GRAN SASSO

SCHOOL OF ADVANCED STUDIES Scuola Universitaria Superior

Pasquale Blasi *Gran Sasso Science Institute* GAMMA RAYS FROM STAR CLUSTERS AND IMPLICATIONS FOR GALACTIC COSMIC RAYS

¹ **TOSCA - Topical Overview on Star Cluster Astrophysics, October 29 2024, Siena**

Why did the community get interested in SC?

We do not find the PeVatrons yet and yet we detect PeV CRs… **Maybe SC can be PeVatrons?**

Even if SNR were the main sources of CR, yet most of them are in SC… **Maybe SC can be main contributors to the CR flux?**

Ultimately, does the detection of high energy gamma rays imply that SC are important CR sources?

Finally we did detect SC in VHE gamma rays, **what does this tell us?**

Recall the anomaly in 22Ne/20Ne

Cristofari, PB & Caprioli 2021, Cristofari, PB & Amato 2020

- t , the ST phase, typically a few TeV. The flux of escaping a few TeV. The flux of escaping \mathbf{r} themselves close to the shock N(p)[arb*.*units] PITCU
-
- $\overline{}$
- $F_{\rm 2}$ masses that $F_{\rm 2}$ in $F_{\rm 2}$ in Fig. $F_{\rm 2}$ is a $F_{\rm 2}$ of $F_{\rm 2}$

$\overline{}$ $\overline{}$

Why are SNRs are not PeVatrons? 107 \overline{a} Np loss Np tot \Box the normal ISM, with a spatially constant gas density and back- $\sqrt{2}$ energy is a few tens of TeV (left panel of TeV (left panel of TeV (left panel of TeV \sim additional superiors at some \mathcal{L} 10 Np

The fastest instability to do so is the non-resonant hybrid instability 16 er
.un 4*.*0 But even in the presence of this phenomenon... what happens is shown below... LU UII The problem is that even this instability is insufficient to confine for long enough particles UPSTREAM of the SNRs can accelerate particles to "decent" energies only if CRs can self-confine themselves close to the shock shock!

Figure **1.** Schematic structure of a wind by a structure of a wind by a starting by a starting by a starting of cluster into the ISM: *Rs* is the position of the TS, *R*^b is the radius of the FS. ie gas density is constant and the velocity dro , a

, *v*⁸ $\frac{1}{3}$, *m* $\frac{1}{3}$ In the downstream of the termination shock, the gas density is constant and the velocity drops as 1/r² In the downstream of the termination shock, the gas *r R*s constant and λ ˙ ³*/*¹⁰ *P* velocity dro 2*/*5 $\frac{1}{10}$ as $\frac{1}{10}$. where *Reportant and the velocity drops* as $1/r^2$ **S** constant and the velocity drops as $1/T^2$ In the downstream of the termination shock, the gas density is constant and the velocity drops as 1/r²

$$
\rho_{w,d}=4\rho_w(R_s)
$$

2000 mmmmmmmmmmmmmmmmmmmmmmmmmm **1** *x t e*₁ where \mathcal{L} is the ISM density in the region around the region around the star clus-Since the typical cooling time-scale of the shocked ISM is only the shocked ISM is only the shocked ISM is only [∼]10⁴ yr, while the cooling time for the shocked wind isseveral ¹⁰⁷ yr spectrum and spatial morphology of the gamma-ray emission from the City City conclusions. In the Cocoon of City Conclusion 6, we obtain

very close to the FS. The region between the contact discontinuity \mathcal{L} uster is sufficiently compact the collective wind of the stars in the ly excavate a bubble with an outer boundary (forward shock) and $\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$ is gas in the bubble inside the bubble is gas in the bubble in the bubble is gas in the bubble in the bub ation shock at a distance that is fixed by dynamics *i*e a bubble with an outer boundary (forward shock) and the abubble with an outer boundary (forward shock) and $\frac{1}{2}$ **PLONDEP INDEP IS** λ at a distance that is fixed by dynamics collective wind of the starslocated in the starslocated in the starslocated in the central region. We explicit

$$
R_s = 24.3 \dot{M}_{-4}^{3/10} v_8^{1/10} \rho_{10}^{-3/10} t_{10}^{2/5} pc
$$

$$
R_b(t) = 139 \rho_{10}^{-1/5} \dot{M}_{-4}^{1/5} v_8^{2/5} t_{10}^{3/5} pc
$$

 \overline{a} wind region the plasma velocity is constant C WINU LESION LIIC PIASINA VEIOCILY IS CONSTANT, $\frac{d}{v}$ drops as $1/r^2$ ed
com/more
com/mnrs In the wind region the plasma velocity is constant, hence the density $r = 10$ per cent. We stress a control per n the plasma velocity is constant, hence the density the entire bubble structure evolves slowly and can be considered bubble structure evolves slowly and can be co m the plasma velocity is constant, hence the density objects merges into a constant, we have the density window a velocity is constant, hence the density density is obtained from mass conservation: the conservation: the conservation: the conservation: the conservation:
The conservation: the conservation: the conservation: the conservation: the conservation: the conservation

$$
\rho_w(r) = \frac{\dot{M}}{4\pi r^2 v_w}, r > R_c
$$

$$
v_{w,d} = \frac{v_w}{4} \left(\frac{r}{R_s}\right)^{-2}
$$

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Particle acceleration at the Termina

- The TS is expected to be rather strong, M \gg 1
- The collision between winds in the core and in the wind region is expected to an approximate the set of the set transform some fraction η_B of the kinetic energy of the wind to MHD turbulence… at the shock: Badman et al. (2022) and the wind to with da fraction of the function of the term of the term in the ter me fraction _{nB} of the kinetic energy of the wind to MHD and many expect a turbulent magnetic material t the shock:

