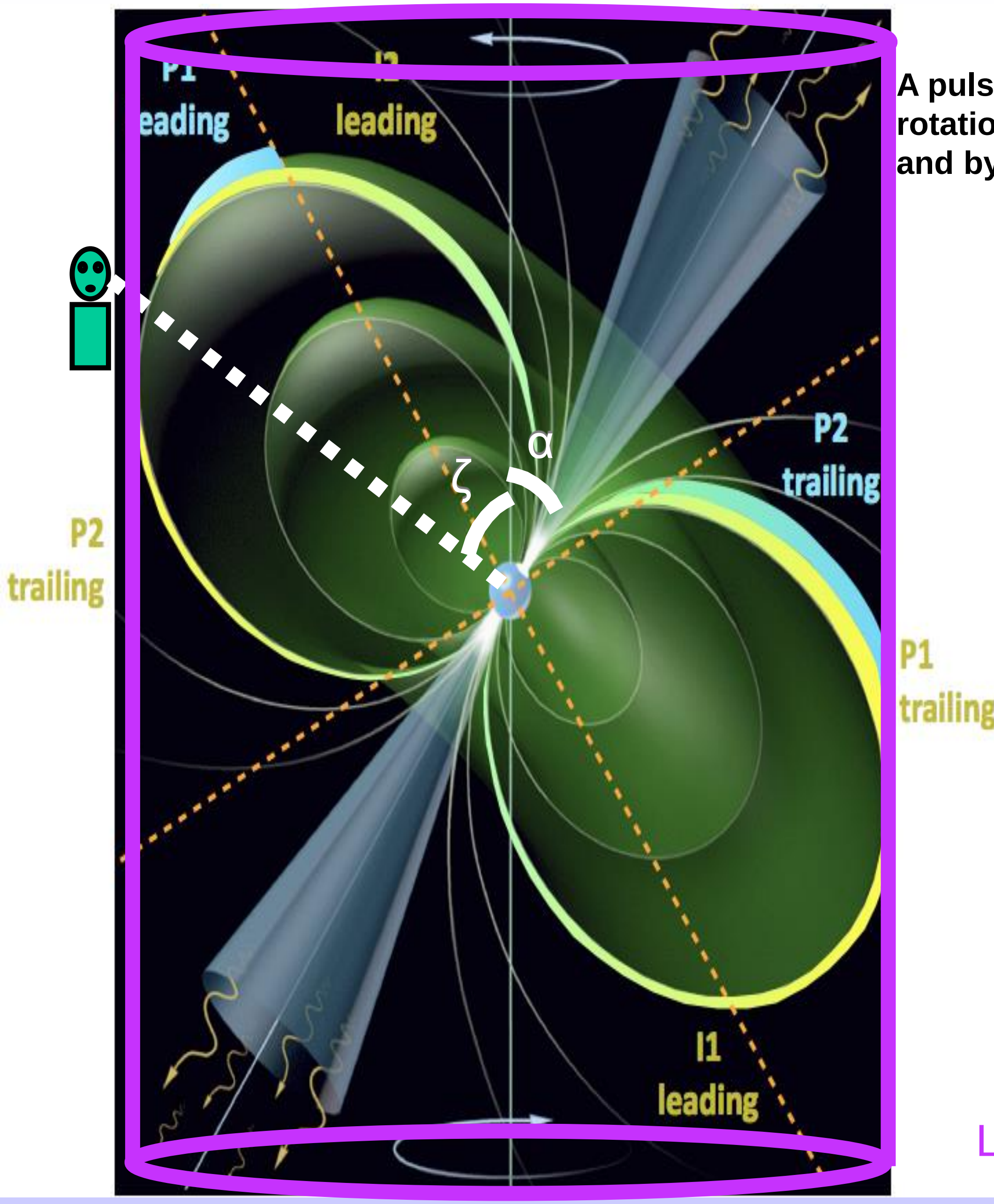
Neutron stars as particle accelerators

Patrizia Caraveo
IASF-Milano

A pulsar



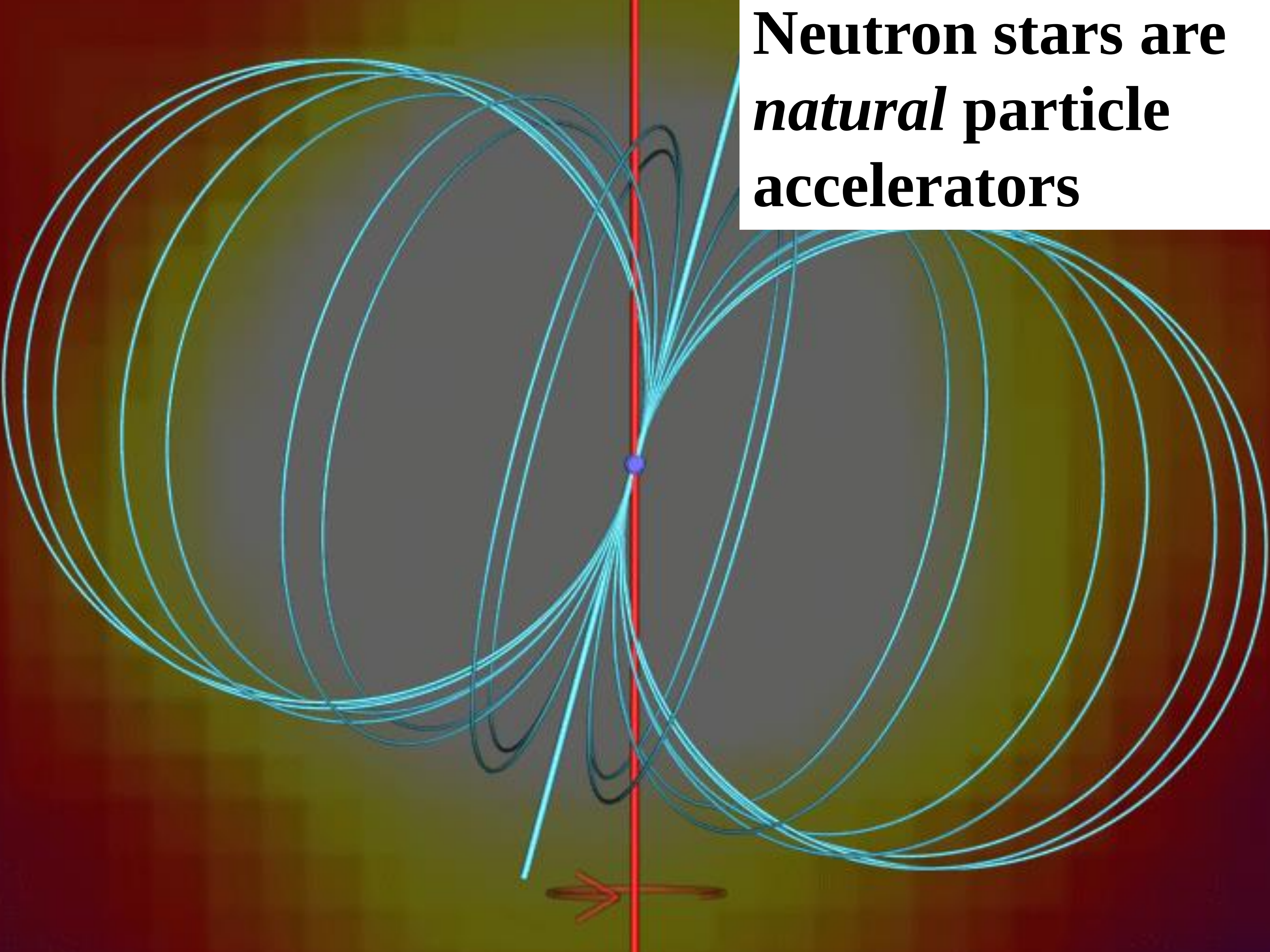
A pulsar is a neutron star (NS) characterised by a rapid rotation around its axis, by a very intense magnetic field, and by a secular increase of its spin period

Classical description

- rotational frequency Ω
- magnetic obliquity α
- observer line of sight ζ
- light cylinder (LC)
- lighthouse effect

Light cylinder $R_{LC}=c/\Omega$

Neutron stars are *natural* particle accelerators



- **Particles are produced**
- Particles are accelerated
- Particles radiate and photons interact with B field–
  gamma-ray emission

- Particles impinge into the surface Hot spot X-rays

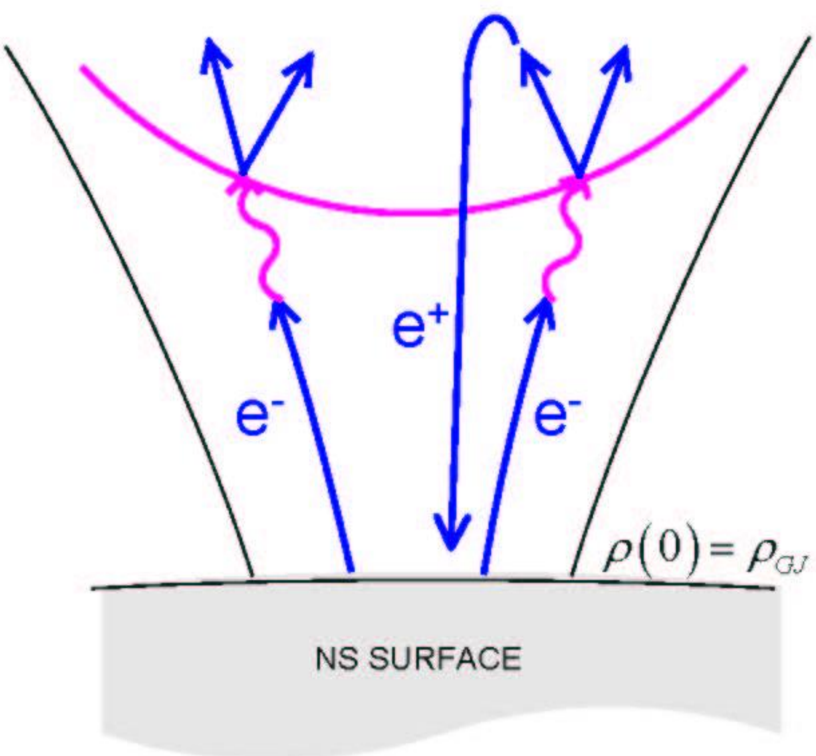
- Particles escape into the ISM PWNe   X-rays VHE gamma-rays

Polar cap accelerators

SPACE CHARGE "GAP"

$T_s > T_{e,i}$

$\Omega \bullet B > 0$

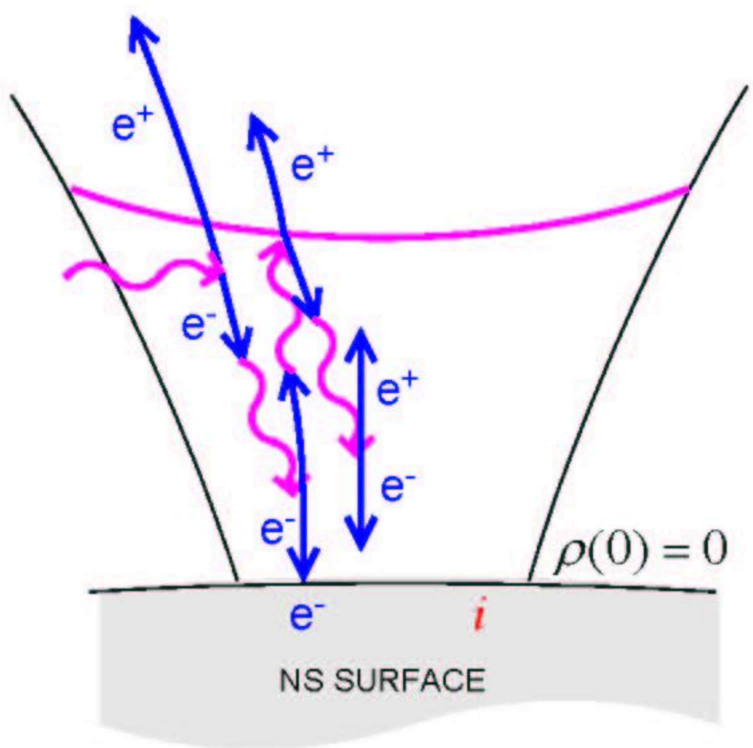


$$\nabla \bullet E = -4\pi(\rho - \rho_{GJ})$$

VACUUM GAP

$T_s < T_{e,i}$

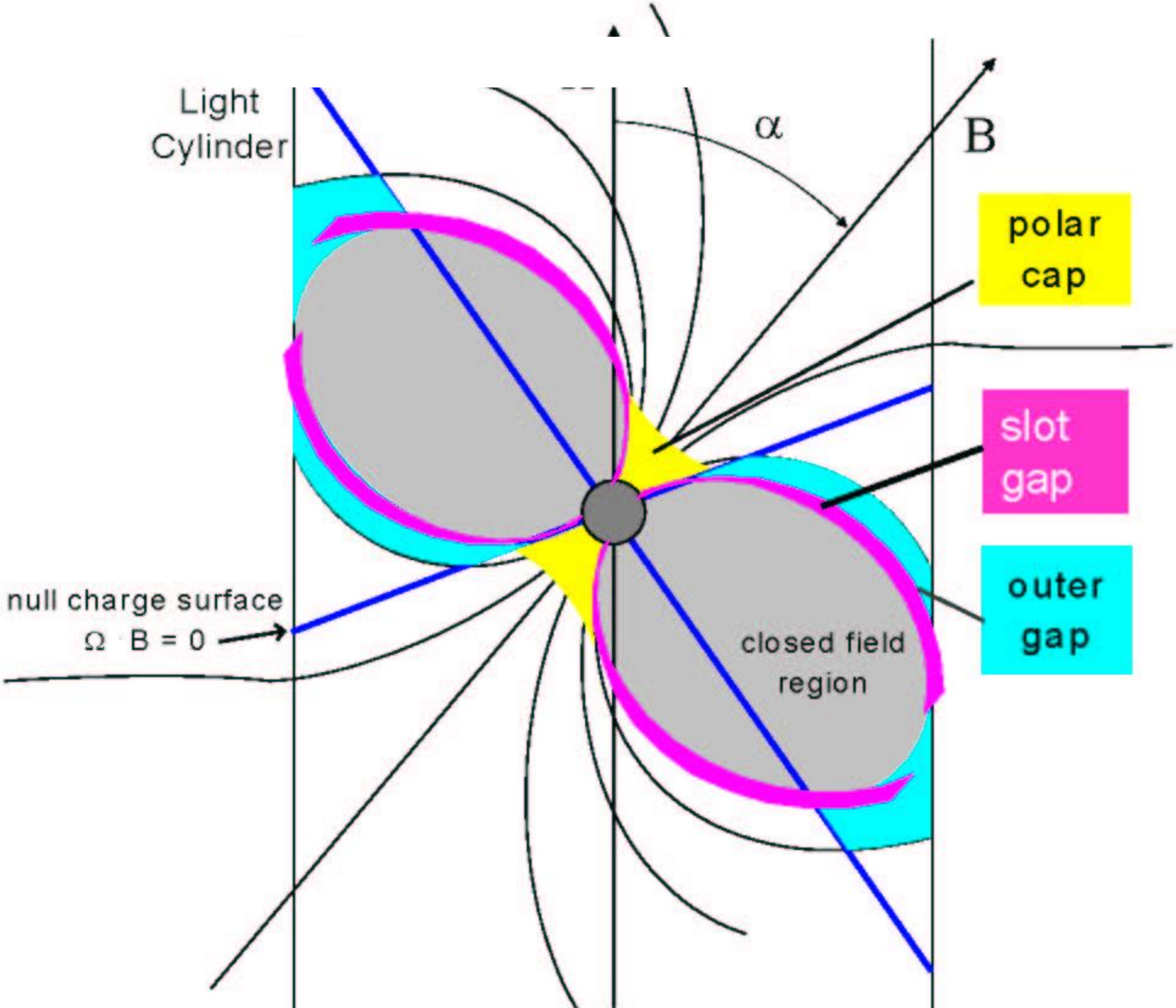
$\Omega \bullet B < 0$



$$\nabla \bullet E = 4\pi\rho_{GJ}$$

A. Harding

- Particles are produced
- **Particles are accelerated**
- Particles radiate and photons interact with B field– gamma-rays
- Particles impinge on the surface. Hot spots X-rays
- Particles escape into the ISM: PWNe X-rays VHE gamma-rays

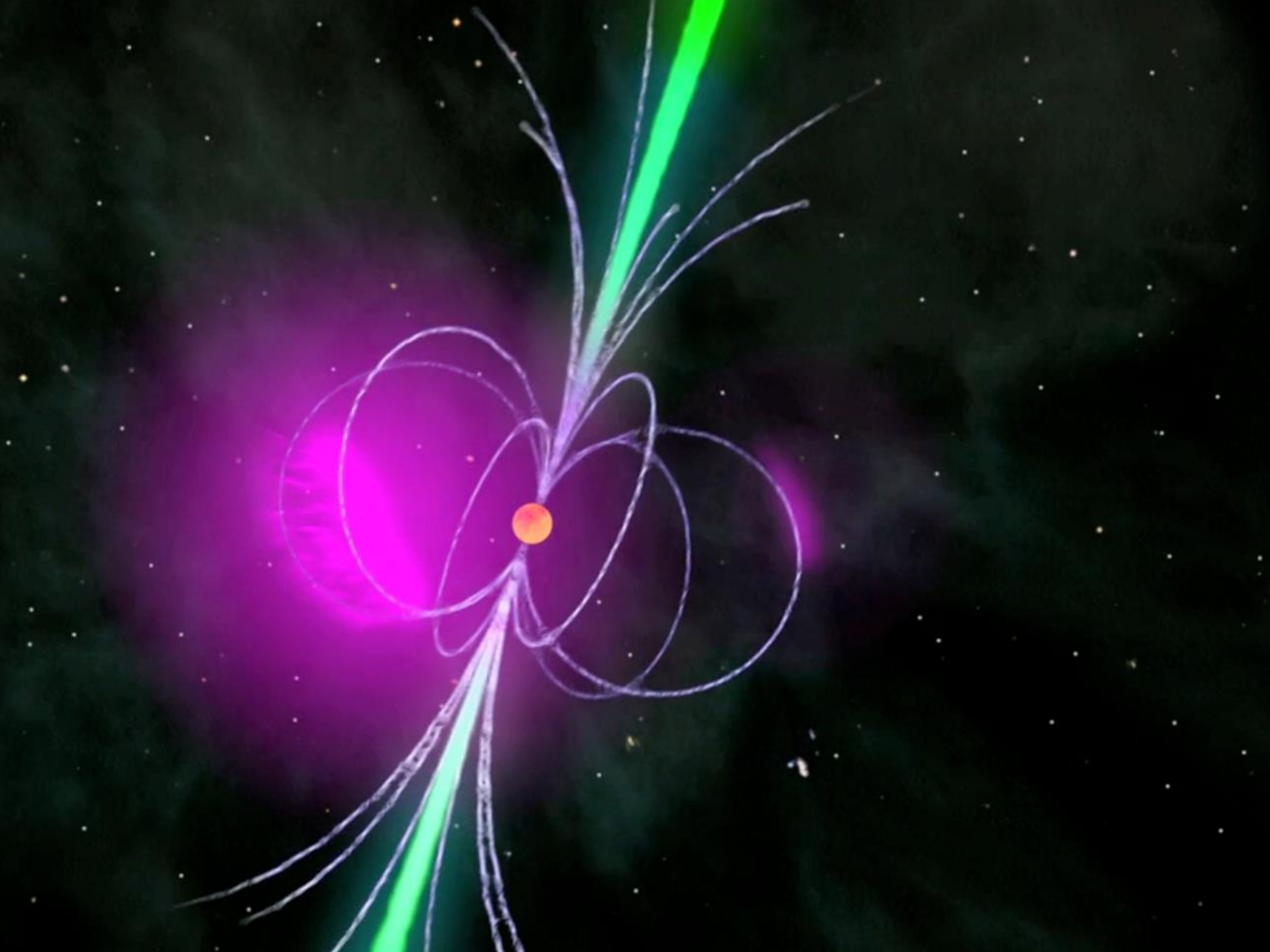

Light
Cylinder
α
B
polar
cap
slot
gap
outer
gap
null charge surface
Ω · B = 0
closed field
region

