# **Cosmic rays from Galactic star clusters**

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TOSCA-2024 Siena

# **Outline of my talk**

✤ **Introduction.** 

- ✤ **General picture of cosmic-ray origin.**
- ✤ **Issues/concerns of cosmic-ray properties between 1016-1018 energies.**
- ✤ **How star clusters (as cosmic-ray sources) can fit into this?**
- ✤ **Results on the cosmic-ray spectrum and composition with star clusters.**
- ✤ **Summary.**



# **Origin of Cosmic rays: The general picture**





# **Contribution of Regular Supernova remnants to the CR spectrum**



 $\blacktriangleright$  The "knee" is dominated by helium nuclei, not by proton.  $\blacktriangleright$ protons at E<sup>c</sup> = 4.5 × 10<sup>6</sup> GeV. Other model parameters, and the low-energy data are the same as in Figure 1. Error bars are ✤ The "knee" is dominated by helium nuclei, not by proton.

 $\ket{\text{ }*}$  Maximum energy: E<sub>m</sub> (Fe)= 26 E<sub>m</sub>(p) =1.17x10<sup>8</sup> GeV.

- III (Amenomori et al. 2008), the Pierre Auger Observatory (Schulz et al. 2013), and HiRes II (Abbasi et al. 2009). ✤ Prediction close to the "second knee", but not enough in intensity.
- ├ُ Regular SNRs alone cannot account for CRs above ~2x10<sup>16</sup> eV. │ ergy Z×10<sup>8</sup> GeV is 36 pc, much smaller than the size of the

measurements have shown that helium nuclei become more abundant than protons at energies at the protons at  $\sim$  105  $\mu$ They contribute only ~30% at 10<sup>8</sup> GeV (10<sup>17</sup> eV).



to be a few kpc in cosmic-ray propagation studies, keep-

# **Measured CR mass composition above the knee**



### **Mean logarithmic mass**

✦ **Above ~ 1017 eV, composition becomes lighter.**



#### Cj is the corresponding MC prediction. As a practical nposition apove the knee the likelihood value obtained when  $\alpha$  is value of  $\alpha$  ,  $\alpha$  is value of  $\alpha$ **0.8 1 Sibyll 2.1 Fe fraction Measured CR mass composition above the knee**

**process. The added added as the added added a**  $\overline{O(12)}$  **c**  $\overline{O(12)}$ **Elemental fraction at 1017-1019 eV**

is a constant factor, the maximization is not affected by the maximization is not affected by this not affected

 $\overline{\mathcal{F}}$  are fit, mock data sets of the fit



✦ Both LOFAR and Pierre-Auger measurements show light elements (P+He). 10-1<sup>1</sup> (color online). Fig. 4 (color online). Fig. 1 (complex mixture of protons, helium nuclei, nitrogen nuclei, nitrogen nuclei, and protons, helium nuclei, nitrogen nuclei, and and protons, and protons, and protons, an  $\mathsf{row}$  ngm elements ( $\mathsf{r+ne}$ ).

 $\epsilon$  both LOFAR and Fiorio August mousulements brow hym clothing ✦Theoretically expected to be iron or heavy-element dominant. **10-2** w<br>dc

◆ Extra-galactic component unlikely to extend down to 10<sup>17</sup> eV (*Thoudam+ 2016, A&A, 595, A33*) 122006-7

27% on energy and are indicated with a shaded band. The Pierre Auger Observatory measures the ✦ **A second/additional Galactic component above ~ 1017 eV?** *(e.g. Hillas 2005, J. Phys. G, 31, R95)* **10-4 10<sup>18</sup> 10<sup>19</sup>**

# **Additional Galactic component: Reacceleration by Galactic wind termination shocks (GW-CRs)**



Thoudam et al.: Cosmic-ray energy spectrum and composition up to the ankle *Thoudam+ 2016, A&A, 595, A33*



# **Additional Galactic component: Reacceleration by Galactic wind termination shocks (GW-CRs)**



✤ **Galactic wind scenario has tension when compared with the observed composition at ~ 1016 - 1018 eV.** 

