Particle Acceleration

(and colliding stellar winds)

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An Inter-disciplinary Workshop/Forum on
Magnetospheric Activities in Moons, Planets, Stars
and Black Holes

MSSL, 19th Sept 2007

Outline

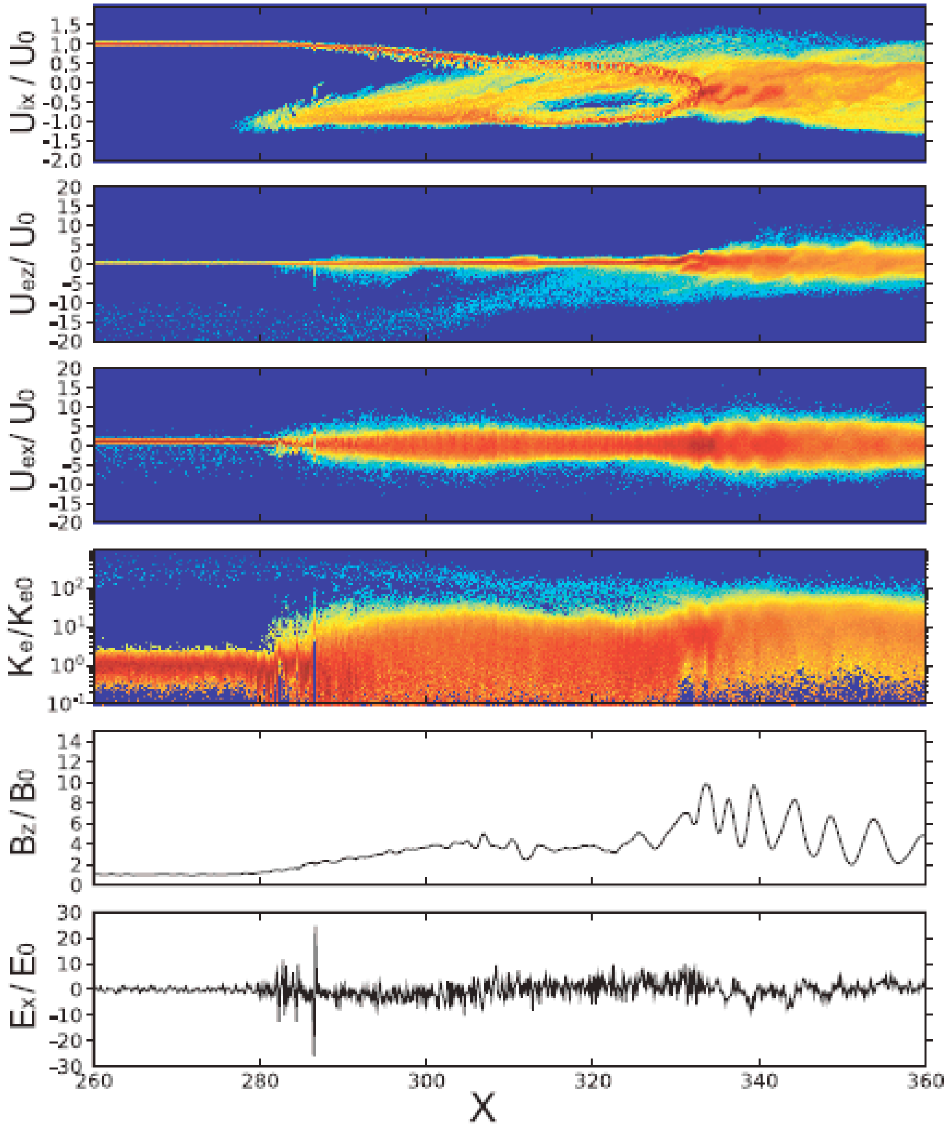
I. Basic Review of Particle Acceleration
  - concentrating on non-relativistic DSA

II. Particle Acceleration at Colliding Stellar Winds

Techniques

- Semi-analytical
- Monte-Carlo
- Particle-in-cell (PIC)

Complemented by lab experiments



Amano & Hoshino (2007)

Reconnection and stochastic acceleration

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Reconnection

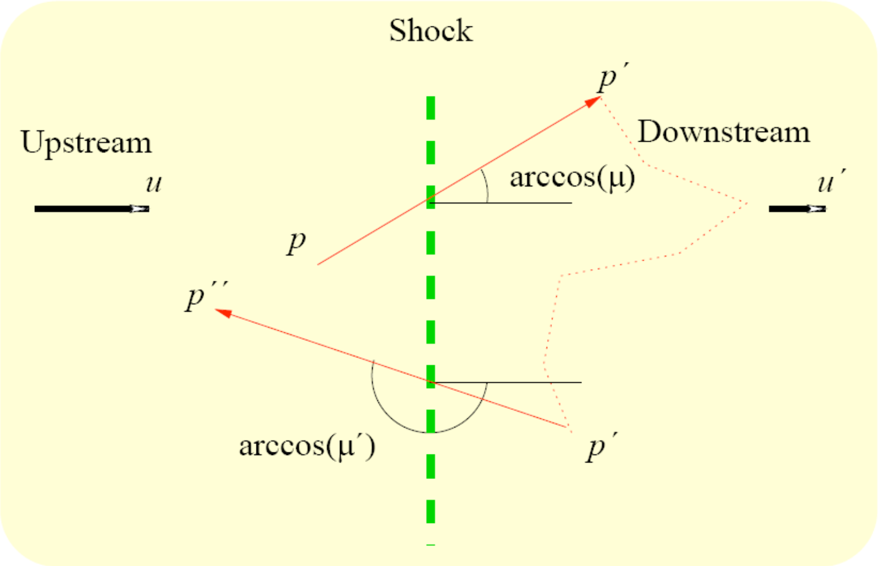
- Usually thought to produce steep spectra
- Complex and intricate magnetic environment
- Particles can be accelerated:
  - Directly (through strong electric fields)
  - Stochastically (2nd order Fermi process due to high turbulence)
  - At MHD shock waves (i.e. through DSA)

2nd order Fermi

- Can give a hard spectrum at low energies (falls off at high E)
- Spectral index depends on additional unknown factors such as the residence time of the particles in the accn. region.
- Mean change in mtm:

$$\frac{\square p}{p} \square \frac{V^2}{v^2}$$

Diffusive Shock Acceleration (DSA)



Scattering by (self-excited) turbulence around shock front

Converging plasma

Isotropy implies

$$\frac{\langle \Delta p \rangle}{p} = \frac{4\Delta u}{3v}$$

Escape probability downstream = $4u_2/v$

Test particle predictions of DSA: $N(E) \propto E^{-p}$

where $p = \dfrac{r_{tot}+2}{r_{tot}-1}$

and r_{tot} is the overall compression ratio

For strong, unmodified shocks, r_{tot} = 4, and p=2

Nonrelativistic (DSA) vs. Relativistic

pitch-angle diffusion _ near-isotropy _ spatial diffusion

solution of PDE in x, p required

small escape probability, small ‹Δp›/p per cycle

spectral index of power-law of particle distribution is independent of scattering law

pitch-angle diffusion, particles in narrow, forward directed cone

solution of PDE in _, x, p required

escape probability ~ 0.5, ‹Δp›/p ~ _^{2} for first cycle, then ~ 2

Spectral index asymptotes as __ ∞, weakly dependent on scattering law

Shock crossings/reflections

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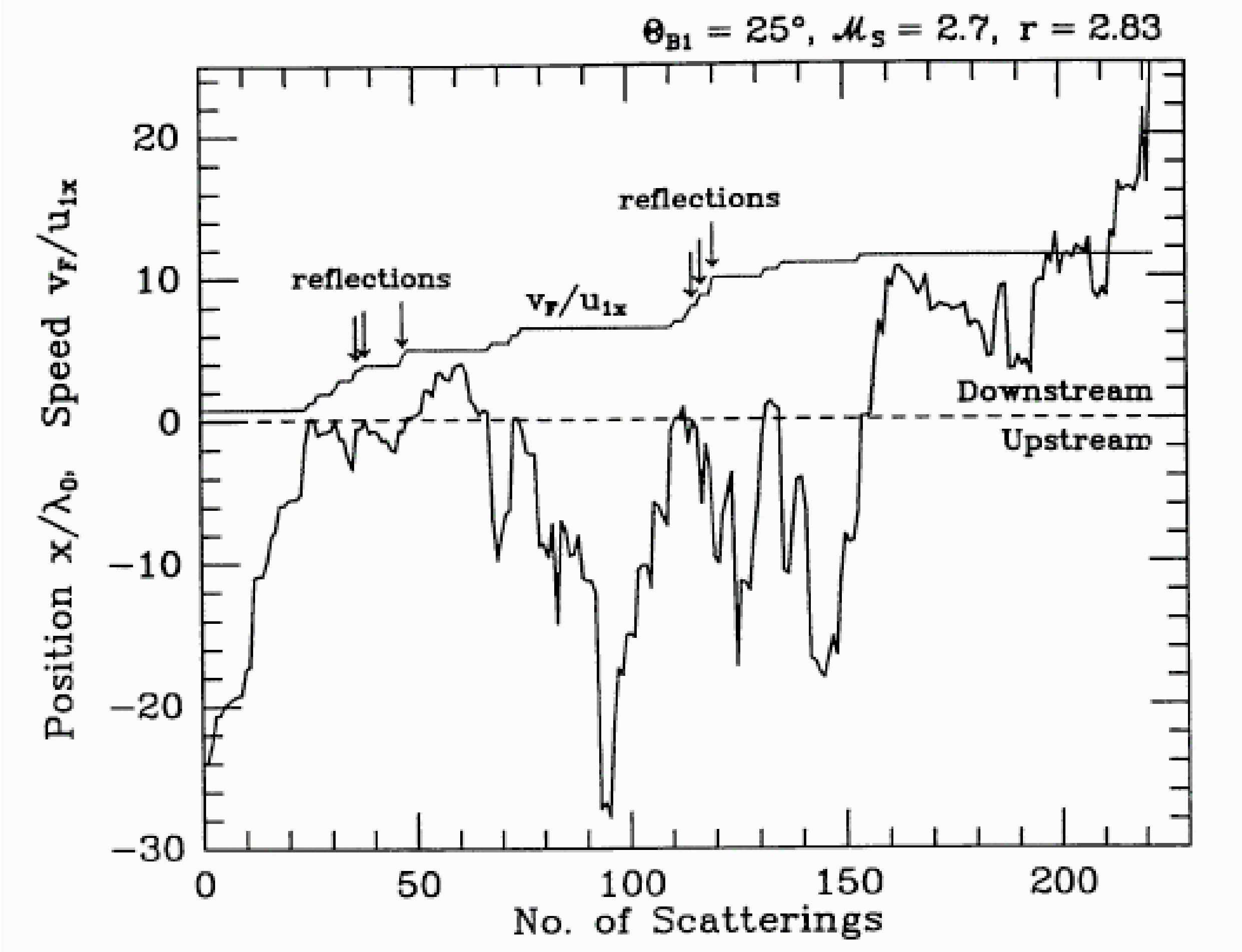
Monte Carlo model – particles pitch-angle scatter elastically and isotropically

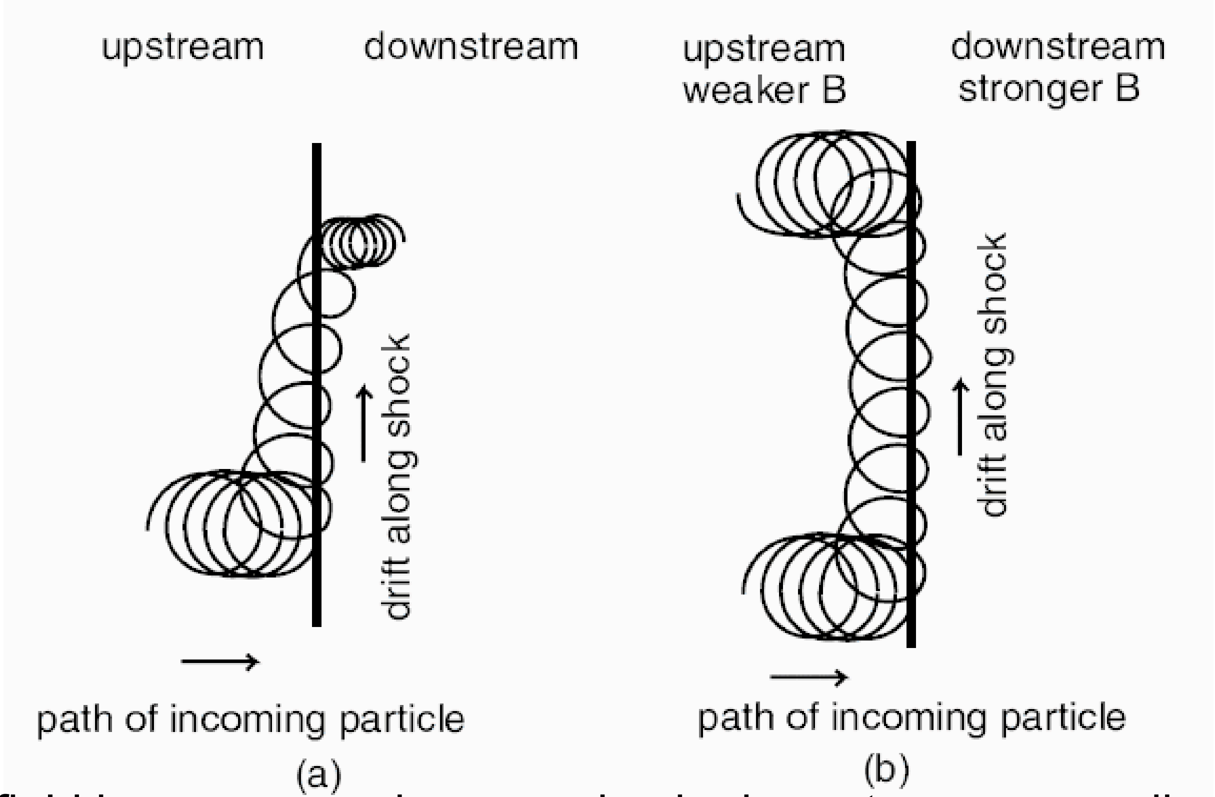


Any “thermal” particle which manages to diffuse back upstream across the shock gains energy and becomes superthermal. The viscous subshock is assumed to be transparent to all particles, even thermal ones, and any downstream particle with v ≥ u2 has a chance to be injected.

Baring et al. (1994)

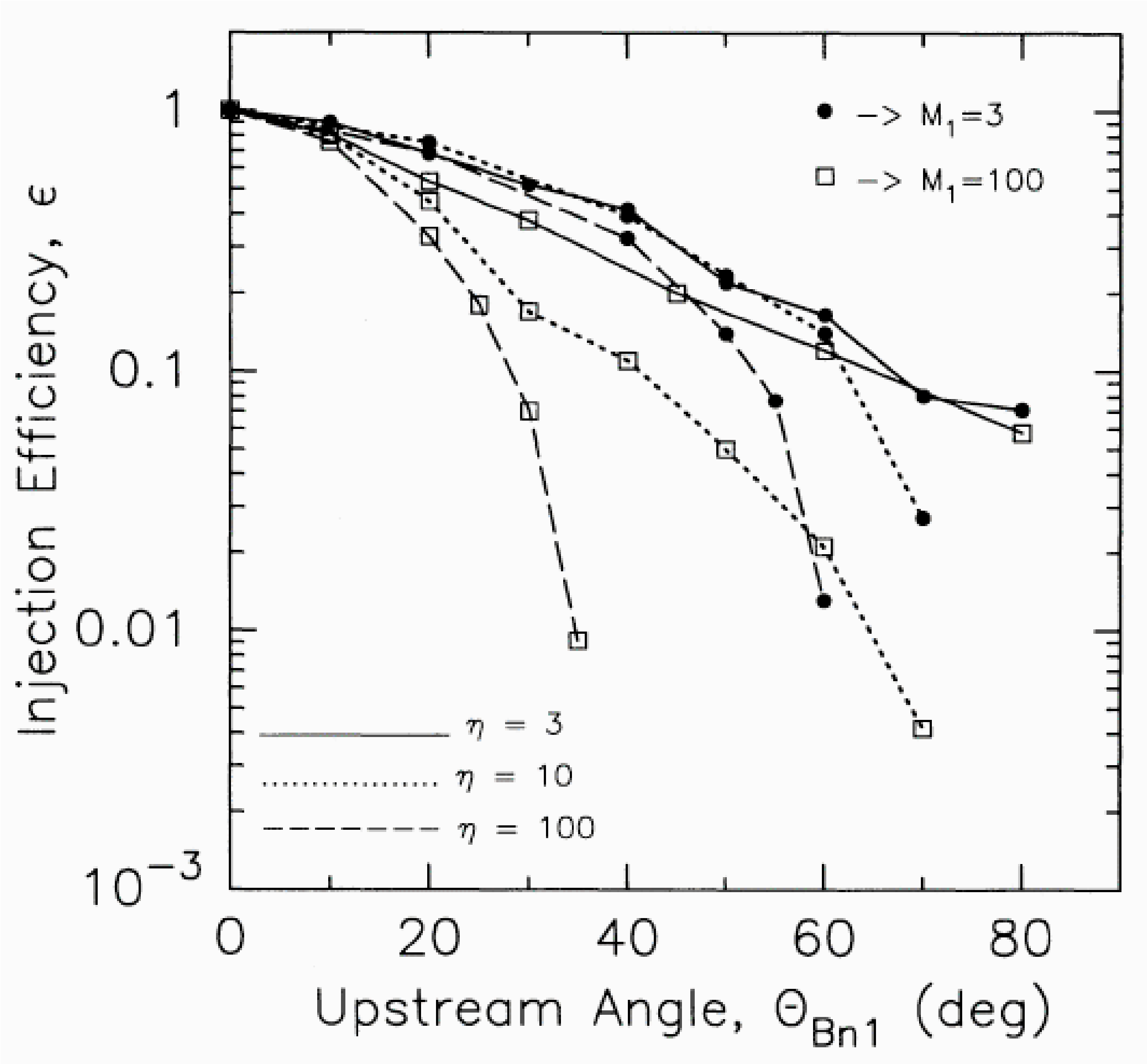
Shock drift

Occurs for oblique shocks



- When B-field is compressed across shock, downstream gyroradius is smaller than upstream gyroradius – causes particle to “drift” along the shock front
- If particle moves at an angle to the B-field it sees an electric field which may either accelerate/decelerate the particle depending on the direction of motion
- Accn is more rapid in oblique shocks due to shock drift along the shock surface and slower diffusion in the shock normal direction.

