Fermi Symposium 2015

CRAFT: the Cosmic Ray Analytical Fast Tool

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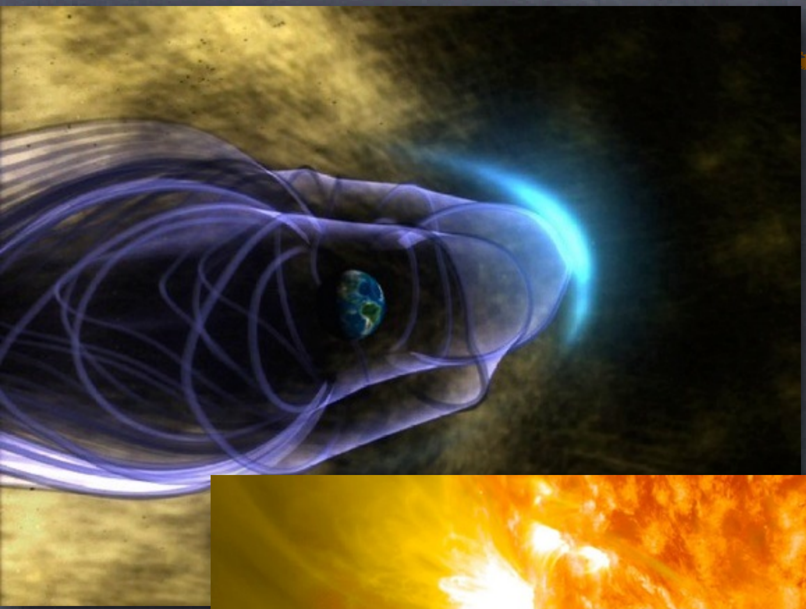
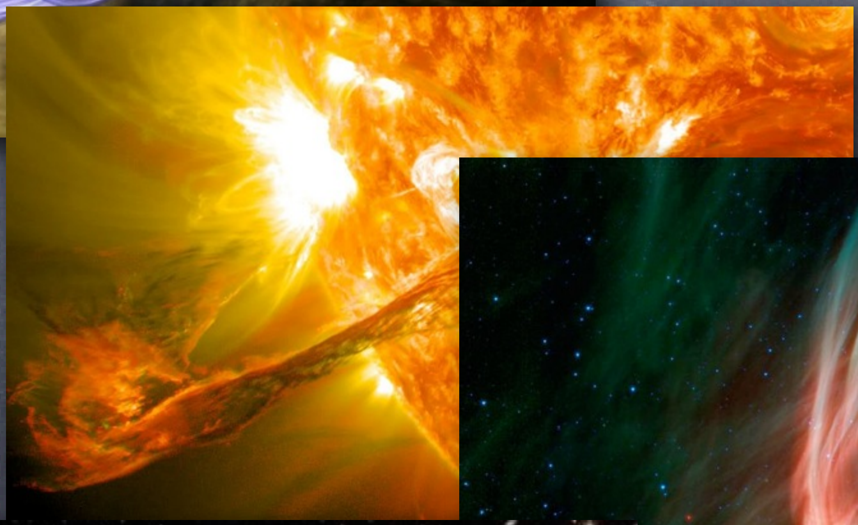
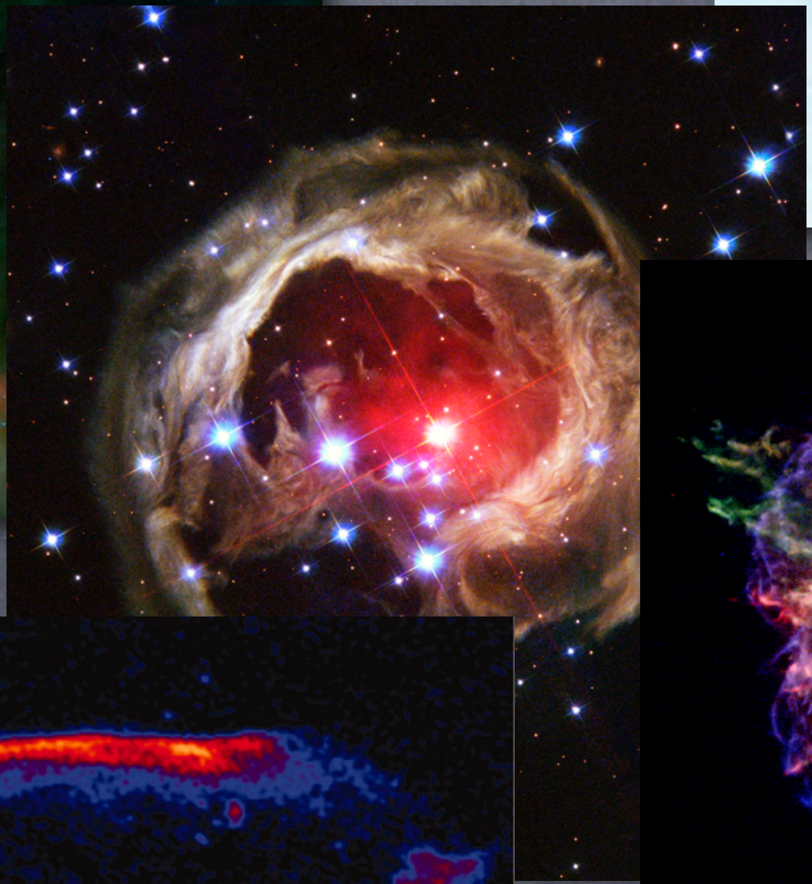
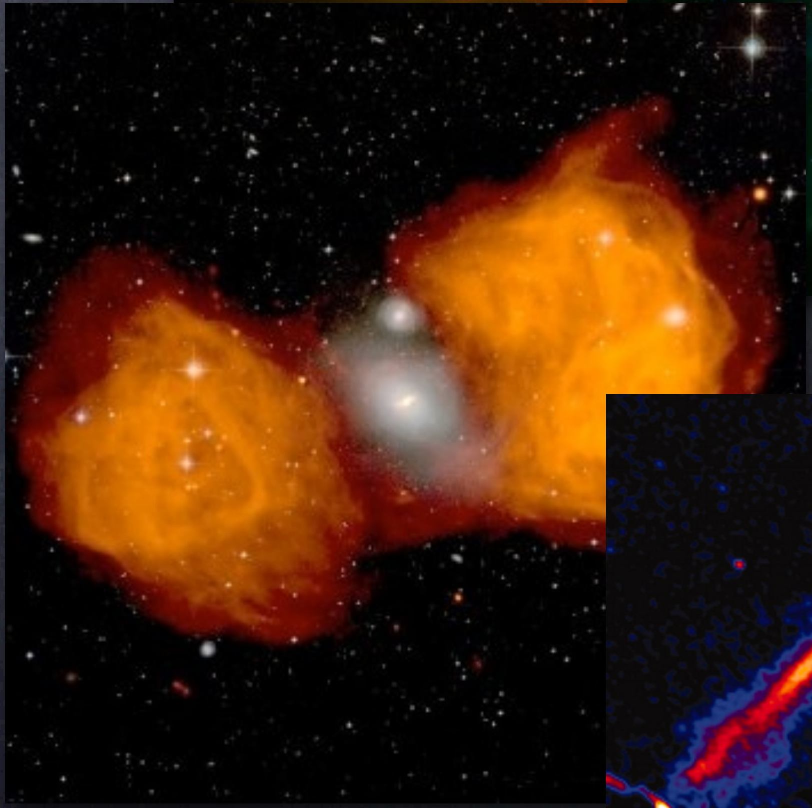
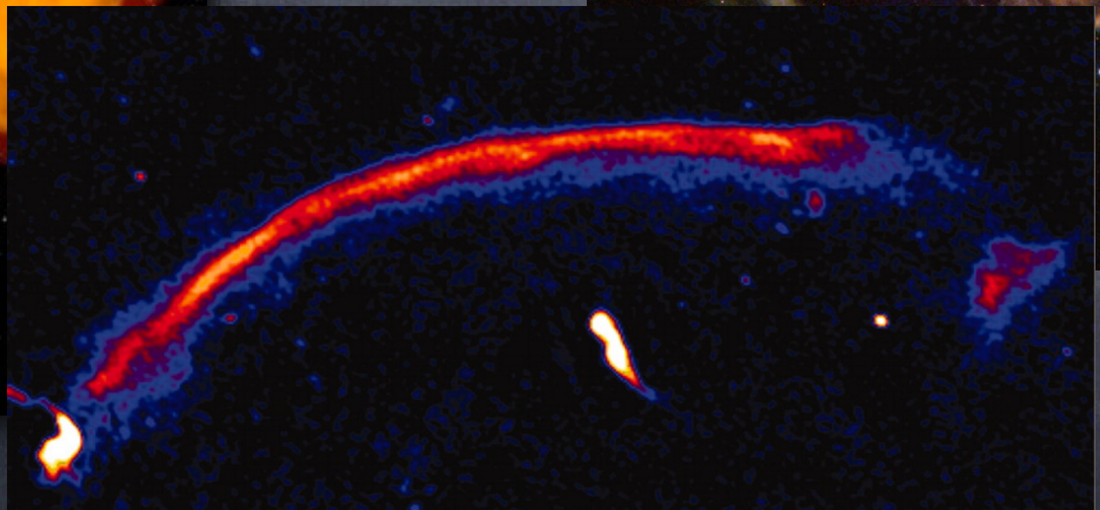
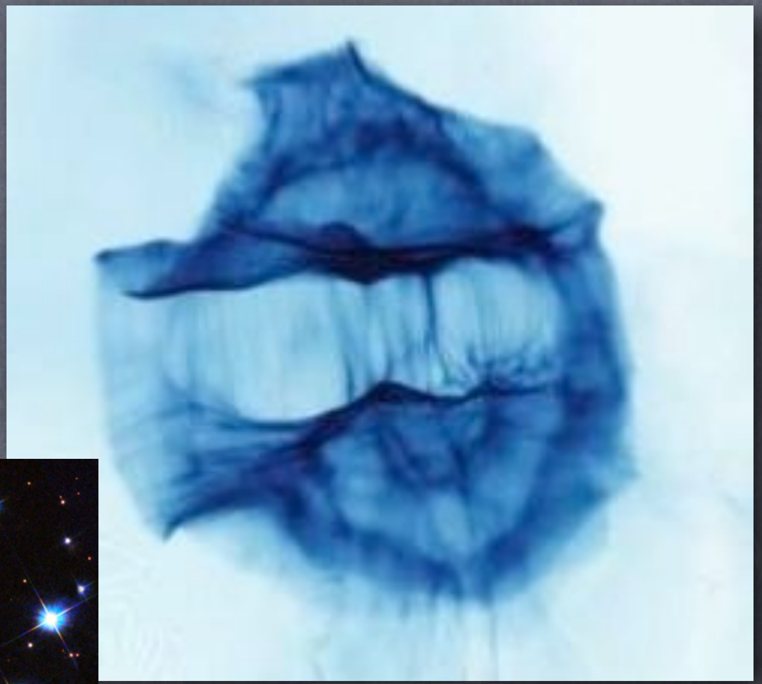
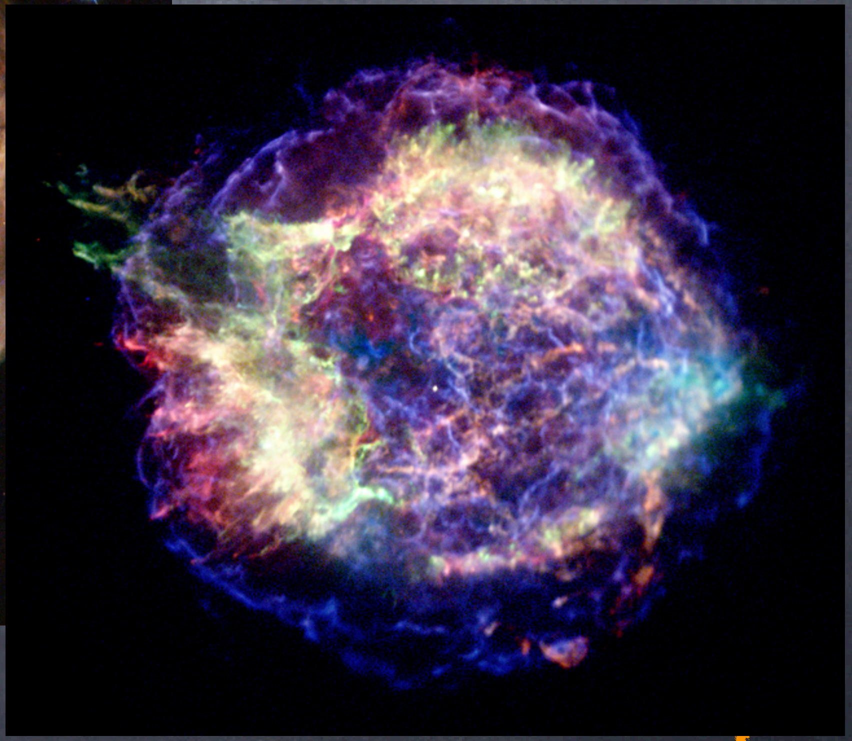
Collisionless shocks

