Extragalactic sources and ultra-high energy cosmic rays

Athina Meli

(Peter Biermann, John Quenby, Julia Tjus, Paolo Ciarcelluti)

Faculty of Sciences
Department of Physics and Astronomy
University of Ghent
Belgium

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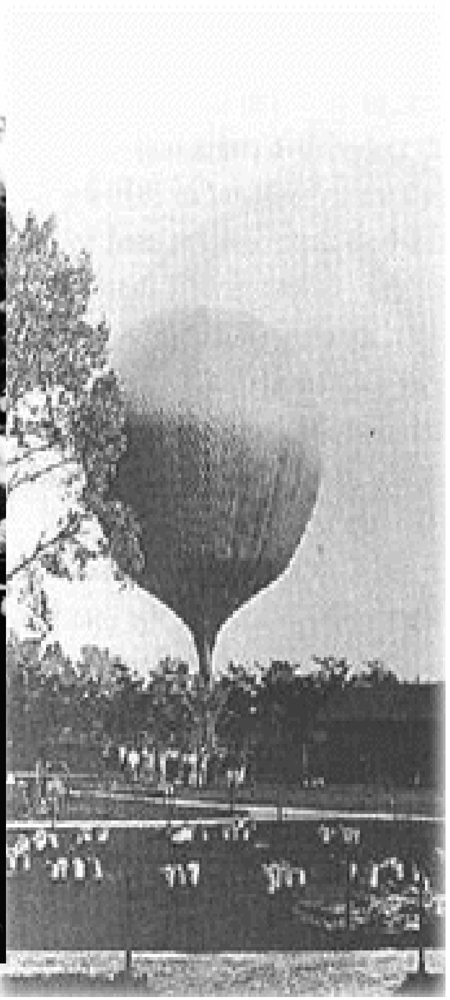
Outline

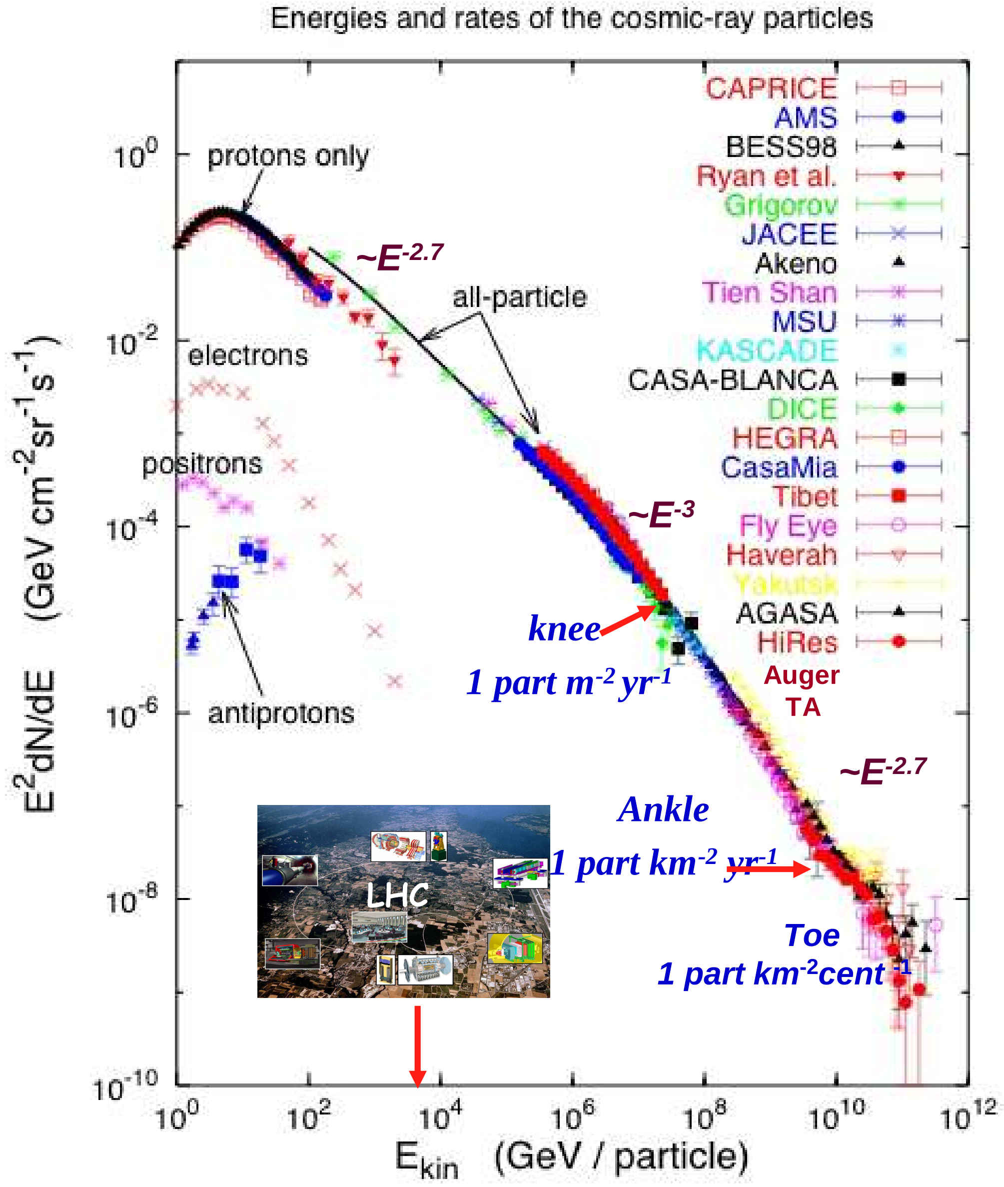
- **Cosmic-ray spectrum characteristics**
- **Sources (non- & relativistic)**
- **Shocks and jets**
  - **Properties**
  - **Particle acceleration mechanism**
- **Shock acceleration simulation studies *overview***
  - **Numerical method**
  - **Individual and multiple relativistic shocks in AGN**
  - **Propagation and radiation**
- **Conclusion**

Cosmic-rays



- ***Cosmic-rays* are subatomic particles & radiation of extra-terrestrial origin.**
- **First discovered in *1912* by *Victor Hess*, measuring radiation levels aboard a balloon up to 5300m**
- **Hess found increased radiation levels at higher altitudes: named it *Cosmic Radiation***

Cosmic-ray spectrum



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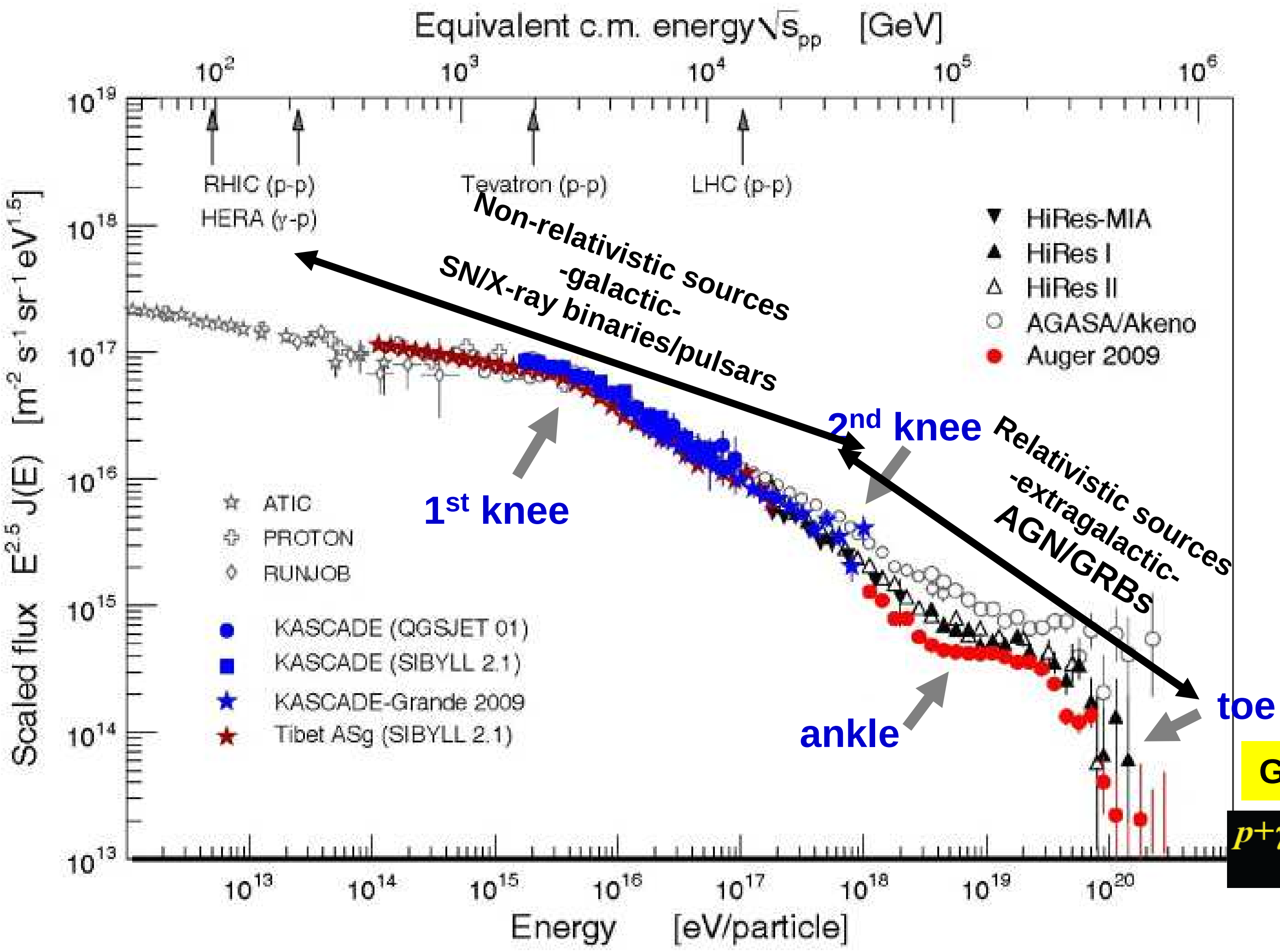
The high energy regime - ‘knee(s)’ & ‘ankle’



Or run-out of fuel ?

