Particle acceleration in pulsar magnetosphere

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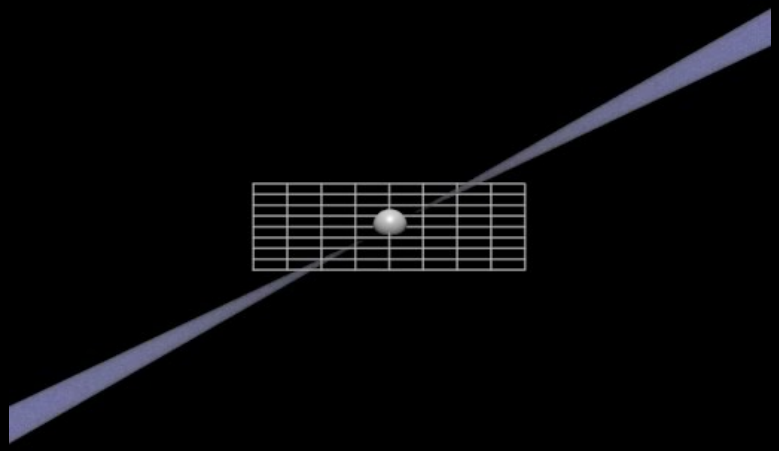
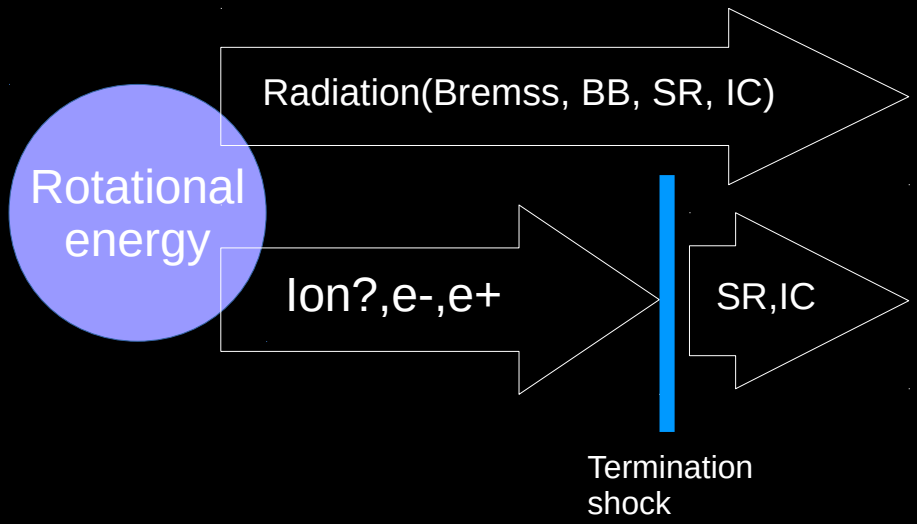
Outline of our presentation

- Pulsar
  - High energy radiation, Pulsar wind
- Outstanding problem
- Numerical simulation
  - Force-free model
  - Particle method
- Our model
- Result
  - Static solution > Active solution
  - Outer gaps and E>B region
  - Sigma < 1 in several light radii
- Summary

Pulsar





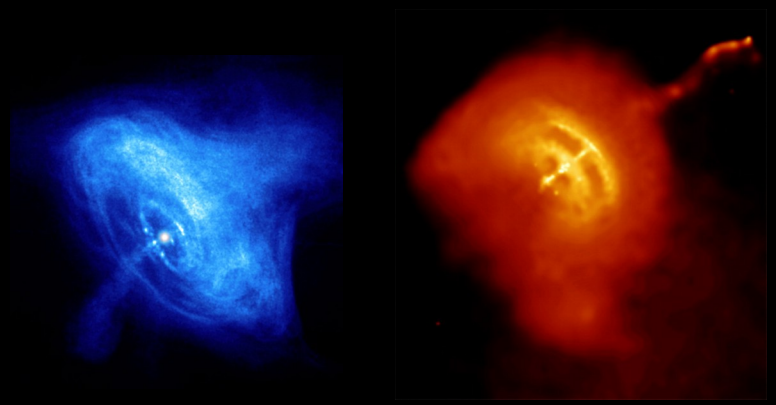
M=1.4M_s, B_0=10^{12}G, P=0.1sec

$$E_{\rm rot} = 10^{49} M_\odot R_6^2 P_{0.03}^{-2}\,{\rm erg}$$

From observation,

$$\dot{P} = 4.2 \times 10^{-13}\,{\rm sec/sec}$$

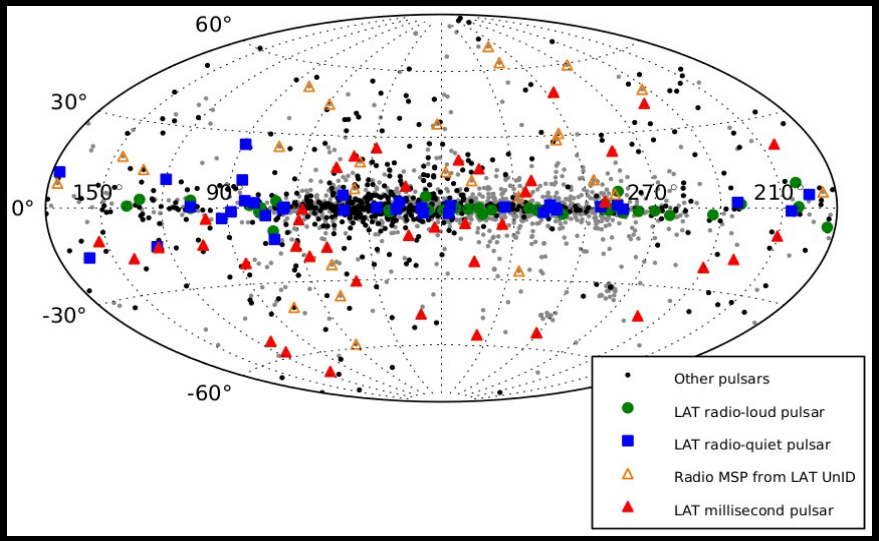
$$\dot{E}_{\rm rot} = 10^{38} M_\odot R_6^2 \dot{P}_{0.03} P_{0.03}^{-3}\,{\rm erg/sec}$$



Crab nebula (left panel), Vela nebula (right panel),
Image credit by NASA

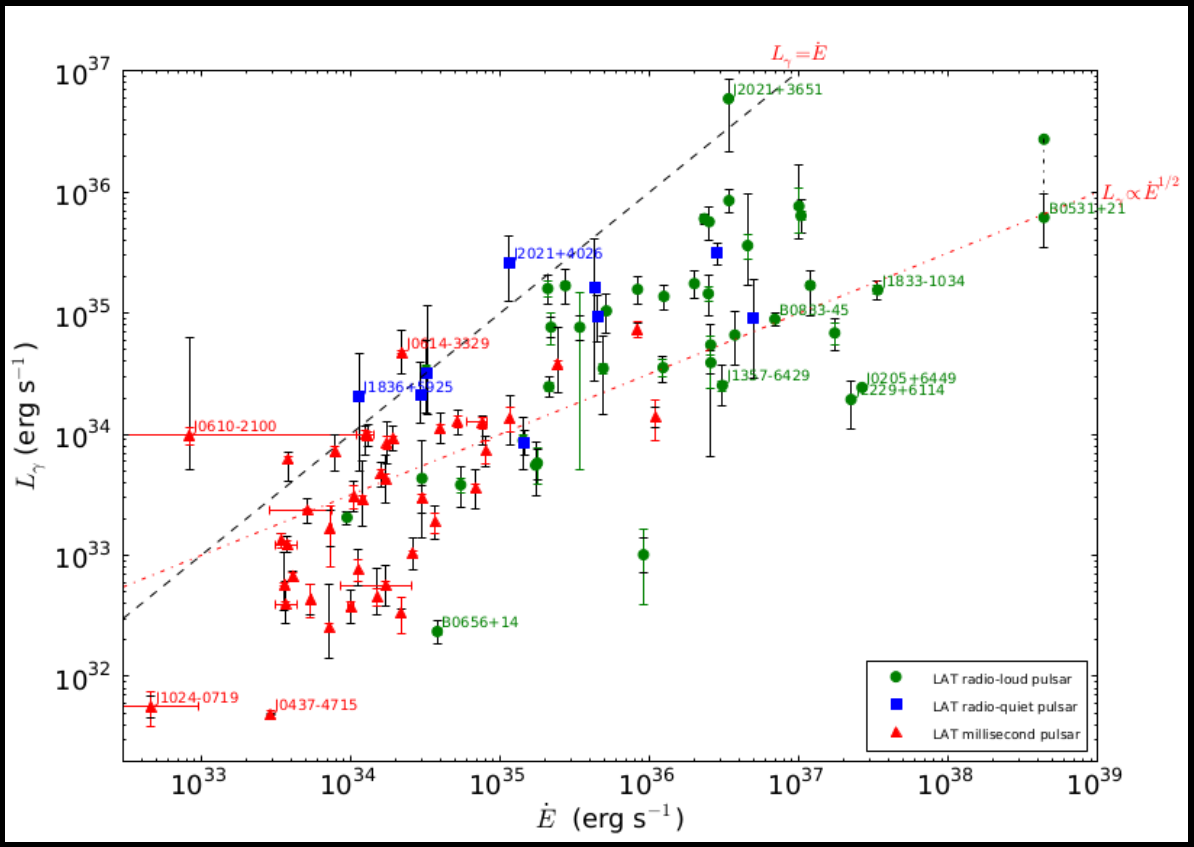
The 2ND Fermi LAT Catalog of gamma-ray PSR

Abdo et al 2013 ApJS



$$\epsilon_{\rm c} = 0.1\gamma_7^3 \left(\frac{R_{\rm c}}{R_{\rm l}}\right)^{-1} \ {\rm GeV}$$