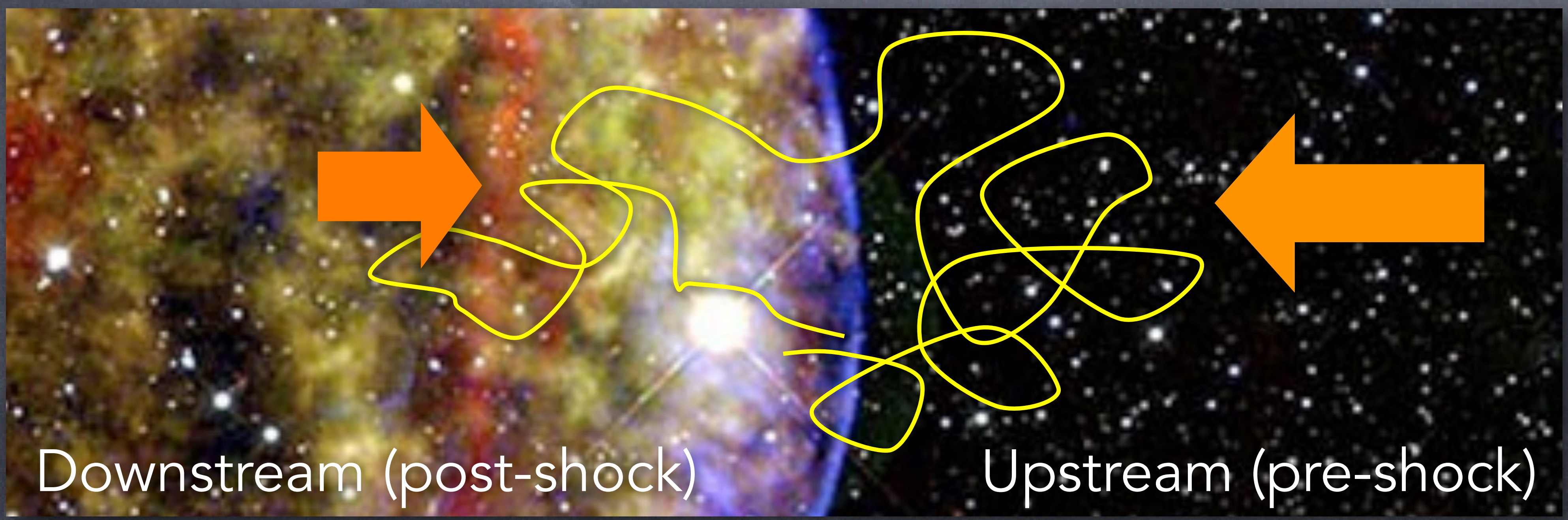
- Mediated by collective electromagnetic interactions
- Sources of non-thermal particles and emission
- Reproducible in laboratory

