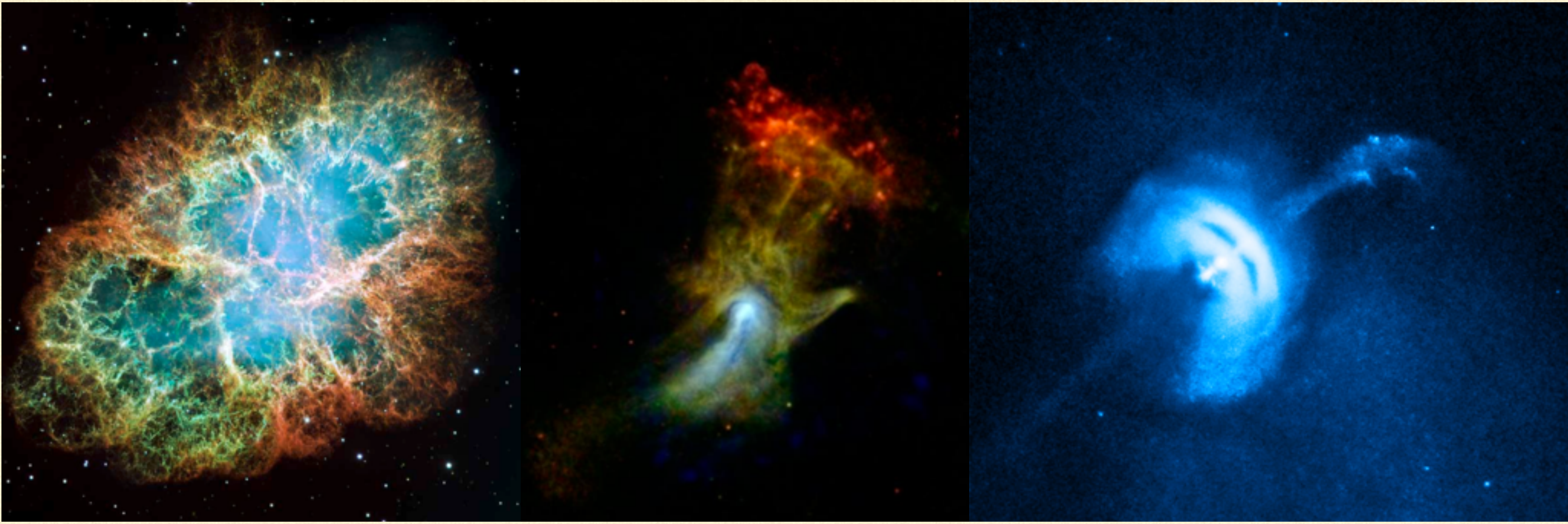

# Pulsar Wind Nebulae

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Princeton University

Collaborators: R. Blandford, W. East, K. Nalewajko, J. Zrake, A. Spitkovsky

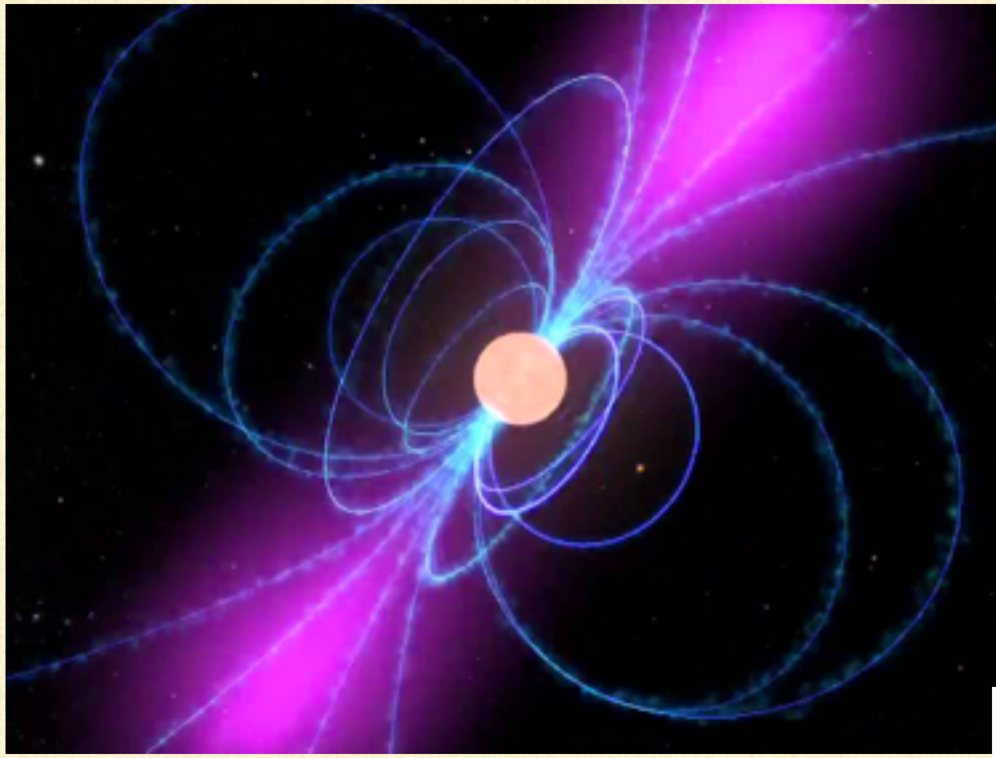
# Why are pulsars and PWN important?

- Pulsars:
  - Matter under extreme conditions
  - Best known cosmic clocks
  - Test of general relativity
  - Source of antimatter
  - Potential drop $\gtrsim$ PV
- PWN:
  - Most of the pulsar spin down energy
  - Best laboratory of relativistic plasmas
  - Highly relativistic shock ($\Gamma \sim 10^4$-$10^7$)
  - Evidence of PeV electrons

# Outline

- Pulsar electrodynamics and the launching of the wind
- Structure of pulsar wind nebulae
- Modeling the PWN emission
  - Simple 1-zone model
  - 1D, 2D and 3D MHD models
- Particle acceleration in PWN

# Pulsar electrodynamics



- Rotating dipole in vacuum

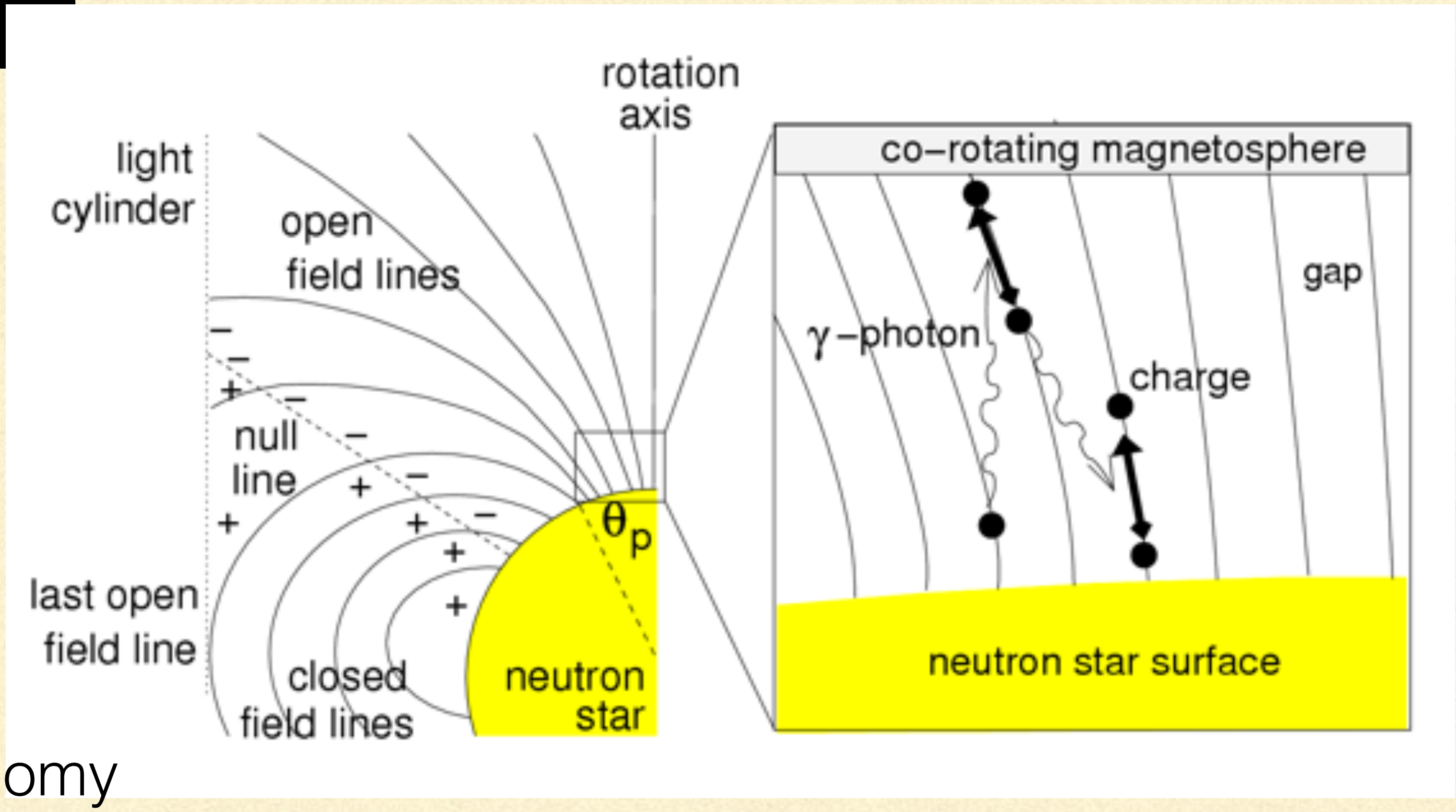
$$P_{\rm rad} = \frac{2(\ddot{\mu}_\perp)^2}{3c^3} = \frac{2\mu_\perp^2\Omega^4}{3c^3}$$

- But a rotating magnetic neutron star cannot be surrounded by vacuum!

Charge multiplicity

$\kappa \sim 10^3$-$10^4$

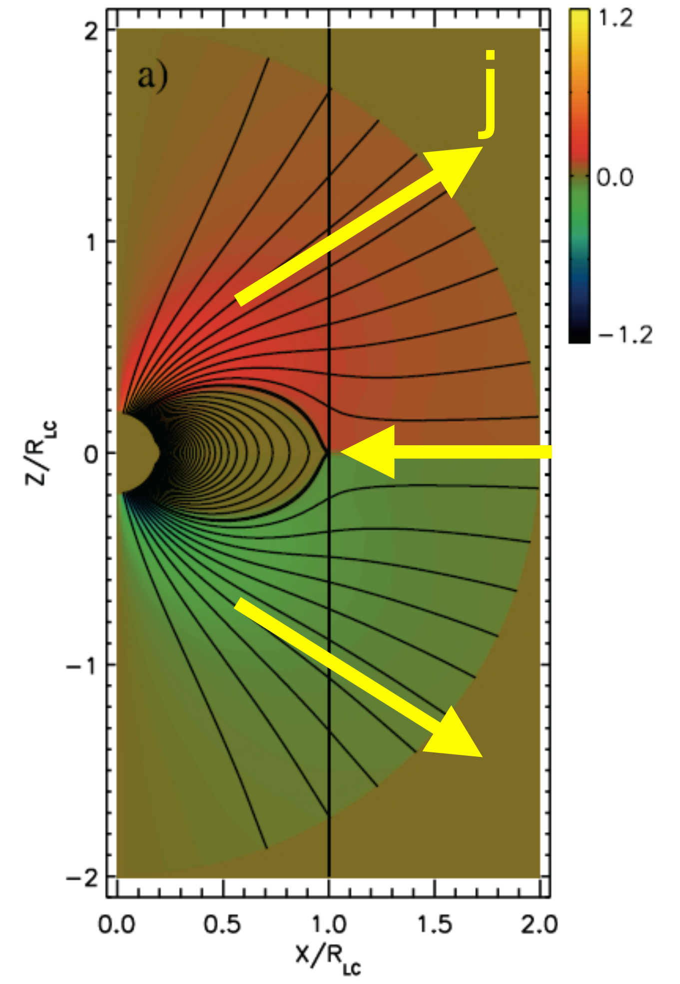
(Timokhin & Arons 2013)

