A Hierarchical Interpretation of the Observed Cosmic Ray Spectrum

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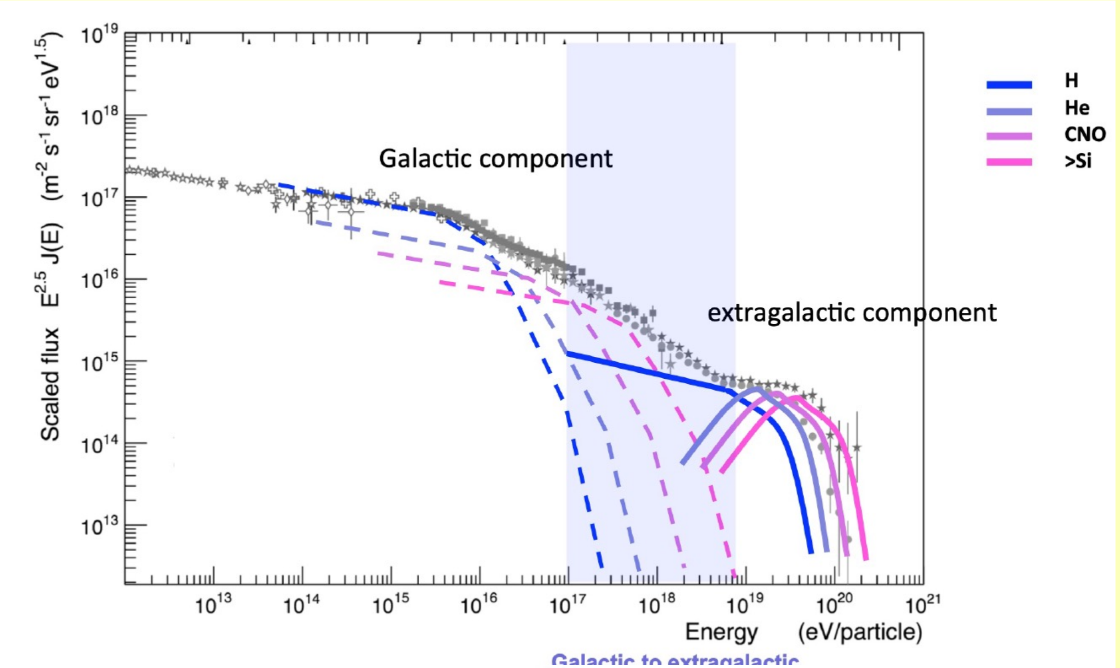
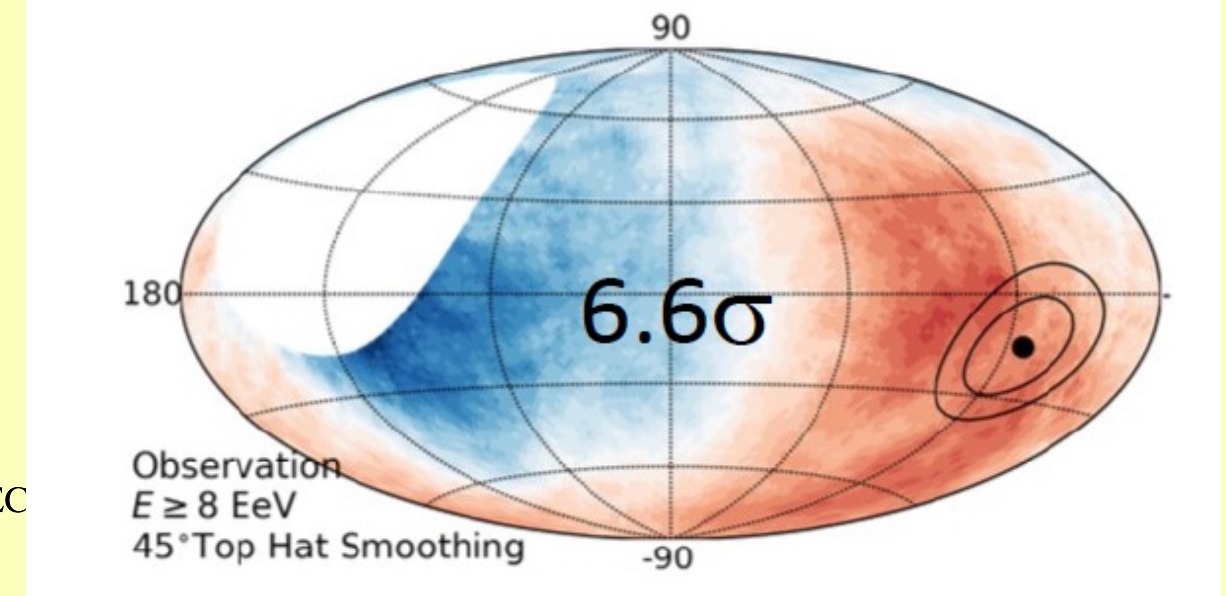
Observational Oversimplification