$L_\gamma / \dot{E}_{\rm rot}$; Efficiency



Old PSR ← Young PSR

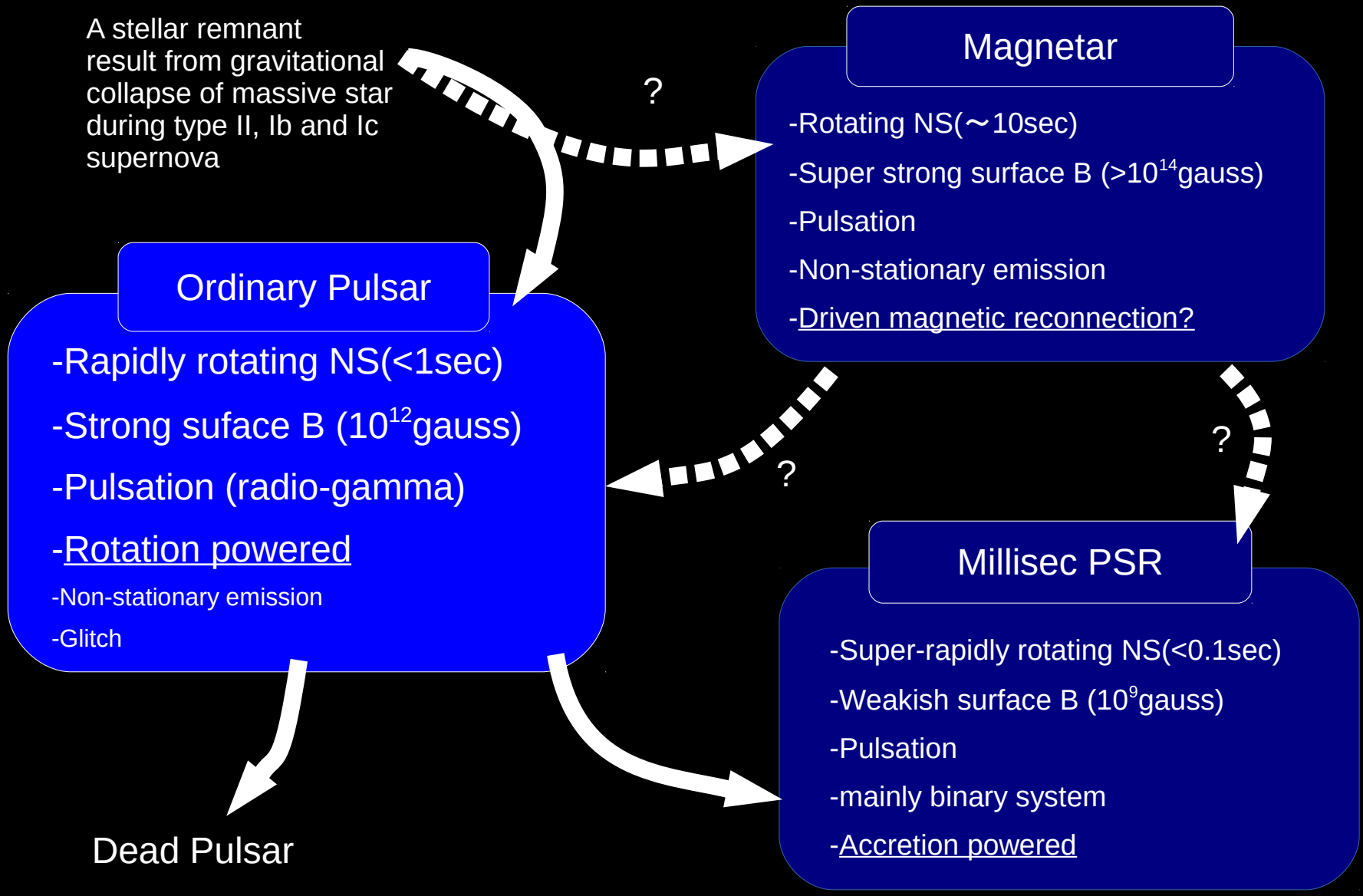
Efficiency shows flat relation (Takata et al 2010 ApJ) rather than conventional dot{E}$^{1/2}$ relation

< May acceleration mechanism have variety?

Number of acclerated plasma?, voltage?, dominant pair creation process(B-γ, X-γ)?

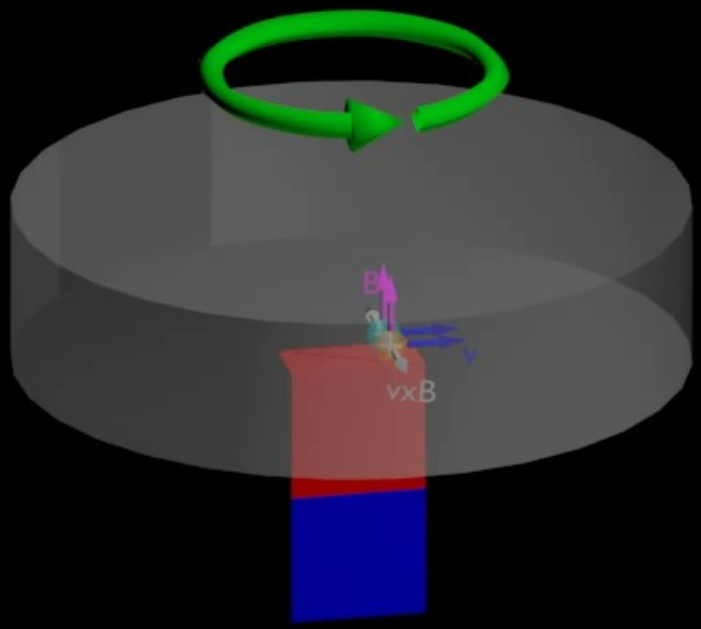
Rotation powered pulsar(RPP)

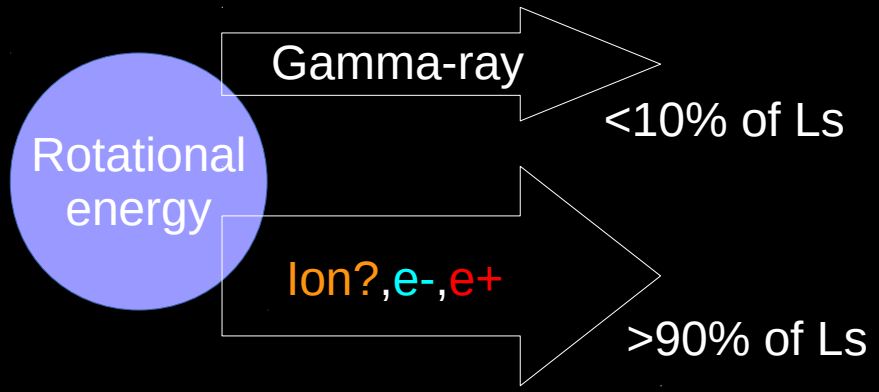
Evolution path of NS is still uncertain.



Central engine of RPP

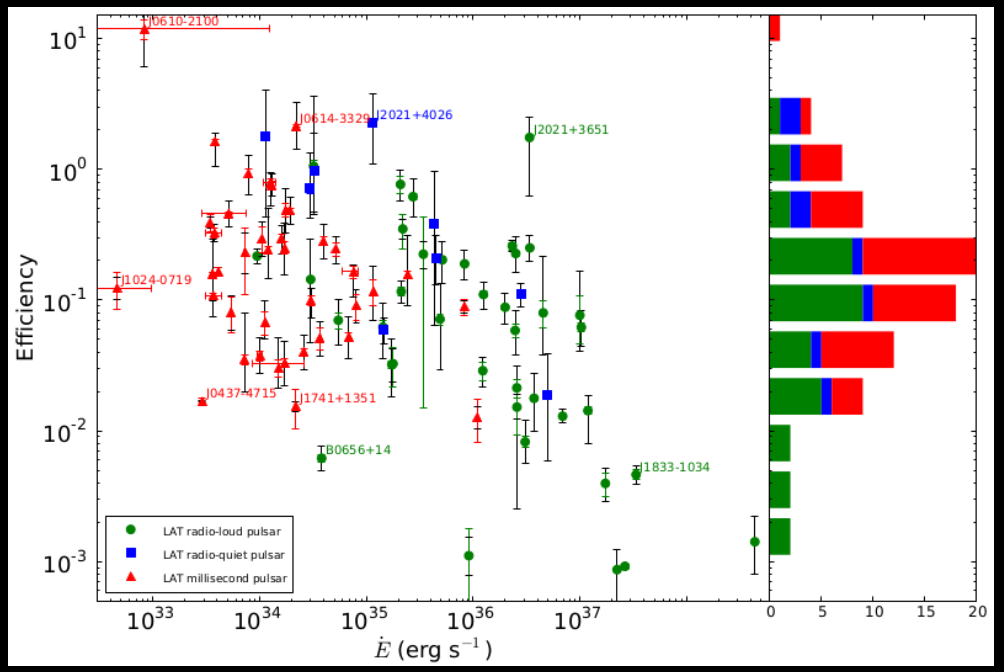
Unipolar dynamo by rotating magnetized star





