Cosmic Ray Acceleration at Galactic Wind Termination Shocks

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Relevant papers:
Bustard, Zweibel, and D'Onghia 2016, ApJ
Bustard, Zweibel, and Cotter 2017, ApJ

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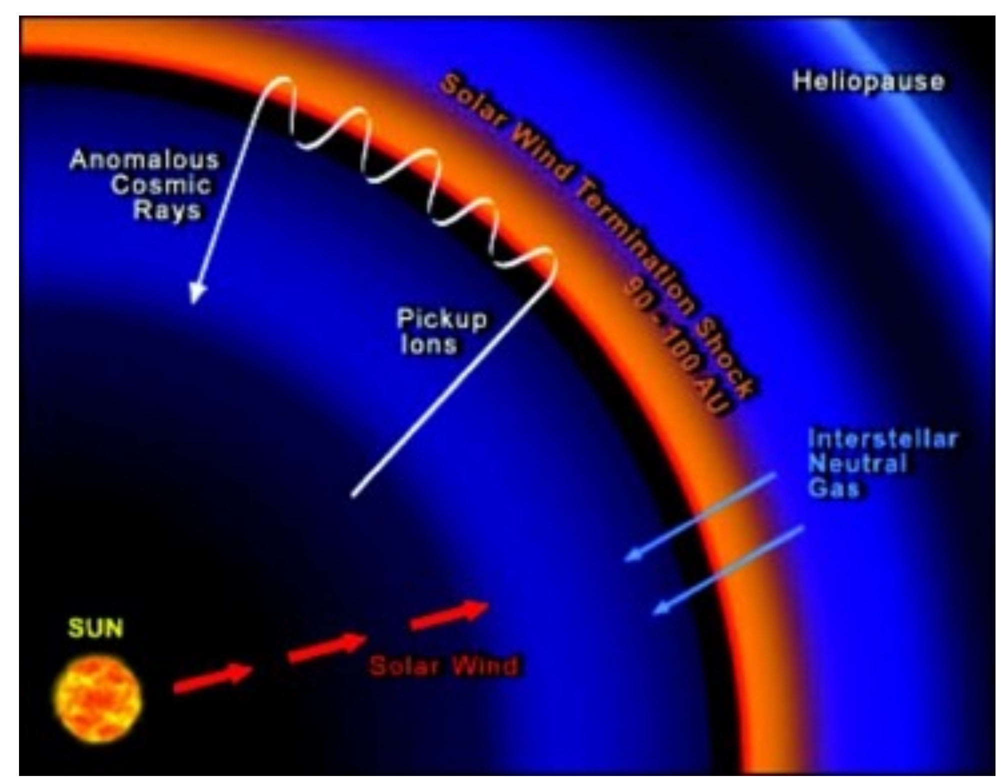
Galactic Winds

- Extended outflows of material formed by stellar feedback
- Can be driven thermally, as well as by cosmic rays and radiation pressure on dust grains
- Hot topic in galaxy formation community
  - Winds recycle energy and metals into the intergalactic medium (IGM)
  - Quench star formation in galaxies

Termination shock when:

