Origin of the most energetic particles in the Universe

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Lecture 3

1. Non-relativistic accelerators
   - Clasters of galaxies
   - Giant radio lobes
   - Accretion discs

2. Relativistic accelerators
   - changes in diffusive acceleration
   - converter acceleration

Summary of Lecture 2

- Several object types meet fundamental criteria for proton acceleration up to 10^{20} eV and even more so for iron nuclei
- Considering more realistic (actually model-dependent) limitations may result in substantially lower energy limit for Cosmic Rays

Perseus galaxy cluster (Abell 426)

X-ray image by Chandra (2014)

Accretion shocks in clusters of galaxies

- size $R \sim 1$ Mpc
- upstream velocity (= free-fall velocity) $V_{\rm sh} \sim 1000$ km/s
- acceleration efficiency is $\eta = V_{\rm sh}^2/c^2 \sim 10^{-5}$
- equipartition magnetic field $B_{\rm eq} = \sqrt{4\pi\rho V_{\rm sh}^2} \sim 15\,\mu$G

  assuming number density $n \sim 10^{-3}$ cm^{-3}

Acceleration in clusters of galaxies

Escape-limited acceleration (substitute $R \sim 1$ Mpc and $\eta \sim 10^{-5}$)

$$E_{\rm max} = \sqrt{\eta} qBR \sim Z \left(\frac{B}{1\,\mu\text{G}}\right) \times 3 \cdot 10^{18}\ \text{eV}$$

acceleration to 10^{20} eV

- protons require $B \gtrsim 30\,\mu$G
- iron nuclei require $B \gtrsim 1\,\mu$G

protons are at tension with equipartition magnetic field estimate ($\sim 15\,\mu$G)

iron nuclei can be accelerated to 10^{21} eV (optimistic estimate)

Acceleration in clusters of galaxies

Loss-limited acceleration (substitute $\eta \sim 10^{-5}$)

$$E_{\rm max} = \eta q B D_{\rm att} \sim Z \left(\frac{B}{1\,\mu\text{G}}\right)\left(\frac{D_{\rm att}}{100\ \text{Mpc}}\right) \times 10^{18}\ \text{eV}$$

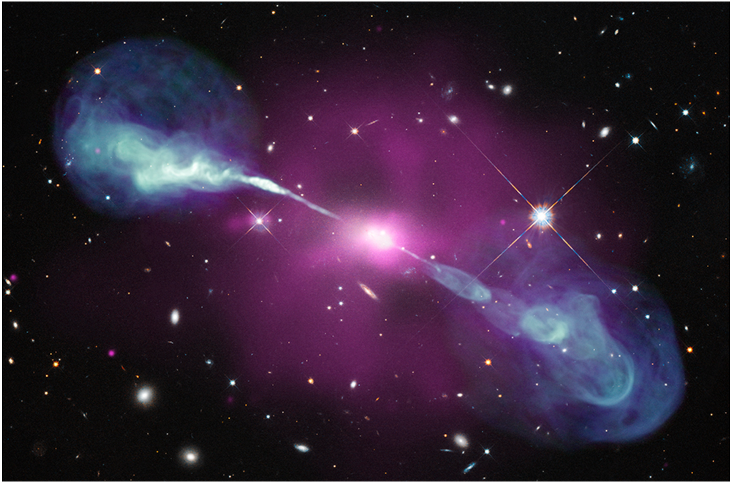
acceleration to 10^{20} eV

- protons ($D_{\rm att} \sim 100$ Mpc) require $B \gtrsim 100\,\mu$G
- iron nuclei ($D_{\rm att} \sim 700$ Mpc) require $B \gtrsim 0.6\,\mu$G

protons are at tension with equipartition magnetic field estimate ($\sim 15\,\mu$G)

iron nuclei can be accelerated to 2×10^{21} eV (optimistic estimate)

Hercules A radiogalaxy (3C 348)



radio (blue)	NSF/NRAO/VLA
optical (true color)	NASA/STScI
X-ray (purple)	NASA/CXC/SAO