$$qE_{\rm uni} = q\frac{\phi_{\rm uni}}{R_0} = q\frac{\Omega_0 R_0}{c}B_0$$

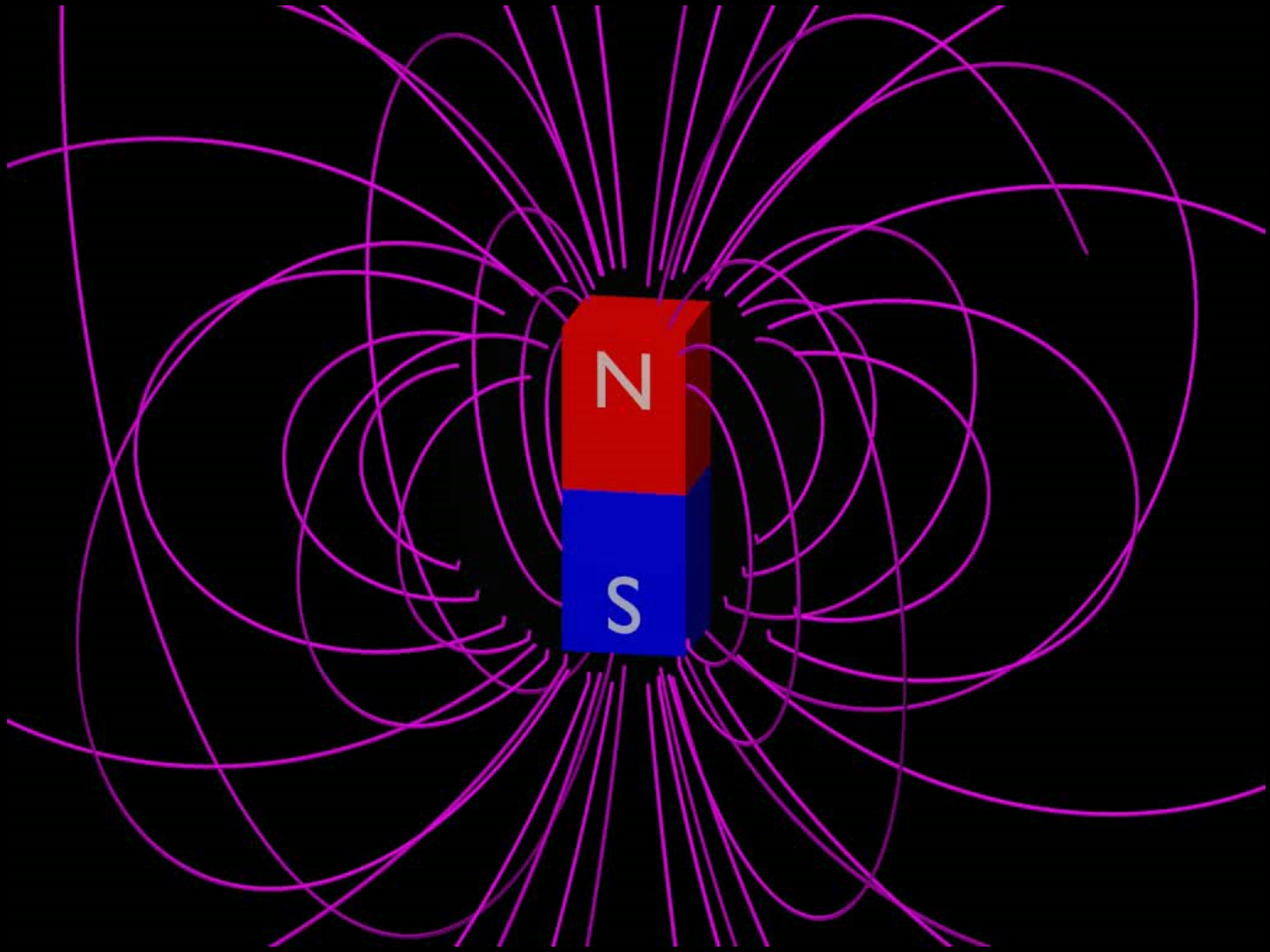
$$\phi_{\rm uni} = 2\times 10^{18} B_{12} R_6^2 P_{0.03}^{-1}\ {\rm Volt}$$



Abdo et al 2013 ApJS

< Why different pair creating processes(B-gamma,X-gamma) makes similar efficiency?

Simple unipolar induction model of NS



Magnetic field line
Electric field line

$$F_E / F_{\mathrm{g,proton}} \sim 10^{10}, \quad F_E / F_{\mathrm{g,electron}} \sim 10^{13}$$

↳ Induced electric field pulls out plasma from stellar surface and forms magnetosphere

(Goldreich & Julian 1969 ApJ)

High energy emission mechanism

$$r_{\rm g} = 1.7 \times 10^{-2} R_6^3 B_{12}^{-1} \gamma_7 \,{\rm cm}$$

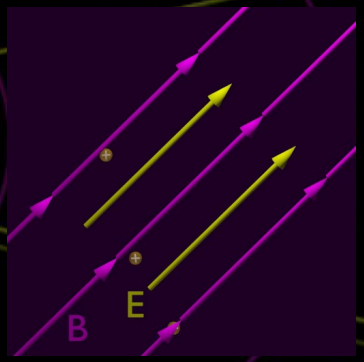
$$\frac{{\rm d}\epsilon_{\rm ph}}{{\rm d}t} = \frac{2}{3}\frac{q^2 c}{R_{\rm c}^2}(\beta\gamma)^4 \sim \vec{f}_{\rm rad} \cdot \vec{v}$$

$$\epsilon_{\rm c} = 0.1 \gamma_7^3 \left(\frac{R_{\rm c}}{R_{\rm l}}\right)^{-1} \,{\rm GeV}$$

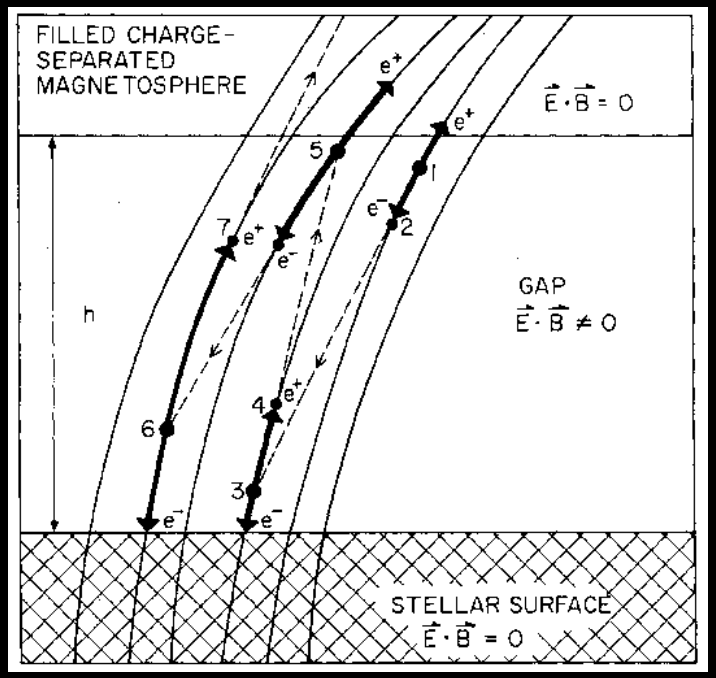
$$\gamma_{\rm sat} = 2.8 \times 10^6 \left(\frac{E_{\parallel}}{B_{\rm l}}\right)^{1/4} \left(\frac{R_{\rm c}}{R_{\rm l}}\right)^{1/2}$$

$$\dot{n}_{\rm ph} = 6.8 \times 10^6 P_{0.03}^{-1} \gamma_7 \ /{\rm e\text{-}},{\rm e}+$$

※$R_{\rm l}$ is a maximum size of accelerating region

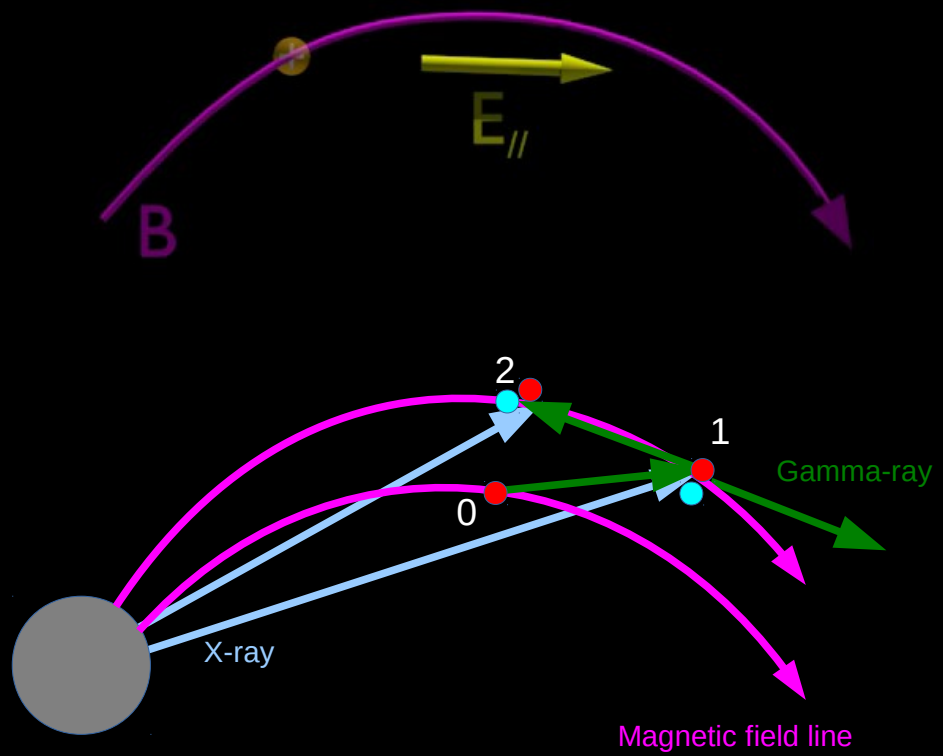


Pair creation



Ruderman & Sutherland 1975 ApJ

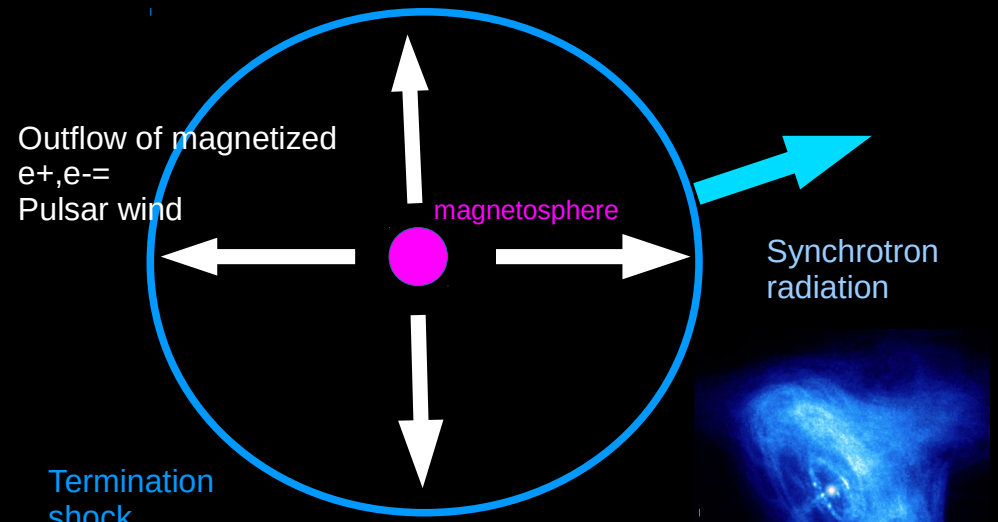
$$\frac{\mathrm{d}E_{\parallel}}{\mathrm{d}s} = -4\pi(\rho - \rho_{\mathrm{GJ}})$$



Sorry, I could not make movie.

