Review on Pulsar magnetosphere structure and role of **pair-creation process**

Jumpei Takata

Huazhong University of Science and Technology

華中科技大学（中国　武漢）

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II. Pair-creation processes in the magnetosphere

III. Radiation process and pair-creation process; some unresolved issues

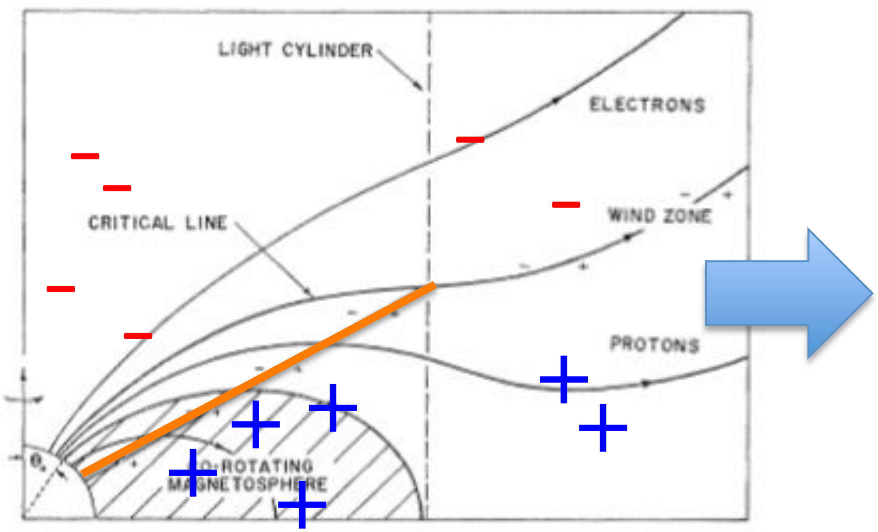
Goldreich-Julian (1969)

- **Charge filled** magnetosphere : $\frac{\text{Electric force}}{\text{Gravity force}} \sim 10^9$

  -- Charge particles are extracted from the NS surface

- **Force-free and charge separated** magnetosphere :

$$\vec{E} + \vec{v}_{co} \times \vec{B} = 0 \longrightarrow \rho_{GJ} \sim -\frac{\vec{\Omega}\cdot\vec{B}}{2\pi c}$$



Pulsar wind

FIG. 1.—Schematic diagram showing the corotating magnetosphere and the wind zone. Star is at lower left.

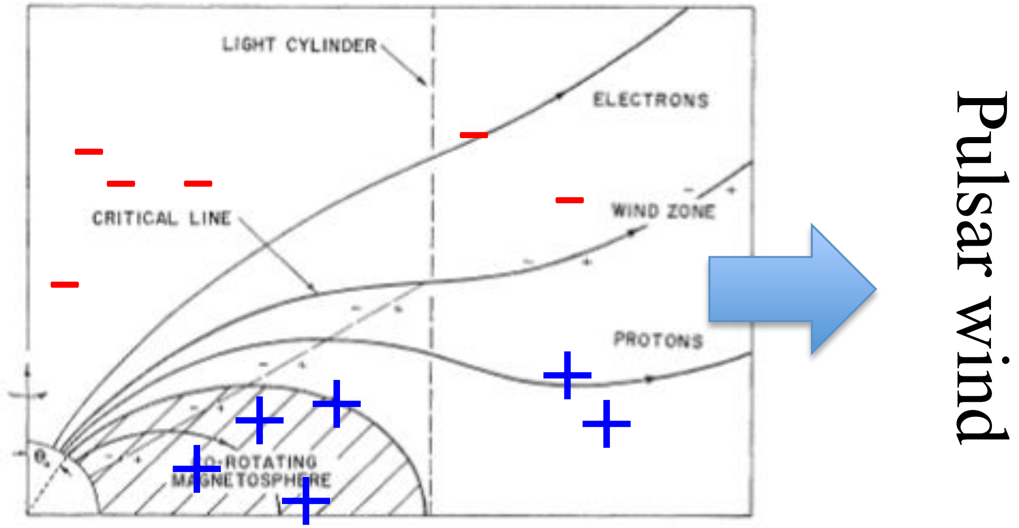


Fig. 1.—Schematic diagram showing the corotating magnetosphere and the wind zone. Star is at lower left.

Some issues about GJ view :

- Charge loss from the star.

  → Formation of the current loop (Jackson 1976).

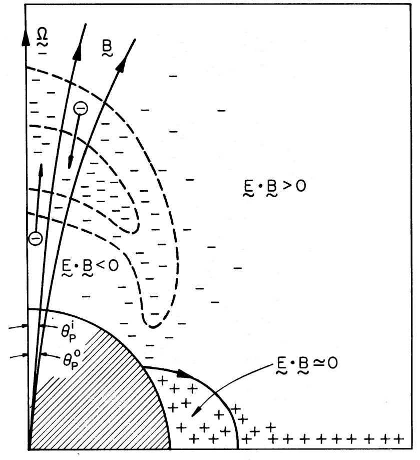
- Positive charge region connecting to the negative charge region of the star.

  → Formation of a vacuum gap around the null charge surface (Holloway 1975).

Jackson's idea (1976 +)

-- Electrons (primary current) are freely ejected from the polar cap region and can reach at a distant region.

-- Polar cap accelerator produces **electron/ positron pairs** that can reach to the PWN.

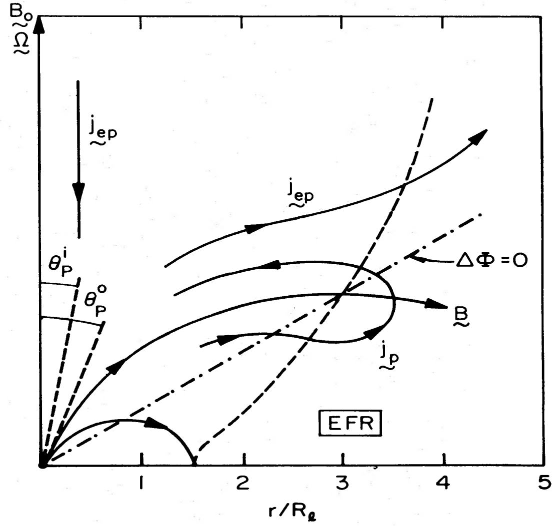


-- Positive charges are ejected from the equator region and forms *a torus*.

-- **Star is positively charged up** and creates a monopole electric field, which enable the primary electrons to cross the magnetic field lines and to return to the star.

$$Q \sim \frac{\Omega B_s R^3}{3c}$$

(if star and PWN are equipotential)



Mestel et al. (1985+)   and Shibata (1988+)

- **Particle inertia (no system charge).**
- Electrons from the polar cap can be relativistic near the light cylinder.
- The energy loss due to the gamma-ray emissions, which causes a drift motion to cross the magnetic field line (***FxB* drift**).

→ transition region from field-aligned flow to trans-field flow.

Charge separated magnetosphere with a circuit current and a vacuum gap between the electron dome and ions domes was a standard picture in analytical study.

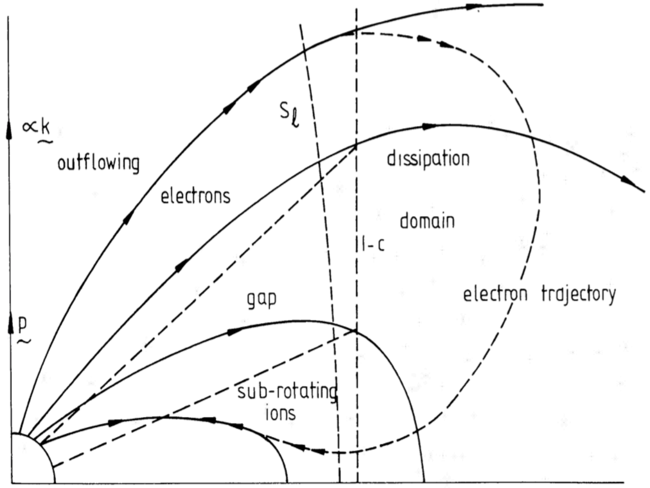
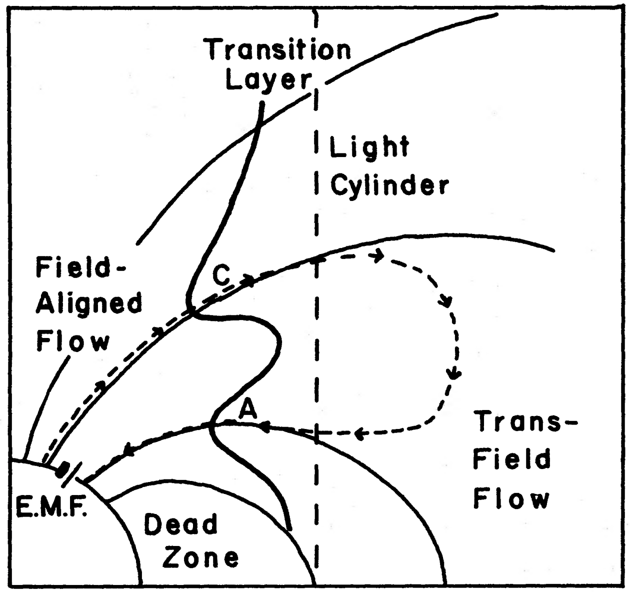


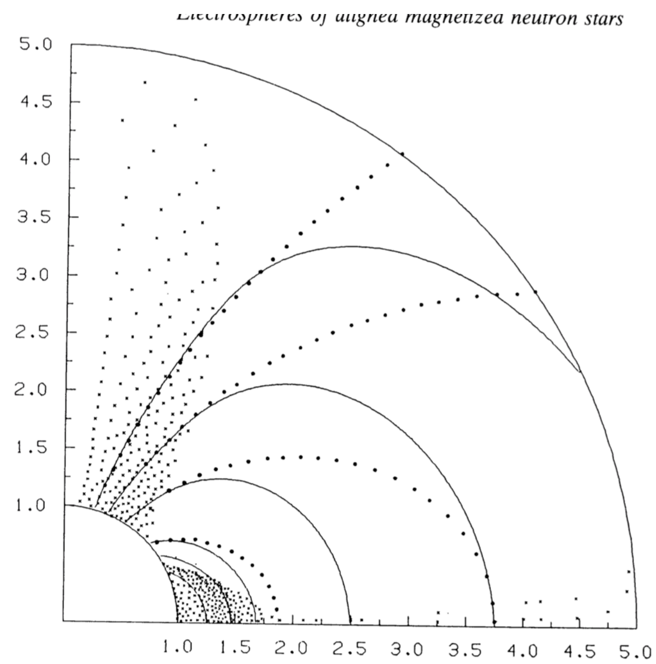
Figure 1. Schematic magnetospheric model.



Particle simulation

Krause-Polsorff & Michel (1985)

-- Charged and magnetized rotating star.



(i) Starting from vacuum state around star.
→ Electric field along the magnetic field line at the stellar surface

(ii) Emission of charges from the stellar surface
→they are moved along the magnetic field to **zero electric potential.**

(iii) Calculate new electric field with new charge.

(iv) Repeat until **zero electric field** parallel to the magnetic field line at the stellar surface.

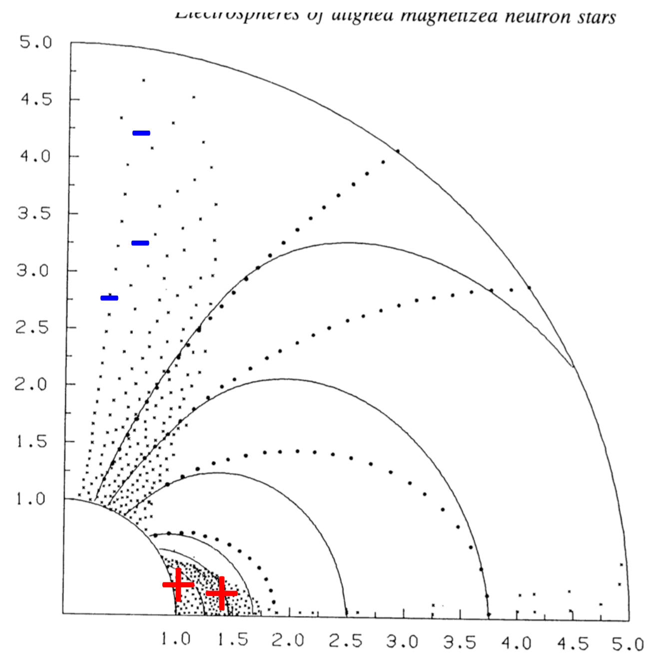
Krause-Polsorff & Michel (1985)

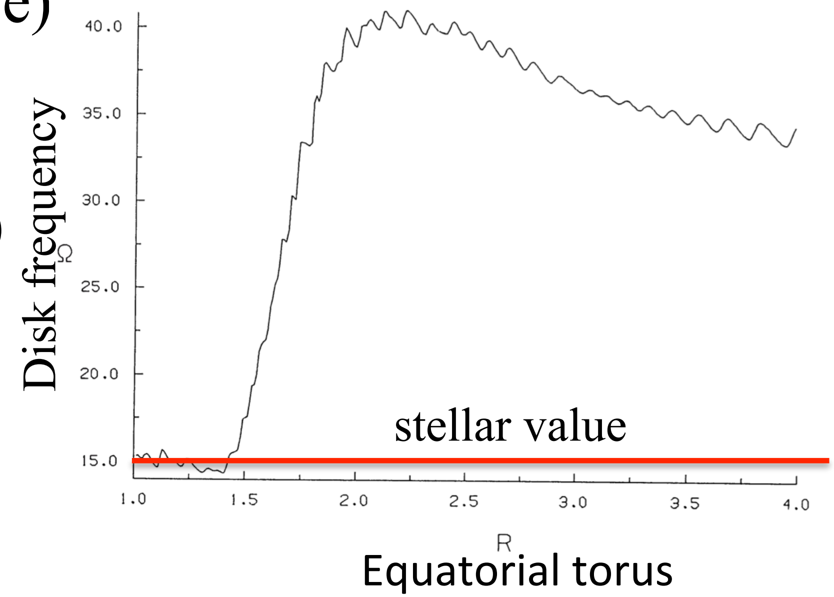
- **Charge separated magnetosphere**.