- While the magnetic energy is expected to be injected at some large scale, the resulting diffusion coefficient depends on t<mark>he</mark> MHD cascade to smal<mark>l sc</mark>al<mark>es</mark> \mathbf{a} $\overline{\bigvee}$ agnetic energy is expected to be injected at some large scale, the the stately results of the setting of the same scale, $\frac{1}{2}$ ion coefficient depends on t<mark>he</mark> MHD cascade to small scales and the order to the order to the order to be of order
- Esulting different coefficient depends on the MHD cascade to sinan scales
One can study different cases (Kolmogorov, Kraichnan, Bohm), non particularly compelling...some less credible than others ...compelling
1004×101×2004 ne less credible than others ly different cases (Kolmogoro<mark>v,</mark> Kraichnan, Bohm), no<mark>n p</mark>art A as a credible than others a Kraichnan case A Kraichnan case A Kraichnan case A
	- Intermittency can make the effective $D(E)$ more dependent upon quantities other than the spectrum (Lemoine 2024) y can make the effective $D(E)$ more dependent upon quantities $20-$
	- For parameters typical of star clusters, self-generation is not expected to play an important role \overline{c} <mark>*star clus</mark></mark>* $\frac{1}{2}$
 $\frac{1}{2}$ "−1*/*²

$$
B(R_s) = 7.4 \eta_B^{1/2} \dot{M}_{-4}^{1/5} v_8^{2/5} \rho_{10}^{3/10} t_{10}^{-2/5}
$$

 $R_{\rm cd} \simeq R_{\rm fs} = R_b$

1 is not expected \overline{a} \overline{b} $\overline{1}$

Particle acceleration at the Termination Shock

The TS behaves as a standard spherical Newtonian shock of CRs, with special care for those that produce a spectrum extending

- While the main limitation to particle acceleration at a shock is usually due to escape from upstream, here the upstream is closed! All particles remain inside mitation to par<mark>ticle acceleration</mark> at a shock is usually due
- Transport equation needs to be solved accounting for the spherical symmetry \blacksquare tion heeds to be solved accounting for the spitel
- Particles with low energies probe the region very close to the shock surface (weak effect of sphericity) —> standard power law spectrum the region another the region were close to the sheek surfa $\frac{1}{2}$ westerly westerly when the shock suite (2) Cricity) \rightarrow Statiuaru power law spectrum
- Higher energy particles move farther from the shock and feel gradually lower effective plasma speed due to sphericity —> gradually steeper spectrum eticles move farther from the shock and feel gradually love waad dus to ophoricity = xradually stooper spectrum Collaboration 2015). The subset of the speech unit

How spectrum approaches p_{max} depends on $D(E)$ more than for a standard planar shock or an expanding spherical shock (Morlino+21) α expanding spherical shock (Morlino+21) energies *>*100 TeV are reached. These findings would, than, suggest

Morlino+2021

Particle acceleration at the Termination Shock

- If a few percent of the wind kinetic energy is channeled into MHD turbulence \rightarrow diffusivity in the bubble reduced by 2-3 orders of magnitude wrt ISM
- \bullet Maximum energy determined by the size of the confinement region \sim R_s

Easily pmax~PeV but for Kraichnan and Kolmogorov turbulence, substantial suppression at $p \ll p_{\text{max}}$

Recall that Bohm diffusion corresponds to equal power on all scales, unjustified unless for self-generation with a p⁻⁴ spectrum (not the case here) S <mark>to</mark> e

The effective maximum energy much smaller than the nominal value

 This seems confirmed by what we see in gamma rays! a
and the see in gamma ray of it we see in gamma rays:

solutions are matched at *r* = *Rs* so that *N* = *N*0. Such a solution is $\mathbb{P}^{2b'}$ **For protons** $b(E,r) = c\dot{p}$ can internet *D*¹*,*² ∂*N* **r**
article $\frac{u}{\tau_{\text{env}}(x)}$ **For nuclei** b' \mathbb{I} For protons $h(E)$ N_{α} N_{α} $N_{\alpha'}$ **Equiplei** $+\frac{1}{3}$ $\frac{1}{dx}$ N_α – $\frac{1}{\tau}$ + \sum $\frac{1}{\tau}$ for nuclei $\alpha' > \alpha$ sp, $\alpha \rightarrow \alpha$ sp, $\alpha \rightarrow \alpha$ *D*¹*,*² \vec{c} \vec{D} For protons the spectrum of accelerated particles as a result of proximity to $\n *p*$ For protons $\n *b*(*E*,*r*) = *c*$ $$ $\overline{\mathbf{M}}$ $\frac{1}{2}$ is solved in a similar way for puclei. $\frac{\partial}{\partial s}$ $\iota_{sp,\alpha'} \to \alpha$ \mathbf{r} ∂*N*^α ∂*E* r prc $+\sum$ α"*>*α $N_{\alpha'}$ $\tau_{\text{sp},\alpha'\to\alpha}$ **For nuclei** $= c\,\dot p$ is solved in a similar way for primary nuclei. rotons $b(E,r) = c\dot{p}$ *b*" (*E,r*) = ∂*b*(*E,r*)*/*∂*E*. For high-energy protons energy losses are dominated by interesting problems of $\mathbf p$ in the Morlin See Blasi $\mathbf p$ $\left[1 \frac{d(\tilde{u}r^2)}{r^2}\right]$ 1 $b(E, r) = \frac{1}{3}$ time, hence the spectrum at the spectrum at the spectrum at the shock is weakly affected by losses. In the spec $\frac{d(\tilde{u}r^2)}{N}$ N_{α} $\sum_{\alpha'}$ $N_{\alpha'}$ Equiportant, in the unit of the $\frac{dr}{\cos \alpha}$ $\frac{d\cos \alpha}{dr}$ $\frac{d\cos \alpha}{dr}$ $\frac{d\cos \alpha}{dr}$ in the downstream region. This is in the downstream region in Fig. 4, where we have we have well as the downstr

