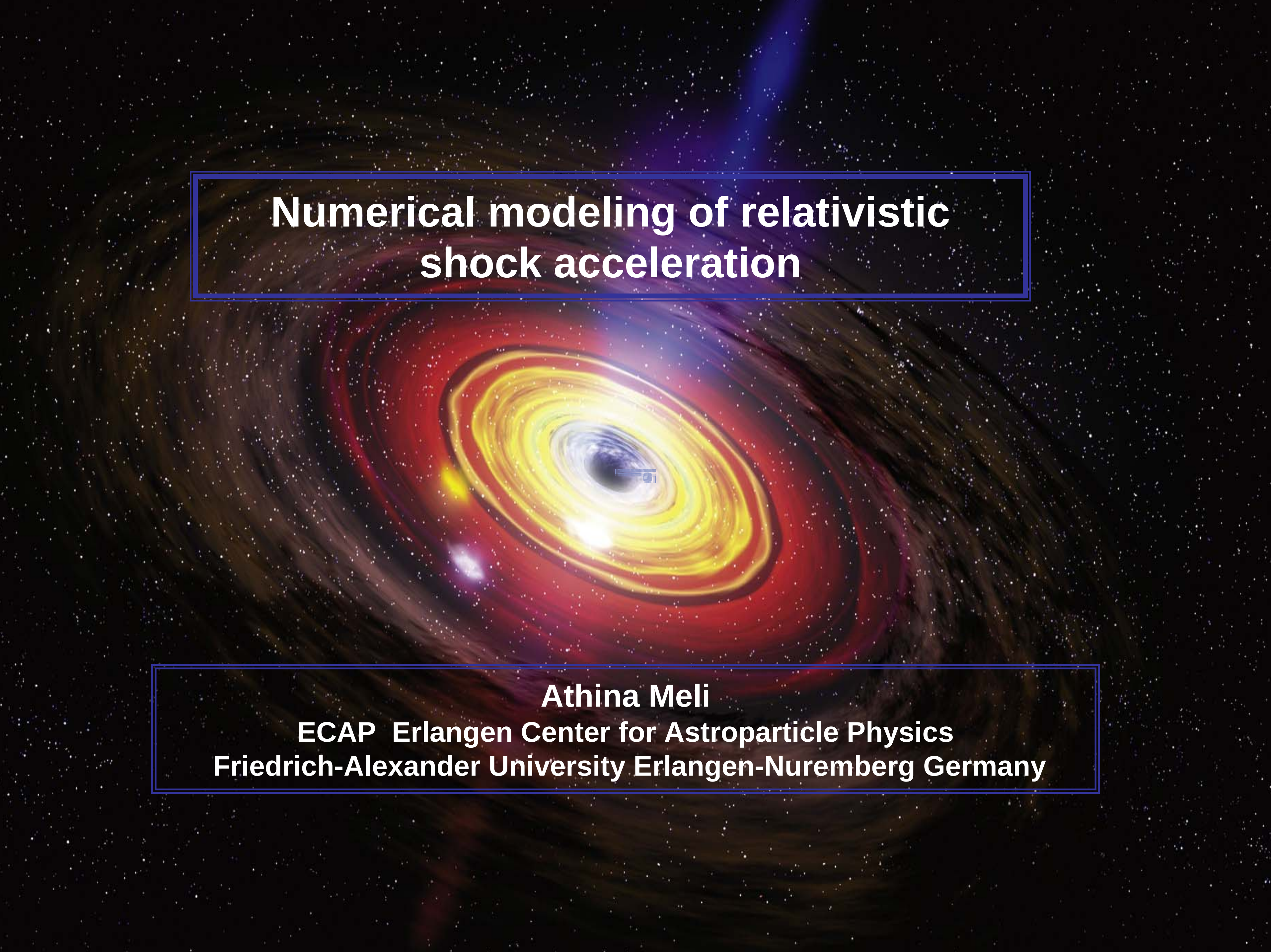

Numerical modeling of relativistic shock acceleration

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Friedrich-Alexander University Erlangen-Nuremberg Germany

Outline

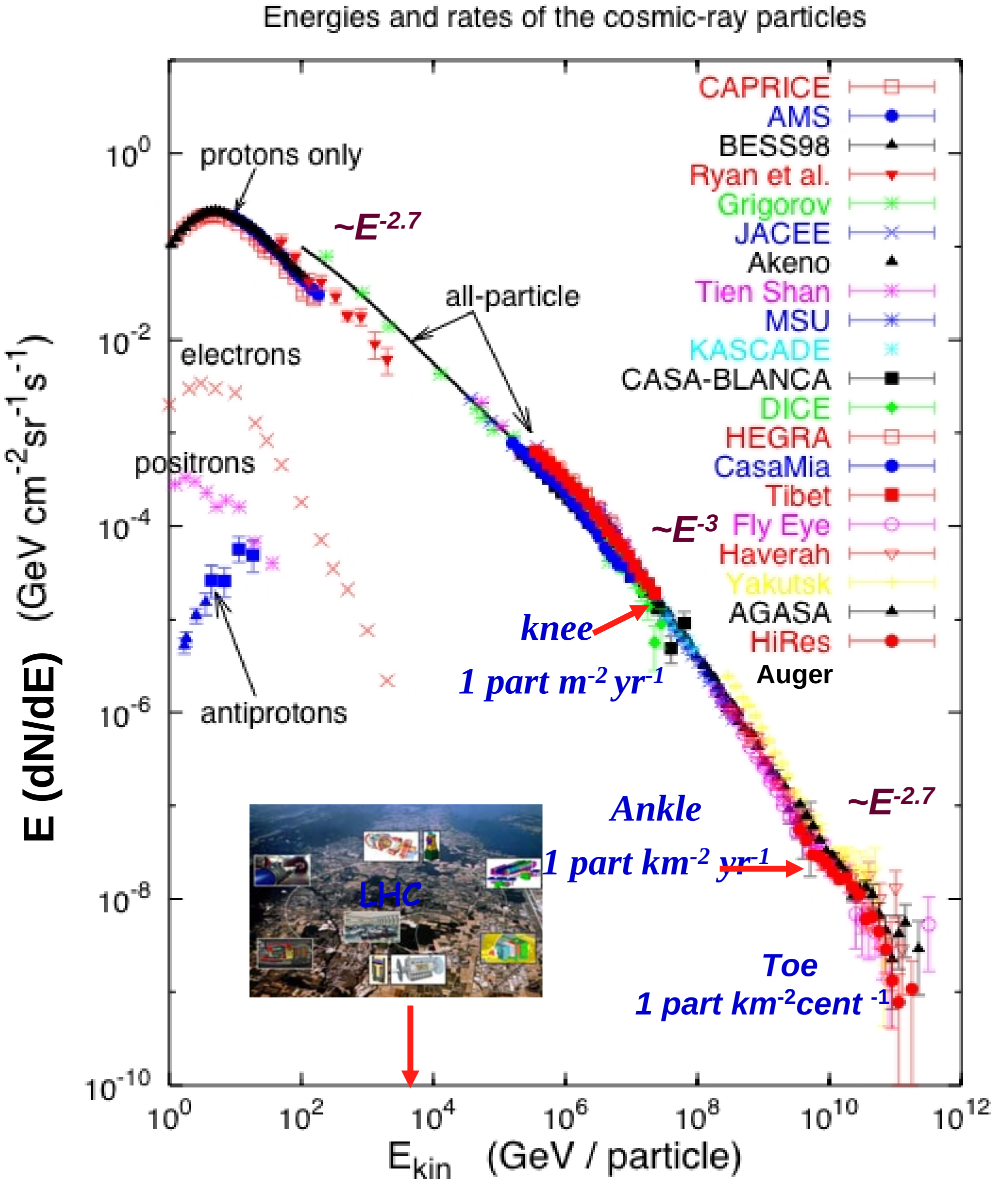
- **Cosmic ray spectrum and relativistic sources**
- **Shocks**

  - Properties

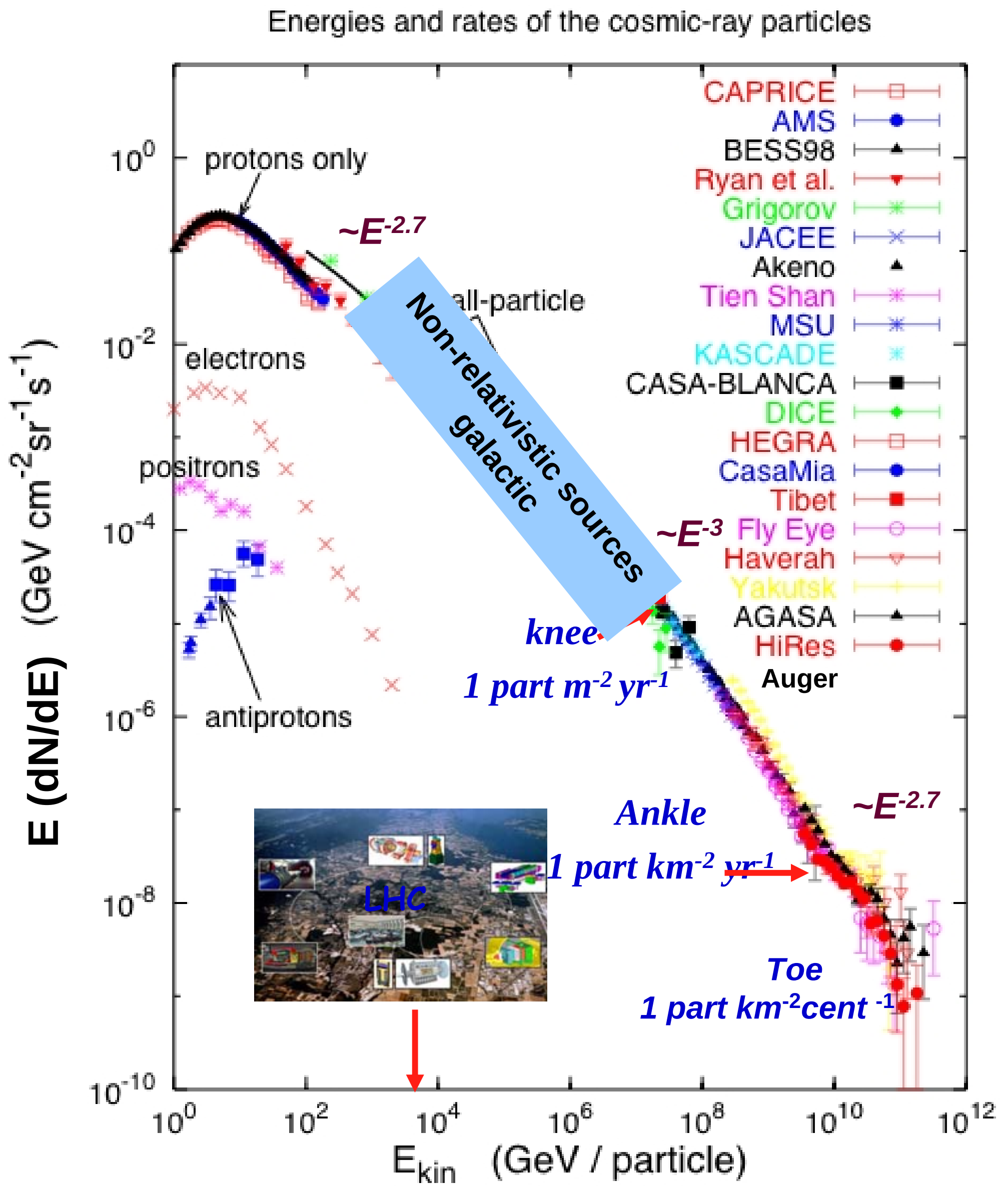
  - Particle acceleration mechanism
- **Simulations**