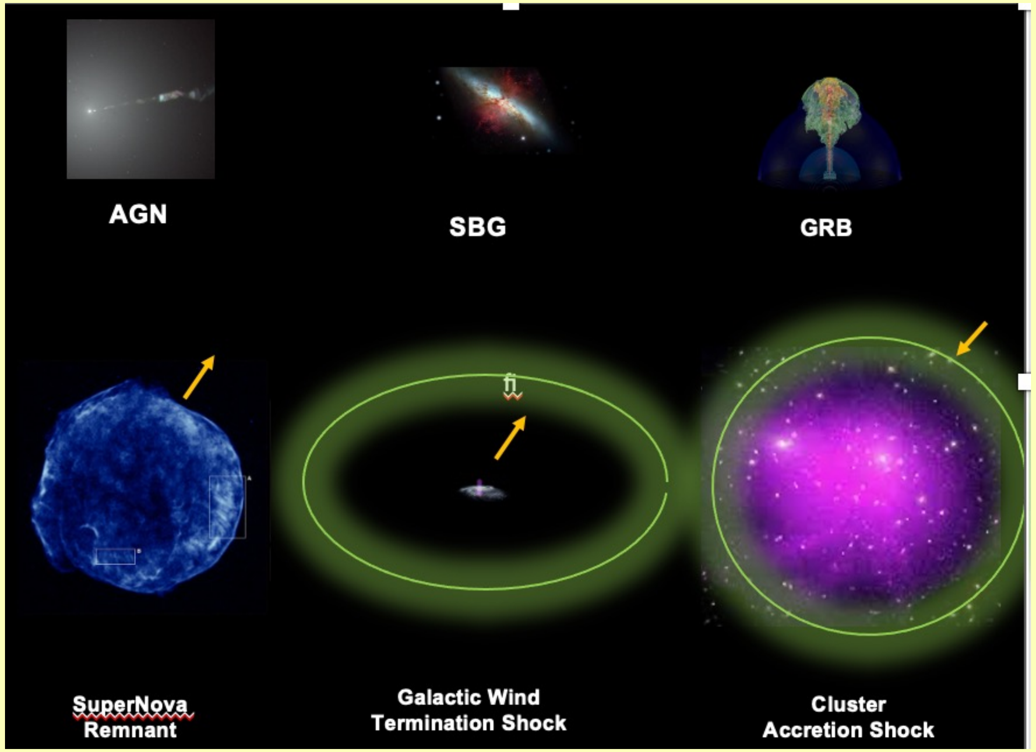
- GeV-PeV – Thigh
  - Knee
- PeV-EeV – Shin
  - Ankle
- EeV-ZeV – Foot
  - UHECR





Phenomenological Oversimplification

- Cosmic rays accelerated by shocks
  - Bulk kinetic energy -> GeV – ZeV CR
- Hierarchical model
  - SNR -> GWTS -> CAS/ FAS
- Confront with observations
  - Each E_{max} requires maximal acceleration

