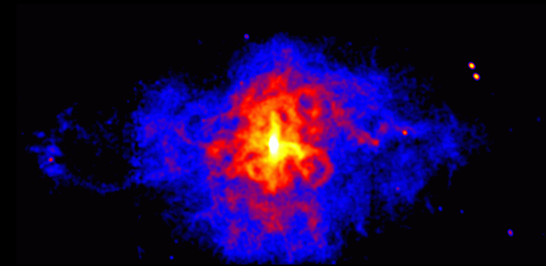
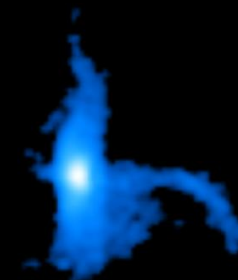
Pulsar Winds and Jets

Pat Slane (Harvard-Smithsonian Center for Astrophysics)

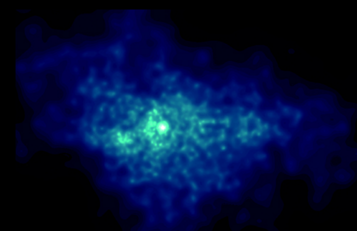
Outline



- Pulsar Winds and Their Nebulae

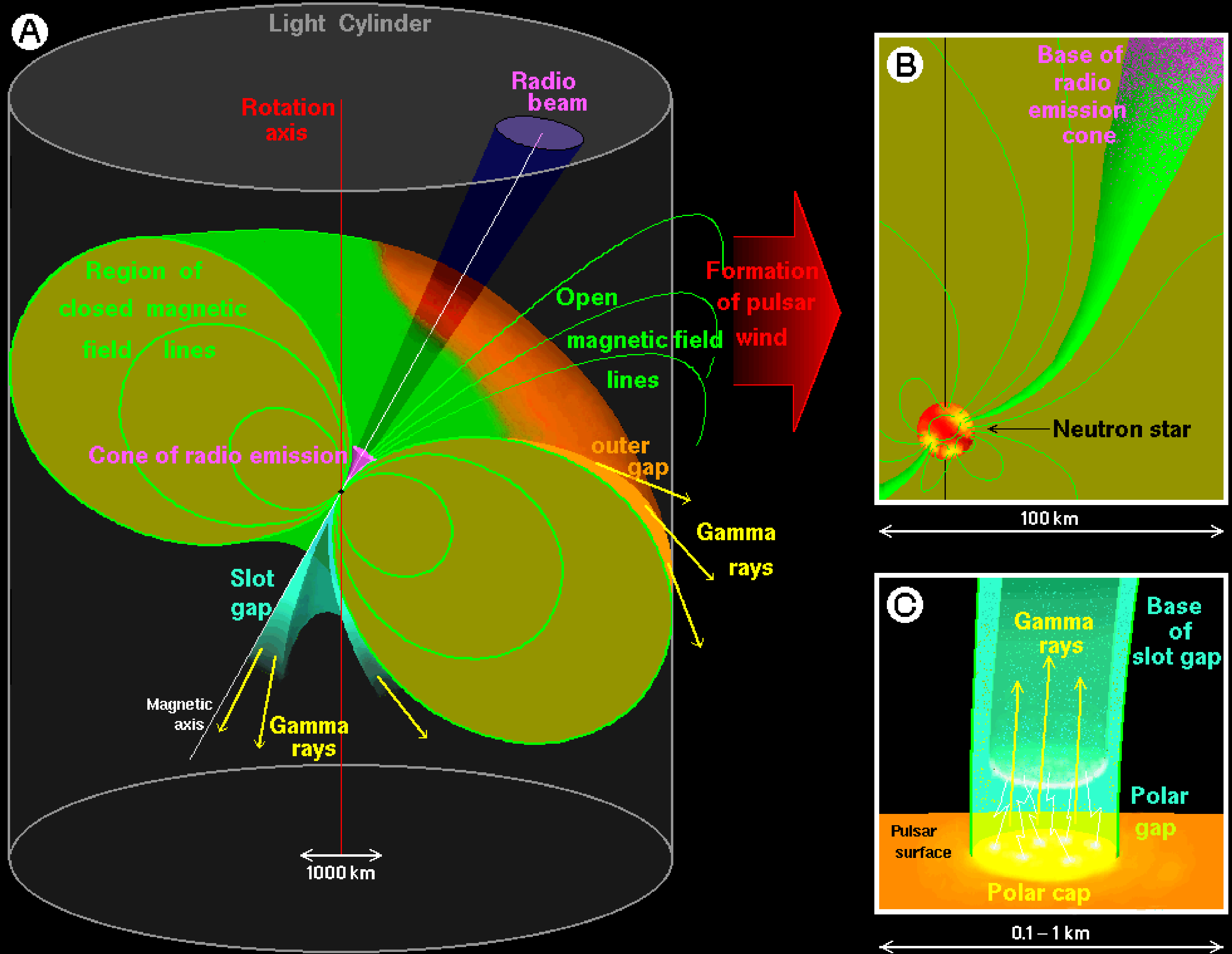


- Jet/Torus Structure in PWNe



- Observations of Pulsar Jets
  - Jet sizes and luminosities
  - Curved jets and instabilities
  - Jet/counterjet asymmetries: Doppler beaming

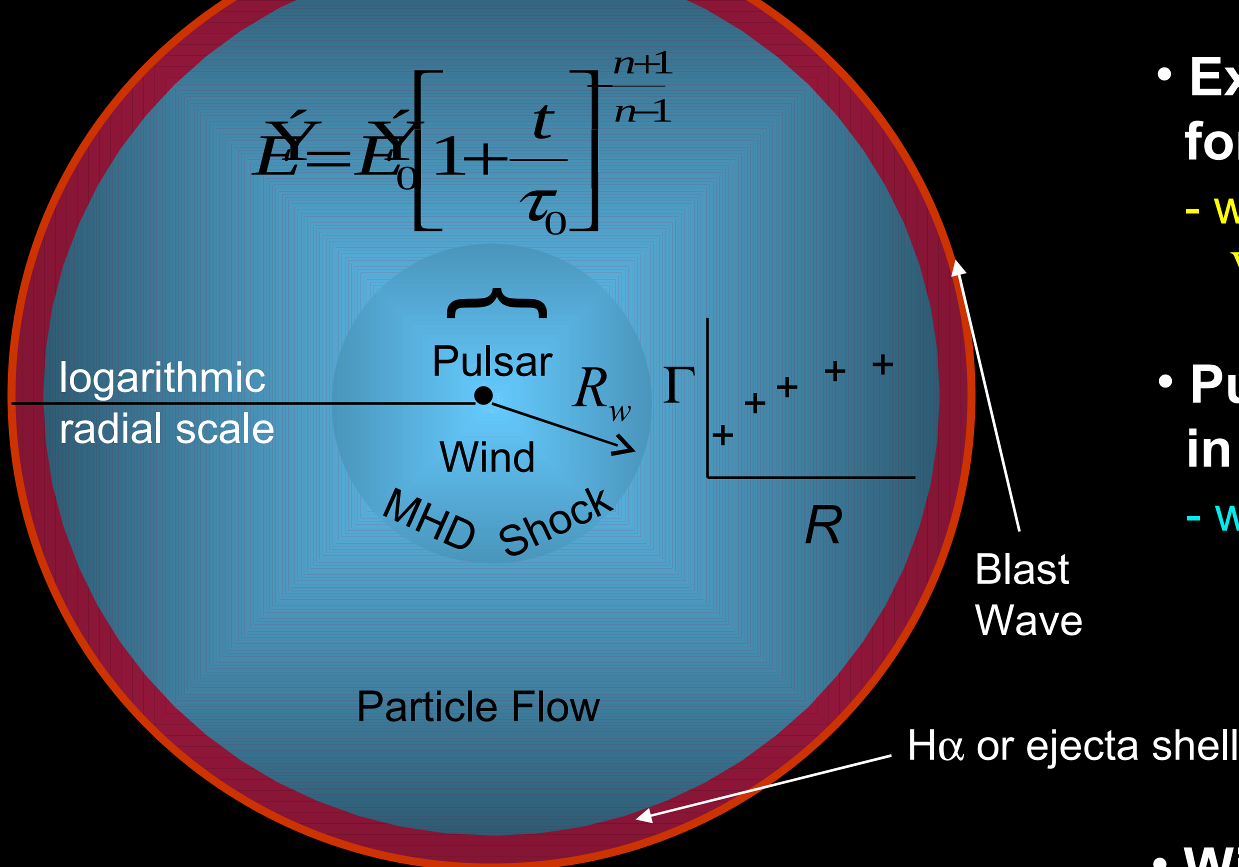
- Geometry from jets: spin-kick alignment



Dany Page

http://www.astroscu.unam.mx/neutrones/home.html

Pulsar Wind Nebulae



- **Expansion boundary condition at forces wind termination shock at**
  - wind goes from $v \approx c/\sqrt{3}$ inside to $v \approx R_N / t$ at outer boundary

