Pulsars and Magnetars as cosmic ray accelerators

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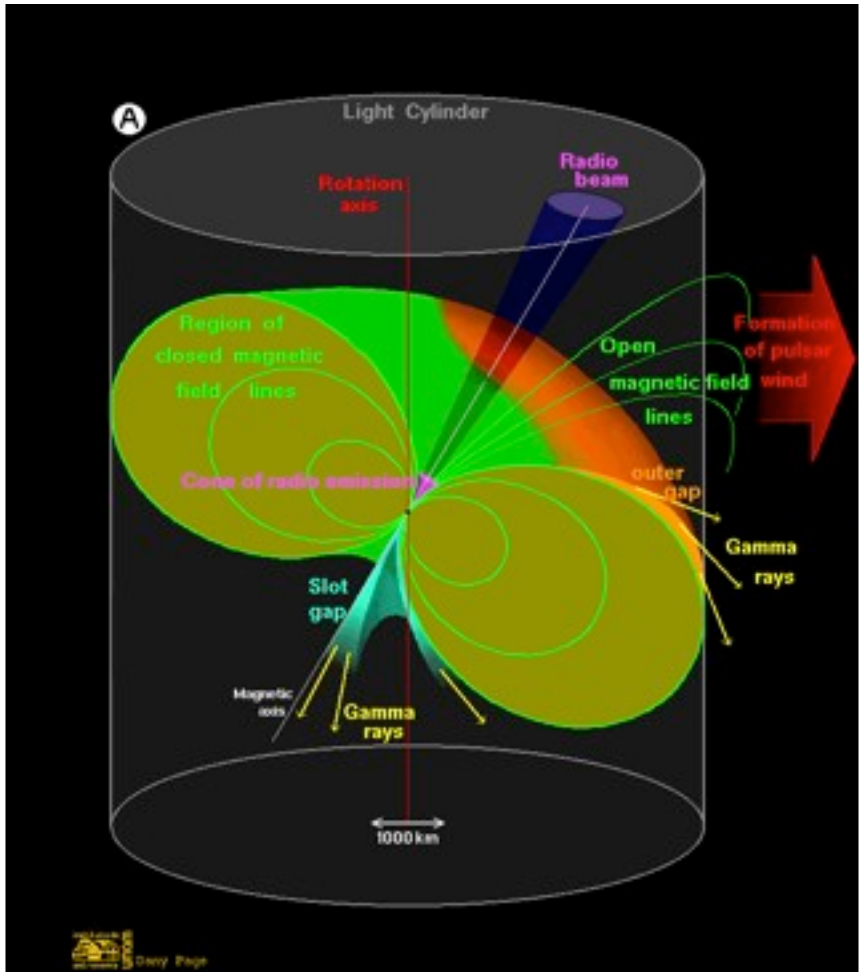
Outline

- **Pulsar properties and physics**
- **Pulsar as accelerators**
- **Polar Gaps - Outer Gaps**
- **Wind and Nebulae**
- **Multiplicity**
- **Confinement - Young vs old**
- **Pulsars as source of UHECR**
- **Magnetars**
- **Acceleration in Magnetars**
- **Open problems**

The NS magnetosphere



$$R_{NS} = 10km$$
$$P = 0.001 - 7s$$
$$B_{surf} = 10^{8-12} G$$

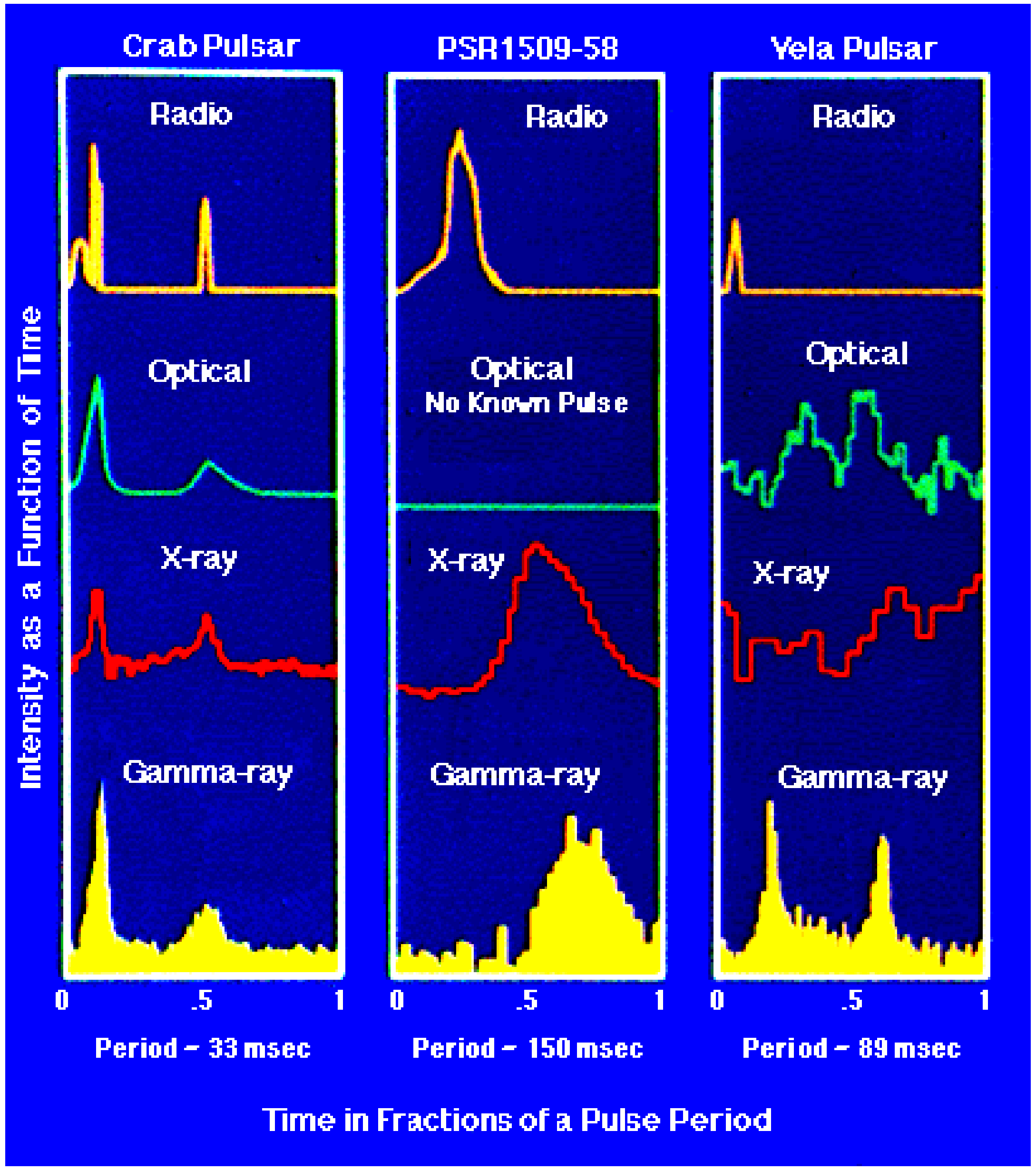
Unipolar inductor (AGN, GRB, Magnetar)
EM extraction of rotational energy.

Acceleration sites and efficiency?

