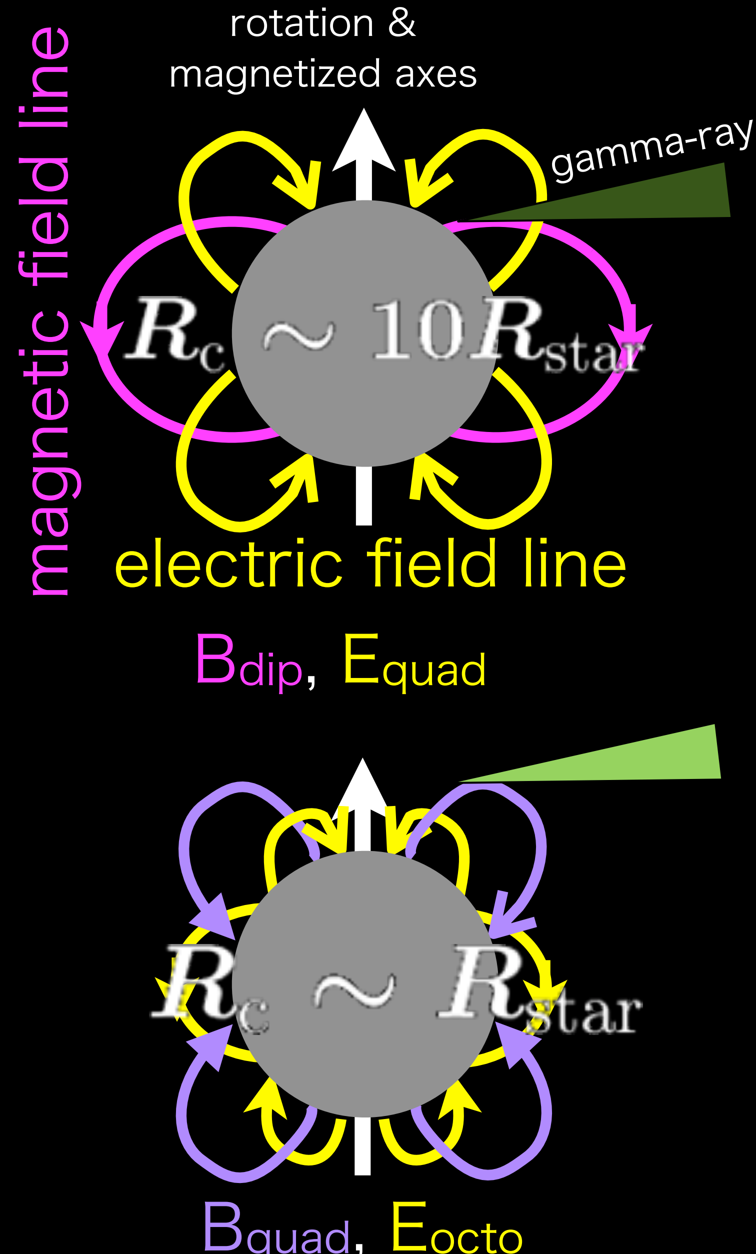
To maintain activity, $l_B \ll l_\mathrm{mag}$