Giant radio lobes

- size $R \sim 100$ kpc
- power supply by the AGN jet at the rate $P_{\rm jet} \sim 10^{45}$ erg/s over $t_{\rm jet} \sim 100$ Myr
- accumulated energy $W_{\rm lobe} = P_{\rm jet}\, t_{\rm jet} \sim 3 \times 10^{60}$ erg
  corresponds to energy density $w_{\rm lobe} = \dfrac{3W_{\rm lobe}}{4\pi R^3} \sim 3 \times 10^{-11}$ erg/cm^3
  and magnetic field estimate (equipartition) $B_{\rm eq} \sim 25\,\mu$G
- expansion into surrounding gas with number density $n \sim 10^{-3}$ cm^{-3}
- shock velocity calculated from energy balance $m_p n \dfrac{V_{\rm sh}^2}{2} = w_{\rm lobe}$
  $\Rightarrow$ $V_{\rm sh} \sim 2000$ km/s
- acceleration efficiency is $\eta = V_{\rm sh}^2/c^2 \sim 4 \times 10^{-5}$

Acceleration in giant radio lobes

Escape-limited acceleration (take $R \sim 100$ kpc and $\eta \sim 4 \times 10^{-5}$)

$$E_{\max} = \sqrt{\eta} qBR \sim Z \left(\frac{B}{1\,\mu\mathrm{G}}\right) \times 6 \cdot 10^{17}\ \mathrm{eV}$$

acceleration to 10^{20} eV

- protons require $B \gtrsim 170\,\mu\mathrm{G}$
- iron nuclei require $B \gtrsim 6\,\mu\mathrm{G}$

protons are at tension with equipartition magnetic field estimate ($\sim 25\,\mu\mathrm{G}$)

iron nuclei can be accelerated to 4×10^{20} eV (optimistic estimate)

Acceleration in giant radio lobes

Loss-limited acceleration (substitute $\eta \sim 4 \times 10^{-5}$)

$$E_{\max} = \eta q B D_{\rm att} \sim Z \left(\frac{B}{1\,\mu\mathrm{G}}\right) \left(\frac{D_{\rm att}}{100\ \mathrm{Mpc}}\right) \times 4 \cdot 10^{18}\ \mathrm{eV}$$

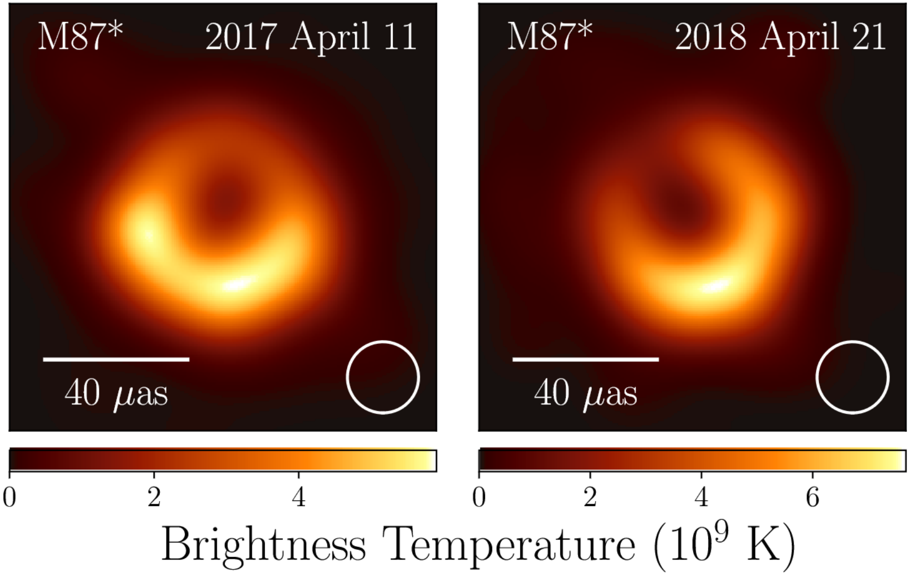
acceleration to 10^{20} eV

- protons ($D_{\rm att} \sim 100$ Mpc) require $B \gtrsim 25\,\mu$G
- iron nuclei ($D_{\rm att} \sim 700$ Mpc) require $B \gtrsim 0.15\,\mu$G

protons are consistent with equipartition magnetic field estimate ($\sim 25\,\mu$G)
but their acceleration is not possible because of escape

iron nuclei can be accelerated to 1.5×10^{22} eV (optimistic estimate)

Accretion discs



The Event Horizon Telescope Collaboration, A&A (2024)

How to accelerate particles in accretion discs?

