Stochastic acceleration and magnetic damping in Tycho's SNR

Alina Wilhelm

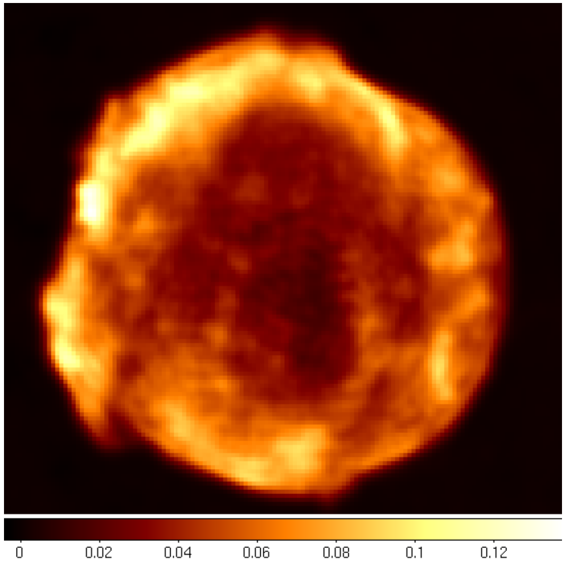
In collaboration with Igor Telezhinsky, Vikram Dwarkadas and Martin Pohl

Chania, 09.06.16

Tycho's supernova remnant

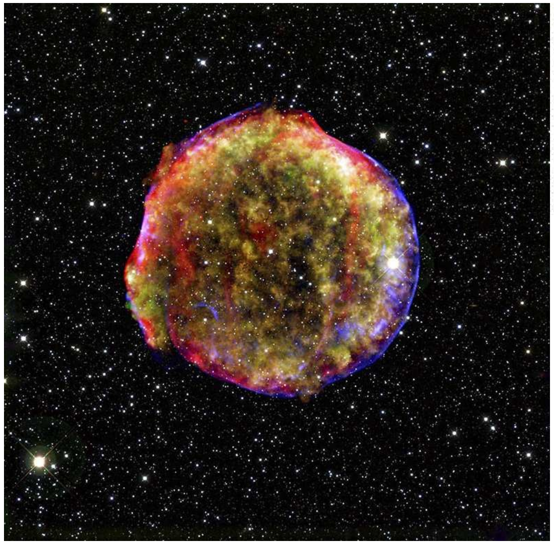
Young historical type Ia SNR

NRAO/VLA Archive Survey



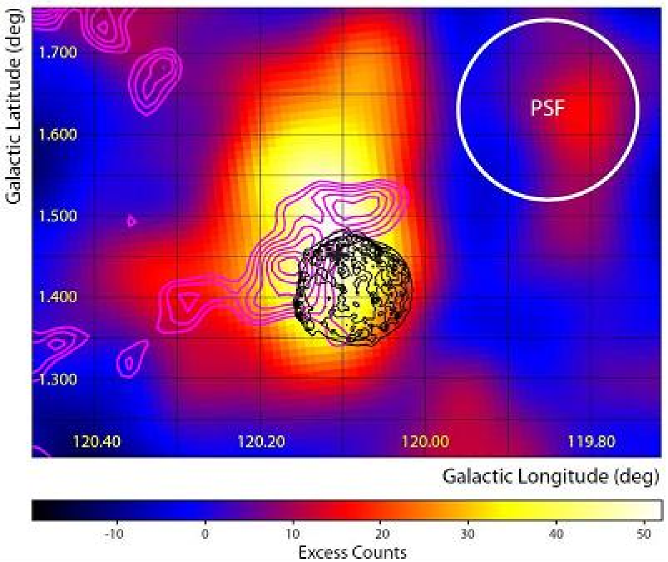
radio

O.Krause et.al.



x-ray

VERITAS Collaboration Acciari et al.