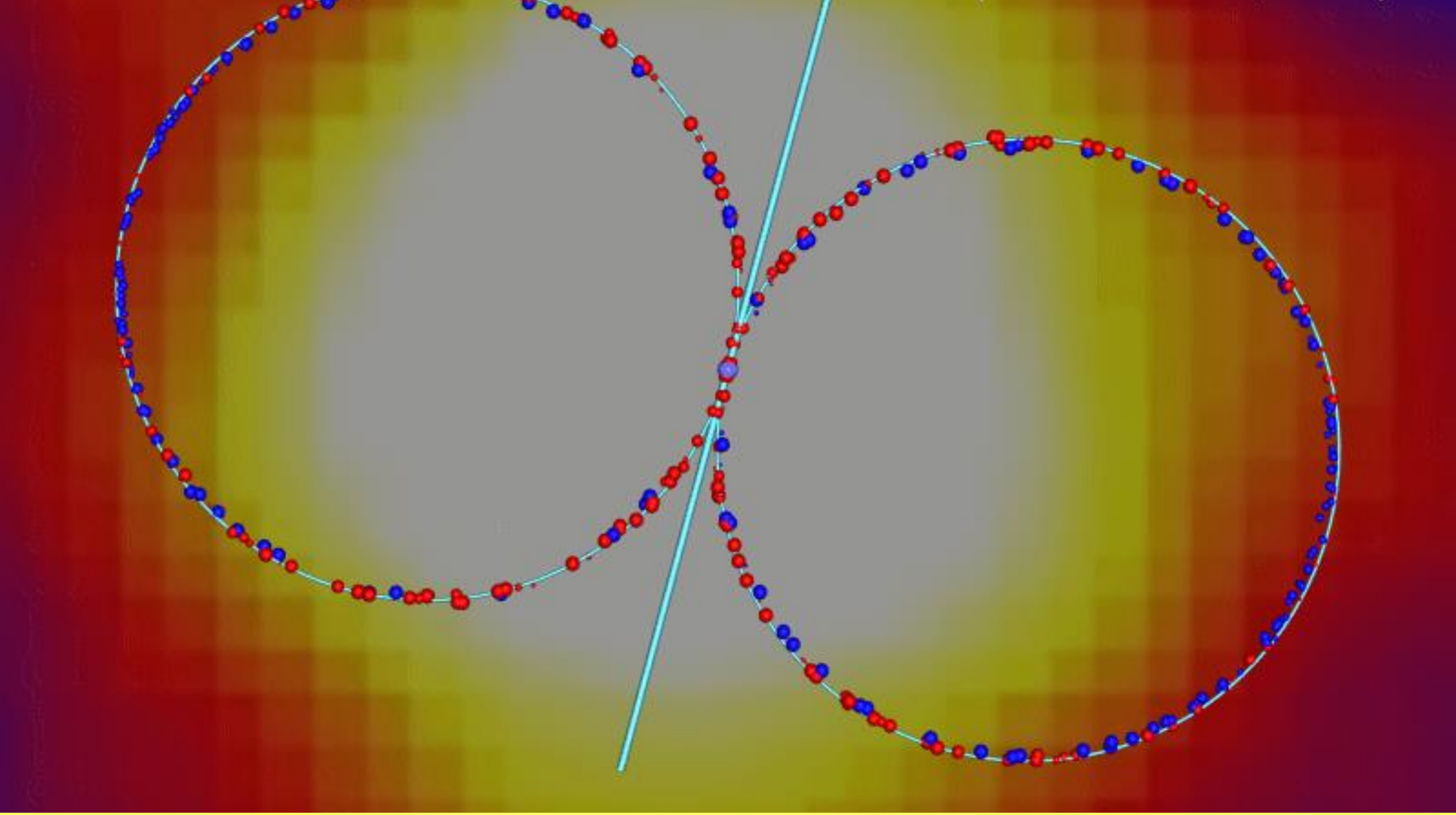
A. Harding

- Particles are produced
- Particles are accelerated
- **Particles radiate and photons interact with B field– gamma-ray emission**

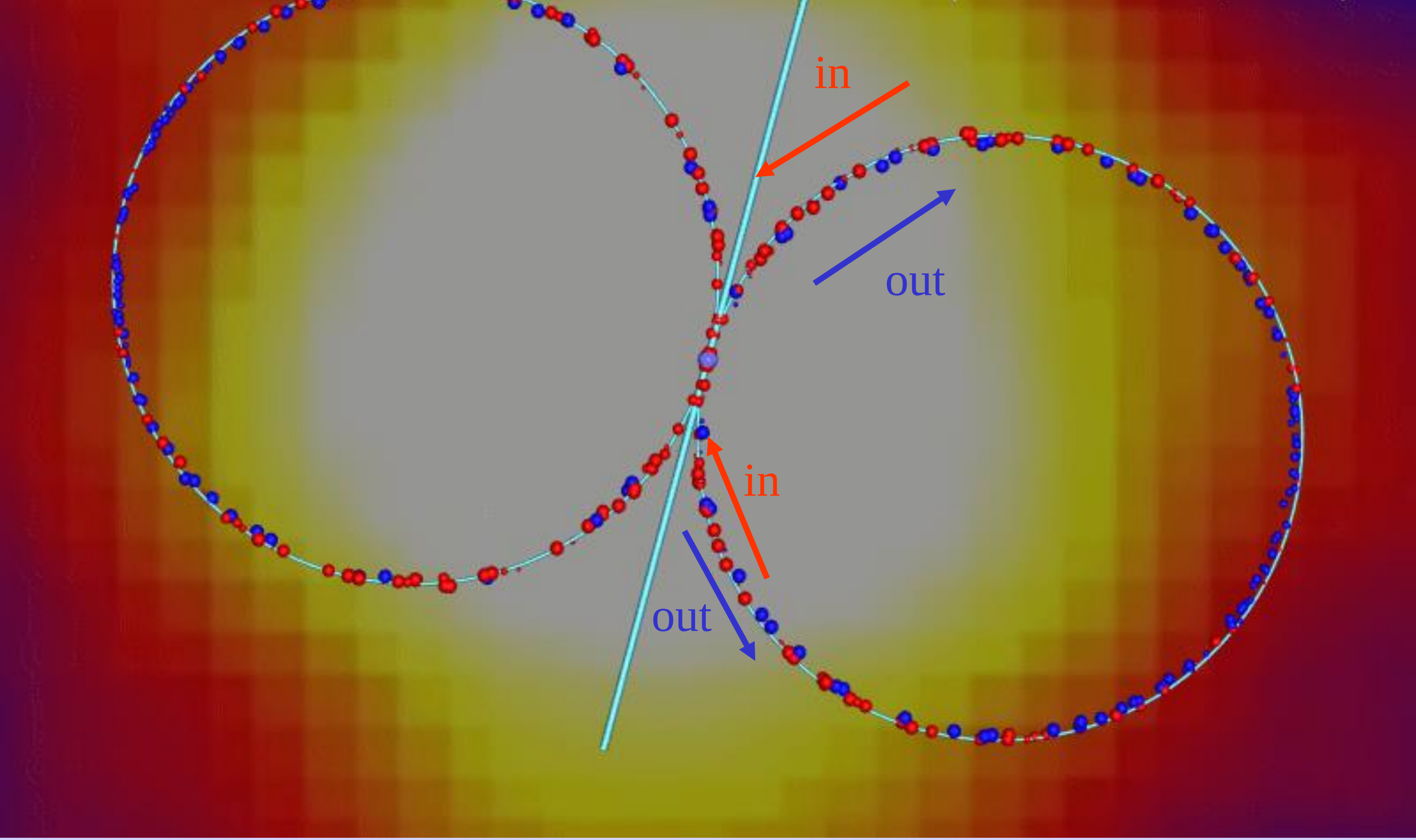
- Particles impinge on the surface. Hot spots X-rays

- Particles escape into the ISM: PWNe   X-rays VHE gamma-rays





Gamma-ray astronomy tells us that the magnetosphere of a NS (of sufficient Edot) is filled with high energy e+ e-

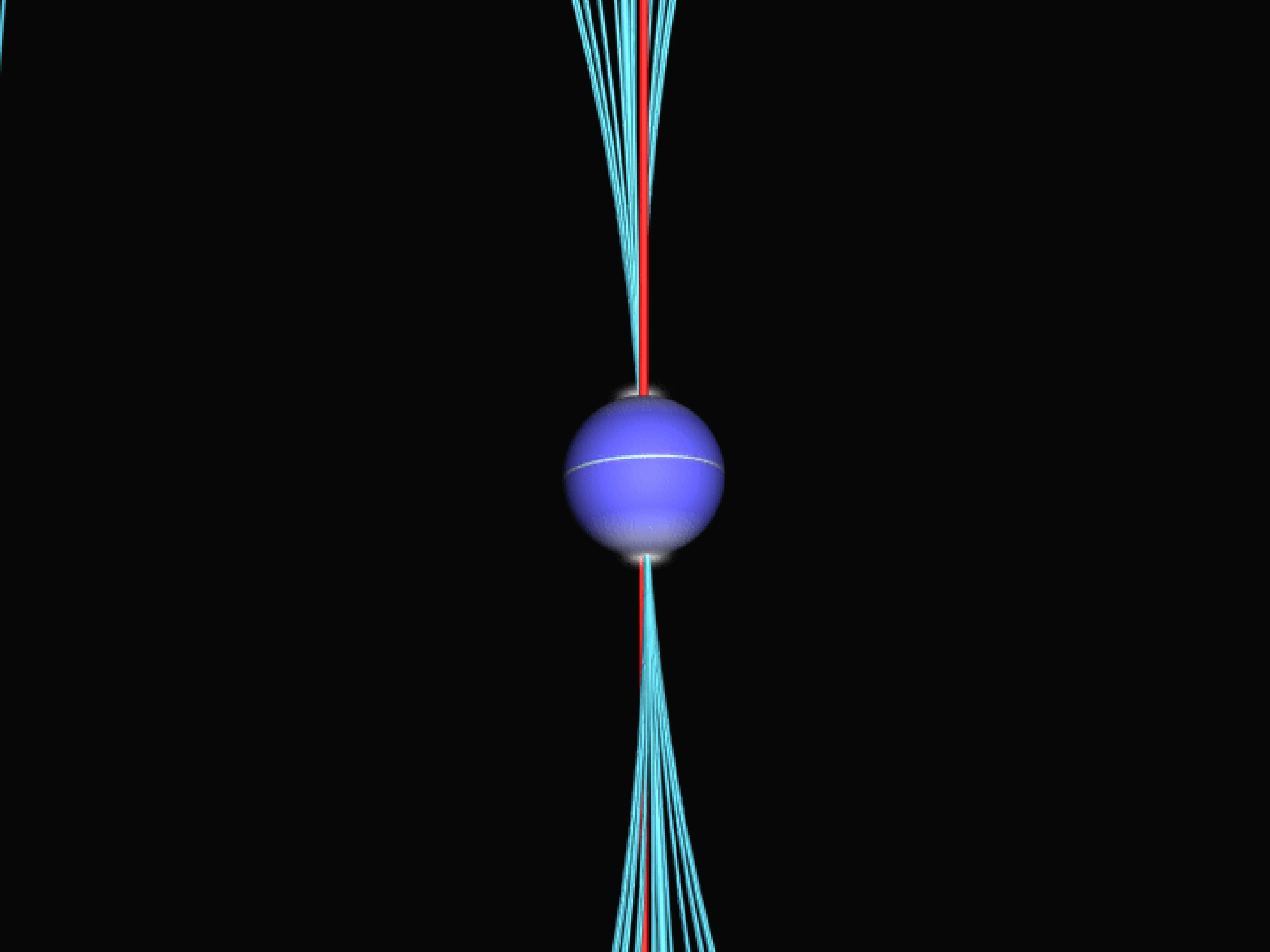


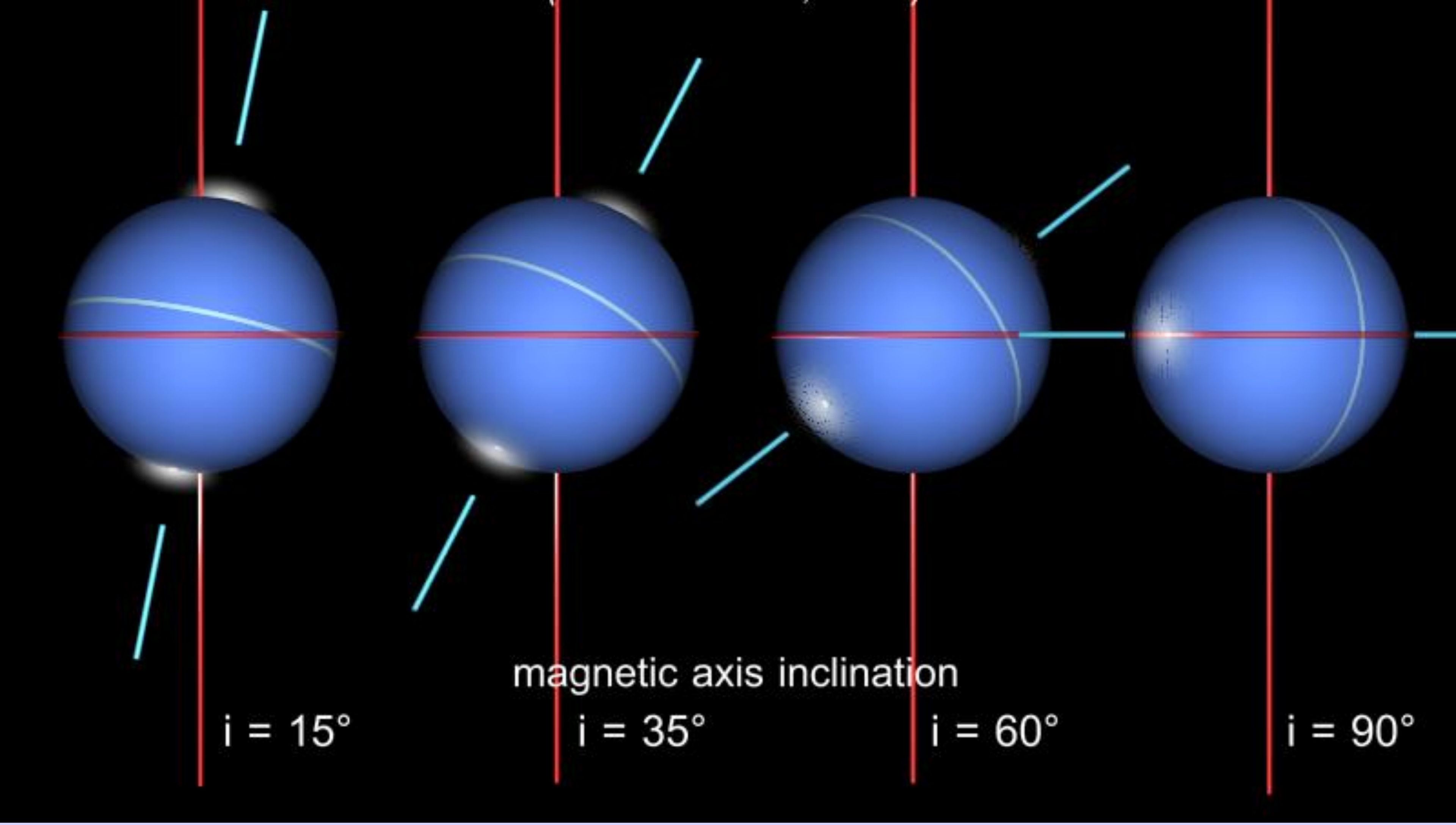
Magnetic field lines are 2-way streets

- Particles are produced
- Particles are accelerated
- Particles radiate and photons interact with B field– gamma-rays

- **Particles impinge on the surface**
  Hot spots X-rays

- Particles escape into the ISM PWNe X-rays VHE gamma-rays

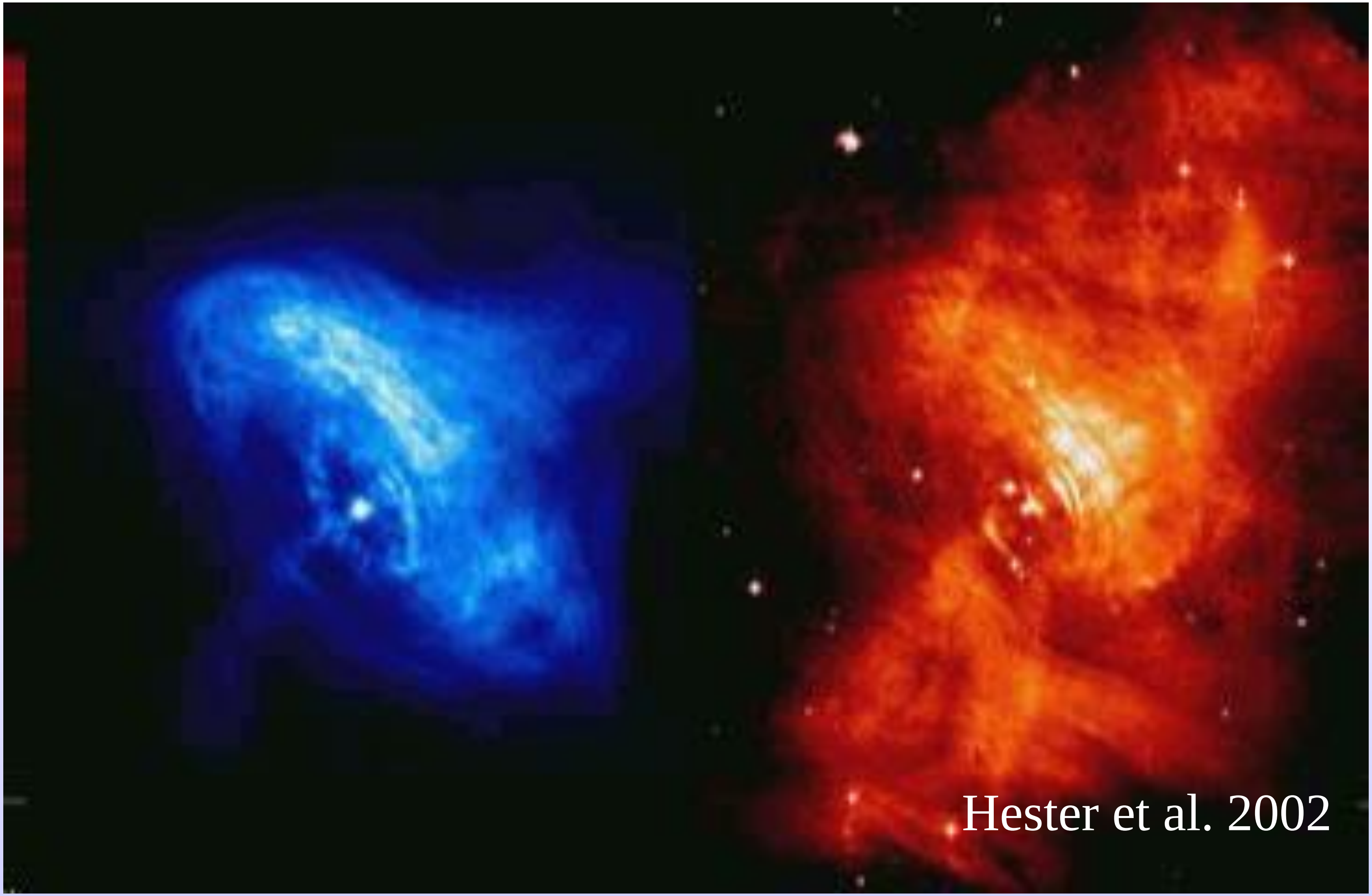



magnetic axis inclination
i = 15°
i = 35°
i = 60°
i = 90°

- Particles are produced
- Particles are accelerated
- Particles radiate and photons interact with B field– gamma
- Major channel

- Particles impinge into the surface Hot spot X-ray

- **Particles escape into the ISM PWNe**
  X-rays- VHE gamma-rays

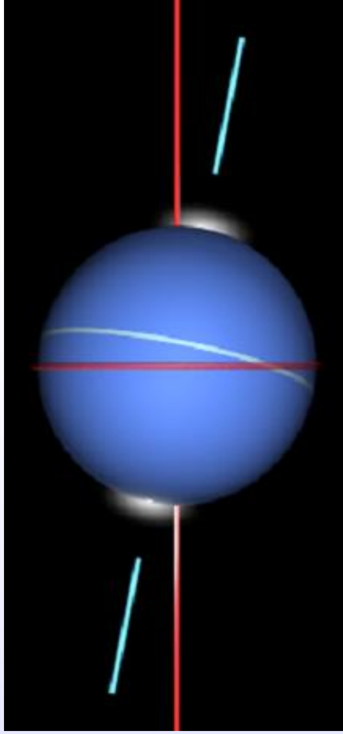


What happens to particles accelerated away from the star?

