**Pasquale Blasi Gran Sasso Science Institute**

October 3, 2024 - In memory of Venya



# **GRAN SASSO<br>SCIENCE INSTITUTE** G SCHOOL OF ADVANCED STUDIES Scuola Universitaria Superiore  $\delta(PR) \delta(r-R)$ **PHYSICS OF PARTICLE ACCELERATION TO UHE**

# *Memory Lane*



*Memory Lane*

 **February 1994, From CP violation in B0-B0 mixing to white dwarves and the Colgate mechanism (explode things in decreasing density)** 

 **1994 - Navarra and Ginzburg… from SNR1987a to anomalous γ's** 

 **1995 - Clusters of Galaxies —- Venya and Vladimir Ptuskin** 

 **1996 - Relativistic shocks — Venya and Bohdan Hnatyk** 

 **July 1997 - End of the Ph.D…. offer from Ray Protheroe… ops no, by David Schramm** 

 **December 1997 - David passes…** 

 **1998 - Super-heavy relics - Venya and Alex Vilenkin** 

 **2007: Venya passes the baton to me, Editor of Astroparticle Physics (now Damiano)** 

 **2012: neutrinos from PopIII stars - back to the bright phase of an old idea** 

 **Continued collaboration with Roberto and Venya and a deep friendship that continued to the very end** 

 **Venya did not teach only a lot of Physics,.. he was proud of saying that he could teach a way to be a physicist … and he taught me the art of story telling, in which he was not less of a master**



# What do we need to understand?

A couple of decades ago it would have been unthinkable to think of nuclei as UHECR

- acceleration
- phenomena occurring around the sources or en route)
- \* Yet extra-Galactic protons appear to have a much different spectrum than nuclei
- Issue of transition from Galactic to extra-Galactic CRs crucial and not understood

Now it is unthinkable to ignore nuclei and **Rmax~5 EV** … much easier problem of particle

Disturbingly **hard source spectra** required (perhaps what we get is heavily affected by

**How can one not consider this a "disappointing model"?**

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### Stochastic particle acceleration in relativistic turbulence

### **M** Particle acceleration at fast rotating neutron stars

### Starburst galaxies and UFOs

## **Particle acceleration during large scale structure formation**

# OUTLINE

### **See talk by D. Caprioli for acceleration in jetted sources**

- 
- 

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## SIMPLE CONSIDERATIONS

**• MOST OF THE UNIVERSE IS IN A PLASMA STATE: THE ONLY ELECTRIC FIELDS YOU GET ARE INDUCED BY PLASMA MOTION: δE~(V/c)B**

**• ONLY ELECTRIC FIELDS CAN CHANGE THE PARTICLE ENERGY**

# $\frac{dp}{dt} = q\frac{V}{c}B \rightarrow \frac{dE}{dt} \approx qVB$

If the electric field could stay coherent over a scale R and the particles were moving at c then

 $E_{max} \approx qBR$  *Hillas Criterion* 

But in a plasma this does not usually happen (unless some specific conditions are fulfilled)

Hence: **NEED TO STAY IN THE ACCELERATION REGION MUCH LONGER THAN R/c**



# The Hillas Plot (1984) Simple things to catch your attention



*But do not be fooled*:

- The Hillas Plot only provides the absolute most optimistic picture, since it ignores the details of the acceleration process
- $$ Most of the sources are unable to reach this limit$
- \* Energy losses are not taken into account
- Notice the absence of GRBs and Starburst galaxies

Nowadays we know that the requirement on the acceleration are much weaker (Max Energy 5x1018 Z eV)



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### GENERAL LIMITS ON ACCELERATORS OF UHECR

IN THE NON RELATIVISTIC CASE ONE CAN WRITE A GENERIC EXPRESSION:  $1 \; E(eV)$  $3300ZB$ 

THIS IMPLIES THAT:

THE SOURCE ENERGETIC MUST BE AT LEAST AS LARGE AS THE MAGNETIC ONE:

$$
L = \frac{1}{2}\rho u^3 4\pi R^2 > 1.8 \times 10^{46} erg/s \left(\frac{E}{Z10^{20} eV}\right)^2 \left(\frac{\xi}{0.1}\right)^{-2} \beta^{-1}
$$

PROBABLY THE ONLY NON RELATIVISTIC SOURCES THAT MAY SATISFY THIS BOUND ARE LARGE SCALE STRUCTURE FORMATION SHOCKS AND ONLY MARGINALLY, ALTHOUGH NOTICE THE ROLE OF Z

$$
\frac{c}{u} = \xi R \quad \xi < 1
$$

$$
\epsilon_B = \frac{B^2}{4\pi} > 9.8 \times 10^{-8} \frac{E(eV)^2}{Z^2 \beta^2 \xi^2 R^2}
$$



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# **WITH LORENTZ FACTOR**  $\Gamma$  **(Waxman 2005)**