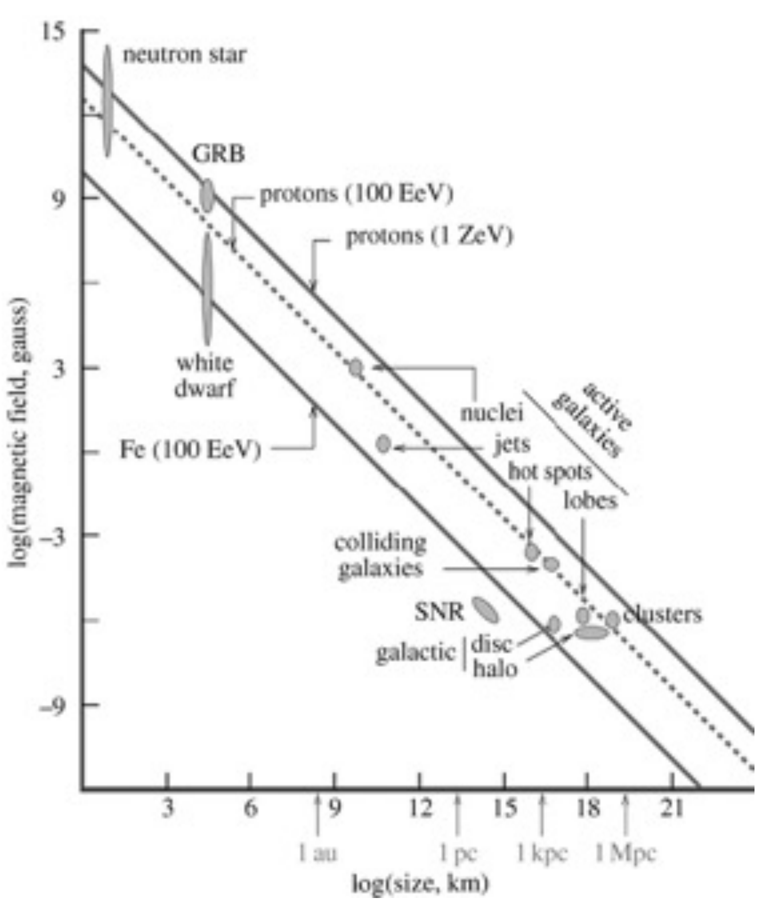
$$\rho V_{shock}^2 = P_{IGM}$$

M82
Ionized hydrogen (magenta) from the WIYN telescope



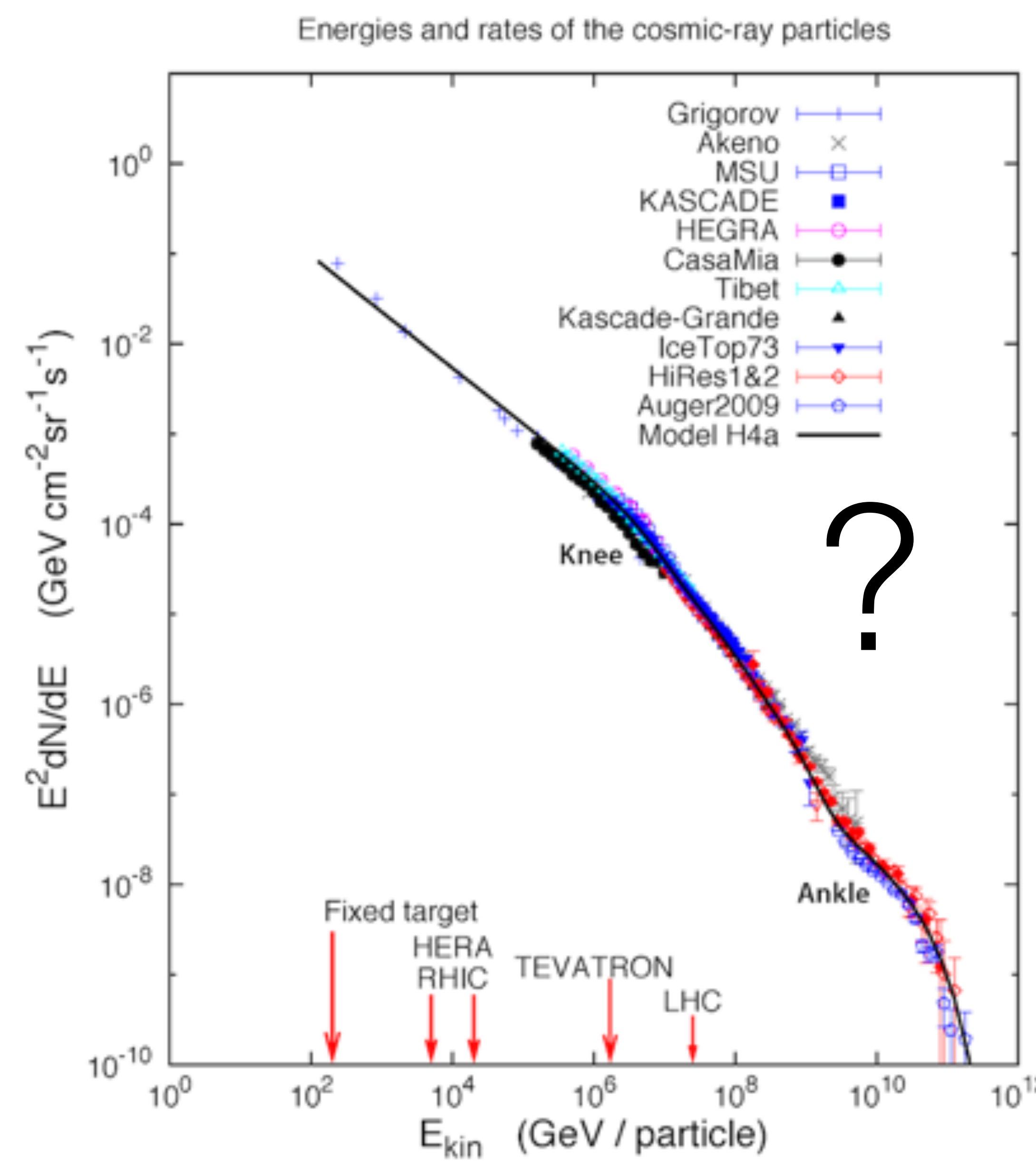
Motivation

- Cosmic ray (CR) spectrum steepens around 3×10^{15} eV — the *knee*
- Diffusive shock acceleration of CRs at supernova remnants (SNRs) likely accounts for E < 3×10^{15} eV
- Past the *ankle*, CRs should be accelerated by extragalactic sources
- Between the knee and ankle (the *shin*, if you will), the source of CRs is unclear