- Partially filled magnetosphere with **a large vacuum** between the **electron dome** and **ion torus**.

- **No current** (inactive magnetosphere)

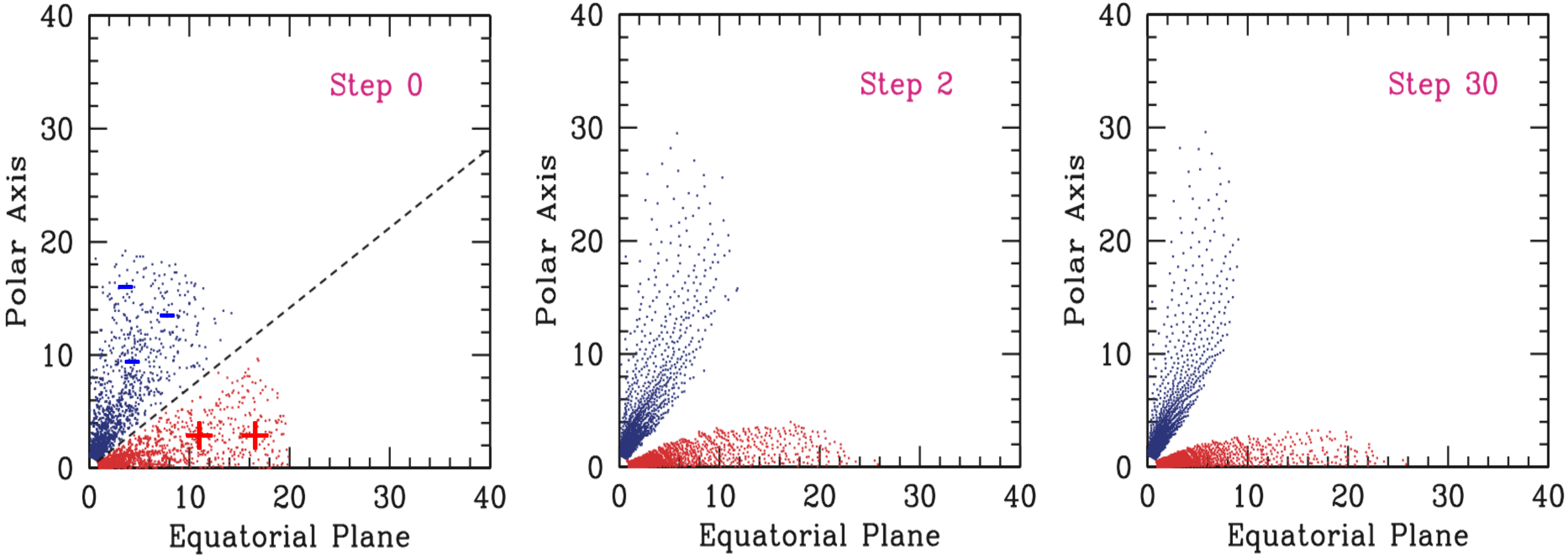
- Super-rotating ion torus.
  (light cylinder is located inside c/Ω)





Smith et al. 2001

A vacuum region is inherently nature.



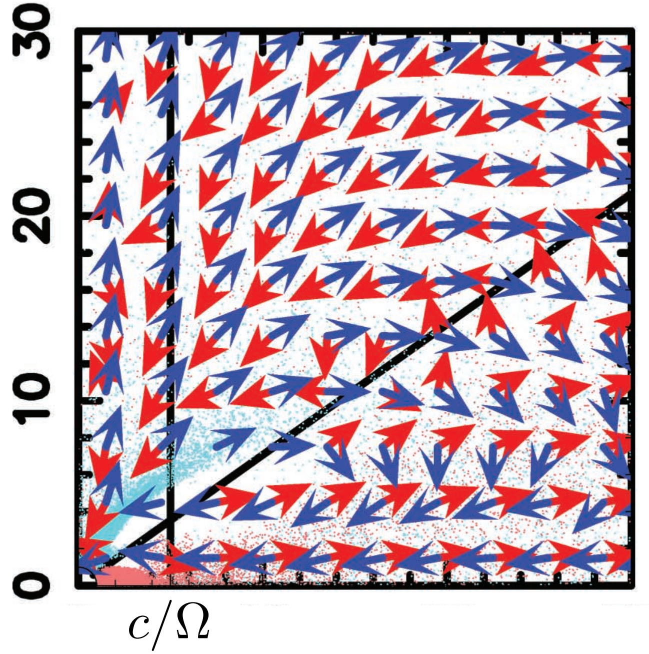
- GJ distribution within r<R_c

- Negative dome and positive torus expands (~ GJ charge inside it)
- A vacuum gap develops around the null charge surface of GJ.

- Pair-creation in the vacuum region, but no circuit current was observed. → Aligned-rotator is inactive (no particle acceleration and no emission).

Wada & Shibata 2007 +

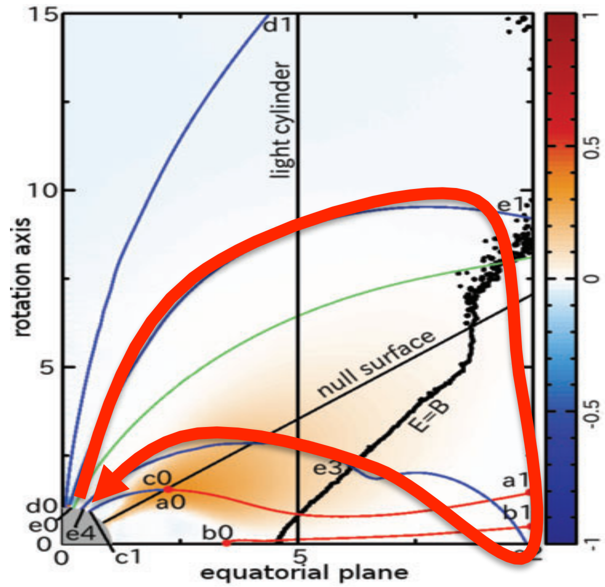
(i) **Solving the equation of motion** and radiation drag force.
(ii) Pair-creation at the vacuum region between the dome and torus.



- **Current circuit** :

Polar cap rim→ Vacuum region → light cylinder→ Trans-filed current (E>B)→ Polar cap core.

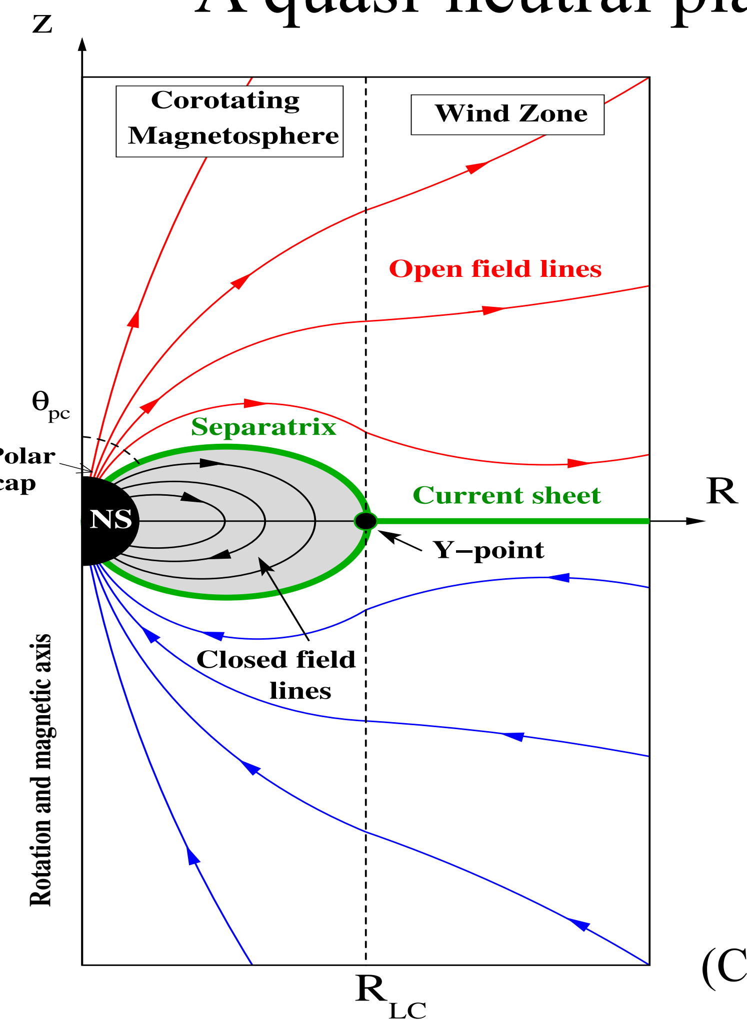
- **Pulsar wind** supplied by the pair-creation at the vacuum region.



Very similar picture to previous analytical models.

Ideal force-free magnetosphere

- Contopolous et al. (1999), Spitkovsky (2000) ….
  - A quasi-neutral plasma with $n_+ \sim n_- >> n_{GJ}$



- **Y-shaped current sheet** along interference between open and close field lines.
  -- It carries most of return current.
  -- Charge density is much larger than GJ value.

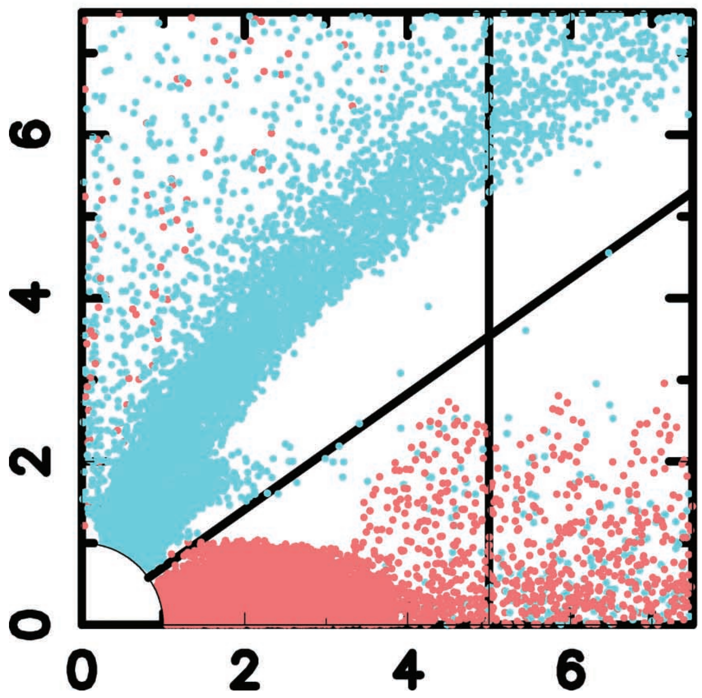
- Current sheet beyond the light cylinder is main particle acceleration and emission regions.

(Cerutii and Beloborodov 2017)

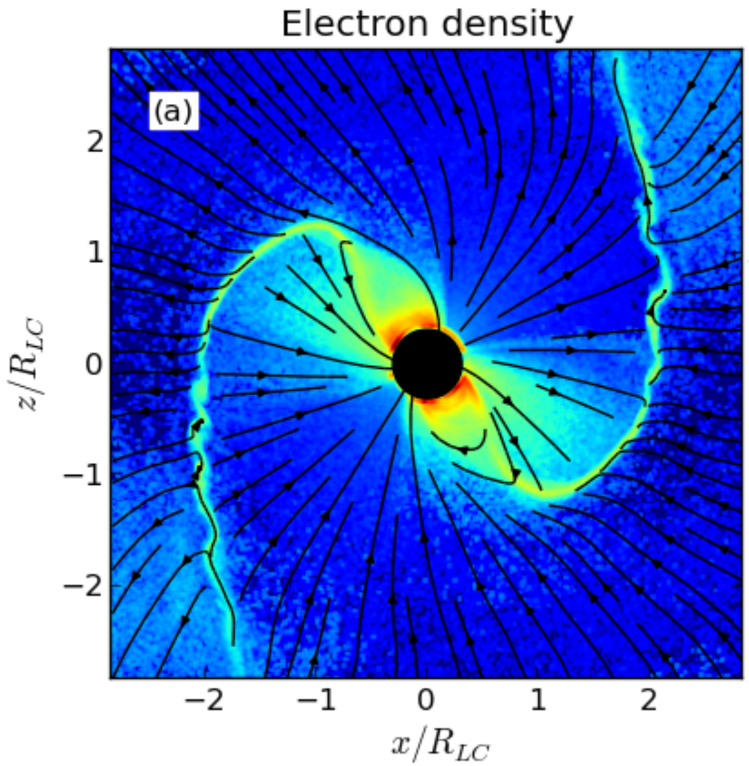
Charge separated magnetosphere (with vacuum region)

or

Ideal MHD magnetosphere (with current sheet)?