GZK cut-off ?

$$p+\gamma_{cmb} \rightarrow \Delta^+ \rightarrow p + \pi^0$$
$$\rightarrow n + \pi^+$$

Greizen, Zatsepin & Kumzin (1966)

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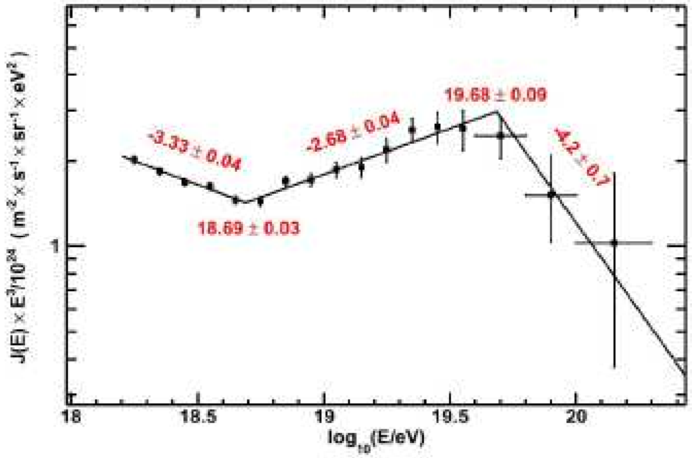
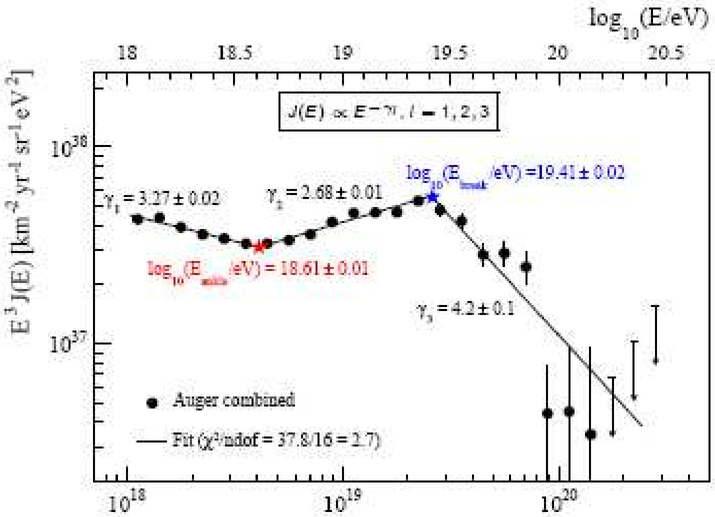
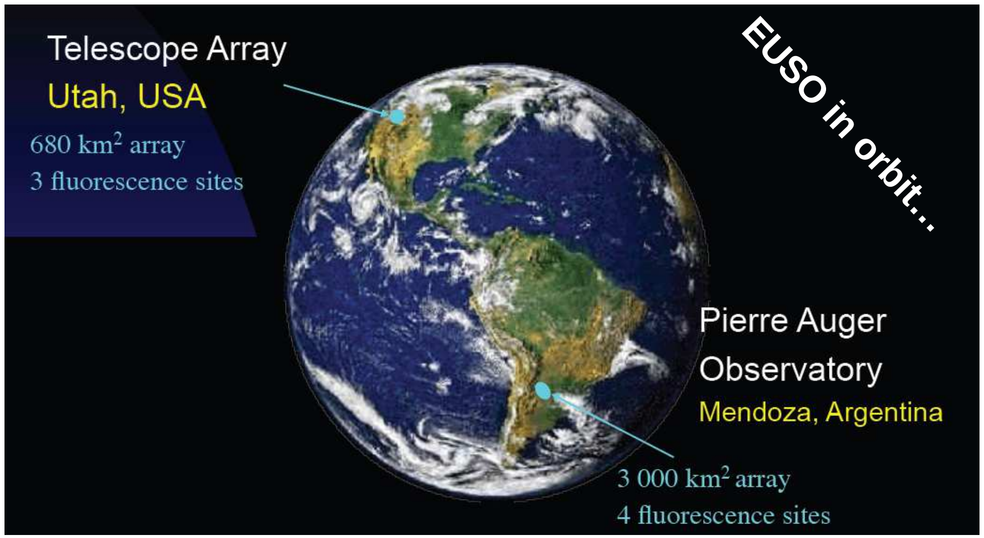
The ultra-high energy regime – the 'toe'





	TA	Auger
γ_1	3.33 ± 0.04	3.27 ± 0.02
γ_2	2.68 ± 0.04	2.68 ± 0.01
γ_3	4.2 ± 0.7	4.2 ± 0.1
$\lg(E_1/\mathrm{eV})$	18.69 ± 0.03	18.61 ± 0.01
$\lg(E_2/\mathrm{eV})$	19.68 ± 0.09	19.41 ± 0.02



Cosmic-ray sources and maximum energies

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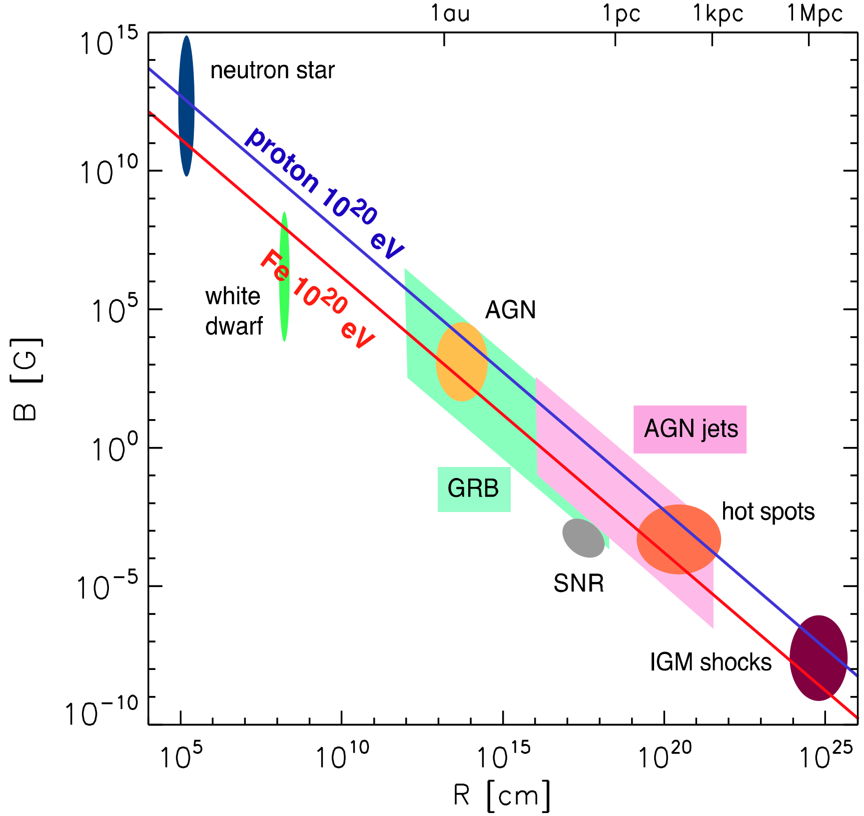
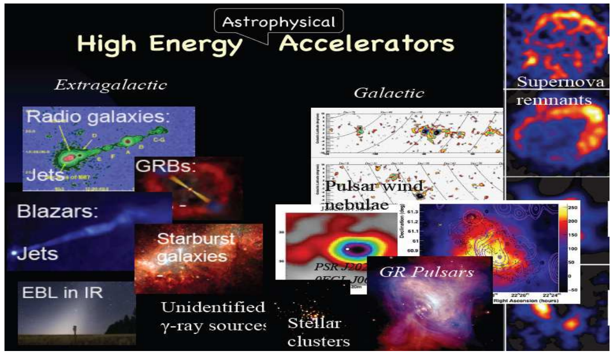
- **Magnetic field *dimensions* sufficient to contain the accelerating particles**
- ***Strong fields* and *large* plasma *speeds***

$$E_{max} \approx \beta_{shock} Z \cdot B[\mu G] \cdot L[kpc] \cdot 10^{18} eV$$

ISM-SN: (Lagage & Cesarsky, 1983)
Wind-SN: (Biermann, 1993)
AGN radio-lobes: (Rachen & Biermann,1993)
AGN Jets or cocoon: (Norman et al.,1995)
AGN multiple-shock-jet: (Meli & Biermann, 2013)
GRB: (Meszaros & Rees, 1992,1994)
Neutron stars: (Bednarek & Protheroe, 2002)
Pulsar wind shock: (Berezhko, 1994)

Hillas criterion





Hillas (1984)

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Sources:
Non-relativistic
Relativistic

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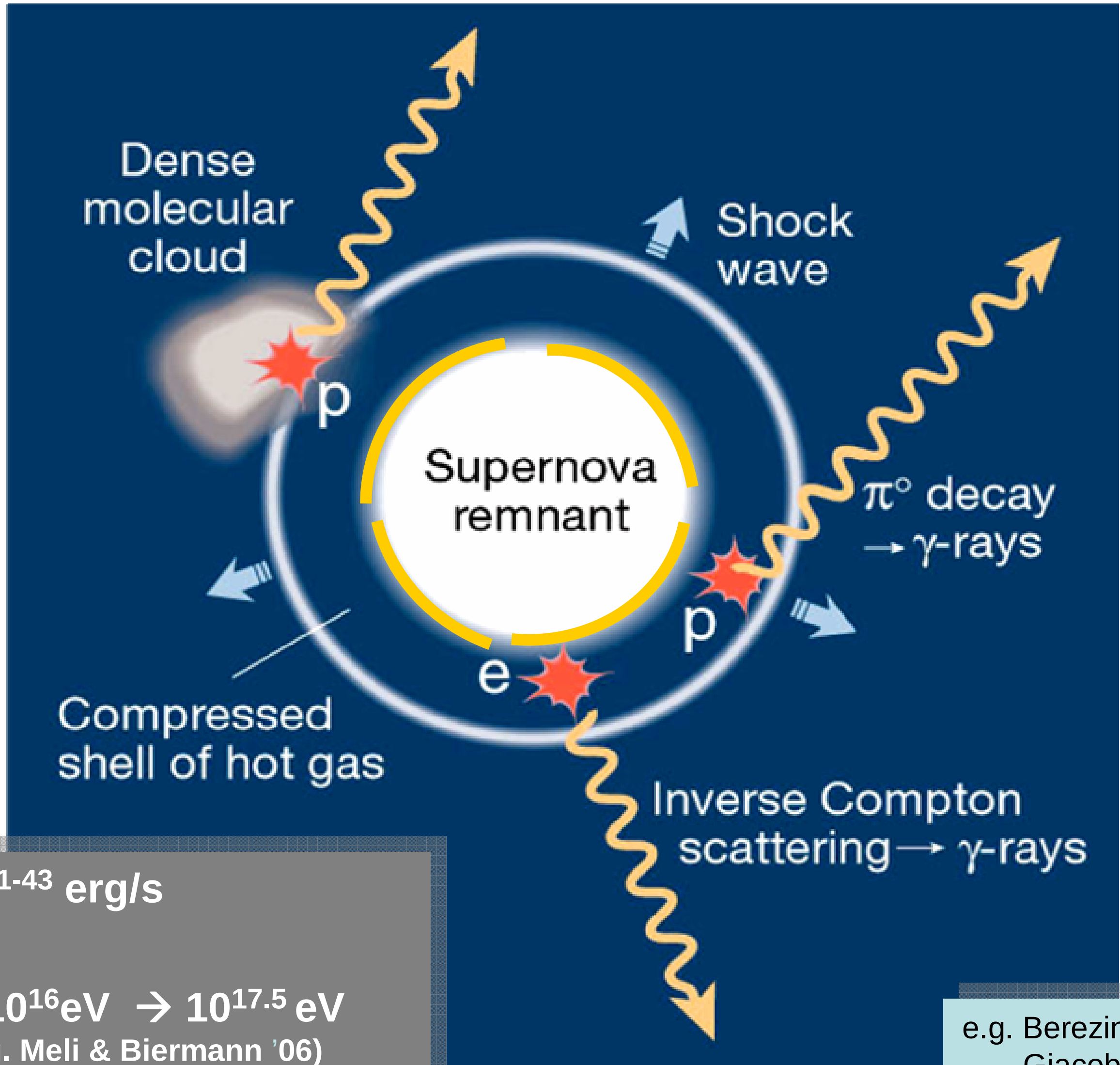
Sources:

