# Pulsar wind nebulae

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## useful bibliography

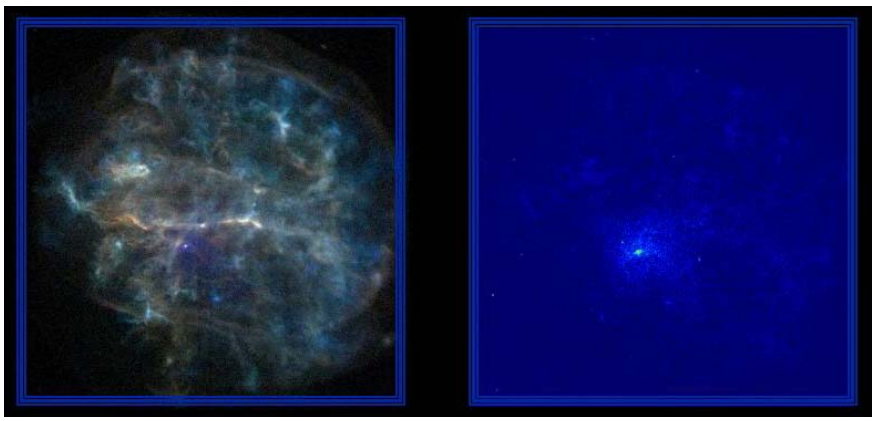
- Gaensler & Slane, astro-ph/0601081 (with many references to observations)
- Arons J. 2004, Adv. in Space Research 33, 466
- Rees & Gunn 1974, MNRAS 167, 1
- Kennel & Coroniti 1984, ApJ 283, 694 and ApJ 283, 710
- Chevalier, R. 1982, ApJ 258, 790
- Romanova, Chulsky & Lovelace 2005, ApJ 630, 1020
- Wilkin 1996, ApJ 459, L31
- Bucciantini et al. 2003, A&A 405, 617
- Blondin, Chevalier, Frierson 2001, ApJ 563, 806
- van der Swaluw et al. 2003, A&A 397, 913
- de Jager et al. 1996, ApJ 457, 253
- Aharonian et al. for HESS, 2005, A&A 448, L43 and A&A 432, L25 and A&A 435, L17 and A&A 442, L25

## synchrotron nebula in a supernova remnant

- **SNR G292.0+1.8 + PSR J1124-5916**
  P = 135 ms, age = 1.7 kyr

SNR emission
0.6-2 keV

synchrotron nebula
2-7 keV



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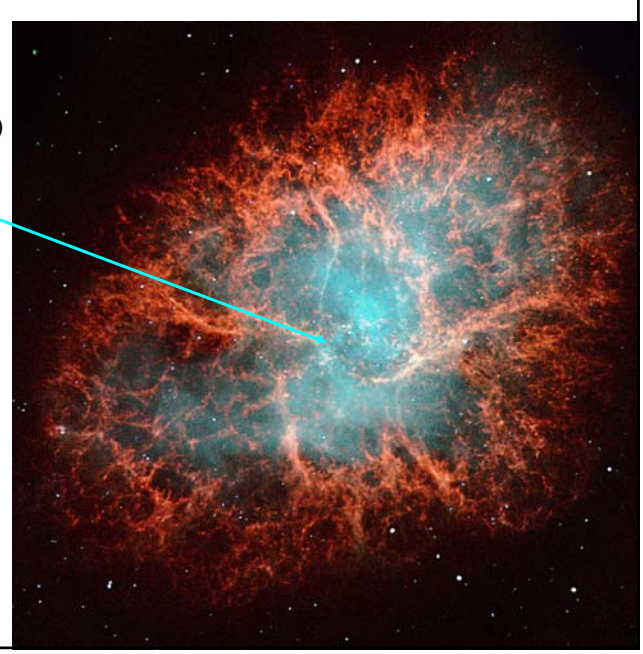
## plerion

- **optical Crab nebula**
  - blue synchrotron rad.
  - wind nebula fills the remnant (plerion)

pulsar



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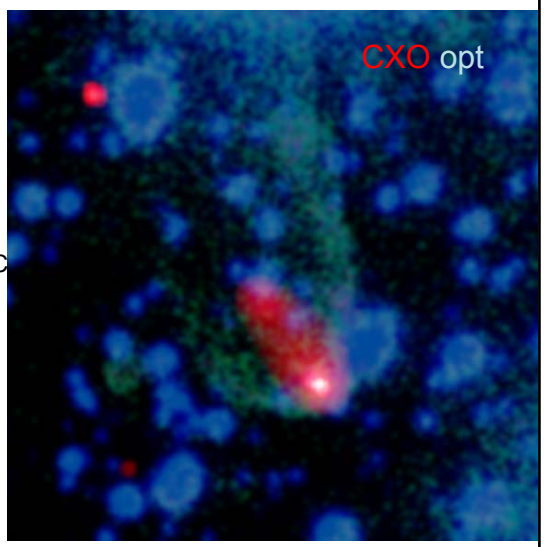
## bow shock pulsar wind nebula

- **PSR 1957+20 « Black Widow »**
  - recycled ms pulsar
  - supersonic motion in the ISM
  - bow shock confines the wind nebula
  - D ~ 1.5 kpc




- **40 to 50 PWN known**
  - in the Milky Way + LMC + SMC
- **from most energetic young pulsars (bias)**
  - $4\ 10^{29}$ W ≤ $\dot{E}_{psr}$ ≤ $5\ 10^{31}$ W
- **"round" PWNe for young pulsars**
  - $\tau_{psr}$ ≤ 20 kyr
- **"bow shock" PWNe for older pulsars**



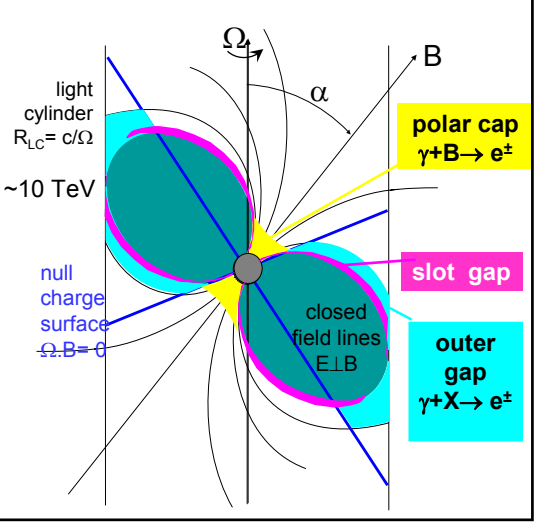
## pulsar magnetosphere

$\dot{E}_{psr} = I\Omega\dot{\Omega}$ for $I \approx 10^{38}$ kg m$^2$

- **unipolar inductor field** $\vec{E} = -(\vec{\Omega} \wedge \vec{r}) \wedge \vec{B}$ **from B rotation**
  - extracts charges from the neutron star
- **mgnsph. filled with force-free charge density** $\rho_{GJ} = -2\varepsilon_0 \vec{\Omega} \cdot \vec{B}$
  - Goldreich & Julian '69
- **acceleration sites in open mgnsph. where**

$$\rho \neq \rho_{GJ} \Rightarrow E_{//}$$

  - primary charges accelerated to ~10 TeV
  - emit $\gamma$ photon (curvature rad.)
- **$\gamma$ initiate $e^{\pm}$ cascades**
- **question: are ions also accelerated?**



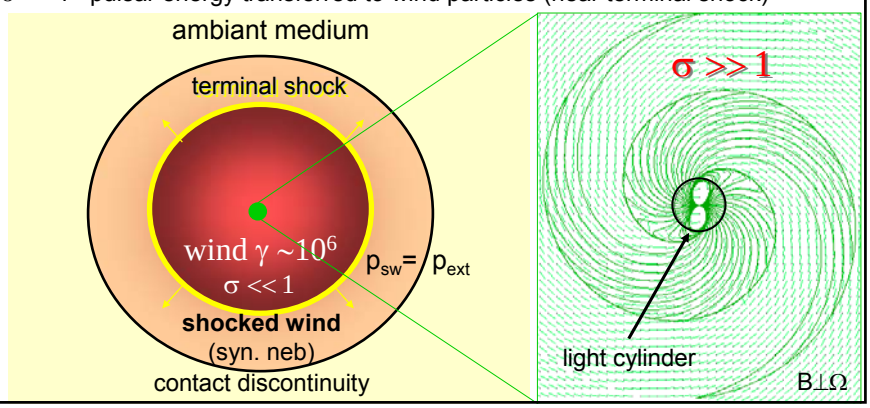
## pulsar wind

- **retarded potentials => elmgn. wave outside the light cylinder**
- **wind = toroidal (wound up) field frozen to an $e^{\pm}$- ion plasma**
- **$\sigma$ ratio = Poynting flux / particle energy flux** (Rees & Gunn '74, Kennel & Coroniti '84)

$$\sigma = \frac{B_{1w}^2 c/\mu_0}{n_{1w} v_{1w} (\gamma_{1w} mc^2)}$$

$$\dot{E}_{psr} = \dot{E}_w + \dot{E}_{EB} \quad \Rightarrow \quad \dot{E}_w = \frac{\dot{E}_{psr}}{1+\sigma} \qquad \dot{E}_{EB} = \frac{\dot{E}_{psr}}{1+1/\sigma}$$

  - $\sigma >> 1$ EM wave takes the pulsar energy away (near light cylinder)
  - $\sigma << 1$ pulsar energy transferred to wind particles (near terminal shock)