Injection efficiency



DSA - spectral index

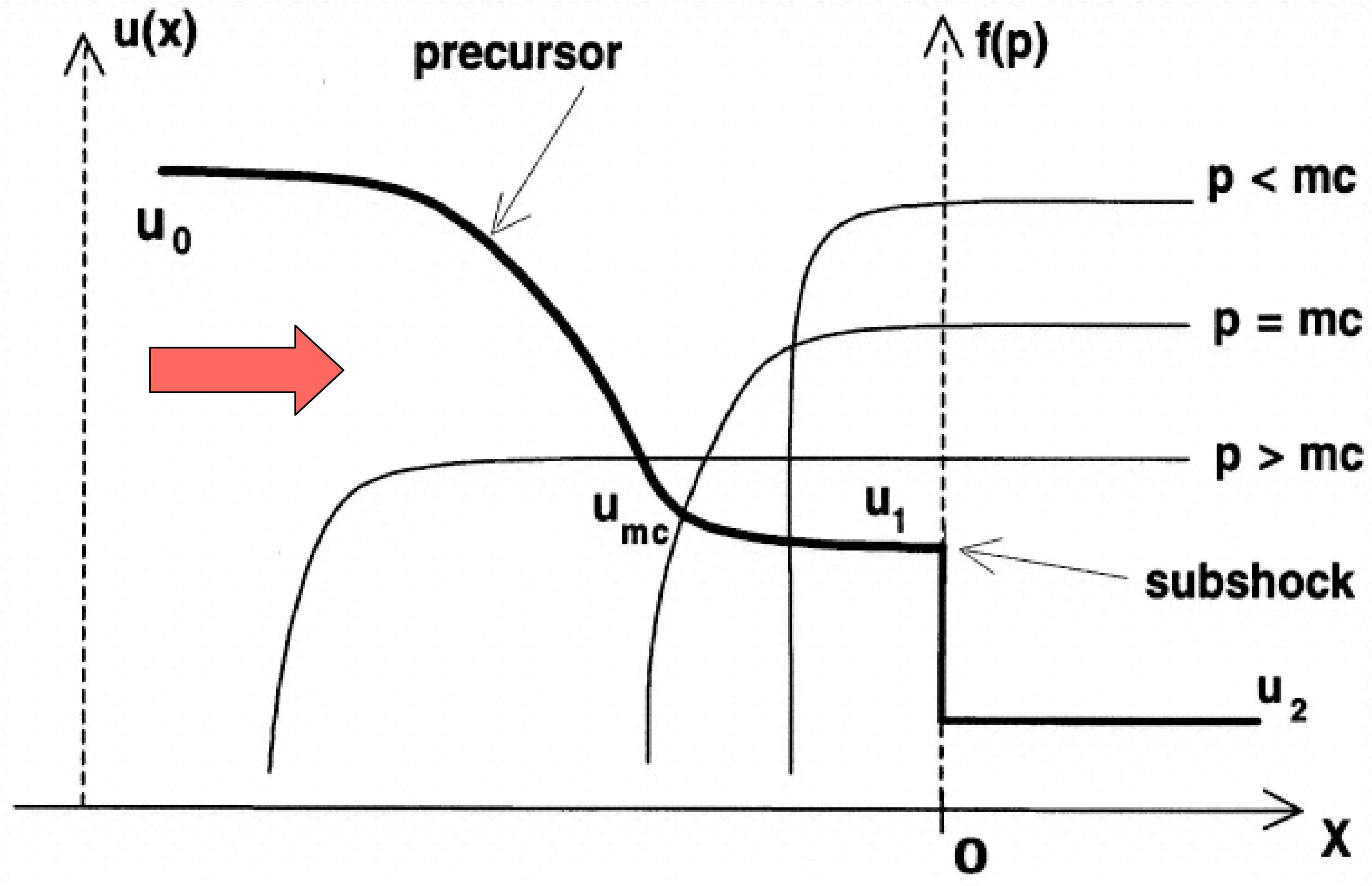
Harder (flatter) CR spectra can be obtained by

1) Shock modification (at high energies)
2) Radiative losses (compression ratio increases)
3) Non-standard DSA (e.g. anisotropic scattering)
4) More complex flow (e.g. multiple shocks)
5) Various turbulence mechanisms
6) If plasma _ is low, scattering center compression ratio ≠ gas compression ratio

Softer (steeper) spectra can be obtained by

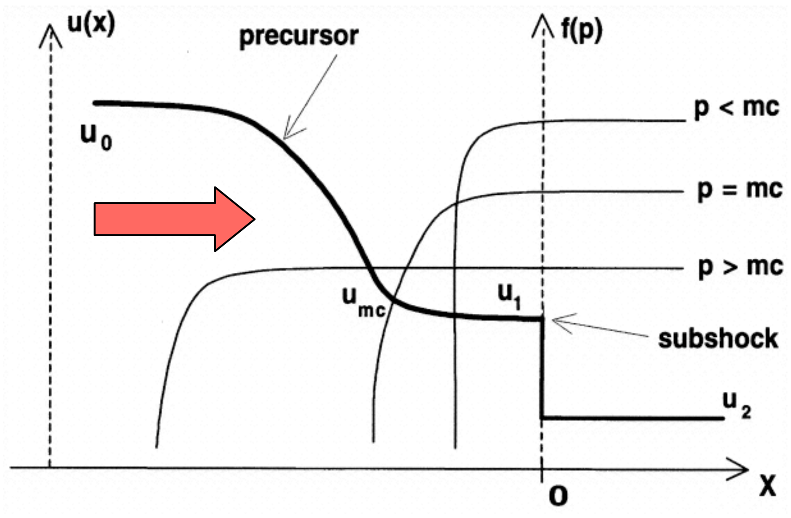
1) Shock modification (at low energies)
2) Shock curvature (high energy particles escape more readily)
3) Non-standard DSA (e.g. subdiffusive regimes)

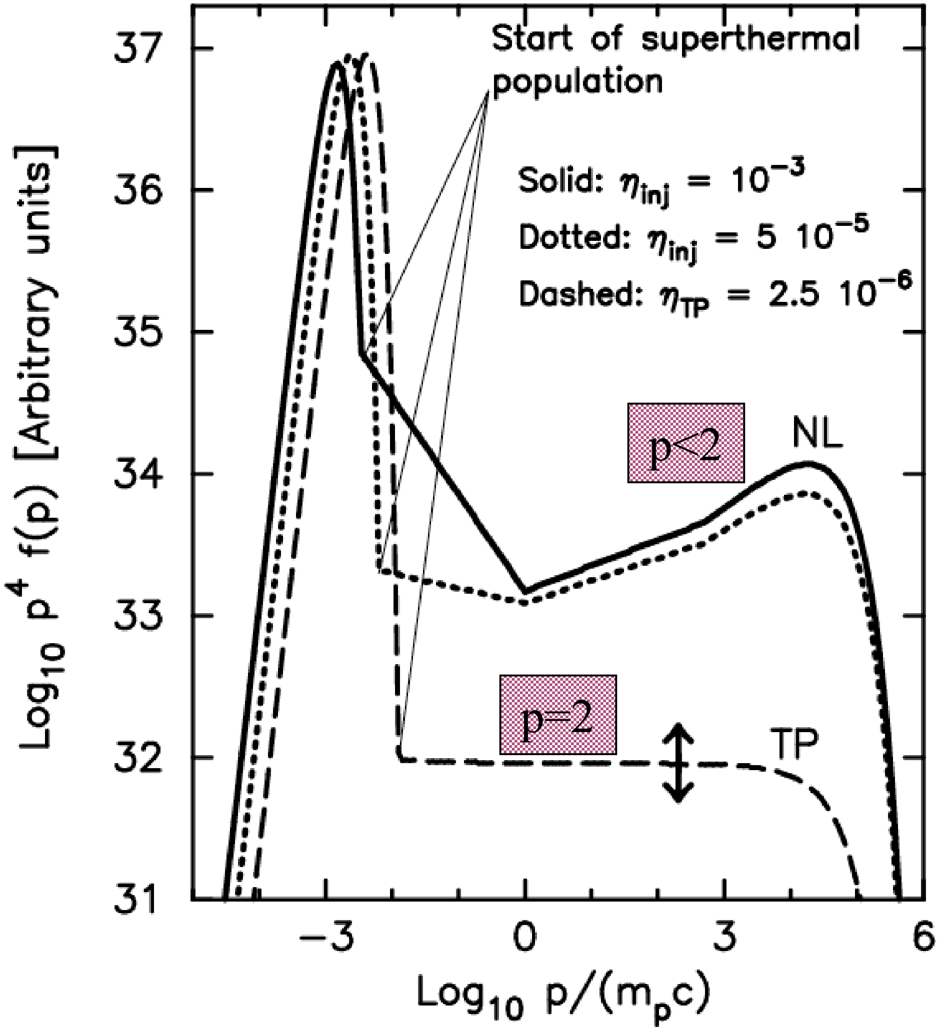
Shock modification



Berezhko & Ellison (1999)

Concave NT particle spectra





Ellison et al. (2004)

Shock modification evidence

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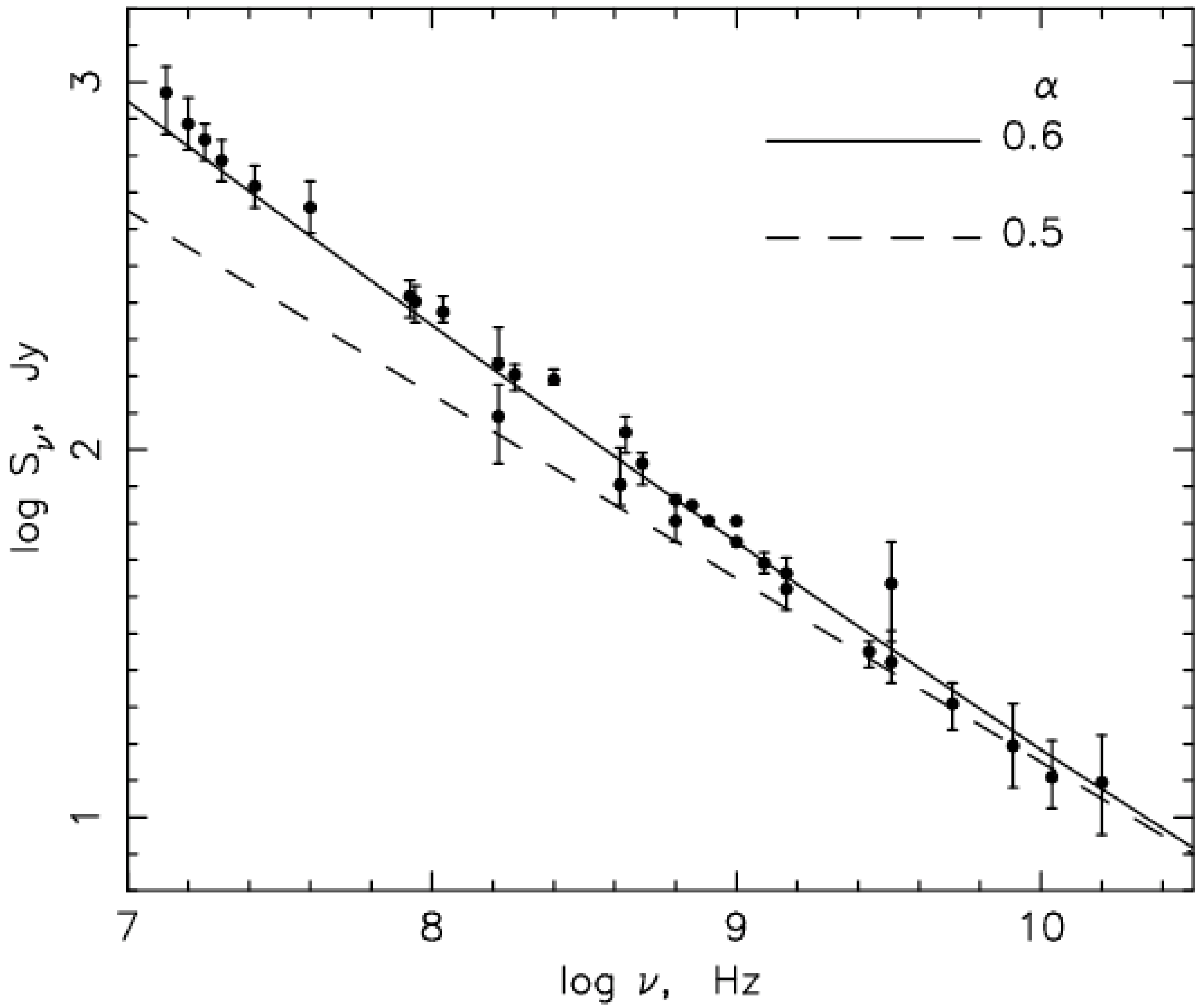
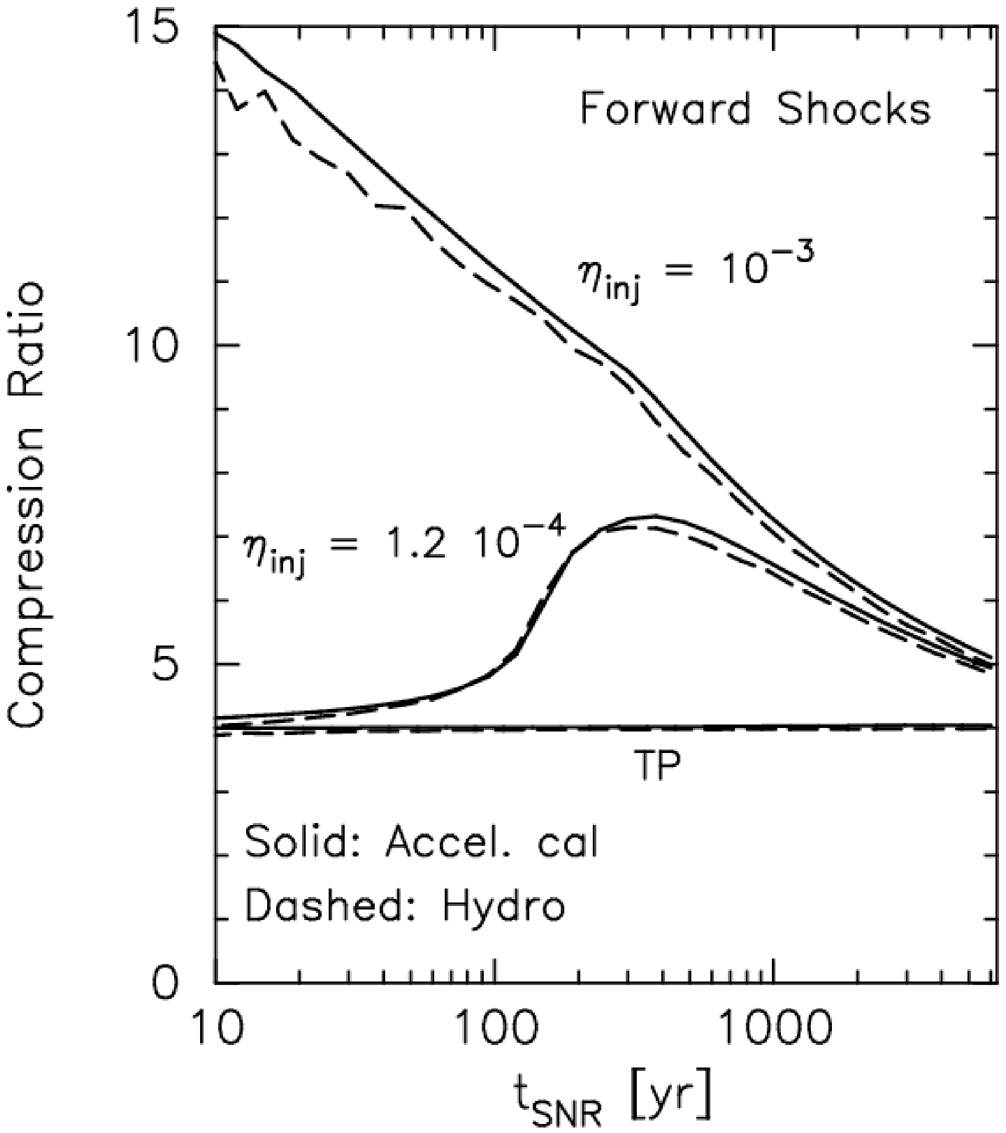
Tycho SNR



Volk et al (2002)

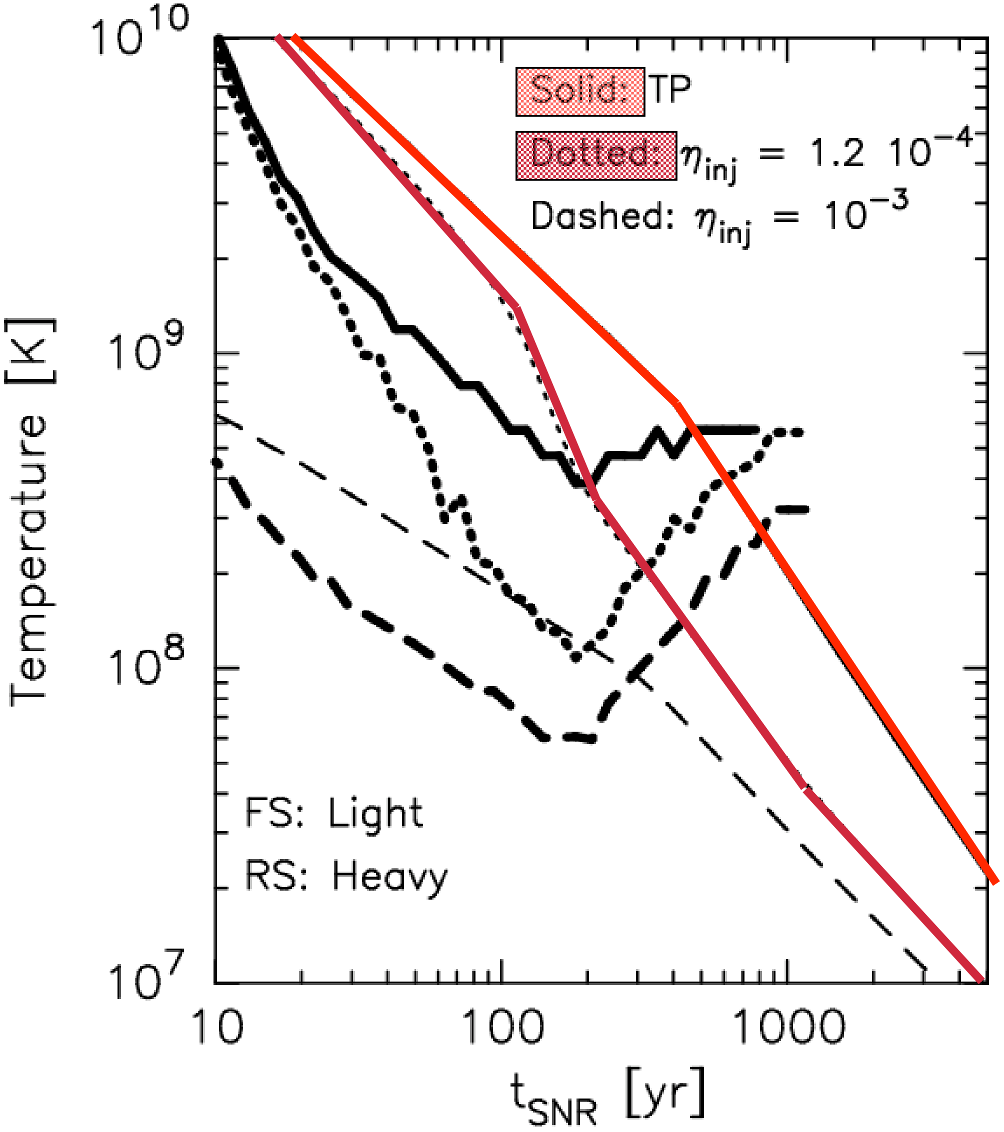
Shock Modification



Higher overall compression ratios

Ellison et al. (2004)

Shock modification



Lower post-shock
ion temperatures

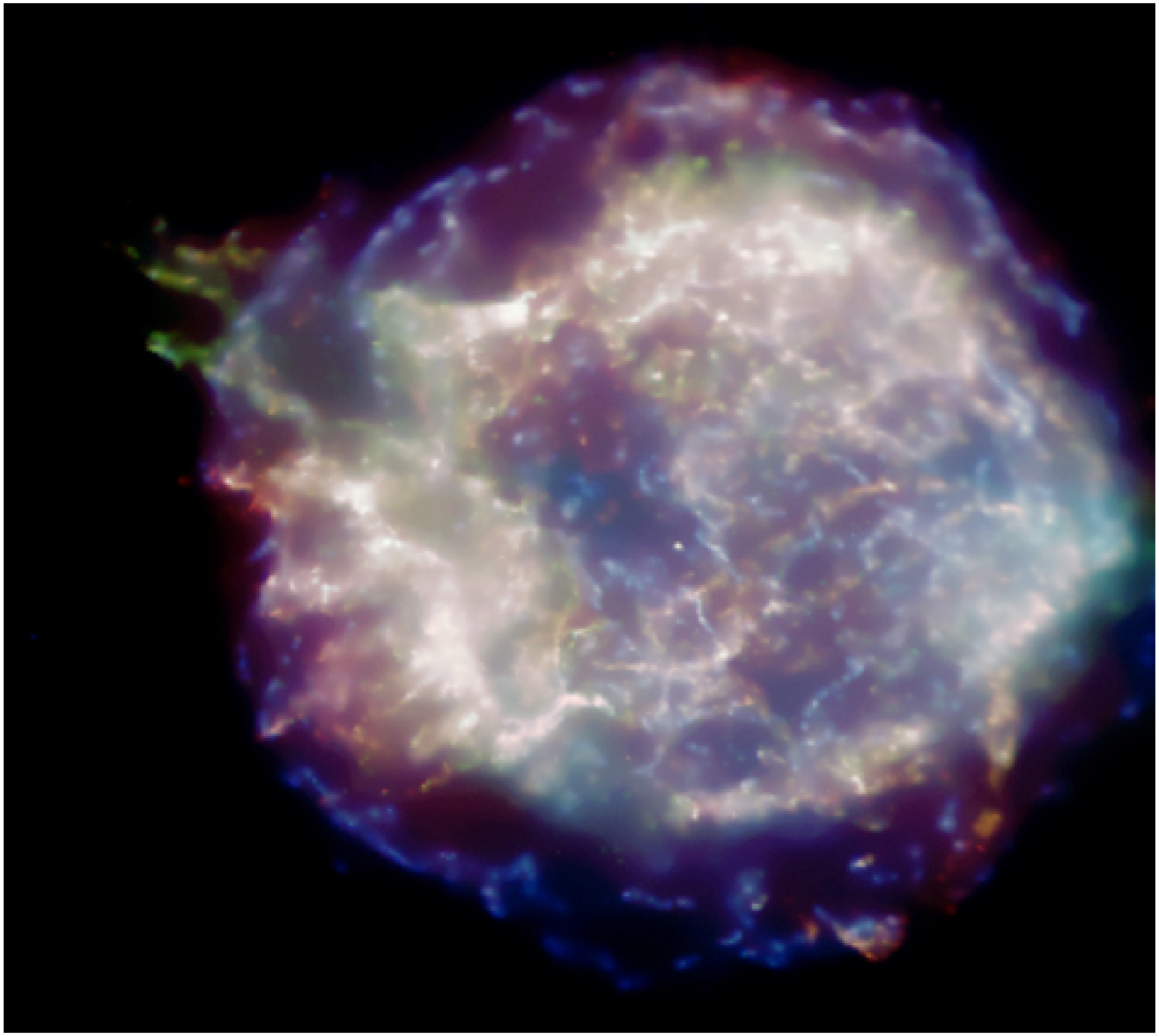
Ellison et al. (2004)