- Shear-flow acceleration (certainly!)
- Diffusive-shock acceleration (questionable)
- *Magnetic field dissipation via reconnection etc.* (very likely)

The last item looks most promising, mainly because it is poorly understood

Acceleration in accretion discs (escape limit)

$$E_{\max} = \sqrt{\eta} qBR$$

- efficiency $\eta \sim (V_{\rm orb}/c)^2 \sim R_g/R$
- equipartition magnetic field $B_{\rm eq} = \sqrt{4\pi\rho V_{\rm orb}^2}$
- thick accretion disc, $H \sim R$
- accretion rate $\dot{M} = L/(\epsilon c^2)$, where radiative efficiency is $\epsilon \approx 0.05$

$$E_{\max} \sim Z \left(\frac{L}{L_{\rm Edd}}\right)^{1/2} \left(\frac{M_{\rm BH}}{10^9\, M_\odot}\right)^{1/2} \left(\frac{R}{R_g}\right)^{-3/4} \times 4 \cdot 10^{21}\ \text{eV}$$

Mind losses due to interaction with photons from accretion disc!

Acceleration in accretion discs (photon-induced losses)

Radiation from accretion discs

- locally black-body emission with $T \propto R^{-3/4}$
- overall spectrum is dominated by inner disc (at $R \approx 3R_g$)
- losses are photo-pion (for protons) and photodisintegration (for nuclei)
- accretion disc produces enough photons to cut off acceleration at $R_{\gamma,\mathrm{lim}} \gg 3R_g$

"photo-interaction" radius in the disc

- for protons: $R_{\gamma,\mathrm{lim}}/R_g \sim \left(\frac{L}{L_{\mathrm{Edd}}}\right)^{3/4} \left(\frac{M_{\mathrm{BH}}}{10^9\, M_\odot}\right)^{1/4} \times 600$
- for iron: $R_{\gamma,\mathrm{lim}}/R_g \sim 4 \cdot 10^3$ with the same scaling

Acceleration in accretion discs (photon-induced losses)

Photon-induced energy loss rate peaks at

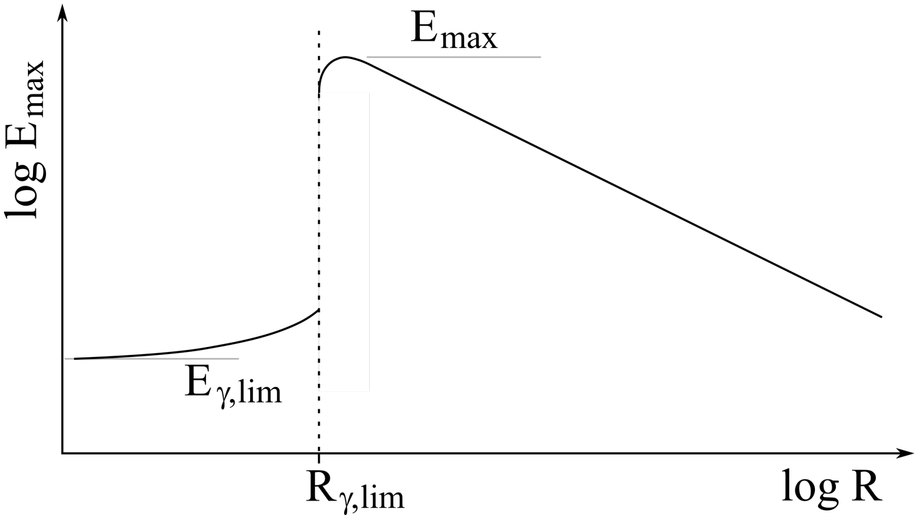
- for protons: $E_{\gamma,\mathrm{lim}} \sim \left(\frac{L}{L_{\mathrm{Edd}}}\right)^{-1/4} \left(\frac{M_{\mathrm{BH}}}{10^9\, M_\odot}\right)^{1/4} \times 2 \cdot 10^{16}$ eV
- for iron nuclei: $E_{\gamma,\mathrm{lim}} \sim 5 \cdot 10^{16}$ eV with the same scaling

Protons and nuclei of energy $E_{\gamma,\mathrm{lim}}$ are well confined in the disc

✗ Iron nuclei disintegrate completely at $R < R_{\gamma,\mathrm{lim}}$

✓ protons survive photo-pion reactions
and may recycle even if they turn into neutrons