Hillas plot shows objects that can confine CRs of various energies

$$E_{\mathrm{GeV}} = \frac{10^{-2} B_{\mu \mathrm{G}} R_{\mathrm{shock}}}{3 \times 10^{10}}$$



Images from Fraschetti 2008 and the IceCube Collaboration

Ingredients for Cosmic Ray (CR) Acceleration

- CR gyroradius < size of accelerator (Hillas Plot)

$$E_{\rm GeV} = \frac{10^{-2} B_{\mu {\rm G}} R_{\rm shock}}{3 \times 10^{10}}$$

- Maximum rate of particle acceleration by a strong, parallel shock (Lagage and Cesarsky 1983, Zweibel 2003)

$$\frac{dE}{dt} = 1.5 \times 10^{-18}\, Z B V_{\rm shock}^2 {\rm GeV\ s^{-1}}$$

- Acceleration time is the duration of the shock

$$E_{\rm max} = \frac{dE}{dt} t_{\rm acc}.$$

Galactic Winds as Cosmic Ray Accelerators?

- Jokipii and Morfill (1985, 1987) proposed that diffuse shock acceleration at galactic wind termination shocks could accelerate CRs up to 10^{20} eV (UHECR)!
  - R_{shock} ~ 100s of kpc, so high energy CRs will be <u>confined</u>
  - Wind velocities in M82 measured up to 2500 km/s, so <u>acceleration rate is high</u>
  - Acceleration time ~ ~~age of a galaxy ~ Gyrs~~

Assumptions

- Termination shock occurs when total wind pressure = pressure of surrounding intergalactic medium (IGM)

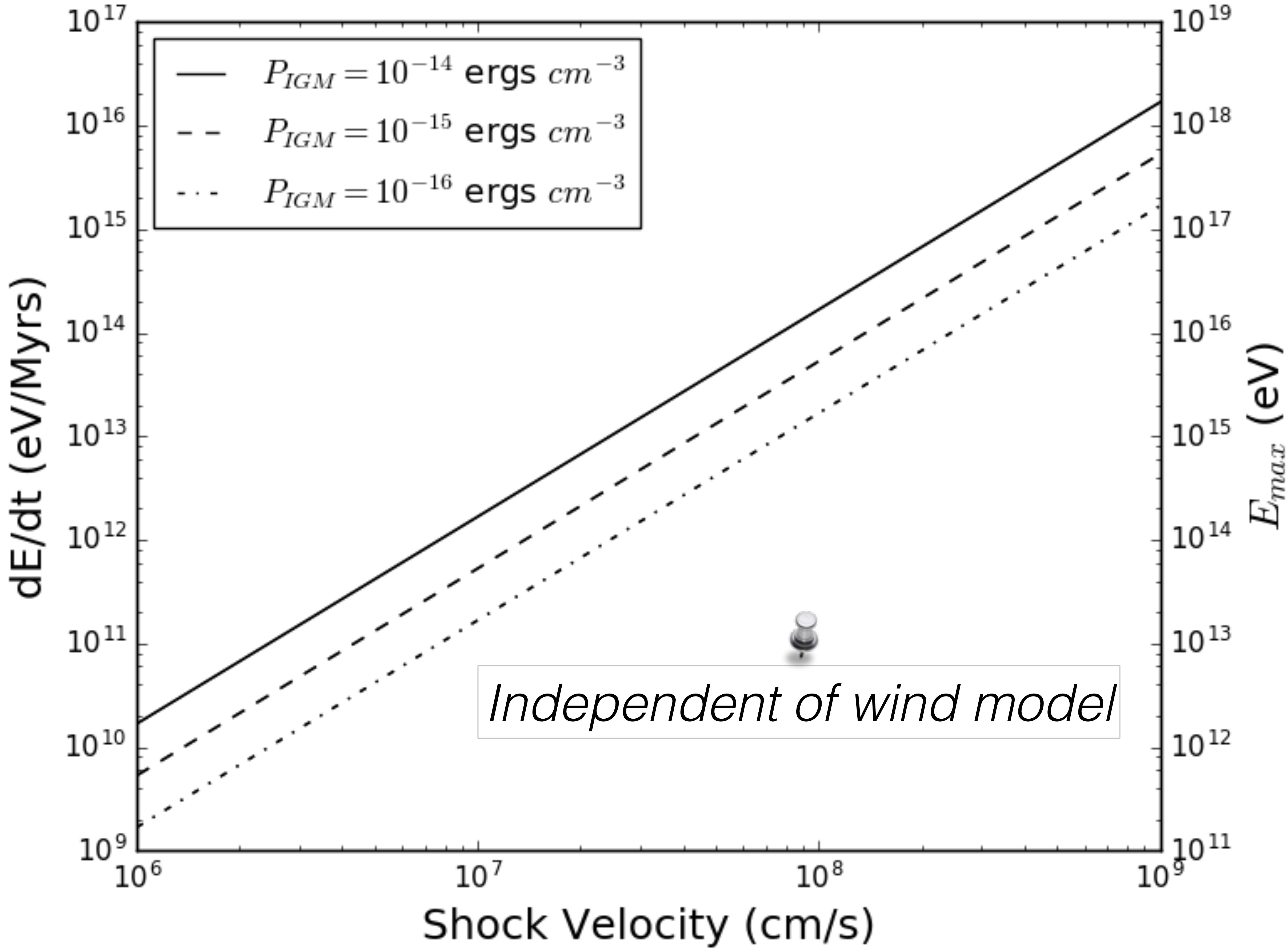
$$\rho V_{shock}^2 = P_{IGM}$$

- Magnetic field **amplified*** to equipartition $\frac{B^2}{4\pi} = \rho V_{shock}^2$