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## open questions

- **how are particles accelerated in the magnetosphere?**
  - how many secondaries produced in the cascades?
- **how is the elmgn energy transferred to the particles in the wind?**
  - $\sigma >> 1$ at the light cylinder, $\sigma = 0.001 - 0.1$ at the terminal shock
  - 'silent' transfer since charges follow B $\Rightarrow$ syn. radiation <<
  - large equatorial to pole asymmetries (torii and jets)
- **how is this energy transformed to radiation in the shocked wind?**
  - physics of a relativistic shock
- **how does the wind nebula evolve?**
  - early expansion in 'cold' SN ejecta
  - later expansion in 'hot' ejecta shocked by the SNR reverse shock
  - bow shock confinement from pulsar supersonic motion in SNR or in ISM
- **applications**
  - blazar and $\gamma$-ray bursts jet formation and relativistic shocks
  - Sag A*

**« The answer, my friend, is blowing in the wind » (Bob Dylan)**

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# PWN structure



## MHD shock wave

- **conservations => jump conditions in the shock frame**

$$(1)\ \text{mass}: \rho u_\perp = \text{cte}$$

$$(2)\ \text{momentum}: p + \rho u_\perp^2 + \frac{1}{2\mu_0}(B_{//}^2 - B_\perp^2) = \text{cte} \quad \text{and} \quad \rho u_{//} u_\perp - \frac{1}{\mu_0} B_{//} B_\perp = \text{cte}$$

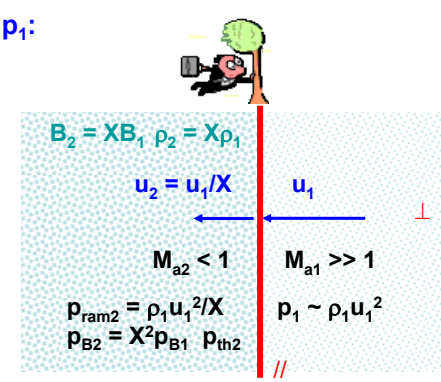
$$(4)\ \text{energy}: \left[\tfrac{1}{2}\rho(u_\perp^2 + u_{//}^2) + u_{int} + p\right] u_\perp - \frac{1}{\mu_0}\left[B_\perp u_{//} - B_{//} u_\perp\right] B_{//} = \text{cte}$$

$$(5)\ \text{magnetic flux}: B_\perp u_{//} - B_{//} u_\perp = \text{cte} \quad \text{and} \quad B_\perp = \text{cte}$$

- **strong perpendicular shock $p_2 >> p_1$:**
  - compression ratio X

$$X = \frac{u_{\perp 1}}{u_{\perp 2}} = \frac{\rho_2}{\rho_1} = \frac{B_2}{B_1}$$

  - X → 4 if $p_B$ → 0 (Rankin-Hugoniot)
  - X → 0 if large $p_B$



## relativistic shock wave

- (*) = relativistic wind rest frame
- upstream = 1, downstream = 2

Kennel & Coroniti '84, Blandford & McKee '76, Double '04

$$\text{field}: B_{\oplus} = B = \gamma B^*$$
$$\text{density}: n_{\oplus} = n = \gamma n^*$$
$$\text{pressure}: p = p^*$$
$$\text{internal energy}: e^* = \frac{p}{\gamma_{ad} - 1} + n^* mc^2$$

- **jump conditions**

$$\text{mass}: \gamma\beta n^* = \text{cte} \qquad \text{momentum}: \gamma^2\beta^2\left(e^* + p + \frac{B^{*2}}{\mu_0}\right) + p + \frac{B^{*2}}{2\mu_0} = \text{cte}$$

$$\text{field}: \gamma\beta B^* = \text{cte} \qquad \text{energy}: \gamma^2\beta\left(e^* + p + \frac{B^{*2}}{\mu_0}\right) = \text{cte}$$

- **compression ratio:**
  - perpendicular case

$$Y = \frac{B_2}{B_1} = \frac{n_2}{n_1} = \frac{\beta_1}{\beta_2} = \frac{v_1}{v_2} = f(\sigma_1, \gamma_1)$$

- **if $\sigma << 1$ Y → 3 modest shock (lower for oblique B)**
- **if $\sigma >> 1$ Y → 1+(1/2σ) hardly any shock and thermalization of incident ram pressure**

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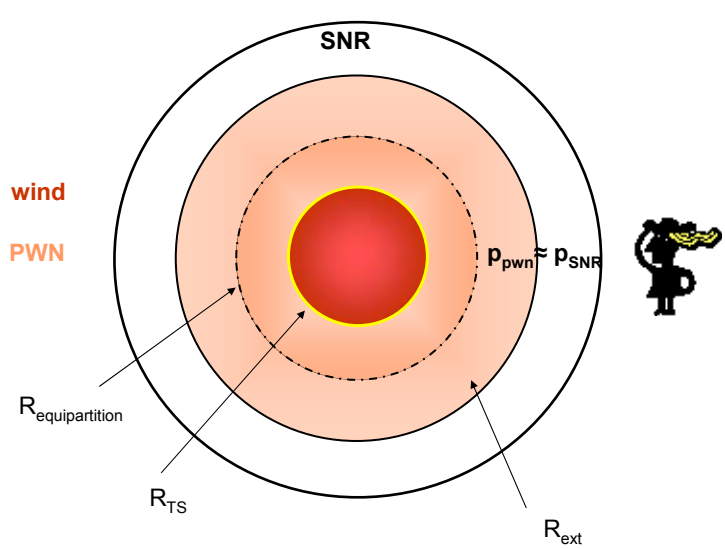
## spherical PWN $\sigma << 1$

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## spherical PWN $\sigma$ <<1

Rees & Gunn '74
Kennel & Coroniti '84

❖ **density, velocity, B profiles**

$pn^{-\gamma_{ad}} = \text{cte}, \quad \gamma_{ad} = 4/3$

subsonic $\Rightarrow$ isobaric $\Rightarrow$ n = cte

mass conserved : $\text{div}(n\vec{v}) = 0 = \frac{d}{dr}(nvr^2)$

$\Rightarrow \quad v_r \propto r^{-2}$

MHD + stationnary : $\text{rot}(\vec{v} \wedge \vec{B}) = 0$

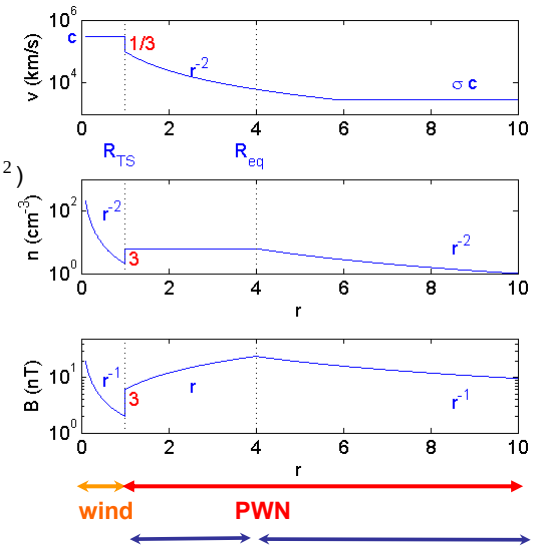
$\frac{d}{dr}(Bvr) = 0 \quad \Rightarrow \quad B_\phi \propto r$

$R_{equipartition}$ for $\frac{B_\phi^2}{2\mu_0} \approx nkT$

asymptotic velocity : $v_r \to v_\infty \approx \sigma c$

$\Rightarrow \quad n \propto r^{-2}, \quad B_\phi \propto r^{-1}$

$$p_{th2+ram2} \approx (\tfrac{2}{3} + \tfrac{1}{3}) \frac{\dot{E}_w}{4\pi R_{TS}^2 c}$$




wind — PWN

$p_{th} > p_B$ $R_{equip}$ $p_B > p_{th}$

$p_{th} \approx$ cte $\quad p_B \approx$ cte

$p_{tot} = \text{cte} = p_{ext}$ $\quad v_\infty \neq 0$ to carry B flux

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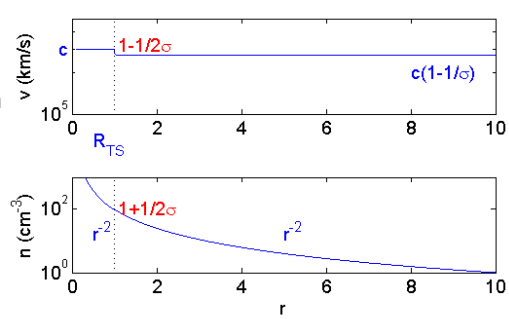
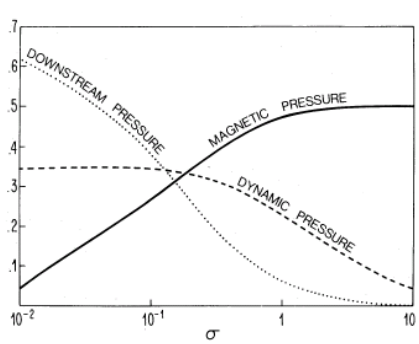
## $\sigma$ >> 1 case: no PWN

❖ **density, velocity, B profiles**

- elmgn wave dominates
- goes on
- $p_{th2} << p_{B2} \Rightarrow$ little $e^\pm$ dispersion and little synchrotron
- $p_{B2}/p_{ram2} = 2\sigma$ et $p_{ram2}/p_{th2} = 8\sigma^2$




wind

$p_B >> p_{th}$

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## spherical PWN $\sigma << 1$

- **terminal shock radius**

$$p_{pwn} = p_{th2+ram2} = \frac{\dot{E}_w}{4\pi R_{TS}^2 c} = p_{ext}$$

$$\Rightarrow \quad R_{TS} = \left( \frac{\dot{E}_w}{\Delta\Omega\, c p_{ext}} \right)^{1/2}$$