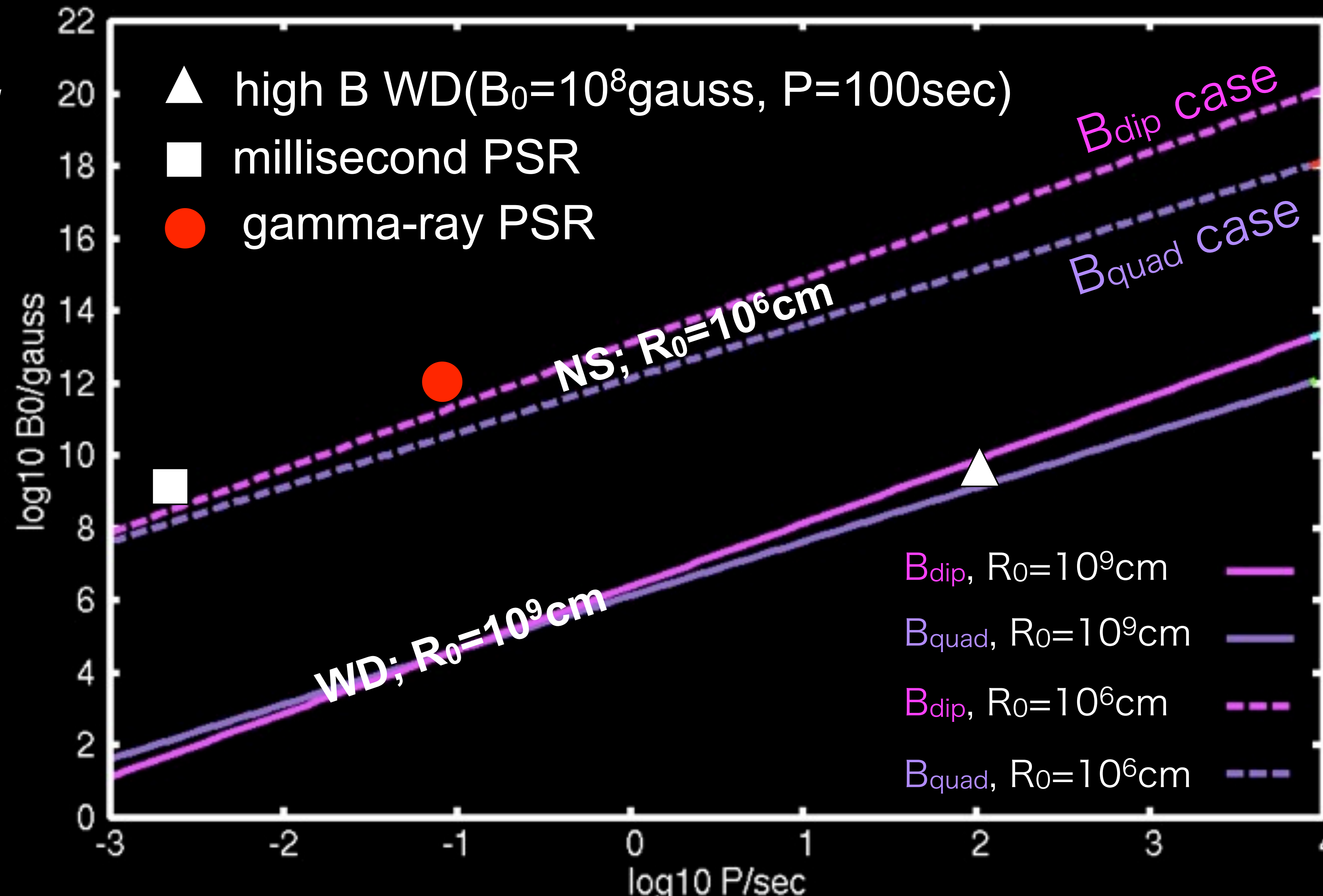
B_dip: $$-\frac{13}{2}\log 10P + 4\log 10B_0 + \frac{17}{2}\log 10R \geq 96.5$$

B_quad: $$-\frac{14}{2}\log 10P + 4\log 10B_0 + \frac{19}{2}\log 10R \geq 106.5$$

e.g., Kashiyama 2011 PhRvD

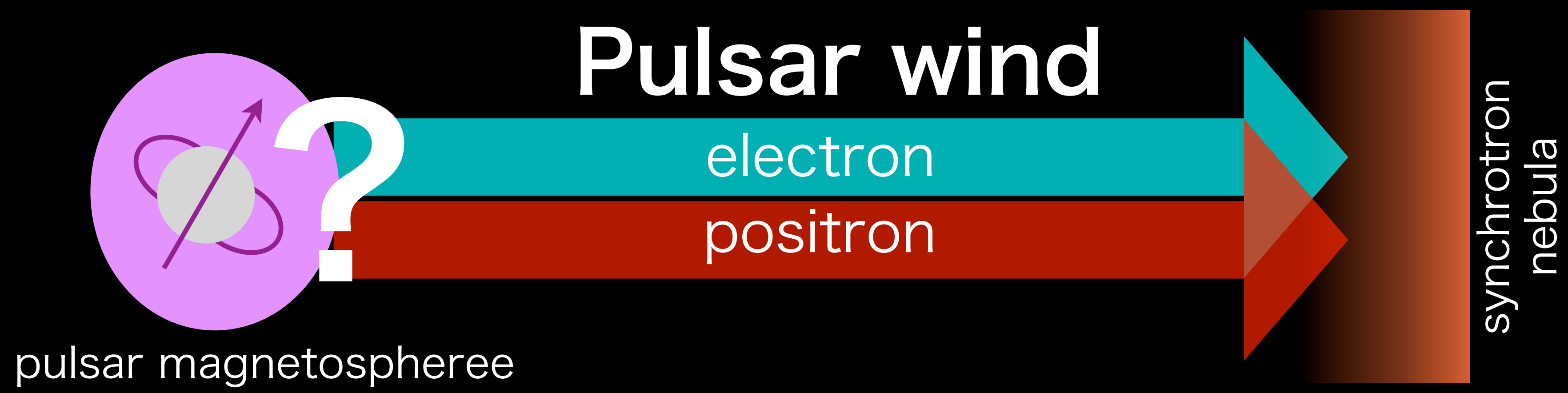
Effects on Death line by B_{quad}





If multipole stellar magnetic field is considered, curvature radius along the magnetic field line become smaller than that of dipole case. As a result, the higher energy photon would be emitted and convert into pairs easily. It could maintains pair cascading with larger P star.

Motivation of our study



Aim of study is to understand the origin of pulsar wind. For this, we have to know **how and where particles accelerated in the magnetosphere**.

We chose particle method and focus on the effects,

-radiation drag force for accelerated plasma

-pair creation in the gaps

-distortion of stellar field by manetospheric current

-stellar multipole magnetic field

Basic equations(with **steady** condition)

To obtain steady solution, we solve Maxwell's equations **in steady state** and EOM iteratively.