- Cosmic rays accelerated at maximum rate (Lagage and Cesarsky 1983) for acceleration time of 100 Myrs

$$\frac{dE}{dt} = (1.5 \times 10^{-18} Z)\sqrt{4\pi P_{IGM}} V_{shock}^2 \mathrm{GeV/s}$$

***but how is it amplified?**



$P_{IGM} = 10^{-14}$ ergs cm^{-3}
$P_{IGM} = 10^{-15}$ ergs cm^{-3}
$P_{IGM} = 10^{-16}$ ergs cm^{-3}
dE/dt (eV/Myrs)
E_{max} (eV)
Shock Velocity (cm/s)
10^{6}
10^{7}
10^{8}
10^{9}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
Independent of wind model

Results Using Bustard+ 2016 Wind Model

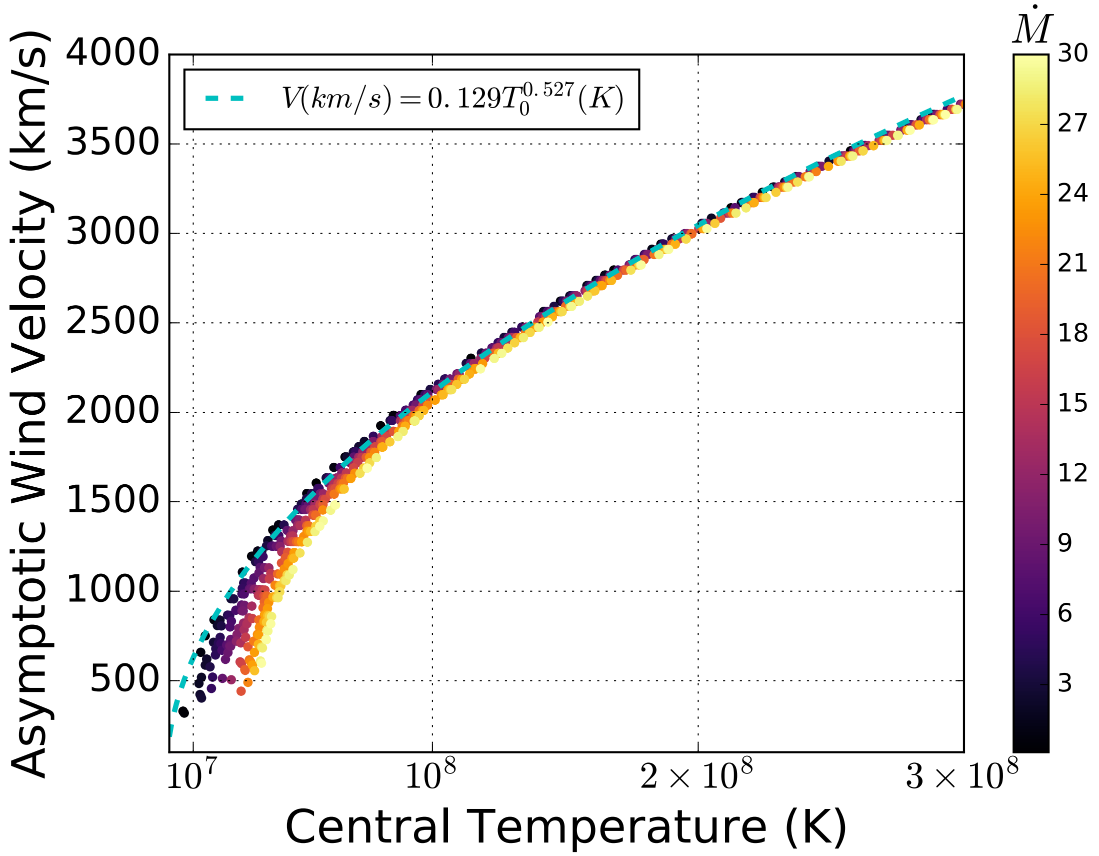
- Thermally driven, spherically symmetric, steady-state model
  - Gravitational potential from extended mass distribution
  - Radiative losses affect wind dynamics