Pair cascading model in the local accelerating region(gap)
Magnetic pair creation near the pole: Ruderman & Sutherland 1975 ApJ
Photon collision around the LC: Cheng et al 1986 ApJ

Pulsar wind nebula



画像提供: NASA

$$\sigma \equiv \frac{B^2/(4\pi)}{n v_r m\gamma c^2}$$; magnetized parameter

Kennel & Koroniti 1984b ApJ
-Spherical symmetry for PSR wind
-Special relativistic Ideal MHD
-Adiabatic cooling by SR
>Rankine-Hugoniot equation

σ>>1 → σ=0.003<<1

Magnetosphere — Termination shock

-Synchrotron Radiation (Shklovsky 1953)
-Energy equipartition (B, plasma)
-Multi-wavelength spectra

$$h\nu = \frac{3}{2}\hbar\frac{qB}{mc}\gamma^2$$

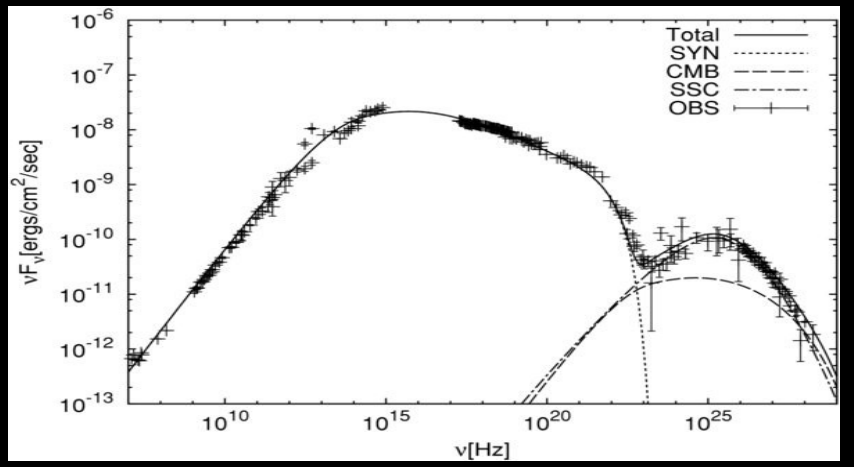
$$\gamma mc^2 n = \frac{B^2}{8\pi}$$

$$P_{\rm sy} = \frac{4}{3}\sigma_{\rm T} c\beta^2\gamma^2\frac{B^2}{8\pi}$$

$$B \sim 10^{-4}\,{\rm gauss}\,,\ \dot{n}_{\rm crab} \sim 10^{38}\,/{\rm sec}$$

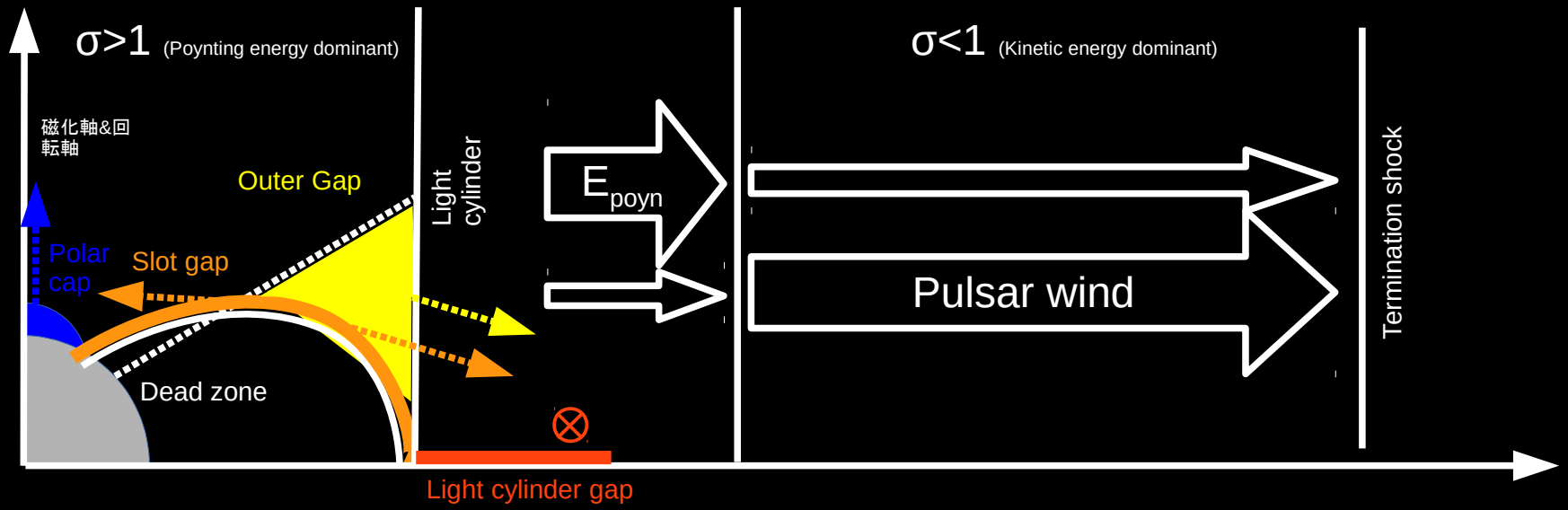
$$\frac{m\gamma c^2}{P_{\rm sy}} = 21\,{\rm yr}$$

Nebula need steady supply of accelerated plasma



Tanaka & Takahara 2010 ApJ

Outstanding problems of pulsar



From NS to nebula,

1.Accelerating region

2.The origin of pulsar wind

3.Energy conversion rate(particle flux)

-Statistical study by Fermi observation

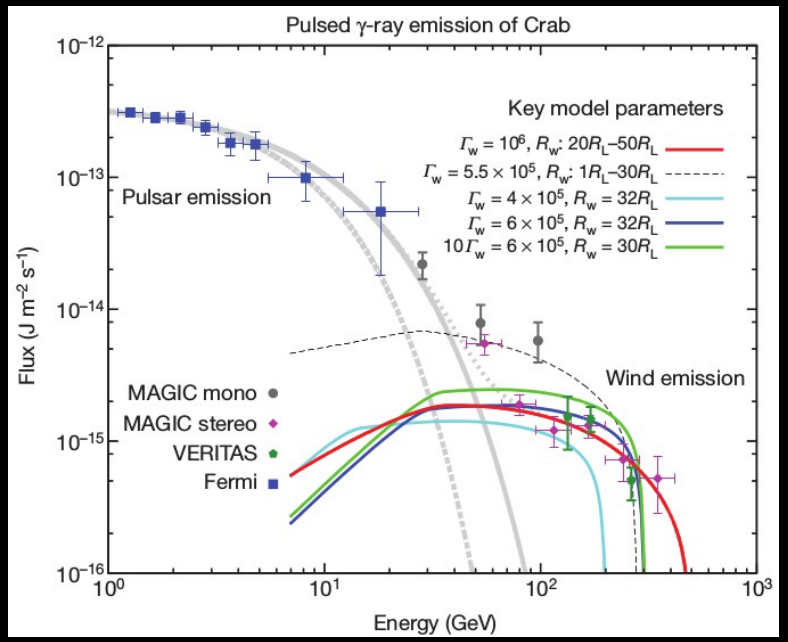
Outer gap model is favorable

< peak number of pulse (Watter & Romani 2011 ApJ)

< spectrum (Hirotani 2014 ApJ)

-Observation >GeV(Fermi,MAGIC,VERITAS)

>Is there any possibility for another accelerating region?



2012 Nature, Ahalonian et al

Numerical solutions of force-free model

Assumption:
Axisymmetric, steady state

$$\Rightarrow \quad \vec{B} = -\frac{\vec{e}_\varphi}{\varpi} \times \nabla\psi$$

$$+ \quad \vec{E} + \vec{\beta} \times \vec{B} = \vec{0} \quad \Rightarrow \quad (1-\varpi^2)\left(\frac{\partial^2\psi}{\partial\varpi^2} + \frac{\partial^2\psi}{\partial z^2}\right) - \frac{1+\varpi^2}{\varpi}\frac{\partial\psi}{\partial\varpi} = -\frac{\mathrm{d}\mathcal{I}}{\mathrm{d}\psi}\mathcal{I}$$

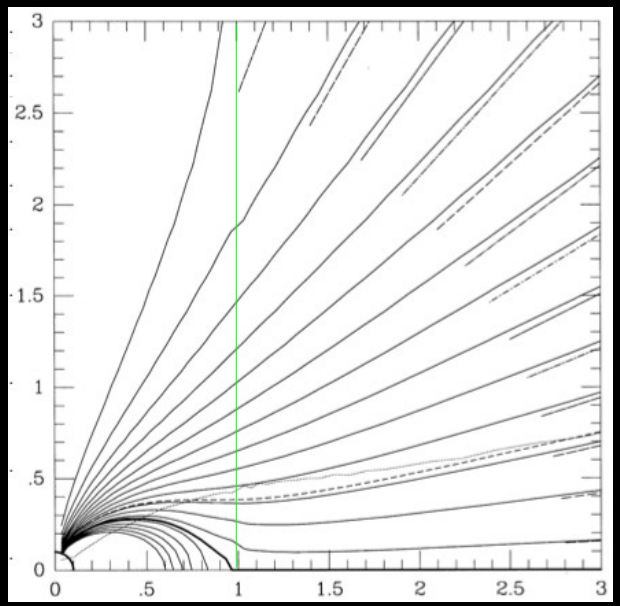
※omit the effect of pariticle inertia

-Different field structures (radial structure or Jet like structure)

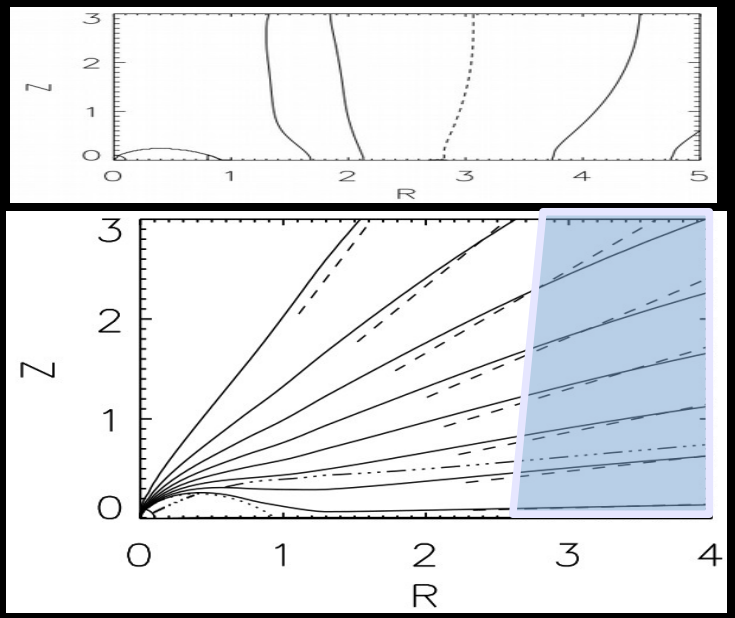
<CS(return current) is important to determine the solution