Electric field

$$-\nabla^2\phi = 0$$; quadrepole+monopole+octopole

$$-\nabla^2\phi = 4\pi\rho$$

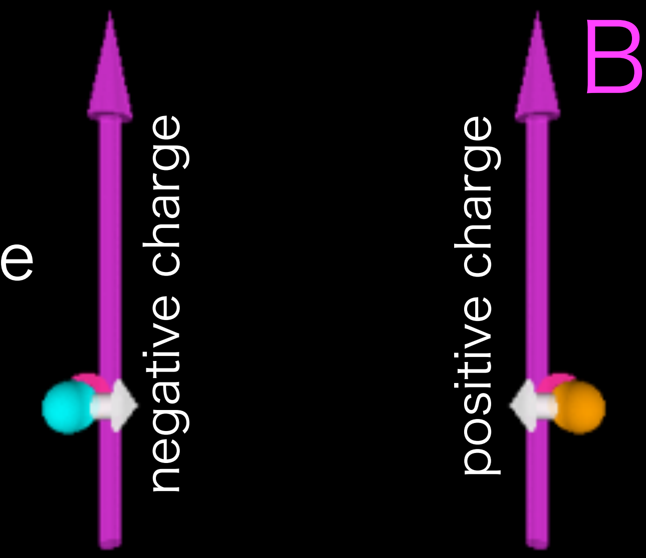
B.C. $\phi(\vec{R}) = \dfrac{\mu\Omega\sin^2\theta}{cR} + \mathrm{const}, \quad \phi(\infty) = 0$

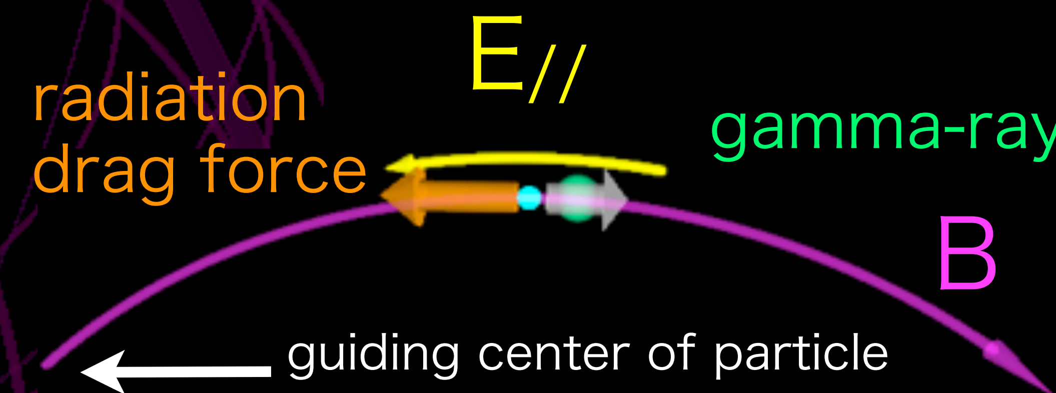
Magnetic field

$$-\nabla^2\vec{A} = \vec{0}$$; dipole+quadrupole

$$-\nabla^2\vec{A} = \frac{4\pi}{c}\vec{j}$$

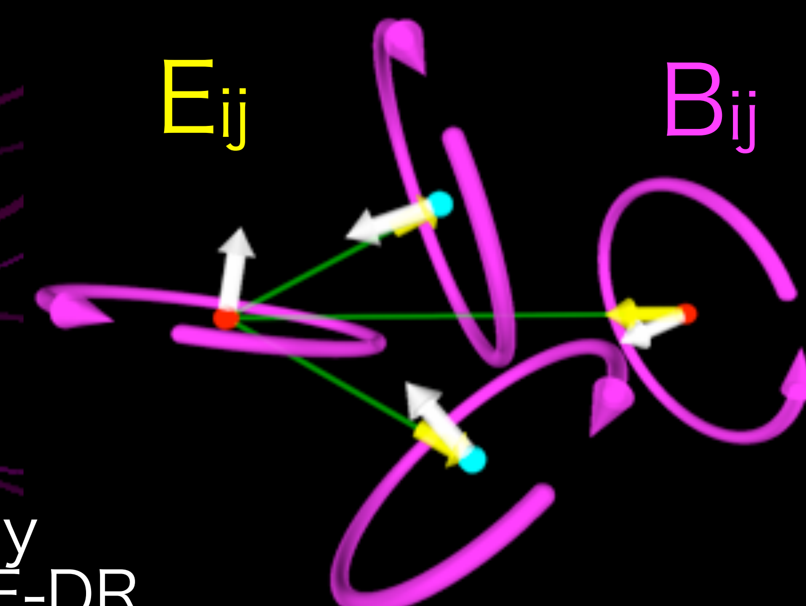
B.C. $\vec{A}(\vec{R}) = \vec{e}_\varphi\dfrac{\mu\sin\theta}{R^2}, \quad \vec{A}(\infty) = \vec{0}$