#### **B' → MAGNETIC FIELD IN THE COMOVING FRAME**

**THIS RESULT CAN BE GENERALIZED TO THE CASE OF RELATIVISTIC SOURCES** 

 $\frac{E}{\sqrt{eB'}} < T_{dyn} \approx \frac{r}{c\Gamma}$ 

$$
=\frac{B^{\prime 2}}{4\pi}>\left(\frac{E}{ZeB^{\prime}r}\right)^{2}/4\pi
$$

THIS IS HUGE AND ONLY THE UPPER END OF THE AGN AND GRB APPEAR TO SATISFY THIS BOUND, ALTHOUGH NOTICE THE ROLE OF Z <sup>9</sup>

#### **E'=E/**Γ **PARTICLE ENERGY IN THE COMOVING FRAME**

THE CONDITION FOR MAXIMUM ENERGY IS:



WHICH IMPLIES:

 $B' > \frac{E}{Z \rho R' r} \rightarrow \epsilon'_B =$ 

AND FINALLY THE

SOURCE ENERGY INPUT MUST SATISFY:  
\n
$$
L > 4\pi r^2 c \Gamma^2 \epsilon'_B = c \Gamma^2 (2\pi E/Ze)^2 \approx 10^{47} \Gamma^2 \left(\frac{E}{Z\ 10^{20} eV}\right)^2 erg/s
$$

# ACCELERATION AT RELATIVISTIC SHOCKS

- One would expect the same process as DSA (Kirk & Schneider, Ostrowsky, PB&Vietri, ...) N(E)~E-2.3
- <sup>8</sup> We speculated that the energy of the particles would increase by Γ2 each time it crosses the shock…
- <sup>8</sup> But the fact that the shock and the particles are all moving at the speed of light complicates things
- <sup>8</sup> The distribution function of the accelerated particles is anisotropic in any frame
- <sup>8</sup> The spectrum becomes not universal if acceleration occurs at all

In the time of one gyration the shock has moved more than one larmor radius: particles are stuck





### **NEED FOR SMALL SCALE TURBULENCE FOR THE MECHANISM TO WORK** <sup>10</sup>

### The Modern Era invoked as efficient sites of acceleration for protons and elec-

- PIC simulations show that the formation of a relativistic shock is mediated by Weibel instability the show instability sion, which is usually detected in the X-ray, optical, and some-
- This process is heavily dependent upon the magnetisation of the upstream medium  $(\sigma$ **<3x10-5**)  $t$  radio bands, and recently up to sub-GeV energies by the sub-GeV energies • Inis process is heavily dependent upon
- Particle acceleration is also there only in that **Case and**  $\mathsf{E}_\mathsf{max}$ **~t<sup>1/2</sup> (small scale turbulence)** or the woodstation to did there only in *<sup>n</sup>* <sup>≡</sup> *<sup>n</sup>*<sup>0</sup> cm−<sup>3</sup> and the magnetic field is *<sup>B</sup>*ISM <sup>≡</sup> <sup>3</sup>*B*ISM*,*−5*.*<sup>5</sup> *<sup>µ</sup>*G,



$$
\sigma = \frac{B_{\text{ISM}}^2}{4\pi n m_i c^2} \simeq 0.5 \times 10^{-9} B_{\text{ISM},-5.5}^2 n_0^{-1} \xrightarrow{\text{Lorentz invariant}}
$$



The Lorentz factor of the shock follows the Blandford & McKee (1976) behaviour: In the follows the following for the following the process of the process of  $\mathbb{R}^n$  $\frac{1}{\sqrt{2}}$ The Lorentz fo & McKee (1976) solution at distances larger than the deceleration radius *R*dec ≡ The Lorentz for radius as *<sup>n</sup>* <sup>∝</sup> *<sup>R</sup>*−2. As discussed in Section 1, the magnetization the shock follows the Blandford & McKee (1976) behaviour:  $\frac{1}{\sqrt{2}}$ IN THE FOLLOWING TO COLLOCESS ON THE PROCESS OF PARTICLE ACCELERATION TO PROCESS OF PARTICLE ACCELERATION TO P<br>IN THE POLLOT LIKE ACCELERATION TO PROCESS OF PARTICLE ACCELERATION TO PROCESS OF PARTICLE ACCELERATION TO PRO landford & McKee (1976) behaviour:

Hence the maximum Lorentz factor (in the lab frame) is: Hence the maximum Lorentz factor (in the lab frame) is: the wind is primarily toroidal, thus decreasing as <sup>∝</sup> *<sup>R</sup>*−1. We  $Hence the ma$ so that the magnetization parameter in the wind will be Also, we can construct the particles reachest reachest