B-field amplification – evidence (I)

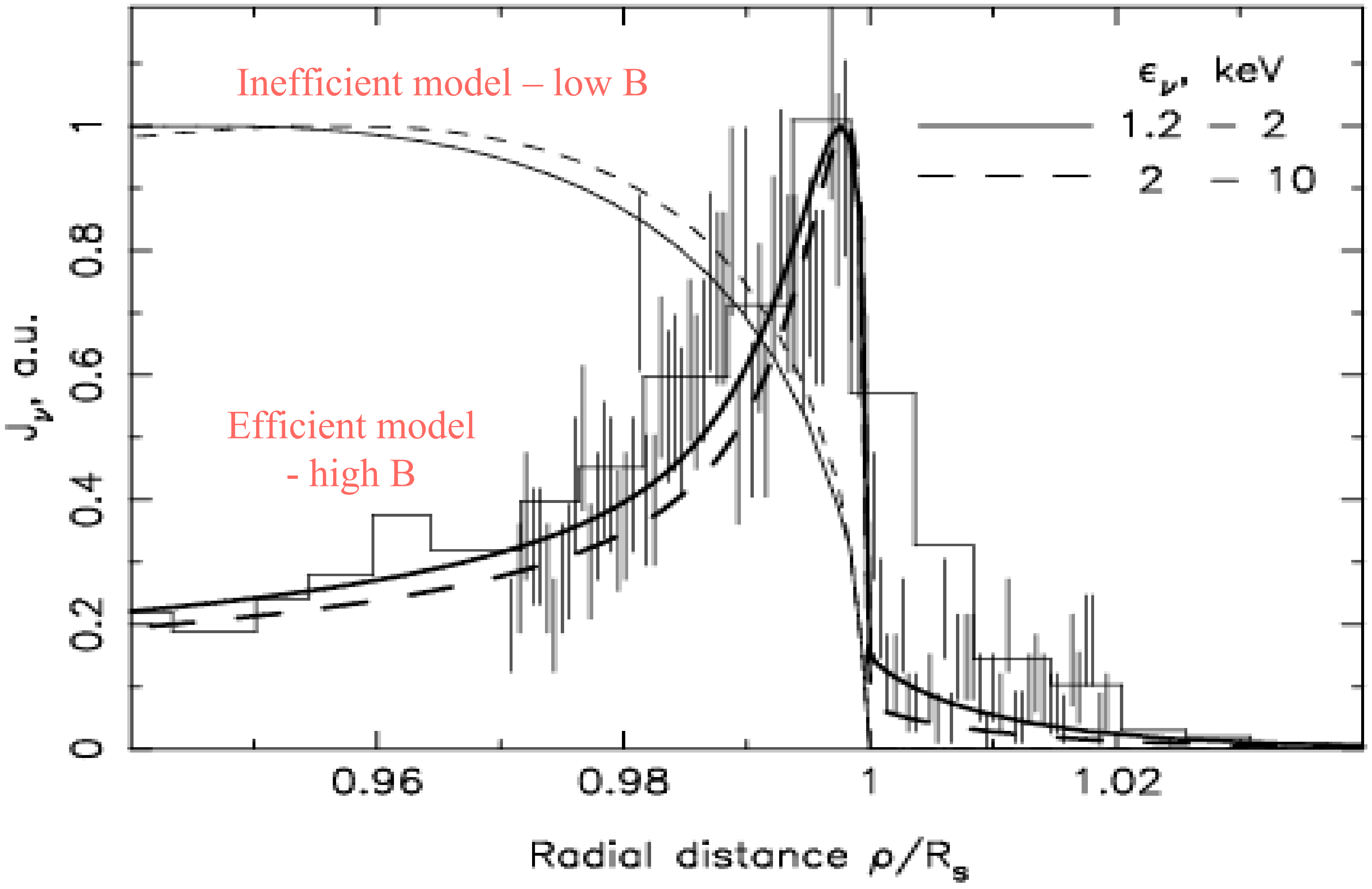
Several young objects well studied in X-ray synchrotron radiation

Thin filaments suggest rapid cooling of electrons: $B_{shock} >> B_{ISM}$

Also brightness contrast of sync X-rays upstream and downstream of the shock is ~50, whereas it is expected to be <16 with simple MHD compression at the shock.



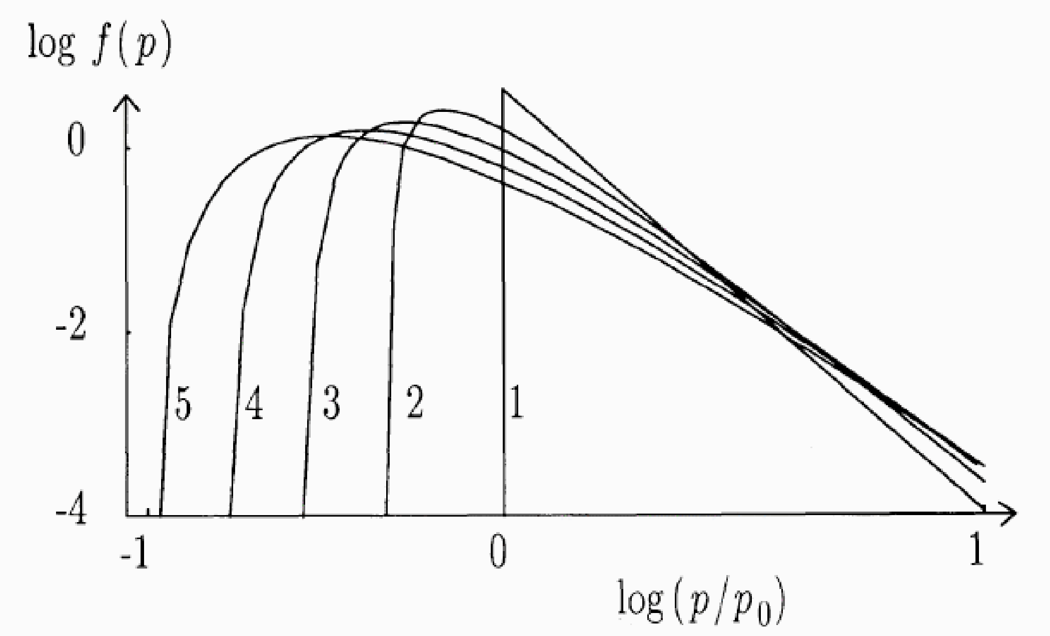
B-field amplification – evidence (II)



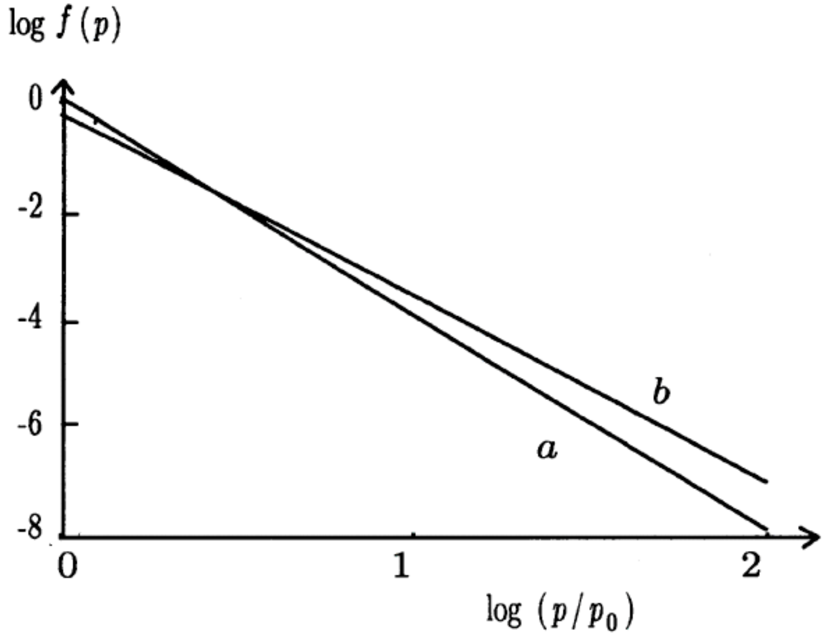
Berezhko et al. (2003)

Re-acceleration

- Acceleration at a sequence of shocks can flatten the spectral index
- p_1 after an arbitrary number of shocks (independent of shock strength)
- Adiabatic decompression between each shock is a central assumption (causing decrease in mtm)



Spectrum of particles injected at 1st shock, after subsequent shocks



Total spectrum of all particles

Melrose & Pope (1993)

Westerlund 2

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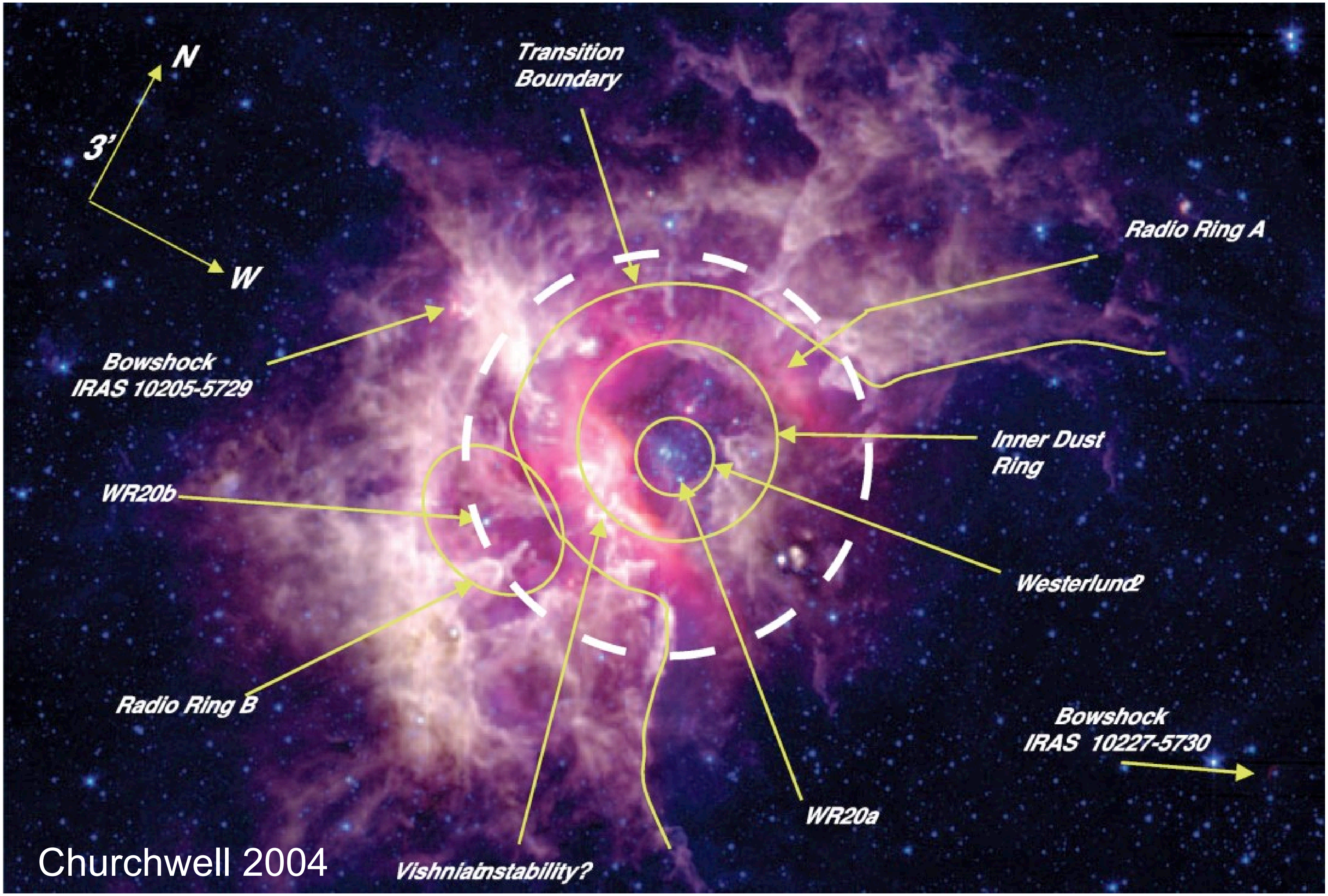

Churchwell 2004

HESS J1023-575

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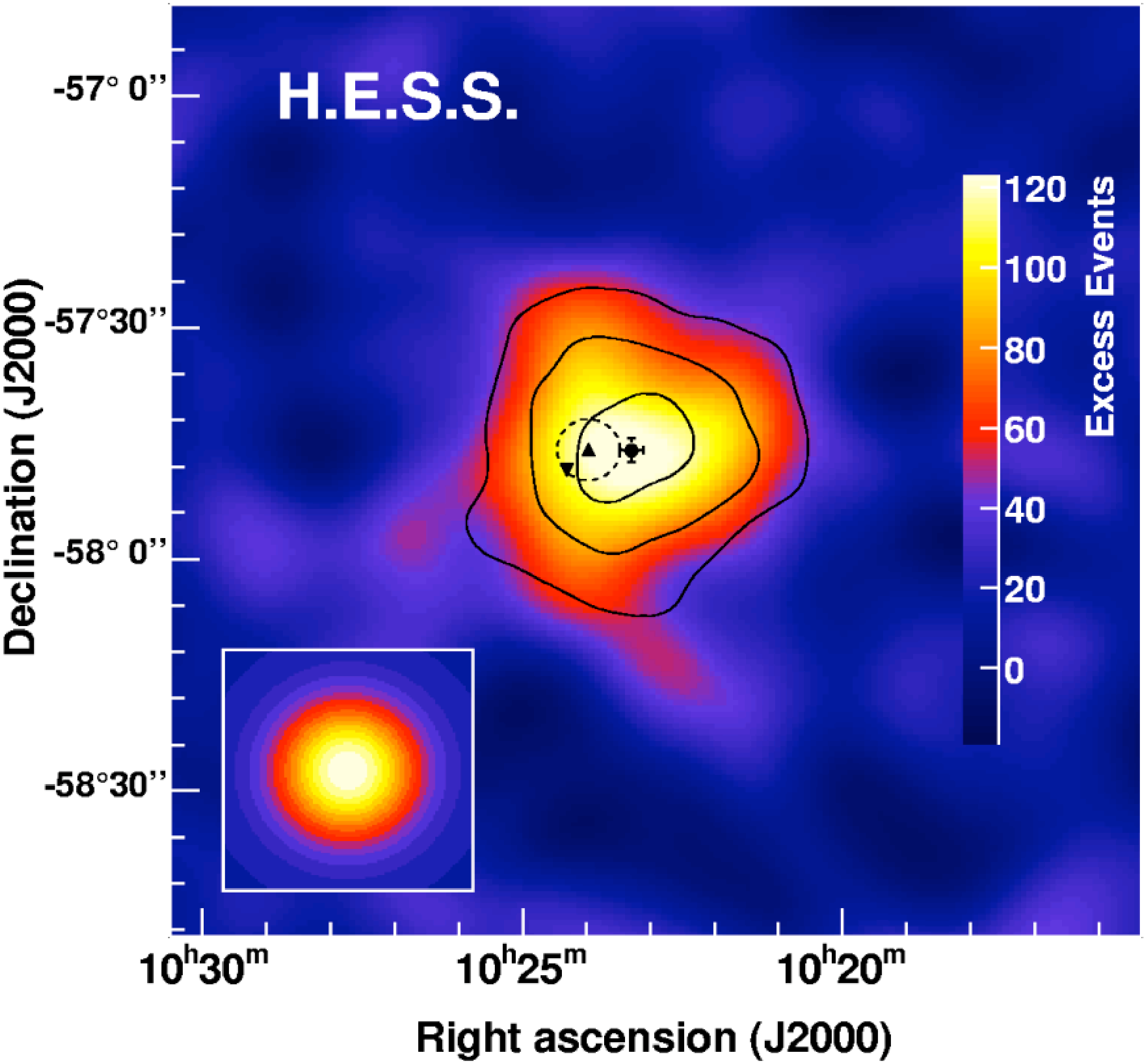
Extended gamma-ray emission covering (but offset from) Westerlund 2

Due to collective effects of stellar winds in the cluster?



Outstanding issues

(Electron) Injection

DSA is only applicable to particles which gyrate on a lengthscale larger than the lengthscale of the subshock (~ a thermal particle gyroradius) – ie those which are already suprathermal

B-field amplification

There should be some form of conversion of CR particle energy into magnetic turbulence in the precursor. But what form is the heating (adiabatic or Alfven heating?)

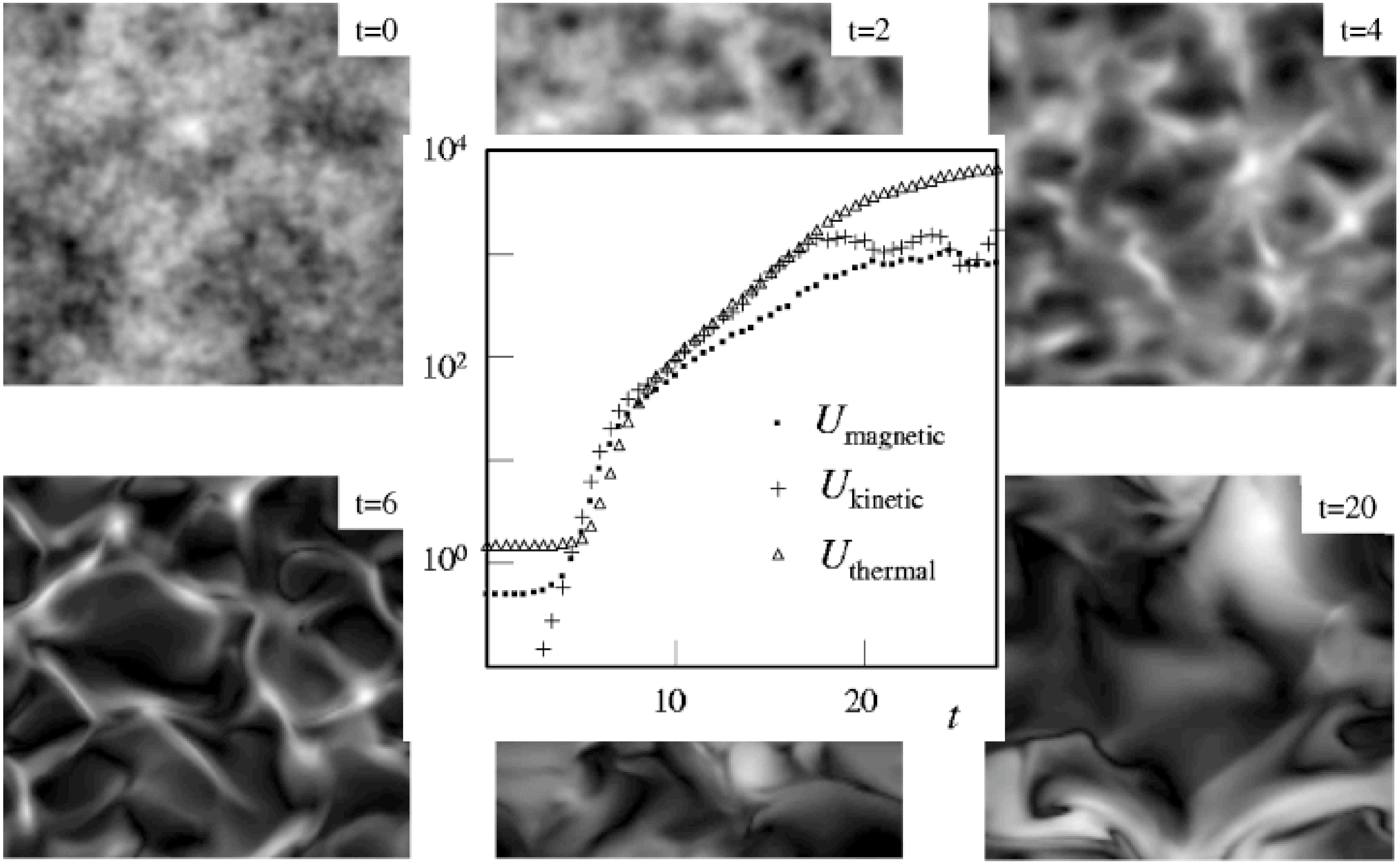
If this process is efficient, the rate of work done on the upstream Alfven turbulence of energy density U_A naturally scales with the CR pressure gradient:

$$\frac{dU_A}{dt} = v_A \left| \nabla P_{CR} \right|$$

The associated field amplification should then scale as $\left(\delta B / B\right)^2 \sim M_A P_{CR} / \rho u_2^2$