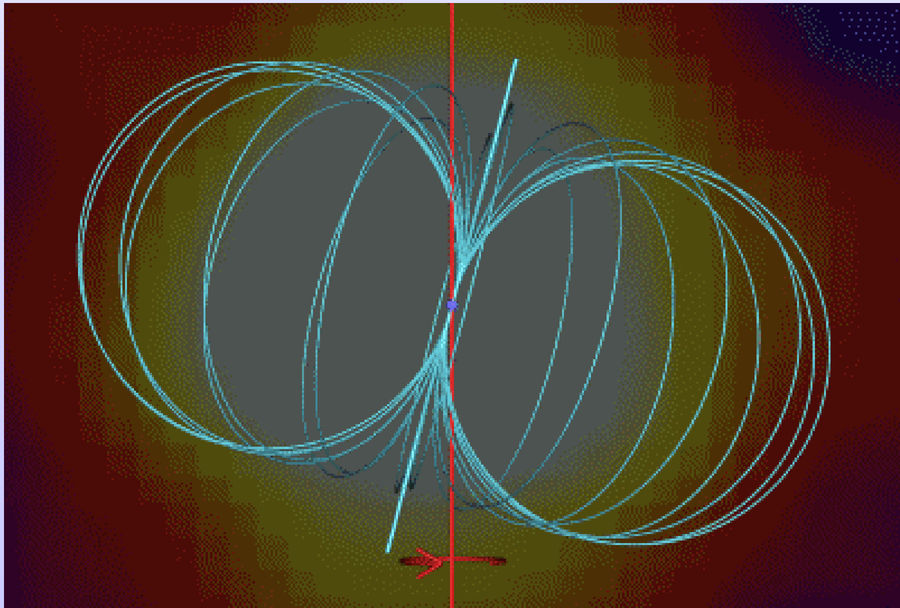
Anatomy of NSs' emission

X-rays

- (rotating) surface emission
  primeval heat, particle re-heating



- (rotating) magnetospheric emission
  particle acceleration- rot. energy loss



- NS surroundings
  relativistic wind
  (escaping particles),
  interaction with ISM

Anatomy of NSs' emission

- **(rotating) surface emission**
  primeval heat, particle re-heating

  X-rays

- **(rotating) magnetospheric emission**
  particle acceleration- rot. energy loss

  Radio
  Optical
  X-rays
  → γ-rays

- **NS surroundings**
  relativistic wind
  (escaping particles),
  interaction with ISM

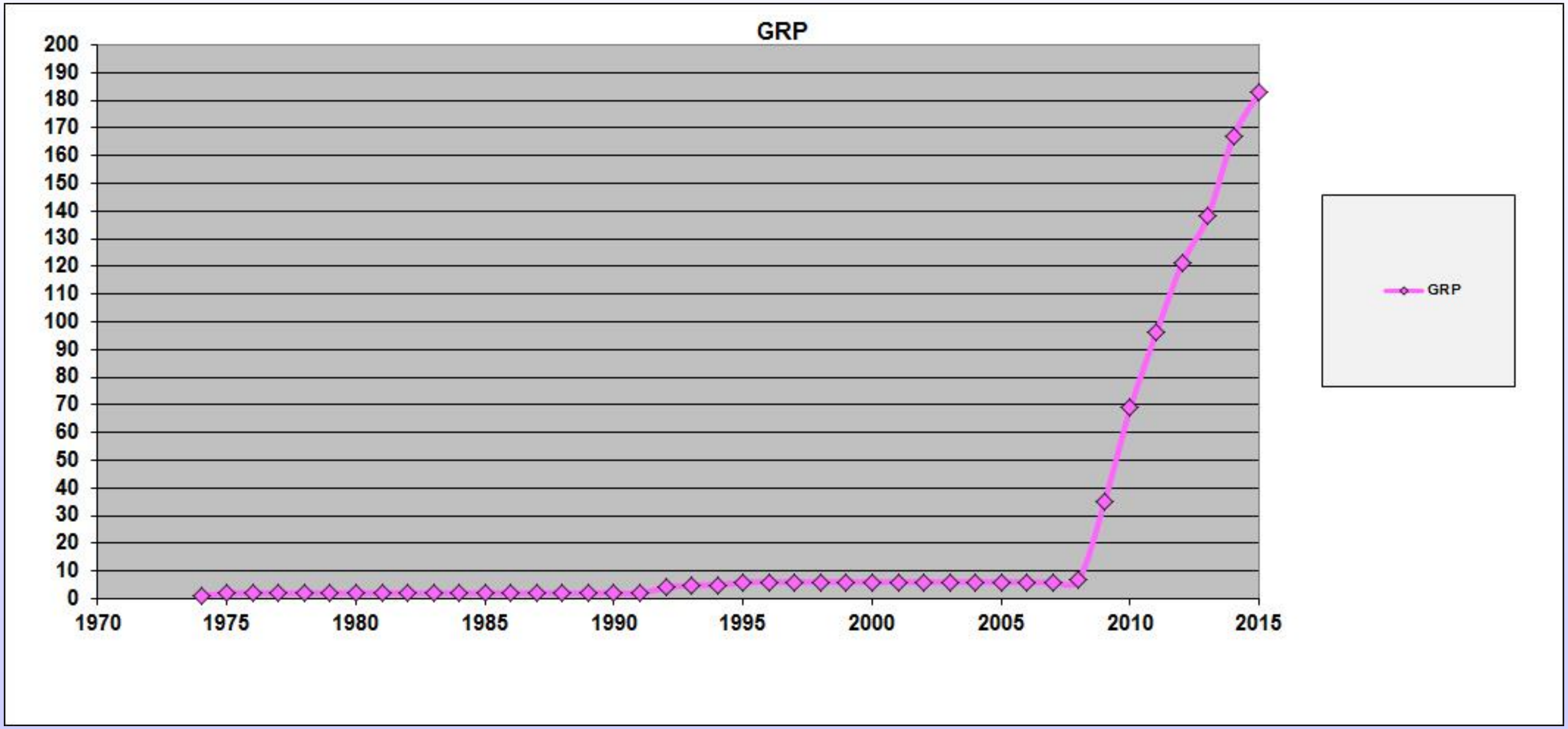
  X-rays
  γ-rays

Gamma-Ray Pulsar Revolution

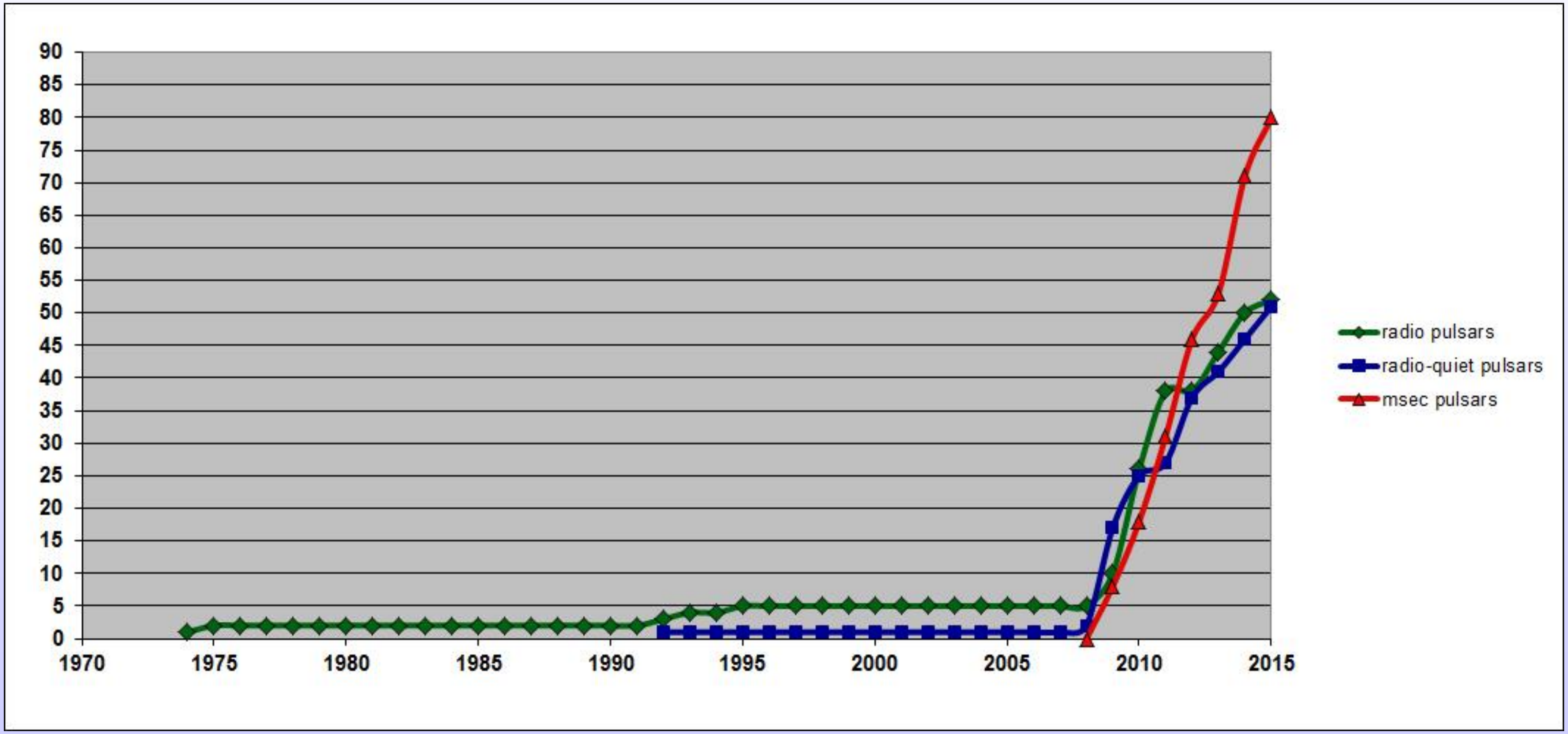
Patrizia A. Caraveo

Istituto di Astrofisica Spaziale (IASF) - Istituto Nazionale di Astrofisica (INAF), 20133 Milano, Italy; email: pat@iasf-milano.inaf.it

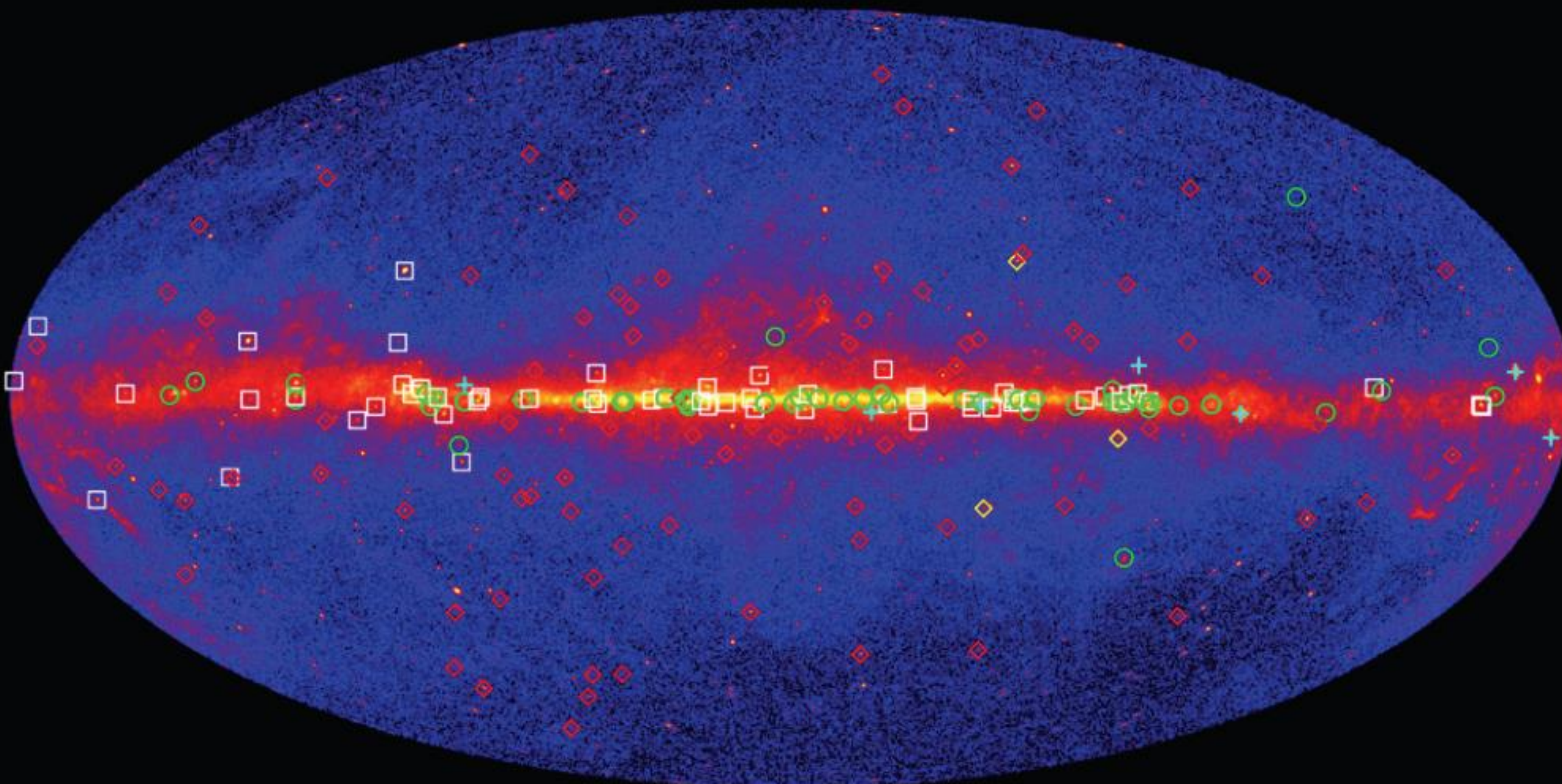
40 years of gamma-ray PSRs



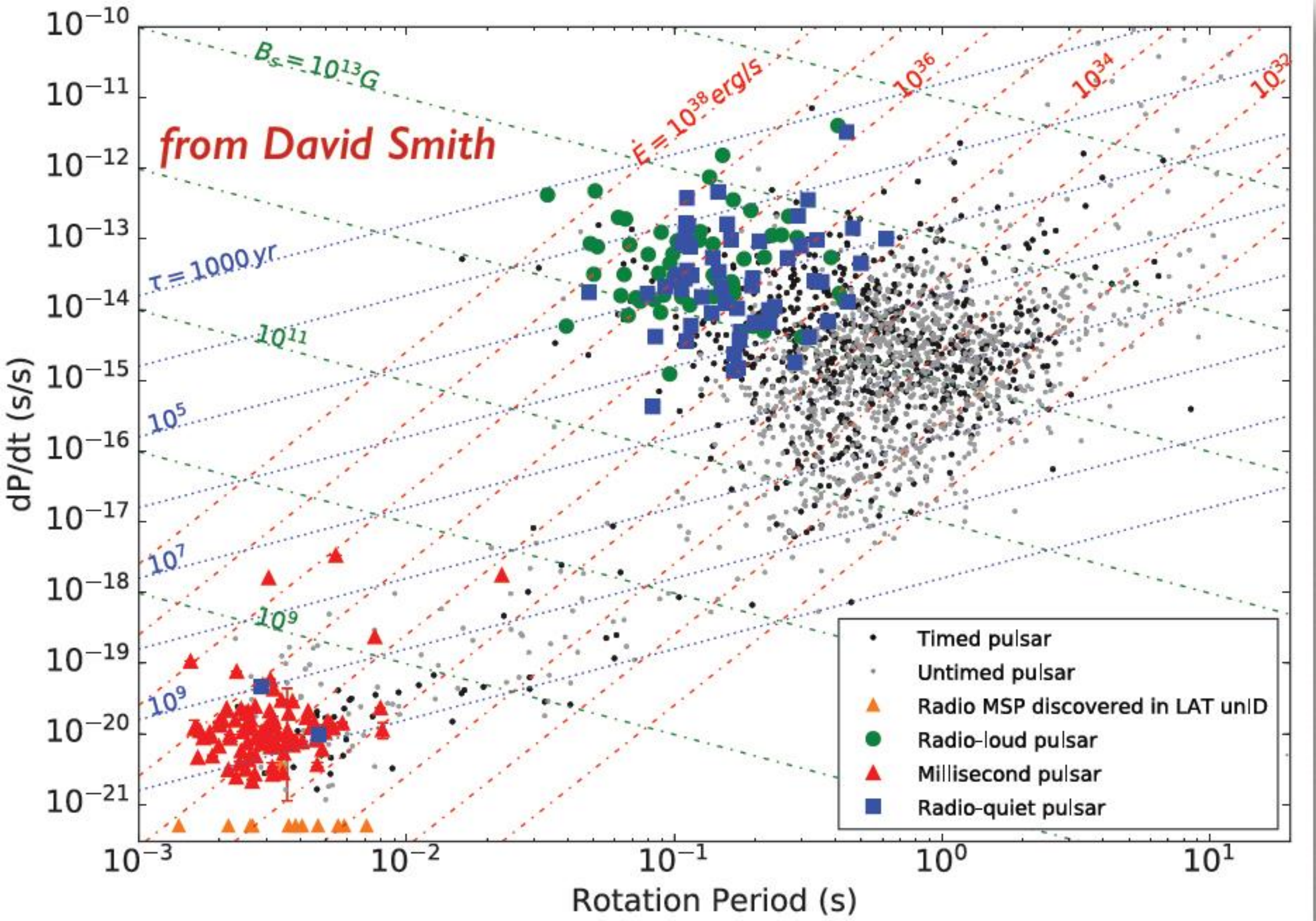
PSRs’ families



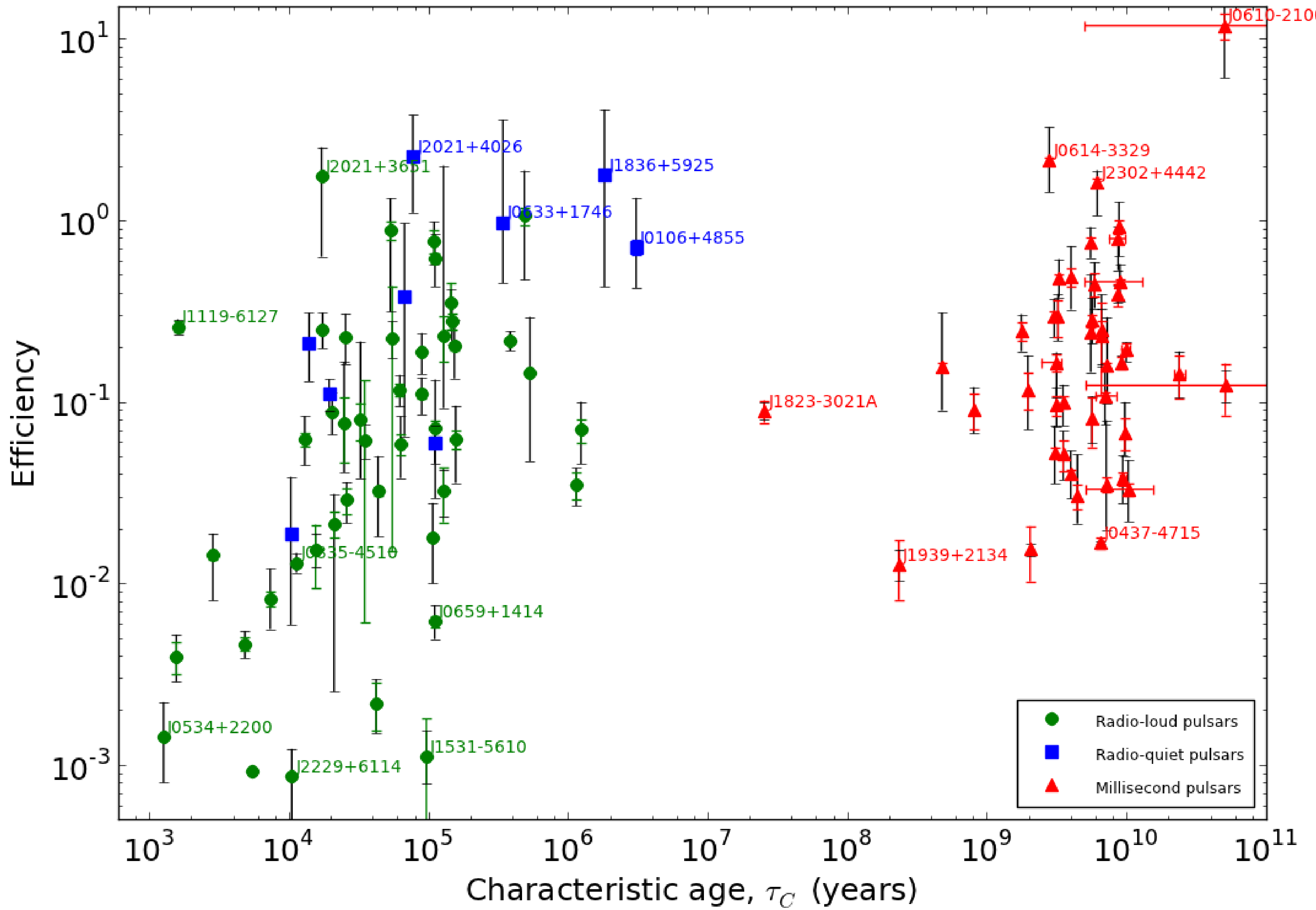
TODAY
> 200 gamma-ray pulsars



58 young radio- and X-ray-selected (green circles, cyan crosses: EGRET pulsars)
57 young gamma-ray-selected (white squares)
93 radio-selected MSPs (red diamonds), 3 γ-ray-selected MSPs (yellow diamonds)



from David Smith
$B_s = 10^{13}$G
10^{11}
10^9
$\dot{E} = 10^{38}$ erg/s
10^{36}
10^{34}
10^{32}
$\tau = 1000$ yr
10^5
10^7
10^9
dP/dt (s/s)
Rotation Period (s)
Timed pulsar
Untimed pulsar
Radio MSP discovered in LAT unID
Radio-loud pulsar
Millisecond pulsar
Radio-quiet pulsar



Efficiency
Characteristic age, τ_C (years)
Radio-loud pulsars
Radio-quiet pulsars
Millisecond pulsars
J0610-2100
J0614-3329
J2302+4442
J2021+4026
J2021+3651
J1836+5925
J0633+1746
J0106+4855
J1119-6127
J1823-3021A
J0835-4510
J0437-4715
J1939+2134
J0659+1414
J0534+2200
J2229+6114
J1531-5610

MSPs resemble young pulsars.