#### Sironi, Spitkovsky & Arons 2013 Application to GRBs the wind is primarily toroidal, thus decreasing as <sup>∝</sup> *<sup>R</sup>*−1. We ation to (ERRC) ECTATT CA ATTAN wind at *<sup>R</sup>* <sup>=</sup> 1018 cm is *<sup>n</sup>* <sup>≡</sup> <sup>0</sup>*.*<sup>3</sup> *<sup>n</sup>*−0*.*<sup>5</sup> cm−3, and the strength of the magnetic field at *<sup>R</sup>* <sup>=</sup> 1018 cm is *<sup>B</sup>*<sup>W</sup> <sup>≡</sup> <sup>10</sup>−<sup>5</sup>*B*<sup>W</sup>*,*−<sup>5</sup> G, The Astrophysical Journal, 771:54 (22pp), 2013 July 1 Sironi, Spitkovsky, & Arons  $\mathcal{L} = \{ \mathcal{L} \mid \mathcal{L} \in \mathcal{L} \}$  , the number density in the number of  $\mathcal{L} = \{ \mathcal{L} \}$ wind at *<sup>R</sup>* <sup>=</sup> 1018 cm is *<sup>n</sup>* <sup>≡</sup> <sup>0</sup>*.*<sup>3</sup> *<sup>n</sup>*−0*.*<sup>5</sup> cm−3, and the strength of the magnetic field at *<sup>R</sup>* <sup>=</sup> 1018 cm is *<sup>B</sup>*<sup>W</sup> <sup>≡</sup> <sup>10</sup>−<sup>5</sup>*B*<sup>W</sup>*,*−<sup>5</sup> G, *<sup>R</sup>*dec <sup>≃</sup> <sup>1</sup>*.*<sup>3</sup> <sup>×</sup> 1017*E*<sup>1</sup>*/*<sup>3</sup>

For a typical GRB exploding in the wind of the pre-burst progenitor star, the magnetisation is: so that the magnetization parameter in the magnetization parameter in the wind will be wind  $T_{\text{max}}$  is usually attributed to usually  $T_{\text{max}}$ Moding in the wind of the pre-burst progenitor star, the magnetisation is: <sup>1</sup>*/*<sup>3</sup> <sup>≃</sup> <sup>6</sup>*.*<sup>1</sup> <sup>×</sup> <sup>1018</sup>*E*<sup>1</sup>*/*<sup>3</sup>

small enough that acceleration does take place ( $\sigma$ <3x10-5). relativistic deceleration phase  $\sqrt{2}$  and by the Blandford by the Blandford by the Blandford by the Blandford  $small$  anough shock propagates either in the ISM, with constant density, or in 16π*nmic*<sup>2</sup> small enough that acceleration does  $u \in \mathcal{U}$  (action  $\mathcal{U}(\mathbf{r})$ the previous sections coincides with the instantaneous Lorentz

$$
\sigma = \frac{B_{\rm W}^2}{4\pi n m_i c^2} \simeq 1.7 \times 10^{-8} B_{\rm W, -5}^2 n_{-0.5}^{-1}
$$

$$
\Gamma(R) = \left(\frac{17E_0}{16\pi nm_i c^2}\right)^{1/2} R^{-3/2}
$$

The analog of the Sedov phase (deceleration phase) starts at: at distance (deceleration priuse) starts are ≡erration radius and model ≡erration radius and *Republicance ≡erration* radius and *Republicance ≡erration* radius and *Republicance —erration* radius and *Republicance —errati* The analog of  $\frac{a}{2}$ The analog of the Sedov phase (deceleration phase) starts at: upstream frameworks are the ISM frameworks with the ISM frameworks with the ISM frameworks with the result in the result in

$$
R_{\rm dec} \simeq 1.3 \times 10^{17} E_{0,54}^{1/3} \Gamma_{0,2.5}^{-2/3} n_0^{-1/3} \, \rm cm
$$





# STOCHASTIC ACCELERATION IN A RELATIVISTIC PLASMA

- <sup>9</sup> Large scale turbulence advected downstream of the FS leads to stochastic acceleration in a B-field:  $B = \sqrt{32\pi\epsilon_B n m_p c^2 \Gamma^2}$
- $\frac{3}{5}$  Spatial diffusion and p-diffusion are connected:  $D_{zz}D_{pp}$  $\sim$  $p^2$   $v_A^2$
- $\bullet$  In the ultra-relativistic case vA=c/31/2
- The time scale for escape and acceleration are related through

FIG. 1. UHECR protons spectra resulting from joint stochastic acceleration, particle diffusive escape, and adiabatic energy loss and their Zhang+, 2021  $C^{1.501}$  function of  $C^{1.501}$  and  $C^{1.501}$ 



**The spectrum can be shown to be harder than E-2 and depends on the spectrum of the turbulence**

> $0.1000$  s in observer to dark blue to dark blue to dark red represent the evolution of proton spectrum under the case  $\alpha$ 13



# The case of the hidden cocoons (Berezinsky 1977)

 $\mathcal{G}_\mathcal{A}$ Figure 2. Optical depths for two-photon pair annihilation, photomeson …because E<sub>max</sub> is not high enough… lines are for <sup>R</sup> <sup>=</sup> <sup>30</sup> RS and <sup>R</sup> <sup>=</sup> 104 RS, respectively, and <sup>t</sup>\* <sup>=</sup> <sup>10</sup>R/<sup>c</sup> is



Turbulent acceleration would lead to acceleration with an absolute upper limit at

