Origin of the most energetic particles in the Universe

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Lecture 4

1. Theoretical perspectives
2. Assumptions and predictions of shock models
3. Diffusive shock acceleration vs. converter acceleration
   - GRB 190114C
   - GRB 190829A

Summary of Lecture 3

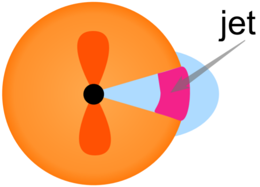
- 10^{20} eV iron nuclei in Cosmic Rays can be produced in:
  accretion shocks in clusters of galaxies
  giant giant radio lobes (metallicity uncertain)

- Helium nuclei are not expected in 10^{20} eV Cosmic Rays

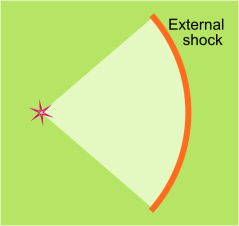
- Accretion discs in AGNs can barely reach 10^{20} eV for protons
  but the are promising sources of neutrino emission at $\sim 10^{15}$ eV

- Relativistic bulk motion enables one more acceleration mechanism — converter acceleration

Gamma-ray bursts



prompt
emission



afterglow

Jet Lorentz factor
at prompt phase $\Gamma > 100$

Baring & Harding (1997)

Deceleration of the blast wave at afterglow phase is well understood

Blandford & McKee (1976)

After confirming synchrotron-self-Compton emission model by observing TeV radiation (MAGIC Collaboration Nature 575, 2019)

afterglows of Gamma-Ray Bursts become the most clear-cut instance of relativistic shock problem:

- straightforward estimate for the shock's Lorentz factor
- no external photon field

Shock's microphysics

Radiation processes

this is what we see on the stage

Synchrotron-self-Compton radiation (possibly with external Compton) from energetic electrons

Particle acceleration

behind the scenes

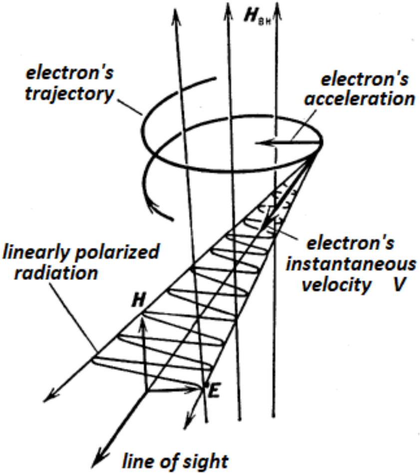
- Diffusive shock acceleration
- Converter acceleration
- ...

Magnetic field

behind the scenes

- Weibel instability
- MHD instabilities
- ...

Synchrotron radiation



ultrarelativistic

perpendicular momentum

quasi-continuous

spectrum of emission

typical photon energy

$$\epsilon_{sy} \approx \gamma_e^2 \hbar \omega_B$$

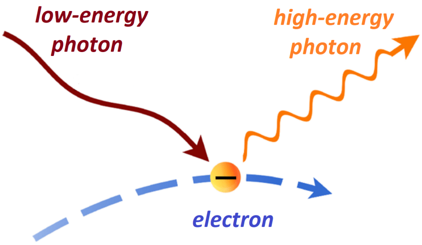
radiated power

$$P_{sy} = \frac{4}{3} \gamma_e^2 \sigma_T c \frac{B^2}{8\pi}$$

Radiation at the limit of acceleration

$$\epsilon_{sy,max} \sim m_e c^2 / \alpha_f \approx 70 \text{ MeV}$$

Inverse Compton radiation



energy is transferred from electron to photon

radiated power

$$P_{IC} = \frac{4}{3}\gamma_e^2 \sigma c w_{ph}$$

Thomson regime $(\gamma_e \epsilon_{low} \ll m_e c^2)$

energy of scattered photons $\epsilon_{high} \approx \gamma_e^2 \, \epsilon_{low}$

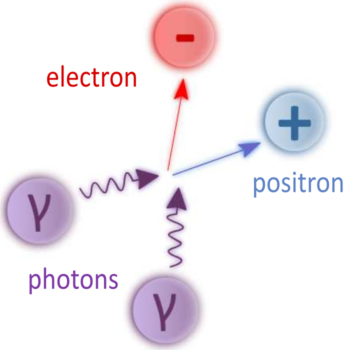
scattering cross-section $\sigma \approx \sigma_T$