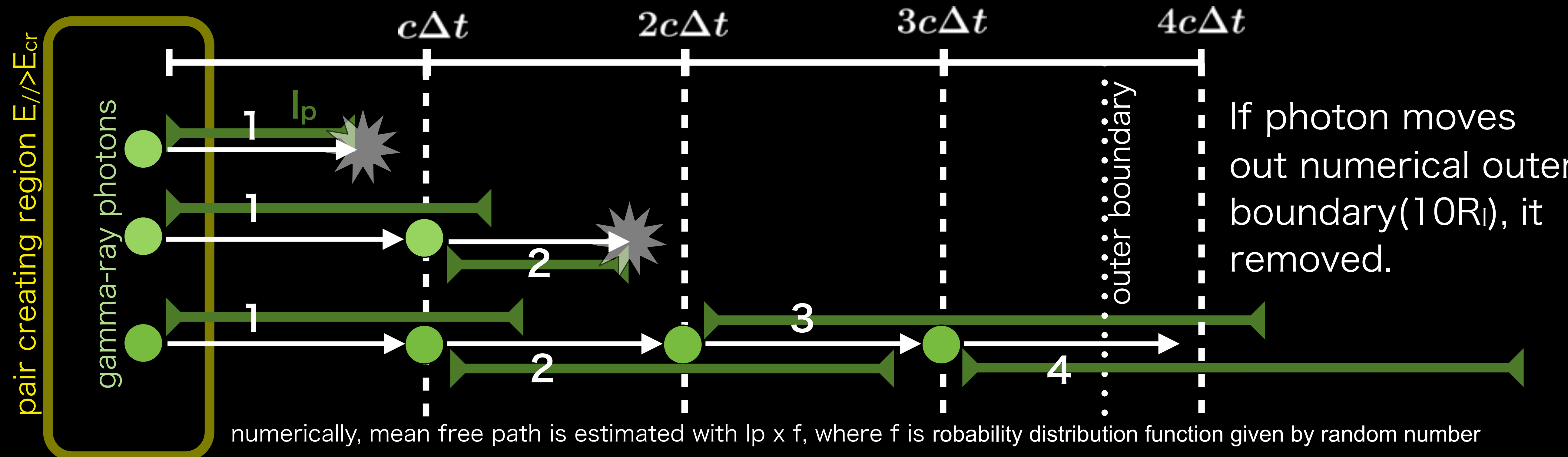
Equation of motion(3D)

$$m_i\frac{\mathrm{d}\boxed{\gamma_i}\vec{v}_i}{\mathrm{d}t} = q_i\left[\vec{E}_i + \frac{\vec{v}_i}{c}\times\vec{B}_i\right] + \boxed{\vec{f}_{\mathrm{rad},i}}$$



Static electro-magnetic interaction is calculated by special purpose programmable computer, GRAPE-DR.
CfCA web site: http://www.cfca.nao.ac.jp

Treatment of pair creation



numerically, mean free path is estimated with lp x f, where f is robability distribution function given by random number

X-gamma

$$l_\mathrm{p} = \frac{1}{n_\mathrm{X}\sigma_\mathrm{p}}$$

$$\sigma_\mathrm{p} = \frac{3}{16}\sigma_\mathrm{T}(1-v^2)\left[(3-v^4)\ln\frac{1+v}{1-v} - 2v(2-v^2)\right]$$

$$v = \sqrt{1 - \frac{2}{1-\mu_\mathrm{c}}\frac{(mc^2)^2}{\epsilon_\gamma \epsilon_\mathrm{X}}}$$

$\mu_\mathrm{c} = \cos^{-1}\theta$; collision angle

σ_T ; Thomson cross section

B-gamma

$$l_\mathrm{p} = \frac{4.4}{\alpha}\frac{\hbar}{mc}\frac{B_\mathrm{q}}{B_\perp}\exp\left(\frac{4}{3\chi}\right)$$

$B_\perp = B\sin\theta$;perpendicular component of magnetic field for propagating direction of

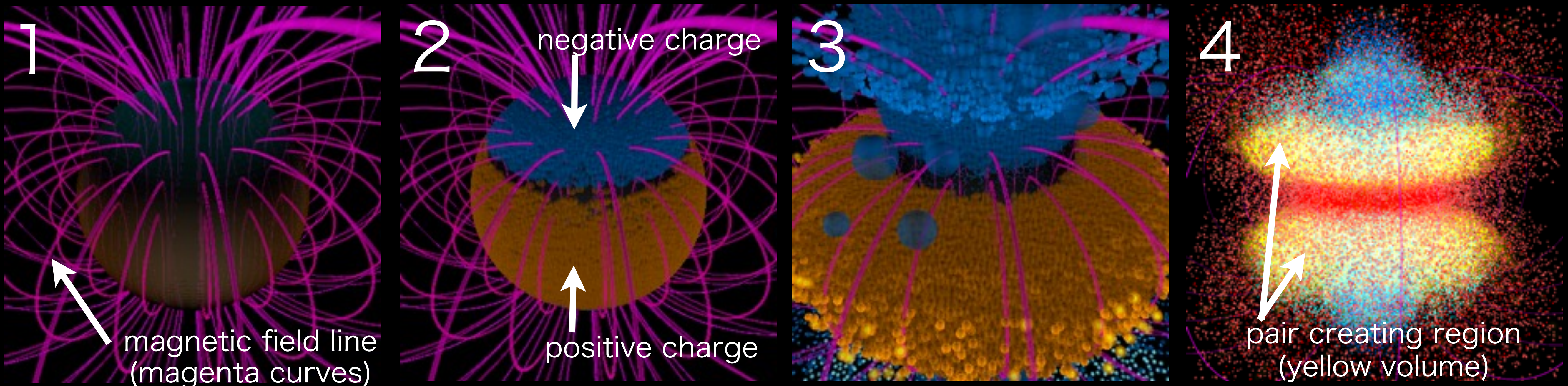
$$\chi = \frac{\epsilon_\gamma}{2mc^2}\frac{B_\perp}{B_\mathrm{q}}$$