 $r_L(E_{max}) = L \equiv \lambda R_s \rightarrow E_{max} = 8 \times 10^{10} GeV \ \chi M_7^{1/2} \beta_P^{-1/2} \tau_T^{-1/2}$ 

but the actual maximum energy is limited by Bethe-Heitler pair production and is <100 TeV

So, it looks like we might have found the sources of high energy neutrinos but at least most of them cannot be the source of UHECRs…



…and because they cannot escape the corona



#### Extraction of nuclei from the surface processes in the magnetosphere are started), and/or if they can be boiled off the surface by stellar heat [31, 32]. In the case of a pulsar with millisecond periods at a pulsar with millisecond periods a<br>In the electrical periods at a pulsar with millisecond periods at a pulsar with millisecond periods at a pulsa  $2 \times 2$  Ion extraction and acceleration  $\epsilon$  $\overline{p}$ √ 6.3 × 1014 B13Ra, 6P −1 −3 V cm−1 +3 V cm−1 +3 V<br>Cm−1 +3 V cm−1 +3 V

The electric field associated with the rotation of magnetised sphere is field that can be provided at the surface of the star can be estimated as (see, e.g., [3]) electric field associated with the rotation of magnetised sphere is where B is the B is the dipole magnetic magnetic magnetic strength of the strength of the strength of its report of the strength of the streng period. In production to the does not period. In production of this group is expected to the set of the set of <br>The contract to the set of the se

to be compared with the binding energy of nuclei in the lattice that forms the surface of the NS (with lattice spacing l): energy of nuclei in the lattice that forms and P its radius and P inding energy of nuclei in the lattice that forms period of the NR (with lattice concinal). surface of the NS (with lattice spacing I):  $\frac{1}{2}$  $\frac{H_{\text{max}}}{\sigma}$  to be eerested with the binding energy of puolei in the lettice that formed

#### (PB, Epstein & Olinto 2000, Arons 2003, Kotera, Amato & PB 2015) ACCELERATION IN A FAST ROTATING NEUTRON STAR IONS CAN THUS CAN THUS BESTRIPPED ON TRIPPO OF THE SURFACE PROVIDED THE SURFACE A SURFACE A SURFACE A SURFACE A SURFACE ELECTRIC FIELD US EN EN EN FRANCIA −<br>−1 VL the supernova ejecta region for further processing. We discuss our results and conclude in  $\begin{array}{c} \begin{array}{c} \end{array} \end{array}$  $\Lambda$ ACCELEF PATIO (PB Epstein & Olinto 2000 Arons 2003 Kotera Amato & PB 2015) IN A FAST ROTATING NEUTRON STAR



tion in the surface of the N  $\tilde{f}$  is a also be stripped of with milder electric fields if the surface is bombarded of the surface is bombarded of  $\tilde{f}$ by particles (for the two), since it gets sureened by the intense production of<br>tensionies processes in the magnetosphere are started of the magnetosphere are started of the surface by boiled of the surface by boi The induced electric field survives for a short distance from the surface of the NS, since it gets screened by the intense production of electron-positron pairs that short circuit it. The total available potential is The induced electric field survives for a short distance from the surface of the NS, since it electron-positron pairs that short circuit it. The total available potential is  $\sum_{i=1}^{n}$ 

> $\mathbf{B}$  $15$ 15

$$
\mathcal{E} = \frac{2\pi R_{\star}B}{Pc} \sim 6.3 \times 10^{14} B_{13} R_{\star,6} P_{-3}^{-1} \,\mathrm{V}\,\mathrm{cm}^{-1}
$$

$$
\mathcal{E}_0 = 14 \,\text{keV} / (Zel) \sim 5.4 \times 10^{11} \, Z_{26}^{-1} l_{-9}^{-1} \,\text{Vcm}^{-1}
$$

$$
{}_{\star,6}^{3}P_{-3}^{-2}V \qquad \qquad \gamma_{\text{fpd}} = \frac{Ze}{Am_pc^2} \Phi = 7 \times 10^{10} \frac{Z}{A} B_{13} P_{-3}^{-2}
$$



$$
\Phi = \frac{2\pi^2 BR_{\star}^3}{P^2 c^2} \sim 6.6 \times 10^{19} B_{13} R_{\star,6}^3 P_{-3}^{-2} V
$$

A nucleus extracted from the surface gains energy in the electric field in the gap of size ξRL where R<sub>L</sub> is the size of the light cylinder ( $R_{\rm L} = cP/(2\pi) \sim 4.8 \times 10^6 P_{-3}$ cm) but suffers severe curvature  $\mathcal{L}$   $\left\{\left\{\right\}$  and beam  $\left\{\right\}$  is most severe and the surface guitar that the todine energy in the electric field in the gan of size CD. and onorgy in the Ground nera in the gap of bize give  $R_{\rm L}$  =  $cP/(2\pi)$  ~ 4.8 × 10<sup>6</sup>  $P_{-3}$ cm) but suffers severe curvature beam A nucleus extracted from the surface agins energy in the electric field in the gap of size  $\epsilon$ Ri where Ruis the size of the light cylinder ( $R_{\rm L} = cP/(2\pi) \sim 4.8 \times 10^6 \, P_{\rm m} \, {\rm cm}$ ) but suffers severe curvature magnetized objects, show a profile that can vary as a function of that can vary as a function of the polar angle. Composition of the UHECR flux from a new first recognition of the Sunney of the UAR first recognition of t knowledge  $k_{\text{L}}$  is the size of the light cylinder ( $R_{\text{L}} = cP/(2\pi) \sim 4.8$ 