Klein-Nisina regime $(\gamma_e \epsilon_{low} \gtrsim m_e c^2)$

energy of scattered photons $\epsilon_{high} \approx \gamma_e \, m_e c^2$

scattering cross-section $\sigma \sim \sigma_T m_e c^2 / (\gamma_e \epsilon_{low})$

Two-photon e^-e^+ pair creation



kinematic threshold

$$\epsilon_1\epsilon_2 > 2m_e^2c^4/(1-\cos\theta)$$

usually $\epsilon_1 \gg \epsilon_2$ —
there are more low-energy photons

then electron and positron are born relativistic and divide energy roughly in half

Symmetry of Feynman diagram with Compton scattering

- cross-sections at high energies differ by factor **2**
- pair-production cross-section at low energies is suppressed by kinematic threshold

SSC parameter space

- Magnetic field strength B
- Compton potential $k_{SC} \equiv \epsilon_e/\epsilon_B$
- Injection function's scale γ_b
- Shock's Lorentz factor $\Gamma_{\rm sh}$ that sets effective timescale t_{eff} (or cooling Lorentz factor γ_c)

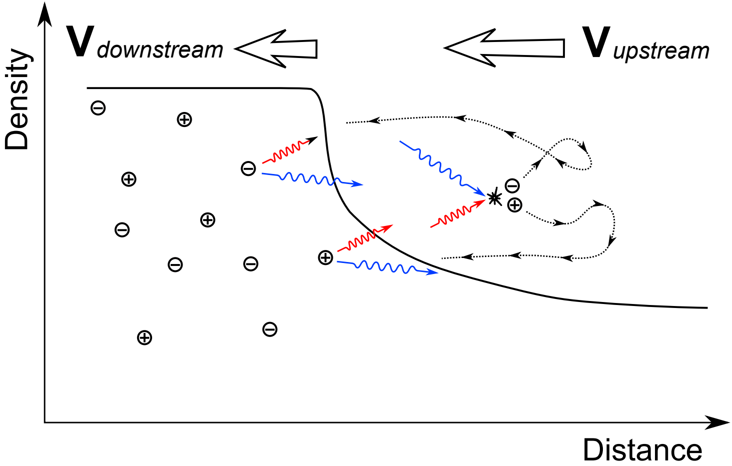
Distribution of injected electron's is *assumed* to be a power-law with low-energy cut $\frac{d\dot{N}}{dt} \propto \frac{\gamma^2}{(\gamma+\gamma_b)^{p+2}}$

Assumptions of diffusive shock acceleration

- Avg. Lorentz factor of injected electrons $\langle\gamma_{\rm inj}\rangle = (\epsilon_e/\xi_e)\Gamma_{\rm sh}(m_p/m_e)$.
- Fraction of energy in accelerated electrons $\epsilon_e \sim 0.1$, similar to what is seen in PIC simulations.
- Fraction of electrons being accelerated $\xi_e = 1$. PIC simulations show $\xi_e \sim 0.1$.

Pair-balance shock

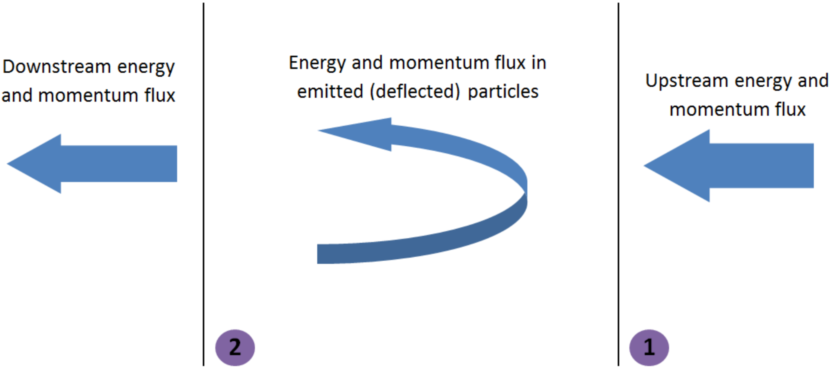
Figure from Derishev and Piran, ApJ 923 (2021)



$\langle\gamma\rangle > \gamma_0$ — prevails absorption of IC photons
$\langle\gamma\rangle < \gamma_0$ — prevails acceleration of electrons

$$\langle\gamma\rangle \simeq \gamma_0 = \left(\frac{B_{cr}}{B}\right)^{1/3}$$

Energy-momentum transport in relativistic shocks



The (flux conservation) equations

Assume that there is a steady state 1D solution

- Momentum flux conservation

$$w_1\beta_1^2\Gamma_1^2 + p_1 = w_2\beta_2^2\Gamma_2^2 + p_2 + S_{mom}$$

- Energy flux conservation

$$w_1\beta_1\Gamma_1^2 = w_2\beta_2\Gamma_2^2 - S_{en}$$

- Energy and momentum fluxes for outgoing particles

$$S_{en} = a\, w_2\beta_2\Gamma_2^2 \qquad\qquad S_{mom} = b\, S_{en}$$

w – specific enthalpy, p – pressure

Approximate solution

Assume relativistic equation of state $p = w/4$

- This is guaranteed if shock modification is strong.