Evidence of acceleration

Main evidence for the presence of accelerated plasma produced by the pulsars are:

- ***Pulsed Radio emission***
- ***Pulsed Gamma-ray emission***
- ***Presence of synchrotron nebulae***



Polar caps physics

NS surface electric field

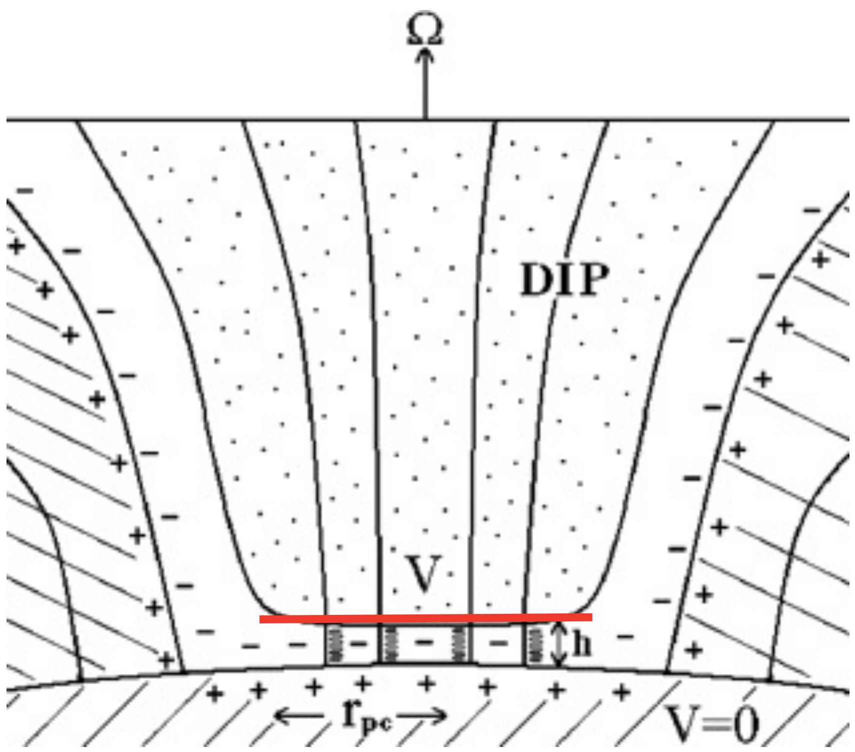
$E \sim \Omega RB/c$
$\Phi \sim \Omega BR^2/c$

Particle acceleration to high lorentz factors

Accelerated electrons cool in strong field

$dE/dt \sim e^4B^2\gamma^2/m^2c^3$
$\omega \sim e\gamma^2B/mc$

Particles move along field lines - curvature radius ~ Light Cylinder radius



Curvature radiation is emitted as gamma rays
$\omega \sim \gamma^3c/R$
$h\omega > mc^2$ then one can have secondary pair creation

Curvature radiation from accelerated new pairs can give rise to a pair creation cascade

For young objects also ICS on the thermal surface emission

Gap acceleration

If the entire magnetosphere is in FF equilibrium then E•B = 0 - No acceleration

There are regions where the FF charge is not achieved Those regions can lead to vacuum acceleration and are called gaps

One gap is on the polar cap - We already noticed that the field there can pull electrons out of the surface

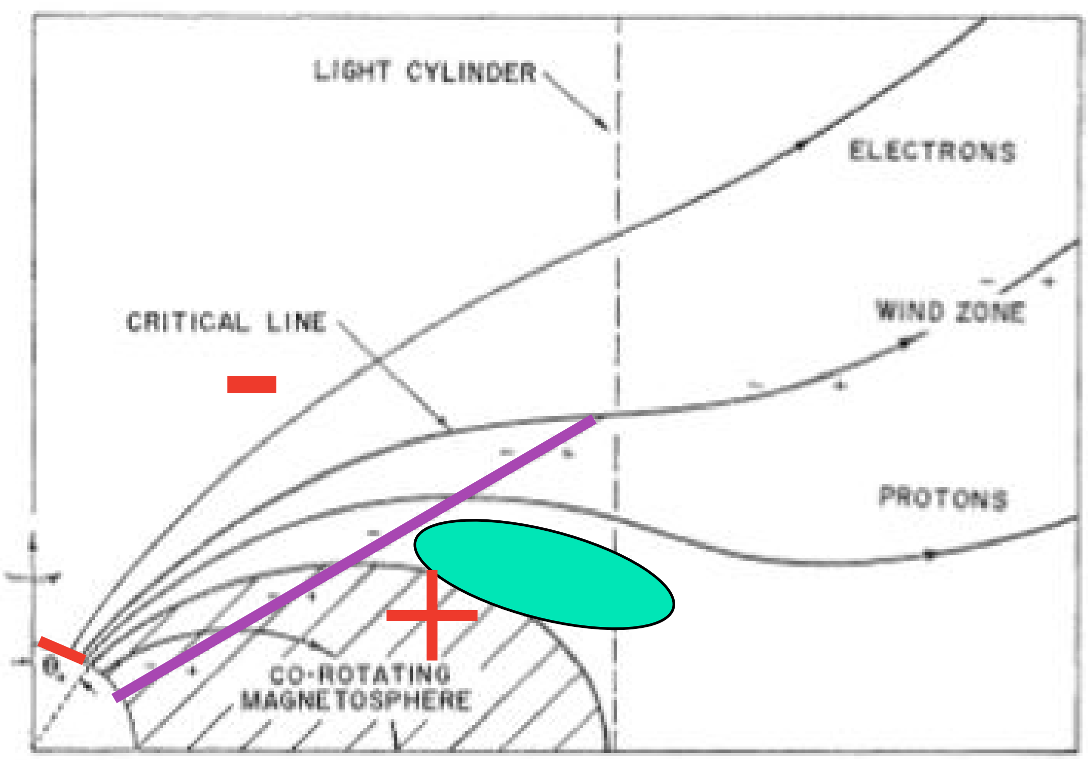


FIG. 1.—Schematic diagram showing the corotating magnetosphere and the wind zone. Star is at lower left.

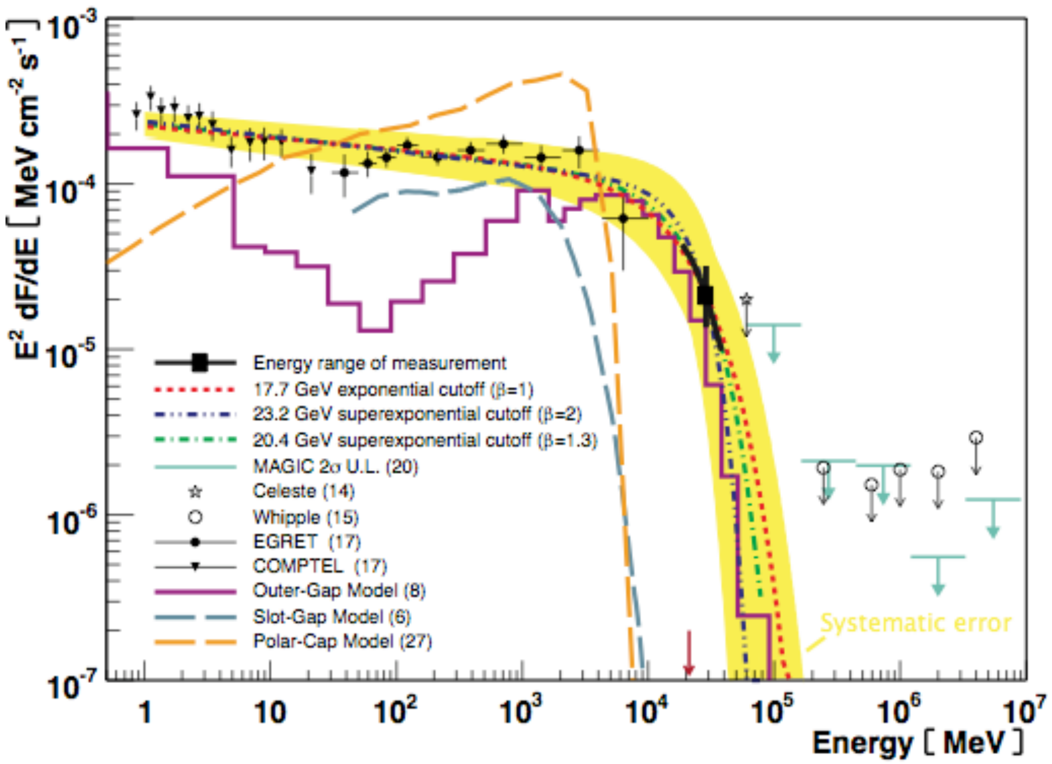
Note that the GJ charge goes like B•Ω So there are regions of positive and negative charges