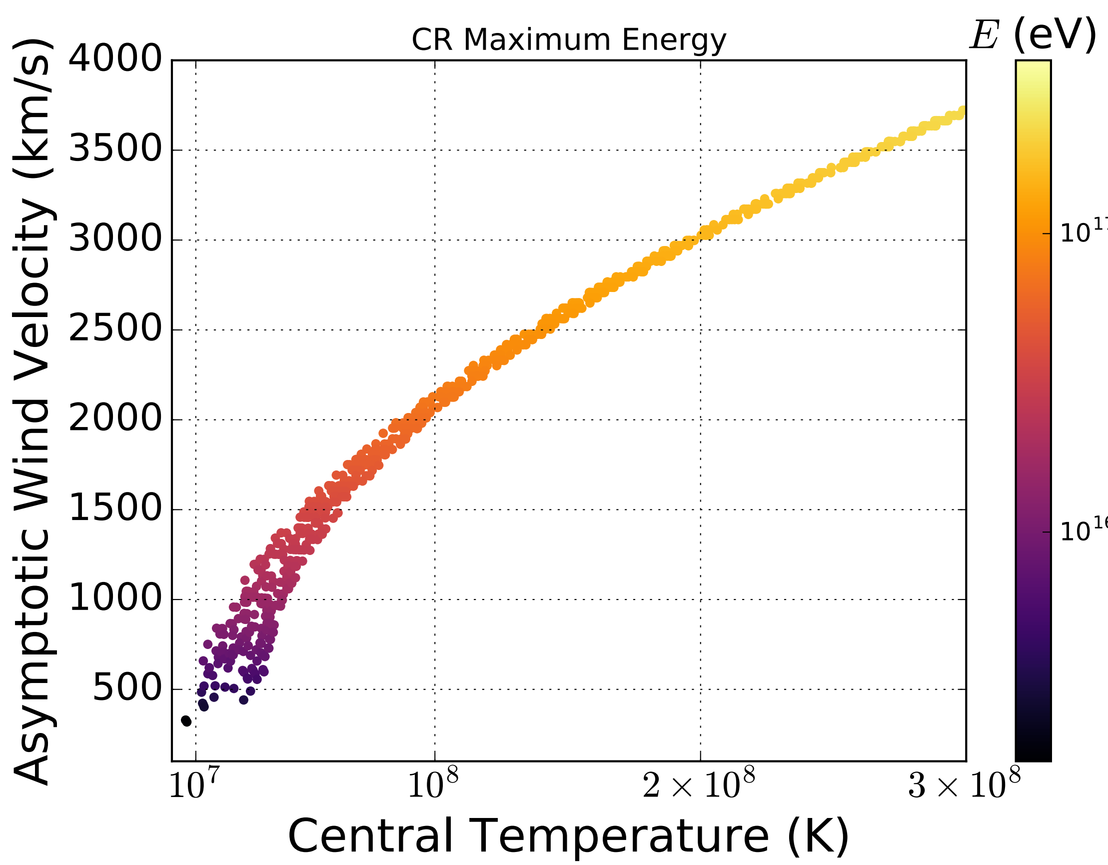
- Can run models very quickly. Each point is for a 10^9 solar mass, 200 pc radius galaxy with different mass injection and central temperature

$$\frac{dE}{dt} = (1.5 \times 10^{-18} Z)\sqrt{4\pi P_{IGM}} V_{shock}^2 \mathrm{GeV/s}$$

$$P_{IGM} = 10^{-14} \mathrm{ergs/cm^3}$$

$$t_{acc} = 100 \mathrm{Myrs}$$





Bustard, Zweibel, and Cotter 2017

Can Cosmic Rays Diffuse Back to the Galaxy?