- **Pulsar wind is confined by pressure in nebula**
  - wind termination shock

$$R_w = \left[\frac{\dot{E}}{4\pi c P_N} \right]^{1/2}$$

obtain by integrating radio spectrum

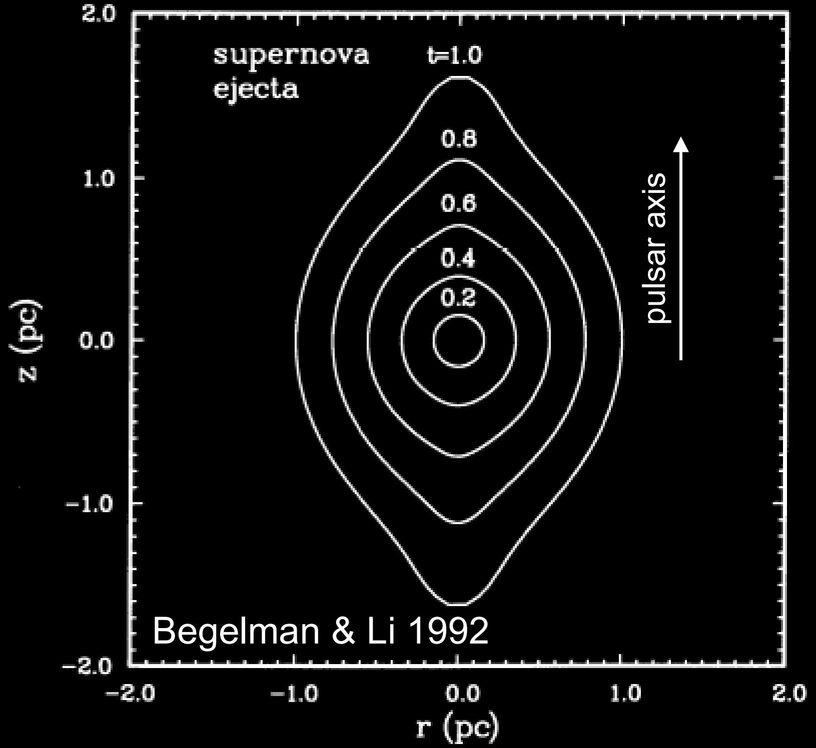
- **Wind is described by magnetization parameter**

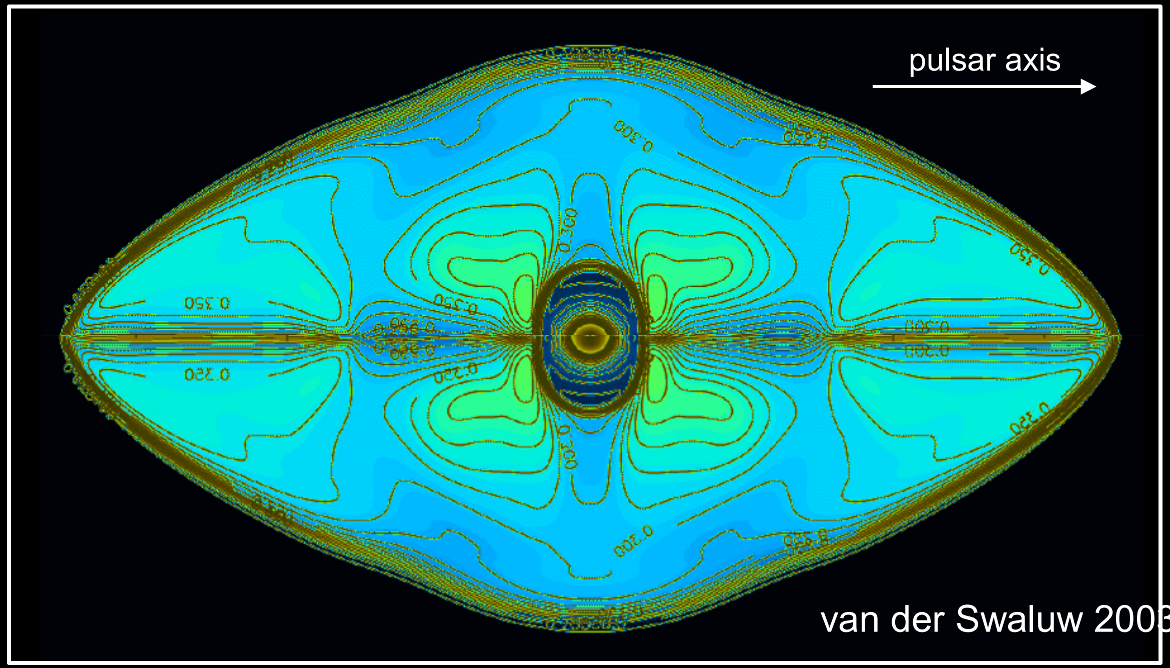
  σ = ratio of Poynting flux to particle flux in wind

$$\sigma \equiv \frac{F_{E\times B}}{F_{particle}} = \frac{B^2}{4\pi\rho\gamma c^2}$$

- **Pulsar accelerates particle wind**
  - wind inflates bubble of particles and magnetic flux
  - particle flow in B-field creates synchrotron nebula
  - spectral break at $\nu_{br} \approx 10^{21} B_{\mu G}^{-3} t_3^{-2}$ Hz where synchrotron lifetime of particles equals SNR age
  - radial spectral variation from burn-off of high energy particles

Elongated Structure of PWNe





- **Dynamical effects of toroidal field result in elongation of nebula along pulsar spin axis**
  - profile similar for expansion into ISM, progenitor wind, or ejecta profiles
  - details of structure and radio vs. X-ray depend on injection geometry and B
- **MHD simulations show B field variations in interior**
  - turbulent flow and cooling could result in additional structure in emission

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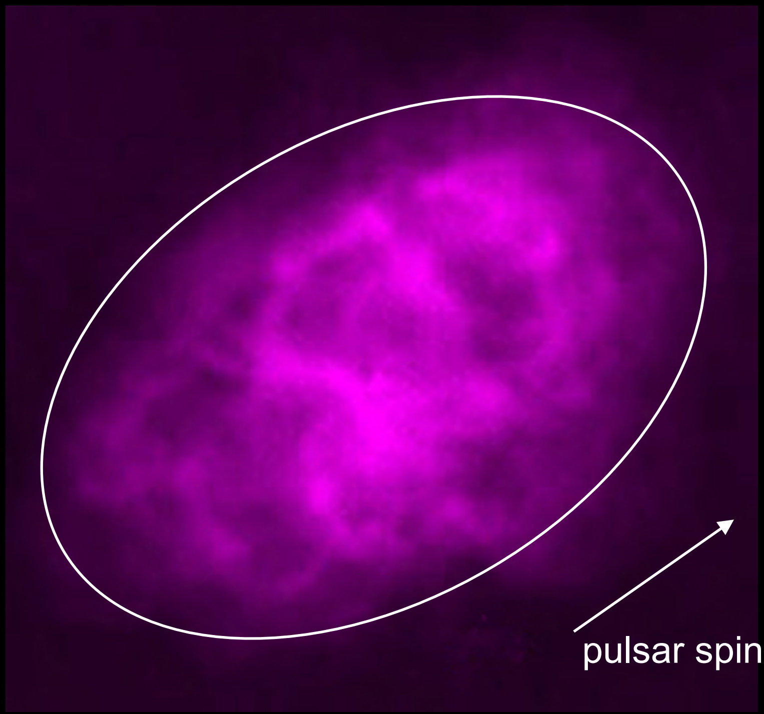
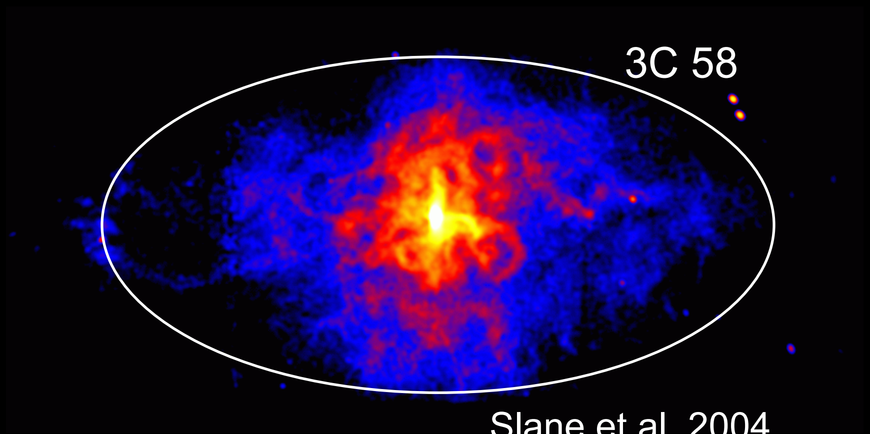
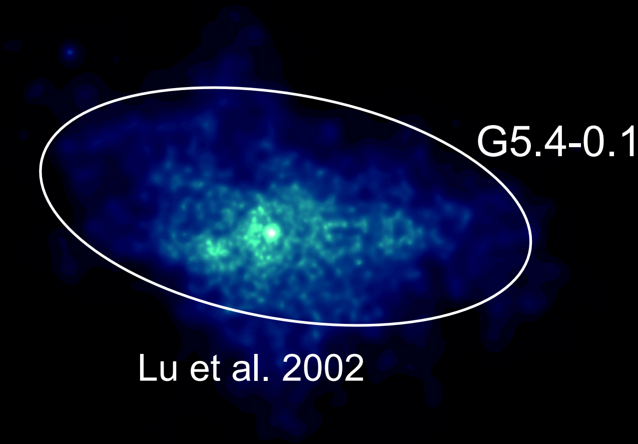
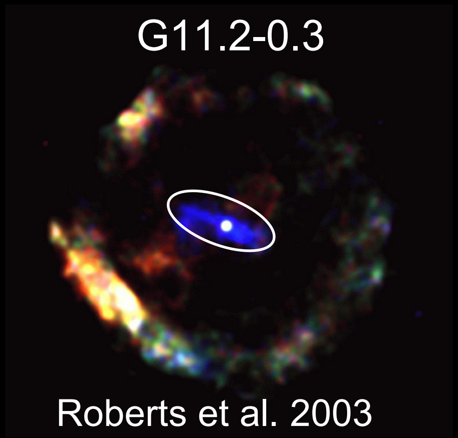