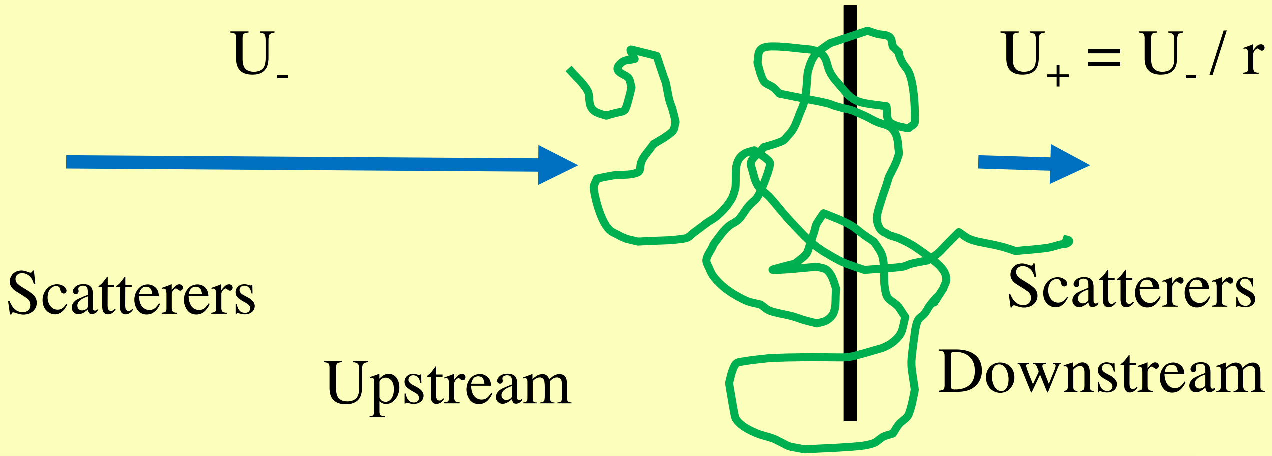


GeV **SNR** PeV **GWTS** EeV **CAS** ZeV

Enrico Peretti

Theoretical Oversimplification

- Diffusive Shock Acceleration at Plane Shock



Scale height ~ (c/u) mfp
scatterings ~$(c/u)^2$

Isotropic phase space distribution function f(x,p)

$$\nabla \cdot (f\vec{u} - D\nabla f) = \nabla \cdot \vec{u}\, \partial_{p^3} f p^3$$

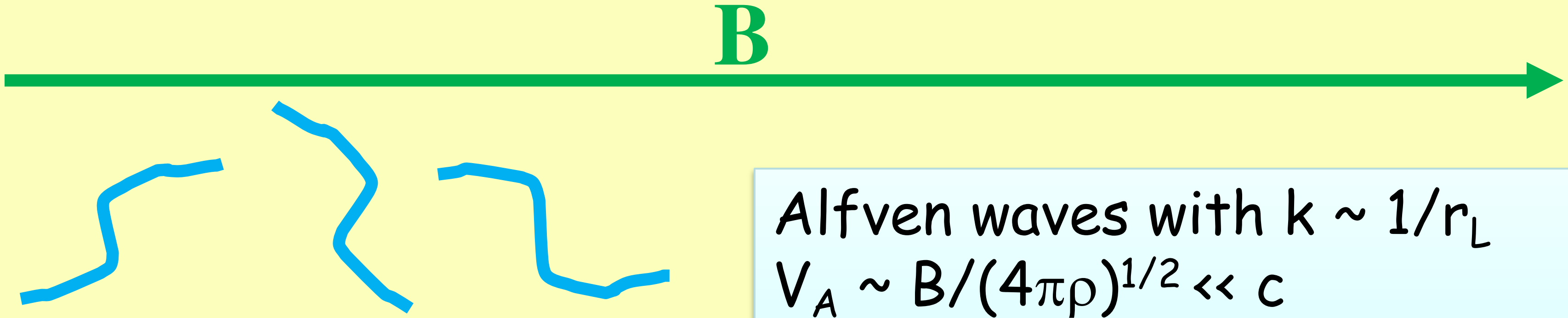
fluid convection | isotropic diffusion | adiabatic heating $p \sim \rho^{1/3}$

Shock: $[-up\partial_p f - D\nabla f] = 0$

$P_{trans} = 4U_+ / v$
$\Delta p/p = 4 (U_- - U_+) / 3v$

$f(p) \sim dN / p^2\, dp \sim p^{-3r/(r-1)}$
Downstream Greens function

Plasma Physics Oversimplification

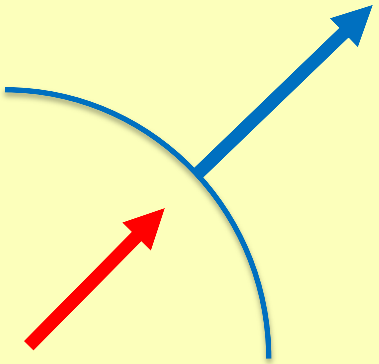


Alfven waves with $k \sim 1/r_L$
$V_A \sim B/(4\pi\rho)^{1/2} \ll c$
mfp $\sim r_L \, (B/\delta B)^2 \sim r_L$ in Bohm limit
$r_L \sim R_{EV} / B_{\mu G}$ kpc