$\Delta\Omega < 4\pi$ if anisotropic wind

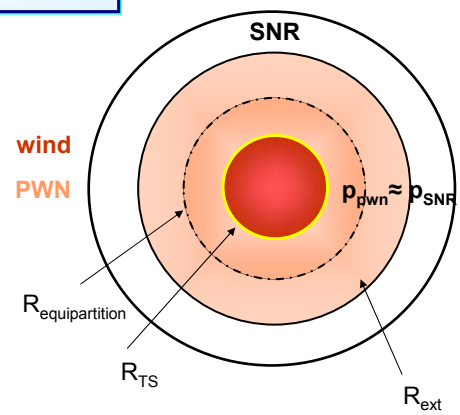
- **adiabatic losses**

$$\dot{E}_{ad} = -\frac{E_e}{3} \vec{\nabla} \cdot \vec{v}_{2w} = -\frac{E_e}{3} \frac{d}{dr}(vr^2)$$

$$r < R_{equip}: \quad v \propto r^{-2} \Rightarrow \dot{E}_{ad} = 0$$

$$r >> R_{equip}: \quad v = \sigma c \Rightarrow \dot{E}_{ad} = -\frac{2E_e}{3} r$$

- **PWN radiation**
  - synch. dominates losses
  - in the wind: $L_{syn\ wind} \approx 0$
  - in the PWN $L_{syn\ pwn} \propto nB^2$
    $L_{syn} \propto r^2$ for $R_{TS} \le r \le R_{eq}$,
    $L_{syn} \propto r^{-4}$ for $R > R_{eq}$ ↓↓↓




$$e^{\pm} + B \rightarrow \text{radio} - X$$

$$e^{\pm} + h\nu \begin{vmatrix} \text{CMB} \\ \text{IR} \\ \text{X} \end{vmatrix} \rightarrow \begin{vmatrix} \text{TeV} \\ << \\ \gamma \end{vmatrix}$$

$$e^{\pm} + h\nu_{syn} \rightarrow \gamma + \text{TeV}$$

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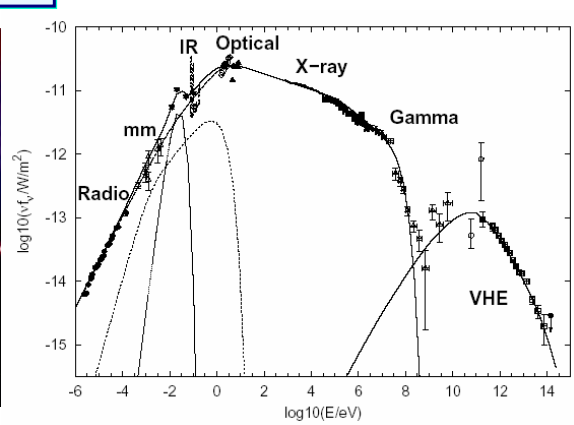
## Crab nebula




- $R_{TS} \sim 2\ 10^9\ R_{LC} = 0.1$ pc (10")
- opt. polarization $\Rightarrow B_\phi$
- $\sigma \sim 0.001 - 0.003 - 0.005$
  - from expansion velocity
  - from syn. brightness and $E_{break}$ between radio and optical
  - from IC emission

- cut-off 25 MeV
- inflection 150 MeV
- B = 30 nT B(equip, opt) = 30 nT
- synchrotron + IC (80% synchro-self-Compton, 20 % IC sur CMB, mm, FIR)

de Jager et al. '96 Aharonian '04

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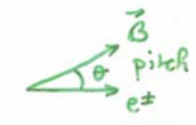
## Crab nebula

❖ **continuous injection !**

- if syn. losses dominate

$$\tau_{acc} \approx \alpha(\chi_{\vec{B},\vec{v}_C})\left(\frac{u_{vent}}{c}\right)^2 \tau_{Larmor} \approx \alpha\, \tau_{Larmor} = \alpha \frac{2\pi E}{eBc^2}$$




$$\tau_{syn} \approx E/\dot{E}_{syn} \approx 2.64\,10^6 s\left(\frac{E}{1eV}\right)^{-1}\left(\frac{B\sin\theta}{1T}\right)^{-2}$$

$$\tau_{acc} \approx \tau_{syn} \Rightarrow E_{max} = 6.14\,10^{14} eV\left(\frac{B\sin\theta}{10^{-7}T}\right)^{-1/2}\left(\frac{\alpha}{1}\right)^{-1/2}$$

synch. rad. $h\nu_{max} \propto \mathcal{D} B E^2 \sin\theta \quad = 25 MeV\left(\frac{\mathcal{D}}{\alpha\sin\theta}\right)$

- synchrotron break depends only on geometry and acceleration efficiency!
- B(Crab) ~30 nT => $E_{max}$ ~ $10^{15}$ eV => synchrotron lifetime ~ 30 days

De Jager et al. '96

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## Crab nebula

❖ **how many pairs?**

- if single $E_e^{-2.3}$ power-law for the syn. rad. above the IR => $\gamma_{1w}$ ~ 2 $10^6$

$$\dot{E}_w = \frac{\dot{E}_{psr}}{1+\sigma} \approx \dot{E}_{psr} = \dot{N}_{\pm}\gamma_{1w} m_e c^2$$

$$\Rightarrow \dot{N}_{\pm} = 2.8\,10^{38}\ s^{-1} \approx 10^4 \dot{N}_{GJ}$$

multiplicity ~ ok for pulsar models

but it does not explain the radio data that requires ~ $10^{40}$ $e^{\pm}$ $s^{-1}$ over the 952 yr lifetime

- if broken power-law ($E_e^{-1.5}$ for the radio, $E_e^{-2.3}$ for opt. to X) $\Rightarrow$ $\gamma_{1w}$ ~ $10^3$ and

$$\dot{N}_{\pm} = 5.7\,10^{41}\ s^{-1} \approx 2\,10^7 \dot{N}_{GJ}$$

❖ **what acceleration process?**

- $E_e^{-2.3}$ ok from relativistic Fermi
- what at lower energies?
- why a break between the radio and higher ν?

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## spectral aging

- **synchrotron lifetime**

$$t_{syn} = 55.8\ \mathrm{kyr}\left(\frac{<B>}{1\,\mathrm{nT}}\right)^{-2}\left(\frac{E}{1\mathrm{TeV}}\right)^{-1}$$

- **maximum distance reached before e± radiate all their energy (roughly)**

$$\dot{E}_{syn} = -aB^2E^2 \quad \text{with} \quad B_{2w}(r) = B_{1w}Y\left(\frac{r}{R_{TS}}\right)$$

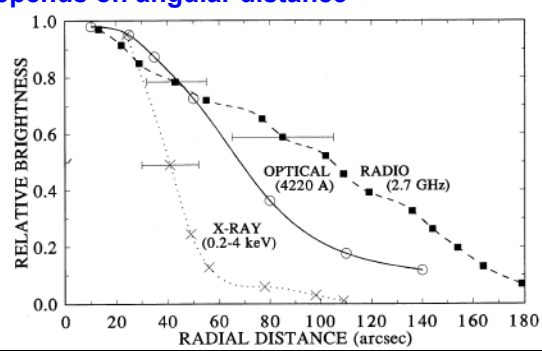
$$dE = \dot{E}_{syn}\frac{dt}{dr}dr = \frac{\dot{E}_{syn}}{v(r)}dr \quad \text{with} \quad v_{2w}(r) = \frac{c}{Y}\left(\frac{r}{R_{TS}}\right)^{-2}$$

$$\text{integrate from } E_0(R_{TS}) \text{ to } E(r) \Rightarrow \quad E_{max}(r) \propto \frac{c}{R_{TS}Y^3B_{1w}^2}\left(\frac{r}{R_{TS}}\right)^{-5} \quad \text{if } E << E_0$$

- **synchrotron break energy depends on angular distance**

$$h\nu_{max} \propto E_{max}^2 B$$

$$\Rightarrow \quad h\nu_{max} \propto \frac{c^2}{R_{TS}^2Y^5B_{1w}^3}\left(\frac{r}{R_{TS}}\right)^{-9}$$




- **PWN size in the Crab**

  radio > opt > X

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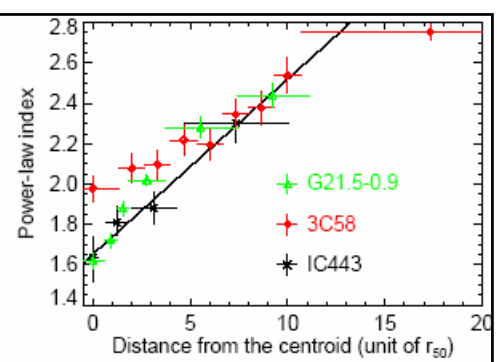
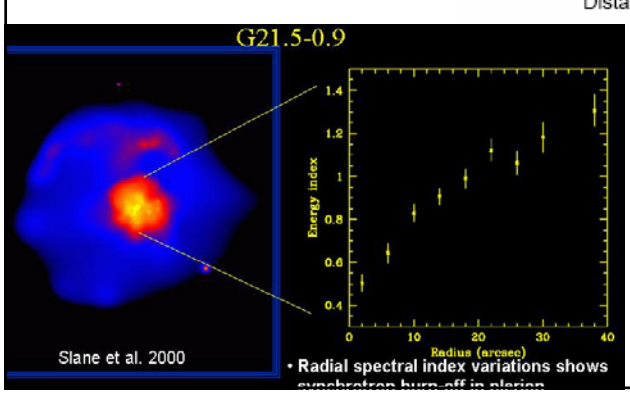
## spectral aging