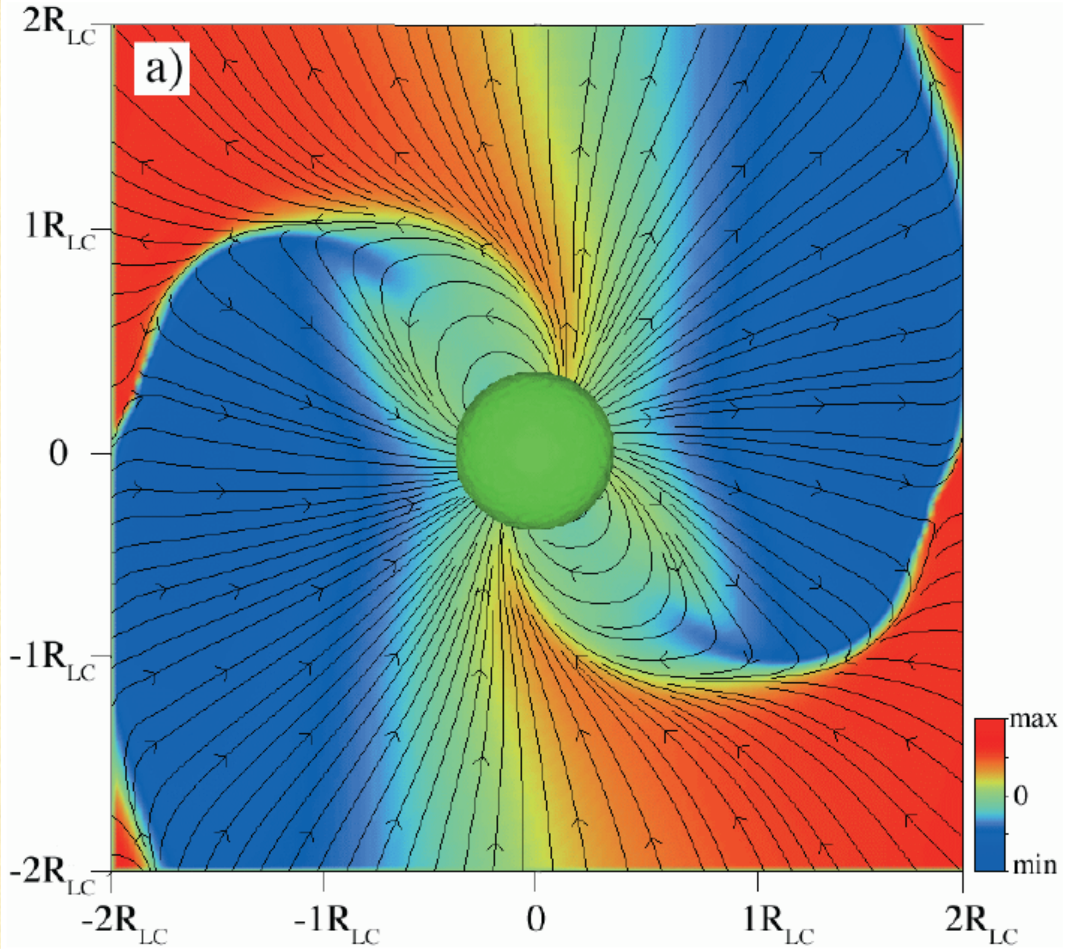


Lorimer and Kramer,
Handbook of Pulsar Astronomy

# Pulsar electrodynamics

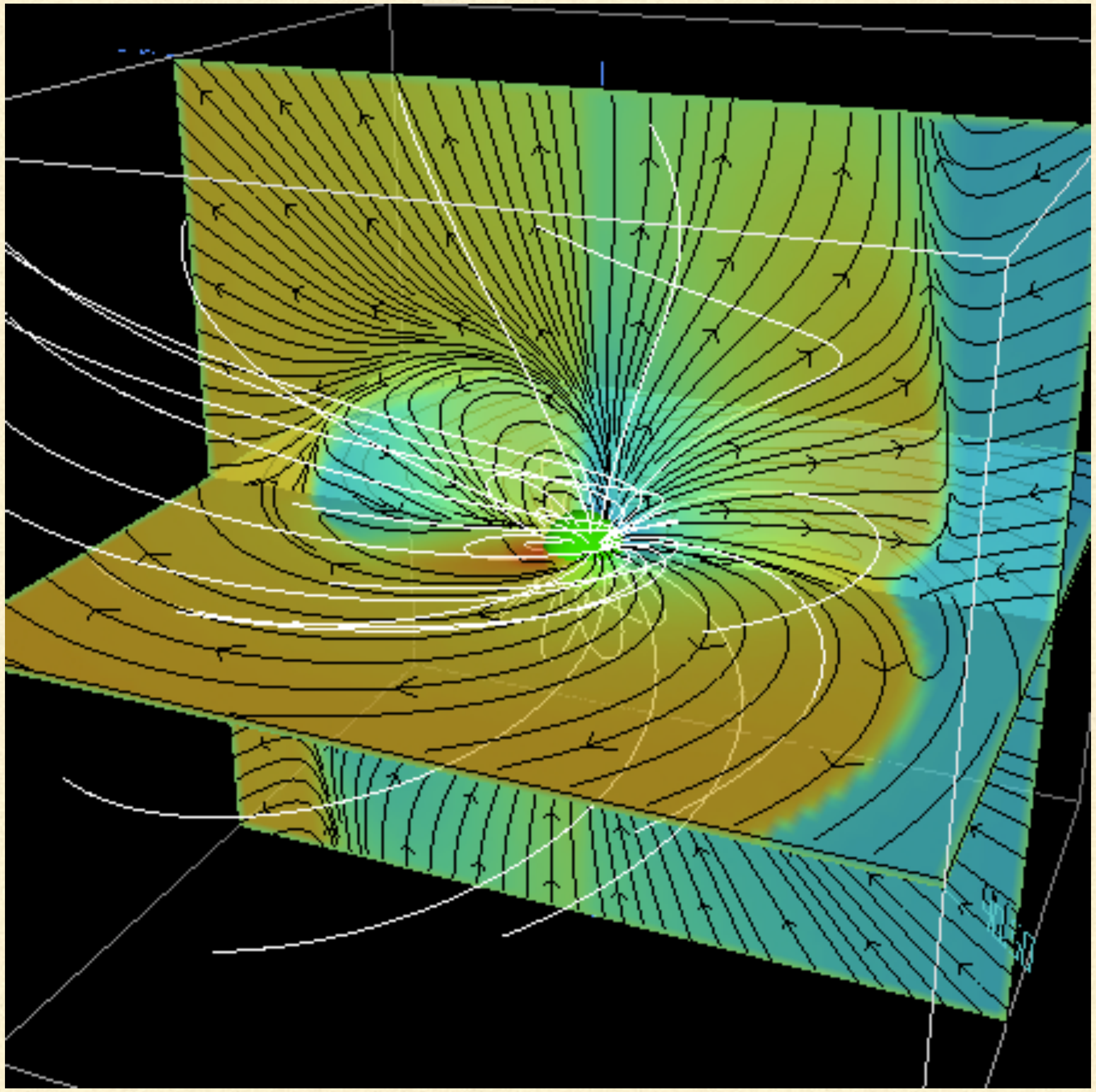
- When there is abundant plasma, a corotating magnetosphere develops;
- Corotating, closed field lines can only extend up to the light cylinder;
- At large distances field lines are open, and becomes more and more toroidal.





Spitkovsly 2006 ApJL 648, L51

# Pulsar magnetosphere and wind



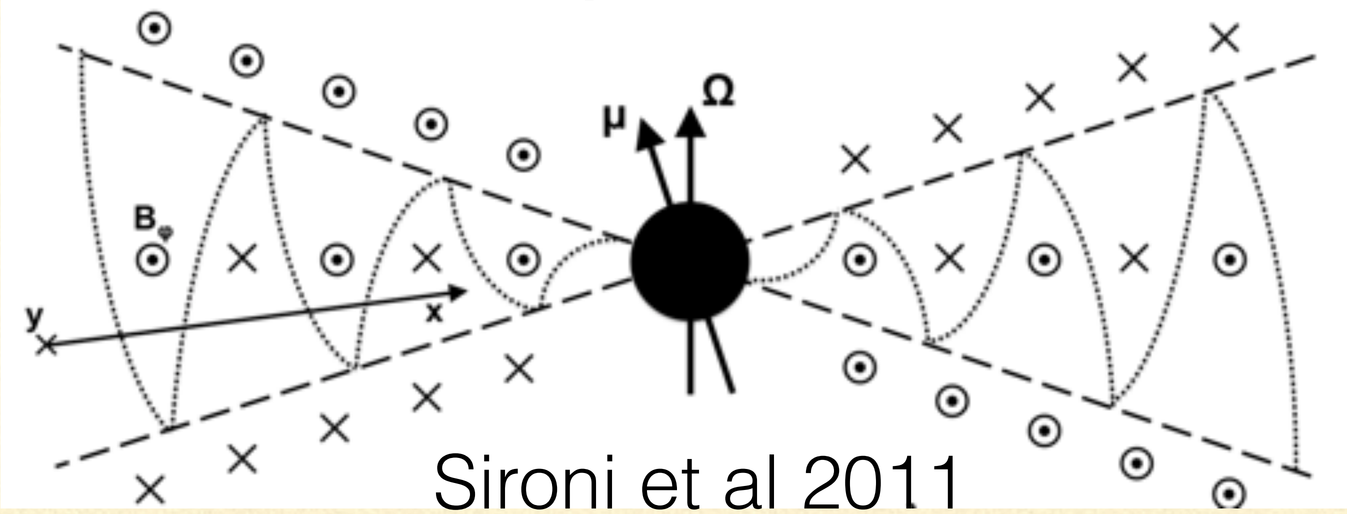
Spitkovsly 2006

$$L_{\rm pulsar} = \frac{\mu^2\Omega^4}{c^3}(1+\sin^2\alpha)$$

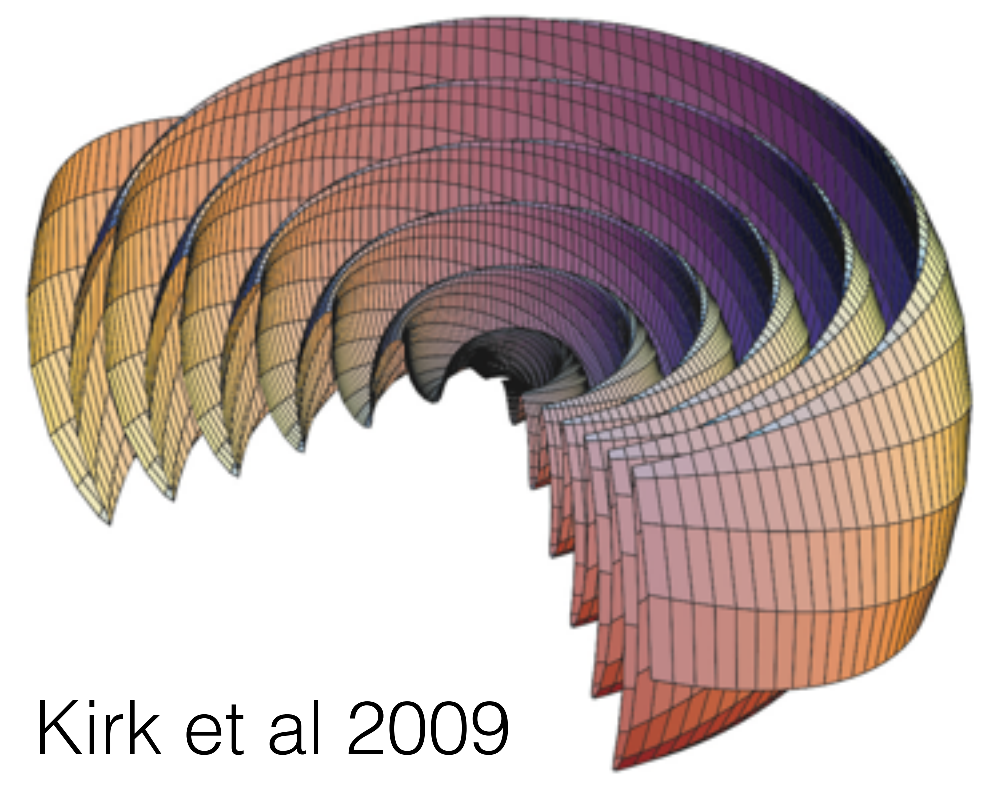
- Most of the pulsar spin down power is carried away by the wind
- The wind magnetic field is dominated by the toroidal component at large distances

# Properties of the wind—open questions

Striped wind



Sironi et al 2011



Kirk et al 2009

- What is the multiplicity κ?
- What is the wind Lorentz factor Γ?
- What is the wind magnetization σ?

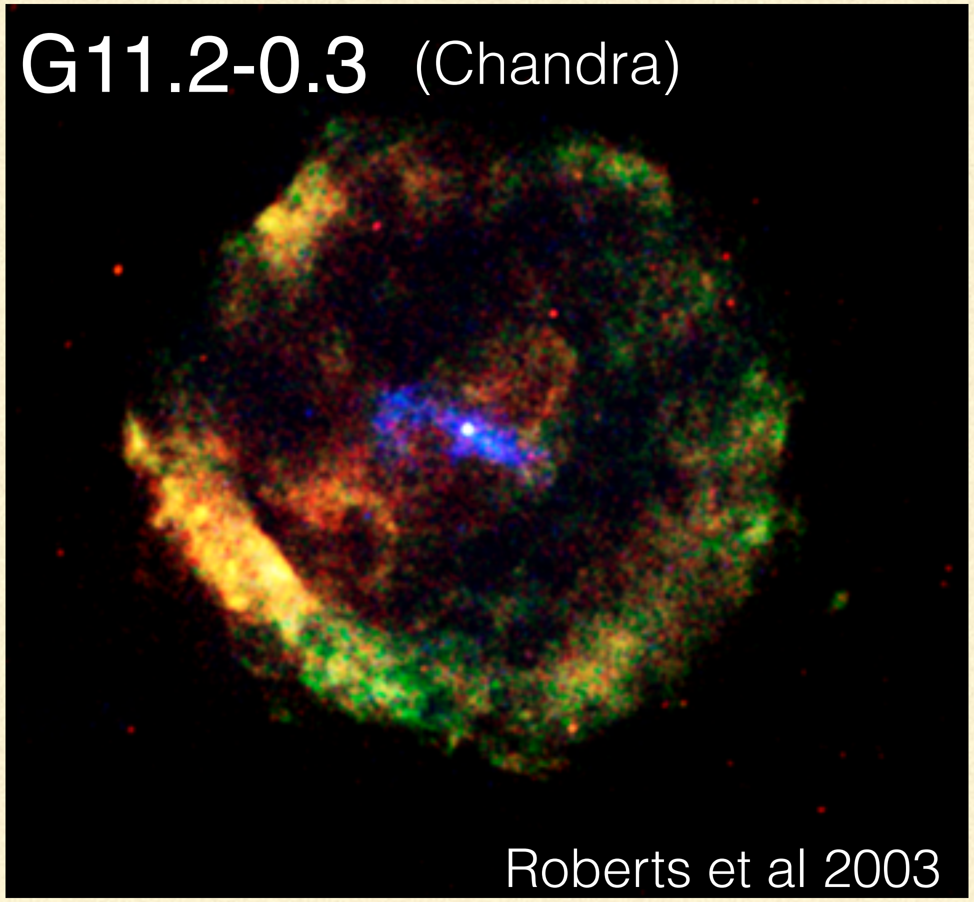
$$\sigma = \frac{B^2}{4\pi m_{\rm eff} n_{\rm eff} c^2 \Gamma^2}$$

- Are there energetically important ions in the wind?