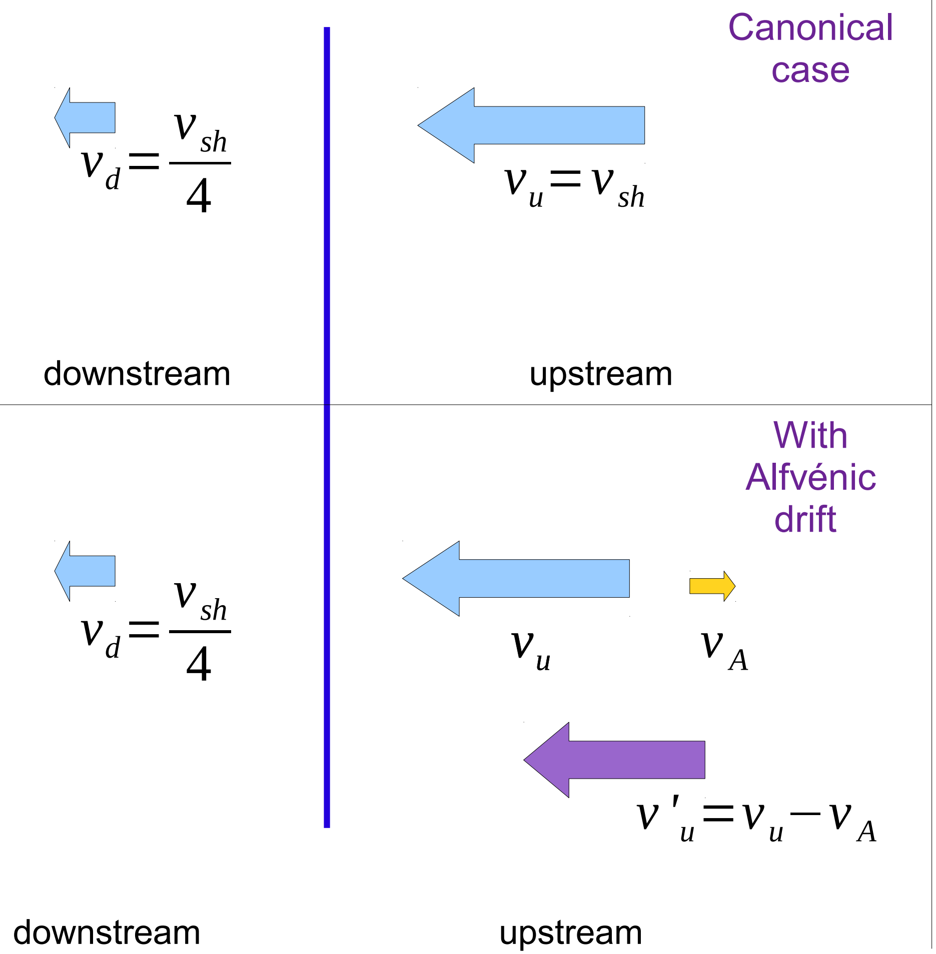
gamma

Soft radio spectrum ~ 0.65 (Kothes et al. 2006)

Inconsistent with the standard prediction of Diffusive Shock Acceleration

Possible explanation: Alfvénic drift

Shock restframe



For radio data compression factor r=3.5 is required!

$$r = \frac{v'_u}{v'_d} = \frac{v_u - v_{A,u}}{v_d + h \cdot v_{A,d}}$$

For Tycho:

M_A=10
with h=0

Morlino & Caprioli 2012; Slane et. al 2014

Contradictions:

Alfvén wave transmission: helicity h negative!

⇨ r>4 → harder spectrum!