*^N*0(*E*) ⁼ *KE*[−] *^R*+² **Example 28 and 20 a** 23 and 20 and 20 a 21 and 20 an The spectrum of H only marginally affected by pp It is useful to notice that in the case of a plane-parallel shock, $\frac{1}{2}$ $\frac{1}{2}$ \mathbf{d} to the shocked \mathbf{d} to the shock to the production \mathbf{d} any marginally antititum by pp there *r* to roses \rightarrow *NIC spectrum of h only marginary anected by pp energy for* It affected by nn energy losses The spectrum of H only marginally affected by pp energy losses

$$
\frac{\partial}{\partial r} \left[\tilde{u}r^2 N - r^2 D \frac{\partial N}{\partial r} \right] = E \frac{\partial N}{\partial E} \left[\frac{1}{3} \frac{d(\tilde{u}r^2)}{dr} - r^2 \frac{b}{E} \right] + N \left[\frac{1}{3} \frac{d(\tilde{u}r^2)}{dr} - r^2 \right]
$$

$$
\frac{\partial}{\partial r} \left[\tilde{u}r^2 N_{\alpha} - r^2 D \frac{\partial N_{\alpha}}{\partial r} \right] = E \frac{\partial N_{\alpha}}{\partial E} \frac{1}{3} \frac{d(\tilde{u}r^2)}{dr} + \frac{1}{3} \frac{d(\tilde{u}r^2)}{dr} N_{\alpha} - \frac{N_{\alpha}}{\tau_{sp,\alpha}}.
$$

The transport of particles in the bubble, including acceleration at the TS is described by: $\frac{1}{2}$ The transport of particles in the bubble including and more complete that \mathbb{R}^2 ration at the TS is described by: downstream using a grid discretized in radius and \mathcal{C} ∂ ! *uding acce* ² = *E* at the TS is describ \mathbf{s} and \mathbf{s} Fire transport of particles in the bubble, including accele law *^N*⁰ [∝] *^E*[−] *^R*+² on at the TS is described by: The effect of energy losses and the effect of energy losses in the energy losses thble, including acceleration at the TS is described by: ϵ **coefficients in the bubb** \mathbf{r} in The bubb reluding acceleration at the TS is described by: the blue and red curves in Fig. 3.

Particle acceleration at the Termination Shock 3 ACCELERATION AND TRANSPORT O F C R nuclei that have not been included explicitly included explicitly in the spanish of the spanish of the spa It the Termin WE SOLVE EN DIA MIXED EQUATION CONTROL **PROTONS AND NUCLEI** GUIVII AU UIIU A UI IIIII. We solve equation (6) using a mixed technique, numerical and \mathbf{a} for the case of protons. For a given ansatz on the solution at the the plasma speed *u*(*r*) and the net speed of the waves responsible **Farmele acceleration** a $\overline{}$, when the parameter $\overline{}$ is chosen to be zero (equal number of $\overline{}$ \mathbf{r} 0 *E*" [−] ³*D*² ¹ [−] *^R* ⁺ ¹ [−] *^R*(*D*¹ [−] 1) *.* (10) It is useful to the case of a plane-parallelshock, \overline{P} *v*A. When the parameter η is chosen to be zero (equal number of pration at the liermin disappears. It is useful to notice that in the case of a plane-parallelshock, *D*¹ → 1 and *D*² → 0, so that the solution reduces to the standard power law *^N*⁰ [∝] *^E*[−] *^R*+² **PRIVER** Formin stion Shook particles, so that *E* # *pc*. In equation (6) we omitted, for simplicity, alternatively there is a 4 per cent excess of waves moving aways moving aways moving aways moving aways moving a from the shock toward downstream (*u*˜2 = *u*² + 0*.*04*vA,*2, dashed black lines). The latter case is expected to a steeper spectrum of the latter spectrum r_{100} of the Demond to r_{20} period a small deviation in the shape of the cutoff Downloaded from https://academic.oup.com/mnras/article/523/3/4015/7190644 by Gran Sasso Science Institute user on 21 October 2024

1 The advection *,* (9) *w* aded the sasso SH ection time as well as the time r spallation and for *R*−1 \$% *^E* produced in the region upstream of the TS are advected toward the $\frac{1}{2}$ $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ acceleration, and $\frac{1}{2}$ $\langle B_1 u_2 \rangle \langle R_s \rangle$ are shorter than the buying straight E are shorter than the for secondary secondary securities and by Blasica σ Stationary solution σ K The advection time as well as the time $\left| \frac{1}{1} - \left(\frac{R_s}{R}\right)^3 \right|$ scales for spallation and for diffusion at In order to correct it is useful to the relationships the relationships of $\lfloor \frac{(R_b)}{s} \rfloor$ higher E are shorter than the age —> do so, we integrate the transport equation from *r* = 0 to *r* = *Rs* to *^b /D*2(*E*), the time-scale of advection scales for spallation and for diffusion at stationary solution OK

 \mathbb{R}^n 0 *E*" *P*
1 − *Phe spectrum of He sizeably changed by spallation, with pr* It is useful to notice that in the case of a plane-parallelshock, *D*¹ → 1 uclei heavier than He severely affected The spectrum of He sizeably changed by spallation, with production of 3He <u>E</u> \sim The spectrum of He sizeably changed by spallation *D* ∂*N*^α ∂*r* <u>'</u> **Nuclei heavier than He severely affected** the speech and six shocked y entirely specified ∂*r* ' $\overline{\mathbf{O}}$ = *u*˜1*N*α*,*⁰ + δ*uN*α*,*⁰ − *Rs* for particle evolution is due to spallation reactions, treated as **e spectrum of He sizeably changed by spallation, with production of 3He** of He si <u>u</u> than *II* couc *b*¹ **V** *Changed by Spanation, with* μ **The spectrum of He sizeably changed by spallation, with production of 3He Nuclei heavier than He severely affected**

$$
\tau_{\text{adv}} = \int_{R_s}^{R_b} \frac{dr}{u(r)} = \frac{1}{3} \frac{R_b}{u_2} \left(\frac{R_b}{R_s}\right)^2 \left[1 - \left(\frac{R_s}{R_b}\right)^3\right]
$$

 The advection time as
scales for spallation and
higher E are shorter th
stationary solution OK

Acceleration of H and gamma ray emission Figure 7. Volume integrated gamma-ray flux for Models 1, 2, and ³ described in the text and reported in Table 1. The gas density in the bubble is *ⁿ* ⁼ ¹⁰ cm−³

