Cosmic rays, Gamma rays and Galactic Neutrino Astronomy

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Some very basic points....

- We know that cosmic rays of Galactic origin exist with energies from below 1GeV up to about 3×10^{17} eV (and extragalactic above this!).
- We know that HE hadronic interactions produce lots of HE pions.
- We know that the charged HE pions produce HE neutrinos on decay.
- Therefore there is a HE Neutrino Astronomy to be developed - the signal is there!

Second set of basic facts...

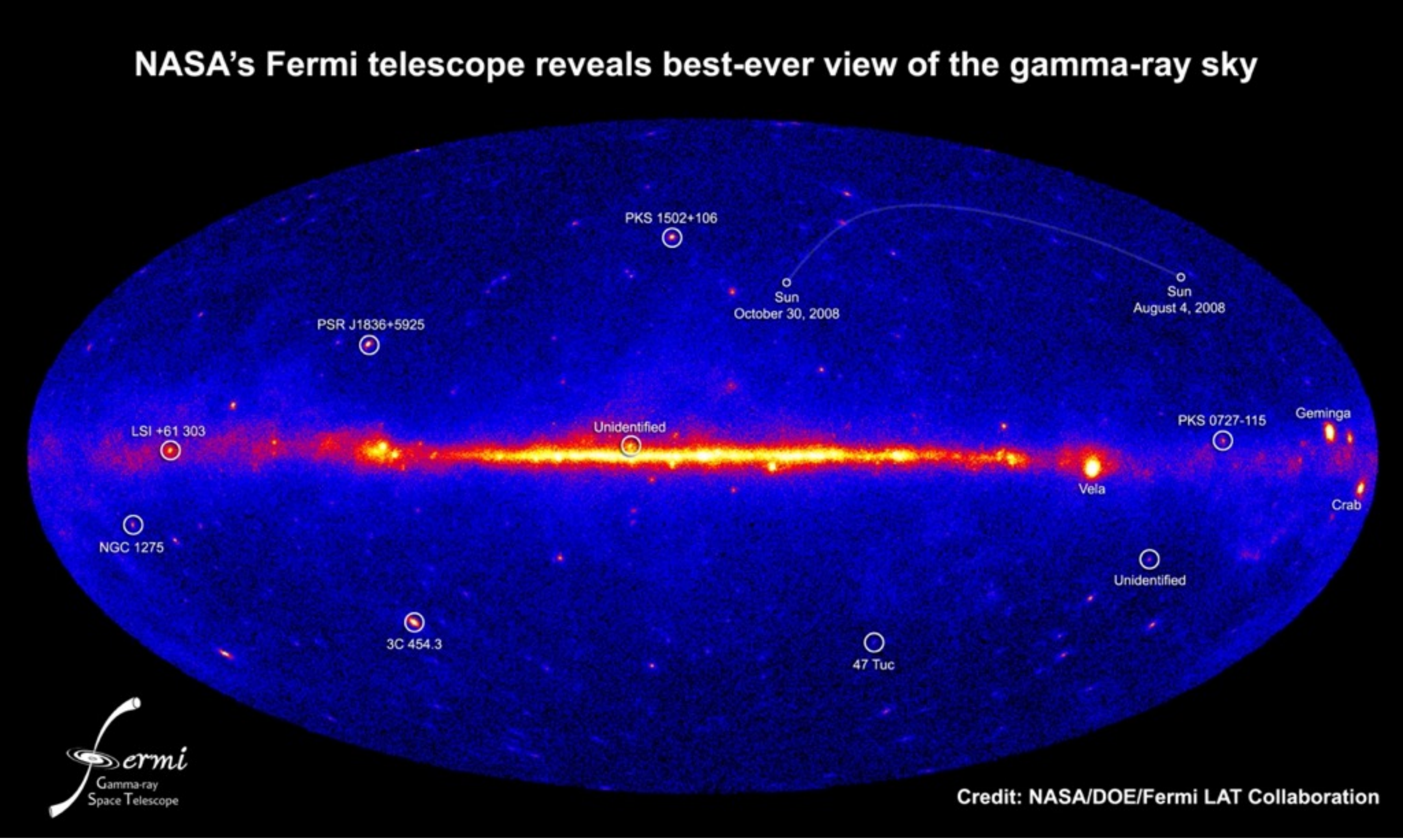
- The hadronic channel is the only way to make high-energy neutrinos.
- Expect roughly equal numbers of positive negative and neutral pions to be produced.
- The neutral pions produce gamma-rays on decay.
- Therefore all neutrino sources are high-energy gamma-ray sources and the neutrino flux can be related to the gamma-ray flux rather simply through very well understood particle physics.

- But unlike neutrinos HE gamma-rays can also be made by electronic channels.
- Surprisingly hard to disentangle the relative contributions of IC, Pion decay and Bremstrahlung to the observed gamma-rays.
- Great virtue of neutrino astronomy is that it is (or will be) completely insensitive to electrons! This is the USP for HE Neutrino astronomy - absolute identification of cosmic hadron accelerators!