# Pulsar wind nebulae

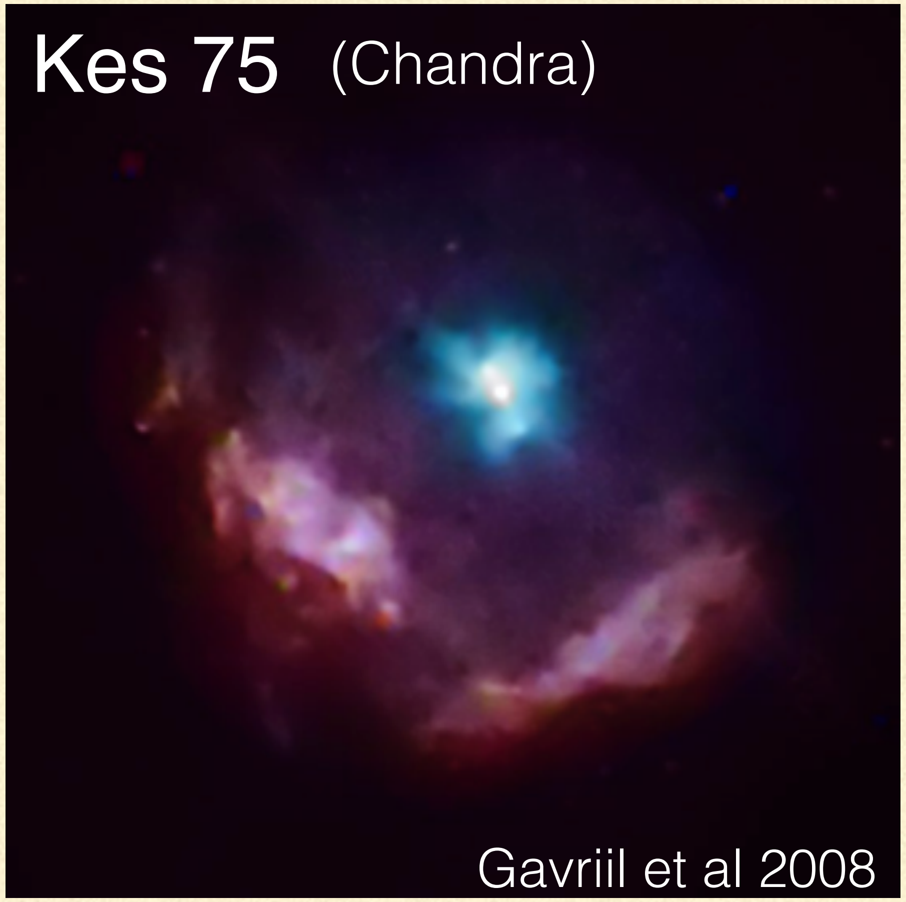
3C 58

VLA/Reynolds
Chandra/Slane et al



G11.2-0.3 (Chandra)

Roberts et al 2003



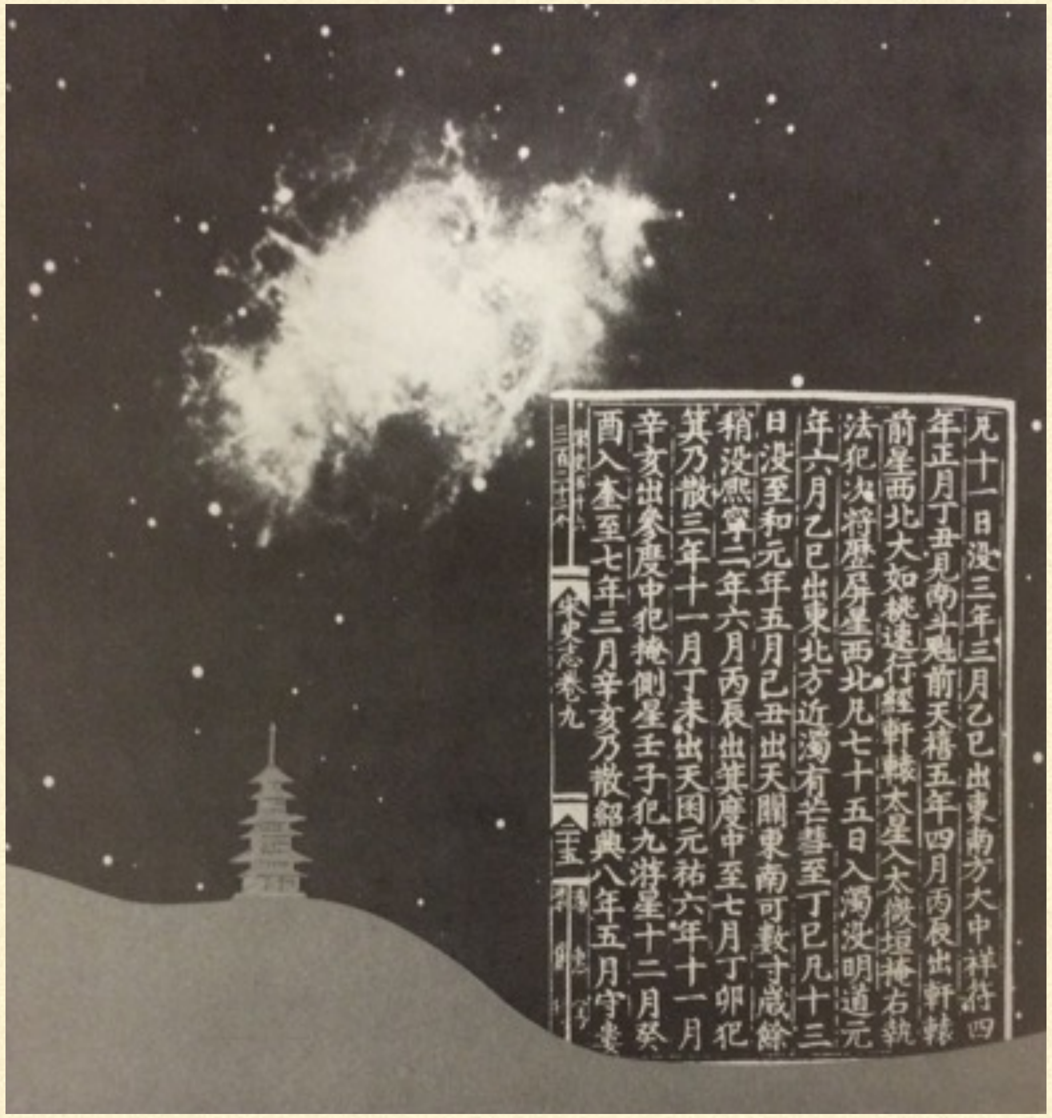
Kes 75 (Chandra)

Gavriil et al 2008

- Supernova remnant with a center-filled morphology;
- Flat radio spectrum $S_\nu \sim \nu^{-\alpha}$, $\alpha=0.0-0.4$ (mostly)
- Broadband nonthermal emission (from radio to X-ray and even $\gamma$-ray)
- Typically size shrinks with increasing photon energy

# The best studied case: Crab

Supernova 1054



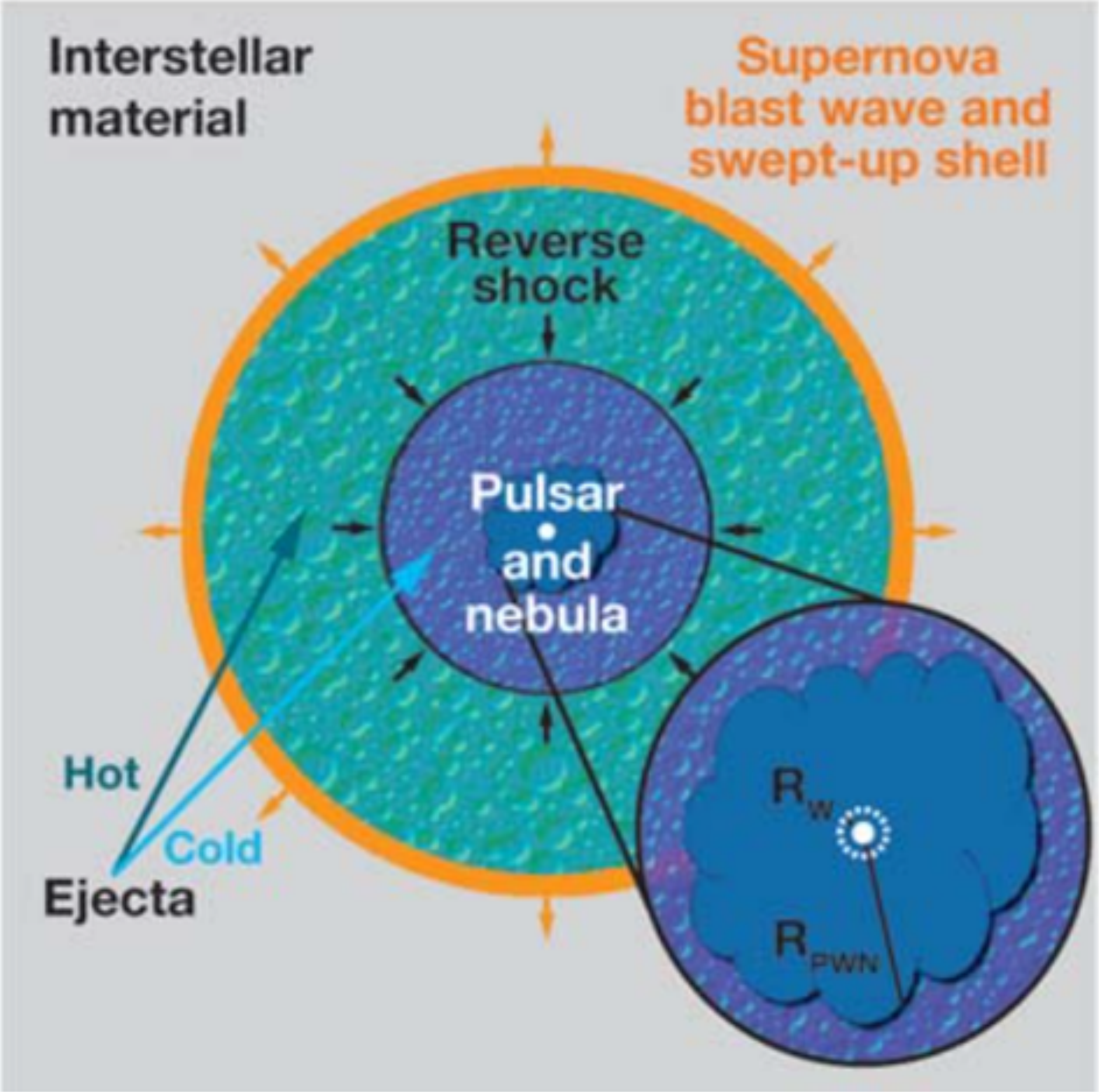
凡十一日沒三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅大星入太微垣掩右執法犯次將歷屏星西北凡七十五日入濁沒明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日沒至和元年五月己丑出天關東南可數寸歲餘稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

Distance ~ 2 kpc
Size: 4.4 pc x 2.9 pc

# Structure of pulsar wind nebulae

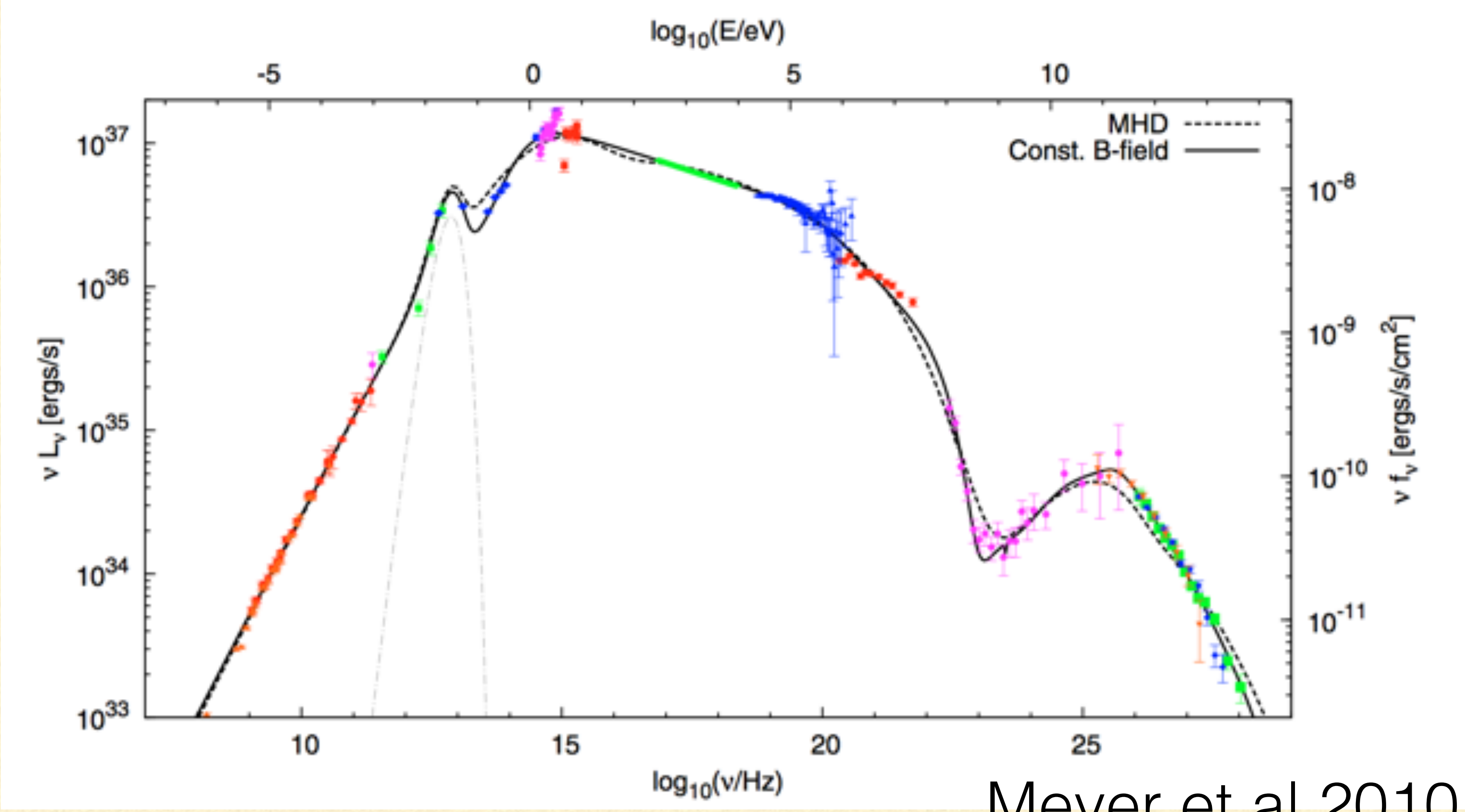
(Matheson & Safi-Harb 2005)



Gaensler & Slane 2006

# Modeling of PWN

# Spectral features



Meyer et al 2010

- Emission mechanisms: synchrotron and inverse Compton
- Crab: pulsar spin down power: 5e38 erg/s; synchrotron nebula luminosity: 1.3e38 erg/s
- High degree of polarization (Oort & Walraven 1958: 17.2% within central 0.8’ in optical)—> strong and relatively ordered magnetic field

# One-zone model: a few rules of thumb

- Synchrotron radiation from a single particle (δ-function approximation)

$$
\begin{aligned}
P_\nu(\gamma) &= a_1 \gamma^2 B^2 \delta(\nu - \nu_s(\gamma)), \\
\nu_s(\gamma) &= a_2 \gamma^2 B \approx \gamma^3 \omega_g
\end{aligned}
$$

- For a power law distribution of particles $N(\gamma) = k\gamma^{-p}$, the synchrotron spectrum is

$$S_\nu^{\rm sync}(\nu) = \frac{a_1}{2} a_2^{\alpha-1} k B^{\alpha+1} \nu^{-\alpha}, \quad \alpha = \frac{p-1}{2}$$

- Historically (when high energy IC spectrum is not yet available), equipartition is an expedient way to estimate the magnetic field and particle content.

$$N(\gamma) = k\gamma^{-p},\ \gamma_{\rm min} \le \gamma \le \gamma_{\rm max}$$

$$W_{total} = V\left(\frac{B^2}{8\pi} + \int_{\gamma_{\rm min}}^{\gamma_{\rm max}} N(\gamma)\gamma mc^2\, d\gamma\right)$$

$$S_\nu^{\rm sync}(\nu) = \frac{a_1}{2}a_2^{\alpha-1}kB^{\alpha+1}\nu^{-\alpha} \Longrightarrow k = \frac{2S_\nu\nu^\alpha}{a_1a_2^{\alpha-1}B^{\alpha+1}}$$

$$\gamma_{\rm min,\ max} = \left(\frac{\nu_{\rm min,\ max}}{a_2B}\right)^{1/2}$$

$$W_{total} = V\left(\frac{B^2}{8\pi} + G(\nu)B^{-3/2}\right)$$

Minimum of W$_{\rm total}$ happens at $B = (6\pi G(\nu))^{2/7}$, and this in turn gives $W_{\rm mag} = \frac{3}{4}W_{\rm particle}$, close to equipartition.