Non-relativistic

Relativistic

Supernovae

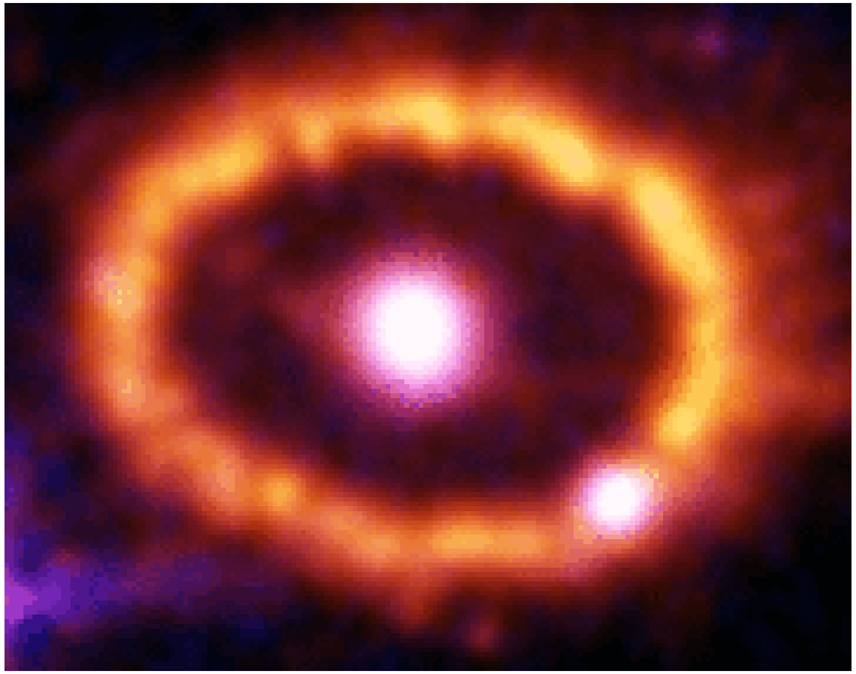


L ~ $10^{41\text{-}43}$ erg/s

Γ ~ 1-2

E_{max} ~ 10^{16}eV → $10^{17.5}$ eV (e.g. Meli & Biermann '06)

e.g. Berezinsky & Ginzburg '87,
Giacobbe '05,
Aharonian et al. (HESS) '06



SN 1987A

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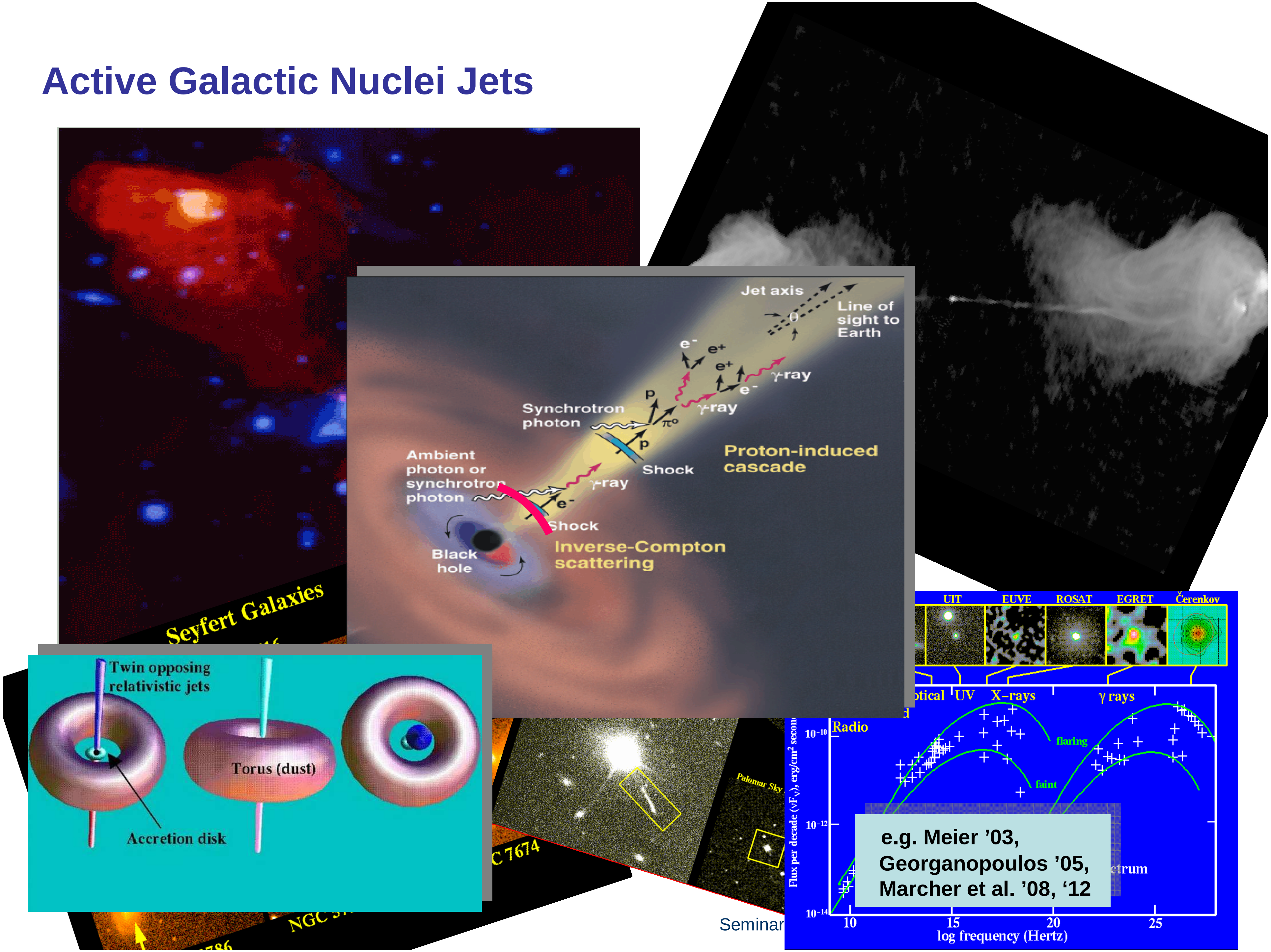
Sources:

Non-relativistic

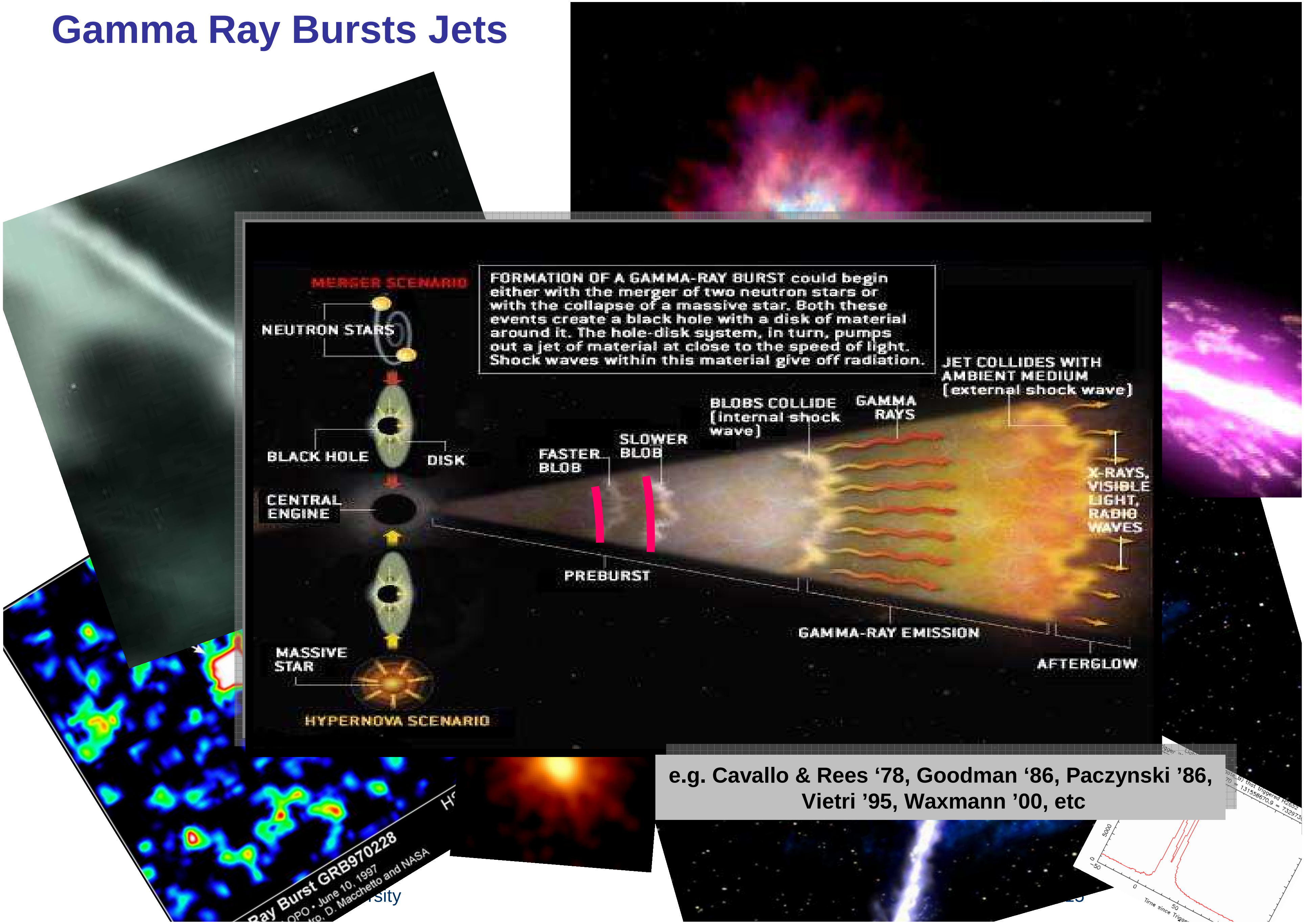
Relativistic

Active Galactic Nuclei Jets



e.g. Meier '03,
Georganopoulos '05,
Marcher et al. '08, '12

Gamma Ray Bursts Jets



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

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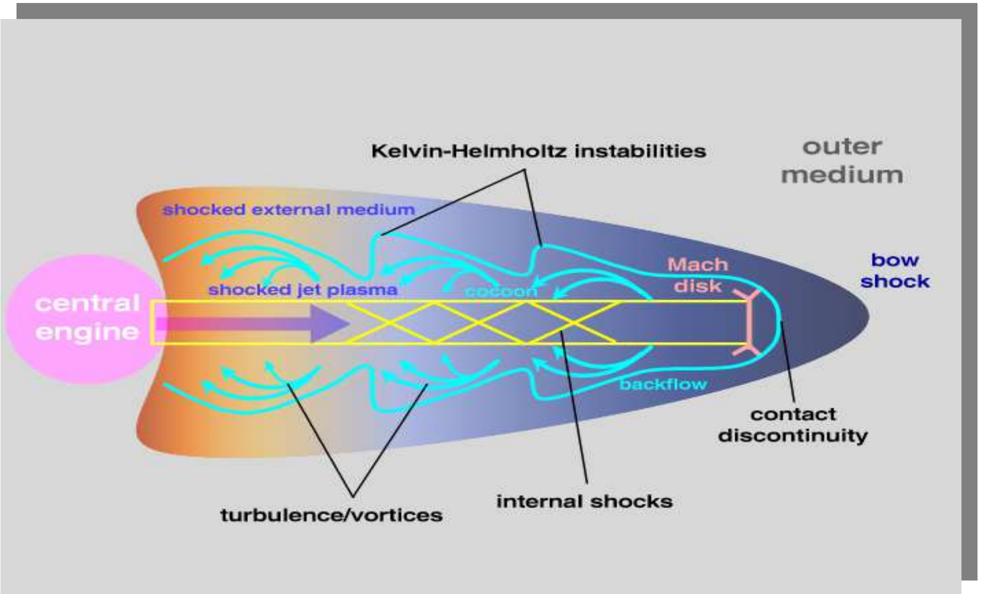
A ‘hidden force’ in extragalactic jets:

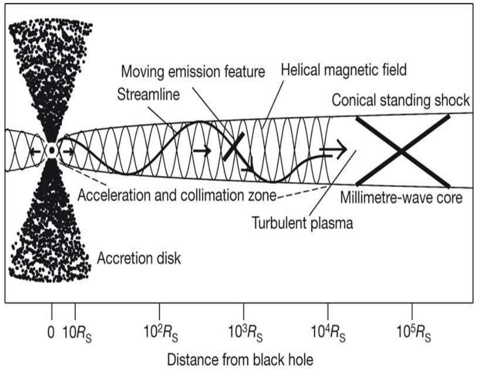
Shocks

Individual or multiple shocks

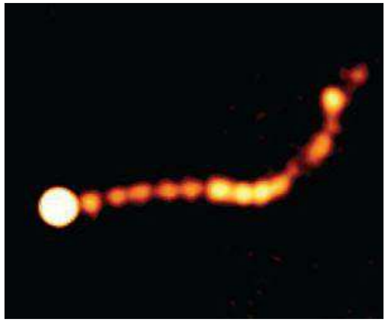


Supersonic/superalfvenic strong compression waves →
change gas/plasma's *v, d, p, T*

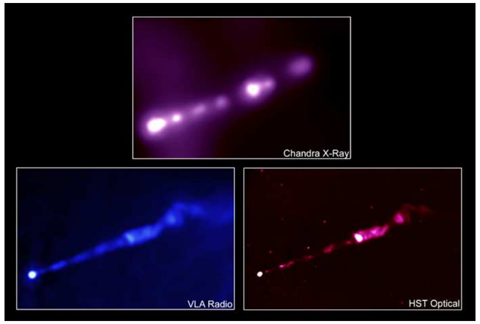
- **Collisional shocks (ordinary fluid)**
- **Colissionless astrophysical shocks:**
  In diffuse regions, low densities, large bulk speeds



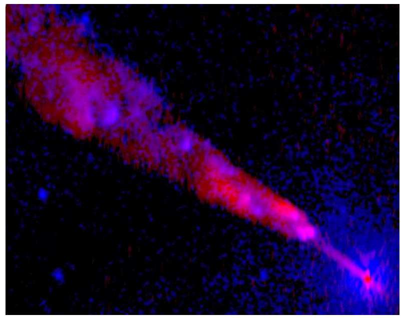
PKS 1510-089



PKS 0637-752

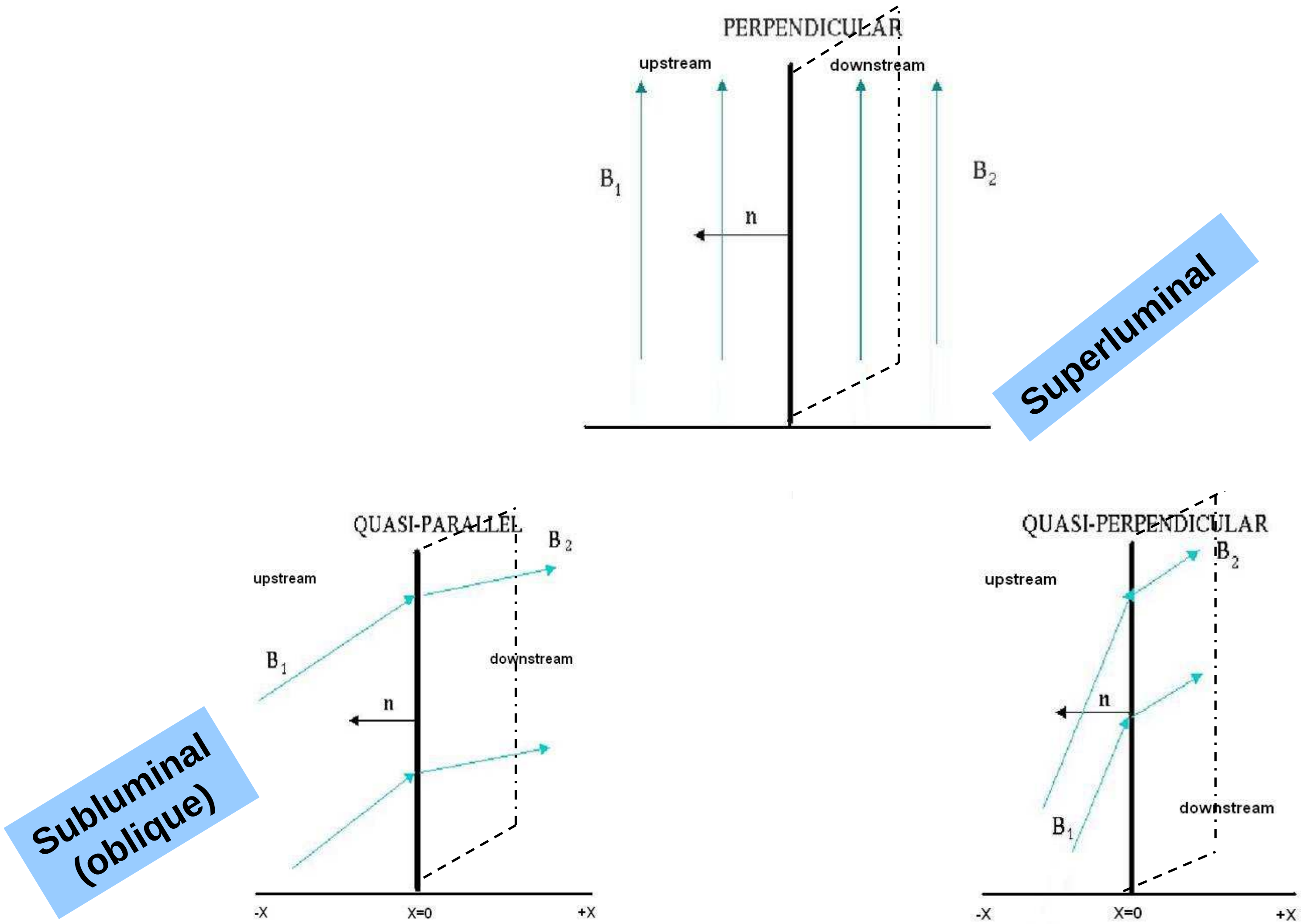


M87

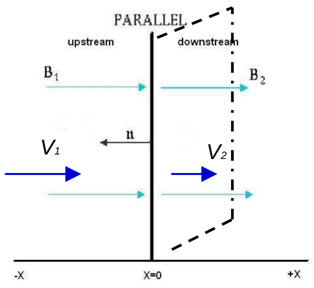


CenA

Shock classification - magnetic field orientation



Shock jump-conditions
(Rankine-Hugoniot relations)



→ HD jump conditions (planar shocks, $[X]_1^2 \equiv X_2 - X_1$)

$$[\rho_m V_z]_1^2 = 0 \qquad \text{mass conservation}$$

$$[\rho_m \vec{V} V_z + p\vec{e}_z]_1^2 = 0 \qquad \text{momentum cons.}$$

$$[\tfrac{1}{2}\rho_m V^2 V_z + \gamma p V_z/(\gamma - 1)]_1^2 = 0 \qquad \text{energy cons.}$$

→ MHD

$$[\rho_m V_z]_1^2 = 0$$

$$\left[\rho_m \vec{V} V_z + \left(p + \frac{B^2}{2\mu_0}\right)\vec{e}_z - \frac{B_z \vec{B}}{\mu_0}\right]_1^2 = 0$$

$$\left[\left(\tfrac{1}{2}\rho_m V^2 + \frac{\gamma p}{\gamma - 1} + \frac{B^2}{\mu_0}\right) V_z - \frac{B_z \vec{B}\cdot\vec{V}}{\mu_0}\right]_1^2 = 0$$

$$[B_z]_1^2 = 0$$

$$[V_z \vec{B}_\mathrm{t} - B_z \vec{V}_\mathrm{t}]_1^2 = 0$$

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

Particle acceleration *mechanism* at shocks

No doubt collisionless *astrophysical* shocks accelerate particles

Convincing evidence (early 80s) for efficient acceleration in heliospheric shocks and in SNRs

The Fermi mechanism

Transfer of the macroscopic kinetic energy of moving magnetized plasma to individual charged particles → non-thermal distribution

- ***2nd order* Fermi acceleration** (Fermi '49,'54)

  @magnetic plasma clouds

- ***1st order* Fermi acceleration - diffusive acceleration**

  (Krymskii '77, Bell '78, Blandford & Ostriker '78, Axford et al. '78)

  @plasma shocks

1st order Fermi acceleration – diffusive acceleration of CRs

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

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

- **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**

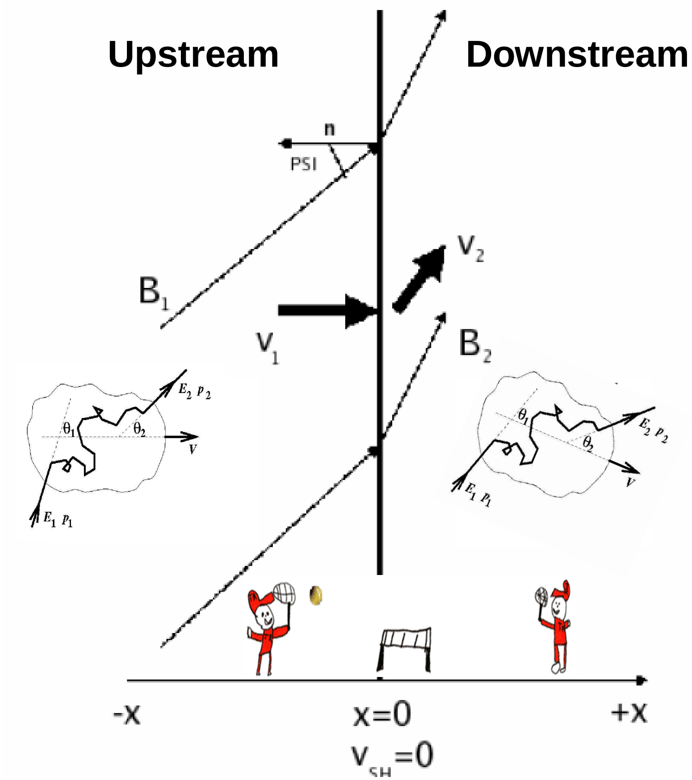
$$N(>E) = \sum_{i=n}^{\infty} (1 - P_{esc})^{n(E)} = \ldots \propto E^{-\sigma}$$

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

for mono-atomic gas:

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

Probability of scattering x av.no. scatterings x ΔE



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

Important: **<u>Non-relativistic shocks</u>: σ is *constant* (~ 2.2) independent of shock-B inclination (Drury, '83)**
<u>Relativistic shocks</u>: Different story…

Note: 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 (σ) <u>independent</u> of: scattering nature (κ), inclination (ψ) and strength of magnetic field (B)**

Concepts are well understood and well studied - they work well

as a comparison basis for *<u>relativistic</u>* studies

Acceleration time scale & diffusion

The *acceleration rate* wins in competition with the time scale of the energy *losses* and the *escape rate*, defining the limit for the possible highest energies to be achieved.