Frincoriora for ofaric and the shold for photo-disintegration<br>Dipole resonance

losses: quantities involved in the photo-hadronic processes. that potential drop  $\text{where } R_L$  is the size of the light cylinder  $(R_L = cP/(2\pi) \sim 4.8 \times 10^{-3}$ composition of the UHECR flux from a newborn pulsar, we first recall briefly our current

#### (PB, Epstein & Olinto 2000, Arons 2003, Kotera, Amato & PB 2015) ACCELERATION IN A FAST ROTATING NEUTRON STAR **FNT** ∼ 6.6 × 10<sup>19</sup> B13R<sup>3</sup> <sup>⋆</sup>,6<sup>P</sup> <sup>−</sup><sup>2</sup> <sup>−</sup><sup>3</sup> <sup>V</sup> , (2.2) ZOOO, KOlCIQ, AIHQIO OCHD ZOIO)<br>1 A B13 P −2 .<br>A B13 P −2 .<br>A B13 P −2 . (2.3) P +2 . (2.3) P +2 . (2.3) P +2 . (2.3) شا  $\vert \vert$  $\overline{a}$ K∪IN DIAK which corresponds to a maximum achievable particle  $\mathcal{N}$ knowledge on the pulsar surface of the pulsar surface at  $\sim$ quantities involved in the photo-hadronic processes.

$$
\text{M}_{\text{gap}}^{\text{inner}} \frac{d\gamma}{d t} = \frac{Ze\Phi}{Am_p c^2} \frac{2\pi}{\xi P} - \frac{8\pi^2}{3cP^2} \frac{Z^2 e^2}{Am_p c^2} \gamma^4 \qquad \text{M}_{\text{curv}} = \left(\frac{3\pi BR_\star^3}{2Ze cP\xi}\right)^{1/4} \sim 1.1 \times 10^8 Z_{26}^{-1/4} \xi^{-1/4} B_{13}^{1/4} P_{-3}^{-1/4} R_{\star,6}^{3/4}
$$

FUIC HUCICI, WHICH CHU UP HUVING UTHACU CONPOSITION UL CAIL. real vature losses is diso pornidarded A nucleus of iron extracted from the surface and surviving curvature losses is also bombarded from behind by thermal photons emitted from the hot star surface. This causes photodisintegration of the nuclei, which end up having a mixed composition at exit. for the servention of the observations of the stars of the stars with magnetized envelopes matters of the stars with magnetized envelopes of a constructed material surface temperature in the surface temperature of the temperature of the temperature<br>The material surface mannetized objects, show a profile that can vary a profile that can vary and profile that can vary and polar a<br>The polar angle.  $\alpha$  the surface and surviving curvature losses is also bombarded section, and the section, and section at the resonance can be written as  $\frac{1}{2}$ 8×10−26 A56 A56 A56 cm2. Threshold energy is one threshold energy in the courses priote-<br>A end up baying a mixed composition at exit ϵ<sup>2</sup> − ϵ<sup>1</sup> = ∆ϵ [38–40]. The corresponding threshold Lorentz factor for particles thus reads The the the thermal photons emitted from the interval as from the neutron stars in the neutron stars.  $\sqrt{ }$  disintegration of the nuclei which end un having a mixe

Energy of thermal Threshold for Giant  $\epsilon_{\gamma,th} = k_{\rm B}T \sim 86 \, {\rm eV} \, T_6 \qquad \qquad \bar{\epsilon}_{A\gamma} = 18.31 A_{56}^{-0.21} {\rm MeV}$ a threshold energy of order order a threshold energy of order  $\Gamma$ Energy of thermal photons  $s_{\text{inter}}$ sicher energies [38, 39]. The cross-section at the resonance can be written as  $\sum_{i=1}^n s_i$ 

$$
\epsilon_{\gamma,th} = k_{\text{B}}T \sim 86 \,\text{eV} \, T_6 \qquad \qquad \bar{\epsilon}_{A\gamma} = 18.31 A_{56}^{-0.21} \text{MeV} \qquad \qquad \gamma_{A,\text{thres}} = \frac{\bar{\epsilon}_{A\gamma}}{\epsilon_{\gamma,\text{th}}} \sim 2.1 \times 10^5 \, A_{56}^{-0.21} \, T_6^{-1}
$$
\nEnergy of thermal