✤ **This is mainly due the large proton fraction at these energies.**

✤ Bad fit above the Ankle is due to the all-proton extra-galactic model *(Rachen, Stanev, & Biermann, 1993, A&A, 273, 377)*





**10**

**10**

**20**

**30**

**40**

**50**

**60**

**70**

**80**

**90**

**<sup>100</sup> <sup>1</sup>**≤ **A** ≤**<sup>2</sup>**





# **Why star clusters as the second galactic component?**

- ✤ Most stars are expected to evolve in clusters.
- ✤ Potential candidates for CRs beyond the knee (*Knödlseder 2013; Bykov 2014; Aharonian+ 2019*).
- ✤ Very-high-energy gamma rays detected from several massive young star clusters (*Abeysekara+ 2021; Cao+ 2021*).
- ✤ Complex environment: Massive stars, supernova explosions, turbulent medium, superbubbles, fast stellar winds, wind termination shocks, …..
- ✤ Possible multiple sites for CR acceleration (*Cesarsky & Montmerle 1983; Webb+ 1985; Gupta+ 2018; Bykov+ 2020, Morlino+ 2021, Vieu+ 2022*).



**Westerlund 1 Cygnus OB2**

*Credit: ESO/VPHAS+ Survey/N. Wright*



*Credit: Chandra X-ray Observatory*



### ✤ **Superbubble surrounding star cluster**

 $\overline{S}$  can contribute only  $\overline{S}$ inflated region (e.g. *Bykov+, 2020, SSRv, 216, 42*) fore, additional components are required to explain the all-Acceleration in the highly turbulent, low diffusivity, highly Schematic of a star cluster environment

#### 2.2. Extragalactic Component ✤ **Supernove shocks embedded in stellar winds**

Acceleration by supernova shocks running through stellar  $\overline{\phantom{a}}$  and  $\overline{\phantom{a}}$  are CR spectrum at 109 GeV can be can be calculated by  $\overline{\phantom{a}}$ winds of young compact clusters (e.g. *Vieu & Reville,*  $\,$ extragalactic component (mainly proton) in the evolving microwave background (Hillas 1967; Berezinskii & Grigor'- *2023, MNRAS, 519, 136*). eva 1988; Berezinsky et al. 2006; Aloisio et al. 2012, 2014).

#### n choolie of the minimal (di Matteo 2015) and primordial (di Matteo 2015) and primordial (di Matteo 2015) and **❖ Wind termination shocks** → Wind termination shocks

2016). We refer to this combined model as the "MPCS model." Acceleration at the wind termination shocks produced by  $\alpha$  the shocks associated with gamma-ray bursts or tidal  $\alpha$ the collective wind effect (e.g. *Morlino+ 2021, MNRAS,*  $\,$ the photon background present inside the source region. In this model, only the highest-energy particles having an escape time *504, 6096; Vieu+ 2022, MNRAS, 515, 2256; Bhadra,*  shorter than the photodisintegration time can escape the source *Thoudam+ 2024, ApJ, 961, 215*)  $r_{\rm F}$  below the angle the  $\mu$ 



#### spectrum, data of the primary composition in the ultrahigh ewing, r will mailliy focus on with observed spectrum. This is a "second knee" feature in the CR [In the following, I will mainly focus on wind termination shocks case.]



# **CR acceleration in star clusters**

### **CR acceleration at the wind termination shocks**

- ✤ Collective wind flow leads to a wind termination shock.
- ✤ CRs can be accelerated at the termination shock (*Bhadra, Thoudam+ 2024, ApJ, 961, 215*).
- ✤ Maximum CR energy depends on the cluster size, magnetic field and the wind speed. aura, Thouuantr 2024, Apu, 901, 2<br>Ionatic fiald and the wind sneed



positions, respectively.

model, only the highest-energy particles having an escape time  $s_{\rm max}$  the photodisintegration than the source than the sou region, leading to a strong proton component in the energy of the energy strong proton component in the energy of the energy strong proton component in the energy strong proton component in the energy strong proton compone region below the ankle. We call this the "UFA model" of the