Acceleration vs. losses across accretion disk



Acceleration in accretion discs: the bottom line

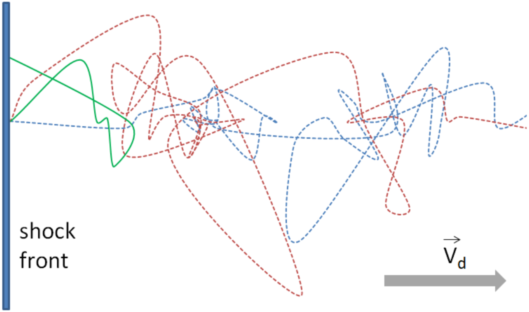
- accretion discs do not emit nuclei (they are destroyed inside)

- nucleons are accelerated and emitted as neutrons reaching energy

$$E_{\max} \equiv E_{\max}(R_{\gamma,\mathrm{lim}}) \sim \left(\frac{L}{L_{\mathrm{Edd}}}\right)^{-1/16} \left(\frac{M_{\mathrm{BH}}}{10^9\, M_\odot}\right)^{5/16} \times\, 3 \cdot 10^{19}\ \mathrm{eV}$$

- secondary neutrino emission from inner parts of accretion discs
- typical neutrino energy $E_\nu \approx 0.05\, E_{\gamma,\mathrm{lim}} \sim 10^{15}$ eV
- neutrino luminosity is very uncertain,
  may be as large as 10% of the bolometric luminosity

Particle acceleration in relativistic shocks: analytics



Effective width of downstream "reflection layer" is $\simeq \frac{1-\beta_d}{\beta_d}$ mean free paths

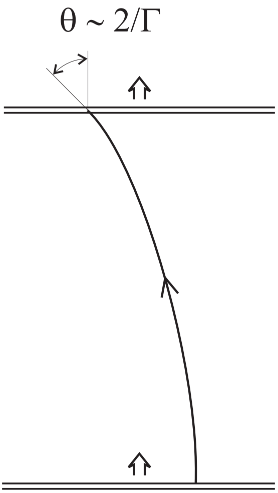
This is only $\simeq$ 2 m.f.p. in relativistic shocks ($\beta_d = 1/3$) — diffusion approximation is questionable

Expectations

- No Fermi acceleration with regular magnetic field
- Within diffusion approximation accelerated particles form a power-law distribution with $p = \frac{\beta_d^3 - 2\beta_d^2 + 2\beta_d + 1}{1-\beta_d}$, that is $p = \frac{20}{9} \simeq 2.22$

Keshet & Waxman 2005

Diffusive acceleration at relativistic shock



- distribution of accelerated particles remains highly collimated
- energy gain factor $g = (1/2)\,(\Gamma\theta)^2 \simeq 2$
- efficient acceleration requires probability of particle injection back to upstream ~ 1
- actual probability depends on the (unknown) magnetic field geometry

Favorable geometry gives $\dfrac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-22/9}$

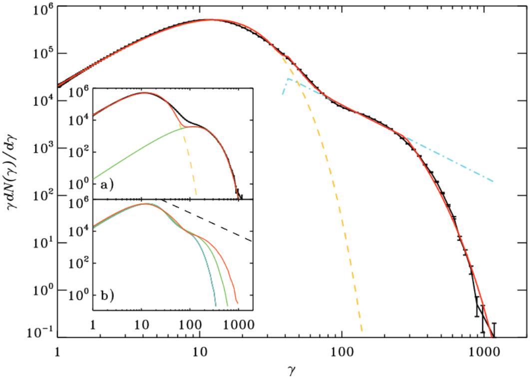
Keshet & Waxman, PRL 2005

"Realistic" geometry leads to very soft particle distributions, with energy concentrated near $\Gamma^2 mc^2$

Niemiec & Ostrowski, ApJ 2006

Lemoine, Pelletier & Revenu, ApJ 2006

Particle acceleration in relativistic shocks: numerical results



High-energy tail has cut-off which moves towards higher energies as simulations runs longer

The tail approaches a power-law with $p = 2.4 \pm 0.1$

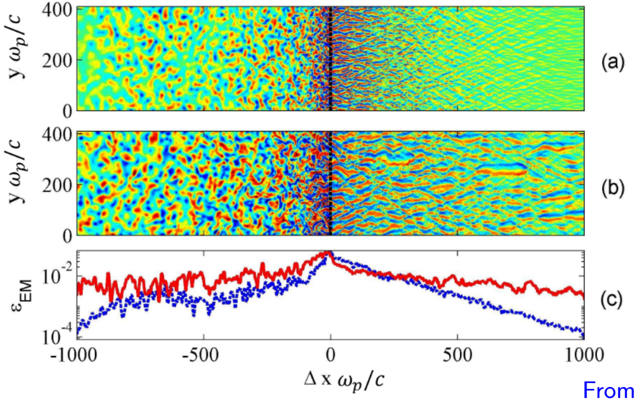
From Spitkovsky ApJ 682 (2008)