Figure 5. Spatial distribution of accelerated particles upstream and downstream of the TS, for three energies (as indicated) and for density *n* = particles downstream of the TS For low energy particles, the effect of energy losses is that of changing the spatial distribution of Fitting to the Fermi+HAWC (2 degrees) data, for the nominal σ ray emission from the Cygnus Obelian from the Cygnus Obelia. It is in the contract of larger than normally assumed, or additional production of turbulence downstream Download
Social
Compara Figure **8.** $\frac{1}{2}$ **8.** $\frac{1}{2}$ **8.** Therefore integrated situ n-10 cm-3 requires either loss rates and speed 0.04 and *ⁿ* ⁼ ¹⁰ (solid) and ²⁰ cm−³ (dashed), and for Model ³ with \blacksquare is downstream respectively. The prediction of the prediction of the point (Cao et al. 2021b) has been point (Cao et al. 2021 density n=10 cm-3, requires either loss rates and speed slightly turbulence downstream

about ∼50 pc at a distance of 1.4 kpc appropriate for the Cygnus 9

Acceleration of nuclei

⁹ 3He produced upstream of the TS is advected back onto the shock and gets reaccelerated

Both 3He and 4He suffer spallation downstream of the termination shock

Bc
The [©] The spectrum of the escaping particles at the edge of the bubble is given as

$$
\Phi(E)=-D_2(E)\frac{\partial N_2(E,r)}{\partial r}|_{r=R_b}
$$

 We assume that 3He is mainly produced as spallation reaction of 4He

The role of spallation of He nuclei is that of changing the ratio H/He injected into the ISM

-
-
-
-

 4π 3

Limitations of spherical symmetry 3.1 Limitations of a spherically symmetric approach Introduced symmetric may actual the actual target for \mathcal{L} in the form of dense cloudstate fill a limited fraction of the volume of the volume of the volume of the volume subject to the grammage contributed by the clouds. Since the wind density is typically very low, the average density *n* is matrix contributed by the contribution \mathcal{L} = −*s N*α*,*⁰ + 3*N*α*,*⁰ *r* − 1 2 U *u*˜2 # + *F*(*E*)*,* (13)

PB & Morlino 2023

- R_{cl} of gamma-ray production. **R**_{cl}
- *n*
 *r*equire
 require
-
- *N*α*,*0. A simple iterative technique leads to the solution.

• It may be argued that the cold gas is not distributed homogeneously but in clouds — what is the effect on spallation? It may be argued that the cold gas is not distributed homogeneously but in clouds ϵ R ¹ homogeneously but in \mathbf{c} It may be argued that the cold gas is not distributed homogeneously but in clouds
— what is the effect on spallation? ut
->
ea

• The assumption of mean density works fine in terms of gamma ray emission ne assumption of mean density works line in terms of ga Since the wind density is typically very low, the average density *n* inc assumption of incan uchsity works inte in the mass of common you emission $\frac{1}{6}$ refigured to the integral of the second to the bubble of the bubble of the bubble of the bubble of the bubble o (τo mean acholer works miching or gamma iar

$$
R_b^3 n m_p = N_{\rm cl} M_{\rm cl} = N_{\rm cl} \frac{4\pi}{3} R_{\rm cl}^3 n_{\rm cl} m_p \qquad N_{\rm cl} = \frac{n}{n_{\rm cl}} \left(\frac{R_b}{R_{\rm cl}}\right)^3
$$

• For typical values of parameters, the typical distance between two clumps is d-4 contributed by the windows, and cyprem encessive see where *n*cl and *R*cl are the typical density and radius of a cloud of The typical values of parameters, the typical distance between two clumps is d~4
R33 It is a notice that worder that is the parameters of the parameters of the parameters of the parameters, *n* and *n* n{max} is denoted by a nonfeters, the typical distance between two clui *Ne* typical *Vb* = *N*cl etween two clump:

• The time required to cover such a distance by diffusion is $\frac{1}{2}$ y different to cover such a distance by diffusion is $\frac{1}{2}$... (18) $\frac{1}{2}$... (18) $\frac{1}{2}$... (18) $\frac{1}{2}$ **own** an all about the shocked wind a selection of **decision** the time required to cover such a distance by diffusion is the the time such a distance by diffusion is

$$
\tau_{c} = \frac{d^{2}}{6D(E)} = 16 \frac{R_{cl}^{2}}{6D(E)} = 16 \left(\frac{R_{cl}}{R_{b}}\right)^{2} \frac{\tau_{dif}(E)}{\tau_{adv}} \tau_{adv}
$$

• This is shorter than both advection and diffusion time in the bubble \rightarrow particles cross numerous clumps while escaping approximations dumps while according cross numerous clumps while escaping tv
boup
article This is shorter than both advection and diffusion time in the bubble —> particles and the one of the one of the one of the shorter than both advection and diffusion time-in-the-bubb *for a given and nucleiral cross numerous clumps while escaping* with other relevant time-scales discussed in the next section, for a section, for a section, for a section, for dvection and diffusion time in the bubble \rightarrow particles le escaping

• As long as the number of clumps traversed is >>1 the assumption of mean density makes sense and we can introduce a mean grammage in the bubble *R* long as the number of clumps traversed is >>1 the assu and school and we can incroduce a mean grammage in th as long as the number of clumps traversed is >>1 the assumpt To travel the transferred travel through diffusion between the computation of $\frac{1}{2}$ *X*(*E*) = *n*cl*c mp* τesc *f ,* (20) **20,** *F* **F F F** *C*** F** As long as the number of clumps traversed is >>1 the assumption of the assumption of $\frac{1}{2}$ d we can introduce a mean grammage in the bubble of we can mercure a mean grammage in the bubble individual clump. In the last part of equation (21) we use \mathcal{C} we use the last part of equation (21) we use \mathcal{C} μ and the control of the assumption of incall density. The second terms is the bubble

$$
X(E) = n \, c \, m_p \, \tau_{\rm esc}
$$

-
-

General implications of gamma rays from SC for CR

the region of the Cygnus cocoon, the grammage felt by CR while escaping must be **~50 g cm-2 >> Galactic**