Crab Nebula



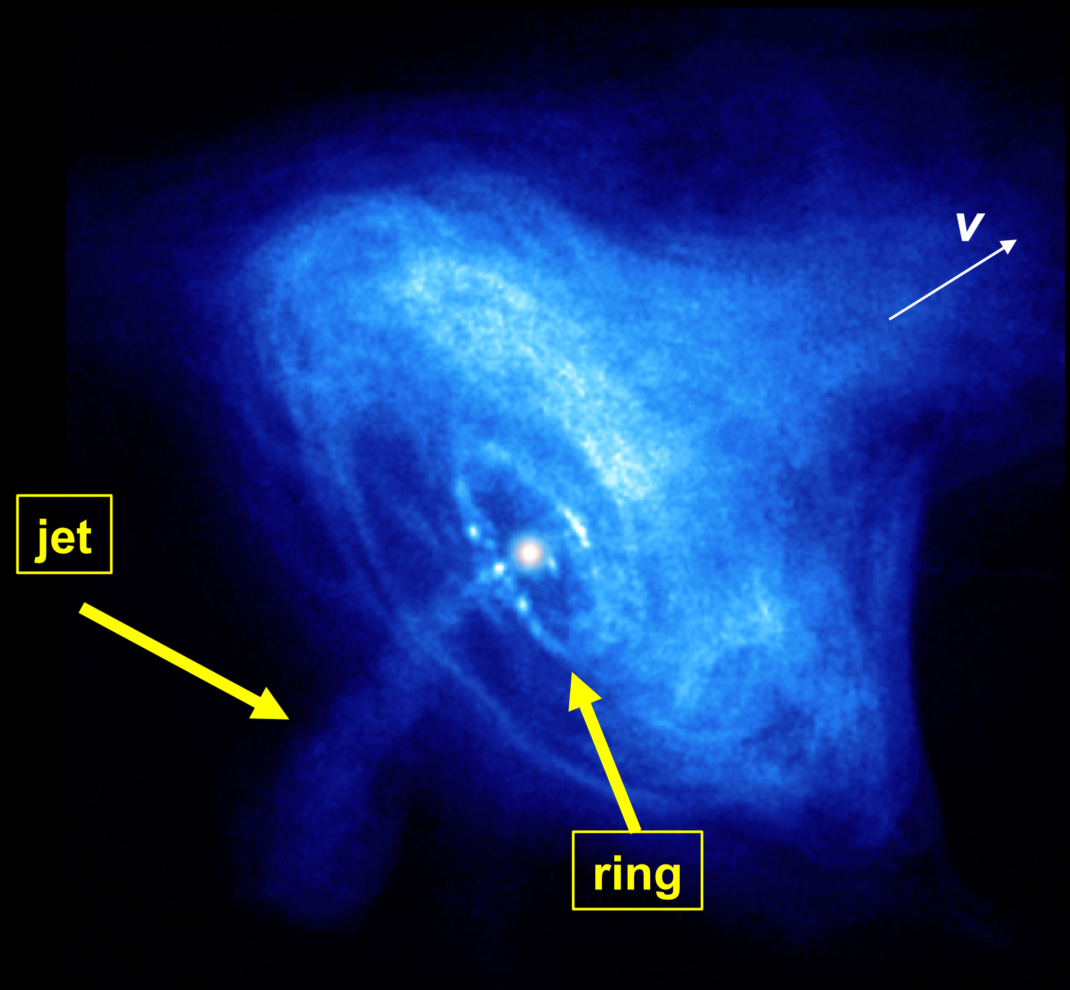




The Crab Nebula in X-rays

Just like the cartoon! Except for all the details…

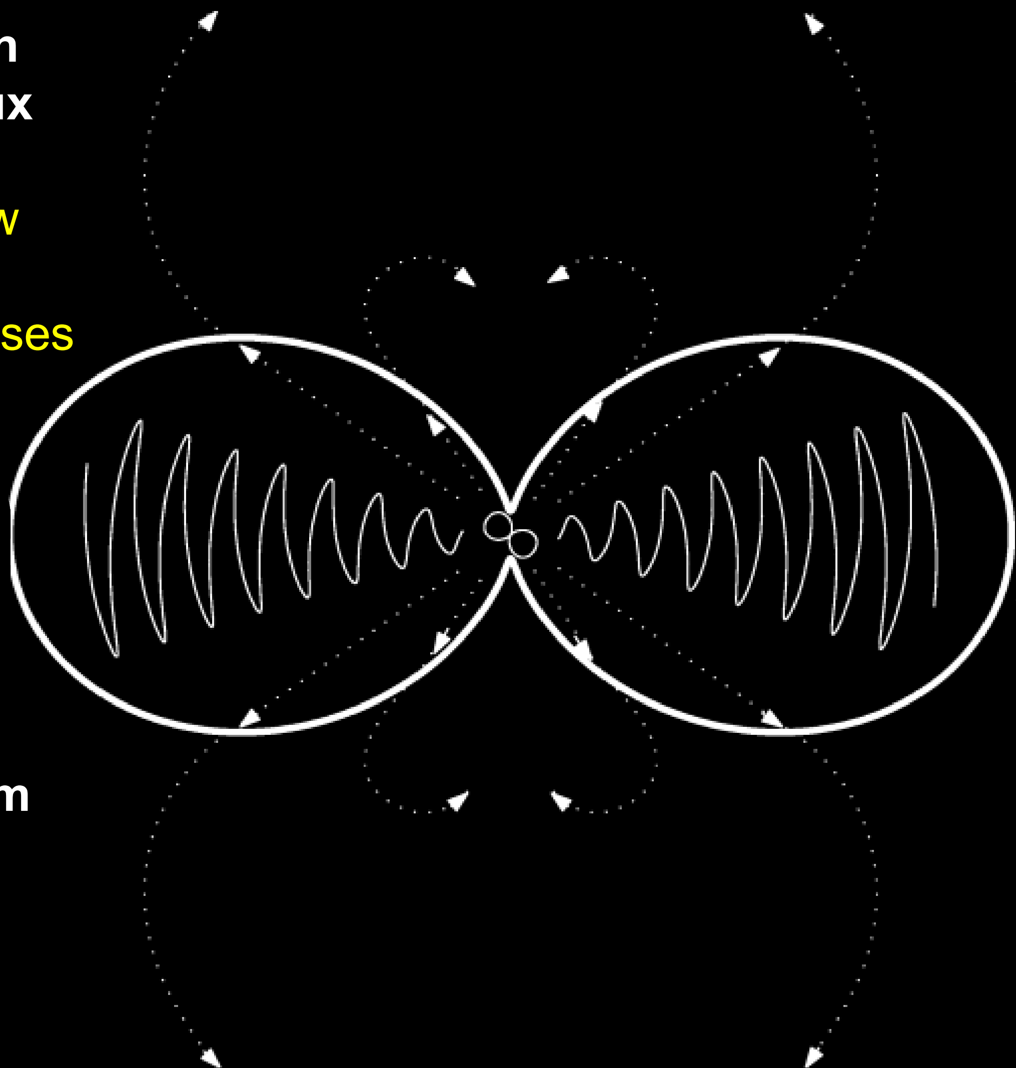
- **Emission is dominated by a bright toroidal structure**
  - equatorial-dominated outflow
- **Inner ring of x-ray emission associated with shock wave produced by matter rushing away from neutron star**
  - corresponds well with optical wisps delineating termination shock boundary
- **Curved X-ray jet appears to extend all the way to the neutron star**
  - faint counterjet also seen
  - jet axis ~aligned with pulsar proper motion, as with Vela Pulsar (more on that later…)



Jet/Torus Structure in PWNe

- **Anisotropic flux with maximum energy flux in equatorial zone**
  - radial particle outflow
  - striped wind from Poynting flux decreases away from equator