(Wada and Shibata 2007+)



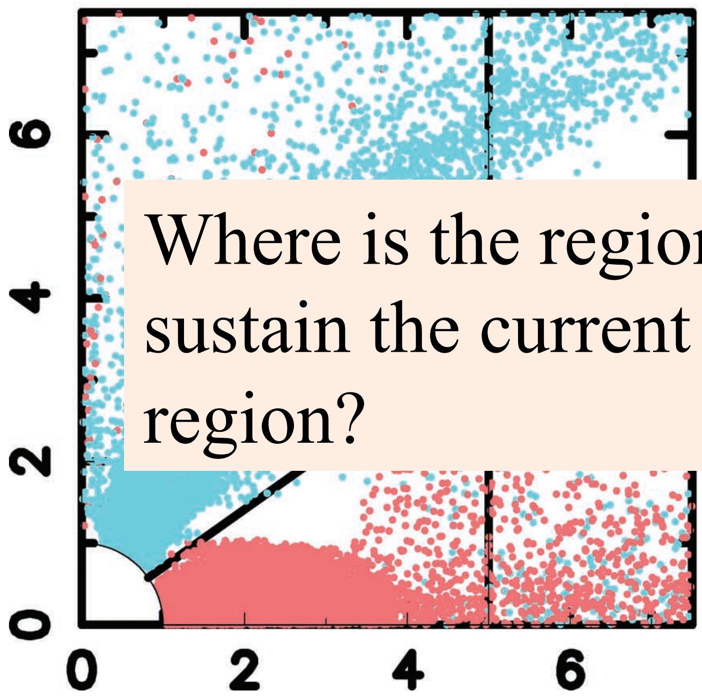
(Philippov et al.2015)

small **Injection rate of the pairs** large

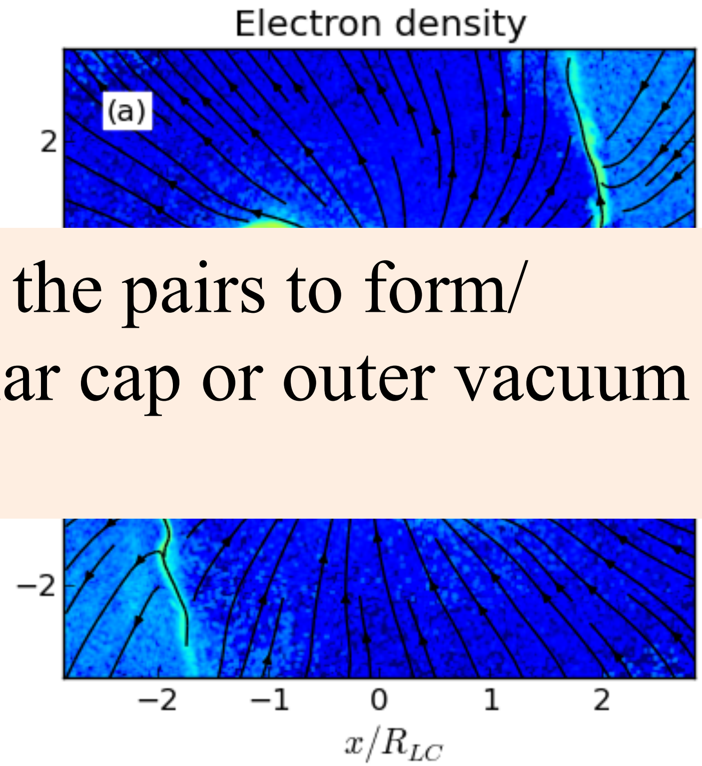
Charge separated magnetosphere (with vacuum region)

or

Ideal MHD magnetosphere (with current sheet)?



Where is the region to supply the pairs to form/ sustain the current sheet? Polar cap or outer vacuum region?



(Wada and Shibata 2007+)

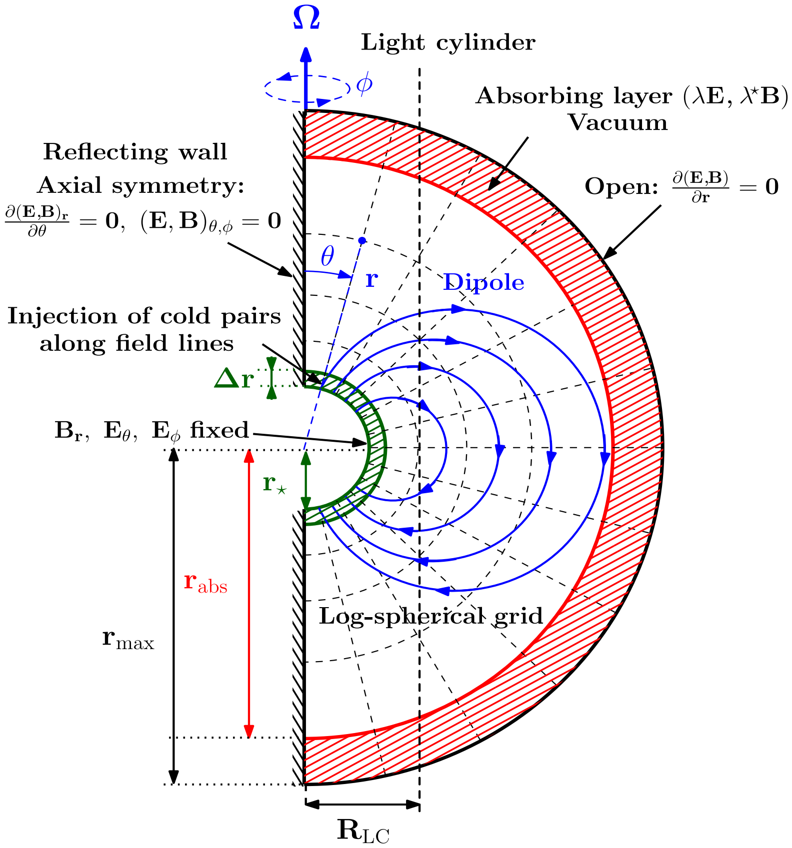
(Philippov et al.2015)

small — Injection rate of the pairs → large

Is the pair-creation process around the **polar cap essential**?

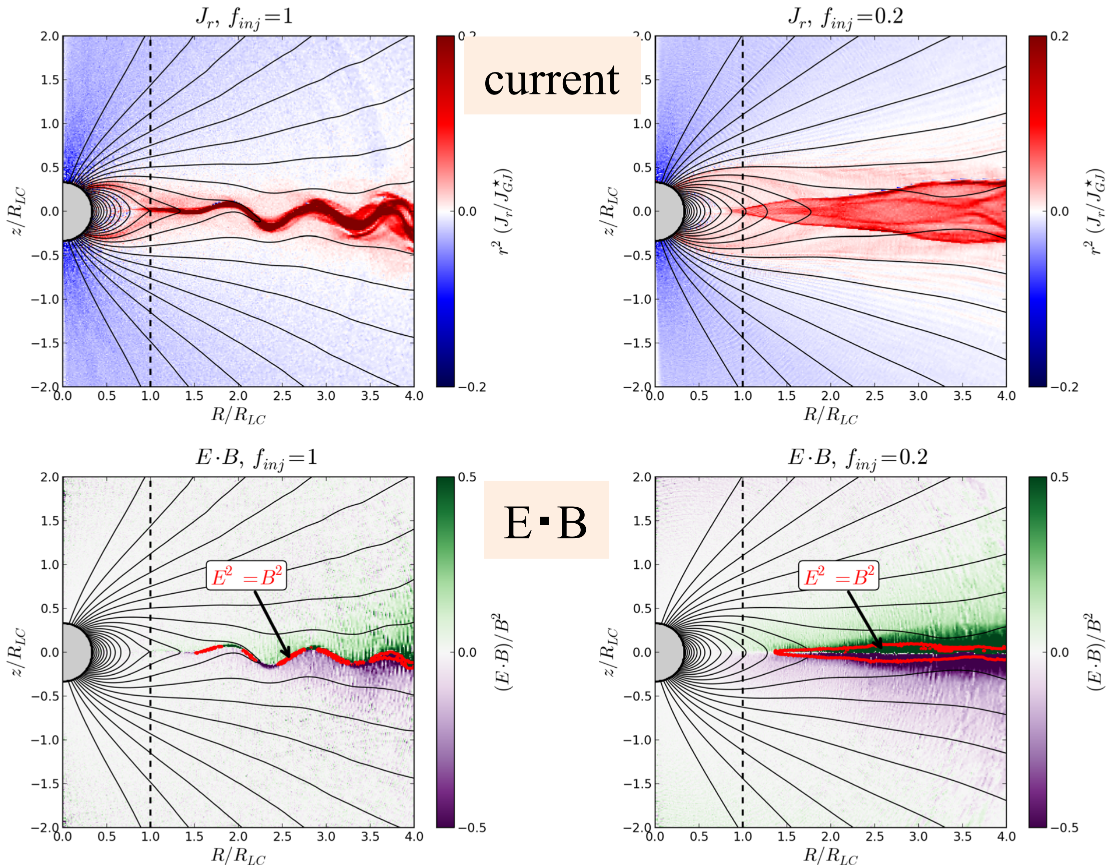
Cerutti et al. (2015)+

-- pair injection from the surface



GJ rate

0.2 GJ rate



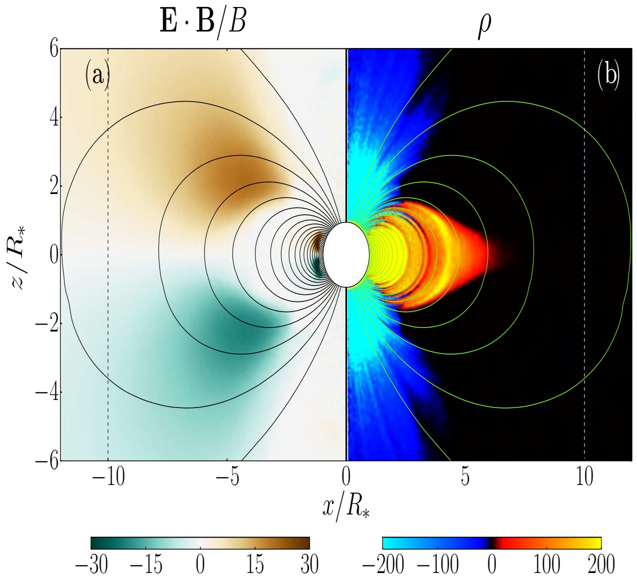
~FF solution

Charge separated

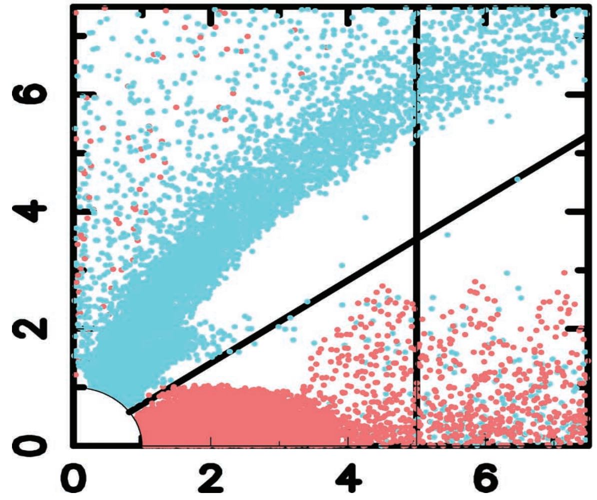
Is the pair-creation process around **the light cylinder essential?**

- PIC simulations by Chen and Beloborodov (2014) : Polar cap is inactive for a smaller oblique rotator : **sub-GJ flow** (Shibata 1997)

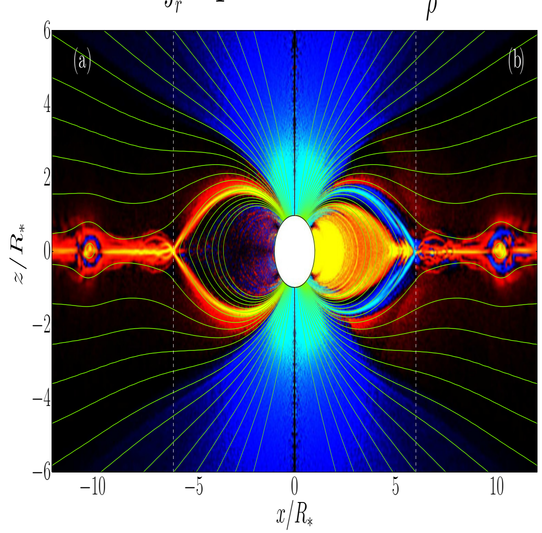
Pair-creation limited at PC



Pair-creation limited at OG (Wada and Shibata 2007+)



Very high injection rate with $\ell_p < R_{lc}$



- Charge separated magnetosphere **without circuit current**
- Charge separated magnetosphere **with circuit current**
- Ideal FF solution

Small — Optical depth around the LC. — Large

	inclination	Pair-creation		Magnetosphere
		Polar cap	Outer magnetosphere	
Shibata, Wada, and Yuki (2007 +)	aligned	✖	○ (low rate)	Charge separated
Chen and Beloborodov (2014)	aligned	inactive	✖	Charge separated
		inactive	○ (high rate)	FF
Philippov et al. (2015)	small	inactive	✖	Charge separated
		inactive	○ (high rate)	FF
	large	active	○ (high rate)	FF
	large	active	✖ or low rate	??

- Recent global simulations have revealed that the pair-creation process is essential for the magnetosphere structure.

- However, the current simulations have not treated a realistic *pair-creation cascade* such as

(i) Pair created in the acceleration region can be easily discharged :

$$\frac{e\Phi_{pc}}{m_e c^2} \sim 10^{7-8} \quad (\frac{e\Phi_{pc}}{mc^2} \sim 10^{2-3} \text{ in the simulation})$$

→it could affect to the current flow pattern.

(ii) Photon-photon mean free path around the light cylinder ~1000R_{lc}, (current simulation assumes <R_{lc})

→ it could affect to the size of the acceleration (vacuum) region.