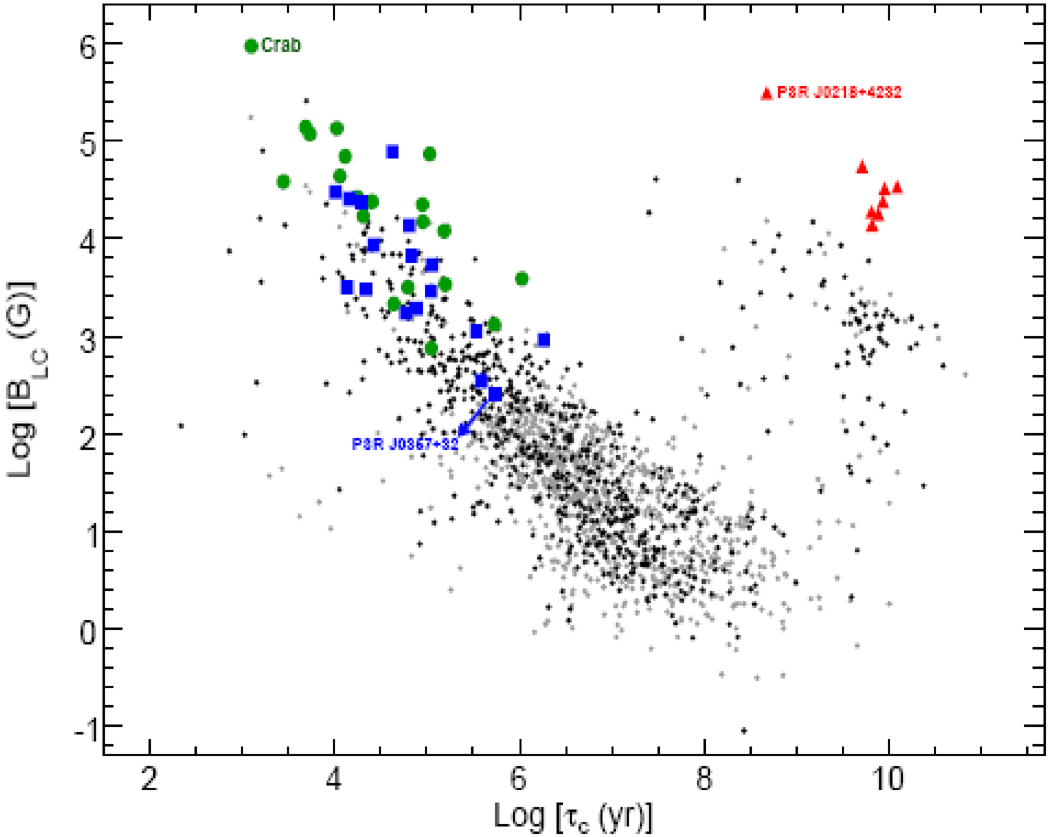
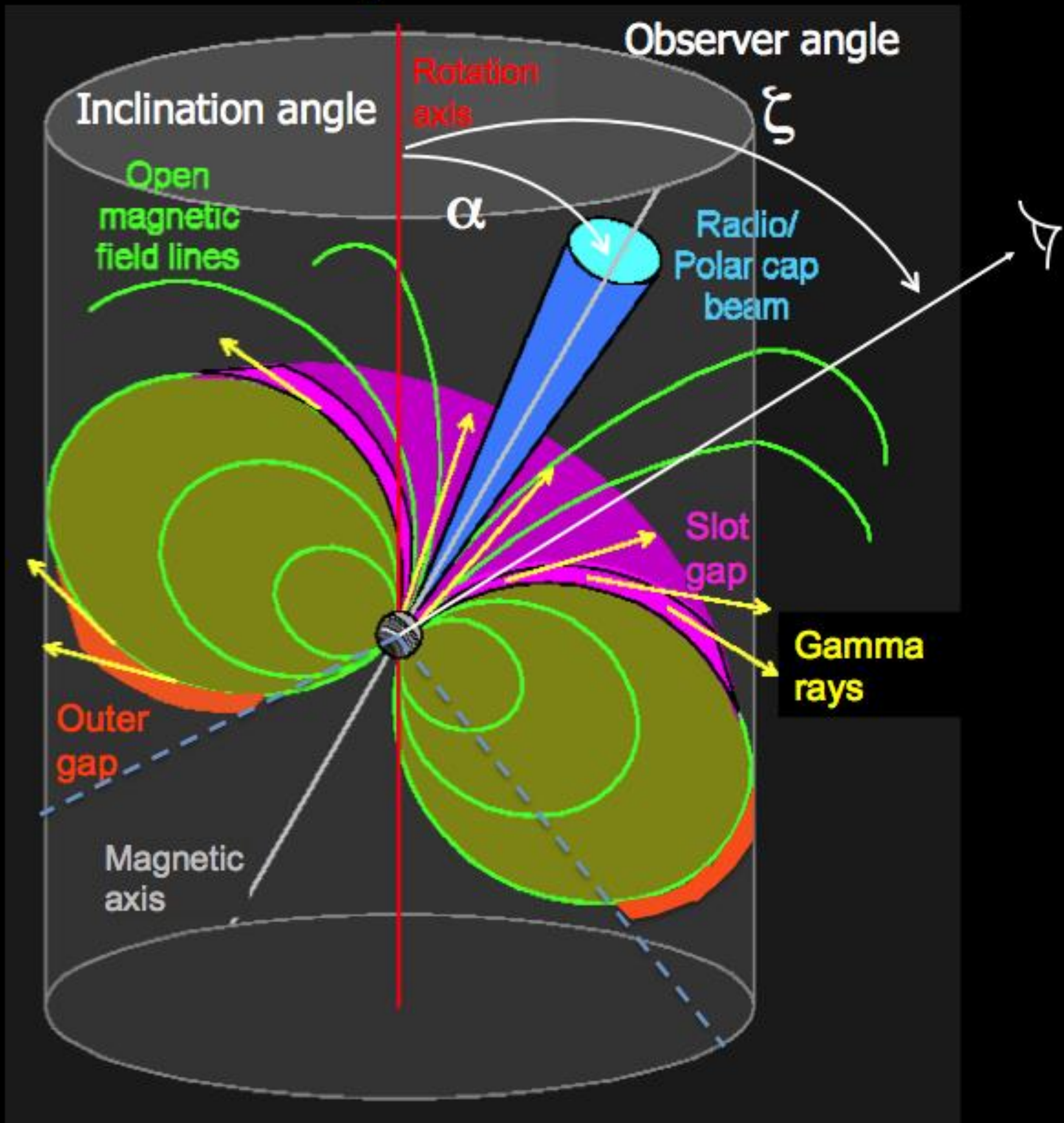


Fig. 5.— Magnetic field strength at the light cylinder B_{LC} versus pulsar characteristic age

Gamma-ray emission sites



Key Observables: Energy spectrum

Fermi Gamma-ray Space Telescope

The energy spectrum can be described by a power law with an (hyper) exponential cutoff :

$$\frac{dN}{dE} = N_0 \left(\frac{E}{1 \text{ GeV}} \right)^{-\Gamma} \exp \left(-\frac{E}{E_c} \right)^{\beta}$$

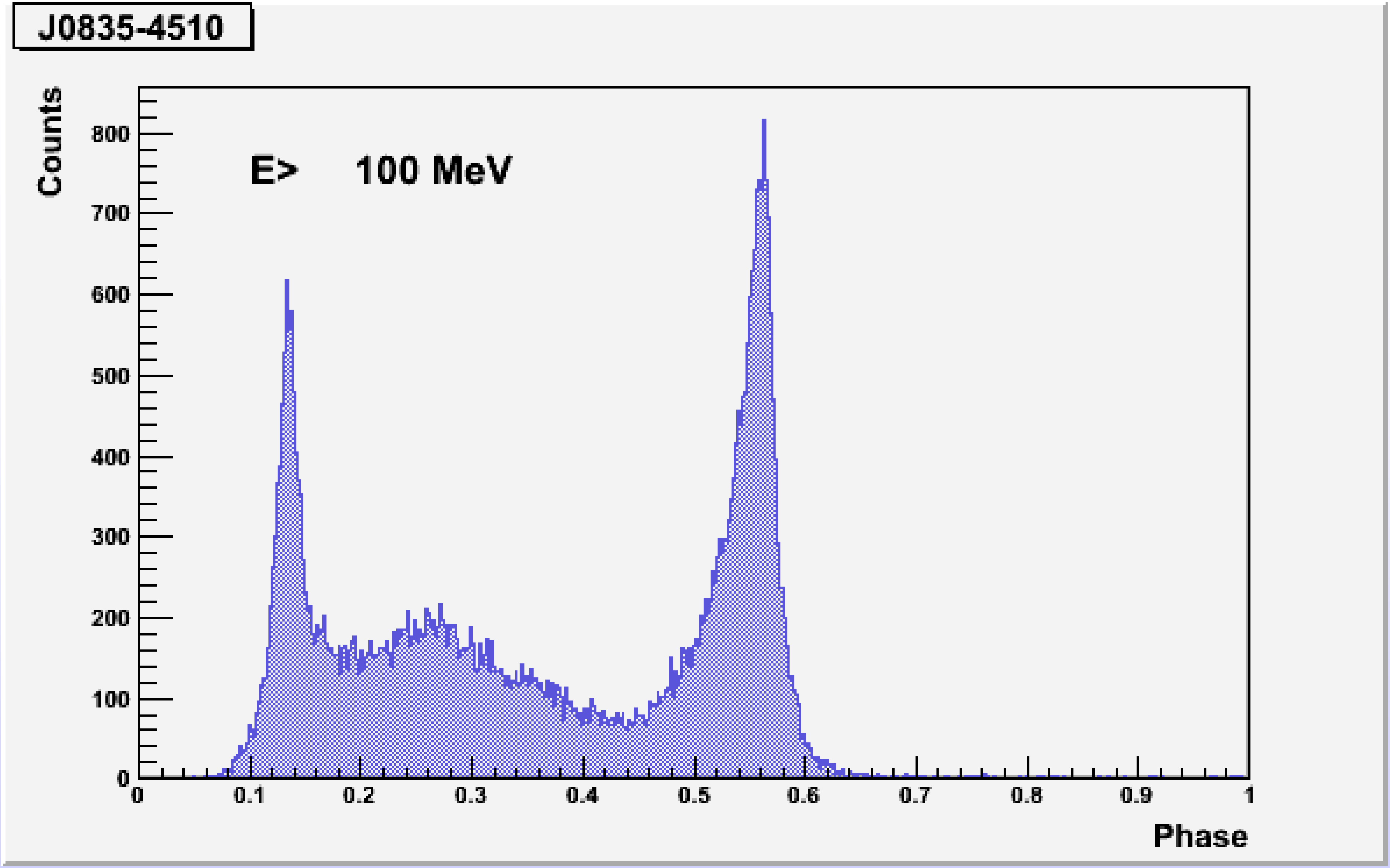
Spectral Index ($-\Gamma$)

Cutoff Energy (E_c)

β : cutoff index

~ 1 : Slot Gap and Outer Gap models (high altitude emission)

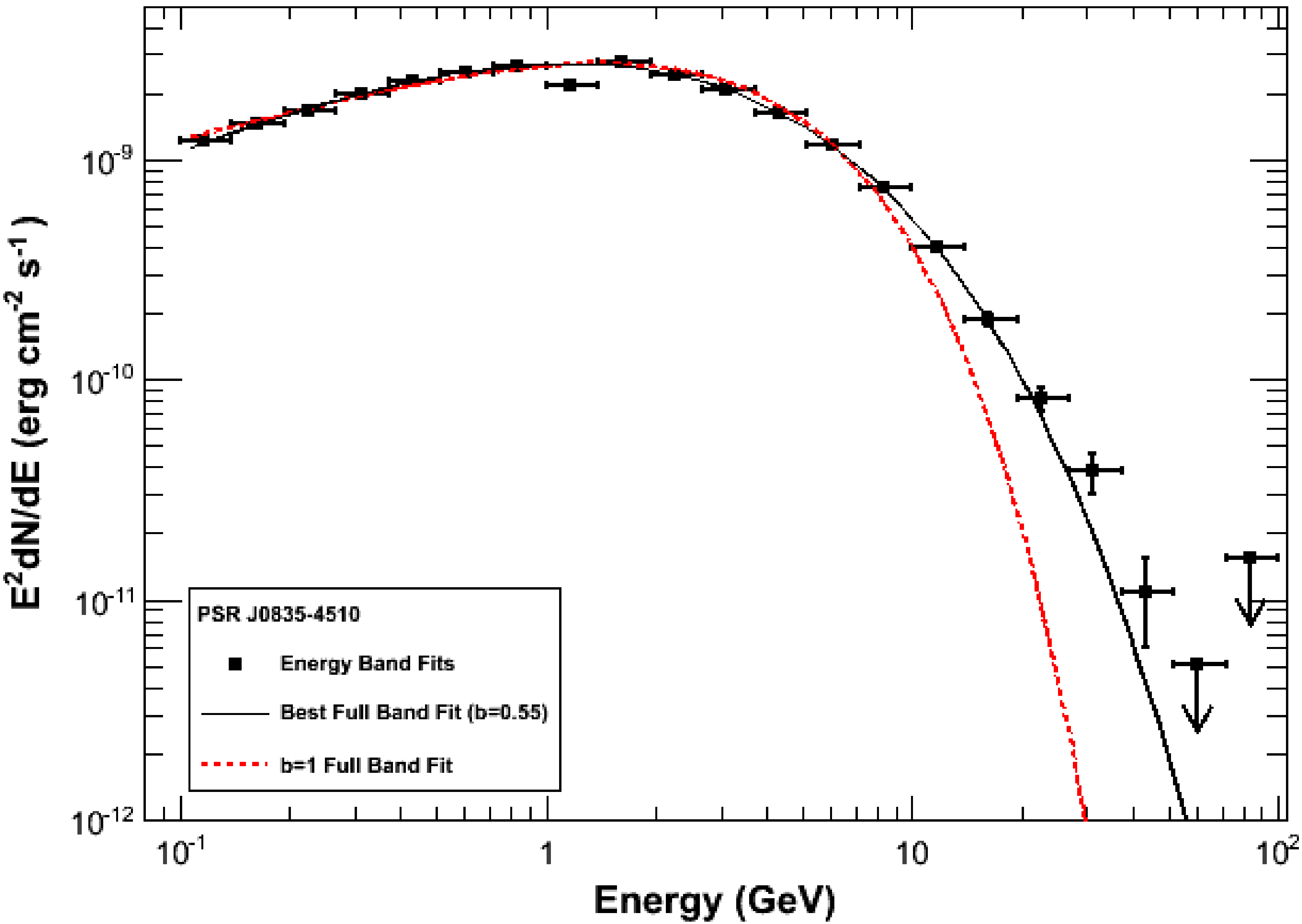
~ 2 : Polar Cap model (low altitude emission)



Vela pulsar. Abdo, A. A. et al. 2009, ApJ, 696, 1084

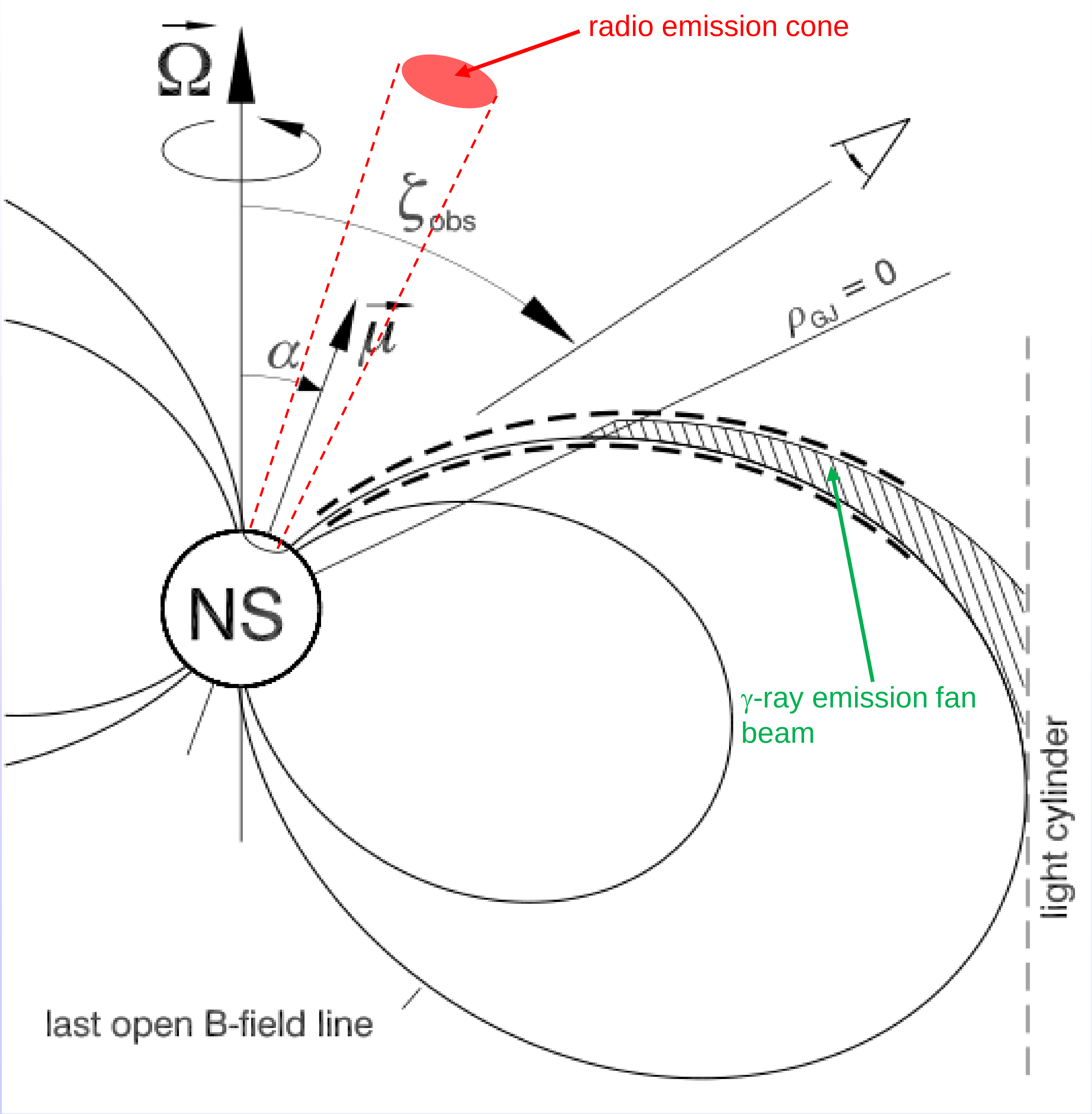
Atypical 3rd peak ("shoulder") drifts with phase. Two main peaks are typical.
(here, 3 years of data.)