- **e± aging with distance**
  **=> spectrum softens with r**

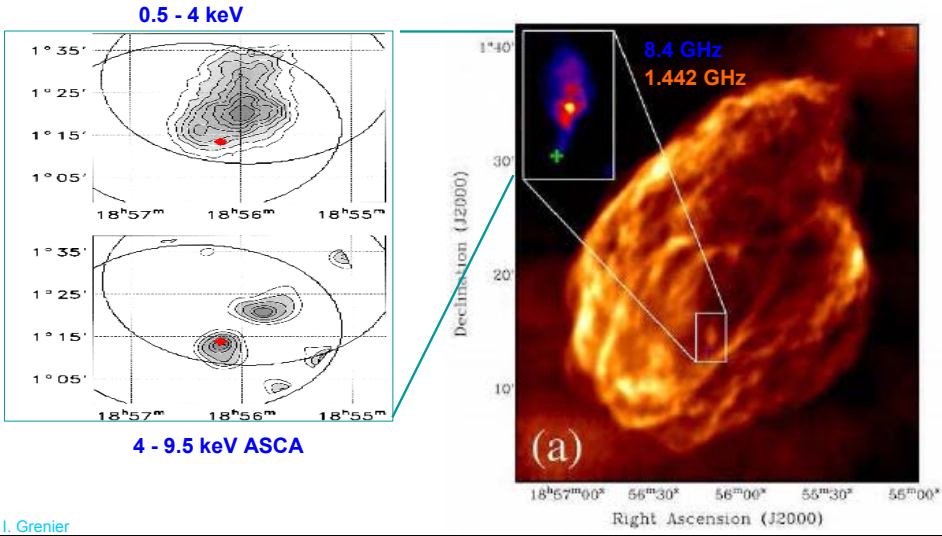



• Radial spectral index variations shows synchrotron burn-off in plerion

## spectral aging

- **difficulty: integrated history in the tail when the pulsar has substantially moved**
  - ex: W 44 and PSR B1853+01






## PWN evolution

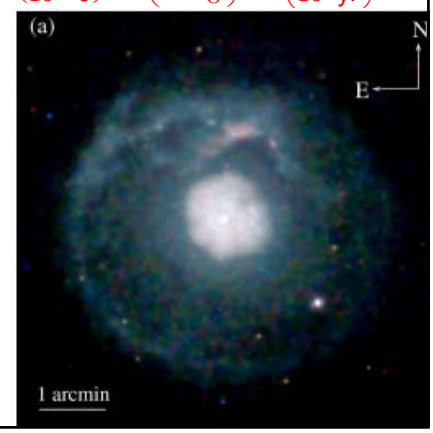
## phase I: free spherical expansion

- **during the first hundred years**
  - pulsar motion <<
  - $\dot{E}_{psr}$ ~ cte $\quad E_{SN} = ½ M_{ej} v_{ej}^2$
  - pressure-driven expansion since $p_{pwn} >> p_{ejecta}$
  - adiabatic losses dominate
  - => $R_{pwn} \approx 1.1\,\mathrm{pc} \left(\frac{\dot{E}_{psr}}{10^{31}\mathrm{W}}\right)^{1/5} \left(\frac{E_{SN}}{10^{44}\mathrm{J}}\right)^{3/10} \left(\frac{M_{ej}}{10 M_{\Theta}}\right)^{-1/2} \left(\frac{t}{10^{3}\mathrm{yr}}\right)^{6/5}$

Chevalier '77 & '82

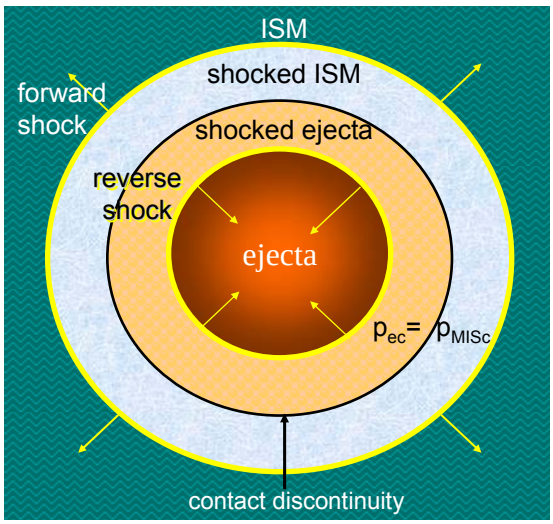
- **supersonic expansion**
  - with increasing speed $v_{pwn} \propto t^{1/5}$
  - PWN isobaric ($p = 1/3\, \rho c^2 \Rightarrow c_s = c/\sqrt{3}$)
    $\Rightarrow$ spherical symmetry
- **drives a shock in the ejecta**

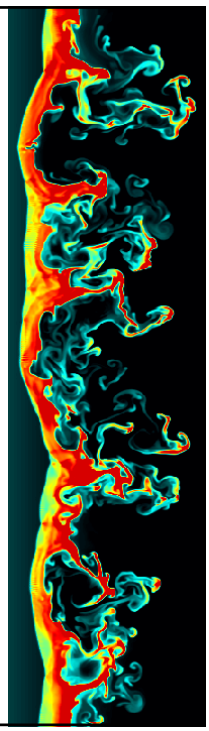
- **ex: G21.5-0.9 + PSR J1833-1034**
  - P + 61.8 ms, age < 1 kyr ≠ $\tau_{psr}$
  - $\dot{E}_{psr}$ = 3 $10^{30}$ W, D ~ 4.7 ± 0.4 kpc
  - $R_{pwn}$ ~ 1 pc, $R_{SNR}$ ~ 3.4 pc






## SNR structure

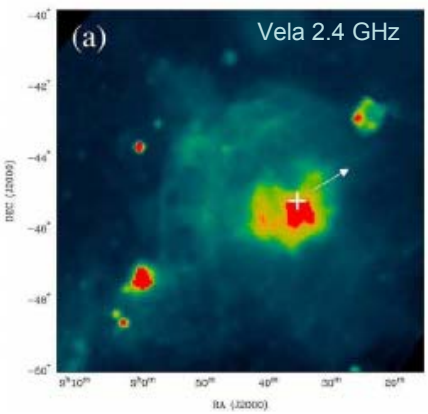


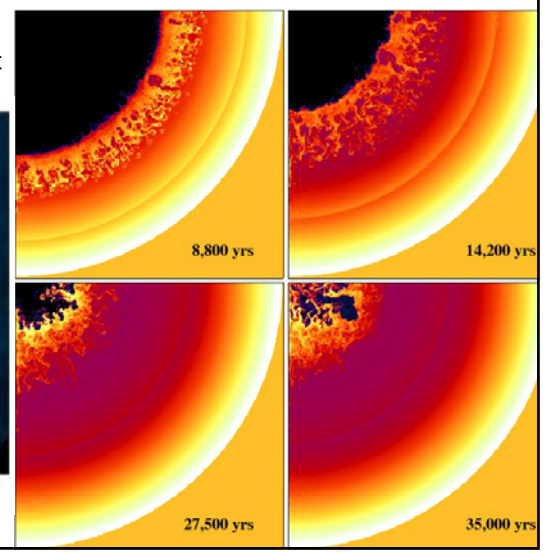



## Phase II: crushed by SNR reverse shock

Blondin '01
Bucciantini '03

- **compression by the SNR reverse shock**
  - PWN had freely expanded $\Rightarrow p_{pwn} < p_{SNR} \Rightarrow$ large compression
  - ex: Vela: pulsar not at PWN center nor moving away from it

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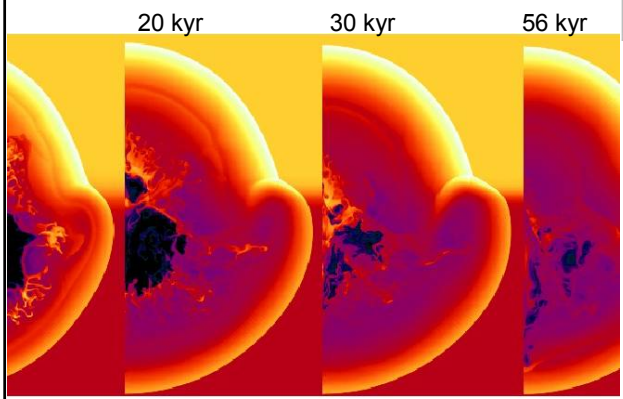
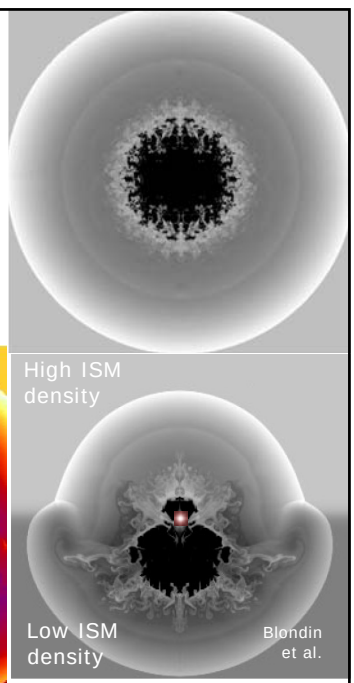
## crushed by SNR reverse shock