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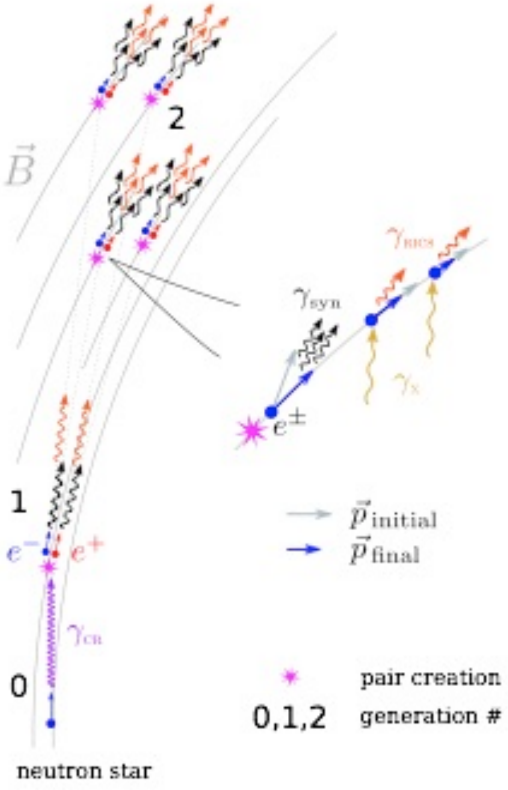
Pair-creation process

Polar cap accelerator

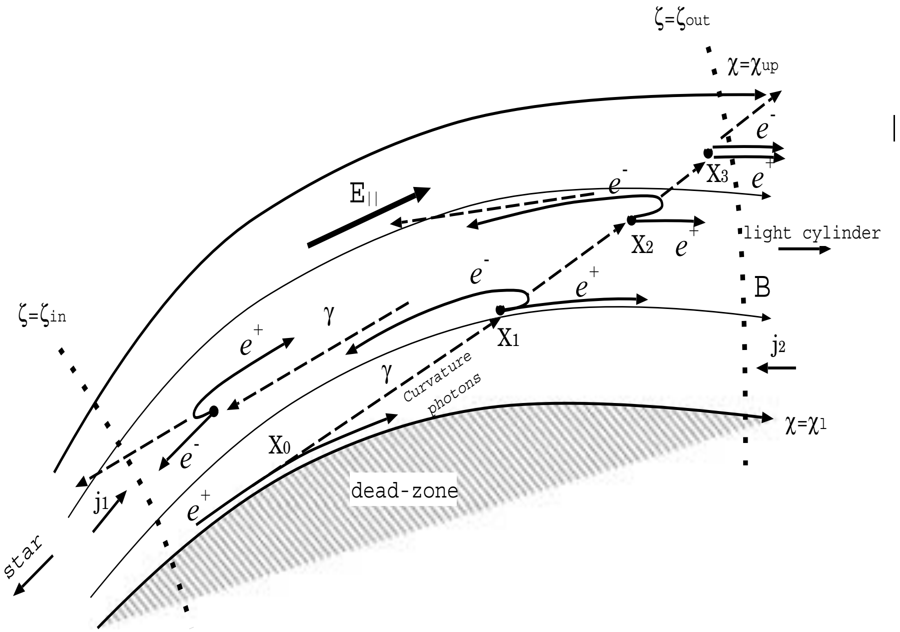
- **Magnetic pair-creation**
- Cascade outside accelerator



(Timokhin & Harding 2019)

Vacuum region (OG) accelerator

- **Photon-photon pair-creation**
- Cascade inside accelerator



(Takata et al. 2004+)

Polar cap accelerator

- Polar cap acceleration
  (**size along the magnetic field line : *h***)

(i) Electric potential drop : $\delta V \sim \frac{B\Omega}{c} h^2$

(ii) Primary Lorentz factor : $\gamma_p \sim \frac{\delta V}{m_e c^2}$

(iii) Curvature gamma-ray: $E_{cur} \sim \frac{\gamma_p^3 \hbar c}{R_c}$

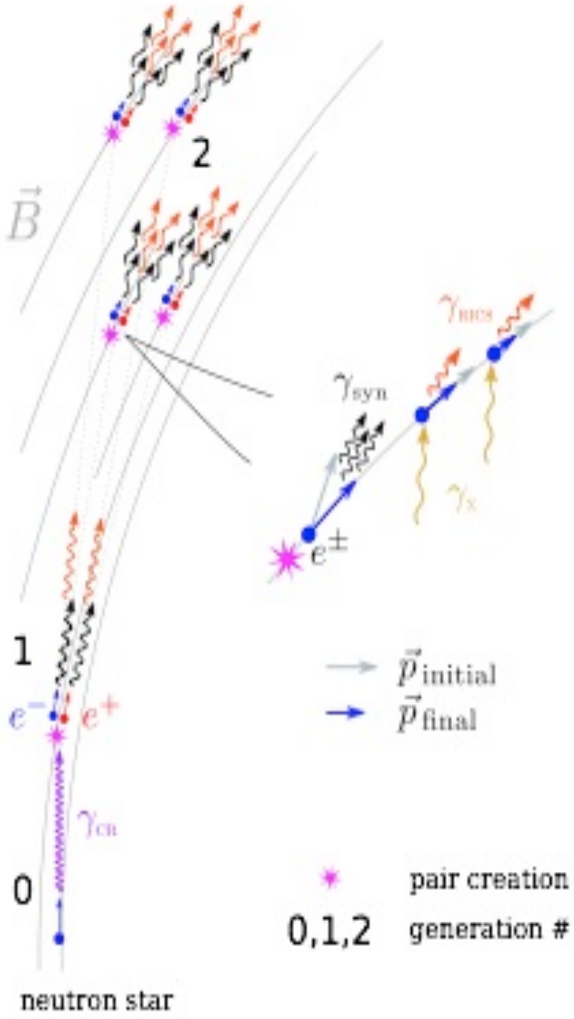
(iv) Magnetic pair-creation :

$$\frac{E_{cur}}{m_e c^2}\frac{B_\perp}{B_Q} \sim 1 \quad B_\perp \sim \frac{h}{R_c} B$$

$$h \sim 5\times 10^3 P^{3/7} B_{12}^{-4/7}\mathrm{cm} << R_{NS}$$

$$\gamma_p \sim 3\times 10^6 P^{-1/7} B_{12}^{-1/7}$$

$$E_{cure} \sim 0.8 P^{-3/7} B_{12}^{-3/7}\mathrm{GeV}$$

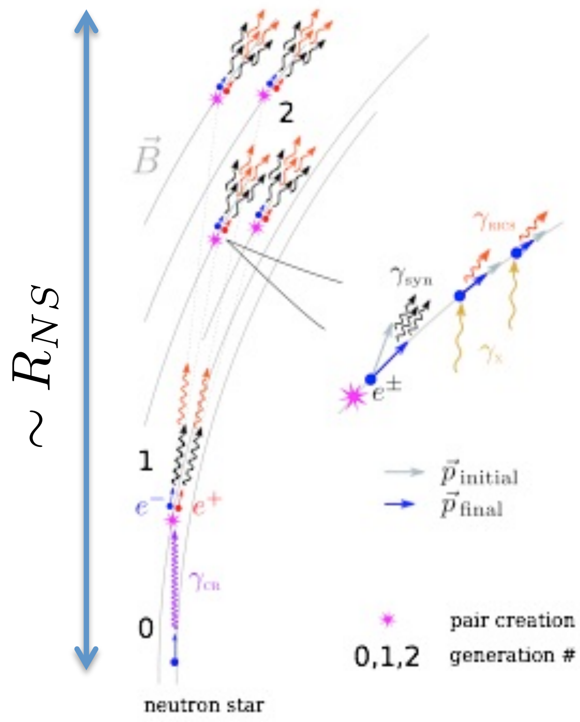


(Timokhin & Harding 2019)

Polar cap cascade

- Pair cascade above accelerator

  -- Curvature radiation → new pairs→ synchrotron radiation/RICS → new pairs →…



- Escape photon energy :

$$E_{esc} \sim \frac{B_Q}{B} m_e c^2 \sim 22 B_{12}^{-1} \mathrm{MeV}$$

- **Multiplicity** $\kappa \sim \dfrac{\gamma_p m_e c^2}{E_{esc}} \sim 10^5 P^{-1/7} B_{12}^{6/7}$

  -- it explains the pulsar wind.

Polar cap cascade

- The multiplicity of the order of $\kappa \sim 10^5$ is consistent with the observation of PWNe.

- However, the magnetic pair-creation will not control the polar cap accelerator/cascade for ***the millisecond pulsars***, whose surface magnetic field is $\sim 10^{8\text{-}9}$G.

For MSPs, magnetic pair-creation will not be the source of the pairs

- Polar cap acceleration
  (size along the magnetic field line $\sim h$)

(i) Potential drop : $\delta V \sim \frac{B\Omega}{c}h^2 \quad E_{||} \sim \delta V/h$

(ii) Saturation motion is important $\rightarrow \gamma_p = \left(\frac{3R_c^2}{2e}E_{||}\right)^{1/4}$

(if $h > 10^5 B_8^{-3/4} P_{1ms}\mathrm{cm}$)

(iii) Magnetic pair-creation : $\frac{E_{cur}}{m_e c^2}\frac{B_\perp}{B_Q} \sim 0.1\chi_{0.1} \quad B_\perp \sim \frac{h}{R_c}B$

↓

$$h \sim 5 \times 10^5 B_8^{-1} P_{1ms}^{3/7} \chi_{0.1}^{4/7}\mathrm{cm}$$

$$\gamma_p \sim 1.3 \times 10^7 P_{1ms}^{-1/7} \chi_{0.1}^{1/7}$$

$$E_{curv} \sim 50 P_{1ms}^{-3/7} \chi_{0.1}^{3/7}\mathrm{GeV}$$

For MSPs, magnetic pair-creation will not be the source of the pairs

- Polar cap acceleration
  (size along the magnetic field line $\sim h$)

(i) Potential drop : $\delta V \sim \frac{B\Omega}{c}h^2 \quad E_{||} \sim \delta V/h$

(ii) Saturation motion is important $\rightarrow \gamma_p = \left(\frac{3R_c^2}{2e}E_{||}\right)^{1/4}$

(if $h > 10^5 B_8^{-3/4} P_{1ms}\mathrm{cm}$)

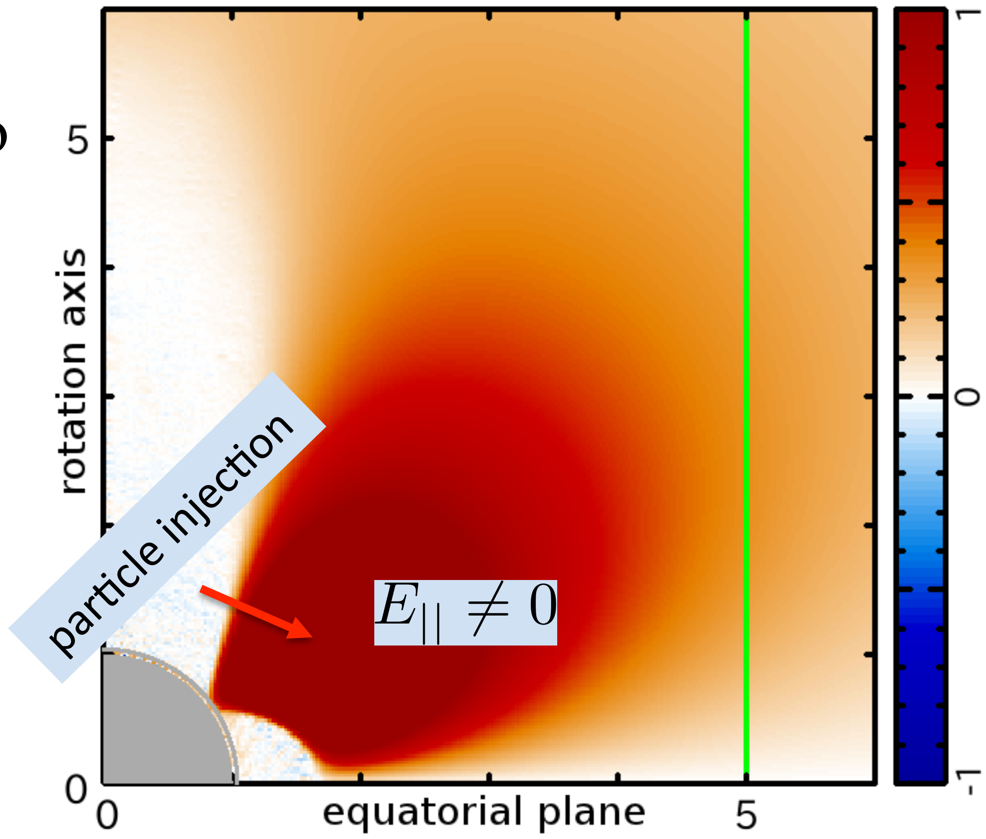
(iii) Magnetic pair-creation : $\frac{E_{cur}}{m_e c^2}\frac{B_{\perp}}{B_Q} \sim 0.1\chi_{0.1} \quad B_{\perp} \sim \frac{h}{R_c}B$

- The photon-photon pair-creation and resonant inverse Compton scattering would be main processes for MSPs.
- A detail cascade simulation has not been done yet.

Acceleration/Pair-creation in outer magnetosphere

- If some particles are injected into the vacuum gap, they initiate the pair-creation cascade (but if >GJ current is injected, no outer gap)

- Some part of the gap is filled by the copious pairs created by the photon-photon pair-creation process.



Wada & Shibata 2007

Outer magnetospheric accelerator

- Outer gap / Slot gap - slab-like geometry
  (dimensionless trans-field thickness: $f_{gap}=D/R_{lc}$)

(i) Acceleration electric field : $E_{||} \sim f_{gap}^2 B_{lc}$

(ii) Saturated motion :

$$\Gamma_{sat} = \left(\frac{3R_c^2}{2e} E_{||}\right)^{1/4} \sim 3 \times 10^7 (f_{gap}/0.3)^{1/2} B_{12}^{1/4} P_{0.1}^{-1/4}$$

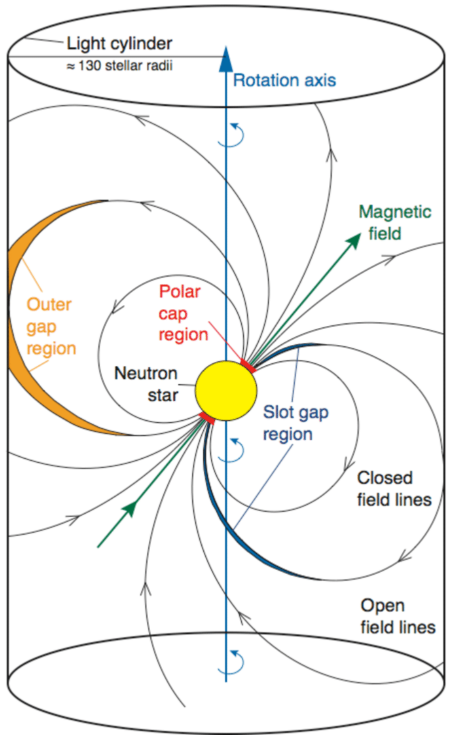
$$(R_c = R_{lc})$$

- Curvature photon energy

$$E_{cure} = \frac{3}{4\pi} \frac{hc\Gamma_c^3}{R_c} \sim 1.3\mathrm{GeV}(f_{gap}/0.3)^{3/2} B_{12}^{3/4} P_{0.1}^{-7/4}$$

- For millisecond pulsar

$$E_{cure} \sim 4\mathrm{GeV}(f_{gap}/0.3)^{3/2} B_8^{3/4} P_{1ms}^{-7/4}$$



- Photon-photon pair-creation condition:

$$E_{cure}E_X \sim (m_e c^2)^2$$

↓

$$f_{gap,min} \sim 0.5 B_{12}^{-1/2} P_{0.1}^{7/6} E_{0.1keV}^{-2/3}$$

  - Crab (P~0.033s, B_{12}~3.8) : f_{gap}~0.07
  - Geminga (P~0.237s, B_{12}~1) : f_{gap}~1.4

- This is the **minimum thickness** to initiate the pair-creation.
- The acceleration region can be thicker owing to the finite value of the mean-free pass (**cascade/screening region**).