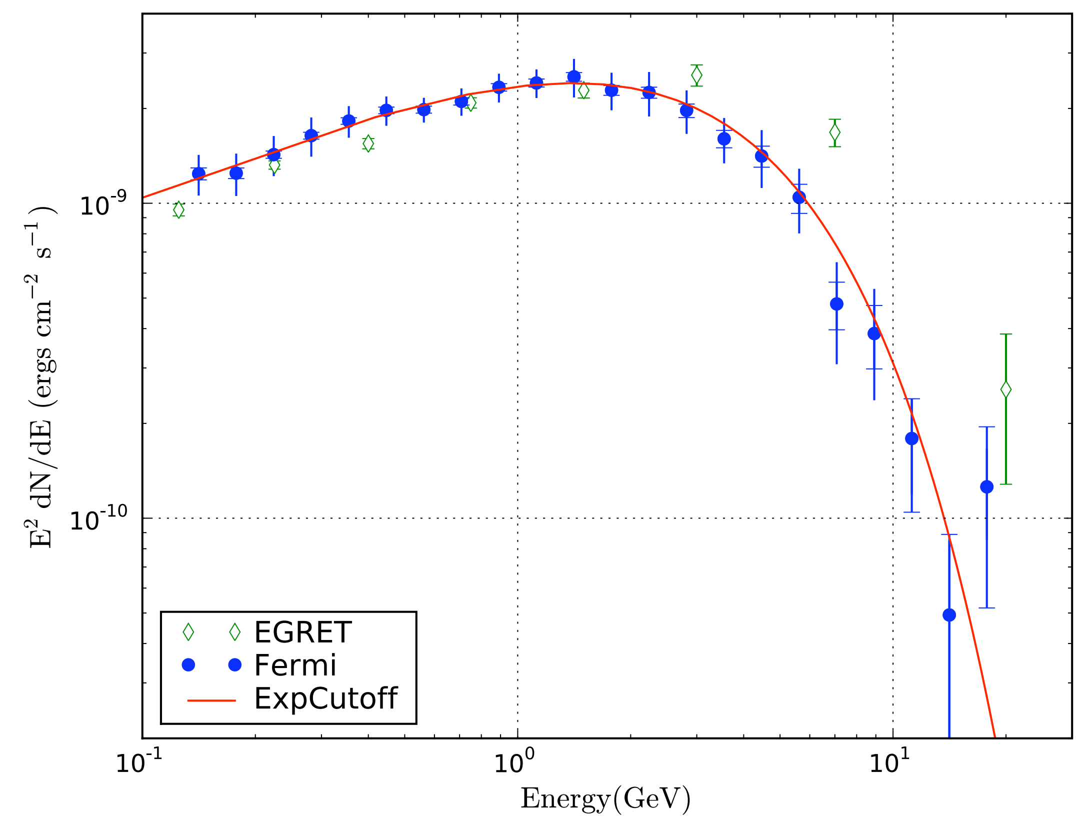
Outer gaps?

Polar or Outer ?

Polar caps are more successful at explaining radio emission - Outer are favored for gamma-ray emission

Crab





Vela

Maximum energy - Composition

To shorten the electric field a typical change density (GJ) is required

$$\rho_{\rm GJ} \equiv -\frac{\Omega B_z(s,z)}{2\pi c}$$

$$\dot{E} = -\frac{B_s^2 R_s^6 \Omega^4}{6c^3} \approx 10^{31} B_{12}^2 R_{10}^6 P^{-4}\ {\rm erg\ s^{-1}},$$

$$\dot{E} \simeq \frac{B_p^2 \Omega^4 R^6}{6c^3} = \frac{2\Phi_{\rm cap}^2 c}{3}.$$

Maximum energy achievable is

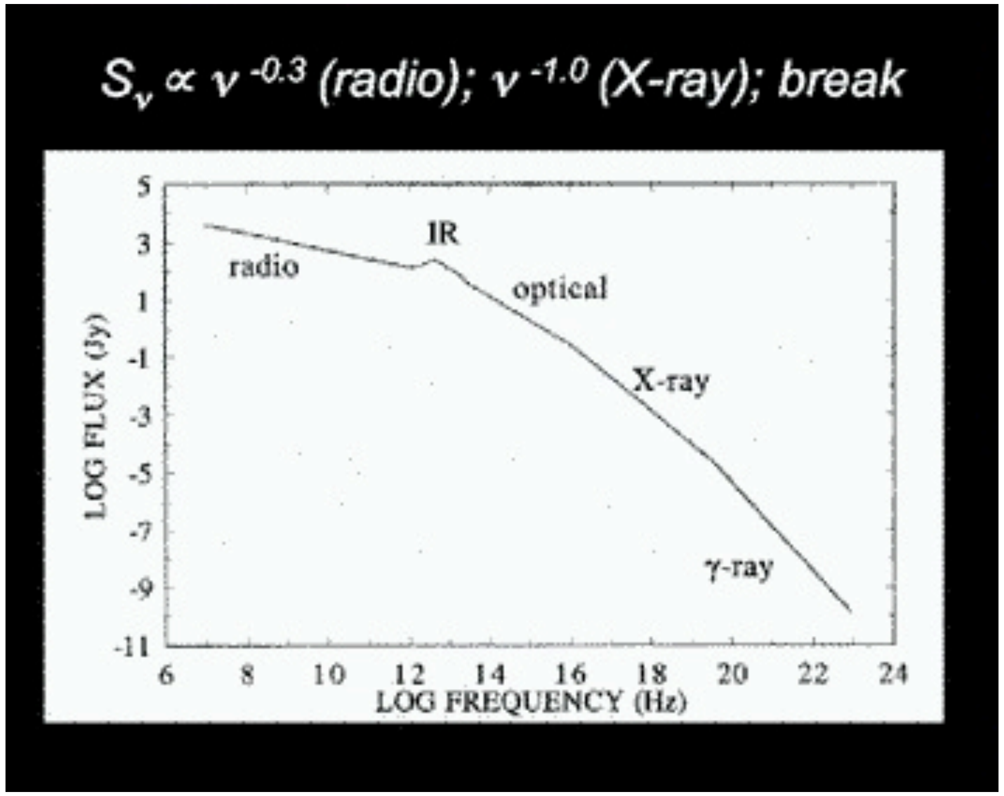
$$\Phi_{\rm cap} \simeq \frac{\Omega B_p}{2c}\frac{R^3\Omega}{c} = 7\times 10^{12} B_{p,12} P_0^{-2}\ {\rm V}$$

To be compared with typical pair creation energies ~ $10^{3\text{-}4}$ eV

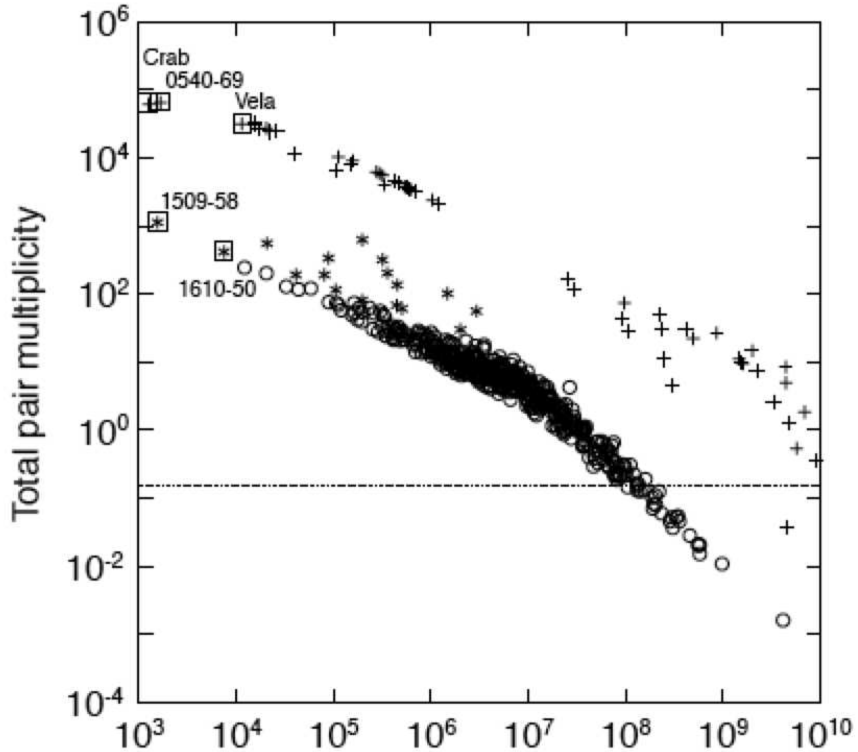
$$\epsilon_a = \frac{32}{3}\frac{B_q}{B}\frac{\rho_e}{r_e \ln\Lambda} = 2166 B_{12}^{-1} P^{1/2} r_6^{-1} f_\rho\,, \qquad (1)$$

Pair production

How many particles are produced? What limits production?



We know from emission from the nebulae that the pair injection rate is ~ 10^{4-5} times higher than the GJ current.