- **asymmetrically crushed if**
  - collimated wind
  - or ISM anisotropy

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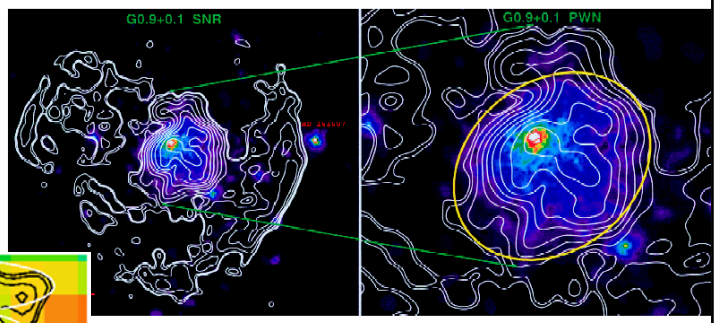
Blondin '01

# G0.9+0.1

- **crushed PWN or X-ray hardening from Doppler boosting of jet/torus ?**

Porquet '03
Gaensler '02




*von* EPIC image of SNR G0.9+0.1 and its PWN in the energy band 1.5–12 keV with an adaptative smoothing filter wi
quirement of 5 and Gaussian smooth of 10″. The *VLA* radio contours at 1.5 GHz (20 cm) are superimposed in white.
nant. *Right panel*: Pulsar Wind Nebula (PWN). The yellow ellipse represents the region taken for spectra analysis of

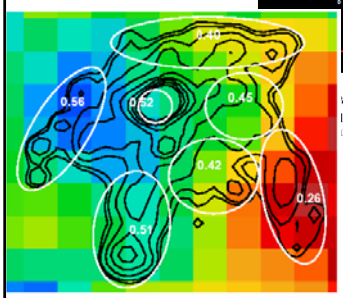
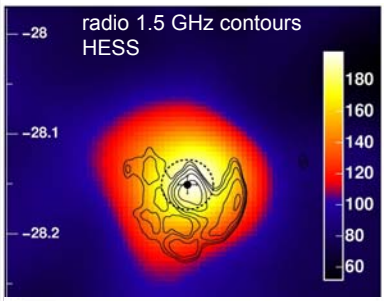


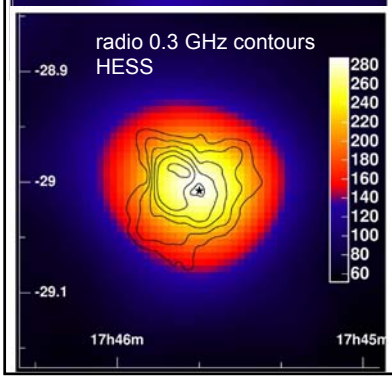

**Fig. 7.** Background subtracted hardness ratio map ([6–10] keV/[3–6] keV) of the small-scale structures with a pixel size of 8″. The colour coding goes from blue (hard spectrum) to red (soft spectrum). To guide

distance uncertain

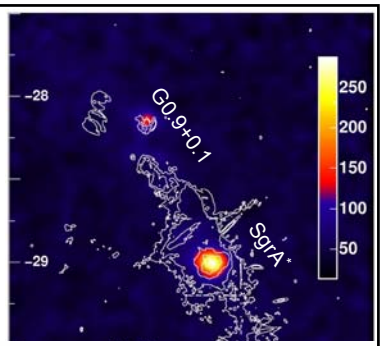
pulsar not discovered

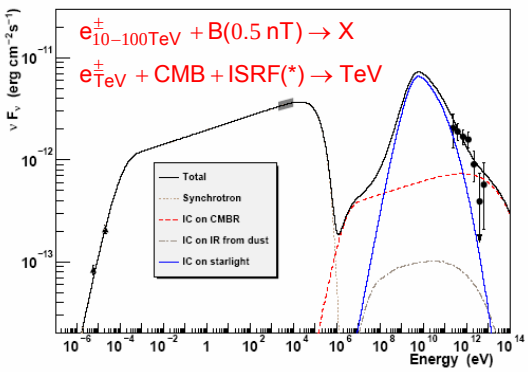
# G0.9+0.1




assuming starlight field in central Galaxy



## phase III: expansion in a Sedov SNR

- **subsonic expansion in hot ejecta (shocked by RS)**
- **SNR in Sedov phase**

  $R_{FS} \propto t^{2/5}$, $v_{FS} \propto t^{-3/5}$, $p_{shocked\ ISM} = p_{shocked\ ejecta} \propto v_{FS}^2 \propto t^{-6/5}$
- **PWN in pressure equilibrium with surrounding ejecta**

  $p_{pwn} = p_{shocked\ ejecta}$ and $p_{pwn} \propto V^{-\gamma_{ad}} \propto V^{-4/3} \propto R^{-4} \Rightarrow R_{pwn} \propto t^{3/10}$
- **deceleration of PWN**

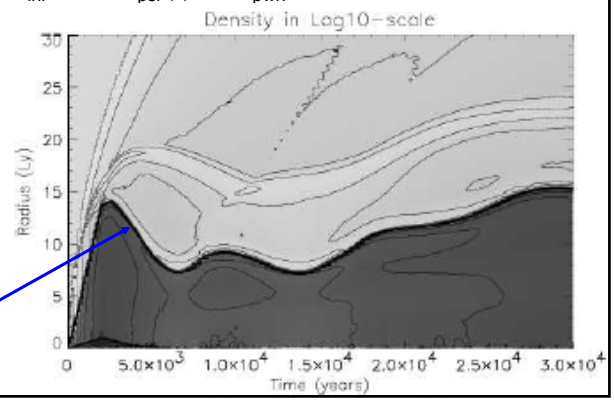
  $t < \tau_{ini} \Rightarrow \dot{E}_{psr} = cte \quad R_{pwn} \propto t^{11/15}$ van der Swaluw '01

  $t > \tau_{ini} \Rightarrow \dot{E}_{psr}(t) \downarrow \quad R_{pwn} \propto t^{3/10}$ Reynolds & Chevalier '84

simulated example:
free expansion t < 1.8 kyr
crushed: 1.8-15 kyr
(reverberations)
expansion in Sedov SNR :
15-30 kyr

Bucciantini '03

contact discontinuity






## phase IV: bow shock confinement

- **crossing time for the pulsar to cross the SNR shell**

$$R_{psr} = v_{psr} t = R_{SNR\,Sedov} \approx 1.15 \left(\frac{E_{SNR}}{\rho_{ISM}}\right)^{1/5} t^{2/5}$$ van der Swaluw '03

$$\Rightarrow t_{cross} = 44\ \text{kyr} \left(\frac{E_{SN}}{10^{44}\,\text{J}}\right)^{1/3} \left(\frac{n_{ISM}}{10^{6}\,\text{m}^{-3}}\right)^{-1/3} \left(\frac{v_{psr}}{500\,\text{km/s}}\right)^{-5/3}$$

- **Mach number at crossing**

$$v_{SNR} = \frac{2}{5}\frac{R_{SNR}}{t} = \frac{2}{5}\frac{R_{psr}}{t} = \frac{2}{5} v_{psr}$$

$$v_{sh.ISM} = \frac{3}{4} v_{SNR} \quad \text{for } X = 4 \Rightarrow v_{rel} = v_{psr} - v_{sh.ISM} = \frac{7}{4} v_{SNR}$$

$$p_{th\,sh\,ISM} = \frac{3}{4}\rho_{ISM} v_{SNR}^2 \qquad \rho_{sh.ISM} = 4\rho_{ISM} \Rightarrow M_{psr} = \frac{v_{rel}}{(\gamma p_{sh.ISM} / \rho_{sh.ISM})^{1/2}} = \frac{7}{\sqrt{5}} = 3.13$$

- **pulsar motion becomes supersonic at ½ $t_{cross}$ or 0.68 $R_{SNR}$**
- **PWN confined by the pressure behind the bow shock**

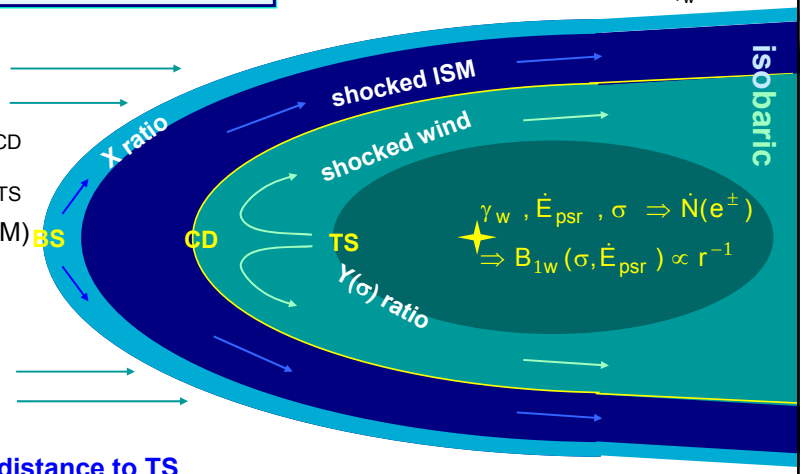
## bow shock PWN

$\sigma \le 0.1 \quad \gamma_w \ge 10^3$

$R_{BS} = \frac{X}{X-1} R_{CD}$

$R_{CD} = \frac{Y}{Y-1} R_{TS}$

$R_{TS}(\sigma, \Gamma_w, ISM)$




- **forward distance to TS**

$$p_{2BS} = \rho_{ISM} v_{psr}^2 = p_{2TS} \approx \left(\tfrac{2}{3} + \tfrac{1}{3}\right) \frac{\dot{E}_w}{4\pi R_{TS}^2 c} \quad \Rightarrow \quad R_{TS} = \left( \frac{\dot{E}_w}{4\pi c \rho_{ISM} v_{psr}^2} \right)^{1/2}$$