Acceleration rate:

$$\tau(E)=(E\cdot\tau_{cycle})/\Delta E=[3/(V_1-V_2)](\kappa_1/V_1+\kappa_2/V_2)$$ (Drury '83)

Confinement distance

One cycle:

$$\tau_{cycle}(E)=(4/c)(\kappa_1/V_1+\kappa_2/V_2)$$

Diffusion coefficient:

$\kappa = \kappa_{\|} \cos^2\psi$ $\kappa_{\|}=(1/3)\lambda\upsilon$ $\lambda = 10 r_l$ (Quenby & Meli '05)

i.e. Proton 10GeV: κ about 10^{22} cm^2/s → τ_{cycle} about 10^4 sec

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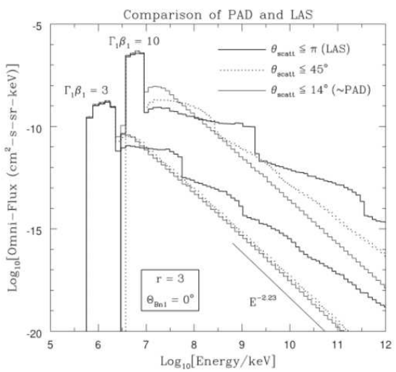
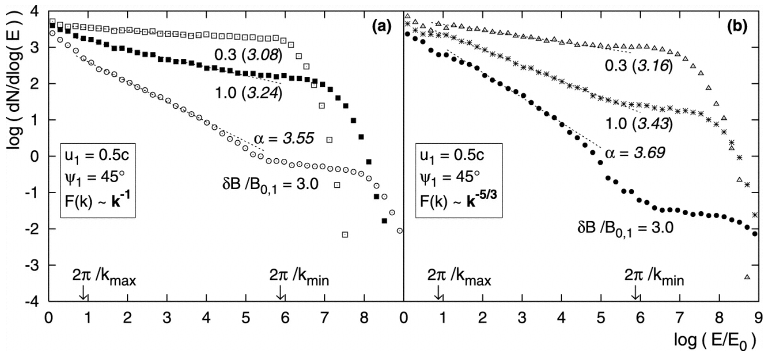
Simulations of relativistic shock acceleration

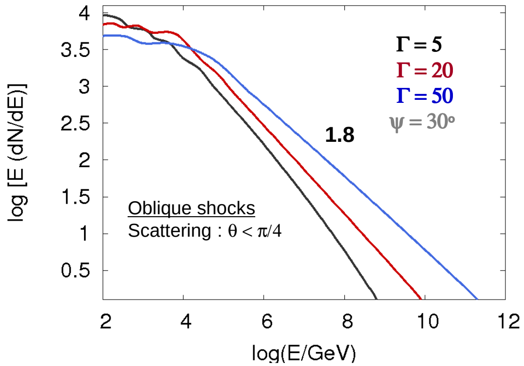
Relativistic shock acceleration: Questions

- **Is spectral index (σ) <u>universal</u>? Flat or steep?**
- **σ *depends* on: gamma shock speed, inclination and scattering modes (turbulence of the media) ?**
- **Efficient acceleration → UHECRs ?**

see: Ellison et al. (1995), Meli & Quenby (2003a,b, 2005), Niemec & Ostrowski (2004), Ellison & Double (2004), Stecker et al. (2007), Meli et al. (2008)







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Numerical approaches

- **Semi-analytic solutions to diffusion-convection equation**

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

- **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)

- **Monte Carlo simulations (‘test-particle’ approach)**

  (e.g. Ellison et al. ’02-’12, Baring ‘03-’13, Meli et al. ‘03-’14)

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

  (e.g. Dieckmann, Meli, et al. ’08-’10, Nishikawa et al. (Meli), ’13,‘14)

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Monte Carlo 'test-particle' approach principles

- **Notion of 'test-particles' - very efficient & very fast in describing particle random walks - large number of particles**

- **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**

- **Scattering can be treated via *large angle* and *pitch angle* diffusion approach**
  (e.g. Kennel & Petscheck '66, Forman et al. '74, Jokipii '87, Quenby & Meli '05, Meli & Biermann '06)

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

- **Fully relativistic Lorentzian transformations**

- P_{esc} **(probability of escape)**

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Relativistic jets and UHECRs:
Individual shocks
Multiple shocks

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Relativistic jets and UHECRs:

Individual shocks

Multiple shocks

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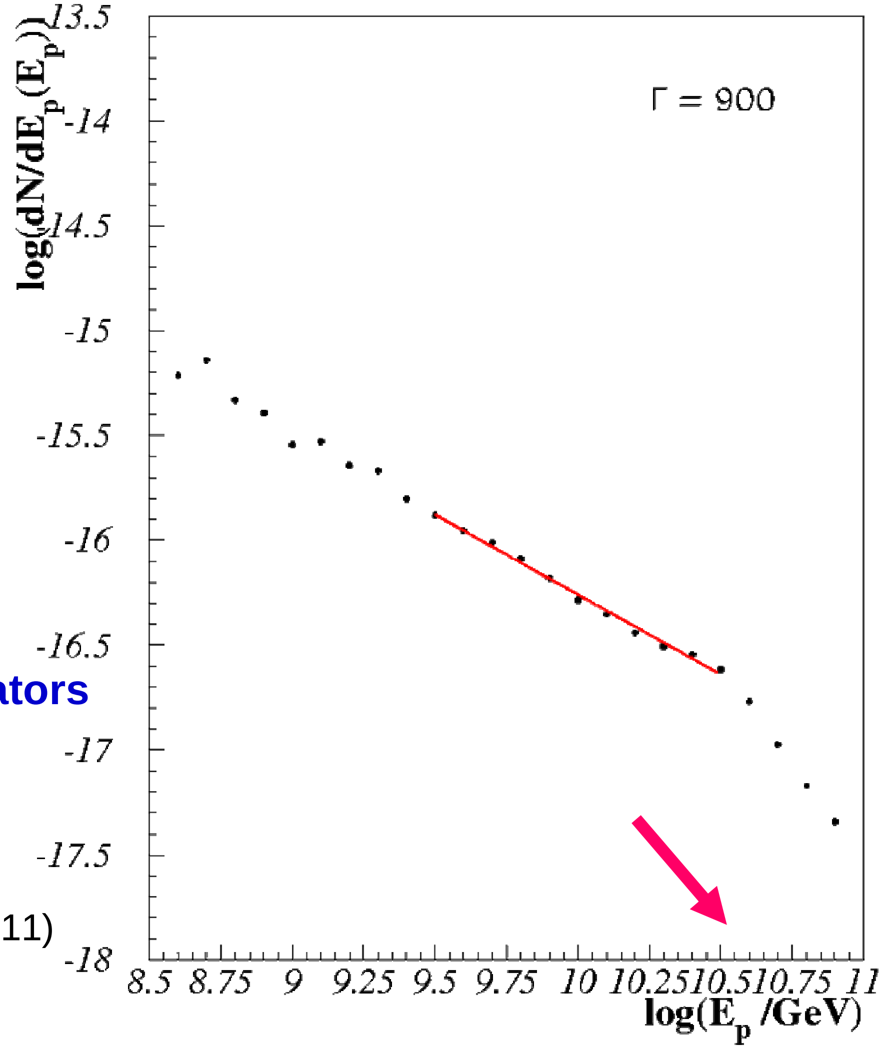
Sub-luminal (oblique) shocks - spectra

Scattering : $1/\Gamma < \theta < 10/\Gamma$

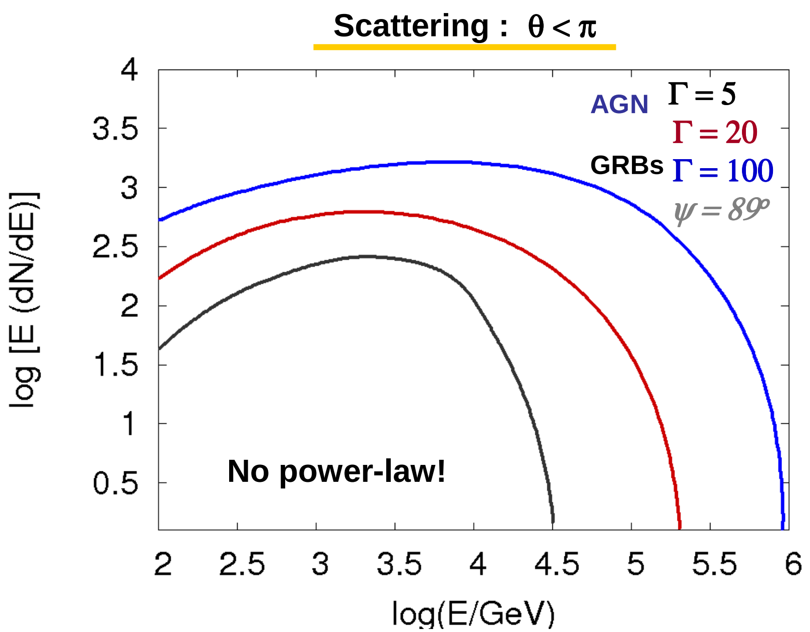
	Γ_{sh}	s (ψ_{sh}= 23°)	s (ψ_{sh}= 33°)	s (ψ_{sh}= 43°)
AGN	10	2.1	2.1	2.3
AGN	20	2.0	2.0	2.3
AGN	30	2.1	2.0	2.2
GRBs	100	1.8	1.8	2.2
GRBs	300	2.0	1.8	2.0
GRBs	500	1.9	1.7	1.6
GRBs	700	1.8	1.4	1.7
GRBs	900	1.5	1.0	1.3
GRBs	1000	1.2	1.2	1.5

