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PIANO NAZIONALE DI RIPRESA E RESILIENZA

Studying young massive stellar clusters at VHE: current status and prospects

Gaia Verna (RTDa - University of Siena) - gaia.verna@unisi.it

Outline

I. **Stellar Clusters** as:
   - CRs accelerators
   - gamma-ray emitters

II. Famous examples and **current studies at VHE**

III. **Prospects** with current and future VHE instruments

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I. **Stellar Clusters** as:
   - CRs accelerators
   - gamma-ray emitters

II. Famous examples and **current studies at VHE**

III. **Prospects** with current and future VHE instruments
   - News since the **I VHEgam Meeting** [flash talk]

Stellar clusters

- **Stellar or Star Clusters (SCs)** are **groups of stars** contained in the galaxies. No single definition can be used universally see e.g. [Portegies Zwart et al. (2010)] or [Lada & Lada (2003)]
    - globular clusters: 100-1000 old stars, spherical shape
    - open clusters: 100-1000 young stars

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  - globular clusters: 100-1000 old stars, spherical shape
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- They are **laboratories for studying**:
  - **star formation mechanism** since stars usually born in clustered environments
  - **stellar properties** (e.g. initial mass function, stellar evolution and dynamic)
  - properties of the **host galaxies** (e.g. size and structure)

HE and VHE astrophysics

  - the **production and acceleration of Galactic Cosmic Rays (CRs)**...in particular in **young massive stellar clusters (YMSC)** (Age < 30 Myr; Mass > 10^3 $M_\odot$)

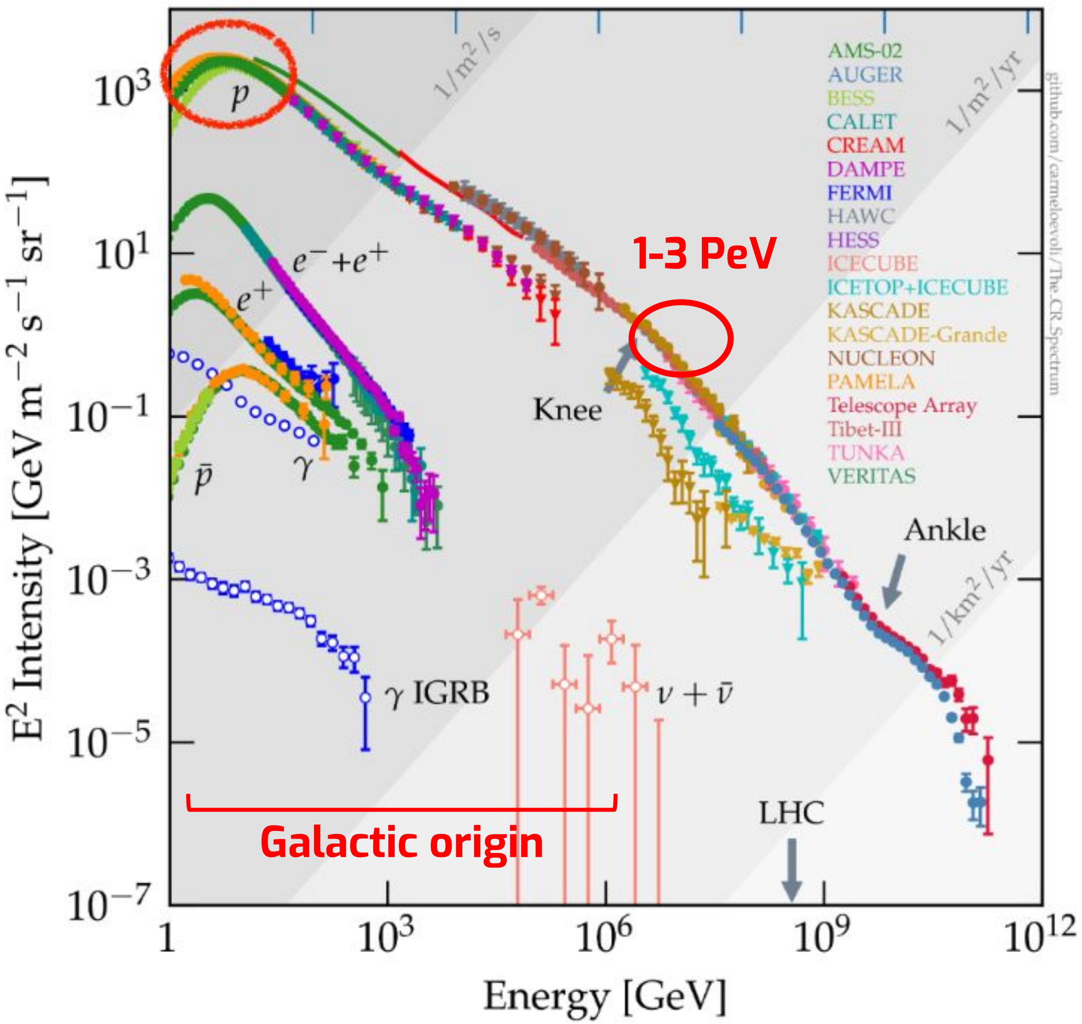
How to explain the origin of Galactic CRs?

…by studying their:

- arrival direction distribution
- chemical composition
- energy spectrum

→ 100 yr of measurements

Local CR flux



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Observational constraints on Galactic CR accelerators:

- Luminosity: **10^{40} erg/s**
- Power law spectrum: **$Q_{inj,gal} \propto E^{-2.3}$**
- **$E_{max,p} \leq$ PeV** + Z dependent spectral break and **spectral anomalies** (p, He, C, O) in the "knee region"
- **Composition anomalies** w.r.t. Solar system (overabundance of Li-Be-B and $^{22}Ne/^{20}Ne$)