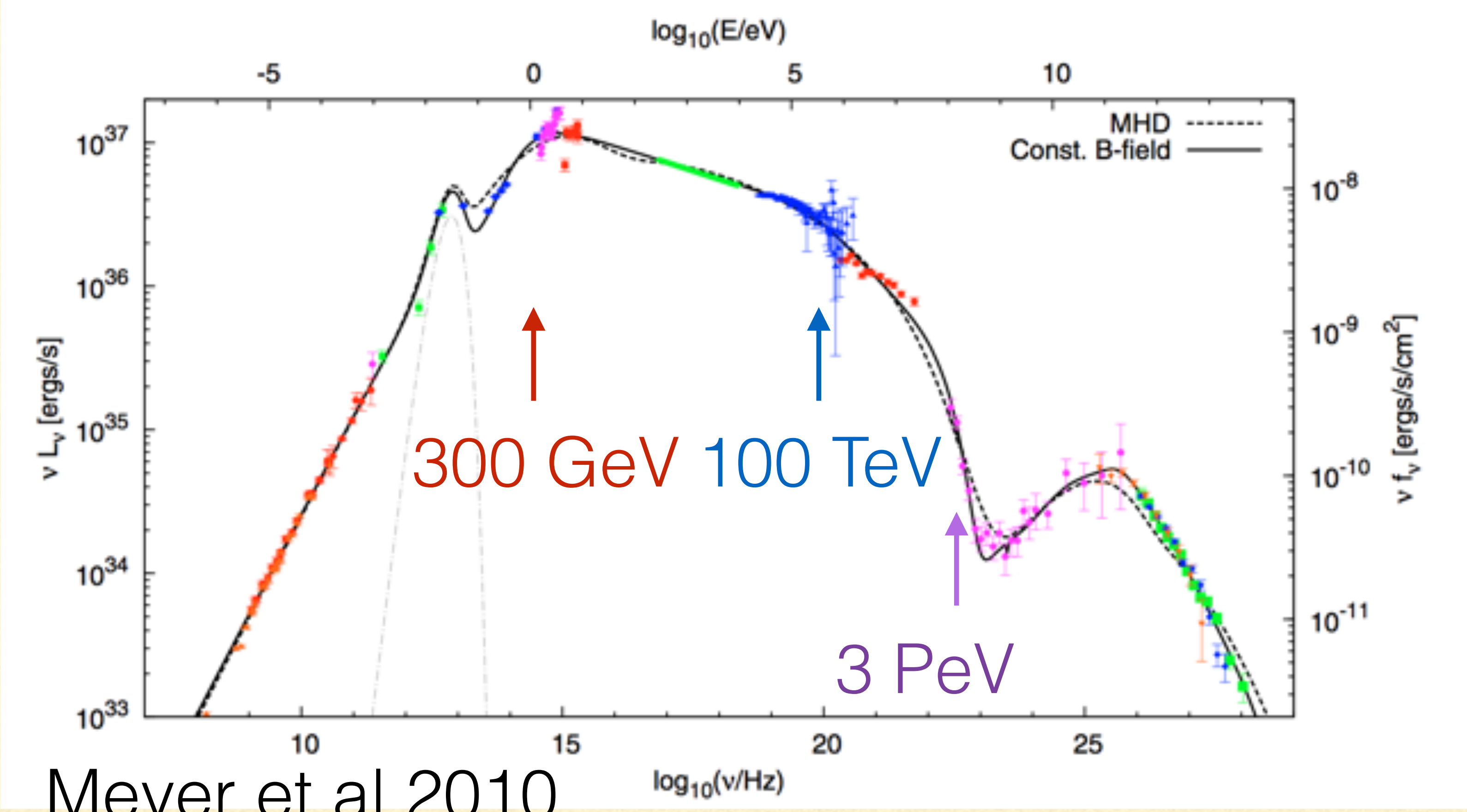
Caveats!

- For Crab, the equipartition magnetic field is B~300μG. As a consequence:
  - Spectral peak (optical/UV) corresponds to TeV particles;
  - The injection rate of radio emitting particles is $10^{40}$ $s^{-1}$, and optical/X-ray emitting particles $10^{38.5}$ $s^{-1}$.
- But we have the IC information nowadays!

For example, Meyer et al (2010) fitting with a constant magnetic field gives

B=124 μG.

(Not a 1-zone model)



Meyer et al 2010

# Evolution of particle distribution—a few rules of thumb

- Relevant loss terms
  - Synchrotron loss $-\left(\frac{dE}{dt}\right)_{\rm syn} = \frac{4}{3}\sigma_T c\gamma^2 U_{\rm mag}$
  - Inverse Compton loss $-\left(\frac{dE}{dt}\right)_{\rm IC} = \frac{4}{3}\sigma_T c\gamma^2 U_{\rm rad}$
  - Adiabatic loss $-\left(\frac{dE}{dt}\right)_{\rm ad} = \frac{1}{3}(\nabla\cdot\boldsymbol{v})E$
- Diffusion-loss equation

$$\xcancel{\frac{\partial N}{\partial t}} + \frac{\partial}{\partial E}(\dot{E}N(E)) = \xcancel{D\nabla^2 N} - \xcancel{\frac{N}{\tau_{\rm esc}}} + Q(E) + \frac{1}{2}\xcancel{\frac{\partial^2}{\partial E^2}(d(E)}N(E))$$

Consider only energy loss and particle injection, steady state

$$\frac{d}{dE}(\dot{E}N(E)) = Q(E), \quad Q(E) = kE^{-p}$$

$$N(E) = \frac{kE^{-(p-1)}}{(p-1)(-\dot{E})}$$

# Evolution of particle distribution—a few rules of thumb

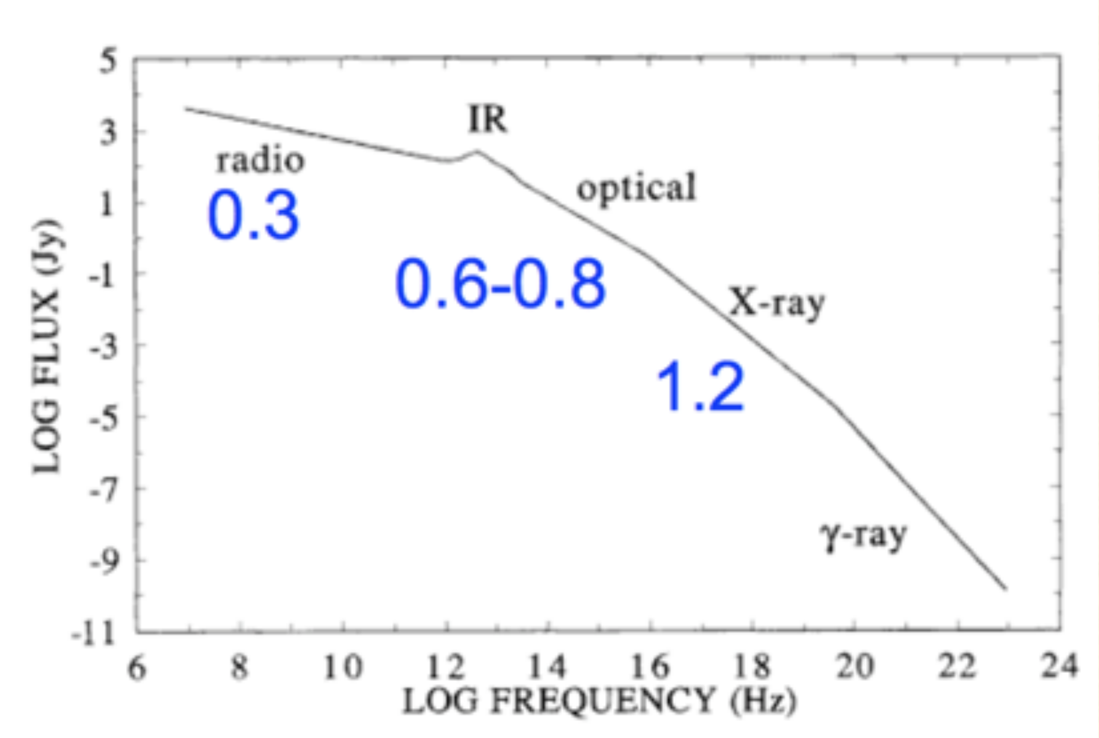
$$N(E) = \frac{kE^{-(p-1)}}{(p-1)(-\dot{E})}$$

- If adiabatic loss dominates, $-\dot{E} \propto E,\ N(E) \propto E^{-p}$, the particle spectrum is unchanged from injection spectrum;
- If synchrotron or inverse Compton loss dominates,

  $$-\dot{E} \propto E^2,\ N(E) \propto E^{-p-1}$$

  particle spectrum is steeper by 1 power of E, and radiation spectrum is steeper by 0.5 power of ν. There should be a spectral break where the cooling time equals to the nebula age.
- Low energy end adiabatic loss dominates; high energy end synchrotron/IC dominates; there's a spectral break when the two equal.

# Apply to the Crab



Consider the possibility of an age break and/or an adiabatic/synchrotron break (assume the nebula is expanding with constant speed)

$$\nu_b \approx 5 \times 10^{13}\,\mathrm{Hz} \Longrightarrow B \approx 3 \times 10^{-4}\,\mathrm{G}$$

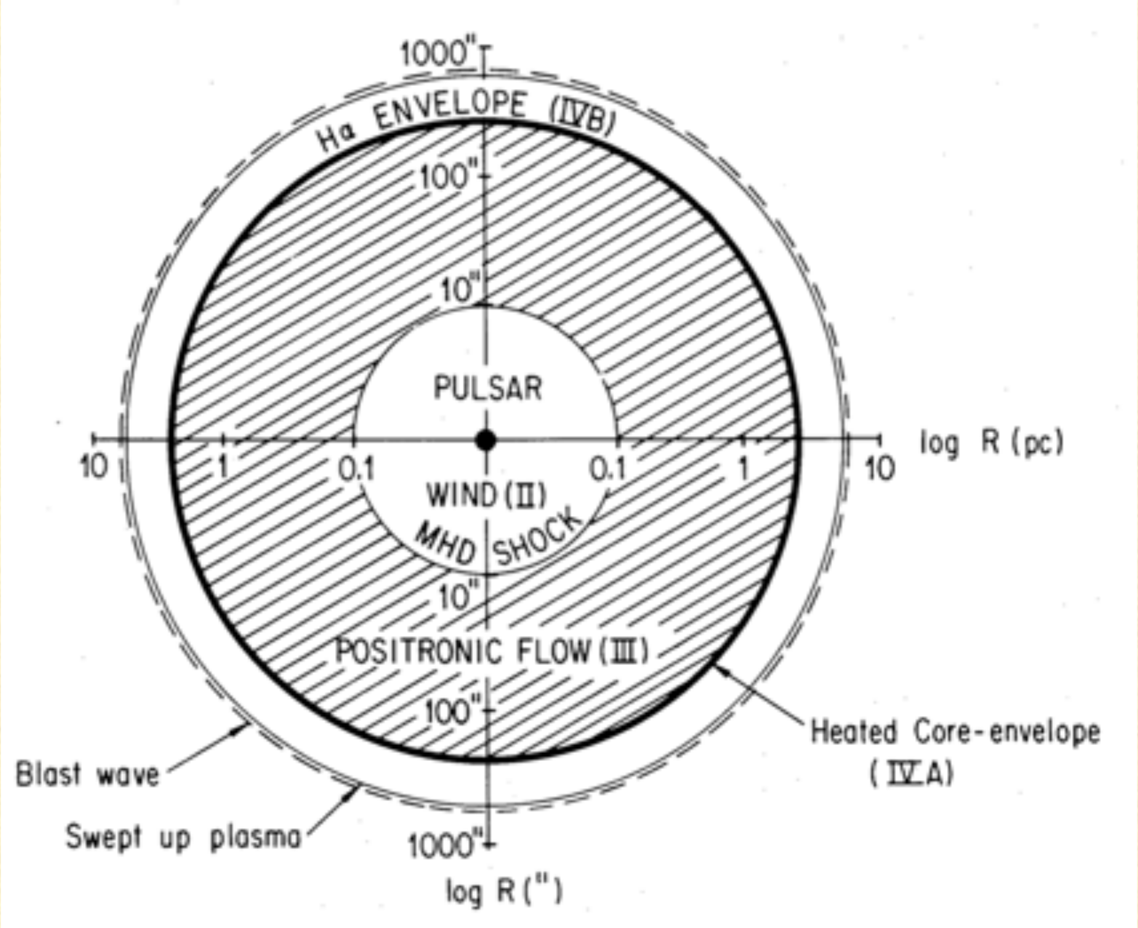
$$\nu_b \approx 2 \times 10^{15}\,\mathrm{Hz} \Longrightarrow B \approx 10^{-4}\,\mathrm{G}$$

Both consistent with equipartition within the uncertainties.

More detailed modeling is needed!