This becomes very effective for strong shocks with large CR pressures

B-field Amplification

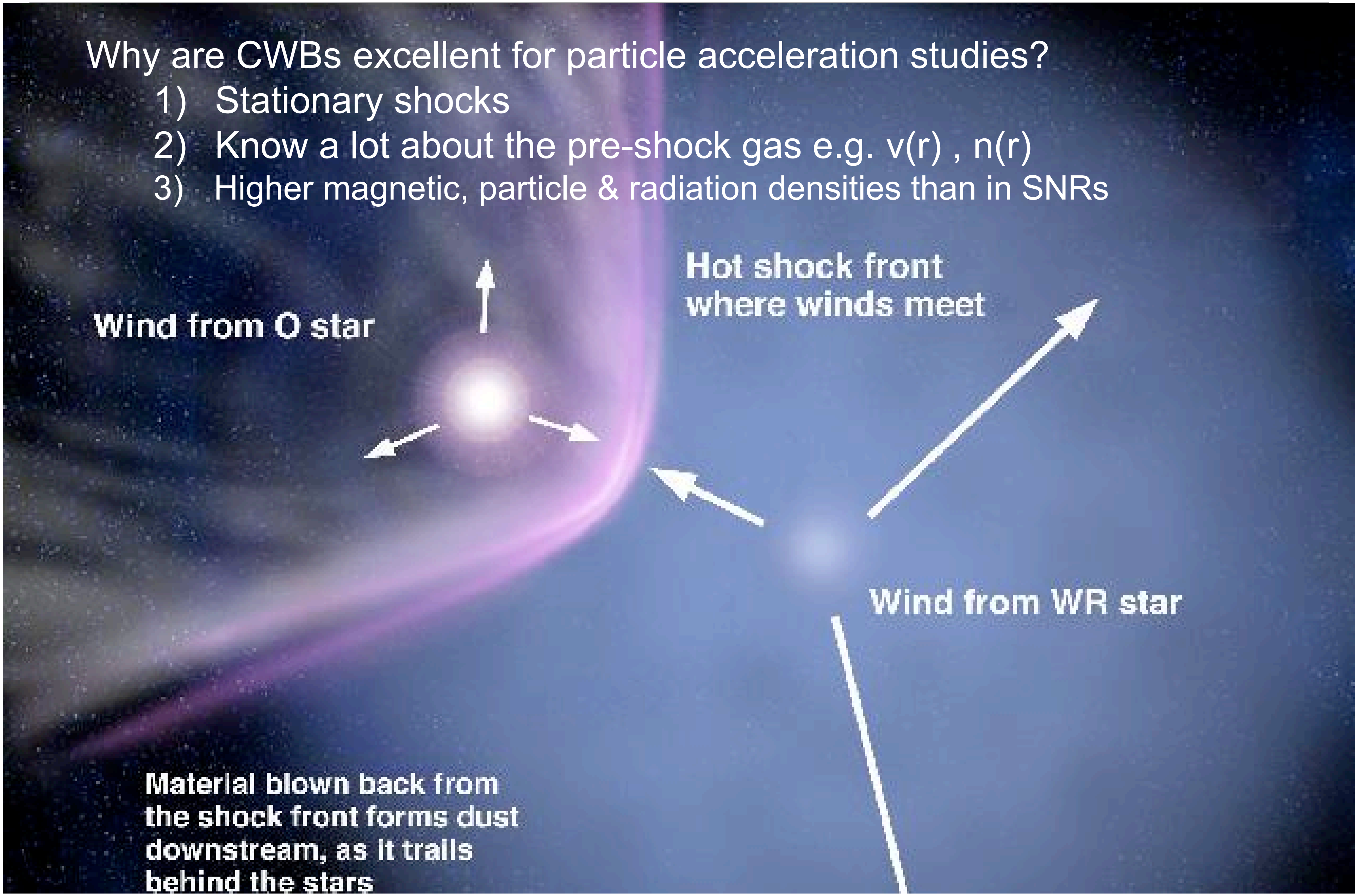


Bell (2004)

Artists Impression of a Colliding Wind Binary

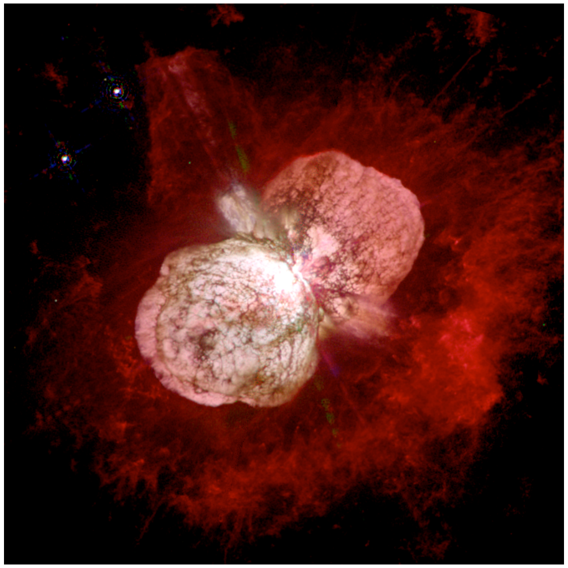
Why are CWBs excellent for particle acceleration studies?

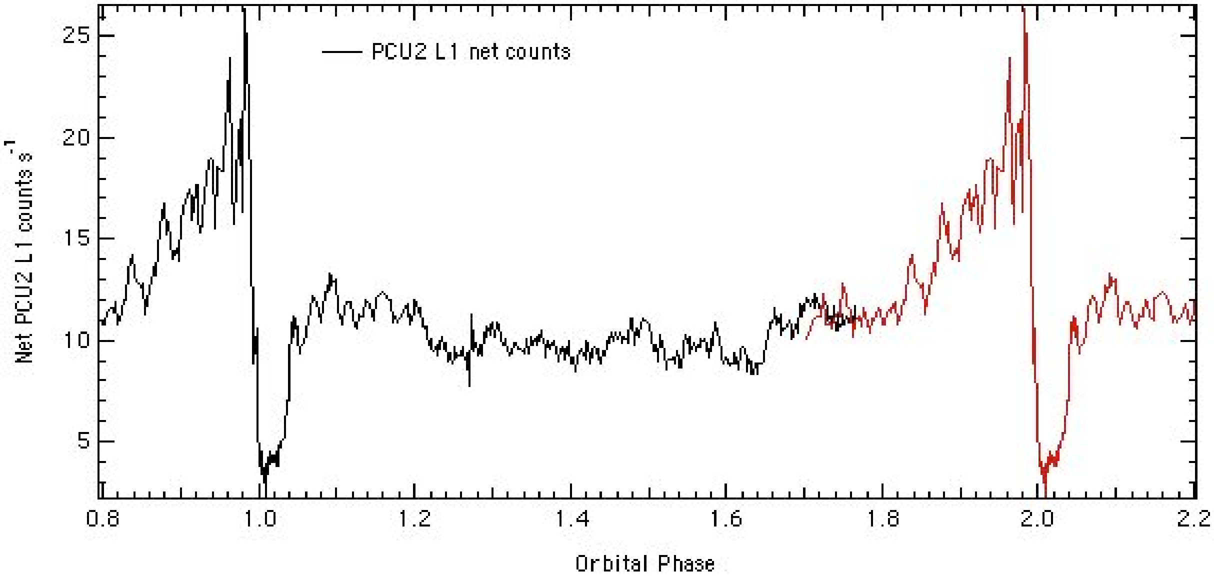
1) Stationary shocks
2) Know a lot about the pre-shock gas e.g. v(r) , n(r)
3) Higher magnetic, particle & radiation densities than in SNRs



CWBs probe wide range of parameters

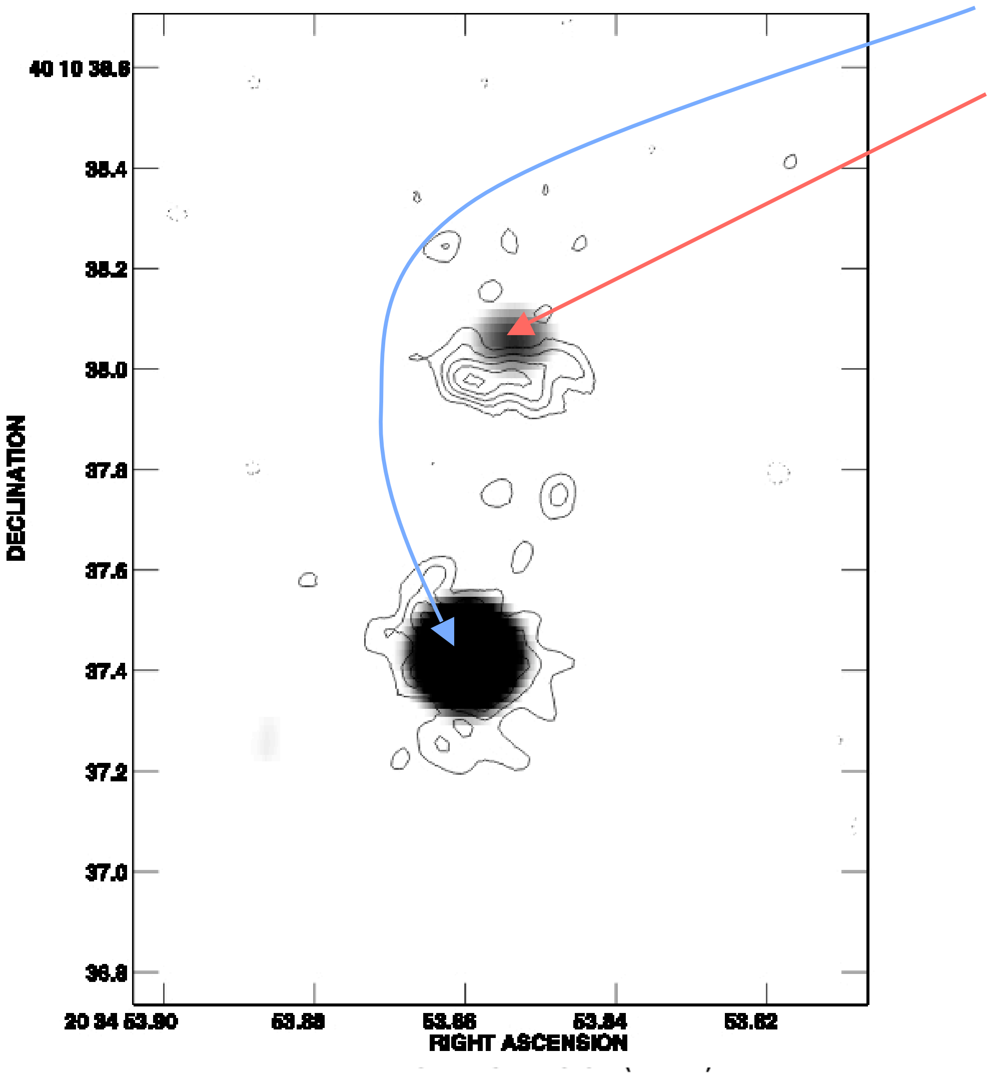
System	Orbital Period (d)	Separation (AU)	Density (cm^{-3})	÷$_{WR}$	÷$_{O}$
WR 139 (V444 C	4.2	0.2	~10^{10}	<<1	?
WR 11 (ã^{2} Vel)	78.5	0.81-1.59	~10^{9}	~0.5-1	~250-500
WR 140	2899	~1.7-27.0	~10^{9}-10^{7}	~2-50	~150-2000
WR 147	>10^{5}	>410	□10^{4}	>30	>1000





Corcoran et al.

Radio structure of the WR+OB CWB - WR 147



Two components, one thermal one non-thermal

High resolution observations - MERLIN @ 5GHz:

50 mas = 77AU @ 650pc

WR+OB binary

NT emission => relativistic electrons + magnetic fields

NT emission consistent with wind-collision position

Williams et al. (1997)

WR 140 - the CWB laboratory

WR 140 is the best studied WR+OB binary

- WR + O in a 7.9 year, eccentric (e=0.88) orbit - orbit size ~ 2-28 AU
- X-ray spectra reveal non-equilibrium ionization, and (probably) $T_e < T_i$
- Radio-bright; dramatic variations in radio emission as orbit progresses
- WCR resolved by VLBI
- Orbit well defined
- IC cooling important
  - Flow time ~ R_{OB}/v_{WR} ~ 100 hrs at apastron
  - IC Cooling t_{IC} ~12 hrs at apastron (at periastron ~250 times shorter!)
  - IC cooling important at all radio frequencies under consideration
- High eccentricity + good data

→ excellent lab for studying shock phenomena

Cartoon of the colliding-wind region in WR140

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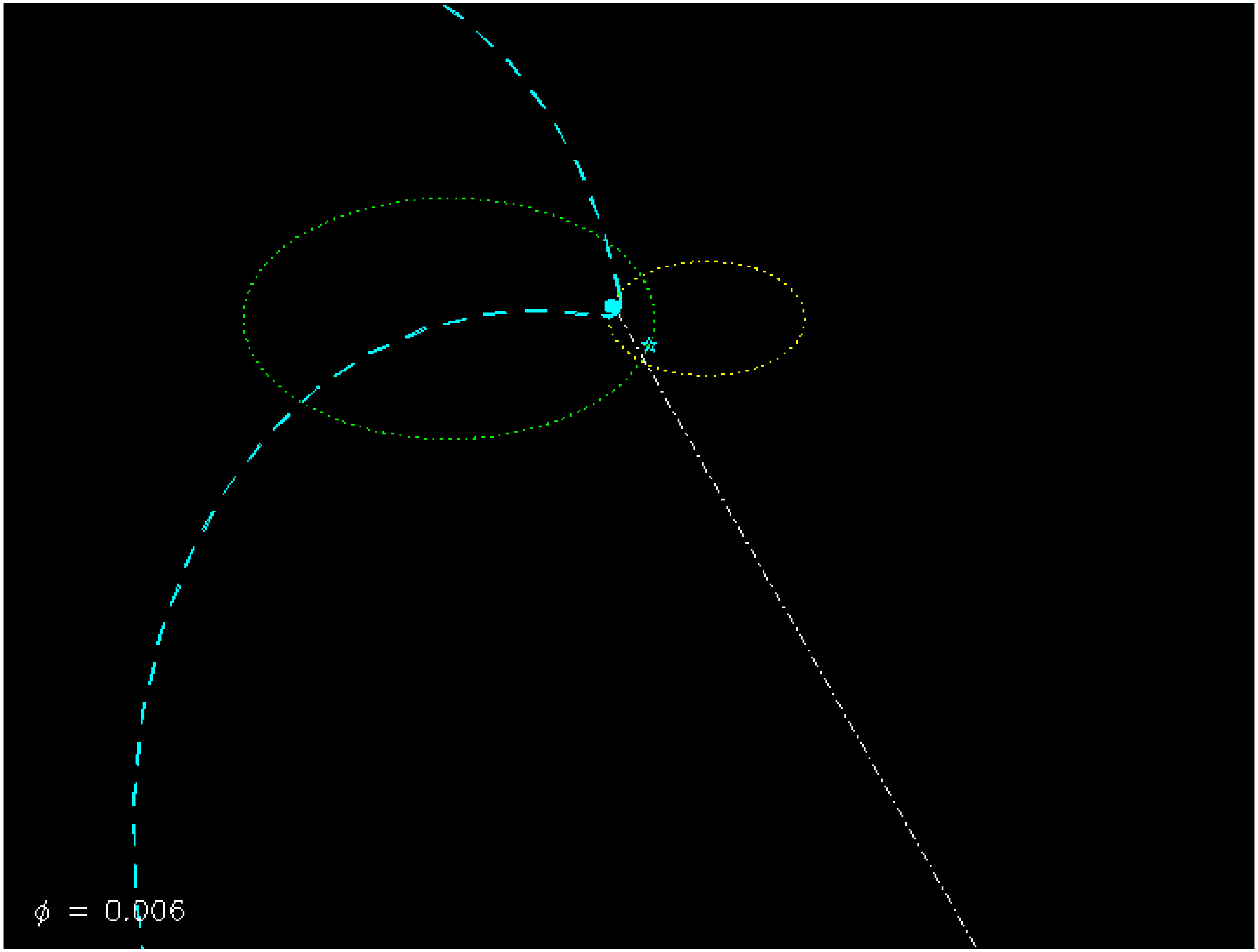
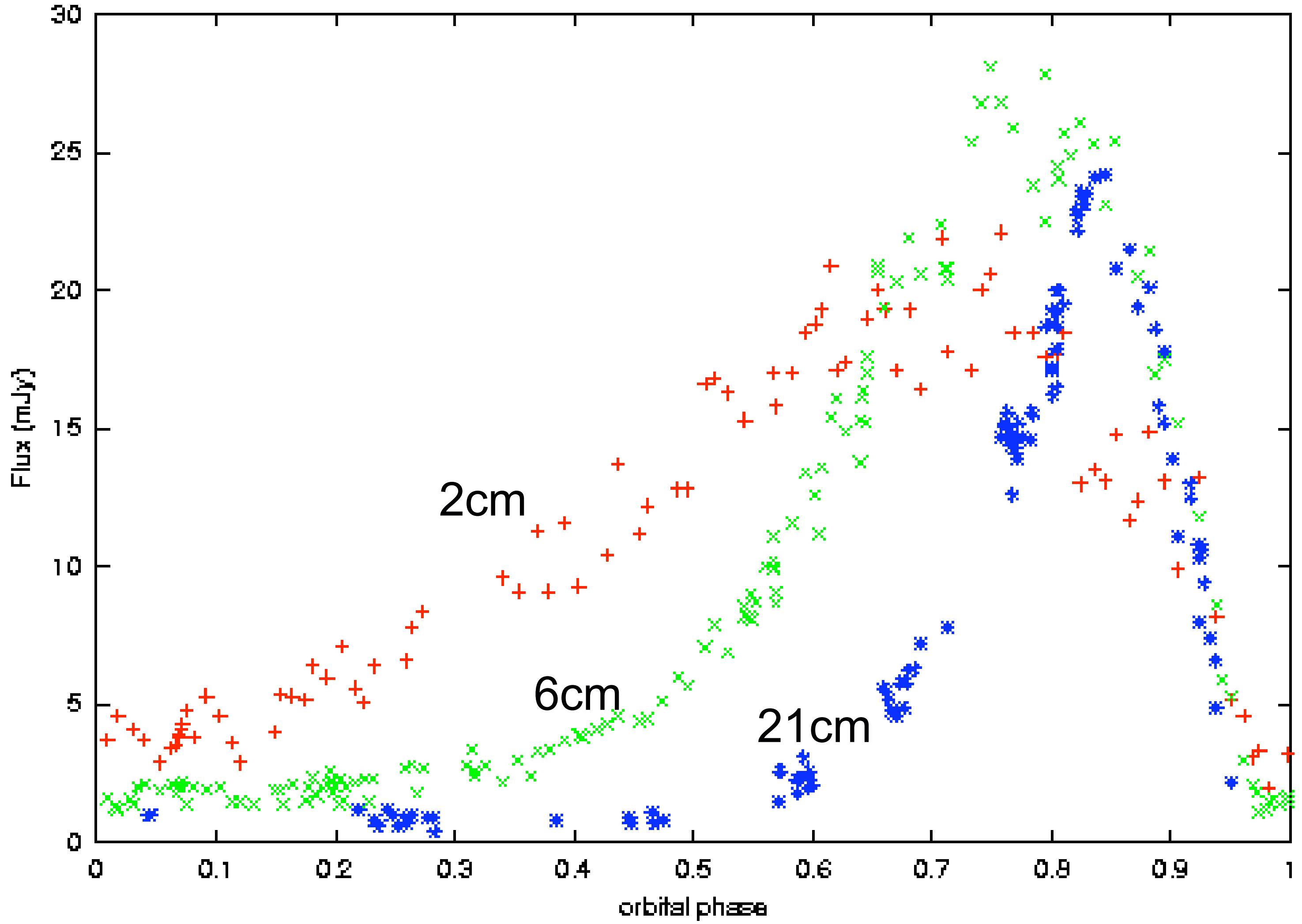


Orbit parameters from Williams et al. 1990 - interaction region based on Eichler & Usov 1993

The radio light curve of WR140



8 years of VLA (White & Becker 1995) +
WSRT (Williams et al 1991) data

VLBA images

State of the Art imaging!

