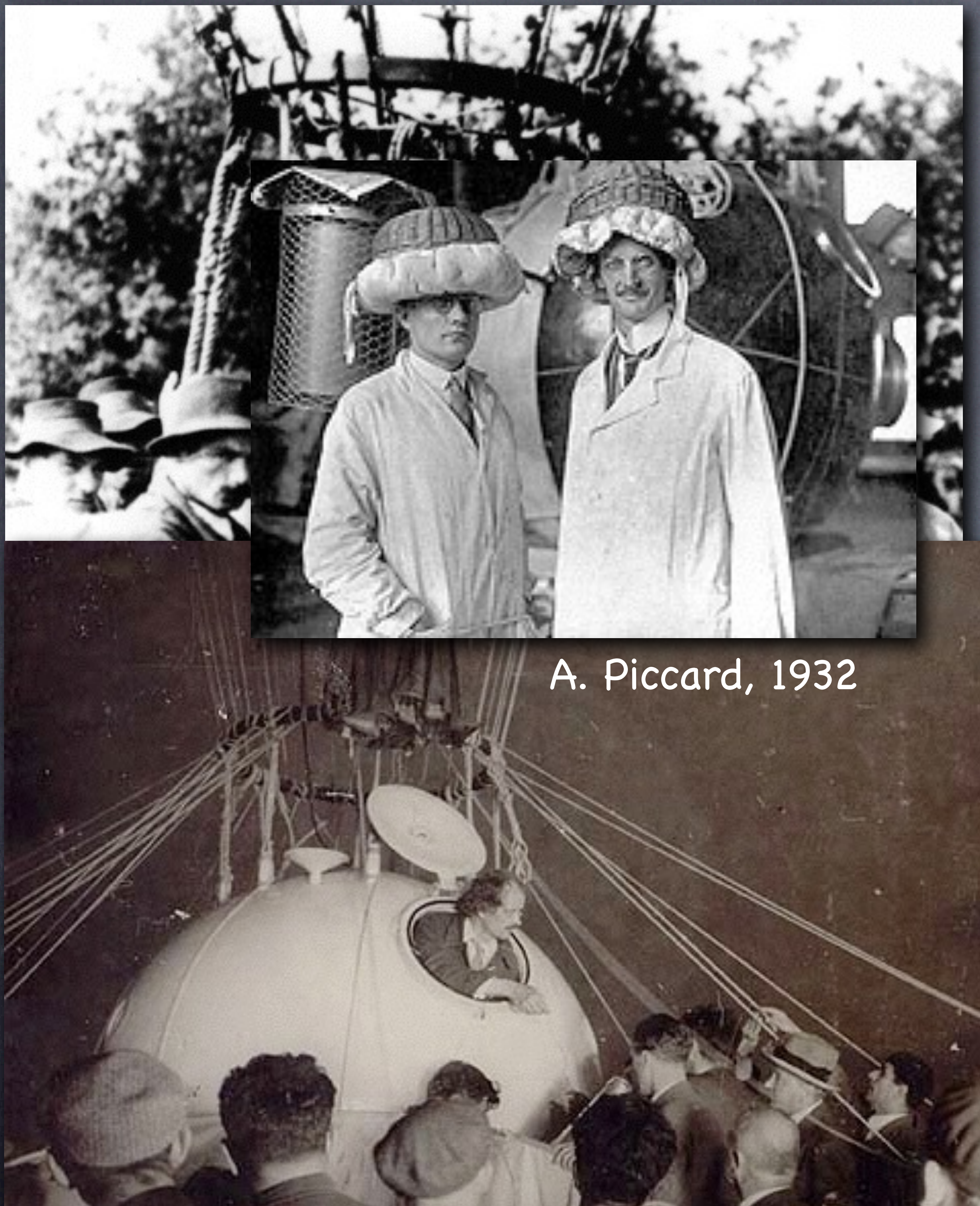
OA Bologna - June 2015

# New Insights on the Origin of Cosmic Rays

**Damiano Caprioli**
Princeton University

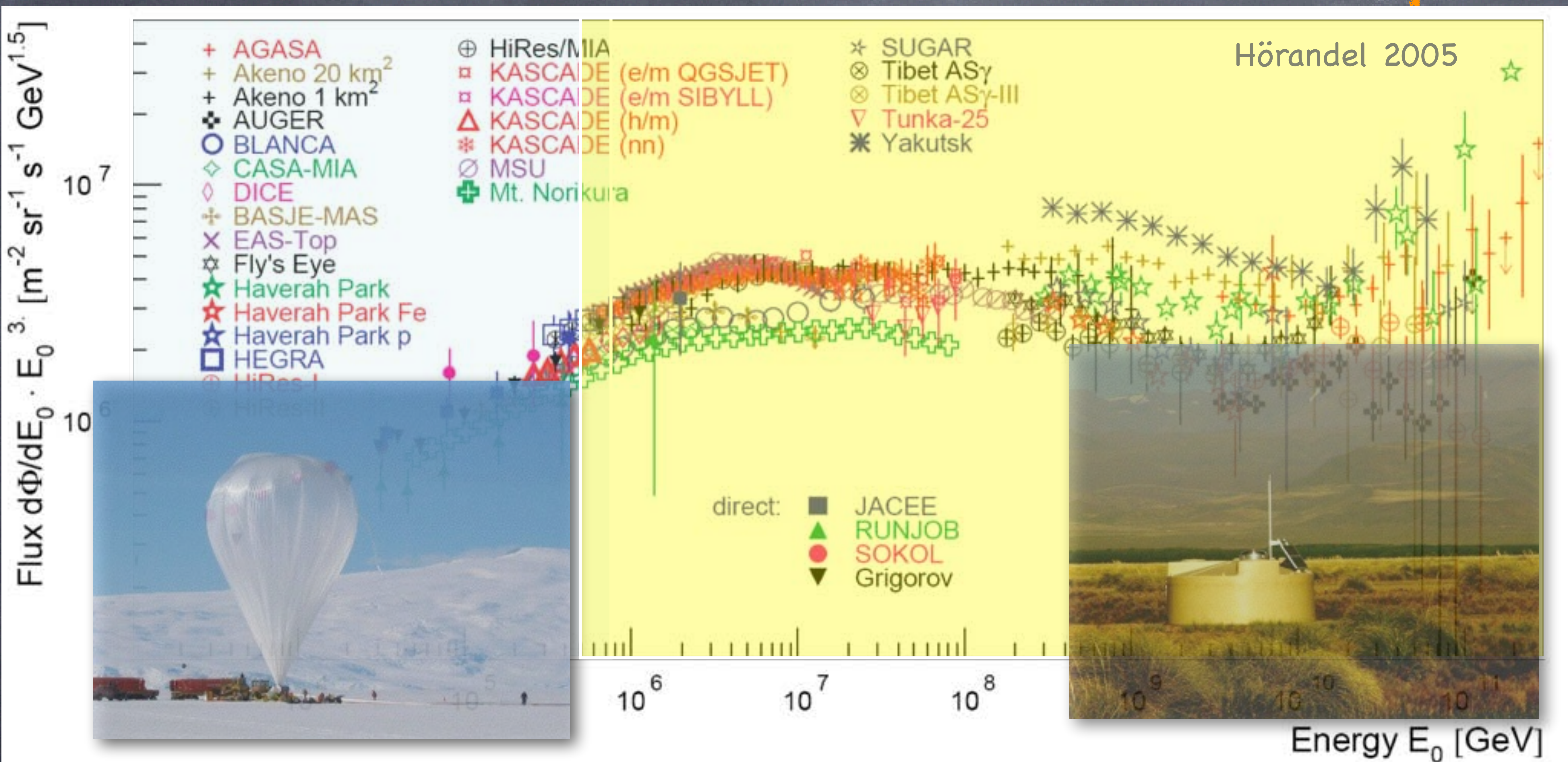
# An extraterrestrial radiation!



A. Piccard, 1932

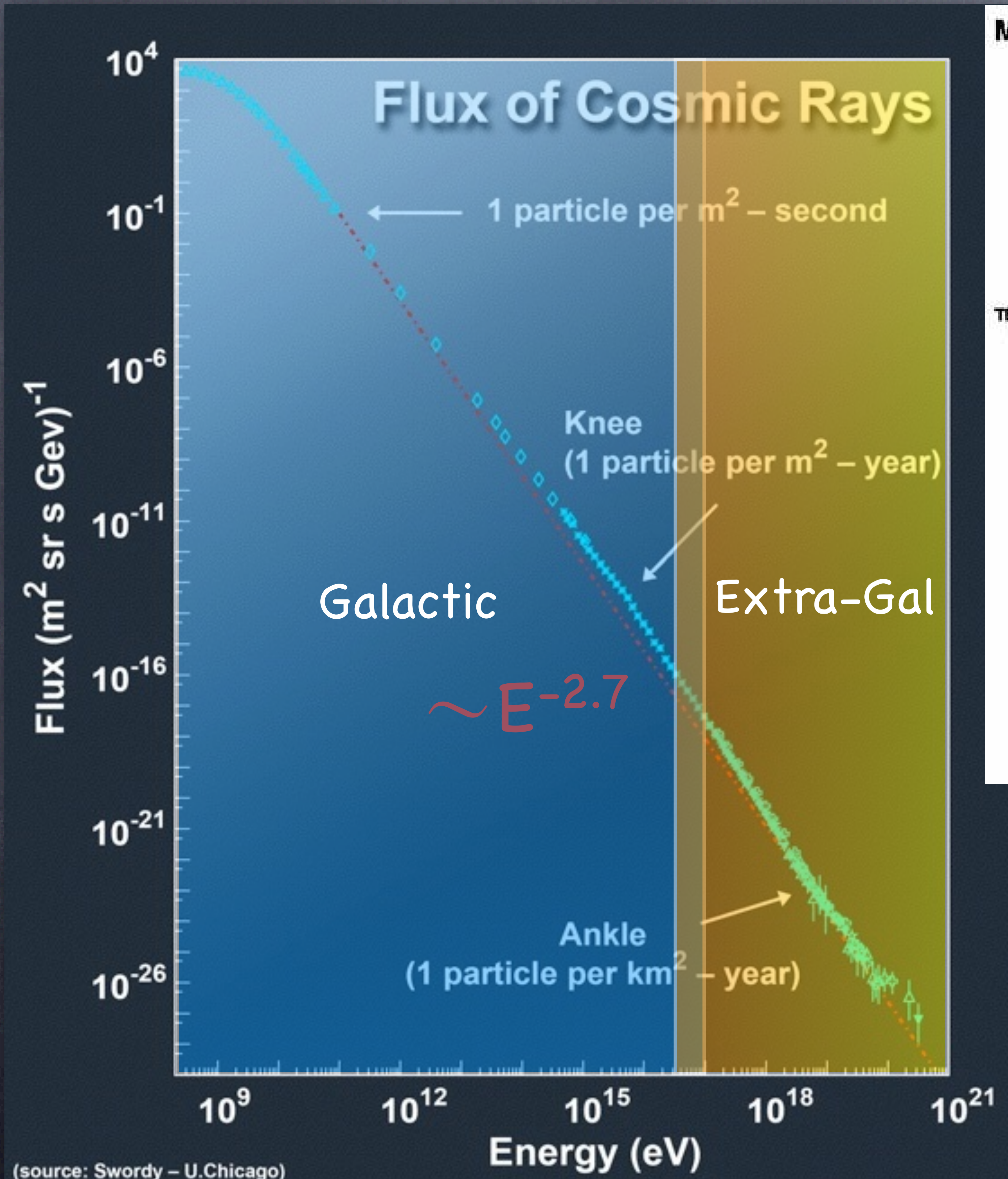
- 1912: V. Hess discovers an extraterrestrial source of ionization: Cosmic Rays
- 1930-1932: A. Piccard reaches the stratosphere with a pressurized aluminum gondola attached to a ballon
- 1940: B. Rossi and P. Auger measure Extensive Air Showers:
  - CRs up to $10^4$-$10^5$ GeV

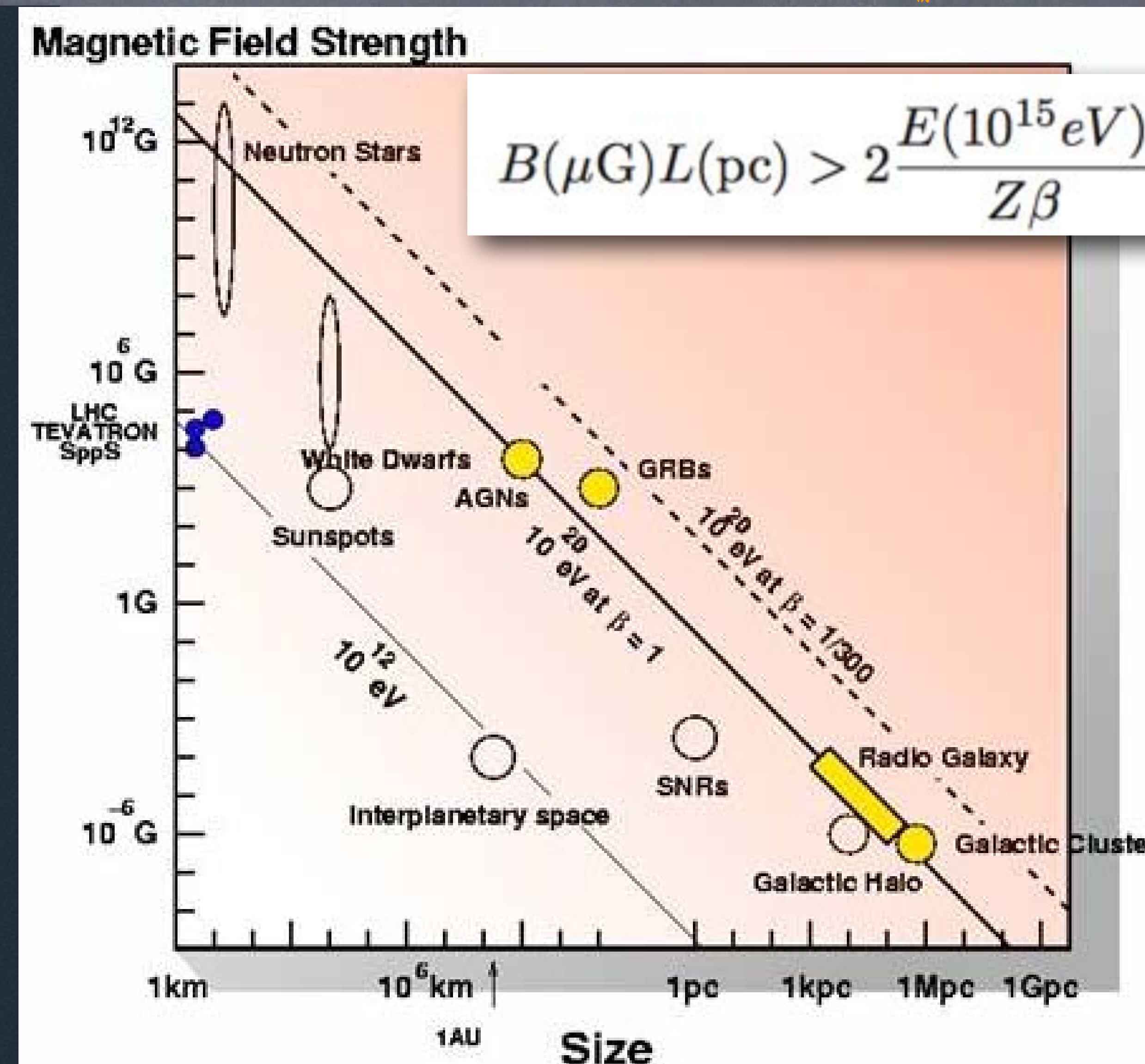
# Cosmic ray flux at Earth




- Below ~1 PeV: satellites and balloons
- Above: ground-based arrays, fluorescence telescopes for showers triggered by primary CRs