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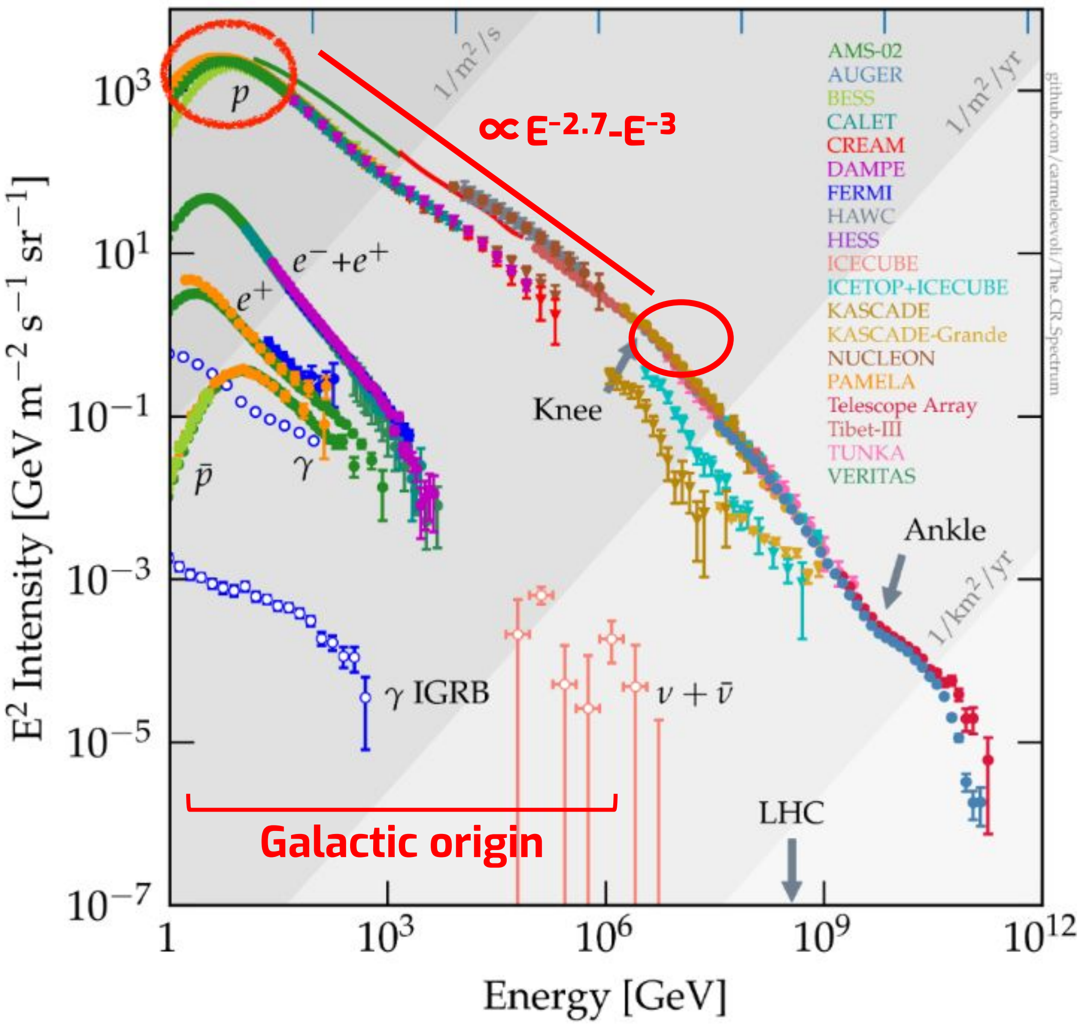

How to explain the origin of Galactic CRs?

Which **energy** powers the acceleration of CRs?

What is the source of the accelerated **matter**?

Which is the **physics** beyond the acceleration?

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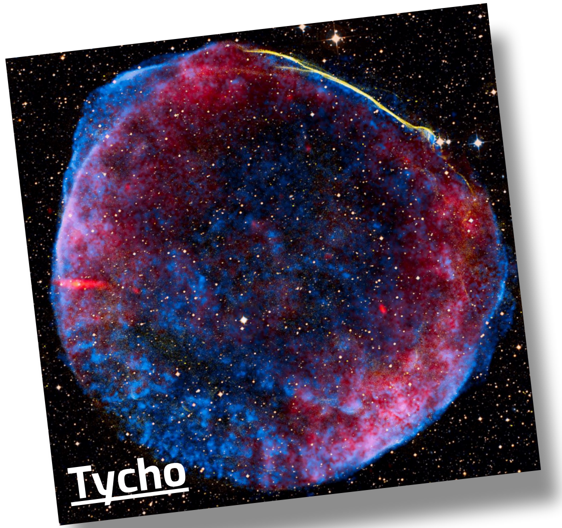

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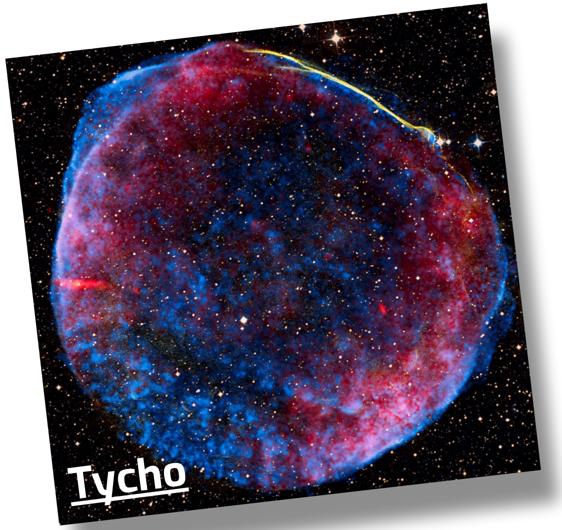
Since 1934, **SuperNova Remnants (SNRs)** have been proposed as the prominent sources of Galactic CRs

PROS

- ✔ SN explosions provide **enough power to supply CR energy density** (~10% of the explosion energy)
- ✔ The **spatial distribution of SNRs** compatible with the CR distribution
- ✔ **Diffusive shock acceleration (DSA)** theory applicable to SNR shocks
- ✔ Detection of **non-thermal emission** from SNRs (e.g. gamma-rays)

How to explain the origin of Galactic CRs?



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- ✘ SNRs alone **cannot explain the CR spectral and chemical composition anomalies**

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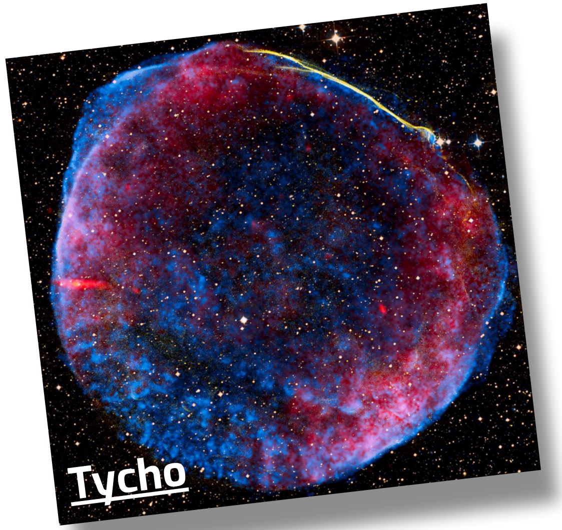

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...Incorrect/incomplete models for SNRs?
Looking for additional sources?

Possible contribution from SCs (and SNRs)

SNR types
- ~20% type Ia
- **~80% core collapse**
  - **(60-80)% explode inside the parent star cluster**
  - (20-40)% explode outside the cluster (runaway massive stars)

- 1979 T. Montmerle pointed out a **possible role of OB stars** (M☆ > 3 M☉) **in galactic CRs production** and acceleration
- Search for **gamma-ray emission associated to SNRs in OB associations** or HII regions (**SNOBs**)

ON GAMMA-RAY SOURCES, SUPERNOVA REMNANTS, OB ASSOCIATIONS, AND THE ORIGIN OF COSMIC RAYS

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Section d'Astrophysique, Centre d'Etudes Nucléaires de Saclay, France