Note the subtlety

Regular magnetic field upstream kills acceleration

Even very small magnetization $\sigma_m \sim 10^{-5}$ can do this

Magnetic field: numerical results



One of the longest simulations still does not converge to a steady state

(a) $t = 2250\ \omega_p^{-1}$

(b) $t = 11925\ \omega_p^{-1}$

From Sironi, Keshet & Lemoine Space Sci. Rev. 191 (2015)

- magnetic field is short-lived; persists for longer distance in longer runs
- energy share in the magnetic field at shock's front $\epsilon_{\rm B} \sim 0.01$
- energy share in accelerated electrons $\epsilon_e \sim 0.1$

Various conversion cycles

Leptonic conversion cycle

(1) $e^- + \gamma_{soft} \to e^- + \gamma_{hard}$ (2) $\gamma_{hard} + \gamma_{soft} \to e^- + e^+$

Hadronic conversion cycles

Electromagnetic channel (low density environment)

(1) $p + \gamma_{soft} \to n + \pi^+$ (2) $n + \gamma_{soft} \to p + \pi^-$ (or $n \to p + e^-$)

Collisional channel (high density environment)

(1) $p + p \to n + p + \pi^+$ (2) $n + p \to p + p + \pi^-$ (or $n \to p + e^-$)

In a uniform emitting zone all these are merely dissipation (cascade): energy of individual particles decreases at each conversion while the number of particles goes up

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energy of individual particles decreases at each conversion
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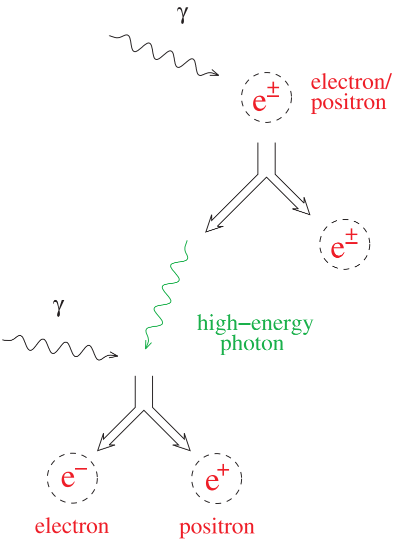
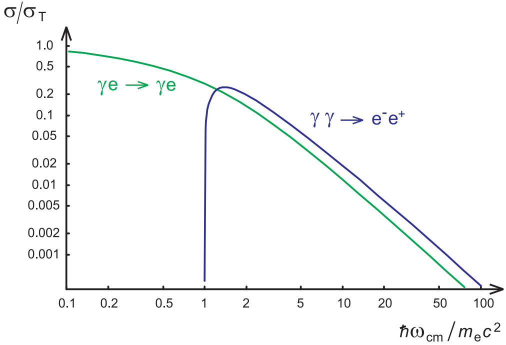
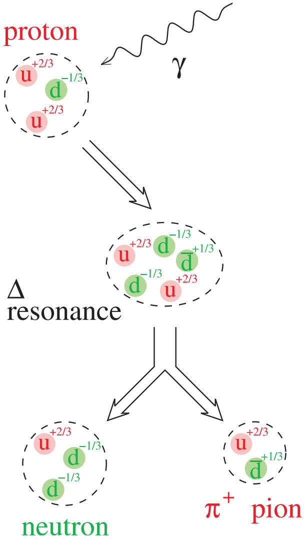
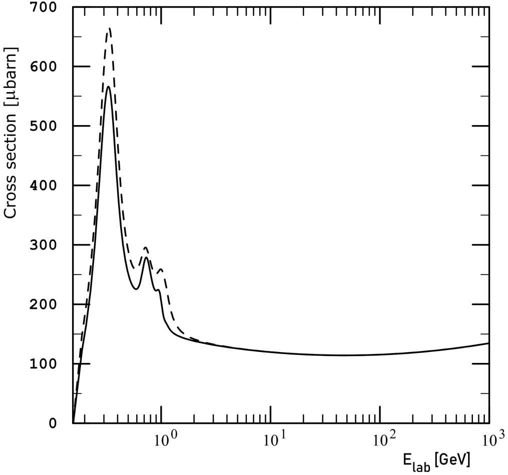
Conversion to neutrals for electrons/positrons