Diffusive Shock Acceleration

- Fermi mechanism (Fermi, 1949): random scattering leads to energy gain
- In shocks particles gain energy at any interaction (Blandford & Ostriker; Bell; Axford et al.; 1978): Diffusive Shock Acceleration (DSA)



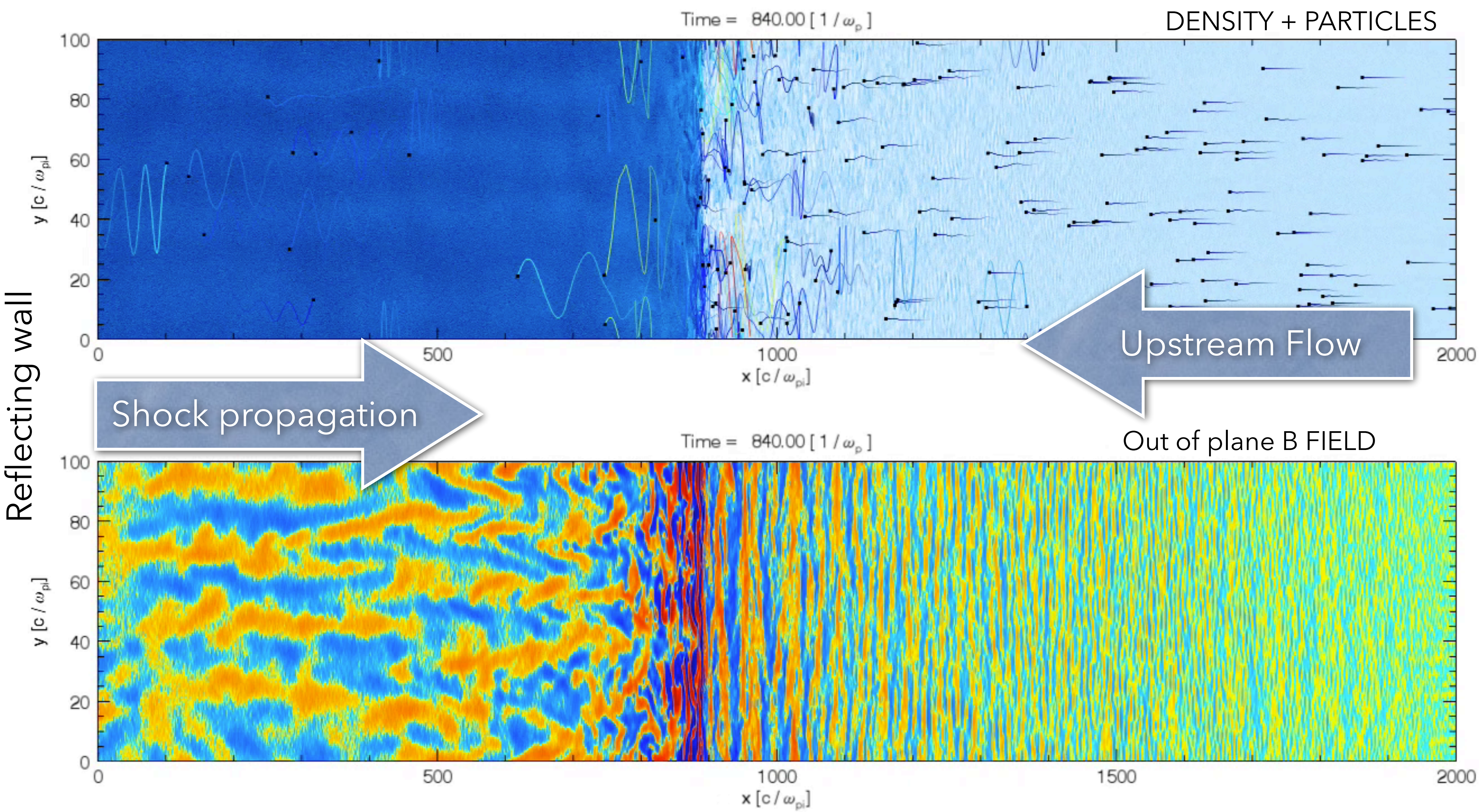
Test-particle squeezed between converging flows

- DSA produces power-laws $N(p) \propto 4\pi p^2 p^{-\alpha}$ in momentum, depending on the compression ratio $R=\rho_d/\rho_u$ only