Use "magic"variable $\chi = \left(3\beta + \frac{1}{\beta}\right)$

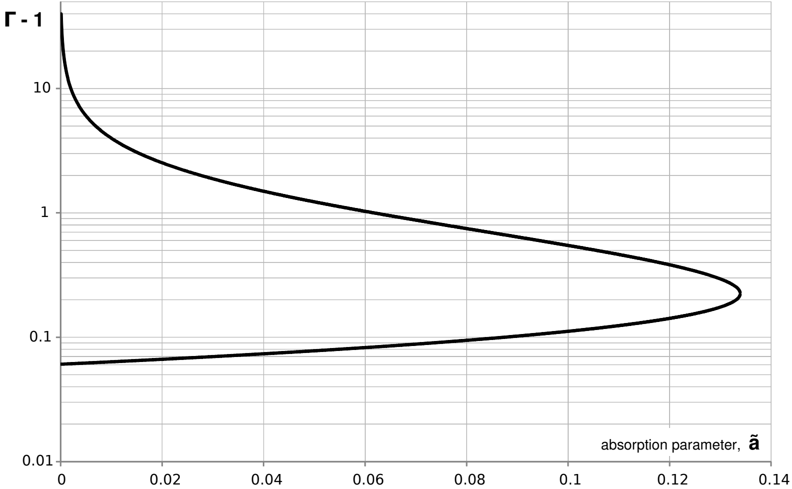
- The conservation equations become

  $\mathrm{d}\chi = -\chi\,\mathrm{d}\tilde{a}$, where $\tilde{a} = a(1+b)$

- Approximate solution in the case where $\Gamma \gg \Gamma_u \gg 1$:

  $$\Gamma_u = \frac{1}{2\tilde{a}^{1/2}}$$

Precursor structure



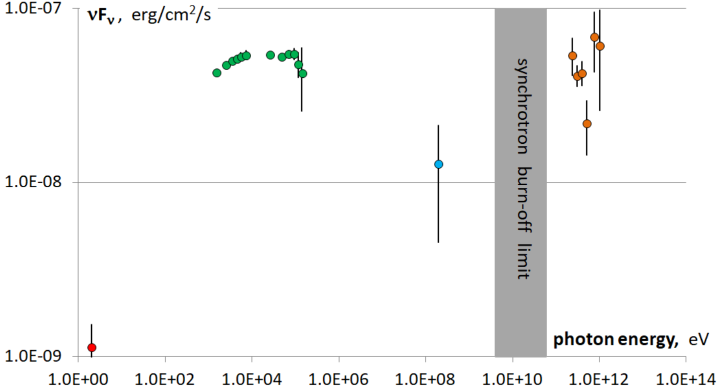
Bulk Lorentz factors in shock-front comoving frame

upper branch – the upstream
lower branch – the downstream.

Main predictions of pair-balance model

- Ratio of IC luminosity to synchrotron luminosity ~ 1.
- Typical Lorentz-factor of accelerated electrons $\gamma_{\rm b}$ is adjusted to keep the fraction of absorbed radiation constant (saturated regime) or to maximize it (starved regime).
  As the shock decelerates, $\gamma_{\rm b}$ grows (following decreasing magnetic field) while the fraction of accelerated electrons decreases.
- Fraction of internally absorbed radiation (in saturated regime) is constant (≈ 0.1).
- Average Lorentz factor of injected electrons (in starved regime) $\langle\gamma_{\rm inj}\rangle = (B_{cr}/B)^{1/3} \simeq 3.5 \times 10^4\,(B/1\,\mathrm{G})^{-1/3}$.
- Fraction of energy in accelerated electrons $\epsilon_e \sim 1$

Broad-band afterglow spectrum of GRB 190114C



Observations:

Swift-UVOT

Swift-BAT

Fermi-LAT

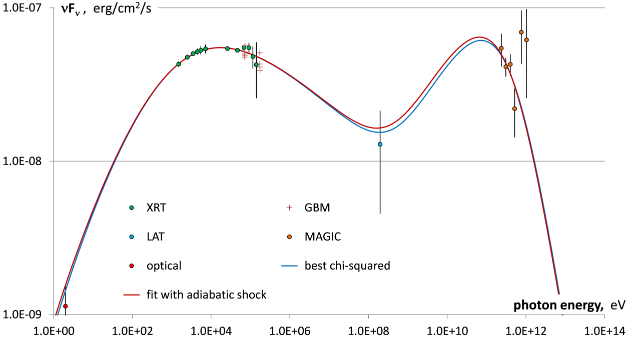
MAGIC

MAGIC Collab. Nature 575 (2019)

- Observing time $50 \div 1000$ s from trigger
- Photons' energy ~ 0.3 TeV
- Luminosity $L_{TeV} \simeq 0.4 L_{keV}$

GRB 190114C — SED at early time

ED & T.Piran, ApJ 923 (2021)



$t_{\rm obs} = 90$ s

$\gamma_{\rm b} = 6500$

$\epsilon_B = 0.0061$

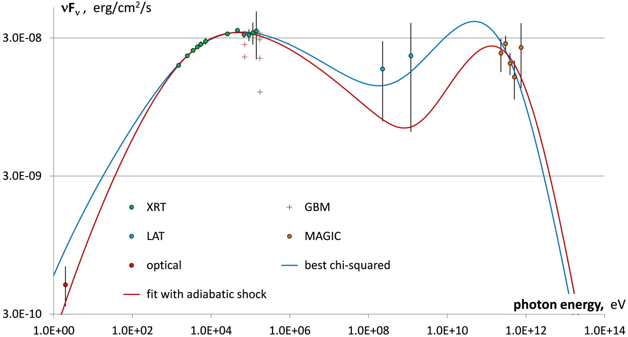
$\epsilon_e = 0.12$

$p = 2.5$

$E_{\rm kin} = 3 \times 10^{53}$ erg

GRB 190114C — SED at late time

ED & T.Piran, ApJ 923 (2021)



$t_{\rm obs} = 145$ s

$\gamma_{\rm b} = 16700$

$\epsilon_B = 0.0027$

$\epsilon_e = 0.096$

$p = 2.5$

$E_{\rm kin} = 3 \times 10^{53}$ erg

Assuming constancy of ϵ_e, late-time fit favours $\sim 20\%$ decrease of shock's energy. Though statistical significance isn't high.

GRB 190114C time evolution

ED & T.Piran, ApJ 923 (2021)

$t_{\rm obs} = 90$ s

$\gamma_{\rm b} = 6500$
$\epsilon_B = 0.0061$
$\epsilon_e = 0.12$

$(p = 2.5,\ E_{\rm kin} = 3 \times 10^{53}$ erg$)$

$t_{\rm obs} = 145$ s

$\gamma_{\rm b} = 16700$
$\epsilon_B = 0.0027$
$\epsilon_e = 0.096$

$(p = 2.5,\ E_{\rm kin} = 3 \times 10^{53}$ erg$)$

A surprise? Not really — ED & T.Piran, MNRAS 460 (2016)

$\gamma_{\rm b}$ increases as shock decelerates, while ϵ_e stays approximately constant
$\Rightarrow$ fraction of upstream electrons being accelerated decreases with time