\nThreshold for Giant

\nThreshold for photo-disintegration





### Acceleration of nuclei in the gap

### (PB, Epstein & Olinto 2000, Arons 2003, Kotera, Amato & PB 2015) ACCELERATION IN A FAST ROTATING NEUTRON STAR

- \* Depending on the temperature of the surface of the NS the photo-disintegration of Fe nuclei leads to a mixed composition
- The amount of mixture depends on the temperature
- Take into account that the photo-disintegration occurs in a very anisotropic, time-dependent scenario











 $10^{-2}$ 

 $10^{-2}$ 

17

#### *Gone with the wind (PB, Epstein & Olinto 2000, Arons 2003, Kotera, Amato & PB 2015)* ACCELERATION IN A FAST ROTATING NEUTRON STAR MOORE PRECISELY ASSESSED TO THE TYPICAL COMPOSITION TO BE in the wind region before being altered by the supernova ejecta and the propagation in the intergalactic medium was ∼ 50% protons, ∼ 30% CNO and ∼ 20% Fe. These authors discuss in the wind region of the supernoval alternation by the supernoval energy in the supernoval energy  $\Lambda$  of  $\Lambda$   $\Gamma$  in the  $\Lambda$ intergalactic medium was ∼ 50% protons, ∼ 30% CNO and ∼ 20% Fe. These authors discuss Gone with the wind (PB, Epstein & Olinto 2000, Arons 2003, Kotera, Amato & PB 2015)  $\Omega$  accelerated in the gap are in the pulsar wind, and reach  $\Omega$ with fluxes that we estimate below. They subsequently reach the nebula region and the in the wind region before alternation by the supernoval alternation  $\overline{\phantom{a}}$ intergalactic medium was ∼ 50% protons, ∼ 30% CNO and ∼ 20% Fe. These authors discuss Superinted in the team of the theories of the theories and baryonic fields. As mentioned in the set of the set o the introduction, the effects of these backgrounds were calculated extensively in [6, 7, 22]. Gone with the wind (PR Epstein & Olinto 2000, Arons 2003, Kotera, Amato & in  $\bigcap$  of a the  $\bigcap$  of altered by the propagation in the propagat intergalactic medium was ∼ 50% protons, ∼ 30% CNO and ∼ 20% Fe. These authors discuss or 2003, Kotera, Amato & PB 2015). The narrow range of all uncessions allowed for successive for successive and

The general picture is that once the particles reach the light cylinder, they can take part in the wind, namely they move with the wind Lorentz factor, EVEN IF THEY SUFFERED LOSSES EARLIER ON! or on the narrow range of pulsar parameters allowed for successful UHECR acceleration). LOIENIZ IQCLOI, EVEN IF THEY SUFFERED LOSSES EARLIER ON!<br>LOIENIZ TOCLOI, EVEN IF THEY SUFFERED LOSSES EARLIER ON! t once the particles reach the light cylinder they can take part in the wind namely they move with the wind that this result is rather robust (the composition weakly depends on the supernova parameters that the purificies reduit the fight to<br>IEV CHEEEDEN I ASSES EADHED AN p pintuon, and y contracted portain and winto, nonnony and il i Jufflned Lujjed lateric vin:<br>N γww.externalistic the latter as: N γww.externalistic the latter assembly written as: N γww.externalistic The general picture is that once the particles reach the light cylinder, they can take part in the Lorentz factor, EVEN IF THEY SUFFERED LOSSES EARLIER ON!  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  in the following  $\frac{1}{2}$  pulsar,  $\frac{1}{2}$  for  $\frac{1}{2}$   $\frac{$ ter, they can take part in the wind, namely they move with the wind

**Notice that it drops down with time!!!**<br> **Notice that it drops down with time!!!** Here, we have expressed the pulsar spin down luminosity E˙



in the wind region before before being altered by the supernova ejecta and the propagation in the propagati

that the result is result is rather robust (the composition weakly depends on the supernova parameters on the s

It follows that the wind <sup>γ</sup>w(t) <sup>≃</sup> (1 <sup>−</sup> <sup>η</sup>B) <sup>E</sup>˙ Here, we follow the putting the pulsar spin down in th It follows that the wind Lorentz factor can be estimated as follows:  $\mathsf{S}$ :

$$
\gamma_w(t) \simeq (1 - \eta_B) \frac{\dot{E}_p}{\dot{N}mc^2}
$$
  
\n $\sim 3 \times 10^9 (1 - \eta_B)(1 + x_A)^{-1} (1 + t/t_{sd})^{-1} \kappa_4^{-1} L$ 

$$
\dot{E}_{\rm p} = (8\pi B_{\star}^{2} R_{\star}^{6})/(3c^{3}P^{4}) \longrightarrow \dot{N}\gamma_{\rm w}mc^{2} \equiv 2\kappa m_{e}c^{2}\dot{N}_{\rm GJ}\gamma_{\rm w}(1+x_{A})
$$

$$
\begin{array}{c}\n\ddot{N}_{\rm GJ} = e^{-1}(\dot{E}_{\rm p}c)^{1/2} \\
\ddot{N}_{\rm GJ} = e^{-1}(\dot{E}_{\rm p}c)^{1/2} \\
\ddot{N}_{\rm GJ} = e^{-1}(\dot{E}_{\rm p}c)^{1/2}\n\end{array}
$$

$$
t_{\rm sd} = \frac{9Ic^3P_1^2}{8\pi^2B^2R^6} \sim 3.1 \times 10^7 \, \text{s} \, I_{45}B_{13}^{-2}R_{\star,6}^{-6}P_{\rm i,-3}^2
$$
\n
$$
{}_{3}^{2}B_{13}R_{\star,6}^{3}
$$
\nSpin down time of the pulsar