⁵ One might wonder whether this implication can somehow be weakened, for instance changing the acceleration efficiency or

- \bullet The results presented above suggest that with the standard values of the gas density inferred from observations of clouds in **Grammage!!!**
- ² This would have dramatic implications for the origin of CRs if at least a fraction of them are produced in star **clusters that resemble the Cygnus cocoon**
- even the whole scenario of particle acceleration in star clusters
- Here I will consider two very different models and explore the question: **what do these two models imply in terms of the LHAASO data at Eγ>1 TeV from Cygnus?**

CR are accelerated in the center by a continuous source and diffuse outward

CR are accelerated at the Termination Shock and produce gamma on their way out

General implications of gamma rays from SC for CR d assuming a homogeneous 'Cosmic Ray Sea', while α the GDE in the outer Galaxy is almost consistent with predictions. Here, the INSTERNATION of IOR is estimated by re-scaling ac-

LHAASO 2024

. (1)

(*mpc*²)²

Model 1: diffusion from a central source $10<\epsilon$ assuming here that transport is purely different is purely different is purely different is purely different in ¹⁰⁵ sion coe"cient *D*(*E*). In the energy region of interest here, 10 CONGRATION CAN BE USED CONGRATION COMPUTER COMPUTER COMPUTER COMPUTER COMPUTER COMPUTER COMPUTER COMPUTER COM ¹⁰⁶ *E* ↭ 1 TeV, the di!usion equation can be used in its station-¹⁰⁷ ary form, so that the CR density of energy *E* at distance *r* As discussed above, this is a simple model, adopted in ¹⁵⁷ LOAVAA AA VAAA OG COLLABORATION (2024), w ¹⁶⁵ Using the assumption that *E*^ω = ω*E*, one can write It follows that the gamma ray flux from the entire bubble **II d CCIII** P 0 *dr ^r*² **d**
2017 *LSC* (ϑ → 2) $r_{\rm{max}}$ 166 *E*² ^ω!ω(*E*ω) = ²ε*CRLw*(^ϑ [→] 2)ω^ε→¹

given energy can be estimated ^ω!ω(*E*ω) = ³ε*CRLSC* (^ϑ [→] 2)ω^ε→¹ *F* and the grammage $X(E)$ in the bubble and the 4ϖ*d*² ! *E*^ω *m^p* "→ε+2 *X*(*E*) *Xcr* ¹⁷¹ where *Xcr* = *mp/*ϱ*pp* is the critical grammage for *pp* inter-¹⁷² actions. As written here, the dependence of the gamma ray mma ray emission at a given energy can be estimated as only function of t conversion efficiency of the SC luminosity L_{SC} to CR $gramma \propto Y(F)$ in the bubble and the *E*2 anning C₁(E) in the bubble and the The expected gamma ray emission at a given energy can be estimated as only function of the grammage X(E) in the bubble and the

$$
n_{CR}(r, E) = \frac{Q(E)}{4\pi r D(E)}
$$

Density of CR at distance r

$$
J_{\gamma}(E_{\gamma})dE_{\gamma} = n_{CR}(E)dE n_{gas}c\sigma_{pp}
$$

Simple scaling relation good enough
with $E_{\gamma} = \eta E$

$$
E_{\gamma}^{2}\Phi_{\gamma}(E_{\gamma}) = \int_{0}^{R_{\alpha}} dr_{B}^{r^{2}} \xi_{CR} \frac{L_{SC}(\alpha - 2)}{4\pi r D(E)} \eta^{\alpha - 1} \left(\frac{E_{\gamma}}{m_{p}}\right)^{\alpha} n_{gas}c\sigma_{pp} = \xi_{CR} \frac{L_{SC}(\alpha - 2)}{4\pi c^{2} D(E)} \eta^{\alpha - 1} \left(\frac{E_{\gamma}}{m_{p}}\right)^{-\alpha + 2} \frac{R_{b}^{2}}{2} n_{gas}c\sigma_{pp}
$$

And introducing the grammarge: $X(E) = n_{gas} m_{p}c\tau_{b}(E) = n_{gas} m_{p}c \frac{R_{b}^{2}}{6D(E)}$

$$
E_{\gamma}^{2}\Phi_{\gamma}(E_{\gamma}) = \frac{3\xi_{CR}L_{SC}(\alpha - 2)\eta^{\alpha - 1}}{4\pi d^{2}} \left(\frac{E_{\gamma}}{m_{p}}\right)^{-\alpha + 2} \frac{X(E)}{X_{cr}} \chi_{cr} = m_{p}/\sigma_{pp}
$$

flux $18⁴$ **L**
*a*ssume tha *<u>ssume that this</u>* sume that this density re

^M˙ */*(10−4M# yr−1) and *^t*¹⁰ isthe dynamical time in units of ¹⁰ million

Model 2: Acceleration at the TS EXAMPLE AND INTERNATION (2024), where \mathcal{L}^* and \mathcal{L}^* ⁸² and di!use outwards in the bubble. In §3 we discuss the *r derati* 4ϖ*r*²*v^w <i>SECULTERS* ¹⁷⁶ of *ngas* on radius is not flat. \mathbf{A} F. Blasi: Gamma and cosmic rays from star clusters from star clusters \mathbf{A}

⁸⁷ conclusions. **FORWARD** shock
The assumption that R_b and R_b 88 2. Models of gamma rate 89 As we discuss below, the electronic state is so matches that the electronic state is so matches the grammage is so matches that the grammage is so matches that the grammage is so matches that the grammage is so matches "→ε+2 *I*
E
E LSC (ϑ → 2) TERMINA
SHOC