$$B_\mathrm{q} = \frac{m^2c^3}{c\hbar} = 4.41\times10^{13}\,\mathrm{G}$$

Outline of particle method

We obtain the steady magnetosphere

- without pair creation(B_{dip}, B_{quad})
- with pair creation <------- **ongoing work**



1. calculate surface charge density
2. replace surface charge density with simulation particle
3. calculate fields (stellar field plus field by space charge and current) at the position of particle and solve equation of motion for each particles
4. Gamma-ray photon is emitted in the accelerating region and convert into e+e-
5. delete particle outside of the outer boundary
6. repeat 1-4 until steady state is obtained

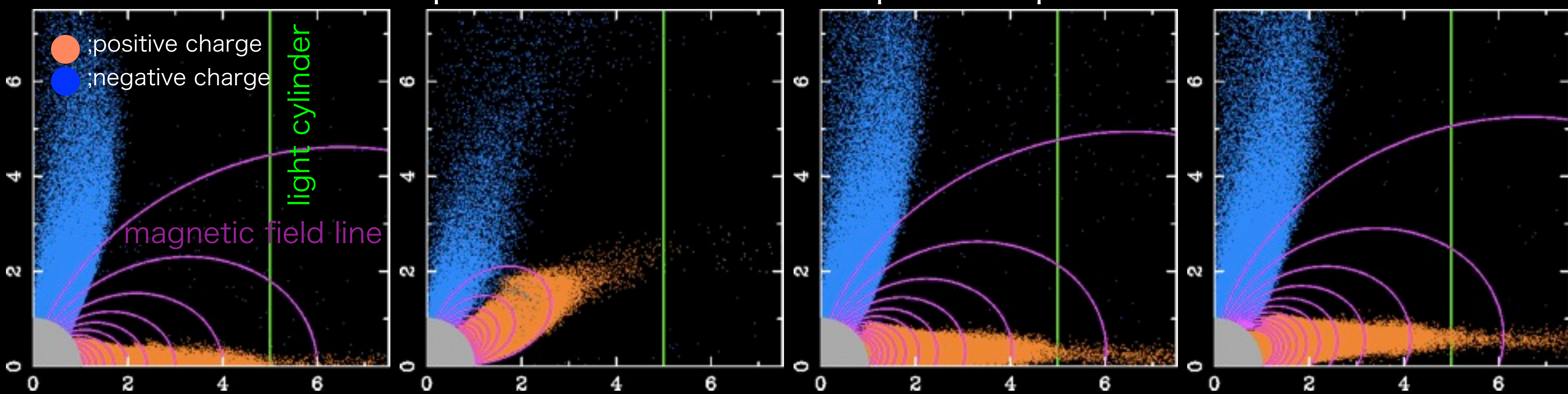
Simulations

We carried out three cases of magnetic field, that is pure dipole case, equivalent case in which intensity of dipole field and quadrupole field has same at the pole and quadrupole dominant case.
After obtaining steady state with no pair case, pair creation model is carried out successively.For pair creation, energy dependence of photon is considered, but the multiplicity is fixed low value artificially.
“X-gamma”: photon-photon collision process
“B-gamma”: magnetic pair creation