- **Wind termination shock is farther from pulsar at equator than along axis**

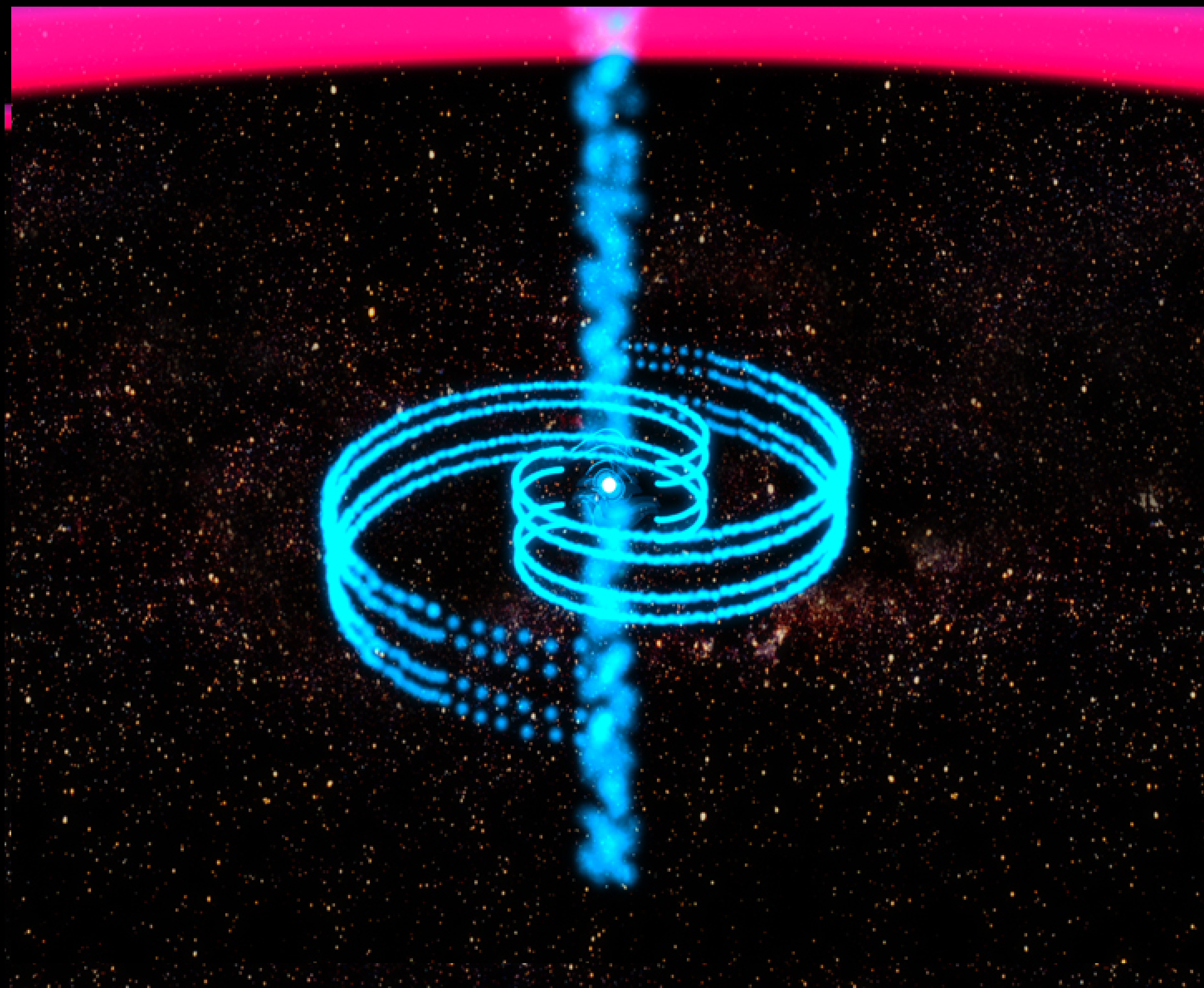


Lyubarsky 2002

- **Magnetization σ is low in equatorial region due to dissipation in striped wind (reconnection?)**
  - no collimation along equator; an equatorial disk (i.e. torus) forms

- **At higher latitudes, average B field is a maximum**
  - this can turn the flow inward at high latitudes, collimating flow and forming a jet beyond TS, where flow is mildly (or non-) relativistic

The Pulsar Wind Zone



- **Rotating magnetosphere generates E X B wind**
  - direct particle acceleration as well, yielding $\approx 10^{-4}\,\dot{E}$ (e.g. Michel 1969; Cheng, Ho, & Ruderman 1986)
- **Magnetic polarity in wind alternates spatially**
  - magnetically “striped” wind
  - does reconnection result in conversion to kinetic energy? (e.g. Coroniti 1990, Michel 1994, Lyubarsky 2002)

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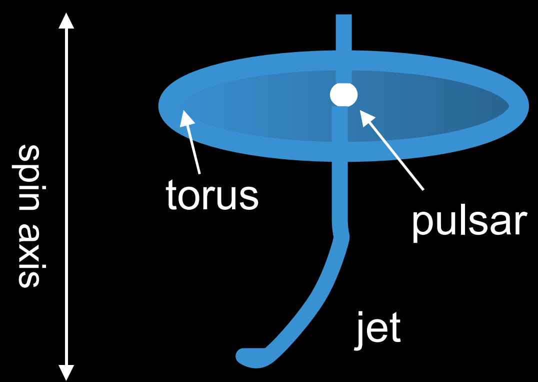
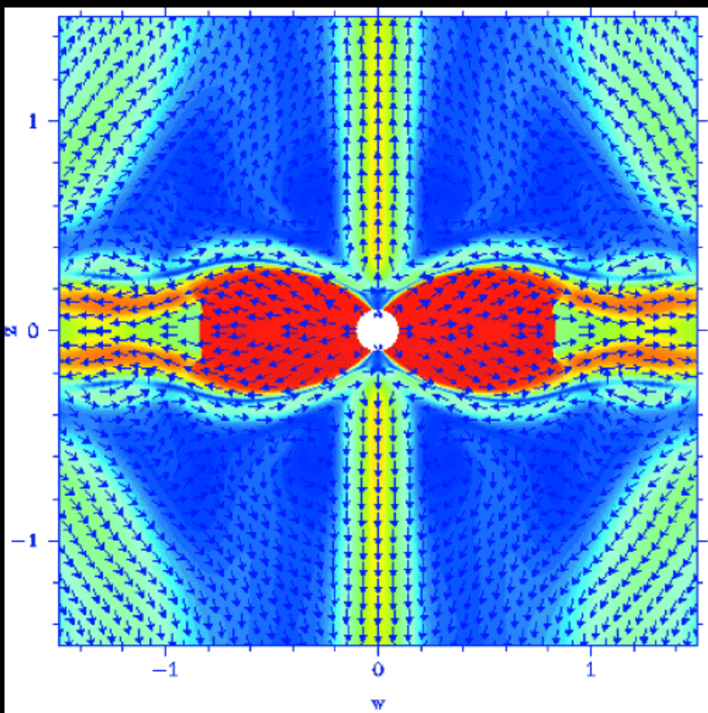
- **Wind expands until ram pressure is balanced by surrounding nebula**
  - flow in outer nebula restricts inner wind flow, forming pulsar wind termination shock

PWN Jet/Torus Structure



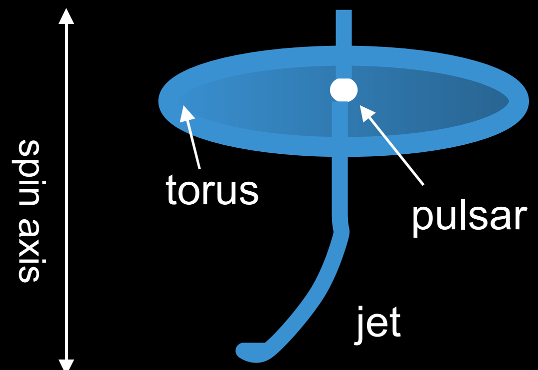


Komissarov & Lyubarsky 2003

- Poynting flux from outside pulsar light cylinder is concentrated in equatorial region due to wound-up B-field
  - termination shock radius decreases with increasing angle from equator (Lyubarsky 2002)

- For sufficiently high latitudes, magnetic stresses can divert particle flow back inward
  - collimation into jets may occur
  - asymmetric brightness profile from Doppler beaming

- Collimation is subject to kink instabilities
  - magnetic loops can be torn off near TS and expand into PWN (Begelman 1998)
  - many pulsar jets are kinked or unstable, supporting this picture



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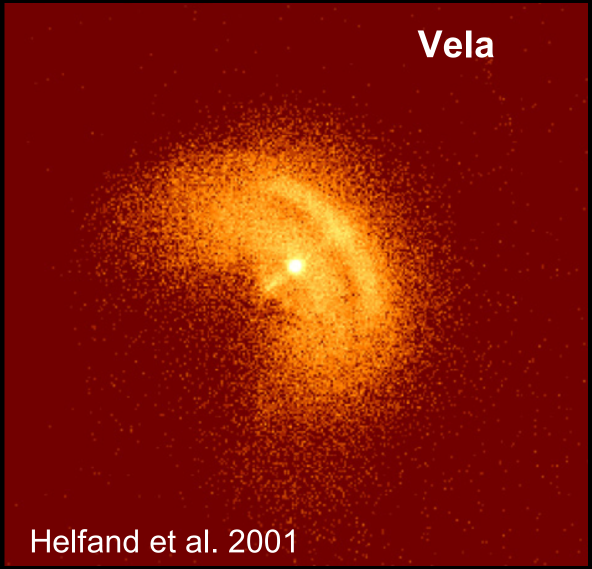
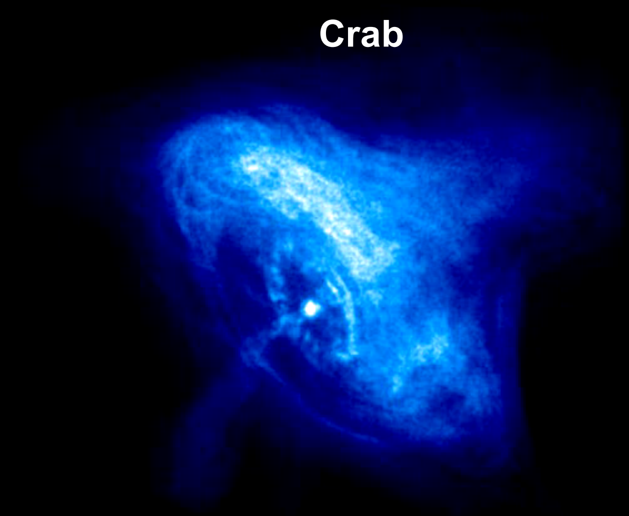
Del Zanna et al. 2006

See poster 53: "Simulated Synchrotron Emission from Pulsar Wind Nebulae (D. Volpi)