$$R = \frac{4M_s^2}{M_s^2+3} \qquad \alpha = \frac{3R}{R-1}$$

  - For strong shocks (Mach number M_s>>1): R=4 and α=4

Kinetic simulations of collisionless shocks

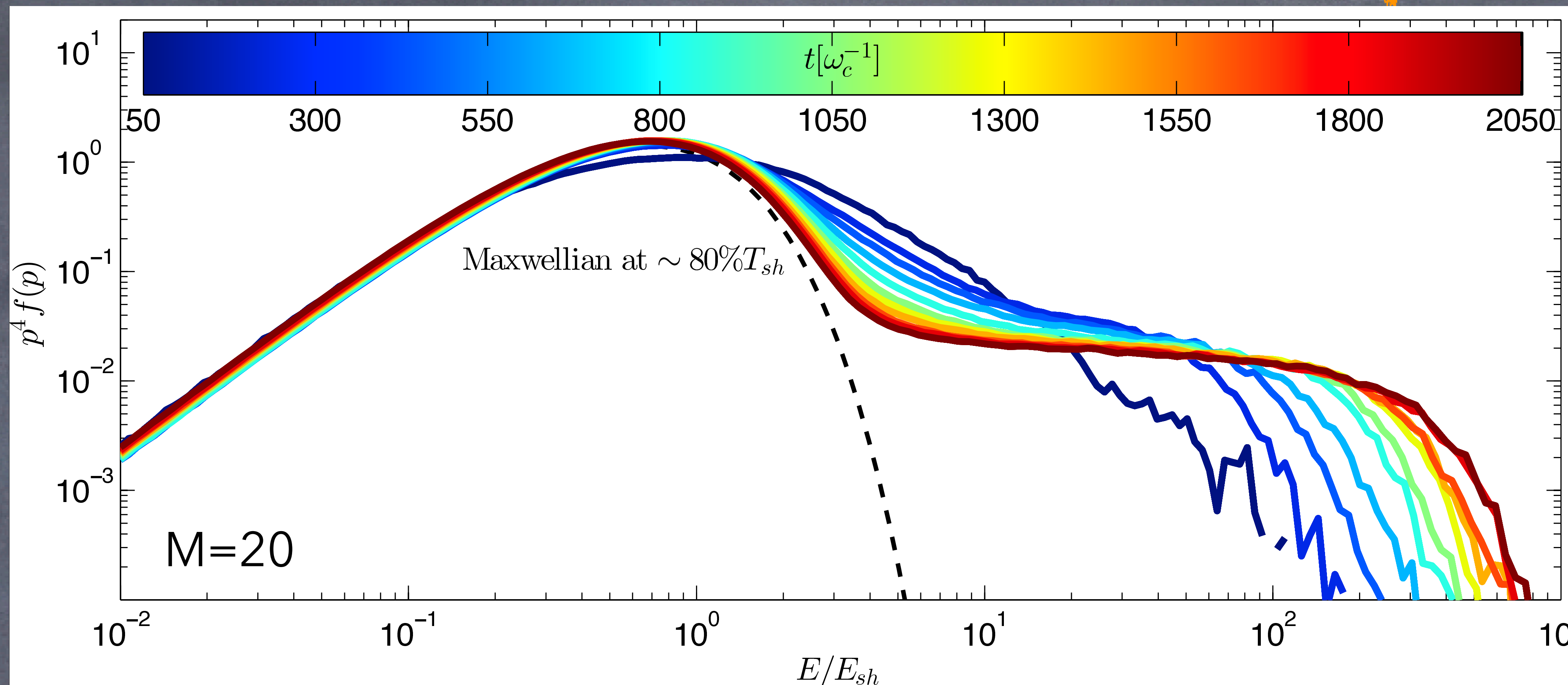


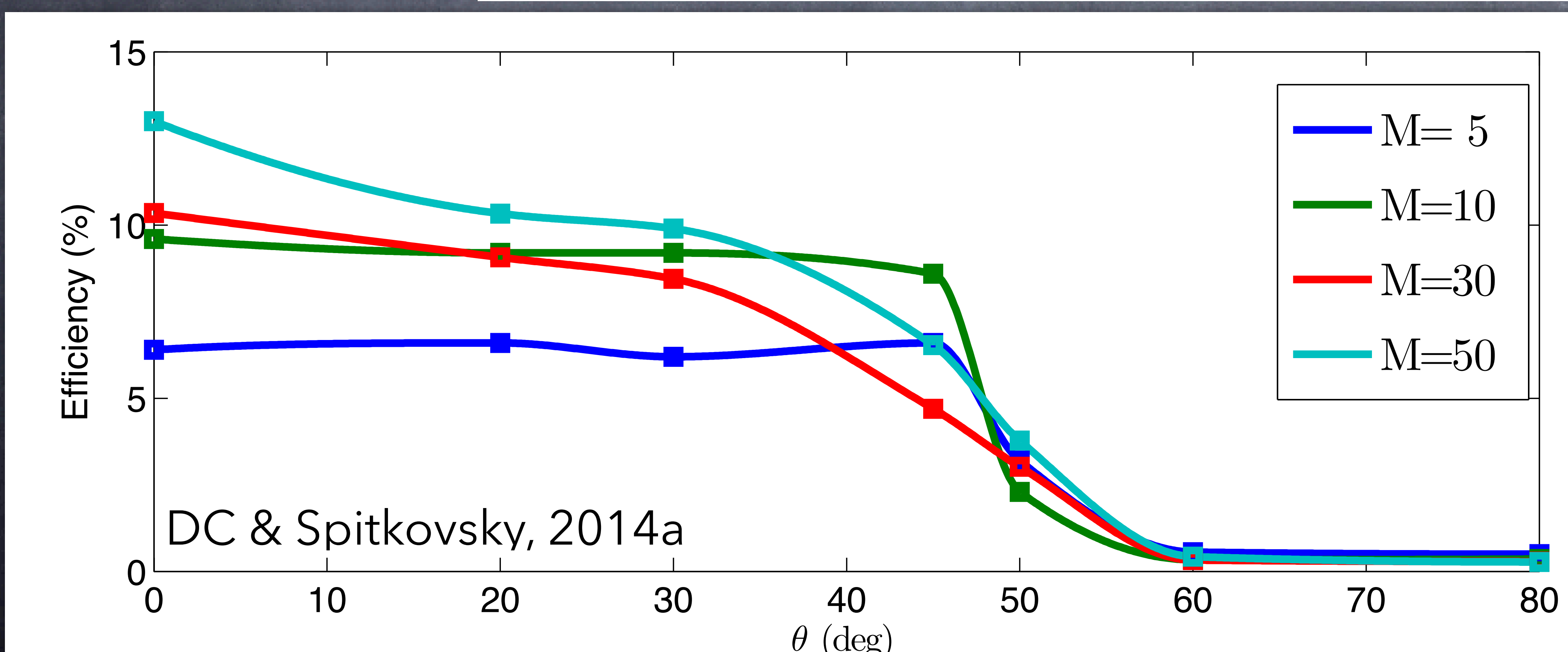
- With **dHybrid** (DC & Spitkovsky 2014a,b,c)

Initial B field

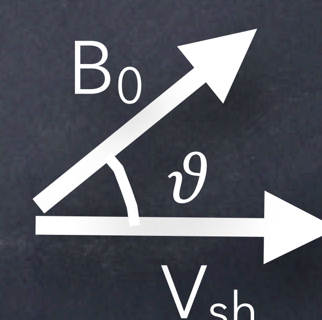
DSA efficiency

DSA from first-principles: ~15% of the shock kinetic energy converted in CRs with universal power-law spectrum