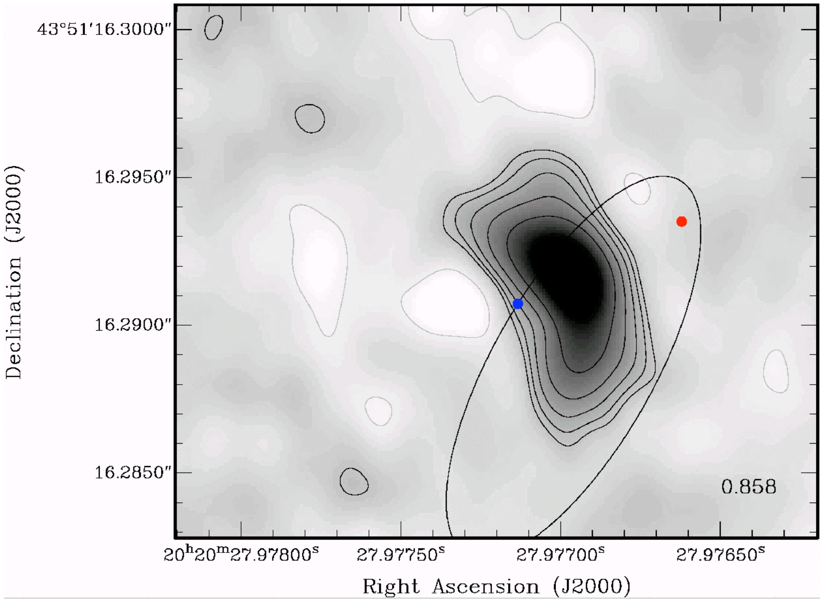
23 epochs @ 3.6 cm

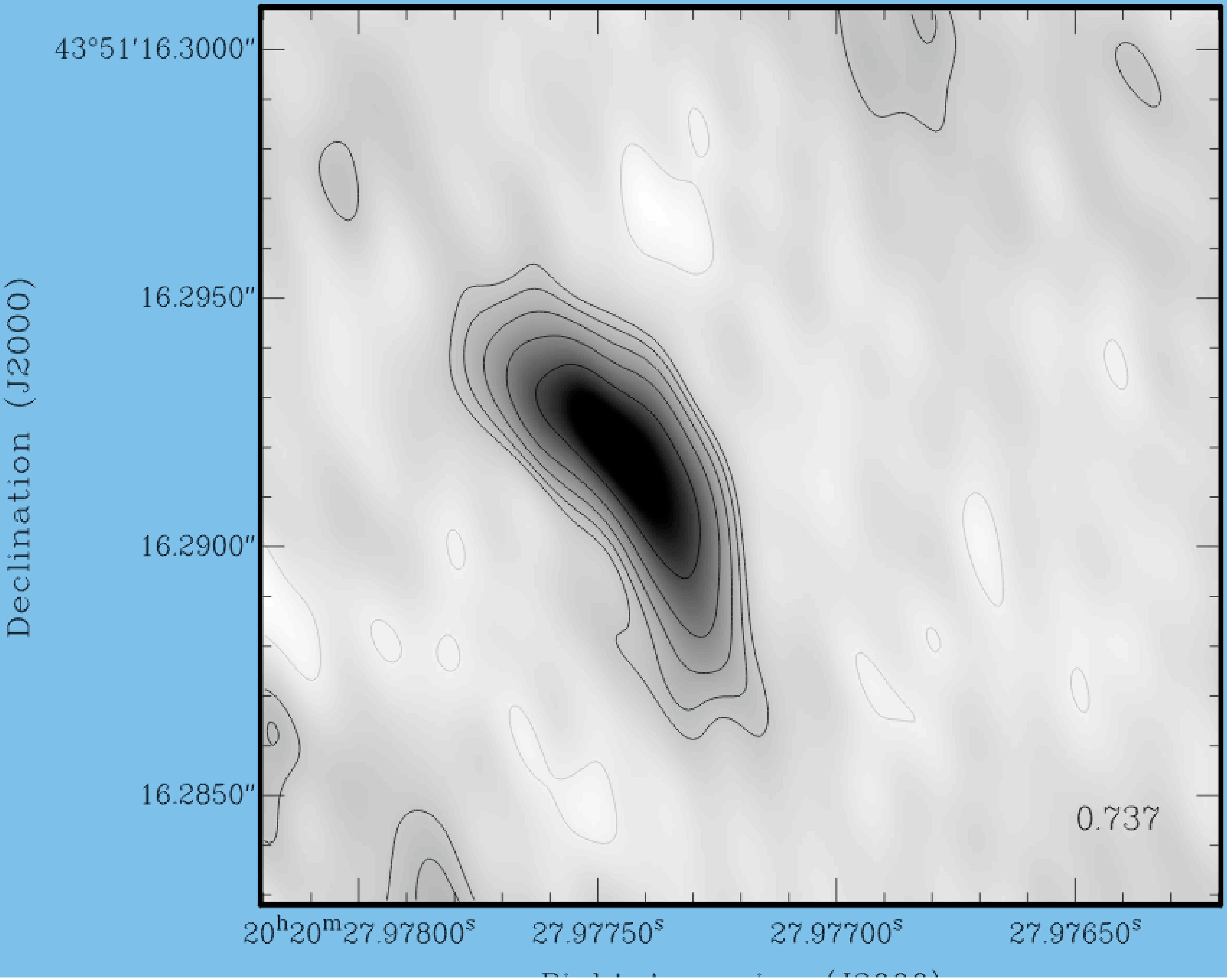
Phase ~ 0.74 -> 0.93

(Jan 1999 to Nov 2000)

Resolution ~ 2 mas

Linear res ~ 4 AU




Declination (J2000)
43°51′16.3000″
16.2950″
16.2900″
16.2850″
20^{h}20^{m}27.97800^{s}
27.97750^{s}
27.97700^{s}
27.97650^{s}
0.737

VLBA images

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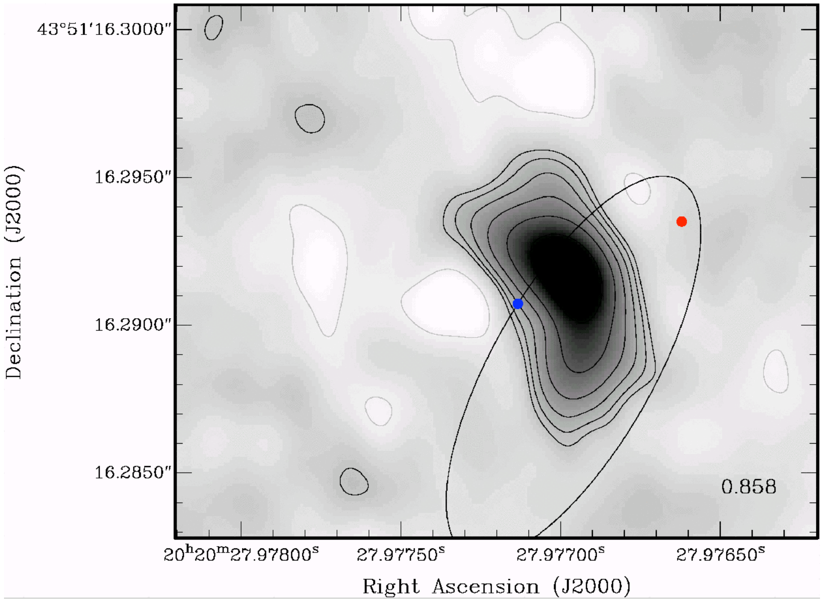


- Non-thermal emission (T_b~10^7 K)=> wind-collision region
- Resolved – “curved” emission region
  - – cannot determine if NT arises in shocks or at CD
- Observe rotation and pm of emission region
  - – gives full orbit definition – most importantly inclination
  - very important modelling constraint !
    - … but wind mtm ratio still unconstrained

Previous models

Models of NT emission tend to be simple

Radio:

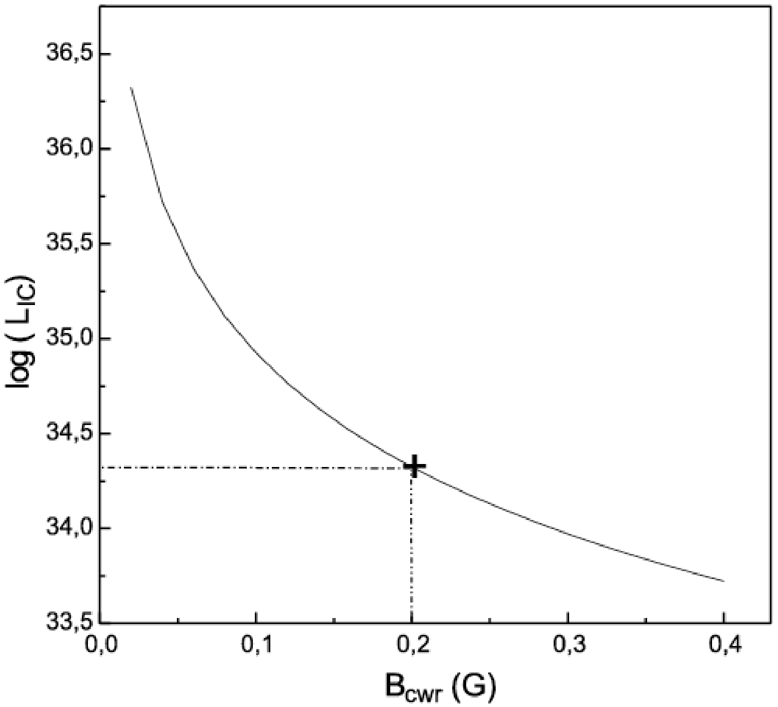
- Point source non-thermal emission, radially symmetric winds –

$$S_\nu^{obs} = S_\nu^{thermal} + S_\nu^{nt} e^{-\tau_\nu^{ff}}$$

  - maintains analytic solutions
- No consideration cooling mechanisms (e.g. IC cooling – important - even for wide systems c.f. 146, 147) or other absorption

NT X-ray/_-ray:

$$\frac{L_{sync}}{L_{ic}} = \frac{U_B}{U_{ph}}$$



Benaglia & Romero (2003)

Issues: L_{ic} is highly sensitive to the assumed B-field

Need the intrinsic (NOT observed) L_{sync}

Model fits to the radio data directly determine the NT particle population

Modelling radio emission from CWBs

Hydro modelling of CWBs

- radially symmetric, terminal velocity isothermal winds
- axis-symmetric WCR

Treatment of non-thermal emission

- not determined from 1st principles! $U_{rel} = \zeta_{rel,e} U_{th}$ and $U_B = \zeta_B U_{th}$

Tangled magnetic field

Assume shock acceleration

- power-law energy distribution at the shocks (p is a free parameter)

Electron energy spectrum evolves downstream due to IC cooling.

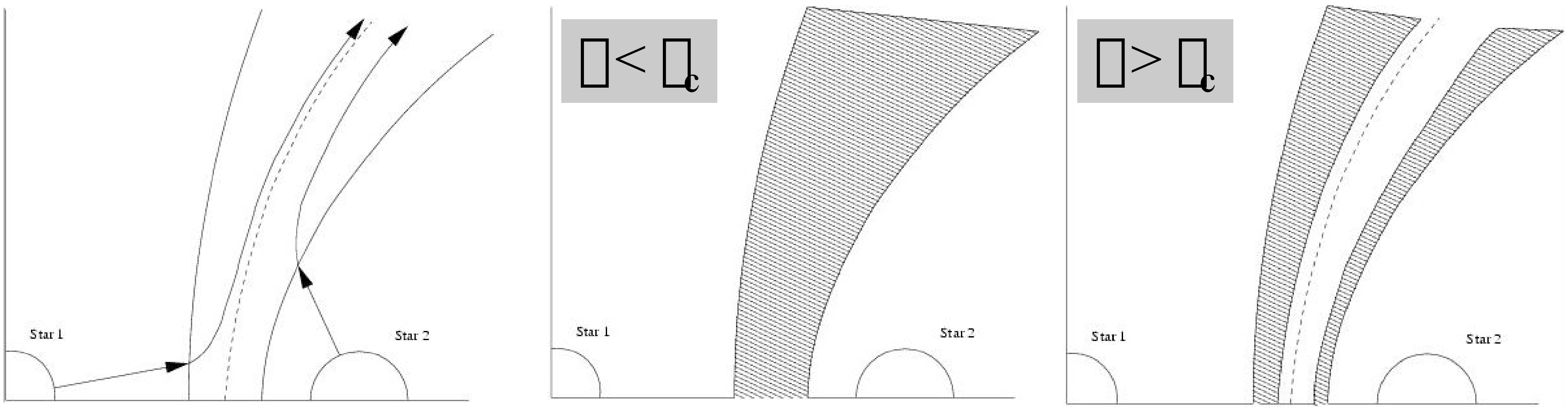
Spatial distribution of emission & absorption – determined by plasma spatial distribution from hydro

Constrained by radio spectra and images

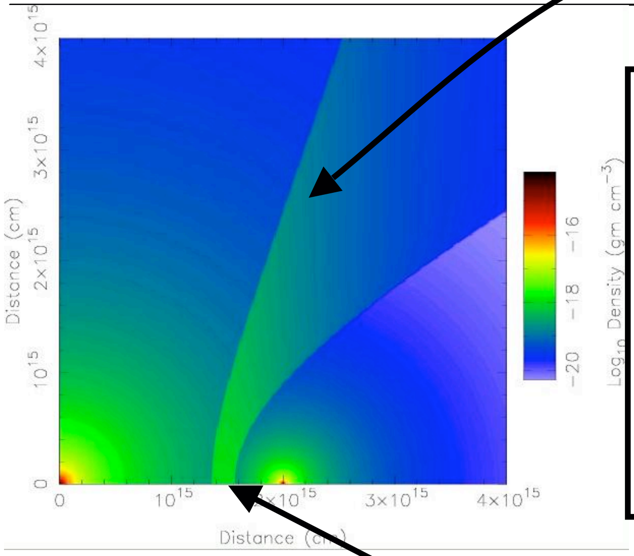
Inverse Compton cooling

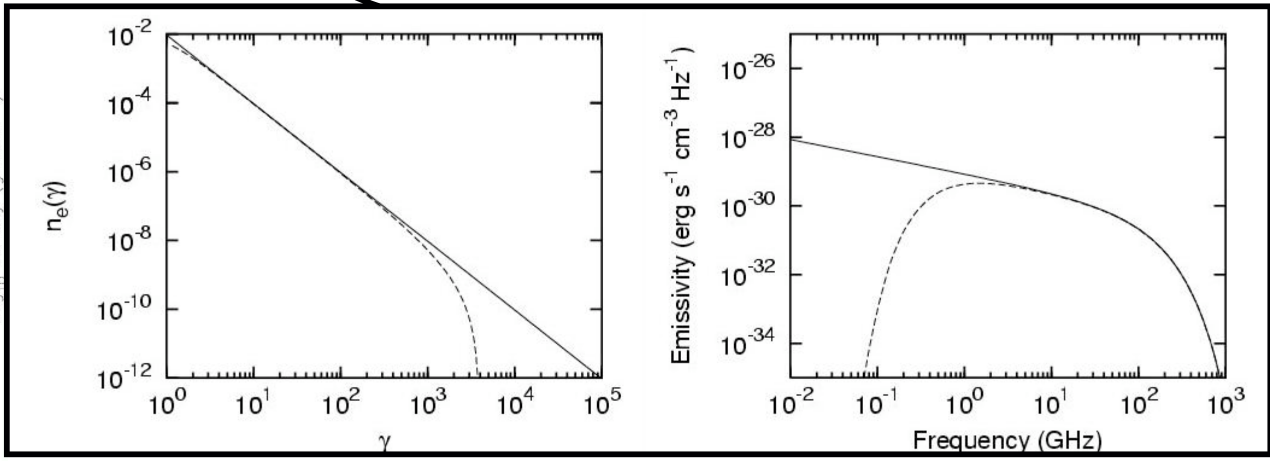
Rate of energy loss: $\left(\frac{d\gamma}{dt}\right)_c \propto \gamma^2$

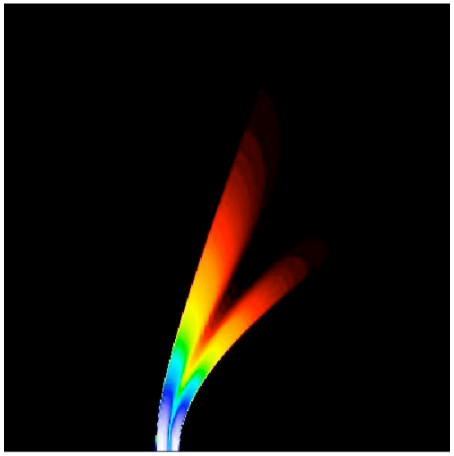
Distribution of relativistic electrons:



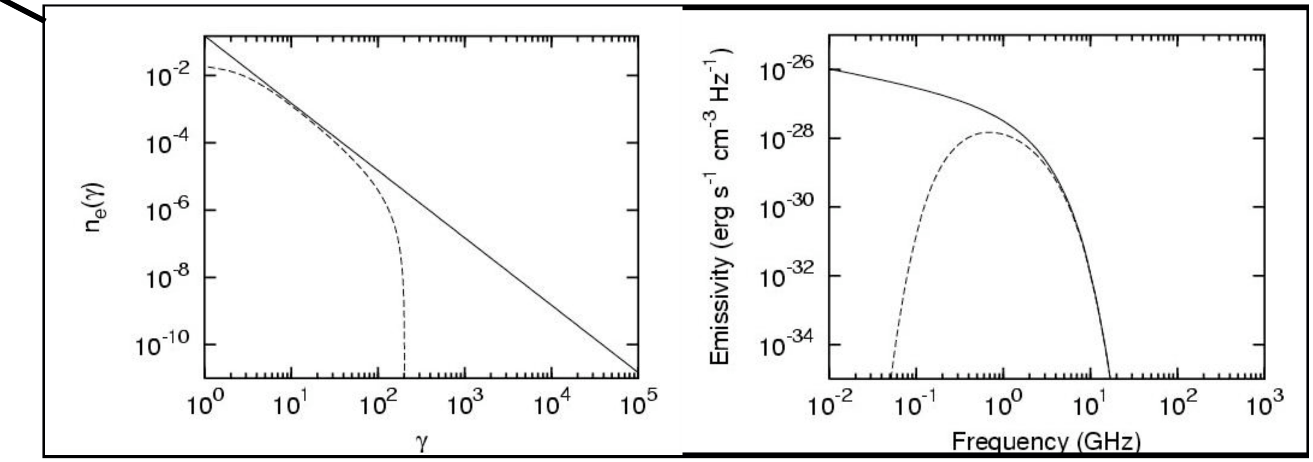
Salient features of modelling IC cooled spectra