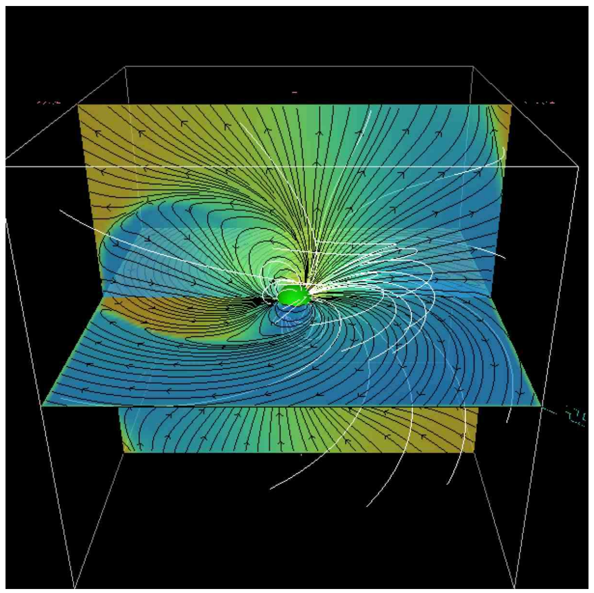


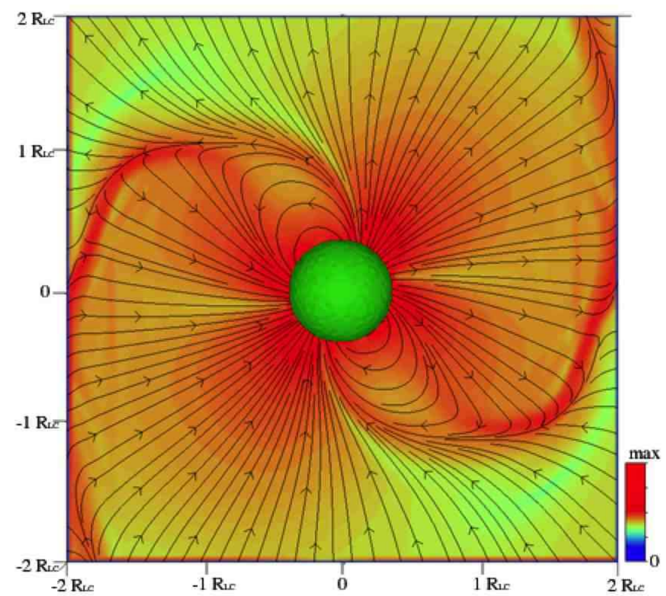
Hibsman & Arons 07

Multiplicity depends on emission mechanism CR/ICS
It is strongly dependent on age

Wind

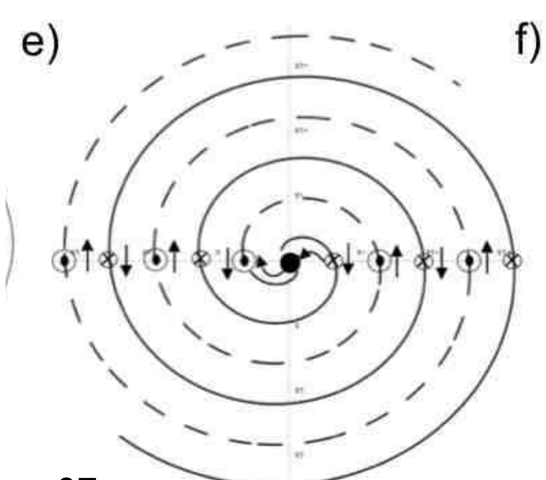
The ration of particle energy vs total spin down power at the LC is generally << 1 - FF magnetic dominated wind

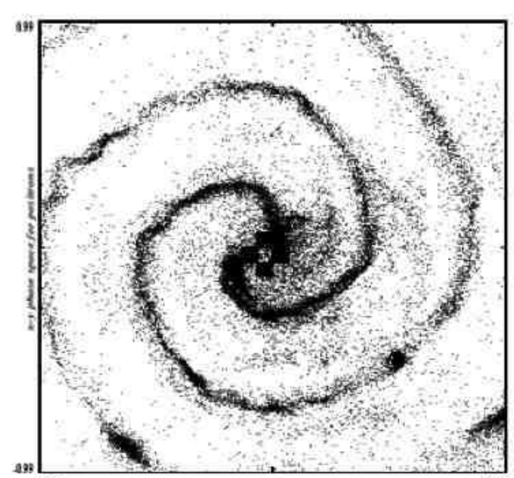




Data from nebulae show that at larger distances the flow has small magnetization and higher lorentz factor

Plasma is reaccelerated before the nebula and magnetic energy is dissipated



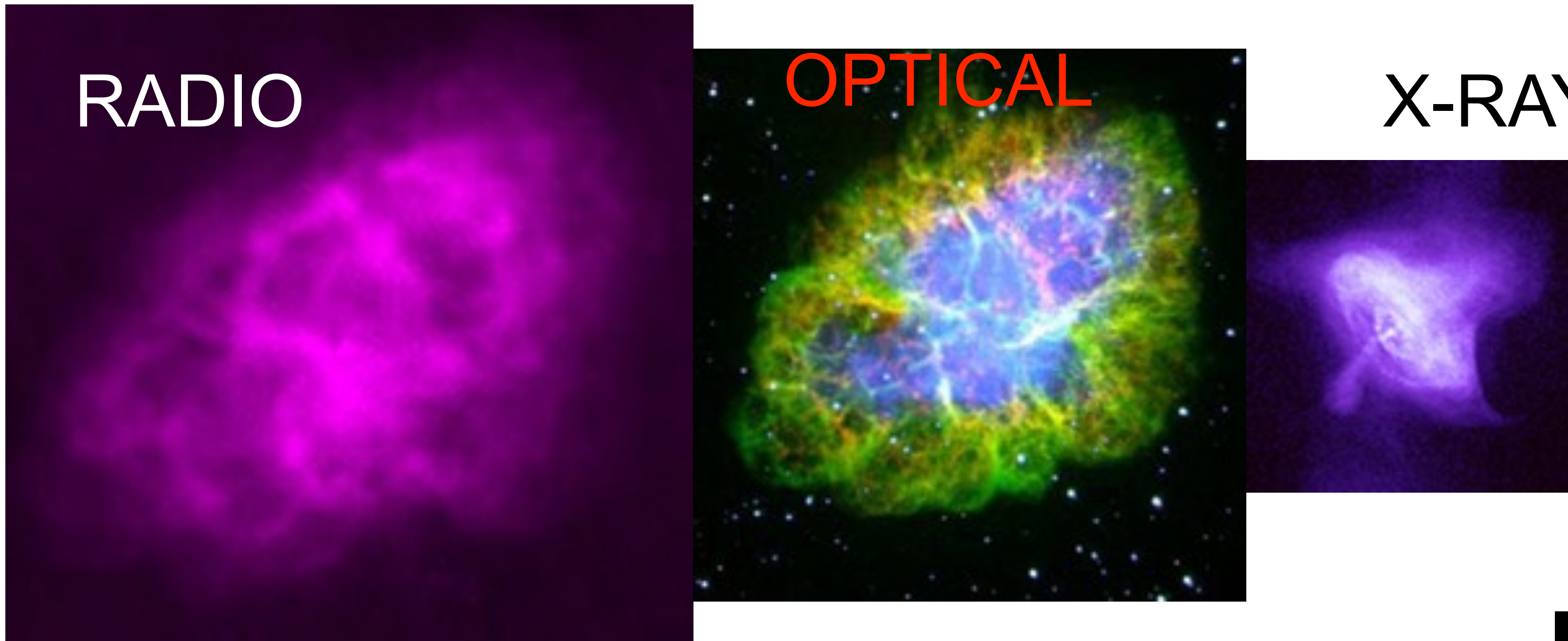


Arons 07

Efficient dissipation of the striped wind can accelerate the plasma to energies ~
$\Phi/K \sim \Omega BR^2/c/K$