PWNe with Anisotropic Axisymmetric Winds

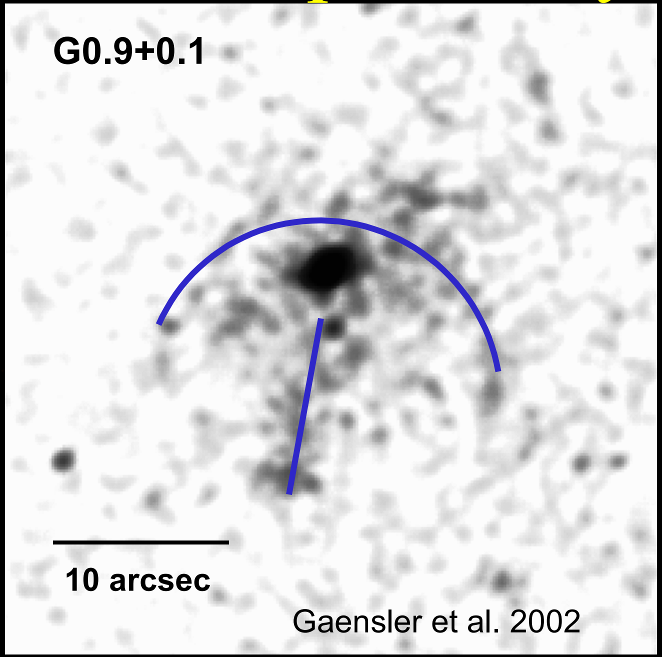




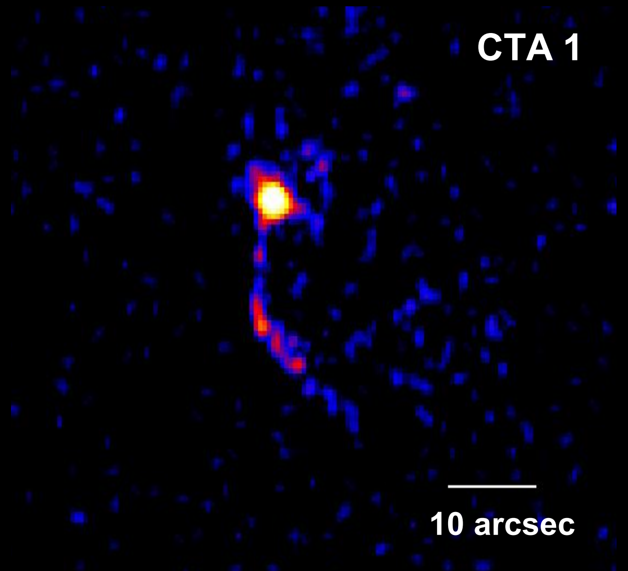
- **Optical and X-ray studies of Crab have long indicated axisymmetric structure.**
  - Chandra and HST observations confirm inner ring, torus, jet, and counter-jet
- **High resolution X-ray image of Vela Pulsar also reveals jets and arc-like features**
  - For both Crab and Vela, jet is ~along direction of proper motion; geometry related to kicks?
- **PWN associated with PSR 1509-58 shows complex outflows and arcs**
  - All suggest equatorial flows and jets from axisymmetric winds

PWNe with Anisotropic Axisymmetric Winds

Gotthelf & Wang 2000



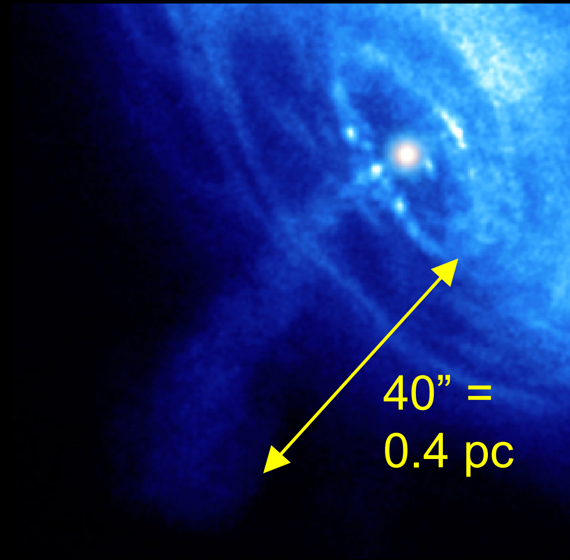
Gaensler et al. 2002



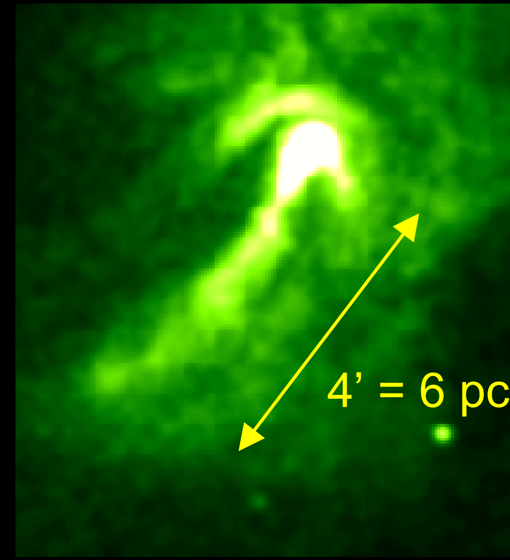
- **The closer we look…**
  - SNR 0540-69 shows a Crab-like nebula surrounding the 60 ms pulsar
  - G0.9+0.1 shows a faint point source (pulsar?), a jet axis with arcs, and bright extended feature that seems to break the symmetry
  - CTA 1 shows extended source and jet; no pulsations (yet), but we now know it's a pulsar…
- **These axisymmetric structures are now the rule. What are they telling us?**

Jet Sizes and Luminosities

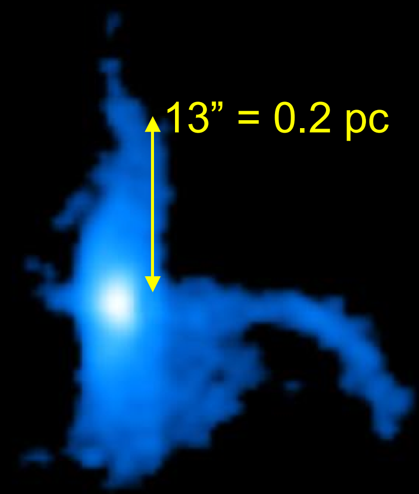
- **Jets are observed for ~8-12 young pulsars**
  - the more we look the more we find, though evidence is weak for some
- **Sizes vary from <0.1 pc (CTA 1) to >10 pc (PSR B1509-58)**
  - no strong connection with Edot
- **Jet luminosity ranges from**
- **Typical photon index $\Gamma \sim 1.5 - 2$**
  - generally, uncooled synch. spectrum
- **Where known, outflow velocities are subsonic**



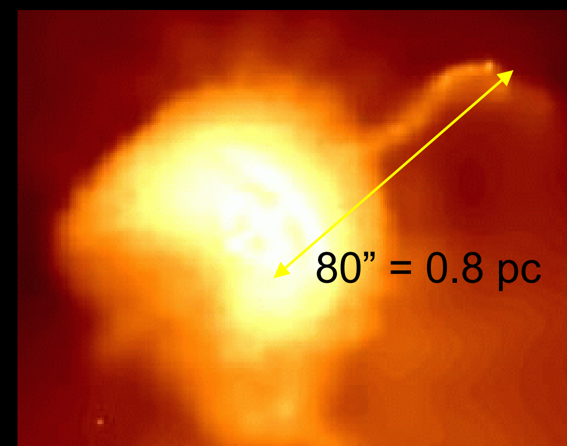
Crab Nebula (Weisskopf et al 2000)



PSR B1509-58 (Gaensler et al 2002)



3C 58 (Slane et al. 2004)



Vela Pulsar (Pavlov et al. 2003)