# The CR spectrum at Earth

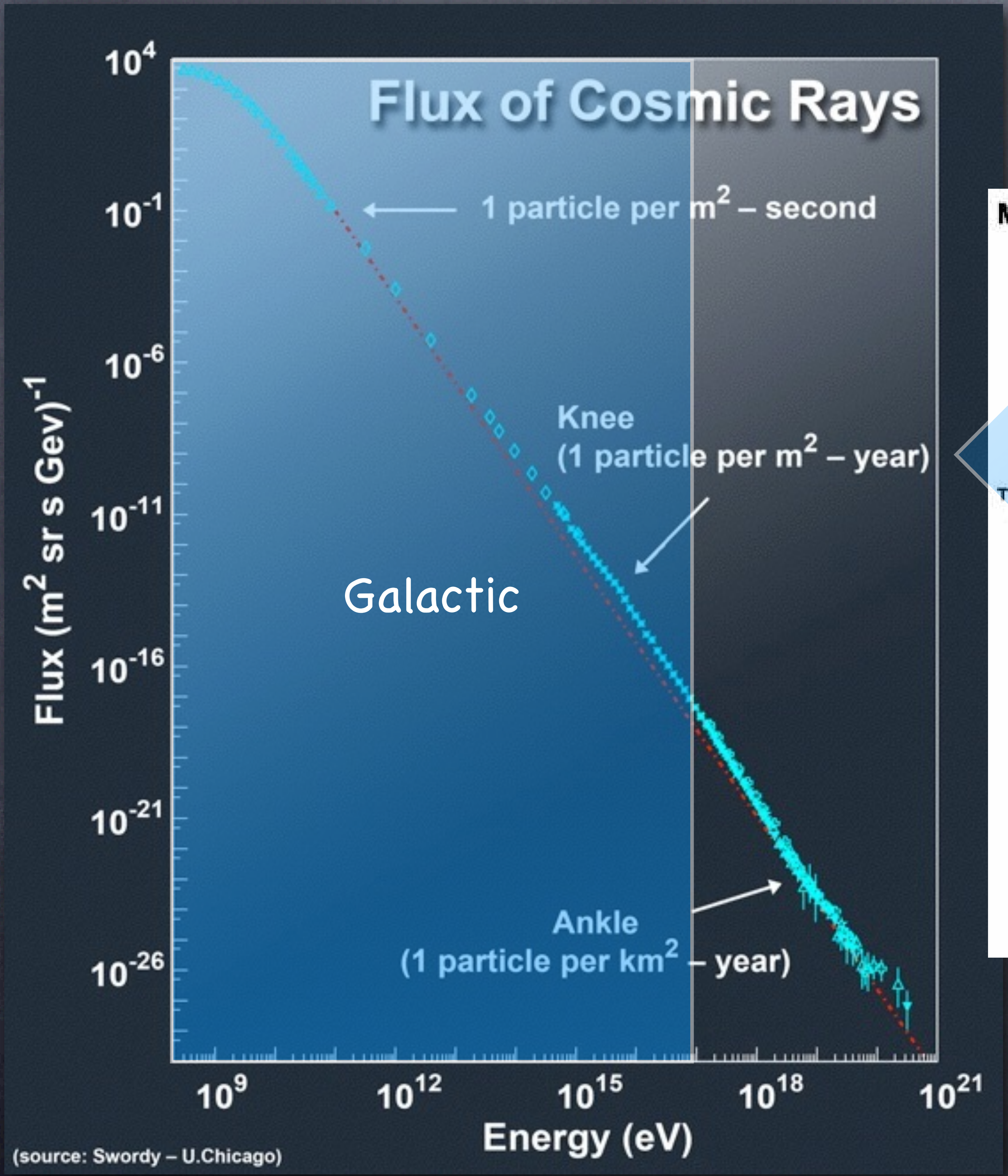


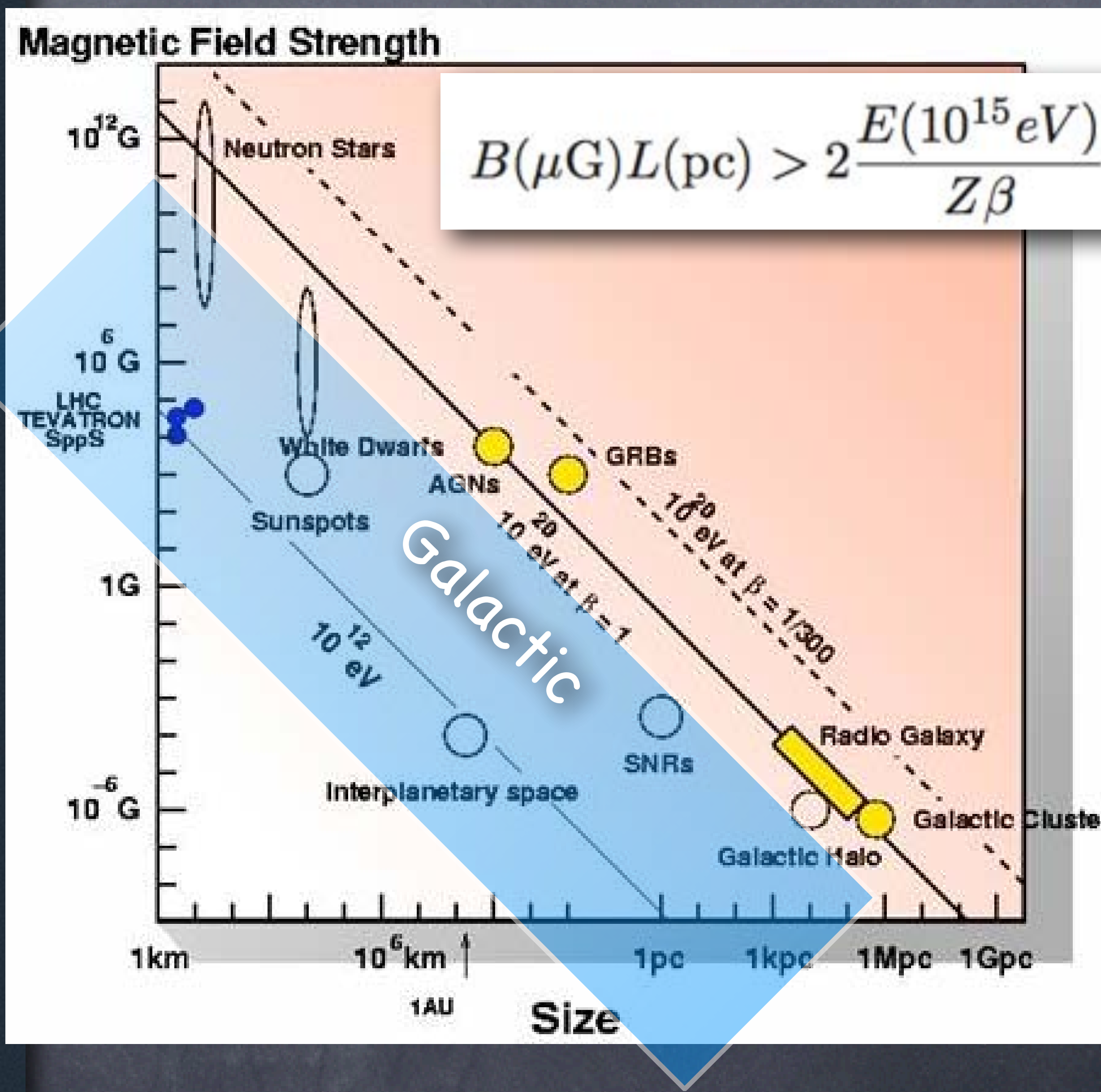




$$B(\mu\mathrm{G})L(\mathrm{pc}) > 2\frac{E(10^{15}eV)}{Z\beta}$$

- Hillas criterion: size of the system larger than the particle gyroradius

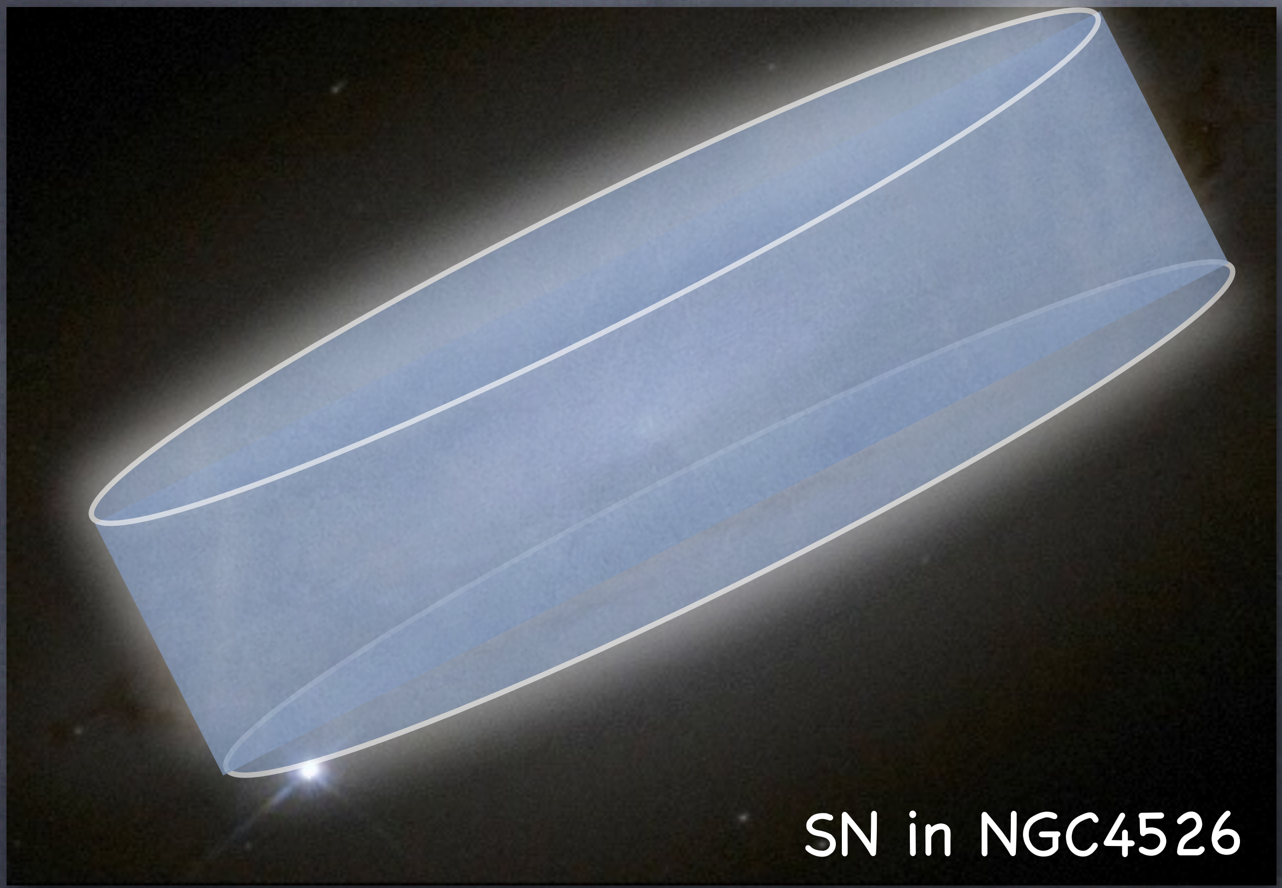
# Galactic Cosmic Rays



# SNR paradigm: energetics

- Baade-Zwicky (1934) energetic argument, updated




$$\varepsilon_{CR} = 0.5 eVcm^{-3}$$

$$V_{conf} = \pi R^2 h = 2 \times 10^{67} \text{ cm}^3$$

$$W_{CR} = \varepsilon_{CR} V_{conf} \approx 2 \times 10^{55} \text{ erg}$$

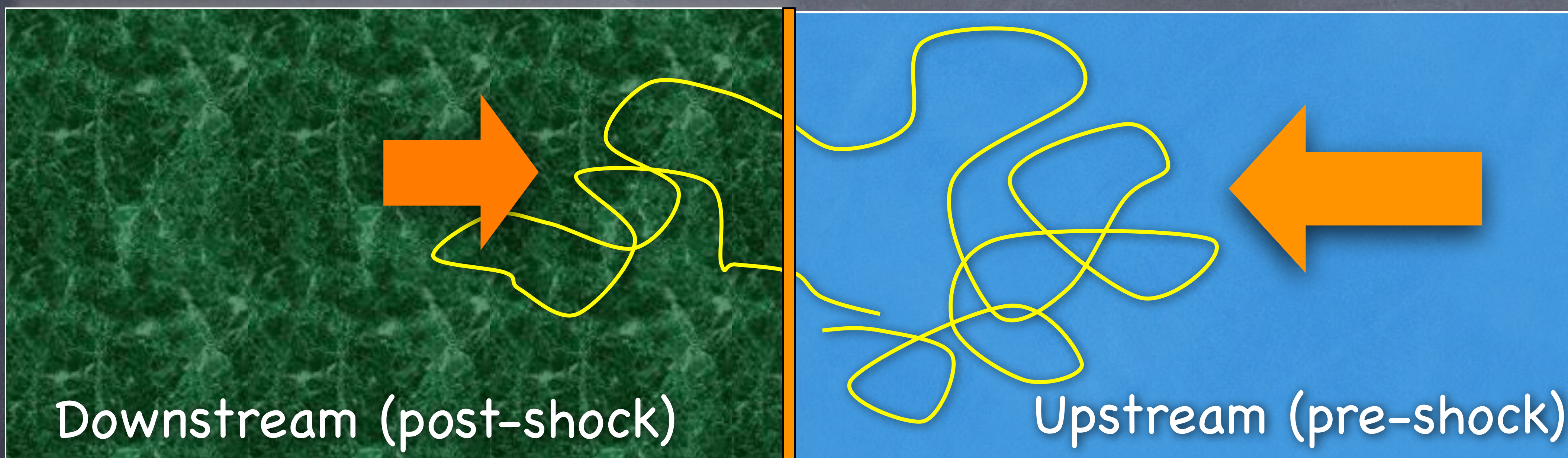
$$L_{CR} \approx \frac{W_{CR}}{\tau_{conf}} \approx 5 \times 10^{40} \text{ erg s}^{-1}$$

$$L_{SN} = R_{SN} E_{kin} \approx 3 \times 10^{41} \text{ erg s}^{-1}$$

10-20% of SN ejecta kinetic energy converted into CRs can account for the energetics

# SNR paradigm: acceleration mechanism

- Fermi mechanism (Fermi, 1954): random scattering leads to energy gain
- In a shock a particle gains energy at any reflection (Blandford & Ostriker; Bell; Axford et al.; 1978): Diffusive Shock Acceleration (DSA)

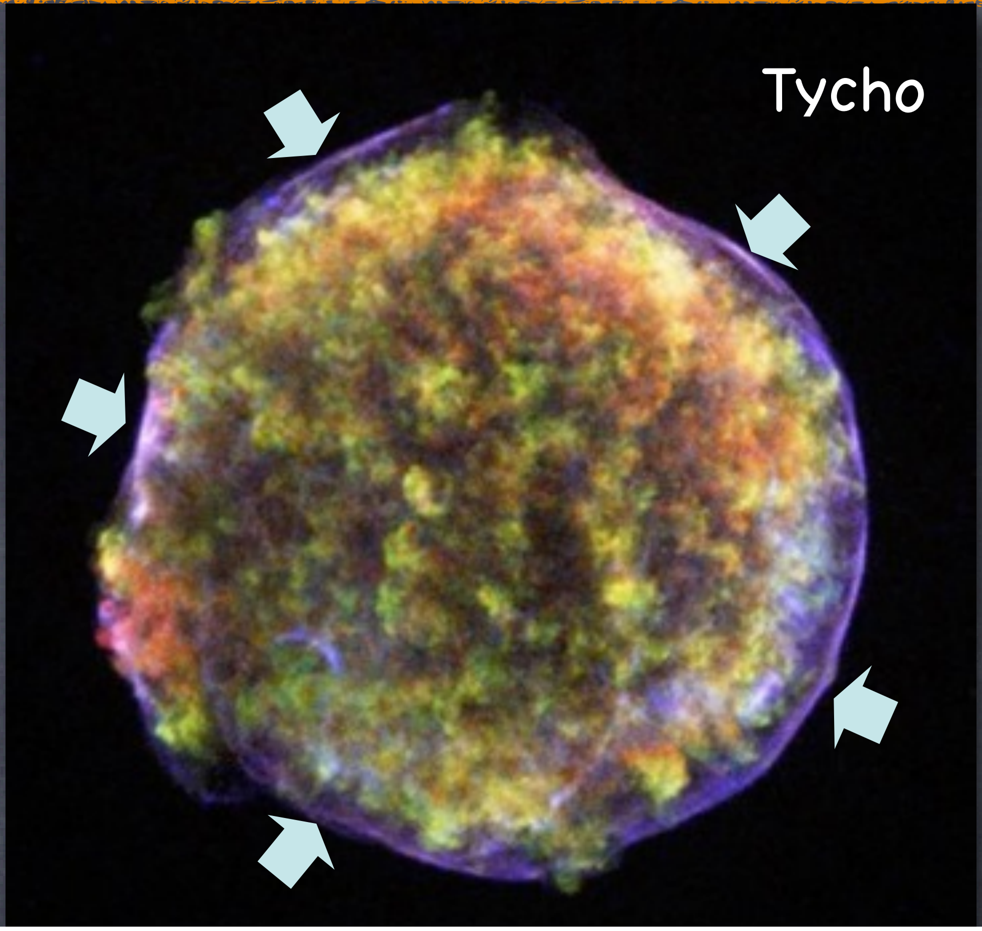



Test-particle squeezed between converging flows

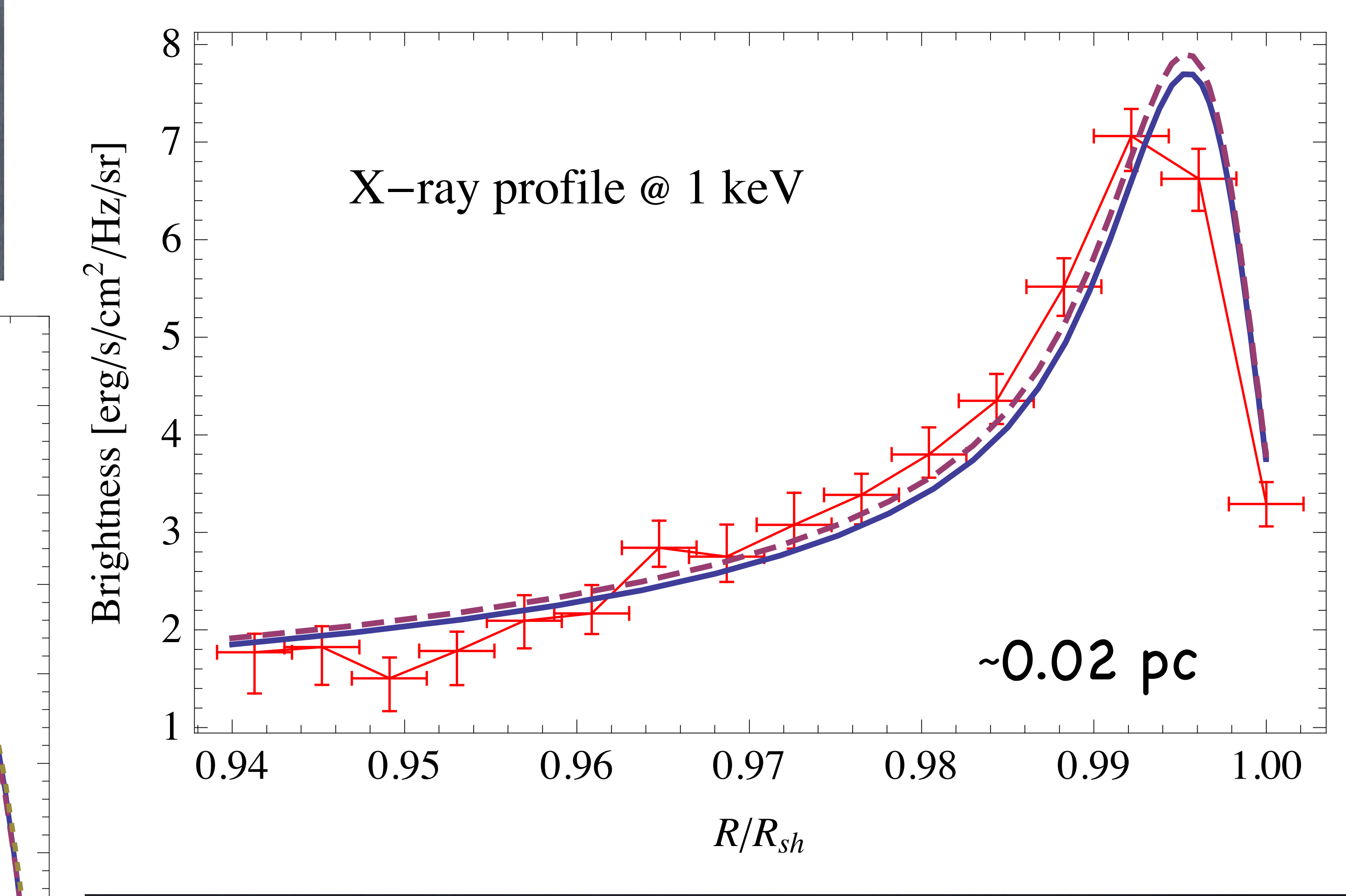
- DSA produces power-law $p^{-\alpha}$ in momentum, depending on the compression ratio $R=\rho_d/\rho_u$ only. For strong shocks: $\alpha=4$

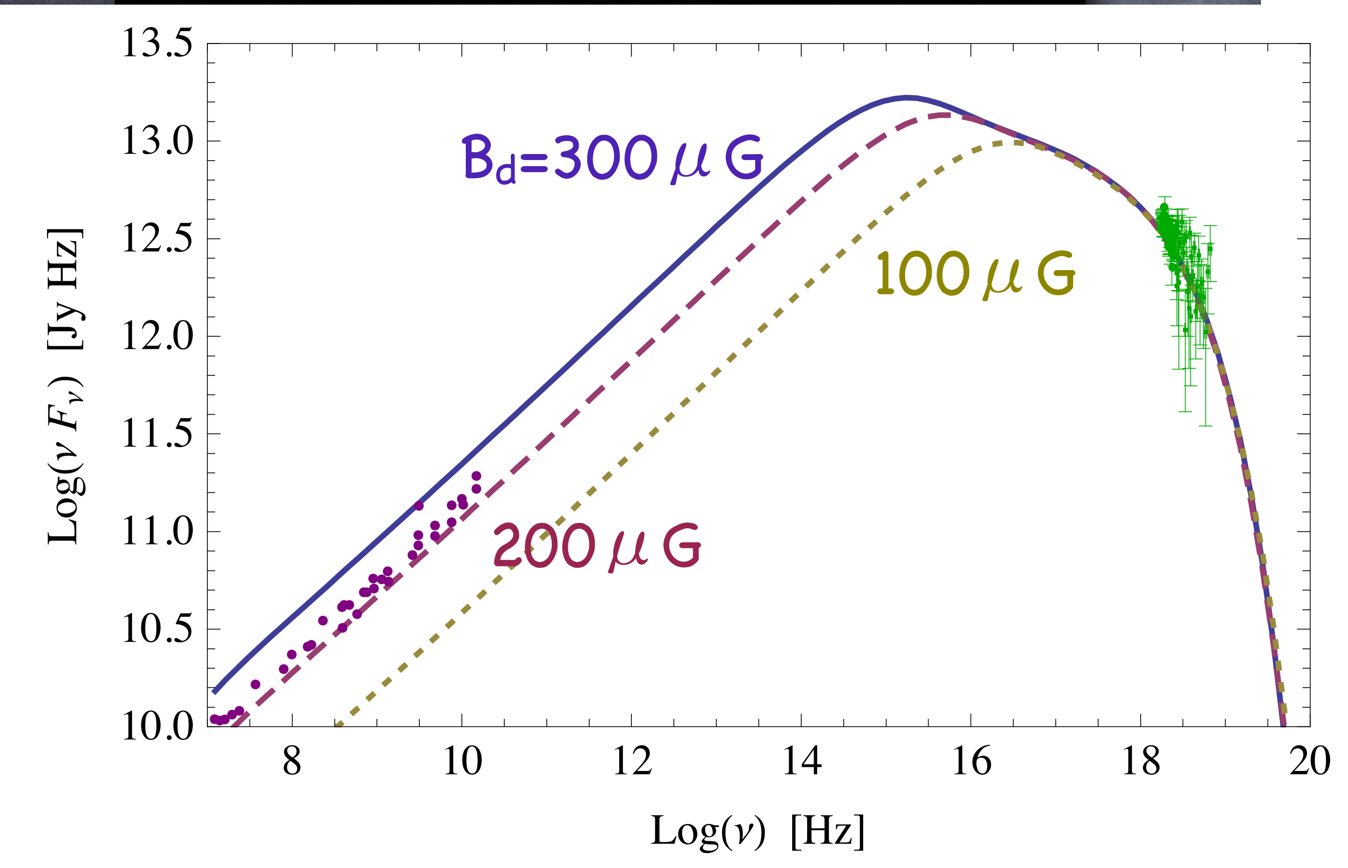
$$R = \frac{4M_s^2}{M_s^2+3} \quad \alpha = \frac{3R}{R-1}$$