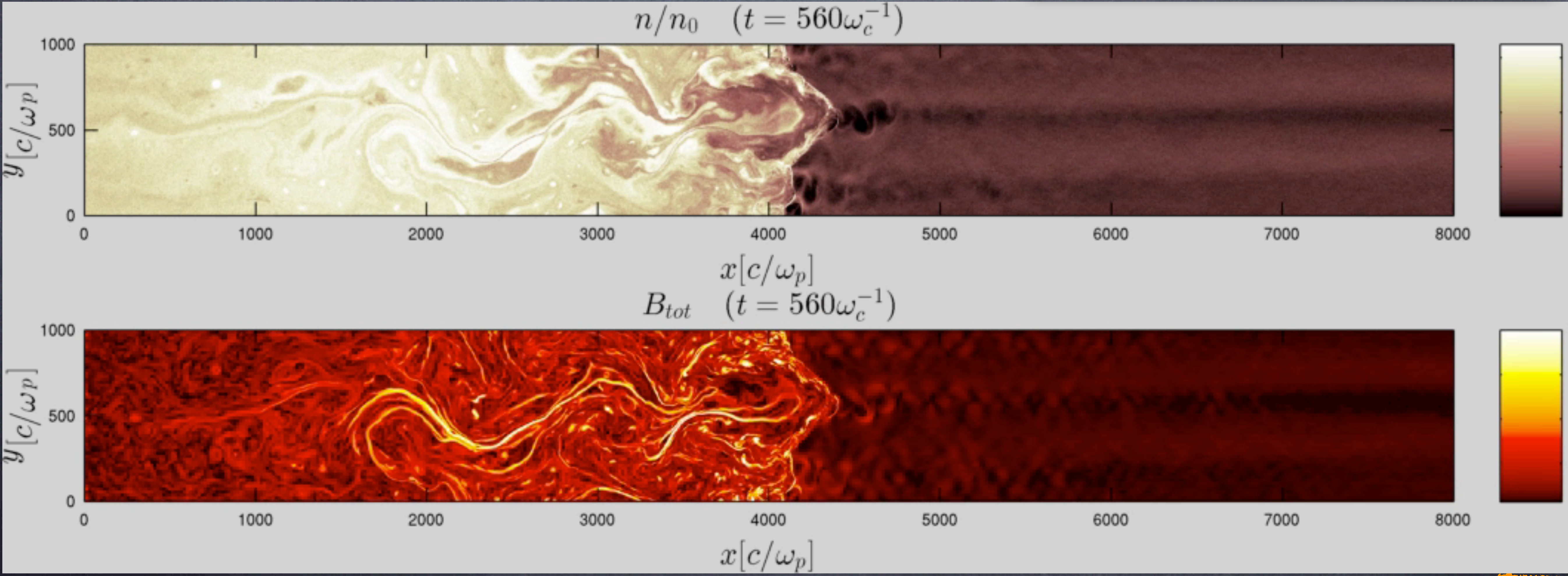


CR acceleration depends on shock strength and inclination



Non-linear DSA

- Efficient CR acceleration modifies the shock structure (Jones & Ellison 1991, Malkov & Drury 2001, DC 2012,...)
  - Hydrodynamics <—> CR spectra
  - CR-driven plasma instabilities



Hybrid simulation of a strong parallel shock (DC & Spitkovsky 2014a)

Kinetic approaches to non-linear DSA

- Solve CR transport and shock hydrodynamics self-consistently

1D Diffusion-convection eq.

$$\frac{\partial f(t,x,p)}{\partial t} + \tilde{u}(x)\frac{\partial f(t,x,p)}{\partial x} = \frac{\partial}{\partial x}\left[D(x,p)\frac{\partial f(t,x,p)}{\partial x}\right] + \frac{p}{3}\frac{\partial f(t,x,p)}{\partial p}\frac{d\tilde{u}(x)}{dx}$$

  - **FULLY NUMERICAL**: time-dependent
    - Kang & Jones 1997-2008; Berezhko & Völk 1997-2007; Zirakashvili & Aharonian 2009; …
  - **MONTE CARLO**: account for anisotropic distributions $f(p_x,p_y,p_z)$
    - Jones & Ellison 1991; Ellison et al. 1990;1995; Vladimirov, Ellison, & Bykov 2006; …
  - **SEMI-ANALYTICAL**: versatile, computationally extremely fast
    - Malkov 1997; Blasi 2002; Amato & Blasi 2006, DC et al. 2009; 2010; DC 2012, …
- Require an a priori description of
  - Magnetic field generation
  - Particle scattering (diffusion)
  - CR injection

This information can be provided only by kinetic simulations

CRAFT: Cosmic-Ray Fast Analytic Tool

(DC et al. 2009-2015, to be publicly released soon)

- Iterative solution of the CR transport equation:

$$\tilde{u}(x)\frac{\partial f(x,p)}{\partial x} = \frac{\partial}{\partial x}\left[D(x,p)\frac{\partial f(x,p)}{\partial x}\right] + \frac{p}{3}\frac{d\tilde{u}(x)}{dx}\frac{\partial f(x,p)}{\partial p} + Q(x,p)$$

$$Q(x,p) = \eta\frac{\rho_1 u_1}{4\pi m_p p_{inj}^2}\delta(p-p_{inj})\delta(x)$$

Injection

$$f(x,p) = f_2(p)\exp\left[-\int_x^0 dx'\frac{\tilde{u}(x')}{D(x',p)}\right]\left[1-\frac{W(x,p)}{W_0(p)}\right]$$

$$\Phi_{esc}(p) = -D(x_0,p)\left.\frac{\partial f}{\partial x}\right|_{x_0} = -\frac{u_0 f_2(p)}{W_0(p)};$$

$$W(x,p) = \int_x^0 dx'\frac{u_0}{D(x',p)}\exp\left[\int_{x'}^0 dx''\frac{\tilde{u}(x'')}{D(x'',p)}\right].$$

$$f_2(p) = \frac{\eta n_0 q_p(p)}{4\pi p_{inj}^3}\exp\left\{-\int_{p_{inj}}^p \frac{dp'}{p'}q_p(p')\left[U_p(p')+\frac{1}{W_0(p')}\right]\right\}$$

$$U_p(p) = \frac{\tilde{u}_1}{u_0} - \int_{x_0}^0 \frac{dx}{u_0}\left\{\frac{\partial\tilde{u}(x)}{\partial x}\exp\left[-\int_x^0 dx'\frac{\tilde{u}(x')}{D(x',p)}\right]\left[1-\frac{W(x,p)}{W_0(p)}\right]\right\}$$

CR distribution function

u

Mass+momentum conservation eqs.