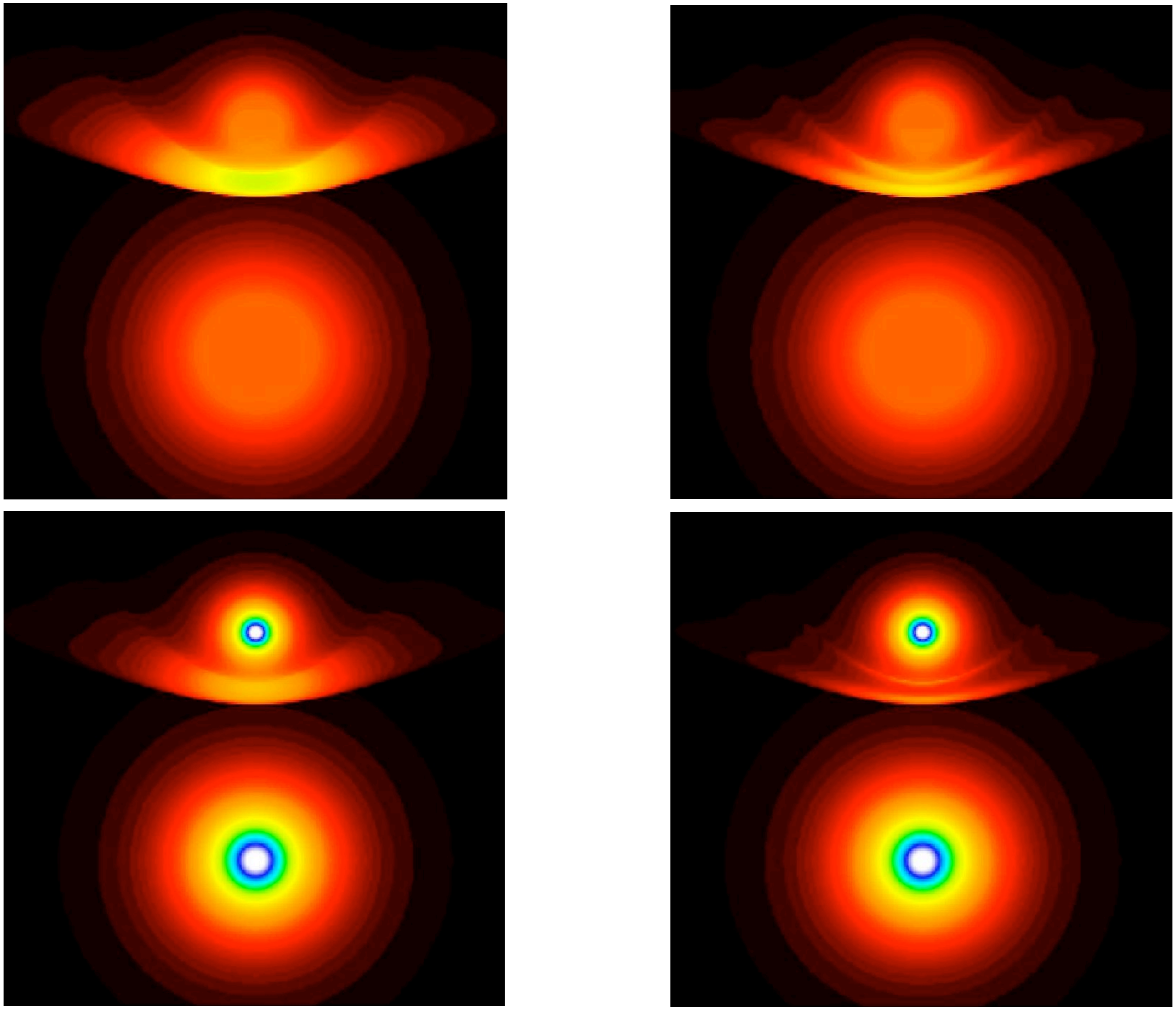




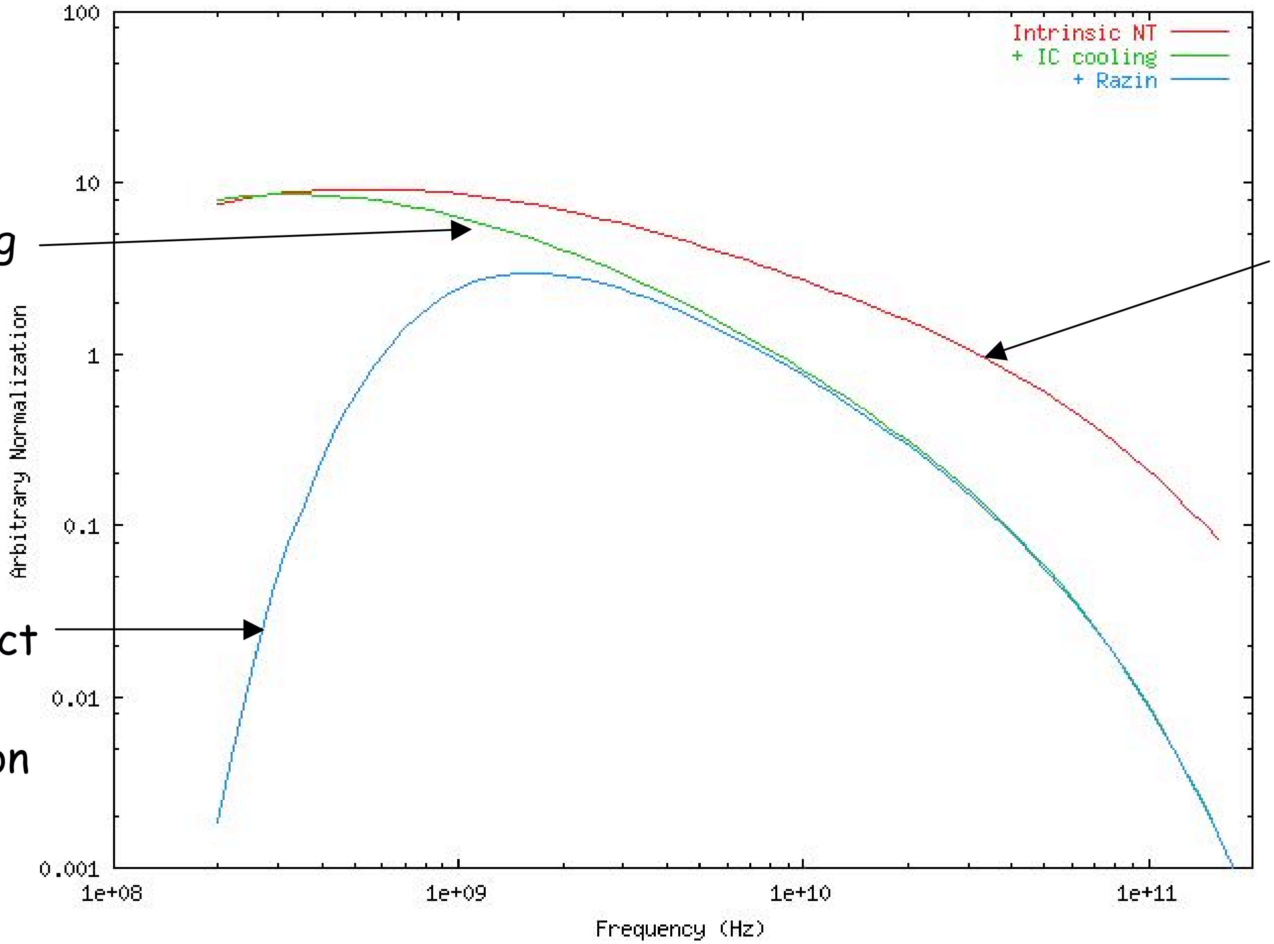
1.6 GHz emission map



Example synthetic emission maps



Typical radio spectra



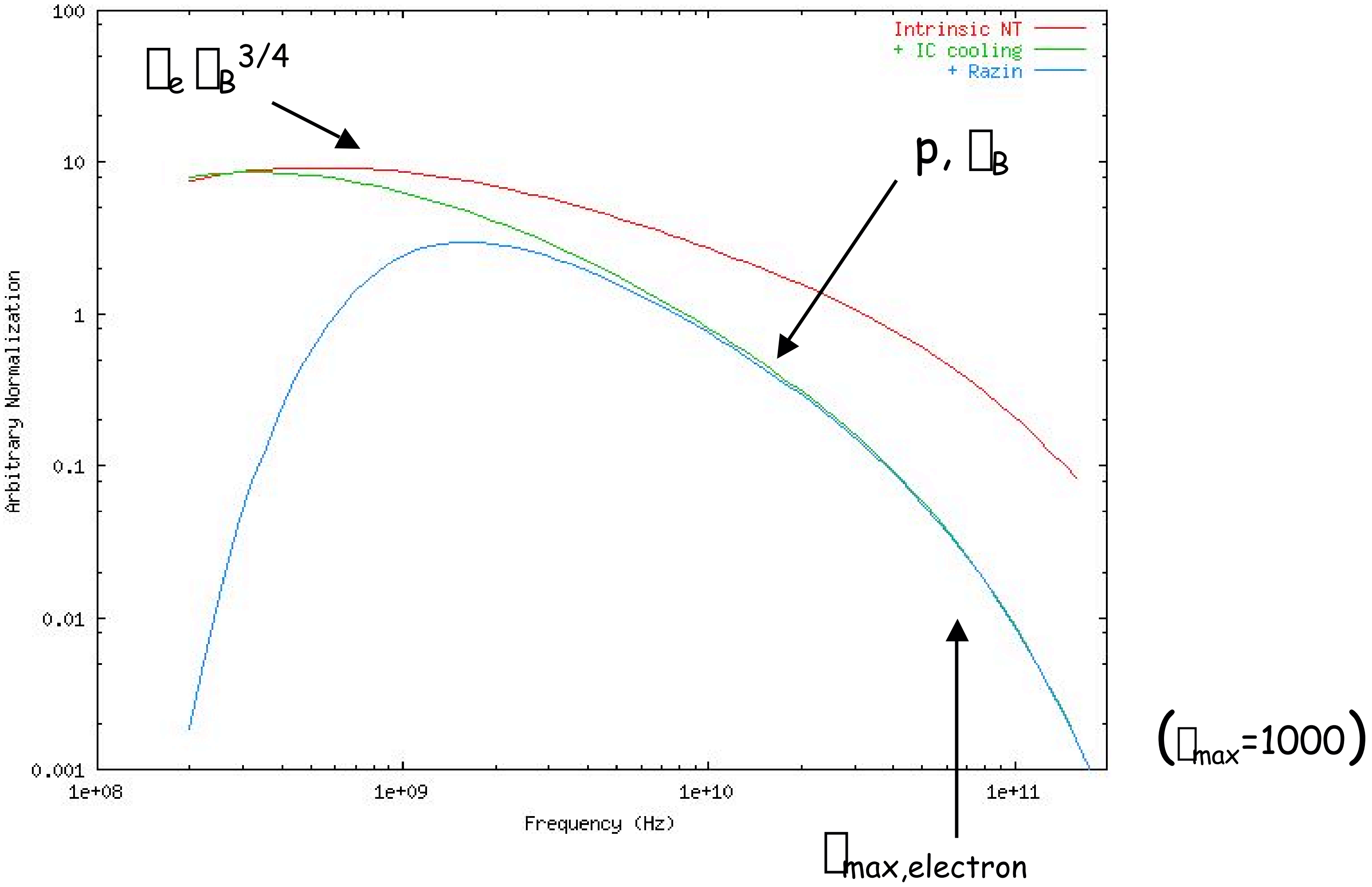
+ IC cooling

Intrinsic NT

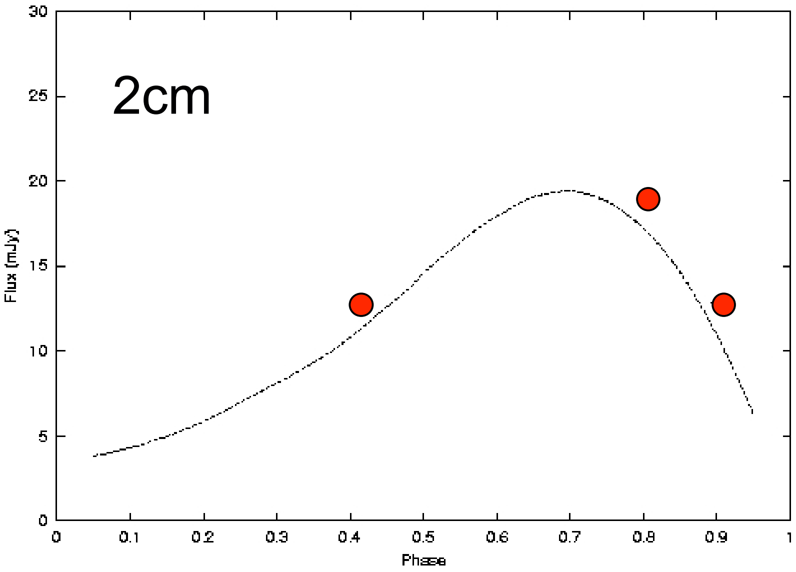
+ Razin effect
&
ff absorption

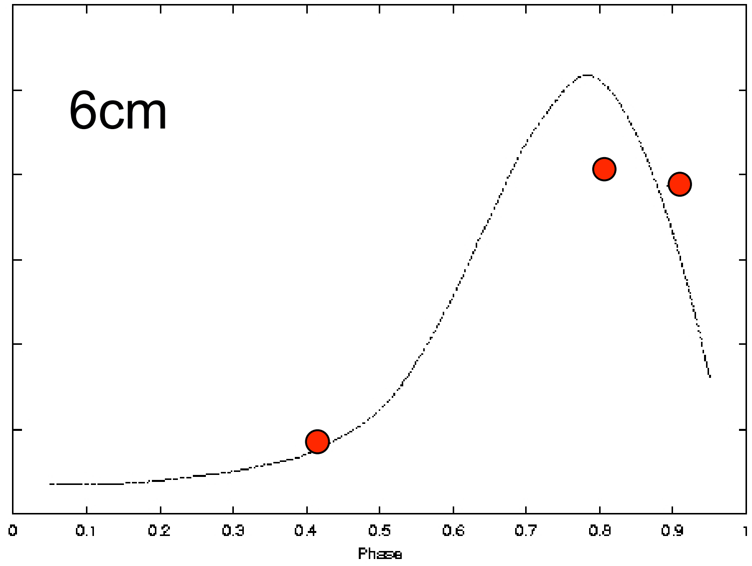
$(\gamma_{max}=1000)$

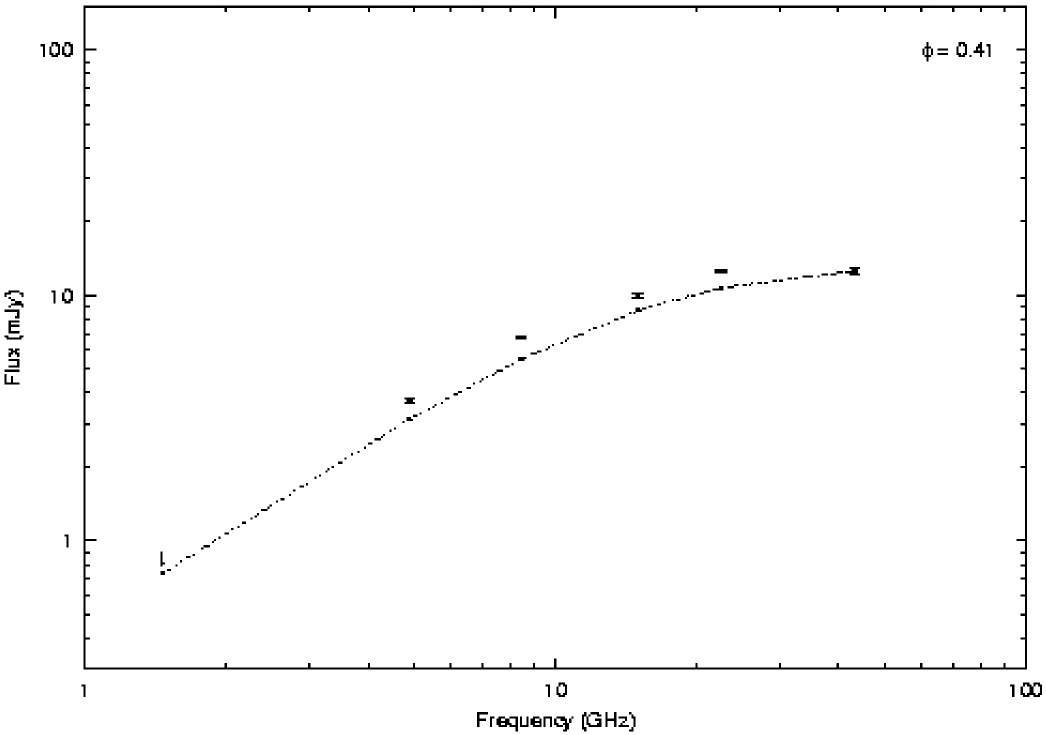
Typical radio spectra



First stab at modelling WR140



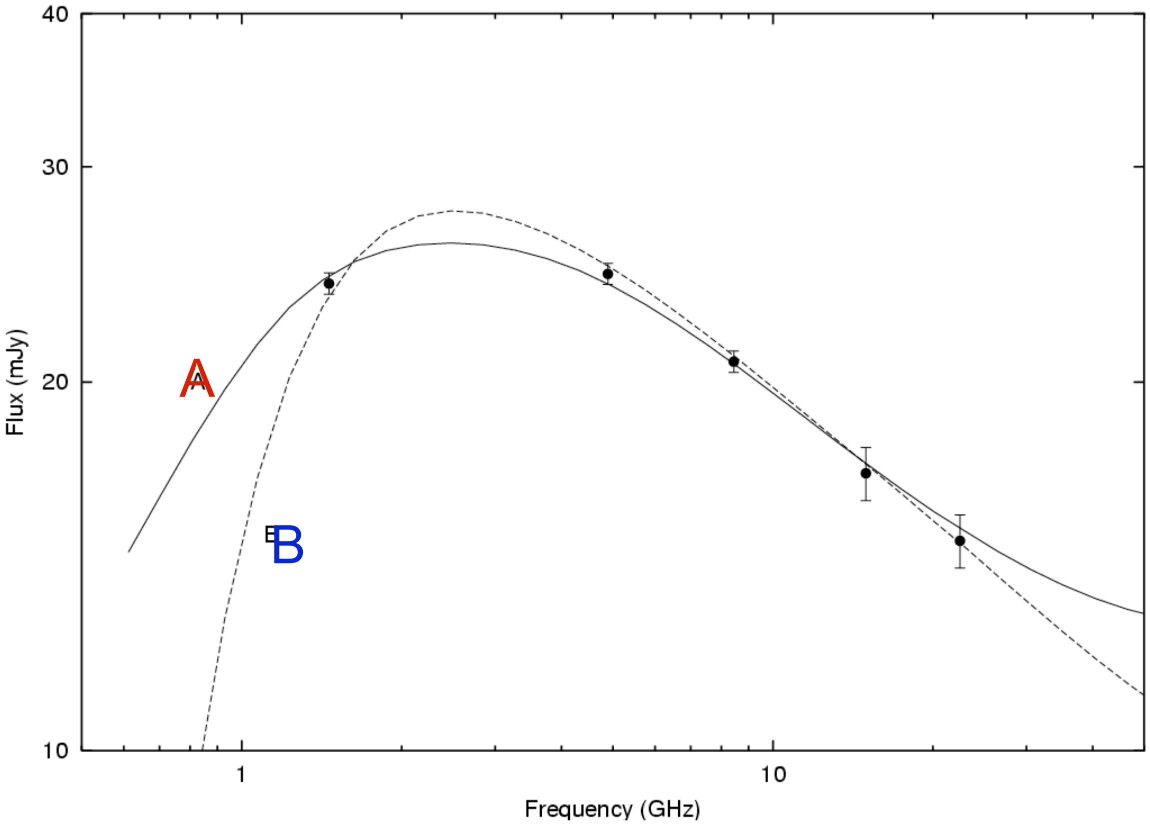




Looking good

But…
Relationship from one phase to another is
UNCLEAR – NOT good!
Continues as a work in progress…

Spectral fits at phase 0.837



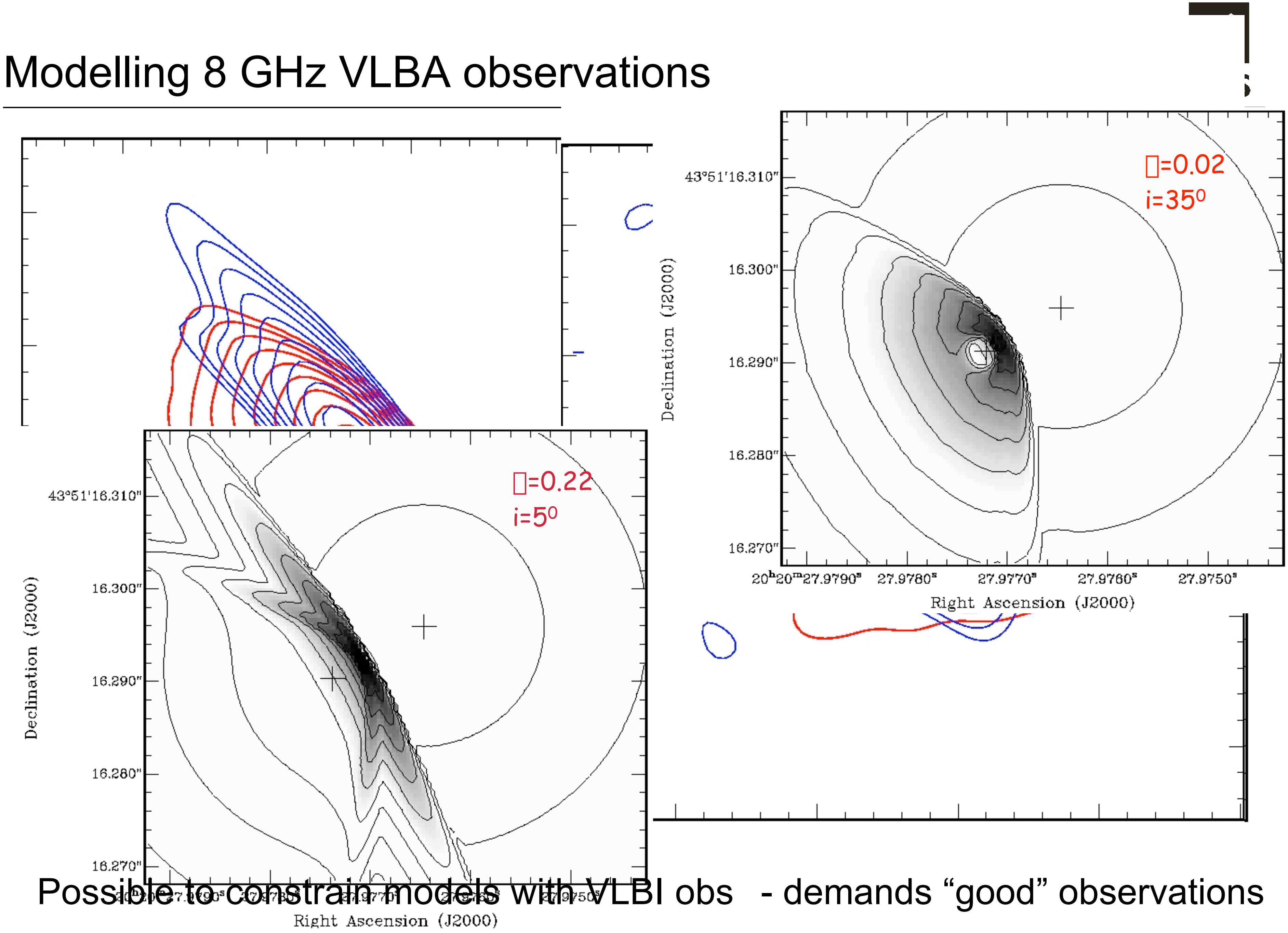
Model A: $\square=0.22$, $p=1.4$, $\square_e=1.4\mathrm{x}10^{-3}$, $\square_B=0.05$

Model B: $\square=0.02$, $p=1.4$, $\square_e=5.4\mathrm{x}10^{-3}$, $\square_B=0.05$

A caveat – p and $\_{}_B$ are degenerate parameters in these models

Crucially, we cannot obtain fits with p = 2!