Received 1978 July 26; accepted 1979 January 5

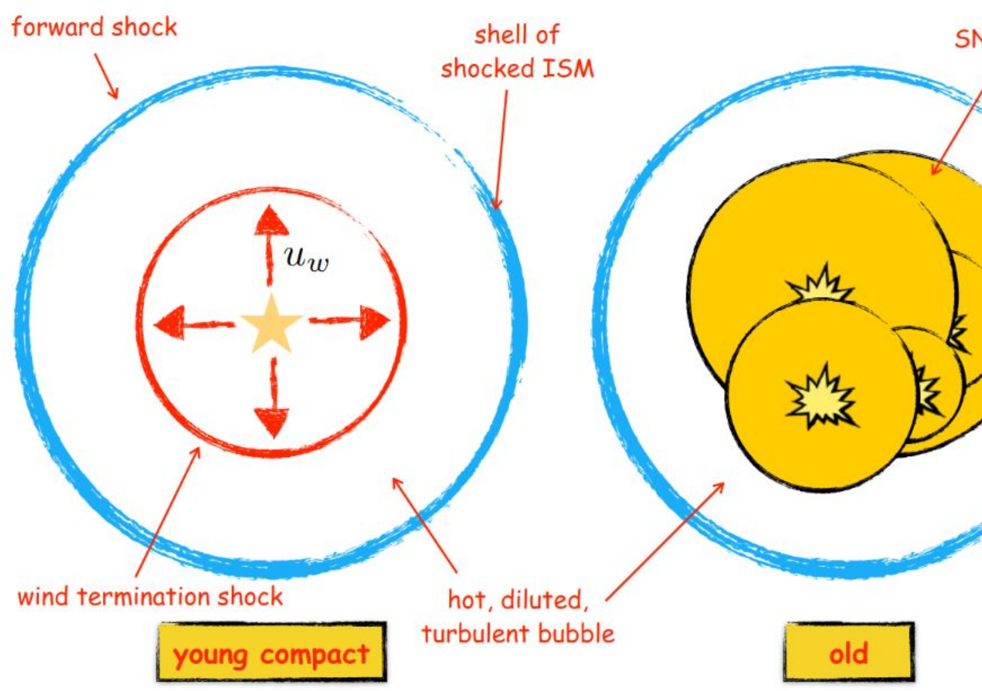
SNRs or OB stars: who provides the energy for CR acceleration?

What powers Stellar Clusters?

...It **depends on the age**:

👶 **Young cluster** (no SNR explosions yet):
the acceleration is provided only by the **collective wind termination shock (TS)**

👵 **Old cluster**:
the power provided by the SNRs is dominant



Credits:
S. Gabici

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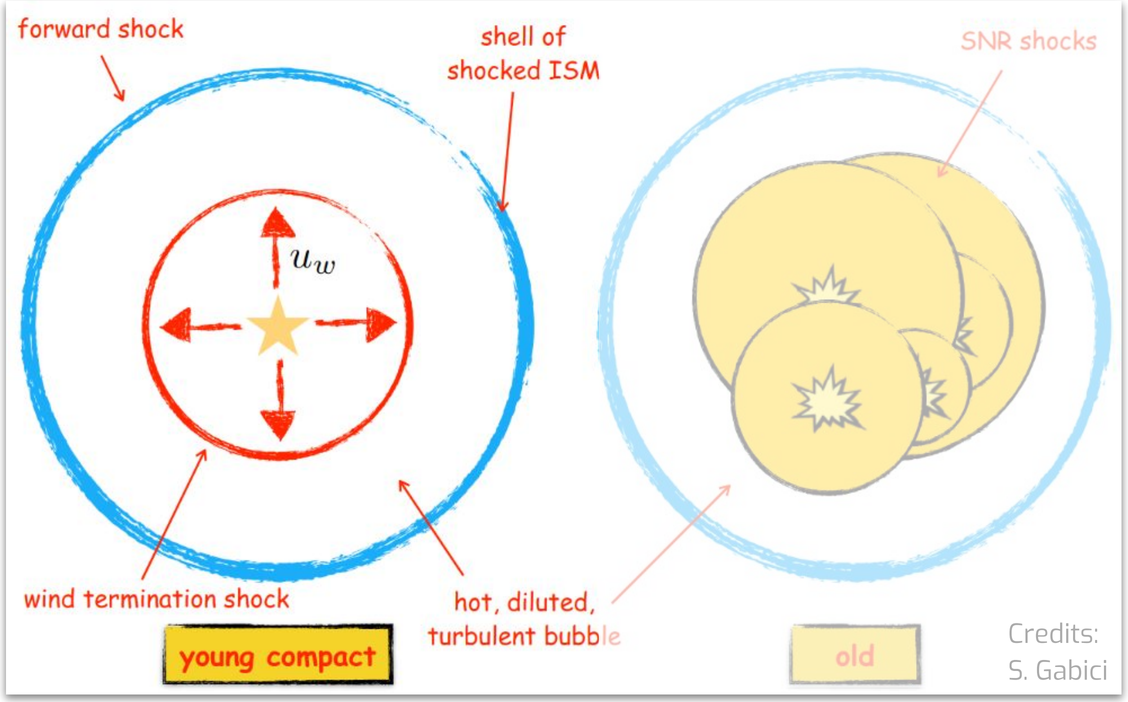
Massive stars emit powerful winds
→ **collective wind of the SC**

↓

The collective wind **interacts with the Interstellar Medium** (ISM)

↓

The heated gas expands creating a **bubble like structure**



Typical size:

★ **Cluster core**: 1 pc
Termination shock: 5-10 pc
Bubble: 50-100 pc

What powers Stellar Clusters?

...It **depends on the age**:

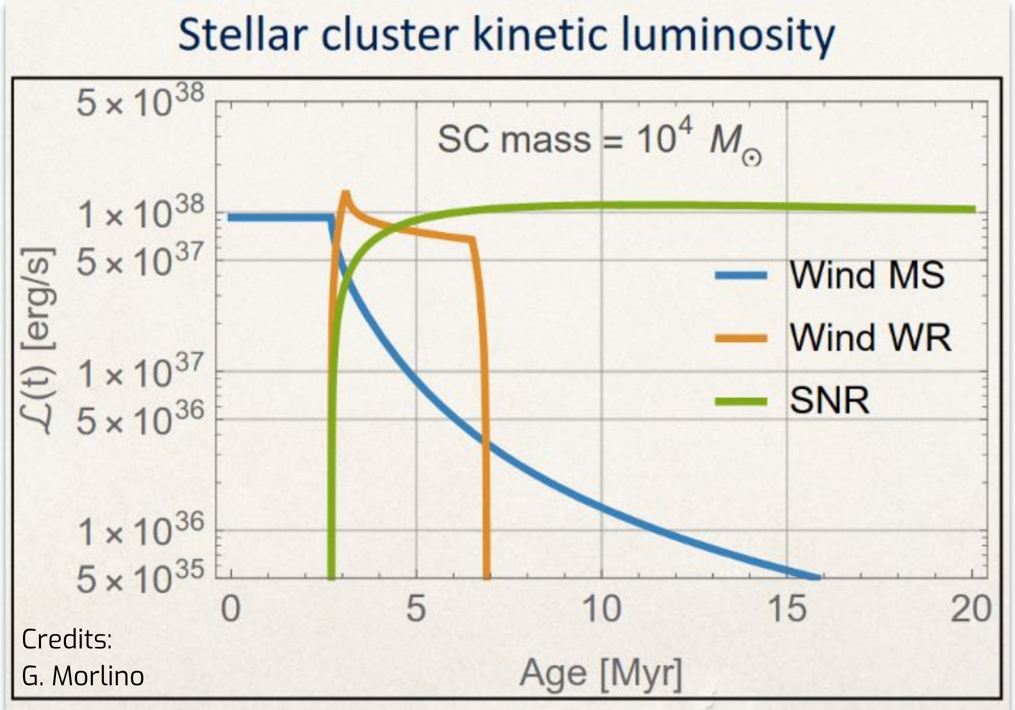
<u>Young cluster</u> (no SNR explosions yet):
the acceleration is provided only by the **collective wind termination shock (TS)**