### maximum energy is achieved when the diffusion length and diffusion length and diffusion length and diffusion le **becomes comparable to the size of the size of the size of the shock (in this case of the shock (in this case of the shock (in this case of the shock**

### **Maximum energy of CRs produced by Wind Termination S Maximum energy of CBs produced by Wind Termination Sk** maximum chergy of ORS produced by wind Termination of **Maximum energy of CRs produced by Wind Termination Shocks (Hillas criterion):**

$$
E_{\text{max}} \sim \zeta q B_{\text{WTS}} R_{\text{WTS}} \frac{V_w}{c}.
$$
 where,  
\n
$$
B_{\text{WTS}}:
$$
 Magnetic field at the WTS  
\n
$$
R_{\text{WTS}}:
$$
 Size of the WTS  
\n
$$
V_w:
$$
 Wind velocity  
\n
$$
q:
$$
 Charge of CR  
\n
$$
= \sum E_{\text{max}} \sim \zeta q B_c R_c \frac{V_w}{c}.
$$
 [For a Parker's magnetic field model,  $B \propto 1/R$ , (Parker 1958)]  
\nwhere,  
\n
$$
B_{\text{C}}:
$$
 Magnetic field at the cluster  
\n
$$
R_{\text{C}}:
$$
 Size of the cluster  
\n
$$
V_w:
$$
 Wind velocity

3 10 cm 0.2 1000  $\overline{IC}$  $R_G = 150 \text{ uG}$   $R_G = 1 \text{ pc}$   $V = 2000 \text{ km/s}$  F  $-$  For  $B_C = 150 \text{ uG}$ ,  $R_C = 1 \text{ pc}$ ,  $V_w = 2000 \text{ km/s}$ ,  $E_{\text{max}} \approx 6 \text{ PeV}$ .

1 pc 2000 km s 2000

 $W$  s), for beyond this limit this limit this limit this limit the particles escape out of the particles escape out of the particles escape of the particles escape of the particles escape of the particles escape of the pa

1pc

⎠

⎝

 $\frac{r}{q}$ - **Example**<br>*R*<sub>max</sub> is obtained E<sub>max</sub> is obtained based on the observed all-particl <u>Ork, E<sub>max</sub> is obtained based of</u> - In our work, E<sub>max</sub> is obtained based on the observed all-particle spectrum (data driven approach).<br>Curie 1990, MNPAS, 493, 3159  $\frac{d}{dt}$ *fXmt dm*  $\begin{array}{c} \begin{array}{c} \end{array} \end{array}$ 

Gupta+ 2020, MNRAS, 493, 3159 models for nucleosynthesis in massive stars and their return to *Morlino+ 2021, MNRAS, 504, 6096 Vieu+ 2022, MNRAS, 515, 2256* 

energy of  $1.4$  PeV for  $1.4$  PeV for  $\sim$ 



#### Average kinetic luminosity of star clusters <u>Magnesium 2.03 3.62 × 1000 × 10000 × 100000 × 100000 × 10000 × 1000</u> 1 7 ( ) – (Vieu et al. 2022). This estimate is a control of the control of the control of the control of the c<br>This estimate is a control of the c mate can give a maximum energy of a few PeV for protons. tic luminosity of star clusters

Silicon 2.24 3.42 × 10−5.<br>Silicon 2.24 3.42 × 10−5.24 × 10−5.24 × 10−5.24 × 10−5.24 × 10−5.24 × 10−5.24 × 10−5.24 × 10−5.24 × 10−5.24 ×

 $\mathcal{O}_{\mathcal{A}}$  assumption requires a certain fraction requires a certain fraction of the total wind  $\mathcal{A}$ 

- Certain fraction of the total wind kinetic energy injects into CRs. region of a compact cluster with velocity  $2 \cdot 2 \cdot 10^4$ \* Certain fraction of the total wind kinetic energy injects into CRs.
- \* Injection fraction kept as a parameter. that the this high velocity of  $\mathbf s$  inside  $\mathbf s$ **Finjection inaction report** of Observe the luminosity range the luminosity range. One can consider the luminosity range of  $\alpha$ d paramotor.
- ♦ Mechanical luminosity function of OB star association:  $\phi(L)$   $\propto$   $L^{−2}$