Plasma instabilities
Streaming: $\langle v \rangle > V_A$
Growth $(n_{CR}/n_i)\,\Omega_L$
Current $k > 1/r_L$
MHD $k < 1/r_L$

PIC Simulations of initial value problems with limited dynamic range
Lab astro experiments have begun

Spherical Shocks - Geometry

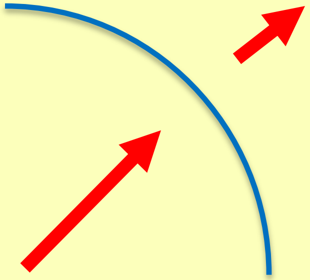


Supernova shock

(Also hot star winds)

Downstream particles
cool before escaping

PeV upstream particles?

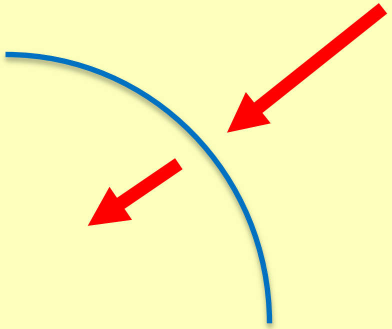


Termination shock

Magnetocentrifugal wind

Cosmic ray initiated

Sink of interstellar mass,
energy, angular momentum?



Cluster accretion shocks

r~ Mpc; u ~ 1000km/s

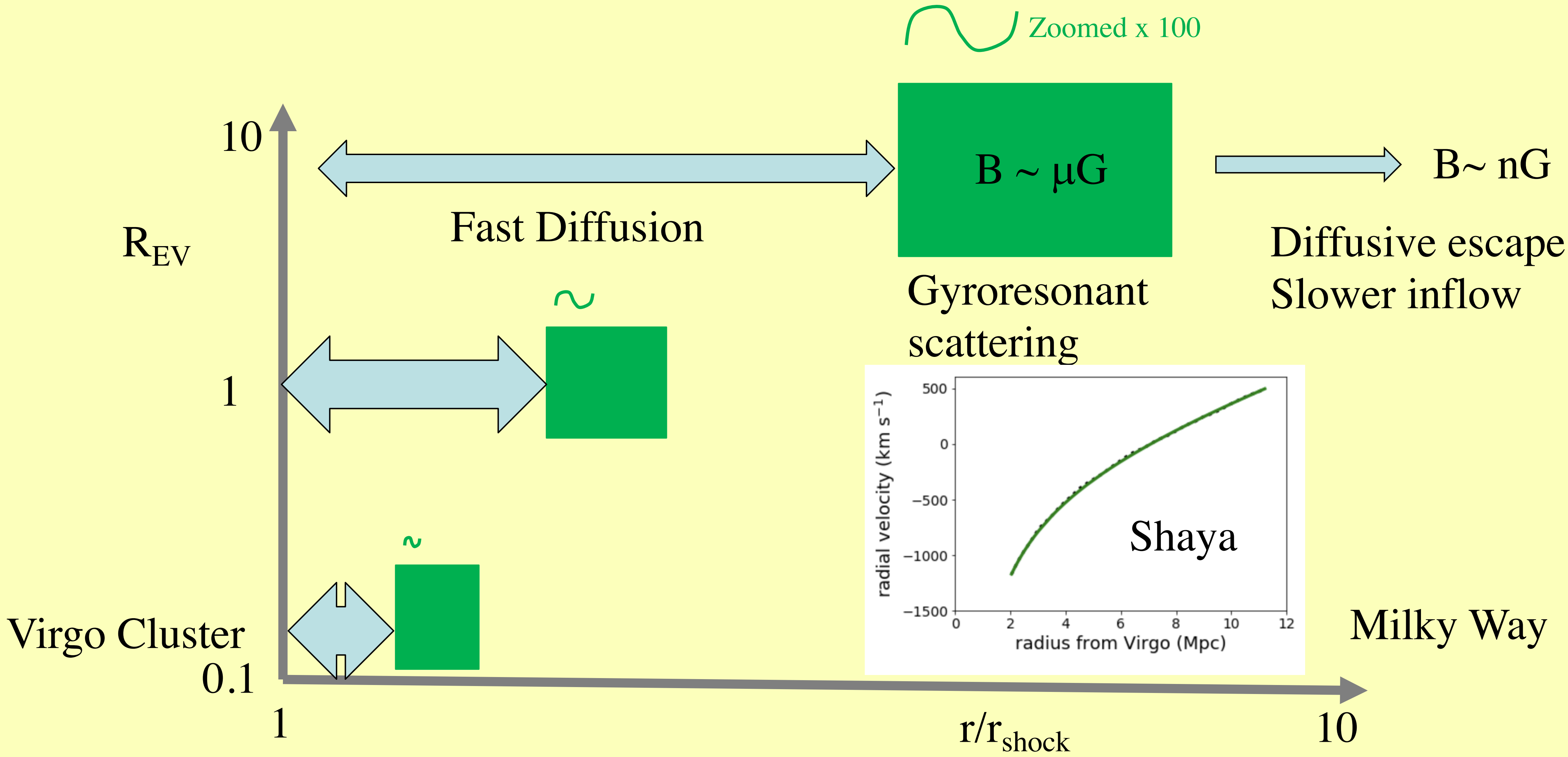
CR from termination shocks?