Modelling 8 GHz VLBA observations



Possible to constrain models with VLBI obs - demands "good" observations

MeV/GeV emission?

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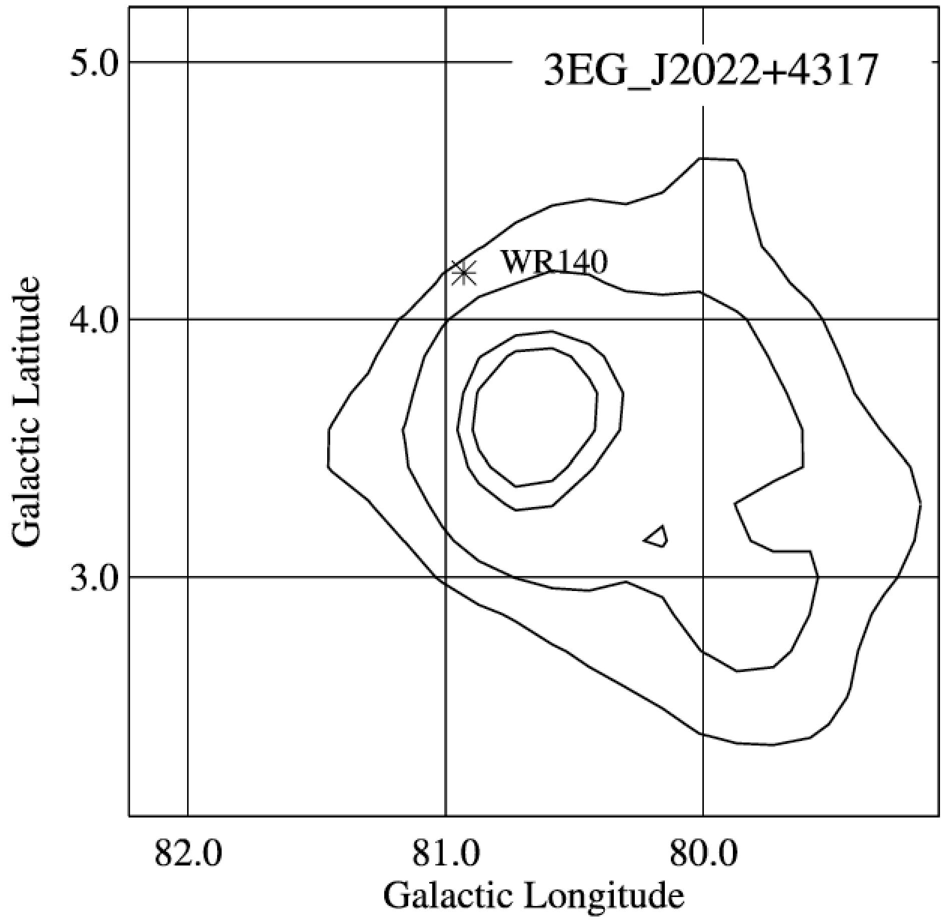

EGRET (100MeV – 20 GeV)

$f_{□} = (24.7 \pm 5.2) \times 10^{-8}$ ph s^{-1} cm^{-2}

□=2.31±0.19 (where N(E) E$^{-□}$)

Benaglia & Romero (2003)

High energy emission at phase 0.837

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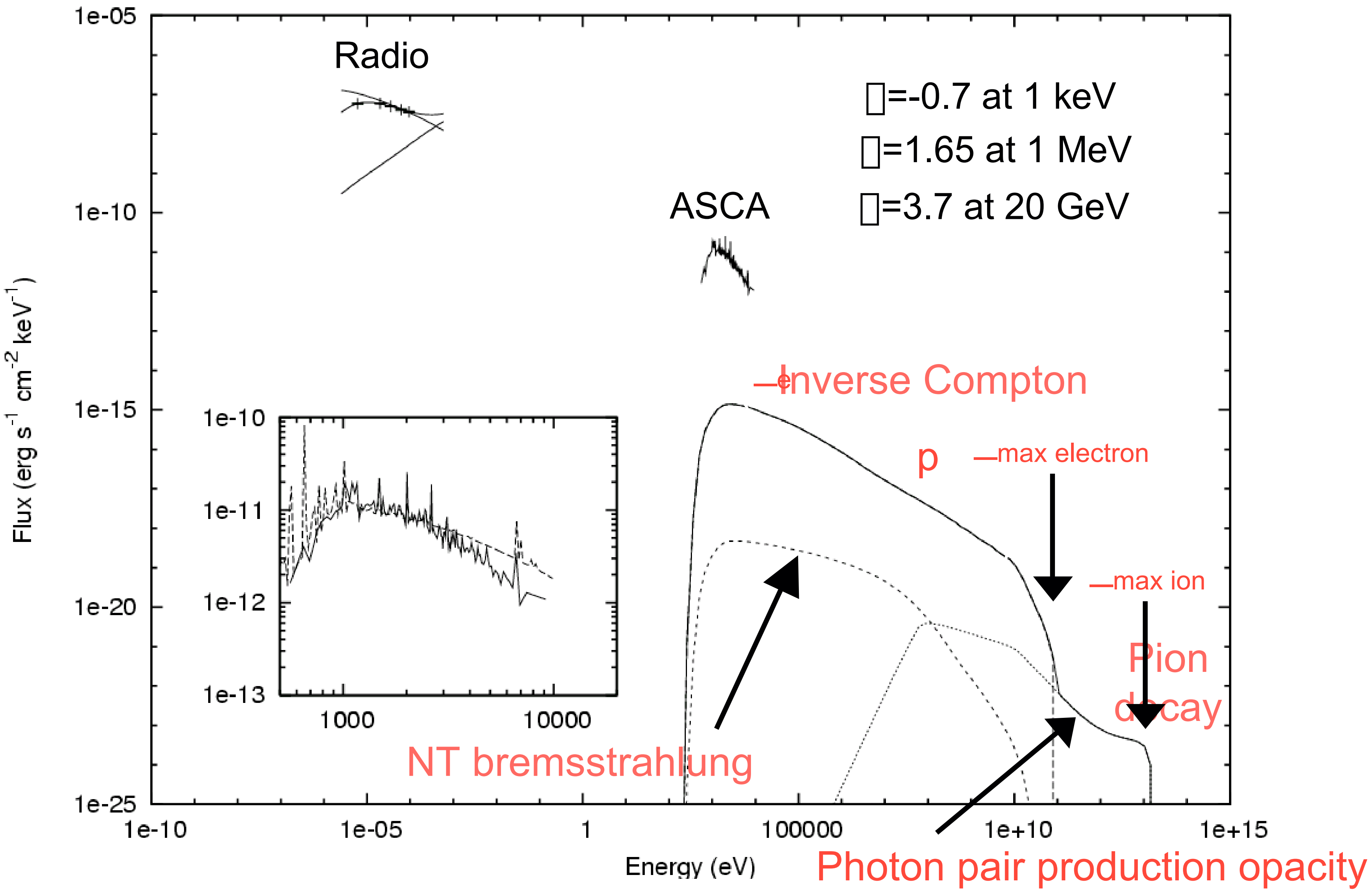

High energy emission at phase 0.837

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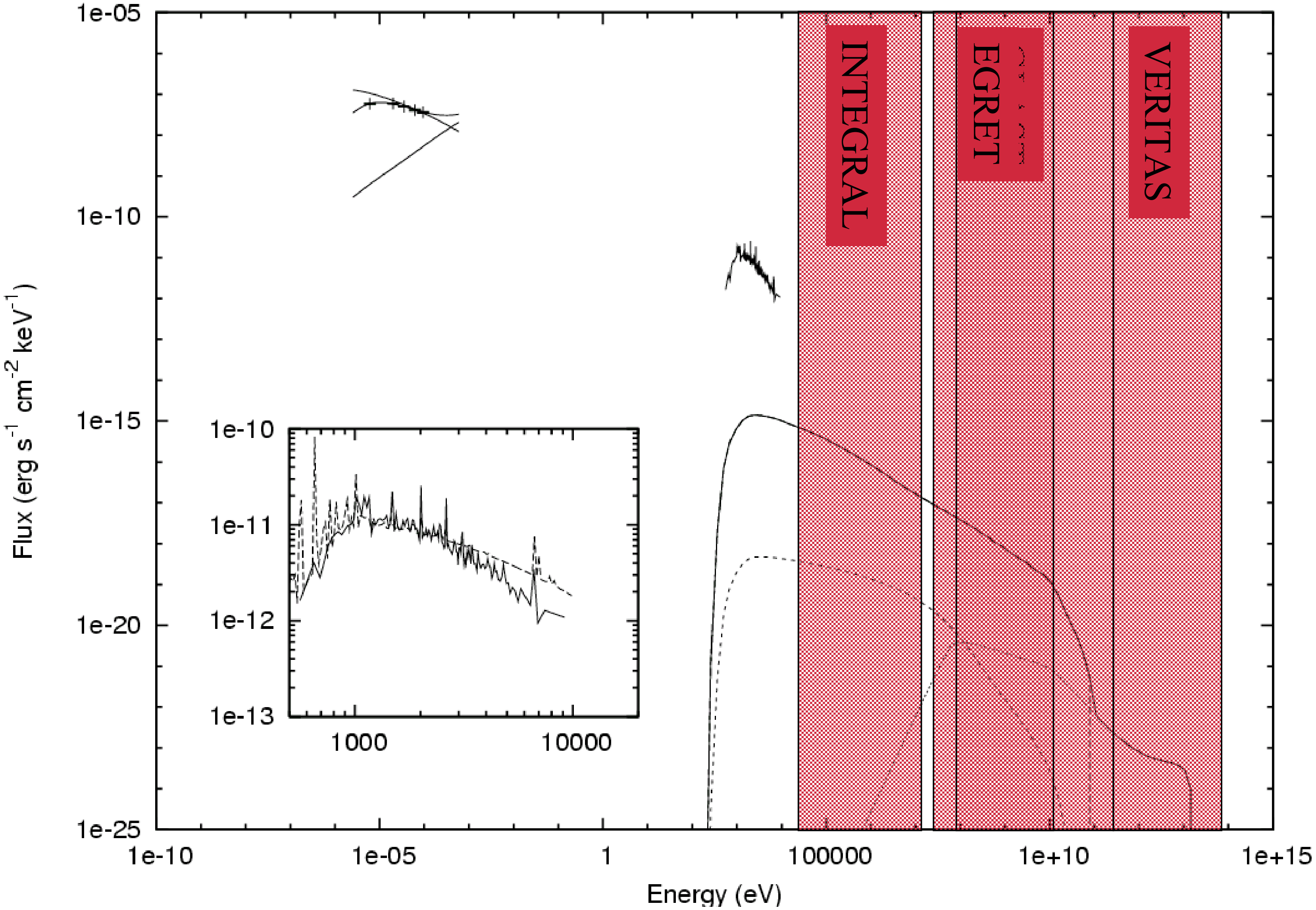
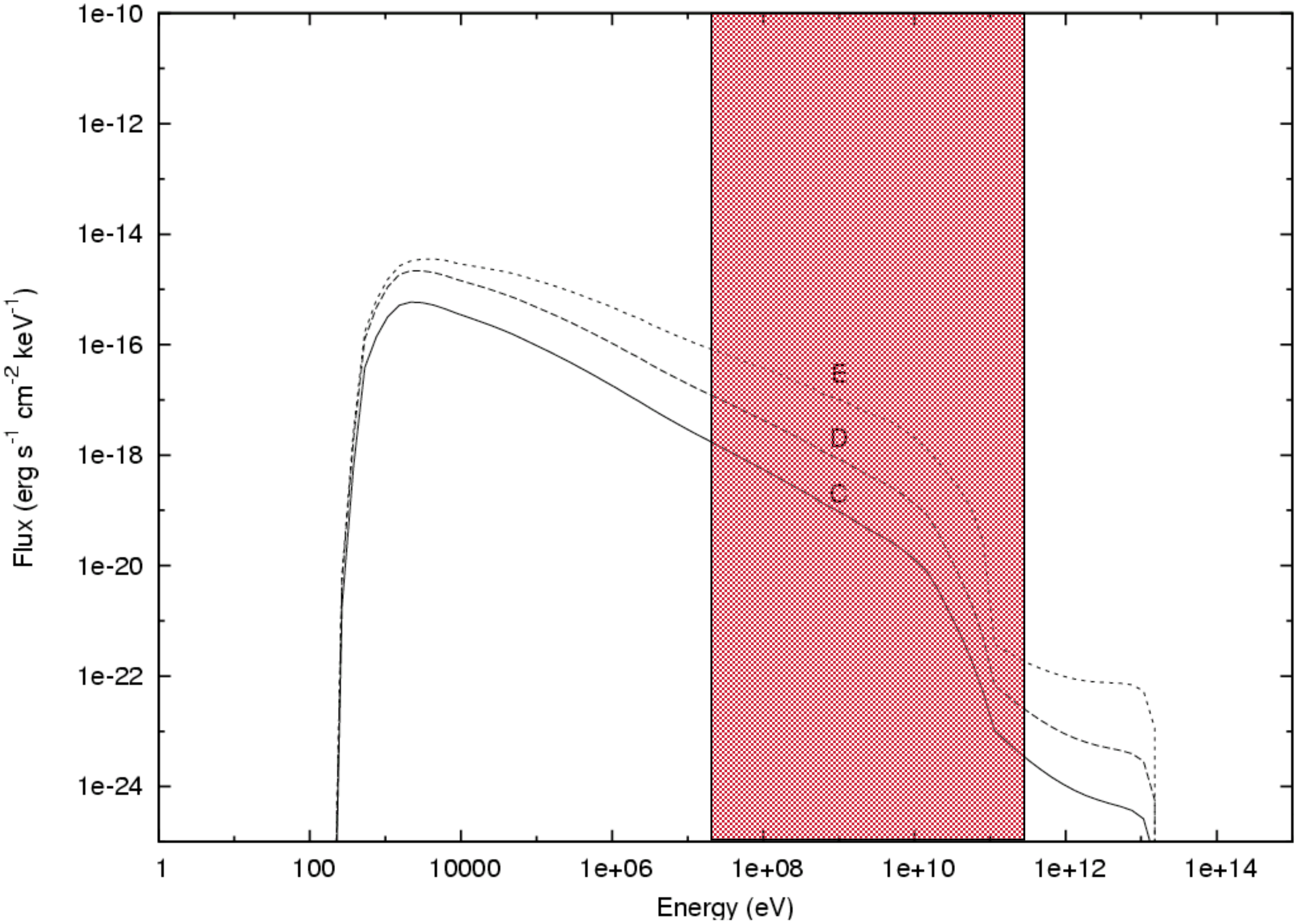


Model discrimination

GLAST will be able to discriminate between models



Will place constraints on the spectral index and B-field

Flux at TeV energies in VERITAS band

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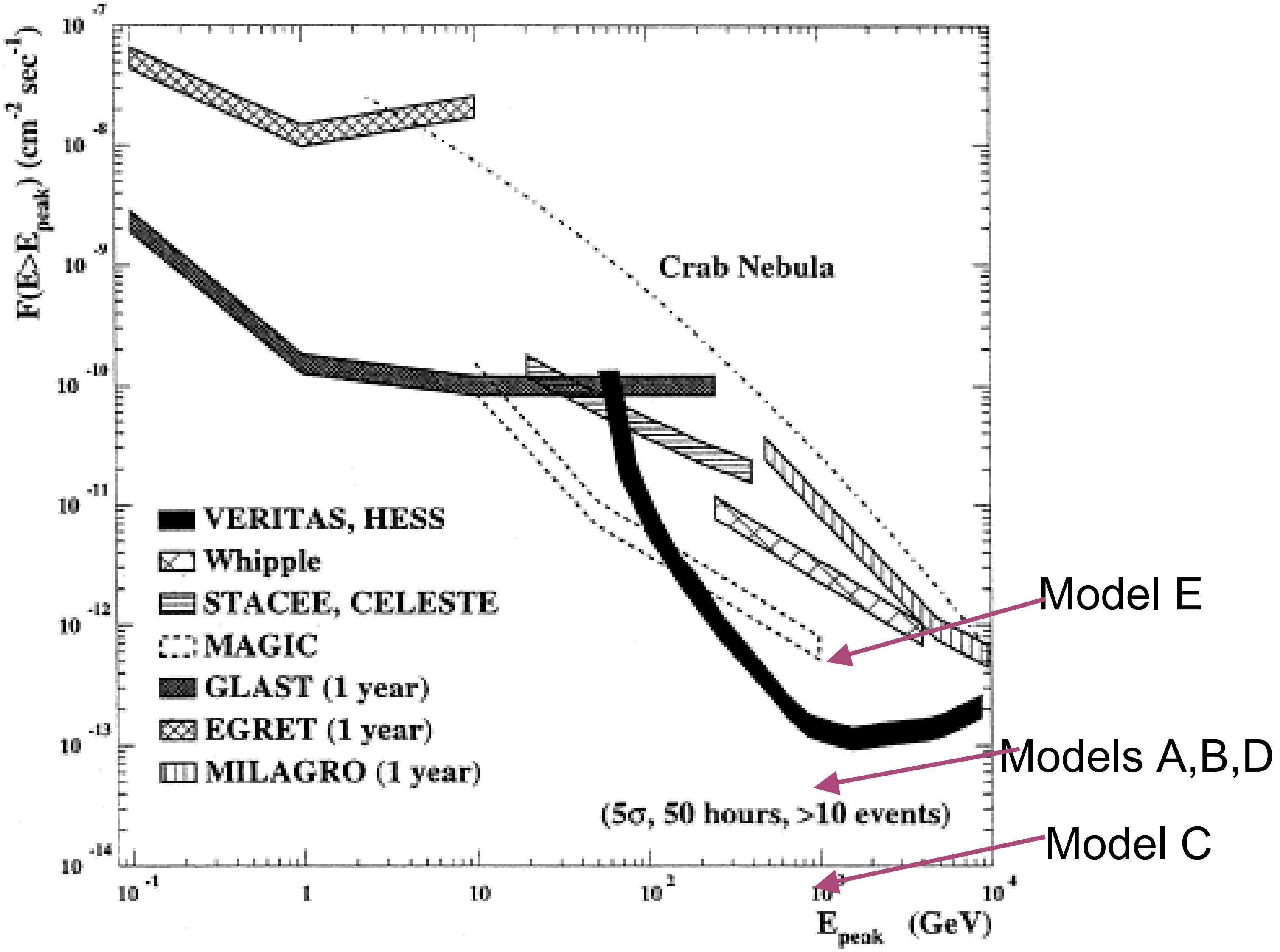
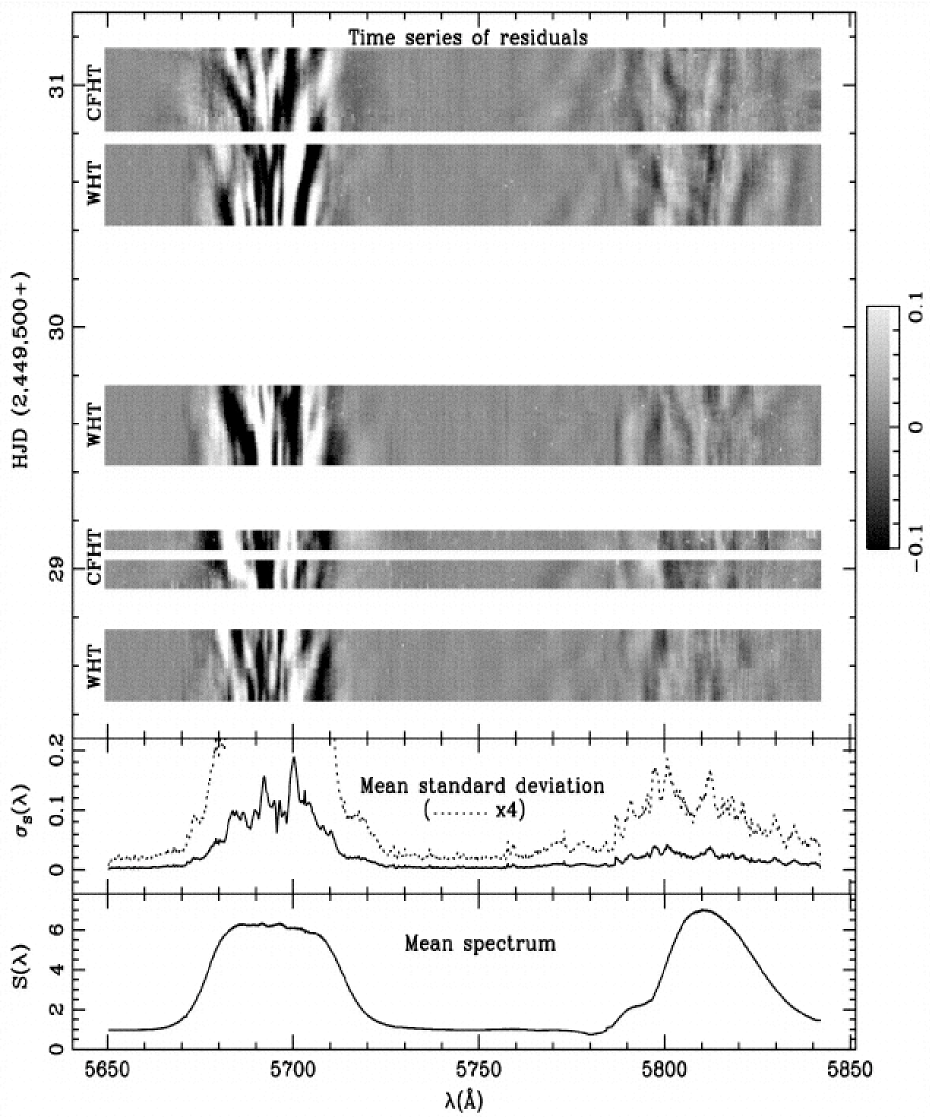