  - Numerical Method

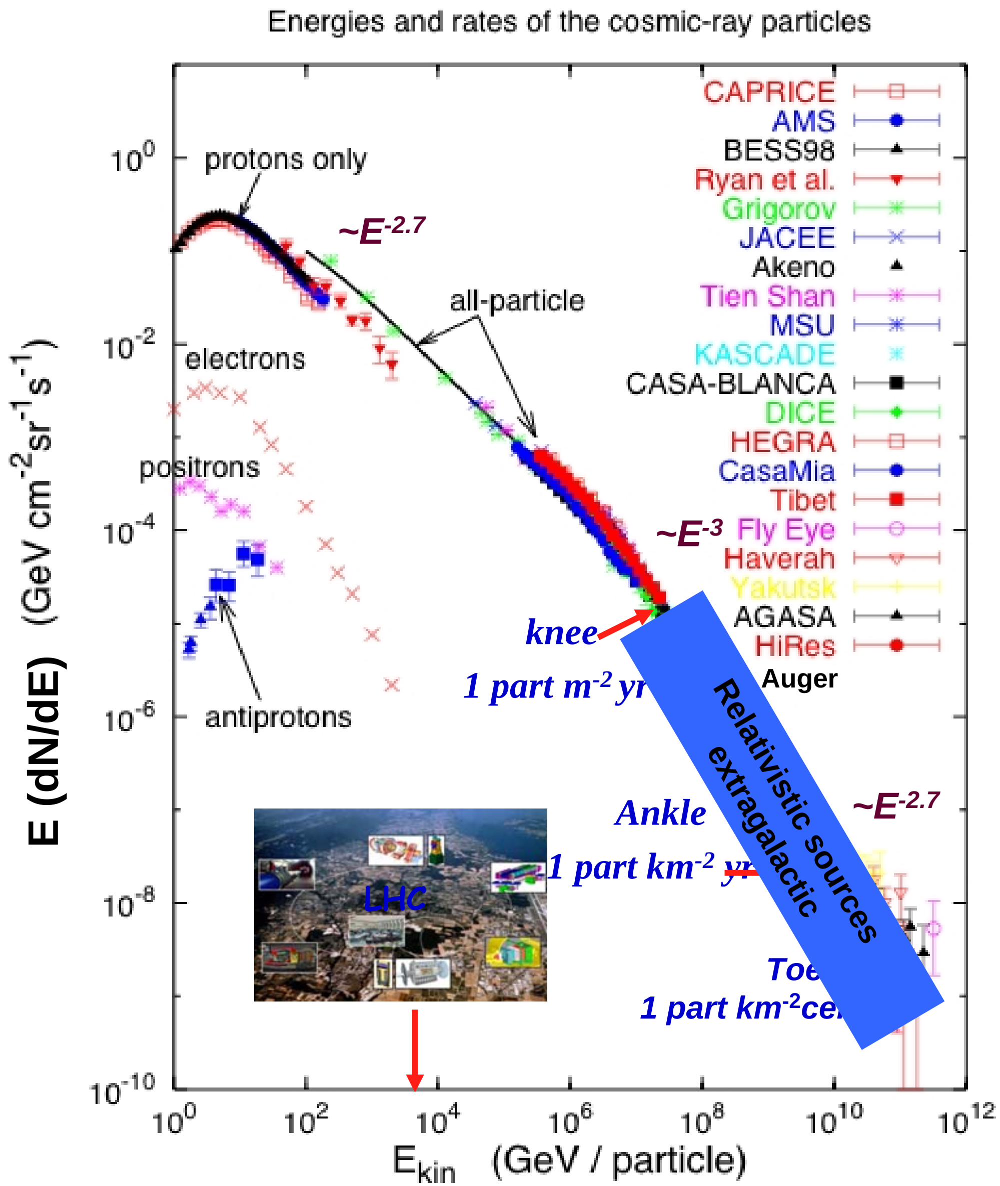
  - Studies
- **Conclusions**



10 decades of energy – 30 decades of flux



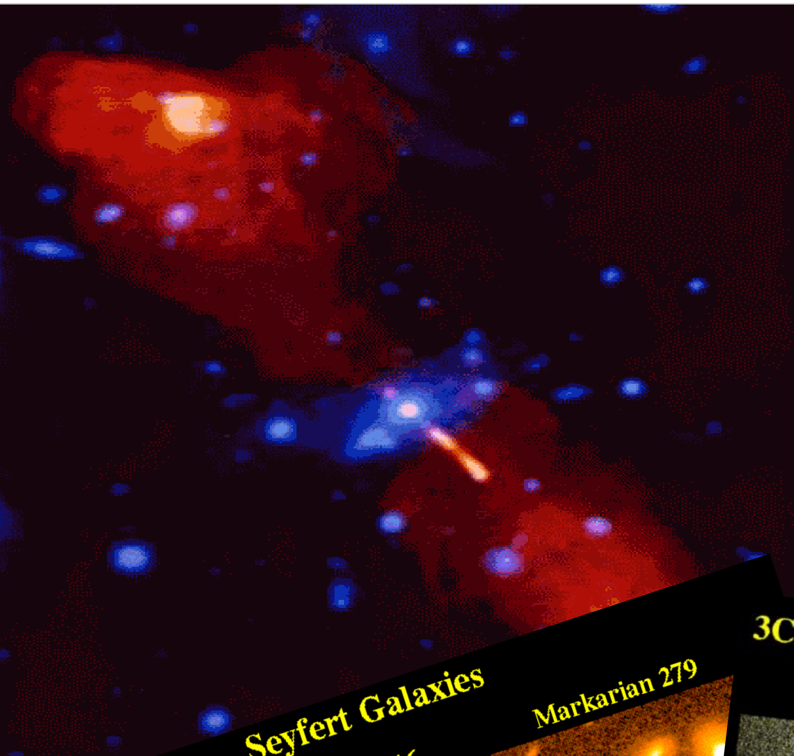
10 decades of energy – 30 decades of flux

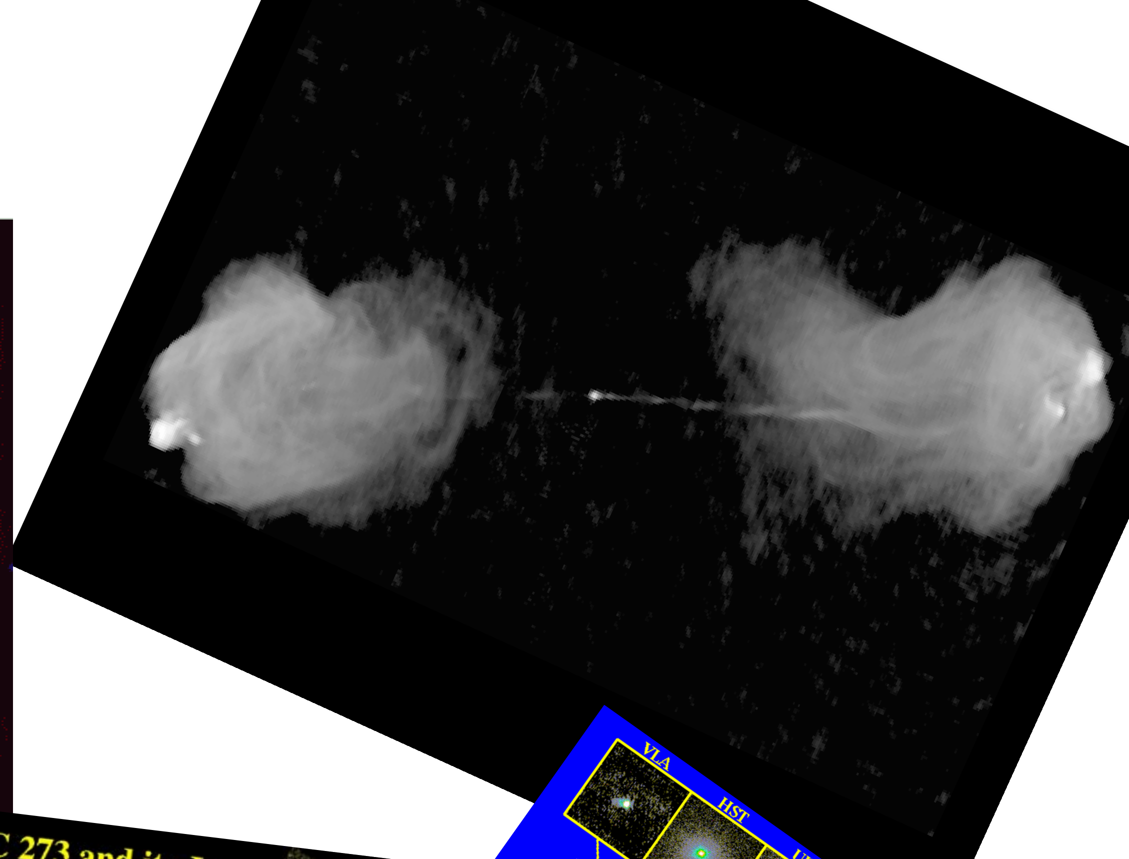


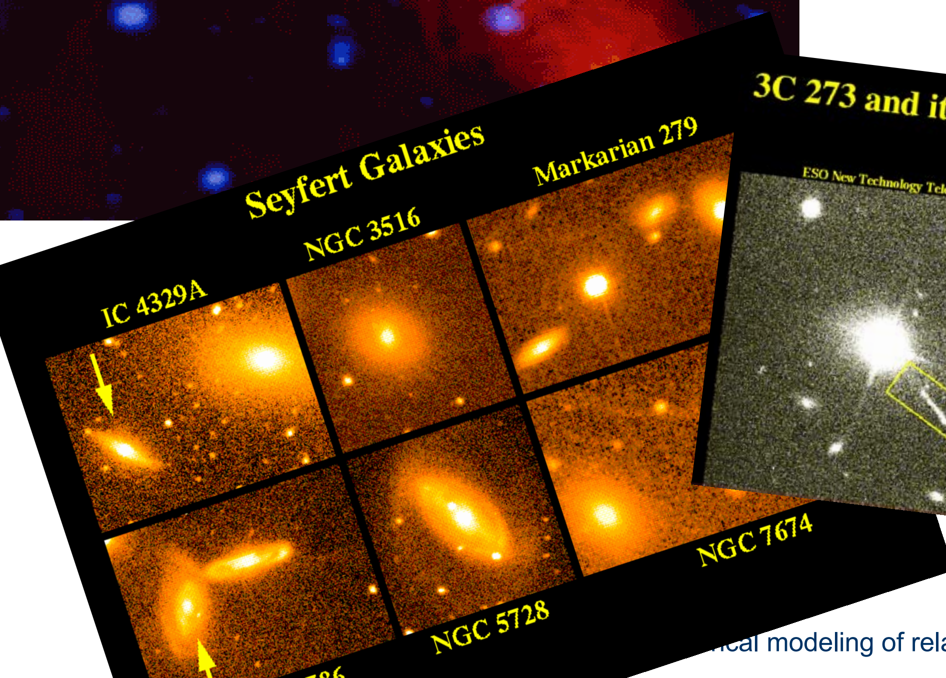
10 decades of energy – 30 decades of flux