By Thierry Reposeur, Bordeaux.



E²dN/dE (erg cm⁻² s⁻¹)
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹
1
10
10²
Energy (GeV)
PSR J0835-4510
Energy Band Fits
Best Full Band Fit (b=0.55)
b=1 Full Band Fit

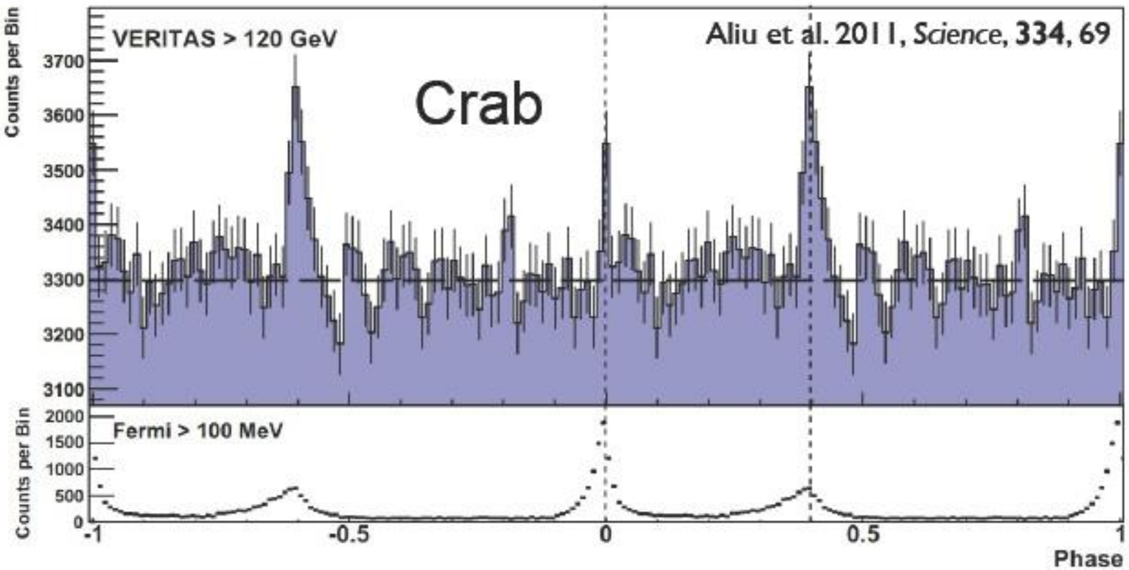
Radio-loud versus Radio-quiet.

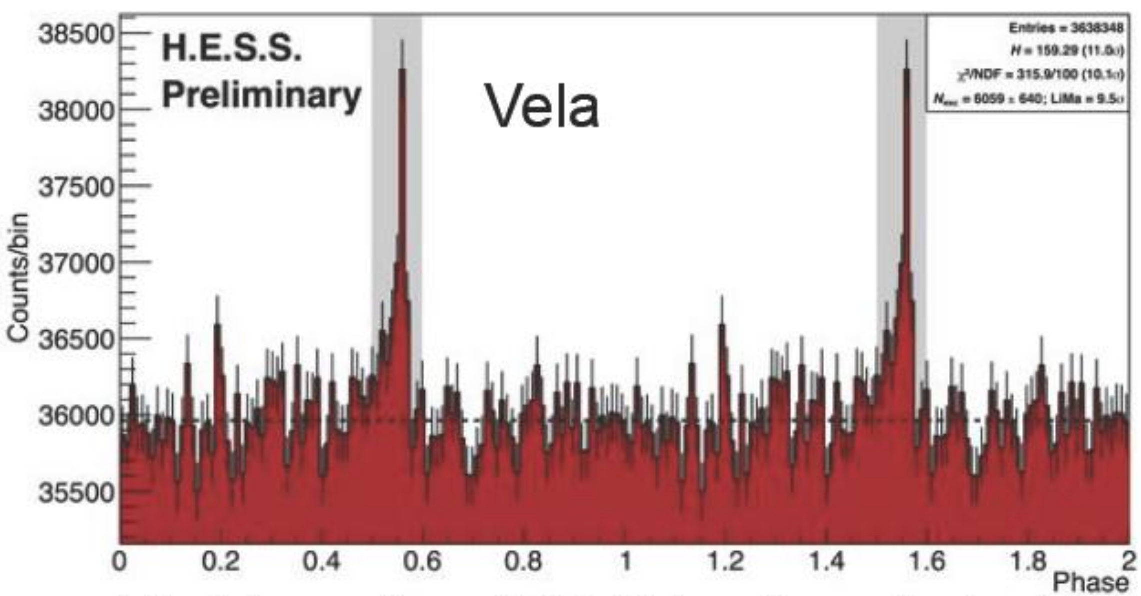


High-E γ-rays

→Production sites far from the star

Pulsars at VHE

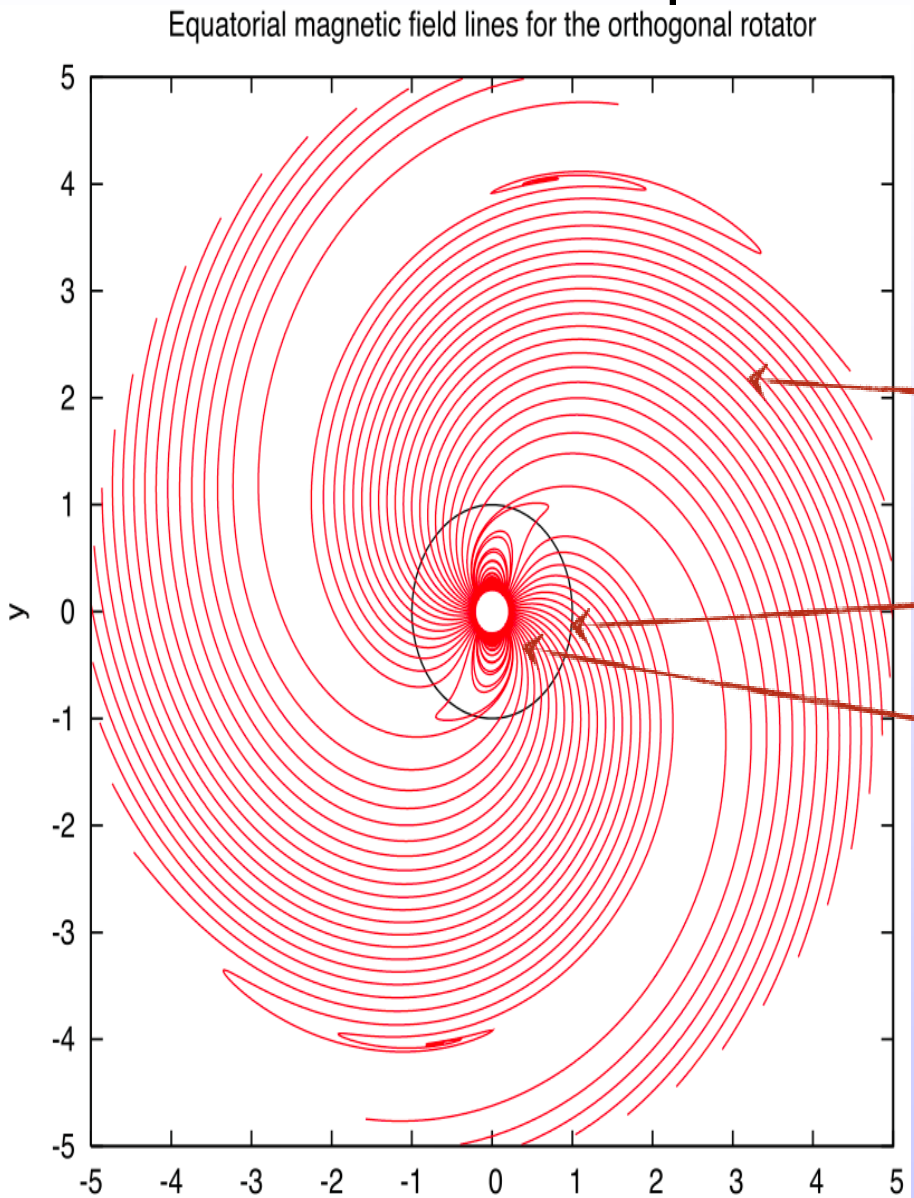




http://phys.org/news/2014-07-hess-ii-reveal-pulsar.html

Are there other γ-ray emission models? The striped wind model

Pétri 2012a and b



From Pétri 2012a

Striped pulsar wind introduced from Coroniti 1990. The γ-ray emission is generated outside the pulsar light cylinder in the striped wind region, where the magnetic field switches from dipolar to toroidal.

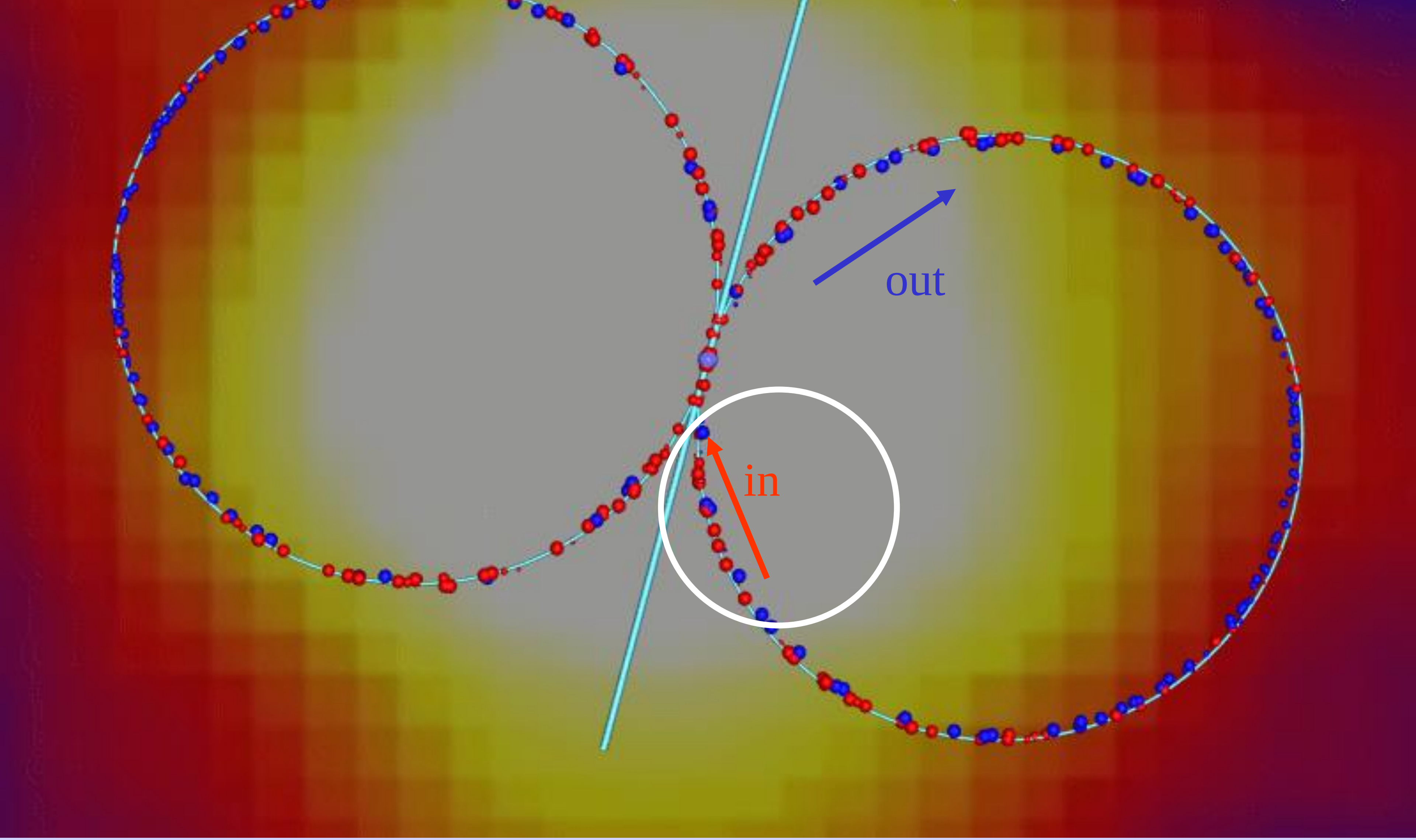
Striped win sheet, opened toroidal magnetic field

Light cylinder (black circle)

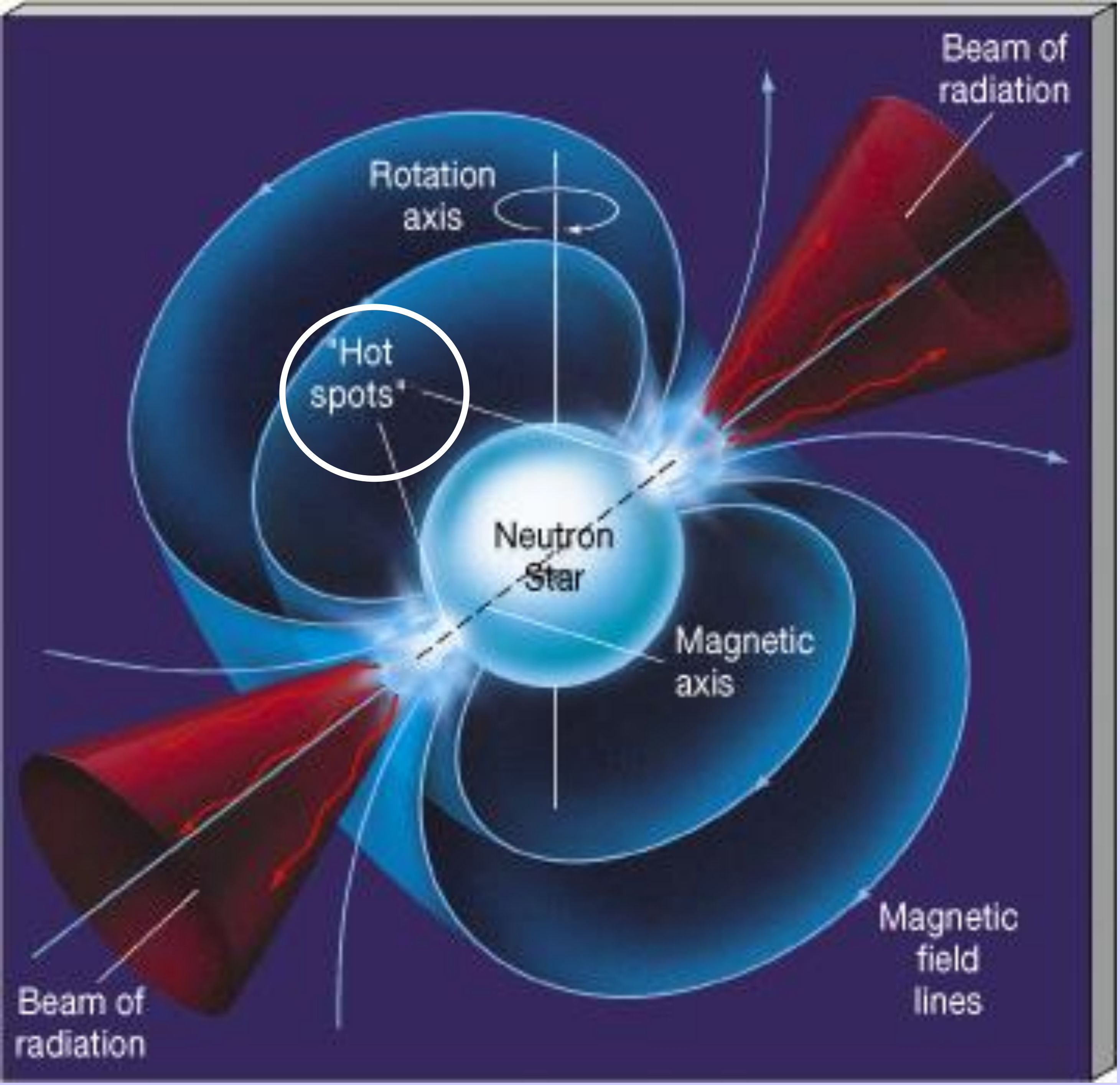
Dipolar magnetic field region, closed dipolar magnetosphere

$L_\gamma \propto (\dot{E}/P)^{0.5}$ Synchrotron, Pétri 2012b

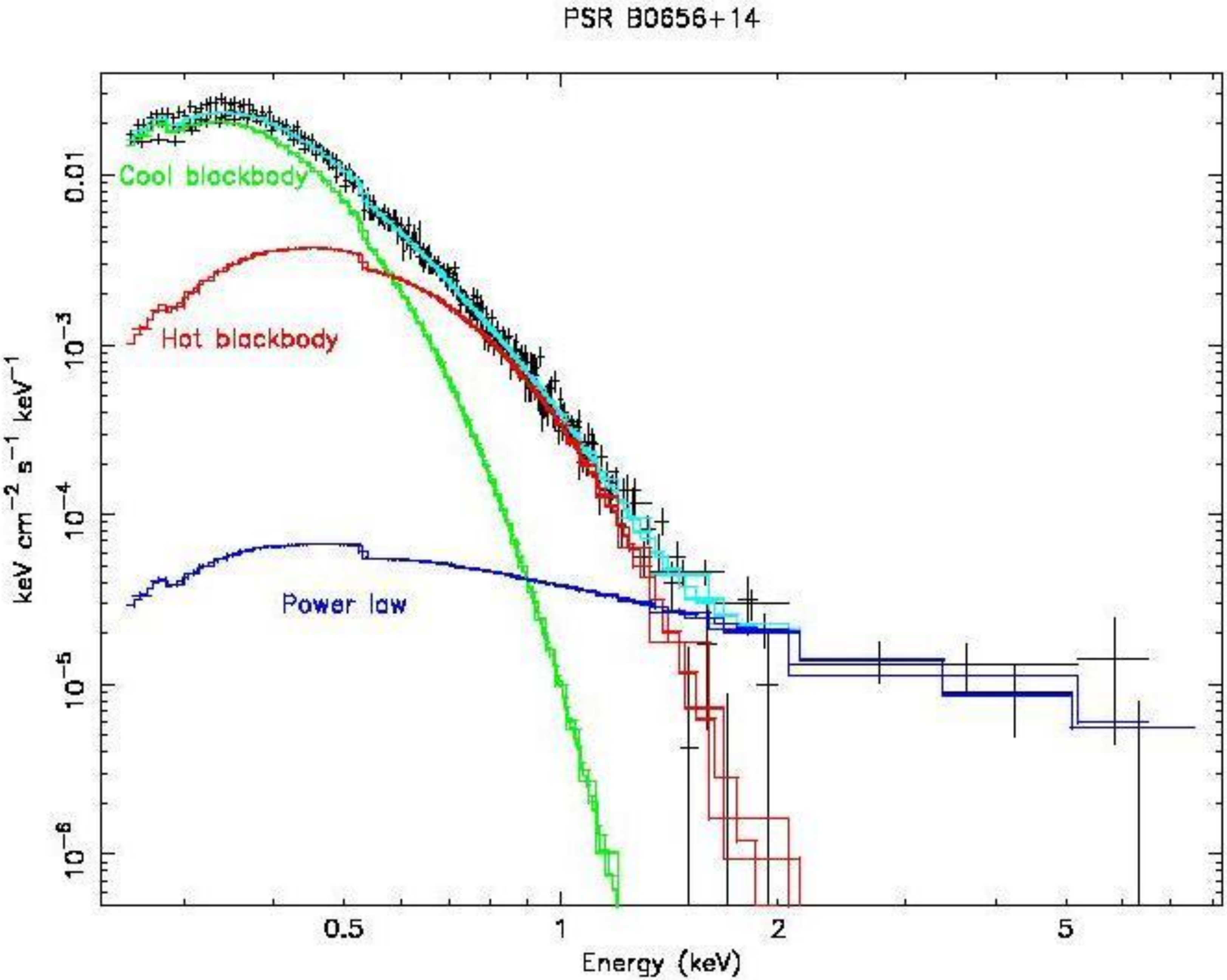
Emission is due to the current flowing in the toroidal striped wind sheets.