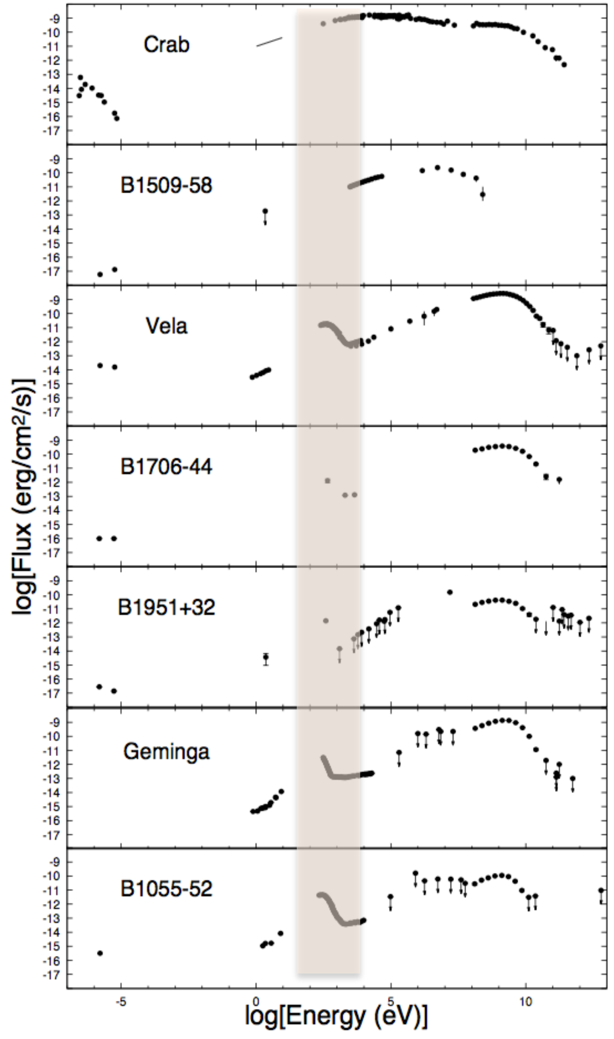
Pair-creation in outer magnetosphere

- Photon-photon pair-creation process between X-rays and GeV gamma-rays.
  --- Magnetospheric X-rays (Crab/PSR 0540-6919 : $L_X \sim 10^{35}$ erg/s)
  --- NS cooling emission (Others: $L_X \sim 10^{30\text{-}32}$ erg/s)

- Mean free path around light cylinder

$$\ell_p/R_{lc} \sim 2000 P_{0.1} (L_X/10^{32}\mathrm{erg/s})^{-1} (E_X/0.1\mathrm{keV})$$

-- except for Crab-like pulsar (and maybe energetic MSP), **the mean free path is much longer than light cylinder radius.**



Multiplicity

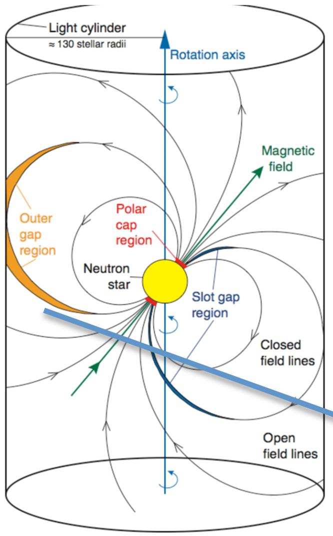
- Number of the curvature photons emitted in the accelerator by **one primary**: $N_{ph} \sim P_{cur} R_{lc} \sim 10^5 (\Gamma / 3 \cdot 10^7)$

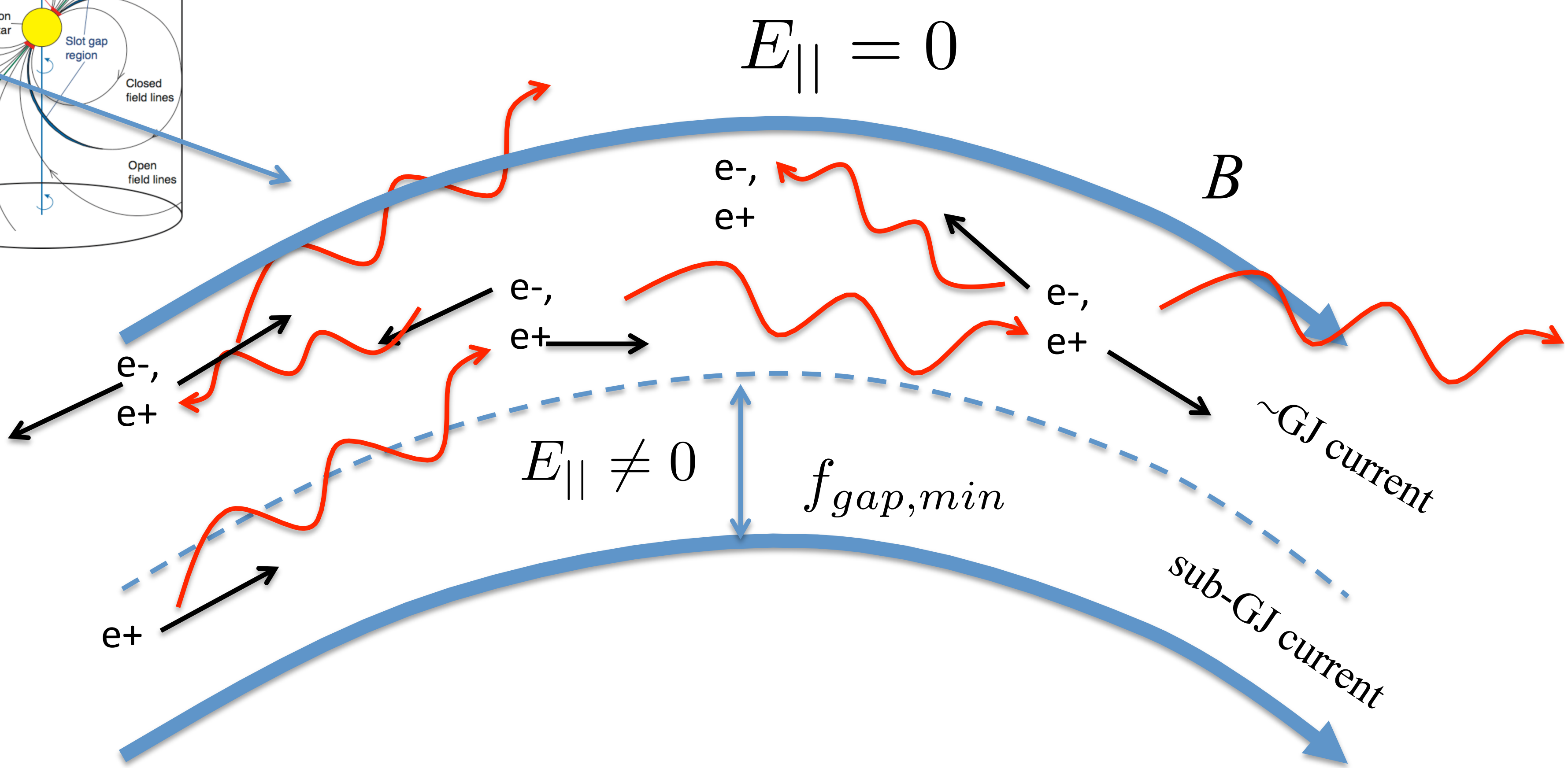
- Pairs created by one primary within the light cylinder:

$$\kappa \sim N_{ph} \frac{R_{lc}}{\ell_p} \sim 50 P_{0.1}^{-1} (L_X / 10^{32} \mathrm{erg/s}) (E_X / 0.1 \mathrm{keV})^{-1} (\Gamma / 3 \cdot 10^7)$$

- Pairs created outside the acceleration region produces the synchrotron photons in the X-ray/soft gamma-ray bands.

Two layer structure



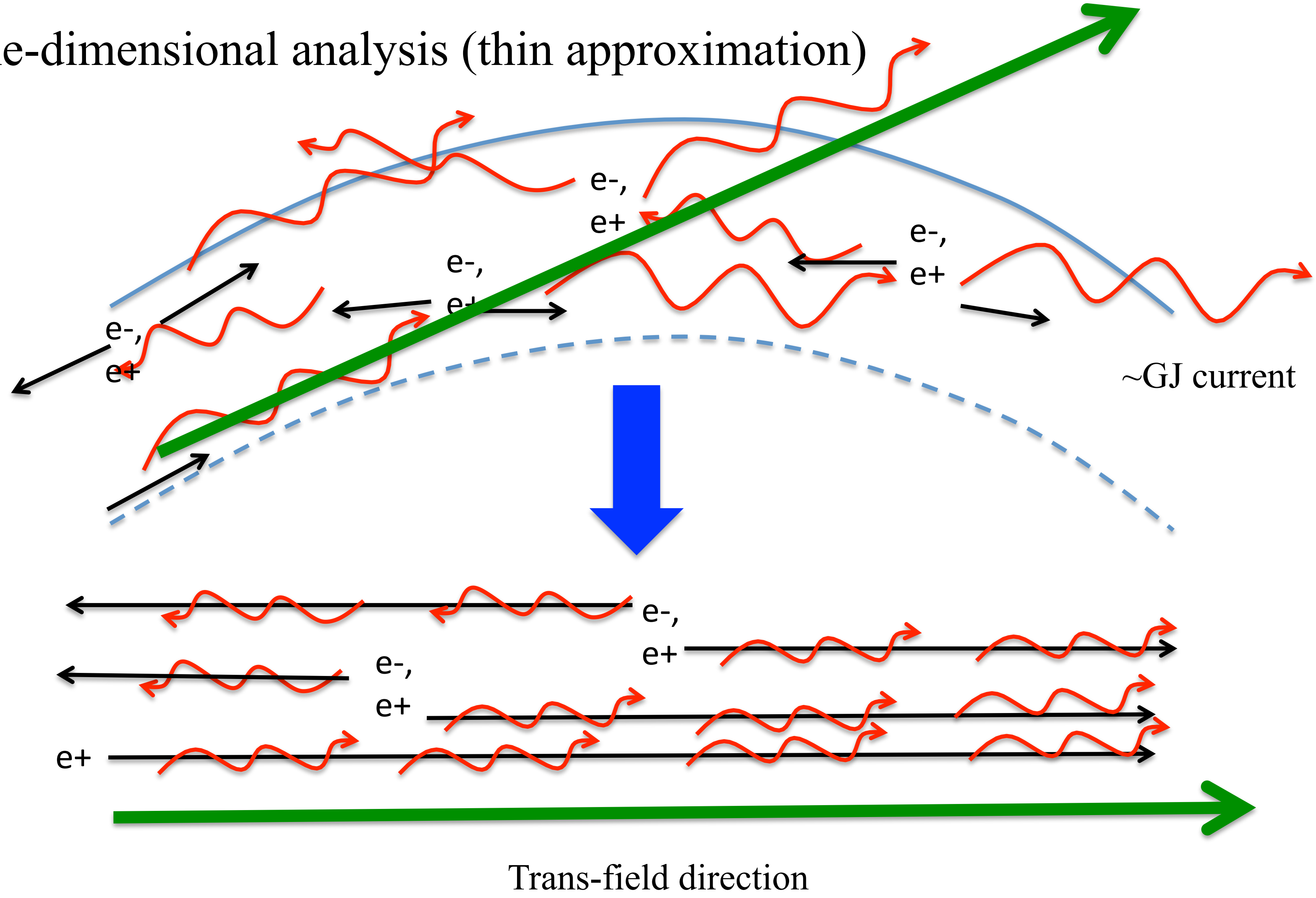


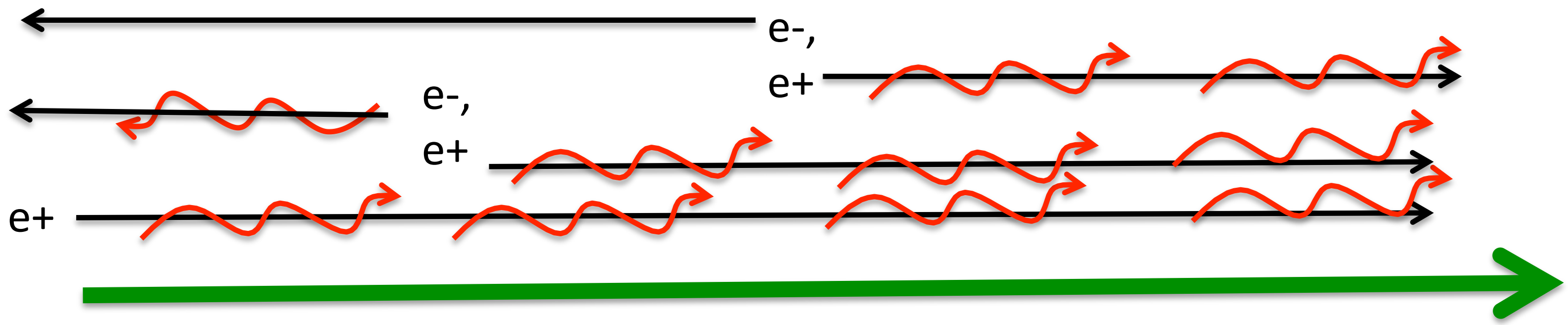
- **Main-acceleration region** above last-open field line (sub-GJ current)
- **Cascade region** (>GJ current)