$\sim 10^{12}\, B\, P^{-2} / K$ eV

Nebulae



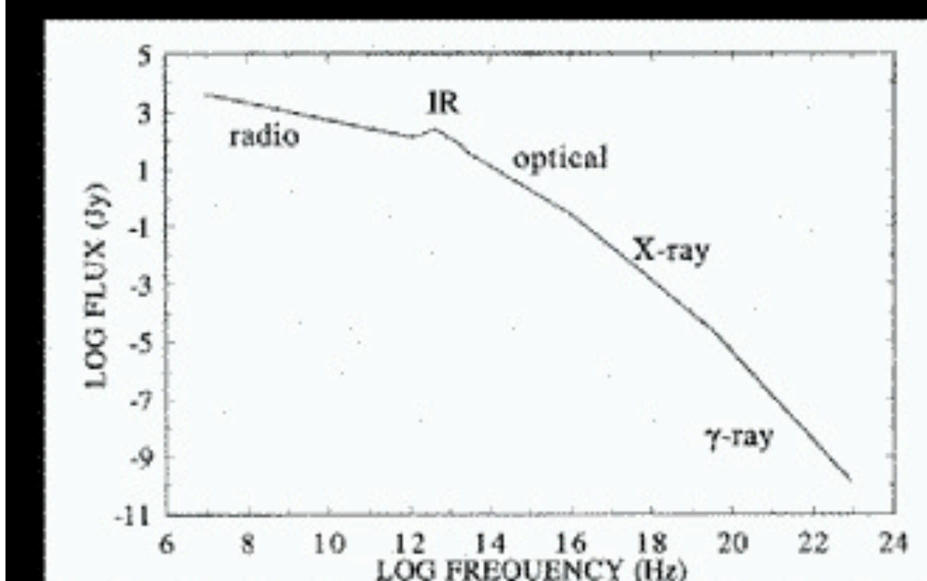
?

γ–rays (<100 MeV)

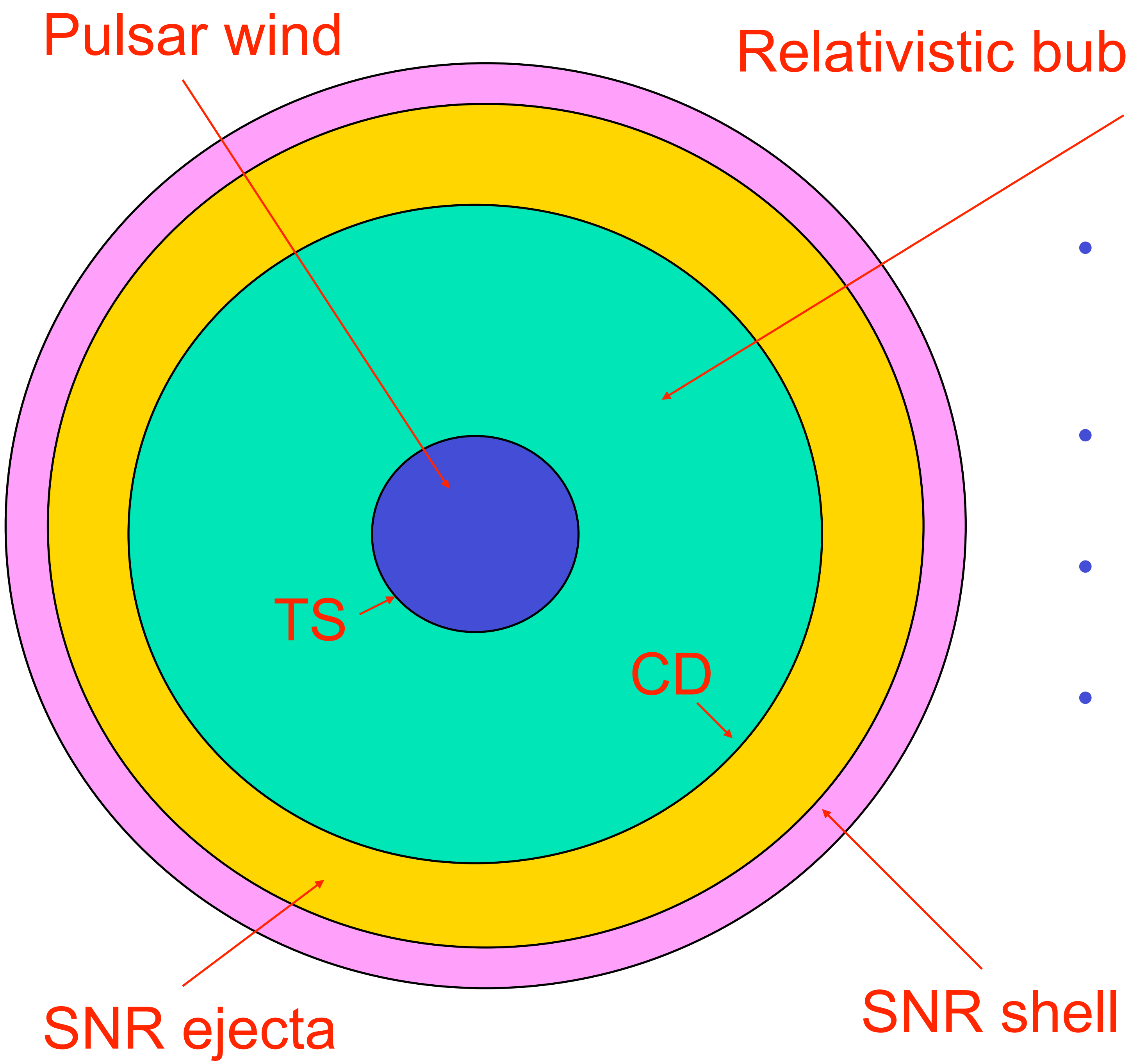
Lifetime: X-rays -- few years, γ-rays -- months. Need energy input!
Crab pulsar: $E_R = 5\times10^{38}$ erg/s, 10-20% efficiency of conversion to radiation.

Max particle energy > 3×10^{15} eV, comparable to pulsar voltage.
Nebular shrinkage indicates one accelerating stage:
require $10^{38.5} - 10^{39}$ $e^{\pm}$ /s, radio mystery
PSR also injects B field into nebula (~10^{-4} G)

$S_\nu \propto \nu^{-0.3}$ (radio); $\nu^{-1.0}$ (X-ray); break



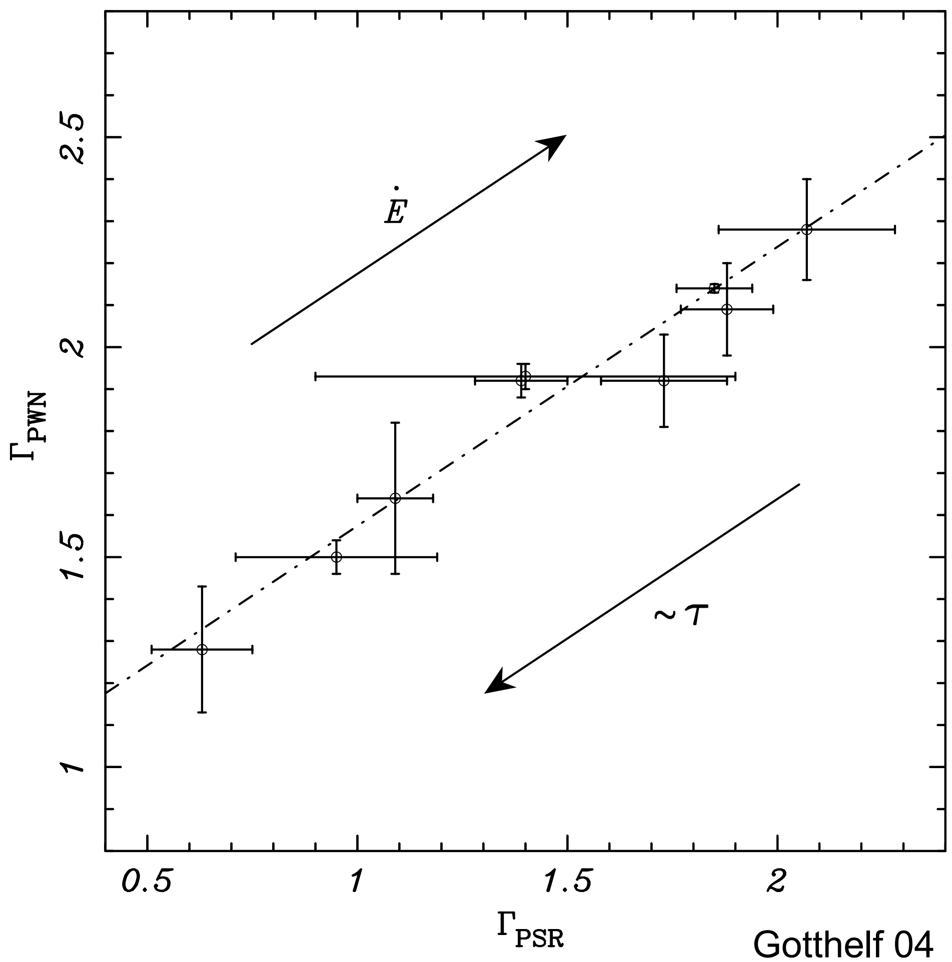
Sketch of PWN / SNR interaction



- Particles are accelerated at the termination shock where magnetic field could be dissipated
- Maximum energy of accelerated particles can be as high as the voltage
- Bulk energy dominated by 10GeV particles
- Possible presence of ions?

$$E_{pw} = 10^{49}\ \text{erg}$$

Role of the Nebula



Gotthelf 04

PSR pulsed emission have X-ray spectral properties that correlate with the X-ray spectrum of the nebula. How many particles are produced? What limits production?