$$\frac{p(x)}{\rho(x)^\gamma} = \frac{p_0}{\rho_0^\gamma};$$

$$\rho(x)u(x) = \rho_0 u_0$$

$$\rho(x)u(x)^2 + p(x) + p_{cr}(x) + p_B(x) = \rho_0 u_0^2 + p_{g,0} + p_{B,0}$$

$P_B + P_{cr}$

P_{cr}

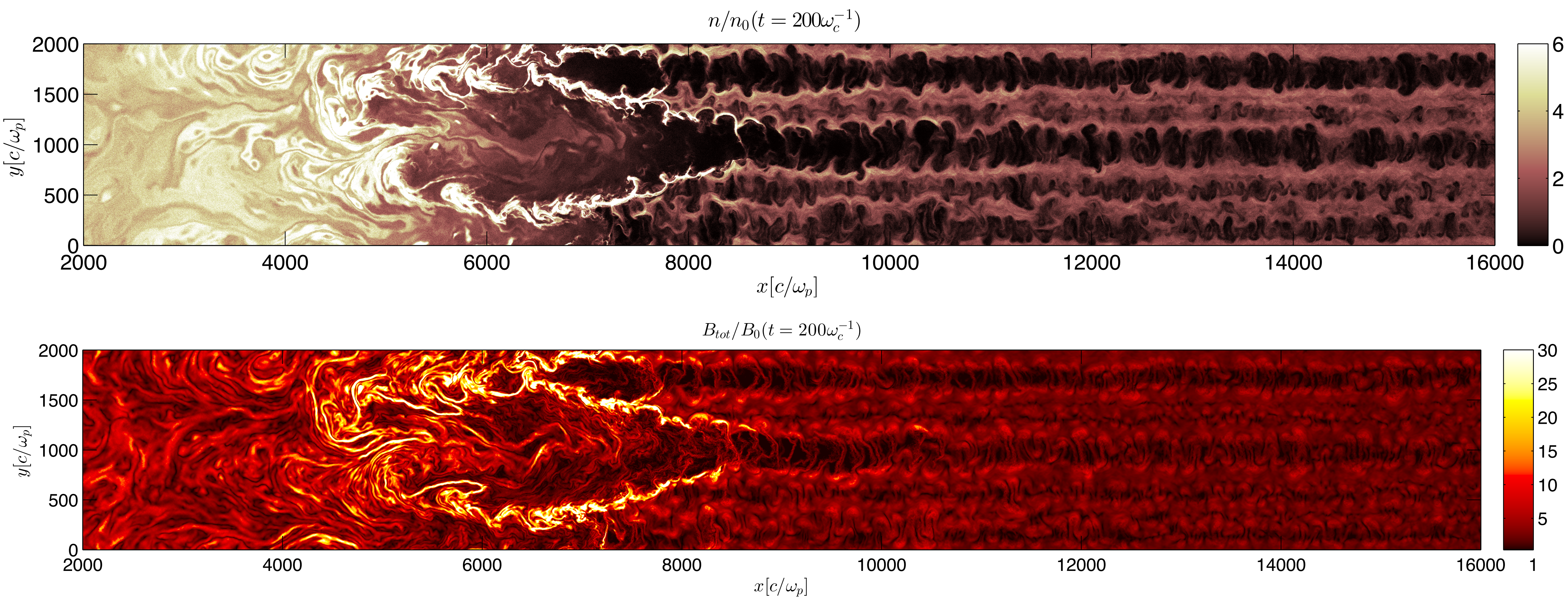
$$2\tilde{u}(x)\frac{dp_B(x)}{dx} = v_A(x)\frac{dp_{cr}(x)}{dx} - 3p_B(x)\frac{d\tilde{u}(x)}{dx}$$

Magnetic turbulence transport eq.

- CR spectrum at the shock + spectrum of escaping CRs
- Very fast: a few seconds on a laptop