  - the thickness of the cascade region is usually smaller than main-acceleration region

Thickness of the cascade region

One-dimensional analysis (thin approximation)





- Continuity equations (created pair is immediately discharged)

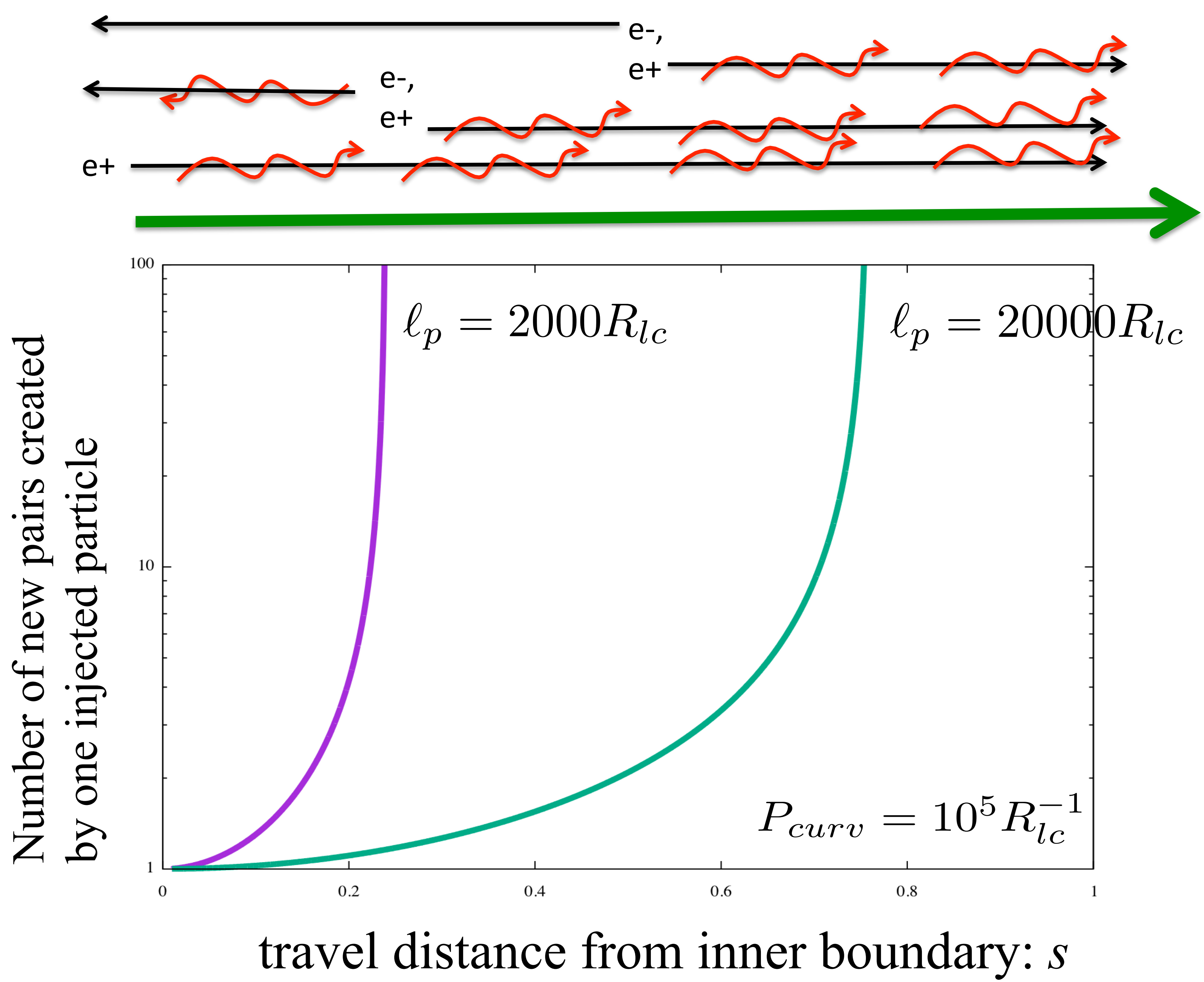
$$\frac{dn_\pm(s)}{ds} = \pm\frac{g_+(s)+g_-(s)}{\ell_p}$$

$$\frac{dg_\pm(s)}{ds} = \pm P_{curv} n_\pm(s) \qquad P_{curv} = 10^5 R_{lc}^{-1}$$

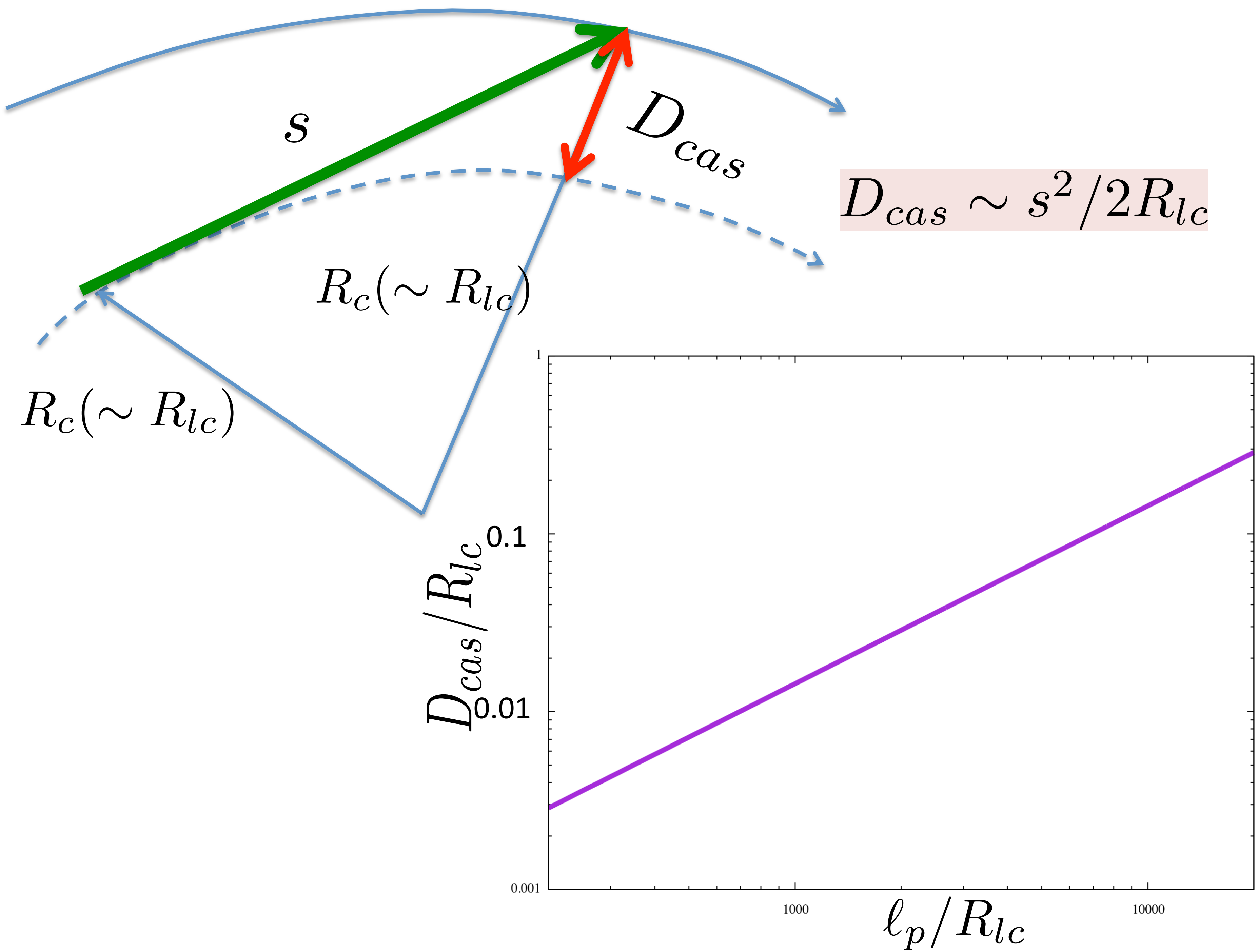
- Boundary conditions

$$n_+(0) = n_1,\ \ n_-(s_{out}) = n_2$$ ← injection

$$g_+(0) = 0,\ \ g_-(s_{out}) = 0$$



e-,
e+
e-,
e+
e+
$\ell_p = 2000 R_{lc}$
$\ell_p = 20000 R_{lc}$
$P_{curv} = 10^5 R_{lc}^{-1}$
100
10
1
0
0.2
0.4
0.6
0.8
1
Number of new pairs created by one injected particle
travel distance from inner boundary: s



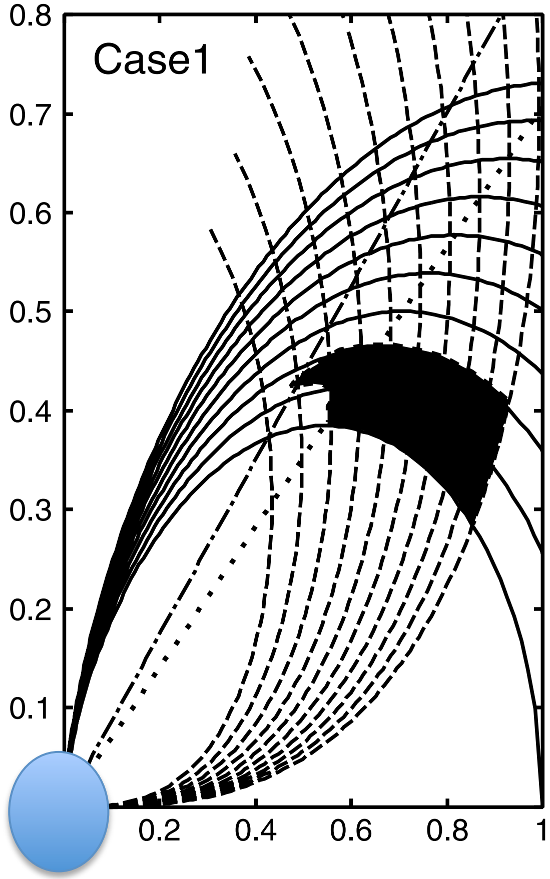
s
D_{cas}
$D_{cas} \sim s^2/2R_{lc}$
$R_c(\sim R_{lc})$
$R_c(\sim R_{lc})$
1
0.1
0.01
0.001
1000
10000
D_{cas}/R_{lc}
ℓ_p/R_{lc}

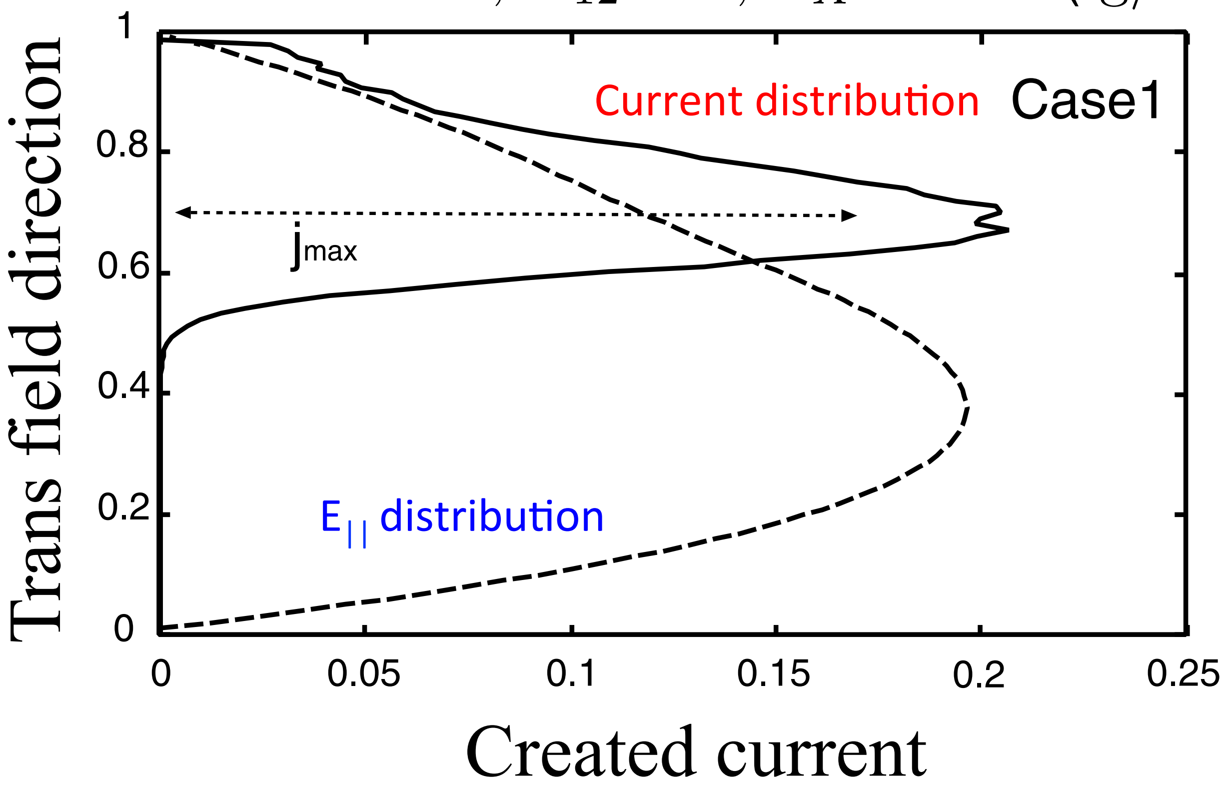
A 2-D calculation

(Takata et al. 2004+)