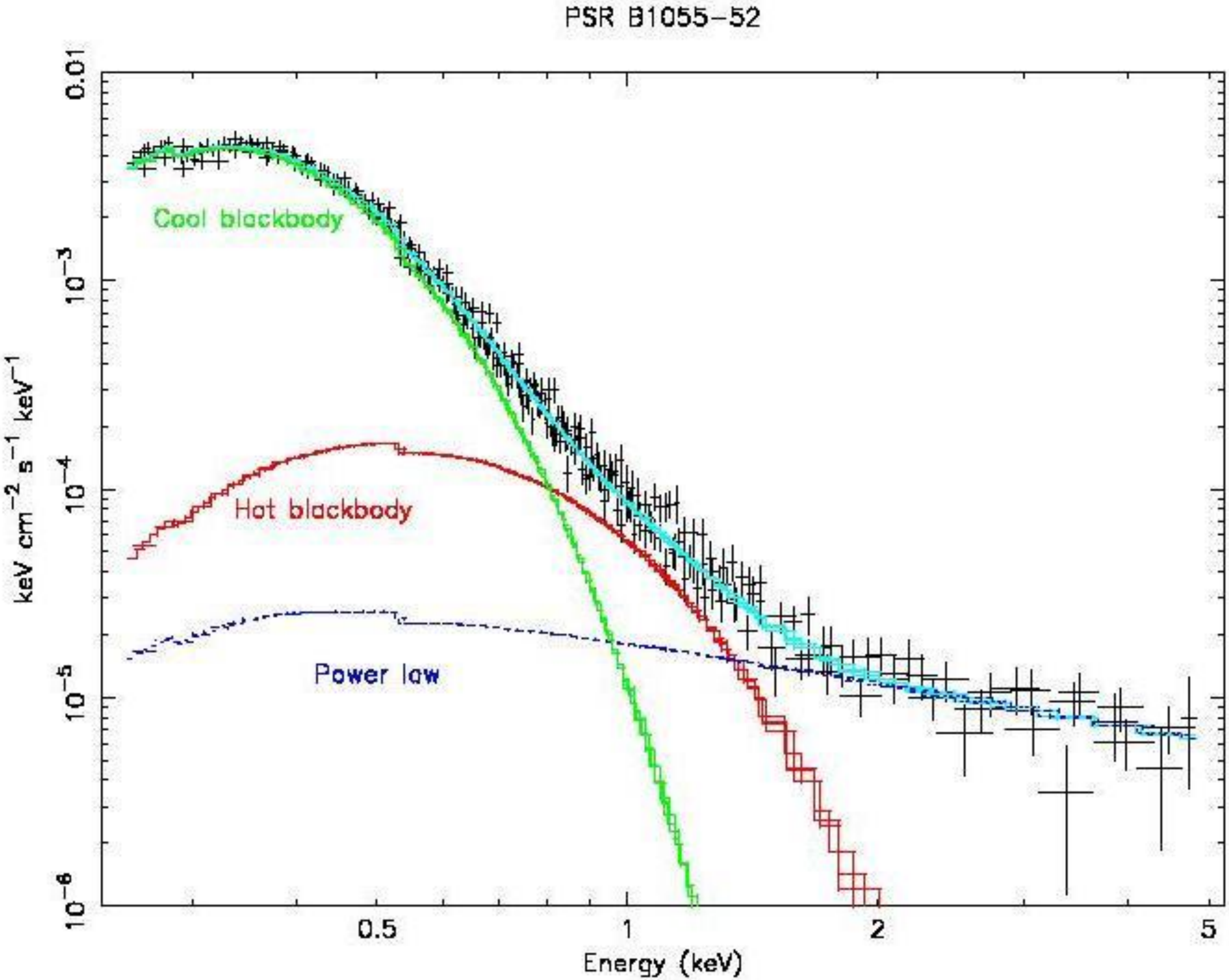
What happens to the inbound particles?

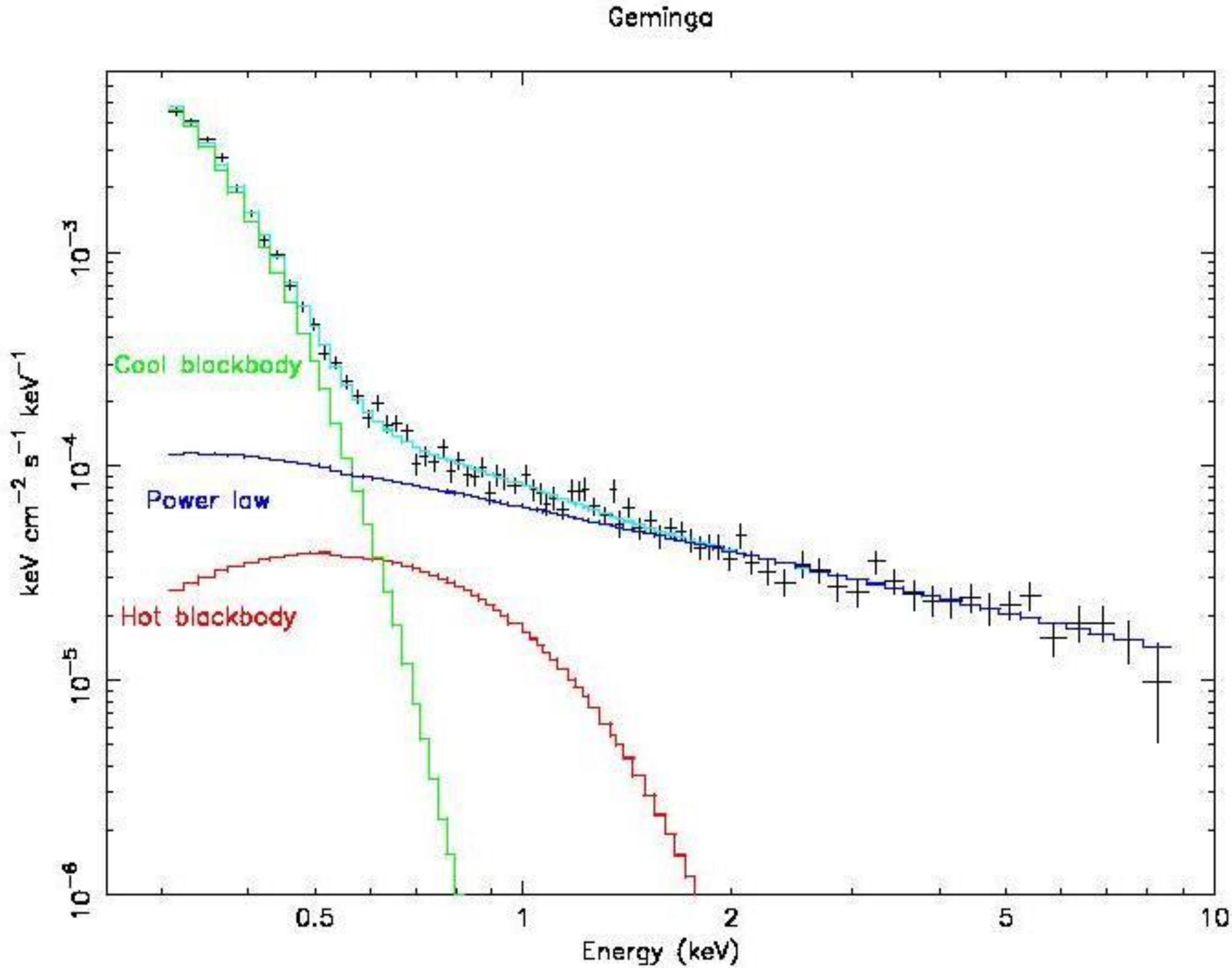


Temperature on the NS surface is not uniform

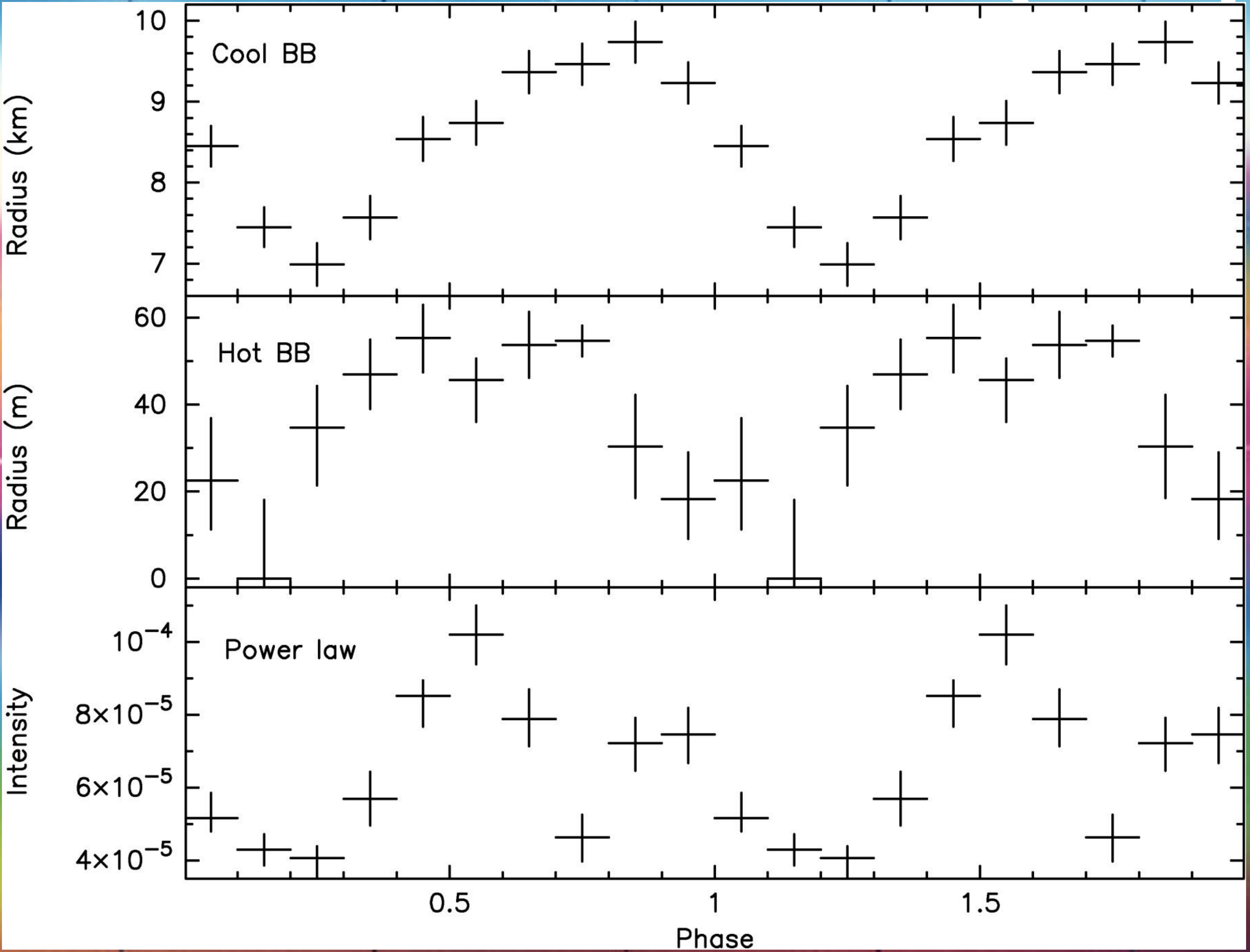


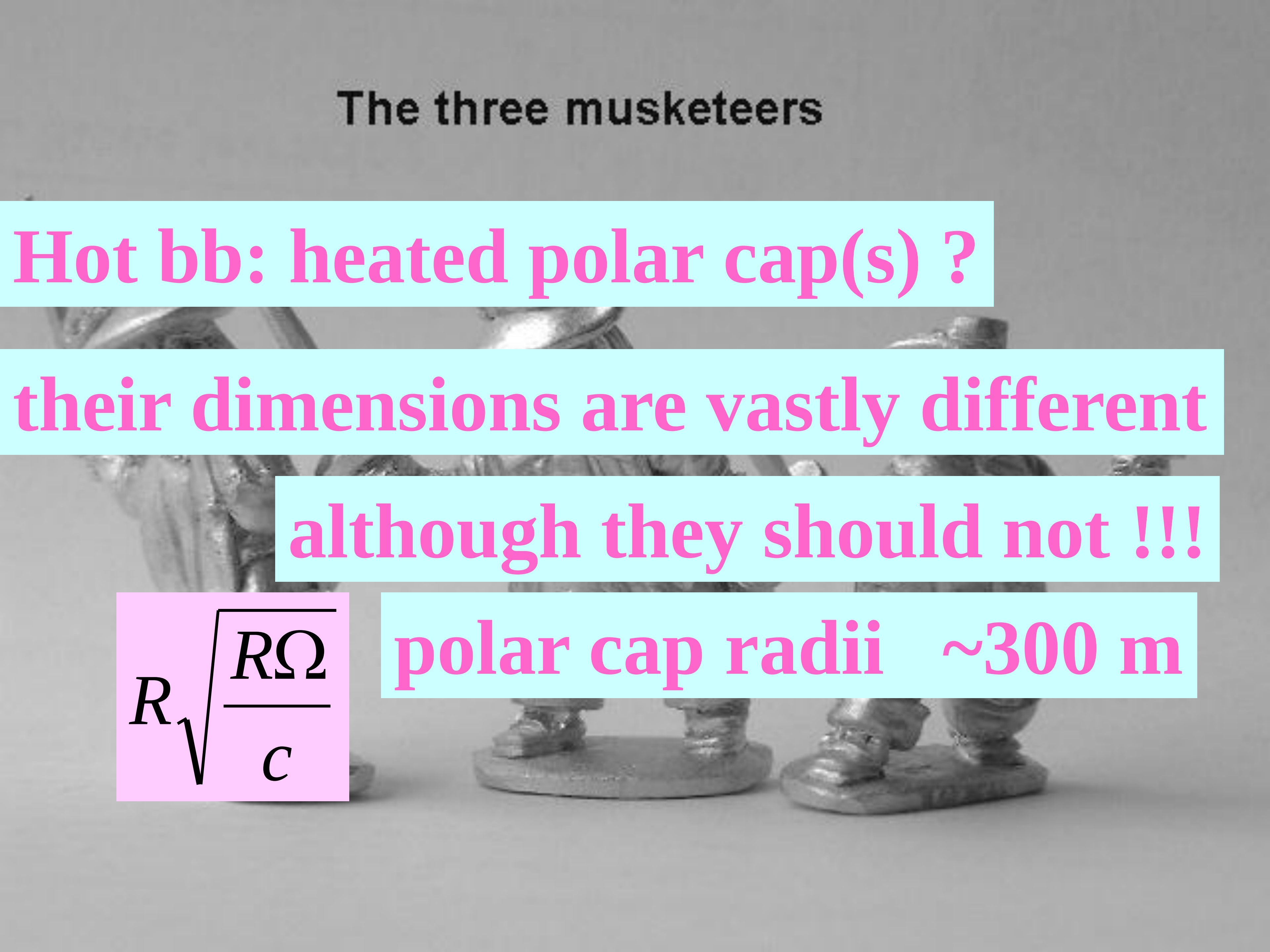
PSR B0656+14
Cool blackbody
Hot blackbody
Power law
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
keV cm^{-2} s^{-1} keV^{-1}
0.5
1
2
5
Energy (keV)


PSR B1055-52
Cool blackbody
Hot blackbody
Power law
keV cm^{-2} s^{-1} keV^{-1}
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0.5
1
2
5
Energy (keV)


Geminga
Cool blackbody
Power law
Hot blackbody
keV cm^{-2} s^{-1} keV^{-1}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0.5
1
2
5
10
Energy (keV)

Phase-resolved emission (160 pc)





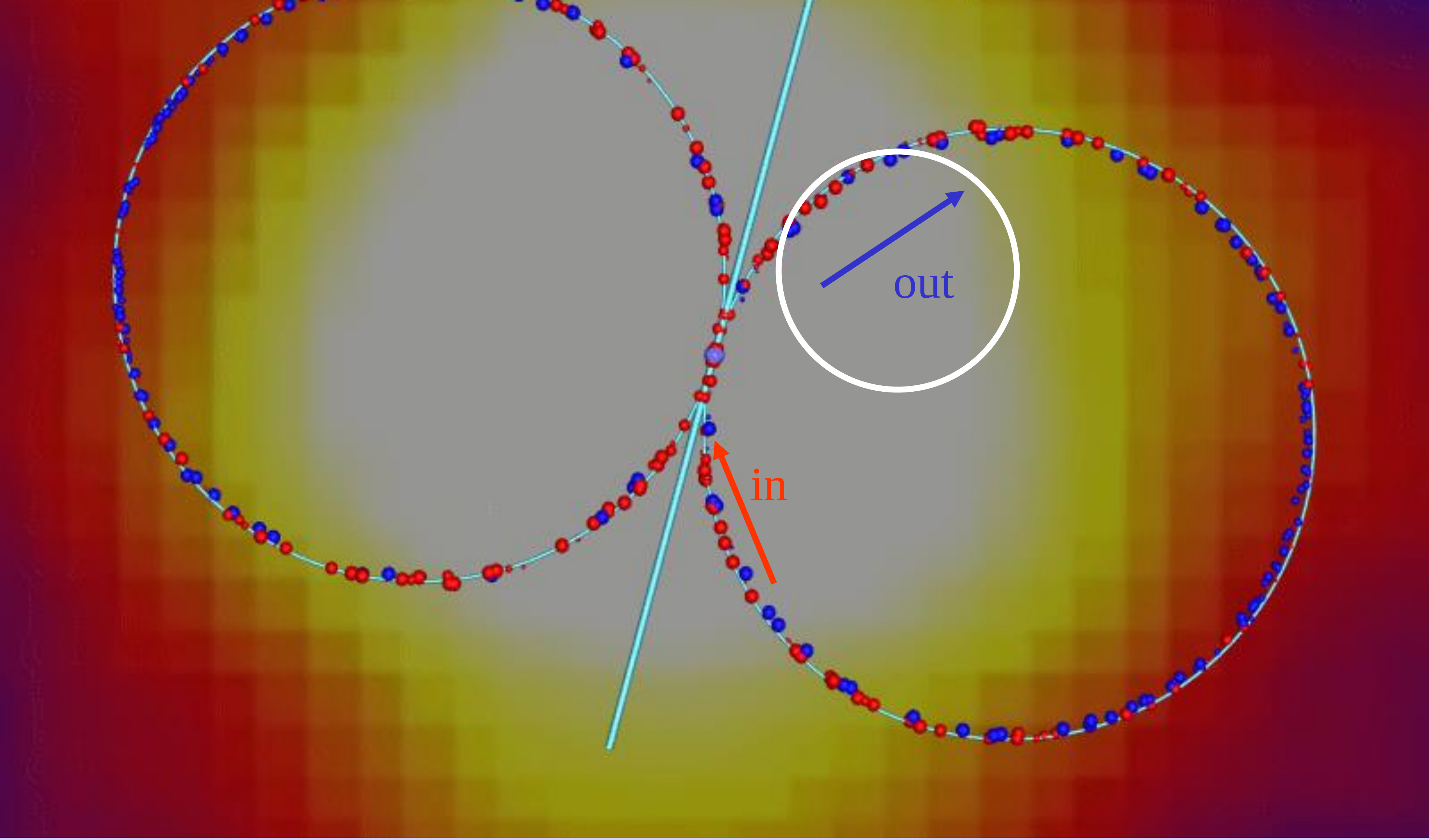
Hot bb: heated polar cap(s) ?

their dimensions are vastly different

although they should not !!!