So Galactic Neutrino Astrophysics comes down to two key issues

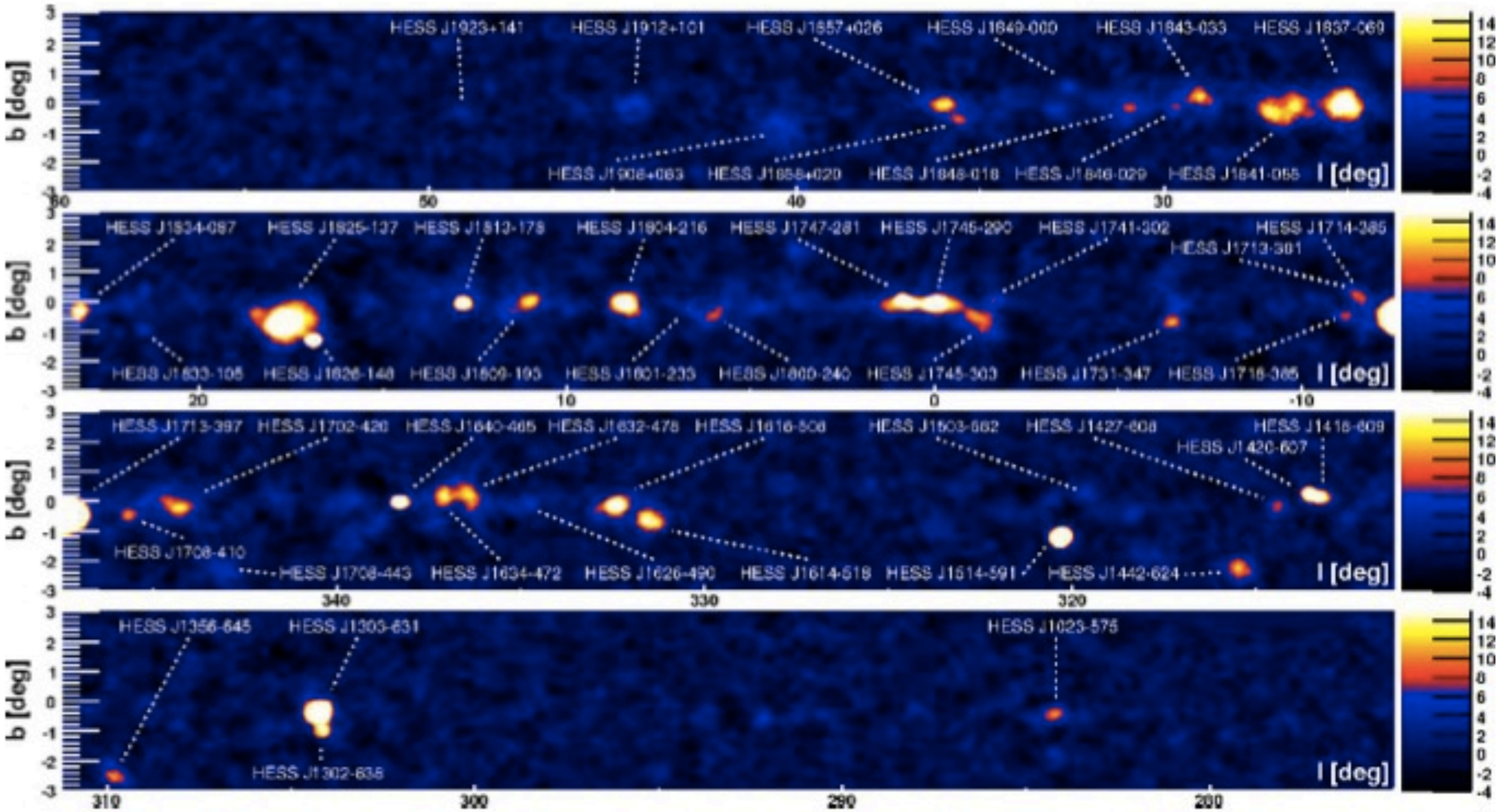
- Distribution of HE cosmic-rays and interaction targets in the Galaxy, and related to this....
- Production sites and mechanisms for cosmic ray origin.

To get `point-like' sources need either localised high-density targets, or localised powerful sources, or ideally both.



The GeV gamma-ray sky

Dominated by diffuse emission from Galactic plane



HESS galactic plane survey -100GeV or so

NB background subtraction removes diffuse features!

ArXiV:0907.0768v1

Shock acceleration in SNR's has now the status of a "standard model" for the origin of the GCRs....

- Compelling body of theory in DSA
- Strong, if still largely circumstantial, observational evidence
- No plausible alternative (not a good argument!)
- But still no direct and unambiguous observation of shock precursors....
- Also worrying divergence between propagators and accelerators on optimal parameters.....

But no show-stopper!

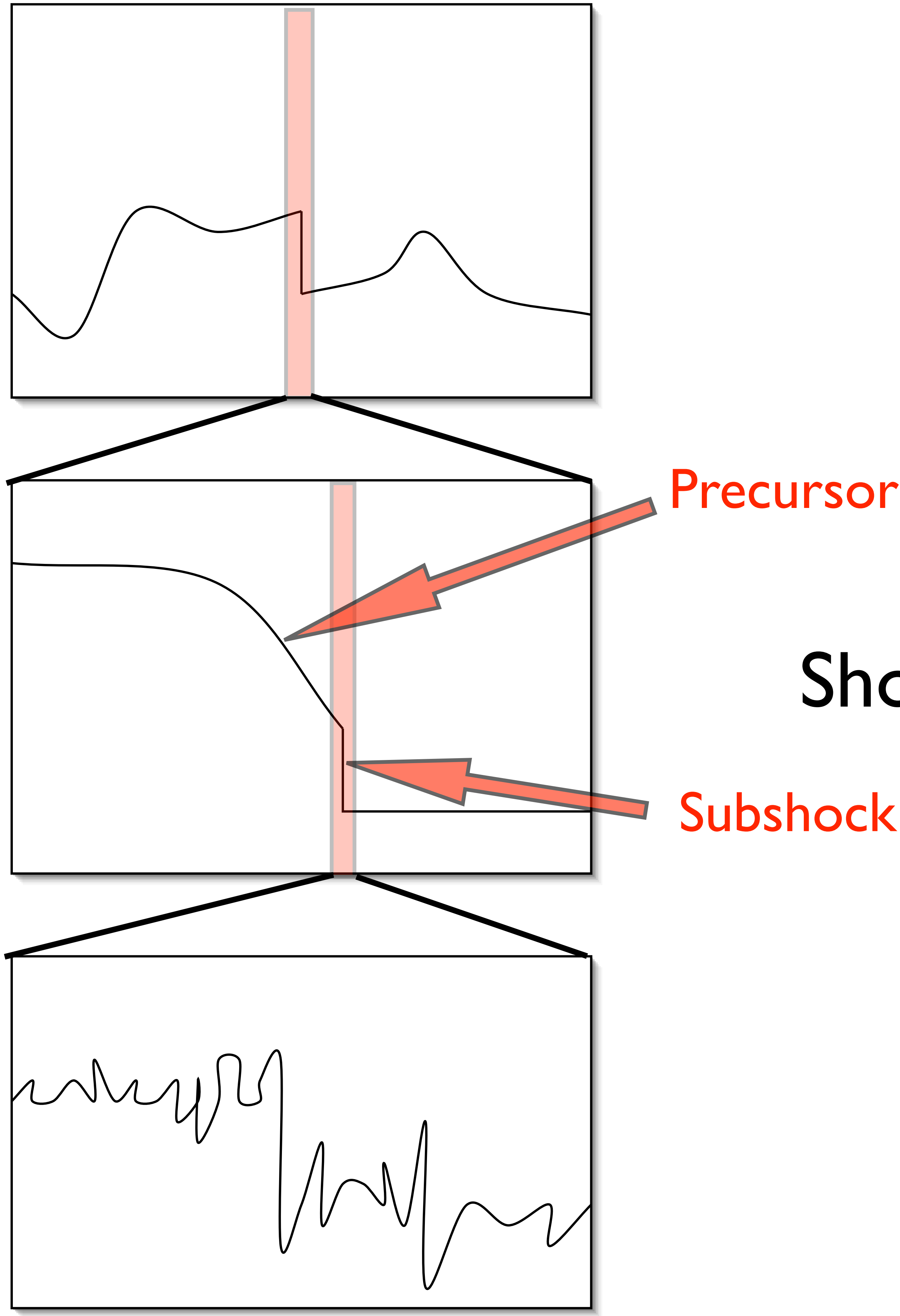
Three essential components

- Initial "injection" of particles - mainly a question for collisionless shock physics and simulations.
- Further Fermi acceleration in nonlinear regime from suprathermal energies to ultra-relativistic.
- Escape from the accelerator into the ISM as Galactic cosmic rays - source for propagation codes and neutrino production models.