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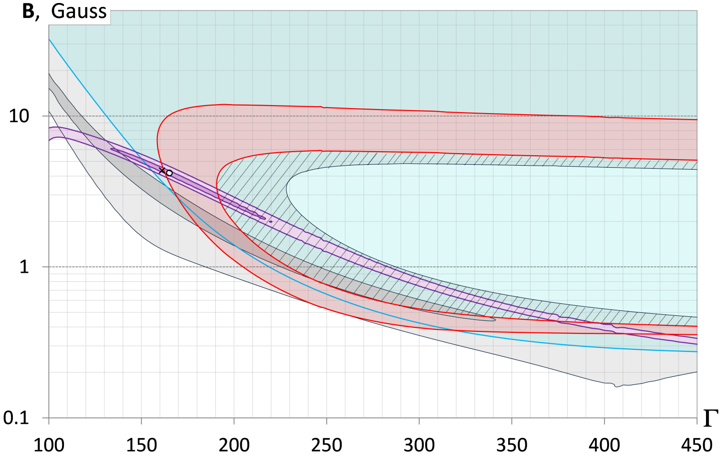
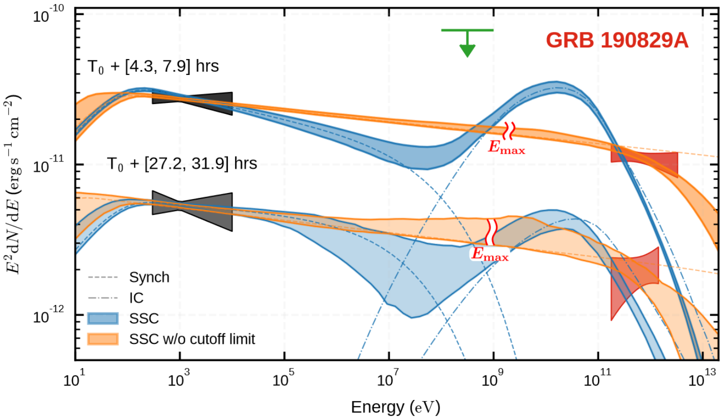
The fraction of internally absorbed radiation remains constant at $\simeq 10\%$

Parameters space for GRB 190114C



gray area — good agreement with X-ray data
pink area — good agreement with optical data
cyan area — good agreement with GeV (LAT) data
magenta area – good agreement with TeV data

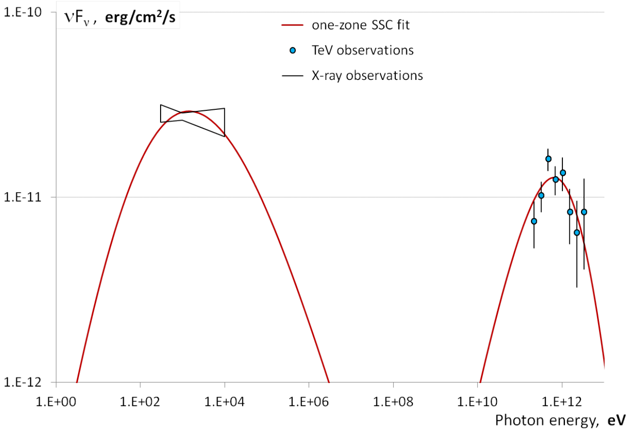
GRB 190829A — conventional scenario clearly fails



From H.E.S.S. Collaboration Science 372 (2021)

Conventional scenario (blue lines) is not consistent with observations.
Radiating electrons must be much more energetic.

GRB 190829A — SED at early time



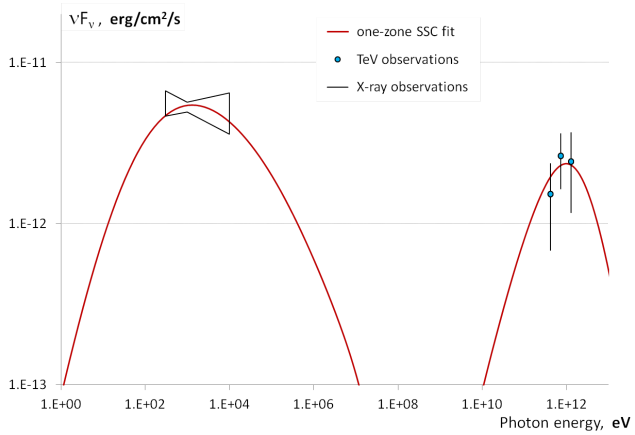
$t_{\rm obs} = 2.1 \times 10^4$ s

$\Gamma = 18$
$\langle \gamma_{\rm inj} \rangle = 1.1 \times 10^5$
$\epsilon_B = 1.4 \times 10^{-3}$
$\epsilon_e = 0.17$

$p = 3.5$
$E_{\rm kin} = 3 \times 10^{51}$ erg

No good fit exists for standard $p = 2.5$. Need soft injection with $p > 3$.

GRB 190829A — SED at late time



$t_{\rm obs} = 1.06 \times 10^5$ s

$\Gamma = 12$
$\langle \gamma_{\rm inj} \rangle = 2.1 \times 10^5$
$\epsilon_B = 7.5 \times 10^{-4}$
$\epsilon_e = 0.46$

$p = 3.5$
$E_{\rm kin} = 3 \times 10^{51}$ erg

Data in the second observation interval are not restrictive. Let's use Blandford-McKee solution to extrapolate $\Gamma_{\rm sh}$ from the first interval's fit.