# Evidence of magnetic field amplification




- Narrow (non-thermal) X-ray rims due to synchrotron losses of 10-100 TeV electrons…
- …in fields as large as B~100-500 μG




Morlino & DC, 2012

# Conclusions?

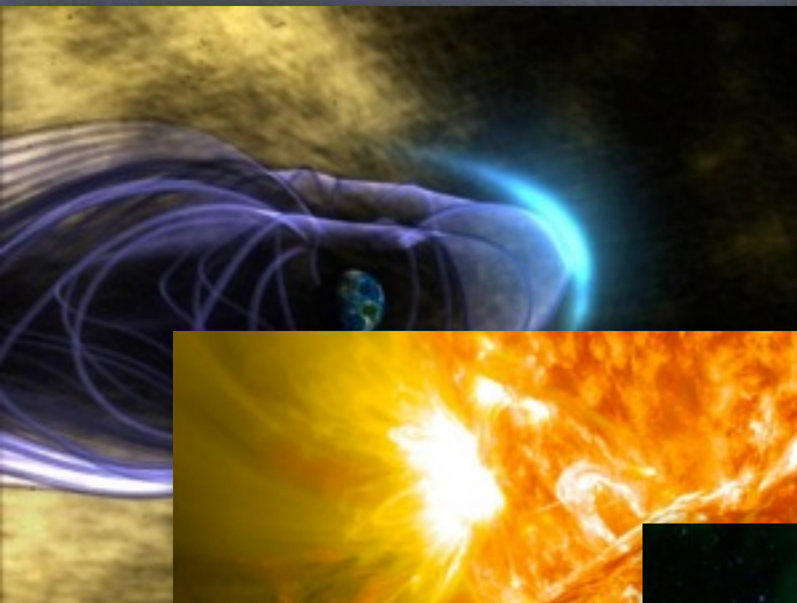
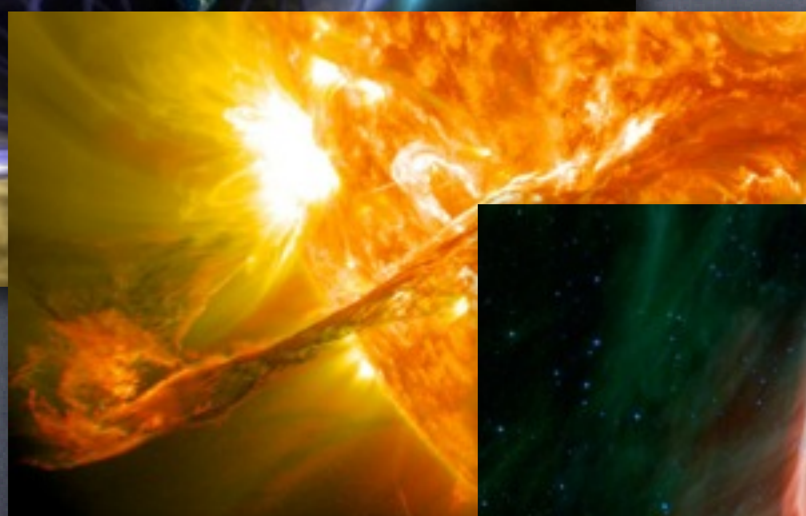
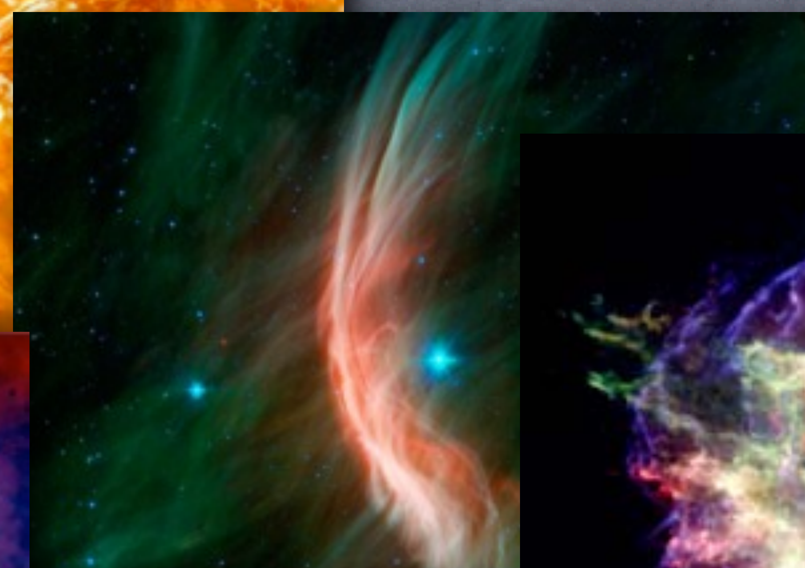
- Supernova Remnants
  - Have the right energetics
  - Diffusive shock acceleration produces power-laws
  - B amplification may help reaching the knee

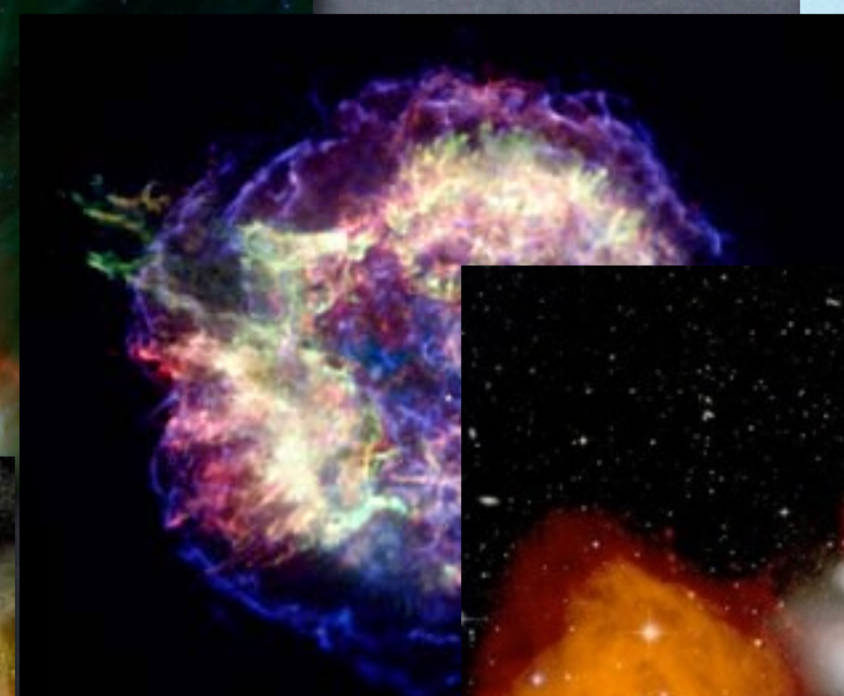
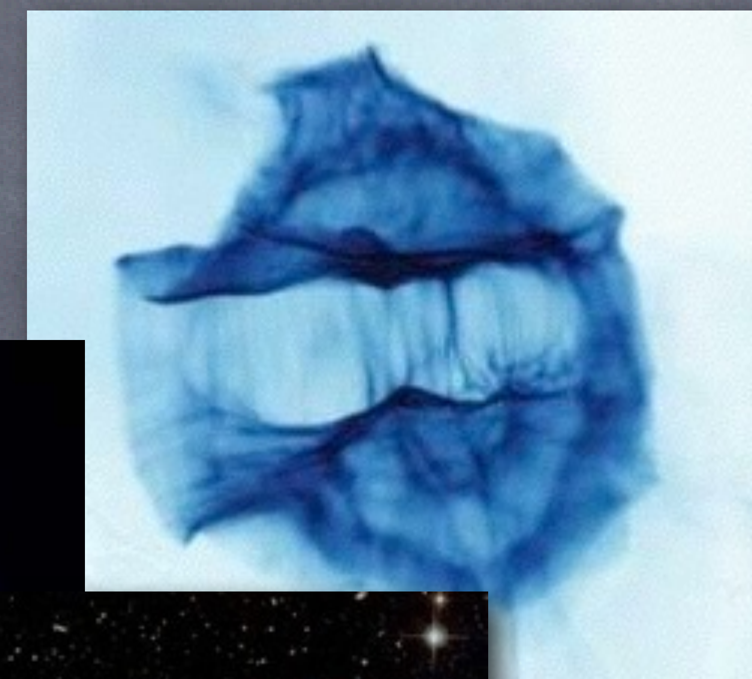

**BUT**

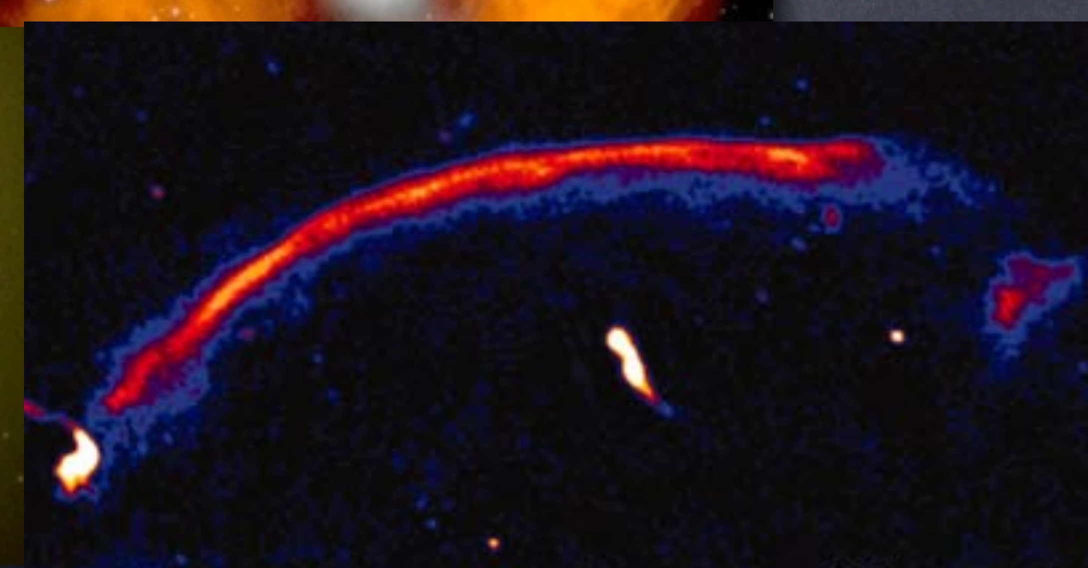
- Is acceleration at shocks efficient?
- How do CRs amplify the magnetic field?
- When is acceleration efficient?
- How are ions and electrons injected?

# Collisionless shocks

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

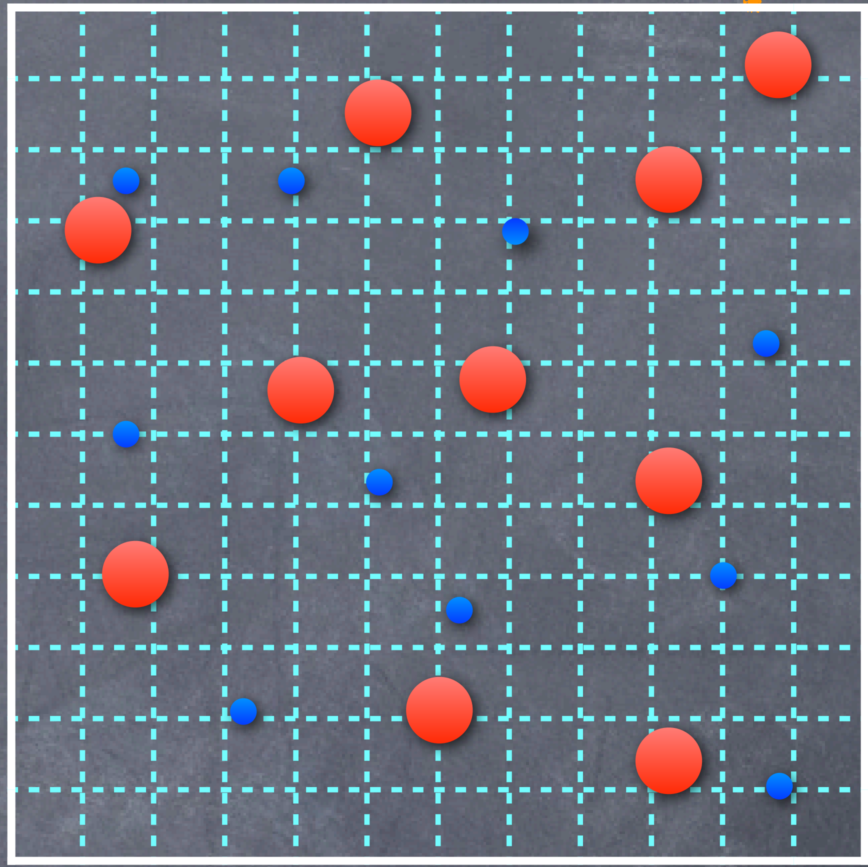




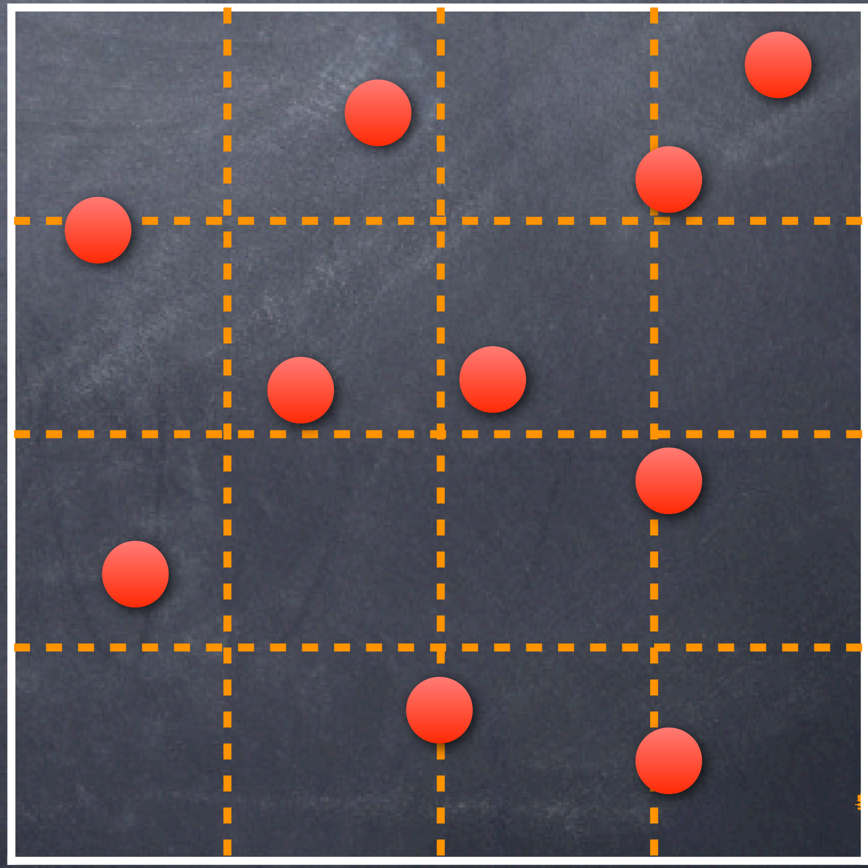



# Acceleration from first principles

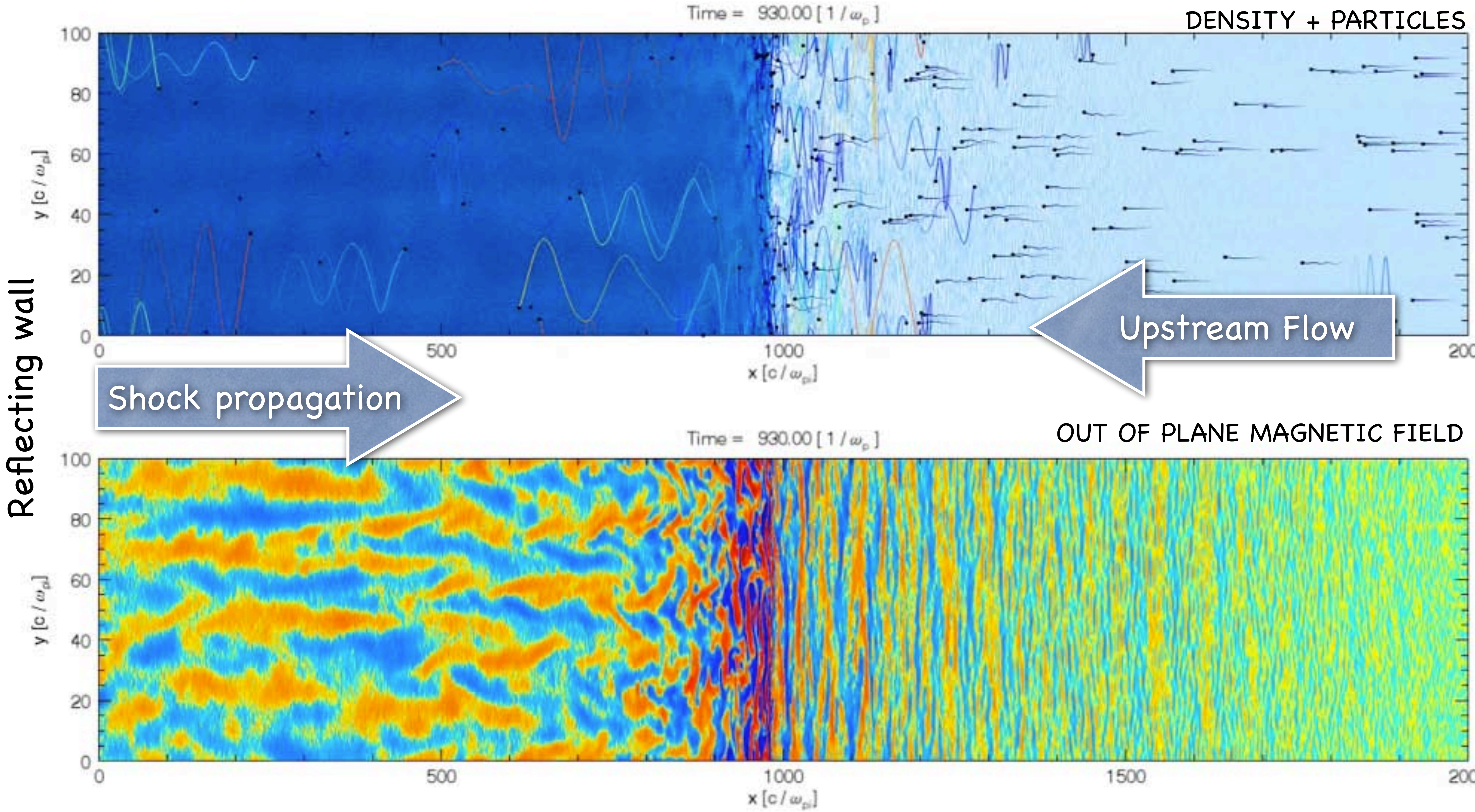
- Full particle in cell approach
  (..., Spitkovsky 2008, Niemiec+2008, Stroman+2009, Riquelme & Spitkovsky 2010, Sironi & Spitkovsky 2011, Park+2012,2015, Niemiec+2012, Guo+2014, DC+15...)
  - Define electromagnetic field on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!