Will discuss only the last two points

A short aside

- To talk of SNR origin is slightly misleading
  - ALL sufficiently strong shocks in the ISM should contribute to CR production
  - Of course these are dominated by SNR forward shocks (note low power in reverse shocks!).
  - However there are other shock drivers, OB association winds, high velocity cloud impacts etc...



Outer scale:
Astrophysics

Intermediate scales:
Shock acceleration theory

Inner scale:
Plasma physics
Injection!

Very wide scale separation - numerical nightmare, but useful for analytic approaches. Can distinguish two extreme scales..

Outer scale of macroscopic system and maximum energies.

Inner scale of injection processes and kinetic effects

Aim of (semi-)analytic theory is to bridge the gap between these two regimes (mesoscopic theory), but not to try to be a complete theory. Useful analogy to inertial range theories of turbulence.

Shock modification

- Extended upstream precursor + subshock structure
- Increased total compression due to
  - softer equation of state
  - additional energy flux to high energy particles (escape, geometrical dilution, diffusion)

Aside on compression in a strong shock....

$$\begin{aligned} \rho_1 U_1 &= \rho_2 U_2 = A \\ A U_1 &= A U_2 + P_2 \\ \frac{1}{2} A U_1^2 &= \frac{1}{2} A U_2^2 + U_2(\mathcal{E}_2 + P_2) + \Phi \end{aligned}$$

$$\Longrightarrow \frac{U_1}{U_2} = 1 + \frac{2\mathcal{E}_2}{P_2} + \frac{2\Phi}{U_2 P_2}$$

$\frac{2\mathcal{E}_2}{P_2}$: $> 3, < 6$

$\frac{2\Phi}{U_2 P_2}$: > 0

Typically see compression rations of 10 and more in simulations

- Spectrum at low energies given by test-particle theory applied to the sub-shock, thus softer.
- Spectrum at high energies should reflect much increased compression of total shock structure, thus harder.
- Concave spectrum - no longer perfect power-law.

Semi-analytic approach to steady mesoscopic structure

Can (hopefully) assume steady planar structure with fixed mass and momentum fluxes.

$$\begin{aligned} \rho U &= A \\ AU + P_G + P_C &= B \end{aligned}$$

and we still have the steady balance between acceleration and loss downstream...

$$\frac{\partial \Phi}{\partial p} = -4\pi p^2 f_0(p) U_2$$

.. but the problem is that the acceleration flux now depends on the upstream velocity profile ***and*** the particle distribution.

However, if one makes an *Ansatz*

$$f_0(p) \to f(x,p)$$

the particle conservation equation and the momentum balance equations, become two coupled equations (in general integro-differential) for the two unknown functions.

$$U(x), \quad f_0(p)$$

An obvious *Ansatz* would be to assume a distribution similar to that familiar from the test-particle theory,

$$f(x,p) = f_0(p)\exp\int\frac{U(x)\,dx}{\kappa(x,p)}$$

This is actually close to Malkov's *Ansatz* who, however, uses

$$f(x,p) = f_0(p)\exp\int\left(-\frac{1}{3}\frac{\partial\ln f_0}{\partial\ln p}\right)\frac{U(x)\,dx}{\kappa(x,p)}$$

which he claims is better for strongly modified shocks.

Conclusions I

- Good agreement between semi-analytic treatments, MC studies and direct finite difference approach to shock modification.
- Key weakness is assumption of steady structure - in reality many instabilities.
- Instabilities have great advantage though in allowing Magnetic field amplification.
- Turbulence, reconnection in the precursor and wave dissipation are major complicating factors, but hopefully do not change basic physics which is quite robust.

Importance of field amplification

- Maximum rigidity to which particles are accelerated is of order $BR\dot{R}$
- In Sedov phase $R\dot{R} \propto t^{-1/5}$
- Hard to get more than about $10^{14}\,\mathrm{V}$ (Lagage and Cesarsky limit) if field is only $B \approx 3\,\mu\mathrm{G}$ and normal SNR parameters used.
- To get to the \`ankle' and \`knee' need field amplification.
- Falling maximum rigidity then means that \`escape' is important.

Now focus on transfer of GCRs from the accelerator into the Galaxy - the escape from the accelerator.

- Based on arXiv:1009.4799
- Important question:
  - In its own right - what is the effective source function for propagation codes such as Galprop?
  - But also for illumination of molecular clouds and resulting gamma-ray and neutrino production (Gabici et al).
- Has acquired new significance because of general acceptance of magnetic field amplification.

Escape is not as easy as one might think...

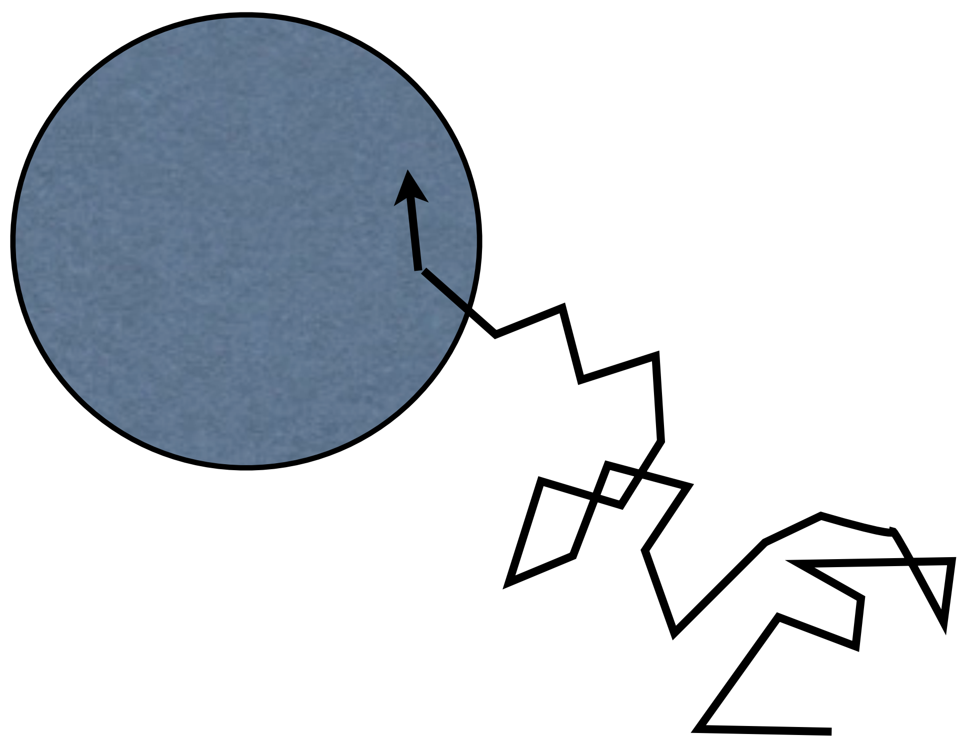
- In one dimension, and in the simple standard theory of shock acceleration, there is no escape; accelerated particles accumulate behind the shock and there is no flux to upstream infinity.
  - A plane front moving at constant speed will always overtake a randomly walking particle, and even if the plane is stationary the particle will always return and cross it infinitely many times.