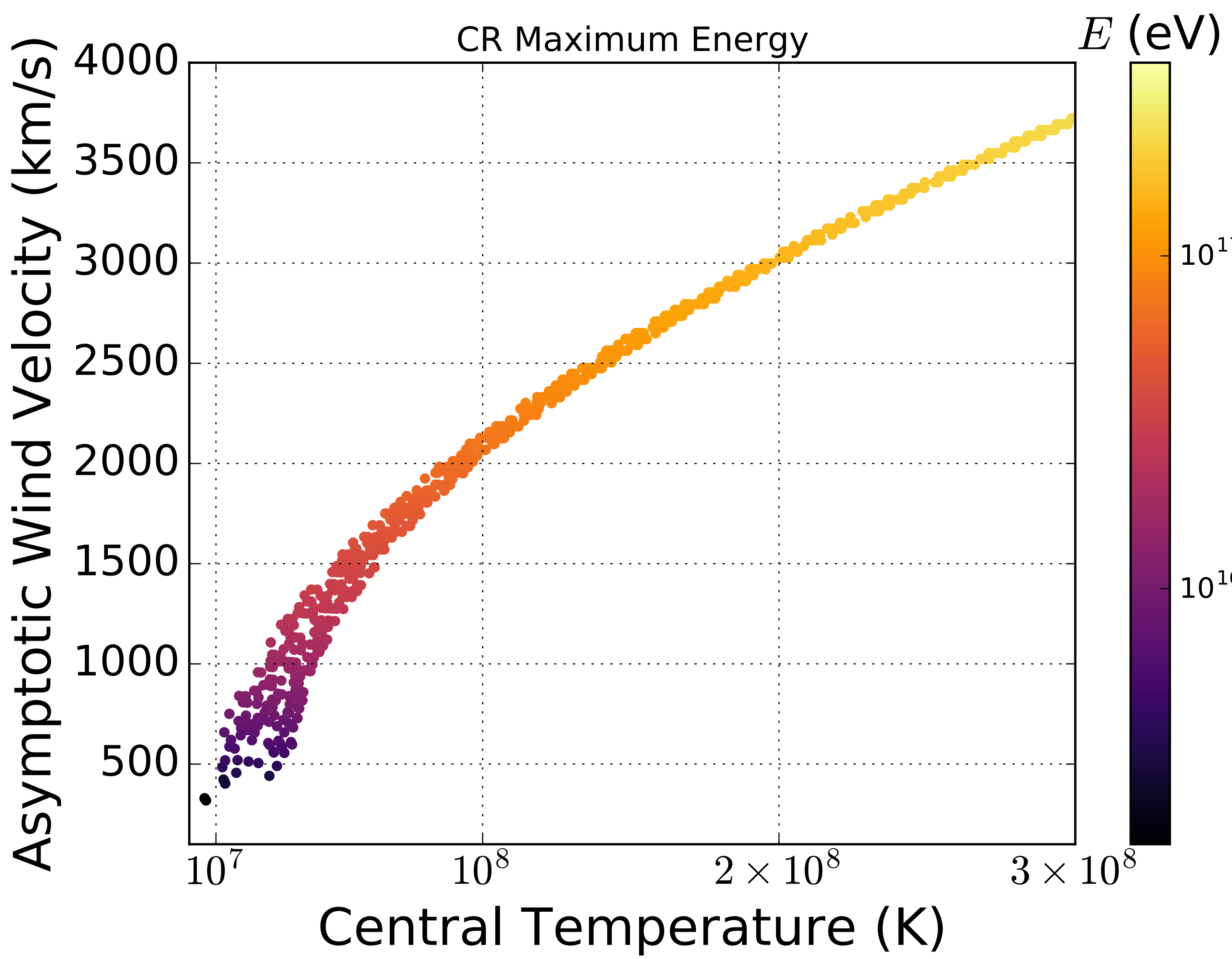
Diffusion Coefficient: $\kappa(E) = D_0 \times 10^{28} cm^2 s^{-1} E_{GeV}^a$

a = 0.4; D_0 = 5

Can cosmic ray diffusion overcome advection by the outflow?