They are not the same!

Stronger PSR tend to be softer!

Not necessary age trend!

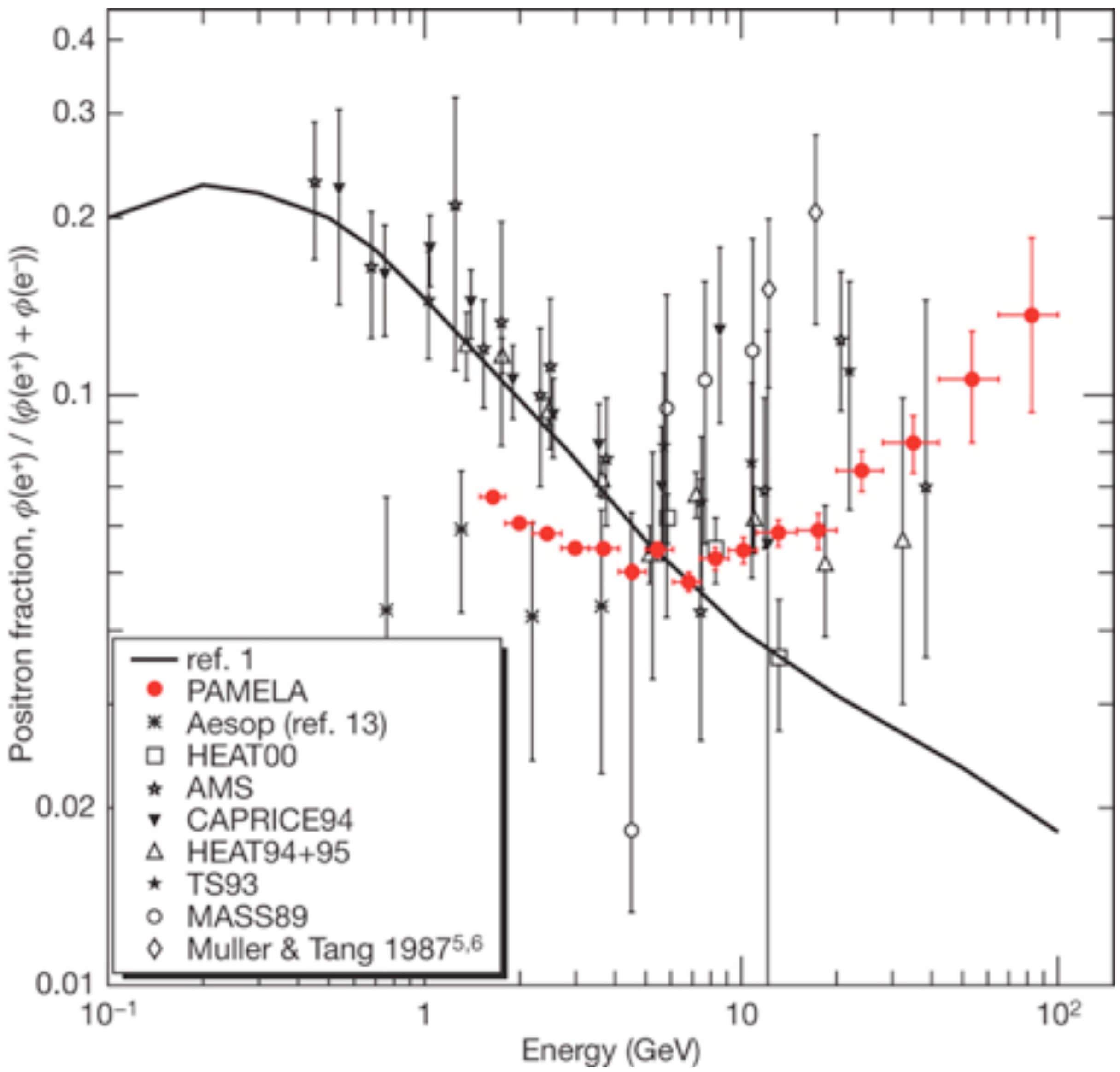
The particle distribution function responsible for the pulsed emission, does not survive unaltered till the nebula!

Positrons.

Pulsar acceleration mechanism can produce non-equal numbers of positron and electrons.

Typical energies of the accelerated particles in the PSR magnetosphere are of the order of the PAMELA positron excess

How to account for PSR contribution?



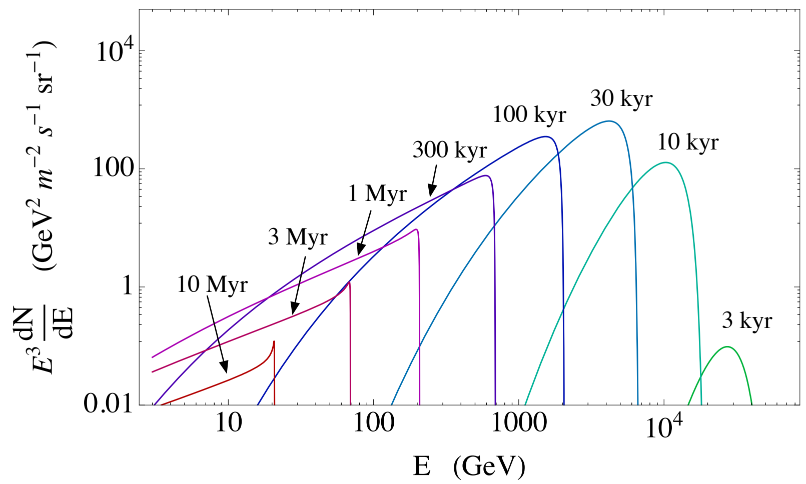
Positron excess

Mylishev et al 09

Mylishev et al 09

Positron excess

Get your favorite pair creation model for PSRs.
Polar/outer gaps? Acceleration mech? Losses?



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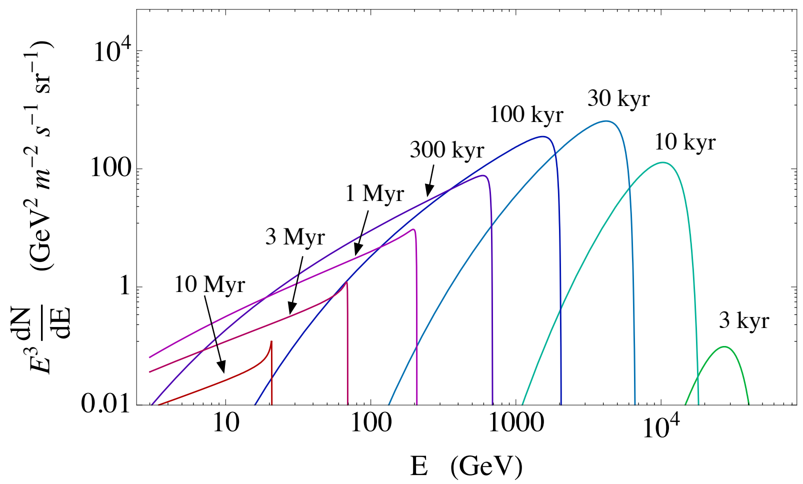
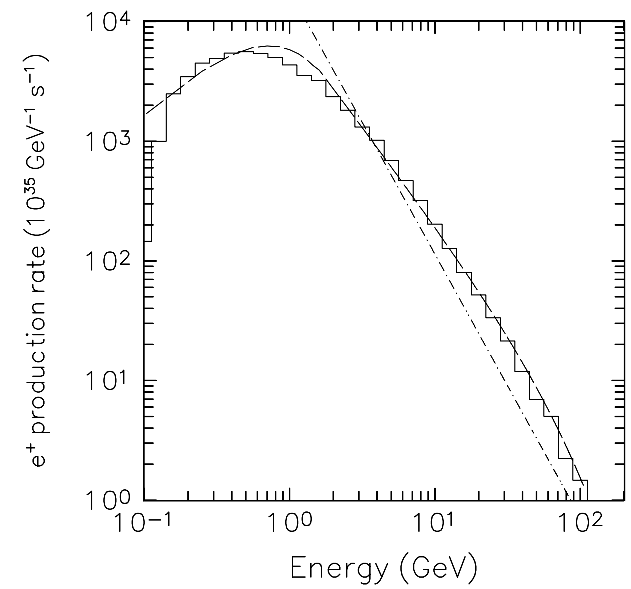


Mylishev et al 09

Convolve with a suitable PSR population. What is suitable?