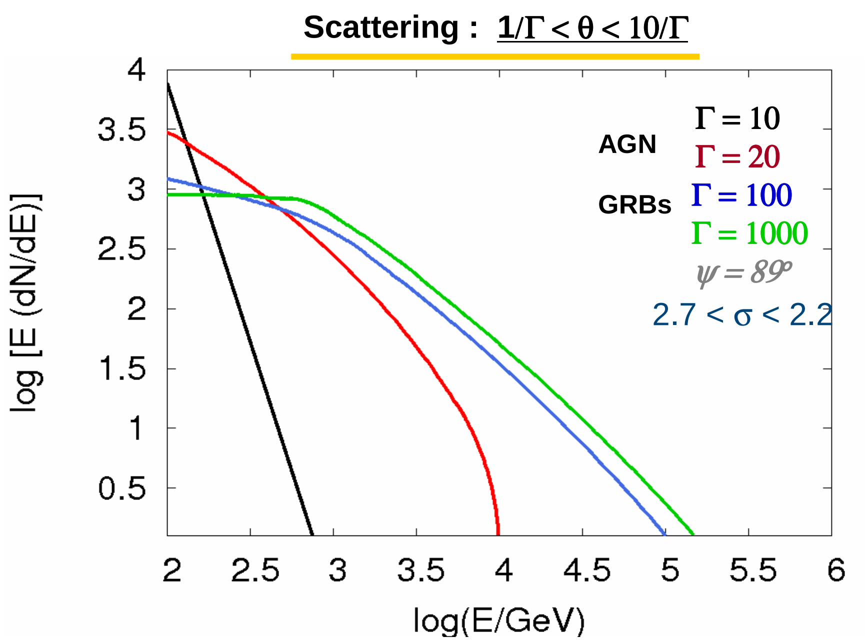


Subluminal shocks → Efficient (flat) accelerators

Meli, Becker & Quenby (2011)

Super-luminal (perpendicular) shocks - spectra



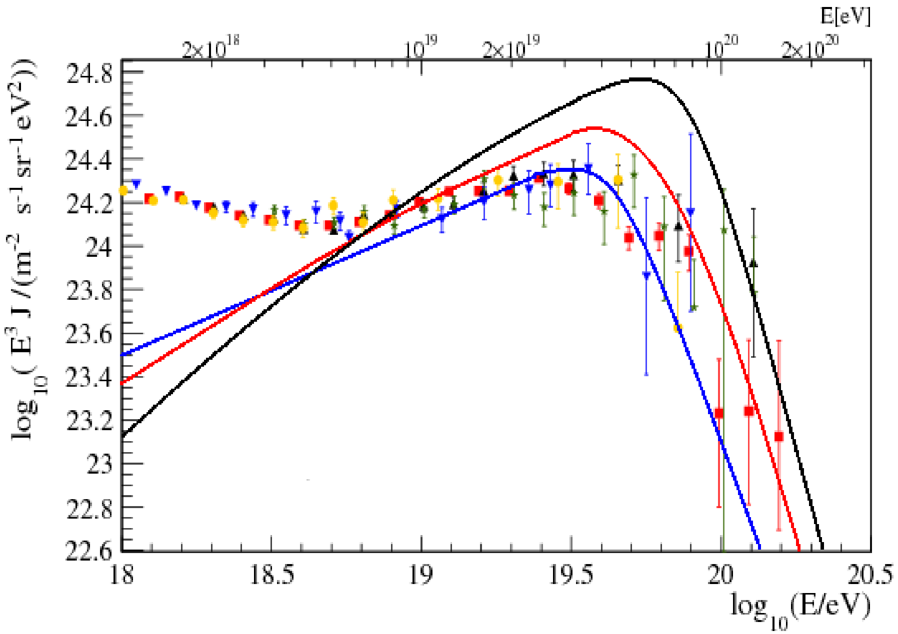


Meli, Becker, Quenby (2011)

Superluminal shocks → Not efficient accelerators → Irregular spectra

Application to extragalactic astronomy

Contribution to the diffuse UHE cosmic-ray signal ?



After averaging various spectra, we assume that a diffused proton spectrum measured at Earth is given by:

$$\frac{dN_p}{dE_p} = A_p \int_{z_{min}}^{z_{max}} \left(x \cdot \frac{d\Phi_{2.1}}{dE_p}(E_p(z)) + (1-x) \cdot \frac{d\Phi_{1.5}}{dE_p}(E_p(z)) \right) \times (1+z)^{-1} \cdot \exp\left(-\frac{E_p(z)}{E_{cut}(z)}\right) \cdot g(z) dz$$

Condition 1: UHECRs produced in subluminal relativistic shocks with spectra of mean σ = -2.1, contribute a fraction $0 \le x \le 1$, and UHECRs with flat spectra of σ =–1.5 contribute 1-*x*. (0.001<*z*<7)

Fitting between: 3EeV and 30EeV
Black line: assumed contribution of UHECR from GRBs with flat spectra, σ=1.5.
Red line: half-half contribution with σ=1.5 and σ=2.1 respectively.
Blue line: only UHECRs from AGN with σ=2.1.

Condition 2: We take into account particle propagation, adiabatic energy losses, source evolution *g(z)*, absorption at the highest energies and normalized the flux using observations above the ankle.

Meli and Ciarcelluti (2014)

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Relativistic jets:

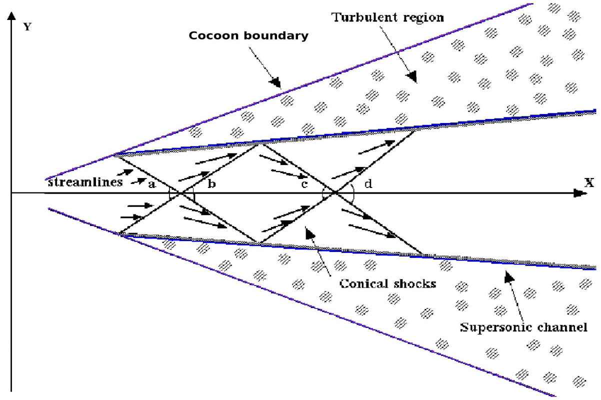
Individual shocks

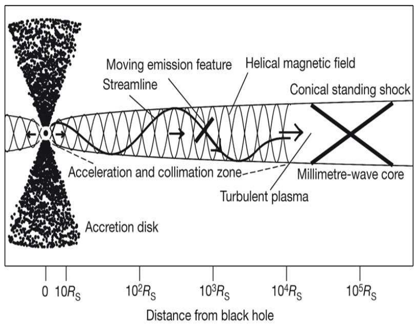
Multiple shocks

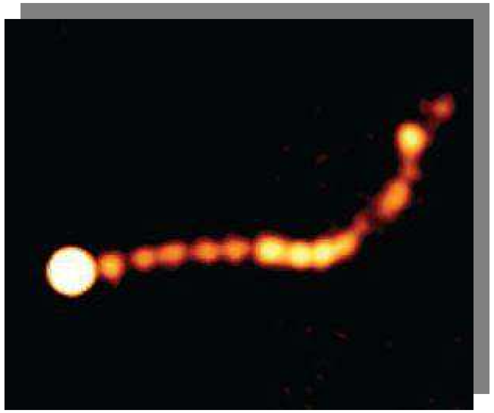
Model: Multiple **shock patterns and cosmic-ray acceleration in extragalactic jets**

with

a *single* particle-injection (Meli and Biermann, 2013)