- Hybrid approach:
  Fluid electrons - Kinetic protons
  (Winske & Omidi; Lipatov 2002; Giacalone et al.; Gargaté & Spitkovsky 2012, DC & Spitkovsky 2013-2015,...)
  - massless electrons for more macroscopical time/length scales



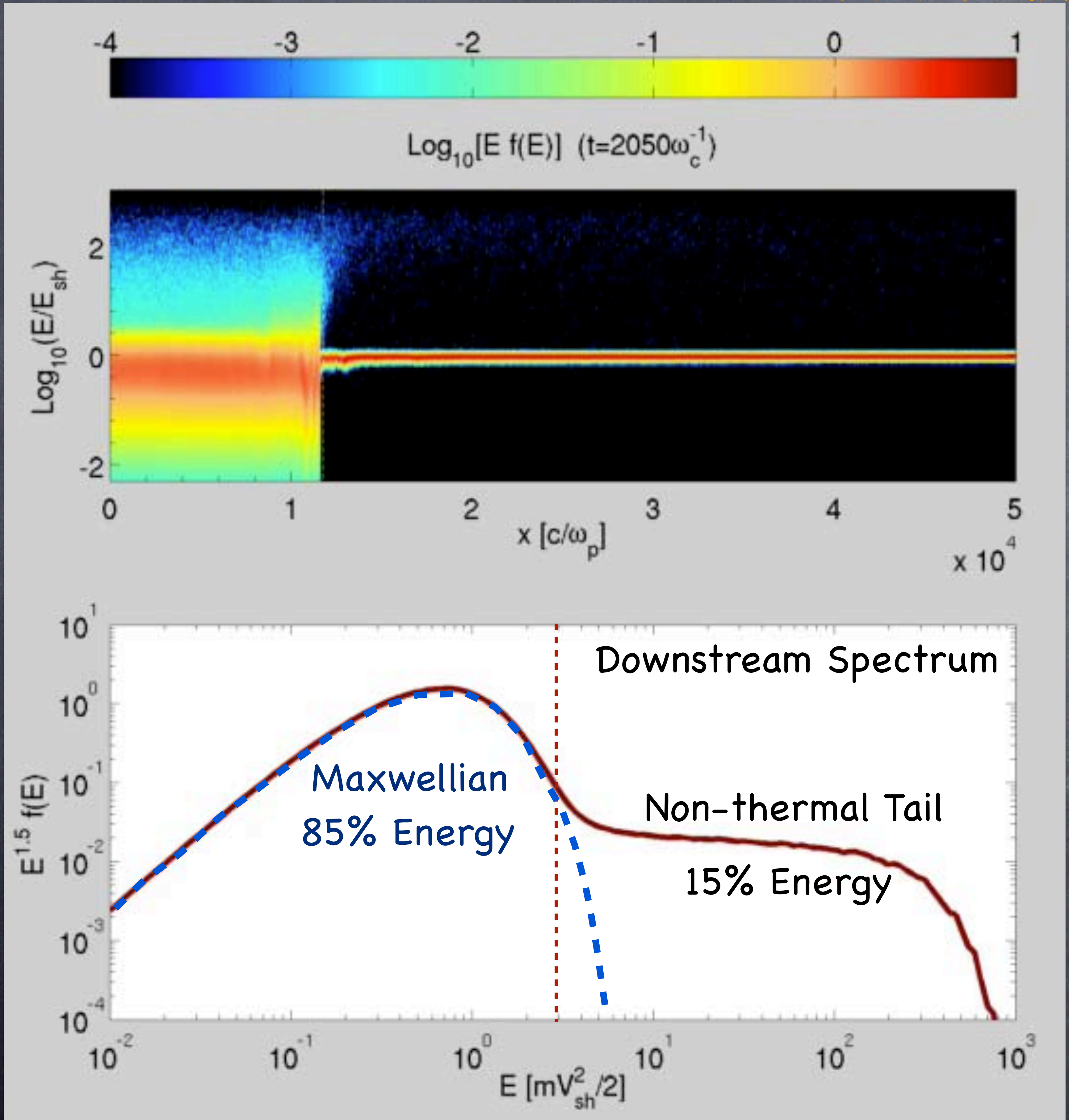
# Hybrid simulations of collisionless shocks




- **dHybrid** code (Gargaté et al, 2007)

Initial B field

# Spectrum evolution




First-order Fermi acceleration:

$f(p) \propto p^{-4}$

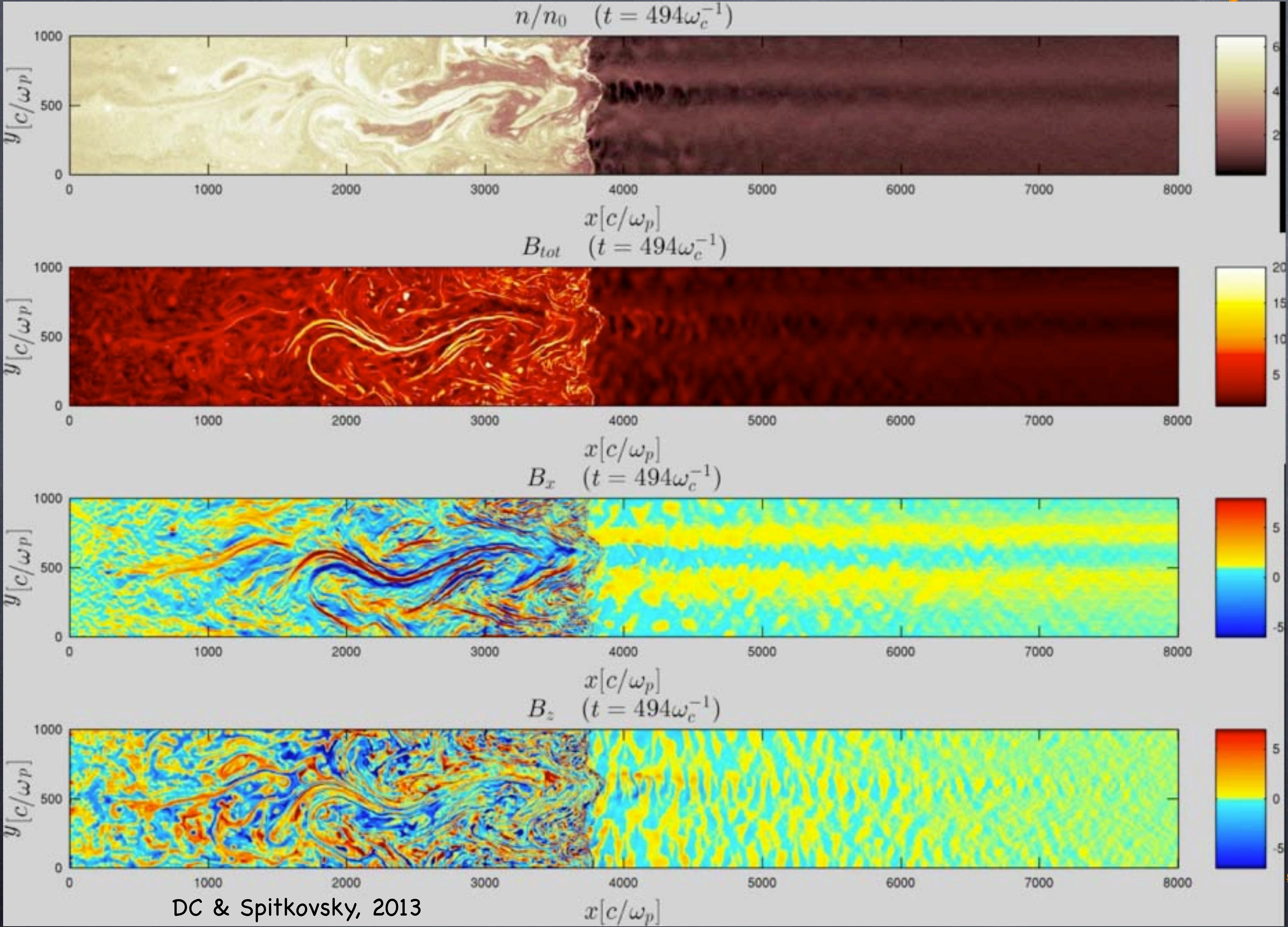
$4\pi p^2 f(p)dp = f(E)dE$

$f(E) \propto E^{-2}$ (relativ.)

$f(E) \propto E^{-1.5}$ (non rel.)