Old cluster:
the power provided by the SNRs is dominant

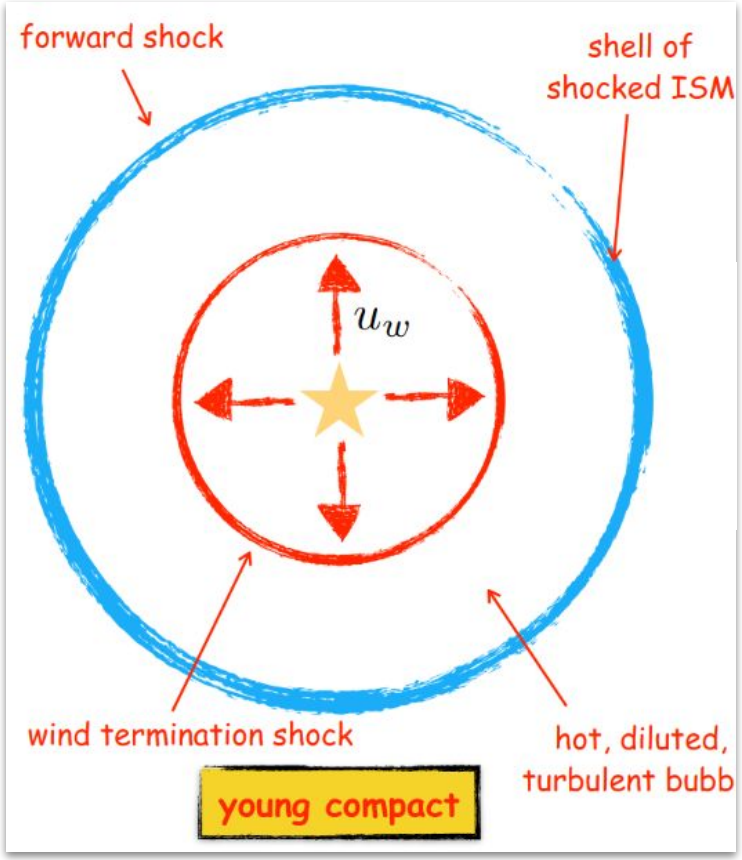
only stellar wind → first row

stellar wind + SNe → second and third rows

Phase	Source	Time-scale
$t \lesssim 3\,\mathrm{Myr}$	MS stellar winds	$t \gtrsim \mathrm{Myr}$
$3\,\mathrm{Myr} \lesssim t \lesssim 7\,\mathrm{Myr}$	WR stellar winds	$t \sim 10^5\,\mathrm{yr}$
$3\,\mathrm{Myr} \lesssim t \lesssim 30\,\mathrm{Myr}$	SNe	$t \sim 10^3 - 10^4\,\mathrm{yr}$



What powers Stellar Clusters?



...It **depends on the age**:

<u>**Young cluster**</u> (no SNR explosions yet):
the acceleration is provided only by the **collective wind TS**

Ingredients for **CRs accelerations in YMSCs (wind-dominated)**:

- powerful particle winds from **OB-type/WR stars**
- 10-100-1000 **massive stars in a small volume** (compact clusters: 1 pc)
  → boost of particles

The **acceleration and propagation mechanism** inside YMSCs is **still under debate**:

- stellar **wind-wind interaction** (Reimer et al. 2006)]
- II-order Fermi acceleration through **supersonic turbulence** (Bikov et al. 2020)
- particle acceleration at the **collective cluster wind TS** (Morlino et al. 2021) → **accelerations up to PeV**

How to explain the origin of Galactic CRs?

Not only SNRs but also SCs can play a role in the production and acceleration of Galactic CRs

Observational constraints on Galactic CR accelerators:

- Luminosity: **10^{40} erg/s**
- Power law spectrum: $Q_{inj,gal} \propto E^{-2.3}$
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- **Composition anomalies** w.r.t. Solar system (overabundance of Li-Be-B and $^{22}Ne/^{20}Ne$)

PROS

✔ SCs release the **same energy of SNRs** so they provide enough power to supply CR energy density

✔ Particle acceleration at the collective cluster wind TS → **accelerations of hadrons up to PeV**

✔ WR wind material enriched in ^{22}Ne!

✔ **Detection of gamma-rays from SCs up to PeV energies**

Northern Sky: Cygnus OB2

- Cygnus OB2: **one of the most massive YMSC in the Galaxy** hosting 100-1000 OB stars
  - Dist = 1.5 - 4 kpc, Age = 2-7 Myr
  - Log(M/M☉) = 4.7
  - P = 4-8 × 10^{38} erg/s

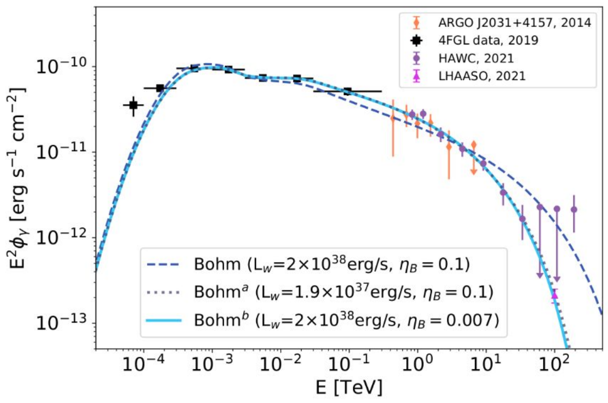
- Best visibility from the **Northern hemisphere**

- Modeling see e.g. Menchiari et al. 2024:
  - purely hadronic emission produced by CRs accelerated at the collective wind TS

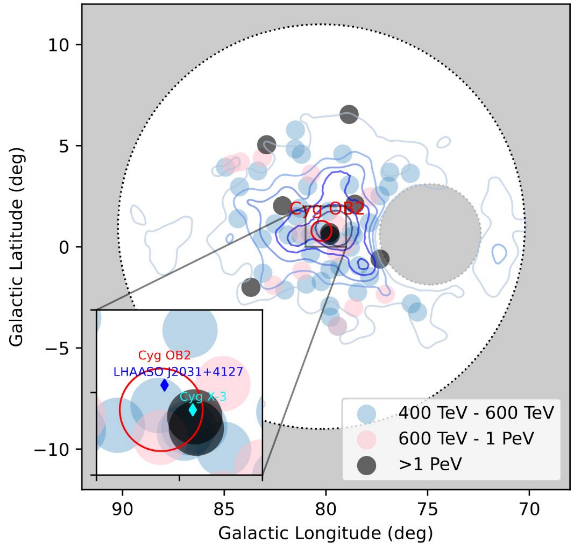
- Observations see e.g. Fermi, LHAASO:
  Extended gamma-ray emission: as measured by Fermi-LAT (emission size: up to 4°) and LHAASO (up to PeV energies) → Galactic PeVatron