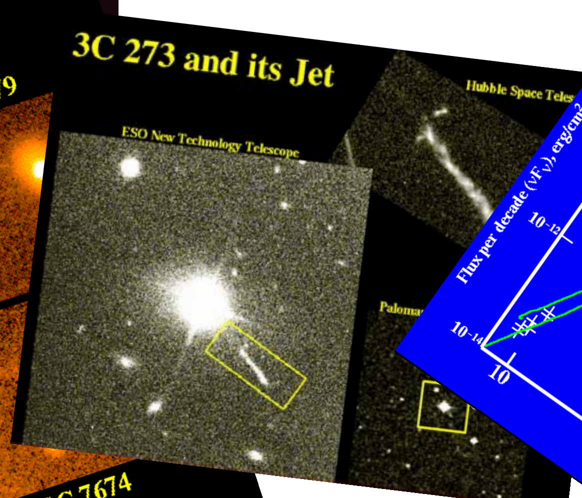
Relativistic sources

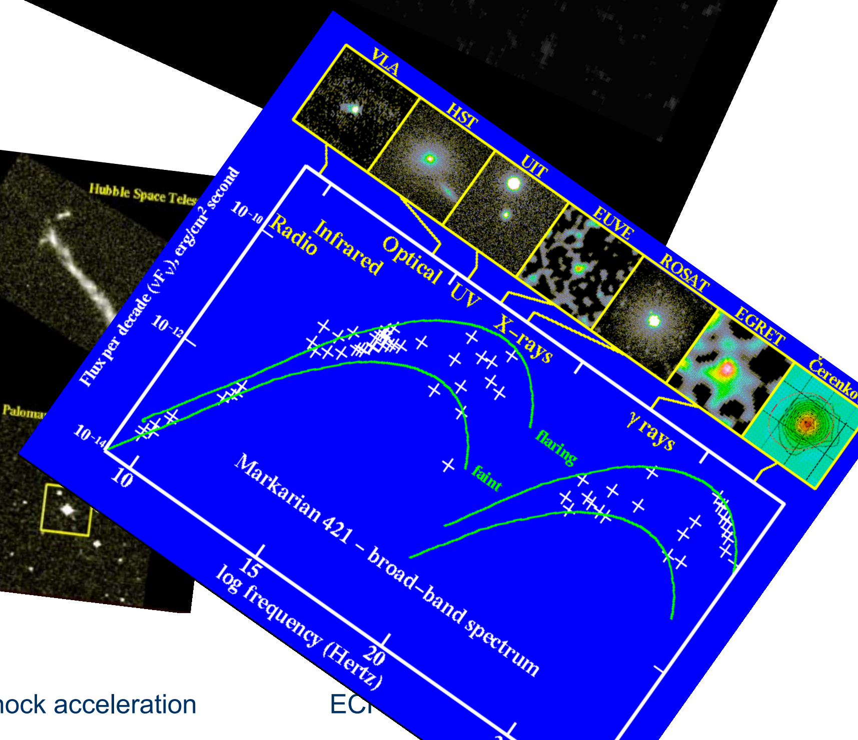
Active Galactic Nuclei case



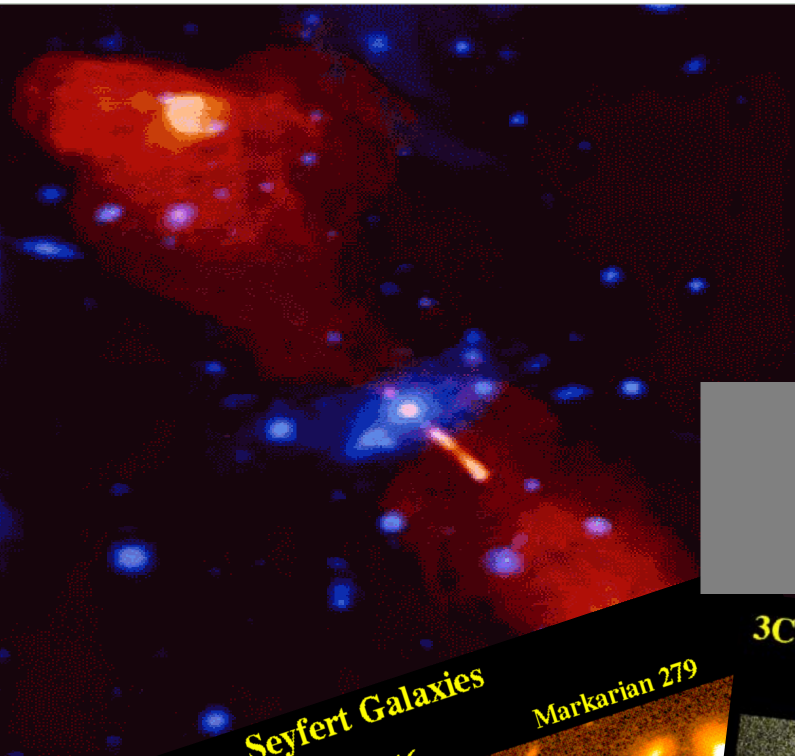


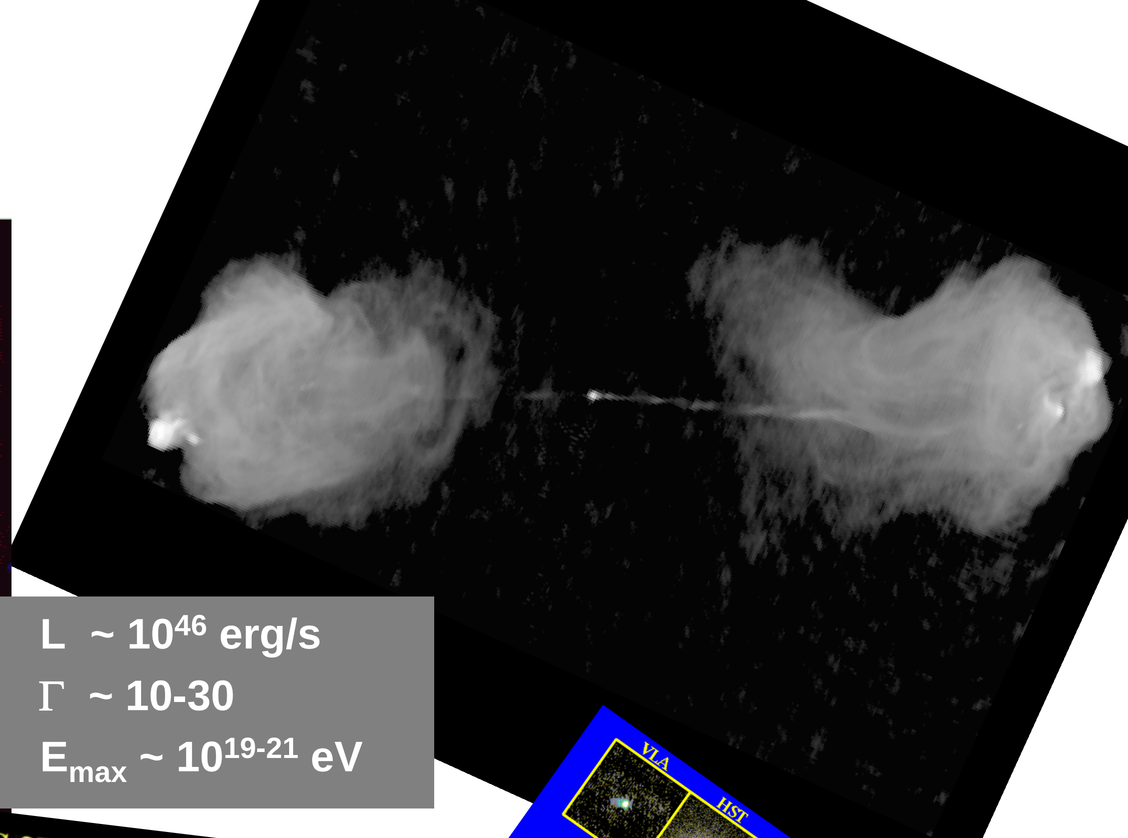






Active Galactic Nuclei case

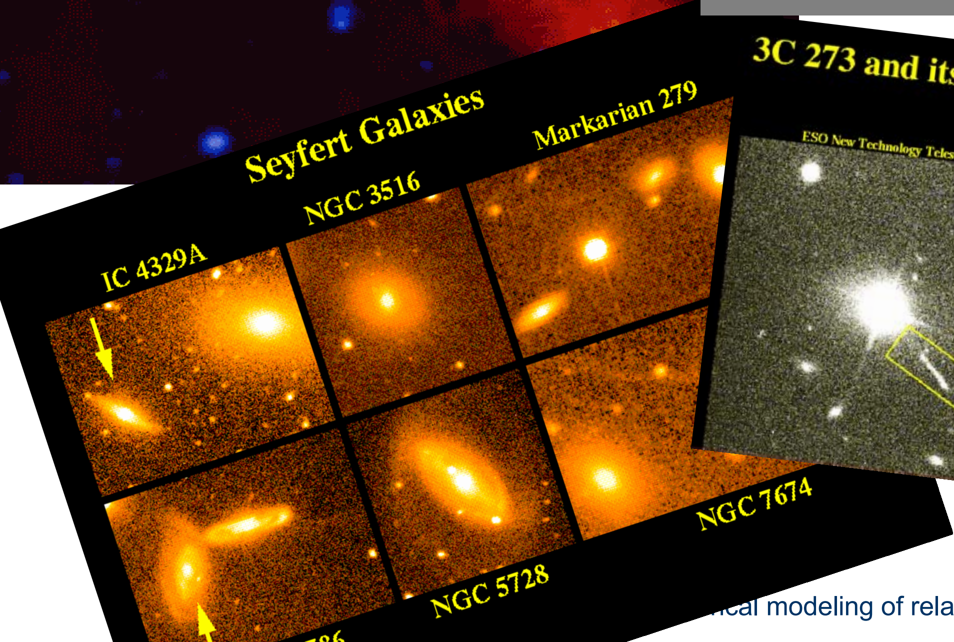


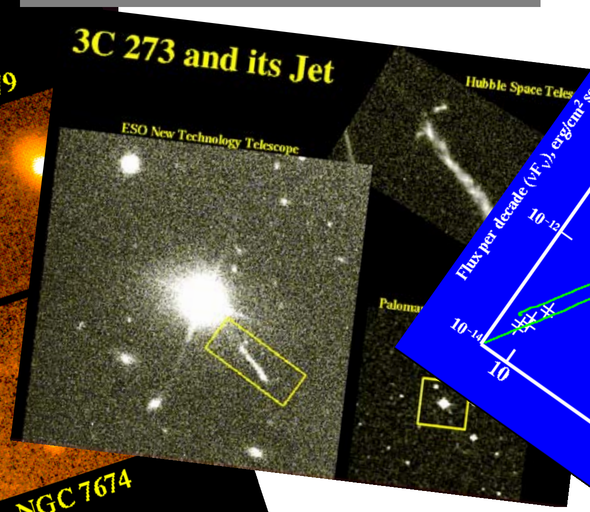


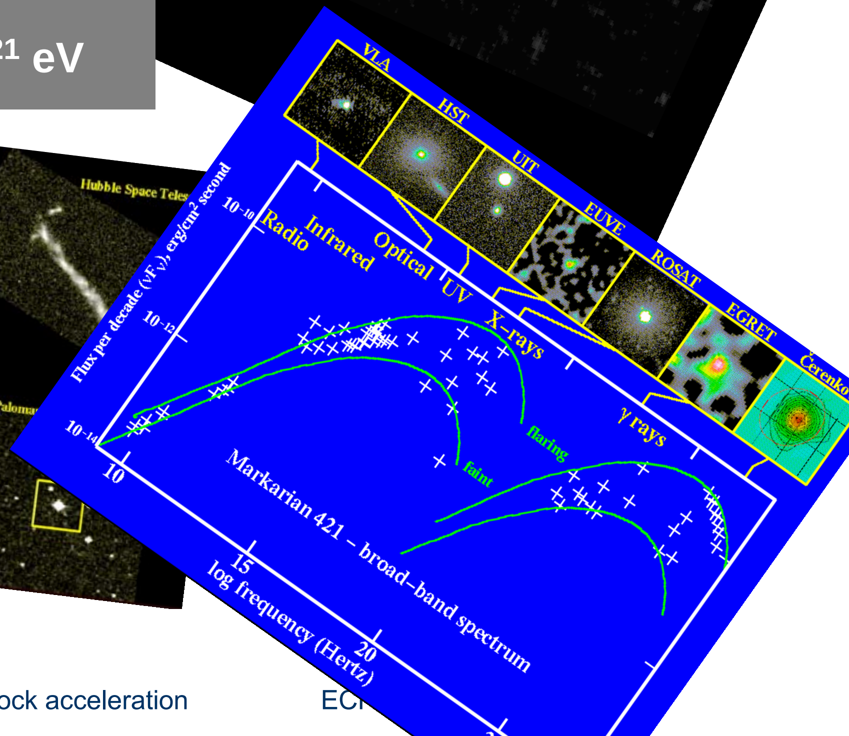
$L \sim 10^{46}$ erg/s

$\Gamma \sim$ 10-30

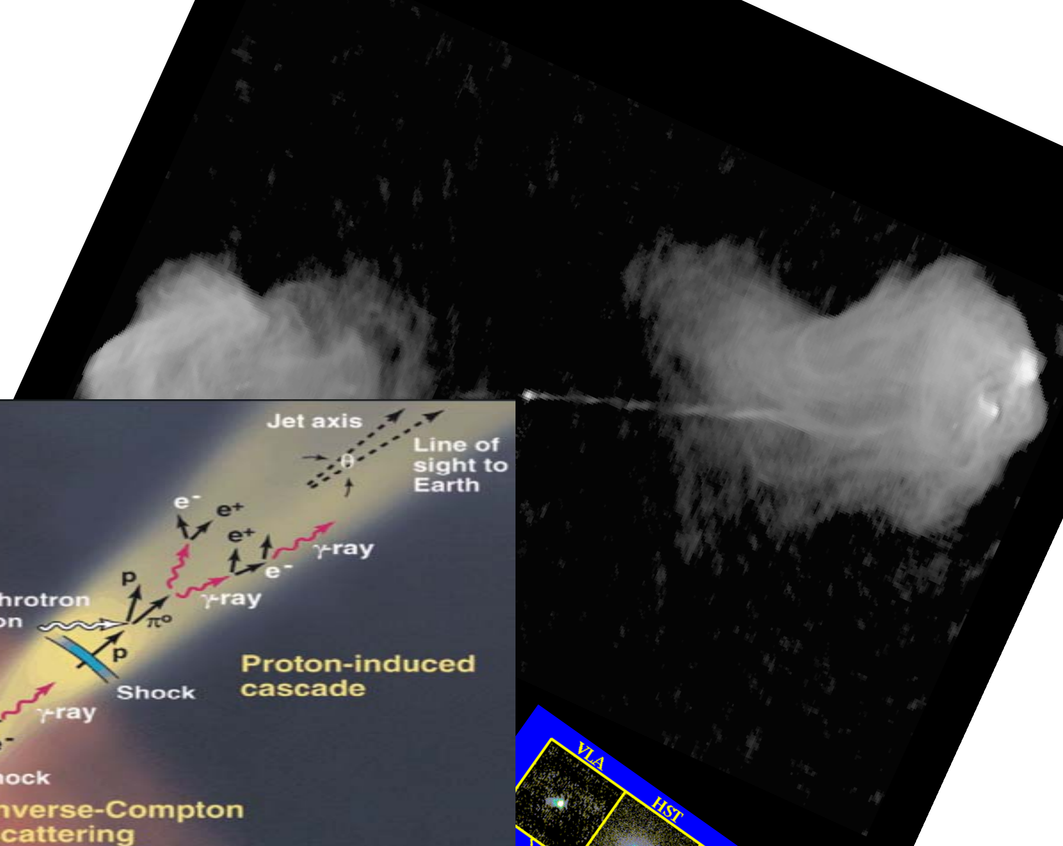
$E_{max} \sim 10^{19\text{-}21}$ eV