# 1D MHD modeling

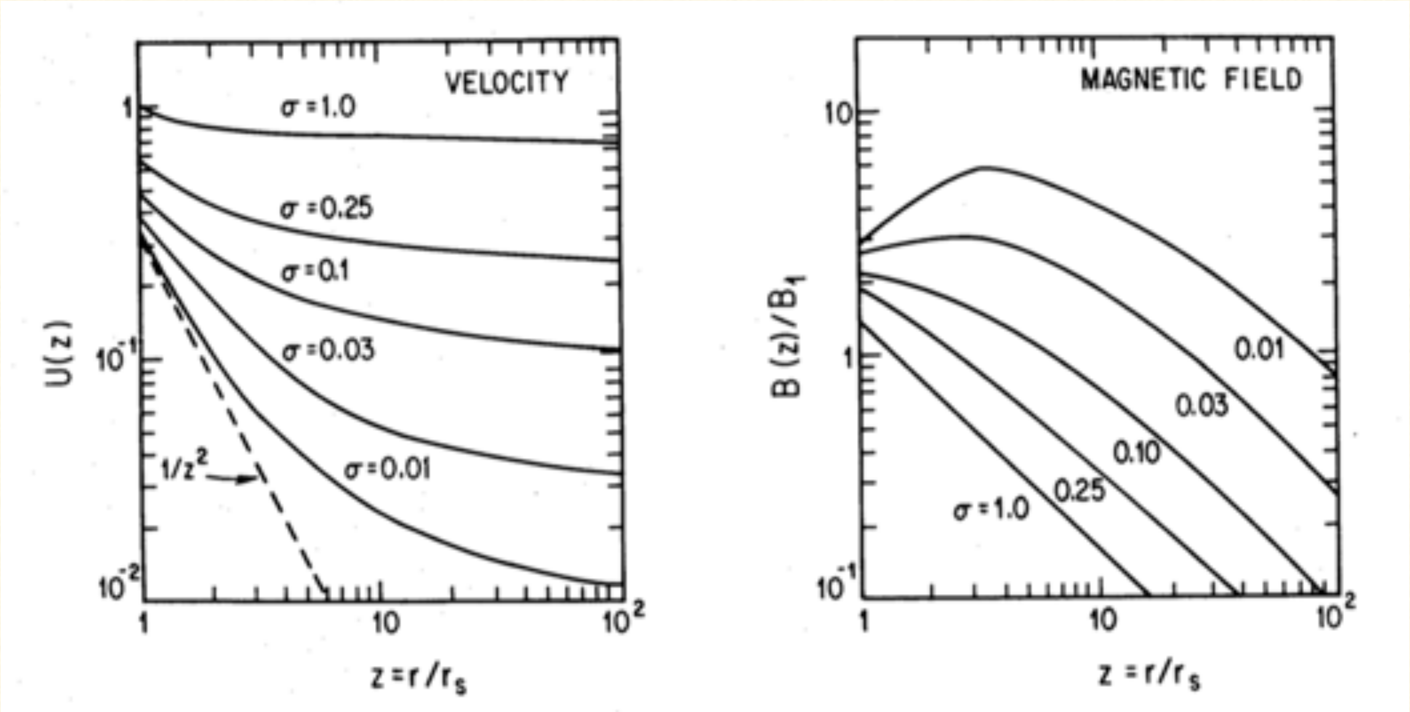
Rees & Gunn 1974; Kennel & Coroniti 1984



- Spherically symmetric wind
- Purely toroidal magnetic field
- Ideal MHD
- Relativistic termination shock
- Adiabatic post-shock flow
- Power-law particle distribution injected at the shock and advected with the downstream flow

# 1D MHD modeling

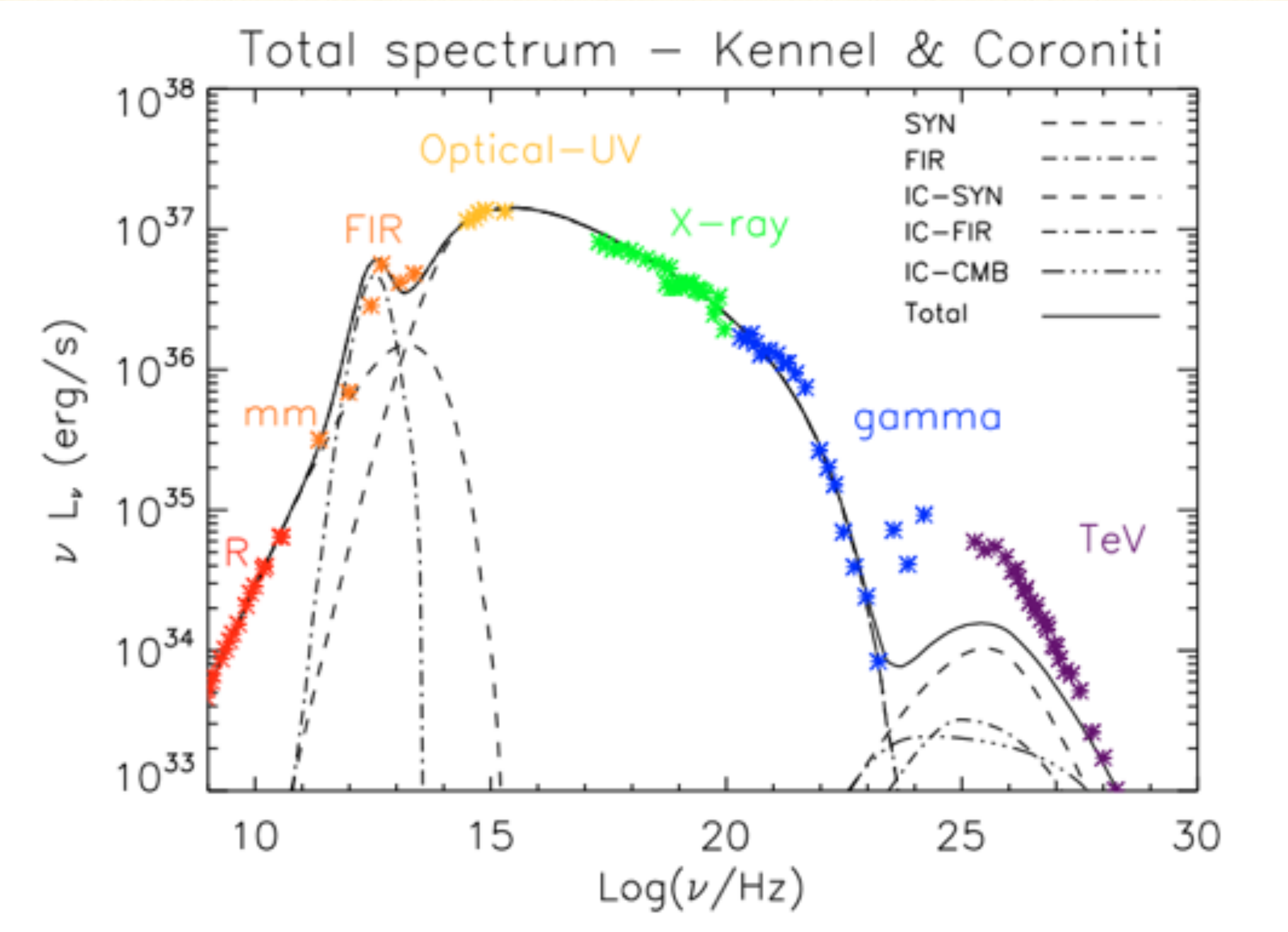
Rees & Gunn 1974; Kennel & Coroniti 1984



So-called σ problem!

- Only with very low magnetization σ~0.003 can the post shock flow match the boundary conditions and synchrotron spectrum
- Best fit parameter $\Gamma = 10^6,\ r_s = 3 \times 10^{17}\,\mathrm{cm},\ p = 2.2,\ \alpha = 0.6$
- Radio particles have to be a separate population

However, IC component does not agree well with data…

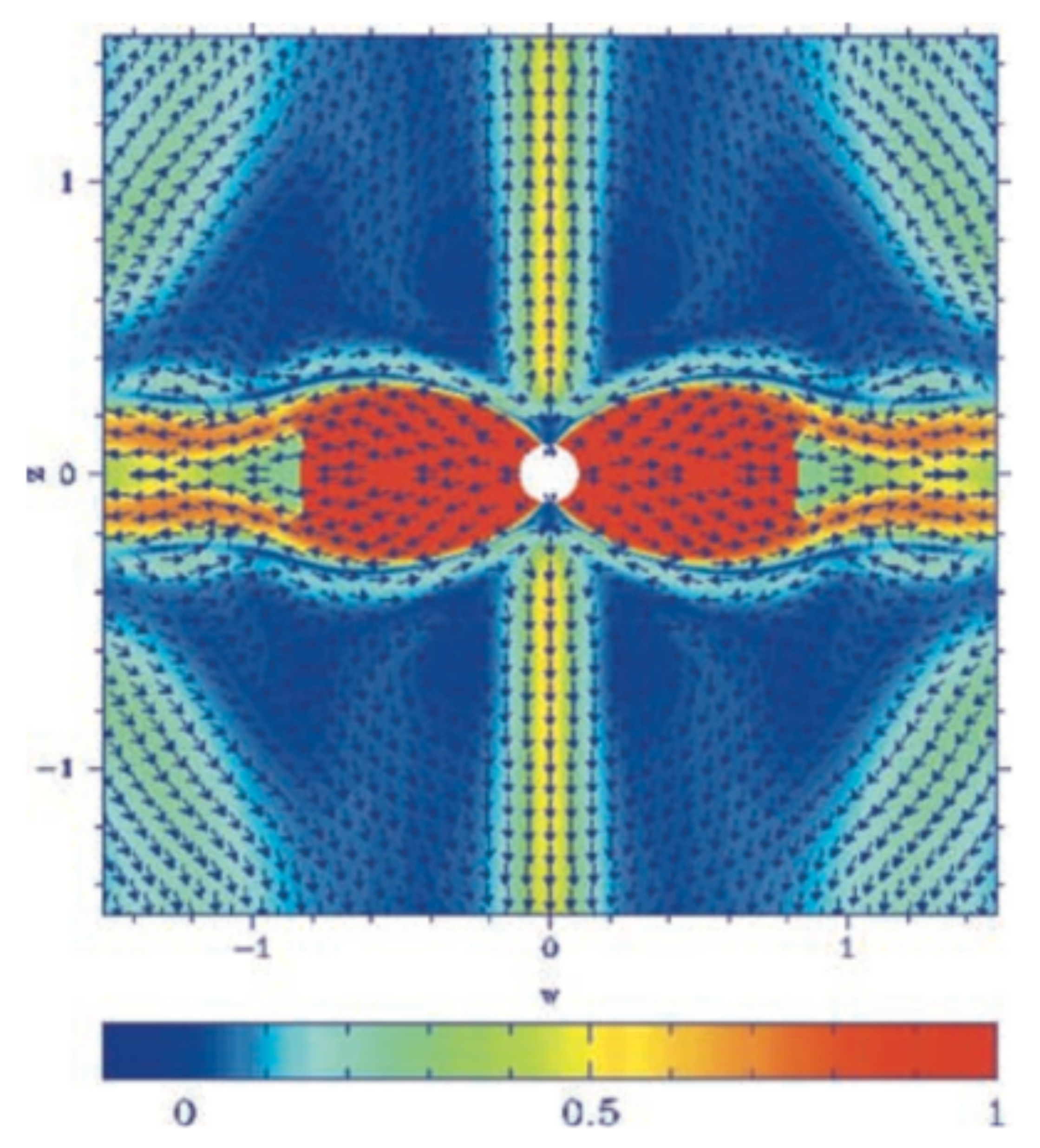


Volpi et al 2008

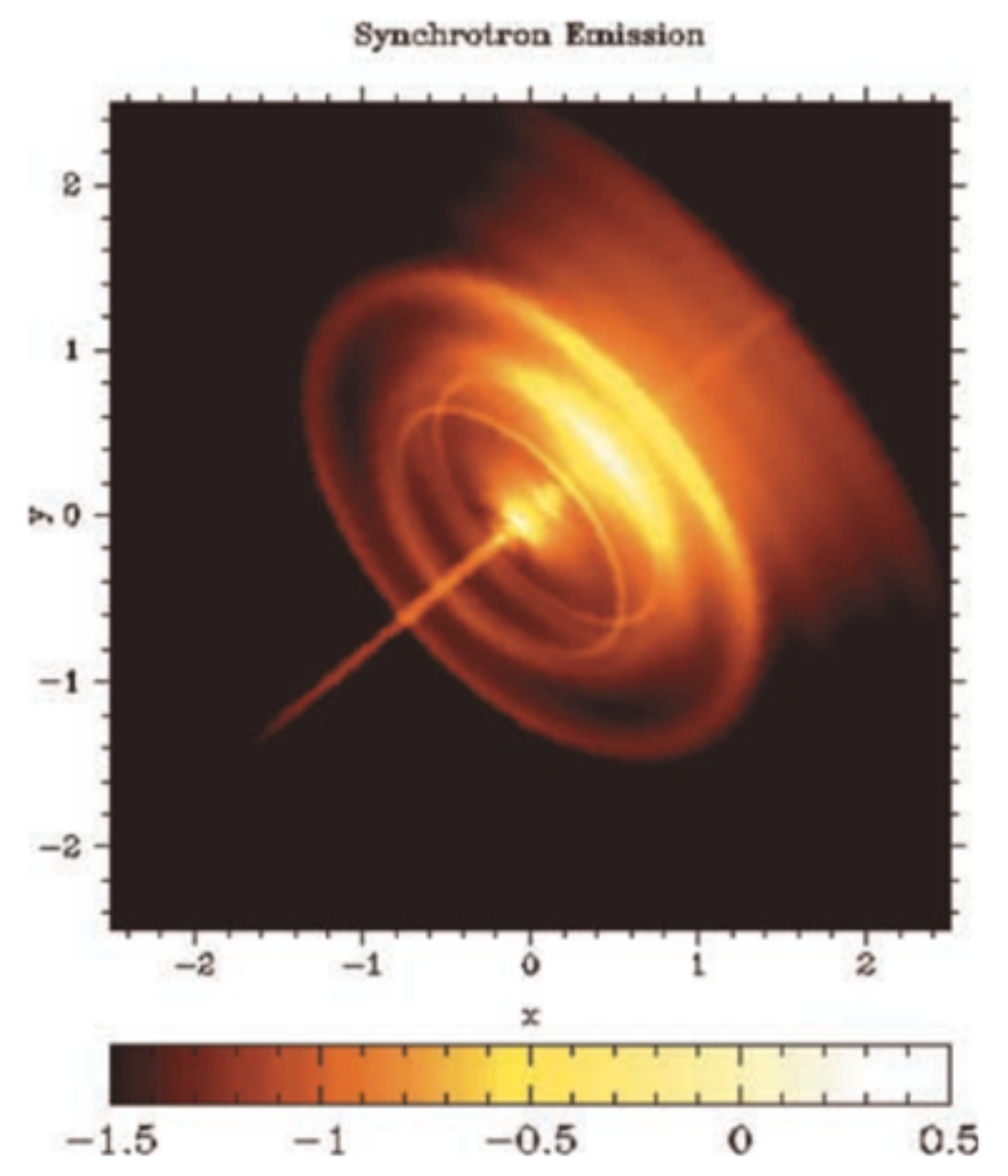
The energy flux in the wind is not isotropic…