 $\kappa_4^{-1}P_{\rm i,-3}^{-2}B_{13}R_{\star,6}^3$  $\sum_{i, -3}$ D13 $n_{\star, 6}$  $D^{-2}$   $D^2$  $_{4}^{-1}P_{\rm i,-3}^{-2}B_{13}R_{\star,6}^{3}$ 





#### ACCELERATION IN A FAST ROTATING NEUTRON STAR CELERATION IN A FAST ROTATING ACCETEKATIOM IM & LA2T KOTATIMG

Gone with the wind (PB, Epstein & Olinto 2000, Arons 2003, Kotera, Amato & PB 2015) Gone with the wind (PB Epstein & Olinto 2000, Arons 2003, Kotera, Amato

Since the Lorentz factor of the wind decreases, the energy of the particles also decreases in time and results in a SPECTRUM (PB,  $\frac{10^{10}}{10^{9}}$ Epstein & Olinto 2000):  $\sum_{z=10^{-2}}^{z}$  the neutron-star spins down, consider with the wind with the wind will have an energy  $\sum_{z=10^{-2}}^{z}$  and  $\sum_{z=10^{-2}}^{z}$ 

and the spectrum is: ray in the set of the s<br>
in the set of the set

$$
E_{\rm CR}(t) = E_0 \left(1 + t/t_{\rm sd}\right)^{-1}
$$
  
~  $\sim 1.2 \times 10^{20} \, \text{eV} \, \eta A_{56} \kappa_4 I_{45} B_{13}^{-1} R_{\star,6}^{-3} t_{7.5}^{-1}$  fc

$$
\frac{dN_{CR}}{dE} = \int_0^\infty dt \dot{N}_{GJ}(t) \delta(E - E_{CR}(t)) = \frac{\dot{N}_{GJ}(0)t_{sd}}{E} \sim \boxed{\frac{\text{I}}{\text{F}}}
$$
\nVery hard spectrum





# ACCELERATION IN STARBURST GALAXIES



#### THE DISTRICT OF STARBURST WINDS OF STARBURST WINDS (STRICKLAND WINDS

 $D_{\alpha}$  is the medium is  $\Omega$ Peretti+ 2022



Eu,

 $R_{FS} \approx R_{esc}$ 

potion shock of the collective wi Particle acceleration is expected to take place at the termination shock of the collective wind induced by the star forming region

et al. 2022). On the other hand, in the case of a less intense and The acceleration at the termination shock is standard DSA at a newtonian shock, but in star-forming galaxies, where energy losses are usually negligible, the spherical symmetry

The maximum energy is fixed by geometry and **IT IS NOT SUFFICIENT TO REACH THE OBSERVED MAXIMUM RIGIDITIES!** 

20

### ACCELERATION IN ULTRA-FAST-OUTFLOWS (UFO) *DSA and multimessenger flux from UFOs* 185







 $\frac{1}{21}$ 21



### ACCELERATION AT ACCRETION SHOCKS IN LSS 1996<br>|<br>|

- Large scale structures, such as clusters and superclusters of galaxies, are firmed through two processes: mergers of smaller structures and accretion of gas over cosmological scales (Bertschinger 1985)
- <sup>9</sup> The mergers typically lead to weak shocks inside the structures, as it must be, because each structure is virialized to its own thermal velocity, which is of the same order of magnitude as the free fall velocity…
- $\bullet$  Hence the Mach number of the merger shocks formed in two equal size structure is of order unity, while the Mach number of the merger between a small and a large cluster can be higher.
- The accretion of gas onto a LSS develops a strong shock in the outskirts of the cluster
- The shocks developing in the LSS filaments are tightly related to this accretion phenomenon





F. VAZZA, D. WITTOR AND J. WEST, 2023





#### CLUSTERS OF GALAXIES AS STORAGE ROOM FOR COSMIC RAYS

V. S. BEREZINSKY, $^1$  P. Blasi, $^{1,2}$  and V. S. Ptuskin $^3$ Received 1996 September 6; accepted 1997 May 9 1,2 AND V. S. PTUSKIN33, A<br>1971 - PTUSKIN33, AND V. S. PTUSKIN33, AND V. S. PTUSKIN33, AND V. S. PTUSKIN33, AND V. S. PTUSKIN33, AND V. S