UHECR escape upstream

Bootstrap Hypothesis / Maximal Acceleration

- Highest rigidity, escaping CR create strong, gyro-resonant turbulence, with $D/u \sim r_{shock}$ ahead of subshock
- mfp ~ gyroradius; $D \sim Rc/3eB$
- Shorter wavelengths reflect lower rigidity particles closer to the subshock and weakly perturb higher energy particles
- Kinetic ~ electromagnetic ~ CR >> gas thermal energy fluxes
- Determines maximum rigidity accelerated by shock
- Gas remains cold until it passes through strong subshock
- Operates at SNR, GWTS, CAS with different geometries

Cluster Accretion Shocks



Energetics

- Conserved Energy
  - Kinetic Energy + Cosmic Rays + Poynting Flux
- Spherical Accretion (e.g. M87)
  - $r_{shock} \sim 2$ Mpc, $V_{shock} \sim 1000$ km s^{-1}, $\dot{M} \sim 1000\, M_{\odot} yr^{-1}$
  - $L_{gas} = \frac{1}{2} \dot{M}\, V^2_{shock} \sim 3 \times 10^{44}$ erg s^{-1}
  - L_{UHECR}(M87) ~ 6 x 10^{43} erg/s (propagation model - dependent)
  - Equipartition => $\frac{B^2}{4\pi} < \frac{L_{gas}}{4\pi V_{shock} r^2_{shock}}$,
  - $r_{L\,max} \sim \left(\frac{V_{shock}}{c}\right) r_{shock} \sim \frac{R_{max}}{eB}$

$\Longrightarrow R_{max} < (L_{gas} V_{shock})^{\frac{1}{2}} \sim 20$ EV, $B_{max} \sim 1\mu$G