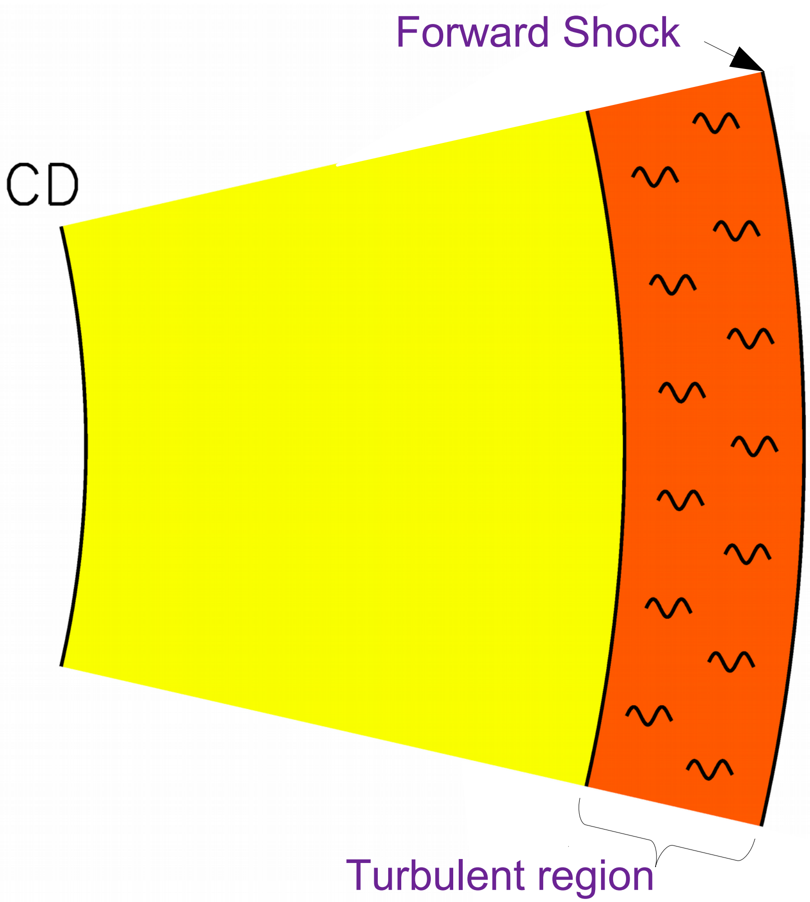
Vanio and Schlickeiser1999

Growth of Bell's instability to $v_\phi = v_A$ debatable

Niemiec et al. 2008

Alternative approach

Magnetic turbulence in the post-shock region
Additional mechanism to Diffusive Shock Acceleration:



Stochastic Acceleration

Fast-mode waves are efficient

Acceleration time: τ_{acc} ~ of few years

Damping mechanism: particle acceleration

➡ Thickness of the turbulent region is small

More details: Pohl et. al. 2015

Momentum diffusion coefficient

Calculated at lower energies:

$$\tau_{acc} = const := \tau \quad \text{for} \quad p \leqslant p_0 \sim 1 \text{ GeV}$$

Parametrization at higher energies:

$$\tau_{acc} = \tau \left(\frac{p}{p_0} \right)^m$$

$$D_p = \frac{p^2}{\tau} \quad for \quad p \leqslant p_0$$

$$D_p = \frac{p^2}{\tau} \left(\frac{p}{p_0} \right)^{-m} \quad for \quad p > p_0$$

Modeling SNR

Particle acceleration via kinetic approach:

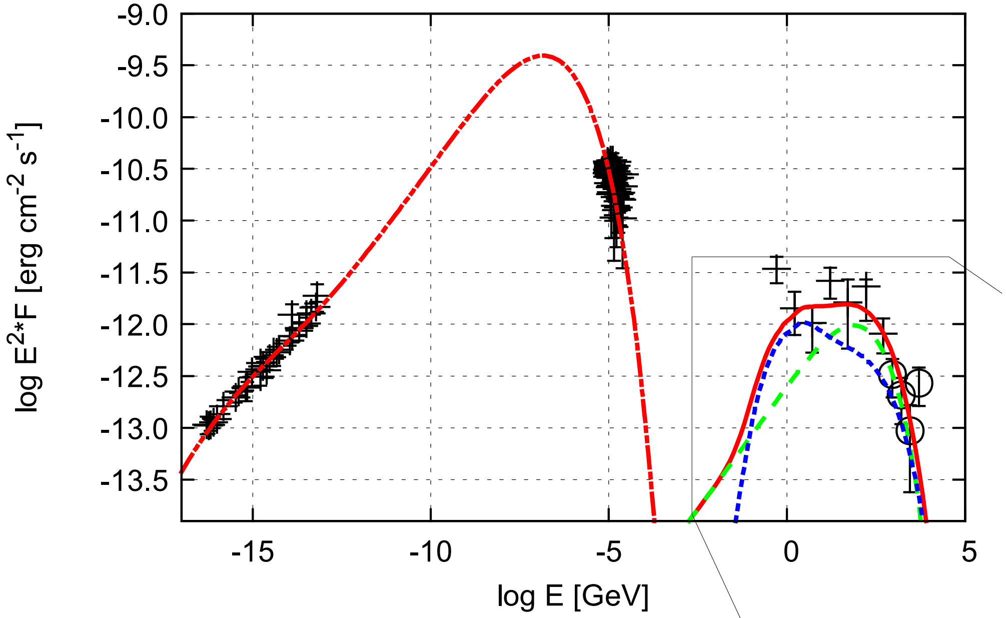
$$\frac{\partial N}{\partial t} = \underbrace{\nabla(D_s \nabla N}_{\text{Diffusion}} \underbrace{- \mathbf{v} N)}_{\text{Advection}} \underbrace{- \frac{\partial}{\partial p}\left((N\dot{p})\right.}_{\text{Losses}} \underbrace{\left. - \nabla \frac{\mathbf{v}}{3} Np\right)}_{\text{DSA}} + \underbrace{\frac{\partial}{\partial p}\left(p^2 D_p \frac{\partial}{\partial p} \frac{N}{p^2}\right)}_{\text{SA}} + \underbrace{Q}_{\text{Injection}}$$