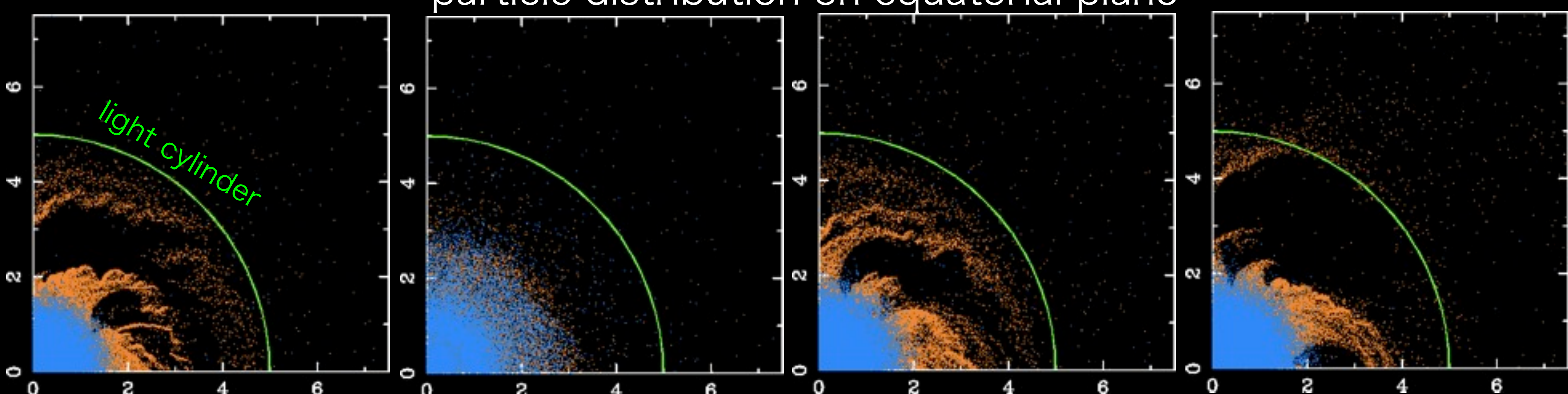
	no pair	X-gamma	B-gamma
B_{dip}	done	ongoing	ongoing
B_{quad}	done	not-yet	not-yet
$B_{dip}=B_{quad}$	done	not-yet	not-yet
$B_{dip}<B_{quad}$	done	not-yet	ongoing

Result 1: pair suppressed case

particle distribution on poloidal plane



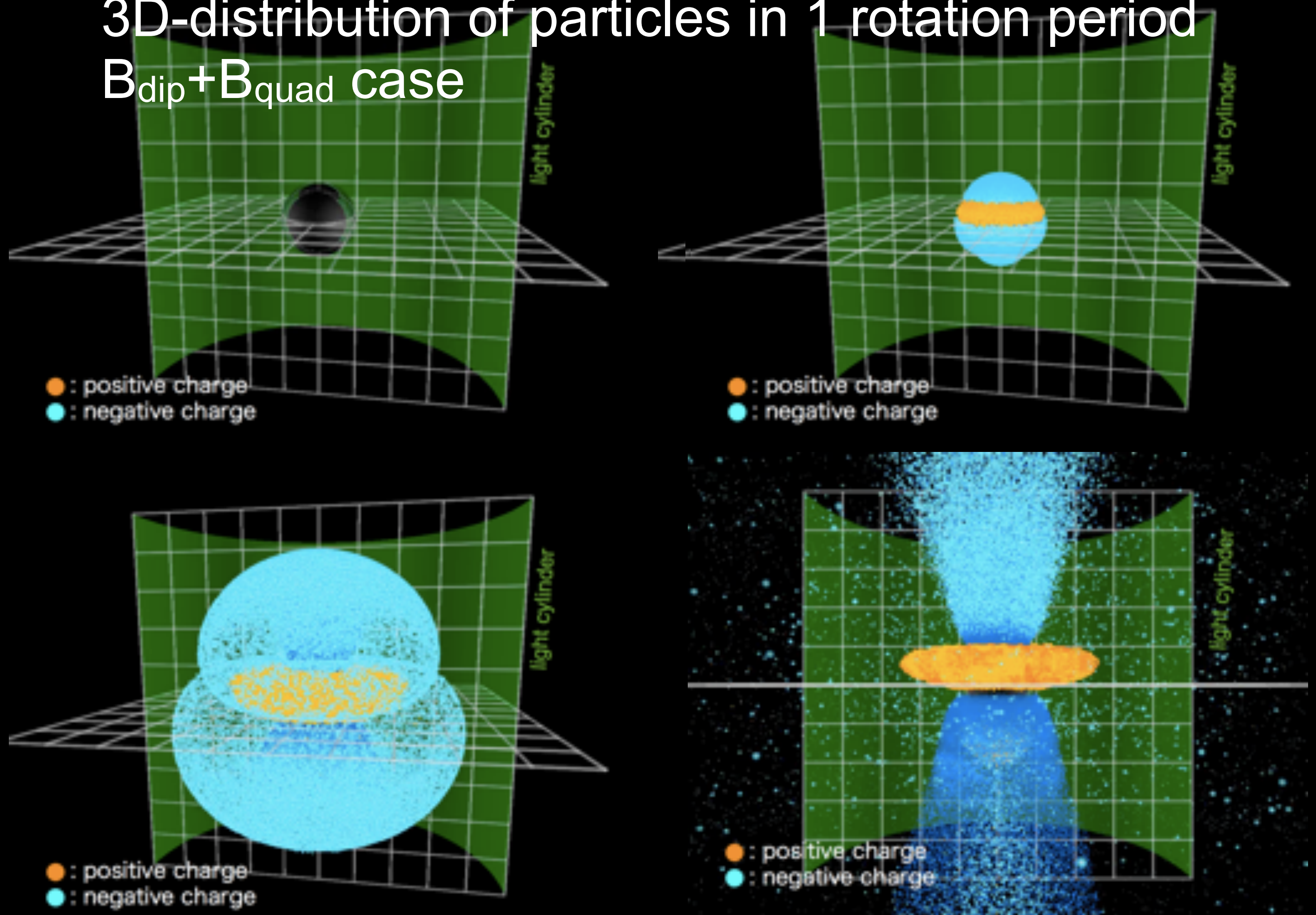
particle distribution on equatorial plane