($\begin{array}{c} \text{SHOCK} \\ \text{SHOCK} \end{array}$ = ε*CR ngasc*ϱ*pp. J*ω(*E*ω)*E*² *m^p* $\begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}$ energies where the contract of (6) $\frac{1}{2}$ are such that $\frac{1}{2}$ and $\frac{1}{2}$ are such that $\frac{1}{2}$ and $\frac{1}{2}$ are $\frac{1}{2}$ and $\frac{1}{2}$ are $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ are $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1$ It for the grown of the gamma ray of the gamma ray of the gamma ray flux from the entire bubble of the entire bubble S_{avity} and S_{avity} the produced by $E_{\gamma} \Psi_{\gamma} (E_{\gamma}) =$ can be estimated as essential protons with energy $\frac{1}{2}$ such that **E**ucharan is a such that $\frac{1}{2}$ such that $\frac{1}{2}$ is a second to $\frac{1}{2}$ such that $\frac{1}{2}$ is a second to $\frac{1}{2}$ such that $\frac{1}{2}$ such that $\frac{1}{2}$ such t nterstellar en 196 tion for interactions in the pp. interactions is considered as constant of the pp. interactions is considered as constant of the pp. interactions is considered as constant of the pp. interactions is considered as co "→ε+2 ^ω!ω(*E*ω) = # *^R^b* # *^R^b* **E** *dr ^r*² *LSC* (ϑ → 2) ⁹⁷ ε*pp* = 32 mb. The slight increase of the cross section with ⁴ϖ*rD*(*E*) ^ω^ε→¹ *^d*² ^ε*CR m^p* ⁹⁸ energy would make the result below even more prominent.

$$
n_{CR}(\boldsymbol{E}) = \xi_{CR} \frac{\dot{M} v_w(\alpha - 2)}{4 \pi R_{sh}^2 (m_p c^2)^2} \left(\frac{\boldsymbol{E}}{m_p}\right)^{-\alpha}
$$

 $\frac{1}{2}$ ϵ assume that this uchsity remains constant u If we assume that this density remains constant downstream we maximise the gamma ray If we assume that this density remains constant downstream we maximise the gamma ray mage traversed in the SC by protons with 10 TeV en- 227 protons with 10 TeV en- 227 protons with 10 TeV en- 22
The SC by protons with 10 TeV en- 227 protons with 10 TeV en- 227 protons with 10 TeV en- 227 protons with 10 \overline{R} "→ε+2 $\overline{\mathbf{a}}$ *i*ns cons $t_{\rm eff}$ inside the bubble that the bubble that the plasma ϵ downstream we maximise the gamma ray e assume that this density remains constant downstream we maxin *d*
d **L**
SCONSTANT 8 constant down **Extream** we m where for simplicity we assumed that *R^b* ↗ *Rsh*. Replacing ¹⁹⁶ nise the gamma ray

 \overline{a}

Since the typical cooling time-scale of the shocked ISM is only [∼]10⁴ yr, while the cooling time for the shocked wind isseveral ¹⁰⁷ yr (Koo & McKee 1992a, b), we can safely assume that the wind-blown bubble evolves quasi-adiabatically. Following Weaver et al. (1977) and Gupta et al. (2018), Morlino et al. (2021b) provided some useful approximations for the position of the FS and the TS, that we use here. The position of the FS is at *Rb*(*t*) ⁼ ¹³⁹ρ[−]1*/*⁵ where ρ¹⁰ is the ISM density in the region around the star cluster in units of 10 protons cm–3 ⁹⁹ Here we consider two models of CR transport in the ¹⁰⁰ SC. In Model 1 we assume, following (Lhaaso Collabora-¹⁰¹ tion 2024), that a source in the center of the SC continu-*E*² ¹⁸⁵ In order to maximize the gamma ray flux predicted by the ¹⁸⁶ model and strengthen our conclusions, we assume here that ¹⁸⁷ particle escape from the bubble is dominated by advection. ¹⁸⁸ As discussed by Blasi & Morlino (2024), at energies ↭ 1 ¹⁸⁹ TeV escape becomes dominated by di!usion, but this leads ¹⁹⁰ to a smaller e!ective emission region for gamma rays and It follows that the gamma ray flux from the entire bubble 0 ↑*ngasc*ϱ*pp* = ε*CR LSC* (ϑ → 2) ⁴ϖ*d*²*D*(*E*) ^ω^ε→¹ *dr dt* where for simplicity we assumed that *R^b* ↗ *Rsh*. Replacing ¹⁹⁶ this expression in Eq. 11, we easily obtain: ¹⁹⁷ *E*² ^ω!ω(*E*ω) = ²ε*CRLw*(^ϑ [→] 2)ω^ε→¹ ¹⁶⁷ The escape time from the bubble in a purely di!usive case *^b* ¹⁶⁸ */*6*D*(*E*), so that we can introduce the grammage ¹⁶⁹ traversed by particles while escaping the bubble as

$$
E_{\gamma}^{2}\Phi_{\gamma}(E_{\gamma}) = \frac{\xi_{CR}\dot{M}v_{w}(\alpha-2)}{4\pi R_{sh}^{2}}\eta^{\alpha-1} \left(\frac{E_{\gamma}}{m_{p}}\right)^{-\alpha+2} \frac{R_{b}^{3}}{3d^{2}}n_{gas}c\sigma_{pp}
$$

$$
\tau_{adv} \approx \frac{4}{3} \frac{R_{sh}}{v_{w}} \left(\frac{R_{b}}{R_{sh}}\right)^{3}
$$

$$
E_{\gamma}^{2}\Phi_{\gamma}(E_{\gamma}) = \frac{2\xi_{CR}L_{w}(\alpha-2)\eta^{\alpha-1}}{4\pi d^{2}} \left(\frac{E_{\gamma}}{m_{p}}\right)^{-\alpha+2} \frac{X(E)}{X_{cr}}
$$

$$
X(E) = n_{gas}m_{p}c\tau_{adv}
$$

$$
V(E) = n_{gas}m_{p}c\tau_{adv}
$$

³⁹ g cm→²) for ϑ = 2*.*2 (ϑ = ²³³

0

Most gamma rays are produced downstream of the termination shock A ssuming again that the density of accelerated particles \mathcal{A} lost gamma rays are produced downstream of the termination shock $\hspace{0.1mm}$