Model E

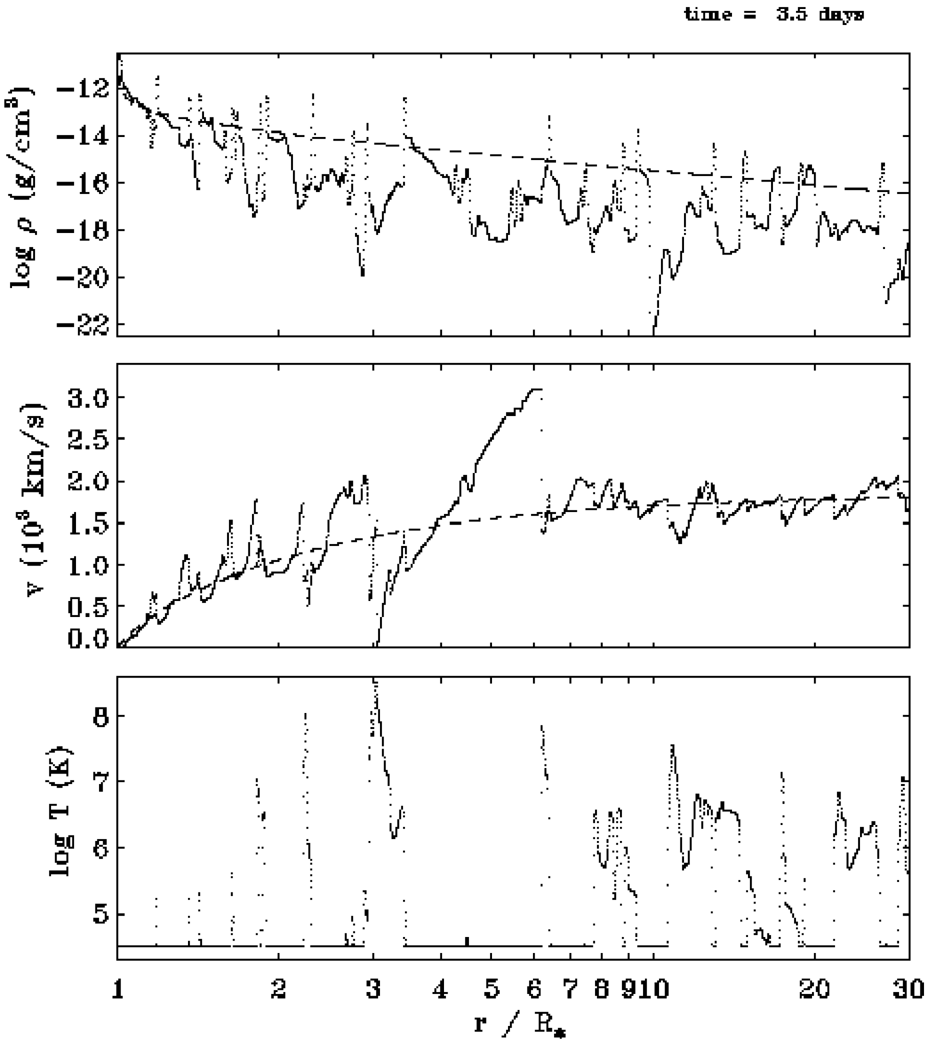
Models A,B,D

Model C

Hot star winds are very clumpy

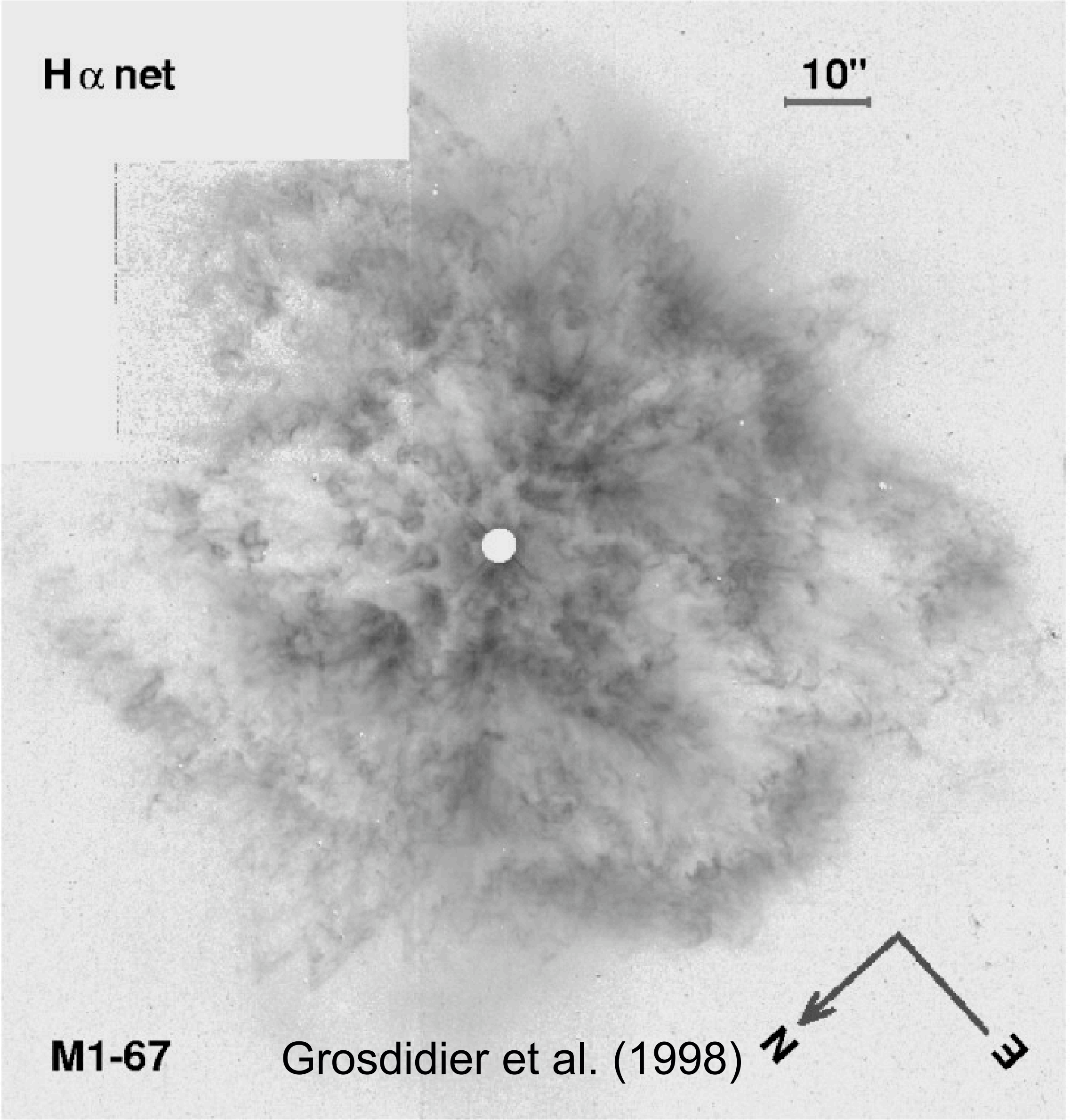


Lepine et al. (2000)



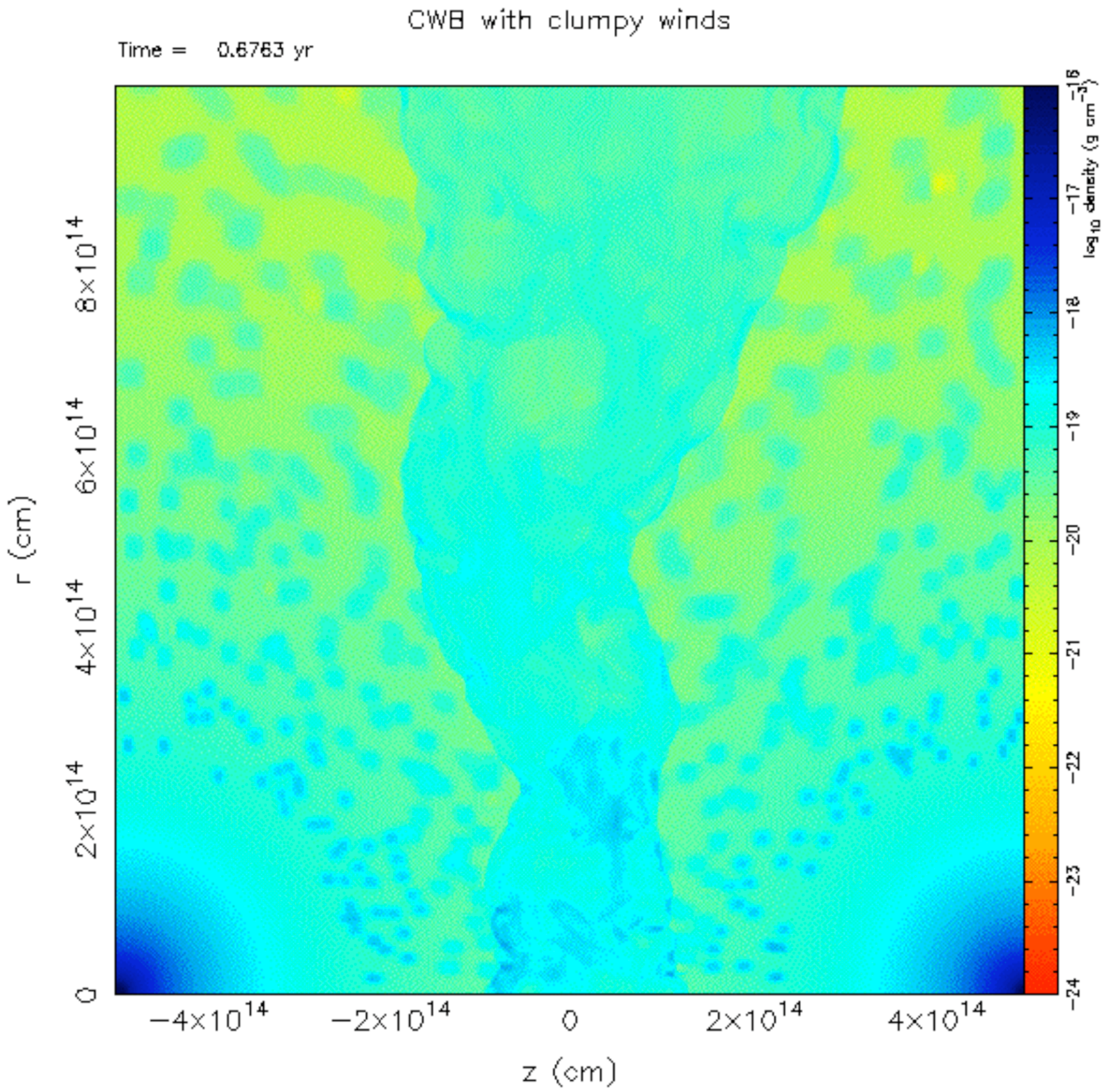
Feldmeier et al. (1997)

Hot star winds are very clumpy



Grosdidier et al. (1998)

Clump destruction in adiabatic CWBs



Implications for particle accn?

Reconnection?

Stochastic accn?

Colliding Winds in Stellar Clusters

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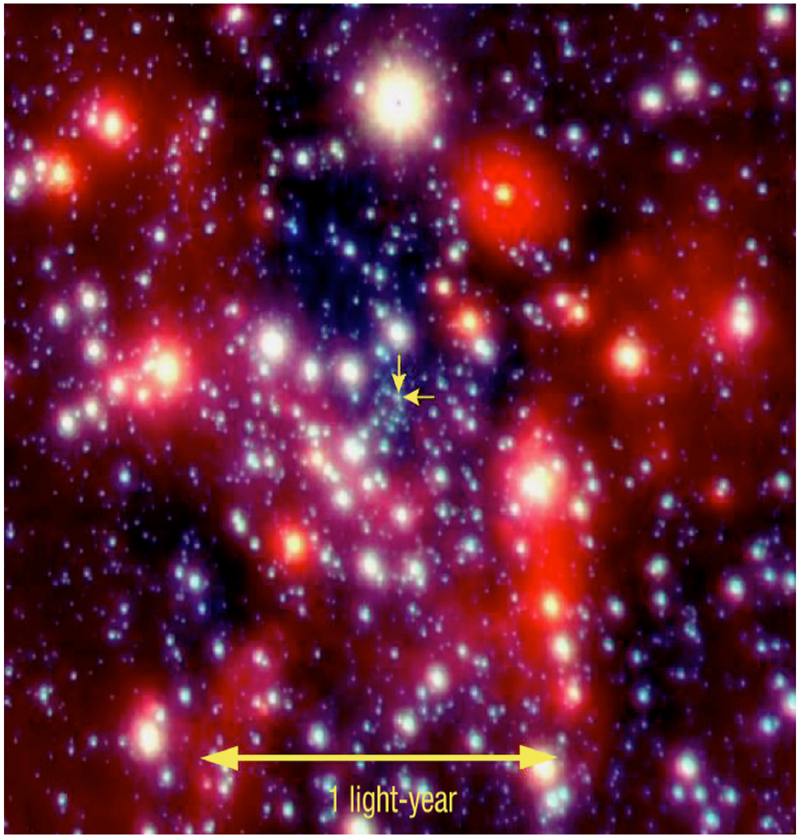
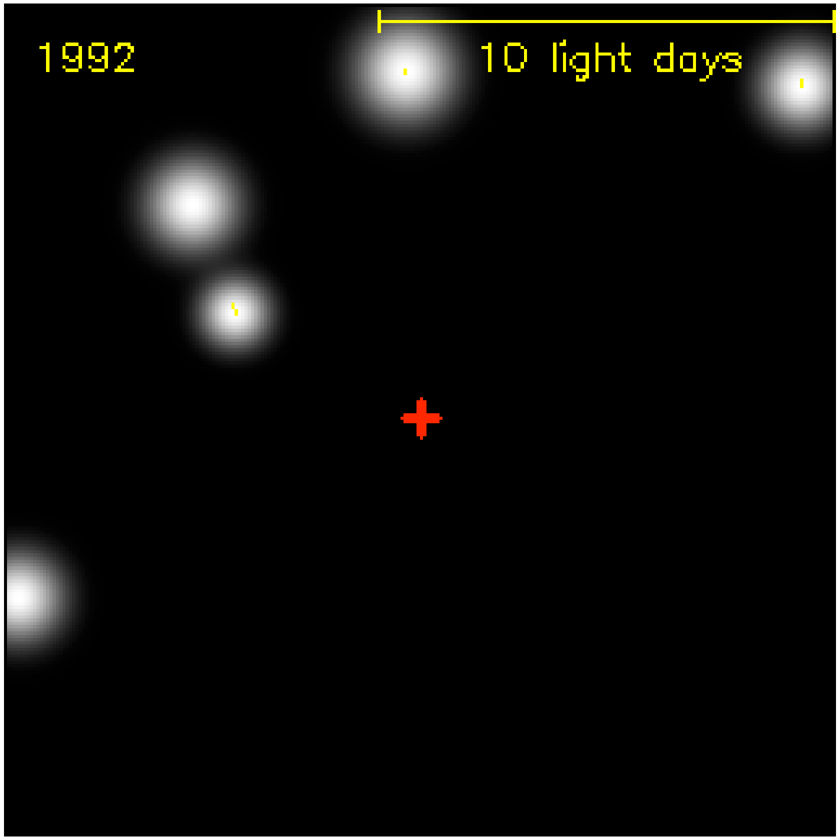
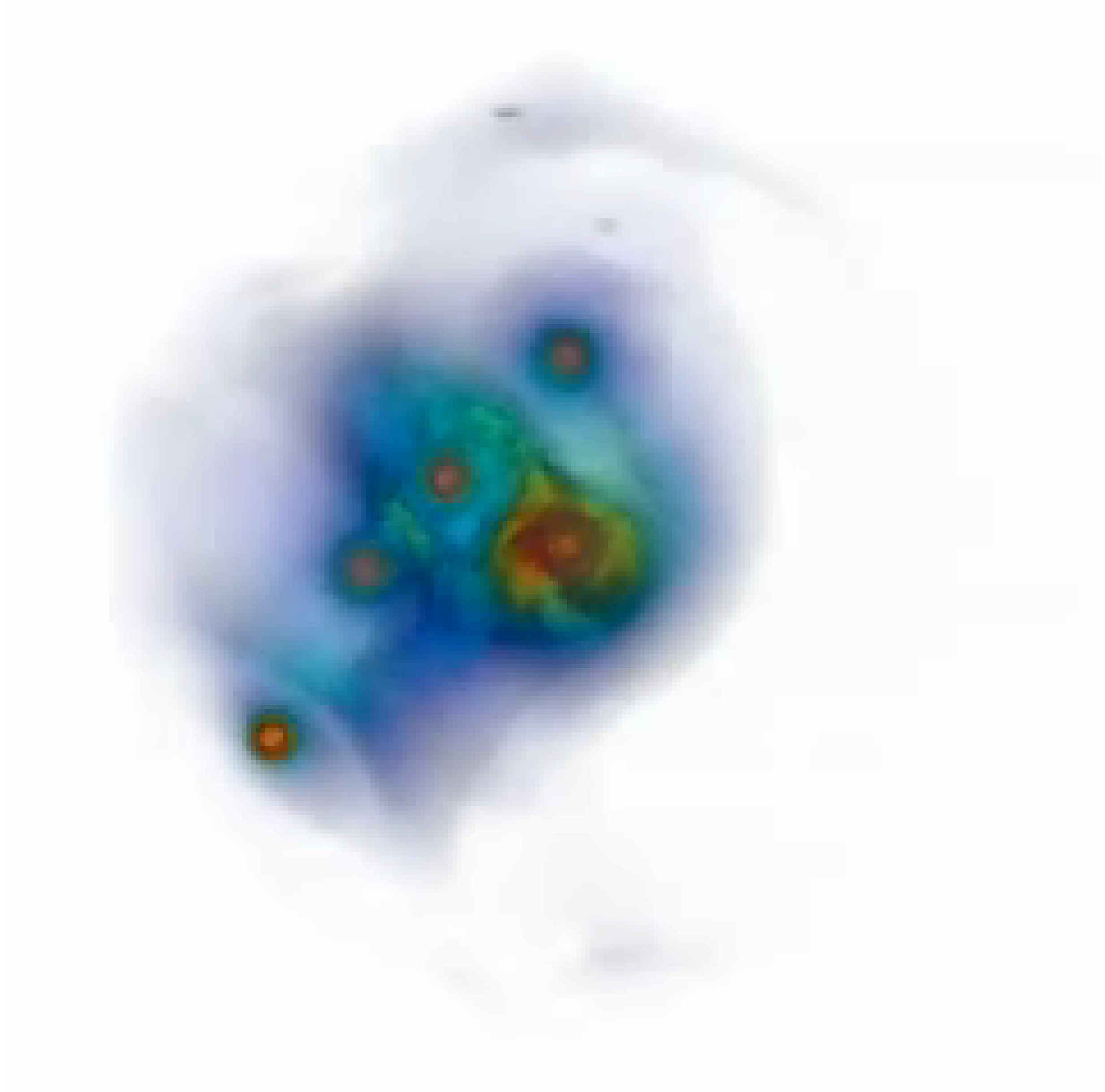
Stars seen in IR are rotating around a faint radio, IR and X-ray source: Sgr A*





MPE / R. Genzel et al.

Movie of the Galactic Center



Coker &
Pittard

Conclusions

Colliding winds in early-type binaries are important laboratories for investigating shock physics and particle acceleration

Highly eccentric systems – like WR140 – are particularly useful

Models of radio/X-ray/_-ray emission suggest…

i) adiabatic WCR gives clumping independent measure of Mdot's
ii) $T_e < T_i$, and/or shock modification
iii) a low value of wind mtm ratio
iv) the NT electron distribution has p <2
- reacceleration at shocks internal to WCR?

…and have provided insight into particle acceleration efficiencies, and the strength of the B-field

Exciting period in the next few years (GLAST, VERITAS)

Expect to see large variations in the high energy NT emission with phase

Further details:

Pittard & Dougherty (2006, MNRAS, 372, 801)