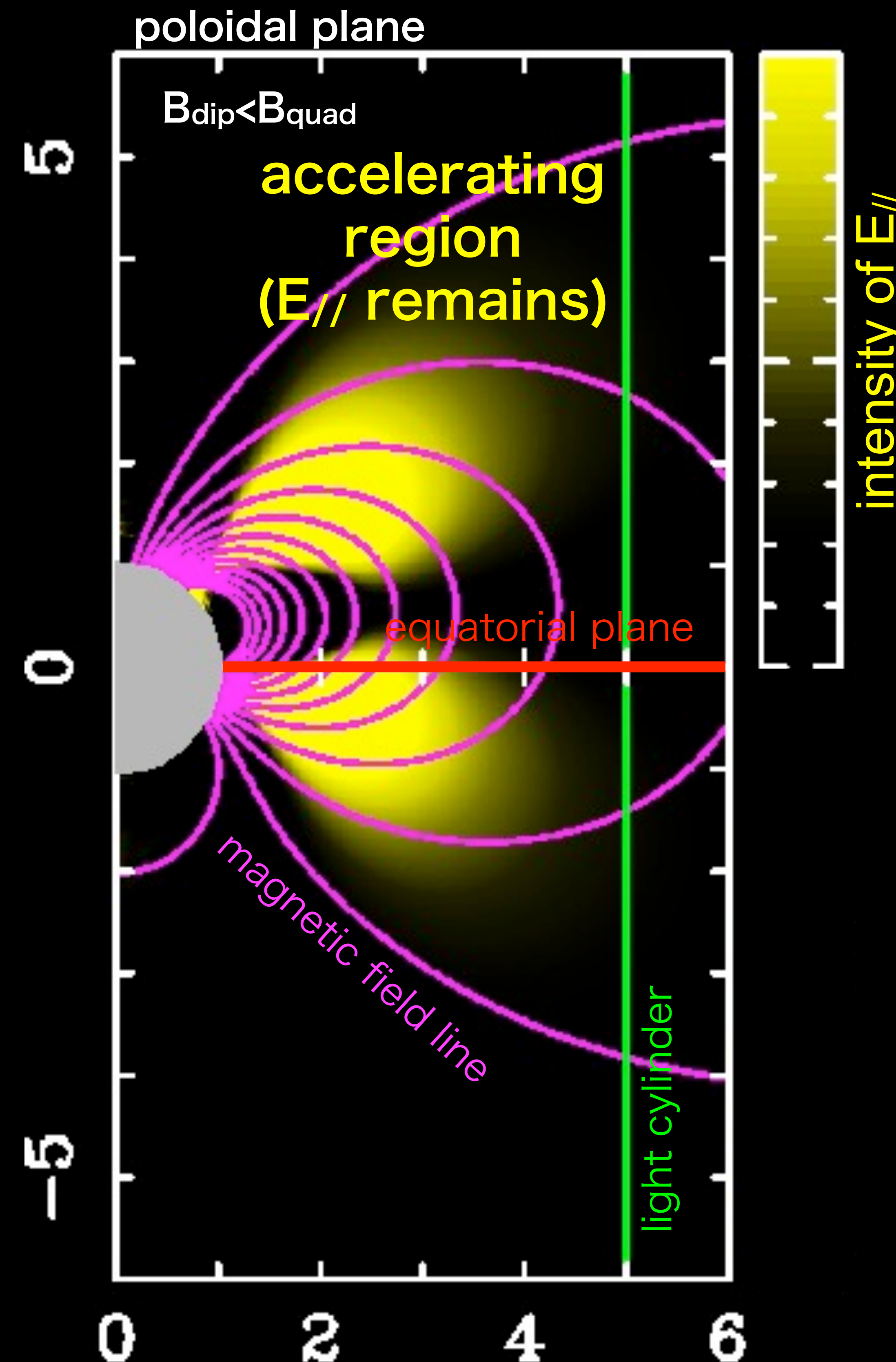


Static electrosphere(polar domes and equatorial disc)+weak outflow of plasma(diocotron instability and f_{rad} x B drift)