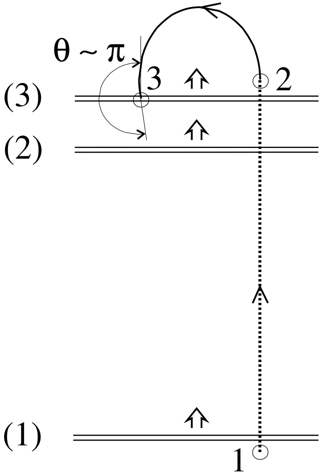
Conversion to neutrals for protons





Bhattacharjee & Sigl, Phys. Rep. 2000

Converter acceleration mechanism



1. Electron produces high-energy IC photon
2. The photon overtakes the shock and produces $e^- e^+$ pair in the upstream
3. Shock catches up with isotropized particles and boosts them

Energy gain factor $\sim \Gamma^2$ in each cycle

Derishev, Aharonian, Kocharovsky & Kocharovsky, PRD 2003

Converter acceleration mechanism

Efficiency of converter acceleration $= p_c \Gamma^2$

acceleration cycle probability p_c =

probability of photon escape from downstream ($\simeq 1/3$) $\times$

$\times$ relative efficiency of IC radiation ($= y/(1+y)$) $\times$

$\times$ radiative cooling efficiency

Depending on efficiency of converter acceleration:

- $p_c \Gamma^2 \ll 1$ — forget about it (non-relativistic shocks or extremely inefficient shocks)
- $p_c \Gamma^2 \sim 1$ — can be put to good use
- $p_c \Gamma^2 \gg 1$ — goes wild and tears apart our carefully built models

- Is inequality $p_c \lesssim 1/\Gamma_{sh}^2$ realistic? (GRBs have $\Gamma_{sh} \sim$ hundreds)
- How does the shock know about its "allowed" value of p_c?

Estimations of the conversion probability

	Active Galactic Nuclei	Gamma-Ray Bursts
Luminosity/ Energy release	$L_{\rm BLR} \sim 10^{44}$ erg/s	$E_{\rm Xray} \sim 10^{52}$ erg
Distance	$R \sim 3 \times 10^{17}$ cm	$R \sim 3 \times 10^{16}$ cm
Avrg. photon energy	$\varepsilon_* \sim 6$ eV	$\varepsilon_* \sim 600$ keV
Conversion threshold	$\varepsilon \sim 10^{15}$ eV	$\varepsilon \sim 10^{12}$ eV
Optical depth: $\frac{\sigma_{p\gamma} L}{\pi R c \varepsilon_*}$ or $\frac{\sigma_{p\gamma} E}{4\pi R^2 \varepsilon_*}$	$\tau \sim 0.07$	$\tau \sim 2 \times 10^{-4}$

$L_{\rm BLR}$ – luminosity of the broad-line region

$E_{\rm Xray}$ – energy released in the form of hard X-rays

Compare diffusive and converter acceleration mechanisms

Diffusive acceleration

Acceleration process is sensitive to the magnetic field geometry

Smoothing out sharp discontinuities progressively decreases efficiency

Acceleration starts right from thermal ion energy

Does not depend on presence of photon fields

Works in non-relativistic and (maybe) relativistic outflows

Converter acceleration

Injection back to upstream is equally easy at any point in the downstream

Acceleration does not depend on the magnetic field geometry

Efficiently works even in absence of any discontinuities,
also efficient in shear flows

Acceleration is efficient only past certain energy threshold

Requires relativistic hydrodynamical velocities

Summary 3

- Giant radio lobes and accretion shocks in clusters of galaxies are good candidates for producing 10^{20} eV Cosmic Rays with heavy composition (iron nuclei)
  protons will have a lower cut-off energy there
  Helium is strongly disfavored due to photodisintegration losses
- Accretion discs in AGNs can marginally reach 10^{20} eV for protons
  nuclei of all flavors will not escape from accretion discs
  CR-producing accretion discs can be powerful sources of neutrinos
  neutrino emission spectrum then peaks at $\sim 10^{15}$ eV
- Relativistic bulk motion enables one more acceleration mechanism — converter acceleration