(Oey & Clarke, 1997, MNRAS, 289, 570) NOB = 10) to *L*max = 1039 erg s−<sup>1</sup> (corresponds to NOB =

ical (kinetic) lumino 6 ✤ **Average mechanical (kinetic) luminosity:**

$$
\langle L_w \rangle = \frac{\int_{L_{\min}}^{L_{\max}} \phi(L) L \, dL}{\int_{L_{\min}}^{L_{\max}} \phi(L) dL} \sim 4.5 \times 10^{37} \, \text{erg s}^{-1}
$$

where  $\blacksquare$  $L_{\rm min}$  = 10<sup>37</sup> erg/s (Corresponding to N<sub>OB</sub> = 10 stars in a cluster)  $L_{\text{max}} = 10^{39}$  erg/s (Corresponding to  $N_{\text{OB}} = 1000$  stars) where

Note: For spectrum calculation, we take N<sub>OB</sub> = 10 stars.



However, if an  $\mathcal{H}(\mathcal{A})$  is a very fast shock in the free wind

### **Distribution of star clusters in the Galactic plane**   $\frac{1}{2}$  ion of star clusters in the Galactic plane  $\frac{1}{2}$ assis of Galactic distribution of Star Clusters in the Galactic Plane

tion (see Figure 2) to peak at Rp



**Schematic of star cluster** 

# **Surface density profile of star clusters** are clusted that the Surface density profile of star clusters

= 0.55R0, (R<sup>0</sup> = 8.5 kpc is the



### **2.5. Elemental abundance in star cluster winds** We consider a simple stellar population for  $\mathcal{L}$  at time the simple stellar population for  $\mathcal{L}$ Flemental abundance in star cluster winds energy of 1.4 PeV, which corresponds to the CROSS to tens of PeV for CROSS to the PeV for CROSS to the PeV for

\* Initial mass function of stars: β(*m*)  $\,\propto m^{-}$ *dm* <sup>2.35</sup> (Salpeter, 1955, ApJ, 121, 161). : Initial mass function of stars: R(m)  $\propto m^{-2.35}$  (Salneter 1955 An.I).  $\ddot{\cdot}$  $\mathcal{L}$  in the number of  $\mathcal{L}$ 

We consider a simple stellar population for  $\mathcal{C}$  at time the  $\mathcal{C}$  population for  $\mathcal{C}$ 

can calculate the elemental abundances in the elemental abundances in the wind material abundances in the wind<br>The wind material abundances in the wind material abundances in the wind material abundances in the wind mater

protons.

 $\boldsymbol{\cdot}$  Obtain elemental mass-loss rate  $\ \dot{m}_{w}(X,\,m,\,t')$  of massive stars in the form of winds using nucleosynthesis model (*Roy+ 2021, MNRAS, 502, 4359*).  $\epsilon$  can calculate the elemental abundances in the wind material mat Obtain elemental mass-loss rate  $\left| \dot{m}_w(X,\,m,\,t') \right.$  of massive stars in *t* using nucleosynthesis model (*Roy+ 2021, MINRAS, 502, 4359*).  $\mathcal C$  al mass-loss rate  $\stackrel{\textstyle n}{m}_w(X,\,m,\,t')$  of massive stars in t  $\cdot$  Ob into the free wind region has a 1/r radial profile. Therefore, the magnetic field at the position of the position of the position of the position of the  $\mu$ 3.5. Elemental Abundances in Star Cluster Winds  $W(x, y, w)$  contains for  $\theta$  and  $\theta$  at the stellar population for the stellar population form  $\epsilon$ leosynthesis model (*Roy+ 2021, MNRAS dm*  $(5.502, 4359).$ 