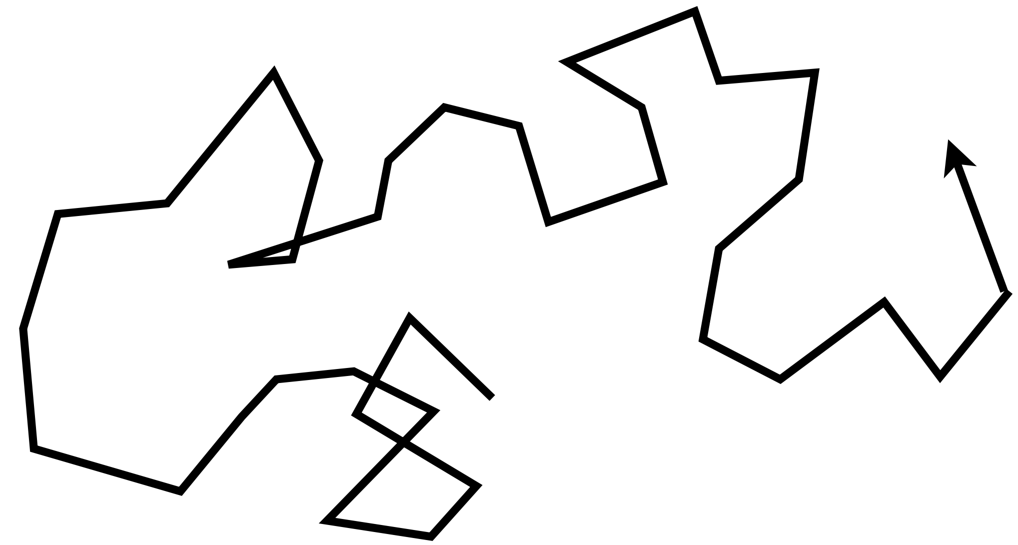
$\Delta \propto t$ Uniform motion

$\Delta \propto t^{0.5}$ Random walk

- But of course much too simple a picture:
  - SNR shocks are spherical and not plane;
  - decelerating and not moving at constant speed;
  - and the upstream scattering is non-uniform and depends on magnetic field strength, ion-neutral damping etc and may even vanish in some regions.

Escape is possible, even with uniform scattering, in more than two dimensions.





But so is return....

$$\Delta \propto t^{0.4}$$

Sedov expansion

$$\Delta \propto t^{0.5}$$

Random walk

Easy to show that a uniformly diffusing particle released at distance R_1 from the origin will enter a sphere of radius R_0 centred on the origin with probability

$$P_{\mathrm{return}} = \frac{R_0}{R_1}$$

and escape to infinity with probability

$$P_{\mathrm{escape}} = 1 - \frac{R_0}{R_1}$$

Thus even at 10 shock radii there is still a 10% chance of returning to the shock!

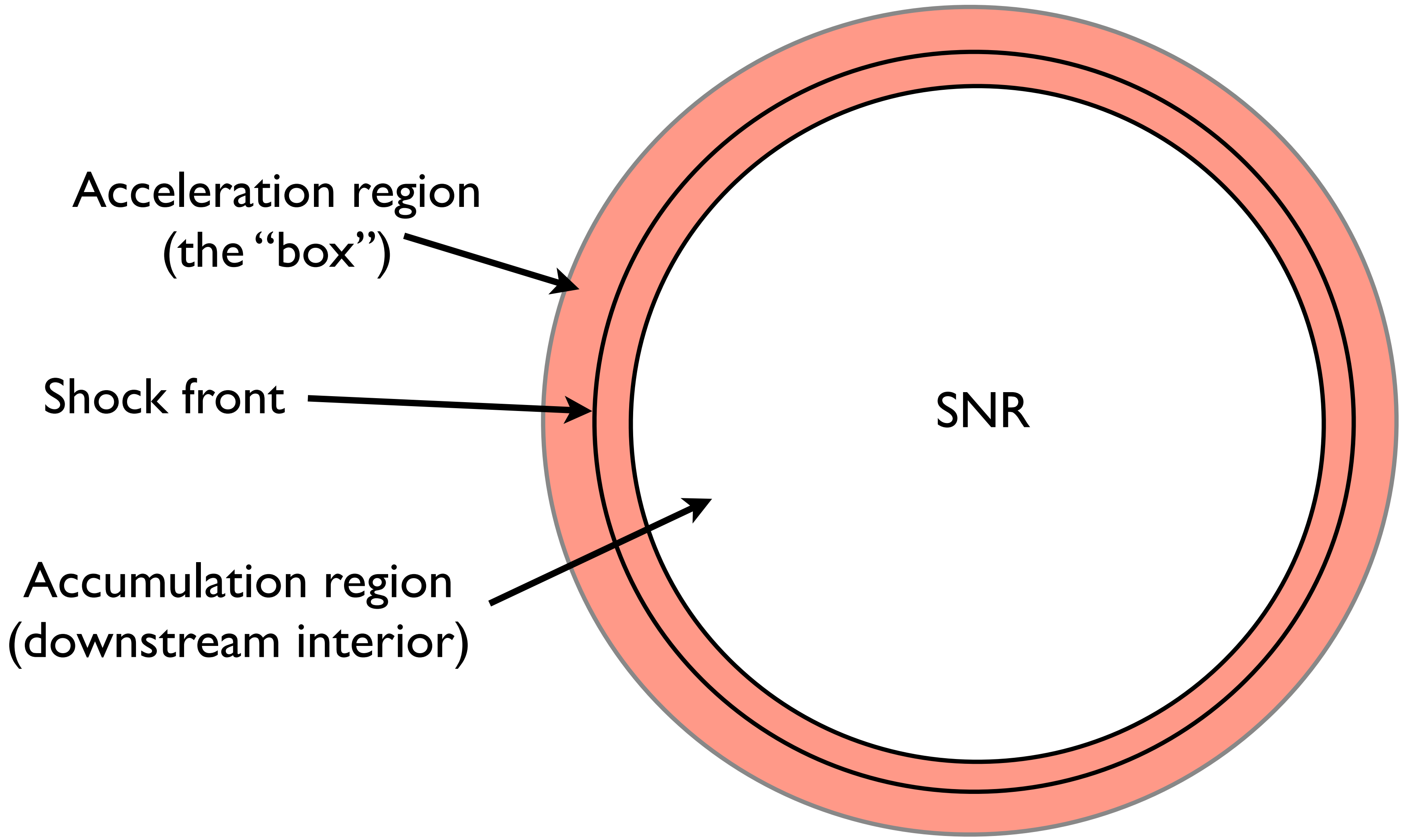
- Of course assumes uniform and isotropic diffusion in 3D which is over-simplified
    - Reduced scattering away from the shock will increase the escape rate....
    - But confinement to a field line leading to quasi one-dimensional transport will reduce it....
- Essential point is that particles do not suddenly escape and that even at quite large radii there can be particles that are still interacting with the shock.