cf relativistic accelerator

$R_{max} < (L_{EM} Z_0)^{1/2} \sim 20\, L^{1/2}_{EM\,43}$ EV

Hybrid Model

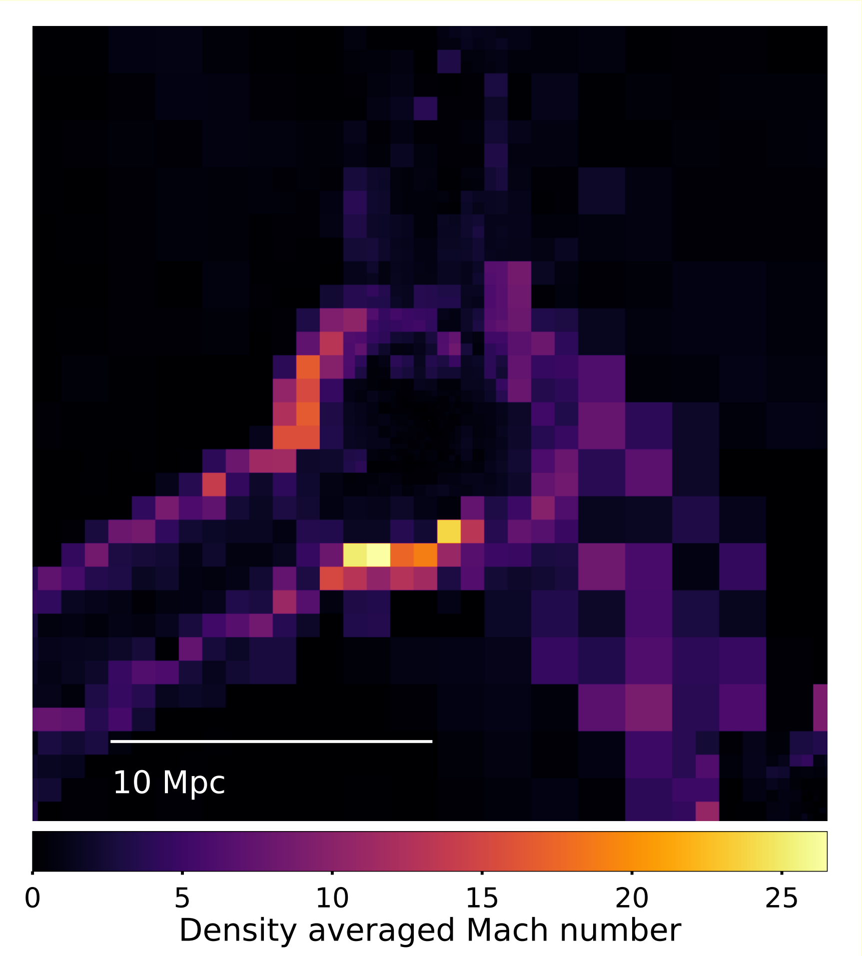
- Convection-diffusion model with strong magnetic turbulence
- Convert to diffusion equation $\nabla \cdot A(u,r)D(r,R)\nabla f = B(u,r)\,\partial_{lnR} f$
- Choose D(r,R), u(r,R)
- Solve for f(upstream, R), f(downstream, R) for R_{inject}
- Calculate associated cosmic ray and magnetic energy fluxes
- Iterate using generalized Bernoulli equation
- Explore time-dependence
- Take solution as initial condition for PIC simulation with enough dynamic range to investigate if Bohm turbulence is self-sustaining at kinetic level

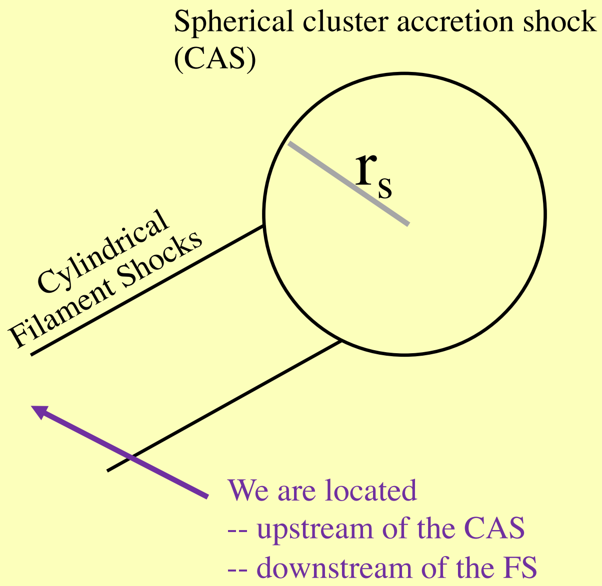
Confrontation with spectrum, composition, anisotropy

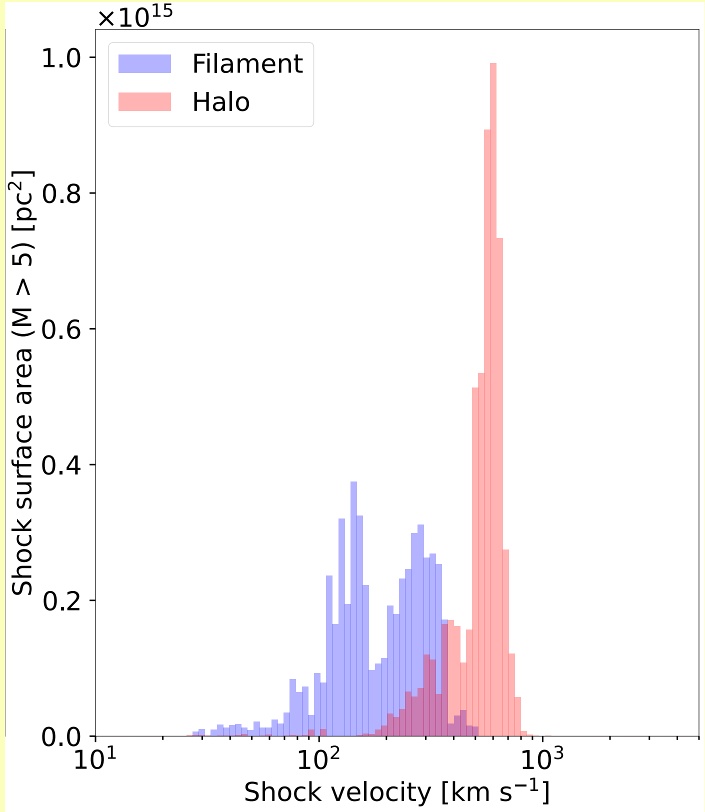
- Supernova Remnants etc, Termination shocks etc
  - Observations at earth
  - Astrophysical constraints
  - Intergalactic / infalling input spectrum
- Cluster shock acceleration mechanism
  - General principles
  - Input spectrum -> upstream output spectrum
- Filamentary contribution at lower rigidity
  - Downstream spectrum