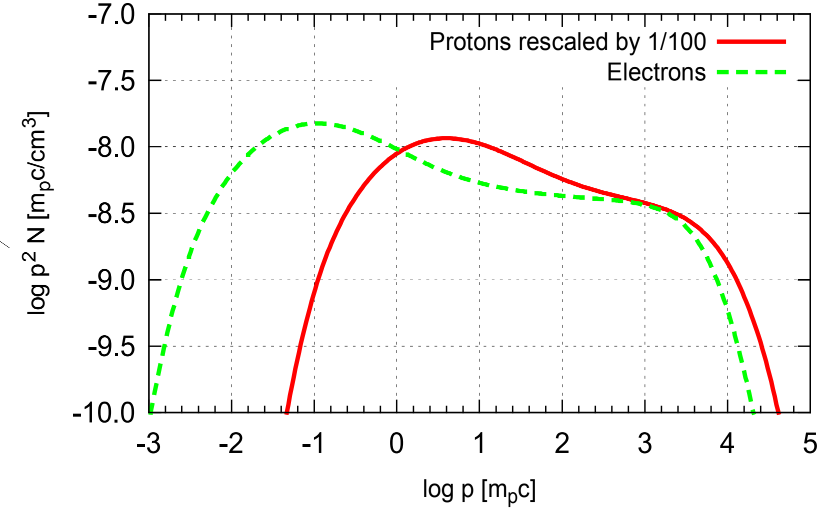
Diffusion Advection Losses **DSA** **SA** Injection

- Plasma velocity profiles **v** from hydrodynamical simulations
- Computation of advected magnetic field (alternative: analytical profiles)
- Solving Transport equation for particle number density N (electrons & protons)
- Synchrotron emission from electrons in magnetic field **B**
- γ-rays from protons via neutral pion decay
- γ-rays from electrons via inverse Compton scattering

} Emission spectrum

Results





Electron-to-proton ratio:

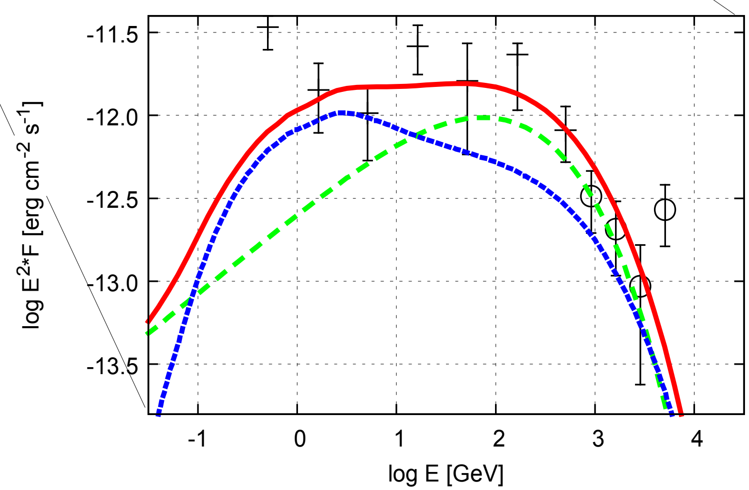
$$K_{e/p} := \frac{N_e}{N_p} \approx \frac{1}{100}$$

Minimum magnetic field:

$B_d \sim 80\ \mu G$

Reacceleration region:

$\sim 10^{-3}\ R_{sh}$

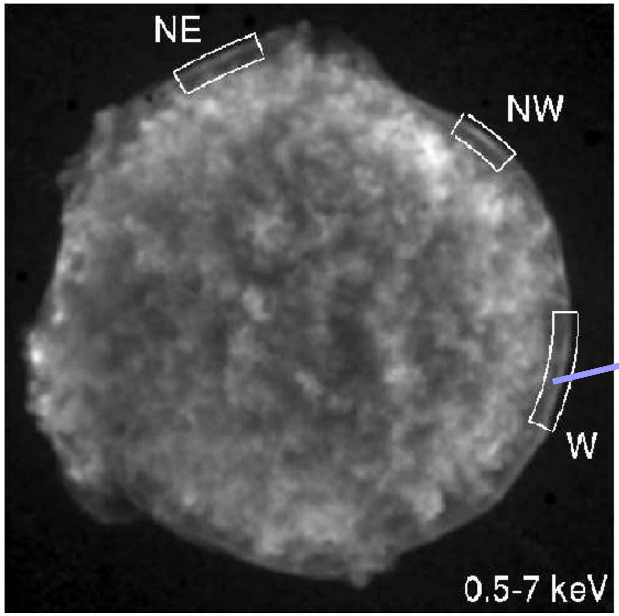


γ-ray data:

Park for the VERITAS Collaboration 2015

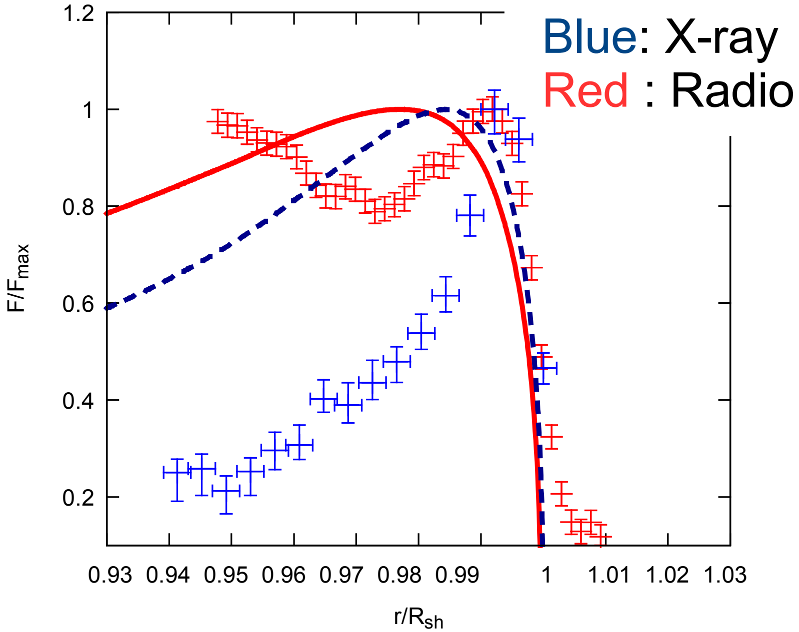
Filaments

X-ray map



Extract data

Intensity profile



$B_d \sim 80\ \mu G$ fails to produce filaments

How can we explain the narrow rim structure in x-ray and radio?

Tran et al. 2015

Two scenarios

Synchrotron losses limited case

- Lack of electrons!
- B_d = 330 μG required (Morlino & Caprioli 2012)
- Strong energy-dependence → radio filaments unexplained

Magnetically limited case

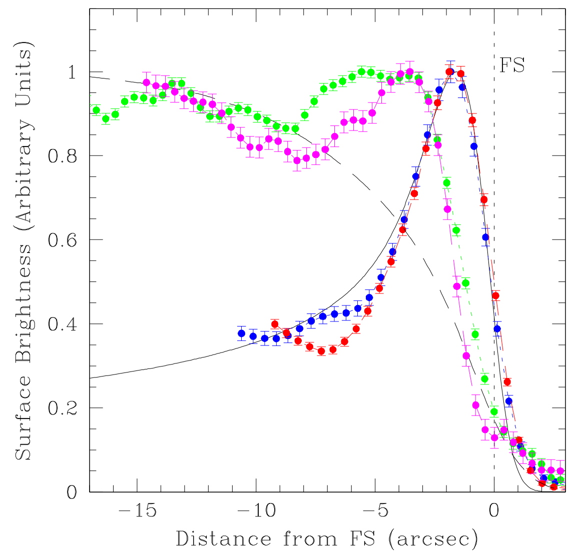
- Lack of magnetic field!