<Magnetic reconnection in equatorial current sheet (ECS)

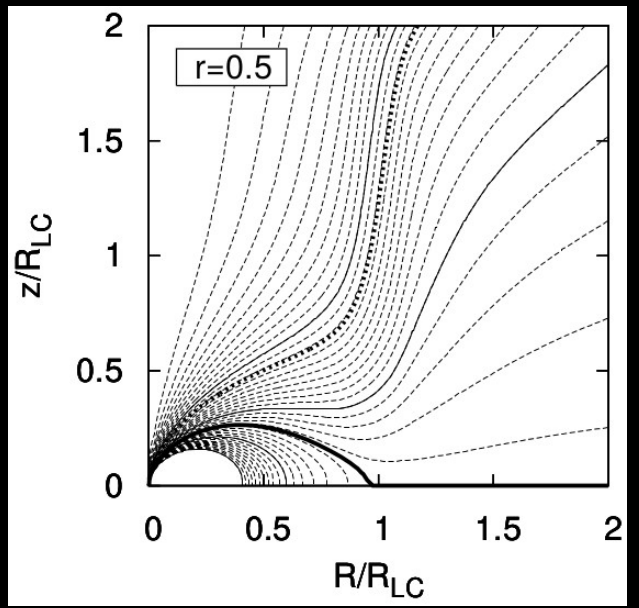
-ExB drift velocity exceeds light speed; force-free approximation is broken (Ogura & Kojima 2003)



Contopoulos et al 1999 MNRAS



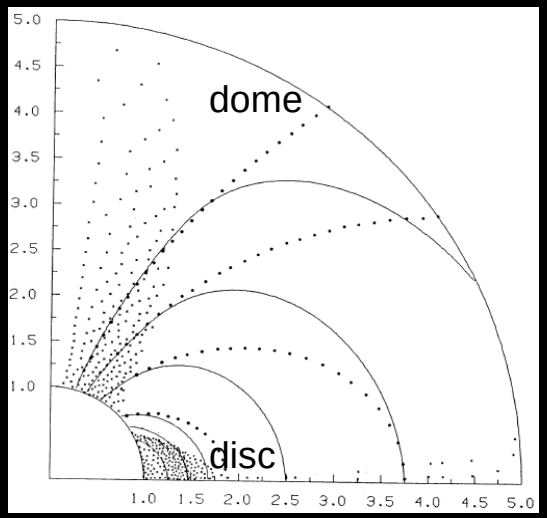
Ogura & Kojima 2003 PThPh



Takamori et al 2014 PASJ

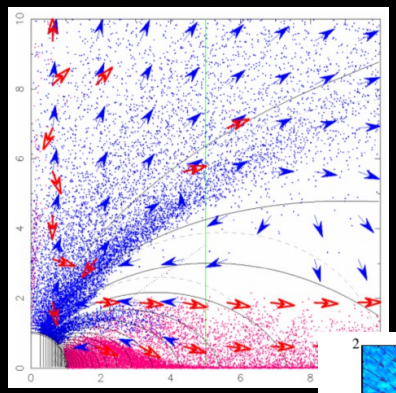
Recent progress of particle method 1

Static state
(No PSR wind)



Krause & Michel 1985 MNRAS

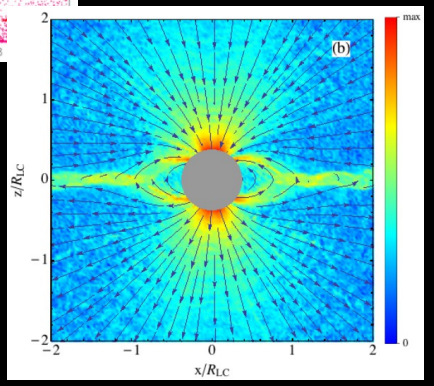
Weak outflow solution



Yuki & Shibata 2012 PASJ
Charge distribution(e+・e-)
Current density(arrows)
Active solution?

Force free like solution

Active state
(PSR wind + Poynting flux)

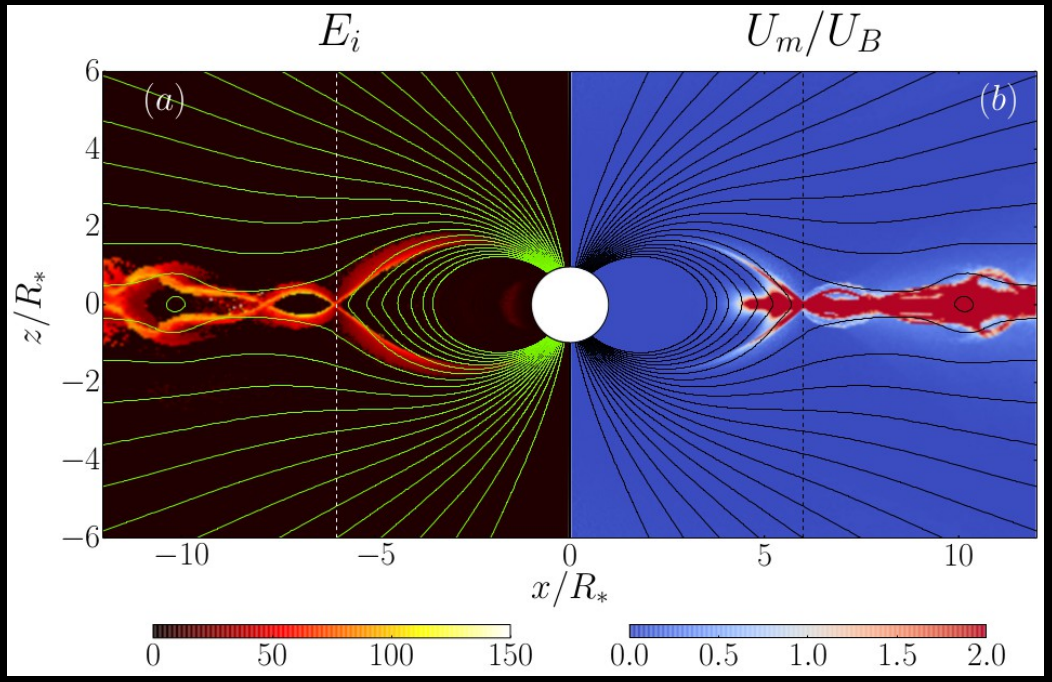


Philippov & Spitkovsky 2014
ApJ(PS2014)
B-field(arrows)
Current density(color map)

-Without pair, Charge separated electrosphere is formed (Disc+Dome)
-Pair creation changes the static state to active state (Pulsar wind + Poynting flux)
(ex. Philippov & Spitkovsky 2014, Yuki & Shibata 2012, WS 2011)
-Poynting energy > Kinetic energy (Philippov & Spitkovsky 2014, all of force-free or mhd simulation)
For sigma < 1, magnetic reconnection at termination shock with stripe wind model (Kirk & Lybarusky 2001)
Sigma < 1 in 10^4Rl (Takata & Taam 2009)
-Outer gap exists (WS 2012) but PIC simulation shows force-free-like solution.

Where does kinetic energy dominant flow form? and Where is pair creating region(accelerating region of gamma-ray)?

Recent progress of particle method 2



Alexander Y et al 2014 astro-ph
-2D PIC(512x512 for RNS, Rob=30RNS)
-e+,e-,ion (mi=5me)
-pair creation
<Rl; dead state
>Rl; active state
Pair creation is sustained by a strong electric field in CS.

	method	Pair insertion	T_{calc}	d/dt effect
PS2014	3DPIC	σ_{cr}	～5P	possible
ACB2014	2DPIC	Γ_{cr}, fixed l_{path}	～5P	possible
WS	3DEM-staticPIC	E_{cr}	～50P	impossible

- Path of gamma-ray for pair creation is not considered(PS2014,WS)
- Radiation drag force is included only WS
- The effect of obliqueness can be considered only with 3DPIC

Outline of our presentation

- Pulsar
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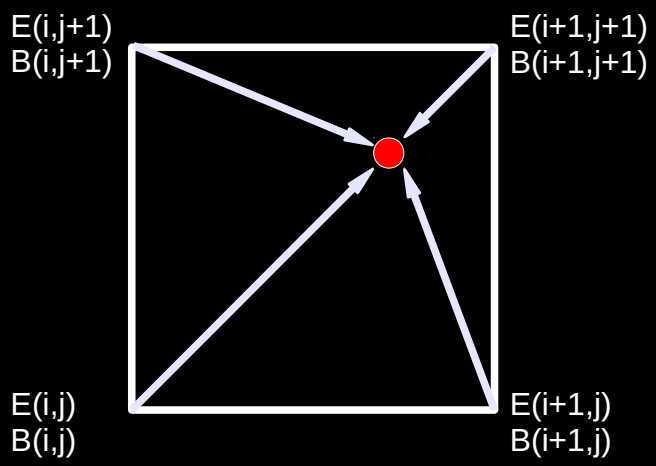
- Outstanding problem
- Numerical simulation
  - Force-free model
  - Particle method
    - PIC
    - Electro-magneto-static PIC
- Our model
- Result
  - Static solution > Active solution
  - Outer gaps and E>B region
  - Sigma < 1 in several light radius
- Summary

PIC method .vs. static PIC method

Particle in Cell (PIC)

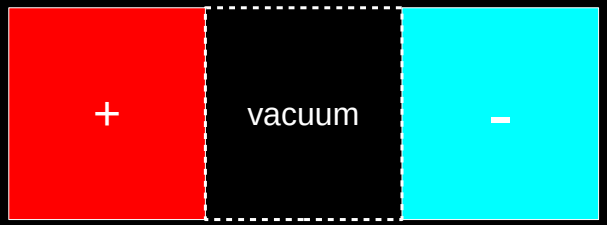
- First principle calculation with classical electromagnetism
- ✗ Require 大規模計算機