# 2D MHD modeling

Komissarov & Lyubarsky 2003, 2004; Del Zanna et al 2004, 2006, Camus et al 2009



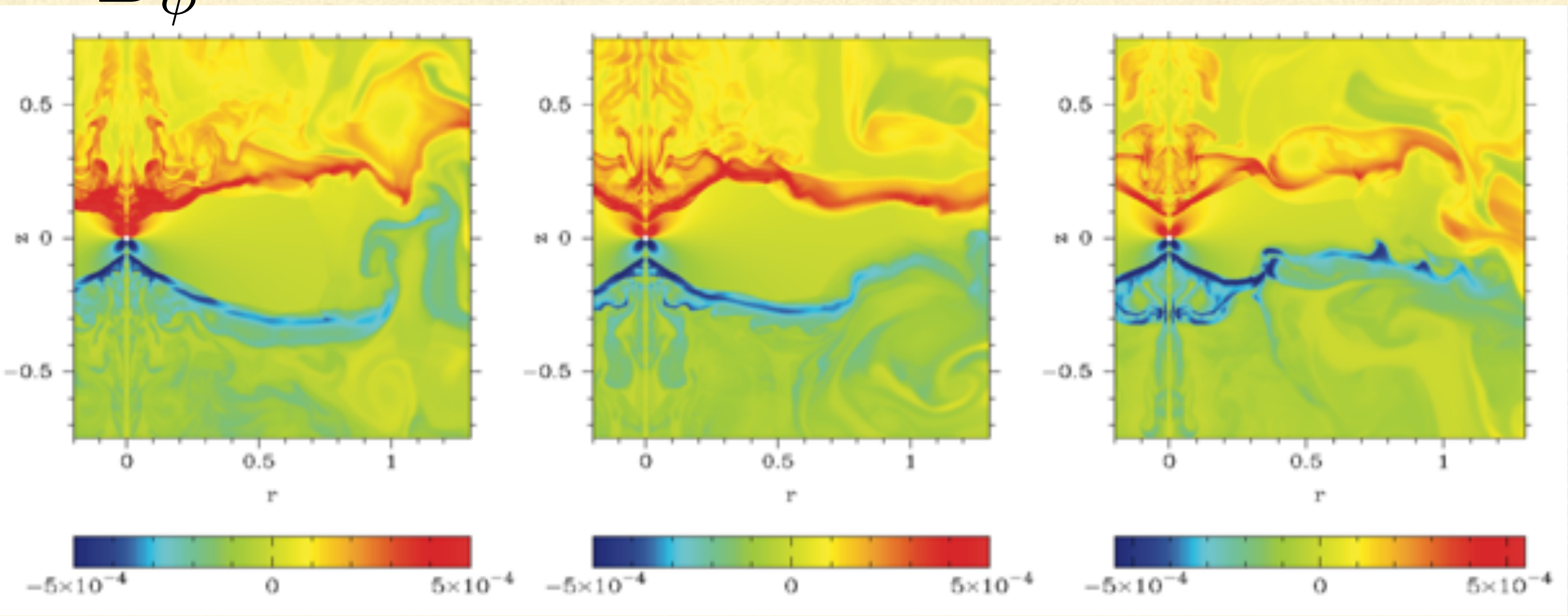
Flow velocity

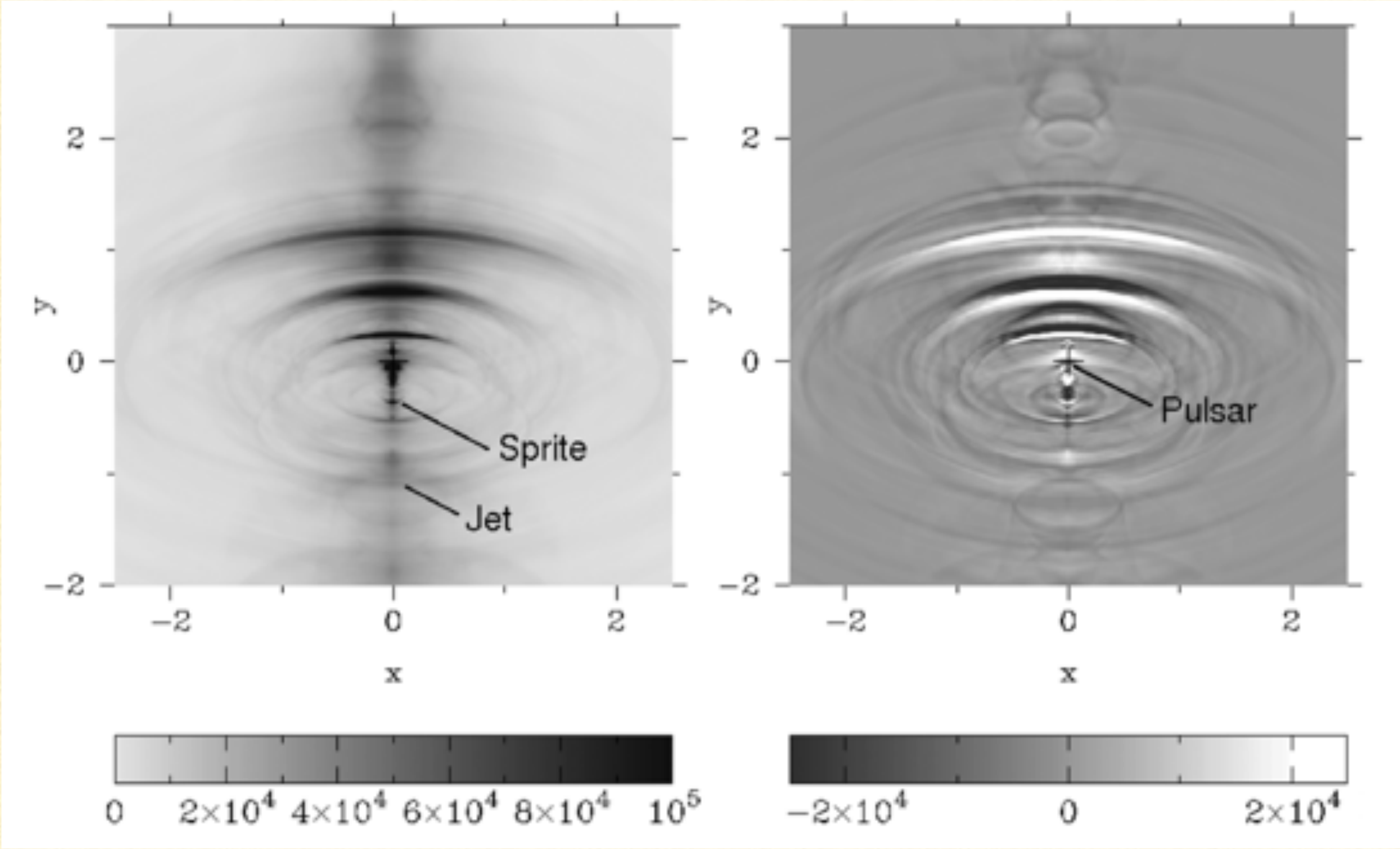


Jet-torus structure!!

# 2D MHD modeling—Variability

$B_\phi$

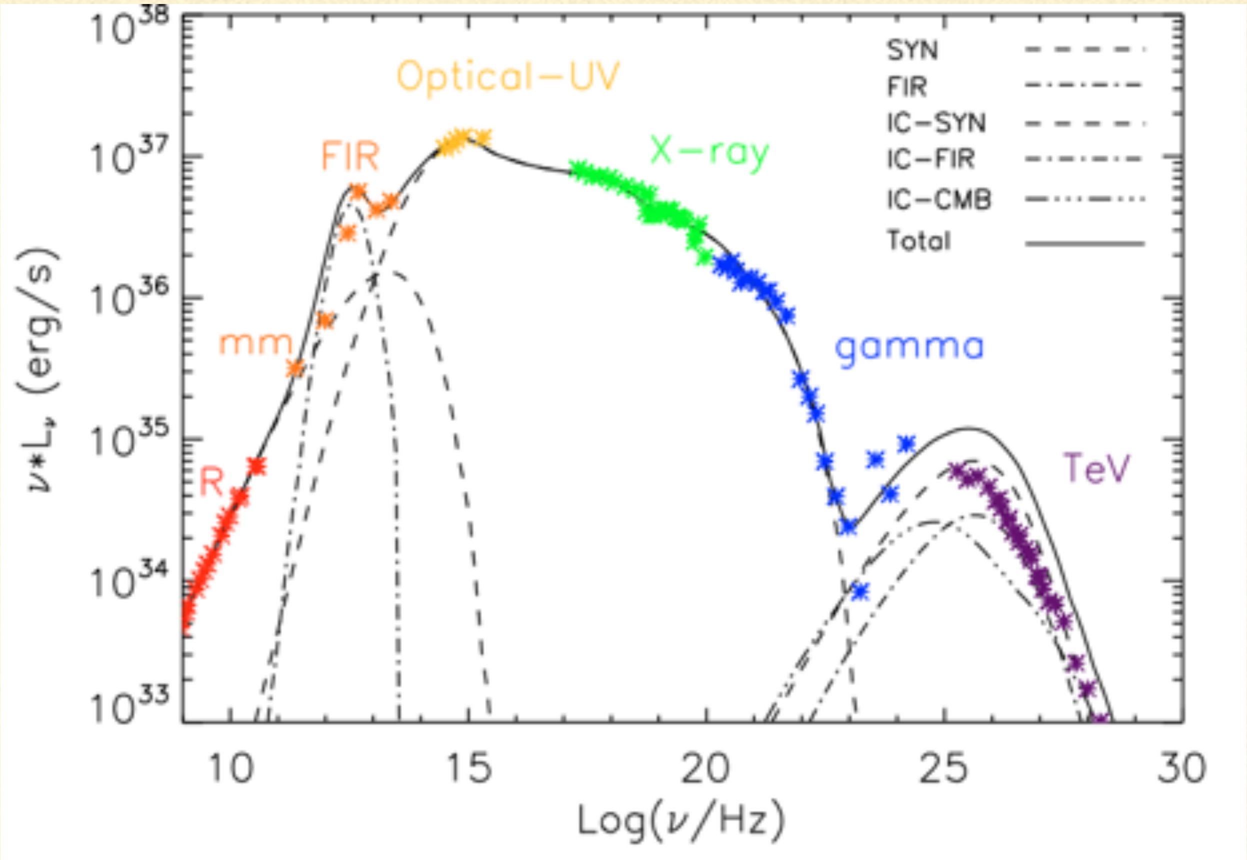




- The termination shock is highly variable due to the large scale waves and vortices downstream of the shock.
- Variability time scale 1-2 years.
- Equatorial outflow highly inhomogeneous, producing the wisps.

Camus et al 2009

# 2D MHD modeling

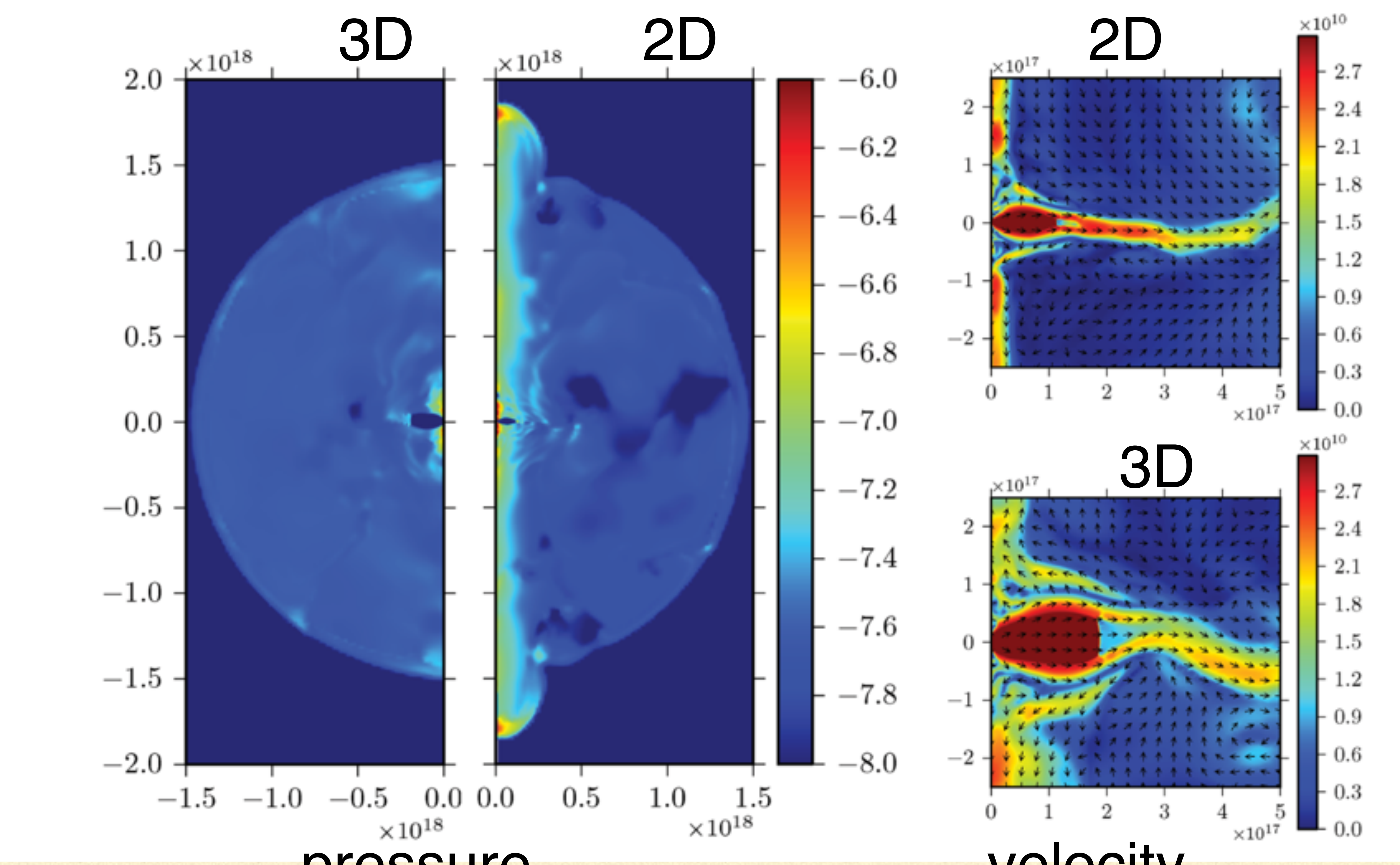


Volpi et al 2008

- This still does not give a good fit to the IC spectrum
  - In order to reproduce the morphology and shock location, σ~0.01
  - Magnetic field has to be weak, since the 2D constraint leads to excessive hoop stress from the toroidal magnetic field
  - Thus, more particles are needed to reproduce the synchrotron spectrum, leading to an over-prediction of IC.