- Wide regions...challenge for IACTs

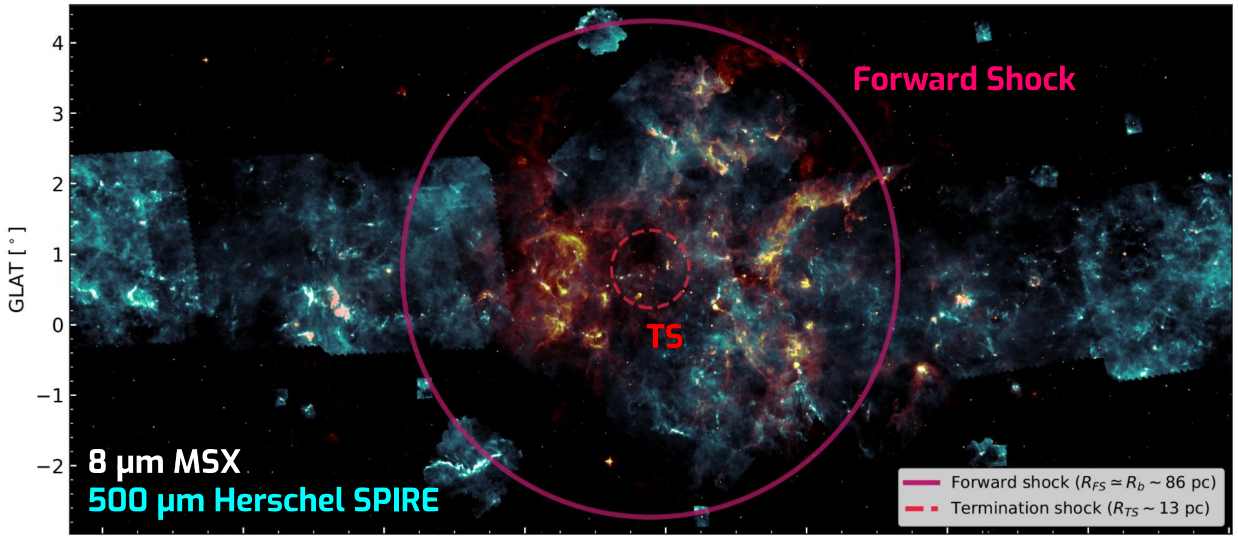
[Menchiari et al. 2024]



[LHAASO 2024]



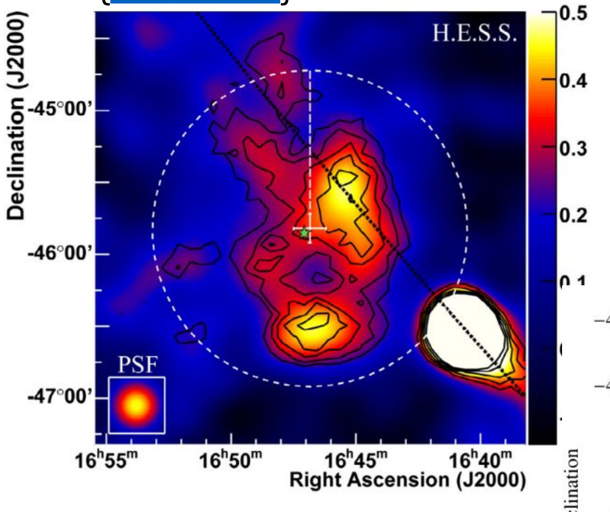
[Menchiari et al. 2024]



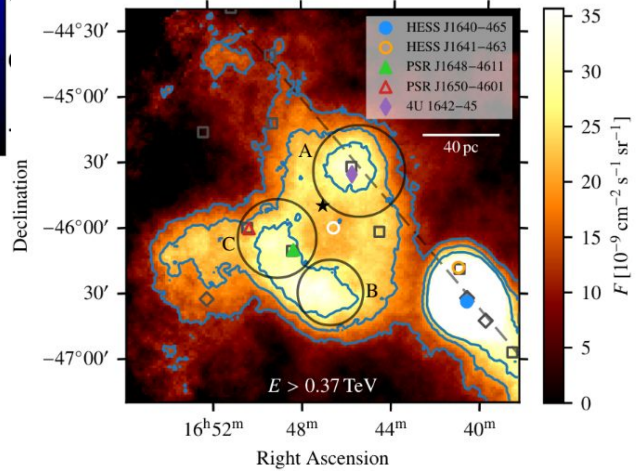
Southern Sky: Westerlund 1 and 2

- **Westerlund 1**
  - Dist = 4 kpc, Age = 4-10 Myr
  - Log(M/M☉) = 4.6
  - P = 10^{39} erg/s
- **Westerlund 2**
  - Dist = 4 kpc, Age = 1-2 Myr
  - Log(M/M☉) = 4.6
  - P = 1-2 × 10^{38} erg/s

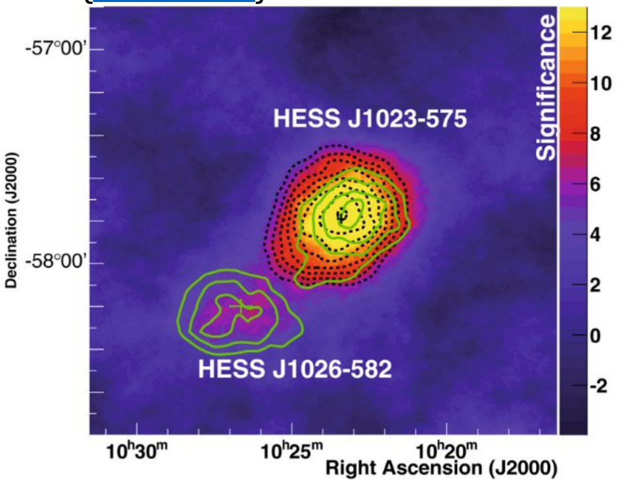
[HESS 2012]



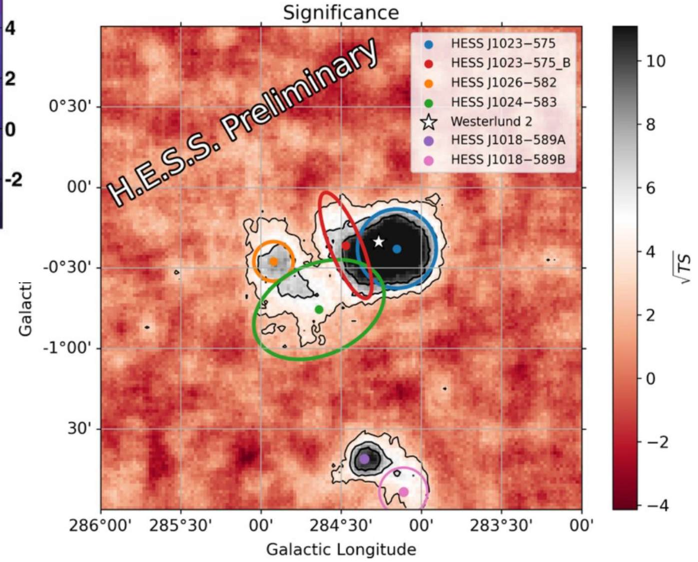
[HESS 2021]



[HESS 2011]



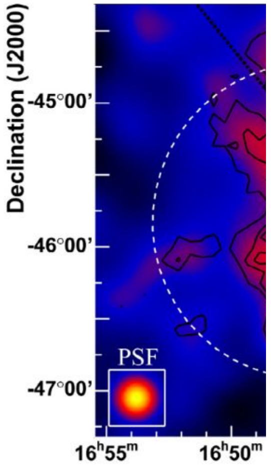
[HESS 2023]