$$\mathcal{R}_{\rm CR} = \frac{R_{\rm shock} V_{\rm shock}}{\kappa(E)}.$$

$$E_{\rm min,GeV} = \left(\frac{R_{\rm shock} V_{\rm shock}}{5 \times 10^{28}}\right)^{1/a}.$$



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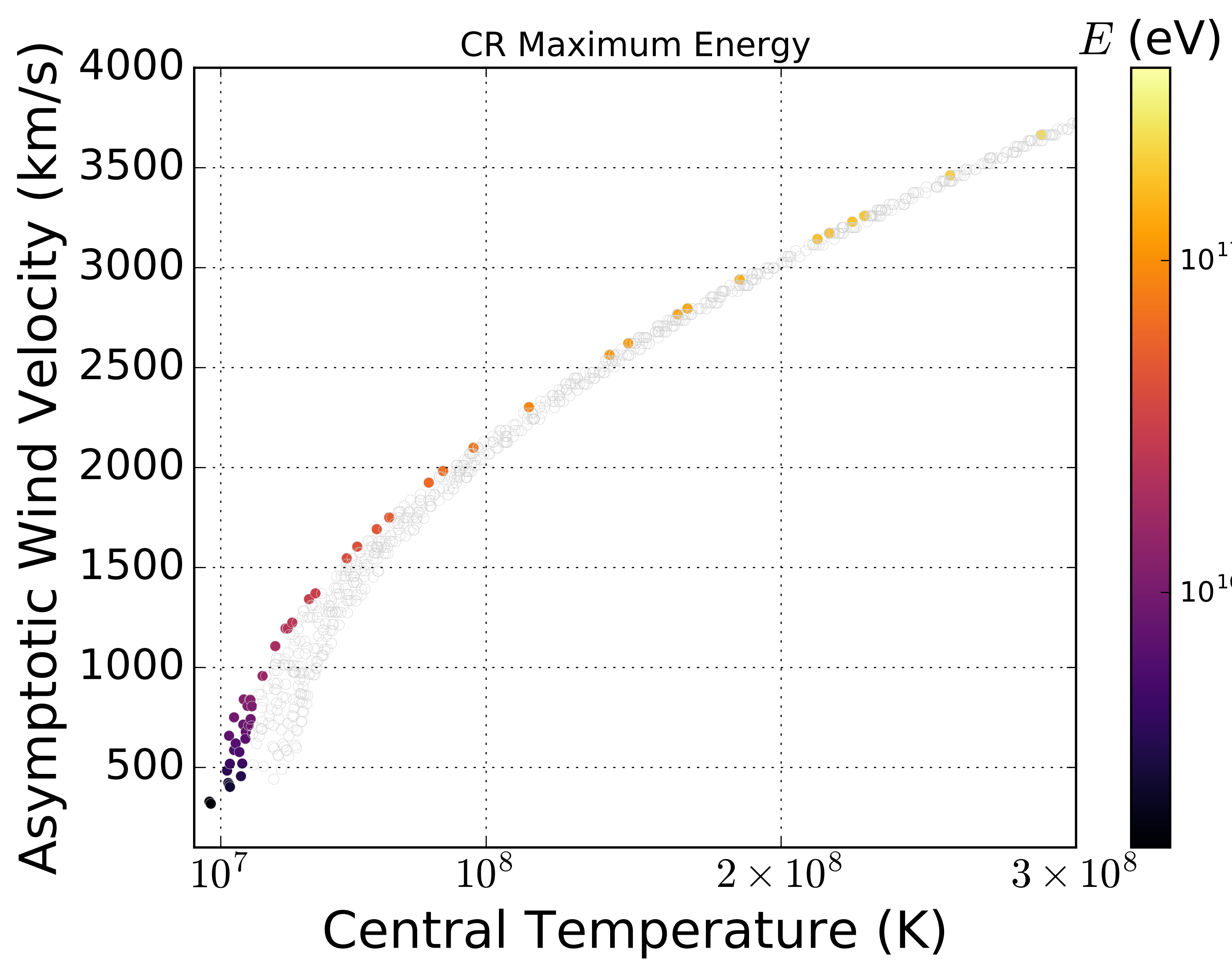