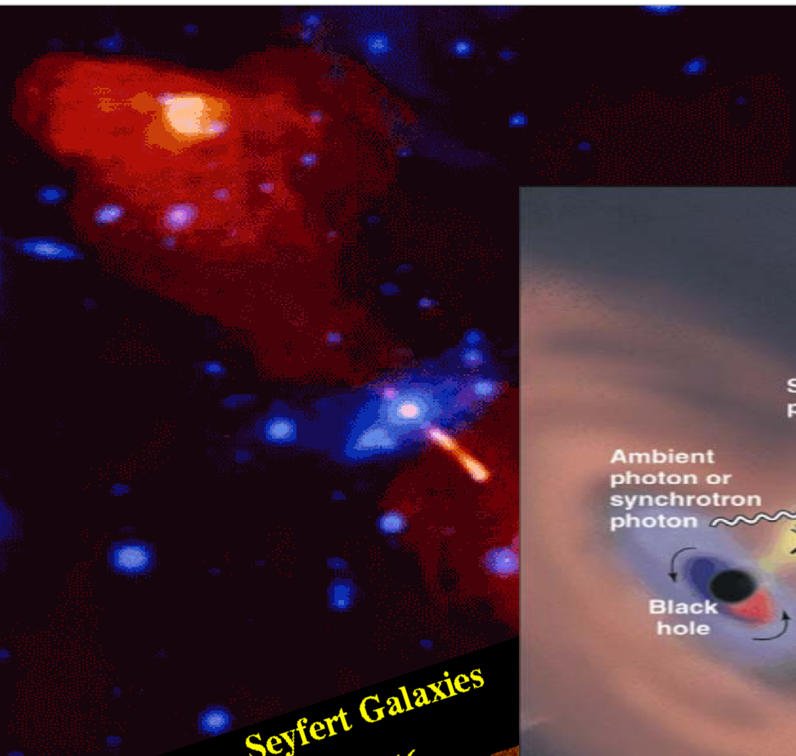


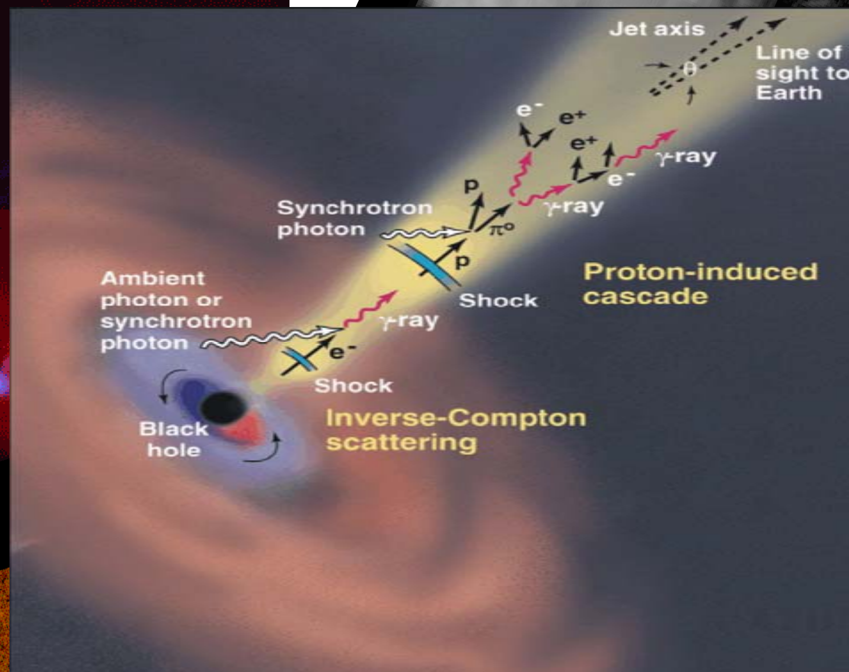


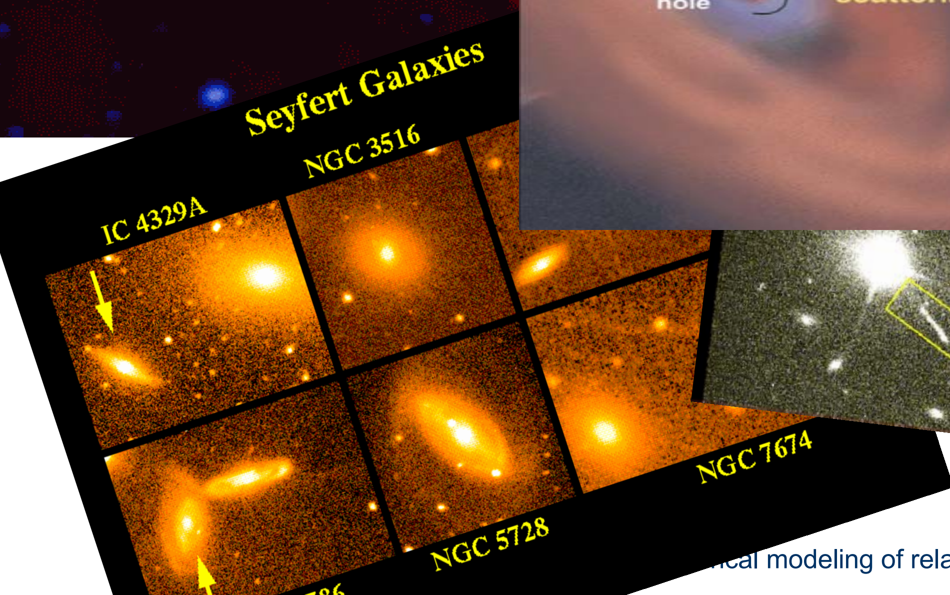


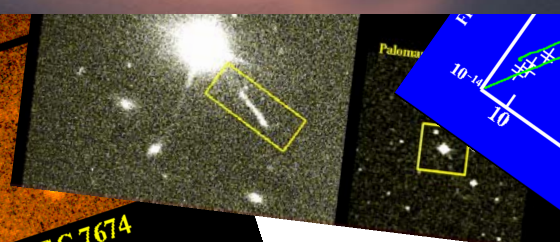
Active Galactic Nuclei case

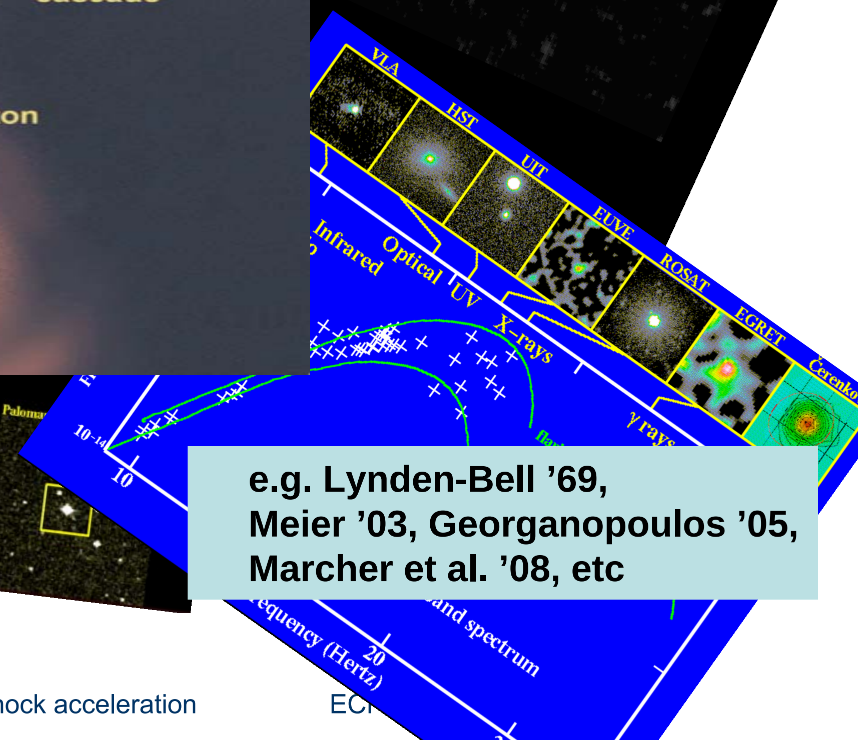






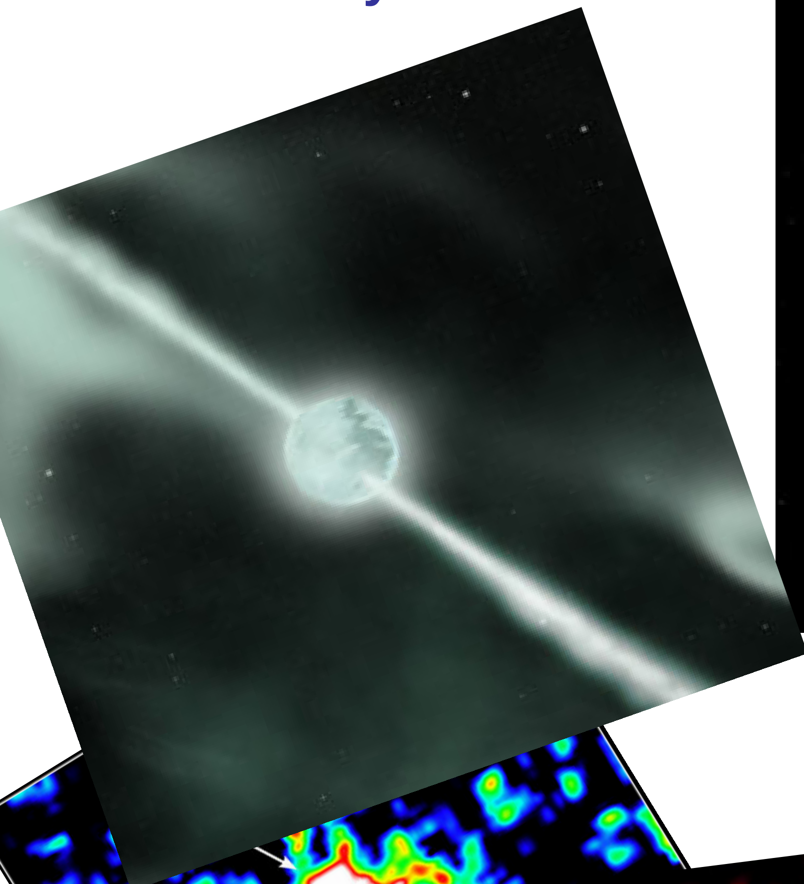


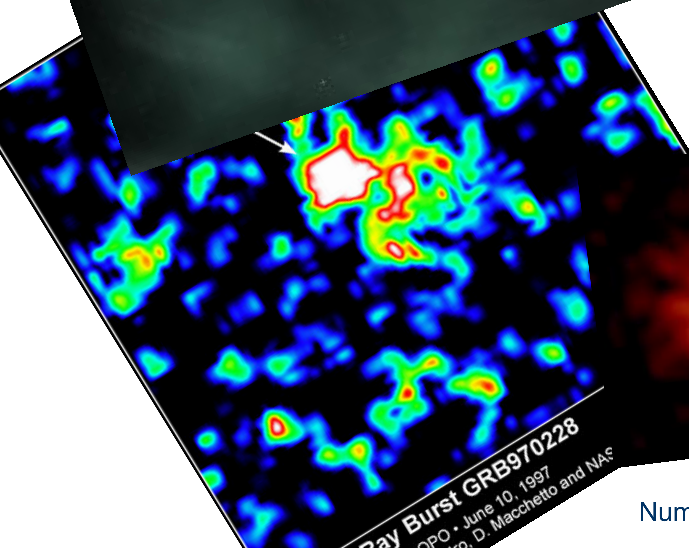


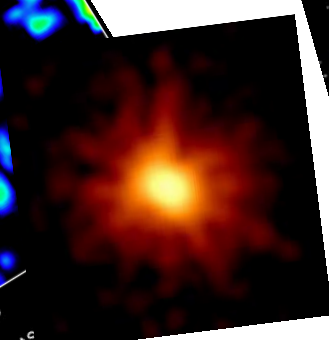


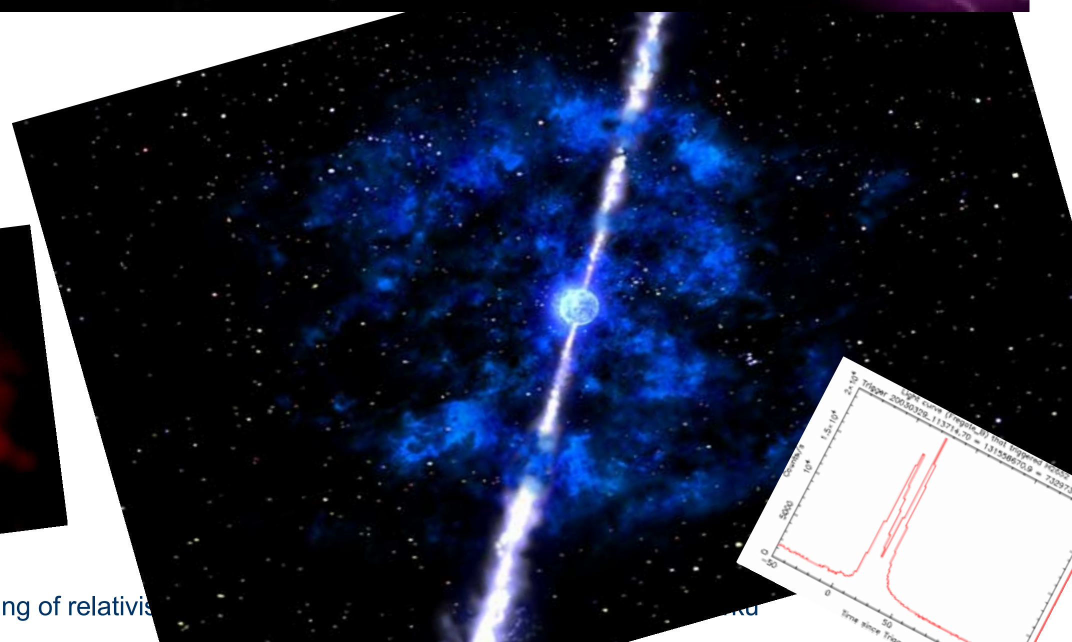
e.g. Lynden-Bell ’69,
Meier ’03, Georganopoulos ’05,
Marcher et al. ’08, etc