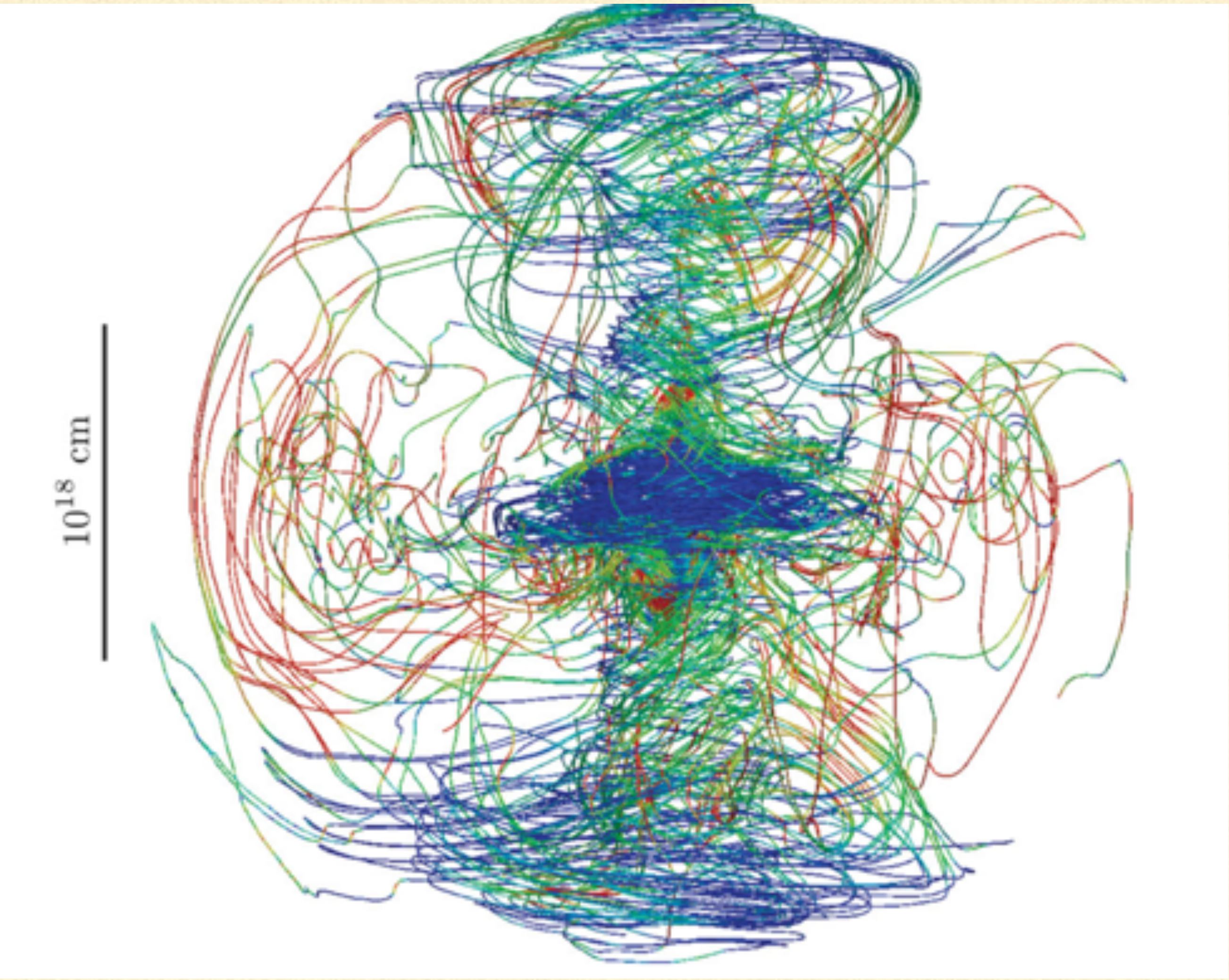
# 3D MHD modeling

Porth et al 2013, 2014



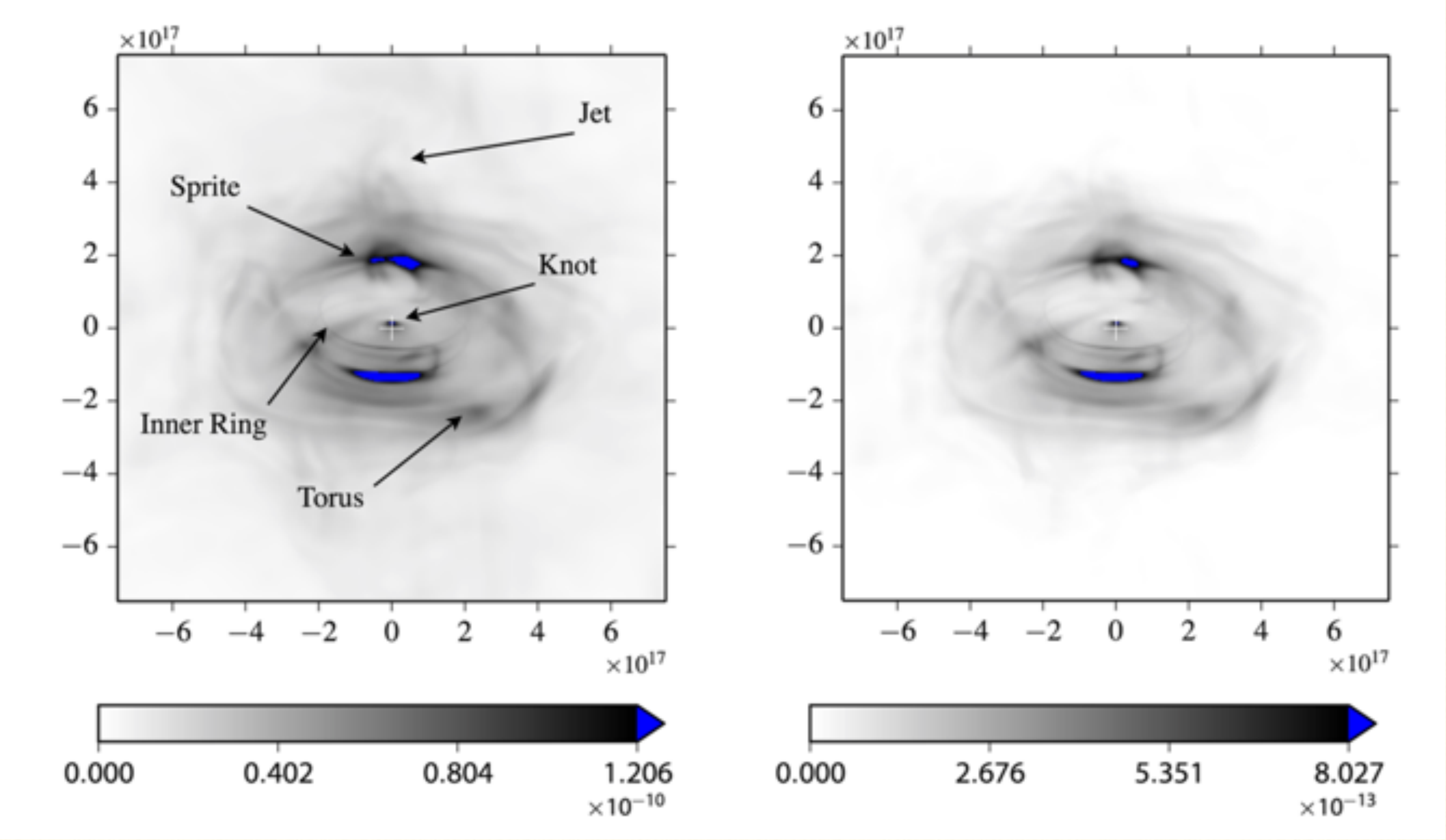
# 3D MHD modeling

## Porth et al 2013, 2014



- Wind magnetization σ as large as 3 is OK
- Magnetic dissipation happen through the following ways:
  - Striped wind is dissipated before or at the termination shock
  - Kink instability of the toroidal field in the nebula

# 3D MHD modeling (Porth et al 2013, 2014)

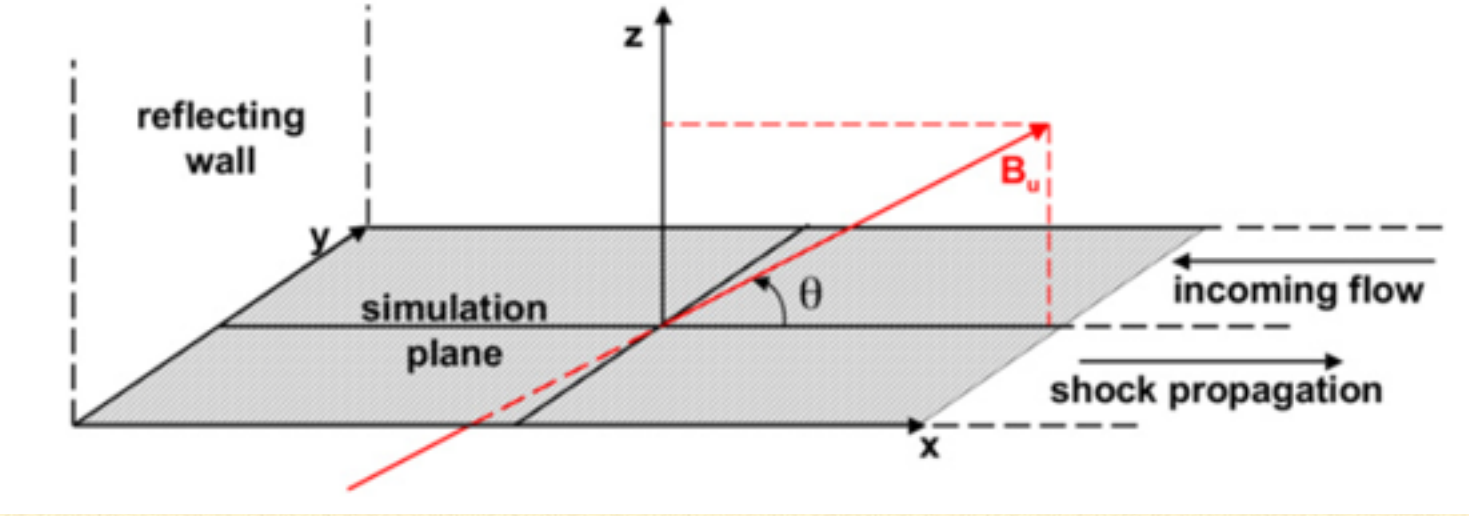


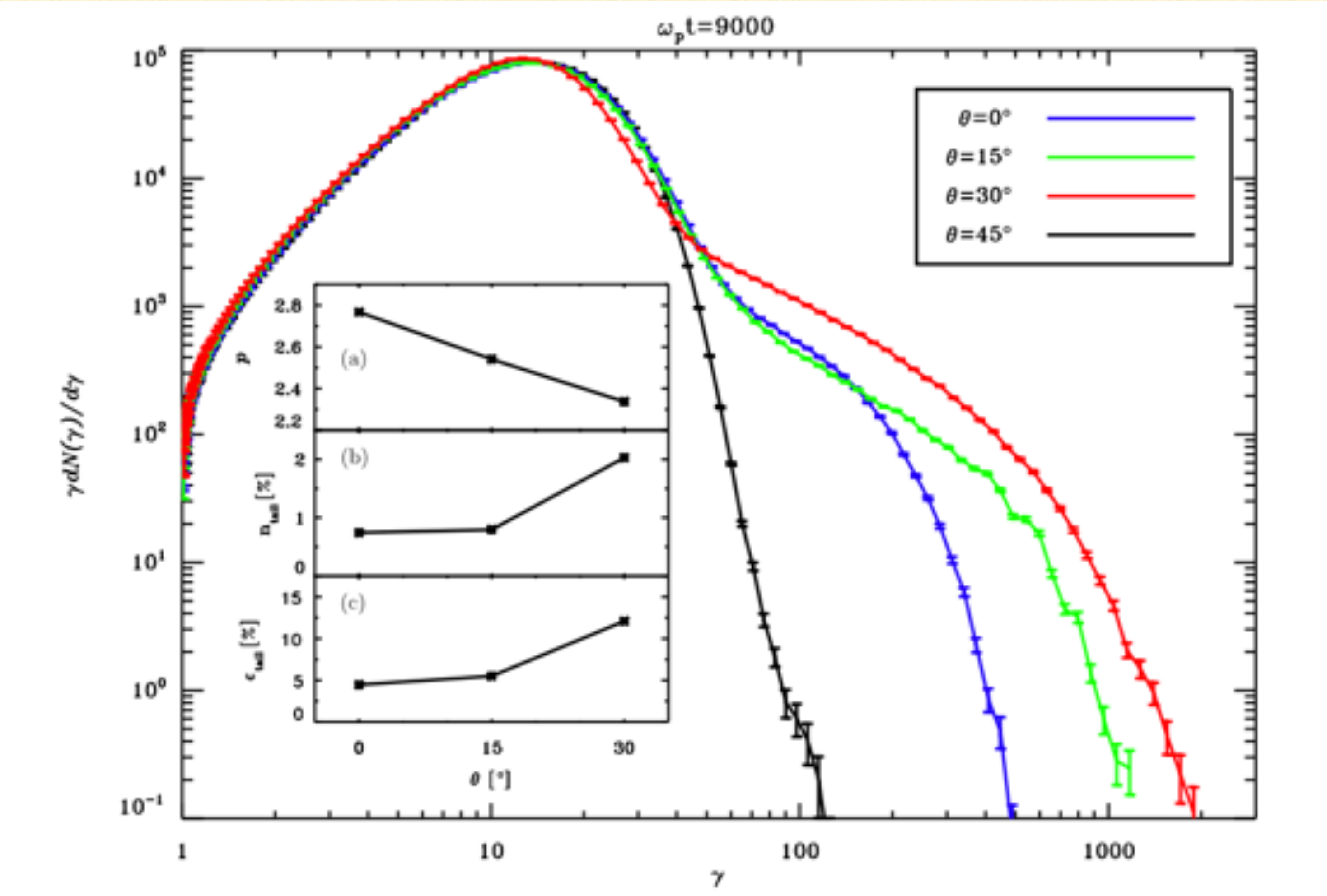
Optical and X-ray synthetic map

- Variability agrees with observations, but the jets are not satisfactorily reproduced. Needs better particle acceleration prescription
- Turbulent flow in 3D—> particle (re)acceleration and diffusion (Porth et al 2016, Tang & Chevalier 2012)

# Particle acceleration at the termination shock of PWN

# A highly magnetized perpendicular shock?





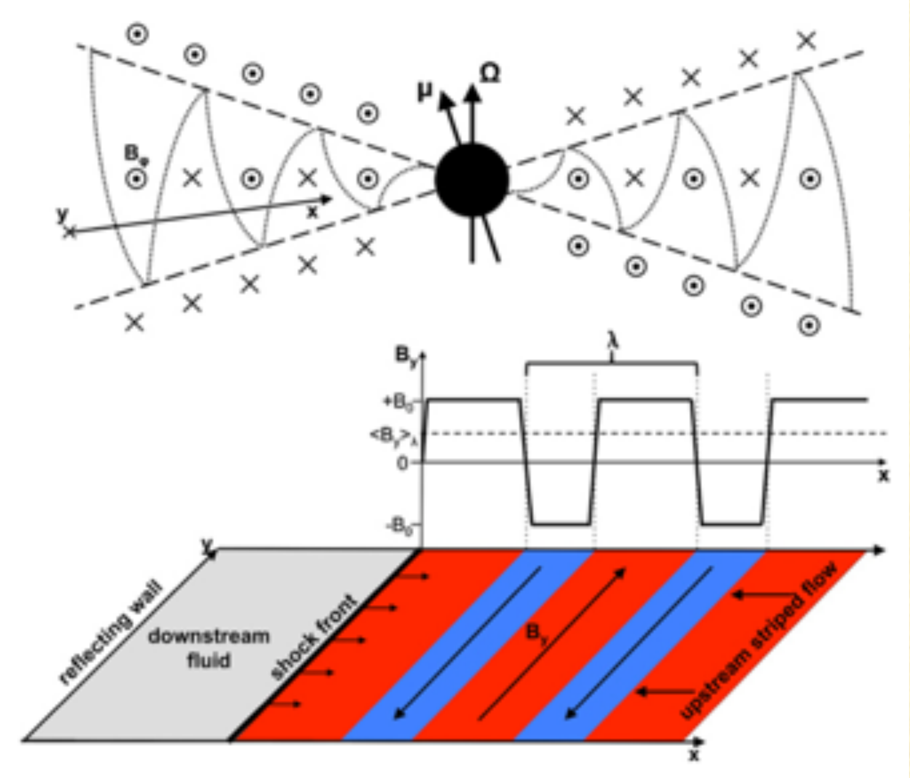
Magnetic field perpendicular to the shock normal