✤ Obtain total mass of element *X* injected by a star of mass *m* over an age *t* as  $\boldsymbol{\ast}$  Obtain total mass of element  $X$  iniected is the cumulative mass of elements of elements by a starting in winds by a starting in winds by a starting by<br>The cumulative mass of elements by a starting by a starting in winds by a starting in winds by a starting of  $\clubsuit$  Oh can calculate the elemental abundances in the wind material tal mass of element  $X$  injected by a star of mass  $m$  over an age  $t$  a.

$$
M_w(X, m, t) = \int_0^t \dot{m}_w(X, m, t') dt'
$$



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 $\frac{1}{\sqrt{2}}$ 

#### **Elemental abundance in star cluster winds** energy of 1.4 PeV, which corresponds to the CROSS to tens of PeV for CROSS to the PeV for CROSS to the PeV for ò *M X m t m X m t dt <sup>w</sup>* , , , , 13 <sup>=</sup> ¢ ¢ 0 is the cumulative mass of element X ejected in winds by a starting in winds by a starting by a starting by a s<br>The cumulative mass of element X ejected in winds by a starting by a starting by a starting by a starting by a **3.5. Elemental abundance in star cluster winds** We consider a simple stellar population for  $\mathcal{L}$  at time the simple stellar population for  $\mathcal{L}$

 $\ddot{\cdot}$  $\mathcal{L}$  in the number of  $\mathcal{L}$ of initial mass m up to age t, where \* Initial mass function of stars: β(*m*)  $\,\propto m^{-}$ *dm* <sup>2.35</sup> (Salpeter, 1955, ApJ, 121, 161). : Initial mass function of stars: R(m)  $\propto m^{-2.35}$  (Salneter 1955 An.I).

We consider a simple stellar population for  $\mathcal{C}$  at time the  $\mathcal{C}$  population for  $\mathcal{C}$ 

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Sobtain total mass of clomont *V* injected by a star of mass *m* over an ago t as  $\dot{f} = \dot{f} + \dot{f$ = ¢ ´ 2, 4 *m X m t X m t mm t* , , mass fraction , , , , , . 14  $\mathcal{L} \left( \mathbf{V} \right)$ ( ) ()  $\boldsymbol{\cdot}$  Obtain elemental mass-loss rate  $\ \dot{m}_{w}(X,\,m,\,t')$  of massive stars in the form of winds using nucleosynthesis model (*Roy+ 2021, MNRAS, 502, 4359*).  $\epsilon$  can calculate the elemental abundances in the wind material mat Obtain elemental mass-loss rate  $\left| \dot{m}_w(X,\,m,\,t') \right.$  of massive stars in *t* using nucleosynthesis model (*Roy+ 2021, MINRAS, 502, 4359*).  $\mathcal C$  al mass-loss rate  $\stackrel{\textstyle n}{m}_w(X,\,m,\,t')$  of massive stars in t
	- $\clubsuit$  Oh can calculate the elemental abundances in the wind material tal mass of element  $X$  injected by a star of mass  $m$  over an age  $t$  a. **∗ Obtain total mass of element** *X* **injected by a star of mass** *m* **over an age** *t* **as**  $\boldsymbol{\ast}$  Obtain total mass of element  $X$  iniected is the cumulative mass of elements of elements by a starting in winds by a starting in winds by a starting by<br>The cumulative mass of elements by a starting by a starting in winds by a starting in winds by a starting of

$$
M_w(X, m, t) = \int_0^t \dot{m}_w(X, m, t') dt'
$$

is the cumulative mass  $m$  is the cumulative mass  $m$  is the cumulative mass  $m$  in  $\mathbb{R}$  .  $\cdot$  Lionion be calculated using ✤ Elemental fraction injected by a single star of mass *m*: n injected by a single star of mass  $m$ :

protons.

into the free wind region has a 1/r radial profile. Therefore, the

 $\frac{1}{\sqrt{2}}$ 

• Lemma induction injected by a single star of mass *m*.  
\n
$$
f(X, m) = \frac{M_w(X, m, t)}{M_{w, \text{tot}}(m, t)} = \frac{\int_0^t \dot{m}_w(X, m, t') dt'}{\int_0^t \dot{m}(m, t') dt'}.
$$