DC & Spitkovsky, 2014a

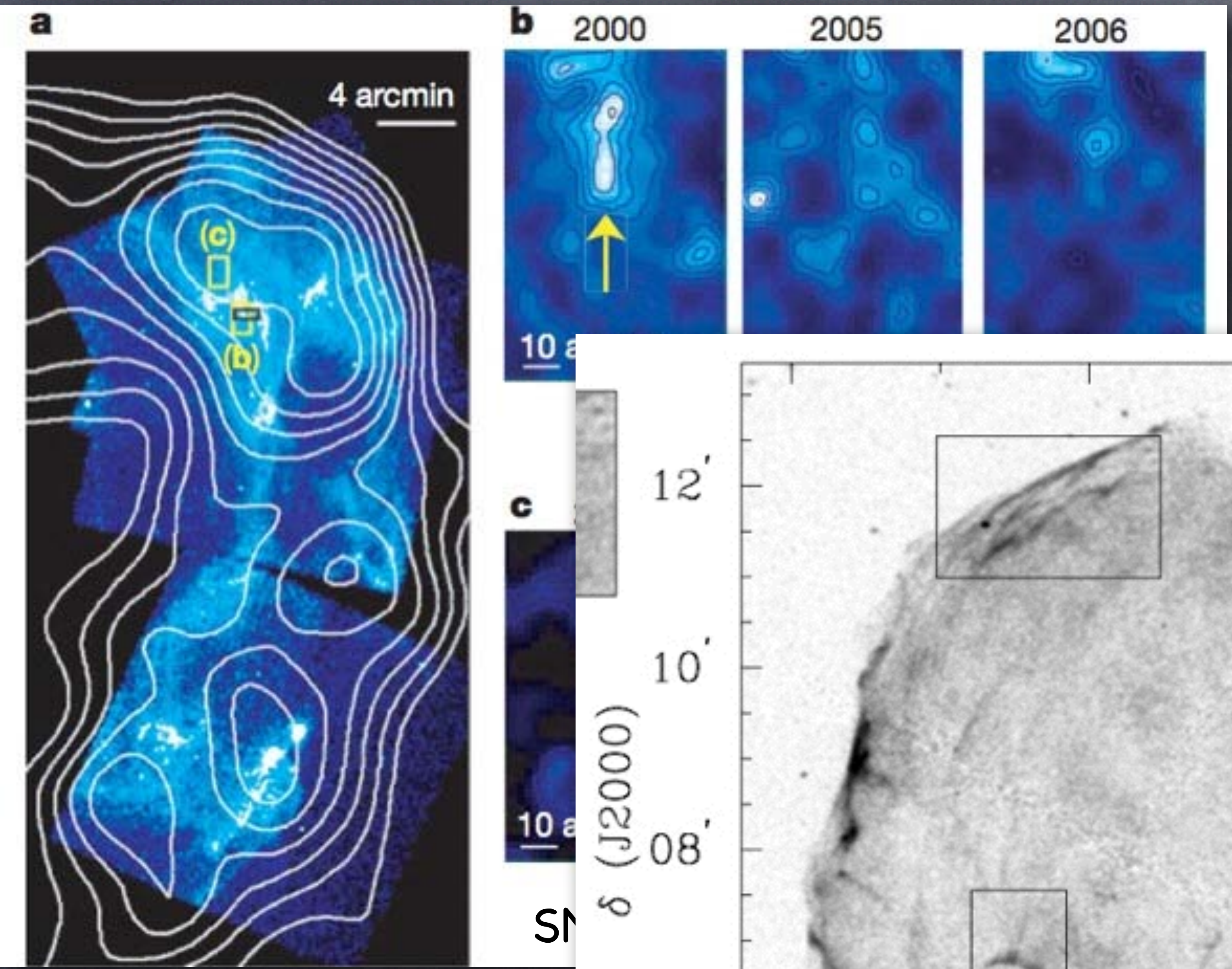
# Filamentation instability



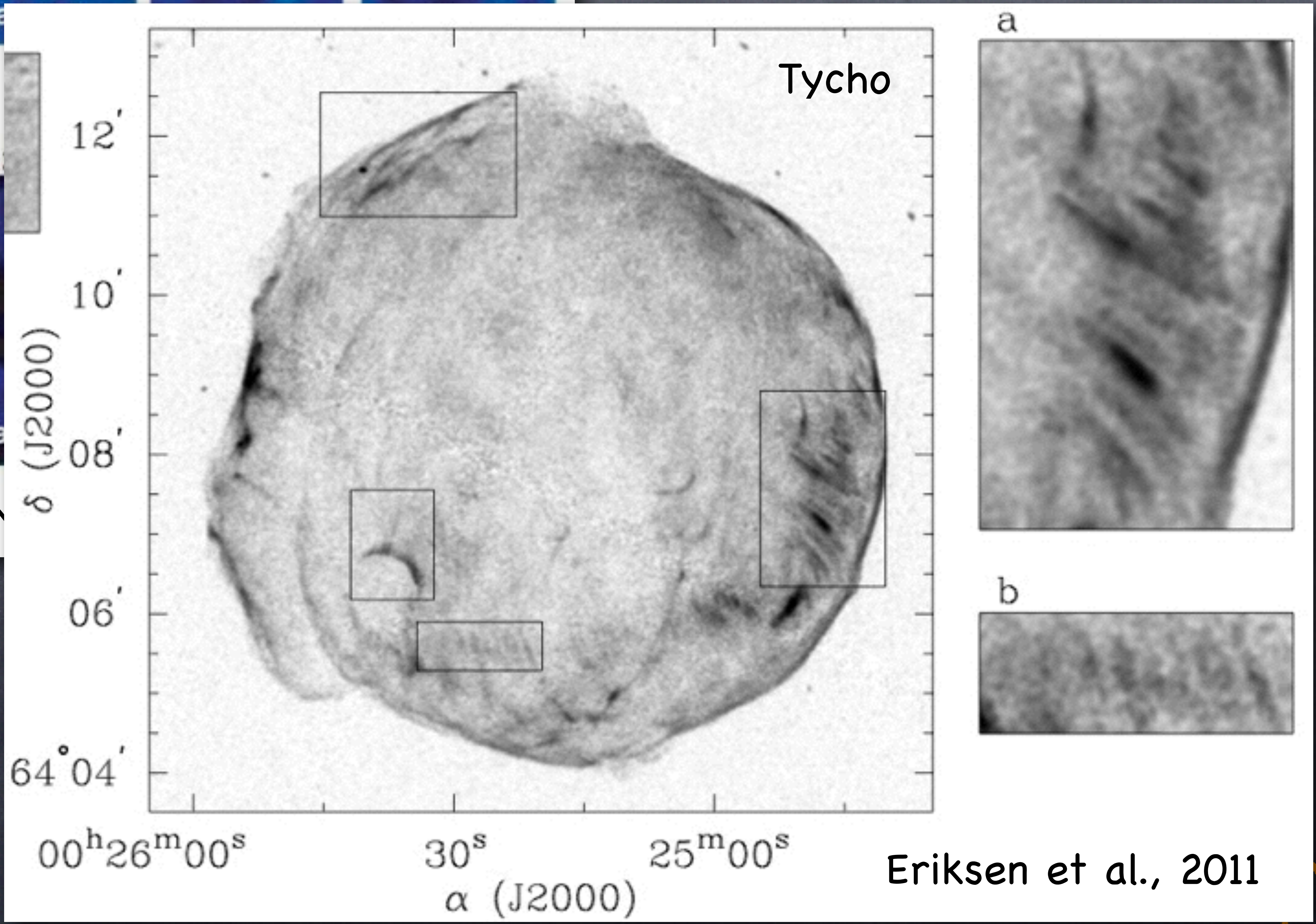

DC & Spitkovsky, 2013

# Knots and filaments

- Knots $\delta B/B \sim 100$
- Radial filaments

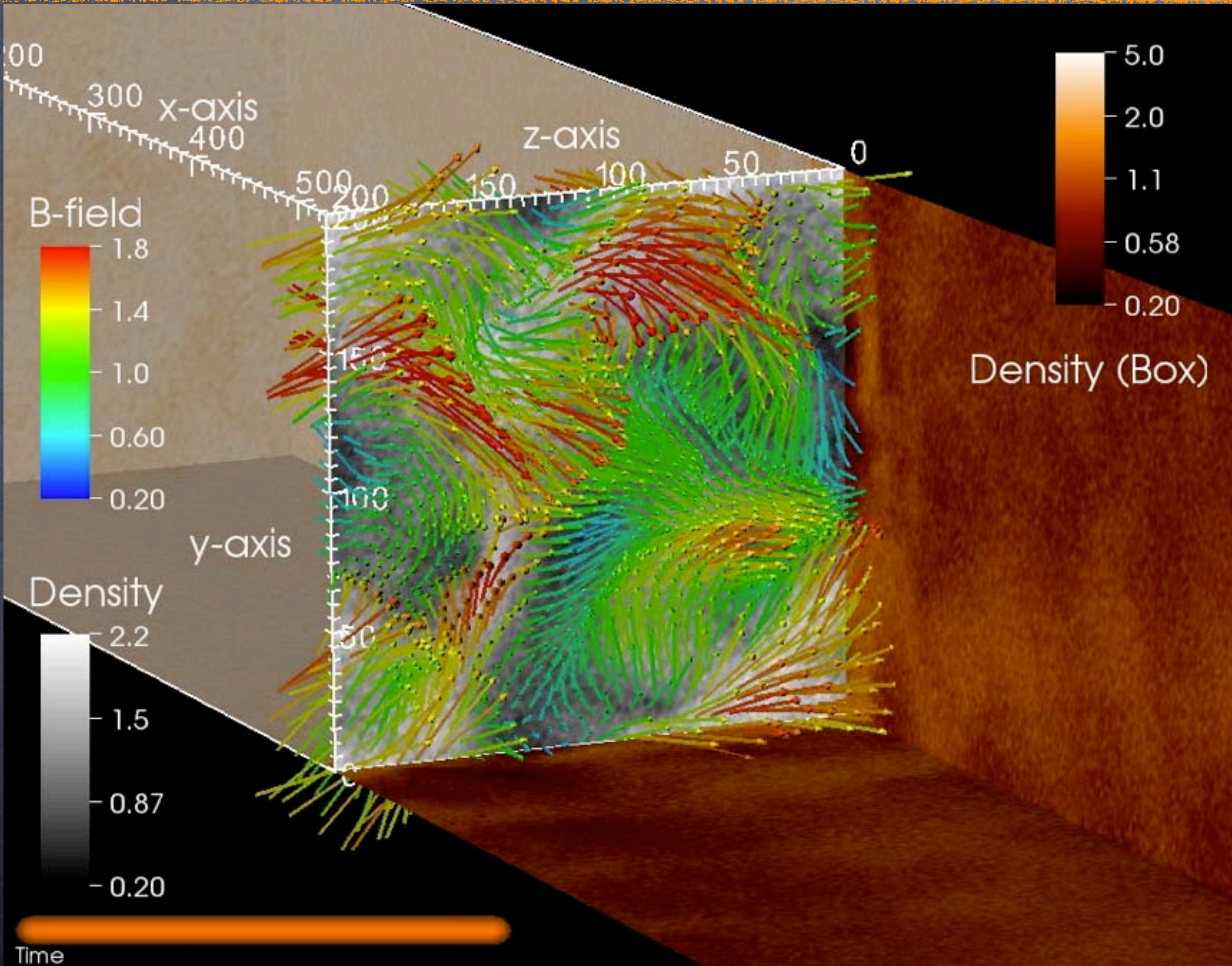



Uchiyama et al 2007



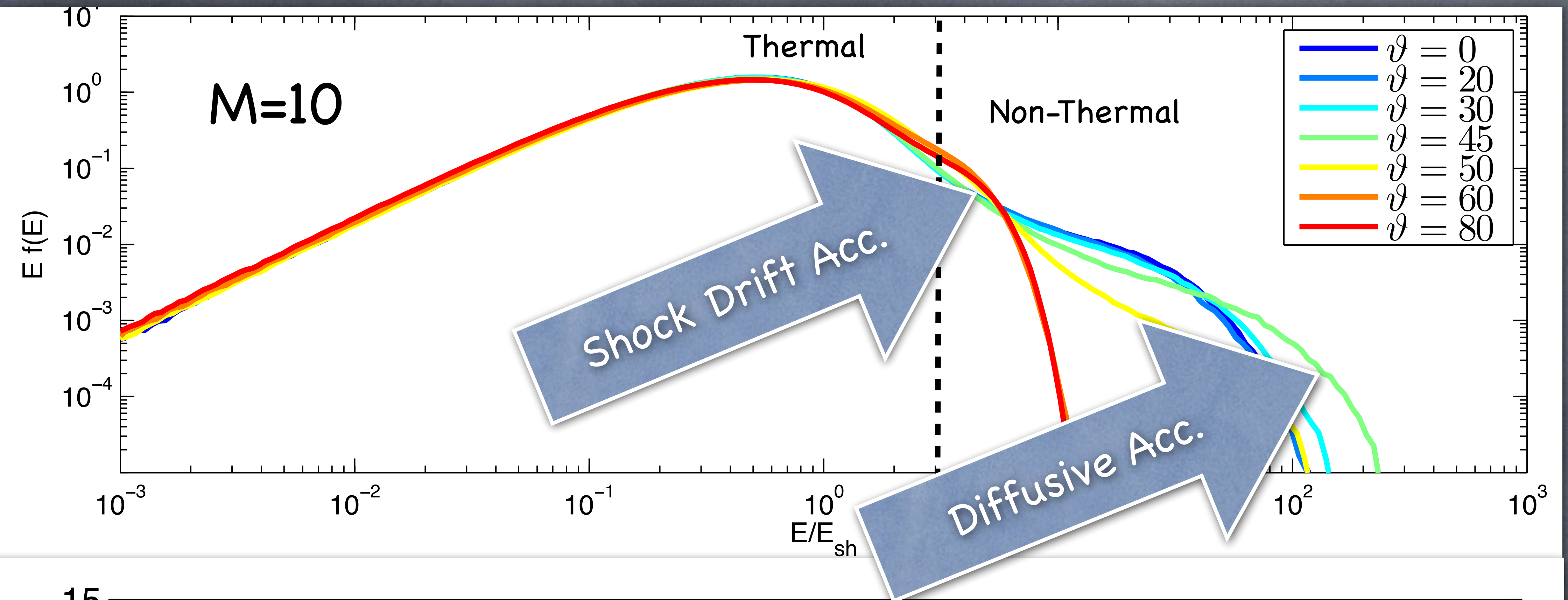

Eriksen et al., 2011

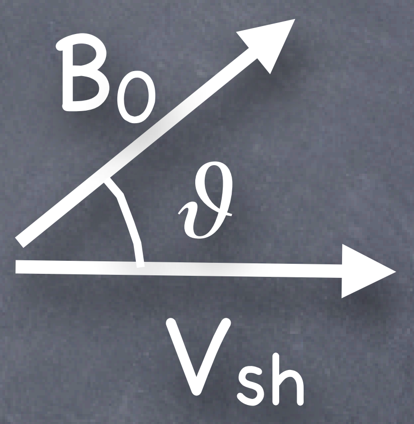
# 3D simulations of a parallel shock

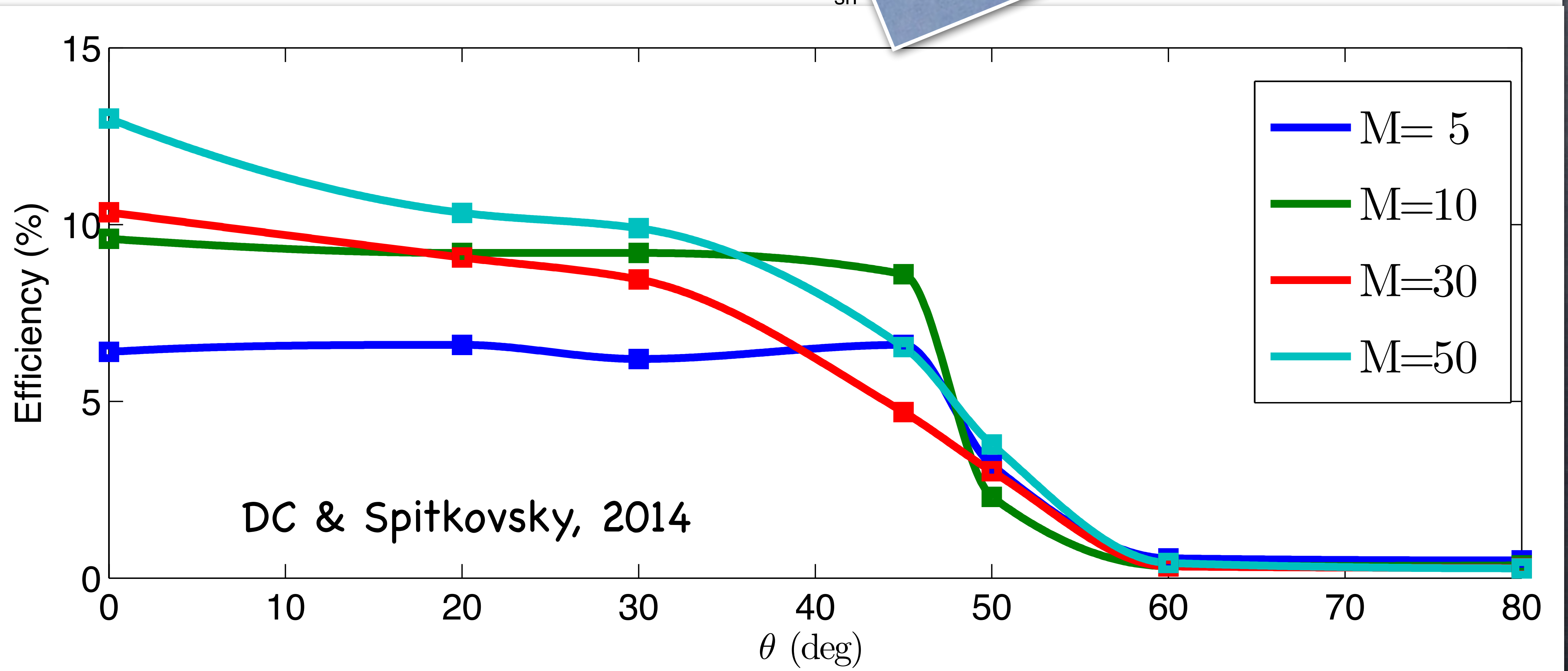



DC & Spitkovsky, 2014a

# Parallel vs Oblique shocks



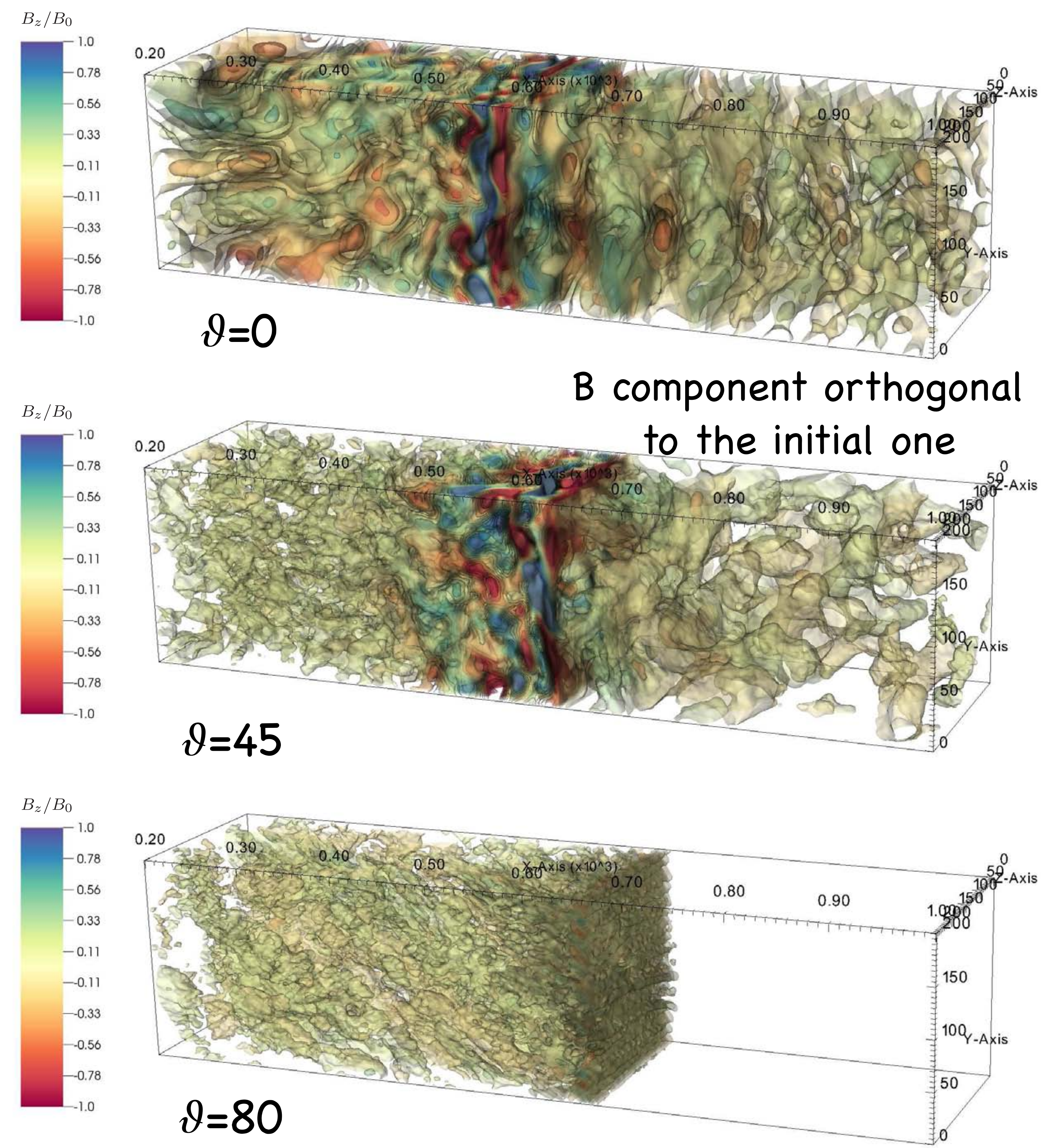




Each point corresponds to a simulation with about $10^9$ particles

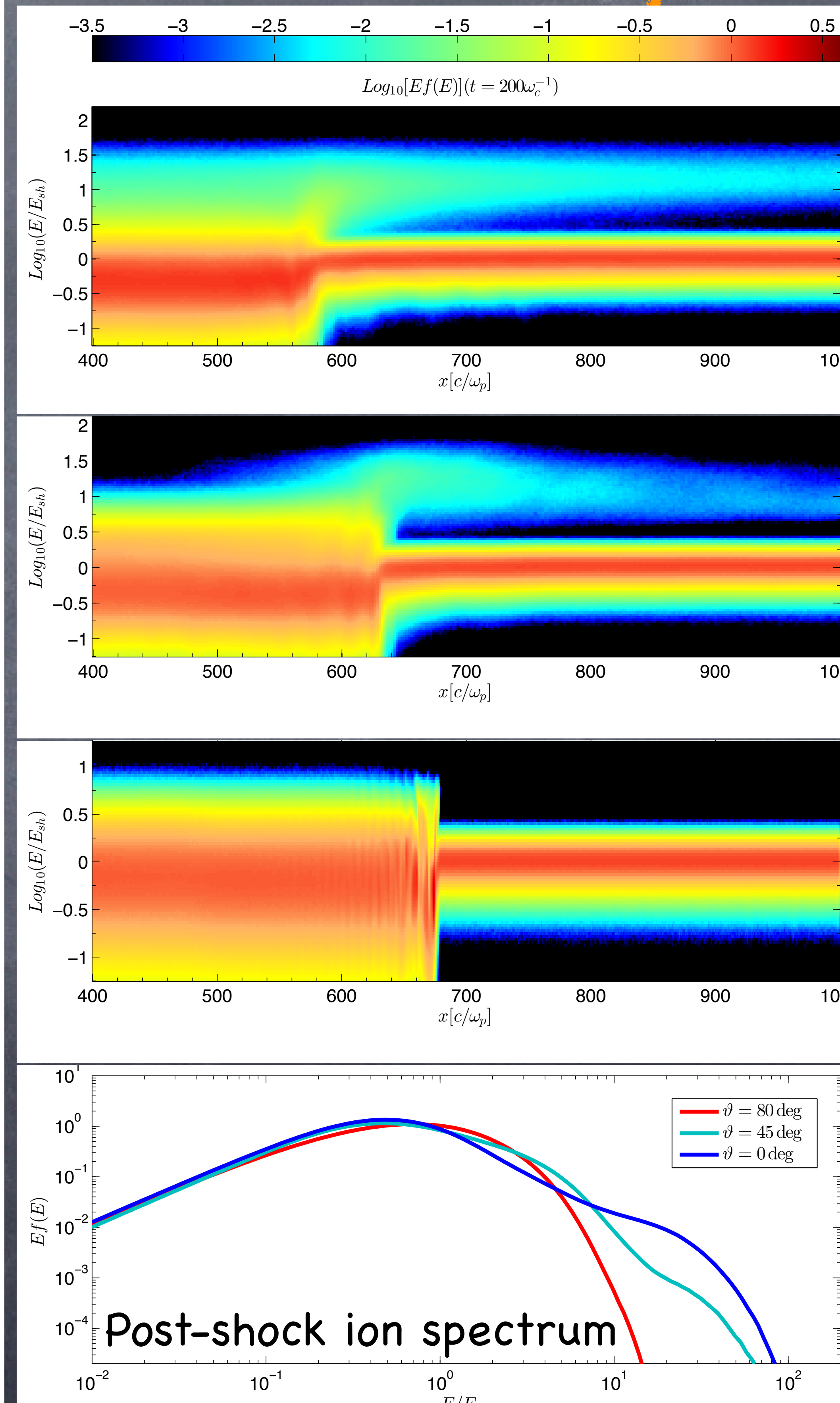
Computation time: almost

$2\times10^6$ cpu h

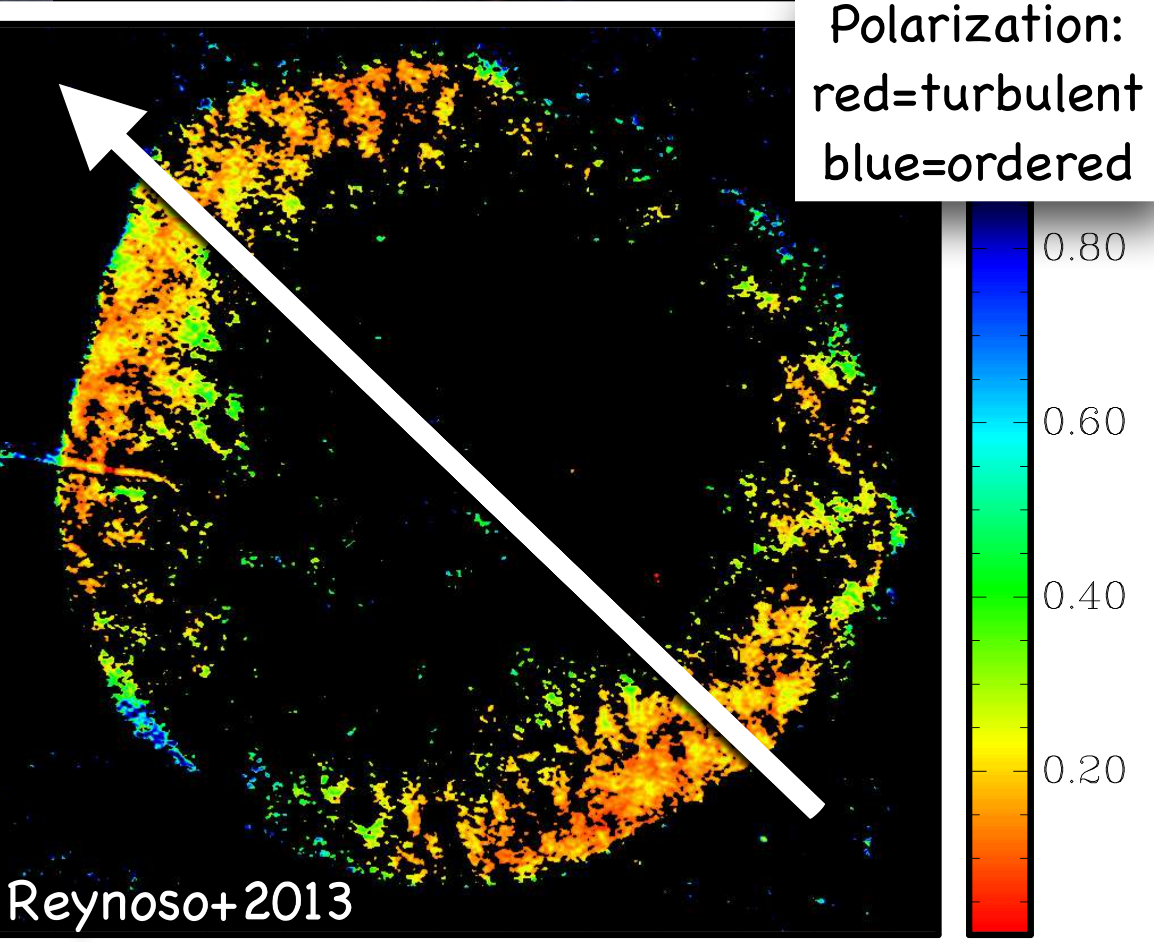
# 3D simulations

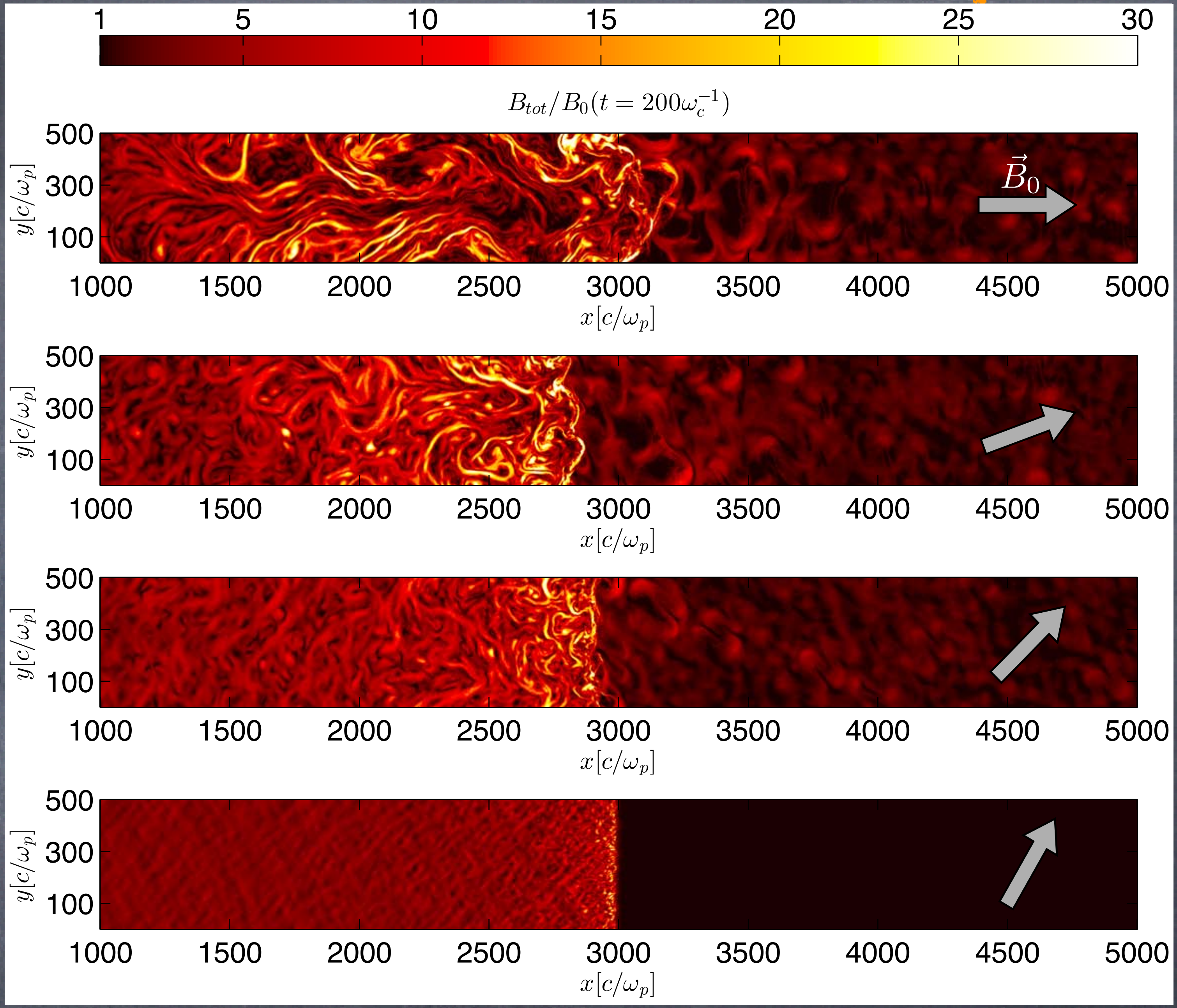