- Magnetized, perpendicular shocks are not efficient for particle acceleration

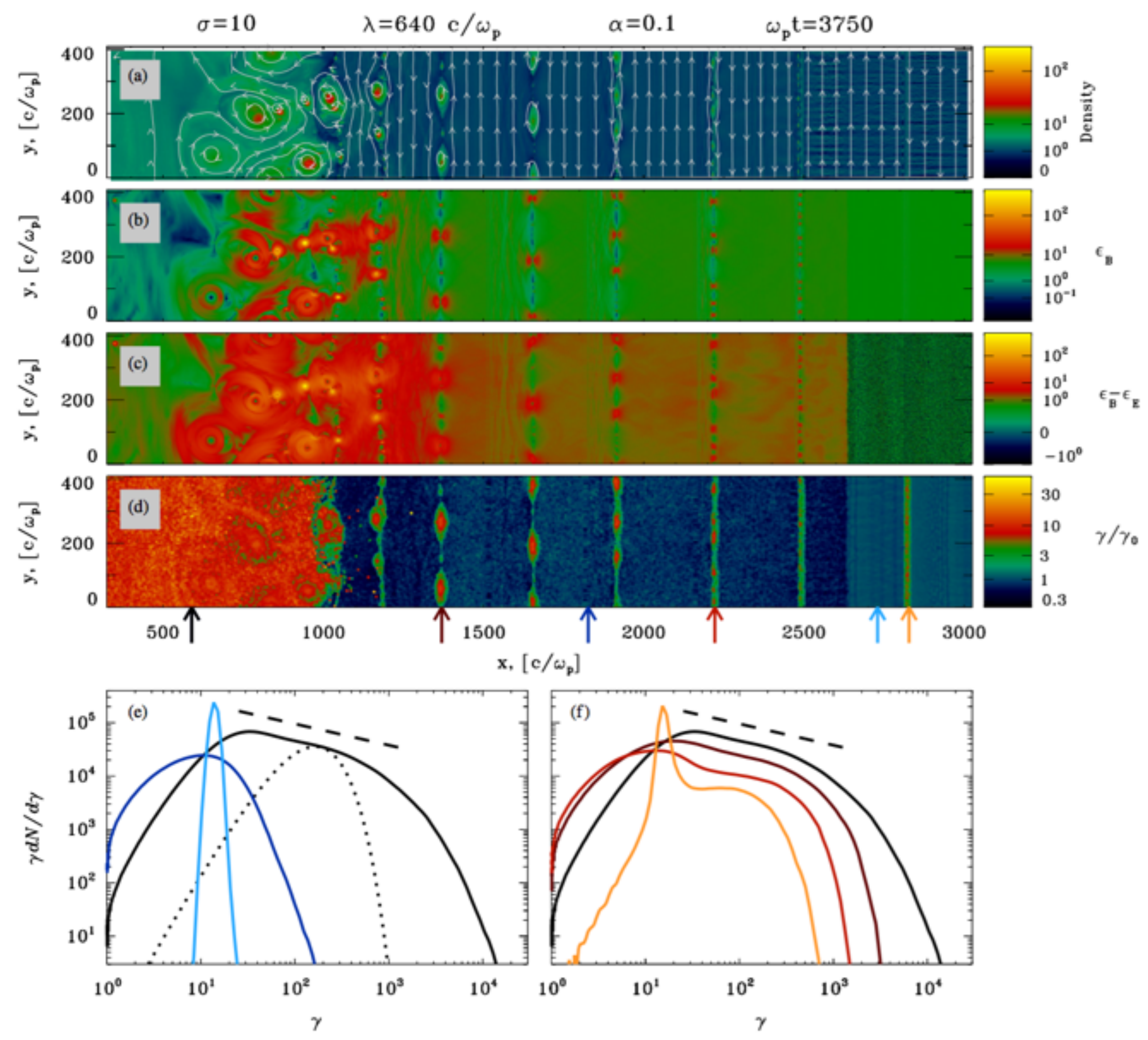
σ=0.1

Sironi&Spitkovsky2009

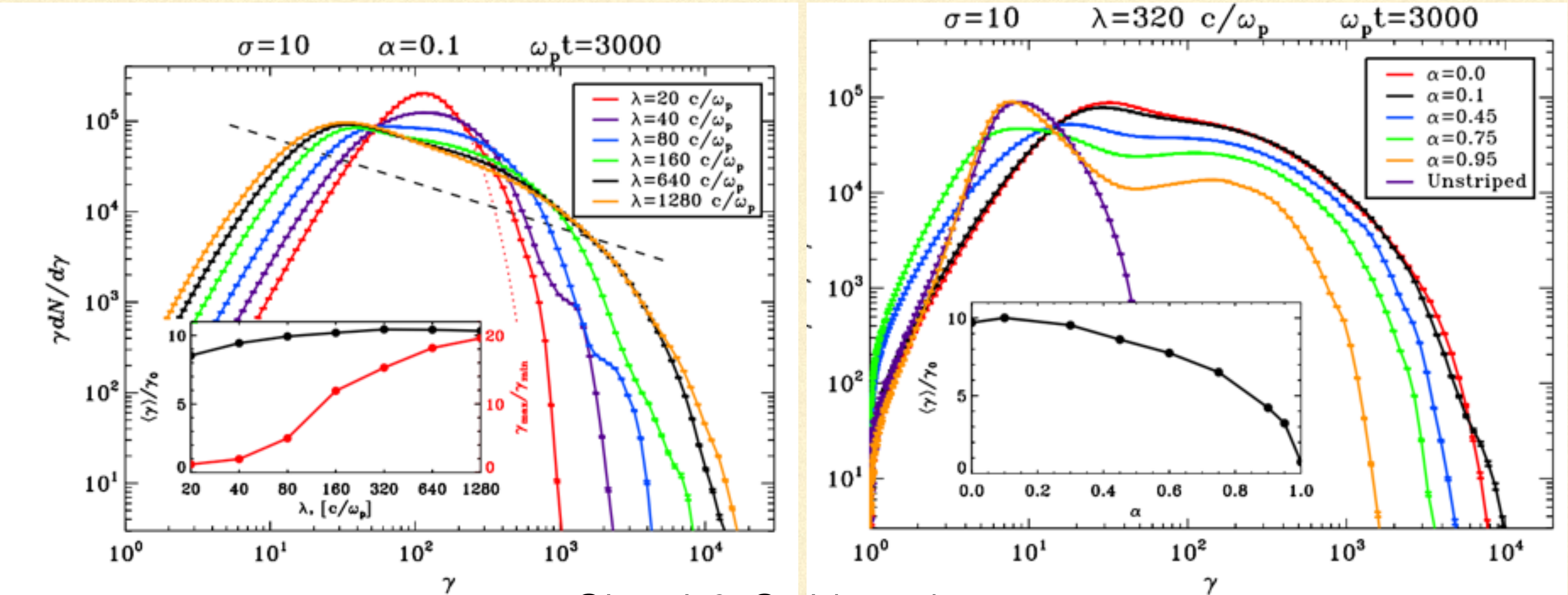
# Driven reconnection of the striped wind



Sironi & Spitkovsky 2011



# Driven reconnection of the striped wind

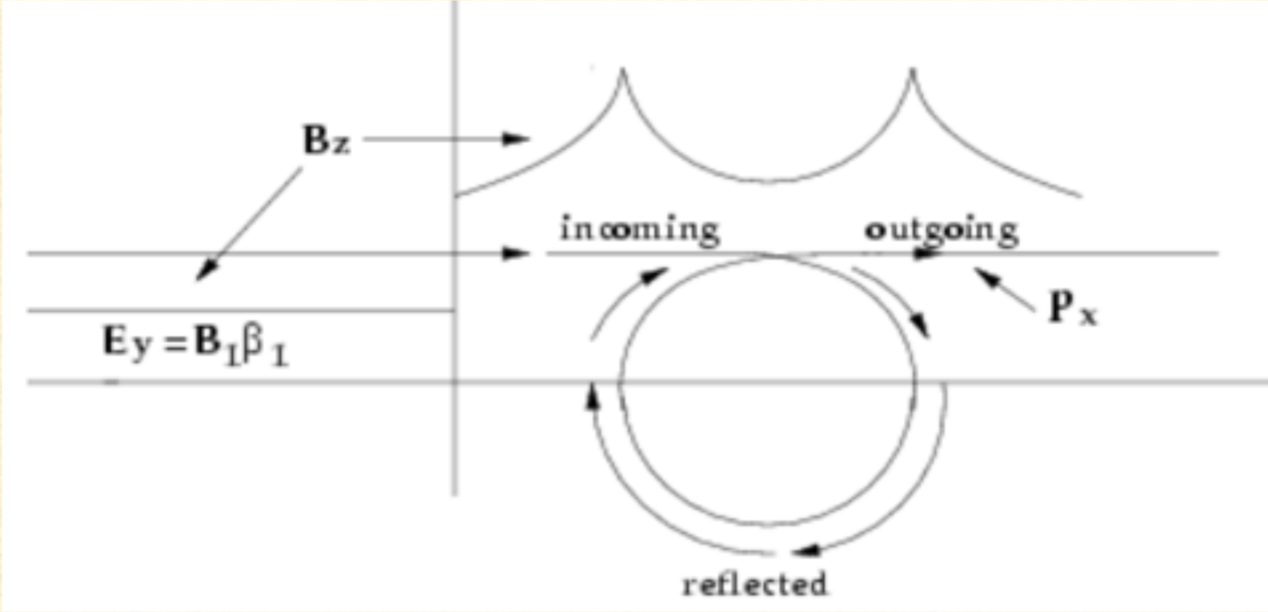


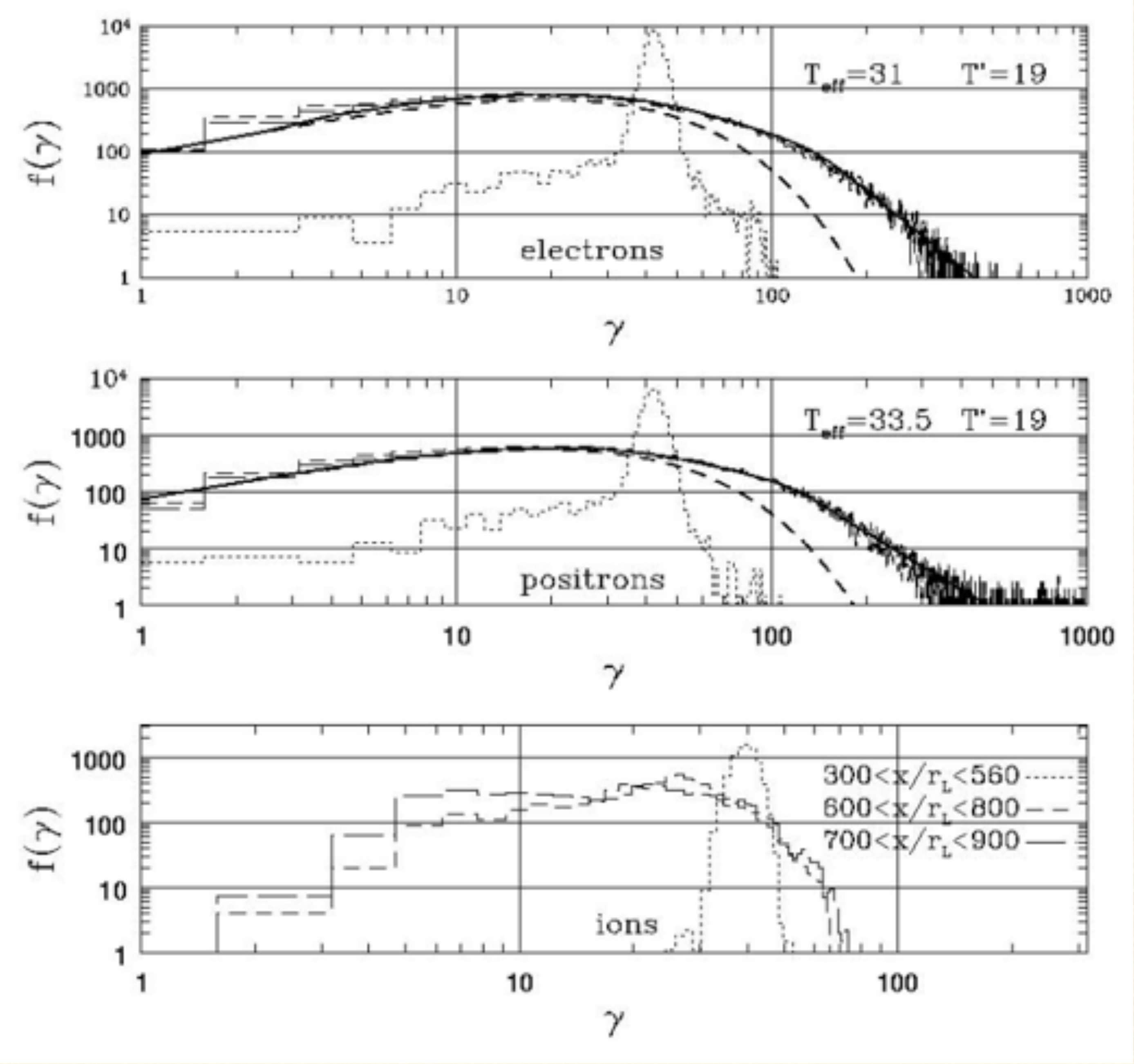
Sironi & Spitkovsky 2011

- Hard spectrum can be produced
- Needs λ/($r_L$σ)>>1, which may not be the case, especially if stripes dissipate before reaching the shock

# Resonant absorption of ion cyclotron waves

(Hoshino & Arons 91, Hoshino et al. 92,
Amato & Arons 06, Stockem et al 12)





- Needs ions to carry a significant amount of energy in the wind

# Summary

- MHD modeling has made good progress in understanding the morphology and spectrum
  - 3D is necessary to account for the dissipation of injected magnetic energy
- Some questions remain open
  - What’s the magnetization, multiplicity, Lorentz factor of the wind?
  - How and where are the particles accelerated?
  - Observation and modeling of gamma-ray binaries etc may help

# Some references

- Lectures by E. Amato at the Cargese summer school 2013.
- Very helpful introductory text:
  - Longair 2011, High energy astrophysics
- Good reviews
  - Arons, J. 2012, Space Science Reviews, 173, 341
  - Buehler, R., & Blandford, R. 2014, Reports on Progress in Physics, 77, 6901
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  - Olmi, B., Del Zanna, L., Amato, E., Bucciantini, N., & Mignone, A. 2016, Journal of Plasma Physics, 82, 635820601
  - Porth, O., Buehler, R., Olmi, B., et al. 2017, Space Science Reviews
  - Reynolds, S. P., Pavlov, G. G., Kargaltsev, O., et al. 2017, Space Science Reviews