#### ABSTRACT Received 1996 September 6; accepted 1997 May 9



It is demonstrated that clusters of galaxies are able to keep cosmic rays for a time exceeding the age of the universe. This phenomenon reveals itself by the production of the diffuse flux of high-energy gamma and neutrino radiation due to the interaction of the cosmic rays with the intracluster gas. The produced flux is determined by the cosmological density of baryons,  $\Omega_b$ , if a large part of this density is provided  $\Gamma$ by the intracluster gas. The signal from relic cosmic rays has to be compared with the flux produced by<br>the late courses which can be considered as a heckeround in the seemeb for cosmic ray production in the the late sources, which can be considered as a background in the search for cosmic-ray production in the past. We calculate this flux considering the normal galaxies and active galactic nuclei (AGNs) in the clusters as the sources of cosmic rays. Another potential cosmic-ray source is the shock in the gas accreting to a cluster. We found that this background is relatively high: the diffuse fluxes produced by relic cosmic rays are of the same order of magnitude that can be expected from AGNs in the clusters. In all cases the predicted diffuse gamma-ray flux is smaller than the observed one, and the diffuse neutrino flux can be seen as the small bump at  $E \sim 10^6$  GeV over the atmospheric neutrino flux. A bright phase in the galaxy evolution can be a source of the relic cosmic rays in clusters, revealing itself by diffuse gamma and neutrino radiation. We found that the observation of a signal from the bright phase is better for an individual cluster. IT  $\sigma$  is demonstration to that clusters are able to the contrated to keep cosmic rays for a time exceeding the age of  $\sigma$ and neutrino radiation que to the interaction of the cosmic rays with the intractuster gamma cases the predicted diffuse gamma-ray from it smaller than the observed one, and the difuse  $\Delta$ can be seen as the sman bamp at ED 106 GeV over the atmospheric neutrino near. A<br>the galaxy evolution can be a source of the relic cosmic rays in clusters revealing itself l the galaxy evolution can be a source of the relie cosmic rays in clusters, revealing fisch to and neutrino radiation. We found that the observation of a signal from the bright phase. individual cluster.

gamma and neutrino telescopes. The processes of particle acceleration in clusters are thought to be potentially related R. The magnetic fields in the accretion filamen  $abelianed$  to offect the trepenet of  $I\Pi FCP$ UHEUR. The magnetic fields in the accretion filaments are believed to affect the transport of UHEURS Subject heading: cosmic rays È di†use radiation È galaxies : clusters : general È intergalactic medium  $i_{\text{long}}$  in opto ore boliared to offect the transport of tialiterits are believed to affect the transport o The diffusive confinement of CRs in clusters of galaxies has numerous implications that are still being checked with to UHECR. The magnetic fields in the accretion filaments are believed to affect the transport of UHECRs 23

#### Clusters as storage rooms of CR: mergers  $t_{\rm c}$  for a cluster can be simulated as discussed in the pre- $\sim$  34  $\sim$  35  $\sim$  0.000  $\sim$  10  $\pm$  10  $\bigcap$ r $\bigcap$  $\overline{\phantom{a}}$  and Machine the Machine with the merger associated with the merger  $\overline{\phantom{a}}$ events. A value D<sup>m</sup> ¼ 0:05 is assumed. Note that this value of Miniative and  $\mathcal{L}$ D, montann  $\blacksquare$ resolution achieved in these simulations is 0.315 h#<sup>1</sup> Mpc, very close to the size of the size of the size of the region (1.5  $\mu$  Mpc) where the region (1.5  $\mu$ small mergers , which are the interpreted as events more similar  $\overline{\phantom{a}}$  $A \cap A \cap A \cap A \subset A$ accoretion is in the LC is easy to use the LC nerr 7 UC  $\frac{1}{2}$  $\mathcal{L}(\mathcal{A})$  $\overline{v}$

 $\begin{array}{c}\text{Number}\\ \text{a}\end{array}$ 

- Particle acceleration in clusters can take place during merger shocks
- …at accretion shocks
- … or inside one of the hundred of astrophysical objects (galaxies, AGN, …) that are hosted by the cluster
- The spectra are different in these cases







**Accretion**

Accretion occurs in the outskirts of the cluster —> shocks with M>10 where the IGM is processed and heated up to 10<sup>8</sup>

K

 For massive clusters there are the conditions for streaming instability to be induced

### Spectrum at shock

### Spectrum/ we get

Particle acceleration to EeV possible

Careful: we are sitting in the upstream (hard spectrum at



Earth)



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E

# Summary

• The source spectrum required by observations is weird (effects in the source or en route) but not absurd (reacceleration, turbulent acceleration, reconnection, upstream of a cluster shock)

\* The picture that arises for the origin of UHECR and the transition from the Galactic component is complicated, not a simple, elegant picture as one would expect from a well



- Giant change in paradigm from the times of AGASA and HiRes
- A change provided by reliable observation of the mass and spectrum…
- Plenty of classes of sources are able to reach EeV energies
- 
- behaved mother Nature (disappointing model)