GRB 190829A time evolution

$t_{\rm obs} = 2.1 \times 10^4$ s

$\Gamma = 18$

$\langle \gamma_{\rm inj} \rangle = 1.1 \times 10^5$

$B = 0.028$ G $\Rightarrow$ $\gamma_0 = 1.2 \times 10^5$

$\epsilon_B = 1.4 \times 10^{-3}$

$\epsilon_e = 0.17$

$p = 3.5$

$E_{\rm kin} = 3 \times 10^{51}$ erg

$t_{\rm obs} = 1.06 \times 10^5$ s

$\Gamma = 12$

$\langle \gamma_{\rm inj} \rangle = 2.1 \times 10^5$

$B = 0.006$ G $\Rightarrow$ $\gamma_0 = 1.9 \times 10^5$

$\epsilon_B = 7.5 \times 10^{-4}$

$\epsilon_e = 0.46$

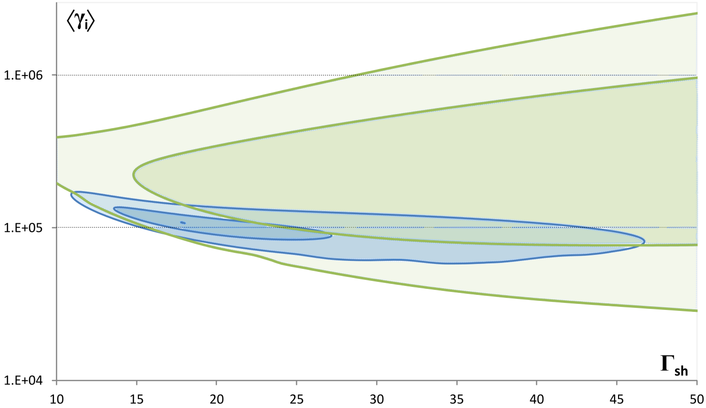
$p = 3.5$

$E_{\rm kin} = 3 \times 10^{51}$ erg

Lorentz factor of injected electrons closely follows $\langle \gamma_{\rm inj} \rangle \simeq \gamma_0$ *prediction.*

Assuming constancy of ϵ_e, late-time fit implies $\sim 3 - \text{fold}$ increase of shock's energy. This **is** statistically significant.

Evolution of injection Lorentz factor



4.3 to 7.9 hrs since trigger

27.2 to 31.9 hrs since trigger

Change in parameters of best fit implies
$\simeq$ 80% increase of injection Lorentz factor from first to second observation.
Very similar increase is expected from $\langle\gamma_{inj}\rangle \simeq \gamma_0 \propto B^{-1/3}$ rule

Model expectations vs observations

	conventional model (SSC + DSA)	pair balance model (SSC + converter)
IC to sy flux ratio	changes with time	constant at ~ 1
IC to sy flux ratio	differs in different GRBs	universal at ~ 1
$\langle \gamma_{inj} \rangle$ as function of time	decreases with time	increases with time
absorbed fraction at early afterglow	varies	universal at ~ 0.1
$\langle \gamma_{inj} \rangle$ at late afterglow	$\propto \Gamma_{sh}$	$\sim \gamma_0 \propto B^{-1/3}$

green — agrees with observations
gray — not enough data
red — contradicts observations

Summary 4

- Gamma-Ray bursts with their broad-band observations provide a unique (so far) test case for studying particle acceleration process
- There is good evidence that actually working acceleration mechanism in GRB shocks is converter
- It is not clear whether we can extend this conclusion to acceleration of nucleons — mainly because of poor knowledge of magnetic turbulence in relativistic shocks

What do we know?

- There are potential sources of $\lesssim 10^{20}$ eV Cosmic Rays:
  accretion shocks in clusters of galaxies (for iron nuclei)
  giant radio lobes (for iron nuclei)
  accretion discs in Active Galactic Nuclei (for protons)
  AGN jets and Gamma-Ray Bursts (for protons)

- None of them is really certain

- Proton-producing sources generally have a lower (theoretical) cut-off energy

- By coincidence, all of the potential sources can not go much beyond the already observed CR energy $\sim 3 \times 10^{20}$ eV

What do we need to go further?

— mostly more observational data and a bit of numerical experiment

- Detection/non-detection of galaxy clusters and giant radiolobes in GeV – TeV domain
- Detection/non-detection of Active Galactic Nuclei as neutrino sources
- Detection/non-detection of Gamma-Ray Bursts as neutrino sources
- Improvements in numerical (Particle-In-Cell or hybrid) methods to simulate relativistic shocks