$$B(r) = (B_d - B_0)\exp\left(\frac{-(r - R_{sh})}{l_d}\right)$$

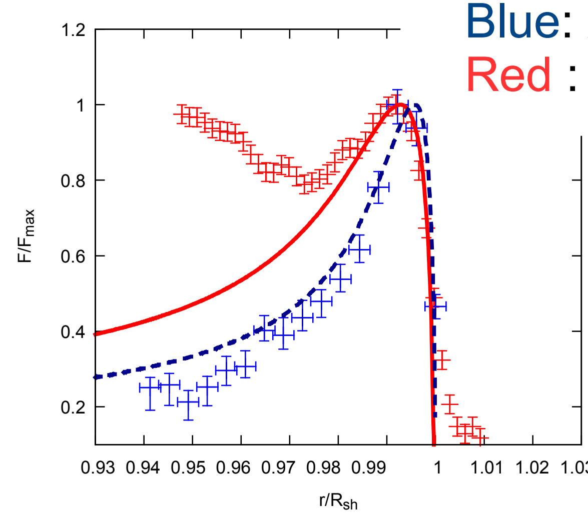
where l_d is the damping length

- Energy-dependence at the cut-off
- B_d = 173 μG B_0 = 20 μG l_d=0.015 R_{sh}

P. Slane et al. 2014



Blue/Red: X-ray
Magenta/Green: Radio



Blue: X-ray
Red : Radio

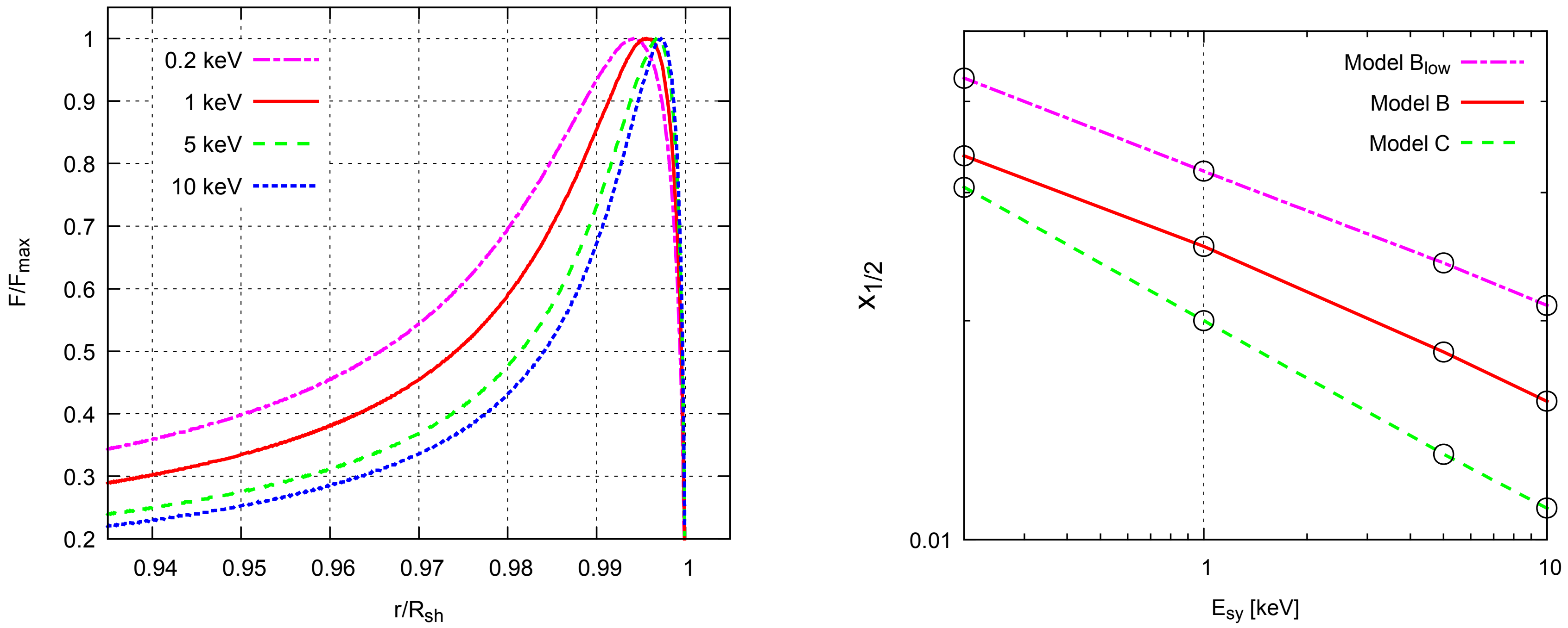
Summary

- Stochastic acceleration can explain soft radio spectrum
- No Alfvénic drift needed
- Soft hadronic γ-spectrum in GeV band
- Filaments:
  - X-ray filaments require 330 µG in loss-limited case
  - 173 µG needed in damping scenario
  - Radio profiles prefer magnetic field damping

Thank you for your attention!