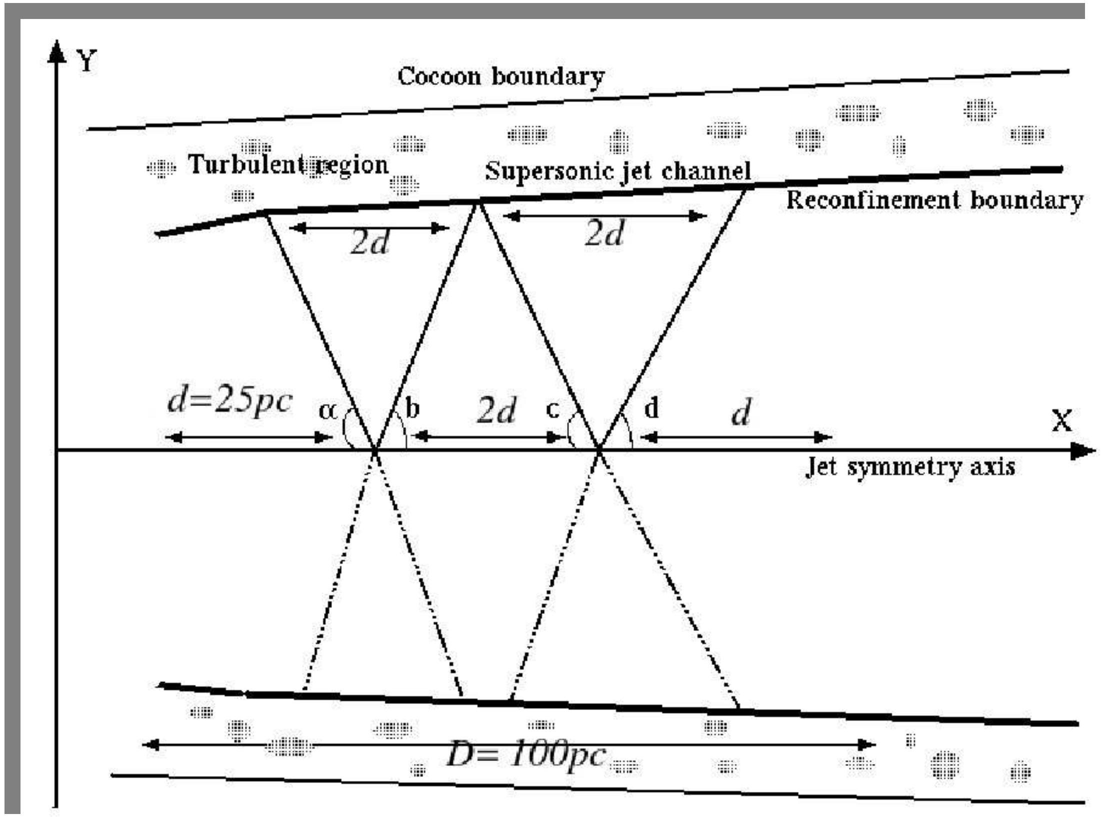


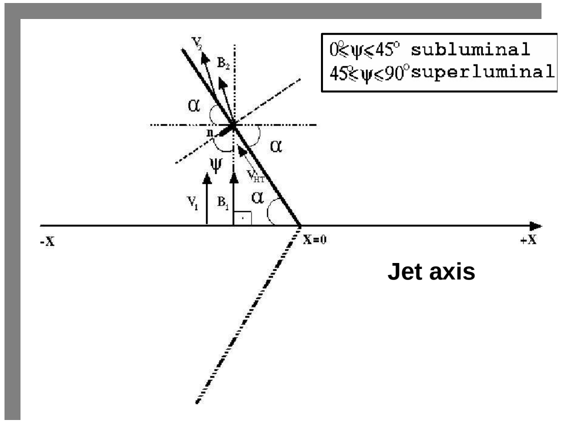


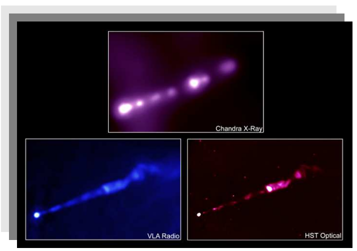


Repeated multiple shocks with opening angles *a*, *b*, *c*, *d*,

in an AGN jet, e.g., PKS 1510-086, CenA, M87, NGC6251, etc

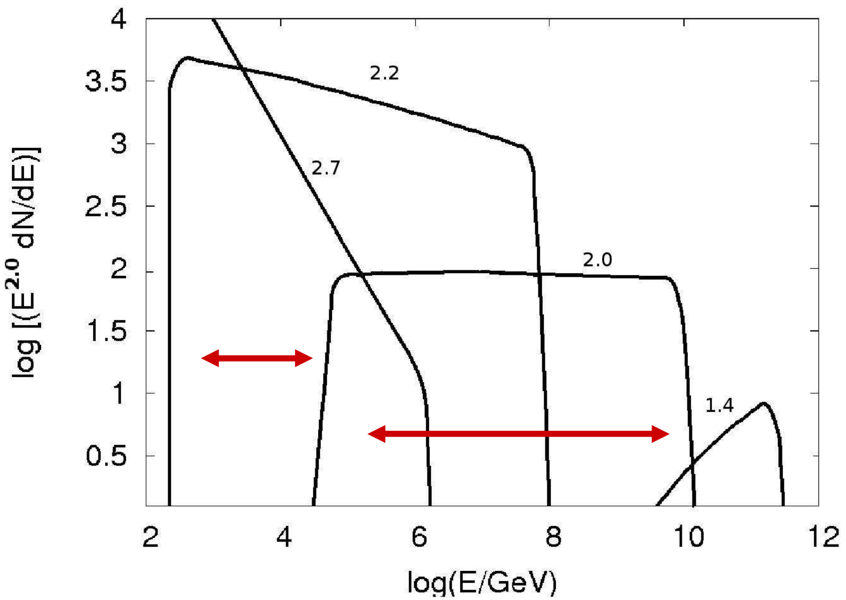


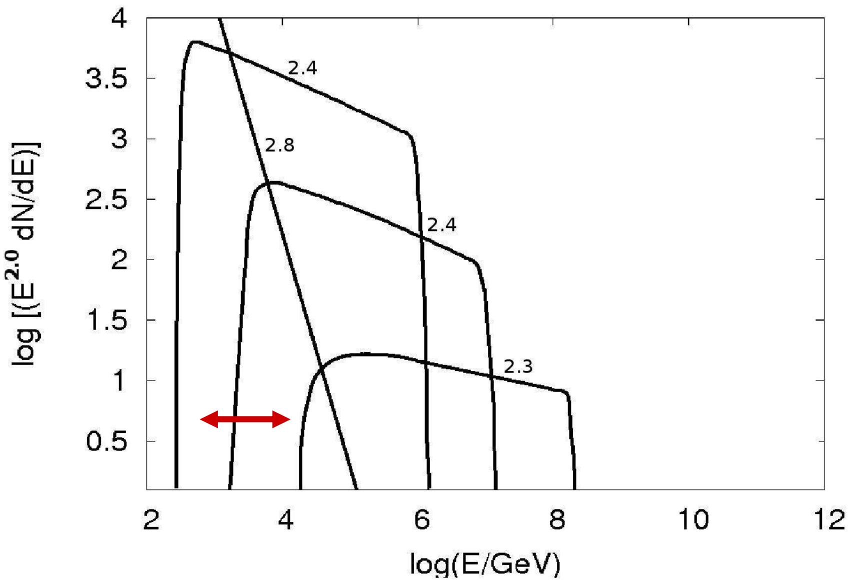




Simulation framework: An overall view of the proposed jet and shock topologies (not to scale)

Proton spectra at the source (in a shock sequence)





Γ_{sh1}= 35, Γ_{sh2} =25, Γ_{sh3} =15, Γ_{sh4} = 5

Shock inclination	Spectral index	E_{max}[GeV]
45^o subluminal	-2.7	10^6
45^o subluminal	-2.2	10^8
45^o subluminal	-2.0	10^{10}
45^o subluminal	-1.4	$10^{11.5}$

Γ_{sh1}= 35, Γ_{sh2} =25, Γ_{sh3} =15, Γ_{sh4} = 5

Shock inclination	Spectral index	E_{max}[GeV]
85^o superluminal	-2.8	10^5
85^o superluminal	-2.4	10^6
85^o superluminal	-2.4	10^7
85^o superluminal	-2.3	10^8

Meli & Biermann (2013)

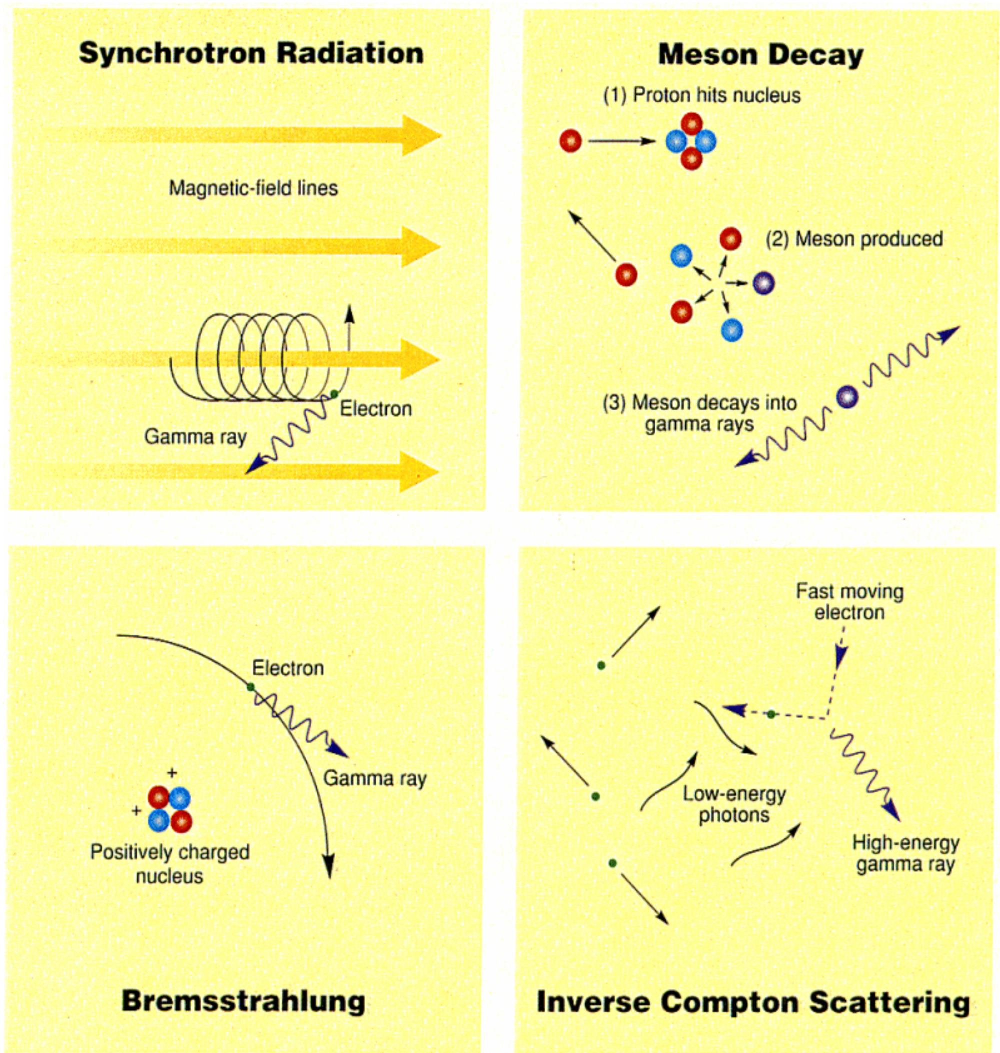
Cosmic-rays ⟷ gamma-ray and neutrino astronomy

Radiation by cosmic-rays

$e^{\pm} + B$

Leptonic model

$e^{\pm}$ + matter



Hadronic model

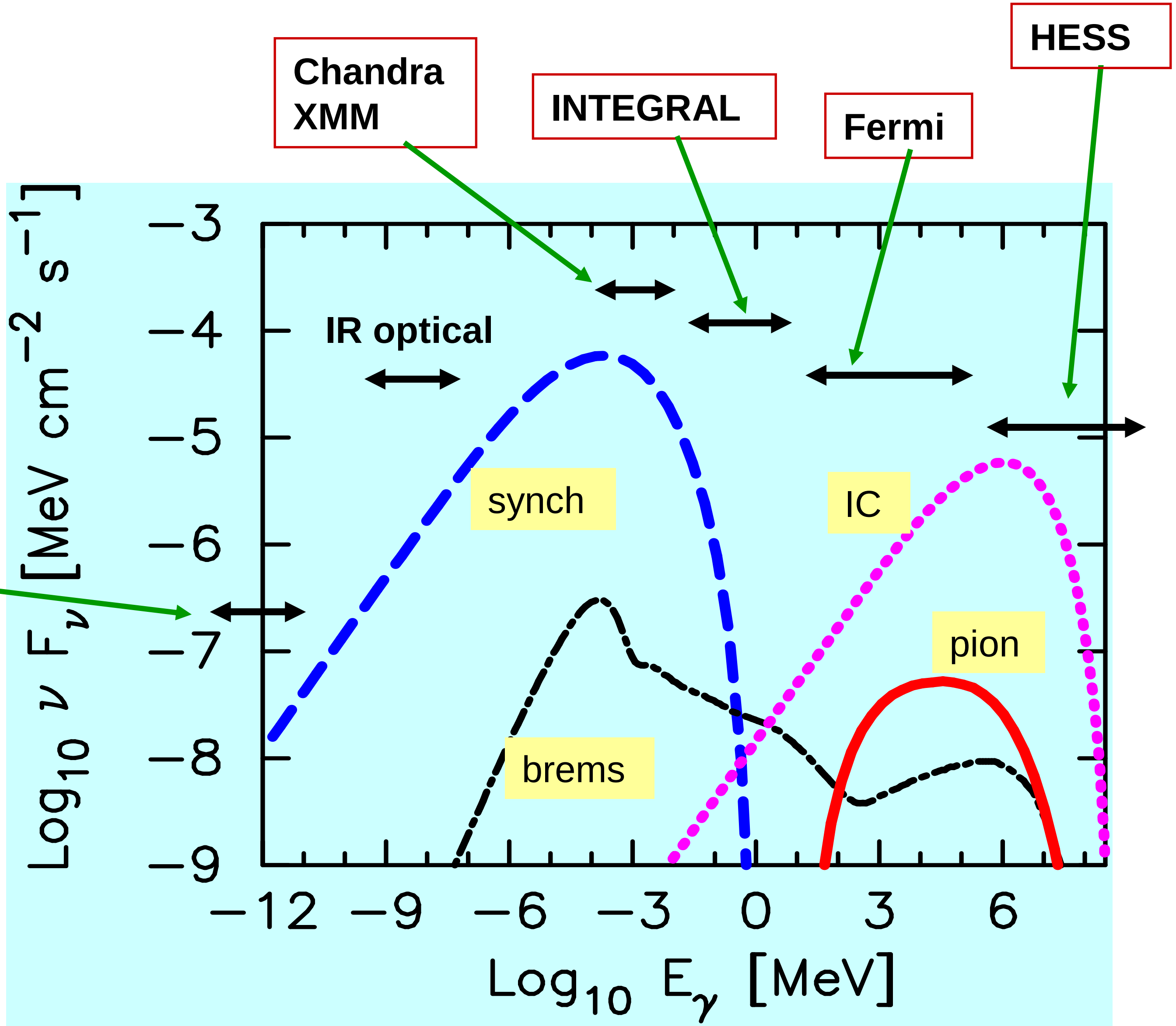
p + matter

p + p

$p + \gamma$

$e^{\pm} + h\nu$

Leptonic continuum emission from AGN



In addition, emission lines in X-rays

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Hadronic interactions

$$p + p \rightarrow \pi^{+} + X$$
$$\rightarrow \pi^{-} + X$$
$$\rightarrow \pi^{0} + X$$
$$p + \gamma \rightarrow \pi^{0} + p$$ **photopion production**