B component orthogonal to the initial one



# SN 1006: a parallel accelerator

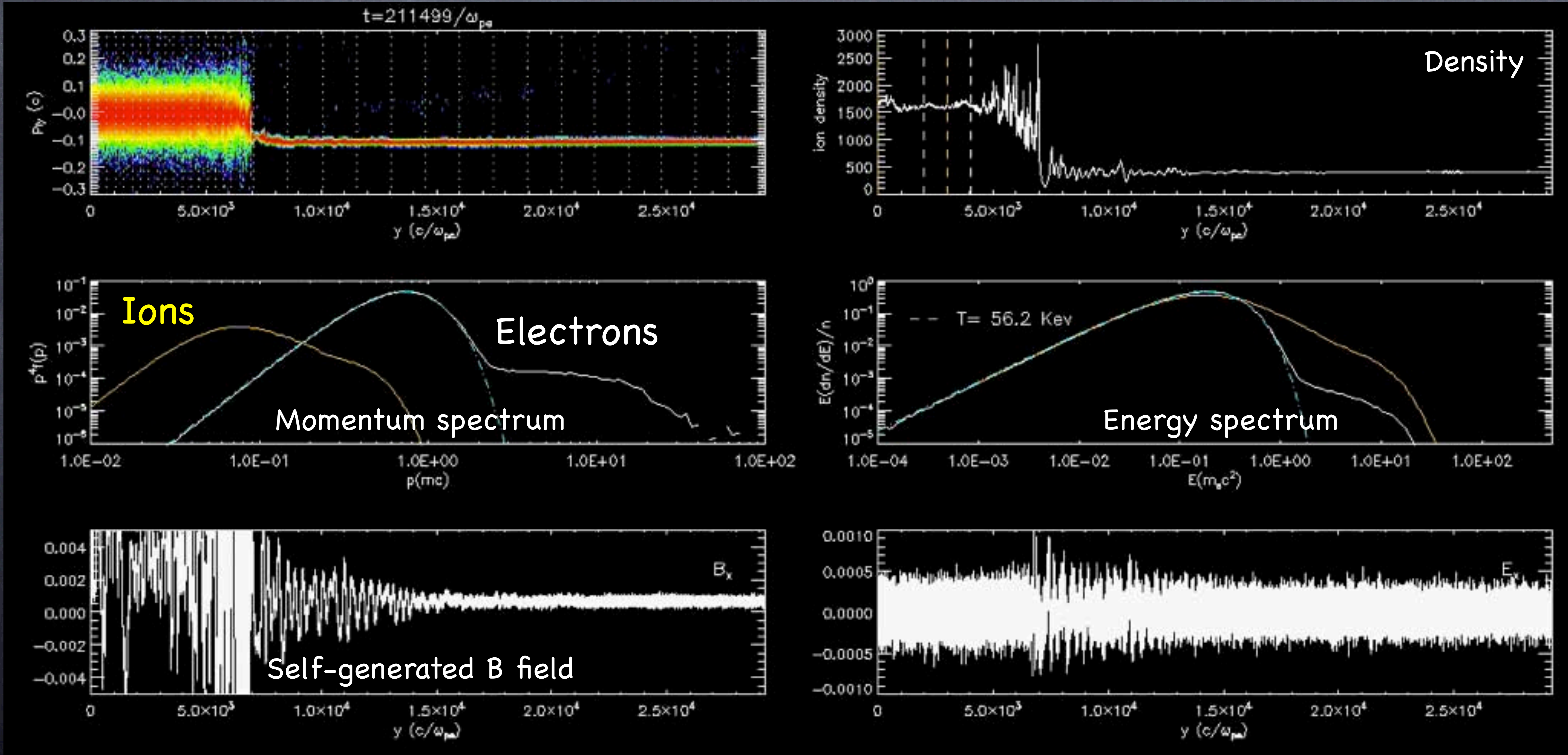




Ion acceleration and B field amplification where the shock is parallel

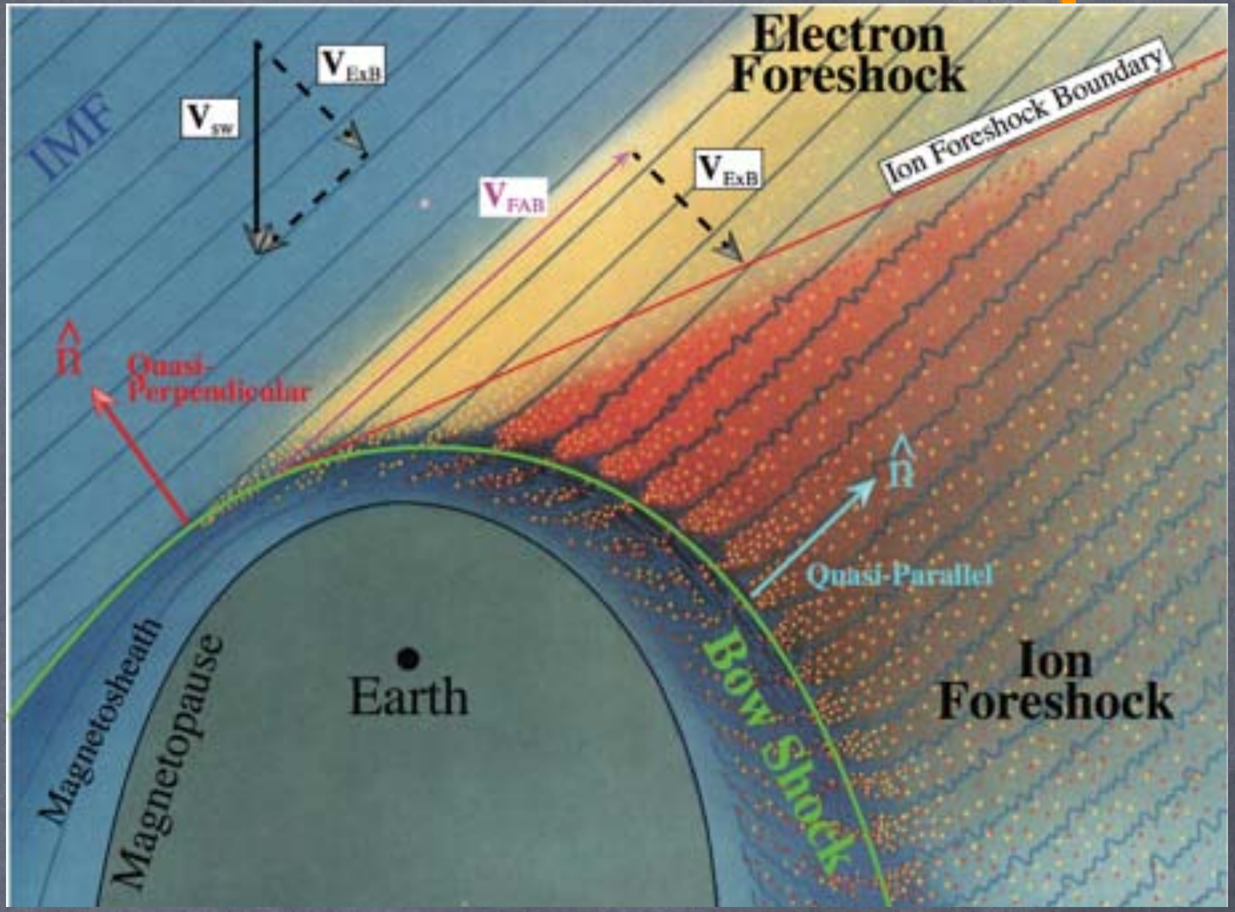
# Electron/ion acceleration

- Full PIC simulations: Tristan-MP (Park, DC, Spitkovsky 2015, PRL)
  - M=20, $v_{sh}$=0.1c, quasi-parallel shock
  - Electrons are accelerated, but ele/proton ratio is a few %

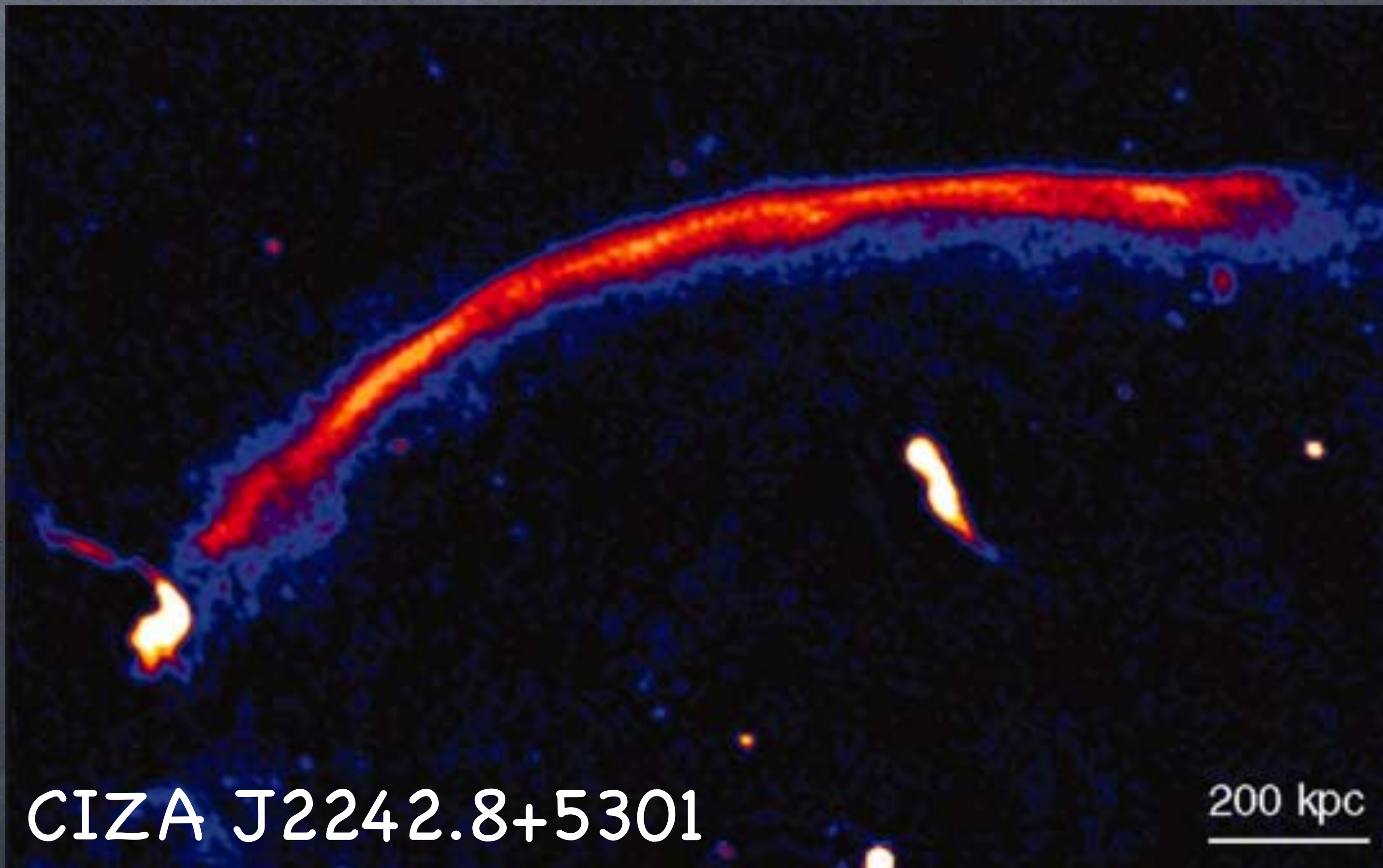


# Electron acceleration

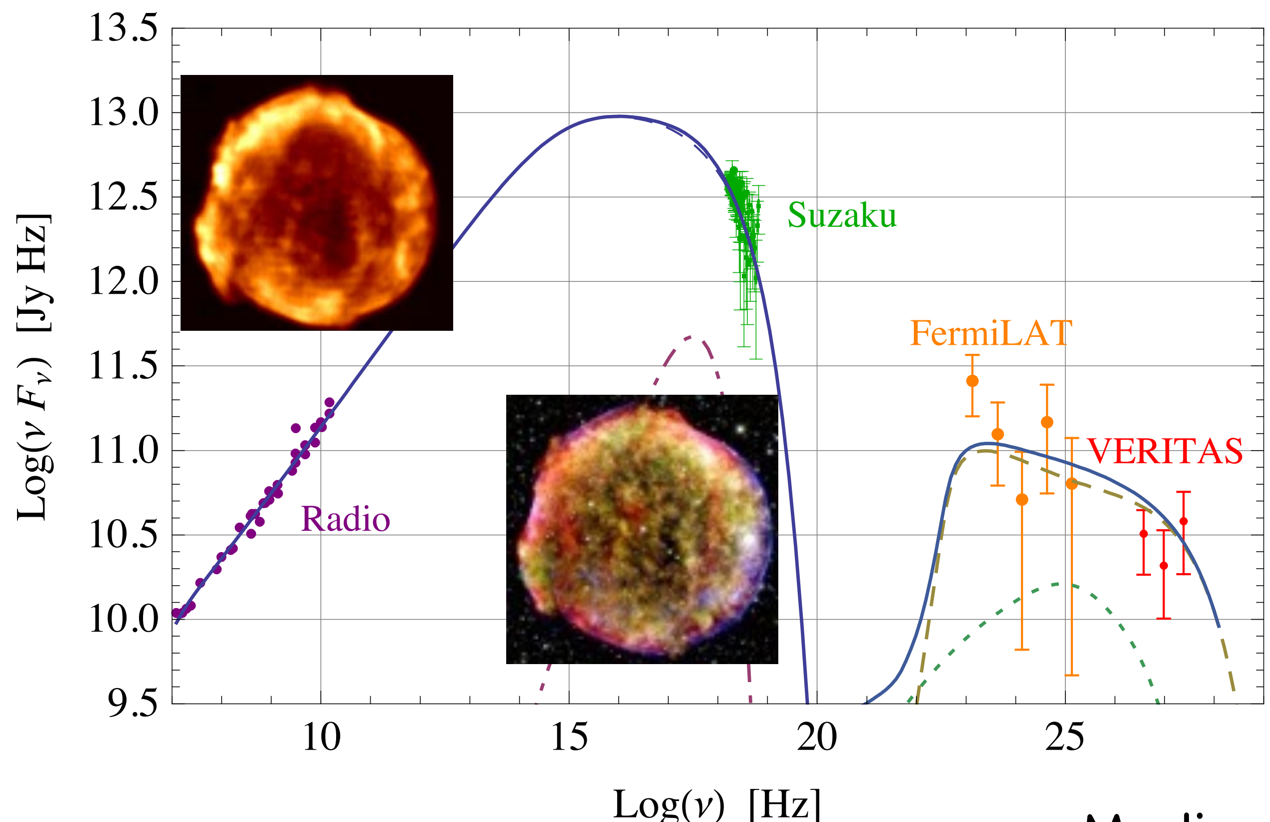
- Planetary bow shocks (Earth, Venus, Saturn,...)
- In situ measurements: Geotail, Polar, SoHO, WIND, THEMIS, Cluster,...

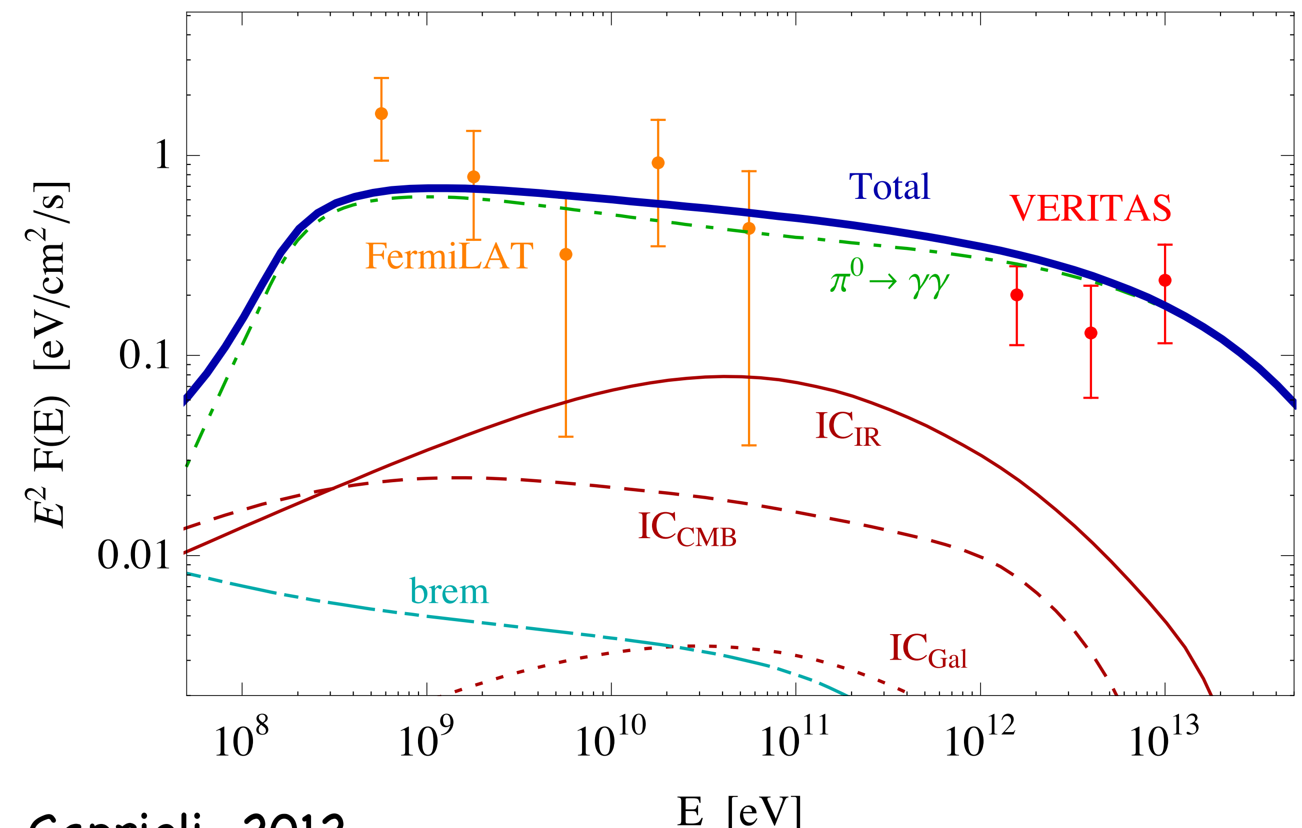



- Radio relics in galaxy clusters (sausage, toothbrush,...)
- Extended polarized structures
- Fermi-LAT limits on $\gamma$-ray emission: constrain e/p ratio!