#### **Elemental abundance in star cluster winds** energy of 1.4 PeV, which corresponds to the CROSS to tens of PeV for CROSS to the PeV for CROSS to the PeV for ò *M X m t m X m t dt <sup>w</sup>* , , , , 13 <sup>=</sup> ¢ ¢ Elementel ehundenee<sup>in</sup> eter elueter is the cumulative mass of element X ejected in winds by a starting in winds by a starting by a starting by a s<br>The cumulative mass of element X ejected in winds by a starting by a starting by a starting by a starting by a *fXmt dm* Elamantal ahundanga in etar eluetary **3.5. Elemental abundance in star cluster winds** We consider a simple stellar population for  $\mathcal{L}$  at time the simple stellar population for  $\mathcal{L}$

, , . 14  $\mathcal{L}(\mathcal{L})$  (see Fig. ). The contract of the contract of  $\mathcal{L}(\mathcal{L})$  (see Fig. ). The contract of  $\mathcal{L}(\mathcal{L})$ 

 $\ddot{\cdot}$  $\mathcal{L}$  in the number of  $\mathcal{L}$ protons.  $\frac{1}{2}$  in the contract mass m up to a general mass measurement of  $\frac{1}{2}$  and  $\frac{1}{2}$  an PeV. 11  $\bullet$   $\parallel$ abo function of state:  $p(m)$  is  $m$  (balpeter, rood,  $npo$ ,  $n\succeq n$ ,  $n\varepsilon$ \* Initial mass function of stars: β(*m*)  $\,\propto m^{-}$ *dm* <sup>2.35</sup> (Salpeter, 1955, ApJ, 121, 161). : Initial mass function of stars: R(m)  $\propto m^{-2.35}$  (Salneter 1955 An.I).

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can calculate the elemental abundances in the elemental abundances in the wind material abundances in the wind<br>The wind material abundances in the wind material abundances in the wind material abundances in the wind mater

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	- $\clubsuit$  Oh can calculate the elemental abundances in the wind material tal mass of element  $X$  injected by a star of mass  $m$  over an age  $t$  a. ❖ Obtain total mass of element *X* injected by a star of mass *m* over an age *t* as However, in the realistic scenario, the magnetic field may be  $\boldsymbol{\ast}$  Obtain total mass of element  $X$  iniected is the cumulative mass of elements of elements by a starting in winds by a starting in winds by a starting by<br>The cumulative mass of elements by a starting by a starting in winds by a starting in winds by a starting of

$$
M_w(X, m, t) = \int_0^t \dot{m}_w(X, m, t') dt'
$$

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$$
f(X, m) = \frac{M_w(X, m, t)}{M_{w, \text{tot}}(m, t)} = \frac{\int_0^t \dot{m}_w(X, m, t') dt'}{\int_0^t \dot{m}(m, t') dt'}.
$$

Pev. 21 C ∗St We use the mass-loss rate for each nucleus *mX m t* ( , ,  $\clubsuit$  Star-ma  $U(x)$ uncertainties as well (e.g., in  $\alpha$ ghted elemental fraction is obtained by convolving with the Salpeter fur  $\sim$   $\sim$  C element X can be calculated using the following expression ass weighted elemental inaction is obtain ✤ Star-mass weighted elemental fraction is obtained by convolving with the Salpeter function:  $\sim$ Startings weighted elemental haction is obtained by convolving w \* Star-mass weighted

$$
\langle f(X) \rangle = \frac{\int_0^m f(X, m)Am^{-2.35} dm}{\int_0^m Am^{-2.35} dm}
$$
 where *A* is a constant.

where  $A$  is a constant.



into the free wind region has a 1/r radial profile. Therefore, the

 $\frac{1}{\sqrt{2}}$ 

# **Elemental abundance in star cluster winds**

 $S_{\rm eff}$  is the Spectral Indices q and  $F_{\rm eff}$  and  $F_{\rm eff}$  and  $F_{\rm eff}$  and  $F_{\rm eff}$  indices of  $D_{\rm eff}$ 

the Wind Material

Elements	$\Gamma$	Fractional Abundances in Winds
Proton	2.25	$\longrightarrow 0.86$
Helium	2.23	0.13
Carbon	2.20	$3.32 \times 10^{-3}$
Oxygen	2.24	$8.51 \times 10^{-4}$
Neon	2.24	$8.83 \times 10^{-5}$
Magnesium	2.28	$3.62 \times 10^{-5}$
Silicon	2.24	$3.42 \times 10^{-5}$
Iron	2.24	$3.72 \times 10^{-5}$