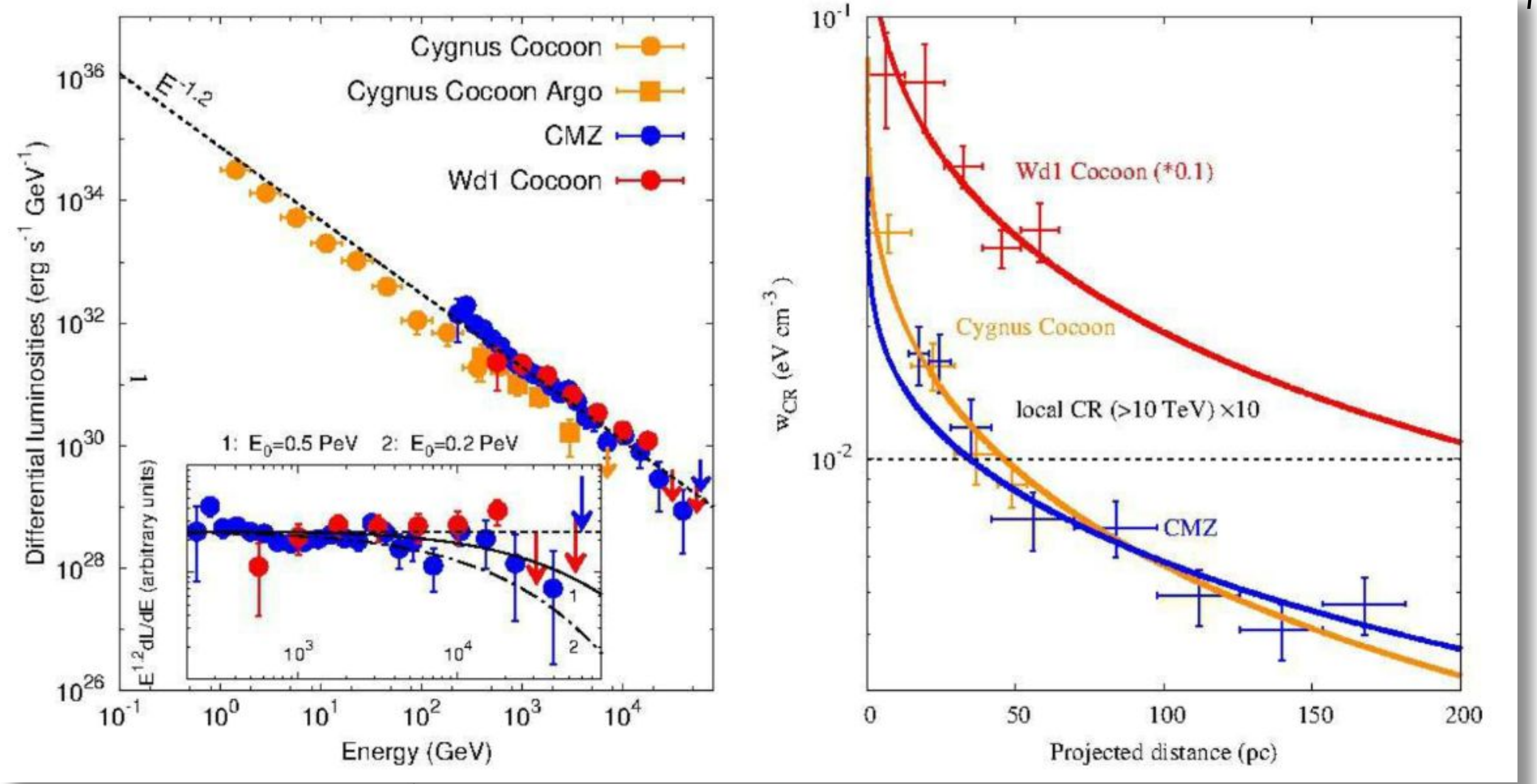
From VHE gamma-rays to CRs physics

- **Westerlund 1**
  - l
  - l

[HESS 201



(Aharonian et al. 2019)



- **Westerlund 2**

Myr

Summary

- **Stellar Clusters** and in particular **YMSC are powerful CR accelerators and gamma-ray emitters**:
    - VHE-UHE emitters → **PeVatron candidates**

- The **SNR + SC scenario** is very promising in the **quest of galactic CR origin**, it can explain:
    - the “knee”
    - some anomalies in the CR chemical composition thanks to OB/WR stars (e.g. $^{22}Ne/^{20}Ne$)

- **Very young YMSC (Age < 3 Myr)** are a key target to study the **contribution of stellar wind** to the galactic CR production and acceleration

- **VHE observations are crucial t**o study spectral and spatial characteristics of these source and study CR physics

Ongoing activities

- Create a **community interested in star cluster physics**
  - first edition of the **Topical Overview on Star Cluster Astrophysics (TOSCA)** organised in Siena on October 2024 [(indico)]

- **Challenge**: many scientific topics involved:
  - stellar evolution and feedback
  - stellar wind physics
  - particle acceleration and propagation
  - gamma-ray observations…

- …search for **interesting targets at VHE**

Prospects

- Search for **interesting targets at VHE**
  - **Not only "extreme" clusters** such as Cygnus OB2, Westerlund 1 and 2...clusters with **masses between 10^3–10^4 $M_\odot$**
  - focus on the **Northern target** visible from MAGIC, LST-1, CTAO Northern Array and ASTRI

- More and more **new proposals** on stellar clusters:
  - e.g. LST-1:
    - Cycle I (2023): 0
    - Cycle II (2024): 2 (...**I VHEgam**!)
    - Cycle III (2025): 3 (...**I CTAO School**!)

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- **...data are coming! Stay tuned** 😎

Thanks for your attention!

Backup

How to explain the origin of Galactic CRs?

…by studying their:

- **arrival direction distribution**
  - Spatial anisotropy: ~10^{-3} @ 10 TeV
- **chemical composition**
  - Fully ionised nuclei: ~**90% H**
  - **Anomalies w.r.t. Solar system composition** (overabundance of Li-Be-B and ^{22}Ne/^{20}Ne)
- **energy spectrum (at the sources)**
  - Luminosity: 10^{40} erg/s
  - Power law spectrum: $Q_{inj,gal} \propto E^{-2.3}$
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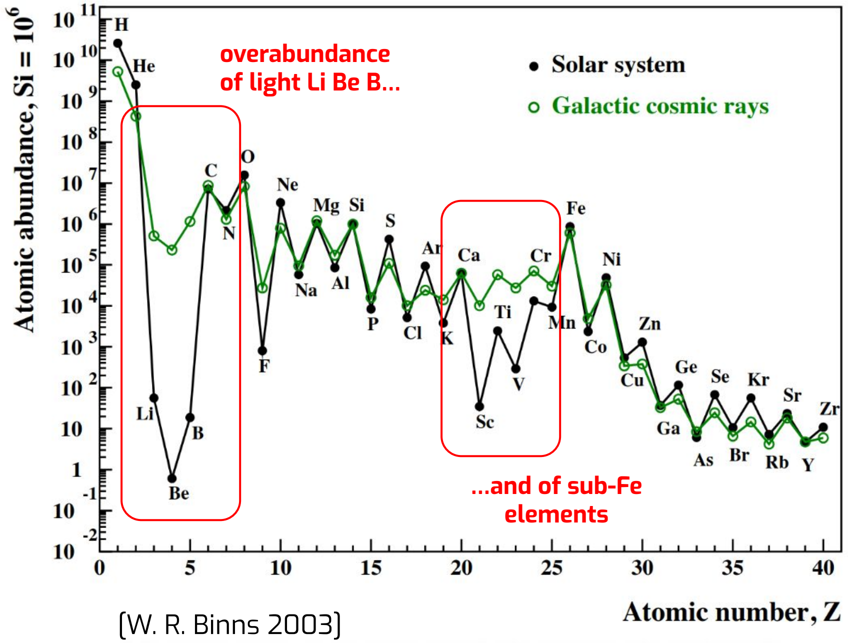
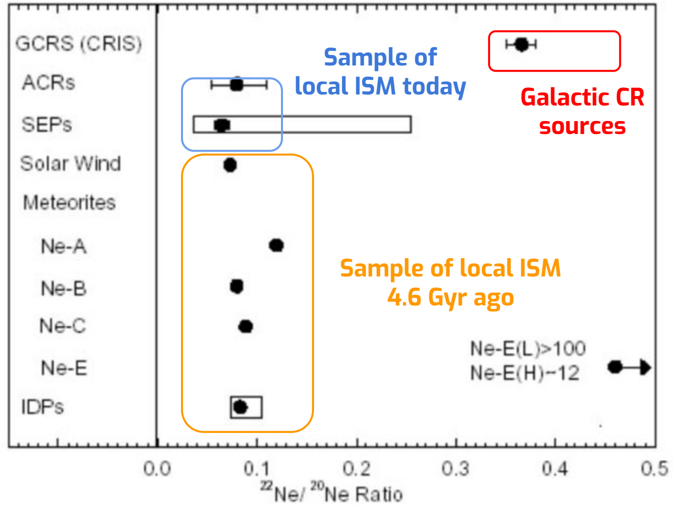
[Tatischeff et al, 2018]