- **backward distance to TS**

$$p_{ISM} \approx p_{2TS} \quad \Rightarrow \quad R_{TS} = \left( \frac{\dot{E}_w}{4\pi c p_{ISM}} \right)^{1/2}$$

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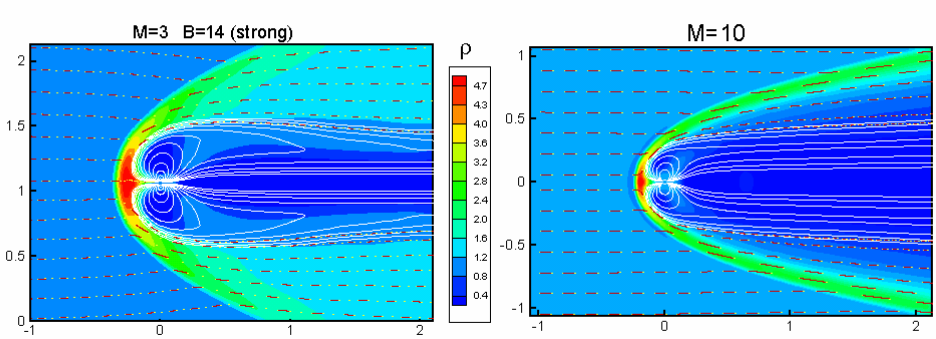
## bow shock PWN

- **analytical profile**
  - cooling thin shell approximation, ok if M >> 1
  - Wilkin '96

$$R_{BS}(\theta) = \frac{R_{BS0}}{\sin\theta} \sqrt{3\left(1 - \frac{\theta}{\mathrm{tg}\theta}\right)}$$

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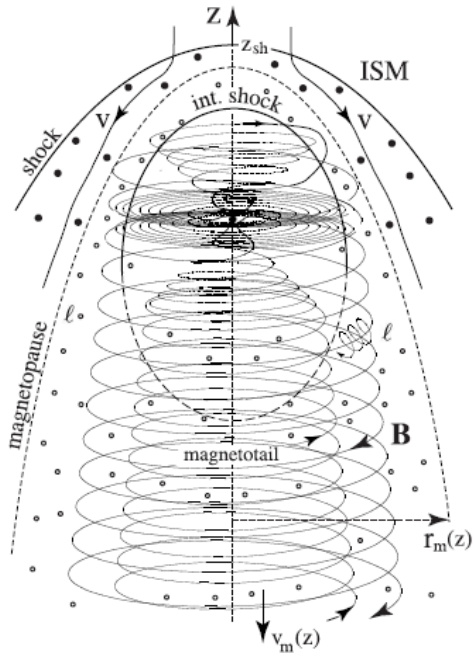
## magnetotail

- **toroidal field and reconnection**

Romanova et al. '05

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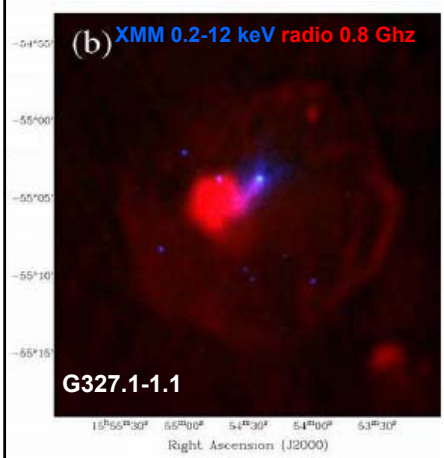
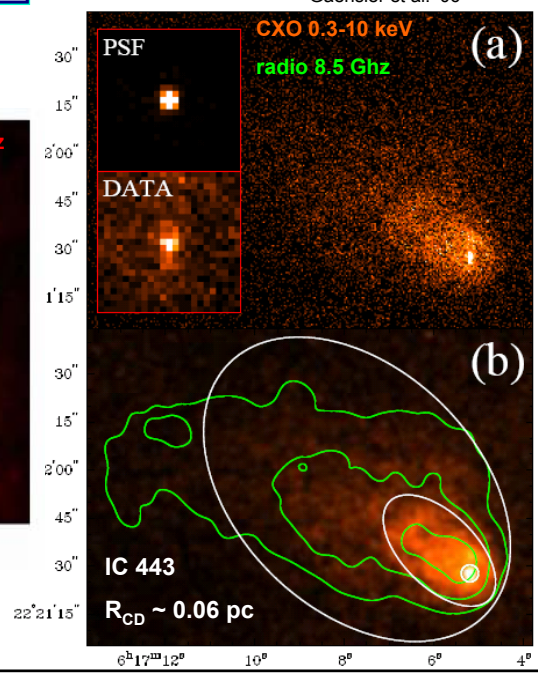
## bow shock PWN in SNR

Gaensler et al. '06




Gaensler & Slane '06

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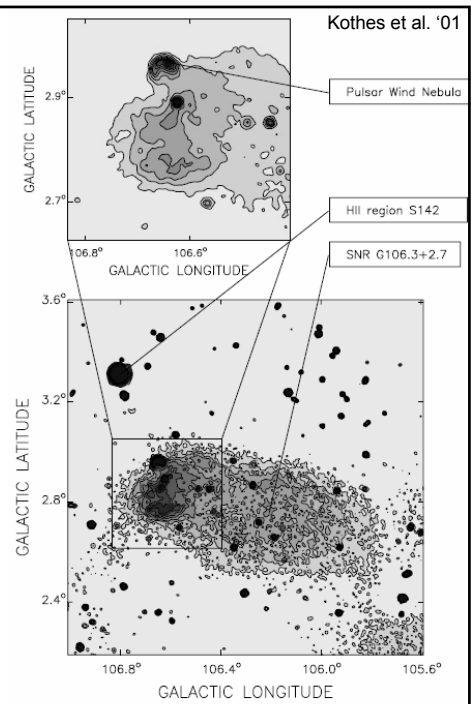
## breaking through the shell

- **PWNe survive the crossing of the SNR shell** van der Swaluw '03
- **ex: the Boomerang G106.3+2.7 + PSR J2229+6114**
  - $\dot{E}$ = 2.25 $10^{30}$ W (2nd to Crab)
  - D = 0.8-3 kpc
  - SNR = 14 × 6 pc at 800 pc
  - PWN 0.8 pc long breaking through?
  - bizarre SNR…

Kothes et al. '01




ξ G106.3+2.7 at 1420 MHz radio continuum. The H II region S142 is indicated, as are the main part of the SNR and



## phase V: bow shock PWN in ISM

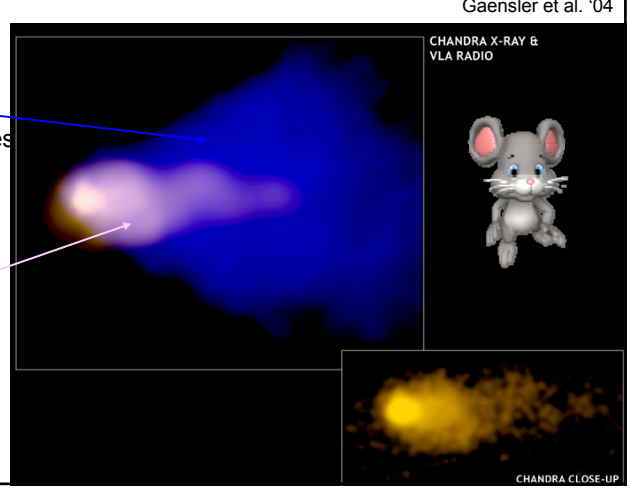
- **M >> 1 in ISM ($c_s$ = 1-10 km/s)**
- **ex: the Mouse**
  - G359.23-0.82 + PSR J1747-2958
  - P = 99 ms, 25.5 kyr, $\dot{E}_{psr}$ = 2.5 $10^{29}$ W, D ~ 5 kpc
  - $R_{CD}$ ~ 0.02 $D_5$ pc

Gaensler et al. '04

radio from highly compressed B behind the front TS (severe losses => only radio emitting e± survive)

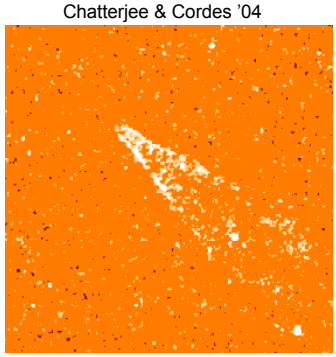
radio + X rays from weakly compressed B behind the rear TS

as in W44

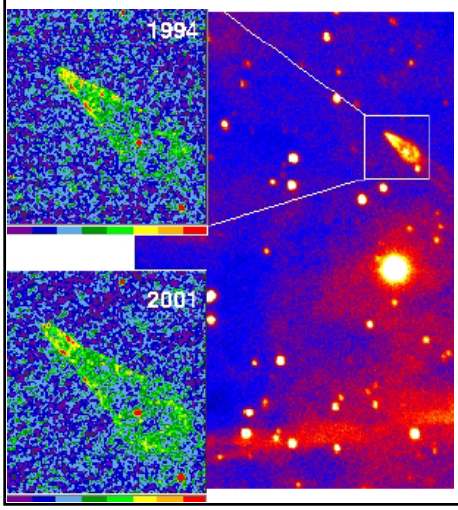


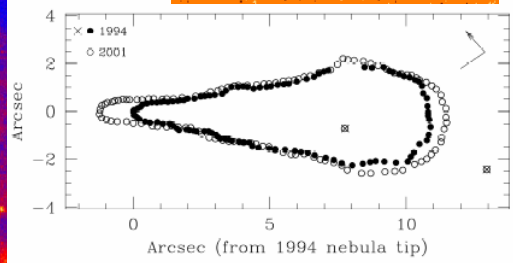
## Guitar PSR 2224+65

Chatterjee & Cordes '04



- the « breathing » PWN
- Hα bow shock from recombining HII
  - photoionized gas and charge exchange
- variability over 7 years, not from the wind