But even though they are still in some sense interacting with the shock it is clear that these particles are not really being accelerated either - they form a sort of halo of old "fossil" particles surrounding the SNR.

This is at high energies; at low energies the simple picture is correct and accelerated particles accumulate behind the shock (in the interior of the SNR) until it dies. Adiabatic losses to PdV work go into driving the shock and get "recycled" into fresh particles, so low energy part of the spectrum is always dominated by freshly injected and accelerated particles

⇒ Possible energy-dependent composition

Picture can be clarified with toy "box" model



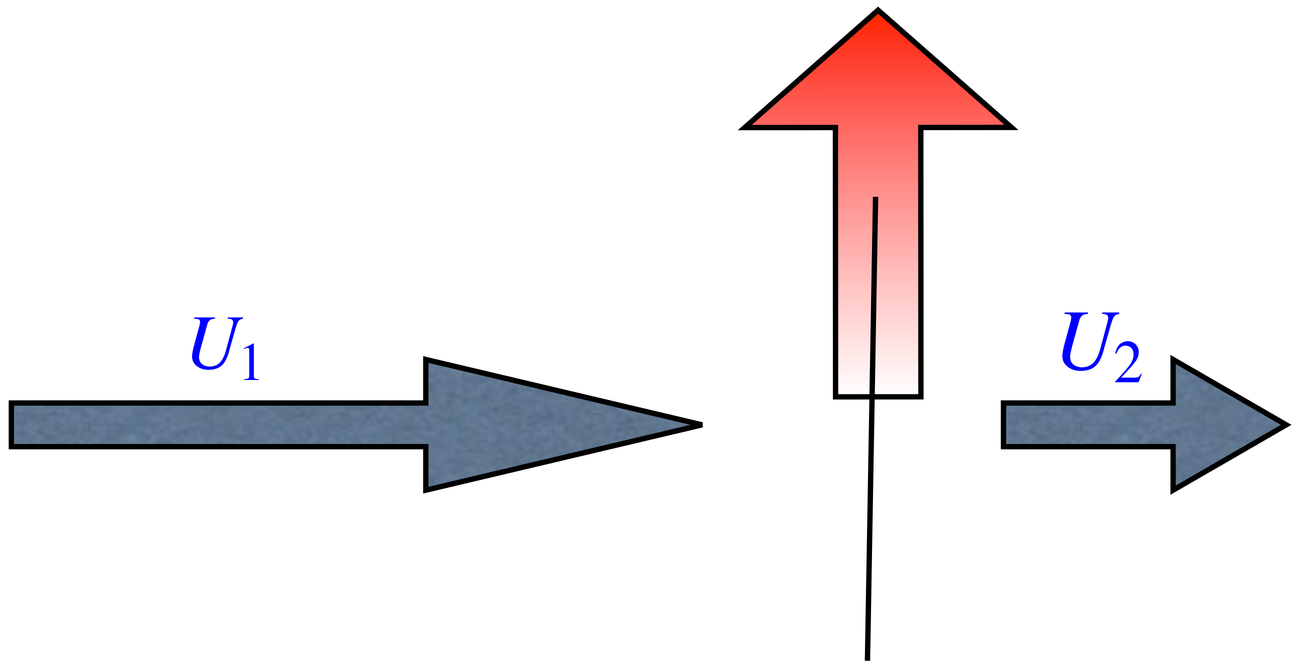
$$A = 4\pi R^2$$

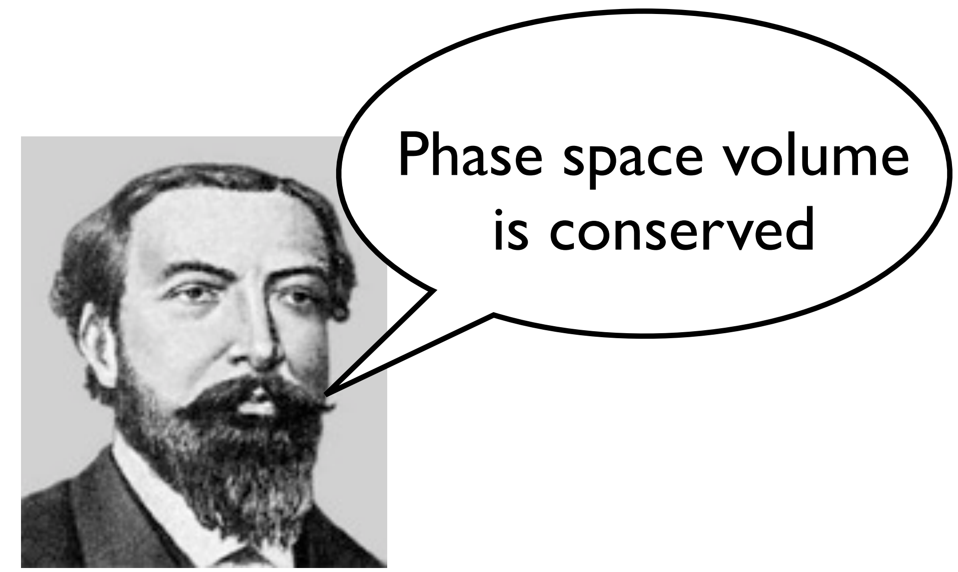
$$L_{1,2} \approx \frac{\kappa_{1,2}}{U_{1,2}}$$

$$\frac{\partial}{\partial t}\left[A(L_1 + L_2) 4\pi p^2 f(p)\right] + A\frac{\partial \Phi}{\partial p} = AQ(p)$$
$$+ AF_1(p) - AF_2(p)$$

Acceleration flux at shock is given by

$$\Phi(p) = \frac{4\pi}{3} p^3 f(p) \left(U_1 - U_2\right)$$





Standard box model except that box is spherical and expanding with volume

$$\approx A(L_1 + L_2)$$

Gives equation for spectrum at shock

$$\frac{1}{A}\frac{\partial A}{\partial t}\left(L_1+L_2\right)f+\frac{\partial L_1}{\partial t}f+\left(L_1+L_2\right)\frac{\partial f}{\partial t}+U_1 f \\ +\left(U_1-U_2\right)\frac{p}{3}\frac{\partial f}{\partial p}=\frac{Q}{4\pi p^2}.$$

which can be reduced to 2 ODEs and integrated by the method of characteristics!