[W. R. Binns 2003]



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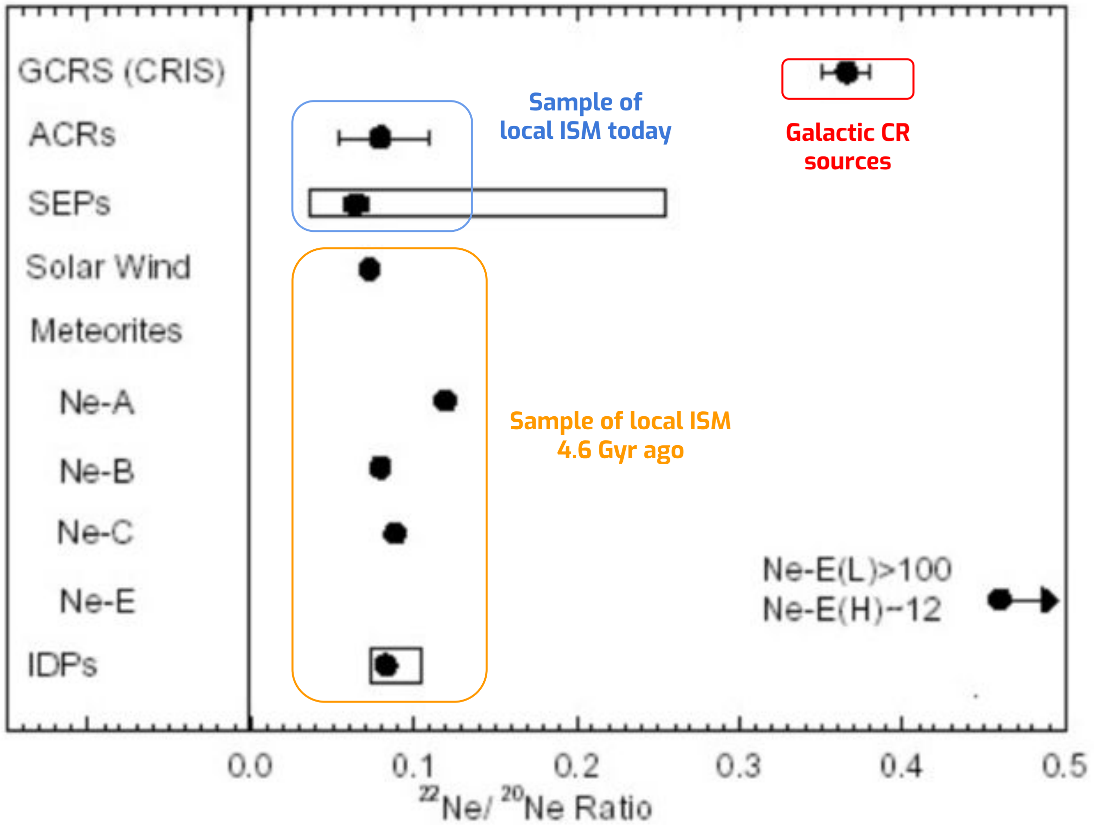