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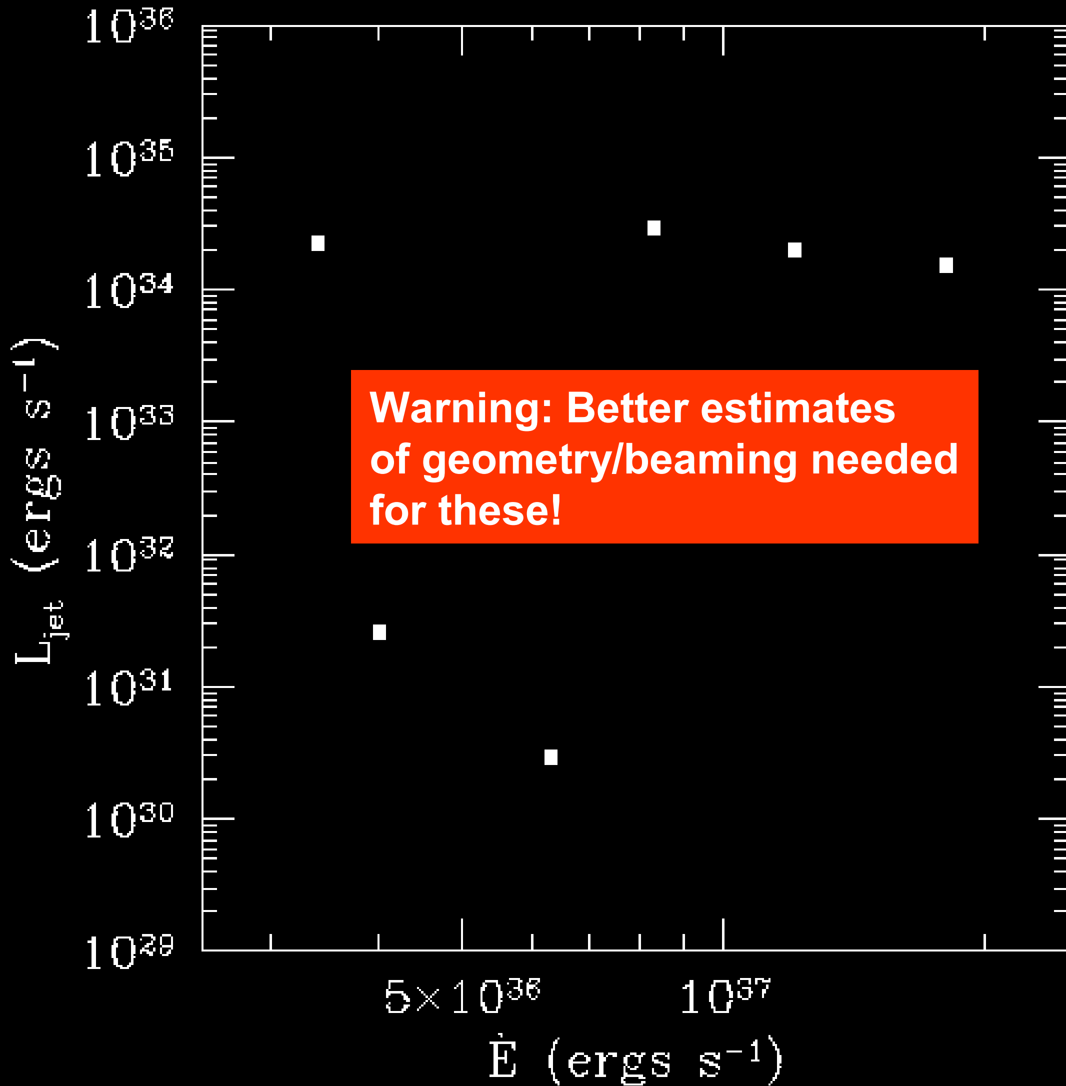
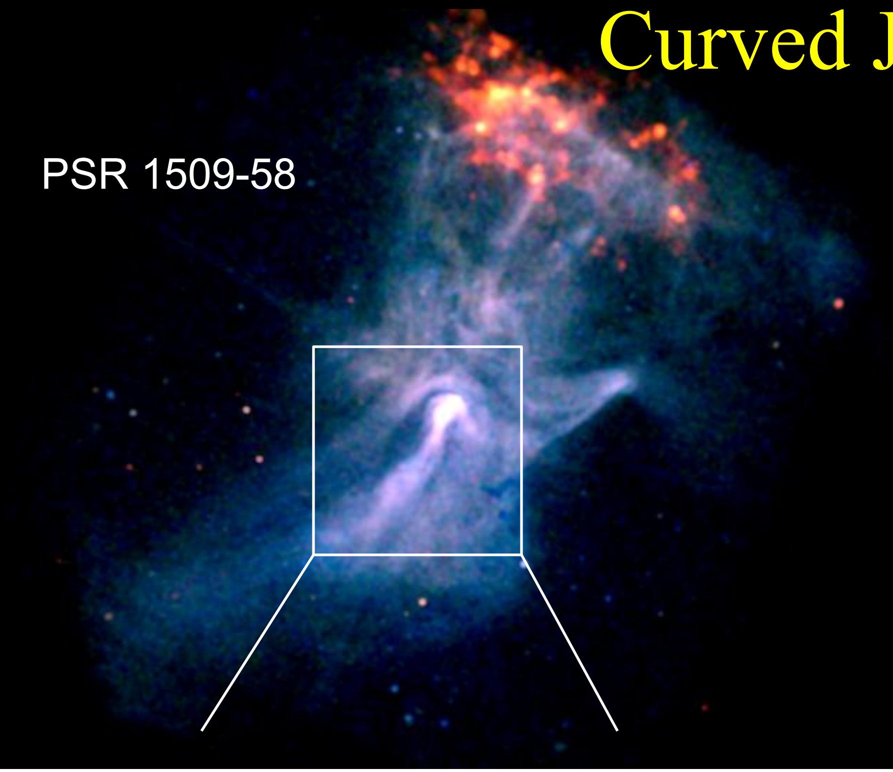
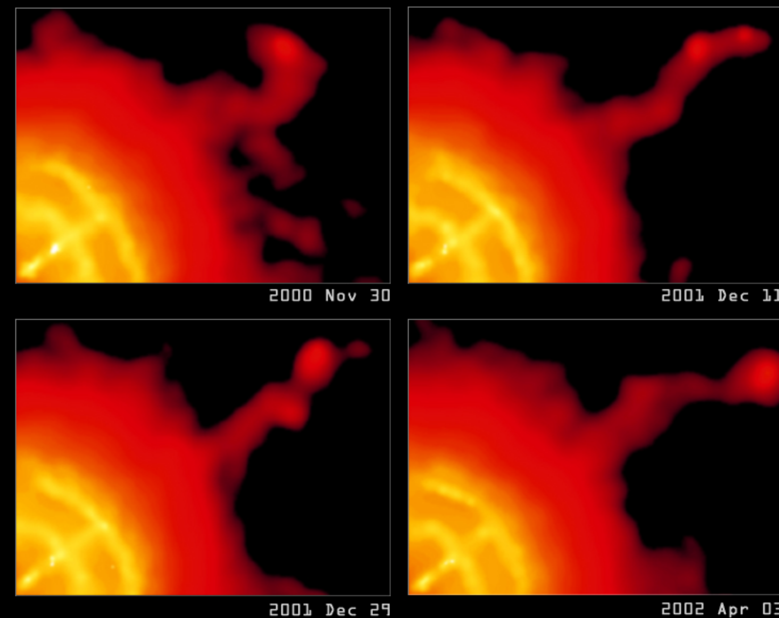


Curved Jets and Instabilities





Pavlov et al. 2003

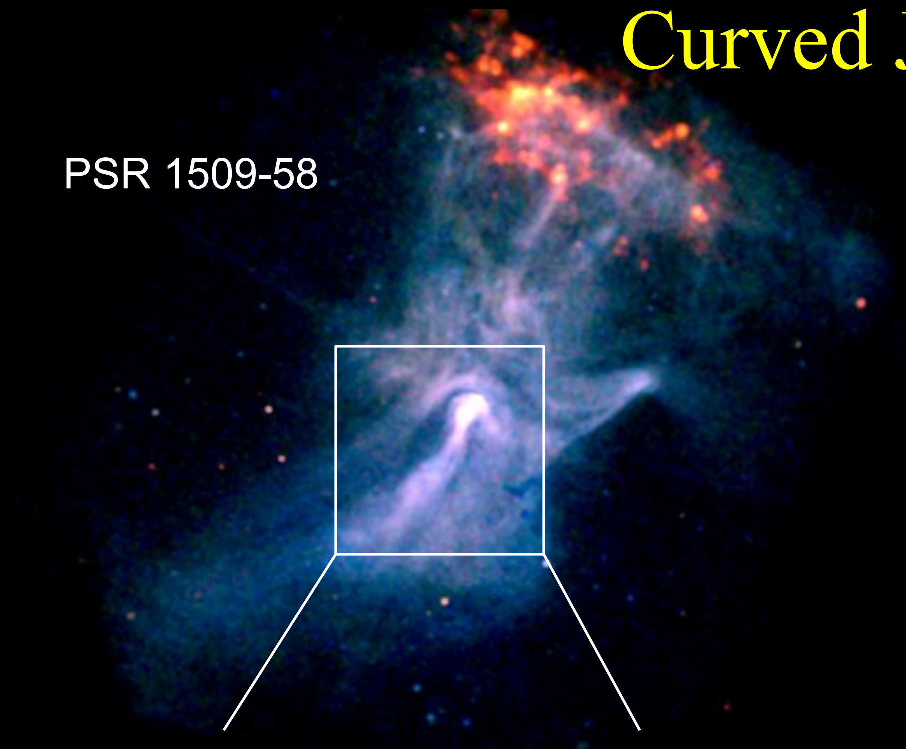
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

DeLaney et al. 2006

- **Jet in PSR 1509-58 is curved, much like in Crab**
  - variations in structure seen on timescale of several months (v ~ 0.5c)

- **Jet in Vela is wildly unstable, showing variations on timescales of weeks to months**
  - changes in morphology suggest kink or sausage instabilities