  Philippov & Spitkovsky 014 ApJ, 800^3, skin depth 0.5
- ✗ Can not treat vacuum gap region



Electro-magneto-static PIC

- We can use analytical solution (Green function) of Poisson eqs > solve E&B with high accuracy
- Can treat vacuum region
- Wider numerical region
- Calculate longer time
- ✗ Can solve only steady state



Charge separated plasma and vacuum gap

Basic equations(Our Model)

Solve Poisson's equation for elcectro-magnetostatic field and equation of motion for plasma(3D,Special relativistic, Radiation drag force)

$$\rho(\vec{r}) = \sum q_i \delta(\vec{r} - \vec{r}_i)$$

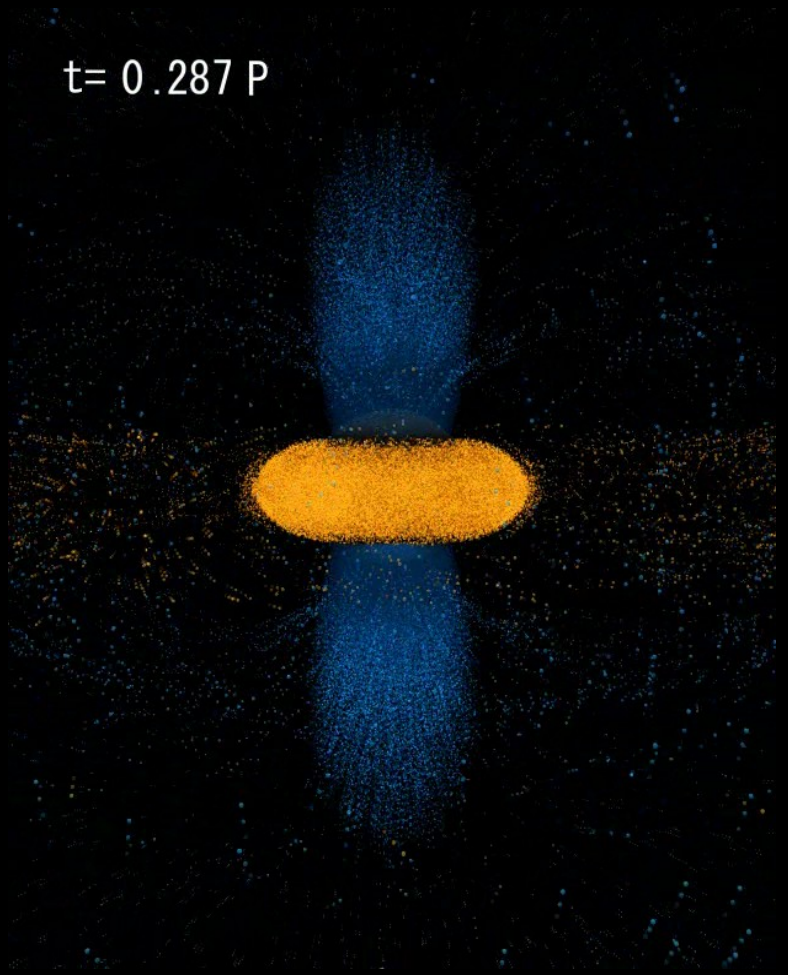
$$\vec{j}(\vec{r}) = \sum q_i \vec{v}_i \delta(\vec{r} - \vec{r}_i)$$

- $-\nabla^2 \phi = 4\pi\rho$ B.C. conductive sphere
- $-\nabla^2 \vec{A} = \frac{4\pi}{c}\vec{j}$ B.C. dipole-magnetized sphere

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

$$\vec{f}_{\mathrm{rad},i} = -\frac{2q_i^4 \gamma_i^2}{3m_i^2 c^5}\left[\left(\vec{E}_i + \frac{\vec{v}_i}{c} \times \vec{B}_i\right)^2 - \frac{1}{c^2}(\vec{E}_i \cdot \vec{v}_i)^2\right]\vec{v}_i$$

Abraham=Lorentz formula



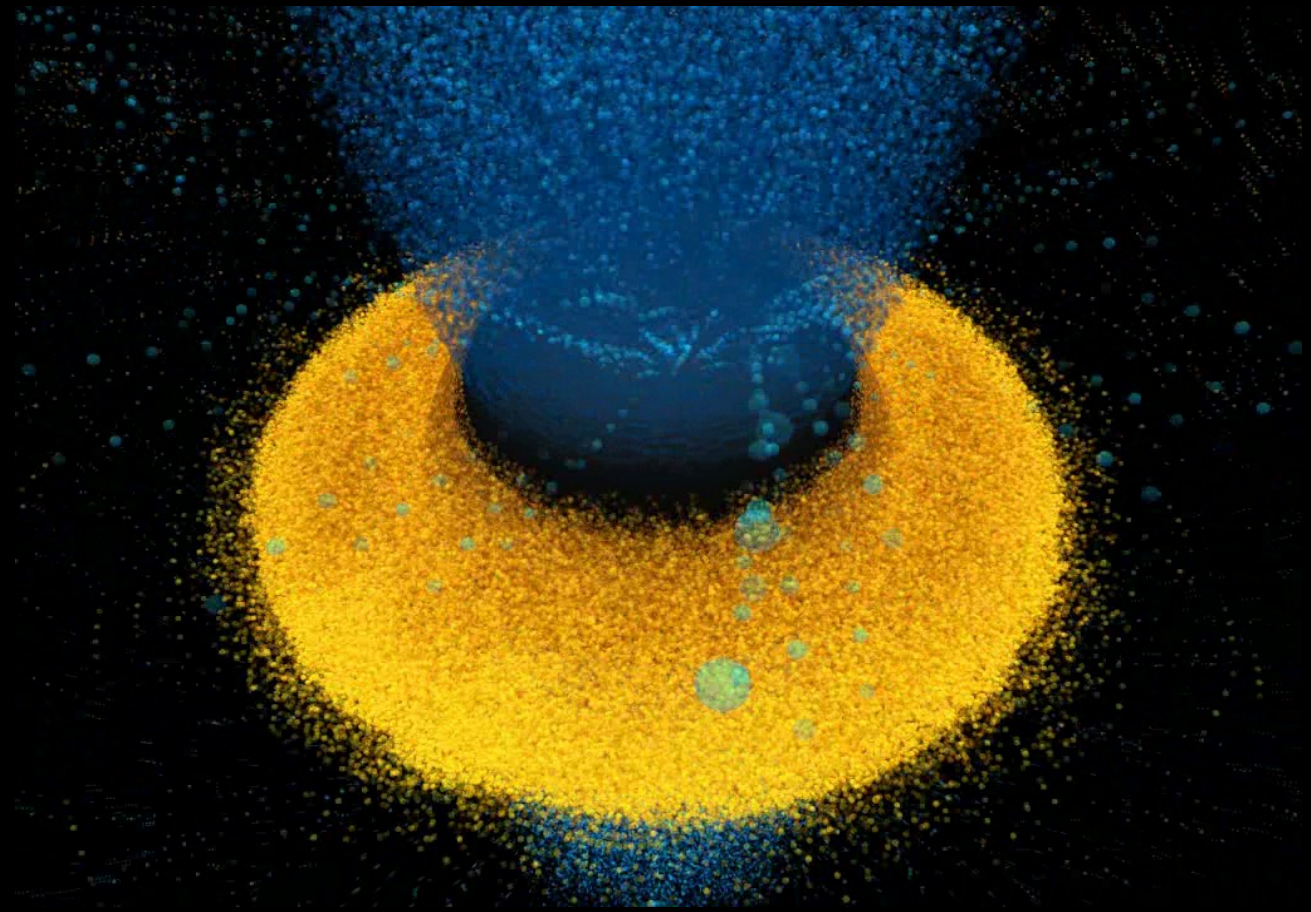
e+, e-

Long time calculation(evolution)

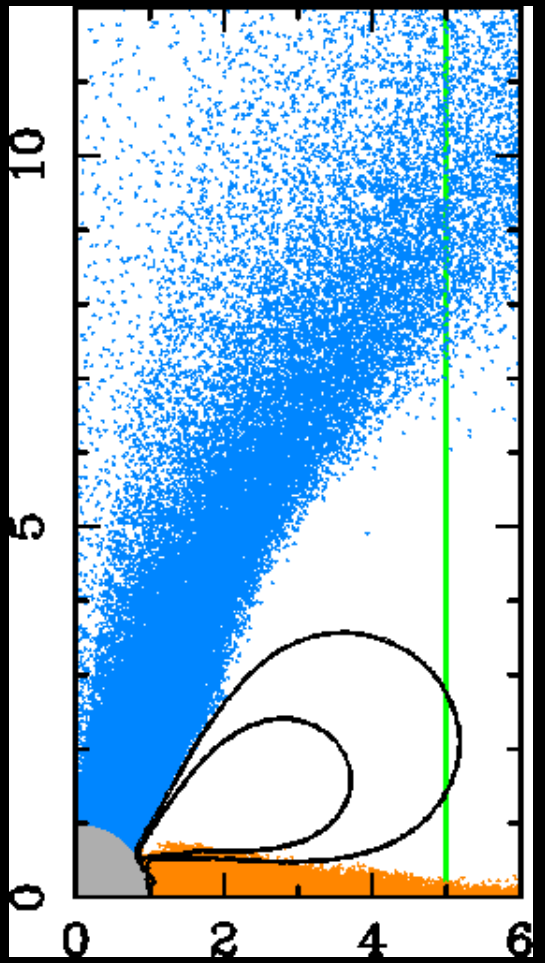
$T_c > 10^{3\text{-}5}$ yr >> $T_{sym,WS}$=50P > T_{sim}=5P ;P=0.1 sec