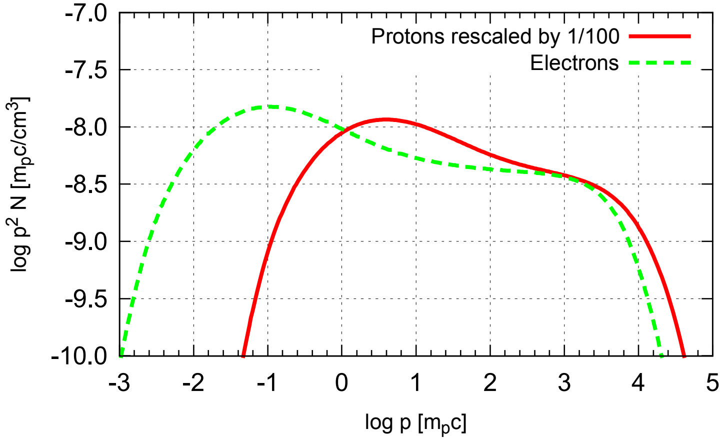
DESY

Backup slides: Filament width

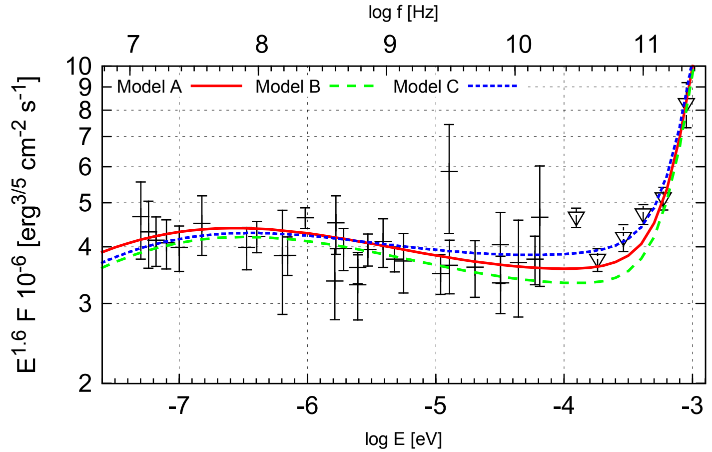


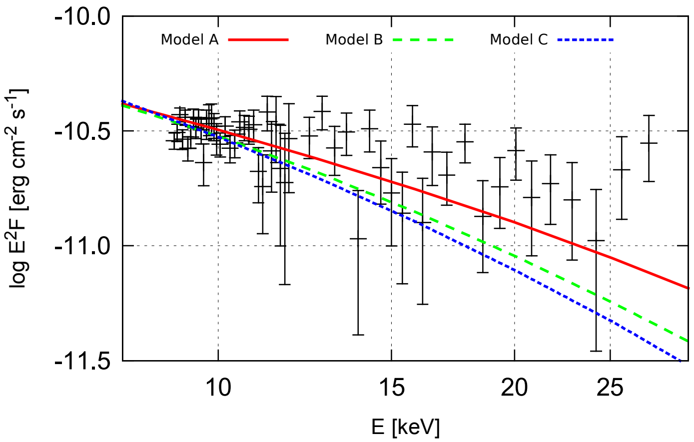
Results: Impact from Stochastic acceleration

Particle number density N



Synchrotron emission





Deviates from DSA prediction: $N \sim p^{-2}$

SA peak determined by m, p_0 and τ

To stay in agreement with radio data:

$$m \in [0.15, 0.25] \quad \tau \in [2.4, 3.0]$$

Results: three different cases

Model A:

Transported MF
B_d=83 μG
$K_{e/p}$=1/100

Model B:

Damped MF
B_d=173 μG
l_d=0.015·R_{sh}
$K_{e/p}$=1/100

Model C:

Damped MF
B_d=330 μG
l_d=0.02·R_{sh}
$K_{e/p}$=1/600