Curved Jets and Instabilities



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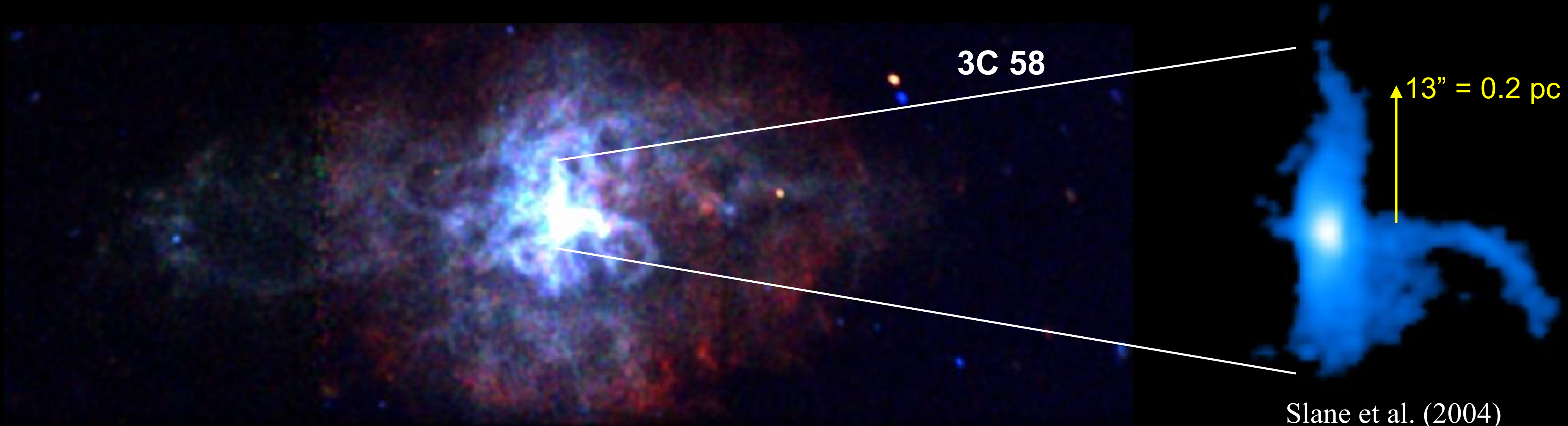
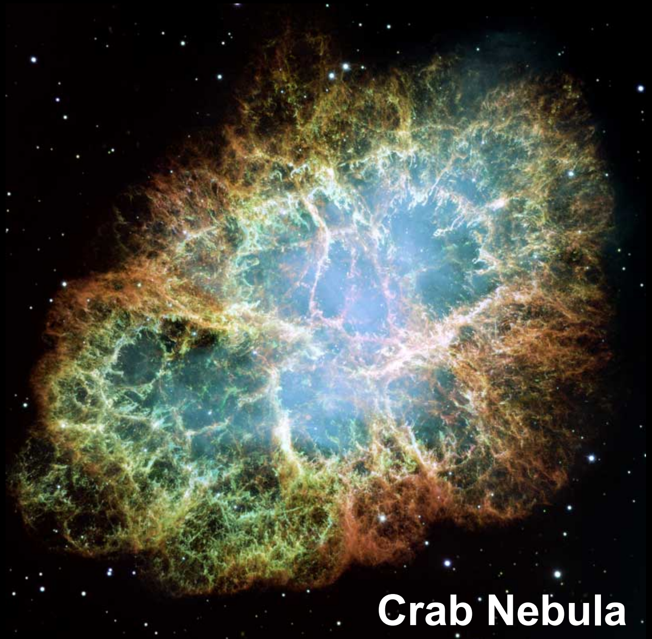
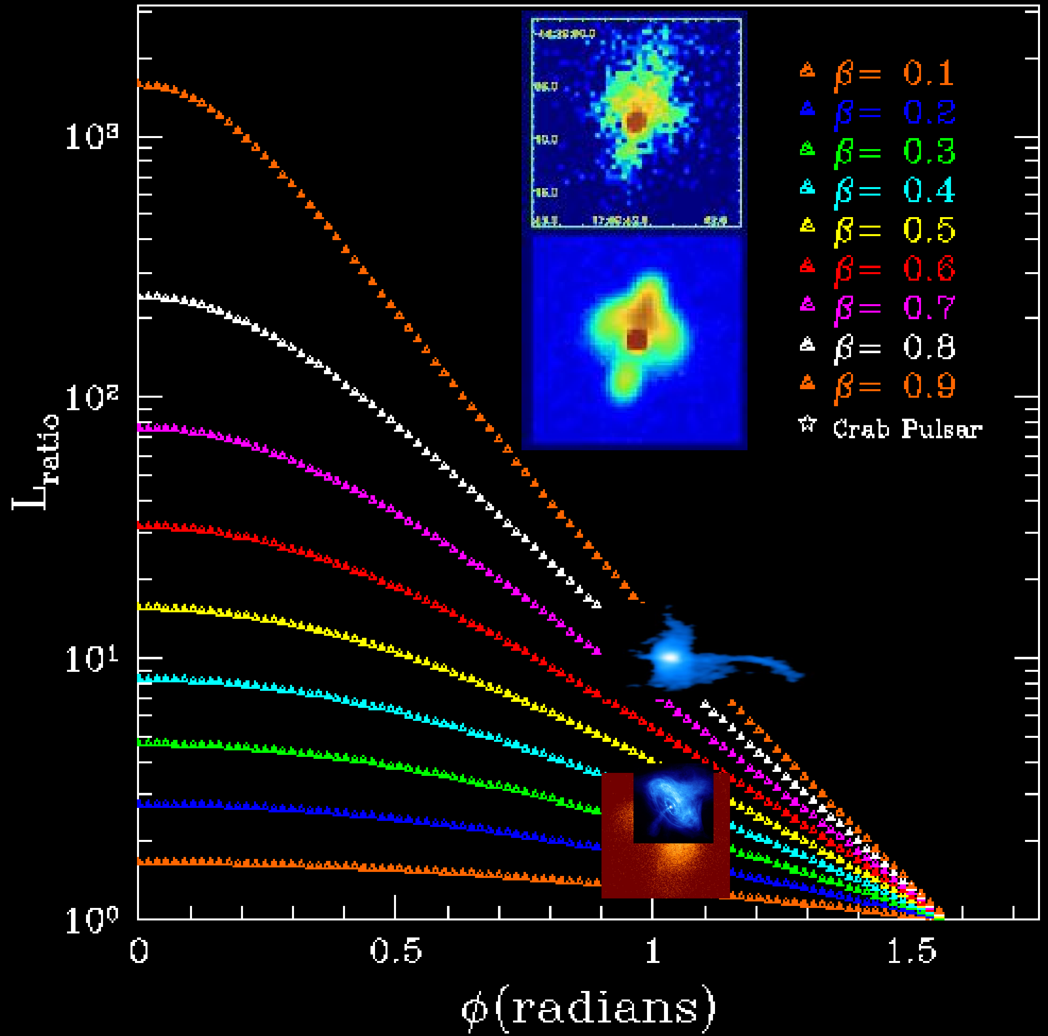


Slane et al. (2004)

- **Pulsar in 3C 58 has curved jet-like structure**
  - jet is opposite bright torus edge; faint counterjet seen
- **Nebula shows complex of loop-like filaments, apparently originating near pulsar**
  - particularly evident in higher energy X-rays; not seen in optical
- **These do not appear similar to Crab filaments, which are from R-T instabilities as PWN expands into ejecta**
  - are 3C 58 structures loops of magnetic flux torn from jet region due to kink instabilities (e.g. Begelman 1998)?



Jet/Counterjet Asymmetries: Doppler Beaming

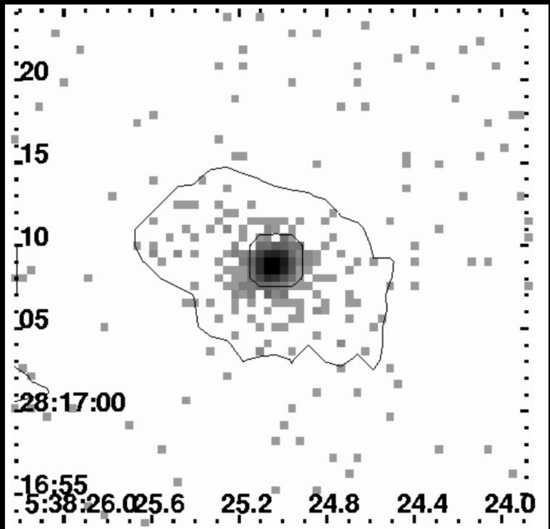


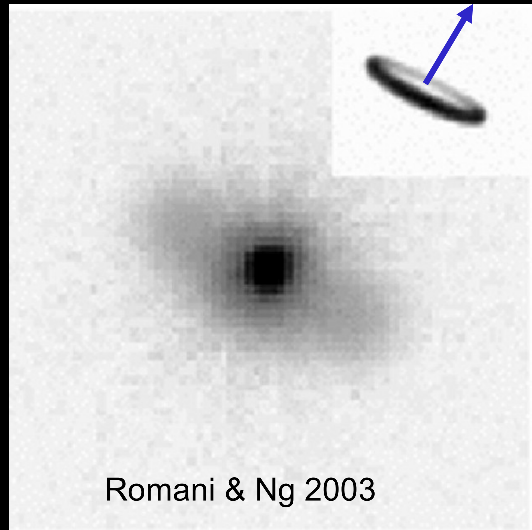
- **For several pulsars, both a jet and a counterjet are observed.**
  - for most, the flux from the counterjet is difficult to measure, both because it is faint and because the surrounding PWN emission is bright

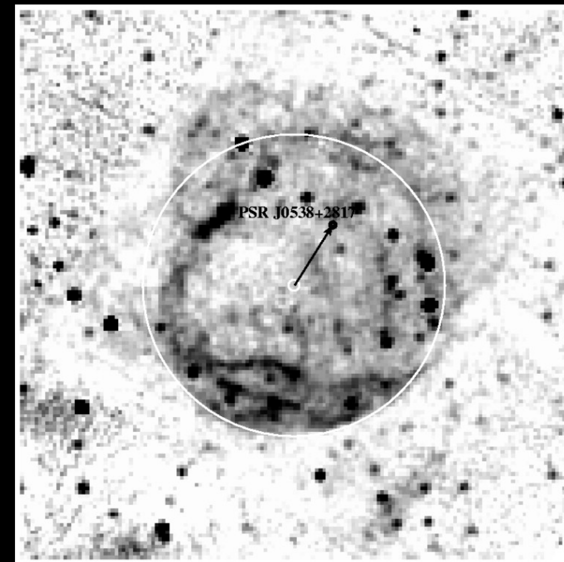
- **The expected intensity ratio from Doppler beaming is**

- **Using inclination angles determined from the torus, along with measured spectrum, predictions can be made for β**
  - these can be compared with measured flow flow speeds, where available (e.g. Crab, Vela)
  - agreement for Crab and Vela is reasonable, but 3C 58 predicts a very large value, though the uncertainties in flux ratio and angle are large
  - for PSR 1706-44, the counterjet seems to be on the wrong side (Romani et al. 2005)!

Spin-Kick Alignments?