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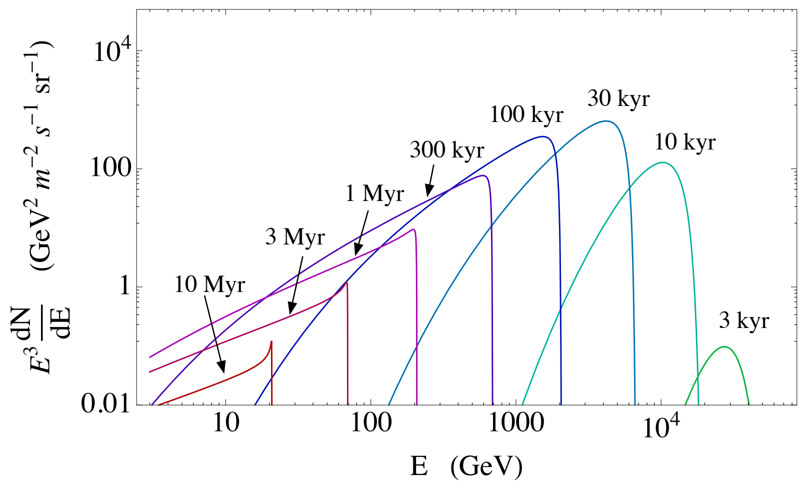

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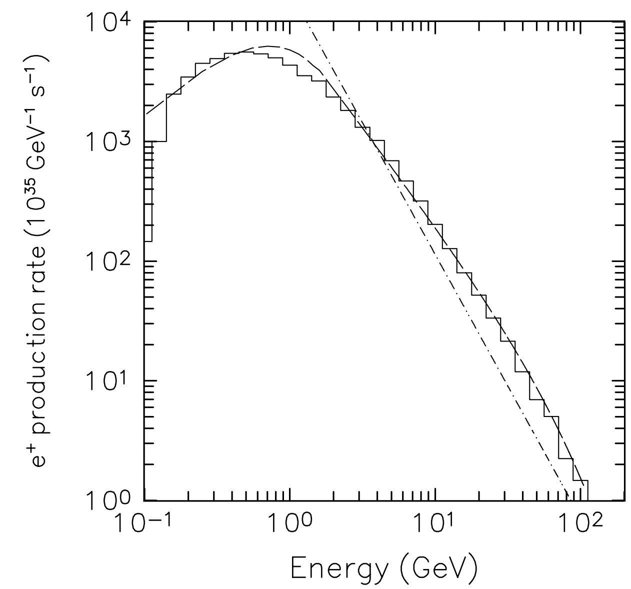
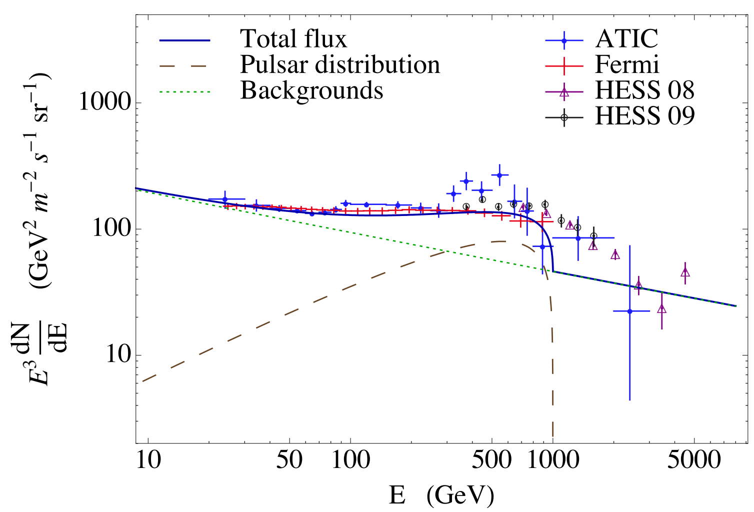


Propagate in the galaxy



Mylishev et al 09

Old pulsars vs young ones

PSR older than 10^7 yr have negligible pair creation.

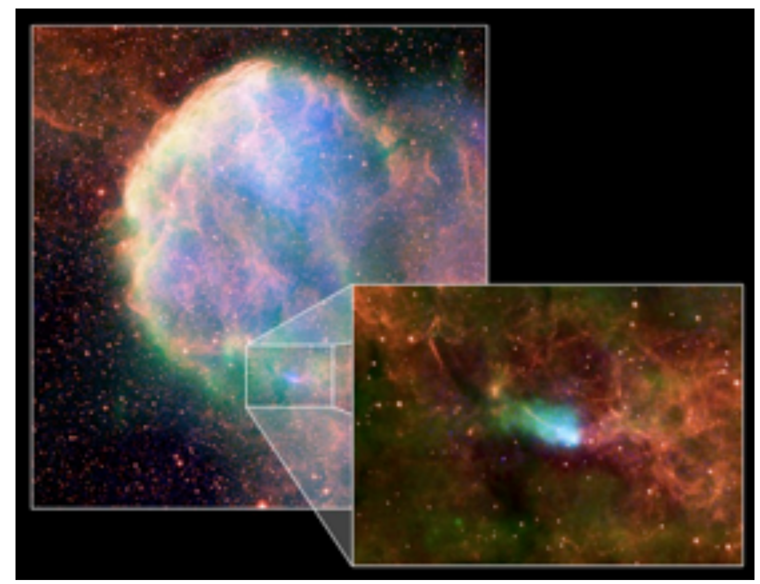
More problematic to establish a limiting constraint for younger PSR.

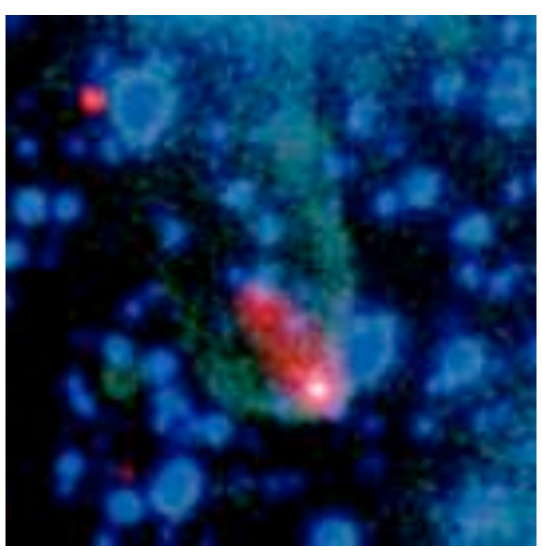
In general the typical age 10^5 yr is used. SNR confinement.

Starting age depends on PSR kick velocity 50-500 km/s.

SNR confinement can be modified by SNR evolution.

Also old system are confined, perhaps up to voltage energy





X-ray / Radio tails are observed formany PSR with enough spin-down power to produce observable nebulae

Tails are many PC long
What causes mixing with eth ISM?