Gamma Ray Bursts case

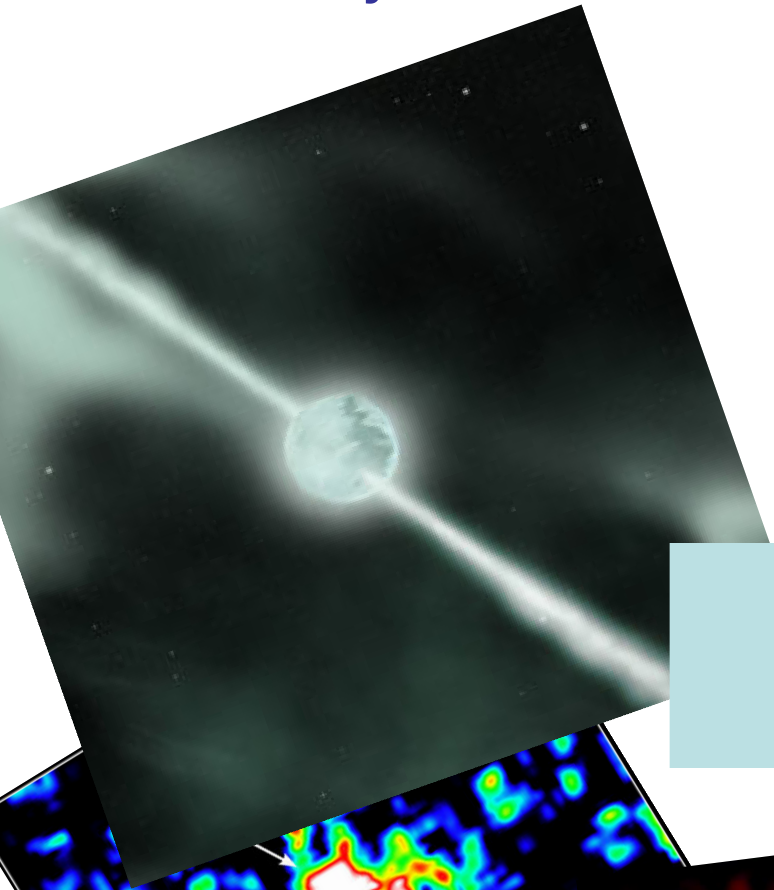


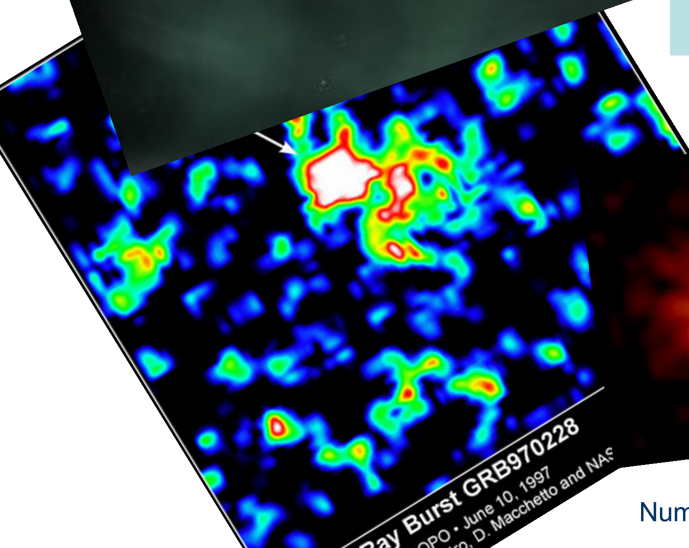


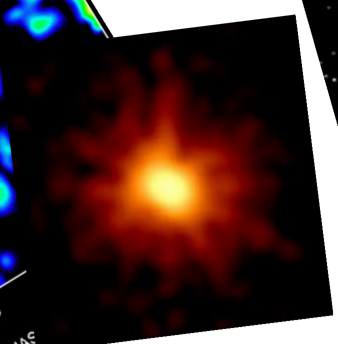


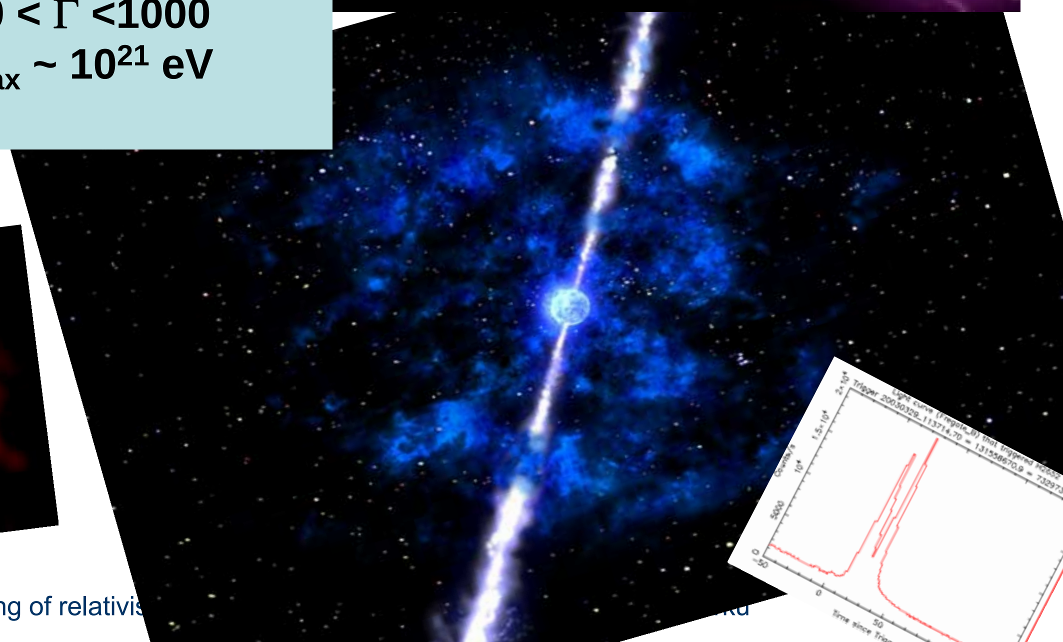


Gamma Ray Bursts case



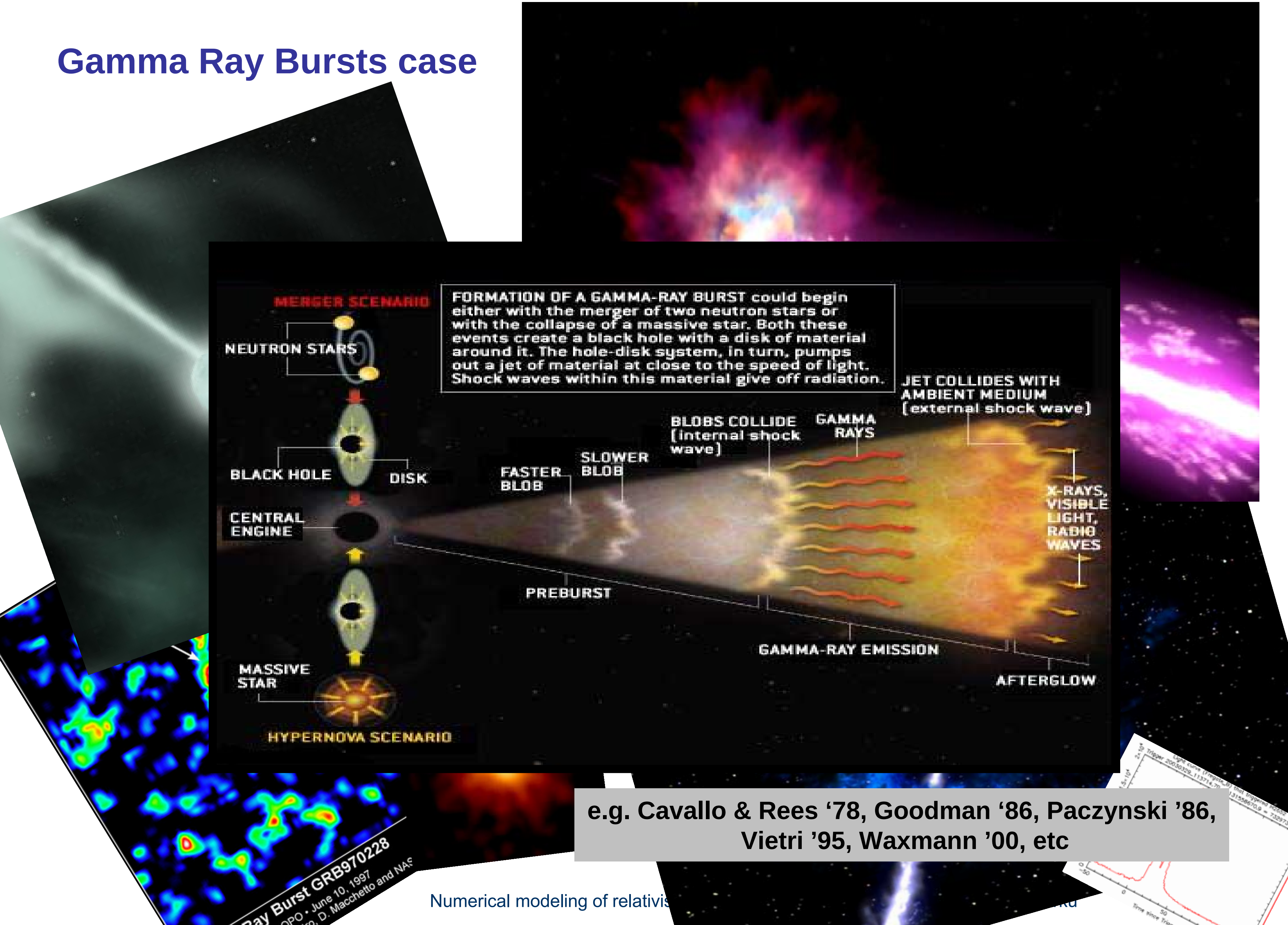






$L \sim 10^{51}$ erg/s
$100 < \Gamma < 1000$
$E_{max} \sim 10^{21}$ eV

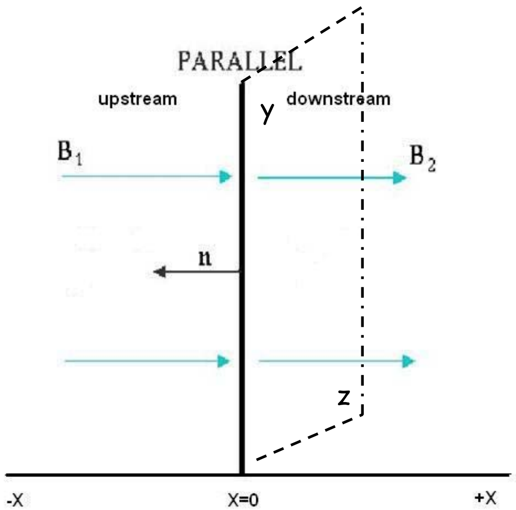
Gamma Ray Bursts case



e.g. Cavallo & Rees ‘78, Goodman ‘86, Paczynski ’86, Vietri ’95, Waxmann ’00, etc

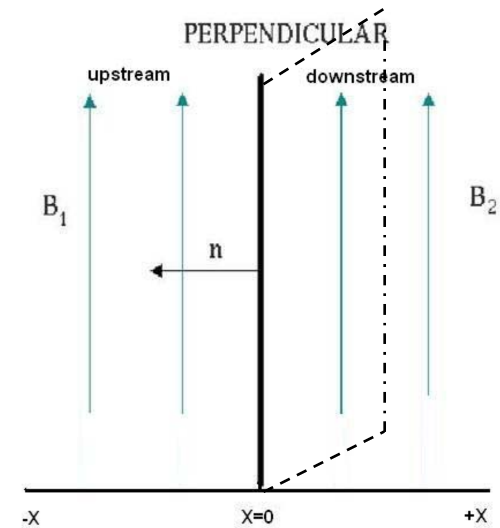
Shocks

Jump conditions and shock inclinations



Rankine-Hugoniot conditions

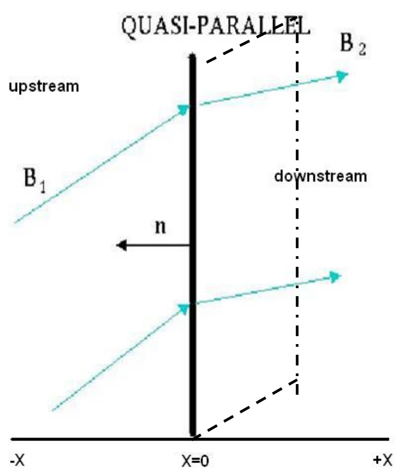
For a stationary HD shock (1D)



$$\rho_1 u_1 = \rho_2 u_2$$

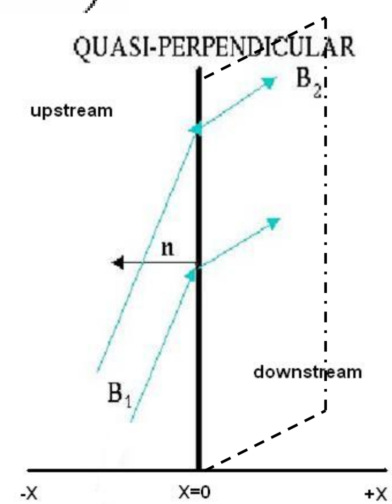
$$\rho_1 u_1^2 + p_1 = \rho_2 u_2^2 + p_2$$

$$\rho_1 u_1 \left(e_1 + \frac{1}{2} u_1^2 + p_1/\rho_1 \right) = \rho_2 u_2 \left(e_2 + \frac{1}{2} u_2^2 + p_2/\rho_2 \right).$$



$$\frac{\rho_2}{\rho_1} = \frac{\frac{p_2}{p_1}(\gamma+1) + (\gamma-1)}{(\gamma+1) + \frac{p_2}{p_1}(\gamma-1)} = \frac{u_1}{u_2}$$

$$\frac{p_2}{p_1} = \frac{\frac{\rho_2}{\rho_1}(\gamma+1) - (\gamma-1)}{(\gamma+1) - \frac{\rho_2}{\rho_1}(\gamma-1)}.$$



Rankine (1870), Hugoniot (1887)
Parker (1965), Hudson (1965), Parks (1984), etc

Particle shock acceleration mechanism

Particle shock acceleration mechanism

No doubt collisionless astrophysical shocks accelerate particles

Convincing evidence for efficient acceleration in heliospheric shocks and in young SNRs

1st order Fermi acceleration
Non-relativistic shocks

- **Test particle - diffusion - *n* acceleration shock cycles**

$$E_n = (x+1)^n \cdot E_0$$

(e.g. Krymskii '77, Bell '78a,b, Drury '83, etc)

- **Energy gain: fraction of initial energy**

$$\Delta E = E - E_0 = x \cdot E_0$$

- **Average energy gain per collision:**

$$< \Delta E / E > \cong (2V/c)$$

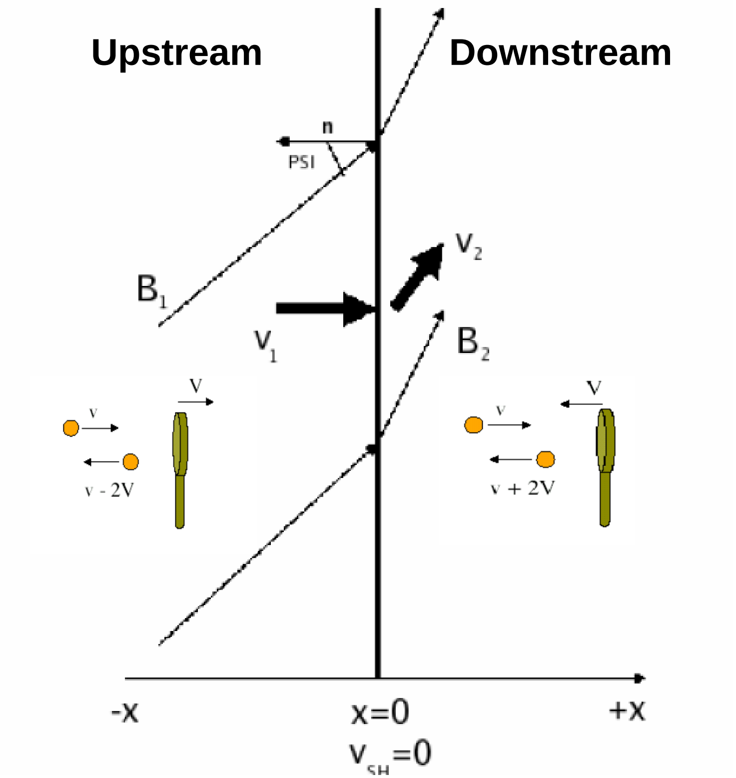
- **Leading to a power-law energy behaviour**

$$N(>E) = \sum_{i=n}^{\infty} (1 - P_{esc})^{n(E)} = \ldots \propto E^{-\sigma}$$

$$\sigma = (r+2)/(r-1), \quad r = V_1/V_2 = (\gamma+1)/(\gamma-1)$$

for mono-atomic gas:

$\gamma = 5/3 \rightarrow r = 4 \rightarrow E^{-2}$



Note: For relativistic shocks V~c **and particle distributions are *not* isotropic across reference frames – difficult analytically**

Facts for *non-relativistic* shock acceleration:

- **Particles are everywhere in <u>isotropy</u> and the diffusive approximation for solution of the transport equation can apply**
- **Spectral index <u>independent</u> of: inclination, scattering nature, strength of magnetic field**

Concepts are well understood and well studied - they work nicely as a comparison basis for *<u>relativistic</u>* studies

Modeling relativistic shock acceleration

Four techniques

- **Semi-analytic (simplified) solutions to diffusion-convection equation**

  (e.g. Eichler ’84, Berezhko & Ellison ’99, Blasi & Gabici ‘02-’05, etc)

- **Numerical solutions to diffusion-convection equation with flow hydrodynamics & momentum dependent diffusion**

  (e.g. Berezhko, Voelk et al. ‘96, Kang & Jones ‘91-’05, Malkov ‘97-’01, etc)

- **Monte Carlo simulations** (!)

  (e.g. Ellison et al. ‘81-’05, Baring ‘03-’05, Meli & Quenby ‘03-’05 etc)

- **Particle-in-cell (PIC) plasma simulations**

  (e.g. Nishikawa et al. ’05, Meli & Dieckmann ‘10, etc)

Monte Carlo technique

- Random number generation → simulation of the random nature of a physical process (Cashwell & Everett ’59)
- *Powerful tool* – large dynamic ranges in spatial and momentum scales
- Notion of ‘test particles’ - very efficient & very fast in describing particle random walks - large number of particles
- Scattering can be treated via pitch angle diffusion approach (e.g. Kennel & Petscheck ’66, Forman et al. ’74, Jokipii ’87, Quenby & Meli ’05, Meli & Biermann ‘06)

$$\kappa_\perp = \kappa_\| \cdot (1 + (\lambda/r_l)^2)^{-1} \qquad \kappa = \kappa_\| \cos^2\psi + \kappa_\perp \sin^2\psi \qquad \kappa_\| \gg \kappa_\perp \quad (!)$$

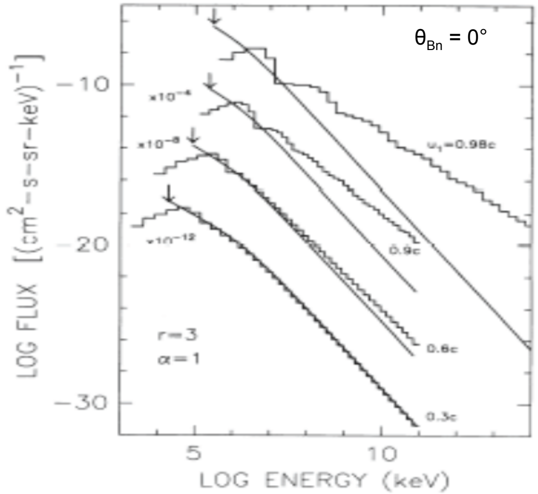
Particles scatter as (Kennel&Petscheck ’66):

$$\delta\theta^2 = 2D_\theta \delta t \qquad \delta\theta^2 = \frac{25}{\Gamma^2} = \frac{2\omega^2}{\upsilon_\| B^2} P_\circ(k) \frac{\omega^s}{\upsilon_\|^s} \frac{10\sqrt{3}\upsilon_\perp}{c\,\omega}$$

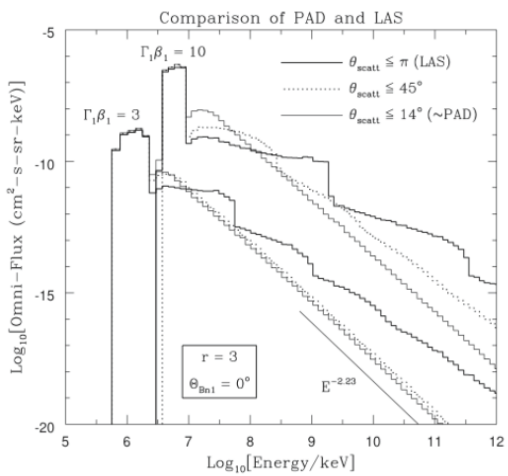
- Fully relativistic Lorentzian transformations