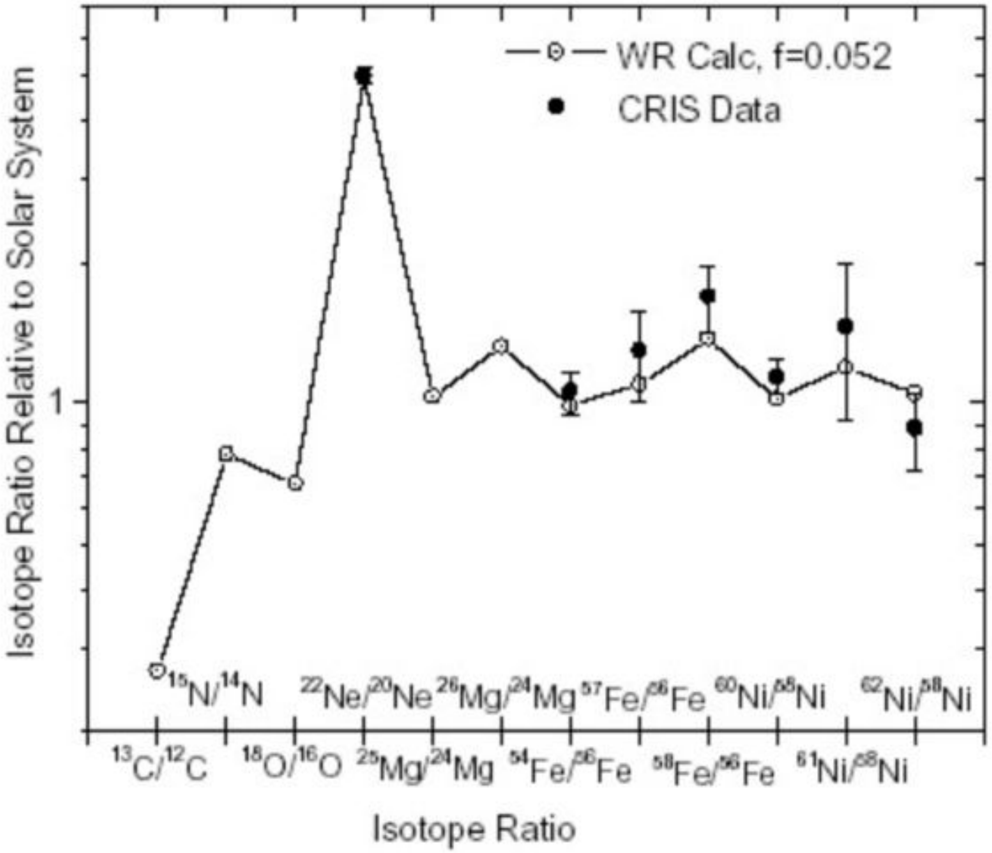

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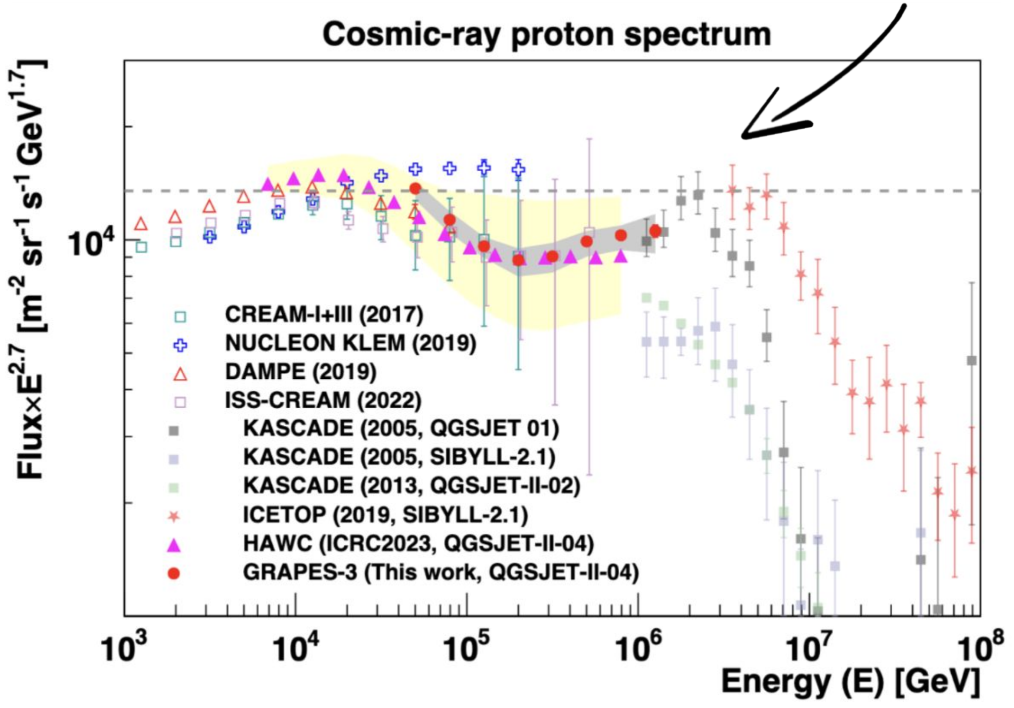
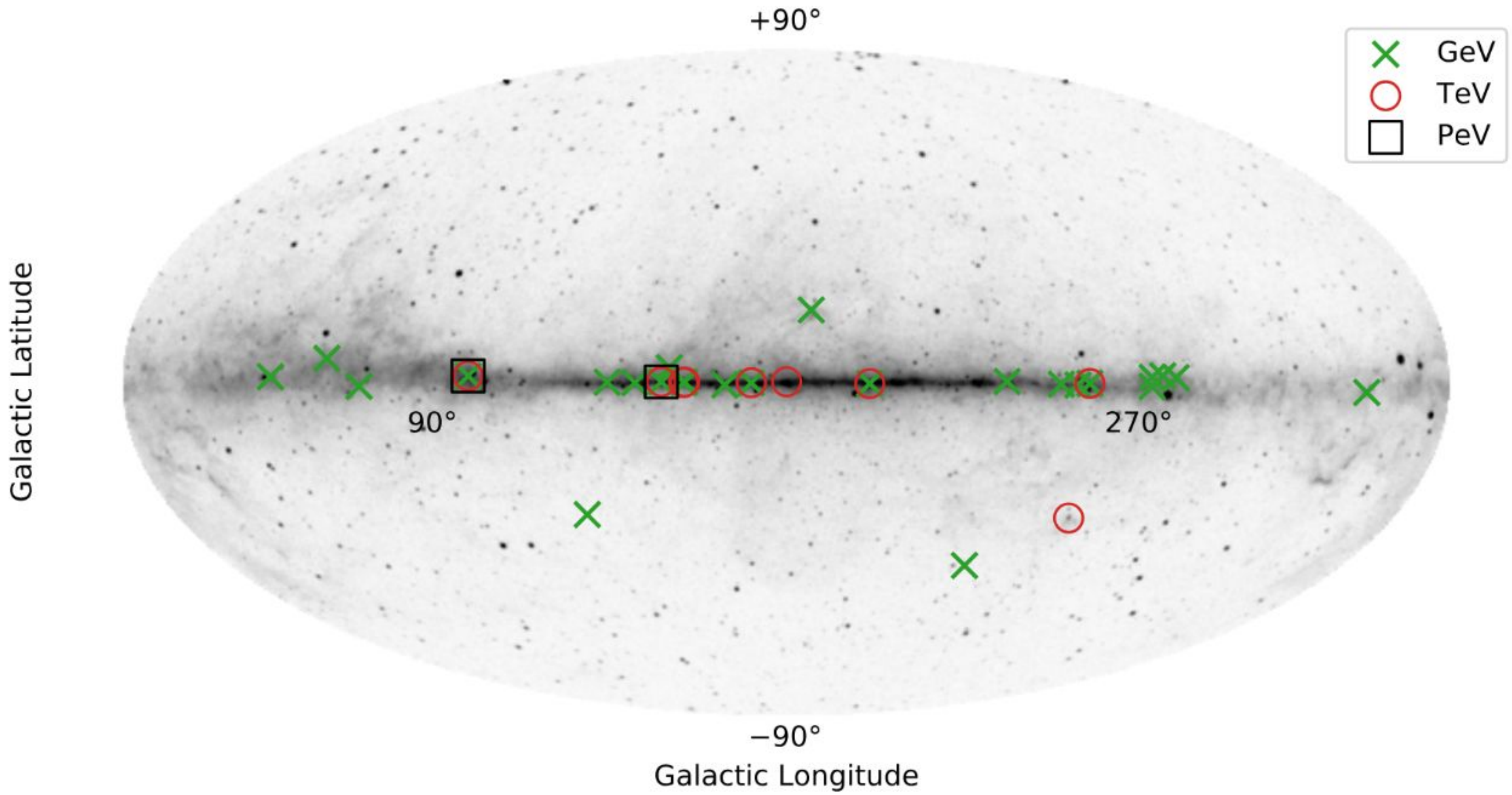
hardening + softening ("bumps") in the p and He spectra



...can a **single source class** explain all this?

Gamma-ray sources towards SFRs

Credits: L. Tibaldo



Compilation of results in Astiasarain (PhD, 2023)
plus Liu et al. (2023, 2024), Peron et al. (2024),Wu et al. (2024), Ge et al. (2024), Lhaaso Collaboration (2024), H.E.S.S. collaboration (2024)

Credits: S. Menchiari

Name	$\log M/\mathrm{M}_\odot$	r_c [pc]	D [kpc]	Age [Myr]	L_w [erg s^{-1}]
Westerlund 1	4.6 ± 0.045	1.5	4	$4-6$	10
Westerlund 2	4.56 ± 0.035	1.1	2.8 ± 0.4	$1.5-2.5$	2
Cygnus OB2	4.7 ± 0.3	5.2	1.4	$2-7$	2
NGC 3603	4.1 ± 0.1	1.1	6.9	$2-3$	-
BDS 2003	4.39	0.2	4	1	-
W40	2.5	0.44	0.44	1.5	-
RSGC 1	4.48	1.5	6.6	$10-14$	-
MC 20	~ 3	1.3	$3.8-5.1$	$3-8$	~ 4
NGC 6618	-	3.3	~ 2	< 3	-
30 Dor (LMC)	$4.8-5.7$	multiple	50	1	-
NGC 2070 / RCM 136	$4.34-5$	subcluster		5	

Table 3.1: List of YMSCs for which a diffuse γ-ray emission has been detected in their coincidence. References of each cluster: Westerlund 1 (Abramowski et al., 2012; Aharonian et al., 2022), Westerlund 2 (Yang et al., 2018), Cygnus OB2 (Bartoli et al., 2014b; Abeysekara et al., 2021b; Astiasarain et al., 2023), NGC 3603 (Saha et al., 2020), BDS 2003 (Albert et al., 2021), W40 (Sun et al., 2020b), RSGC 1 (Sun et al., 2020a), MC 20 (Sun et al., 2022), NGC 6618 (Liu et al., 2022), and the Large Magellanic Clusters (H. E. S. S. Collaboration et al., 2015). Values marked by a '-' are not provided in the literature.