version of a fraction of the kinetic operate of t version of a fraction of the Kniene chergy of t The spectrum of particles accelerated at the TS can be written easily by assuming the conversion of a fraction of the kinetic energy of the wind is converted to CR ⁸⁵ stable elements, comparing the results with standard mod*n*² alog e a acleusted at the TC as relax invition oscily by exergencies the accelerated at the 13 can be written easily by assuming the *right* and *region* $\frac{1}{2}$ ton <mark>of</mark> the kinetic energy of the wind is converted to $\overline{\cup}$ R \sim 180 the gamma ray emission in the case of particle acceleration in t ne spectrum of particles accelerated at the T *Mv*˙ *^w*(^ϑ [→] 2) ! *E*^ω "→^ε at 1 Tev and investigate the dependence of $\frac{1}{2}$ $\frac{1}{2}$ the substitution spectrum. **Example 1, and 1, and 1, we have the luminosity to a large to the star convented to CR** P. Blasi: Gamma and cosmic rays from star clusters *ectrum of particle* **L**
Saccelerate accelerated at t **E** \overline{V} *written easily by assuming the* to CR and the contract of \overline{C}

$\frac{R_b}{\sqrt{R_b}}$ \setminus ³

LHAASO the grammage required for Model 1 has to be ²³⁸ $X(E = 10 TeV) \gtrsim 0.8L_{39}^{-1} \text{ g cm}^{-2} \text{ for } \alpha = 2.2$ 1
1 a.∫
2002 g cm→2 for âleantaire 2003 L the grammatic form $\mathcal{L}_\mathcal{A}$, $\mathcal{L}_\mathcal{A}$ is to be 2388 $\mathcal{L}_\mathcal{A}$, $\mathcal{L}_\mathcal{A}$ has to be 2388 $\mathcal{L}_\mathcal{A}$, $\mathcal{L}_\mathcal{A}$, $\mathcal{L}_\mathcal{A}$, $\mathcal{L}_\mathcal{A}$, $\mathcal{L}_\mathcal{A}$, $\mathcal{L}_\mathcal{A}$, \math $X(E = 10 TeV) \gtrsim 0.8L_{39}^{-1} \text{ g cm}^{-2} \text{ for } \alpha = 2.2$ celeration, say ε*CR* ↫ 0*.*1, we immediately infer that in ²³⁶ $X(E = 10 TeV) \gtrsim 2.5 L_{39}^{-1} \text{ g cm}^{-2} \text{ for } \alpha = 2.4$ $X(E)$ $X(E)$ $10 TeV$) $\gtrsim 0.8 L_{39}^{-1} \text{ g cm}^{-2}$ for $\alpha = 2.2$ *X* $\frac{1}{2}$ **0***D* eV **eV** $\frac{1}{2}$ eV **eV** $\frac{1}{2}$ eV **eV** $\frac{1}{2}$ eV **eV** $\frac{1}{2}$ eV $\frac{1}{2}$ ³⁹ g cm→² for ϑ = 2*.*2 and *X*(*E* = ²³⁹ $\overline{1}$ $X(E = 10 TeV) \gtrsim 0.8L_{39}^{-1} \text{ g cm}^{-2} \text{ for } \alpha = 2.2$ ²⁵⁶ transport being tuned to a few percent after the AMS-02 258 $Y(F - 10T_0 V) > 0.8I^{-1}$ g cm⁻² for $\alpha = 2.9$ $25(L - 1010V) \sim 0.02398V$ $V(T_1 - 10T_0 I) > 9.5I^{-1}$ e cm⁻² for e.g. 9.4 $\Lambda(E = 101 \text{ eV} / \approx 2.0239 \text{ gcm}$ for $\alpha = 2.4$

Lower limits to the grammage in the Cygnus cocoon ³*d*² *ⁿgasc*ϱ*pp.* (2*.*⁶⁴ [↑] ¹⁰→¹⁰ε*CRL*39*X*(*E*) erg cm→² ^s→¹) for ^ϑ = 2*.*² (^ϑ ⁼ ²³⁰ **AWAR limits to the organize** sured by LHAASO we get a grammage *X*(*E* = 10*T eV*) ↔ ²³² ³*d*² *ⁿgasc*ϱ*pp.* (2*.*⁶⁴ [↑] ¹⁰→¹⁰ε*CRL*39*X*(*E*) erg cm→² ^s→¹) for ^ϑ = 2*.*² (^ϑ ⁼ ²³⁰ ower limits to the gramma sured by LHAASO we get a grammage *X*(*E* = 10*T eV*) ↔ ²³² ergy. The gamma ray flux computed using Eq. 9 can be ²²⁸ ^ω!^ω [↔] ⁷*.*⁶ [↑] ¹⁰→¹⁰ε*CRL*39*X*(*E*) erg cm→² ^s→¹ ²²⁹ (2*.*⁶⁴ [↑] ¹⁰→¹⁰ε*CRL*39*X*(*E*) erg cm→² ^s→¹) for ^ϑ = 2*.*² (^ϑ ⁼ ²³⁰ **b** ^ω!^ω [↔] ⁷*.*⁶ [↑] ¹⁰→¹⁰ε*CRL*39*X*(*E*) erg cm→² ^s→¹ ²²⁹ (2*.*⁶⁴ [↑] ¹⁰→¹⁰ε*CRL*39*X*(*E*) erg cm→² ^s→¹) for ^ϑ = 2*.*² (^ϑ ⁼ ²³⁰ 21 INNIUS LU LIIL STANINGS TH sured by LHAASO we get a grammage *X*(*E* = 10*T eV*) ↔ ²³² ²⁴⁵ mage inferred from Model 1 for the grammage accumulated I awas limite to the cream 24 Galactic grammage. It follows that, if \mathbf{u} 248 picture, and if Δ bulk of the sources of the sources of the sources of the bulk of Galactica of termination shock of the collective wind, the lower limits ³⁰⁶ mage in the Grammage in the Galactic Galactic Control Control and the Galactic Galactic Galactic Galactic Galactic Galactic Galactic G independent. In this model the constraints of the constraints obtained above 3099 and 2099 and 3099 and 3099 a $\frac{1}{2}$ galactic grammage. It follows the correction **24 prices in the source of SCS were the sources of the bulk of the sources of the bulk of the bulk of the bulk** ²⁴⁹ CRs, then our interpretation of Galactic transport would α isc III this construction. In this model this model this model is are to be interpreted as strict lower limits to the grammage 310 strict lower limits to the grammage 310 strict