Simulation studies
on relativistic shocks:
flow speed, inclination, scattering

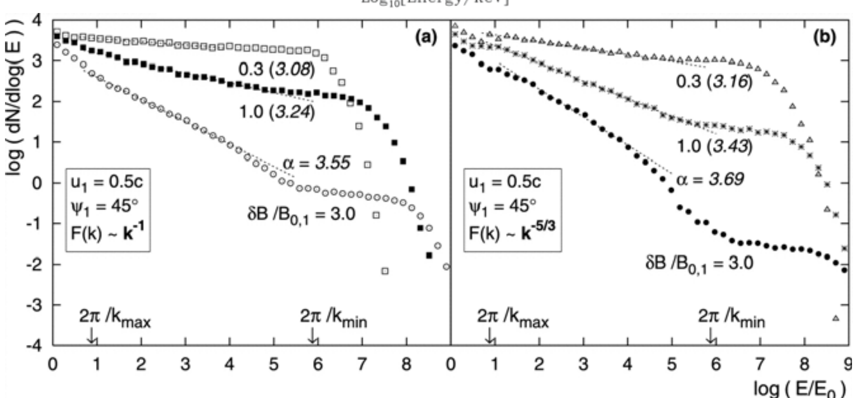
Spectra



Ellison et al. ’90



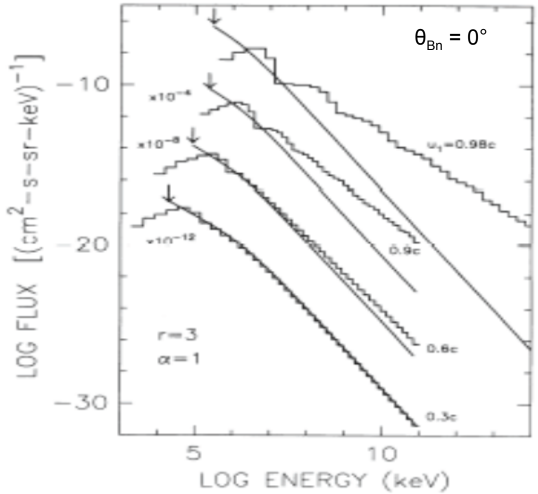
Baring ‘04



Niemec & Ostrowski ‘04

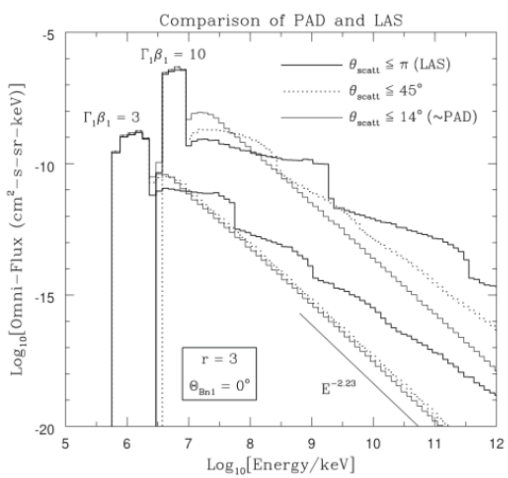
- Spectrum flattens with velocity
- Spectrum depends on the scattering type – magnetic field configurations
- Large angle scattering yields kinematically structured distributions

Spectra



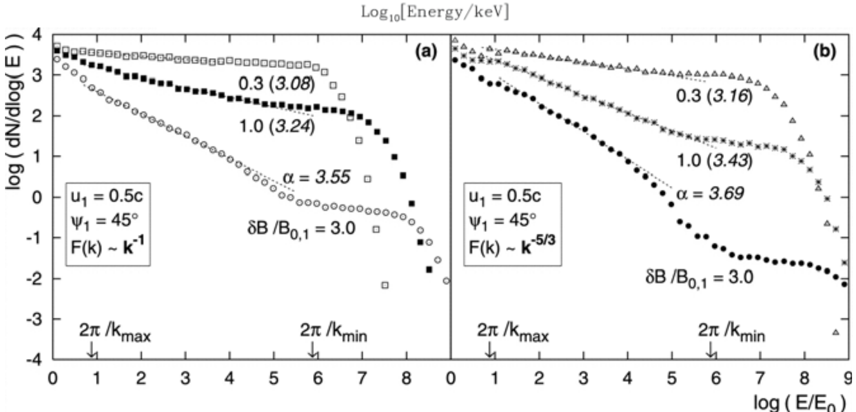
Ellison et al. '90

- **Spectrum flattens with velocity**
- **Spectrum depends on the scattering type – magnetic field configurations**
- **Large angle scattering yields kinematically structured distributions**



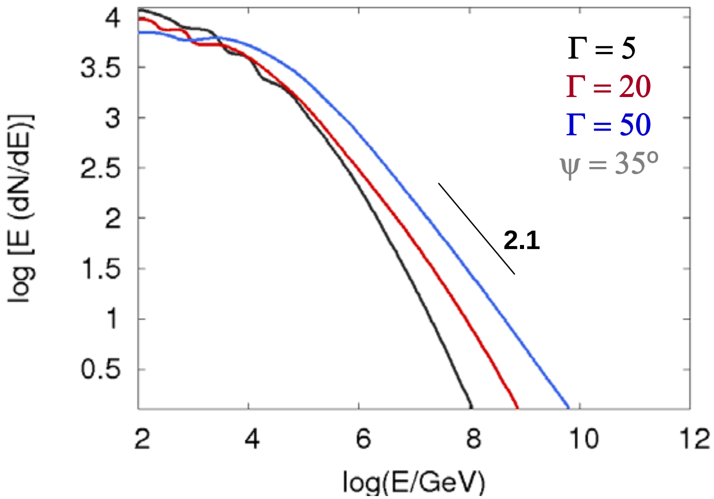
Baring '04

Note: 'Universal power-law of *-2.2*'
(e.g Achterberg et al '01, etc)
→ *only* for 'fine scattering' &
***parallel* relativistic shocks!**

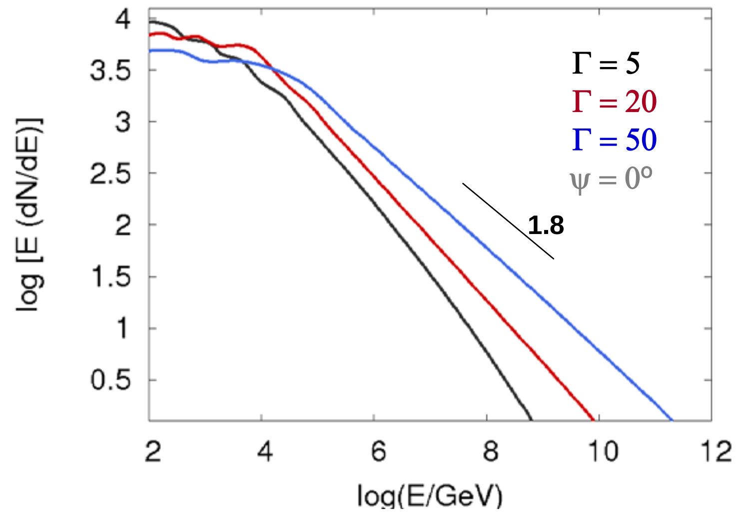


Niemec & Ostrowski '04

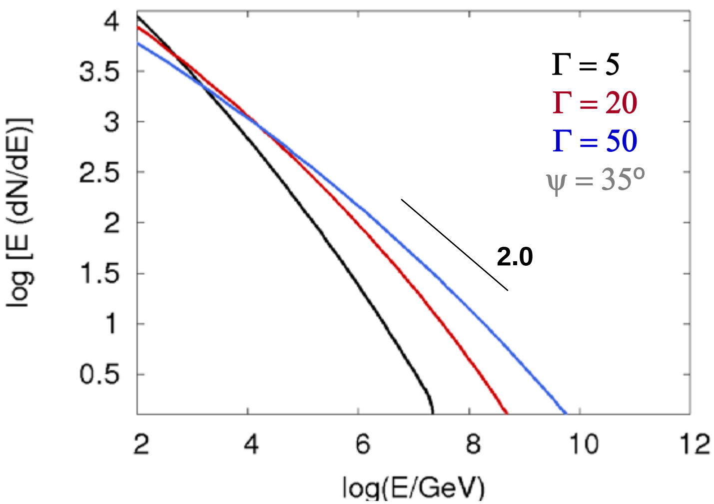
Oblique shock
Scattering : $\theta < \pi$



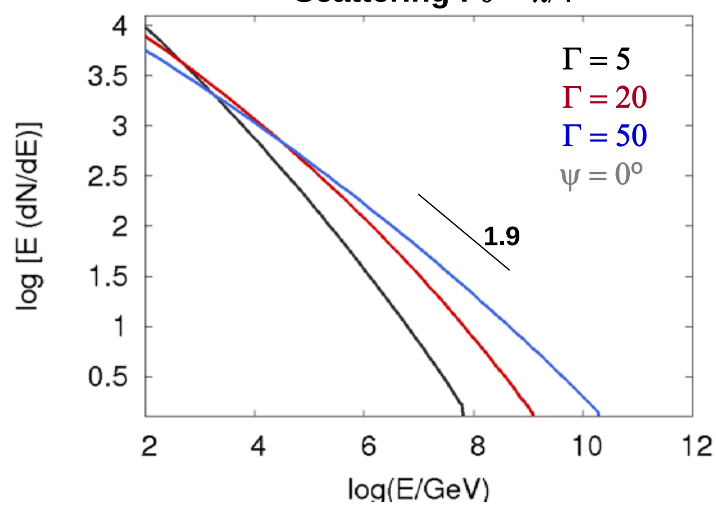
Parallel shock
Scattering : $\theta < \pi$



Oblique shock
Scattering : $\theta < \pi/4$

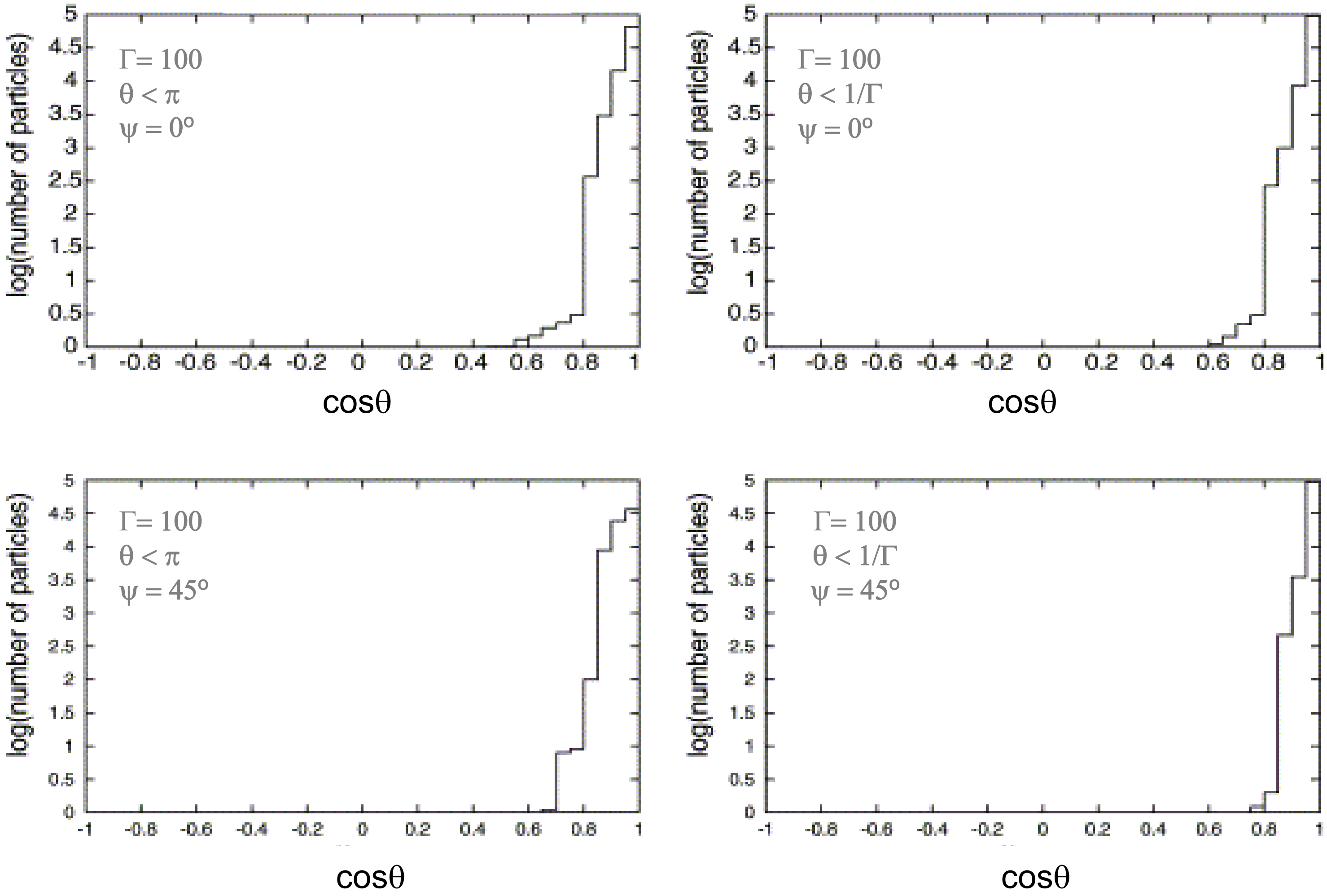


Parallel shock
Scattering : $\theta < \pi/4$



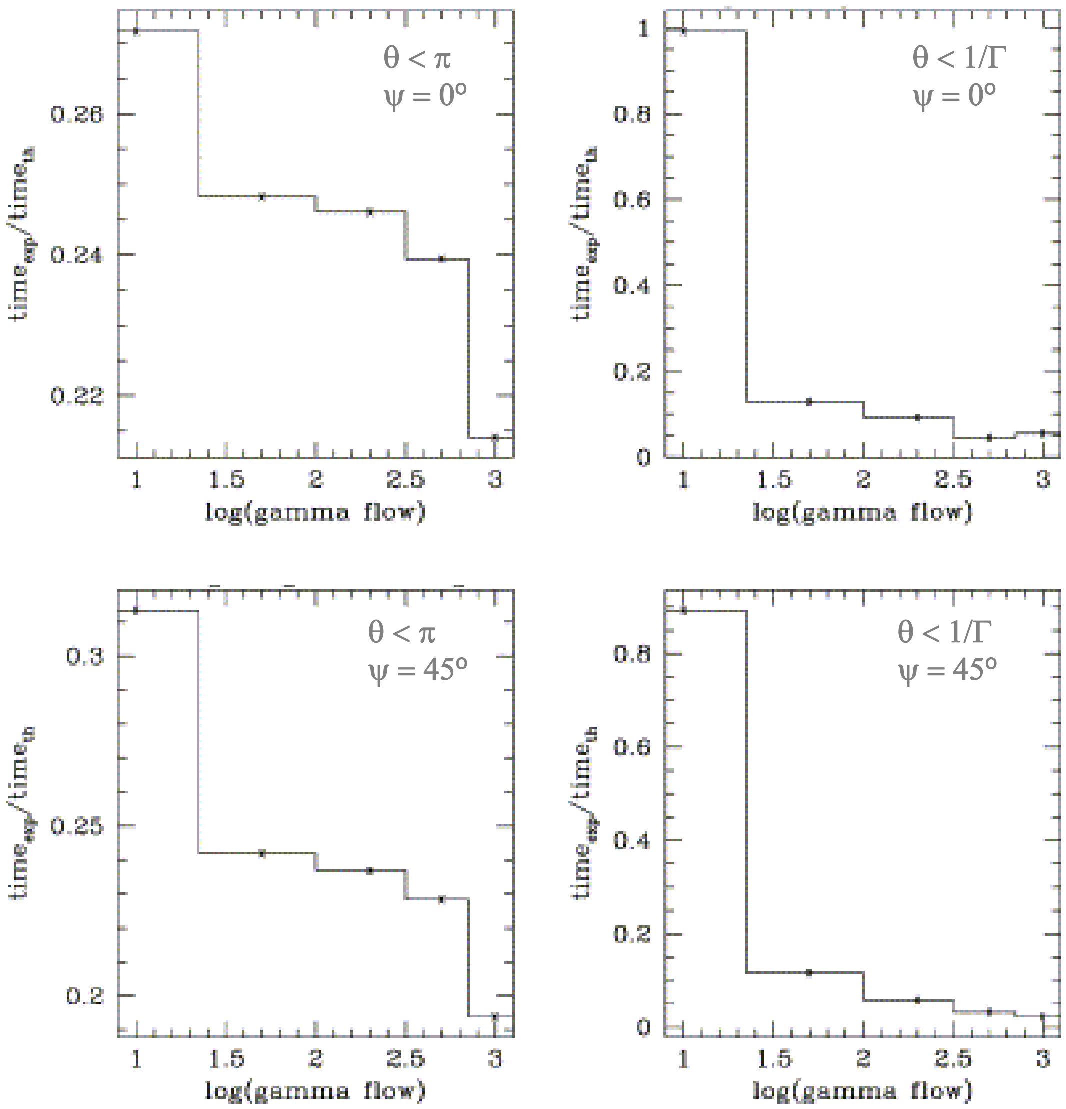
Meli & Quenby ’02

Angular distribution anisotropy



Meli & Quenby '03a

Acceleration ‘speed-up’