- **Assuming jet-toroid geometry, spatial modeling can reveal the geometry of PWN systems**

- **Ex: PSR J0538+2817**
  - Chandra image shows point source surrounded by extended emission
  - image modeling suggests a tilted torus surrounding a NS; torus angle can be estimated by spatial modeling

- **Pulsar is located in SNR S147**
  - offset from center gives kick velocity
  - kick appears to be aligned with spin axis

- **Initial spin period ~130 ms (slow…)**
  - inferred v > 130 km/s; spin-kick alignment constrains models; kick mechanism needs to average over initial spin period
  - EM kick requires initial P < 3 ms; hydro kicks too fast as well; may need asymmetric ν emission to explain alignment

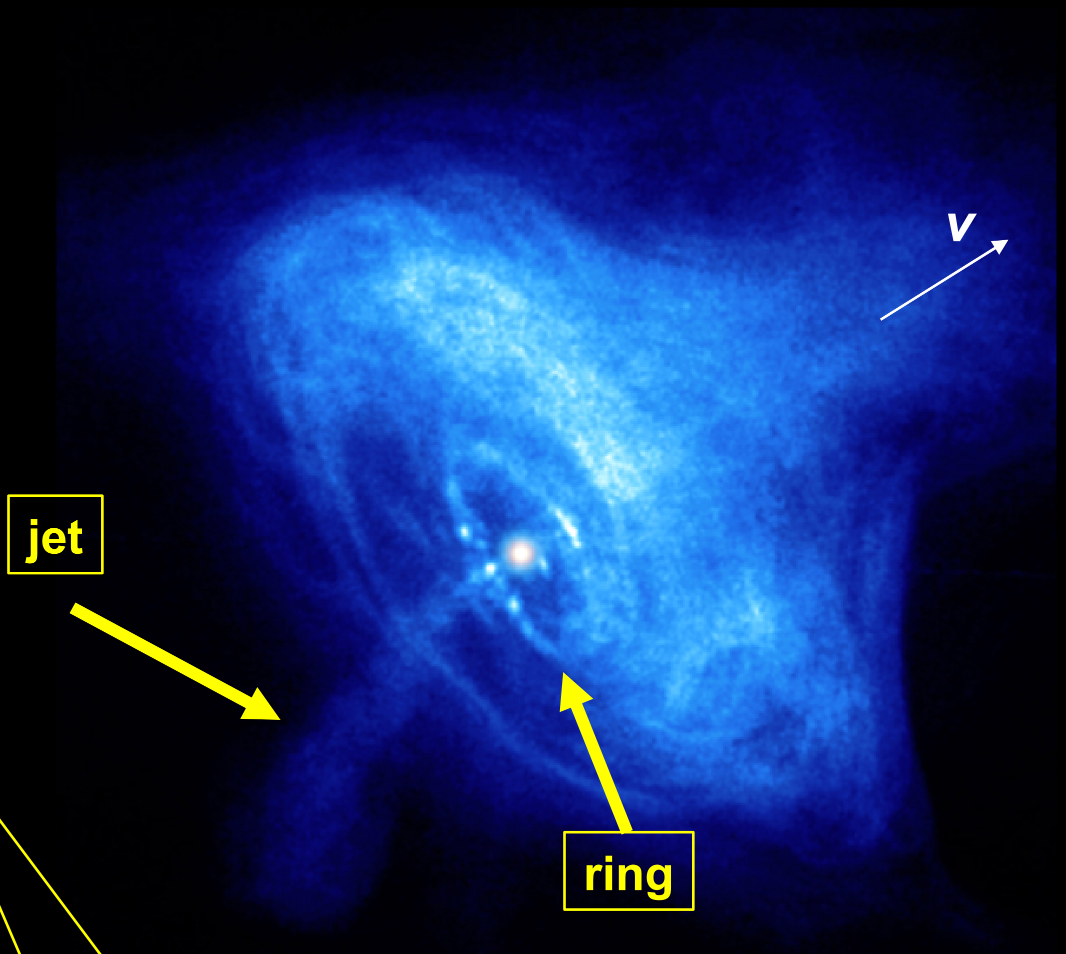
The Crab Nebula in X-rays

How does pulsar energize synchrotron nebula?

Pulsar: $P = 33$ ms
$dE/dt = 4.5 \times 10^{38}$ erg/s

Nebula: $L_x = 2.5 \times 10^{37}$ erg/s

- X-ray **jet-like structure** appears to extend all the way to the neutron star
  - jet axis ~aligned with pulsar proper motion; same is true of Vela pulsar
- **inner ring** of x-ray emission associated with shock wave produced by matter rushing away from neutron star
  - corresponds well with optical wisps delineating termination shock boundary



Recent work by Ng & Romani (2006) shows that proper motion is misaligned from jet axis by ~26 degrees for Crab. This suggests rotational averaging of kick did not occur, suggesting kick timescale < 20 ms.

TeV γ-rays from PWNe

- **Particles are accelerated to high energies in PWNe**
  - for Crab Nebula, inverse-Compton scattering of synchrotron photons produces TeV gamma-rays

- **For lower magnetic field objects, synchrotron-emitting particles radiating in a given band are more energetic than for Crab**
  - these can produce TeV gamma-rays by IC-scattering of CMB photons

- **For fields in PSR B1509-58, electrons producing TeV γ-rays would radiate synchrotron photons in UV**
  - for PWNe, HESS/Veritas are UV telescopes!

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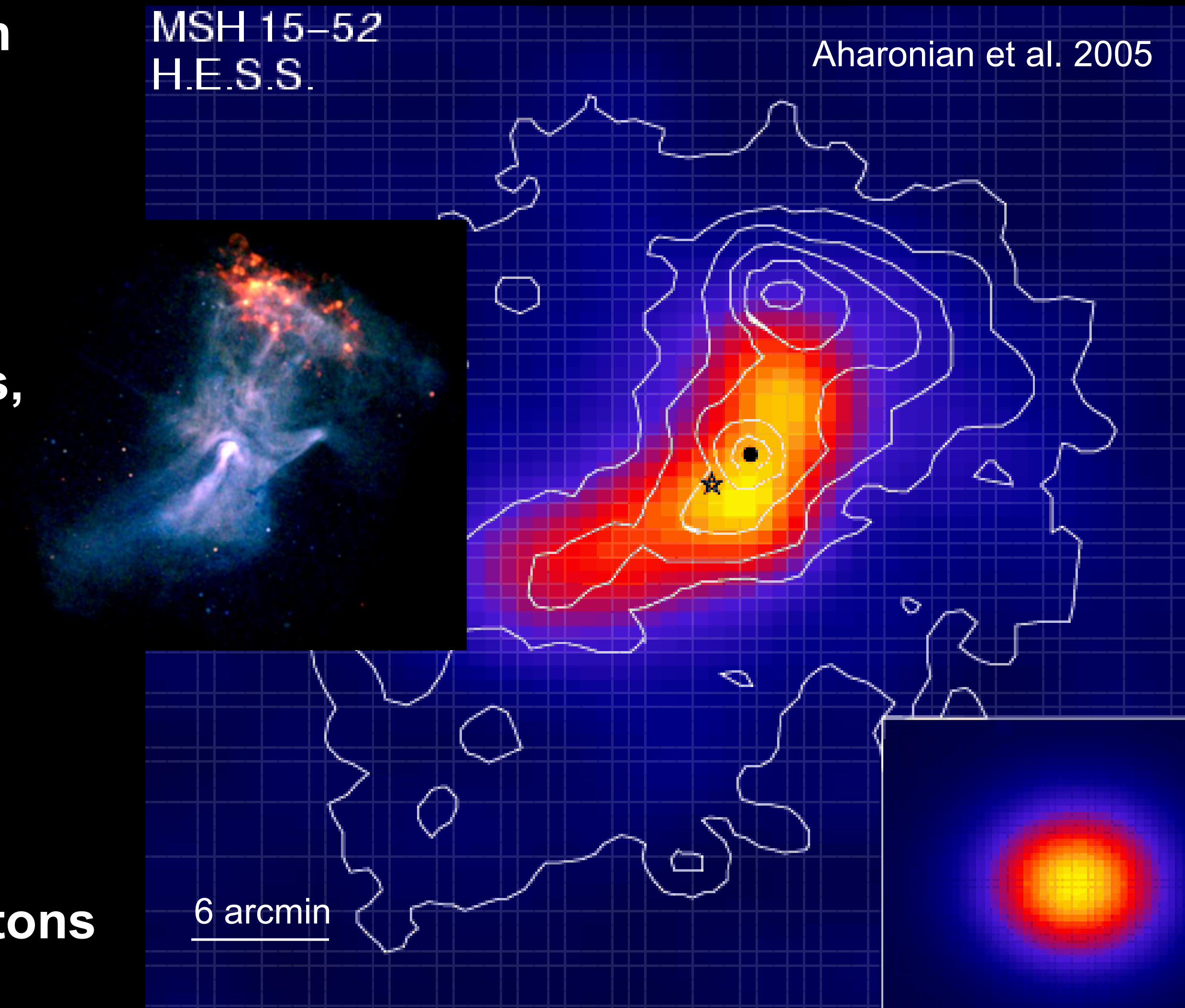

Conclusions

- For "standard" young pulsars, we expect pulsar wind nebulae
  - properties of nebulae point to properties of neutron star
  - high resolution X-ray studies reveal neutron stars, termination shock from pulsar wind, equatorial and axial structures (i.e. jets)

- Jets are often curved and show variable structure
  - kink instabilities in collimated flow?

- Counterjets are faint and can be difficult to detect against PWN
  - consistent w/ Doppler beaming? probably, but hard to get good measurements of flux ratio and flow speeds

- Jet/Torus geometry defines spin axis. Evidence for spin-kick alignment?
  - jury is out, but it is looking less likely that this is the case
  - suggests fast kick mechanism

- TeV γ-rays from pulsar jets observed; new constraints on particle spectrum