Parameters with the **Vela pulsar**

$P = 0.089\mathrm{s},\ B_{12} = 3,\ L_X \sim 10^{32}\mathrm{erg/s}$

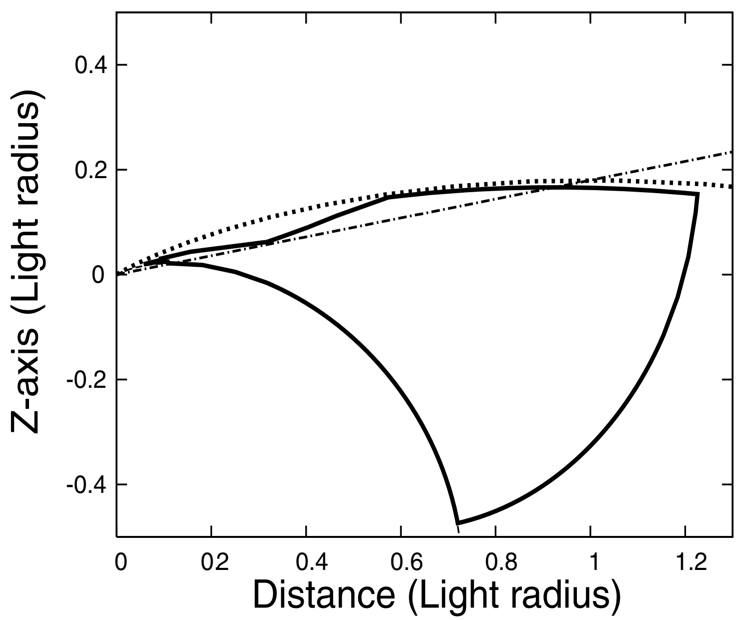


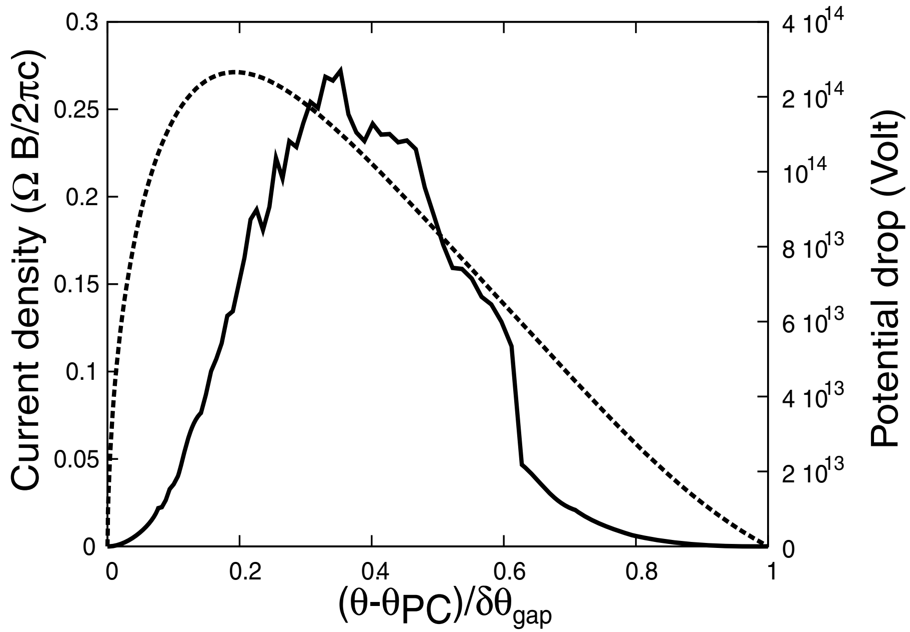


A 2-D calculation

Parameters of the **Geminga pulsar**

$$P = 0.237\mathrm{s},\ B_{12} = 1,\ L_X \sim 10^{31}\mathrm{erg/s}$$





Trans-field direction

A lower spin down pulsar, it is difficult to fill the vacuum region with the pair-creation around LC.

Polar cap accelerator

	Size	Primary radiation	Pair-creation	Multiplicity
Canonical pulsars	$\sim 10^3$cm	Curvature	Bγ	$\sim 10^5$
MSPs	$\sim 10^5$cm	Curvature or RIC	γγ	? (maybe ~10)

Outer magnetospheric accelerator

	Size	Primary radiation	Pair-creation	Multiplicity
Crab-like ($B_{lc}\sim 10^6$G)	$\sim 1\%\ R_{lc}$	Curvature/Inverse-Compton	γγ	$\sim 10^5$
Vela-like ($B_{lc}\sim 10^5$G)	$\sim 10\% R_{lc}$	Curvature	γγ	10-100
Geminga-like ($B_{lc}<10^4$G)	$\sim R_{lc}$	Curvature	γγ	~0

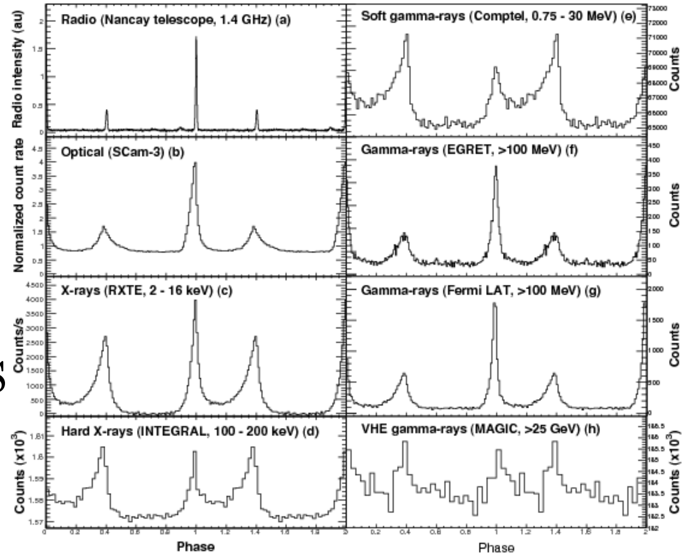
Contents

(i) Non-thermal X-rays

- Non-thermal X-ray emission is observed with a luminosity of

$$L_{n,X}/L_{GeV} \sim 1 \text{ for Crab}$$

$$L_{n,X}/L_{GeV} \sim 10^{-3} - 10^{-4} \text{ for others}$$

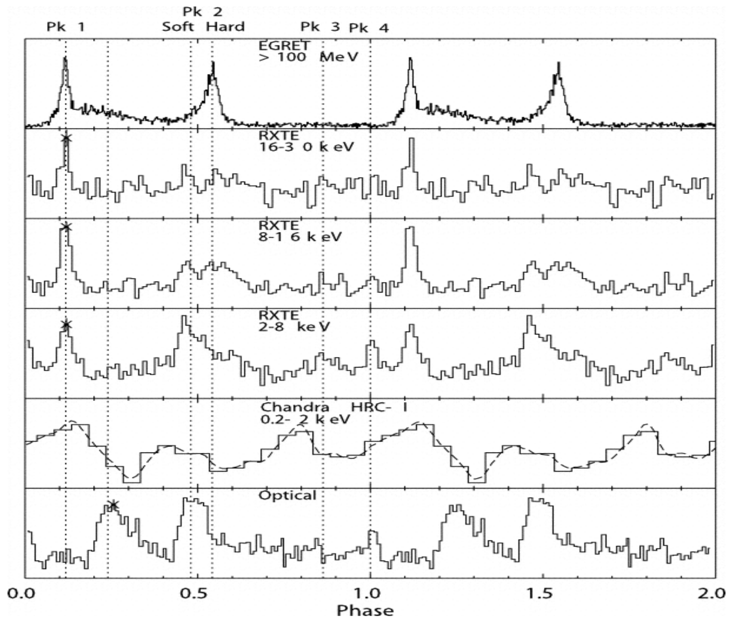


- If synchrotron radiation from the pairs,

$$L_{n,X}/L_{GeV} \sim r_X/\ell_p$$

- Lorentz factor of the secondary (if photon-photon pair-creation is considered)

$$\Gamma_{e\pm} \sim (1\mathrm{GeV})/(2m_ec^2) \sim 10^3$$



- **Required magnetic field strength** is

$$B_\perp(r_X) = 6\times10^5\left(\frac{\Gamma_{e\pm}}{10^3}\right)^2\left(\frac{E_X}{10\mathrm{keV}}\right)\mathrm{G}$$

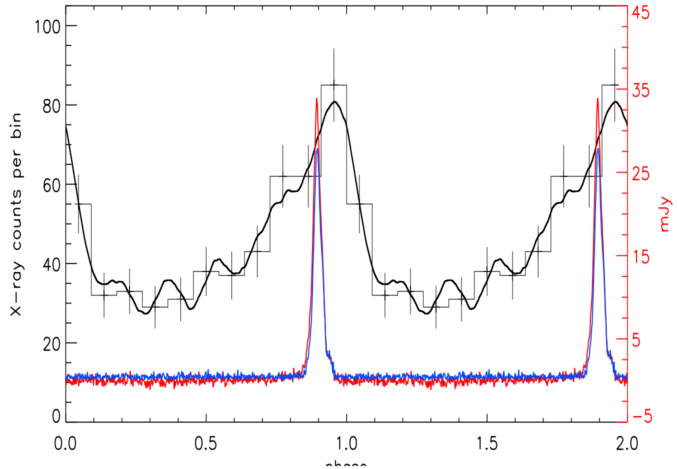
Origin of the non-thermal X-rays from middle age pulsars (see Kisaka and Tanaka 2014+)

- PSR J0108-1431

(lowest E_{sd} among X-ray PSRs)

$\dot{E} \sim 6 \times 10^{30} \mathrm{erg/s} \quad d \sim 0.2 \mathrm{kpc}$

$P \sim 0.8 \mathrm{s} \quad B_{12} \sim 0.25$



- High efficiency of non-thermal X-ray emission

$L_{nh,x} \sim 2 \times 10^{28} \mathrm{erg/s} \qquad L_{nh,x}/\dot{E} \sim 0.003$

- Optical depth of the photon-photon pair-creation :

$\tau_{\gamma\gamma}(r) = \frac{r}{\ell_p} \sim 10^{-4} (r/10^6 \mathrm{cm})^{-1}$

- For low spin down X-ray pulsar, the non-thermal X-ray will be produced at the polar cap region:
  - but the origin of such high efficiency is unknown.

(ii) MeV pulsars

- PSR B1509-58 was considered as a pulsar having Crab-like X-ray/GeV spectrum.

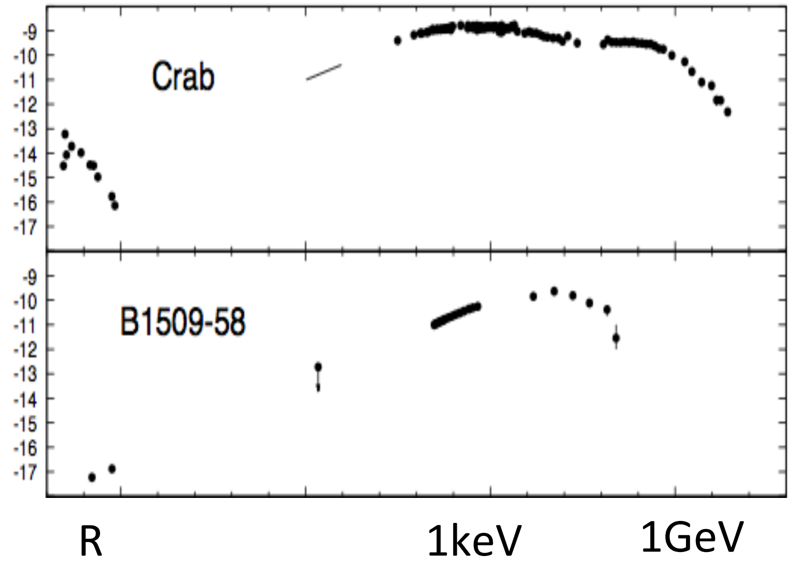
- *Fermi* observed a faint GeV emissions with an energy peak at ~10MeV.

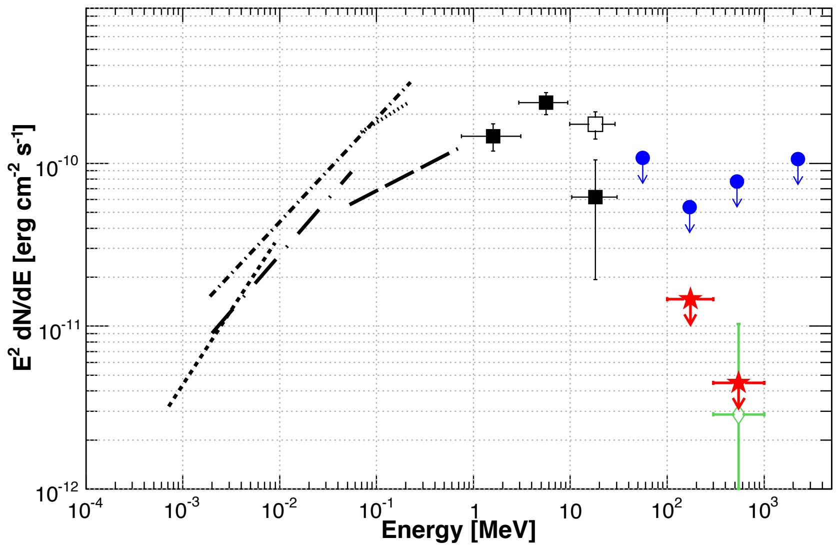
-- Polar cap emission with magnetic pair-creation effect?

$$E_{esc} \sim \frac{B_Q}{B} m_e c^2 \sim 22 B_{12}^{-1} \mathrm{MeV}$$

-- Photon spilling effect (Harding et al. 1997)

-- Geometrical effect (Wang et al. 2014; Harding and Kalopotharakos 2017)