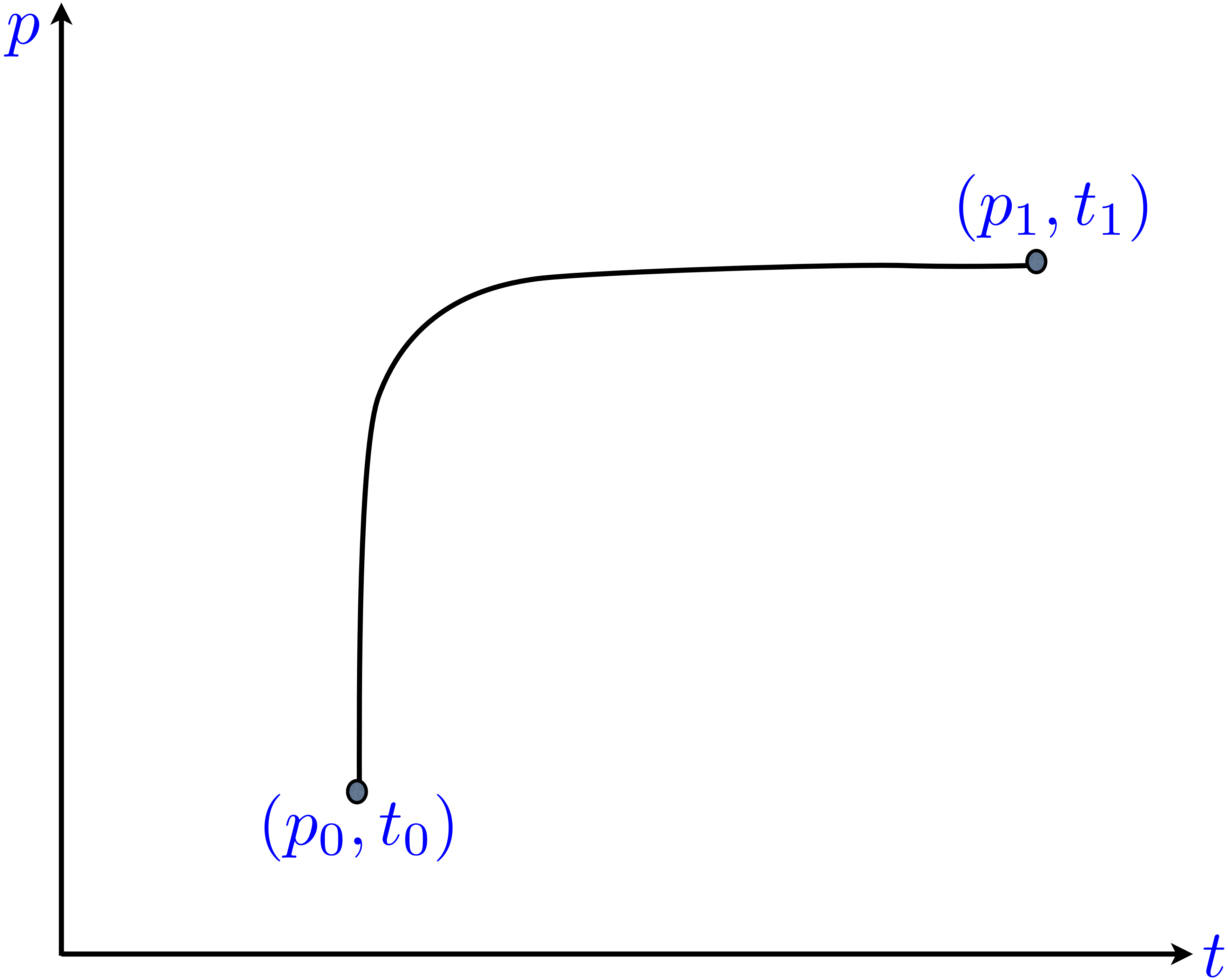
Note no upstream escape in this toy model - only an expanding upstream region.

$$\frac{\mathrm{d}\,p}{\mathrm{d}\,t} = \frac{U_1 - U_2}{L_1 + L_2}\frac{p}{3}$$

Particle acceleration tracks

$$(L_1 + L_2)\frac{\mathrm{d}\,f}{\mathrm{d}\,t} \quad + \quad f\left[(L_1 + L_2)\frac{1}{A}\frac{\partial A}{\partial t} + \frac{\partial L_1}{\partial t} + U_1\right] \quad = \quad \frac{Q}{4\pi p^2}.$$

Variation of spectrum along this track



p
(p_1, t_1)
(p_0, t_0)
t

If Bohm scaling $L = \frac{\kappa}{U} \propto \frac{1}{UB}$,

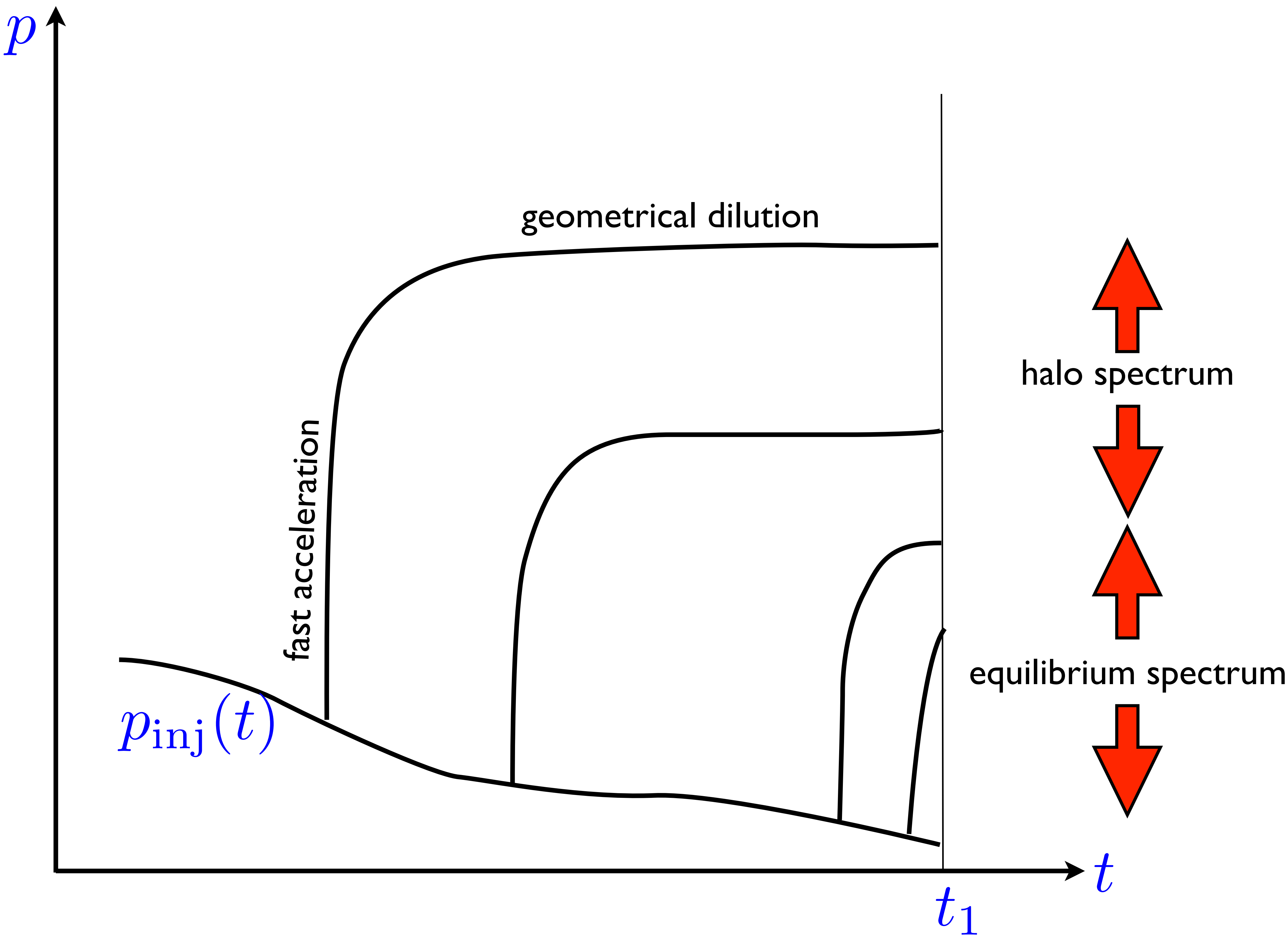
can integrate to get:

$$\frac{f(t_1, p_1)}{f(t_0, p_0)} = \left(\frac{A(t_1)}{A(t_0)}\right)^{-1} \left(\frac{U_1(t_1)B_1(t_1)}{U_1(t_0)B_1(t_0)}\right)^{\vartheta} \left(\frac{p_1}{p_0}\right)^{-s}$$

$$s = \frac{3U_1}{U_1 - U_2} \qquad \vartheta = \frac{L_1}{L_1 + L_2}$$

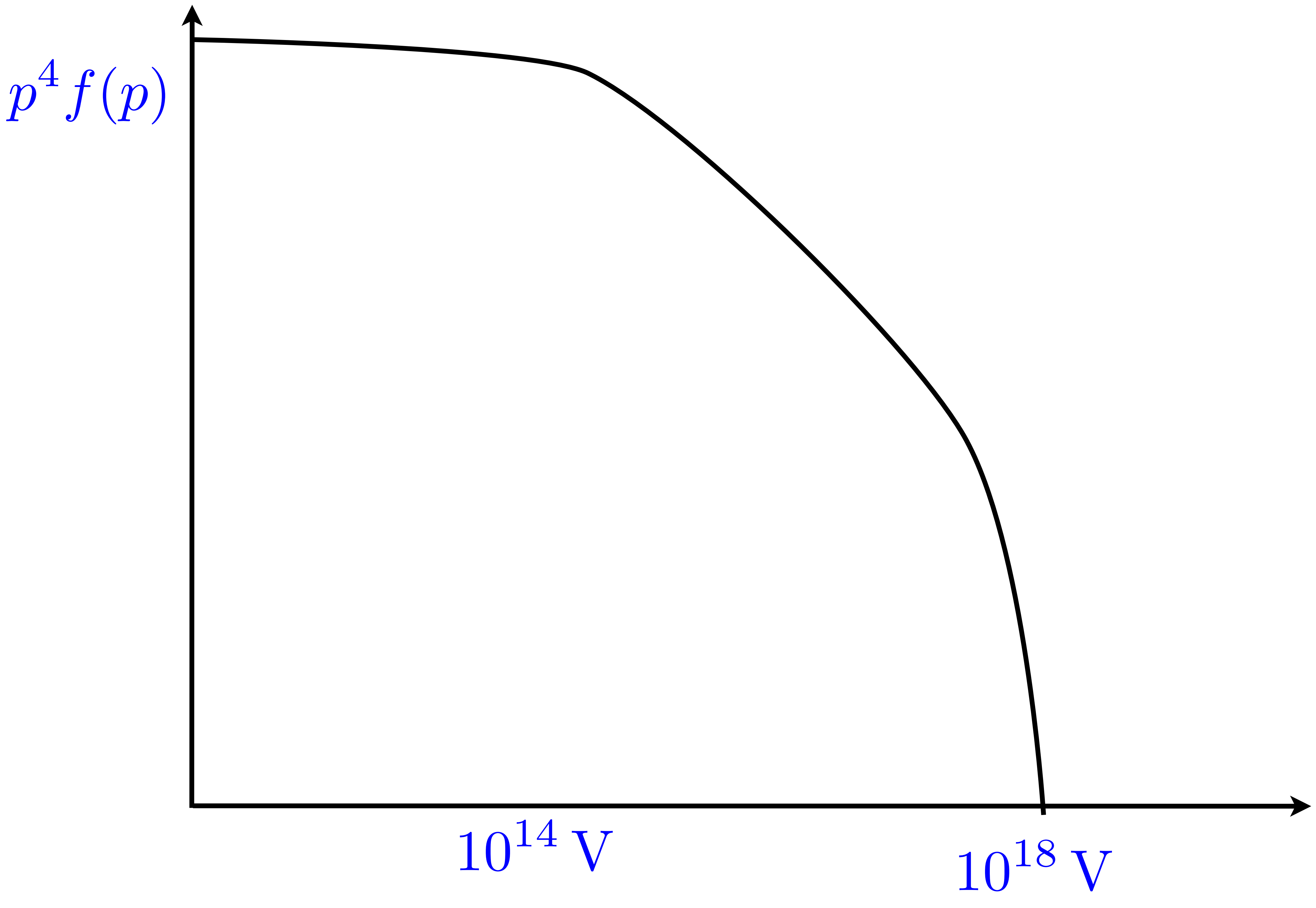
Inject at time t_0 and momentum p_0

Accelerate to momentum p_1 at time t_1

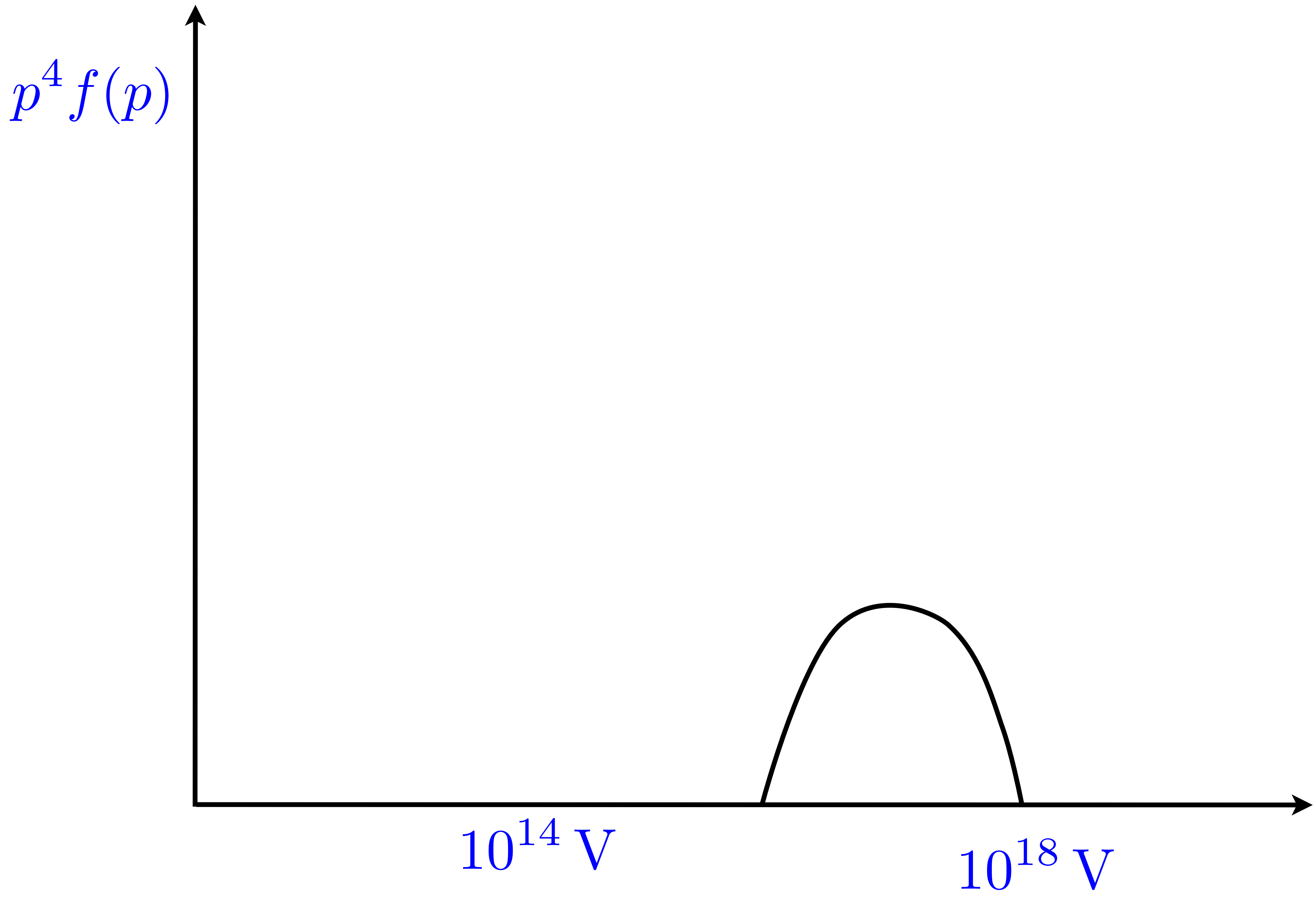


p
geometrical dilution
fast acceleration
halo spectrum
equilibrium spectrum
$p_{\rm inj}(t)$
t_1
t

Sketch of spectrum at the shock



Sketch of spectrum upstream in halo



- Equilibrium part of spectrum is just normal shock acceleration power-law
- Halo part reflects acceleration, but also
  - geometrical dilution
  - injection history
- Halo particles form the “escaping” population from the SNR at high energies (PeV and above).

- If one assumes:
  - Sedov-Taylor expansion law $R \propto t^{2/5}$
  - Bohm scaling $\kappa \propto 1/B$
  - Amplified magnetic field $B \propto U^{\mu}$
  - Injection model (in near future from PIC?)
- Can analytically estimate changes to halo spectrum, but should not be taken too seriously.

- Full details, see preprint on arXiv:1009.4799

- More interesting is the source for propagation calculations (what should we put into Galprop?).

- Have to distinguish those particles which have decoupled from the acceleration (the "halo" population) from those still in equilibrium - the transition occurs at a critical momentum p_* where the acceleration time-scale is equal to the dynamical time-scale.

- If we have field amplification, the critical momentum can be quite a strongly decreasing function of time (in contrast it is almost constant with no amplification and Sedov scaling).
- The flux of particles into the "halo" population has two components
  - The acceleration flux localised at the shock which exists even if p_* is constant.
  - A distributed component of particles left behind as p_* falls.

$$
\begin{aligned}
Q_1 &= \frac{4\pi p_*^3}{3} f(p_*)(U_1 - U_2) 4\pi R^2 \\
Q_2 &\approx -4\pi p_*^2 f(p_*) \dot{p}_* \frac{4\pi R^3}{3}
\end{aligned}
$$

Ratio is basically time-scale ratio

$$
\frac{Q_1}{Q_2} = \left(\frac{-p_*}{\dot{p}_*}\right)\left(\frac{U_1 - U_2}{R}\right)
$$

and thus of order unity if field amplification holds

Source spectrum for propagation codes is just

$$S(p_*)(-dp_*) = (Q_1 + Q_2)dt = -\frac{Q_1 + Q_2}{\dot{p}_*}$$

and thus if the ratio of the two production terms is approximately constant,