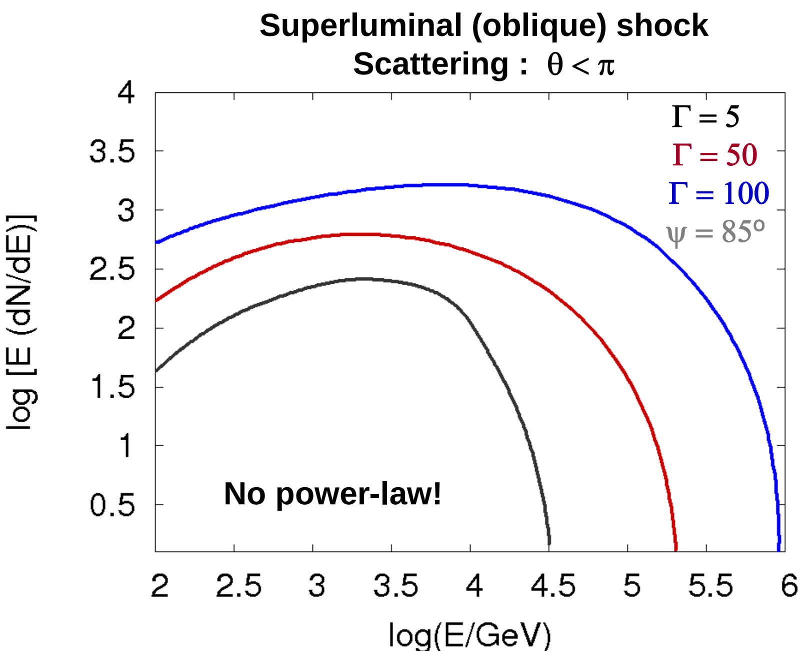


The ratio of the simulation time $time_{exp}$ to the theoretical accel. time constant $time_{th}$
***Versus* the log of flow speed**

$$time_{th}(E) = [3/(V_1-V_2)](\kappa_1/V_1 + \kappa_2/V_2)]$$

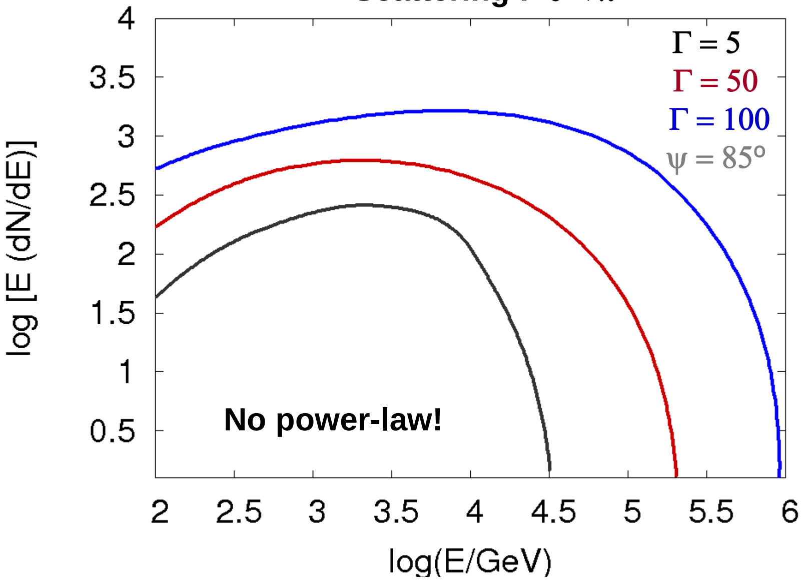
Meli & Quenby ’03b

Applications to UHECR & extragalactic astronomy



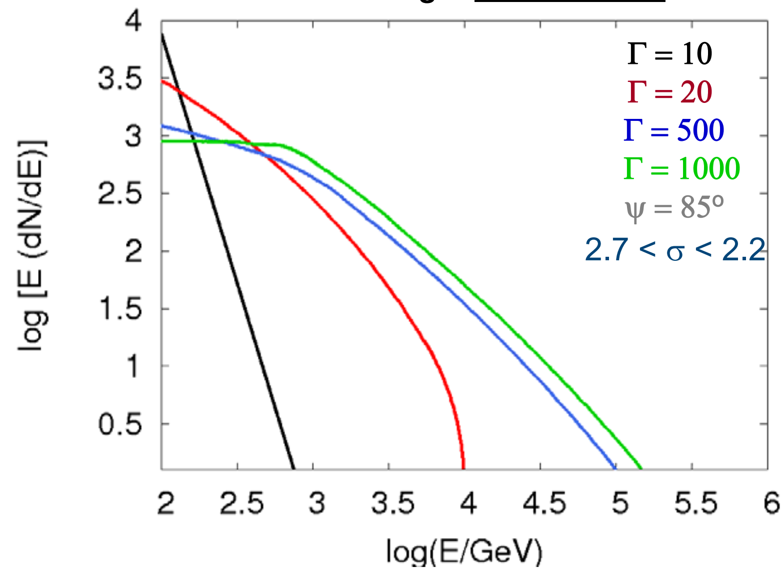
Meli & Quenby ’05

Superluminal (oblique) shock
Scattering : $\theta < \pi$



Meli & Quenby '05

Superluminal (oblique) shock
Scattering : $1/\Gamma < \theta < 10/\Gamma$

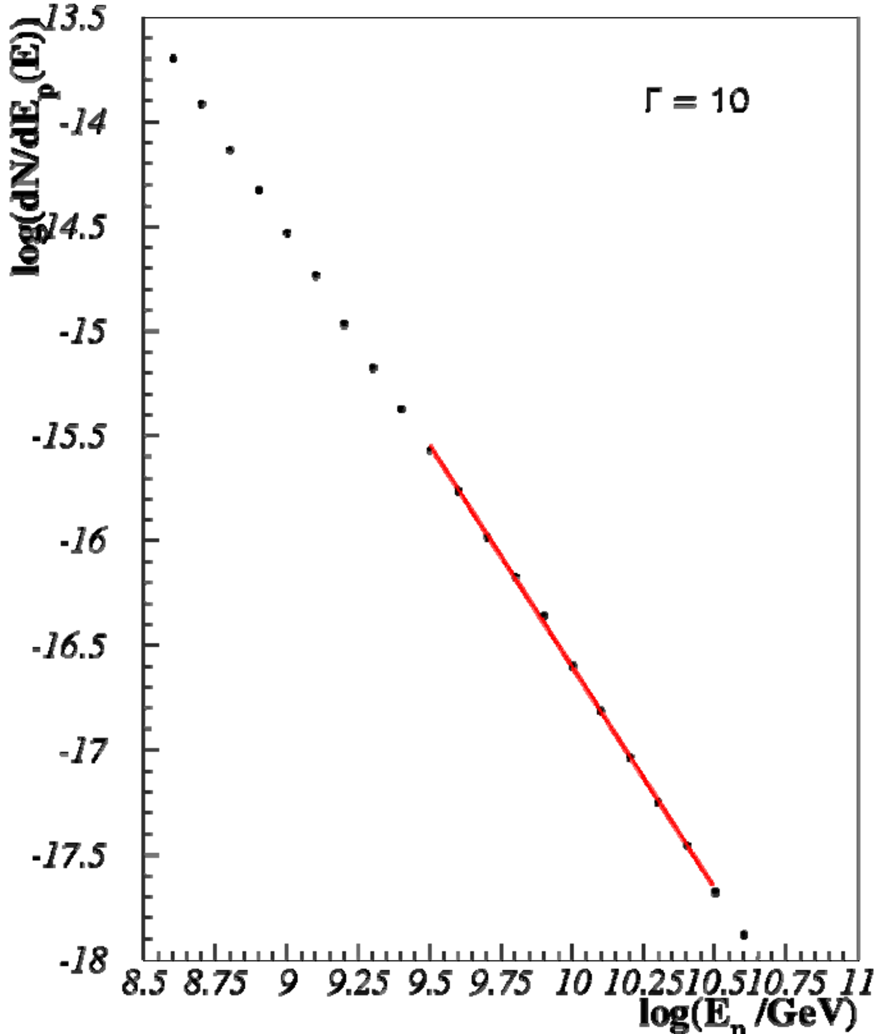


Meli, Becker, Quenby '08

Superluminal shocks → not efficient accelerators

Subluminal (oblique) shocks
Scattering : $1/\Gamma < \theta < 10/\Gamma$

Γ_{sh}	s (ψ_{sh}= 23°)	s (ψ_{sh}= 33°)	s (ψ_{sh}= 43°)
10	2.1	2.1	2.3
20	2.0	2.0	2.3
30	2.1	2.0	2.2
100	1.8	1.8	2.2
300	2.0	1.8	2.0
500	1.9	1.7	1.6
700	1.8	1.4	1.7
900	1.5	1.0	1.3
1000	1.2	1.2	1.5



Meli, Becker, Quenby '08

Subluminal (oblique) shocks
Scattering : 1/Γ < θ < 10/Γ

Γ_{sh}	s (ψ_{sh}= 23°)	s (ψ_{sh}= 33°)	s (ψ_{sh}= 43°)
10	2.1	2.1	2.3
20	2.0	2.0	2.3
30	2.1	2.0	2.2
100	1.8	1.8	2.2
300	2.0	1.8	2.0
500	1.9	1.7	1.6
700	1.8	1.4	1.7
900	1.5	1.0	1.3
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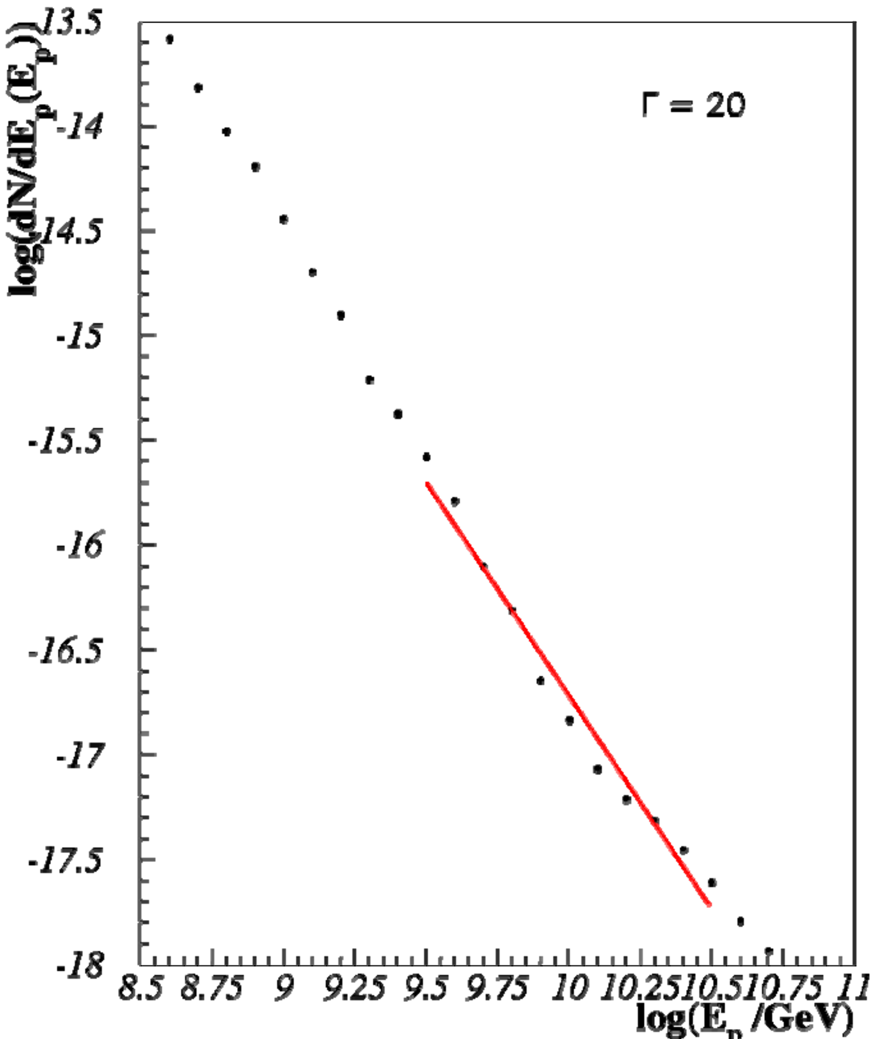