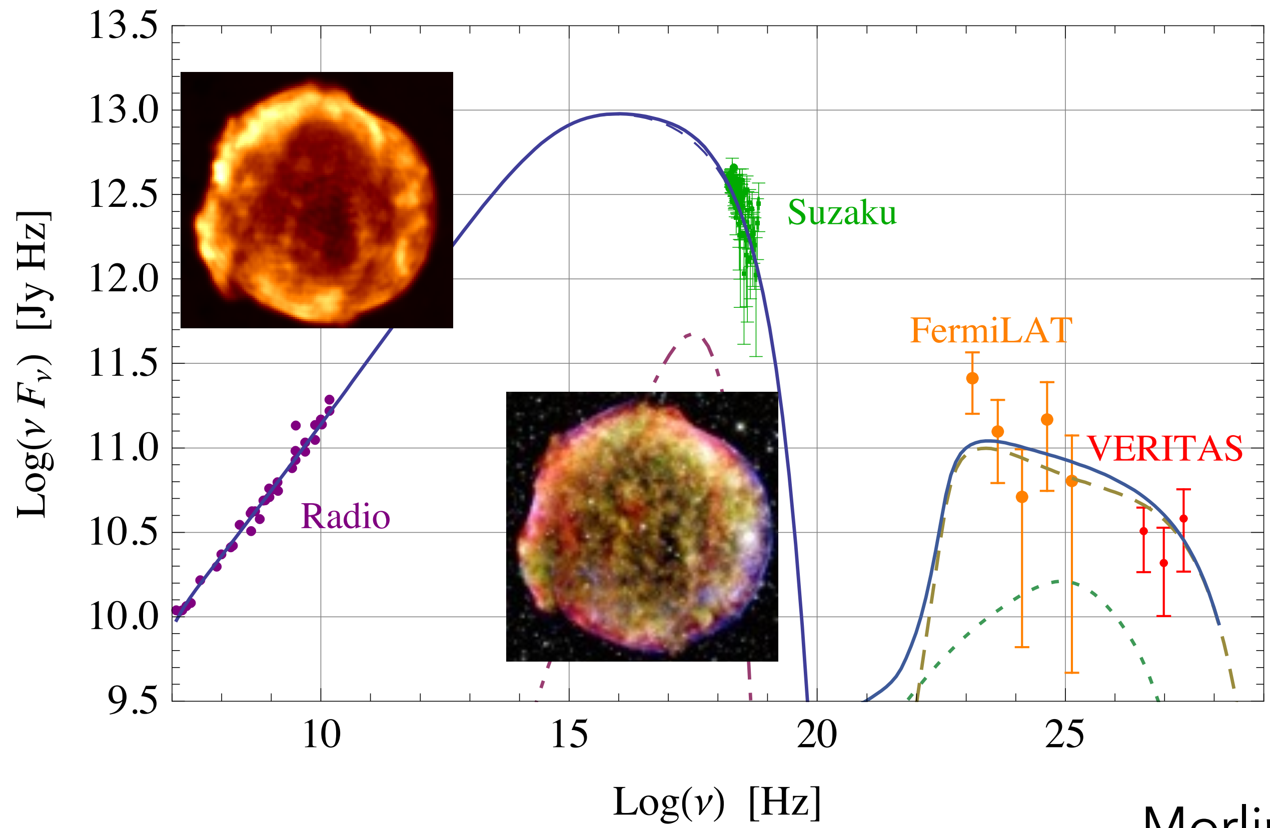
Microphysics under the hood

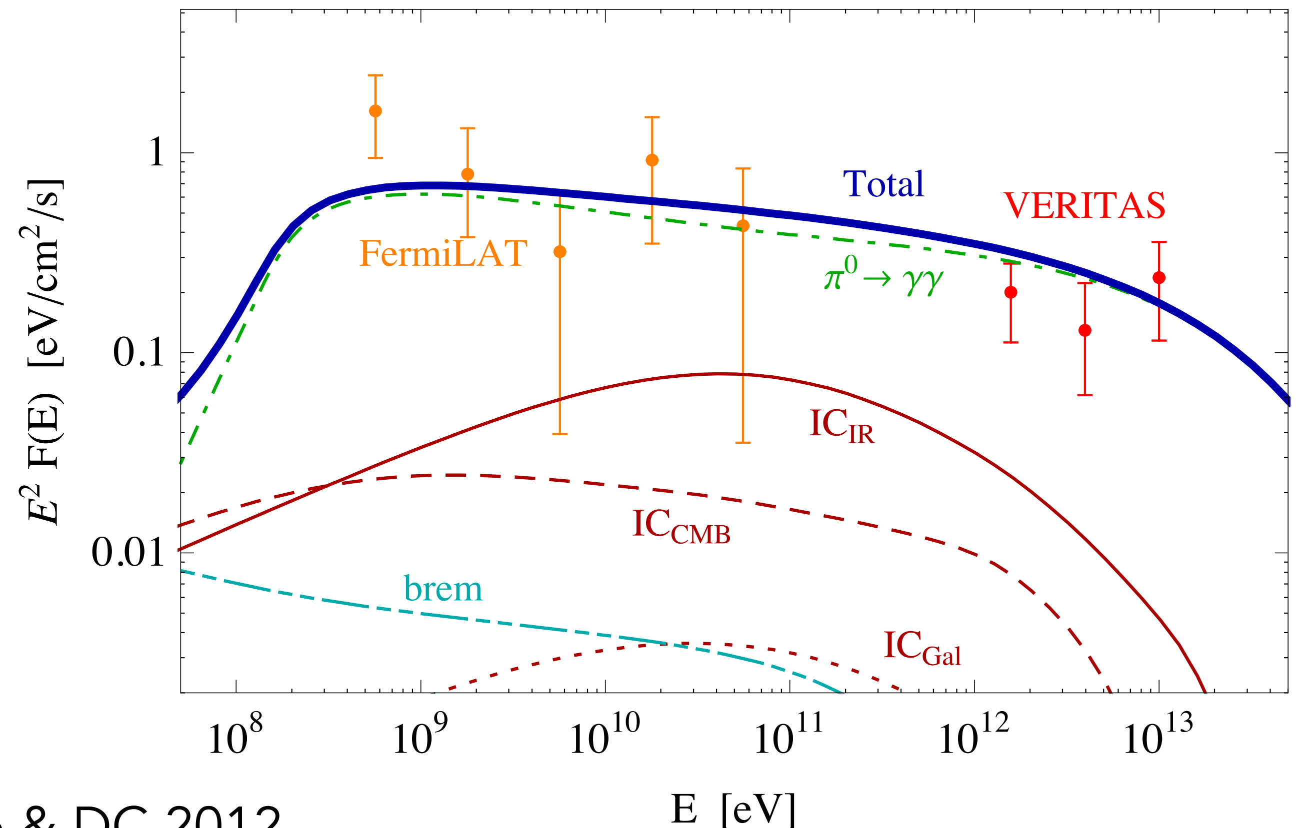
- **CR injection**: minimal model by DC, Pop & Spitkovsky 2015
- **B-field amplification**: resonant and Bell's streaming instabilities (DC & Spitkovsky 2014b)
- **Diffusion**: Bohm, in the amplified B (DC & Spitkovsky 2014c)
- **Electron/proton ratio**: from PIC simulations (Park, DC & Spitkovsky 2015, DC et al, in prep.)



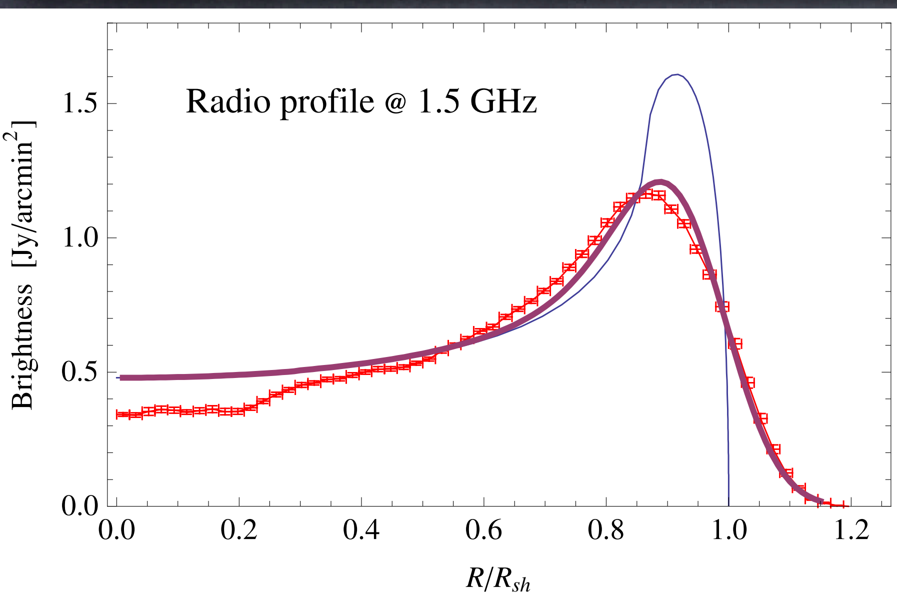
Parallel shock with M=100 (DC & Spitkovsky, 2014b)