Vulnerable to highest rigidity cosmic rays
Less vulnerable to power requirements

Clusters and Filaments







Are we in a filament?
Can we find these shocks at radio wavelengths?

- **Cluster "Halo" component**: hard spectrum (escaping CRs), R_{max} ~ 7 EV
- **Filament component**: softer spectrum (downstream of the shock) R_{max} ~1 EV

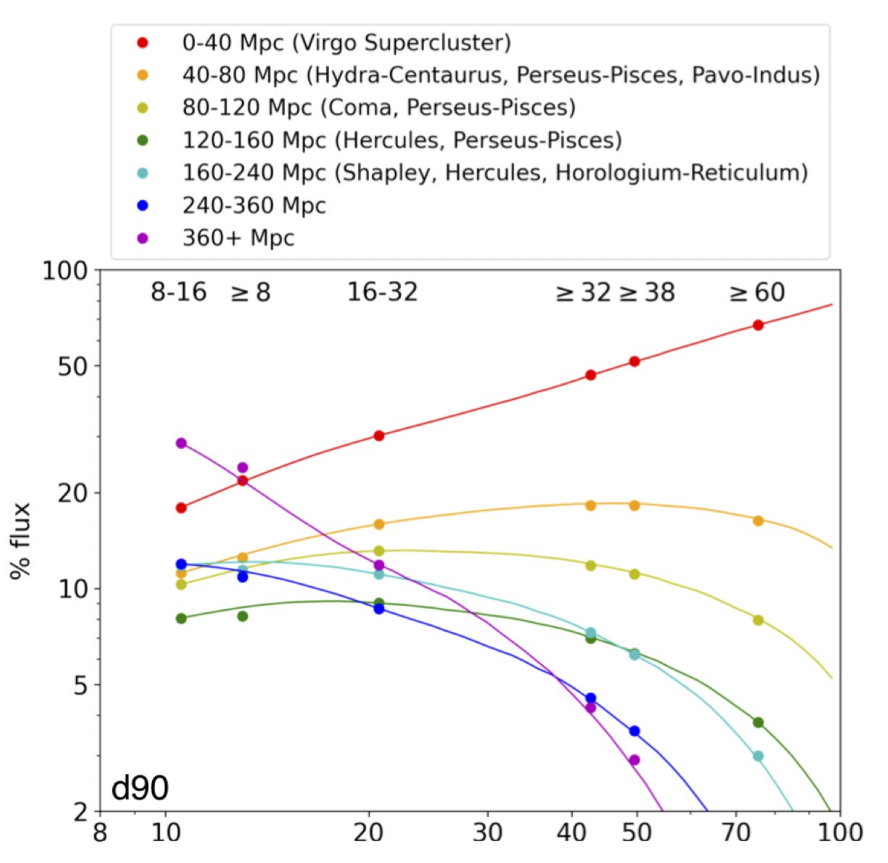
Cluster Downstream Flow

- If cluster shocks are UHECR accelerators, they will be full of lower energy cosmic rays which can emit radio synchrotron radiation in μG magnetic field and gamma rays
- Density increases from ~10^{-6} cm^{-3} to ~10^{-3} cm^{-3}
- Cosmic rays lose 90% of energy relative to gas
- Observational constraint

Summary

- Hierarchical Model, SNR -> GWTS ->CAS
- Maximal diffusive shock acceleration at all levels
- Shock geometry important
- Phenomenological model -> PIC plasma codes
- Confront with improving measurements at highest rigidity
- Astrophysical constraints/implications

Supplementary Slide



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