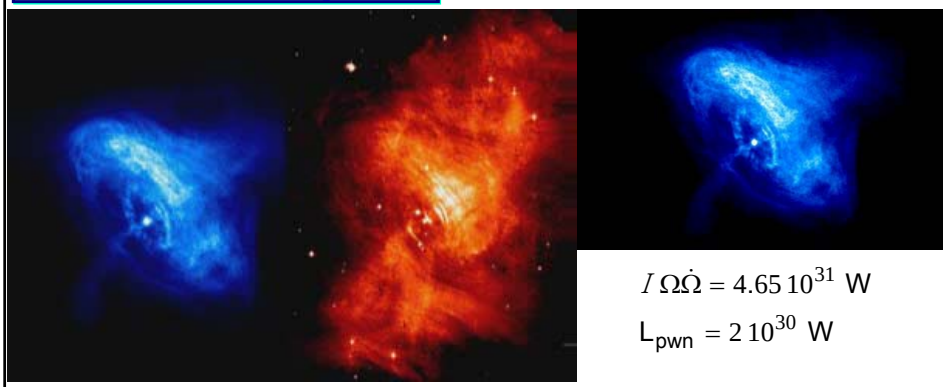




- but loosened confinement (n ↓)
  - ⇒ decreased head flux

## inner wind asymmetries

jets and torii

## Crab torus and jets

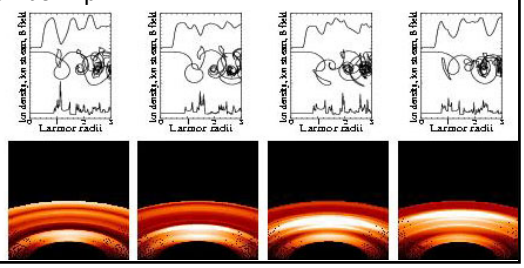


$I\,\Omega\dot{\Omega} = 4.65\,10^{31}$ W

$L_{pwn} = 2\,10^{30}$ W

CXO HST November-April

- **jet 0.25 pc**
- **terminal shock:**
  - $\Delta\Omega \sim 1$ sr => $R_{TS} \sim 0.4$ pc (40'')
  - $\Delta\Omega \sim 4\pi$ sr => $R_{TS} = 0.1$ pc (10'')
  - wisps à 8'' et 12''
- **Doppler amplification & shift**
  - wisp waves travel at 0.5 c

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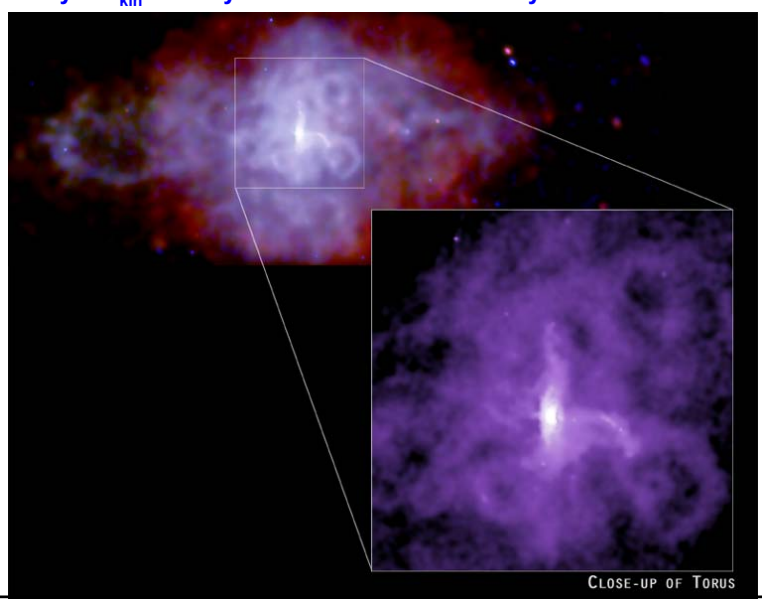
## 3C 58 (SN 1181)

- **65.7 ms**
- **$\tau_{psr}$ = 0.8 kyr ≠ $\tau_{kin}$ = 5.4 kyr**
- **CXO X-ray colours**

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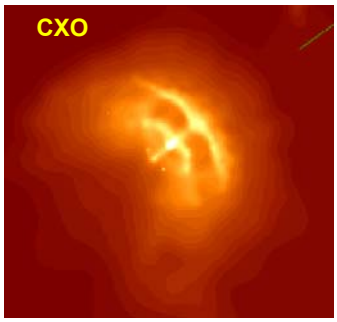
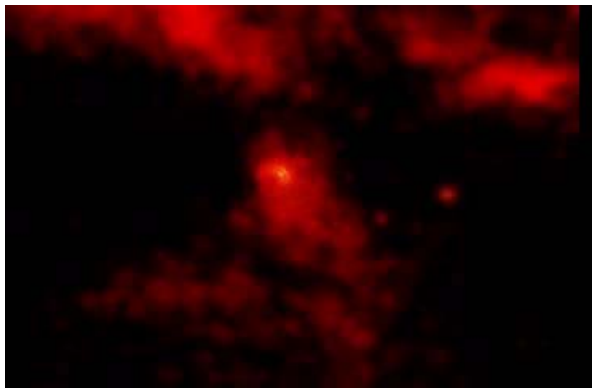
## Vela et PSR 1509-58



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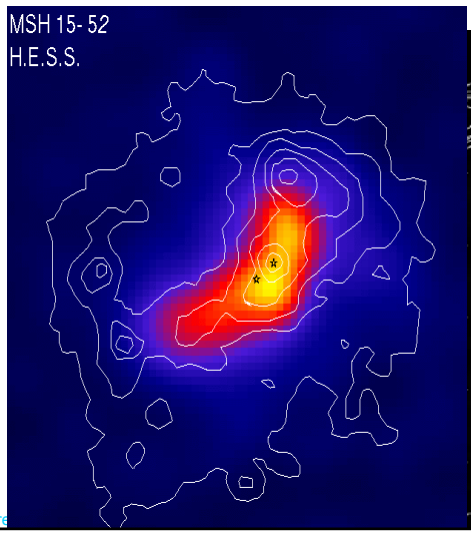
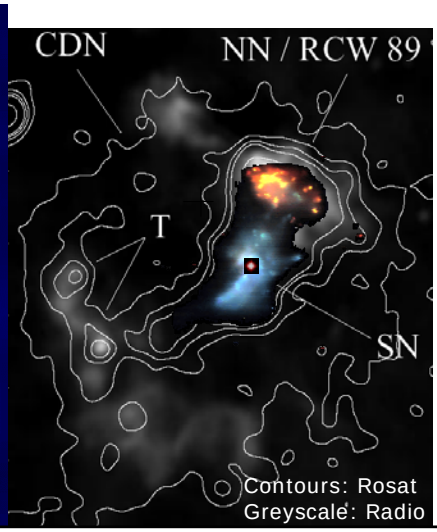
## PSR B1509-58 MSH 15-52

DeLaney '06
Aharonian '05

- 1.7 kyr old pulsar at 5.2 ± 1.4 kpc, $\dot{E}_{psr}$ = 1.8 $10^{30}$ W
- X-ray jets (12 pc, 0.5 c, long-term variability) and variable knots (0.6c)
- 2 TeV arms ± 25 pc long, radiatively more efficient than the Crab

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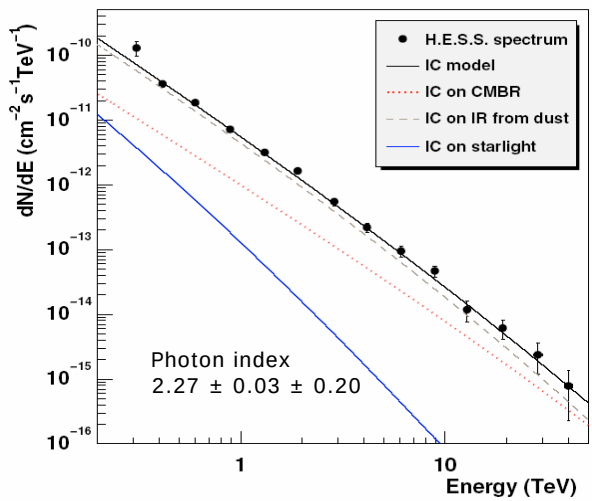
## MSH 15-52

$e^{\pm}_{10-100\mathrm{TeV}} + B(1.7\ \mathrm{nT}) \rightarrow X$

$e^{\pm}_{\mathrm{TeV}} + \mathrm{CMB} + \mathrm{ISRF(IR)} \rightarrow \mathrm{TeV}$