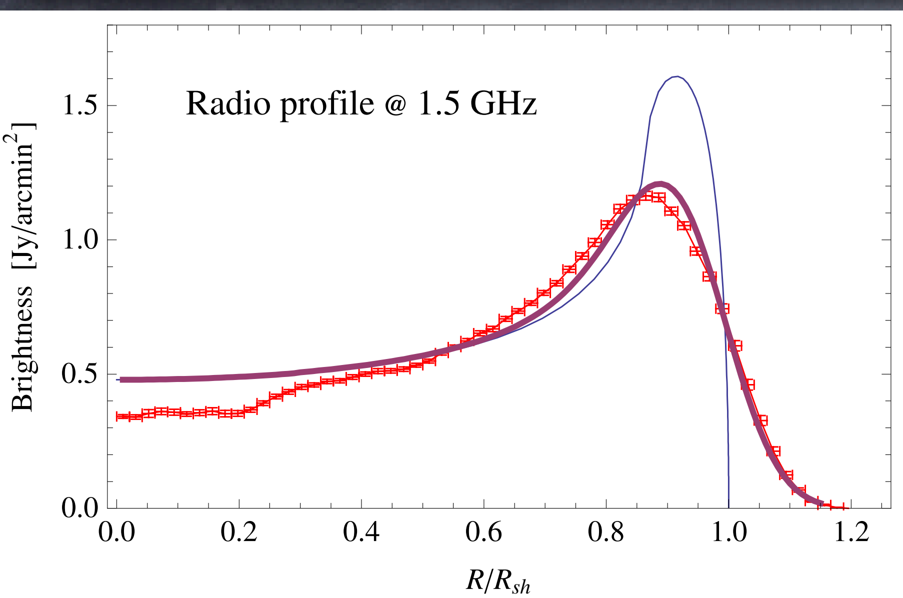


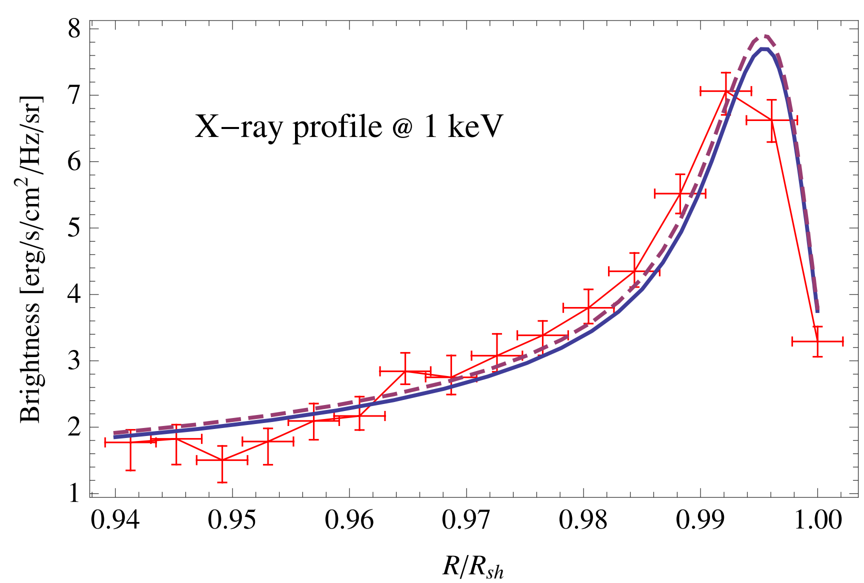
# Tycho: a clear-cut hadronic accelerator




Morlino & Caprioli, 2012

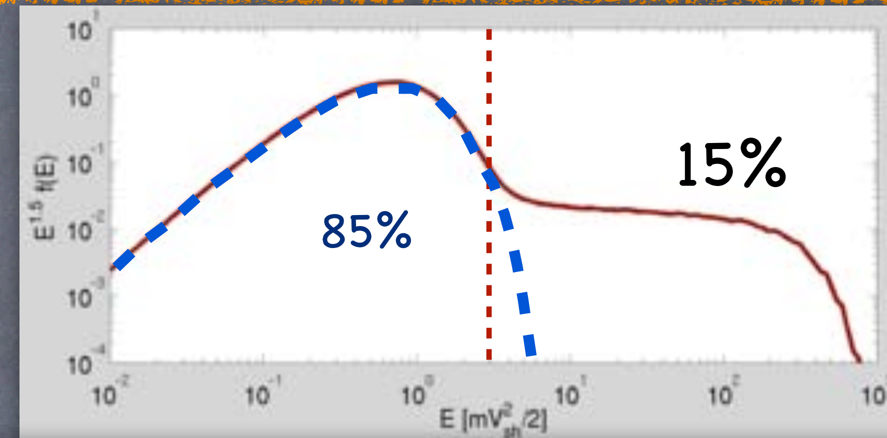


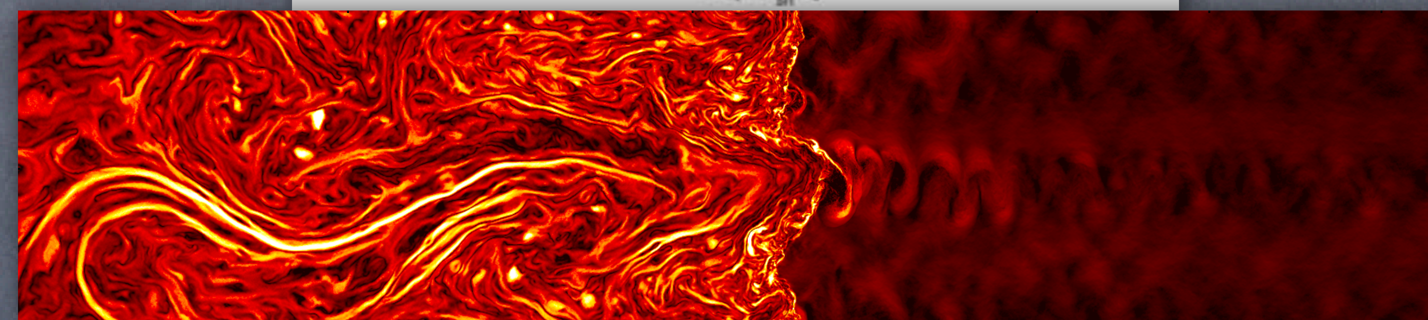



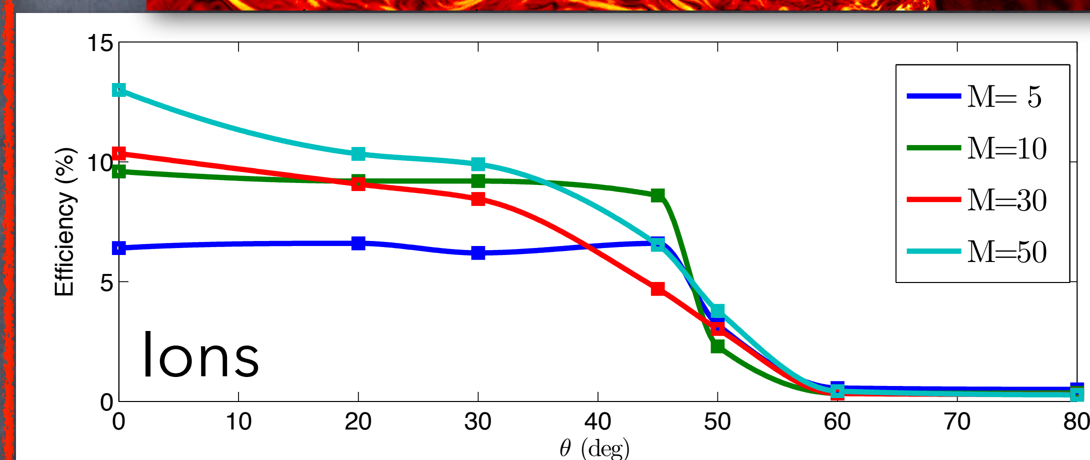

- Account for spectra, SNR hydrodynamics, and morphology
- Hadron acc. eff. ∼10%
- Protons up to 0.5 PeV
- Only two free parameters: injection efficiency and electron/proton ratio

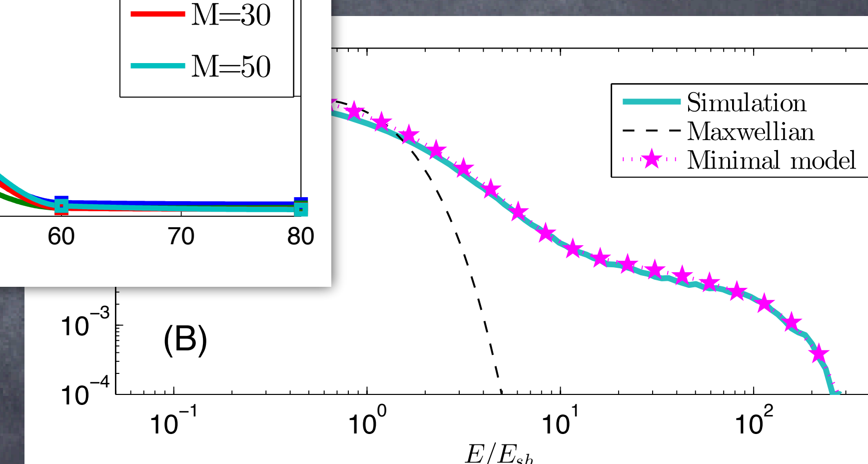
# Galactic CRs: Conclusions!

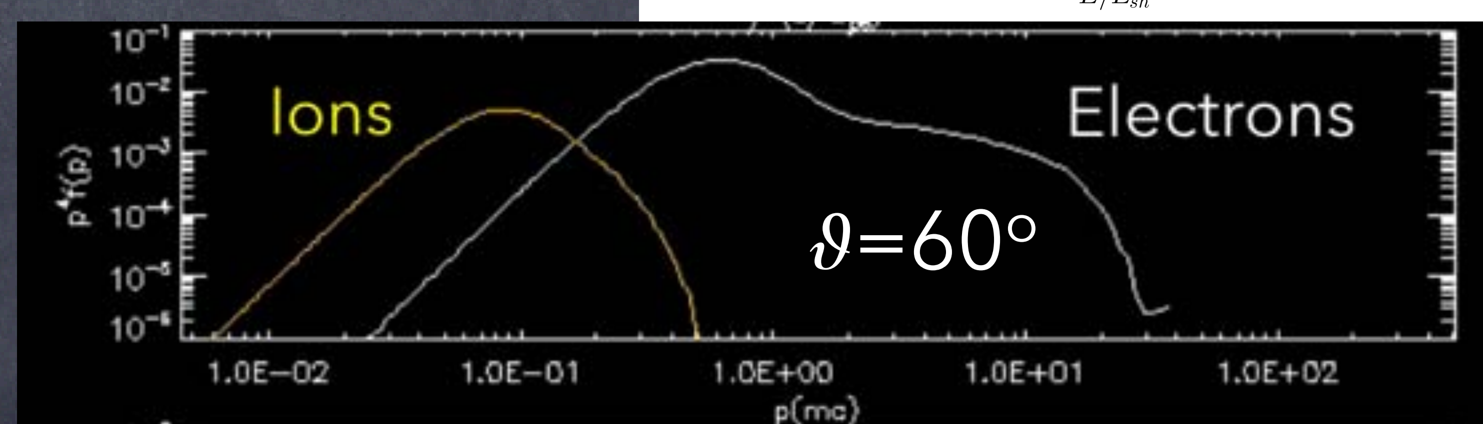
- Acceleration at shocks can be efficient: >15%
- CRs amplify B field via streaming instability
- Ion DSA efficient at parallel, strong shocks
- Ions are injected via reflection and shock drift acceleration
- Electron DSA efficient at oblique shocks



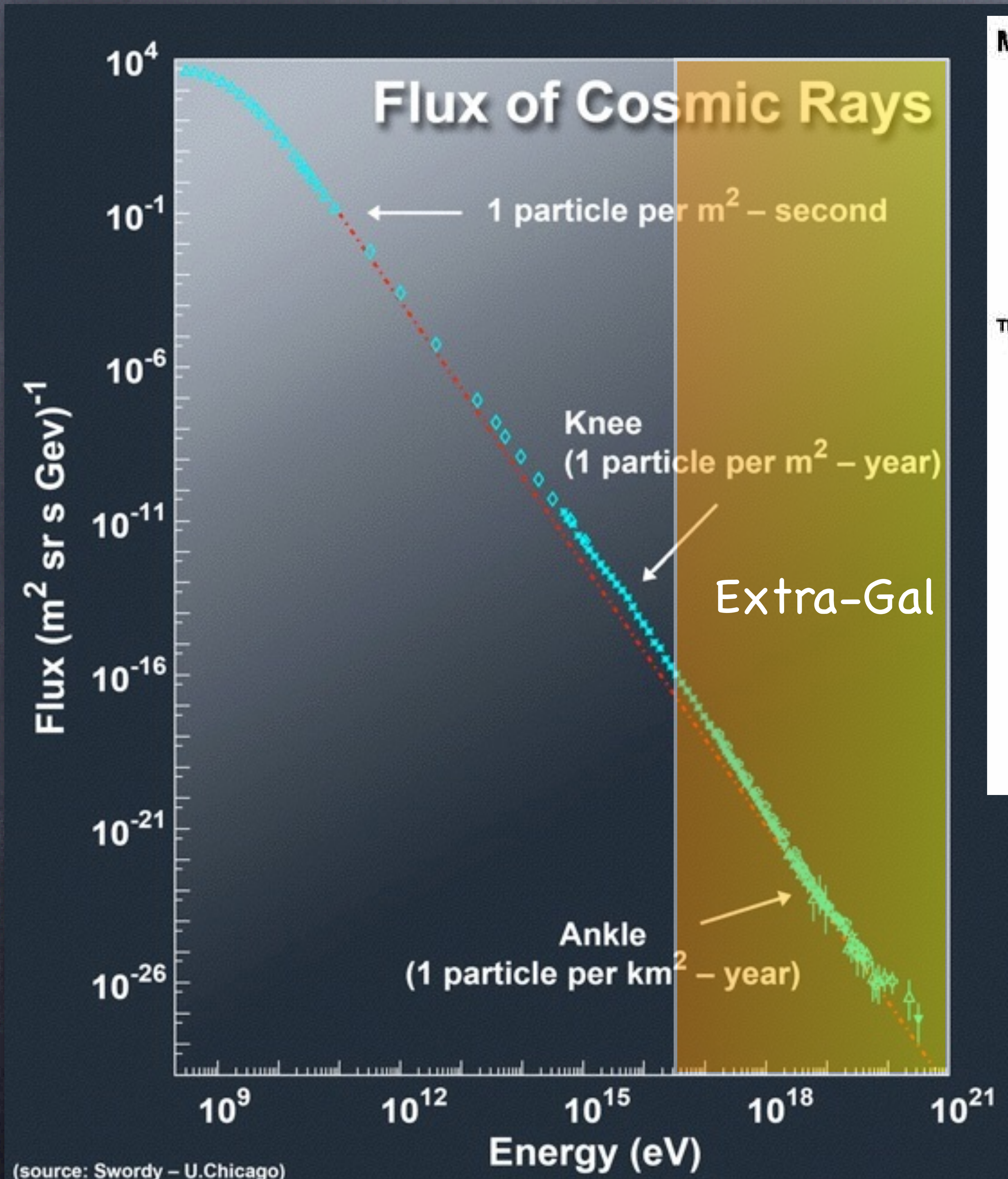



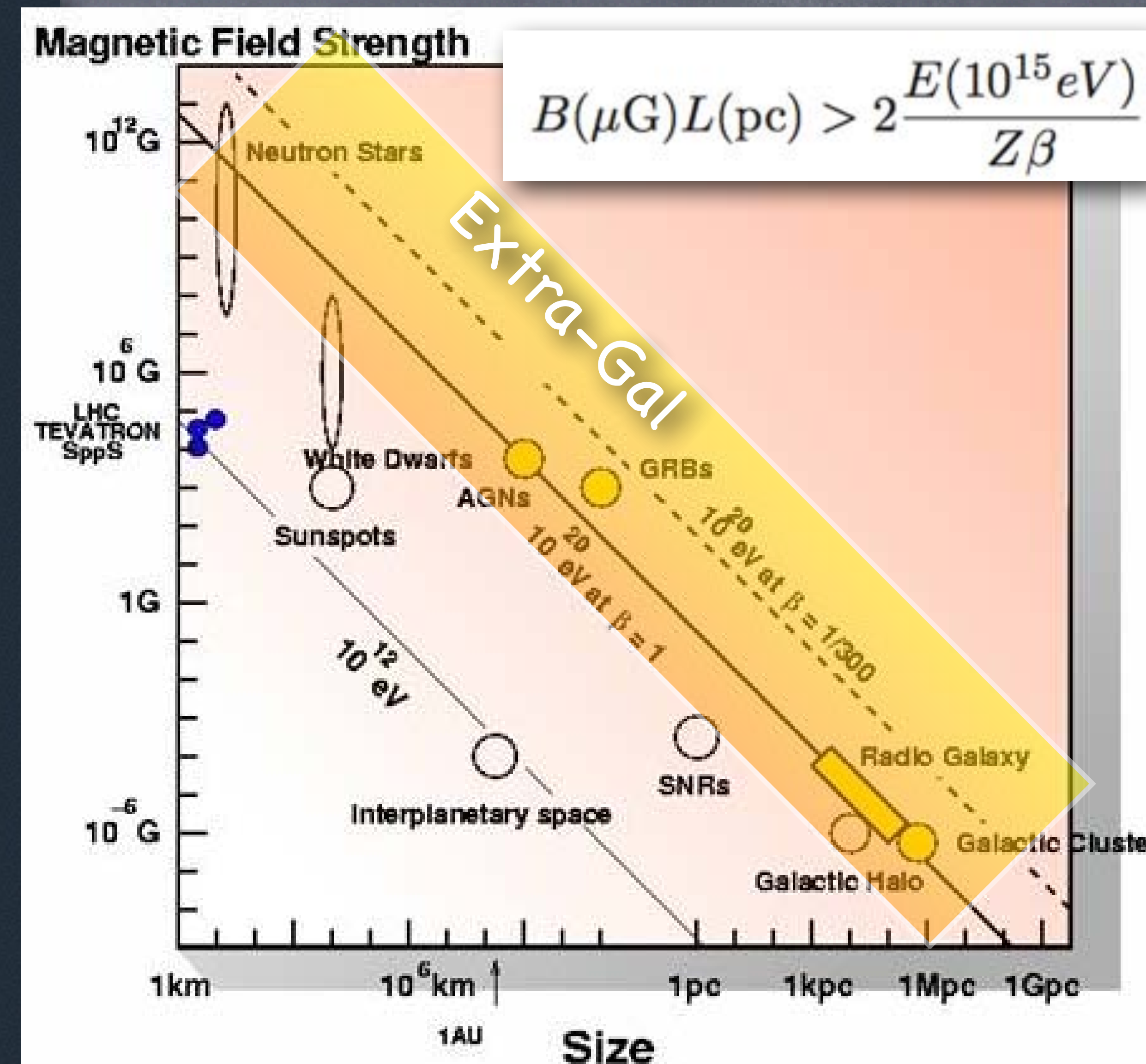


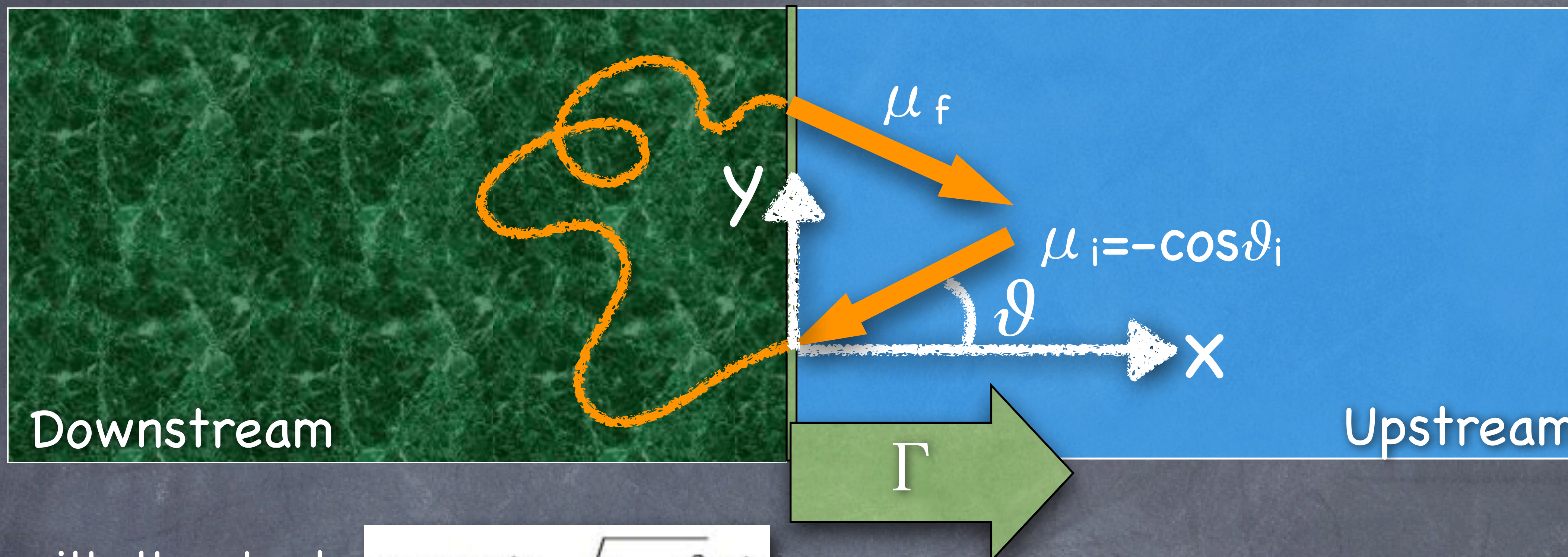
# Extragalactic (UHE) Cosmic Rays




- Candidate sources involve relativistic flows (AGNs, GRBs, PWNe)