Note. The elemental abundances are calculated following Roy et al. (2021). *Bhadra, Thoudam+ 2024, ApJ, 961, 215*

by A. Roy 2023, private communication). We have then

### $\rightarrow$  Note the dominant proton fraction.

- CR spectral index ( $\Gamma$ ) values taken to be same as that of the regular supernova remnants.
- Elemental CR injection fraction scaled with the fractional abundance in the wind material.
- tol CD injootion onorgy Total CR injection energy obtained based on the all-particle spectrum.



#### **Transport of cosmic-rays in the Galaxy-state transport equation for cosmic-rays in the Galaxy-state transport equation for cosmic-ray nuclei and the steady-state transport equation for cosmic-ray nuclei and the Galaxy-sta** ansport of cosm , which is a formula of  $\mathcal{A}^{\mathcal{A}}$  for strong shocks for strong shocks *<sup>N</sup>*(*p*)=4⇡*p*2*f*(*p*) / *<sup>p</sup>*<sup>2</sup> (power law) *<sup>D</sup>*(*p*) / *<sup>p</sup><sup>a</sup> <sup>N</sup>*(*p*)=4⇡*p*2*f*(*p*) / *<sup>p</sup>*<sup>2</sup> (power law) *f* cosmic rays in the Gar

*E*max = Z B R (Hillas limit)

$$
\nabla \cdot (D \nabla N) - \left[ \bar{n} v \sigma + \xi \right] \delta(z) N + \left[ \xi s p^{-s} \int_{p_0}^p du \ N(u) u^{s-1} \right] \delta(z) = -Q \delta(z)
$$



Thoudam & Hörandel 2014, A&A, 567, A33 a distance of *Thoudam & Hörandel 2014, A&A, 567, A33*.  $h_{1}$ dium a Fiorander 2014, Ada, 307, ASS the source can be an undetected old supernova remnant with a characteristic age of ⇠ <sup>1</sup>*.*5⇥10<sup>5</sup> yr located at *Thoudam & Hörandel 2014, A&A, 567, A33*



undergoing diffusion, re-acceleration, re-acceleration and interaction and interaction losses can be written a

# **Results on the CR spectrum and composition**

 $1$ GeV<sup>2</sup>

x Intensity (cm<sup>-2</sup>sr<sup>-1</sup>s

E3

**Regular SNRS**  *(Thoudam+ 2016)* **+ Star clusters**  *(Bhadra+ 2024)* **+ Extra-galactic** *(Unger+ 2015)*

### **Parameters for the star cluster comp.**

- $\triangleleft$  Wind energy injected into protons  $\sim$  5%.
- $E_{\text{max}}$  ~ 5 x107 Z GeV, which is about an  $\frac{5}{10}$ theoretical estimate.
- Predicted <lnA> within the observed band,  $\frac{2}{5}$ but has some tension at  $\sim$  10<sup>16</sup>-10<sup>17</sup> eV.  $\Box$  . The sharp increase near  $\Box$



The Astrophysical Journal, 961:215 (12pp), 2024 February 1 Bhadra et al.



# **Summary**

- ✤ Young massive star clusters have been proposed as potential sources of CRs above the knee.
- ✤ Star clusters seem to have the potential to explain the observed all-particle CR spectrum (when combined with a low-energy galactic component and an extra-galactic component having dominant light nuclei below the ankle).
- ✤ Requires a maximum CR energy which is about an order of magnitude higher than theoretical value (at least for the wind termination shock).
- \* Also, composition shows some tension at  $\sim$  10<sup>16</sup>-10<sup>17</sup> eV, which results mainly from a dominant proton fraction.

Thanks for your attention!