Time evolution of equatorial disc by diocotron instability(2DPIC): Petri 2009 AA

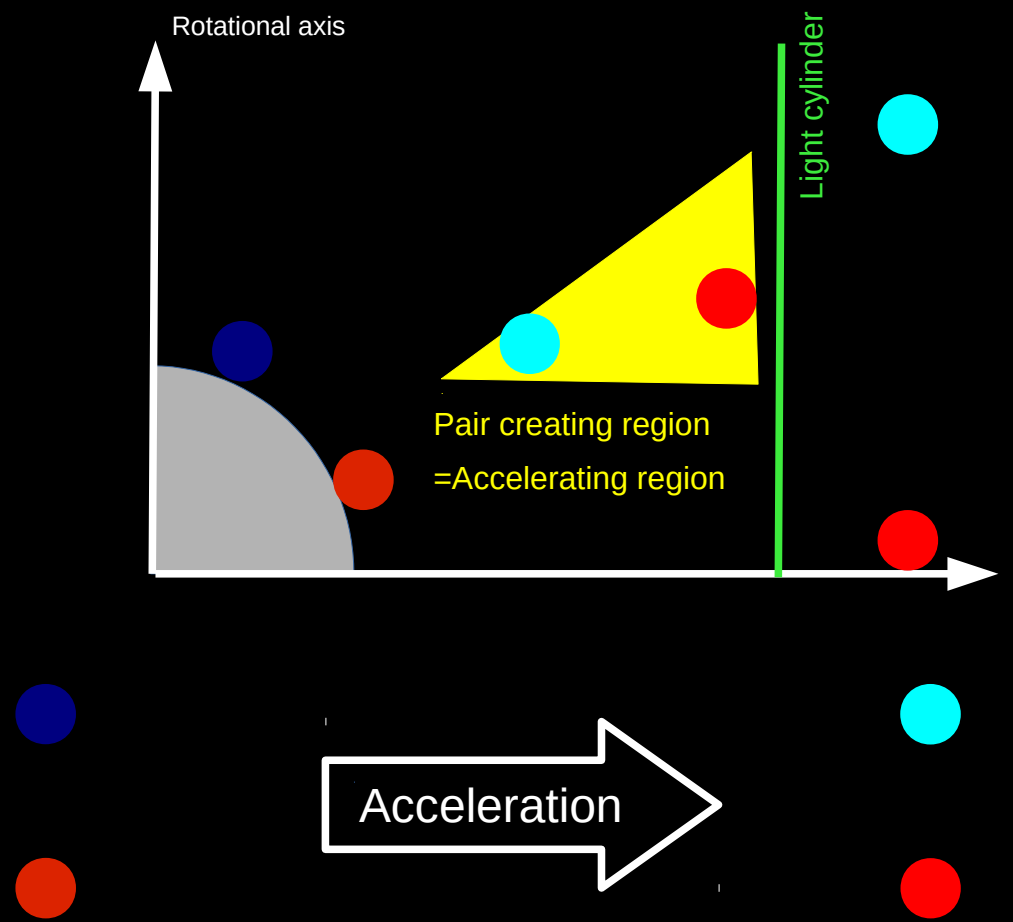
EM-static PIC can calculate global steady structure after 50 rotation periods.