Meli, Becker, Quenby '08

Subluminal (oblique) shocks
Scattering : $1/\Gamma < \theta < 10/\Gamma$

Γ_{sh}	s (ψ_{sh}= 23°)	s (ψ_{sh}= 33°)	s (ψ_{sh}= 43°)
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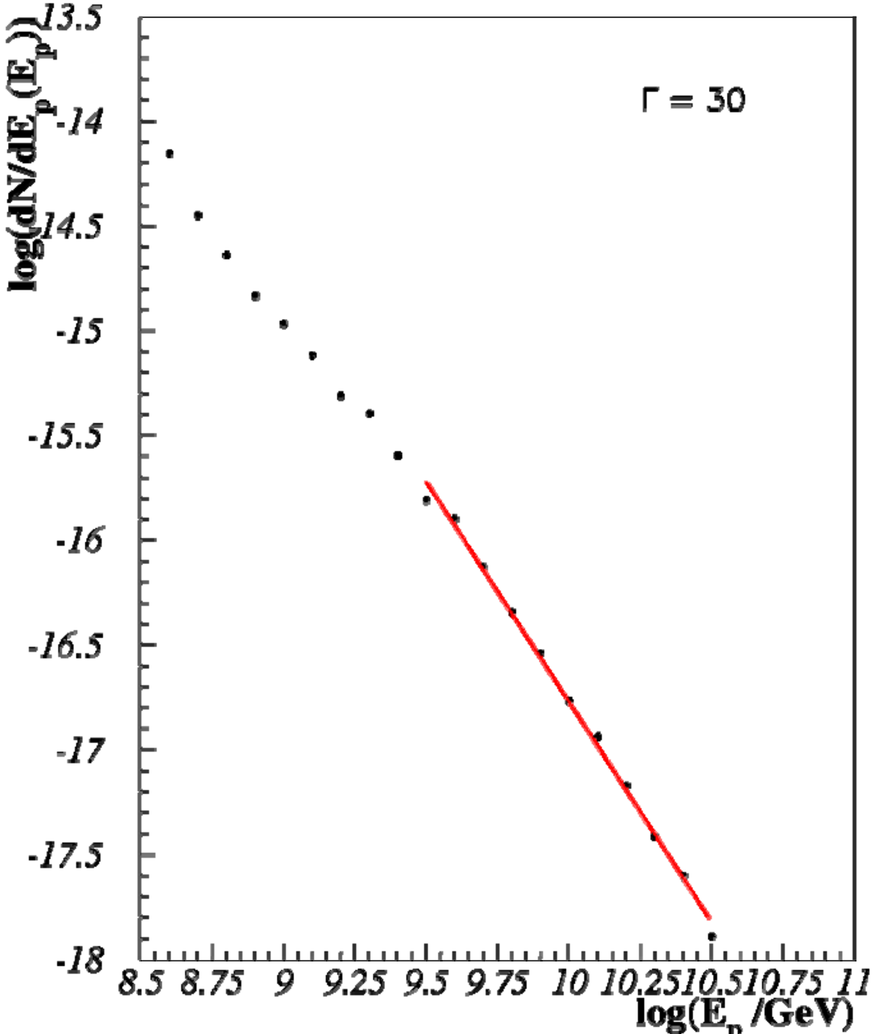
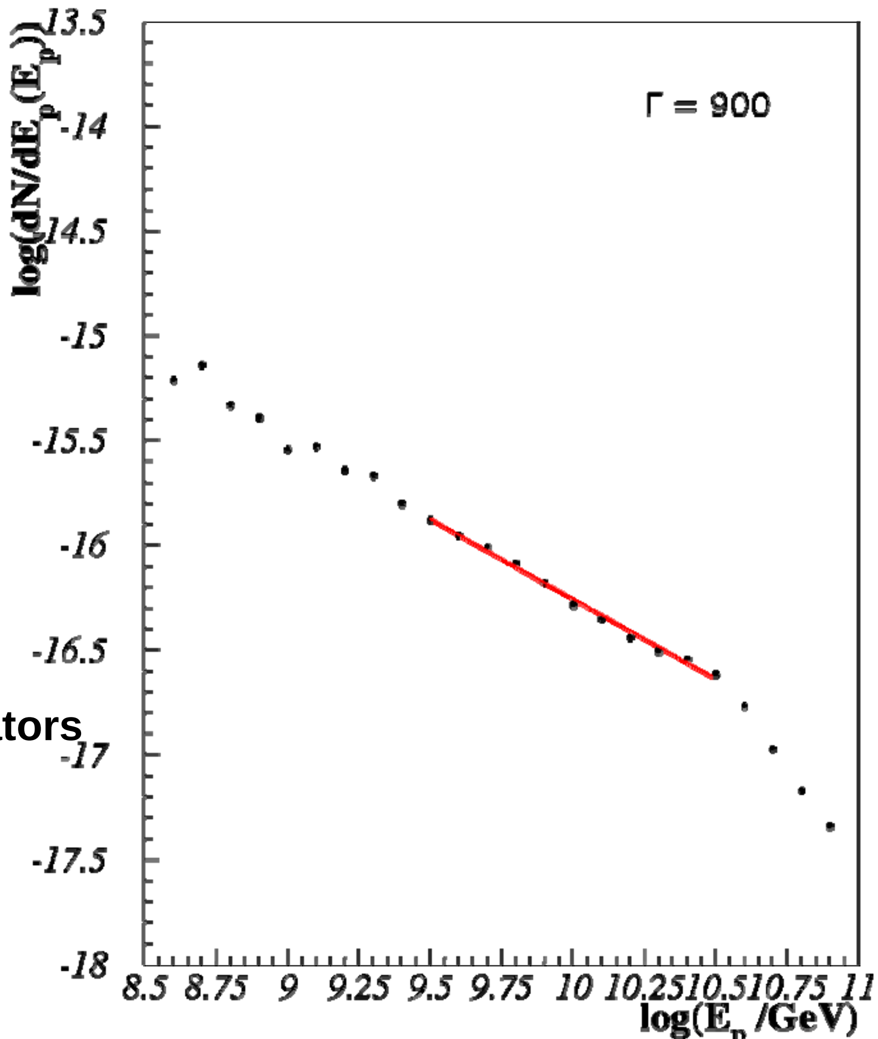


Meli, Becker, Quenby '08

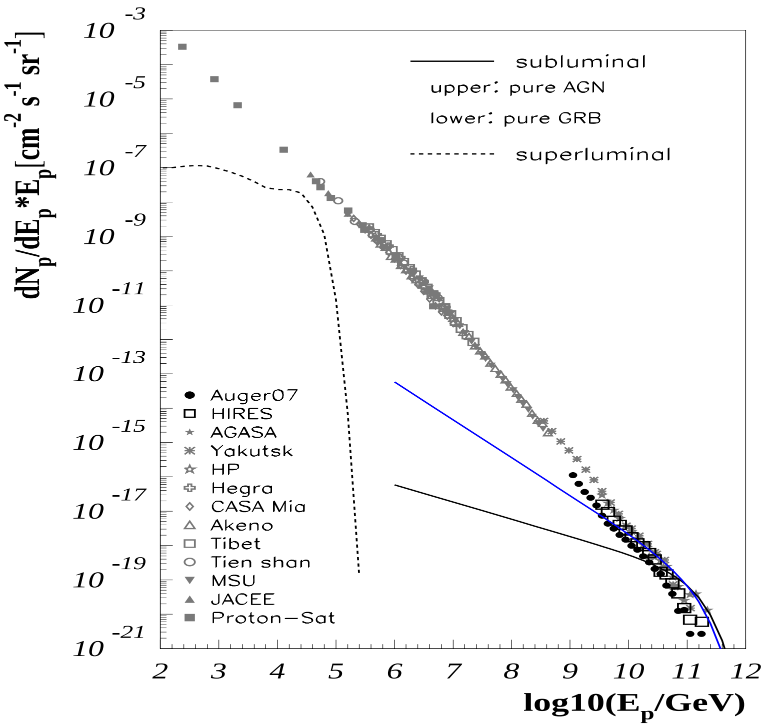
Subluminal (oblique) shocks
Scattering : $1/\Gamma < \theta < 10/\Gamma$

Γ_{sh}	$s\ (\psi_{sh} = 23°)$	$s\ (\psi_{sh} = 33°)$	$s\ (\psi_{sh} = 43°)$
10	2.1	2.1	2.3
20	2.0	2.0	2.3
30	2.1	2.0	2.2
100	1.8	1.8	2.2
300	2.0	1.8	2.0
500	1.9	1.7	1.6
700	1.8	1.4	1.7
900	1.5	1.0	1.3
1000	1.2	1.2	1.5



Subluminal shocks → Efficient (flat) accelerators

Meli, Becker, Quenby '08



The total spectrum as observed at Earth

$$\frac{\mathrm{d}N_\mathrm{p}}{\mathrm{d}E_\mathrm{p}} = A_\mathrm{p}\int_{z_\mathrm{min}}^{z_\mathrm{max}}\left(x\cdot\frac{\mathrm{d}\Phi_\mathrm{AGN}}{\mathrm{d}E_\mathrm{p}}(E_\mathrm{p}(z)) + (1-x)\cdot\frac{\mathrm{d}\Phi_\mathrm{GRB}}{\mathrm{d}E_\mathrm{p}}(E_\mathrm{p}(z))\right) \times (1+z)^{-1}\cdot\exp\left(-\frac{E_\mathrm{p}(z)}{E_\mathrm{cut}(z)}\right)\cdot g(z)\mathrm{d}z \qquad (1$$

Assumption: UHECRs from AGN contribute a fraction $0 \leq x \leq 1$ **and for GRBs** 1-x **with** $0.001<z<7$
(main contribution: z~1-2 → **high no.of sources)**

1a. The diffuse energy spectrum of sources, compared to the total diffuse spectrum
(Meli, Becker, Quenby '08)

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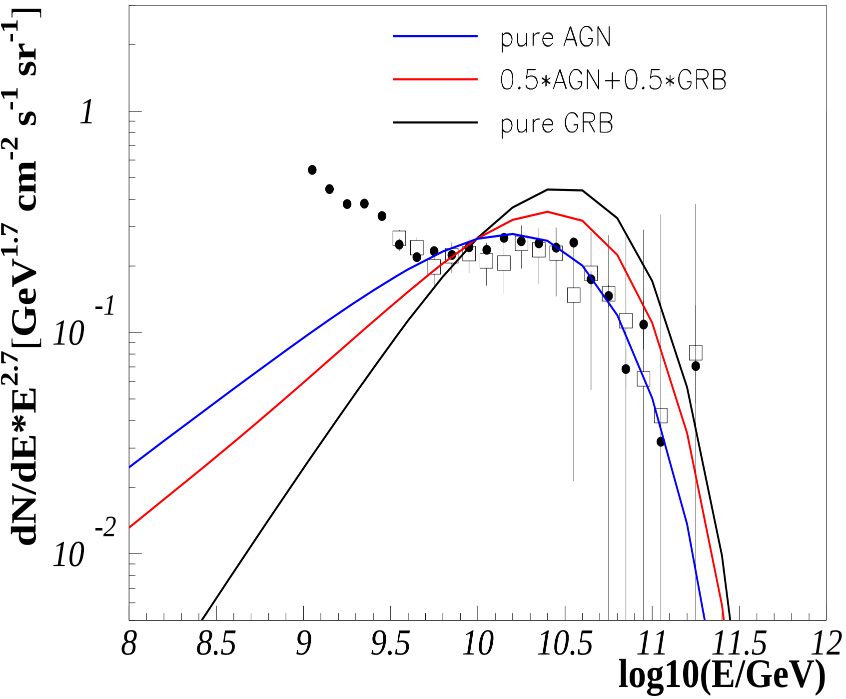
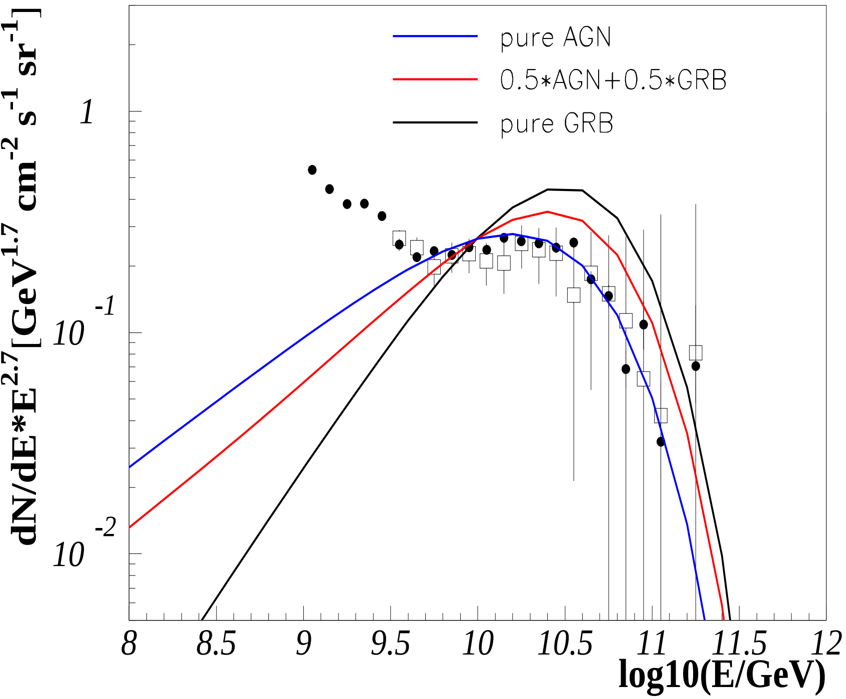


1b. The diffuse energy spectrum of sources, multiplied by an $E^{2.7}$, compared to the total diffuse spectrum. Dots and squares correspond to Hires and Auger data.

The total spectrum as observed at Earth

$$\frac{dN_p}{dE_p} = A_p \int_{z_{min}}^{z_{max}} \left(x \cdot \frac{d\Phi_{AGN}}{dE_p}(E_p(z)) + (1-x) \cdot \frac{d\Phi_{GRB}}{dE_p}(E_p(z)) \right) \times (1+z)^{-1} \cdot \exp\left(-\frac{E_p(z)}{E_{cut}(z)} \right) \cdot g(z) dz \qquad ($$

Assumption: UHECRs from AGN contribute a fraction $0 \le x \le 1$ and for GRBs $1-x$ with $0.001 < z < 7$ (main contribution: $z \sim 1$-2 → high no.of sources)



The total spectrum as observed at Earth

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Assumption: UHECRs from AGN contribute a fraction $0 \leq x \leq 1$ **and for GRBs** $1-x$ **with** $0.001<z<7$ **(main contribution:** z~1-2 → **high no.of sources)**

The diffuse energy spectrum of sources, multiplied by an $E^{2.7}$**, compared to the total diffuse spectrum. Dots and squares correspond to Hires and Auger data.**

2. Flat spectra recent confirmation: GRB090816c → E$^{-1.2}$ **- E**$^{-2.0}$ (Meli et al. ‘09)

Conclusions

High energy cosmic ray acceleration in astrophysical shocks is

a favourable and attractive theme of study (especially numerically)

Relativistic shocks:

- **Power-law spectrum and σ of -2.2 not universal ! (observations confirm)**
- **Relativistic shocks can generate very high energy cosmic rays with a multitude of spectral forms, power-law incides dependent on shock parameters: flow speed, inclination and scattering properties :**

→ **Faster shocks generate flatter primary distributions:**

- **Subluminal shocks (quasi-parallel) *efficient* accelerators → ~10^{21} eV**

- **Superluminal (quasi-perpendicular) shocks *not* efficient → ~10^{15} eV**

→ **LAS ($\theta<\pi$): flatter distributions**

PAD ($\theta<<\pi$): steeper distributions (but still flat)

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Important implications to gamma-ray and neutrino astronomy!

Thank you !

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