# Acceleration at relativistic shocks




Encounter with the shock: $\mathbf{p}_\mathrm{i} \simeq E_\mathrm{i}(\mu_\mathrm{i}, \sqrt{1-\mu_\mathrm{i}^2}, 0),$

in the downstream frame:

$$E'_\mathrm{i} = \Gamma(E_\mathrm{i} - \beta p_{\mathrm{i},x}) = \Gamma E_\mathrm{i}(1 - \beta\mu_\mathrm{i}),$$

Elastic scattering (gyration): $p'_{\mathrm{f},x} \equiv \mu'_\mathrm{f} E'_\mathrm{f}$

$$\mu_\mathrm{f} = \frac{\mu'_\mathrm{f} + \beta}{1 + \beta\mu'_\mathrm{f}},$$

Back in the upstream:

$$E_\mathrm{f} = \Gamma(E'_\mathrm{f} + \beta p'_{\mathrm{f},x}) = \Gamma^2 E_\mathrm{i}(1 - \beta\mu_\mathrm{i})(1 + \beta\mu'_\mathrm{f}),$$

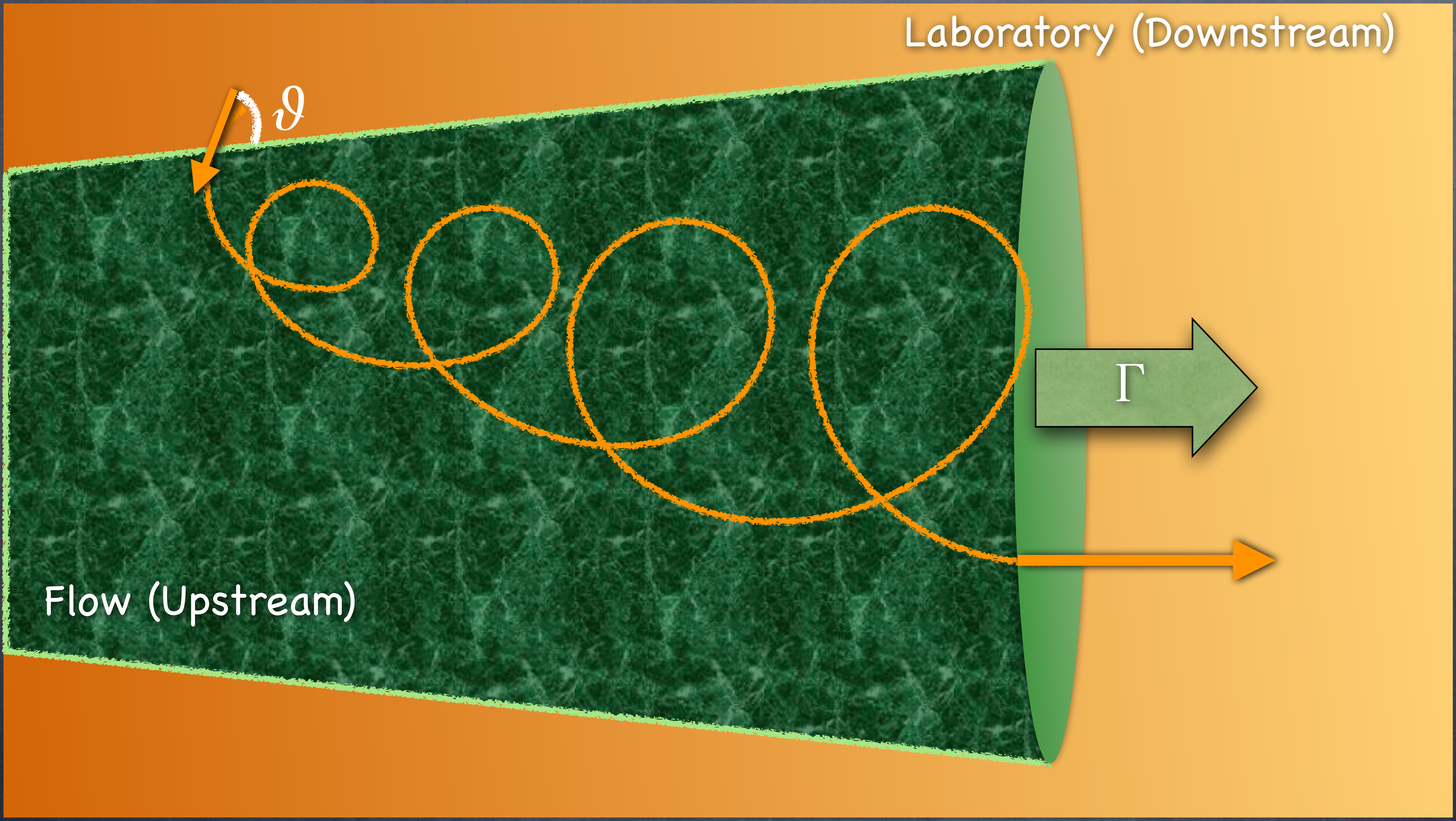
- Energy gain depends on $\mu_f - \mu_i$

**First cycle: $E_f \sim \Gamma^2 E_i$**

- Following cycles: $E_f \sim 2 E_i$
- CAVEAT: return not guaranteed!

# Acceleration in relativistic FLOWS

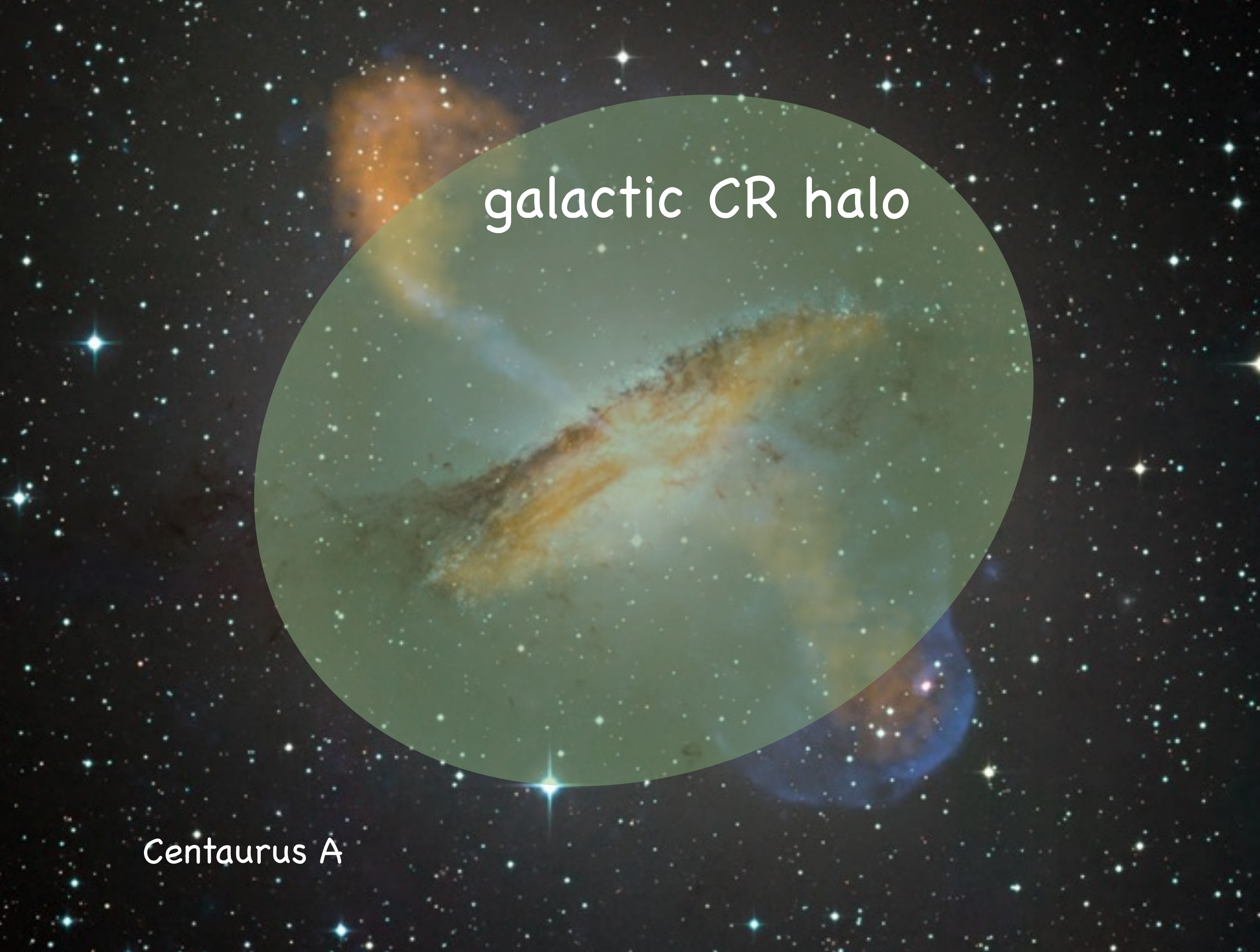
- Requirement: interface thickness << gyroradius << typical flow size




- Most trajectories lead to a $\sim\Gamma^2$ energy gain!

# An “espresso” for UHECRs

- SEEDS: galactic CRs with energies up to $\sim 3Z\times10^{6}$GeV
- STEAM: AGN jets with $\Gamma$ up to 20-30




One-shot reacceleration can produce UHECRs up to $E_{max} \sim 2\,\Gamma^2\, 3Z\times10^{6}$ GeV

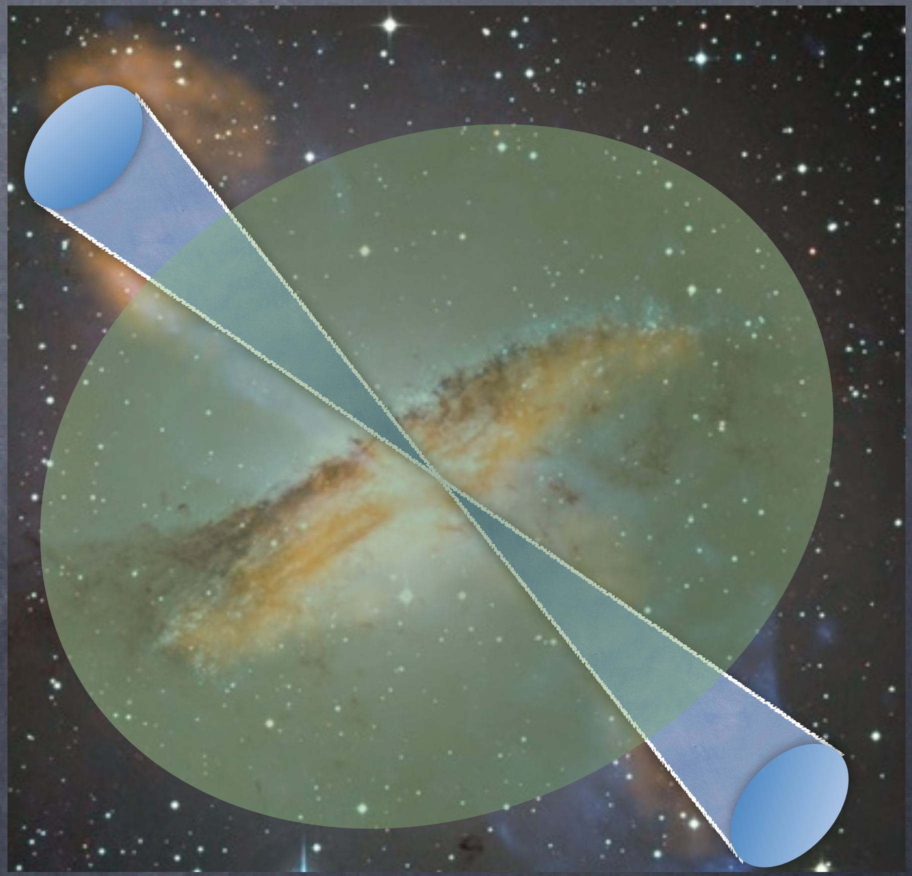
$E_{max} \sim 5Z\times10^{9}$ GeV

# UHECRs from AGN jets: constraints

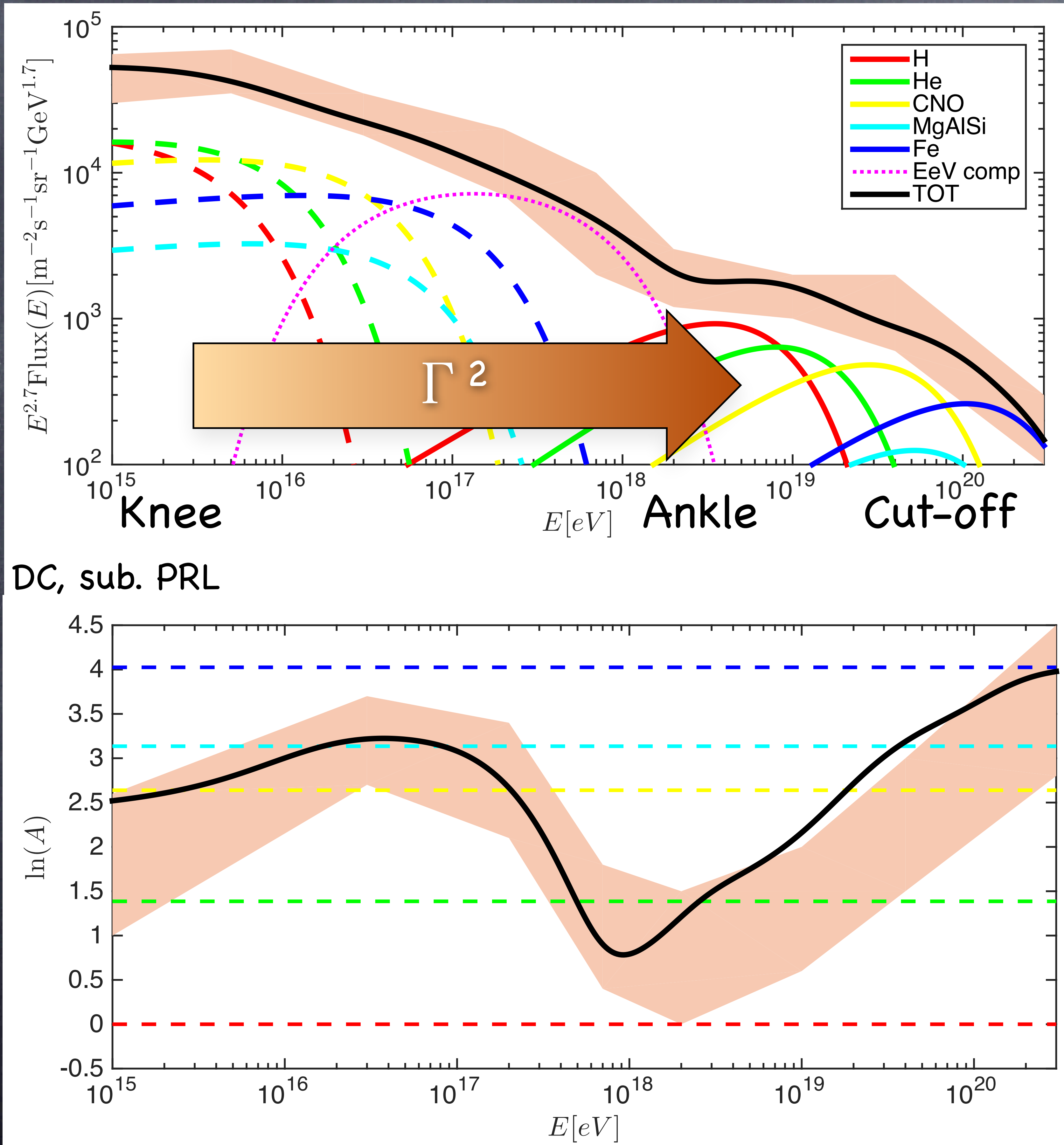
- Confinement (Hillas Criterion): $B_{\mu G} D_{kpc} \gtrsim \frac{4}{Z_{26}} \frac{E_{max}}{10^{20}\mathrm{eV}}$ ✔
- Energetics: $Q_{UHECR}(E \gtrsim 10^{18}\mathrm{eV}) \approx 5\times10^{45}$ erg/Mpc$^3$/yr

  $L_{bol} \approx 10^{43}$-$10^{45}$ erg/s; $N_{AGN} \approx 10^{-4}$/Mpc$^3$

  $Q_{AGN} \approx$ a few $10^{46}$-$10^{48}$ erg/Mpc$^3$/yr >> $Q_{UHECR}$ ✔
- Efficiency depends on:
  - Reacceleration efficiency
  - Jet cross section (angle of a few degrees: $\varepsilon \sim 10^{-1}$-$10^{-2}$)
  - Contributing AGNs
    - Likely radio-loud quasars, blazars, FR-I,...



# Galactic CR + UHECR spectrum




- CR spectral features
- Prediction of UHECR chemical composition!
  - UHECR spectra must be quite flat, $\sim E^{-1.5}$

    (Aloisio+13, Gaisser+13, Taylor 14,...)
  - An additional steep/light component must fill the gal-extragal transition
- Different kinds of AGNs?

# CR summary

| Origin | Sources | Mechanism | E | Spectrum | Evidence |
|---|---|---|---|---|---|
| Galactic | SNRs | Diffusive Acceleration non-rel shocks | 3Zx10 GeV | Universal ~ | e.g., Tycho |
| Extragal | AGNs | Espresso in rel | 5Zx10 GeV | Galactic, boosted | Anisotropy? Neutrinos? |