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## high-energy relic tails

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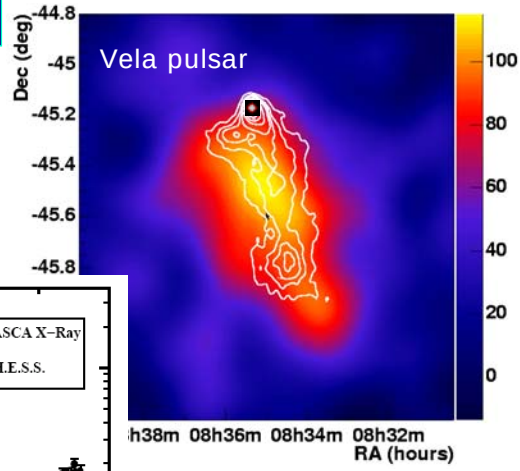
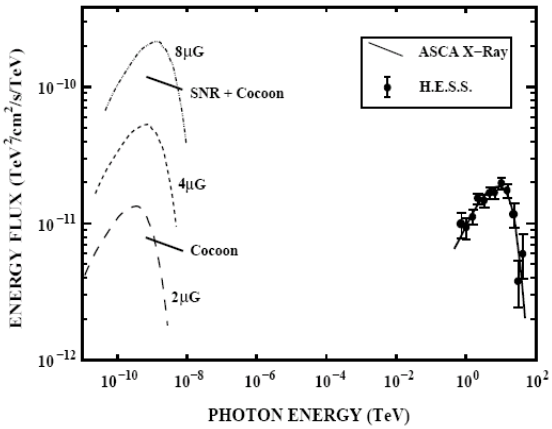
# Vela tail

- ~ 5 pc long tail
- seen up to 50 TeV
  $E^{-1.9}$ ou $E^{-1.5+cutoff}$

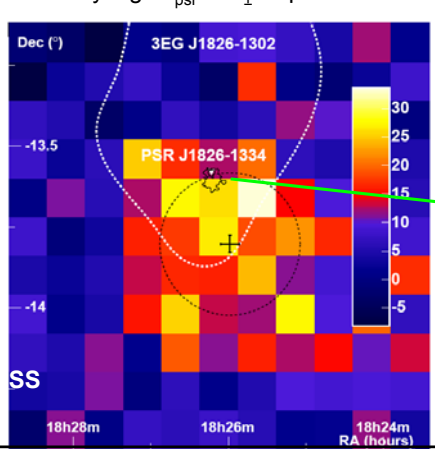


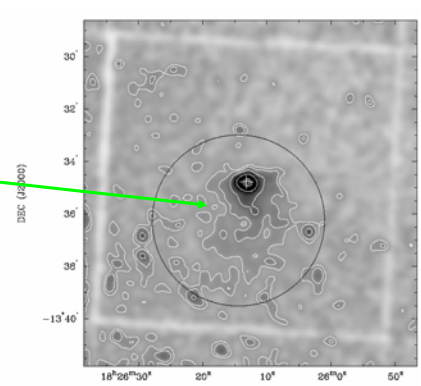




# PSR B1823-13 - G18.0-0.7

- 21.4 kyr old pulsar
  - P = 101 ms, $\dot{E}_{psr}$ = 2.8 $10^{29}$ W, D = 3.9 ± 0.4 kpc
- TeV tail $L_{TeV}$ ~ 50 pc: $e^{\pm}$(TeV) + CMB-IR → γ(≥ 200 GeV)
- X-ray tail $L_X$ ~ 5 pc: $e^{\pm}$(200 TeV) + $B_{equip}$(1 nT) → X
  - $L_{TeV}/L_X$ ok in uniform B
  - but very high $v_{psr}$ or $v_{\pm}$ required

$$\frac{L_{TeV}}{L_X} < \frac{\tau_{syn}(E_{eTeV})}{\tau_{syn}(E_{eX})} = \frac{E_{eX}}{E_{eTeV}} \approx 200 \quad \text{ok}$$




Aharonian et al. '05 Gaensler et al. '03

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# The wings of Geminga

$\dot{E}_{psr} = 3.3\,10^{27}$ W, $\tau = 340$ kyr, $D = 160$ pc

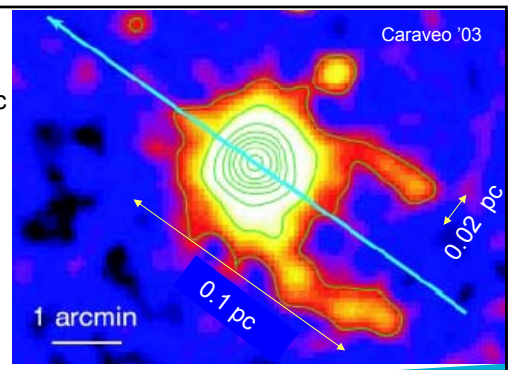
$i \leq 30°$ to the sky plane

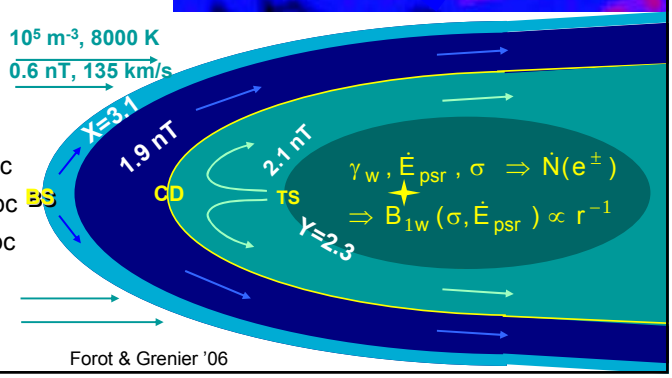
$L_{0.1-2GeV,1sr} = 1.6\,10^{-2}\dot{E}_{psr}$

$L_{0.3-5keV} = 1.9\,10^{-6}\dot{E}_{psr}$

$\nu F_{\nu X} = 2.6\,E_{eV}^{+0.4\pm0.2}$ eV m$^{-2}$s$^{-1}$

$E_{eX} \approx 100$ TeV




$R_{TS} = 0.01$ pc

$R_{CD} = 0.02$ pc

$R_{BS} = 0.03$ pc

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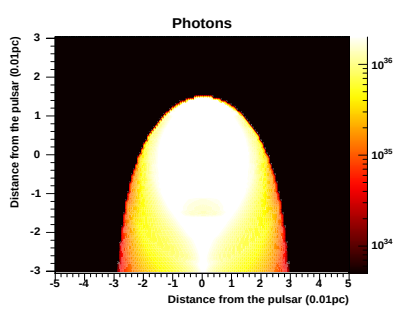
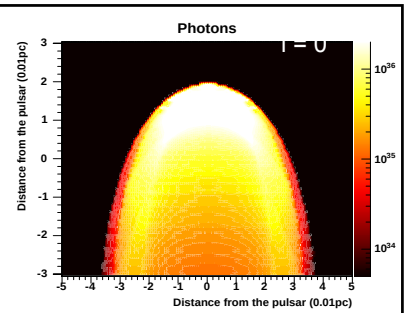
Forot & Grenier '06

# The wings of Geminga

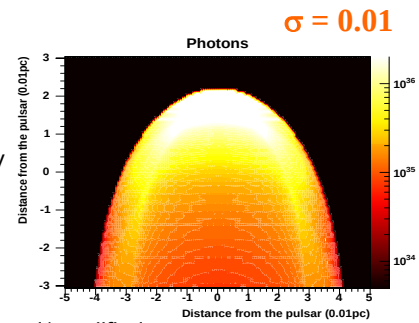



$\sigma = 1$

$\sigma = 0.1$

$\sigma = 0.01$




- **XMM image => $\sigma << 1$**
- **acceleration site?**
  - Fermi at BS:

$E^{-\frac{X+2}{X-1}} \approx$ ok but $\frac{D_{1Bohm}}{u_{1ISM}} \leq R_{BS} - R_{CD} \Rightarrow E_{max} < 30$ GeV

  - Fermi at TS $E^{-2.2}$ ok but $E_{max} < 35$ TeV
  - $E_{max} = e\,\Delta\Phi_{open} = 400$ TeV
- **emissivity problem**

$\dot{N}_{\pm}(\dot{E}_{psr}, \sigma) \Rightarrow L_X << L_{Xobs}$ unless B compressed/amplified

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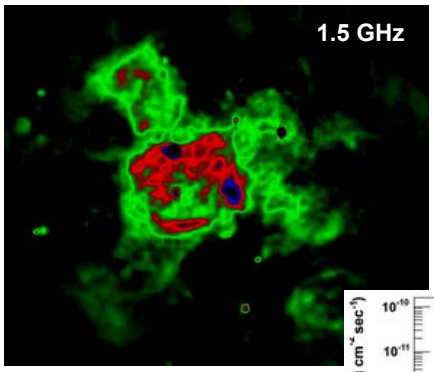
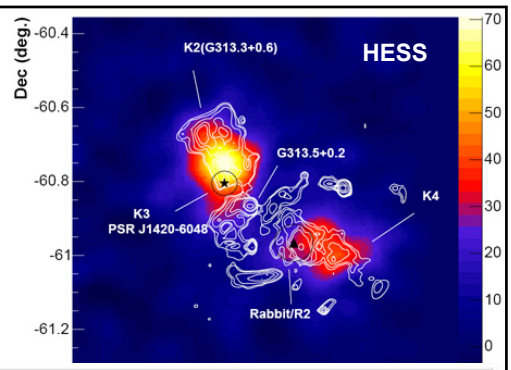
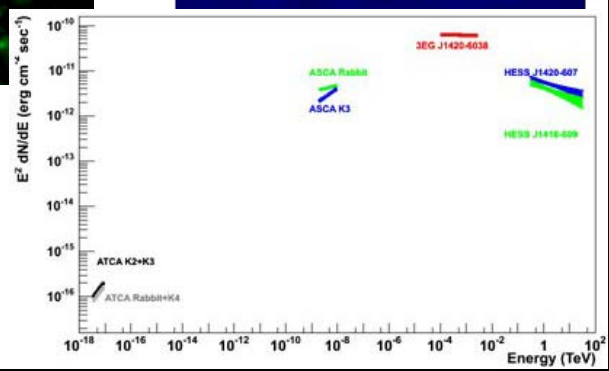
# Kookaburra and Rabbit



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