Remark: B_{quad} dominant case

3D-distribution of particles in 1 rotation period
$B_{dip}+B_{quad}$ case

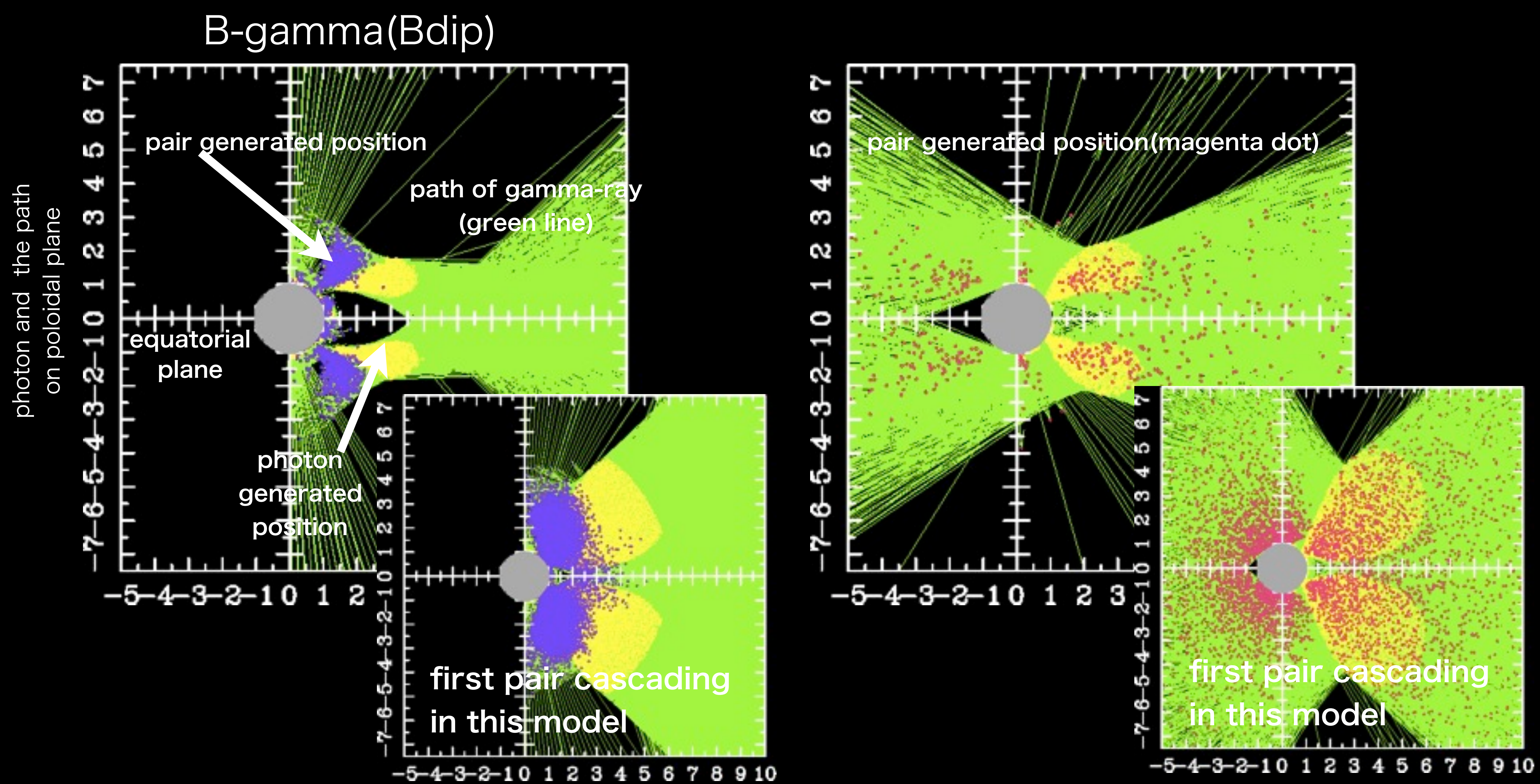




If pair plasma is suppressed and B_{quad} is dominant near the star rather than B_{dip},

- asymmetric stellar field(B_p, induced E_p)
- (quasi-)static electrosphere, no wind
- asymmetric accelerating region on both sides of equatorial plane(see, right panel)
- the number of returning plasma might differ in the north and south hemisphere

Result 2: test run with pairs



Initially, pair cascades in outer gaps, negative charges return star and are emitted from pole again. And then, the potential drop is made polar region. We only carried out this model in one rotation period. To obtain final state is challenges for future,

Summary

We demonstrated the particle simulation for axisymmetric pulsar magnetosphere. As a result of test run,

1. If pair cretion is suppressed, quasi static state is obtained as previous work(Wada & Shibata 2011).
2. Multipole B field makes asymmetric electrosphere to the equatorial plane(i.e. symmetric outer gaps)
3. negative charge returns star and potential arise from polar region

Our simulation has just started. In the future work,

- Detailed structure of gaps
  (Can conventional gap models are coexist?; Yuki & Shibata 2012 PASJ)
- Investigation for higher multiplicity and Lower E_{cr} model
- Simultaneous effect of B-gamma and X-gamma

Acknowledgement

I would like to thank Hiroyuki Takahashi, Syota Kisaka, Yugo Kato, Kotaro Fujisawa and Jun Harayama for insightful suggestion and fruitful discussion. I thanks to kindness to repair the visualizing server against the sudden accident despite the fact that it is the day off. And I am grateful for all the help and discussion for everyone in the workshop. Numerical simulation and visualization of the result were carried out on system at Center for Computational Astrophysics(CfCA), NAOJ and supported by Four-dimensional digital universe project(4D2U), NAOJ.

-CfCA: http://www.cfca.jp
-4D2U: http://www.4d2u.nao.ac.jp/

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End

Thanks