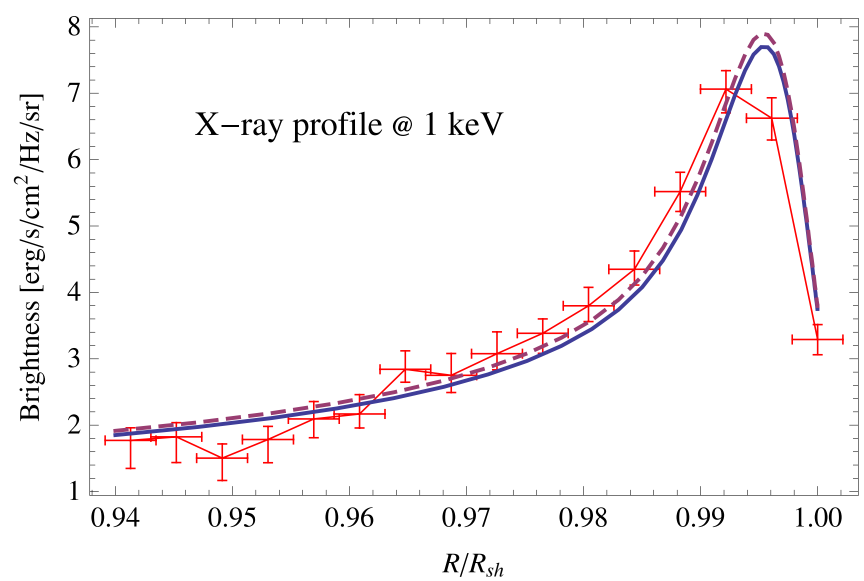
A example of CRAFTwork: Tycho





Morlino & DC 2012





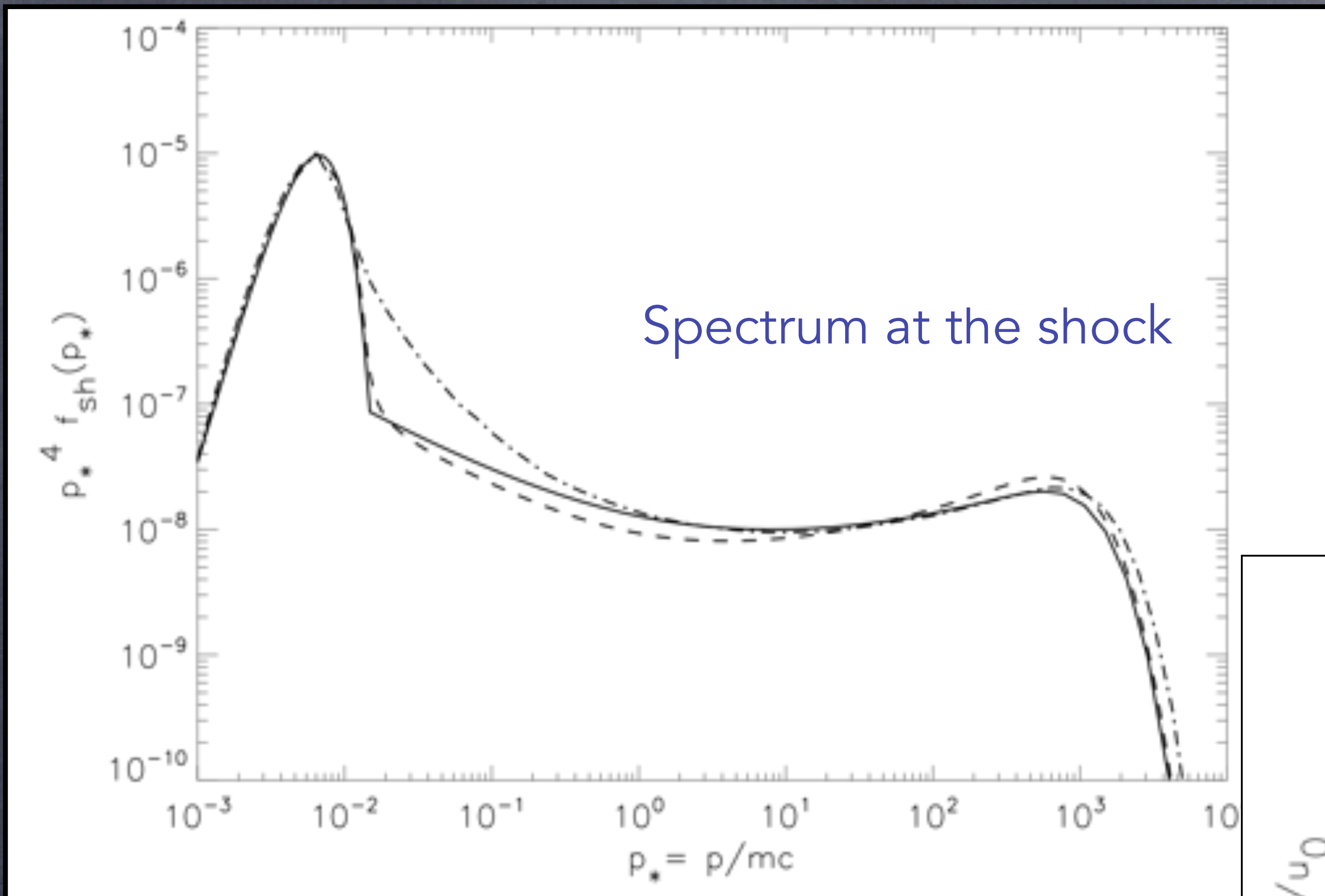
- Account for spectra, SNR hydrodynamics, and morphology
- Hadron acc. eff. ~10%
- Protons up to ~0.5 PeV

- Only two free parameters: injection efficiency and electron/proton ratio

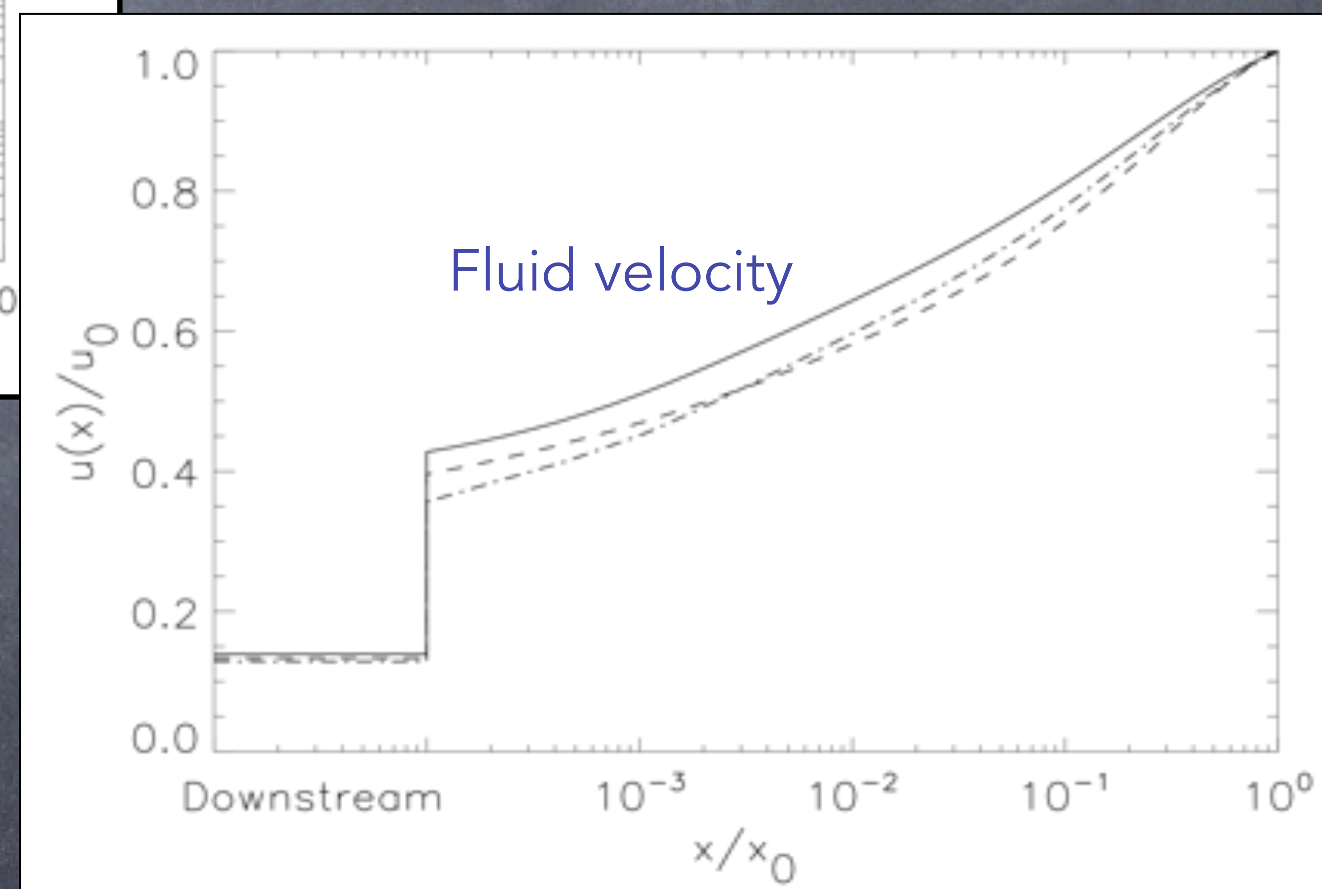
CRAFT

- Currently in beta version (email me if interested in testing)
  - soon on GitHub with extended manual and references
- Will come as:
  - Stand-alone code for SNR evolution
  - Subroutine for subgrid CR physics in hydro/MHD simulations
  - Python interface + visualization suite for particle and photon spectra
- Future developments:
  - Nuclei heavier than hydrogen (DC et al. 2010)
  - Propagation into partially-ionized media (Blasi et al. 2012, Morlino et al. 2013-2015)
  - … and better and better microphysics from kinetic simulations!

Vs Numerical and Monte Carlo approaches



Solid: Caprioli et al. (Semi-Analytic)
Dashed: Kang & Jones (Numerical)
Dot-Dashed: Ellison et al. (Monte Carlo)



- Numerical (AMR): ~2 weeks
- Monte Carlo: ~3 days
- Semi-analytic: ~7 seconds

DC, Kang, Vladimirov & Jones, 2010