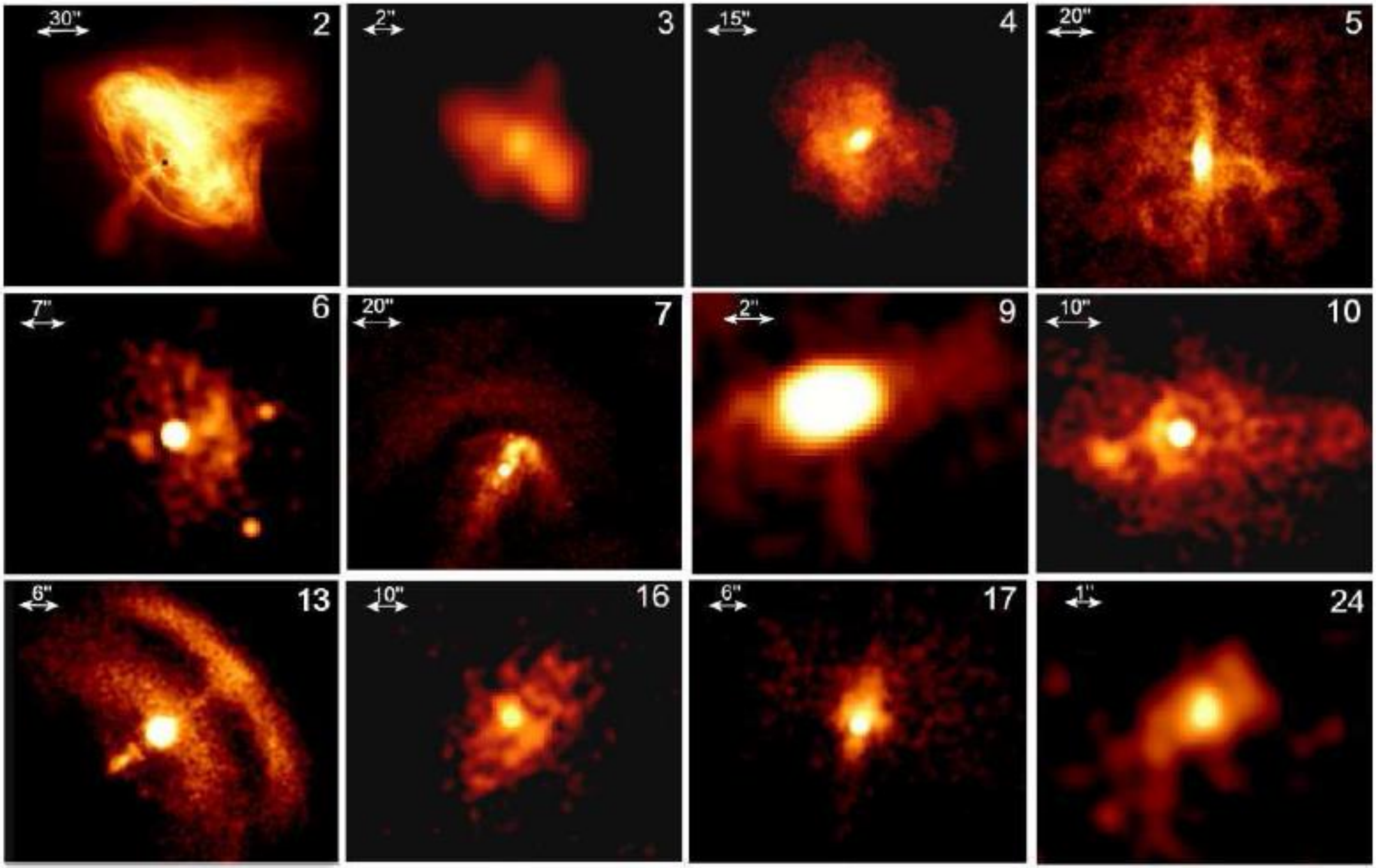
$$R\sqrt{\frac{R\Omega}{c}}$$

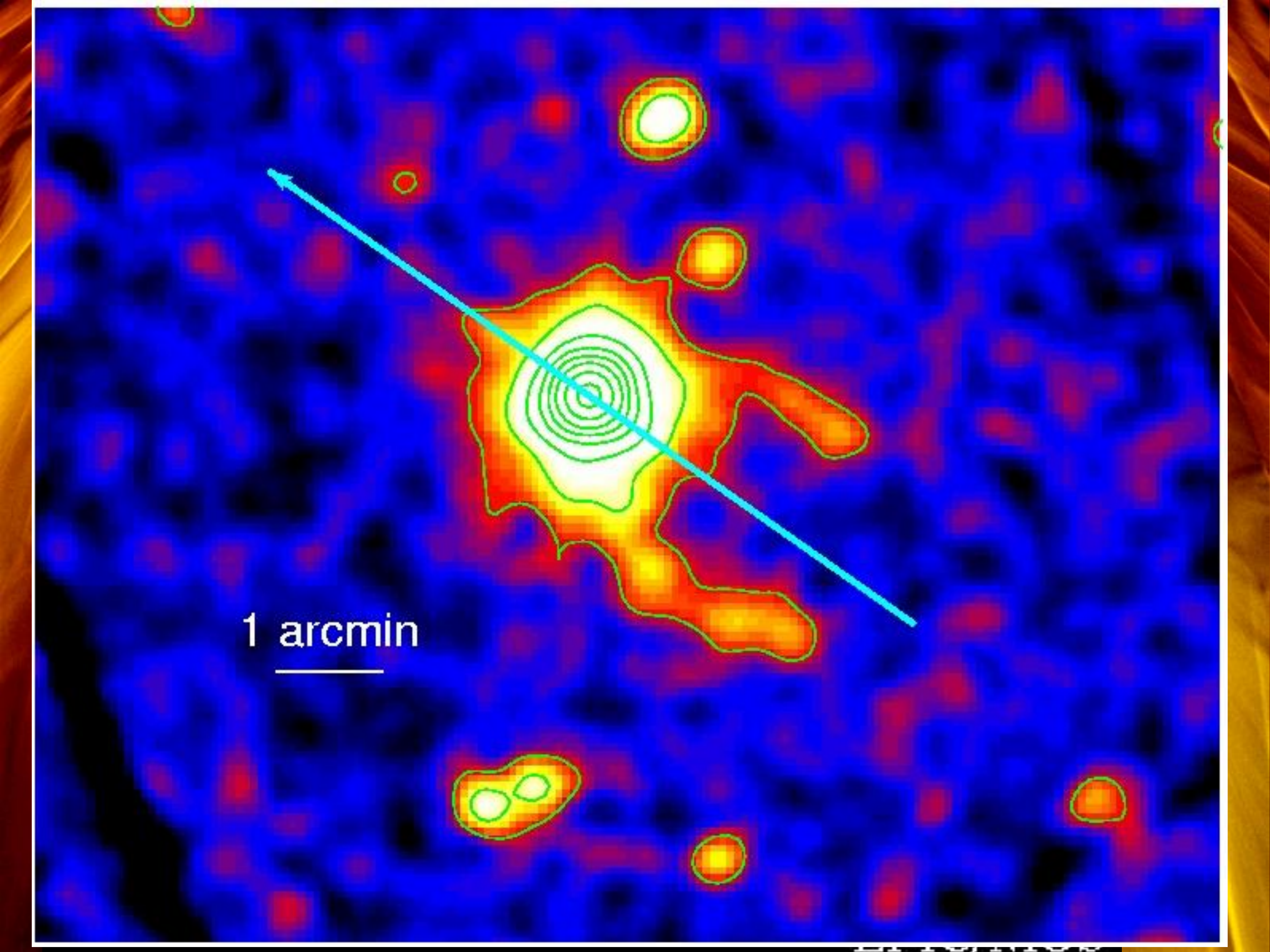
polar cap radii ~300 m

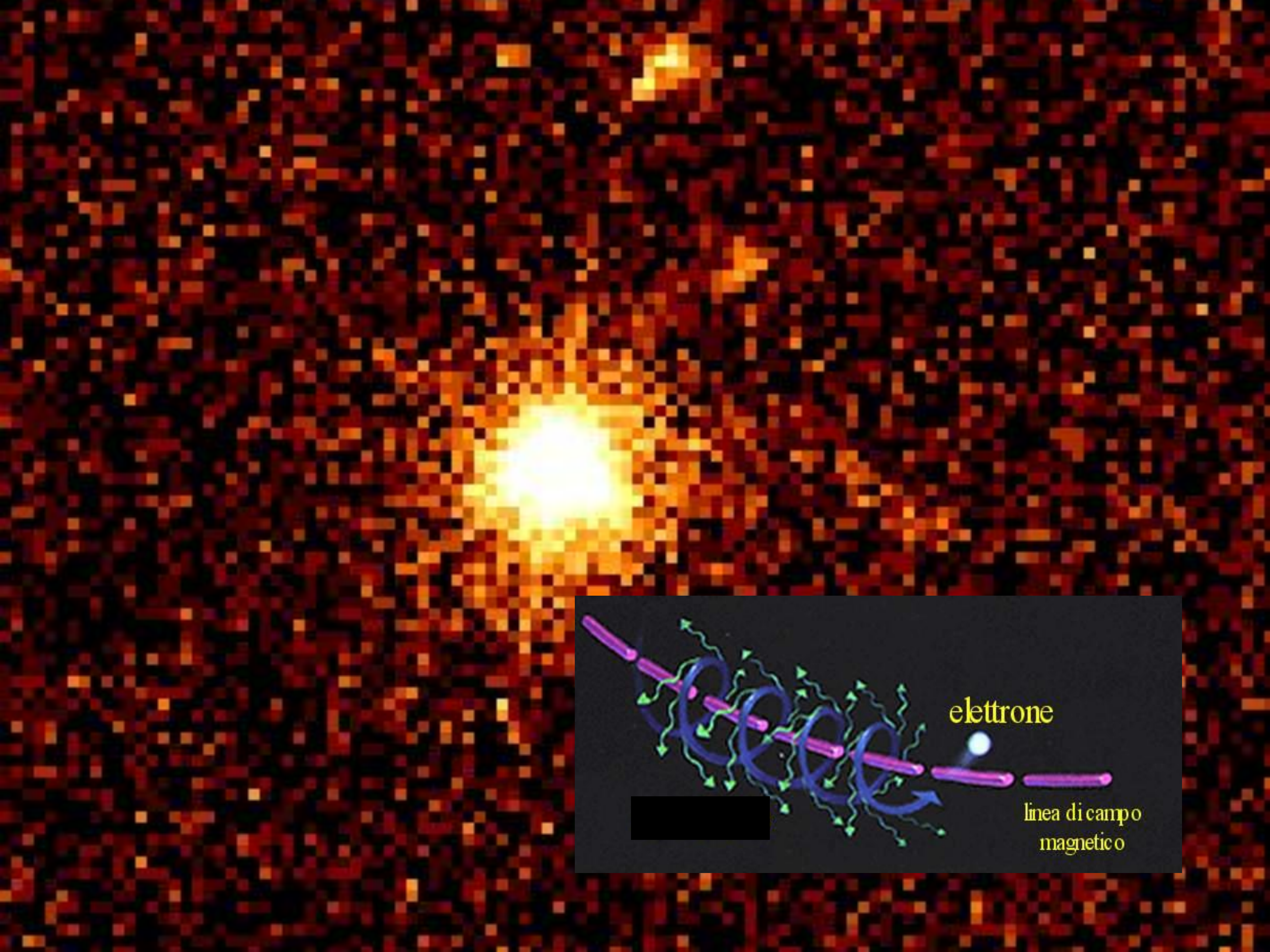


What happens to the outbound particles?

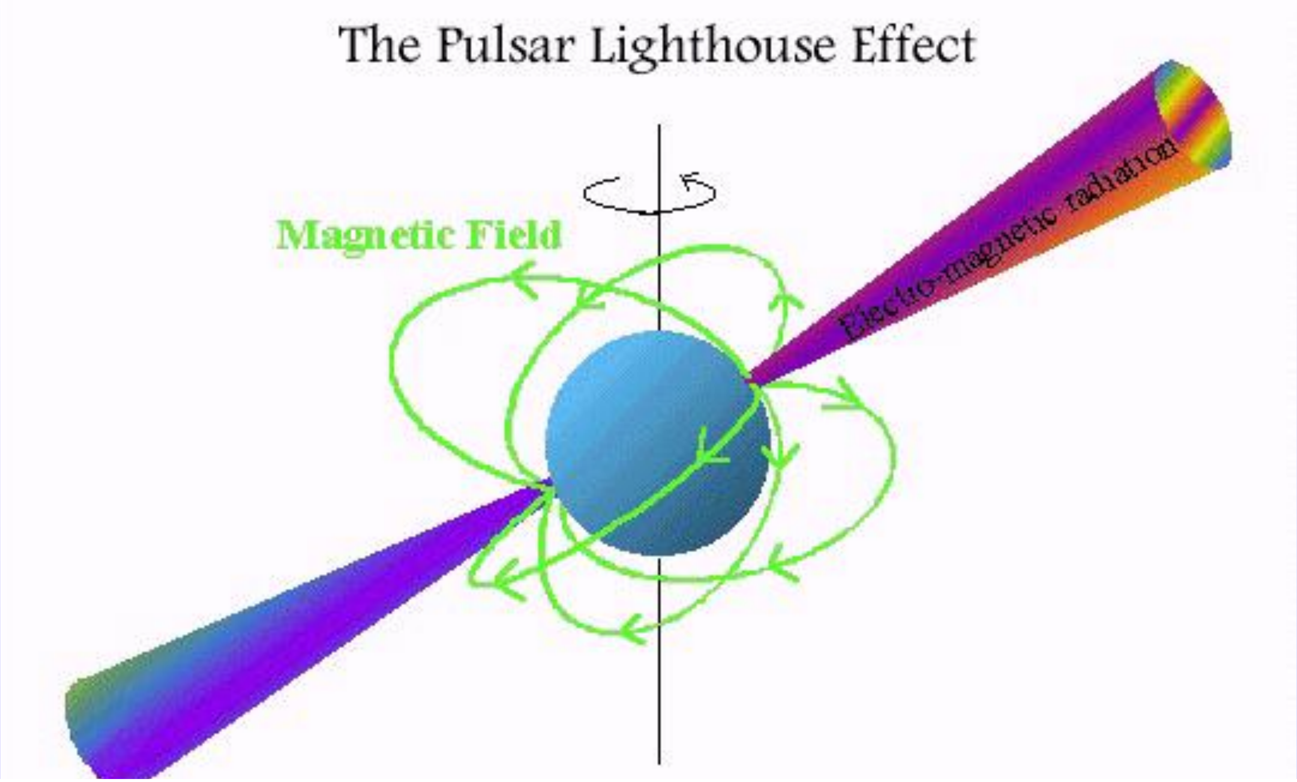
X-ray pulsar wind nebulae




1 arcmin

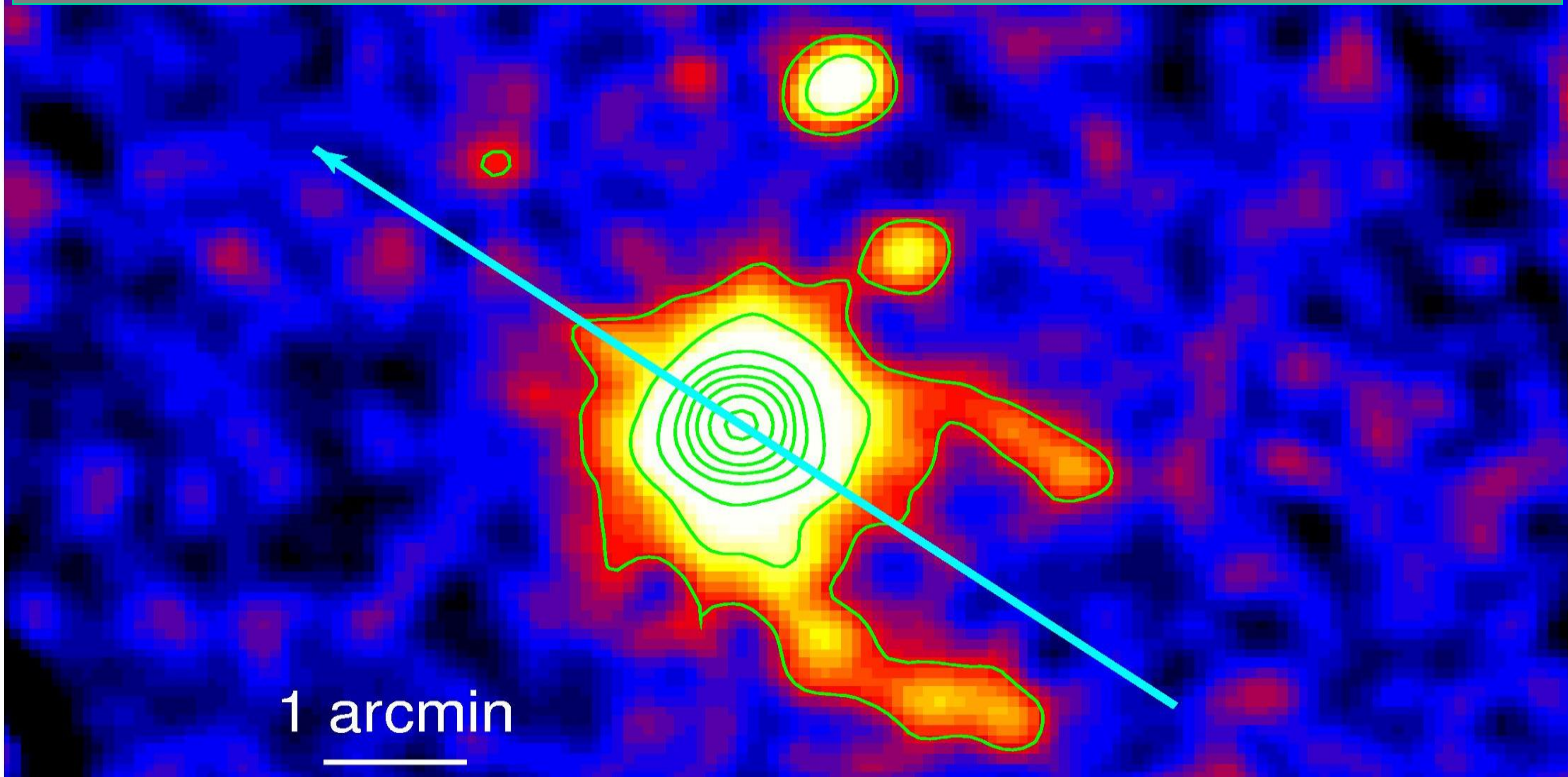

elettrone
[redacted]
linea di campo magnetico

To produce keV photons in 10^{-5} G B field one needs 10^{14} eV electrons



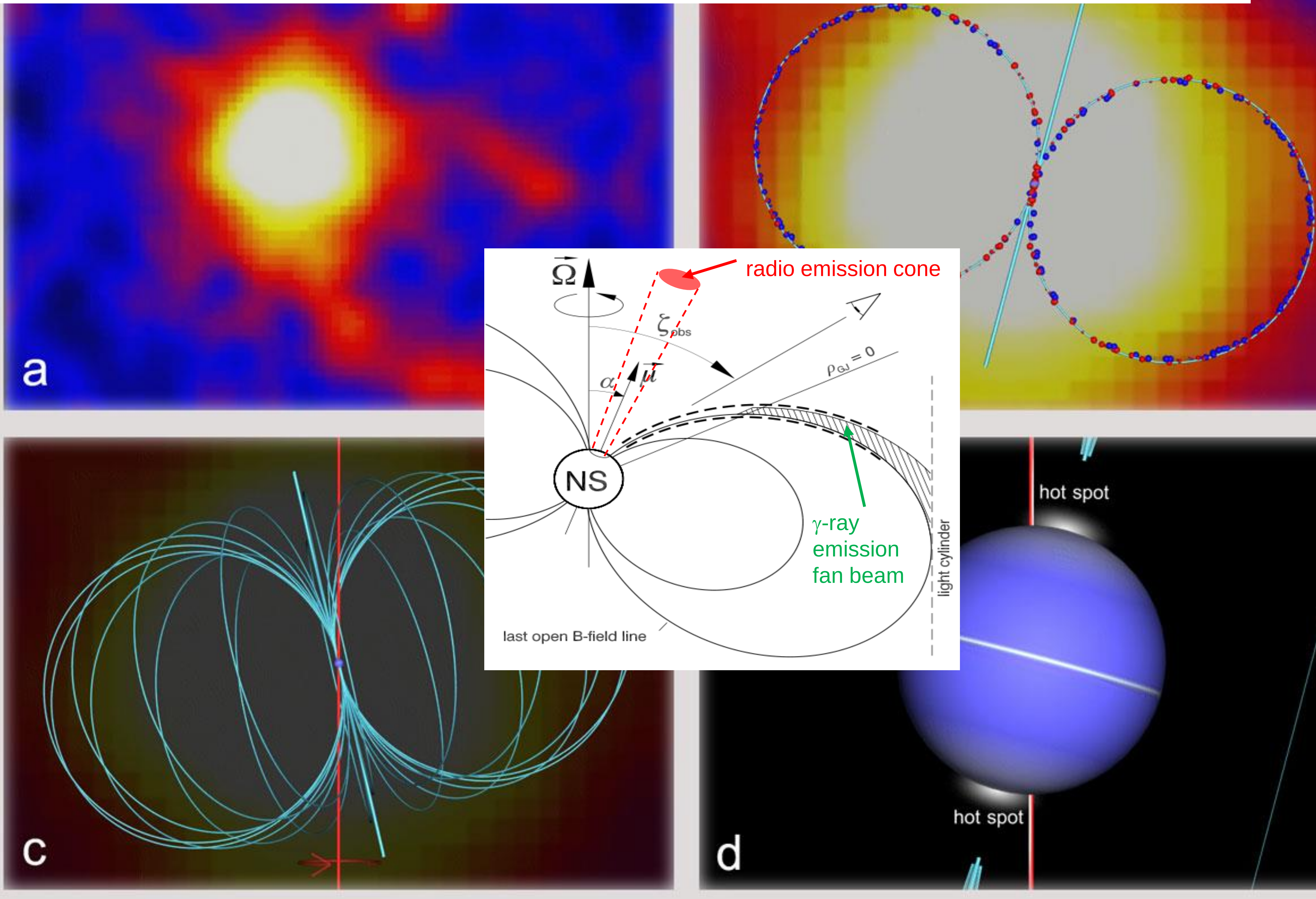
$$\Delta V_{\max} \sim \frac{\Omega^2 B_p R^3}{2c^2} \sim \frac{I\Omega\dot{\Omega}}{e\dot{N}_0} \sim 2 \times 10^{14}\ \mathrm{V}\,,$$