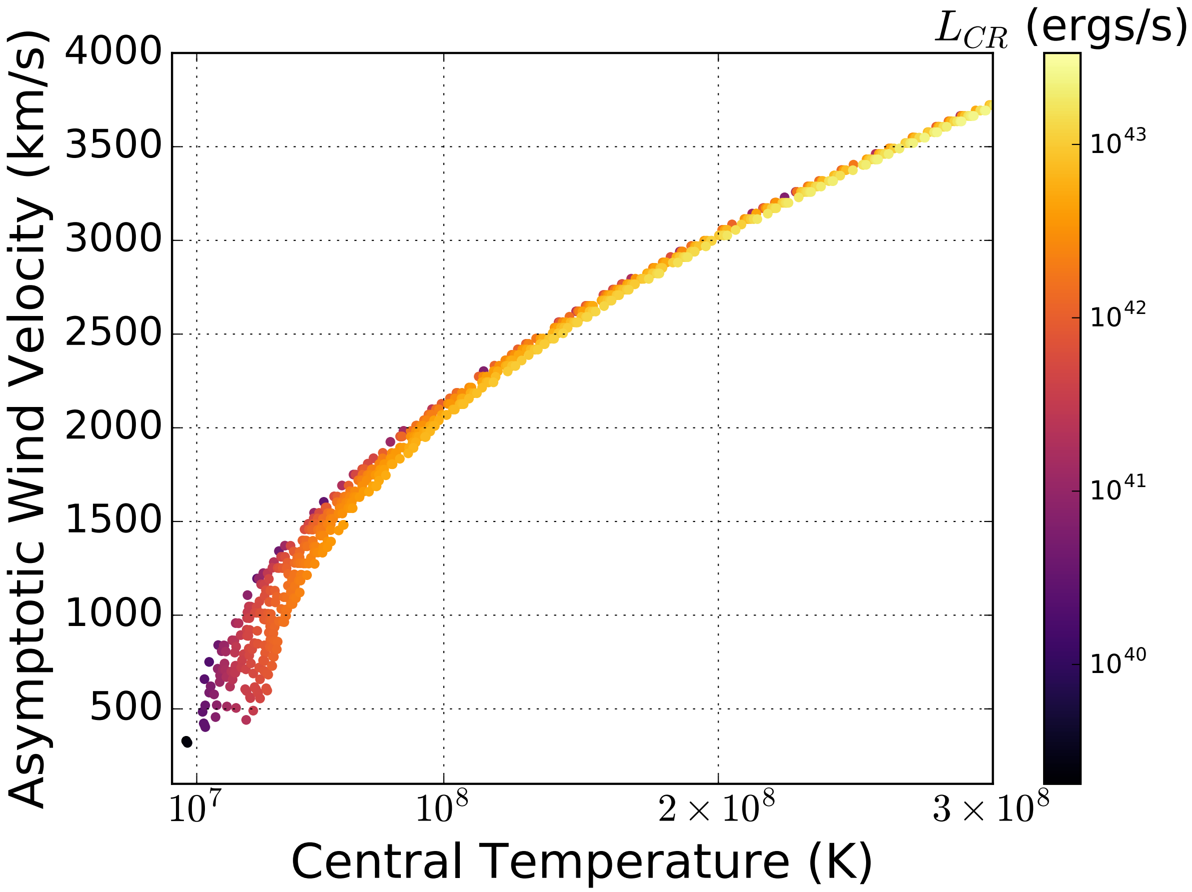

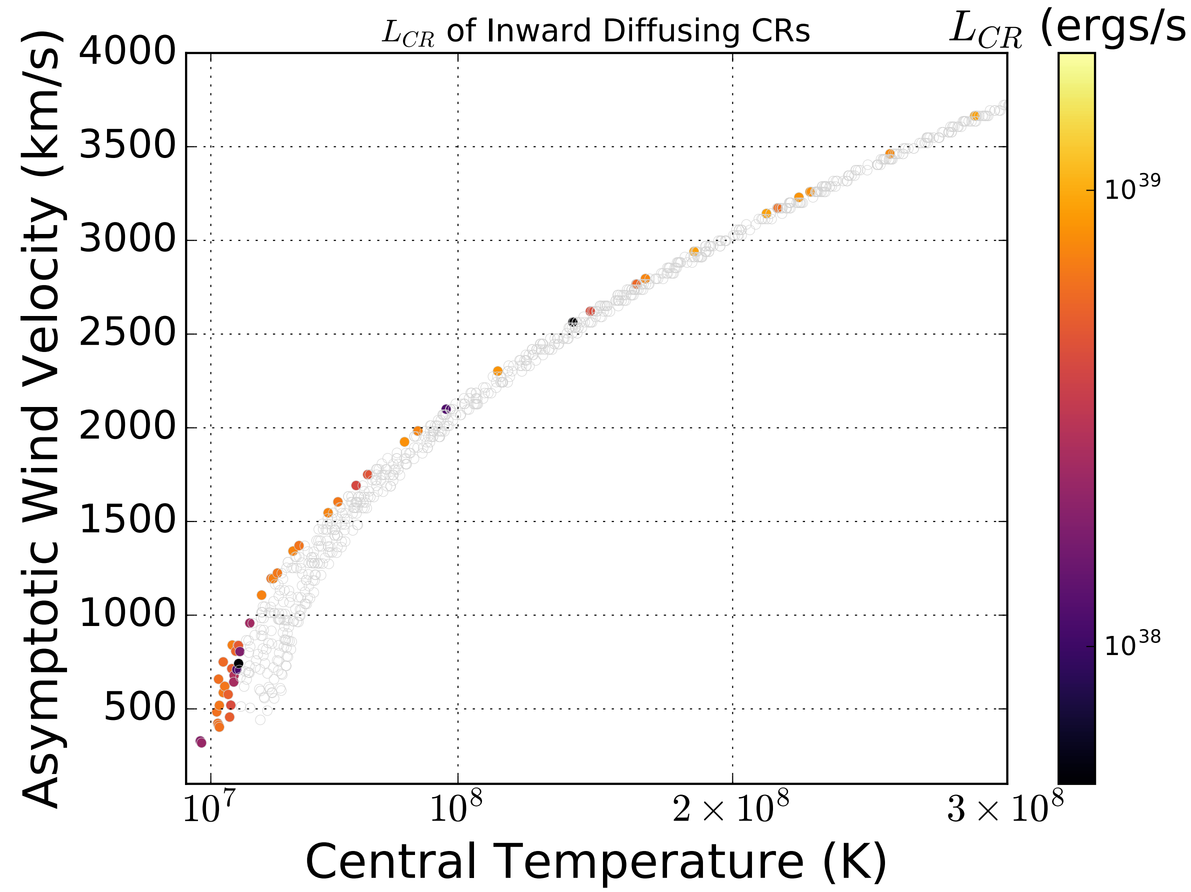

10^{43} ergs/s ~ 1/10 of the total Milky Way luminosity!

Could termination shocks *revitalize* GeV cosmic rays that would otherwise lose energy as they adiabatically expand? Act as a significant source of cosmic rays, neutrinos, gamma rays, etc. in the intergalactic medium and halo of our galaxy?

From models of Everett and Zweibel (2008) for the Milky Way wind,
V_{wind} ~ 600 km/s, dM/dt ~ 2 solar masses/year

—> R_{shock} ~ 260 kpc
—> maximum CR energy ~ 6 x 10^{15} eV
—> total CR luminosity ~ 4.5 x 10^{40} ergs/s
—> total CR luminosity (inward) ~ 9 x 10^{38} ergs/s

Conclusions

- Termination shocks could significantly revitalize cosmic rays and increase the energy flux of cosmic rays into the intergalactic medium
- Likely not a source of cosmic rays > ~10^{17} eV given constraints on acceleration time, shock (wind) velocity, magnetic field amplification
- Outstanding questions and future work:
    - What is the diffusion coefficient at “shin” energies?
    - Neutrino and gamma-ray emission
    - Time-dependent wind model
    - Fluid simulations of magnetic field amplification