celeration, say $A \cap A \cap I$ order to account for the gamma ray flux observed by ²³⁷ celeration, say $A \cap A \cap I$ order to account for the gamma ray flux observed by ²³⁷ $F \circ A \circ I$ **c** and *c* and *c* call that is a same in \sim ²⁵¹ somewhat more serious than that, because the grammage 252 should have the same energy dependence as the same energy dependence as the distribution co-²⁵³ e"cient. This would imply a grammage in the lower energy ²⁵² should have the same energy dependence as the di!usion co-253 et cient. This would imply a grammatic in the lower energy ²⁵⁴ range that is larger or comparable with the Galactic gram-*Model 1*

²⁶⁶ that in order to fit LHAASO data we need a grammage $X(E = 10 TeV) \approx 1.2 L_{w,39}^{-1} \text{ g cm}^{-2} \text{ for } \alpha = 2.2$ $V(F = 10T V) > 9.3I-1 = 26$ $X(E=10 TeV) \gtrsim 3.3 L_{w,39}^{-1}\,\mathrm{g\,cm^{-2}}\ \mathrm{for}\ \alpha=2.4.$ $X(E = 10TeV) > 1.2L^{-1}$ so cm^{-2} for $\alpha = 2.2$ $X(E = 10I eV) \approx 1.2L_{w,39}$ g cm $V = 2.2$ ²⁶⁹ estimates exceed the Galactic CR grammage by at least a

 $2⁷$

(1*.*⁶ [↓] ¹⁰→¹⁰ω*CRLw,*39*X*(*E*) erg cm→² ^s→¹ ²⁶³) for ^ε = 2*.*² ²⁶⁴ (ε = 2*.*4). Following the same procedure outlined for 265 Model 2, and require extensive exten $\mathbf{A} \cdot \mathbf{A} \cdot \mathbf{A}$ ²⁶⁴ (ε = 2*.*4). Following the same procedure outlined for *Model 2*

²⁷³ at *E* ↫ 1 TeV (Blasi & Morlino 2024), which would reduce

The case of Westerlund 1

Model 1

 $X(E = 3TeV) \gtrsim 1.2 \text{ g cm}^{-2} \text{L}_{39}^{-1}$ $\alpha=2.2$ $X(E = 3TeV) \gtrsim 2.9 \text{ g cm}^{-2} \text{L}_{39}^{-1}$ $\alpha=2.4$

Model 2

 $X(E = 3TeV) \gtrsim 1.8 \text{ g cm}^{-2} \text{L}_{39}^{-1}$ $\alpha=2.2$ $X(E = 3TeV) \gtrsim 4.6 \text{ g cm}^{-2} \text{L}_{39}^{-1} \qquad \alpha = 2.4$

Lower limits to the grammage in the cocoon

- Independent of the specific model of CR transport in the bubble, the detection of gamma ray emission with E_y >1 TeV by LHAASO implies a lower limit on the grammage
- \bullet This lower limit is already in excess of the Galactic grammage at the same energy
- $\frac{1}{2}$ How this extends to lower energies depends on Model 1 or 2 (more severe for Model 1)

- **If the gamma ray emission detected from Cygnus is a common phenomenon**, and this is all but guaranteed clearly, then Either Star Clusters do not contribute but a small fraction of Galactic cosmic rays
-
- 2. …or if they do, then a major revision of the transport of cosmic rays on Galactic scales is required… including the production and decay of both stable and unstable secondaries (e.g. 10Be, 26Al, …)
- 3. In alternative the gamma ray emission we see is not of hadronic origin, but then it means that most measurements of the density carried out are not to be trusted!

Leptonic models of the gamma ray emission

- At least for Westerlund $\bf{1}$ it has been proposed that the gamma ray emission is due to ICS of leptons (Harer et al 2023)
- In general these models require low magnetic fields (lower than for hadronic models) to limit energy losses
- But the small fields lead to lower maximum energies of accelerated particles (for electrons about 200 TeV) even for Bohm diffusion
- Either way, for hadronic or leptonic interpretation of the gamma ray emission, it seems that star clusters as sources of CR especially at the knee, raise many doubts
- $\frac{3}{2}$ The issue of SN explosions in star clusters might circumvent some of these issues, but not all...

We ran simulations of the evolution of a SN shock in the environment of the bubble excavated by the collective wind

As expected, the cutoff in thespectrum of accelerated particles at the SN shock depends strongly on the $D(E)$

If to use the turbulence already existing in the wind in which the SN shock moves, E_{max} fails to reach PeV

Bohm diffusion might be justified if turbulence is selfgenerated, and in that case Emax approaches PeV

But it is unlikely to have the right conditions for streaming instability in the bubble

If the gas in the SC is the one we inferred above, we have exactly the same problems raised above: the grammage accumulated in the SC is too large

SN explosions inside a SC

Conclusions

- $\frac{3}{5}$ SC were proposed as possible sources of PeV Galactic CR, but the effective maximum energy is quite lower than PeV (gamma ray emission confirms that Emax<PeV)
- If gamma rays are generally of hadronic origin, $\xi_{CR}=0.5\%$, hence negligible contribution to the CR flux, including at PeV energies
- ⁵ On the other hand, for Cygnus, gamma ray morphology and spectrum agrees well with a hadronic interpretation \rightarrow the low ξ_{CR} leads to requiring a large grammage
- This large grammage reflects in a nice difference between H and He spectra, but...
- The price to pay is that nuclei are all destroyed and the transport on Galactic scales requires major revision
- \bullet We are left with a conundrum: a) Star clusters do now appreciably contribute to CR flux, or b) the gamma ray emission is not of hadronic origin \rightarrow perhaps larger CR contribution from less bright SC, but in this case hardly important at PeV