10^{14} eV electrons will have a Larmor radius of 3.4 10^{16} cm → thickness 6.8 10^{16} cm →27"

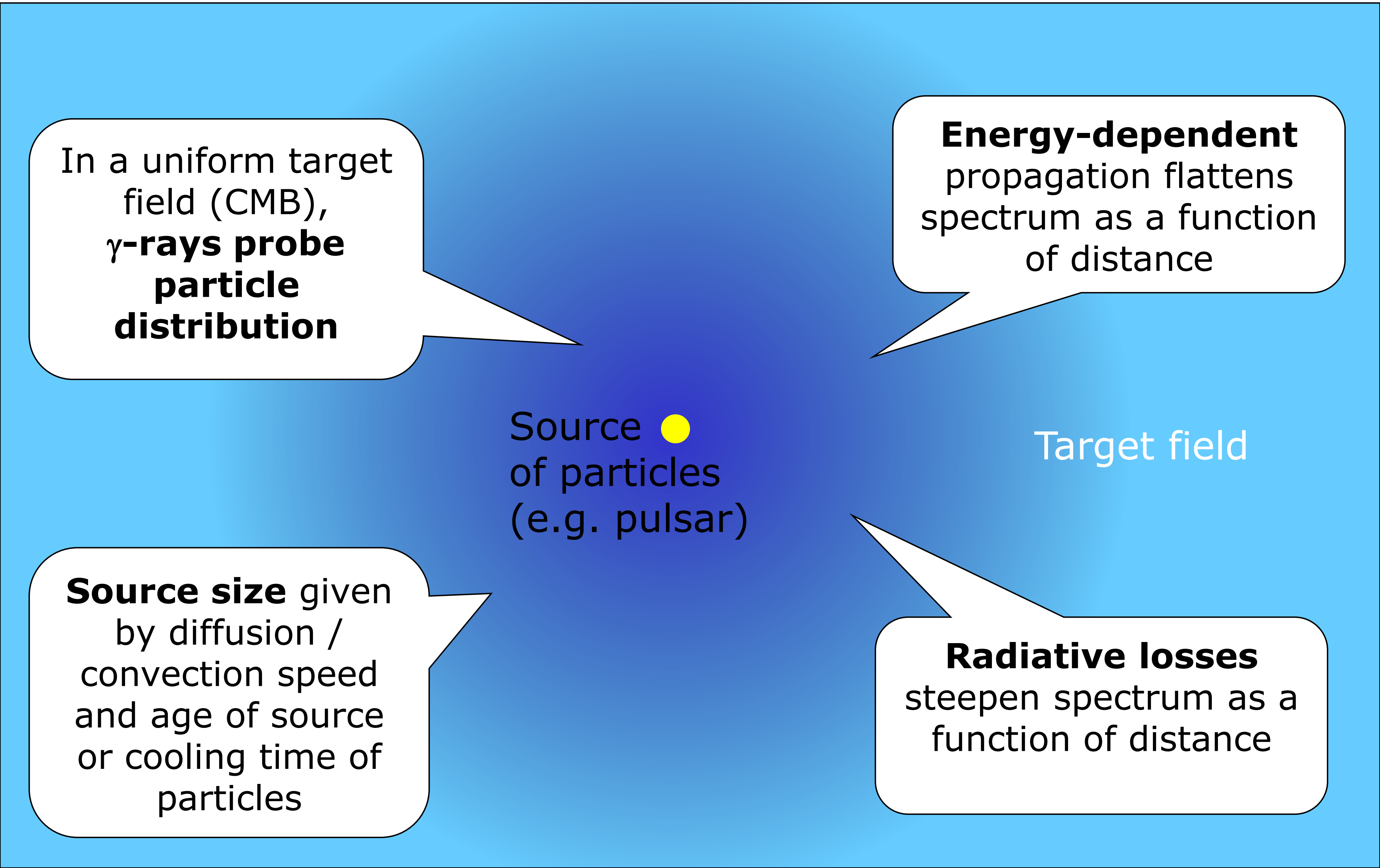


10^{14} eV electrons will loose half of their energy in 800 y .
180 " / 170 mas/y = 1,000 y

End-to-end test for a cosmic particle accelerator

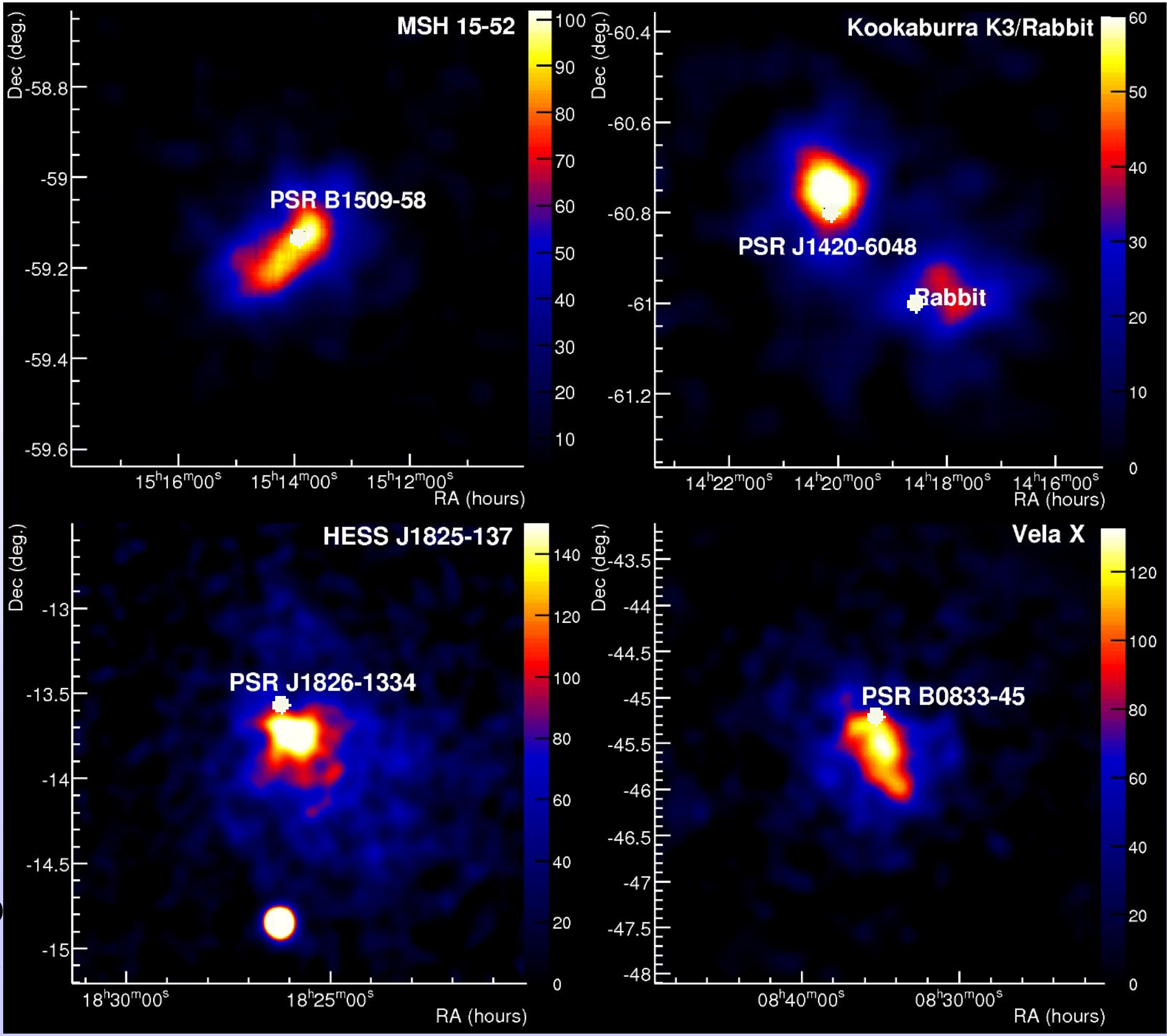


From particles to radiation

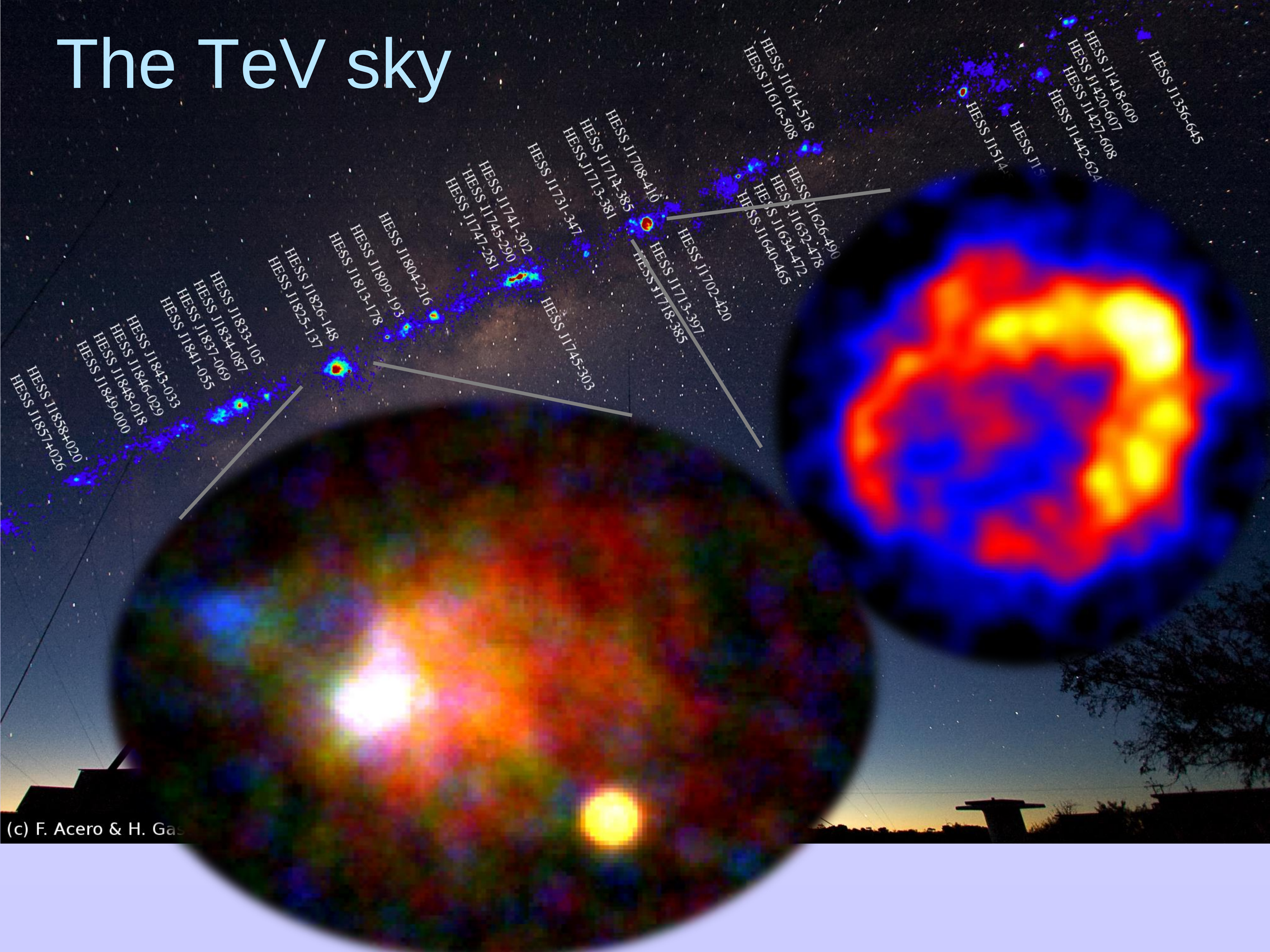


γ-ray sources are

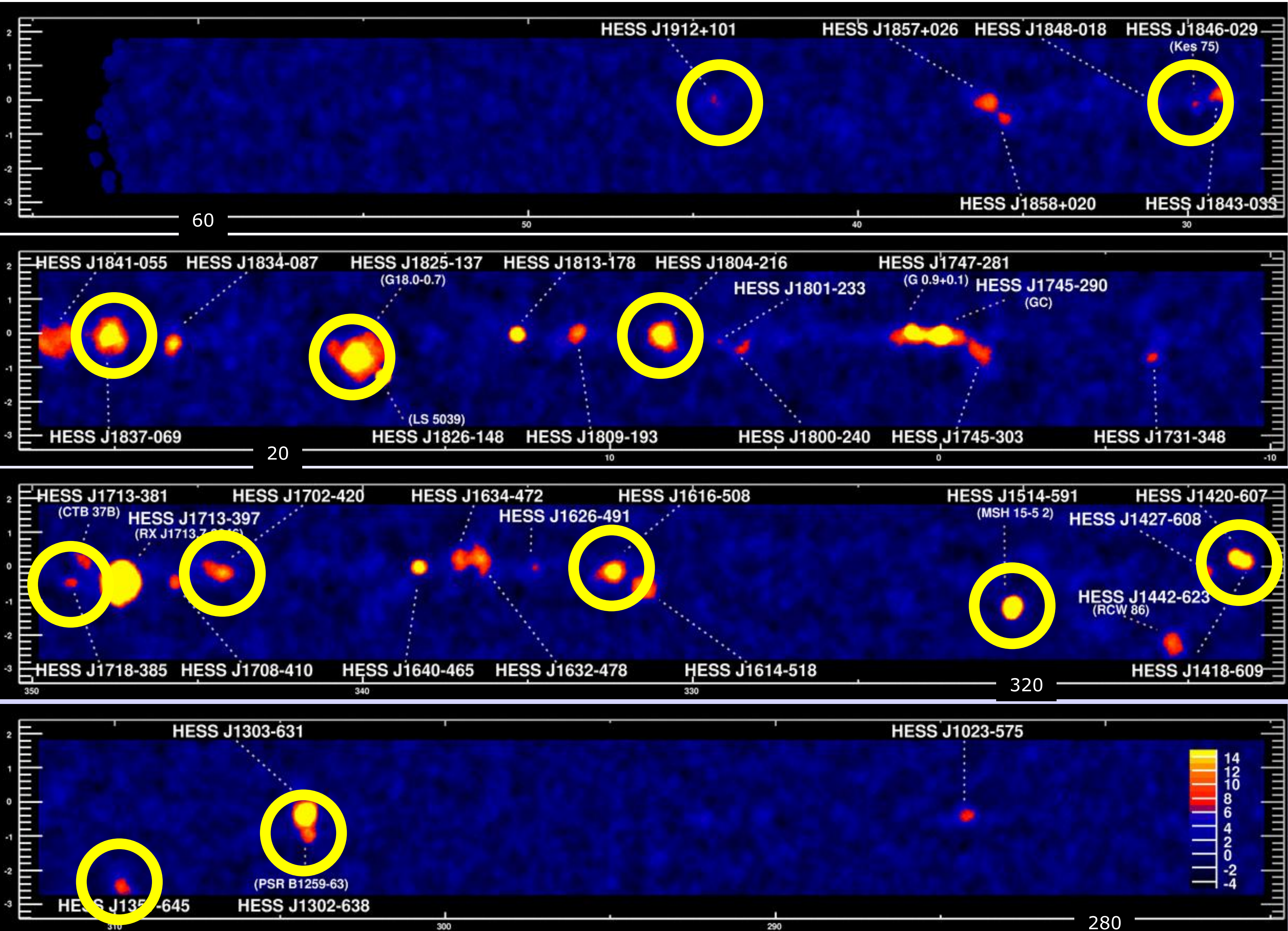
- extended
- displaced from pulsar
- O(1%) of spin-down energy loss converted to gamma rays



The TeV sky



HESS J1356-645
HESS J1418-609
HESS J1420-607
HESS J1427-608
HESS J1442-624
HESS J15
HESS J1514
HESS J1614-518
HESS J1616-508
HESS J1626-490
HESS J1632-478
HESS J1634-472
HESS J1640-465
HESS J1708-410
HESS J1714-385
HESS J1713-381
HESS J1702-420
HESS J1713-397
HESS J1718-385
HESS J1731-347
HESS J1741-302
HESS J1745-290
HESS J1747-281
HESS J1745-303
HESS J1804-216
HESS J1809-193
HESS J1813-178
HESS J1826-148
HESS J1825-137
HESS J1833-105
HESS J1834-087
HESS J1837-069
HESS J1841-055
HESS J1843-033
HESS J1846-029
HESS J1848-018
HESS J1849-000
HESS J1858+020
HESS J1857+026
(c) F. Acero & H. Gas



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(Kes 75)
HESS J1858+020
HESS J1843-033
60
50
40
30
HESS J1841-055
HESS J1834-087
HESS J1825-137
(G18.0-0.7)
HESS J1813-178
HESS J1804-216
HESS J1801-233
HESS J1747-281
(G 0.9+0.1)
HESS J1745-290
(GC)
(LS 5039)
HESS J1837-069
HESS J1826-148
HESS J1809-193
HESS J1800-240
HESS J1745-303
HESS J1731-348
20
10
0
-10
HESS J1713-381
(CTB 37B)
HESS J1713-397
HESS J1702-420
HESS J1634-472
HESS J1626-491
HESS J1616-508
HESS J1514-591
(MSH 15-5 2)
HESS J1420-607
HESS J1427-608
HESS J1442-623
(RCW 86)
HESS J1718-385
HESS J1708-410
HESS J1640-465
HESS J1632-478
HESS J1614-518
HESS J1418-609
350
340
330
320
HESS J1303-631
HESS J1023-575
(PSR B1259-63)
HESS J1302-638
310
300
290
280
14
12
10
8
6
4
2
0
-2
-4