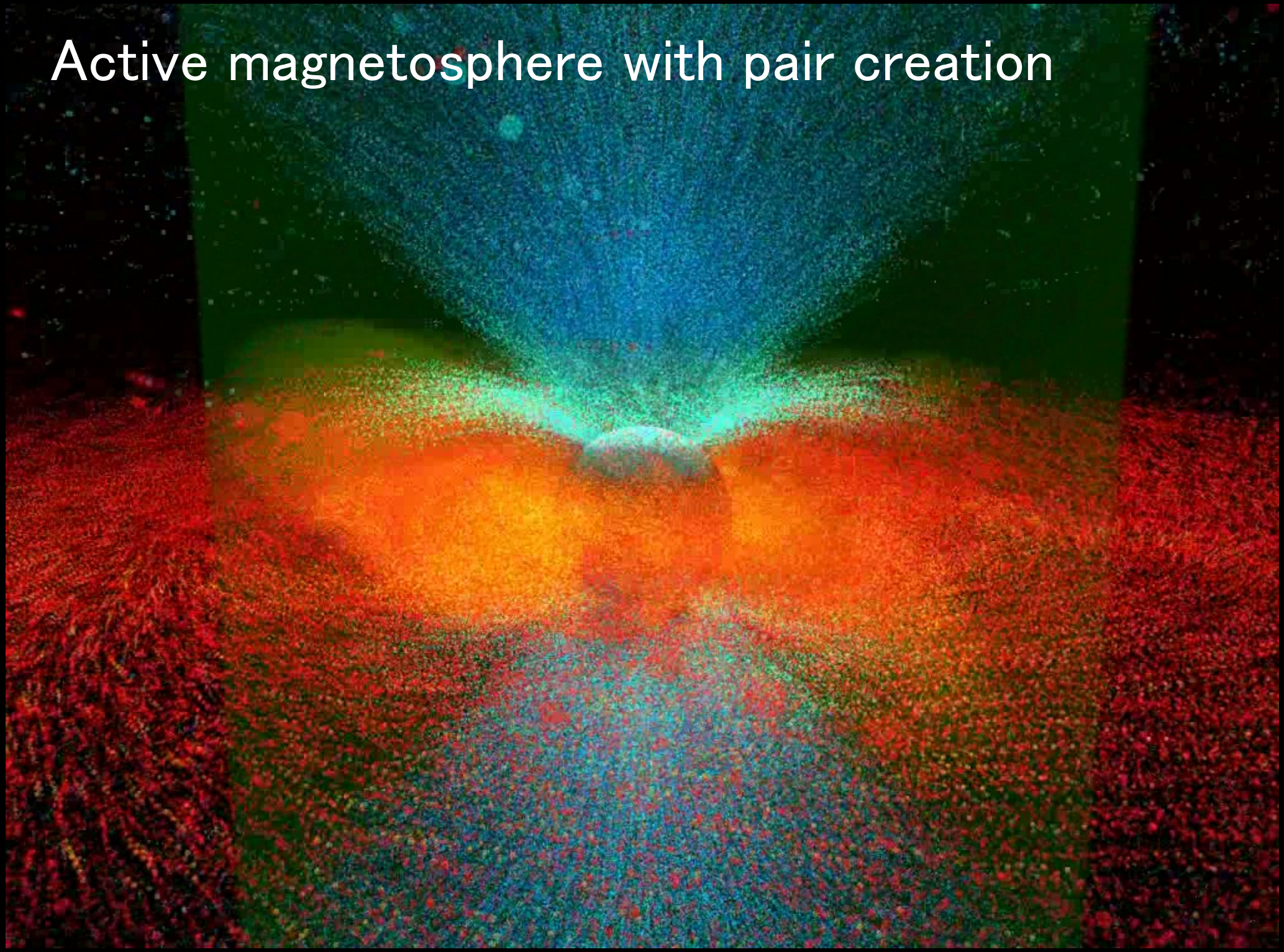
e+, e-



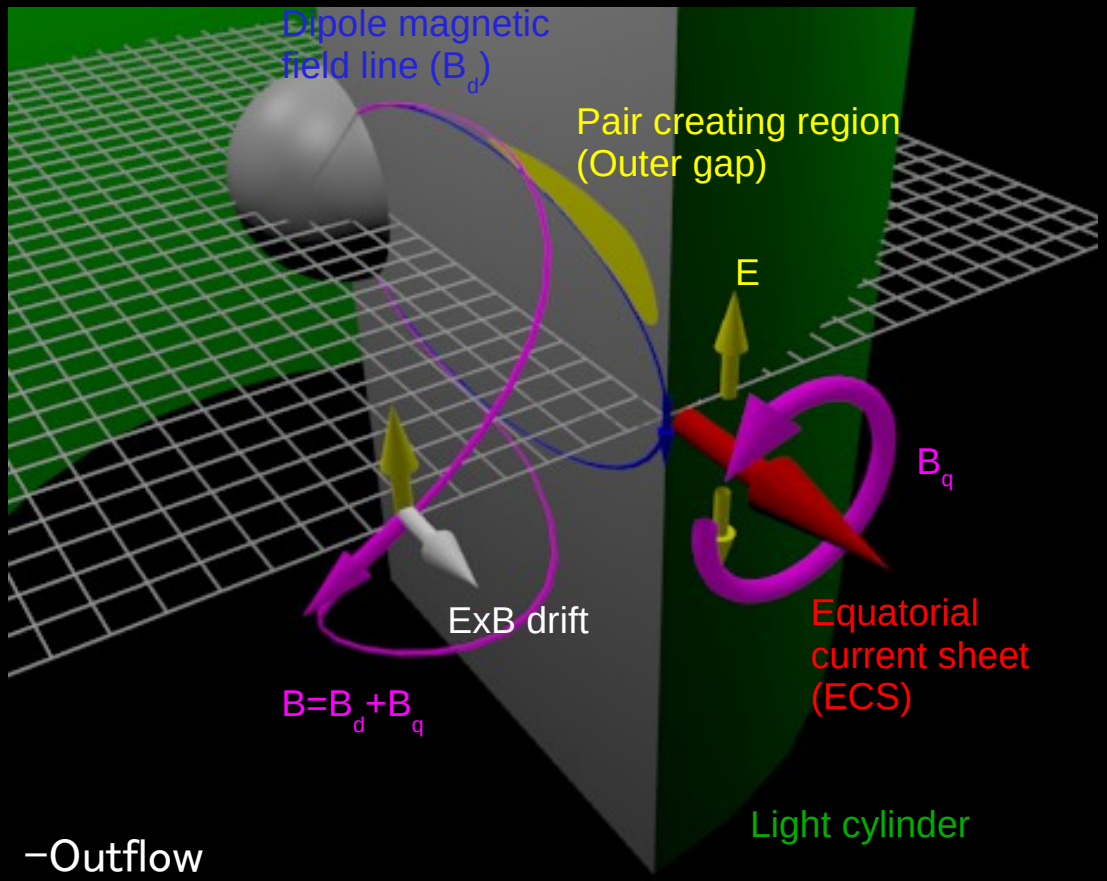
Active magnetosphere with pair creation



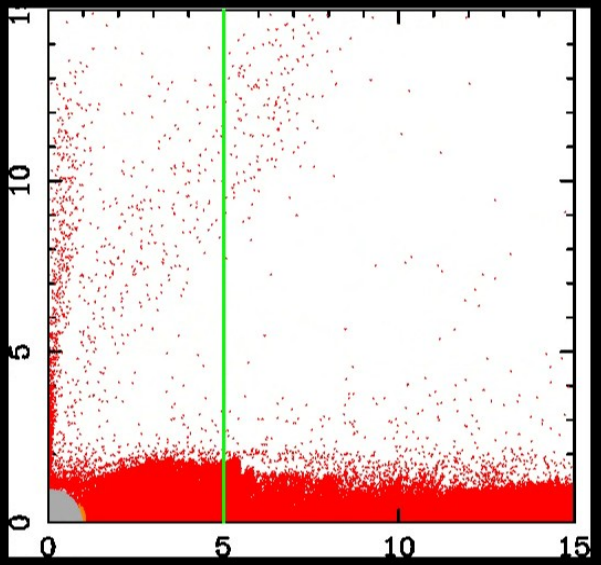
Active magnetosphere with pair creation



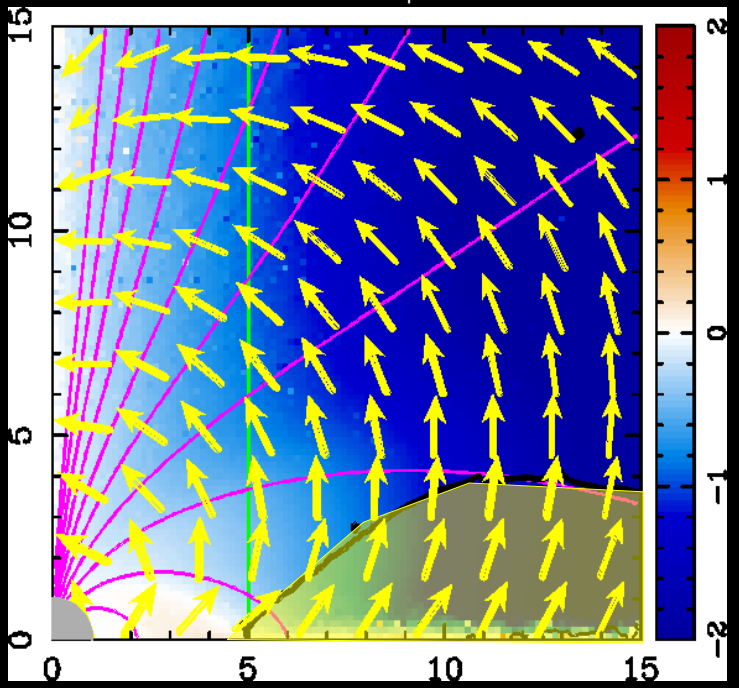
Flow pattern of plasma



Currendensity(arrows)、charges(e+,e-)



E,B: (arrows)、B_{toro}/B_{polo}(color map)



−Outflow

Equatorial plane: e+, Polar axis or radial direction: e−

−Return flow on equatorial plane: e−

In outside of LC, around the ECS, ExB_{toro} drift pulls out plasma > Outer gap is not screened!

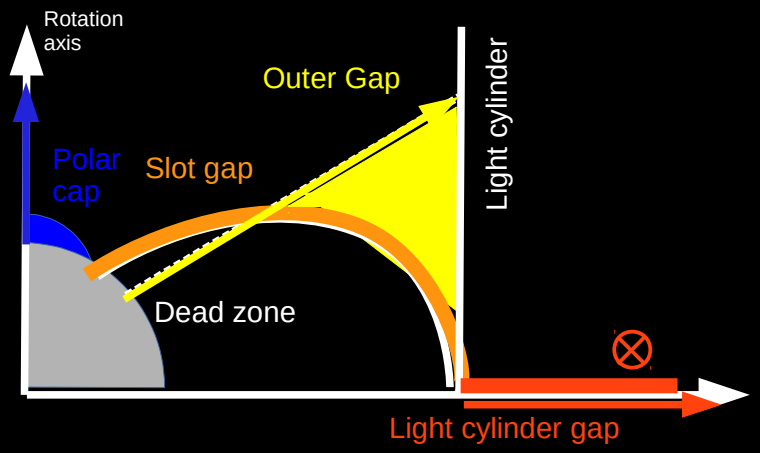
E>B region > Force-free approximation breaks down!

Potential drop in accelerating regions

nM: pair creation rate(parameter)

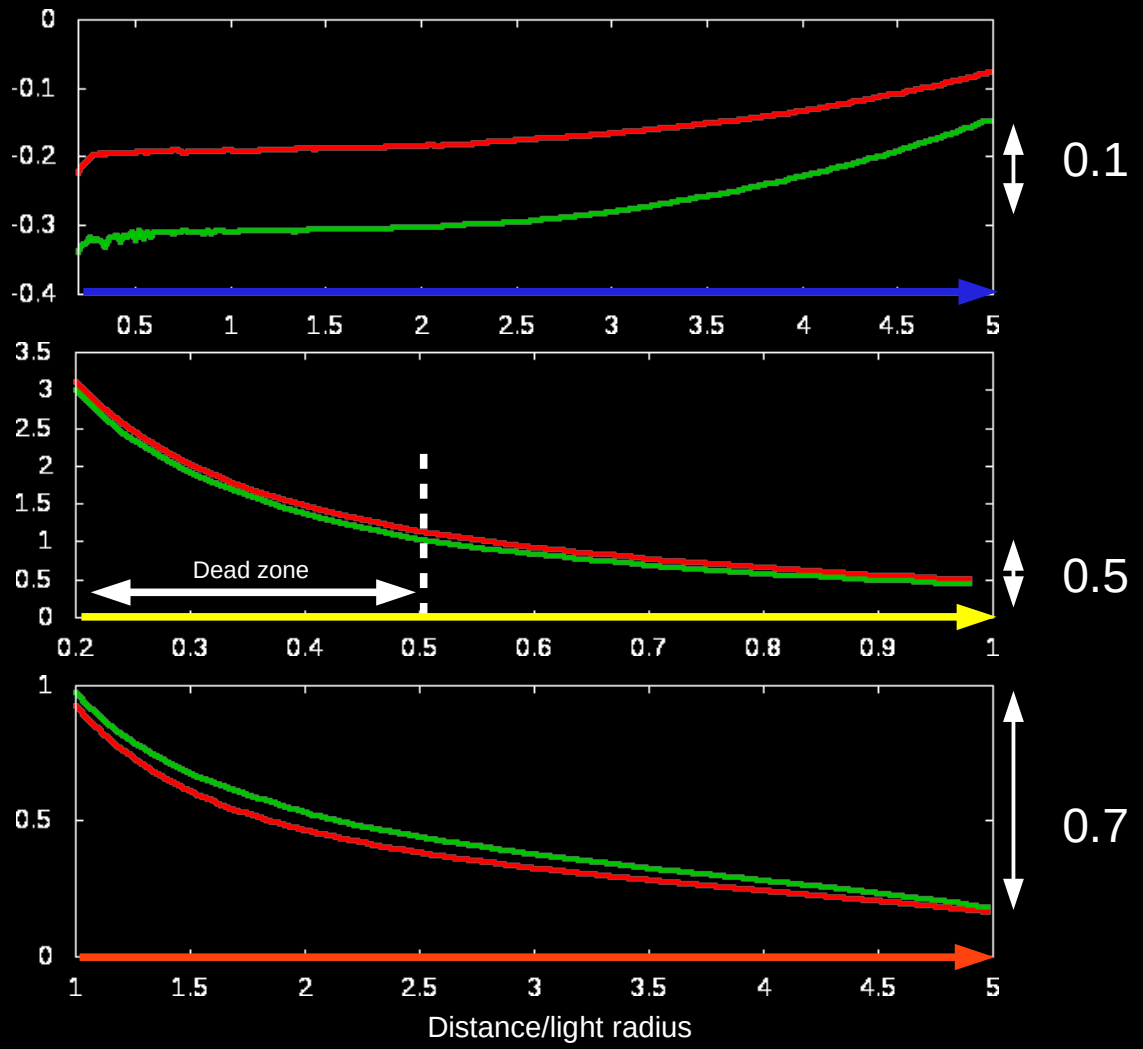
Low nM model; B0

Higher nM model; C0



Normalization constant of voltage(vertical axis):
Open field line voltate

$$\phi_{\max} = 10^{15} B_{12} R_6^3 P_{0.03}^{-2} \ \mathrm{Volt}$$

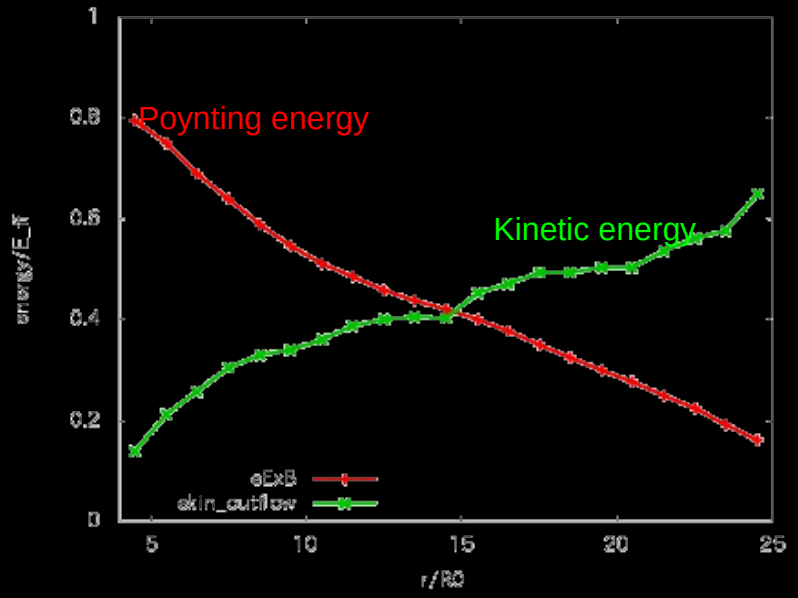


Potential drop; ECS > null surface > Along polar axis

> Epara acceleration in Outer gaps + Eperp acceleration in ECS

Summary

$$\sigma \equiv \frac{B^2/(4\pi)}{n v_r m \gamma c^2}$$



We obtained steady axisymmetric pulsar magnetosphere solution with the effect of pair creation and inertia of plasma.

1. Pair creation changes the system static state to active state (B_{dipole}+B_{ij}, $10n_{sim}$)
2. Accelerating regions
   1. Outer gaps in middlelatitudes (Epara Acc)
   2. Equatorial current sheet (Eperp Acc)
3. Kinetic dominant outflow about in 3 light radii (from σ>1 to σ<1) ↔ PS2014

- Our solution need not any assumption on current sheet or at light cylinder
- (EM-static) PIC with radiation reaction code adopted to pulsar magnetosphere
- The effect of magnetic reconnection is not considered in current work
- Numerical model of pair creation process should be improved
- New measure of characteristic age

+ Carry out full PIC Global simulation?