$$p + \gamma \rightarrow \pi^{+} + n$$ **escape**

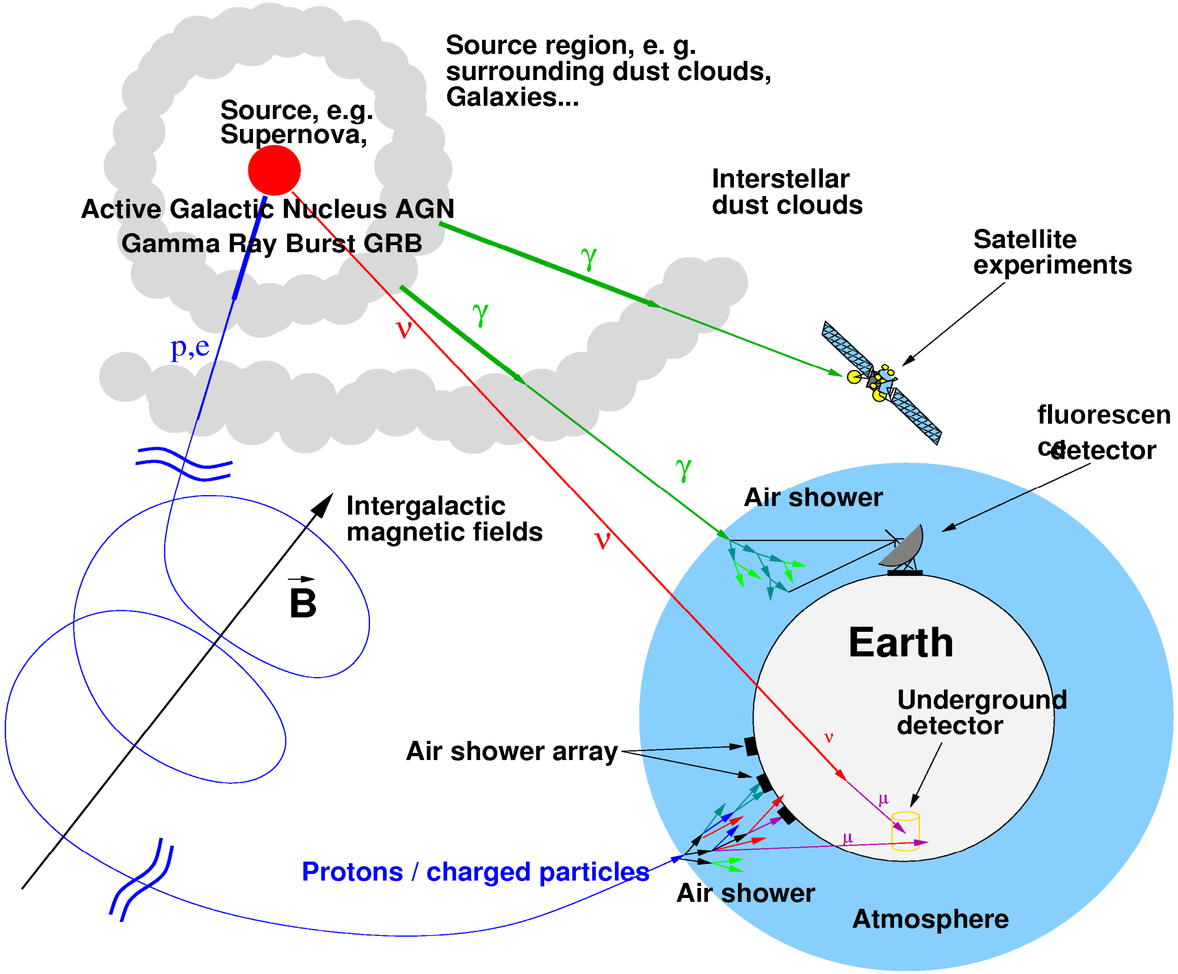
$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu}$$
$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$
$$\pi^{0} \rightarrow \gamma + \gamma$$ **Gamma rays**

$$\mu^{-} \rightarrow e^{-} + \bar{\nu}_{e} + \nu_{\mu}$$
$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$ **Neutrinos**

Correlation: TeV/PeV Photons - PeV Neutrinos - Optically thick environment: $E\gamma$ ~ keV - GeV

(e.g. Halzen et al. "05)

Simulations of extragalactic *propagation* of *hadronic* cosmic-rays



by W.Wagner

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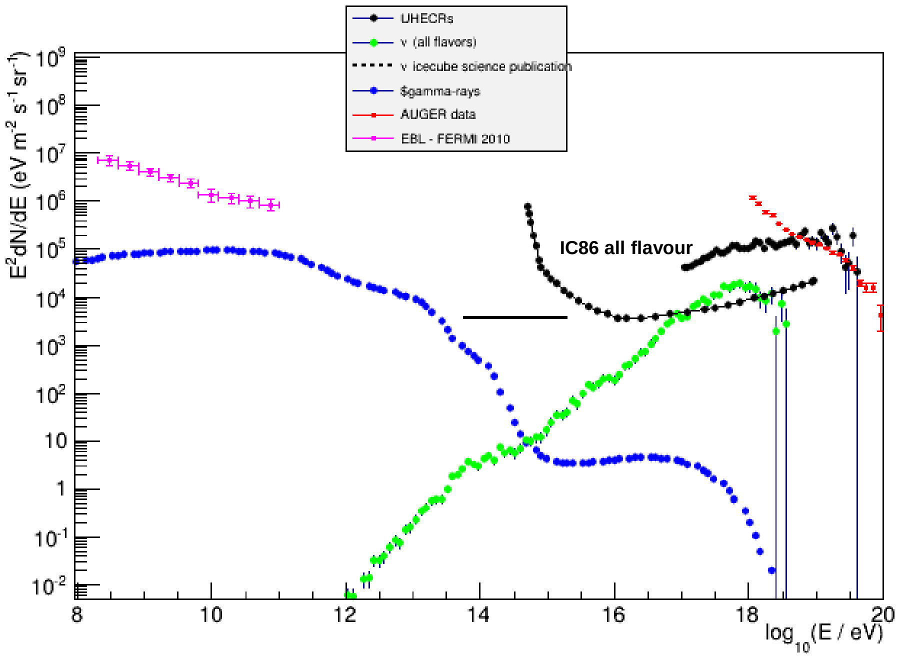

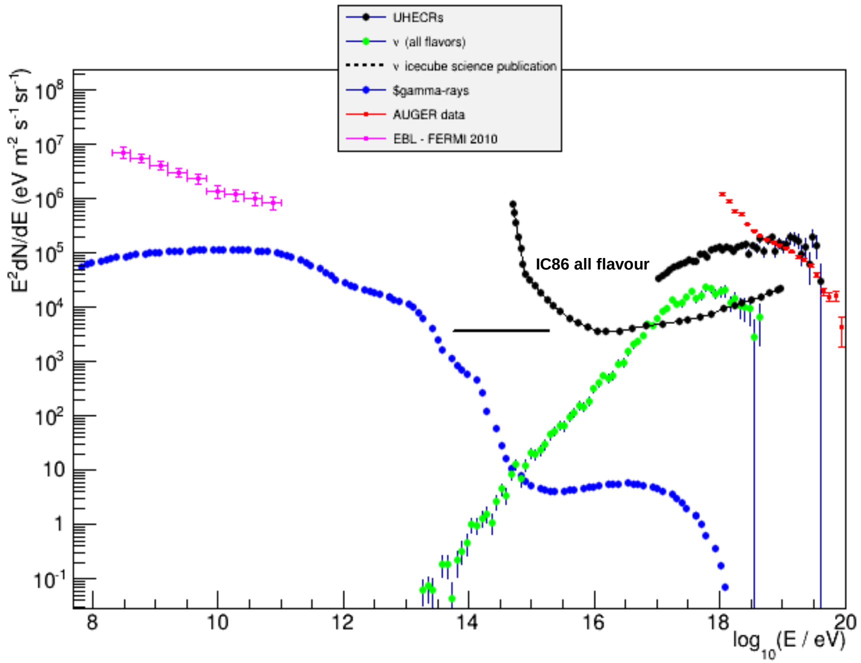

Mix: Fe/p=10, injection σ = 1.7

Preliminary results !

Pure: proton, injection σ = 1.7

E_{cut}: 5×10^{19} eV

Study correlations: High variability - high flare states only? E_{max}? Composition? Source evolution?

Meli, Biermann, Tjus (in preparation)

Questions answered:

- ✓ **UHECRs seem to originate from extragalactic sources such as AGN and GRB jets**

- ✓ **Relativistic shocks *individual or multiple* can accelerate UHECRs with a variety of spectral features**

- ✓ **Spectral index of the *primary* spectrum** (σ) **is <u>not universal</u>: observations→ *gamma-rays, neutrinos***

- ✓ σ ***depends* on: shock speed, inclination and scattering modes (turbulence of the media)**

  - *Faster* **shocks generate** *flatter* **distributions**
  - **Subluminal (quasi-parallel) shocks** efficient **accelerators** → **$\sim 10^{21}$ eV (!)**
  - **Superluminal (quasi-perpendicular) shocks** not **efficient** → **$\sim 10^{15}$ eV**

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Take home lesson (Monte Carlo CR studies)

Relativistic *individual or multiple shocks* in extragalactic jets are powerful engines, producing very high energy CR via the Fermi acceleration mechanism with *distinctive spectral features* and *consequent radiation*

Immediate applications to extragalactic observational astronomy:

- ✓ **Hadronic radiation models**
- ✓ **Gamma-ray & neutrino astronomy**
- ✓ **Multi-messenger approach**


Thank you!