Magnetars

Magnetar are NS with surface B ~ 10^{14-15} G
Typical periods of a few second and spin down age of 10^4 yr

AXPs / SGRs with Lt ~ 10^{46} erg >> Erot ~10^{44} erg

Only a few magnetars are known in the galaxy
5+ -SGRs
7+ -AXPs

They are supposed to be formed in every galaxy with a typical rate of 1 every 1000 yr

Initial period is highly uncertain

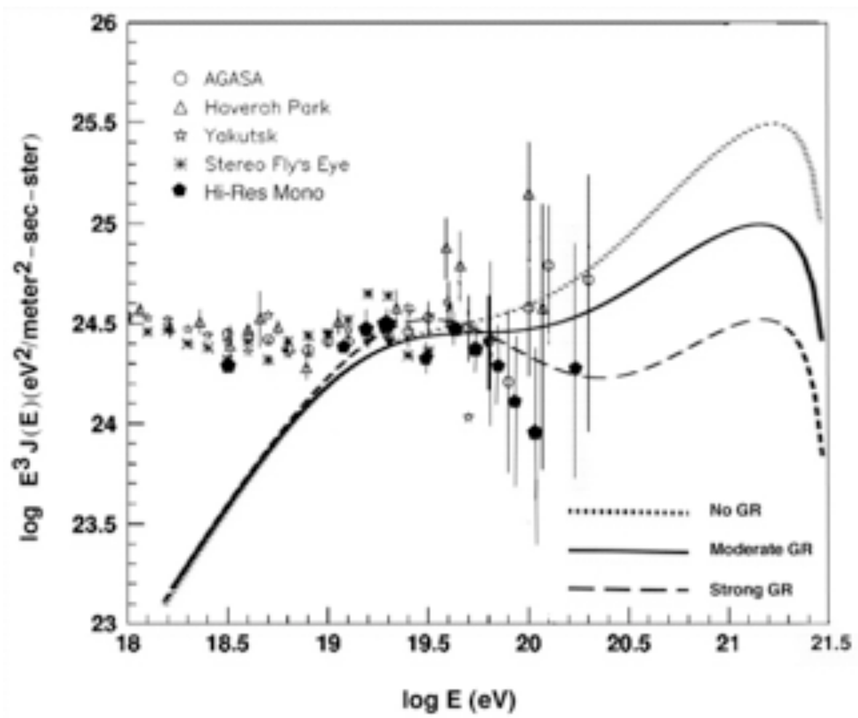
High magnetic filed from dynamo origin at birth implies P ~ t_{conv} ~ ms

If born as ms rotator the associate SN should have ~ 10^{52} erg - GRB.

UHECR can have GRBs origin

UHECR from magnetars

Change in slope at the ankle suggest new contribution to UHECR origin
Possible association with SG-equator suggest “galactic” population



Arons 03

Maximum energy achievable is

$$\Phi_{\rm cap} \simeq \frac{\Omega B_p}{2c}\frac{R^3\Omega}{c} = 7 \times 10^{12} B_{p,12} P_0^{-2}\ {\rm V}$$

For B ~ 10^{14} G and Millisecond period can reach 10^{20} eV

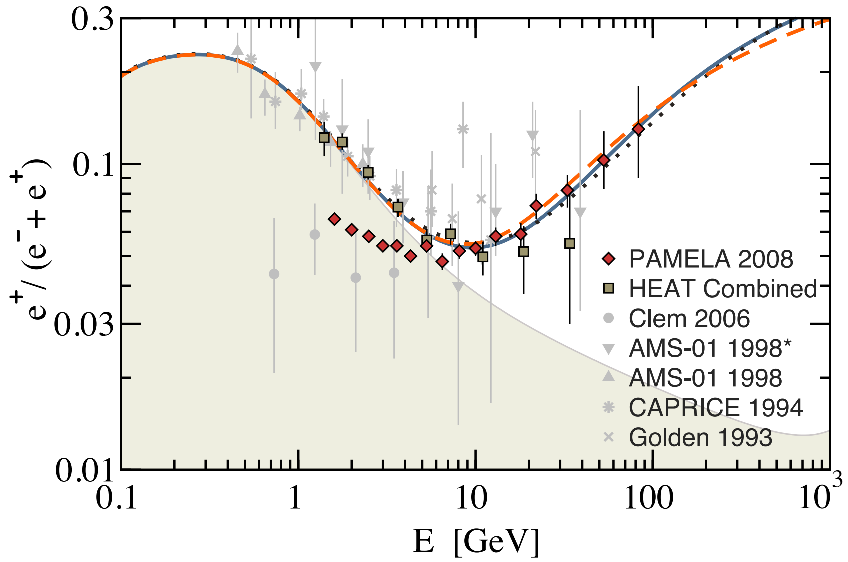
Importance of GW losses and SN confinement (Bubbles/Jets)

Local sources

Local contribution to the positron excess.
Are there nearby sources?

Closest accelerator is GEMINGA

gamma-ray PSR
550 ly
Age = 300000 yr
P = 0.2 sec
L = $3x10^{34}$ erg/s



Yuksel et al 09 &

Coincidence with a MILAGRO TeV source suggest the presence of accelerated particles.

The lack of a detected x-ray/radio nebula was used to assume high diffusion for pairs

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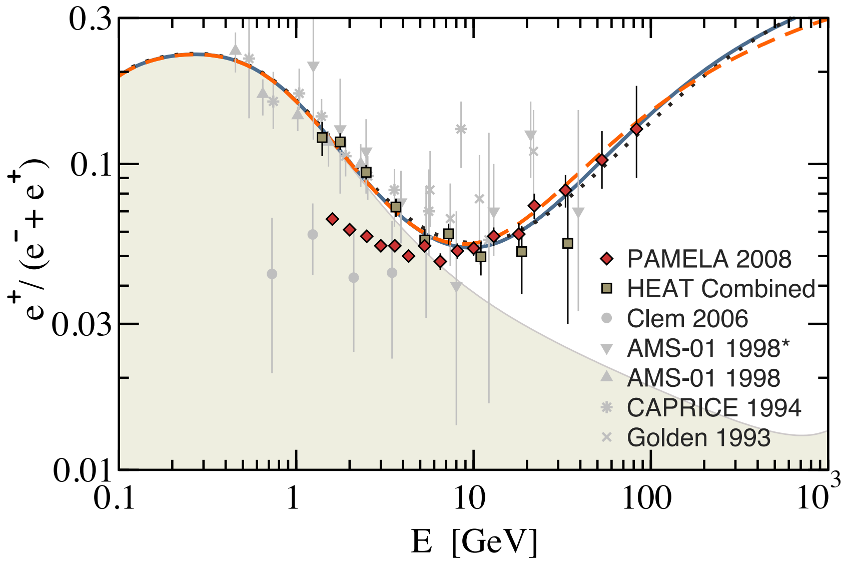

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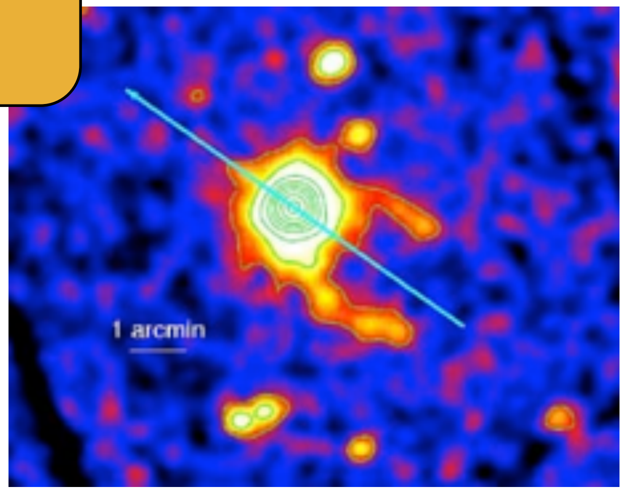

Tail outflow >> PSR speed
Displacement

PSR B1509

Beautiful example of particle accelerated by a PSR.
For once NOT CRAB!

PSR B1509

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For once NOT CRAB!**

However ....

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Too young to contribute
1550 yr

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**Too Faint to contribute
About 1/10 of Crab**

PSR B1509

Beautiful example of particle accelerated by a PSR.
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However ....

Too young to contribute
1550 yr

Too Faint to contribute
About 1/10 of Crab

Too far to contribute
6-10 kpc

Conclusions

- **Pulsar are excellent accelerators**
- **Copious production of pairs**
- **Pair energy is consistent with PAMELA Excess**
- **Uncertainties in multiplicity and population**
- **Confinement**
- **Magnetars can be the origin of UHECR**