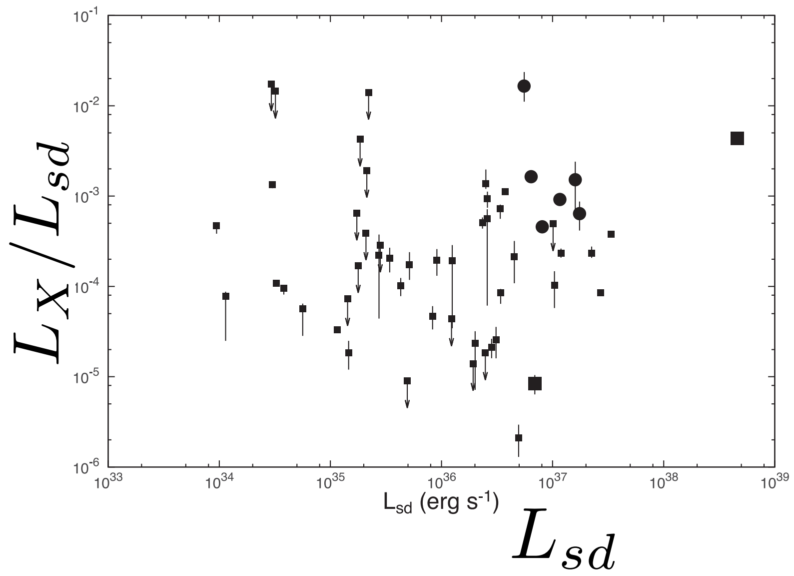


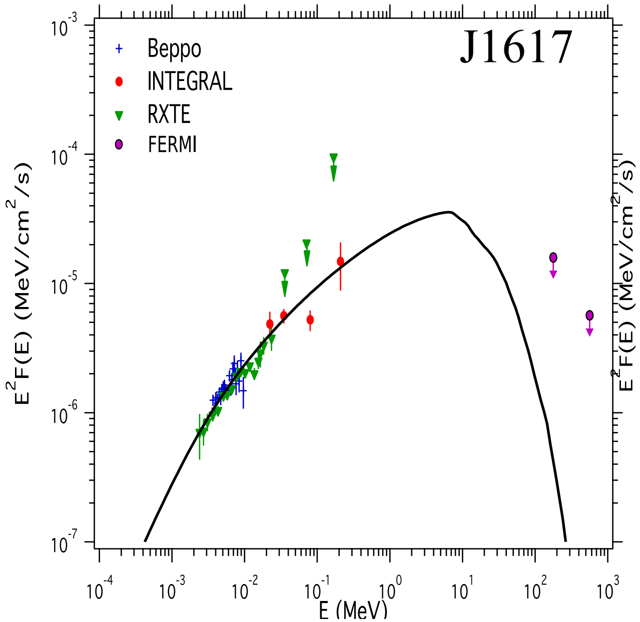


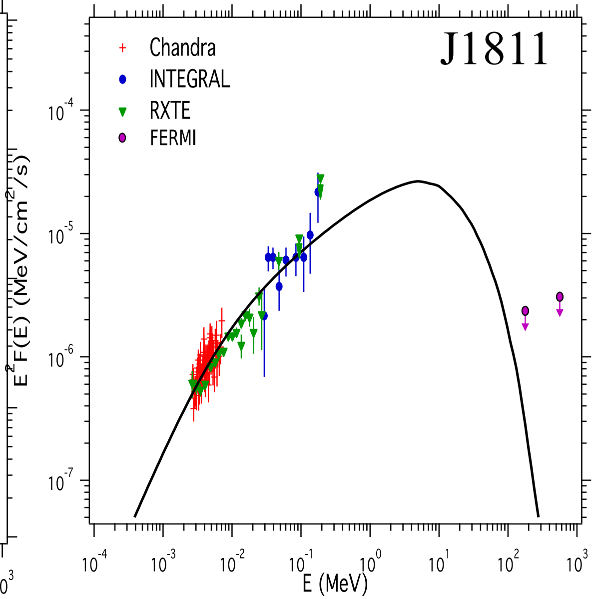
(Abdo et al. 2010)

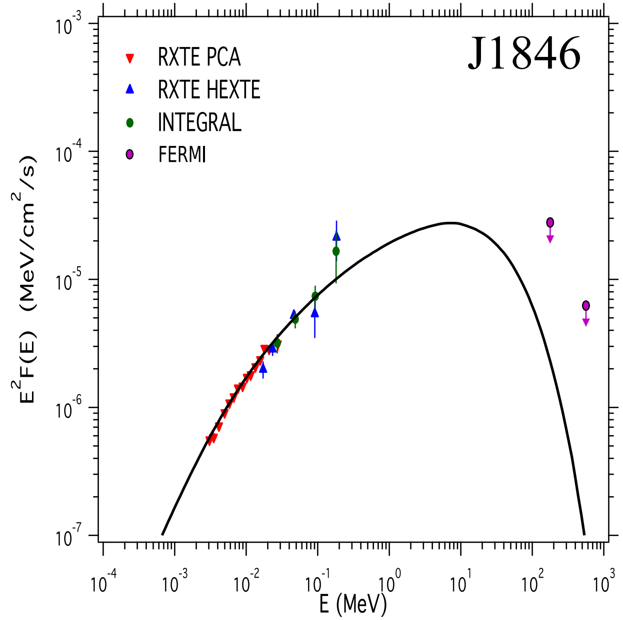
New MeV pulsars

PSRs	P (ms)	L_{sd} (10^{36} erg s^{-1})	B_s (10^{12} G)	D (kpc)	(d
B1509−58	151	17	15	4.4	
J1617−5055	69	16	3.1	6.5	
J1811−1925	65	6.4	1.7	5	
J1838−0655	65	6.4	1.7	6.6	
J1846−0258	326	8.1	48	5.8	
J1930+1852	136	12	10	5	







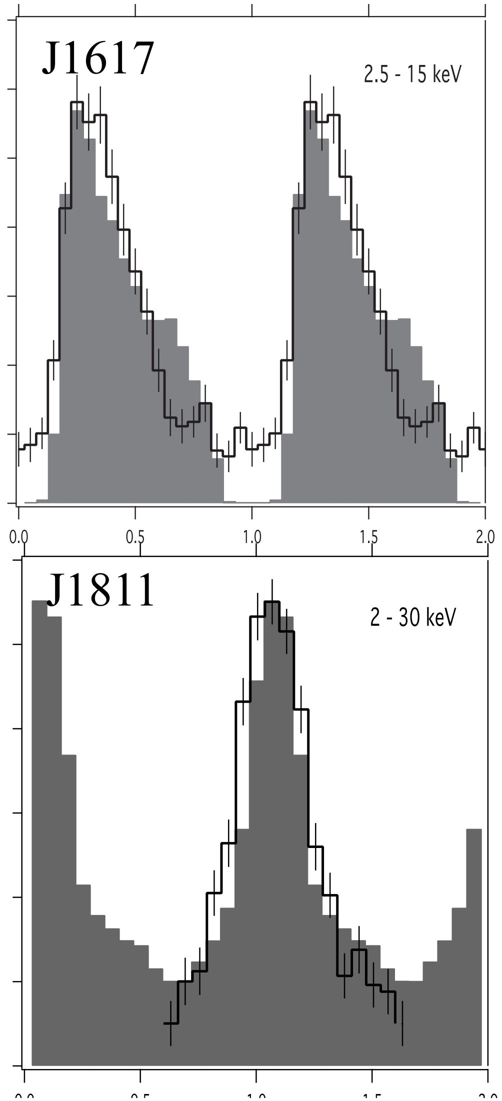


- A MeV observation and cut-off feature are crucial.

Why no (dim) radio emission?

- **Single broad peak** of the X-ray light curve.

  --consistent with the polar cap emission



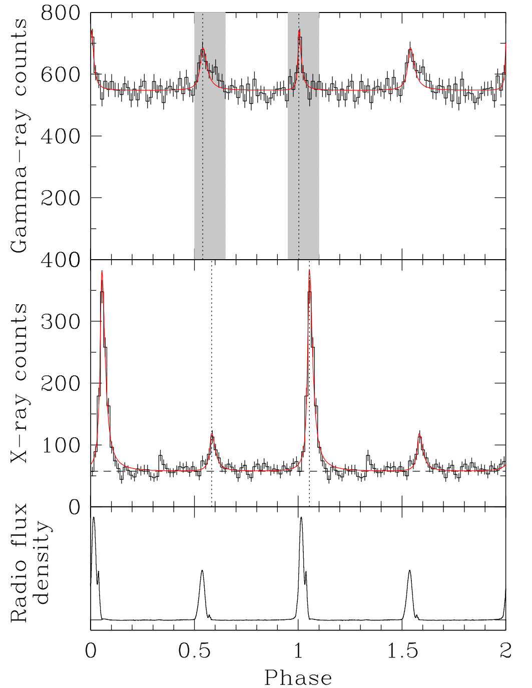
- They are **radio dim** (B1509) or **quiet** (others).

  -- a deep radio observation will be necessary.

(iii) Crab-like *millisecond* pulsars

- Some MSPs are observed with an X-ray luminosity of $L_x \sim 10^{32}$erg/s : $\ell_p/R_{lc} \sim 20 P_{1ms}(L_X/10^{32}\mathrm{erg/s})^{-1}(E_X/0.1\mathrm{keV})$
  - Pair-creation around light cylinder could be more efficient.
  - Radio emission around the light cylinder ?
  - Crab-like MSPs have **higher spin down power and larger B_{lc}**.

PSR B1937+21



(Ng et al. 2014)

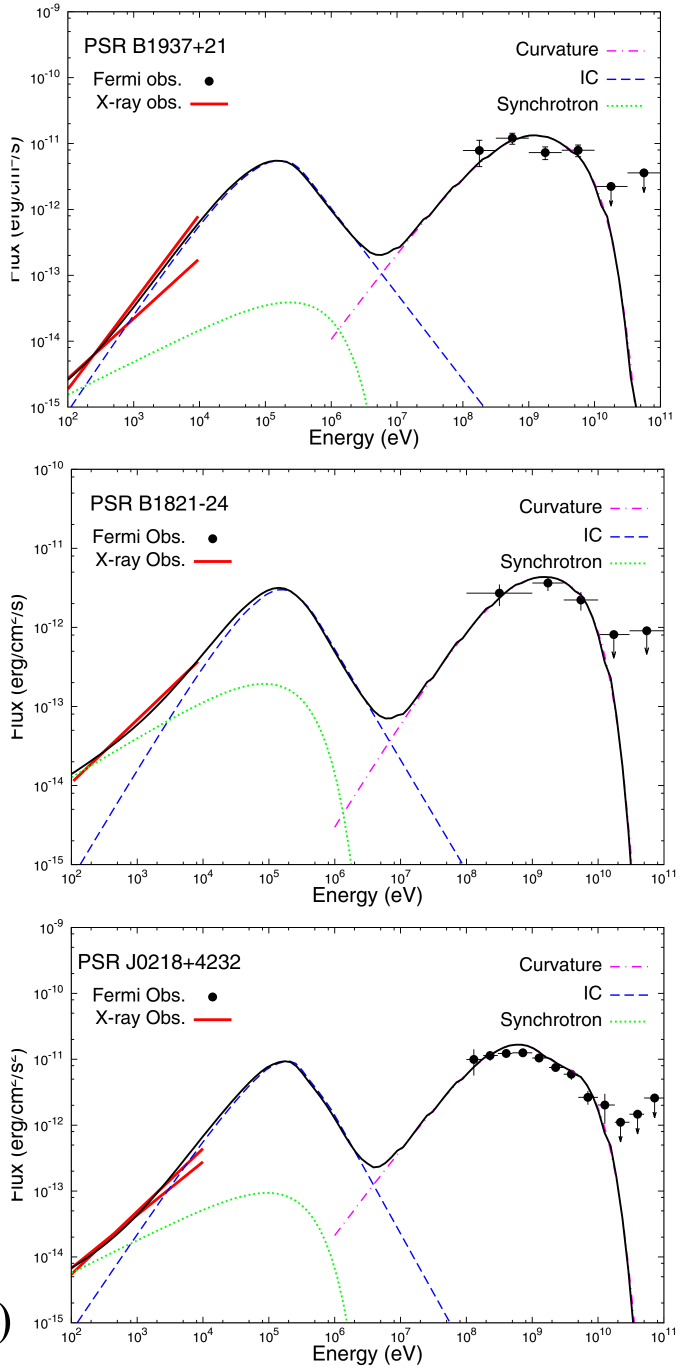
Properties of *Fermi*-LAT-detected MSPs

Name	P (ms)	$\dot{E}$ (10^{34} erg s^{-1})	B_s (10^8 G)	B_{lc} (10^5 G)	X-ray Spectrum[a]	Radio/Gamma-Ray Class[b]
B1937+21	1.6	110	4.1	9.9	PL	II
B1821−24	3.1	220	23	7.3	PL	II
J0218+4232	2.3	24	4.3	3.2	PL	II
J1747−4036	1.7	12[c]	1.5[c]	3.1[c]	...	I/II
B1957+20	1.6	7.6	1.2	2.5	...	II
B1820−30A	5.4	83[c]	43[c]	2.5[c]	...	II
J1902−5105	1.7	6.7[c]	1.3[c]	2.2[c]	...	II
J1810+1744	1.7	4.0[c]	0.9[c]	1.8[c]	...	II
J1125−5825	3.1	8.1[c]	4.4[c]	1.4[c]	...	I
J1446−4701	2.2	3.7[c]	1.5[c]	1.3[c]	...	I
J2215+5135	2.6	5.2[c]	2.5[c]	1.3[c]	...	I
J2241−5236	2.2	3.3[c]	1.4[c]	1.2[c]	...	I
J1658−5324	2.4	3.0[c]	1.7[c]	1.1[c]	...	I
J0034−0534	1.9	1.7	0.75	1.0	...	II
J1124−3653	2.4	1.6[c]	1.2[c]	0.78[c]	...	III
J0614−3329	3.2	2.2[c]	2.4[c]	0.71[c]	...	III
J2043+1711	2.4	1.3	1.0	0.70	...	I
J0102+4839	3.0	1.8[c]	1.9[c]	0.67[c]	...	III
J2214+3000	3.1	1.9[c]	2.2[c]	0.66[c]	...	II/III
J1858−2216	2.4	1.1[c]	1.0[c]	0.66[c]	...	III

Type II : Radio/X-ray/Gamma-ray pulses are in phase

X-ray emission

- **Not synchrotron emission** from pairs
  - Photon index ~1, which is harder than typical value ~1.5.
  - Power law extends beyond Nustar range.
- **Inverse-Compton process** between the primary and radio ? (Ng et al. 2014)



(Ng et al. 2014)

Summary

- **Pair-creation is key physical process to understand the pulsars.**

- もし、ポスドクのポジションをお探しの方がいましたら、声を掛けください。

- 武漢の大学には日本人のポスドク（原子核、素粒子）が数人います。

- ぜひ遊びにお越しください。
  - 赤壁古戦場が近くにあります。