$$S(p_*) \propto -\frac{Q_2}{\dot{p}_*} \propto p_*^2 f(p_*) R^3$$

See arxiv:1009.4799 for further details.....

Interesting case is self-regulated non-linear injection where it can be shown that the source spectrum is essentially the same as the local spectrum at the shock with energy equi-distributed across the spectrum.

If you put a fixed amount of energy into the accelerated particles, and you spread it more or less uniformly through the spectrum (equal amounts per log interval) then it does not matter, at least to lowest order, exactly when the particles decouple from the accelerator!!

See also Caprioli, Amato and Blasi 2010 who reach the same conclusion.

Conclusions II

- High-energy particles leak out of DSA into an extended upstream region throughout the evolution of a SNR (and eventually escape).
- Low-energy particles are trapped and recycled in the SNR until it dies and are then released.
- This should have compositional consequences which may have been observed.
- HE neutrino and gamma production in clouds near SNRs favoured

- The high-energy end of the spectrum should reflect not just shock acceleration (giving the dominant power-law form) but modifications related to geometrical dilution, injection history and the time-evolution of the shock power.

- If full equilibrium is reached between the acceleration and the dynamics the source spectrum is only weakly dependent on exactly when the particles decouple.

- Downturn beyond the "knee" probably points to acceleration in early phase while shock is very fast but not at full power (ie before sweep-up time).

- Instantaneous cut-off in remnant (and thus relevant for gamma ray and neutrino observations) can be lower than the "knee" region even though the total source for the remnant extends up to the "knee" region without a break.

- In this case the missing PeV particles should form a halo population around the remnant which may be detectable by interacting with molecular clouds.

HESS observations

- 5 shell-type SNRs with TeV emission, but no Pevatrons so far!
- But also 4 cases of what look like illuminated molecular clouds near SNRs!
- Supporting evidence from Fermi...
- Looks promising.....

Candidate HE Neutrino sources in the Galaxy

- SNRs - possible, but interpretation is complex
- SNRs with nearby MCs - look promising
- The entire Galactic plane (very diffuse)
- Fermi bubbles - exciting, but a bit speculative
- Surprises? Unlikely but who knows....